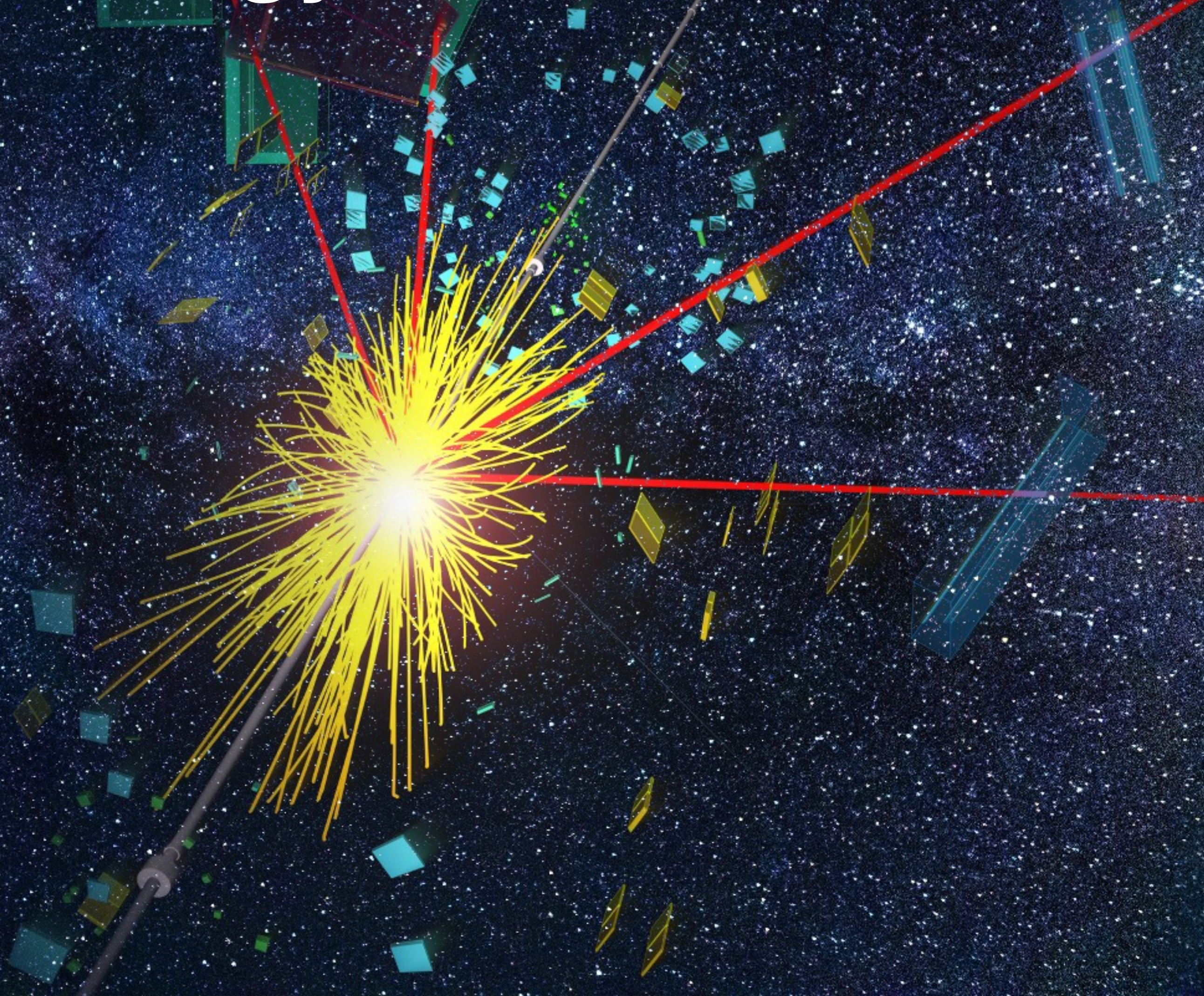
Status and prospects of the LHC — Physics at the High-Energy Frontier



Andreas Hoecker (CERN)

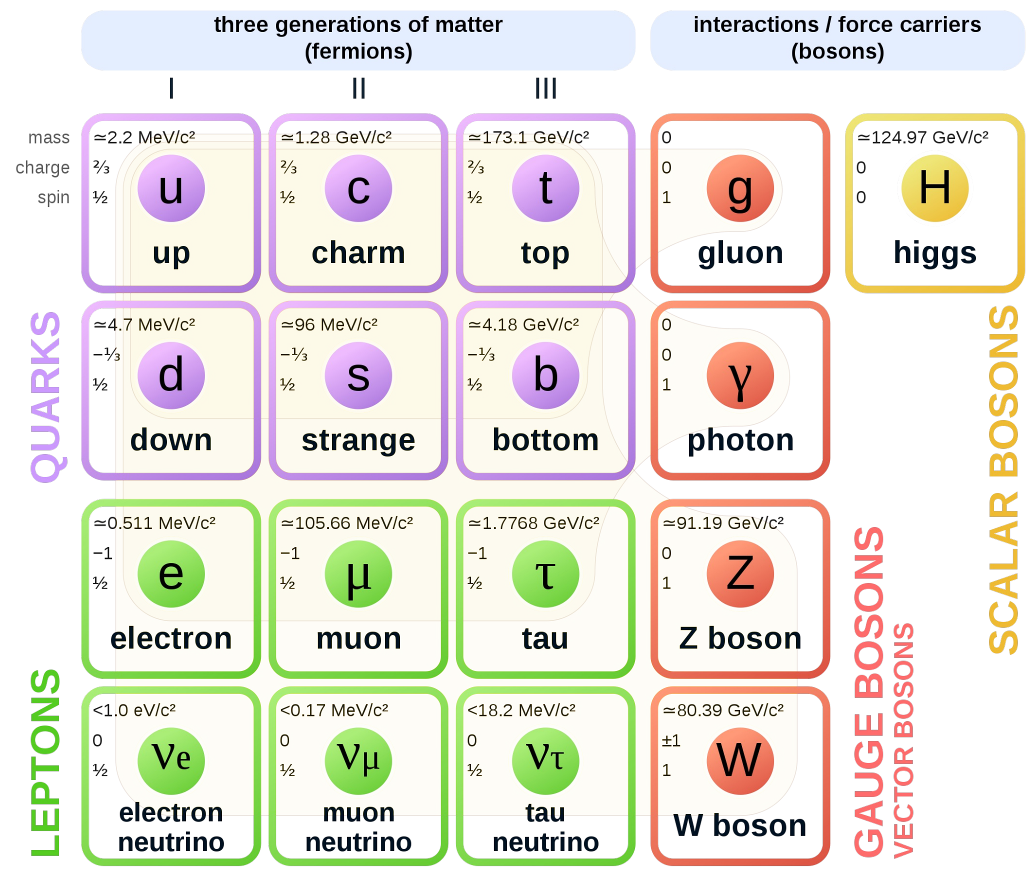
KMI2025 — 6th KMI International Symposium

Nagoya, March 5th, 2025

It’s all made of a handful of particles and forces

The sub-atomic structure of matter and its interactions **is described by the Standard Model**

Standard Model of Elementary Particles



Completely new type of non-universal interactions, nothing to do with known forces

Potential energy of the Higgs field:

$$V(\phi) = -\mu^2|\phi|^2 + \lambda|\phi|^4$$

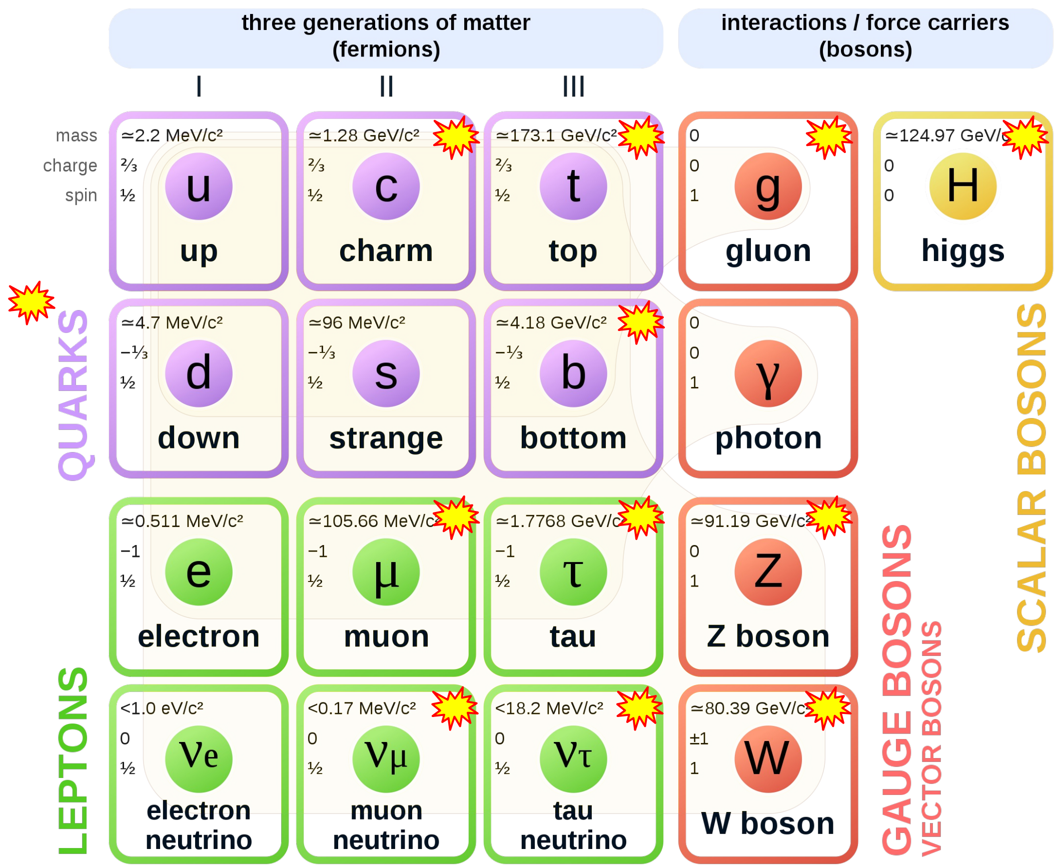
At lowest order (tree level)

It's all made of a handful of particles and forces

The sub-atomic structure of matter and its interactions **is described by the Standard Model**

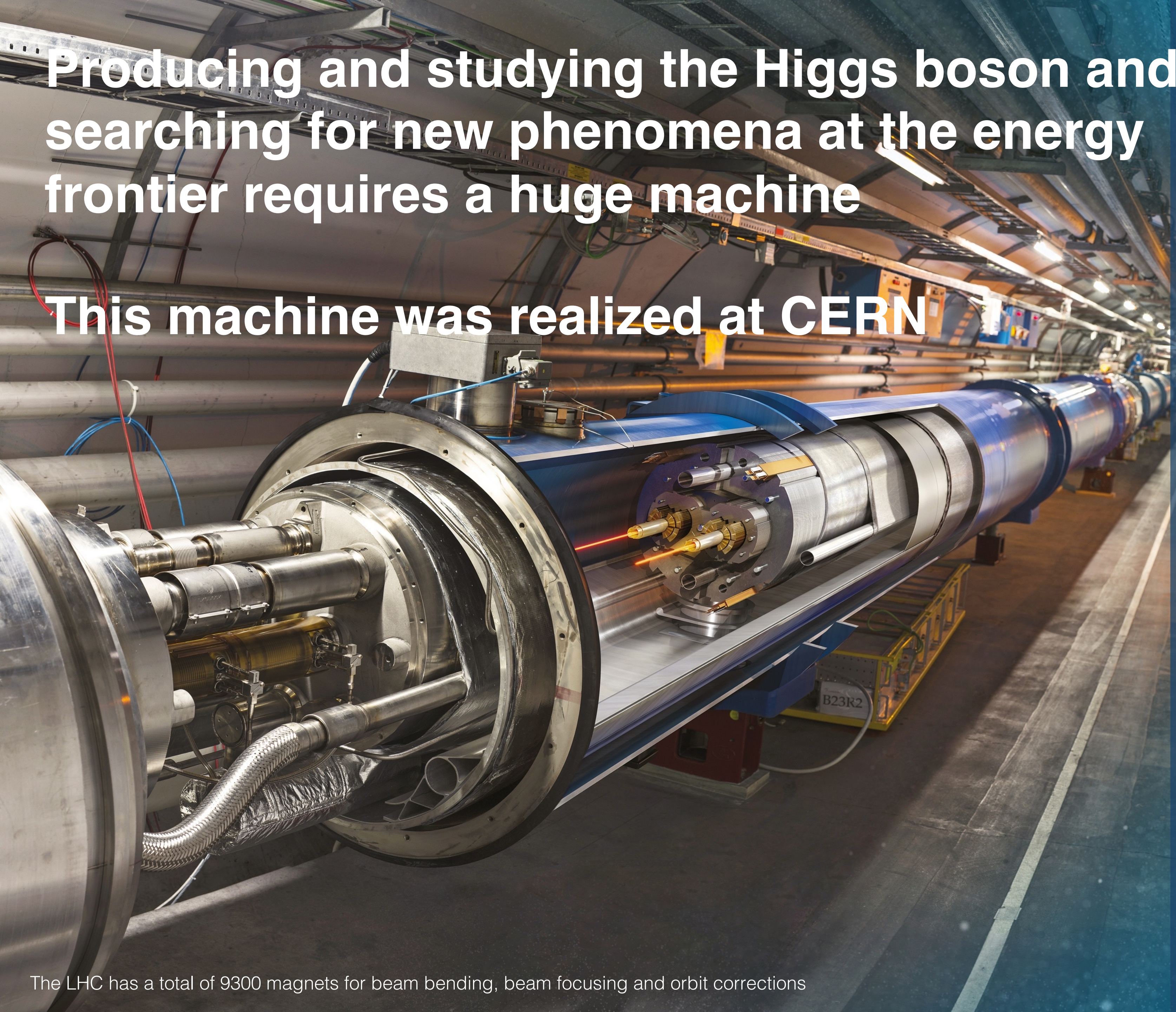
Decades of international high-technology **accelerator-based** research brought us thus far

Standard Model of Elementary Particles



Producing and studying the Higgs boson and searching for new phenomena at the energy frontier requires a huge machine

This machine was realized at CERN

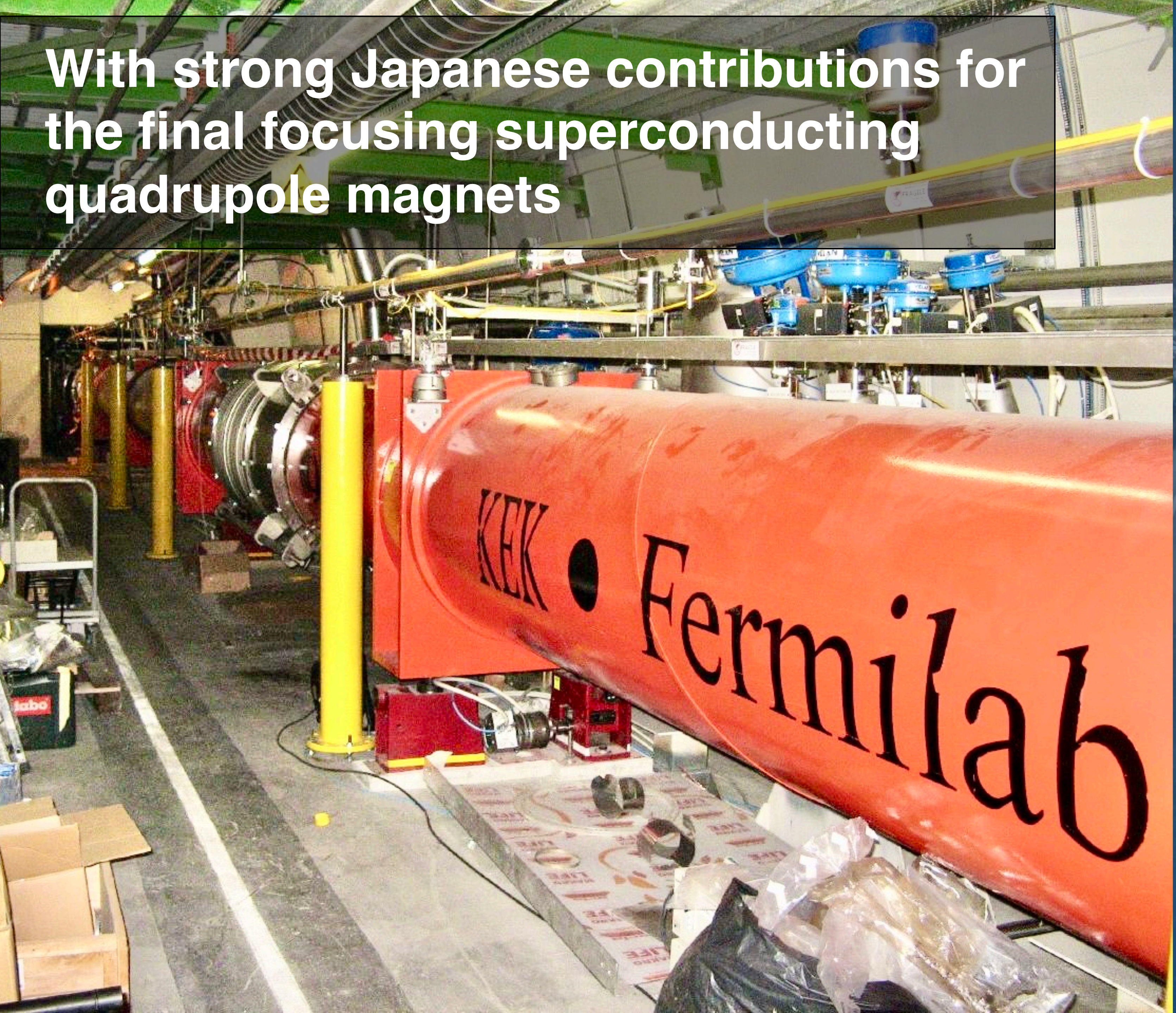


The LHC has a total of 9300 magnets for beam bending, beam focusing and orbit corrections

Large Hadron Collider (LHC)

- 27 km underground accelerator and collider
- Superconducting magnets (1.9 K = –271.3 °C) steer the particles around the ring
- Proton and ions are accelerated to multi-TeV scale energies before they collide

With strong Japanese contributions for the final focusing superconducting quadrupole magnets



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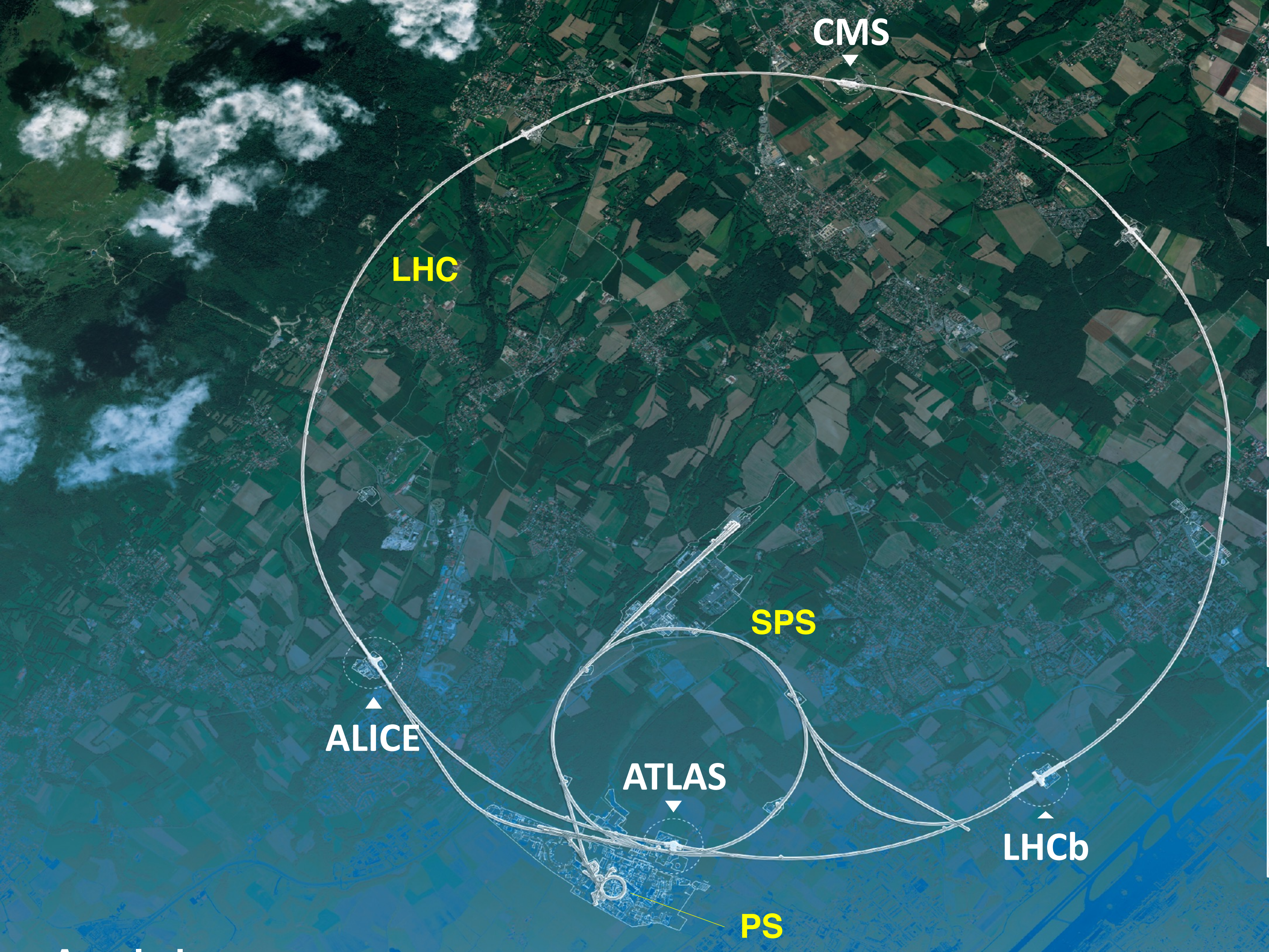
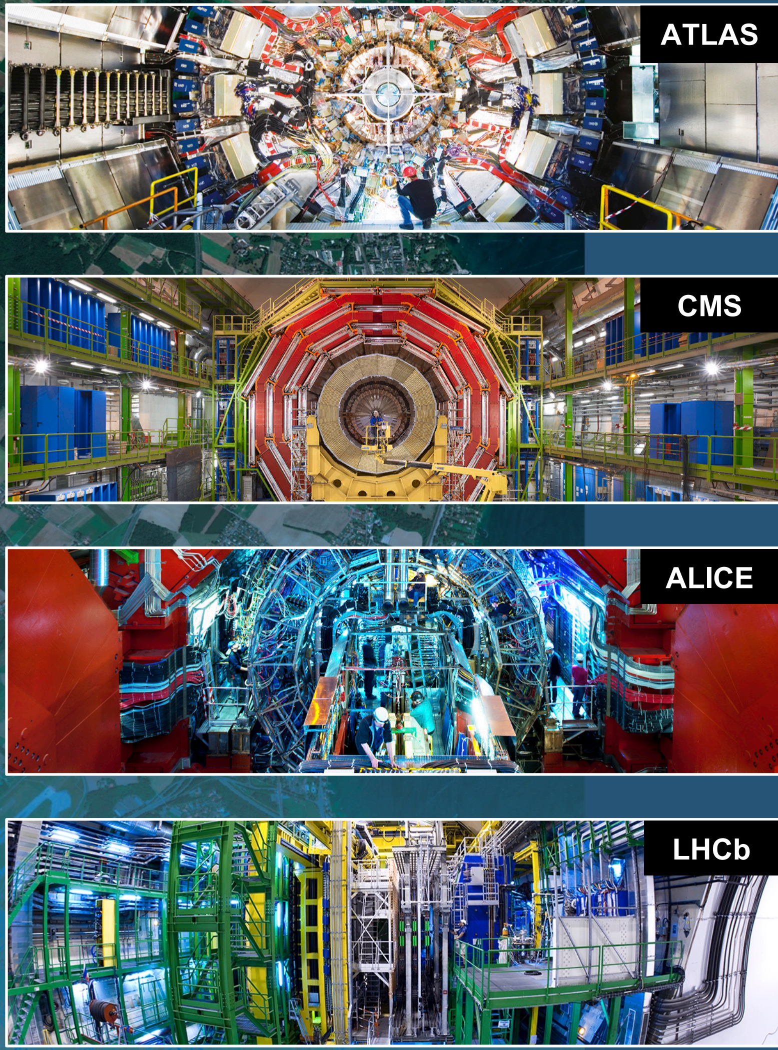
The Large Hadron Collider





Areal view

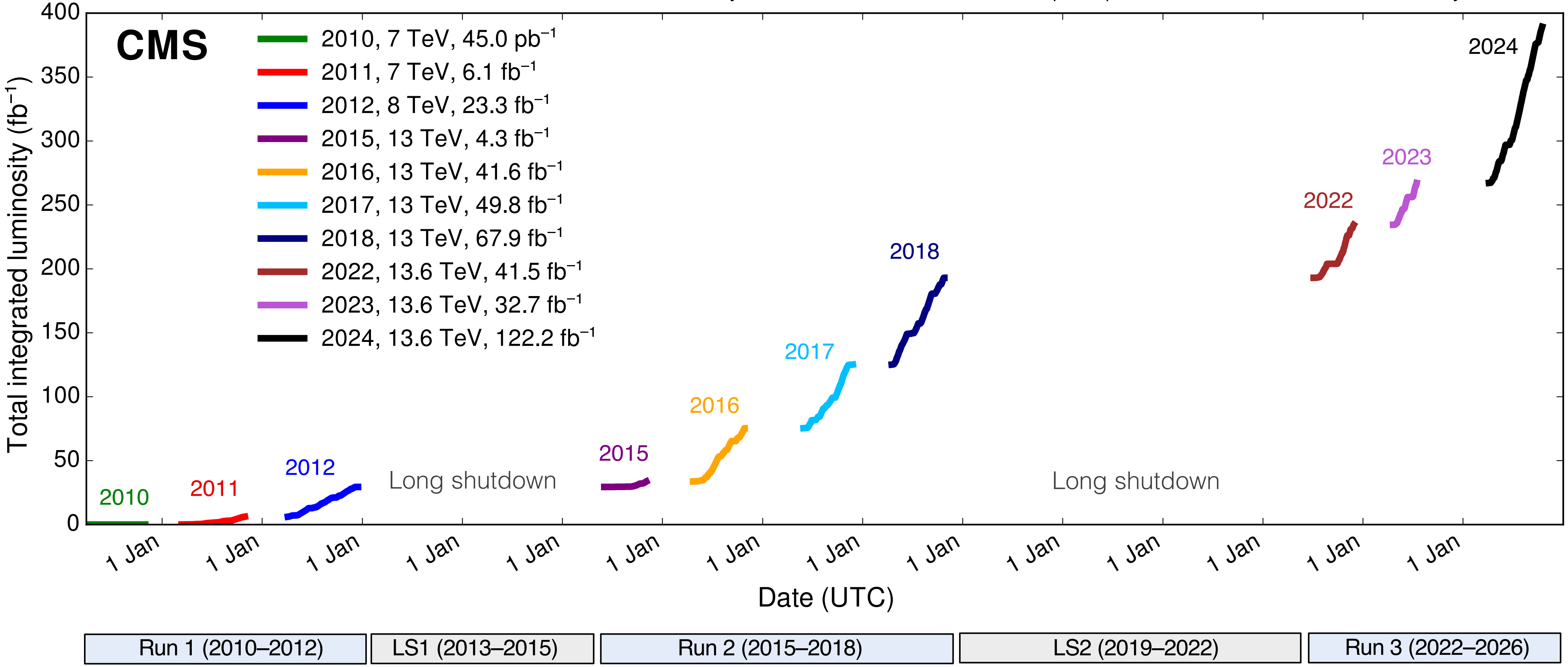
The Large Hadron Collider

CMS

PS

Superb performance of the LHC

Peak luminosity in 2024: 2.1 × 10^{34} $cm^{-2}s^{-1}$, pileup of 63, total delivered luminosity: 389 fb^{-1}

