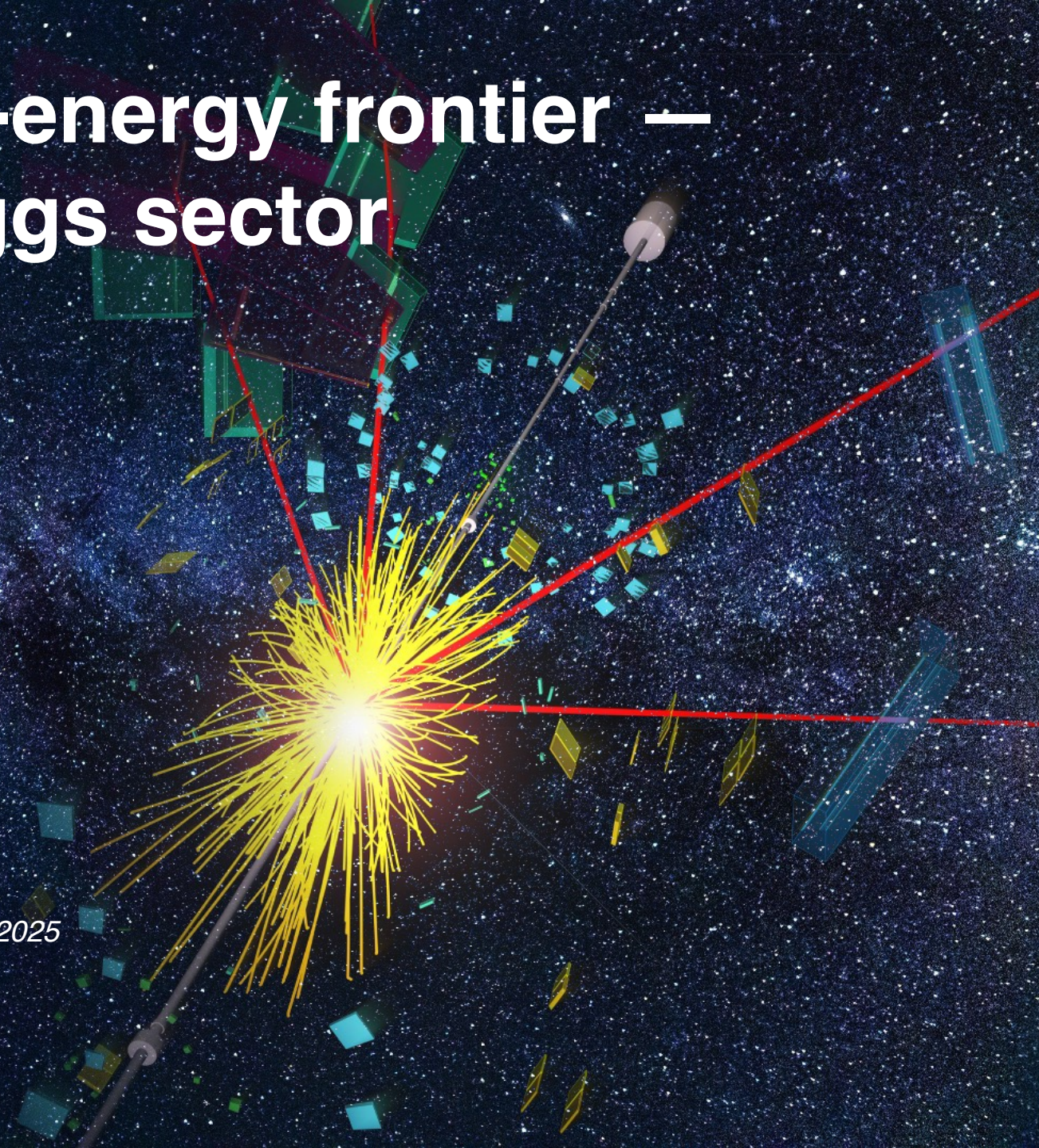


Physics at the high-energy frontier — Deciphering the Higgs sector

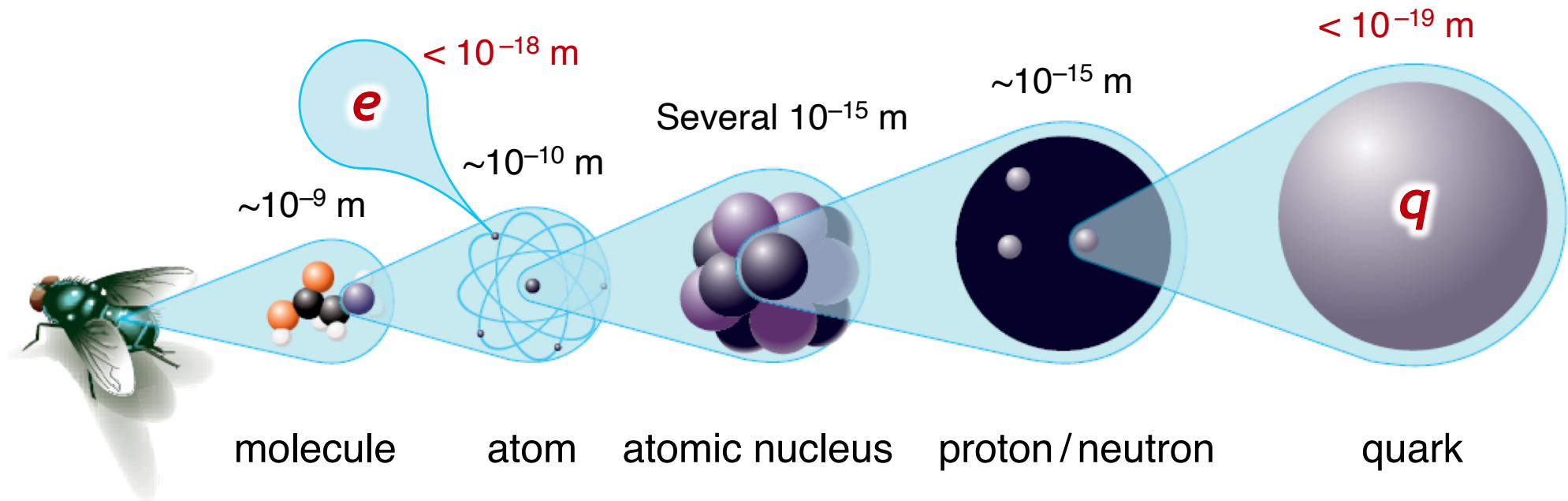
Andreas Hoecker (CERN)

Colloquium, University of Illinois Urbana-Champaign 9 April 2025



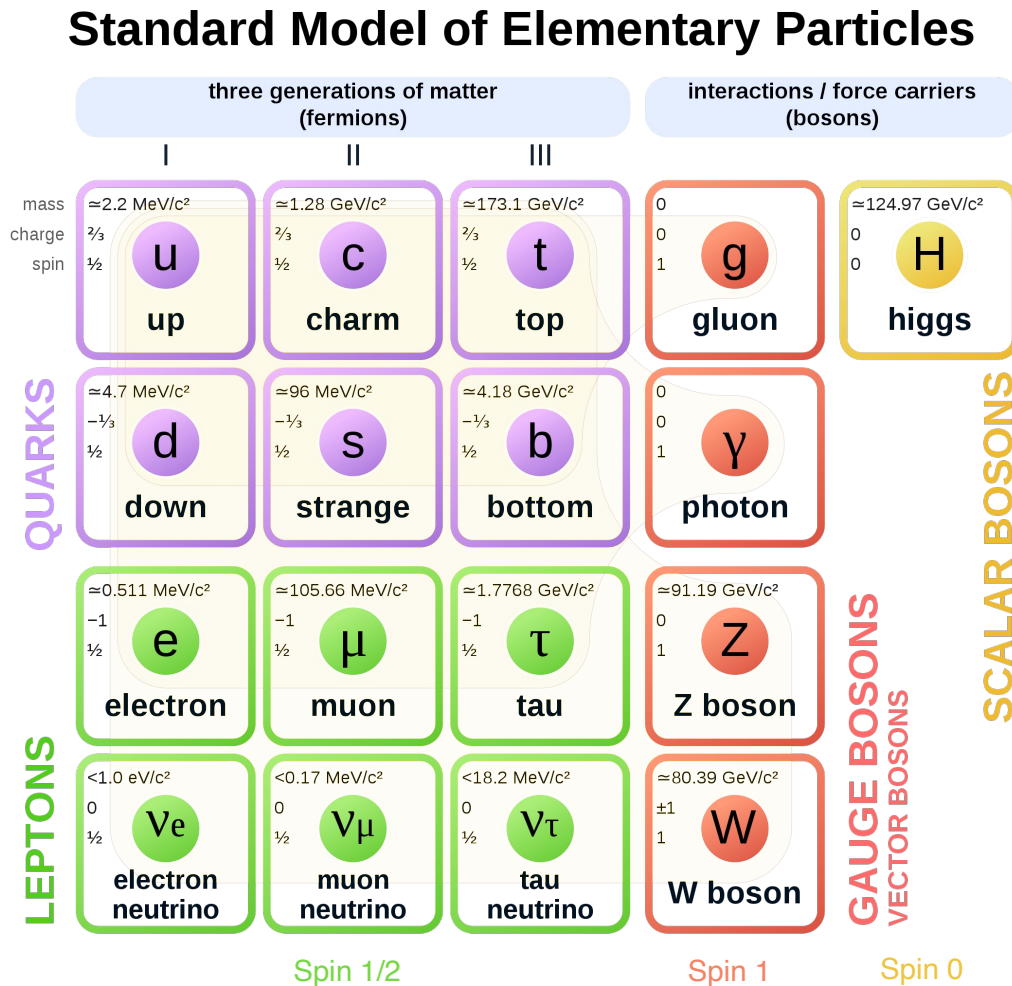
It's all made of a handful of particles and forces

The sub-atomic structure of matter (a very simplified picture)



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**

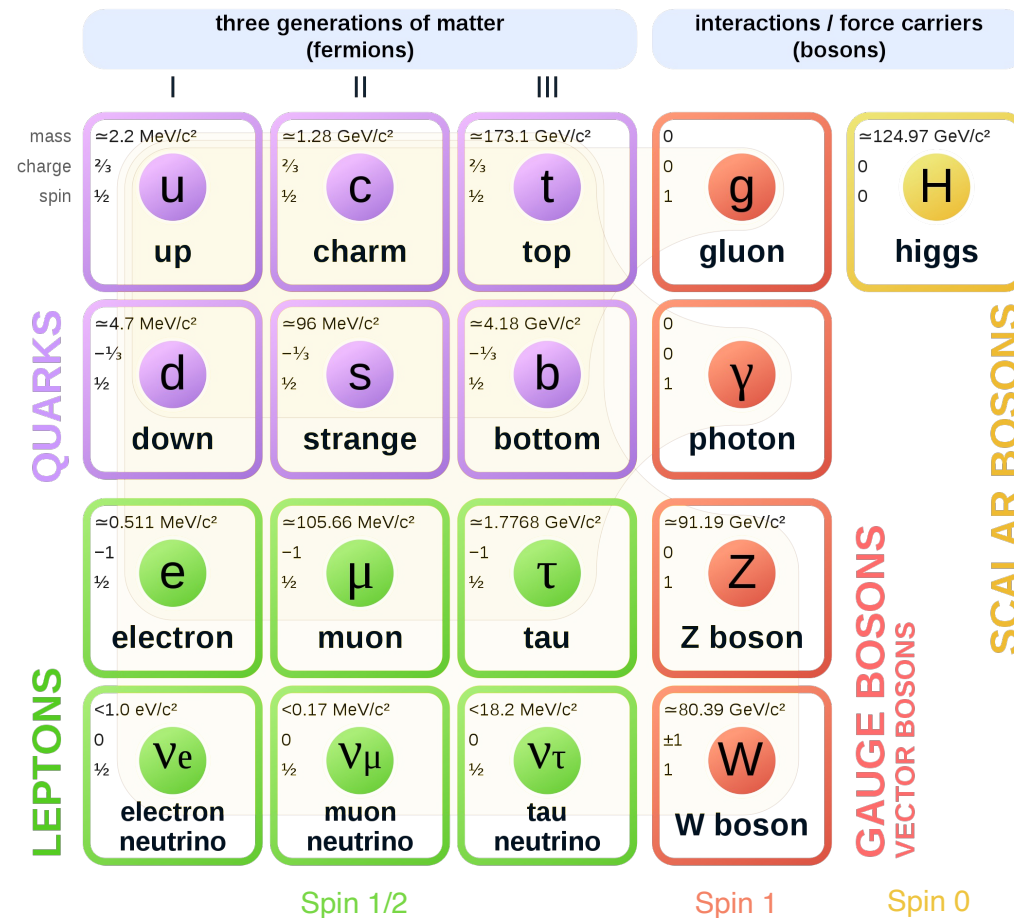


Completely new type of non-universal interactions, nothing to do with known forces

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



Likely still a **very simplified and incomplete picture** (but enough to explain most observations)

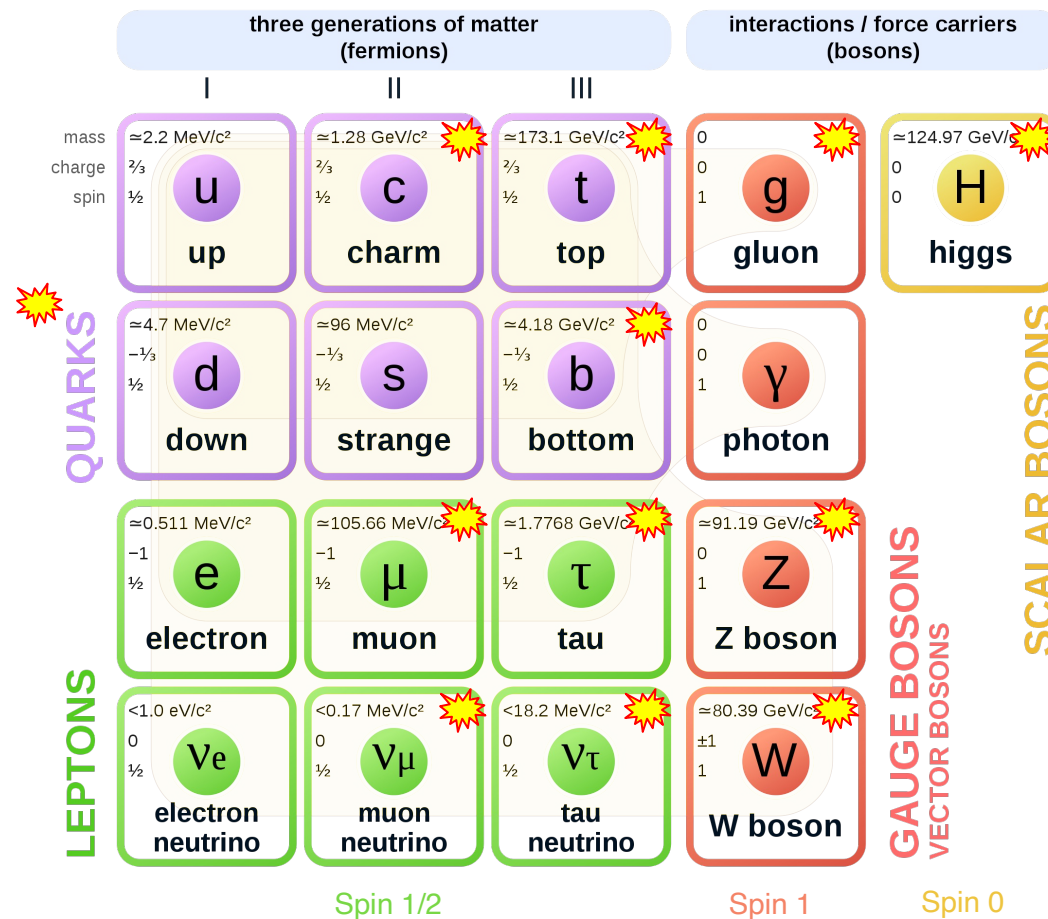
How do we know all this?

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

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Standard Model of Elementary Particles



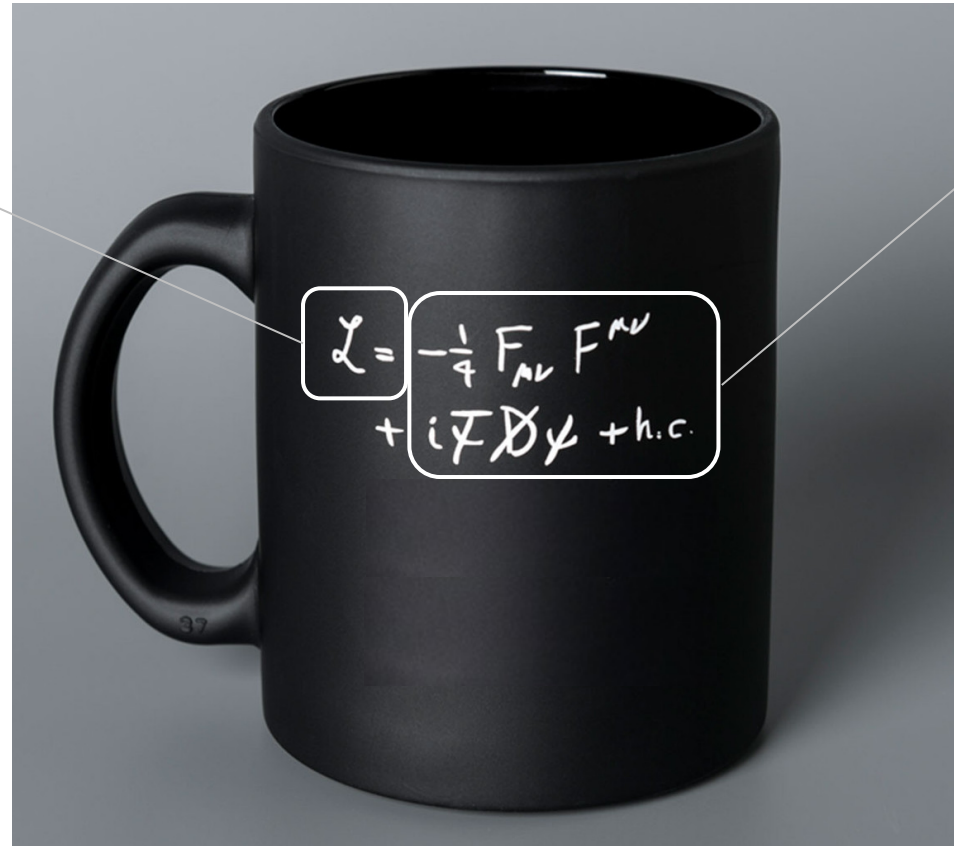
Decades of international high-technology **accelerator-based research** gave us these insights

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

The Standard Model

Interactions in the Standard Model are described by local **gauge theories**

The **SM Lagrangian**



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

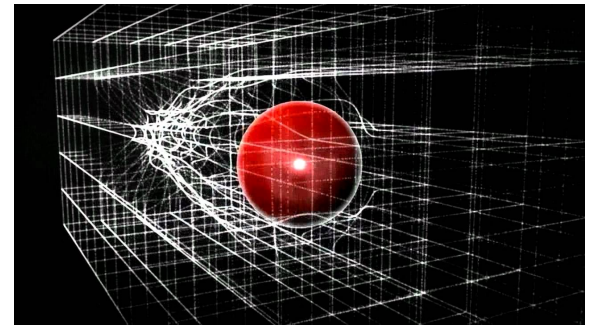
A problem: gauge symmetry requires massless spin-1 bosons and spin-1/2 fermions

Gauge symmetry and the 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 interaction energy and thus 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**

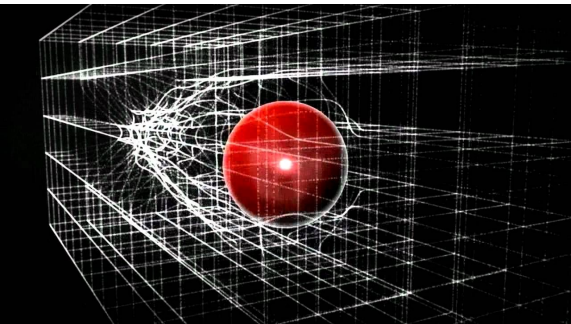


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Peter Ware Higgs (1929 – 2024)

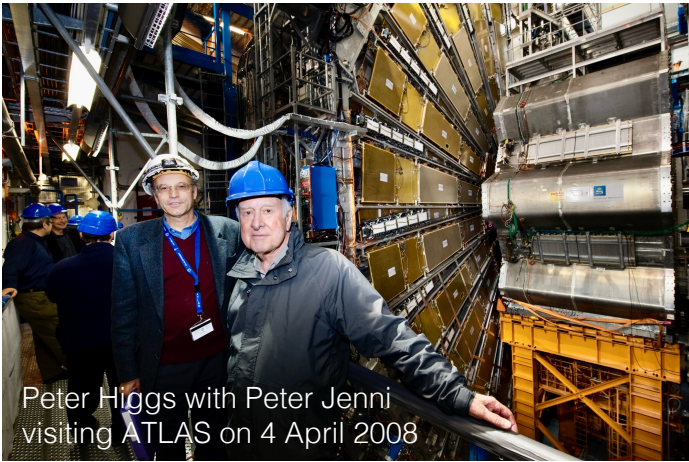


Broken Symmetries and the Masses of Gauge Bosons — or how to change the course of physics with a good idea on two pages — together with the other famous works from his colleagues in 1964

[My life as a boson, 2010]



Peter Higgs and Fabiola on 4 July 2012



Peter Higgs with Peter Jenni visiting ATLAS on 4 April 2008

Gauge symmetry and the Higgs mechanism

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

The Higgs potential energy:

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

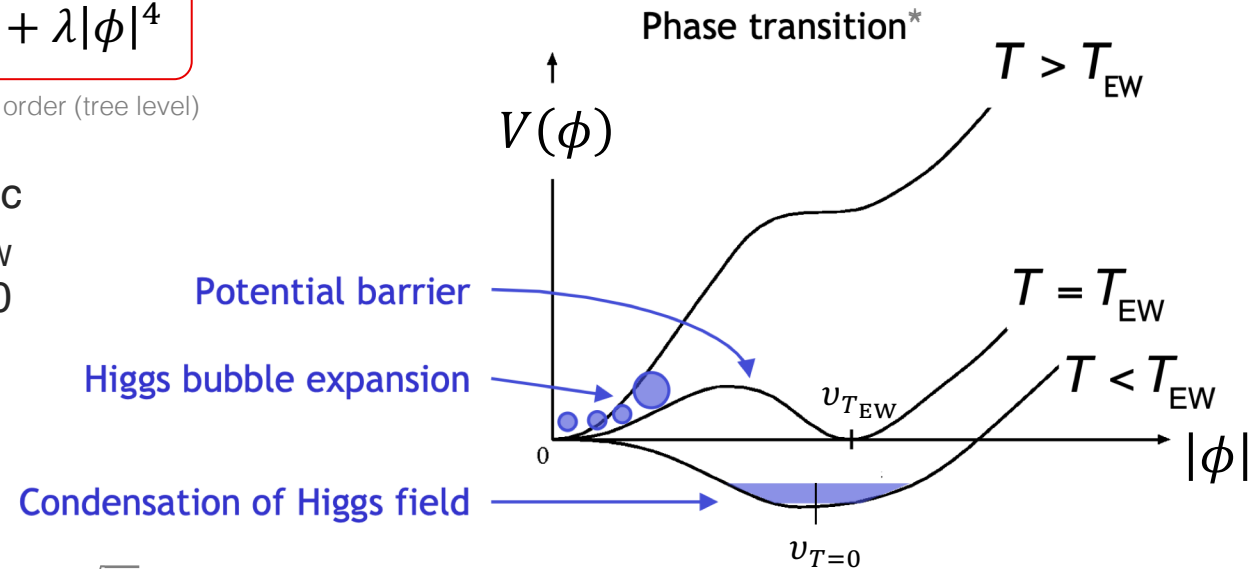
At lowest order (tree level)

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

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

Gauge symmetry and the Higgs mechanism

Remark:

The left-right asymmetric (V–A, maximal parity violation) gauge structure of weak interaction forbids bare fermion masses, mass only through Higgs mechanism $m_f \propto g_f v \rightarrow$ SM fermions are naturally light compared to high-scale physics such as the Planck scale ($\sim 10^{19}$ GeV), no naturalness problem

The SM structure may propose that there are (many?) super-heavy left-right gauge symmetric fermions (beyond our reach), 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, and so why is it not super heavy? $\rightarrow$ This is the ‘hierarchy problem’

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

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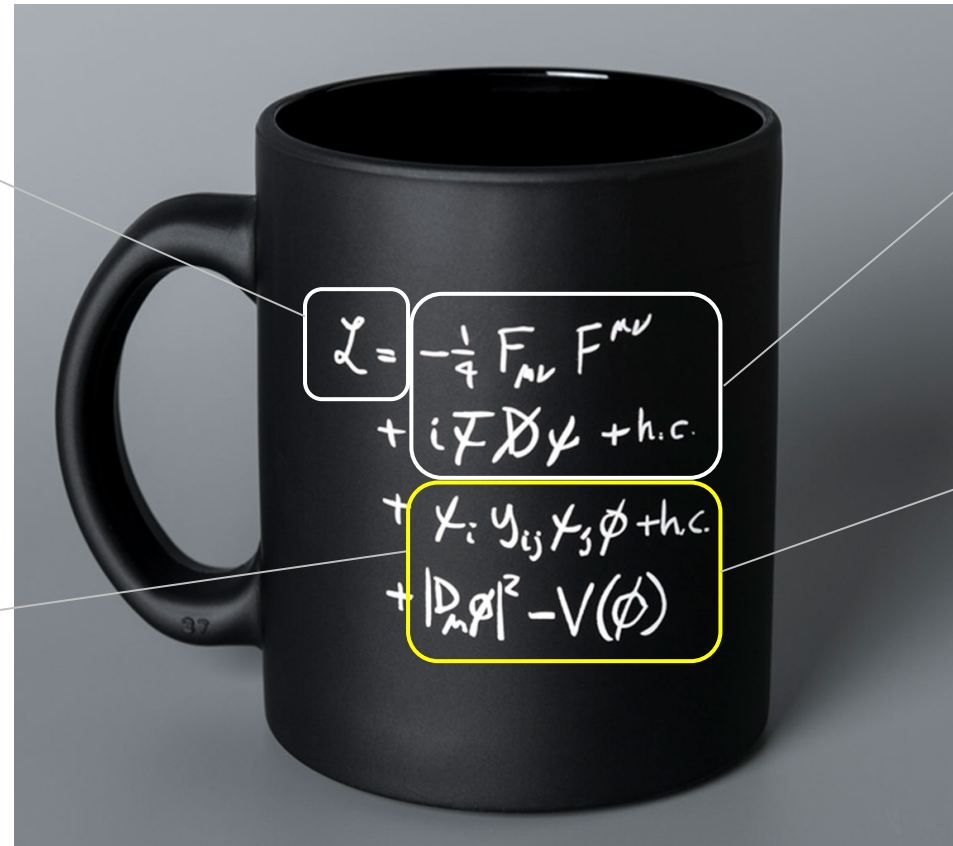
Completing the Standard Model

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

The top term describes how **matter particles couple to the Higgs field ϕ and thereby obtain mass**

The lower left term describes the **interaction of the Higgs field with the weak-interaction bosons, which thereby obtain mass**

The lower right term describes the **Higgs potential $V(\phi)$ with non-zero ground state**

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

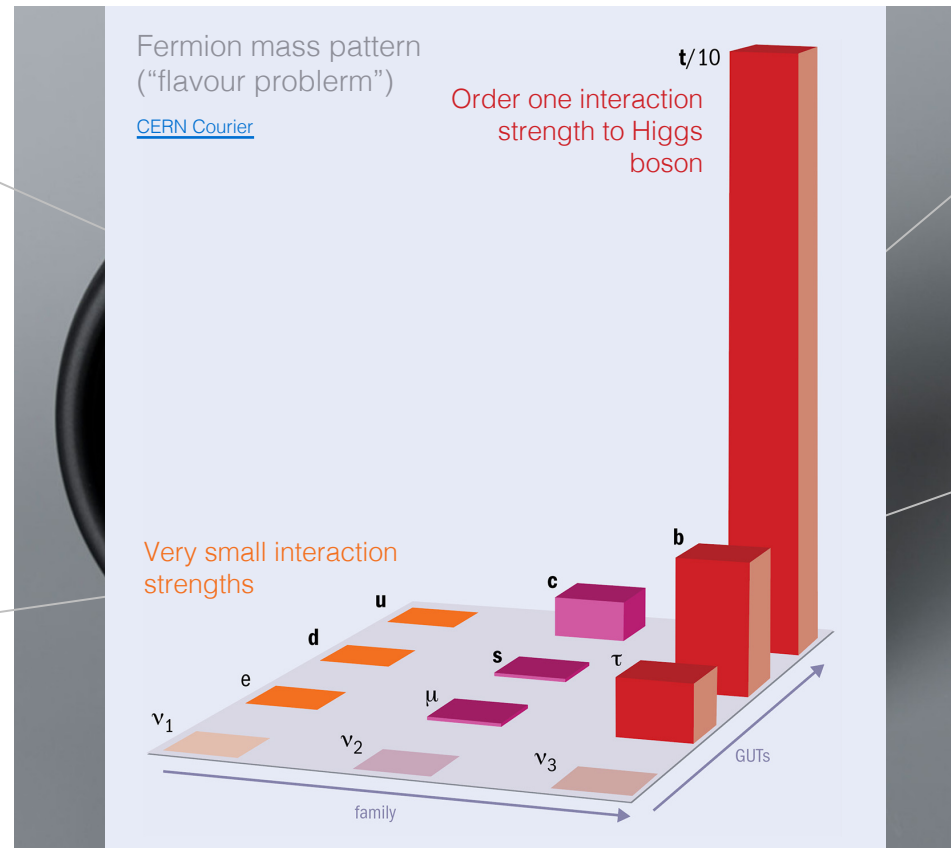
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Completing the Standard Model

The scalar Higgs sector completes the Standard Model

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The Standard Model is an astoundingly predictive theory

For example, the currently best experimental measurement of the magnetic dipole moment of the electron finds: $g/2 = 1.001\,159\,652\,180\,59 \pm 0.000\,000\,000\,000\,13$

Standard Model (QED) and experiment agree within a relative precision of 10^{-10} !

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and 2 (QCD,
) parameters

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gs field ϕ

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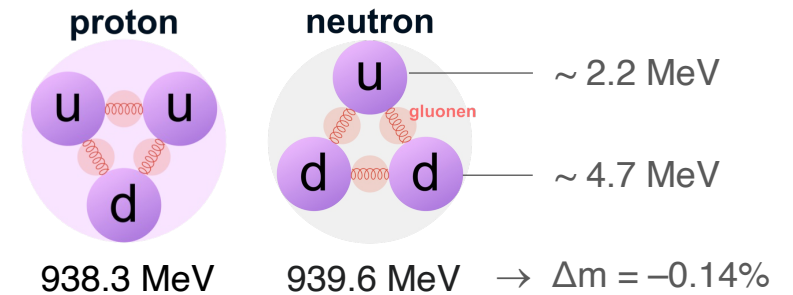
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Completing the Standard Model

A few further comments:

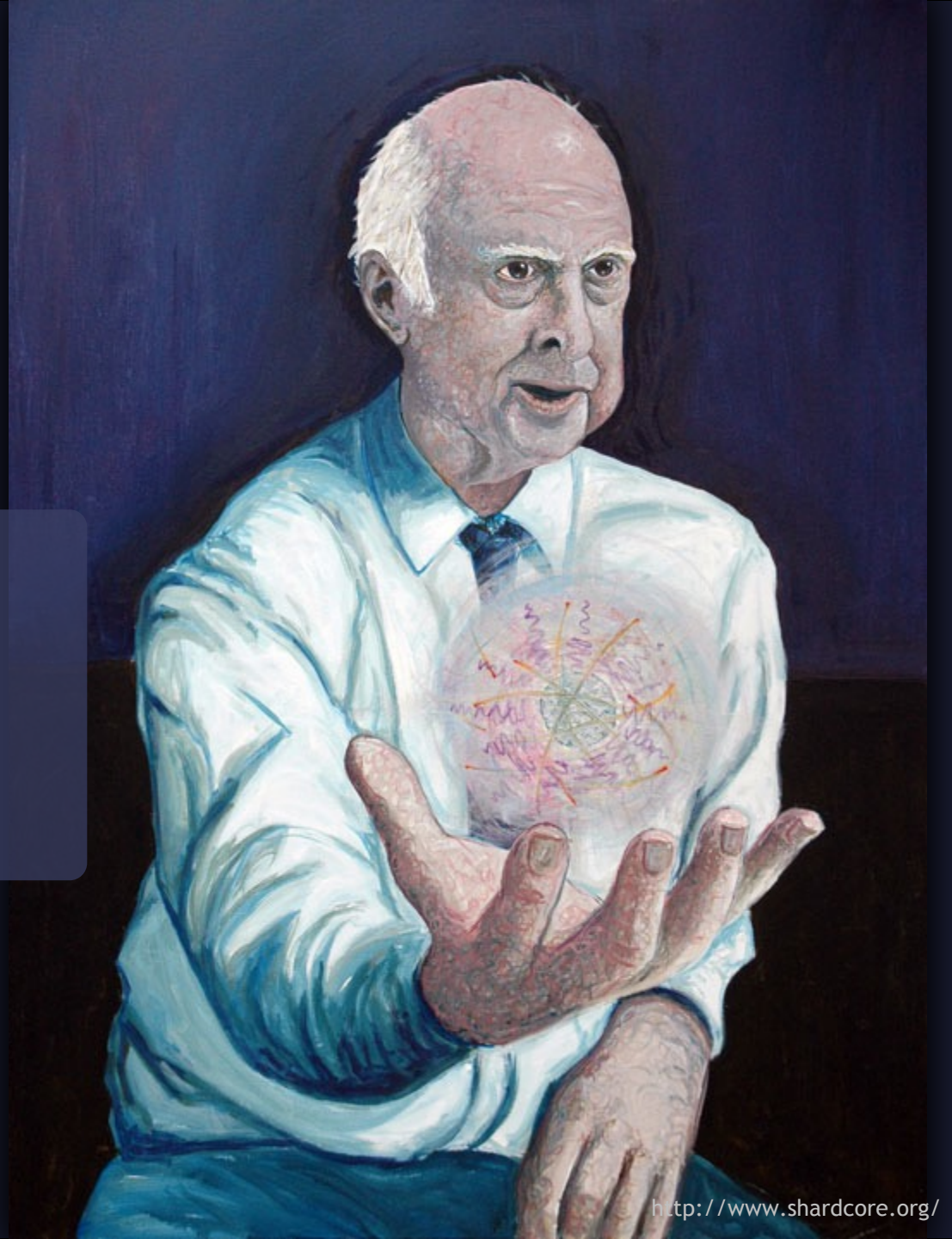
- The Higgs mechanism is required because we assume the bosons and fermions to be elementary. It would be different had they substructure: binding energy could give mass
- The resulting mass values govern the history of the universe (incl. complex chemistry and life) → what would happen had we (or nature) a dial to change the particle masses? [see [R. Cahn](#), 1996*]
- The vacuum energy density of the Higgs field is about 10^{55} times larger than the dark energy observed ($|\rho_{\text{Higgs}}| \sim m_H^2 v^4 / 2 \sim 10^{44} \text{ eV}^4 \gg \rho_\Lambda \sim (2 \times 10^{-3} \text{ eV})^4 \sim 10^{-11} \text{ eV}^4$) → “It would curve the universe into an object roughly the size of a football” (Veltman, 1986)
 - Largest contribution to vacuum energy from zero-point energy of quantum fields $\rho_{\text{QFT}} \propto m_{\text{Pl}}^4 \sim 10^{110} \text{ eV}^4$ [cosmological constant problem]
- The remarkable similarity between the BEH mechanism and the Bardeen–Cooper–Schrieffer theory of superconductivity, where the Bose condensation of a Cooper pair of two electrons plays the role of the Higgs field (note: $T_{\text{crit}} = T_{\text{EW}} \sim 10^{15} \text{ K}$!), raises the question whether the Higgs boson might not be elementary after all

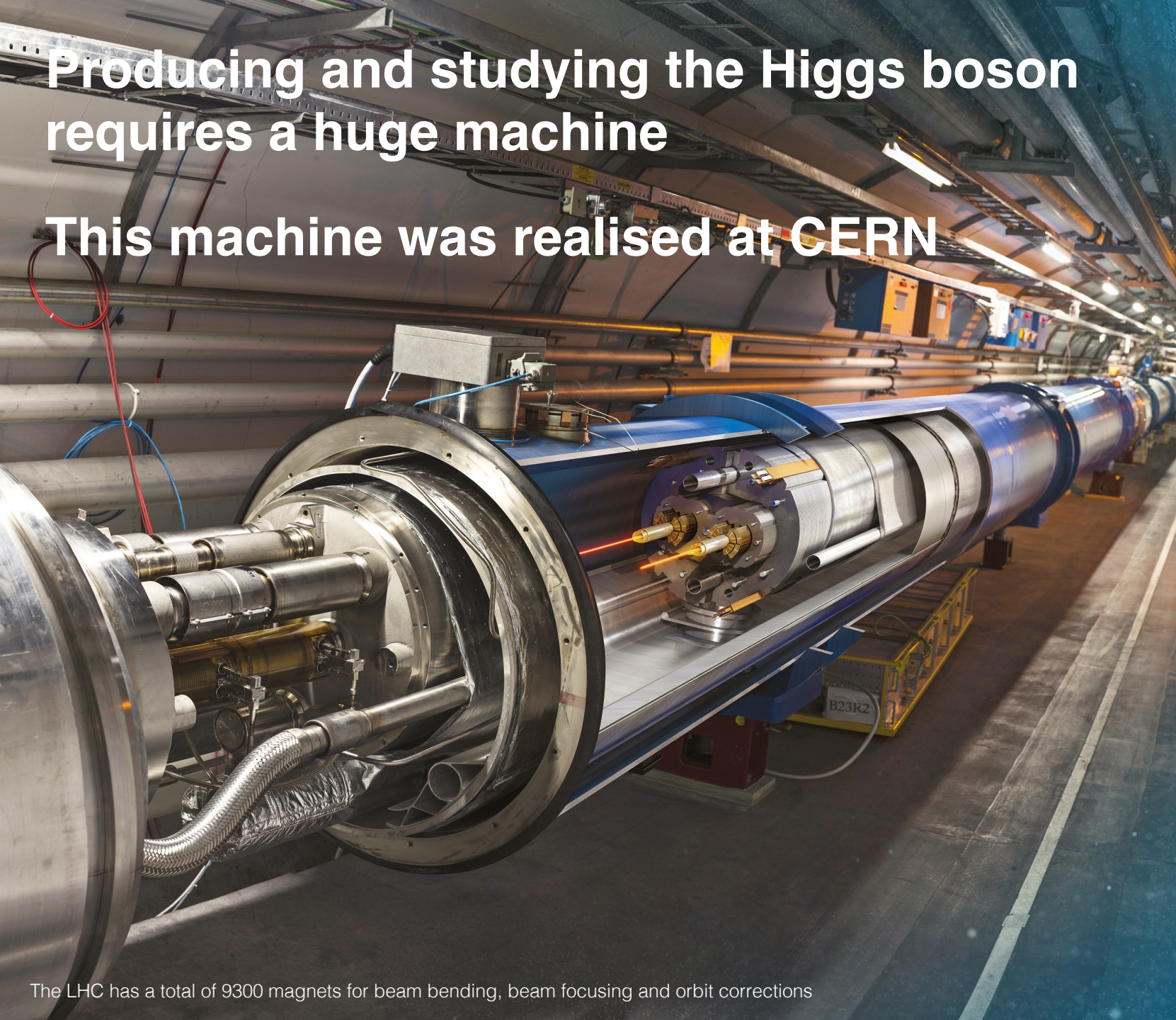


*Electron capture is possible in proton-rich isotopes such as Be-7 decay: $p + e \rightarrow n + \nu_e$ (transition from Be-7 to Li-7), it could go alongside nucleus decay via positron emission

