International Physics School
Simon Eidelman School on Muon Dipole Moments and Hadronic Effects

Detectors for High Energy Physics Experiments

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CERN

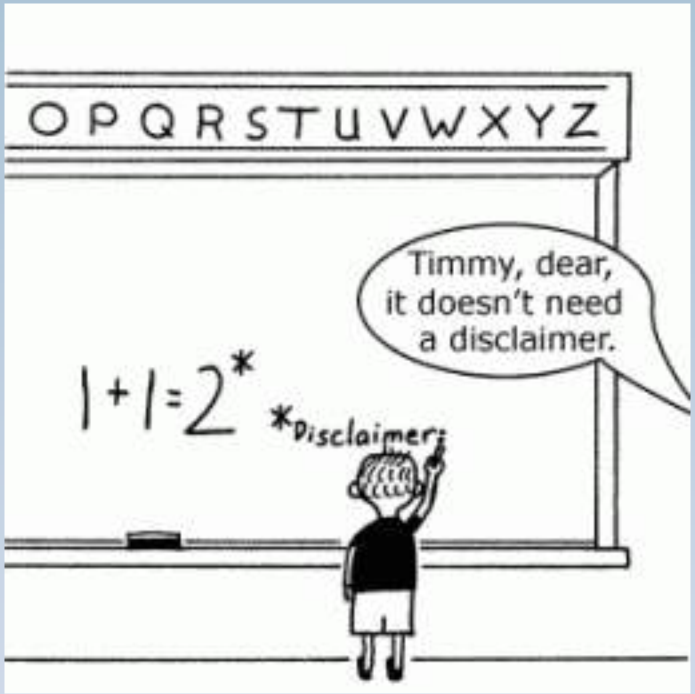
Contents

In this lecture we will discuss some aspects of particle detection and detector design

We will choose a few examples that show that, even though High Energy Physics experiments are built with thousands of collaborators operating under a huge range of constraints, the contribution of individuals thinking outside the box can make an enormous difference

Many slides taken from the fantastic lecture series of:
Werner Riegler: https://indico.cern.ch/event/1347523/
Robert Schoefbeck: https://indico.cern.ch/event/975141/

Disclaimer

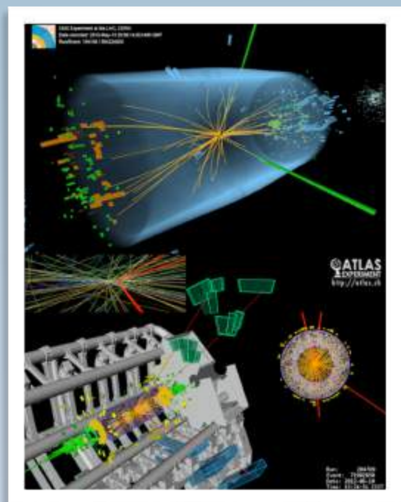


This is a highly personal and incomplete view of the wonderful world of HEP instrumentation

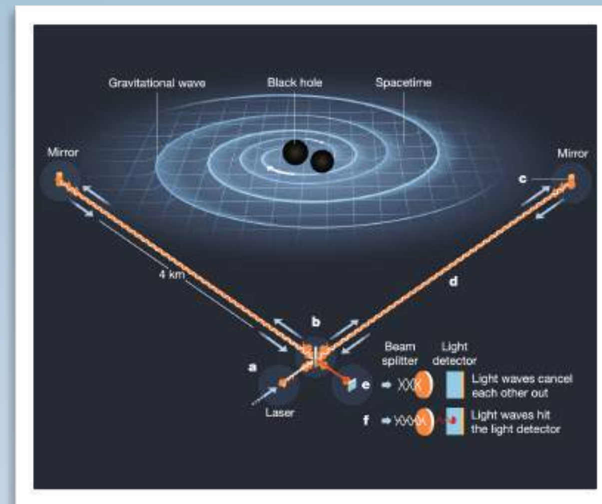
Treat with caution!

Even though I might feel that some of the things I'm saying are obviously true I cannot assume responsibility if you design a detector which does not satisfy your expectations and invite you to consult your personal detector professional immediately in case of queries. For entertainment purposes only. Results may vary. You may be subject to unexpected systematic errors.

Discoveries of the Last Decade

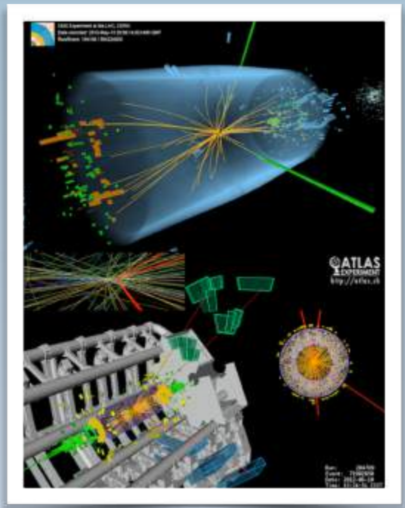


2012 discovery of the Higgs Boson



2015 observation of Gravitational Waves

And major new measurements



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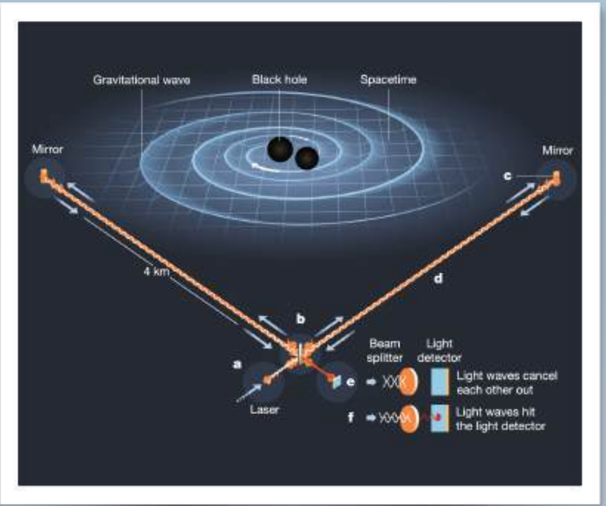

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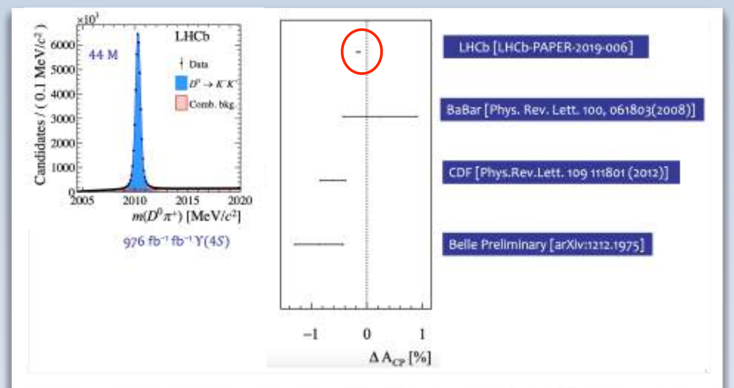
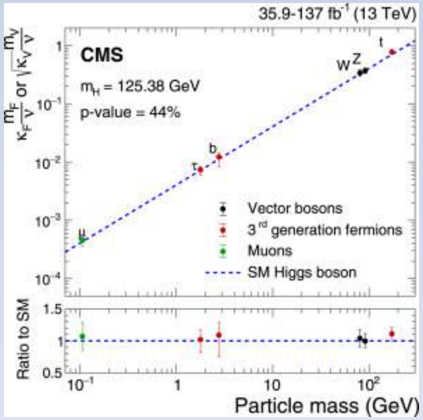
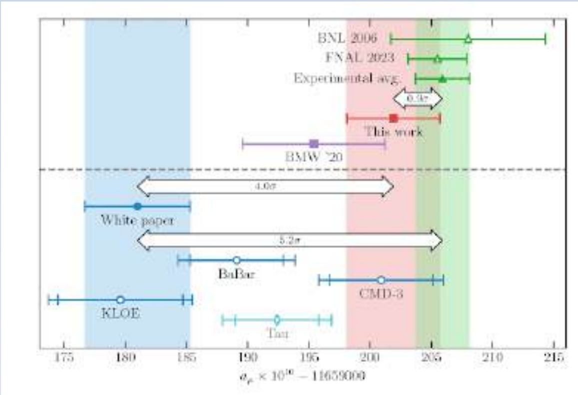


2019 Observation of CP violation in charm



Higgs coupling to particles of different masses



g-2 update sets up challenge to theory

Exciting times

Made possible by the ingenuity of teams of experimentalists

Who design experiments to get the job done

Who interact with the cutting edge of technology to get the experiments built

And the thousands of dedicated people who operate, calibrate, monitor, track, coax, tune, adjust, babysit, nurse, analyse, supply, repair these detectors over the lifetime of the experiment

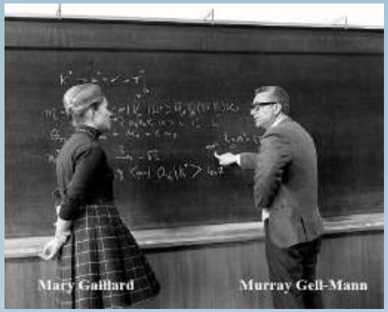
Today we will discuss detector design concepts

Relating the fundamental interactions of particles to the possibility of detecting them

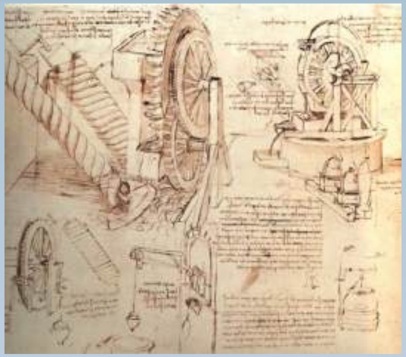
Looking at the impact on detector design

You are our future experimentalists; I wish you wonderful and impactful careers, if I can convince you that each one of you can make a difference - job done

Ingredients for HEP experiment



A theory and an Idefix



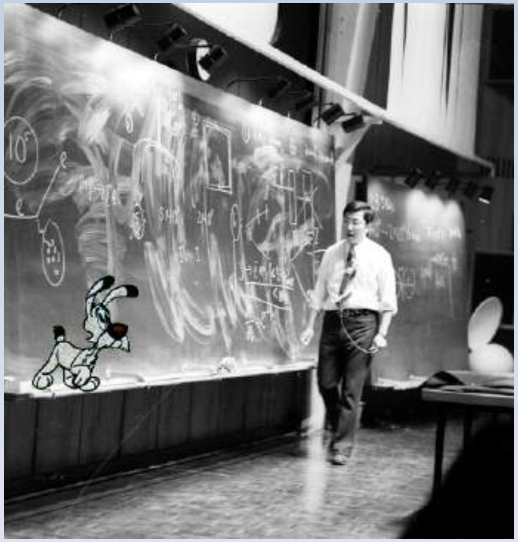
Clear and easy to understand drawings

And a cafeteria

A tunnel for the accelerator and magnets and stuff

Physicists to install, operate, analyse data

And a cafeteria



And a Nobel Prize

Physics Nobel Prizes for Instrumentation

History of particle physics is studded with discoveries
Many of these were surprise discoveries from new tools which gave entirely new insights

- 1927: C.T.R. Wilson, Cloud Chamber
- 1939: E.O. Lawrence, Invention of the cyclotron
- 1948: P.M.S. Blackett, Cloud Chamber & Discoveries
- 1950: C. Powell, Photographic Method & Discoveries
- 1954: W. Bothe, Coincidence method & Discoveries
- 1960: Donald Glaser, Bubble Chamber
- 1968: L. Alvarez, Hydrogen Bubble Chamber & Discoveries
- 1992: Georges Charpak, Multi Wire Proportional Chamber
- 2009: W.S. Boyle and G.E. Smith Invention of CCD sensor

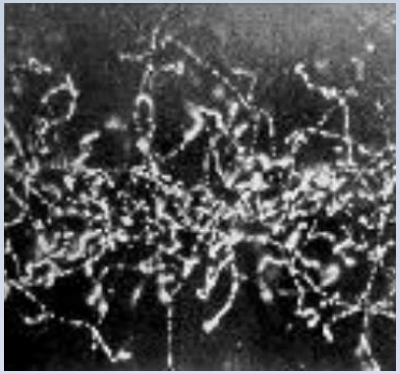
2x more Nobel prizes for experimentation as opposed to theory!

Compilation: Werner Riegler

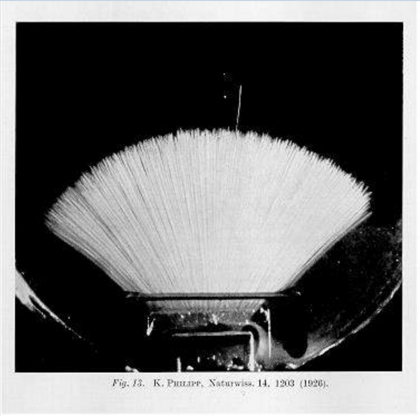
Early "Image detectors" - the Cloud Chamber

Wilson Cloud Chamber 1911

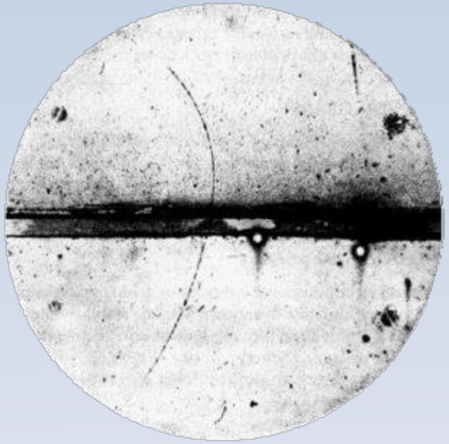
An huge number of types of particle interactions with matter can be directly visualized with incredible precision



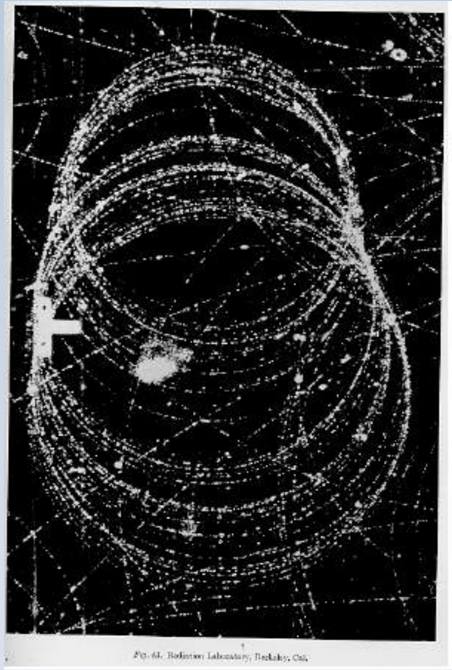
X rays and Compton scattering



α rays of two different energies

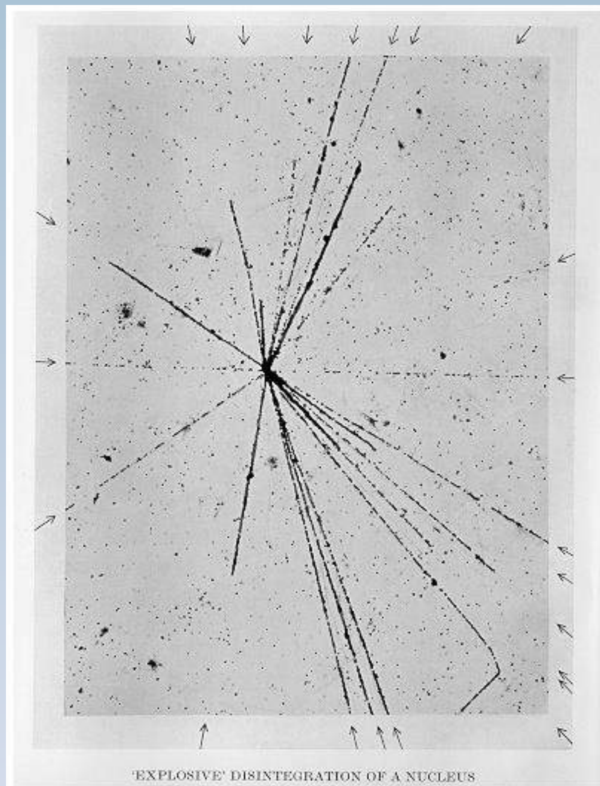


Discovery of positron, energy loss after passing through plate



Spiralling electron losing energy in a.magnetic field

Early Image detectors - Emulsions



Nuclear disintegration provoked by cosmic ray

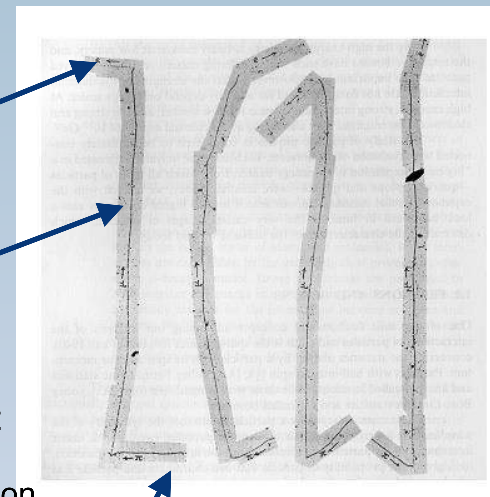
Discovery of the muon and pion

e

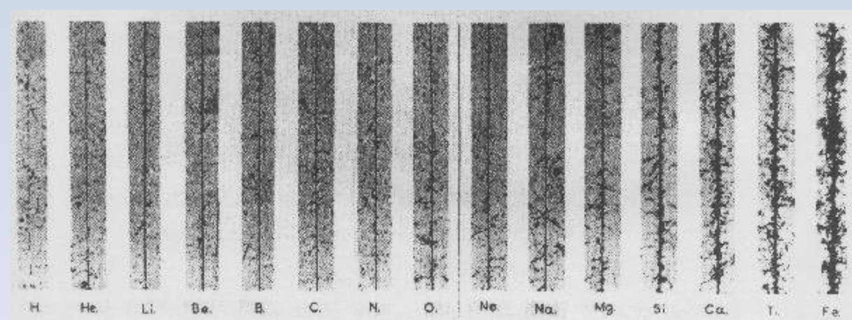
Produced with two neutrinos

μ

With constant range, as originates from 2 body decay, together with muon neutrino



π



Cosmic ray composition - energy loss proportional to Z^2 of particle

Early image detectors - bubble Chamber

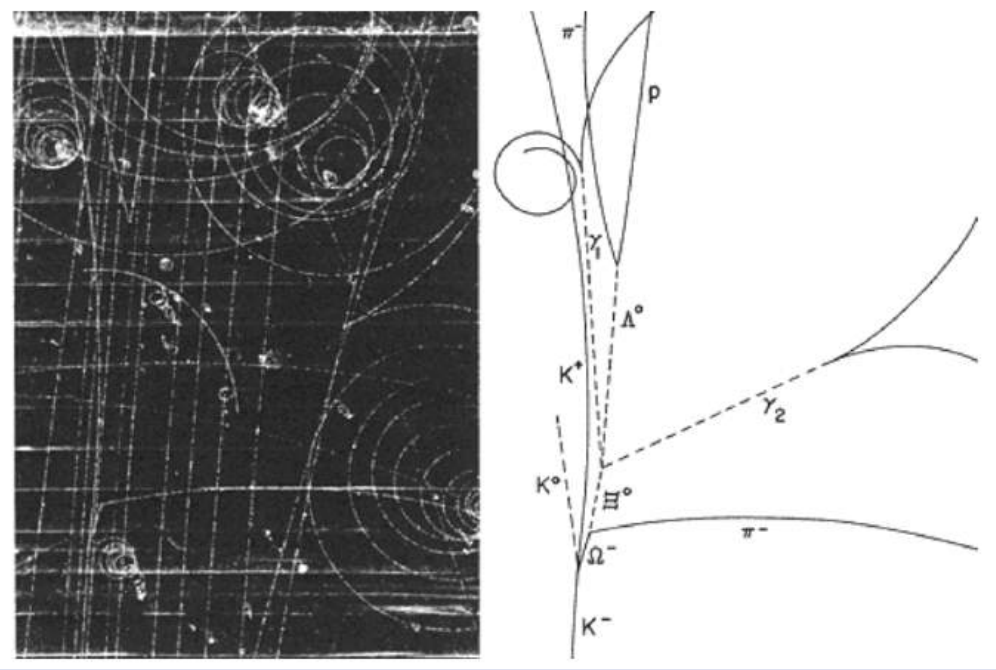
Superheated liquid - entering particle deposits energy along the path, making the liquid boil and form bubbles

Could reach enormous sizes - BEBC 3.7m hydrogen bubble chamber at CERN, equipped with the largest superconducting magnet in the world

Fantastic position resolution and target and detection volume are the same - very sensitive

Rate limited - 6 million photographs from entire BEBC lifetime corresponds to 0.15 seconds at LHC!

BNL, first pictures 1963, 0.03s cycle



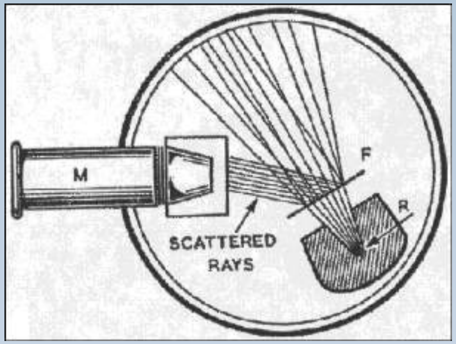
Discovery of Ω^- in 1964

Early logic detectors

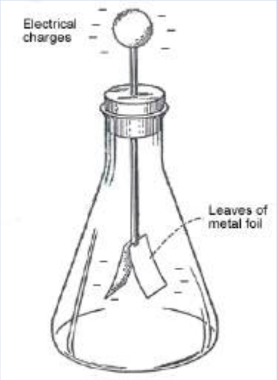
General principle - Passage of particle gives electronic signal

Rutherford Scattering experiment:

Flashes of light from zinc sulfide screen

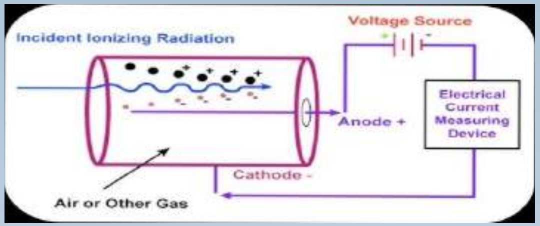


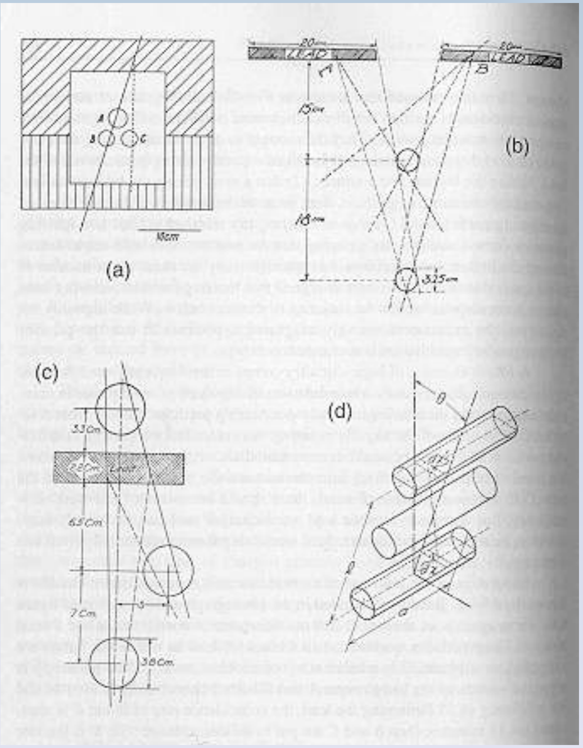
Discovery of cosmic rays from balloon flight of electroscope



Geiger counters

- drifting electrons close to wire cause large avalanche and discharge



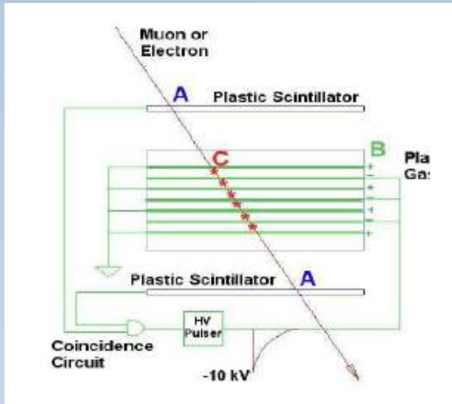


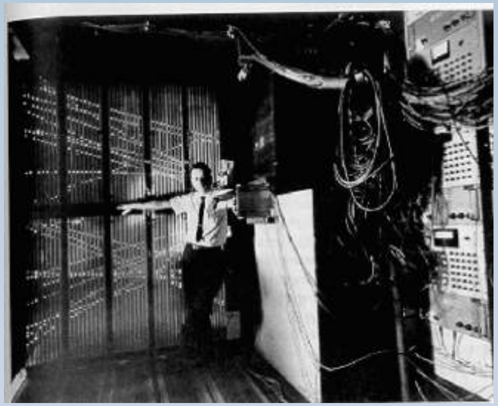
- used in coincidence to measure angular distribution of cosmic ray particles

More logic detectors

Spark Chambers - used in discovery of muon neutrino

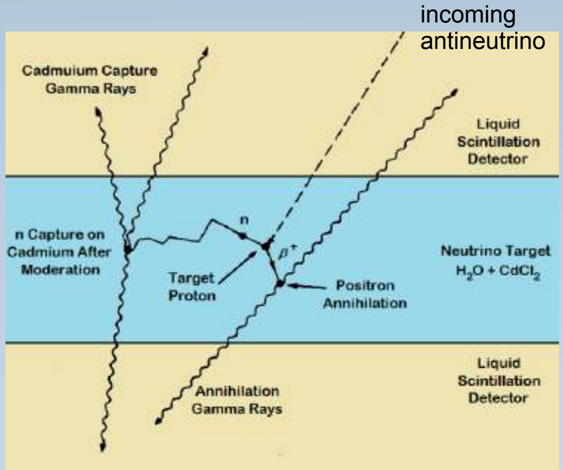
The charged particle makes an ionization trail
The scintillators trigger an HV pulse and sparks form along the path





Anti Neutrino Discovery 1959

Example of a discovery relying on logic



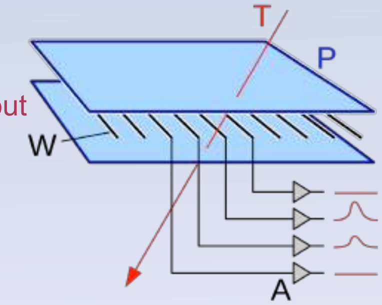
Multiwire Proportional Chamber

Individual amplifier per wire

Perpendicular geometry for 2d readout

Precise positioning from drift time

Move to fast readout speeds



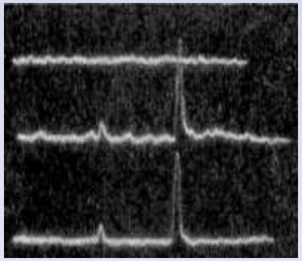
Anti neutrino strikes a proton, producing a neutron and positron

$$\overline{\nu}_e + p \rightarrow n + e^+$$

Positron annihilation with electron gives two simultaneous photons

After moderation ($\sim 15\mu s$ later) the neutron is captured by a cadmium nucleus, with multi photon emission

This delayed coincidence is the signature!

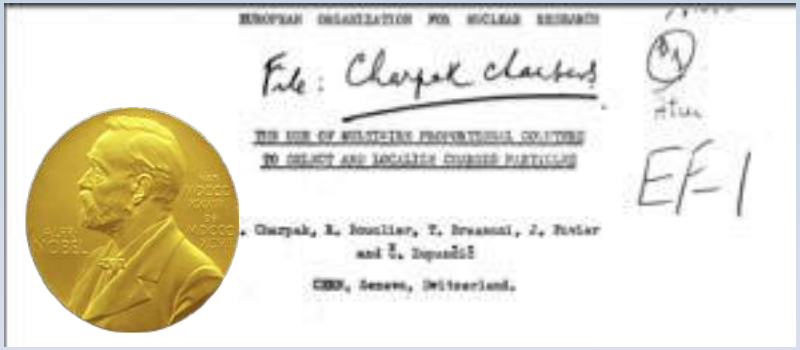


https://indico.physics.lbl.gov/event/1368/contributions/5238/attachments/2543/3343/Discovery_of_the_electron_neutrino.pdf

The Electronics Imaging Revolution

Using laborious and tedious techniques such as the manual analysis of millions of images was not only labour intensive but also totally unsuited to the discovery of rare events

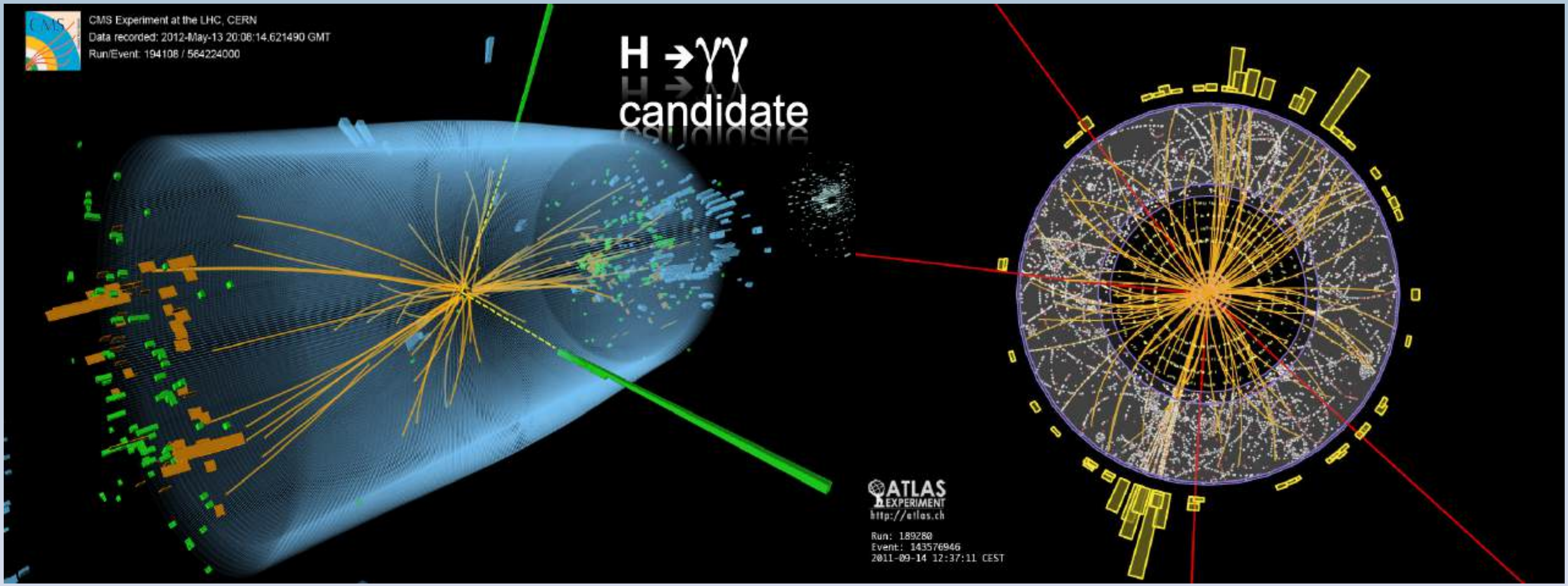
1968: George Charpak developed the MultiWire Proportional Chamber, which revolutionized particle detection and High Energy Physics- which passed from the manual to the electronic era.



Electronic particle track detection is now standard in all particle detectors

Merging of electronic revolution and detector development

2012: Announcement of Observation of the Higgs Boson

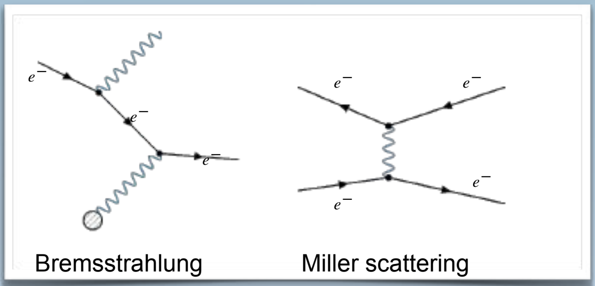


By computer reconstruction we can visualize the tracks of charged particles from proton collisions in ATLAS and CMS (even though analysis no longer based on images)

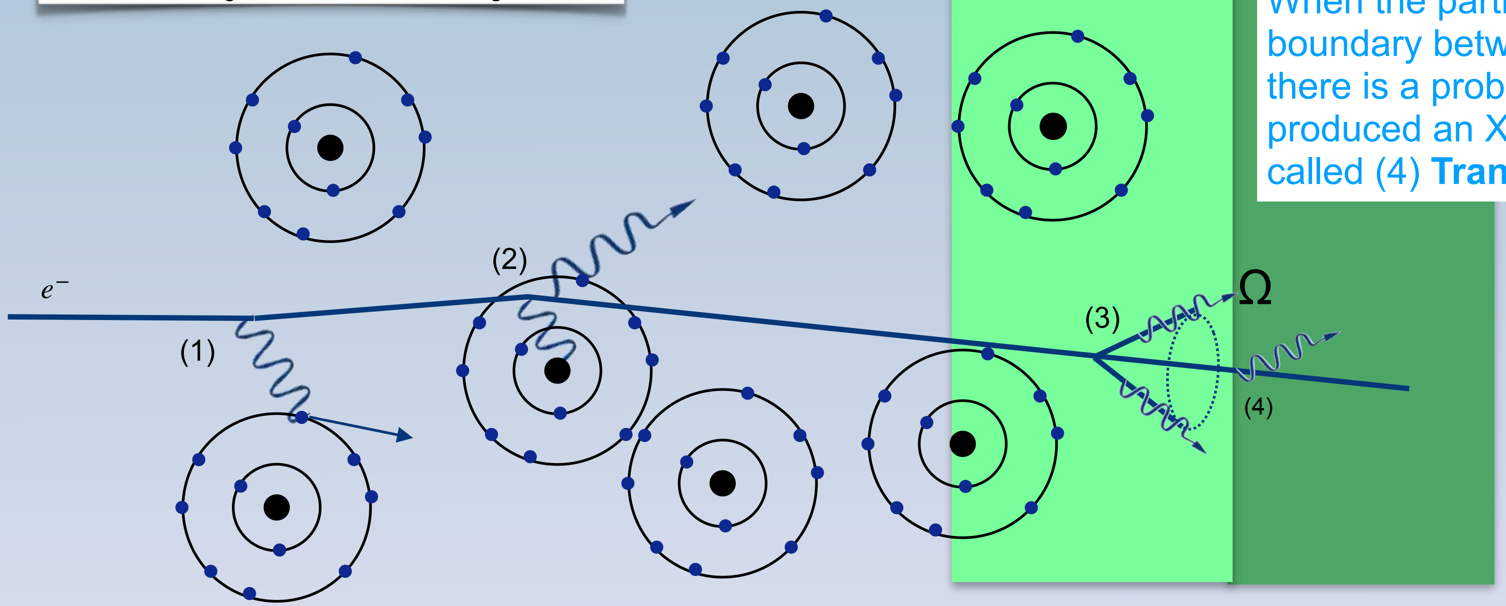
All analysed events have now been selectively triggered

Particle detectors routinely operate with billions of readout channels, at 40 MHz rate

Electromagnetic interactions of charged particles



In case the particle's velocity is larger than the velocity of light in the medium, the resulting EM shockwave manifests itself as (3) **Cherenkov Radiation.** When the particle crosses the boundary between two media, there is a probability (~1%) to produced an X ray photon, called (4) **Transition radiation.**



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The incoming particle loses energy and the atoms are excited or ionized

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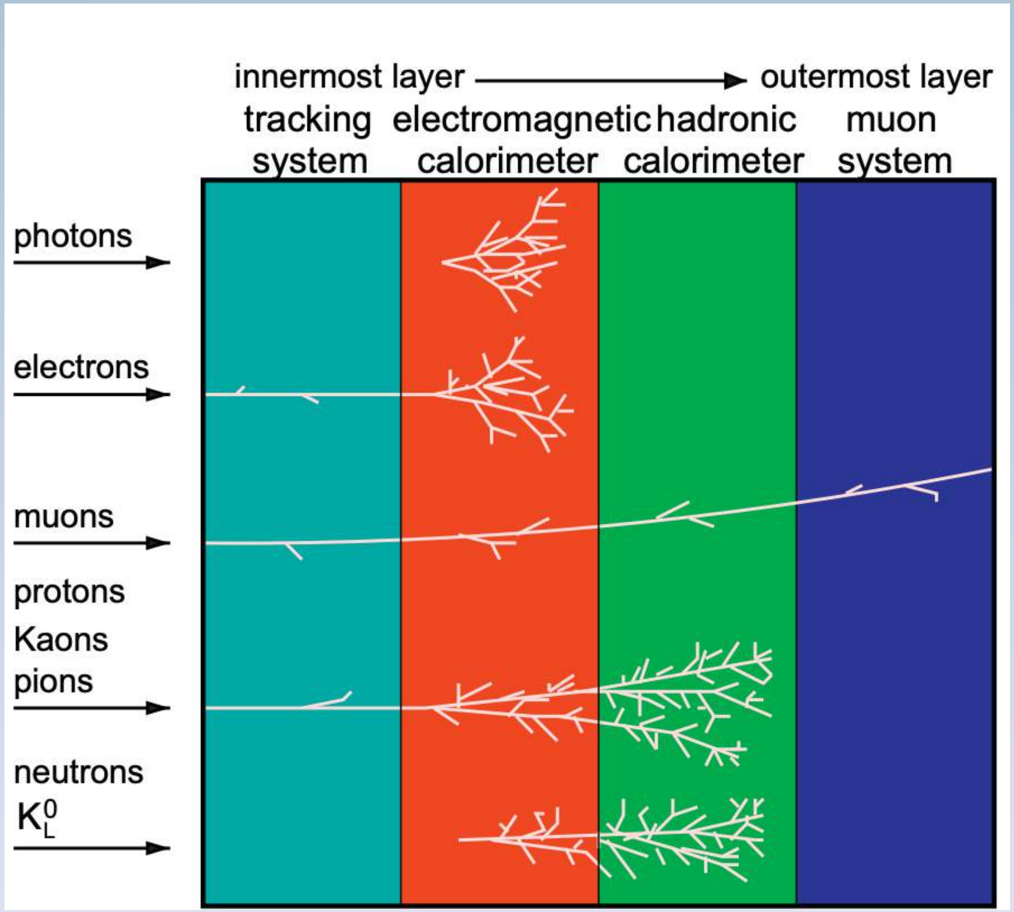
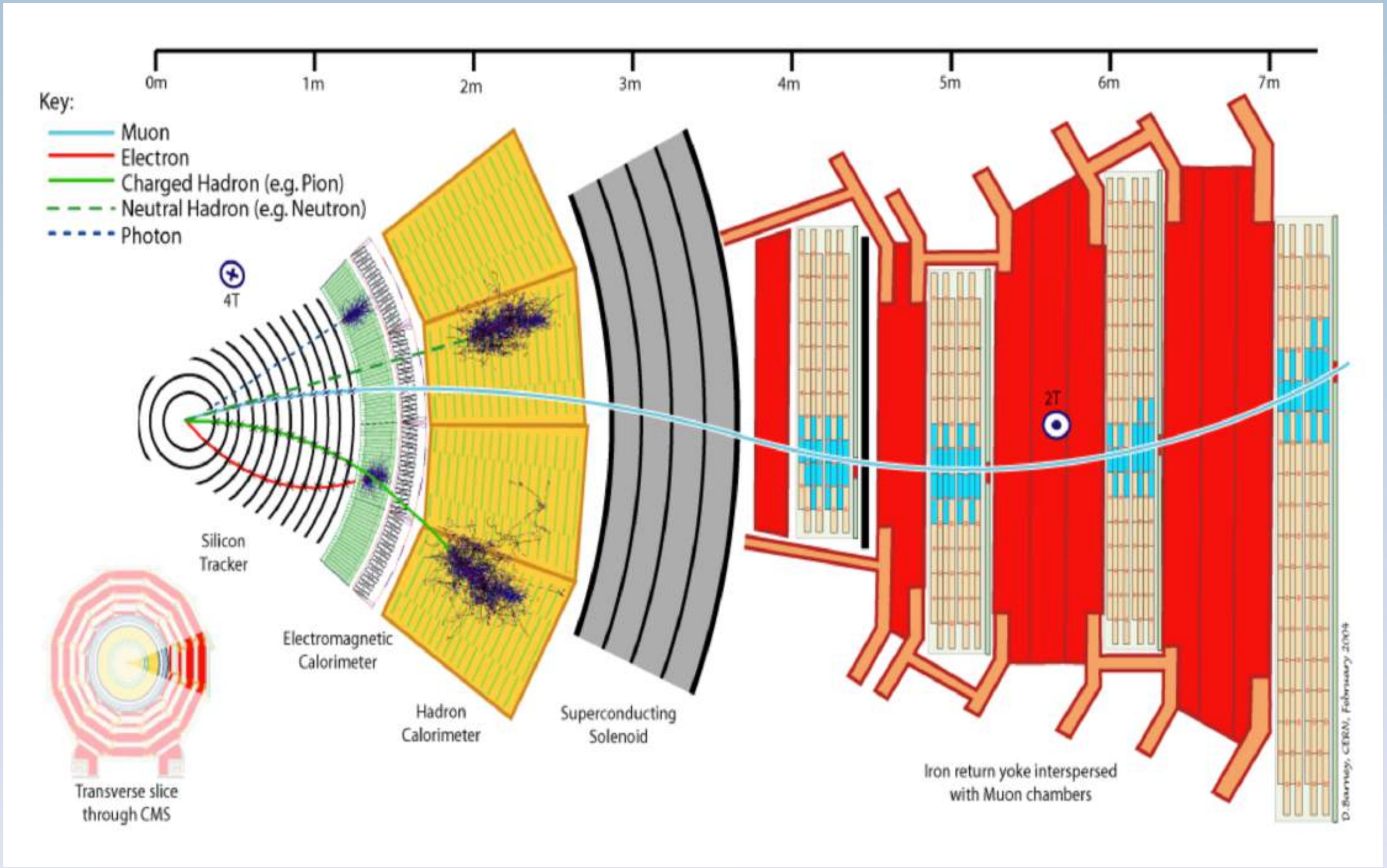
Task of a Particle Detector



- Electrons ionise and show Bremsstrahlung due to the small mass
- Photons don't ionize but show Pair Production in high z material. From then on, equal of $e^{\pm}$
- Charged hadrons ionize and show Hadron Shower in dense material
- Neutral Hadrons don't ionize and show hadron shower in dense material
- Muons ionise and don't shower

"Typical" Detector Layout



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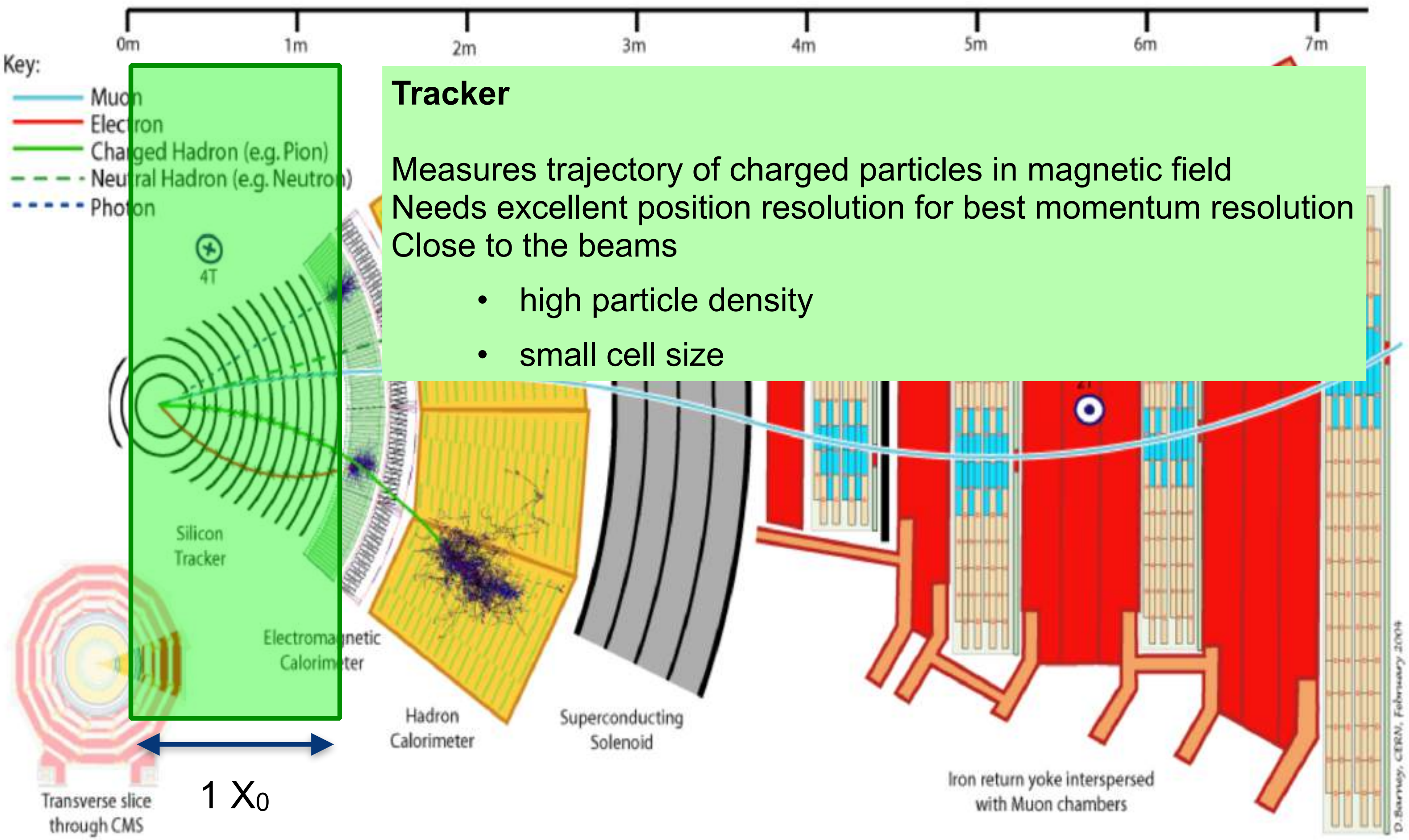
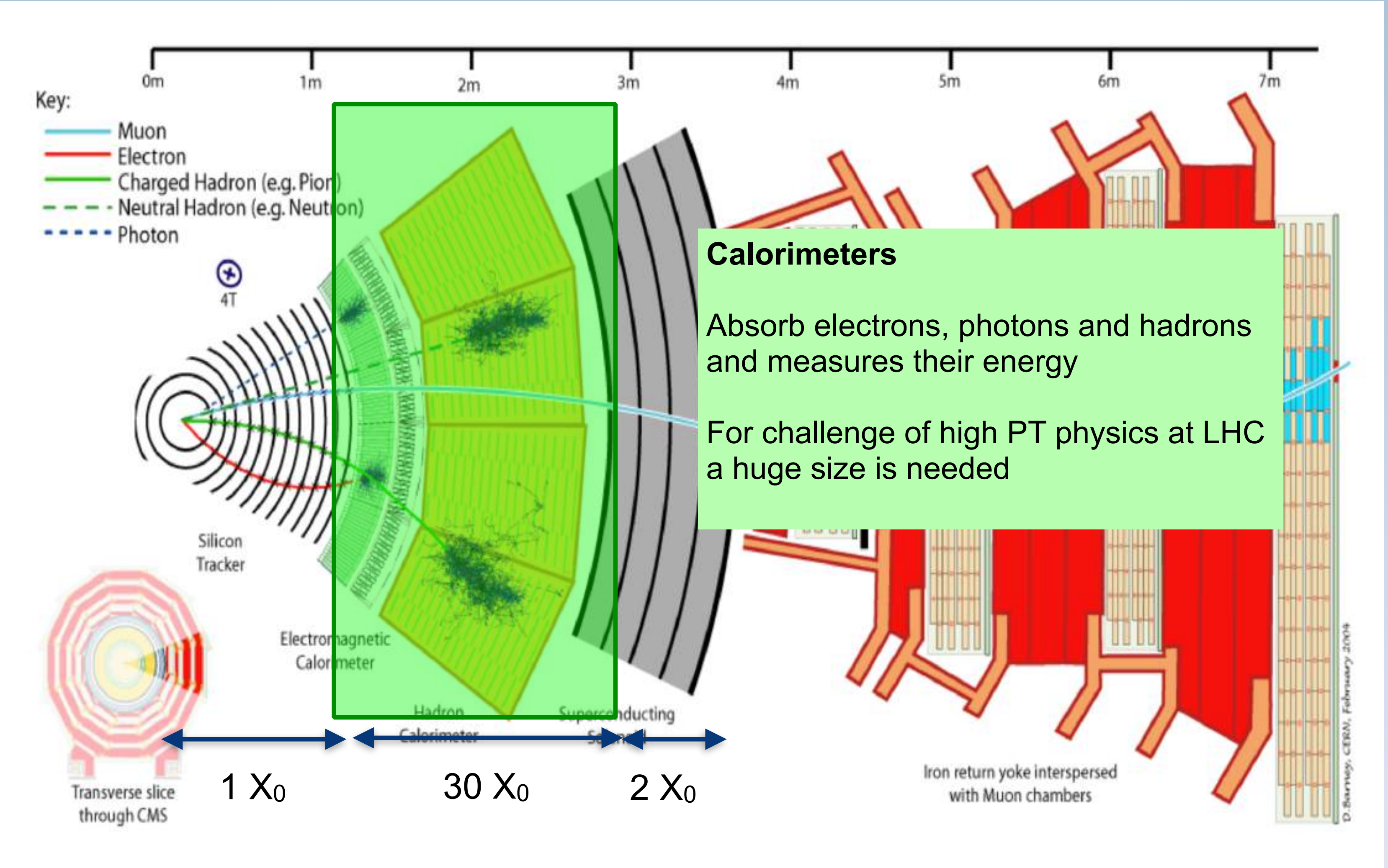


Tracker

Measures trajectory of charged particles in magnetic field
Needs excellent position resolution for best momentum resolution
Close to the beams

- high particle density
- small cell size

Detector Layout

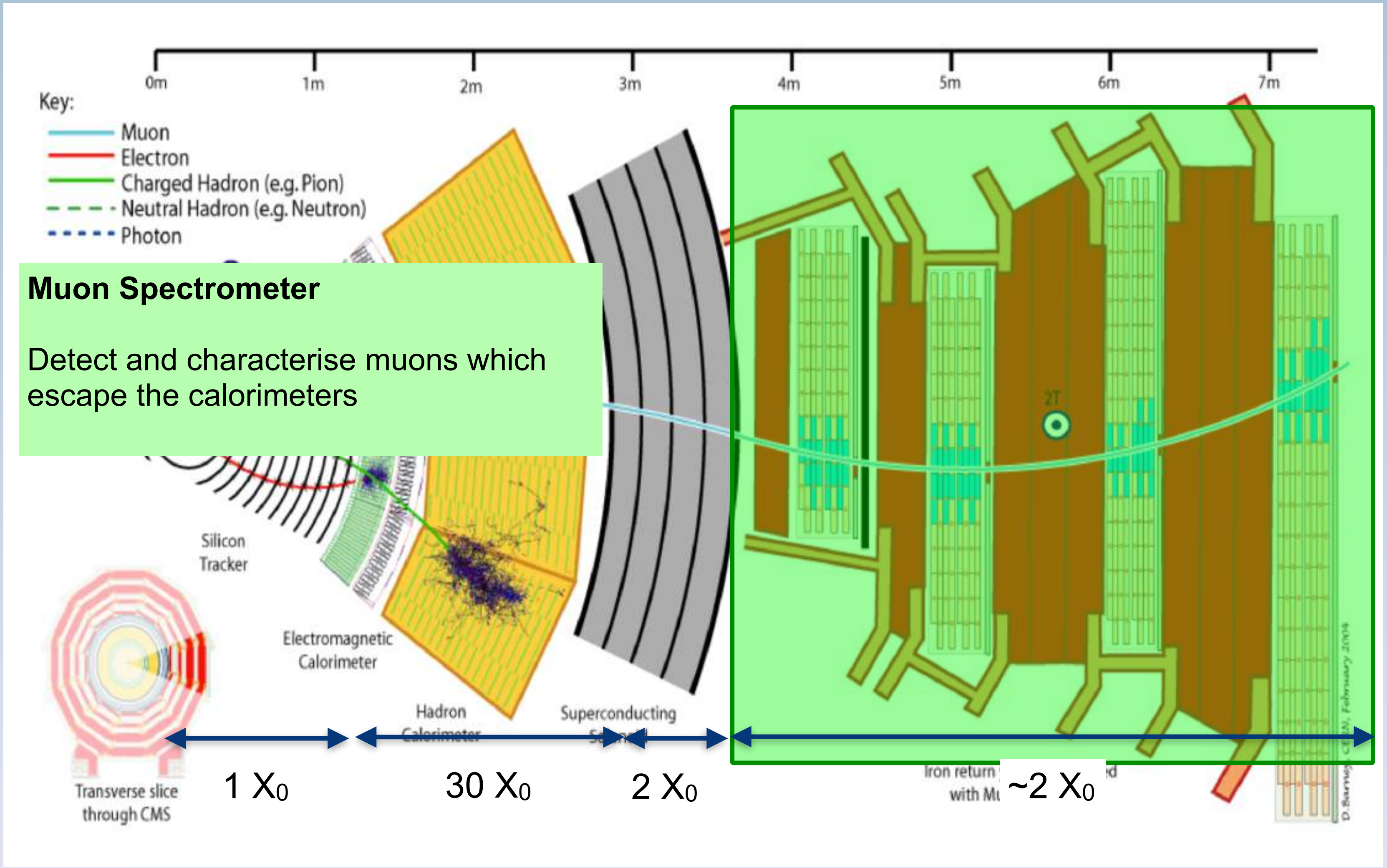


Calorimeters

Absorb electrons, photons and hadrons and measures their energy

For challenge of high PT physics at LHC a huge size is needed

“Typical” Detector Layout



Muon Spectrometer

Detect and characterise muons which escape the calorimeters

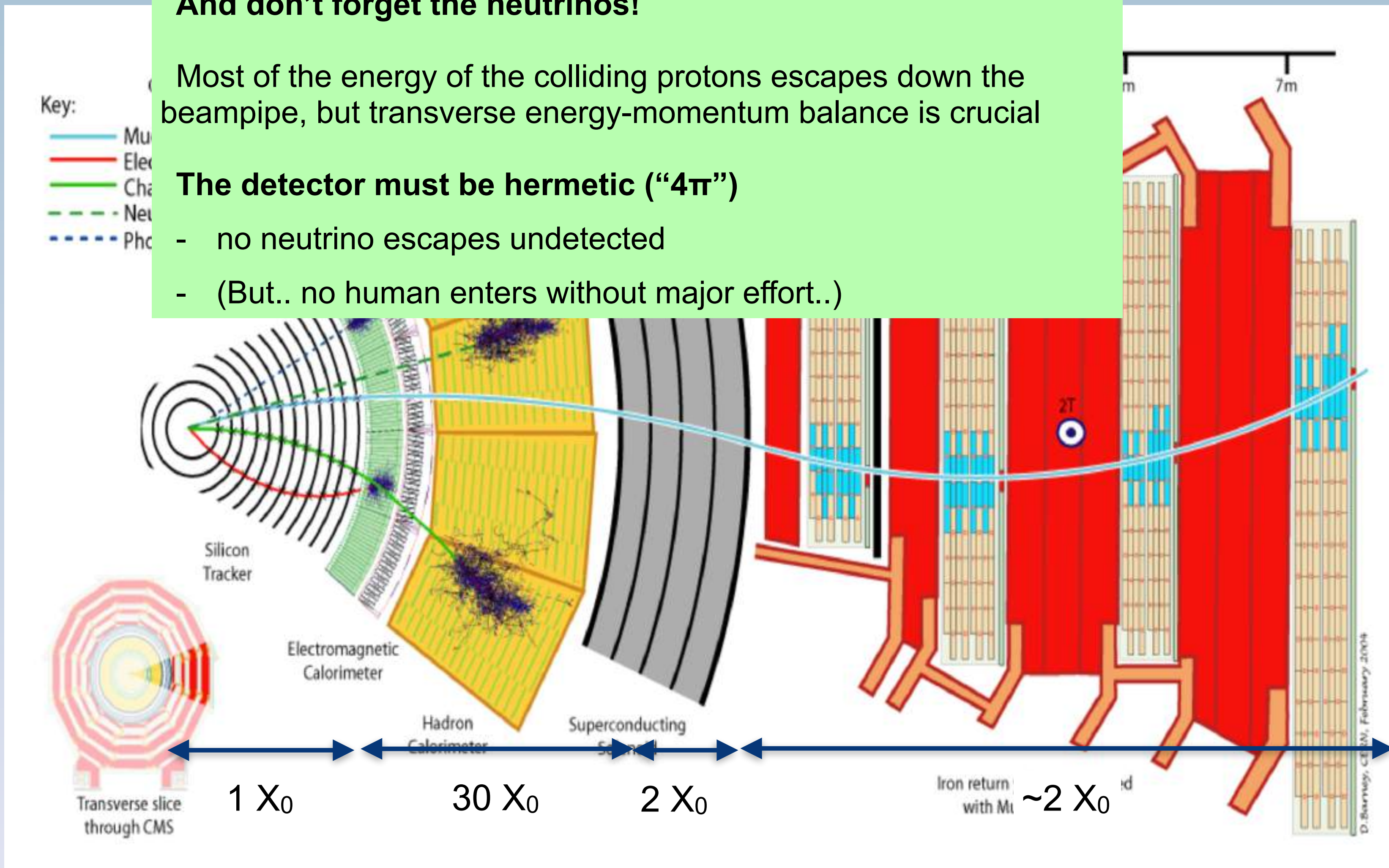
"Typical" Detector Layout

And don't forget the neutrinos!

Most of the energy of the colliding protons escapes down the beampipe, but transverse energy-momentum balance is crucial

The detector must be hermetic ("4π")

- no neutrino escapes undetected
- (But.. no human enters without major effort..)