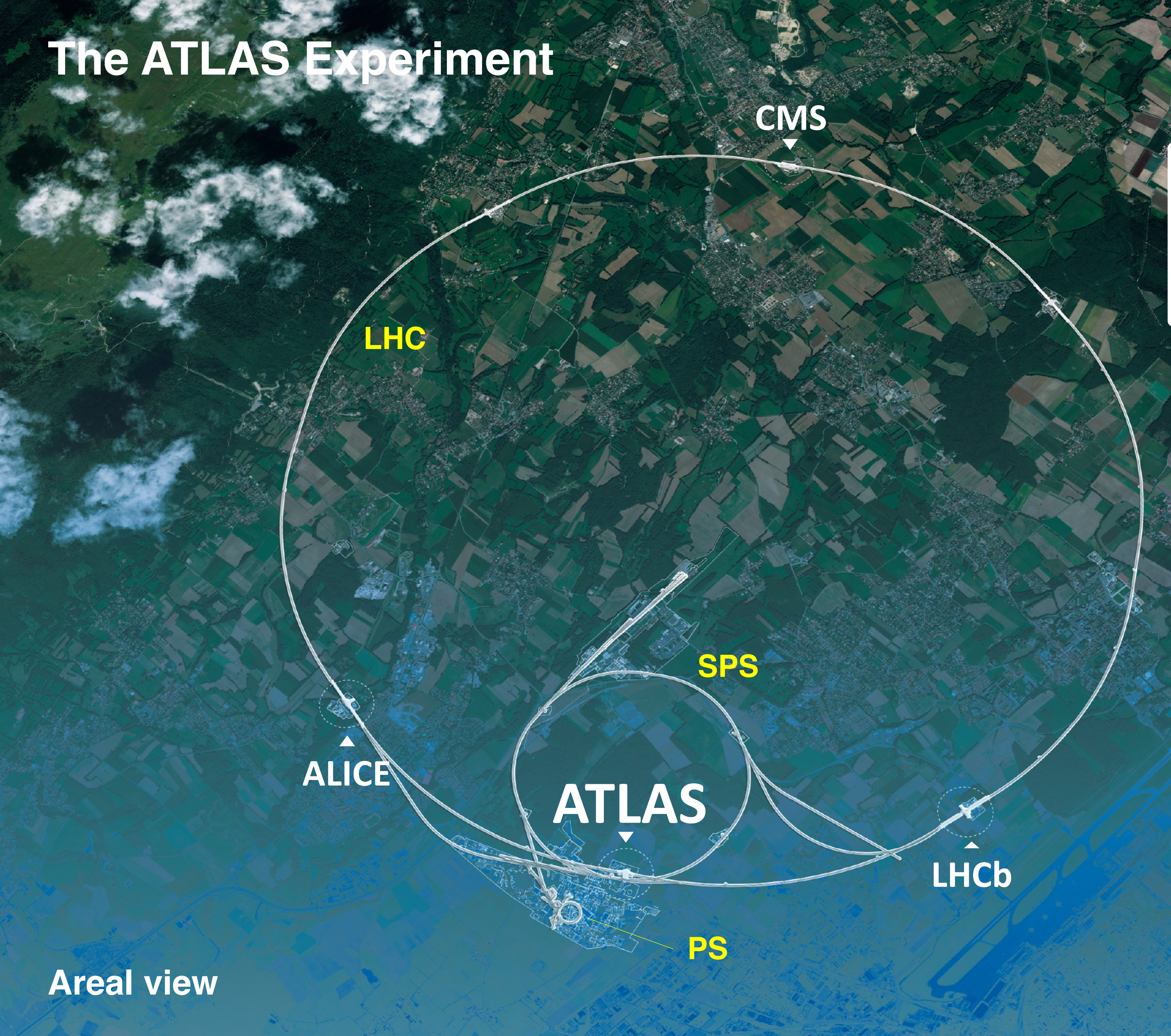


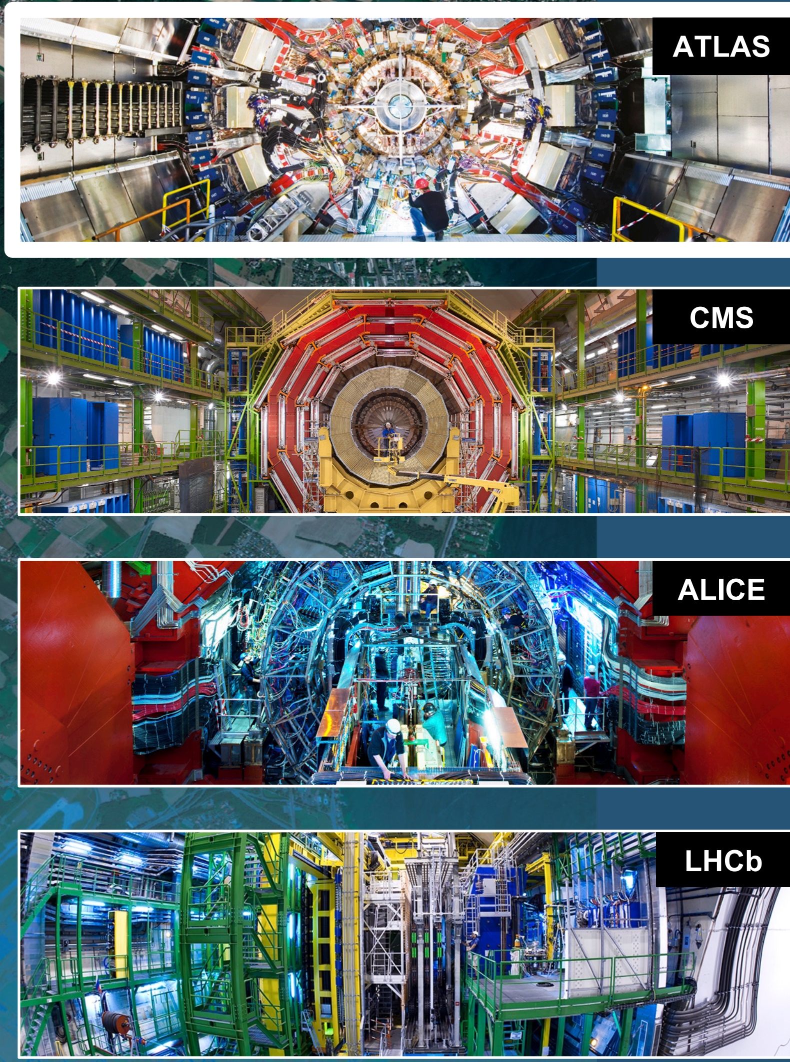
Areal view

LHC Control Room (July 2022)

ISR Control Room (early 70s)

The ATLAS Experiment

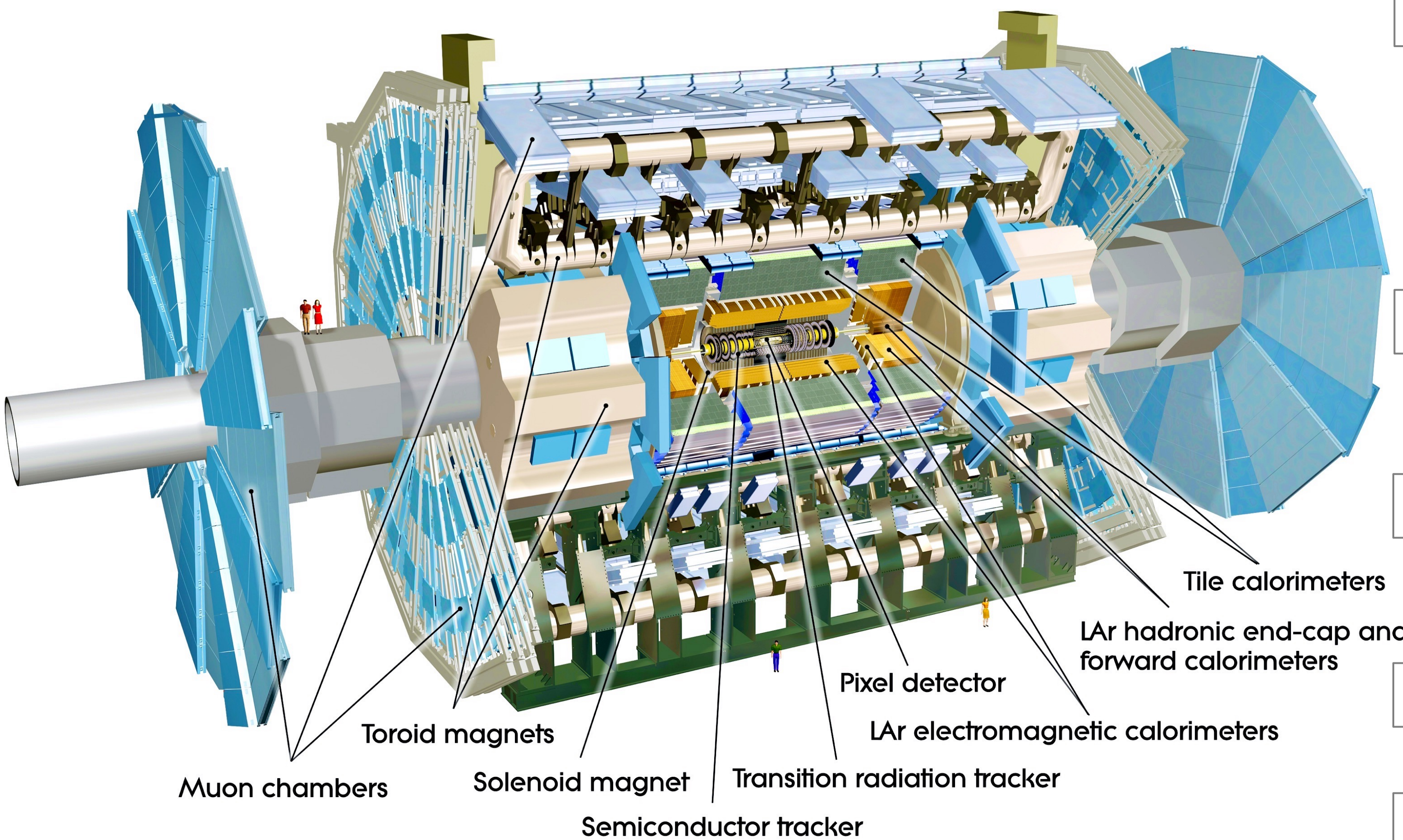





ATLAS Experiment

The ATLAS Detector

ATLAS EXPERIMENT



25 m diameter, 44 m long, 7000 tons weight

- High resolution silicon **detectors**:
  - 100 Mio. channels (50 μm x 250 μm)
  - 6 Mio. channels (80 μm x 12 cm)

  spatial resolution ~15 μm (in azimuthal direction)
- Axial field provided by **solenoid** (2 T) in central region (momentum measurement)
- Energy measurement down to 1° to the beam line with a **calorimeter system**
- Independent **muon spectrometer** (superconducting toroid magnet system)
- **Ultra-fast custom electronics and high-performance computers filter** the collisions: only 1 out of 20,000 collisions is kept

The ATLAS Collaboration

ATLAS is a multi-decade experimental programme involving:

- 242 institutes from 40 countries + 16 Technical Associate Institutes
- 2900 Scientific authors, 1200 Physics PhD students, 1300 Engineers or technicians, 100 Engineering students, 6000 Active members

Japan is a founding member of ATLAS

- 13 institutes, among which the Kobayashi-Maskawa Institute, Nagoya
- 183 members, 30 PhD students
- Huge contributions to detector construction, operation, upgrade (also from Japanese industry), and to ATLAS physics results

Links: ATLAS public home page, Physics results, Interactive ATLAS world map, Static world maps, List of ATLAS institutes

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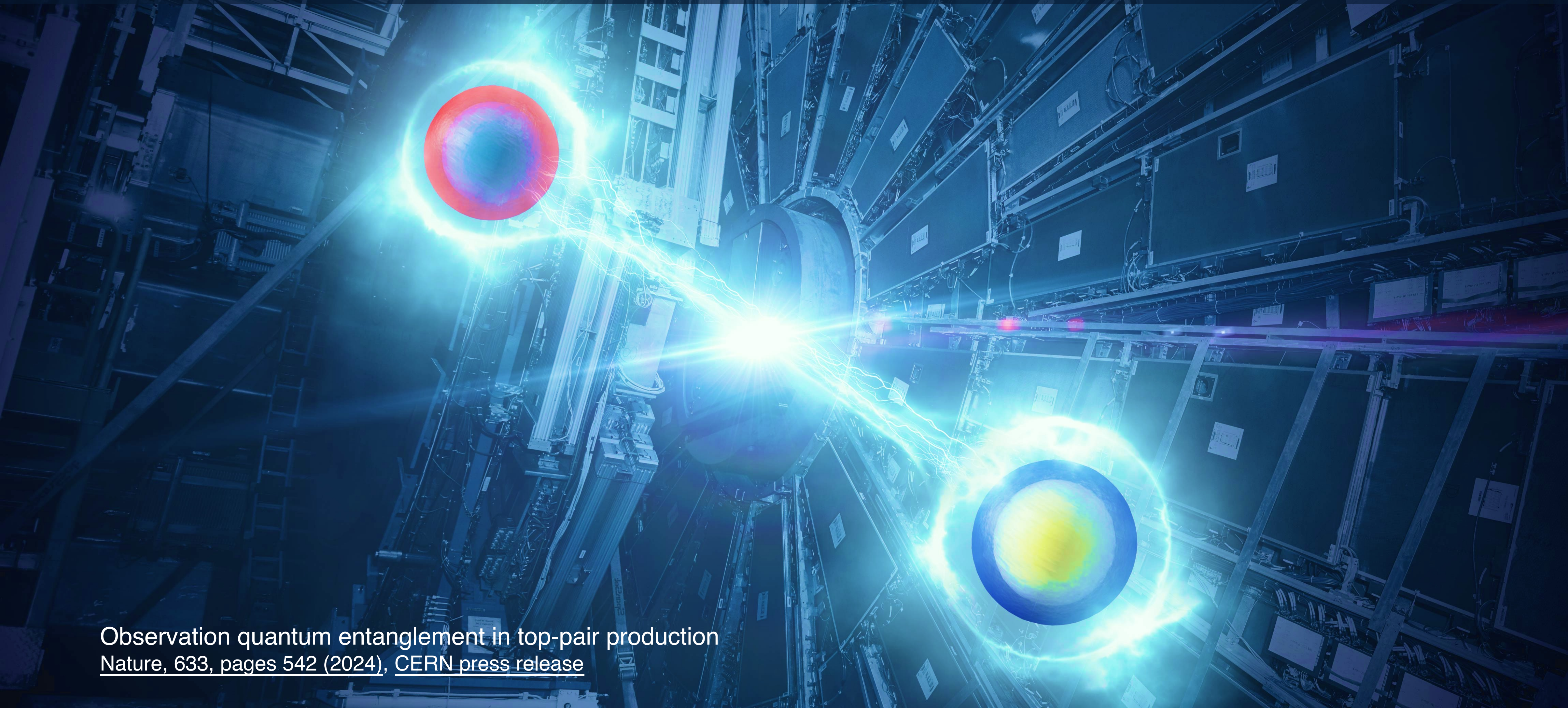
Solenoid built from 4 coils welded together to give a single coil: 1159 turns, 5.3 m long, 1.25 m radius, 7600 A to produce axial field of 2 T at its centre

Insertion of Solenoid into barrel LAr calorimeter cryostat (by Kawasaki HI)


ATLAS
EXPERIMENT
CERN

Physics results

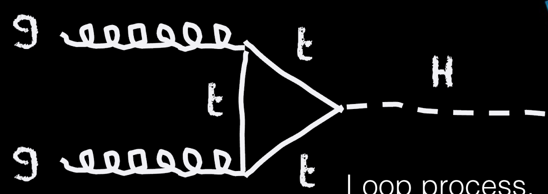
High-energy proton collisions enable an exceptionally broad physics program covering (almost) the full breadth of particle physics. ATLAS and CMS have each released more than 1350 papers



Observation quantum entanglement in top-pair production
Nature, 633, pages 542 (2024), CERN press release

Higgs boson Physics

About 1 Higgs boson per second is produced in ATLAS at the LHC (about 20M total by today), mostly through gluon fusion

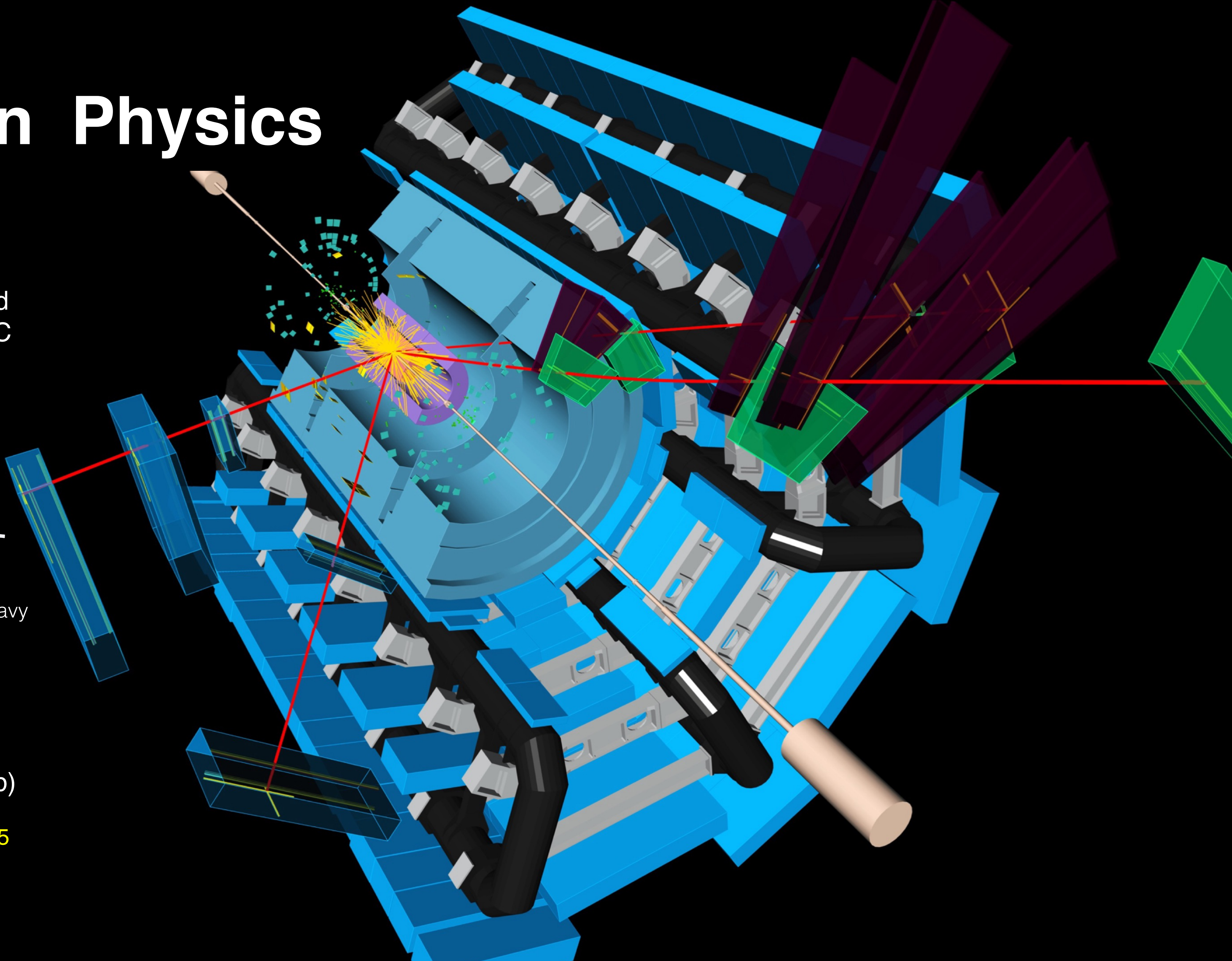


(88% of H production)

Loop process, sensitive to heavy new particles

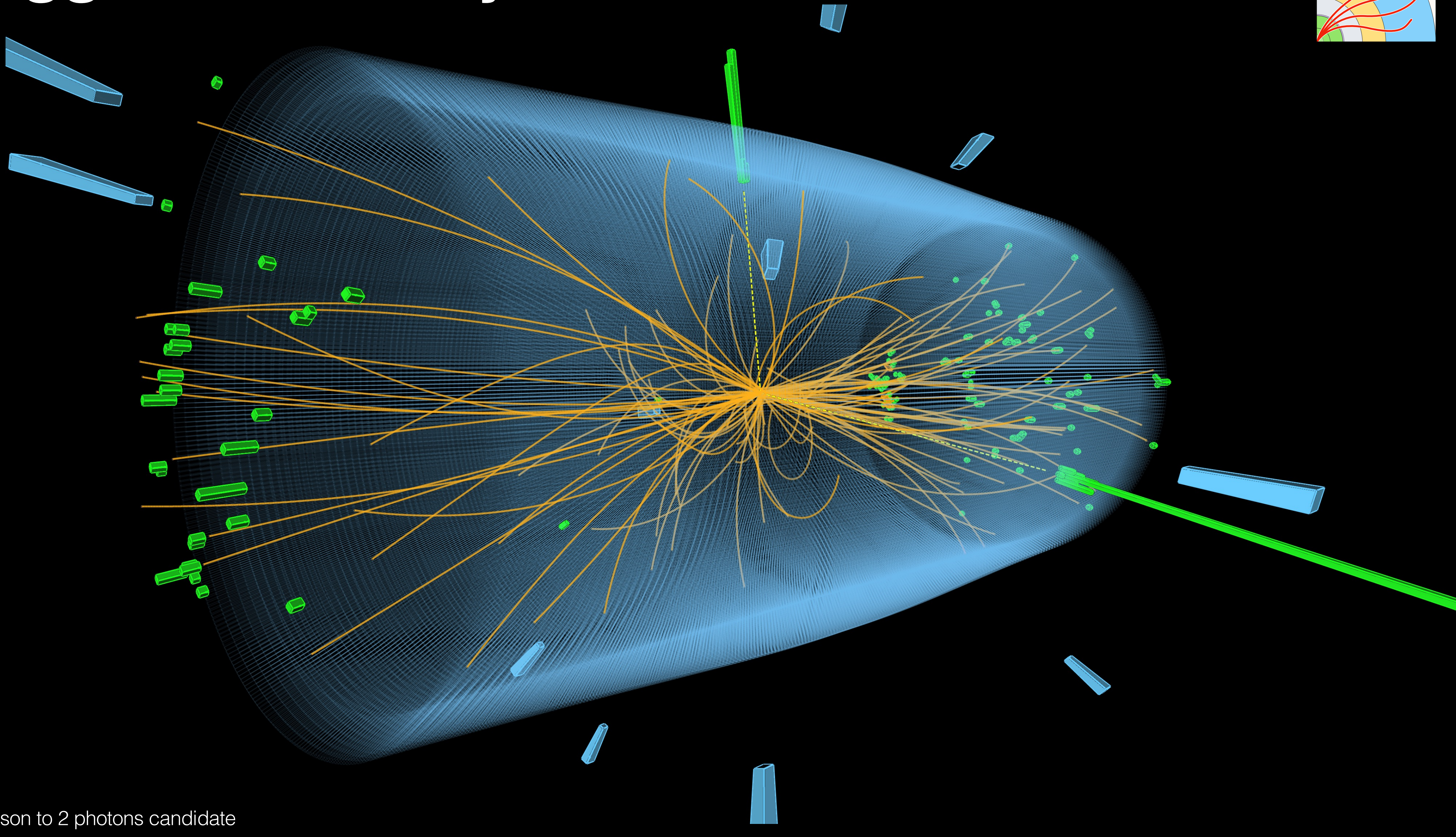
As the Higgs boson couples to mass, it decays predominantly into heavy particles (58% into bb)

