The origin of mass

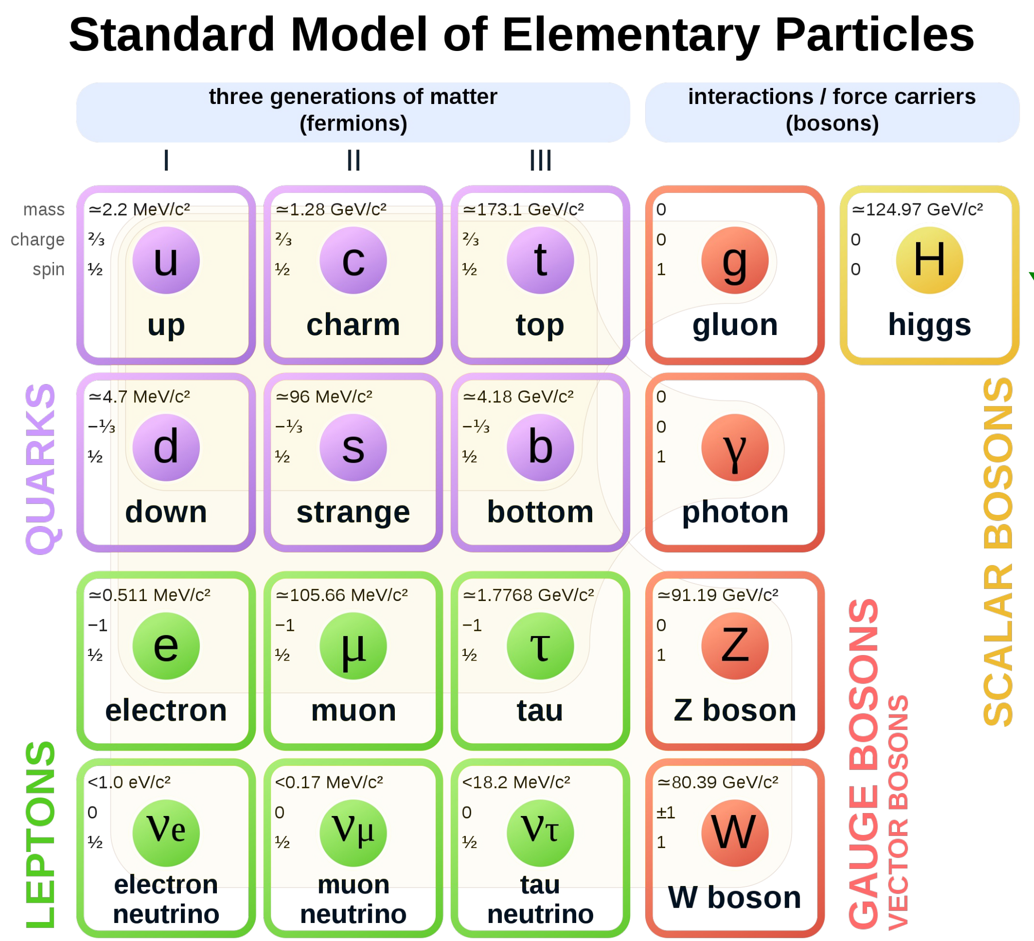
Particle physics at the high-energy frontier

Andreas Hoecker (CERN)

University of São Paolo, 3 July 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**



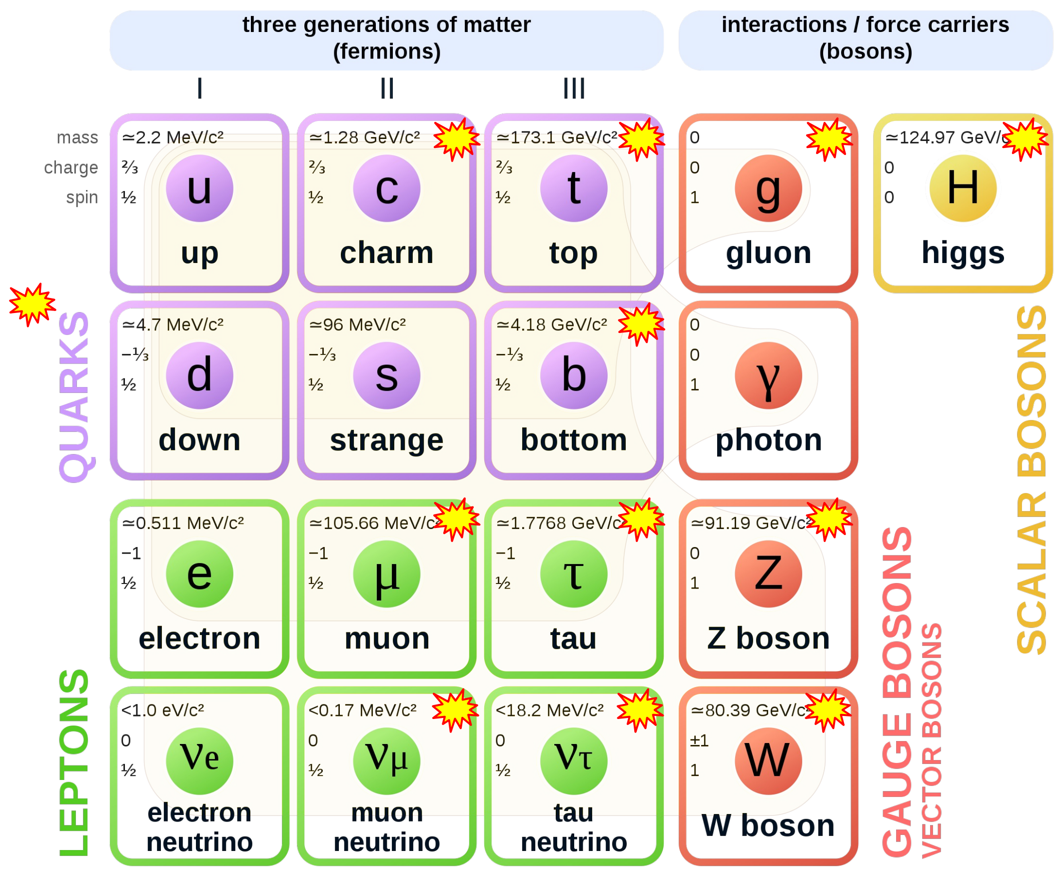
Completely new type of non-universal interactions, nothing to do with known forces

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**

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

Standard Model of Elementary Particles

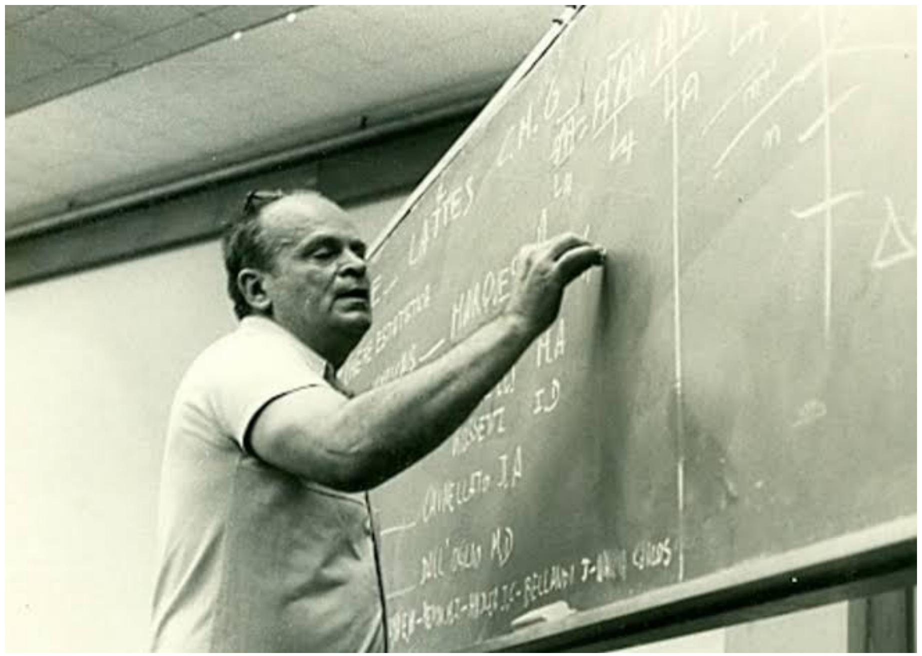


Completely new type of non-universal interactions, nothing to do with known forces

