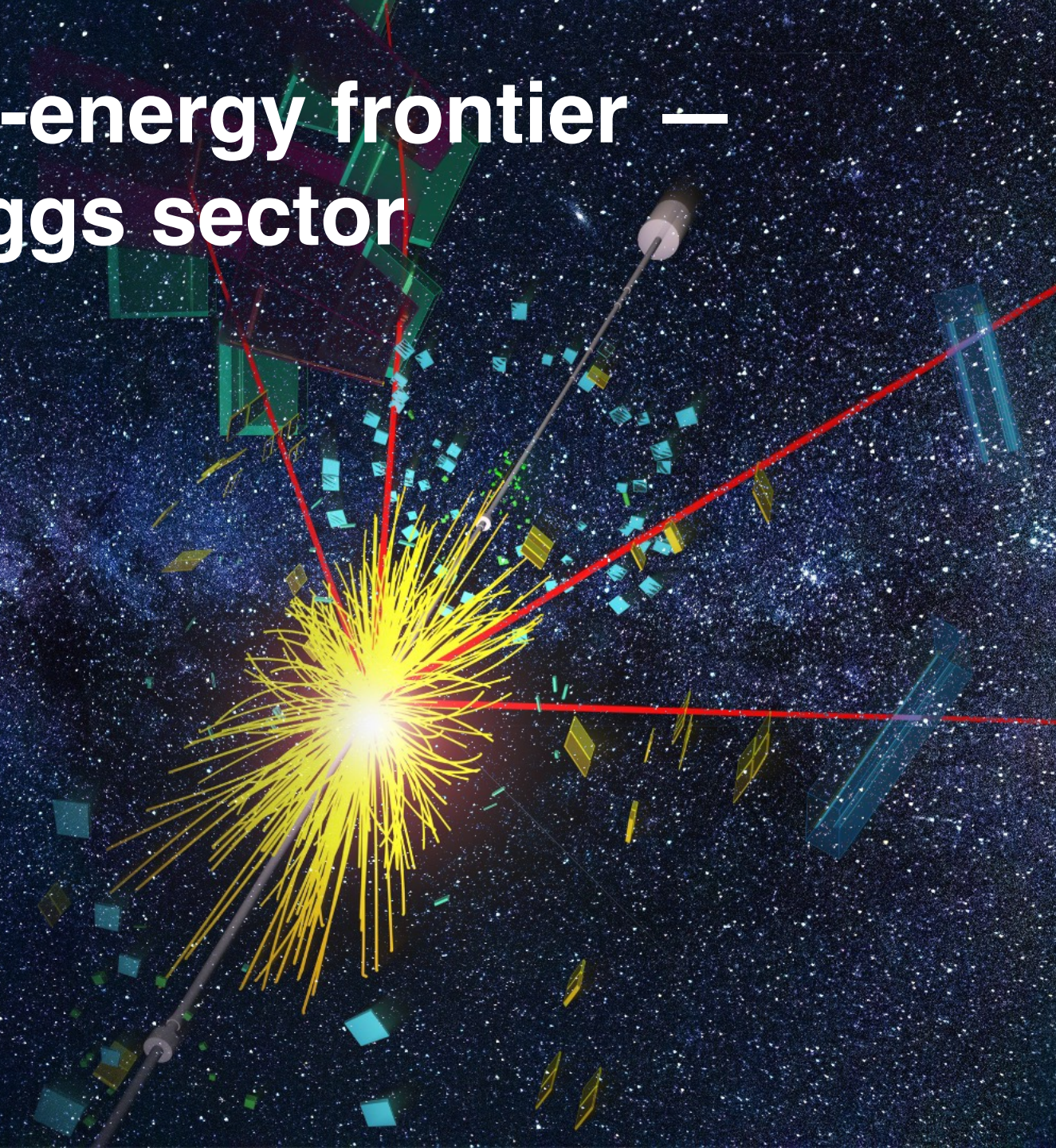


Physics at the high-energy frontier — Deciphering the Higgs sector



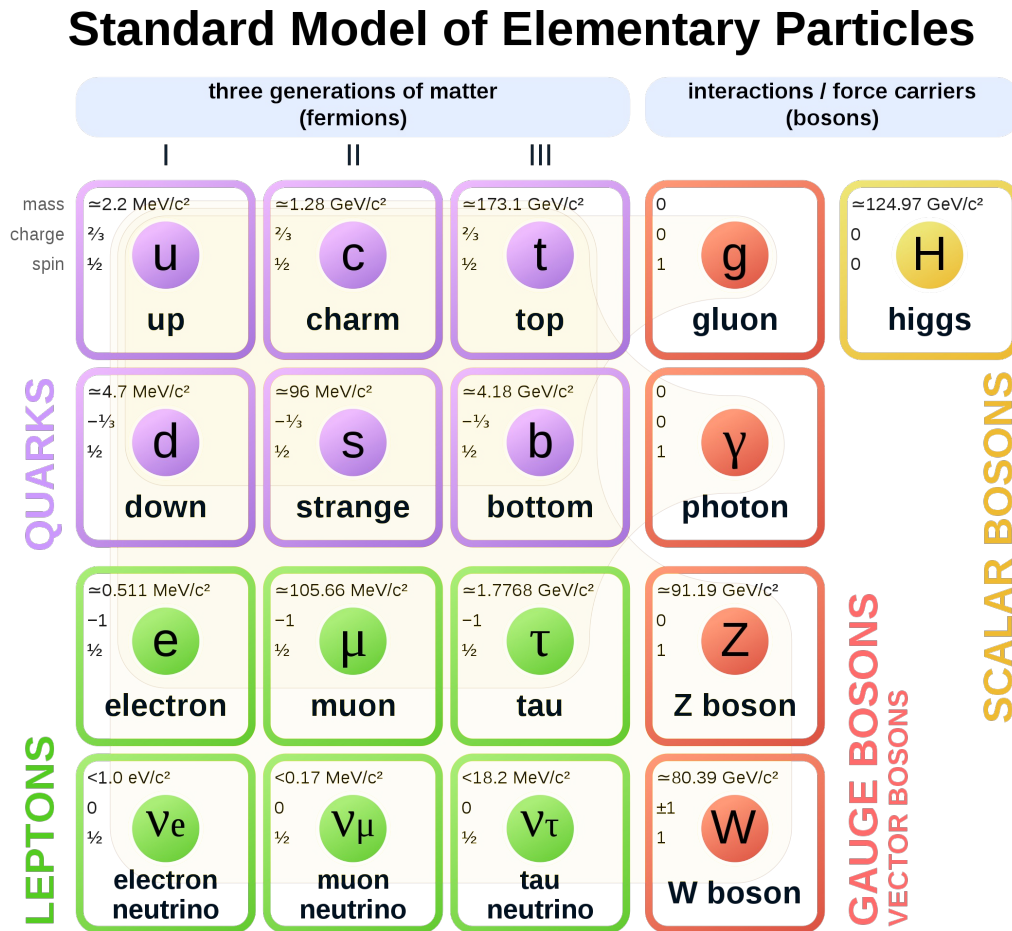
Andreas Hoecker (CERN)

Max-Planck-Institut für Physik, 28 June 2024



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

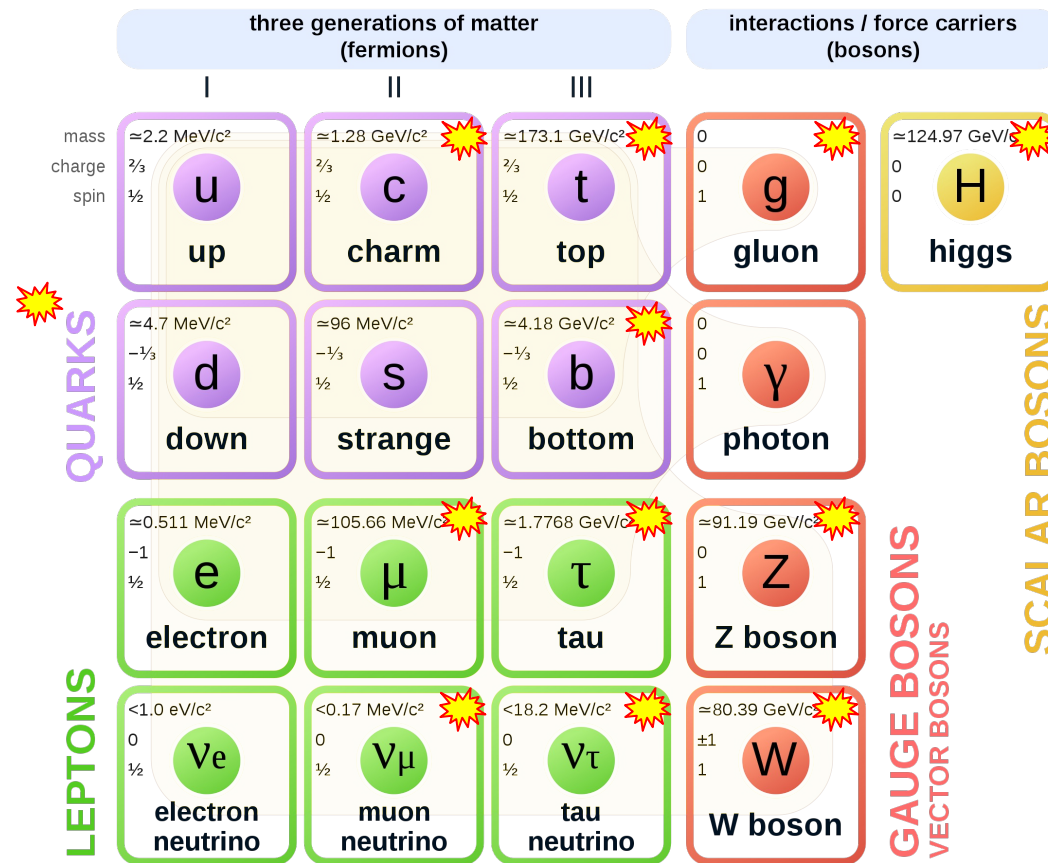
The sub-atomic structure of matter and its interactions **is described by the Standard Model**



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



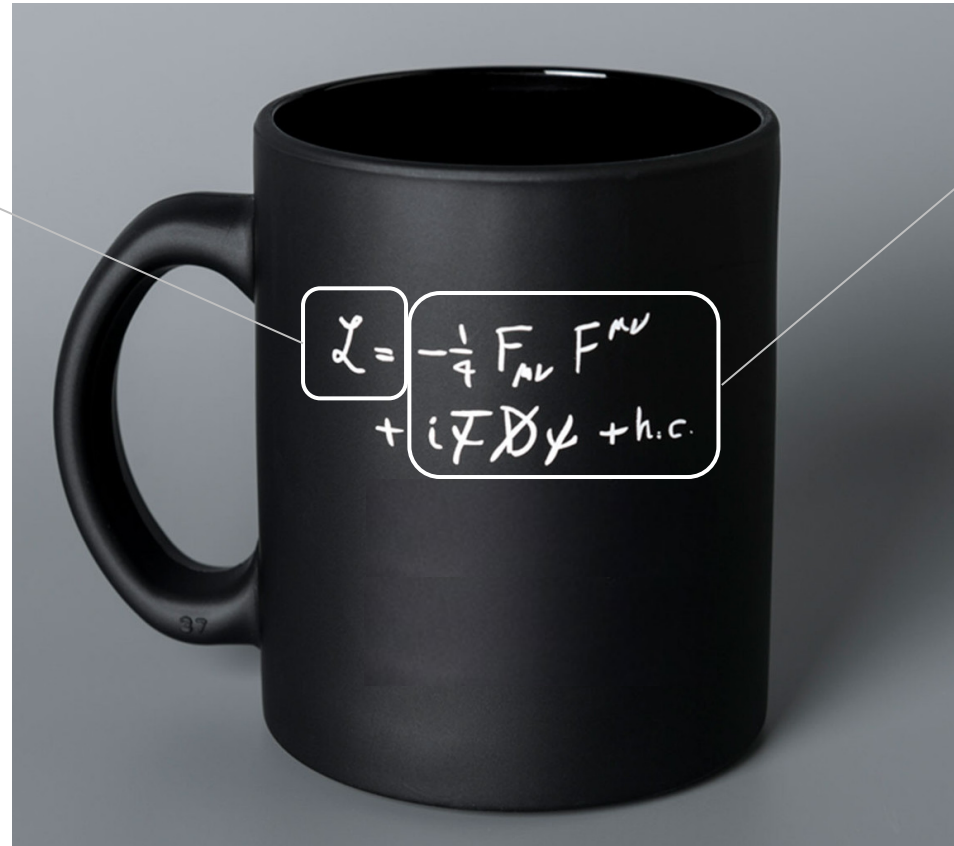
Decades of international high-technology **accelerator-based** research brought us thus far

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

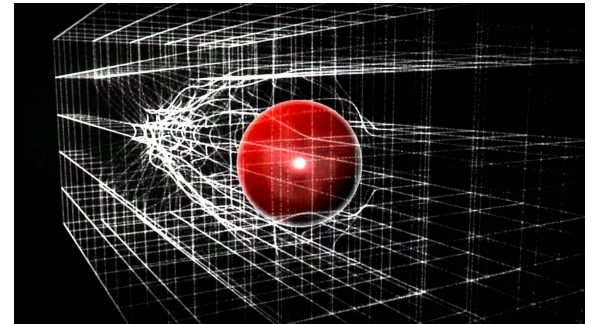
A problem: gauge symmetry requires massless spin-1 “gauge” (=force) bosons

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 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 coupling of the Higgs field with a particle gives the particle potential energy (ie, the particle draws energy out of the Higgs field) and thus mass. The stronger the coupling, the greater the mass.

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

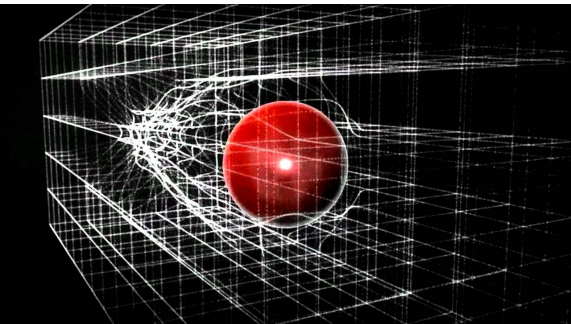


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Peter Ware Higgs (1929 – 2024)

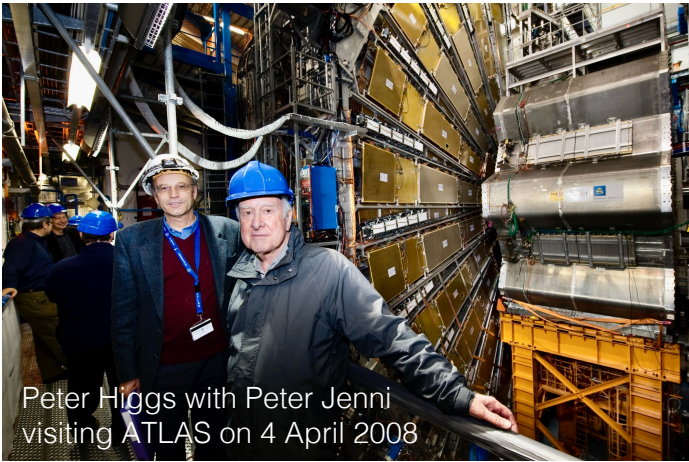


Broken Symmetries and the Masses of Gauge Bosons — or how to change the course of physics with a good idea on two pages — together with the other famous works from his colleagues in 1964

[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:

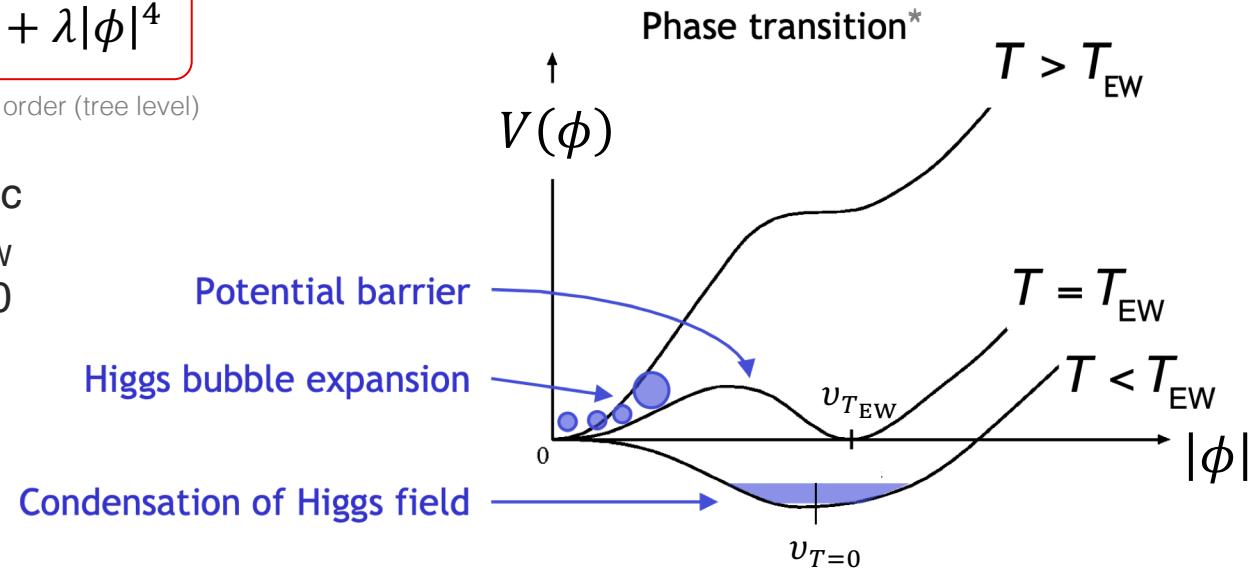
$$V(\phi) = -\mu^2 |\phi|^2 + \lambda |\phi|^4$$

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:

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



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)

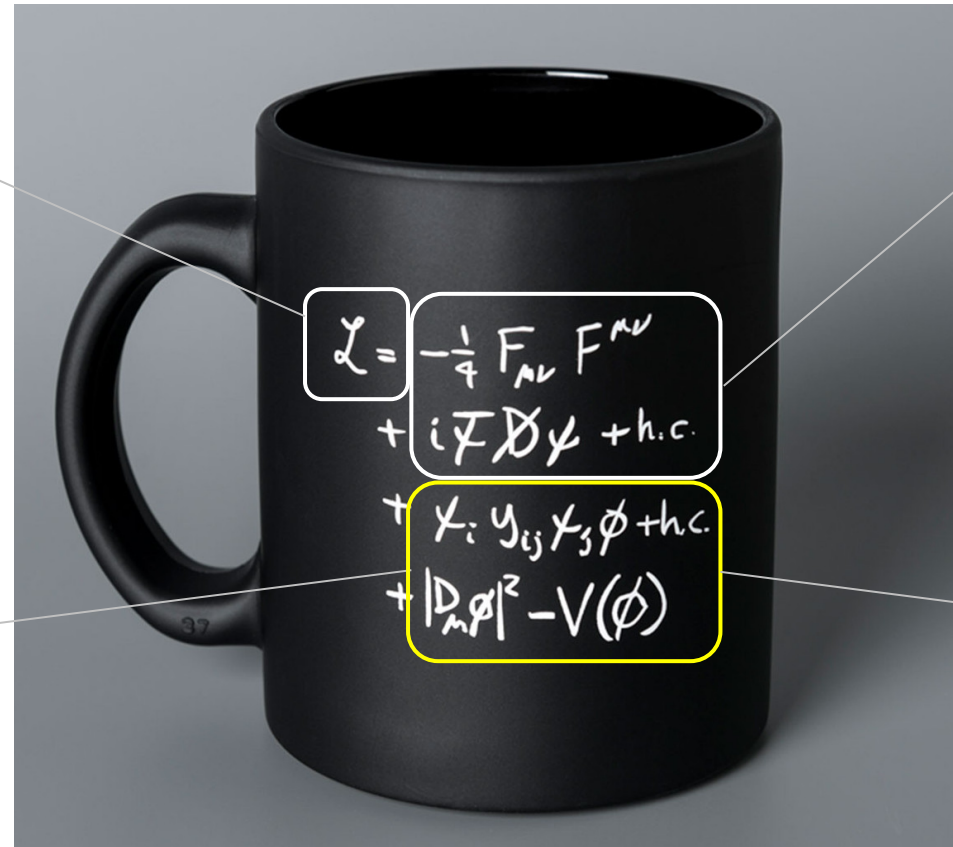
Completing the Standard Model

The scalar Higgs sector completes the Standard Model

The **SM Lagrangian**

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

Unpleasant: not governed by symmetries, 26 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**

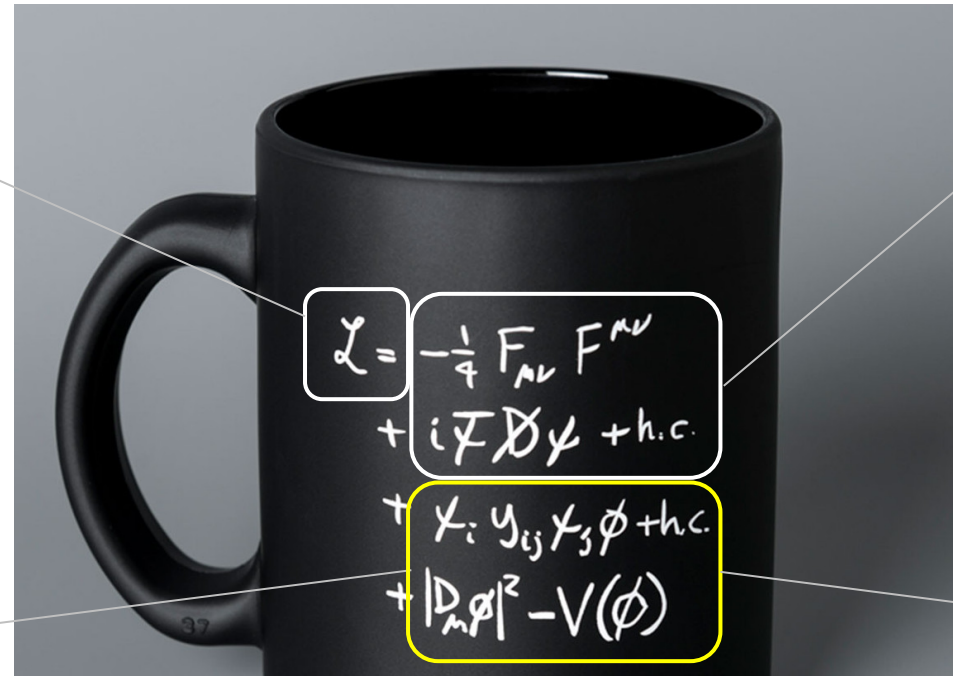
The lower left term describes the **interaction of the Higgs field with the weak-interaction bosons, which thereby obtain mass**

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

Completing the Standard Model

The scalar Higgs sector completes the Standard Model

The **SM Lagrangian**



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

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

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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**

Unpleasant
symmetries, 2
large hierarc

The Standard Model is a highly predictive theory

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

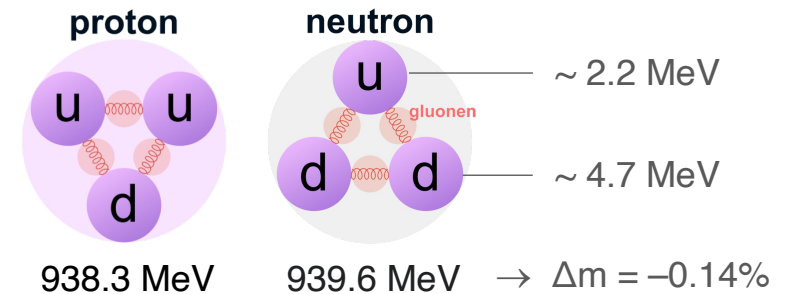
Standard Model and experiment agree within a relative precision of 10^{-10} !

describes the
) with non-zero

Gauge symmetry and the Higgs mechanism

A few comments:

- The Higgs mechanism is required because we assume the bosons and fermions are 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 Higgs mechanism doesn't tell us everything: there is this field which generates mass, but we do not know why some particles draw a lot of energy out of this field and others much less
- The vacuum energy density of the Higgs field is 10^{56} times larger than the dark energy observed*. “It would curve the universe into an object roughly the size of a football” (Veltman, 1986)



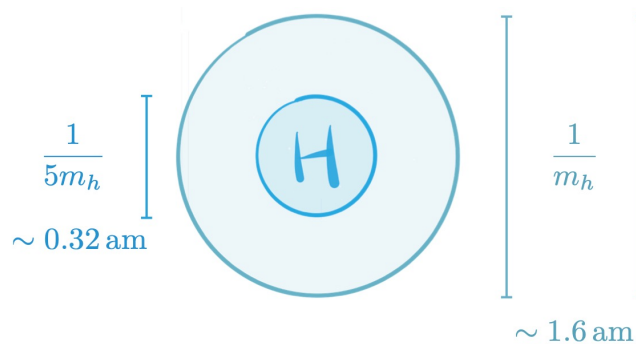
*Accelerating universe (dark energy) corresponds to $\rho_{\text{vacuum}} = \mu^4$, $\mu \sim 0.002$ eV

An analogy to the Higgs mechanism

Superconductivity

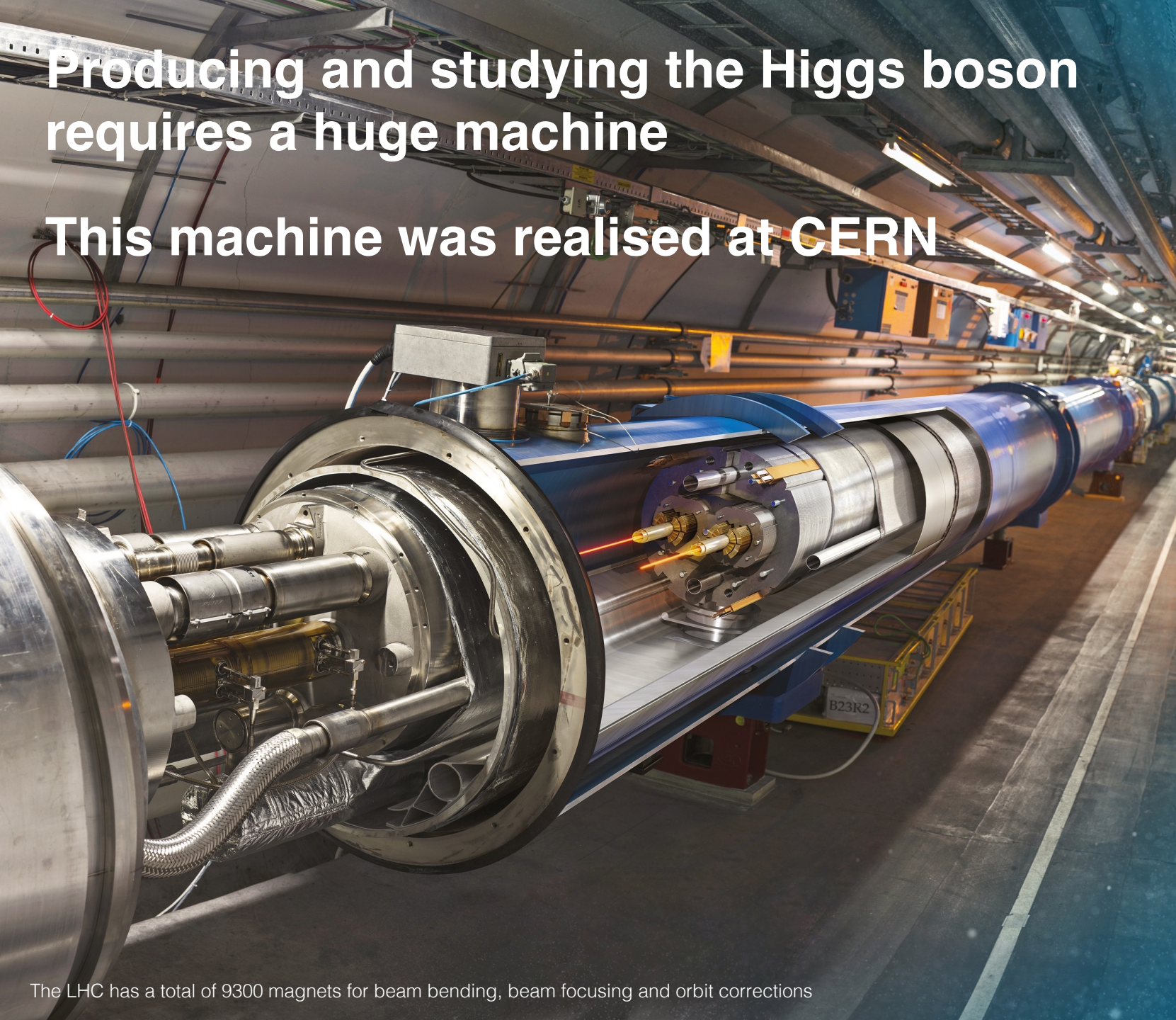
SC (BCS) theory	Higgs mechanism
Cooper pair Bose condensation	Condensed Higgs field
Electrically charged (2e)	Weak charge
Mass of the photon	Mass of W & Z bosons
$T_{\text{crit}} \sim \text{mK} - \text{several 10s of K}$	$T_{\text{crit}} = T_{\text{EW}} \sim 10^{15} \text{ K}$

→ 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



Producing and studying the Higgs boson
requires a huge machine

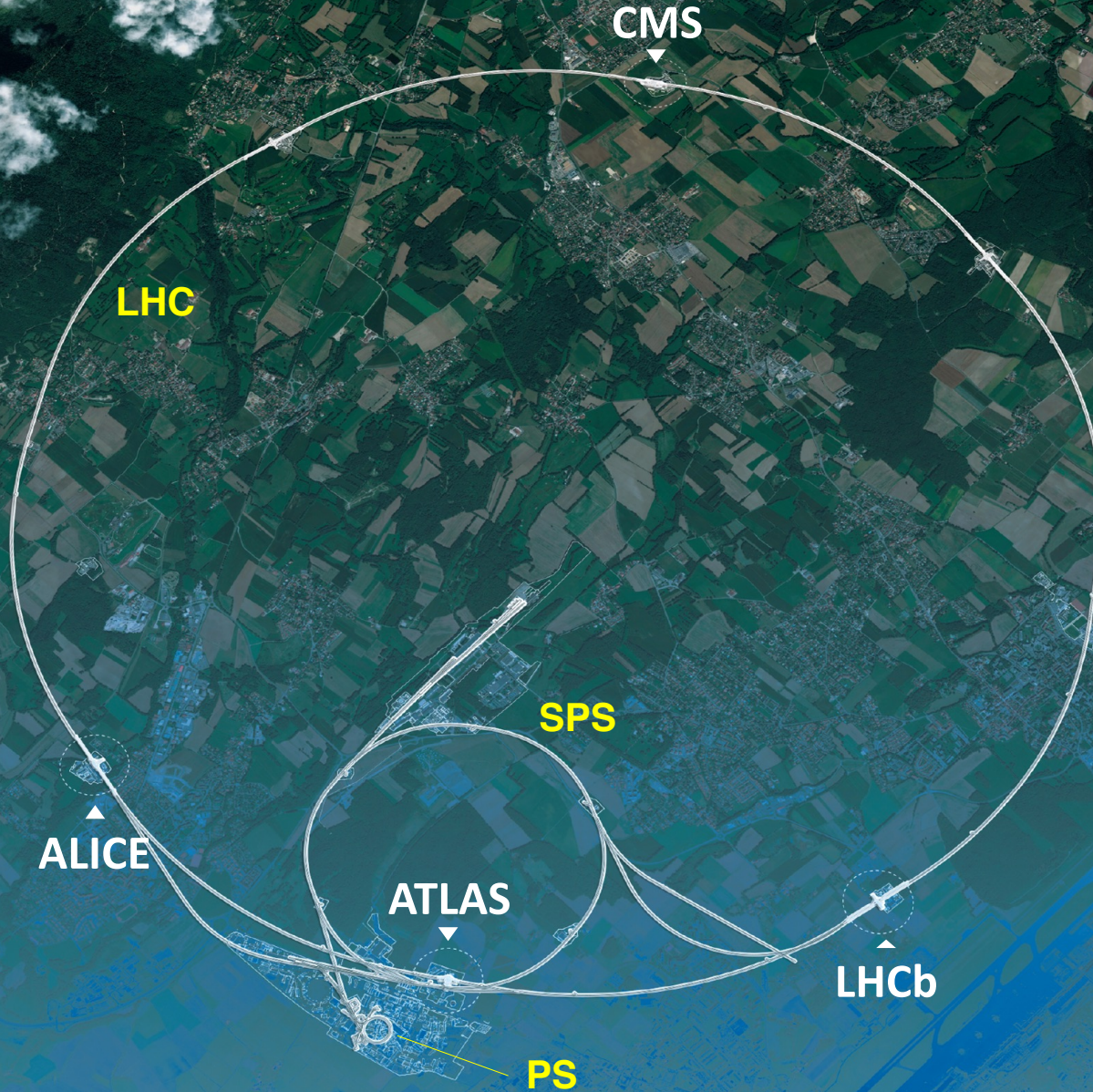
This machine was realised at CERN

Large Hadron Collider (LHC)

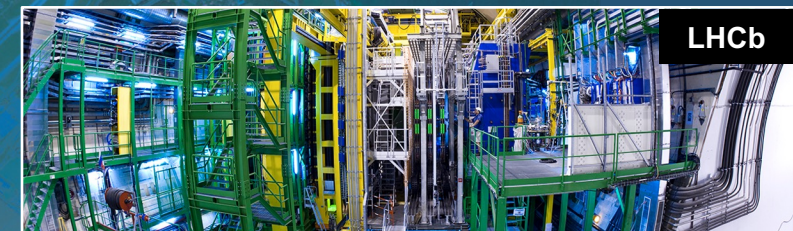
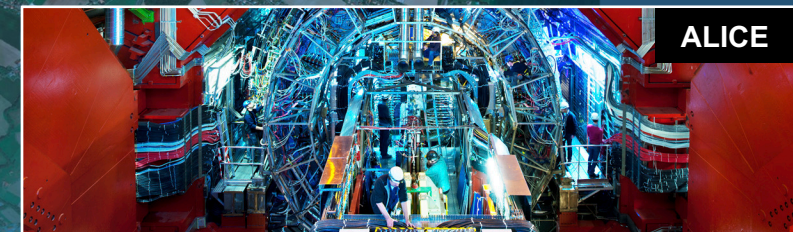
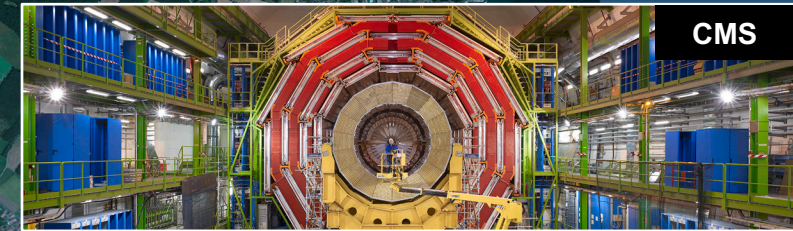
- 27 km underground accelerator and collider
- Superconducting magnets (1.9 K = -271.3°C) steer the particles around the ring
- Proton and ions are accelerated to multi-TeV scale energies before they collide

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

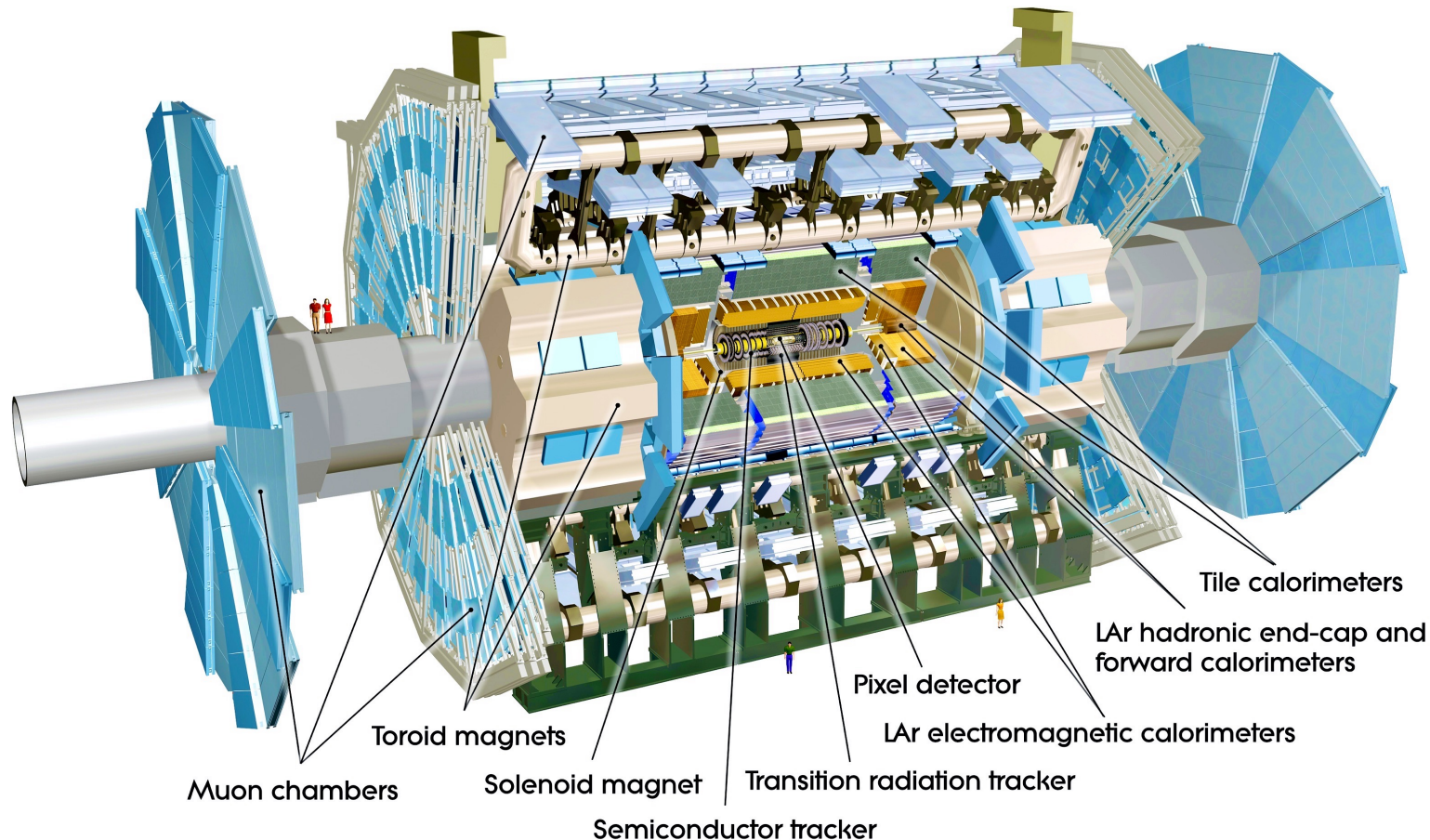
The Large Hadron Collider



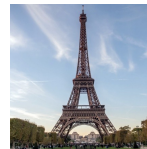
Areal view



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 azimuthal direction)

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

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

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

Ultra-fast custom electronics and high-performance computers filter the collisions: only 1 out of 10,000 collisions is kept

The ATLAS Collaboration

ATLAS is a multi-decade experimental programme involving:

- 185 Institutions (253 institutes) from 42 countries + 15 Technical Associate Institutes
- 2900 Scientific authors
- 1200 Physics PhD students
- 1300 Engineers or technicians
- 100 Engineering students
- 6000 Active members

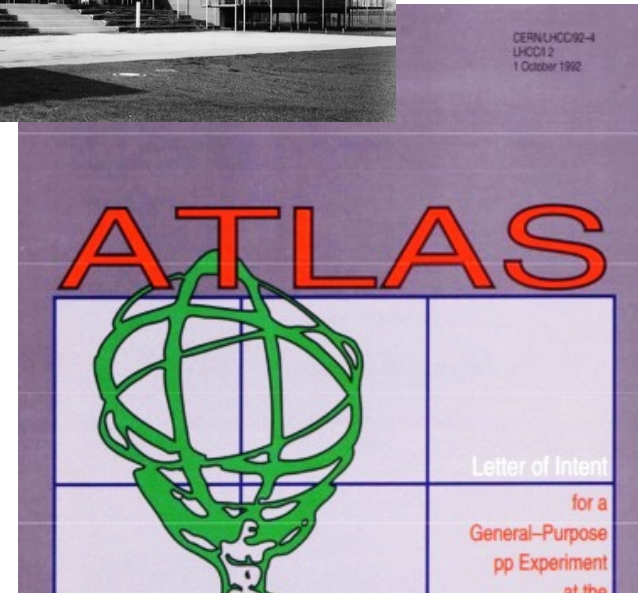
Links:

- [Interactive ATLAS world map](#)
- [Static world maps](#)
- [List of ATLAS institutes](#)
- [ATLAS Composition](#)
- [Join ATLAS information & brochure](#)

The previous MPP, by architect Sep Ruf

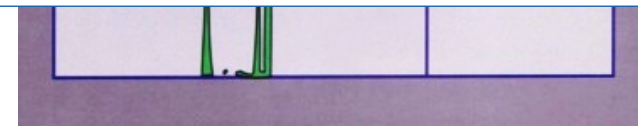


The Max-Planck-Institut für Physik is a founding member of ATLAS



Max-Planck-Institut für Physik, Munich, Germany

M.Aderholz, W.Blum, H.Brettel, F.Dydak*, J.Fent, A.Halley, K.Jakobs, C.Kiesling, H.Kroha, E.Lorenz, G.Luetjens, G.Lutz, H.Oberlack, P.Ribarics, Rainer Richter, Robert Richter, P.Schacht, U.Stiegler, U.Stierlin, R.St.Denis, G.Wolf
(* also at CERN)



ATLAS Letter of Intent, Oct 1992

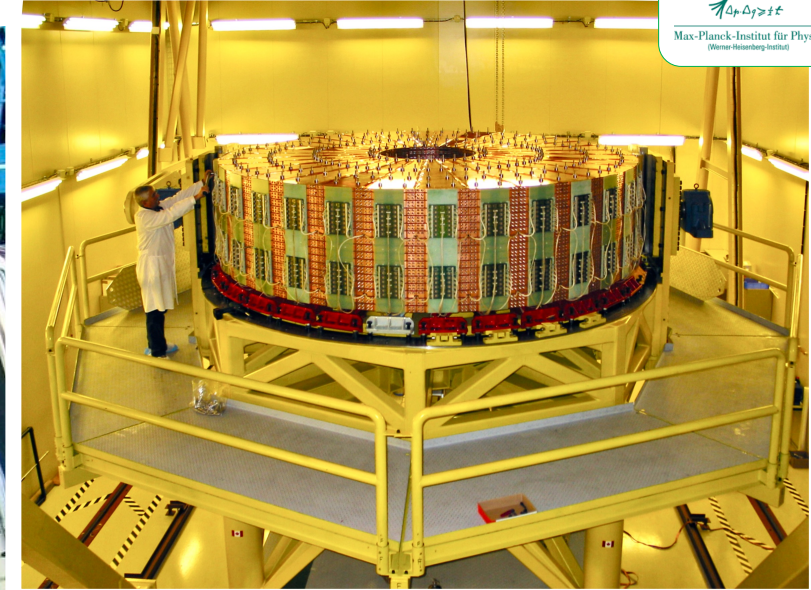
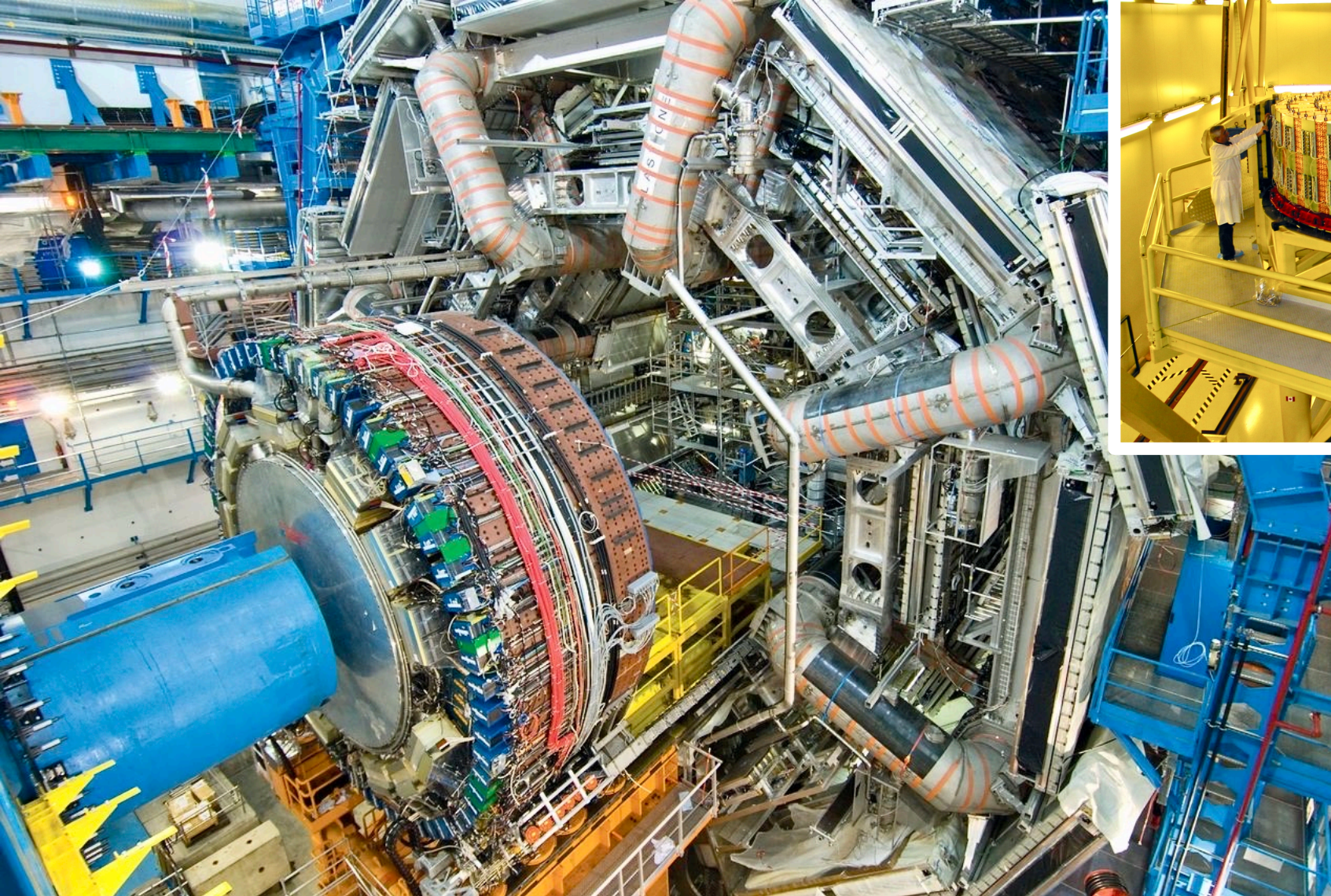
ATLAS Detector construction and installation



ATLAS cavern after excavation in July 2002

- 53 m long
- 35 m high (10-storey building)
- 30 m wide

ATLAS Detector construction and installation – Calorimeters



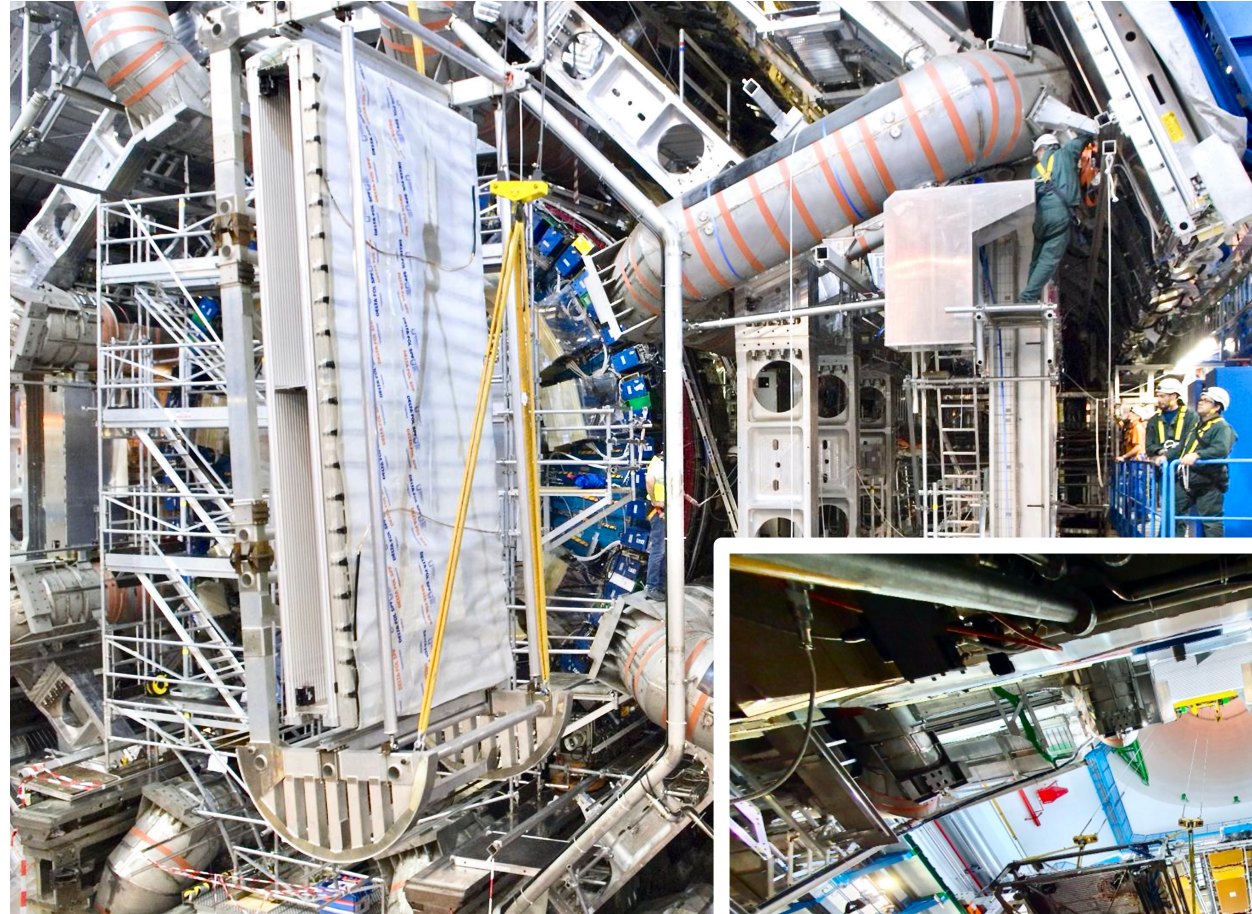
Top: one HEC wheel on the assembly table at CERN's B180 in 2002 prior to the vertical rotation and insertion into the end-cap cryostat

View of the central part of ATLAS during final assembly stages. The wire chambers mounted inside and around the toroid magnet cryostats are well visible, as is part of the end-cap hadronic calorimeter before its insertion inside the magnet

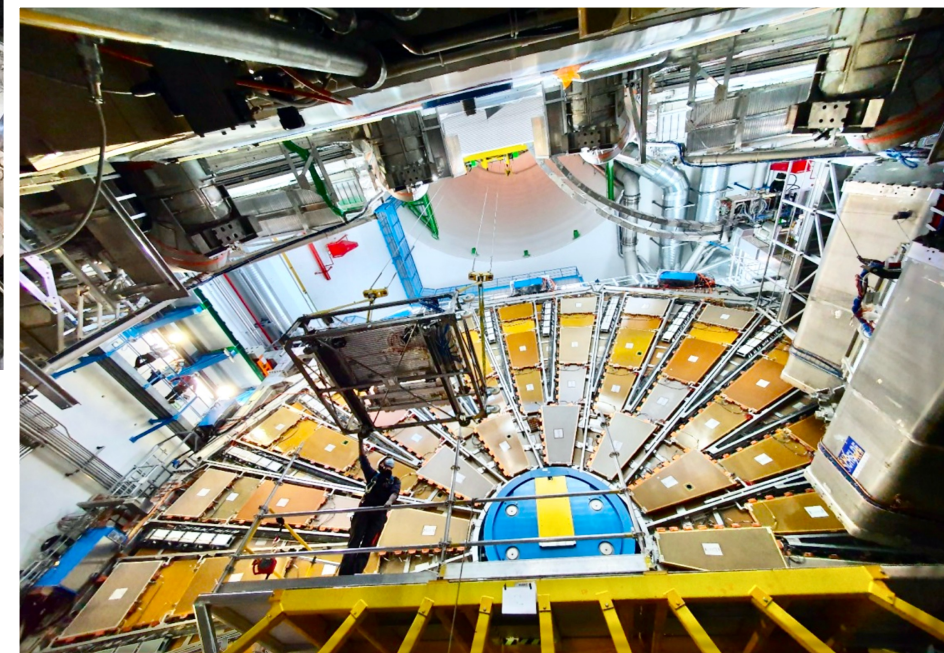
ATLAS Detector construction and installation – Muon system



Top: MDT chamber construction in the clean room at MPP

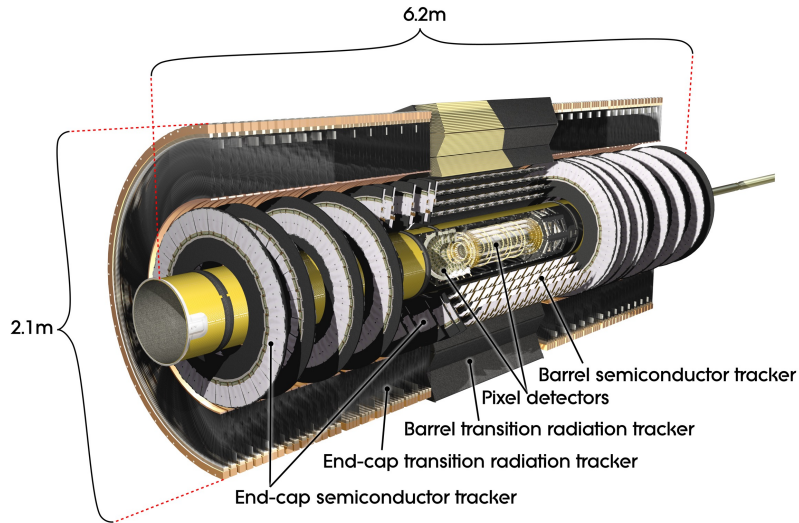


Top: MDT chamber installation in ATLAS



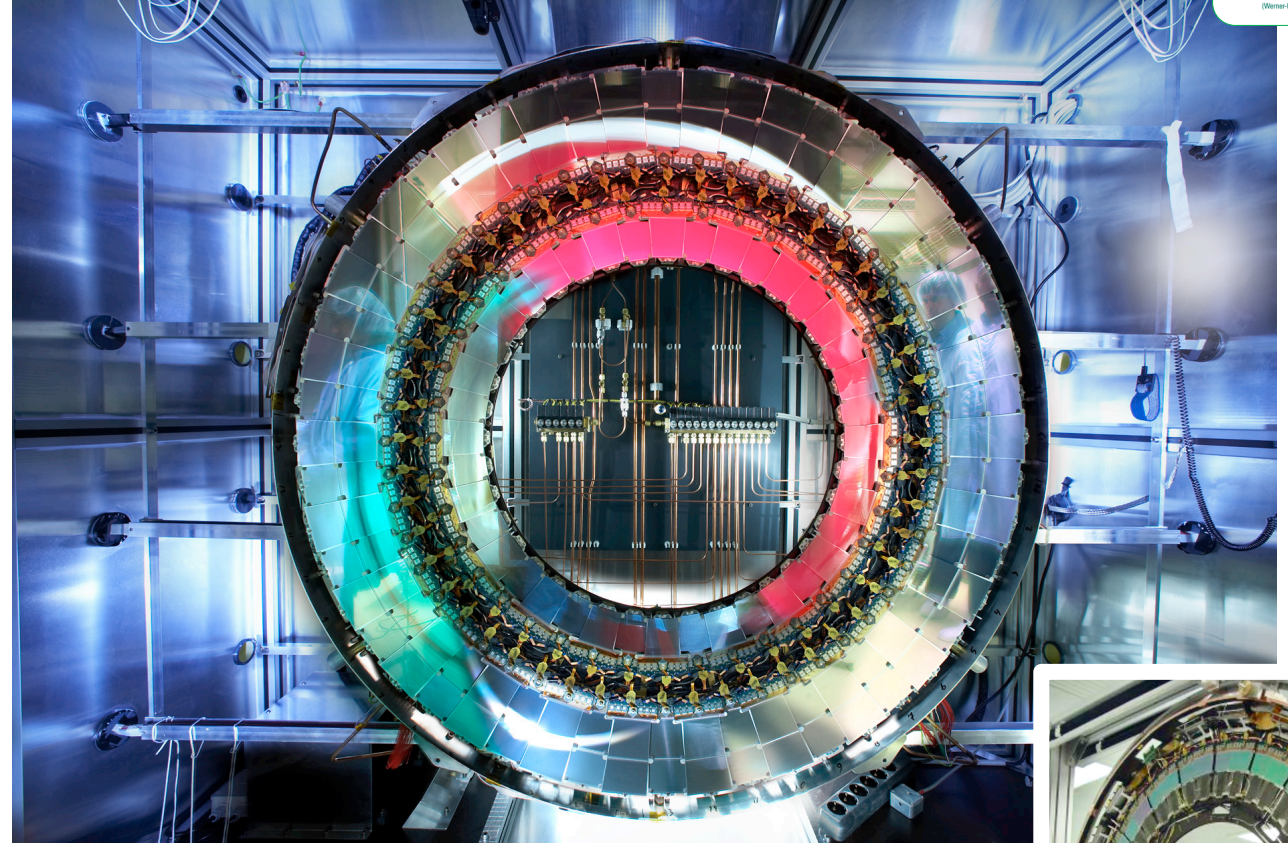
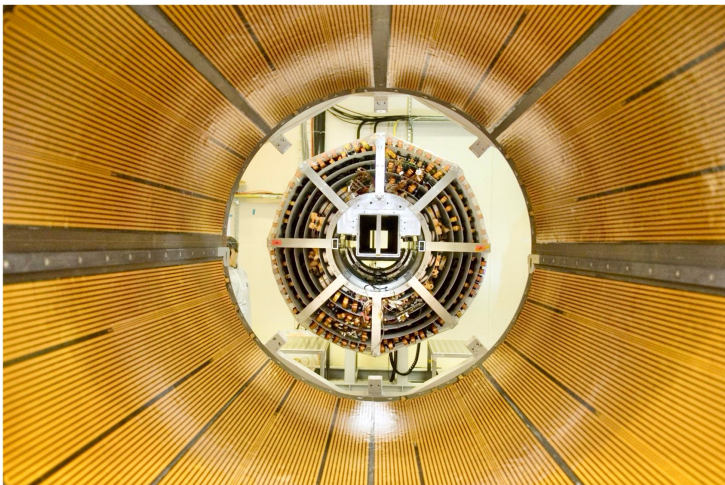
Right: recent sMDT chamber installation in ATLAS

ATLAS Detector construction and installation – Silicon Tracker



Schematic view of the Semicondutor Tracker (SCT) consisting of over 4,000 modules of 6 million “micro-strips” of silicon sensors

Optimised SCT layout

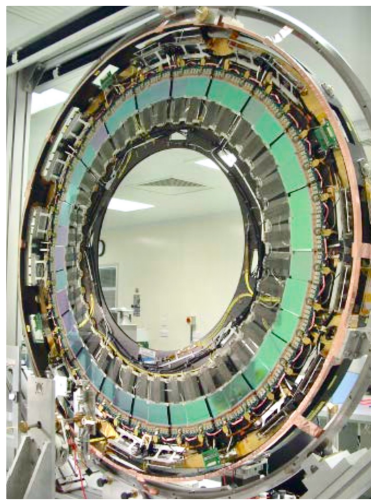


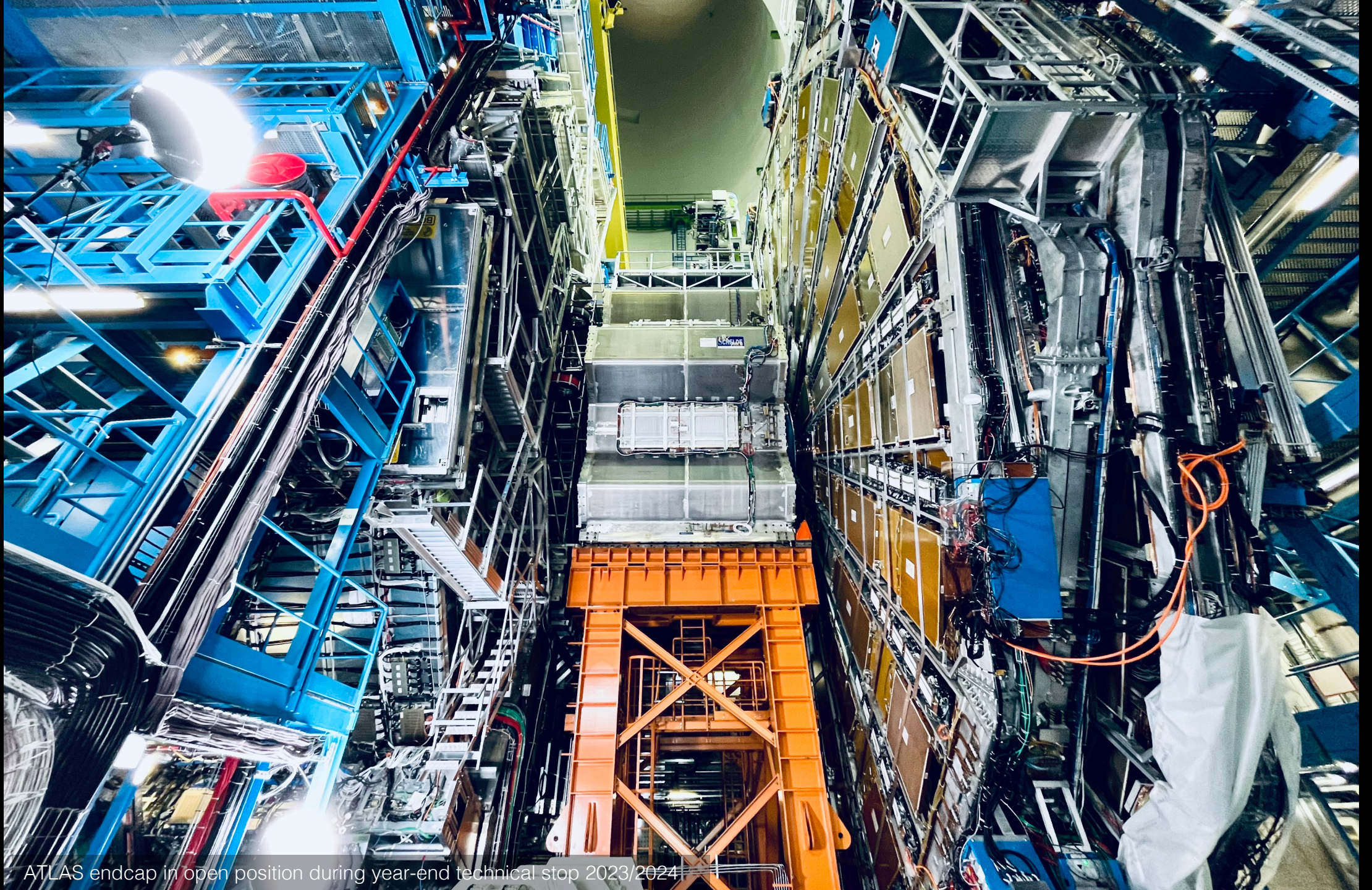
SCT endcap disk with silicon sensors in its test box (Nikhef)



SCT endcap disk module

SCT endcap disk with short middle modules assembled at MPP





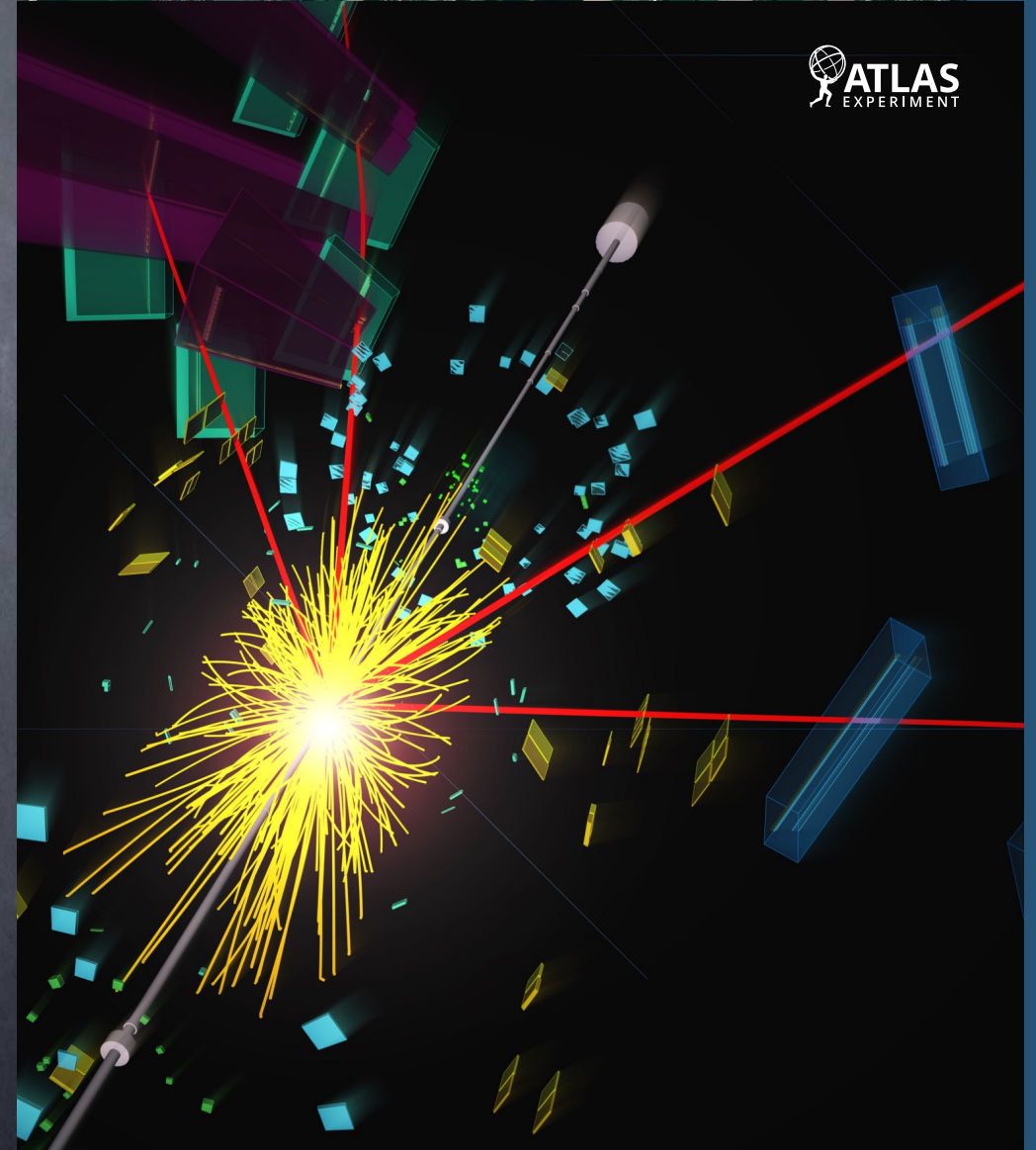
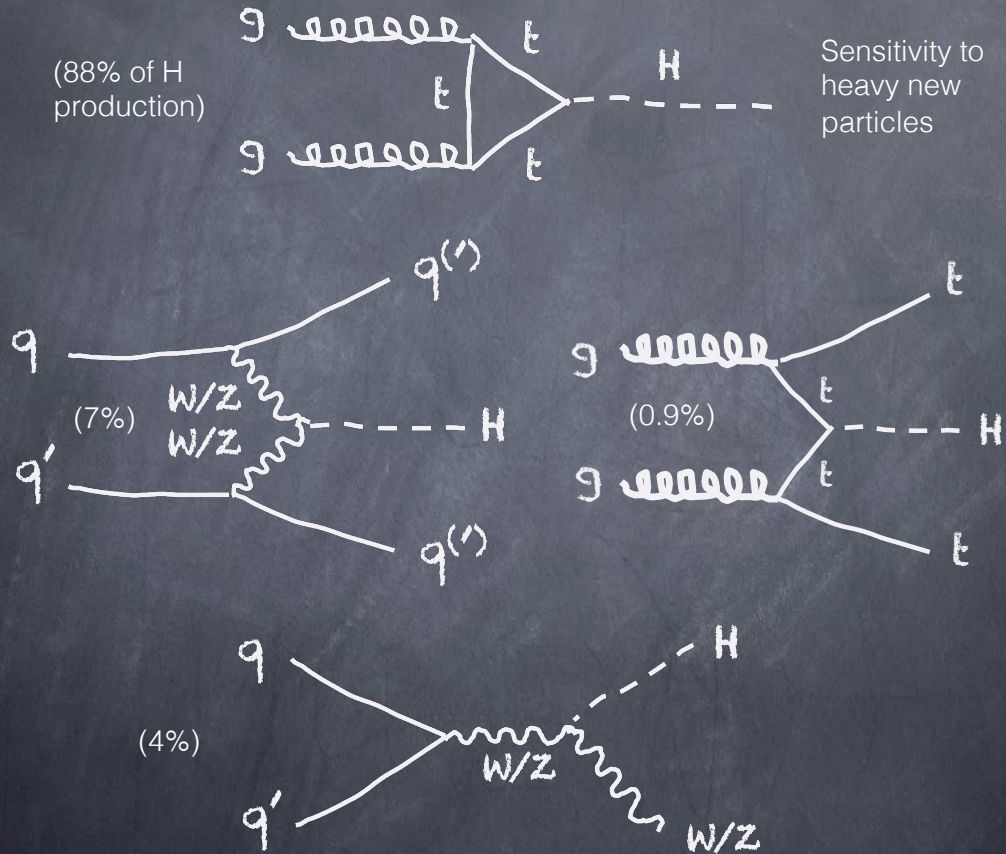
ATLAS endcap in open position during year-end technical stop 2023/2024

The LHC timeline



Higgs boson production at the LHC

About 1 Higgs boson per second is produced in ATLAS at the LHC (about 12M total by today)

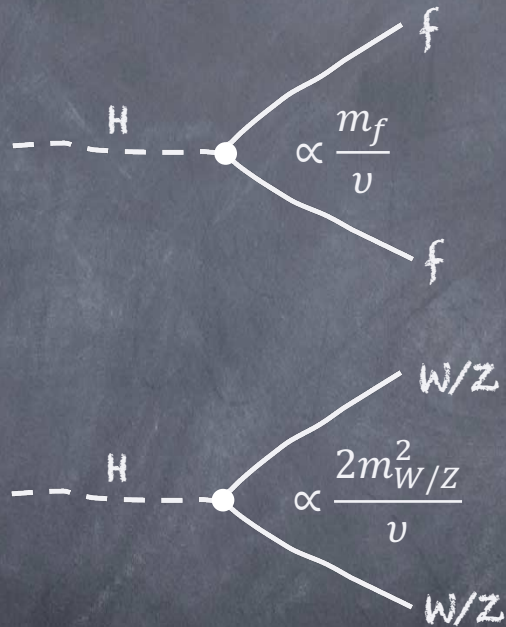


ATLAS
EXPERIMENT

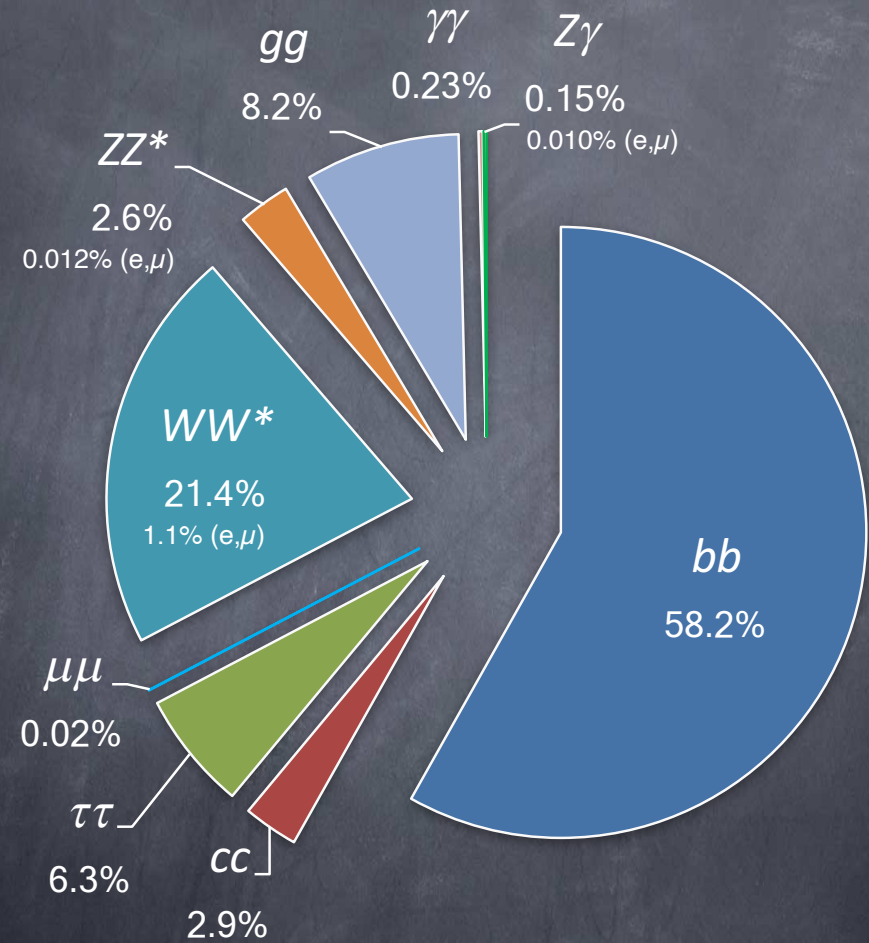
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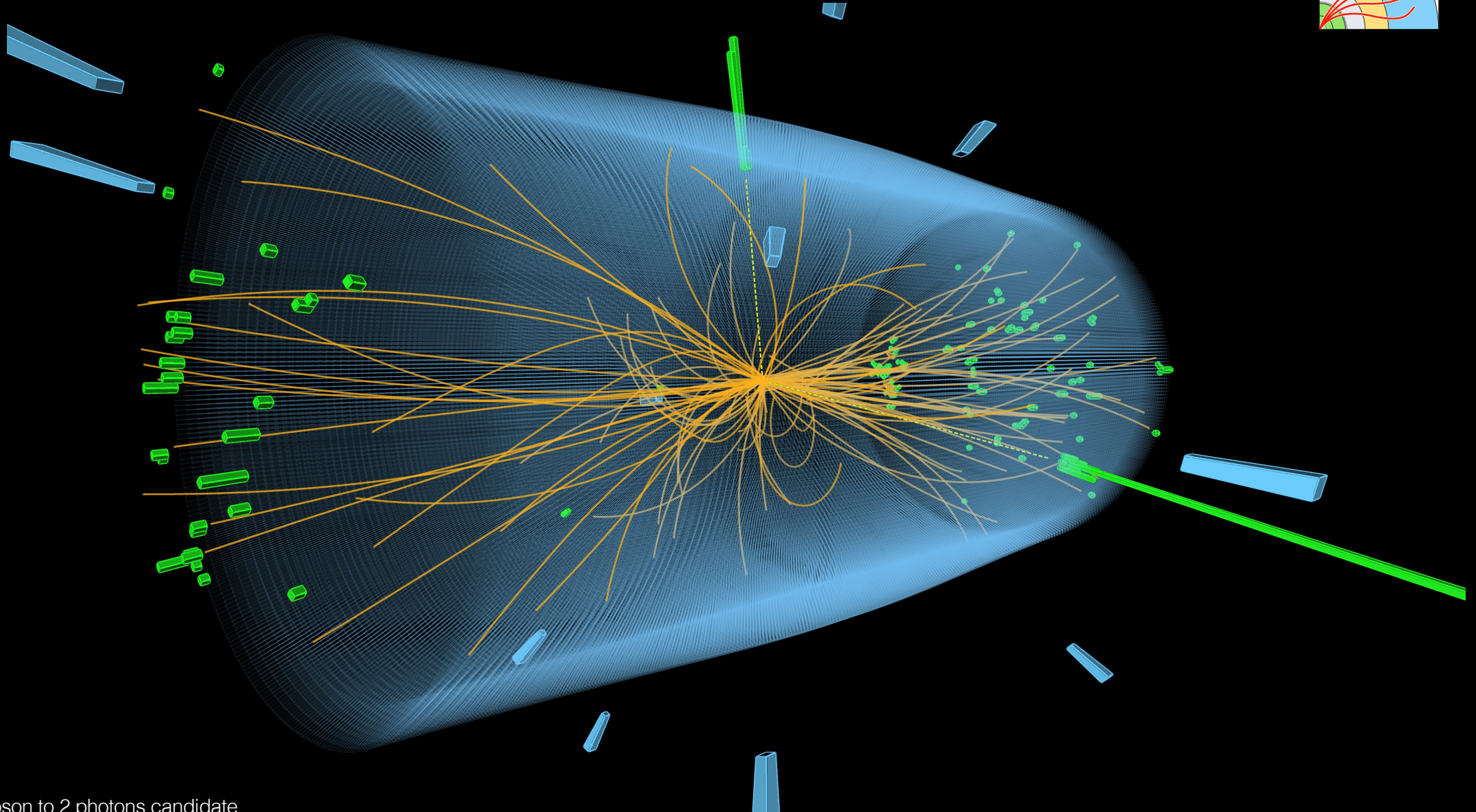
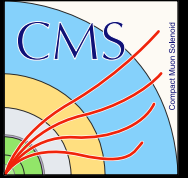
It decays within 10^{-22} s