The Higgs mechanism was only a hypothesis
before the start of the LHC

To prove it one had to find and
measure a new particle: the
mysterious **Higgs boson**





Producing and studying the Higgs boson
requires a huge machine

This machine was realised at CERN

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

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

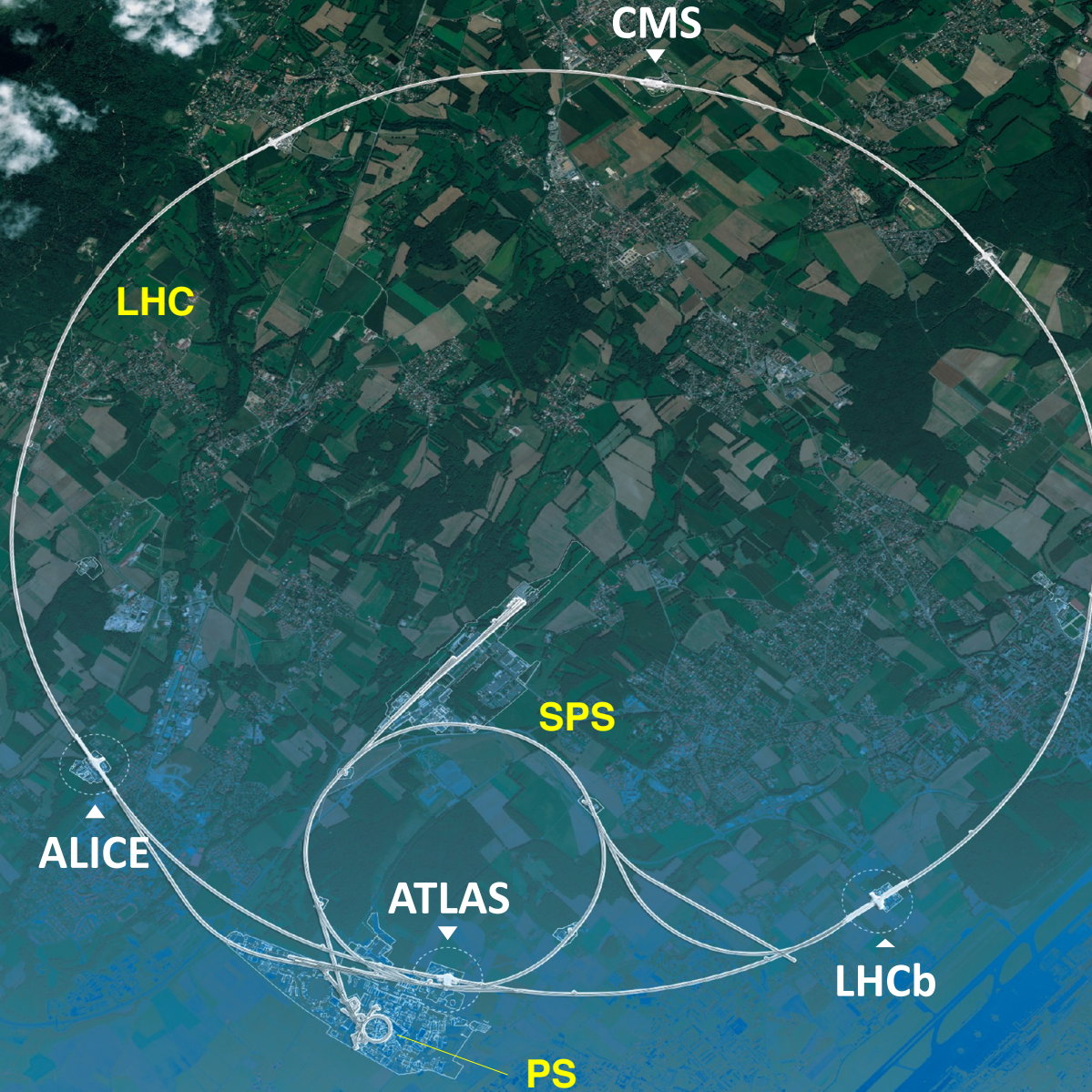
CERN Meyrin campus



YEARS / ANS CERN
1954-2024



The Large Hadron Collider



Areal view



LHC Control Room (July 2022)



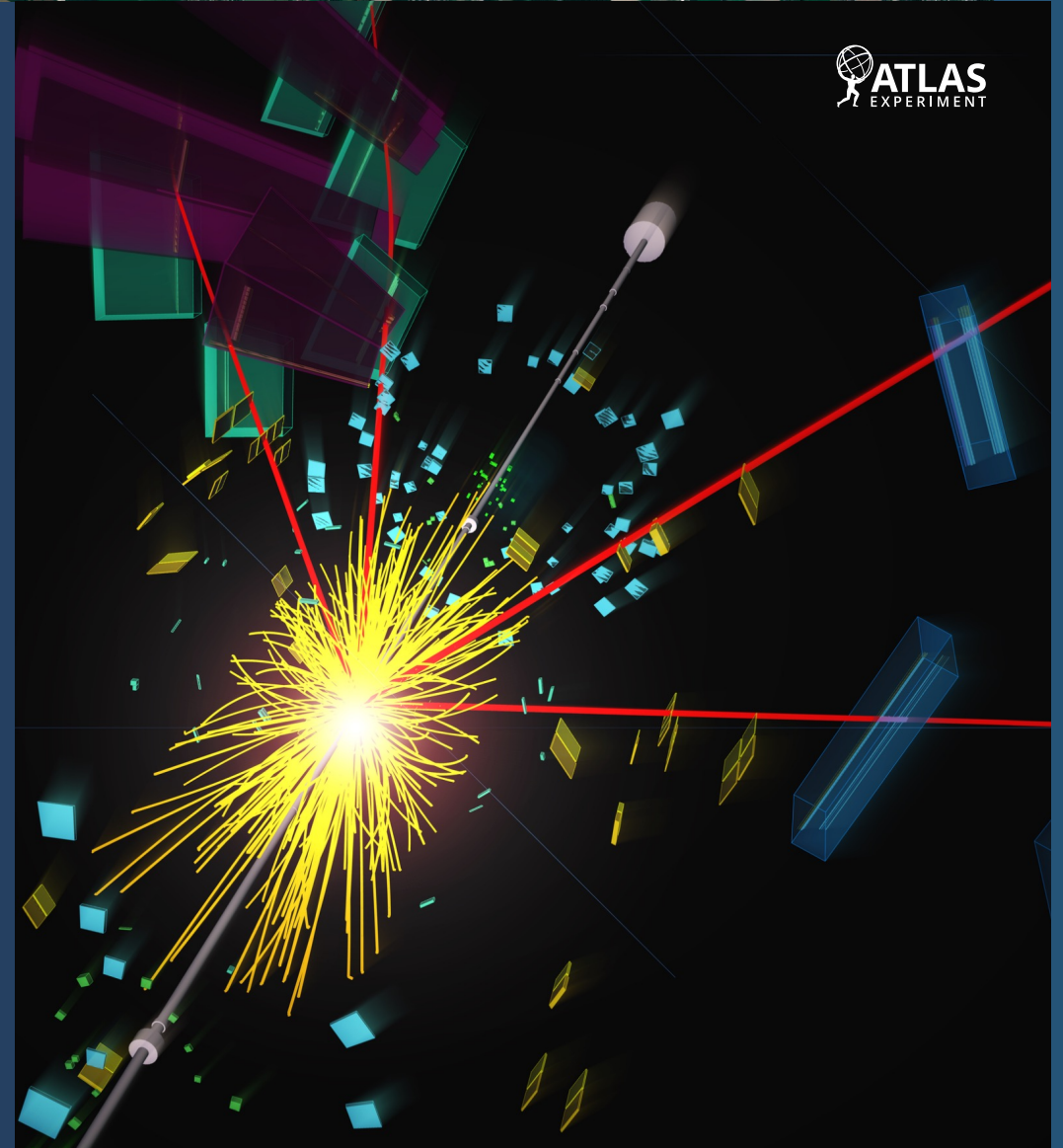
ISR Control Room (early 70s)



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

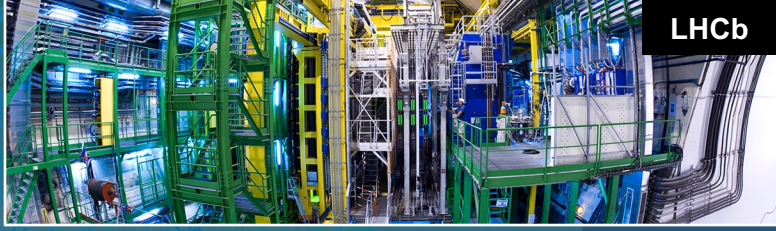
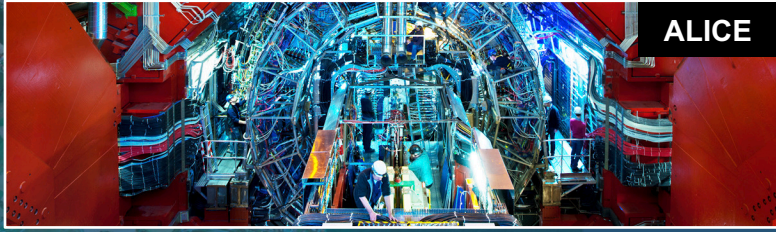
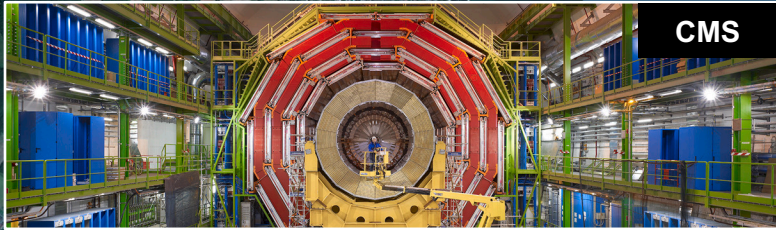
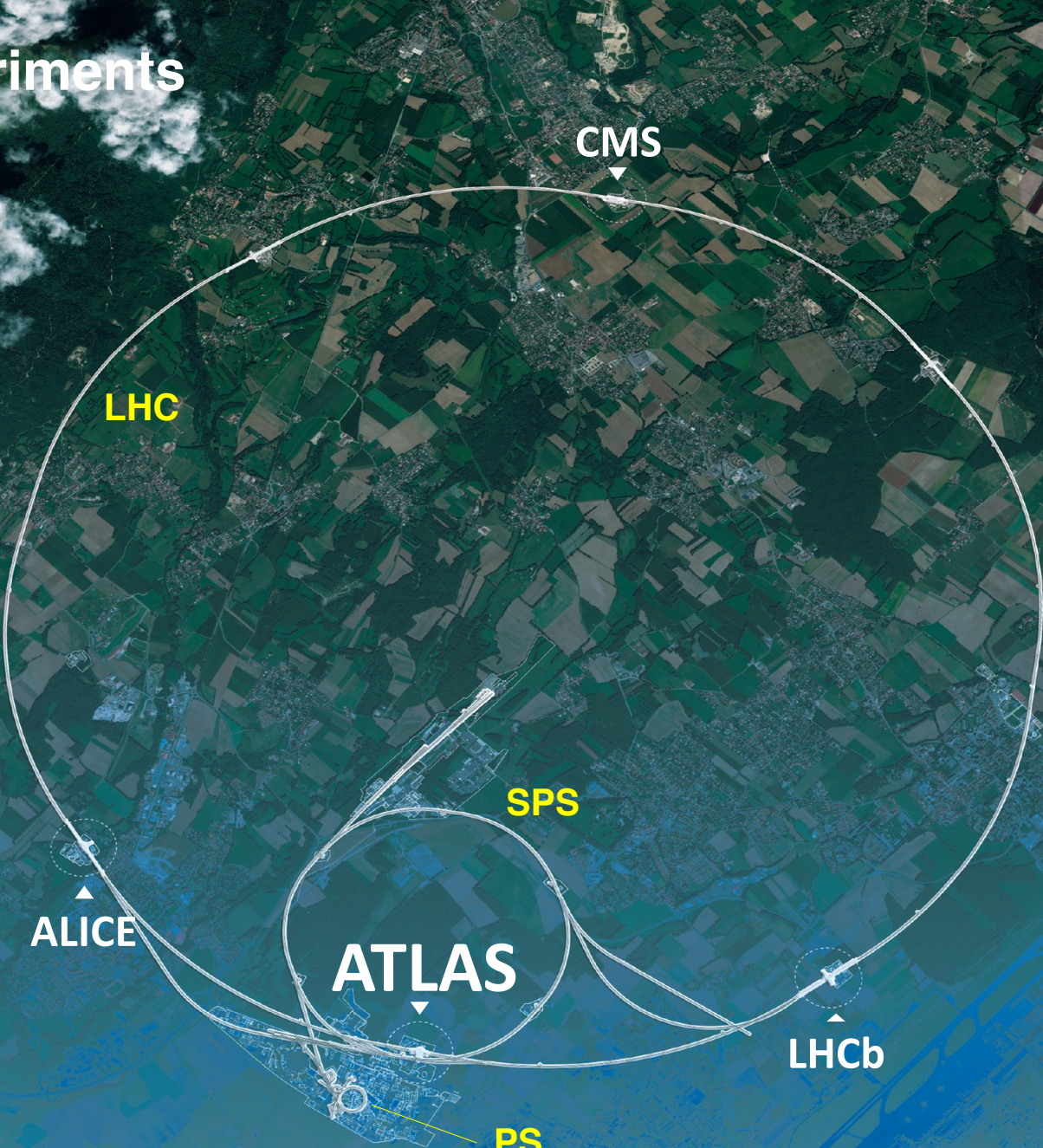
Its constituents fuse and transform into new, sometimes heavy particles with rates depending on the strength of their interaction with the proton and on their mass:

- Light quarks, gluons (“jets”) $\gg$ W, Z $\gg$ top quark $\gg$ Higgs boson
- Heavy particles decay instantaneously to light, stable particles (quarks/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



LHC Experiments

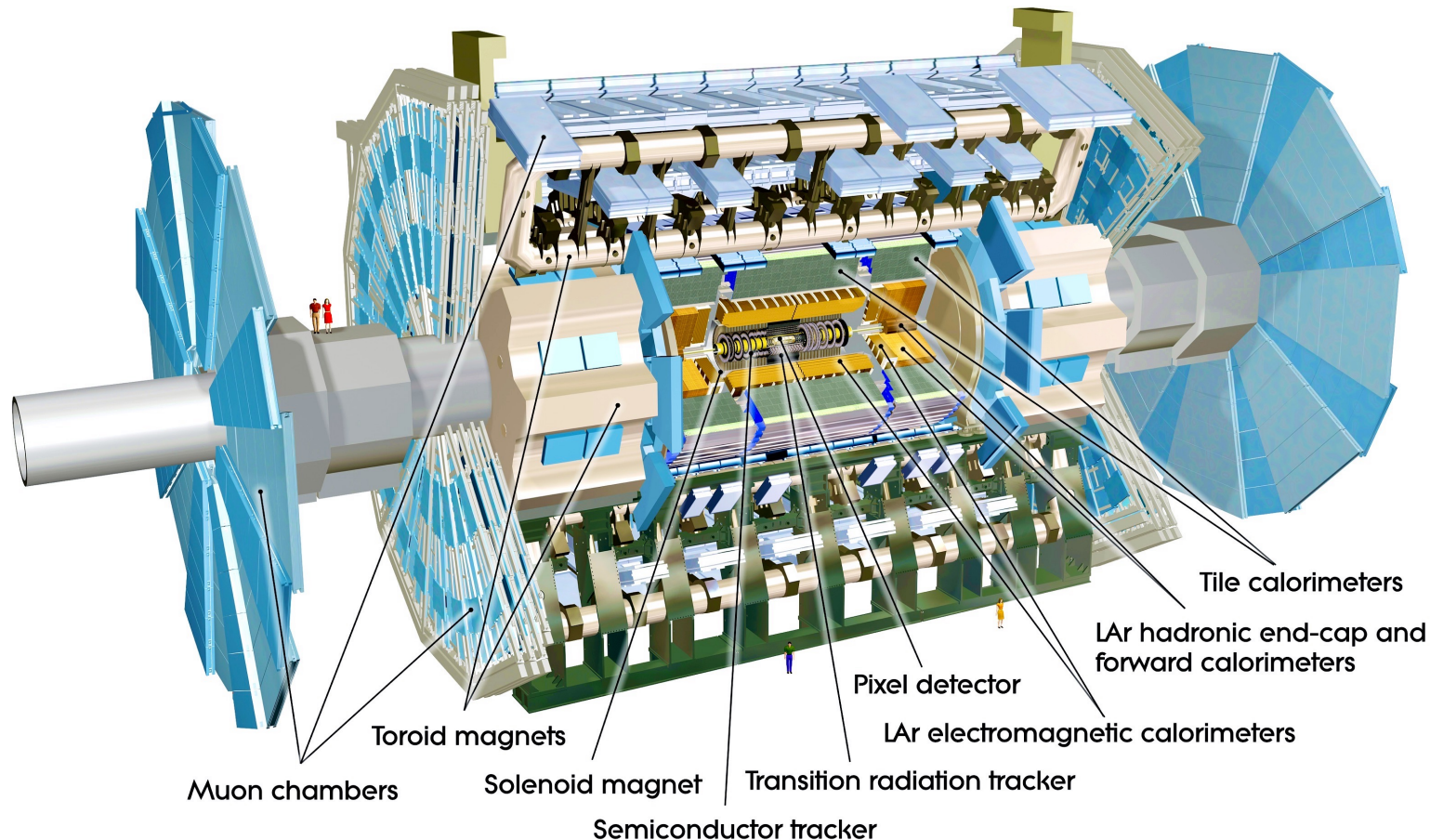
Areal view





ATLAS Experiment

The ATLAS Detector



25 m diameter, 44 m long, 7000 tons weight

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 azimuth).
Complemented by gaseous transition
radiation tracker at large radius

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 10,000
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



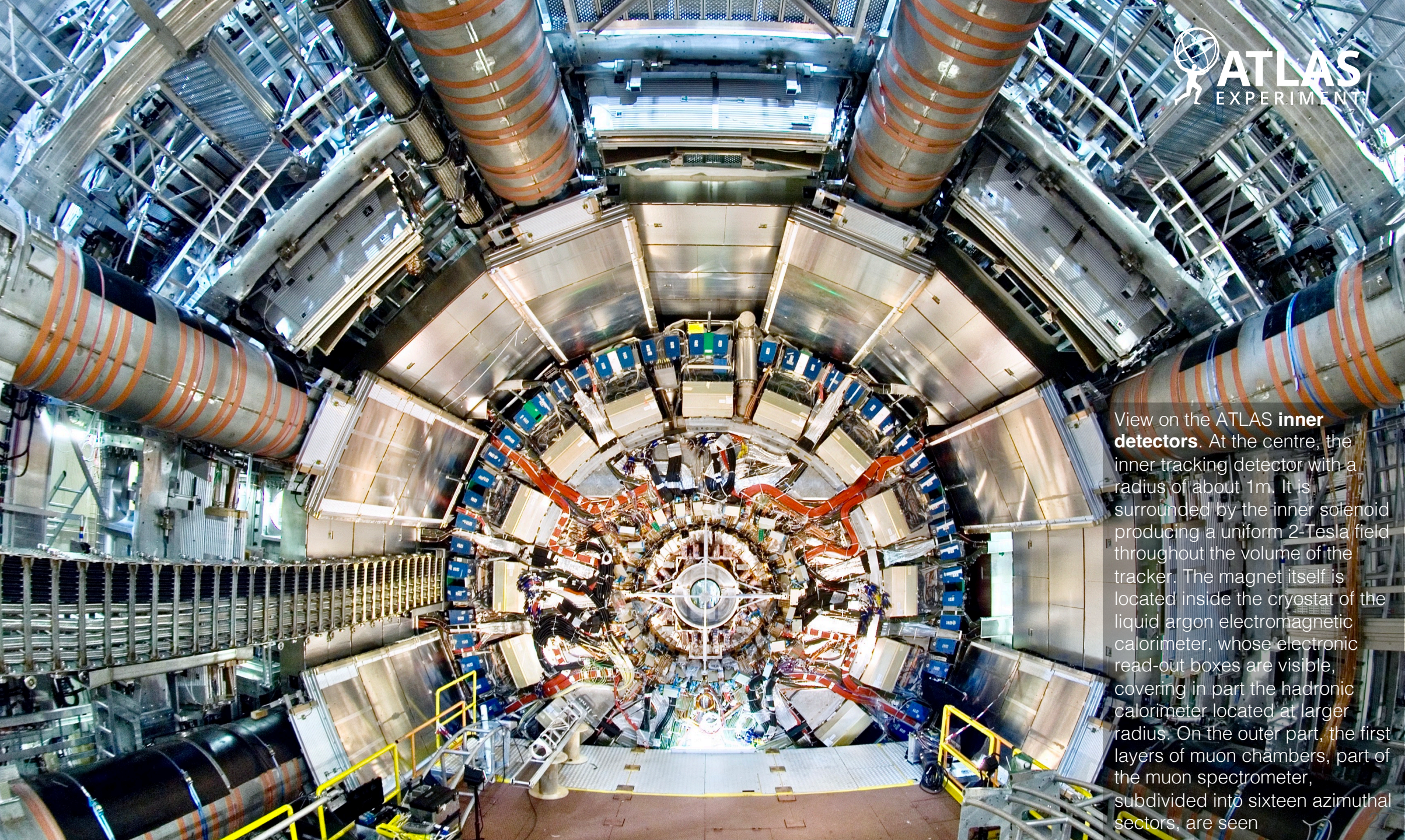
Dynamic evolution (17 PhD students)

Broad and crucial contributions to ATLAS detector, operation, and data analysis



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

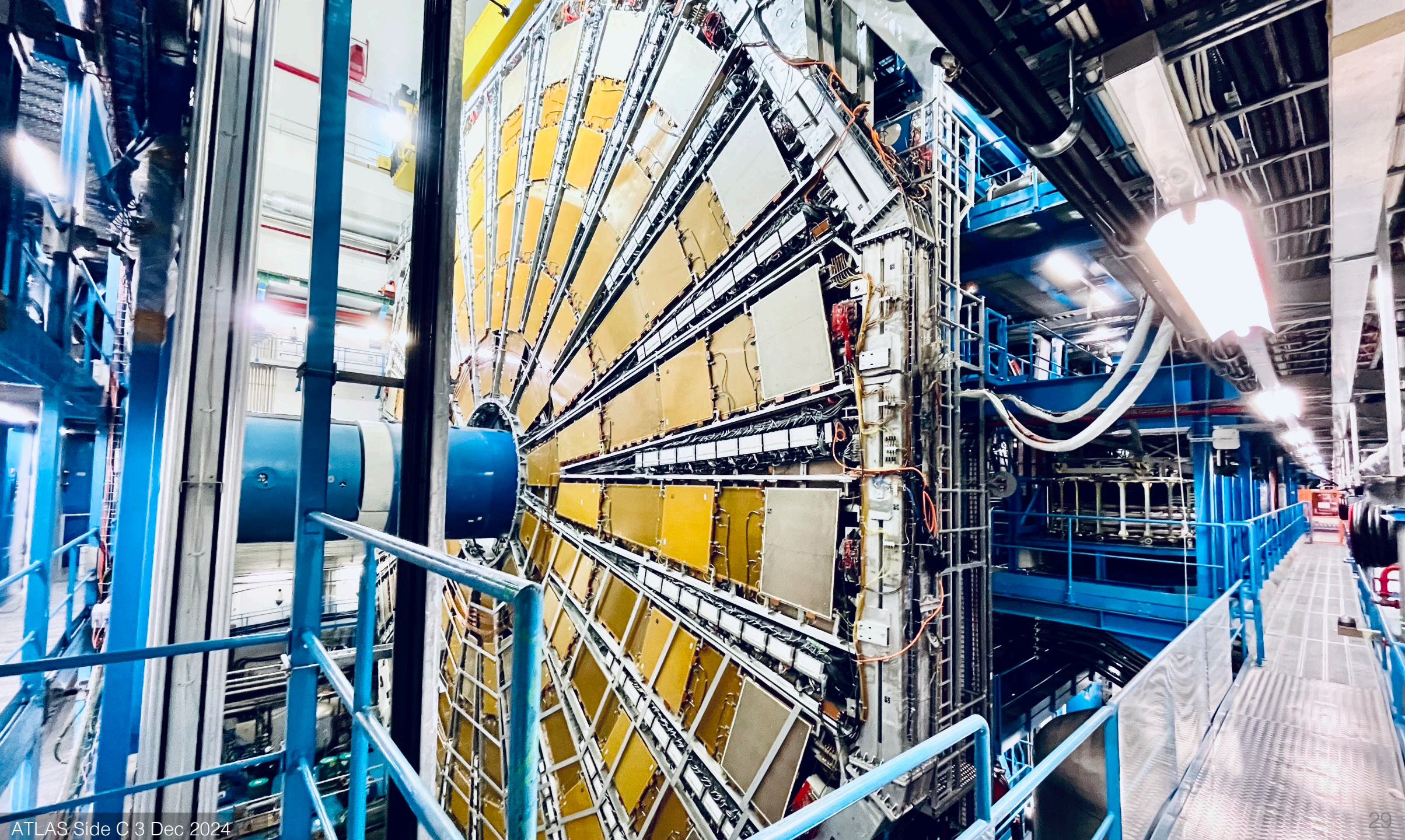
Links: [ATLAS public home page](#), [Physics results](#), [Interactive ATLAS world map](#), [Static world maps](#), [List of ATLAS institutes](#)



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



ATLAS endcap in open position during year-end technical stop 2023/2024



Physics results

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

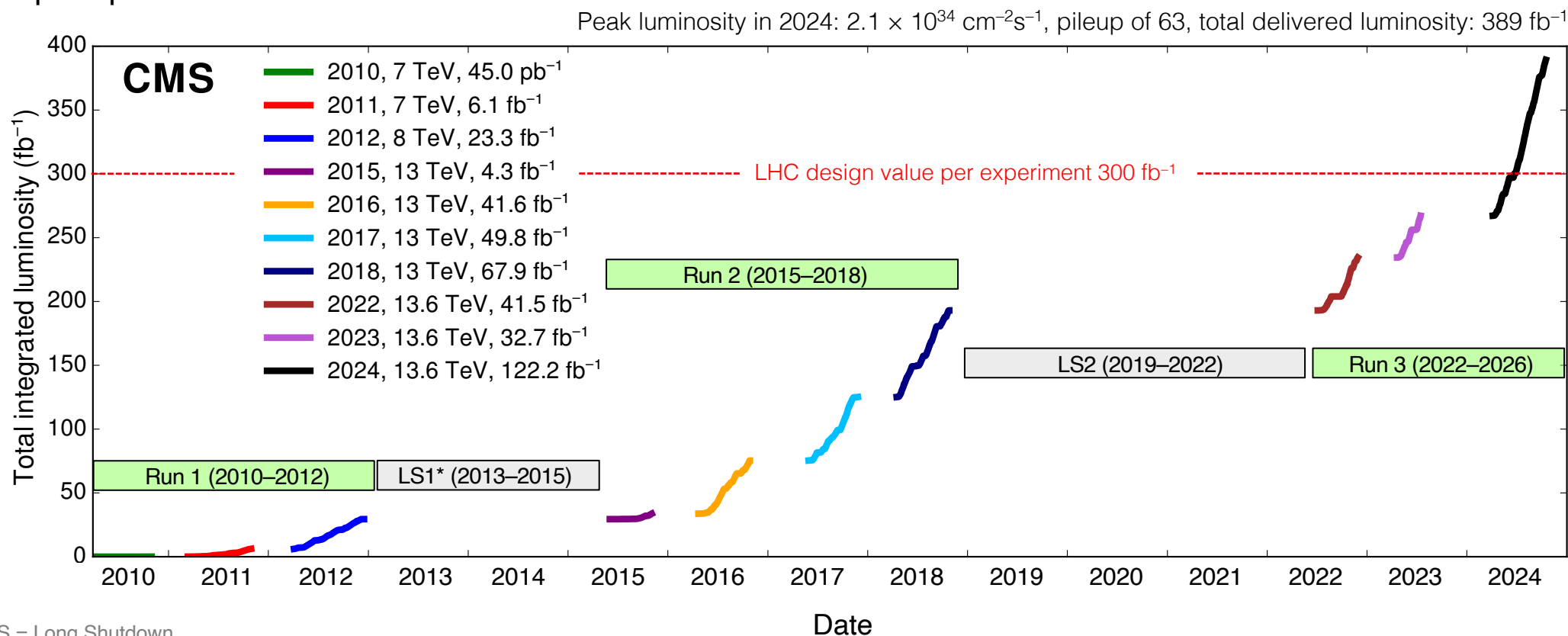


Observation quantum entanglement in top-pair production
[Nature](#), 633, pages 542 (2024), [CERN press release](#)

Physics results

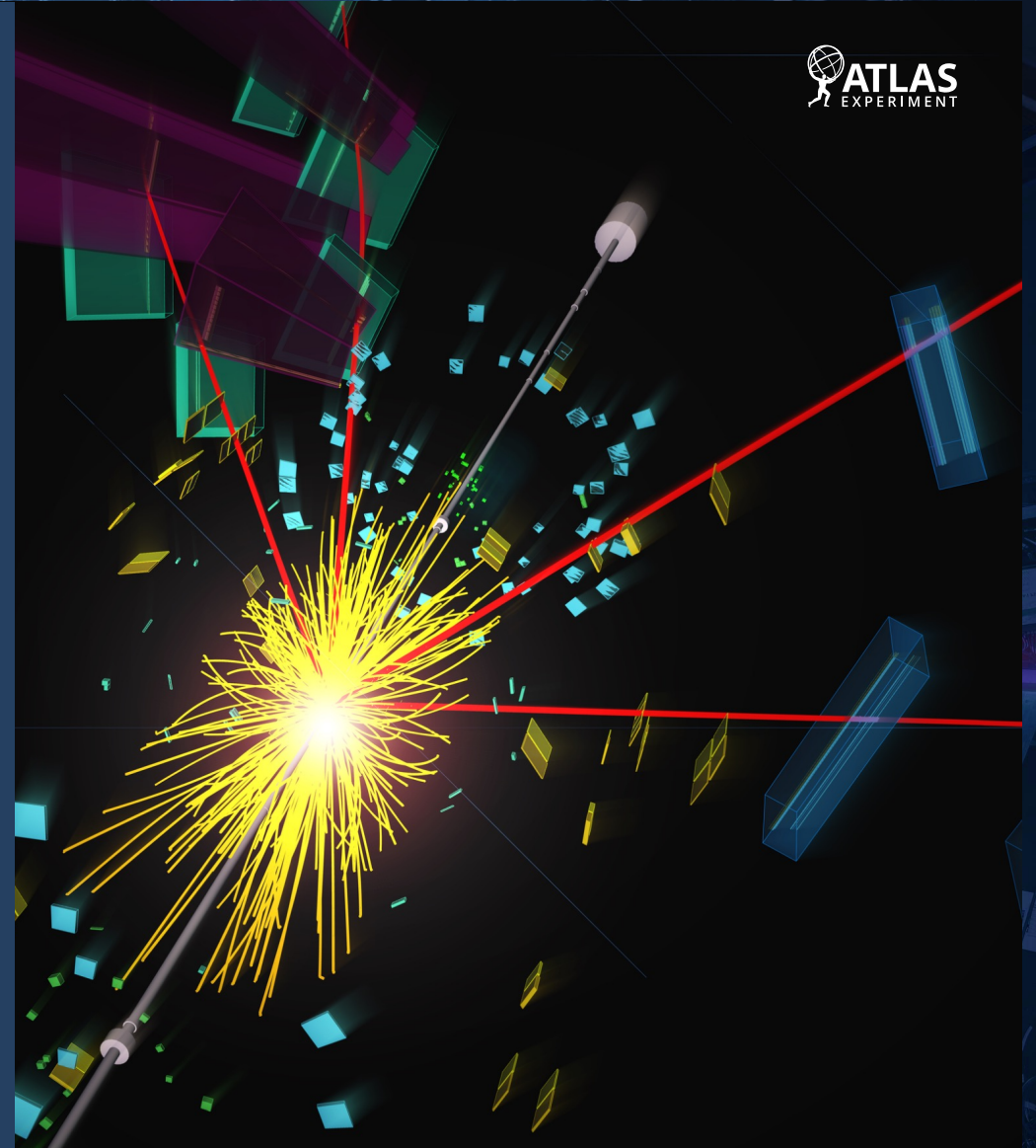
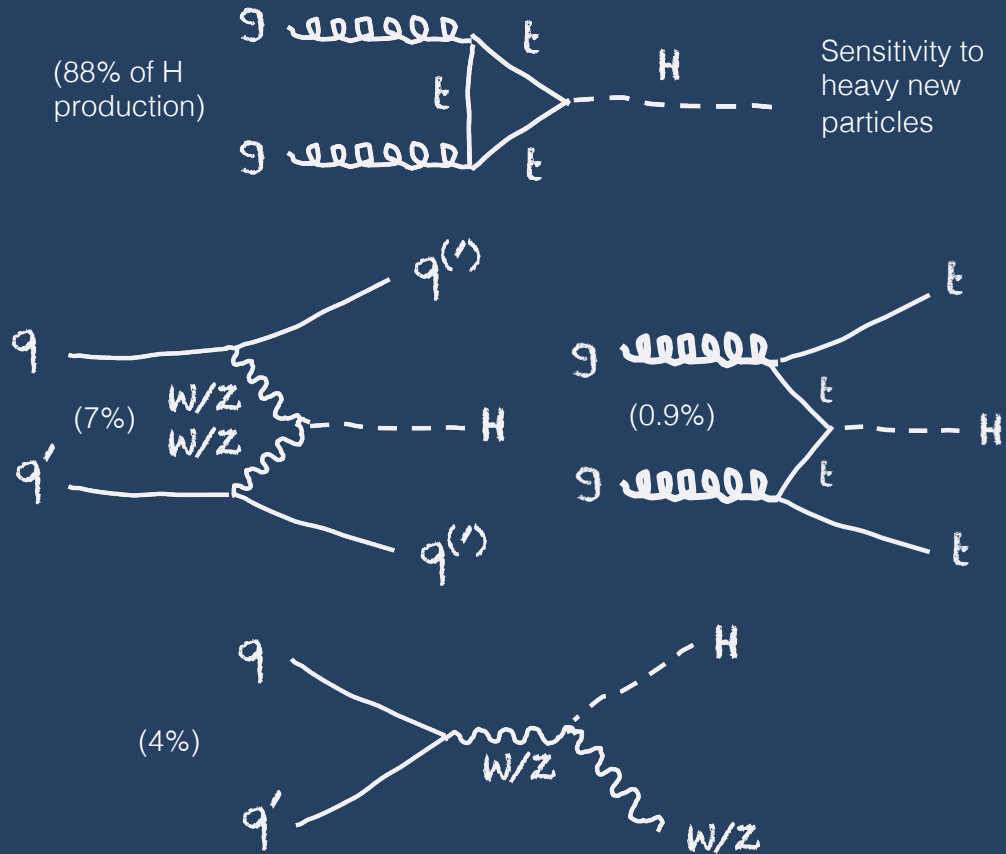
High-energy proton and heavy-ion collisions enable an exceptionally broad physics program covering (almost) the full breadth of particle physics. ATLAS has released more than 1350 papers

Superb performance of the LHC



Higgs boson production at the LHC

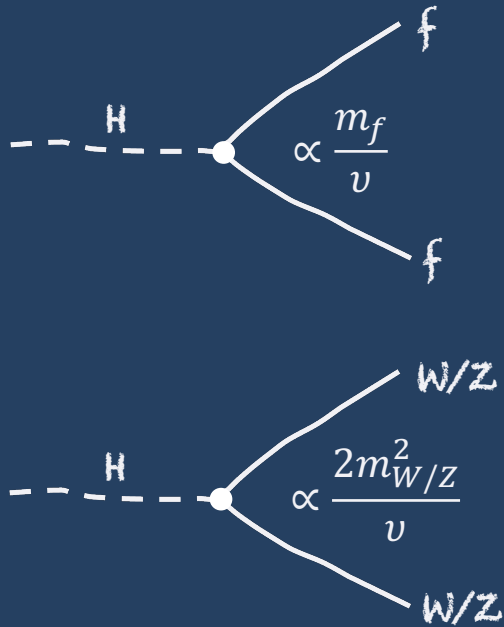
About 1 Higgs boson per second is produced in ATLAS at the LHC (about 20M total by today)