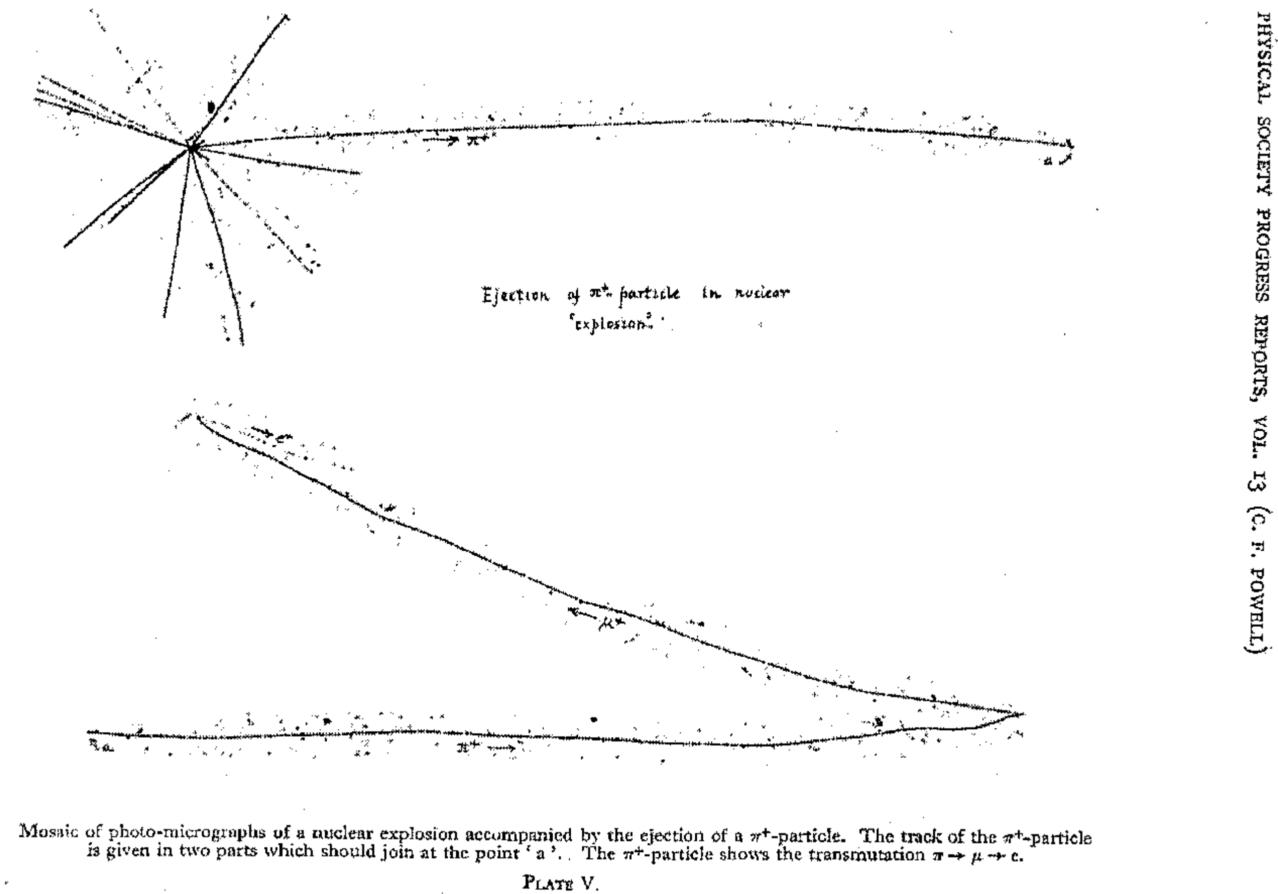
It’s all made of a handful of particles and forces

While accelerators in laboratories have been key, particle physics was pioneered by “**cosmic accelerators**” generating cosmic rays

The discovery of the pion, propagtor of the strong nuclear force acting among protons and neutrons



César Lattes

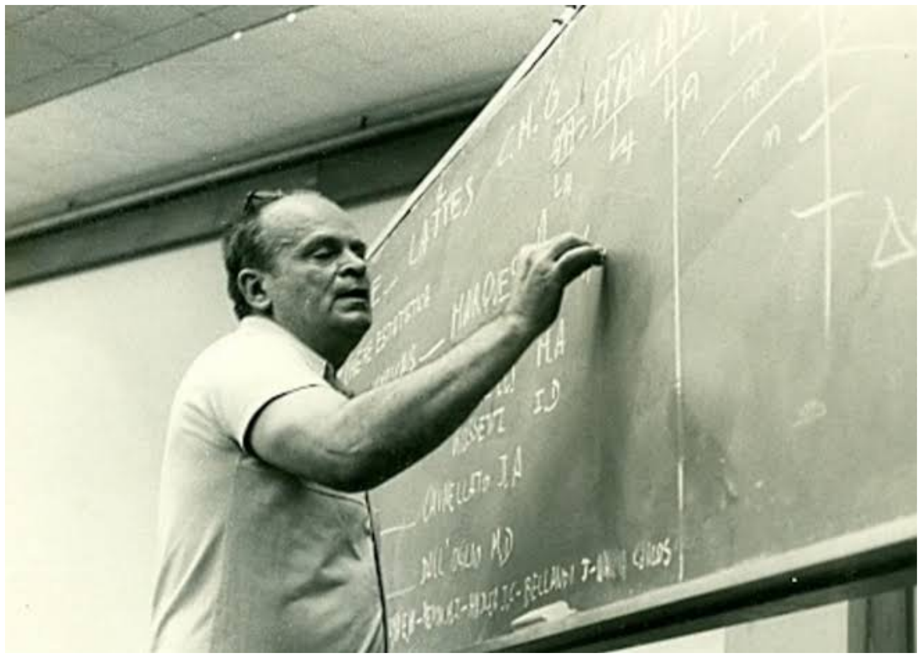


The graph shows a Bristol pion. The track of the positively-charged pion produced in the interaction 'star' (top left) has been cut in two to facilitate presentation. Bottom right, the pion eventually decays into a muon, which after some 600 microns itself subsequently producing an electron. This full decay was recorded in electron-sensitive available from 1948, even more sensitive than the specially-developed nuclear research emulsions in which the pion was discovered in 1947.

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

While accelerators in laboratories have been key, particle physics was pioneered by “cosmic accelerators” generating cosmic rays

The discovery of the pion, propagtor of the strong nuclear force acting among protons and neutrons



César Lattes

OBSERVATIONS ON THE TRACKS OF SLOW MESONS IN PHOTOGRAPHIC EMULSIONS

By C. M. G. LATTES, DR. G. P. S. OCCHIALINI AND DR. C. F. POWELL

H. H. Wills Physical Laboratory, University of Bristol

Part 2: Origin of the Slow Mesons

IN Part 1 of the present article*, we showed that two types of mesons exist, and it was suggested that the heavier, π-mesons, decay to produce the lighter, μ-mesons. In this second part, we discuss the origin of the slow mesons observed in photographic emulsions, and their relation to the mesons forming the penetrating component of the cosmic rays, of which evidence is provided by experiments with Wilson chambers and counters. We also give photomicrographs which show that some slow mesons, ejected from nuclei during ‘explosive disintegrations’, can enter nuclei and produce a second disintegration. Most of the observations on plates exposed at 5,500 m. were made with boron-loaded emulsions and, for the most part, we have confined our analysis to the results obtained with plates of this type. The loading material has an important influence on the rate of fading of the latent image, but by the above procedure we can compare the results of experiments at different altitudes.