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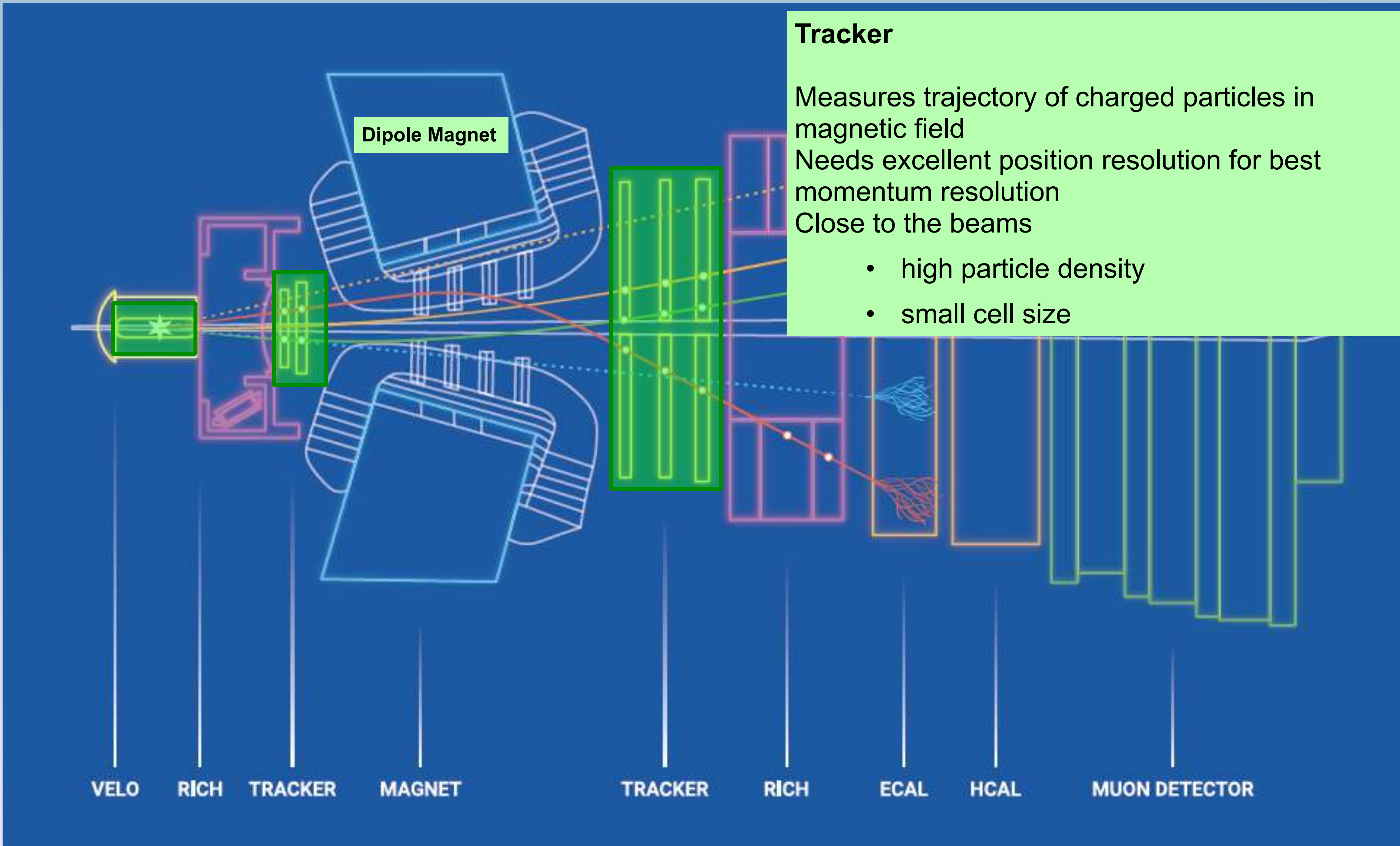

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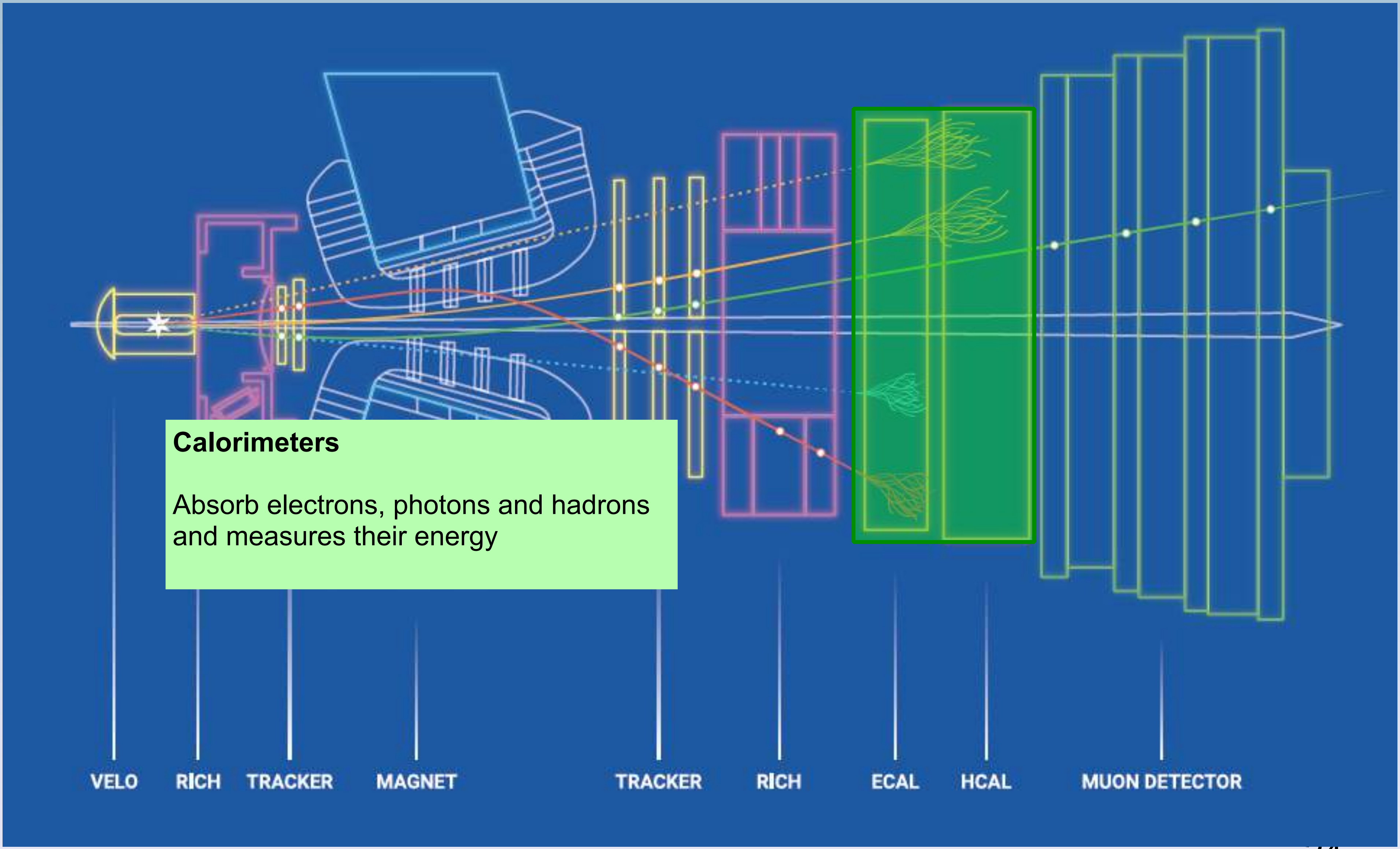

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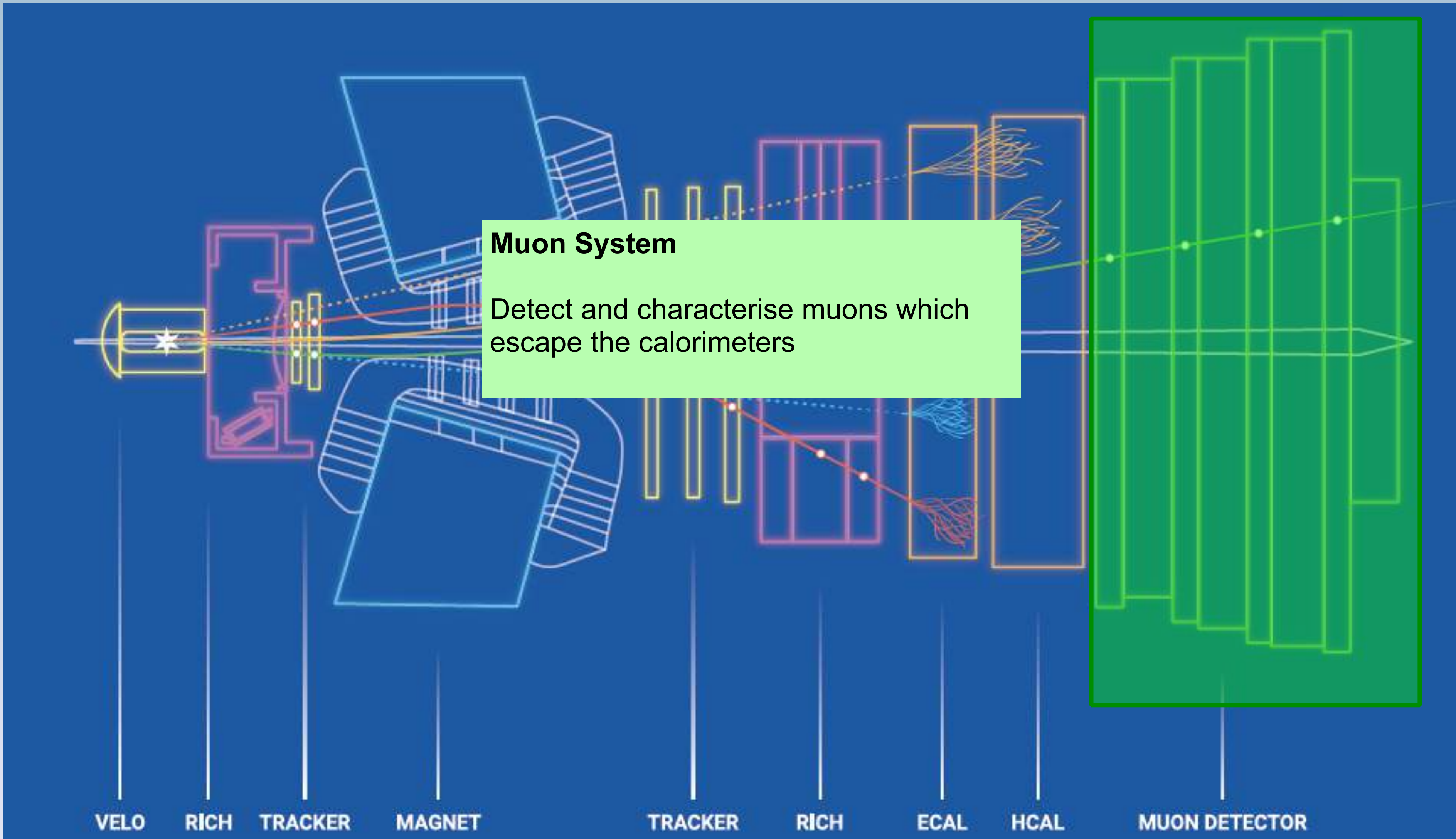
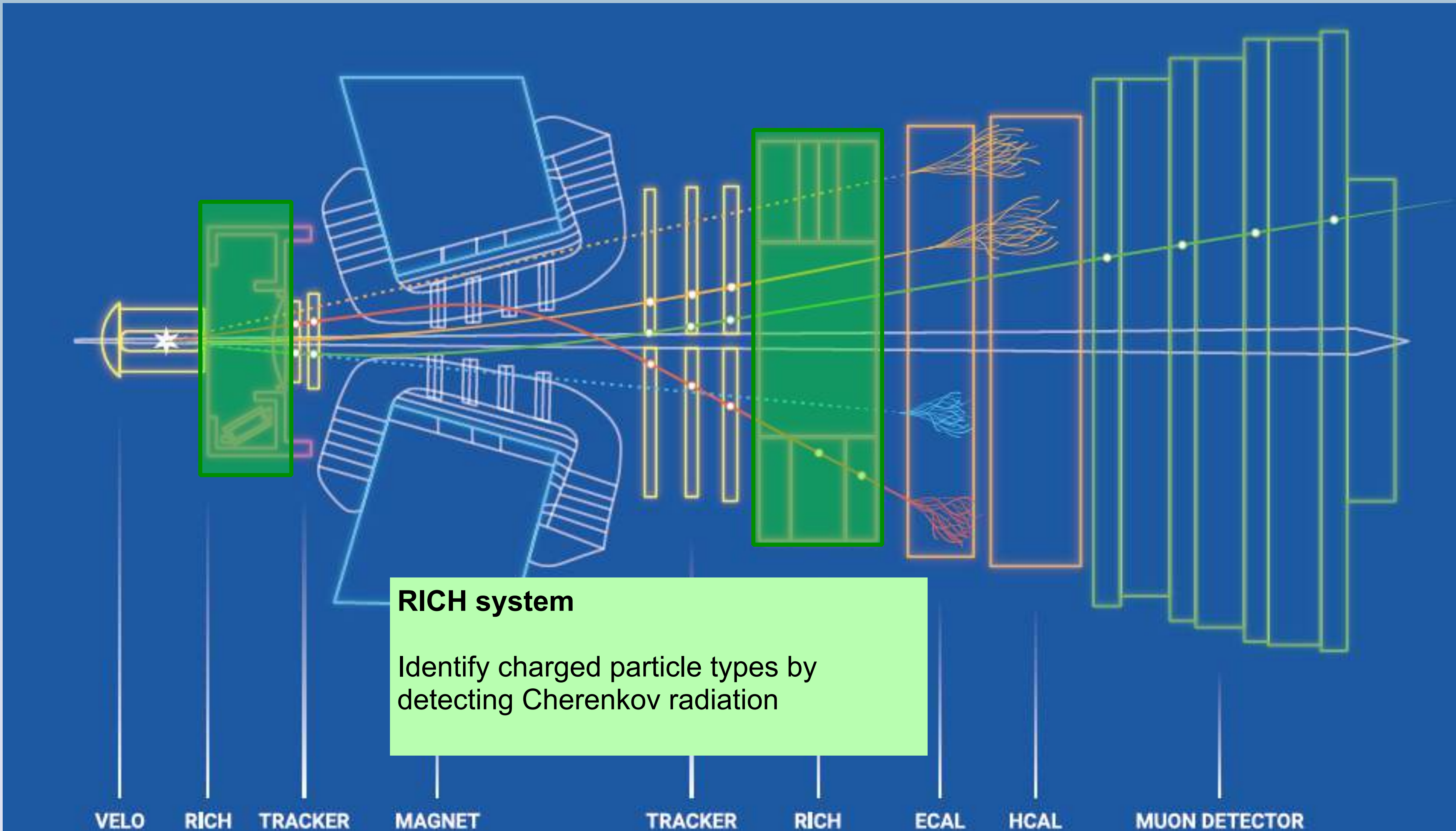


Muon System

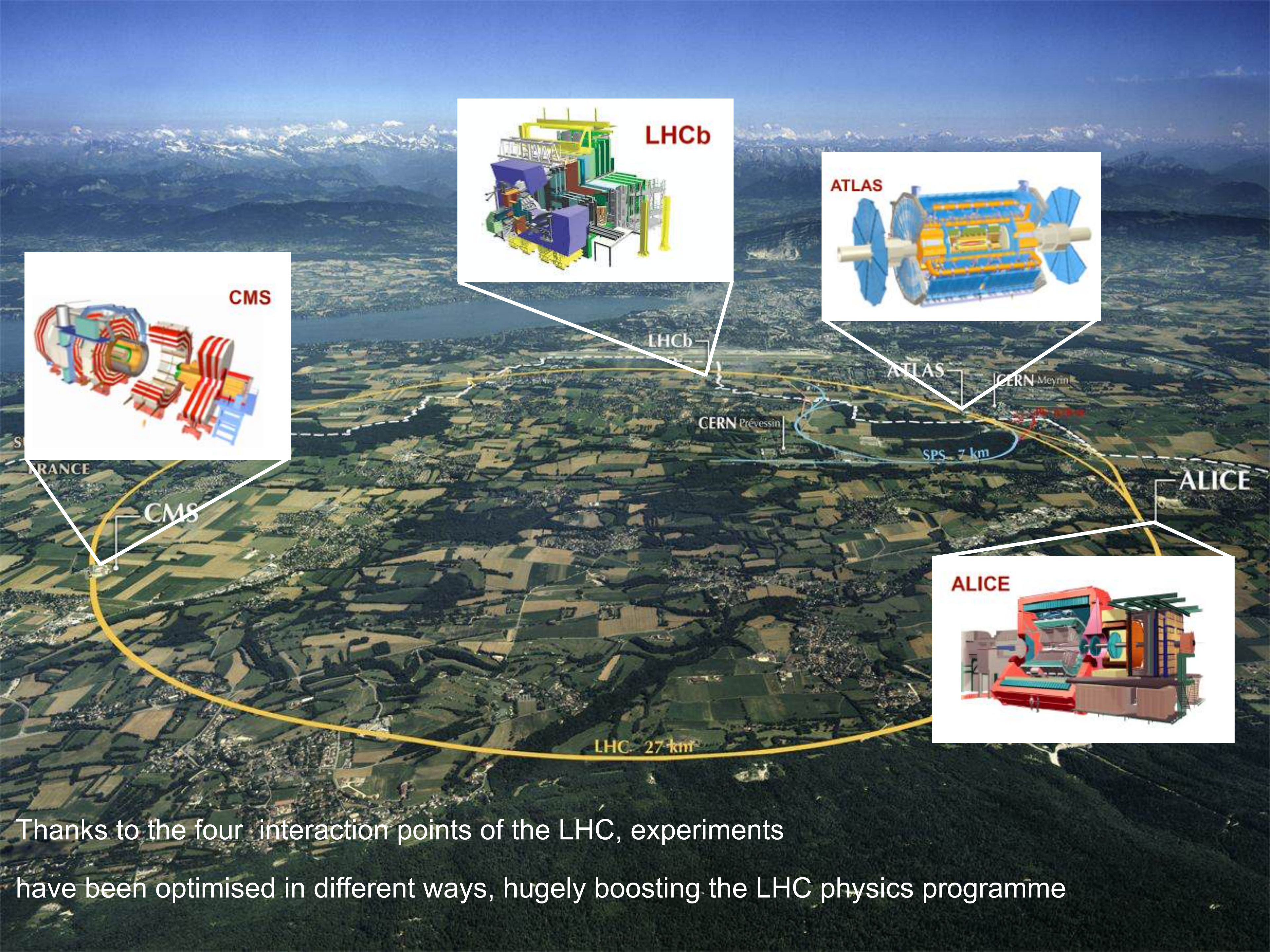
Detect and characterise muons which escape the calorimeters

"Typical" Detector Layout



RICH system

Identify charged particle types by detecting Cherenkov radiation



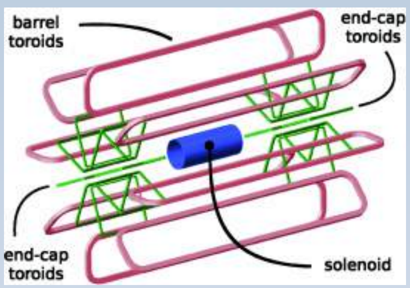
Thanks to the four interaction points of the LHC, experiments have been optimised in different ways, hugely boosting the LHC physics programme

ATLAS/CMS - Discovery

Size of ATLAS and CMS must match tremendous energy of particles produced

- **Absorb** 1 TeV electrons (30 X_0 or 18 cm of Pb)
- **Absorb** 1 TeV pions (11 λ or 2m Fe)

Magnet Systems ($H \rightarrow ZZ^* \rightarrow 4\mu$)



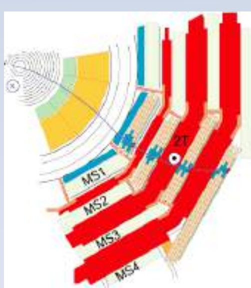
ATLAS:

“small” 2T tracker solenoid

“huge” toroids for muon spectrometer

+ muon acceptance and resolution

- expensive large scale toroid



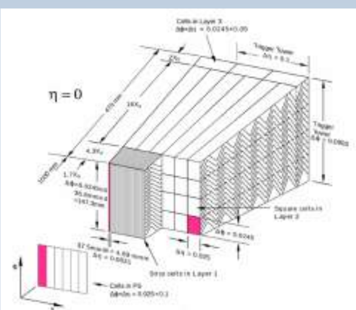
CMS:

“large” 4T solenoid with instrumented return yoke

+ compact, tracking resolution

- calorimeter inside coil

Calorimetry ($H \rightarrow ZZ^* \rightarrow 4e, H \rightarrow \gamma\gamma$)

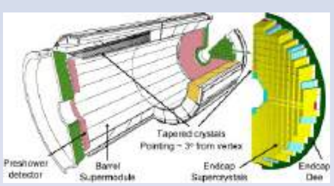


ATLAS:

LAr sampling calorimeter

lateral and longitudinal segmentation

→ reduce fake rate



CMS:

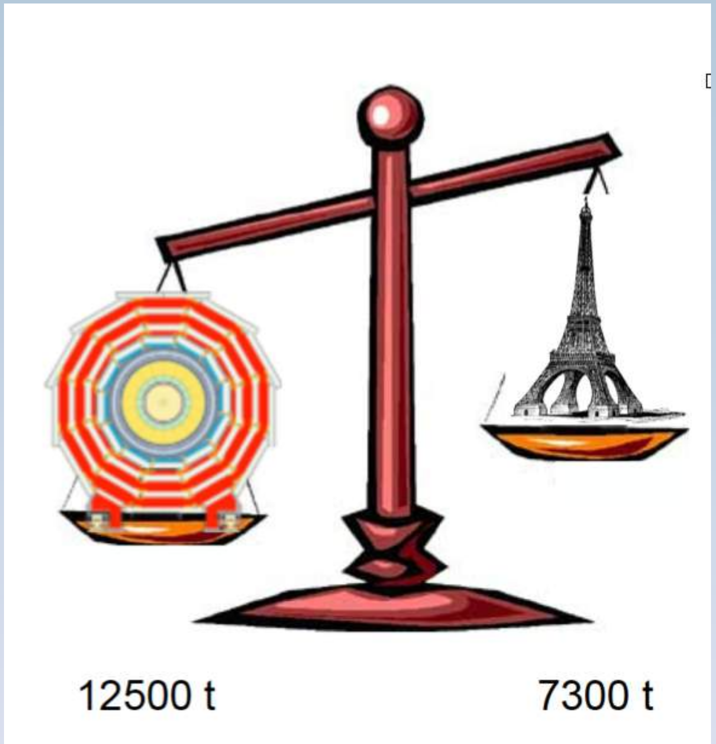
$PbWO_4$ scintillating crystals

lateral segmentation

→ excellent energy resolution

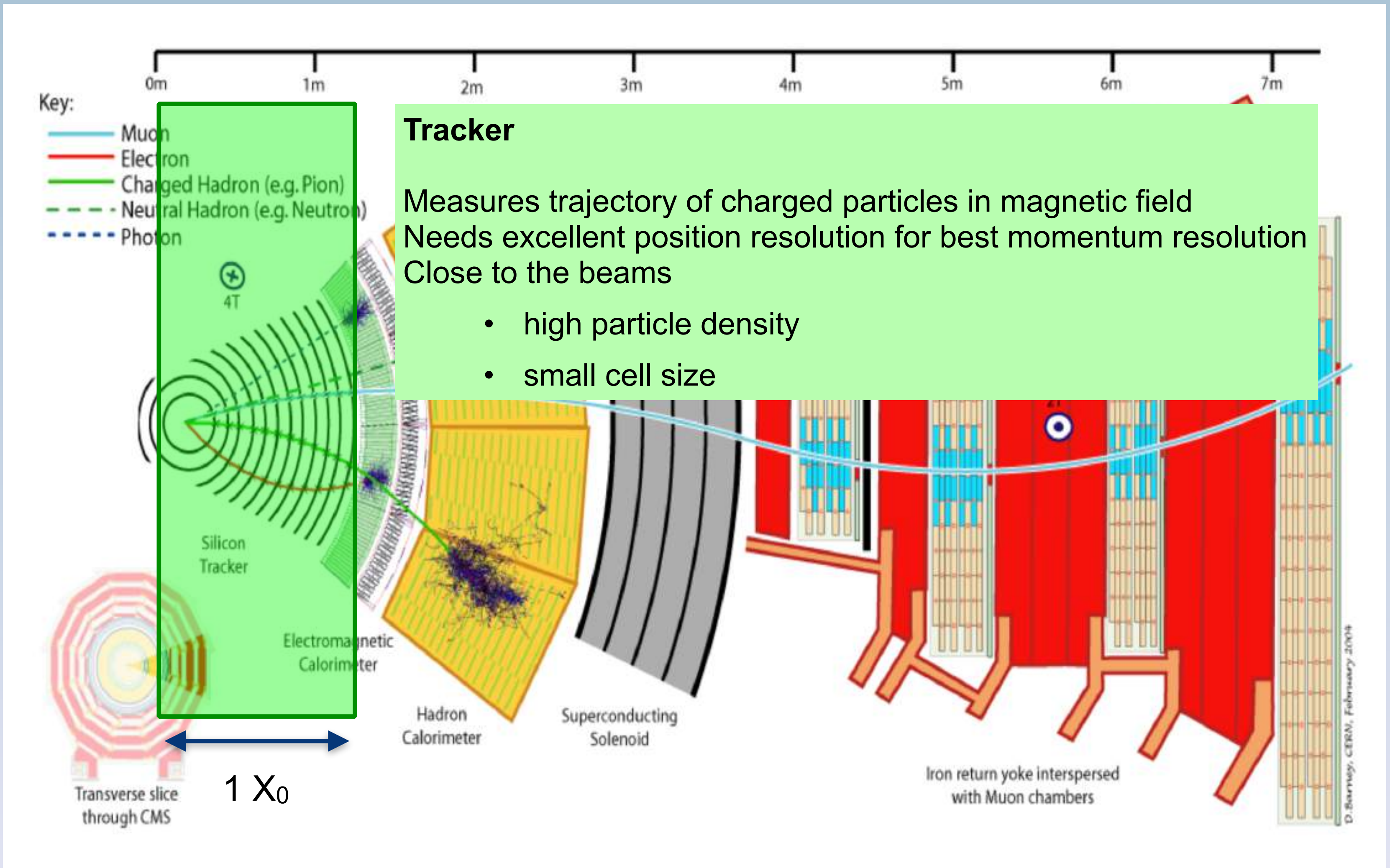
ATLAS/CMS Size and Weight

CMS alone is 65% heavier than the Eiffel tower



Like Nagoya Castle CMS and ATLAS are visually stunning
And in a continuous state of upgrade

Let's come back to detector layout



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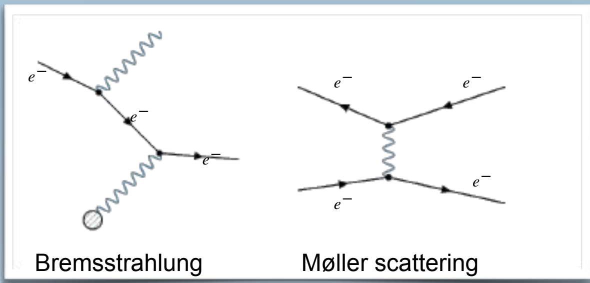
Electromagnetic interactions of charged particles



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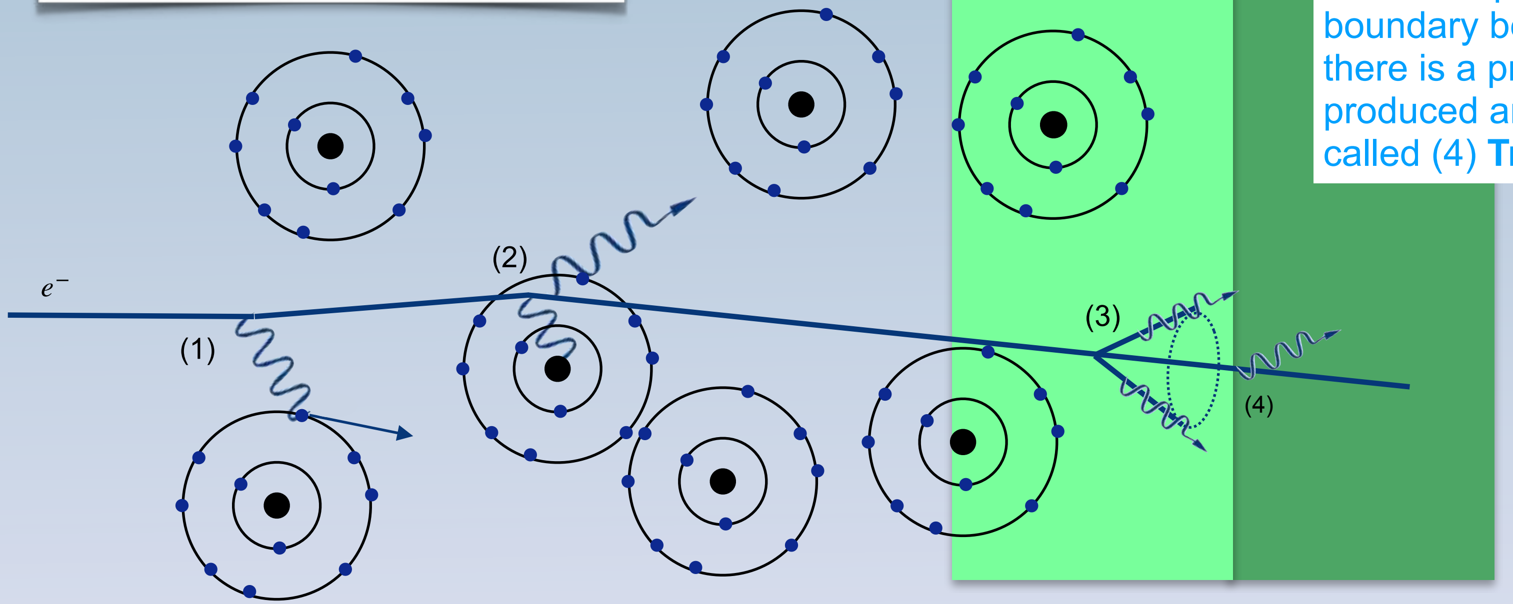

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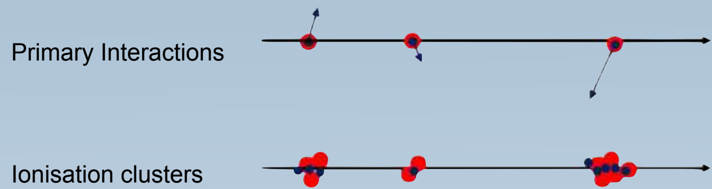
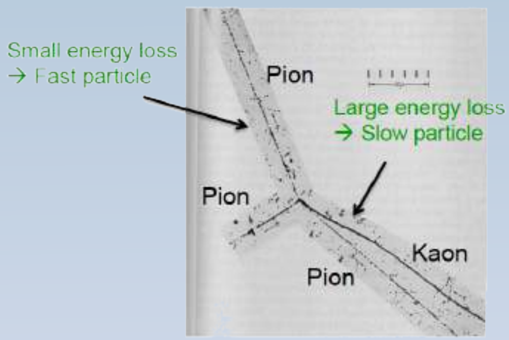
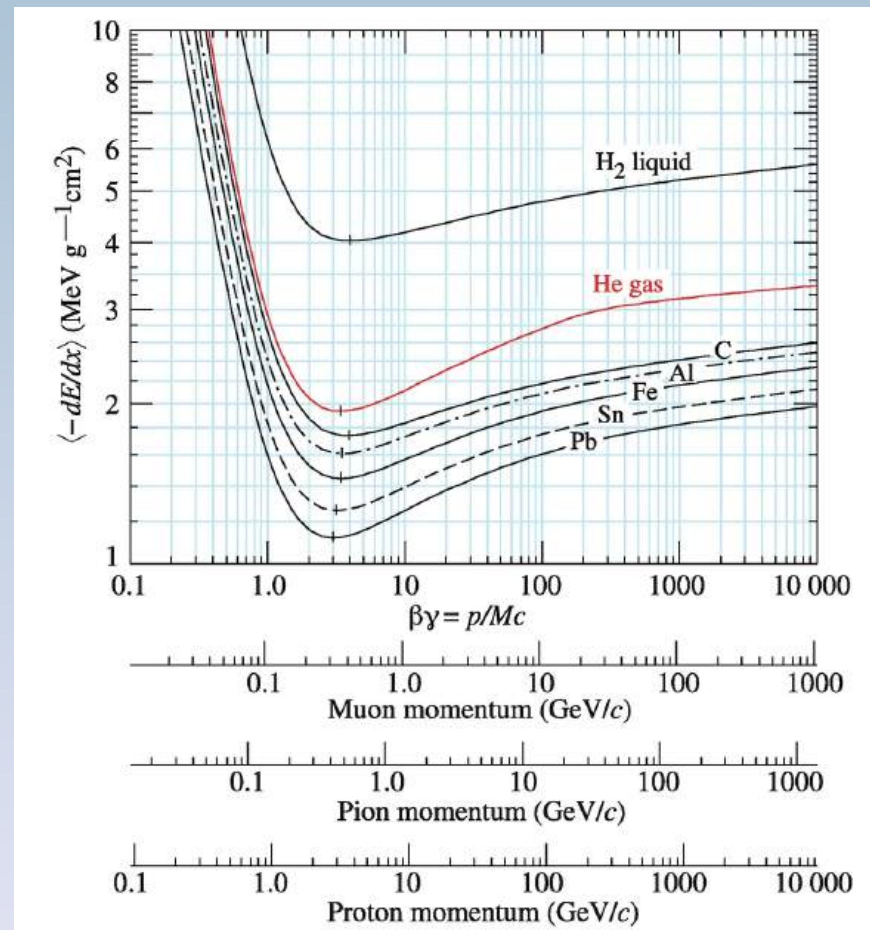
Energy loss through Ionization and Excitation

The charged particles leave a trail of excited and ionized atoms.



Energy transferred by incoming particle is independent of mass but has a very steep dependence on velocity - we have seen this before!





Bethe Bloch formula of the “mass stopping power”*

Electron Spin

Density effect

$$\left\langle -\frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 W_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

Main dependence is on β - steep drop followed by shallow rise

Numerical examples:

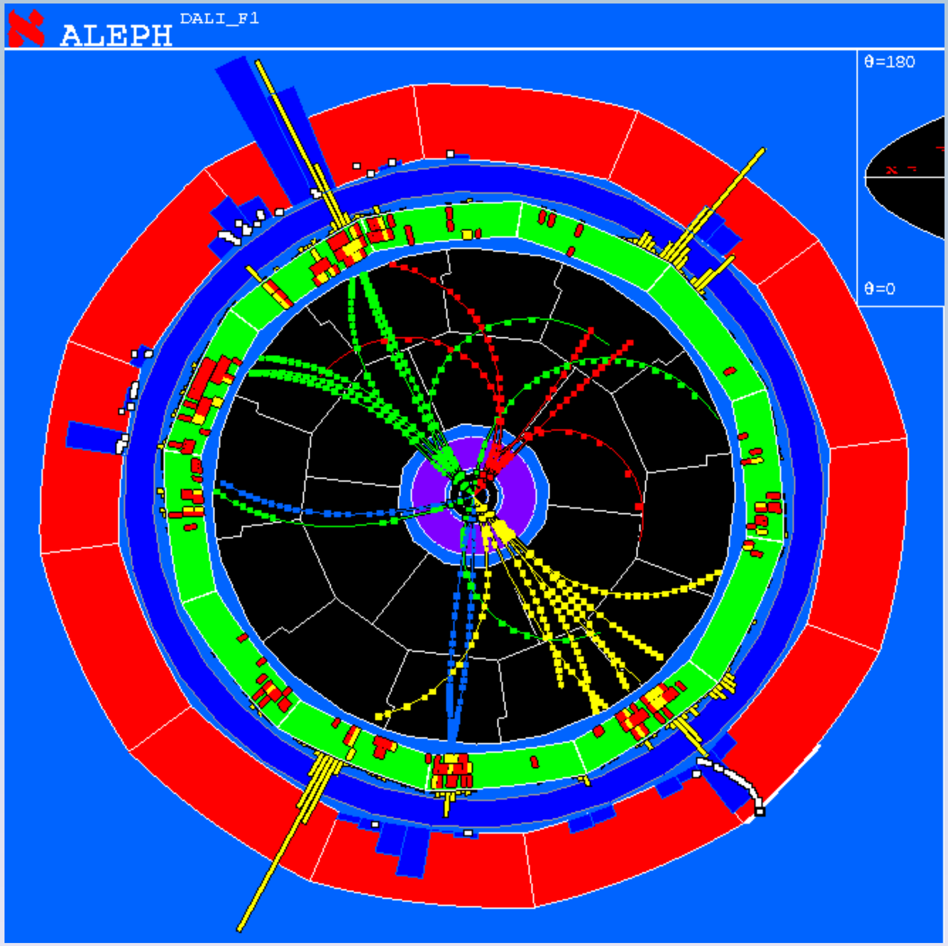
For $Z \approx 0.5\,A$
$1/\rho\ dE/dx \approx 1.4$ MeV cm^2/g for $\beta\gamma \approx 3$

Iron: Thickness = 100 cm; $\rho = 7.87$ g/cm^3
dE ≈ 1.4 * 100* 7.87 = 1102 MeV

* “few concepts in high energy physics are as misused as <dE/dx>” - PDG

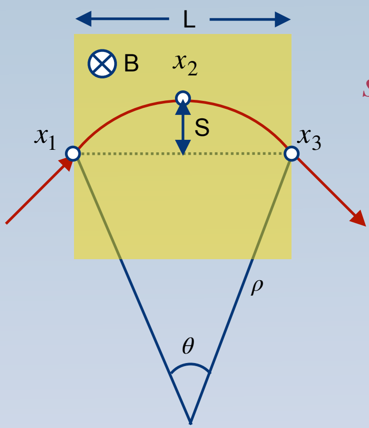
Energy loss as function of momentum

W^+W^- decay candidates in ALEPH (at LEP)
$e^+e^-(\sqrt{s} = 181\ \text{GeV})$
$\rightarrow W^+W^- \rightarrow q q \mu \nu_\mu$
$\rightarrow$ 2 hadronic jets + μ + missing momentum



Measure momentum from curvature ($1/\rho$) of particle track

$$p_T\ [\text{GeV/c}] = 0.3\ B[\text{T}]\ \rho[\text{m}]$$



$$s = \rho\left(1 - \cos\frac{\theta}{2}\right) \approx \frac{0.3}{8}\frac{L^2 B}{p_T}$$

For the simple case of three uncorrelated measurements:

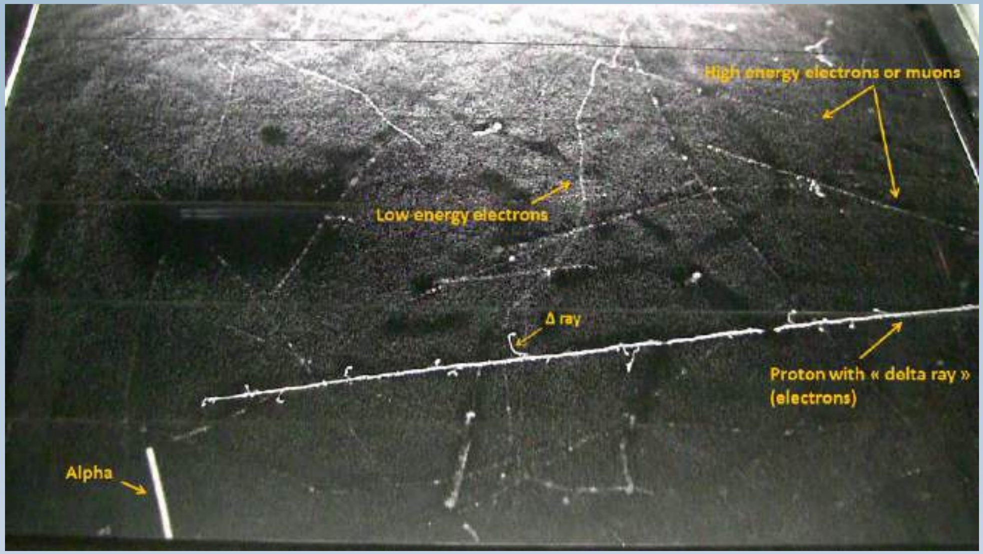
$$s = x_2 - (x_1 + x_3)/2$$

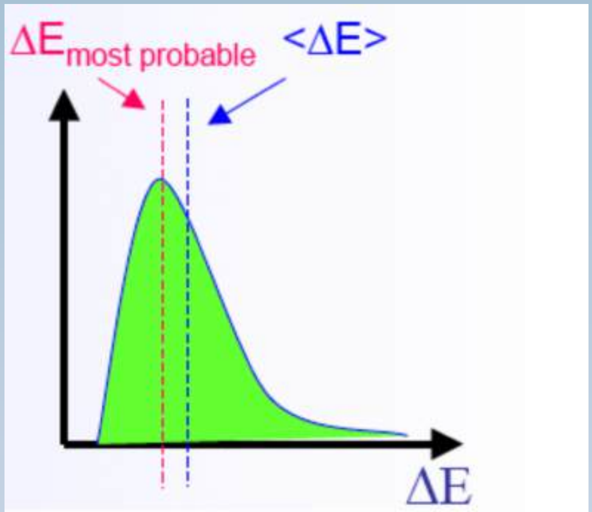
$$\sigma_s^2 = \sigma_x^2 + \frac{\sigma_x^2}{4} = \frac{3}{2}\sigma_x^2$$

Also, measure dE/dx by counting deposited charge along the track

$\rightarrow$ combine for Particle ID

Stochastics of the energy loss

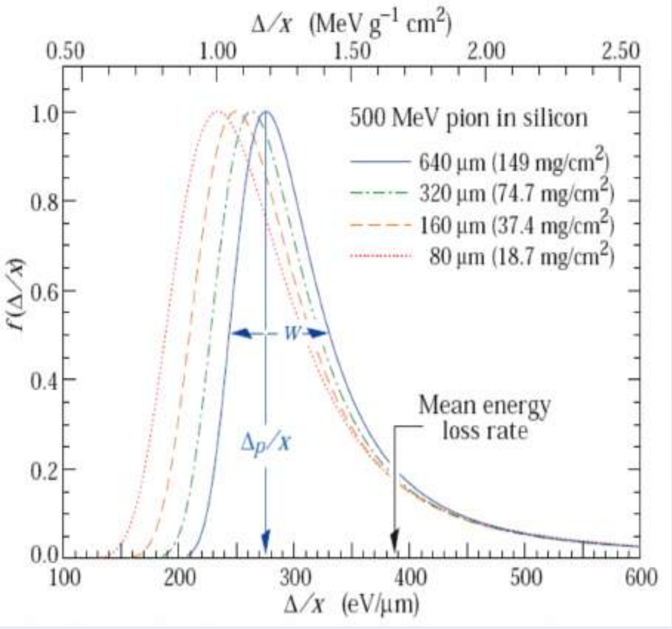




Bethe-Bloch equation describes the **mean** energy loss

For thin layers, or low density materials:

- Few collisions, some with high energy transfer
- Energy loss distributions show large fluctuations towards high losses
- Long Landau tails
- Delta rays may leave, or partially leave the detector and their energy is loss. They may also confuse the pattern recognition and smear the precision
- Most probable energy loss is lower, and a more reliable indicator, than mean energy loss

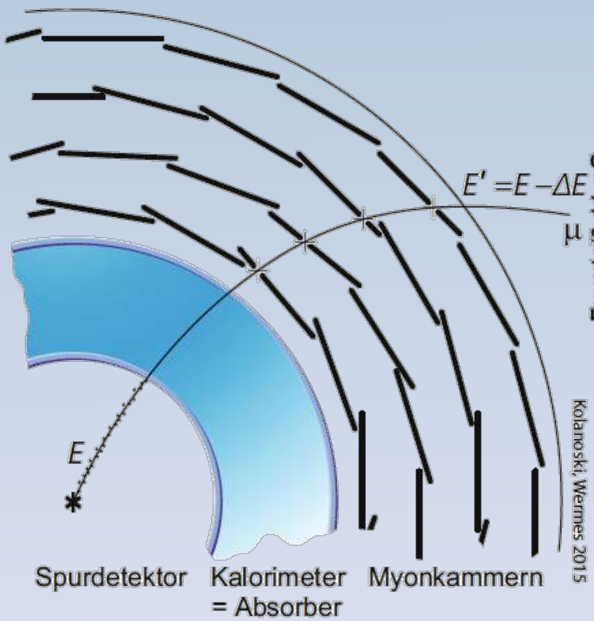


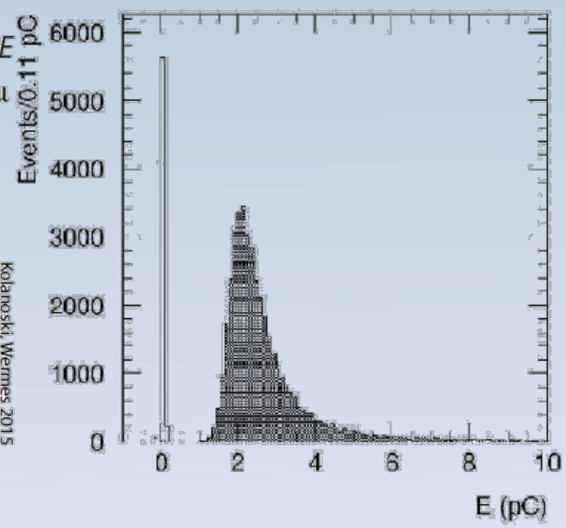
Example: ATLAS muon reconstruction

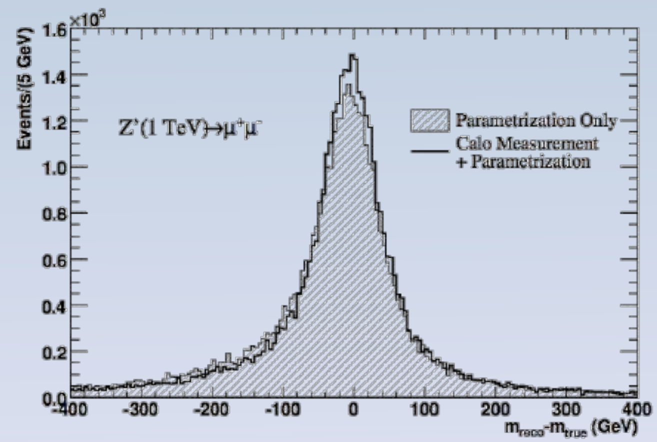
The ATLAS calorimetry for 100 GeV muon is equivalent to 175cm of Fe

A small faction of high energetic muons deposits a significant energy fraction in the calorimetry.

Because this is an instrumented region, the muon reconstruction can correct for the effect.

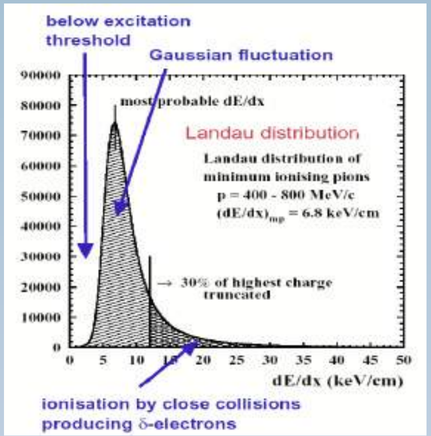




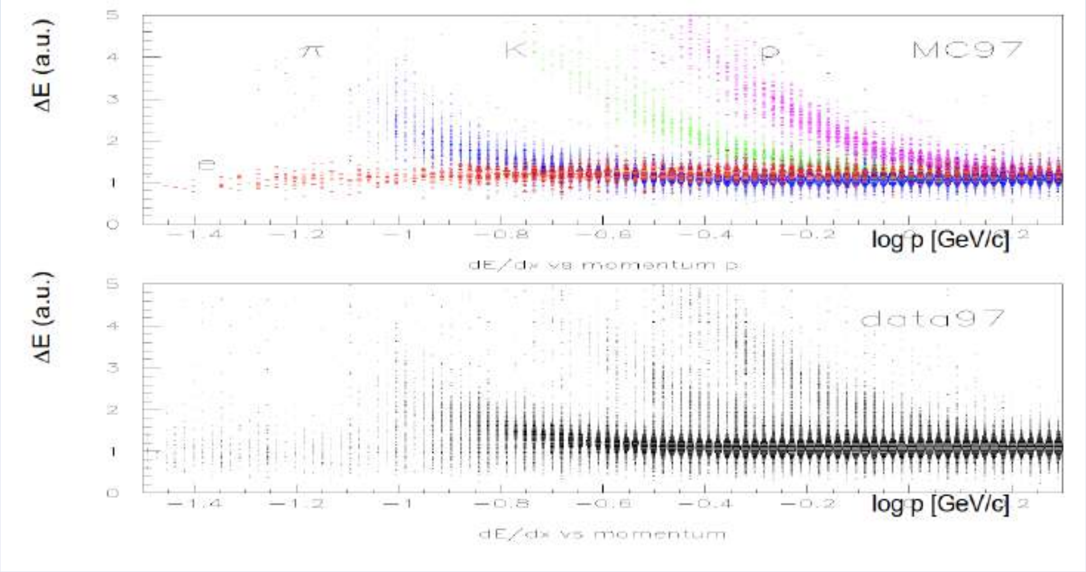


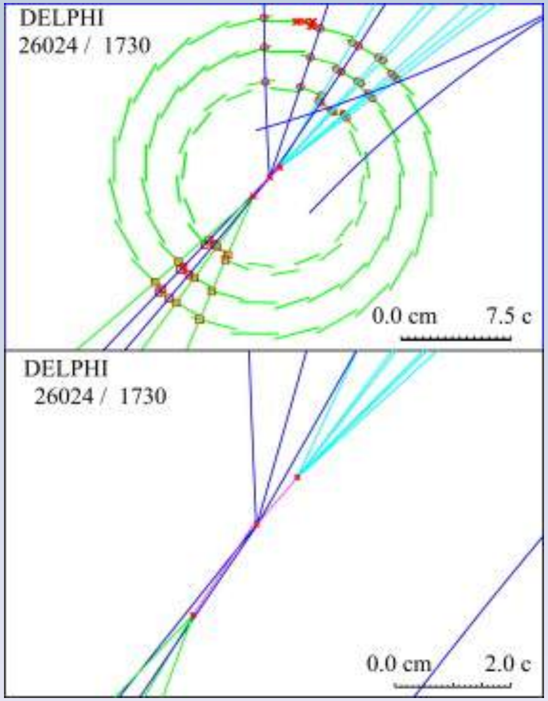
Particle Identification through dE/dx

Using the trick of "charge truncation" even a few pieces of information can - in certain momentum ranges - provide particle ID



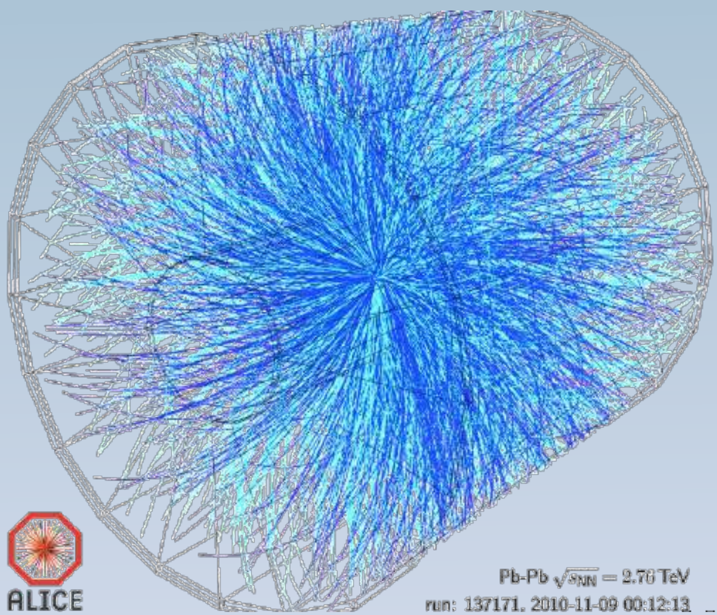
Delphi Microvertex Detector - just three hits (including one correlations from double sided measurements)

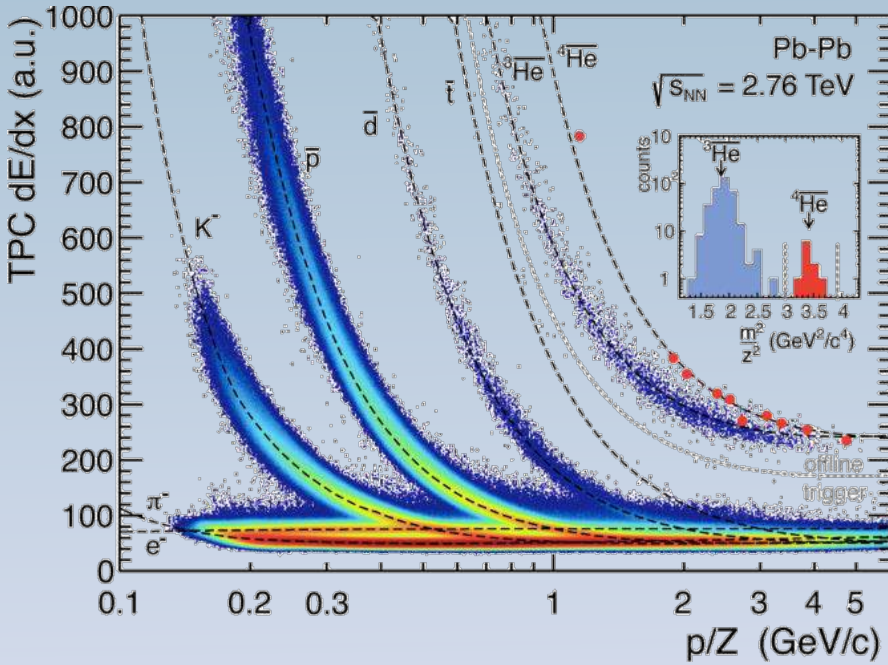




Particle Identification through dE/dx

Spectacular power to identify particles





Time Projection Chamber
(ALICE detector, Ne/CO2 gas).

dE/dx measurement in Pb/Pb collisions.
(dE/dx spread is limit for particle ID)

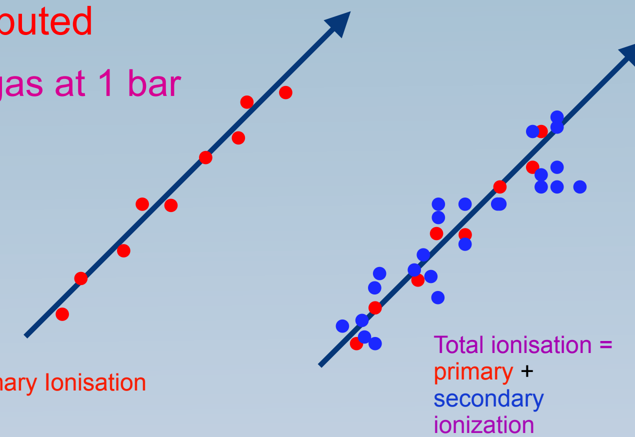
Particle Identification through dE/dx

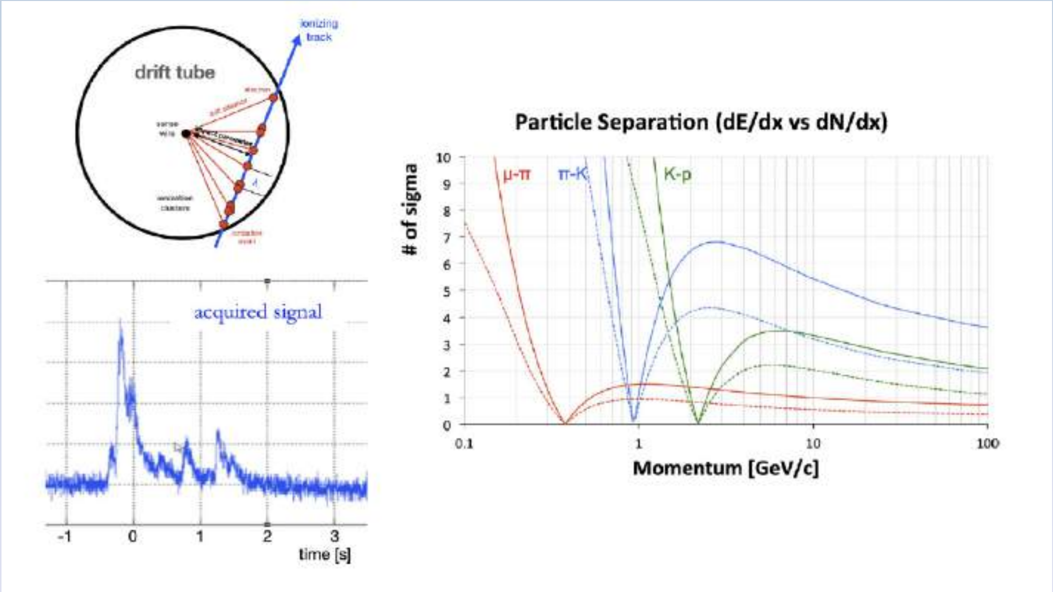
Primary number of ionizations per unit length is Poisson distributed

- Typically ~30 primary interactions (ionization clusters) / cm in gas at 1 bar

However, primary electrons sometimes get large energies

- Can make secondary ionization
- Can create visible secondary track (“delta-electron”);
- Large fluctuations of energy loss by ionization
- Typically: total ionisation = 3 x primary ionisation





Particle ID concept for IDEA central tracker - Proposed experiment for FCC-ee

Direct cluster counting - for instance resolving clusters in time - avoids problems associated with cluster fluctuations, truncated mean, in theory ultimate way to measure dE/dx

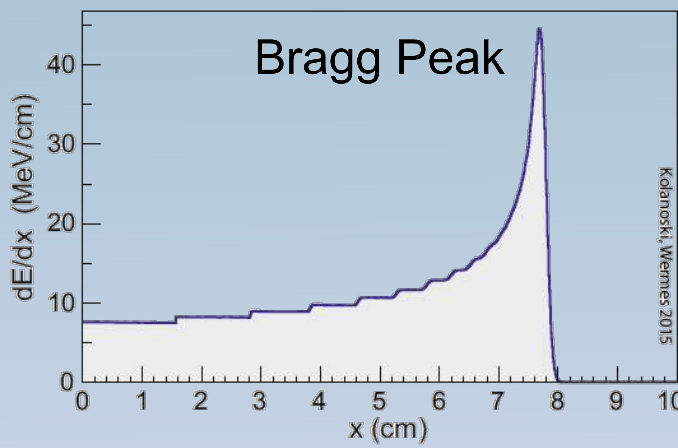
- Need proper detector geometry, with clusters arriving sequentially
- Slow gas with small drift velocity
- Gas with low cluster density
- Gas with low diffusion
- Electronics with sufficient time and multi hit resolution

Bethe Bloch inverted - Bragg peak

<dE/dx> grows rapidly as β^2 falls below the MIP level

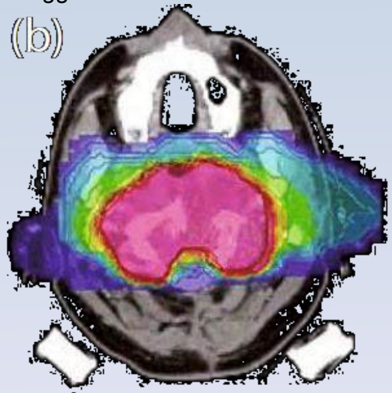
Hence, most heavy charged particles deposit their energy in a relatively narrow region

- Example (right): 100 MeV protons on water
- This “Bragg-Peak” can be exploited, e.g. in cancer treatment

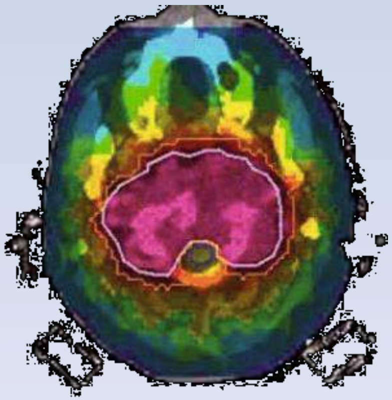


C^{12} ions

Bragg Peak

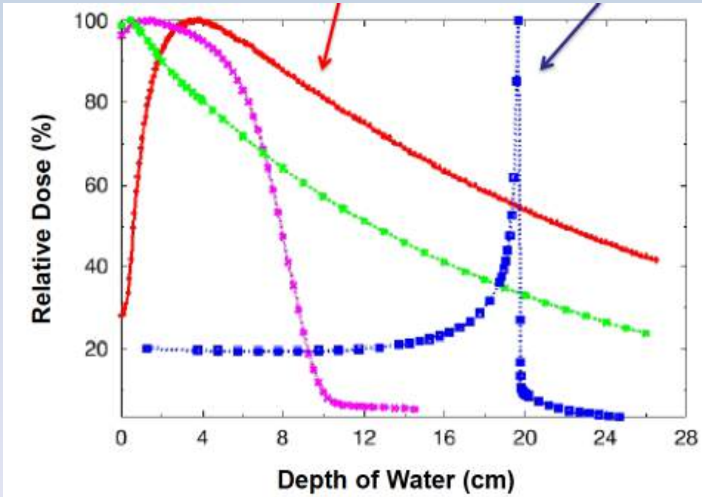


Gamma rays



25 MeV Photons

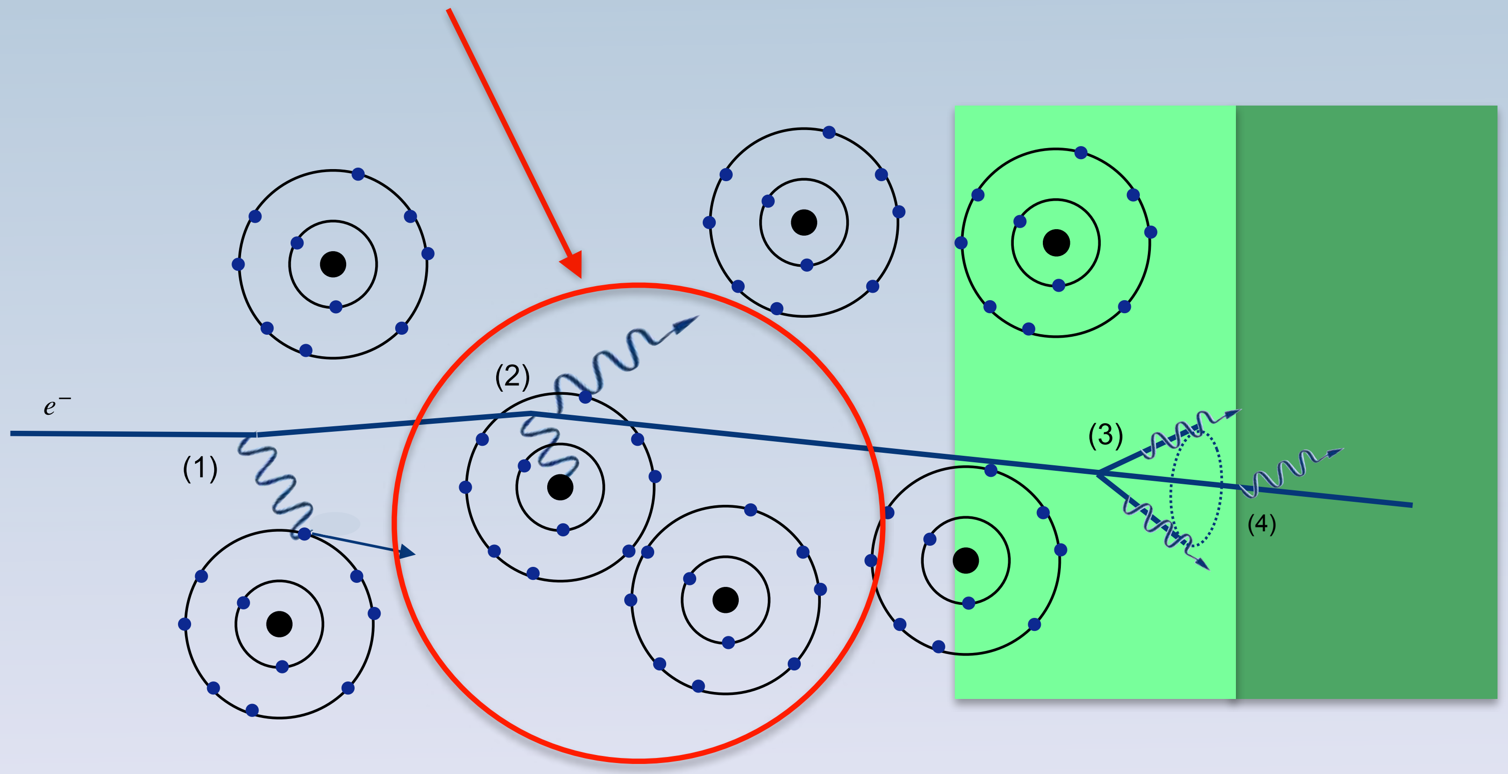
330 MeV Carbon ions



Bremsstrahlung

So far, we have discussed heavy charged particles where the ionization of the atomic shell is the most important source of energy loss

Particles can also lose energy by interacting with the nucleus or the atomic shell. These losses become important at ultra-relativistic energies. For electrons this bremsstrahlung is the dominant



Bremsstrahlung - essential dependencies

Proportional to $1/M^2$ of incoming particle

The bremsstrahlung of the muon is suppressed by a factor $(m_\mu/m_e)^2$ - 40000

The critical energy is defined, where bremsstrahlung (dominant at high energies) and ionization losses (dominant at lower energies) are the same.