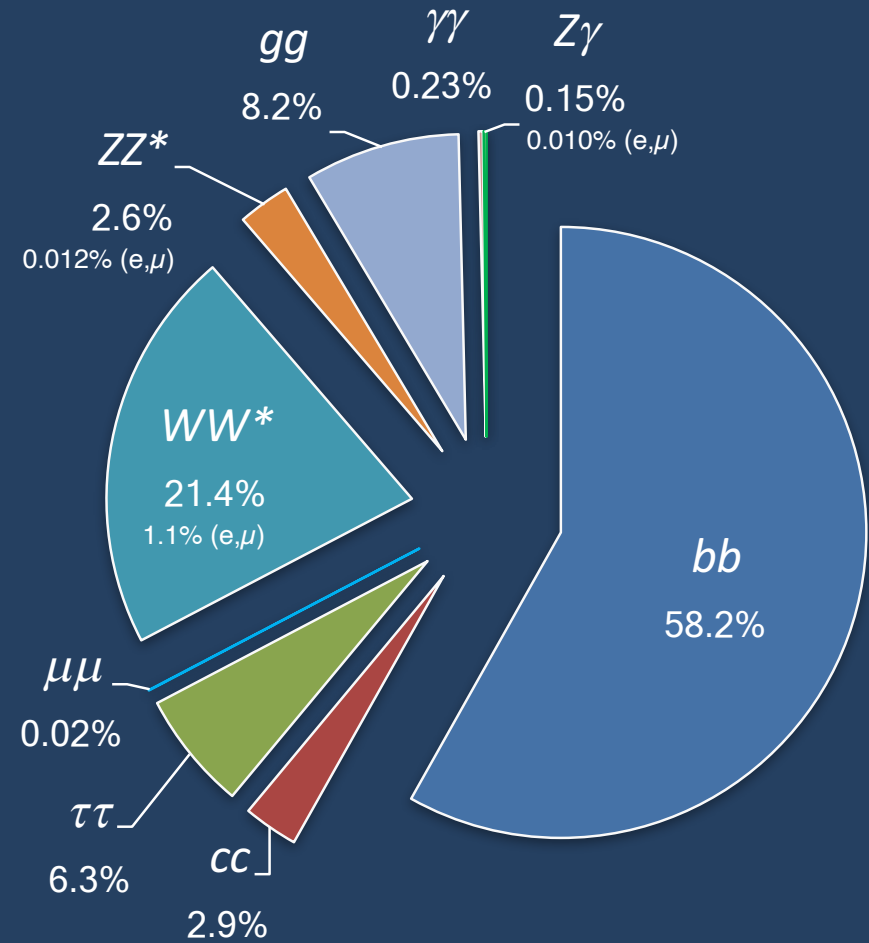
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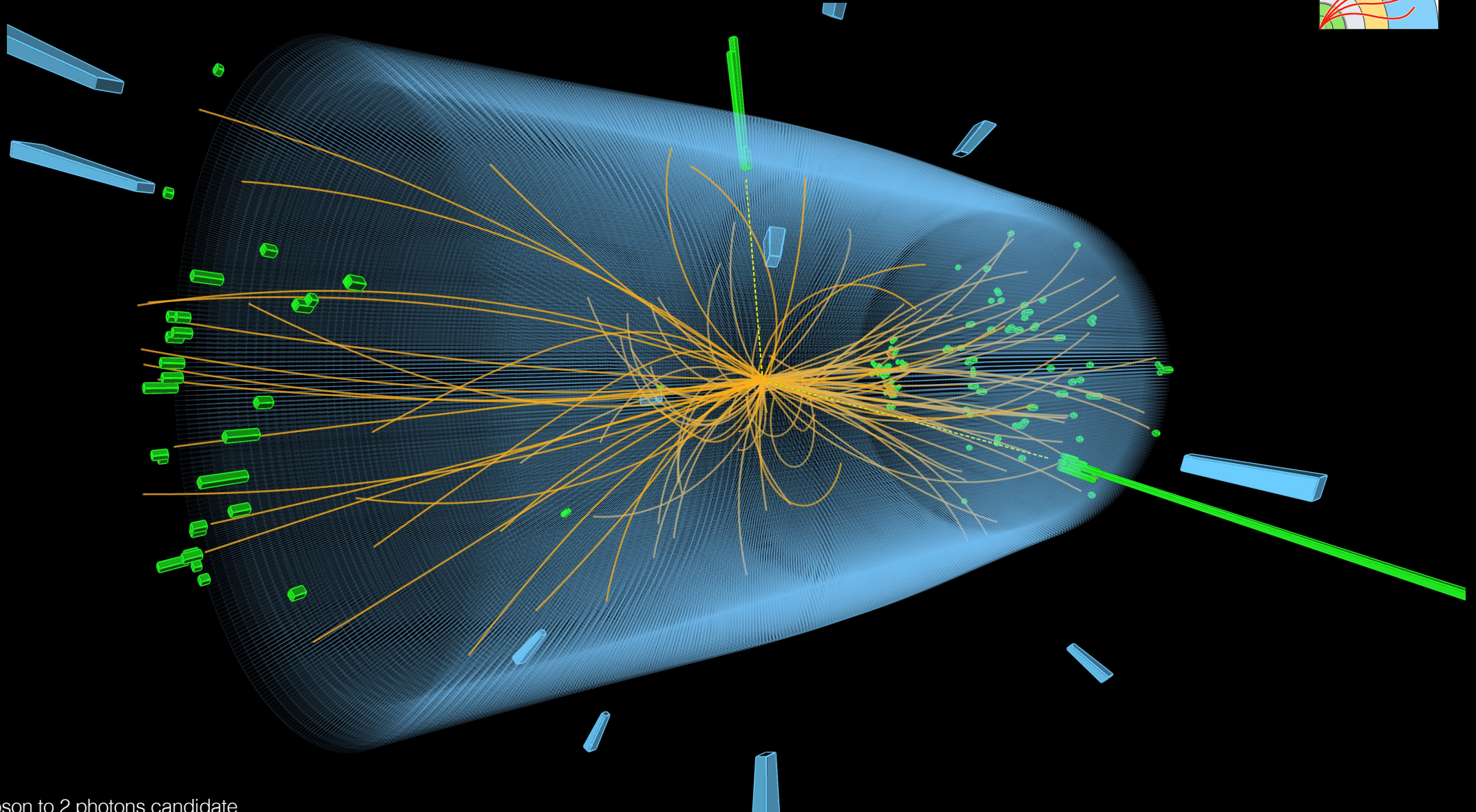
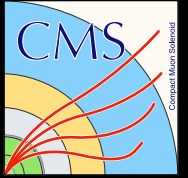
It decays within 10^{-22} s



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

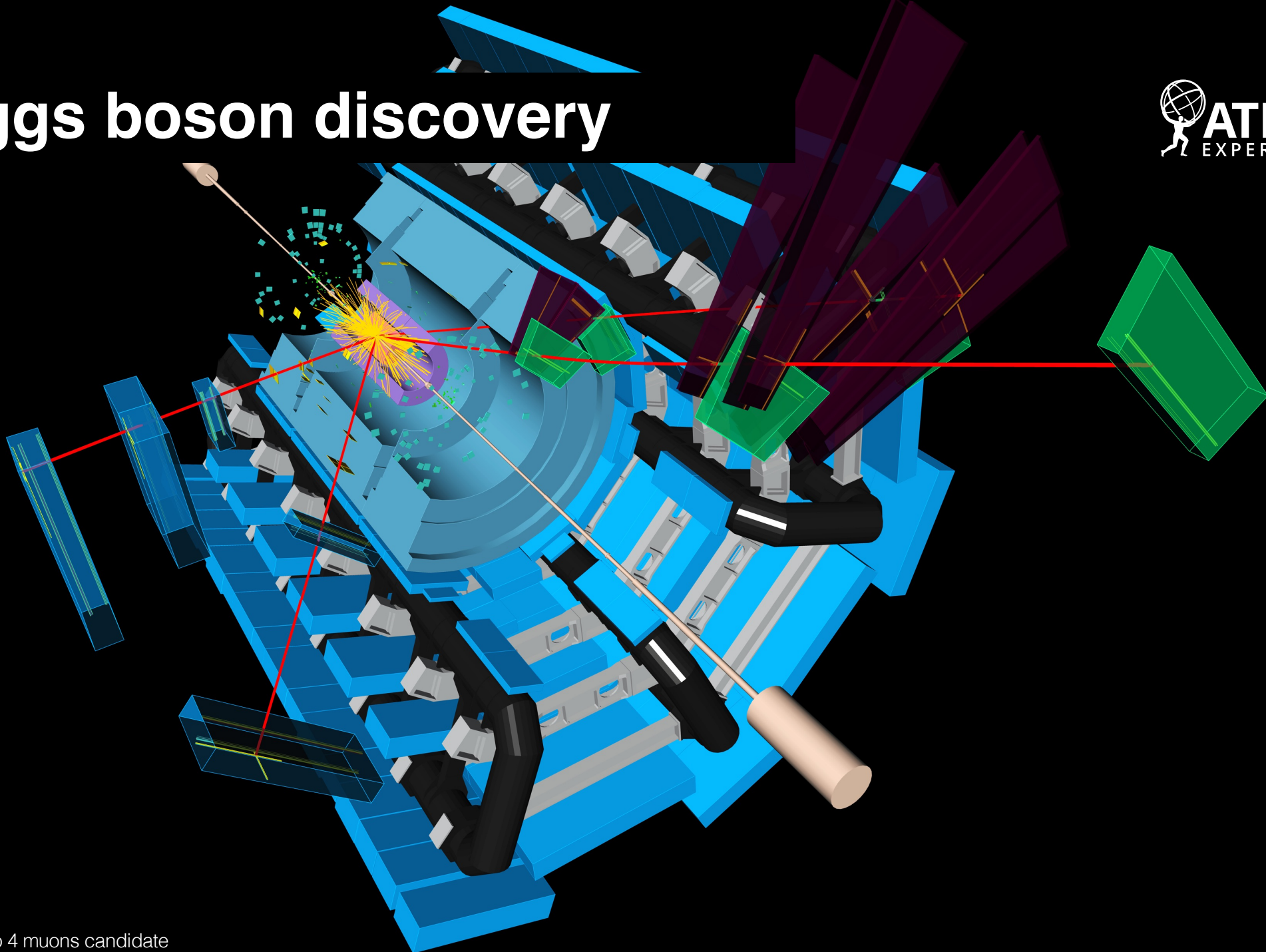


Higgs boson discovery



A Higgs boson to 2 photons candidate

Higgs boson discovery

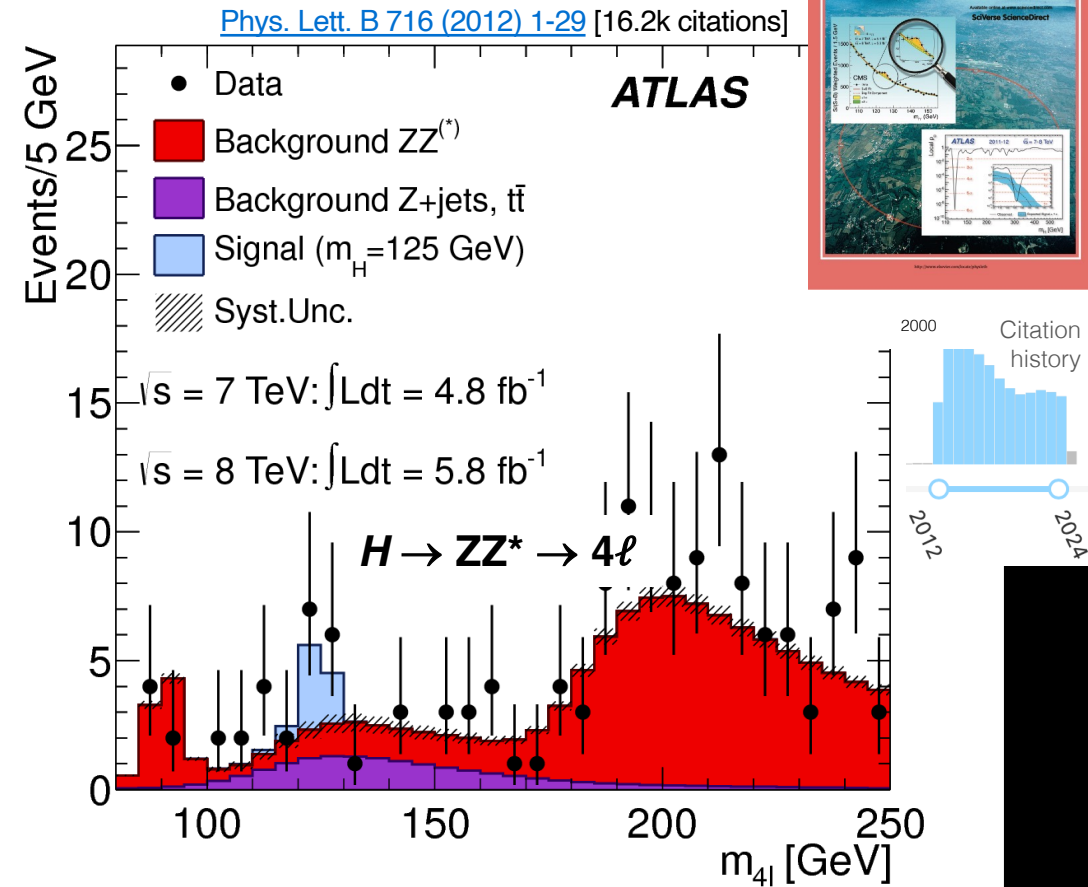
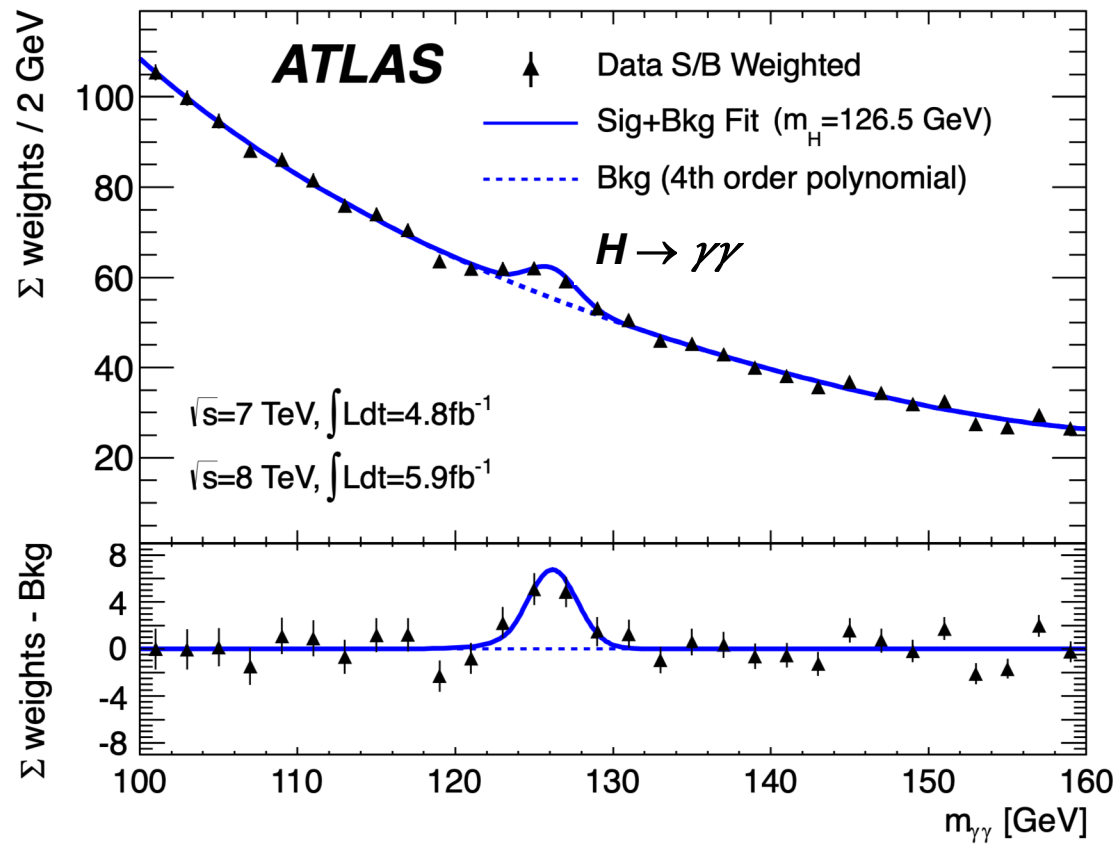


A Higgs boson to 4 muons candidate

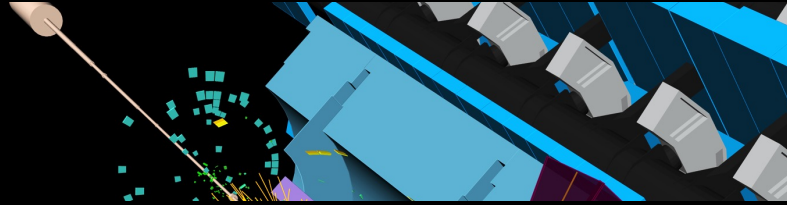
Higgs boson discovery



2012



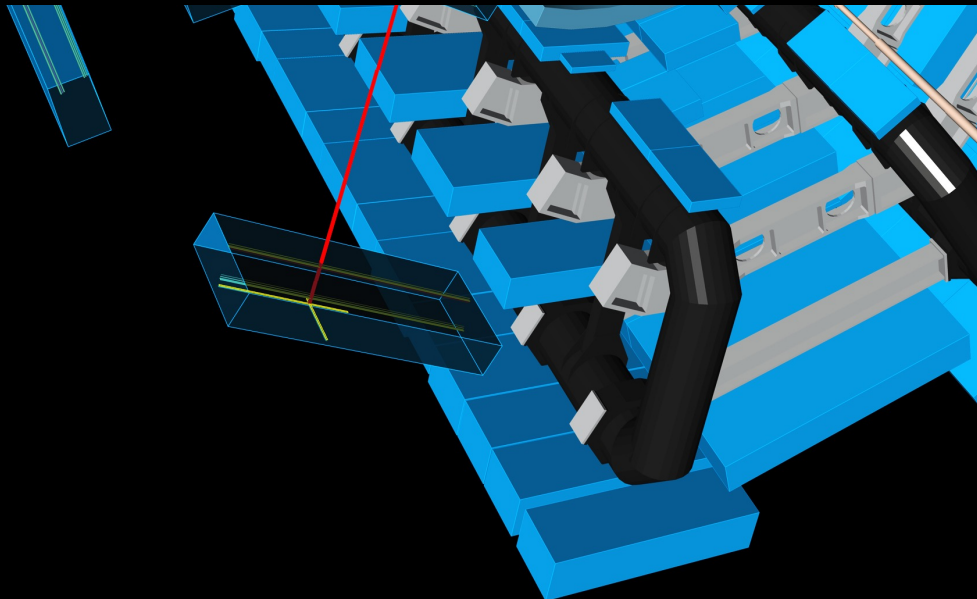
The Higgs boson



The LHC's magnum opus

But is it really the Higgs boson we were looking for?

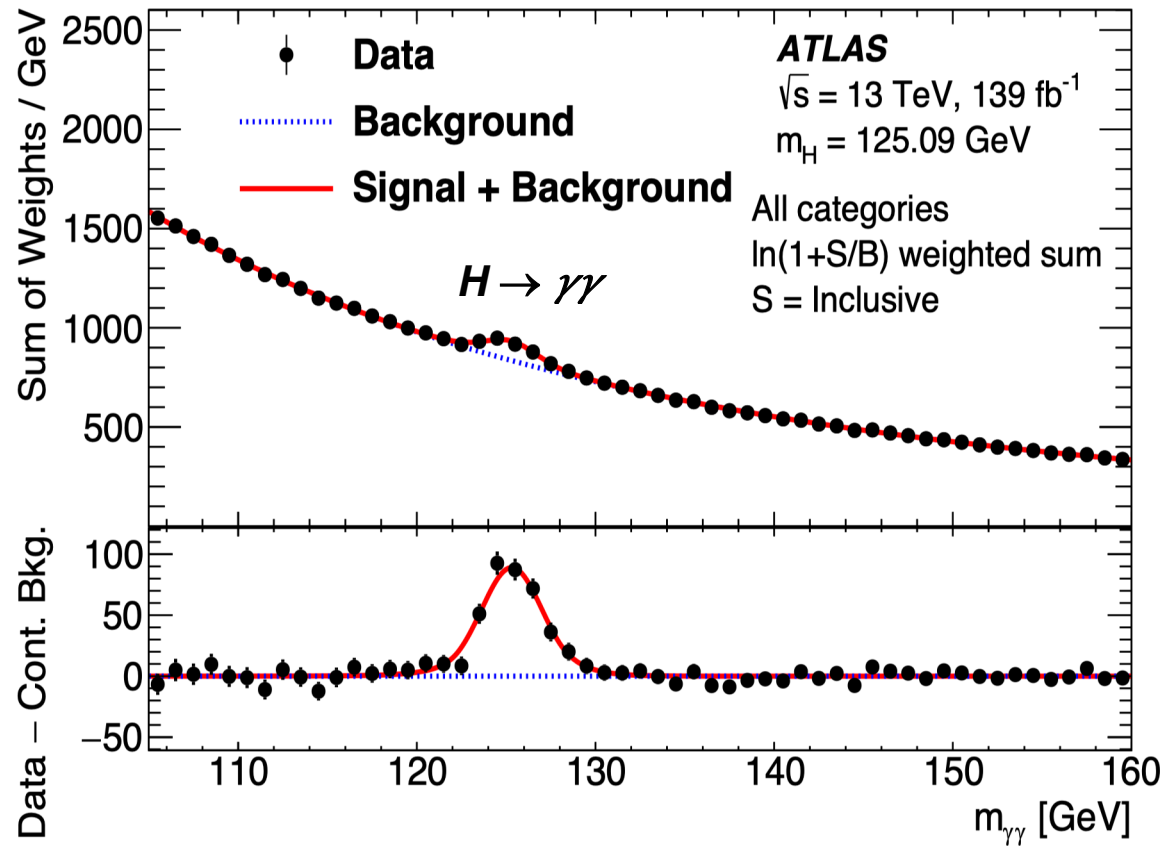
Spin-parity of 0^+ was quickly confirmed using angular analyses. Deeper studies required much more data



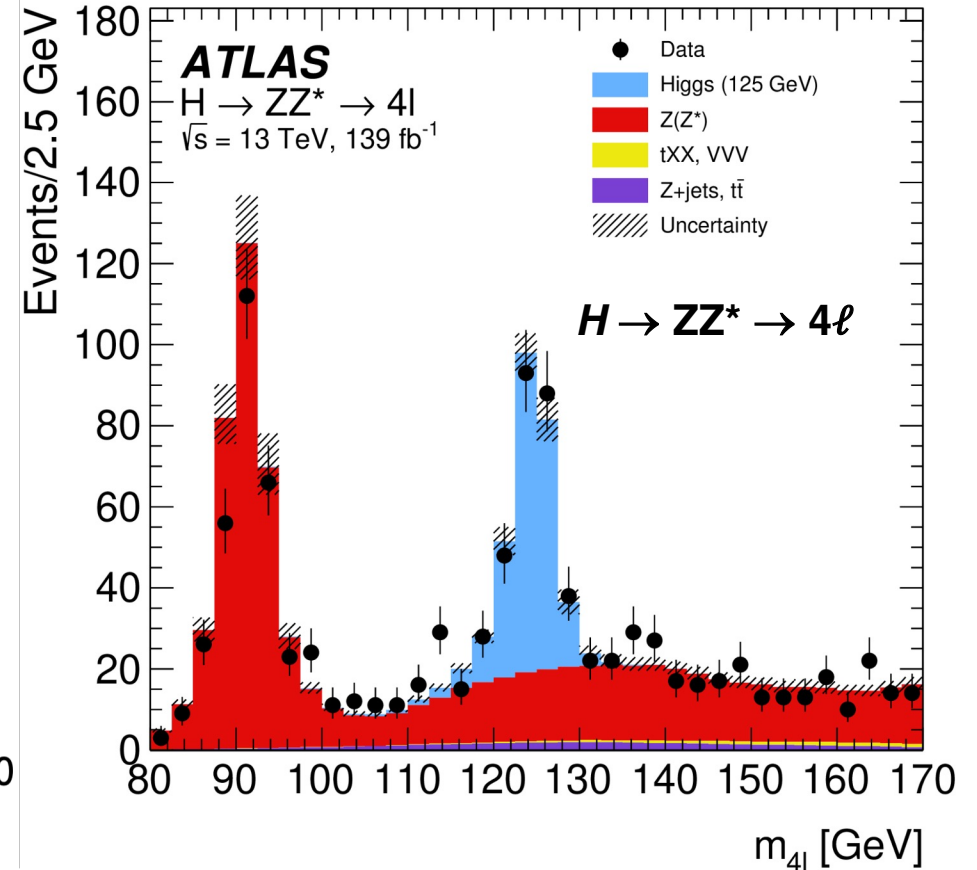
The Higgs boson — At 10

2020

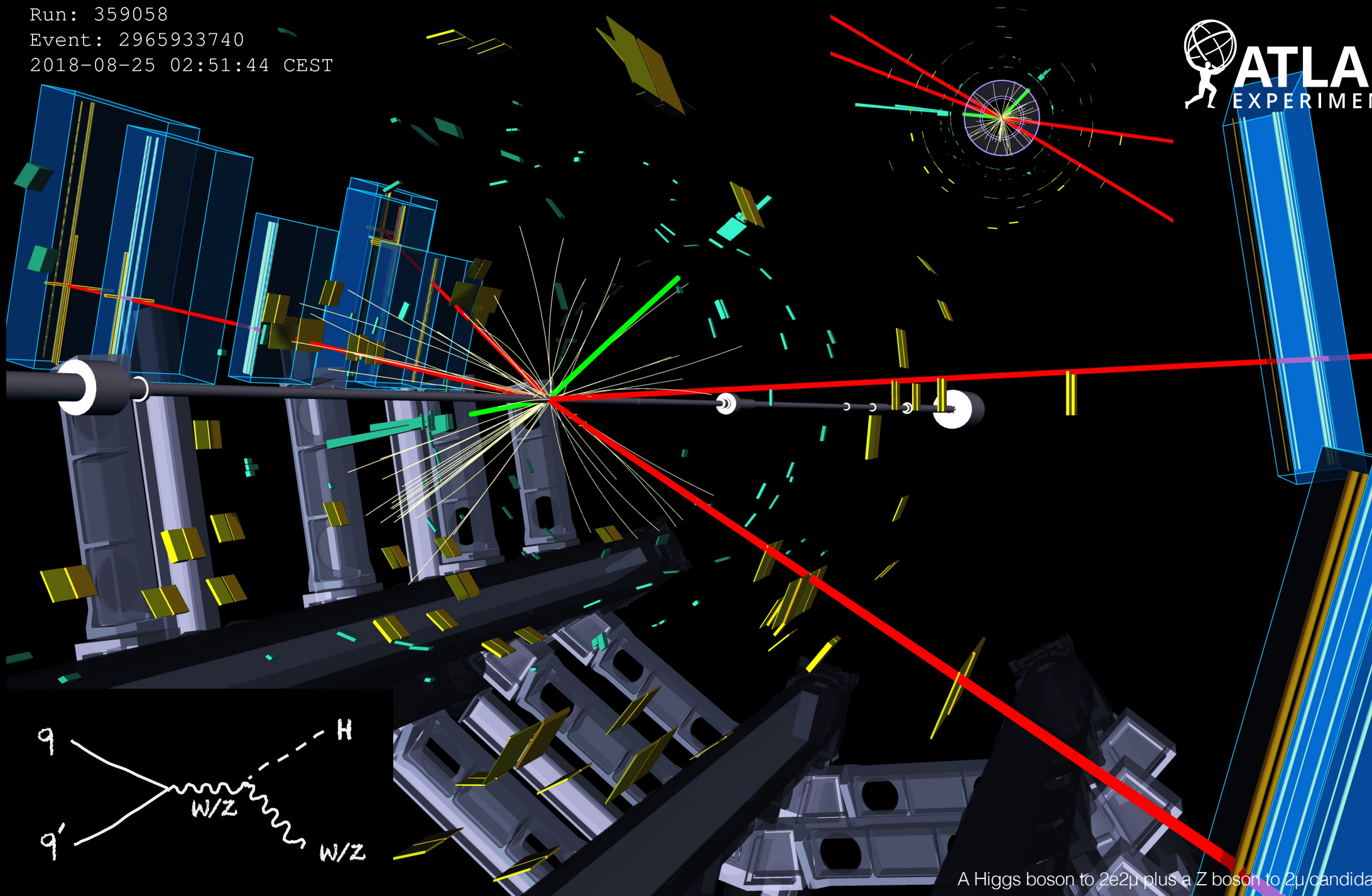
[JHEP 07 \(2023\) 088](#)



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



Run: 359058
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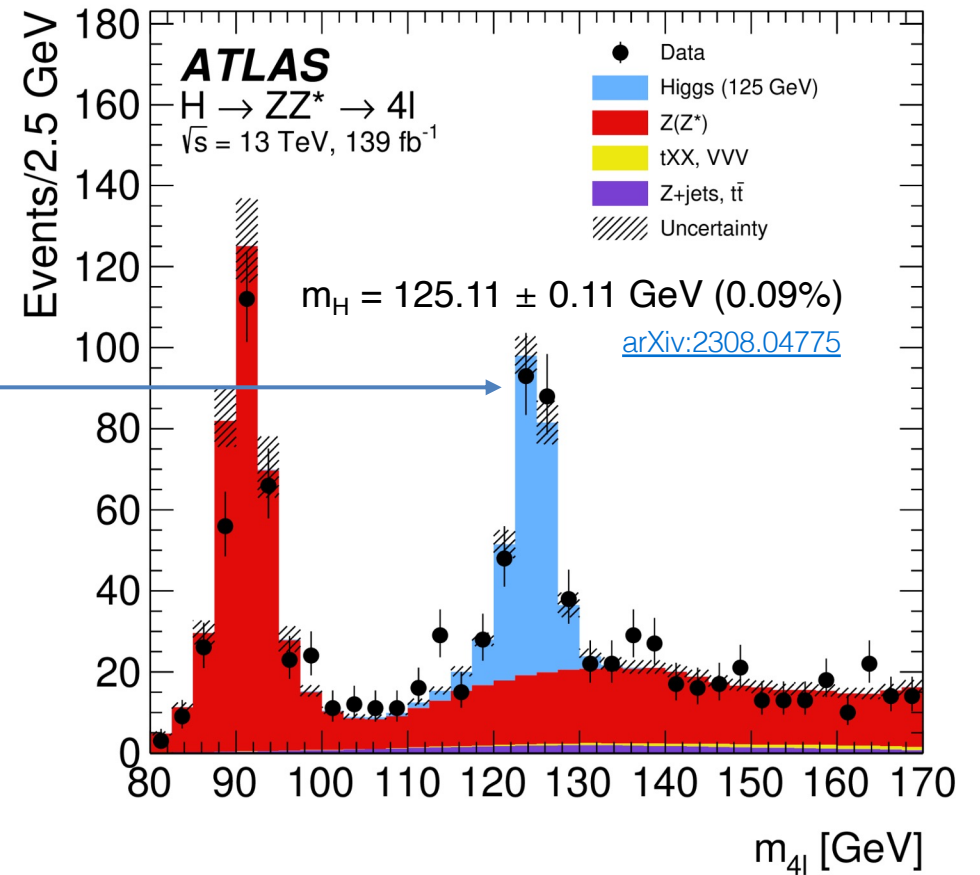
A Higgs boson to $2e2\mu$ plus a Z boson to 2μ /candidate event

Higgs boson mass

The Higgs mass is peculiar

2020

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

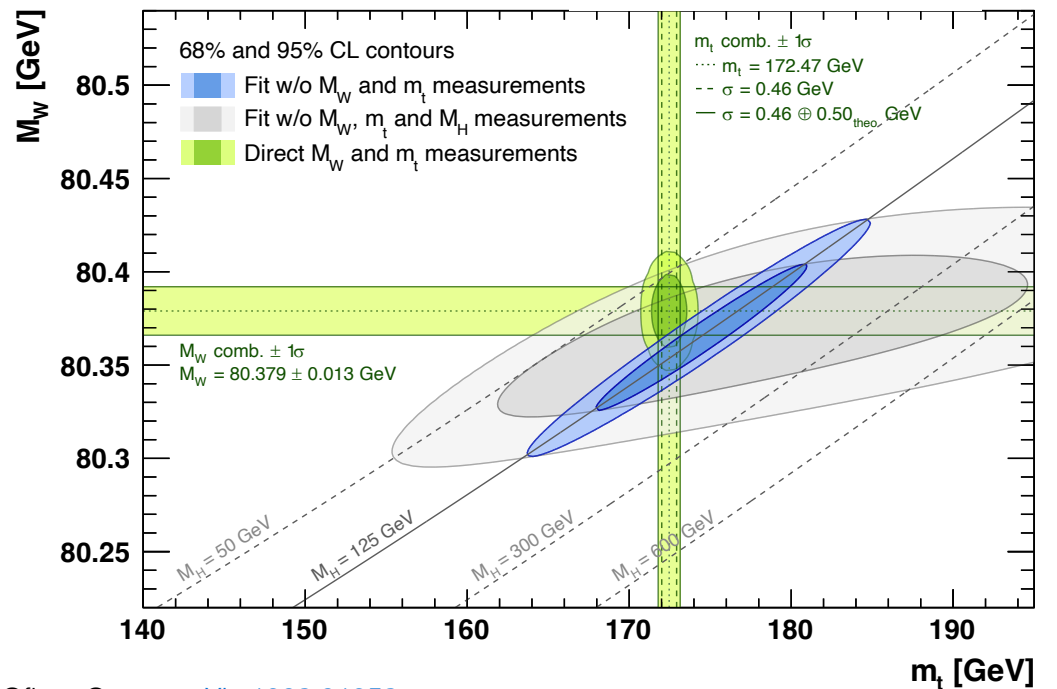
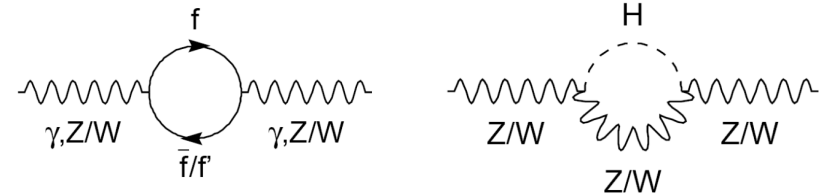


Higgs boson mass

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)

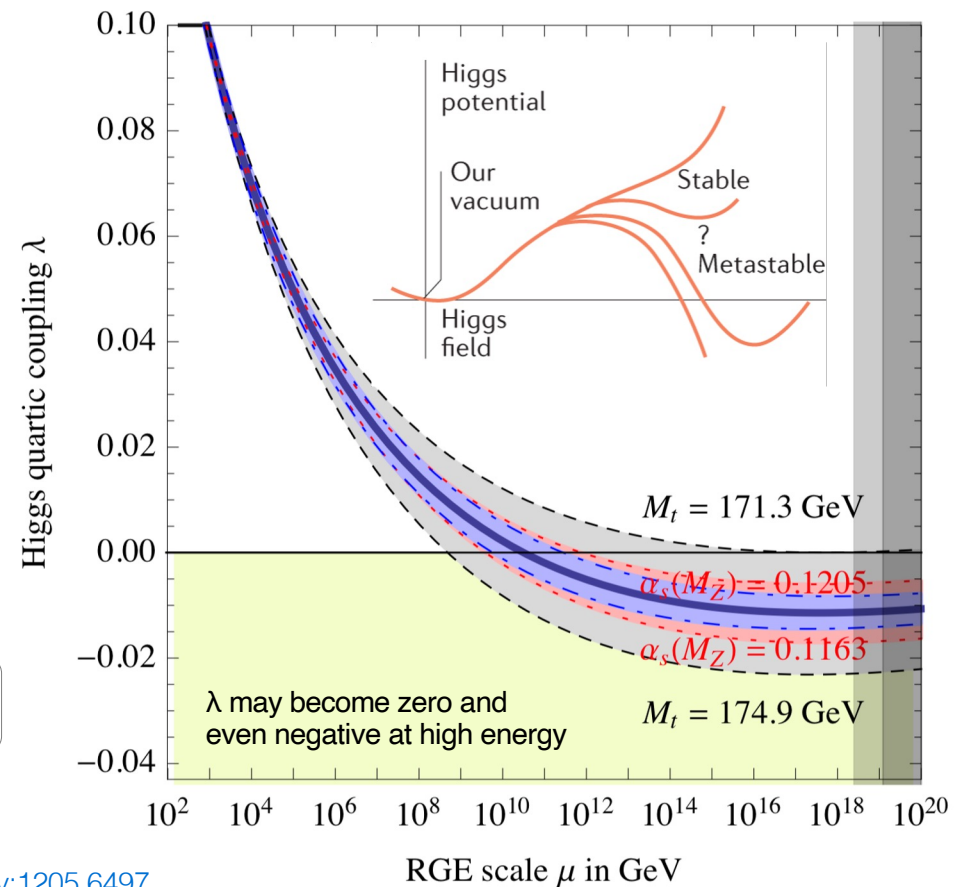
Higgs boson mass

The Higgs mass is peculiar

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

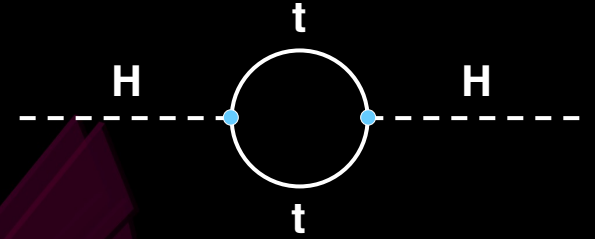
$$V(\phi) = -\mu^2|\phi|^2 + \lambda|\phi|^4$$

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 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

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
$\gamma\gamma$	0.2 %	✓	✓	✓	✓	✓
ZZ	2.6%	✓	✓	✓	✓	✓
WW	21%	✓	✓	✓	✓	✓
$\tau\tau$	6.3 %	✓	✓	✓	✓	✓
bb	58%	✓	✓	✓	✓	✓
$Z\gamma$ (& $\gamma\gamma^*$)	0.2 %	✓	✓	✓	✓	✓
$\mu\mu$	0.02 %	✓	✓	✓	✓	✓

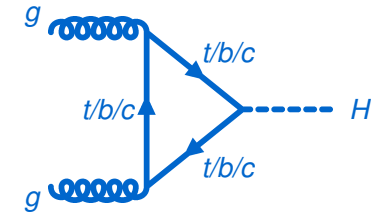
In grey: evidence for decays, but not observed yet

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...)