Disintegrations Produced by Mesons

Nature volume 160, 486 (1947)

Powell wrote: *Unshaved, sometimes I fear unwashed, working seven days of the week till two, sometimes four in the morning, brewing inordinately strong coffee at all hours, running, shouting, quarrelling and laughing, we were watched with humorous sympathy by the … native [habitants] of the Royal Fort* … It was a reality of intense, arduous and continuous work, of deep excitement and incredibly fulfilled dreams. It was the reality of discovery.*

[Reprint from CERN Courier article of 1997 (by Owen Lock)]

*H.H. Wills Physics Laboratory in Bristol

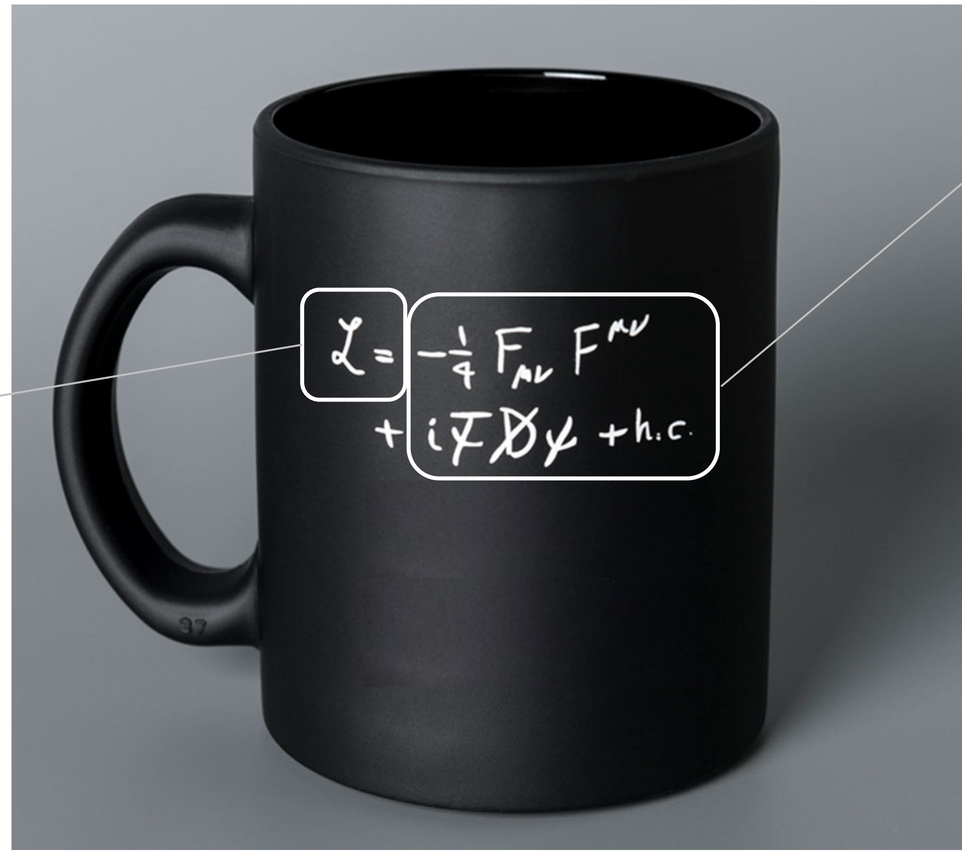
The Standard Model

The **Standard Model** is a *quantum field theory* which describes all known forms of matter and forces, except gravity

The Standard Model unifies quantum mechanics, special relativity and field theory

It also unifies electromagnetic and weak interactions

The **Lagrangian** allows to derive the equations of motion of a system



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 → strong CP problem) parameters

Gauge symmetry and the Higgs mechanism

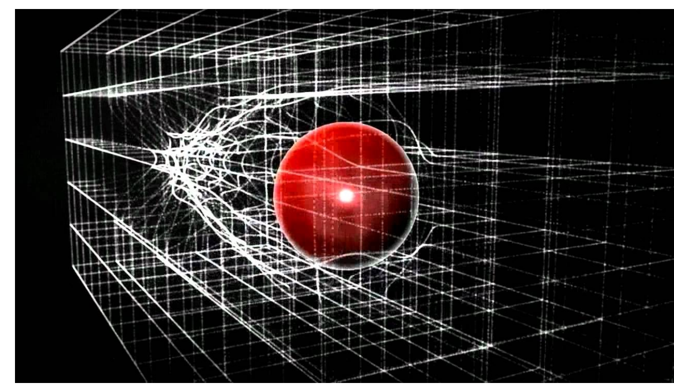
Interactions in the **Standard Model** are described by "**local gauge theories**"

A problem: gauge symmetry requires massless spin-1 "gauge" (=force) bosons and spin-1/2 matter particles
Applying an arbitrary local gauge transformation $A_\mu \to A_\mu + \partial_\mu \alpha$ on a mass term $m^2 A^\mu A_\mu$, invariance requires $m = 0$

However, the W, Z bosons are massive (= finite range of weak interaction ~10^{-15} cm)

A solution 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 "sucks" energy out of the Higgs field) and thus mass. The stronger the coupling, the greater the mass. This mechanism gives mass to the W, Z bosons, and also to the fermions



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

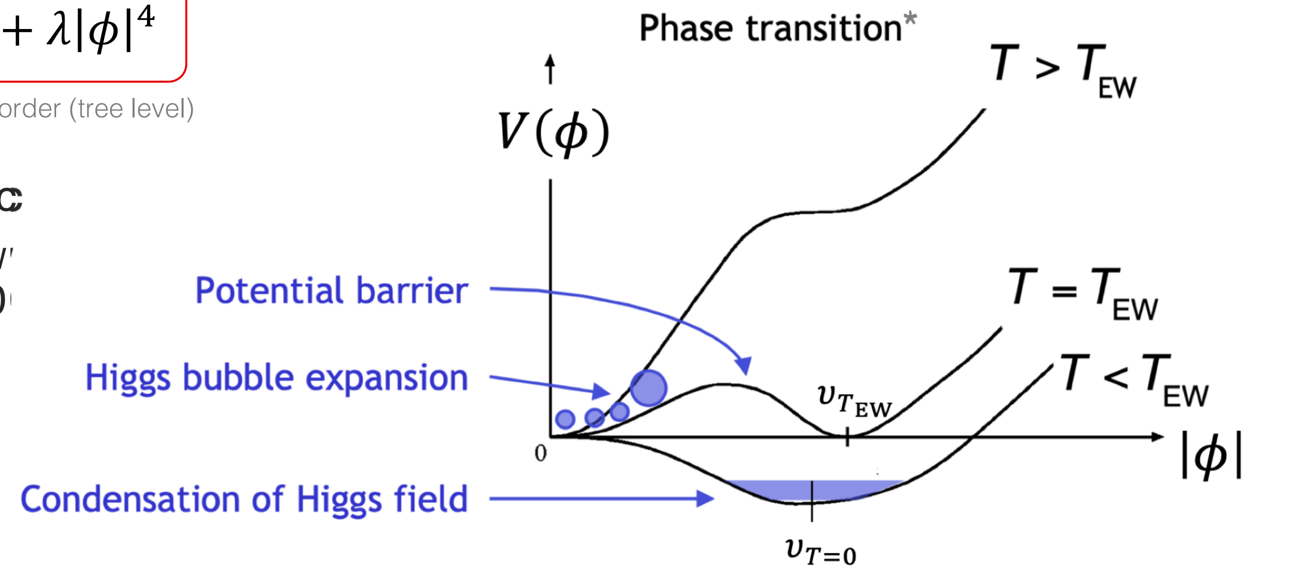
Gauge symmetry and the Higgs mechanism

*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: $\boxed{V(\phi) = -\mu^2|\phi|^2 + \lambda|\phi|^4}$

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 $\sim T_{EW}$ (~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

