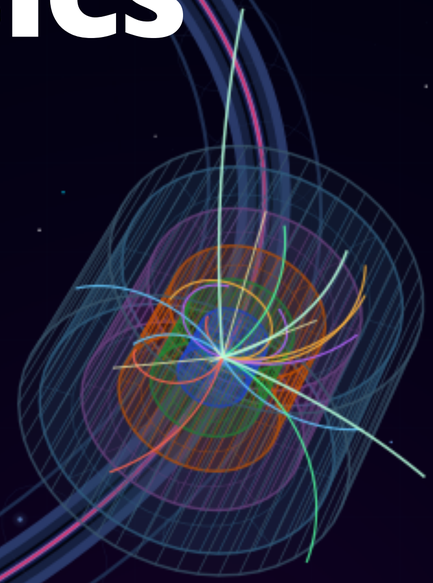
Challenges in Collider Physics



Yasuyuki Horii (KMI, Nagoya University)

FAIRS Japan 2026, 5 Oct. 2026

Scope and Selection of Topics

An overview of collider experiments and their key challenges are presented.

Topics are selected independently of current AI applications —

to avoid overlooking topics that could potentially benefit from AI in the future.

The selection is biased by the presenter's experience and knowledge.

Fundamental Questions Accessible with Colliders

- Origin of mass
- Nature of dark matter
- Matter-antimatter asymmetry
- New particles and forces
- Early Universe

Colliders provide a unique way to address fundamental questions in particle physics!

Examples of Ongoing Collider Experiments

- ATLAS experiment at LHC and HL-LHC (2030-): energy frontier
  - Proton-proton collisions with $\sqrt{s}$ = 13.6 TeV
  - Higgs boson, top quark, searches for new physics, …
- Belle II experiment at SuperKEKB: luminosity frontier
  - Electron-positron collisions with $\sqrt{s}$ = 10.58 GeV
  - CP violation, searches for new physics, …

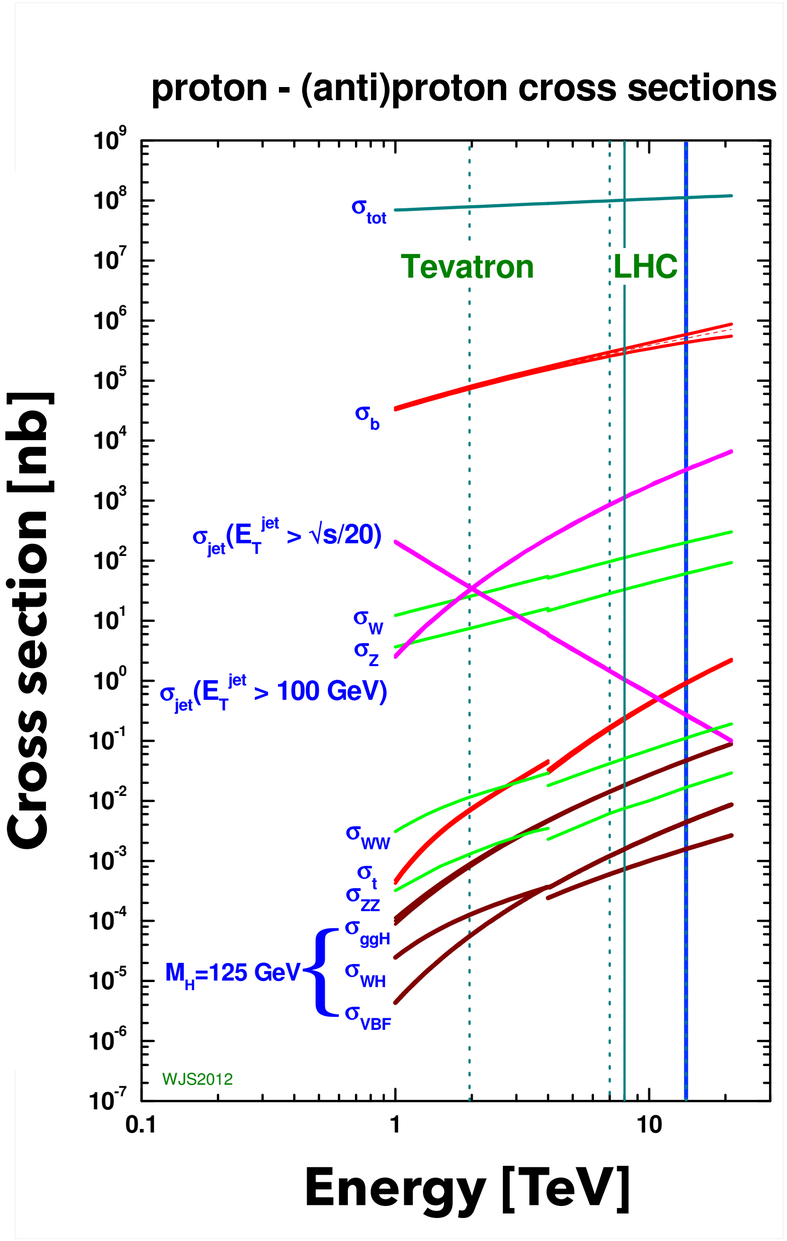
Two complementary approaches to explore fundamental physics

Exploring the Energy Frontier

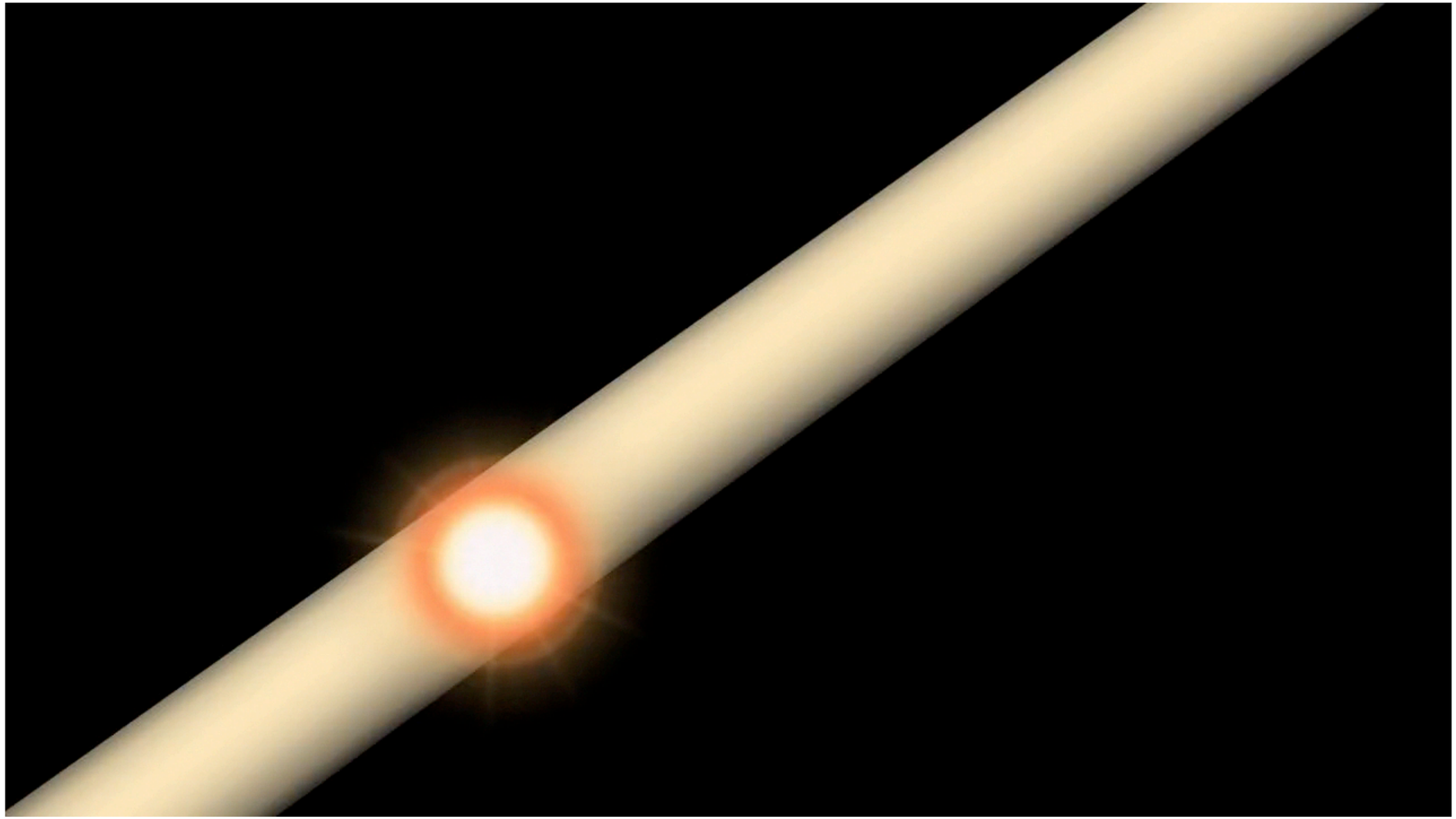
Higher collision energy opens access to physics at higher mass scales.

The Higgs production cross section at the LHC (13.6 TeV) is ~60 times larger than at the Tevatron (1.96 TeV), the previous energy-frontier collider.

Key challenge: achieving higher magnetic fields in superconducting dipole magnets



Animation of the ATLAS Experiment at LHC



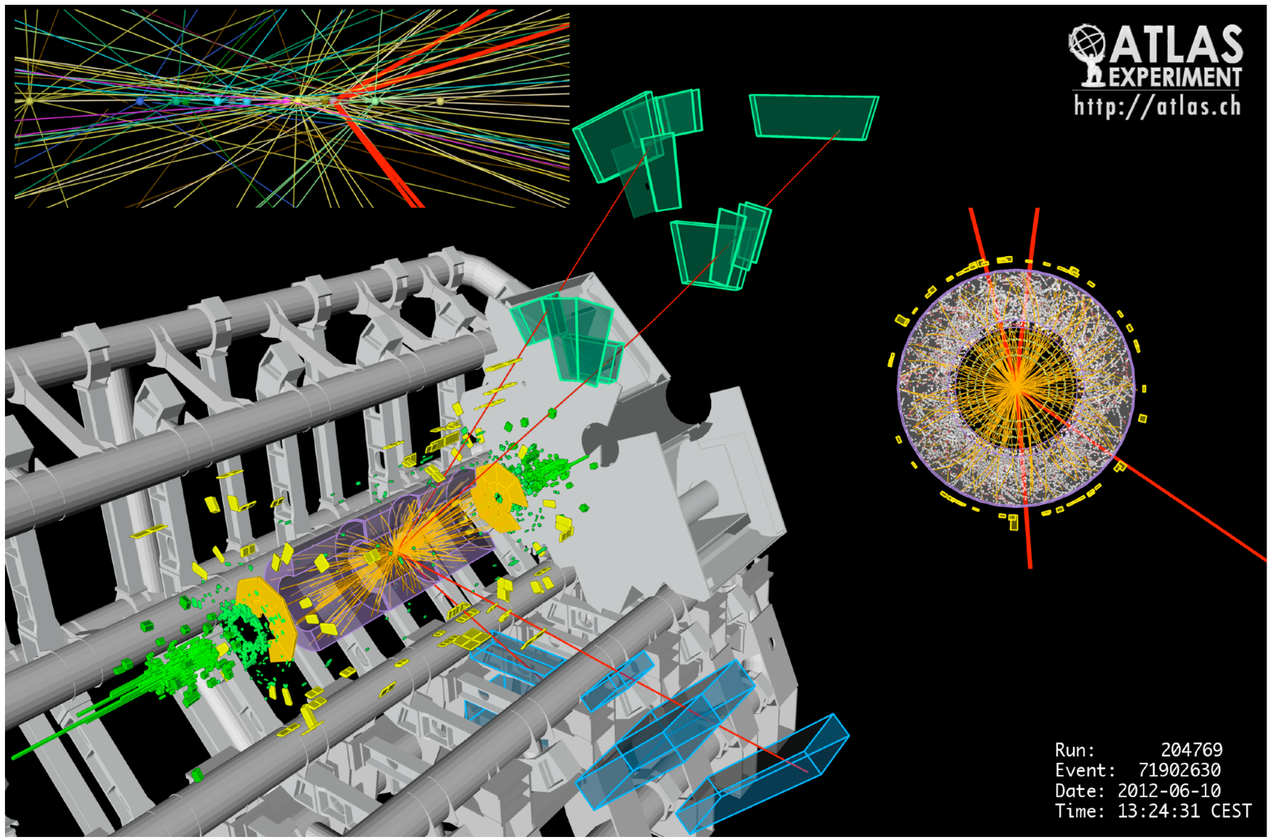
CERN ATLAS Experiment, https://videos.cern.ch/record/1406040

Observation of the Higgs Boson

The Higgs boson observed in 2012

F. Englert and P. W. Higgs awarded the Nobel Prize in Physics in 2013



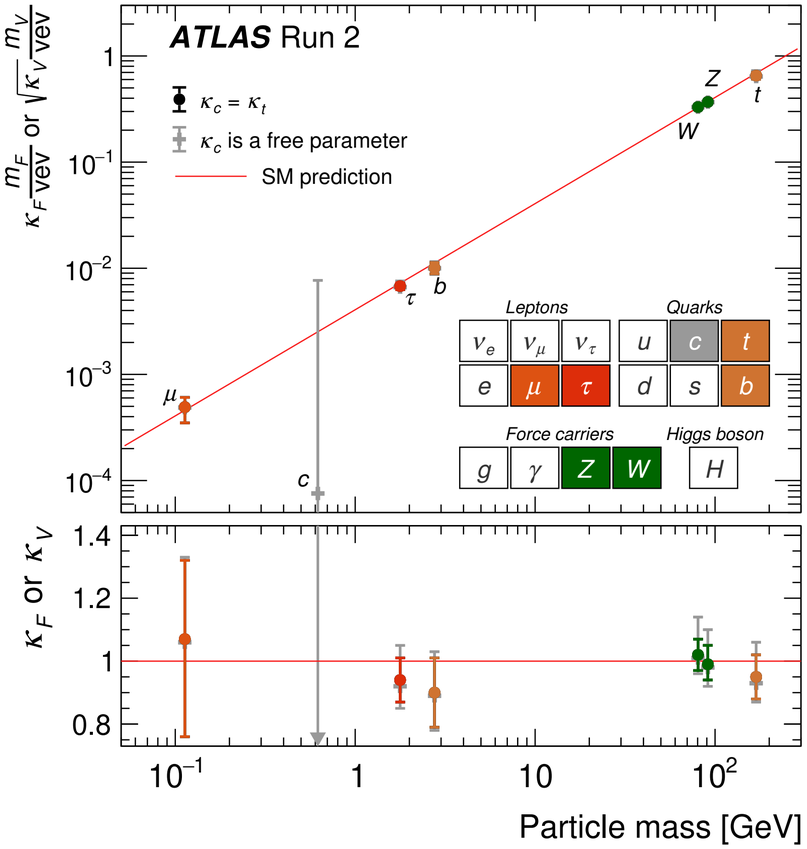


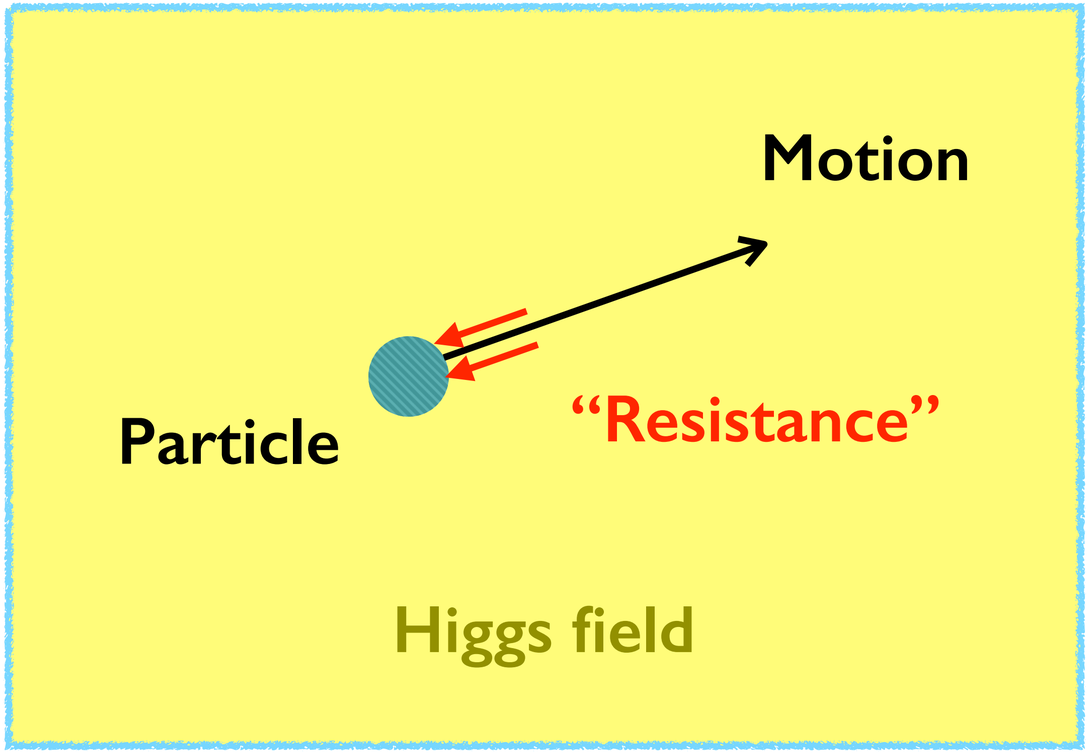


Probing the Origin of Particle Masses

Higgs boson coupling measurements are consistent with the Standard Model, supporting the Higgs mechanism as the origin of masses of Z, W, t, b, and τ.

