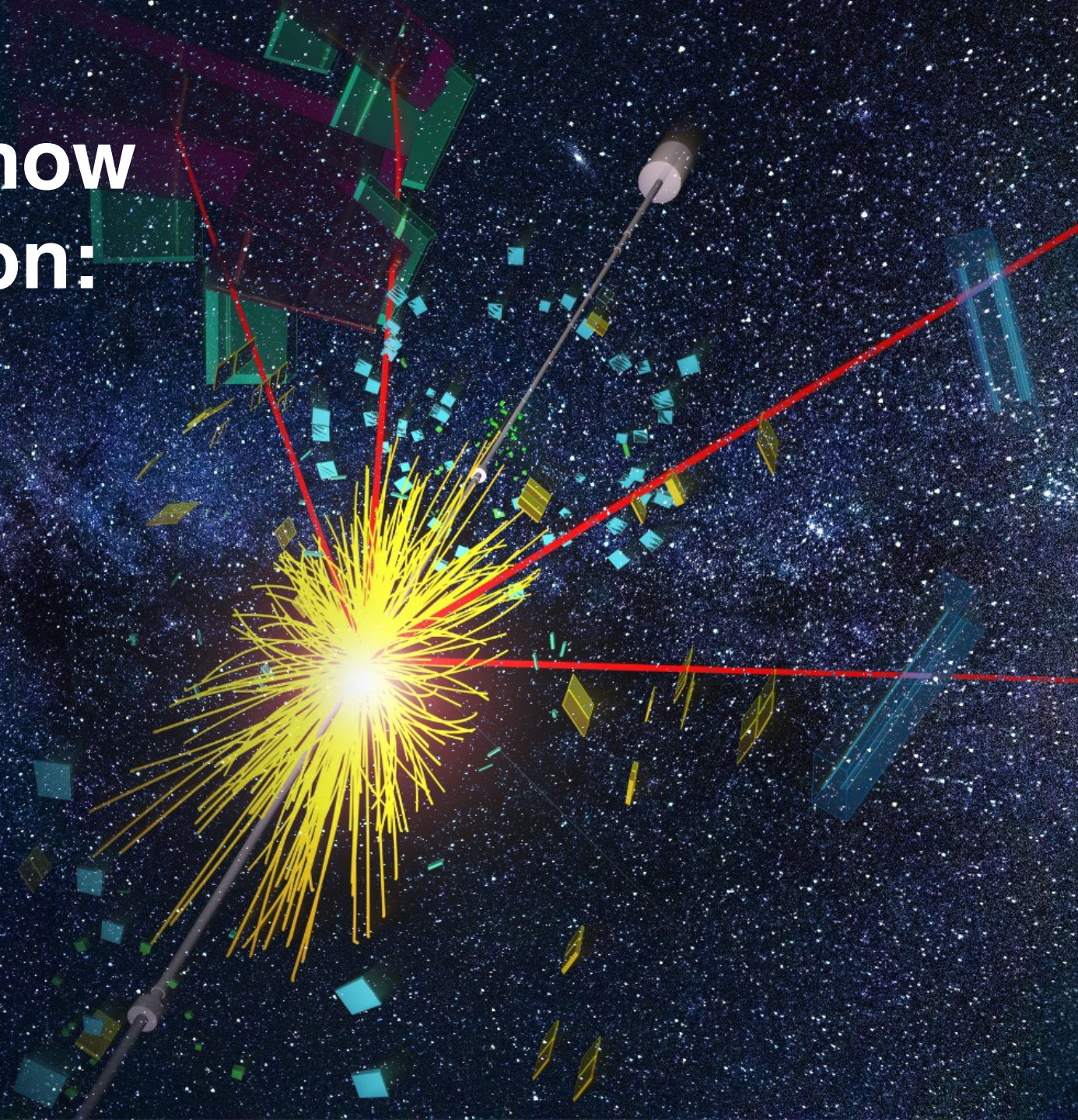


What we still don't know about the Higgs boson: the LHC's next act

Andreas Hoecker (CERN)

Università degli Studi di Milano, 17 March 2026



Hand mit Ringen

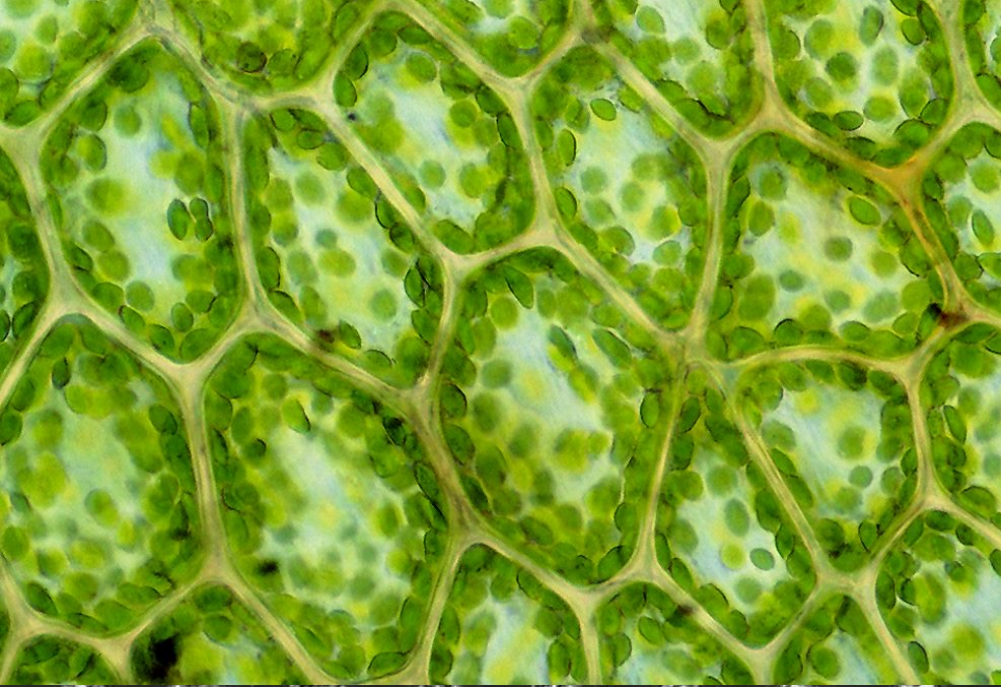


Physicists have long sought to uncover the structure of matter and make the invisible visible

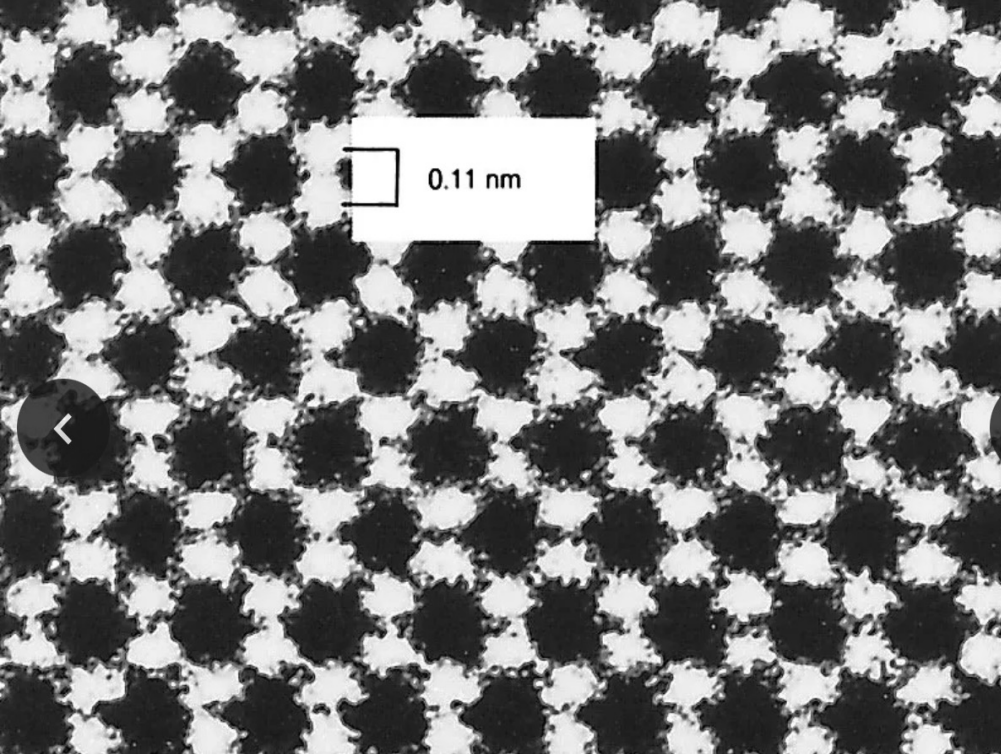
Energetic (= short wavelength) light allows us to visualise hidden structures

Hand mit Ringen (Hand with Rings): print of Wilhelm Röntgen's first "medical" X-ray, of his wife's hand, taken on 22 December 1895.

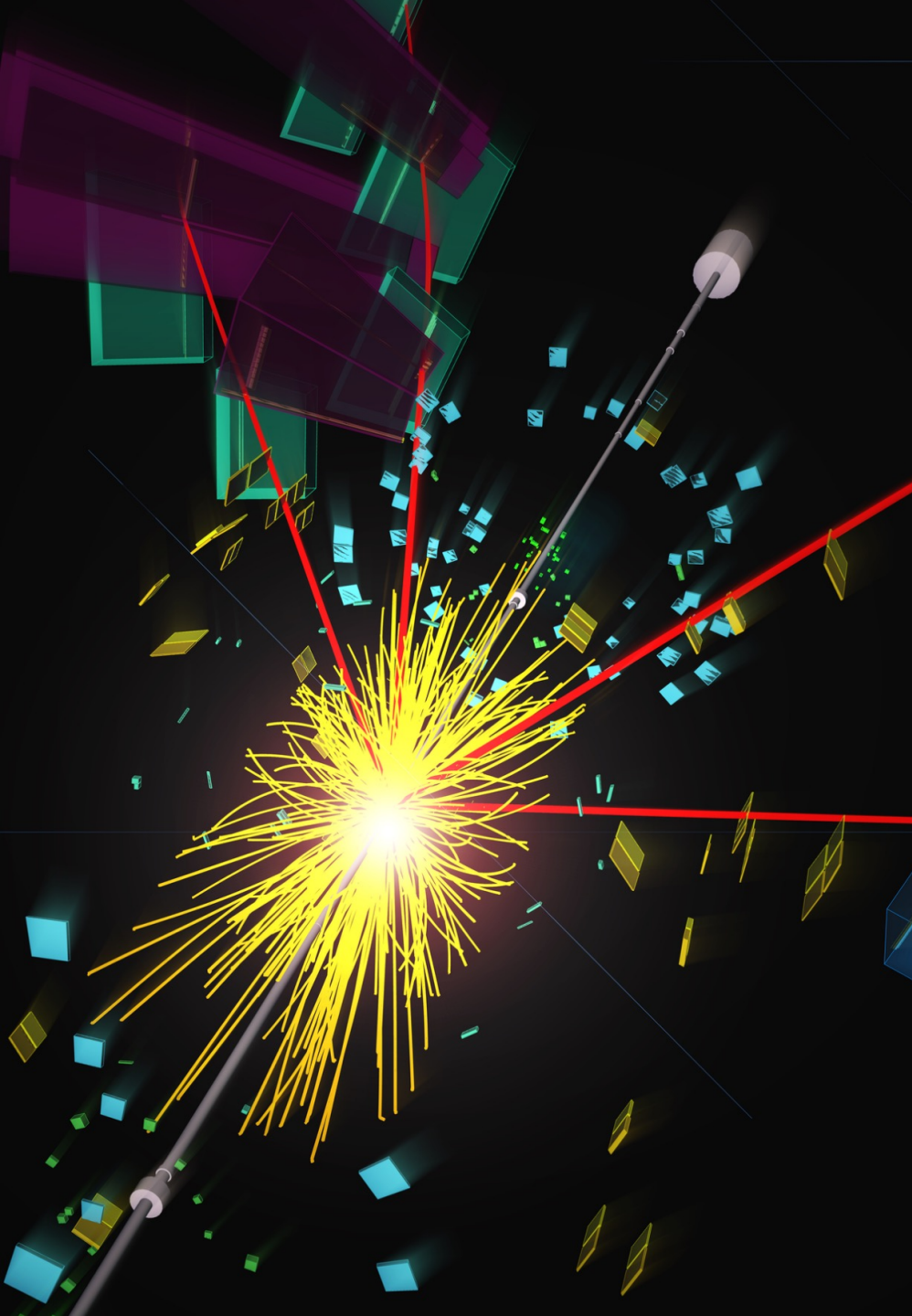
Source: Wikipedia



Light microscopes enabled the discovery of cells



More energetic (shorter-wavelength) electron microscopes resolve far smaller structures, such as viruses, and even reveal details at the atomic scale

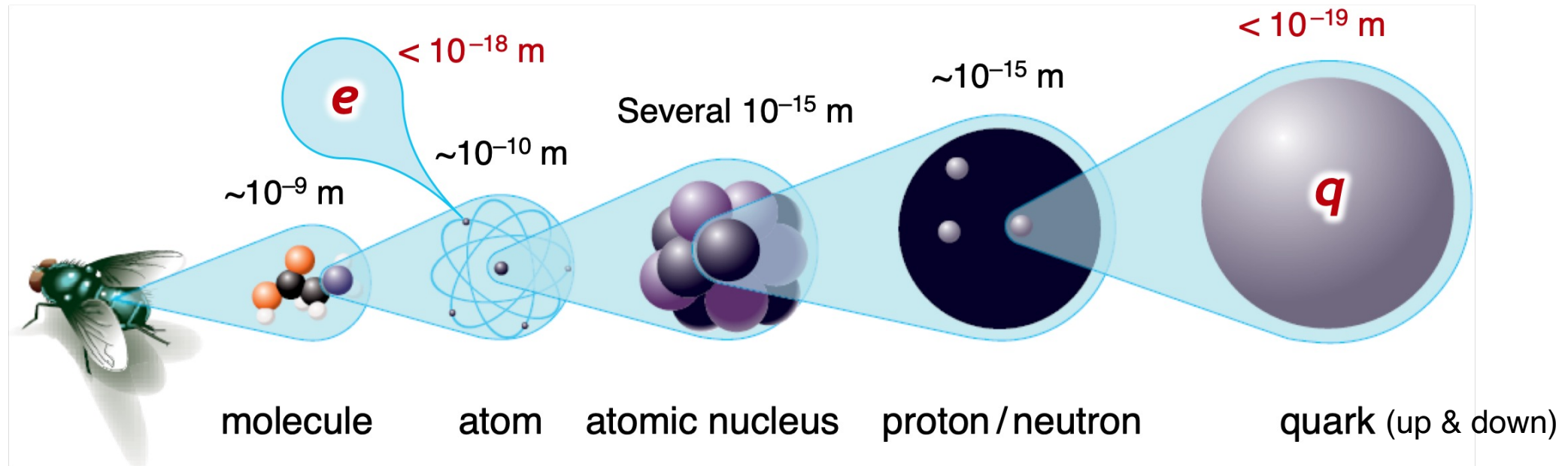


The energies generated in modern particle accelerators and colliders allow to resolve space almost a billion times smaller than today's best electron microscopes ...

... and to produce heavy particles through $E = mc^2$ that governed the early history of the universe

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

The sub-atomic structure of matter and its interactions is elegantly simple (a very simplified picture)



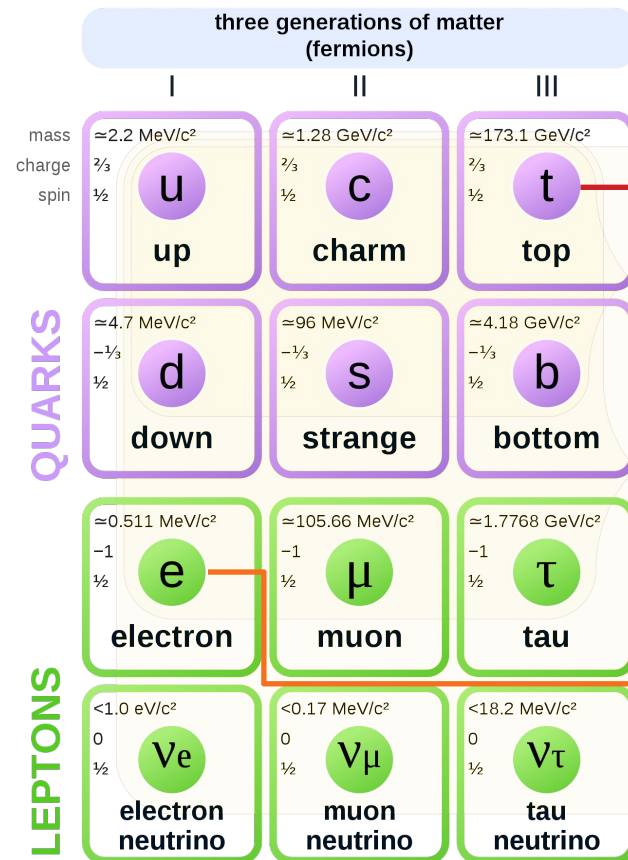
- Elementary particles appear point-like, with no spatial extent at all
- Without some remarkable mechanism at play, elementary particles would have no mass

We are seeing a strange universe, indeed

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

In mathematical terms, **particles are local excitations of quantum fields**. There are matter fields (fermions) and force fields (bosons)

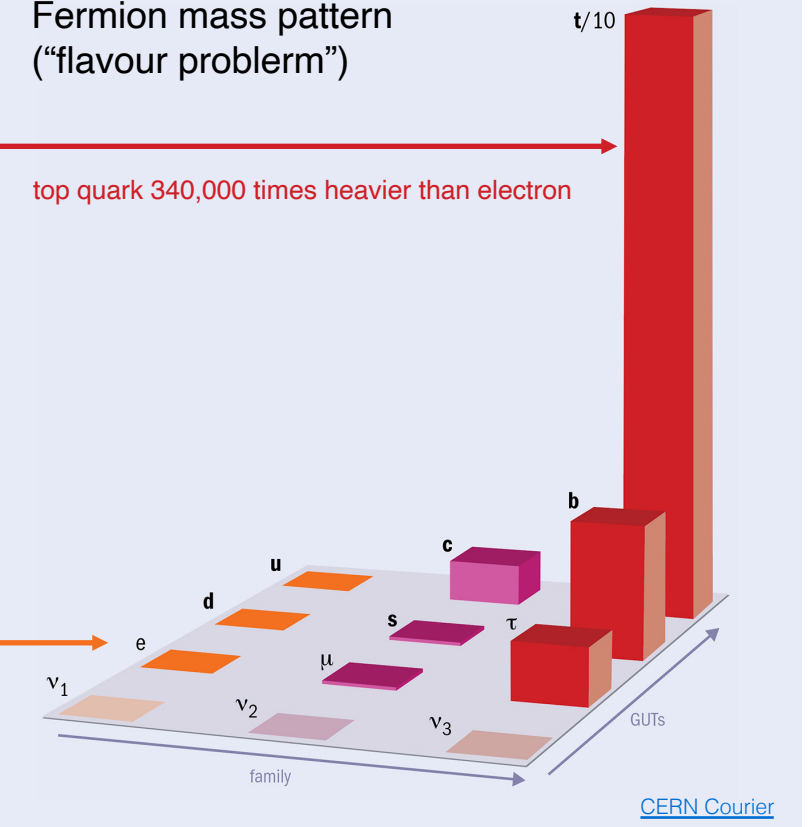
Standard Model of Elementary Particles



Spin 1/2

Fermion mass pattern
("flavour problem")

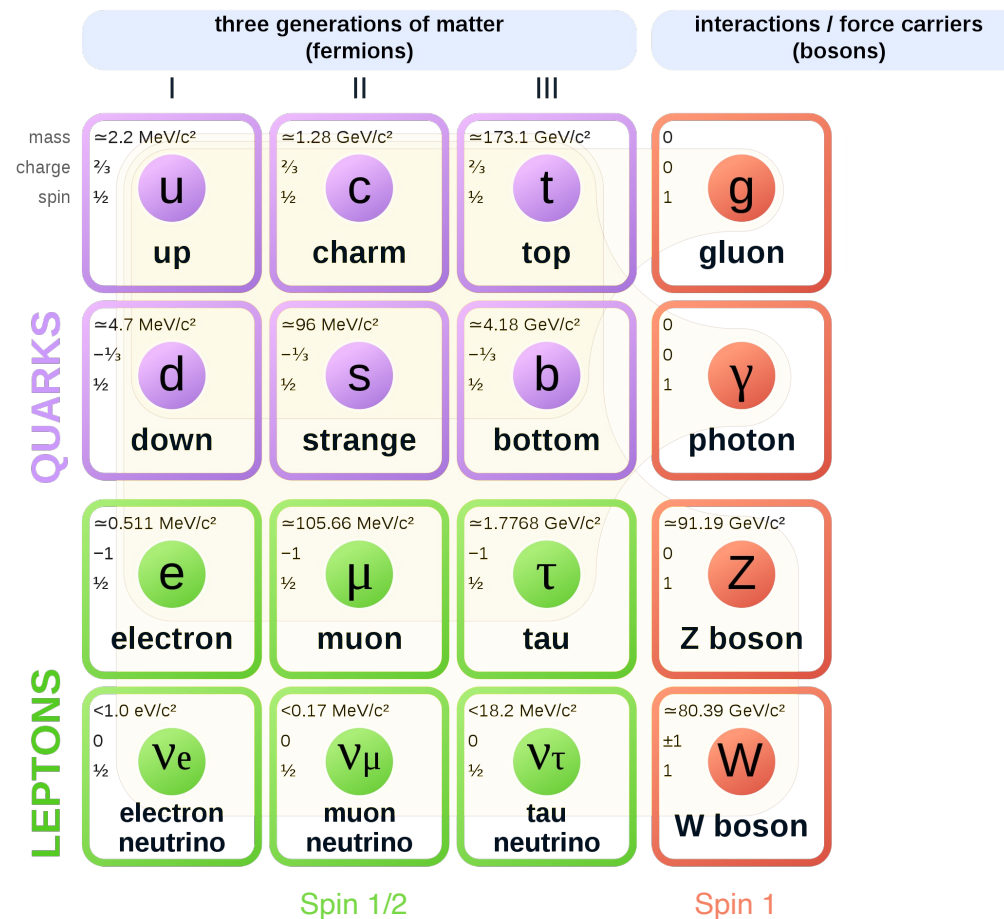
top quark 340,000 times heavier than electron



We are seeing a strange universe, indeed

The sub-atomic structure of matter and its interactions is described by the [Standard Model](#)

Standard Model of Elementary Particles

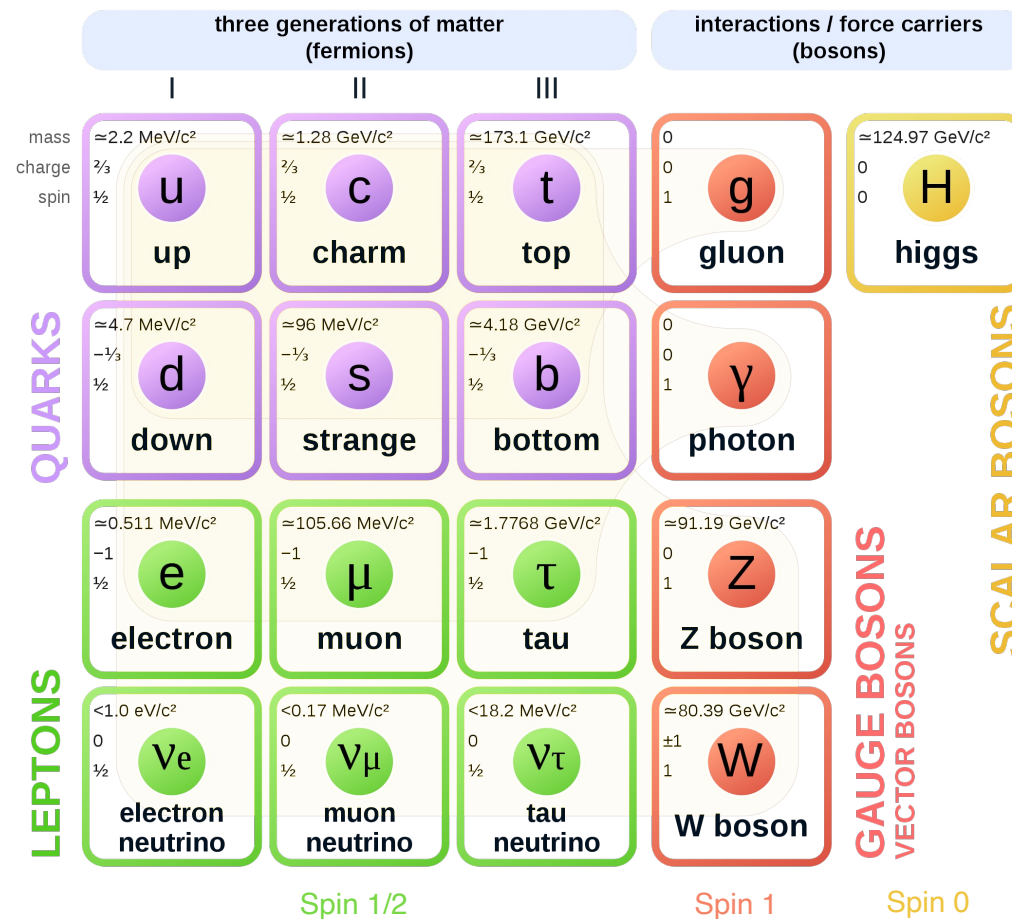


In mathematical terms, **particles are local excitations of quantum fields**. There are matter fields (fermions) and force fields (bosons)

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Standard Model of Elementary Particles



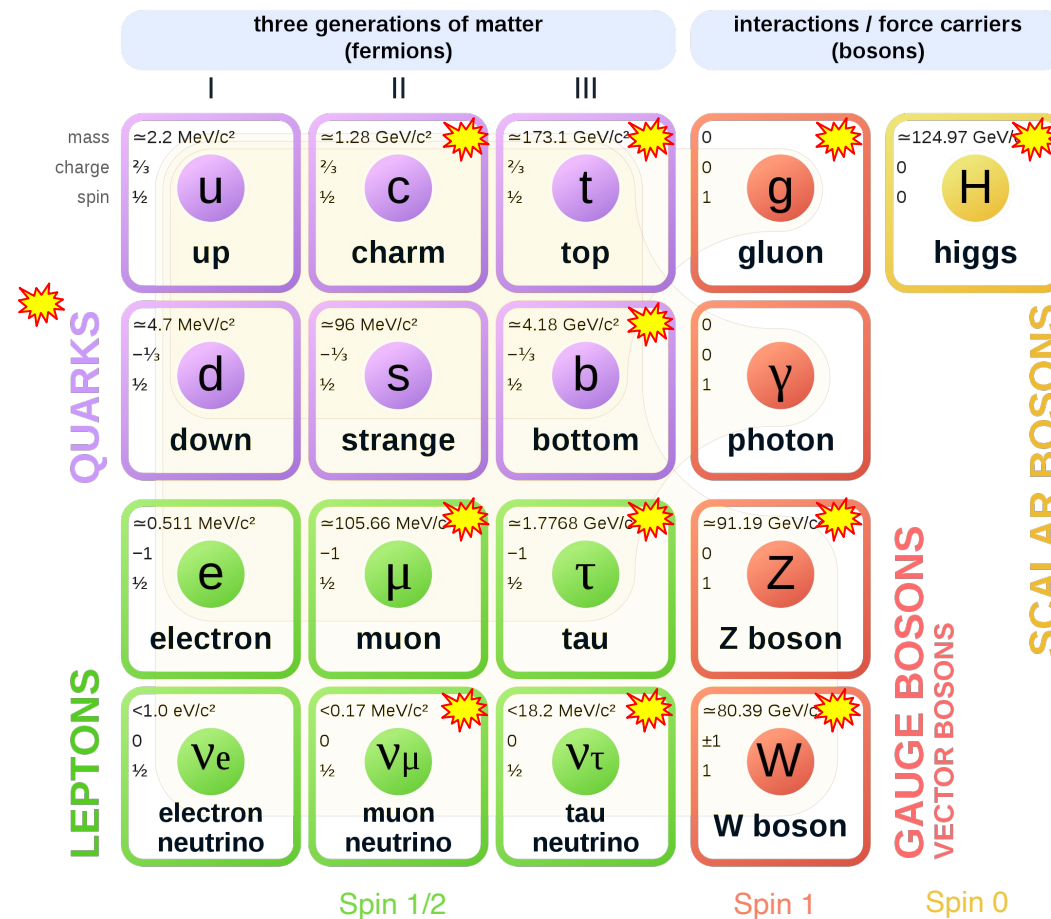
Completely new type of force, nothing to do with known forces

In mathematical terms, **particles are local excitations of quantum fields**. There are matter fields (fermions) and force fields (bosons)

We are seeing a strange universe, indeed

The sub-atomic structure of matter and its interactions is described by the [Standard Model](#)

Standard Model of Elementary Particles

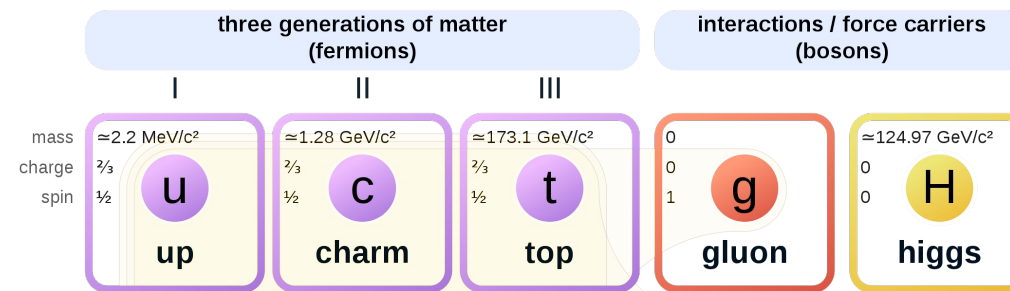


Particles discovered through decades of international, high-technology accelerator-based research

We are seeing a strange universe, indeed

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

Standard Model of Elementary Particles

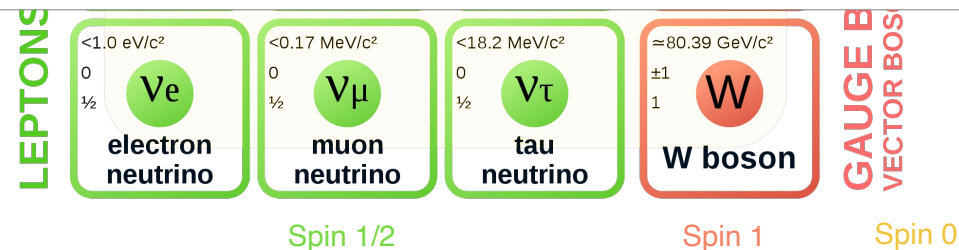


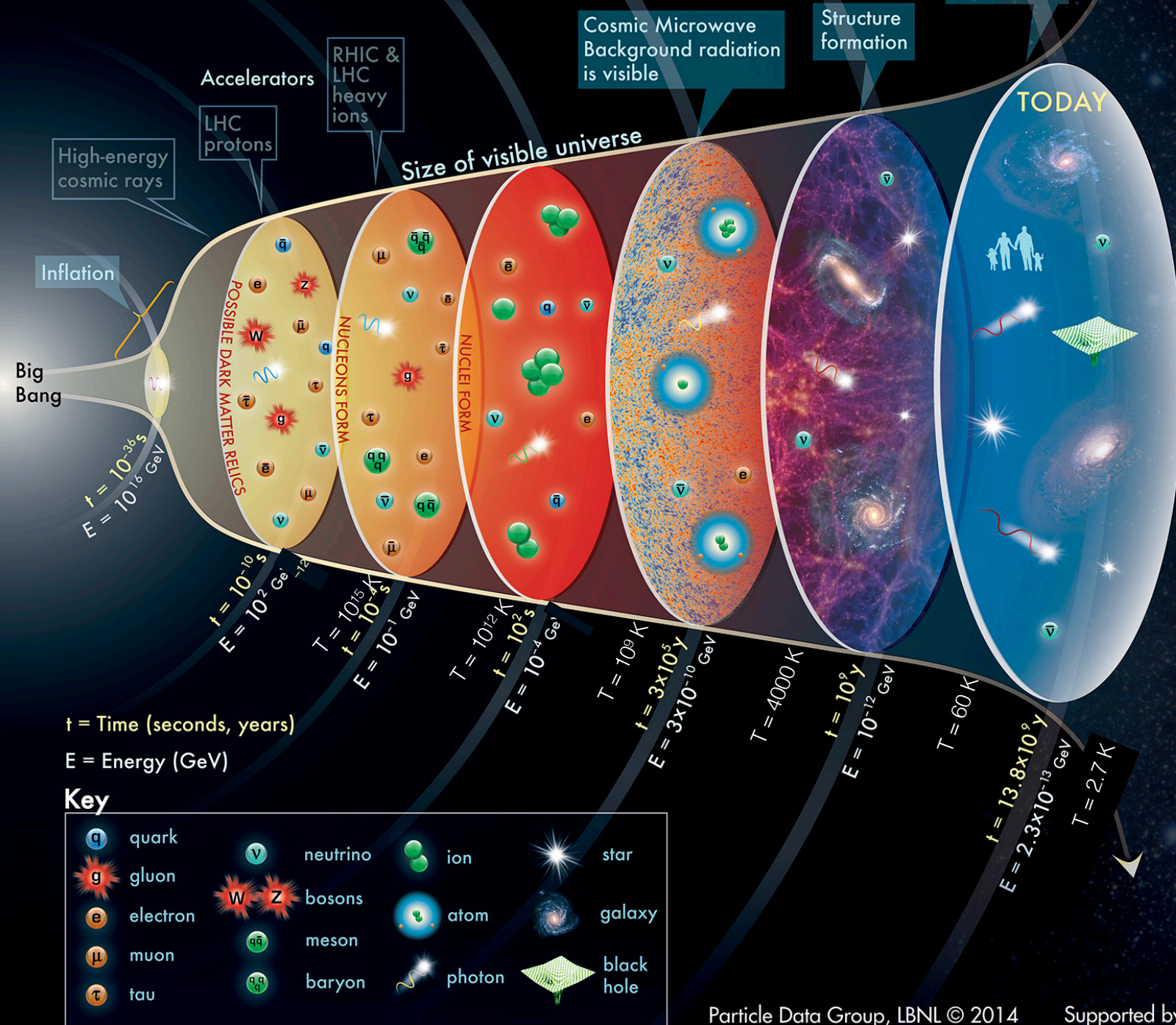
The Standard Model is a highly predictive theory

For example, the g-factor characterising the magnetic moment of the electron is predicted as:

$$g_e = 2.002\,319\,304\,361\,18 \pm 0.000\,000\,000\,000\,26$$

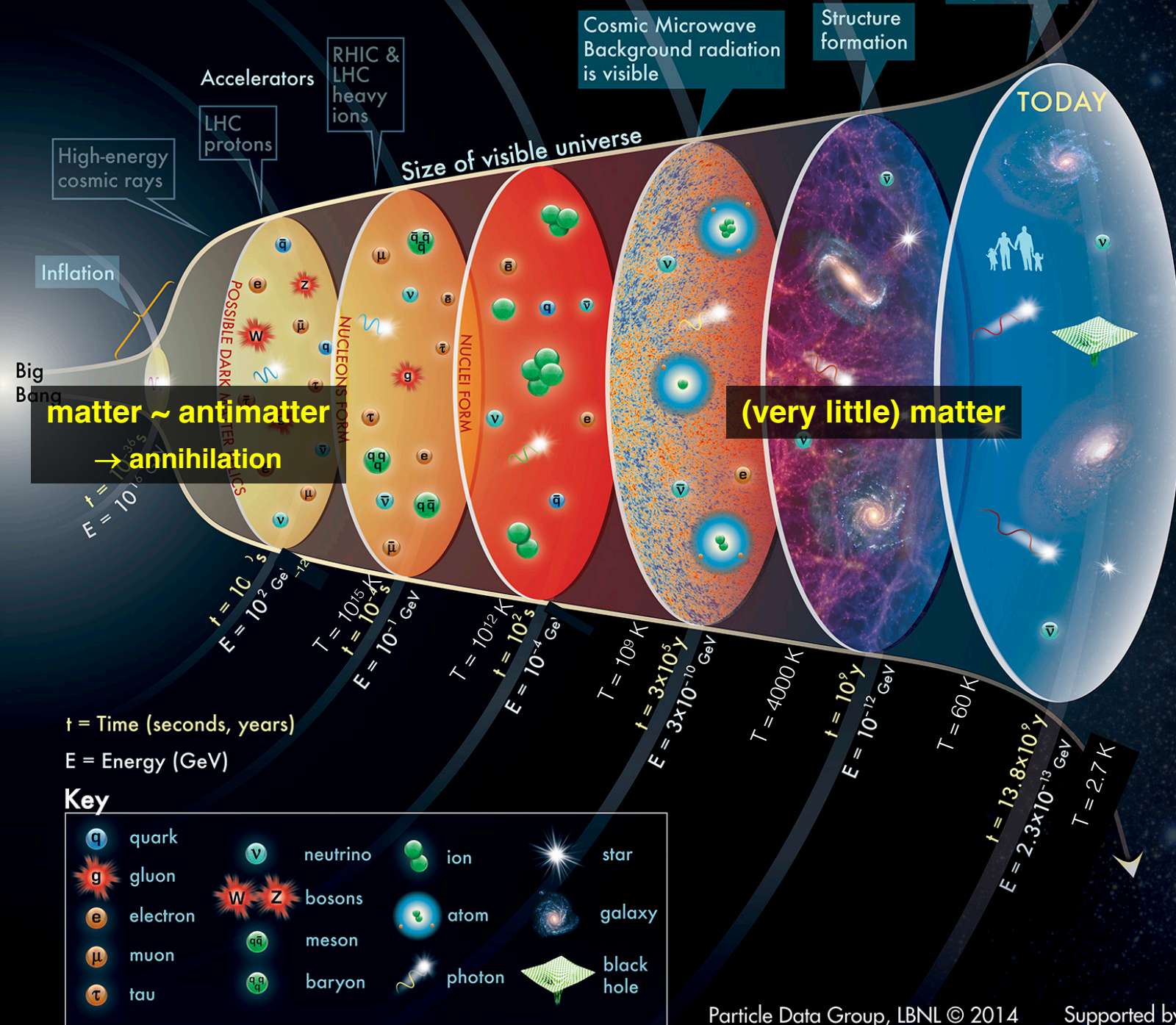
in agreement with experiment within a precision of 10^{-10} !





The Standard Model

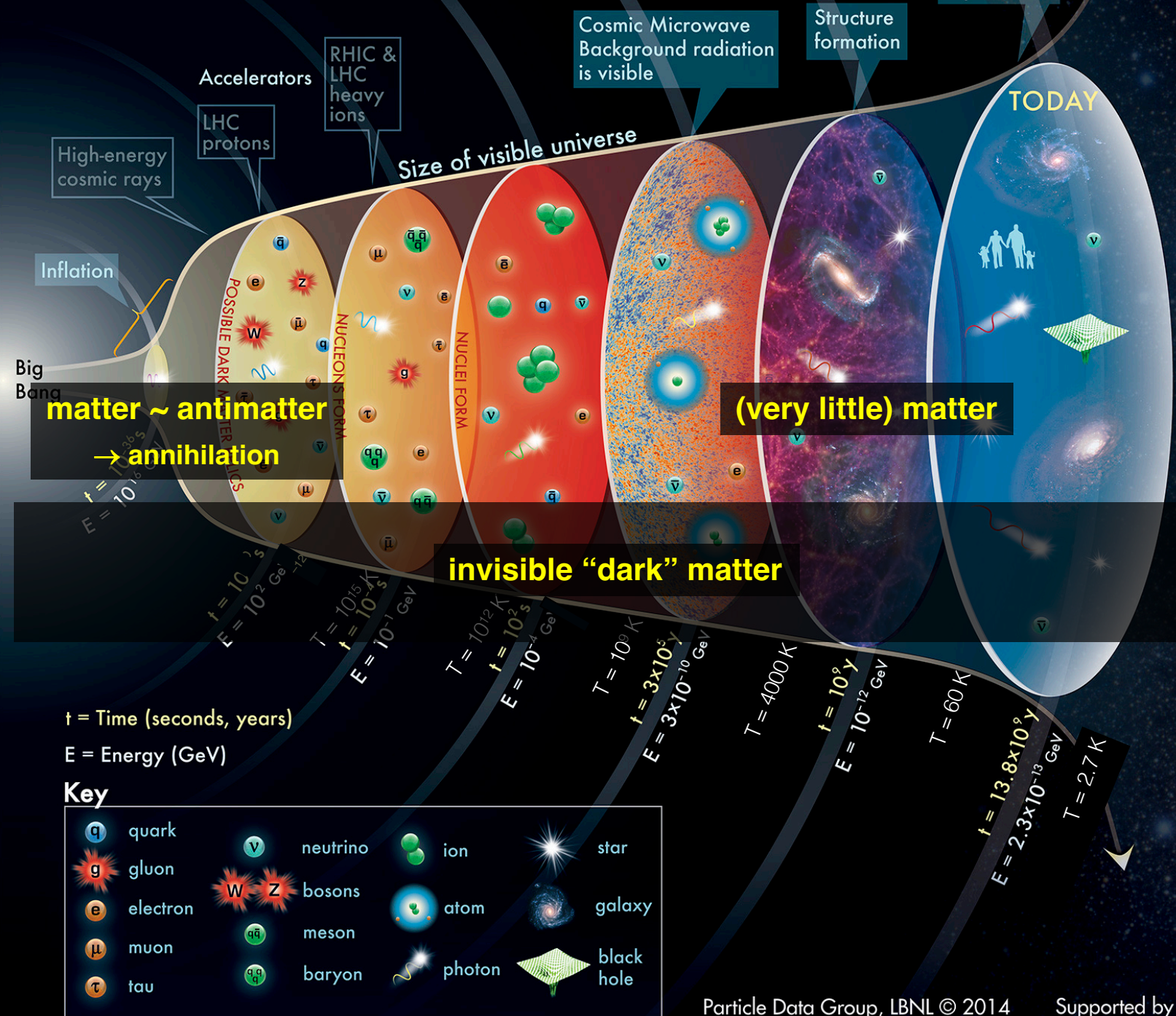
... should not only work today, but also describe the history of the universe since the Big Bang 13.8 billion years ago



The Standard Model

... should not only work today, but also describe the history of the universe since the Big Bang 13.8 billion years ago

But why is there only matter left in the universe?

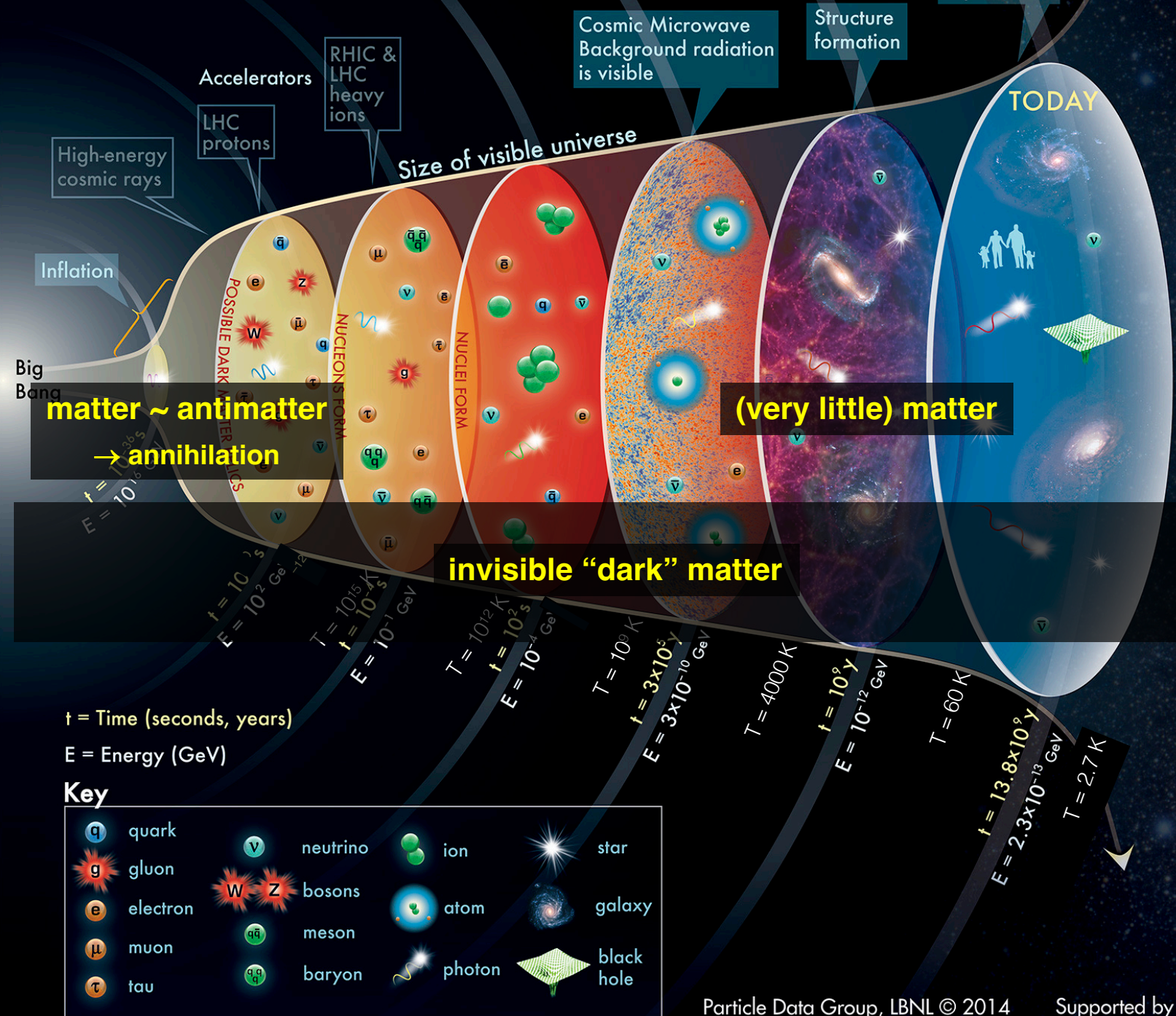


The Standard Model

... should not only work today, but also describe the history of the universe since the Big Bang 13.8 billion years ago

But why is there only matter left in the universe?

And what is the origin of the huge quantity of *dark matter* (5–6 times more than the baryonic matter)?



The Standard Model

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But why is there only matter left in the universe?

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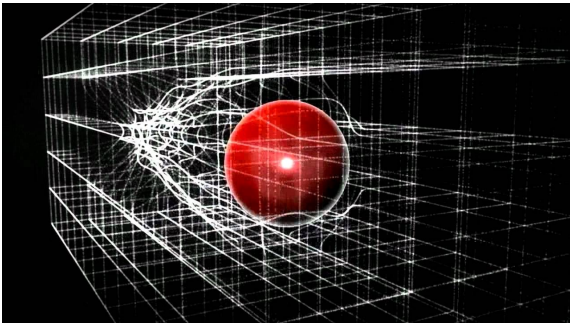
And why do elementary particles have mass at all?
(Simply sticking masses onto particles breaks gauge symmetry)

Gauge symmetry and the Brout-Englert-Higgs mechanism

A solution to the mass problem is to introduce a new complex scalar field ϕ , which couples to the weak bosons and fermions, and whose energy potential is such that the field condensates below a critical temperature T_{EW} with a non-zero vacuum expectation value $\langle 0|\phi|0\rangle = v \neq 0$, thus spontaneously breaking the symmetry of the vacuum

The field pervades all space. The interaction of a particle with the Higgs field gives the particle mass. The stronger the interaction the greater the mass.