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

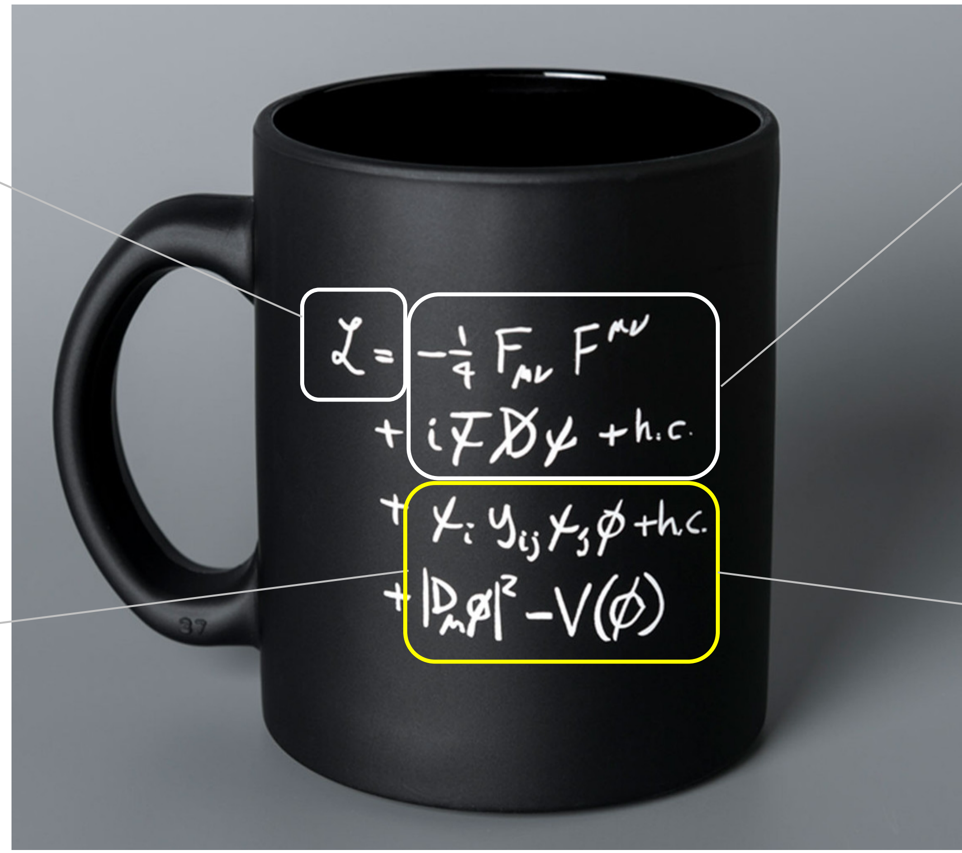
Completing the Standard Model

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 → strong CP problem) parameters

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

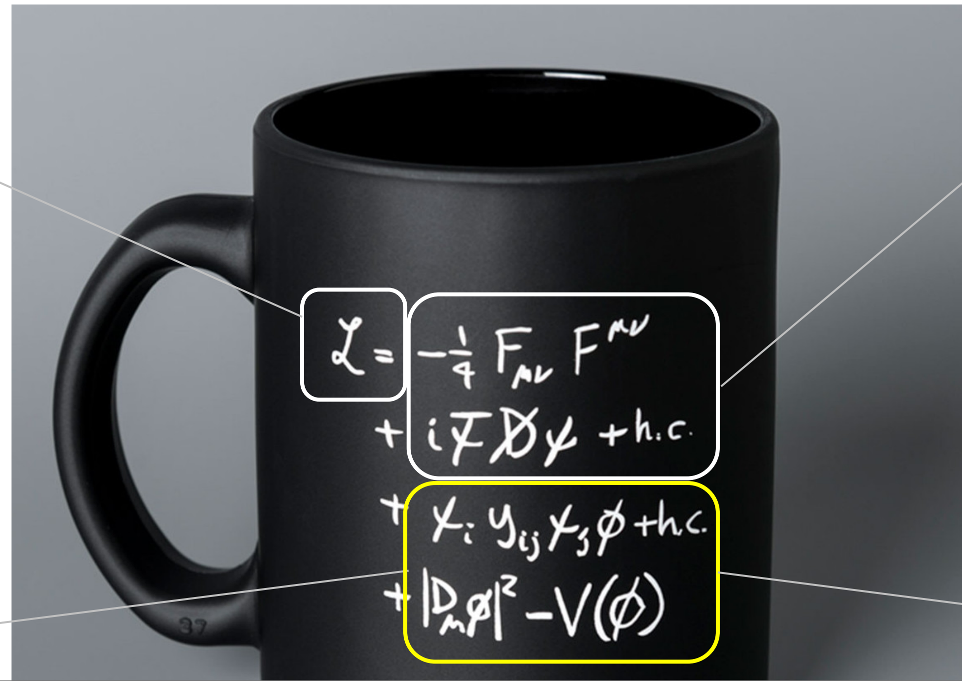
The lower left term describes the **interaction of the Higgs field with the weak-interaction bosons, which thereby obtain mass**

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**



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

Unpleasan
symmetries, 2
large hierarc

describes the
) with non-zero

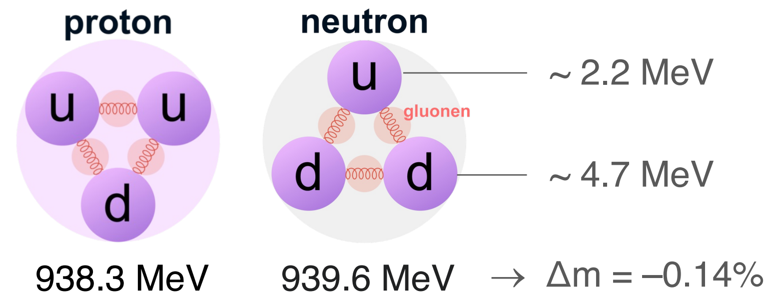
The Standard Model is a highly predictive theory

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} !

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)

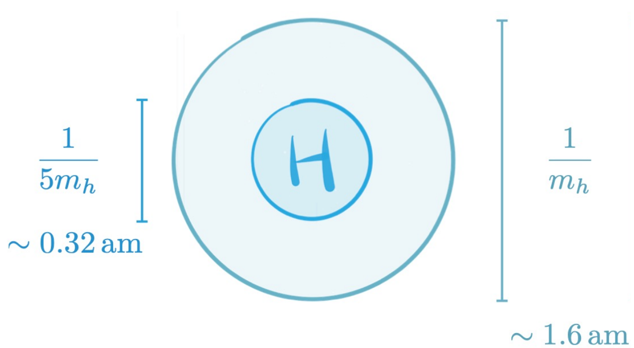
*Accelerating universe (dark energy) corresponds to $\rho_{\text{vacuum}} = \mu^4$, $\mu \sim 0.002$ eV

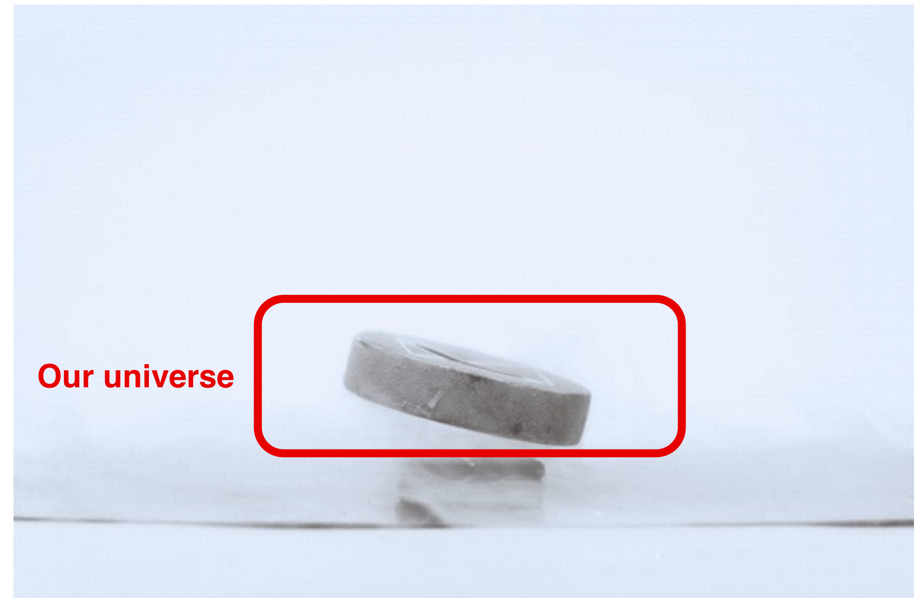
An analogy to the Higgs mechanism

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_{crit} ~ mK – several 10s of K	$T_{\mathrm{crit}} = T_{\mathrm{EW}} \sim 10^{15}$ 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]