Nature, 2022



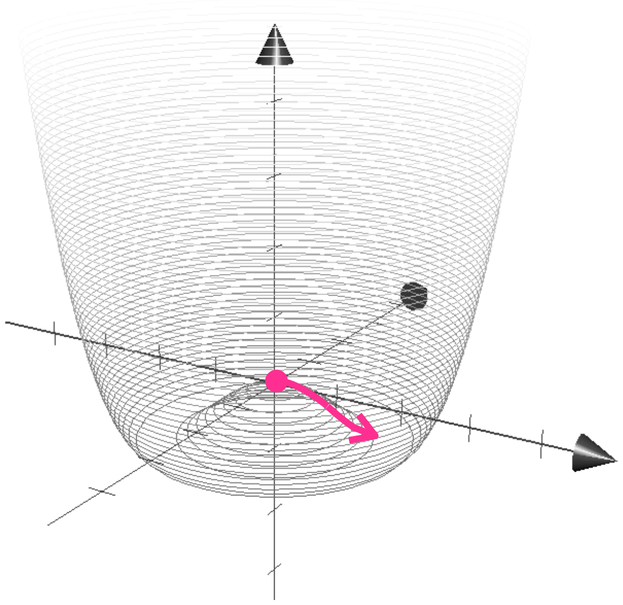


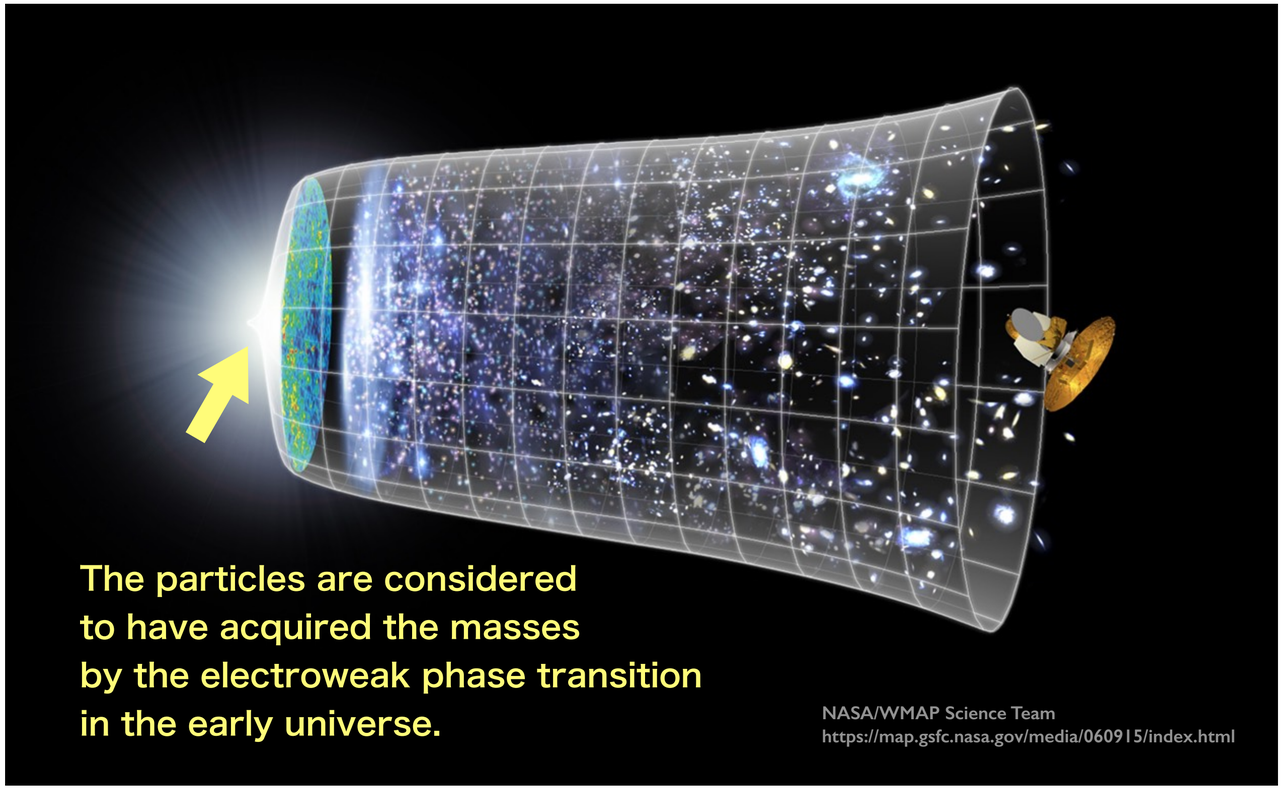
Next: origin of mass for 2nd generation!

Next Step: Exploring the Higgs Potential

Higgs potential measurements may probe the electroweak phase transition.

Higgs potential $V(\phi)$





Matter-antimatter asymmetry may be explained [PLB 606, 361 (2005) etc.]

Challenges: further accumulation of data at HL-LHC and advanced analysis

Exploring the Luminosity Frontier

Higher luminosity enables the discovery and precision measurement of rare phenomena.

Challenges in achieving high bunch populations and small beam sizes.

$$N_{\text{events}} = \sigma \times \int \mathscr{L}\, dt$$

N_{events} : number of events

σ : cross section

$\mathscr{L}$: instantaneous luminosity

$$\mathscr{L} \propto \frac{N^2}{\sigma_x \sigma_y}$$

N : bunch population

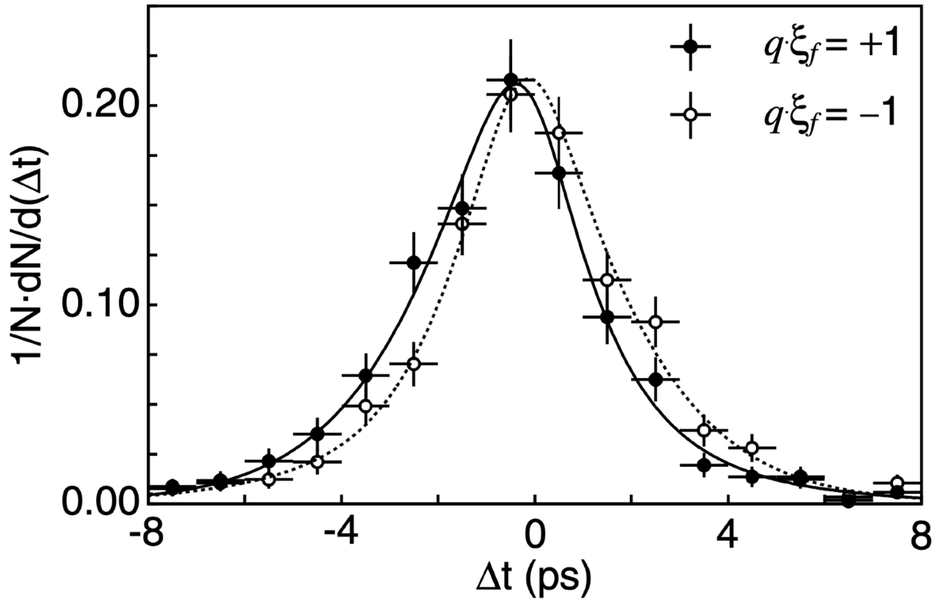
$\sigma_{x,y}$: beam size in the x, y direction

Exploring Flavour Physics with B Factories

CP violation in B-meson decays observed at the B factories in 2001

M. Kobayashi and T. Maskawa awarded the Nobel Prize in Physics in 2008





Belle at KEKB, PRL, 2001



Next step: high-precision tests of the Standard Model and search for new physics at Belle II

Particle Detection and Challenges

Higher energy and luminosity

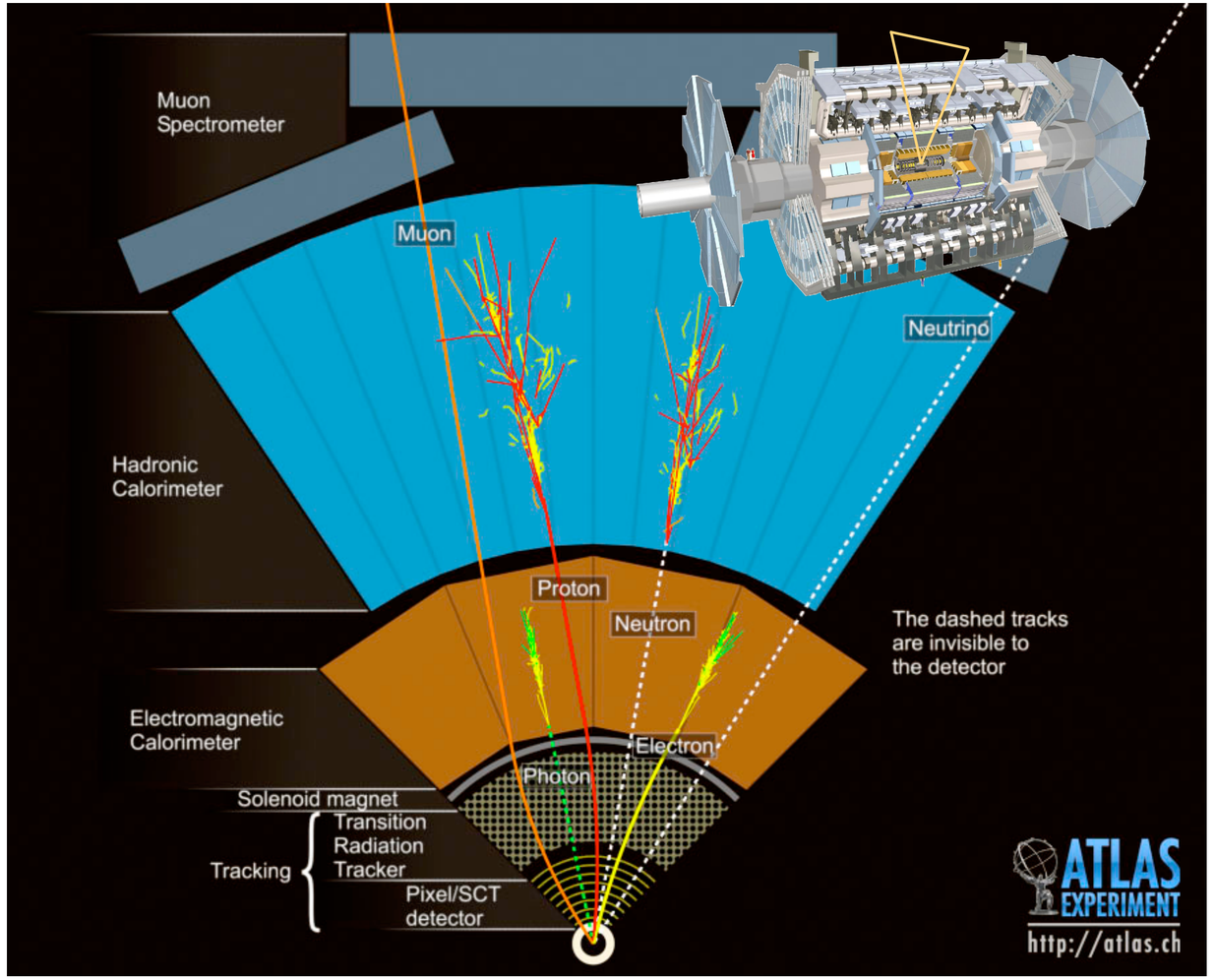
— more particles and complex events

Challenges for particle detectors

- Higher particle rates and detector occupancy
- More pileup and overlapping signals
- Increased radiation damage
- Higher data rates and trigger demands

Key challenge:

Maintaining high detection efficiency and precision under high-rate conditions!

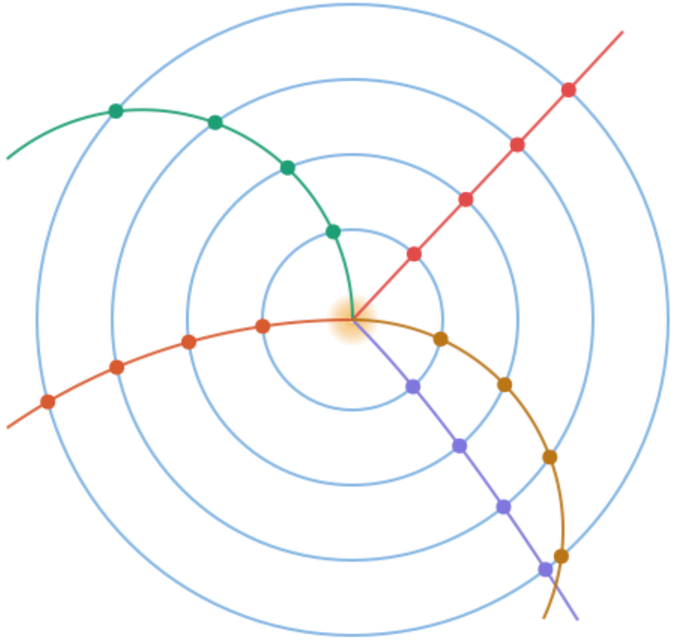


Challenges in Momentum Measurement

Momentum is determined from particle trajectories in a magnetic field.

$$p_{\mathrm{T}} = qBR$$

$\odot\ B$



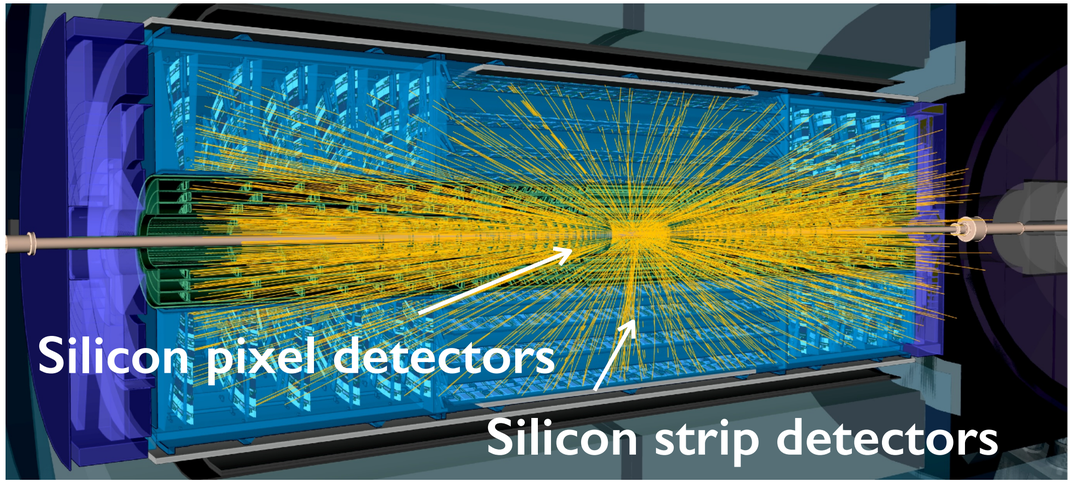
Key challenges:

- Magnetic field — ATLAS: 2 T, CMS: 3.8 T
- Tracking lever arm and detector precision
- High number of particles at high pileup
- Multiple scattering at low momentum

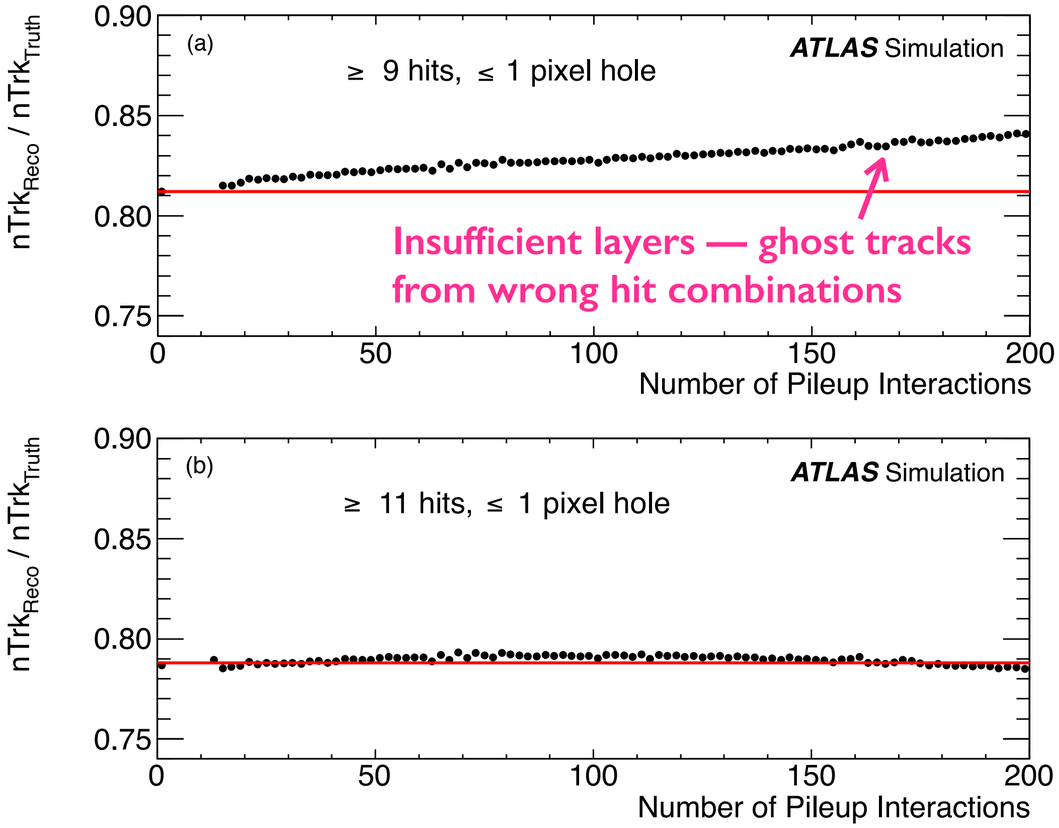
Tracking in High-Pileup Environments

High granularity and sufficient number of detector layers essential for high pileup, ~200 proton-proton collisions in the same proton bunch crossing at HL-LHC

ATLAS inner tracker simulation, pileup 200



- Pixel size: 50 x 50 μm² and 25 x 100 μm²
- Strip size: 75.5 μm x 24.1 mm (inner layer of barrel)