A local excitation of the Higgs field ϕ around its ground state is the **Higgs boson**



Peter Ware Higgs (1929 – 2024)

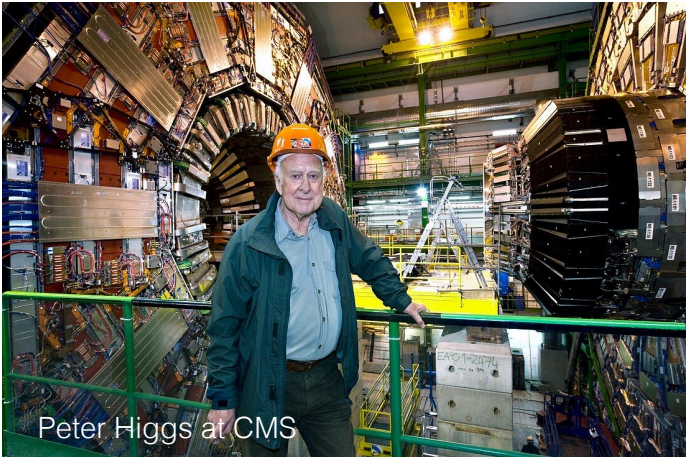


Broken Symmetries and the Masses of Gauge Bosons — or how to change the course of physics with a good idea on two pages — together with the other famous works from his colleagues in 1964

Superconductivity (BCS theory) was key in the development of the BEH mechanism [[My life as a boson](#), 2010]



Peter Higgs and Fabiola on 4 July 2012



Peter Higgs at CMS

The Brout-Englert-Higgs (BEH) mechanism

*Note that in the SM, this phase transition is a smooth crossover, ie, of 2nd order with no Higgs bubble creation

The BEH potential energy:

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

At lowest order (tree level)

The early universe, at $T > T_{EW}$, was in a symmetric phase ($|\phi_{min}| = v_T = 0$), a phase transition at $\sim T_{EW}$ ($\sim 10^{15}$ K, 10^{-12} s after the big bang) led to $|\phi_{min}| = v_{T_{EW}} > 0$

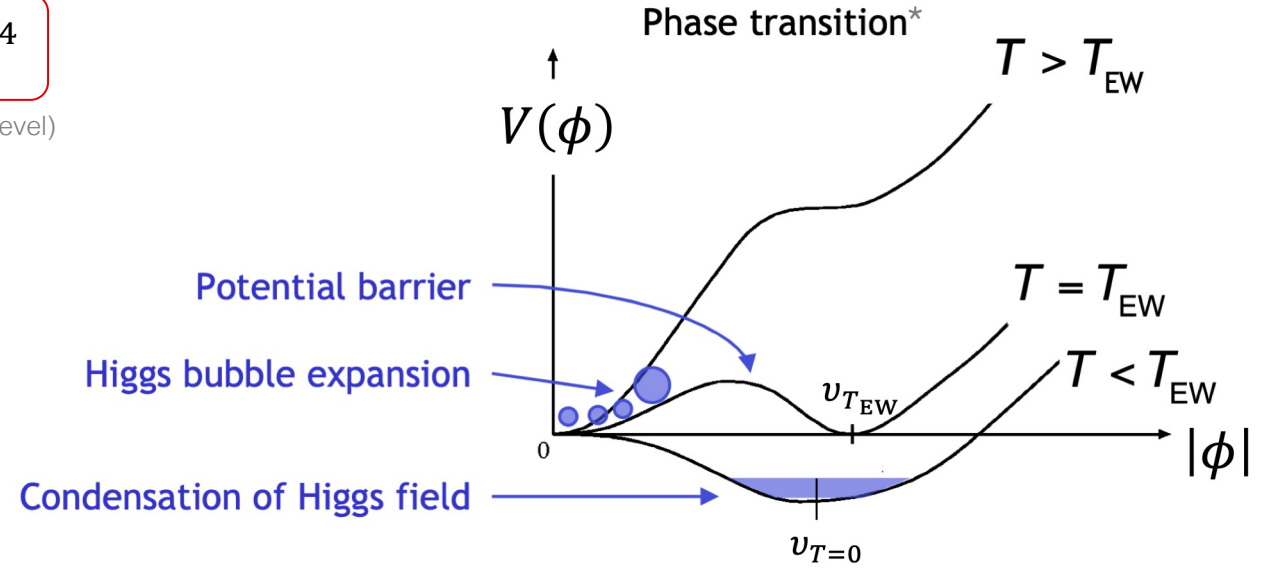
At $T = 0$, $V(\phi)$ has a minimum at:

$$v = v_{T=0} = \sqrt{\frac{\mu^2}{2\lambda}} \quad (v = \frac{1}{\sqrt{\sqrt{2}G_F}} \approx 246 \text{ GeV})$$

where was used: $g/m_W \propto \sqrt{G_F}$

Developing $\phi(x) \propto (0, v + H(x))$ around the minimum and inserting it into the SM Lagrangian expanded by particle interactions with $\phi(x)$, determines the particle spectrum

- $m_\gamma = 0$, $m_W = \frac{1}{2}gv$, $m_Z = \frac{1}{2}\sqrt{g^2 + g'^2} \cdot v$, $m_W/m_Z = \cos \theta_W$
- $m_f = \frac{1}{\sqrt{2}}y_f v$, (y_f (Yukawa couplings) not predicted by Higgs mechanism, note that $y_{top} \approx 1$, but $y_e \approx 0.3 \cdot 10^{-5}$)
- $m_H = \mu = v\sqrt{2\lambda} + \Delta\lambda$ (energy-dependent quantum corrections)



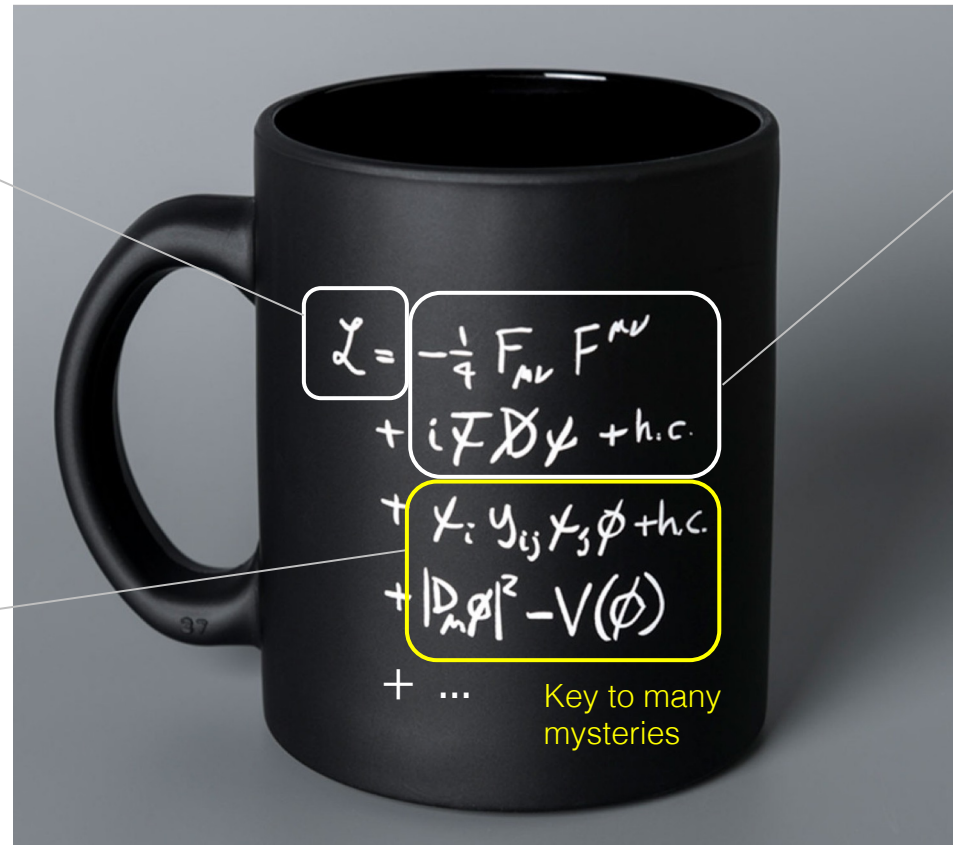
Completing the Standard Model

The scalar Higgs sector completes the Standard Model

The **SM Lagrangian**

This term is related to the **Higgs sector**

Unpleasant: not governed by symmetries, 23 free parameters*, large hierarchy among masses



These terms describe **interactions among force particles (top) and among matter and force particles (bottom)**

Beauty: interactions governed by gauge symmetries with only 3 (EW) and 2 (QCD, θ_{strong} tiny $\rightarrow$ strong CP problem) parameters

Key to many mysteries

*Assuming neutrinos are Majorana particles (total of 9 neutrino related parameters)

The Brout-Englert-Higgs mechanism

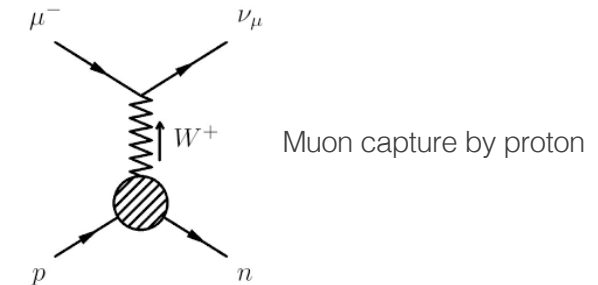
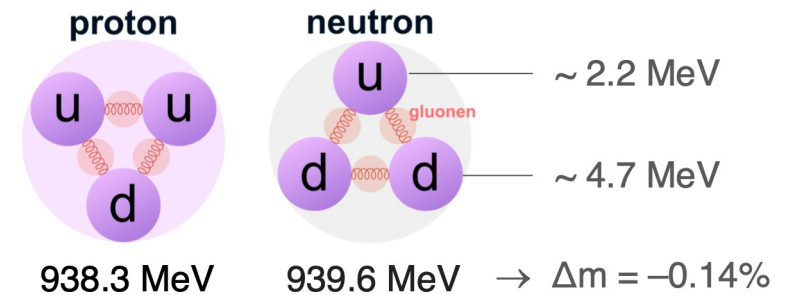
A few remarks:

- The left-right asymmetric (chiral, V–A) gauge structure of weak interaction forbids “bare” fermion masses; they arise only via the BEH mechanism $m_f = \frac{1}{\sqrt{2}} y_f v$, making SM fermions naturally light
- The SM fermion structure may suggest that there are (many?) super-heavy left-right gauge symmetric fermions (beyond our reach) in a grand-unified framework, and the SM fermions only survived down to the EW scale because they cannot have bare masses. This may also explain the very light neutrinos (lepton-number violation has at least D=5, suppressed by super-heavy M)
- The Higgs boson can have bare mass, so why is it (and with it the W and Z bosons) not super heavy?
- **This is the core conceptual challenge of the SM, calling for in-depth study of the scalar sector and potential TeV-scale extensions**

The Brout-Englert-Higgs mechanism

A few further comments:

- The BEH mechanism provides a dynamical origin of mass through spontaneous symmetry breaking. Other forms of mass exist: in composite systems such as hadrons most mass arises from QCD binding energy; in classical mechanics mass is simply a fundamental inertial parameter. The Higgs boson mass itself, $m_H = v\sqrt{2\lambda}$, comes from the curvature of the Higgs potential at its minimum and is a gauge-invariant parameter of the SM
- The masses due to the BEH mechanism govern the history of the universe (incl. complex chemistry and life) → what would happen had we a dial to change the particle masses? [see [R. Cahn](#), 1996]



An analogy to the BEH mechanism

Superconductivity

SC (BCS*) theory

Cooper pair Bose condensation

Electrically charged ($2e$)

Mass of the photon

$T_{\text{crit}} \sim \text{mK} - \text{several } 10\text{s of K}$

Higgs mechanism

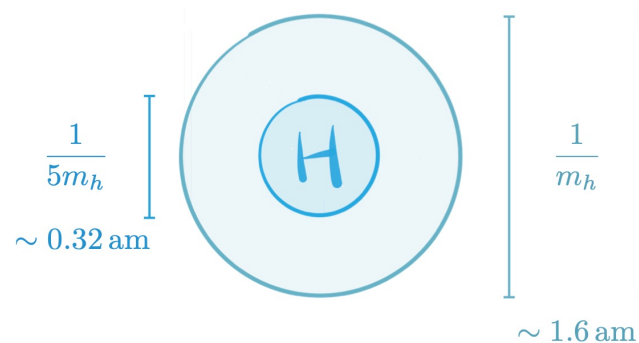
Condensed Higgs field

Weak charge

Mass of W & Z bosons

$T_{\text{crit}} = T_{\text{EW}} \sim 10^{15} \text{ K}$

→ Is the Higgs boson elementary or composite?



A superconductor is locked mid-air in different orientations above a permanent magnet — superconductive levitation due to the expulsion of the static magnetic field (Meissner effect) [[Source](#)]

In response to an externally applied magnetic field, perpetual eddy currents circulate in the superconductor, producing an internal magnetic field that exactly cancels the externally applied one

*Bardeen, Cooper, Schrieffer theory – mid 1950s

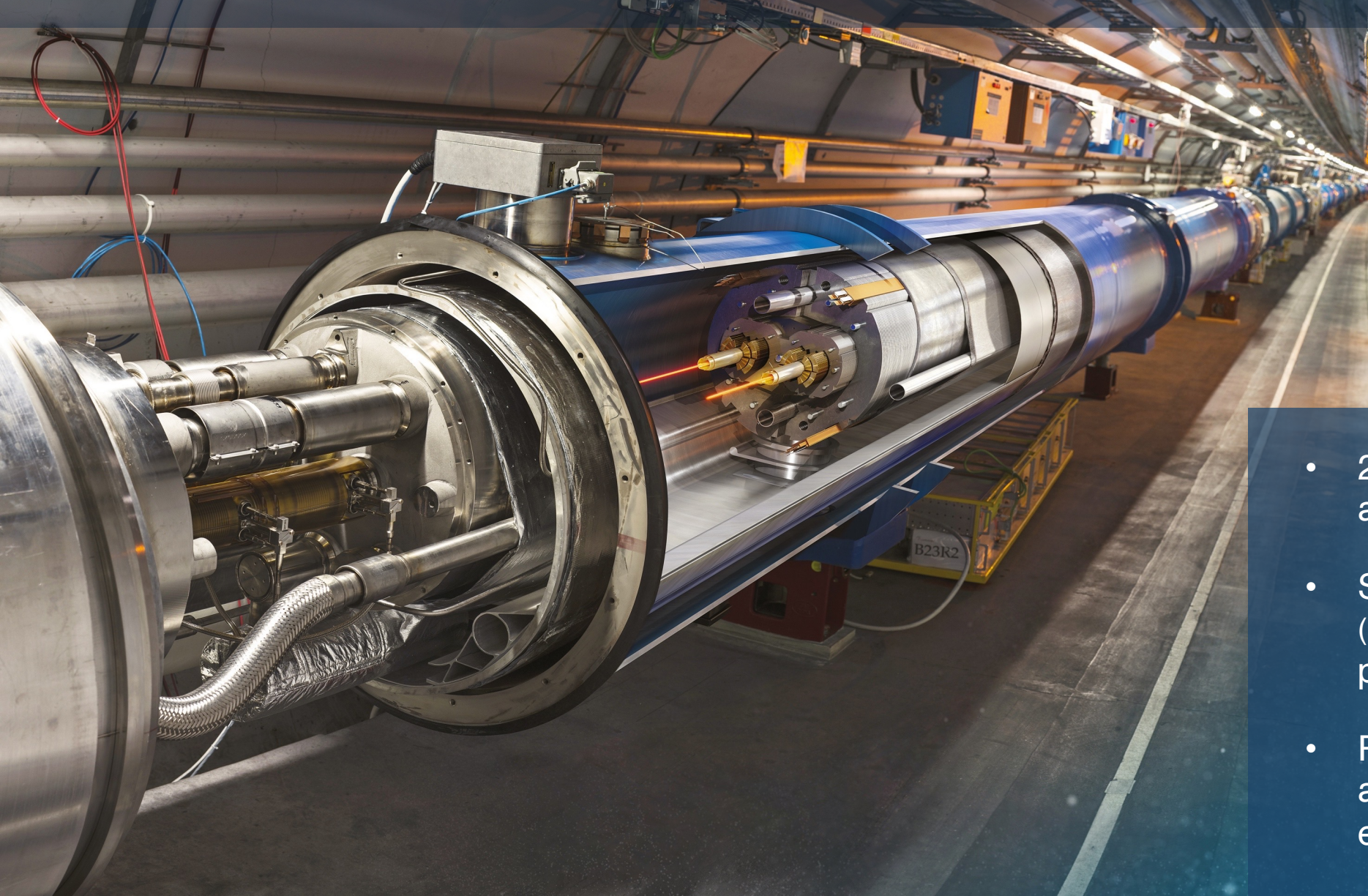
Further reading, eg: [L. Dixon, "From superconductors to supercolliders", 1996](#)

Producing the Higgs boson and pushing the boundaries of our understanding requires a huge accelerator

This accelerator has been built at CERN



Large Hadron Collider (LHC) — the world's largest accelerator reaching unprecedented energies



- 27 km underground accelerator and collider
- Superconducting magnets ($1.9\text{ K} = -271.3\text{ }^{\circ}\text{C}$) steer the particles around the ring
- Proton and ions are accelerated to multi-TeV scale energies before they collide

LHC



CMS

LHC

LHC

CERN
Preessin

ALICE >>

ATLAS

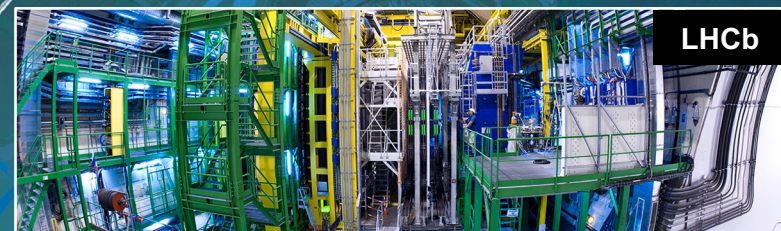
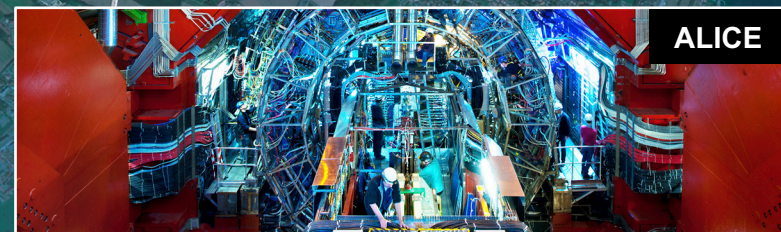
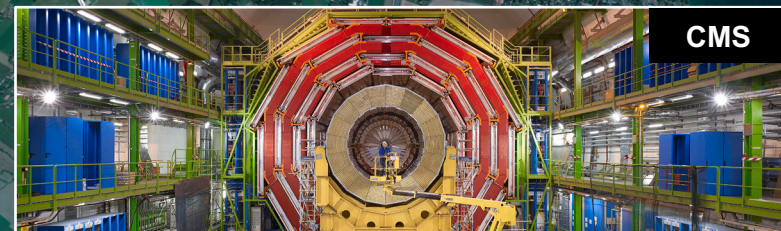
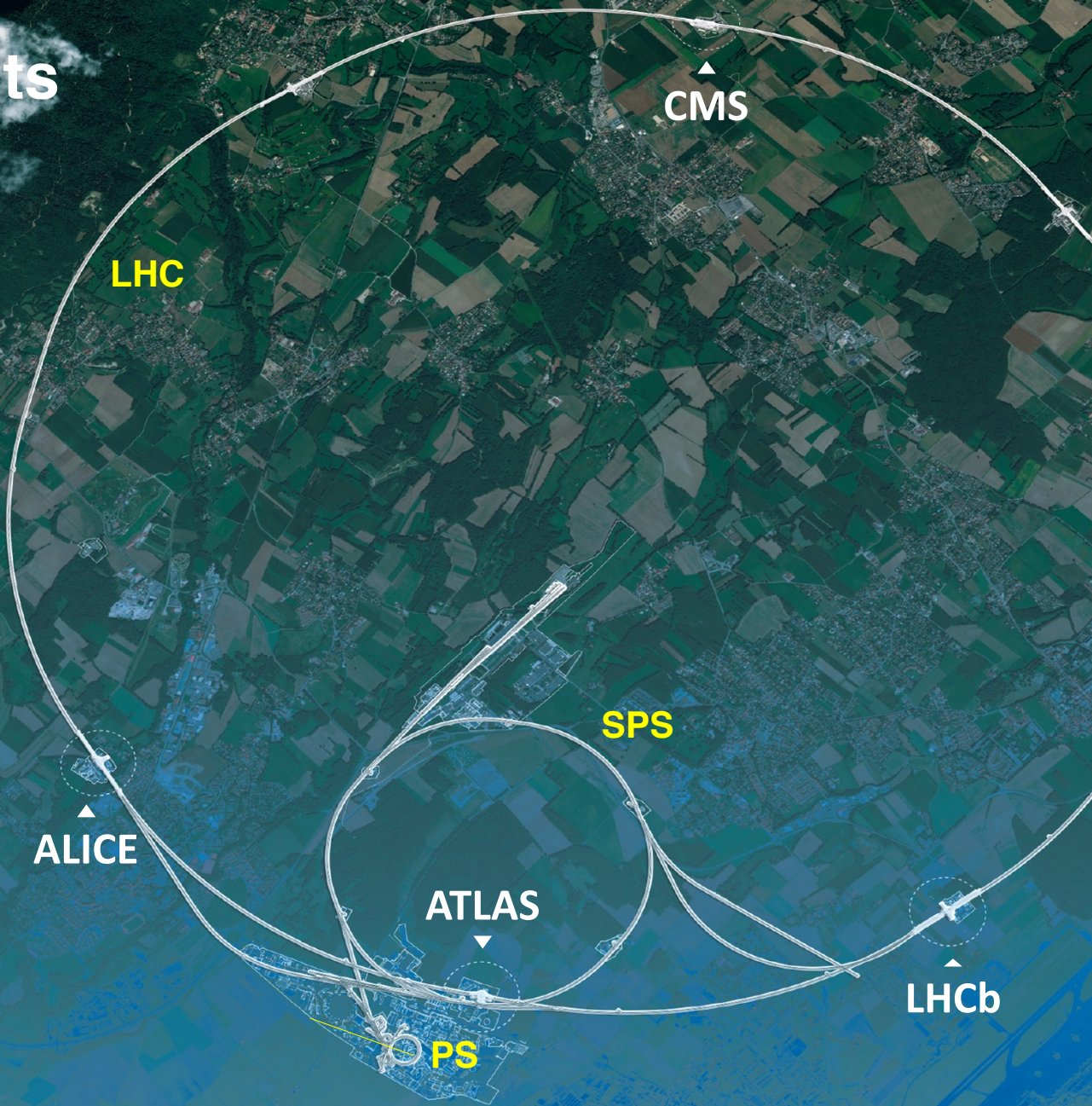
CERN
Meyrin

<< LHCb

Aerial view

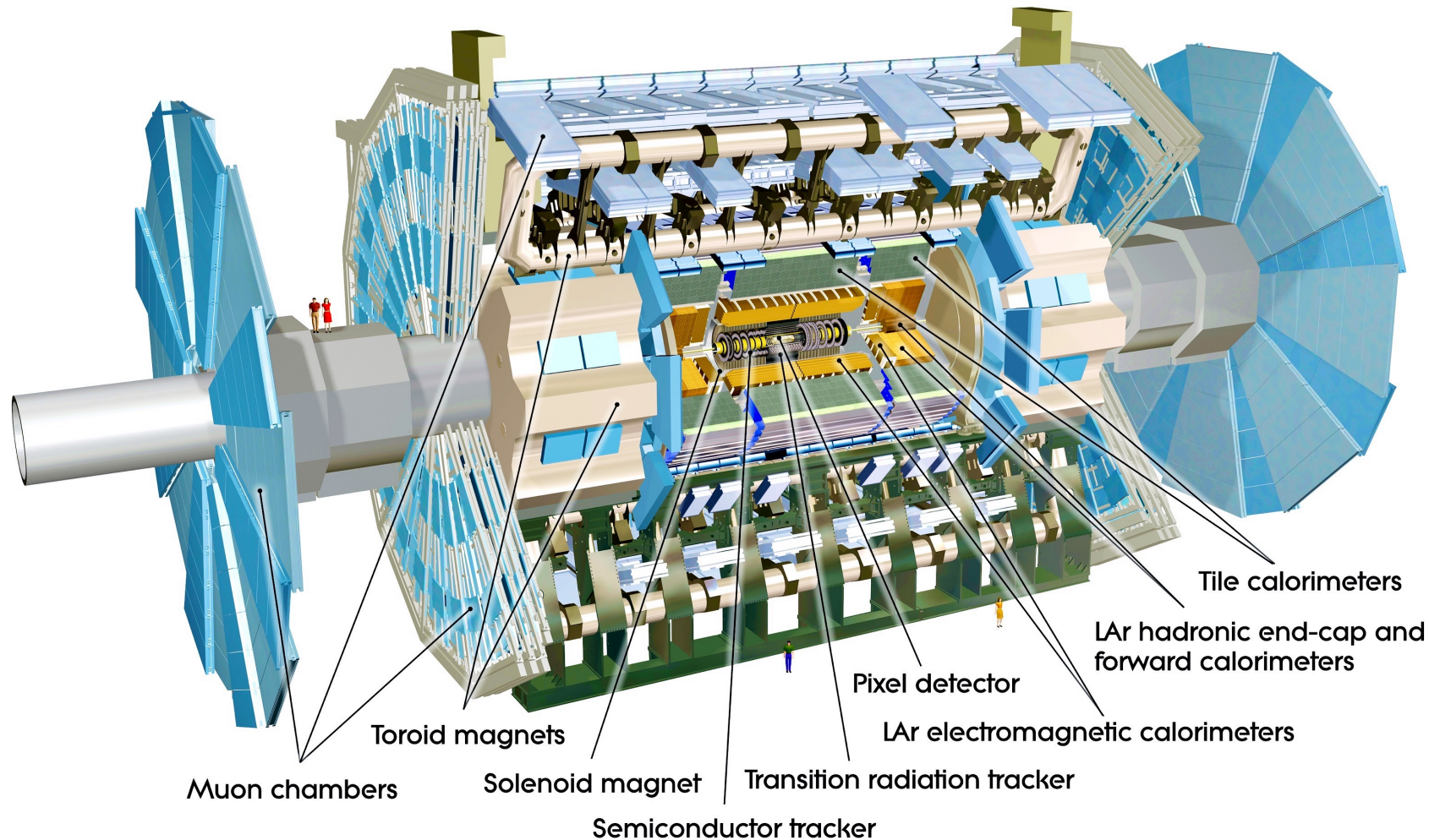
1 km

LHC and Experiments



Aerial view

The ATLAS Detector



Axial field provided by **solenoid** (2 T) in central region (momentum measurement)

High resolution silicon **detectors**:

- 100 Mio. channels ($50\ \mu\text{m} \times 250\ \mu\text{m}$)
- 6 Mio. channels ($80\ \mu\text{m} \times 12\ \text{cm}$)

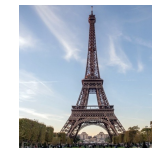
spatial resolution $\sim 15\ \mu\text{m}$ (in azimuthal direction)

Energy measurement down to 1° to the beam line with a **calorimeter system**

Independent **muon spectrometer** (superconducting toroidal magnet system)

Ultra-fast custom electronics and high-performance computers filter the collisions: only 1 out of 20,000 collisions is kept

25 m diameter, 44 m long, 7000 tons weight ~



The ATLAS Collaboration

ATLAS is a multi-decade experimental programme involving:

- 242 institutes from 40 countries
- 2900 Scientific authors
- 1200 Physics PhD students
- 1300 Engineers or technicians
- 100 Engineering students
- 6000 Active members



**UNIVERSITÀ
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DI MILANO**

Is a founding member of ATLAS

Dynamic group with more than 50 active members and broad contributions to the experiment, incl. its construction and upgrade.

Is also a member of LHCb

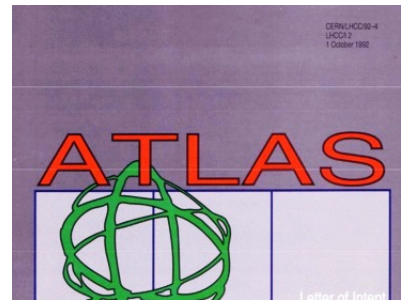
with equally broad contributions to the experiment.



Photo taken in Dec 2024 at the ATLAS detector site at CERN

Links:

[ATLAS public home page](#),
[Physics results](#), [Interactive ATLAS world map](#), [Static world maps](#), [List of ATLAS institutes](#)



ATLAS Letter of Intent
Oct 1992

Milano signatories of ATLAS Lol in 1992

Physics Department, Milan University and I.N.F.N., Milan, Italy

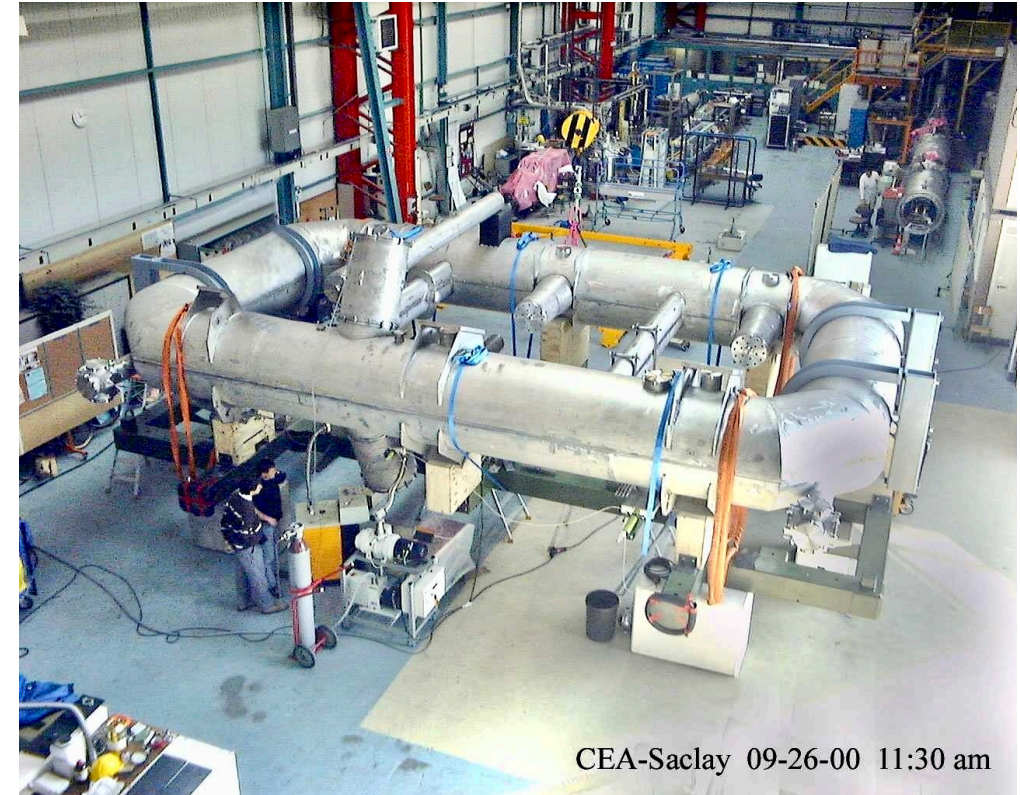
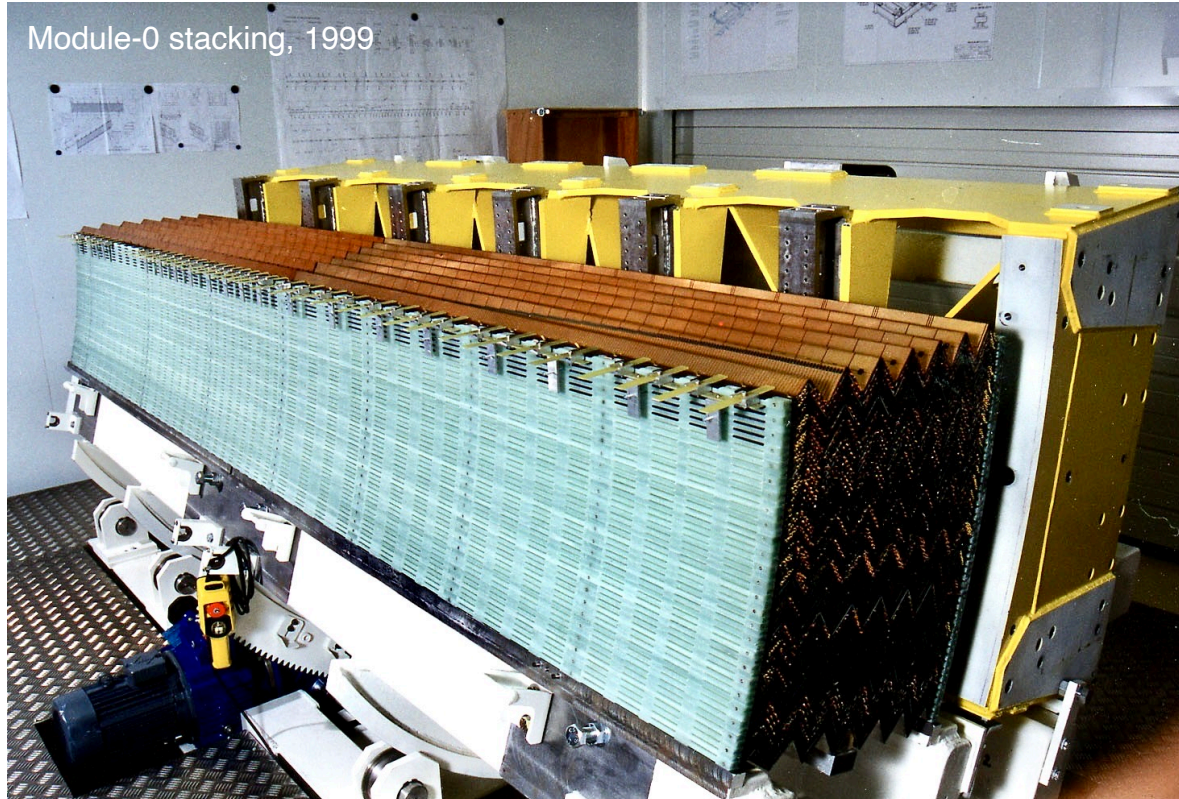
G.Battistoni, G.Bellini, D.Camin, D.Cavalli, G.Costa, L.Cozzi, A.Craverio, M.di Corato, A.Ferrari, F.Gianotti, P.Inzani, L.Mandelli, M.Mazzanti, L.Perasso, L.Perini, P.Sala, M.Sciamanna

Milano's contributions to the ATLAS construction

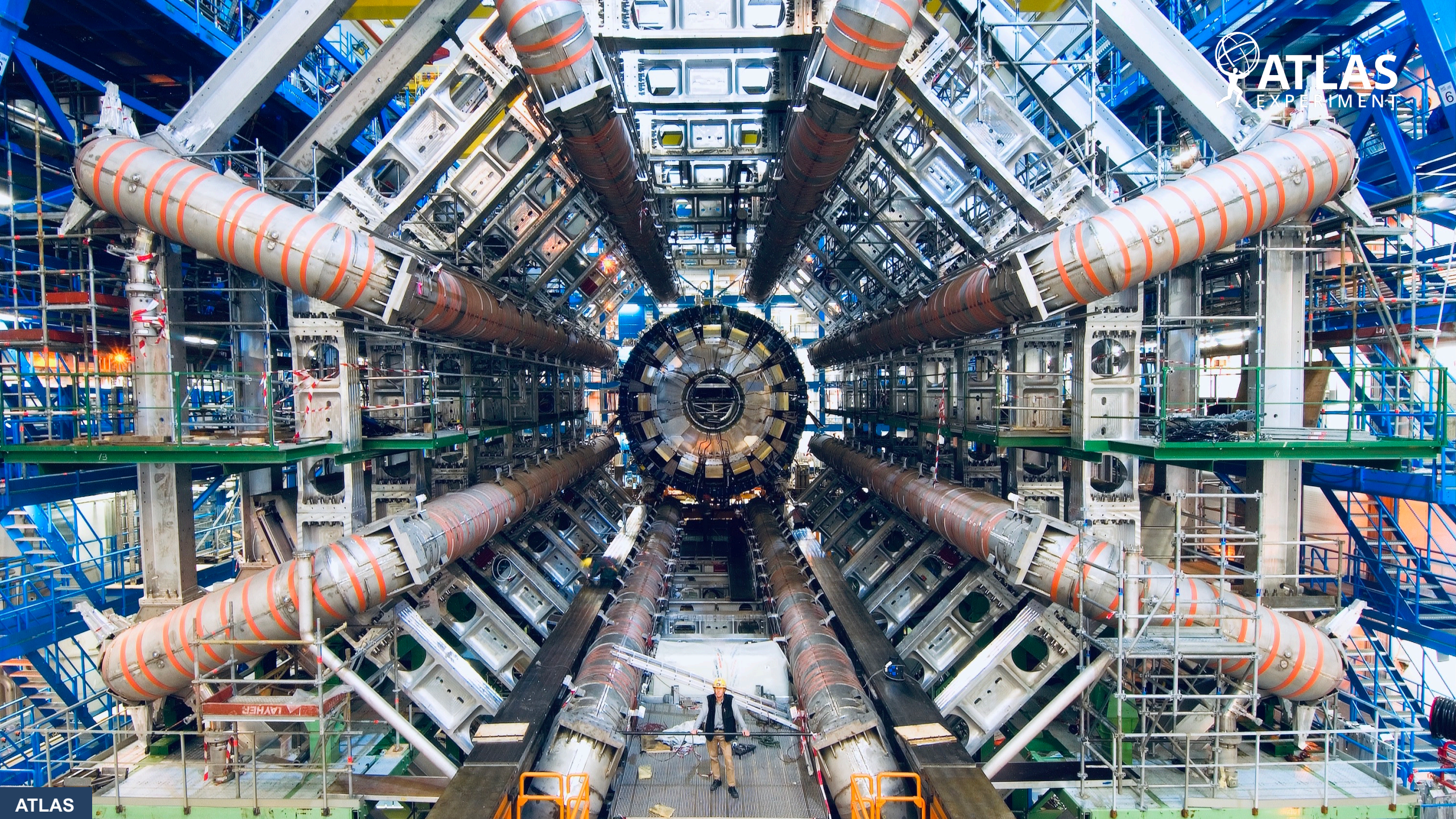


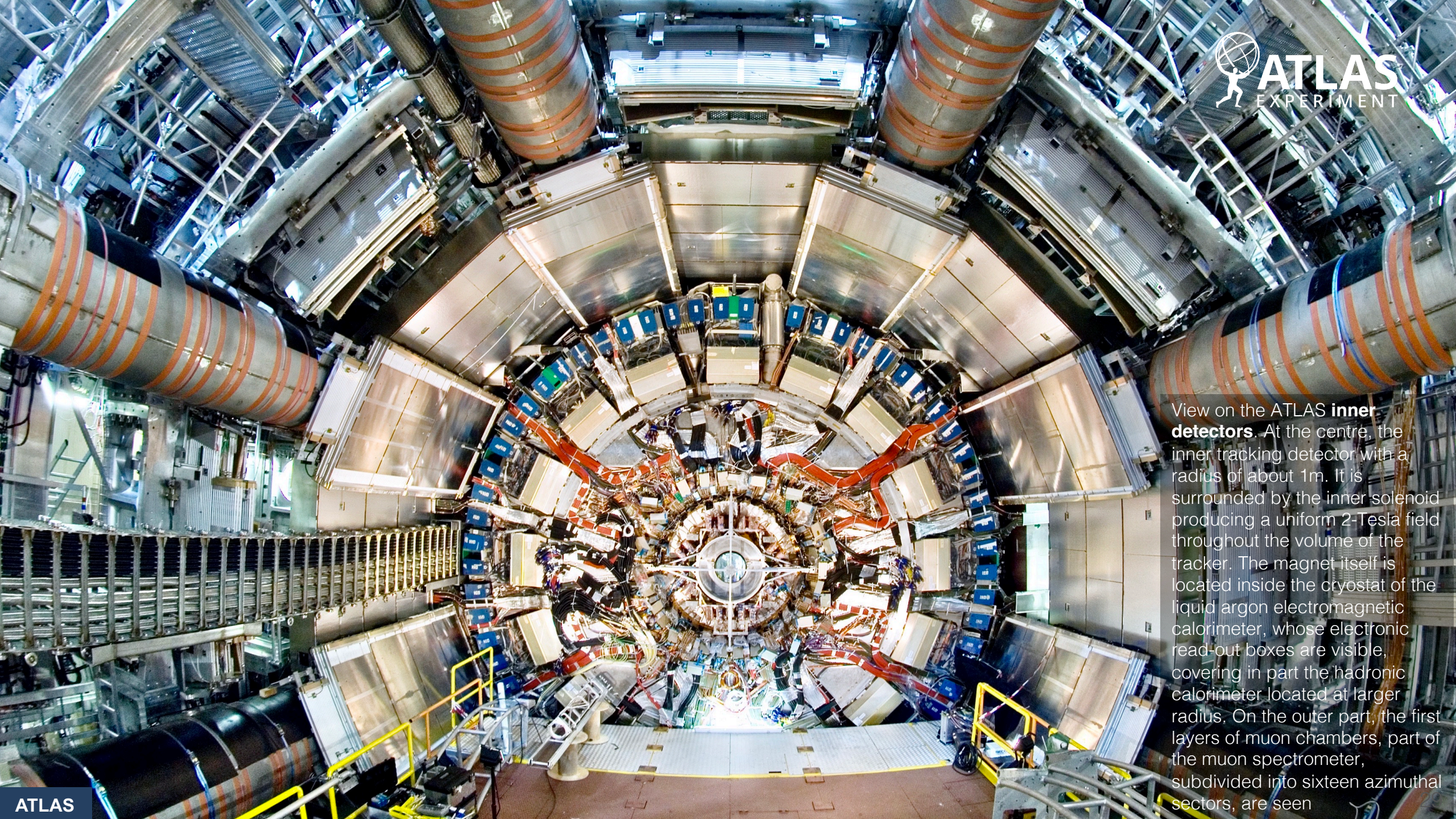
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DI MILANO

Milano contributed crucially to all phases of the Liquid Argon EM calorimeter (left), in particular to the signal read-out electrodes (copper-kapton) and the front-electronics, under the leadership of Luciano Mandelli

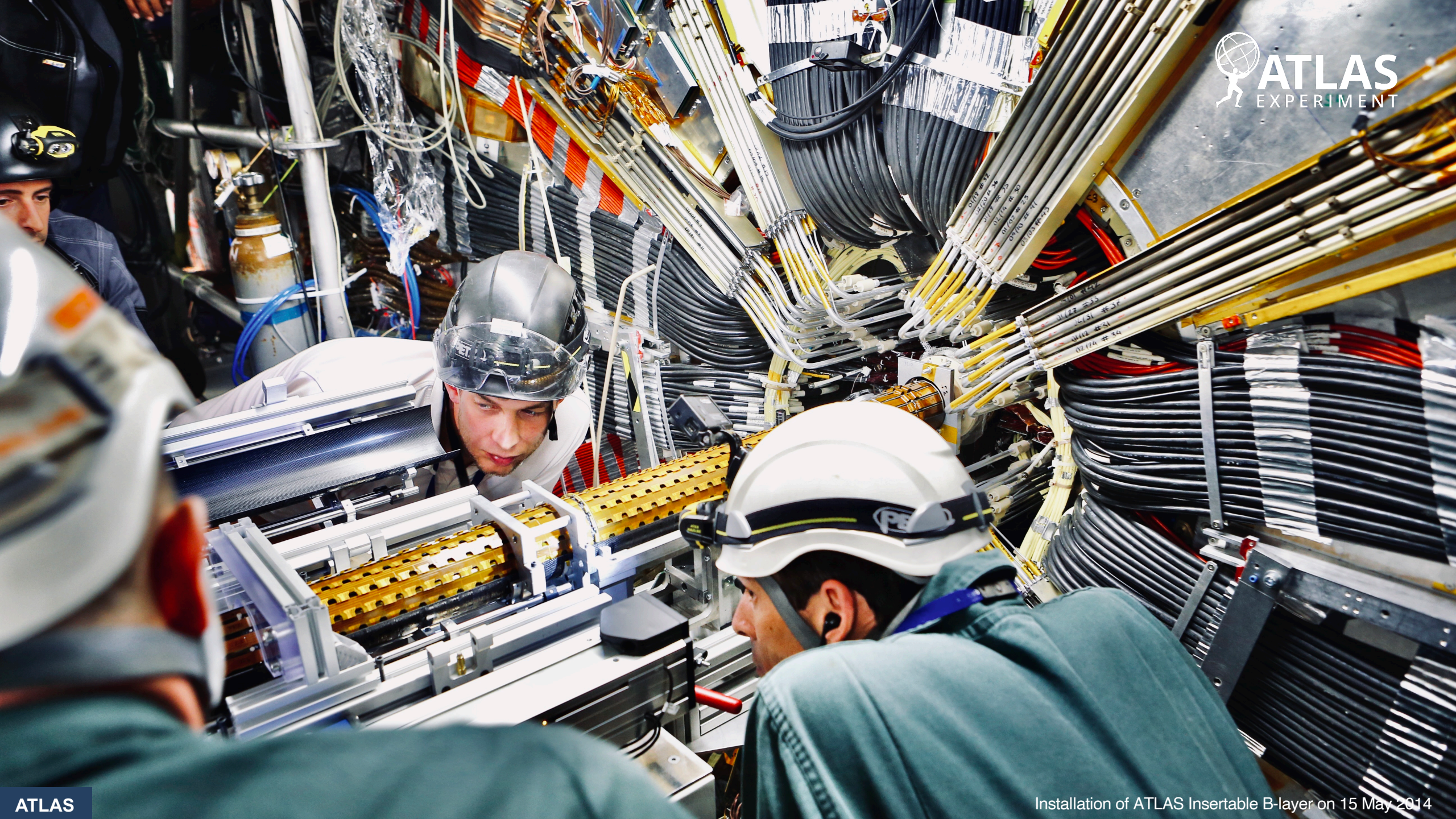


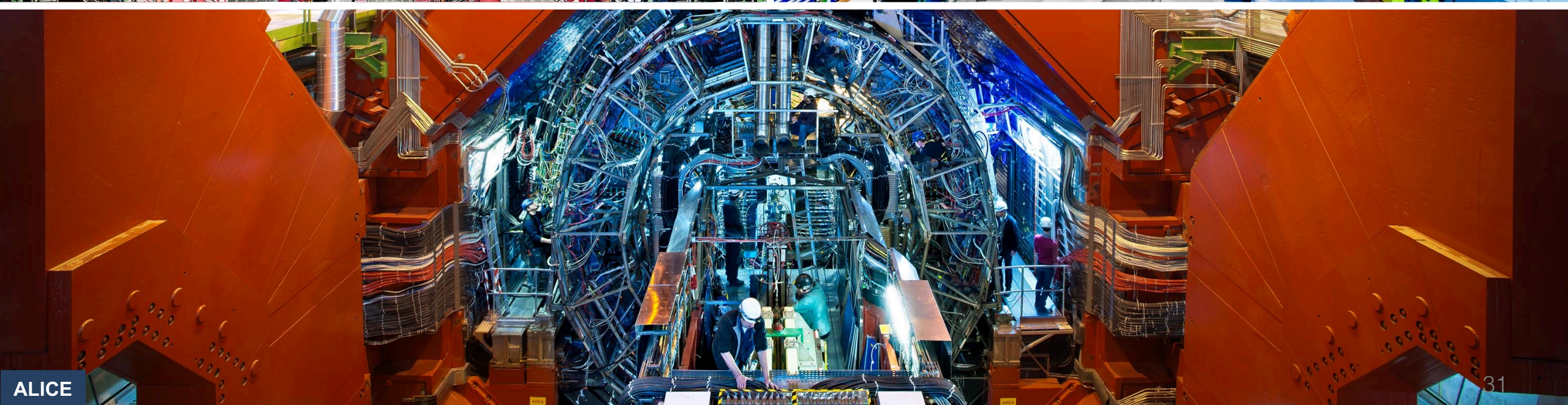
Milano, through the INFN accelerator and applied superconductivity laboratory LASA, made major contributions to the ATLAS toroid magnet project, notably the engineering and construction of the “B0” barrel prototype coil under the leadership of Lucio Rossi and Giovanni Volpini





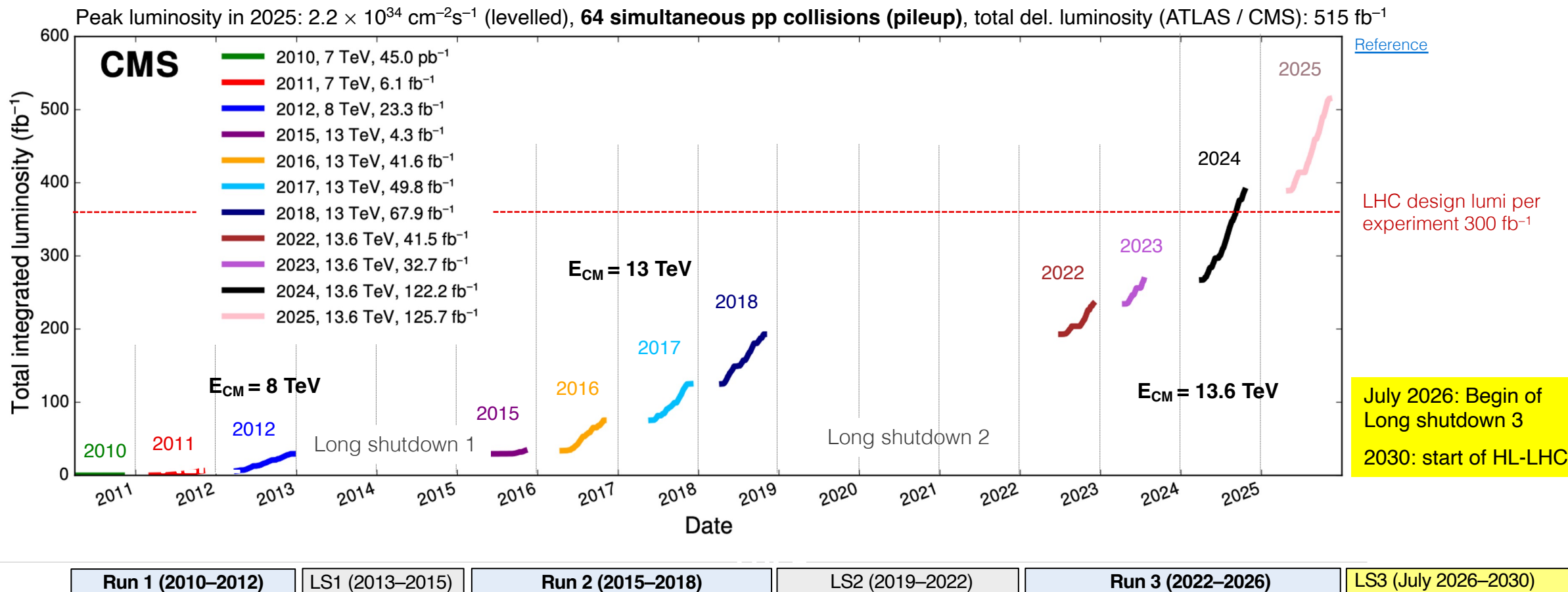
View on the ATLAS **inner detectors**. At the centre, the inner tracking detector with a radius of about 1m. It is surrounded by the inner solenoid producing a uniform 2-Tesla field throughout the volume of the tracker. The magnet itself is located inside the cryostat of the liquid argon electromagnetic calorimeter, whose electronic read-out boxes are visible, covering in part the hadronic calorimeter located at larger radius. On the outer part, the first layers of muon chambers, part of the muon spectrometer, subdivided into sixteen azimuthal sectors, are seen