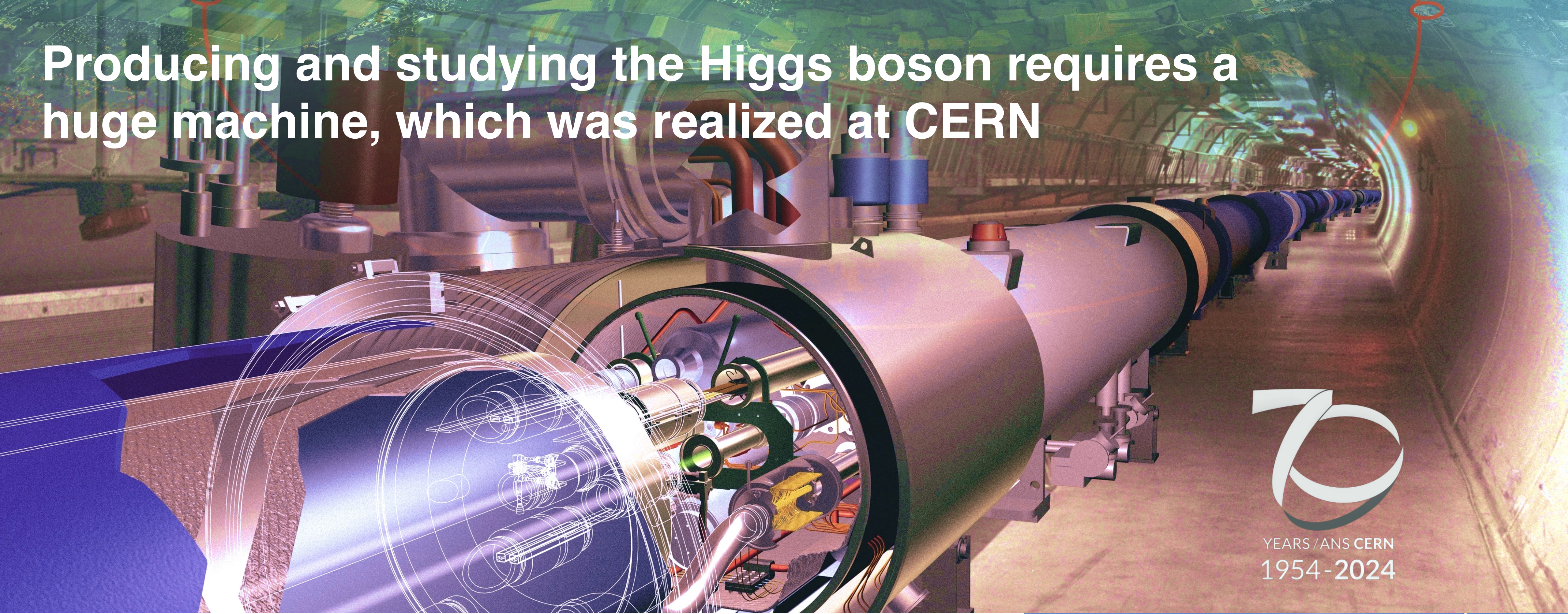
In response to an externally applied magnetic field, perpetual eddy currents circulate in the superconductor, producing an internal magnetic field that exactly cancels the externally applied one

Further reading, eg: L. Dixon, "From superconductors to supercolliders"

The Higgs mechanism was only a theoretical idea

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

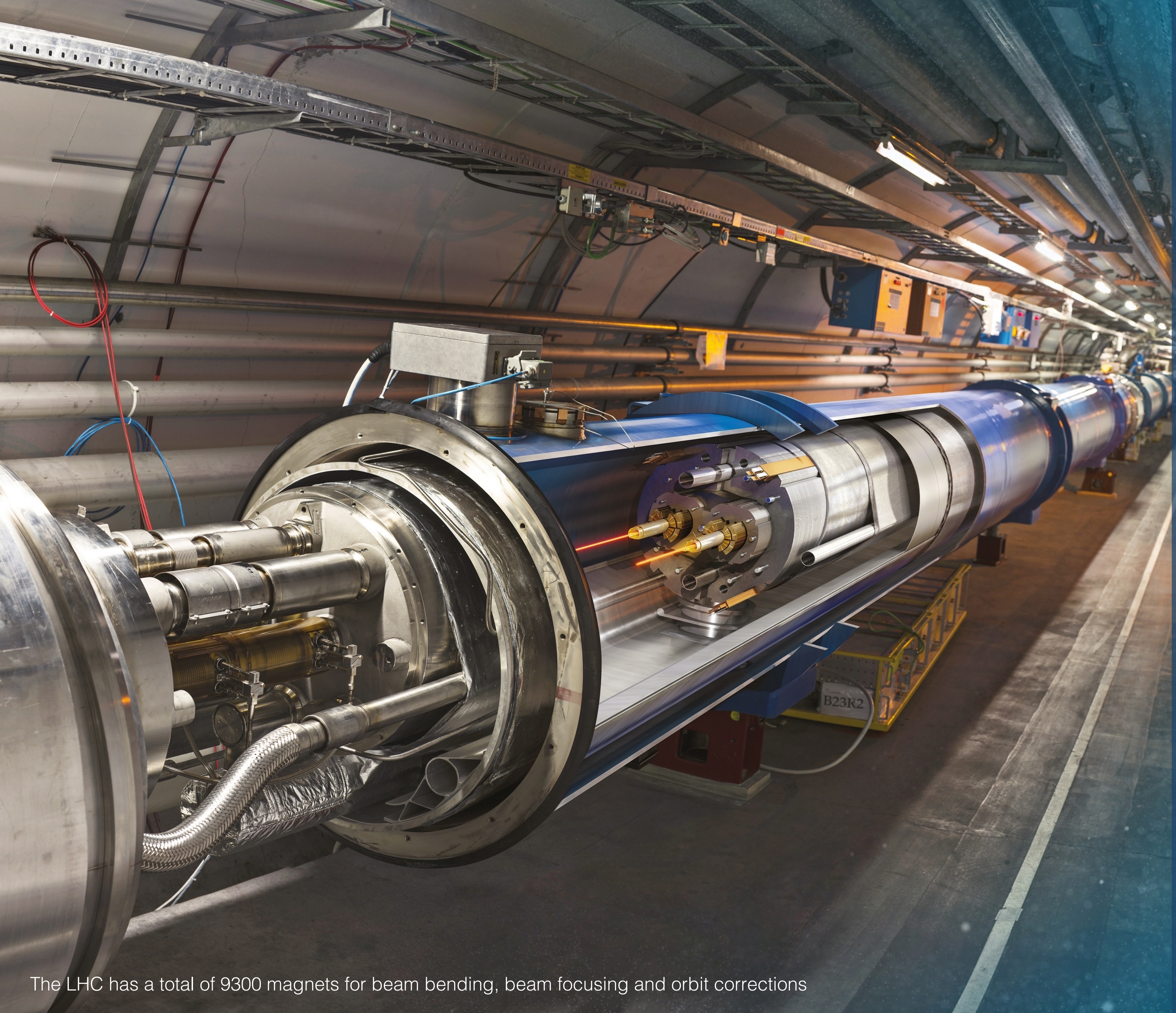
Producing and studying the Higgs boson requires a huge machine, which was realized at CERN