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

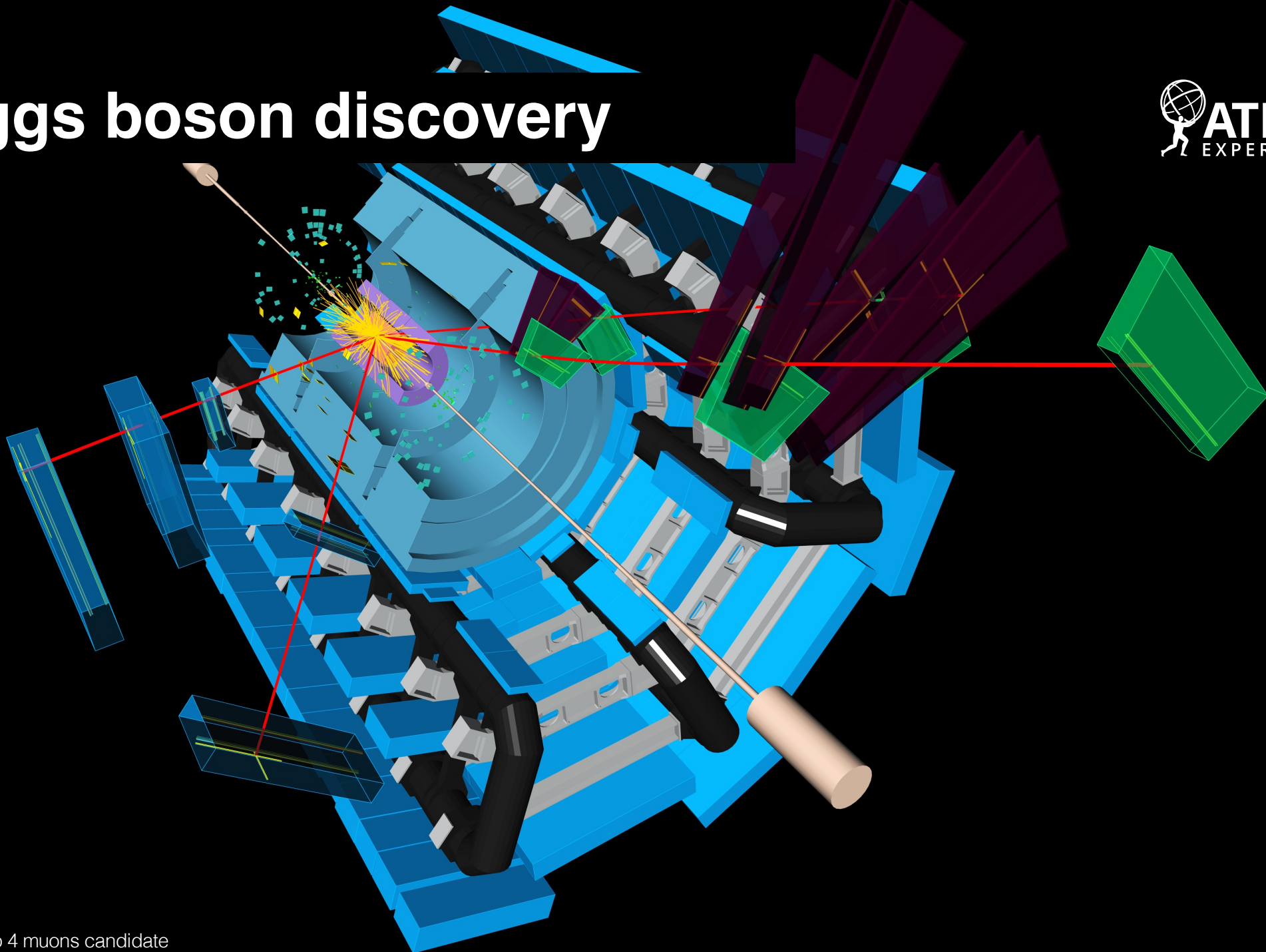


Higgs boson discovery



A Higgs boson to 2 photons candidate

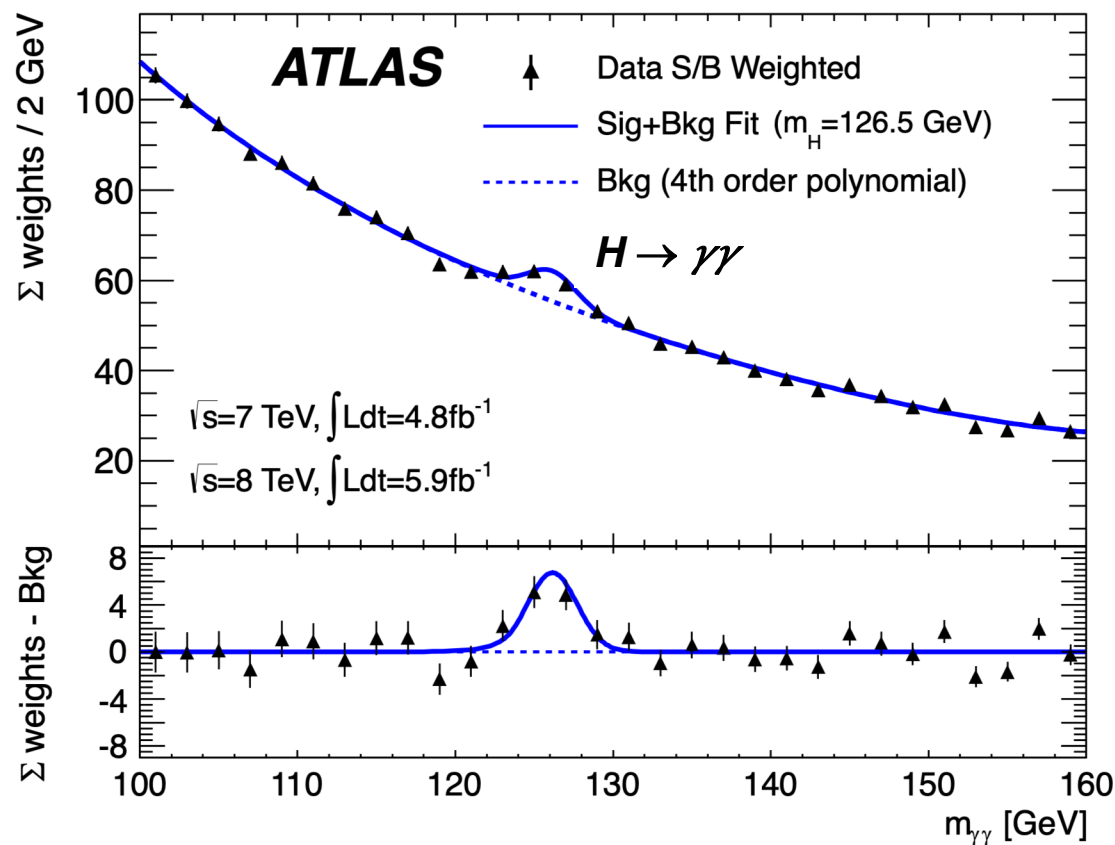
Higgs boson discovery



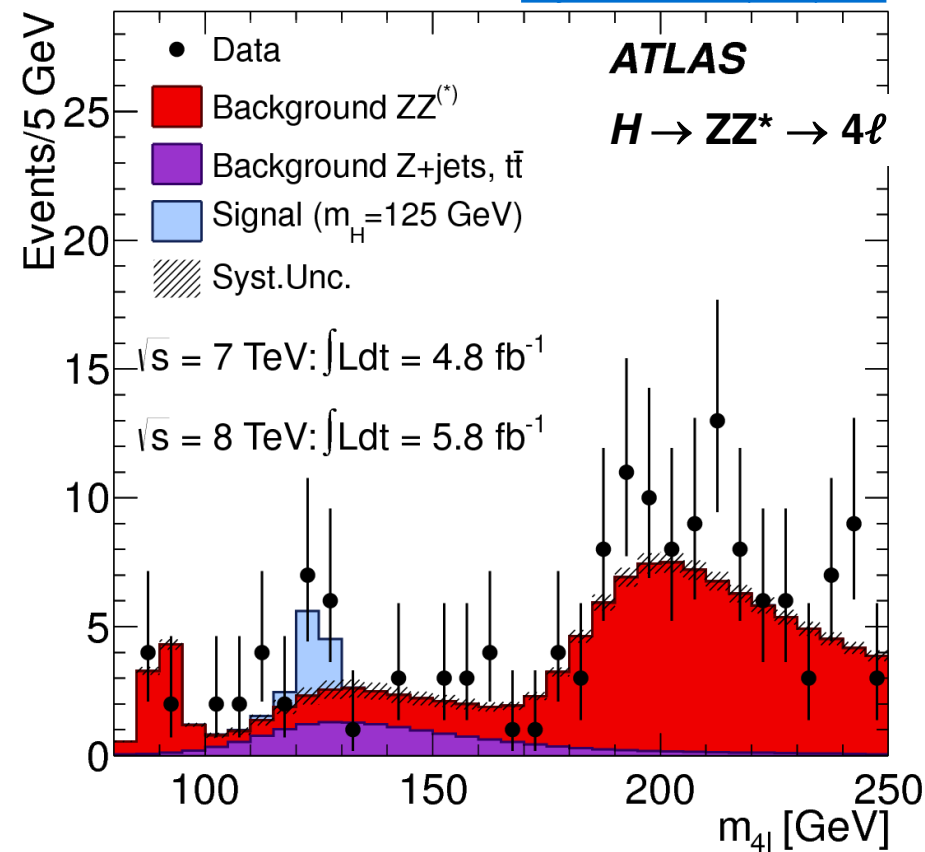
A Higgs boson to 4 muons candidate

Higgs boson discovery

2012



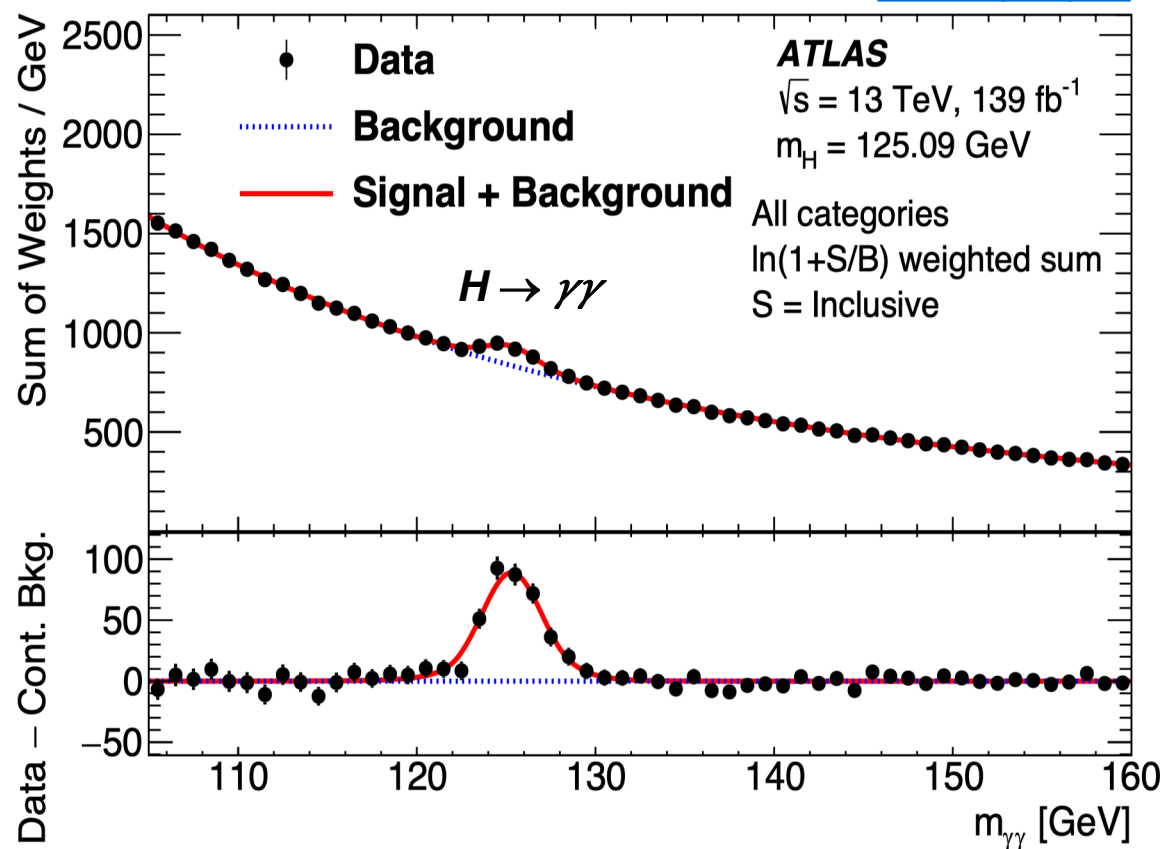
[Phys. Lett. B 716 \(2012\) 1-29](#)



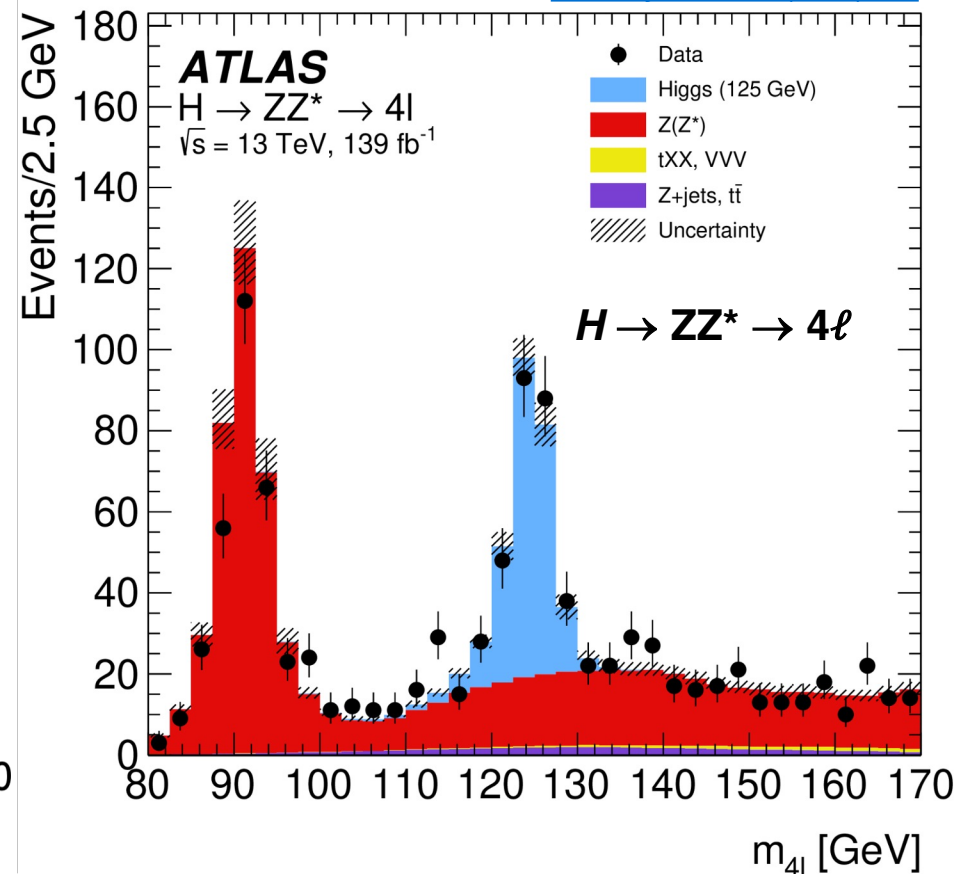
The Higgs boson — At 10

2020

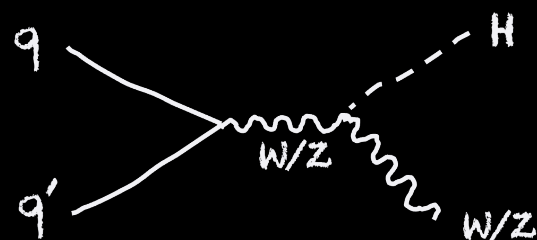
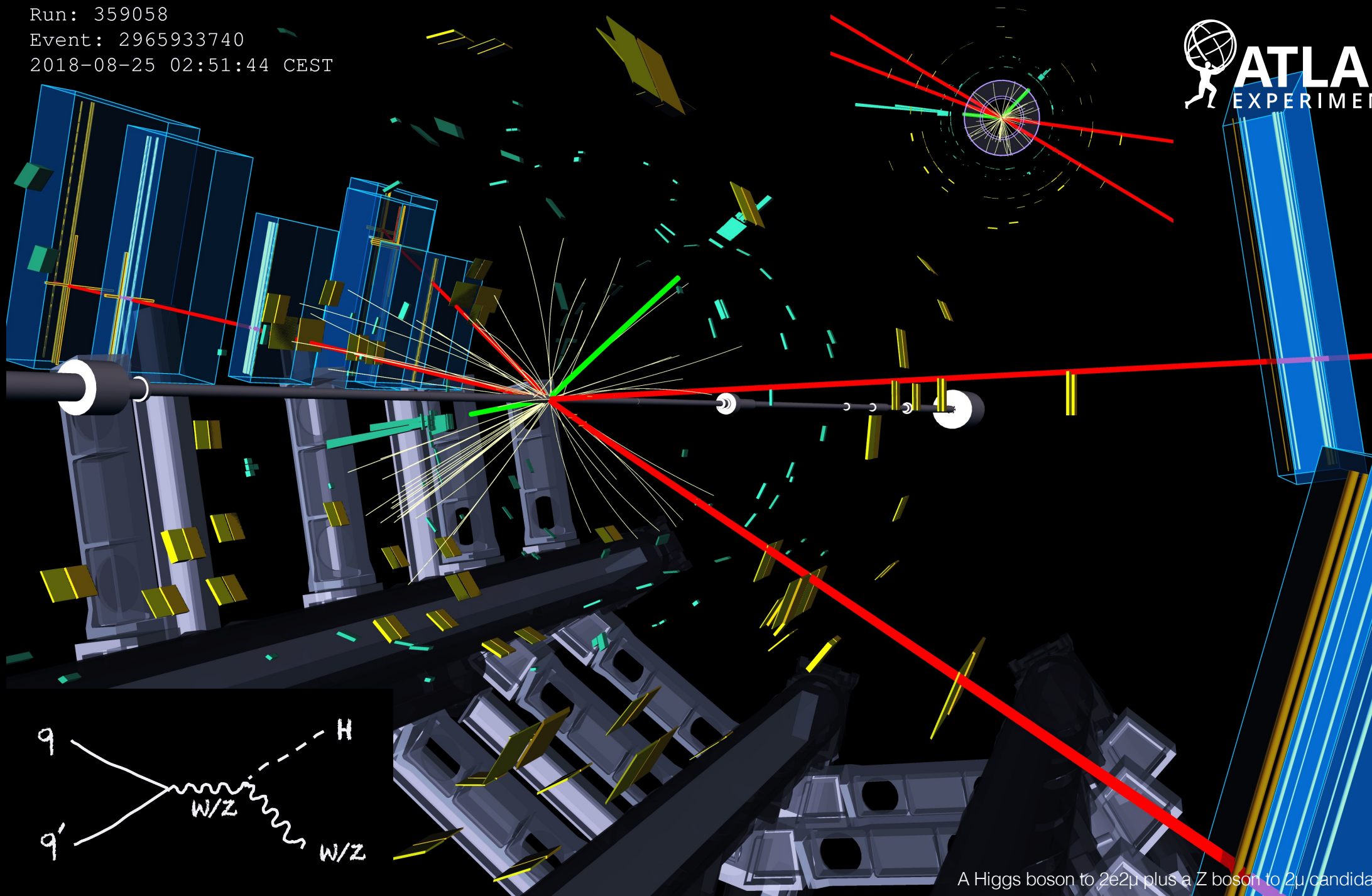
[JHEP 07 \(2023\) 088](#)



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



Run: 359058
Event: 2965933740
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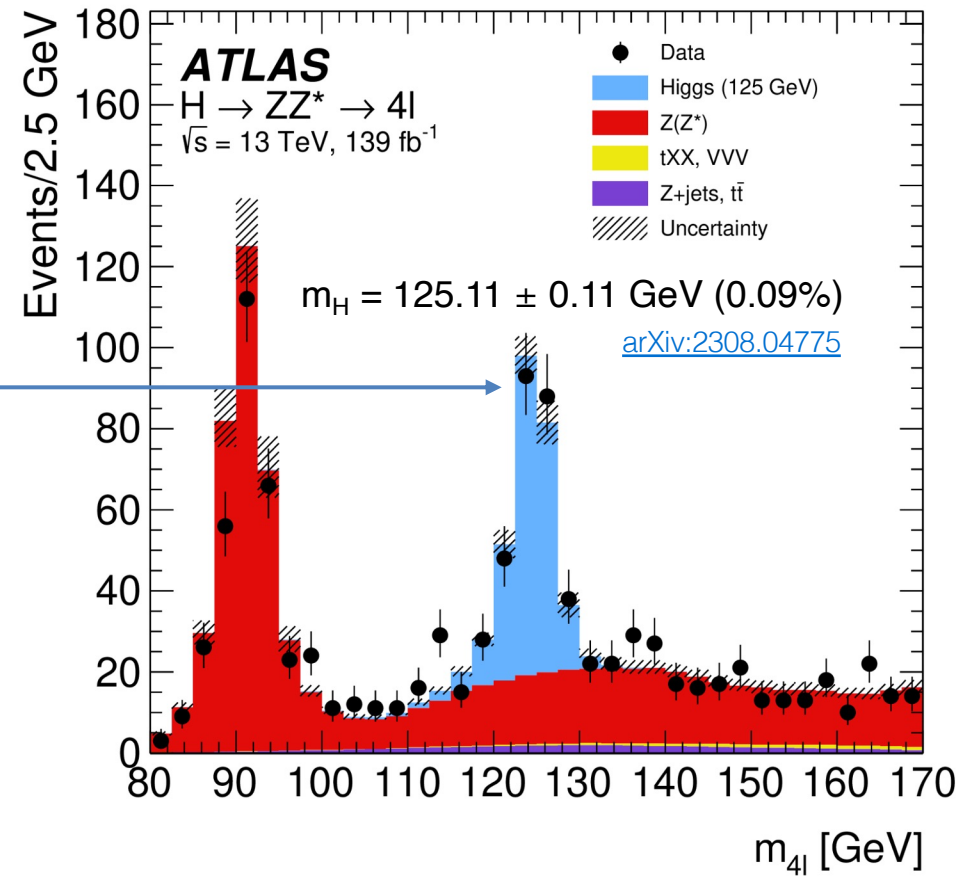
A Higgs boson to $2\gamma 2\mu$ plus a Z boson to 2μ /candidate event

Higgs boson mass

The Higgs mass is peculiar

2020

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

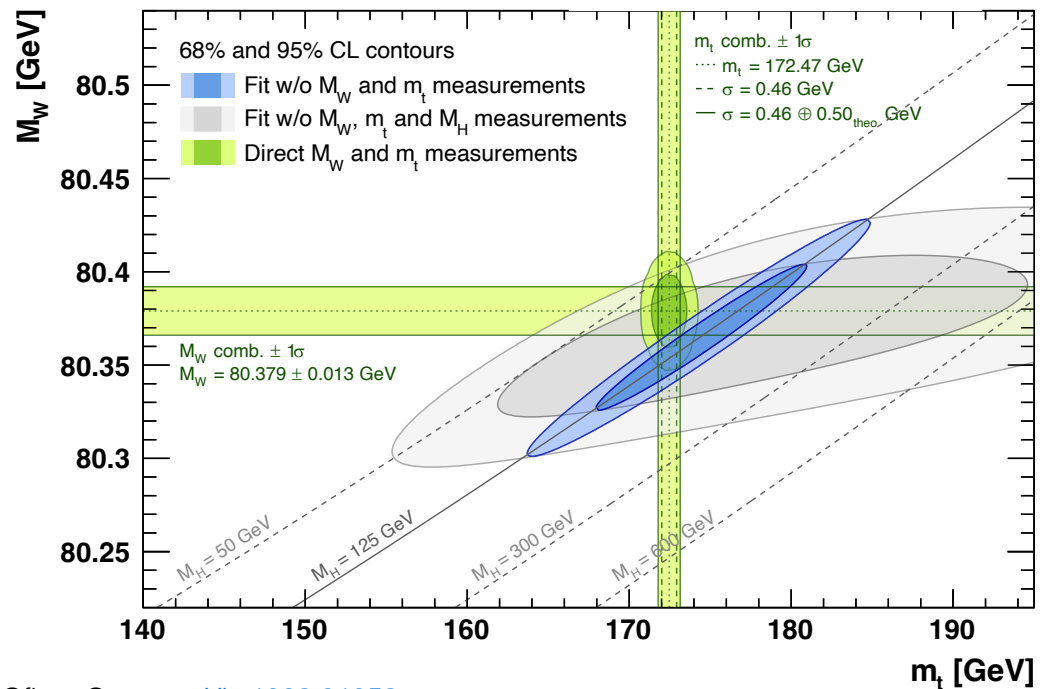
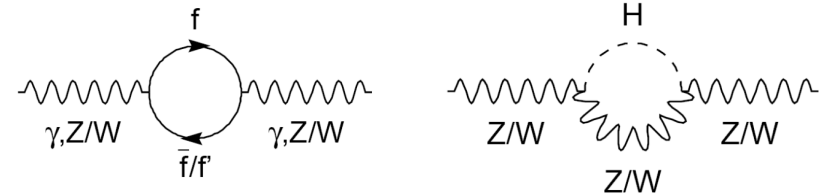


Higgs boson mass

The Higgs mass is peculiar

- It is consistent with the global electroweak fit

Radiative corrections sensitive to heavy particles in loop



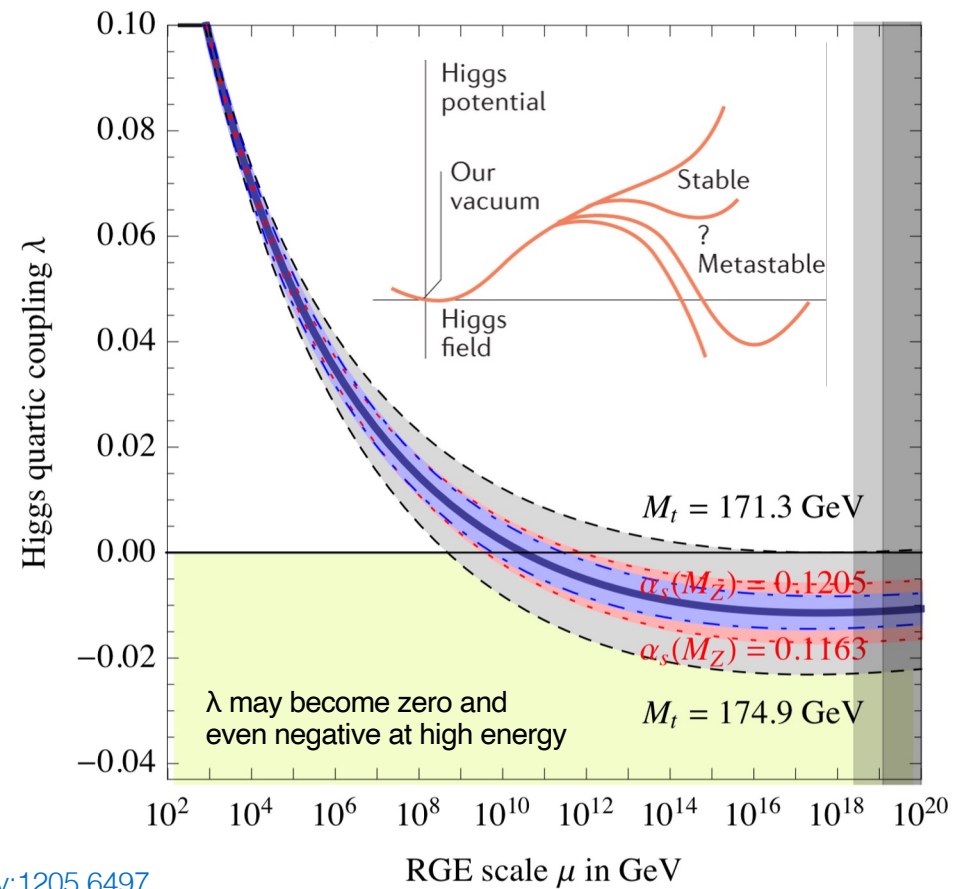
Gfitter Group: [arXiv:1803.01853](https://arxiv.org/abs/1803.01853)

Higgs boson mass

The Higgs mass is peculiar

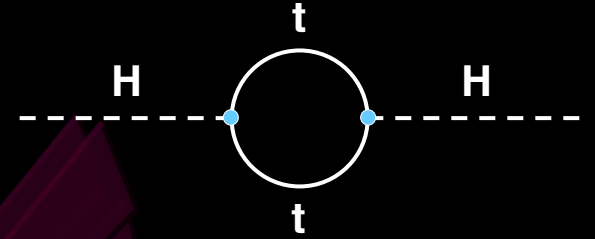
- It is consistent with the global electroweak fit
- But the electroweak vacuum seems to be metastable

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 %	✓	✓	✓	✓	

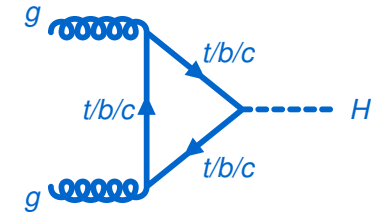
In grey: evidence for decays, but not observed yet

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...)

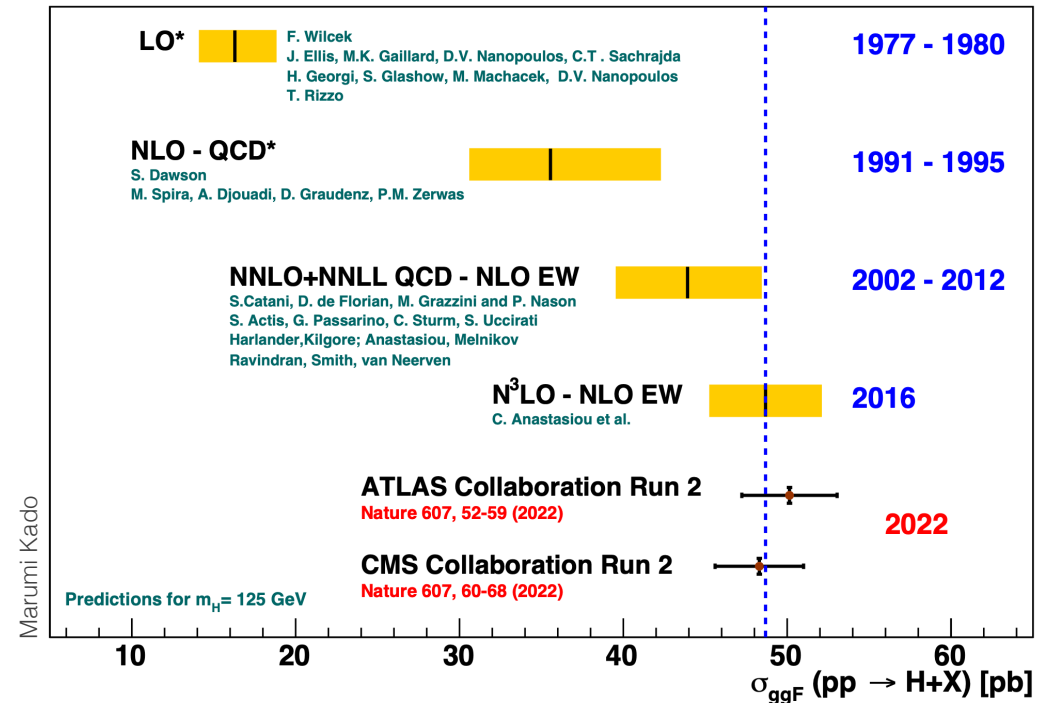
The interpretability of our results relies on our ability to compute accurate and precise predictions

Calculations of Higgs boson production via gluon fusion versus time



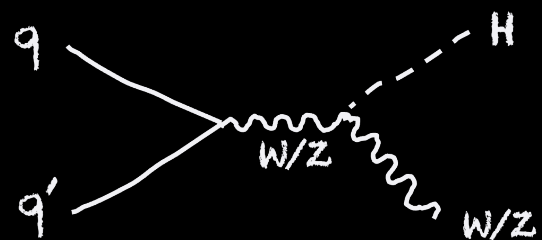
$\sqrt{s} = 13 \text{ TeV}$

* From iHixs



Marumi Kado

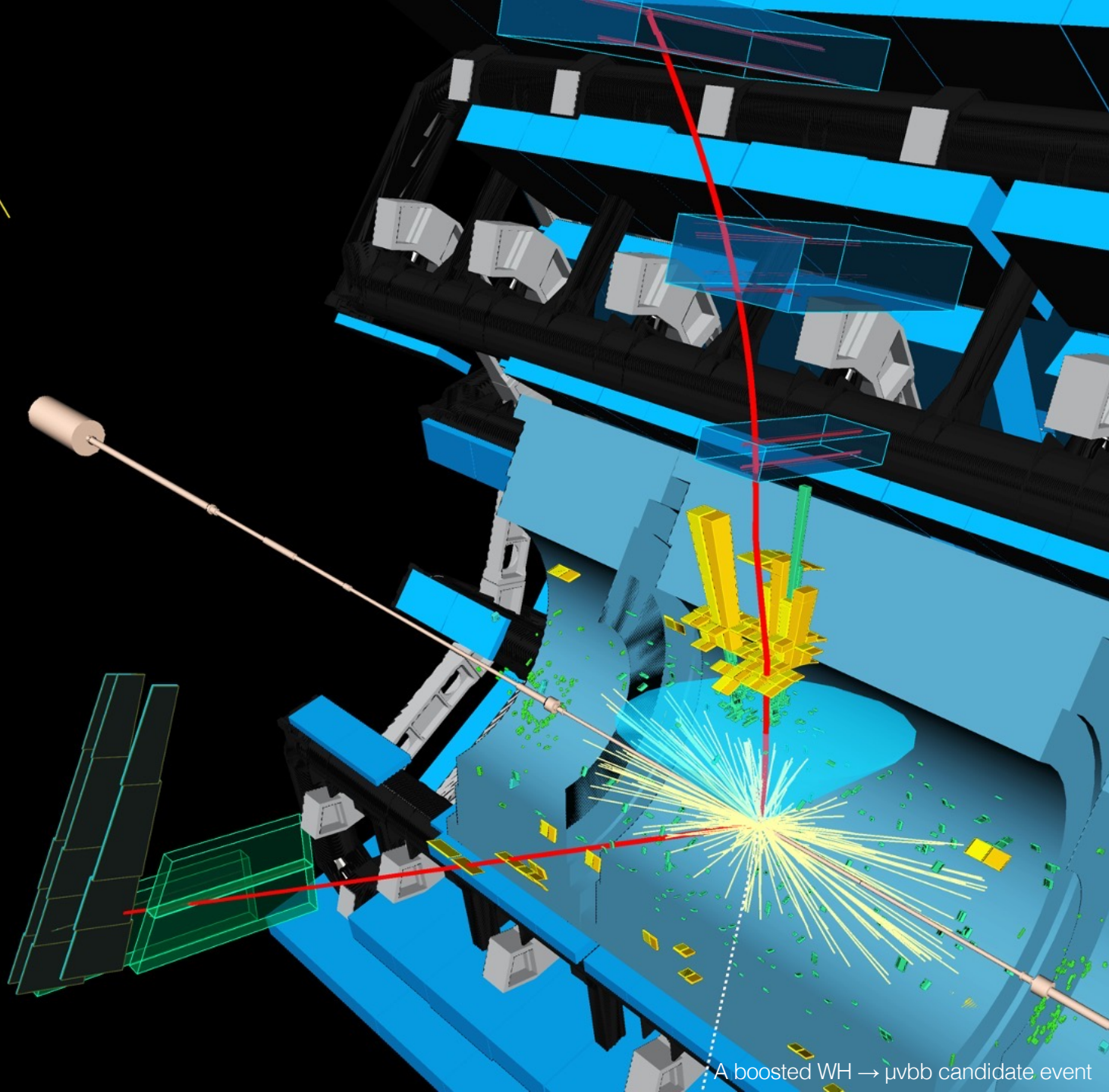
$H \rightarrow bb$



Run: 338349

Event: 616525246

2017-10-16 20:24:46 CEST



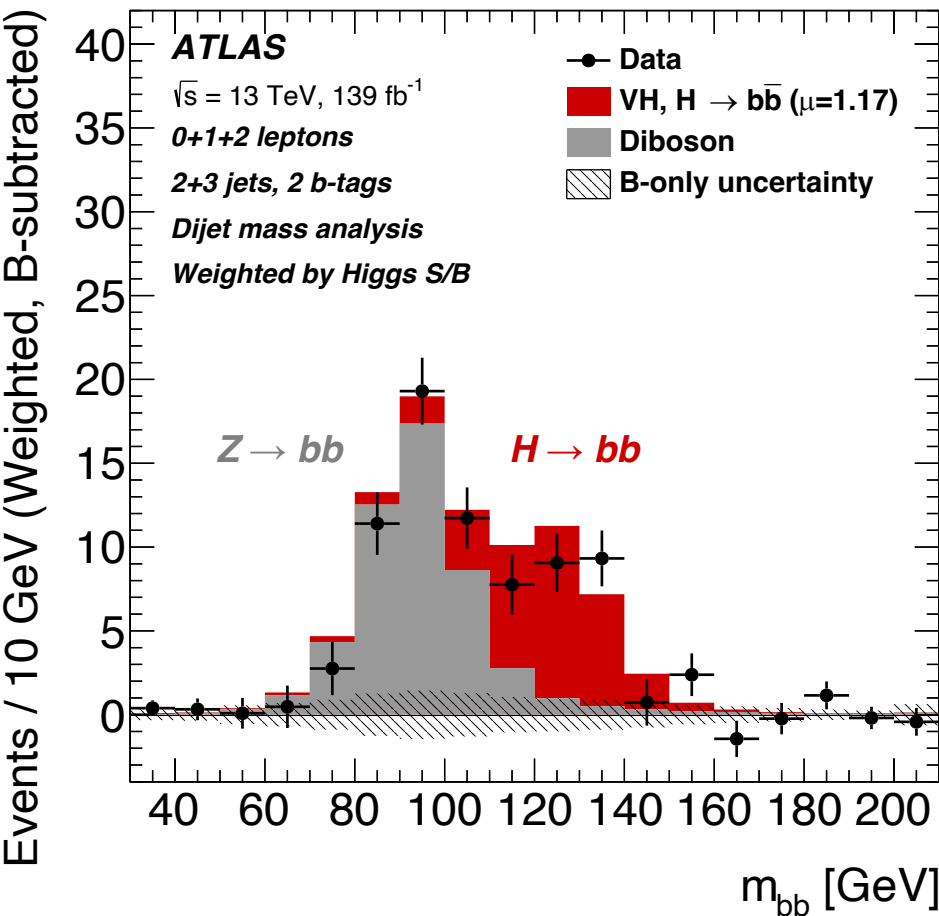
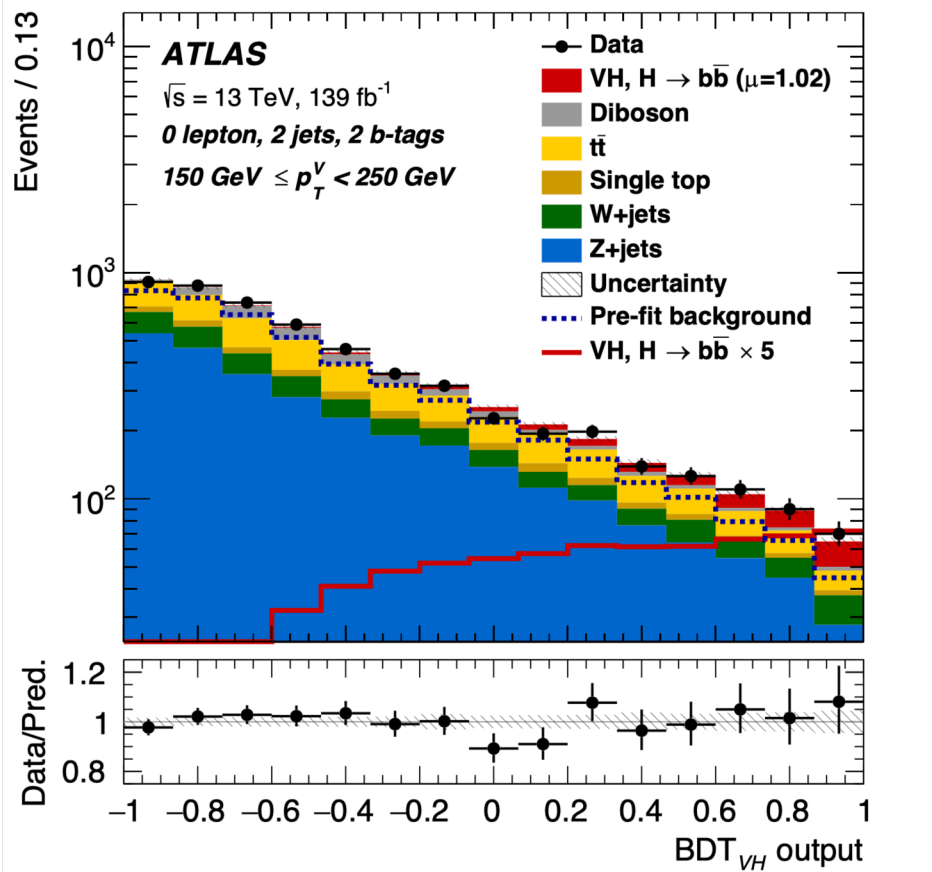
A boosted $WH \rightarrow \mu b b$ candidate event

$H \rightarrow b\bar{b}$

Measurement of $H \rightarrow b\bar{b}$ 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