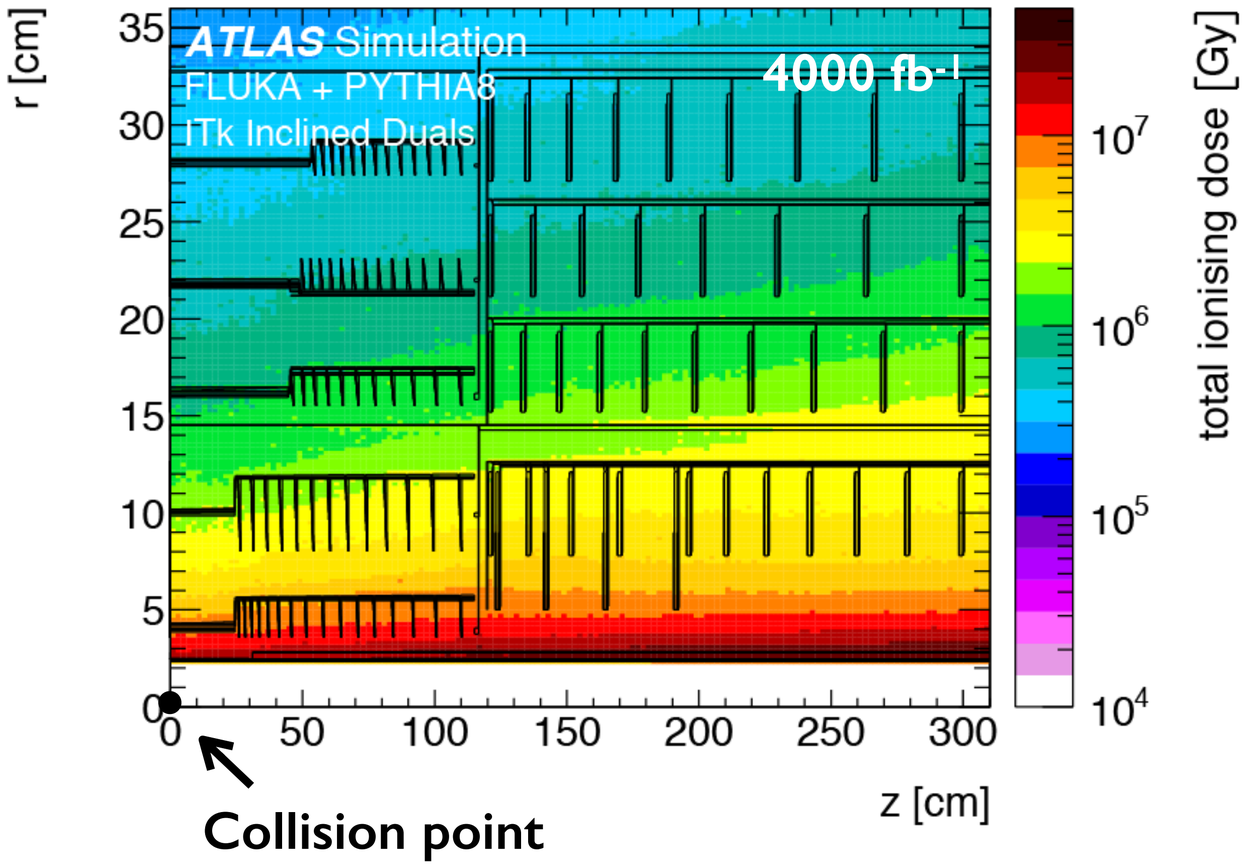
Challenges in High-Radiation Environments

High-radiation environment at HL-LHC

- **Total ionising dose:** ~10 MGy
- **1 MeV neutron-equivalent fluence:** ~10^{16} n_{eq}/cm^2

Radiation damage degrades sensor and electronics performance

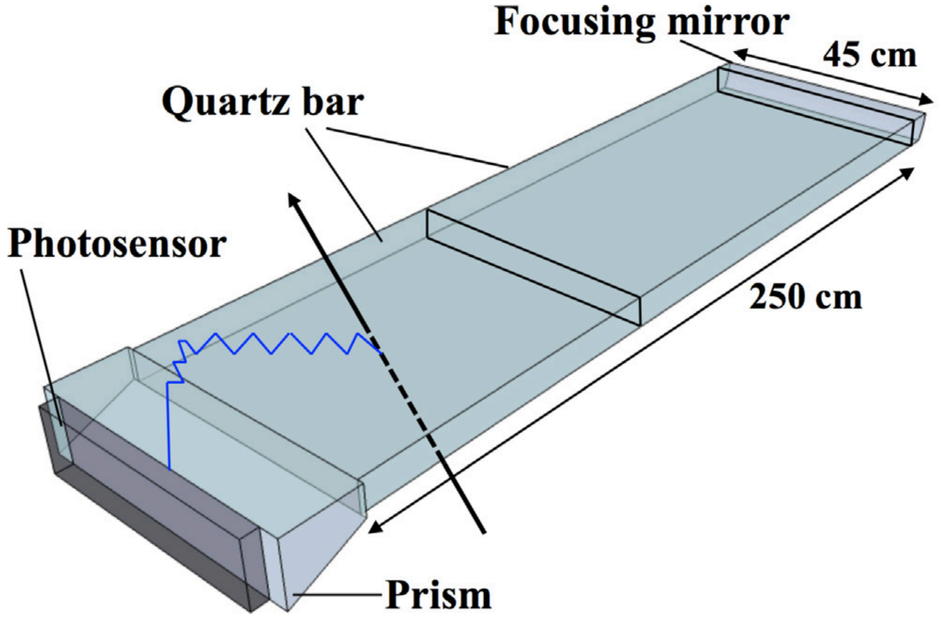
Key challenge: maintaining detector performance under extreme radiation conditions

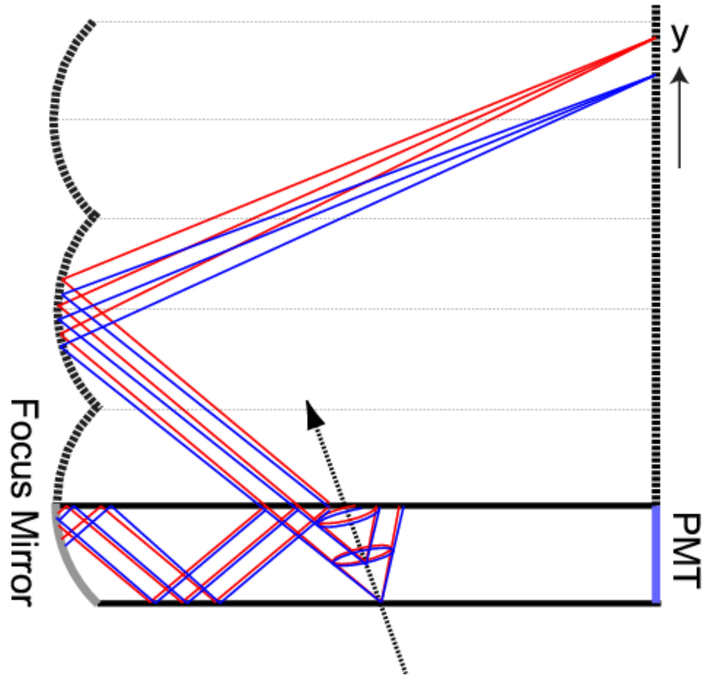


Challenges in Particle Identification

K/π separation is important for Belle II.

Cherenkov ring imaging at the TOP counter provides key information.





NIMA 1080, 170627 (2025)

Challenge: photon detection in high beam background and velocity reconstruction

Challenges in Trigger and Data Acquisition

Increasing data volume at HL-LHC

- More detector readout channels and higher occupancy
- Event size: ~5 MB → ~200 TB/s at 40 MHz

ATL-TDR-029

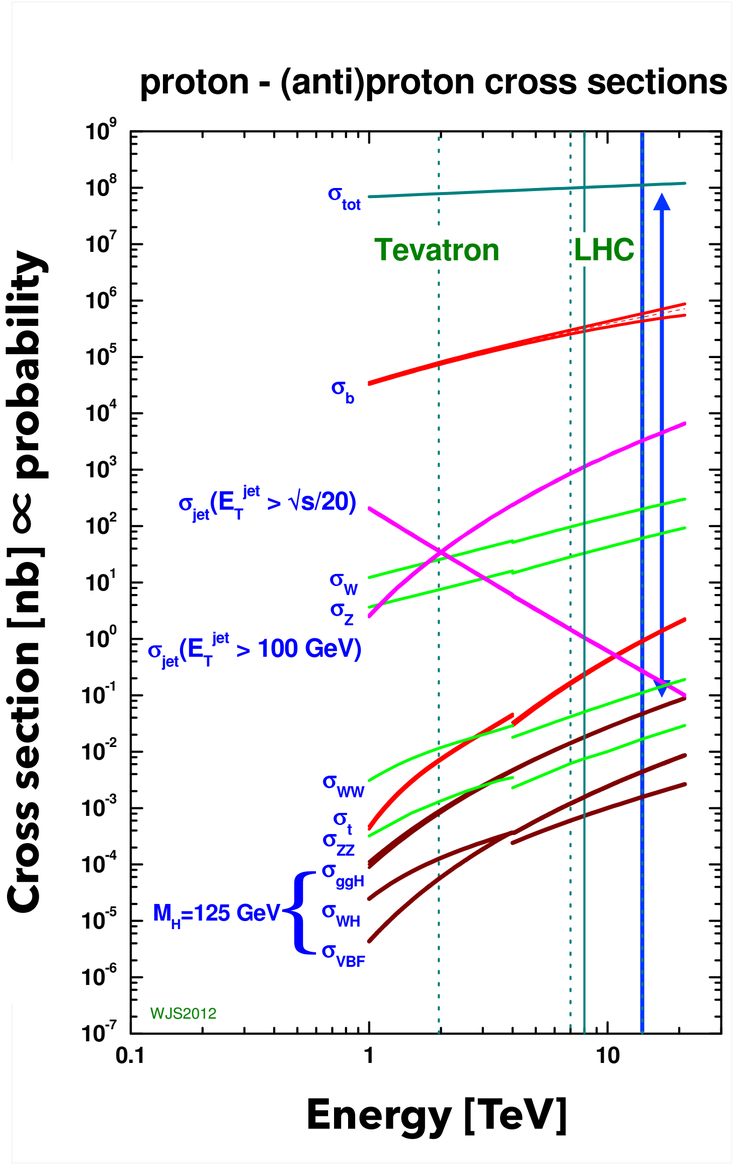
Rare physics processes (right figure)

- Total proton-proton cross section: ~100 mb
- Higgs production cross section: ~50 pb

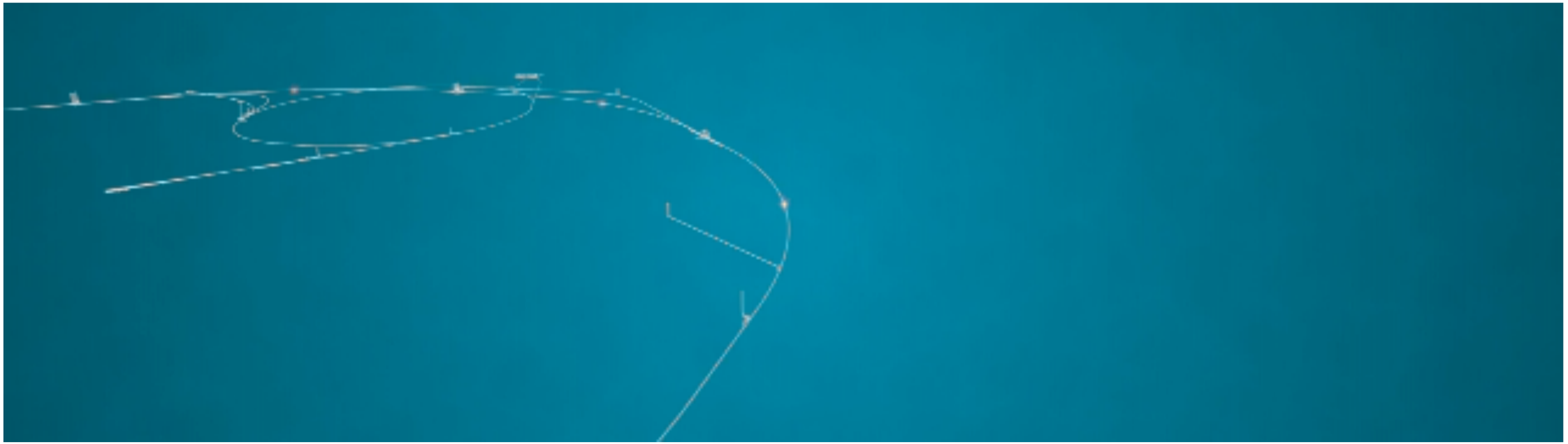
Real-time event selection

- The trigger selects interesting events for recording
- Data rate reduced from 40 MHz to the kHz level

Challenge: selecting rare physics processes in real time



Challenges in Trigger and Data Acquisition



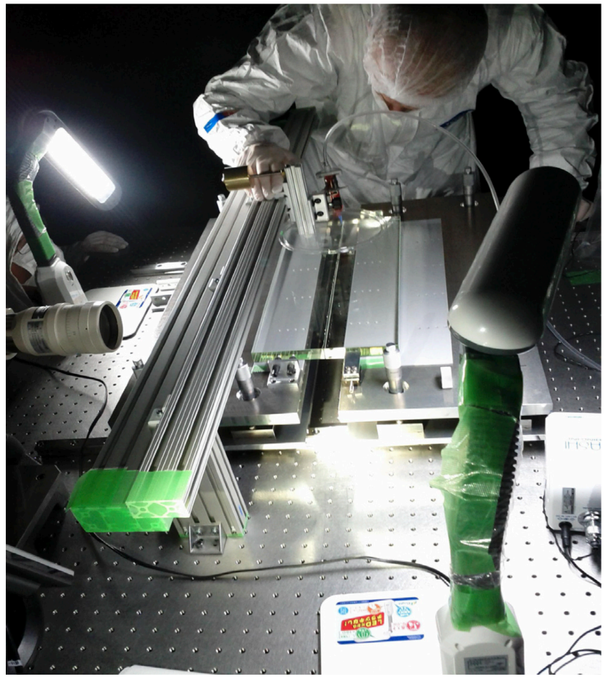
CERN ATLAS Experiment, https://videos.cern.ch/record/1951286

- Level-1 trigger: fast processing (<10 μs at HL-LHC) → FPGA
- Event filter: precise processing → CPU, GPU

Challenges in Detector Construction

Example I: Belle II TOP counter

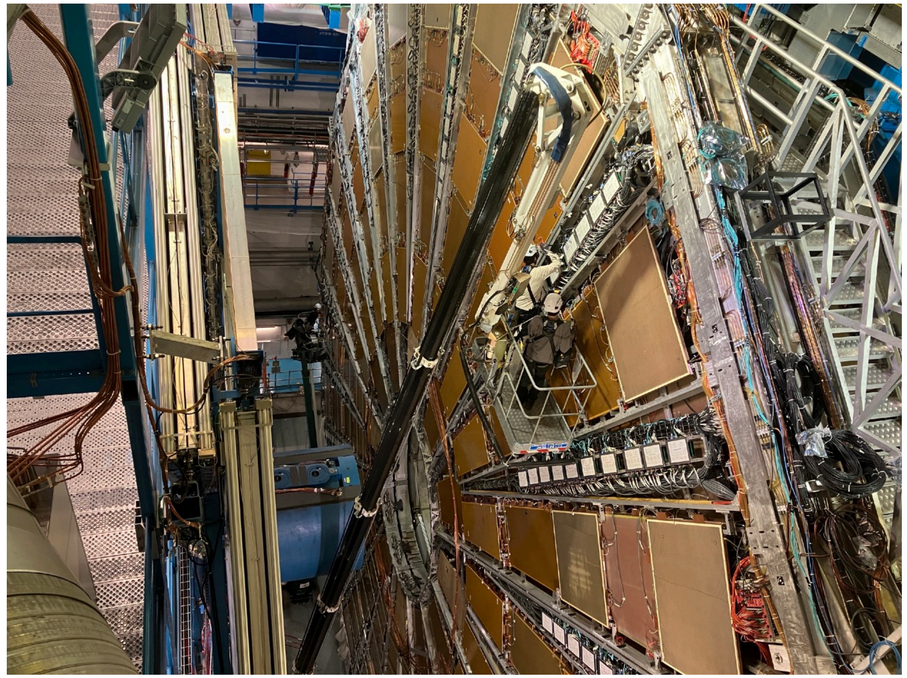
Precise alignment and gluing of quartz bars



NIMA 1080, 170627 (2025)