Brazil became CERN Associate Member State in March 2024

CERN

Founded in 1954 became a role model of international scientific cooperation



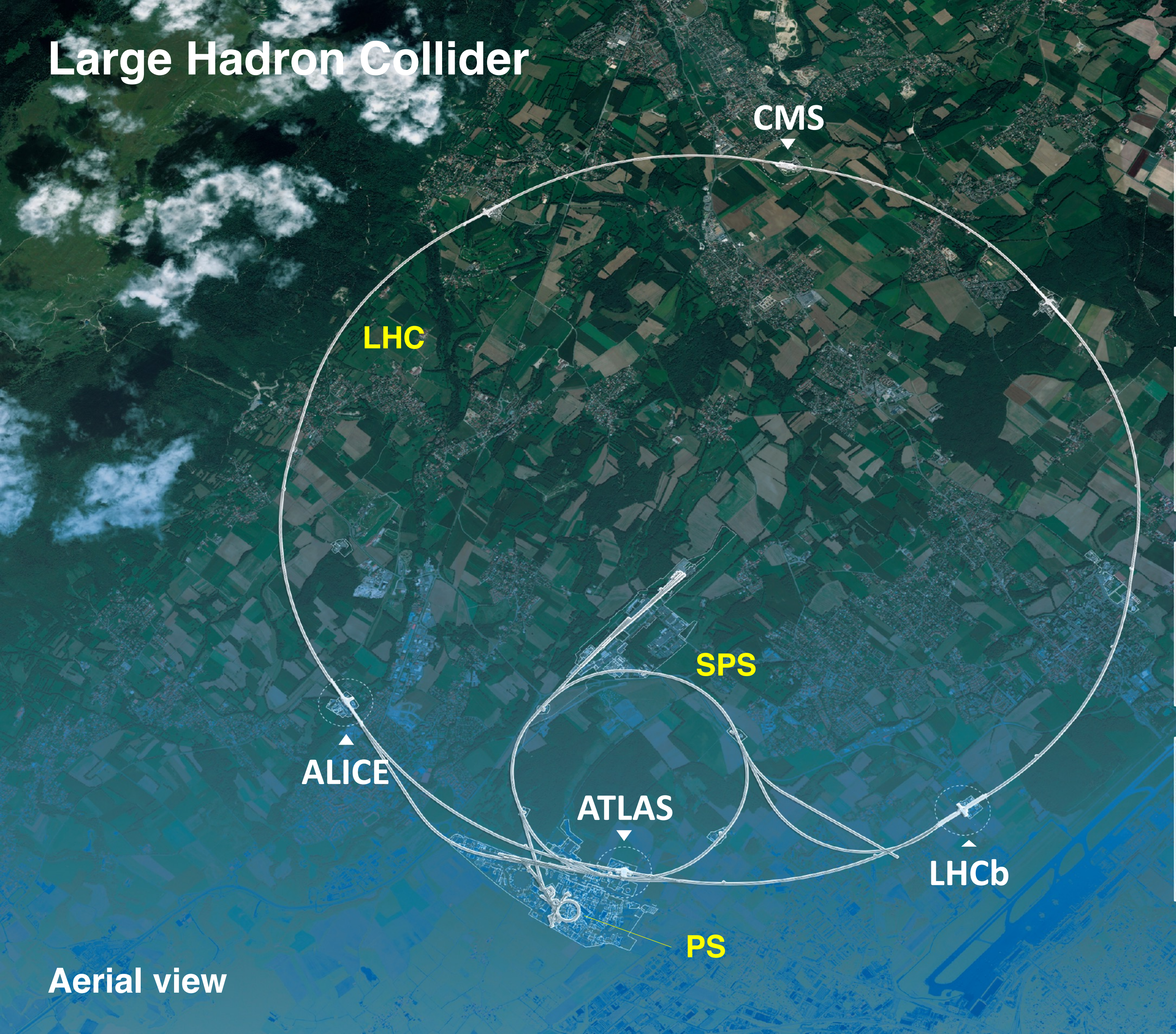
The LHC has a total of 9300 magnets for beam bending, beam focusing and orbit corrections

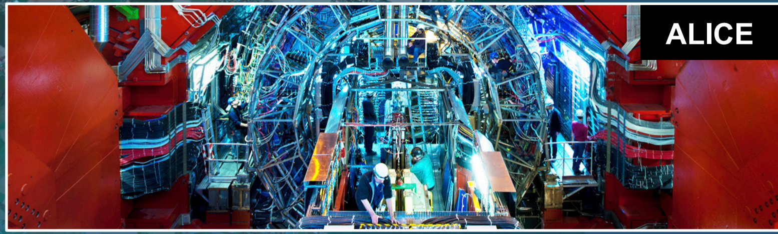
Large Hadron Collider (LHC)

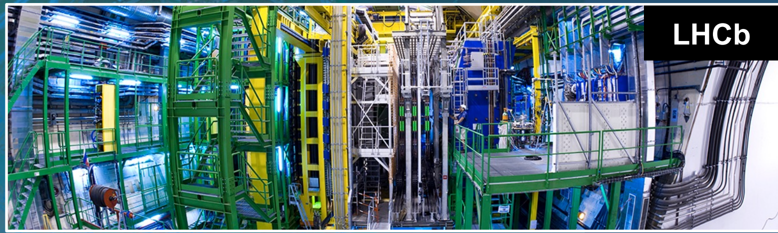
- 27 km circumference underground accelerator and collider
- Superconducting magnets (1.9 K = –271.3 °C) steer the particles around the ring
- Proton and ions are accelerated to multi-TeV scale energies and brought to collision


Large Hadron Collider
CMS
LHC
LHC
CERN
Prevessin
ALICE
ATLAS
LHCb
CERN
Meyrin
Aerial view

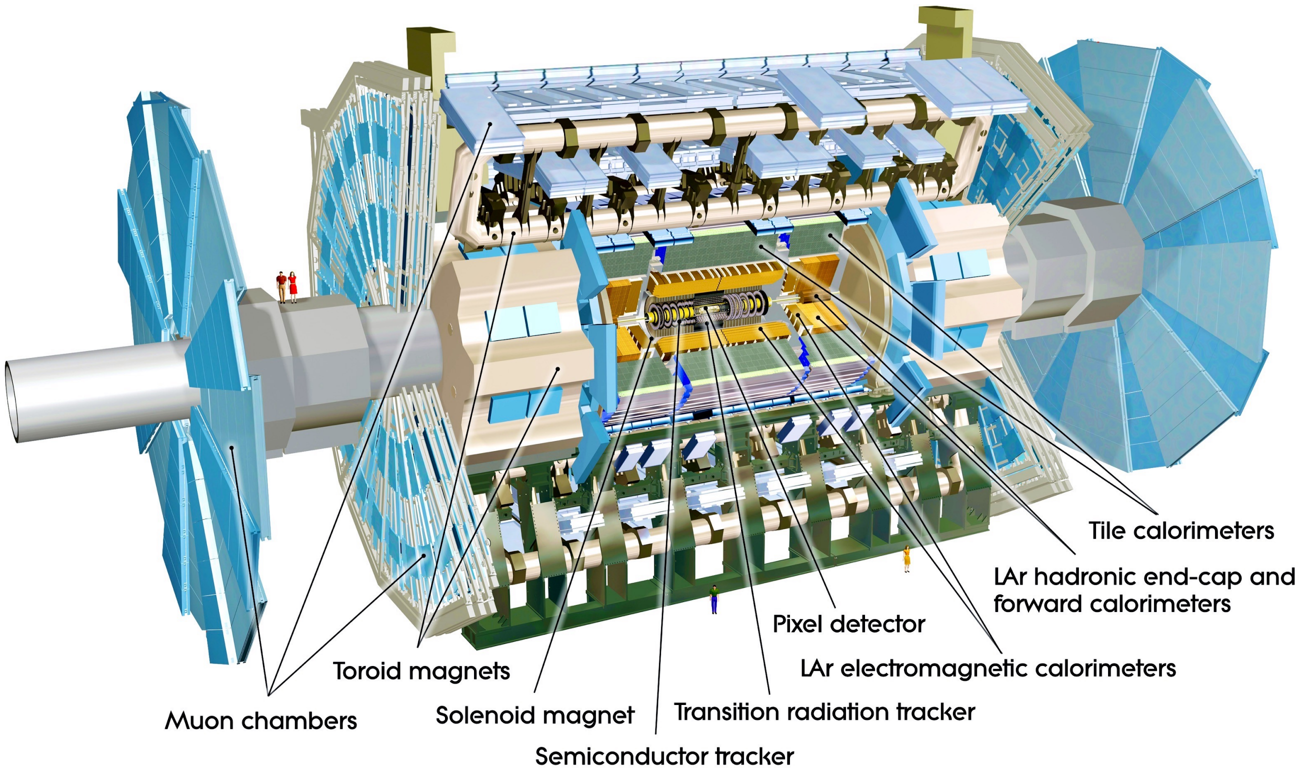
Large Hadron Collider

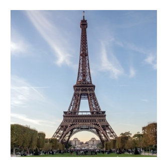






The ATLAS Detector



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

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

High resolution silicon **detectors**:

- 100 Mio. channels (50 μm x 250 μm)
- 6 Mio. channels (80 μm x 12 cm)

spatial resolution ~15 μm (in azimuthal direction)