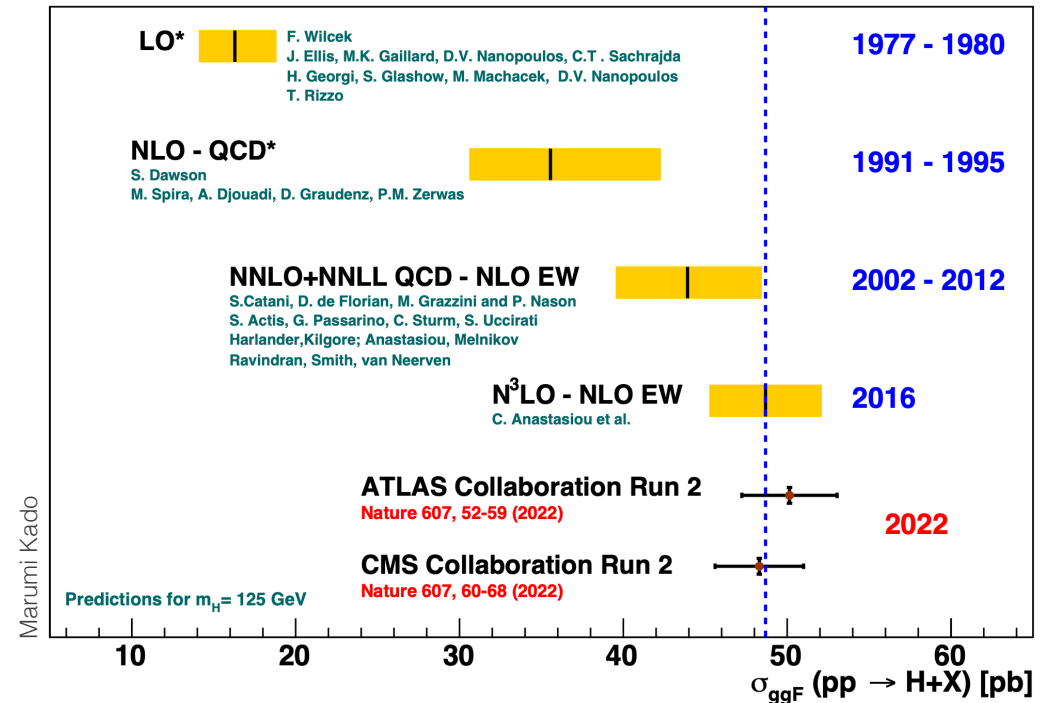
The interpretability of our results relies on our ability to compute accurate and precise predictions

Calculations of Higgs boson production via gluon fusion versus time



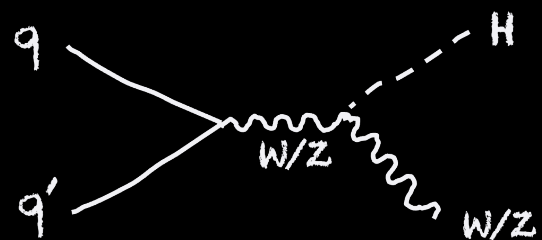
$\sqrt{s} = 13 \text{ TeV}$

* From iHixs



Marumi Kado

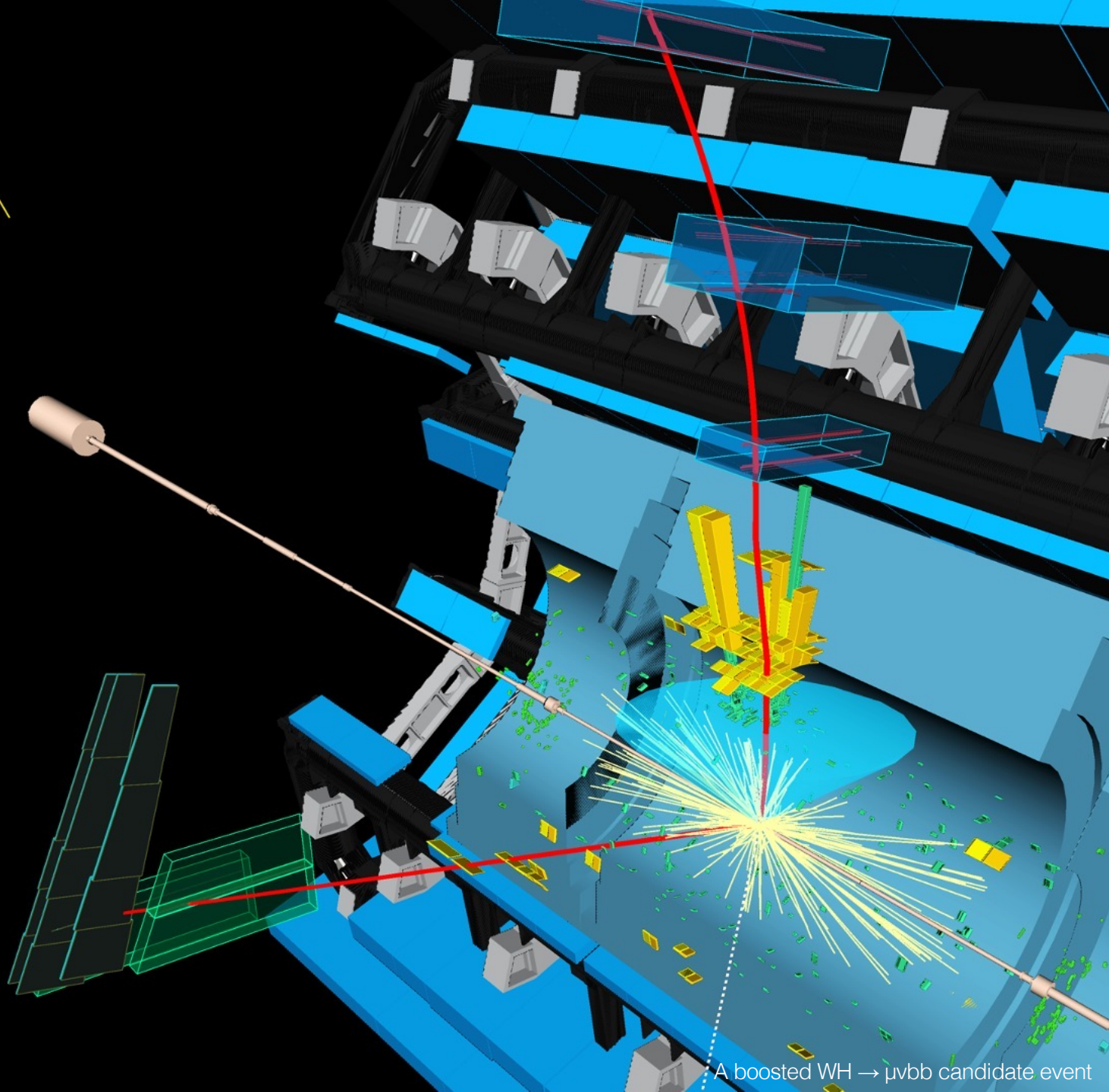
$H \rightarrow bb$



Run: 338349

Event: 616525246

2017-10-16 20:24:46 CEST



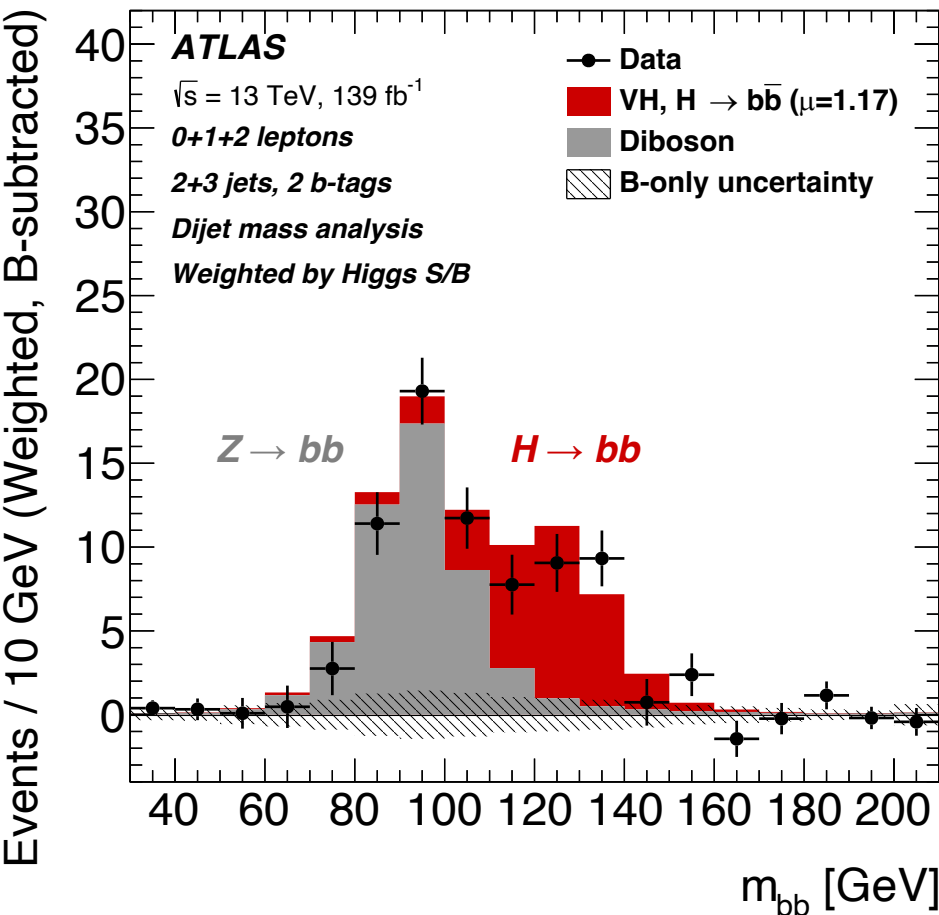
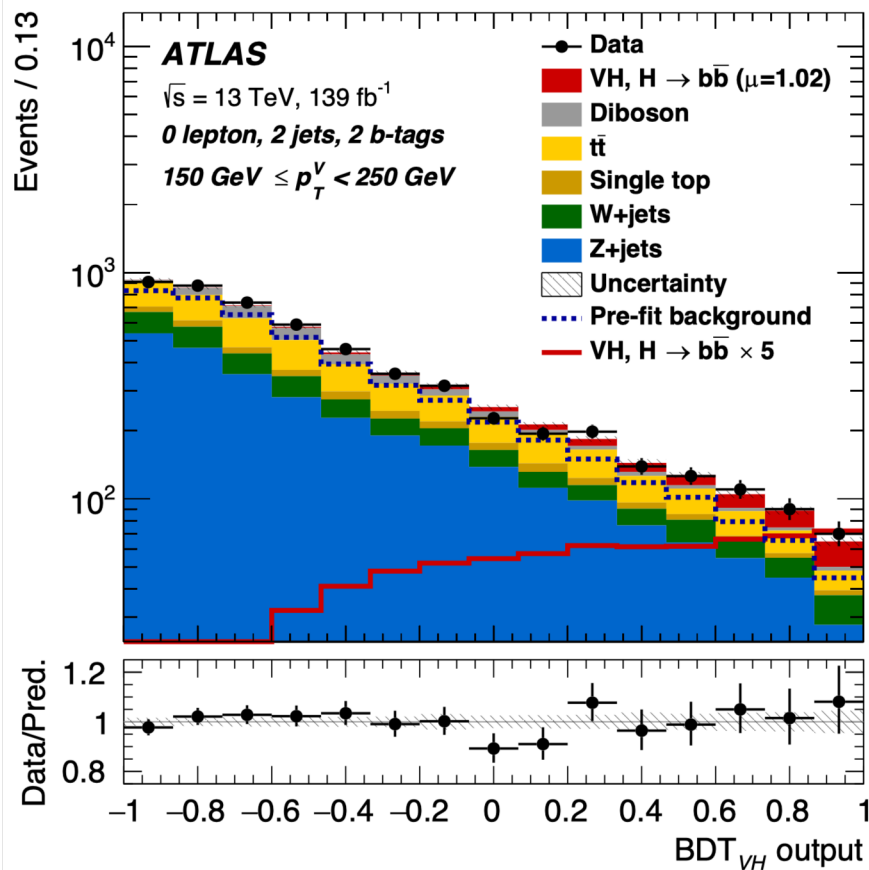
A boosted $WH \rightarrow \mu b b$ candidate event

$H \rightarrow bb$

Measurement of $H \rightarrow bb$ via associated production $pp \rightarrow W/Z + H$ and leptonic W/Z decays

Highly complex analyses requiring excellent control of background processes and signal purification with machine learning

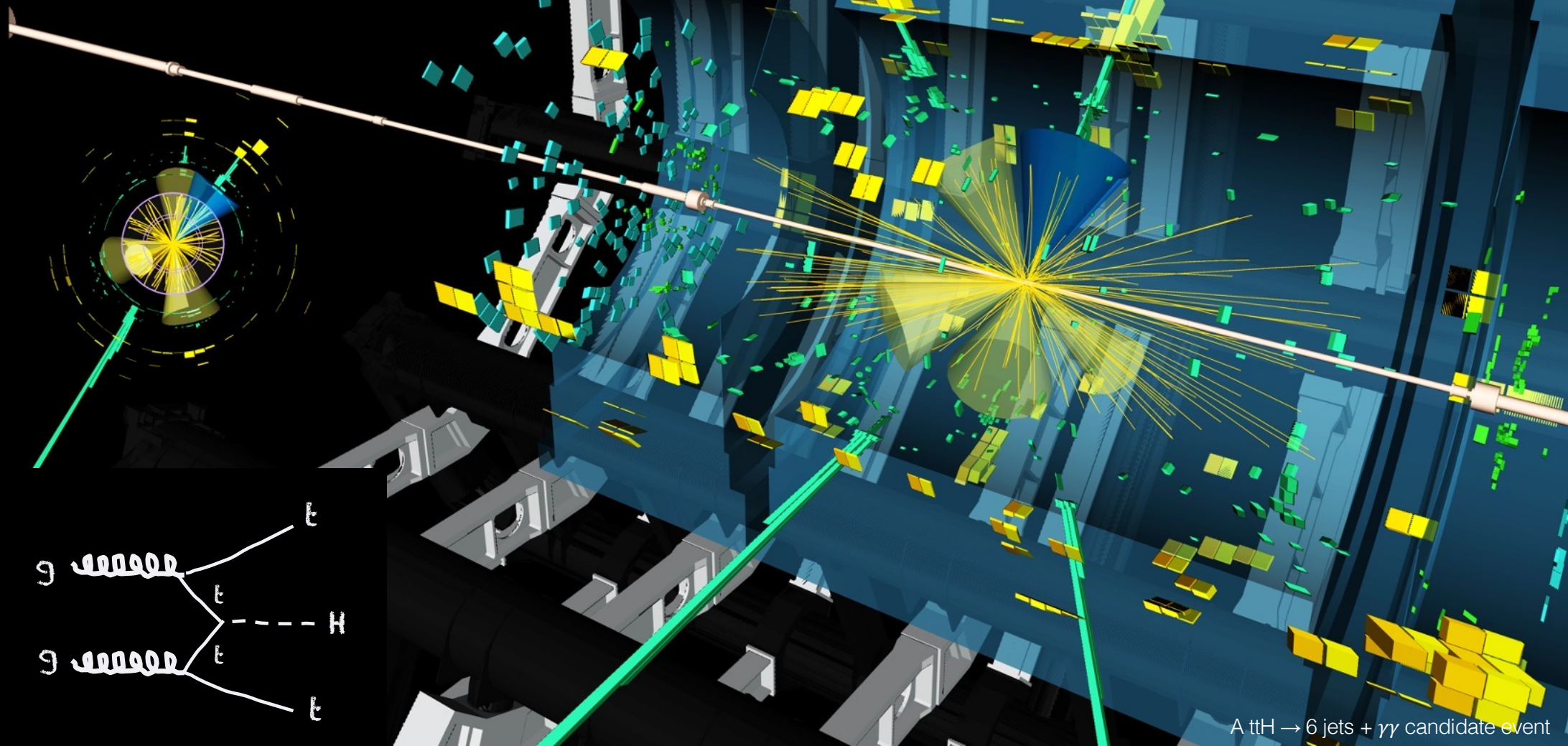
[arXiv:2007.02873](https://arxiv.org/abs/2007.02873)



ttH



Run: 303079
Event: 197351611
2016-07-01 05:01:26 CEST

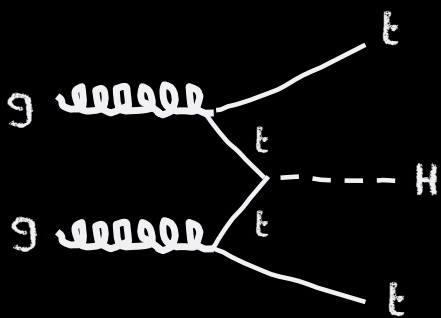
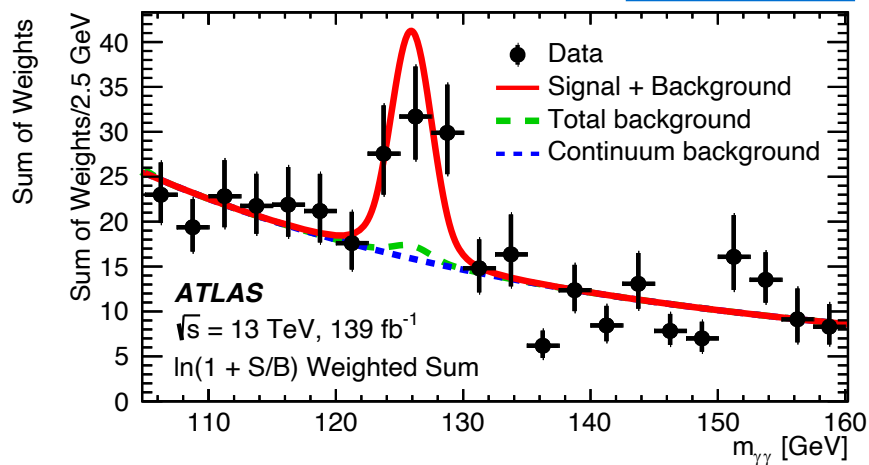


A $ttH \rightarrow 6 \text{ jets} + \gamma\gamma$ candidate event

$t\bar{t}H$

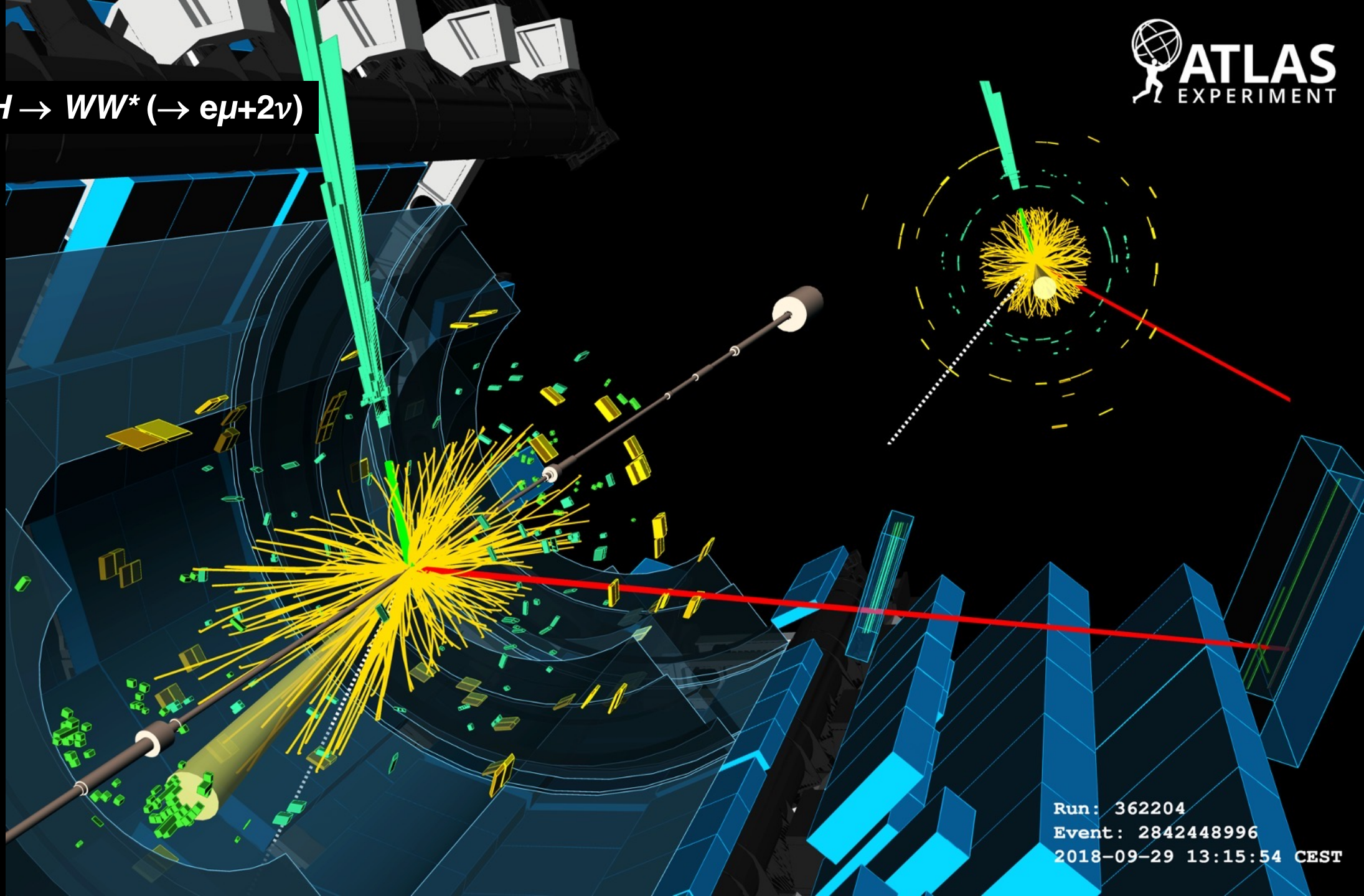
$t\bar{t}H$ production features rich events,
 $H \rightarrow \gamma\gamma$ channel most powerful

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



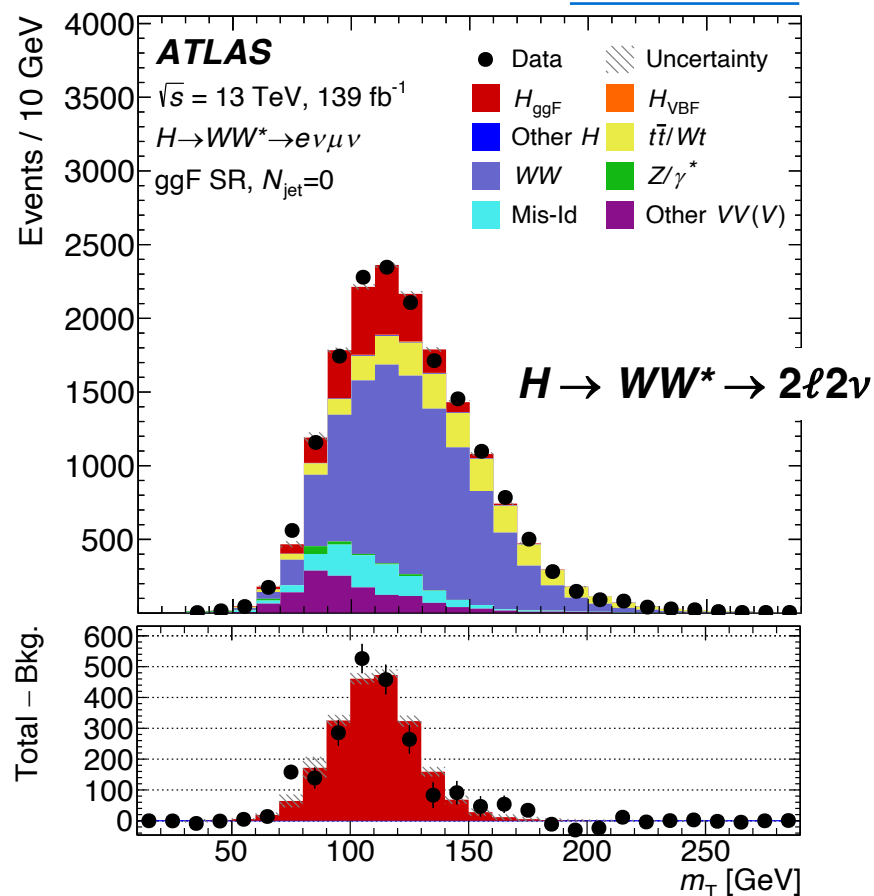
A $t\bar{t}H \rightarrow 6 \text{ jets} + \gamma\gamma$ candidate event

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

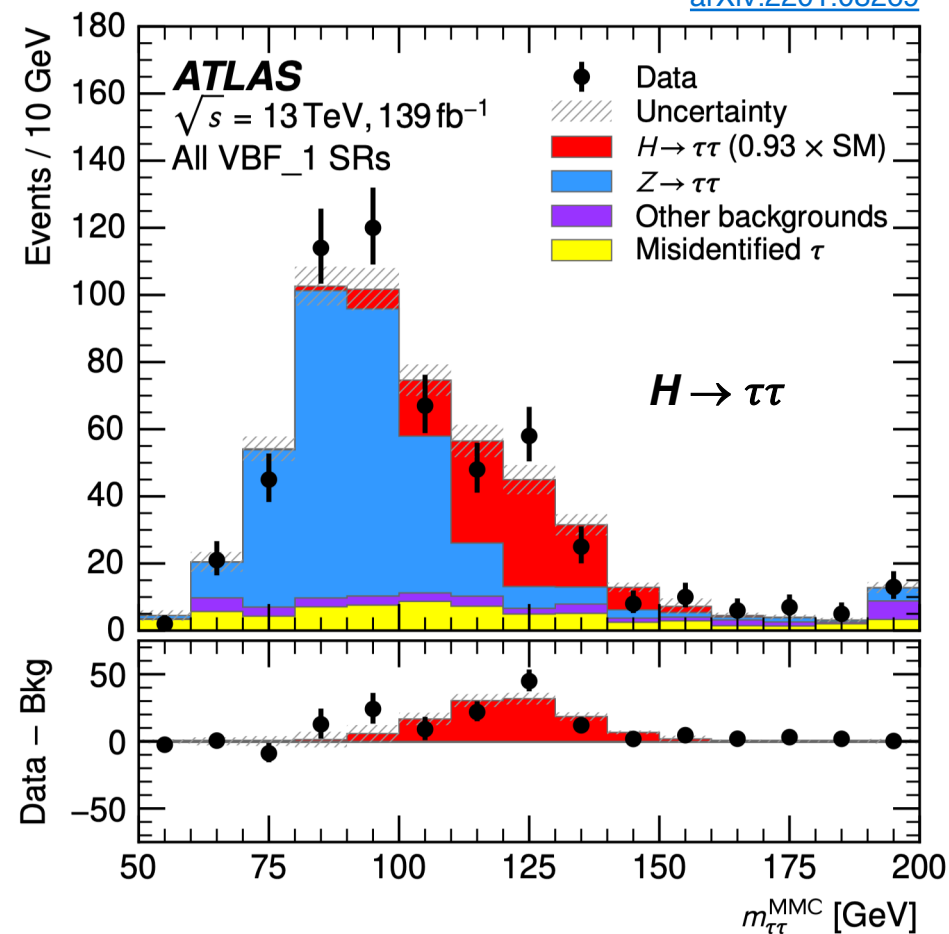


Run : 362204
Event : 2842448996
2018-09-29 13:15:54 CEST

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



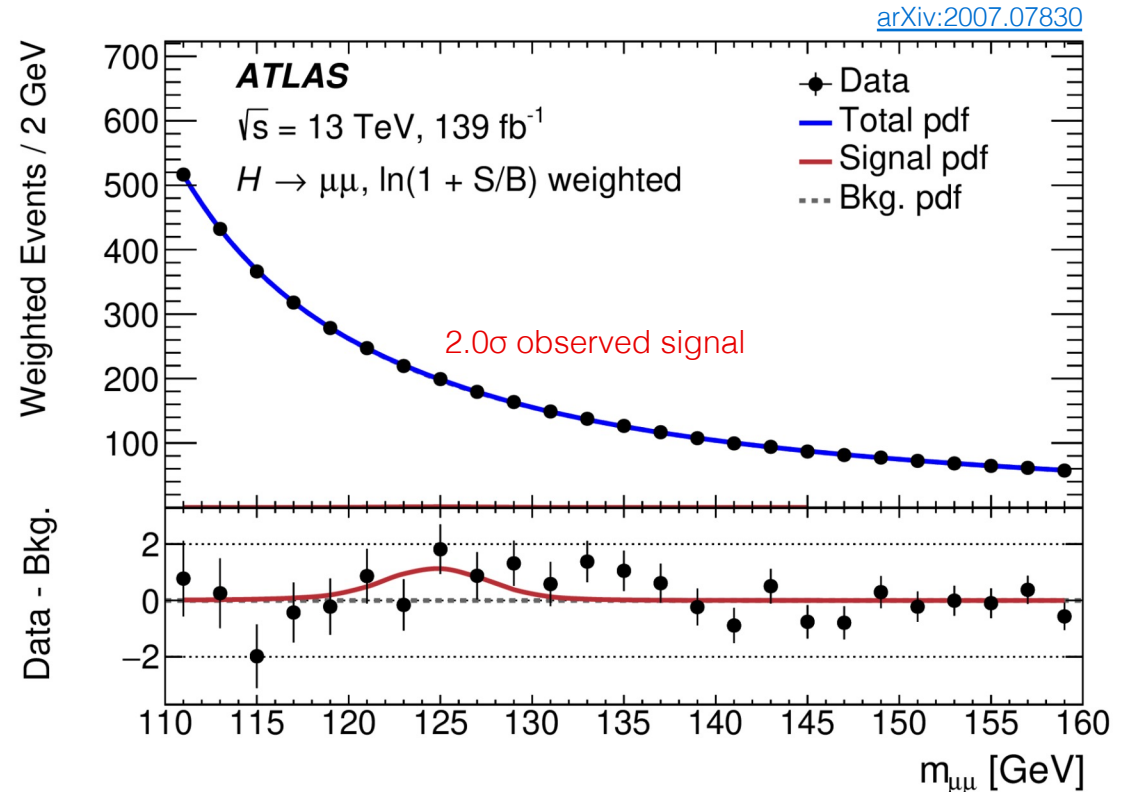
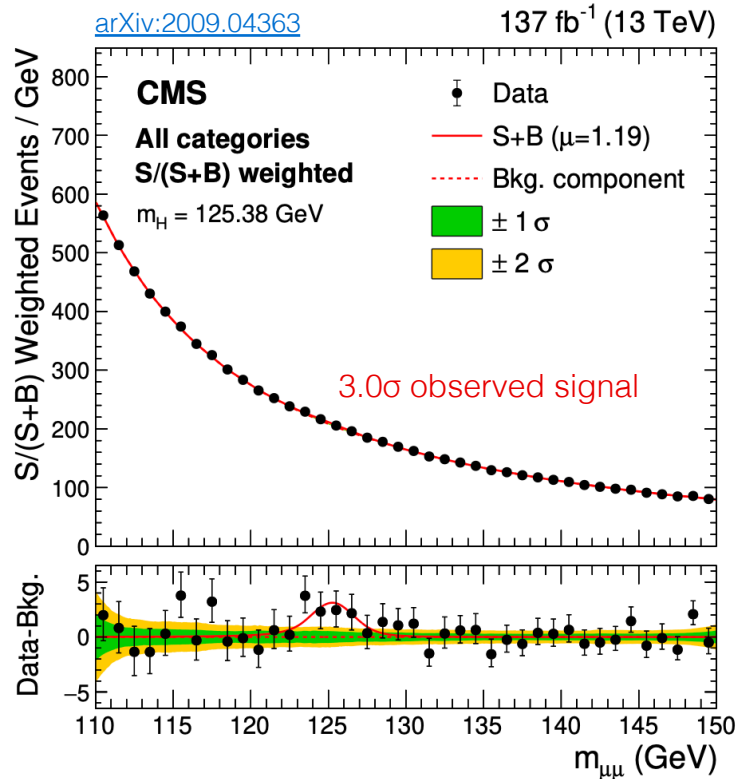
[arXiv:2201.08269](https://arxiv.org/abs/2201.08269)



$H \rightarrow \mu\mu$ — Higgs coupling to light second-generation fermions

$H \rightarrow \mu\mu$, very challenging channel (0.02% branching fraction)

- Approximately 1,600 events produced but very small signal-to-background ratio
- Requires a very accurate description of the backgrounds (via empirical fit)
- Gain in sensitivity by exploiting all production modes gluon fusion, VBF, VH, ttH



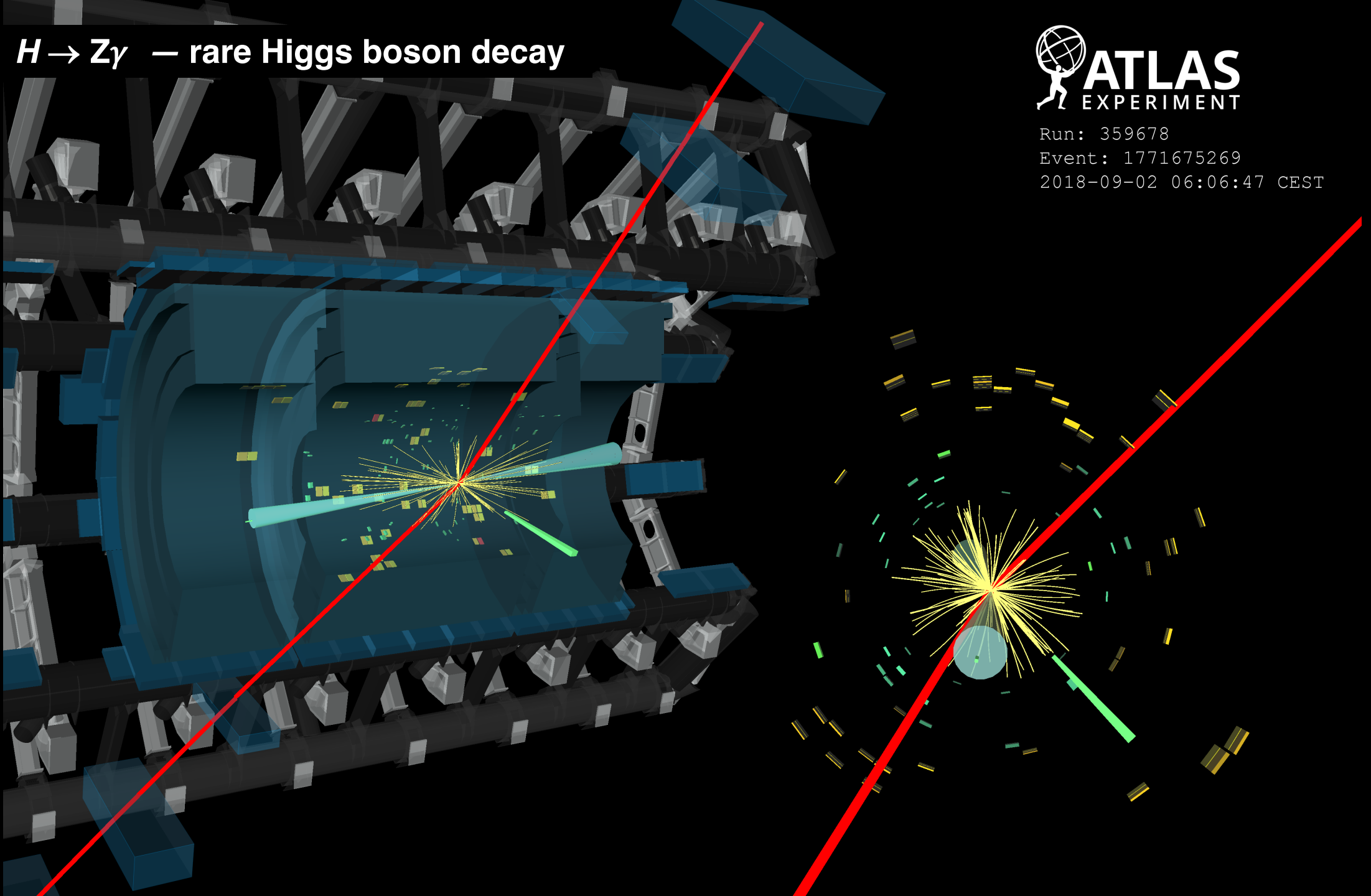
$H \rightarrow Z\gamma$ — rare Higgs boson decay