→ Shota Izumiyama's talk at KMI2025



A Higgs boson to 4μ candidate event

Higgs boson Physics



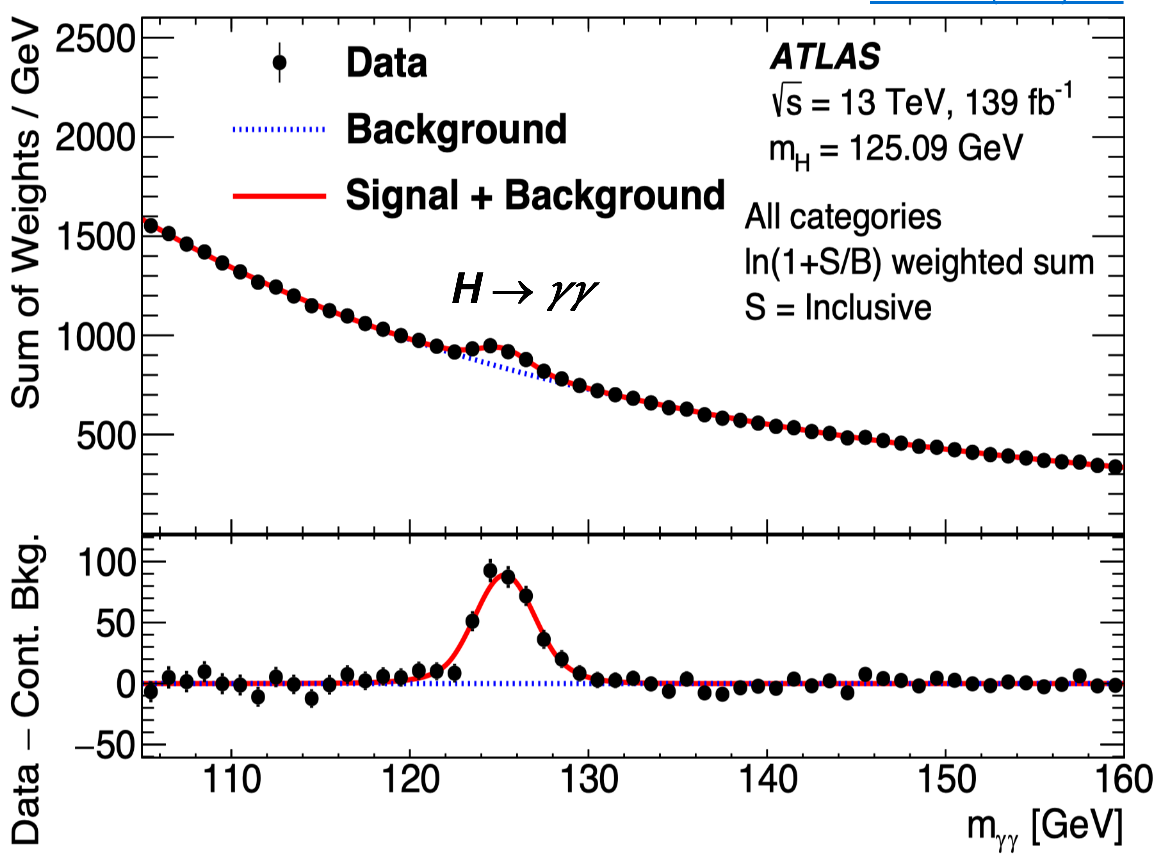
A Higgs boson to 2 photons candidate

The Higgs boson — At 10

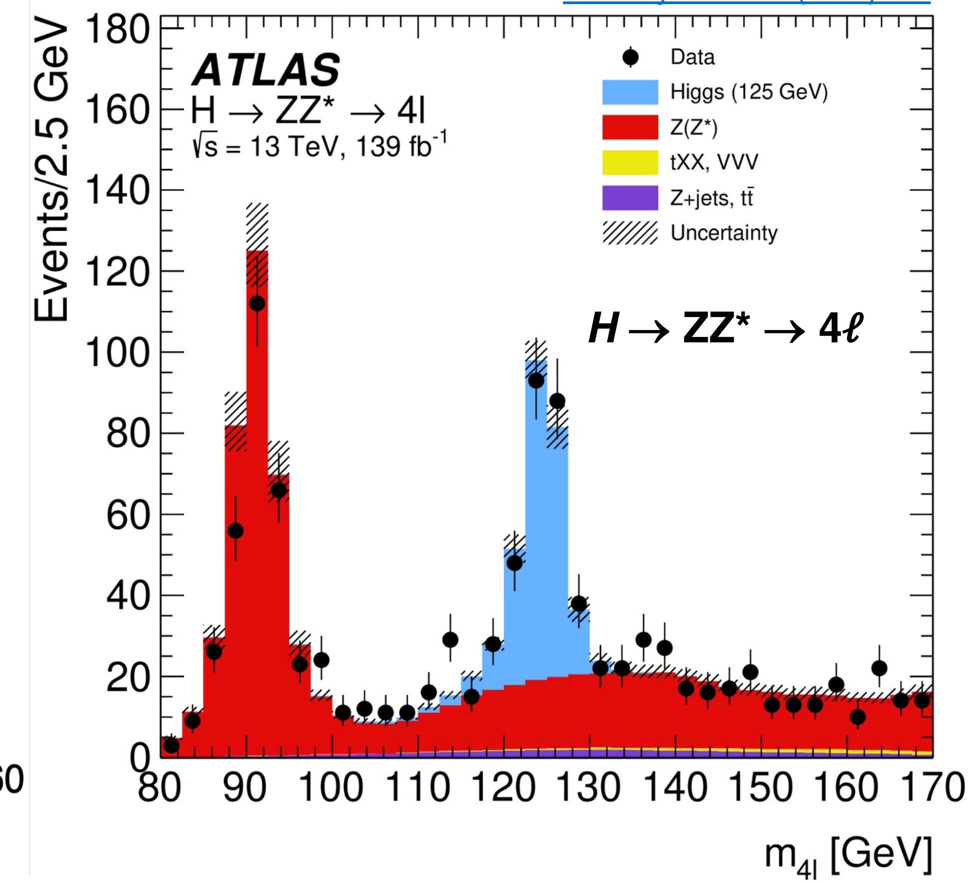
ATLAS EXPERIMENT

2020

JHEP 07 (2023) 088



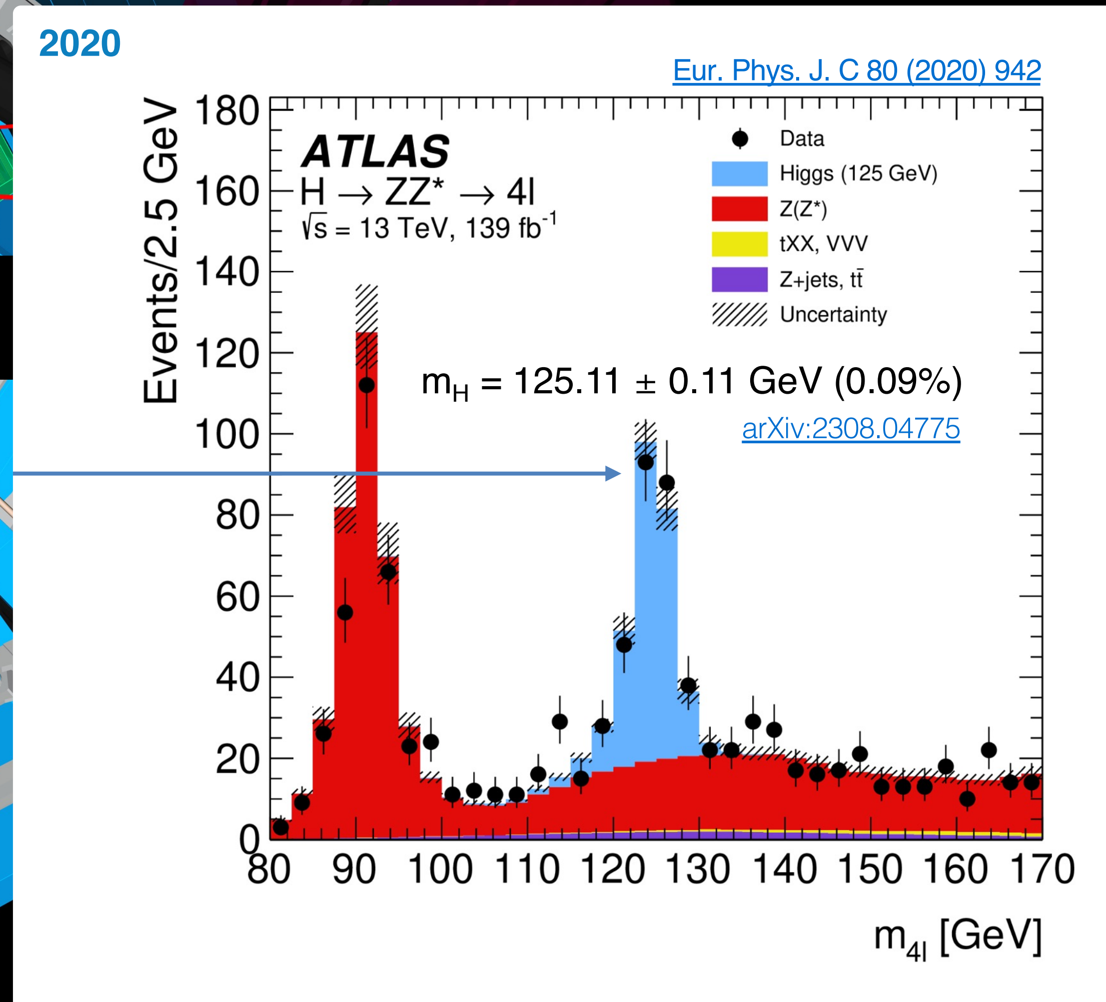
Eur. Phys. J. C 80 (2020) 942



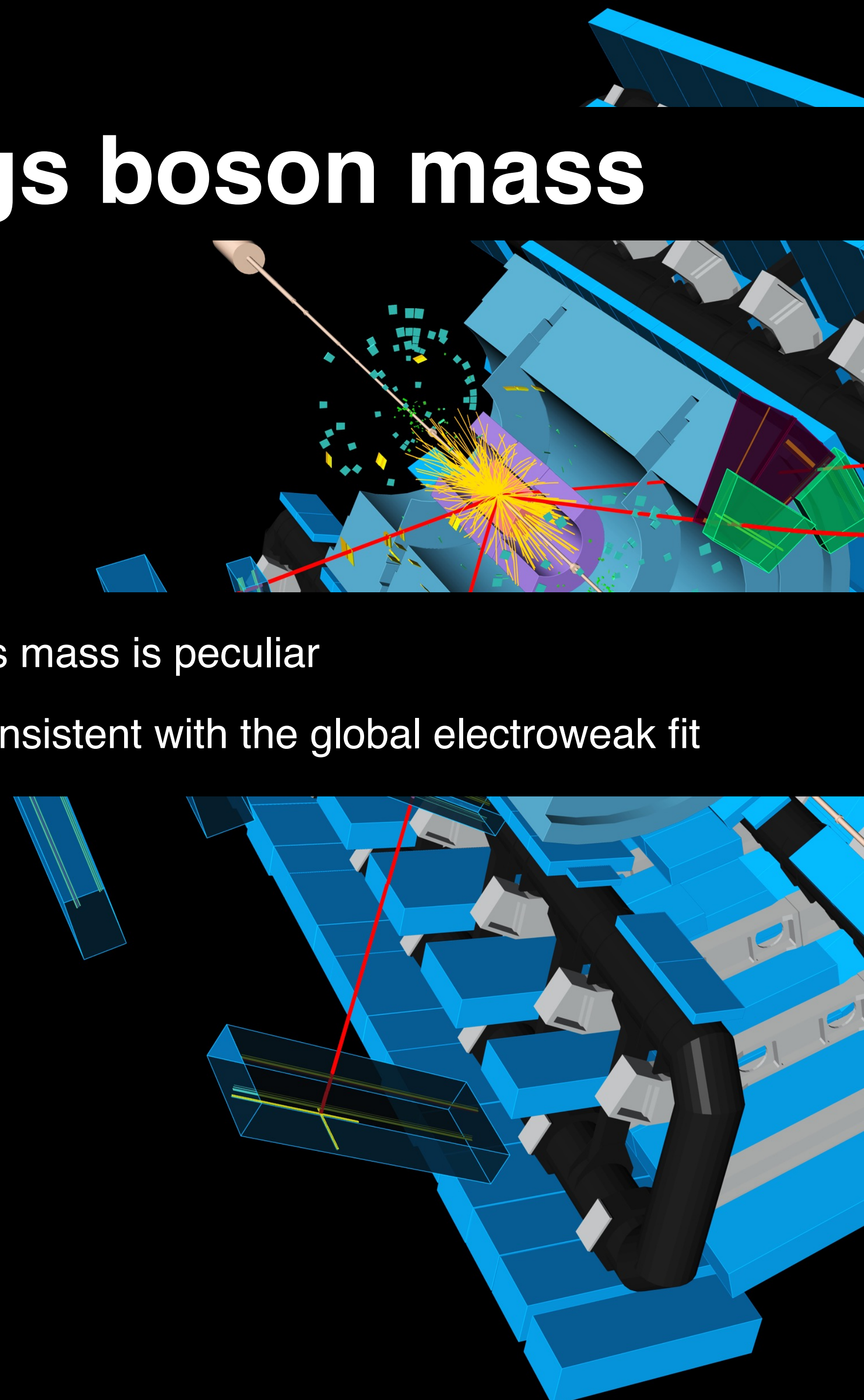
Higgs boson mass

ATLAS EXPERIMENT

The Higgs mass is peculiar



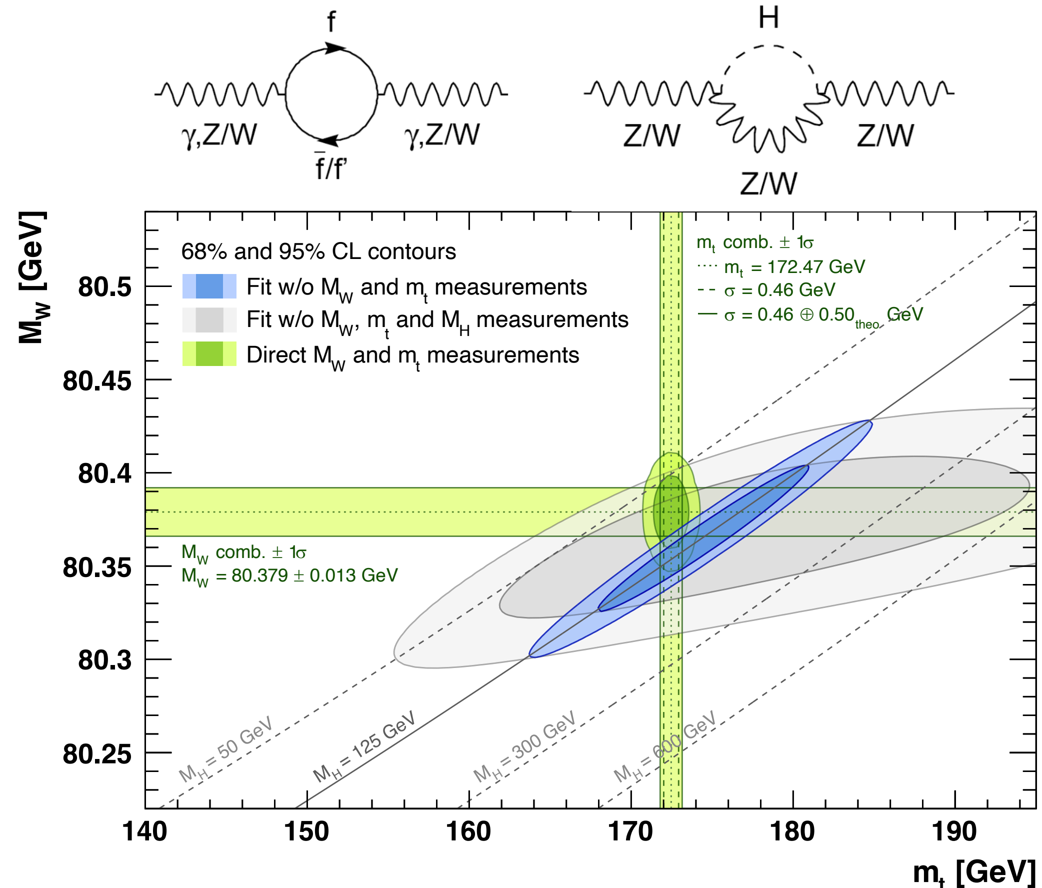
Higgs boson mass



The Higgs mass is peculiar

- It is consistent with the global electroweak fit

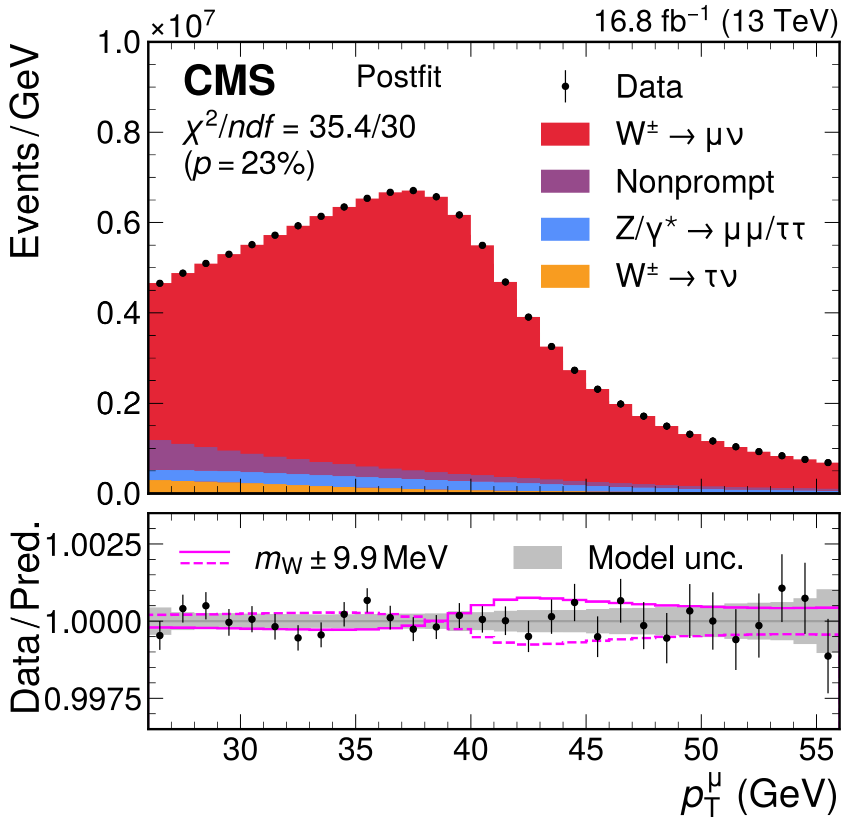
Radiative corections sensitive to heavy particles in loop

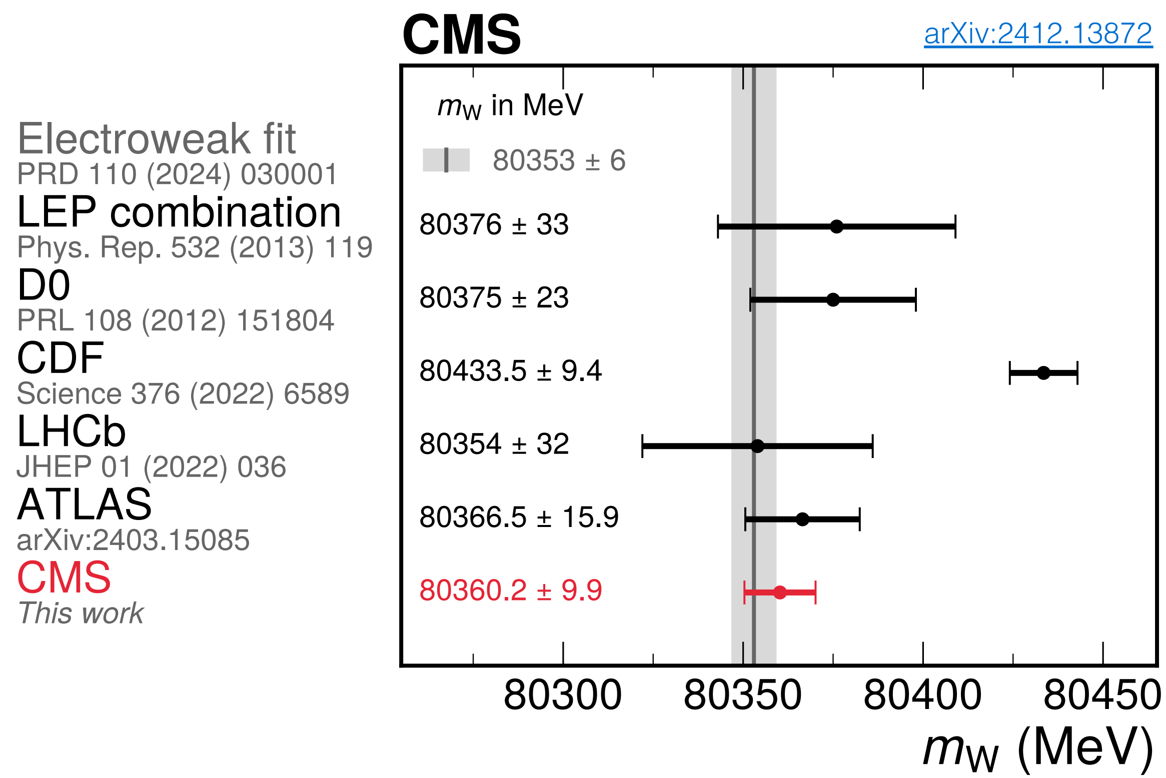


Gfitter Group: arXiv:1803.01853

W mass

Recent CMS W mass meaurement from constrained profile likelihood fit to lepton p_T distribution

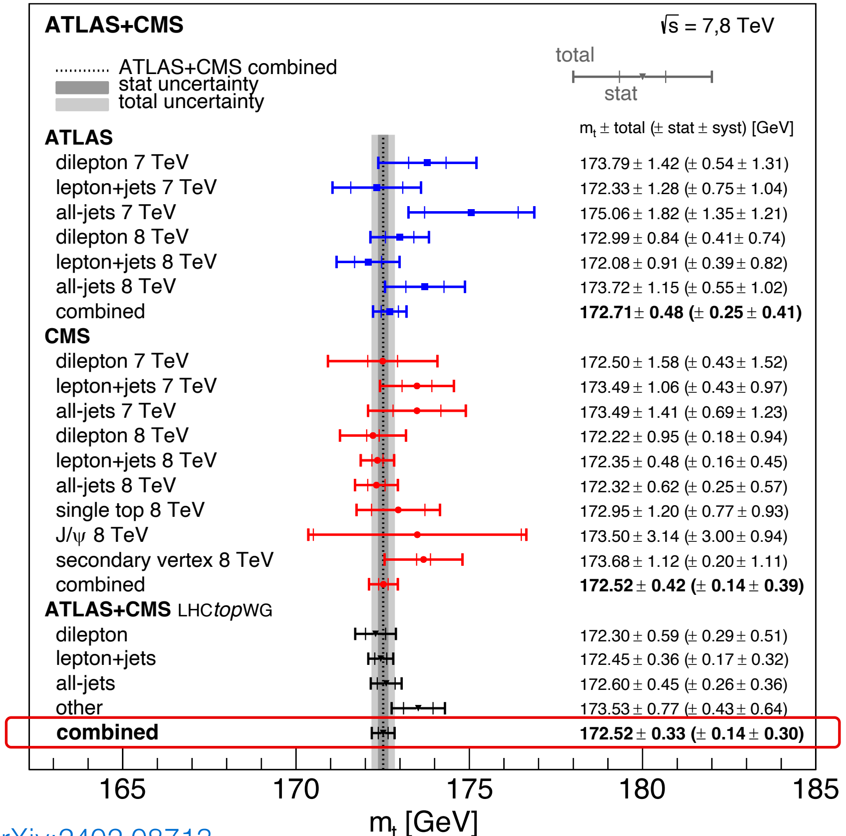




Top mass and strong coupling strength

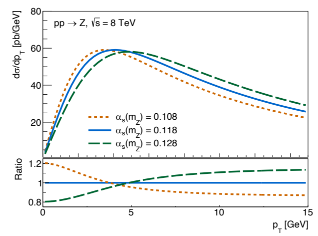
Combination of Run-1 ATLAS and CMS top mass measurements: 0.19% relative precision