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 30,000 collisions is kept

The ATLAS Collaboration

ATLAS Collaboration

253 institutes from 42 countries

2900 Scientific authors

1200 Physics PhD students

1300 Engineers or technicians

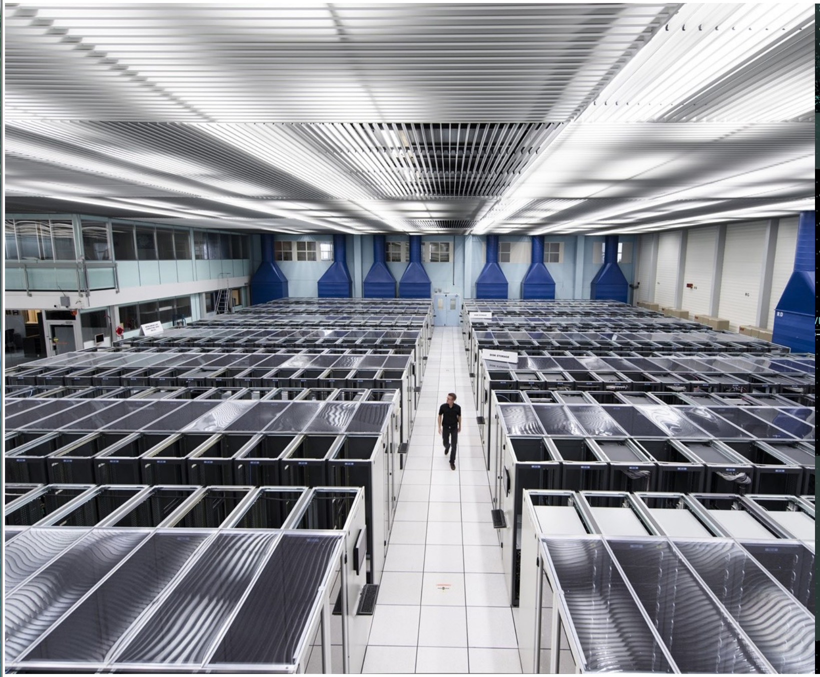
Brazil in ATLAS

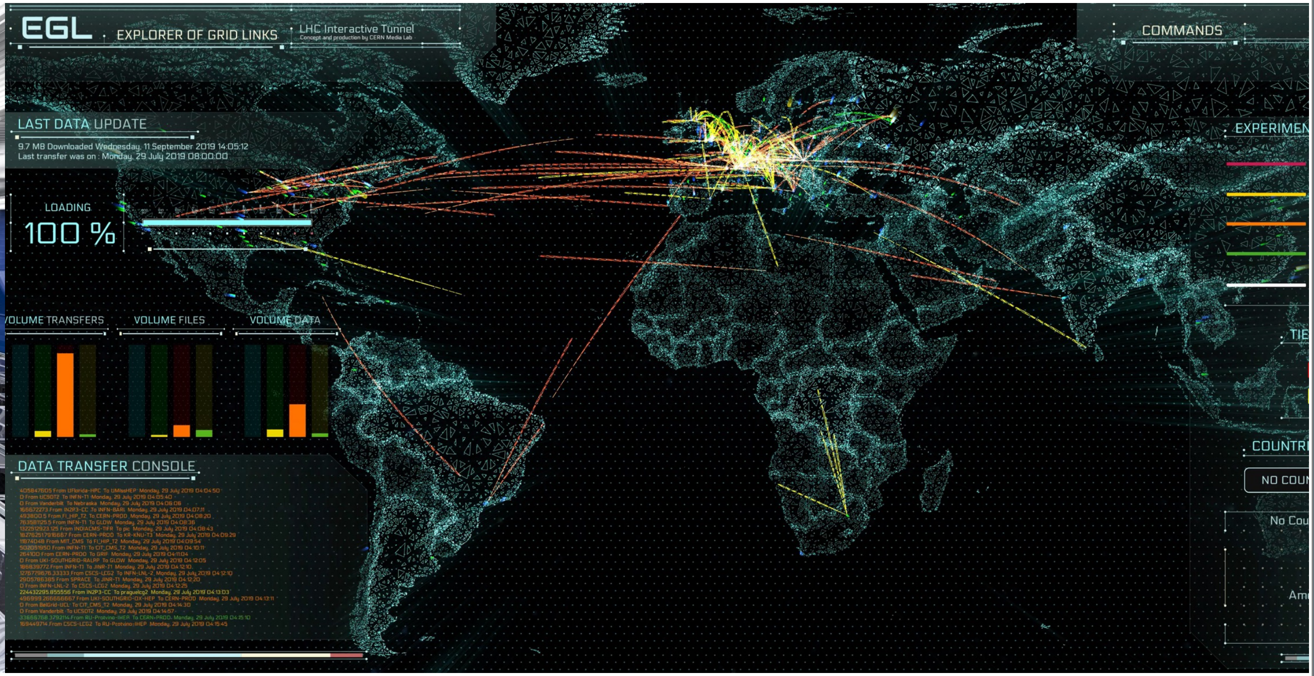
Brazil is founding member (1992) of the ATLAS Collaboration

It evolved to a cluster with today 5 institutes with broad contributions:

- USP, UFRJ, UERJ, UFJF, UFBA (and UFRN)
- 20 authors, 11 Physics PhD students, 13 Engineering students, 12 master students, 23 undergraduate students
- Contributions to detectors, software, computing, physics

The Worldwide LHC Computing Grid





Distribution, processing and analysis of the experimental data

> 1 million processing cores in 160 data centres in 42 countries

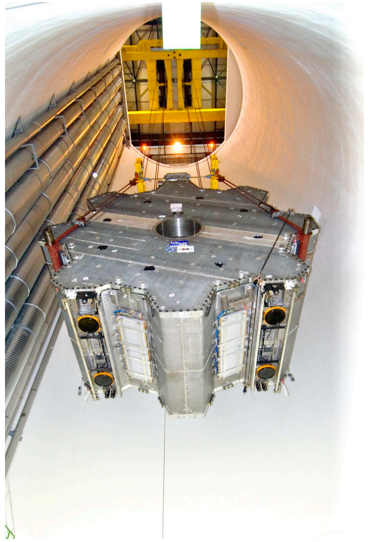
> 1000 petabytes CERN data are stored worldwide

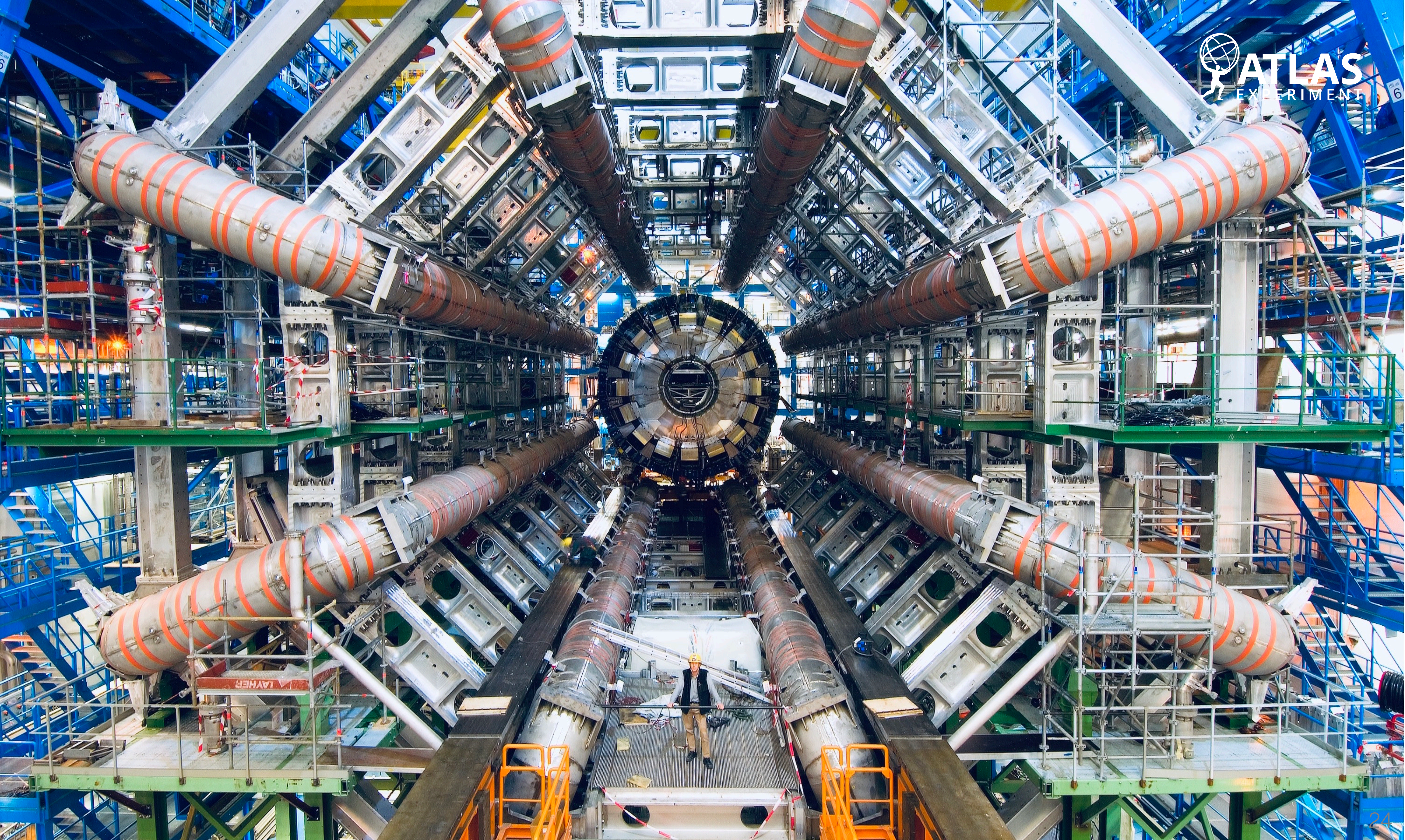
ATLAS Detector: construction und installation