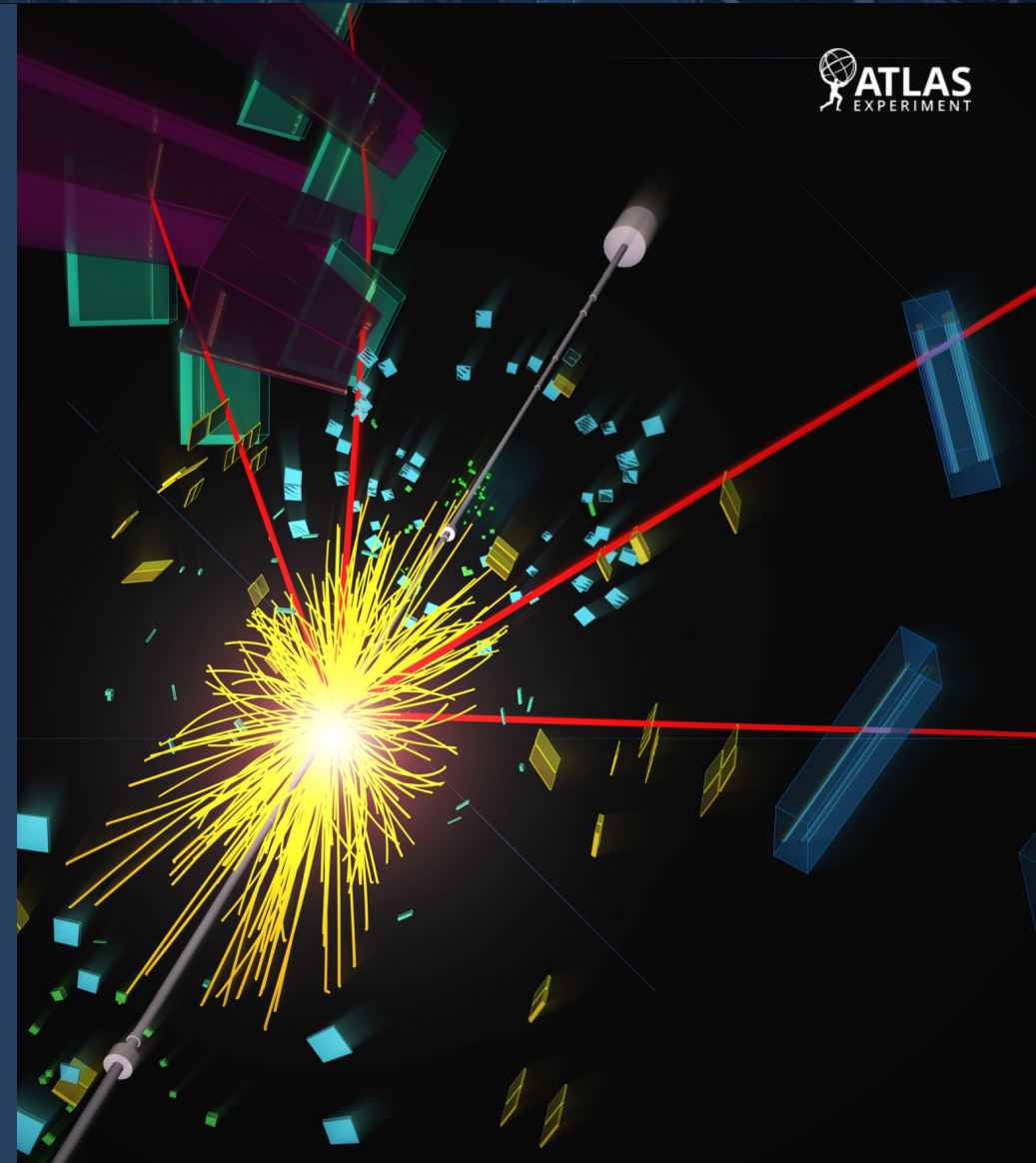
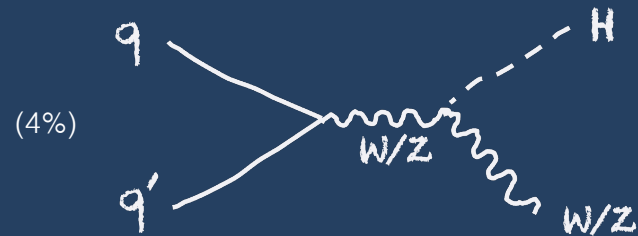
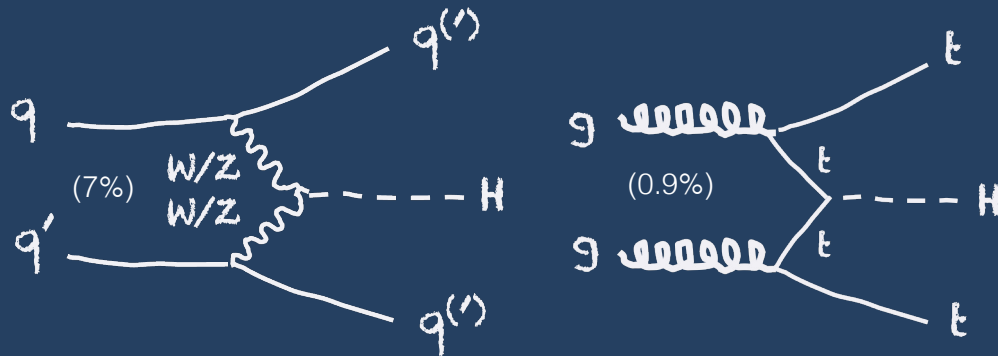
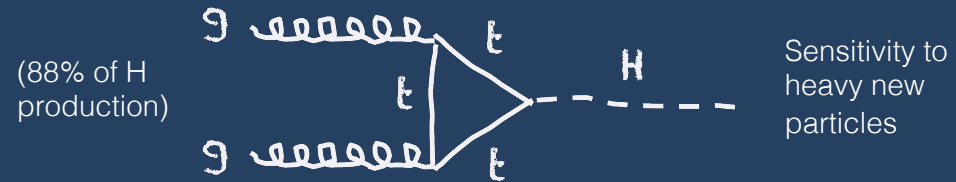
Superb LHC Runs 1, 2, 3

Superb LHC performance — on track for a strong Run-3 finish



Higgs boson production at the LHC

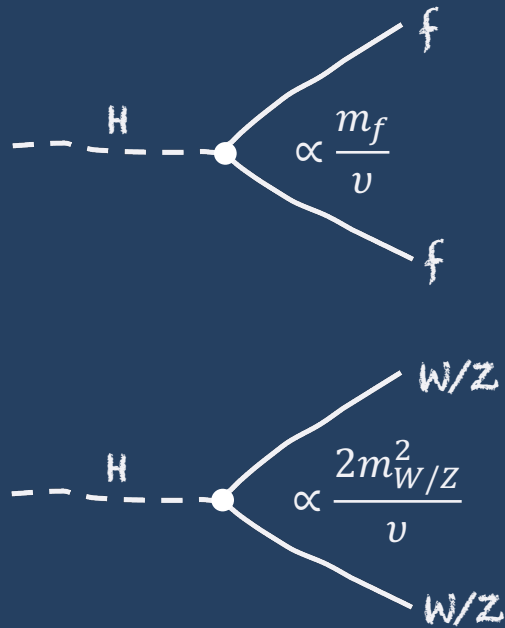
About 1 Higgs boson per second is produced in ATLAS at the LHC (about 20M total by today)



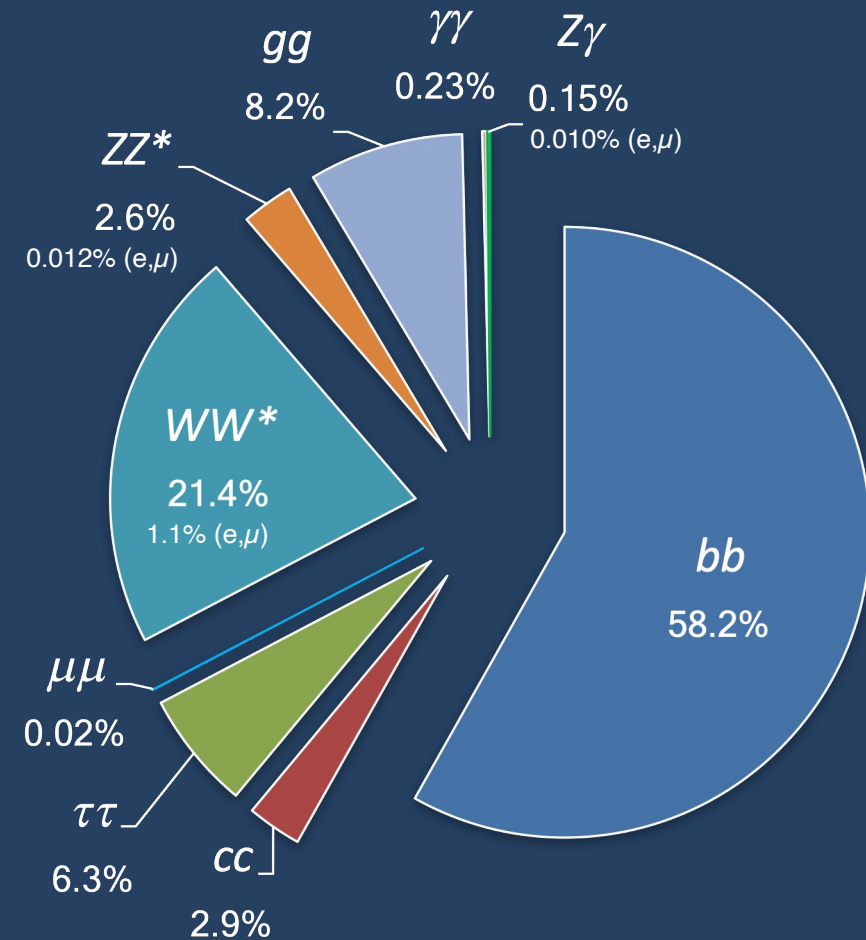
Higgs boson production at the LHC

About 1 Higgs boson per second is produced in ATLAS at the LHC (about 30M 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)

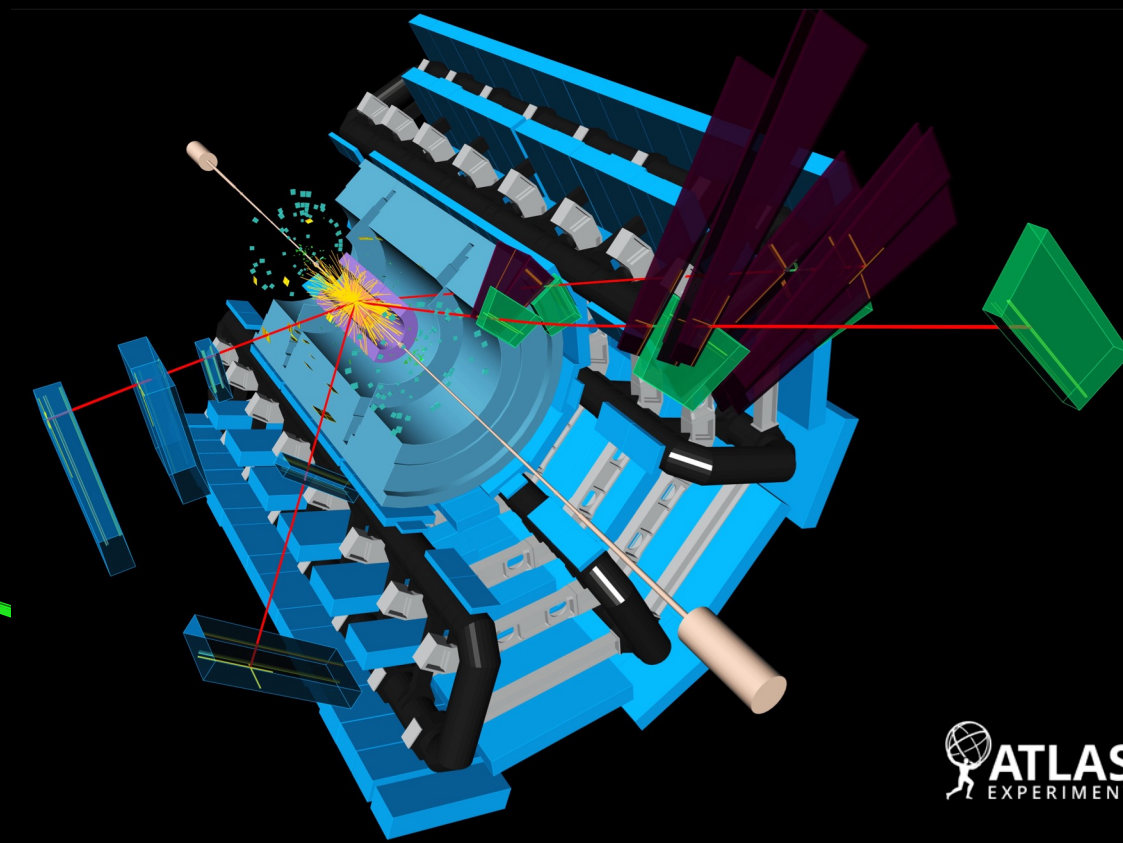
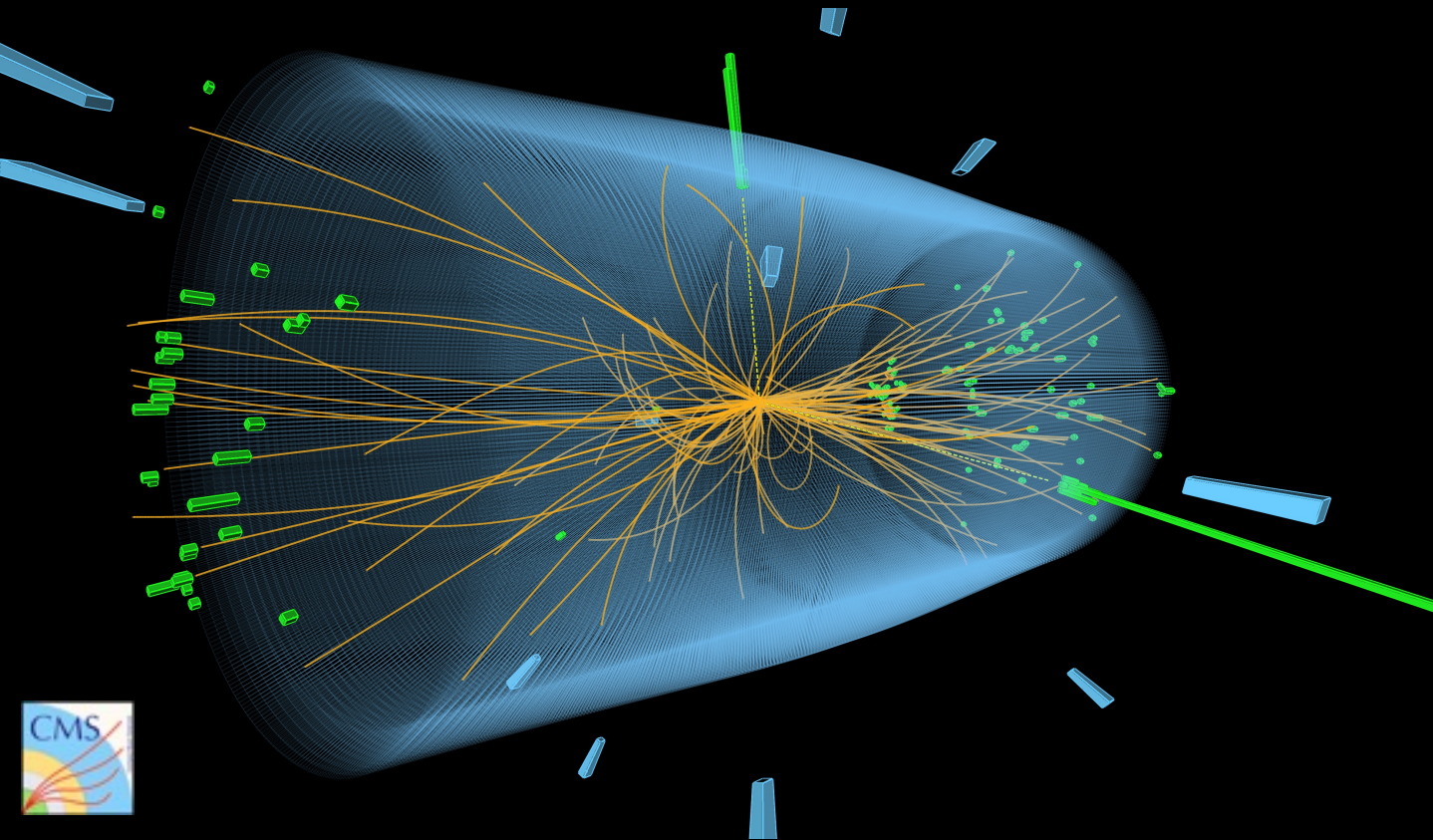


The Higgs boson discovery



Presentation of Higgs boson discovery by ATLAS and CMS at CERN on 4 July 2012

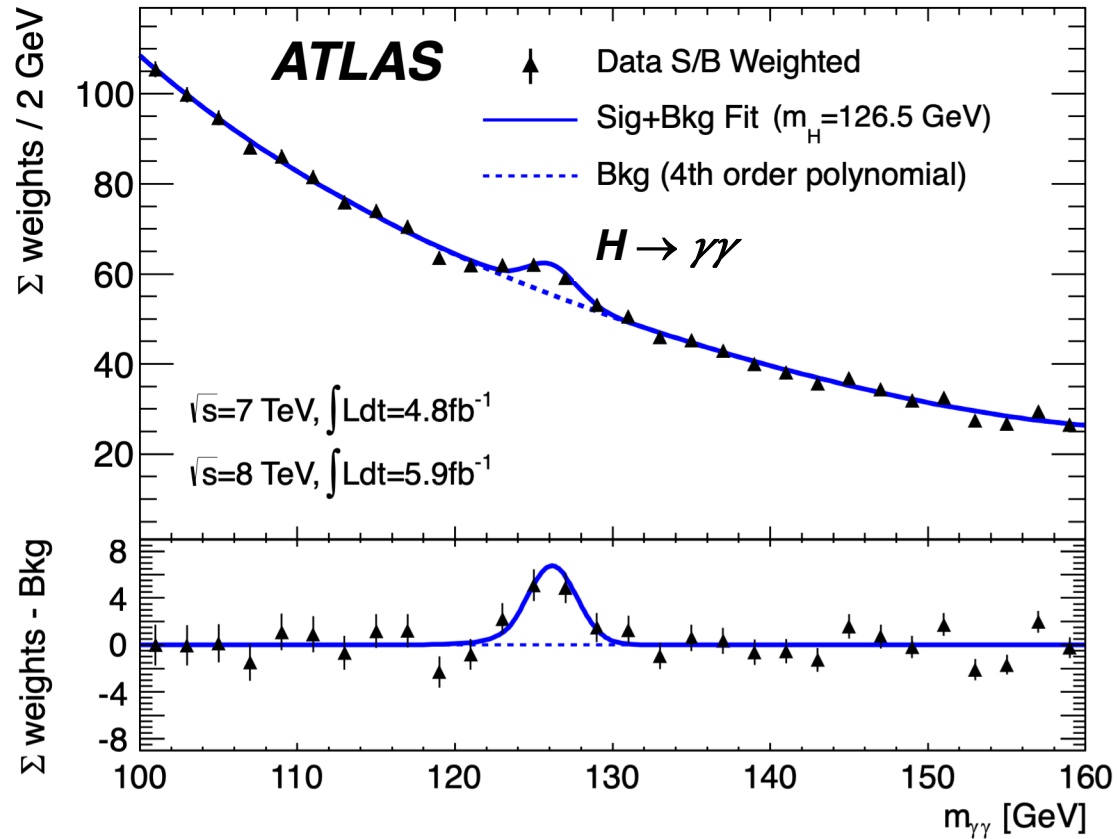
The Higgs boson discovery



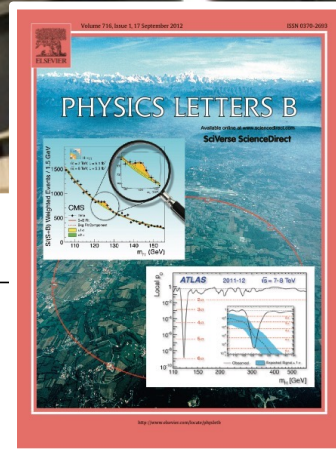
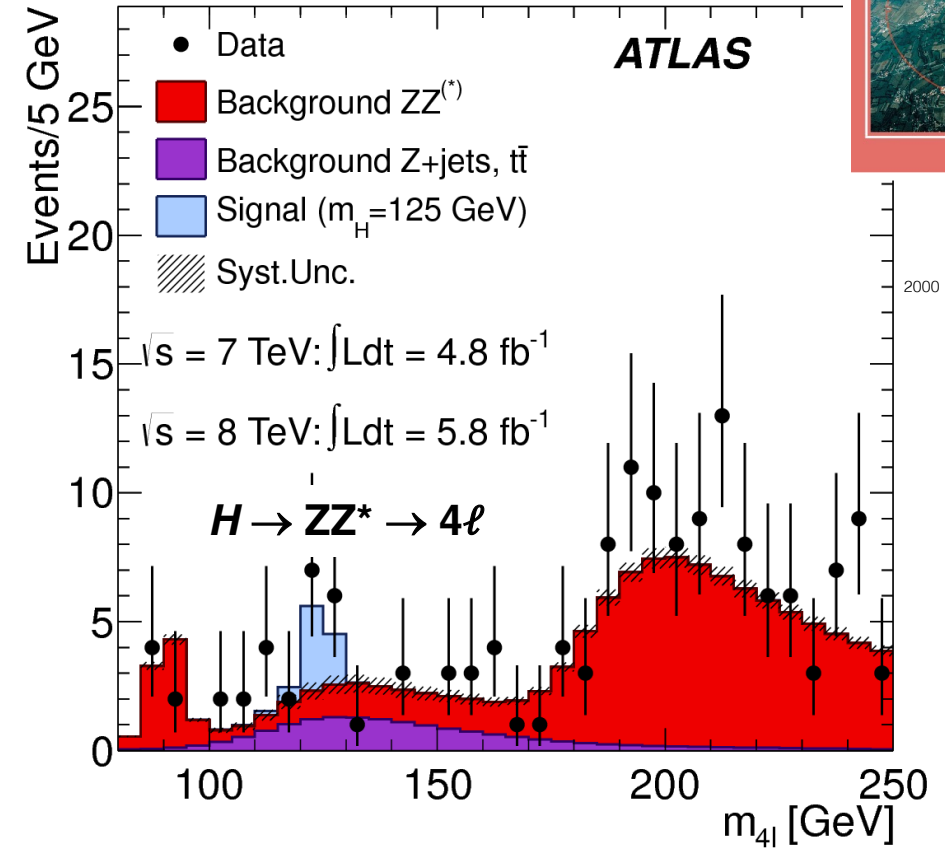
Presentation of Higgs boson discovery by ATLAS and CMS at CERN on 4 July 2012

The Higgs boson discovery

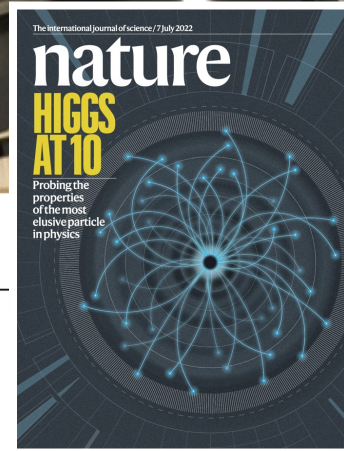
2012



[Phys. Lett. B 716 \(2012\) 1-29](#) [16.2k citations]

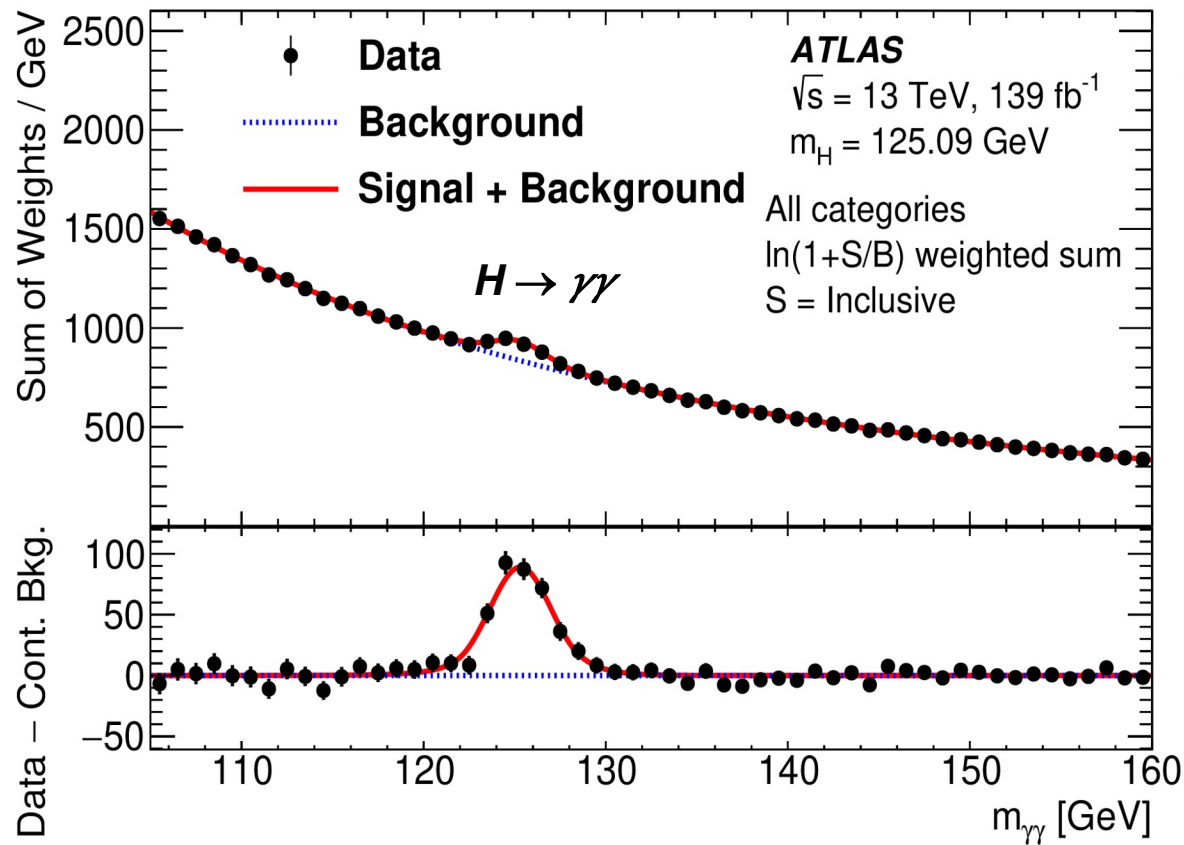


The Higgs boson after Run 2

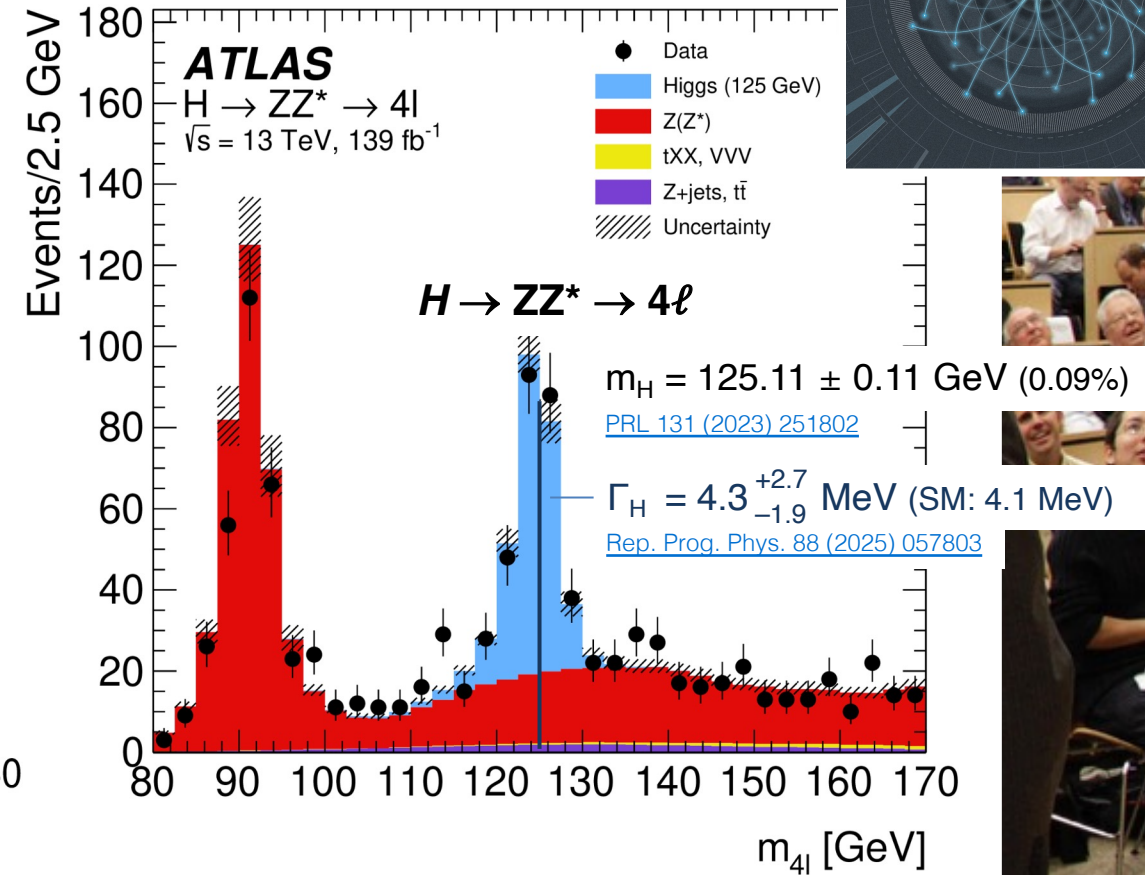


2020

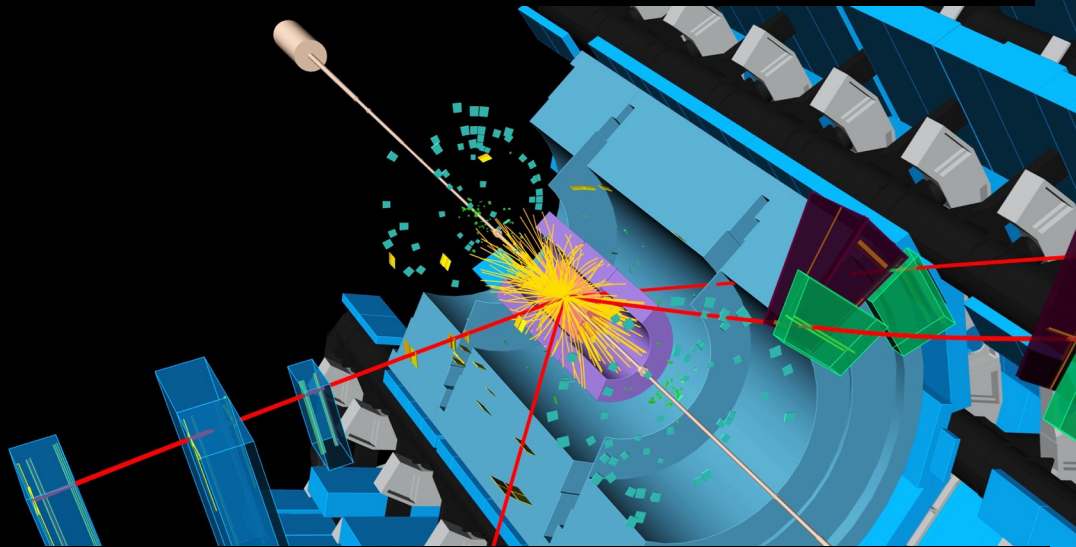
[JHEP 07 \(2023\) 088](#)



[Eur. Phys. J. C 80 \(2020\) 942](#)



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, and by performing a combined fit to all measurements

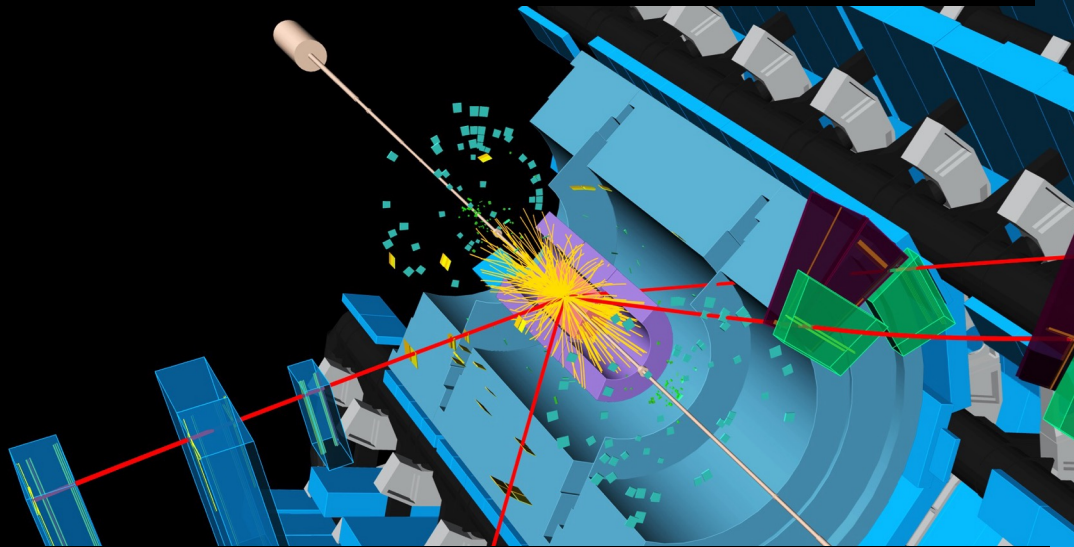
Careful detector and reconstruction calibration, and Machine Learning have substantially improved all analyses

Huge experimental programme, some channels suffer from large backgrounds, big 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
$\gamma\gamma$	0.2 %	✓	✓	✓	✓	
ZZ	2.6%	✓	✓	✓	✓	
WW	21%	✓	✓	✓	✓	
$\tau\tau$	6.3 %	✓	✓	✓	✓	
$b\bar{b}$	58%	✓	✓	✓	✓	
$Z\gamma$ (& $\gamma\gamma^*$)	0.2 %	✓	✓	✓	✓	
$\mu\mu$	0.02 %	✓	✓	✓	✓	

In grey: evidence for decays, but not observed yet

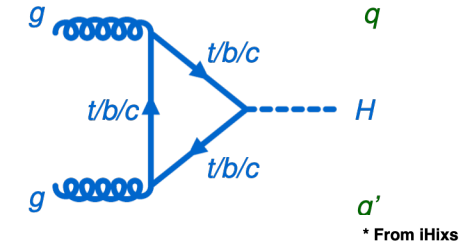
Theory predictions



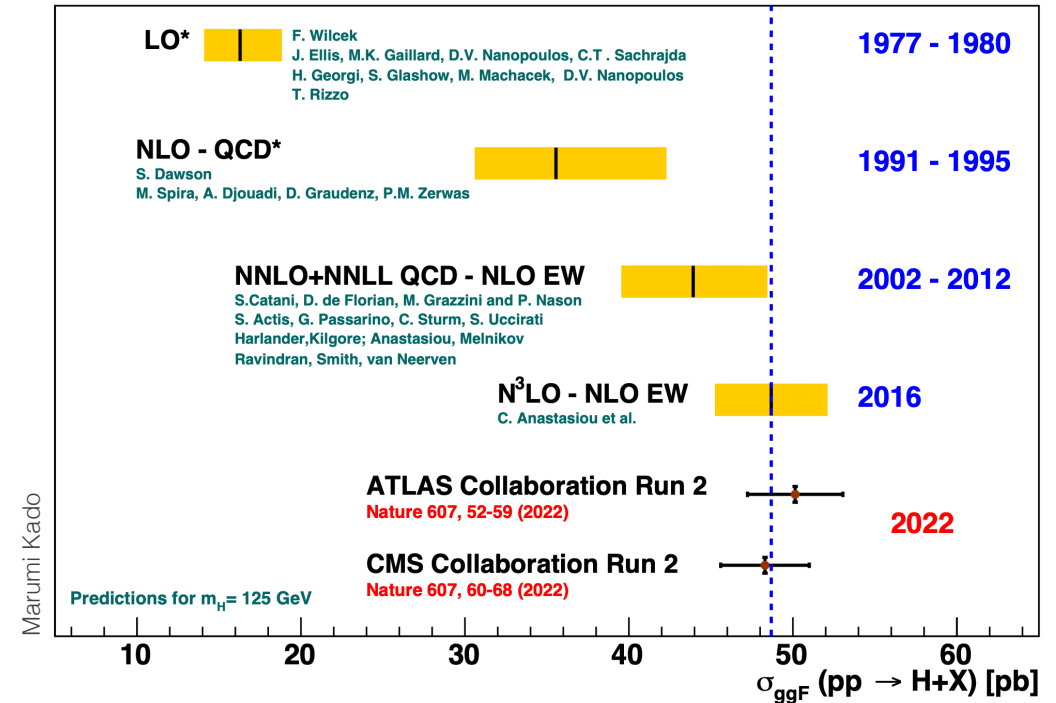
Predictions at hadron colliders are extremely complex and require several levels of modelling and calculations (higher order hard processes, parton fragmentation, hadronization, parton distribution functions, etc...)

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

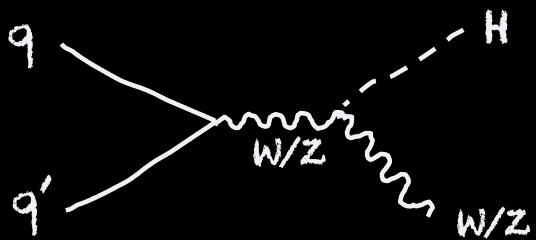
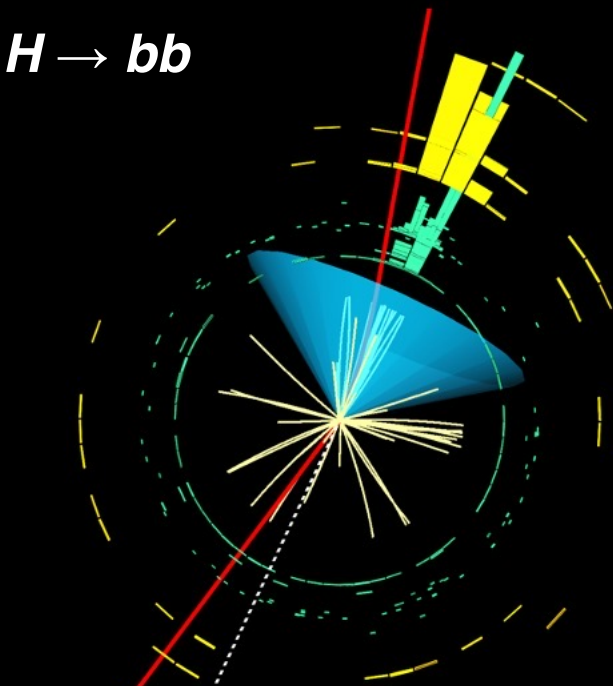
Calculations of Higgs boson production via gluon fusion versus time



$\sqrt{s} = 13 \text{ TeV}$



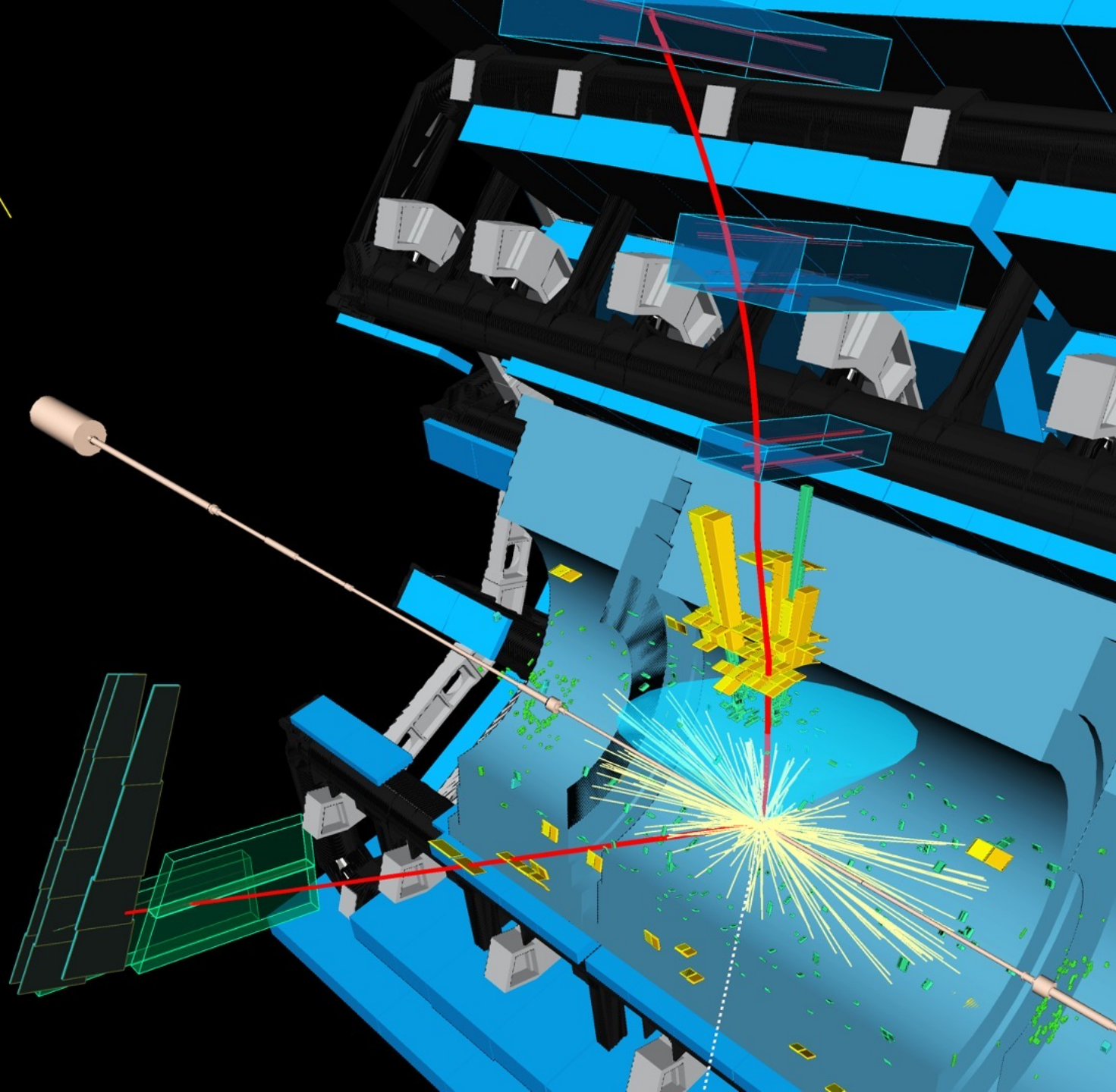
$H \rightarrow bb$



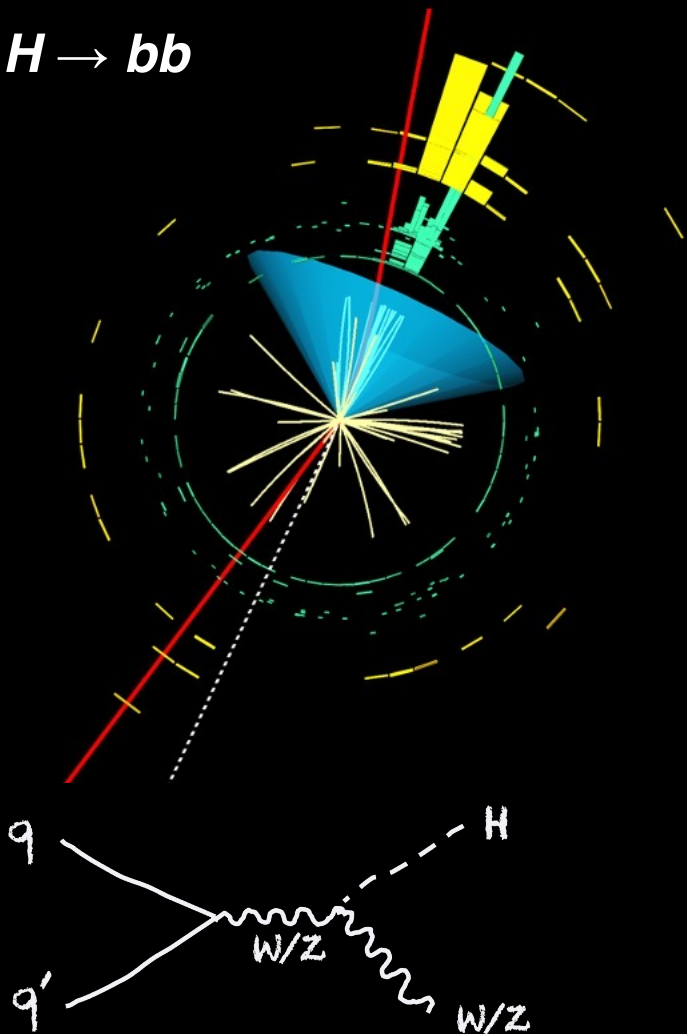
Run: 338349

Event: 616525246

2017-10-16 20:24:46 CEST



$H \rightarrow bb$

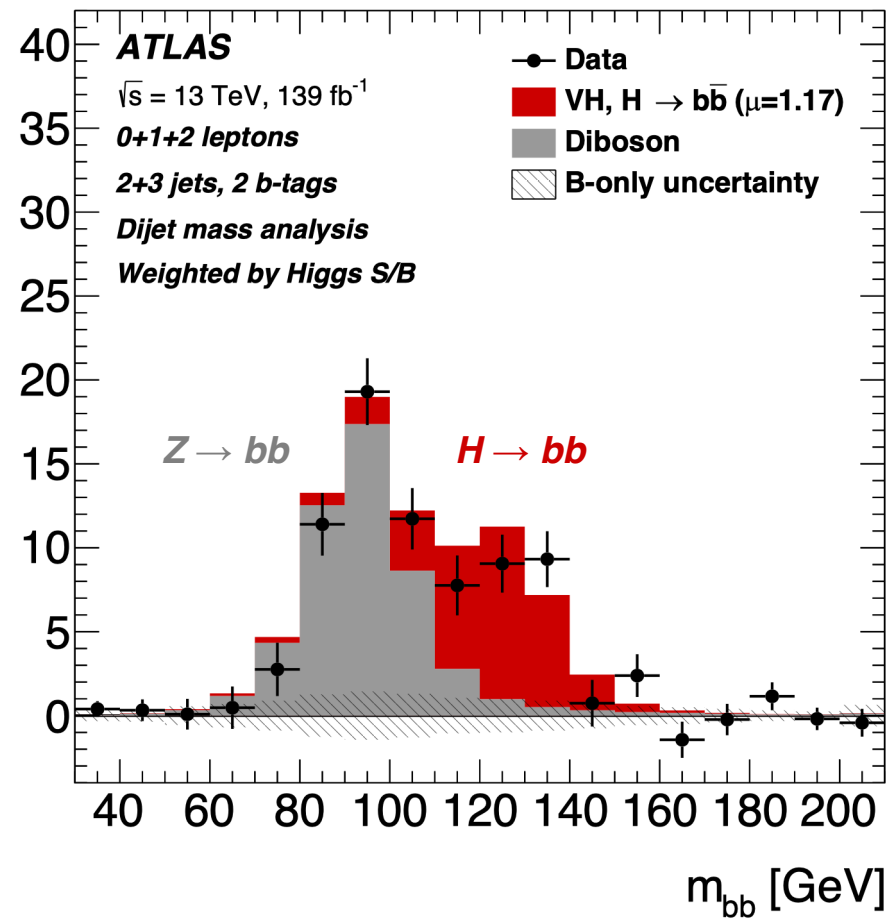


Run: 338349

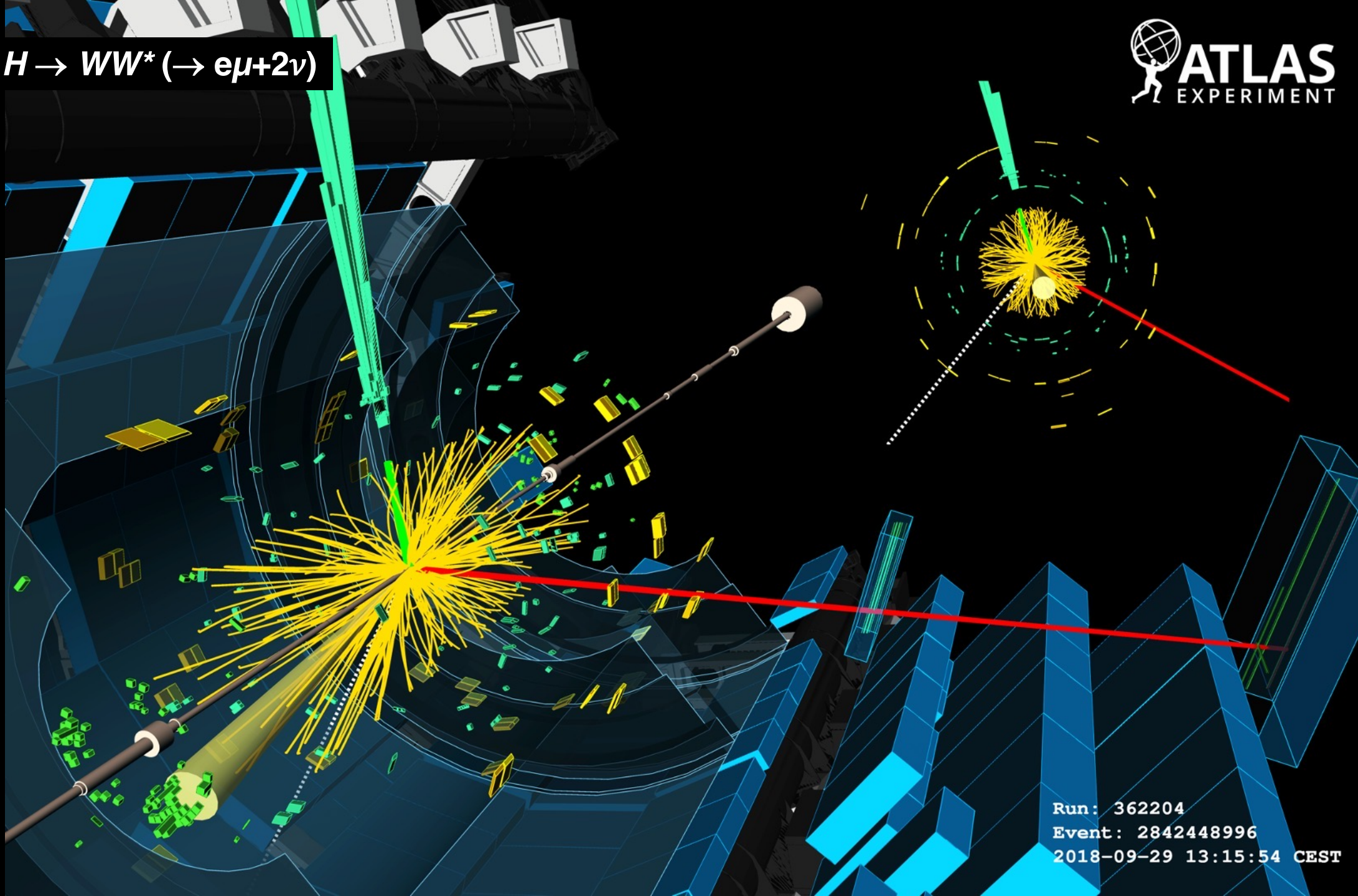
Event: 616525246

2017-10-16 20:24:46 CEST

Events / 10 GeV (Weighted, B-subtracted)