Example II: ATLAS TGC electronics upgrade

Large-scale production, testing, and installation



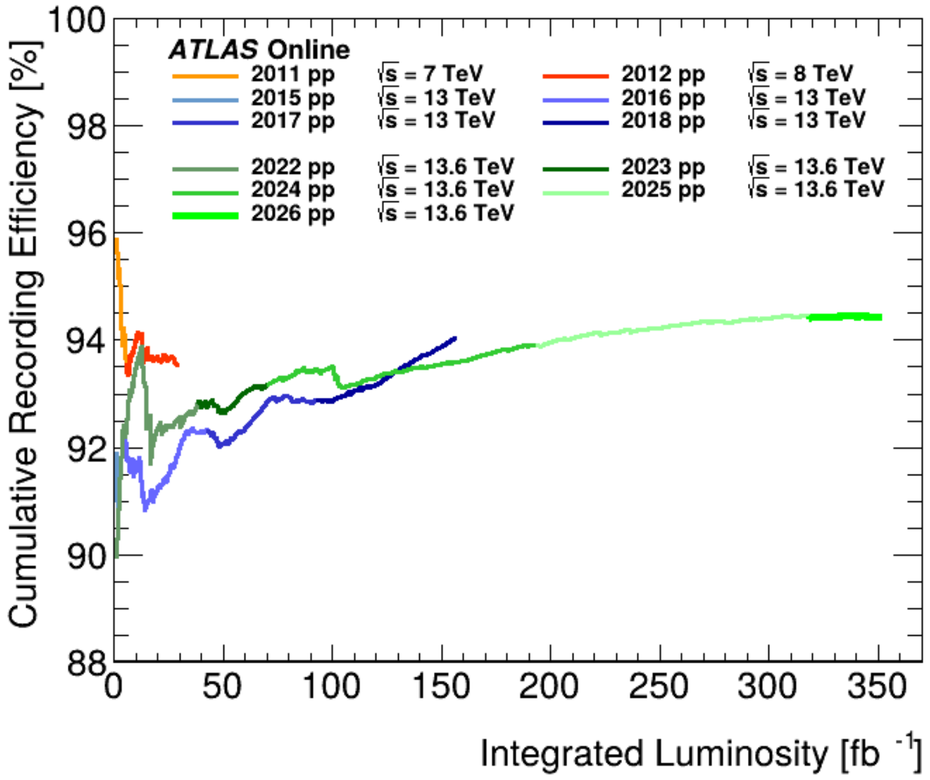
Y. Horii and colleagues, Sep. 2026

Key challenge: building and integrating complex detectors with high reliability

Challenges in Detector Operation

Key challenge: reliable and efficient operation of complex detector systems

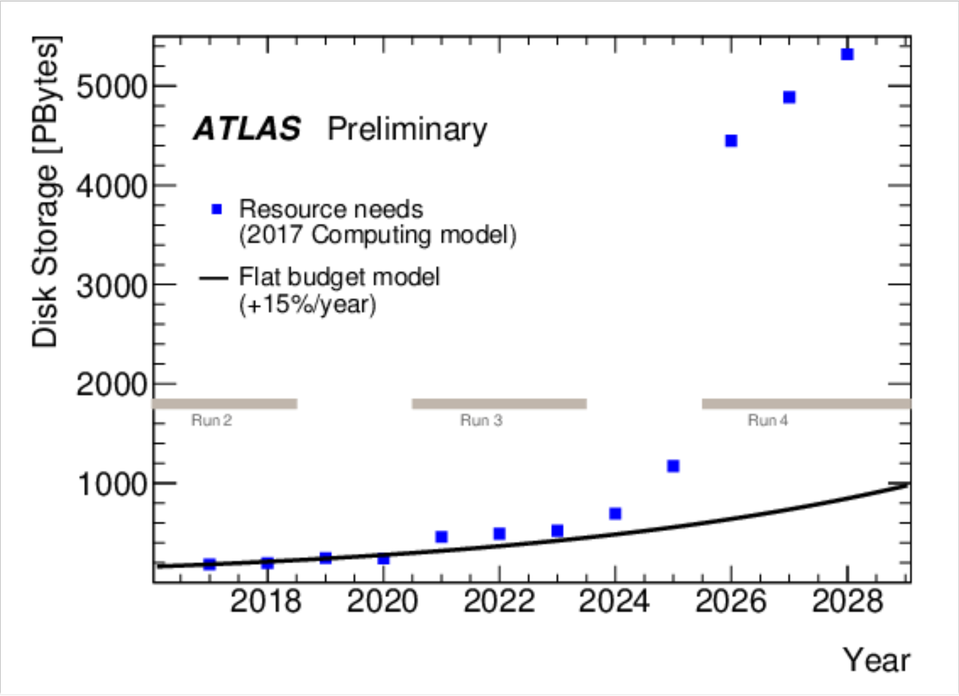
- Monitoring and controlling thousands of detector channels
- Rapid identification and recovery of detector problems



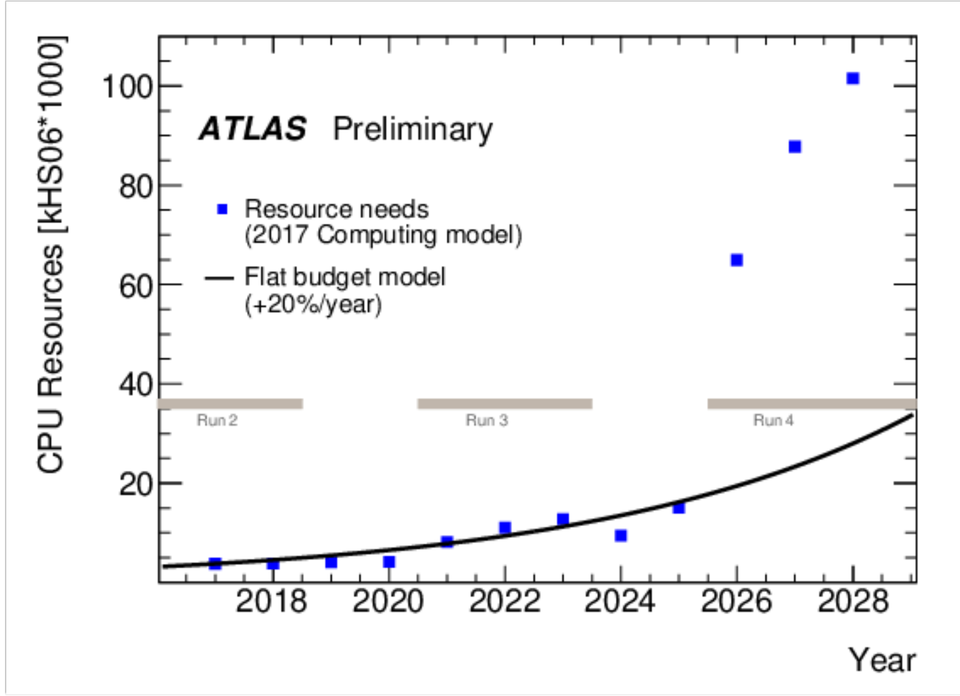


Challenges in Computing

Processing and storing enormous volumes of experimental data



Large-scale computing for simulation and data analysis



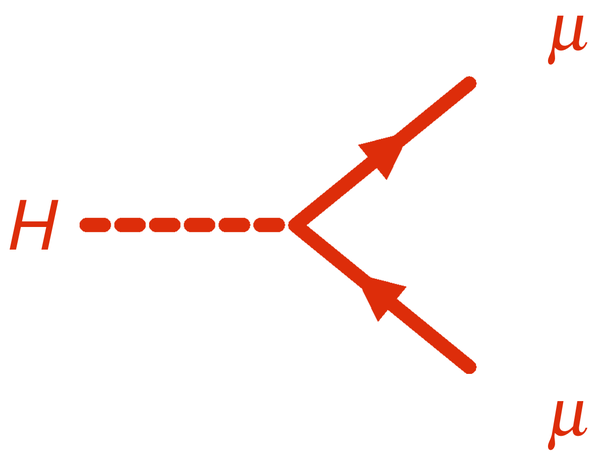
Comput Softw Big Sci 3, 7 (2019)

Challenges in Data Analysis

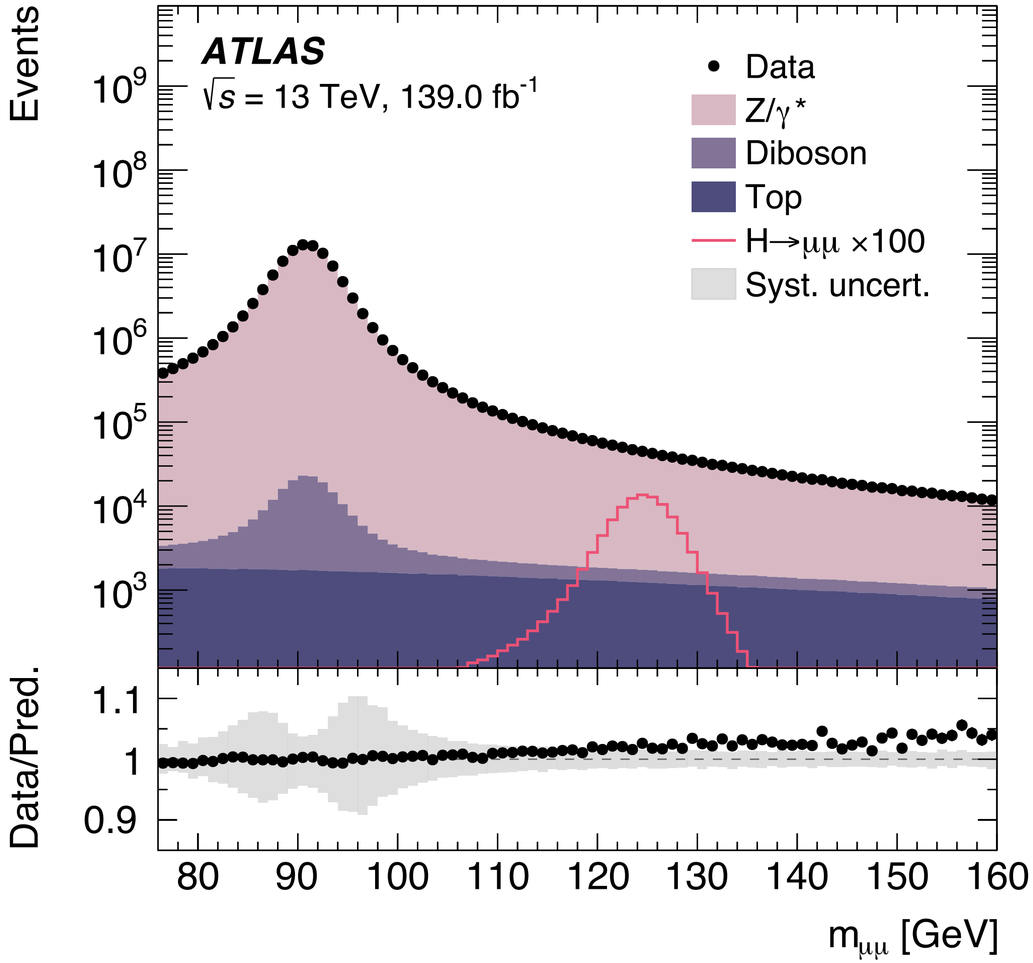
- Various challenges in physics data analysis
- AI has traditionally been widely used and has played an important role; more advanced applications are emerging
- Examples discussed in this presentation:
  - Search for $H \to \mu\mu$ — event classification
  - Search for HH production — jet flavour tagging

H→μμ — Introduction

Probe of the Higgs coupling to muon



- Standard Model predicts a small branching ratio: BR(H→μμ) = 2 x 10^{-4}
- An irreducible background from Z→μμ makes event classification essential



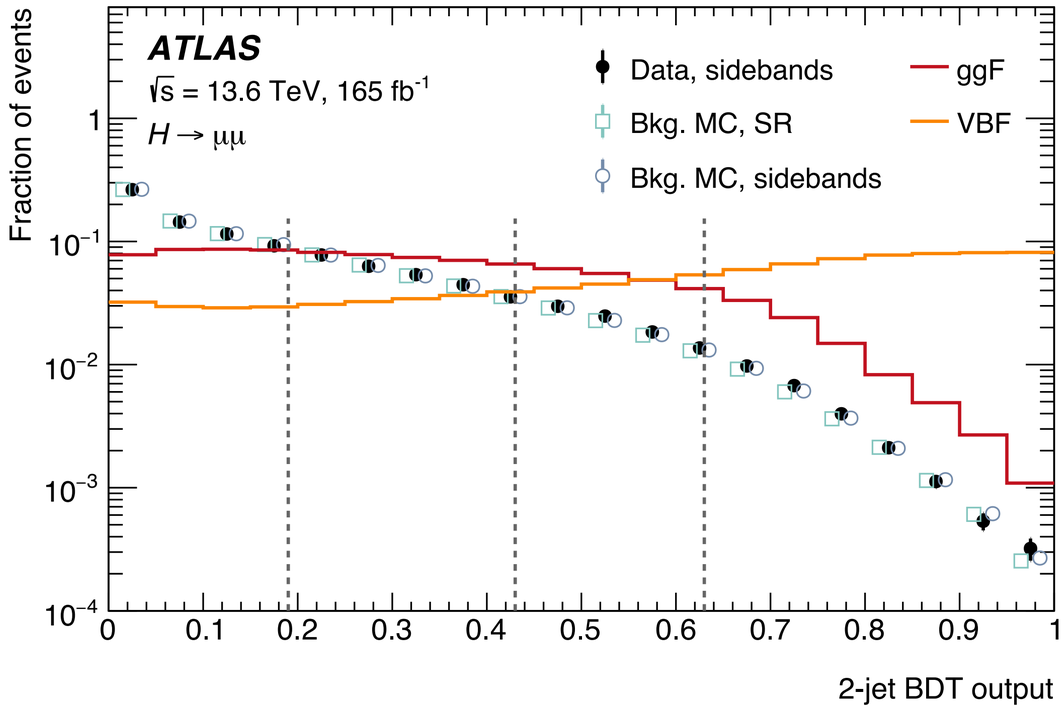
PLB 812 (2021) 135980

H→μμ — Event Classification

Event classification using Boosted Decision Trees (BDTs) in PRL 135, 231802 (2025)

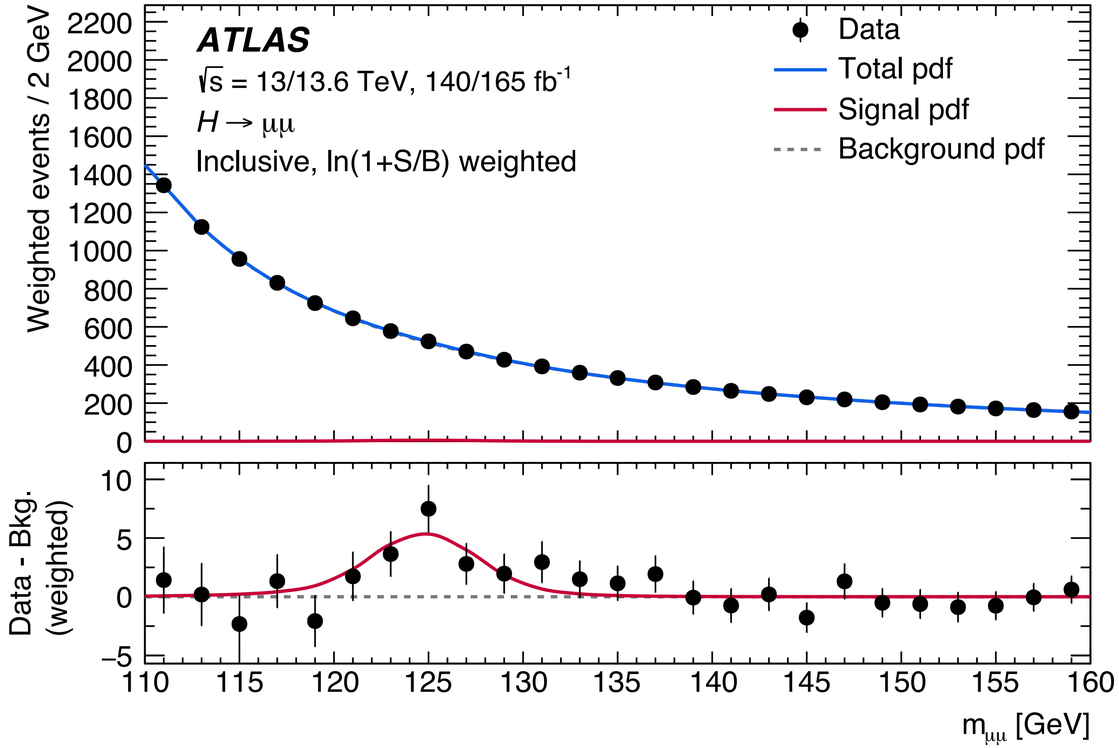
Kinematic variables, such as the transverse momentum of the dimuon system, used as input

Variable	Description
$p_{\mathrm{T}}^{\mu\mu}$	Transverse momentum of muon pair
$Y^{\mu\mu}$	Rapidity of muon pair
$\cos\theta^{*}$	μ^{-} decay angle in the Collins–Soper frame
$p_{\mathrm{T}}^{j_1}$	Transverse momentum of leading jet
η^{j_1}	Pseudorapidity of leading jet
$\Delta\phi(\mu\mu, j_1)$	Azimuthal angle between the muon pair and the leading jet
$N_{\mathrm{Track}}^{j_1}$	Number of tracks in leading jet with $p_{\mathrm{T}} > 0.5$ GeV
$p_{\mathrm{T}}^{j_2}$	Transverse momentum of sub-leading jet
η^{j_2}	Pseudorapidity of sub-leading jet
$\Delta\phi(\mu\mu, j_2)$	Azimuthal angle between the muon pair and the sub-leading jet
$N_{\mathrm{Track}}^{j_2}$	Number of tracks in sub-leading jet with $p_{\mathrm{T}} > 0.5$ GeV
p_{T}^{jj}	Transverse momentum of dijet system
Y^{jj}	Rapidity of dijet system
$\Delta\phi(\mu\mu, jj)$	Azimuthal angle between the muon pair and the dijet system
m^{jj}	Invariant mass of dijet system
$E_{\mathrm{T}}^{\mathrm{miss}}$	Missing transverse energy
H_{T}^{j}	Scalar sum of jet transverse momentum



H→μμ — Evidence and Future Challenges

- Evidence of the H→μμ decay obtained (3.4σ)
- Signal strength relative to the Standard Model prediction: 1.4 ± 0.4 — evidence for the origin of muon mass through the Higgs field

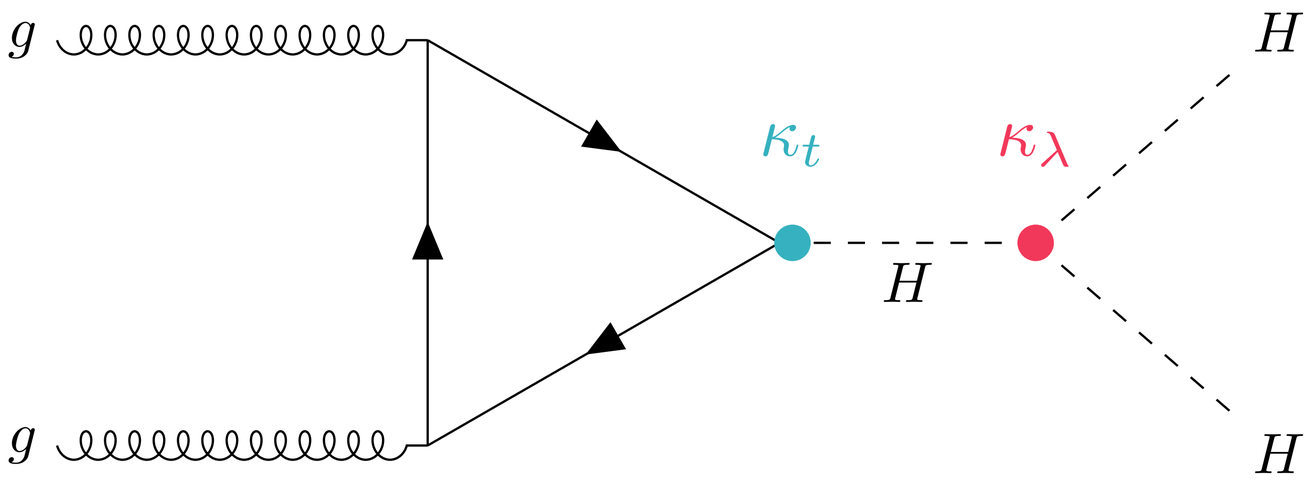


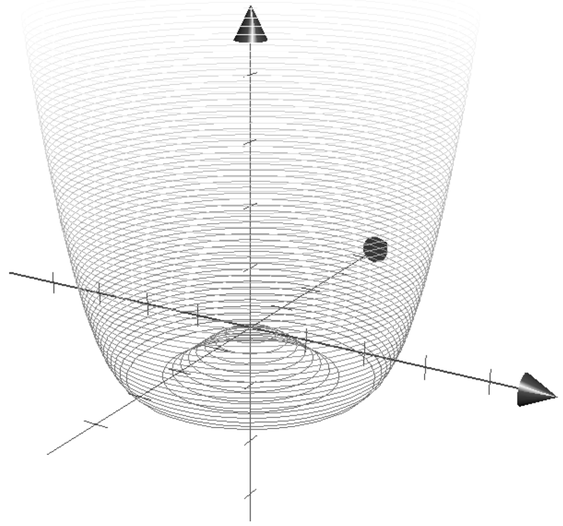
PRL 135, 231802 (2025)