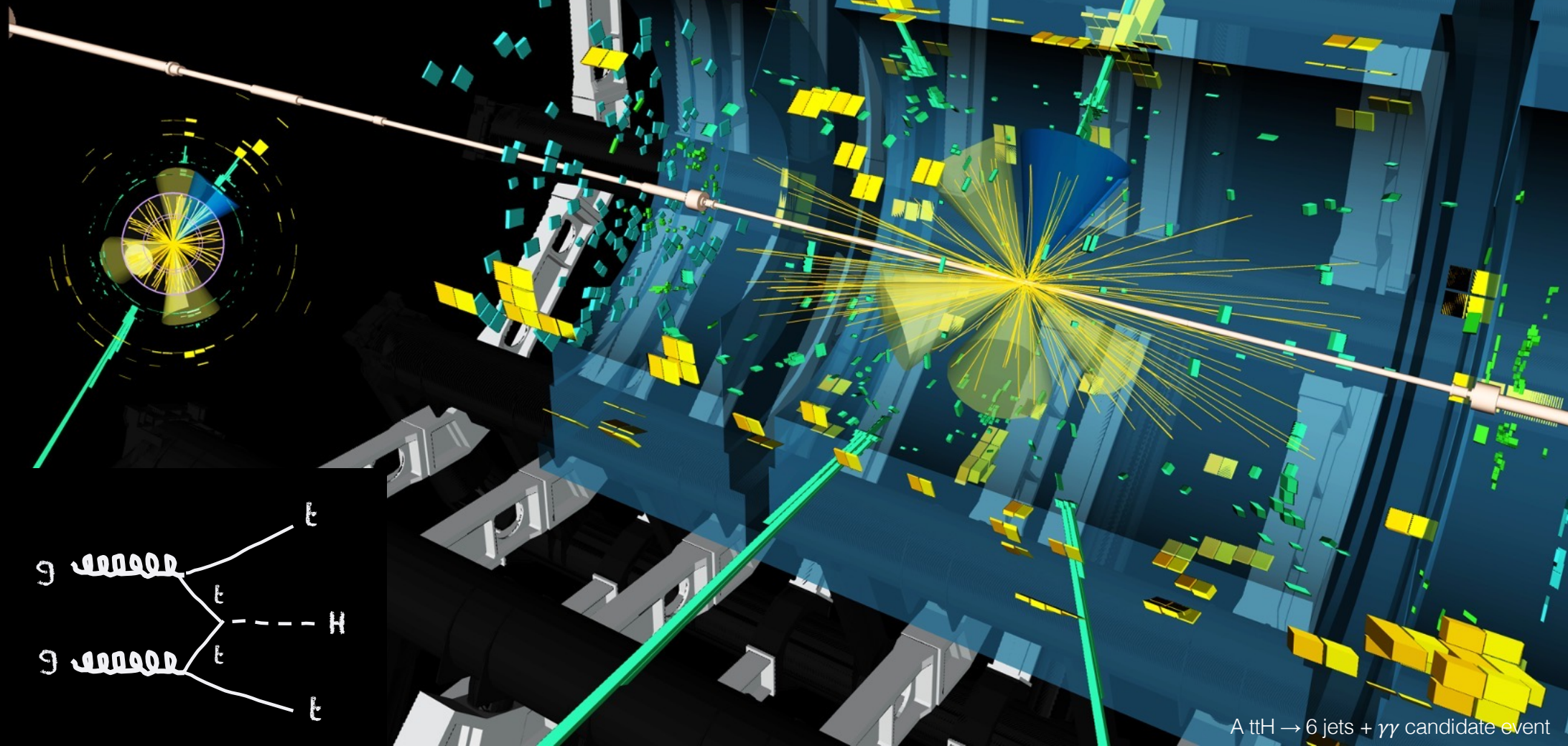
[arXiv:2007.02873](https://arxiv.org/abs/2007.02873)



ttH



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

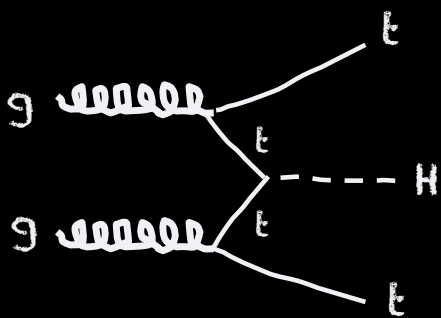
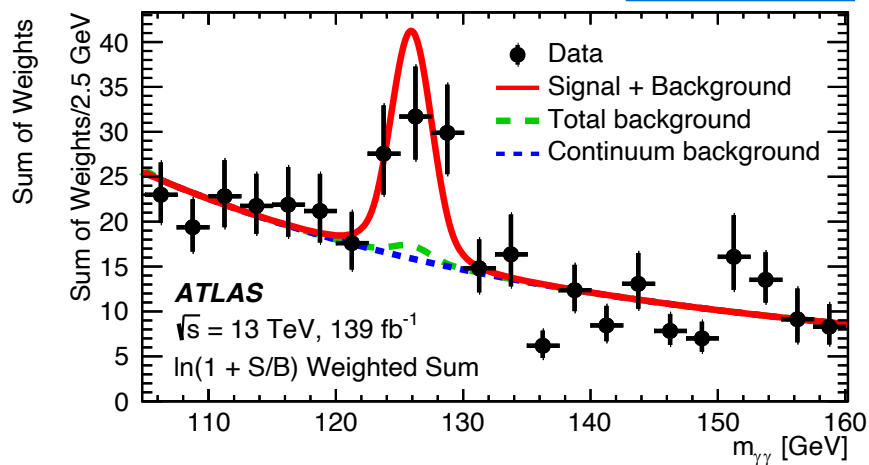


A $ttH \rightarrow 6 \text{ jets} + \gamma\gamma$ candidate event

$t\bar{t}H$

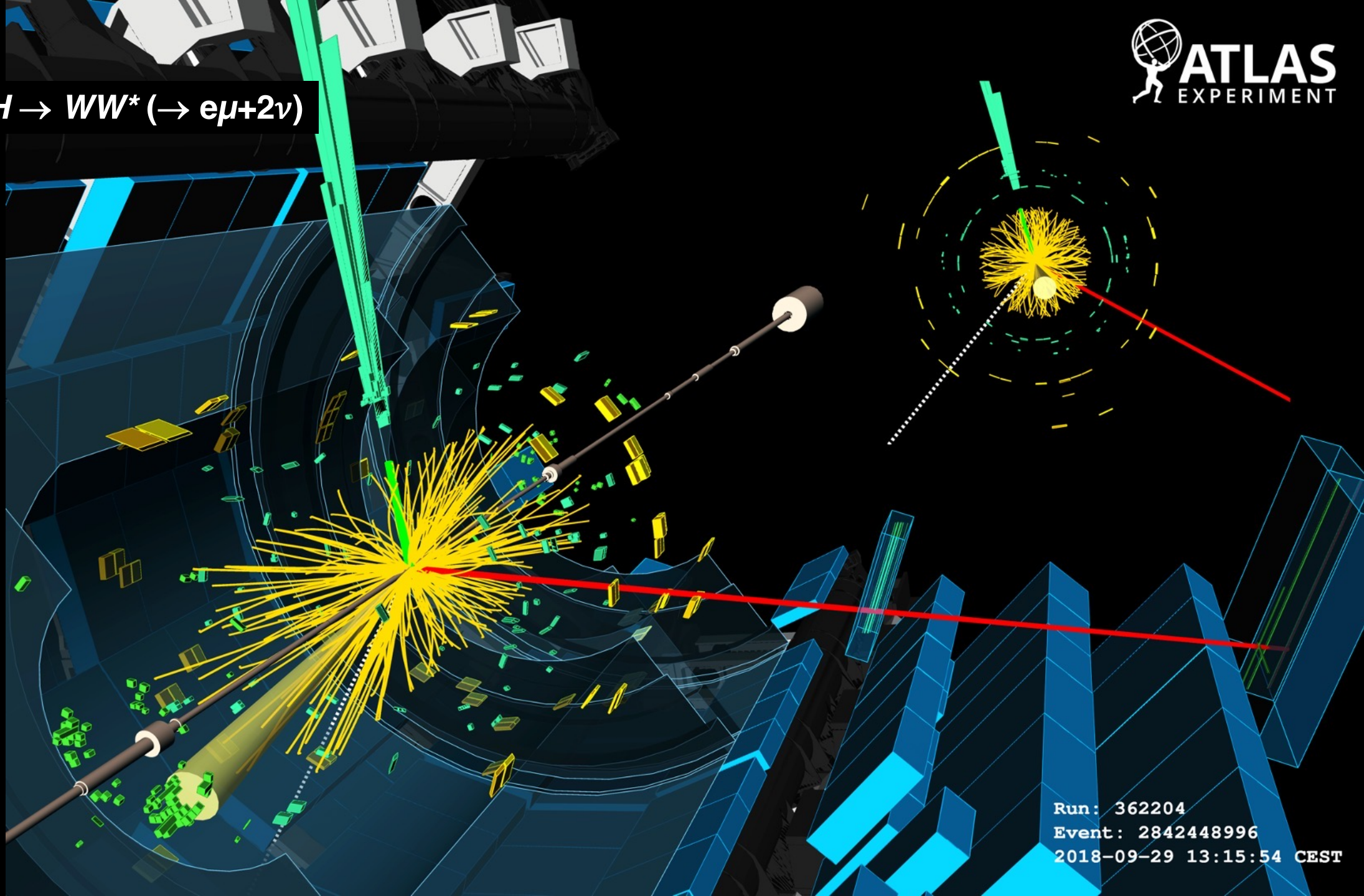
$t\bar{t}H$ production features rich events,
 $H \rightarrow \gamma\gamma$ channel most powerful

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



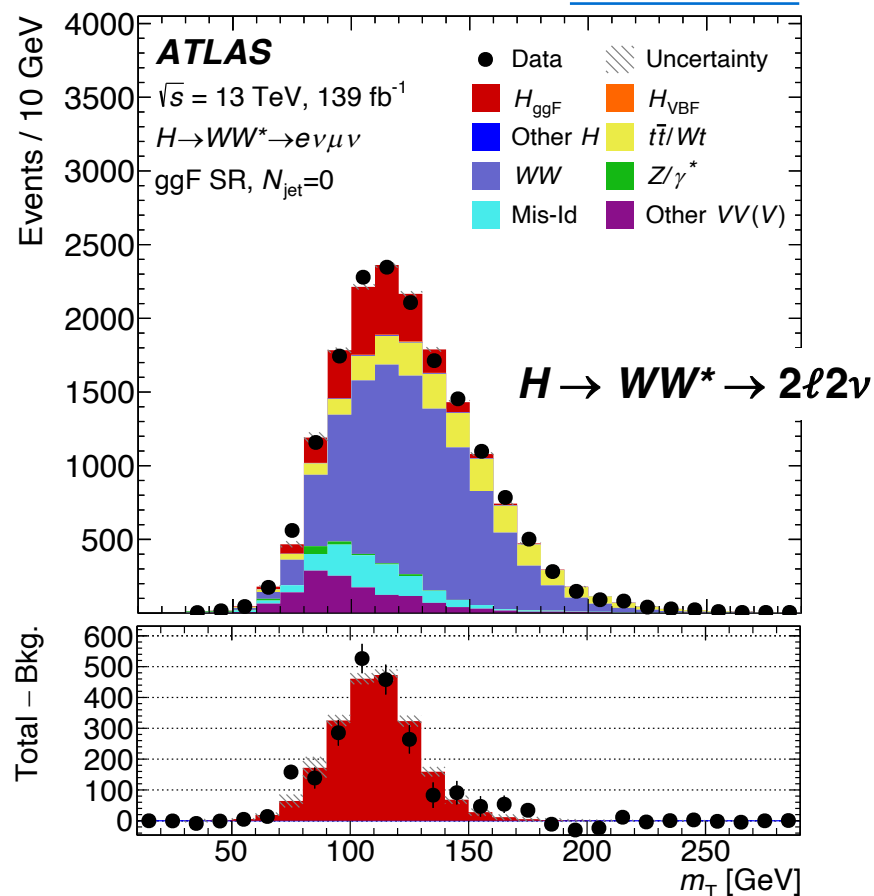
A $t\bar{t}H \rightarrow 6 \text{ jets} + \gamma\gamma$ candidate event

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

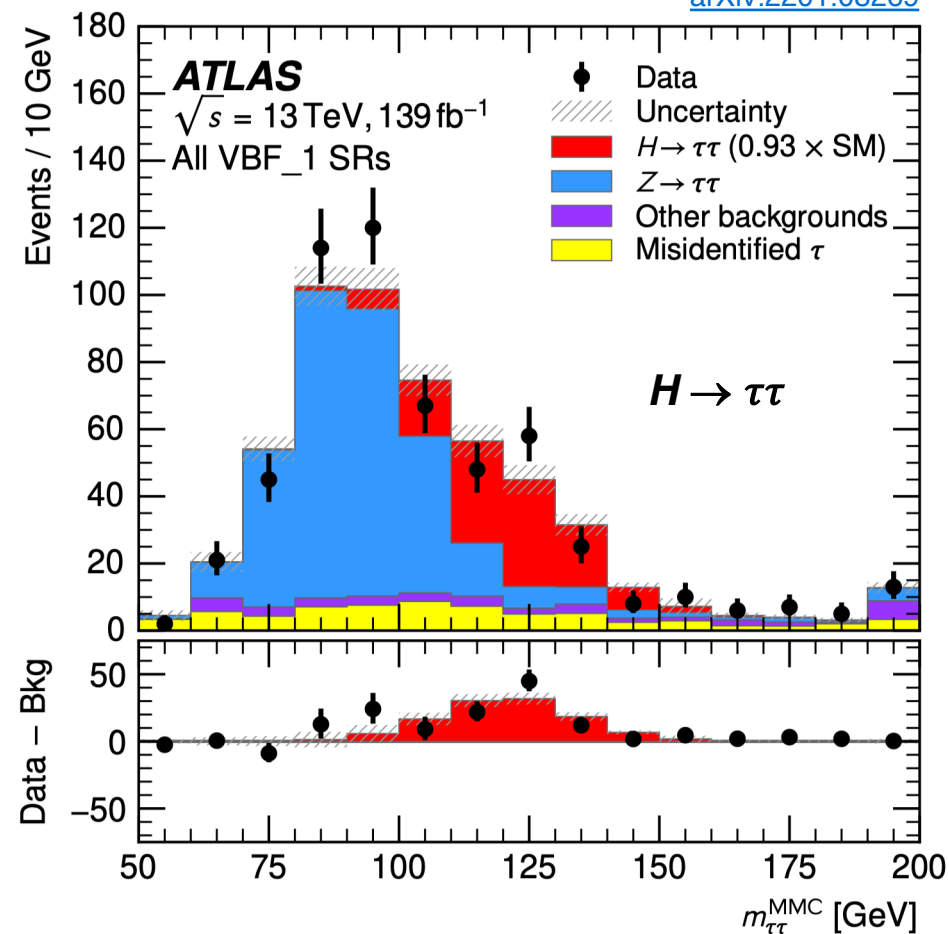


Run : 362204
Event : 2842448996
2018-09-29 13:15:54 CEST

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



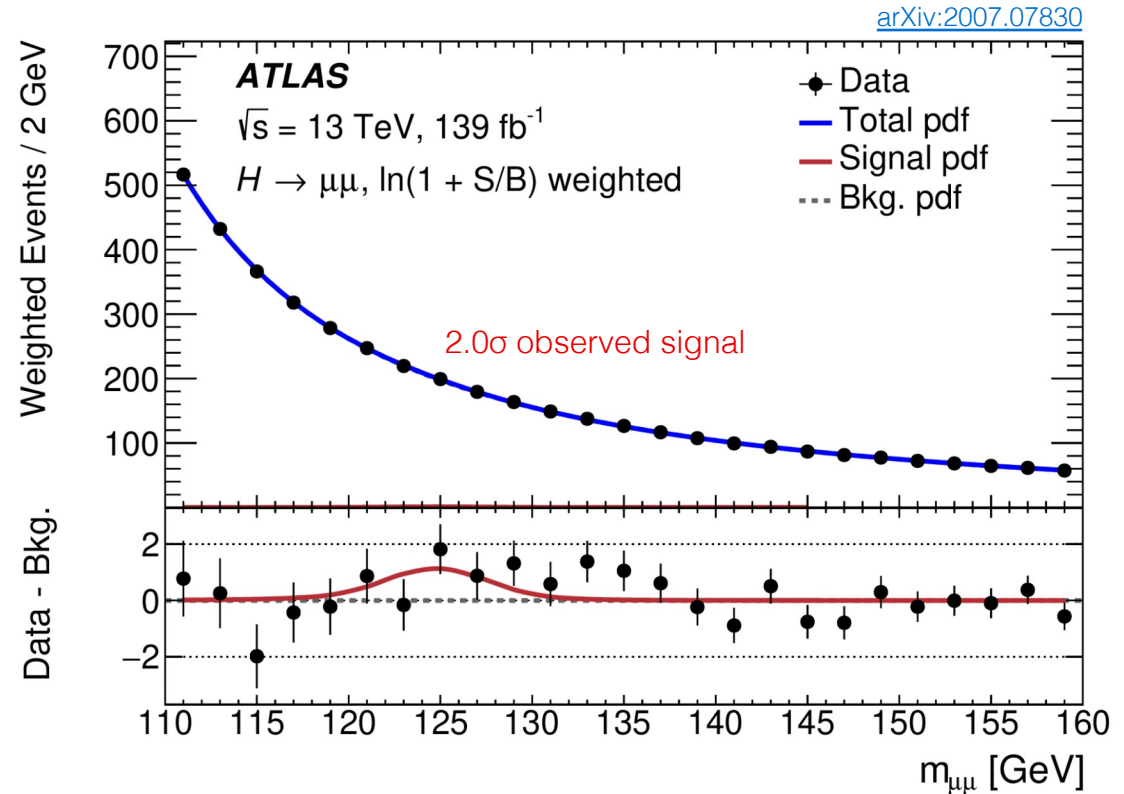
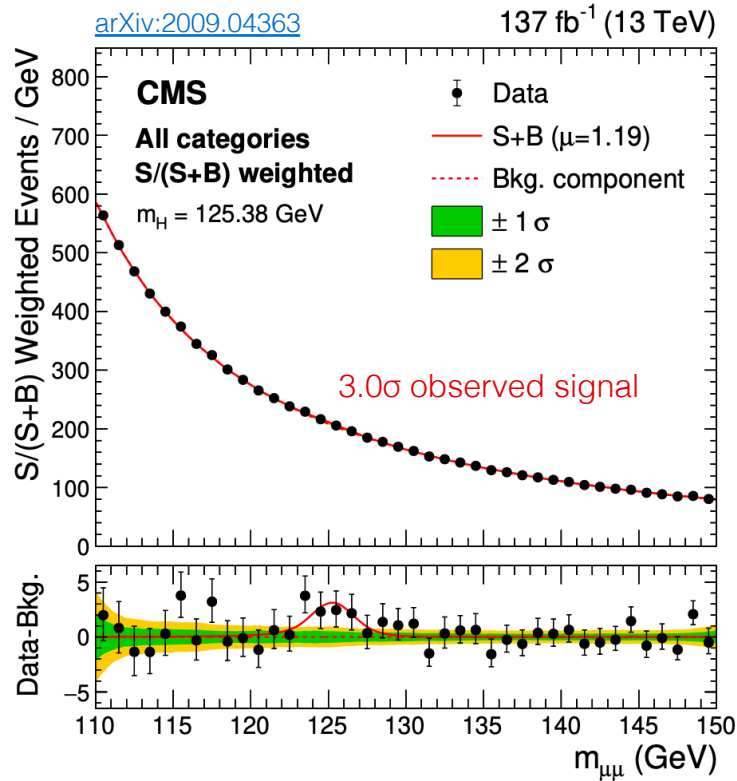
[arXiv:2201.08269](https://arxiv.org/abs/2201.08269)



$H \rightarrow \mu\mu$ — 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



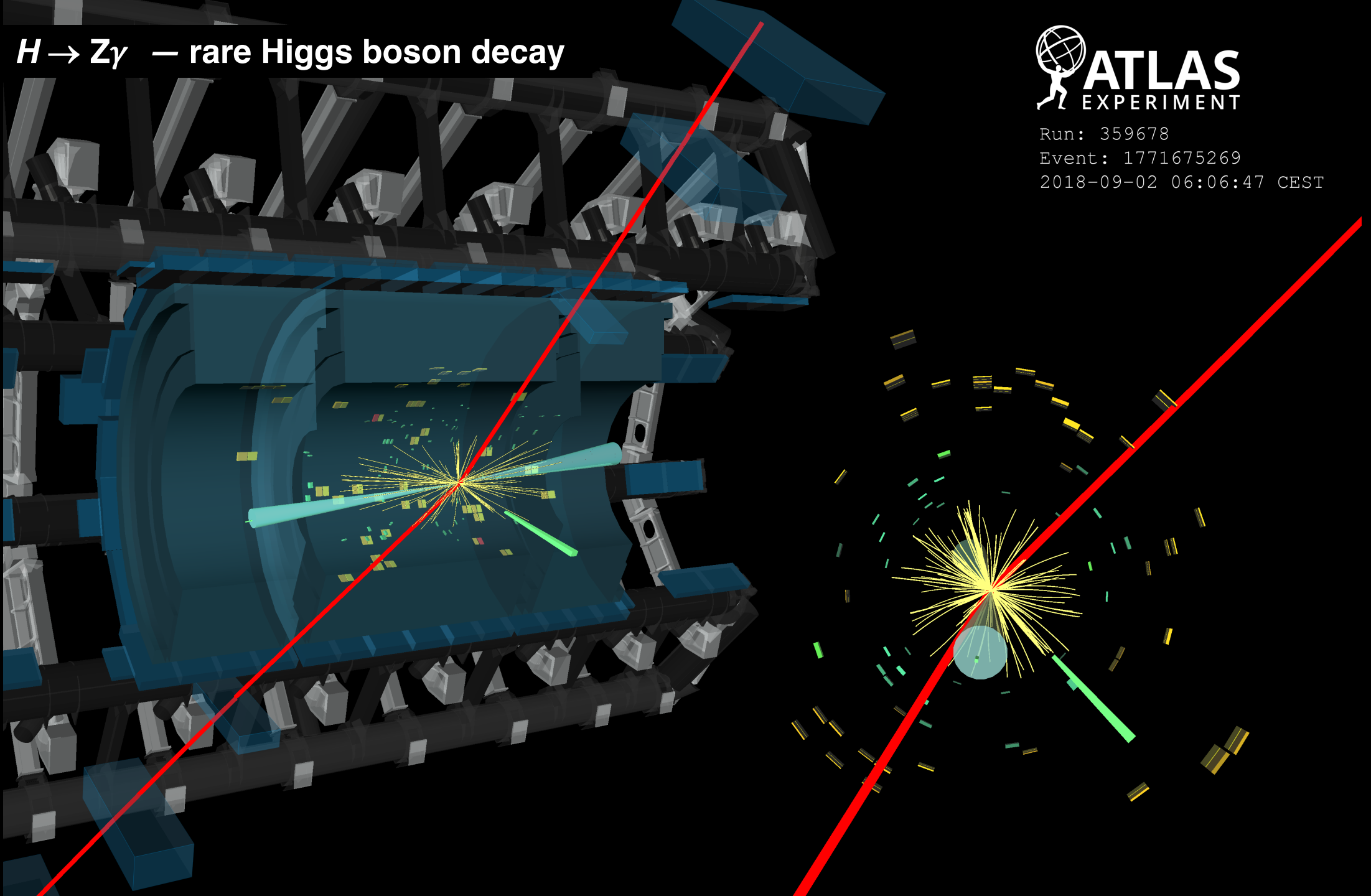
$H \rightarrow Z\gamma$ — rare Higgs boson decay



Run: 359678

Event: 1771675269

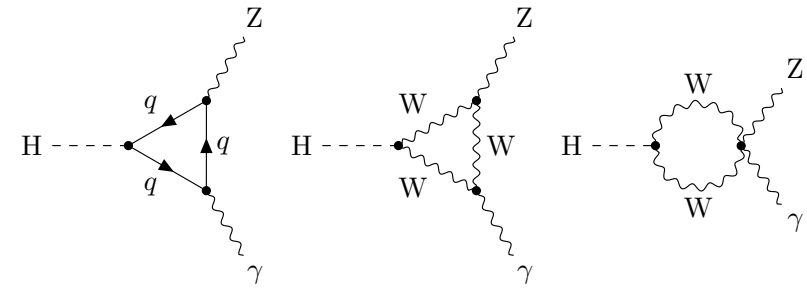
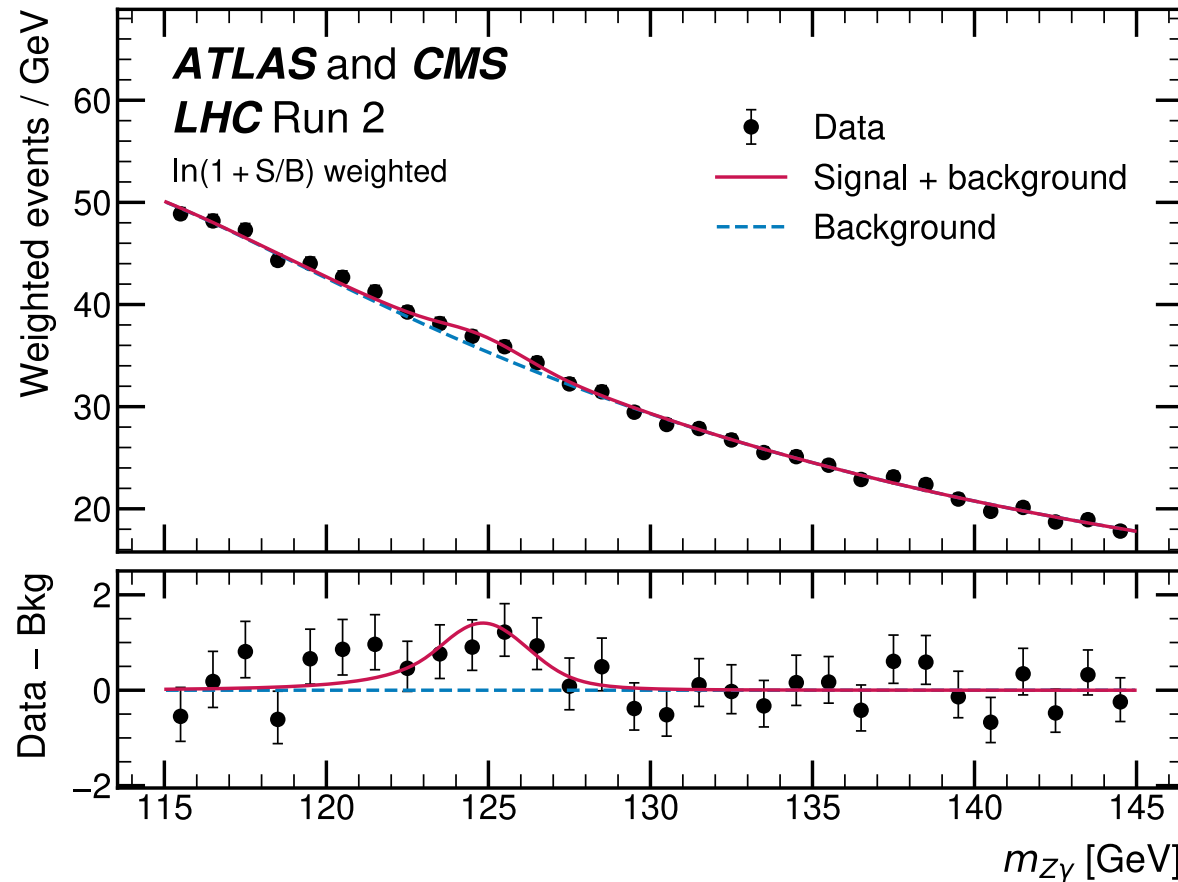
2018-09-02 06:06:47 CEST



$H \rightarrow Z\gamma$ — 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](#)



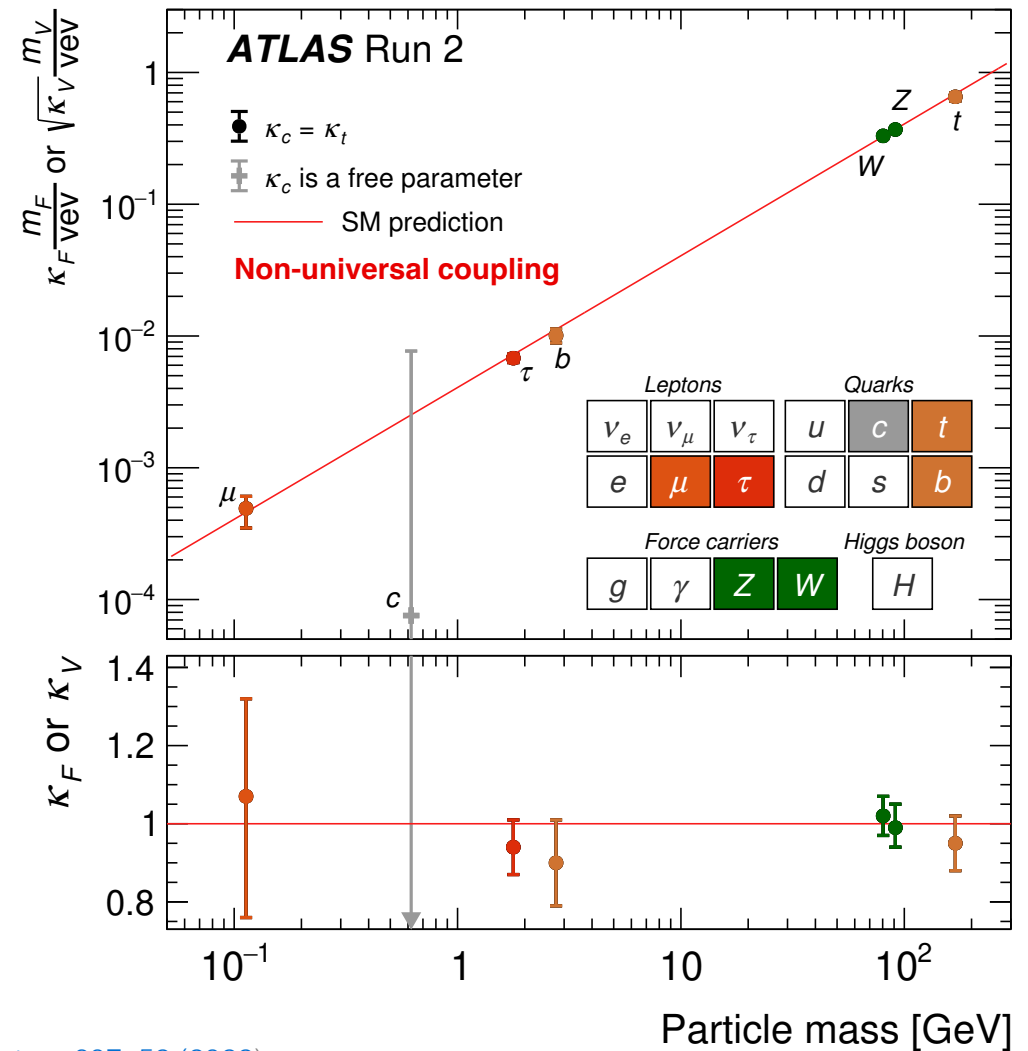
Field tensor not measured yet: $|H^2|A_{\mu\nu}Z^{\mu\nu}$

(Visible) 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 $Z \rightarrow ee, \mu\mu$)**

The Higgs mechanism is real !

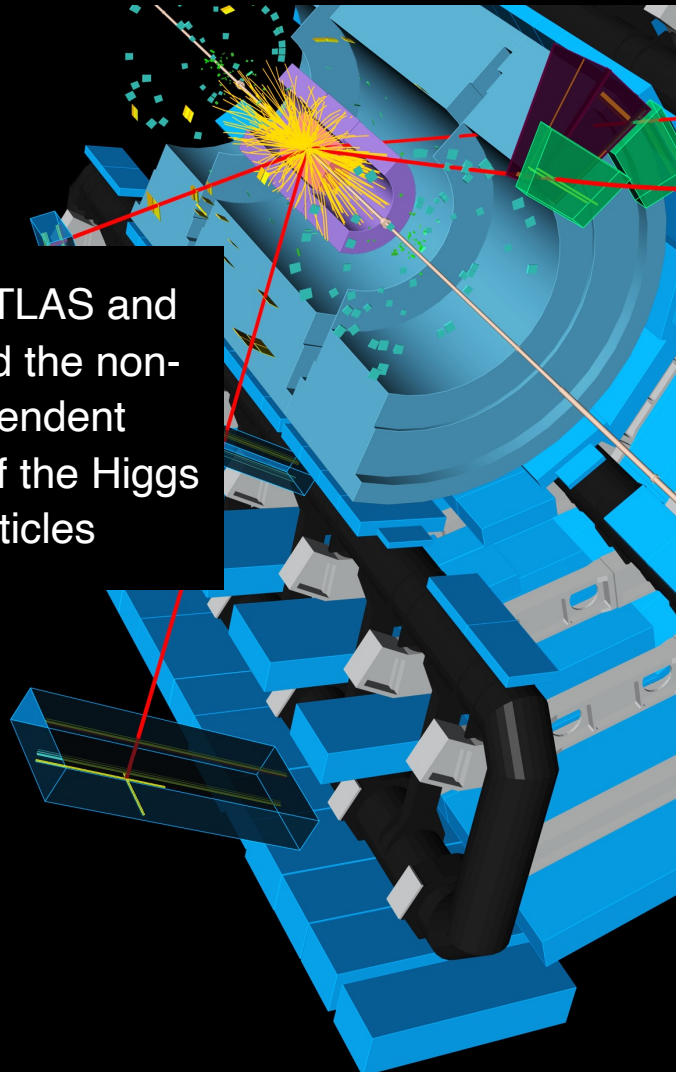
Measurements by ATLAS and CMS have confirmed the non-universal, mass-dependent coupling strengths of the Higgs boson to the SM particles



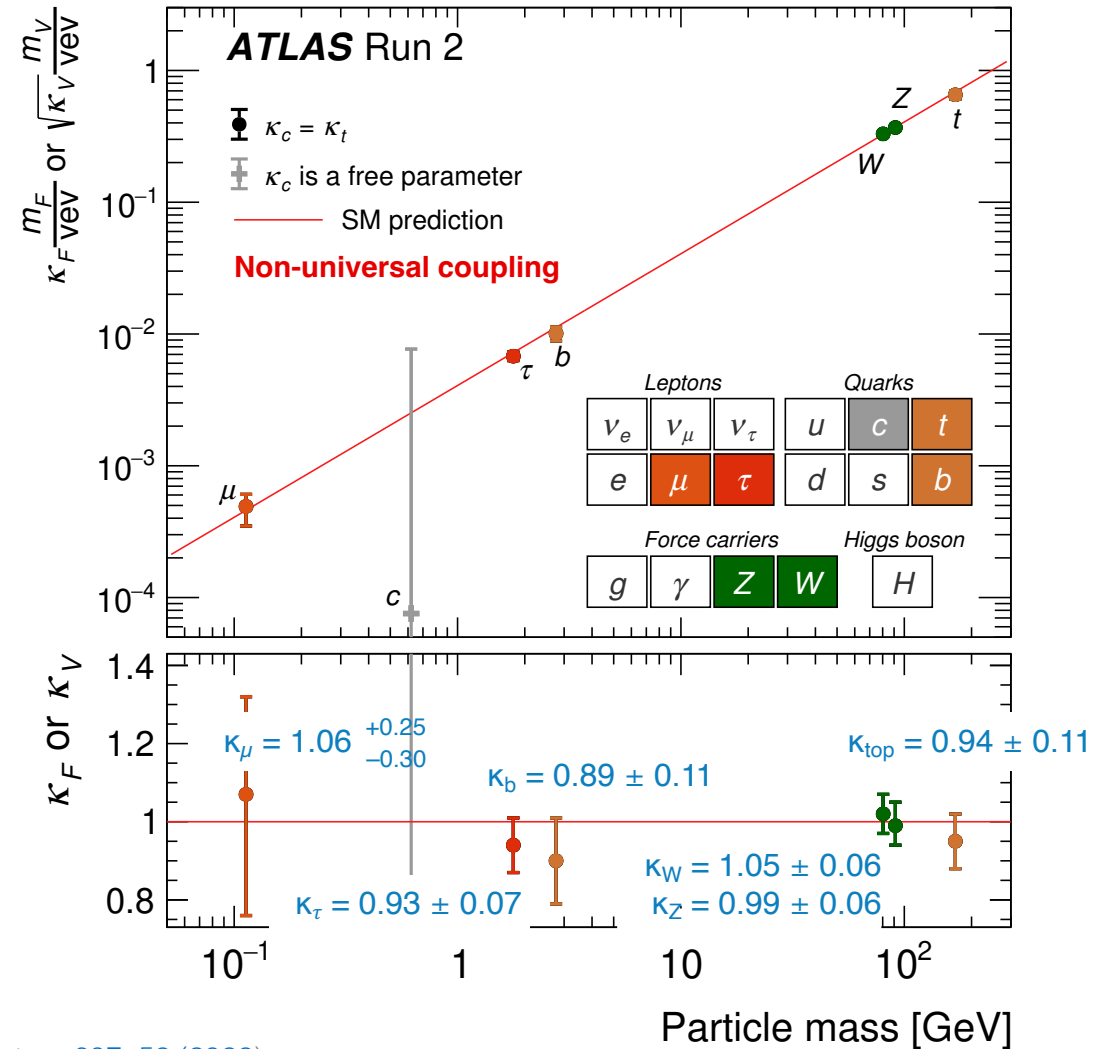
[Nature 607, 52 \(2022\)](#)

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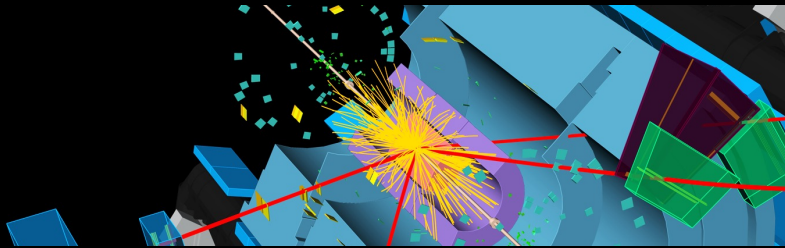


Coupling strengths wrt SM: $\kappa_\gamma = 1.01 \pm 0.06$, $\kappa_g = 0.95 \pm 0.07$



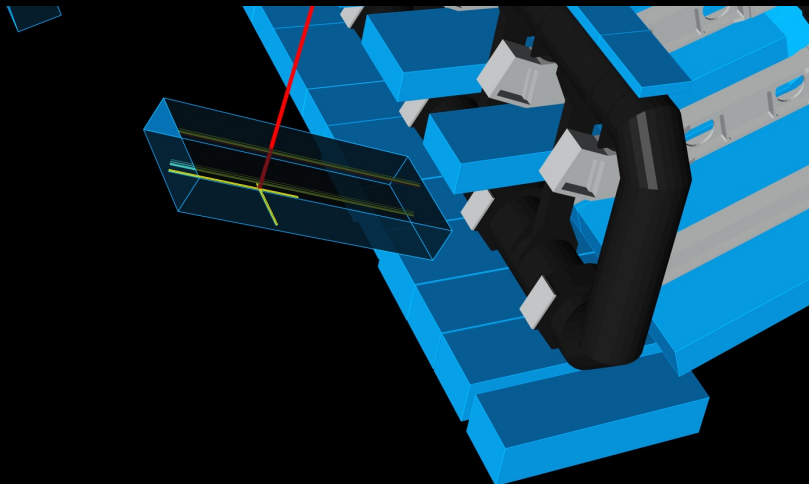
[Nature 607, 52 \(2022\)](#)

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The new sector opens a variety of possibilities and questions

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

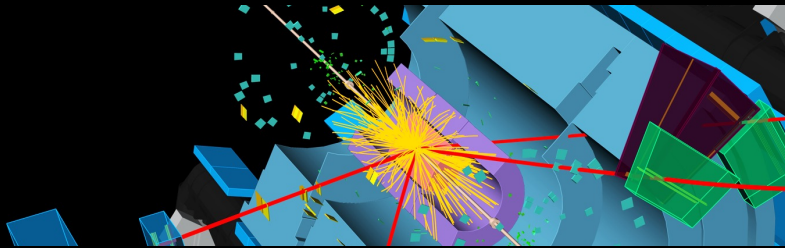


Possible relations between the Higgs boson and open questions in particle physics and cosmology