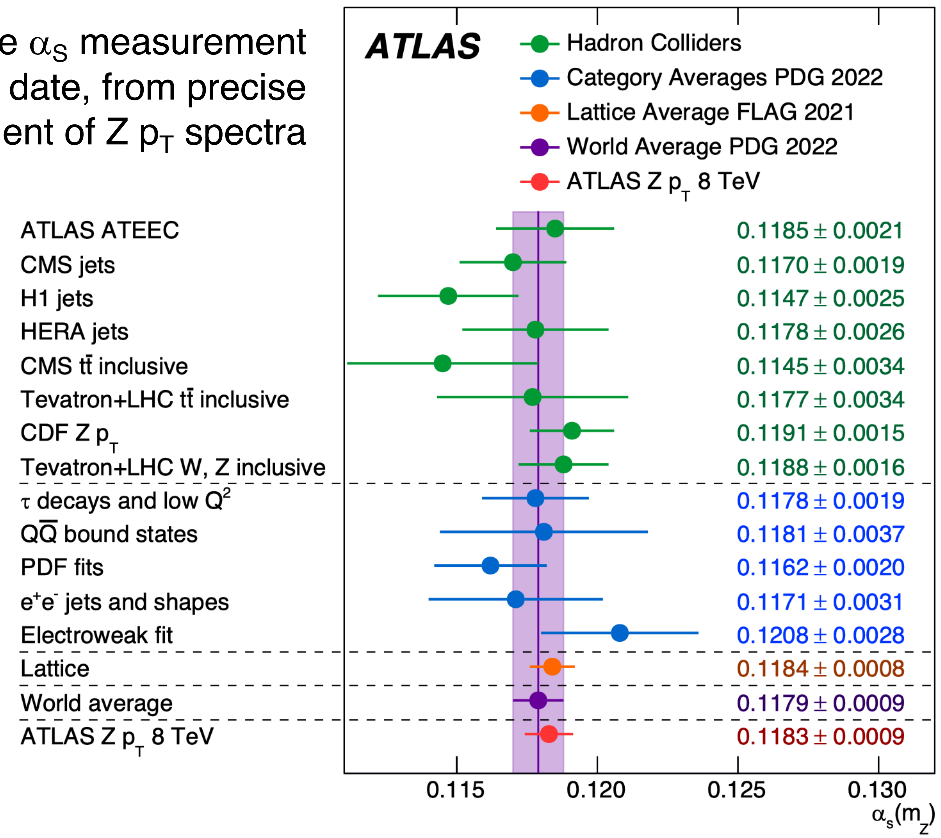
arXiv:2309.12986



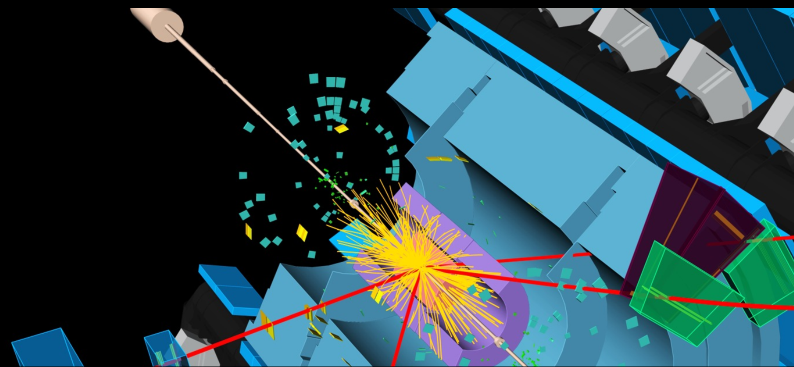
arXiv:2402.08713

Most precise α_S measurement to date, from precise measurement of Z p_T spectra





Higgs boson mass



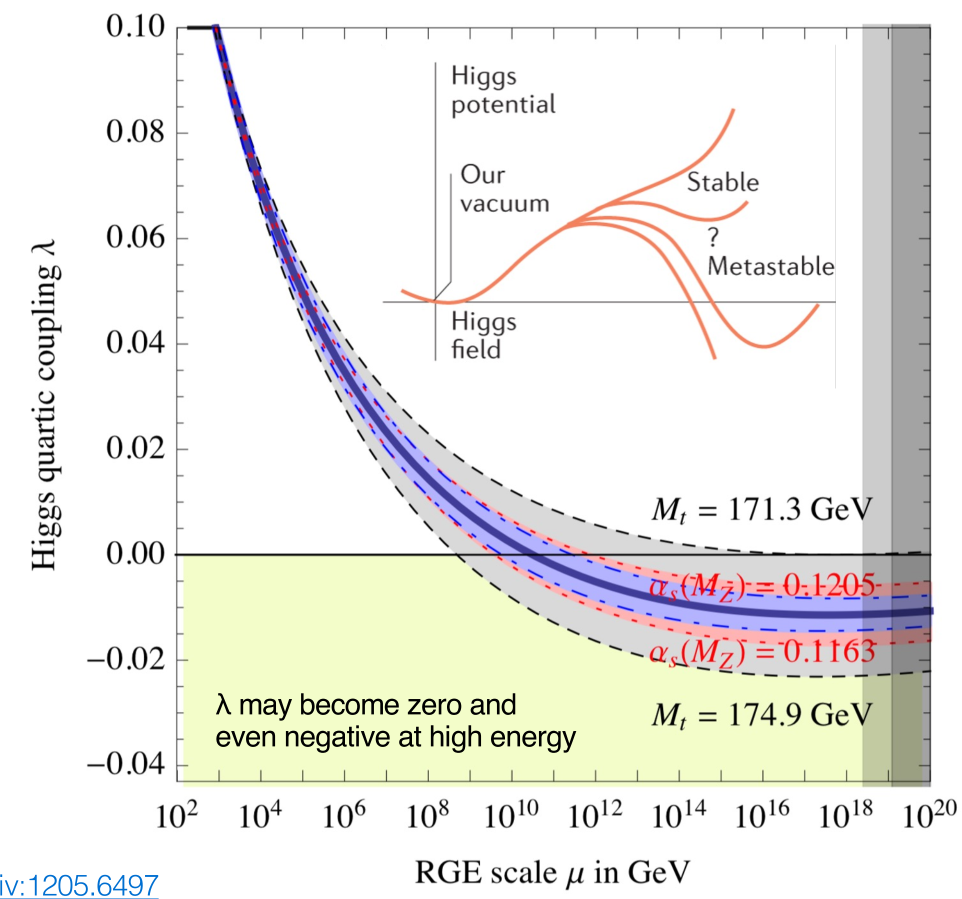
The Higgs mass is peculiar

- It is consistent with the global electroweak fit
- But the electroweak vacuum seems to be metastable

$$V(\phi) = -\mu^2|\phi|^2 + \lambda|\phi|^4$$

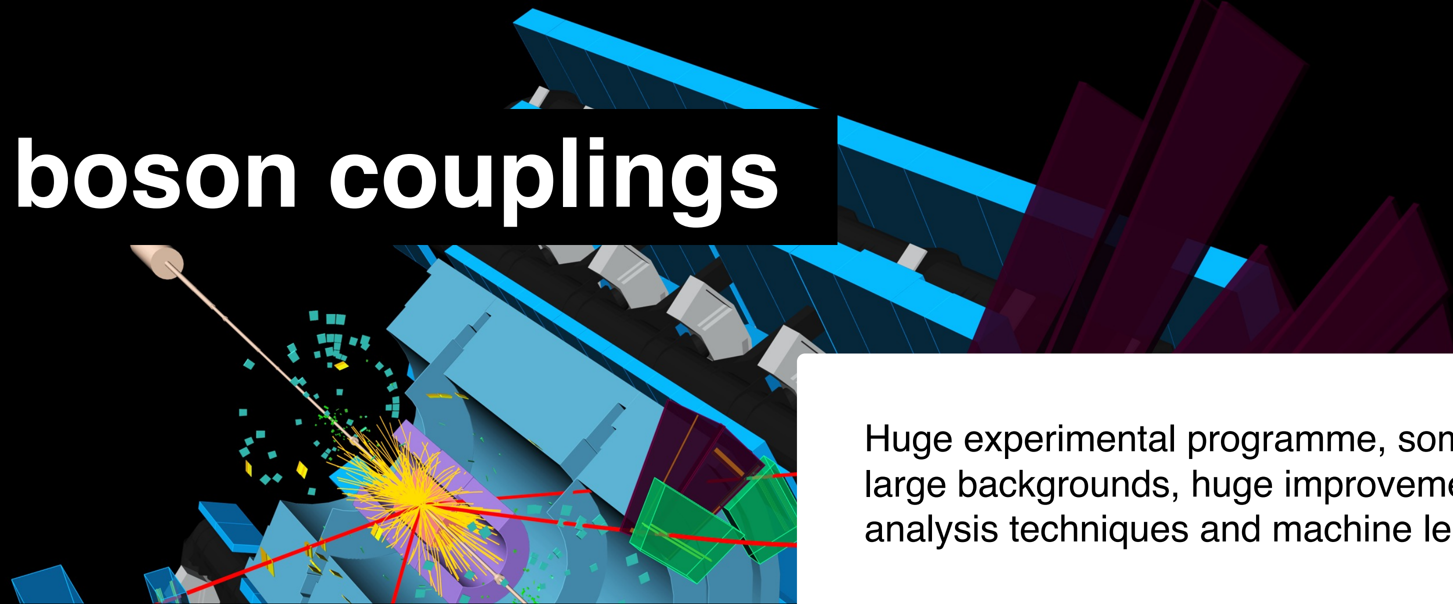
where: $\lambda(\mu) = \frac{m_H^2}{2v^2} + \delta\lambda(\mu)$

Evolution of the Higgs quartic coupling, assuming SM (only)



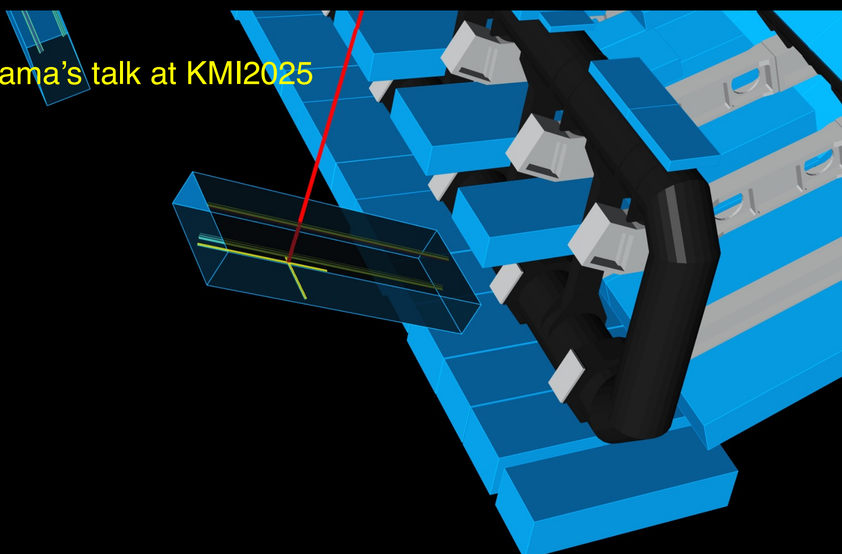
arXiv:1205.6497

Higgs boson couplings



The Higgs boson couplings to the SM particles are experimentally determined by measuring cross-sections of all accessible Higgs boson production and decay modes

→ Shota Izumiyama's talk at KMI2025



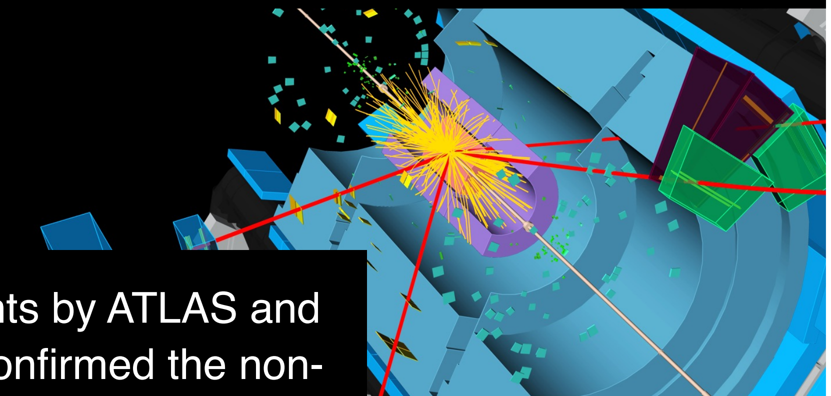
Huge experimental programme, some channels suffer from large backgrounds, huge improvements from smart analysis techniques and machine learning

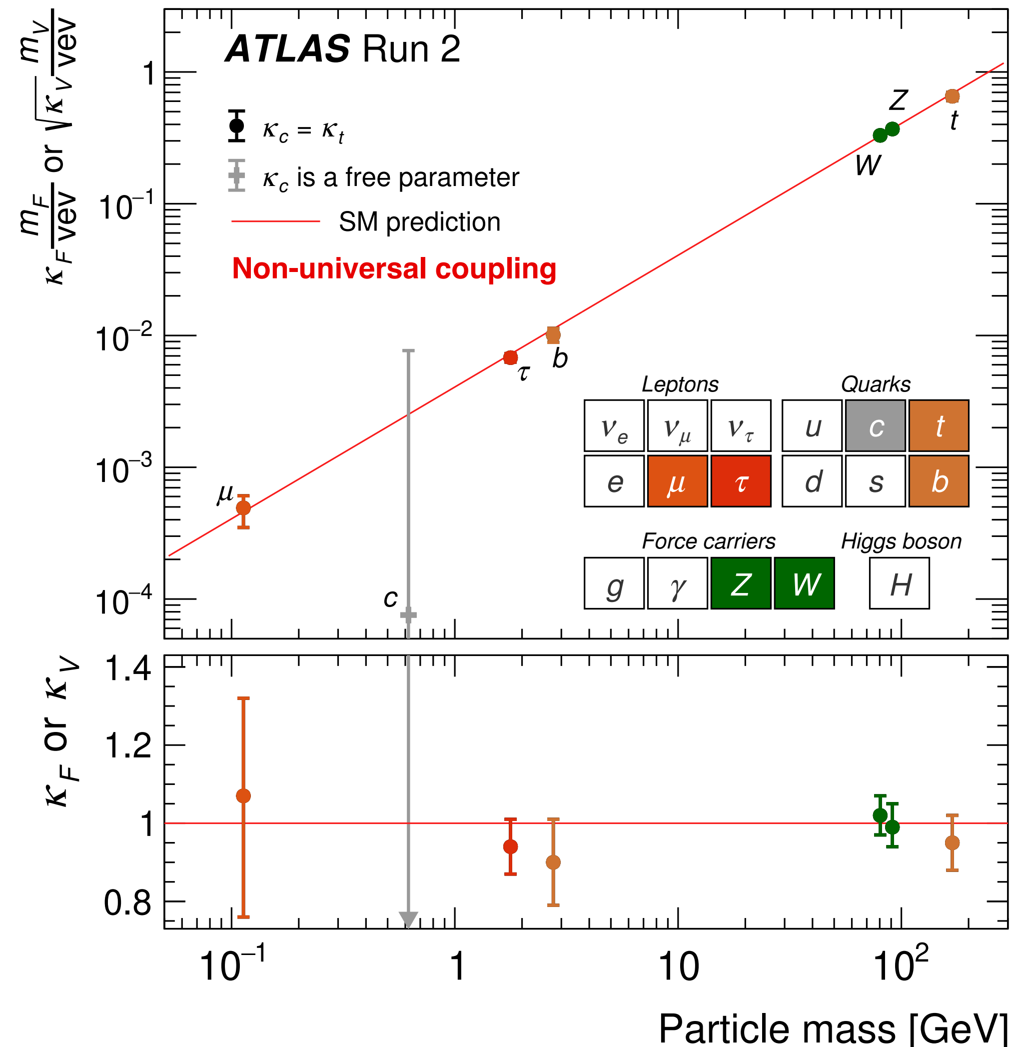
Channel categories	BR	ggF	VBF	VH	ttH
Cross Section (13 TeV)		48.6 pb	3.8 pb	2.3 pb	0.5 pb
γγ	0.2 %	✓	✓	✓	✓
ZZ	2.6%	✓	✓	✓	✓
WW	21%	✓	✓	✓	✓
ττ	6.3 %	✓	✓	✓	✓
bb	58%	✓	✓	✓	✓
Zγ (& γγ*)	0.2 %	✓	✓	✓	✓
μμ	0.02 %	✓	✓	✓	✓

In grey: evidence for decays, but not observed yet

The Higgs mechanism is real !

Measurements by ATLAS and CMS have confirmed the non-universal, mass-dependent coupling strengths of the Higgs boson to the SM particles





Nature 607, 52 (2022)

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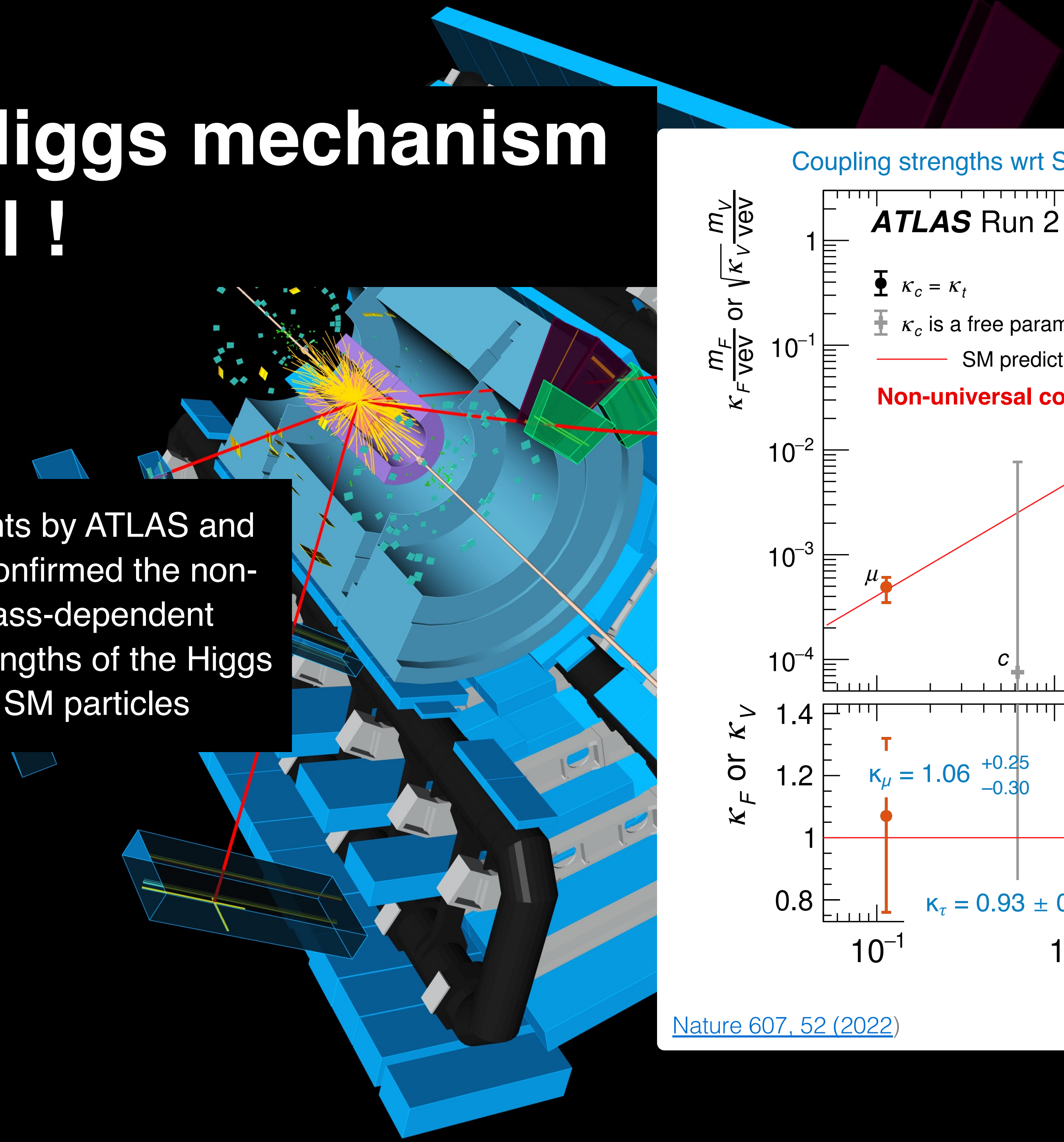
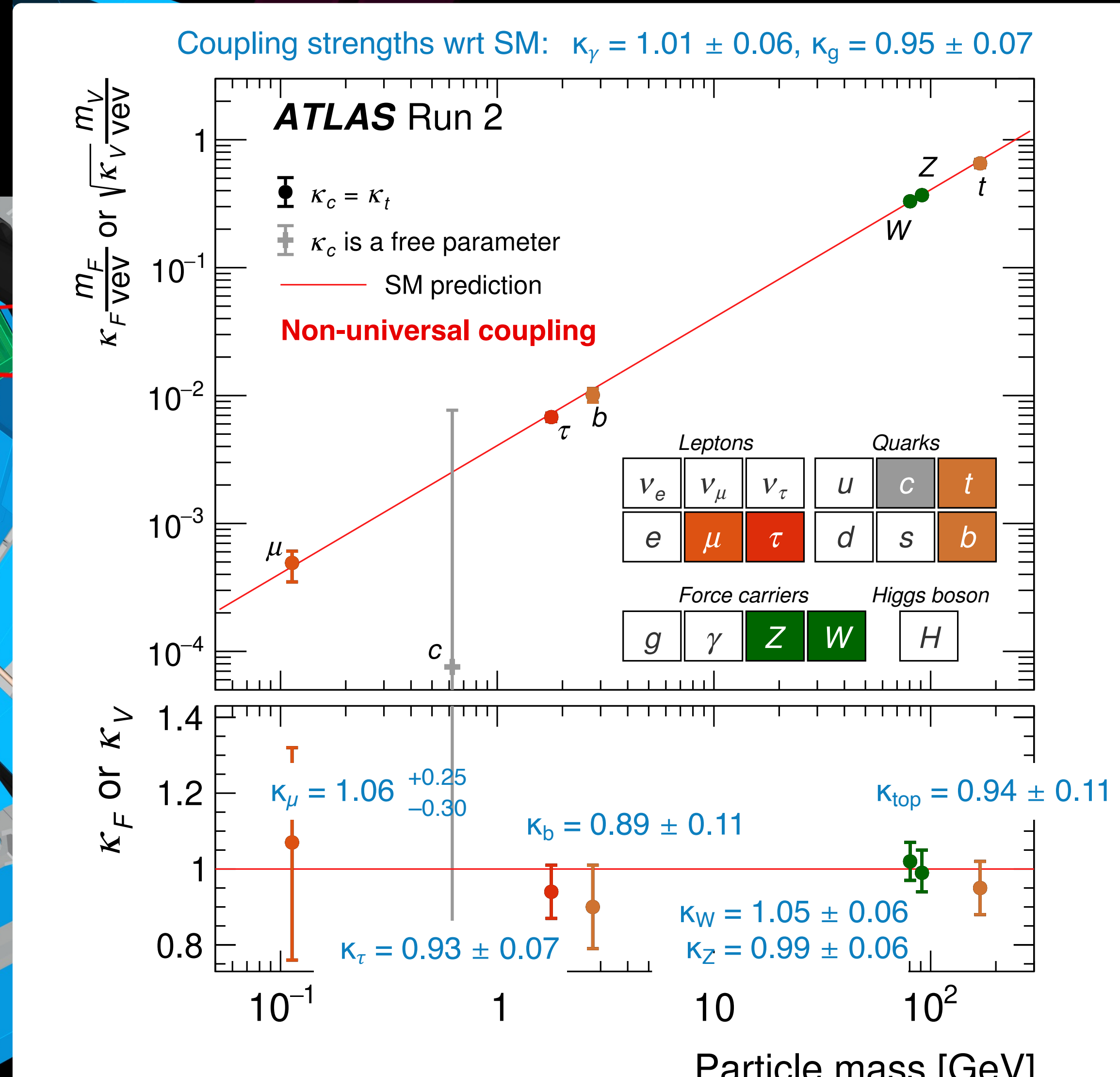
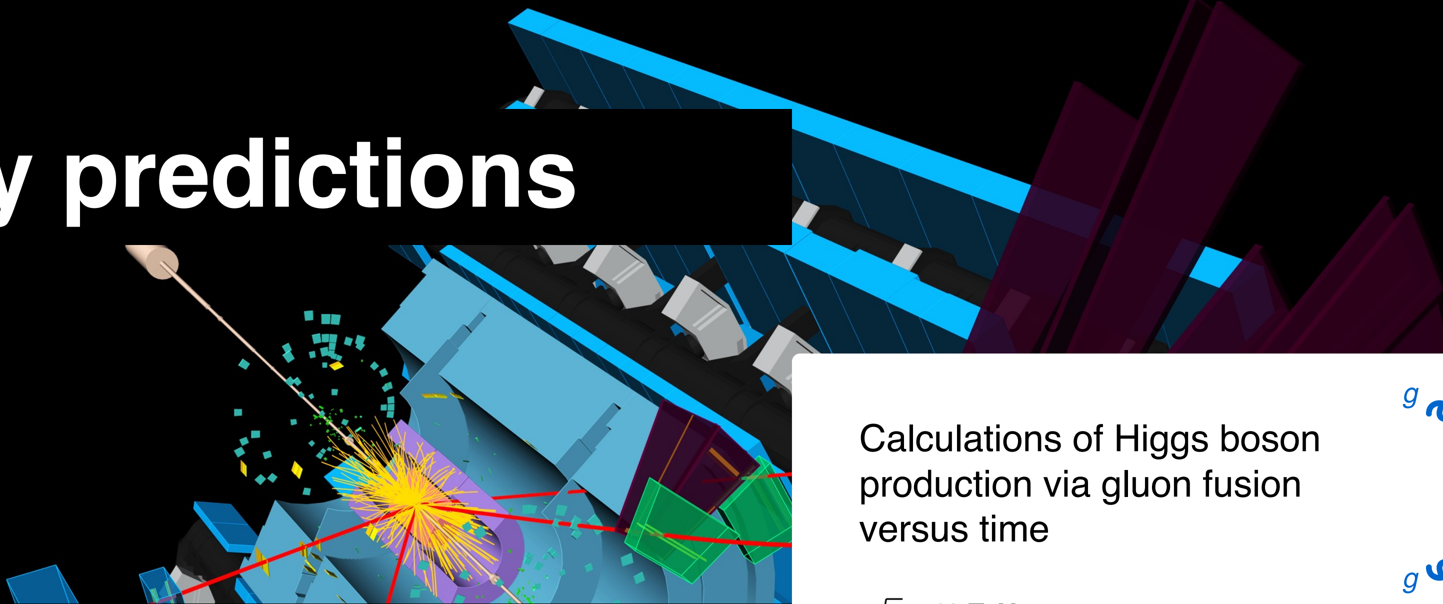




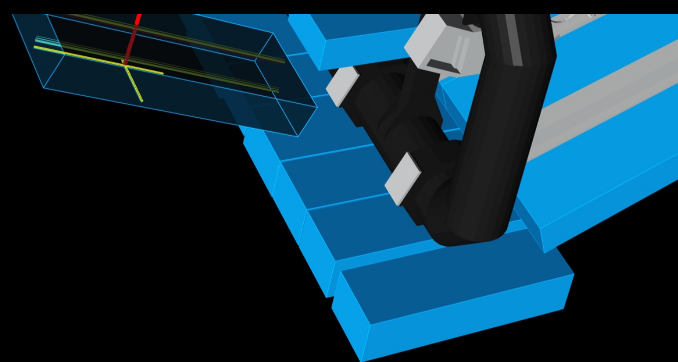
Nature 607, 52 (2022)