Improved event classification is desirable toward observation

HH Production — Introduction

- HH production is sensitive to the Higgs self-coupling λ
- The self-coupling relative to the Standard Model prediction κ_λ is constrained from data





$$V(\phi) = -\mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2$$

$$\phi = \sqrt{\frac{1}{2}}\begin{pmatrix} 0 \\ v + H(x) \end{pmatrix}$$

HH Production — Jet Flavour Tagging

- Key search channels for HH production:

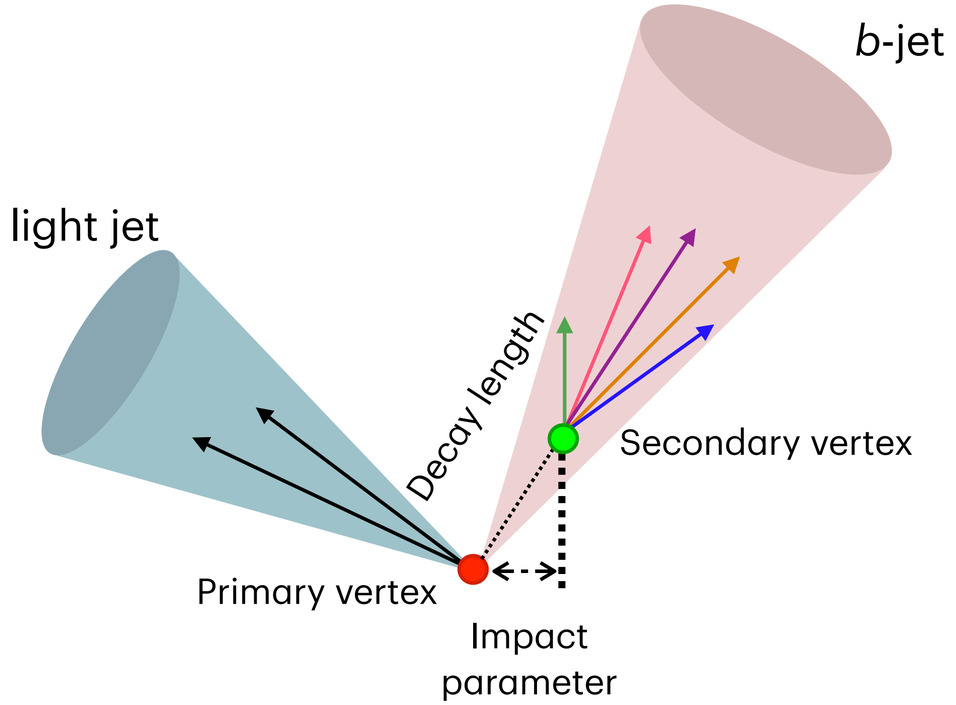
  bbbb, bbττ, and bbγγ

- The b quarks produce b-jets,

  collimated sprays of hadrons

- Flavour tagging is essential for identifying b-jets

  and separating signal from background



Transformer-based flavour tagging already developed [Nature Commun. (2026)]

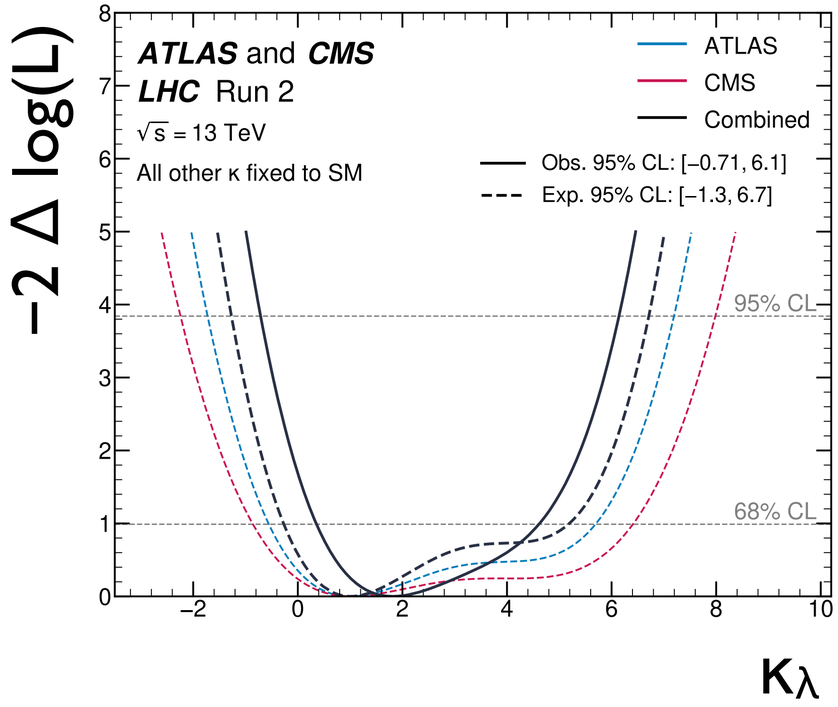
Further advances in AI may improve flavour tagging performance

HH Production — Status and Prospects

Measuring κ_λ, the Higgs self-coupling relative to the Standard Model prediction

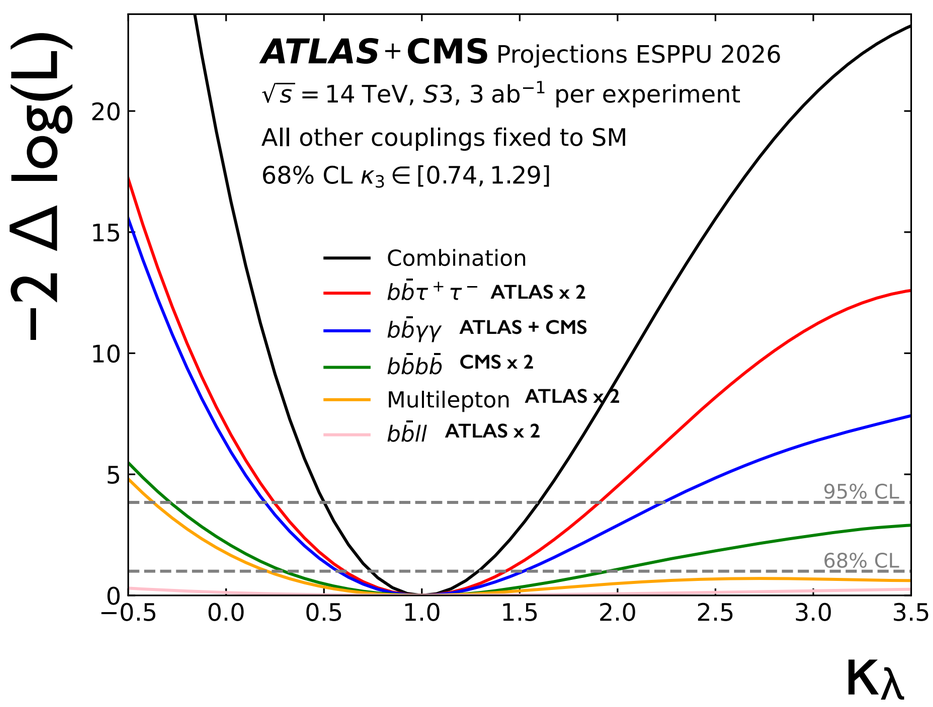
LHC Run 2: $-1.3 < \kappa_\lambda < 6.7$ (95% CL)

arXiv:2602.23991



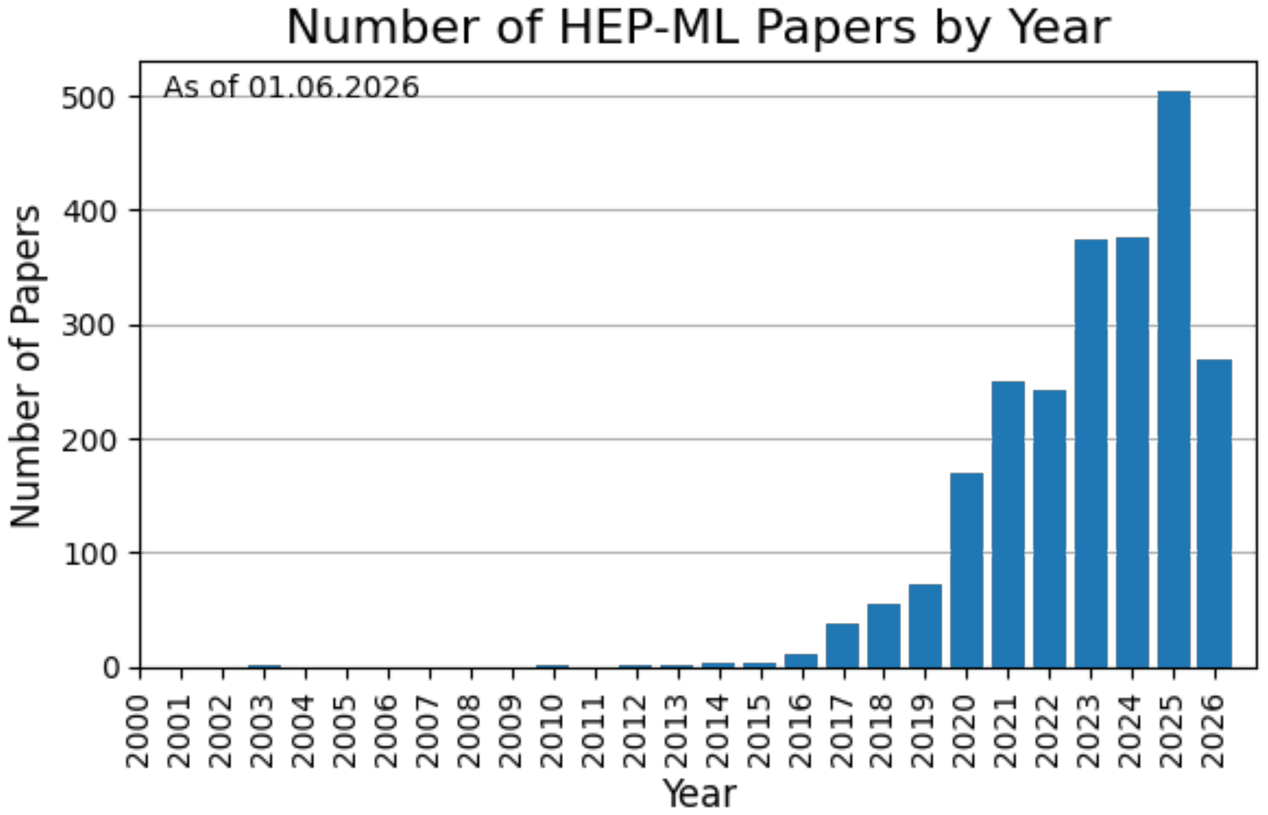
HL-LHC expected sensitivity: −26%/+29%

arXiv:2504.00672



Other Challenges in Collider Physics

- Many other challenges remain in collider physics
- Modern AI techniques are rapidly being applied, adapted, and developed
- A comprehensive list of publications is available at: HEP ML Living Review



Conclusion

- Collider experiments address fundamental questions in particle physics
- Increasing experimental challenges require advanced technologies and analysis methods
- AI can help overcome these challenges and enhance the physics potential of collider experiments

Backup Slides

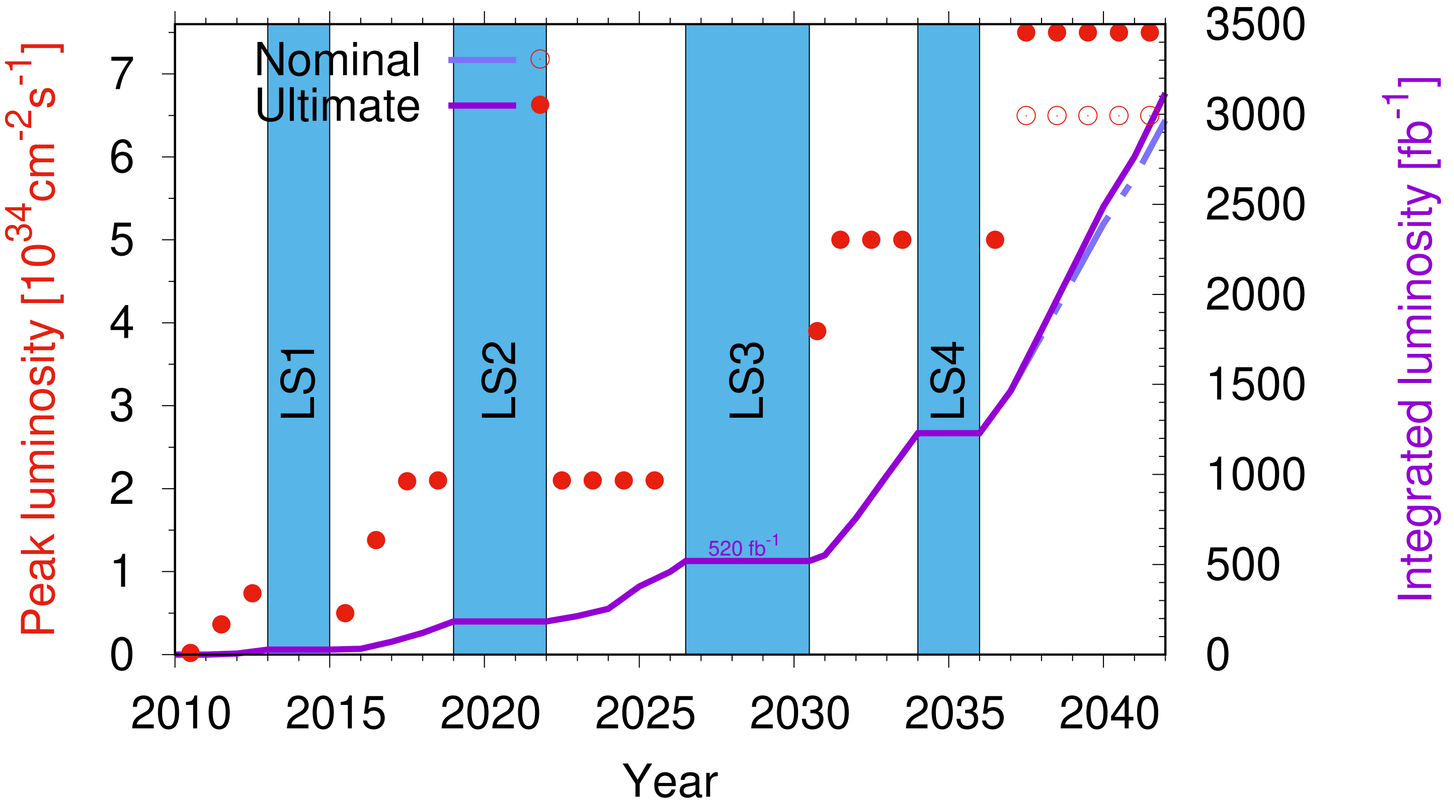
Luminosity Upgrade of the LHC

Luminosity upgrade crucial for improved searches and measurements

HL-LHC operation from 2030

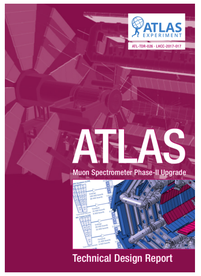
Total integrated luminosity per experiment: 3000 fb^{-1}

For statistics-limited analyses, the gain for luminosity increase would be $\sqrt{3000\ \text{fb}^{-1}/520\ \text{fb}^{-1}} = 2.4$



ATLAS Upgrade

Handle the HL-LHC luminosity, pileup, and radiation levels, and improve the performances