Run: 359678

Event: 1771675269

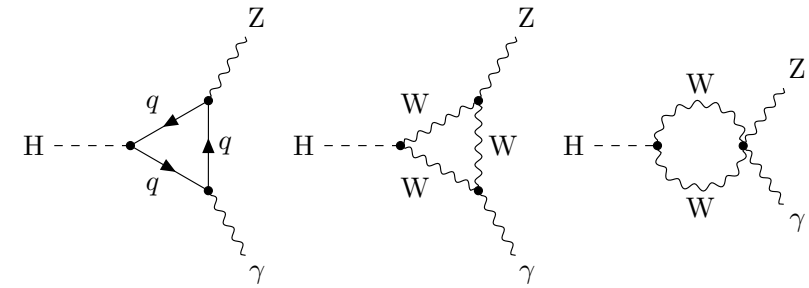
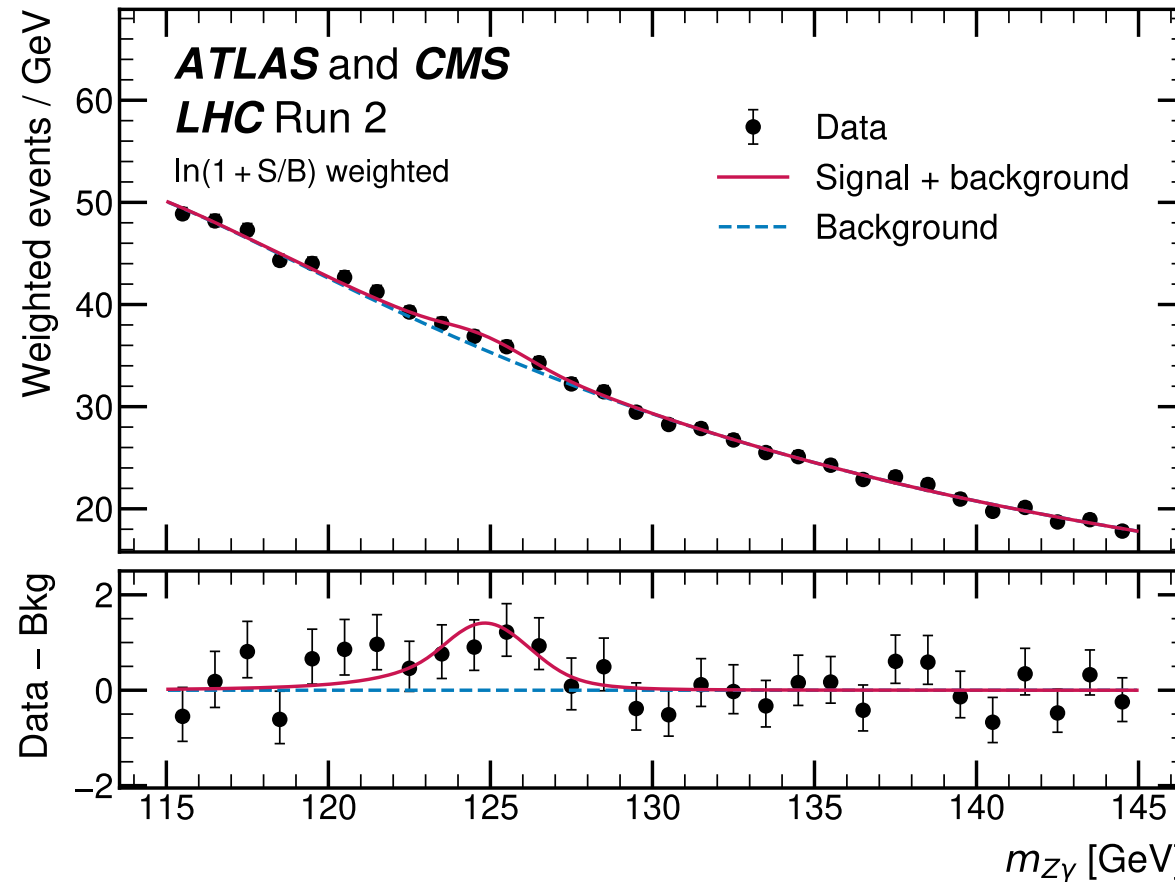
2018-09-02 06:06:47 CEST



$H \rightarrow Z\gamma$ — rare Higgs boson decay

Evidence of rarest channel seen so far in combined ATLAS & CMS
Run-2 datasets: 3.4σ (1.9σ exp), $\mu = 2.2 \pm 0.7$, 1.9σ within SM

[arXiv:2309.03501](https://arxiv.org/abs/2309.03501), [CERN press update](#), [Physics briefing](#)



Field tensor not measured yet: $|H^2|A_{\mu\nu}Z^{\mu\nu}$

Branching fractions:

- $H \rightarrow \gamma\gamma$: 0.23%
- $H \rightarrow \mu\mu$: 0.022%
- $H \rightarrow ZZ^* \rightarrow 4\ell$: 0.012% ($4e + 4\mu + 2e2\mu$)
- $H \rightarrow Z\gamma$: **0.010% (for $Z \rightarrow ee, \mu\mu$)**

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

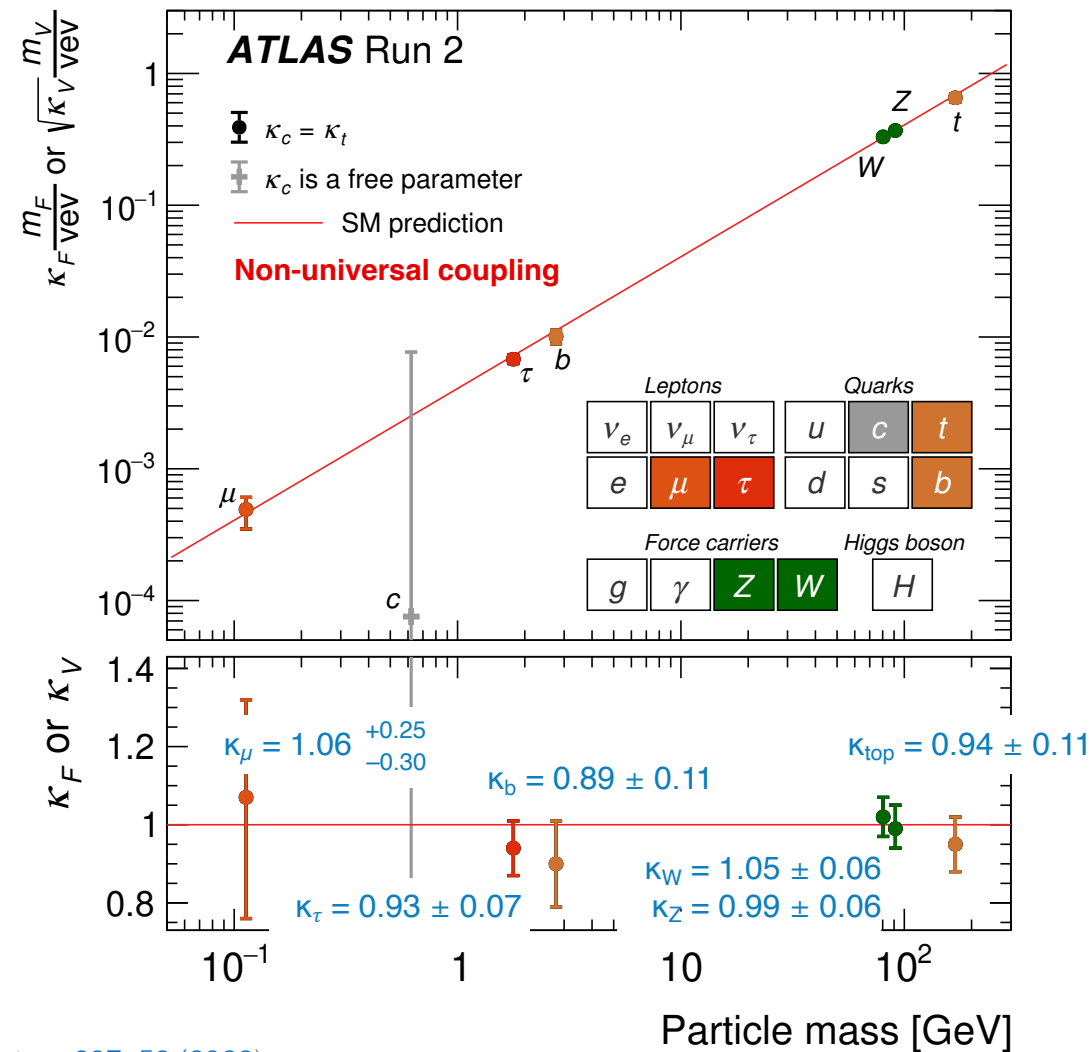


The Higgs mechanism is real !

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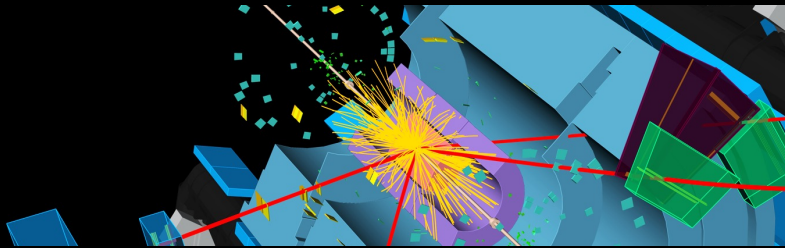


Coupling strengths wrt SM: $\kappa_\gamma = 1.01 \pm 0.06$, $\kappa_g = 0.95 \pm 0.07$



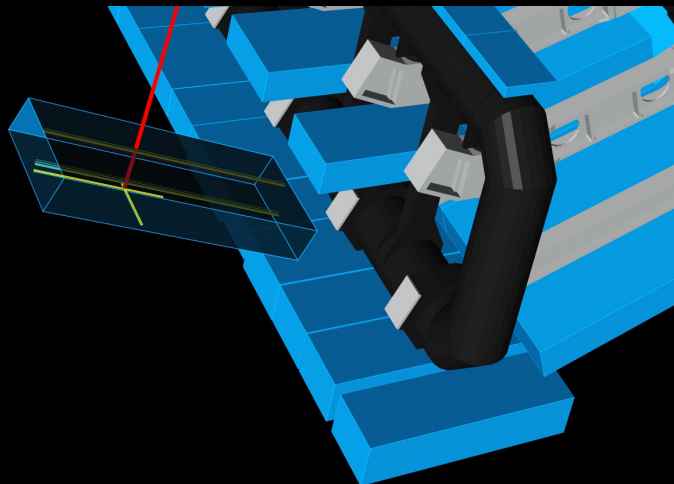
[Nature 607, 52 \(2022\)](#)

The Higgs mechanism is real !



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**

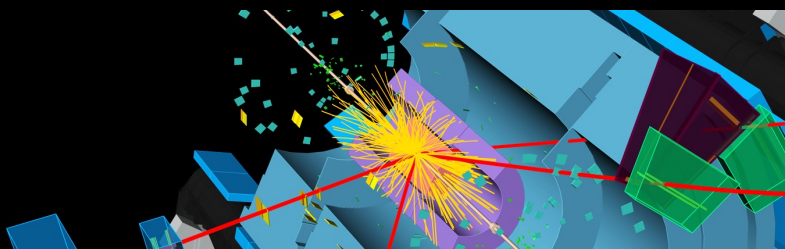


Possible relations between the Higgs boson and open questions in particle physics and cosmology

- 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?
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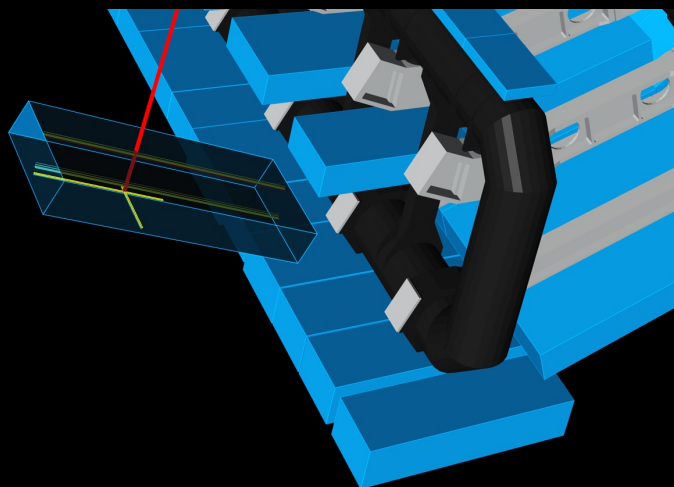
[Salam, Wang, Zanderighi: Nature 607, 41 \(2022\)](#)

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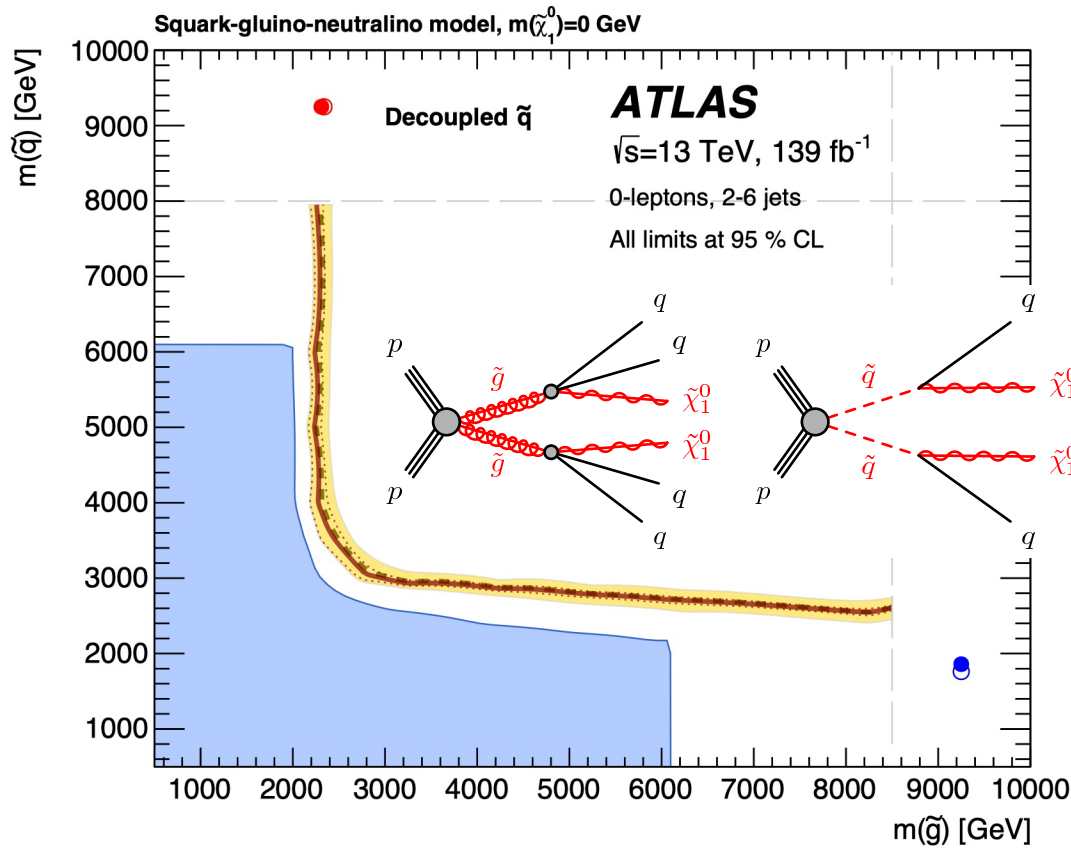
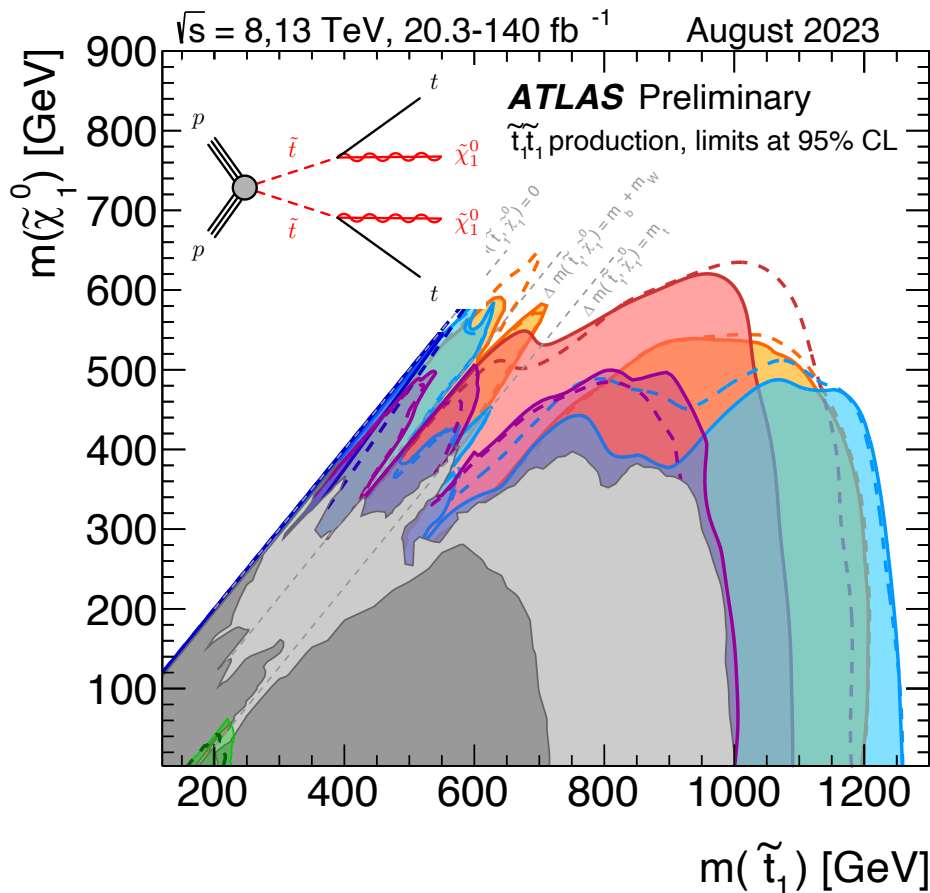


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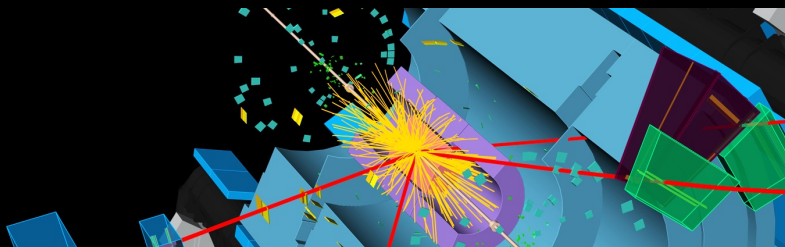
[Salam, Wang, Zanderighi: Nature 607, 41 \(2022\)](#)

Supersymmetry?

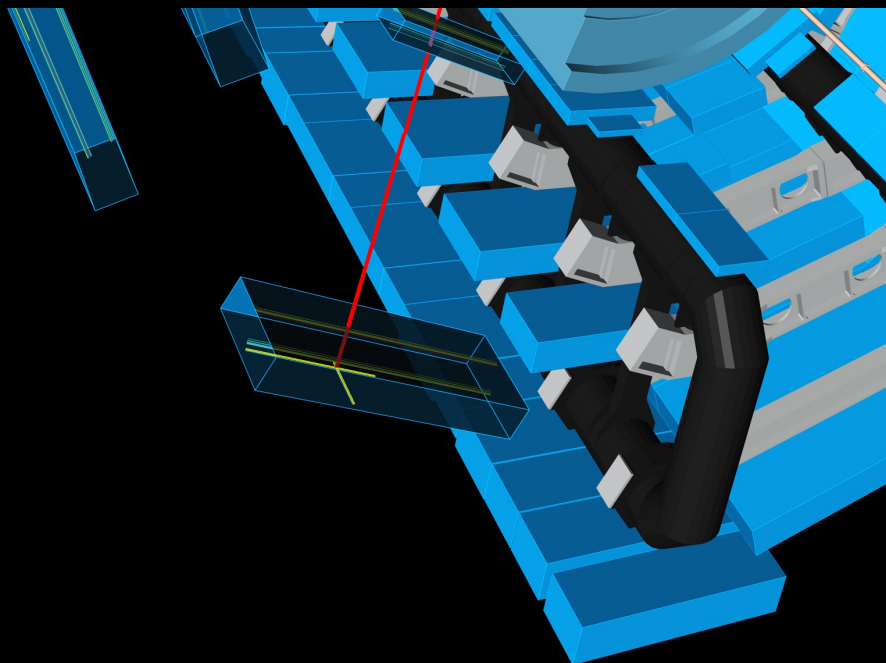


Also: neutralino-chargino pair production excluded up to 1.2 TeV

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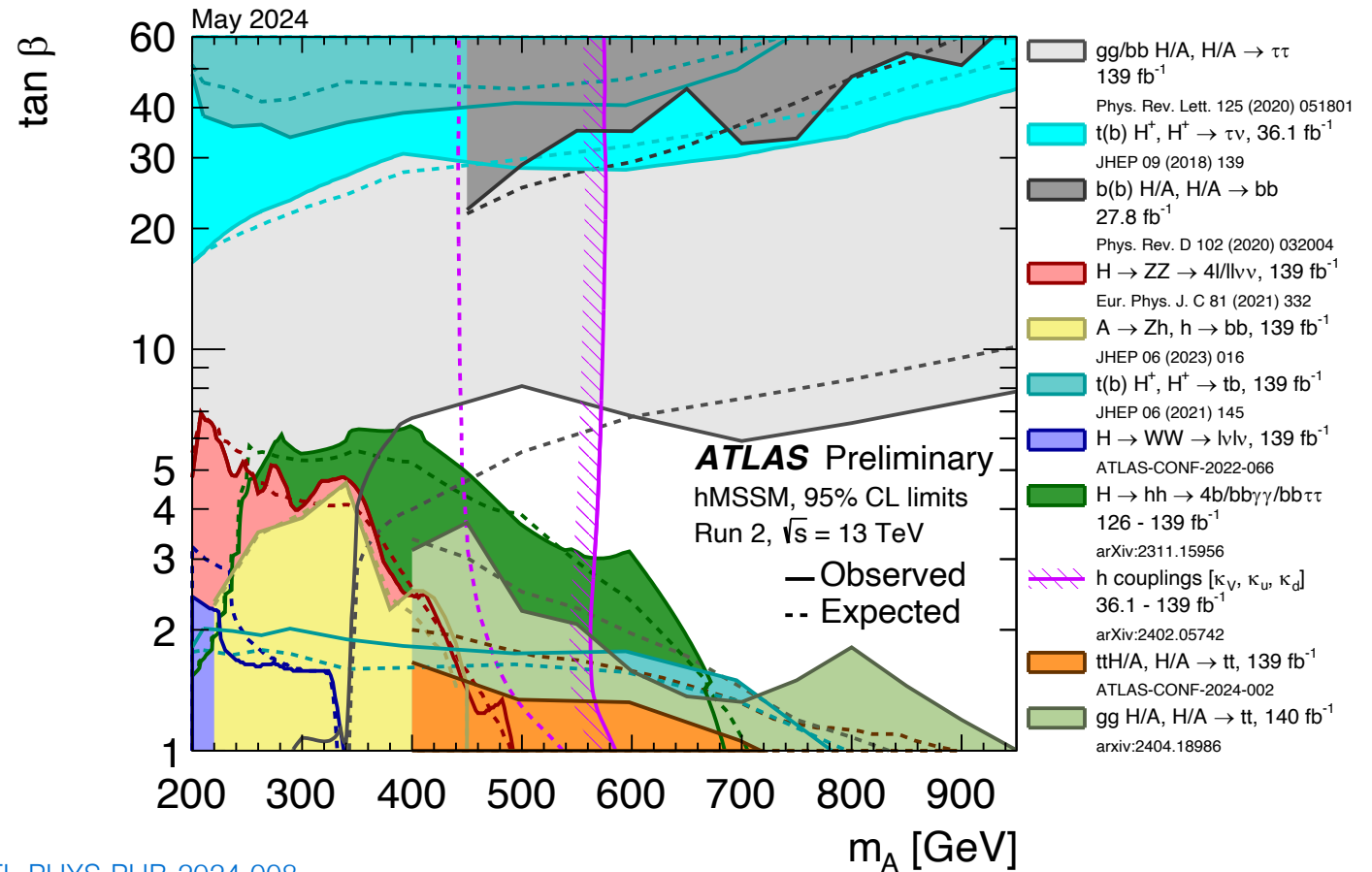
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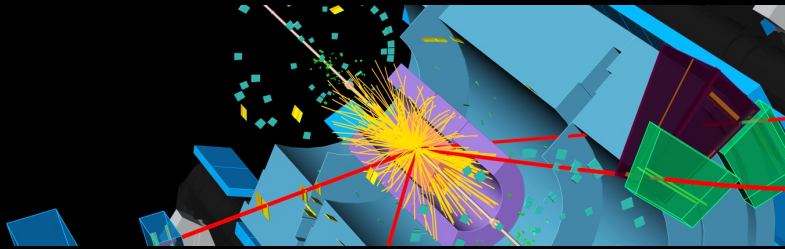
[Salam, Wang, Zanderighi: Nature 607, 41 \(2022\)](#)

Extended Higgs sector ?

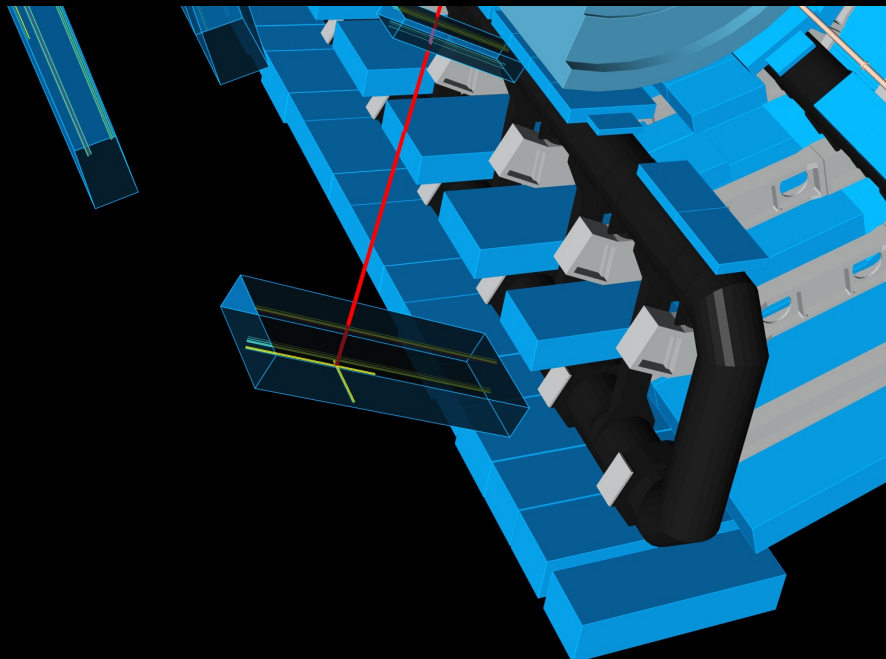
The scalar sector may feature an additional Higgs doublet with opposite weak hypercharge ($\rightarrow h, H, A, H^\pm$) or even triplet ($+ H^{\pm\pm}$) with rich phenomenology



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

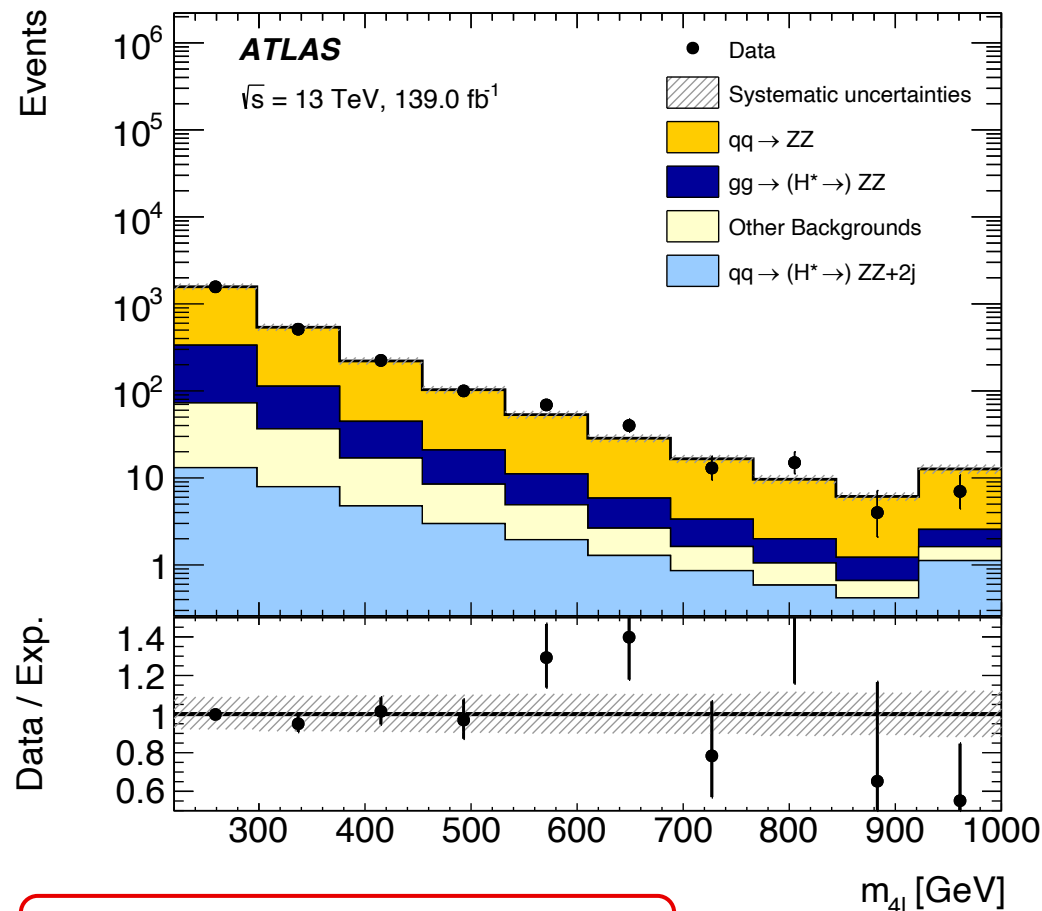
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[Salam, Wang, Zanderighi: Nature 607, 41 \(2022\)](#)

Higgs boson width

On can measure the decay width of the Higgs boson 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

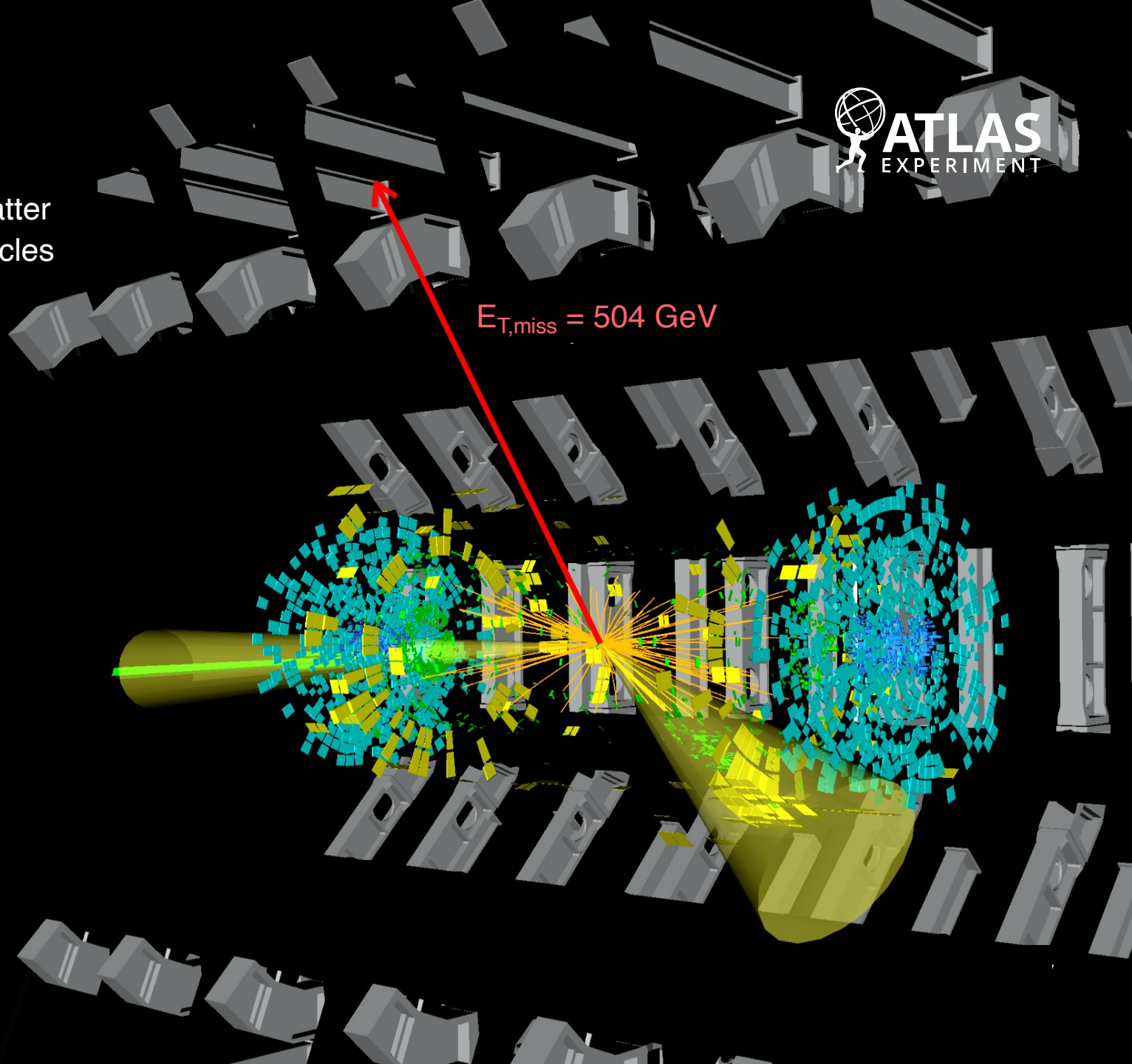
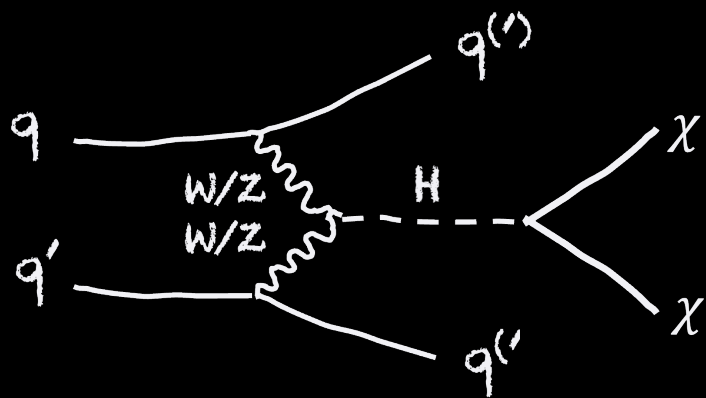


$$\Rightarrow \Gamma_H = 4.3^{+2.7}_{-1.9} \text{ MeV (SM: 4.1 MeV)}$$

[arXiv:2304.01532](https://arxiv.org/abs/2304.01532)
Newest: [arXiv:2412.01548](https://arxiv.org/abs/2412.01548)

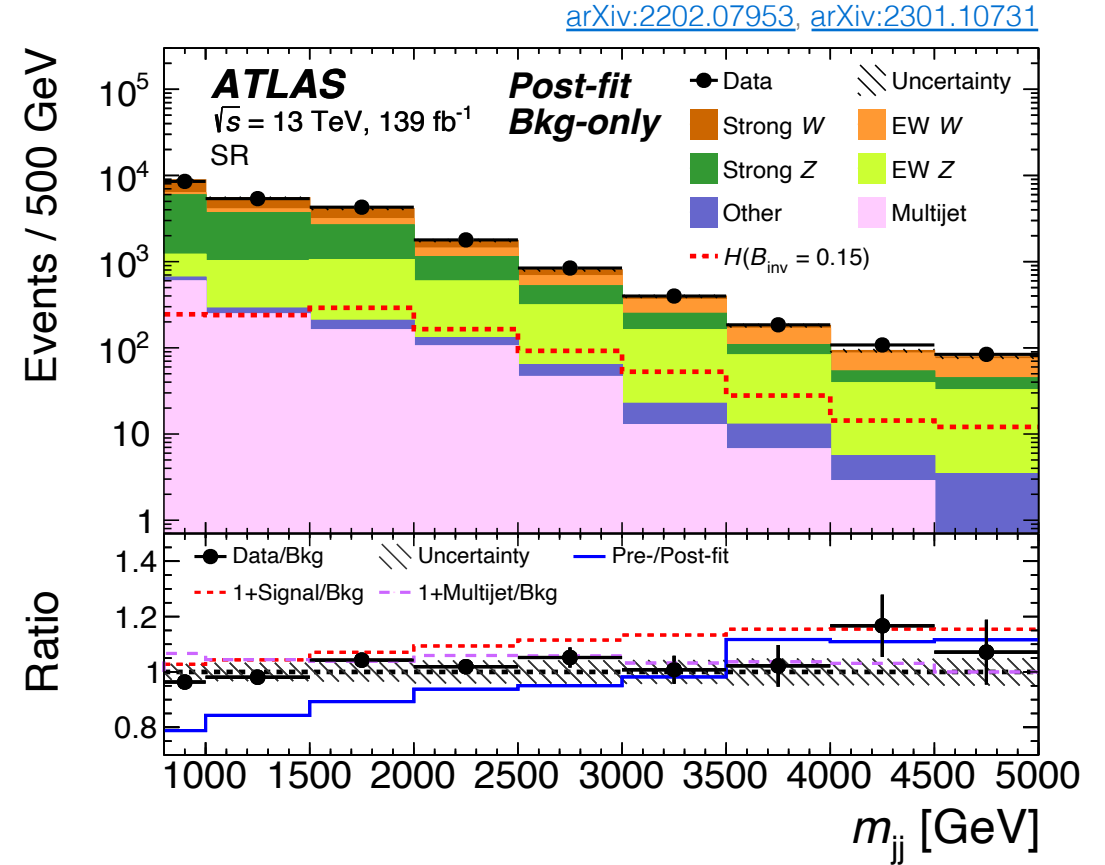
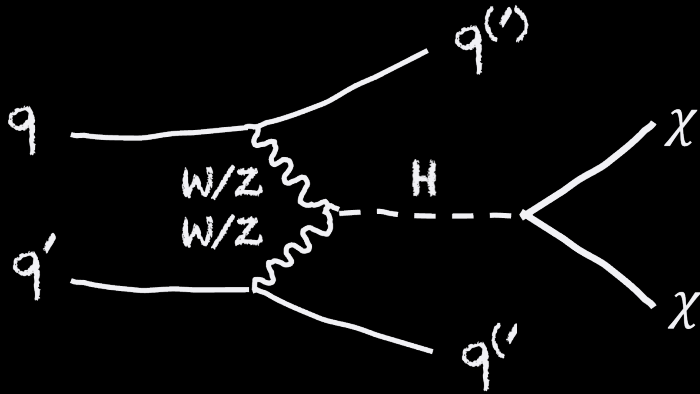
Dark matter

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



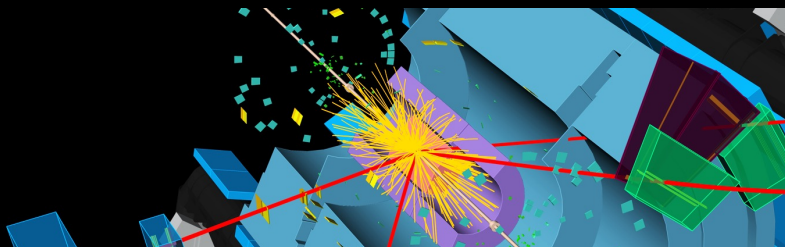
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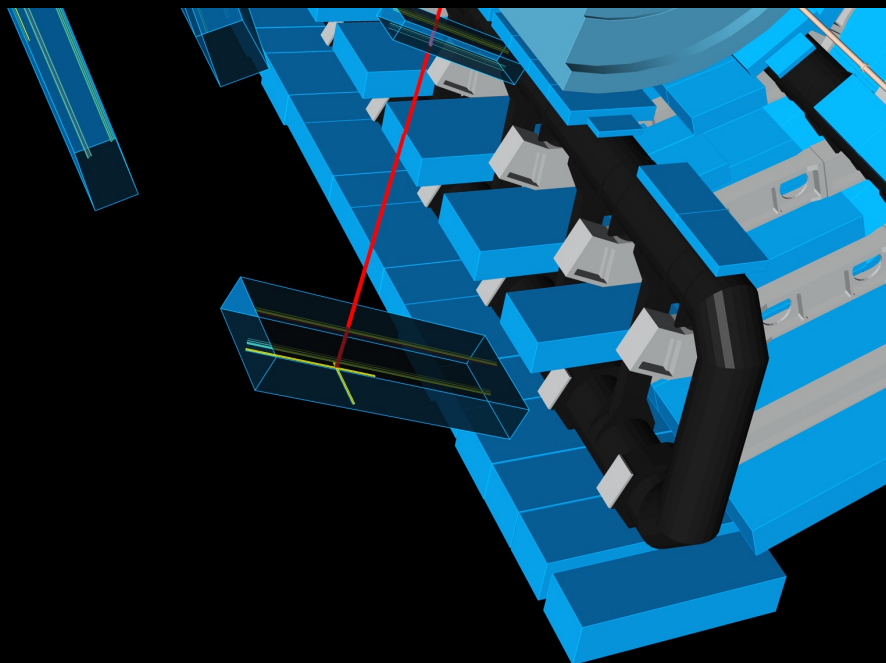


⇒ $\text{BR}(H \rightarrow \text{invisible}) < 0.107 \text{ (0.077) at 95\% CL}$

The Higgs mechanism is real !