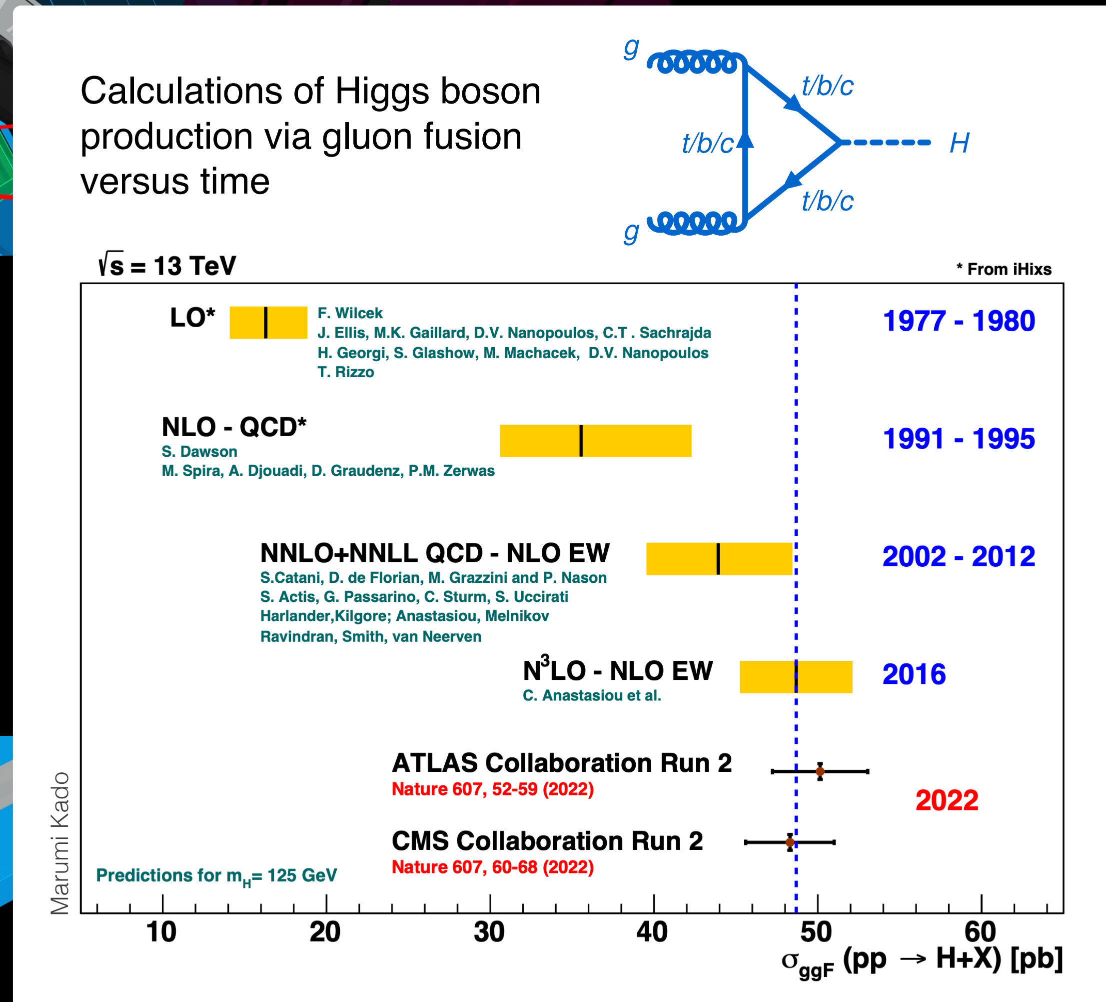
Theory predictions



Predictions at hadron colliders are extremely complex and require several levels of modelling and calculations (higher order hard processes, parton fragmentation, hadronization, parton distribution functions, etc…)

The interpretability of our results relies on our ability to compute accurate and precise predictions





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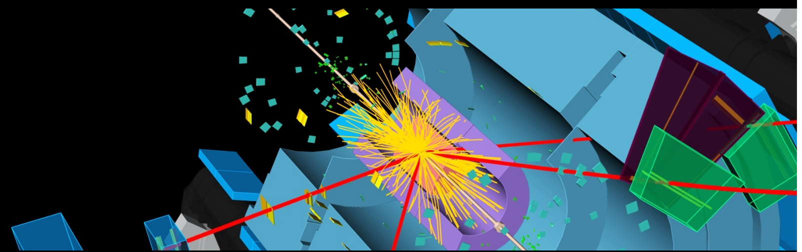

The new sector opens a variety of possibilities and questions

The discovery of an (apparently) fundamental scalar particle, resulting from spontaneous symmetry breaking, fuels renewed interest in other fundamental (pseudo)scalars, such as the **axion**

Possible relations between the Higgs boson and open questions in particle physics and cosmology

- What stabilises the Higgs mass versus high-scale new physics? Are there new TeV-scale symmetries? Is the Higgs boson elementary or composite, are there anomalies in its coupling to the W or Z?
- Do Higgs interactions violate CP? Is there an anomalous Higgs self coupling to allow for a first order electroweak phase transition?
- Is the Higgs boson unique?
- What is the origin of dark matter, is the Higgs mechanism responsible for dark matter? Can the Higgs boson provide a portal to a dark sector?
- What is the origin of the vast range of Yukawa couplings, are there modified interactions, lepton-flavour violation?
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Salam, Wang, Zanderighi: Nature 607, 41 (2022)

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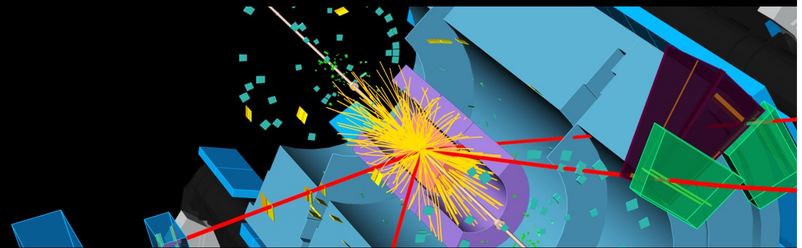

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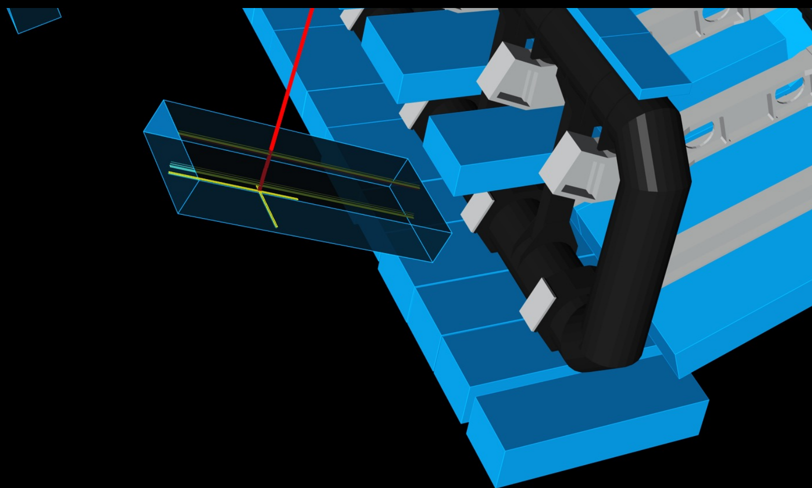

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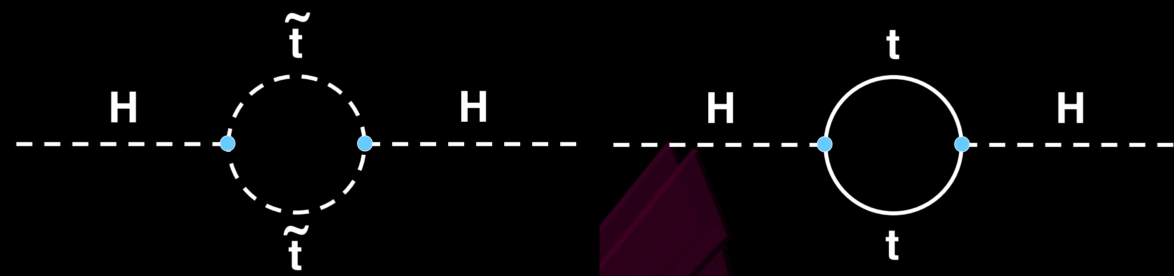
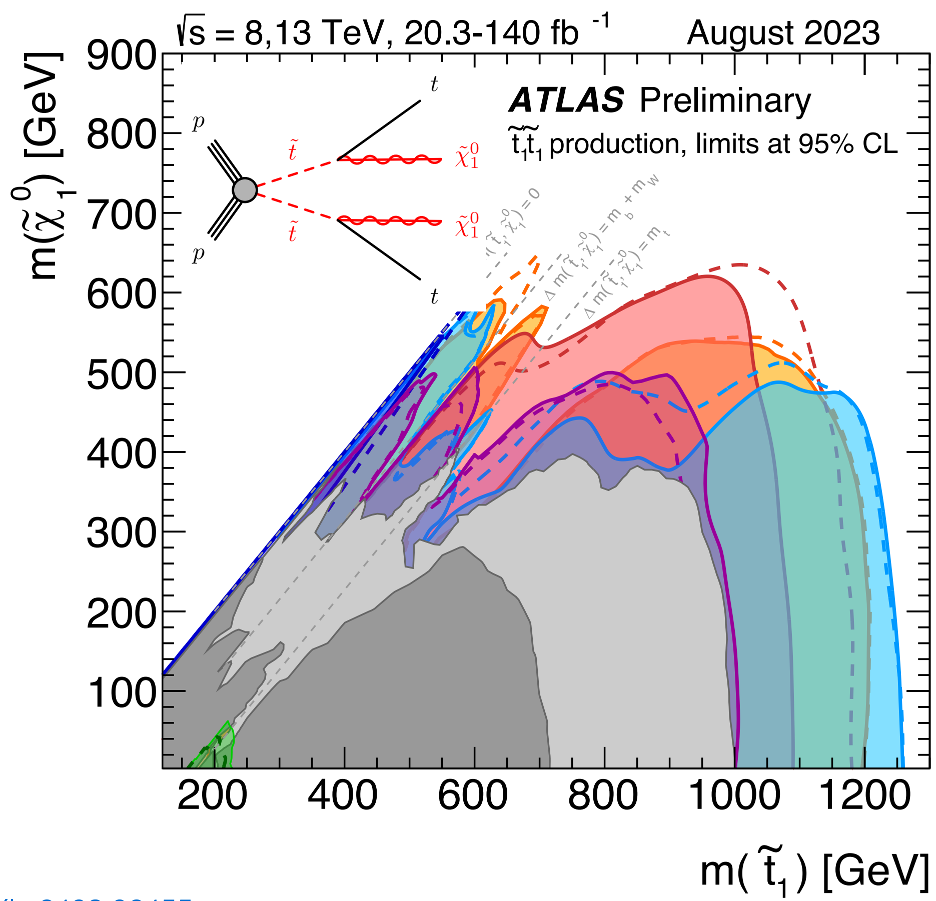
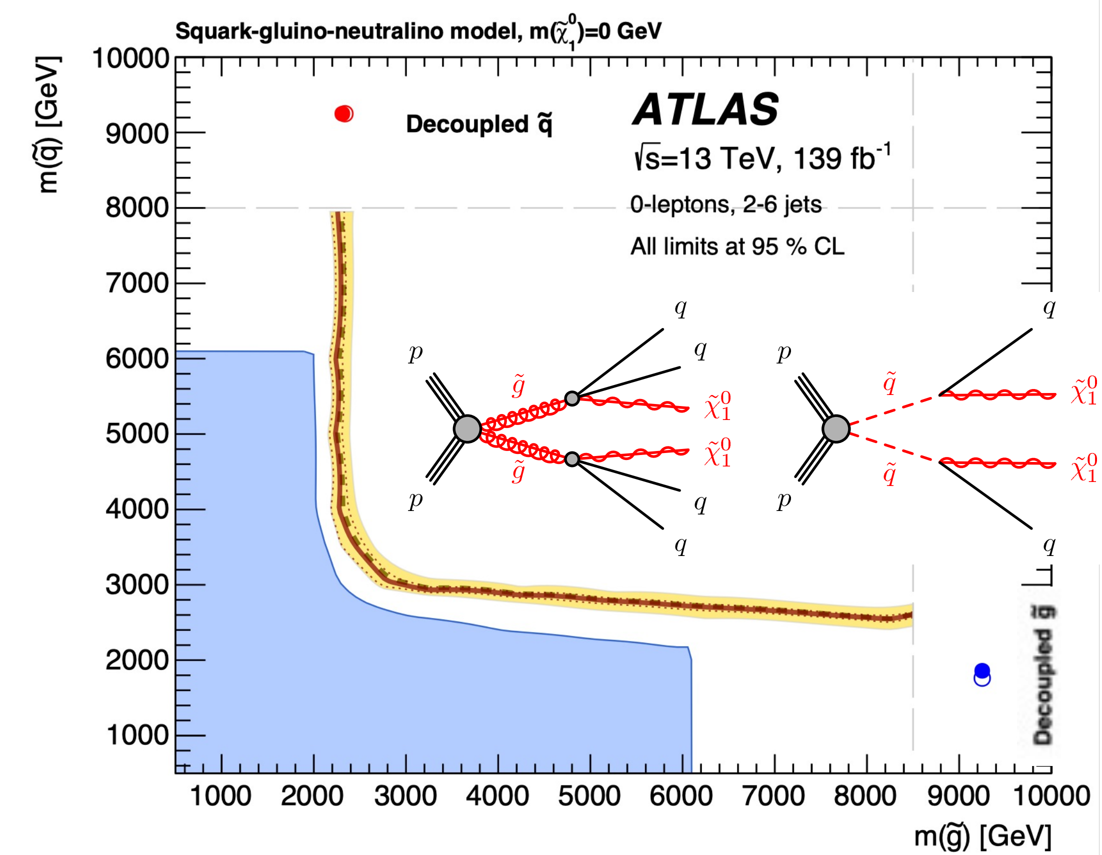
Salam, Wang, Zanderighi: Nature 607, 41 (2022)

Supersymmetry?







arXiv:2403.02455

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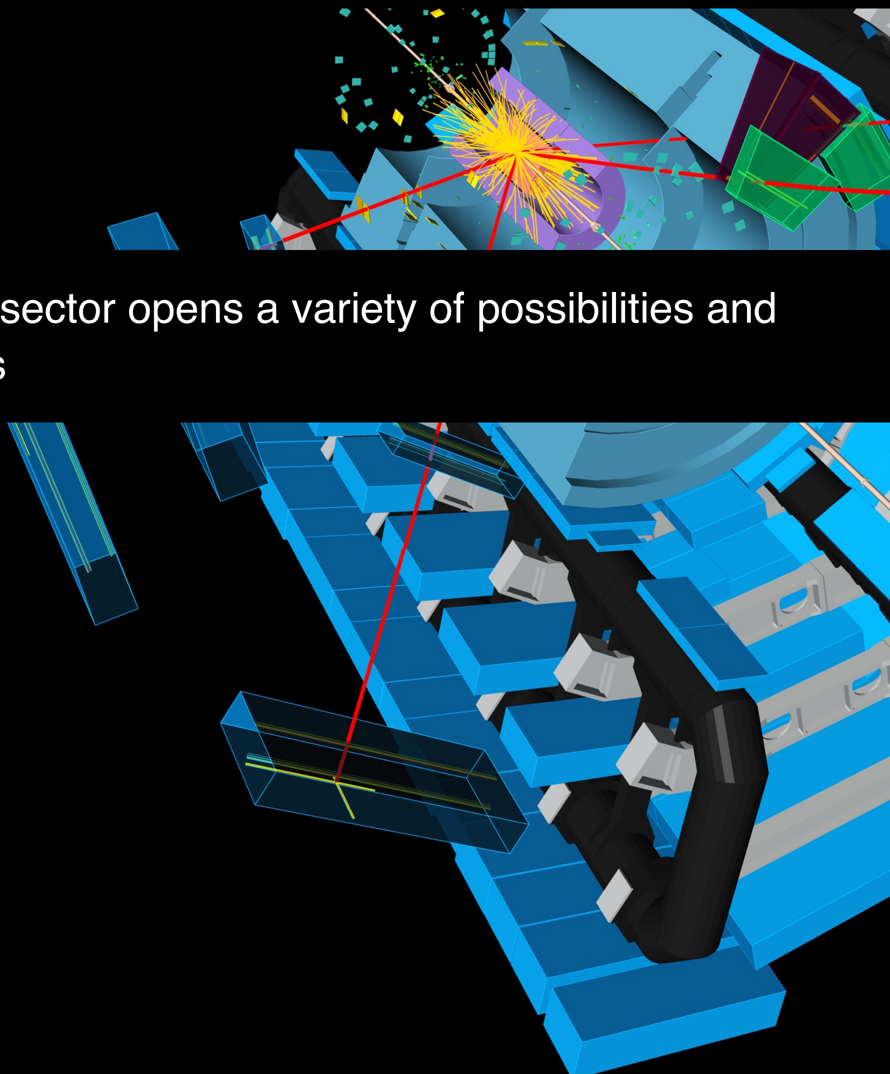

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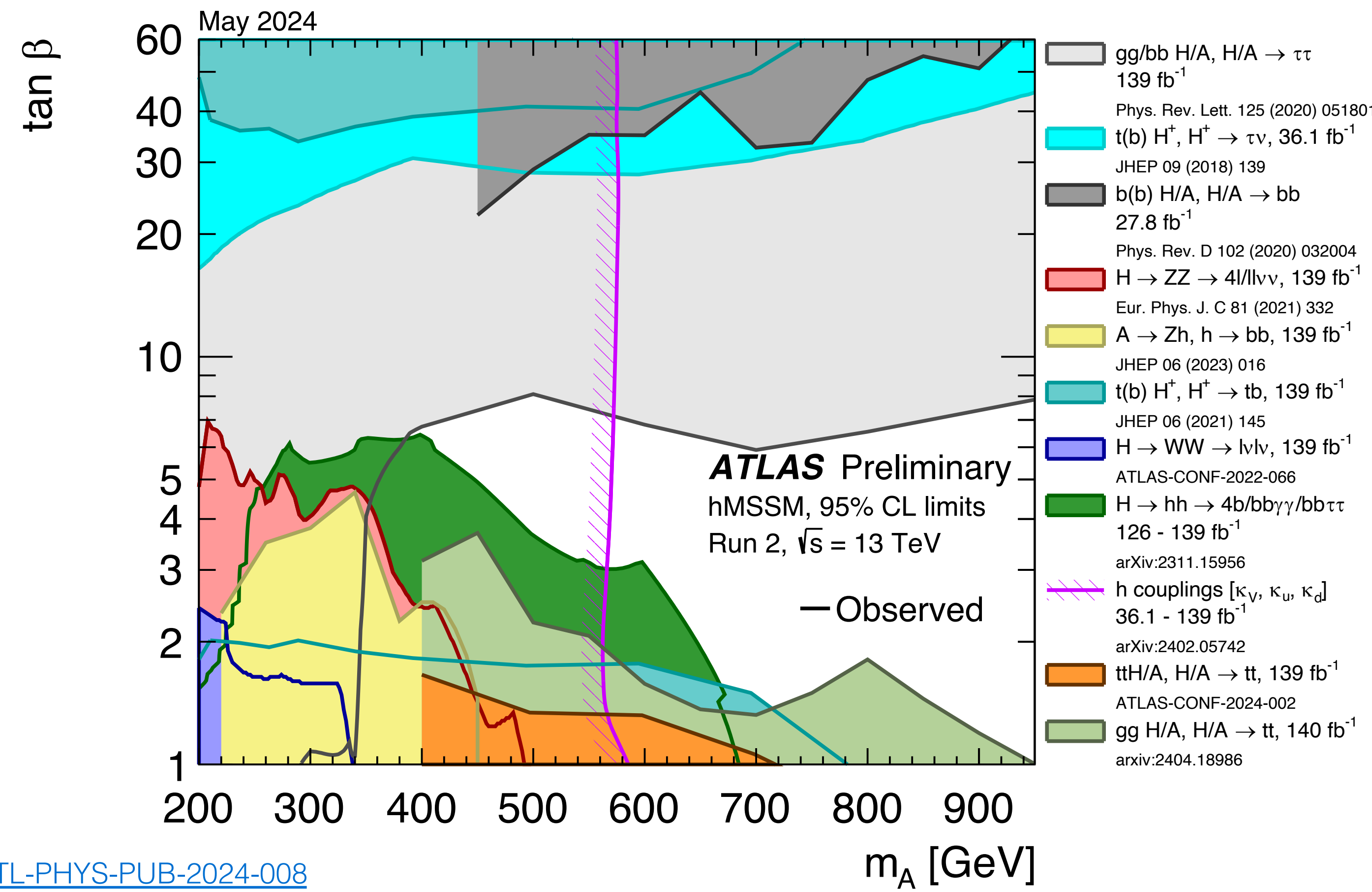
Salam, Wang, Zanderighi: Nature 607, 41 (2022)

Extended Higgs sector ?

The scalar sector may feature an additional Higgs doublet with opposite weak hypercharge (→ h, H, A, $H^{\pm}$) or even triplet (+ $H^{\pm\pm}$) with rich phenomenology

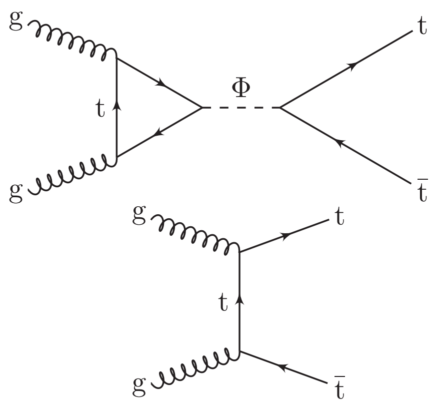


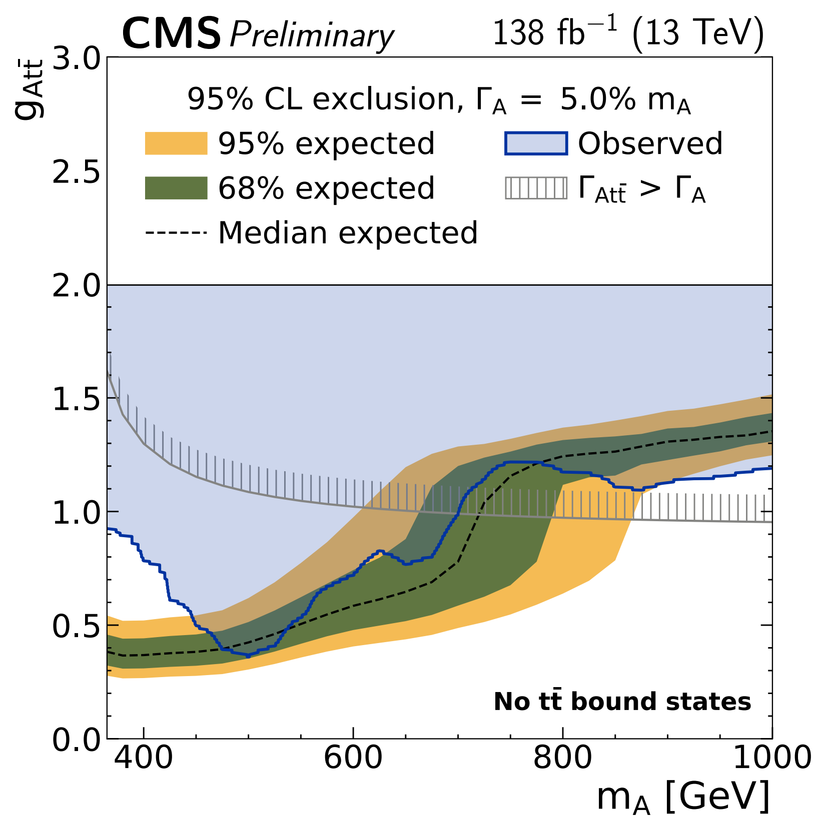
ATL-PHYS-PUB-2024-008

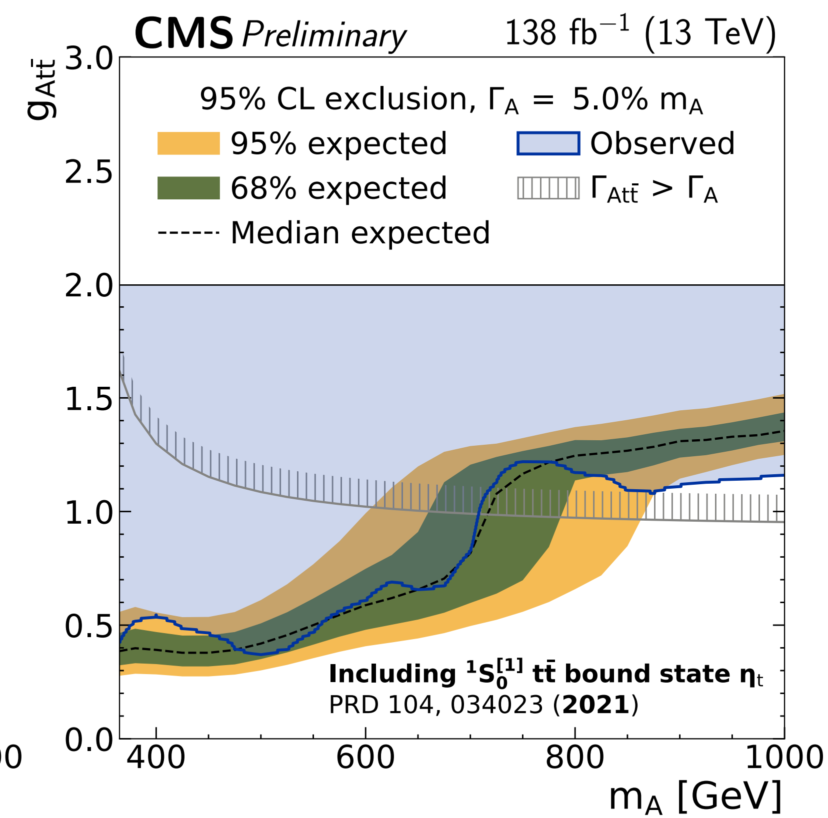
Extended Higgs sector ?