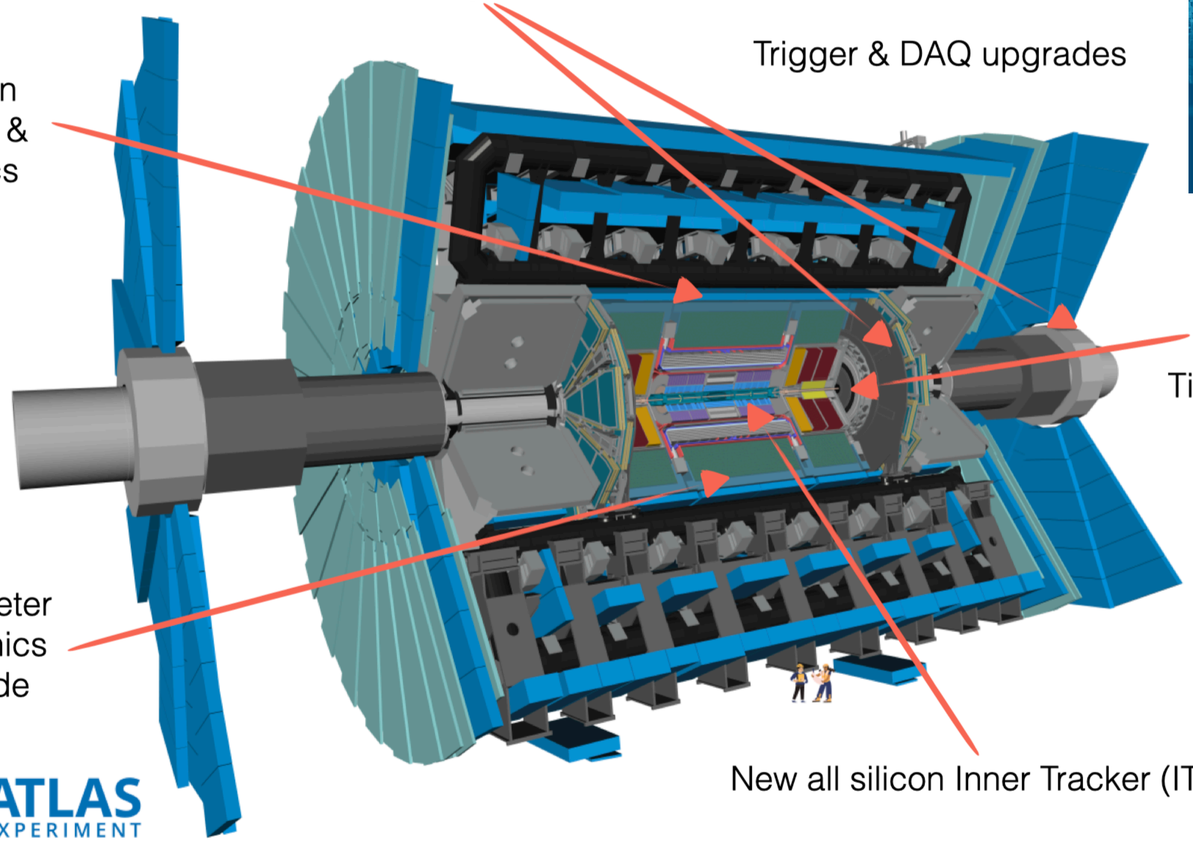


ATL-TDR-026 (408 pages)

New and upgraded forward and luminosity detectors

New muon chambers & electronics

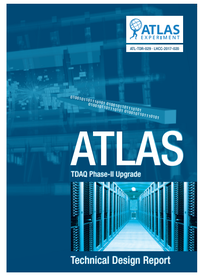
Trigger & DAQ upgrades



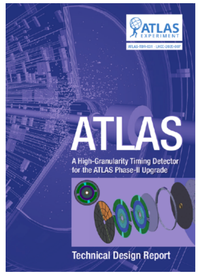
New High Granularity Timing Detector (HGTD)

Calorimeter electronics upgrade

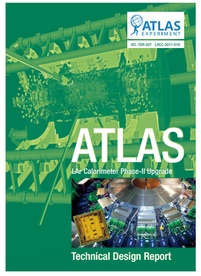
New all silicon Inner Tracker (ITk)

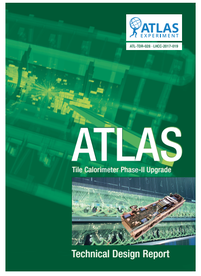


ATL-TDR-029 (608 pages)



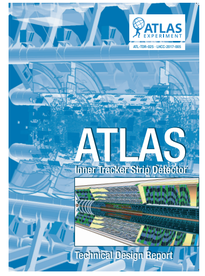
ATL-TDR-031 (412 pages)





ATL-TDR-027 (271 pages)
ATL-TDR-028 (300 pages)





ATL-TDR-030 (482 pages)
ATL-TDR-025 (556 pages)

CMS Upgrade

Handle the HL-LHC luminosity, pileup, and radiation levels, and improve the performances

Barrel Calorimeters
- crystal granularity readout at 40 MHz
- precise timing for e/γ > 30 GeV
- ECAL operation at low temperature (10°)
- upgraded laser monitoring system

CMS-TDR-015

Tracker
- all silicon (strips and pixels)
- higher granularity (>2B channels)
- less material
- coverage extended to |η| = 4

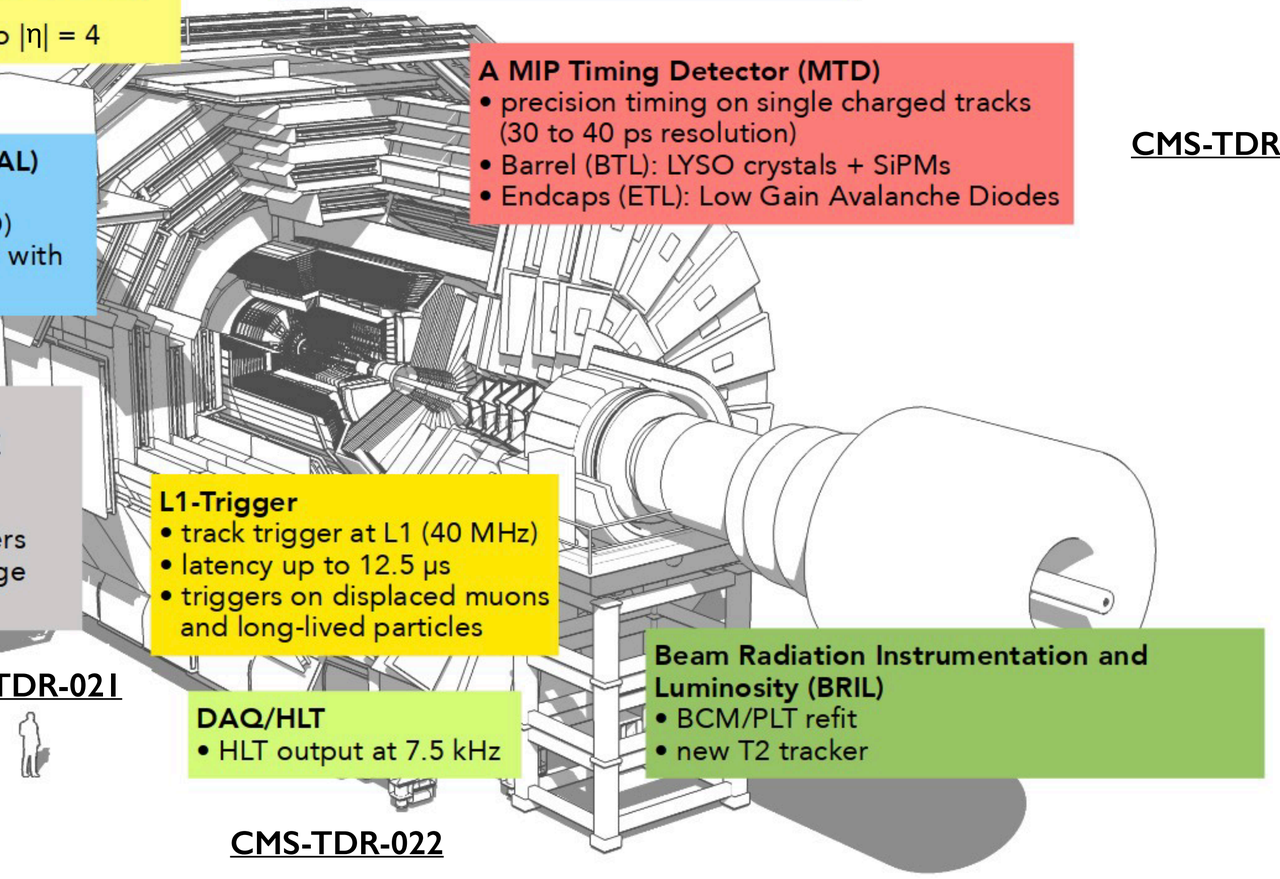
CMS-TDR-014

A MIP Timing Detector (MTD)
- precision timing on single charged tracks (30 to 40 ps resolution)
- Barrel (BTL): LYSO crystals + SiPMs
- Endcaps (ETL): Low Gain Avalanche Diodes

CMS-TDR-020

Endcap Calorimeter (HGCAL)
- silicon pixels (EM) and scintillators + SiPMs (HAD)
- 3D shower reconstruction with precise timing

CMS-TDR-019



Muon Detectors
- DTs & CSCs: new FE/BE readout electronics
- RPCs: new electronics
- new GEM/iRPC chambers
- extended muon coverage to |η| = 3

CMS-TDR-016

L1-Trigger
- track trigger at L1 (40 MHz)
- latency up to 12.5 μs
- triggers on displaced muons and long-lived particles

CMS-TDR-021

DAQ/HLT
- HLT output at 7.5 kHz

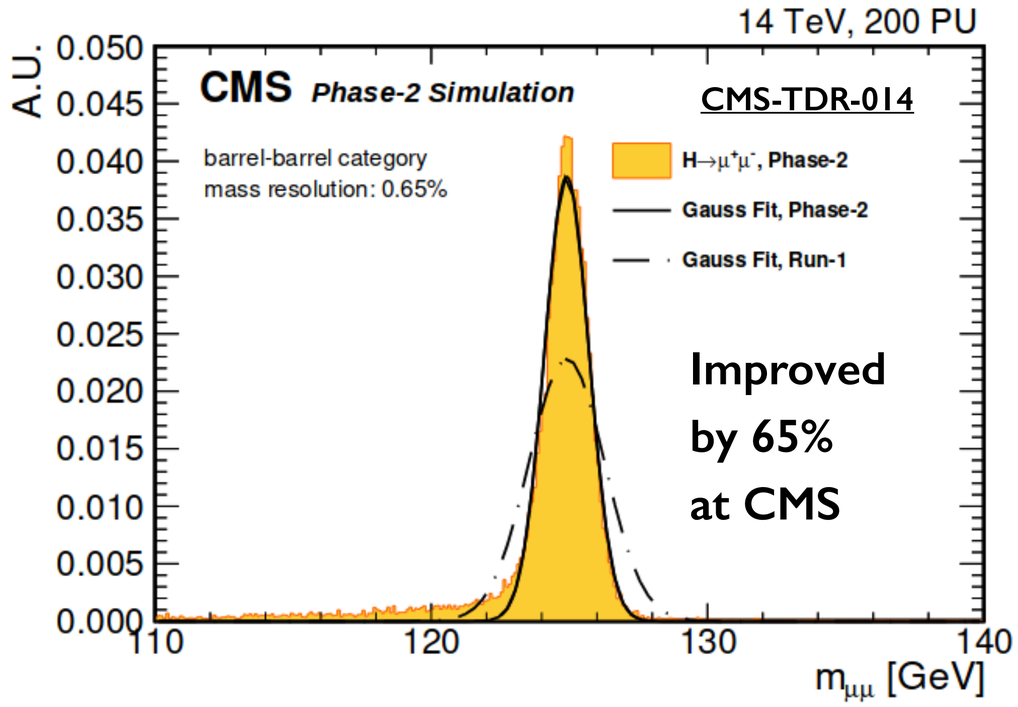
CMS-TDR-022

Beam Radiation Instrumentation and Luminosity (BRIL)
- BCM/PLT refit
- new T2 tracker

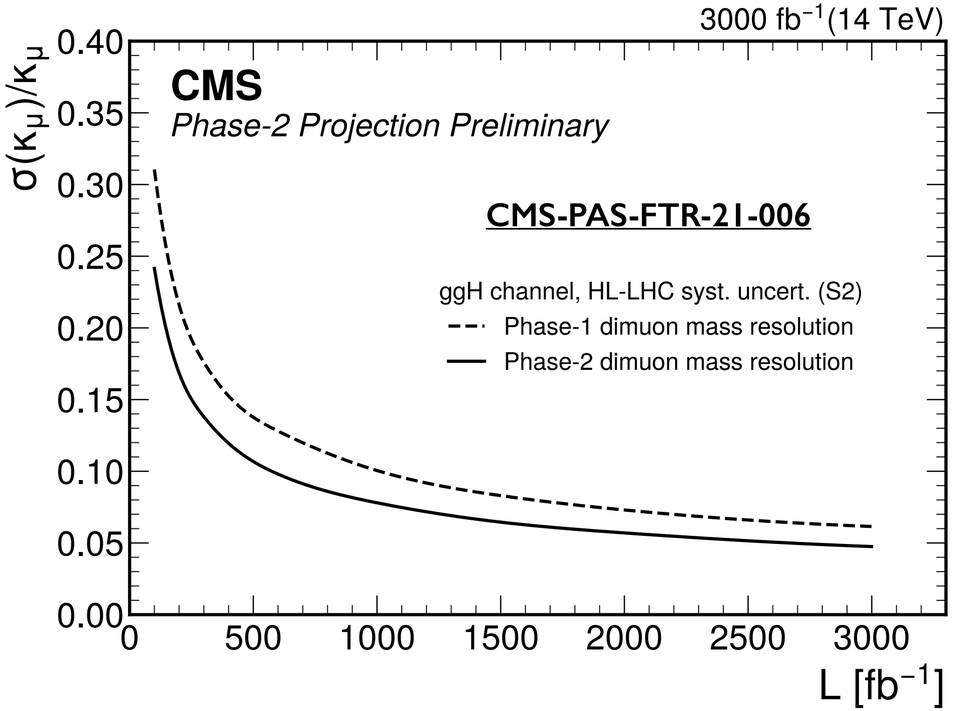
CMS-TDR-023

H→μμ

An improved dimuon mass resolution by the upgraded tracker



Relative uncertainty on the coupling improved by larger statistics



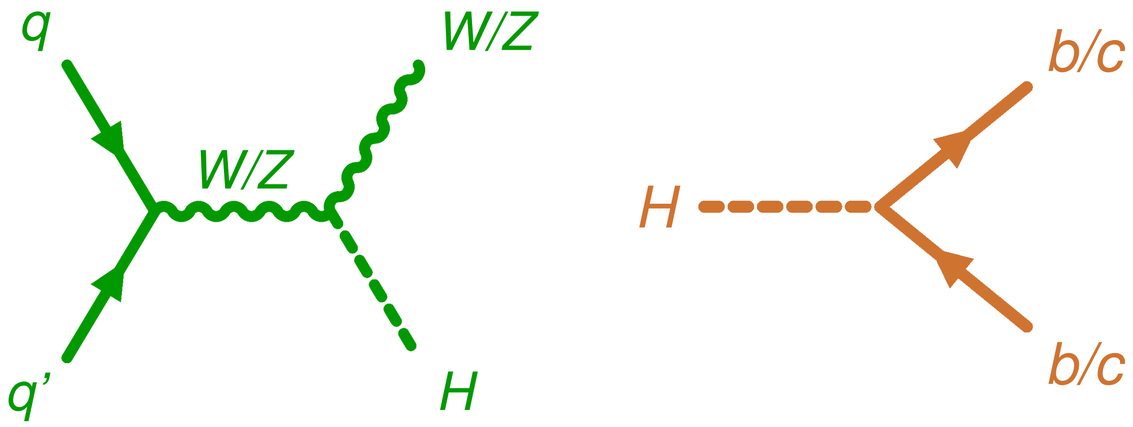
Expected ATLAS+CMS precision on the coupling relative to the SM prediction κ_μ: 3%

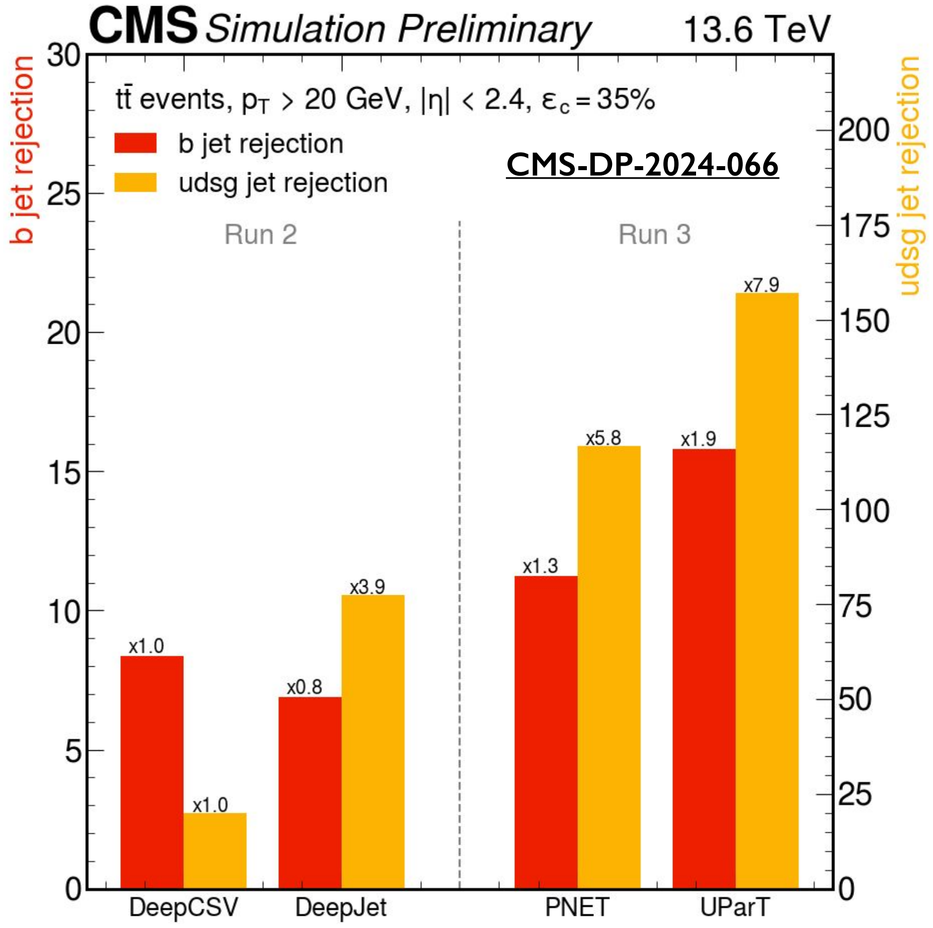
H→cc

Probe of the Higgs coupling to charm quark

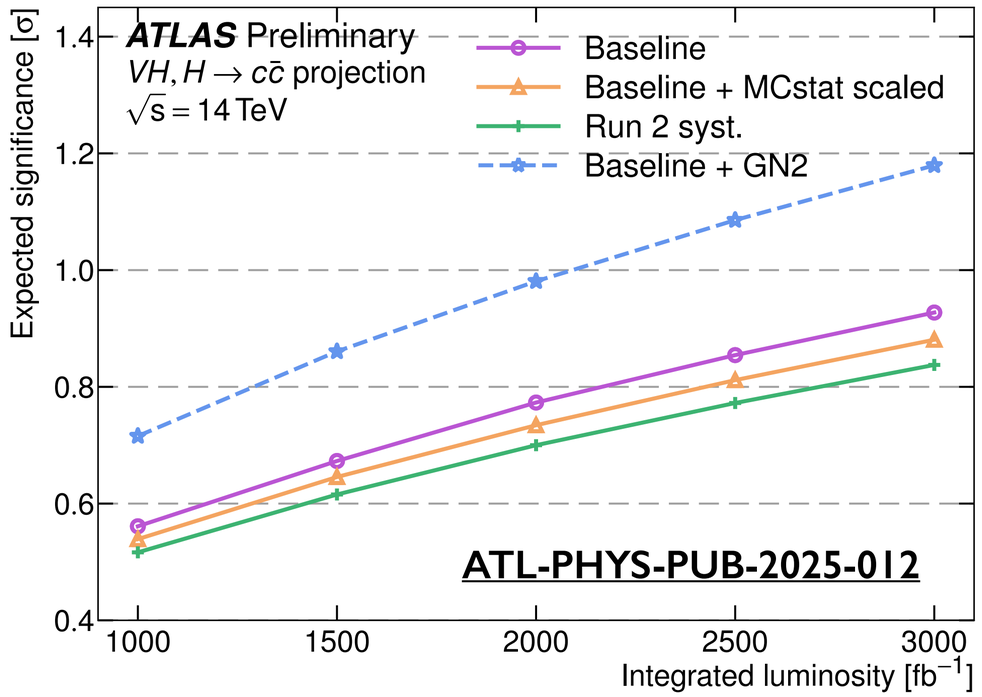
- The most sensitive channel: WH/ZH, H→cc
- The b- and c-jet tagging crucial,