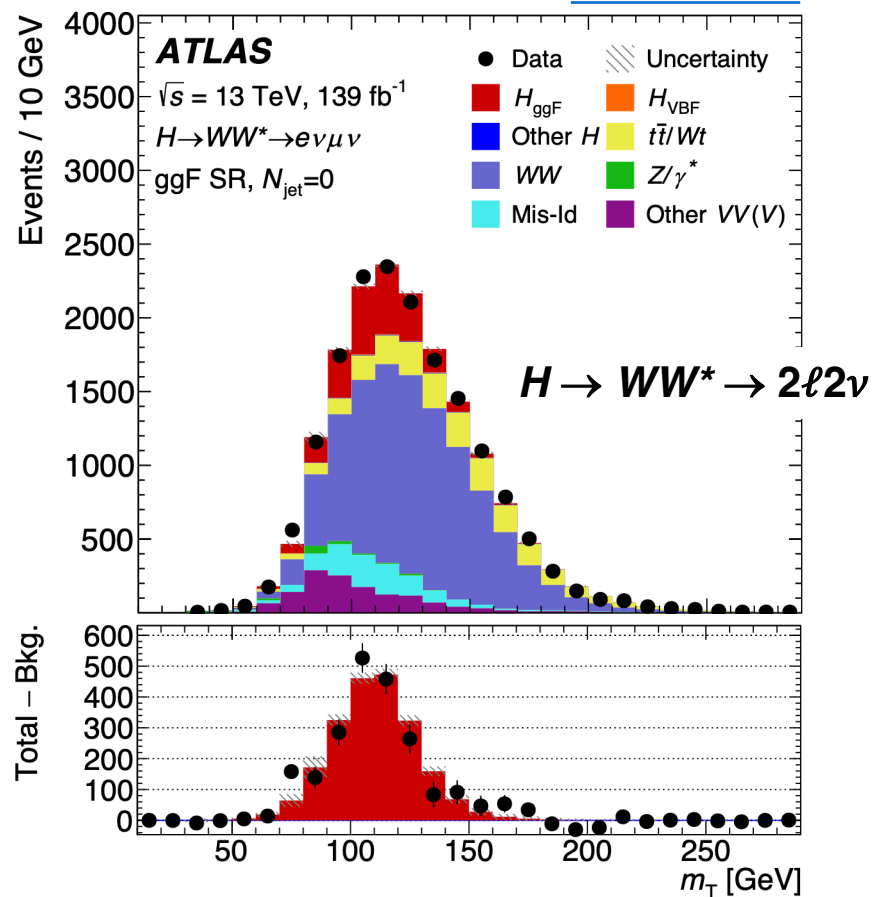
$H \rightarrow WW^* (\rightarrow e\mu + 2\nu)$



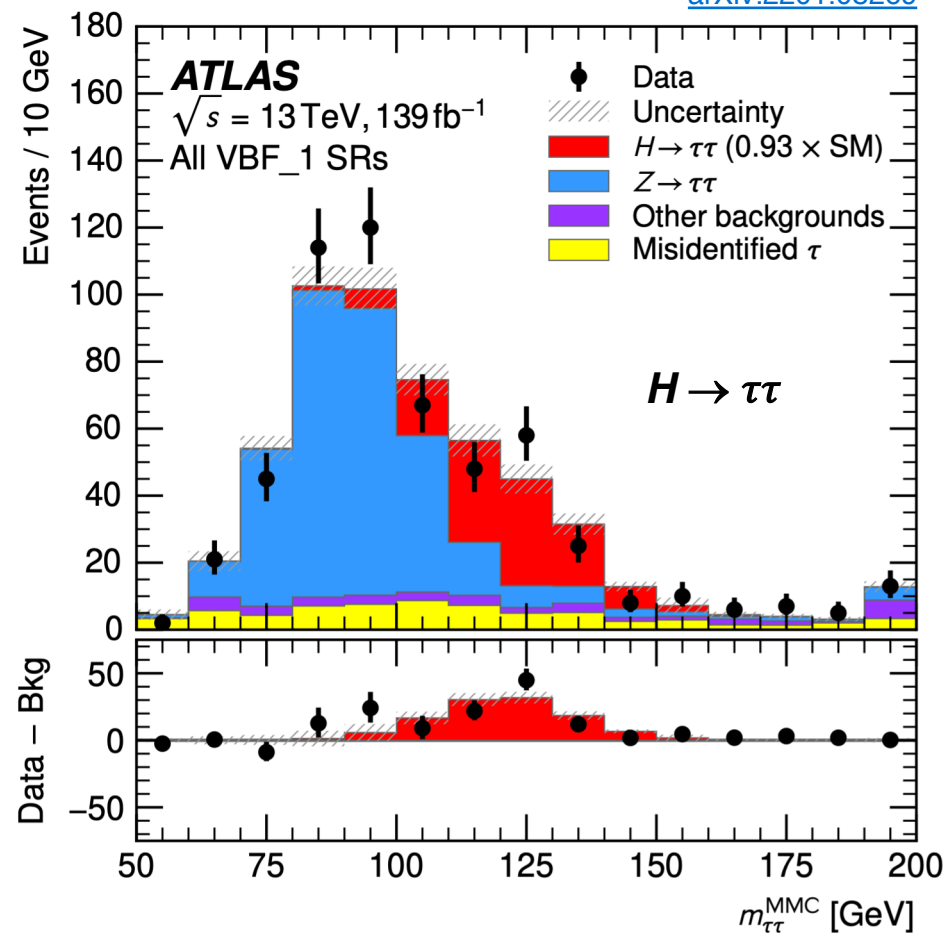
Run: 362204
Event: 2842448996
2018-09-29 13:15:54 CEST

$H \rightarrow WW^* (\rightarrow e\mu+2\nu)$

[arXiv:2207.00338](https://arxiv.org/abs/2207.00338)



[arXiv:2201.08269](https://arxiv.org/abs/2201.08269)

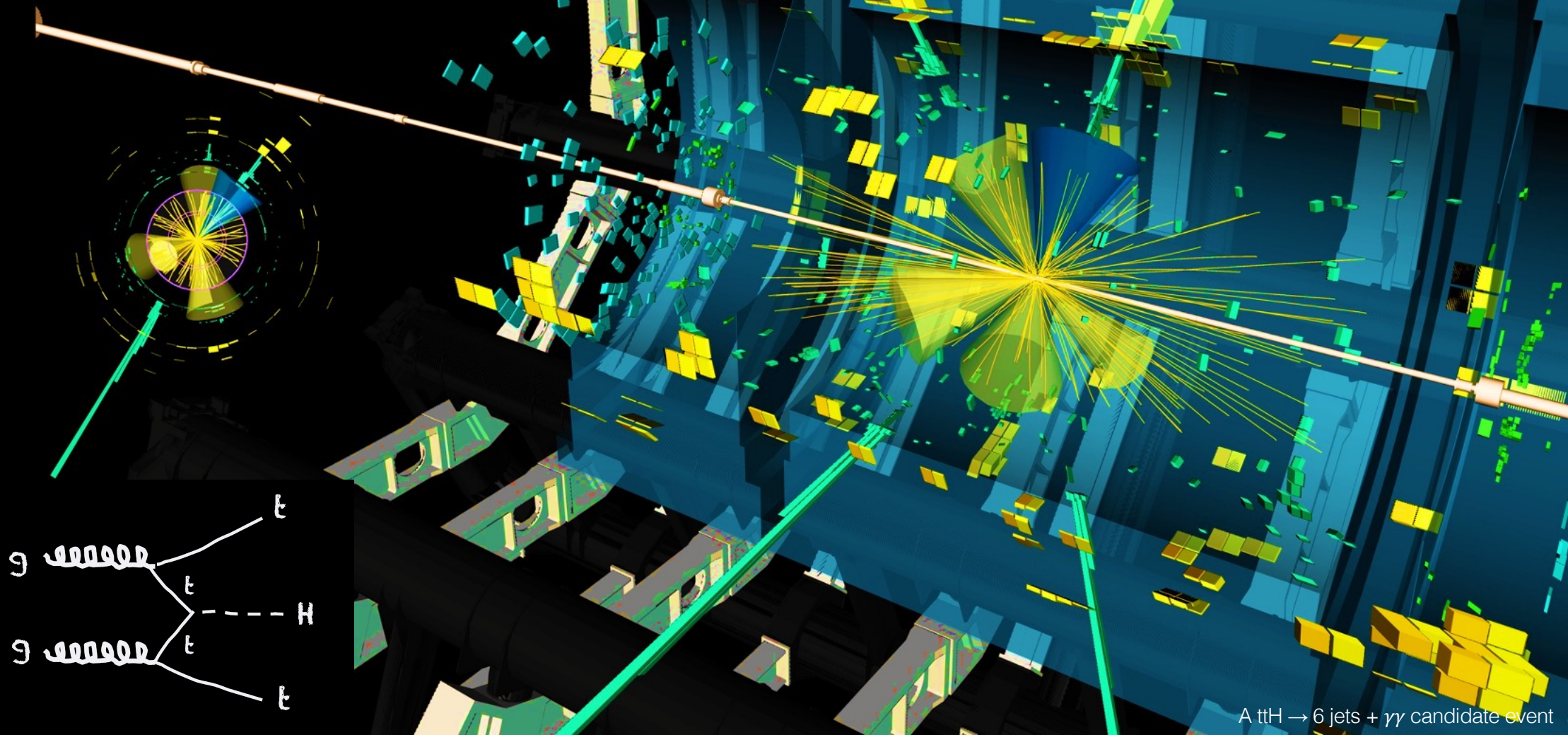


$t\bar{t}H$ production

Run: 303079

Event: 197351611

2016-07-01 05:01:26 CEST

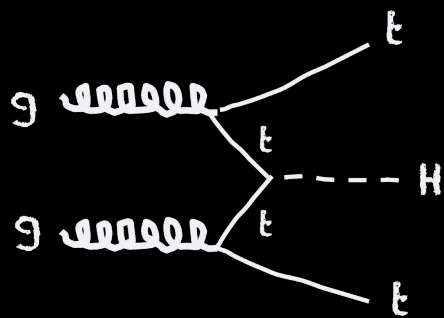
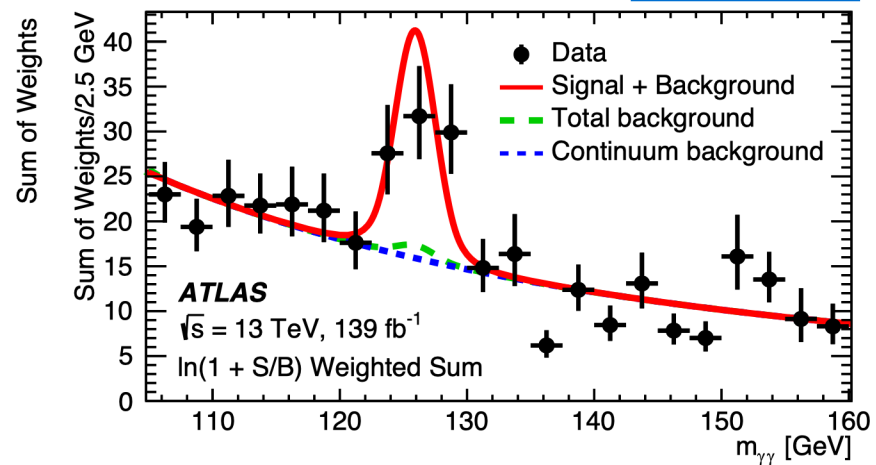


A $t\bar{t}H \rightarrow 6 \text{ jets} + \gamma\gamma$ candidate event

$t\bar{t}H$ production

$t\bar{t}H$ production features rich events,
 $H \rightarrow \gamma\gamma$ channel most powerful

[arXiv:2004.04545](https://arxiv.org/abs/2004.04545)



A $t\bar{t}H \rightarrow 6 \text{ jets} + \gamma\gamma$ candidate event

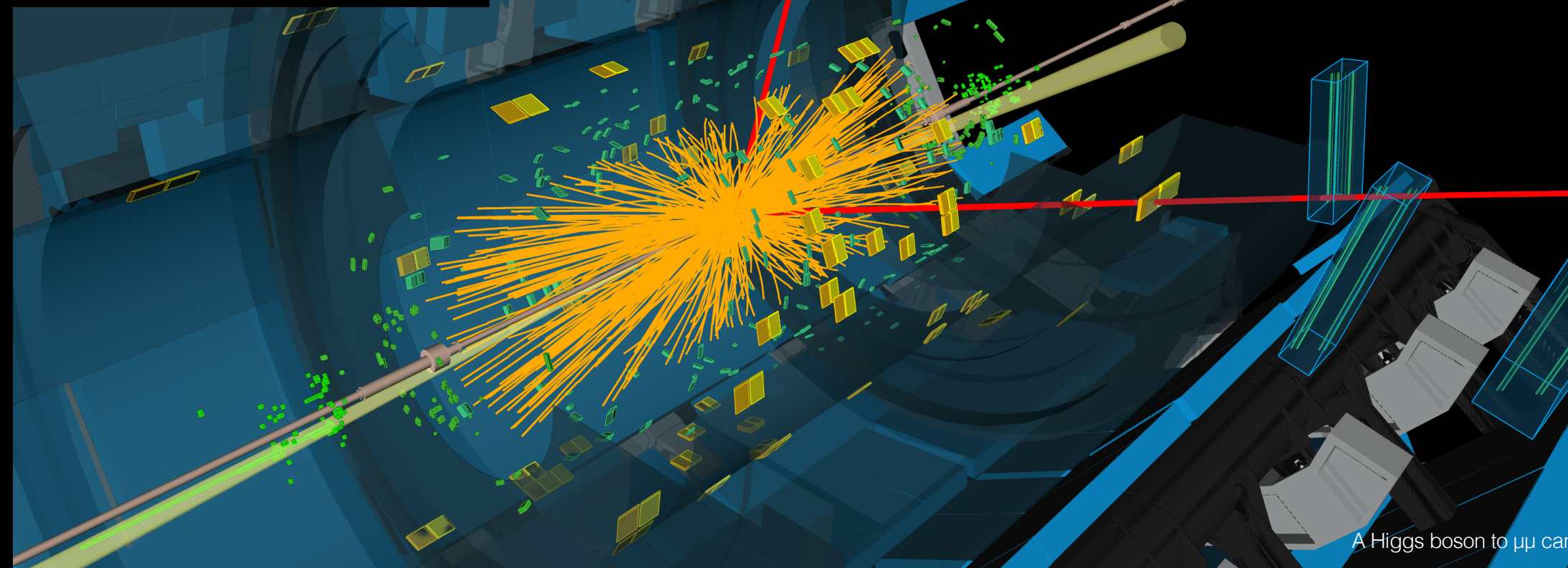
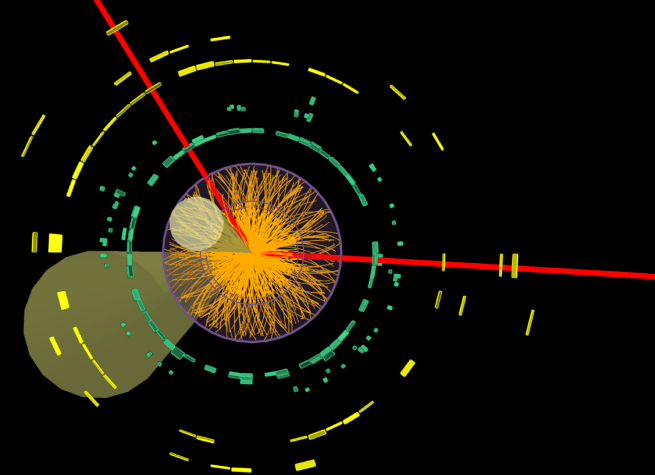


Run: 484466

Event: 3913031636

2024-09-13 05:46:24 CEST

Rare Higgs boson decays



A Higgs boson to $\mu\mu$ candidate event

Run: 484466

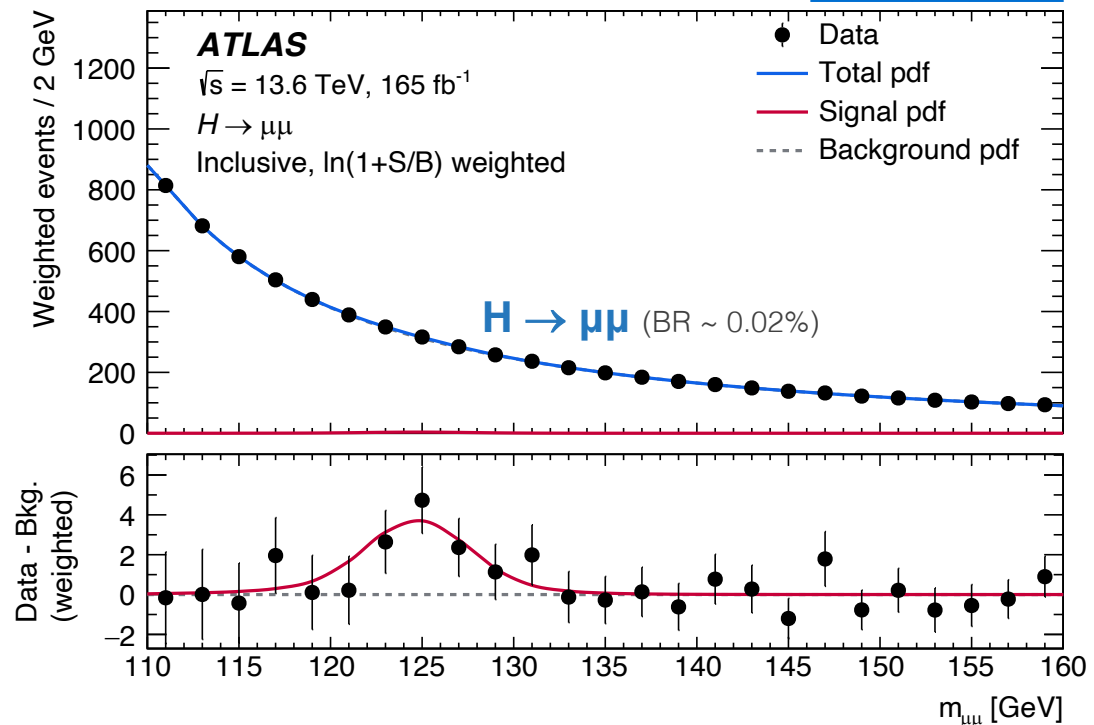
Event: 3913031636

2024-09-13 05:46:24 CEST

Rare Higgs boson decays

Using 305 fb⁻¹ of Run-2 + 3 (2022–2024) data, ATLAS reported evidence for rare 2nd generation $H \rightarrow \mu\mu$ (first seen by CMS)

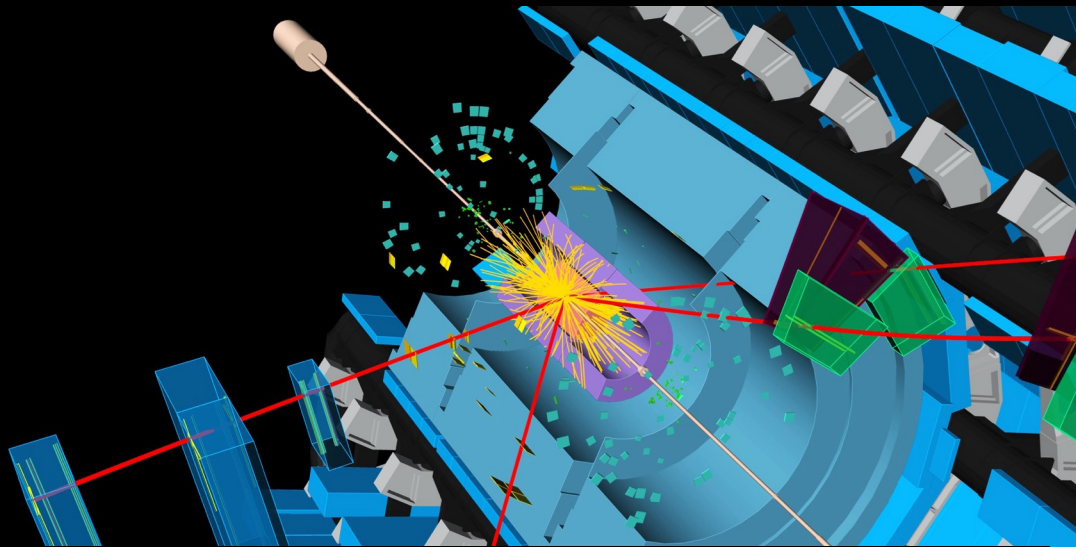
[PRL 135 \(2025\) 231802](#)



Significance: 3.4σ (2.5σ exp), $\sigma_{\text{exp}} / \sigma_{\text{SM}} = 1.4 \pm 0.4$

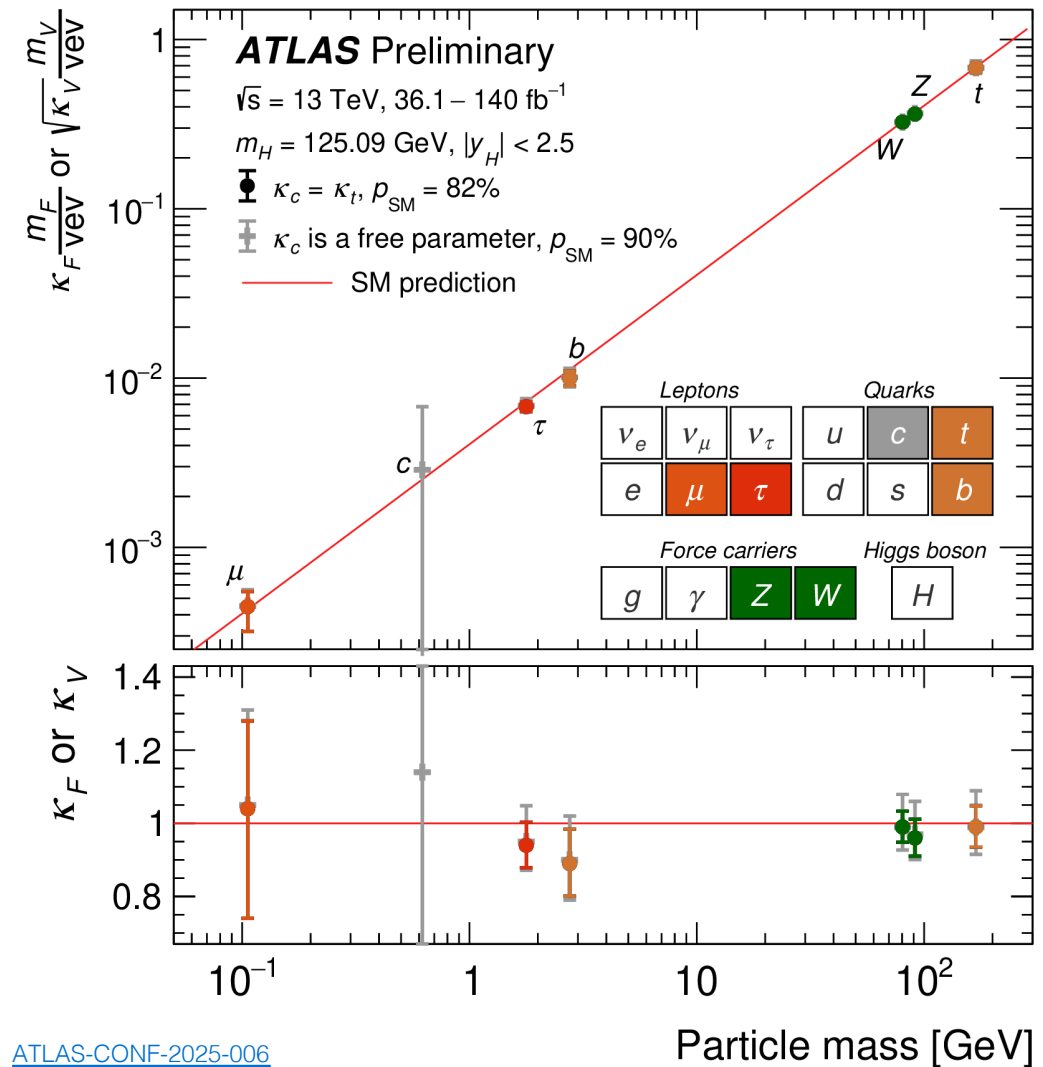
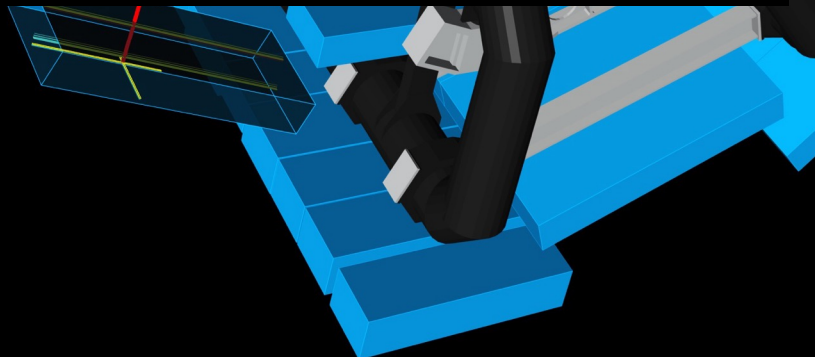
CMS (Run 2): $\mu = 1.19 \pm 0.43$ (3.0σ) [[JHEP 01 \(2021\) 148](#)]

The Higgs mechanism is real



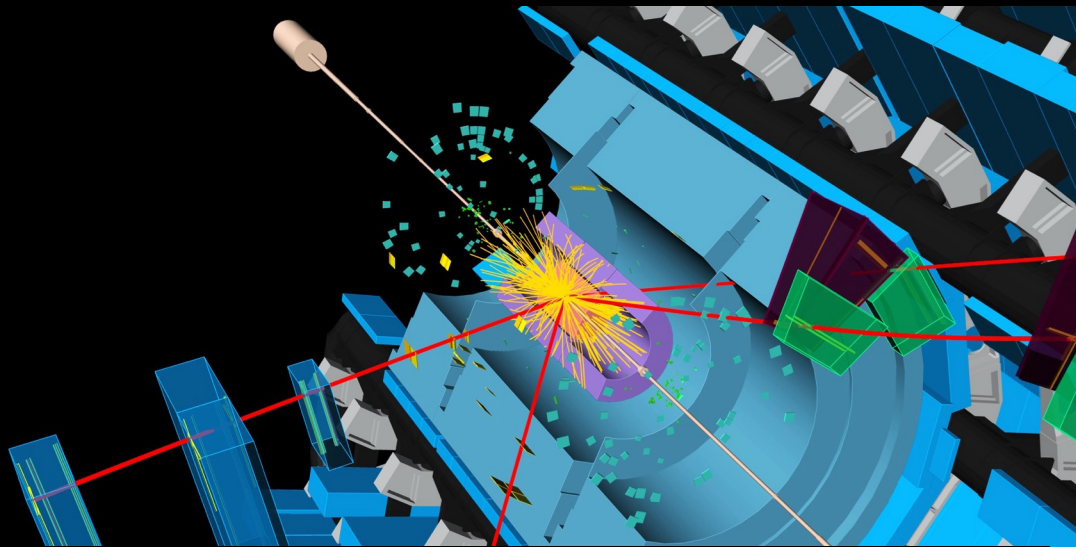
Combinations of Run-2 measurements by ATLAS and CMS have confirmed the non-universal, mass-dependent coupling strengths of the Higgs boson to the SM particles

Measured coupling strength modifiers: $\kappa_i = \kappa_i^{\text{obs}} / \kappa_i^{\text{SM}}$



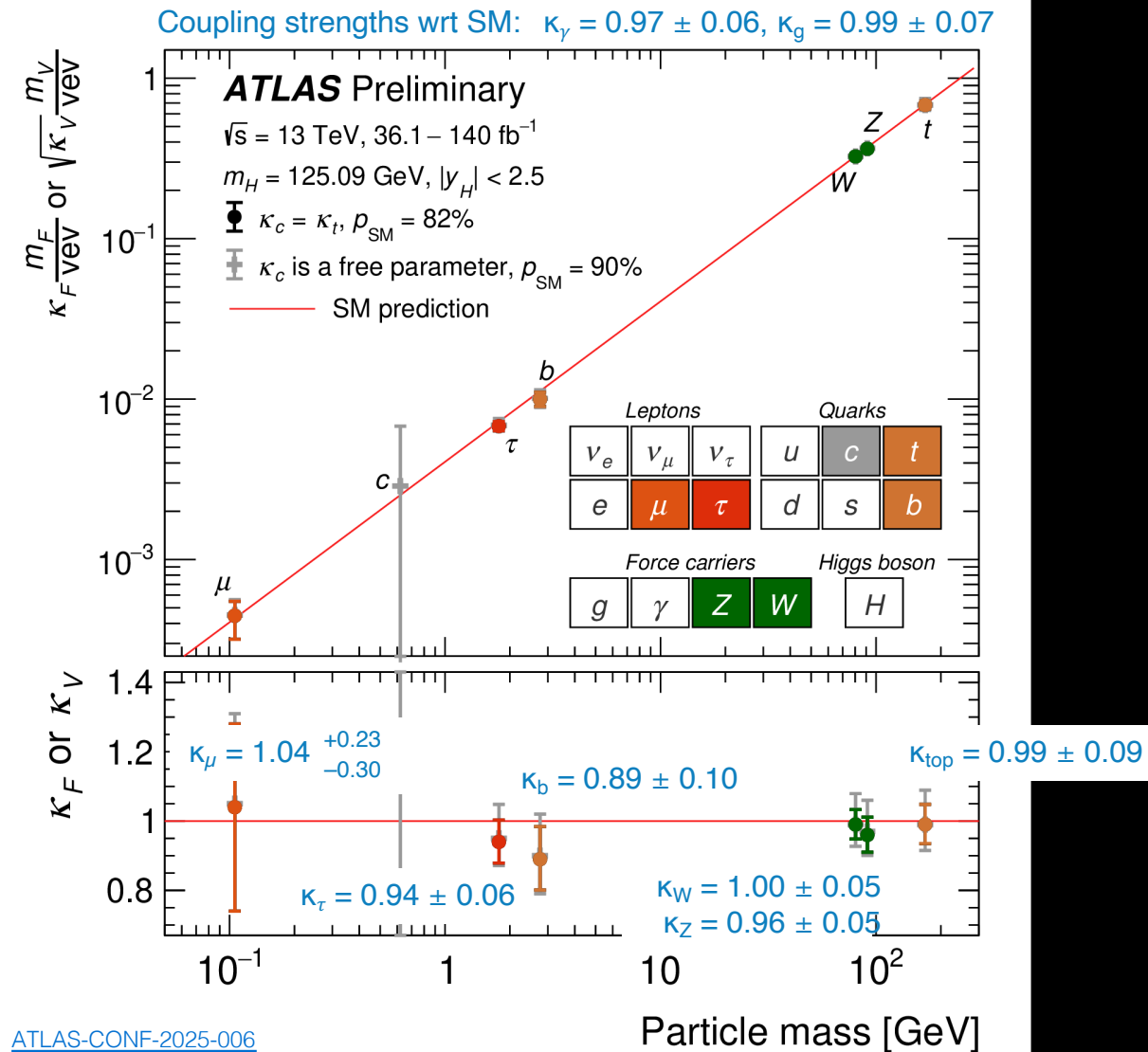
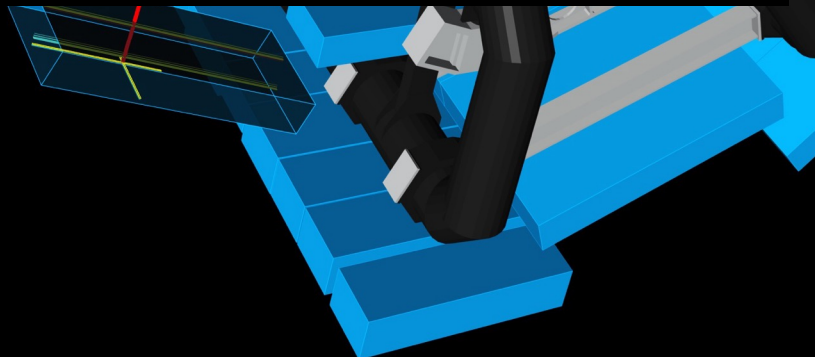
[ATLAS-CONF-2025-006](#)

The Higgs mechanism is real

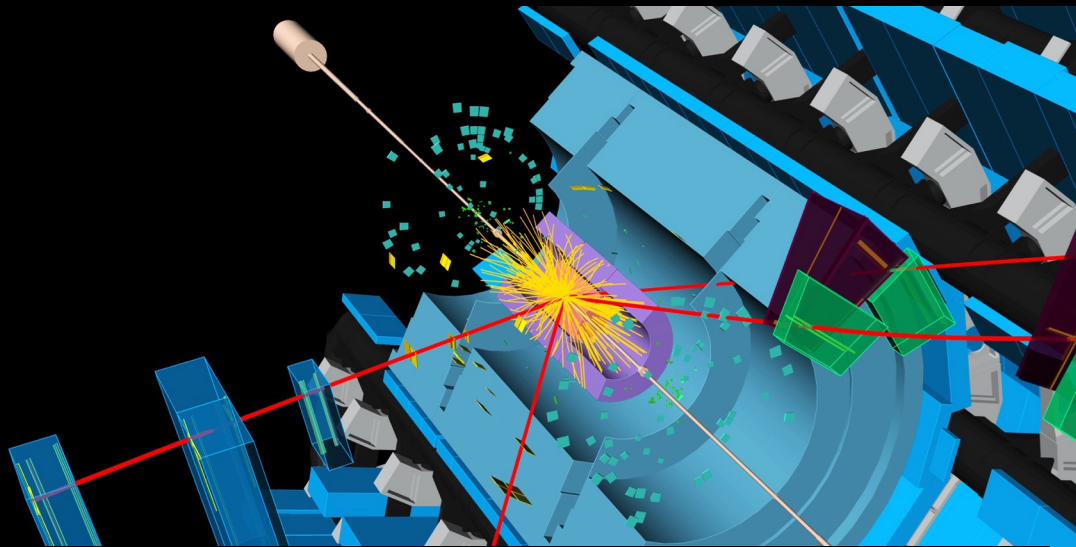
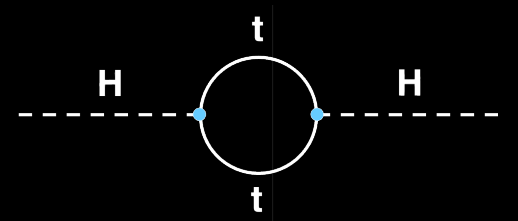


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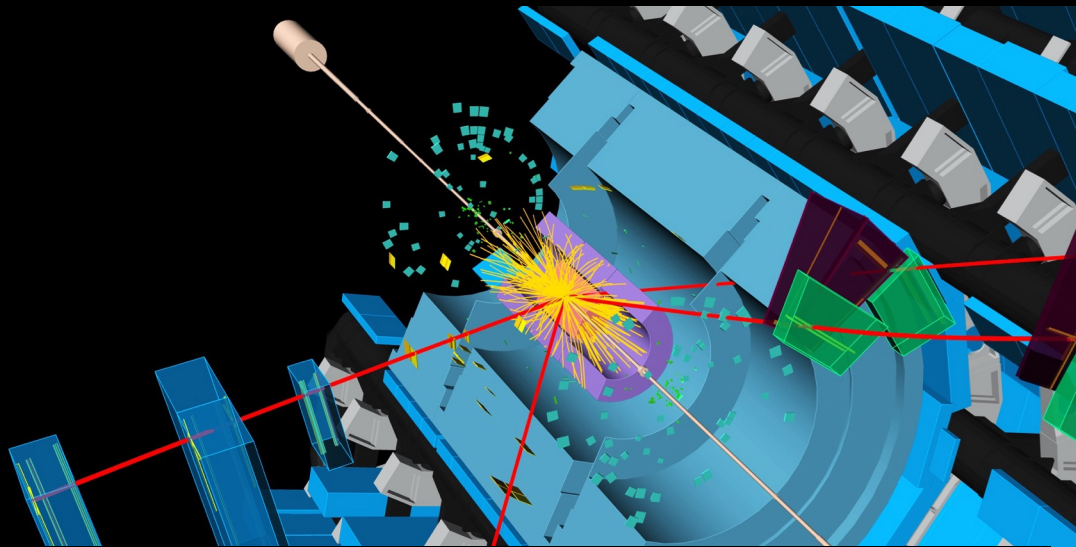
The new Higgs sector opens up a range of possibilities and raises a number of important questions

The Higgs boson and open questions in particle physics and cosmology

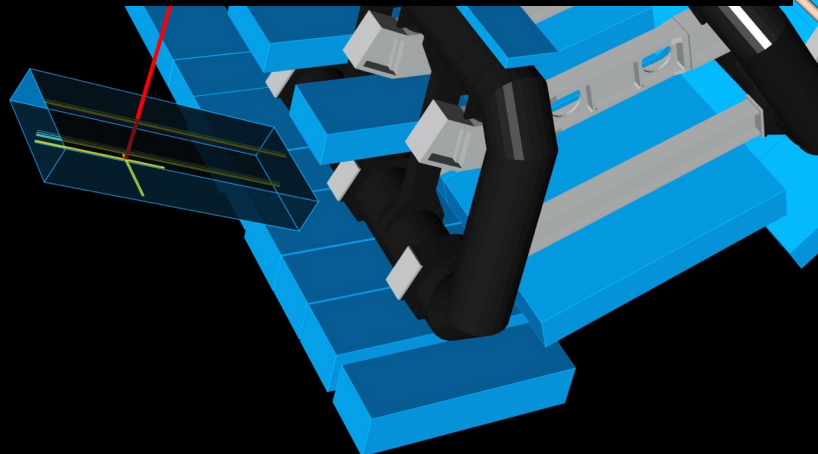
- Why is the Higgs boson so light?
- Is the Higgs boson elementary or composite ?
- Do Higgs interactions violate matter-antimatter symmetry?
- Is the Higgs boson unique?
- Does the Higgs boson couple to dark matter?
- What is the origin of the large mass hierarchy of the fermions in the Standard Model?
- Is the vacuum metastable?
- Is the Higgs field connected with cosmic inflation?
- Why is the dark energy in the universe so much smaller than the Higgs vacuum energy?

See, eg: [Salam, Wang, Zanderighi: Nature 607, 41 \(2022\)](#)

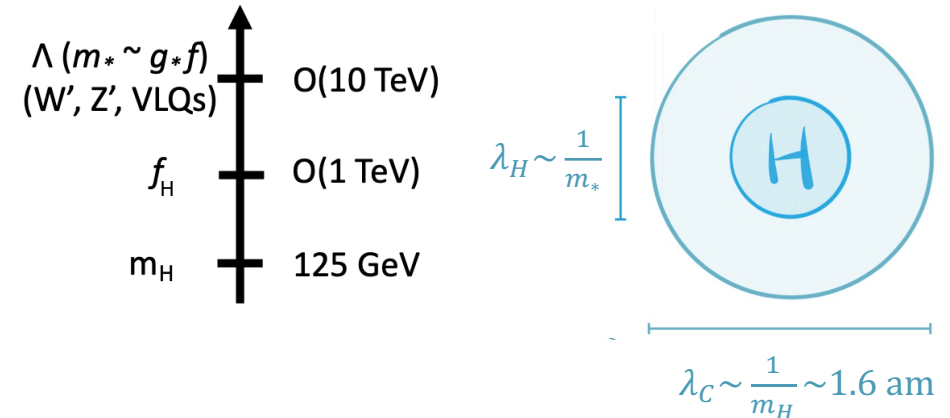
Is the Higgs boson elementary?



Higgs doublet might emerge as a composite bound state of a global symmetry that is spontaneously broken by new strong dynamics



Potential spectrum of putative new strong dynamics



In strongly interacting light Higgs (SILH) models, strong dynamics modifies the Higgs kinetic term, leading to a universal rescaling of all Higgs couplings

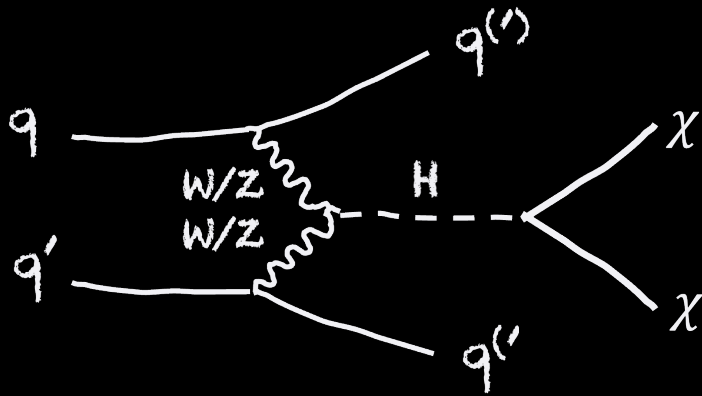
$$\kappa_i \rightarrow \kappa_i \left(1 - \frac{c_H v^2}{f_H^2} \right) = \kappa_i (1 - c_H \xi)$$

The **best measured coupling probes compositeness** of the Higgs boson!

5.0 (0.1)% precision on κ_i probes $f_H \sim 1.1$ (7.8) TeV

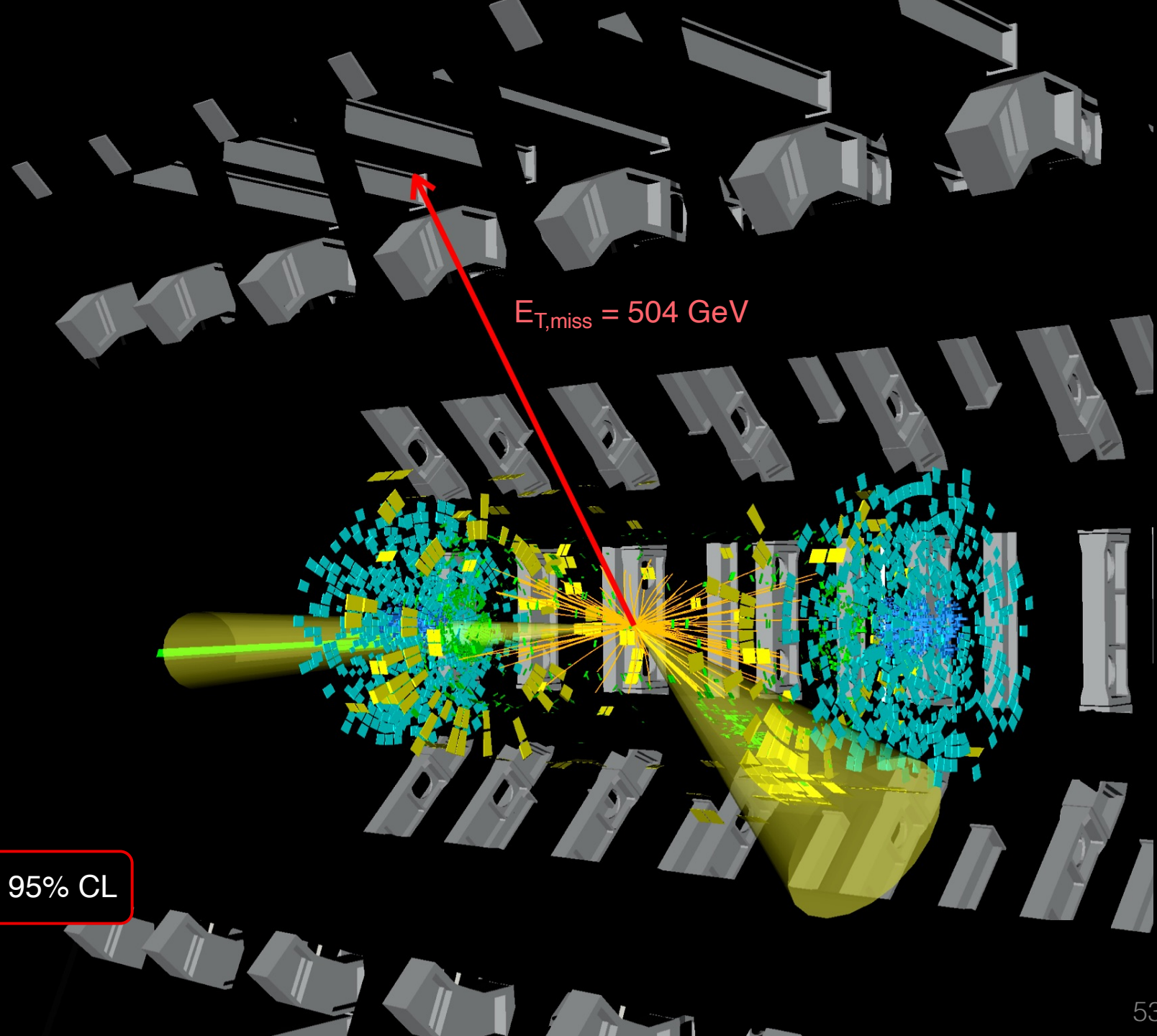
Dark matter

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



[arXiv:2202.07953](#), [arXiv:2301.10731](#)

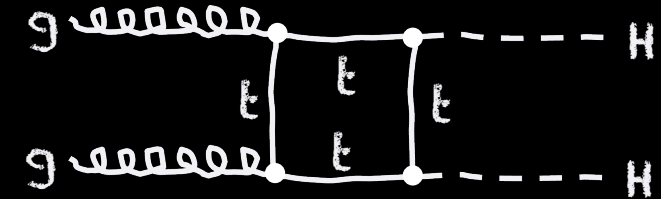
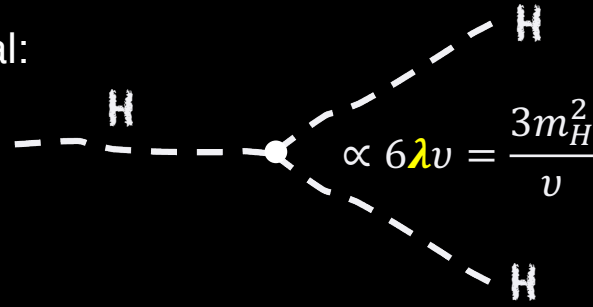
⇒ $\text{BR}(H \rightarrow \text{invisible}) < 0.107$ (0.077) at 95% CL



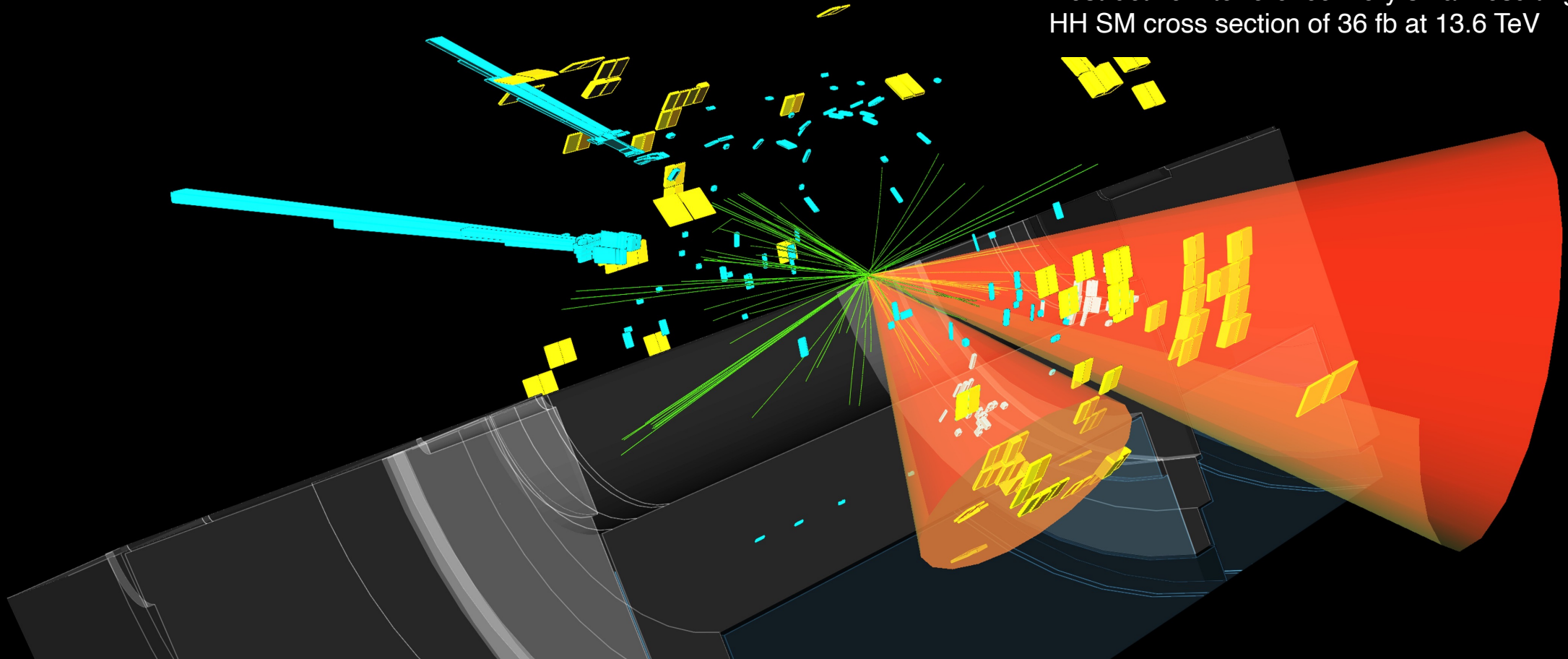
Higgs pair production

Access to Higgs λ term in Higgs potential:

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



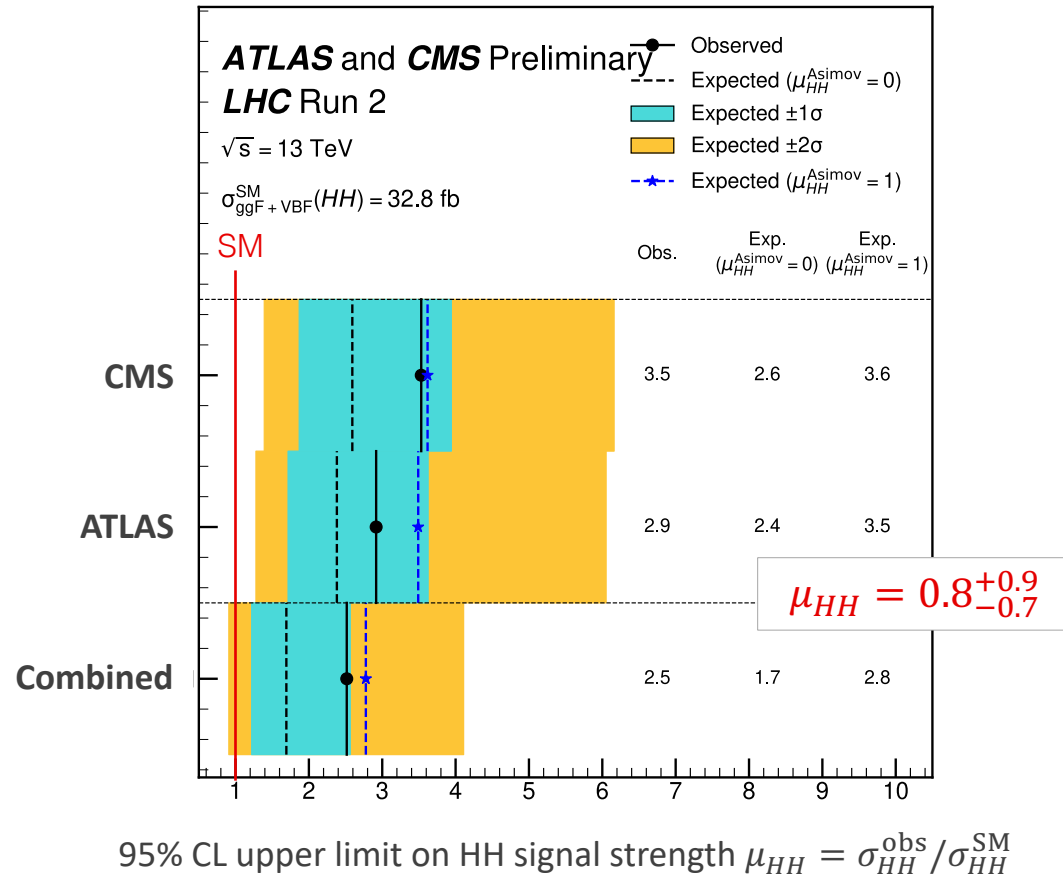
Destructive interference: very small resulting HH SM cross section of 36 fb at 13.6 TeV



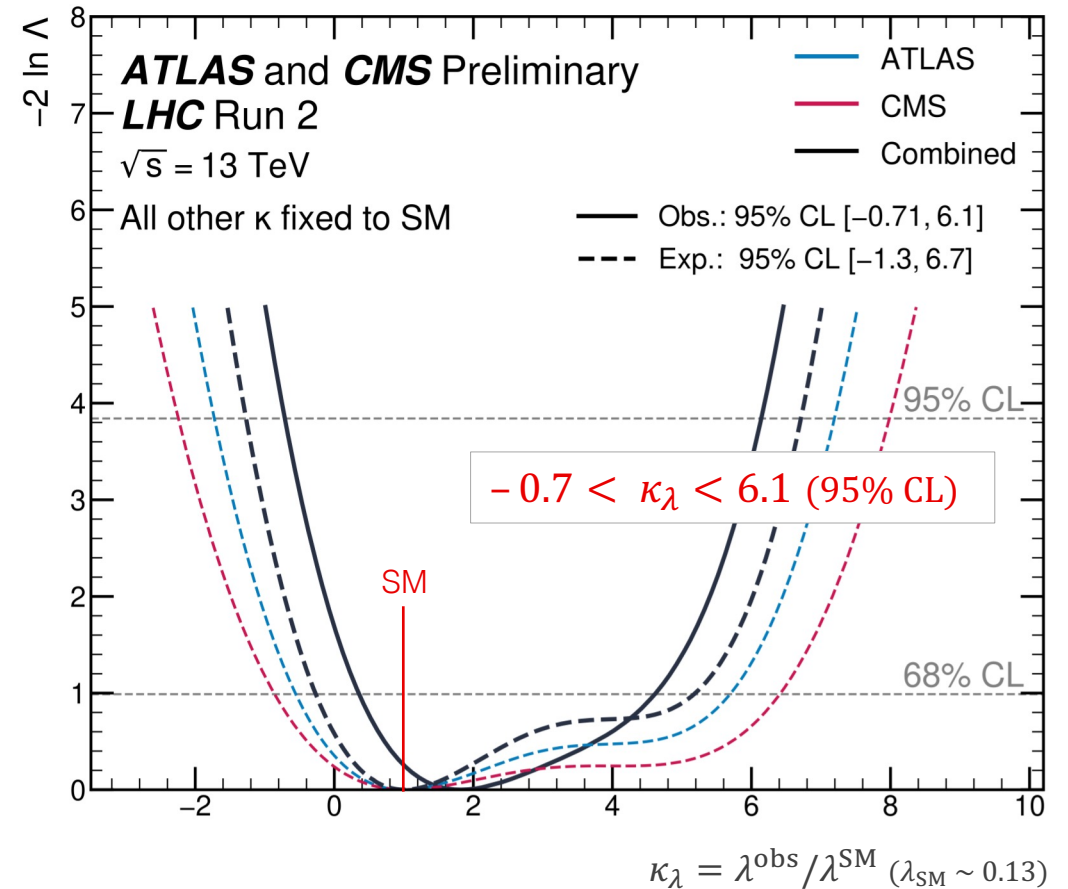
Higgs pair production

[ATLAS-CONF-2025-012](#), [CMS-PAS-HIG-25-014](#)

First ATLAS & CMS combination of HH production
using full Run-2 data

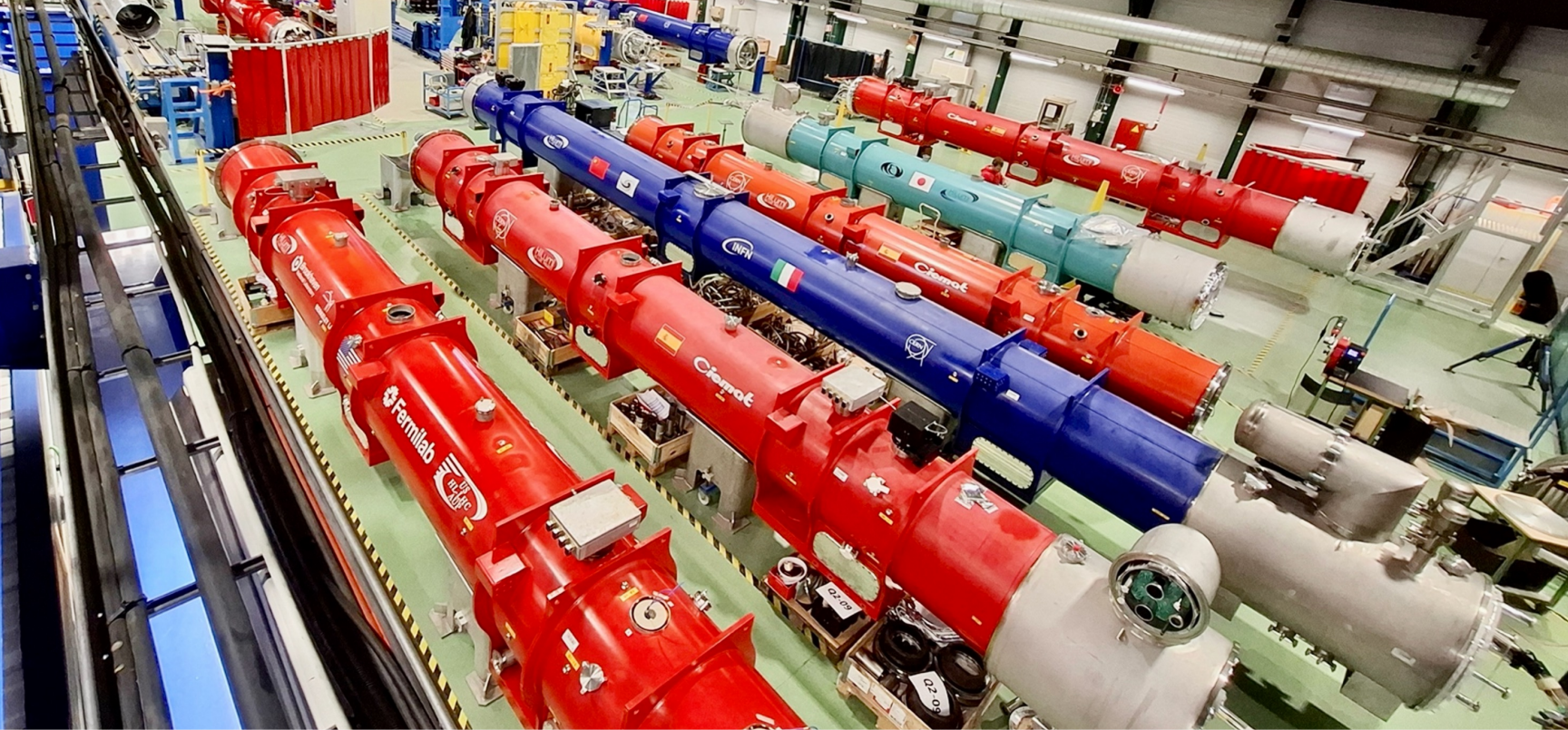


Constraint on $\kappa_\lambda = \lambda / \lambda_{\text{SM}}$, $\lambda_{\text{SM}} \sim 0.13$



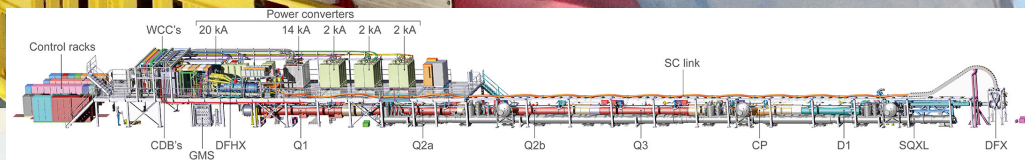
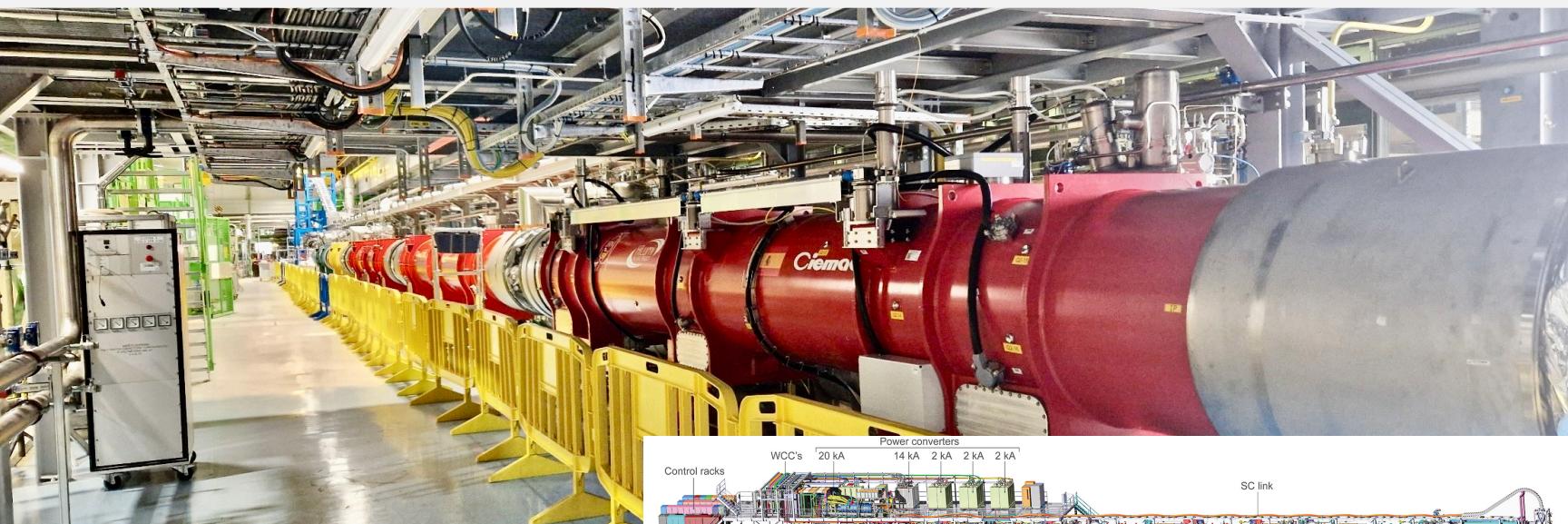
The next act: **High-Luminosity LHC**

New underground LHC service gallery at Point 5 (CMS) to accommodate higher radiation levels, Increased power consumption, complex electronics, cooling, and cryogenic systems



Upgrade to the High-Luminosity LHC is under way

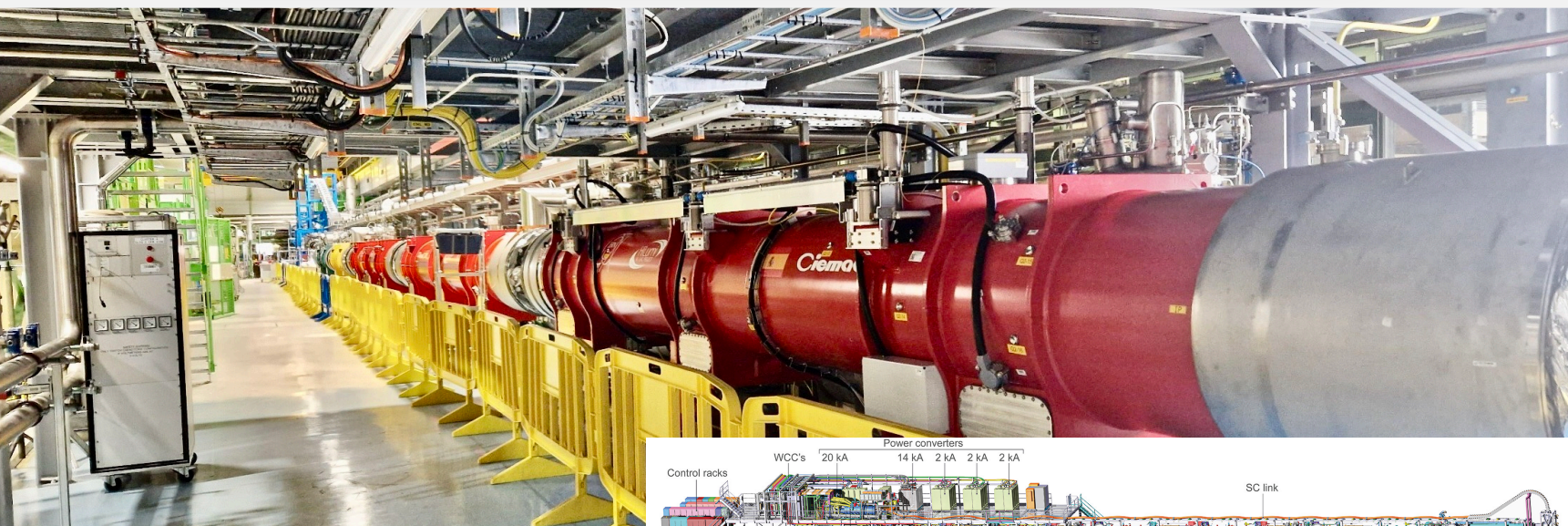
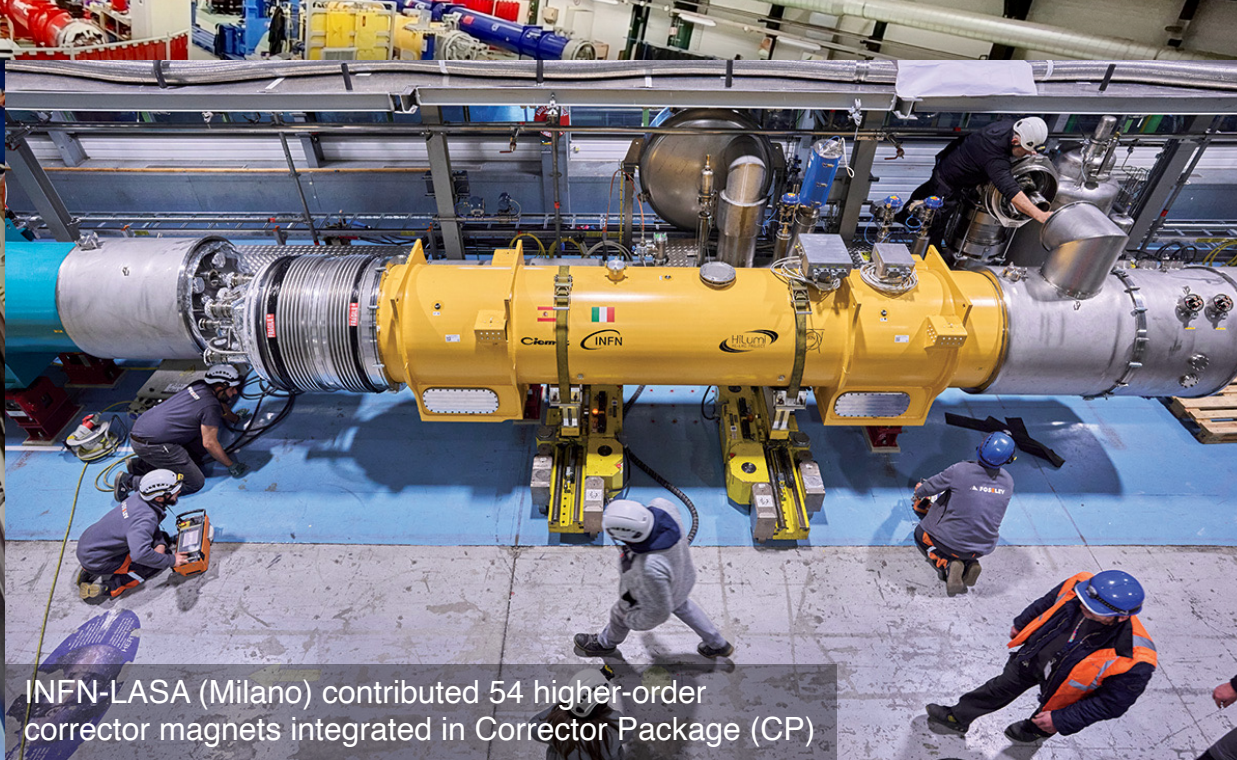
- The HL-LHC will use new technologies to provide up to 7 times more luminosity than the LHC
- We are also upgrading the detectors
- It will give access to rare phenomena, greater precision and discovery potential
- It will start operating in 2030 and run until 2041
- **Largest construction project at CERN for almost 20 years**



Fully realistic inner triplet string test facility at CERN

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Fully realistic inner triplet string test facility at CERN

Accelerator upgrades to HL-LHC

Ambitious goal: $L_{\text{int}} > 2500 \text{ fb}^{-1}$ in 9 years of operation (for a total delivered luminosity of 3 ab^{-1})

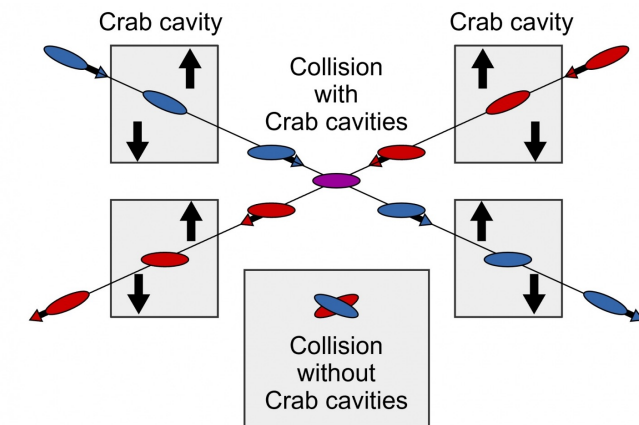
	Bunch intensity [protons / bunch]	β^* [cm]	Peak lumi [$\text{cm}^{-2}\text{s}^{-1}$]	Pileup $\langle\mu\rangle$	Int. lumi / year [fb^{-1}]
LHC design	$1.15 \cdot 10^{11}$	55	$1 \cdot 10^{34}$	23	30
LHC today	$1.6 \cdot 10^{11}$	60/18	$2.2 \cdot 10^{34}$	64	120
HL-LHC	$2.2 \cdot 10^{11}$	15	$5\text{--}7 \cdot 10^{34}$	140–200	up to 300

Improved cryogenic cooling and collimators,
make all systems more radiation hard

LIU high-brightness upgrade during LS2
RF crab cavities restore effective head-on collisions despite a crossing angle via time-dependent transverse kicks

Stronger focussing: 12 new Nb_3Sn^* “inner triplet” quadrupoles at ATLAS & CMS (B-field: 8.5 $\rightarrow$ 11.5 T, aperture: 70 $\rightarrow$ 150 mm)

*First-time use in an accelerator

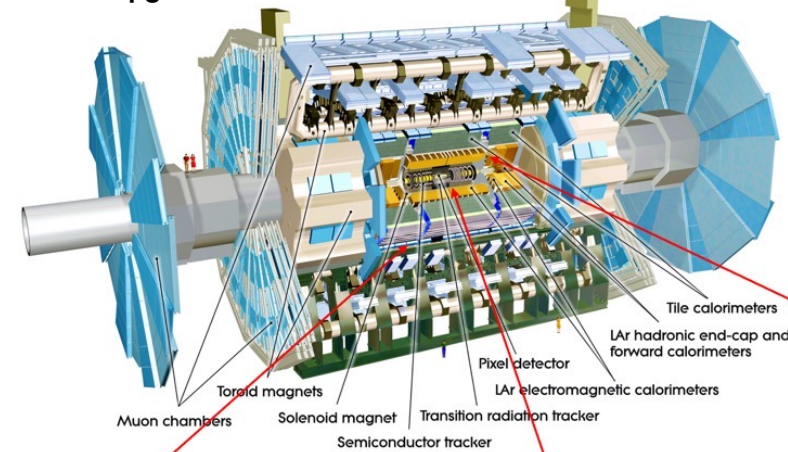


Detector upgrades to HL-LHC

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



New Muon Chambers

Inner barrel region with new RPC and SMDT detectors

New Inner Tracking Detector (ITk)

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

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

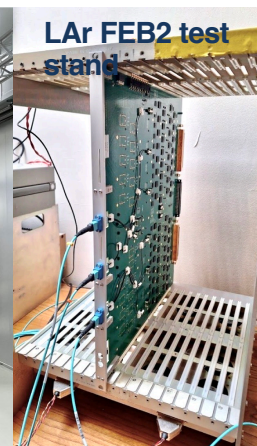
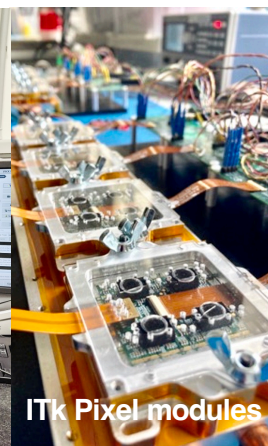
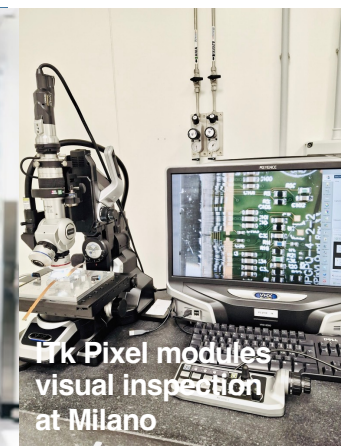
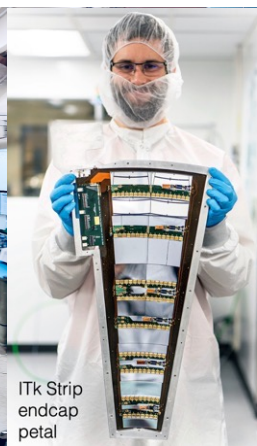
High Granularity Timing Detector (HGTD)

Forward region ($2.4 < |\eta| < 4.0$)
Low-Gain Avalanche Detectors (LGAD) with 30 ps track resolution

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



Detector upgrades to HL-LHC

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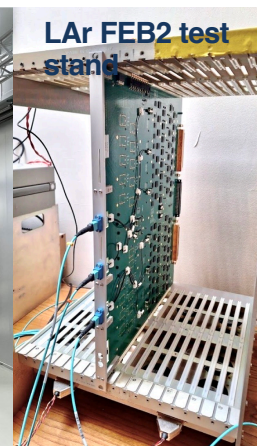
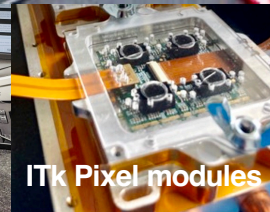
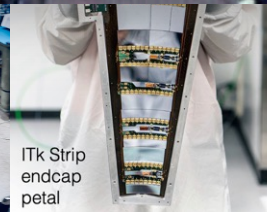
Additional small upgrades

Luminosity detectors (1% precision goal)
HL-ZDC

calorimeters
end-cap and
timers

(ITk)

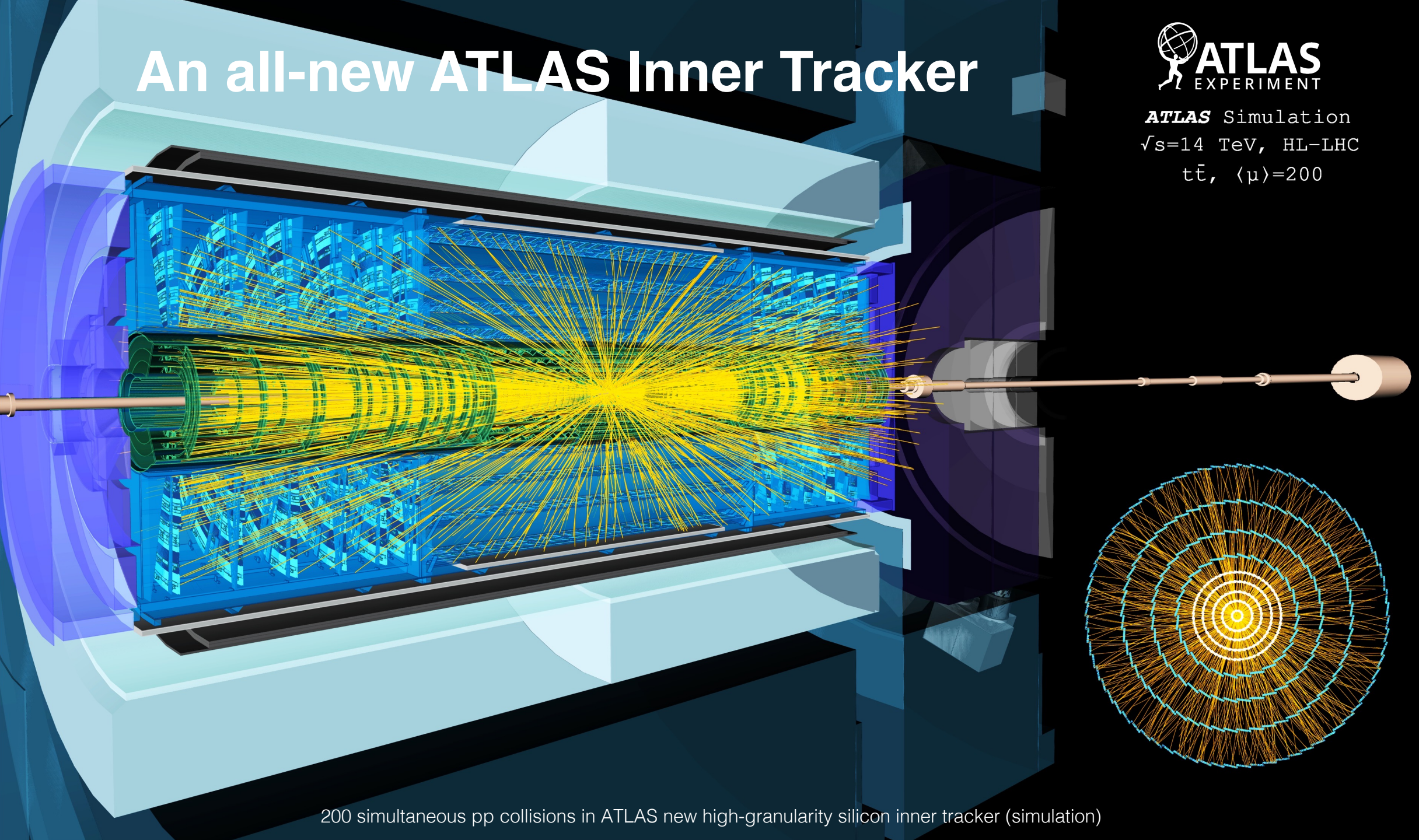
2018, 2020



An all-new ATLAS Inner Tracker



ATLAS Simulation
 $\sqrt{s}=14$ TeV, HL-LHC
 $t\bar{t}$, $\langle\mu\rangle=200$

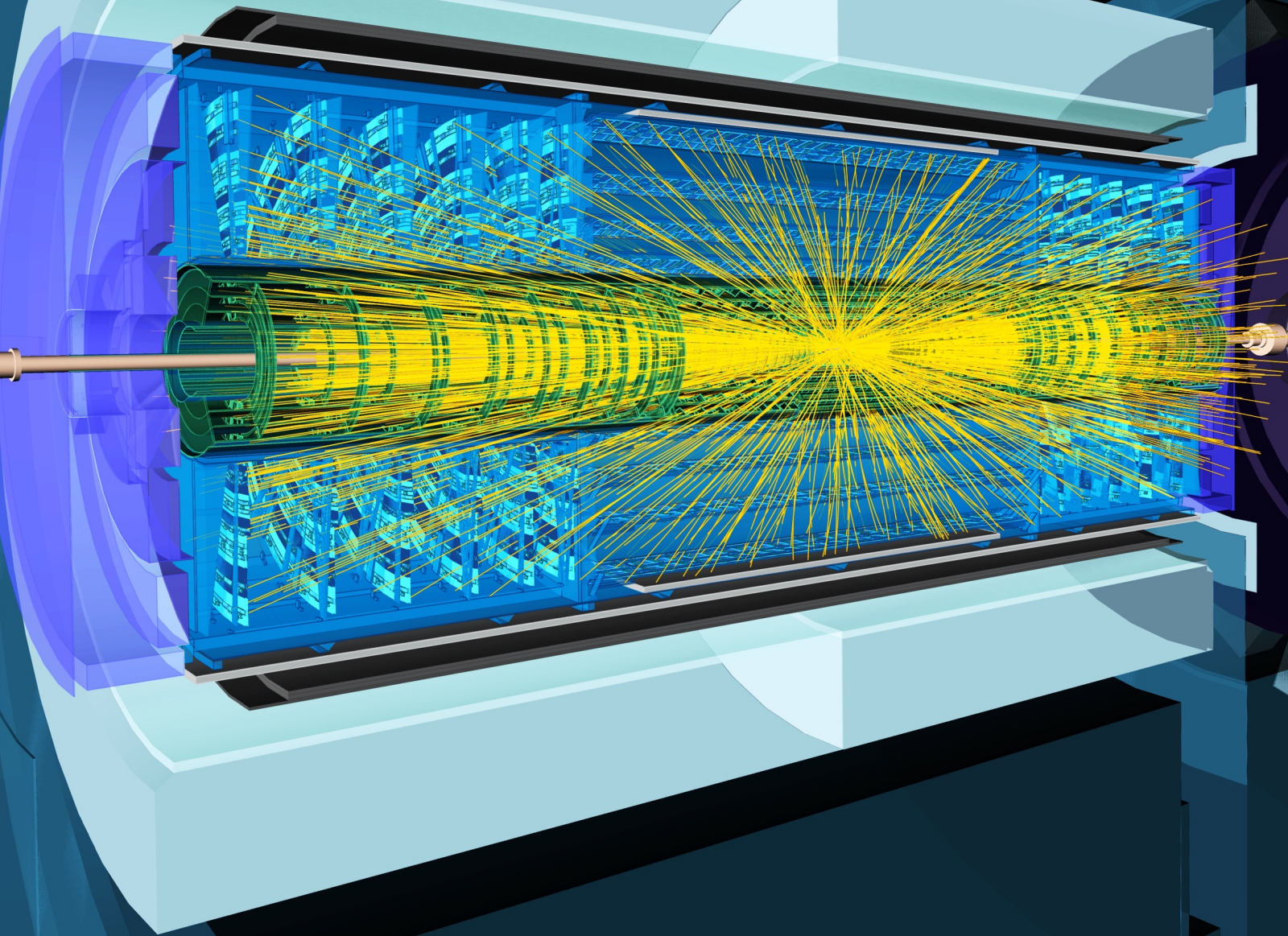


200 simultaneous pp collisions in ATLAS new high-granularity silicon inner tracker (simulation)

An all-new ATLAS Inner Tracker



ATLAS Simulation
 $\sqrt{s}=14$ TeV, HL-LHC
 $t\bar{t}$, $\langle\mu\rangle=200$



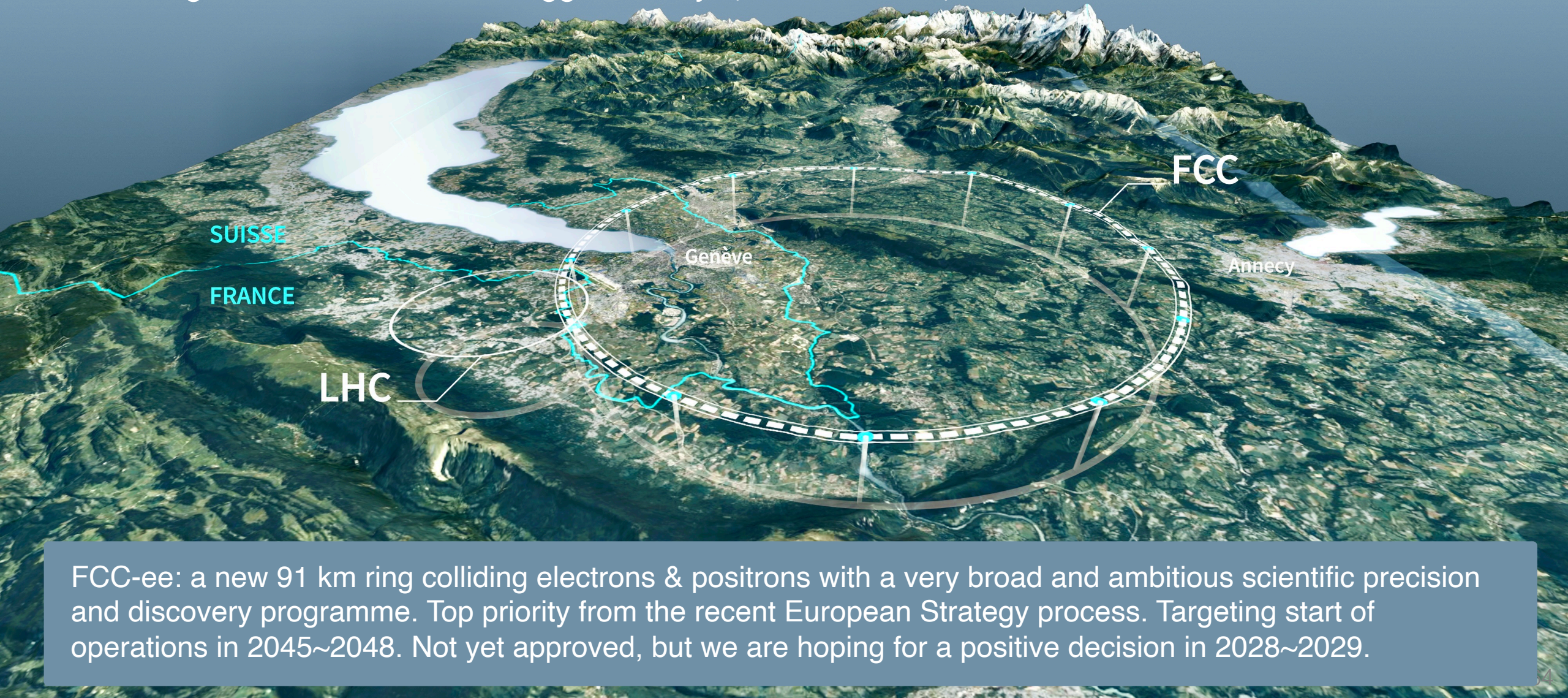
HL-LHC physics goals (ATLAS & CMS):

- Produce 350M H, 240k HH, 13B top, 720M WW, ...
- Percent level Higgs coupling precision
- Unique sensitivity to rare Higgs decays and Higgs-to-top coupling
- $< 20\%$ precision on Higgs width
- $< 2.5\%$ sensitivity on the invisible Higgs decay fraction
- Higgs pair sensitivity of 7.6σ , $< 30\%$ on Higgs self-coupling (λ)
- Greatly enhanced sensitivity for new physics searches

Huge gains also for LHCb flavour physics

Europe's long-term vision: Future Circular Collider (FCC) at CERN

The Higgs boson is a genuinely new and unique type of particle, and a window to discovery — strong scientific case for a “Higgs Factory” (and much more)



FCC-ee: a new 91 km ring colliding electrons & positrons with a very broad and ambitious scientific precision and discovery programme. Top priority from the recent European Strategy process. Targeting start of operations in 2045~2048. Not yet approved, but we are hoping for a positive decision in 2028~2029.

Conclusions

The LHC is the most powerful and versatile particle collider ever built, enabling deep Higgs, EW, top, QCD, flavour, BSM, and quark-gluon plasma studies

Its results have been transformative for particle physics

The Higgs sector relates to very profound questions whose detailed study requires a broad experimental programme that will extend over decades

The ongoing Run 3 and the HL-LHC will provide 95% of the full LHC dataset

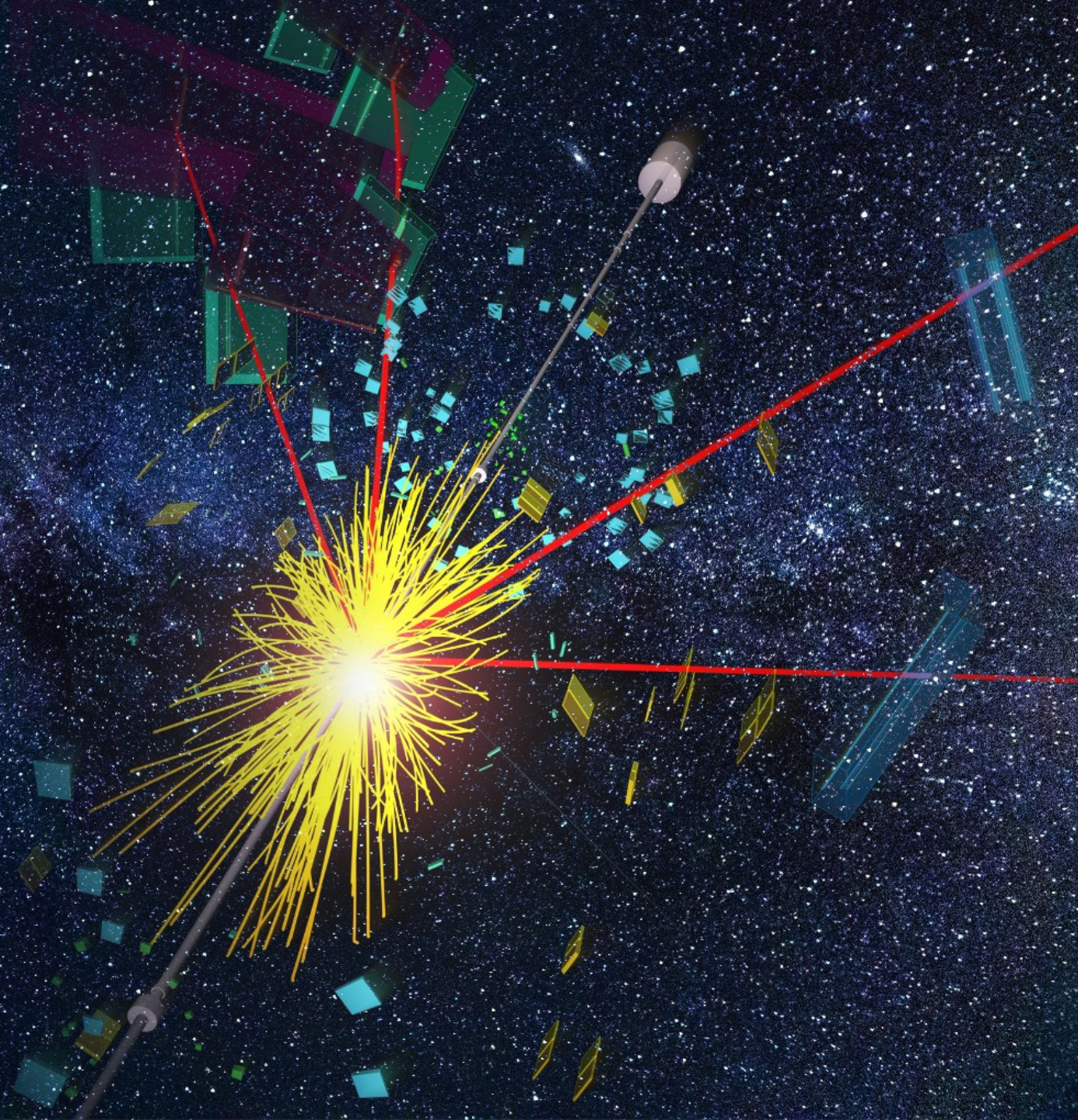
We will do better than any of our physics extrapolations

The HL-LHC and upgraded detectors offer immense opportunities, complementary in many ways to a future e^+e^- collider. We are in the midst of a storm of innovation



Thank you very much for your attention

Extra slides



CERN — the world's largest centre for particle physics



CERN — the world's largest centre for particle physics



ATLAS Experiment

CERN was founded in 1954 by 12 European Member States. Today: 25



A laboratory for people around the world

25 Member States

Austria – Belgium – Bulgaria – Czech Republic
Denmark – Estonia – Finland – France – Germany
Greece – Hungary – Israel – Italy – Netherlands
Norway – Poland – Portugal – Romania – Serbia
Slovakia – Slovenia – Spain – Sweden – Switzerland
United Kingdom

10 Associate Member States

Brazil – Croatia – Cyprus – India – Ireland – Latvia
Lithuania – Pakistan – Türkiye – Ukraine

4 Observers

Japan – USA – European Union – UNESCO

Data as of 31 December 2024

~ 50 Cooperation Agreements

Albania – Algeria – Argentina – Armenia – Australia – Azerbaijan – Bahrain
Bangladesh – Bolivia – Bosnia and Herzegovina – Canada – Chile – Colombia
Costa Rica – Ecuador – Egypt – Georgia – Guatemala – Honduras – Iceland
Iran – Jordan – Kazakhstan – Lebanon – Malta – Mexico – Mongolia – Montenegro
Morocco – Nepal – New Zealand – North Macedonia – Paraguay – Palestine
People's Republic of China – Peru – Philippines – Qatar – Saudi Arabia
South Africa – Sri Lanka – Thailand – Republic of Korea – Tunisia
United Arab Emirates – Uruguay – Vietnam

CERN members:

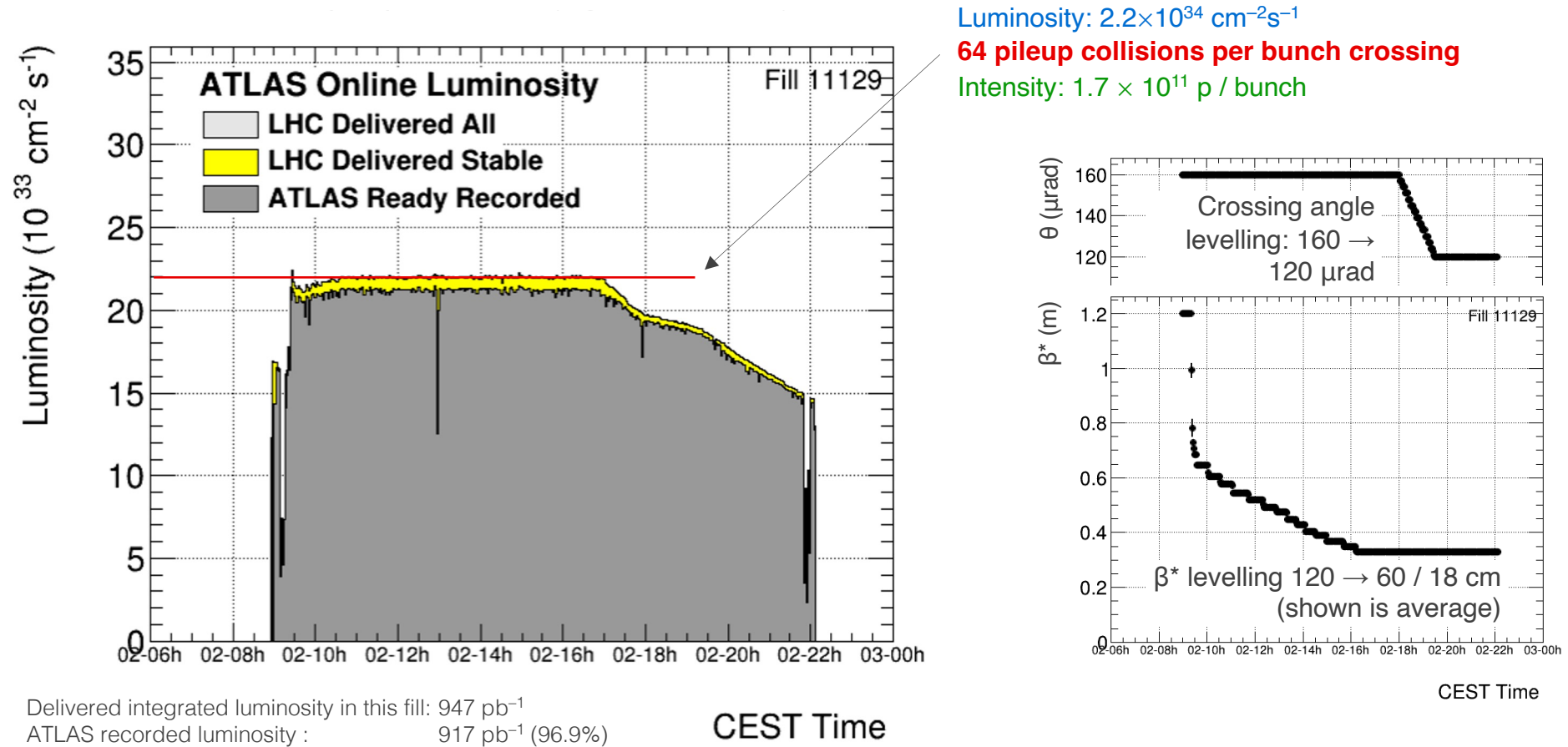
- 2700 staff
- 1200 graduates and fellows
- 14000 users (3000 Ph.D. students)



Education & training is one
of CERN's core mission

Most successful LHC Runs 1, 2, 3

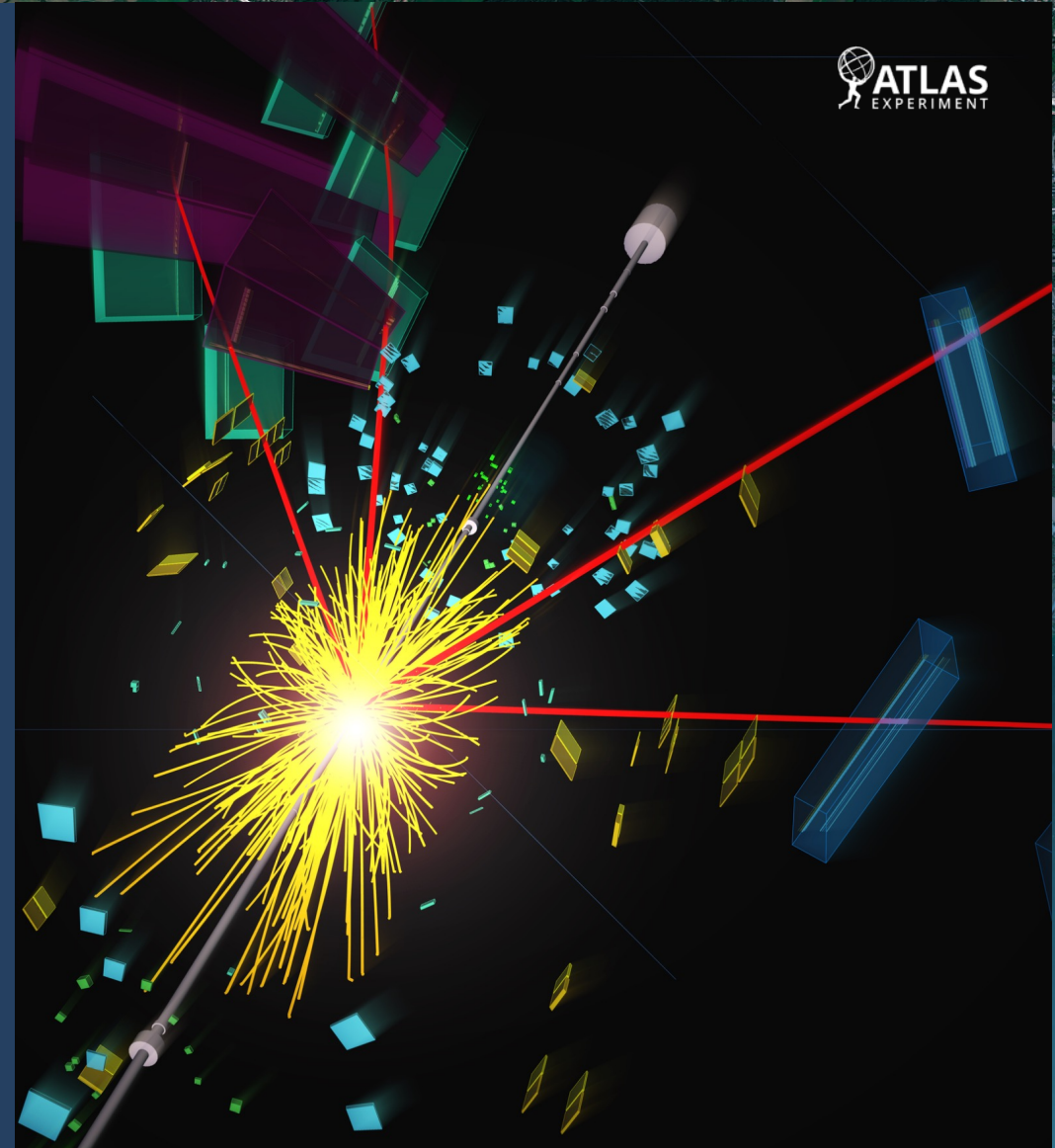
Luminosity profile in ATLAS & CMS during a 15h28 fill (13h07 in stable beams), 2 Oct 2025



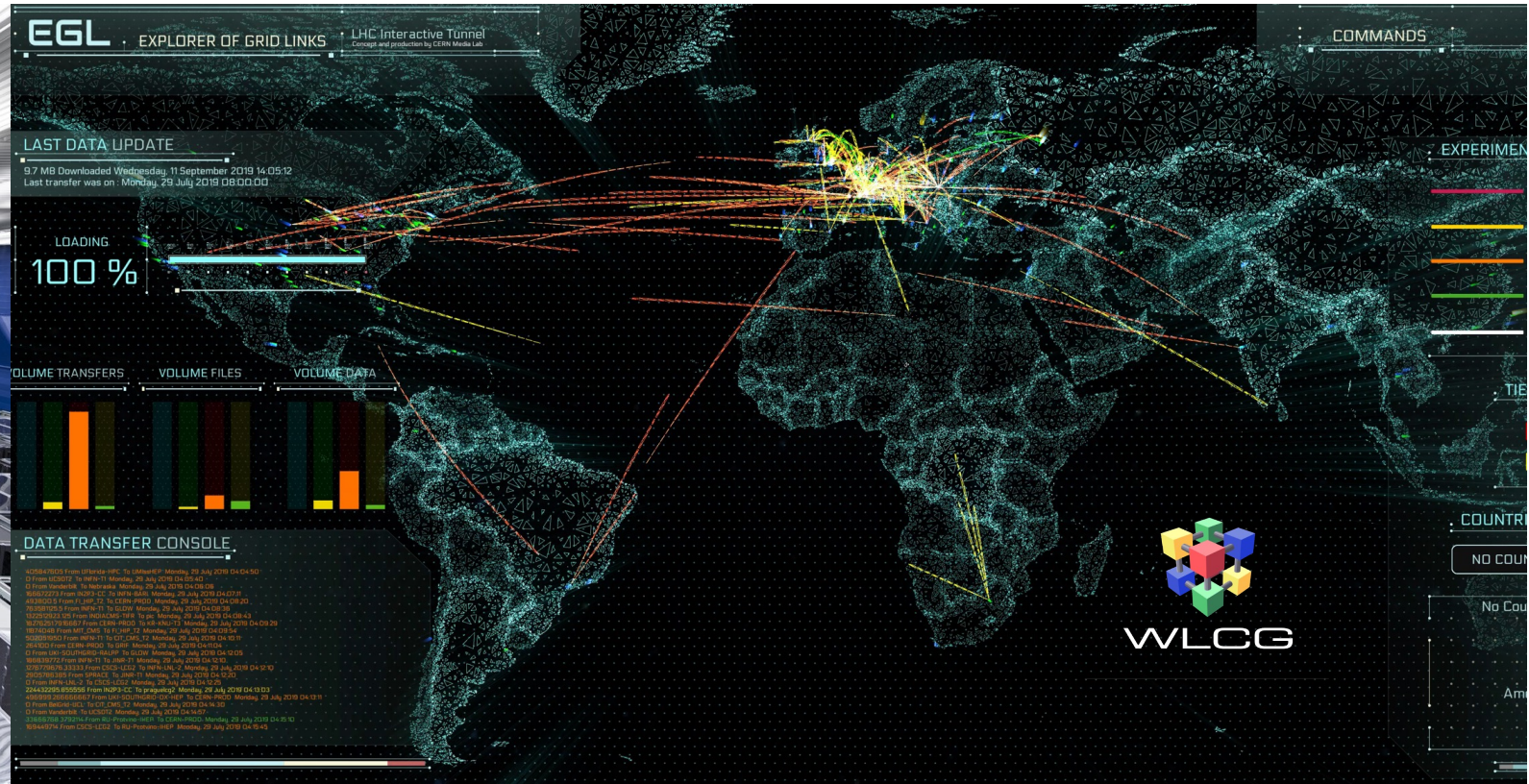
What happens in a high-energy proton–proton collision?