- For muons: around 400 GeV
- For electrons: around 20 MeV

For our energies in past and present detectors, the EM Bremsstrahlung is only relevant for electrons

High Z materials have low E_c

Proportional to Energy of incoming Particle

Fractional energy loss is nearly independent of energy, therefore the loss per unit length is efficiently described by the 'radiation length' , after which the energy of a highly energetic electron reduces to $1/e$ (37%)

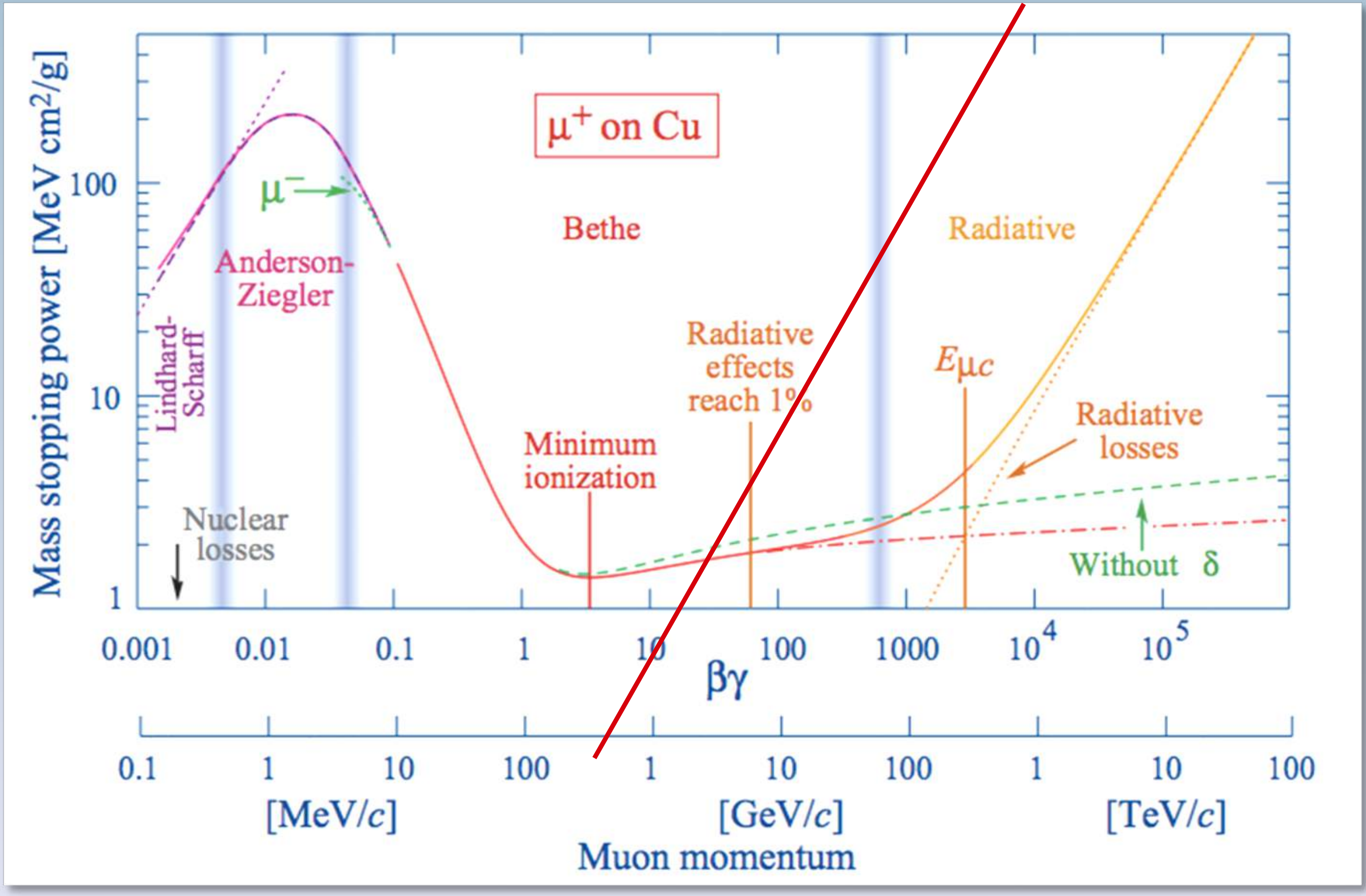
$$\frac{dE}{dx} = -\frac{E}{X_0}$$

The radiation length can be approximated to within 2.5% by the empirical expression:

$$\rho X_0 = \frac{716 \text{ g cm}^{-2} \text{ A}}{Z(Z+1)\ln\frac{287}{\sqrt{Z}}}$$

X_0 is very closely related to the interaction length λ, the distance a high energy photon has to travel before it converts into an e^+e^- pair, a very similar Feynman diagram

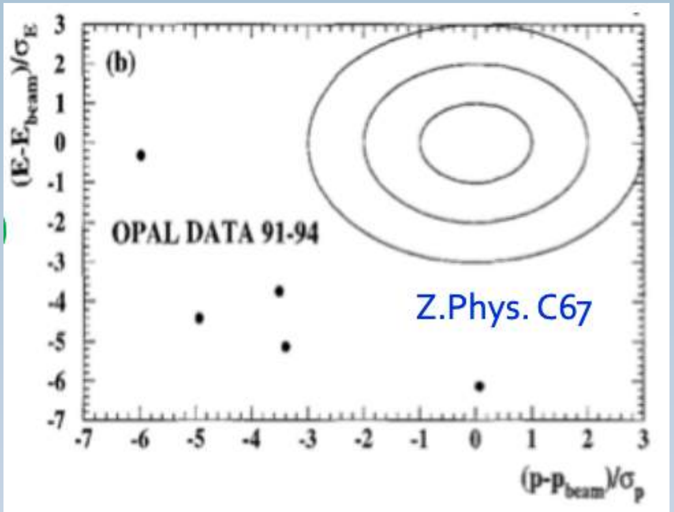
Putting it all together



Electron momentum. 5 50 500 MeV/c

Muon Bremsstrahlung in your future?

$Z \rightarrow e\mu$ search at FCC-ee



Current limit:

- 7.5 x 10-7 LHC/ATLAS (20 fb-1; no candidates)
- 1.7 x 10-6 LEP/OPAL (4×10^6 Z decays: no candidates)

Clean experimental signature:

- Beam energy electron vs. beam energy muon

FCC-ee will observe 10^{12} Z decays!

Main experimental challenge:

- Catastrophic bremsstrahlung energy loss of muon in electromagnetic calorimeter
  - Muon would deposit (nearly) full energy in ECAL: Misidentification μ → e (10^{-6} level)
- Possible to reduce by
  - ECAL longitudinal segmentation: Require energy > mip in first few radiation lengths
  - Aggressive veto on HCAL energy deposit and muon chamber hits
  - If dE/dx measurement available, (some) independent e/μ separation at 45.6 GeV

Misidentification from catastrophic energy loss corresponds to limit of about Br(Z →eμ) ≃ 10^{-7}

Possibly do "(10) better than that? Br(Z →eμ) ~ 10^{-9} - **this is the future, you will solve this!**

More on momentum error - X_0 strikes back

We already saw that for 3 points the relative momentum resolution is given by: $\frac{\sigma(p_T)}{p_T} = \sqrt{(3/2)}\sigma_x \frac{8p_T}{0.3BL^2}$

- Error degrades linearly with transverse momentum
- Error improves linearly with increasing B field
- Error improves quadratically with radial extension of detector

In the case of N equidistant measurements we can use the Gluckstern formula [NIM 24 (1963) 381]

$$\frac{\sigma(p_T)}{p_T} = \frac{\sigma(\kappa)}{\kappa} = \frac{\sigma_x \cdot p_T}{0.3BL^2}\sqrt{\frac{720}{(N+4)}}$$

Example:

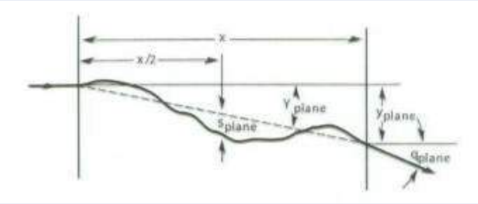
$p_T = 1GeV, L = 1m, B = 1T, \sigma_x = 200\mu m, N = 10 :$

We obtain:

$\frac{\sigma(p_T)}{p_T} = 0.5\ \%$ for a sagitta of 3.8 cm

However, the multiple collisions experienced by the particle lead to a probability of deflection by an angle θ after traveling a distance x in the material. This is a gaussian distribution with sigma of:

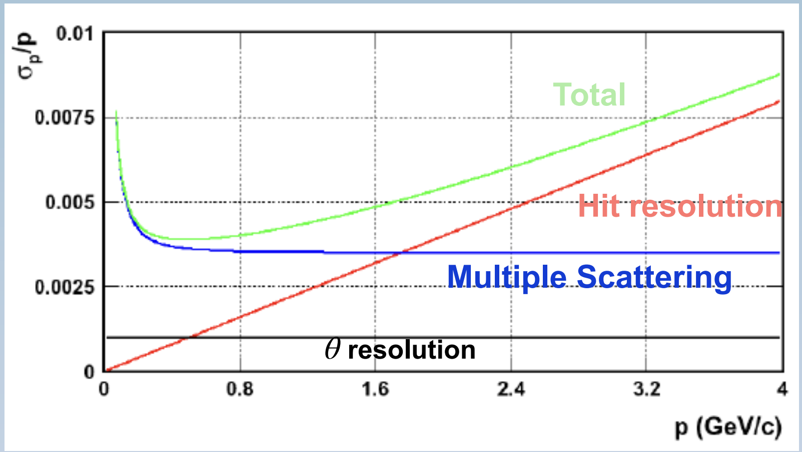
$$\Theta_0 = \frac{0.0136}{\beta cp[\mathrm{GeV/c}]} Z_1 \sqrt{\frac{x}{X_0}}$$



Example: ATLAS muon spectrometer

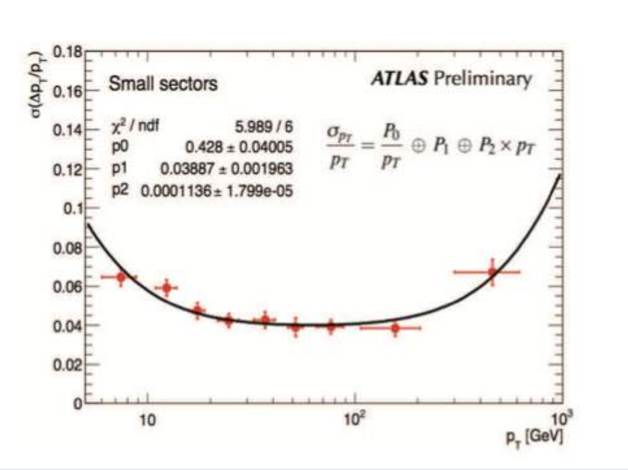
For $\beta \to 1$ multiple scattering error is momentum independent!

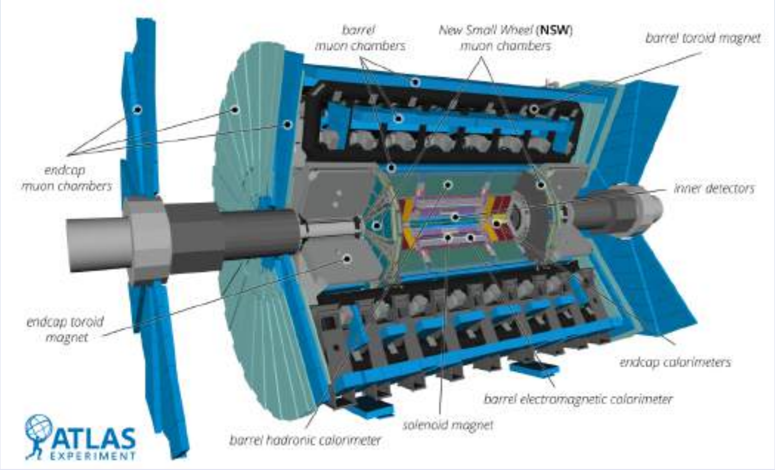
$$\frac{\sigma(p_T)}{p_t} = \frac{0.2}{\beta B\sqrt{(LX_0 \sin\theta)}}$$

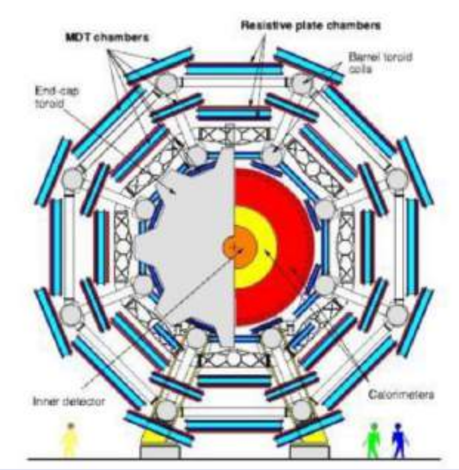


Example: ATLAS muon spectrometer
N = 3, $\sigma_x = 50\mu\text{m}, \text{P} = 1\text{TeV}$, L = 5m, B = 0.4 T

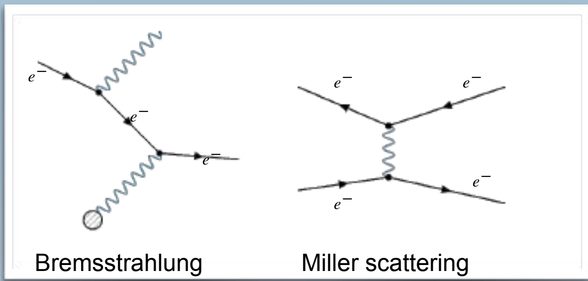
$\Delta p/p \approx 8\,\%$ for the most energetic muons at LHC
Multiple scattering limited for lower momenta



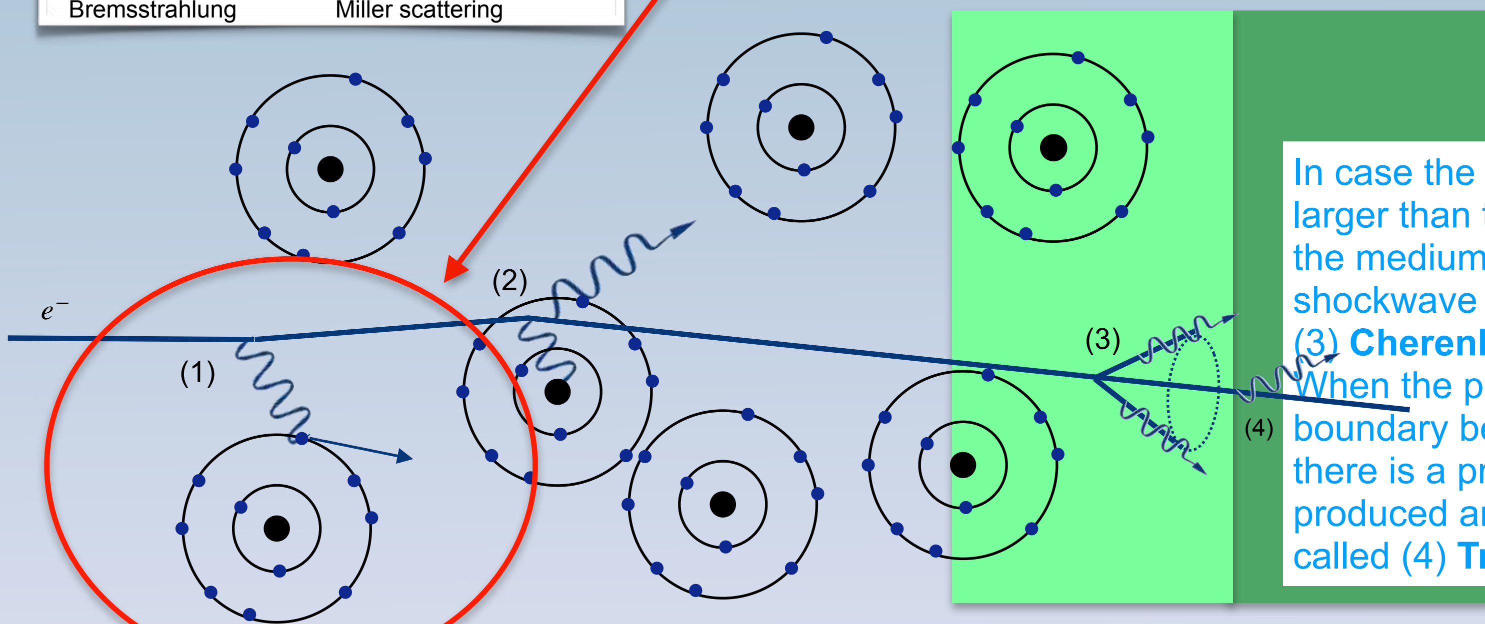




Electromagnetic interactions of charged particles



Let’s now discuss briefly gaseous tracking applications, which are large volume tracking applications principally driven by this EM process



In case the particle's velocity is larger than the velocity of light in the medium, the resulting EM shockwave manifests itself as (3) **Cherenkov Radiation.**
When the particle crosses the boundary between two media, there is a probability (~1%) to produced an X ray photon, called (4) **Transition radiation.**

(1) **Interaction with the atomic electrons.**
The incoming particle loses energy and the atoms are excited or ionized

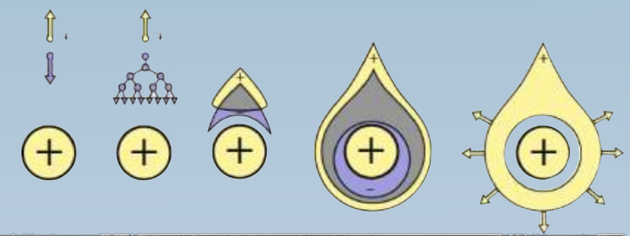
(2) **Interaction with the atomic nucleus.**
The particle is deflected causing multiple scattering in the material. During this scattering a Bremsstrahlung photon can be emitted

Overview

Charged particles ionize atoms, producing electrons and ions

These drift (and diffuse) in applied electric field, inducing signal charges

Typically field close to the anode wire multiplies the signal through secondary ionization



The amplification G is defined as the ratio of collected electrons at the anode wire N_A to the number of primary electrons N, G = NA/N.

$G < 1$: Recombination

- Weak field cannot separate e/ion pairs

$G \approx 1$: Ionisation chamber

- no amplification. Useful for dosimetry/flux meas.

$G \approx 10^3 - 10^5$ Proportional counter / proportional mode

- An avalanche develops; total number of charge carriers is proportional to the number of primary carriers.

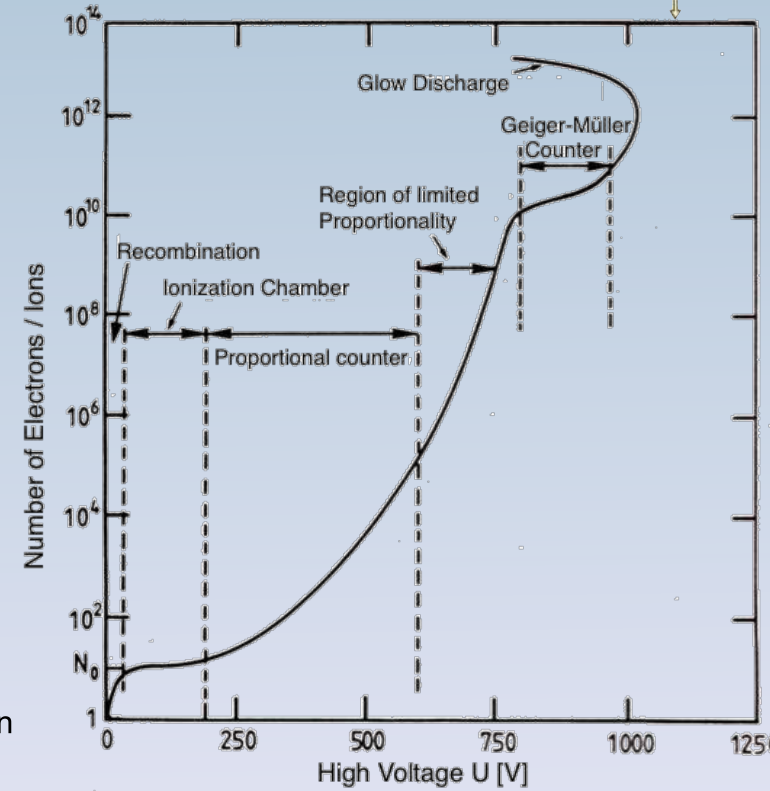
$G \approx 10^5 - 10^8$: Region of limited proportionality

- The slowly moving ions begin to shield the electric field around the anode.This effect increases with the primary ionization

$G > 10^8$: Geiger (or saturation) region

- Signal is independent of the primary ionization. The detector counts.

Discharge operation: triggered by a single e-/ion pair, the electrodes connect by a streamer (extended avalanche in direction of E field) that develops into an extended plasma flux tube which fully discharges the electrodes.



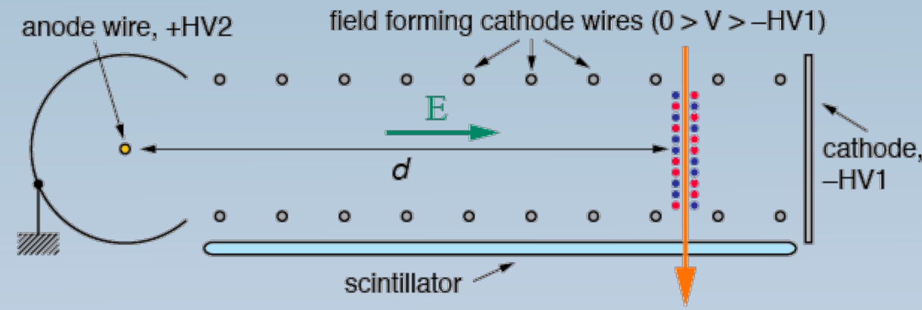
Other factors to consider; mobility, ionization density, radiation length of gas, quenching gas, geometry of field, orientation of cathode readout compared to anode readout,, gas lifetime, environmental, cost…

Drift Chambers

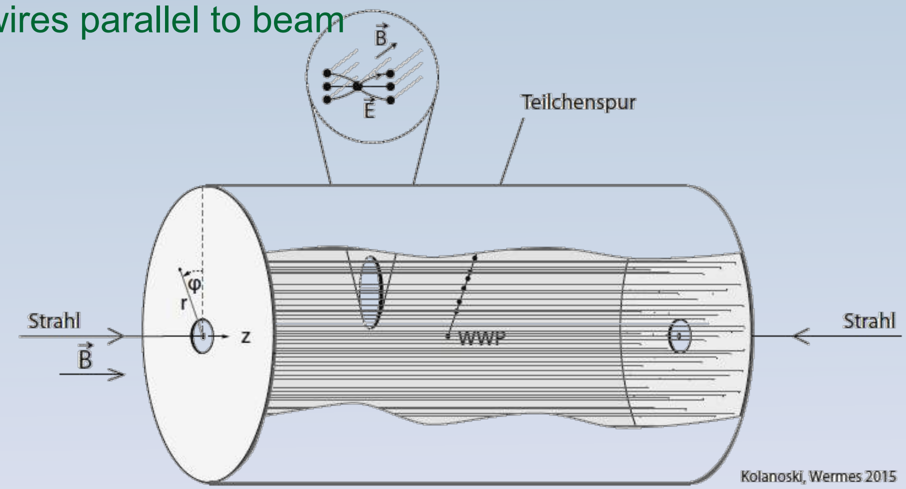
Operating principle: Take into account e^- drift time and separate drift and amplification

Need a homogenous field (can define with additional field wires) and constant and well known drift

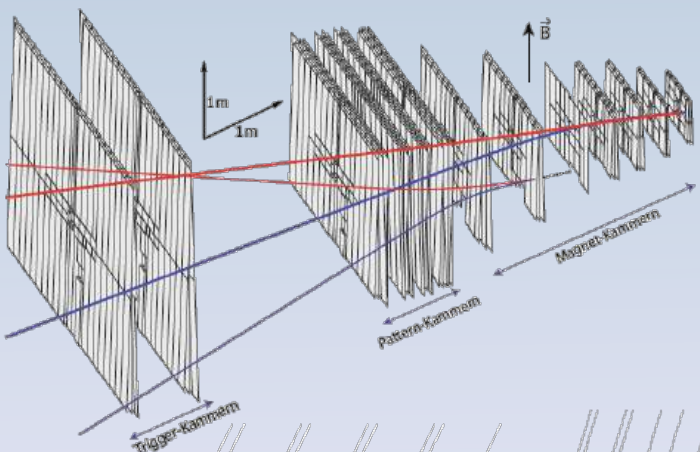
The drift time gives the distance to the wire, allowing a big reduction in the number of wires read out for the same resolution



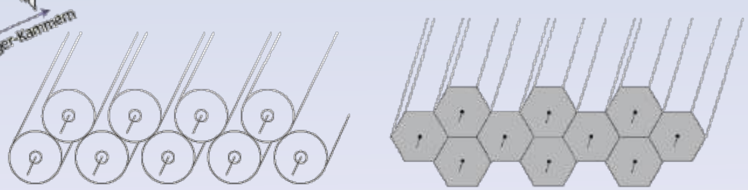
Cylindrical drift chamber with cathode and anode wires parallel to beam



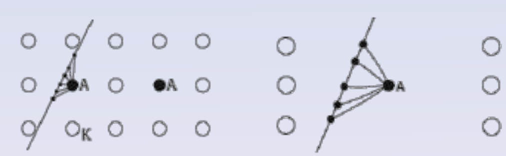
Fixed target (Hera-B outer tracker): planar drift chambers, partially tilted, wires orthogonal to beam



Pipes round/ hexagonal

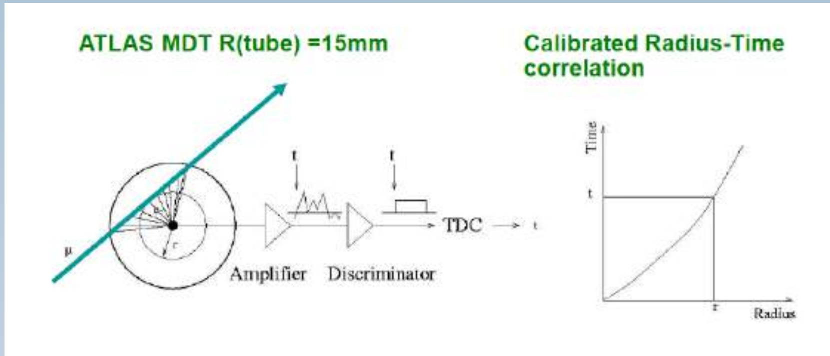


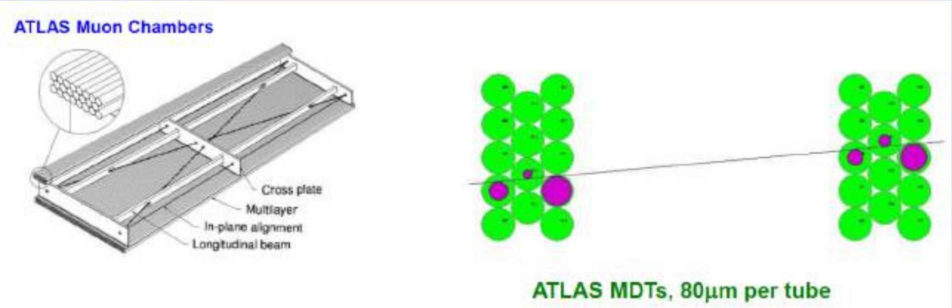
Different cathode and anode wire assemblies



Drift chambers

ATLAS MDT

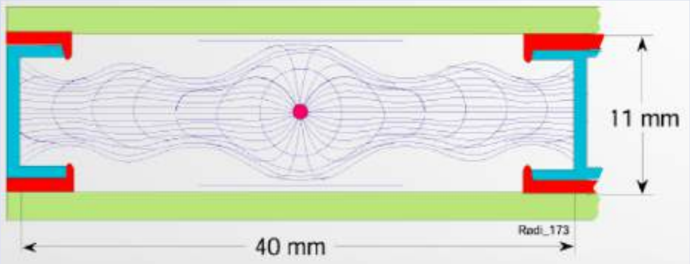


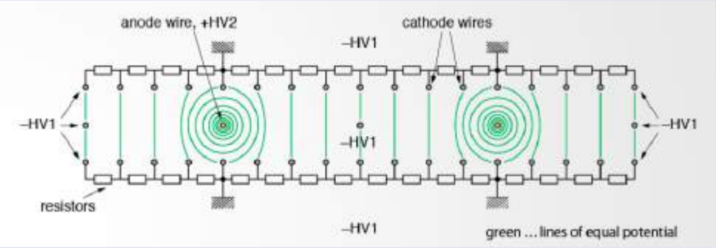


Belle Central drift chamber

50 cylindrical wire layers, 8400 drift cells

CMS DT muon system





Time Projection Chamber (TPC)

Gas volume with parallel E and B field

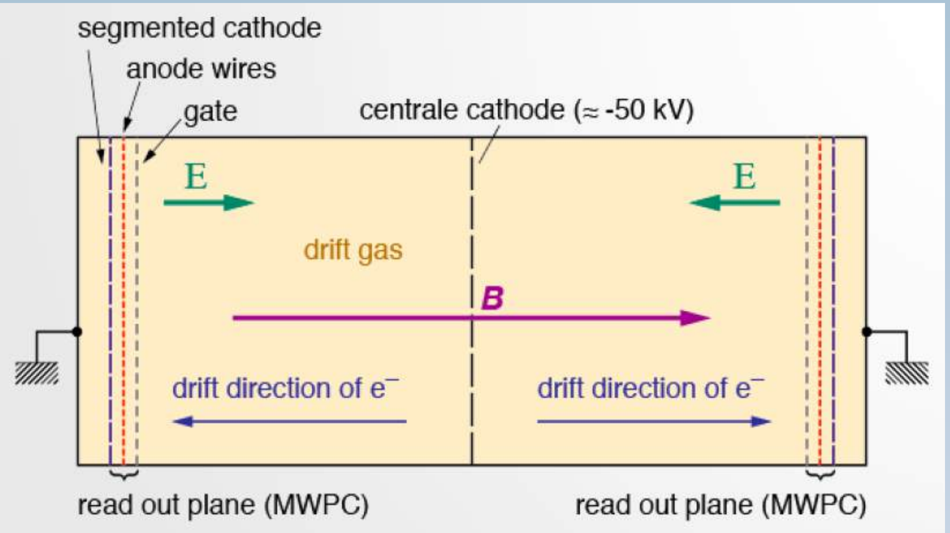
B for momentum measurement, and to strongly suppress diffusion

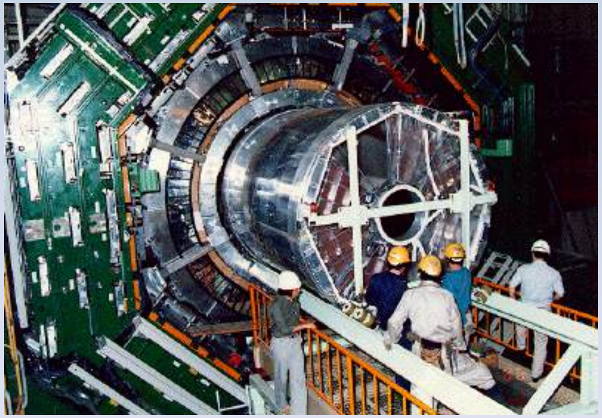
Two dimensions come from the position detectors at the end plates

The third coordinate is deduced from the time of arrival of the electrons at the anode wires

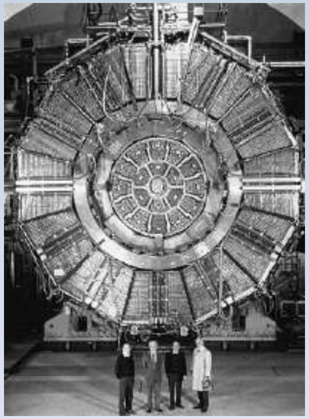
Gate electrodes are used to absorb ions drifting back (most come from the amplification region near the anode wires

New generation of TPCs use MPGD-based readout, e.g. ALICE Upgrade, T2K, CepC



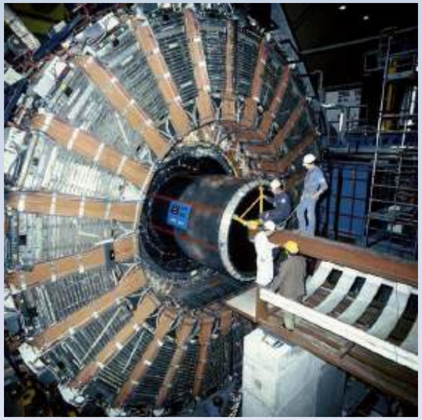


TOPAZ (KEK)



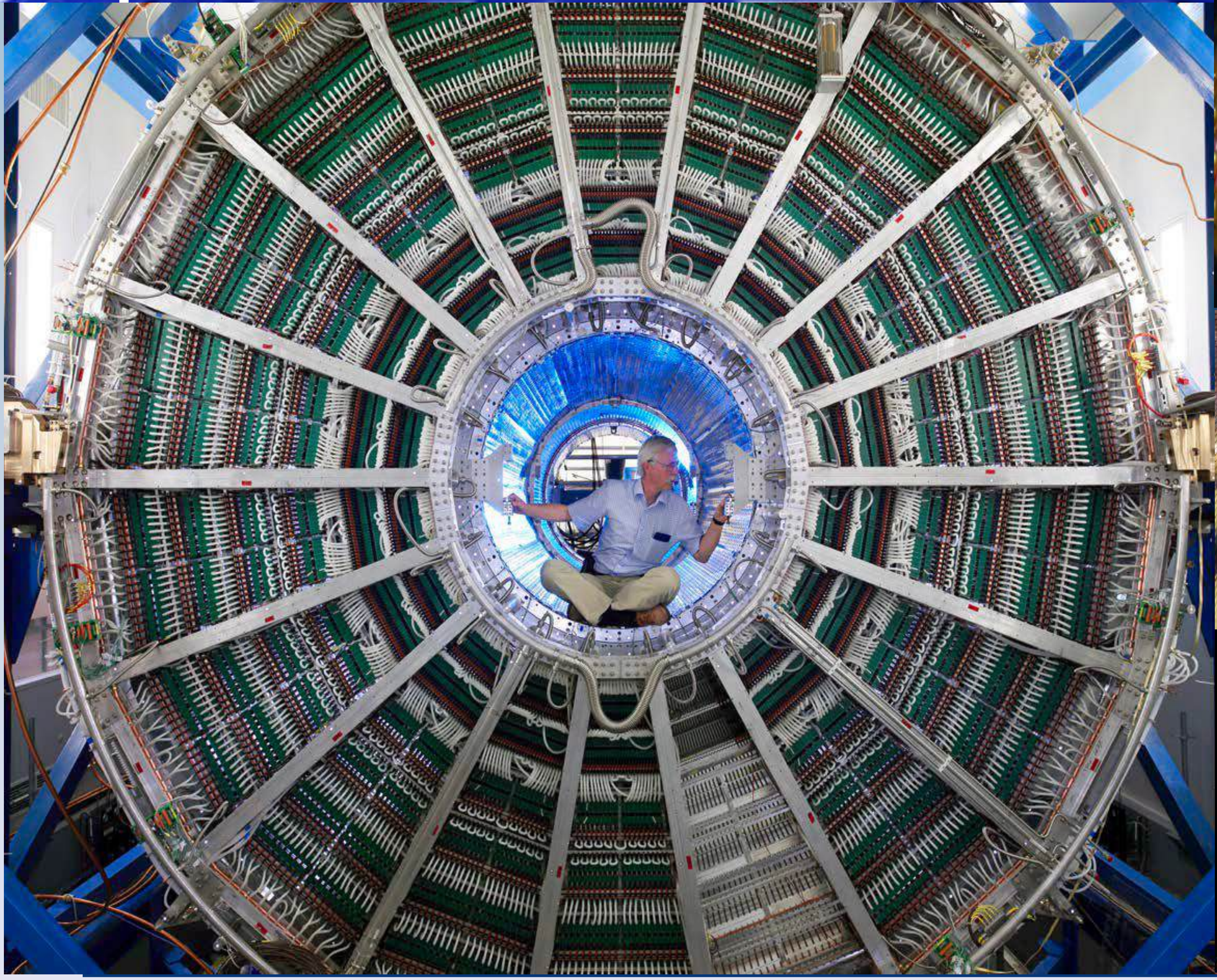
ALEPH (CERN)

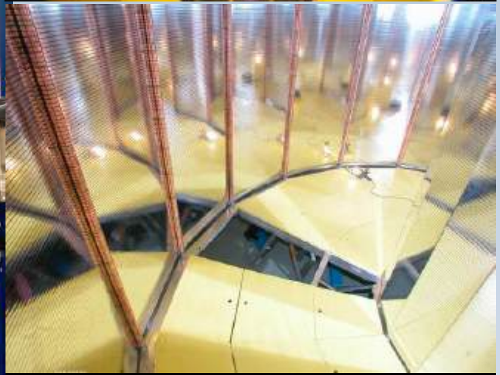
STAR (LBL)

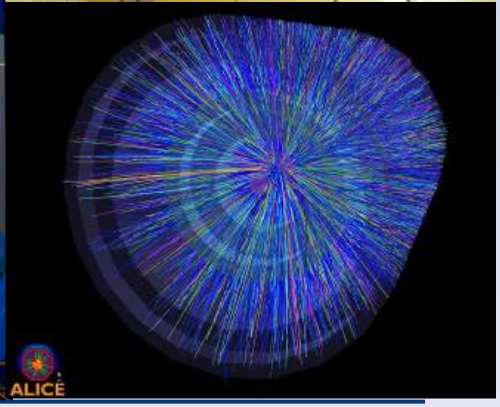


DELPHI (CERN)

Time Projection Chamber (TPC)



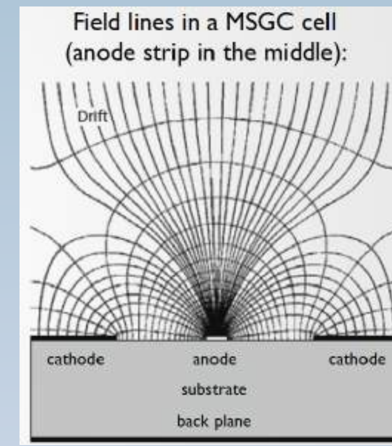




Micro Pattern Gas Detectors

Use of modern techniques, electrodes formed by deposited materials or printed structures, to address the limitations of gaseous detectors with wires.

- Much smaller dimensions possible using techniques such as photolithography
  - $\rightarrow$ improved position resolution $\sim$ 30 μm
- Cathode strips improve field geometry and collect ions from amplification
  - $\rightarrow$ high rate capability $\sim$ MHz/mm^2
- No risk of catastrophic damage from broken wires
- Infinite detector geometries
- Possibility to separate ionization and amplification structures
  - $\rightarrow$ enhanced radiation resistance



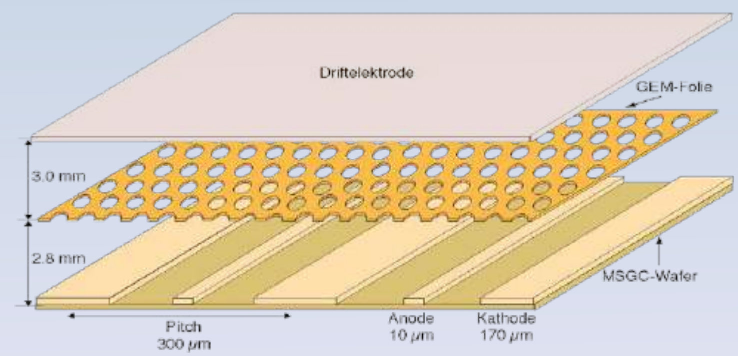
Example: The Gas Electron Multiplier (GEM)

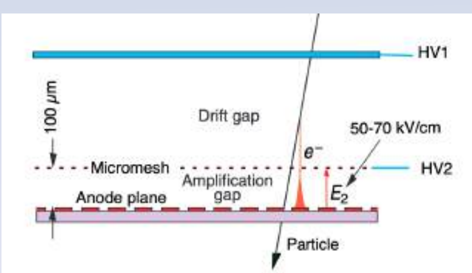
Gas volume is separated into a drift gap and induction gap with a GEM foil or multiple foils metallized on both sides

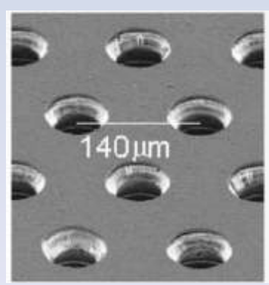
e.g. 50 μm thick,hole pattern e.g. 70 μm with 140 μm pitch

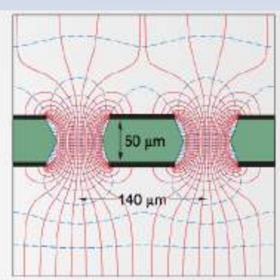
400V HV applied - gains up to 10^5

MSGC readout plane underneath





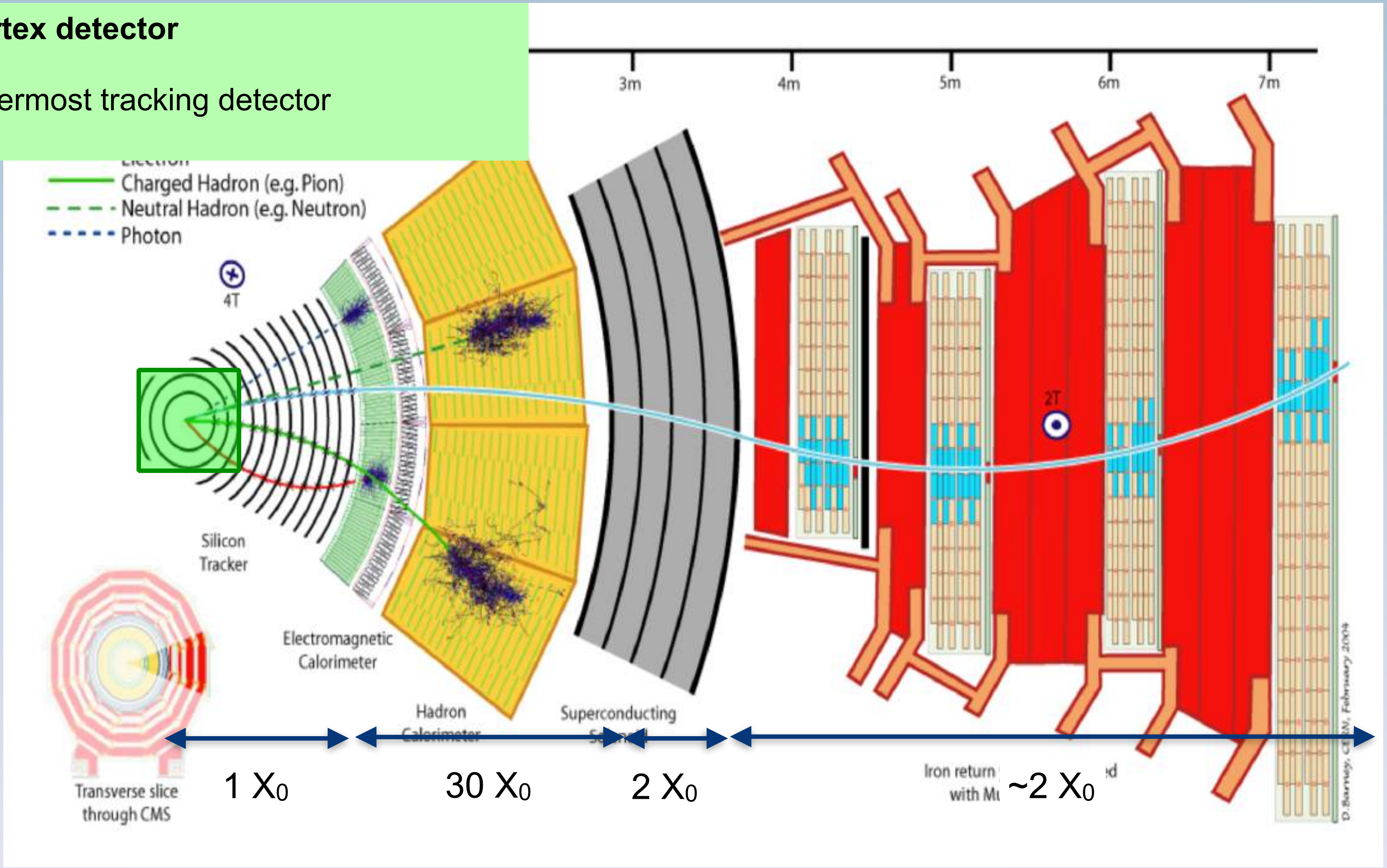




Let's come back to Detector Layout

Vertex detector

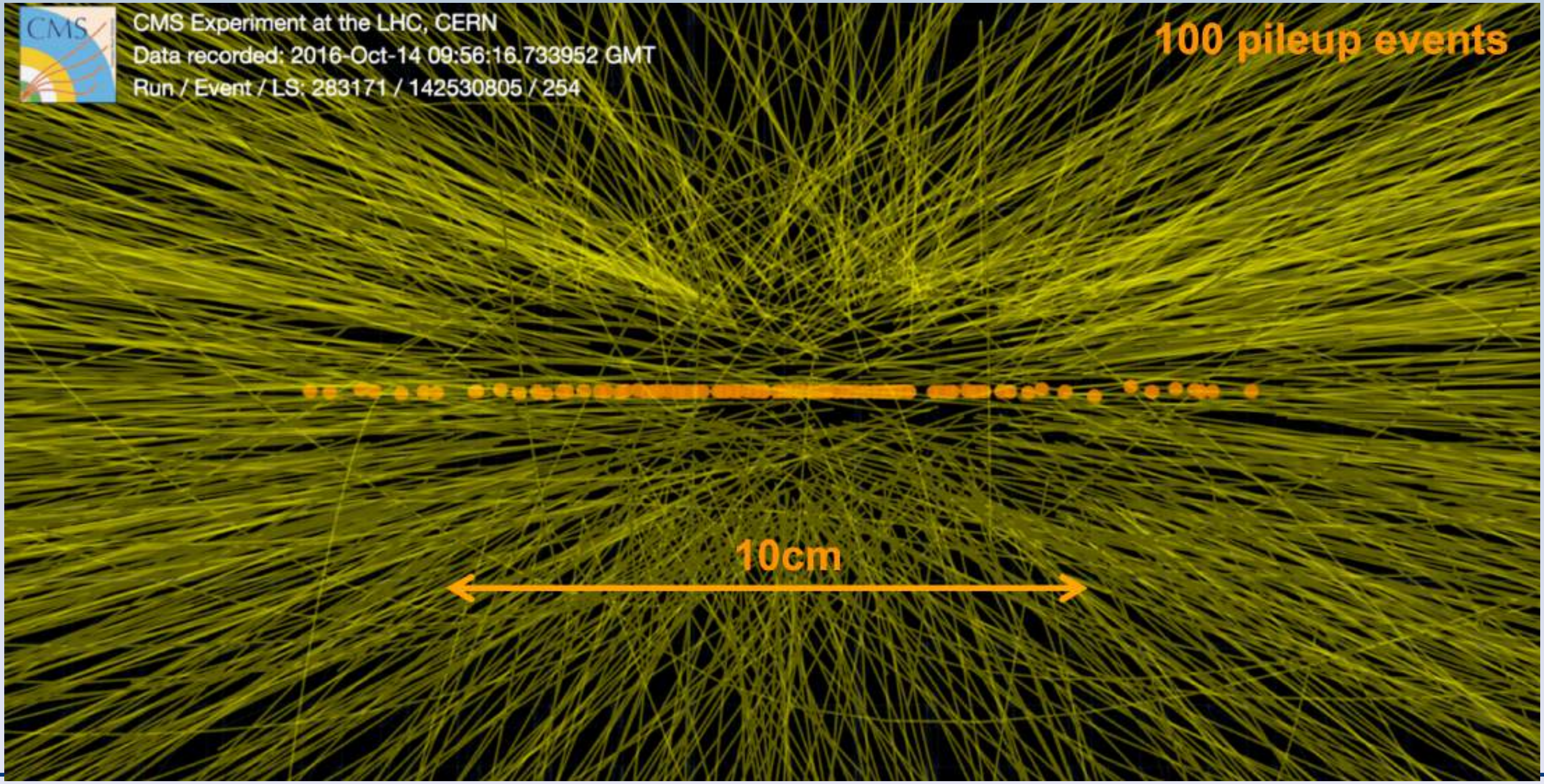
Innermost tracking detector



Vertex Detector tasks

Finding the event origin: Where did the collision occur?