The new sector opens a variety of possibilities and questions



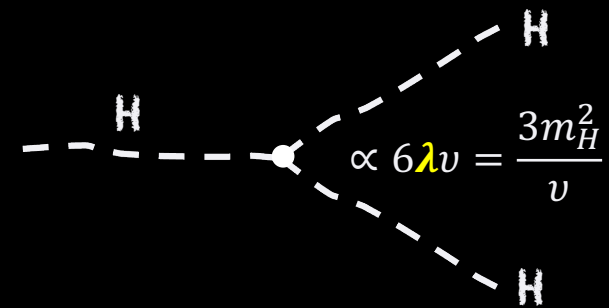
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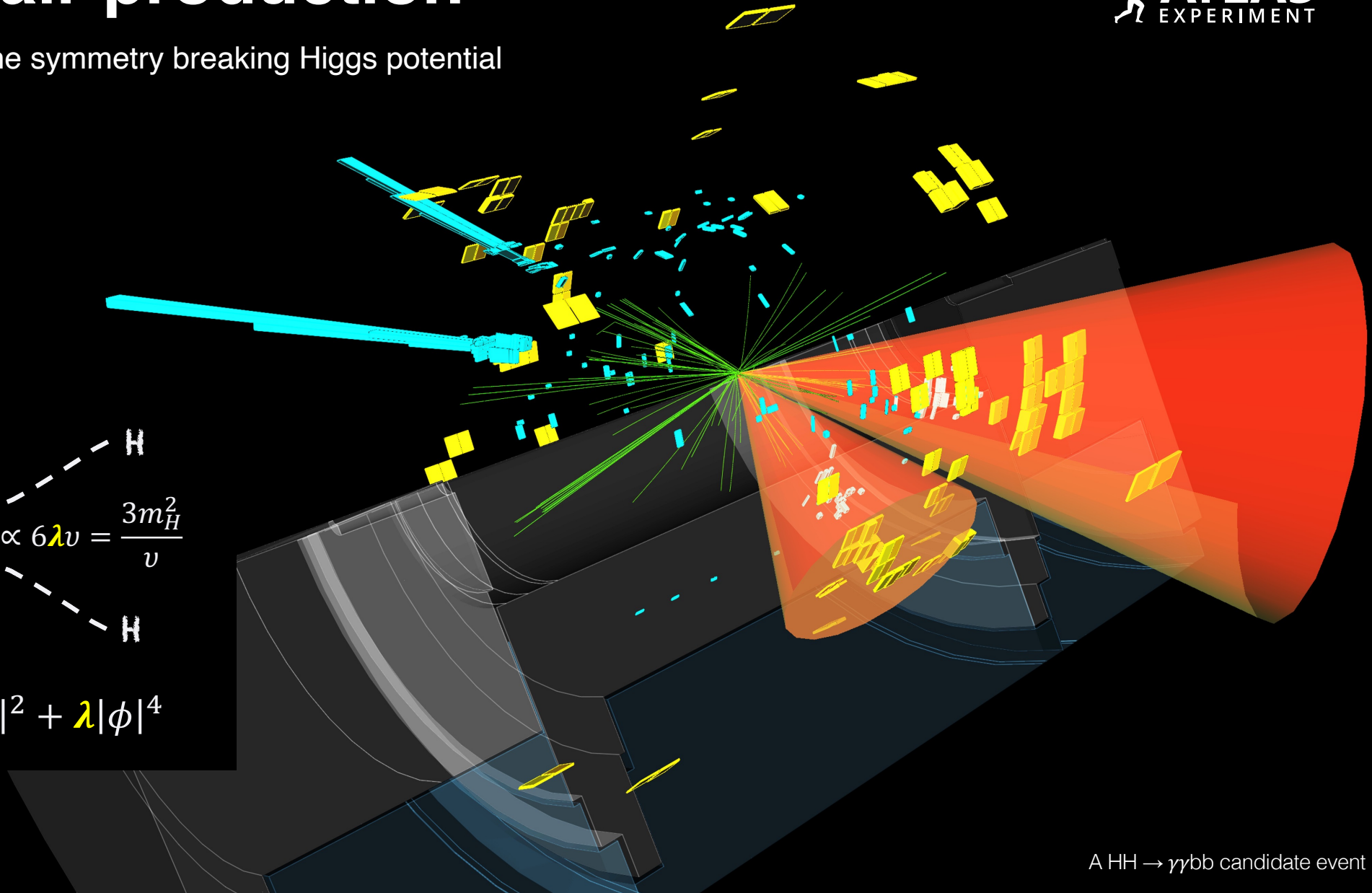
[Salam, Wang, Zanderighi: Nature 607, 41 \(2022\)](#)

Higgs pair production

Direct access to the symmetry breaking Higgs potential



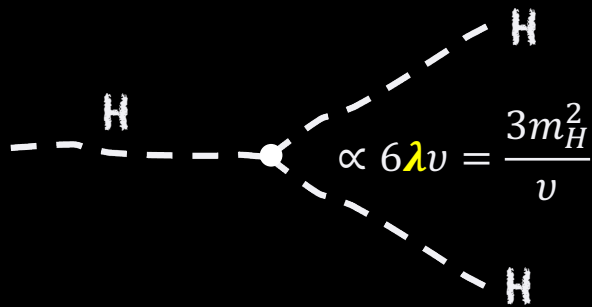
$$V(\phi) = -\mu^2|\phi|^2 + \lambda|\phi|^4$$



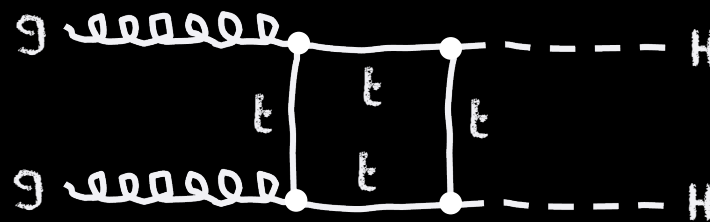
A $HH \rightarrow \gamma\gamma$ bb candidate event

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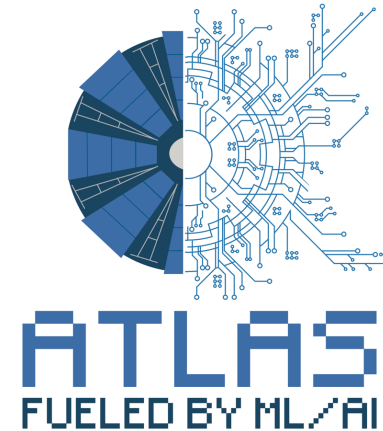
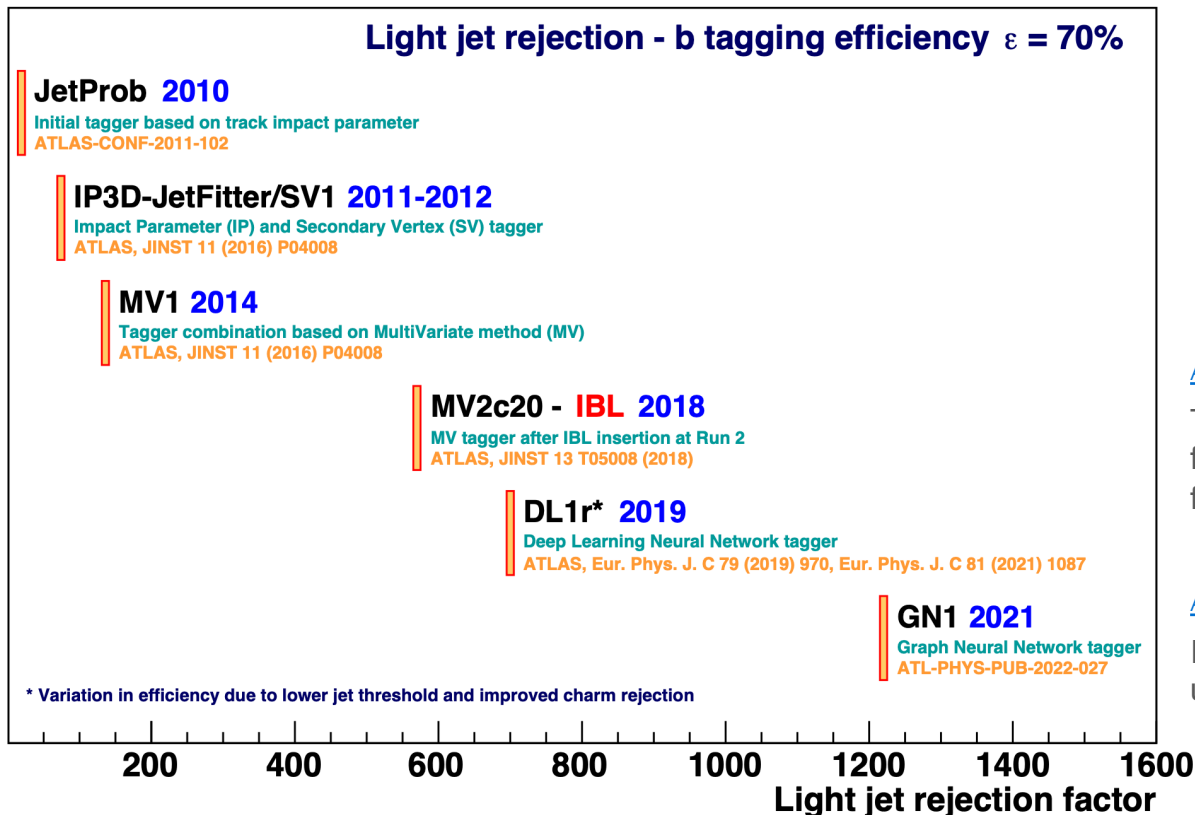
A $HH \rightarrow \gamma\gamma$ candidate event

Improving performance



Machine learning in ATLAS: from the trigger, over reconstruction, to the final selection — the Graph NN revolution

Marumi Kado



[ATL-PHYS-PUB-2022-027](#), [arXiv:2405.03253](#), [Public plots](#) (2022–2024)

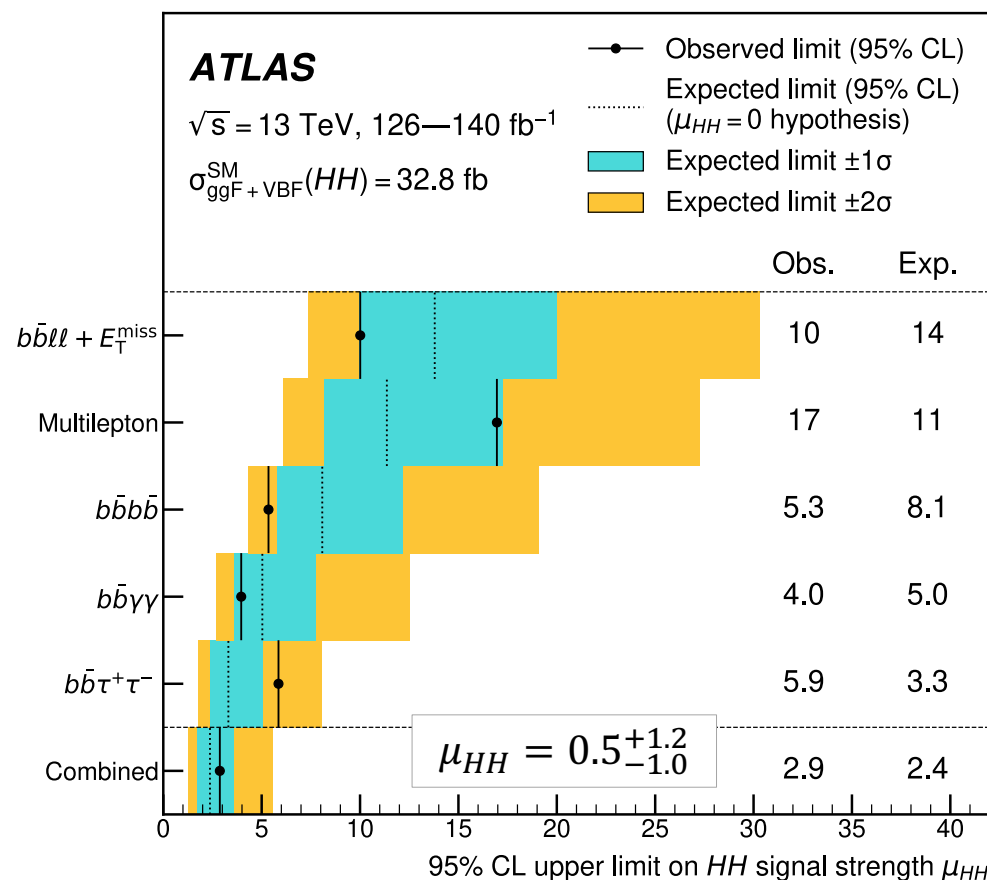
The Graph NN (GNN) family in flavour tagging and tau reconstruction features astounding results (already GN2 and GN3 versions with further improvements)

[ATL-PHYS-PUB-2022-040](#) (2022)

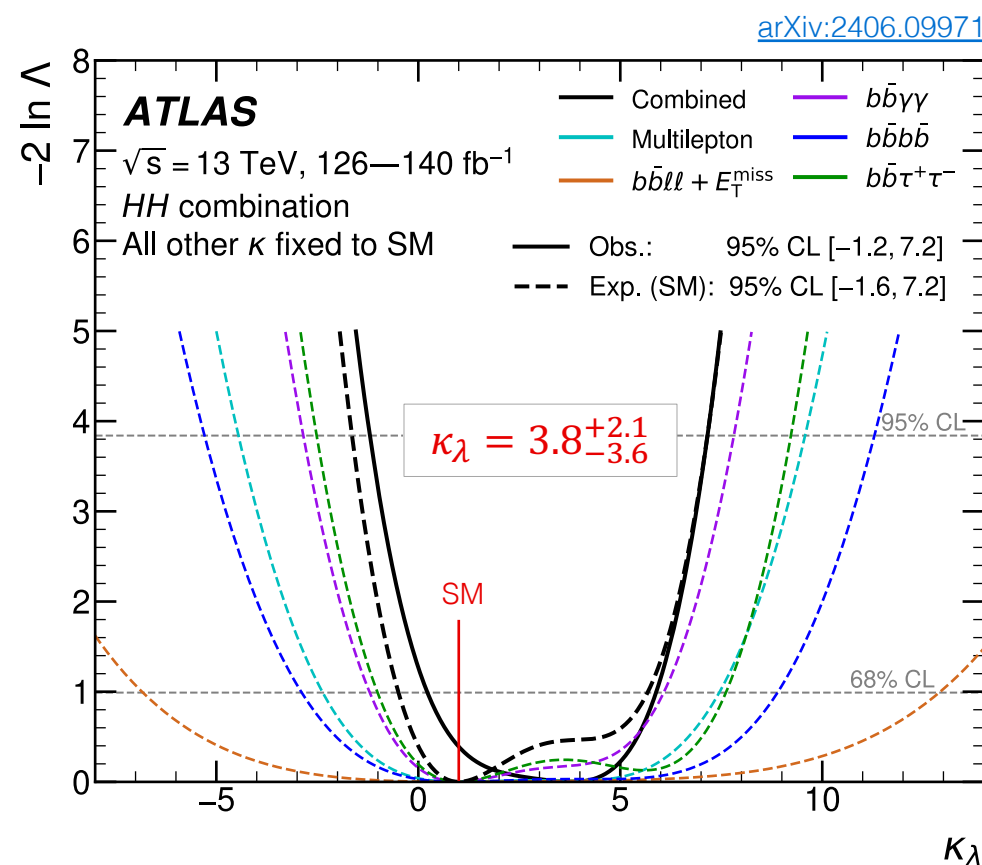
Improved pion energy reconstruction (scale & resolution) using ML regression techniques

Higgs pair production

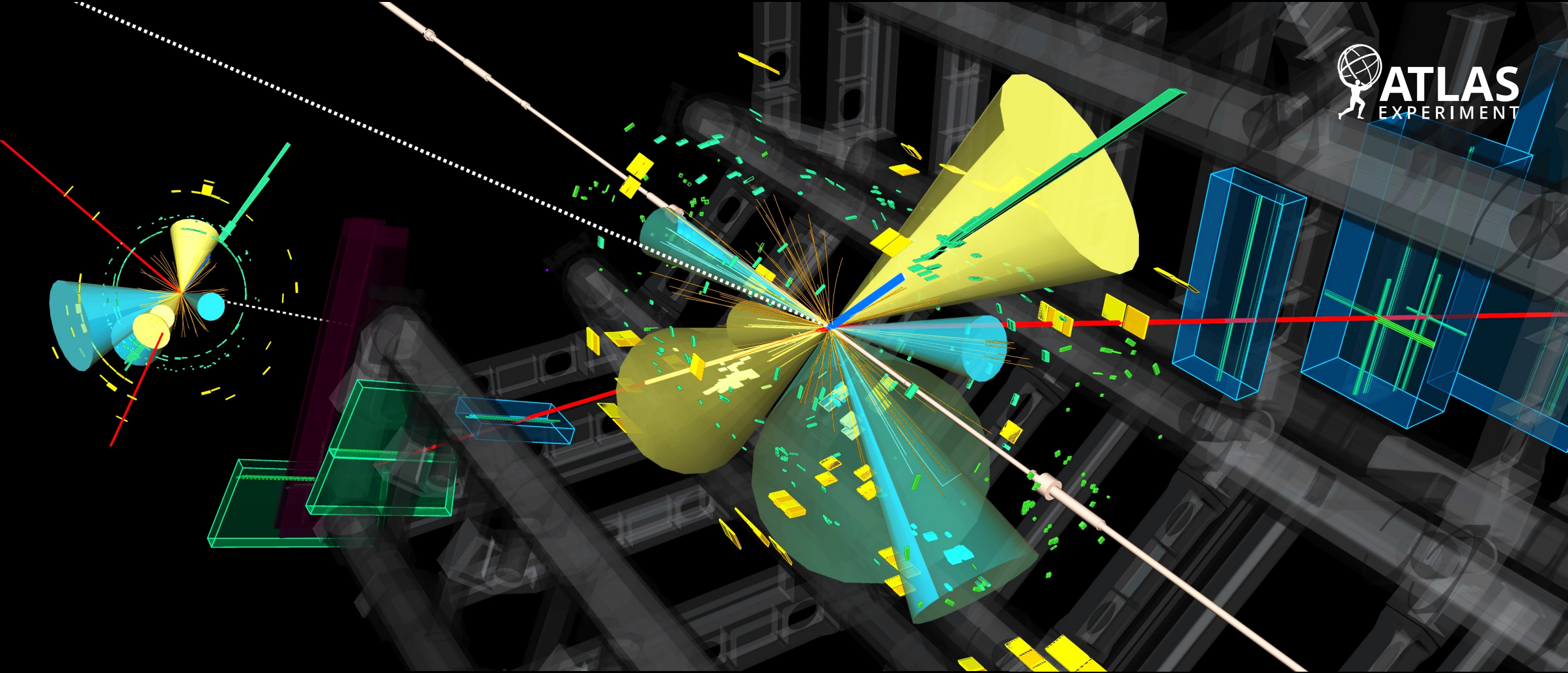
Complex final states, large potential for machine learning, steady analysis improvements



Constraint on $\kappa_\lambda = \lambda/\lambda_{\text{SM}}$, $\lambda_{\text{SM}} \sim 0.13$ also benefits from single-Higgs coupling measurements via quantum loop



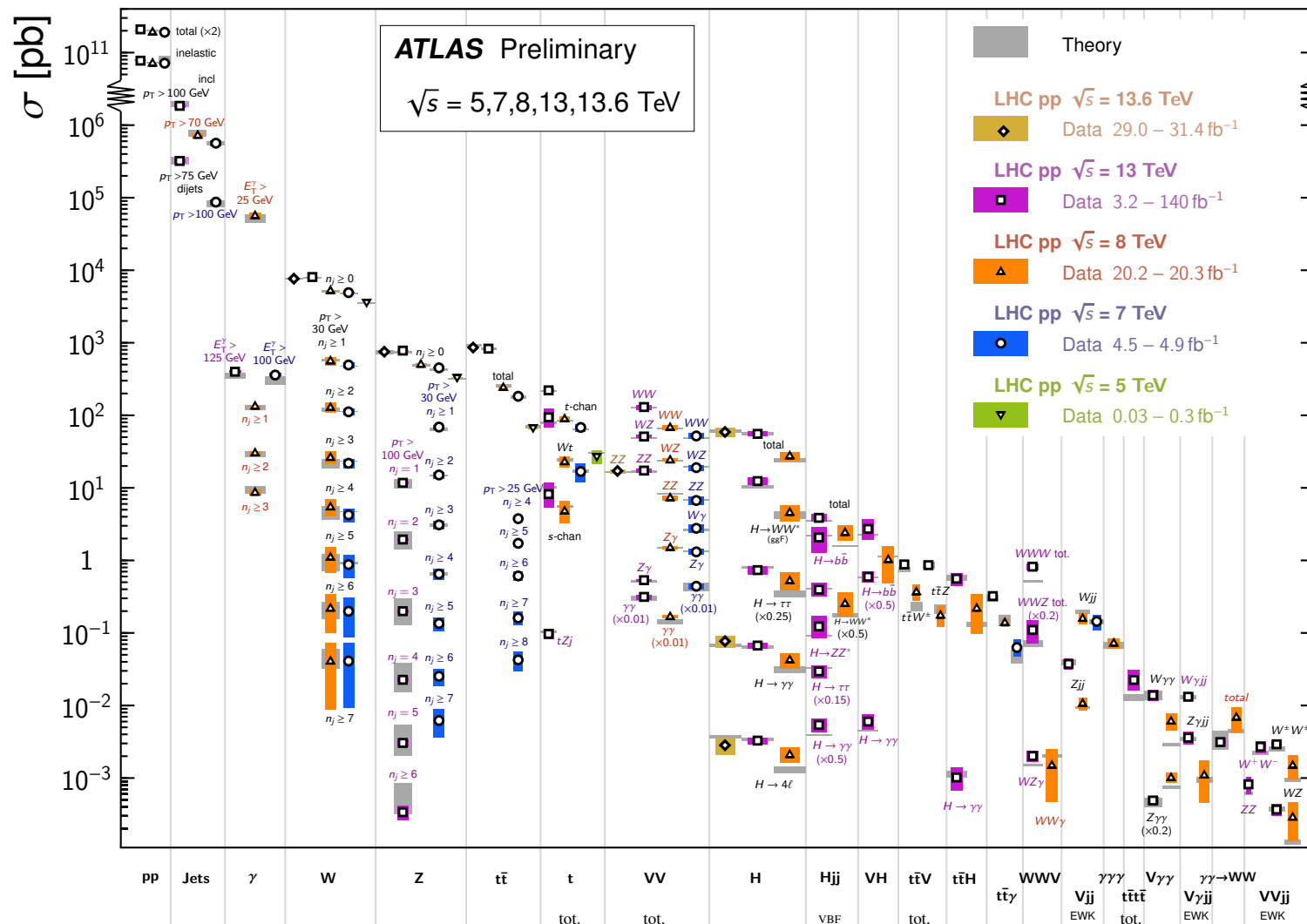
The LHC also provided a new understanding of hadron collider processes: the observation of numerous very rare channels testing the Standard Model



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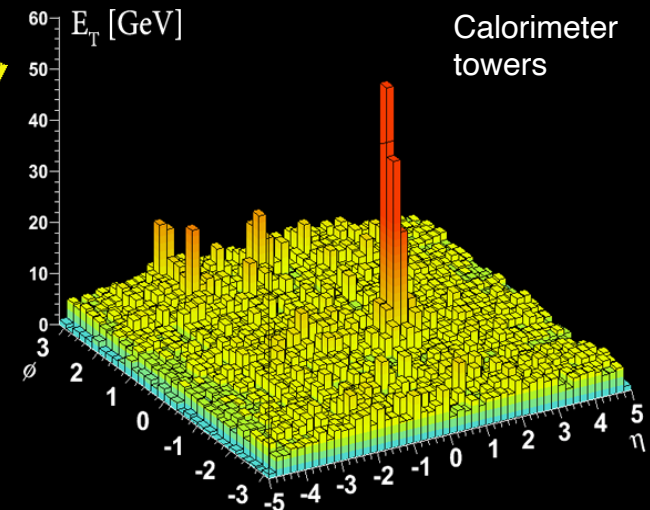
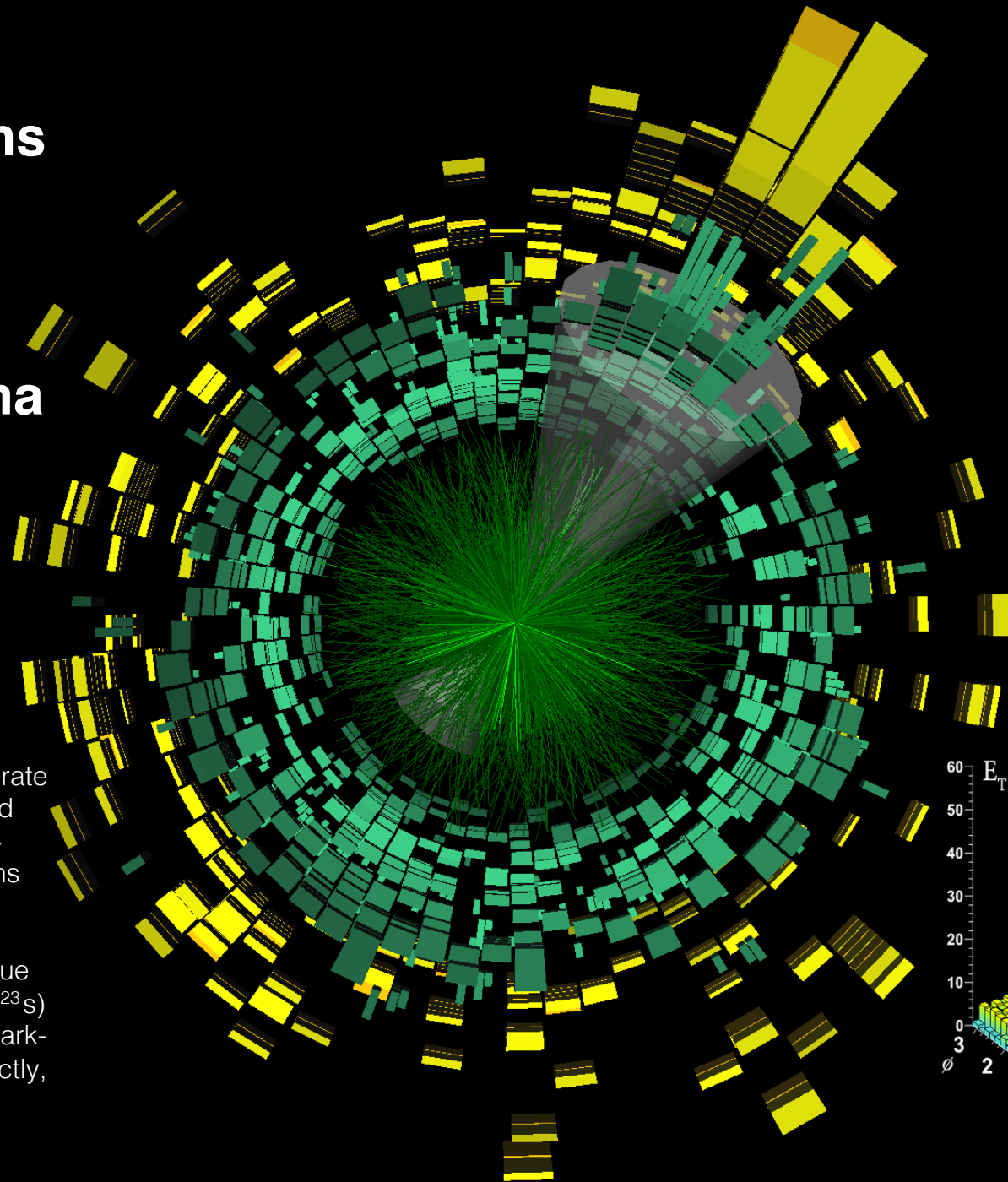
$pp \rightarrow t\bar{t}t\bar{t}$ candidate event (very rare events, 70,000 rarer than $t\bar{t}$, 4,000 rarer than Higgs boson production, with spectacular signature: 4 b-jets, many leptons and jets)

Status: June 2024



Measurements of heavy-ion collisions enabled a detailed mapping of the properties of the quark-gluon plasma with soft and hard probes

Collisions among heavy lead ions generate temperatures several hundred thousand times hotter than the core of the Sun — hot enough to melt protons and neutrons within the nuclei, forming a plasma of deconfined quarks and gluons, a near-perfect fluid with almost no viscosity. Due to its ephemerality (lifetime of about 10^{-23} s) and microscopic size (10^{-14} m), the quark-gluon plasma cannot be observed directly, but only through the particles it emits



The next steps

LHC

CMS

SPS

ALICE

ATLAS

LHCb

PS

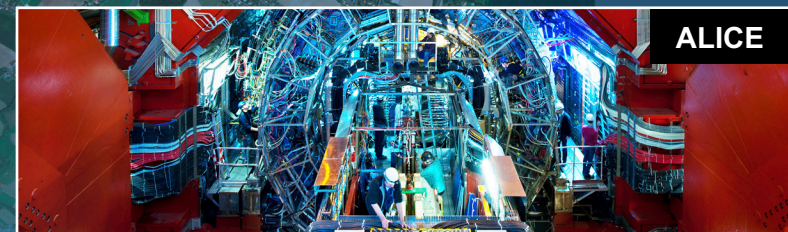
Areal view



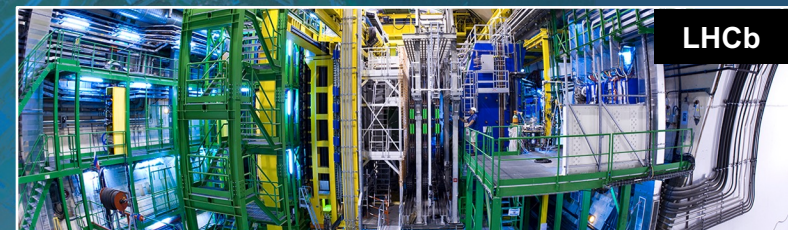
ATLAS



CMS



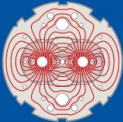
ALICE



LHCb

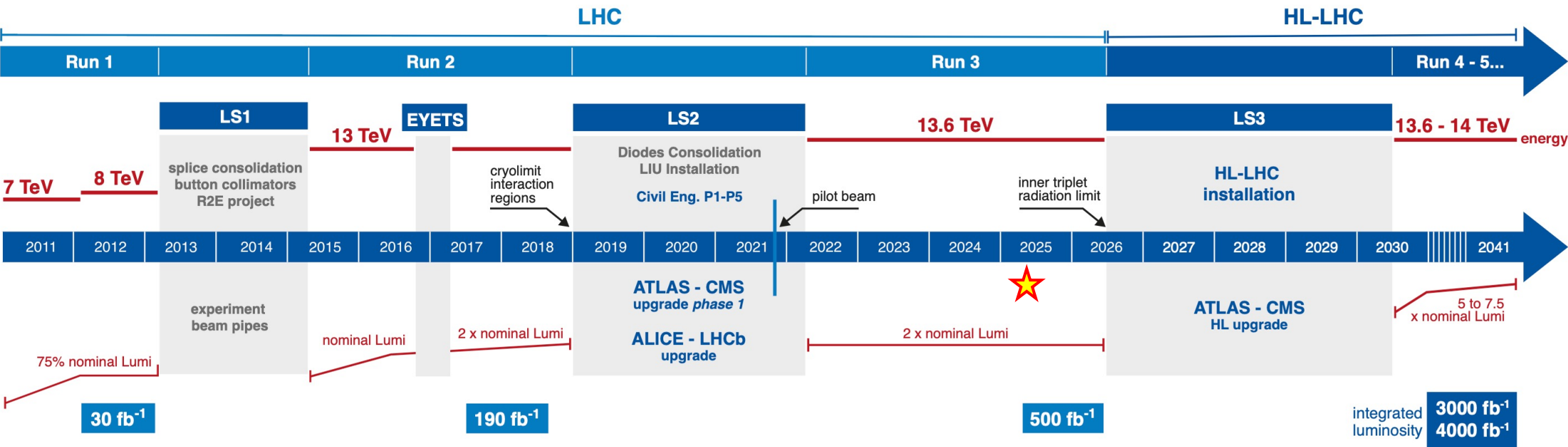
LHC and High-Luminosity-LHC project timeline





LHC / HL-LHC Plan

HL-LHC is the world's flagship collider project during the next decades



HL-LHC TECHNICAL EQUIPMENT:

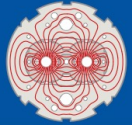


HL-LHC CIVIL ENGINEERING:



CORES

LHC and High-Luminosity-LHC project timeline

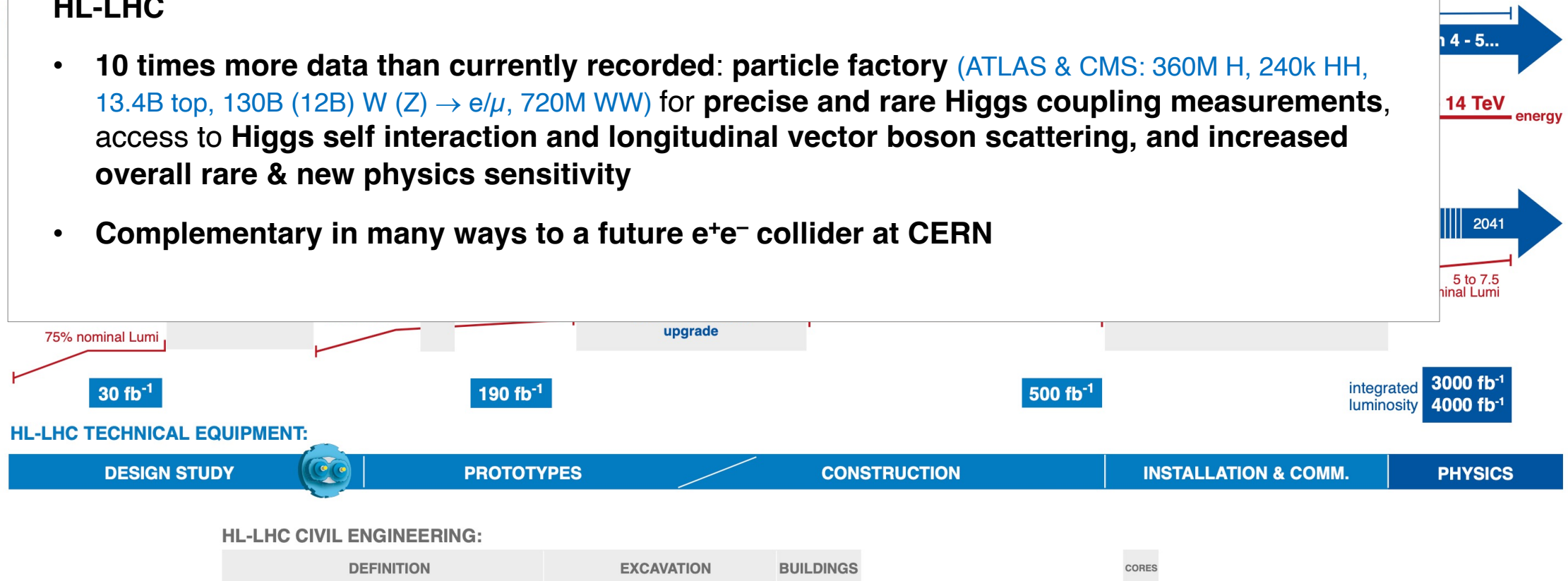


LHC / HL-LHC Plan

HL-LHC is the world's flagship collider project during the next decades

HL-LHC

- **10 times more data than currently recorded: particle factory** (ATLAS & CMS: 360M H, 240k HH, 13.4B top, 130B (12B) W (Z) $\rightarrow e/\mu$, 720M WW) for **precise and rare Higgs coupling measurements**, access to **Higgs self interaction and longitudinal vector boson scattering**, and **increased overall rare & new physics sensitivity**
- **Complementary in many ways to a future e^+e^- collider at CERN**

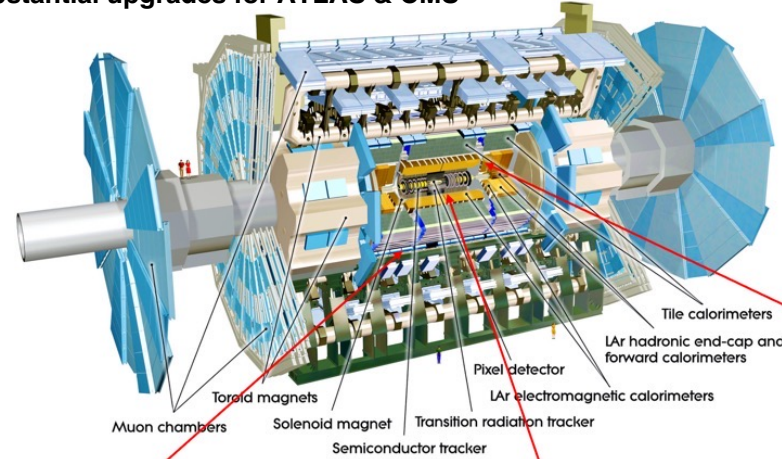


Upgrade to the High-Luminosity LHC (HL-LHC)