Its constituents fuse and transform into new, sometimes heavy particles with rates depending on the strength of their interaction with the proton constituents and on their mass:

- Light quarks, gluons (“jets”) $\gg$ W, Z $\gg$ top quark $\gg$ Higgs boson
- Heavy particles decay instantaneously to light, stable particles (hadrons, leptons, photons)
- A particle detector precisely measures these decay particles, which allows to deduce the properties of the mother particle
- An online filter (“trigger”) reduces the huge rate of particle interactions by a factor of 20,000 focusing on the most interesting processes
- Data reconstruction and analysis is done in computing centers worldwide



CERN is the birthplace of the World Wide Web and the Worldwide LHC Computing Grid (WLCG)



WLCG stores, distributes, processes and analyses LHC experiments' data

1.4 million processing cores in 170 data centres and more than 40 countries

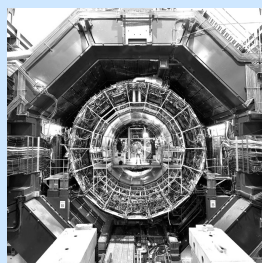
> 2000 Petabytes (2 Exabytes) of LHC data stored worldwide

LHC: A Transformative Leap in Physics

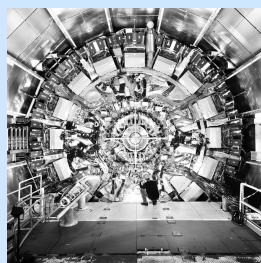
Accelerator, experiments, software & computing, reconstruction and physics analysis all perform beyond design
Many new analyses ideas emerged that were not thought of during the design phase. ML now ubiquitous

2025 Breakthrough Prize in Fundamental Physics awarded to the **ALICE, ATLAS, CMS, and LHCb collaborations** for results from LHC Run 2

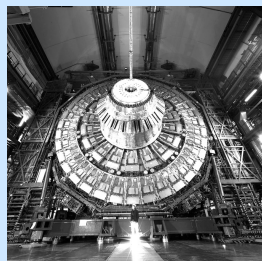
For detailed measurements of Higgs boson properties confirming the symmetry-breaking mechanism of mass generation, the discovery of new strongly interacting particles, the study of rare processes and matter-antimatter asymmetry, and the exploration of nature at the shortest distances and most extreme conditions at CERN's Large Hadron Collider.



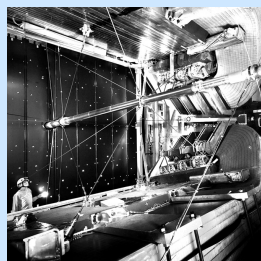
ALICE



ATLAS



CMS



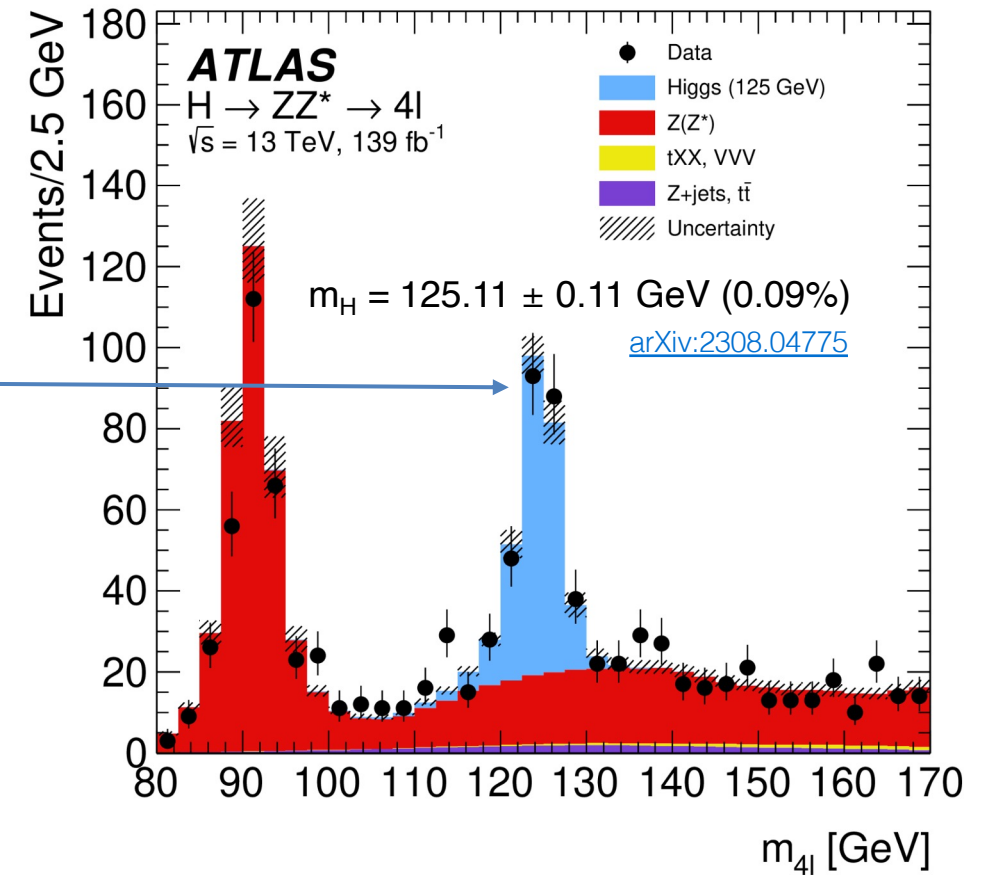
LHCb

Higgs boson mass

The Higgs mass is peculiar

2020

[Eur. Phys. J. C 80 \(2020\) 942](#)

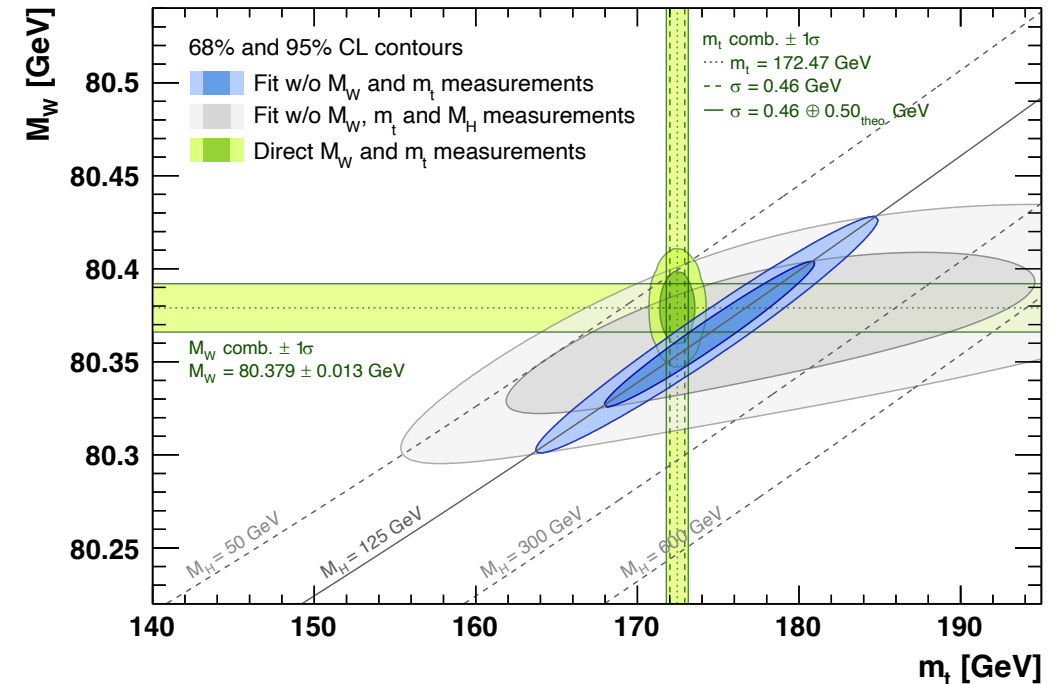
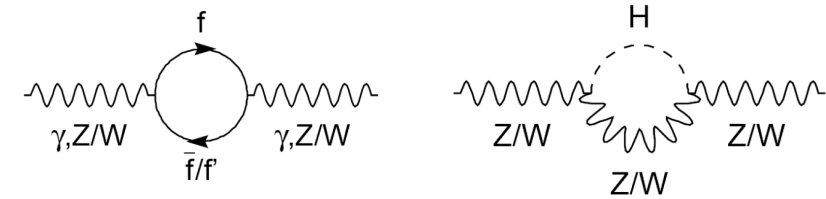


Higgs boson mass

The Higgs mass is peculiar

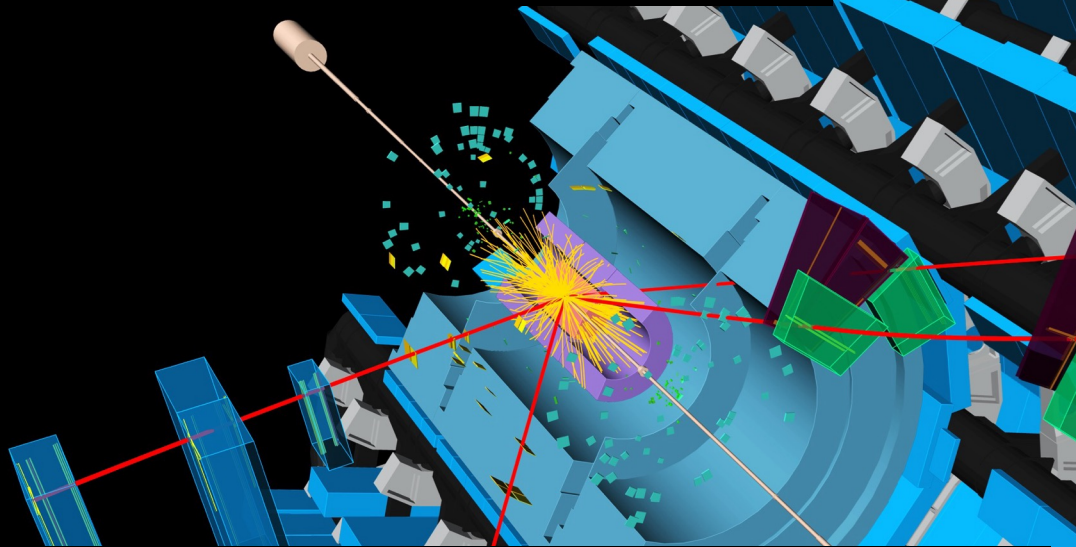
- It is consistent with the global electroweak fit

Radiative corrections sensitive to heavy particles in loop



Gfitter Group: [arXiv:1803.01853](https://arxiv.org/abs/1803.01853)

Higgs boson mass

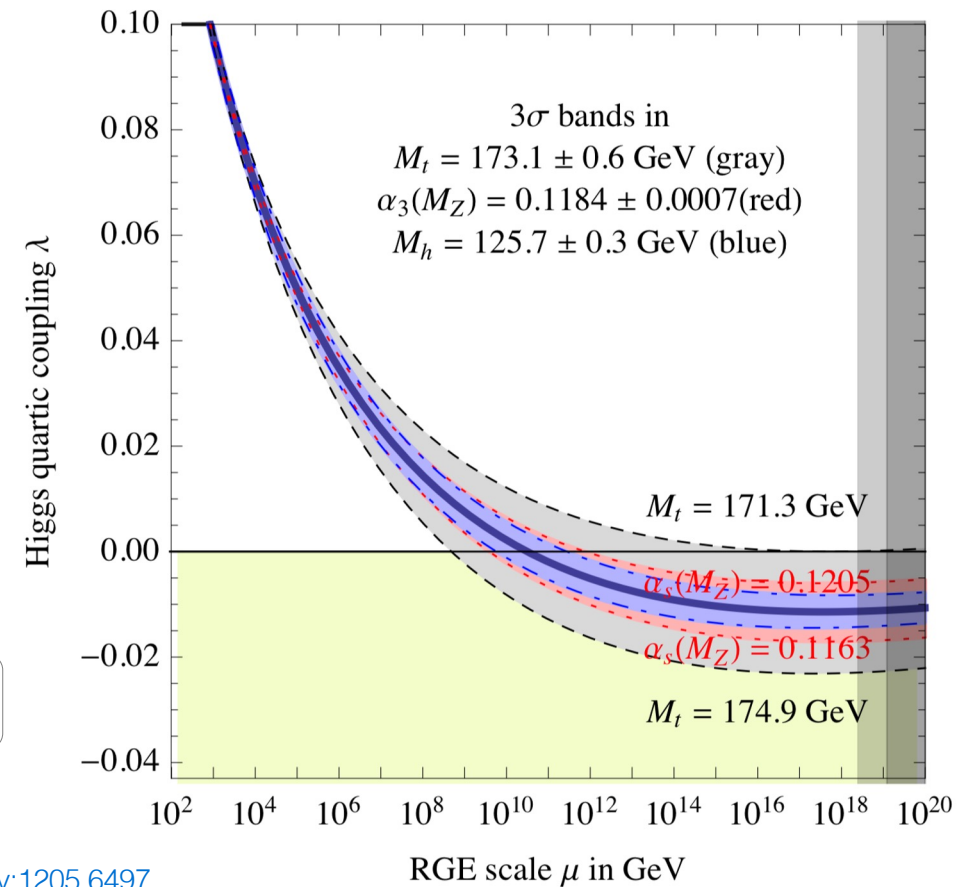


The Higgs mass is peculiar

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

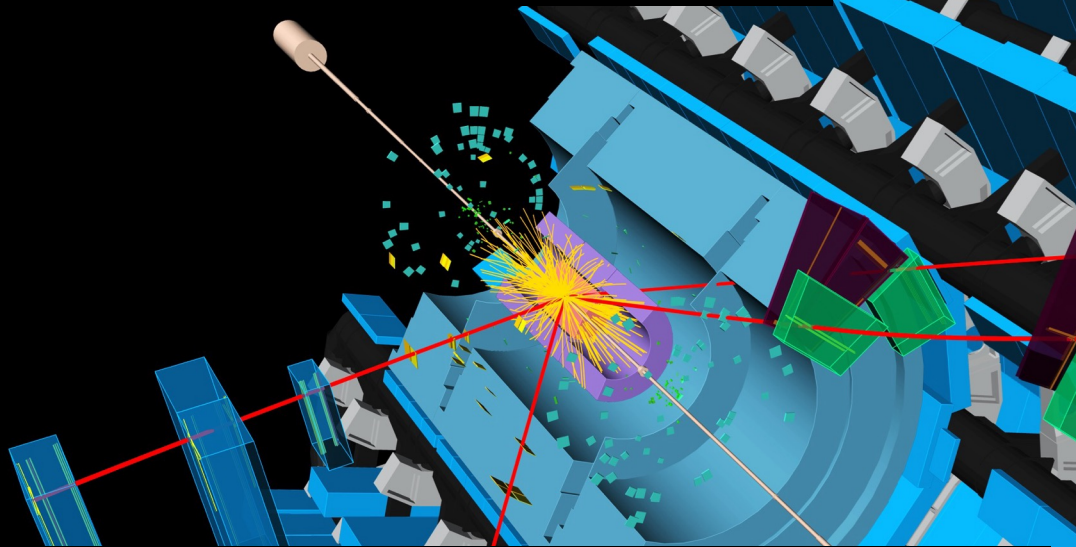
$$V(\phi) = -\mu^2|\phi|^2 + \lambda|\phi|^4$$

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



[arXiv:1205.6497](https://arxiv.org/abs/1205.6497)

Higgs boson mass



The Higgs mass is peculiar

- It is consistent with the global electroweak fit
- But the electroweak vacuum seems to be metastable
- And in case of new high-scale physics, the Higgs mass appears to be highly fine-tuned

The scalar mass term in the SM is not protected by any symmetry, so, in case of high-scale new physics (eg, at m_{Pl}):

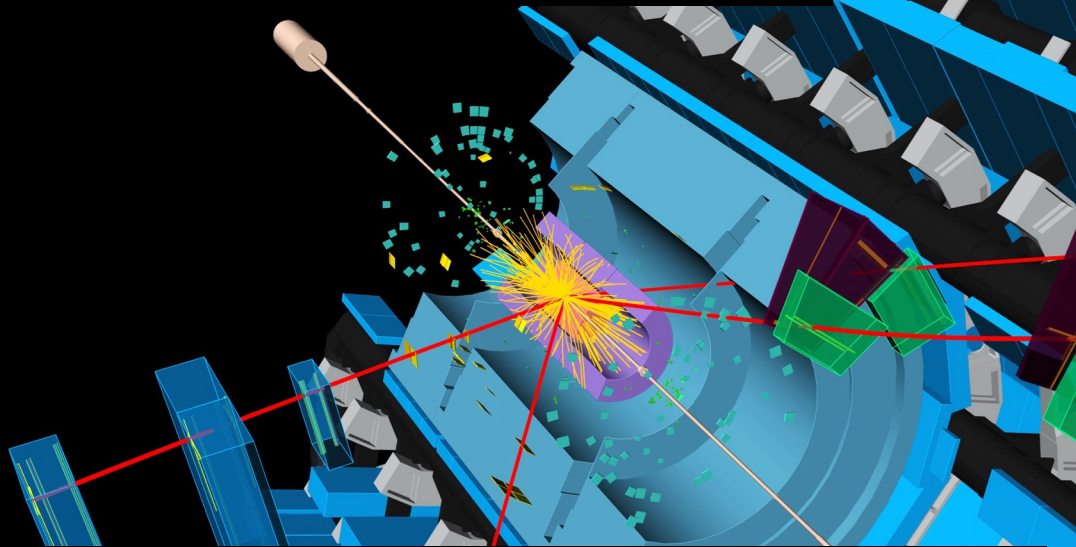
$$m_H^2 = m_{\text{bare}}^2 + \delta m_H^2$$

$$\delta m_H^2 = \frac{\Lambda^2}{16\pi^2} \frac{3}{v^2} (m_H^2 + m_Z^2 + 2m_W^2 - 4m_t^2)$$

This is the **hierarchy problem**: low-energy physics depends on high-energy physics (no scale factorisation)

- Solutions explored may be weakly coupled (eg, SUSY), strongly coupled (eg, Higgs composite), strong gravity (eg, warped extra dimensions)
- To be *natural*, solutions involve new physics at TeV scale. Or invoke a statistical solution (and the anthropic principle) via a landscape of string vacua (multiverse)

Higgs boson width

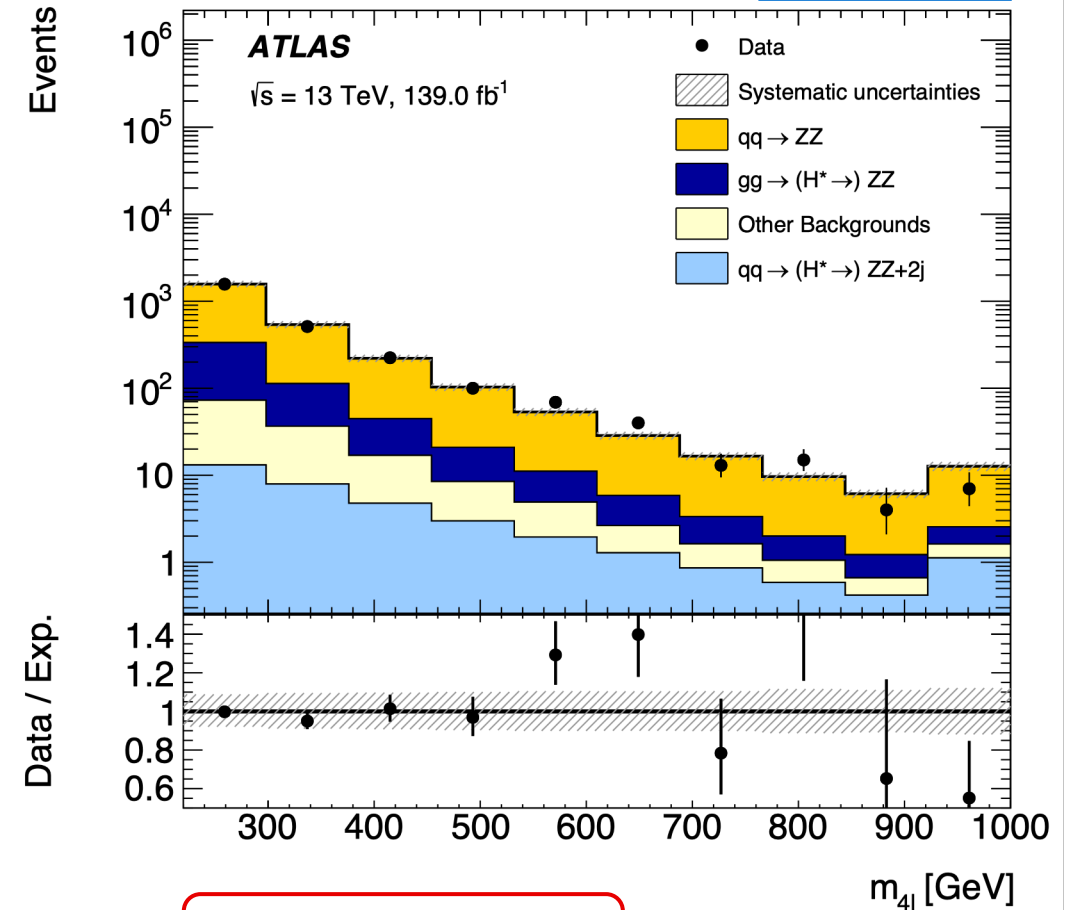


The Higgs is predicted to be very narrow ($\Gamma_H = 4.1$ MeV), far below the resolution of the detectors

One can still measure its decay width by comparing the high-mass off-shell Higgs coupling strength (independent of Γ_H) to the on-shell (125 GeV) one (dependent on Γ_H)

The $pp \rightarrow 4\ell$ spectrum is sensitive to H^* production

[PLB 846 \(2023\) 138223](#)

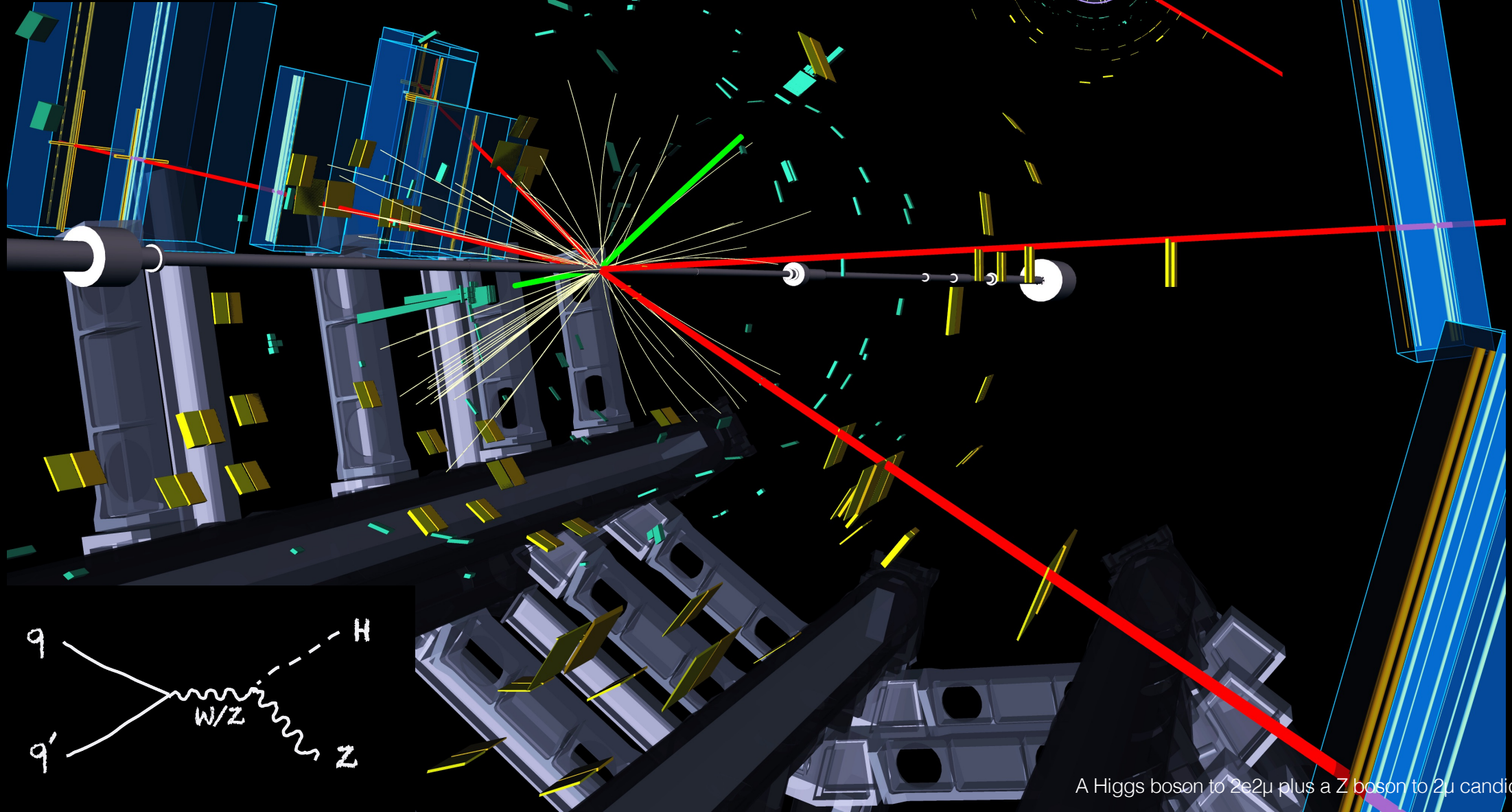


$$\Rightarrow \Gamma_H = 4.3^{+2.7}_{-1.9} \text{ MeV}$$

Newest: [Rep. Prog. Phys. 88 \(2025\) 057803](#)

Run: 359058
Event: 2965933740
2018-08-25 02:51:44 CEST

A pure Higgs boson event

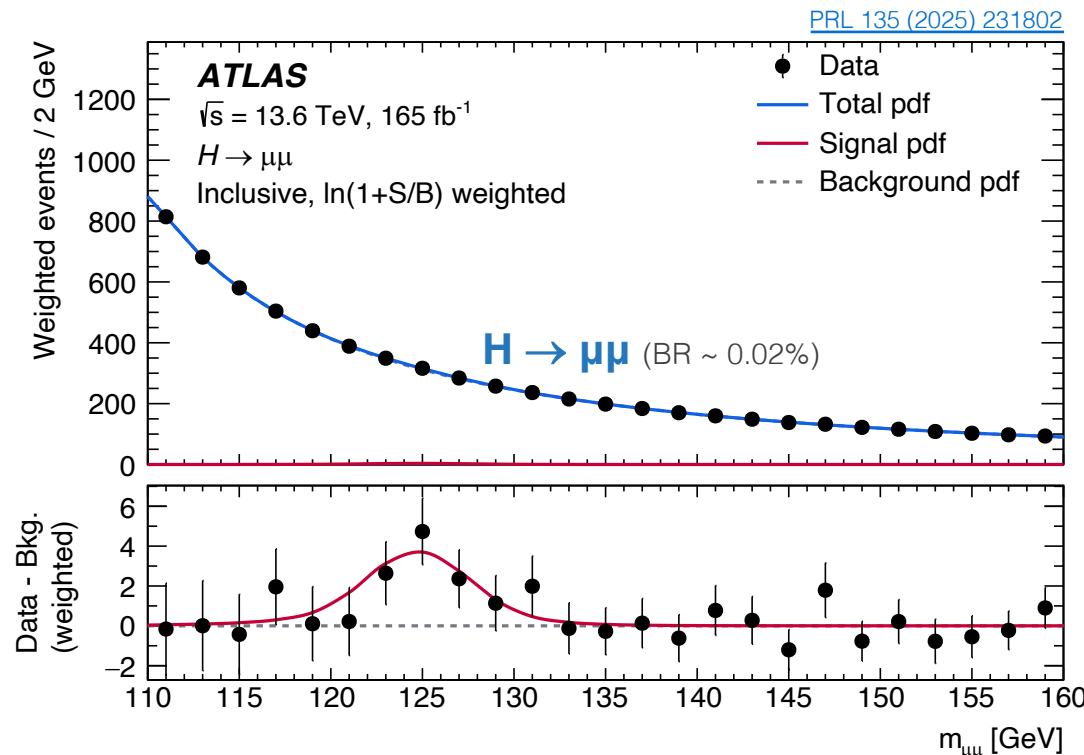


A Higgs boson to $2e2\mu$ plus a Z boson to 2μ candidate event

Rare Higgs boson decays

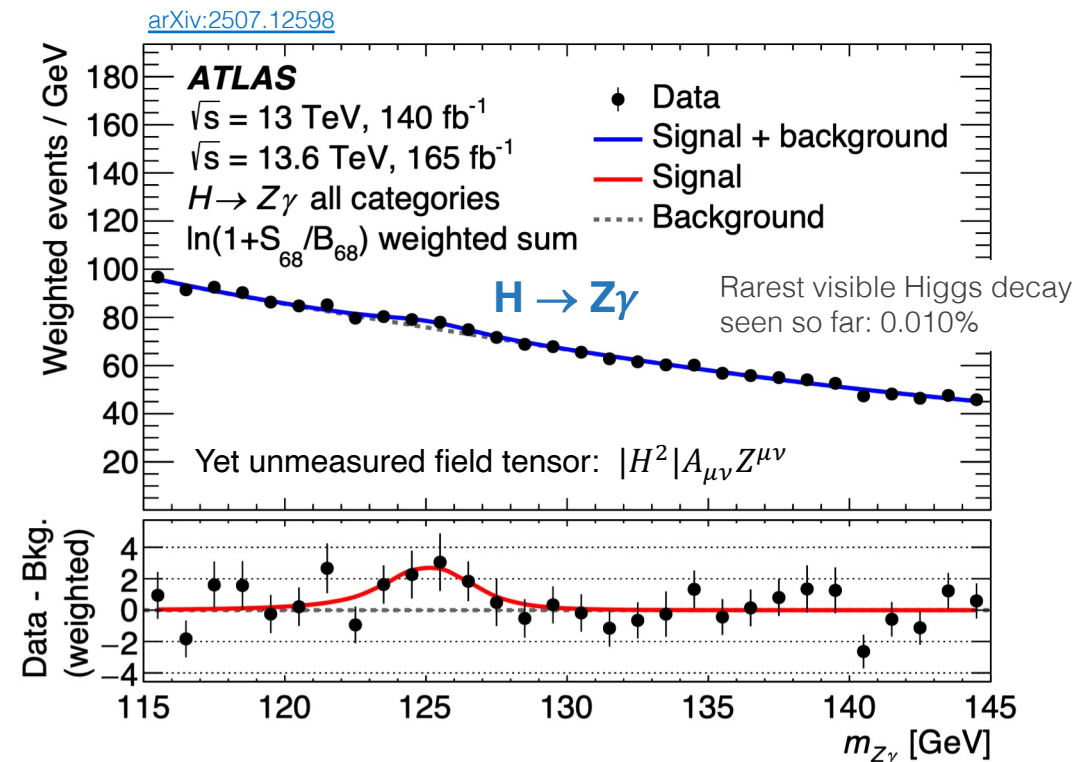


Using 305 fb⁻¹ of Run-2 + 3 (2022–2024) data, ATLAS reported evidence for rare 2nd generation $H \rightarrow \mu\mu$ (first seen by CMS), and released a new result on the loop decay $H \rightarrow Z\gamma$



Significance: 3.4 σ (2.5 σ exp), $\mu = \sigma_{\text{exp}} / \sigma_{\text{SM}} = 1.4 \pm 0.4$

Reminder: CMS (Run 2): $\mu = 1.19 \pm 0.43$ (3.0 σ) [[JHEP 01 \(2021\) 148](#)]

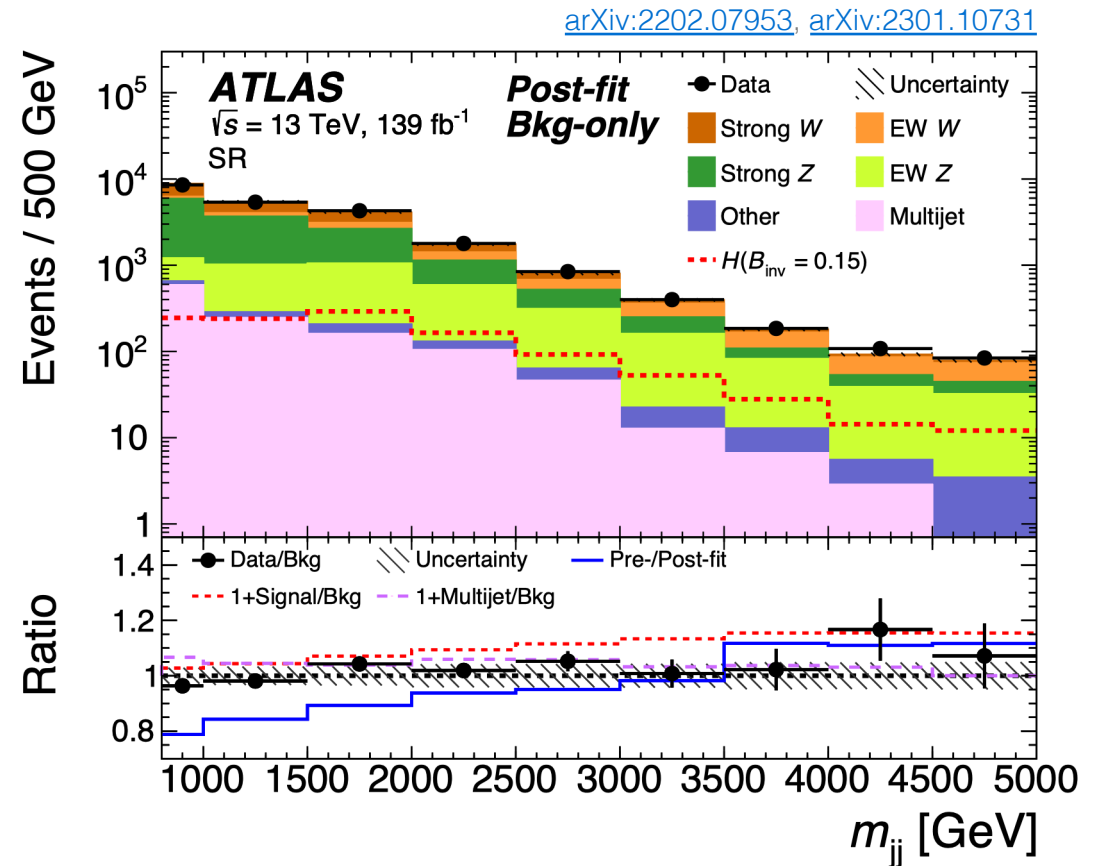
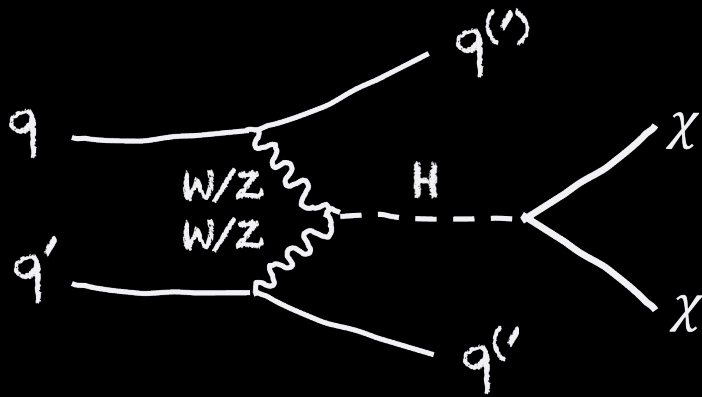


Significance: 2.5 σ (1.9 σ exp), $\mu = 1.3$

Reminder: ATLAS & CMS (Run 2): $\mu = 2.2 \pm 0.7$ (3.4 σ) [[Ref](#)]

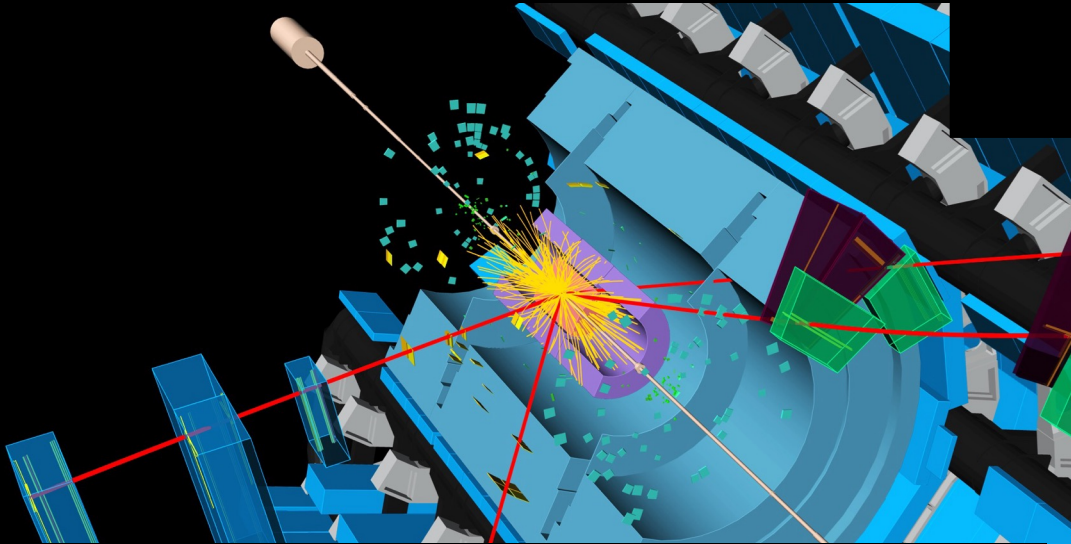
Dark matter

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



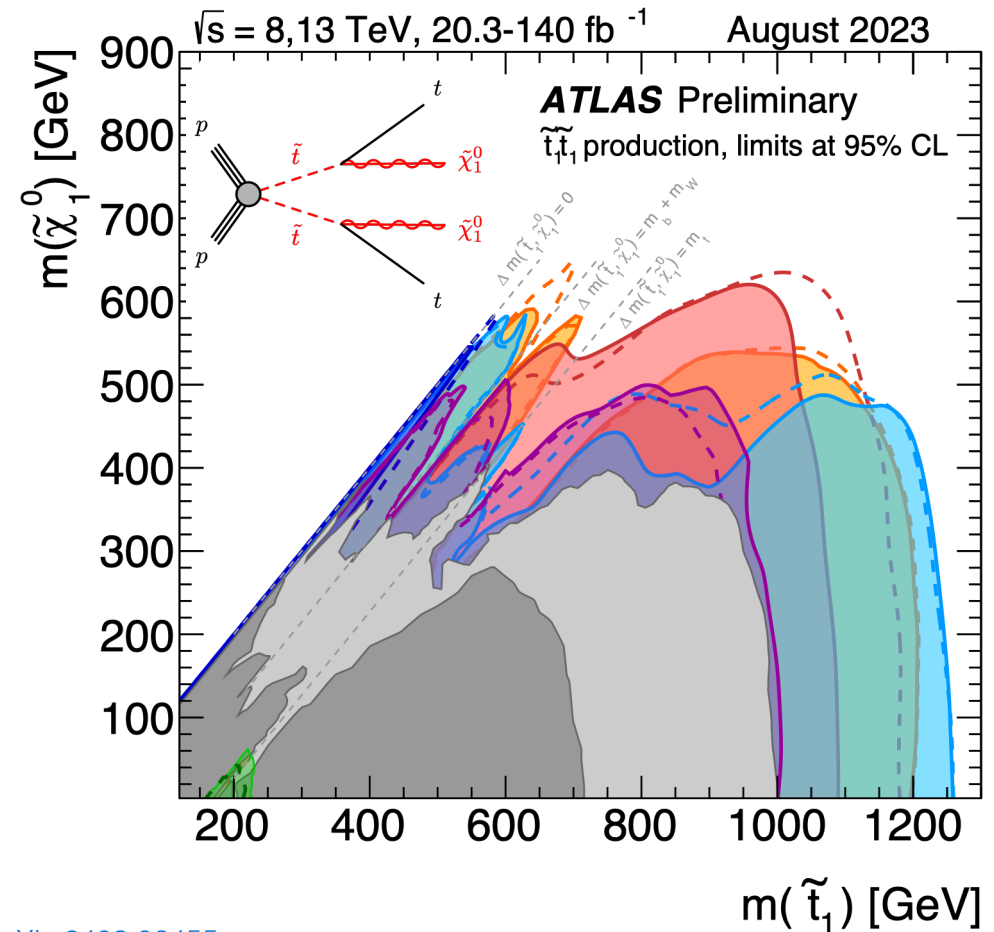
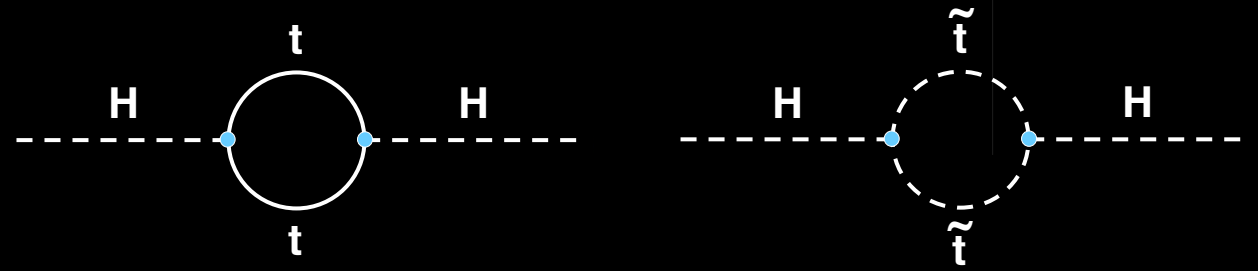
→ $\text{BR}(H \rightarrow \text{invisible}) < 0.107 \text{ (0.077) at 95\% CL}$

Supersymmetry



Supersymmetry is a symmetry relating bosons and fermions that predicts new partner particles for each SM particle, with spins differing by one-half unit

Supersymmetry could help address the hierarchy problem, provide a viable dark matter candidate, and allow gauge coupling unification at high energies consistent with current bounds on proton decay



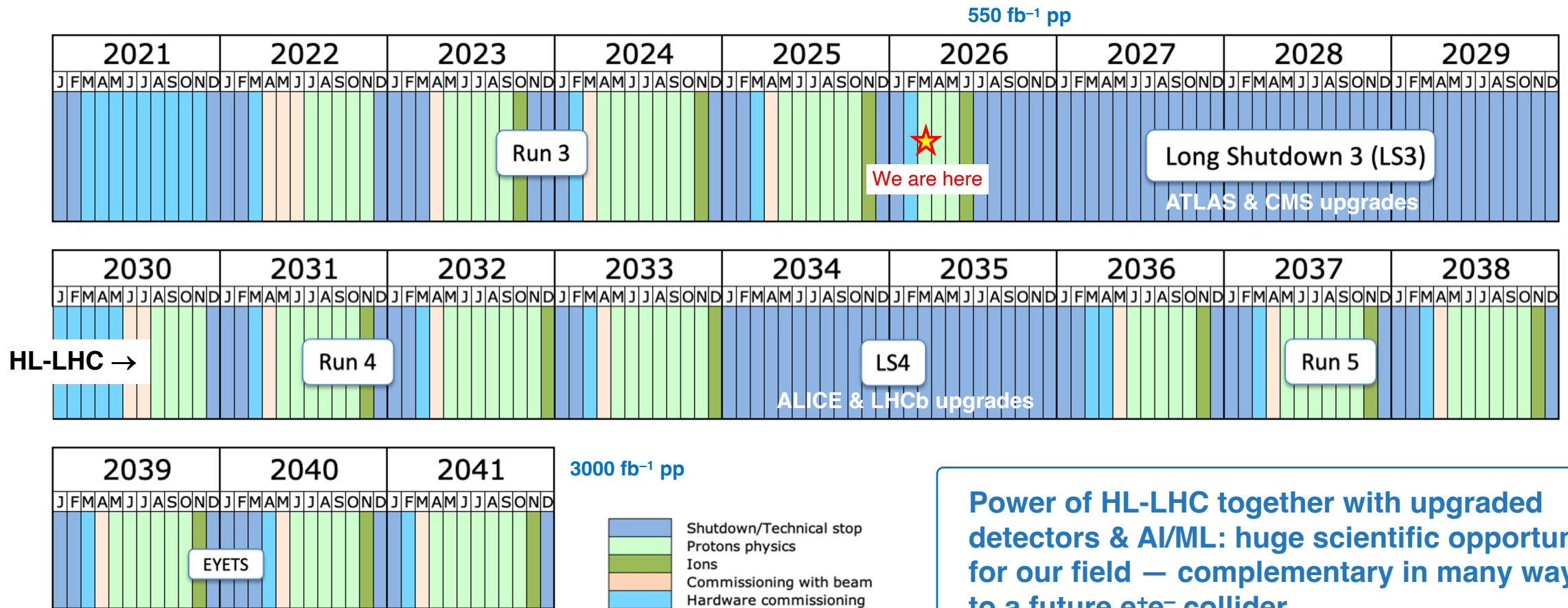
[arXiv:2403.02455](https://arxiv.org/abs/2403.02455)

LHC and High-Luminosity-LHC (HL-LHC) project timeline

Huge effort ongoing to construct HL-LHC and experiment upgrades

World's flagship collider project during the next decade — 10 times currently analysed dataset (350M H, 240k HH, 13B top, 720M WW, ...)