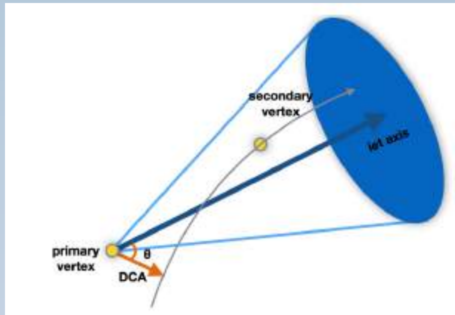
- Primary vertex reconstruction
- Time dependent measurements depend on accurate primary vertex reconstruction and correct assignment of secondary vertex to primary
- Challenging in case of multiple collisions per event

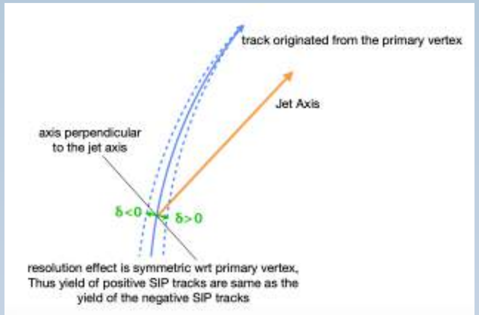


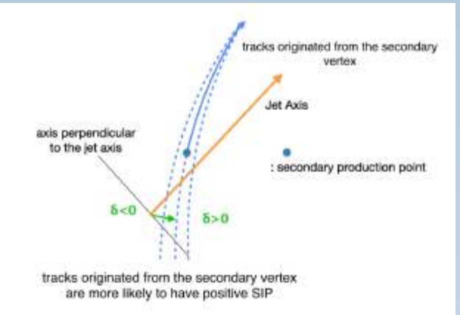
Vertex Detector tasks

Inclusive reconstruction and flavour tagging

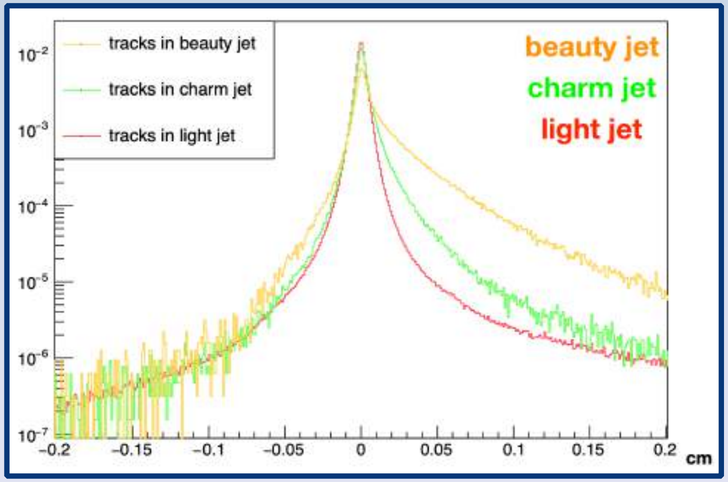
- Use of signed impact parameter for flavour tagging
- Use of secondary vertex taggers







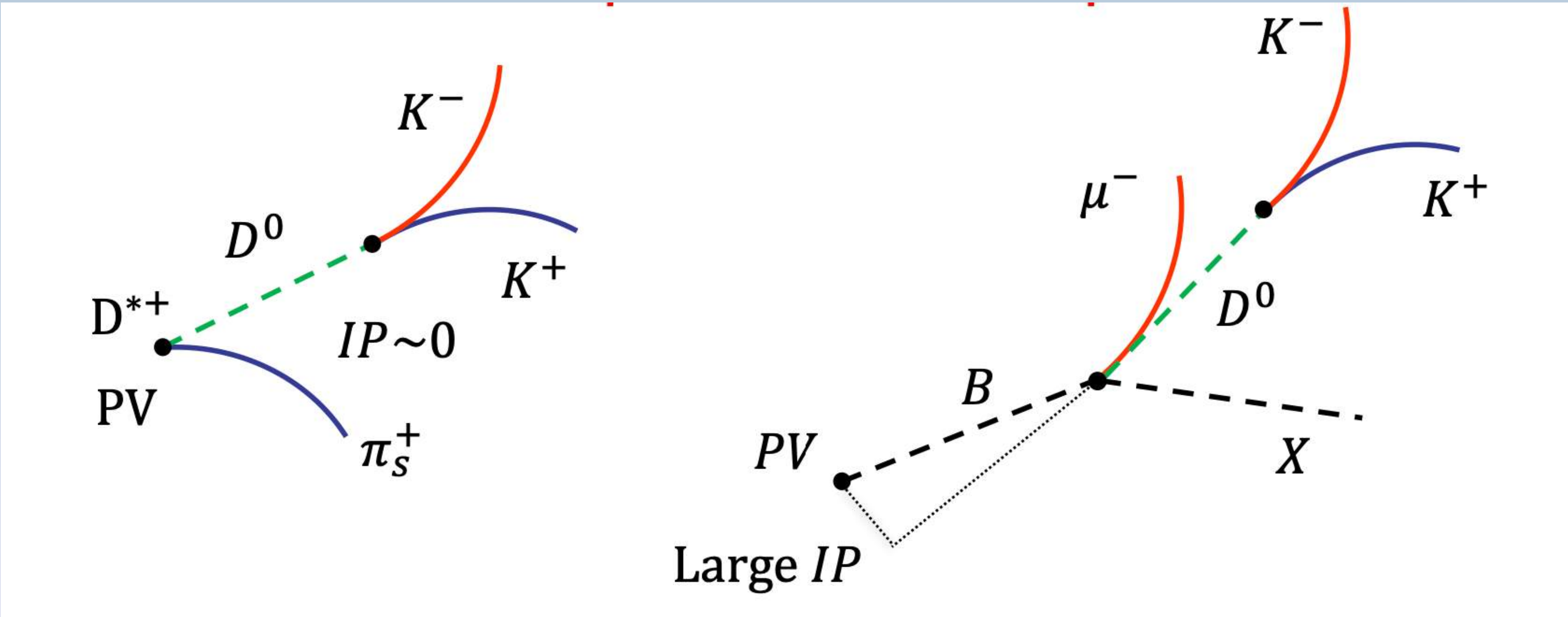
Need impact parameter resolution in the range of 10-100 μm



Vertex Detector tasks

Secondary and tertiary vertex reconstruction

LHCb CP violation measurement uses **both** prompt D^0 and D^0 from B vertex

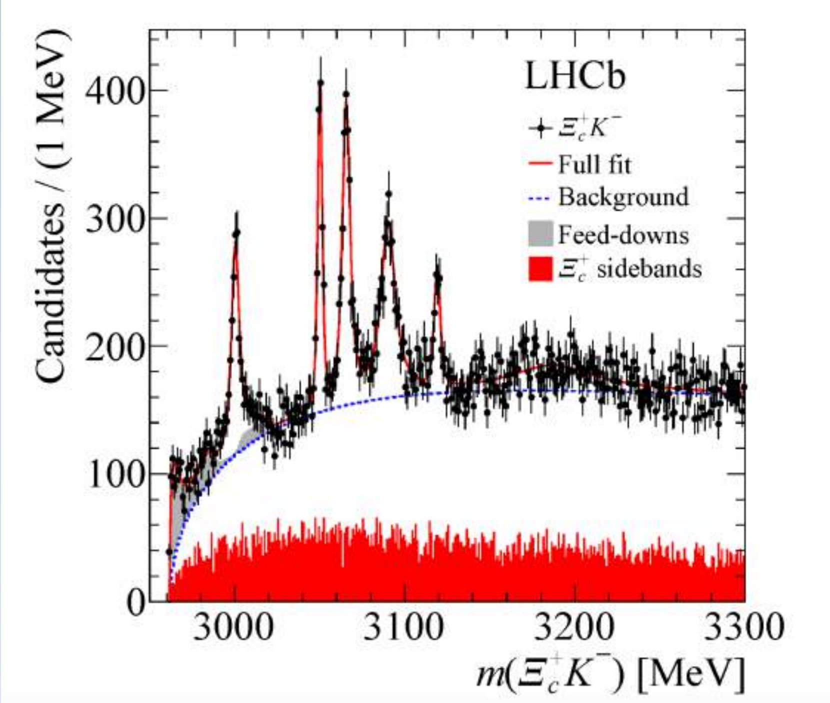


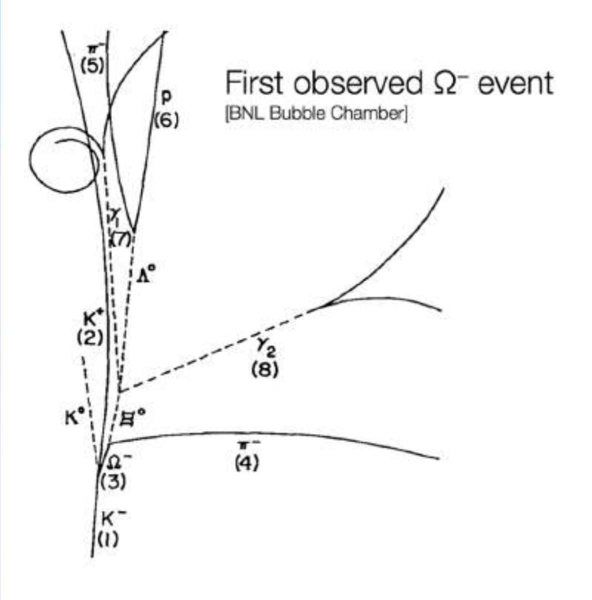
Vertex Detector tasks

Secondary and tertiary vertex resolution

Exclusive reconstruction and mass resolution

Example from LHCb; five narrow Ω_c states, decaying to $\Xi_c K^-$





Spiritual descendant of first bubble chamber Ω^- observation!

Vertex Detector tasks

For all collider experiments the Vertex Detectors have to peer back to the interaction region - usually through a beam pipe

- Irreducible extrapolation uncertainty

Beam pipe design is a crucial and complex part of the vertex detector global design

- Allow the passage of the colliding beams, taking into account beam angles at collision, detector magnetic fields, beam injection…
- Shield the detector from beam pickup
- Provide for beam mirror currents
- Be cooled if necessary
- Be as light as possible
- Be as small as possible
- Withstand beampipe vacuum (or be inside LHC vacuum as for LHCb)
- Provide for vacuum compatible coating and bakeout procedures

4 cm CMS beryllium

Run 1 beampipe

Collider Vertex Detector layouts

At a collider, the vertex detector is extrapolating the tracks back to the interaction region usually through the intermediate material of the beam pipe

Crucial quantities:

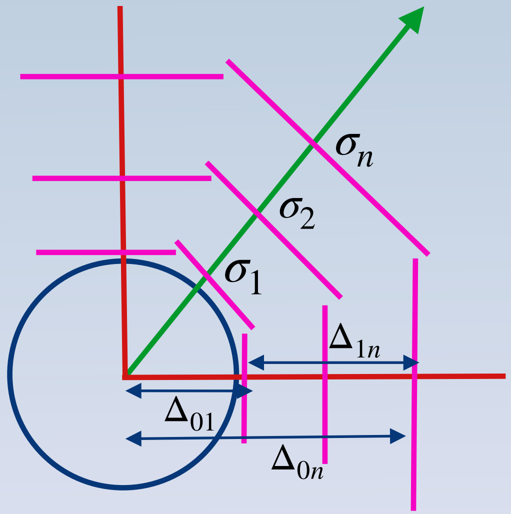
- Point precision, in particular that of the innermost layer, closest to the interaction region
- Material of the beampipe and detector dead material before the first and second measured points
  - Beryllium beam pipes
  - Smallest possible dead area/guard rings around edge of detector ladders
  - Lightweight mechanics and cooling
- Lever arm of the measurement after the first point
  - A detector with minimum material per layer has a larger effective lever arm, because the layers further away play a stronger role, even for low P_T tracks

Keep in mind that tracks from beauty and charm decays typically have lower P_T

Collider Vertex Detector layouts

At a collider, the vertex detector is extrapolating the tracks back to the interaction region usually through the intermediate material of the beam pipe

Geometry dependent term
(illustrated in transverse plane)



$$\sigma_{ip}^2 \propto \frac{\Delta_{0n}^2 \sigma_1^2 + \Delta_{01}^2 \sigma_n^2}{\Delta_{1n}^2}$$

For the best impact parameter precision:

σ (the point resolution) as small as possible
Δ_{01} (the innermost radius) as small as possible

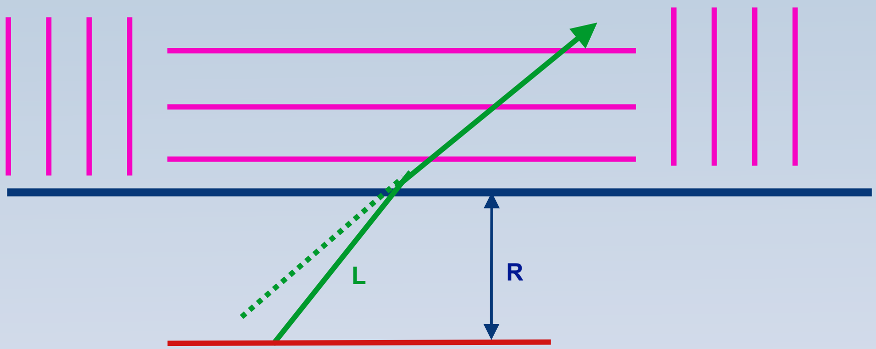
The value of n depends on the momentum of the particle and the material of the tracking layers. For high momentum, the effective lever arm increases.

(layer 1 and layer n are the two layers contributing most to the track measurement)

Collider Vertex Detector layouts

At a collider, the vertex detector is extrapolating the tracks back to the interaction region usually through the intermediate material of the beam pipe

Material budget dependent term (illustrated in longitudinal plane)



$$\sigma_{ip} \propto L\frac{\sqrt{X_0}}{p} \propto \frac{R}{p_T}\sqrt{X_0}$$

For the best impact parameter precision:

$\sqrt{X_0}$ (the material) as small as possible

R (the innermost radius) as small as possible

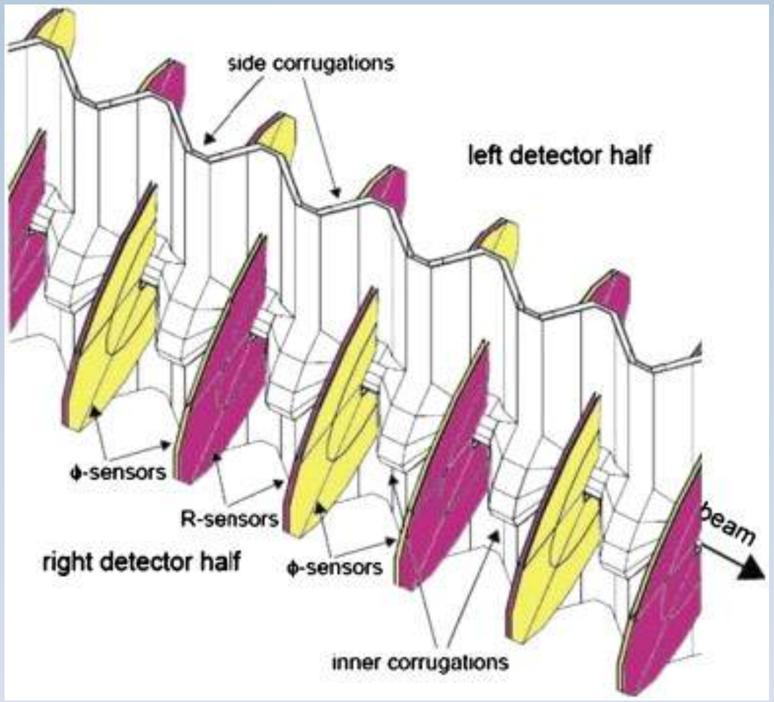
- This is the reason why impact parameter resolution is often plotted as a function of $1/P_T$
- the same formula holds for the forward part, as long as the detector design is arranged in such a way that R is roughly constant
- For circular beampipes there is an additional $1/\sqrt{\sin(\theta)}$ term that comes from the beampipe material
- note that (counterintuitively!) moving the beampipe closer to the beamspot improves the performance

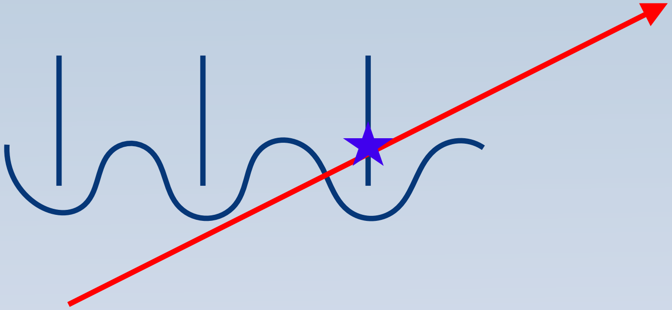
For an excellent discussion of tracking considerations see talk of Jerome Baudot at the ESIPAP conference

Collider Vertex Detector layouts

Note; the beam pipe does not have to be cylindrical

- for instance in the case of roman pot style detectors



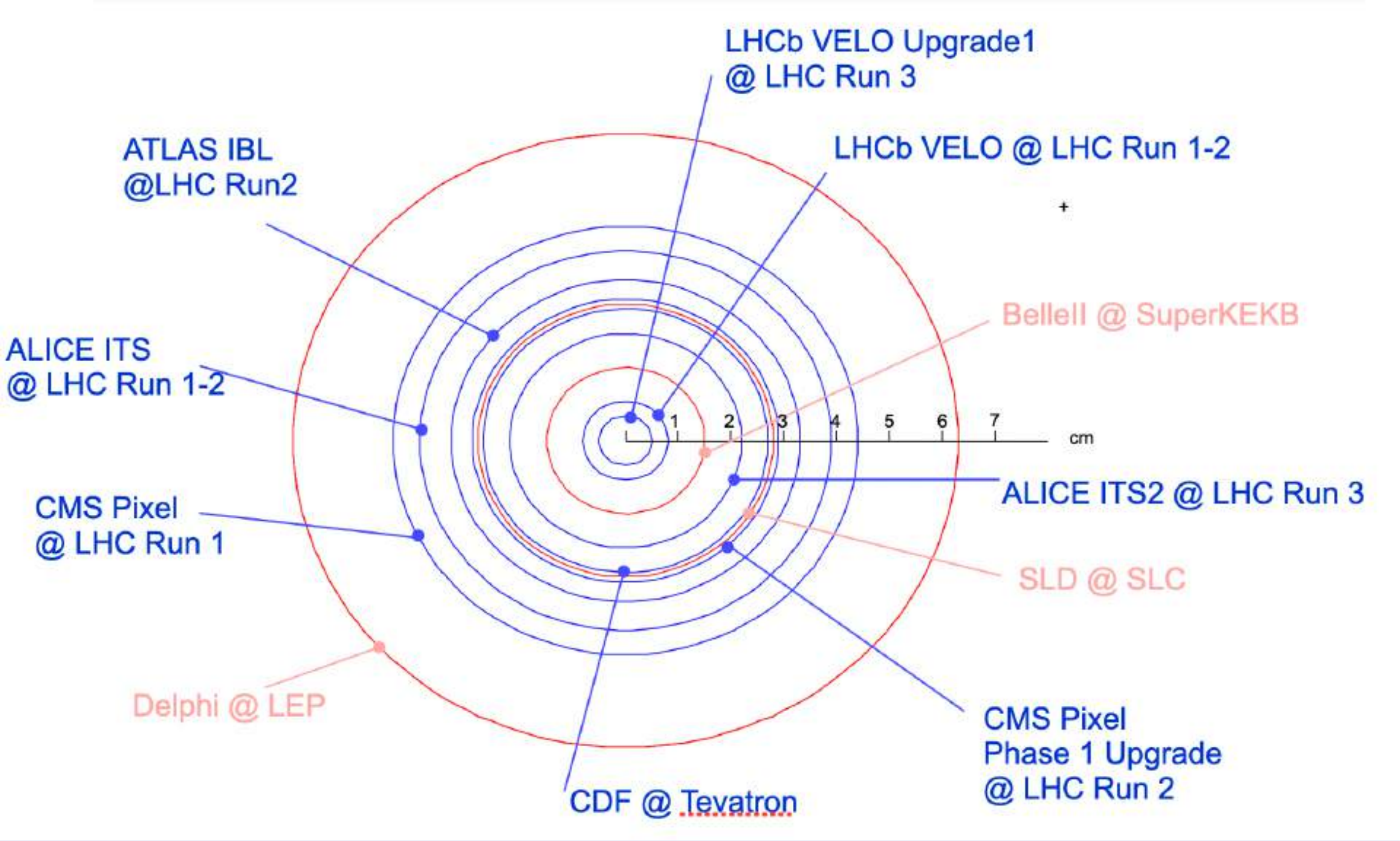


Track passes through "beampipe" perpendicularly, so no additional $1/\sqrt{sin\theta}$ term

For LHCb (which we will discuss more later)
the "beampipe" is extremely thin, and corrugated

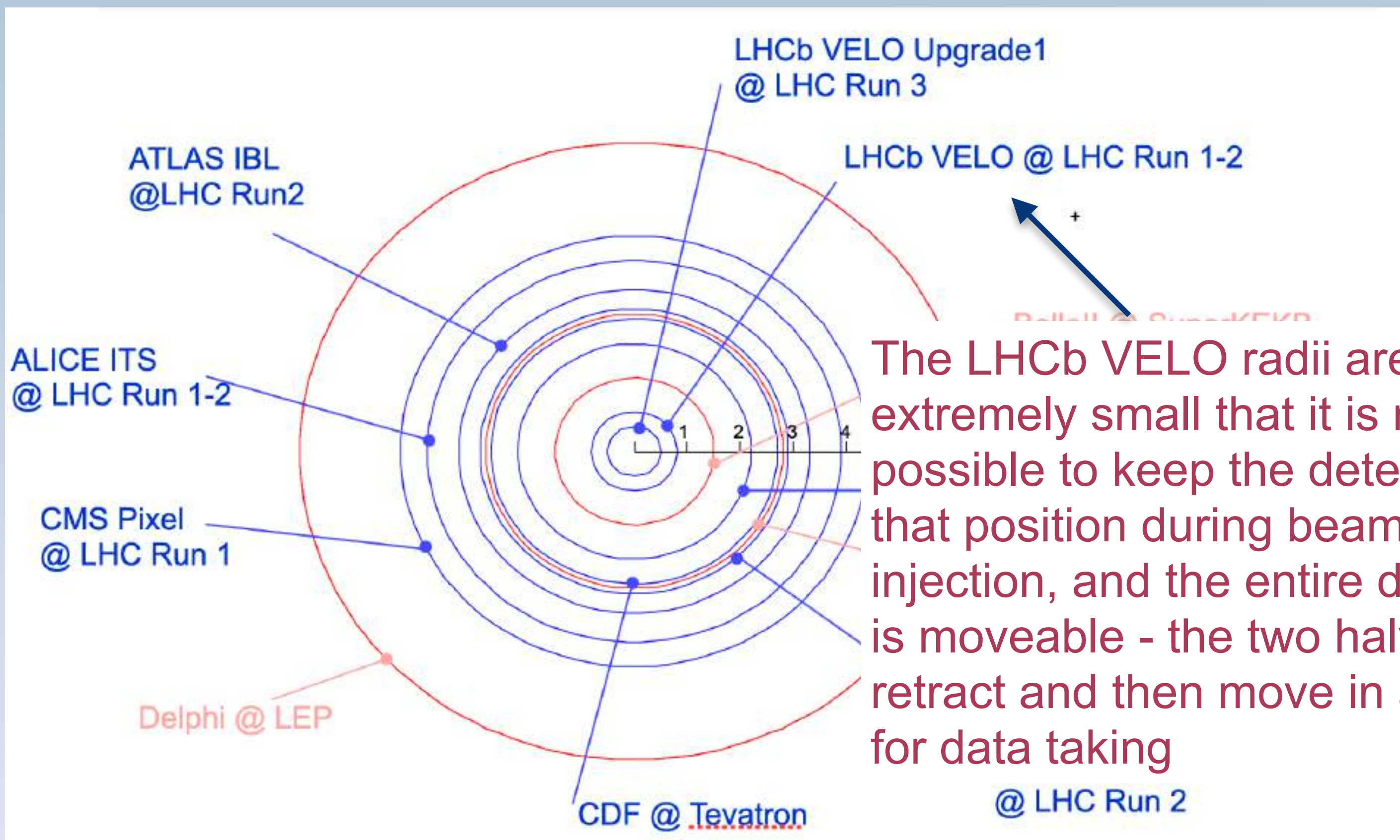
Minimum radius - the holy grail

Minimum radius of silicon vertex detectors at hadron and lepton colliders, up to start of LHC Run 3



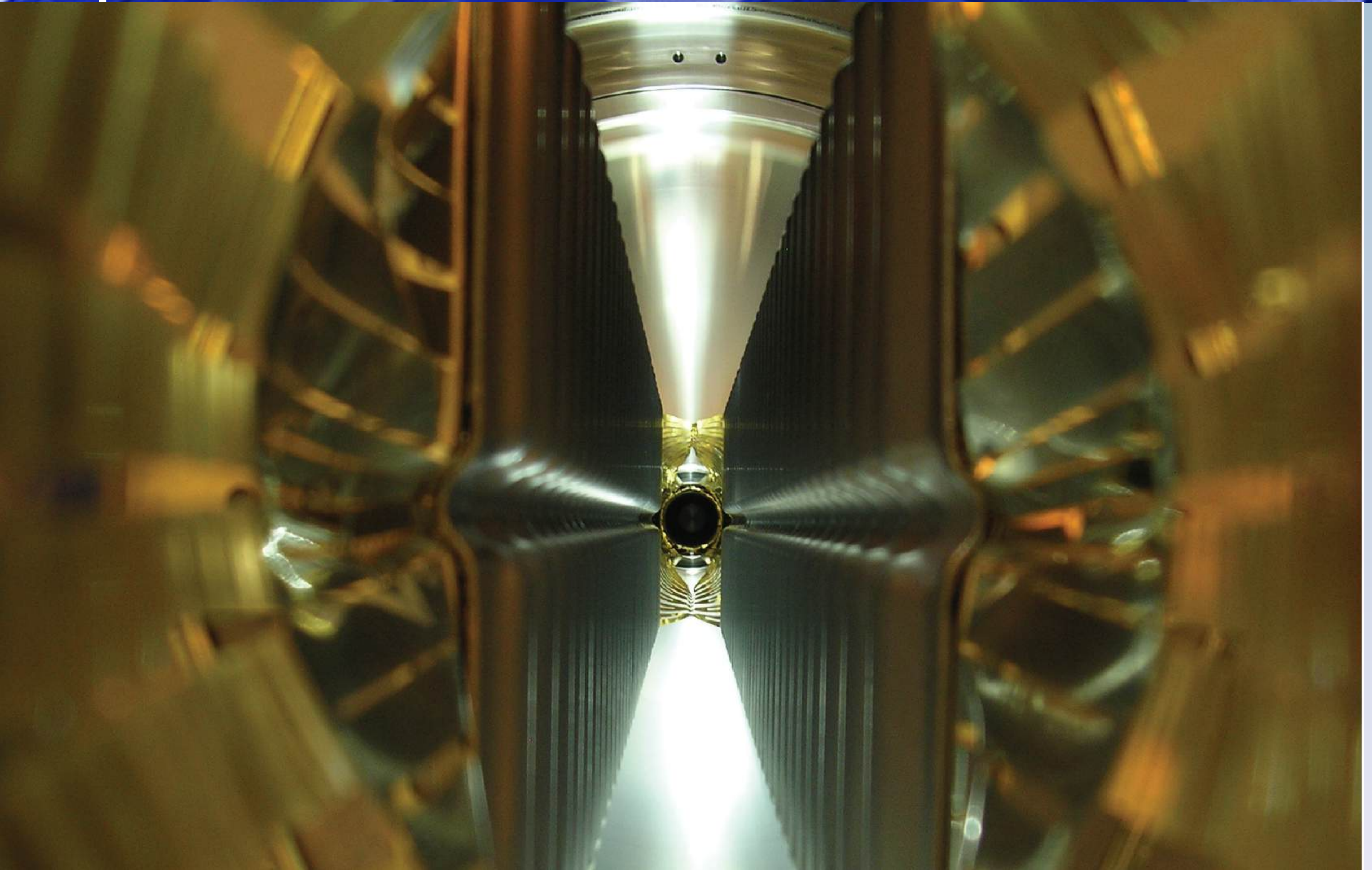
Minimum radius - the holy grail

Minimum radius of silicon vertex detectors at hadron and lepton colliders, up to start of LHC Run 3

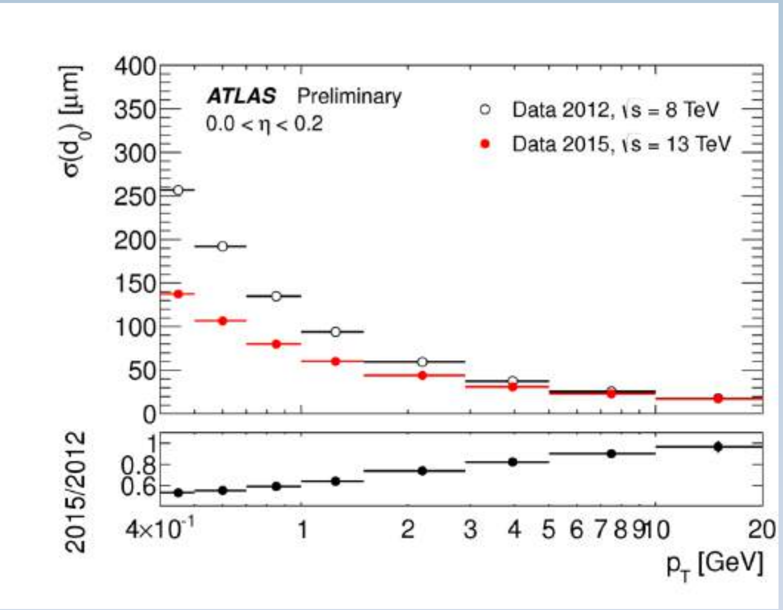


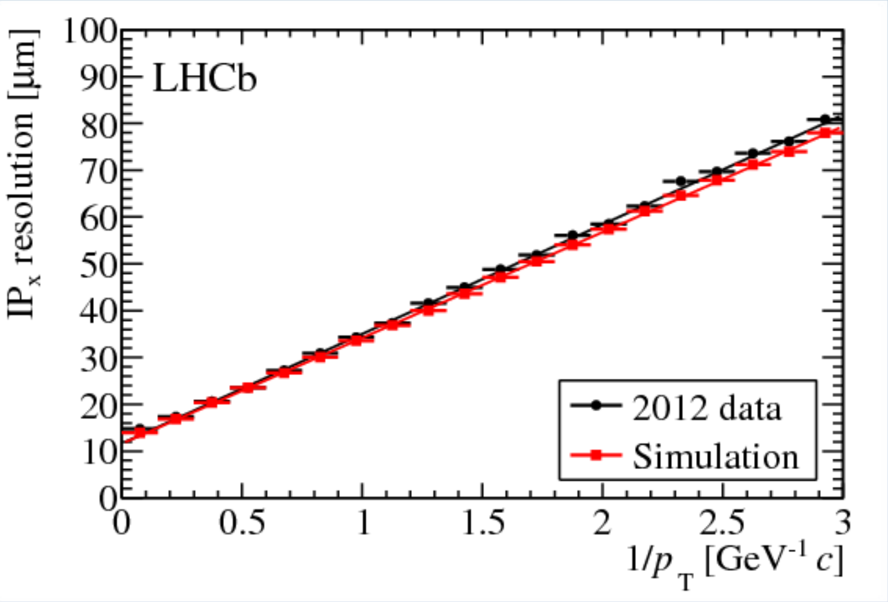
The LHCb VELO radii are so extremely small that it is not possible to keep the detector at that position during beam injection, and the entire detector is moveable - the two halves retract and then move in again for data taking

What the protons see



Example IP resolutions from LHC





ATLAS, before and after the introduction of the IBL which decreased inner radius

LHCb (plotted for $2 < \eta < 5$)

The rise of semiconductor based detectors

The idea of constructing a particle detector from solid state material leads to contradictions:

A small band gap E_g leads to a large signal from ionization - Germanium, Silicon, CdTe… but an enormous number of thermally produced charge carriers, leading to two much noise at room temperature

A large band gap leads to very few intrinsic charge carriers in the conduction band e.g. Diamond, but a smaller signal - production of CVD diamonds with required quality is a challenge!

Starting in the 70's the idea of using fully depleted silicon structures to detect charged particles took off , with the synergies with the micro electronics industry making this an irresistible technology

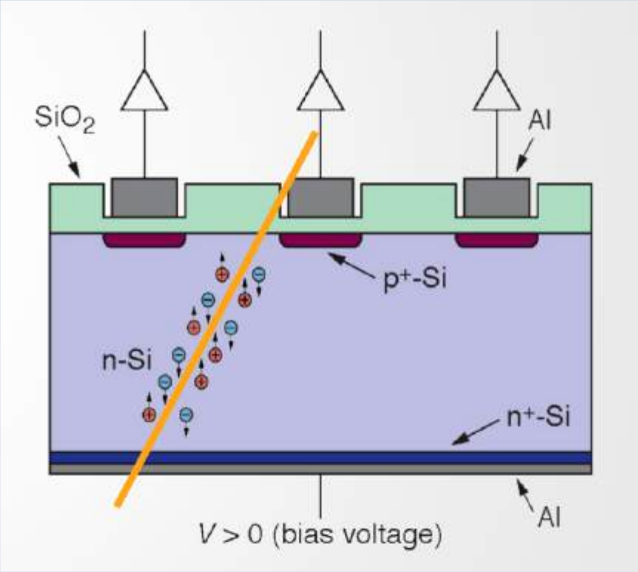
Charged particles traversing sensor create e^-/h^+ pairs in the depletion region

These charges drift to the electrodes

- The drift (current) creates the signal which is amplified by an amplifier connected to each strip (Shockley-Ramo theorem!)
- The SiO_2 dielectric shields the bias potential (AC coupling)
- From the signals on the individual strips the position of the through going particle is deduced

Typical n-type Si strip detector:

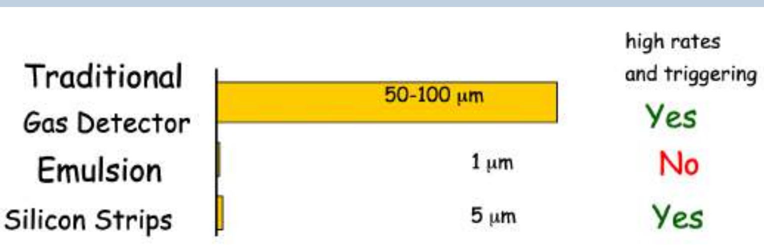
- n-type bulk: r > 2 kΩcm
- thickness 300 μm
- Operating voltage < 200 V.
- n+ layer on backplane to improve ohmic contact to metal
- Aluminum metallization



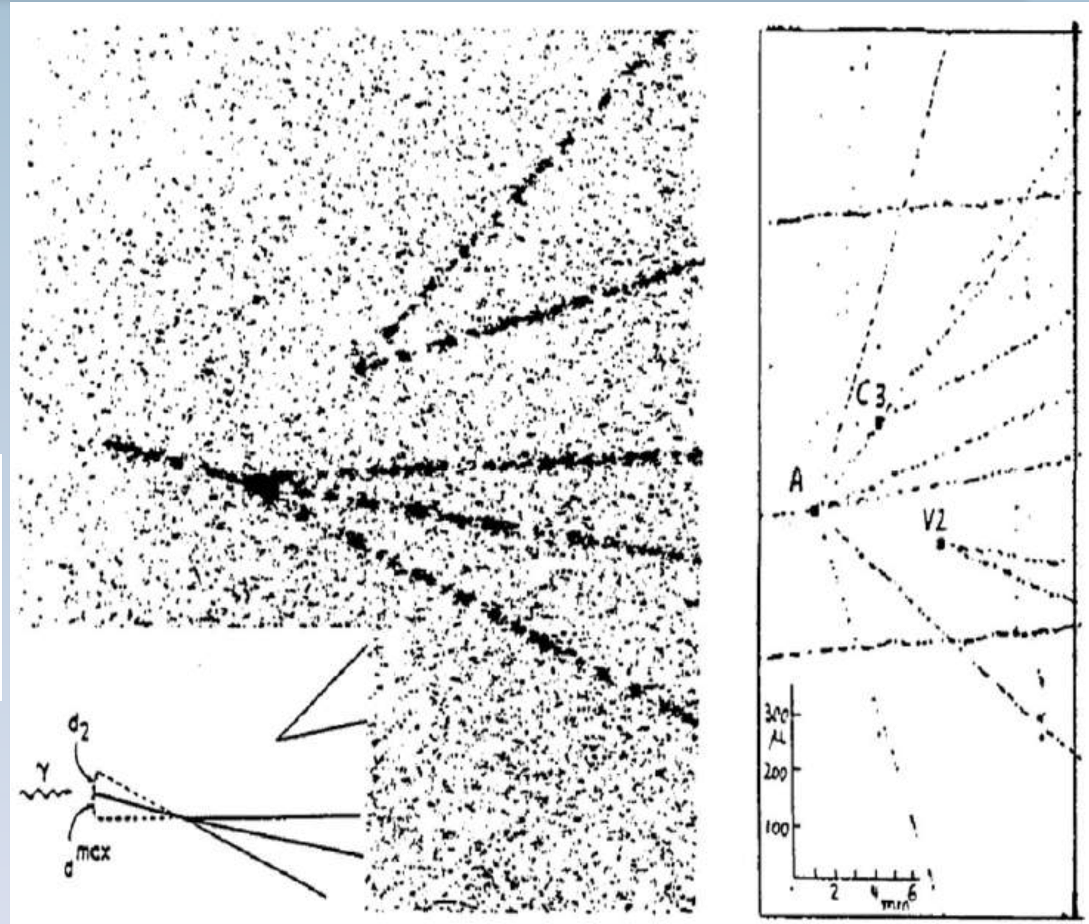
Silicon - High Resolution Electronic Detectors

Discovery of short lived particles with cτ ~ 100 μm gives the required resolution

Si technology planar process plus miniaturised electronics becoming available



Starting in the 70's several groups started to build up expertise and collaboration with industry. In particular Kemmer pioneered transfer of highly developed Si-processing available for elecronics to sensor manufacture



high resolution bubble chambers: SLAC - CERN
(production charm-anticharm)

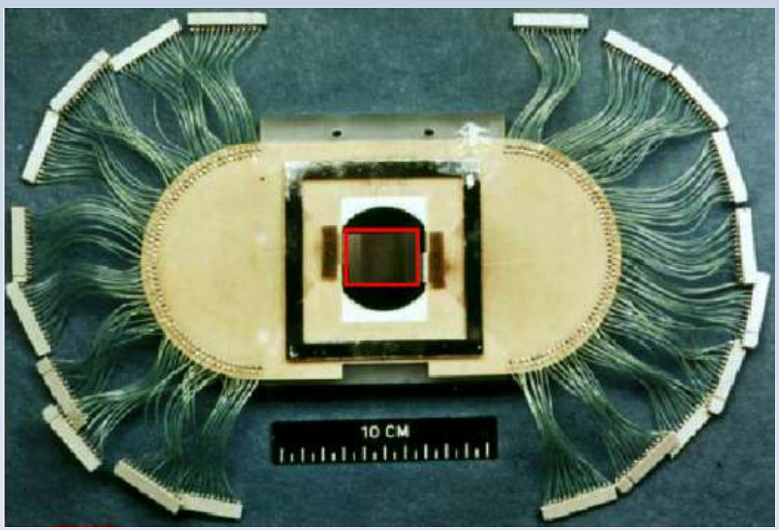
Si-strip Telescope in CERN NA11 Experiment

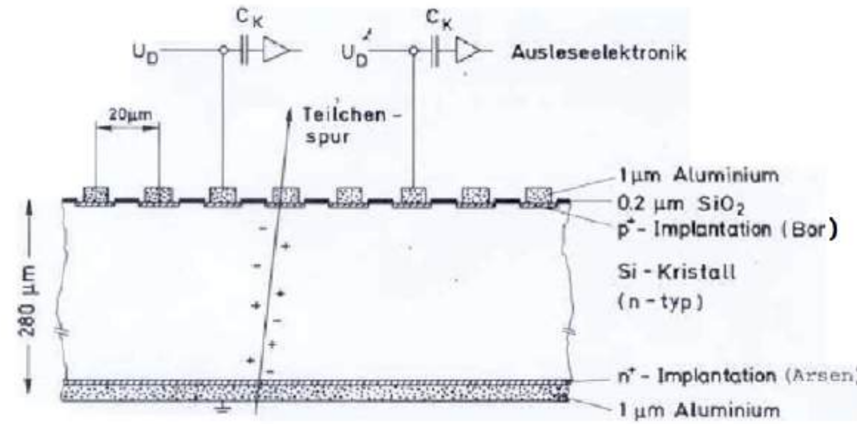
NA - 11/32 experiment

- spectrometer for the study of hadronic reactions e.g. π Be → charm + X

1981 - 6 planes Si-strip detectors

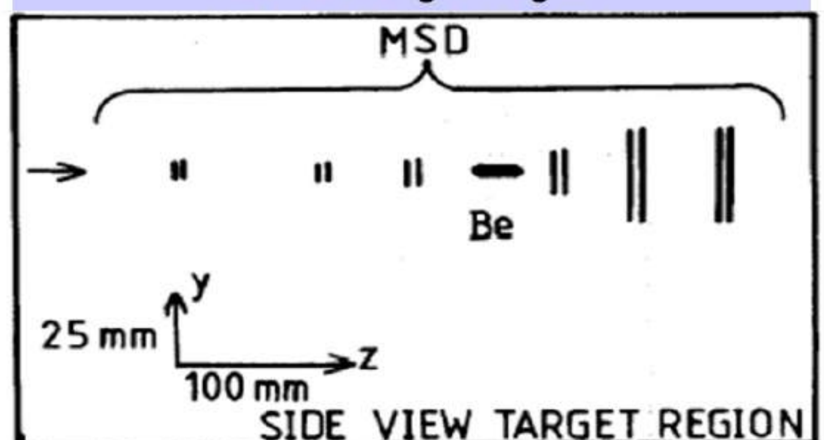
- 24 x 36 mm², 1200 strips/sensor
- strip pitch 20 µm, 280 µm thick
- 60 µm readout → σ = 5.4 µm
- 120 µm readout → σ = 7.8 µm
- total ~ 2000 channels
- 100% efficiency





B.Hyams et al., NIM 205(1983)99

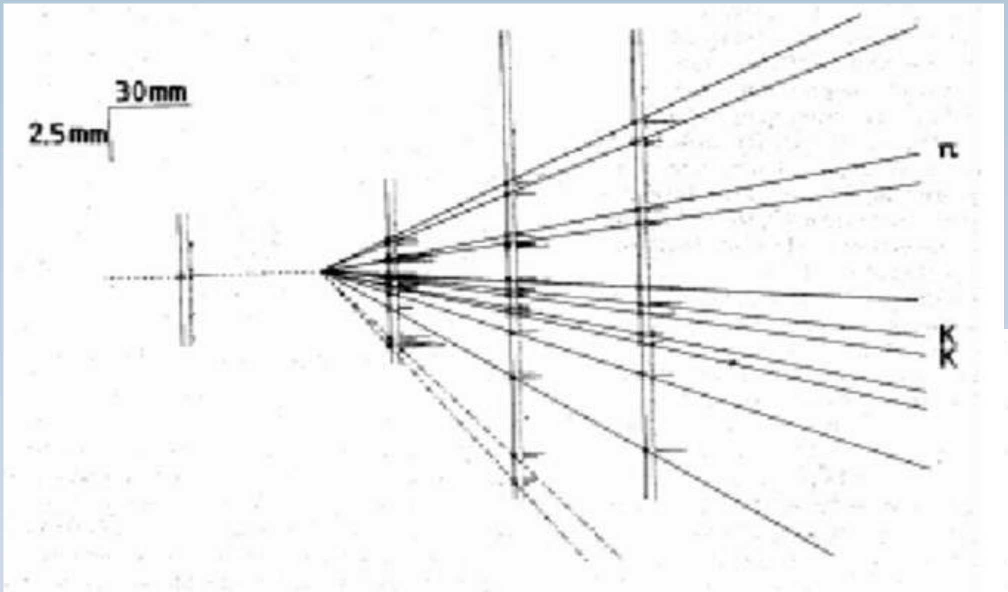
NA-11 target region

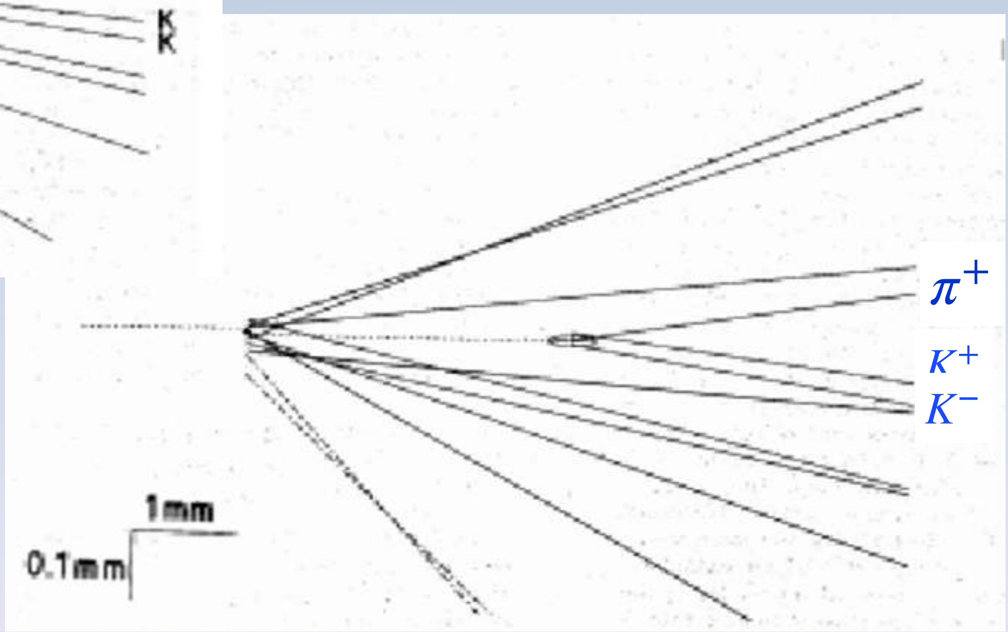


Slide from Robert Klanner

NA11 event display

Observation of $D_s \to \phi\pi$

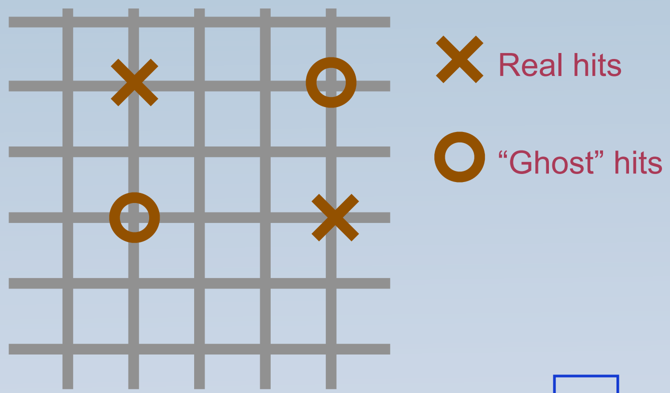




Pattern recognition

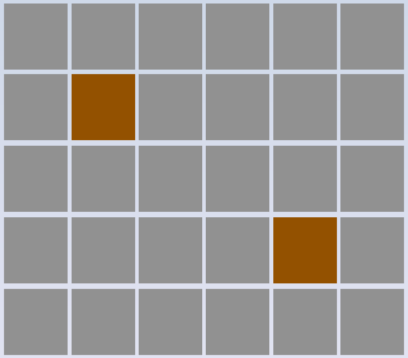
A strip detector measures 1 coordinate only. Two orthogonal ranged strip detectors could give a 2 dimensional position of a particle track. However, if there are than one particle hits the strip detector the measured position is no longer unambiguous. “Ghost-hits” appear!

True hits and ghost hits in two crossed strip detectors in case of two particles traversing the detector:



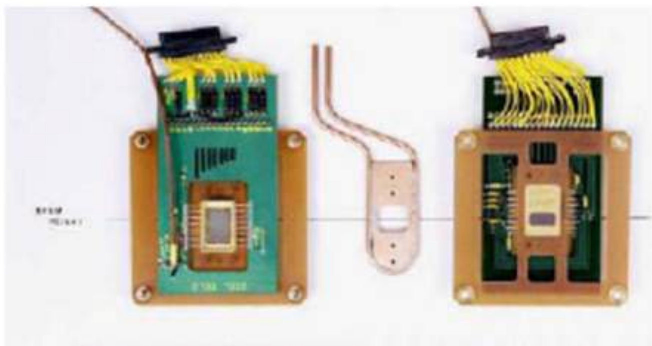
Pixel detectors produce unambiguous hits!

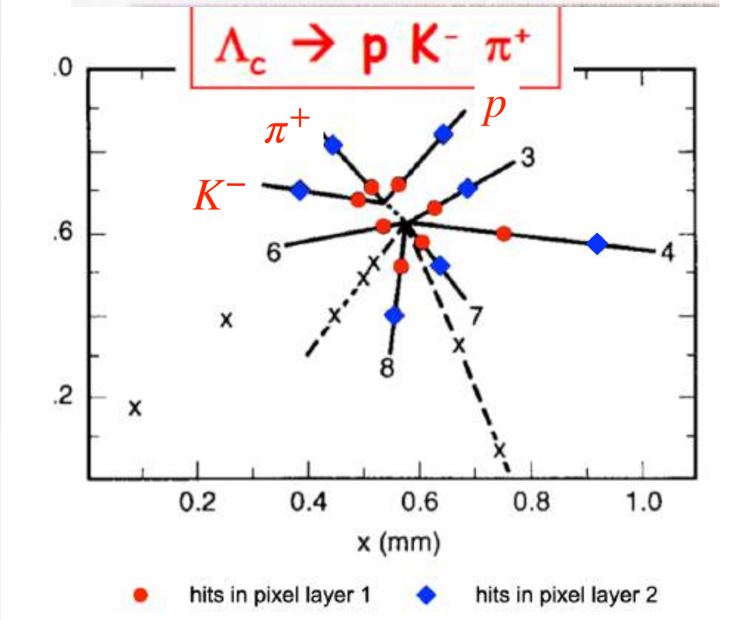
Measured hits in a pixel detector in case of two particles traversing the detector

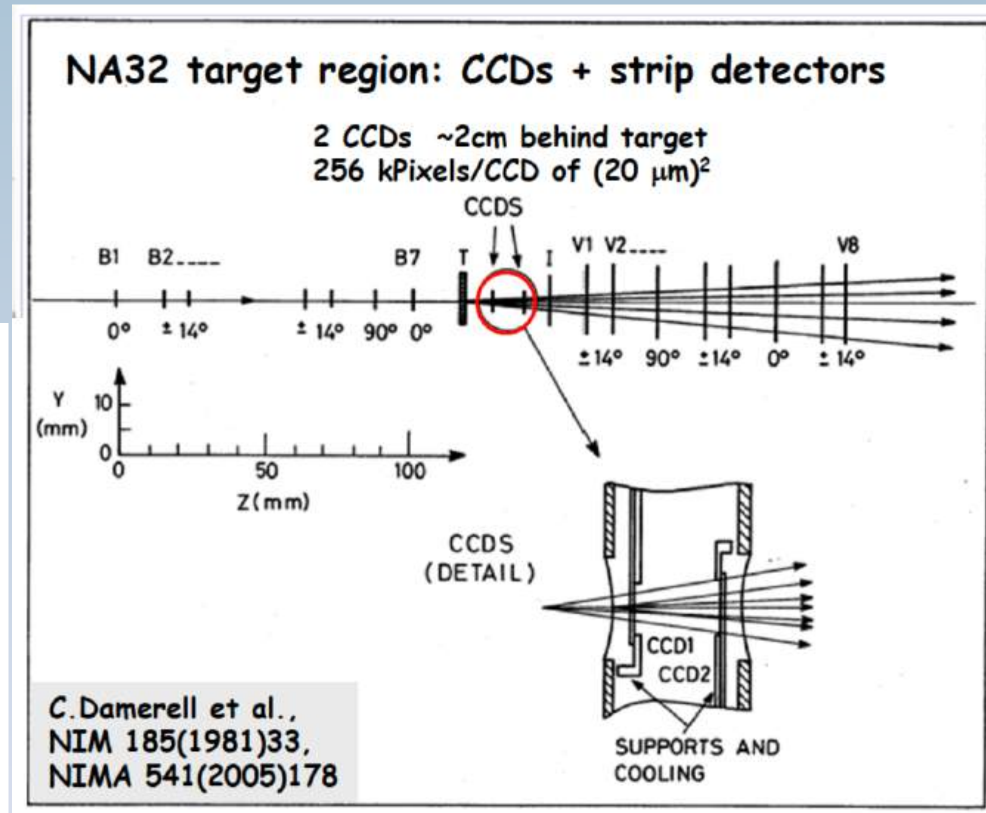


Slide from Manfred Kramer

NA11/32 - adding pixels







Superior pattern recognition convincingly demonstrated

Launch of idea to build CCD vertex detector for SLC

Slide from Robert Klanner

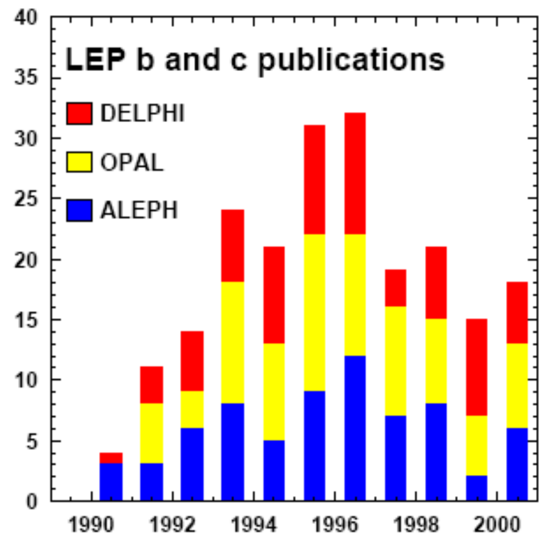
The LEP & SLC Era

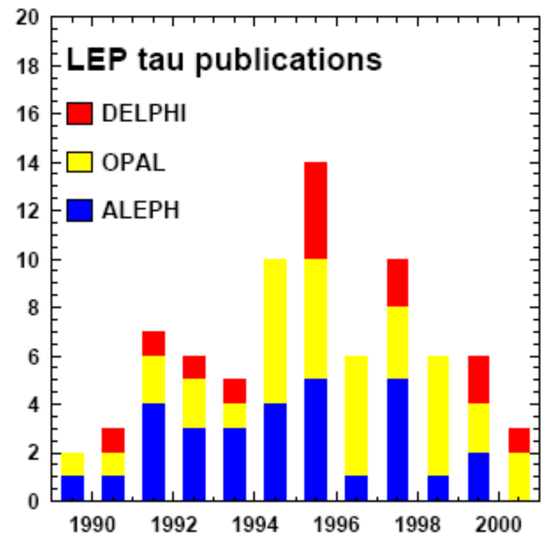
Singapore Conference, 1990

'The LEP experiments are beginning to reconstruct B mesons... It will be interesting to see whether they will be able to use these events'

Gittleman, Heavy Flavour Review

10 fun packed years later, heavy flavour physics represented 40% of LEP publications



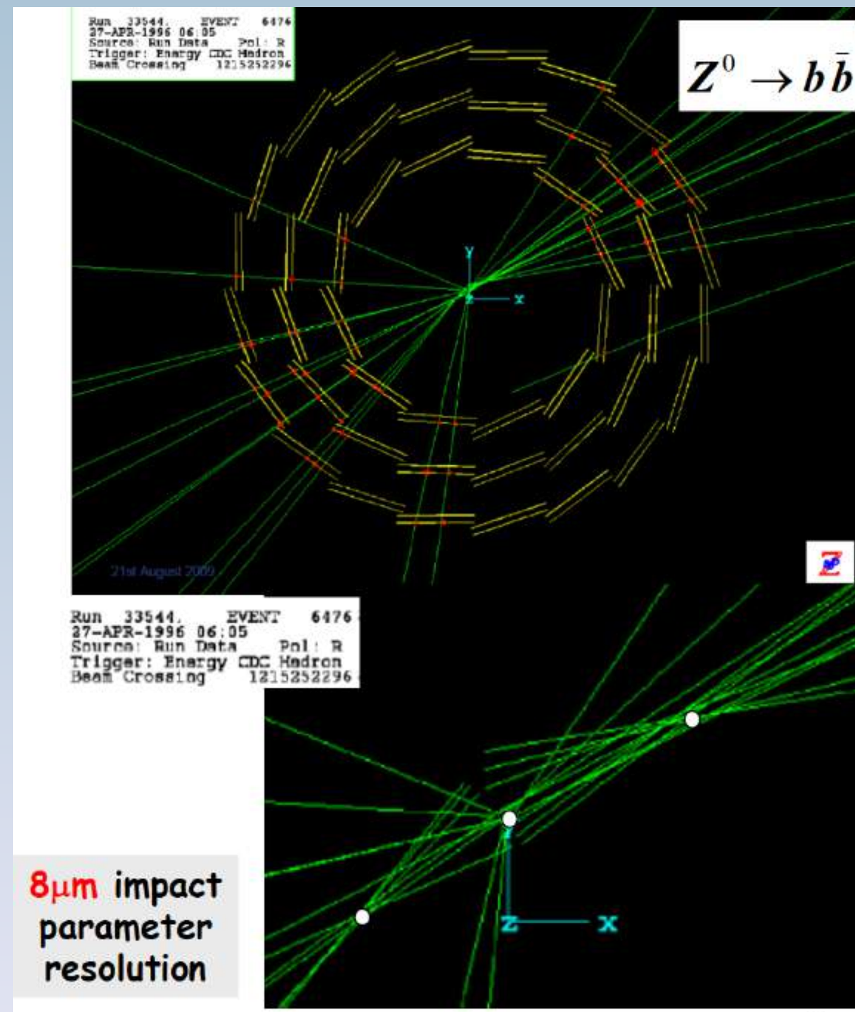


VXD3 detector for SLD@SSC

VXD3@SLD

- installed in 1995
- 307 MPixels (ATLAS: 80Mpixels !)
- 0.4% X_0 (multiple scattering)
- 1st layer < 3cm from beam)

By far most performing vertex detector in terms of resolution → reference point for ILC vertex detectors



Slide from Robert Klanner

LEP Vertex Detector Timeline

1989, ALEPH & DELPHI

install prototype modules

1990, ALEPH & DELPHI

install first complete barrels

ALEPH read rz coordinate with “double sided” detectors

1991, all

Beampipes go from Al with r=8 cm to r=5.3 cm Be

DELPHI installs three layer vertex detector

OPAL construct and install detector in record speed

1992, L3

2 layer double sided vertex detector

1993, OPAL

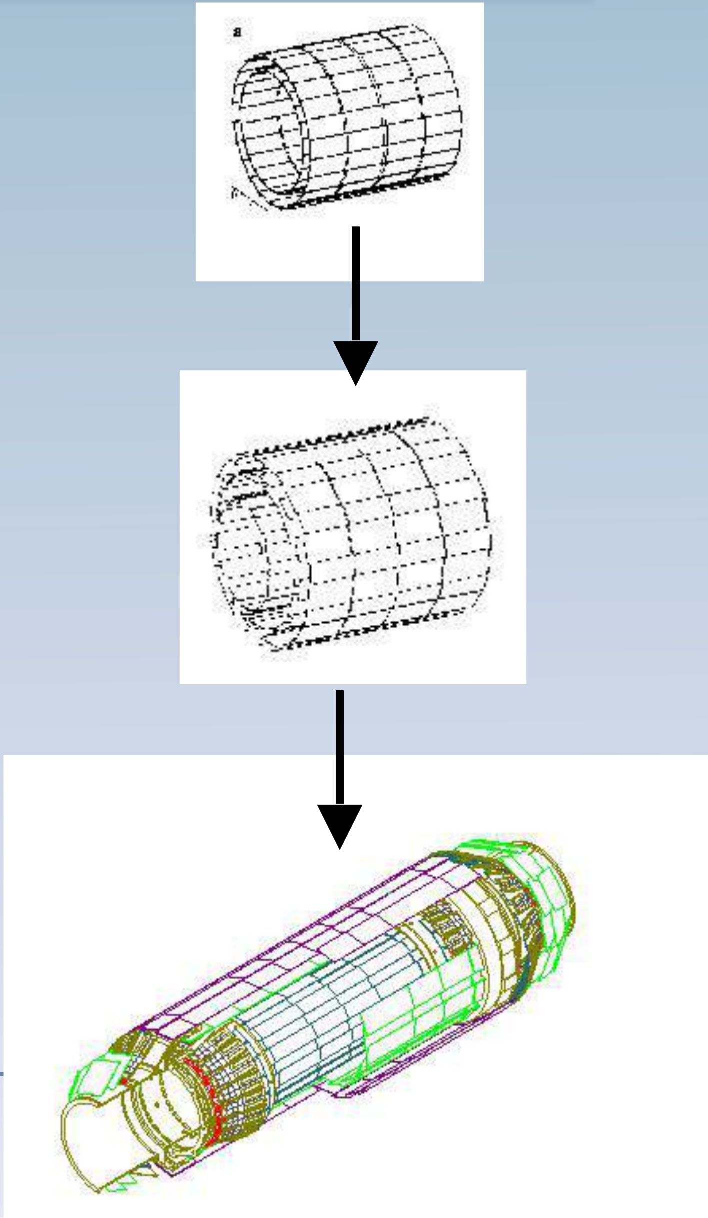
install rz readout with back to back detectors

1994, DELPHI

double sided detectors and “double metal” readout

1996, DELPHI

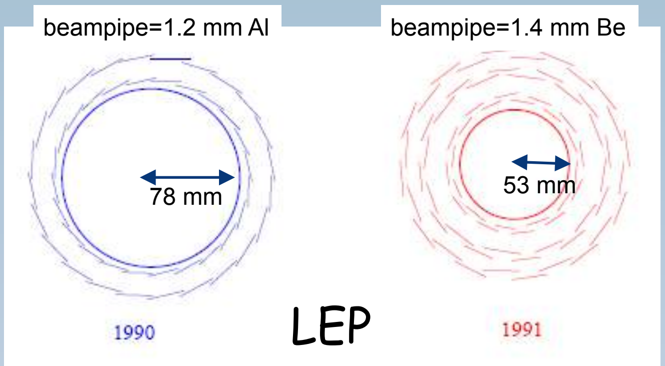
install “LEP II Si Tracker” with μstrips, ministrips & pixels

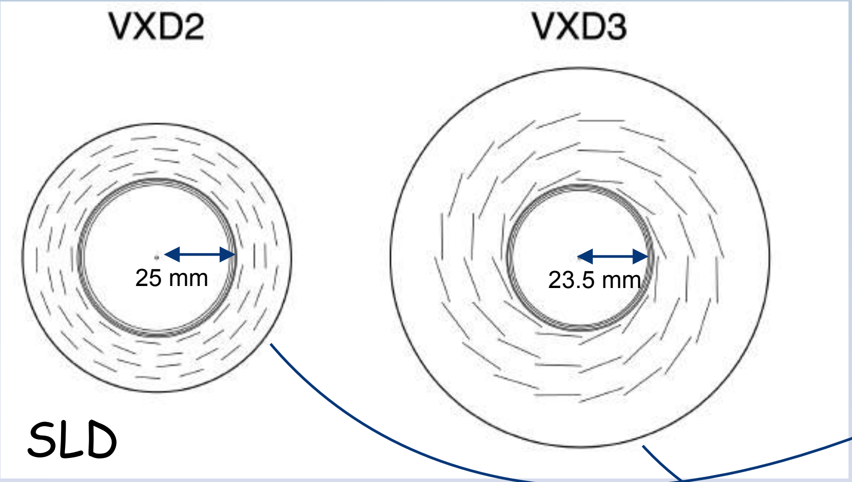


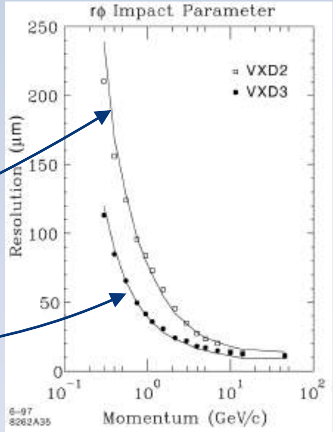
Vertex Detector Performance

Dependent on geometry, precision and material

Drive at LEP and SLD to decrease the radius of the beampipe, use beryllium, add more layers, double sided measurements….