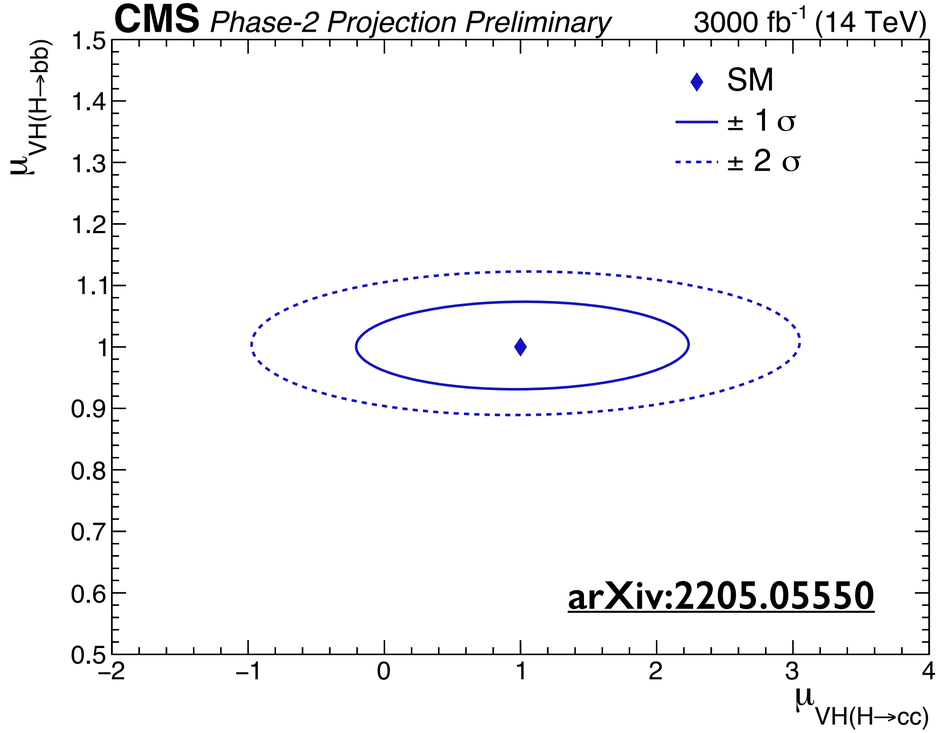
  recent improvements in ATLAS and CMS





H→cc

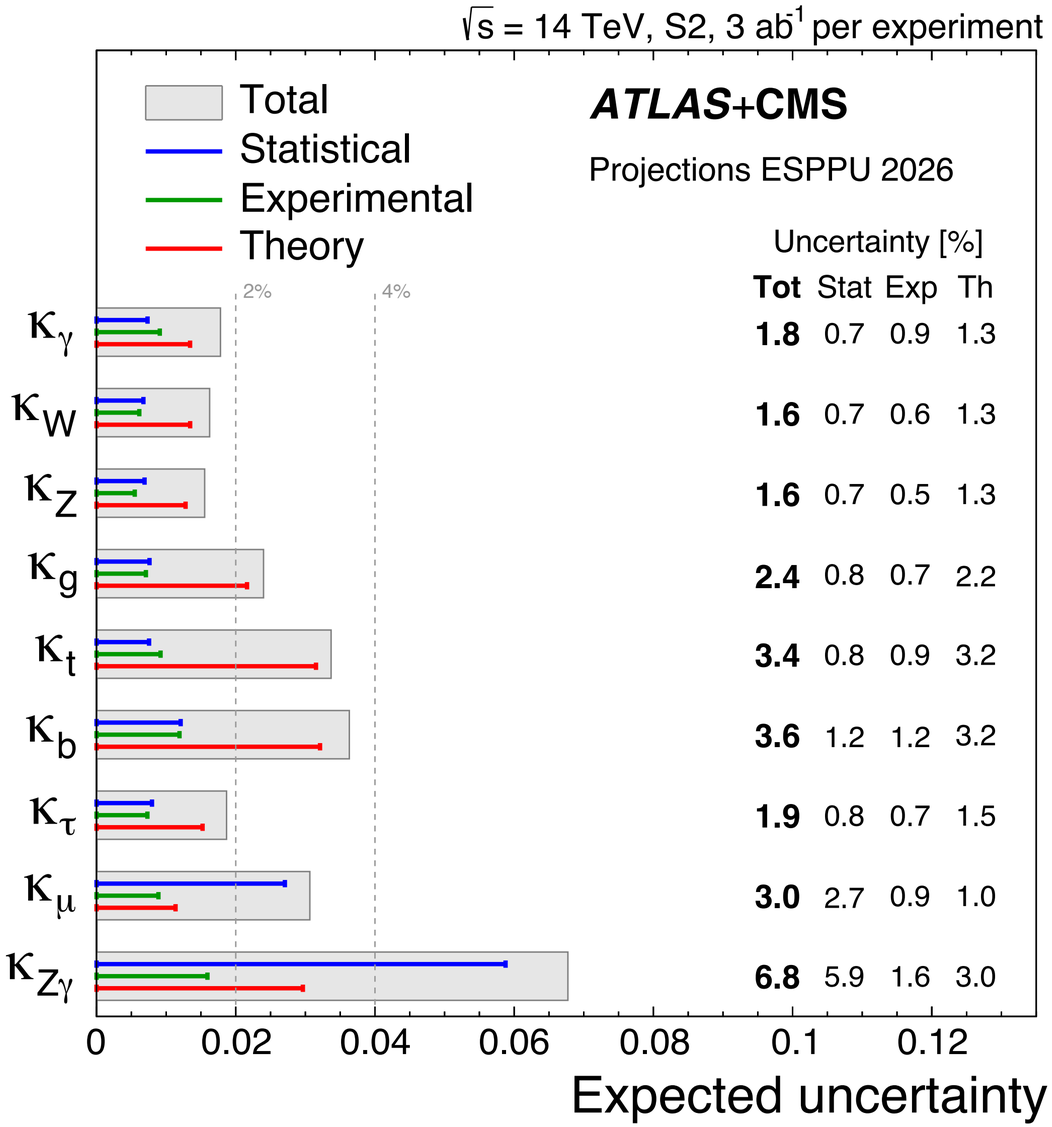




- **A 1.6σ significance is expected for ATLAS+CMS at 3000 fb⁻¹**
- **The H-to-c quark coupling modifier κ_c can be constrained to $|\kappa_c| < 1.5$ at 95% CL.**

ttH, H→cc also important, room for further improvements on κ_c

Higgs Coupling Summary



A few % for various couplings!

Deviation from the SM

— indication of BSM

Consistency with the SM

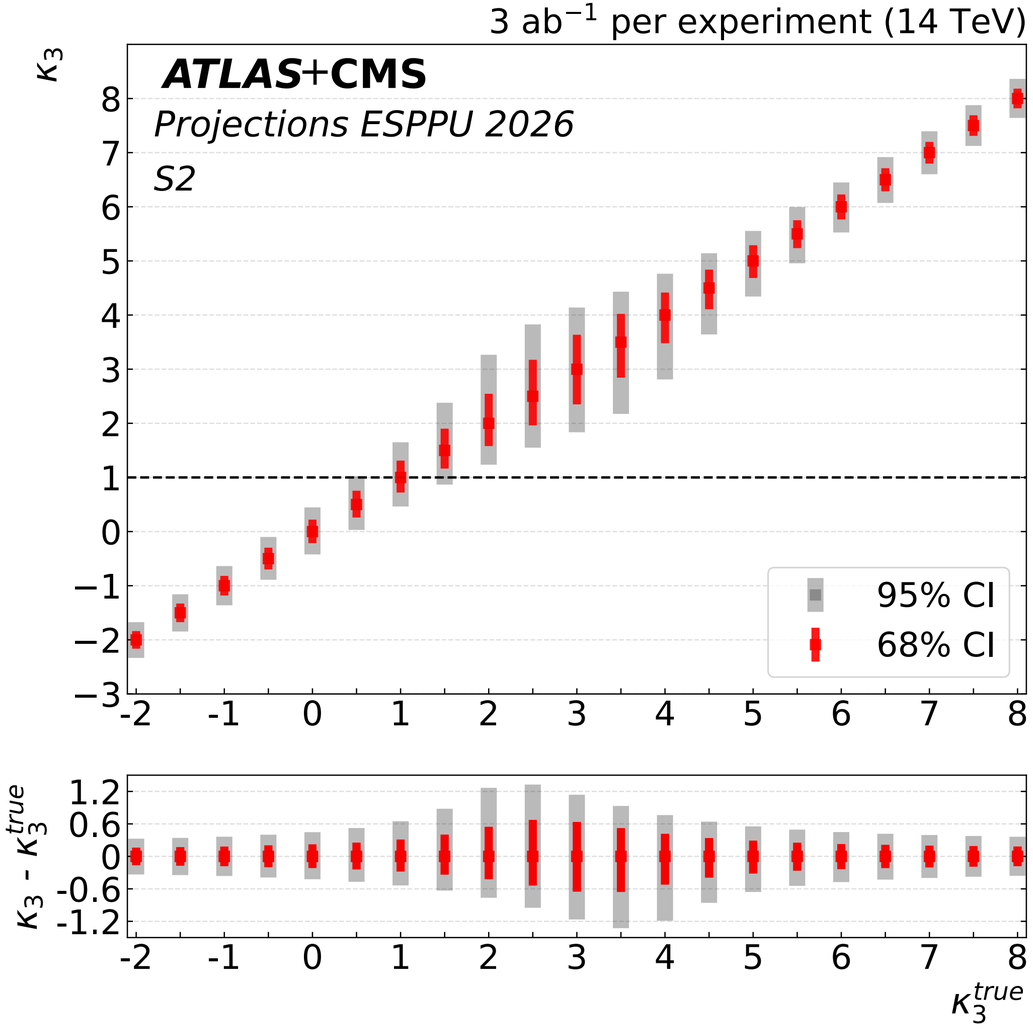
— stringent constraint on BSM

Di-Higgs Production: Dependence on True κ_3

The precision of the determination of κ_3 depends on the true value of κ_3.

Because of a destructive interference between the box diagram and the diagram with the trilinear coupling in ggF production, the HH production cross section at the HL-LHC is minimal when the true value of κ_3 is ~2.5.

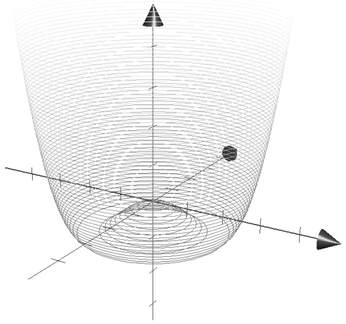
The ATLAS+CMS combination can exclude the SM value of κ_3 at 95% CL for $\kappa_3^{true} \gtrsim 1.7$ and $\kappa_3^{true} \lesssim 0.5$.

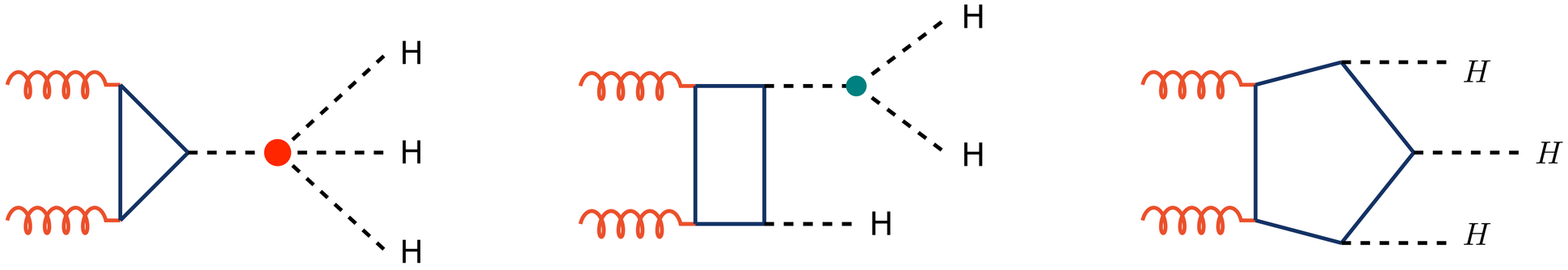


Triple Higgs Production

Triple Higgs production is sensitive to both trilinear and quartic Higgs coupling, can be written as λ_3 and λ_4. The coupling relative to the SM prediction: κ_3 and κ_4.

$$V(H) = \frac{1}{2}m_H^2 H^2 + \lambda\nu H^3 + \frac{1}{4}\lambda H^4$$

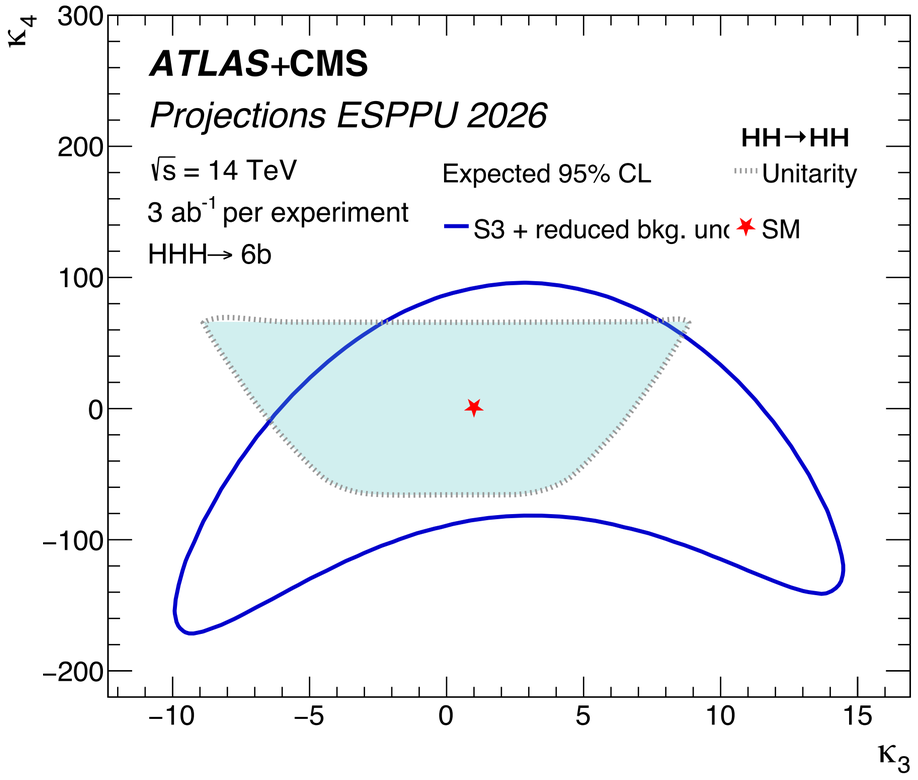




Direct access to the quartic Higgs coupling

Triple Higgs Production

The ATLAS search with 6b channel at Run 2 [PRD 111, 032006 (2025)] projected to 2 x 3000 fb^{-1}.



Expected 95% CL constraint on κ_3 and κ_4

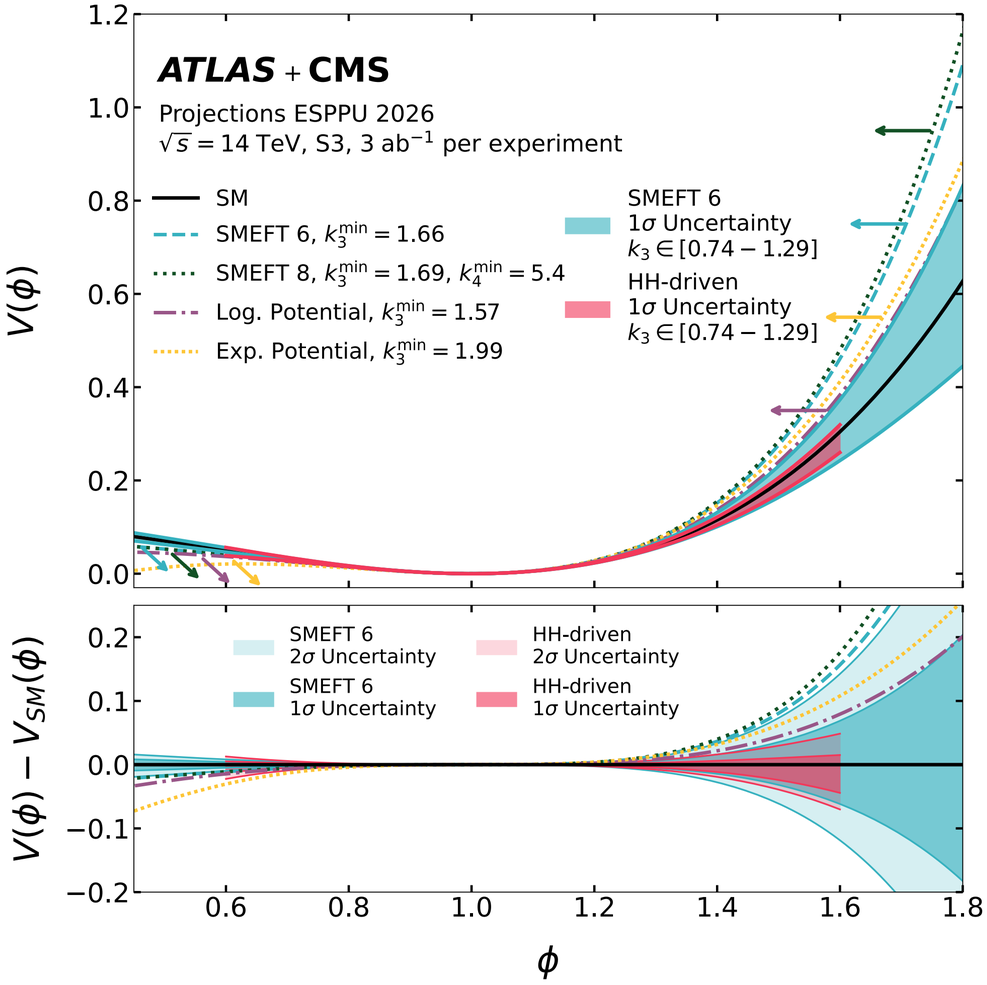
Will start excluding portions of the region bounded by the unitarity limit [P. Stylianou and G. Weiglein (2024)].