Large-scale ATLAS & CMS upgrades under construction, ALICE & LHCb plan significant upgrades for Run 5



Last update: November 24

Power of HL-LHC together with upgraded detectors & AI/ML: huge scientific opportunity for our field — complementary in many ways to a future e⁺e⁻ collider

LHC machine upgrade to HL-LHC

New Nb₃Sn “inner triplet” quadrupoles

- NbTi (known since 1962) is a ductile (malleable) alloy, while Nb₃Sn (1954!) is a brittle intermetallic compound, which cannot be bent or plastically deformed once formed
- This requires a “wind-and-react” process:
 - First, pre-reaction superconducting wire — made of strands consisting of many tiny Nb and Sn filaments (hundreds to thousands) surrounded by a copper stabilizer — is wound into coils (while still ductile)
 - Then, entire coil is heat-treated (reacted) at 650–700 °C to form the Nb₃Sn phase (entire coil must survive high-temperature treatment without distortion or contamination, any mismatch in thermal expansion can induce stress or cracking)
- Nb₃Sn magnets require more training quenches than NbTi to reach nominal field, and they show de-training after thermal cycling

NbTi: $T_c \sim 9.2$ K, $B_c \sim 10\text{--}11$ T (0 K), $B_{\text{practical}} \sim 8\text{--}9$ T (4.2 K)

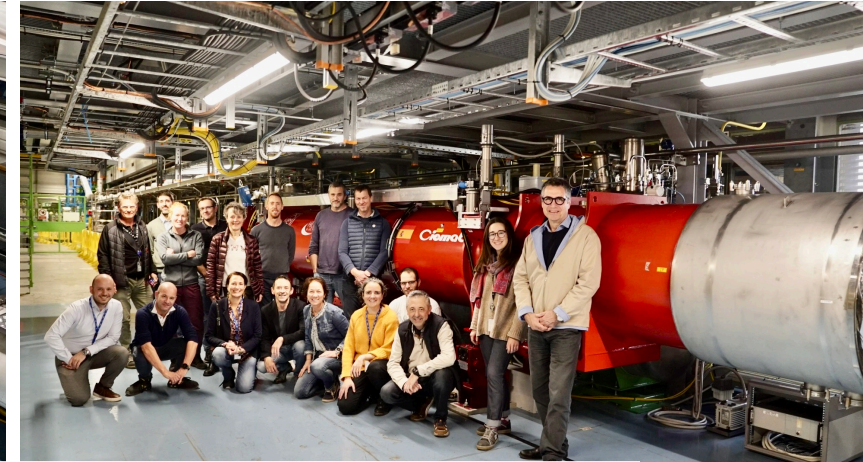
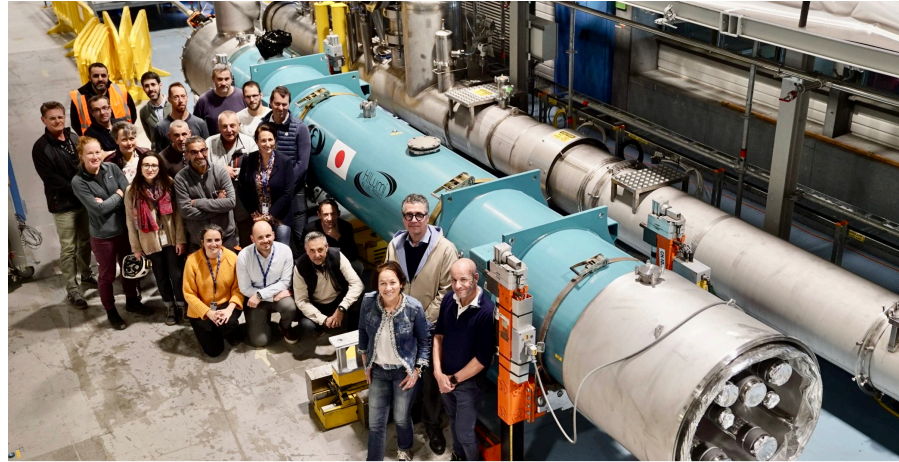
Nb₃Sn: $T_c \sim 18$ K, $B_c \sim 25\text{--}30$ T (0 K), $B_{\text{practical}} \sim 15\text{--}20$ T (4.2 K)



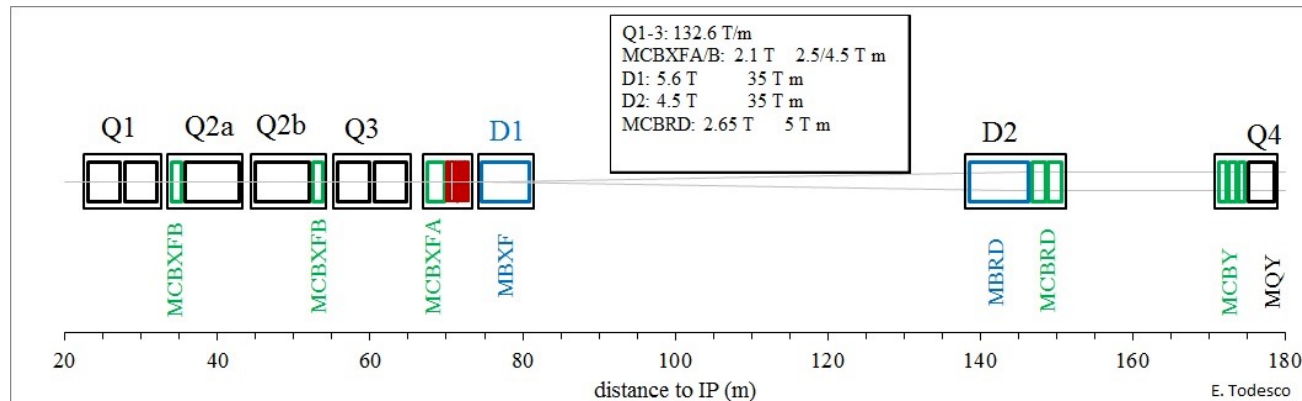
Nb₃Sn cable with single strands and glass-fibre insulation (partially unwrapped). Winding of magnet coil with glass-fibre insulated cables made of multi-filamentary wires that contain Nb and Sn precursors in a Cu matrix. Heat treatment of coil so that precursor elements react chemically and form the desired Nb₃Sn superconducting phase. To protect the then extremely fragile coil, a polymer is injected, which fills the interstitial spaces among cables, and is subsequently cured to become a matrix of hardened plastic providing cohesion and support to the cables

LHC machine upgrade to HL-LHC

New Nb₃Sn “inner triplet” quadrupoles



Fully realistic inner triplet string test facility at CERN, from left to right: installation of superconducting link, installation of D1 and Q2a cryo-assemblies, tests to start in Oct 2025

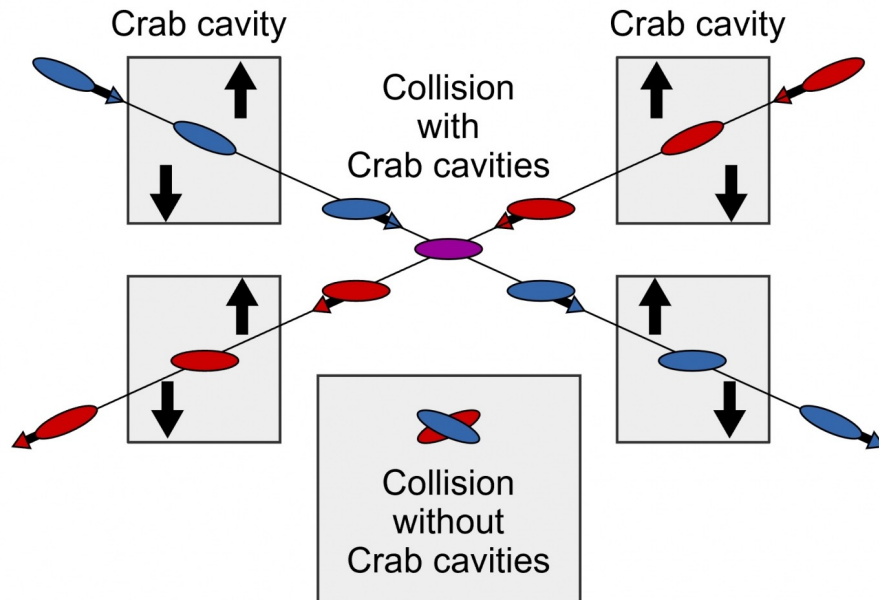


Nb₃Sn technology for new high-field superconducting quadrupole magnets successfully demonstrated for HL-LHC!

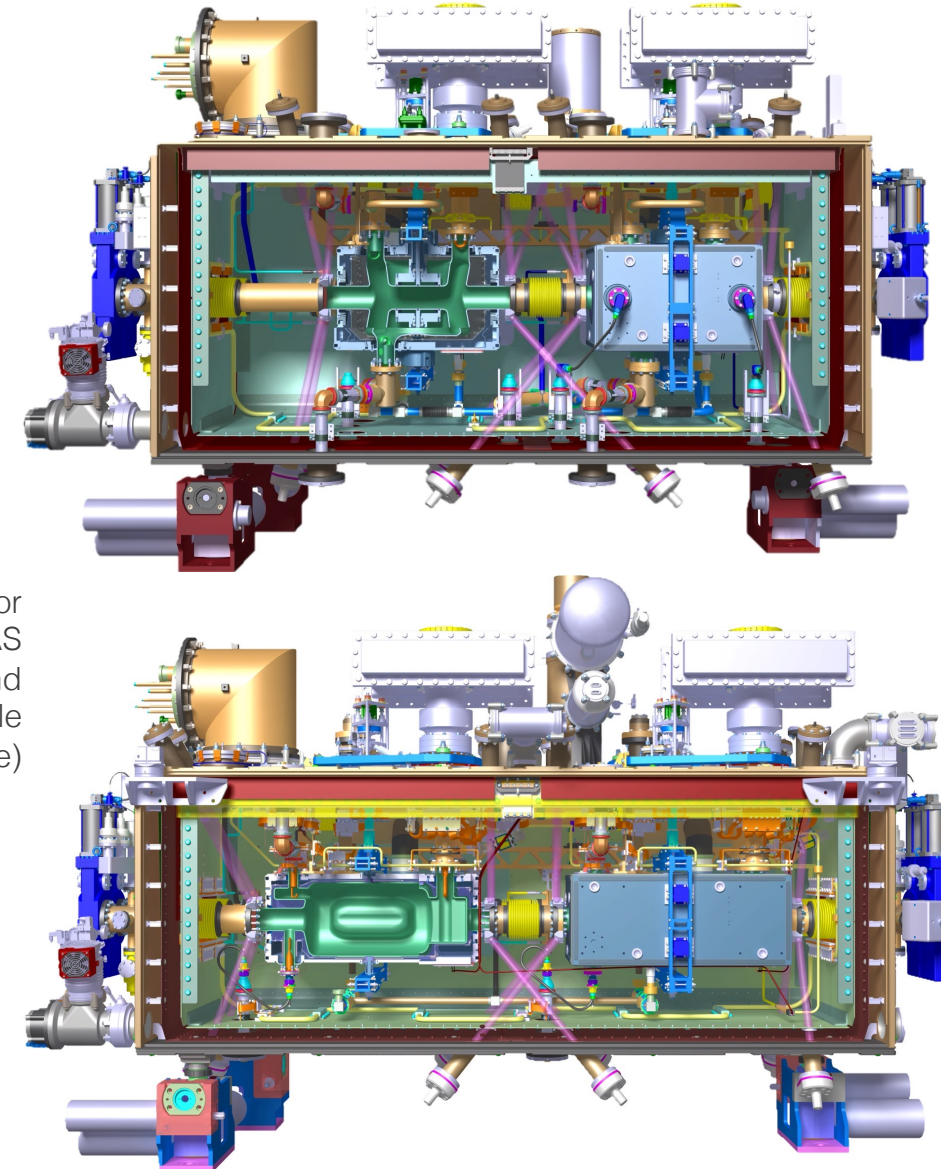
LHC machine upgrade to HL-LHC

Crab cavities at ATLAS and CMS

- 16 (8 around ATLAS/CMS) superconducting RF cavities tilt proton bunches through application of a time-dependent transverse voltage (3.4 MV/cavity) across the bunch such that they effectively collide head-on despite the crossing angle (uncorrected: luminosity loss of up to 30% at HL-LHC)
- Leading (trailing) edge of the bunch gets a kick in one (opposite) direction → rotation of the bunch in the transverse plane
- Already successfully used at SuperKEKB, but never at hadron colliders

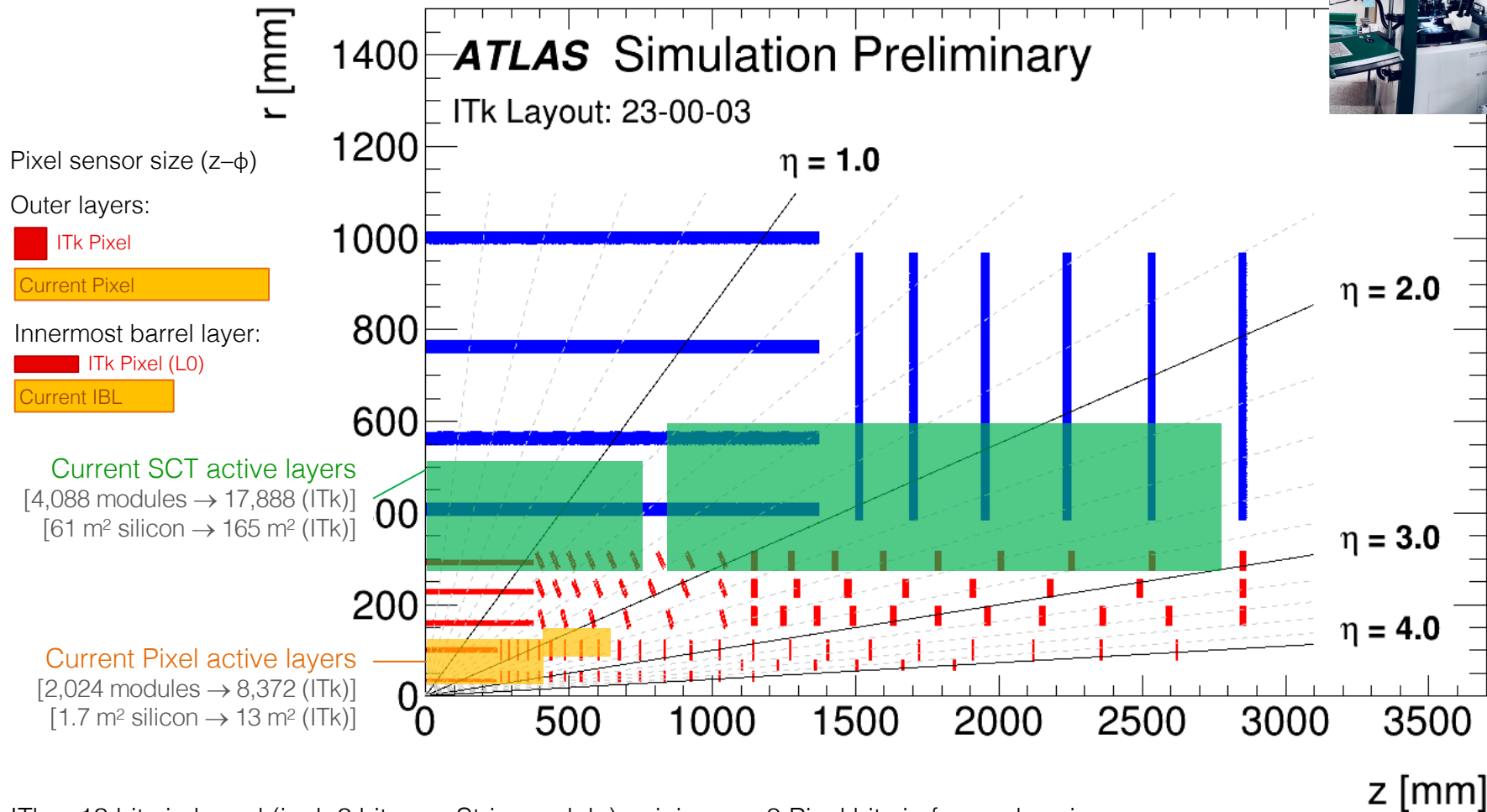


Right: cryomodule designs for crab cavity chain at ATLAS (top, RFD — RF Dipole) and CMS (bottom, DQW — Double Quarter-Wave)

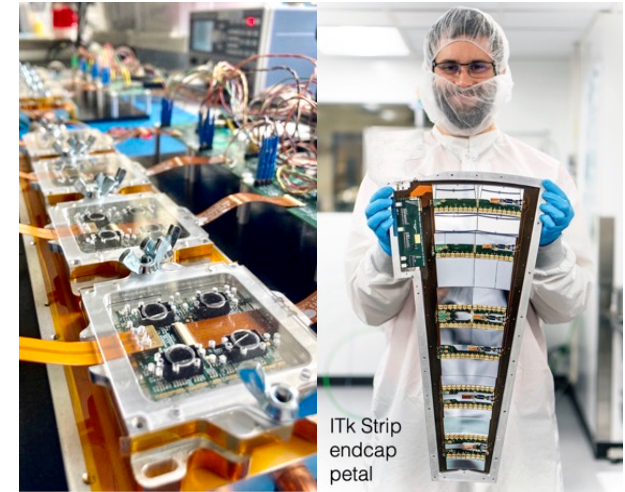


HL-LHC (aka Phase-II) upgrades of ATLAS and CMS

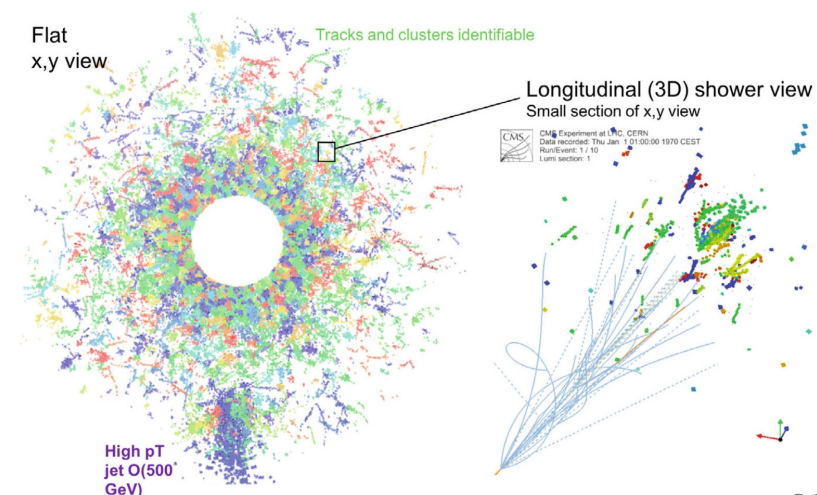
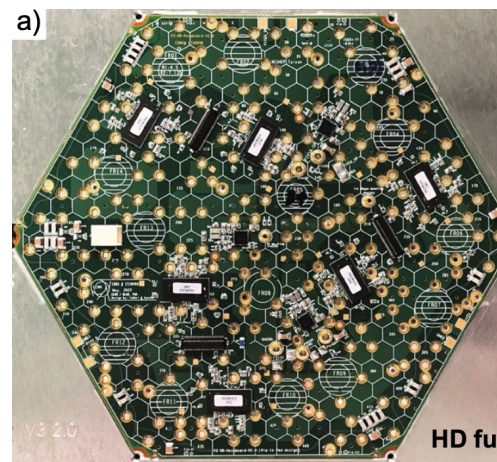
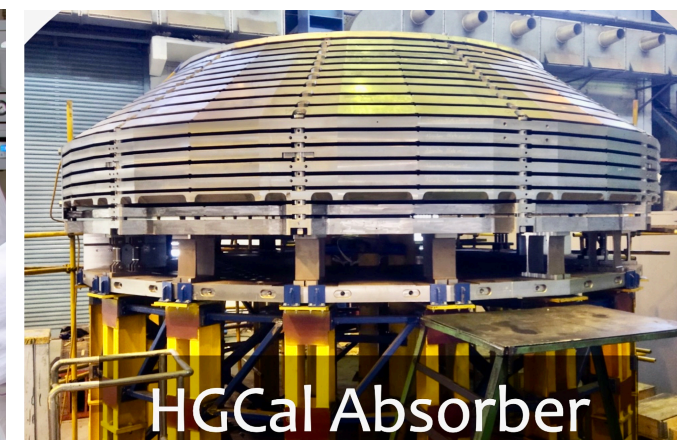
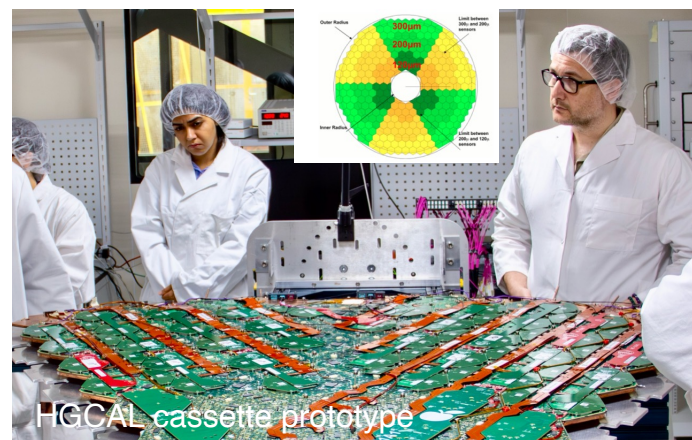
New ATLAS silicon pixel and strip tracker (5B channels, $|\eta| \leq 4$: e.g. in VBF, 30 GeV central-jet veto efficiency rises from 26% to 82% owing to better pileup mitigation)



ITk: ~13 hits in barrel (incl. 2 hits per Strip module), minimum ~9 Pixel hits in forward region



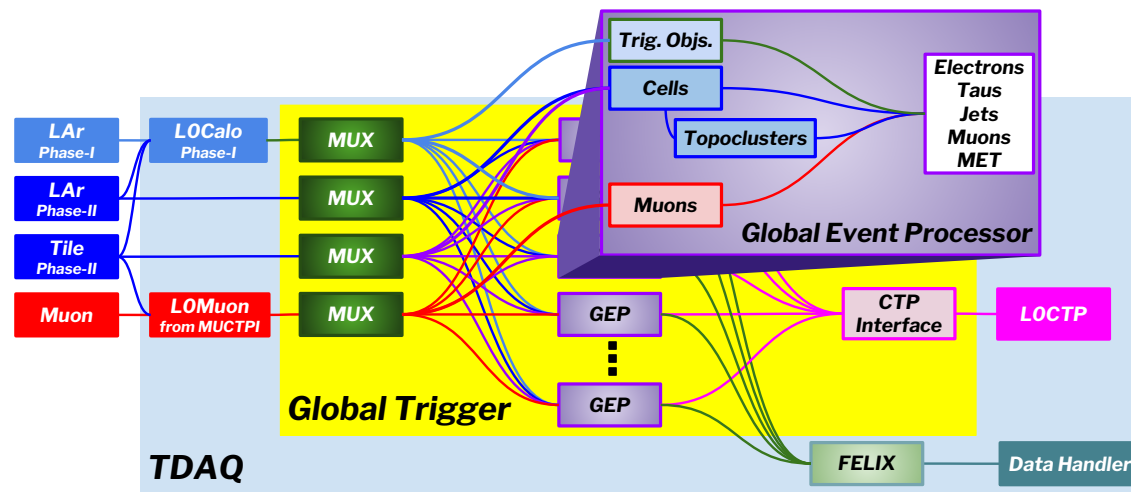
New CMS endcap calorimeter (HGCAL, $1.5 < \eta < 3$) — highly segmented, 3D imaging sampling calorimeter with 26 Si + Pb/CuW/Cu layers in EM section (CE-E), and 7 Si plus 14 scintillator + steel/Cu layers in HAD section (CE-H), to provide precise energy, position, and timing measurements in high-radiation forward region, 6M channels, 140 kW power, 27k Si modules, 620 m² of silicon (ATLAS tracker: 180 m²)



HL-LHC (aka Phase-II) upgrades of ATLAS and CMS

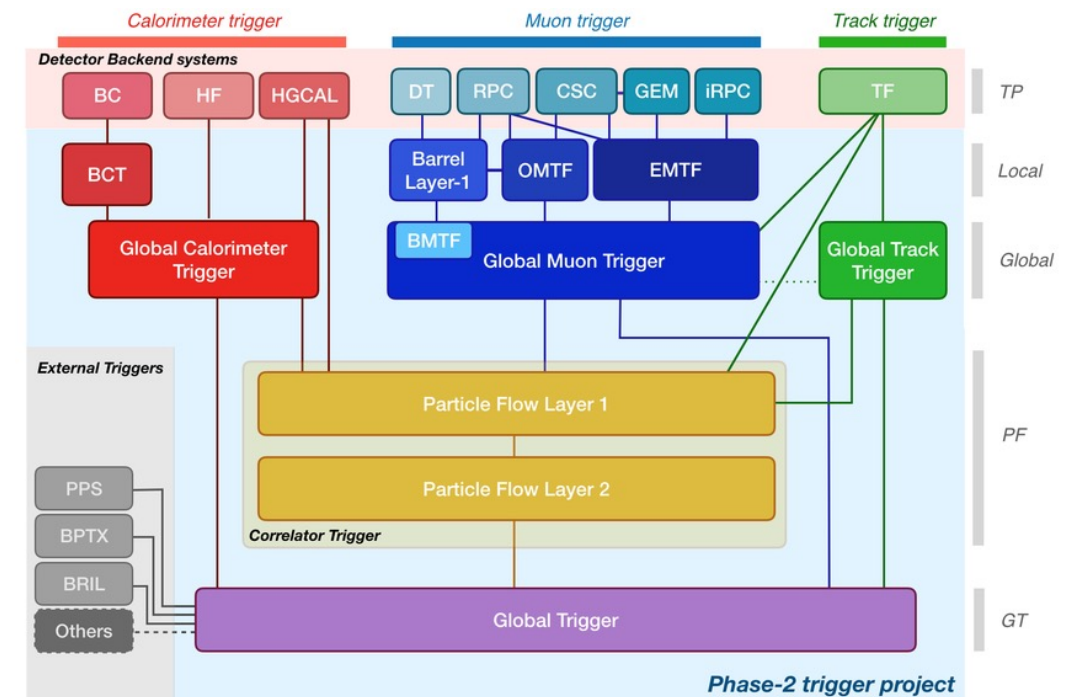
Significantly improved TDAQ especially for the first hardware level: throughput of 1 MHz (ATLAS), 750 kHz (CMS), much more detailed object-level, topological, and global event selection capabilities, including ML, based on powerful FPGAs

Aim: keep and improve over Run-2 selections (low thresholds) in much harder HL-LHC environment, and offer new opportunities



New ATLAS L0 Global Trigger: offline-quality reconstruction using input from calorimeters and muon systems built upon digital improvements realised during Phase-I upgrade

ATLAS Global Common Module prototype (v3)

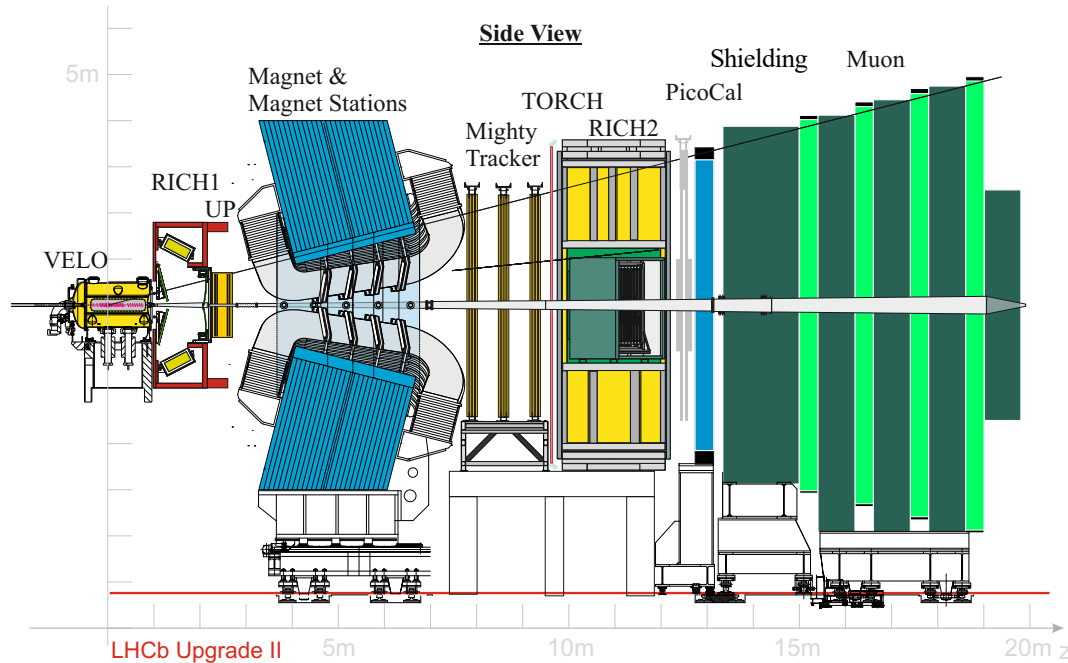


New CMS L1 trigger design: the Global Muon Trigger matches muons to tracks built from outer tracker stubs in the Track Funder, the Global Track Trigger reconstructs the primary vertex, the Correlator Trigger performs particle-flow, and the Global Trigger makes the final decision

Ambitious LHCb Upgrade II and ALICE 3 for Run 5 (2036–2041)

LHCb Upgrade II [\[LHCb Upgrade II scoping document\]](#)

- Goal: enable operating at $L_{\text{inst}} = 1.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ (currently $0.23 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$), for $L_{\text{int}} > 300 \text{ fb}^{-1}$
- Challenge: pileup of 42 (current: ~ 6) $\rightarrow$ efficient tracking and vertexing, excellent PID, precise timing

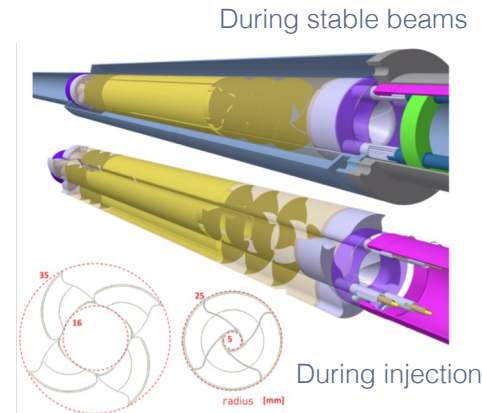
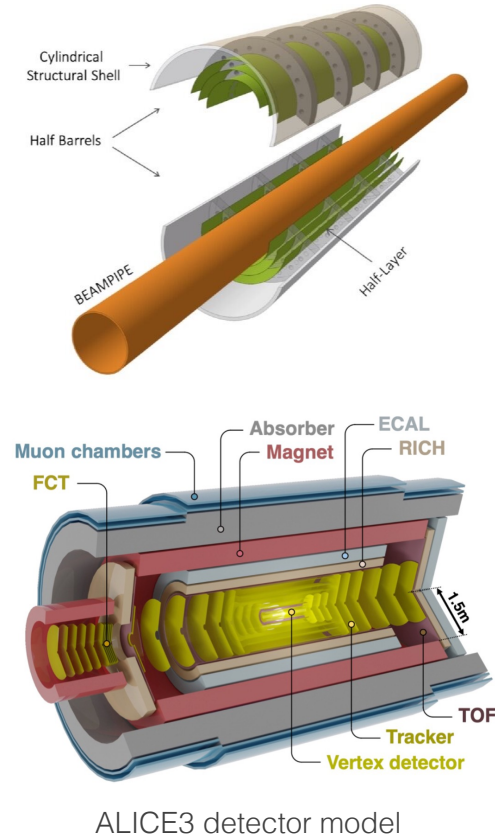


ALICE upgrades during LS3

- New ITS3 (MAPS) and forward calorimeter

ALICE 3 [\[ALICE 3 scoping document\]](#)

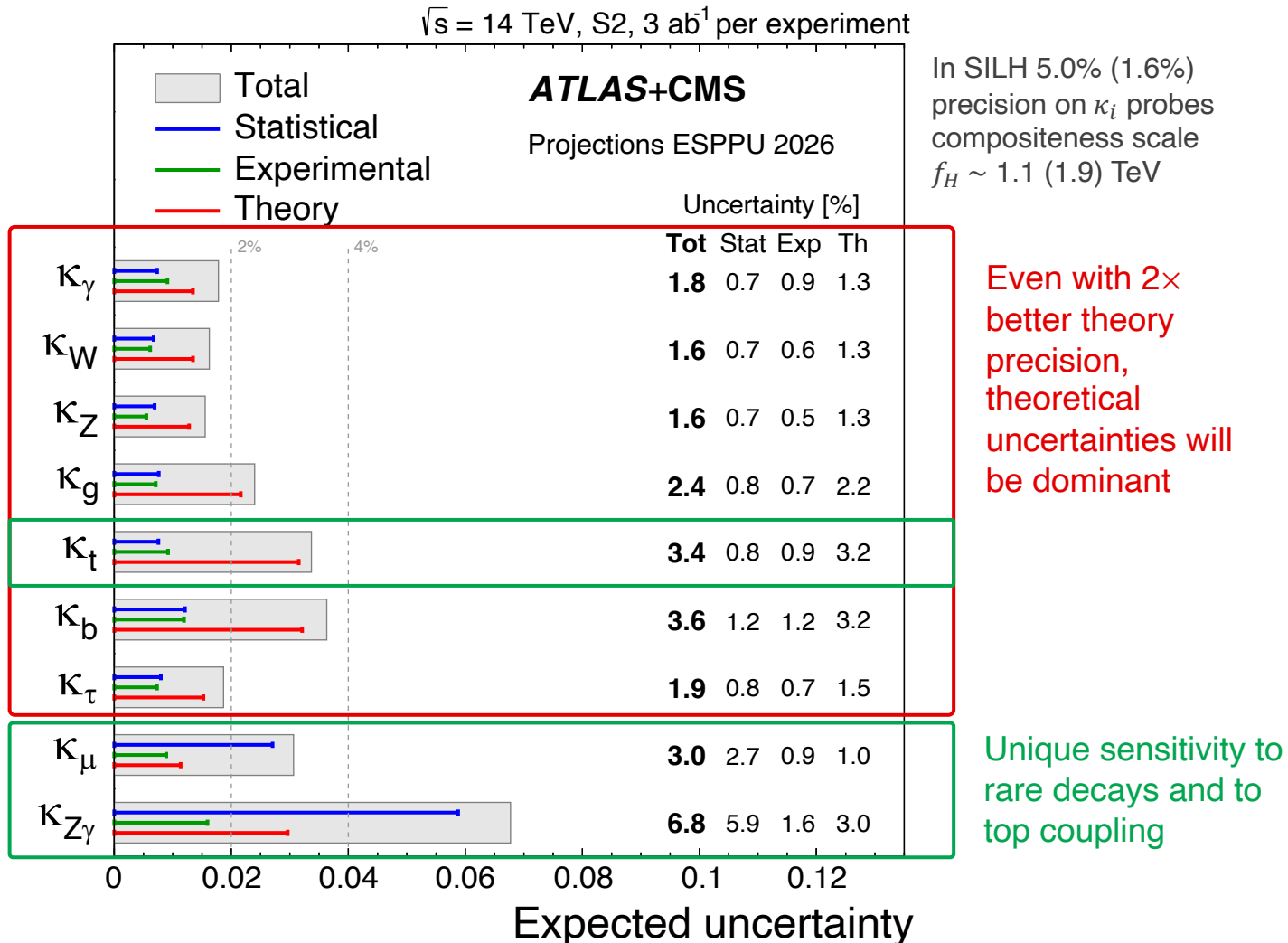
- Key goals: early-stage temperature with dielectrons, properties and hadronisation of QGP with heavy flavour hadrons, low- p_T hadron reconstruction required
- Compact low-mass all-silicon tracker, excellent vertex reconstruction, wide acceptance $|\eta| < 4$, PID in wide p_T range, high readout rate in A-A and pp



Retractable silicon vertex detector at 5 mm (15 mm during injection) from beam, giving $< 10 \mu\text{m}$ pointing resolution for $p_T > 200 \text{ MeV}$ in high-multiplicity environment at ALICE3

HL-LHC Physics prospects — Higgs

Higgs coupling prospects | Coupling strength modifiers ($\kappa_i^2 \equiv \sigma_i/\sigma_i^{\text{SM}}$, assuming SM Γ_H)

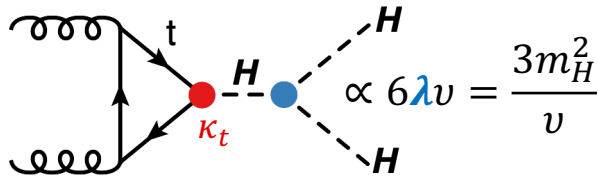


Prospects for Higgs width from off-shell measurement, invisible Higgs decays, Higgs sector extensions (2HDM)

- Γ_H via $\mu_{\text{off-shell}} / \mu_{\text{on-shell}}$ in $H \rightarrow 4\ell$ & $2\ell 2\nu$ with < 20% uncertainty
- $\text{BR}(H \rightarrow \text{invisible}) < 2.5\%$
- Discover or exclude MSSM two Higgs doublets scenario deep into TeV scale for $\tan\beta > 6$

HL-LHC Physics prospects — Higgs

Higgs self-coupling via Higgs pair production: complex final states, eldorado for ML enthusiasts, strongest channels: $HH \rightarrow b\bar{b}\gamma\gamma, b\bar{b}\tau\tau, b\bar{b}b\bar{b}$. Best sensitivity to λ at low $m(HH)$

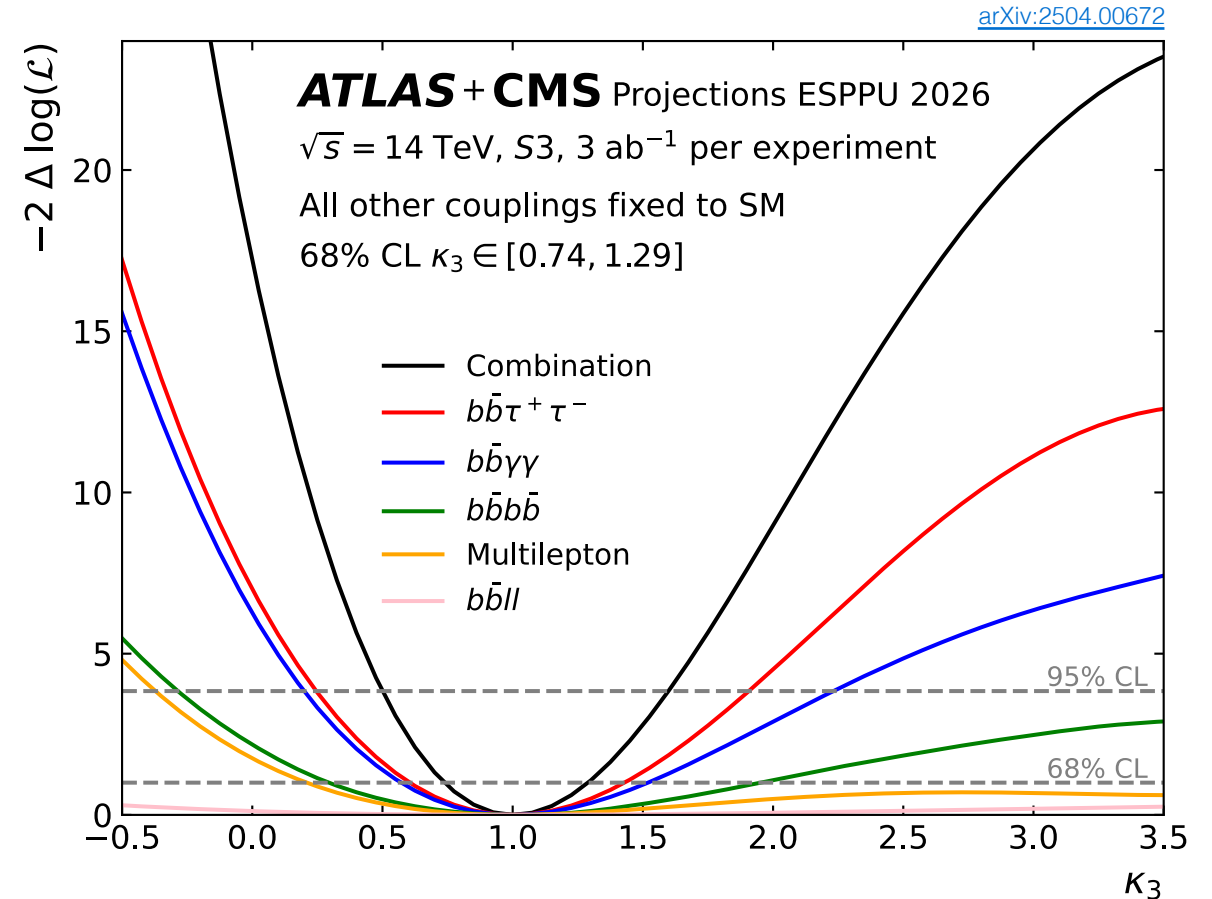


$$V(\phi) = -\mu^2|\phi|^2 + \lambda|\phi|^4$$

$$\kappa_\lambda \equiv \lambda_3^{\text{obs}} / \lambda^{\text{SM}}$$

For SM:

- **Expect HH observation $> 7\sigma$**
- κ_λ **precision better than 30%**



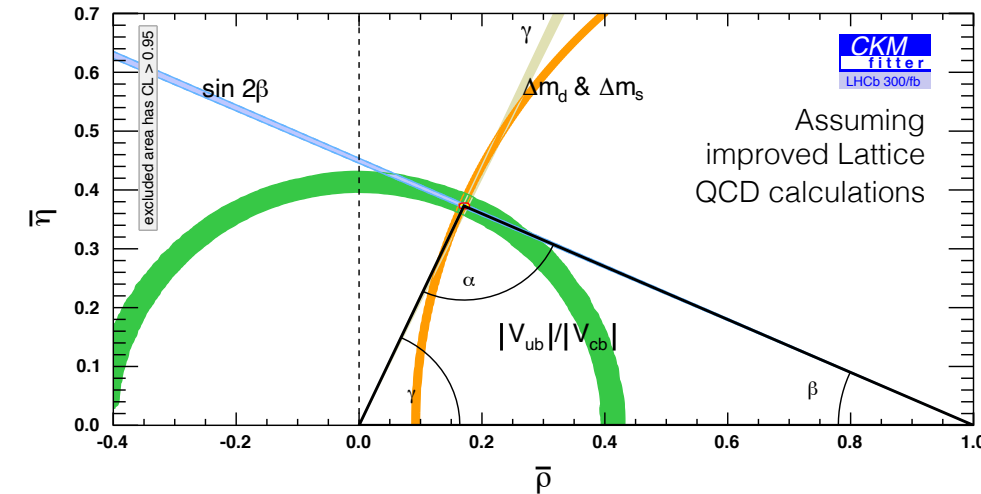
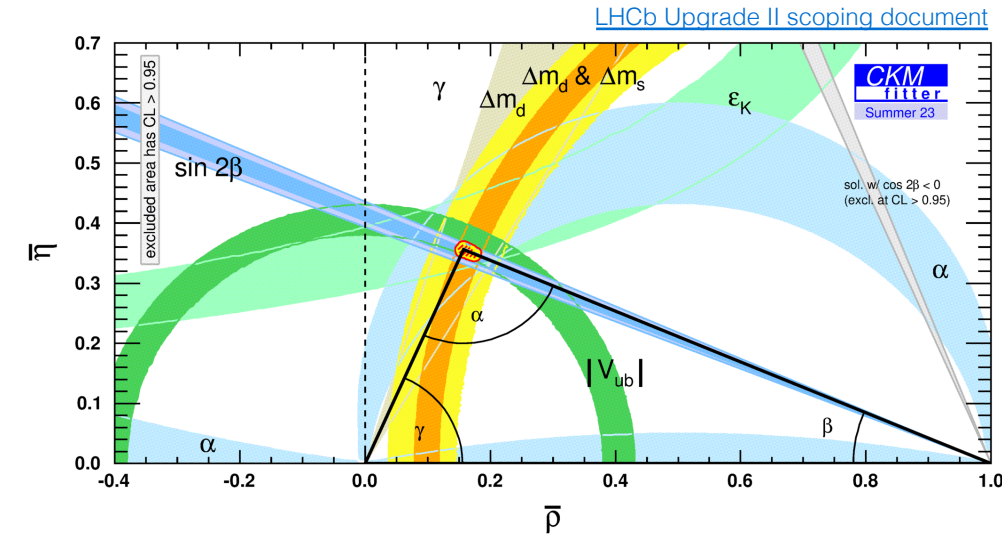
HL-LHC Physics prospects — flavour

Huge opportunities in flavour sector with LHCb Upgrade II

> $\times 5$ Run 3/4 instantaneous luminosity, integrated luminosity of 300 fb^{-1}

Observable	Current LHCb (up to 9 fb^{-1})	Upgrade I (23 fb^{-1})	Upgrade I (50 fb^{-1})	Upgrade II (300 fb^{-1})
CKM tests				
γ ($B \rightarrow DK$, etc.)	2.8° [20, 21]	1.3°	0.8°	0.3°
ϕ_s ($B_s^0 \rightarrow J/\psi\phi$)	20 mrad [24]	12 mrad	8 mrad	3 mrad
$ V_{ub} / V_{cb} $ ($\Lambda_b^0 \rightarrow p\mu^-\bar{\nu}_\mu$, etc.)	6% [56, 57]	3%	2%	1%
Charm				
ΔA_{CP} ($D^0 \rightarrow K^+K^-, \pi^+\pi^-$)	29×10^{-5} [27]	13×10^{-5}	8×10^{-5}	3.3×10^{-5}
A_Γ ($D^0 \rightarrow K^+K^-, \pi^+\pi^-$)	11×10^{-5} [31]	5×10^{-5}	3.2×10^{-5}	1.2×10^{-5}
Δx ($D^0 \rightarrow K_S^0\pi^+\pi^-$)	18×10^{-5} [58]	6.3×10^{-5}	4.1×10^{-5}	1.6×10^{-5}
Rare decays				
$\mathcal{B}(B^0 \rightarrow \mu^+\mu^-)/\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-)$	69% [32, 33]	41%	27%	11%
$S_{\mu\mu}$ ($B_s^0 \rightarrow \mu^+\mu^-$)	—	—	—	0.2
$A_T^{(2)}$ ($B^0 \rightarrow K^{*0}e^+e^-$)	0.10 [59]	0.060	0.043	0.016
$S_{\phi\gamma}$ ($B_s^0 \rightarrow \phi\gamma$)	0.32 [60]	0.093	0.062	0.025
α_γ ($\Lambda_b^0 \rightarrow \Lambda\gamma$)	$^{+0.17}_{-0.29}$ [61]	0.148	0.097	0.038

[LHCb Upgrade II scoping document](#), see also [arXiv:1808.08865](#)



FCC-ee — parameters

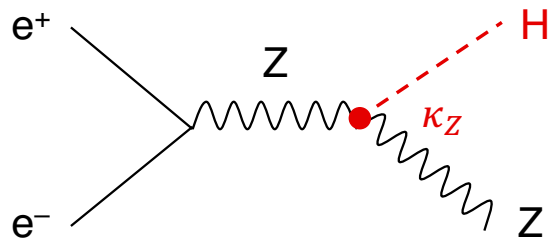
FCC-ee main parameters (assuming 4 IPs / experiments)

Ref: [arXiv:2505.00274](https://arxiv.org/abs/2505.00274)

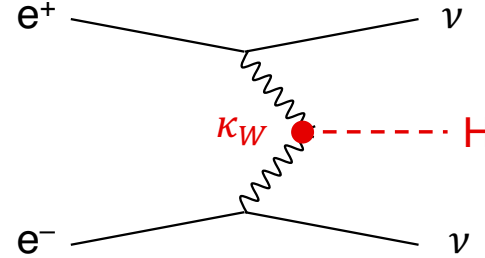
Parameter	Z	WW	H (ZH)	t $\bar{t}$	
Collision energy $\sqrt{s}$ [GeV]	88, 91, 94	157, 163	240	340–350	365
Synchrotron radiation/beam [MW]	50	50	50	50	50
Beam current [mA]	1294	135	26.8	6.0	5.1
Number bunches / beam	11200	1852	300	70	64
Total RF voltage 400 / 800 MHz [GV]	0.08 / 0	1.0 / 0	2.1 / 0	2.1 / 7.4	2.1 / 9.2
Luminosity / IP [10^{34} cm $^{-2}$ s $^{-1}$]	144	20	7.5	1.8	1.4
Luminosity / year [ab^{-1}]	68	9.6	3.6	0.83	0.67
Run time (including lumi ramp-up) [years]	4	2	3	1	4
Total integrated luminosity [ab^{-1}]	205	19.2	10.8	0.4	2.7
Total number of events	$6 \cdot 10^{12}$ Z	$2.4 \cdot 10^8$ WW (incl. WW at higher $\sqrt{s}$)	$2.2 \cdot 10^6$ ZH 65k WW $\rightarrow$ H	$2 \cdot 10^6$ t $\bar{t}$ + 370k ZH + 92k WW $\rightarrow$ H	
	$\sim 350,000 \times$ LEP-1 (~ 6 years) $\sim 26 \times$ HL-LHC (~ 9 years)	$\sim 5,000 \times$ LEP-2 (~ 5 years)	0.5% of HL-LHC (~ 9 years)	0.01% of HL-LHC (t $\bar{t}$) (~ 9 years)	

FCC-ee — Higgs Factory

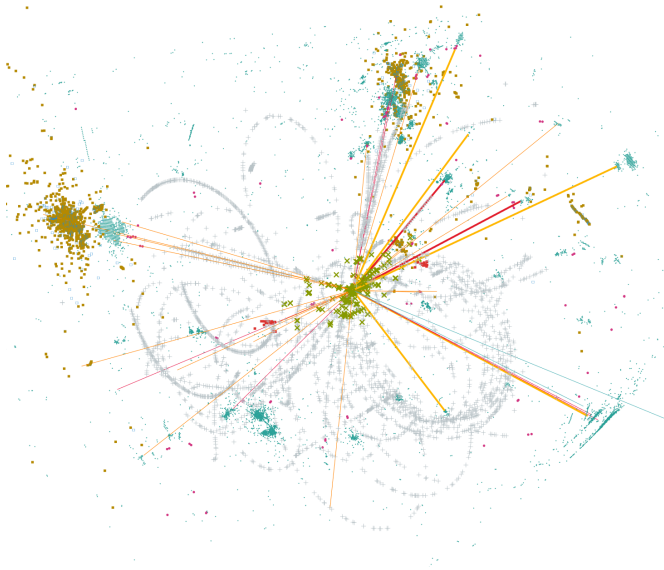
Primary goal: Higgs precision measurements



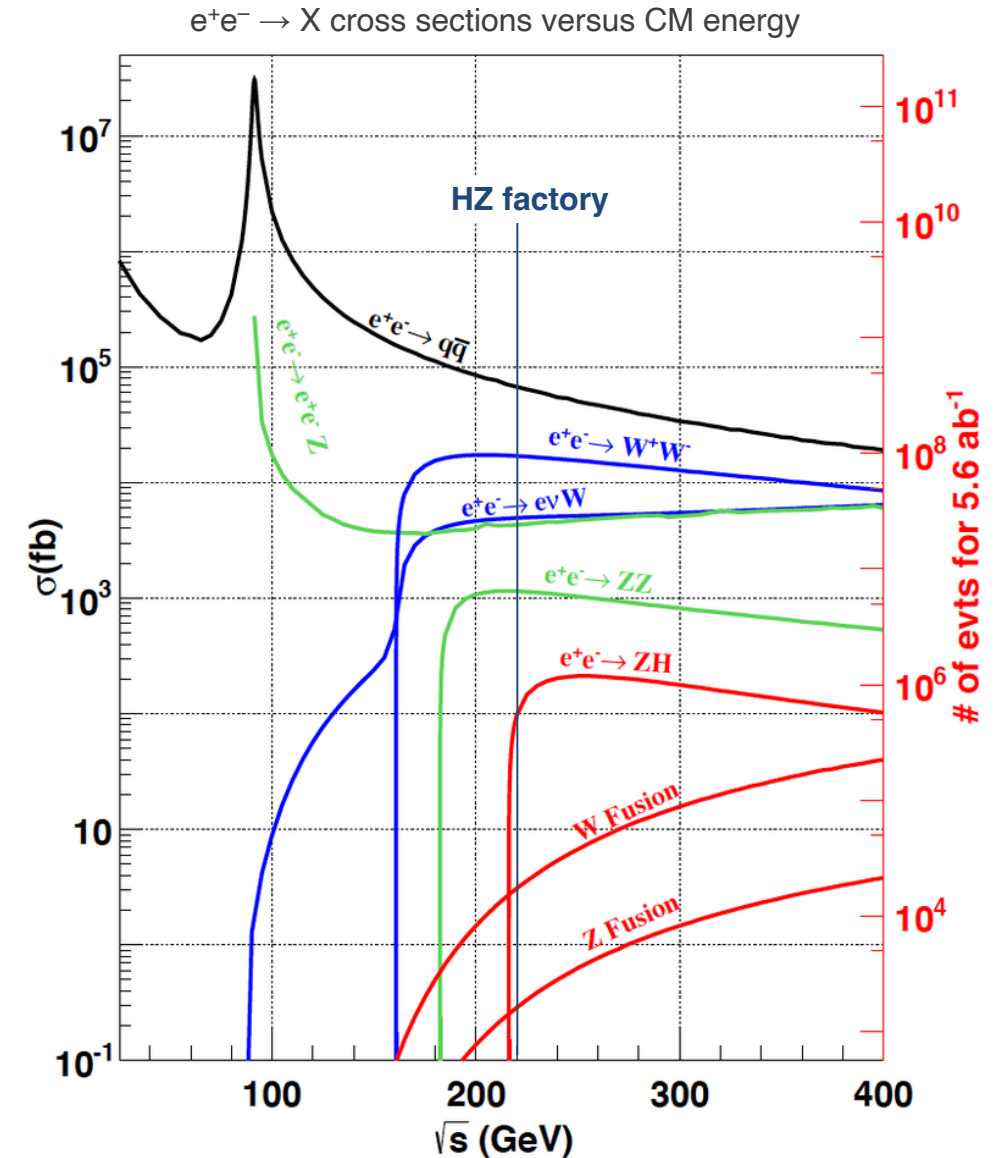
Higgsstrahlung ($\sigma = 232 \text{ fb}$ at $\sqrt{s} = 240 \text{ GeV}$)
 s-channel: $\sigma \propto 1/s$ — falling off a resonance