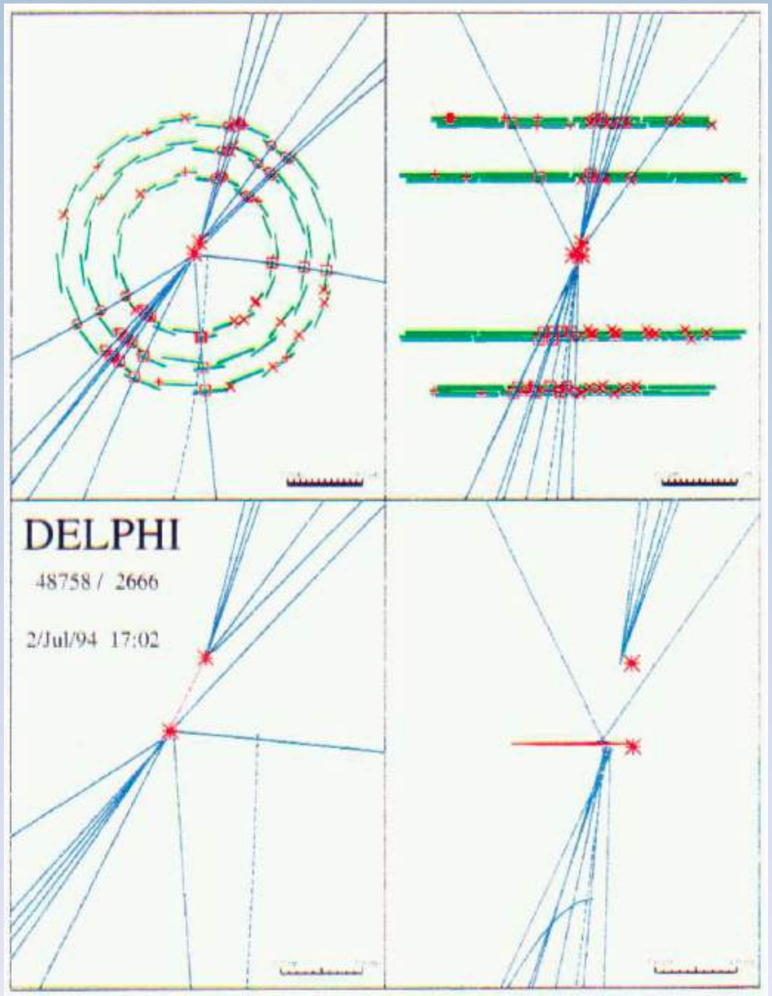


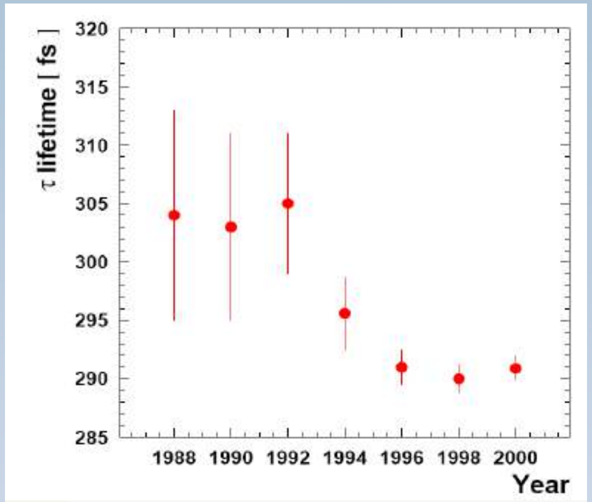


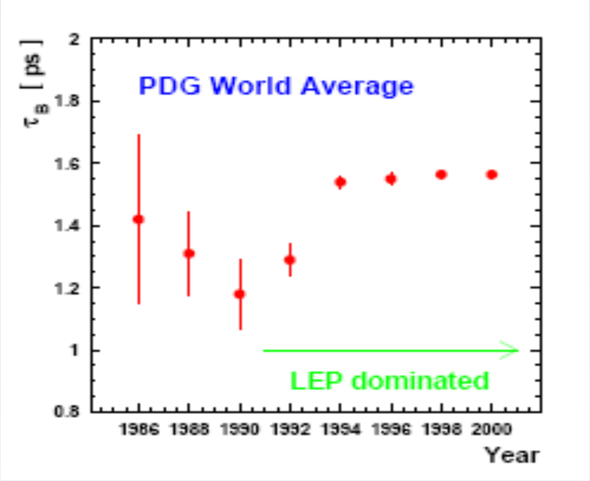
improvement in
- material
- average radius of first measured point
- lever arm

Impact on Physics at LEP

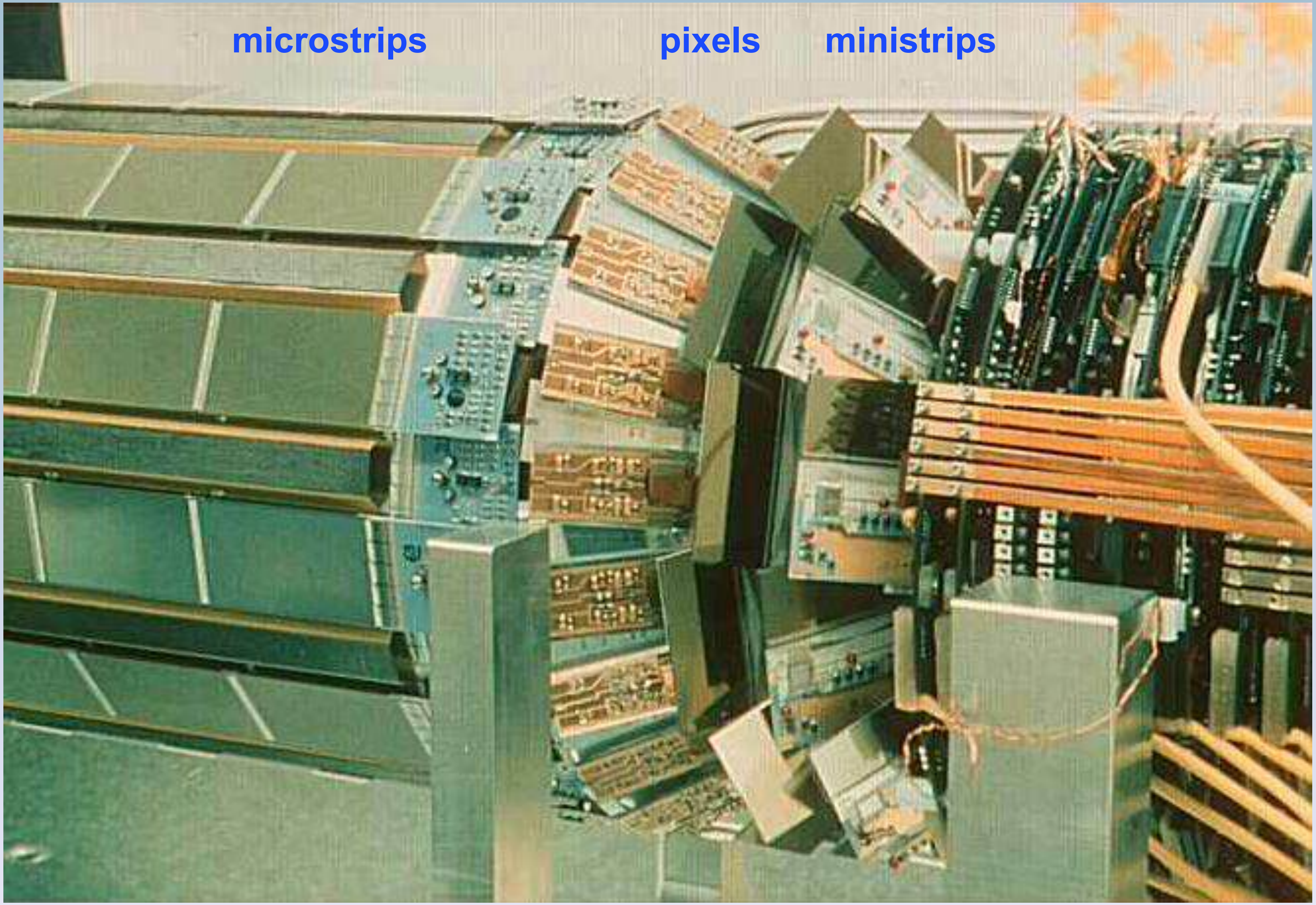
Tasks of vertex detector: vertex reconstruction, flavor tagging, pattern recognition, help in tracking, even dE/dx,



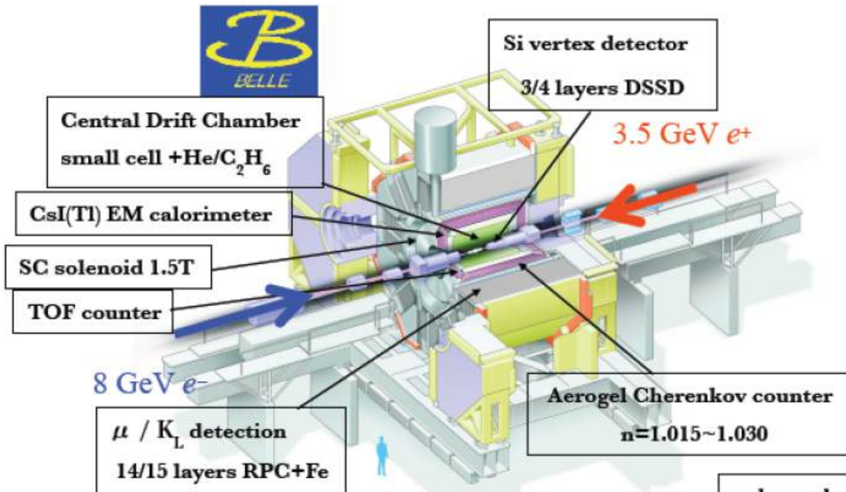


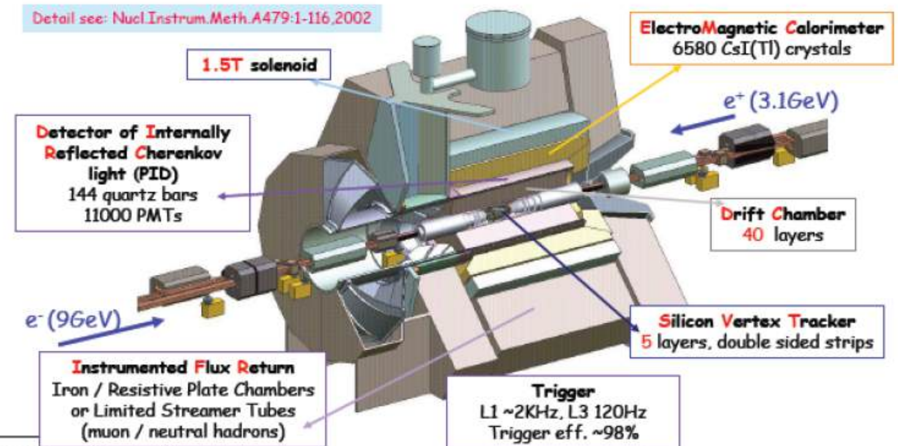


And continued innovation

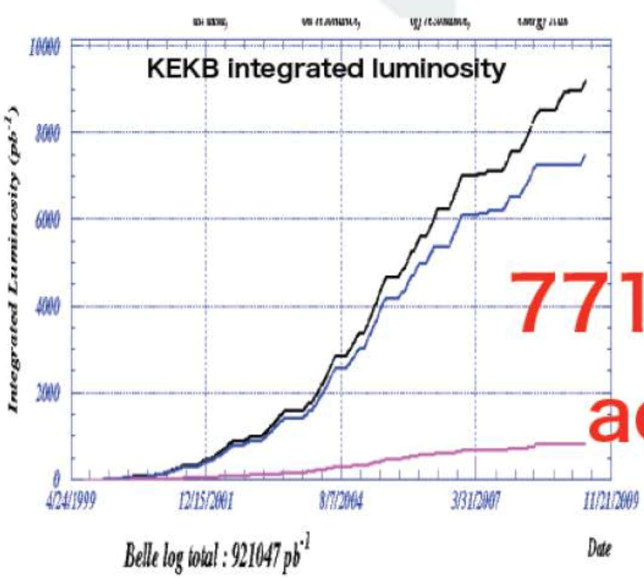


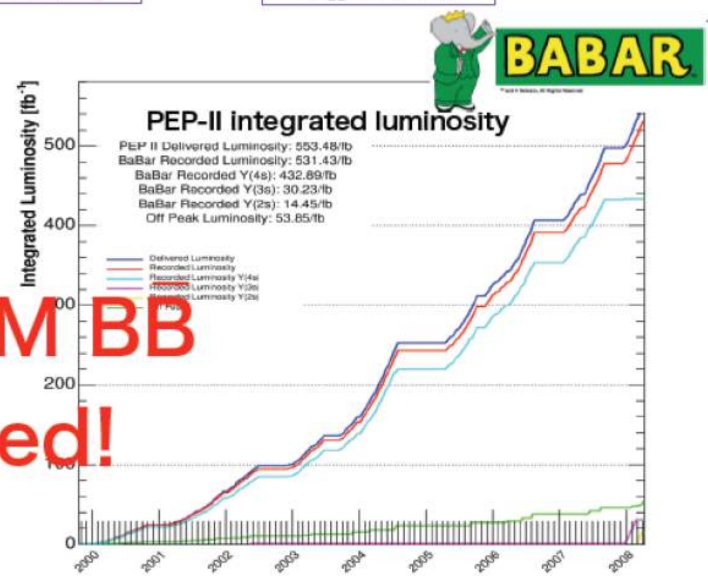
The B factories





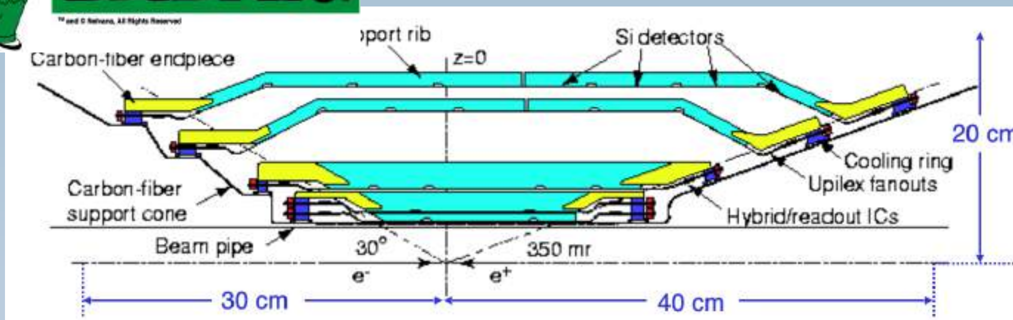
- charged particle tracking
- momentum measurement
- particle identification
- e/γ energy measurement
- K_L cluster detection

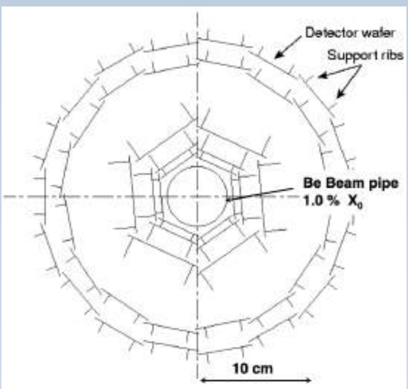




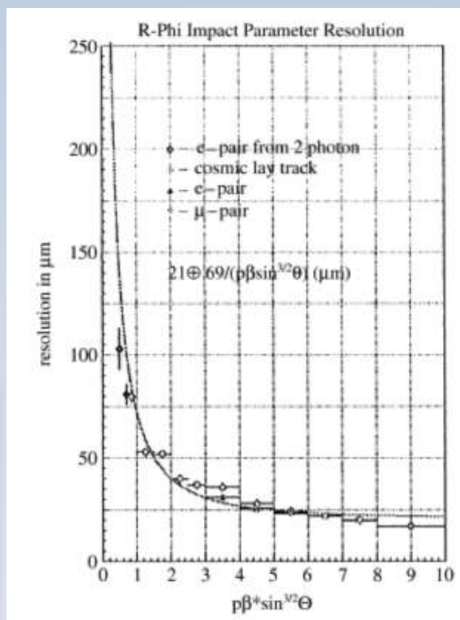
771M + 463M BB accumulated!

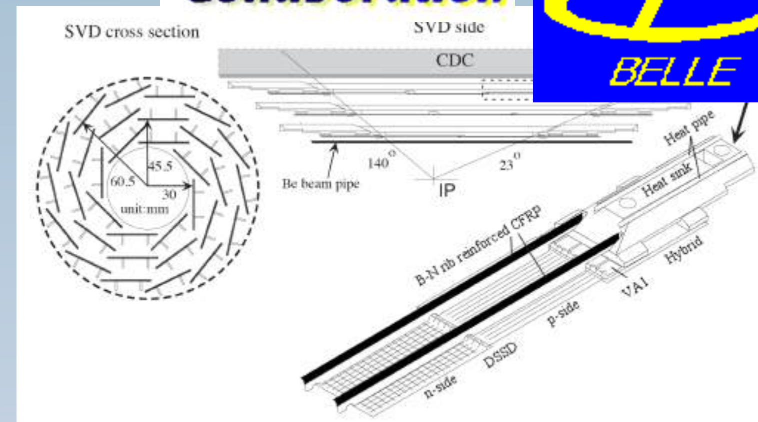
Babar & Belle Vertex detectors

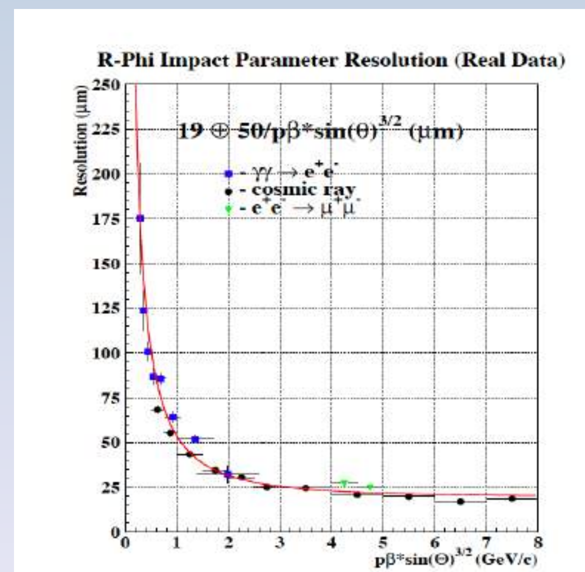




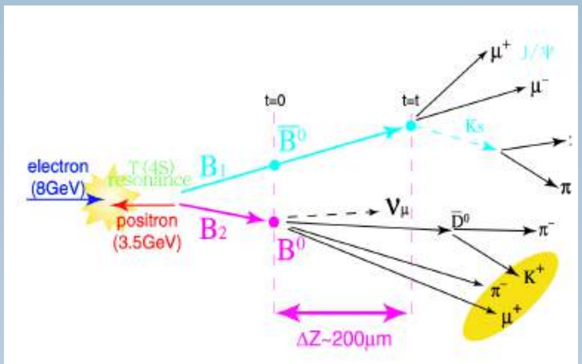
Layer	Radius
1	3.3 cm
2	4.0 cm
3	5.9 cm
4	9.1 to 12.7 cm
5	11.4 to 14.6 cm

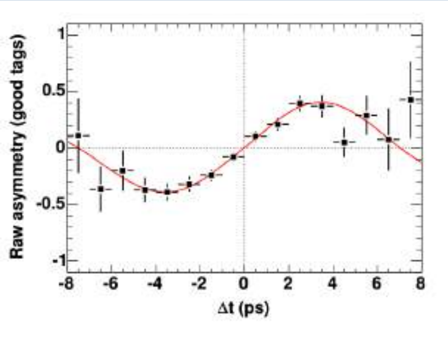


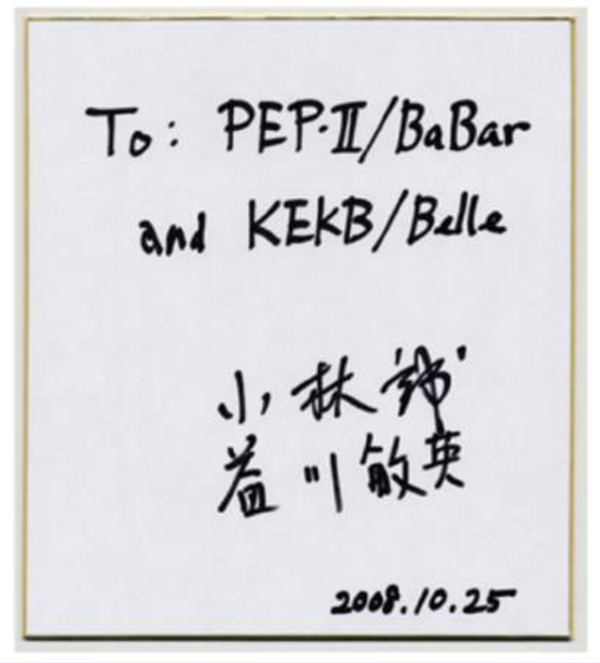




Discovery of CPV in B system



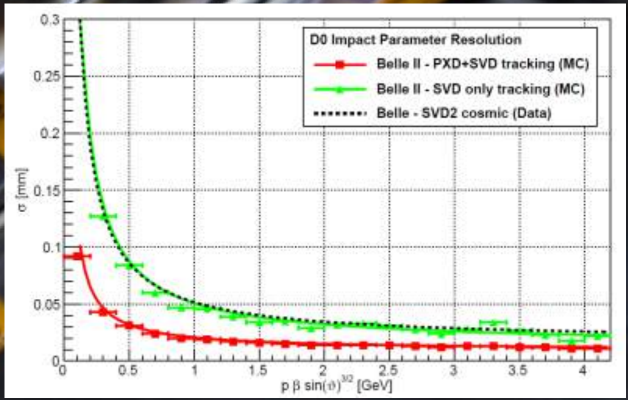




Please accept our deepest respect for the B-factory achievements. In particular, the high-precision measurement of CP violation and the determination of the mixing parameters are great accomplishments, without which we would not have been able to earn the Prize

DEPFET pixel detector @ Belle II

- 50 x 55-85 μm² pixels, 20 μs rolling shutter
- 0.21% X0 per layer, 2 self supporting layers - ultralight!

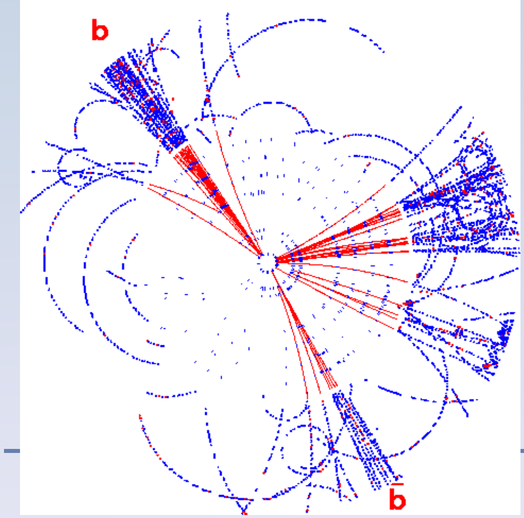


The LHC Era: High rates, High Multiplicity

at Run1 luminosity $L=10^{34}\ cm^{-2}\ s^{-1}$:

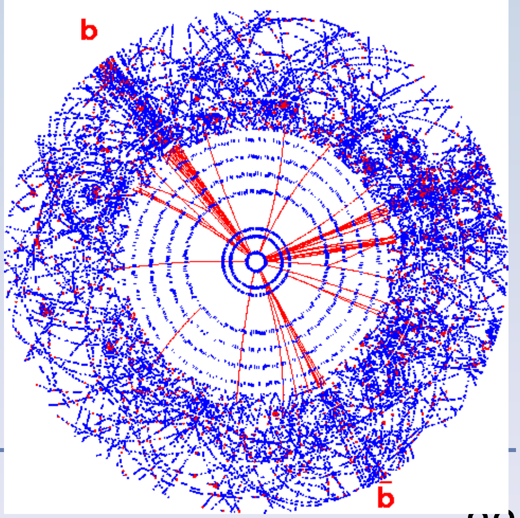
- ~23 overlapping interactions in each bunch crossing every 25 ns (= 40 MHz)
- inside tracker acceptance ($|\eta|<2.5$) 750 charged tracks per bunch crossing
- per year: ~5×10^{14} bb; ~10^{14} tt; ~20,000 higgs; but also ~10^{16} inelastic collisions
- severe radiation damage to detectors
- detector requirements: speed, granularity, radiation hardness

a H->bb event

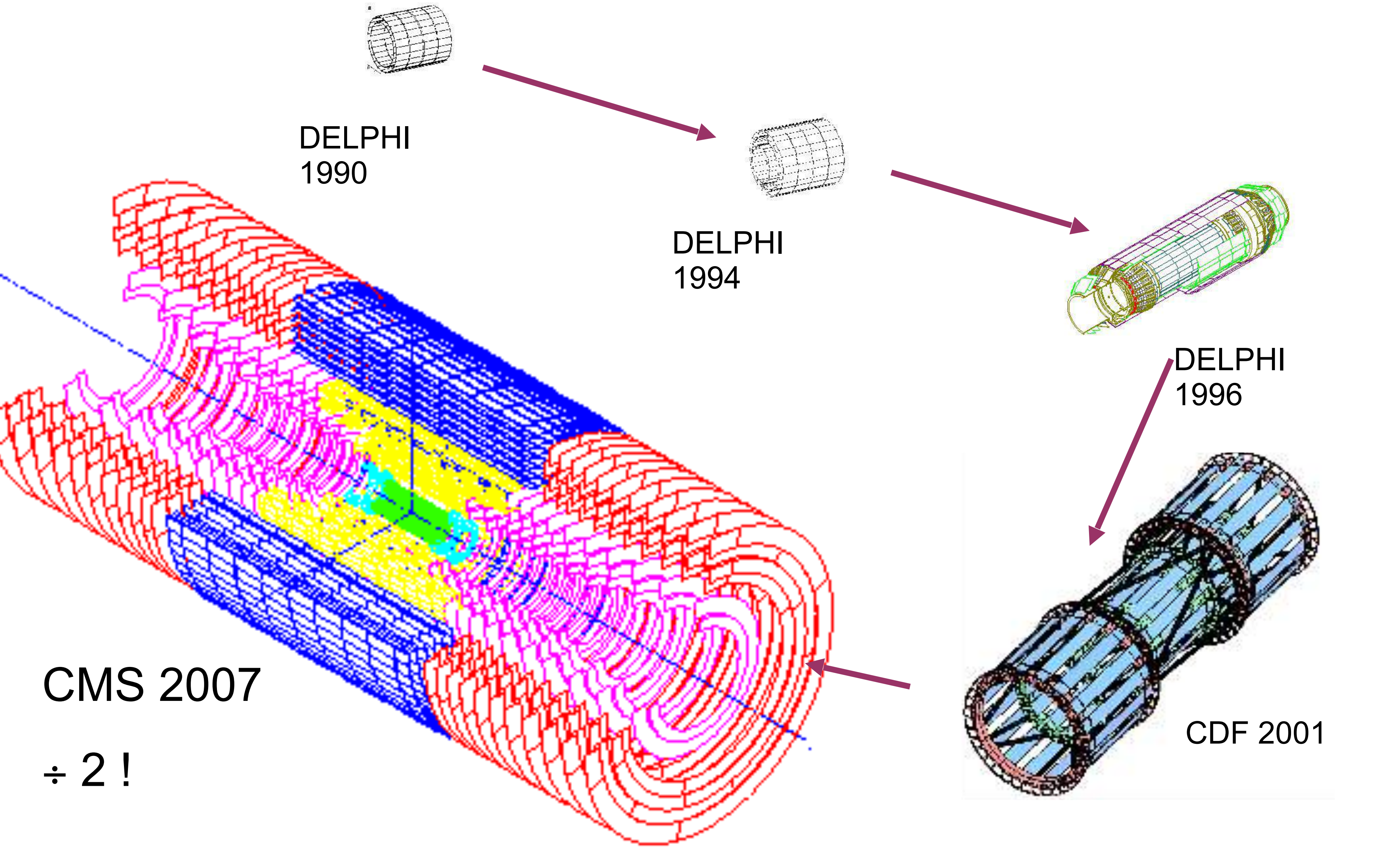


plus 22 minimum bias interactions

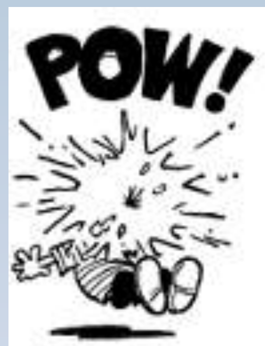
a H->bb event as observed at high luminosity



From Vertex Detectors to Trackers



From Vertex Detectors to Trackers

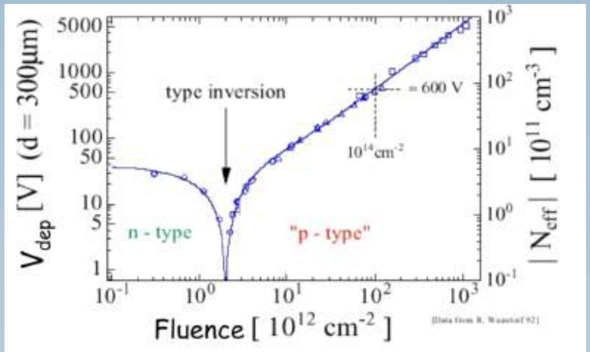


Whoops...

Radiation Damage Enters Game

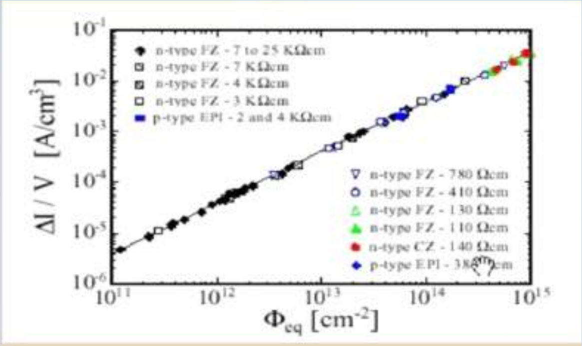
Change of depletion/operation voltage

- Due to charged defect levels in the depleted region ⇒ time and temperature dependent and very problematic!



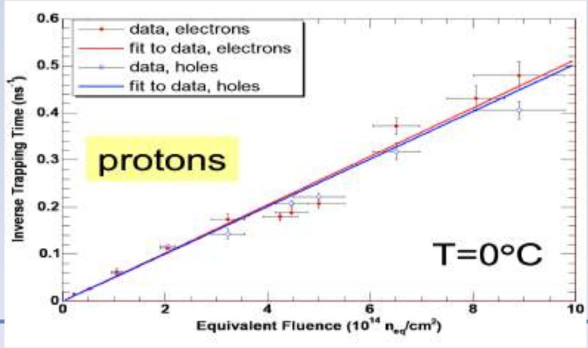
Increase of leakage bulk current due to generation /recombination levels

- increase in noise
- difficult to deliver bias voltage to detectors
- risk or thermal runaway
- temperature dependent
- anneals with time



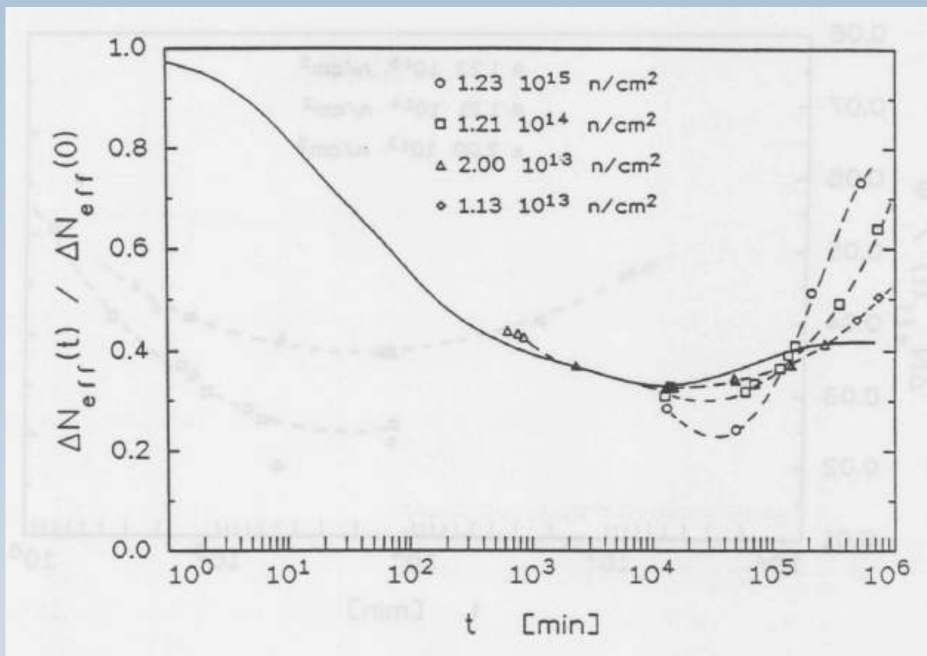
Damage induced trapping centers

- Decrease in collected signal charge



Reverse annealing

>30 years ago in 1991, Renate Wunstorf decided to remeasure some old, irradiated samples
The result astonished her, and this plot was presented in her **PhD thesis**



$$\frac{\Delta N_{eff}(t)}{\Delta N_{eff}(0)} = \sum_{i=1}^{6} A_i \, e^{-\frac{t}{\tau_i}}$$

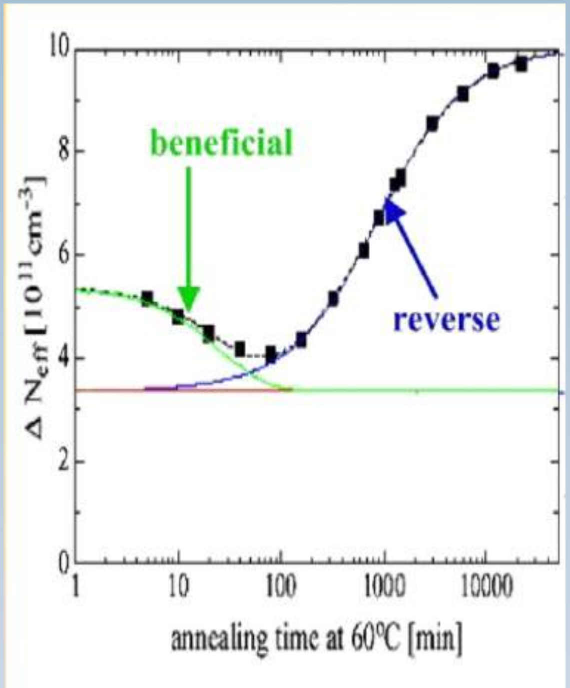
Zeitkonstante τ_i [min]	Relative Amplituden A_i
$(9.40 \pm 0.80)\cdot 10^0$	0.214 ± 0.030
$(6.87 \pm 0.14)\cdot 10^1$	0.262 ± 0.007
$(3.43 \pm 0.12)\cdot 10^2$	0.118 ± 0.008
$(4.00 \pm 0.04)\cdot 10^3$	0.097 ± 0.002
$(7.52 \pm 0.02)\cdot 10^4$	-0.107 ± 0.001
∞	0.417 ± 0.004

It shows, over time, the **decrease**, and then the **increase** of ΔN_{eff} (for normalization related to N_{eff} before exposure to radiation)

Wunstorf **demonstrated** this was due to a negative annealing component with a long time constant that defines the temperature dependence of this component.

This was to have a **profound** effect on the design of silicon detector systems.

Reverse Annealing and Operation



Just after irradiation the damage "heals" and the depletion voltage improves. This "beneficial annealing" is temperature dependent

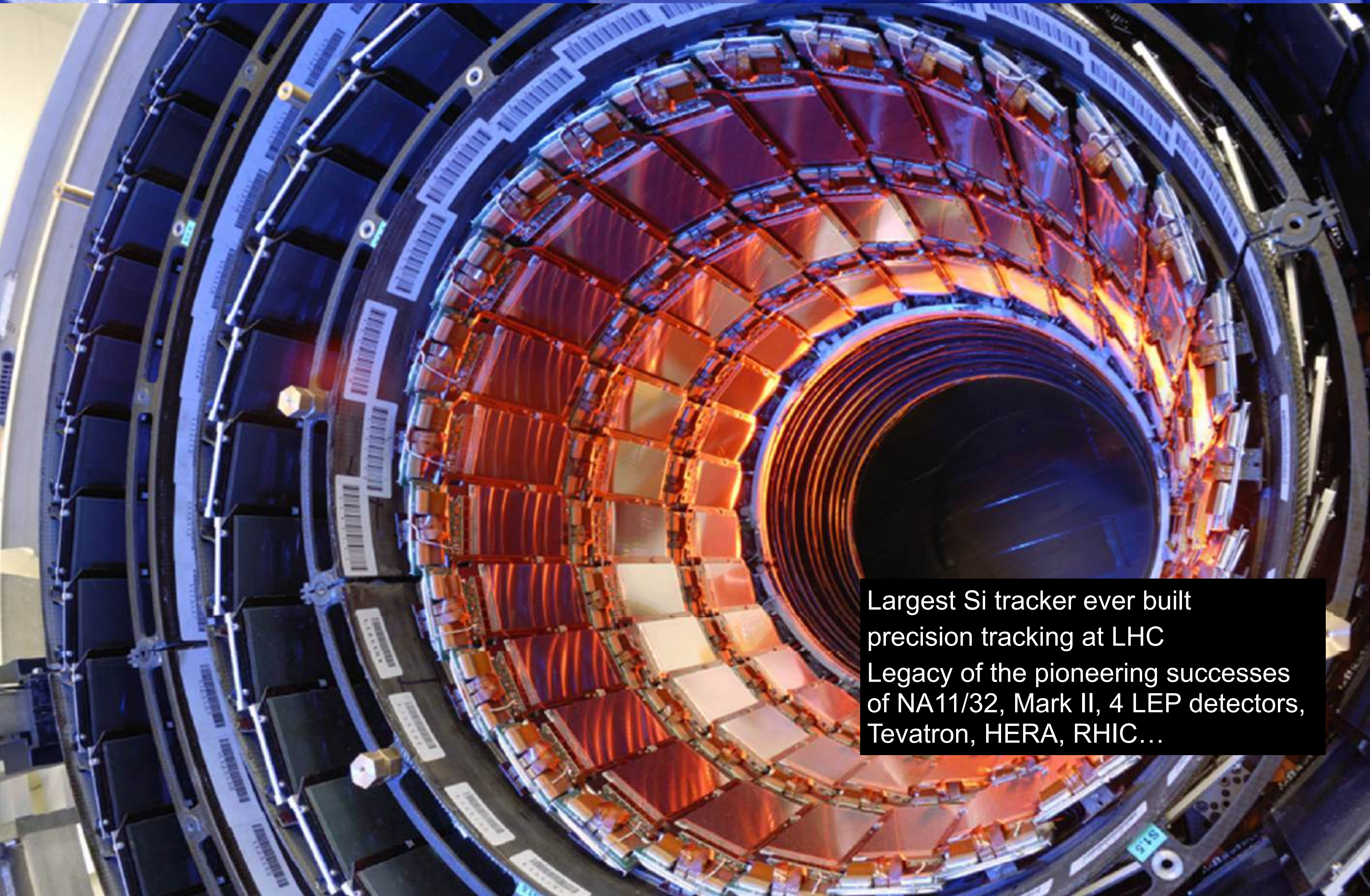
Over a longer period of time the build up of negative space charge increases again; this is known as "reverse annealing". It has a long time constant and can be controlled by cooling.

Knowing this effect and being able to calculate the behaviour allowed the choice of silicon for the innermost layers of the LHC experiments to be made!

The implications of the plot in Wunstorf's PhD thesis have a major effect on detector design and the supporting increasingly complex and beautiful cooling infrastructure, in particular the move to evaporative CO_2 cooling.

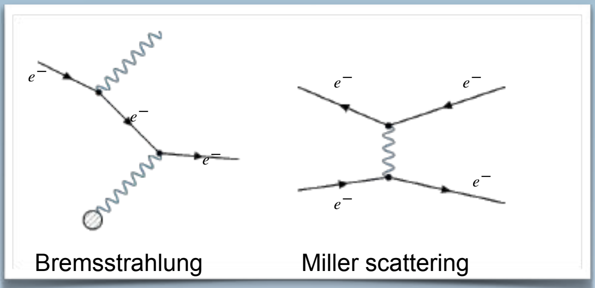
R. Wunstorf et al., Nucl. Instr. and Meth. A315 (1992), presented 1991 at the Elba conference

CMS Tracker

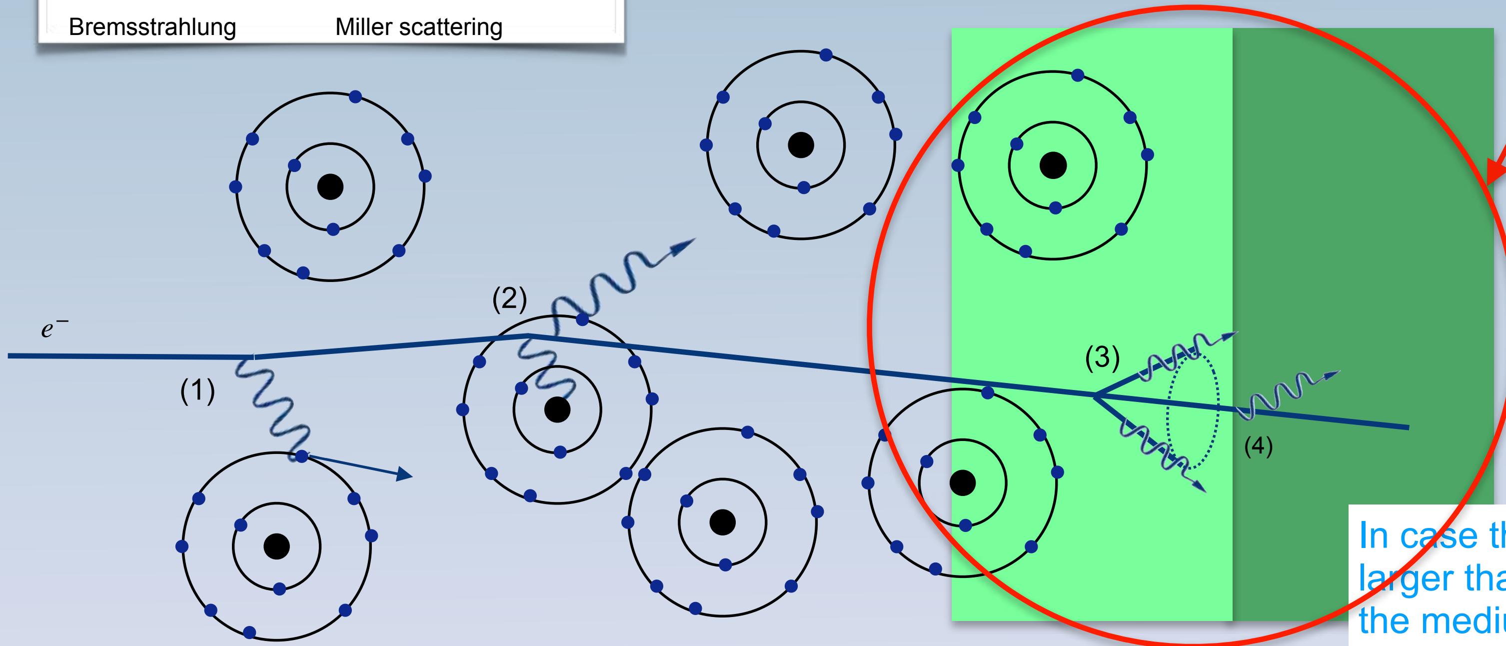


Largest Si tracker ever built
precision tracking at LHC
Legacy of the pioneering successes of NA11/32, Mark II, 4 LEP detectors, Tevatron, HERA, RHIC…

Electromagnetic interactions of charged particles



Let's now discuss briefly Cherenkov and Transition Radiation effects, major drivers of Particle Identification techniques

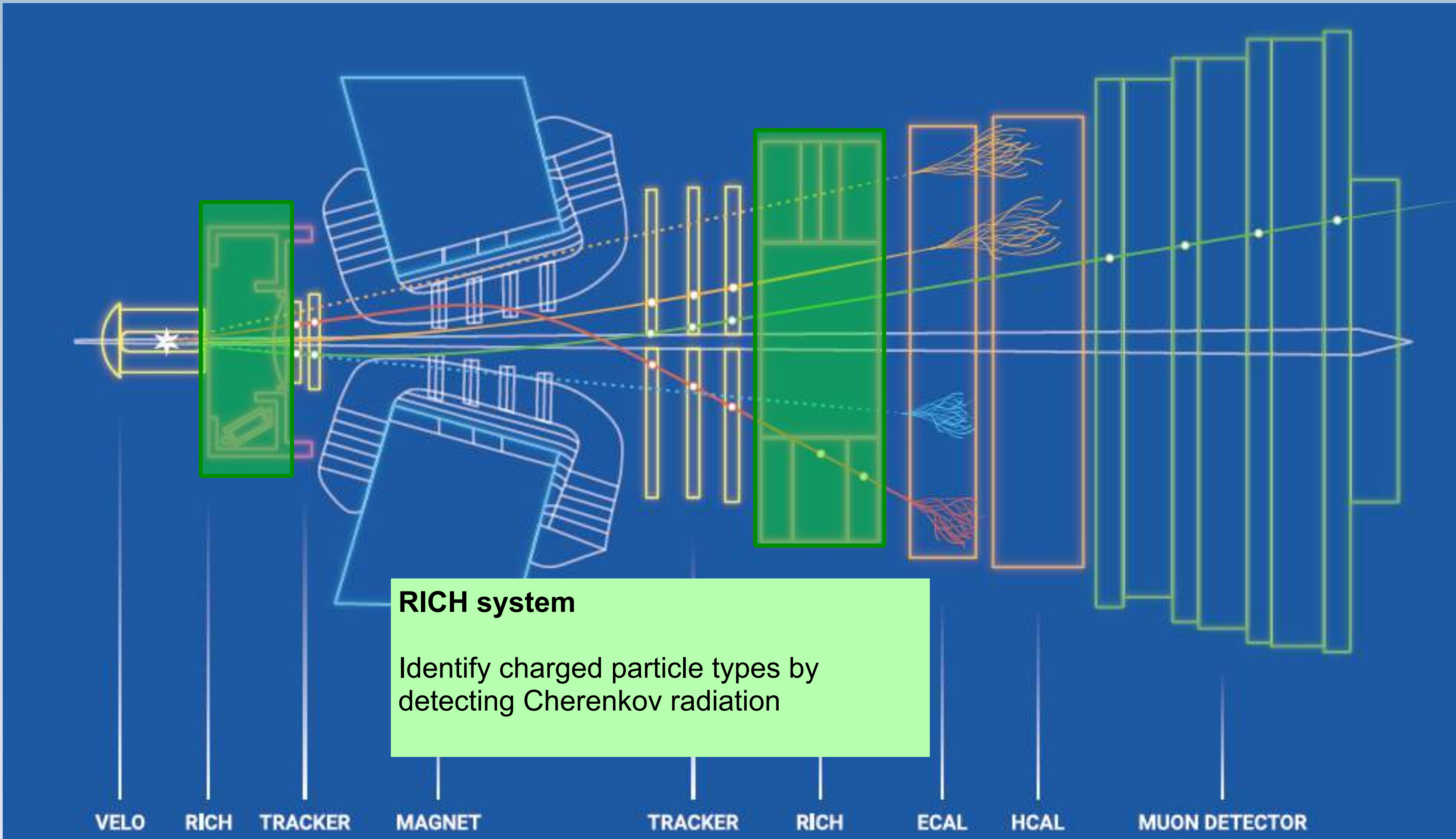


(1) **Interaction with the atomic electrons.**
The incoming particle loses energy and the atoms are excited or ionized

(2) **Interaction with the atomic nucleus.**
The particle is deflected causing multiple scattering in the material. During this scatteri a Bremsstrahlung photon can be emitted

In case the particle's velocity is larger than the velocity of light ir the medium, the resulting EM shockwave manifests itself as (3) **Cherenkov Radiation.** When the particle crosses the boundary between two media, there is a probability (~1%) to produced an X ray photon, called (4) **Transition radiation.**

PID in Detector Layout



RICH system

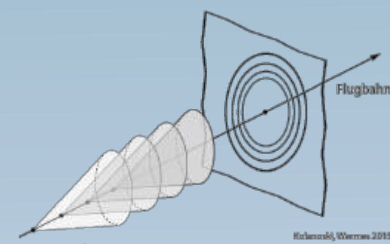
Identify charged particle types by detecting Cherenkov radiation

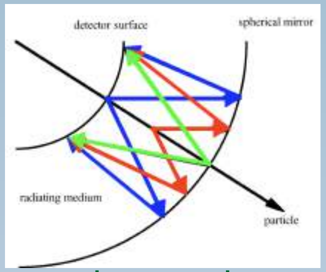
Cherenkov/Transition Radiation

Fundamental Cherenkov relation:

$$\cos\theta_C = \frac{1}{n\beta}$$

This is a *threshold*, and thereafter an *angular dependence* up to saturation





Frank-Tamm relation

$$\frac{dN_\gamma}{dE} = \frac{\alpha}{\hbar c} Z^2 L \sin^2\theta_C$$

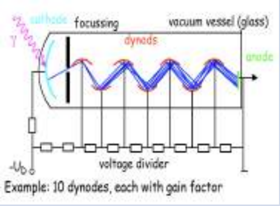
Number of photons will increase with velocity, up to saturation

For a RICH, we need a radiator, a mirror and a photodetector. The focussing mirror turns the photon "splodge" into a circle (or use proximity focussing)

There are only a few photons per event → one needs highly sensitive photon detectors to measure the rings! Detectors may be vacuum, gaseous or solid state based, and use a variety of amplification techniques:

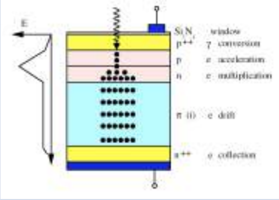
PMT - photomultiplier tube

Series of dynodes, each with gain factor, time resolution ~ 150 ps

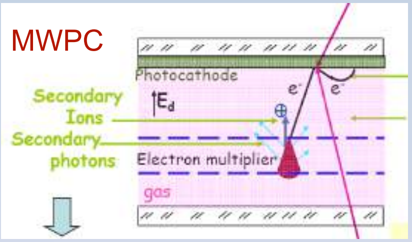


APD - Avalanche Photo Diode

High internal electric field and avalanche formation

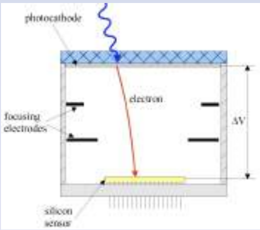


MWPC, GEM, "track detection" solution



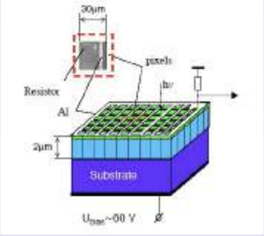
HPD
Hybrid Photo Diode

Combination of Photocathode, acceleration region, and silicon detector



SiPM - Silicon PhotoMultiplier

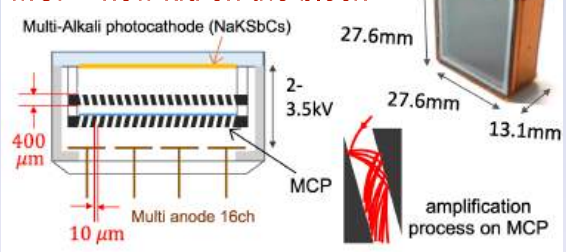
Array of APDs Operating in Geiger mode. Small dimensions, works in magnetic field, time resolution ~ 60 ps



Time resolution ~ 30 ps

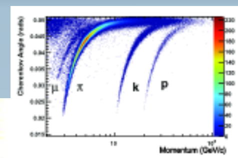
Low dark count rate

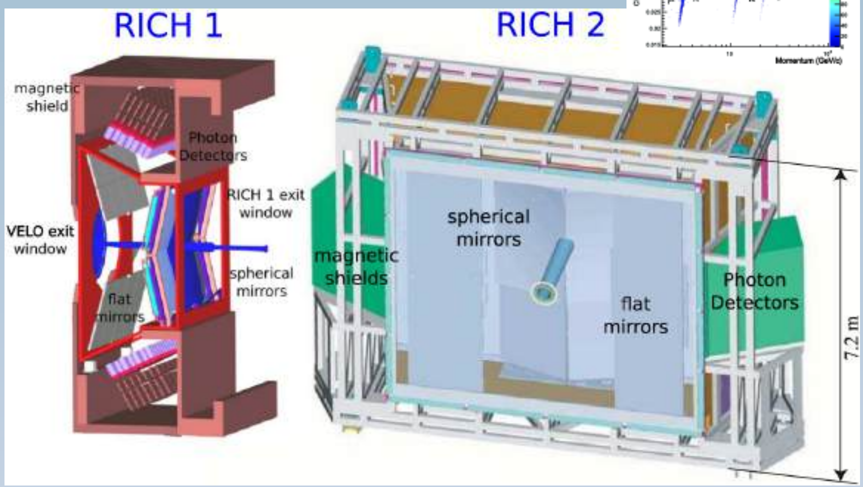
MCP - new kid on the block

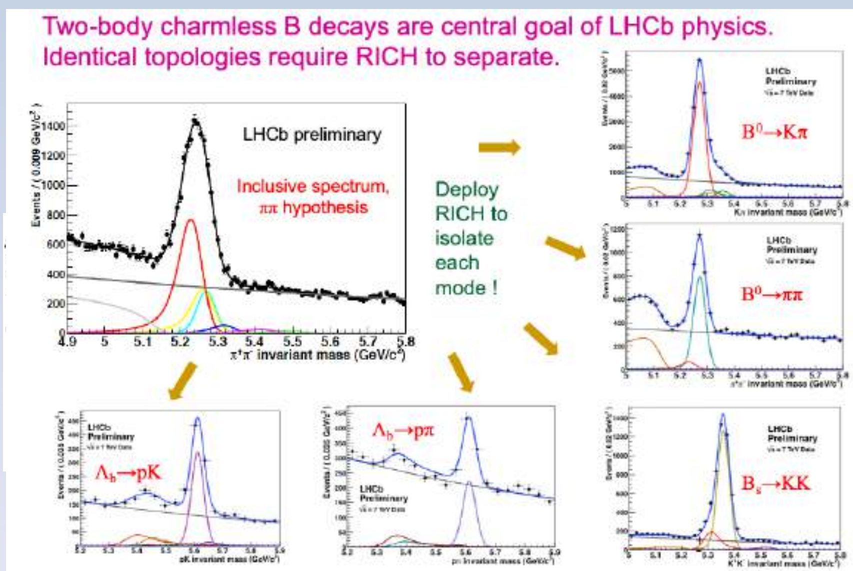


Cherenkov Radiation - Examples

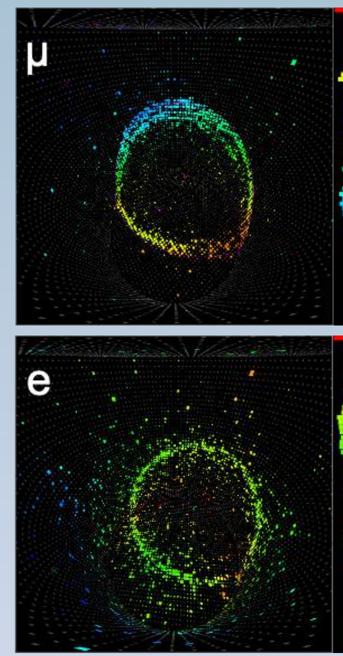
LHCb RICH systems

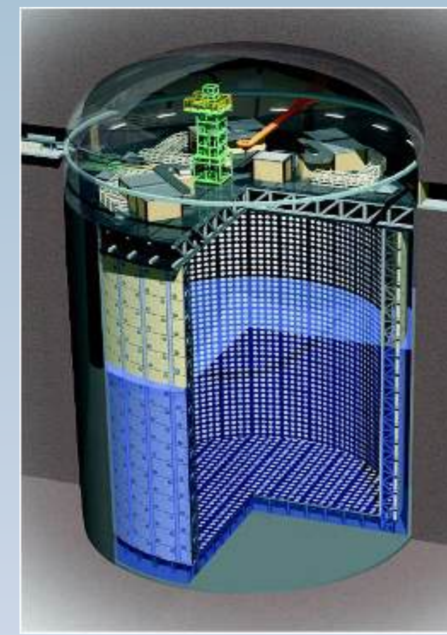






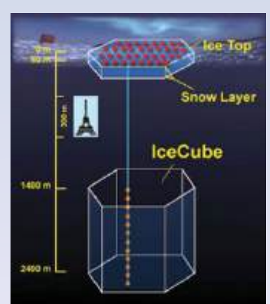
Large water volume neutrino detectors: SNO, Super-Kamiokande..