Interesting recent development in searches for A/H → tt

[CMS-PAS-HIG-22-013](CMS-PAS-HIG-22-013)





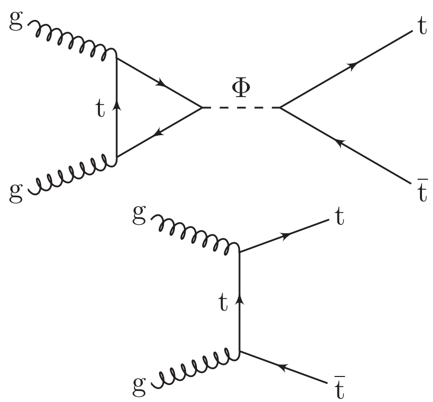


CMS sees a significant excess close to the top–antitop threshold, which is consistent with a pseudoscalar colour-singlet quasi-bound "toponium" state

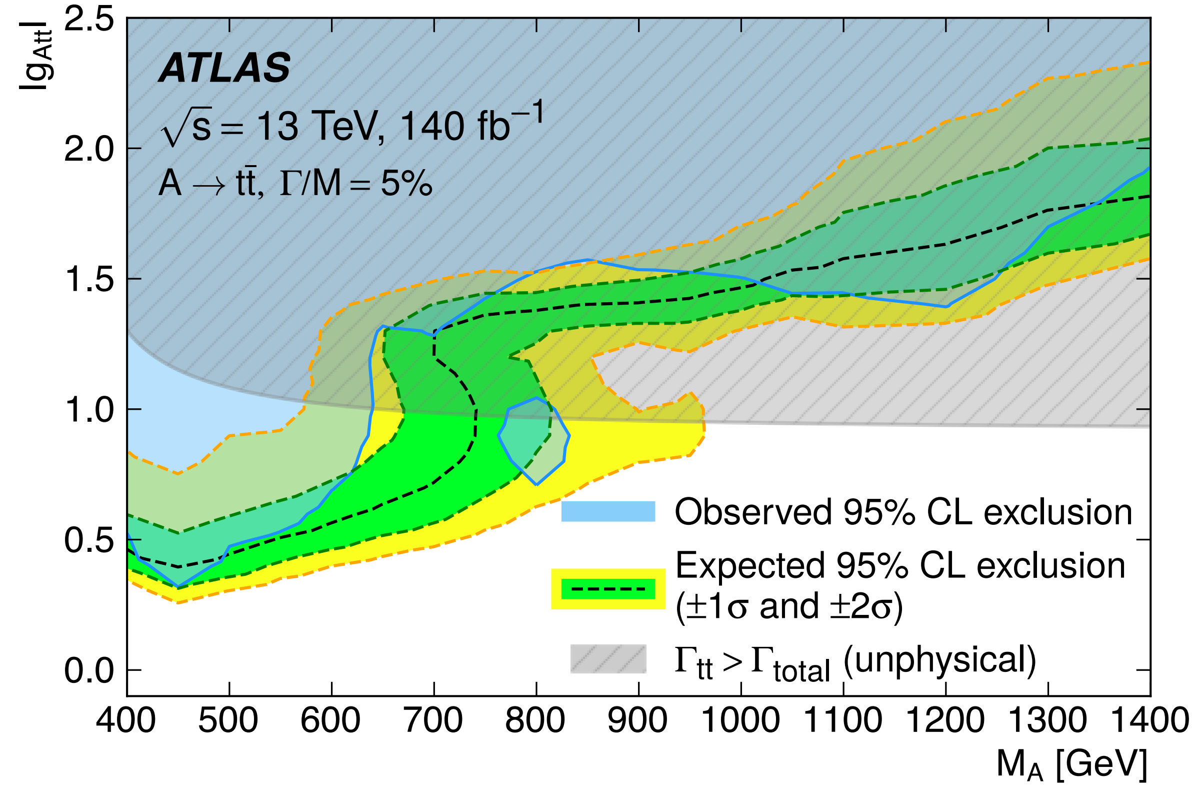
(Note: threshold enhancement ∝ α_S / β expected in NLO QCD)

Extended Higgs sector ?

Interesting recent development in searches for A/H → tt

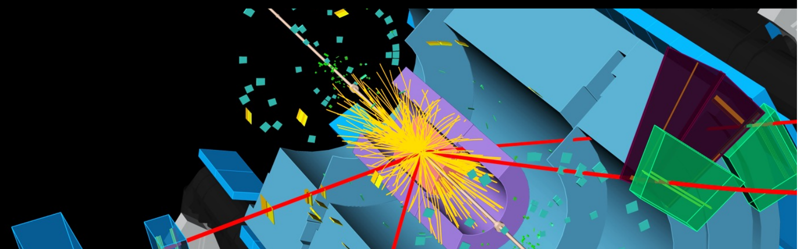


JHEP 08 (2024) 013

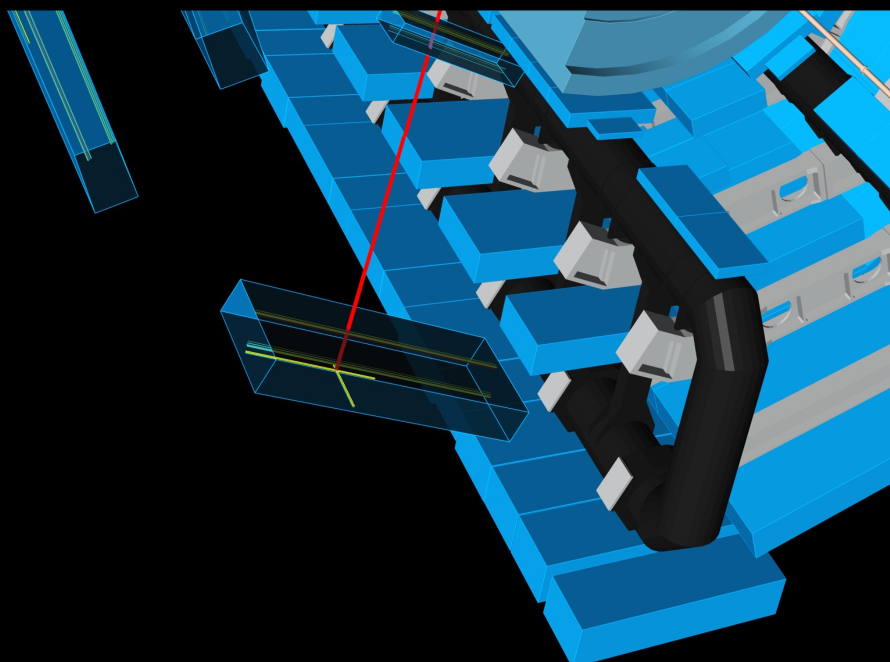


ATLAS has similar but less sensitive analysis, as it did not optimise for toponium. A small threshold excess in data is absorbed by systematic uncertainties

The Higgs mechanism is real !



The new sector opens a variety of possibilities and questions



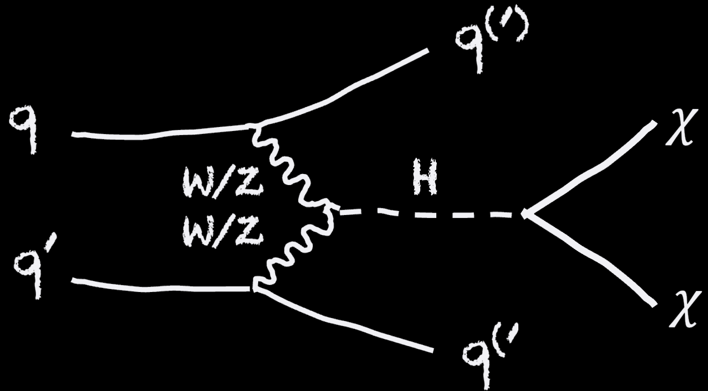
Possible relations between the Higgs boson and open questions in particle physics and cosmology

- What stabilises the Higgs mass versus high-scale new physics? Are there new TeV-scale symmetries? Is the Higgs boson elementary or composite, are there anomalies in its coupling to the W or Z?
- Do Higgs interactions violate CP? Is there an anomalous Higgs self coupling to allow for a first order electroweak phase transition?
- Is the Higgs boson unique?
- What is the origin of dark matter, is the Higgs mechanism responsible for the dark matter mass? Can the Higgs boson provide a portal to a dark sector?
- What is the origin of the vast range of Yukawa couplings, are there modified interactions, lepton-flavour violation?
- Is the vacuum metastable? Is the Higgs field connected with cosmic inflation? Are there possible cosmological observations related to the Higgs field?

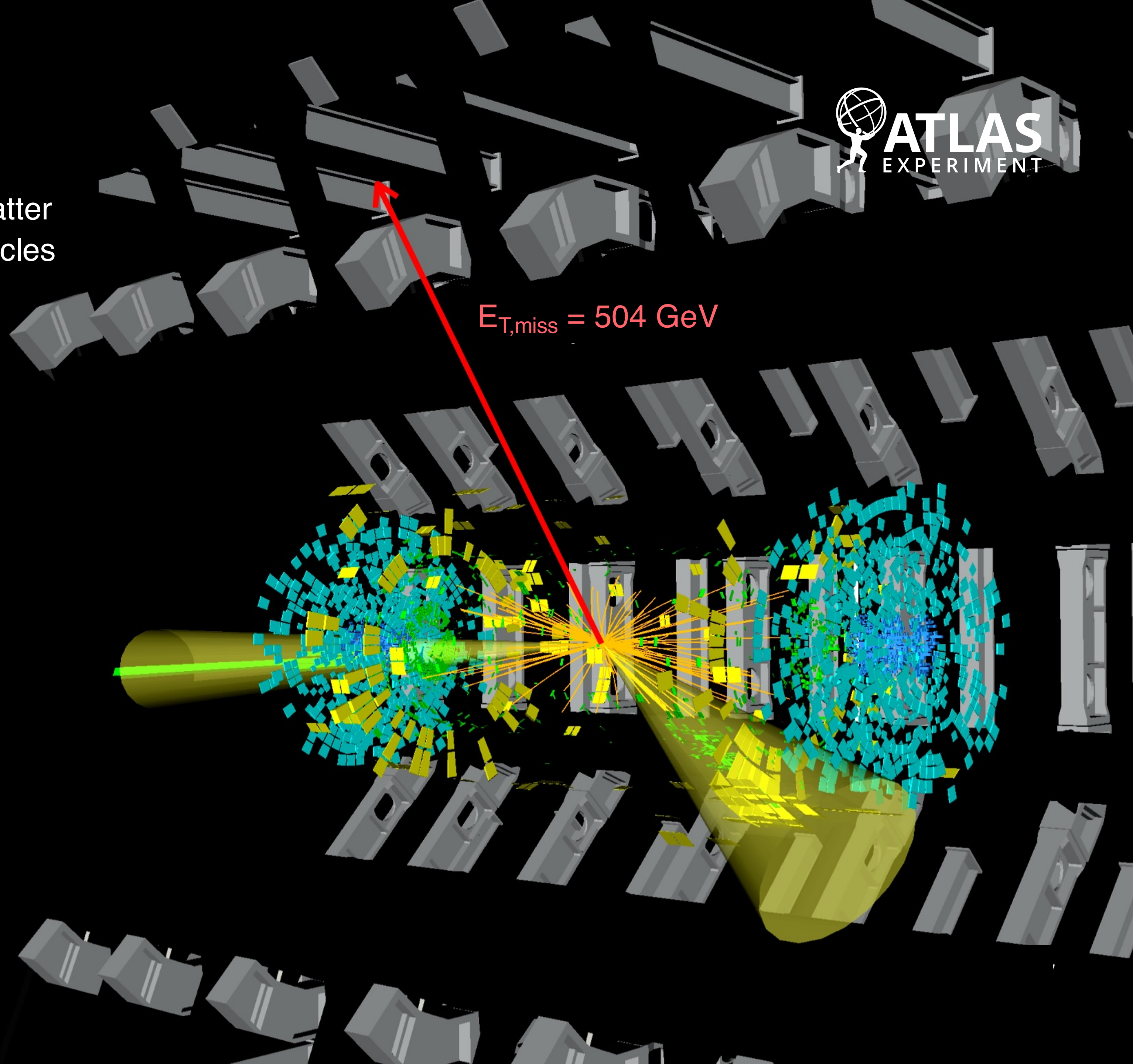
Salam, Wang, Zanderighi: Nature 607, 41 (2022)

Dark matter

The Higgs boson may couple to dark matter and "invisibly" decay to dark matter particles
(if kinematically allowed)



→ Shion Chen's talk at KMI2025



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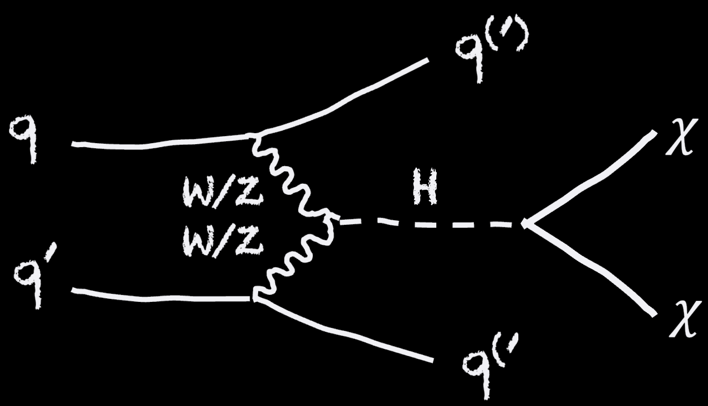
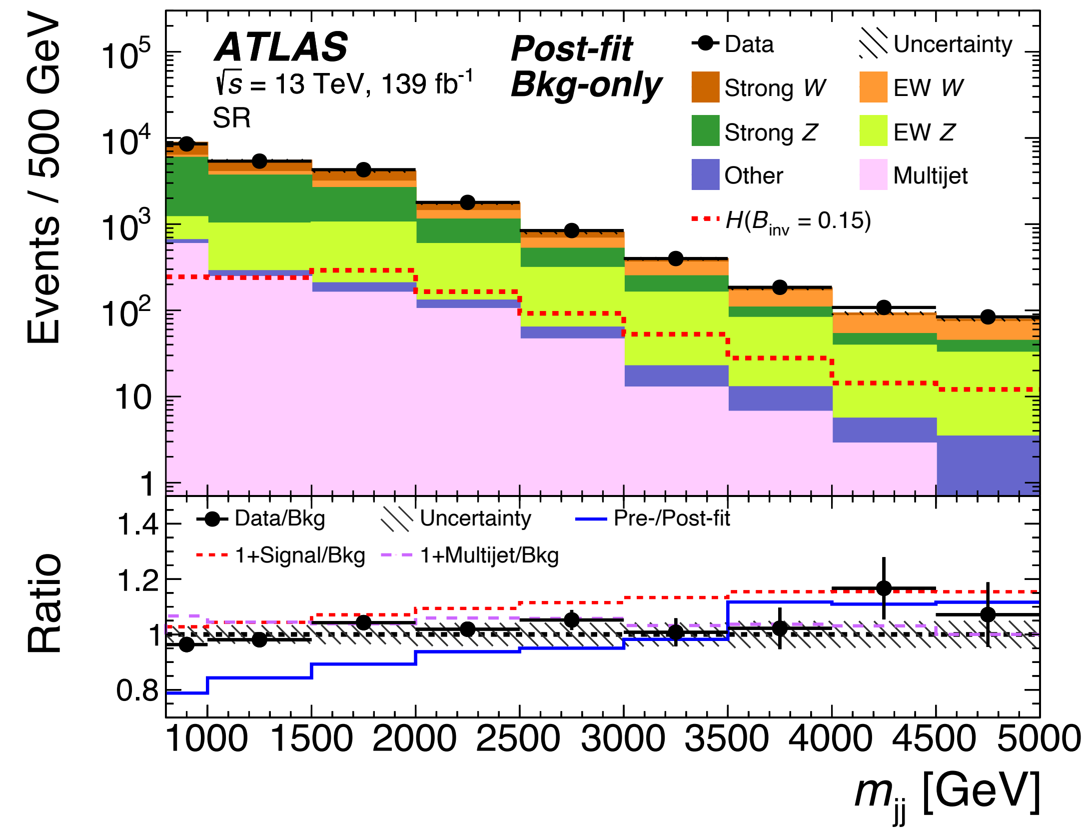


→ Shion Chen's talk at KMI2025

arXiv:2202.07953, arXiv:2301.10731



➠ BR(H → invisible) < 0.107 (0.077) at 95% CL

Dark matter

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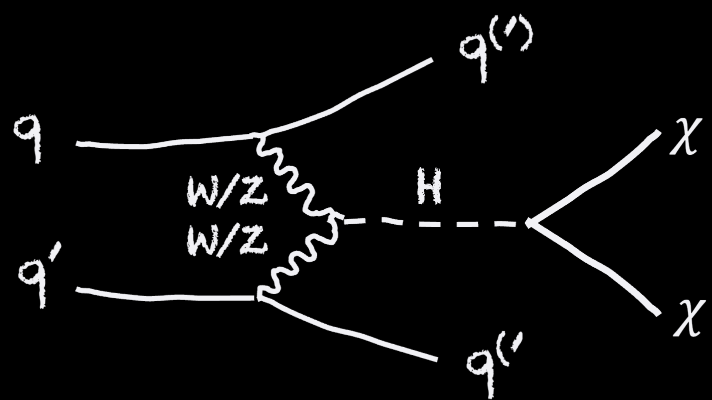
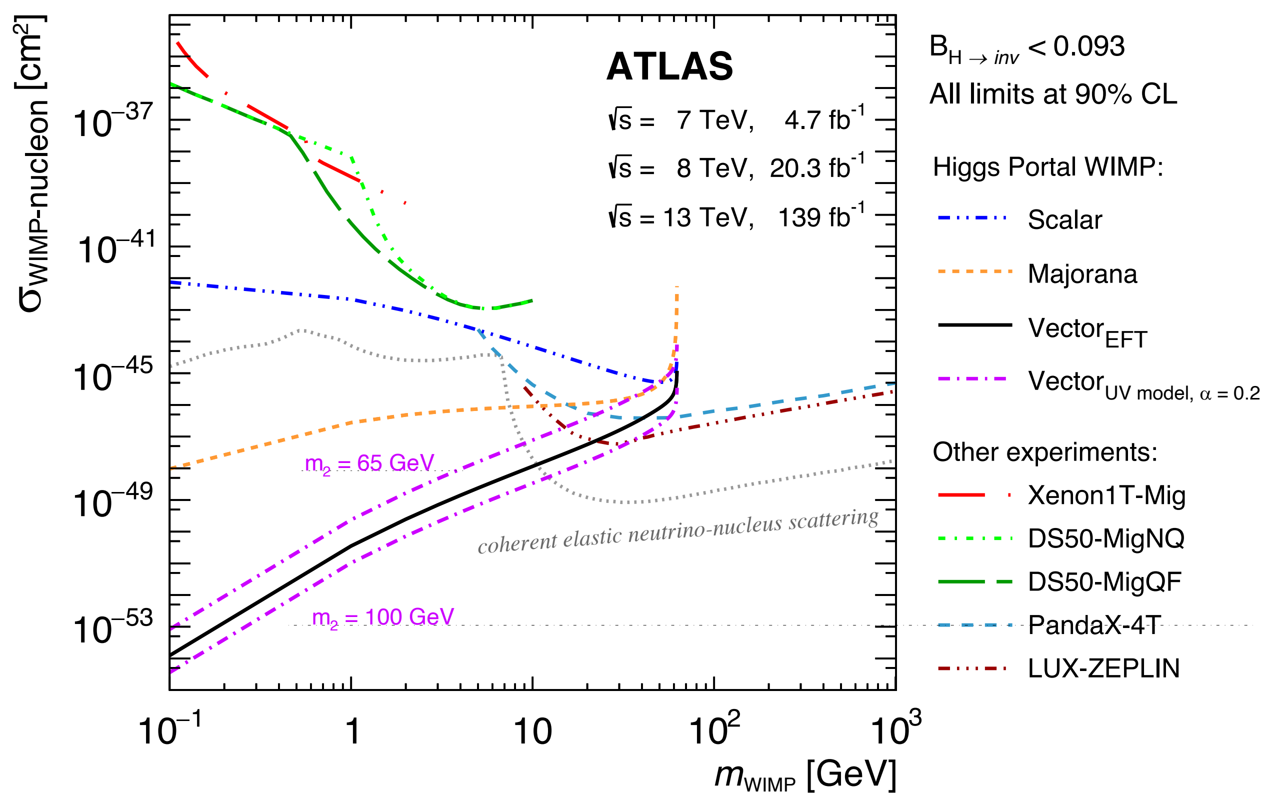


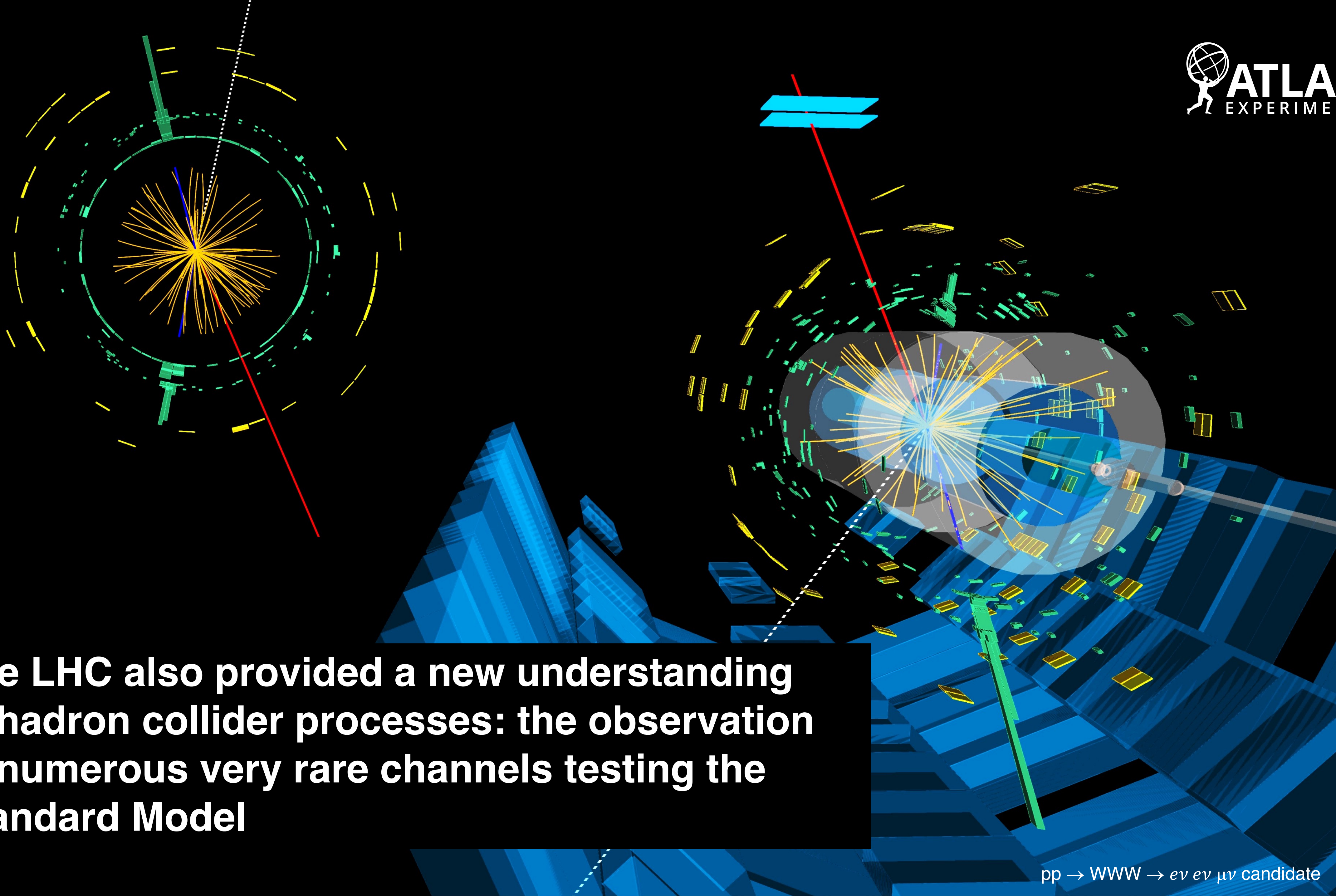
→ Shion Chen's talk at KMI2025

Spin-independent scattering cross-section of a weakly interacting massive particle (WIMP) and a nucleon

arXiv:2202.07953, arXiv:2301.10731

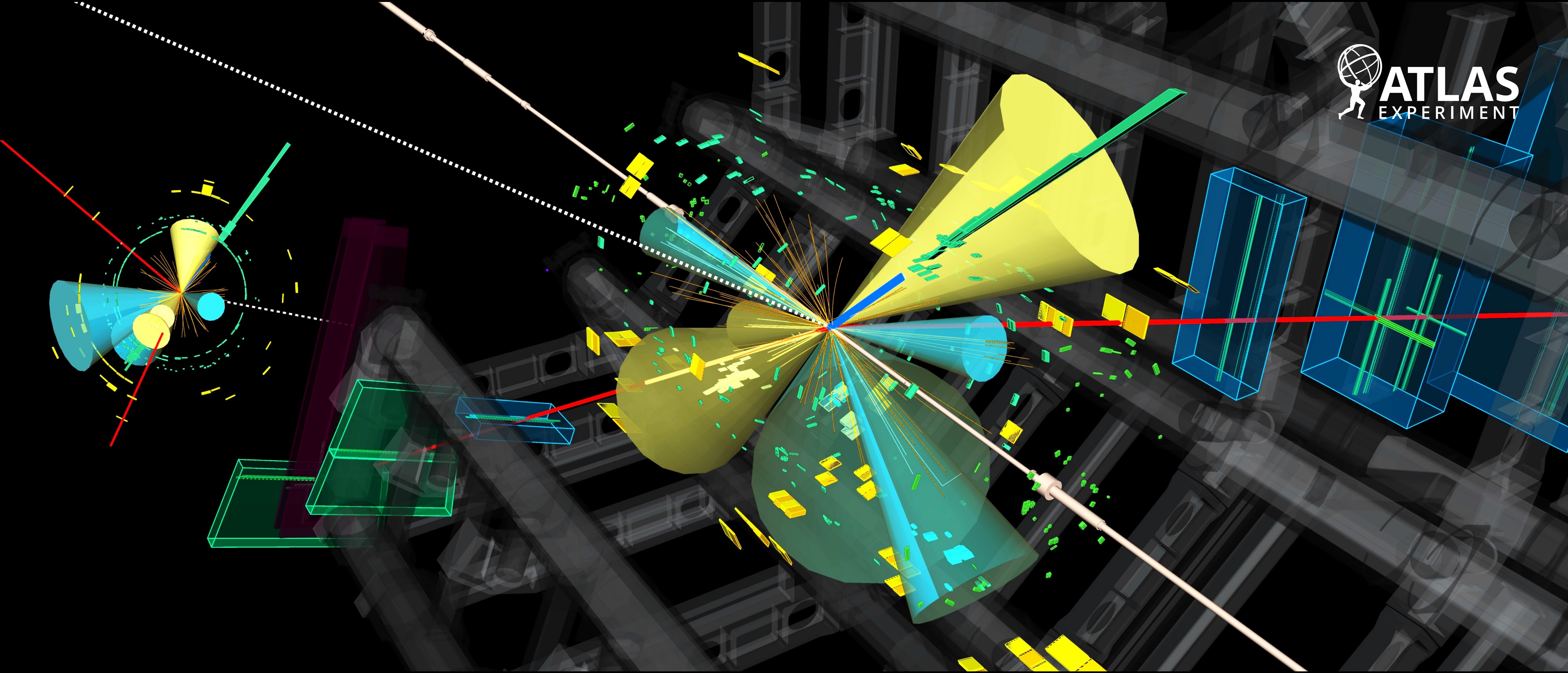


➠ BR(H → invisible) < 0.107 (0.077) at 95% CL



pp → WWW → $e\nu\ e\nu\ \mu\nu$ candidate

The LHC also provided a new understanding of hadron collider processes: the observation of numerous very rare channels testing the Standard Model