W-boson fusion (6.7 fb)
 (Z-boson fusion 0.63 fb)
 WBF: $\sigma \propto \ln^2(s/m_W^2)$ — e^+/e^- radiate
 W/Z, which increases with energy

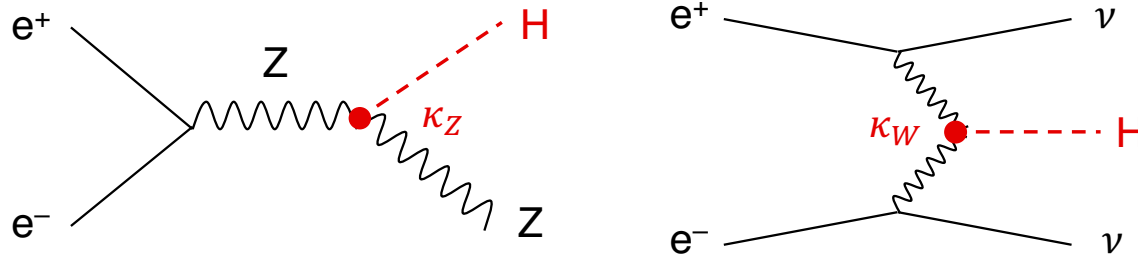


Simulated $e^+e^- \rightarrow ZH$ event at
 $\sqrt{s} = 240 \text{ GeV}$ in IDEA detector



FCC-ee — Higgs Factory

Absolute coupling strengths — difficult at LHC due to weak constraint on Γ_H (current precision $\sim 50\%$, HL-LHC $< 25\%$)



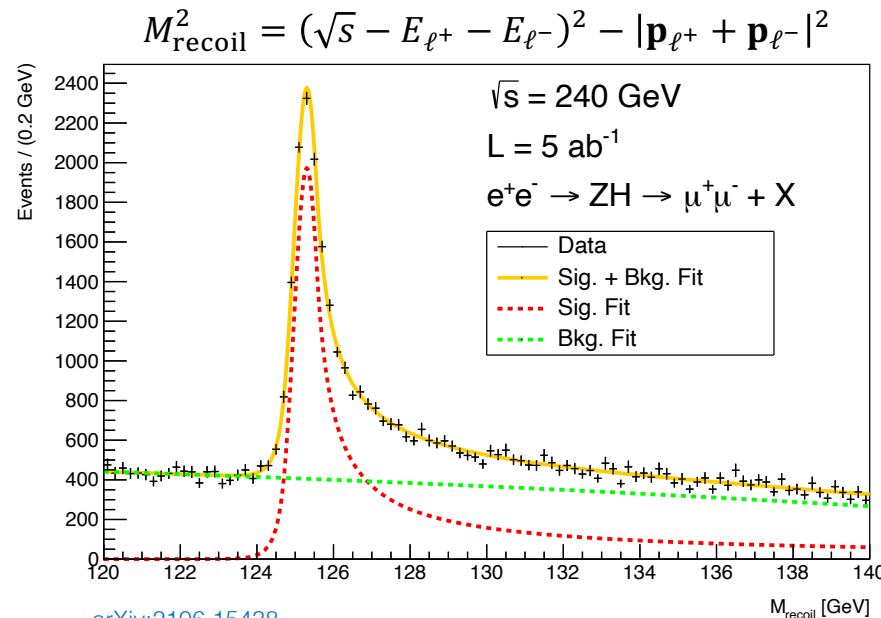
Higgsstrahlung ($\sigma = 232 \text{ fb}$ at $\sqrt{s} = 240 \text{ GeV}$)

W-boson fusion (6.7 fb)

$$\sigma(e^+e^- \rightarrow ZH) \propto \kappa_Z^2$$

Can measure total HZ cross section and hence κ_Z independently of Higgs boson decays via recoil mass (M_{recoil}) by counting events with an identified $Z \rightarrow \ell\ell$

Standard reference to be used by all other Higgs coupling measurements



[arXiv:2106.15438](https://arxiv.org/abs/2106.15438)

Combination with measurement of

$$\sigma(e^+e^- \rightarrow ZH(\rightarrow ZZ^*)) \propto \frac{\kappa_Z^4}{\Gamma_H}$$

allows to determine Γ_H to 0.8% precision ($30 \times$ HL-LHC)

Note that above discussion neglects running coupling (small $< 0.3\%$ effect). Correct formulation would be:

$$\sigma(e^+e^- \rightarrow ZH) \propto \kappa_Z^2(\mu = 240 \text{ GeV})$$

$$\sigma(e^+e^- \rightarrow ZH(\rightarrow ZZ^*)) \propto \frac{\kappa_Z^2(240 \text{ GeV}) \cdot \kappa_Z^2(125 \text{ GeV})}{\Gamma_H}$$

FCC-ee – the Higgs factory

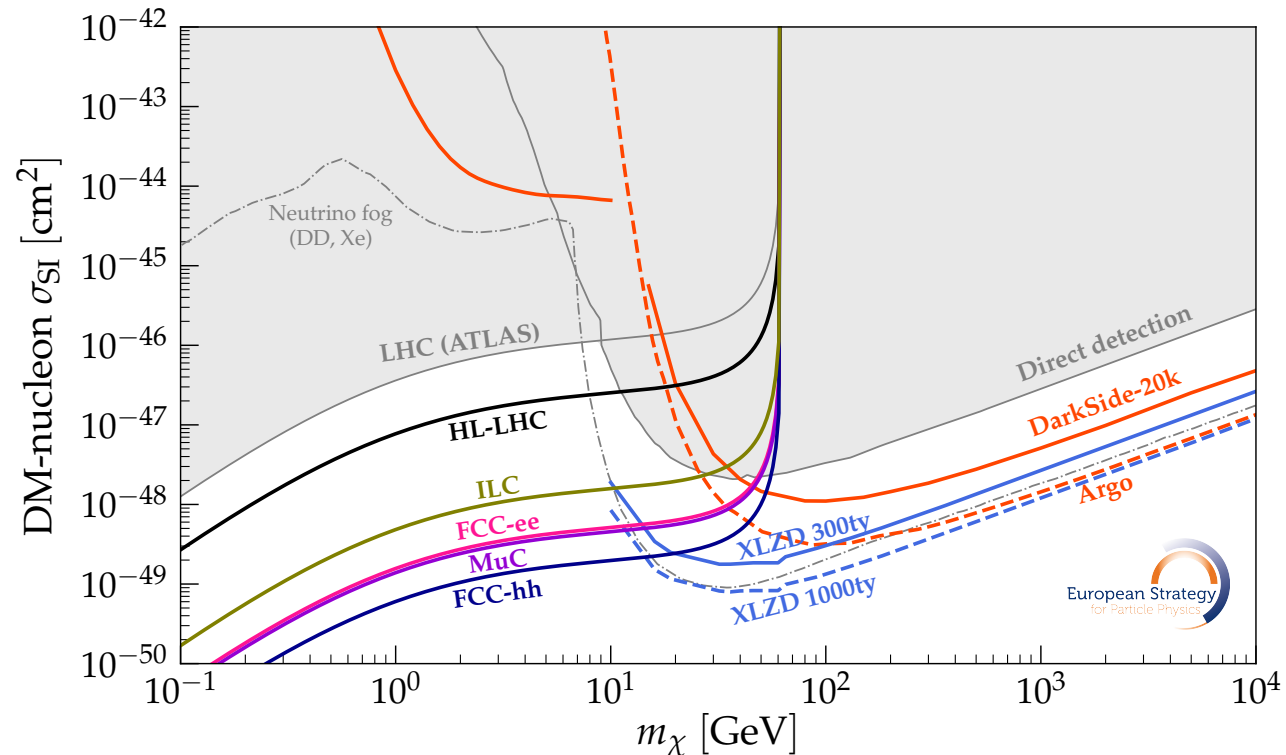
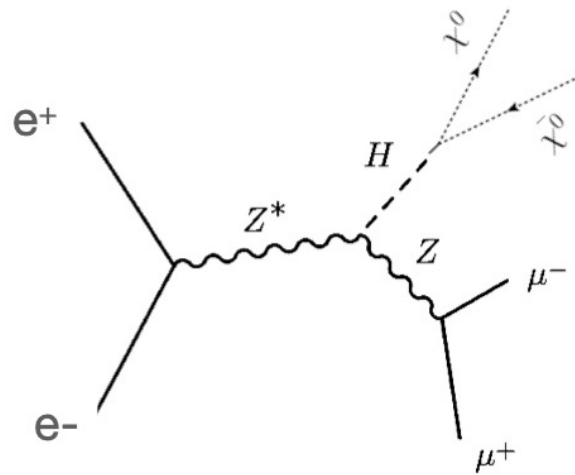
Why “factory”? 2.2M Higgs (FCC-ee) vs 350M (HL-LHC), production through Higgsstrahlung rather than s-channel
→ **e^+e^- collisions offer exceptionally clean Higgs reconstruction, unmatched precision on decays with large branching ratios**

FCC-ee feasibility study (Vol 1): [arXiv:2505.00272](https://arxiv.org/abs/2505.00272)

Coupling		HL-LHC	FCC-ee	FCC-ee + FCC-hh	Uncertainty HL-LHC / FCC-ee	
*Incl. SM parametric uncertainties	κ_Z (%)	1.6	0.10	0.10	16	Most precise coupling, probes $f_H \sim 8$ TeV
	κ_W (%)	1.6	0.29	0.25	5.5	
	κ_b (%)	3.6	0.38 / 0.49*	0.33 / 0.45	7.3	Particularly large improvement over HL-LHC
	κ_g (%)	2.4	0.49 / 0.54	0.41 / 0.44	4.4	
	κ_τ (%)	1.9	0.46	0.40	4.1	
Note: current uncertainties on Higgs branching fraction predictions O(1.5%)	κ_c (%)	~ 40	0.70 / 0.87	0.68 / 0.85	~ 44	
	κ_γ (%)	1.8	1.1	0.30	1.6	
	$\kappa_{Z\gamma}$ (%)	6.8	4.3	0.67	1.6	
	κ_t (%)	3.4	3.1	0.75	1.1	
	κ_μ (%)	3.0	3.3	0.42	0.9	
	$ \kappa_s $ (%)	—	+29 −67	+29 −67	—	BR($H \rightarrow 4\nu$) = $10.6 \cdot 10^{-4}$
	Γ_H (%)	< 25	0.78	0.69	< 32	
	$\mathcal{B}_{\text{inv}} (<, 95\% \text{ CL})$	0.025	5×10^{-4}	2.3×10^{-4}	50	
	$\mathcal{B}_{\text{unt}} (<, 95\% \text{ CL})$	0.04	6.8×10^{-3}	6.7×10^{-3}	5.9	

FCC-ee – the Higgs factory

Why “factory”? 2.2M Higgs (FCC-ee) vs 350M (HL-LHC), production through Higgsstrahlung rather than s-channel
 → e^+e^- collisions offer exceptionally clean Higgs reconstruction, unmatched precision on decays with large BR



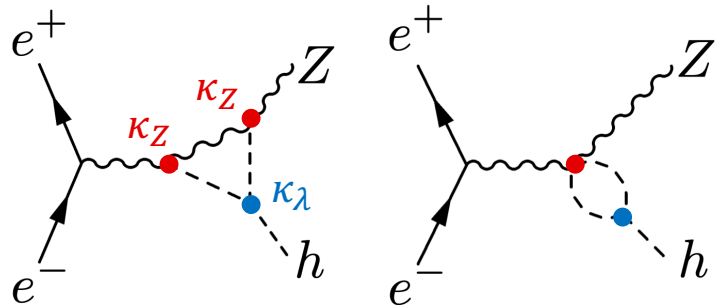
Collider limits overlaid onto direct detection (Higgs portal assuming Majorana DM)

$\mathcal{B}_{\text{inv}} (<, 95\% \text{ CL})$	0.025	5×10^{-4}	2.3×10^{-4}	50
	HL-LHC	FCC-ee	FCC-ee + FCC-hh	

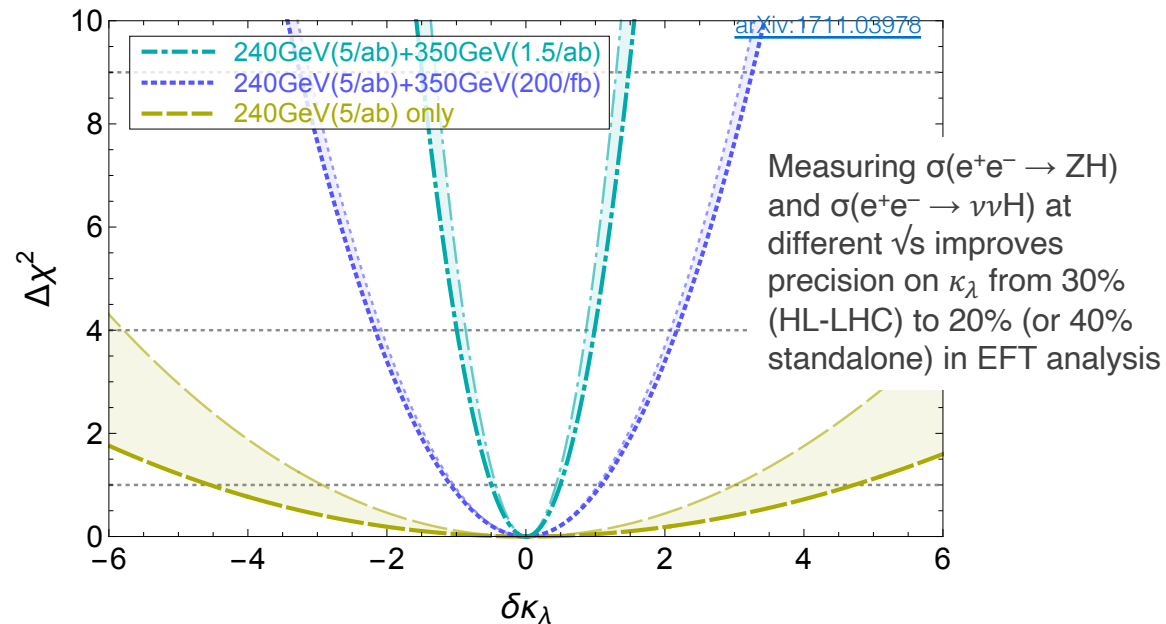
$\text{BR}(H \rightarrow 4\nu) = 10.6 \cdot 10^{-4}$

FCC-ee – the Higgs factory

Higgs self-coupling — no HH production at FCC-ee, sensitivity through H–H–H loops

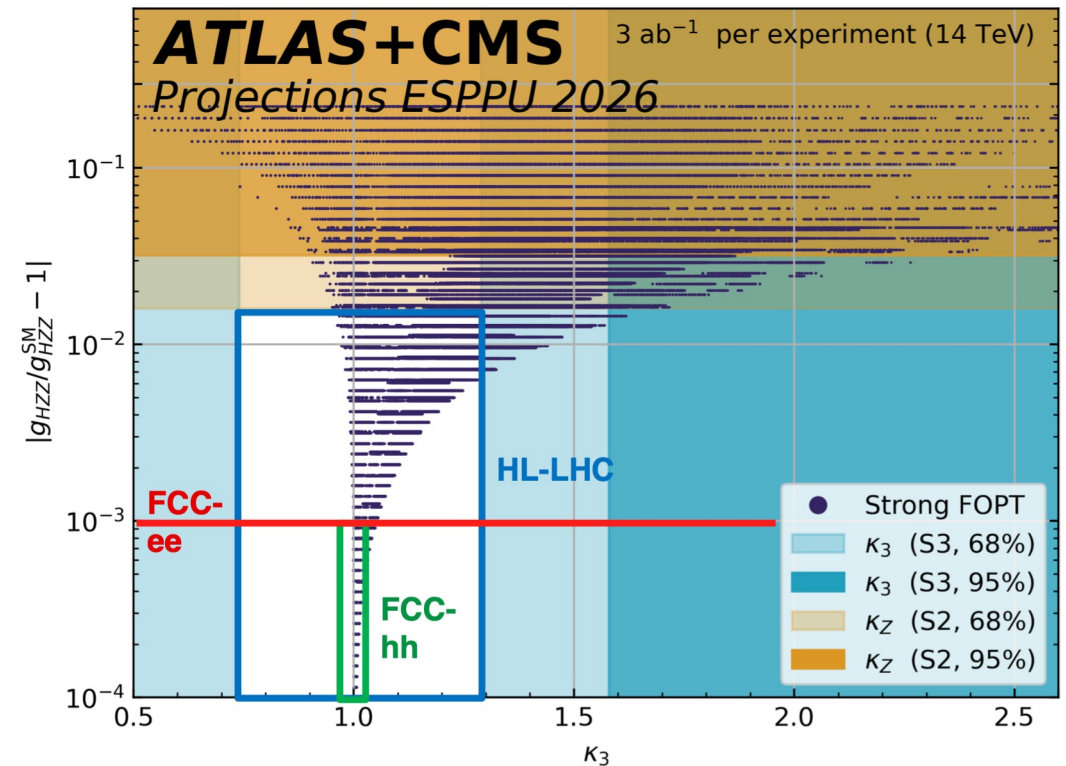


NLO vertex corrections to Higgsstrahlung (similar for W-boson fusion)



FCC-ee+hh tightly constrains BSM models with 1st order EW phase transition

[arXiv:2504.00672](https://arxiv.org/abs/2504.00672)



FCC-ee – the Higgs factory

Extremely challenging — cornering the electron Yukawa coupling: $g_e = \sqrt{2}m_e/v \approx 2.9 \cdot 10^{-6}$

Can we measure the decay? (recall: $\Gamma_H = 4.1$ MeV)

$$\text{BR}(H \rightarrow e^+e^-) \simeq \frac{1}{\Gamma_H} \cdot \frac{G_F m_H m_e^2}{4\pi\sqrt{2}} \approx 5.2 \cdot 10^{-9}$$

The entire HL-LHC may produce 2 such events!

At the FCC-ee, BW s-channel resonance:

$$\sigma(e^+e^- \rightarrow H) \simeq \frac{4\pi\Gamma_H\Gamma(H \rightarrow e^+e^-)}{(s - m_H^2)^2 + m_H^2\Gamma_H^2} \xrightarrow{s=m_H^2} \frac{4\pi}{m_H^2} \text{BR}(H \rightarrow e^+e^-) \approx 1.6 \text{ fb}$$

but ISR and $\sqrt{s}$ spread will lead to smearing of BW peak, so that effective cross section is 0.3 fb (remember: $\mathcal{L}_{\text{ZH}} = 10.8 \text{ ab}^{-1}$). **Can it be done?**

three generations of matter (fermions)			interactions / force carriers (bosons)	
I	II	III		
mass $\approx 2.2 \text{ MeV}/c^2$ charge $\frac{2}{3}$ spin $\frac{1}{2}$ u up	mass $\approx 1.28 \text{ GeV}/c^2$ ✓ charge $\frac{2}{3}$ spin $\frac{1}{2}$ c charm	mass $\approx 173.1 \text{ GeV}/c^2$ ✓ charge $\frac{2}{3}$ spin $\frac{1}{2}$ t top	mass 0 charge 0 spin 1 g gluon	mass $\approx 124.97 \text{ GeV}$ ✓ charge 0 spin 0 H higgs
QUARKS mass $\approx 4.7 \text{ MeV}/c^2$ charge $-\frac{1}{3}$ spin $\frac{1}{2}$ d down	mass $\approx 96 \text{ MeV}/c^2$ ✓ charge $-\frac{1}{3}$ spin $\frac{1}{2}$ s strange	mass $\approx 4.18 \text{ GeV}/c^2$ ✓ charge $-\frac{1}{3}$ spin $\frac{1}{2}$ b bottom	mass 0 charge 0 spin 1 γ photon	SCALAR BOSONS
mass $\approx 0.511 \text{ MeV}/c^2$? charge -1 spin $\frac{1}{2}$ e electron	mass $\approx 105.66 \text{ MeV}/c^2$ ✓ charge -1 spin $\frac{1}{2}$ μ muon	mass $\approx 1.7768 \text{ GeV}/c^2$ ✓ charge -1 spin $\frac{1}{2}$ τ tau	mass $\approx 91.19 \text{ GeV}/c^2$ ✓ charge 0 spin 1 Z Z boson	
LEPTONS mass $< 1.0 \text{ eV}/c^2$ charge 0 spin $\frac{1}{2}$ ν_e electron neutrino	mass $< 0.17 \text{ MeV}/c^2$ charge 0 spin $\frac{1}{2}$ ν_μ muon neutrino	mass $< 18.2 \text{ MeV}/c^2$ charge 0 spin $\frac{1}{2}$ ν_τ tau neutrino	mass $\approx 80.39 \text{ GeV}/c^2$ ✓ charge ± 1 spin 1 W W boson	
			GAUGE BOSONS VECTOR BOSONS	

Almost all Higgs couplings to SM particles will have been measured at HL-LHC & FCC-ee

FCC-ee – the Higgs factory

Extremely challenging — cornering the electron Yukawa coupling: $g_e = \sqrt{2}m_e/v \approx 2.9 \cdot 10^{-6}$

Can we measure the decay? (recall: $\Gamma_H = 4.1$ MeV)

$$\text{BR}(H \rightarrow e^+e^-) \simeq \frac{1}{\Gamma_H} \cdot \frac{G_F m_H m_e^2}{4\pi\sqrt{2}} \approx 5.2 \cdot 10^{-9}$$

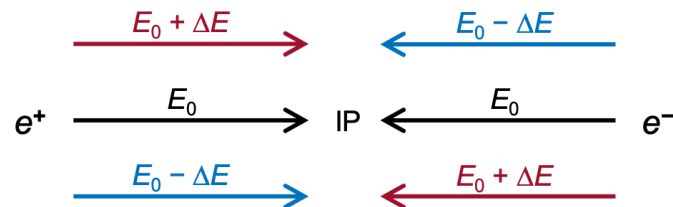
The entire HL-LHC may produce 2 such events!

At the FCC-ee, BW s-channel resonance:

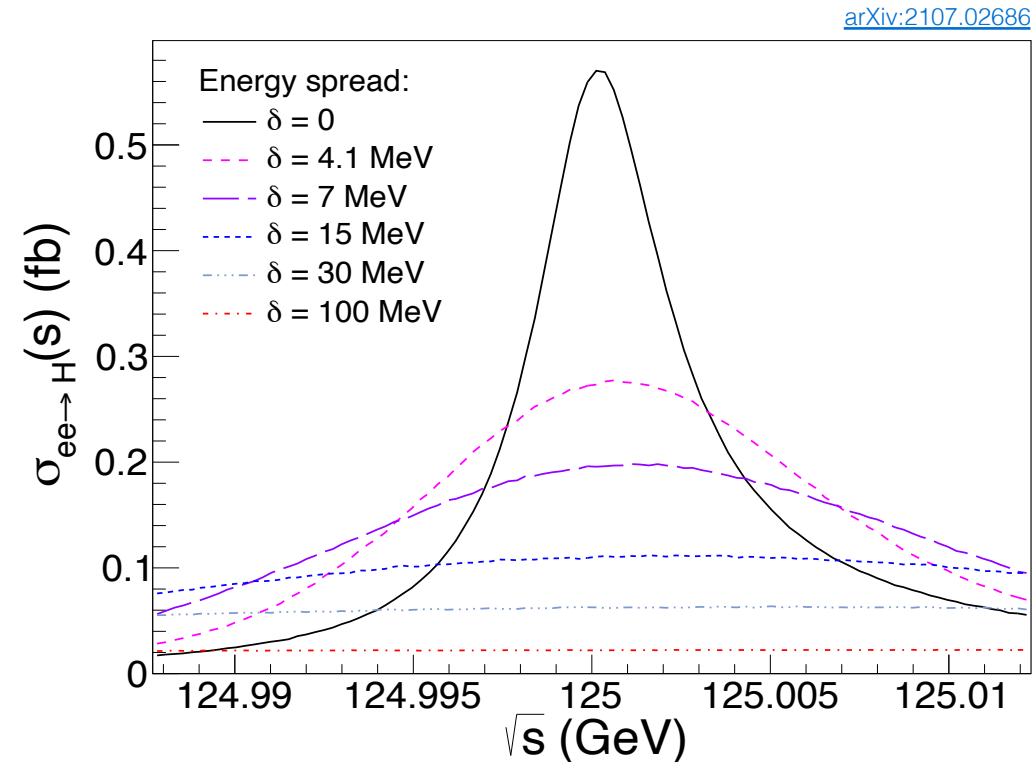
$$\sigma(e^+e^- \rightarrow H) \simeq \frac{4\pi\Gamma_H\Gamma(H \rightarrow e^+e^-)}{(s - m_H^2)^2 + m_H^2\Gamma_H^2} \xrightarrow{s=m_H^2} \frac{4\pi}{m_H^2} \text{BR}(H \rightarrow e^+e^-) \approx 1.6 \text{ fb}$$

but ISR and $\sqrt{s}$ spread will lead to smearing of BW peak, so that effective cross section is 0.3 fb (remember: $\mathcal{L}_{ZH} = 10.8 \text{ ab}^{-1}$). **Can it be done?**

- Requires precise knowledge of Higgs mass to few MeV
- Beam must be monochromatized to match narrow Γ_H [arXiv: 2411.04210]



Correlate energy and transverse position so high-energy particles collide with low-energy ones (opposite beam dispersions at IP) — requires dedicated instruments: proposed for many e^+e^- colliders, but never implemented



Possible sensitivity to g_e of $\sim 0.5\sigma$ per year and IP

FCC-ee – also a Tera-Z, W and top factory

Extreme luminosity on Z pole: $140 \cdot 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ / IP, 205 ab^{-1} & $6 \cdot 10^{12} \text{ Z}$ (4 IPs) — ultimate EW precision data

[arXiv:2505.00272](https://arxiv.org/abs/2505.00272)

Observable	value	present ±	uncertainty	FCC-ee Stat.	FCC-ee Syst.	Comment and leading uncertainty
m_Z (keV)	91 187 600	±	2000	4	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2 495 500	±	2300	4	12	From Z line shape scan Beam energy calibration
$\sin^2 \theta_W^{\text{eff}} (\times 10^6)$	231,480	±	160	1.2	1.2	From $A_{\text{FB}}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{\text{QED}}(m_Z^2) (\times 10^3)$	128 952	±	14	3.9 0.8	small tbc	From $A_{\text{FB}}^{\mu\mu}$ off peak From $A_{\text{FB}}^{\mu\mu}$ on peak QED&EW uncert. dominate
$R_\ell^Z (\times 10^3)$	20 767	±	25	0.05	0.05	Ratio of hadrons to leptons Acceptance for leptons
$\alpha_S(m_Z^2) (\times 10^4)$	1 196	±	30	0.1	1	Combined R_ℓ^Z , Γ_{tot}^Z , σ_{had}^0 fit
$\sigma_{\text{had}}^0 (\times 10^3) \text{ (nb)}$	41 480.2	±	32.5	0.03	0.8	Peak hadronic cross section Luminosity measurement
$N_\nu (\times 10^3)$	2 996.3	±	7.4	0.09	0.12	Z peak cross sections Luminosity measurement
$R_b (\times 10^6)$	216 290	±	660	0.25	0.3	Ratio of $b\bar{b}$ to hadrons
$A_{\text{FB}}^{b,0} (\times 10^4)$	992	±	16	0.04	0.04	b-quark asymmetry at Z pole From jet charge
$A_{\text{FB}}^{\text{pol},\tau} (\times 10^4)$	1 498	±	49	0.07	0.2	τ polarisation asymmetry τ decay physics

Observable	value	present ±	uncertainty	FCC-ee Stat.	FCC-ee Syst.	Comment and leading uncertainty
τ lifetime (fs)	290.3	±	0.5	0.001	0.005	ISR, τ mass
τ mass (MeV)	1 776.93	±	0.09	0.002	0.02	estimator bias, ISR, FSR
τ leptonic ($\mu\nu_\mu\nu_\tau$) BR (%)	17.38	±	0.04	0.00007	0.003	PID, π^0 efficiency
m_W (MeV)	80 360.2	±	9.9	0.18	0.16	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2 085	±	42	0.27	0.2	From WW threshold scan Beam energy calibration
$\alpha_S(m_W^2) (\times 10^4)$	1 010	±	270	2	2	Combined R_ℓ^W , Γ_{tot}^W fit
$N_\nu (\times 10^3)$	2 920	±	50	0.5	small	Ratio of invis. to leptonic in radiative Z returns
m_{top} (MeV)	172 570	±	290	4.2	4.9	From $t\bar{t}$ threshold scan QCD uncert. dominate
Γ_{top} (MeV)	1 420	±	190	10	6	From $t\bar{t}$ threshold scan QCD uncert. dominate
$\lambda_{\text{top}}/\lambda_{\text{top}}^{\text{SM}}$	1.2	±	0.3	0.015	0.015	From $t\bar{t}$ threshold scan QCD uncert. dominate
$t\bar{t}Z$ couplings		±	30%	0.5–1.5 %	small	From $\sqrt{s} = 365 \text{ GeV}$ run

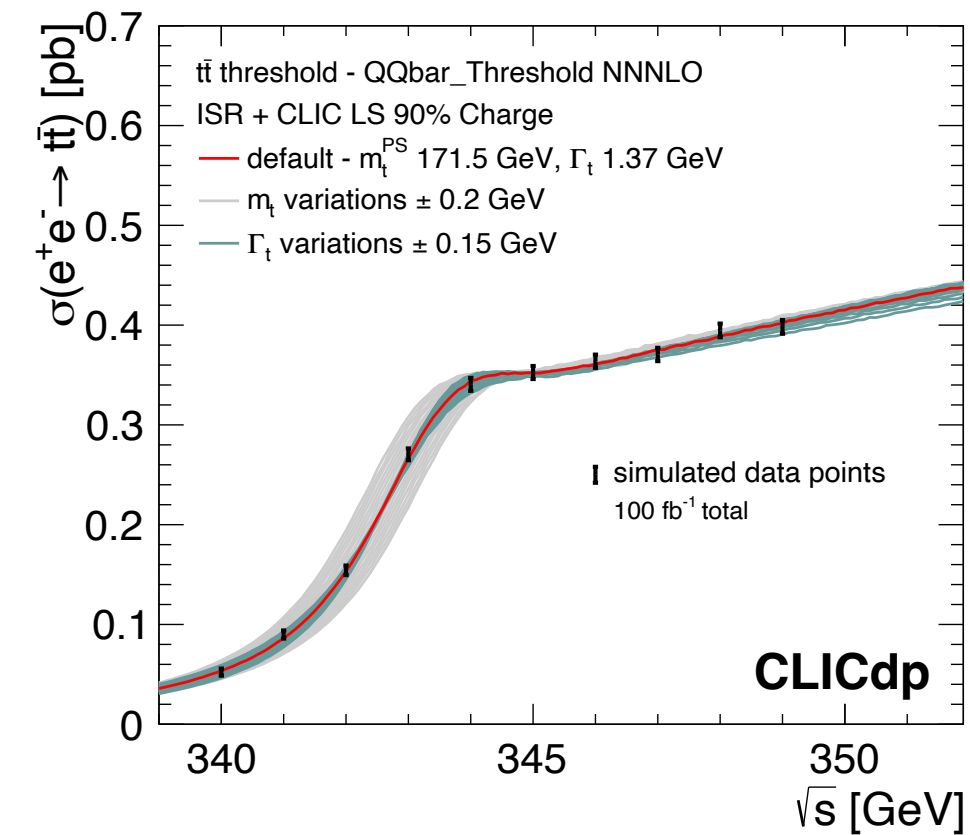
Improvements up to $\times 2000$ over current knowledge

Input to global electroweak fit: **requires significant improvements in theoretical predictions**

FCC-ee – also a Tera-Z, W and top factory

Extreme luminosity on Z pole: $140 \cdot 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ / IP, 205 ab^{-1} & $6 \cdot 10^{12} \text{ Z}$ (4 IPs) — ultimate EW precision data

[arXiv:2505.00272](#)



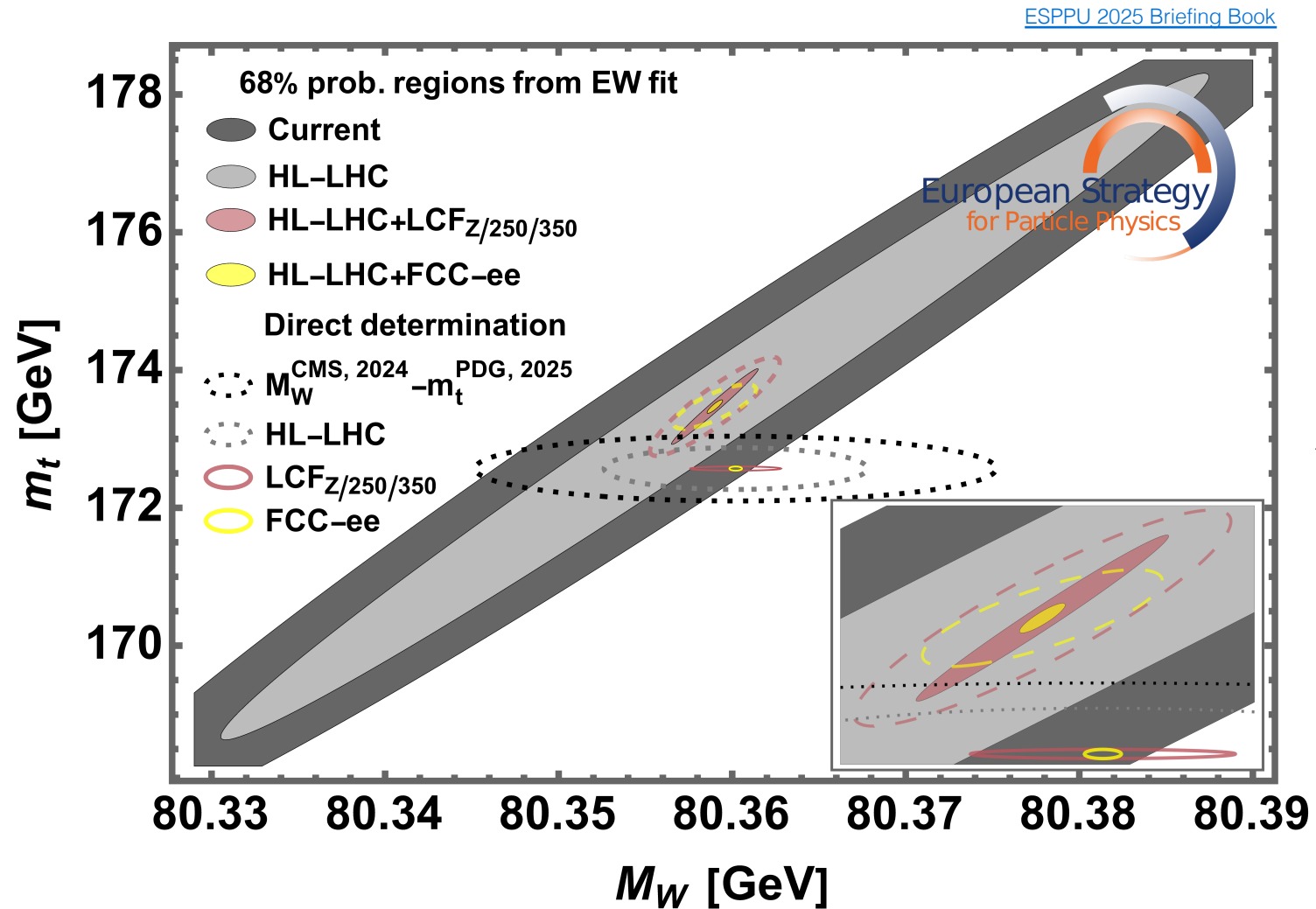
Simulation of tt threshold scan with CLIC [\[arXiv:2503.24168\]](#)

Observable	value	present ±	uncertainty	FCC-ee Stat.	FCC-ee Syst.	Comment and leading uncertainty
τ lifetime (fs)	290.3	±	0.5	0.001	0.005	ISR, τ mass
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ttZ couplings		±	30%	0.5–1.5 %	small	From $\sqrt{s} = 365 \text{ GeV}$ run

Improvements between $\times 50\text{--}2000$ over current knowledge

FCC-ee – also a Tera-Z, W and top factory

Global electroweak fit expressed on top versus W mass



FCC-ee – also a flavour factory (on Z pole)

BR(Z → bb / cc) = 15% / 12%

$\Gamma(Z \rightarrow q\bar{q}) \propto (g_V^2 + g_A^2)$

Large c and b-hadron statistics — combines strengths of Belle-II ($e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$) and LHCb ($pp \rightarrow b\bar{b} + X$)

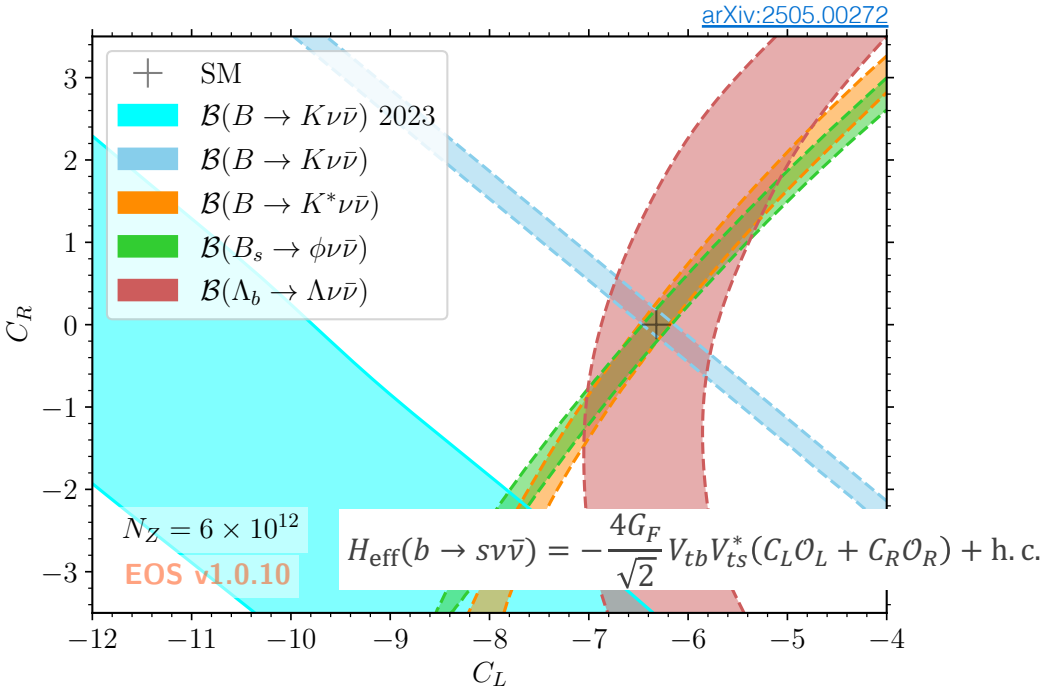
Attribute	$\Upsilon(4S)$	pp	Z
All hadron species		✓	✓
High boost		✓	✓
Enormous production cross-section		✓	
Negligible trigger losses	✓		✓
High geometrical acceptance	✓		✓
Low backgrounds	✓		✓
Flavour-tagging power	✓		✓
Initial-energy constraint	✓		(✓)

Particle species	B^0	B^+	B_s^0	Λ_b	B_c^+	$c\bar{c}$	$\tau^-\tau^+$
FCC-ee ($\times 10^9$)	370	370	90	80	2	720	200
Belle-II ($\times 10^9$)	28	28	—	—	—	33	46

Yields for $6 \cdot 10^{12}$ Z

Yields for 50 ab^{-1}

The larger yield of B mesons than Belle II allows unmatched precision on B decays with neutrinos



Clean reconstruction due to boost and flavour tagging ($> \text{LHCb}$), excellent charm / τ separation (challenging at $\Upsilon(4S)$)

Ultimate CKM angle precision (similar to LHCb)

Ultimate τ factory

$B \rightarrow \tau \nu$ allows 1% measurement of $|V_{ub}|$ and running above WW threshold allows *on-shell* measurement of $|V_{cb}|$ to $\sim 1\%$

Current precision $3.5_{V_{ub}} / 1.1_{V_{cb}}\%$, but discrepancies between exclusive and inclusive results of $17_{V_{ub}} / 5_{V_{cb}}\%$, respectively

LEP3 — a Higgs and EW factory in the LHC tunnel

Backup if (preferred) FCC-ee cannot be realised with long-term goal of an energy-frontier hadron or muon collider:
similar to FCC-ee with booster and collider rings, 2 beampipes, 50 MW / beam, 2 IPs

LEP3	Parameter	Z	WW	H (ZH)		$t\bar{t}$	Construction:
	Inst. luminosity / IP [$10^{34} \text{ cm}^{-2}\text{s}^{-1}$]	40	6.2 (160 GeV)	1.6 (230 GeV)		—	Total cost 3.7B CHF ESPPU input: arXiv:2504.00541
	SR energy loss / turn [GeV]	0.13	1.3	5.4		(~25 GeV)	
	Integrated luminosity / year / IP [ab^{-1}]	4.8	0.7	0.19		—	
	Run time [years]	5	4	6		—	
	Total integrated luminosity [ab^{-1} , 2 IPs]	48	6.0	2.3		—	
	Total number of events [2 IPs]	$1.4 \cdot 10^{12}$	$0.36 \cdot 10^8$	$0.42 \cdot 10^6$		—	
FCC-ee	Inst. luminosity / IP [$10^{34} \text{ cm}^{-2}\text{s}^{-1}$]	144	20 (157, 163 GeV)	7.5 (240 GeV)	1.8 (~350 GeV)	1.4 (365 GeV)	Total cost 13.7B + 1.3B $_{t\bar{t}}$ CHF
	SR energy loss / turn [GeV]	0.036	0.08	1.7	7.8	9.2	
	Integrated luminosity / year / IP [ab^{-1}]	17	2.4	0.9	0.21	0.17	
	Run time (including lumi ramp-up) [years]	4	2	3	1	4	FCC-ee SR loss reference
	Total integrated luminosity [ab^{-1} , 4 IPs]	205	19.2	10.8	0.4	2.7	
	Total number of events [4 IPs]	$6 \cdot 10^{12}$	$2.4 \cdot 10^8$	$2.2 \cdot 10^6$	$2 \cdot 10^6$		

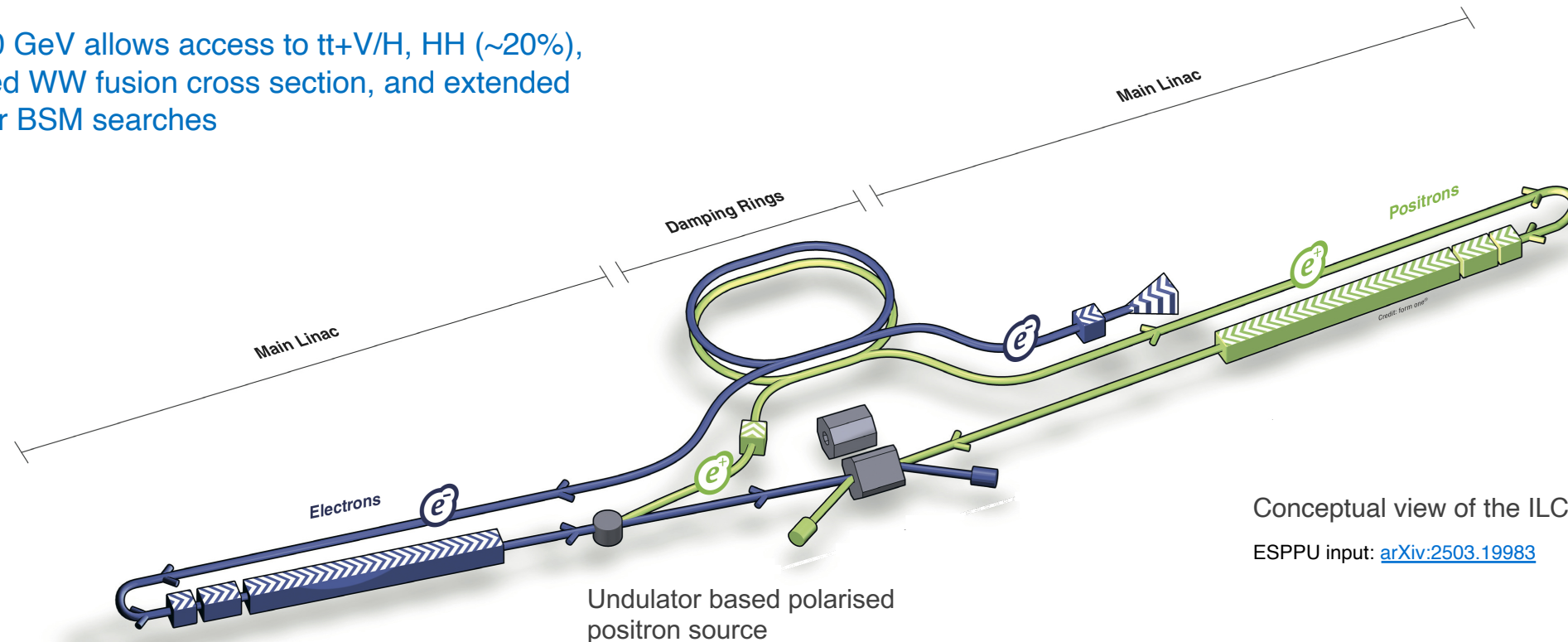
Challenges for LEP3 include design of IRs, large E-loss, need 6.0 GV RF power installed in 4 long straight sections (2 booster, 2 collider), crab-waist scheme requires large crossing angle and widening tunnel on either side of the experiments from ~4m to 7m diameter along 270 m

LEP3 as an ESPPU Plan-B option must include a long-term energy-frontier plan

Linear Collider Facility (LCF) at CERN

Very similar to ILC: baseline is 33.5 km tunnel, 1.3 GHz niobium SRF cavities with an accelerating gradient of 31.5 MV/m, $\sqrt{s} = 250$ GeV upgradable to 550 GeV, 10 Hz repetition frequency, low/full-power (LP/FP) 1312/2625 bunches per pulse, power usage of 140–320 MW at 250–550 GeV, longitudinal polarisation ($\pm 80/30\%$ for e^-/e^+ , $\sim 20\%$ higher $\sigma(ZH)$), 2 IPs (sharing luminosity)

$\sqrt{s} = 550$ GeV allows access to $t\bar{t}+V/H$, HH ($\sim 20\%$), increased WW fusion cross section, and extended reach for BSM searches



Conceptual view of the ILC / LCF

ESPPU input: [arXiv:2503.19983](https://arxiv.org/abs/2503.19983)

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LCF	Parameter	Z	WW	H (ZH)	above $t\bar{t}$	
	Inst. luminosity / IP [$10^{34} \text{ cm}^{-2}\text{s}^{-1}$]	0.28	—	$1.4_{\text{LP}} / 2.7_{\text{FP}}$ (250 GeV)	3.9 (550 GeV)	
	Integrated luminosity / year / IP [ab^{-1}]	30	—	$0.19_{\text{LP}} + 0.64_{\text{FP}}$	2.3	
	Run time [years]	1	—	$5_{\text{LP}} + 3_{\text{FP}}$	10	
	Total integrated luminosity [ab^{-1} , 2 IPs*]	0.07	—	$1.0_{\text{LP}} + 1.9_{\text{FP}}$	8.3	
	Total number of events [2 IPs*]	$0.002 \cdot 10^{12}$	—	$0.8 \cdot 10^6$	$\sim 1.6 \text{ (H)} / 3.9 \text{ (tt)} \cdot 10^6$	
FCC-ee	Inst. luminosity / IP [$10^{34} \text{ cm}^{-2}\text{s}^{-1}$]	144	20 (157, 163 GeV)	7.5 (240 GeV)	1.8 ($\sim 350 \text{ GeV}$)	1.4 (365 GeV)
	Integrated luminosity / year / IP [ab^{-1}]	17	2.4	0.9	0.21	0.17
	Run time (including lumi ramp-up) [years]	4	2	3	1	4
	Total integrated luminosity [ab^{-1} , 4 IPs]	205	19.2	10.8	0.4	2.7
	Total number of events [4 IPs]	$6 \cdot 10^{12}$	$2.4 \cdot 10^8$	$2.2 \cdot 10^6$	$2 \cdot 10^6$	

Construction:

Total cost:

- 8.5B CHF (250 GeV, LP)
- 9.3B CHF (250 GeV, FP)
- 14.8B CHF (550 GeV)

ESPPU input: [arXiv:2503.19983](https://arxiv.org/abs/2503.19983)

Total cost 15.3B CHF

*LCF proposes to share luminosity among two interaction regions, ie, same integrated luminosity as for single IP

Challenges for for LCF include the positron source, final focus and nano-beam stability ($\sigma_y^* \sim 6\text{--}8 \text{ nm}$, FCC-ee: 40 nm)

Options to increase energy beyond 550 GeV with development and installation of higher gradient accelerating technologies (see [here](#) for a discussion of options)