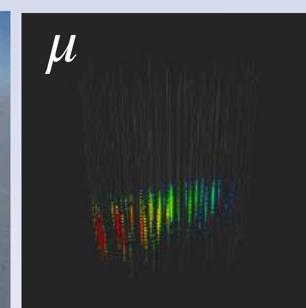




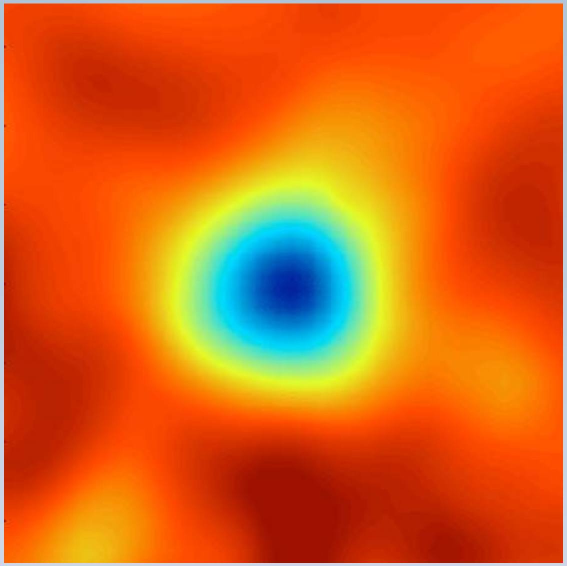
Here, the muon and electron are distinguished by the sharpness of the rings

Ice Cube in Antartica - here the ice is used as the radiator
And the time registered used for the direction

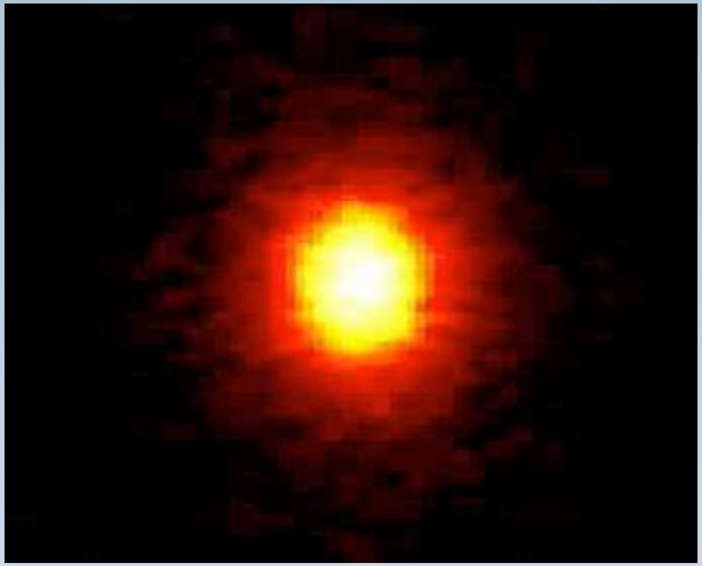




Cherenkov Radiation - Examples

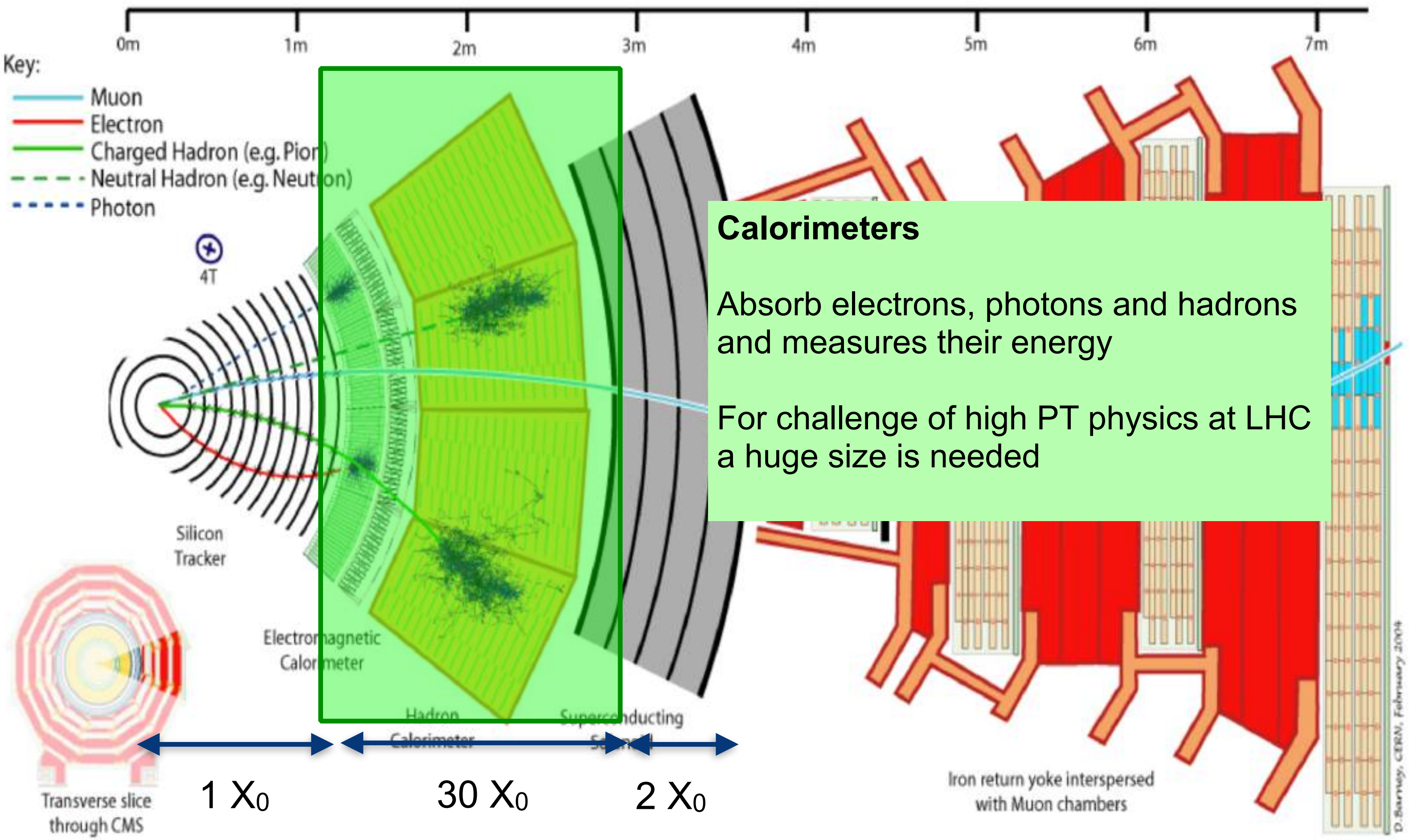


Icecube image of the moon via cosmic ray deficit



SuperK neutrino image of the moon taken through the earth

Detector Layout



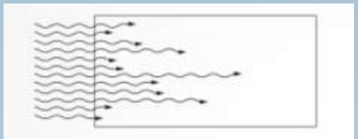
Calorimeters

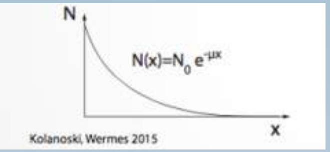
Absorb electrons, photons and hadrons and measures their energy

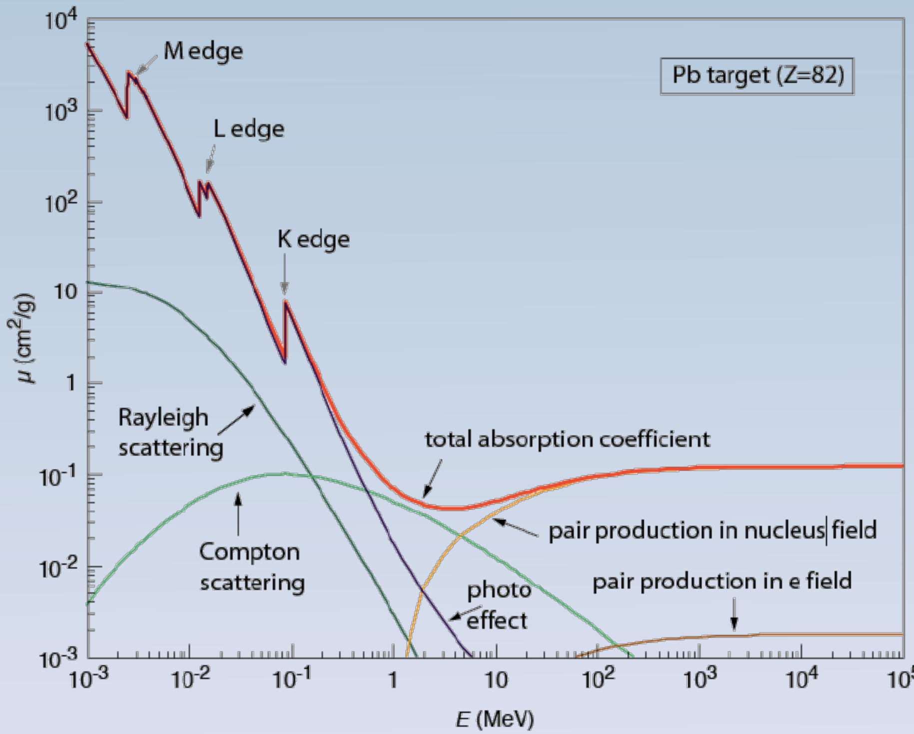
For challenge of high PT physics at LHC a huge size is needed

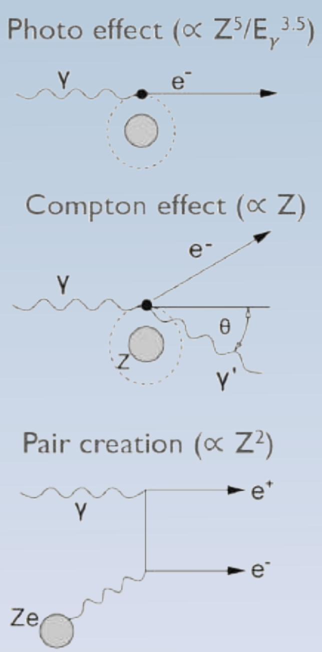
Interaction of photons with matter

Energetic photons typically interact by absorption $N(x) = N_0 e^{-\mu x}$









Photon loses its energy to an atom which emits an electron - secondary emission of characteristic X rays and Auger electrons when holes are refilled

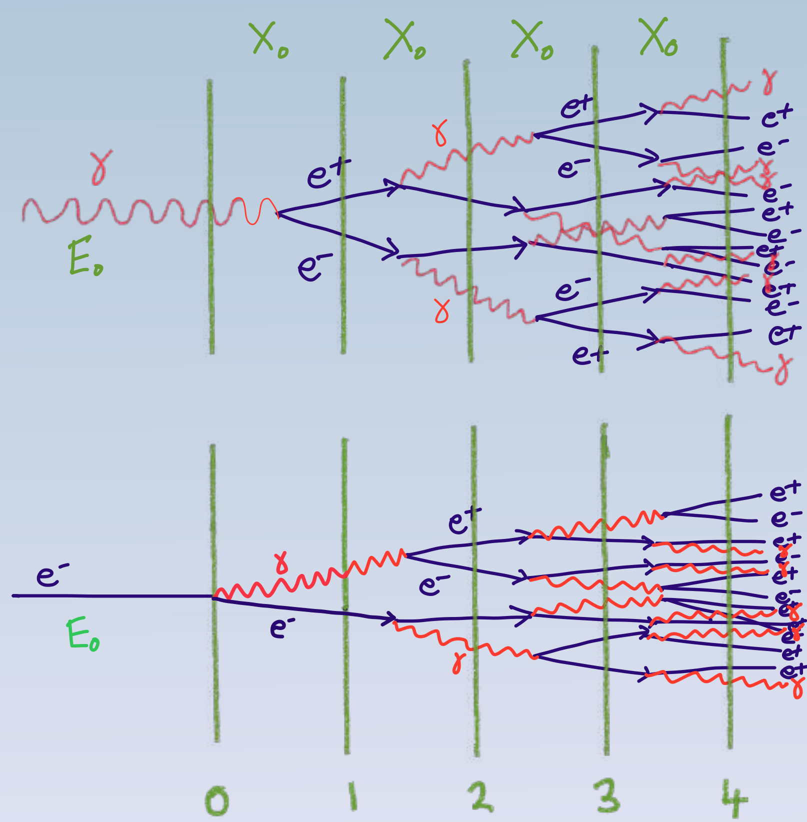
(Quasi-) elastic scattering on an electron in the atomic shell

The photon converts to an e^+e^- pair in the electric field of the nucleus. This process quickly dominates! (With Compton scattering for lower energies)

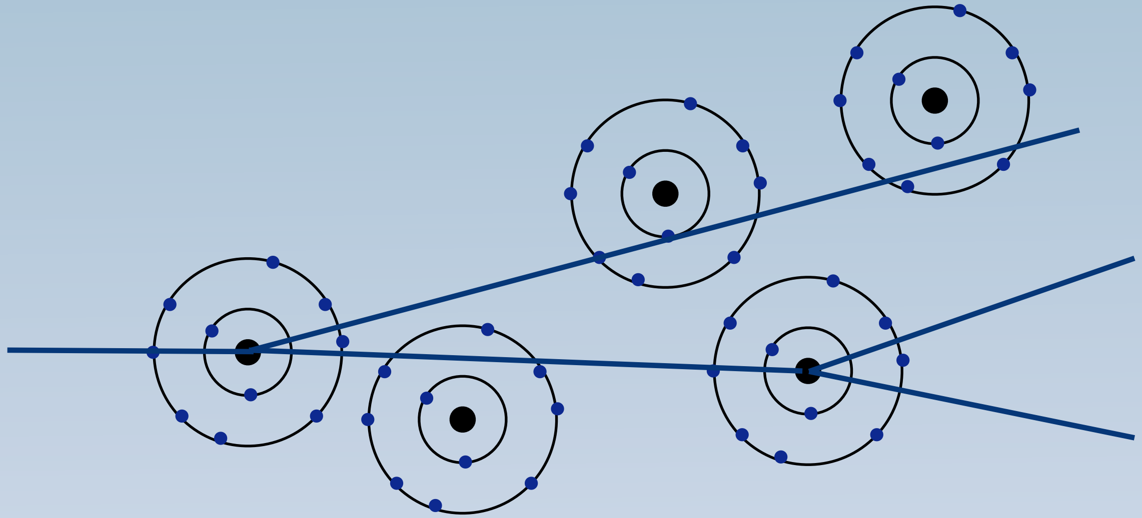
Pair creation (E>1.022 MeV) and electron bremsstrahlung, the two dominant processes at high energies, have the same (leading-order) matrix element (crossed Feynman diagrams) and are very closely related: $\lambda_\gamma = \frac{9}{7} X_0$

Interaction of photons with matter

Bremsstrahlung + Pair Production → EM Shower

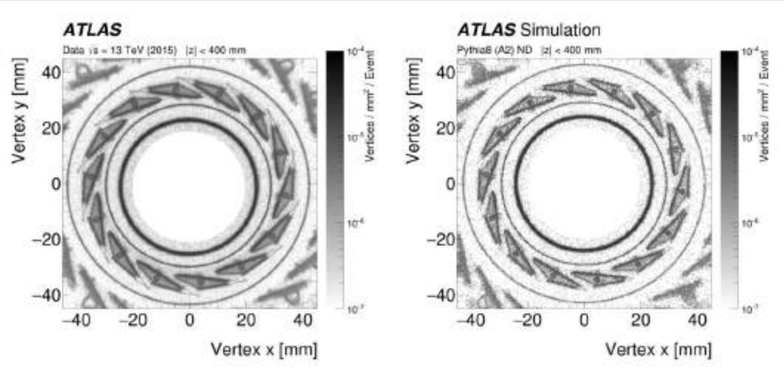


Hadronic Interaction of Particles with Matter



Hadronic interactions with nuclei produce a complex sequence of secondary particles. This is at the basis of hadron calorimetry

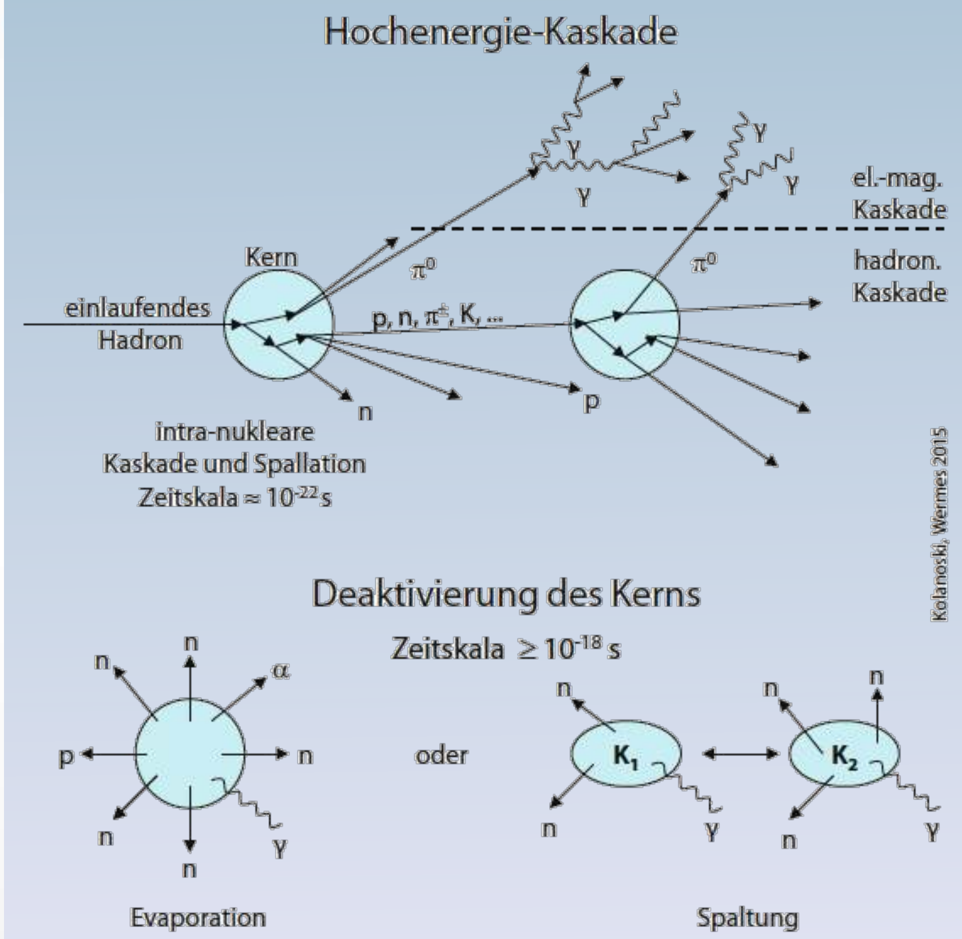
Hadronic interactions taking place in the trackers have a bad impact on the tracker measurements!



Tracing back these secondary particles to their origin gives the place of interaction. Making a map of these points we can image our detectors!

Putting it together:

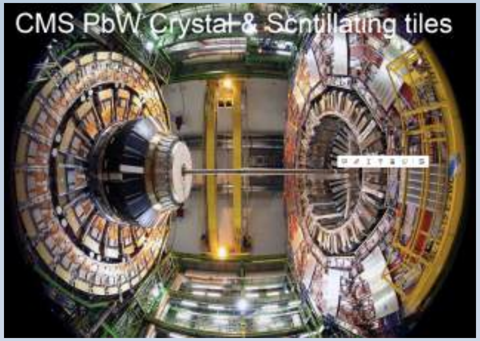
- Hadrons interact inelastically with a single nuclei in the nucleus
- Secondary hadronic decay products interact with other nuclei, leading to shower formation.
- If neutral pions are produced, they decay to photons with subsequent electromagnetic showers.
- Between hadronic interactions, charged shower particle also ionize the material, leading to an EM cascade (also, nuclei can de-excite emitting γ)
- The fluctuation of the shower components is large and, depending on the charge and the momenta of the particles, each has a different reconstruction efficiency.
- This limits the resolution in reconstructing the energy of the incident particle.

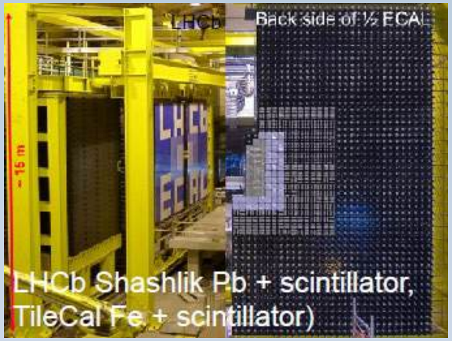


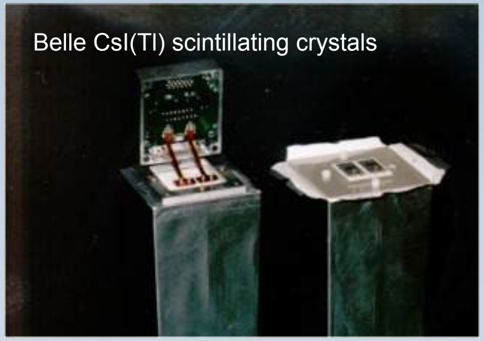
Calorimetry

Calorimetry is Energy Measurement by total Absorption of Particles

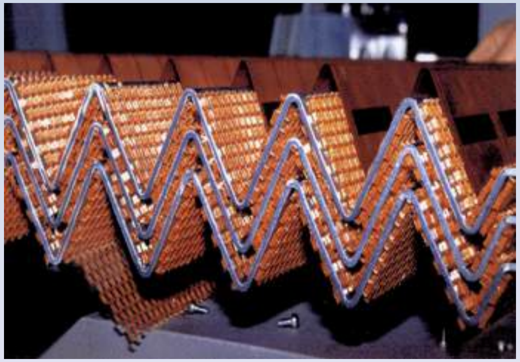
- Electrons and High Energy Photons produce EM cascades
- Strongly interacting particles (Pions, Kaons) produce hadronic showers
- Counting the total number of e^-, I^+ pairs in the material gives the particle energy
- The measurement is destructive. The particle cannot be subject to further study.
- For a calorimeter; $\Delta E/E \propto 1/\sqrt{E}$ - great news for high energy particles at the LHC!







4 main technologies: LAr, Scintillators, Crystals (tiles or fibers), Silicon sensor



Two main concepts:

Homogeneous crystals (CsI, LYSO):
- Best possible resolution
- Application to PET

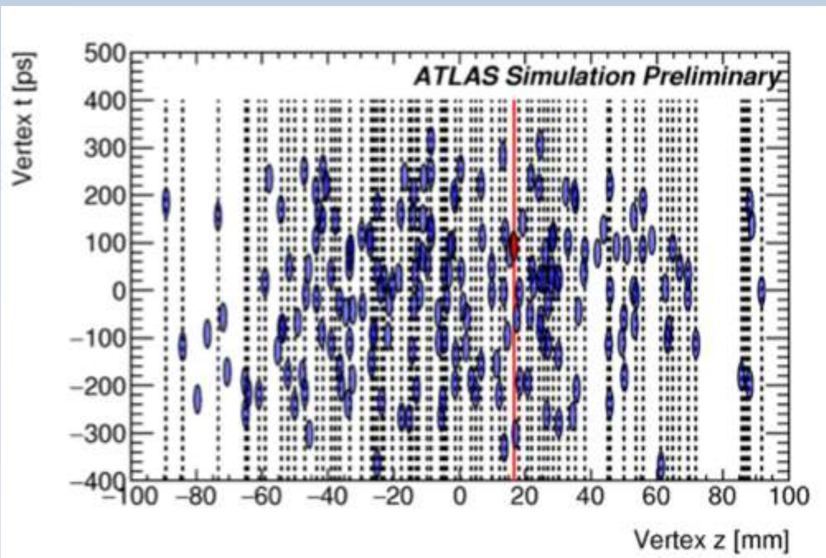
Sampling:
- Imaging: Particle Flow algorithm
- Dream: Dual Readout
- Sampling with crystals, shashlik-type

Adding the 4th dimension

Timing for Tracking

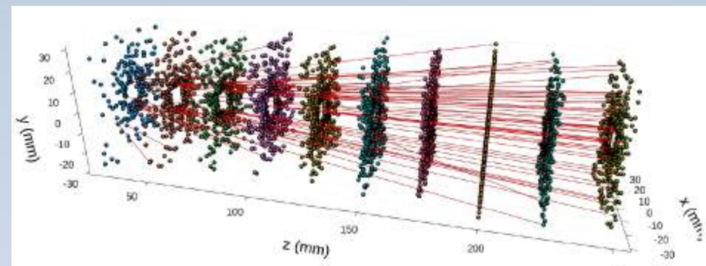
1. Pileup mitigation with timing

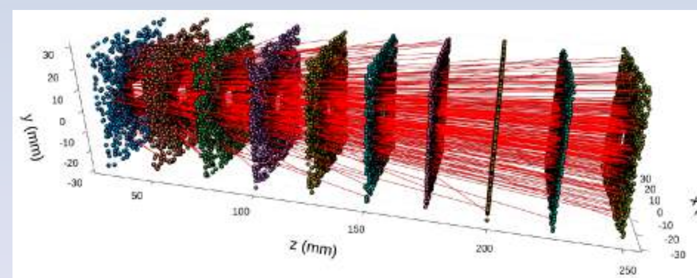
- ~200 collisions / bunch @ GPDs gives overlapping vertices and high pileup in forward
- Track to vertex assignment difficult with worse forward z_0 resolution
- Track resolution of < 50 ps
  - Distinguishes pileup from hard scatter tracks
  - Identifies overlapping vertices
  - allows Time Of Flight tagging and improves physics object reconstruction



2. 4D tracking

- Challenging pattern recognition due to increased number of combinatorics and primary vertices e.g. LHCb UII
- Hit resolution of ~ 50 ps per track
  - recovers efficiency and resolution of reconstructed primary vertices
  - Resolves associations of secondary vertices and displaced tracks
  - Reduced combinatorics for gains in CPU usage, efficiency, ghost rate, control of systematic uncertainties..



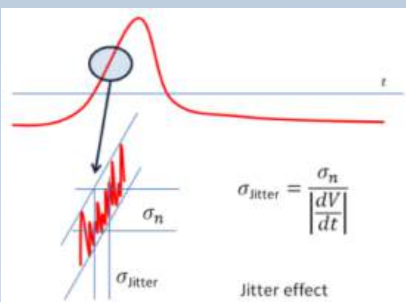


Ultra-Fast Silicon Detectors

Recent design innovations have seen transformation of solid state sensors into high resolution timing detectors (Si, Diamond, APDs, LGADs, SPADs, FASTPIX…)

Parameters which affect the time resolution at leading order:

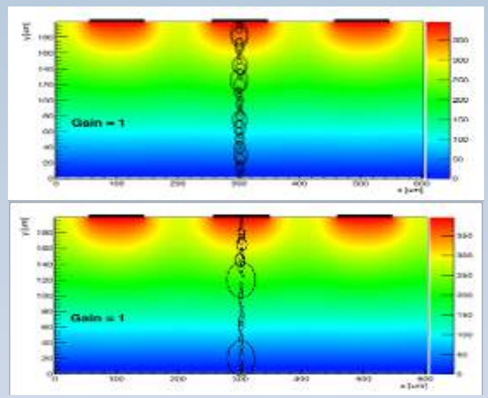
$$\sigma_t^2 = \left(\frac{Noise}{dV/dt}\right)^2 + (\Delta ionization)^2 + (\Delta geometry)^2$$



Variations in time of firing of comparator due to **noise**

- Proportional to noise
- Inversely proportional to signal slope (around comparator threshold)

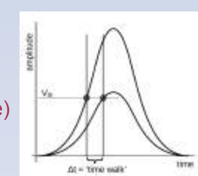
Can be mitigated by chosing electronics technology with the smallest possible noise, and sensors with the largest signal and best slew



Variations in time of arrival due to **signal amplitude variation** → time walk

- Depends on
  - Slew rate
  - Threshold setting (i.e. system noise)

Can be mitigated (at cost) with amplitude compensating circuitry



Variations in uniformity of **energy deposition**→ Landau variations - uncorrectable contribution

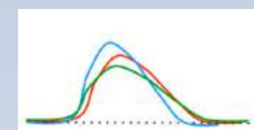
Worse for thinner sensors, but can be mitigated by shorter e-h drift times (if noise not too high) and sensor design

Signal shape is determined by Ramo's theorem

$$i \propto q \; v_{\text{drift}} \; E_{\text{weight}}$$

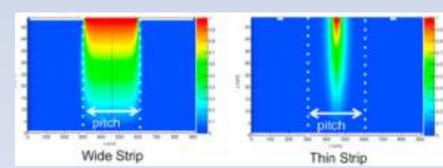
Non-uniform drift velocities induce variations in signal shape as a function of hit position.

→ Ideally use high electric field to move carriers with saturated drift velocity

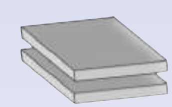


Non-uniform weighting fields induce variations in signal shape as a function of hit position.

→ mitigate with clever sensor geometry design

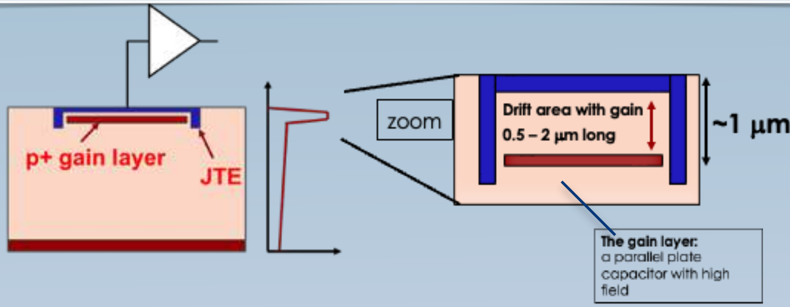


Parallel plate geometry is ideal

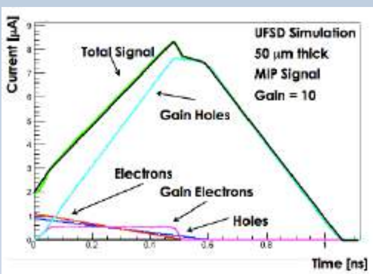


Ultra-Fast Silicon Detectors

Example: LGADs (Low Gain Avalanche Diode)



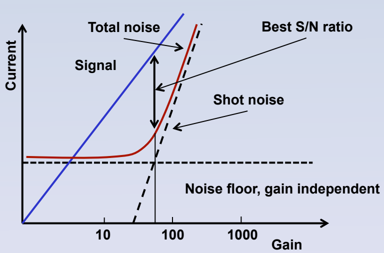
A moderately p-doped implant creates a volume of high field, where charge multiplication happens



Electrons multiply and produce additional electrons and holes.

The gain electron is absorbed immediately
The holes do not multiply but drift to the back of the sensor

<u>The gain holes dominate the signal</u>



A gain of 10 provides a good balance between improvement in signal and degradation due to shot noise and opens the door to the use of thin sensors (e.g. 30 ps for 50 μm active thickness)

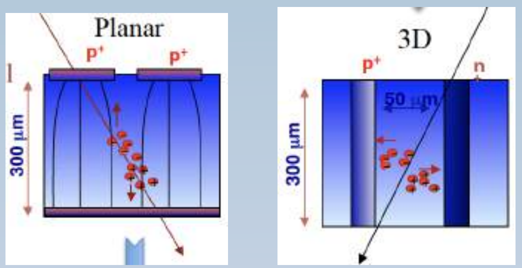
At high fluences the gain layer becomes less active (can be partly compensated with bias voltage)

Fill factor issues can be addressed with iLGADs (segmentation on opposite side)

Example: 3D sensors

3d hybrid pixel detectors are non-planar sensors

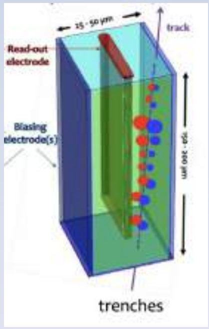
- Deep holes are etched into the silicon bulk and filled with n+ and p+ material
- Depletion is sideways and the distances between the electrodes are small
- Depletion voltage can be much smaller and charge carriers travel much shorter distances

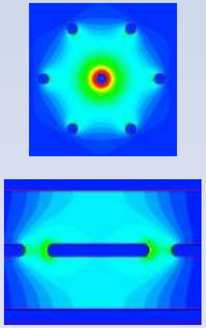


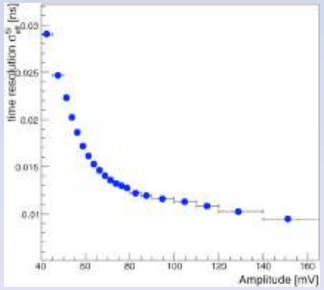
Proven as very radiation tolerant detectors e.g. use in ATLAS IBL layer
However also very effective for timing

- short drift distances and high fields
- Landau fluctuations for a perfectly perpendicular track are eliminated! (Only affect total hight)

Taken a step further by the TIMESPOT collaboration who have realised a parallel plate geometry in a 3d sensor



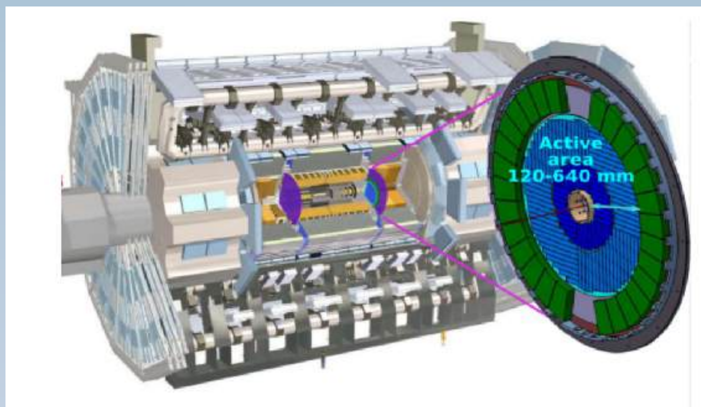




LGADs for ATLAS and CMS timing layers

ATLAS High Granularity Timing Detector | **CMS Endcap Timing detectors**

Both equipped with LGADS with 1.3 x 1.3 mm^2 pads targeting < 50 ps resolution



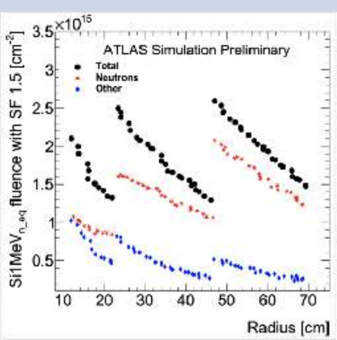
Two double sided layers in front of Calorimeter endcap

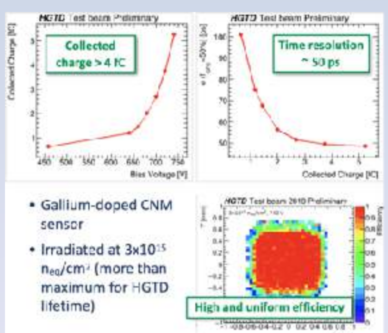
covers: 2.4 < η < 4.0 with 12 cm < R < 64 cm @ z = 3.5 m

3 rings are replaced 4/2/0 times to maintain fluence < 2.5 x 10^{15} n$_{eq}$/cm^2

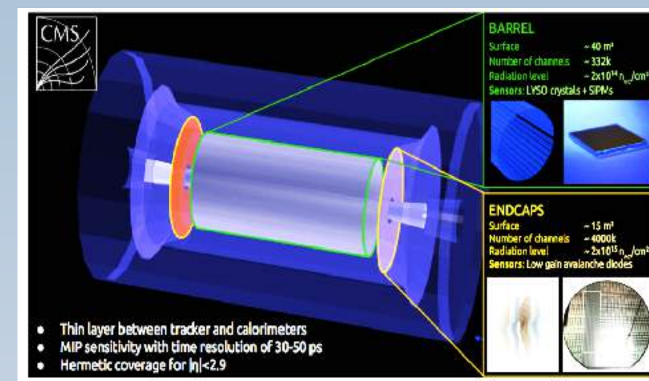
2(3) hits per track for R> (<) 30 cm

ToA and ToT from ALTIROC





Post irradiation:
4 fC and 50 ps achieved!

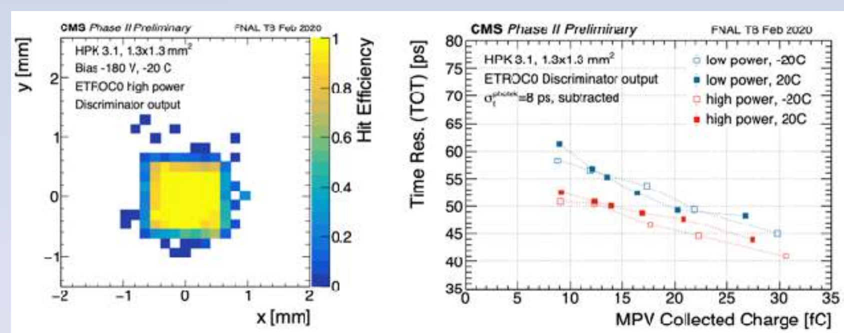


Two double sided layers in front of Calorimeter endcaps; hermeticity with BTL

fluence < 1.7 x 10^{15} n$_{eq}$/cm^2

covers: 1.6 < η < 3.0 with 0.31 < R < 1.2 @ z = 3 m

ToA and ToT with single TDC from ETROC readout



Pre irradiation
40-50 ps after discriminator
with full efficiency!

Other Clever Techniques for Ultra-fast TOF and TOP

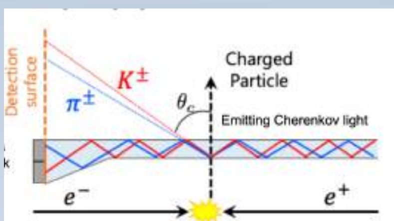
Fast progress in the new DIRC derived concepts, including time-of-propagation counters

Exceptional time resolution of $\mathcal{O}$(10 ps), based on MCP-PMTs

Belle II Time of Propagation RICH (TOP)

The photons are produced in a quartz bar which acts as the **radiator** and the **light guide**

- By principle of total internal reflection the traveling photons preserve the emission angle
- typically 20-40 photons per charged track
- $\sigma_t \propto \frac{\sigma_{\text{MCP}}}{sqrtN_\gamma}$
- Very compact detector



$$\cos\theta_c = \frac{1}{n\beta} = \frac{\sqrt{m^2+p^2}}{np}$$

$$p = 3 \text{ GeV } \pi/K$$

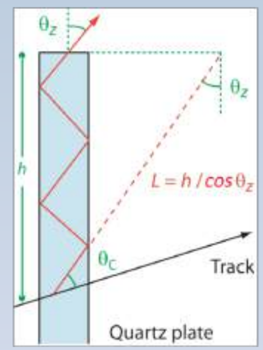
$$\Delta\theta_c \simeq 0.6^\circ \Longrightarrow \Delta t = \mathcal{O}(100) \text{ ps}$$

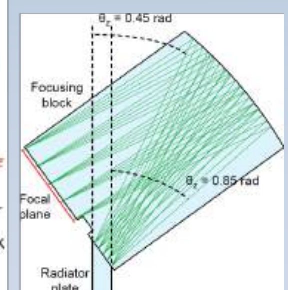
Belle II is taking advantage advantage of the new ALD-MCPs for enhanced lifetime

LHCb TORCH (Time of internally Reflected Cherenkov light) for Run 5/6

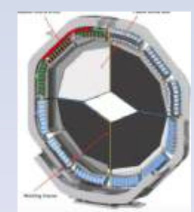
Prompt production of Cherenkov light in quartz plates

- Cherenkov photons travel to detector plane via total internal reflection and cylindrical focusing block
- 70 ps per photon → 15 ps per track
- Photons detector by MCP-PMTs, resolution improved by charge sharing





Panda DIRC has many similar features to LHCb TORCH:



The material frontier

How light can we go?

Monolithic Sensors

Hybrid Pixel detectors

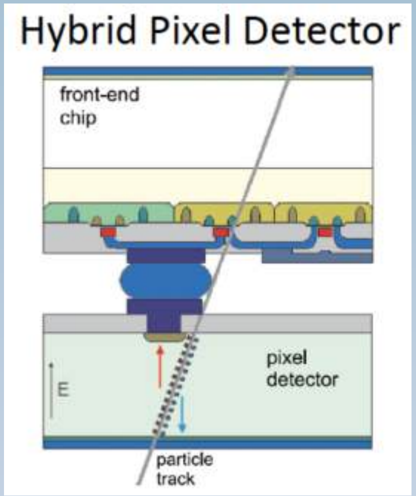
Sensor based on pn junction detector produced in planar process

High resistivity wafers (few kΩcm) with diameters 4”-6”

Specialized producers (~ 10 world wide)

Readout Chip: CMOS chip fabricated in sub-micron technology

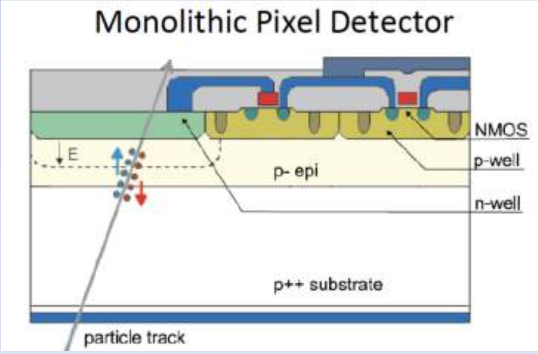
Interconnect technology based on flip-chip bonding



Monolithic Pixel detectors

Combine sensor and all or part of readout electronics in one chip

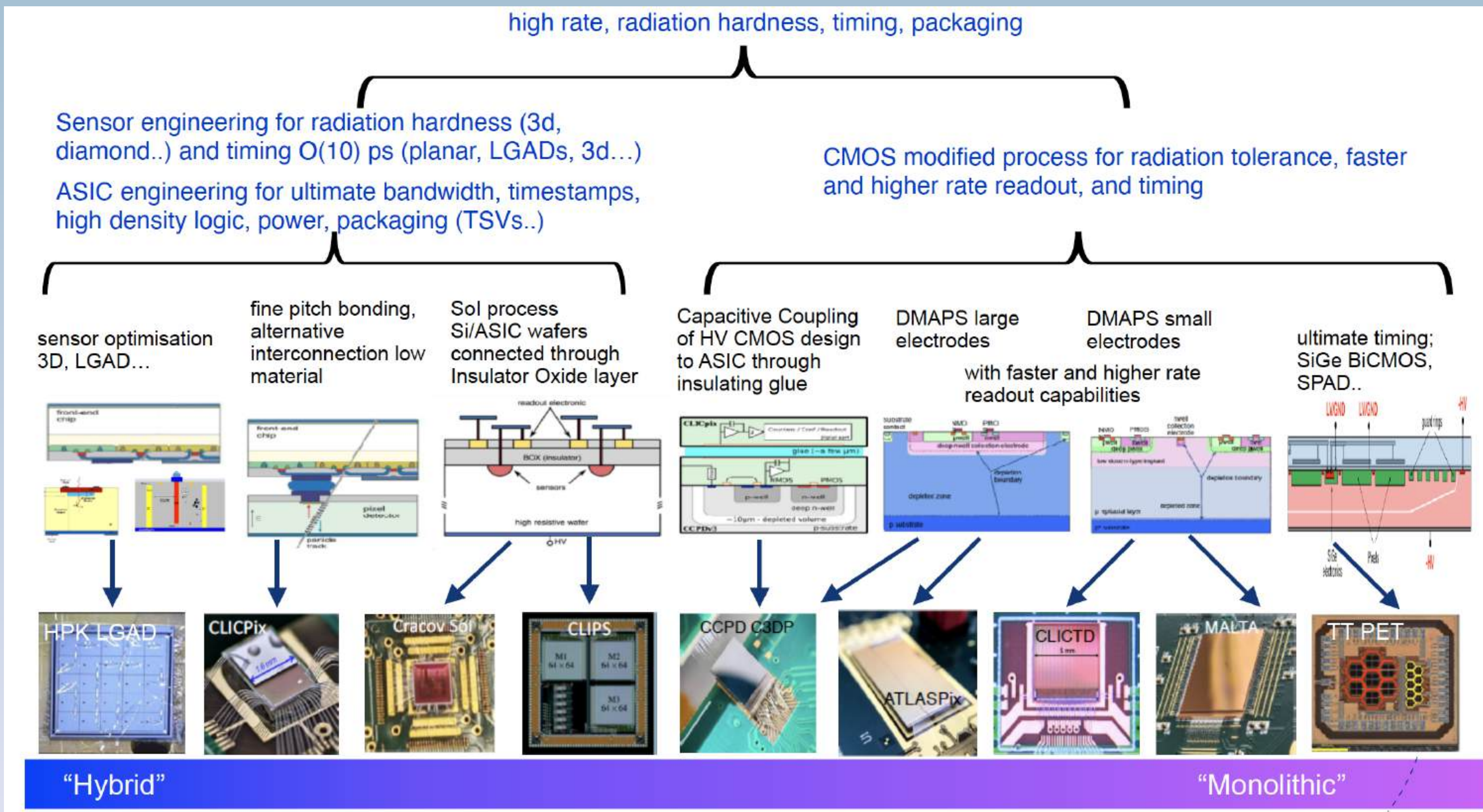
Charge generation volume integrated into the ASIC
No interconnection between sensor and chip needed



Many different flavors with different levels of integration of sensor and readout parts

CCDs, **CMOS MAPs,** HV/HR CMOS, DEPFET, SoI….

Monolithic Sensors



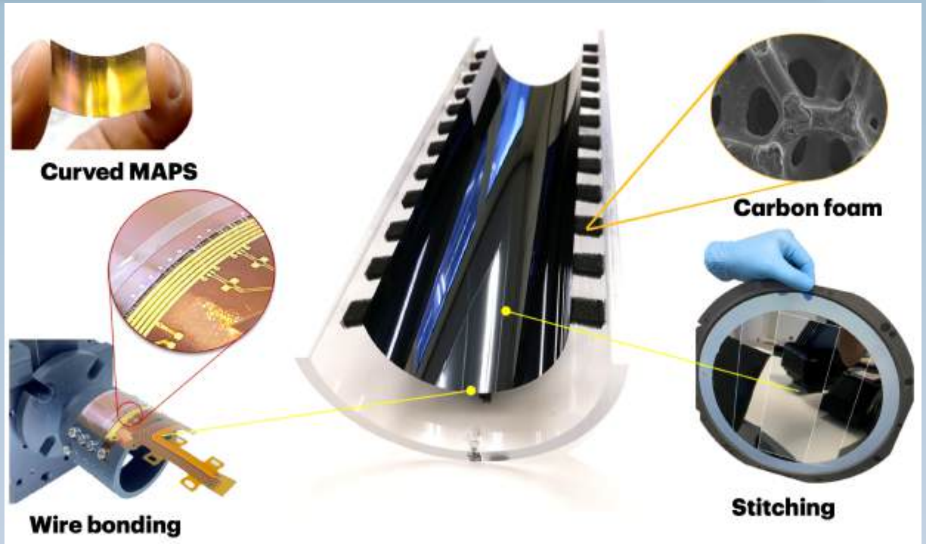
Monolithic: State of the art

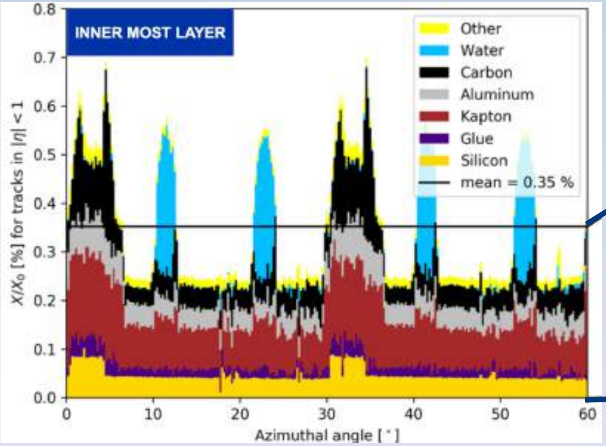
ALICE ITS3 - for Run 4

A cylindrical, near-transparent vertex detector

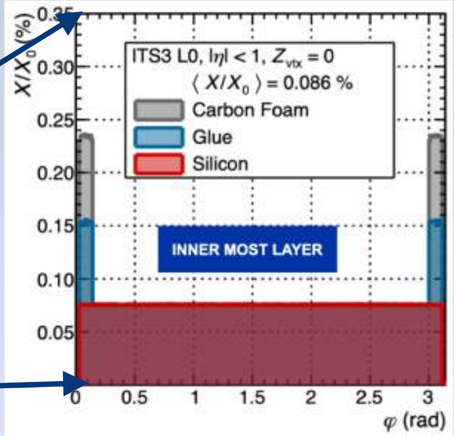
New sensor, scaled up to the wafer size and thinned to 50 μm

- sensor can be bent, and mechanical supports almost completely removed - tiny carbon foam supports only!
- Overlap between staves removed!
- Drop in power density → replace water cooling with air cooling!





ITS2

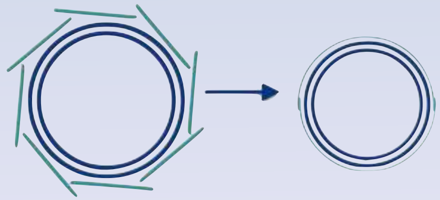


ITS3

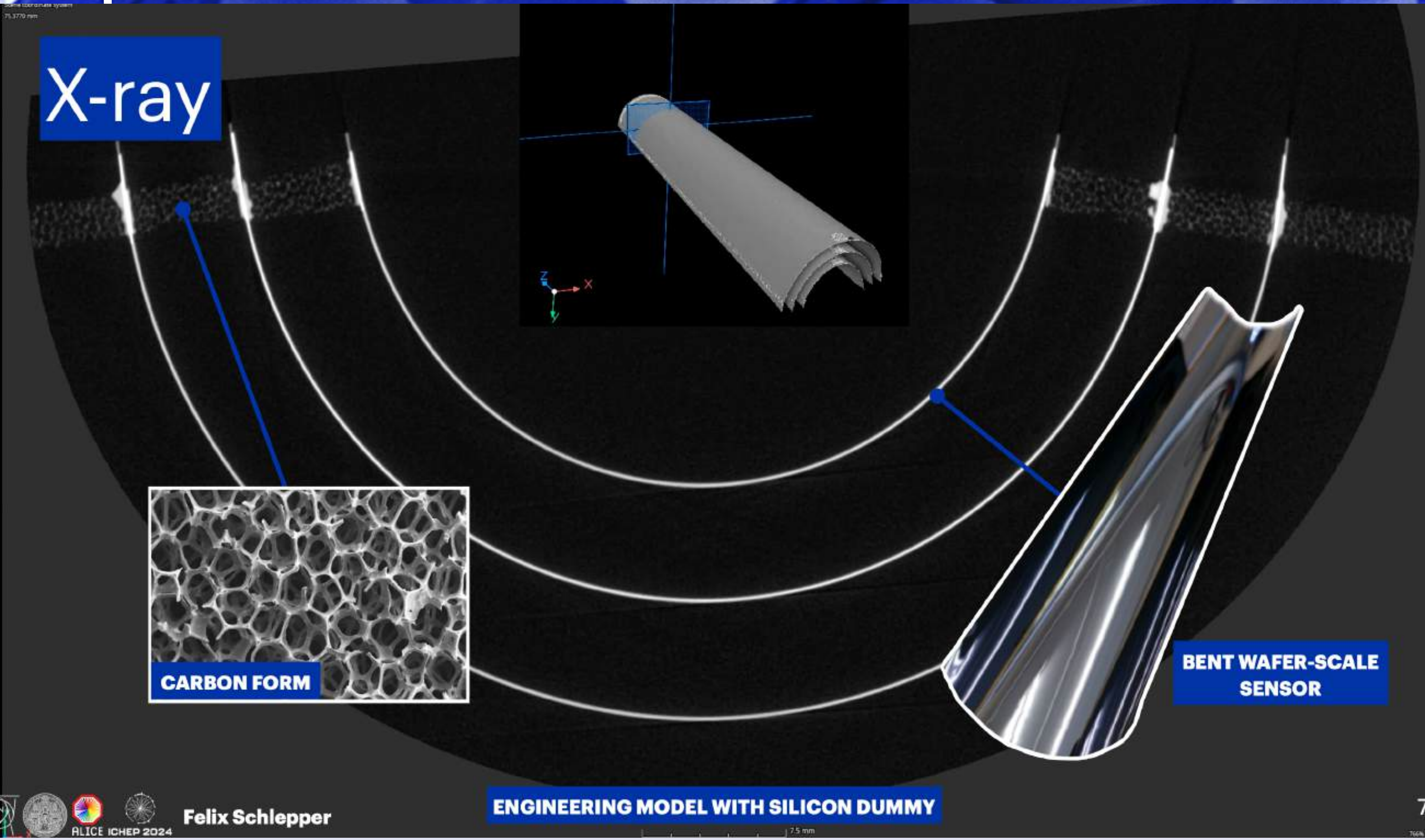
Uniformly distributed material

0.35% X_0 →0.07% X_0 per layer

Beampipe radius reduced



Monolithic - State of the Art



Monolithic - State of the Art

Sensor Stitching

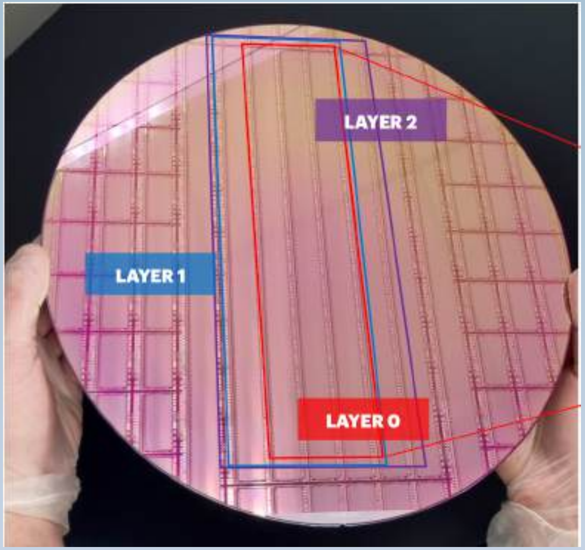
Chip size is traditionally limited by CMOS manufacturing ("reticle size")

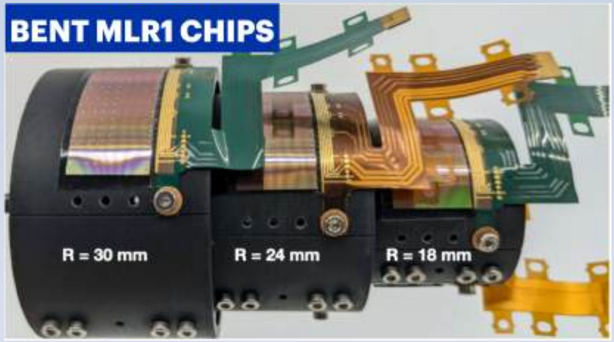
- Typical size of a few cm^2
- Modules are tiled with chips connected to a flexible printed circuit board

New developments: stitching

- Aligned exposures of a reticle to produce larger circuits
- Actively used in industry
- A 300 mm water can house a chip to equip a full half-layer
- 6.72 million pixels on a single chip!
- Requires dedicated chip design

Final circuit is concatenation of different parts of the mask





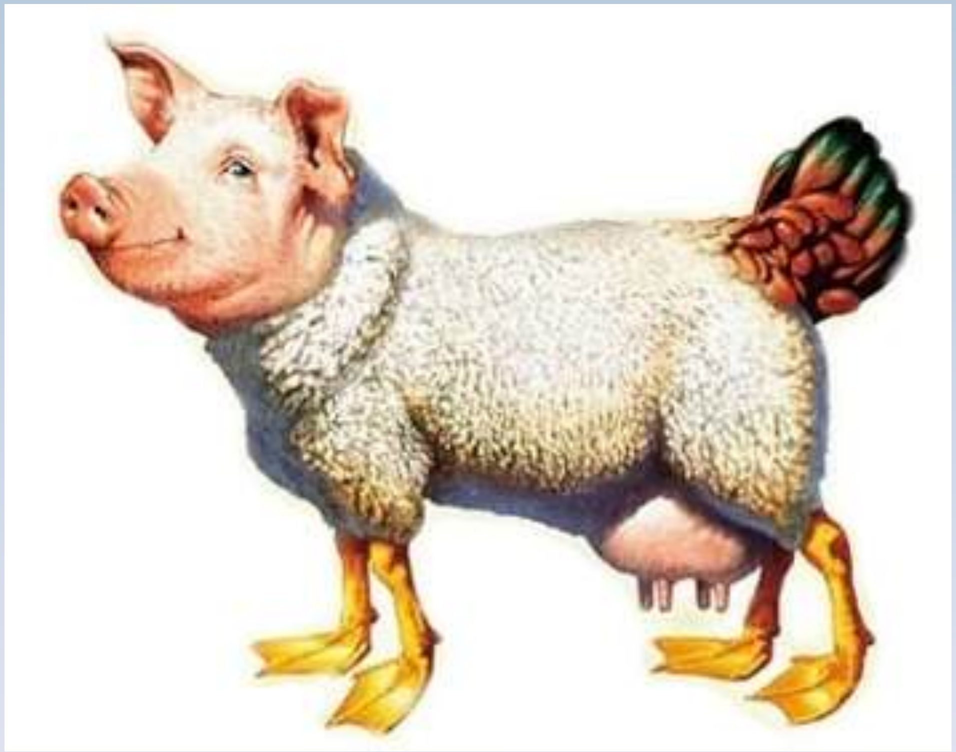
Bent sensors show excellent performance, > 99.99% efficiency, 5 μm resolution

Detector System and Design

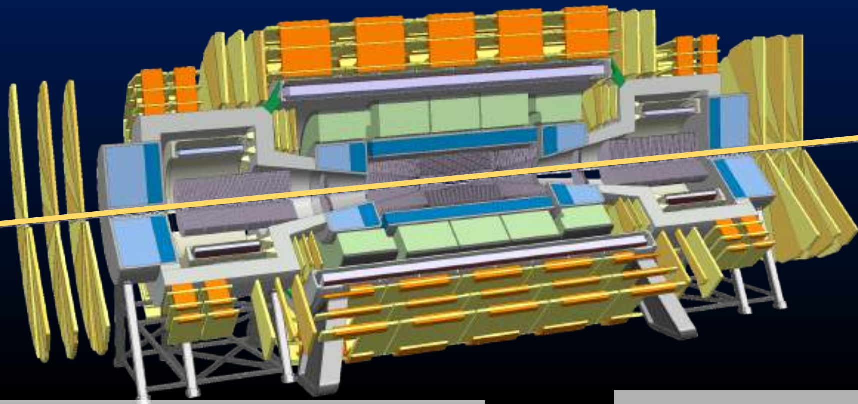
Detector Design Criteria

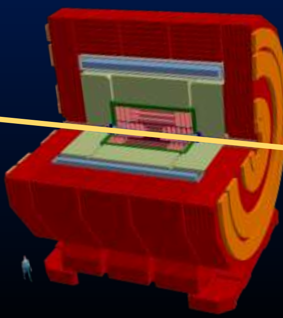
- Little interaction with the measured particle
  - Tracking detectors should trace the passage of a charged particle without disturbing it
- High Efficiency
  - Probability of detection in case of a signal particle
- High Purity (high signal-to-noise ratio)
  - Low probability of instrumental noise and unintended signal
- High resolution
  - Spatial, time, energy, momentum, angle
- Fast signal processing
- Simple maintenance and detector control
- Radiation Hardness
- Low Cost

It is hard to construct a Wollmichsau



Future Detector Needs





FCChh, HE-LHC, …

hh collisions | e^+e^- collisions

CLIC, FCCee, ILC…

- Large dimensions (50m)
- 4T + 4T barrel + forward magnets
- Silicon Tracker Radius 1.6m, Length 32m
- Very High Radiation Levels (up to 90MGy)
- Very High Pile-up Conditions