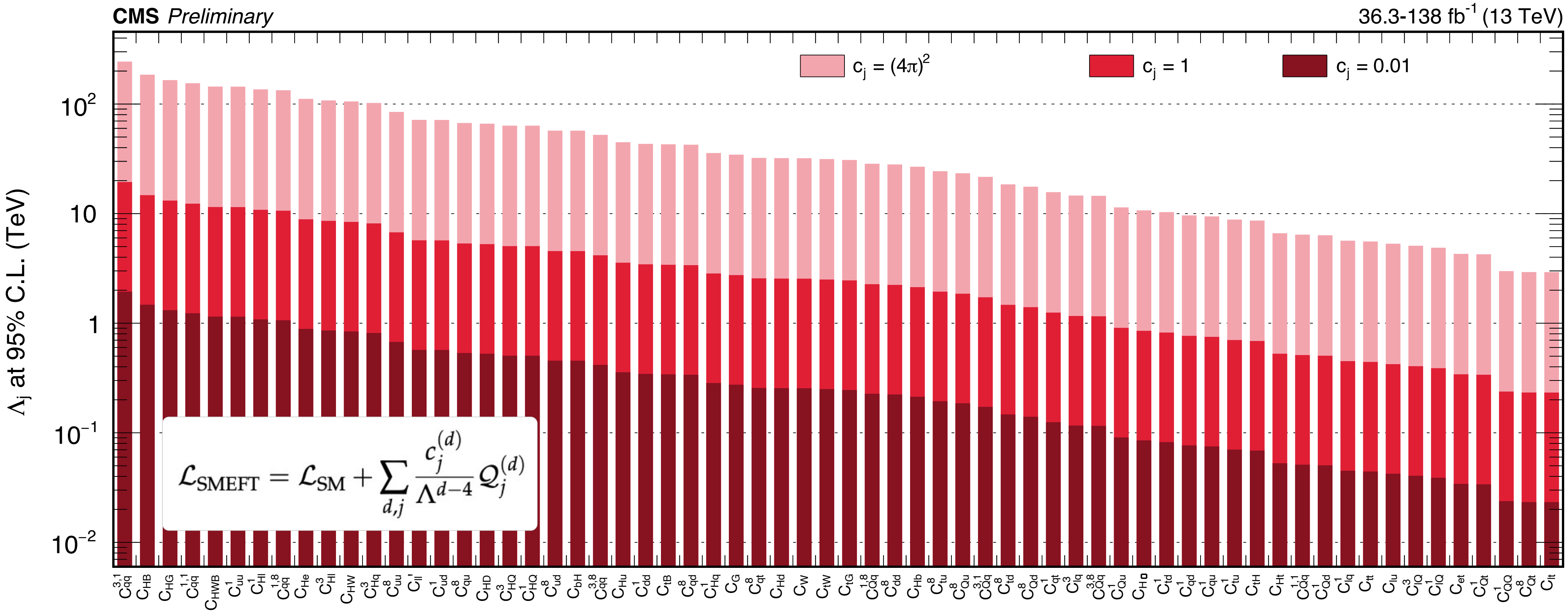
The LHC also provided a new understanding of hadron collider processes: the observation of numerous very rare channels testing the Standard Model

pp → tttt candidate event (very rare events, 70,000 rarer than tt, 4,000 rarer than Higgs boson production, with spectacular signature: 4 b-jets, many leptons and jets)

Consistent parametrisation of new physics with effective field theory (EFT)

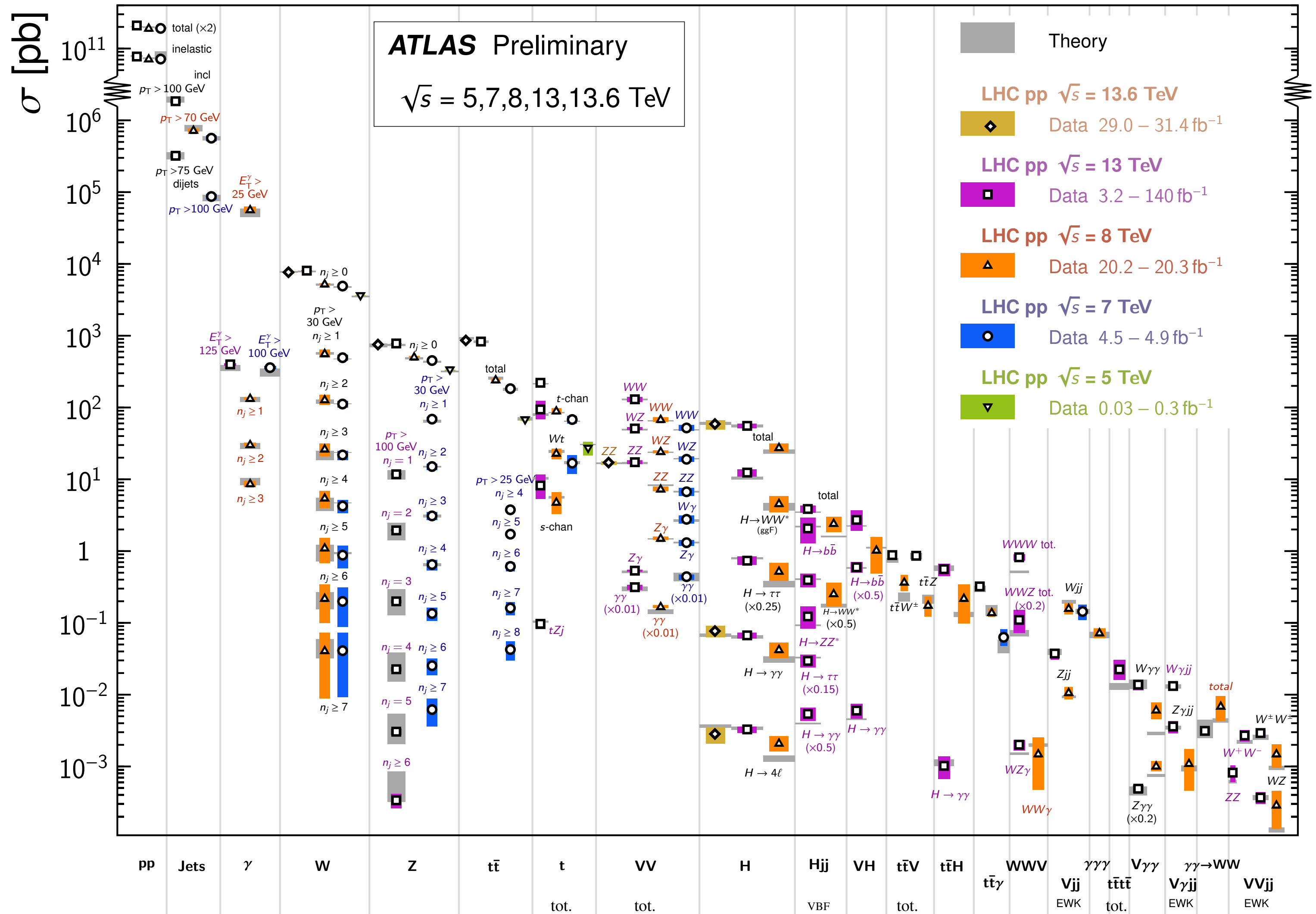
CMS-PAS-SMP-24-003

Global fit of Wilson coefficients of D=6 operators in SM EFT to Higgs, EW, top, and multijet results
Presentation in terms of probed energy scale for benchmark values of the Wilson coefficients



Standard Model Production Cross Section Measurements

Status: June 2024

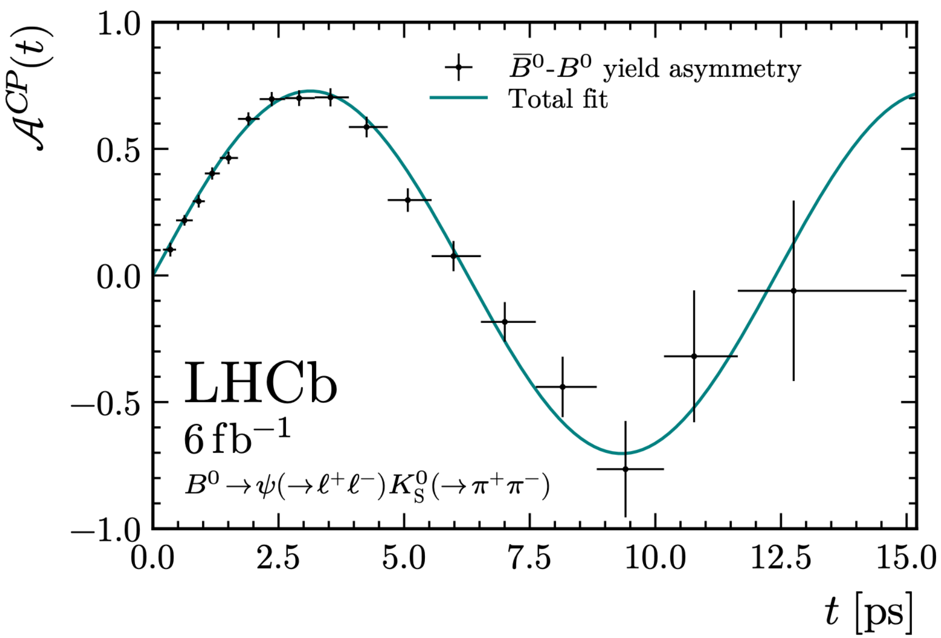


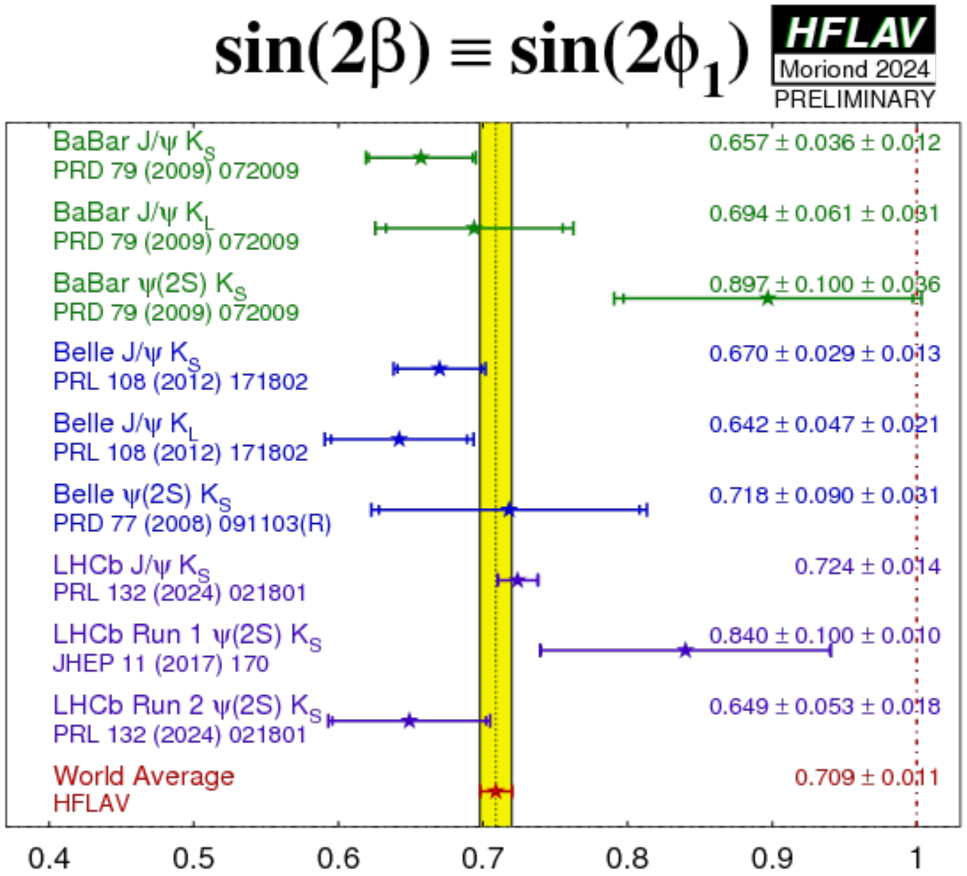
Powerful heavy-flavour measurements, complementary to Belle II

→ Gino Isidori's talk at KMI2025

Precise measurement of CKM angles

- **$\gamma = \phi_3 = 64.6 \pm 2.8$ deg** (CKMfitter: $66.3^{+0.7}_{-1.9}$ deg)
  LHCb-CONF-2024-004
- **$\sin(2\beta / \phi_1) = 0.724 \pm 0.014$** (CKMfitter: 0.742 ± 0.023)
  arXiv:2309.09728



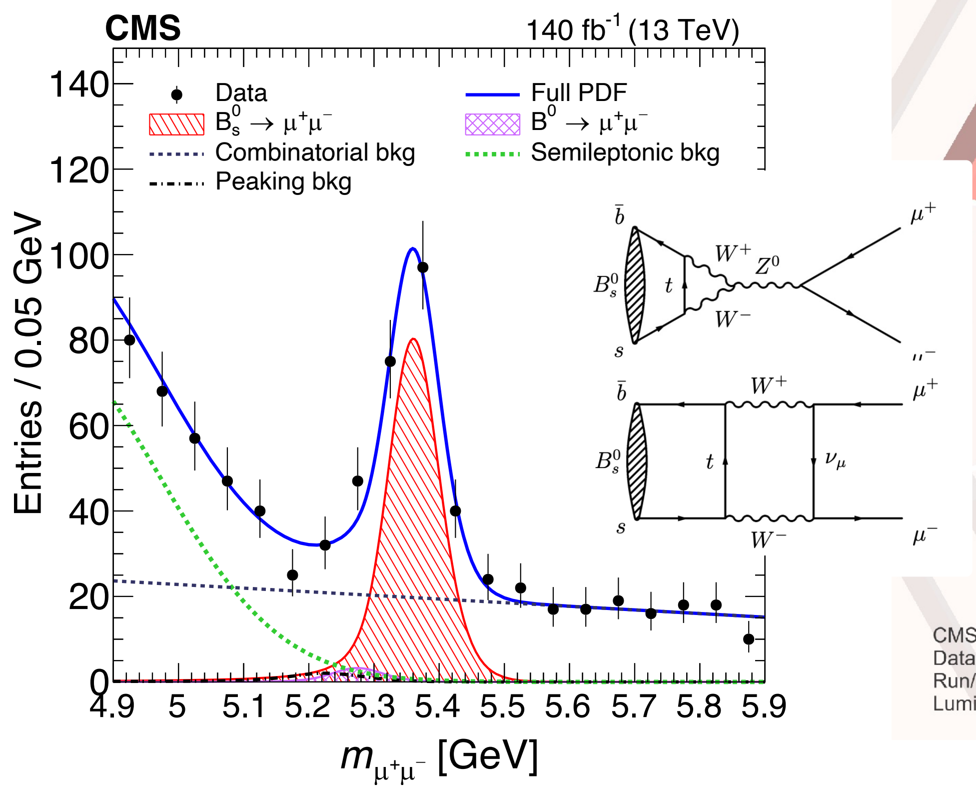


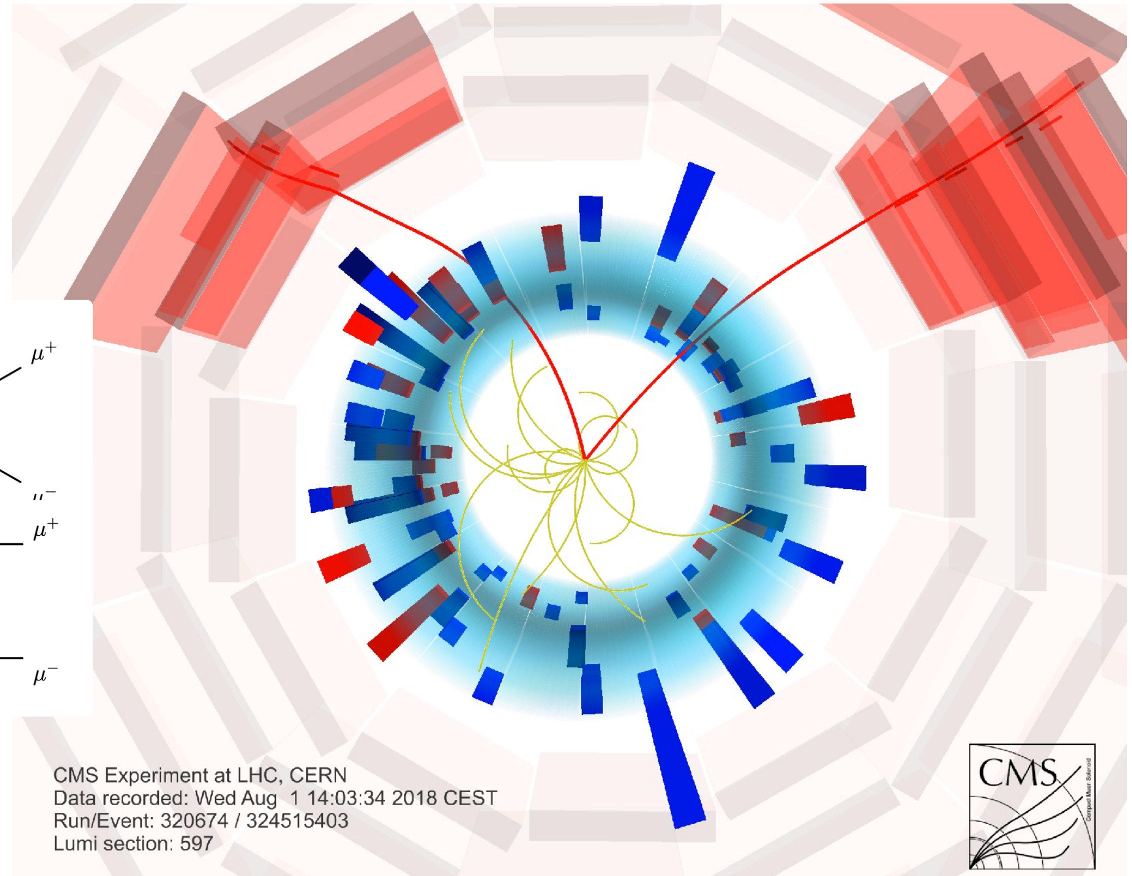
Powerful heavy-flavour measurements, complementary to Belle II

Rare B meson decays

arXiv:2212.10311

- **$\mathcal{B}(B_s \to \mu\mu) = 3.8 \pm 0.4 \times 10^{-9}$** (SM: $3.7 \pm 0.1 \times 10^{-9}$)





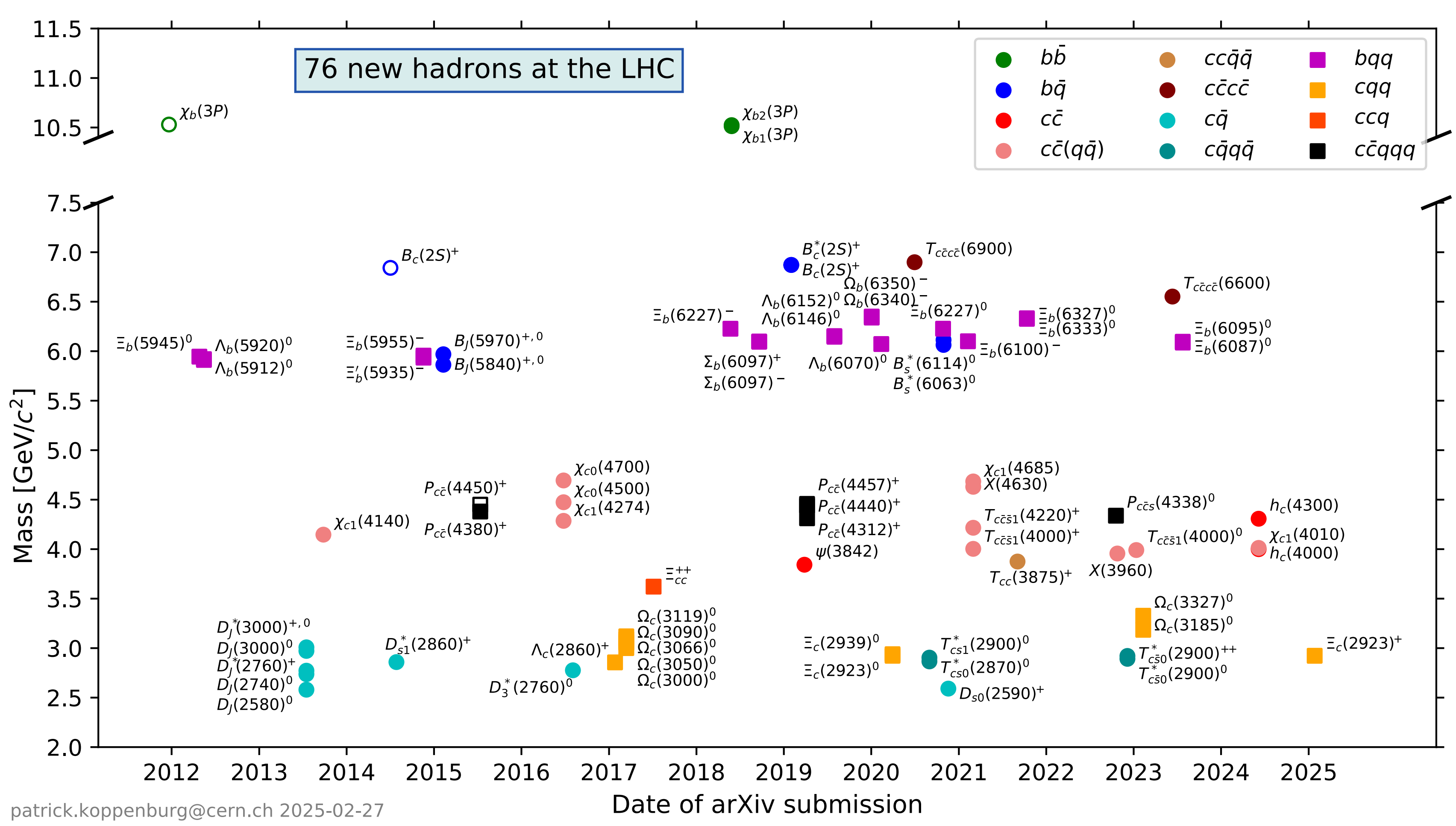
Powerful heavy-flavour measurements, complementary to Belle II

Spectroscopy

76 new hadrons discovered at the LHC (68 by LHCb), among which:

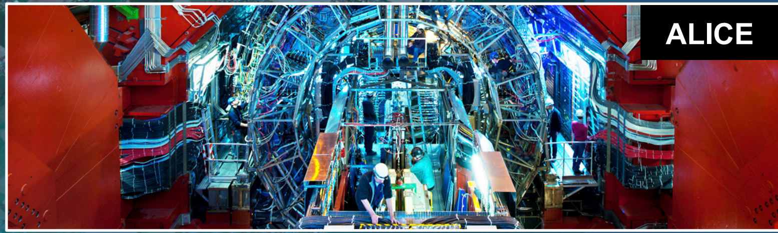
- 22 new mesons
- 31 new baryons
- 23 new exotic hadrons