If an excess in the triple Higgs production process is observed, the correlation with the result for di-Higgs production will be informative.

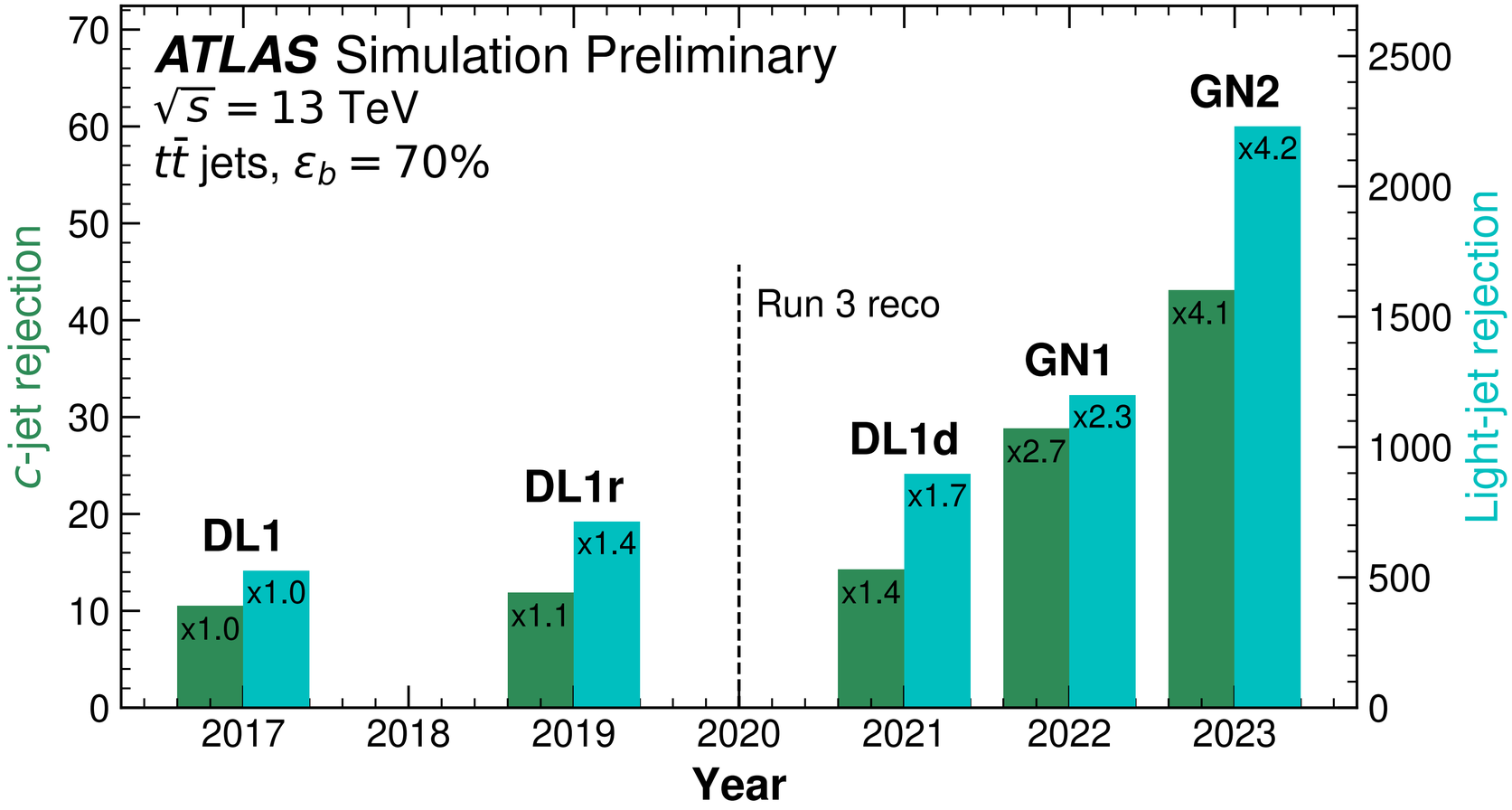
Higgs Potential and Phase Transition

HL-LHC will constrain the Higgs potential and a first-order phase transition

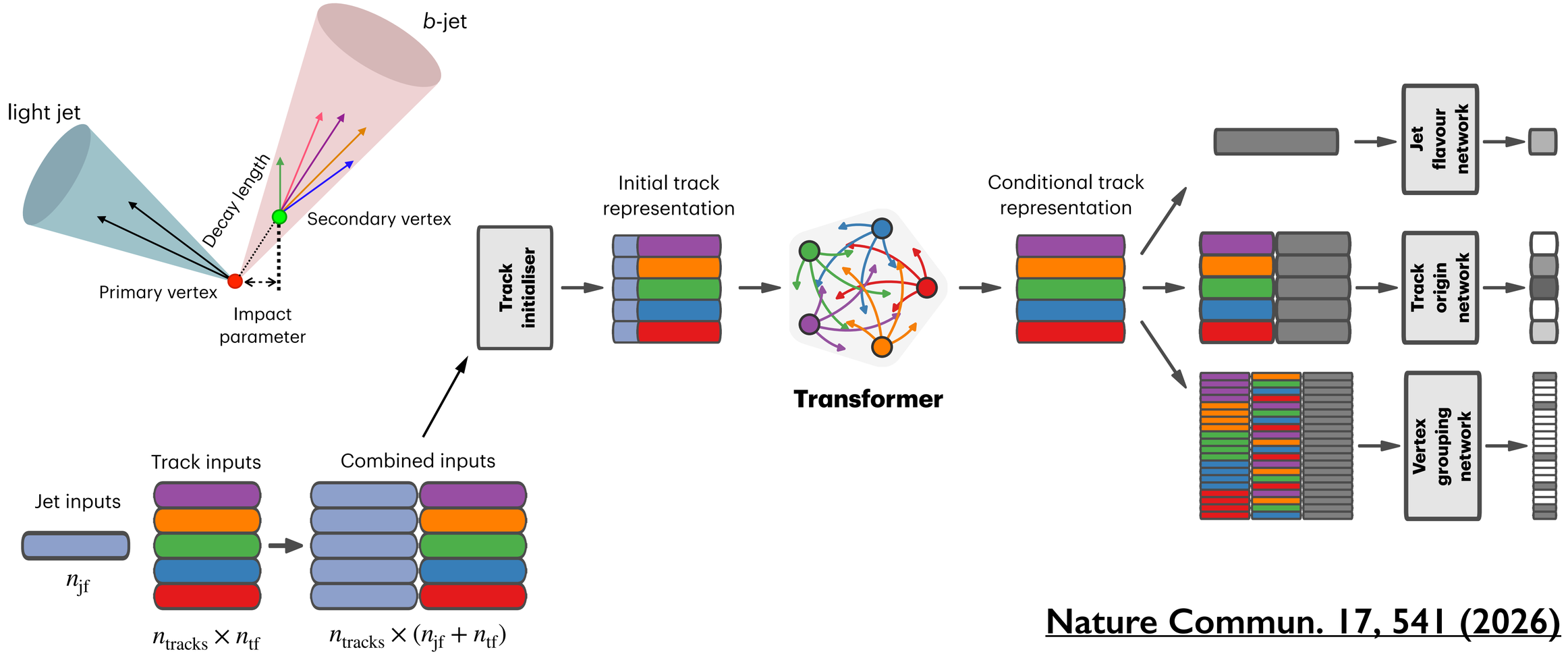
- Solid curve: the SM potential.
- Non-solid curves: alternative potentials at the limit of the variation of the shapes that could imply a strong first-order phase transition in the early universe.
- Red area ("HH driven"): the allowed range from the experimental precision on κ_3 on the third derivative of the potential, ignoring higher-order terms ($\kappa_i = 0$ with $i \geq 4$). Valid only around the minimum.
- Blue area: the allowed range in a dimension-6 EFT.



Jet Flavor Tagging at ATLAS



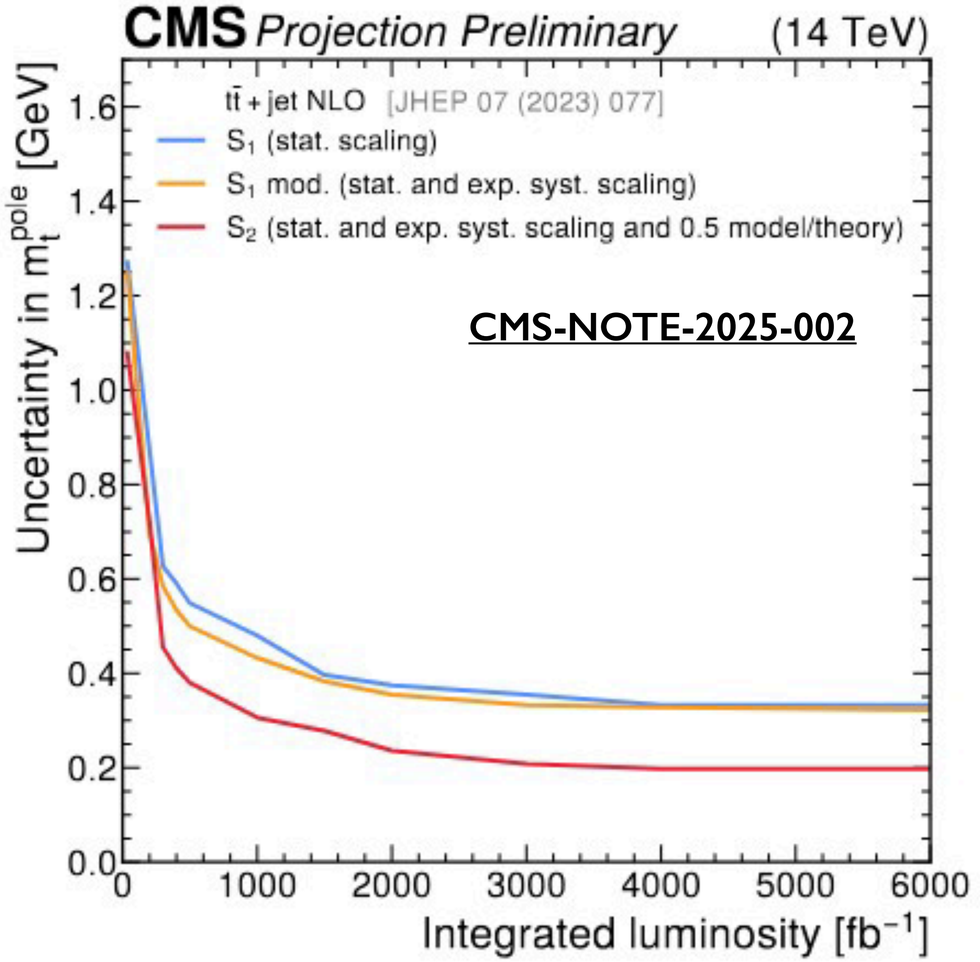
Jet Flavour Tagging with Transformer



Nature Commun. 17, 541 (2026)

Top Quark Mass

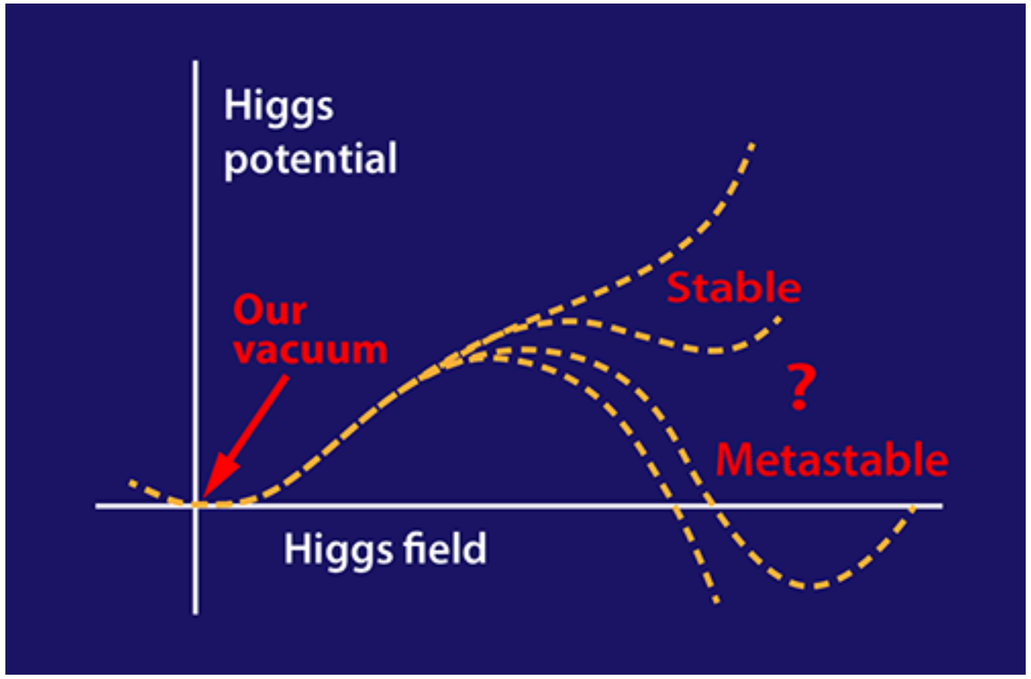
- **The HL-LHC will improve the precision of the top quark mass measurement.**
- **Numerous measurements employing different techniques at ATLAS and CMS, varying sensitivities to theoretical uncertainties**
- **Recent projection study using the differential cross section of the tt+jet production, from the dependence of the gluon radiation on the pole mass (see the right figure)**



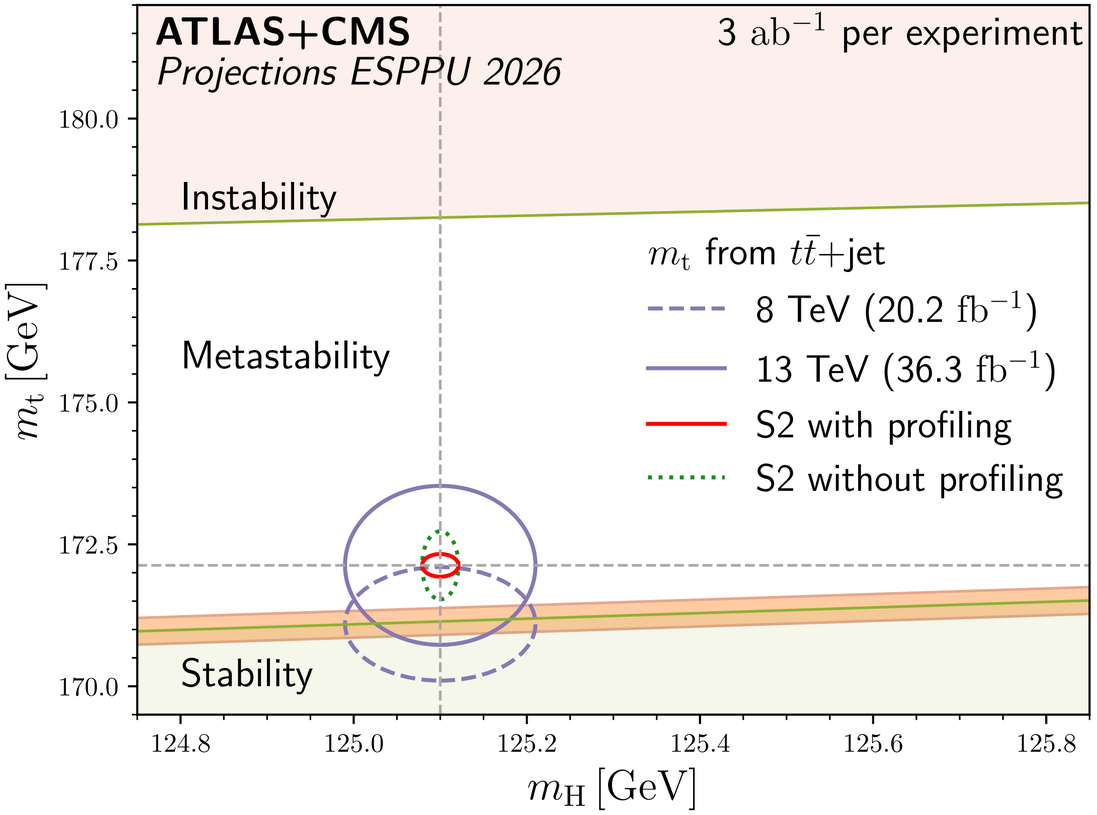
Electroweak Vacuum Stability

In the hypothesis that the SM is valid up to the Planck scale,

the values of m_H and m_t provide information on the stability or metastability of our universe.



APS/Alan Stonebraker, https://physics.aps.org/articles/v8/108



Depending on the central value of m_t, we may make a conclusive statement on the stability.