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



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

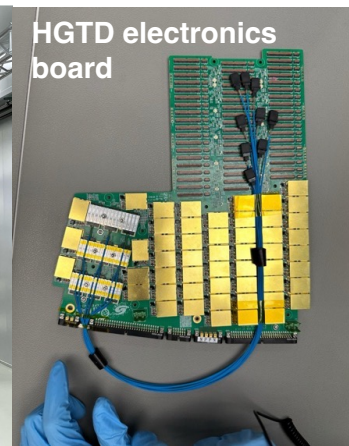
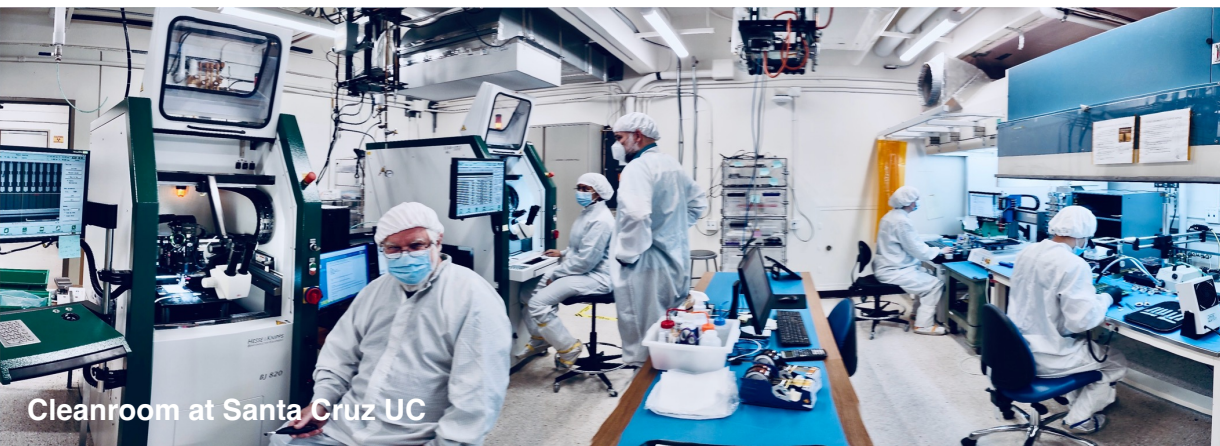
High Granularity Timing Detector (HGTD)

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

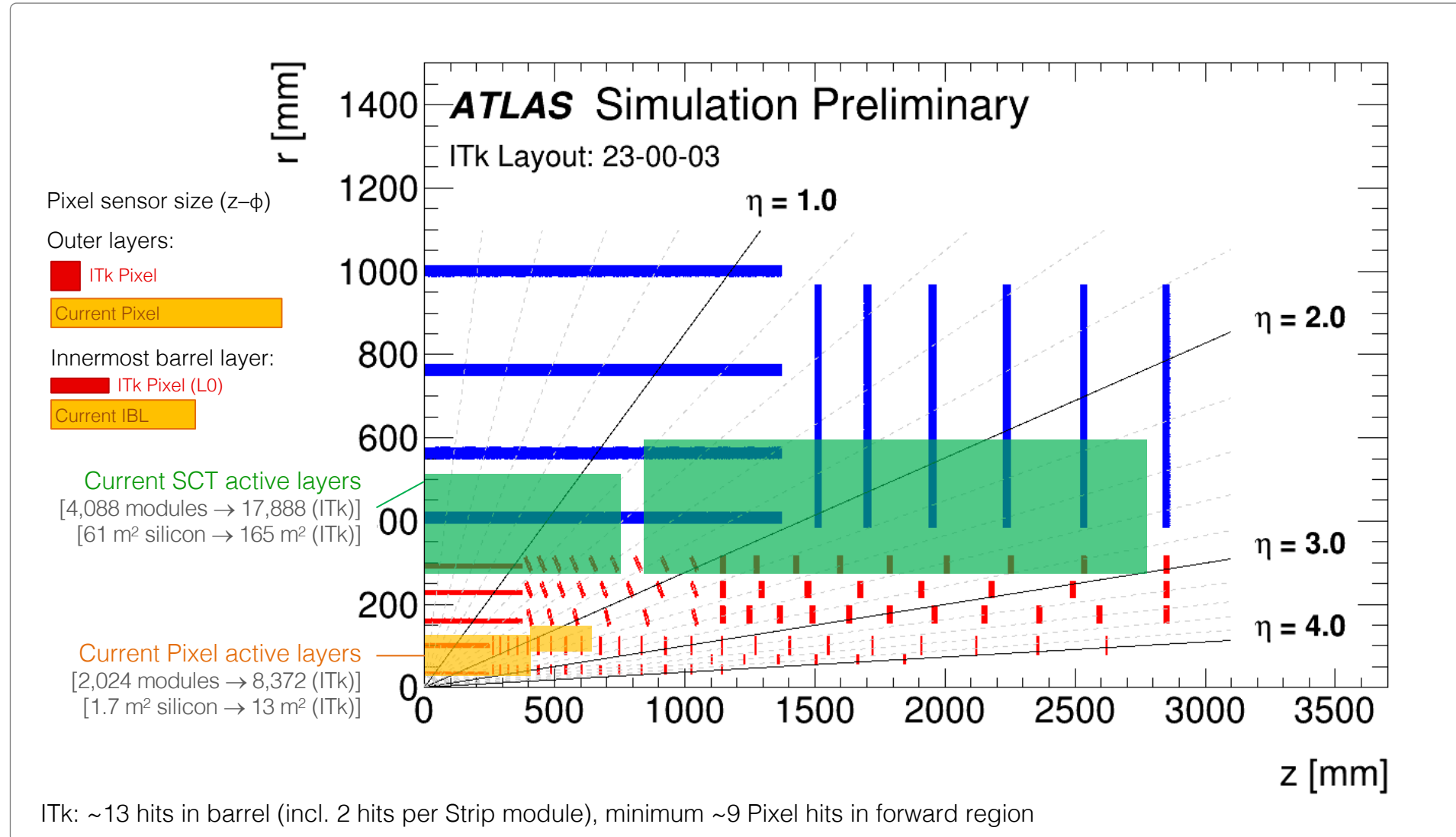
Additional small upgrades

Luminosity detectors (1% precision goal)
HL-ZDC

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



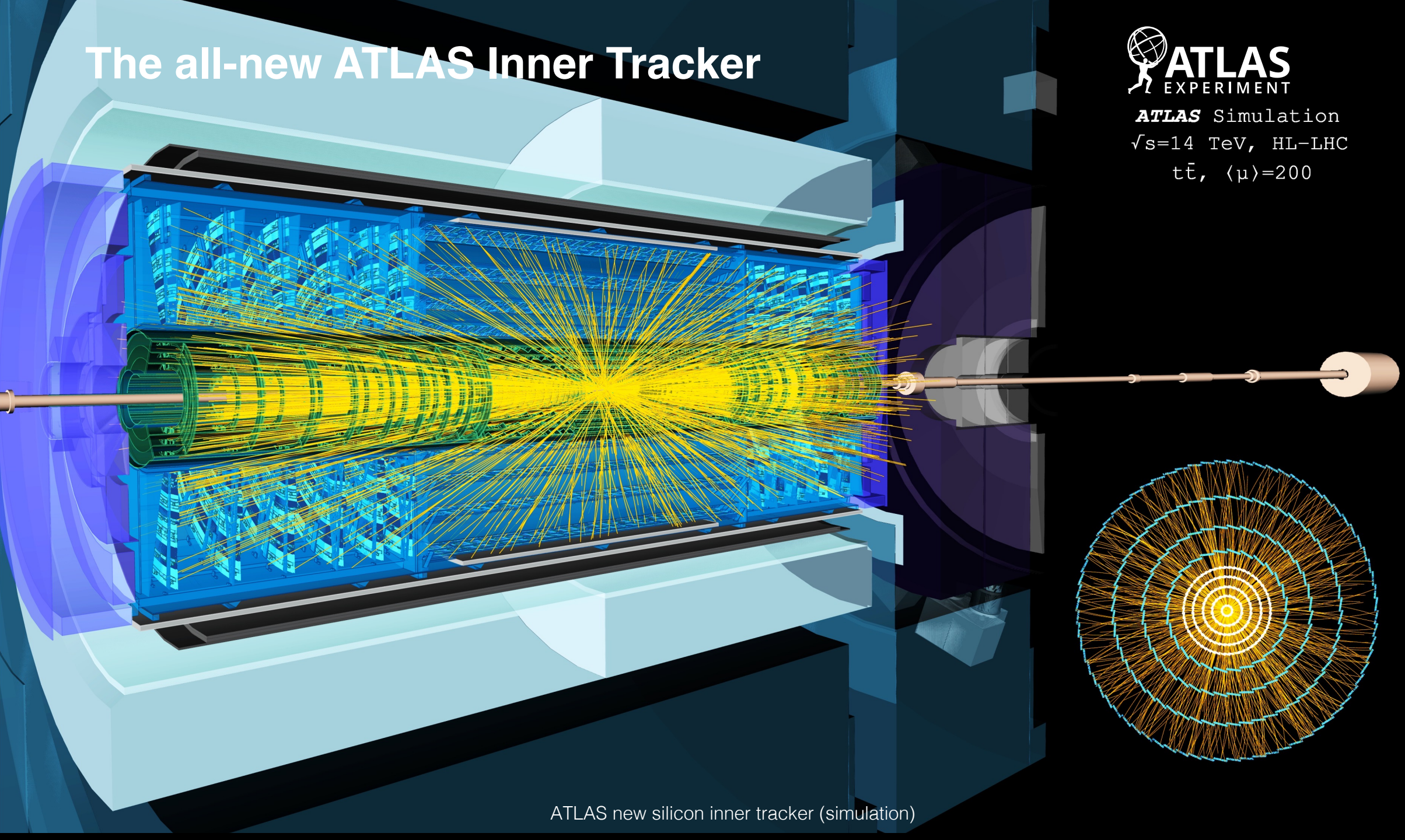
The all-new ATLAS Inner Tracker (ITk)



The all-new ATLAS Inner Tracker



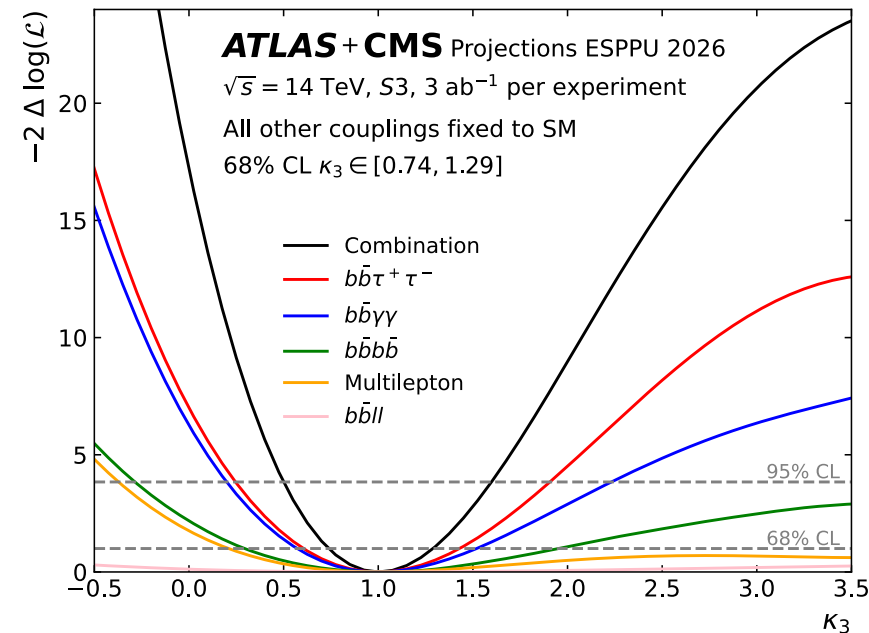
ATLAS Simulation
 $\sqrt{s}=14$ TeV, HL-LHC
 $t\bar{t}$, $\langle\mu\rangle=200$



ATLAS new silicon inner tracker (simulation)

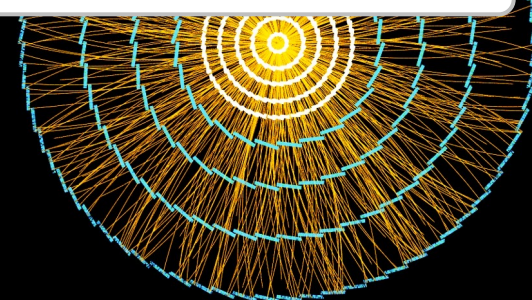
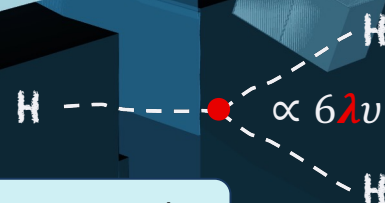
Measuring Higgs self-coupling

ATL-PHYS-PUB-2025-018



$$Z_{HH}[\text{SM}] = 7.6\sigma, \quad \kappa_\lambda[\text{SM}] = 1^{+0.29}_{-0.26}$$

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



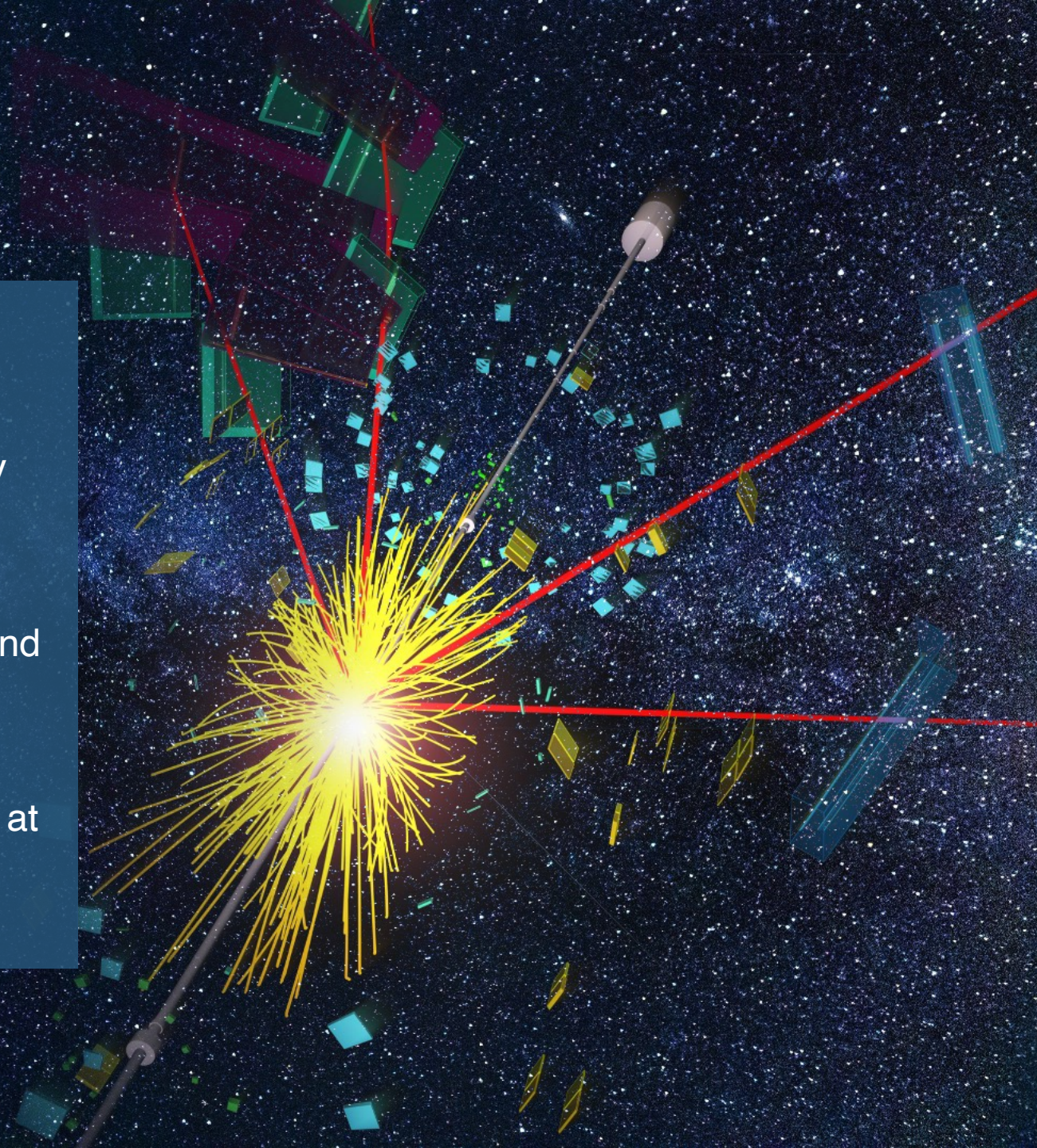
Conclusions

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 very 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



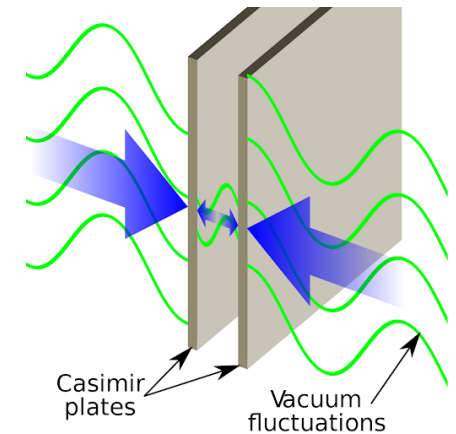


Extra slides

Vacuum energy

Quantum field theory describes the fabric of empty space

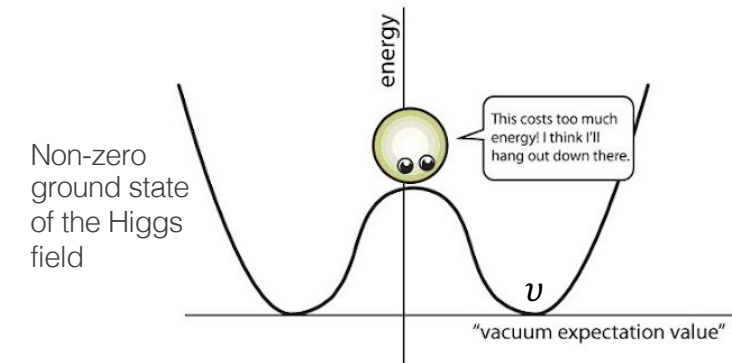
- In QFT, the vacuum is not an empty void but a dynamic and structured entity with **vacuum fluctuations, virtual particles, zero-point energy** (*Nullpunktsenergie*)
- Zero-point energy: quantum fields have vacuum energy even in absence of real particles
(cosmological constant problem: $\rho_{\text{QFT}} \propto m_{\text{Pl}}^4 \sim (10^{19} \text{ GeV})^4 \rightarrow 10^{110} \text{ eV}^4 \gg \rho_{\Lambda} \sim (2 \times 10^{-3} \text{ eV})^4 \sim 10^{-11} \text{ eV}^4$)



Harnessing the zero-point energy

Electroweak theory and Brout-Englert-Higgs mechanism

- Higgs field has vacuum expectation value $\langle 0|\phi|0\rangle = v \approx 246 \text{ GeV}$
($|\rho_{\text{Higgs}}| \sim m_{\text{H}}^2 v^4 / 2 \sim 10^{45} \text{ eV}^4$)

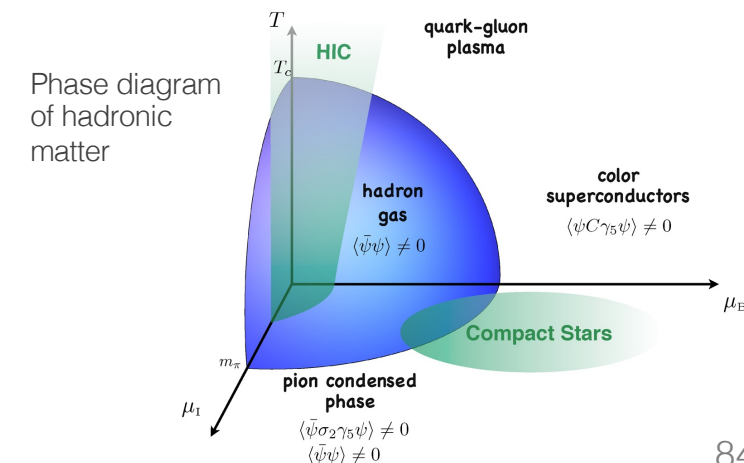


QCD vacuum

- The non-perturbative QCD vacuum involves the quark condensate (breaking chiral symmetry) and gluon condensate characterising the confined phase of quark matter
($|\rho_{\text{QCD}}| \sim (0.1 \text{ GeV})^4 \sim 10^{32} \text{ eV}^4$)

General relativity

- In General Relativity, the cosmological constant (Λ) which can be interpreted as a form of (dark) vacuum energy, drives the accelerated expansion of the universe

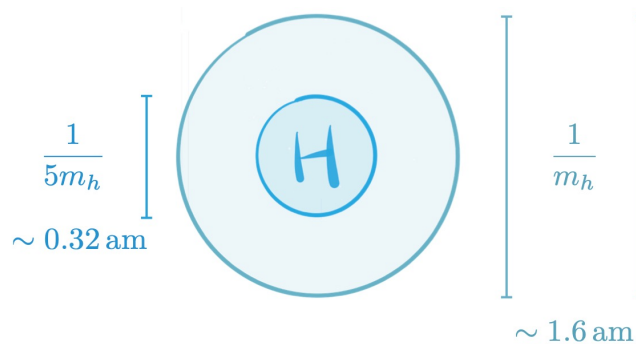


An analogy to the Higgs mechanism

Superconductivity

SC (BCS) theory	Higgs mechanism
Cooper pair Bose condensation	Condensed Higgs field
Electrically charged ($2e$)	Weak charge
Mass of the photon	Mass of W & Z bosons
$T_{\text{crit}} \sim \text{mK} - \text{several } 10\text{s of K}$	$T_{\text{crit}} = T_{\text{EW}} \sim 10^{15} \text{ K}$

→ 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

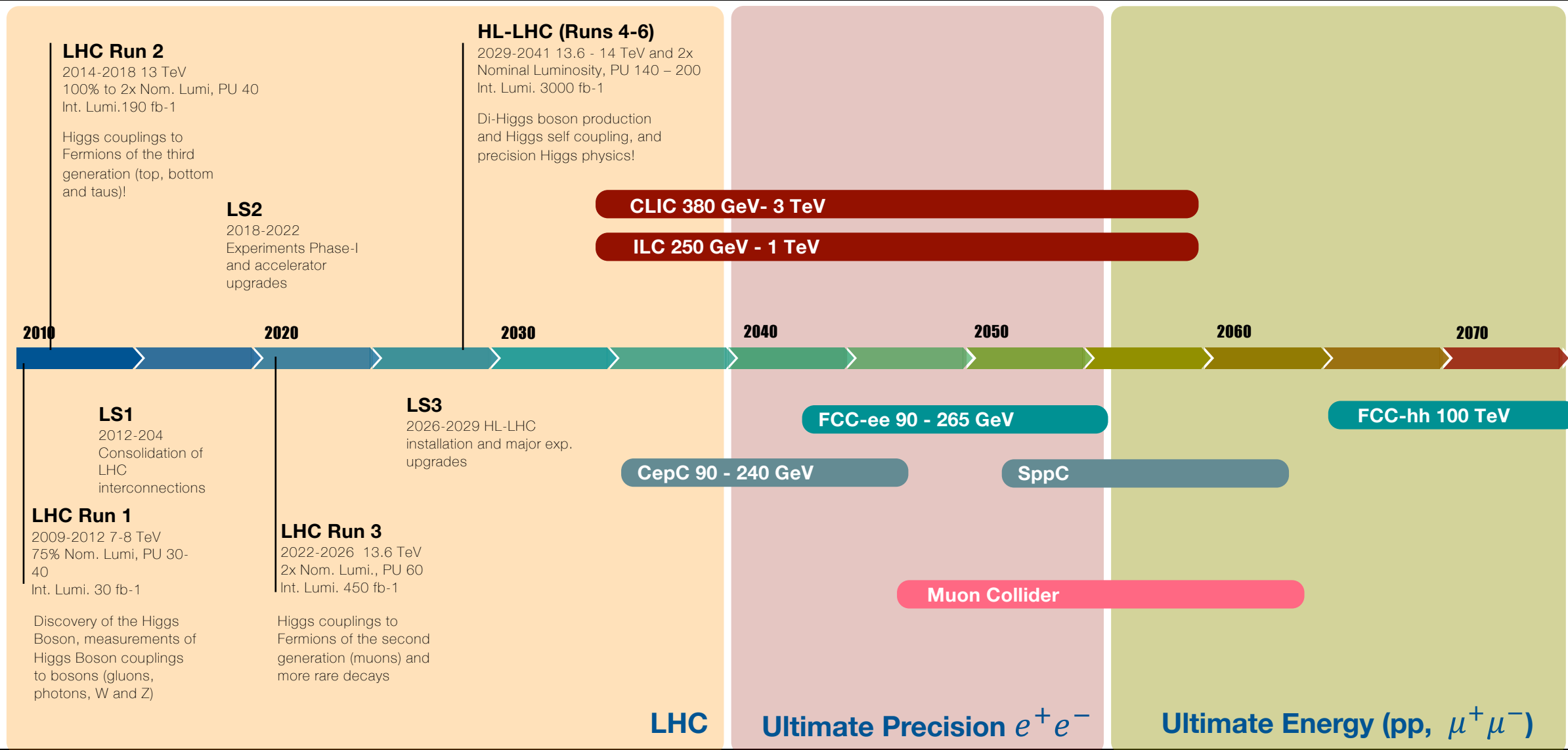
Scientific priorities for future energy- frontier projects



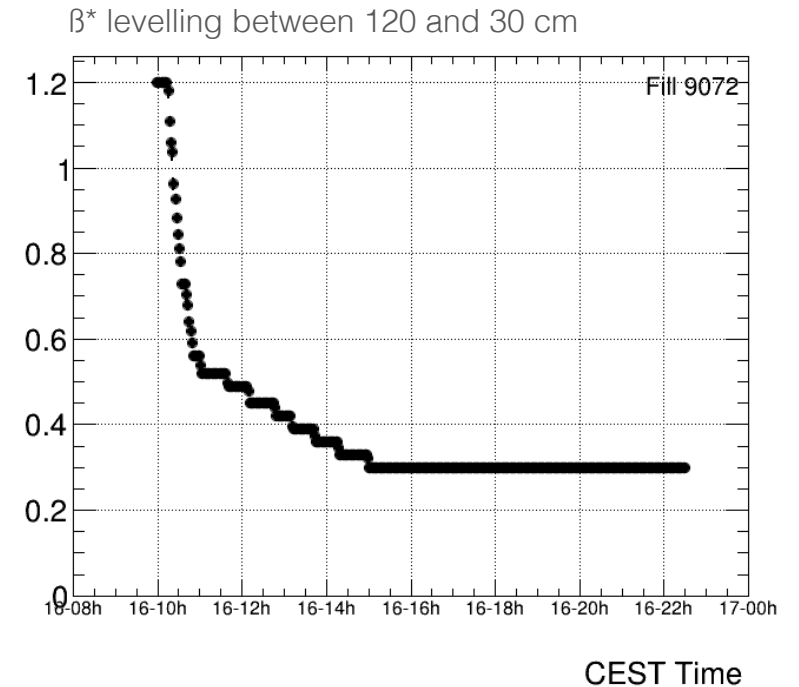
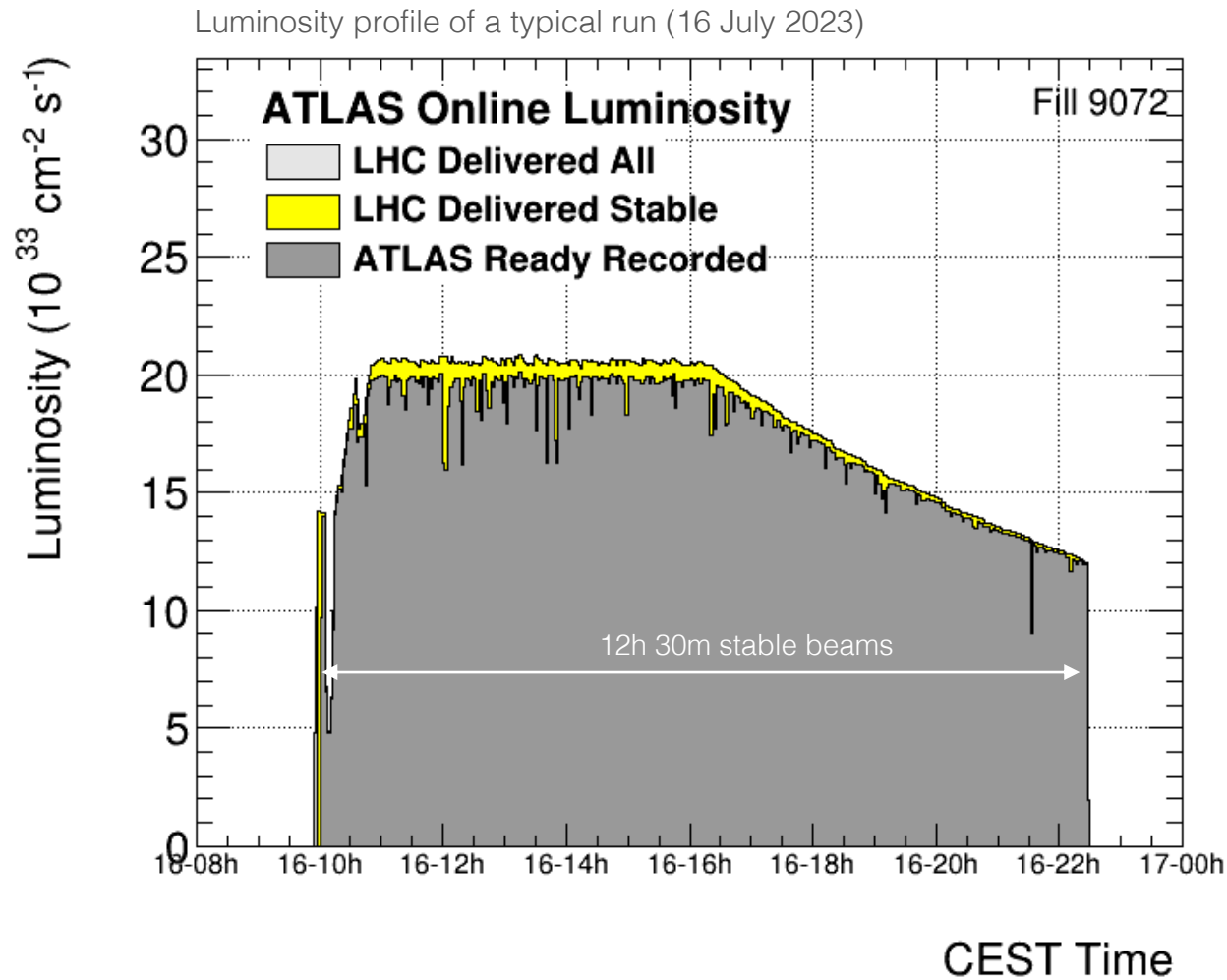
Recommendations of the 2020 Update of the European Strategy for Particle Physics:

- Fully exploit the HL-LHC
- Build an e^+e^- Higgs factory for high-precision studies of this unique particle
- Investigate the technical and financial feasibility of a future 100 TeV energy-frontier collider at CERN
- Ramp up the relevant R&D

A Scientific Mission for the 21st Century



A typical β^* levelled luminosity profile during fill



The LHC Run-2 has been transformative



ATLAS & CMS have released a series of Physics Reports synthesizing Run-2 achievements



**Electroweak, QCD
and flavour physics
studies with ATLAS
data from Run 2 of
the LHC**

[arXiv:2404.06829](https://arxiv.org/abs/2404.06829)

**Climbing to the
Top of the ATLAS
13 TeV data**

[arXiv:2404.10674](https://arxiv.org/abs/2404.10674)

**Characterising the
Higgs boson with
ATLAS data from
Run 2 of the LHC**

[arXiv:2404.05498](https://arxiv.org/abs/2404.05498)

**ATLAS searches for
additional scalars
and exotic Higgs
boson decays with
the LHC Run 2
dataset**

[arXiv:2405.04914](https://arxiv.org/abs/2405.04914)

**The quest to
discover
supersymmetry
at the ATLAS
experiment**

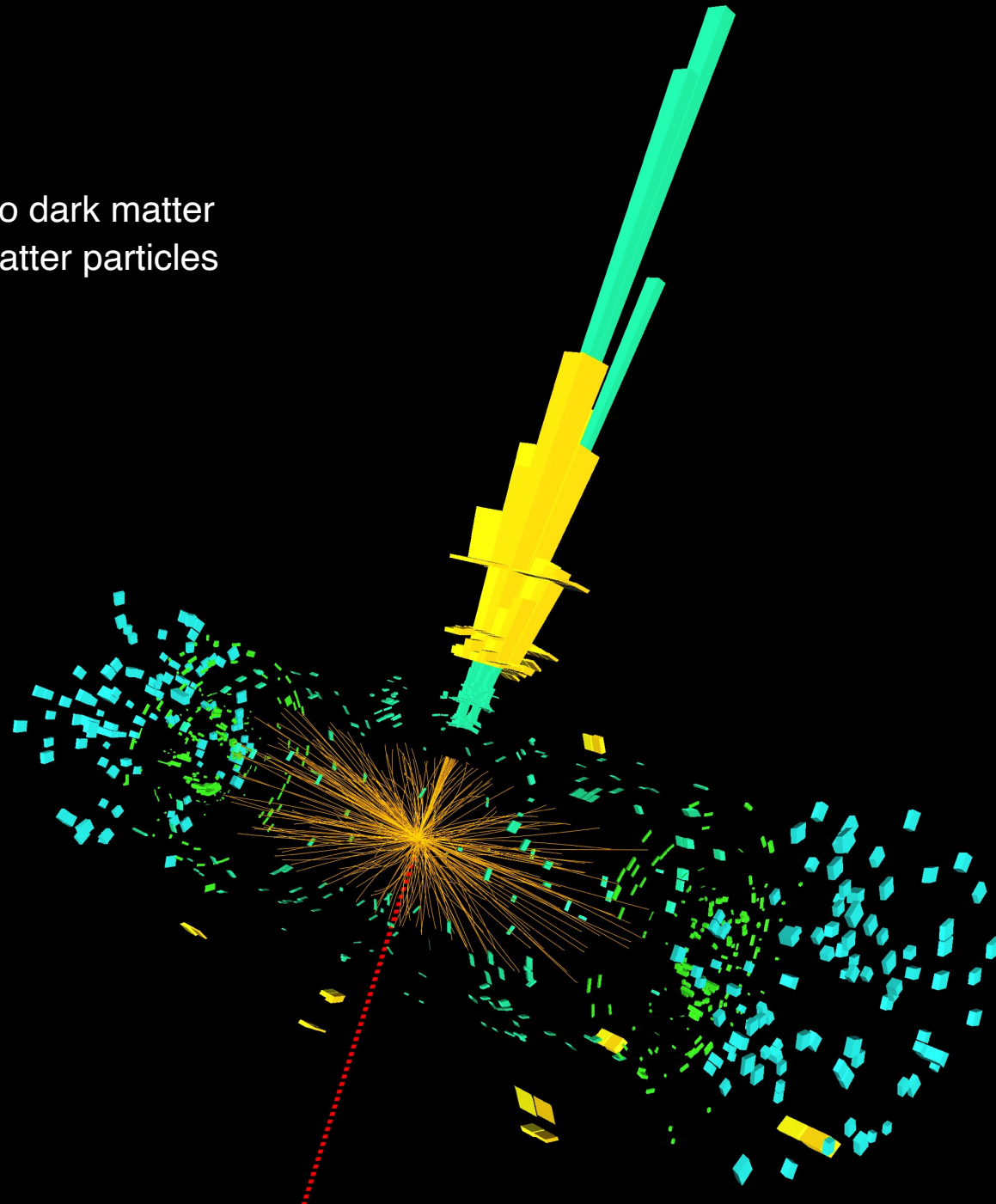
[arXiv:2403.02455](https://arxiv.org/abs/2403.02455)

**Exploration at
the high-energy
frontier ...
investigating
the exotic jungle
beyond the
Standard Model**

[arXiv:2403.09292](https://arxiv.org/abs/2403.09292)