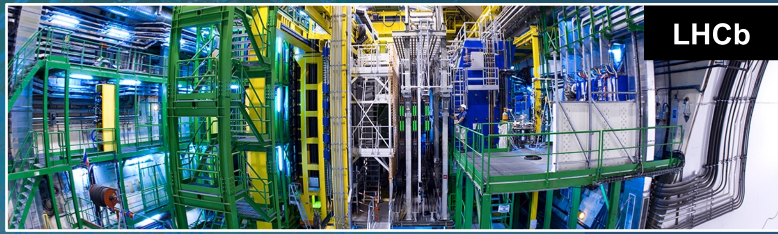
→ Yasuhiro Yamaguchi's talk at KMI2025



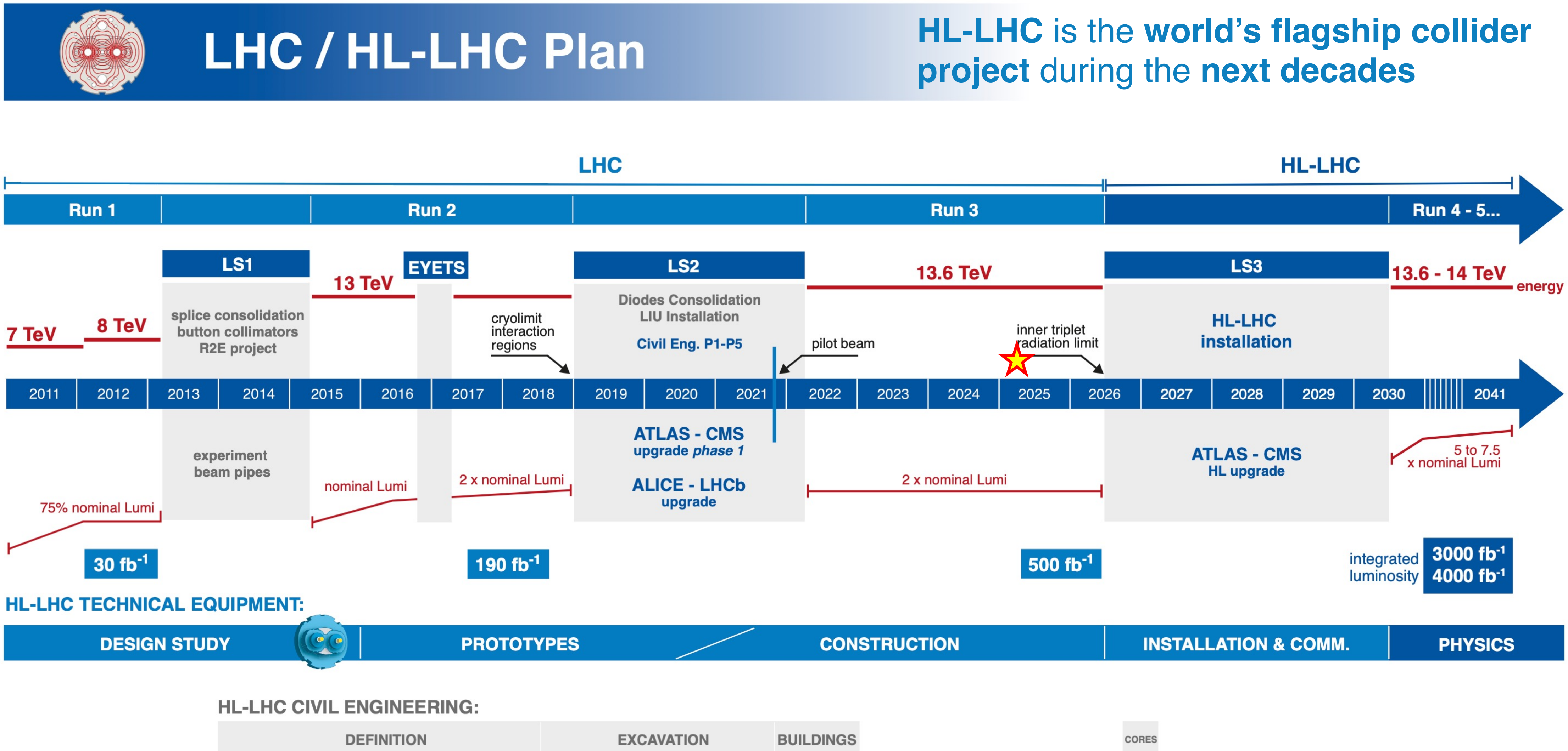
Link to figure and numbers

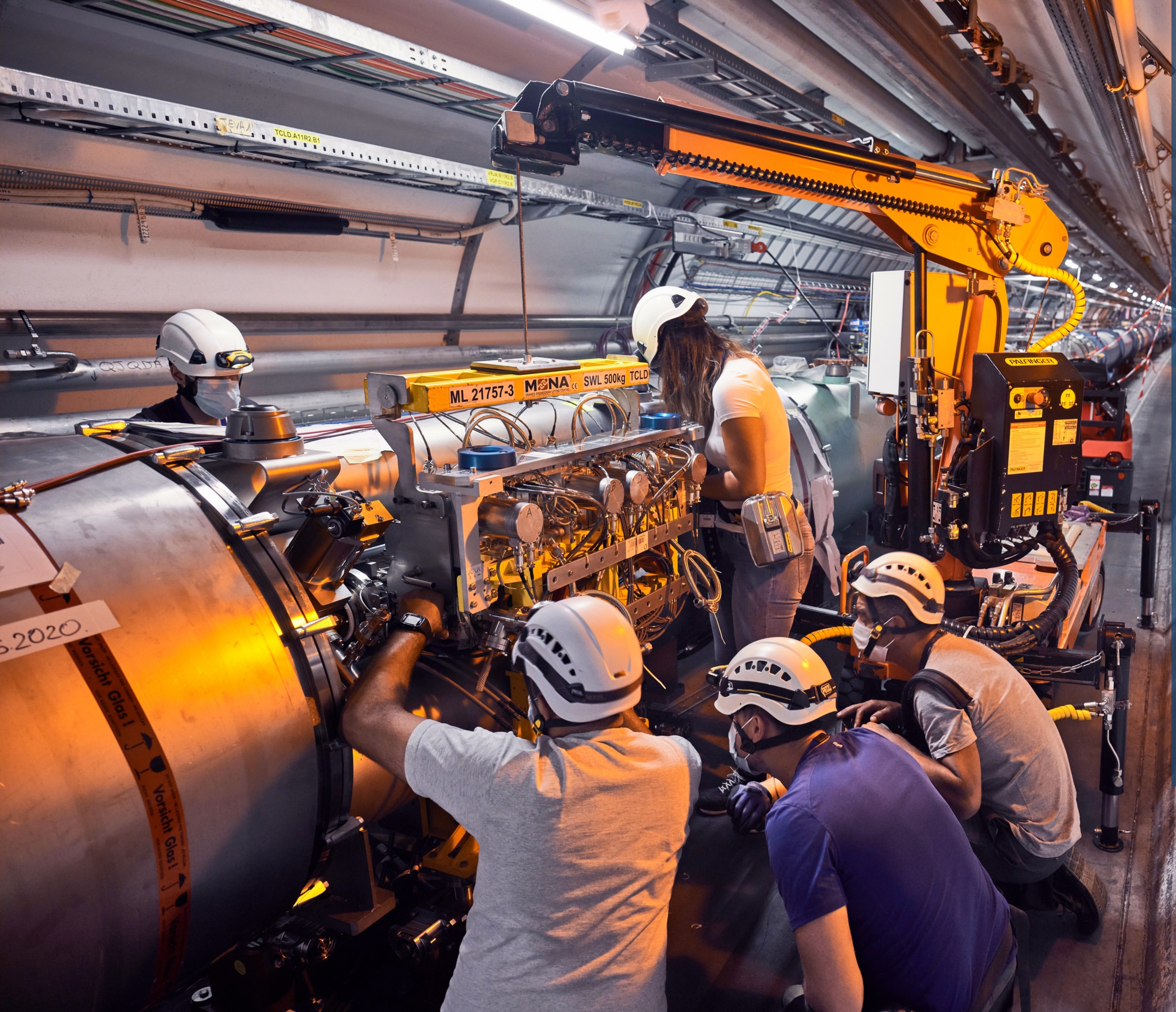
The next steps





LHC project timeline





High-Luminosity LHC (HL-LHC)

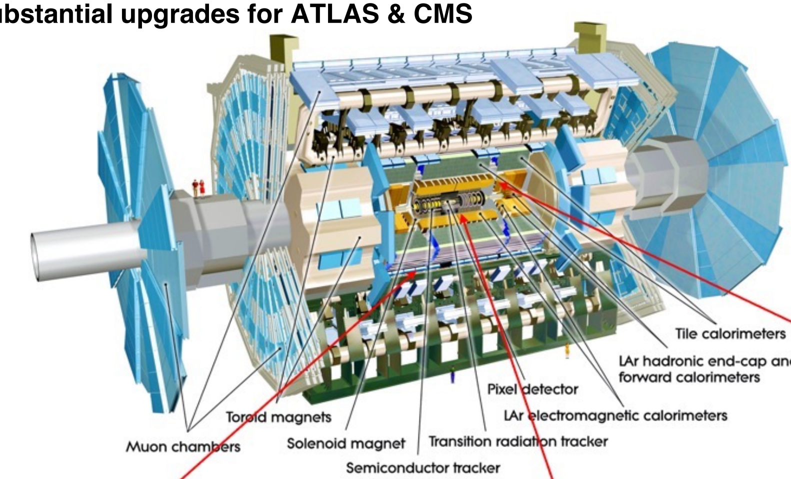
- Higgs factory (360M Higgs bosons produced) for precise Higgs coupling measurements, access to Higgs self interaction and longitudinal vector boson scattering, and increased overall rare & new physics sensitivity
- It will begin operating in 2030, and run until 2041
- Complementary to an e^+e^- Higgs / top / EW factory

Upgrade to the High-Luminosity LHC (HL-LHC)

The HL-LHC's intensity requires unprecedented detector and computing technologies:

- Radiation hardness
- High detection granularity and resolution
- Precise timing detectors
- More powerful triggers
- Deeply embedded ML & AI
- High-performance software & computing

Substantial upgrades for ATLAS & CMS



Upgraded Trigger and Data Acquisition system

Level-0 Trigger at 1 MHz

Improved High-Level Trigger (150 kHz full-scan tracking)

Electronics Upgrades

LAr Calorimeter

Tile Calorimeter

Muon system

High Granularity Timing Detector (HGTD)

Forward region ($2.4 < |\eta| < 4.0$)

Low-Gain Avalanche Detectors (LGAD) with 30 ps track resolution

New Muon Chambers

Inner barrel region with new RPC and sMDT detectors

New Inner Tracking Detector (ITk)

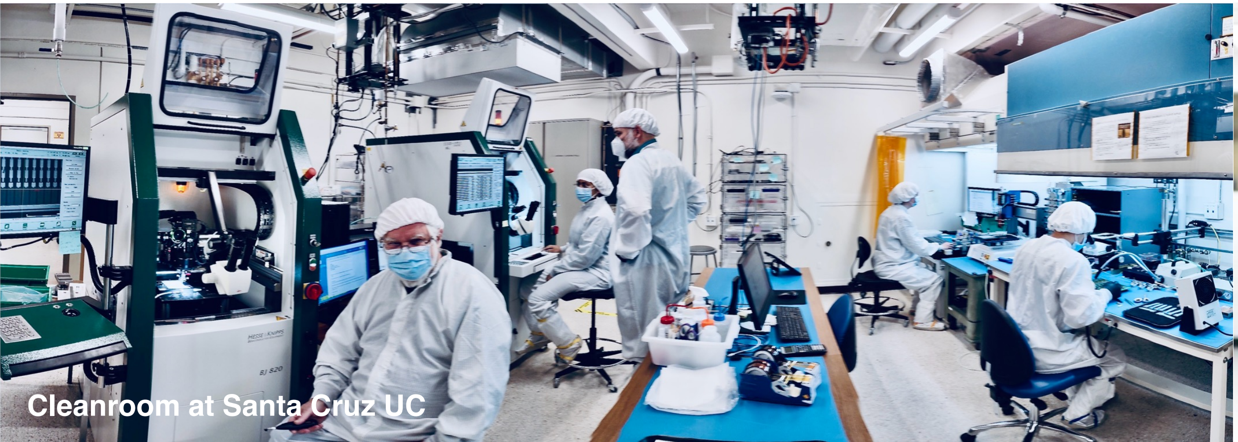
All silicon, up to $|\eta| = 4$

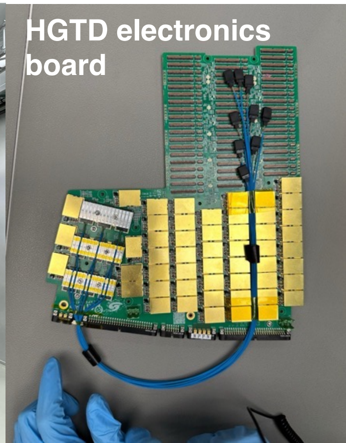
Additional small upgrades

Luminosity detectors (1% precision goal)

HL-ZDC

Detailed scope described in 7 TDRs approved by the CERN Research Board in 2017, 2018, 2020





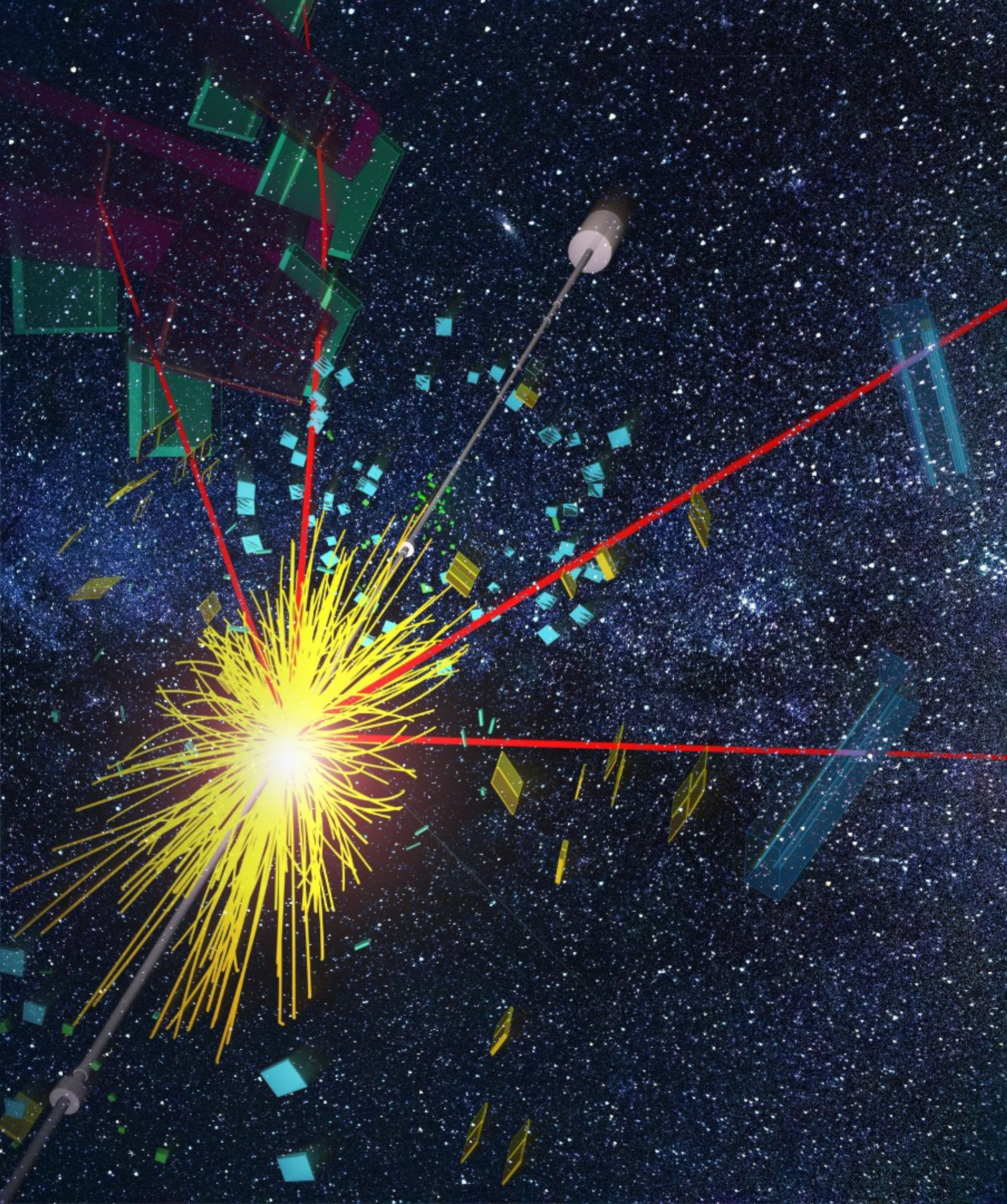
Conclusions

The LHC has been transformative for particle physics

The Higgs boson discovery allows us to directly study electroweak symmetry breaking and the process of mass generation

The Higgs sector is connected with profound questions, whose study requires a broad experimental programme at the energy frontier

A large-scale upgrade programme is underway at the LHC and its experiments to prepare for the next phase of exploration: the HL-LHC



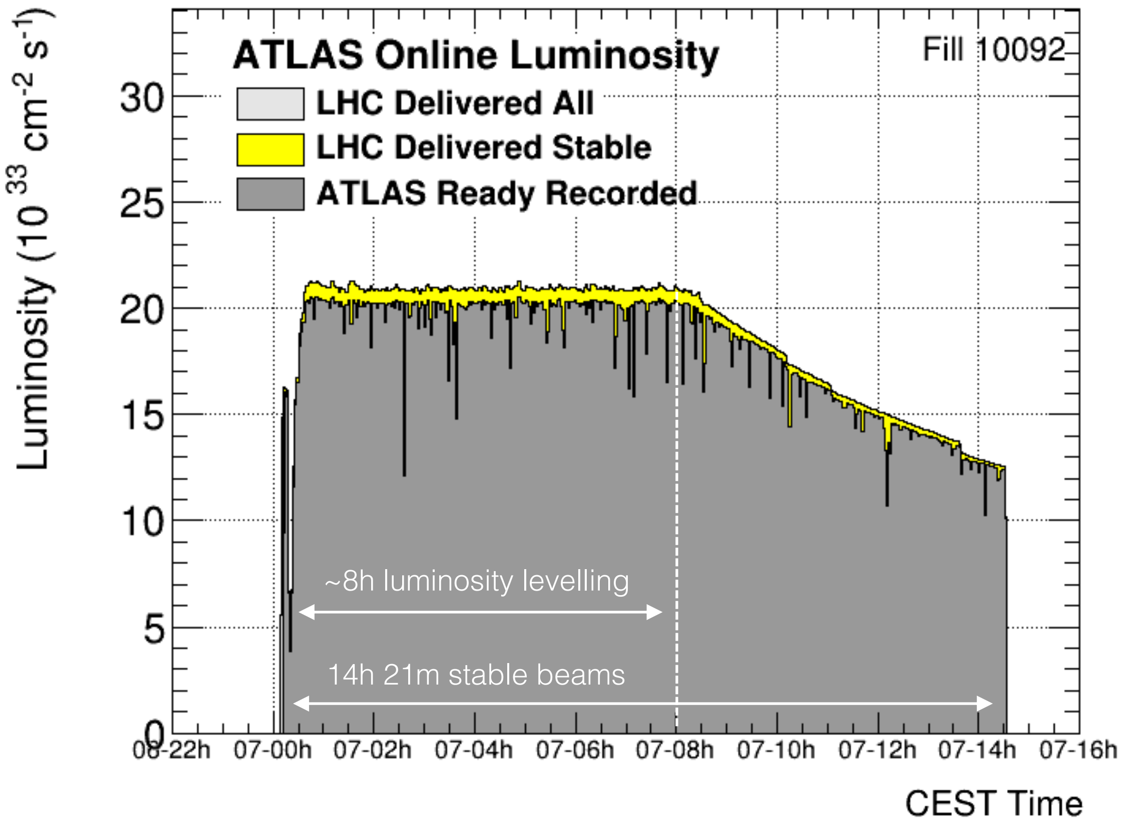
Spare slides

The Large Hadron Collider

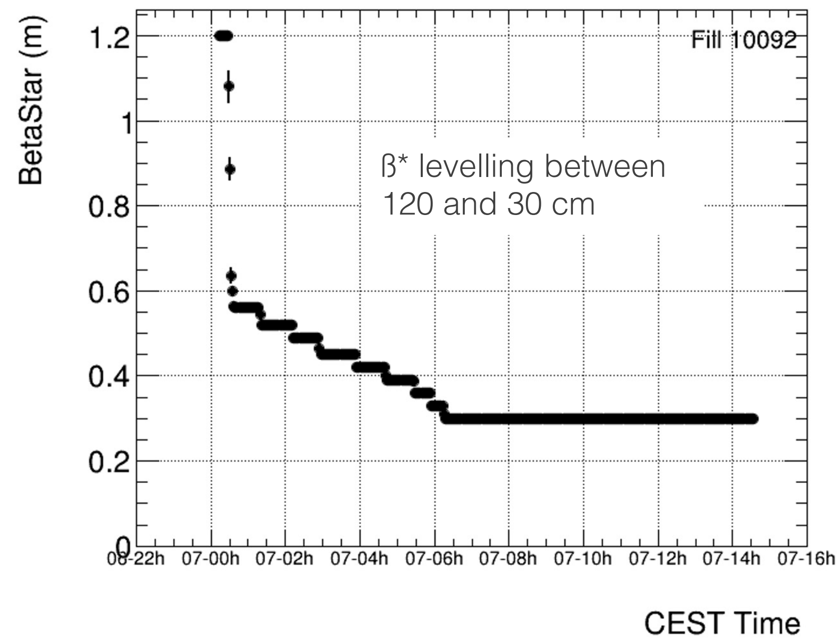
CMS

Superb performance of the LHC

Luminosity profile of a typical run (6 September 2024)



Luminosity levelling at 2.1×10^{34} cm^{-2}s^{-1} through defocusing and beam separation to keep pileup at ~63 until beam intensity has sufficiently dropped

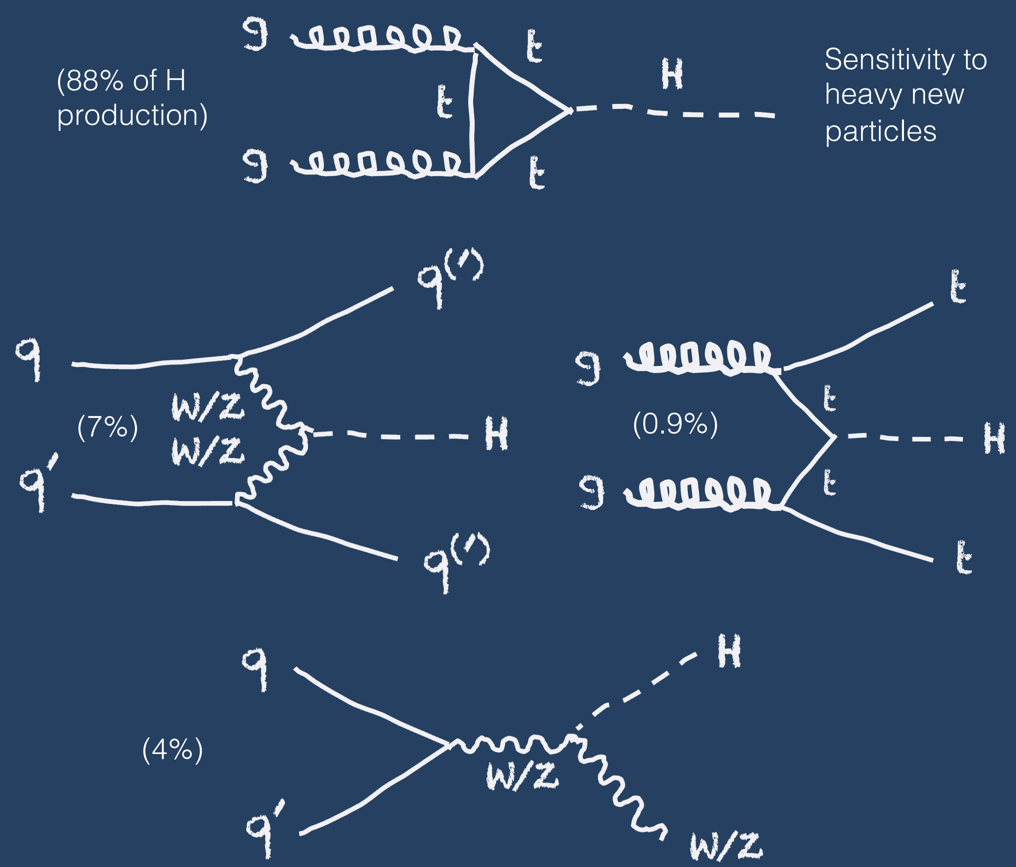


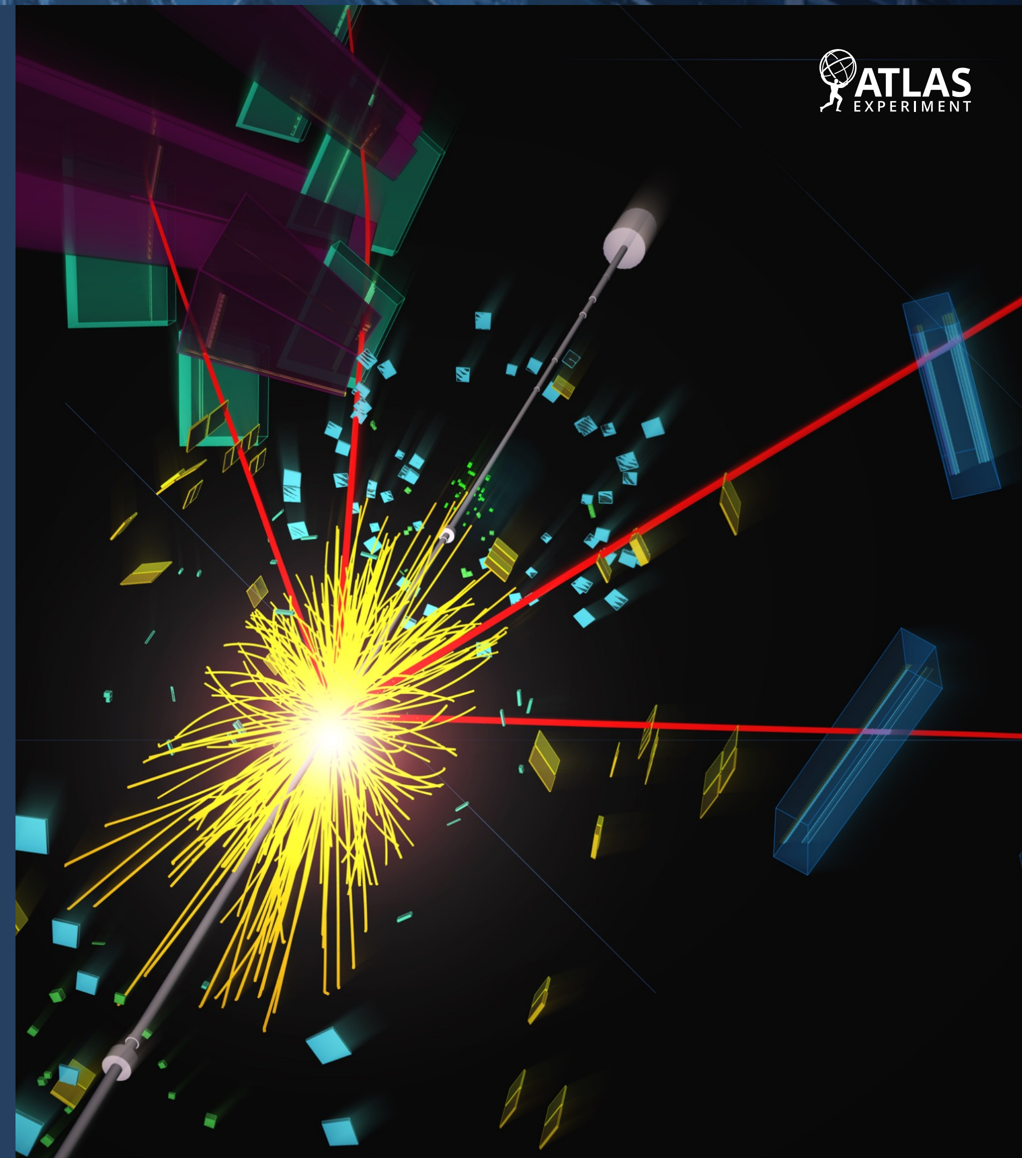
PS

Areal view

Higgs boson production at the LHC

About 1 Higgs boson per second is produced in ATLAS at the LHC (about 20M total by today)

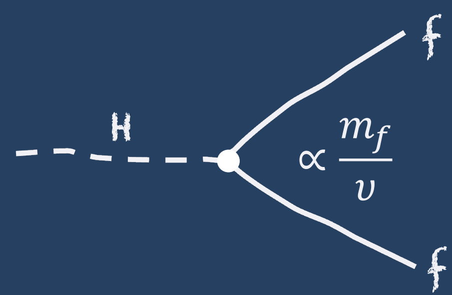


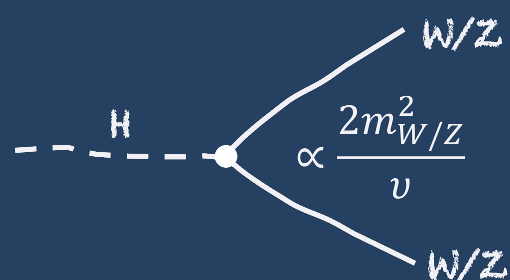


Higgs boson production at the LHC

About 1 Higgs boson per second is produced in ATLAS at the LHC (about 20M total by today)

It decays within 10^{-22} s





$H \rightarrow \gamma\gamma$, $Z\gamma$ occur through virtual top or W loops (no direct Higgs coupling to massless particles)