- What stabilises the Higgs mass versus high-scale new physics? Are there new TeV-scale symmetries? Is the Higgs boson elementary or composite, are there anomalies in its coupling to the W or Z?
- Do Higgs interactions violate CP? Is there an anomalous Higgs self coupling to allow for a first order electroweak phase transition?
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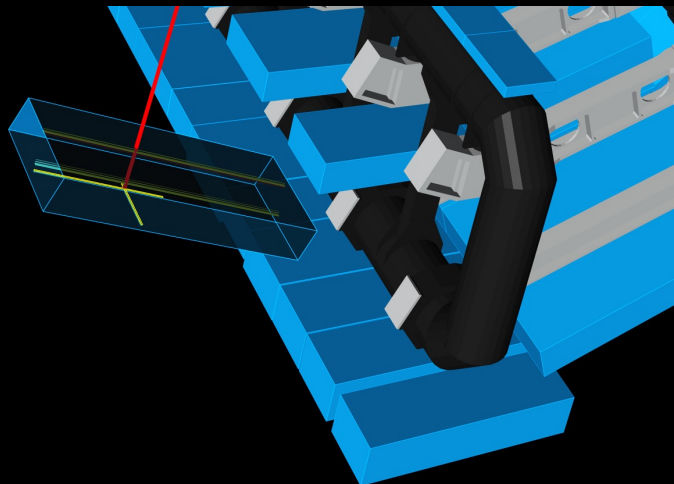
[Salam, Wang, Zanderighi: Nature 607, 41 \(2022\)](#)

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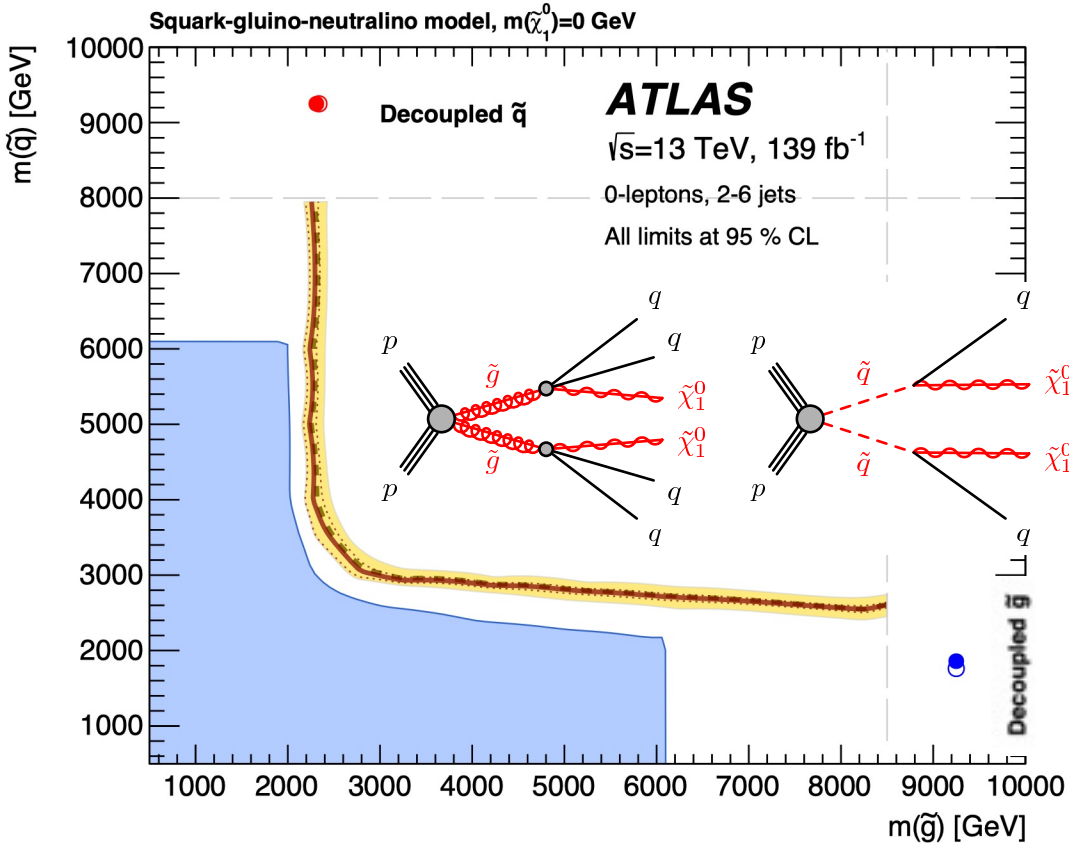
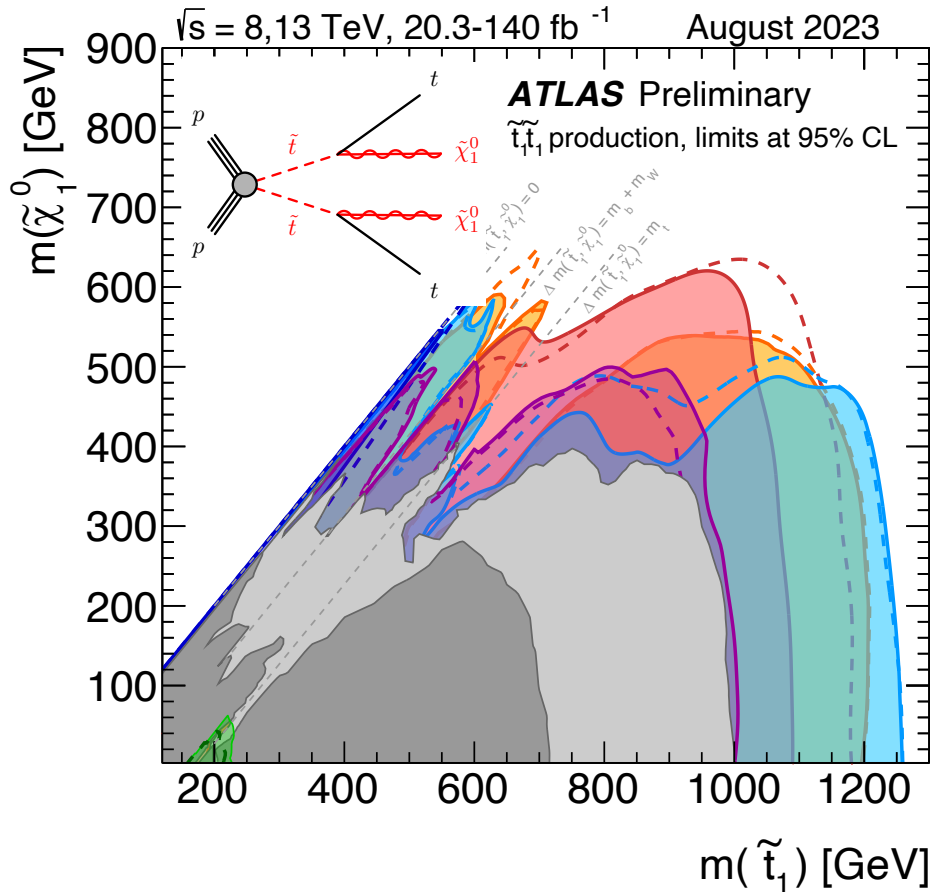
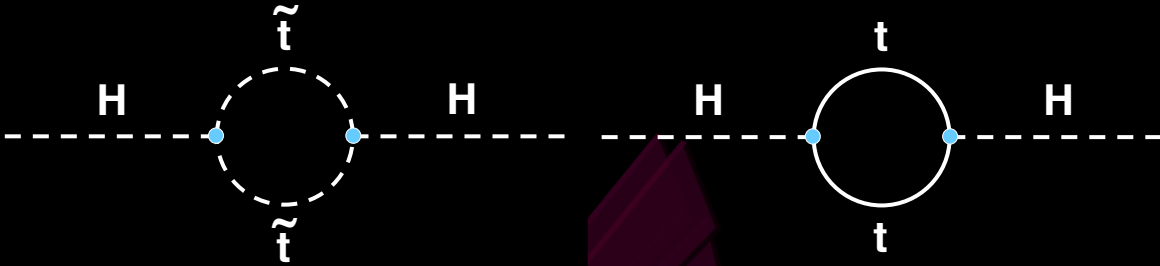


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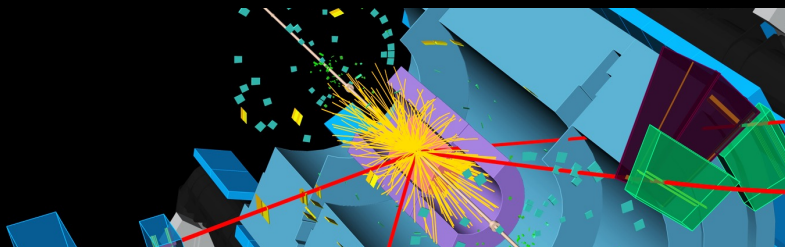
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[Salam, Wang, Zanderighi: Nature 607, 41 \(2022\)](#)

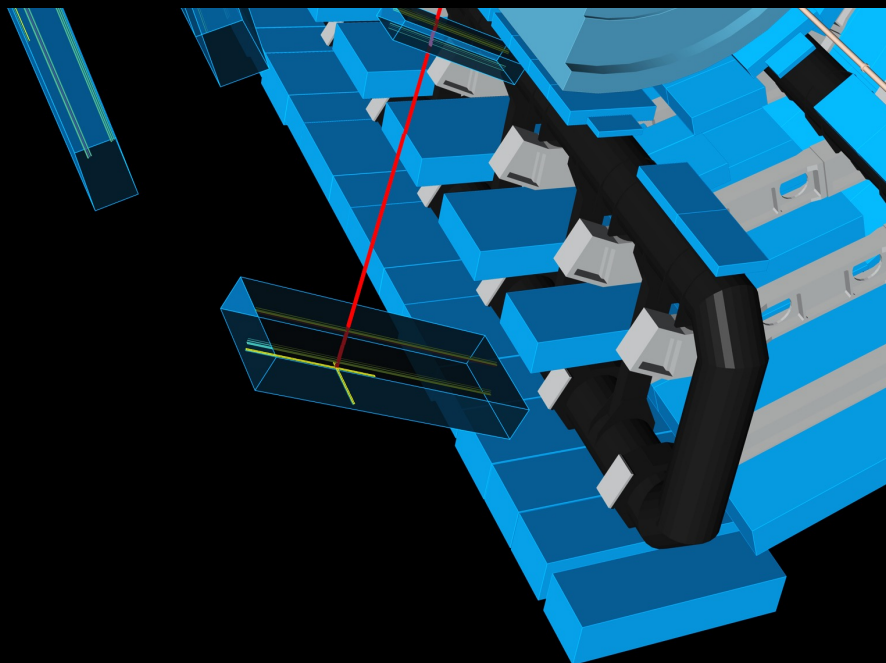
Supersymmetry?



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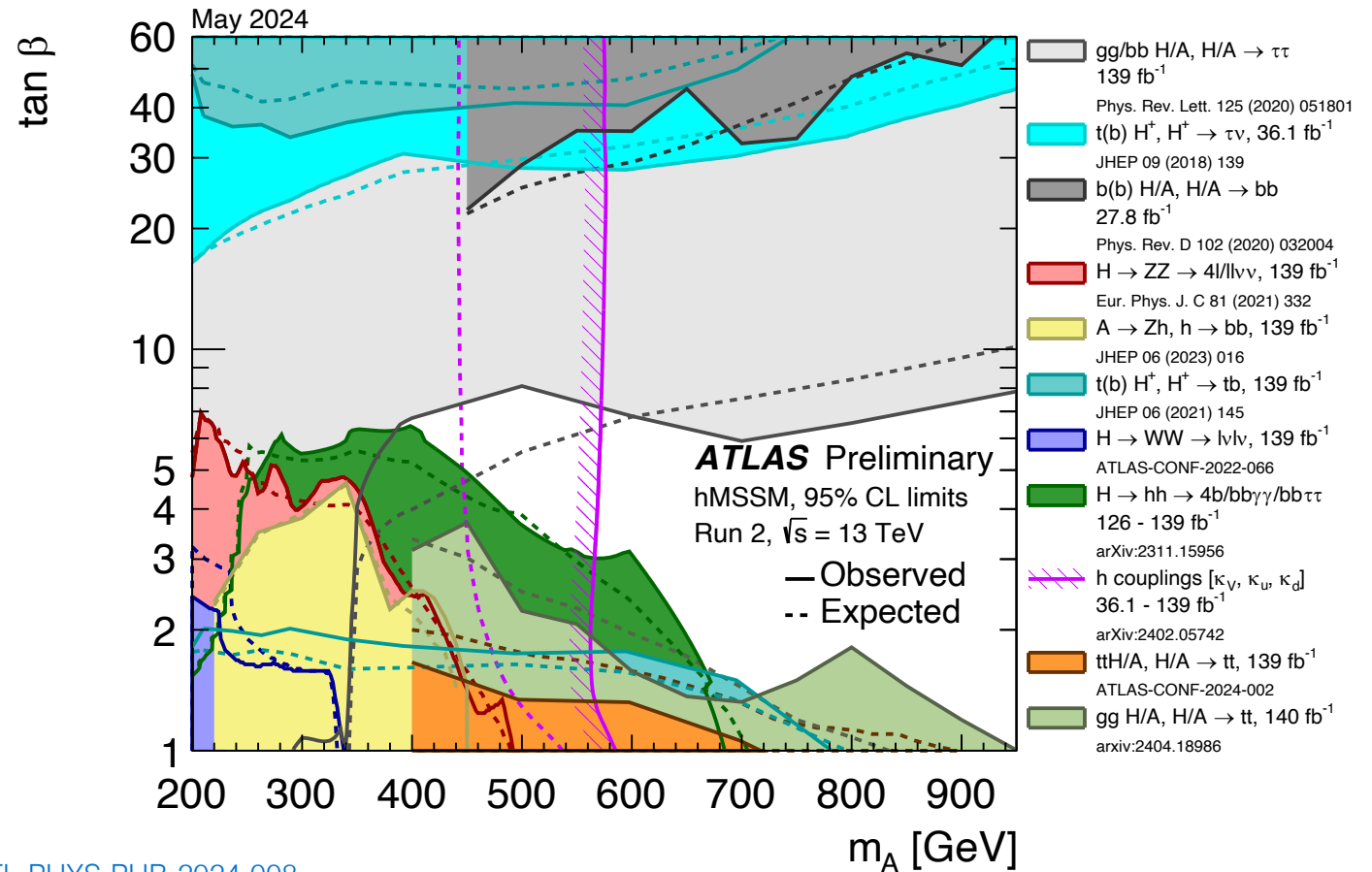
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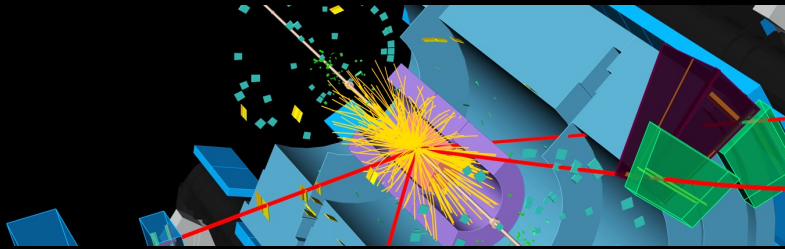
[Salam, Wang, Zanderighi: Nature 607, 41 \(2022\)](#)

Extended Higgs sector ?

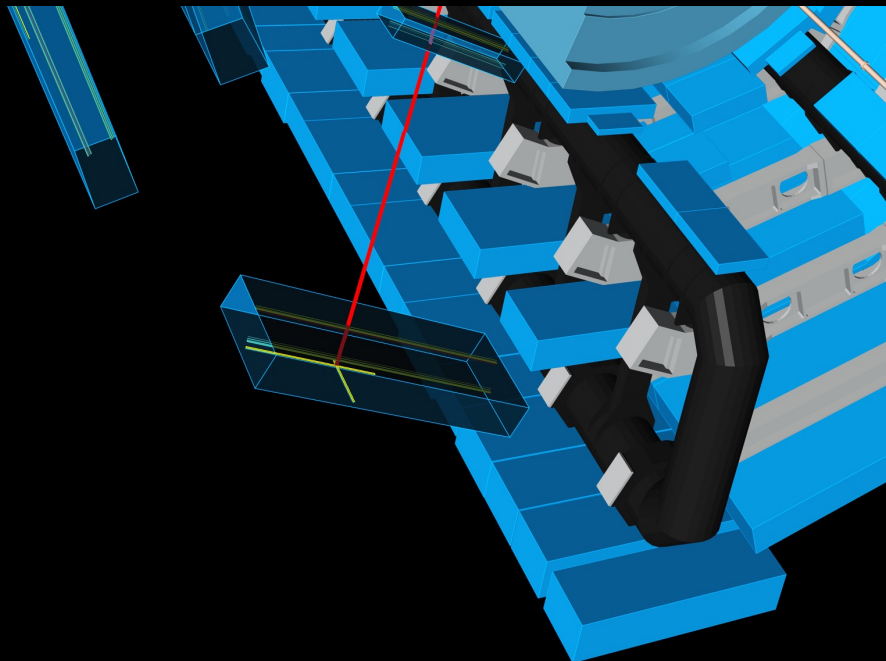
The scalar sector may feature an additional Higgs doublet with opposite weak hypercharge ($\rightarrow h, H, A, H^\pm$) or even triplet ($+ H^{\pm\pm}$) with rich phenomenology



The Higgs mechanism is real !



The new sector opens a variety of possibilities and questions



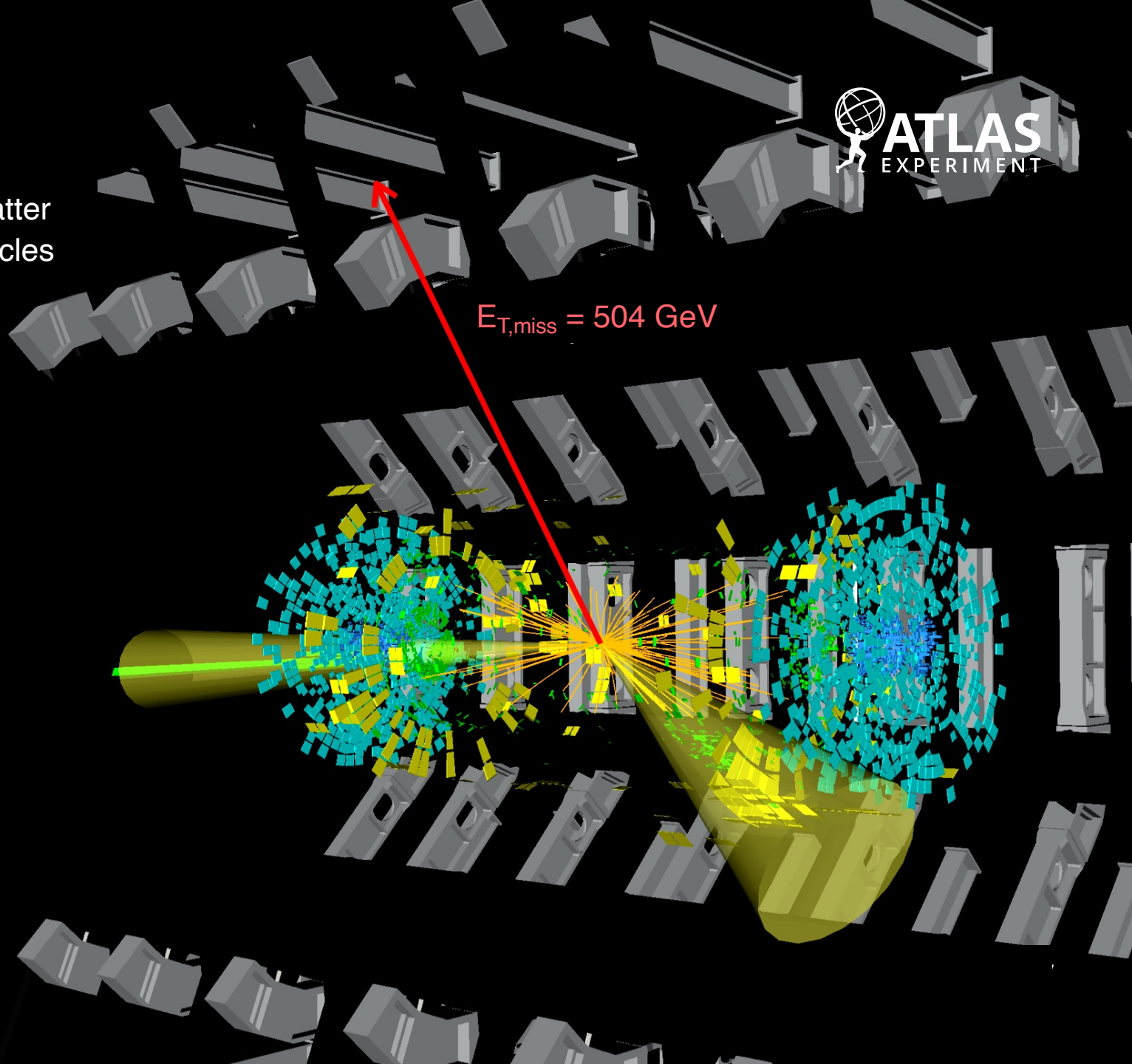
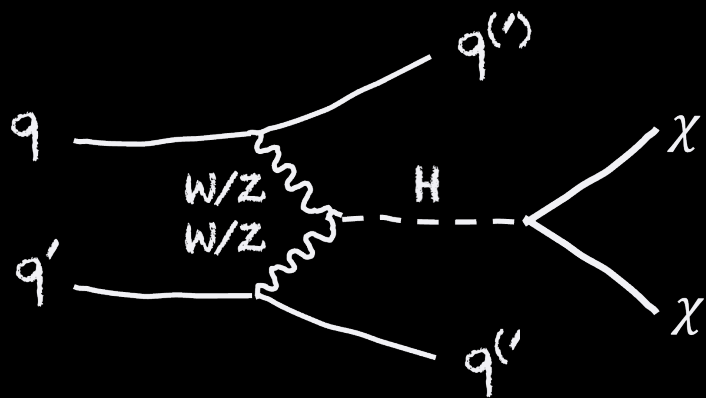
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[Salam, Wang, Zanderighi: Nature 607, 41 \(2022\)](#)

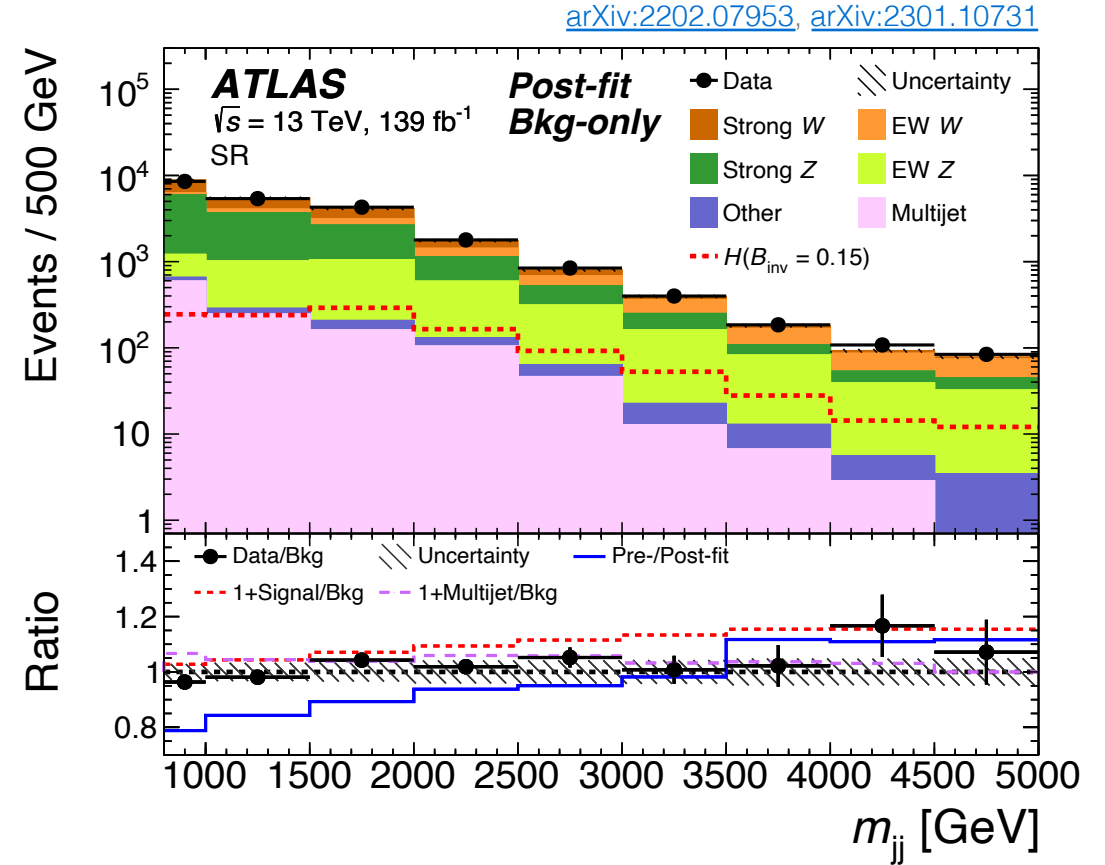
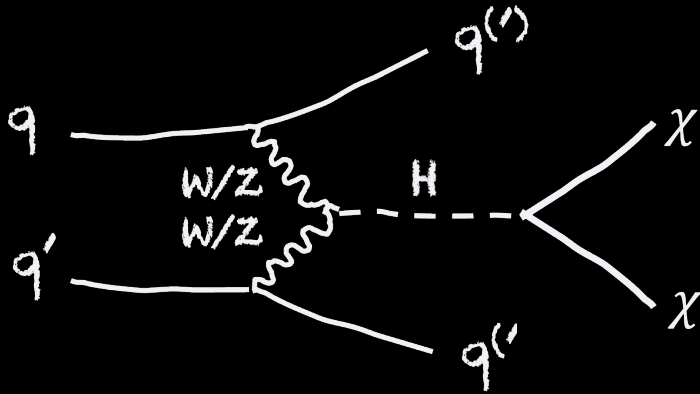
Dark matter

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



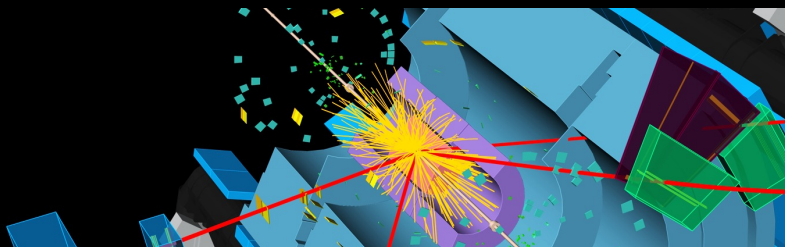
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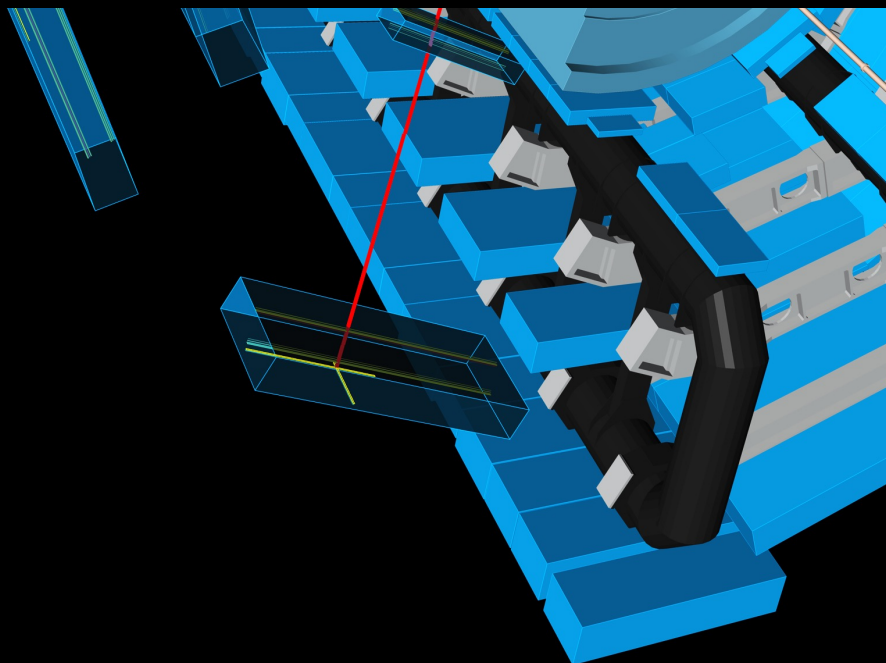


⇒ $\text{BR}(H \rightarrow \text{invisible}) < 0.107 \text{ (0.077) at 95\% CL}$

The Higgs mechanism is real !



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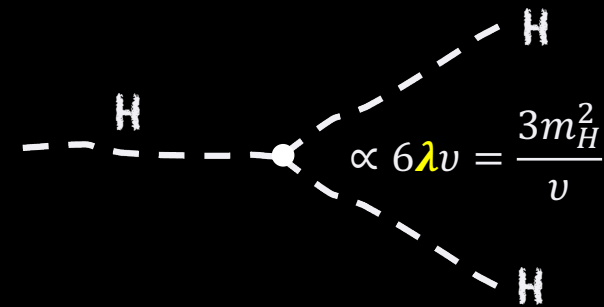
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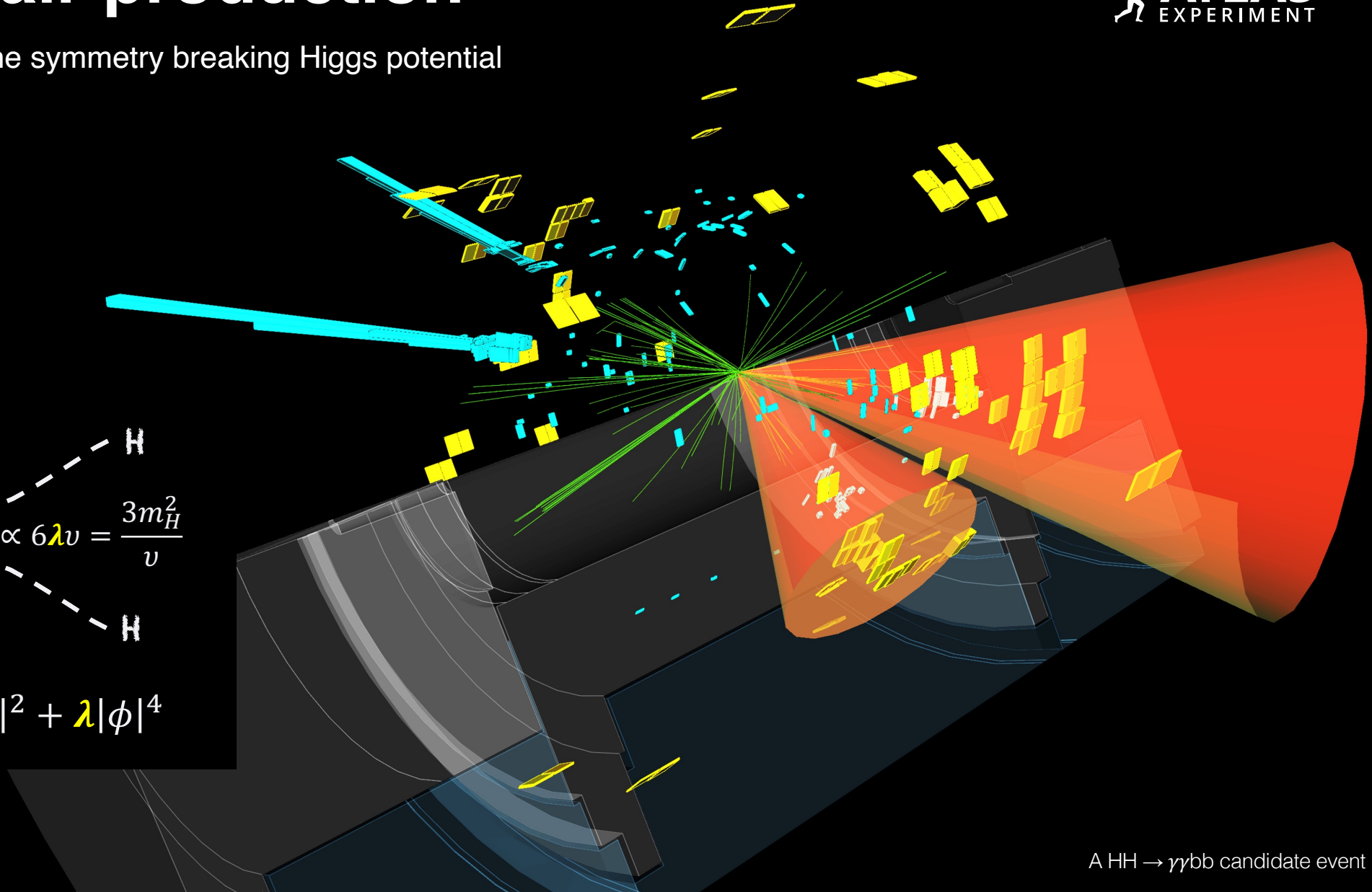
[Salam, Wang, Zanderighi: Nature 607, 41 \(2022\)](#)

Higgs pair production

Direct access to the symmetry breaking Higgs potential



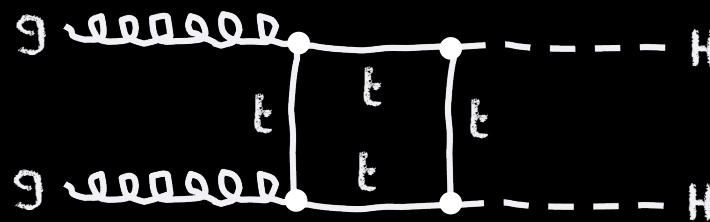
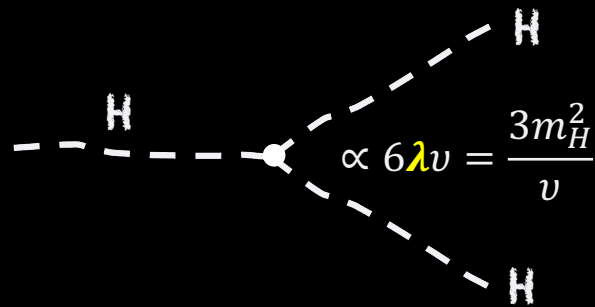
$$V(\phi) = -\mu^2|\phi|^2 + \lambda|\phi|^4$$



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

Higgs pair production

Direct access to the symmetry breaking Higgs potential

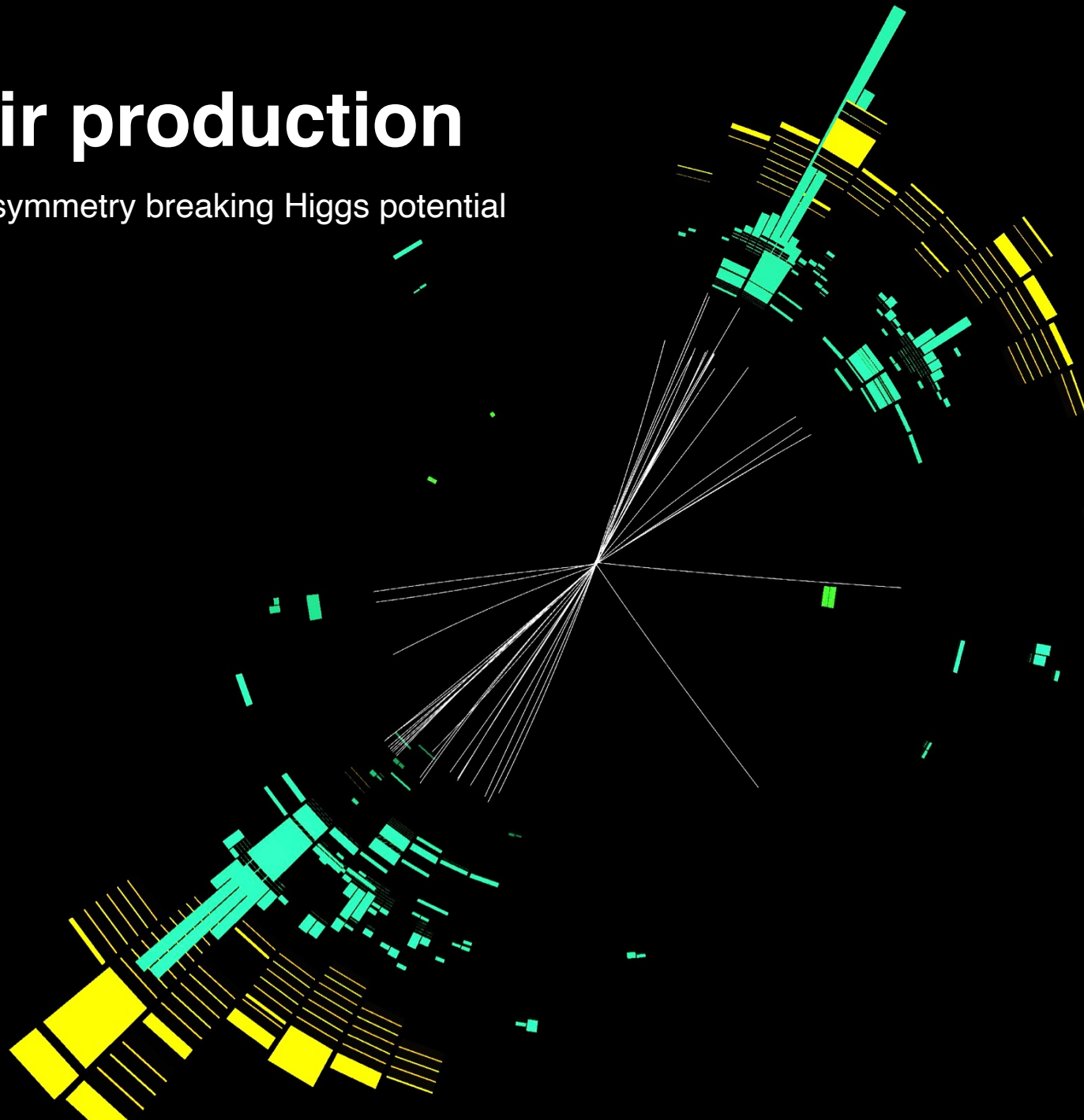


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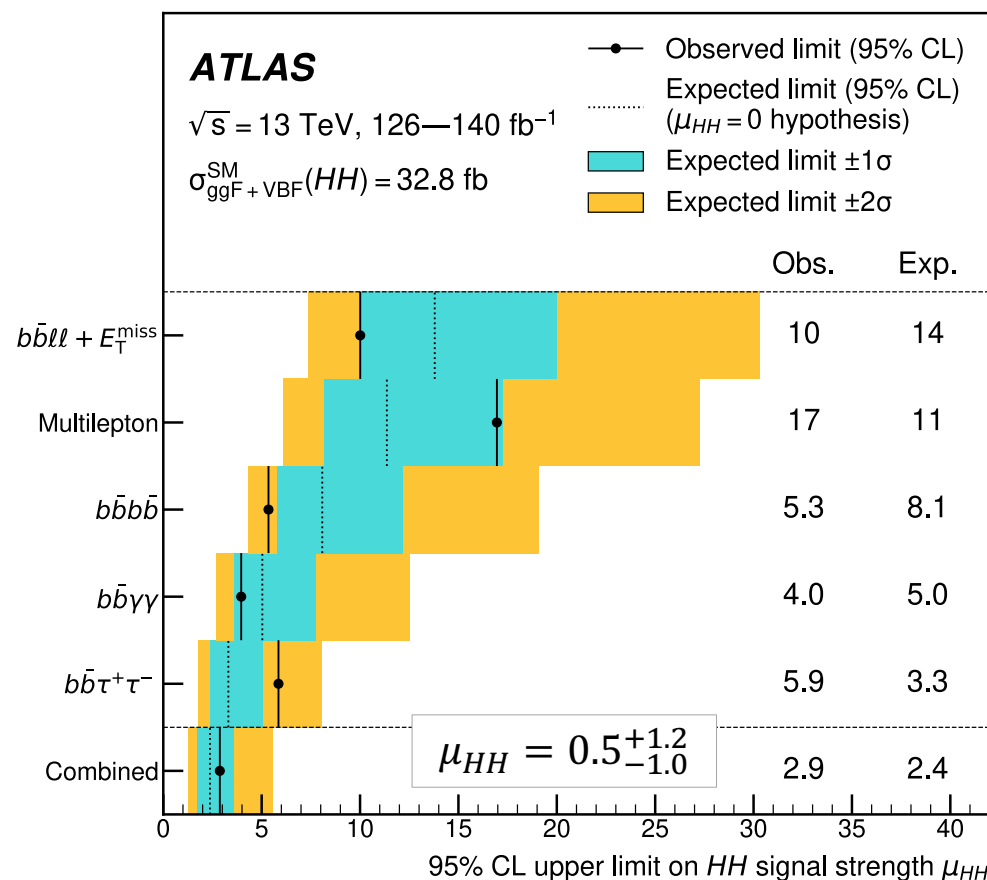
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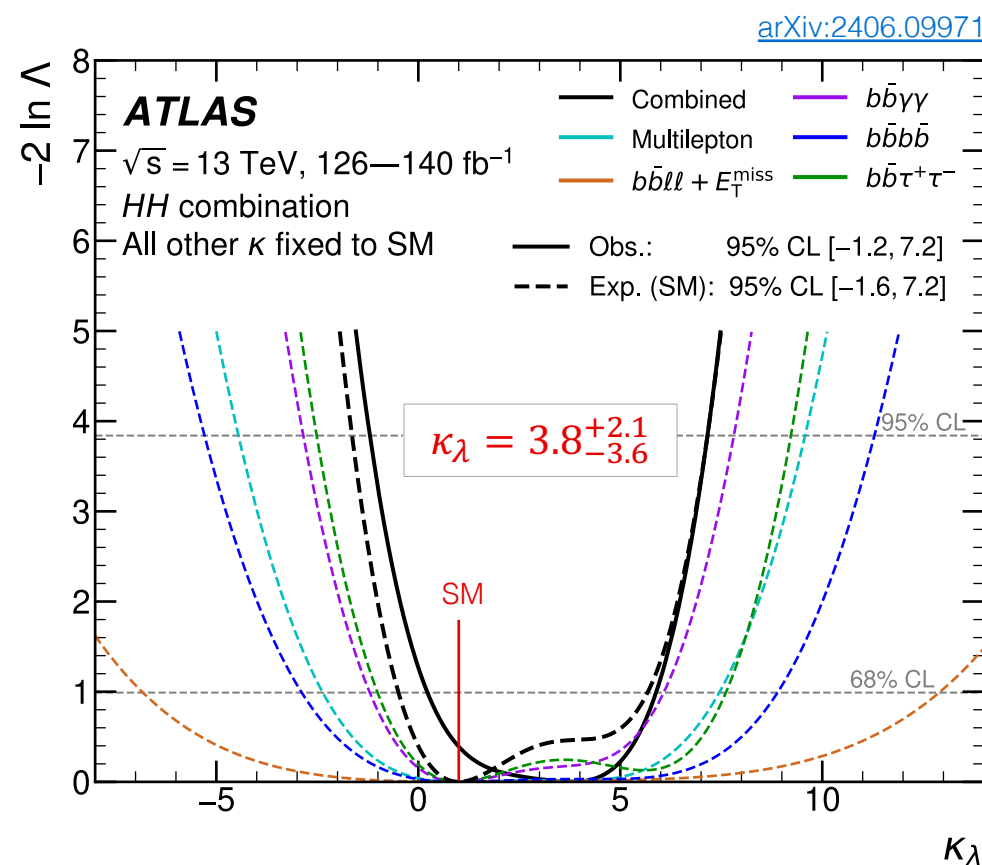
A $HH \rightarrow bbbb$ candidate event