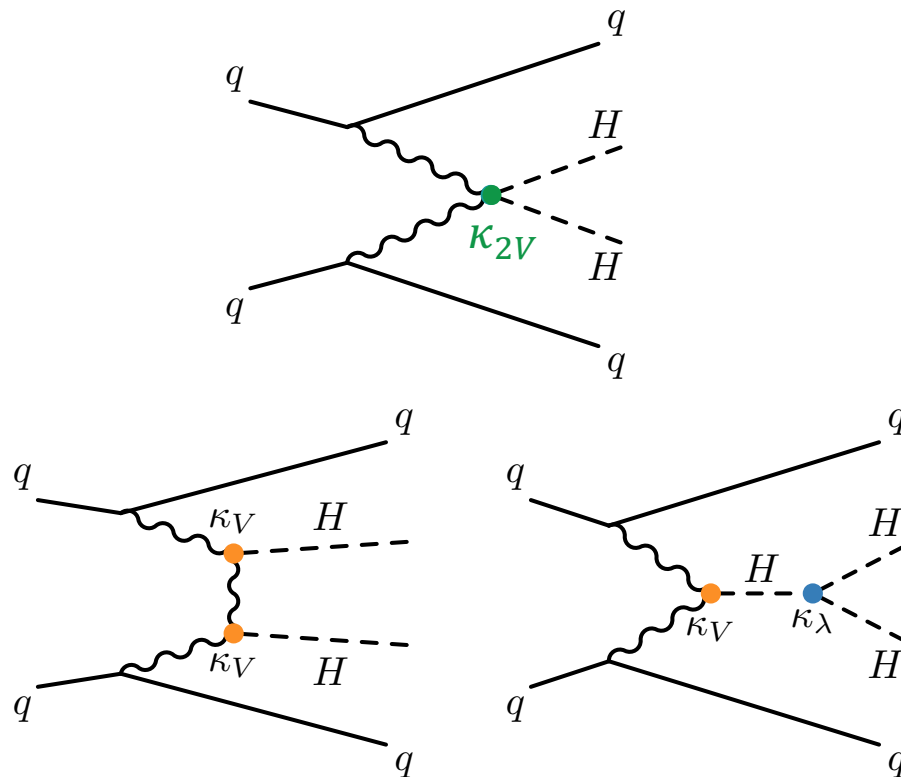
Dark matter

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



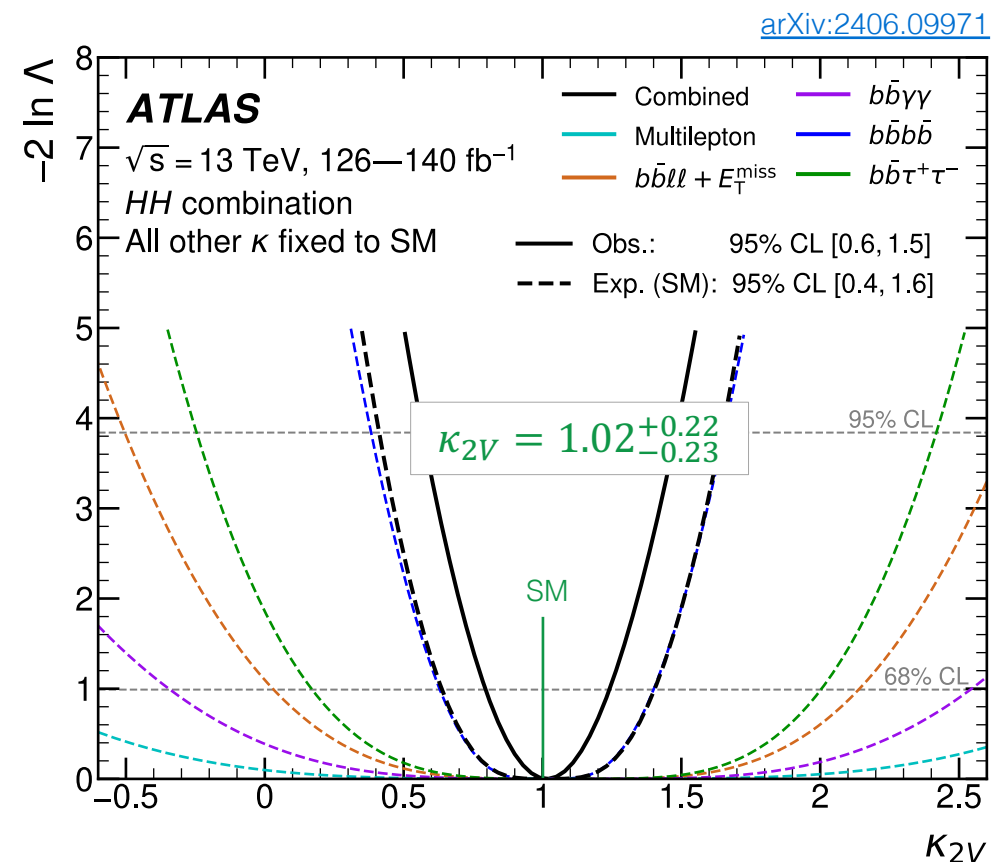
Higgs pair production

Weak boson fusion allows to constrain $VV \rightarrow HH$ scattering coupling $\kappa_{2V} = g_{VVHH}/g_{VVHH}^{\text{SM}}$, with $g_{VVHH}^{\text{SM}} = g_{VHH}^{\text{SM}}/v = 2m_V^2/v^2$



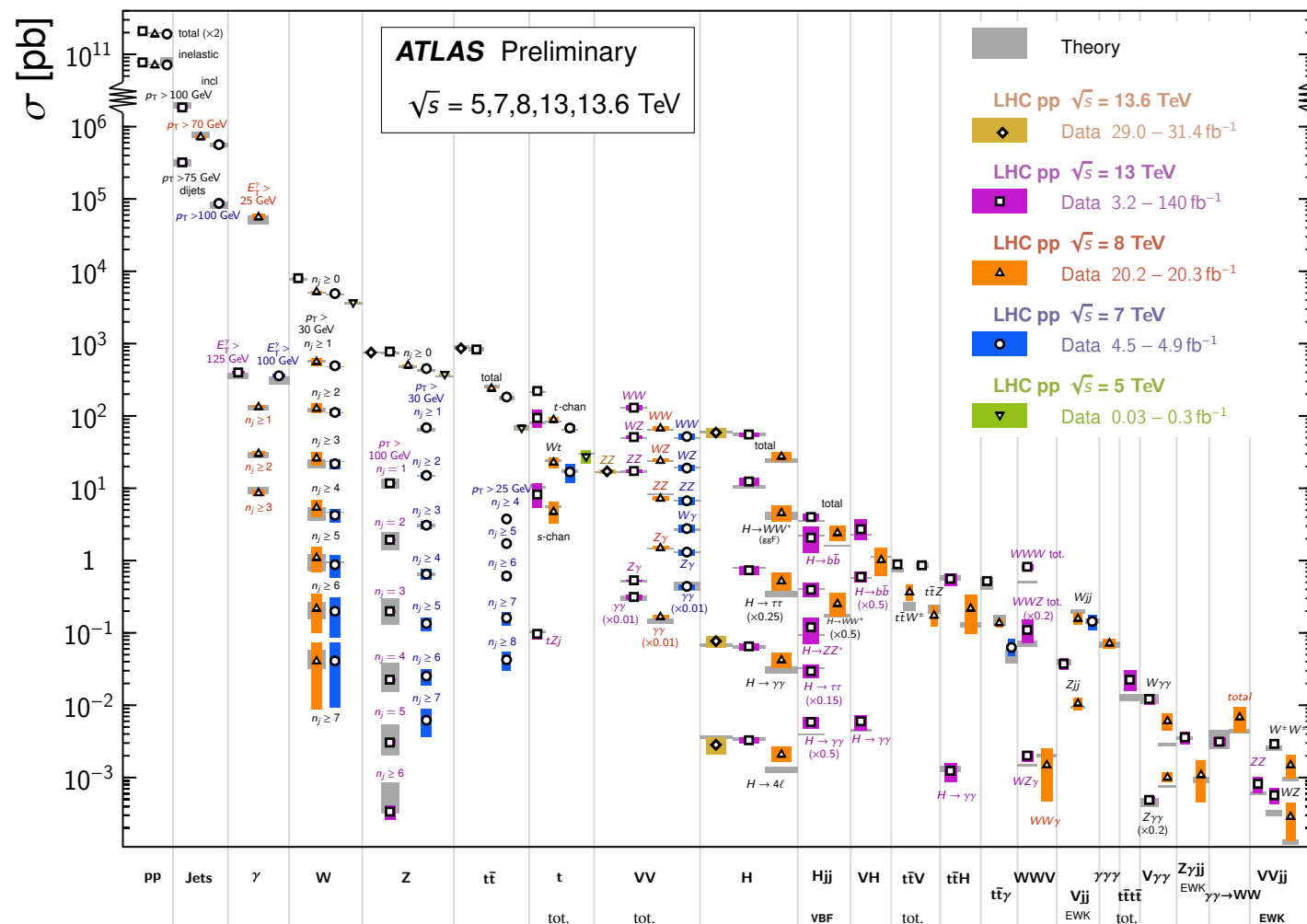
Steep rise in acceptance for $\kappa_{2V} \neq 1$ [arXiv:1611.03860], which provides sensitivity to κ_{2V} despite not being able to observe VBF HH ($\sigma = 1.7$ fb)

Strong dependence of cross section on $\kappa_{2\lambda}$.
 $\kappa_{2V} = 0$ is excluded despite not observing HH!



Status: October 2023

Standard Model Production Cross Section Measurements



A harvest of unique measurements probing new interactions and very rare processes, (so far) confirming the predictive power of the Standard Model

Theory developments and computations are key to this progress

Extremely successful LHC runs between 2010 and 2018, and continuing ...

Run 3 (2022–2025) at 13.6 TeV has begun

First 13.6 TeV collisions on 5 July 2022

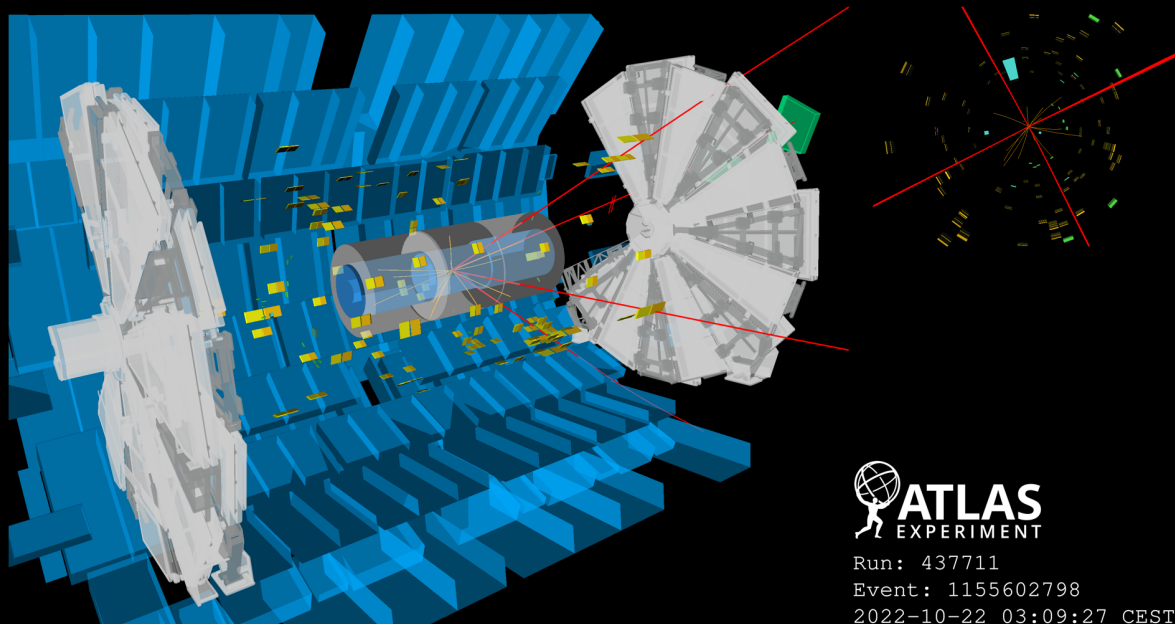
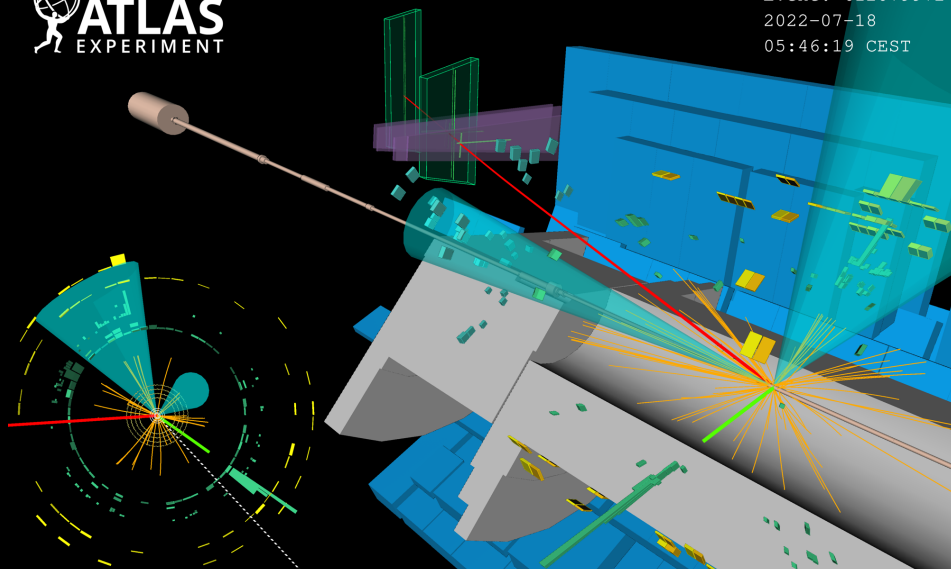


Run-3 data analysis

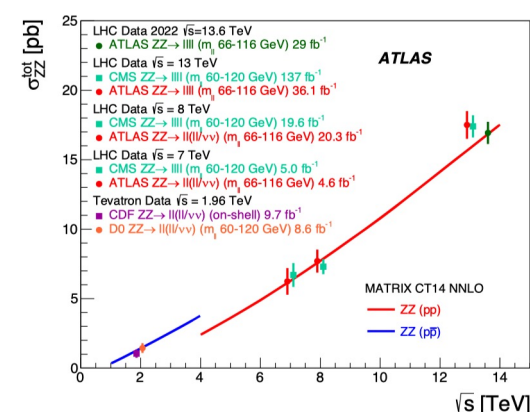
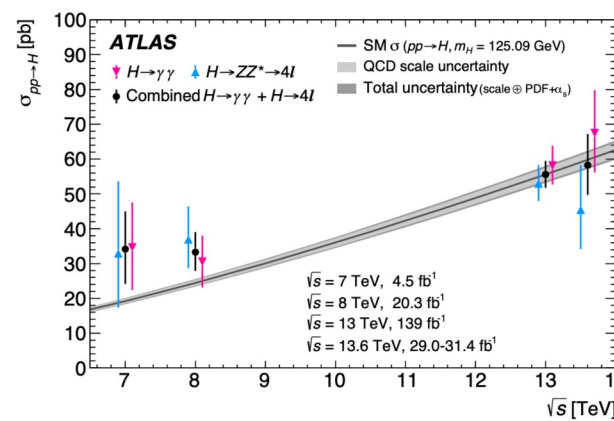
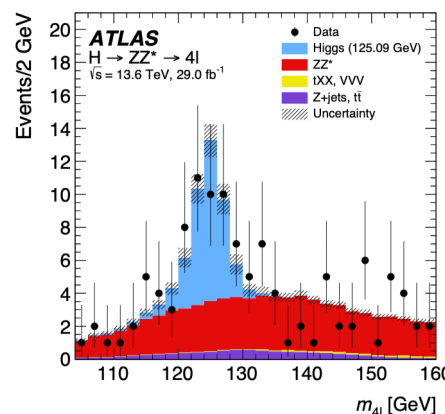
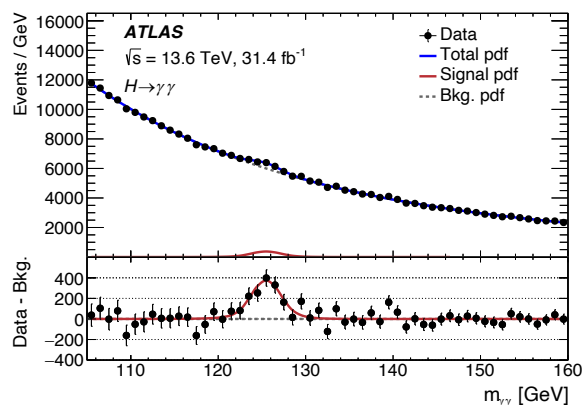
Excellent detector and reconstruction performance, 9 papers, 2 CONF notes, 7 PUB notes released on Run 3



Run: 428580
Event: 612079972
2022-07-18
05:46:19 CEST

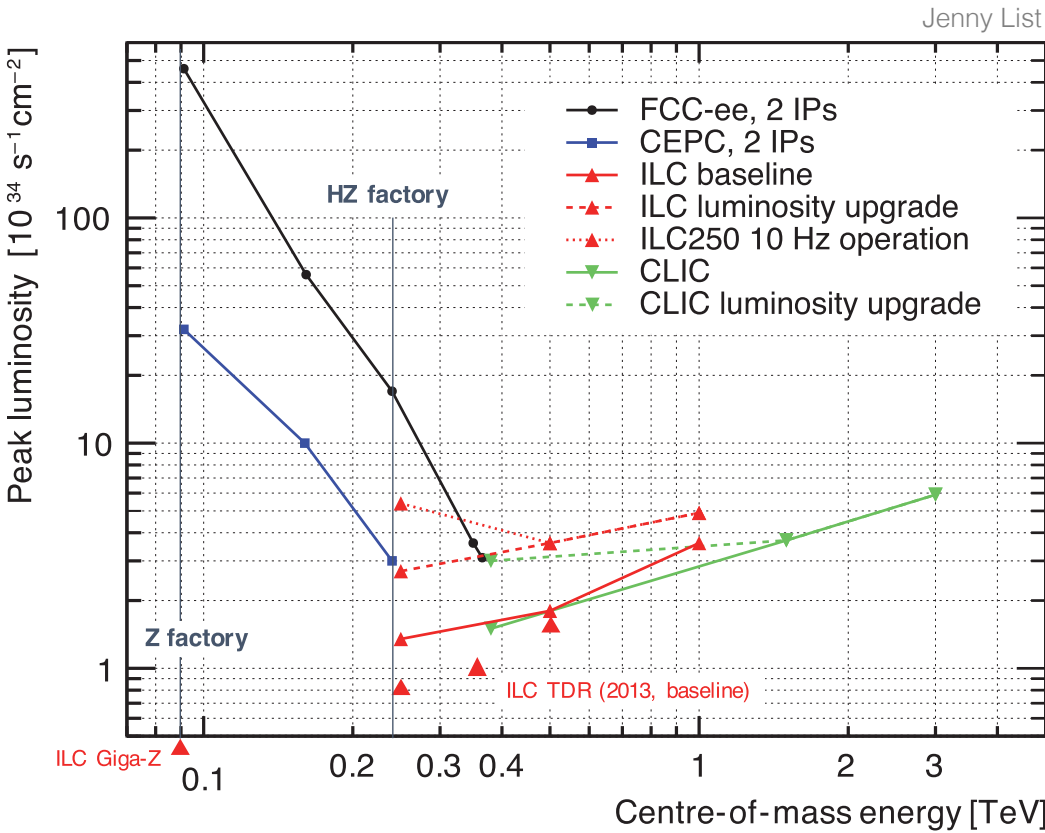


Run: 437711
Event: 1155602798
2022-10-22 03:09:27 CEST



Future e⁺e⁻ colliders

Highest luminosity for best precision and to probe rare and forbidden phenomena: physics the FCC-hh cannot do as well



Another important consideration is **one vs. two running experiments**

FCC-ee (14 years of operation)

All numbers assume 2 experiments

Run duration (years)	Centre-of-mass Energies (GeV)	Integrated Luminosity (ab^{-1})	$> 10^5 \times \text{LEP}$ Event Statistics
4	88-95	150	3×10^{12} visible Z decays
2	158-162	12	10^8 WW events
3	240	5	10^6 ZH events
5	345-365	1.5	10^6 $t\bar{t}$ events

Stable beam time assumed:

- FCC-ee: 1.08×10^7 s
- ILC: 1.6×10^7 s
- CLIC: 1.2×10^7 s

Compare:

- SLD: $< 1.0 \times 10^7$ s
- Belle: $< 1.2 \times 10^7$ s
- LHC: $< 0.7 \times 10^7$ s

ILC (22~24 years of operation)

- Giga-Z: 0.1 ab^{-1} in 1~3 years
- 250 GeV: 2.0 ab^{-1} in 11.5 years
- 350 GeV: 0.1 ab^{-1} in 1 year
- 500 GeV: 4.0 ab^{-1} in 8.5 years

CLIC (> 20 years of operation)

- Giga-Z: ?
- 380 GeV: 1.0 ab^{-1} in 8 years
- Upgrade to $> 1 \text{ TeV}$ in > 15 years

Future e^+e^- colliders

The question whether or not an e^+e^- collider should be upgradable to at least 500 GeV depends on the expected HL-LHC and FCC-hh potential.

Main considerations:

1) Top-Higgs coupling: expectation at HL-LHC: $\sigma(\kappa_t) = 3.4\%$ (from mostly $ttH(\rightarrow \gamma\gamma)$, 3.7M ttH produced in total)

- FCC-hh: 1.0% (systematics limited)
- ILC-500 (4 ab^{-1} , 8.5 years): 6.3% ($\sim 9\text{k}$ ttH produced)
Note: strong cross-section rise for > 500 GeV (2% precision at 600 GeV)

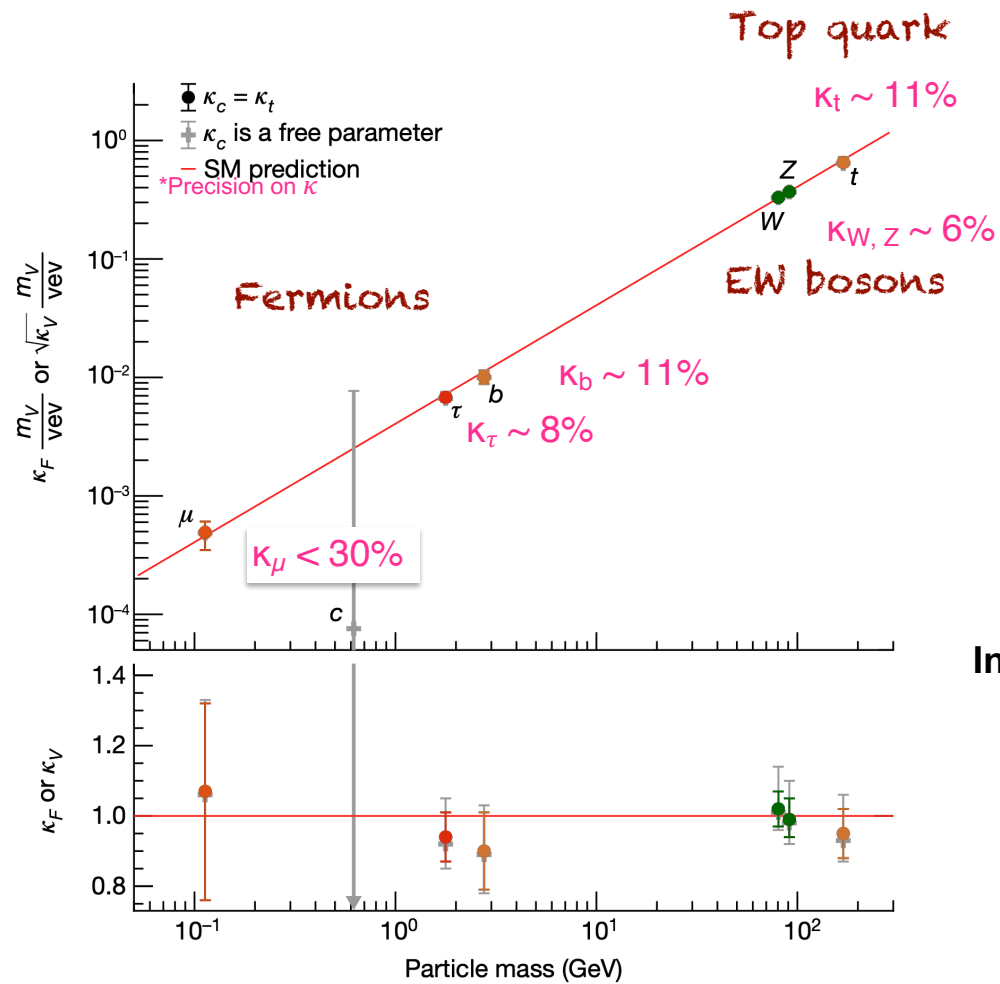
1) Higgs self-coupling: expected precision on λ_3

- HL-LHC: $< 50\%$ (HH) + some constraint on λ_3 in single-H loops
- FCC-ee: 21% from λ_3 in loops* (EFT), note also information from energy dependence of λ_3 at 240 and 365 GeV
- ILC-500: 27% (HH), 32% (λ_3 in loops) [The ILC a Global Project, 1903.01629]
- ILC-1000 and CLIC-3000 achieve $\sim 10\%$ (36% for CLIC-1500)
- FCC-hh: 5% (HH), $530 \times$ events at HL-LHC

* $\sigma_{ZH}^{\text{NLO}} \approx \sigma_{ZH}^{\text{NLO,SM}}(1 + 0.014 \delta\kappa_3)$

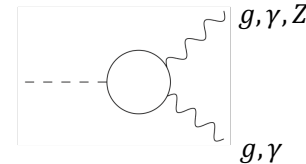
Electron–positron Higgs factories

Expected precision on Higgs couplings: **LHC Run 2 (ATLAS today)**



Nature 607, 52-59 (2022)

Effective loop



$\kappa_\gamma \sim 6\%$

$\kappa_g \sim 7\%$

$\kappa_{Z\gamma} \sim 30\%$

Gluon and photon

Invisible Branching

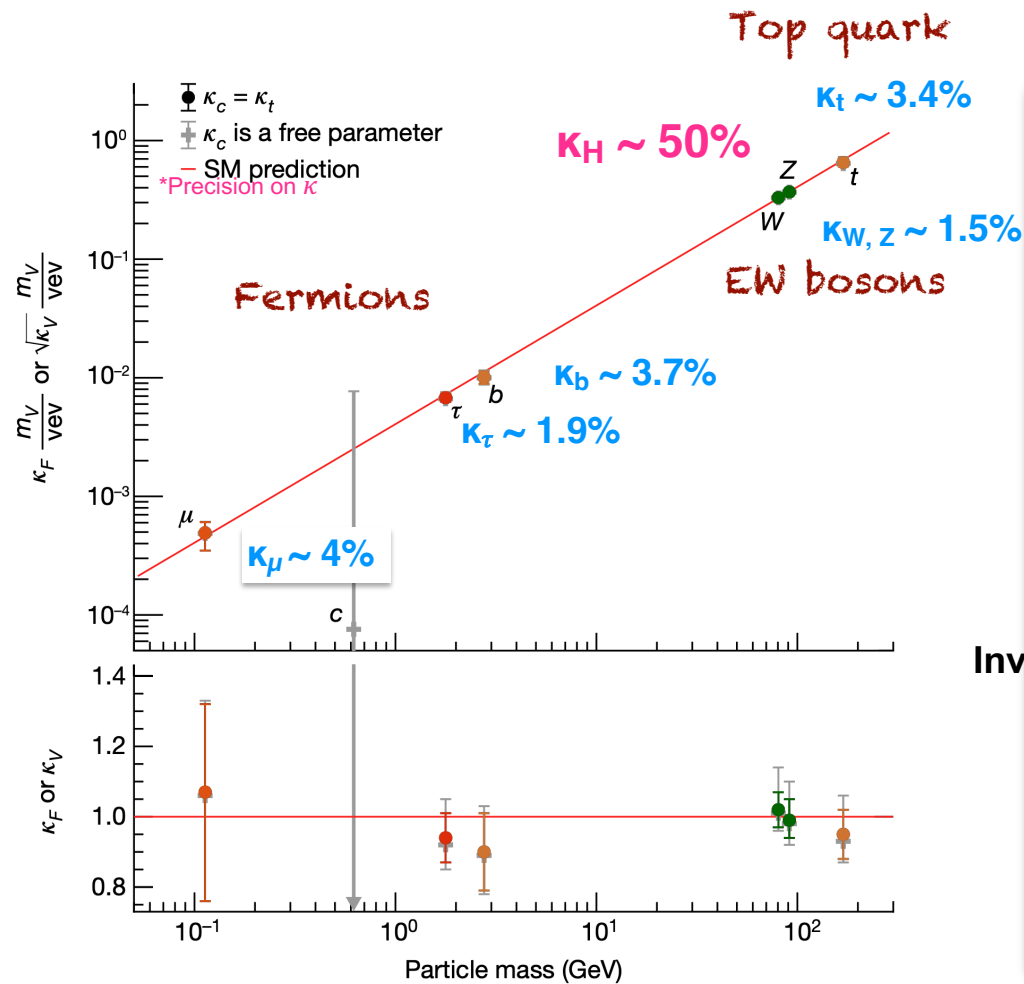
$\text{Br}_{\text{inv}} < 11\%$ **DM?**

Higgs width

$\Gamma_H \sim 100\%$

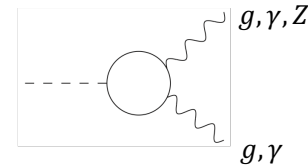
Electron–positron Higgs factories

Expected precision on Higgs couplings: **HL-LHC**



Nature 607, 52-59 (2022)

Effective loop



$\kappa_\gamma \sim 1.8\%$ Gluon and photon

$\kappa_g \sim 2.5\%$

$\kappa_{Z\gamma} \sim 9.8\%$

Invisible Branching

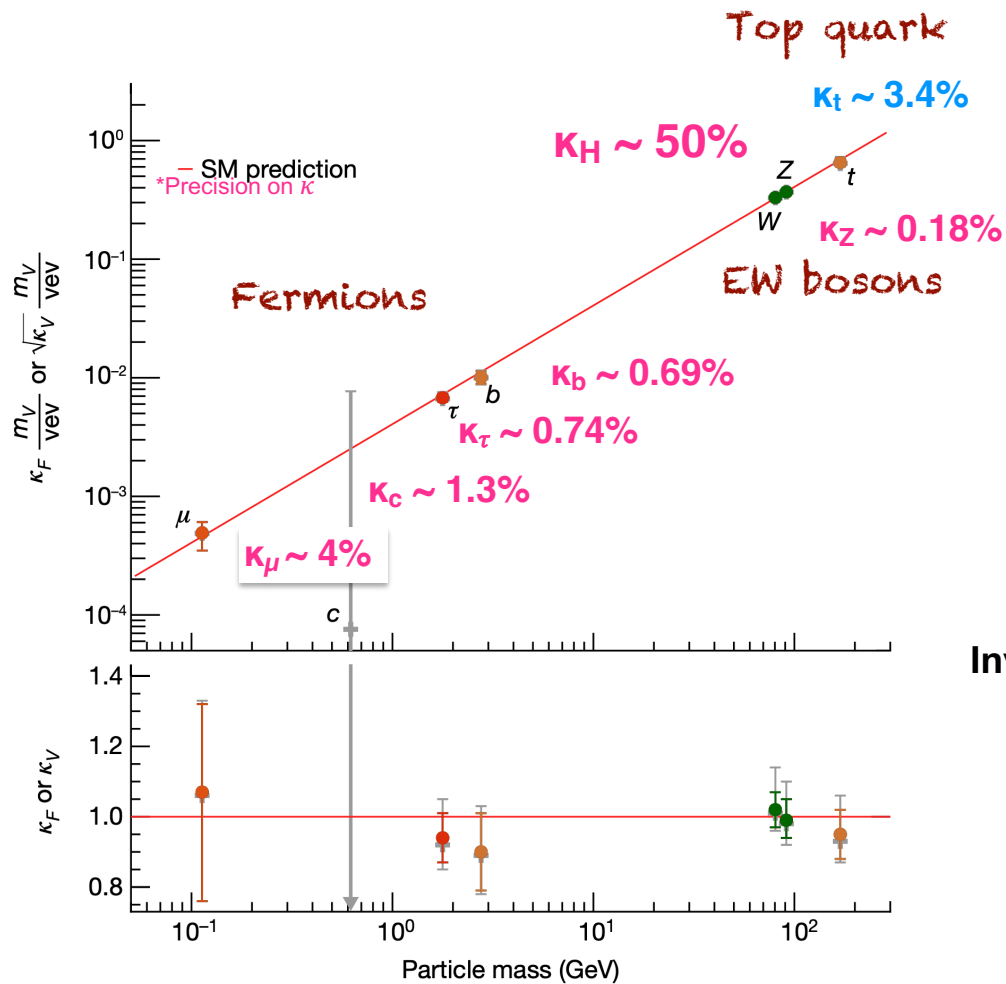
$\text{Br}_{\text{inv}} < 2.5\%$ DM?

Higgs width

$\Gamma_H \sim 20\%$

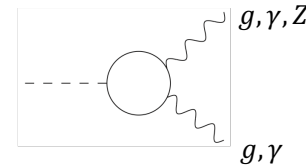
Electron–positron Higgs factories

Expected precision on Higgs couplings: **FCC-ee**



Nature 607, 52-59 (2022)

Effective loop



$\kappa_\gamma \sim 1.8\%$

$\kappa_g \sim 1.0\%$

$\kappa_{Z\gamma} \sim 9.8\%$

Gluon and photon

Invisible Branching

$\text{Br}_{\text{inv}} < 0.5\%$

Higgs width

$\Gamma_H \sim 1.3\%$

Rule of thumb (Higgs):

Probing a scale Λ requires precision of order v^2/Λ^2 , i.e. sub-percent to reach ~ 10 TeV

Precision on key electroweak observables:

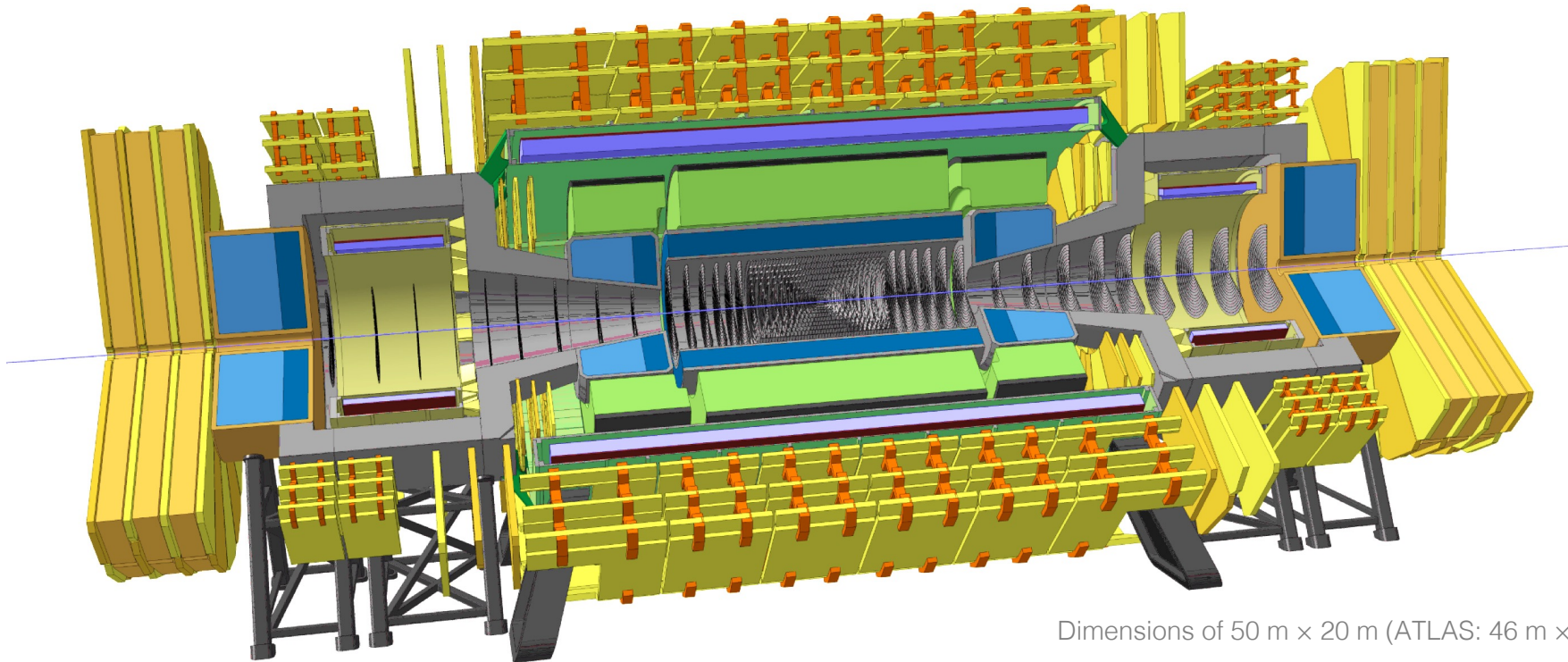
$$m_Z \sim 10^{-6}, m_W \sim 10^{-5}, m_{\text{top}} \sim 10^{-4}$$

$$\sin^2 \theta_W \sim 3 \cdot 10^{-6}, \alpha_{\text{QED}}(m_Z^2) \sim 10^{-5}, \alpha_S(m_Z^2) \sim 10^{-4}$$

Detector challenges for hadron colliders

FCC-hh key detector design challenges

- High luminosity: extremely large pileup, high occupancy and data rates, high trigger rates
- At FCC-hh Higgs produced up to rapidity of ~ 6.5 (0.3 deg) (up to 2.5 (9 deg) at LHC)
- Detector granularity will be critical: decay product of a Z at 10 TeV separated by $\Delta R \sim 0.01$



Dimensions of 50 m $\times$ 20 m (ATLAS: 46 m $\times$ 25 m)

Muon collider

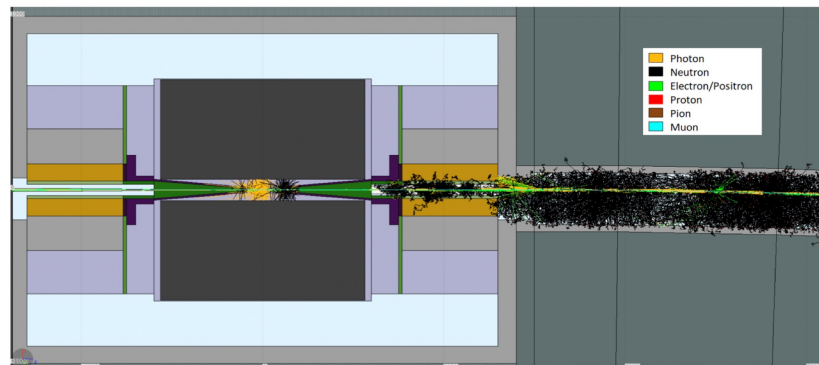
Best of all worlds?

- High energies, high luminosities with excellent luminosity per MW ratio, (relatively) clean lepton collision events
- Similar precision reach as FCC-ee on Higgs precision but not for EW precision measurements at Z and WW thresholds
- Multi-TeV energy reach for new physics searches

...but incredibly challenging!

Conceptual and design challenges

- High neutrino flux (requires mitigation above 3 TeV)
- Beam backgrounds challenge detector design
- Production, cooling and preservation of the muons within ~ 0.1 s



Constant muon decays bring beam backgrounds, and radiation levels similar to LHC

Initial targets for the integrated luminosities have been defined, namely 1, 10 and 20 ab^{-1} for 3, 10 and 14 TeV, respectively

MAP (Muon Accelerator Program) — proton driven scheme

Reduction of the longitudinal and transverse emittance with a sequence of absorbers and RF cavities in a high magnetic field