- Moderate dimensions (50m)
- Moderate Radiation
- 4T + 2T barrel + forward magnets
- Silicon Tracker unprecedented spatial resolution (1-5 μm point resolution)
- very low material budget
- very low dissipated power

➔ Future detector technologies have to cope with a large range of demanding requirements
➔ FCC-hh and HE-LHC : similar detector technology requirements for resolution and radiation hardness.
➔ FCC-hh, HE-LHC, FCC-ee: similar technology requirements for of resolution and material budget

Future

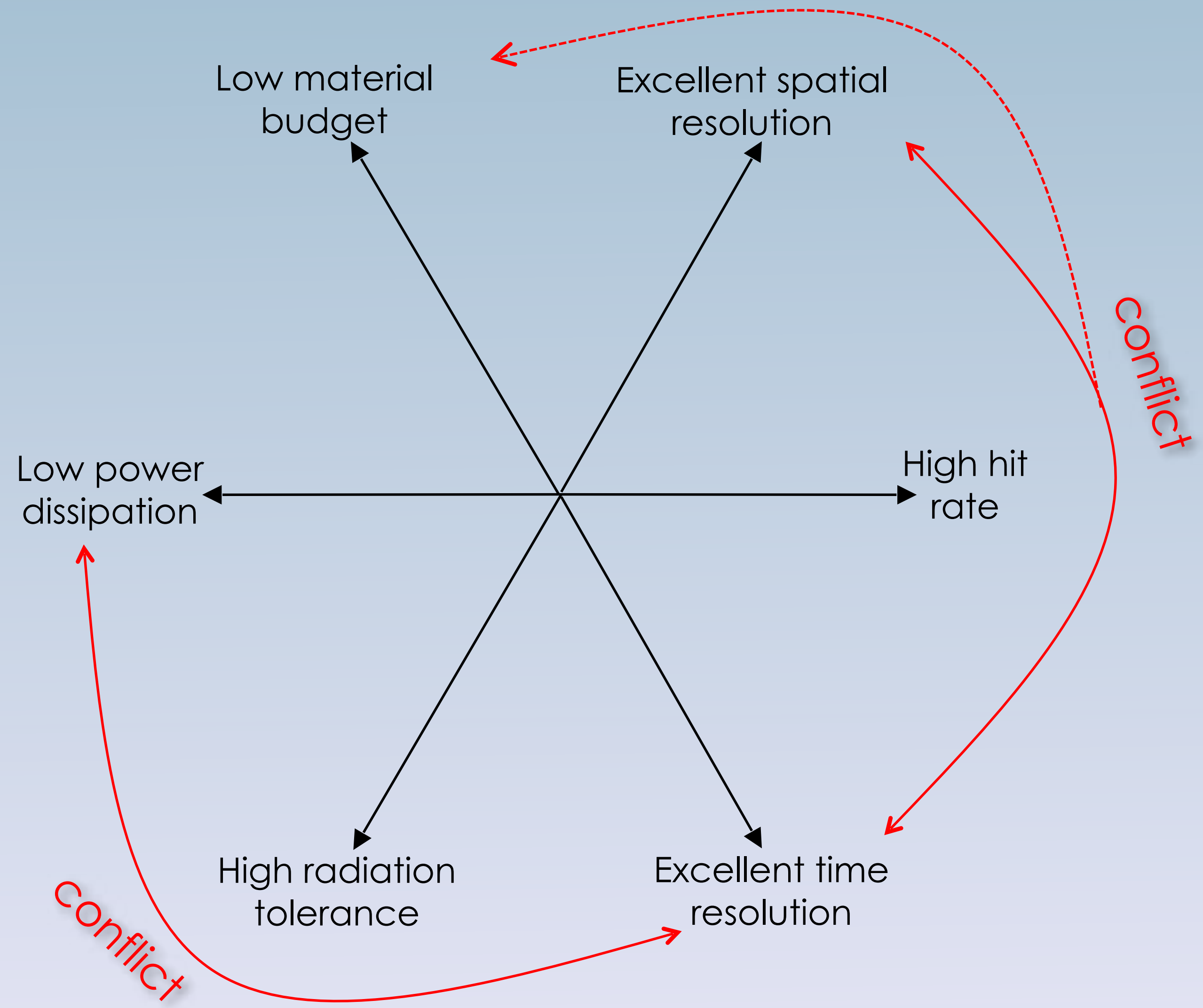
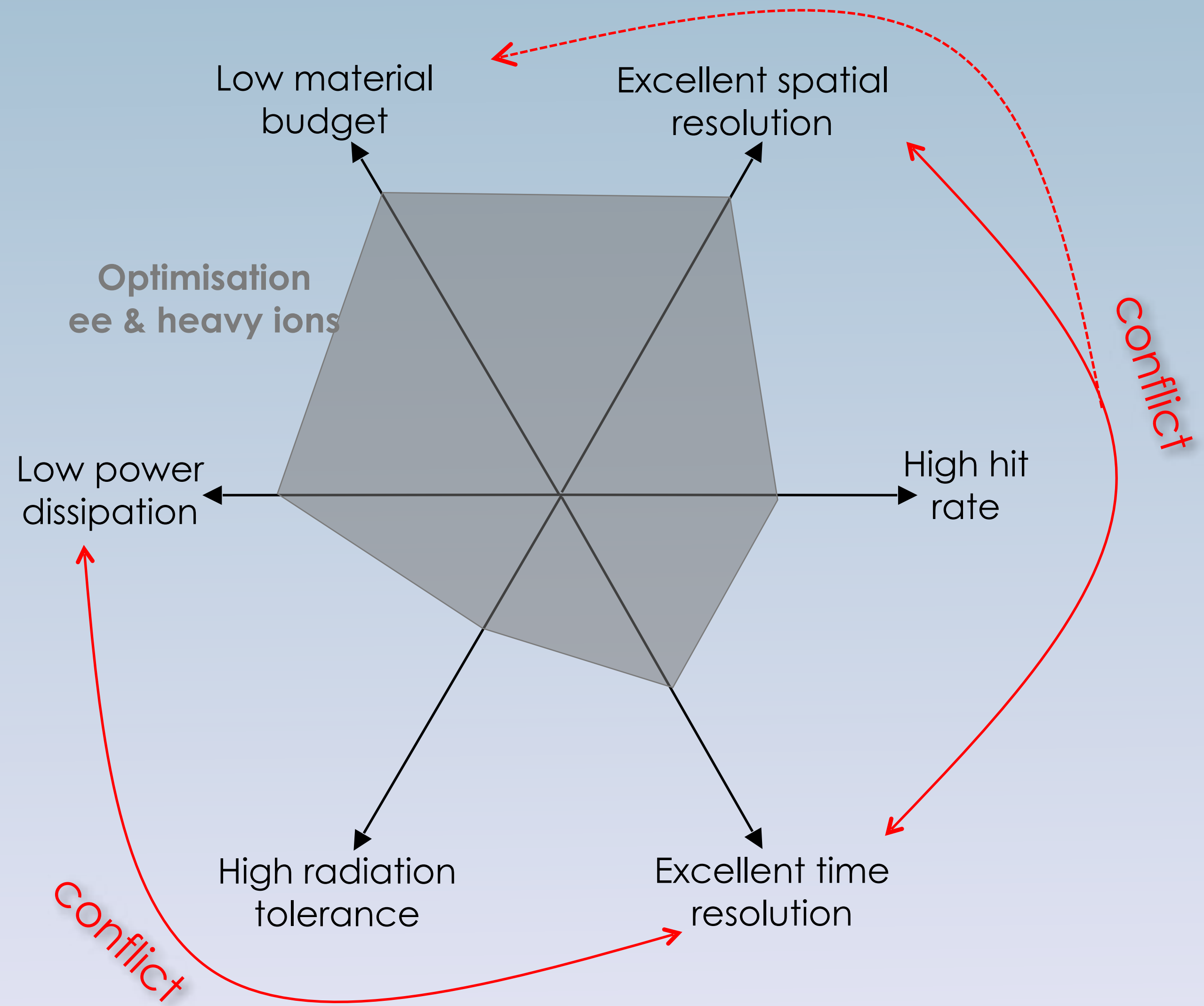


Figure kindly provided by Jerome Baudot

Future



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Future

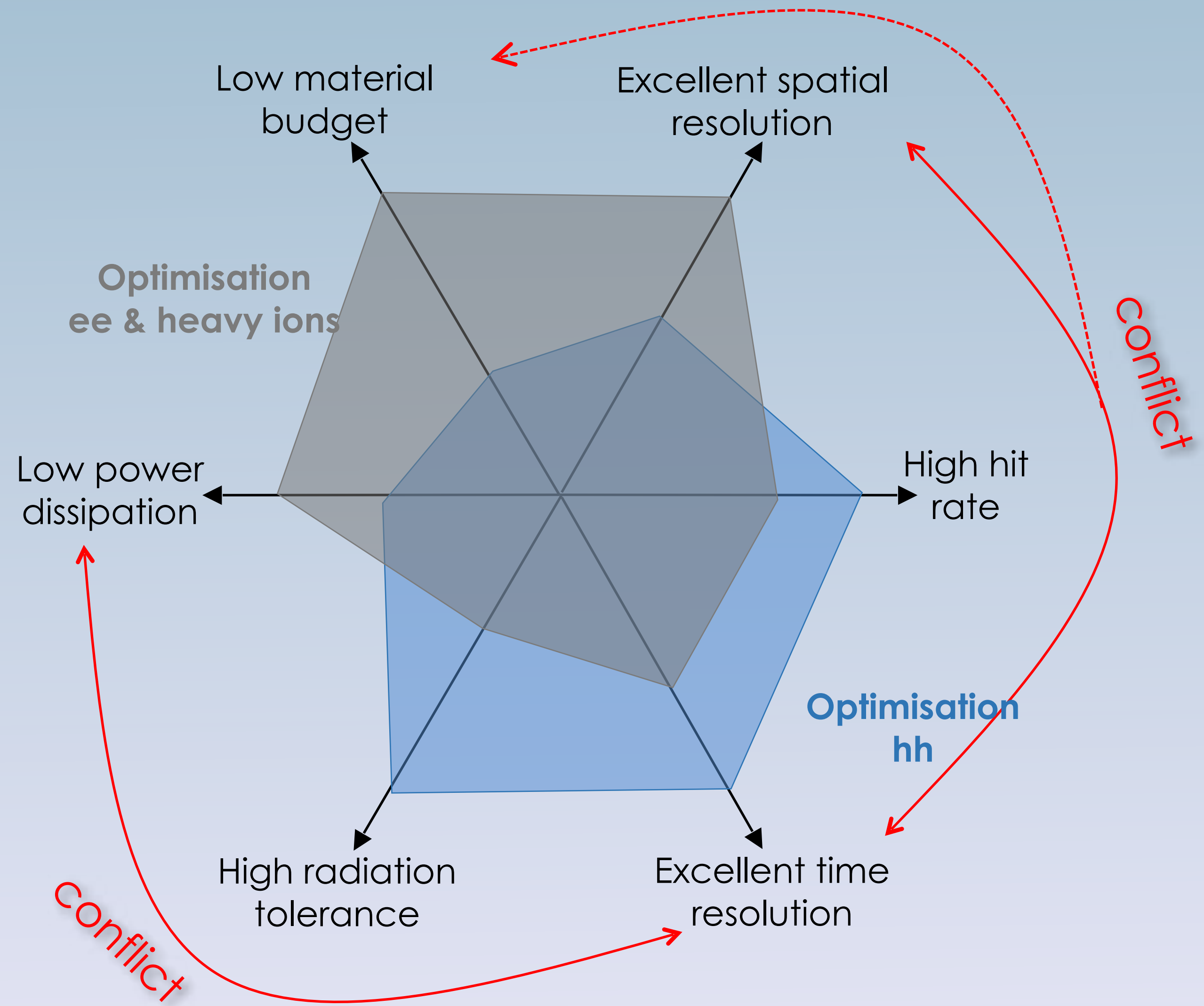
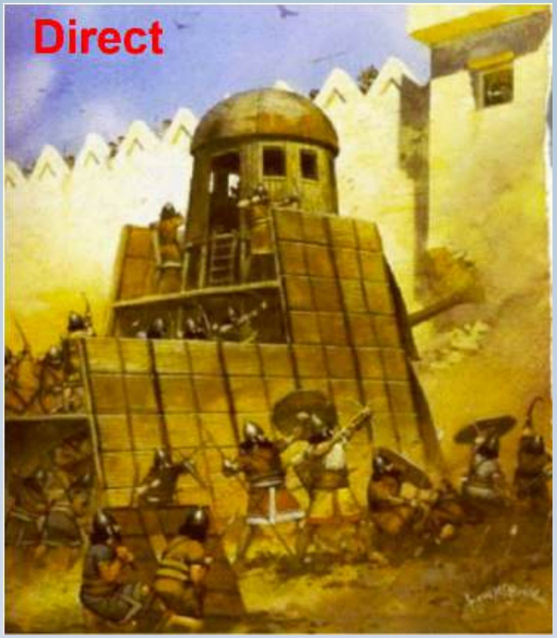


Figure kindly provided by Jerome Baudot

LHCb - forward spectrometer for flavour physics

The experiments at the LHC are attempting to breach the walls of the standard model fortress and discover New Physics, using two strategies



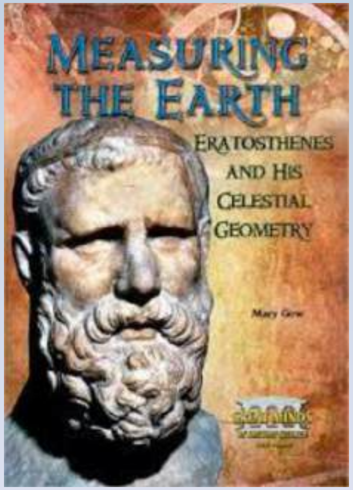
Use the high energy of the LHC to produce new particles, which we then detect

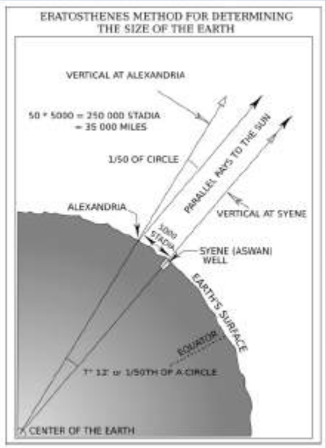
Make precise measurements of processes in which New Physics particles enter through "virtual loops"

Both methods are powerful. LHCb is a specialist in the indirect approach.

Indirect measurements - an established tradition in science

Erastothenes was able to determine the circumference of the Earth using indirect means….





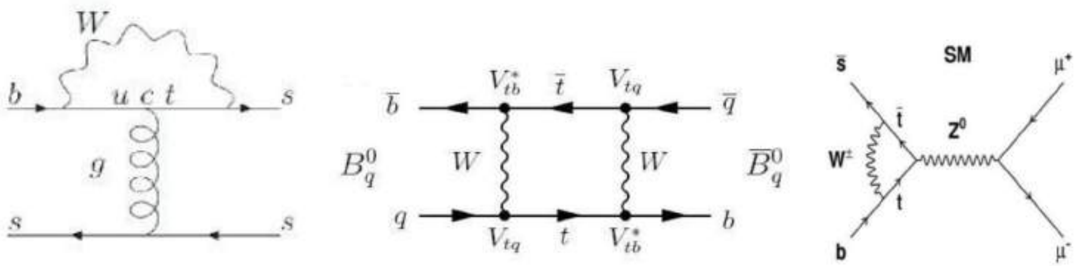
…around 2.2 thousand years prior to the direct observation

Slide kindly provided by Guy Wilkinson

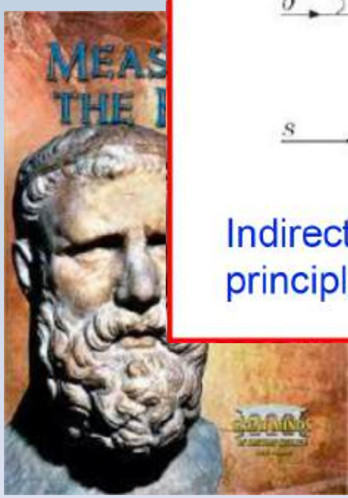
Indirect measurements - an established tradition in science

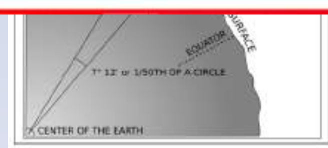
Erasto
determ
Earth

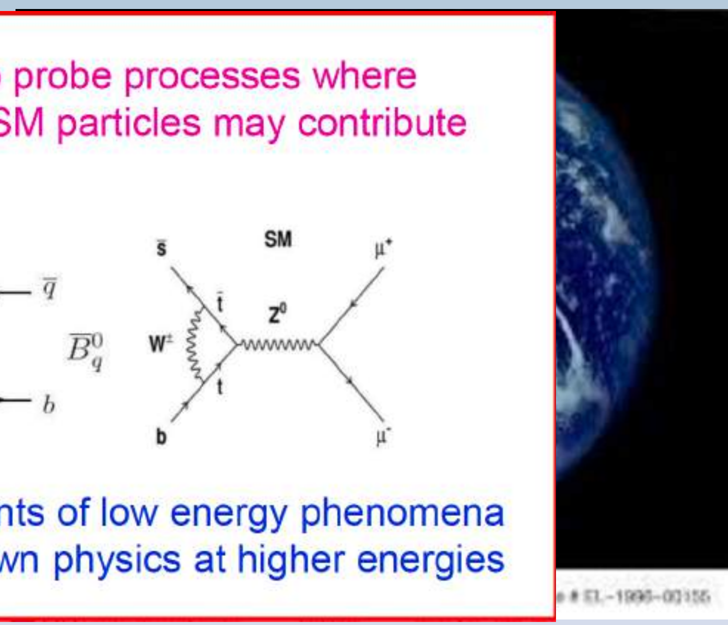
In flavour physics the guiding principle is to probe processes where loop diagrams are important, as here non-SM particles may contribute



Indirect search principle ➡ Precise measurements of low energy phenomena tells us about unknown physics at higher energies







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Slide kindly provided by Guy Wilkinson

LHCb - forward spectrometer for flavour physics

Indirect measurements - an established tradition in science

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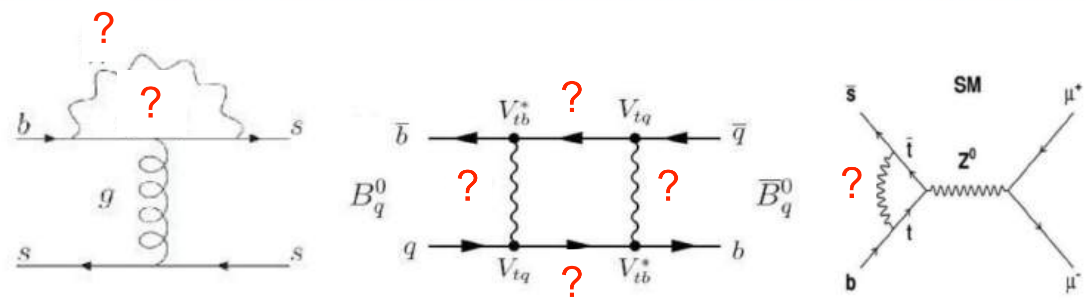

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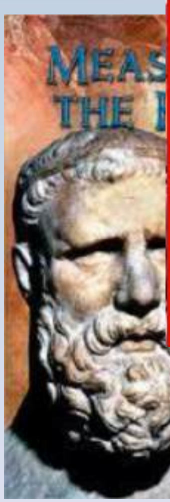
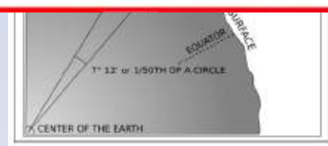


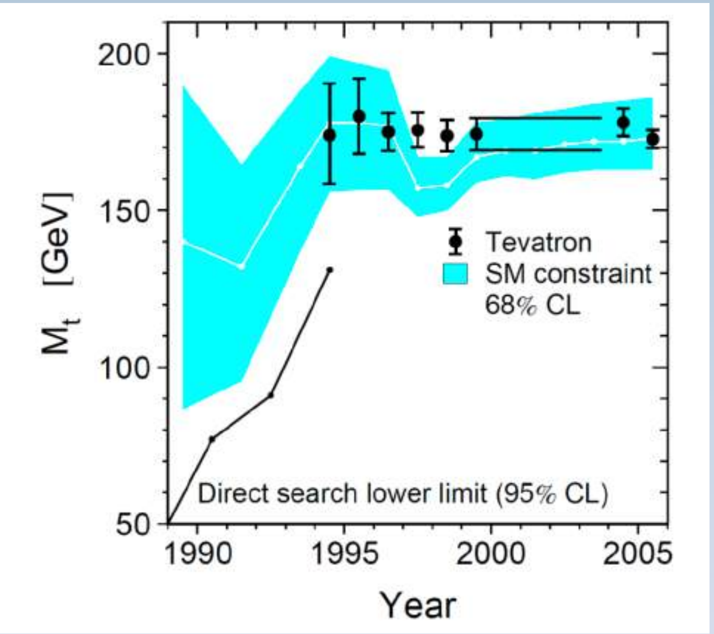


…around 2.2 thousand years prior to the direct observation

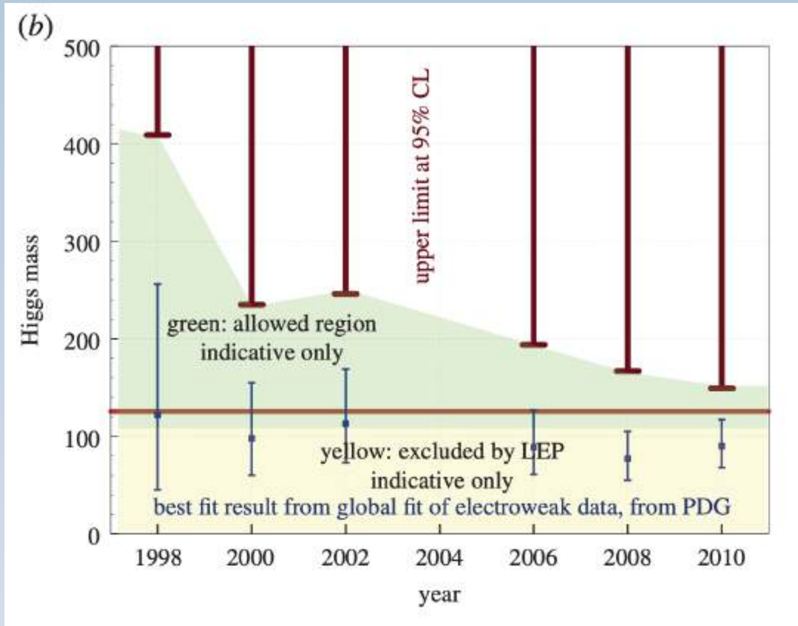
Slide kindly provided by Guy Wilkinson

Pointing the way to the top and Higgs

Electroweak corrections present in the observables have a quadratic dependence on the top mass, and a logarithmic dependence on the Higgs.



http://dx.doi.org/10.1098/rsta.2014.0039



LEP and SLD Z data 'measured' top mass well before discovery

LEP & Tevatron data also constrained the SM Higgs and made a best fit mass prediction

LHCb performance

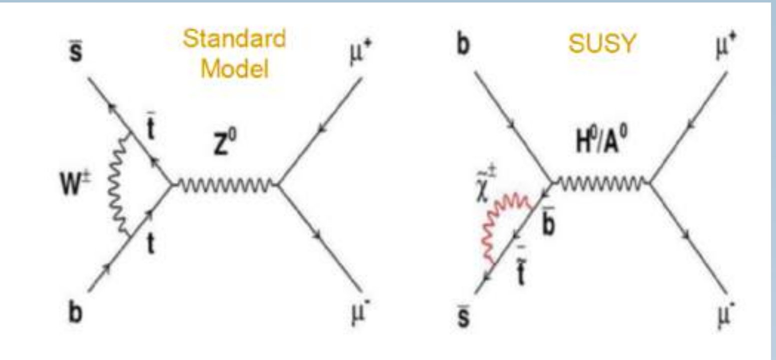
Let's take one example:

$$B_s \to \mu^+\mu^-$$

FCNCs: the search for $B_s \to \mu^+\mu^-$

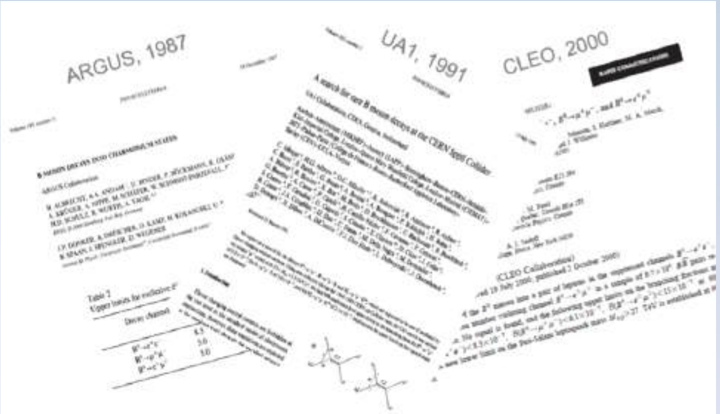
This decay mode can only proceed through suppressed loop diagrams.

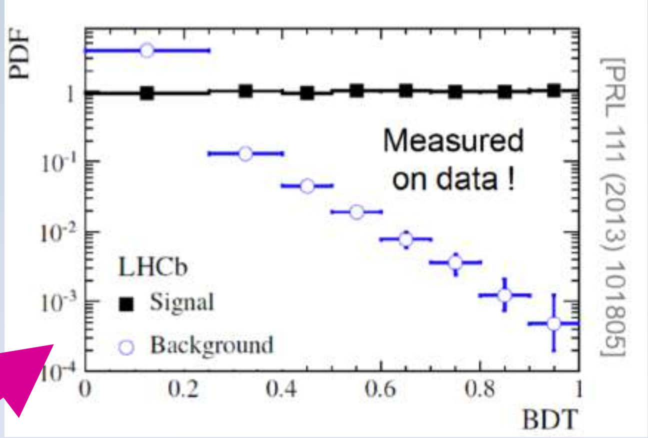
In the Standard Model it happens extremely rarely (10^{-9}), but the exact rate is very well predicted



Many models of New Physics (e.g. SUSY) can enhance rate significantly!

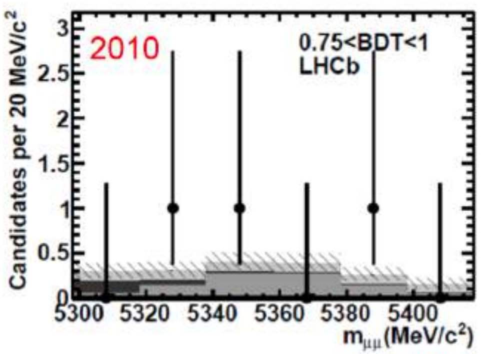
A ‘needle-in-the-haystack’ search, pursued for over 25 years





LHCb uses a multivariant approach

Evolution of $B_s \to \mu^+\mu^-$

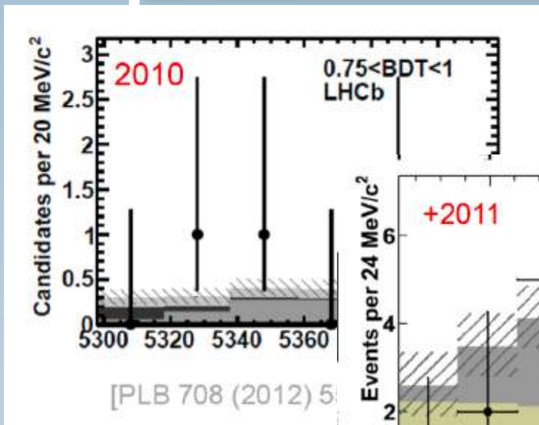


[PLB 708 (2012) 55]

Plot of invariant mass distribution in region of high BDT sensitivity - if there is a signal we should see a peak here (but the BDT uses much more information than the invariant mass alone!)

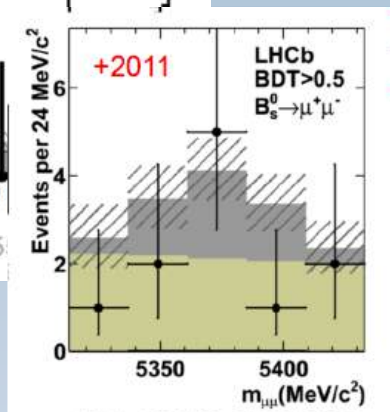
2010, nothing

Evolution of $B_s \rightarrow \mu^+\mu^-$



[PLB 708 (2012) 5

2010, nothing

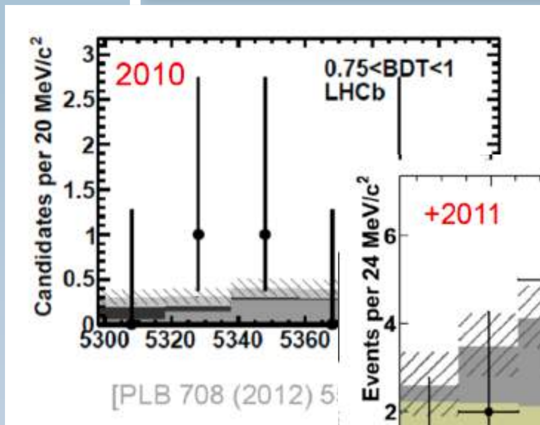


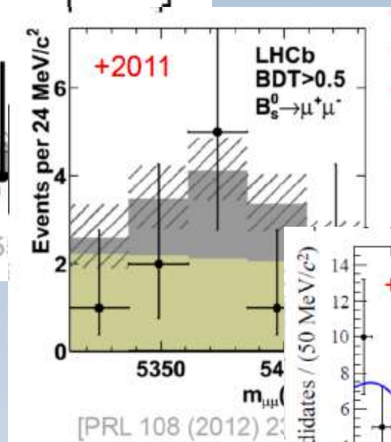
[PRL 108 (2012) 231801]

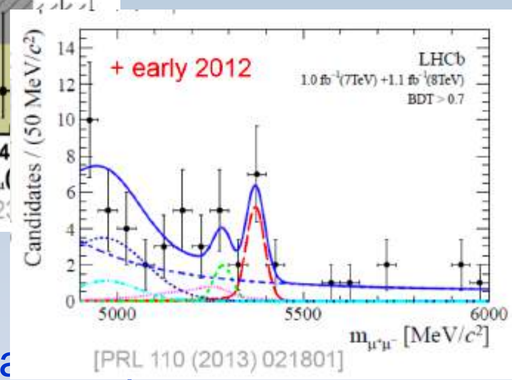
+2011, maybe a hint of a bump
but nothing can be claimed

Plot of invariant mass distribution in region of high BDT sensitivity - if there is a signal we should see a peak here (but the BDT uses much more information than the invariant mass alone!)

Evolution of $B_s \rightarrow \mu^+\mu^-$







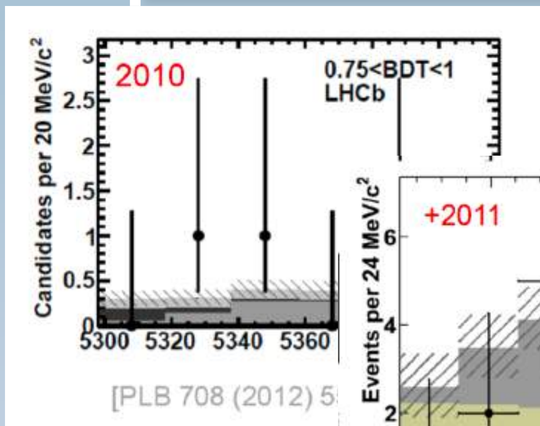
Plot of invariant mass distribution in region of high BDT sensitivity - if there is a signal we should see a peak here (but the BDT uses much more information than the invariant mass alone!)

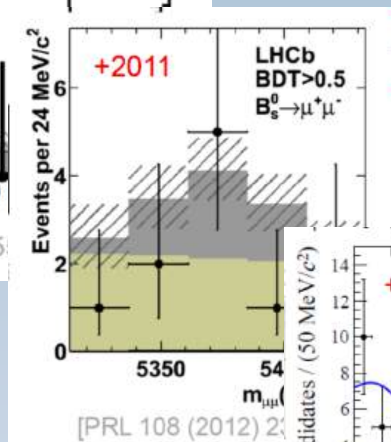
2010, nothing

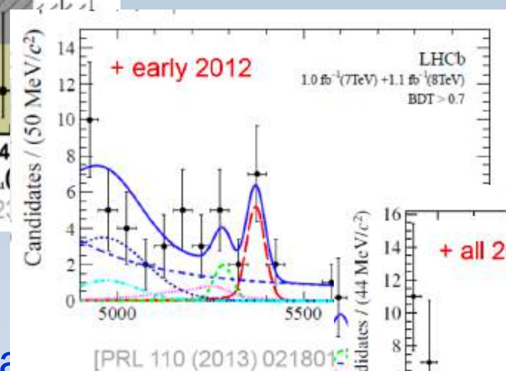
+2011, maybe a hint of a
but nothing can be claimed

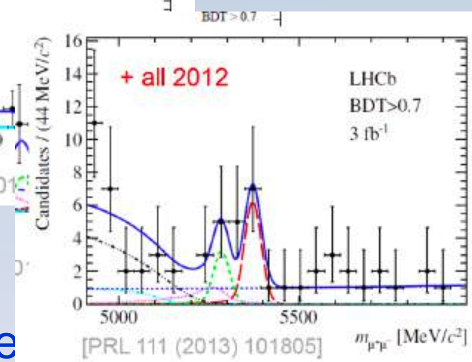
+early 2012, first evidence
that there is something there!

Evolution of $B_s \to \mu^+\mu^-$









Plot of invariant mass distribution in region of high BDT sensitivity - if there is a signal we should see a peak here (but the BDT uses much more information than the invariant mass alone!)

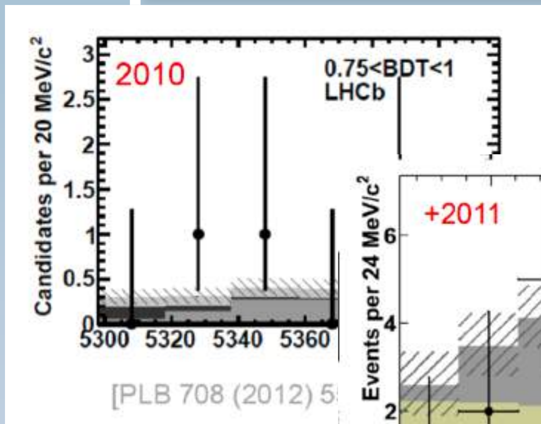
2010, nothing

+2011, maybe a hint of a
but nothing can be claimed

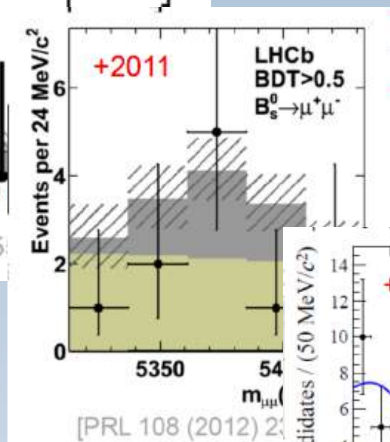
+early 2012, first evide
that there is something there!

+all 2012, the evidence grows

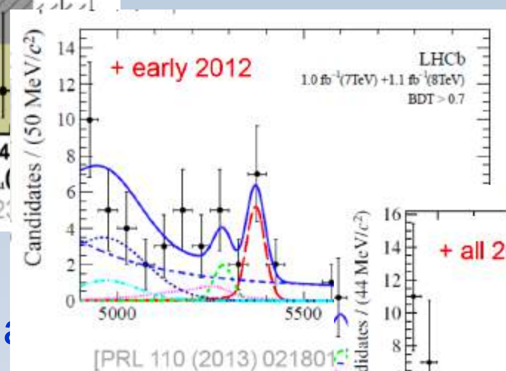
Evolution of $B_s \to \mu^+\mu^-$

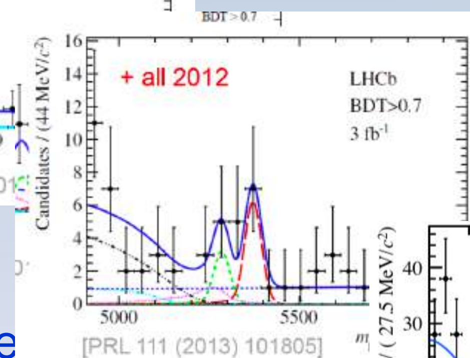


Plot of invariant mass distribution in region of high BDT sensitivity - if there is a signal we should see a peak here (but the BDT uses much more information than the invariant mass alone!)

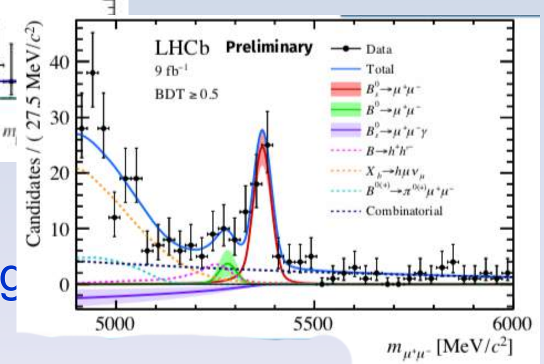


2010, nothing





full dataset - LHCb standalone measurement of $B_s \to \mu^+\mu^-$ at 10 σ



+2011, maybe a hint of a
but nothing can be claimed

+early 2012, first evide
that there is something there!

+all 2012, the evidence g

LHCb performance

Let's take one example:

$$B_s \rightarrow \mu^+ \mu^-$$

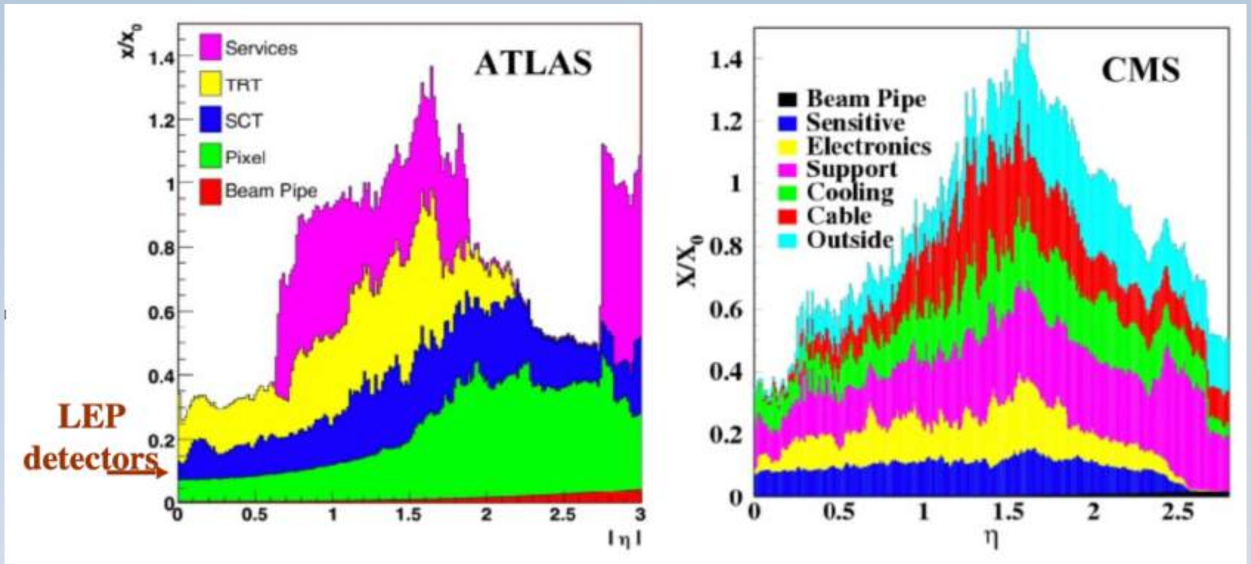
What aspects of the detector design have contributed to this success?

Note that this measurement does not rely on LHCb "specialities" such as time dependent measurements, hadron PID…

Experiments: design → reality

Even when starting with the best of intentions it is **unbelievably hard** to control the amount of material in an experiment, and little increases creep in and add up very fast.

Example from ATLAS and CMS - constructing a tracker where you have to introduce and remove ~70 kW of power is very hard!

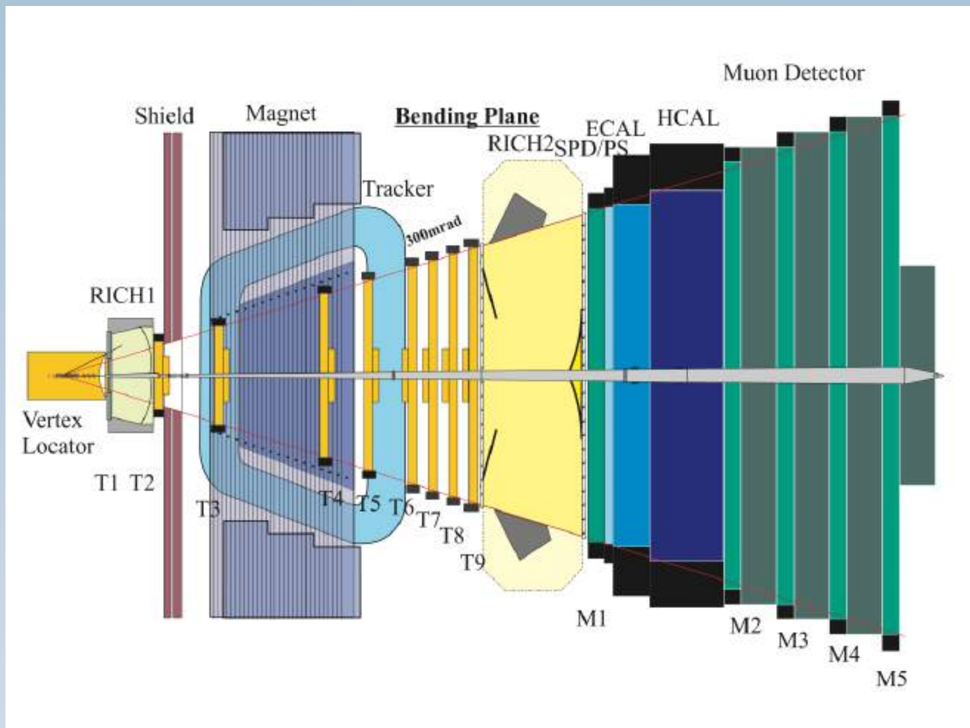


Material increased by a factor 2 between the approval in 1994 and the final construction

Electrons lose between 25% and 70% of their energy before reaching the electromagnetic calorimeter

Between 20% and 65% of photons convert into e^+e^- pairs before reaching calorimeter

Slimming LHCb down

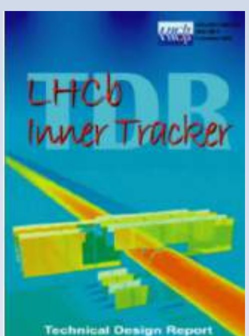


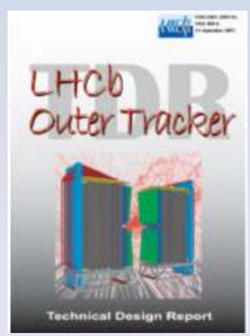
This was the LHCb detector as it was proposed in the Technical Proposal of 1998

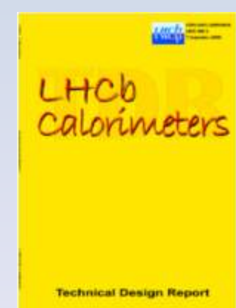
This was a very ambitious experiment, proposing to trigger on beauty particles in hadron collisions - previous attempts had **failed*** and success was **not certain**

In the subsequent years all the Technical Design Reports for the individual subdetectors appeared

The LHCb design was indeed "**fixed**!"
But… just like in ATLAS and CMS, the material had crept up…

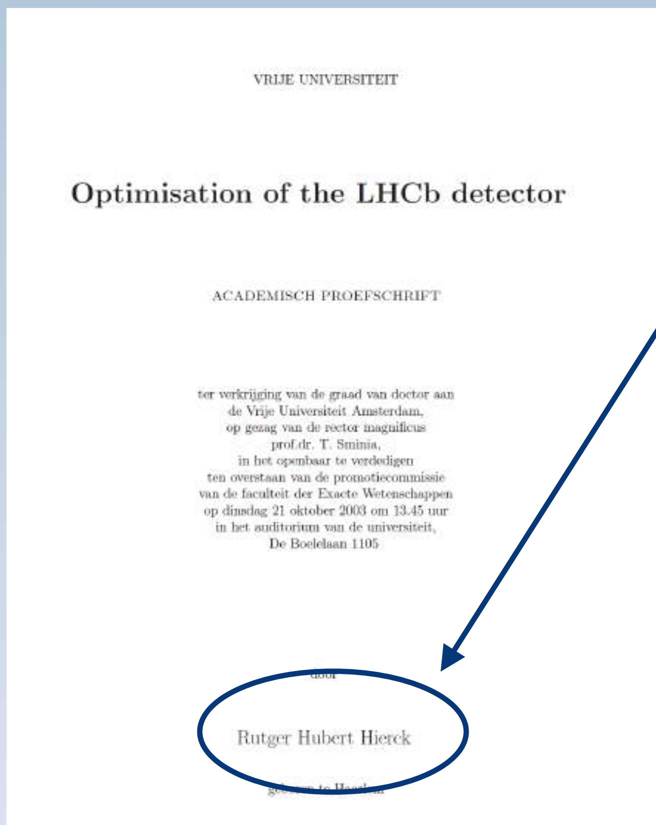






*with the notable exception of CDF

And yet….



VRIJE UNIVERSITEIT

Optimisation of the LHCb detector

ACADEMISCH PROEFSCHRIFT

ter verkrijging van de graad van doctor aan
de Vrije Universiteit Amsterdam,
op gezag van de rector magnificus
prof.dr. T. Sminia,
in het openbaar te verdedigen
ten overstaan van de promotiecommissie
van de faculteit der Exacte Wetenschappen
op dinsdag 21 oktober 2003 om 13.45 uur
in het auditorium van de universiteit,
De Boelelaan 1105

door

Rutger Hubert Hierck

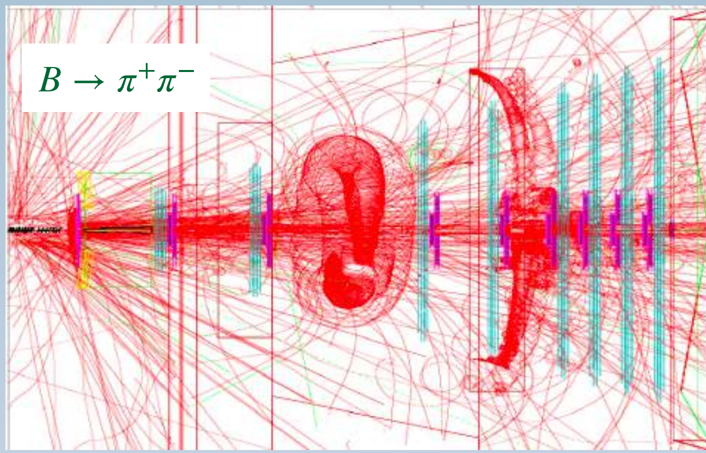
geboren te Haarlem

Following the fantastic $B \rightarrow J/\psi K_s$ measurements from BaBar and Belle, LHCb looked for an ambitious expansion of the physics programme

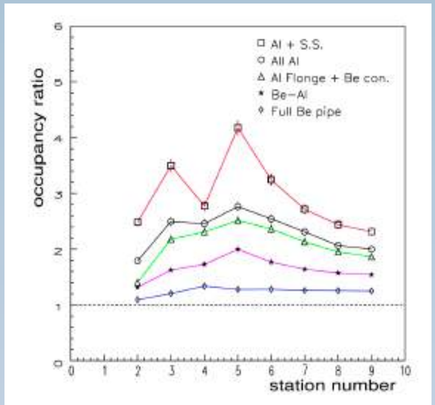
A group of people decided to take a second look at the detector performance

Including Rutger Hierck, who eventually wrote up his findings in his PhD thesis

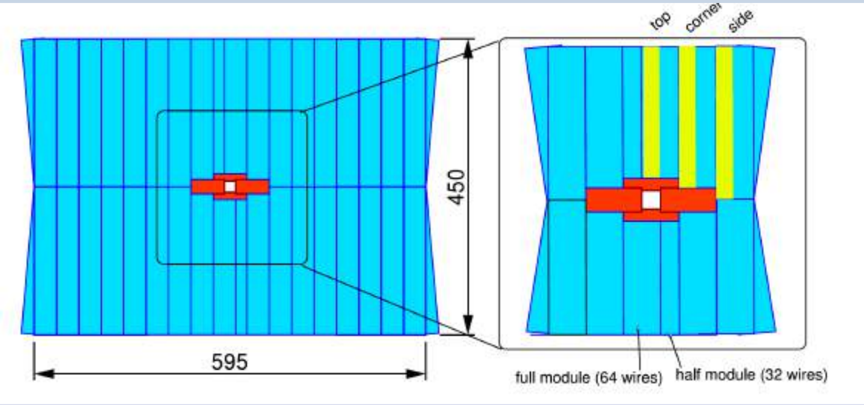
What Hierck saw….



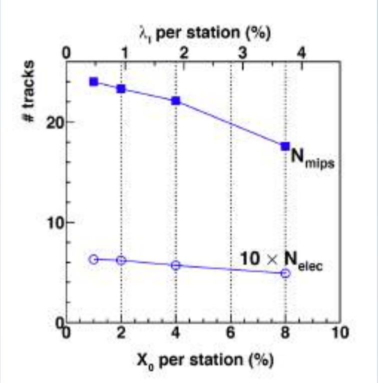
Hierck **saw** low momentum tracks in the magnet for busy events



Hierck **proved** that material in the beam pipe played a major role in the occupancy

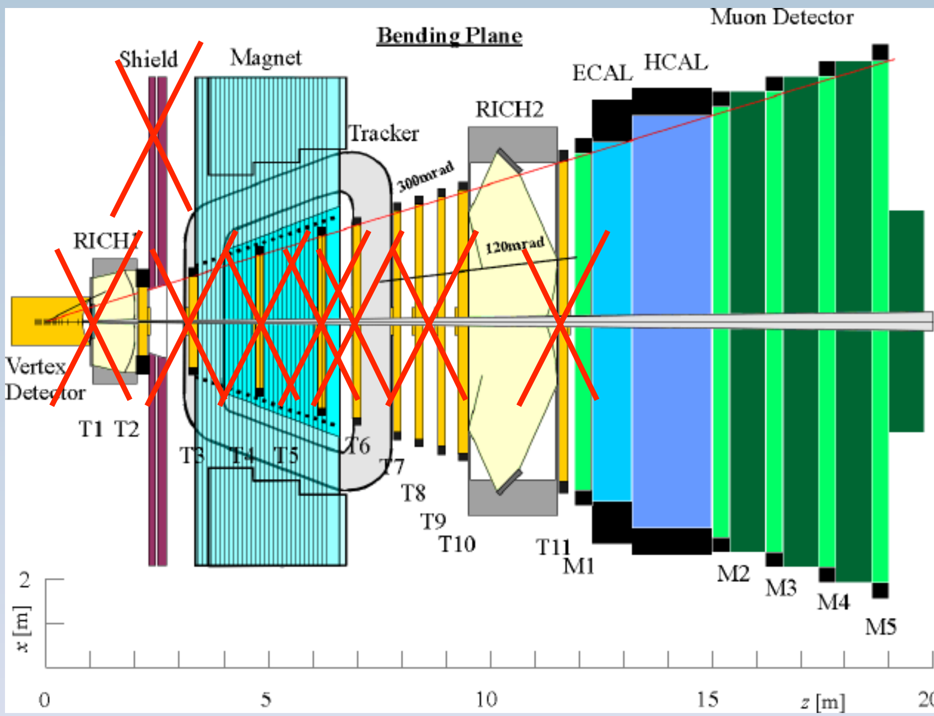


Hierck **optimised** the tracking station design to cope with high occupancy



Hierck **showed** that the interaction length of the detector could result in large efficiency losses e.g. 50% for 4 track final states

What was proposed



Complete removal of 7 tracking stations!

(Plus a lot of material reduction elsewhere, especially in the beampipe design and supports)

This was a sensational proposal

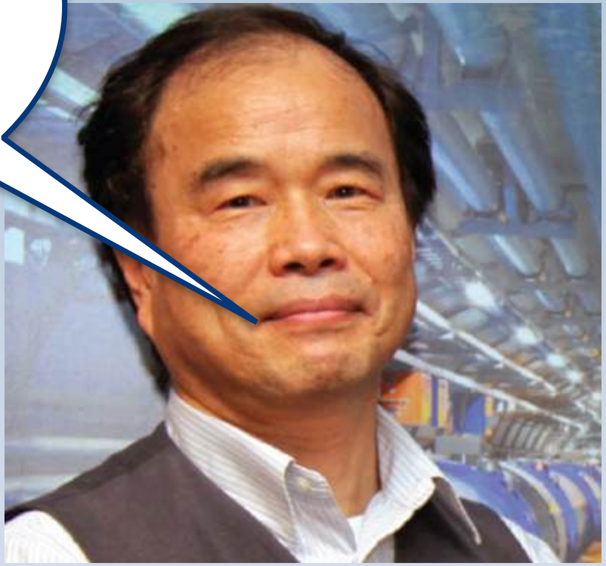
Thanks to the work of Hierck it was proven that without the tracking stations it was still possible to do track finding

More tracking stations do not automatically imply better momentum resolution!

Reaction of our spokesperson

Fantastic study Rutger!

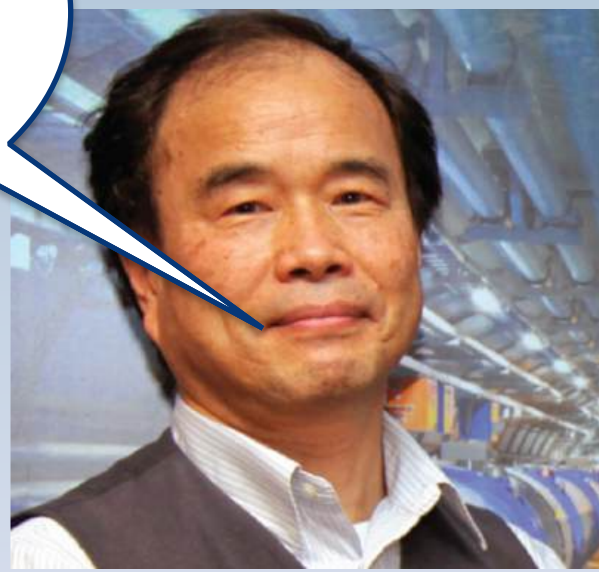
Let's completely change the design of our entire detector just 4 years before installation!



Reaction of our spokesperson

Fantastic study, Rutger!

Let’s completely change the design of our entire detector just 4 years before installation!



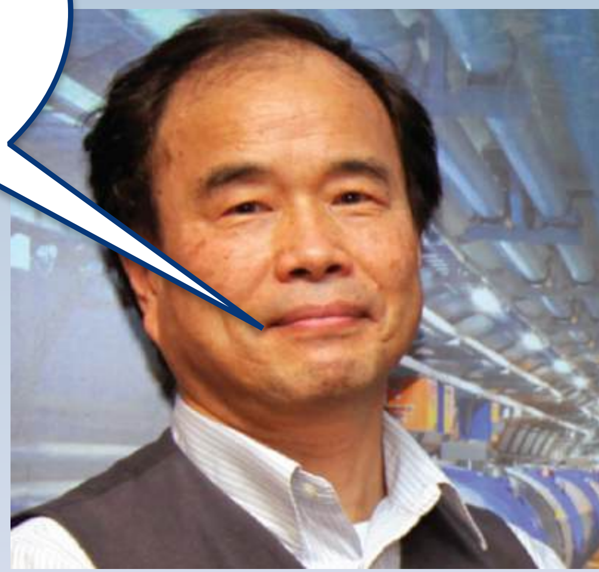
This was a very courageous decision!

(What he was probably thinking)

Reaction of our spokesperson

Fantastic study, Rutger!

Let's completely change the design of our entire detector just 5 years before installation!



(What he was probably thinking)

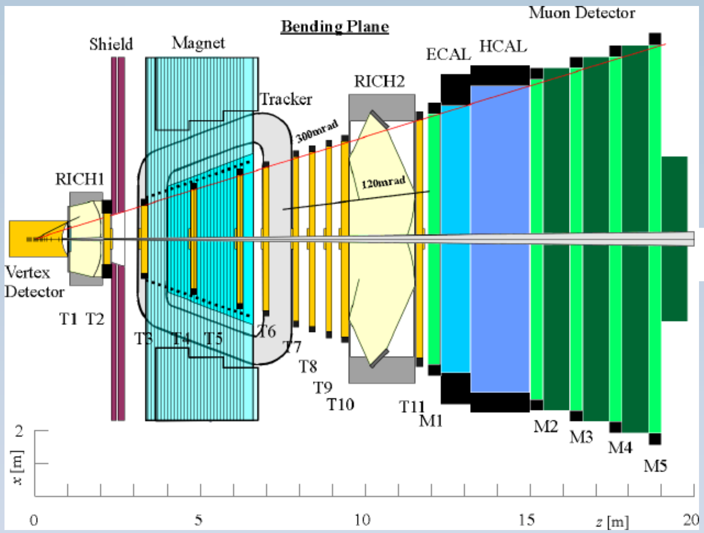
This was a very courageous decision!