Higgs pair production

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

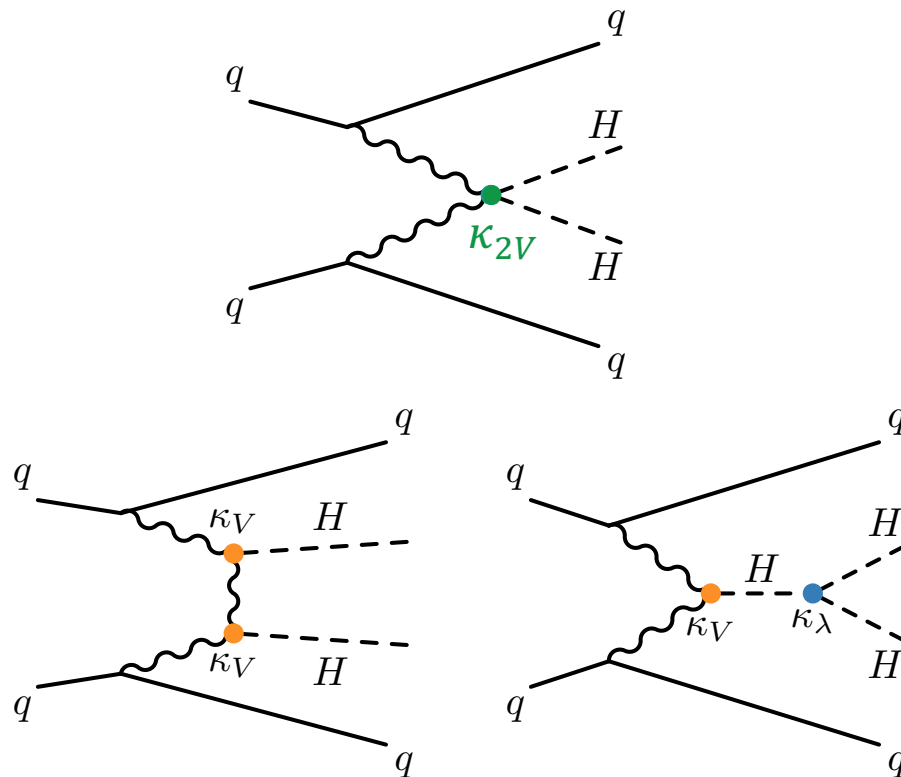


Constraint on $\kappa_\lambda = \lambda/\lambda_{\text{SM}}$, $\lambda_{\text{SM}} \sim 0.13$ also benefits from single-Higgs coupling measurements via quantum loop



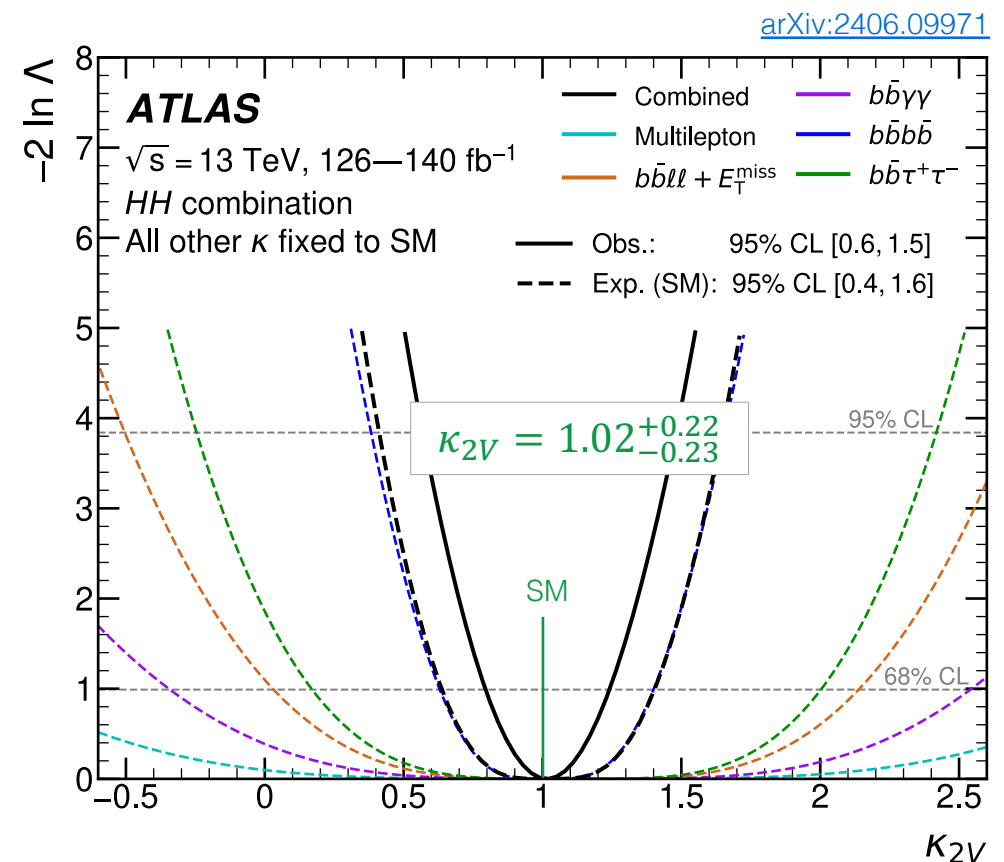
Higgs pair production

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!

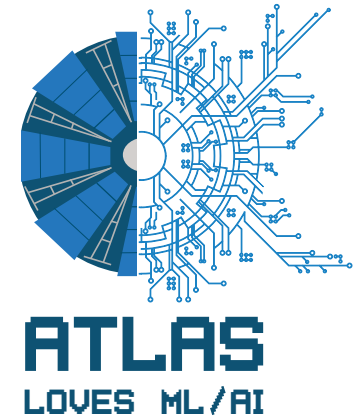
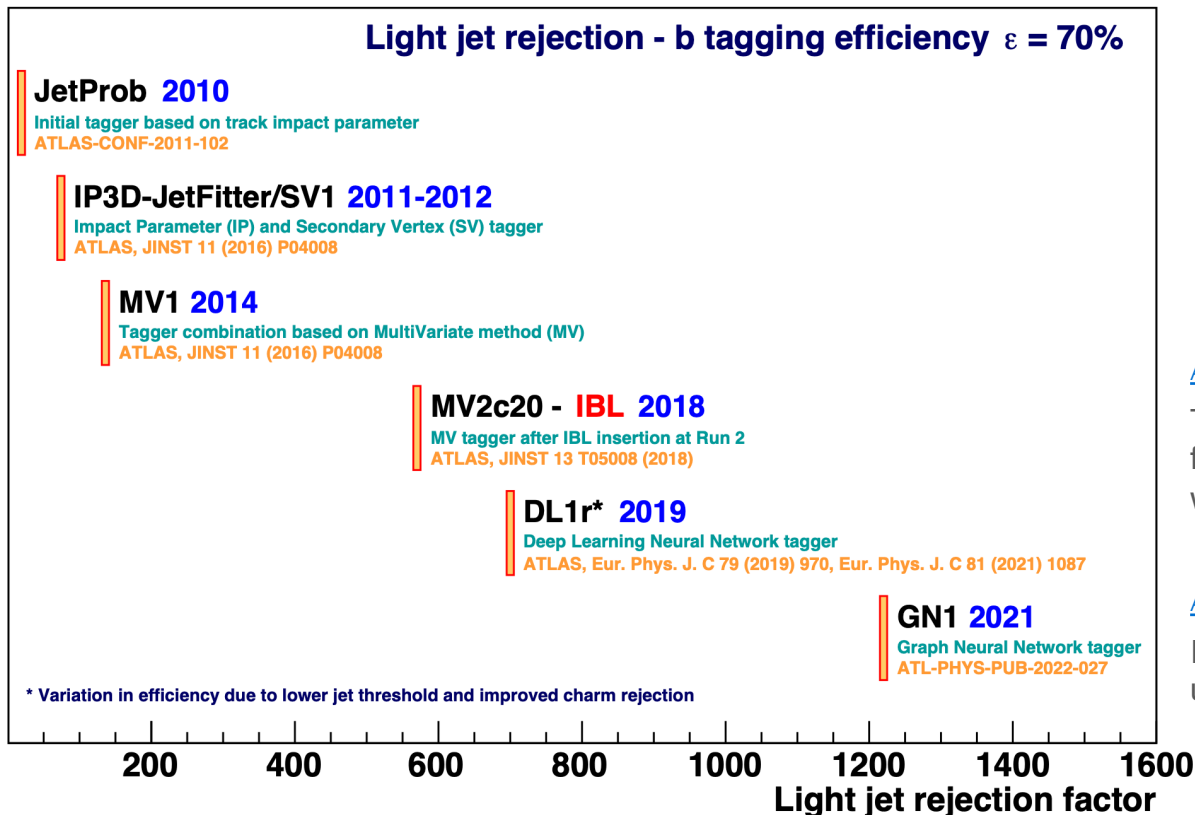


Improving performance



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

Marumi Kado



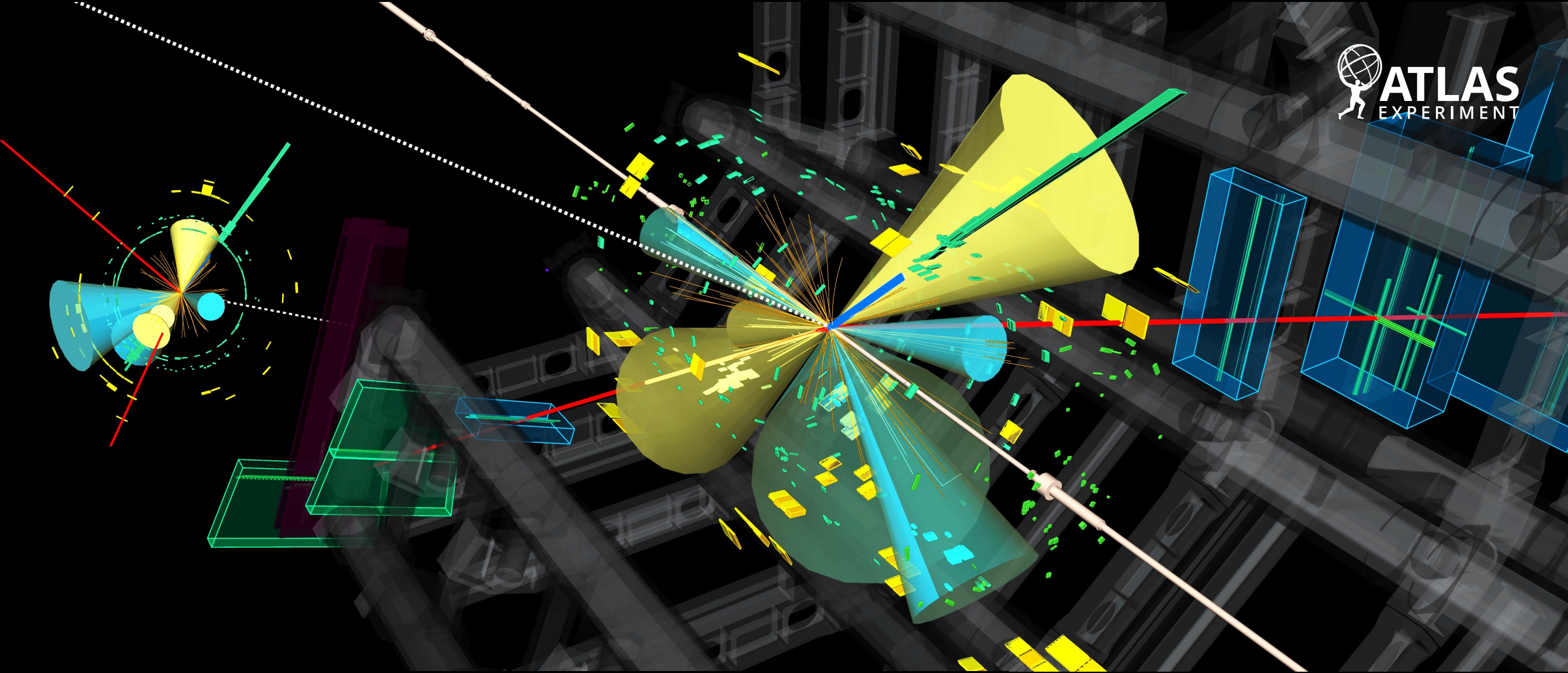
[ATL-PHYS-PUB-2022-027](#) (2022)

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

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

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

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



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

$pp \rightarrow t\bar{t}t\bar{t}$ 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)

High-precision physics at the LHC

Most precise luminosity measurement ever achieved at a hadron collider

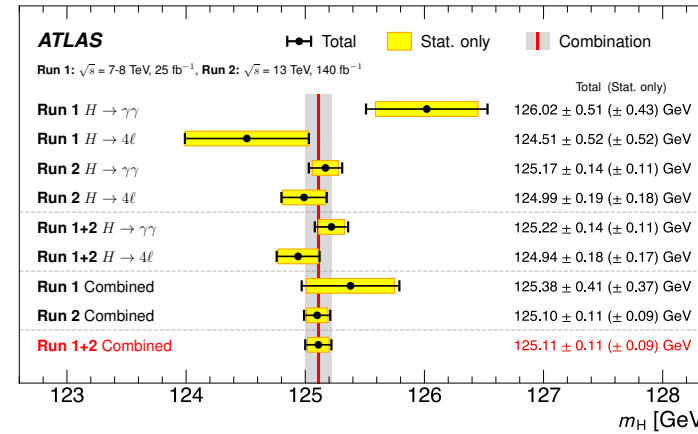
Run 2: $140.1 \pm 1.2 \text{ fb}^{-1}$ (0.83%)

[arXiv:2212.09379](https://arxiv.org/abs/2212.09379), [Physics briefing](#)

[arXiv:2308.07216](https://arxiv.org/abs/2308.07216), [arXiv:2308.04775](https://arxiv.org/abs/2308.04775),
[arXiv:2309.05471](https://arxiv.org/abs/2309.05471),
[CERN press update](#), [Physics briefing](#)

$\sigma(m_H) = 110 \text{ MeV}$ (0.09%)

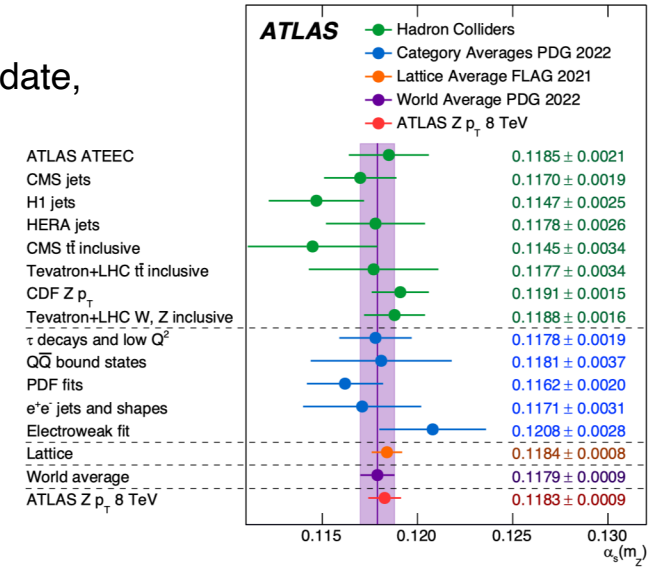
Most precise Higgs mass to date



Most precise α_s measurement to date, from precise measurement of $Z p_T$ spectra

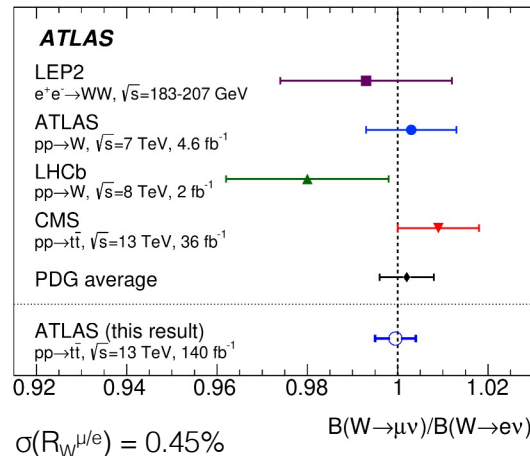
$\sigma(\alpha_s(m_Z)) = 0.0009$

[arXiv:2309.12986](https://arxiv.org/abs/2309.12986),
[CERN press update](#),
[Briefing](#)



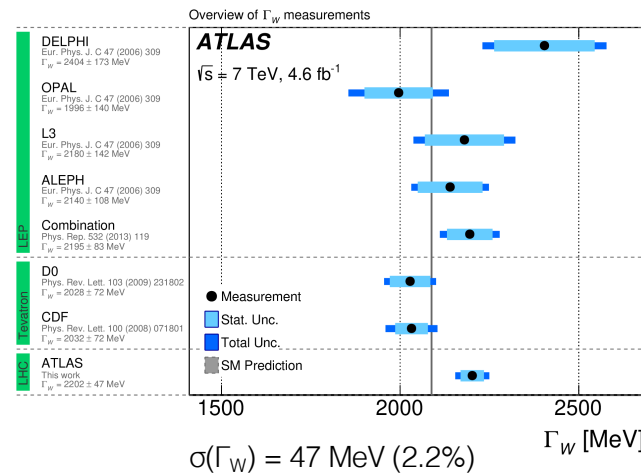
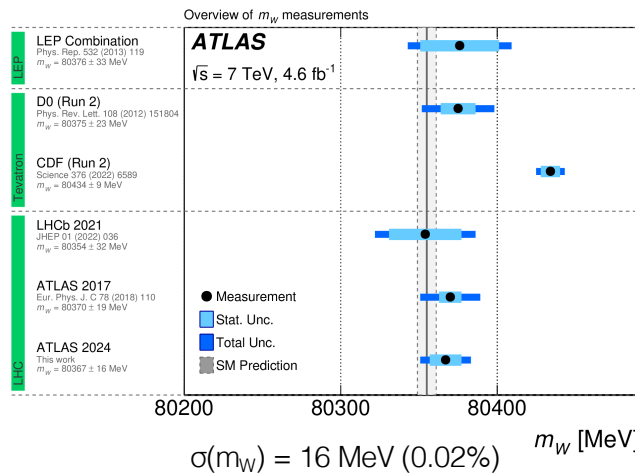
Precise test of lepton universality in W decays

[arXiv:2403.02133](https://arxiv.org/abs/2403.02133), [CERN news article](#)

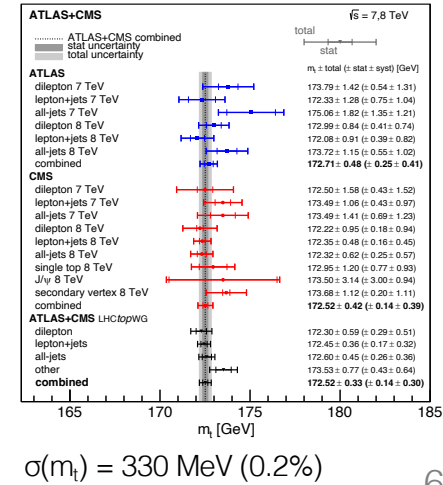


Precise measurements of W p_T , mass & width, as well as top mass (Run-1 combination with CMS)

[arXiv:2403.15085](https://arxiv.org/abs/2403.15085), [CERN news article](#), [ATLAS briefing](#)



[arXiv:2402.08713](https://arxiv.org/abs/2402.08713), [Physics briefing](#)



The next steps

LHC

CMS

SPS

ALICE

ATLAS

LHCb

PS

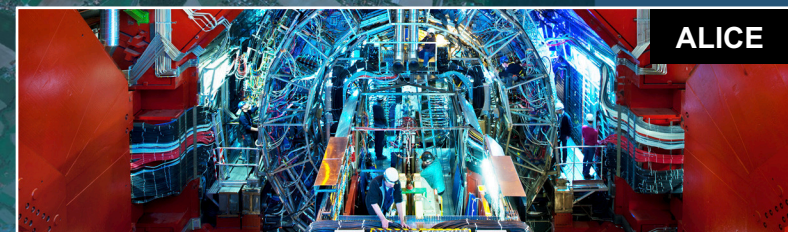
Areal view



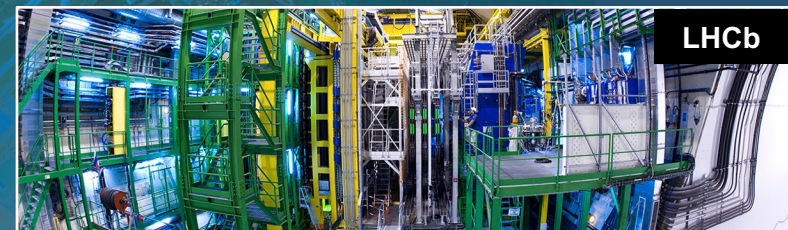
ATLAS



CMS

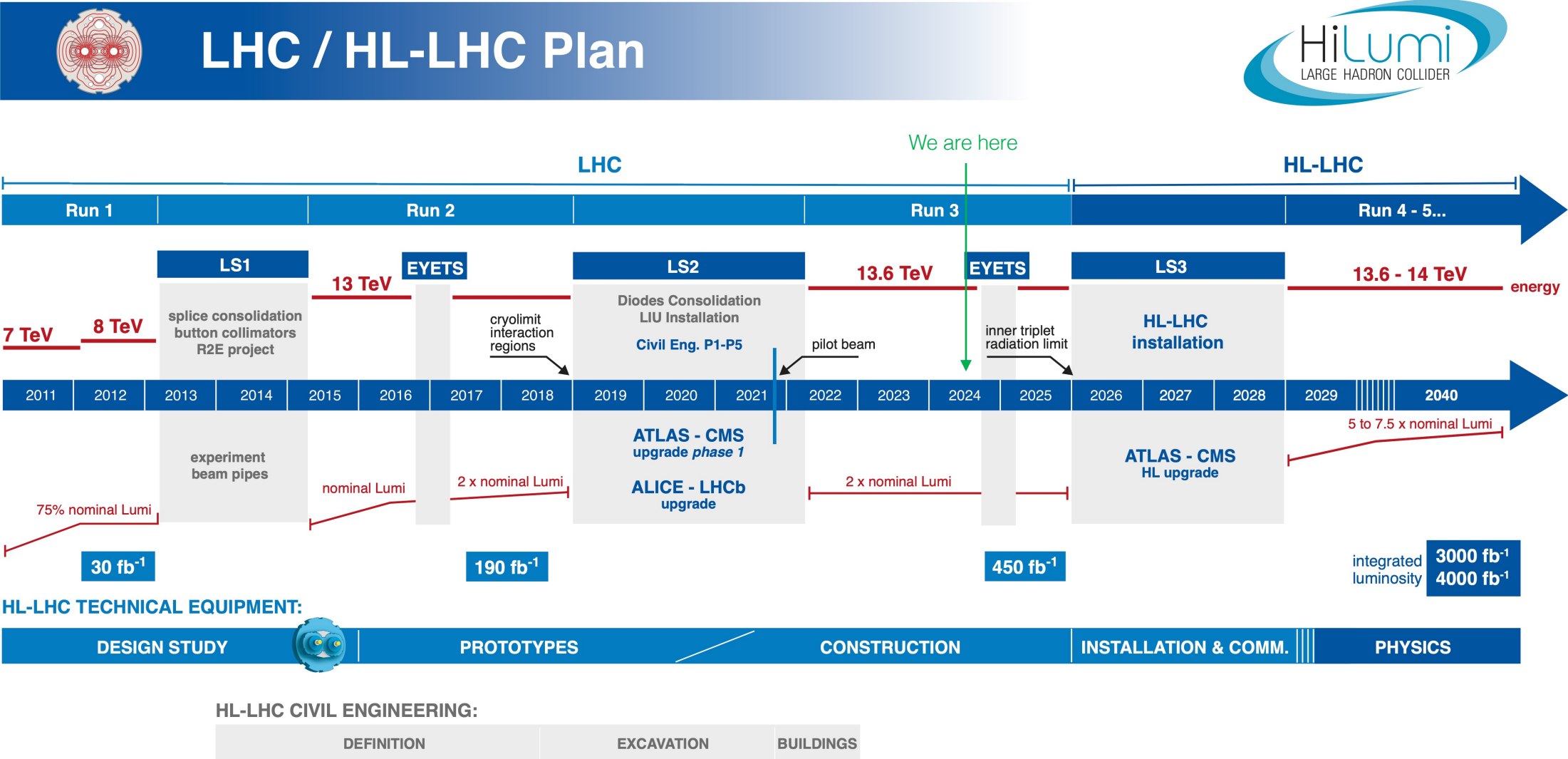


ALICE



LHCb

Preparing the future — the grand plan of the LHC



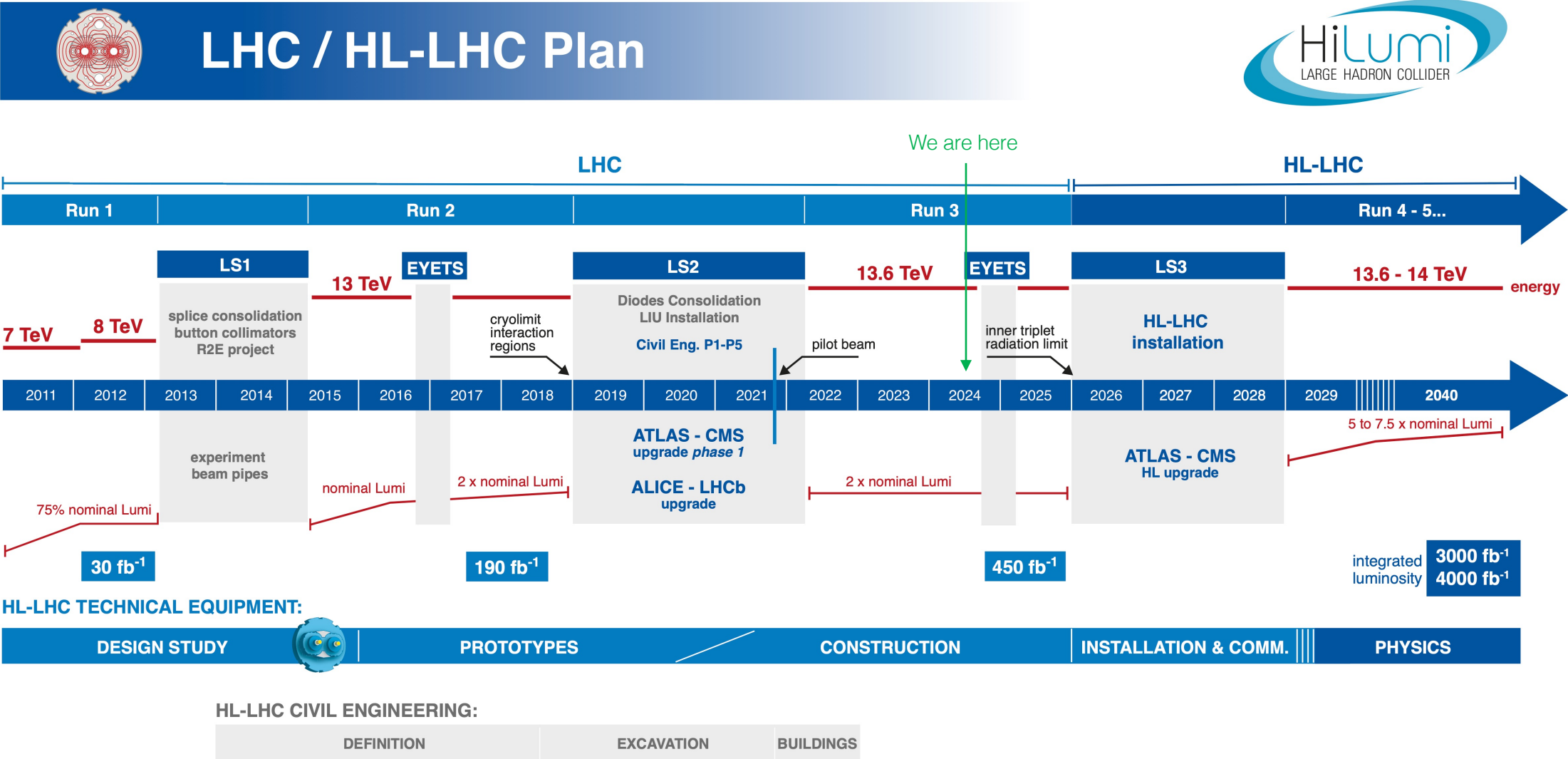
Preparing the future — the grand plan of the LHC

Run 3 (2022–2025) at 13.6 TeV is ongoing

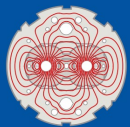
First 13.6 TeV collisions on 5 July 2022



Preparing the future — the grand plan of the LHC



Preparing the future

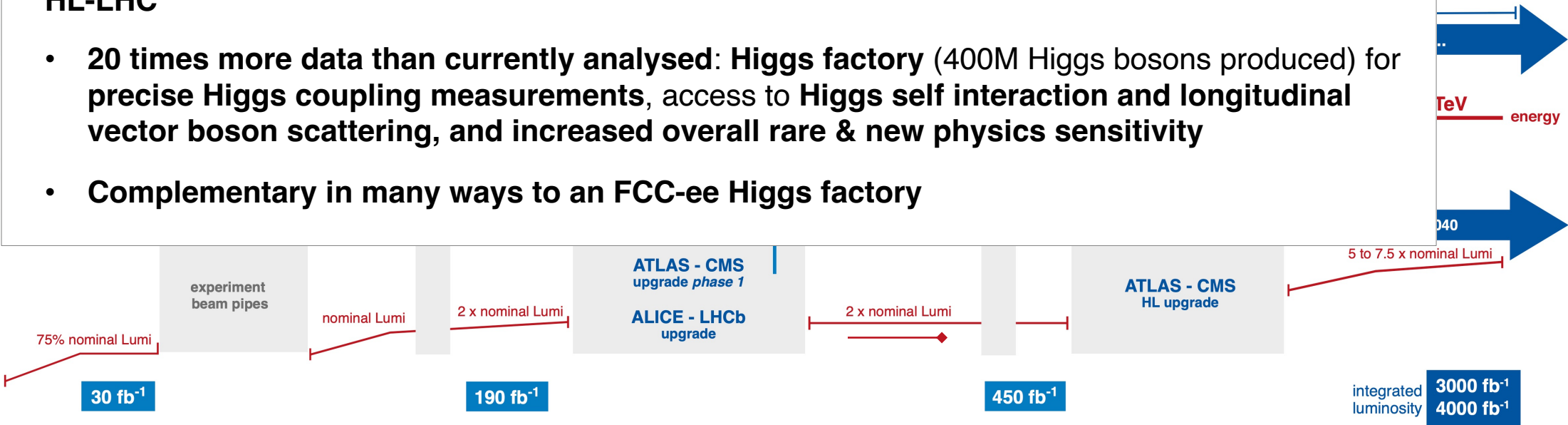


LHC / HL-LHC Plan



HL-LHC

- **20 times more data than currently analysed: Higgs factory** (400M Higgs bosons produced) for **precise Higgs coupling measurements**, access to **Higgs self interaction** and **longitudinal vector boson scattering**, and **increased overall rare & new physics sensitivity**
- **Complementary in many ways to an FCC-ee Higgs factory**



HL-LHC TECHNICAL EQUIPMENT:



HL-LHC CIVIL ENGINEERING:

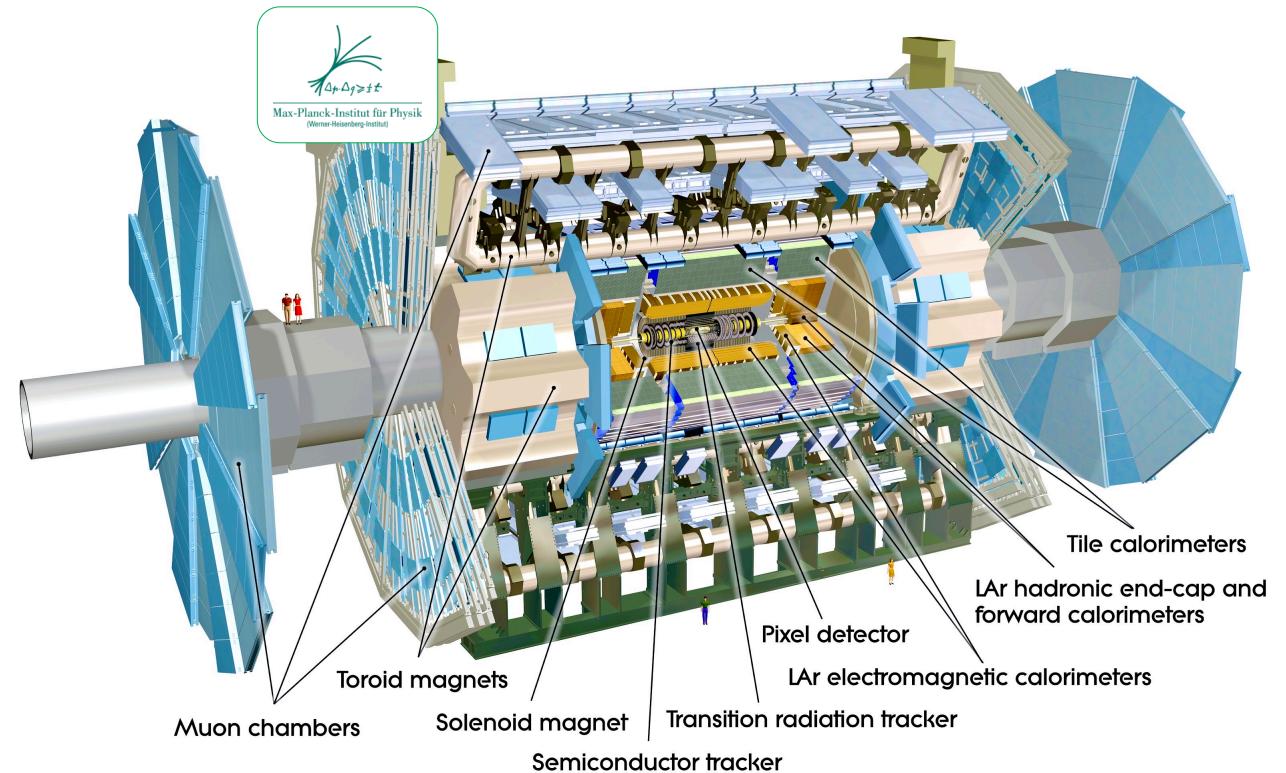


High-Luminosity LHC (HL-LHC)



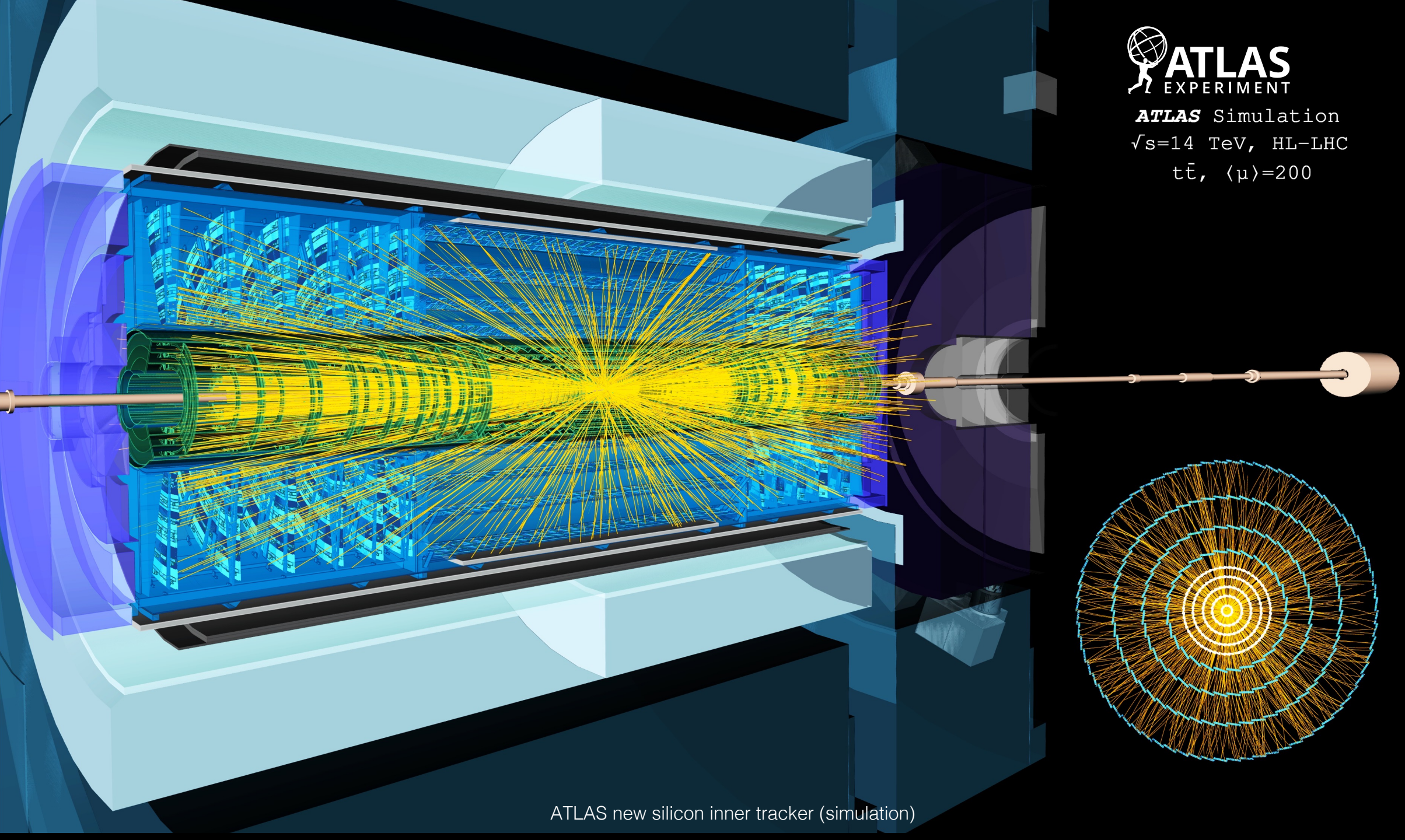
The HL-LHC's luminosity requires unprecedented detector and computing technologies:

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





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



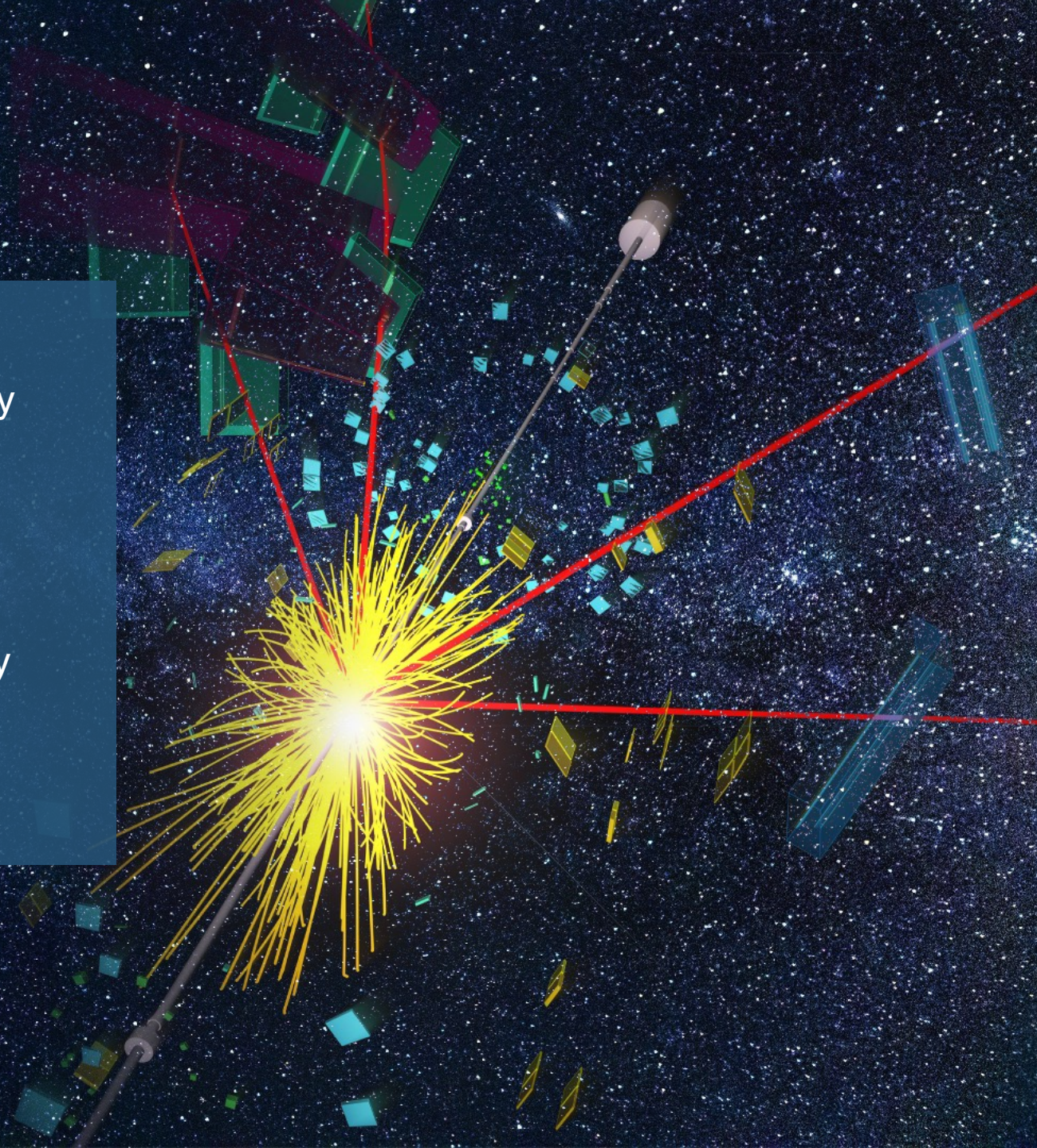
ATLAS new silicon inner tracker (simulation)

Conclusions

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

The LHC Run 2 has been transformative for Higgs boson physics

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





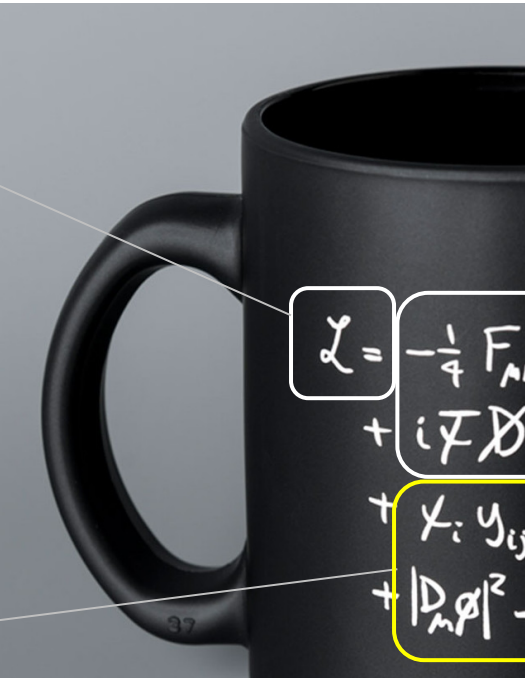
Extra slides

Completing the Standard Model

The scalar Higgs sector completes the Standard M

The **SM Lagrangian**

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



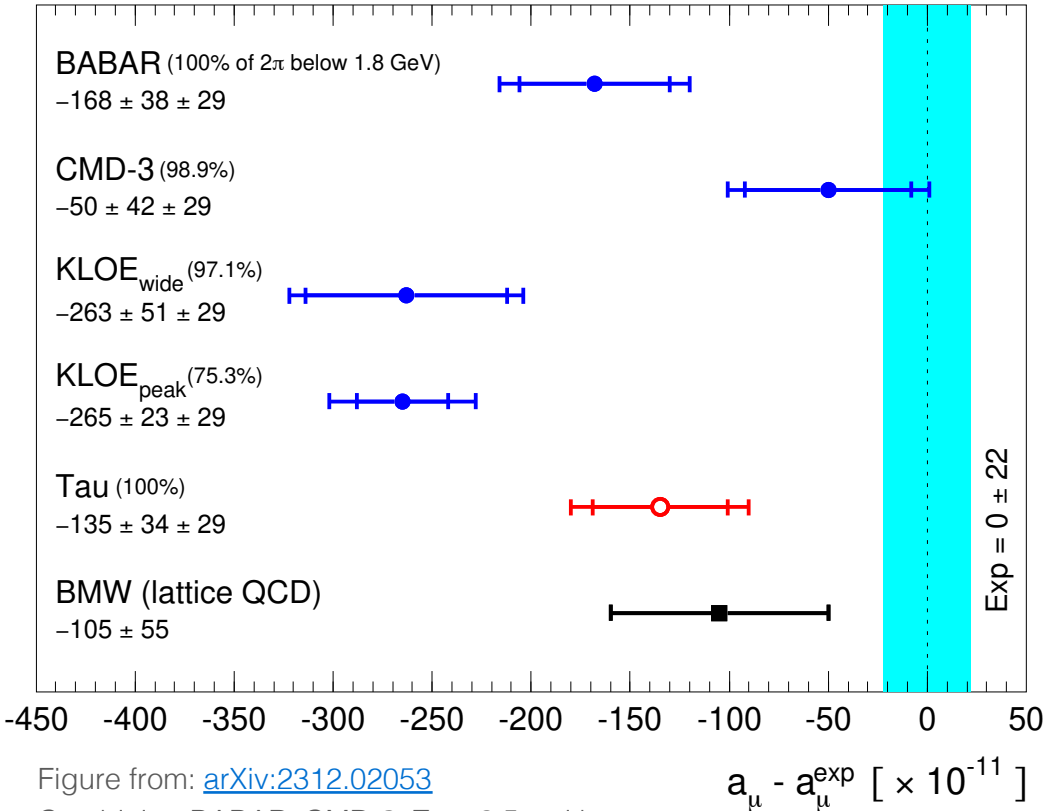
Unpleasant
symmetries, 2
large hierarc

The Standard Model is a highly 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 and experiment agree within a relative precision of 10^{-10} !

Latest predictions of the muon g-2 and experiment:



describes the
) with non-zero

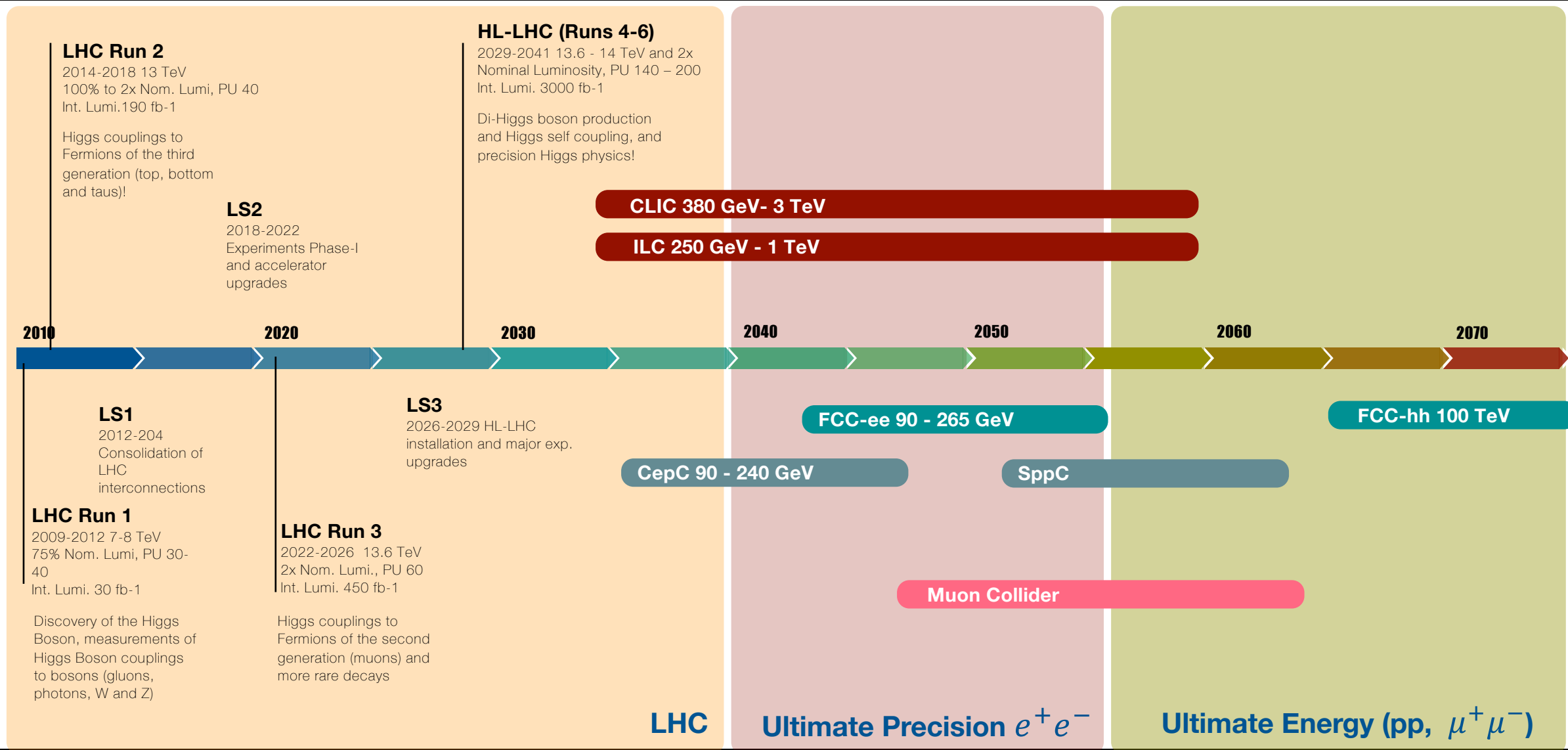
Scientific priorities for future energy- frontier projects



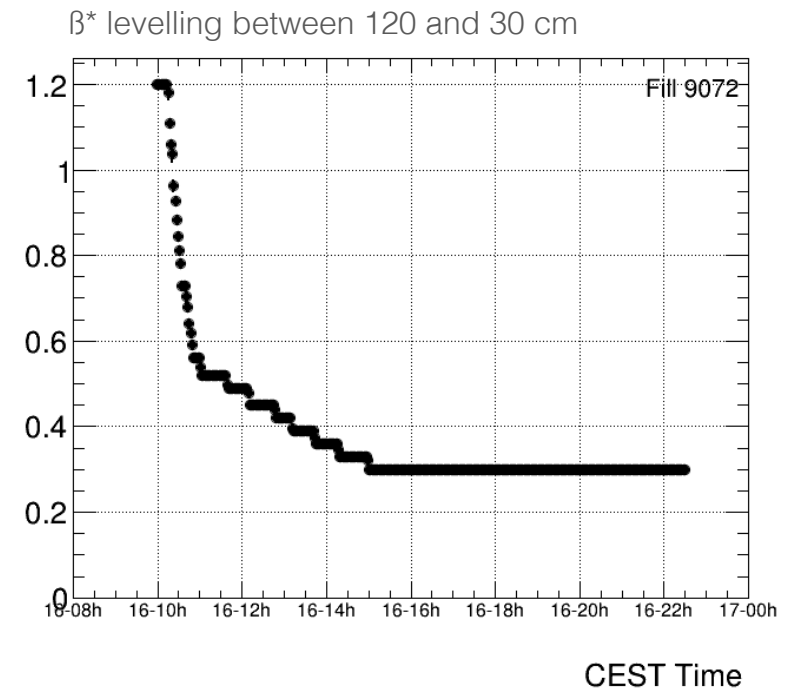
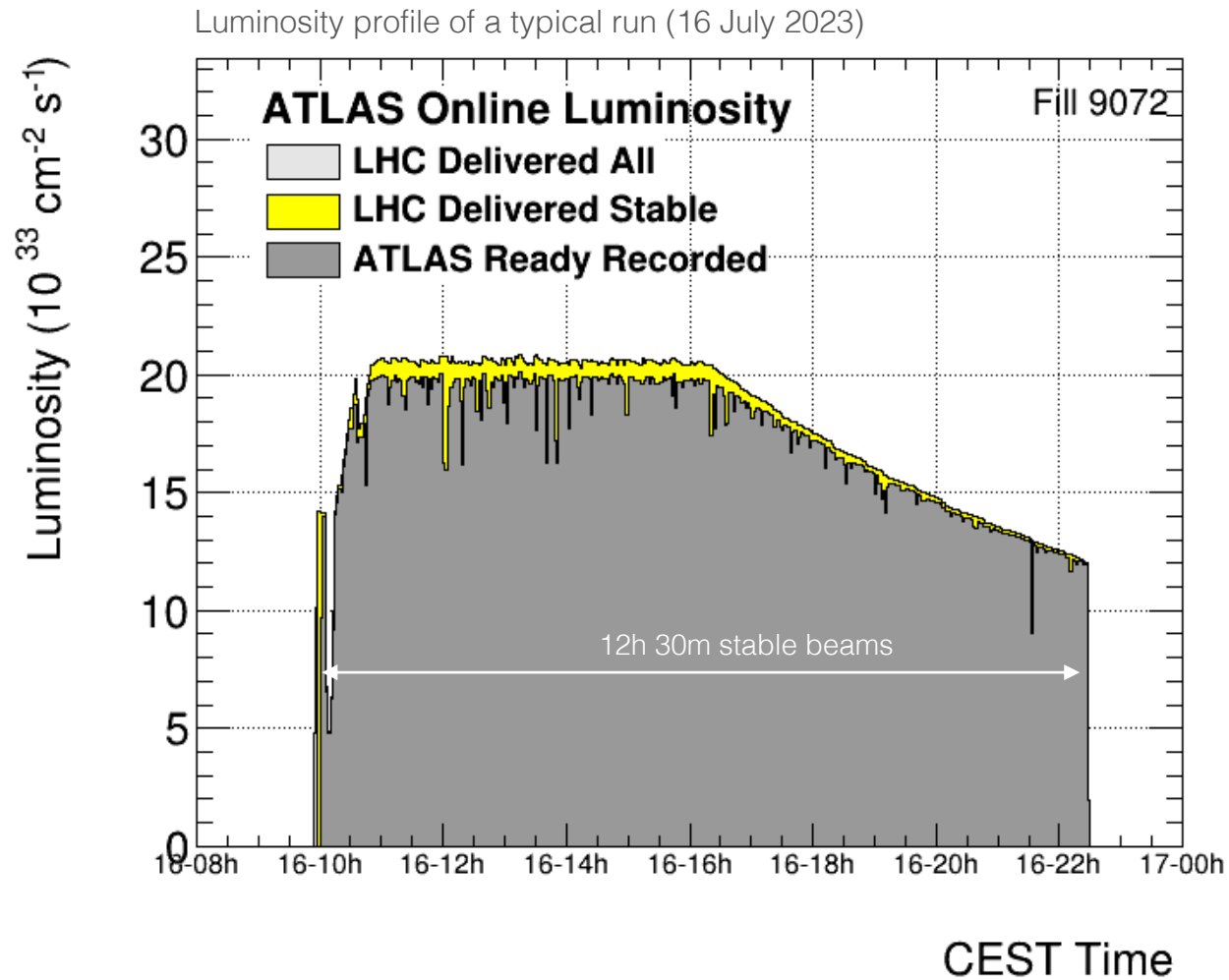
Recommendations of the 2020 Update of the European Strategy for Particle Physics:

- 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

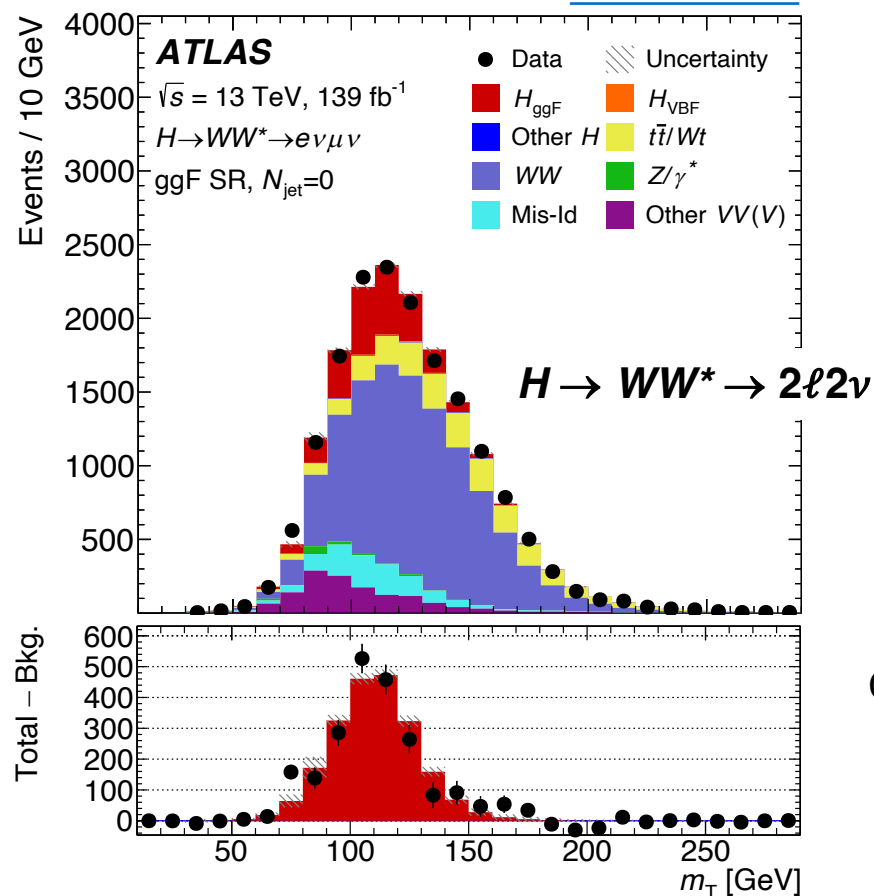
A Scientific Mission for the 21st Century



A typical β^* levelled luminosity profile during fill

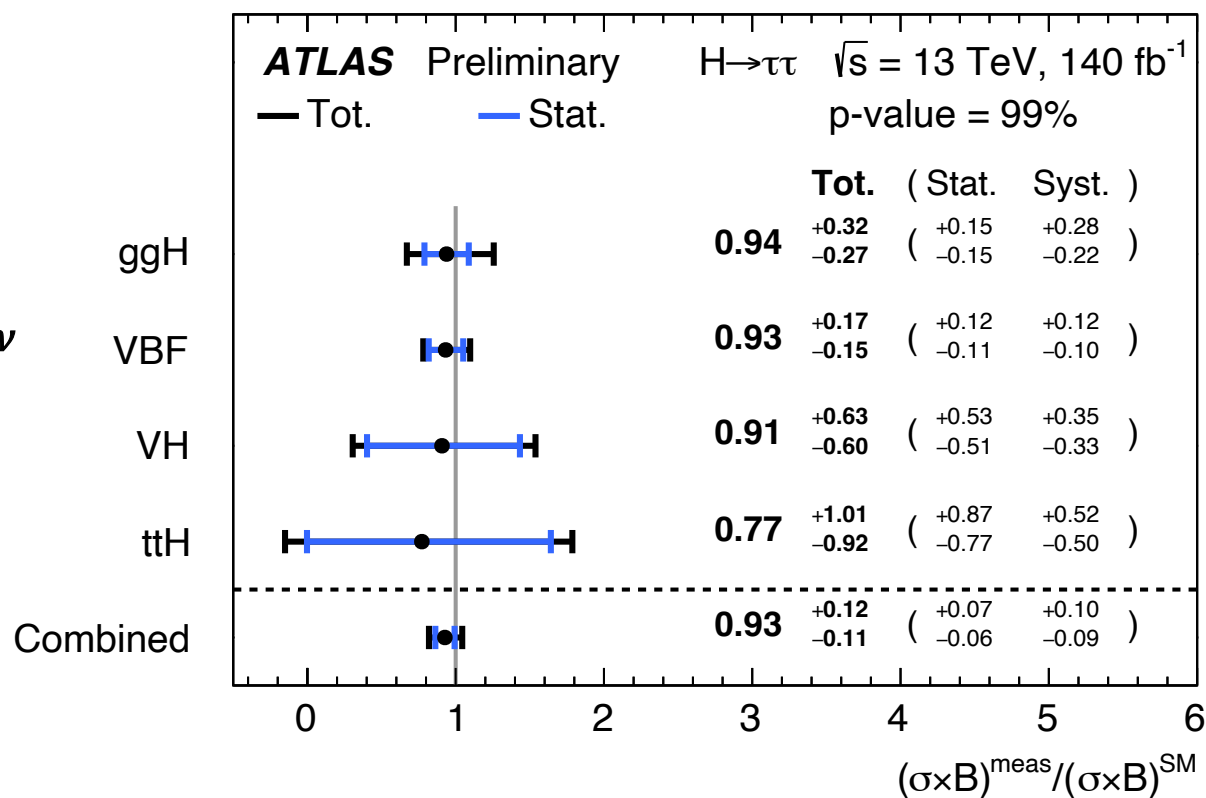


[arXiv:2207.00338](https://arxiv.org/abs/2207.00338)



$H \rightarrow \tau\tau$

[ATLAS-CONF-2024-007](#)



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

Higgs boson production at the LHC

About 1 Higgs boson per second is produced in ATLAS at the LHC (about 12M total by today)

It decays within 10^{-22} s

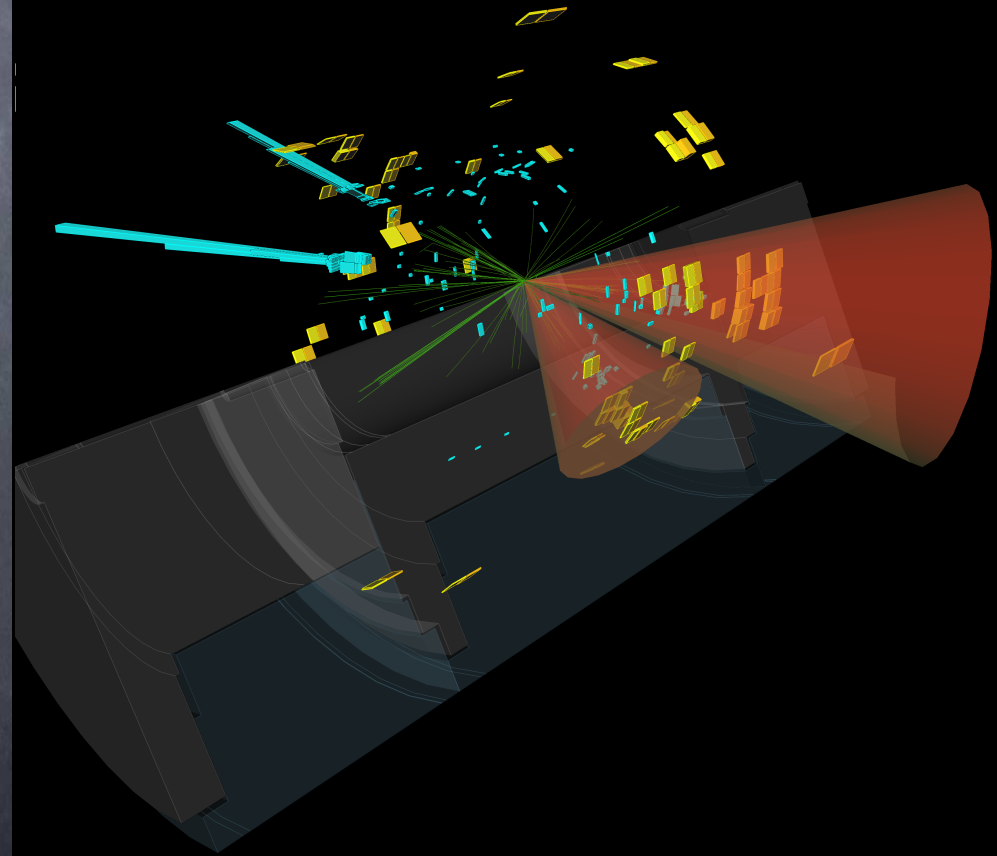
It should also interact with itself



λ determines the size of the quartic term in the Higgs potential after spontaneous symmetry breaking

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

HH production > 1000 times rarer than H!

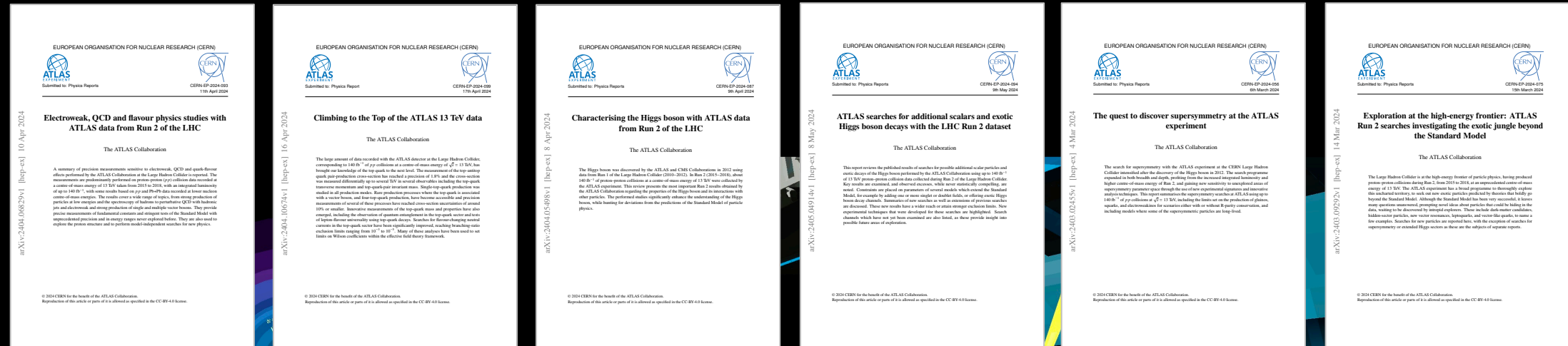


HH $\rightarrow$ bb $\tau\tau$ candidate event recorded in 2017

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)

Higgs boson discovery



Fabiola Gianotti (ATLAS Spokesperson) and Peter Higgs, 4 July 2012



4 July 2012 seminars announcing the Higgs boson discovery by ATLAS and CMS

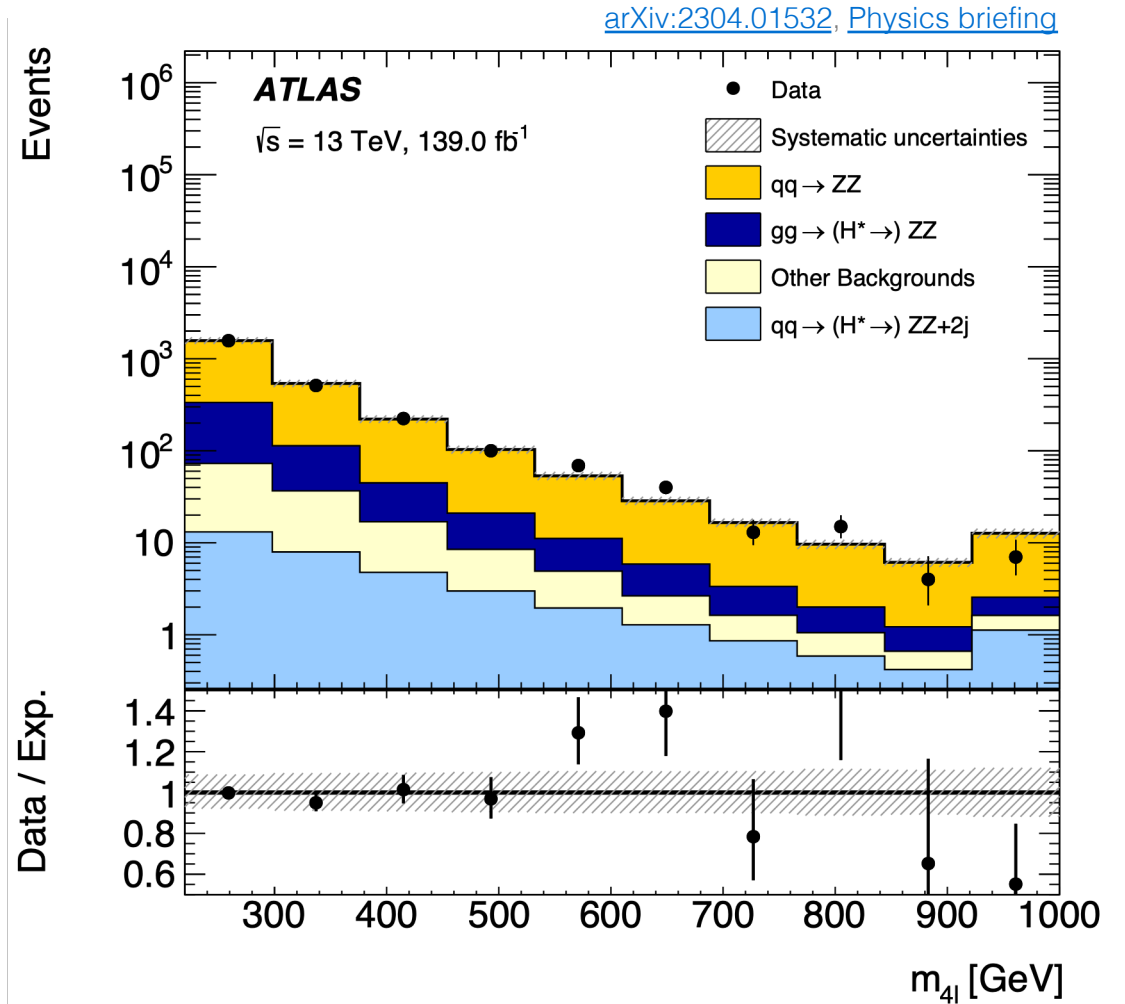
Higgs boson width

Not possible to resolve the 4.1 MeV Higgs width, but can determine Γ_H by comparing on-shell (Γ_h dependent) and off-shell (Γ_h independent) Higgs couplings in $H \rightarrow ZZ^*$ decay

Results:

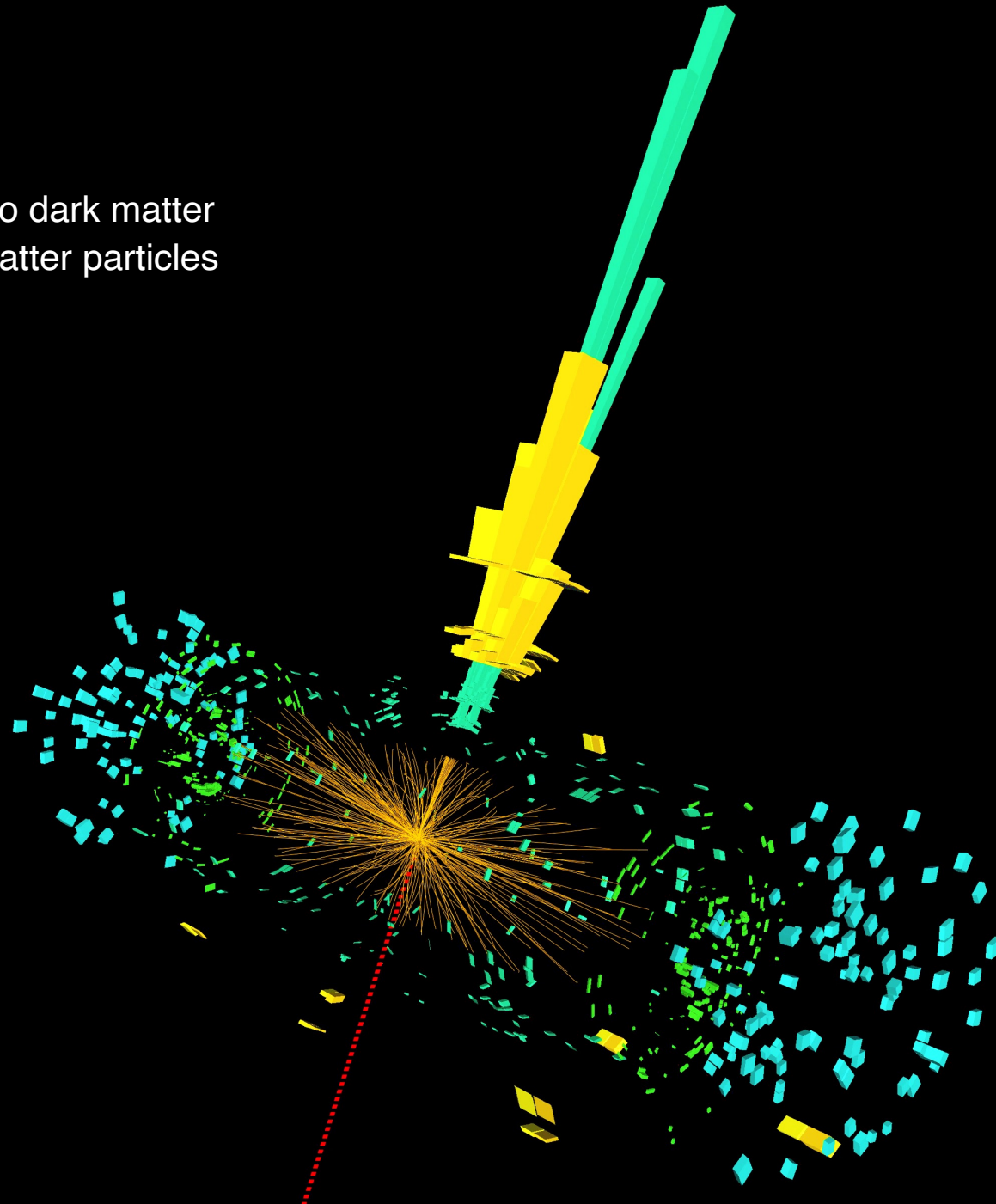
3.3σ exclusion of $\mu_{\text{off-shell}} = 0$

$$\Gamma_H = 4.5^{+3.3}_{-2.5} \text{ MeV}$$



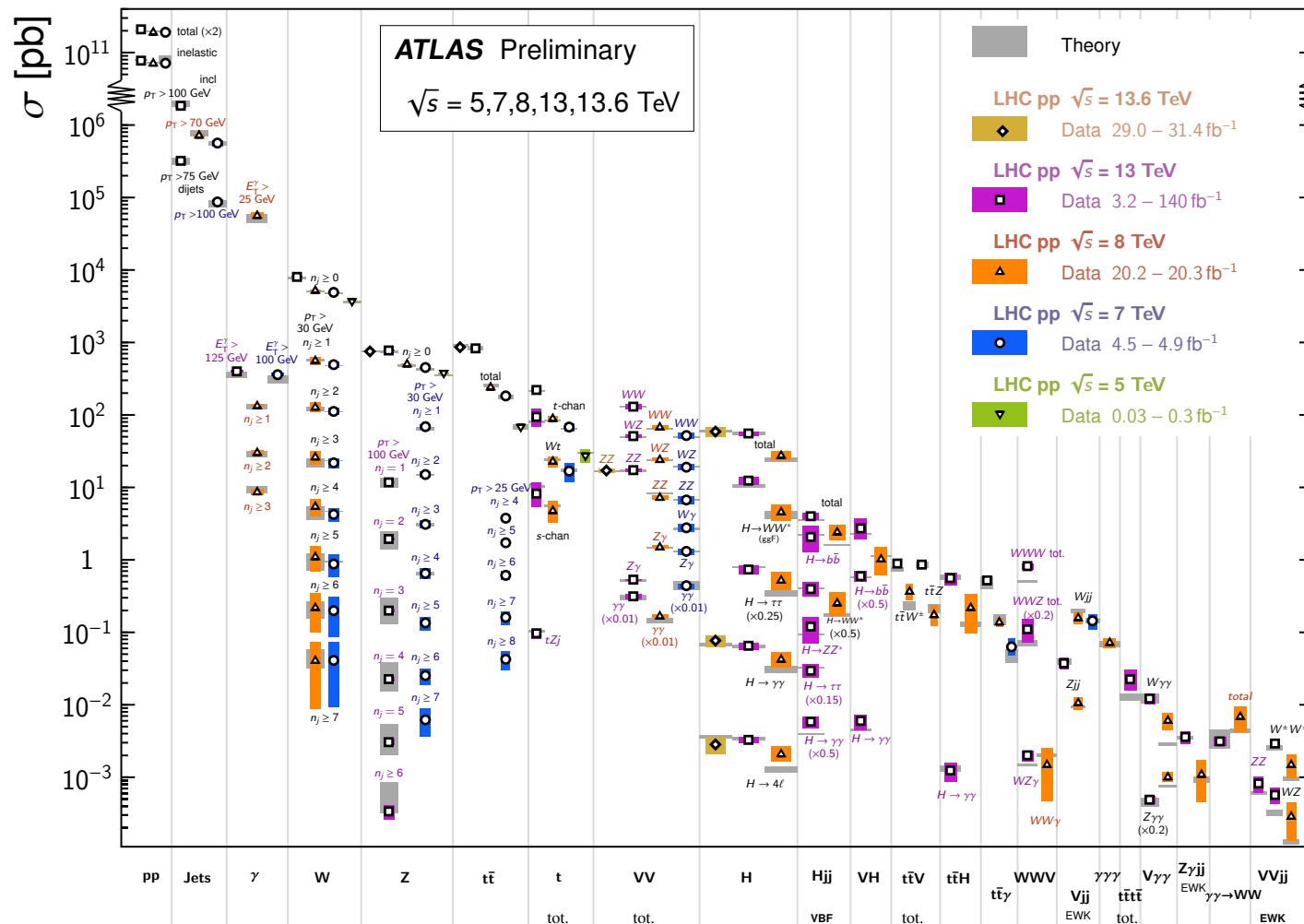
Dark matter

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



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

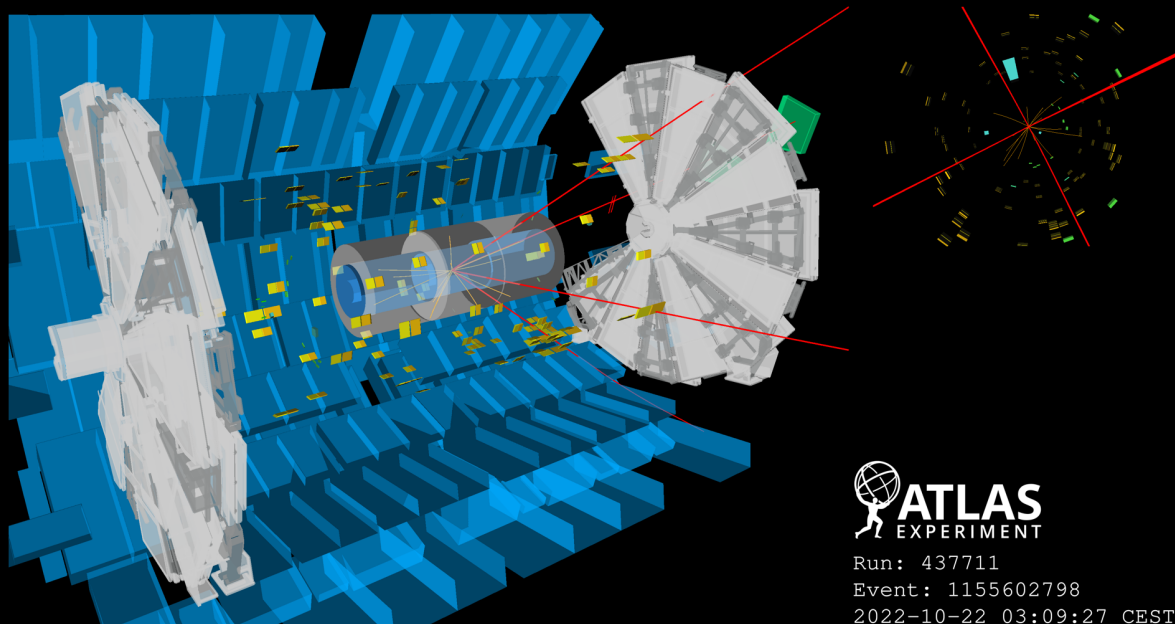
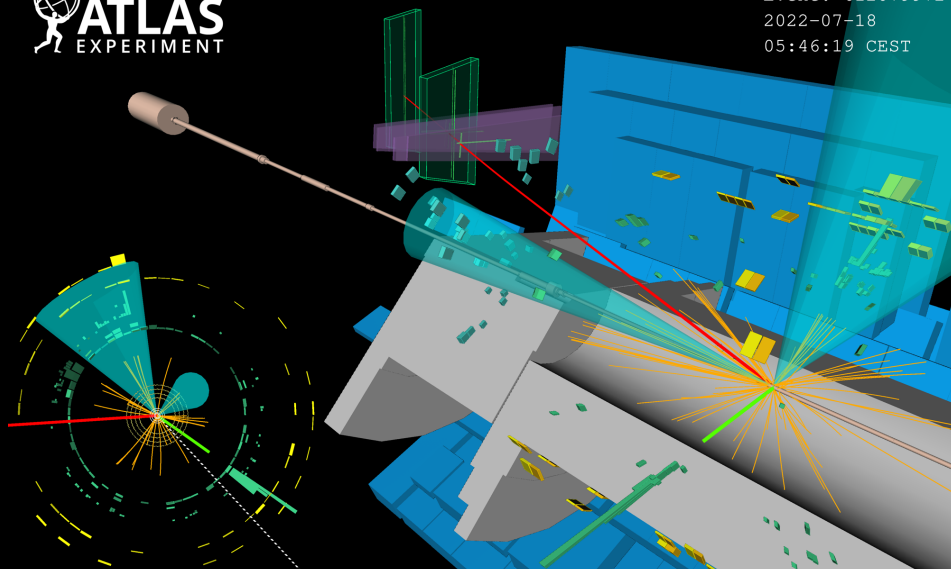