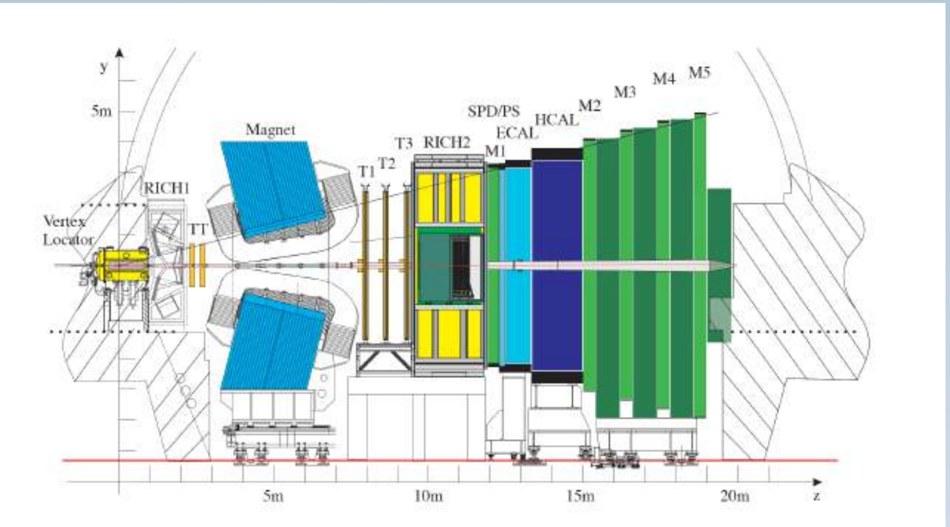
Possible only because the collaboration was sufficiently small and flexible

Very high standard of simulations and software

Supported by work of brilliant and engaged young people

LHCb re-optimisation





The re-optimisation was a success

In the end LHCb ran efficiently at **twice** the design luminosity

the trigger was commissioned successfully in harsher beam conditions than had been anticipated, thanks to the flexible new design

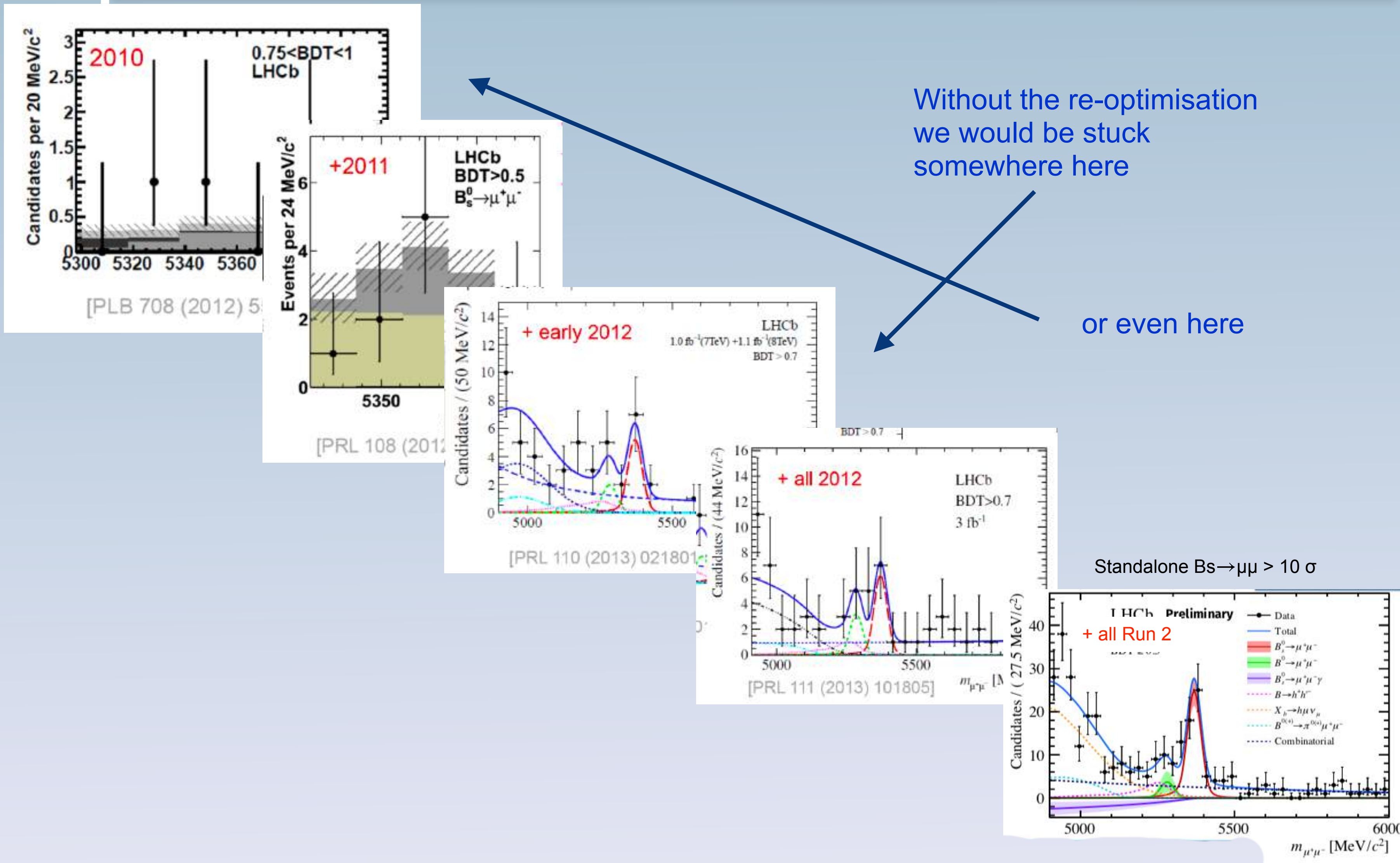
LHCb now has the world leading beauty and charm measurements

$B_s \rightarrow \mu^+\mu^-$: Evolution of measurement

Without the re-optimisation
we would be stuck
somewhere here

or even here

Standalone Bs→μμ > 10 σ



Summary

"*Cutting Edge Science Relies on Cutting Edge Instrumentation*"
(Maxim Titov, ICORE meeting, 2017)

at the same time it has never been more true that

"*today, more than ever before, science holds the key to our survival as a planet and to our security and prosperity*"

(Barack Obama, 2009)

PhD students have made a breathtaking difference
we've discussed today the work of Wunstorf and Hierck which had a major impact on very large scale detector designs.
Always remember to Criticise, Scrutinise, and think outside the box!

Thanks

Huge thanks to the g-2 school organising committee for the smooth organisation and support

I am hugely indebted for historical insights relating to this talk to Renate Wunstorf, Guy Wilkinson, Marcel Merk, Hans Dijkstra, Frederic Teubert, Rolf Lindner, Pippa Wells, Monica Pepe Altarelli

For a definitive history of silicon vertex detectors see:

Robert Klanner, University of Hamburg Joint Detector Seminar, 2011

For definitive guide to detector design see:

Isabelle Wingerter: Instrumentation and Detectors for High Energy Physics, CERN Summer Student Programme, 2018

Daniel Froidevaux, “How does one design a huge detector for the LHC” CERN Summer Student Programme, 2007

For a definitive introduction to silicon detectors see:

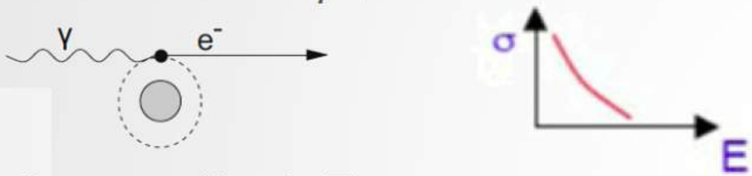
Doris Eckstein, EDIT School, 2020, Hamburg
Petra Riedler, Pixel Detectors in High Energy Physics Experiments, TALENT Summer school 2013

Spare Slides

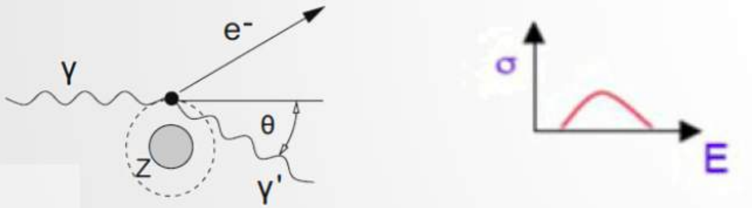
3.4 OVERVIEW OF ELECTROMAGNETIC INTERACTIONS

Photons

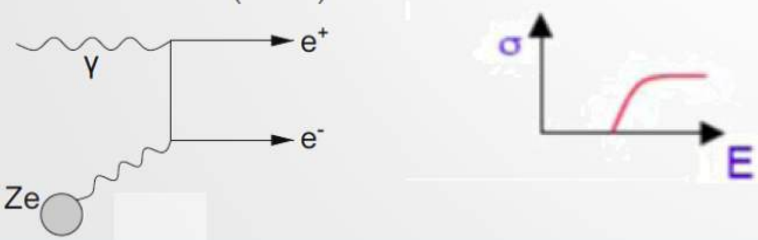
Photo effect ($\propto Z^5/E_\gamma^{3.5}$)



Compton effect ($\propto Z$)

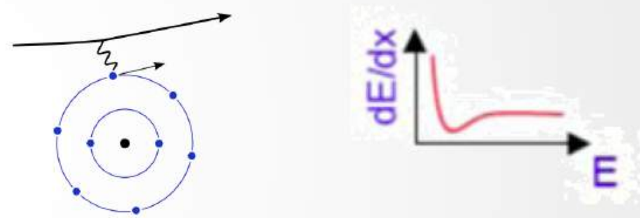


Pair creation ($\propto Z^2$)



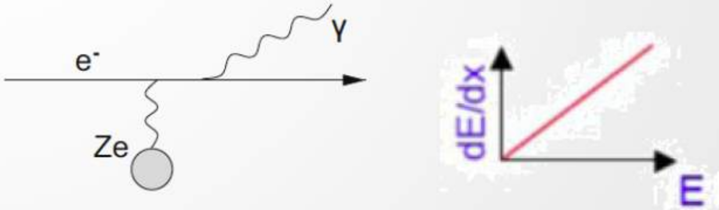
Electrons

Ionization ($\propto Z$)



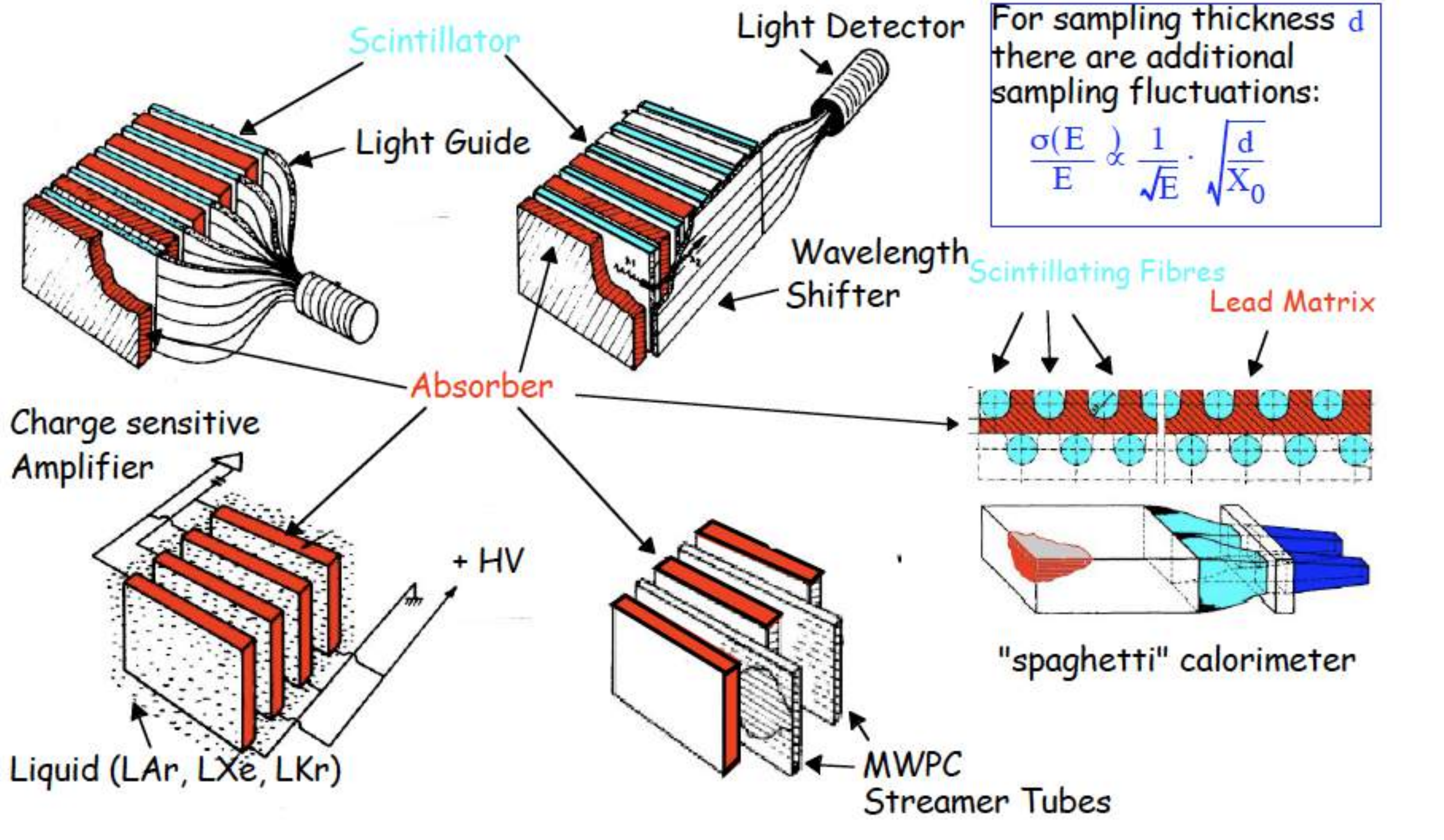
Bremsstrahlung ($\propto Z^2$)

small for all heavier charged particles



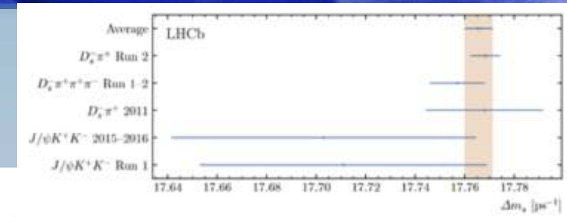
For sampling thickness d there are additional sampling fluctuations:

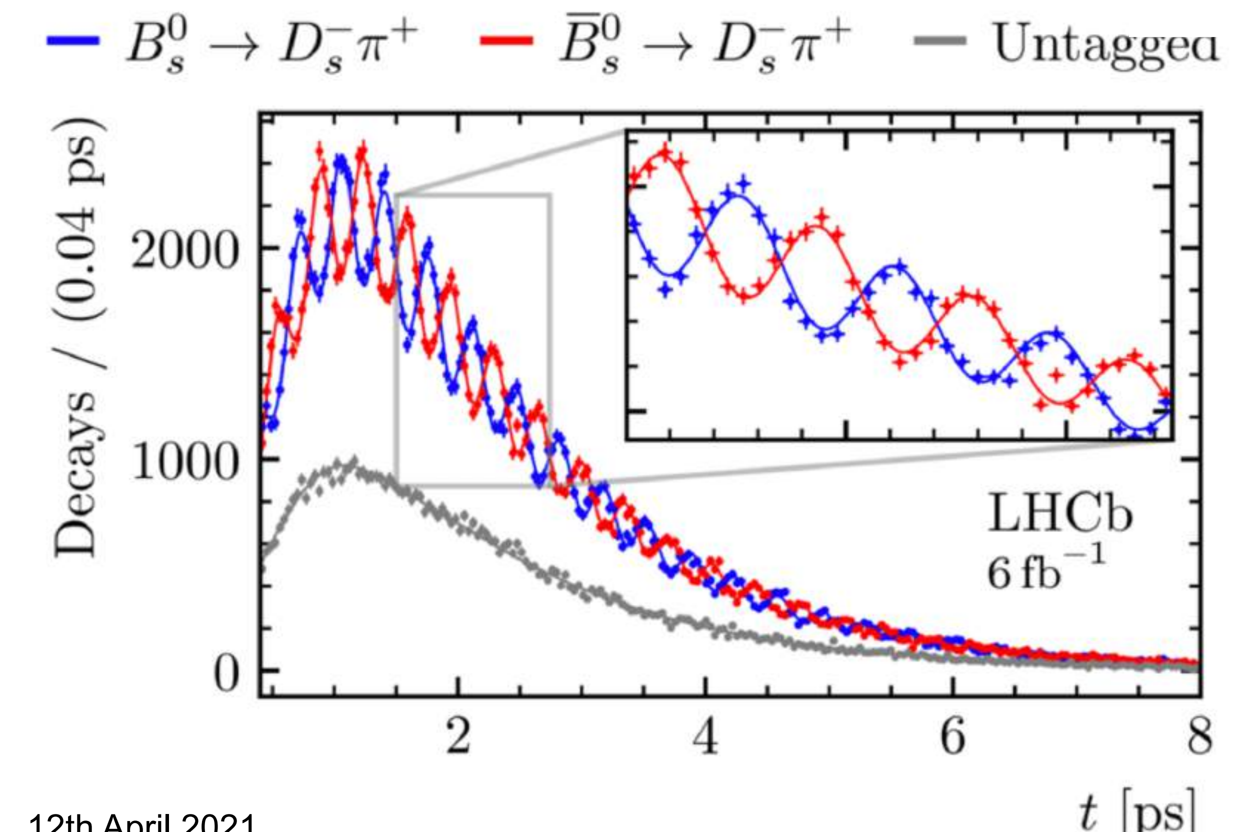
$$\frac{\sigma(E)}{E} \propto \frac{1}{\sqrt{E}} \cdot \sqrt{\frac{d}{X_0}}$$



LHCb performance

Now let's take an example unique to LHCb
2021 measurement of $B_s^0\overline{B}_s^0$ oscillations





12th April 2021

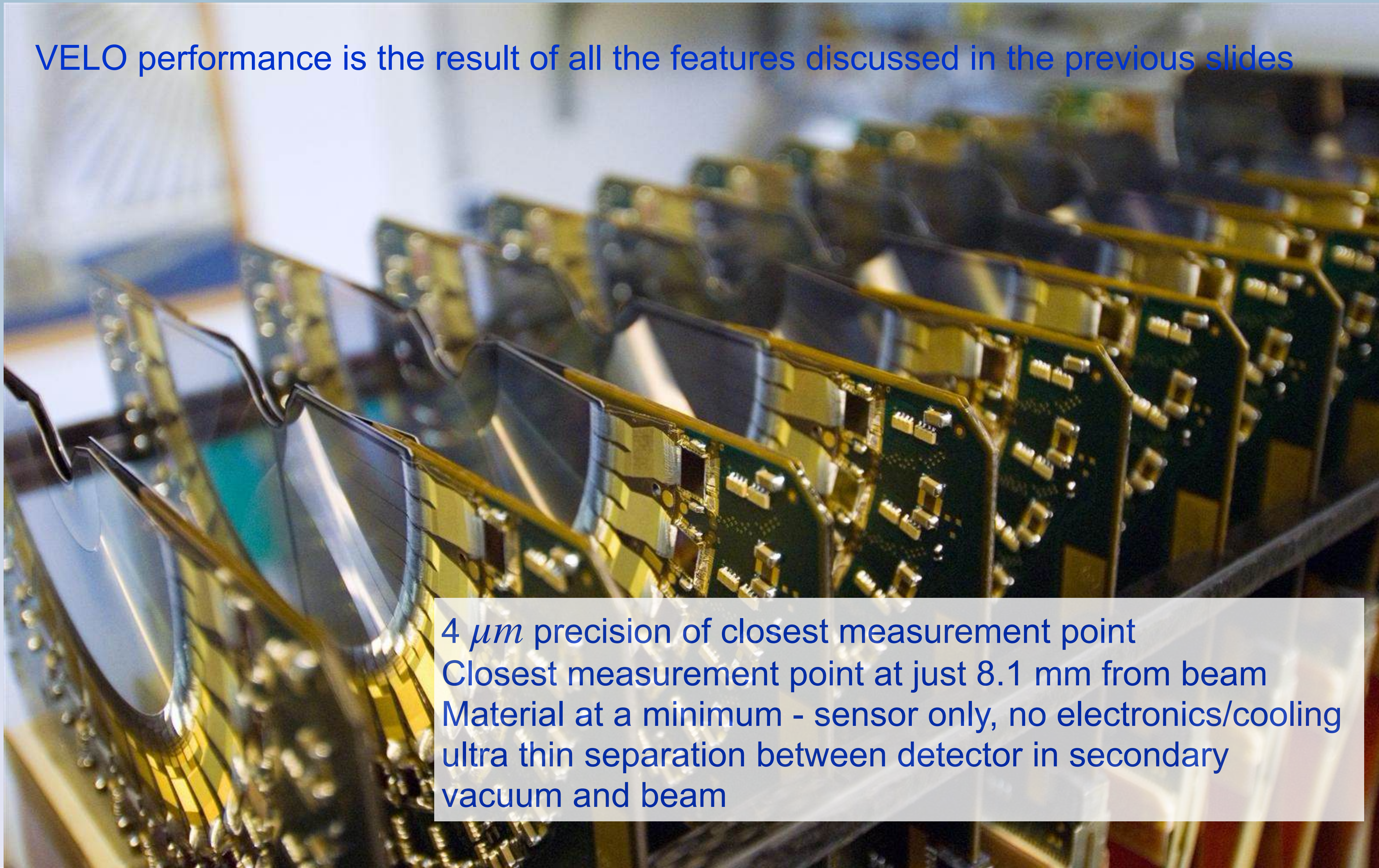
Visual example of the quantum mechanical nature of our universe

Most precise measurement of Δm_s

Possible thanks to precision of VELO and flavour tagging capabilities of LHCb

VELO performance

VELO performance is the result of all the features discussed in the previous slides



- 4 μm precision of closest measurement point
- Closest measurement point at just 8.1 mm from beam
- Material at a minimum - sensor only, no electronics/cooling
- ultra thin separation between detector in secondary vacuum and beam

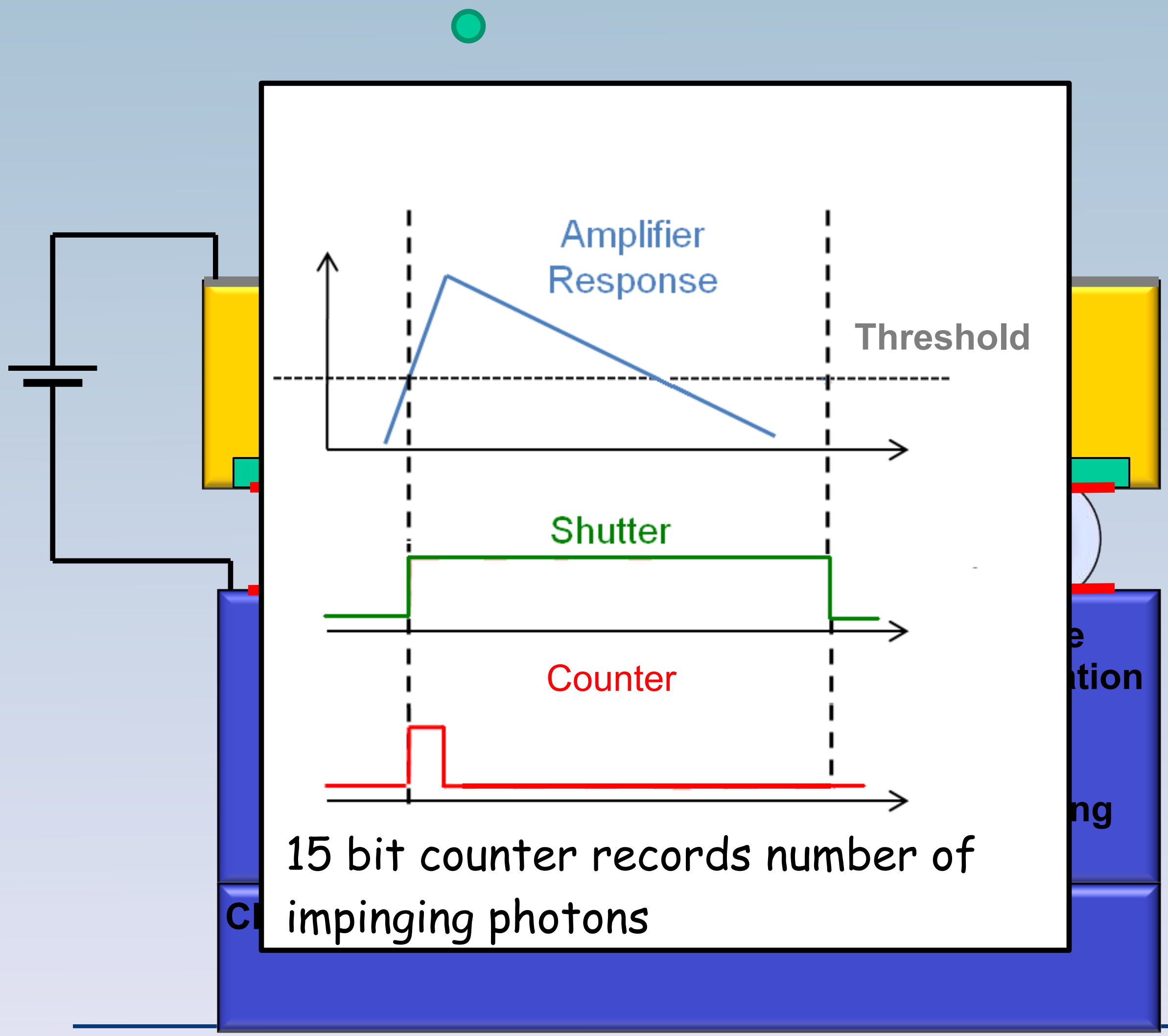
Hybrid Pixels: Medipix/Timepix

VELO Upgrade needed a large scale ASIC capable of blistering readout speeds. Such an ASIC had to be designed from scratch

Could a solution be found from the world of medical imaging?

Let’s look at the Medipix/Timepix family.

Pixels for Medical Imaging

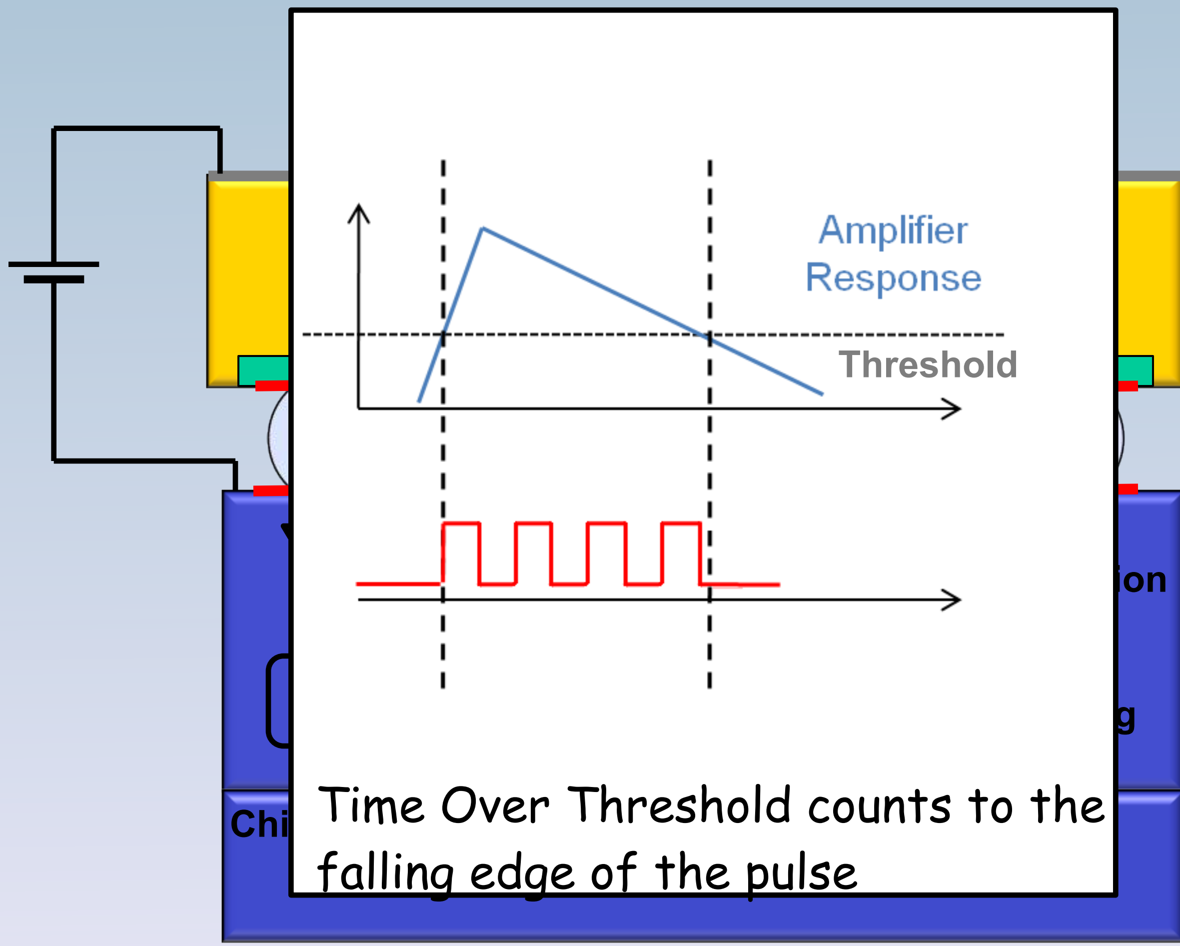


Original idea: take advances in HEP and apply them to photon counting for medical physics

Intensity counter for photons, using individual pre-amp, comparator and counter per pixel

Operates in “camera” mode, reading out the entire pixel array when the shutter closes

Pixels for Medical Imaging



Time Over Threshold counts to the falling edge of the pulse

Timepix design requested and funded by EUDET collaboration

Conventional Medipix2 counting mode remains.

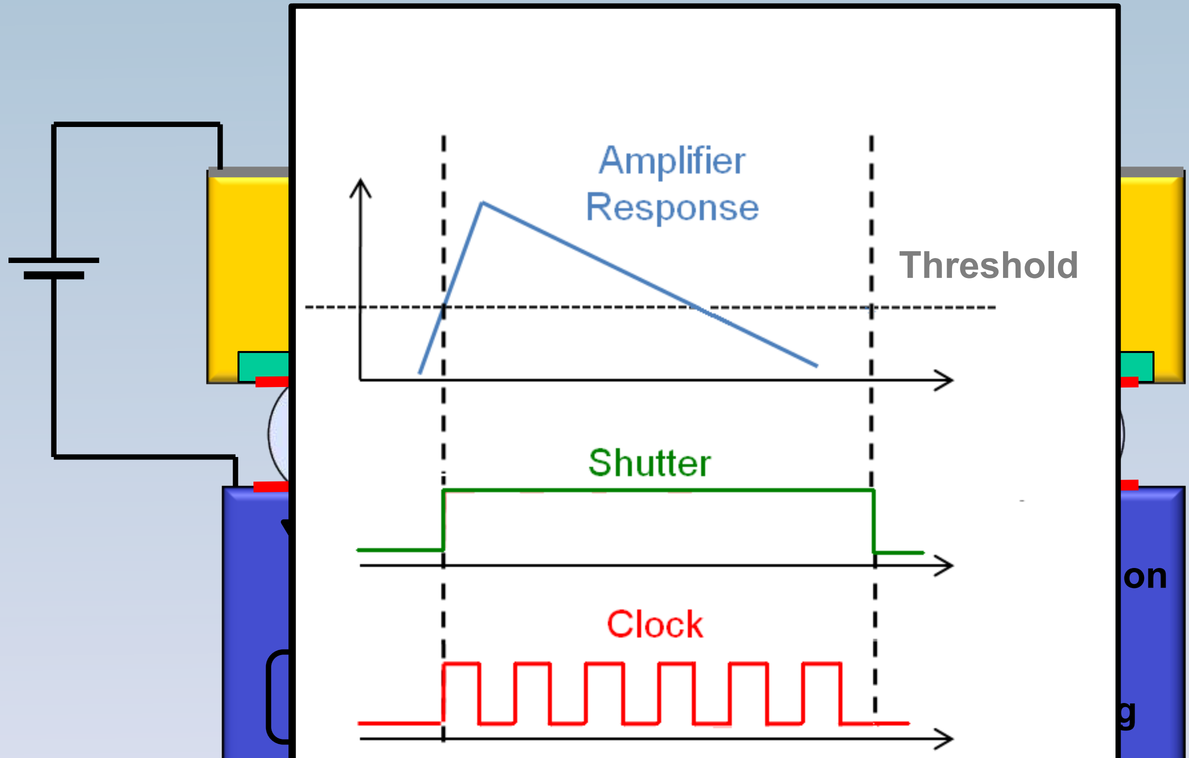
Addition of a clock up to 100MHz allows two new modes.

Time over Threshold

Time of Arrival

Pixels can be individually programmed into one of these three modes

Pixels for Medical Imaging



Time of Arrival counts to the end of the Shutter

Timepix design requested and funded by EUDET collaboration

Conventional Medipix2 counting mode remains.

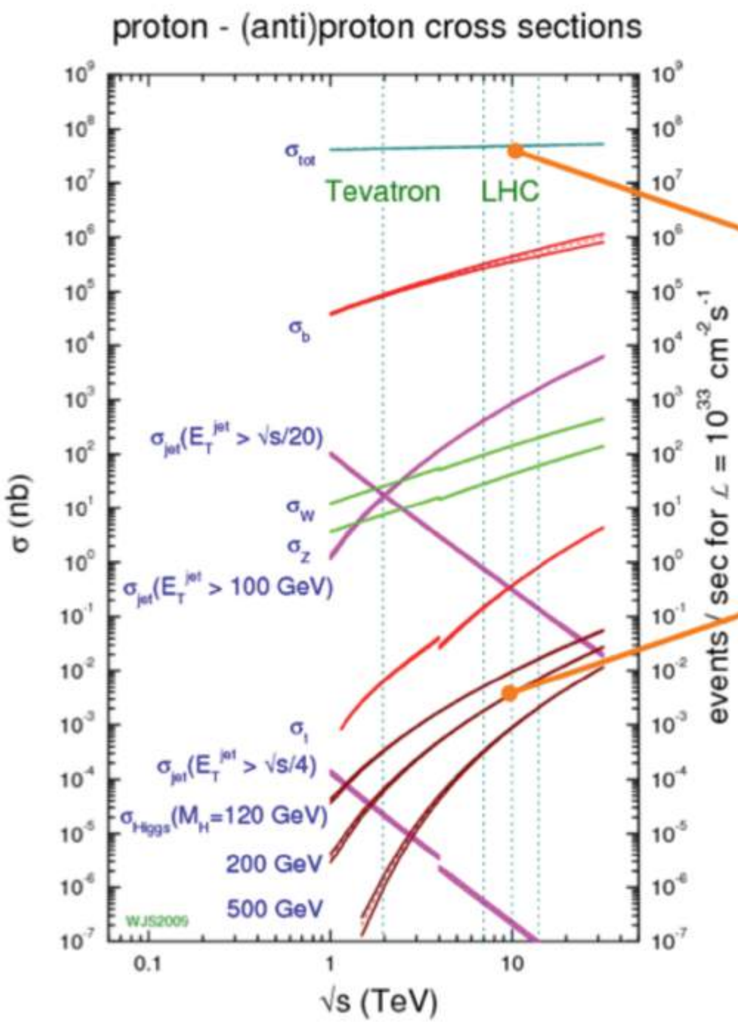
Addition of a clock up to 100MHz allows two new modes.

Time over Threshold

Time of Arrival

Pixels can be individually programmed into one of these three modes

ATLAS / CMS - Discovery



40 millions beam crossing/s
1 billion collisions/s

10^8 events/s

$\sim 10^{10}$

10^{-2} events/s ~
10 events/min

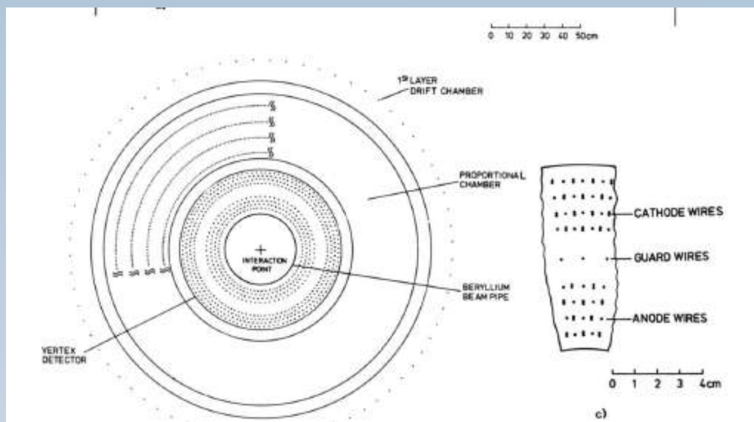
[m_H ~ 120 GeV]

0.2% H → γγ
1.5% H → ZZ

The dawn of vertex detectors

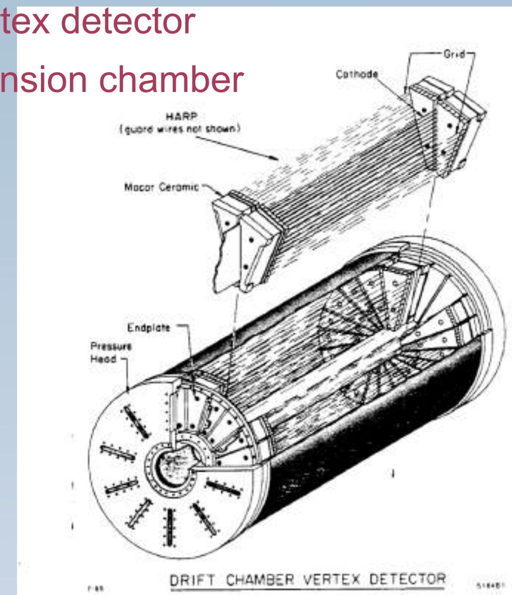
TASSO vertex detector

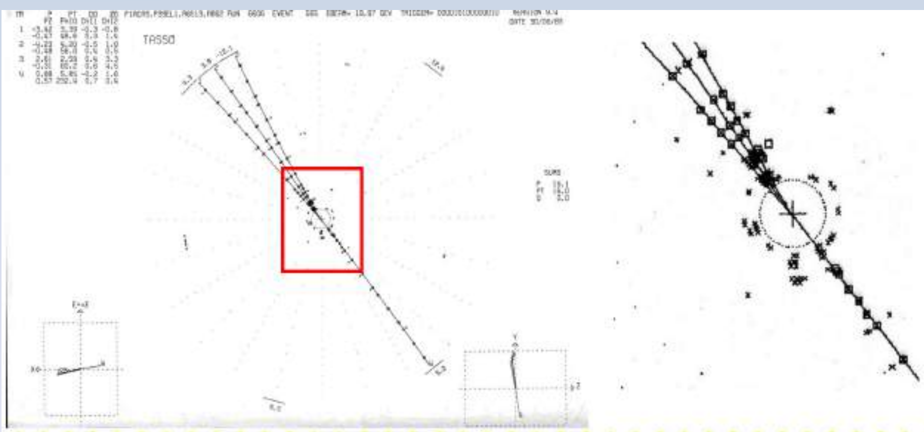
cathode wires with central anode



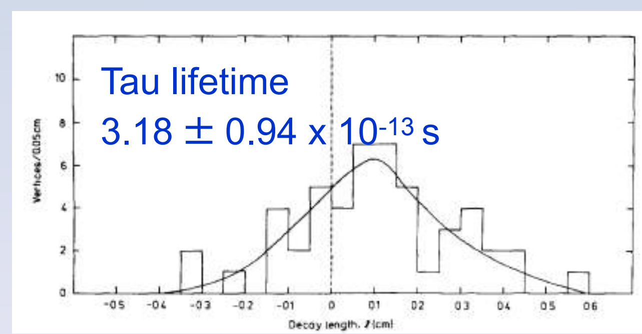
Mark J vertex detector

Time expansion chamber





Capable of resolving τ vertices!

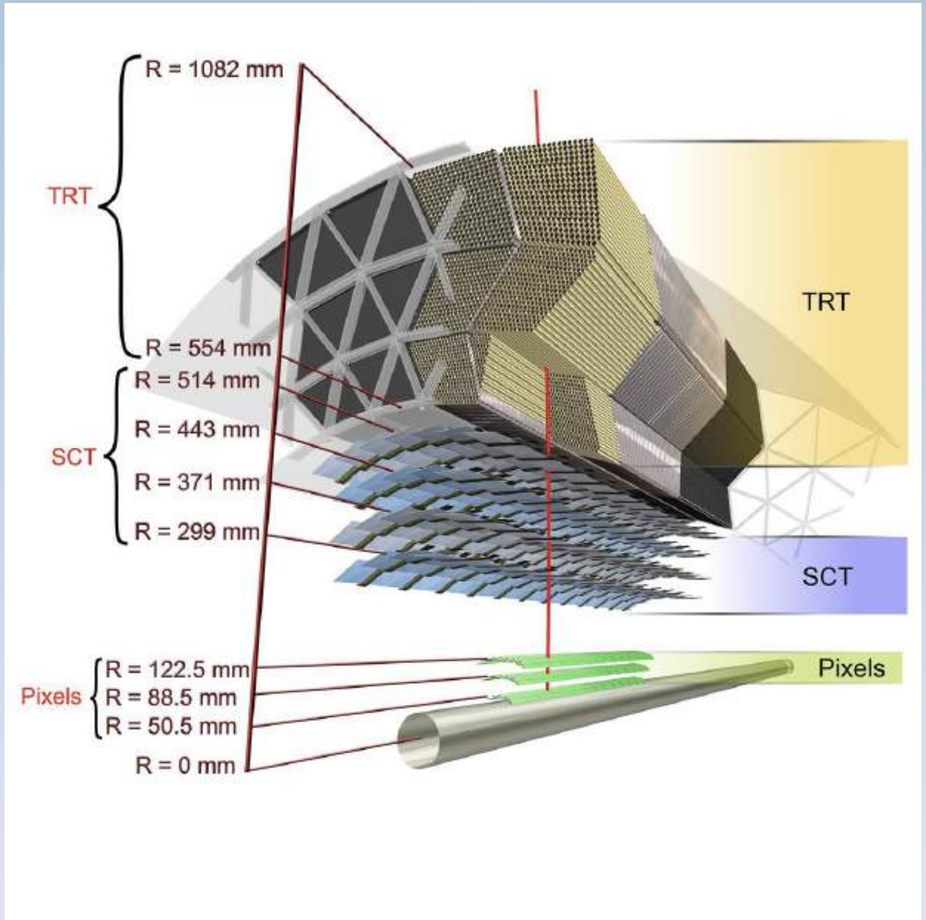


Tau lifetime

$3.18 \pm 0.94 \times 10^{-13}$ s

Transition Radiation - Example

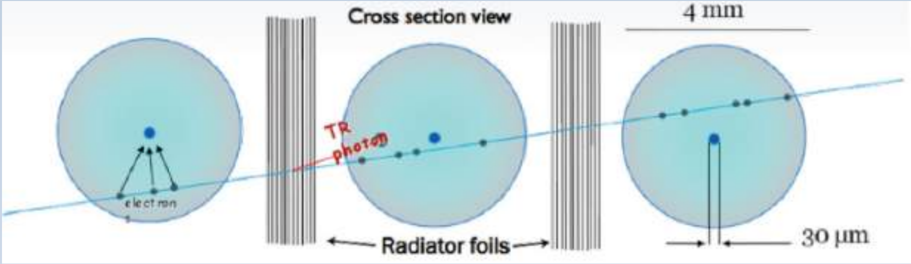
ATLAS Transition Radiation Tracker



Drift chamber of 300k straw tubes

Provides combined tracking, with standalone pattern recognition and electron identification

Layers of Xenon (later, Argon) filled straw tubes interleaved with polymer fibers (and foils in endcaps)



For electron identification the TRT measures the forward peaking soft X ray photon emitted by the charged particle when traversing the boundary.

The emitted photos are detected by absorption and then ionization. The measured dE/dx is then much higher than expected.

Many foils are needed as the radiation is very feeble

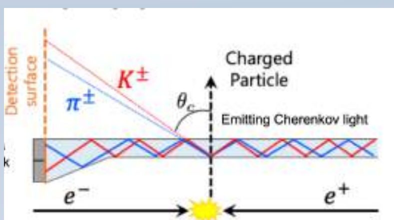
Other Clever Techniques for Ultra-fast TOF and TOP

Fast progress in the new DIRC derived concepts, including time-of-propagation counters
Exceptional time resolution of $\mathcal{O}$(10 ps), based on MCP-PMTs

Belle II Time of Propagation RICH (TOP)

The photons are produced in a quartz bar which acts as the **radiator** and the **light guide**

- By principle of total internal reflection the traveling photons preserve the emission angle
- typically 20-40 photons per charged track
- $\sigma_t \propto \frac{\sigma_{\mathrm{MCP}}}{sqrtN_\gamma}$
- Very compact detector



$$\cos\theta_c = \frac{1}{n\beta} = \frac{\sqrt{m^2+p^2}}{np}$$

$$p = 3\ \mathrm{GeV}\ \pi/K$$

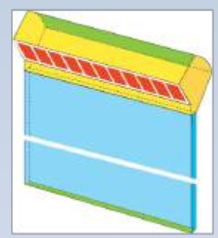
$$\Delta\theta_c \simeq 0.6^\circ \Longrightarrow \Delta t = \mathcal{O}(100)\ \mathrm{ps}$$

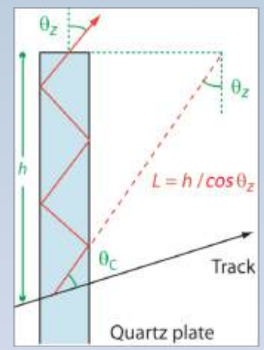
Belle II is taking advantage advantage of the new ALD-MCPs for enhanced lifetime

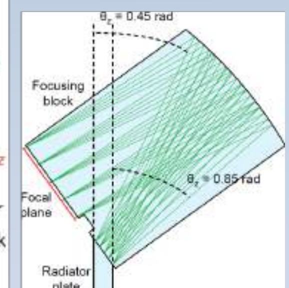
LHCb TORCH (Time of internally Reflected Cherenkov light) for Run 5/6

Prompt production of Cherenkov light in quartz plates

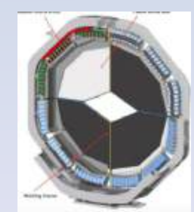
- Cherenkov photons travel to detector plane via total internal reflection and cylindrical focusing block
- 70 ps per photon → 15 ps per track
- Photons detector by MCP-PMTs, resolution improved by charge sharing



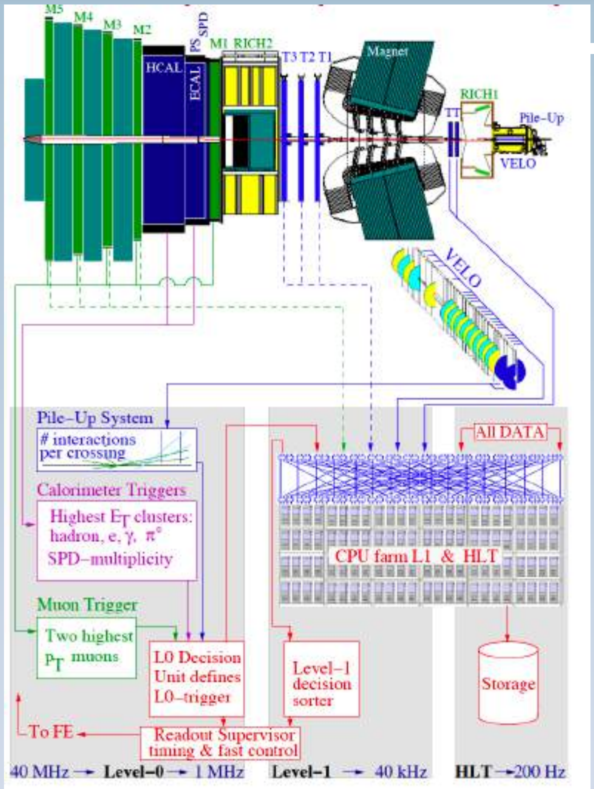




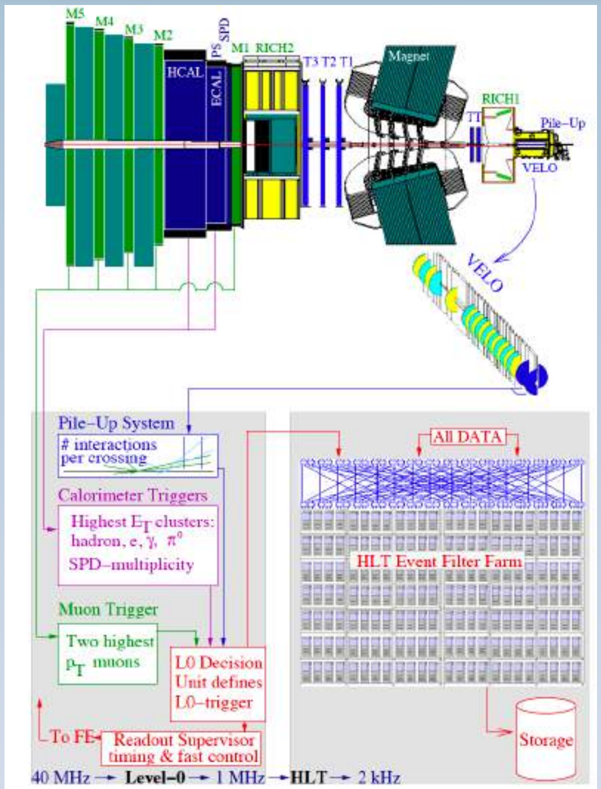
Panda DIRC has many similar features to LHCb TORCH:



What was proposed



BW=5 GB/s (<2005)



BW=50 GB/s (>2005)

Also; major changes the trigger system

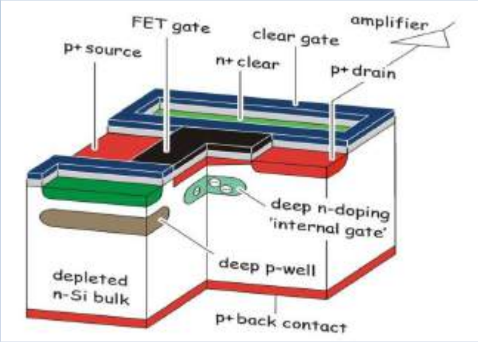
- originally at 40 kHz - major change to 1 MHz - **redesign** of all front end electronics!!
- Removal of magnet shielding to give access to momentum information in the first level trigger
- move to flexible topological trigger - able to cope with unexpected conditions at the LHC (change of pileup)

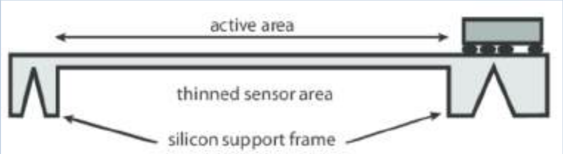
DEPFETs and Belle Pixel Detector

The Depfet (Depleted Field Effect Transistor) is an amplification transistor combined with pixel sensor

A voltage between the substrate and the back plane creates a potential minimum behind the n-implant internal gate. Here, the signal electrons are collected

Belle-II Pixel Detector

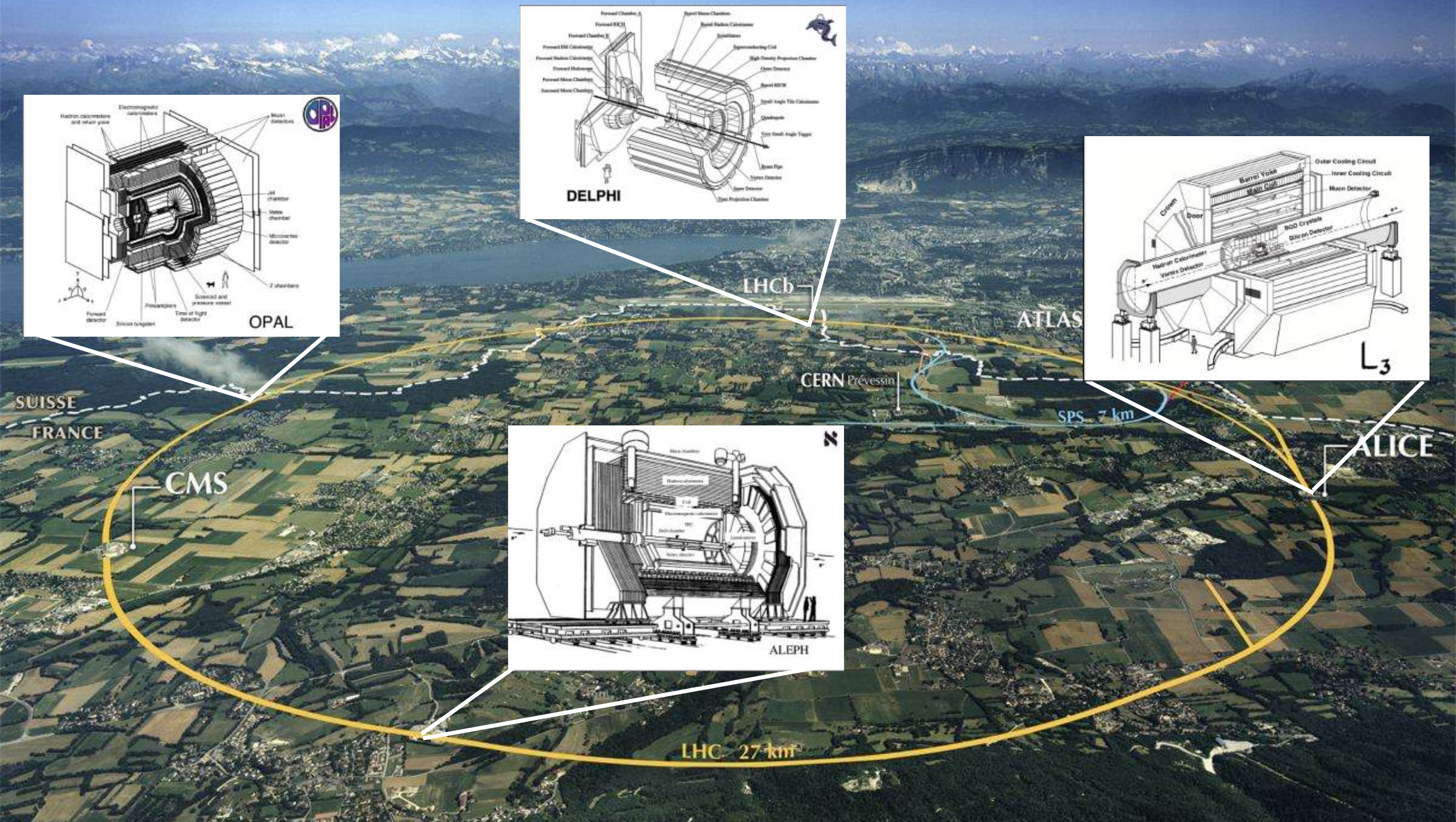




Illustrative cross section through a PXD module. The silicon in the active areas is thinned to 75 um, 450 um thick silicon rims are left on the module sides for stability

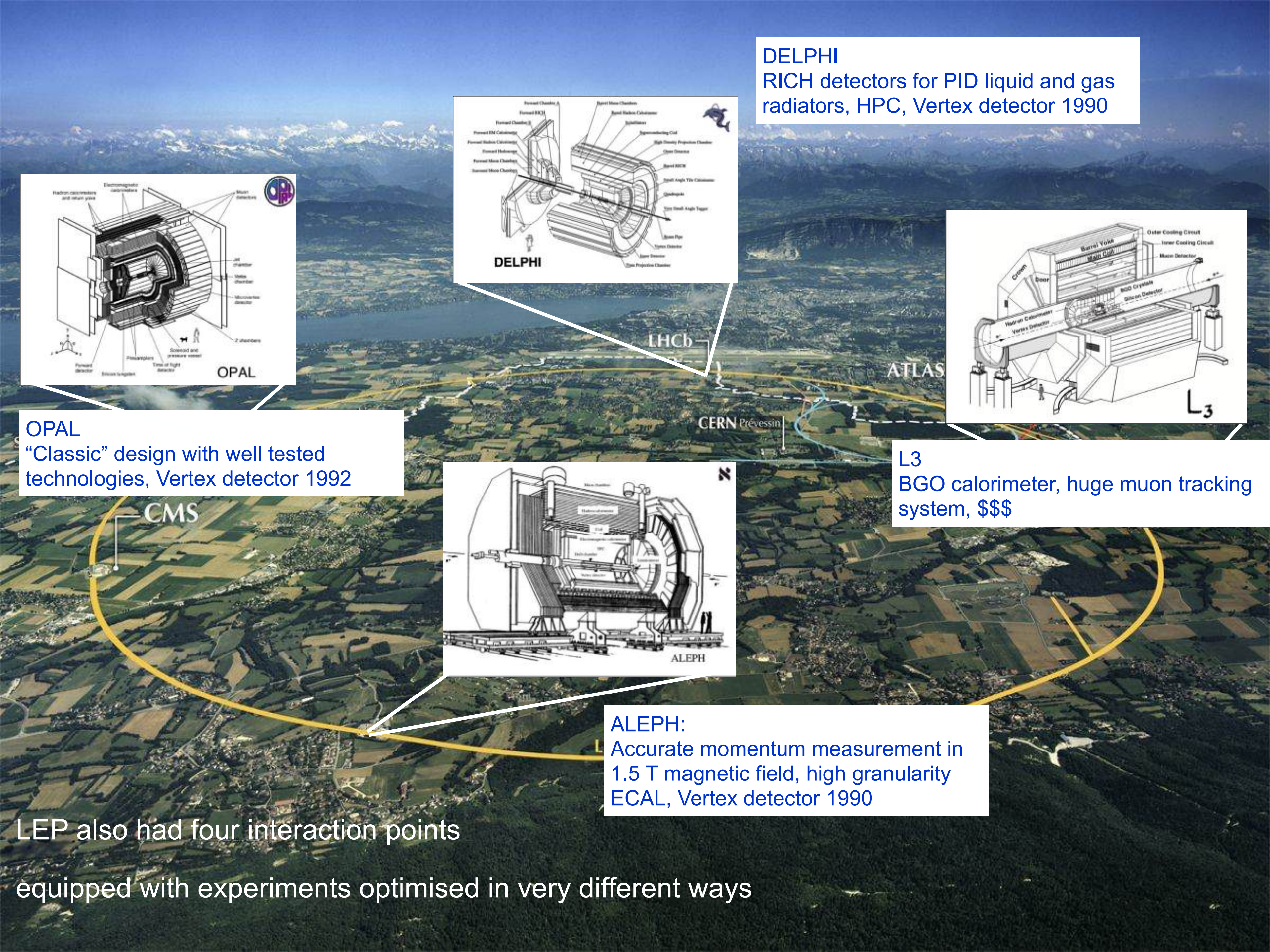
- The collected charge is measured via the source-drain voltage
- Repeated readout possible, very low noise - down to a single e-!
- Positive voltage on clear gate removes charge carriers

The LEP Era



LEP had four interaction points

equipped with experiments optimised in very different ways



DELPHI
RICH detectors for PID liquid and gas radiators, HPC, Vertex detector 1990

OPAL
“Classic” design with well tested technologies, Vertex detector 1992

L3
BGO calorimeter, huge muon tracking system, $$$

ALEPH:
Accurate momentum measurement in 1.5 T magnetic field, high granularity ECAL, Vertex detector 1990

LEP also had four interaction points

equipped with experiments optimised in very different ways


DELPHI
RICH detectors for PID liquid and gas radiators, HPC, Vertex detector 1990
DELPHI
LHCb
OPAL
“Classi
technol
L3
uon tracking
The Economist: The BGO was made in China. The iron (and uranium) came from the Soviet Union, which makes L3 the largest Soviet-Chinese collaboration since Mao and Stalin went their separate ways. Getting that sort of co-operation to work is one reason L3 has kept Dr Ting busy for the best part of a decade
ALEPH
Thank you to Monica Pepe Altarelli for the slide!
Accurate momentum measurement in 1.5 T magnetic field, high granularity ECAL, Vertex detector 1990
LEP also had four interaction points
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