Run-3 data analysis

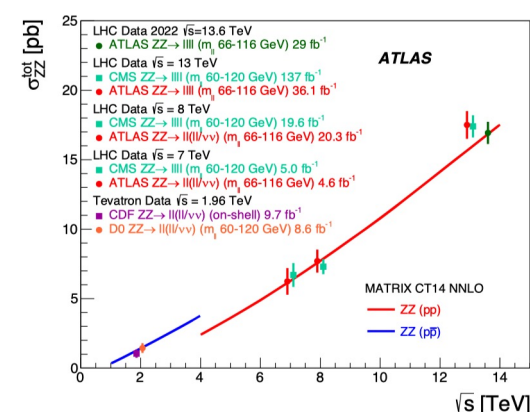
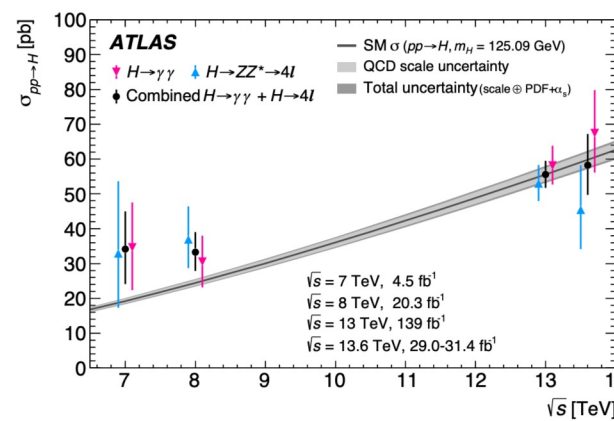
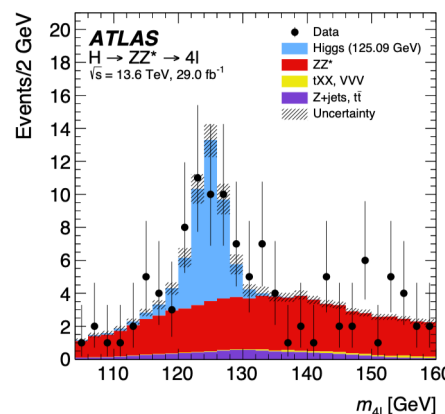
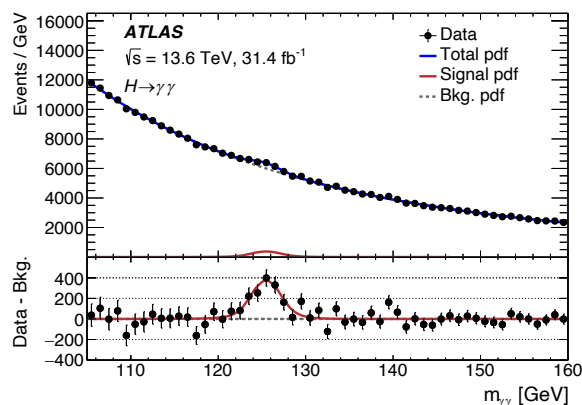
Excellent detector and reconstruction performance, 9 papers, 2 CONF notes, 7 PUB notes released on Run 3



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



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



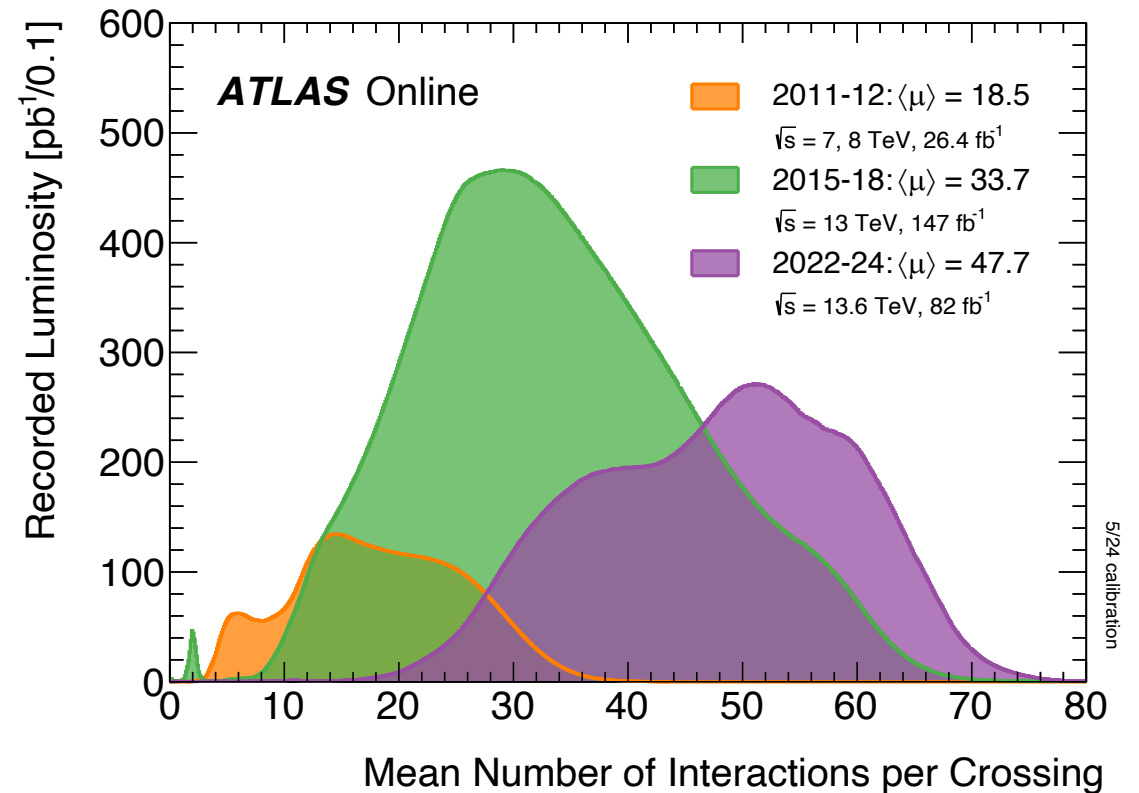
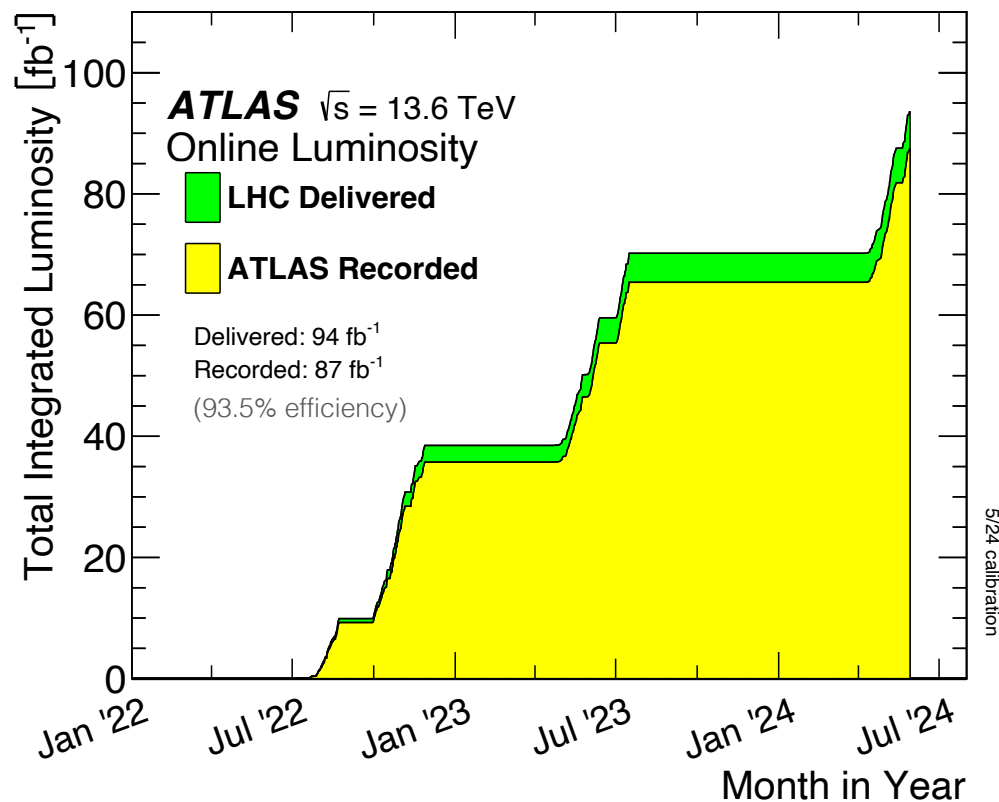
Extremely successful LHC runs between 2010 and 2018, and continuing ...

2024 physics data taking has resumed



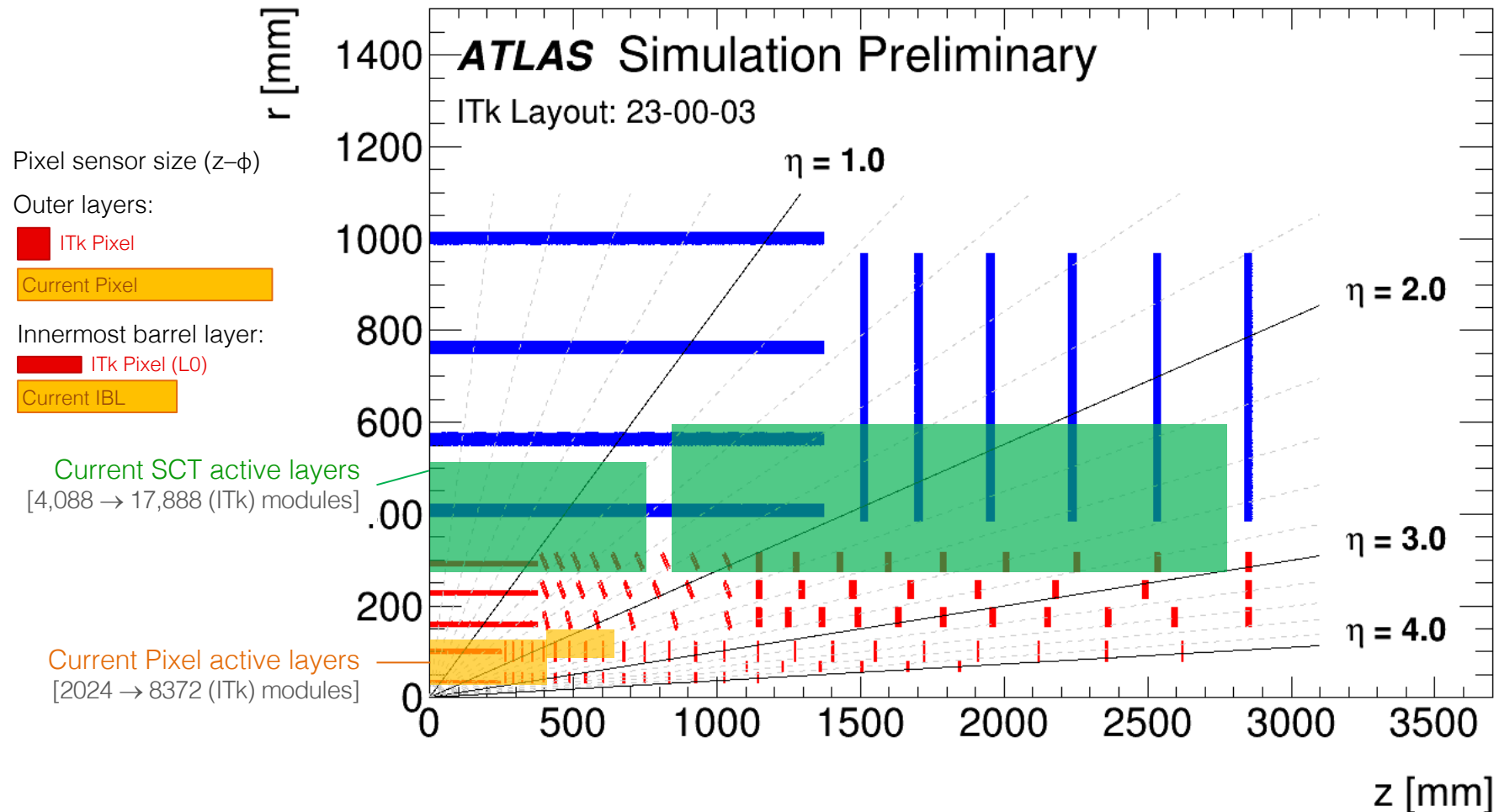
Proton–proton data taking in Run 3

Accelerator problems during 2022 & 2023, less integrated luminosity than anticipated. Good startup in 2024
2024: 23.3 fb⁻¹ delivered and 22.0 fb⁻¹ recorded (94.2%). Higher pileup than in previous years and during Run 2



Successful Pb–Pb run in 2023: almost doubled integrated luminosity of Run 2

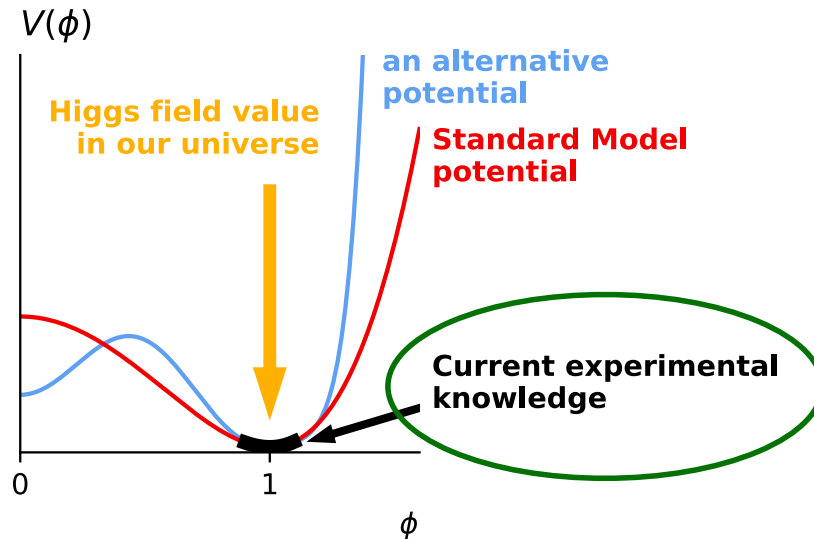
ATLAS Phase-II upgrade



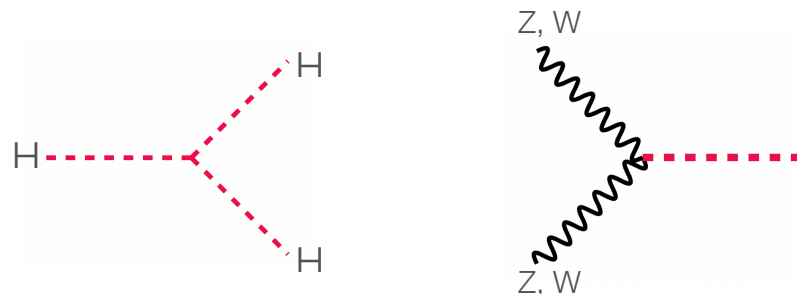
ITk: ~ 13 hits in barrel (incl. 2 hits per Strip module), minimum ~ 9 Pixel hits in forward region

Digression

Interesting talk by **LianTao Wang at LHCP 2024** [\[Link\]](#)



New physics in the alternative scenario often induce changes in other Higgs couplings, such as HZ

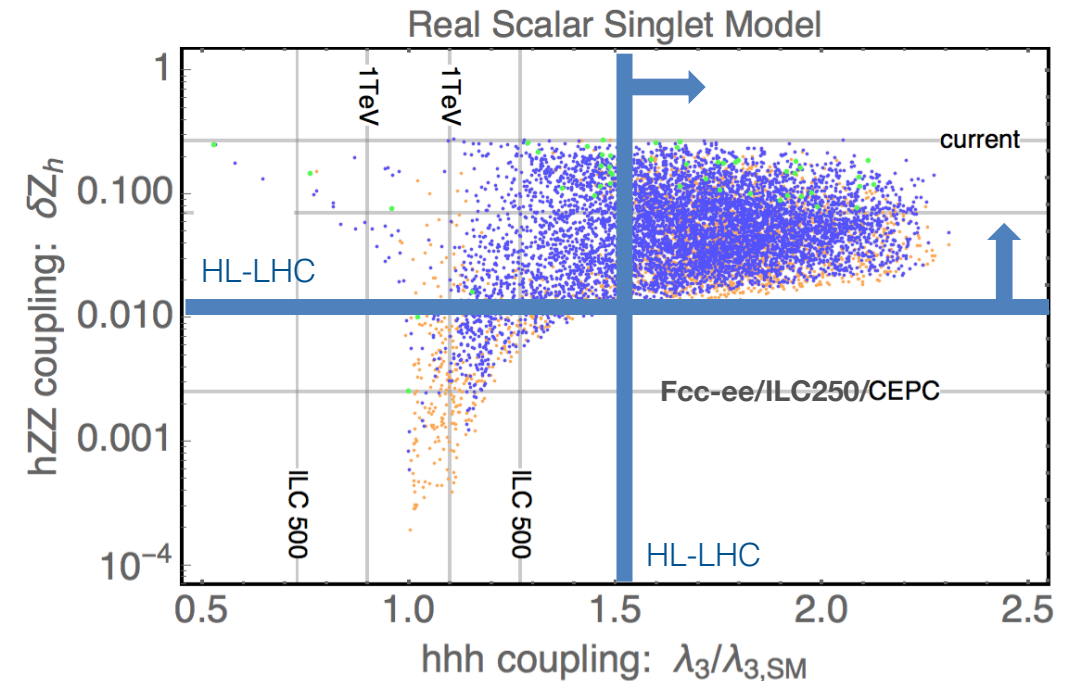


Simple example: Higgs + scalar singlet:

$$\mathcal{L} \supset V(H) + V(S) + \lambda H^\dagger H S^2$$

$$\Rightarrow \frac{1}{\Lambda^2} (H^\dagger \partial H)^2 \quad \text{and} \quad \frac{1}{\Lambda^2} (H^\dagger H)^3 \quad (\text{for large } m_S > m_H)$$

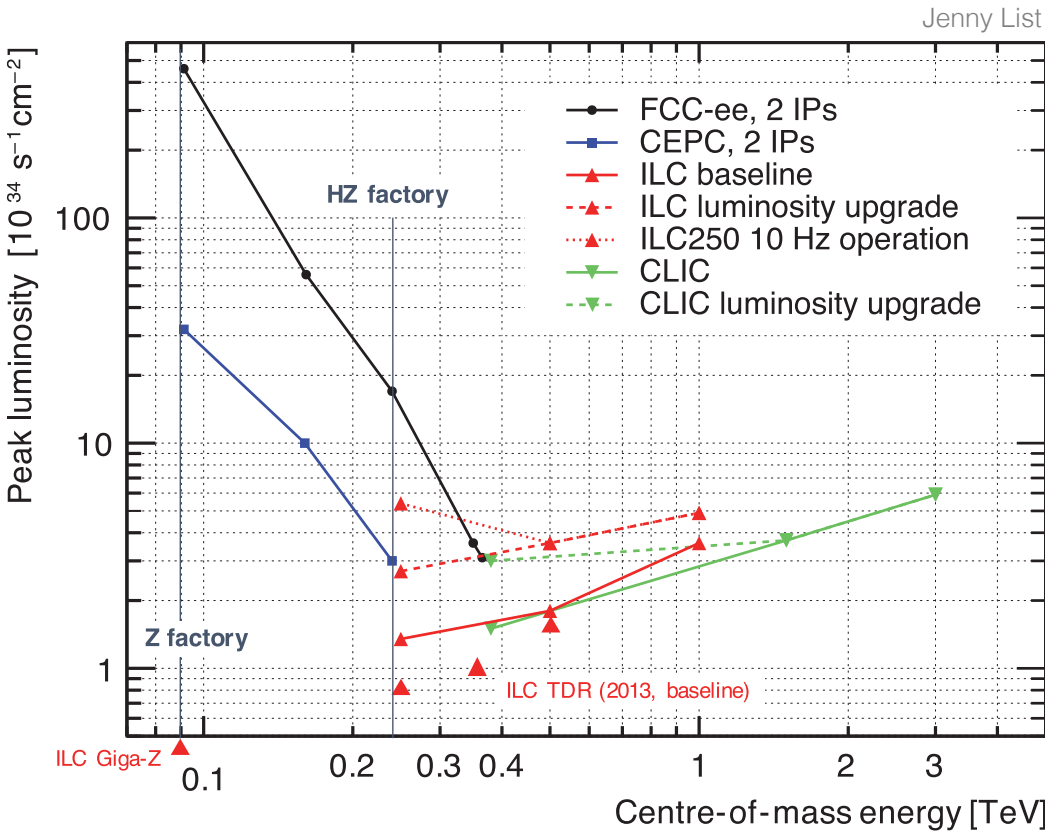
Modify H-Z coupling $\Rightarrow \delta_{Z_h}$ Modify Higgs self-coupling $\Rightarrow \delta_{\lambda_3}$



Models with 1st order EWSB, need large self-interaction

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)

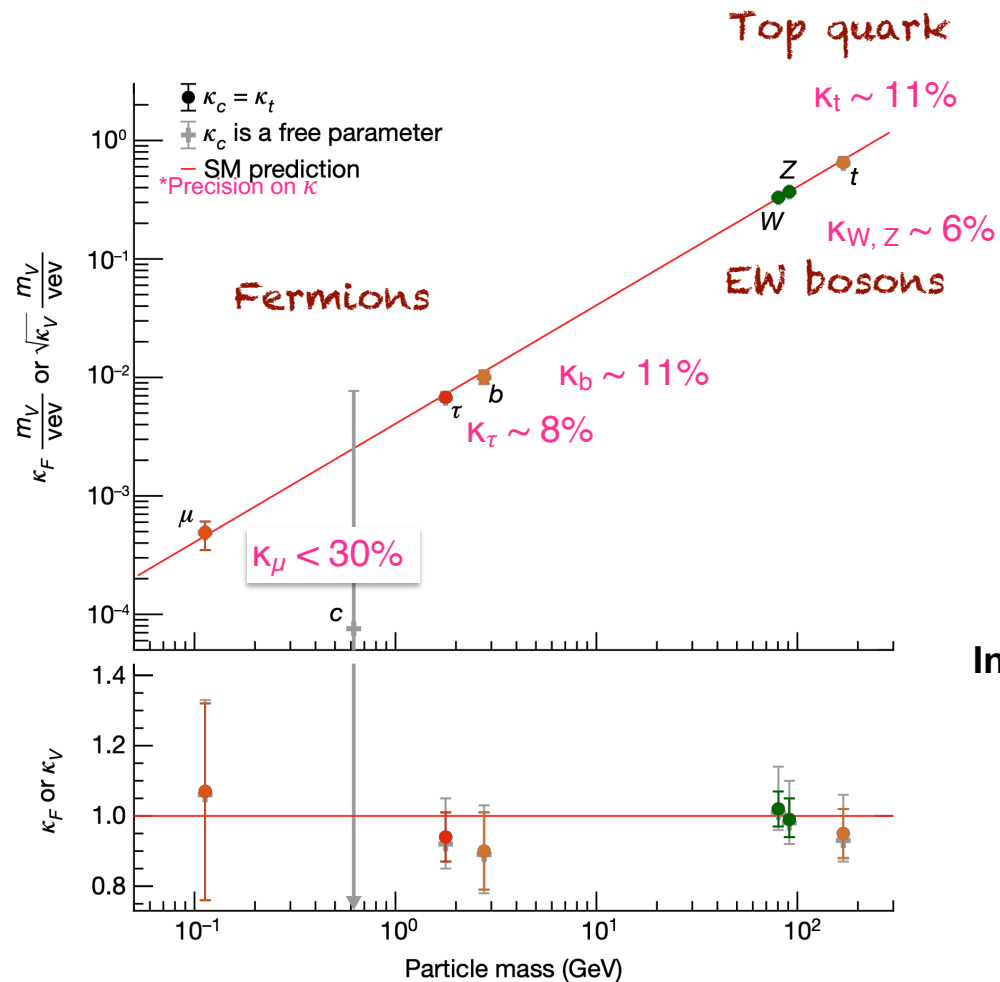
1) Higgs self-coupling: expected precision on λ_3

- 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

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

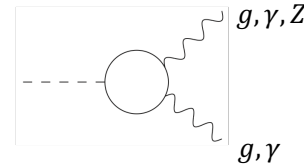
Electron–positron Higgs factories

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

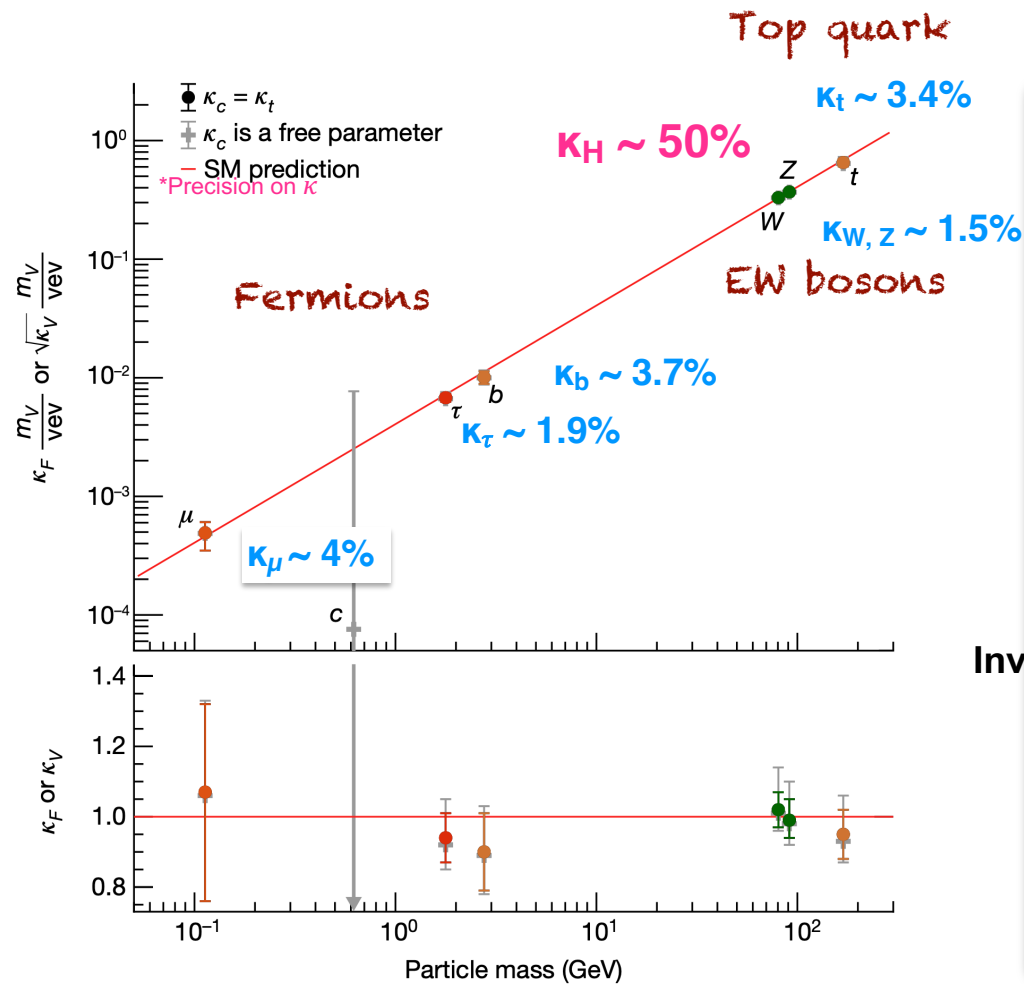
$\text{Br}_{\text{inv}} < 11\%$ DM?

Higgs width

$\Gamma_H \sim 100\%$

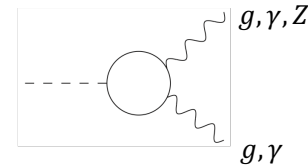
Electron–positron Higgs factories

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

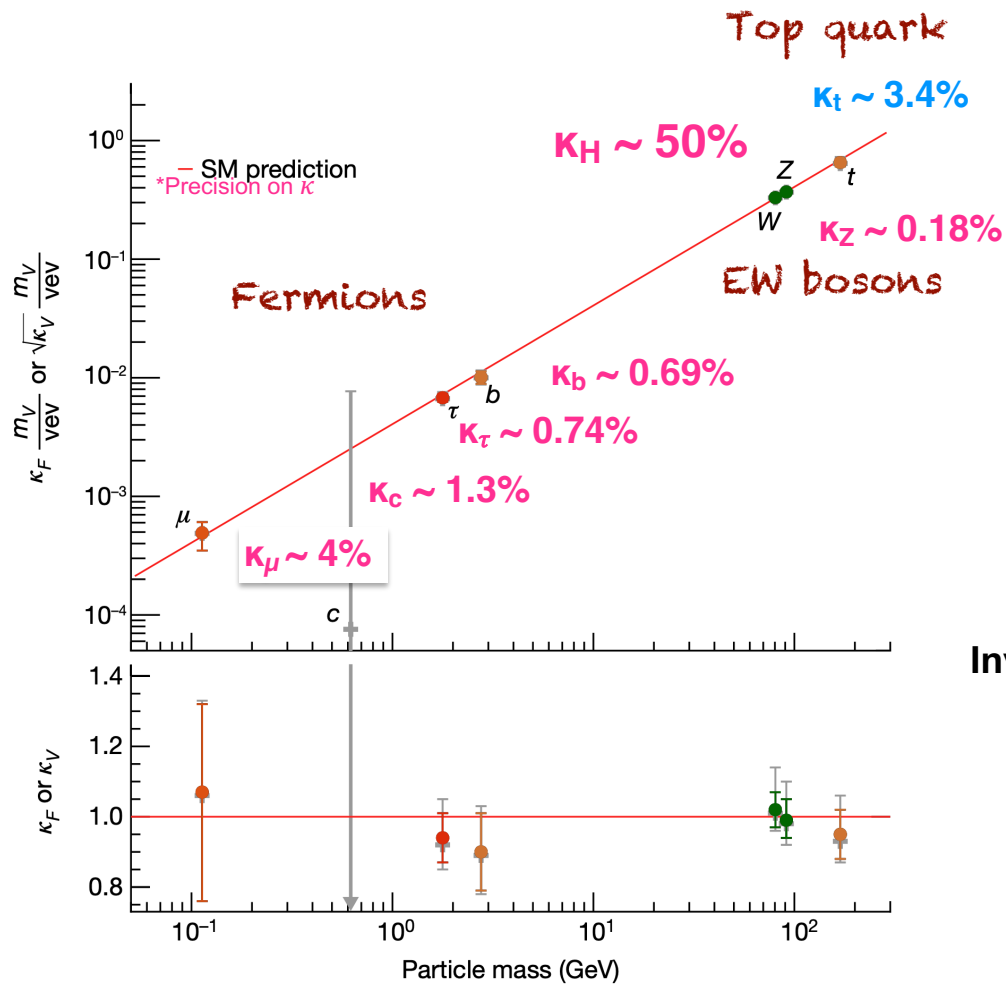
$\text{Br}_{\text{inv}} < 2.5\%$ DM?

Higgs width

$\Gamma_H \sim 20\%$

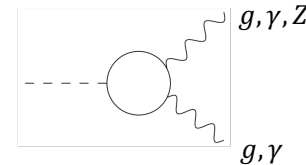
Electron–positron Higgs factories

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

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

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

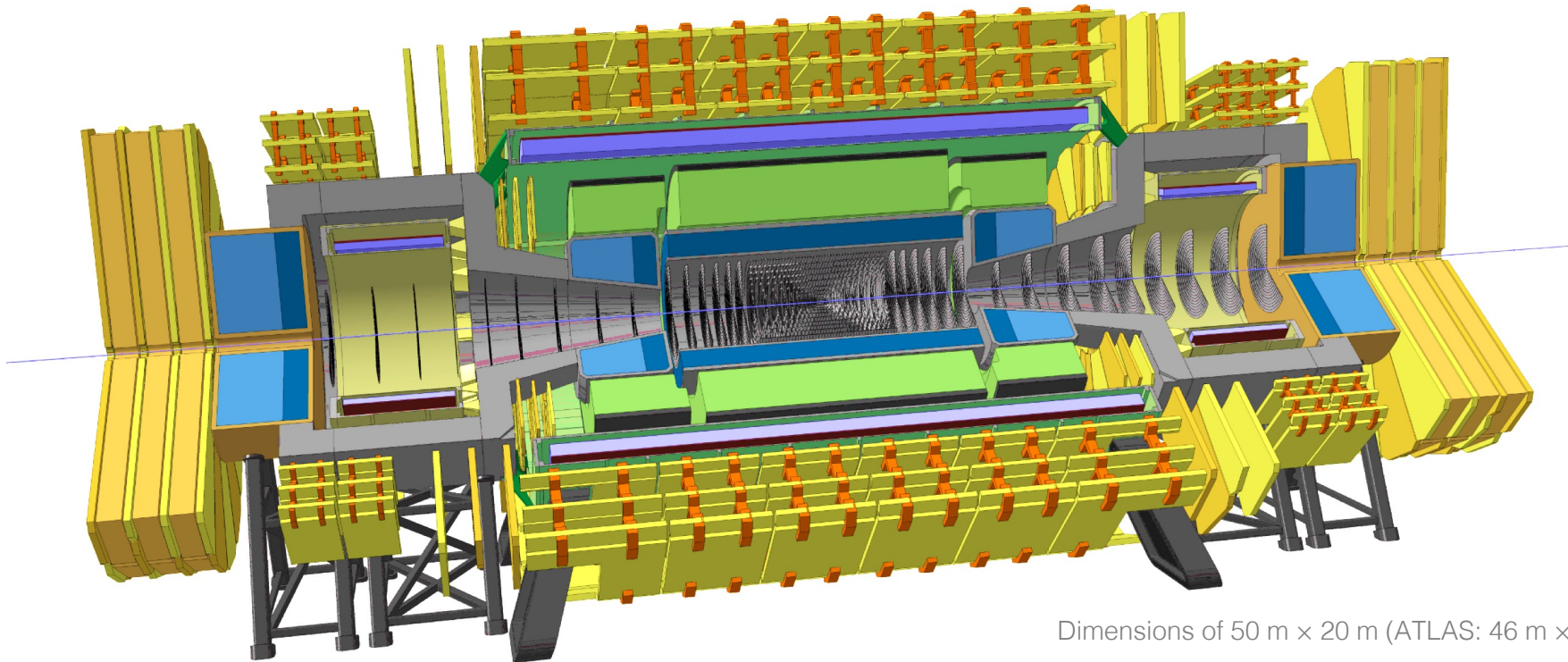
Precision on key electroweak observables:

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

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

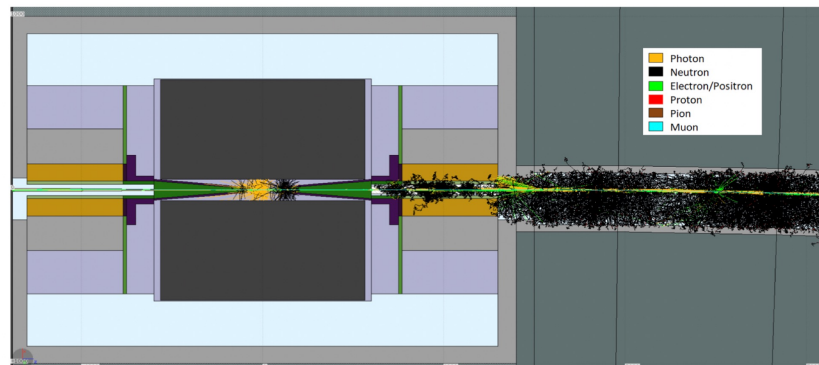
Best of all worlds?

- 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