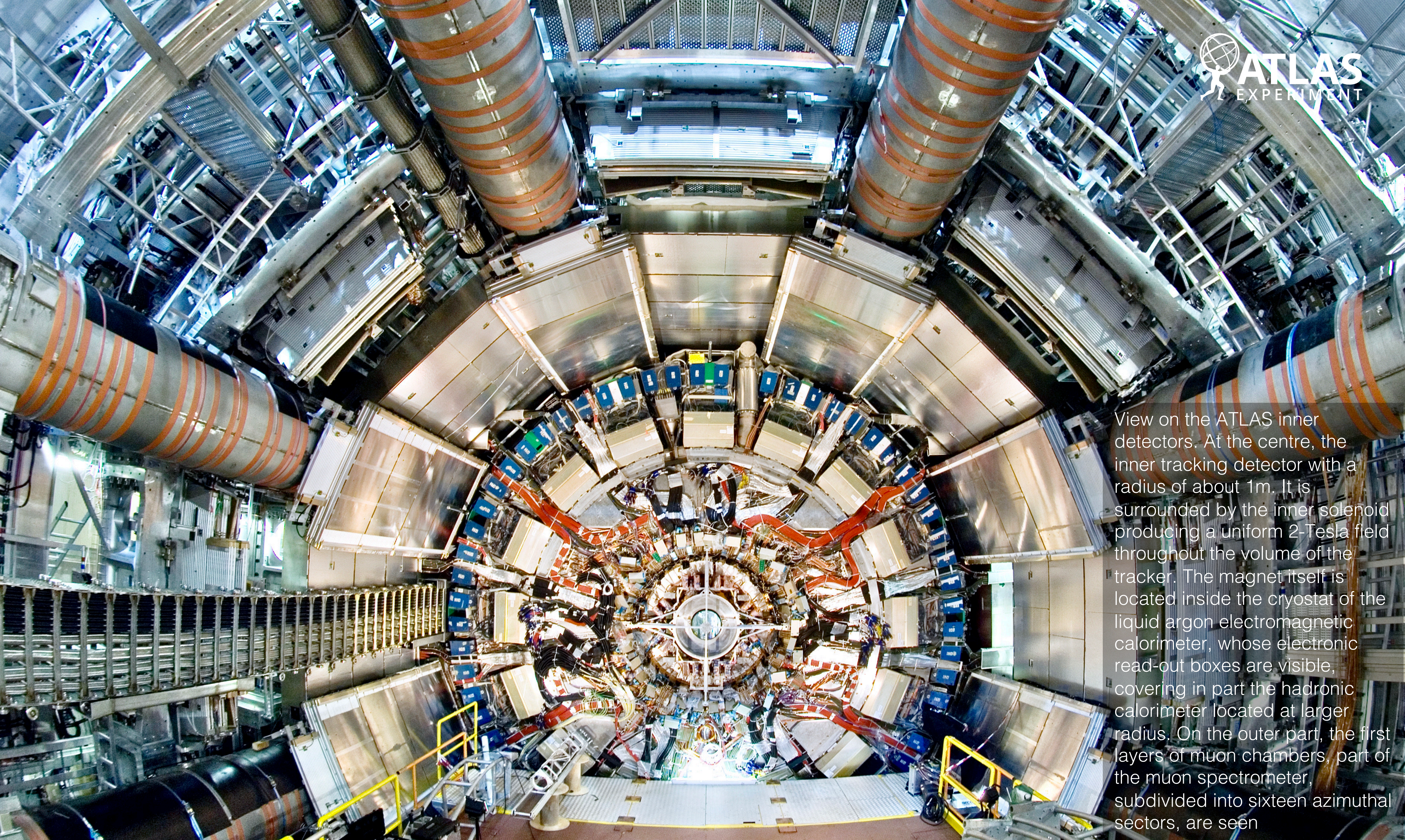
ATLAS cavern after excavation in July 2002

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

ATLAS Detector: construction und installation




ATLAS
EXPERIMENT



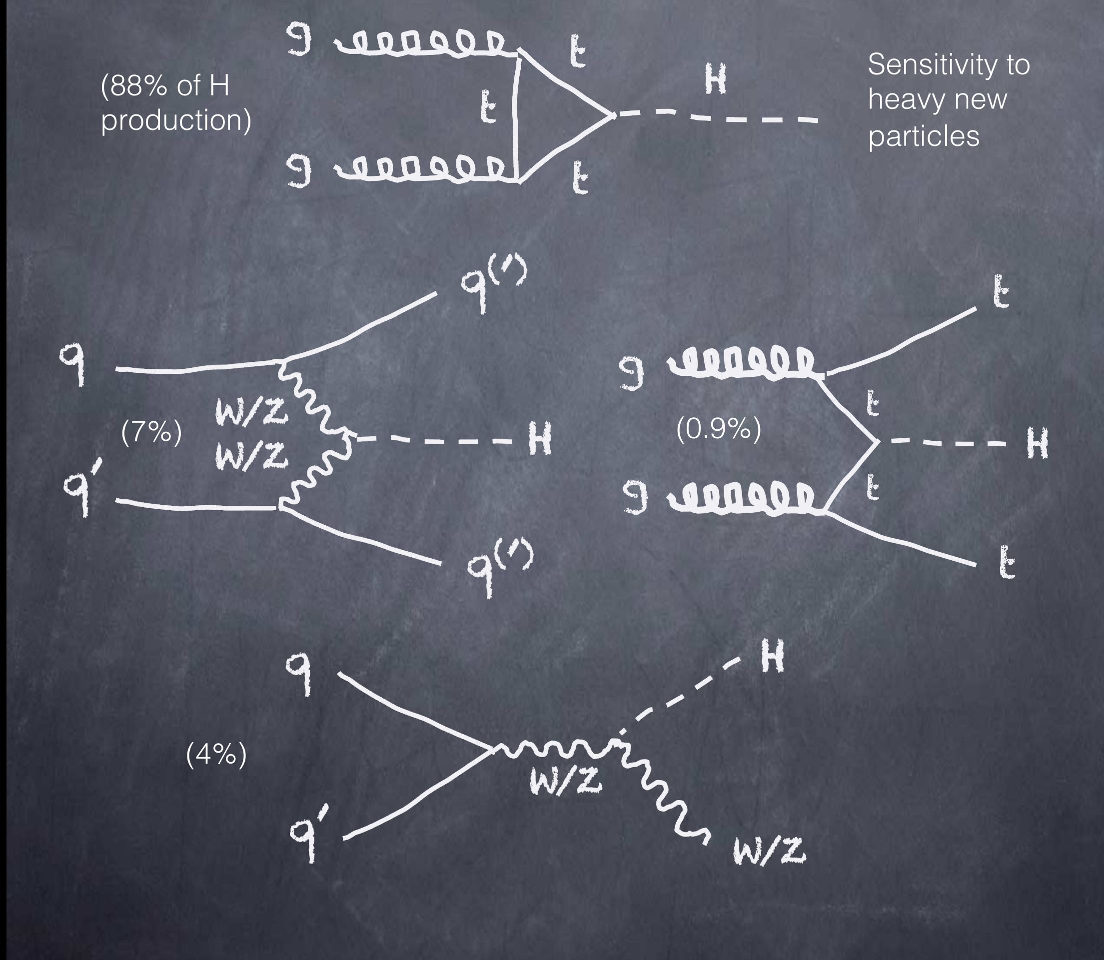
View on the ATLAS inner detectors. At the centre, the inner tracking detector with a radius of about 1m. It is surrounded by the inner solenoid producing a uniform 2-Tesla field throughout the volume of the tracker. The magnet itself is located inside the cryostat of the liquid argon electromagnetic 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

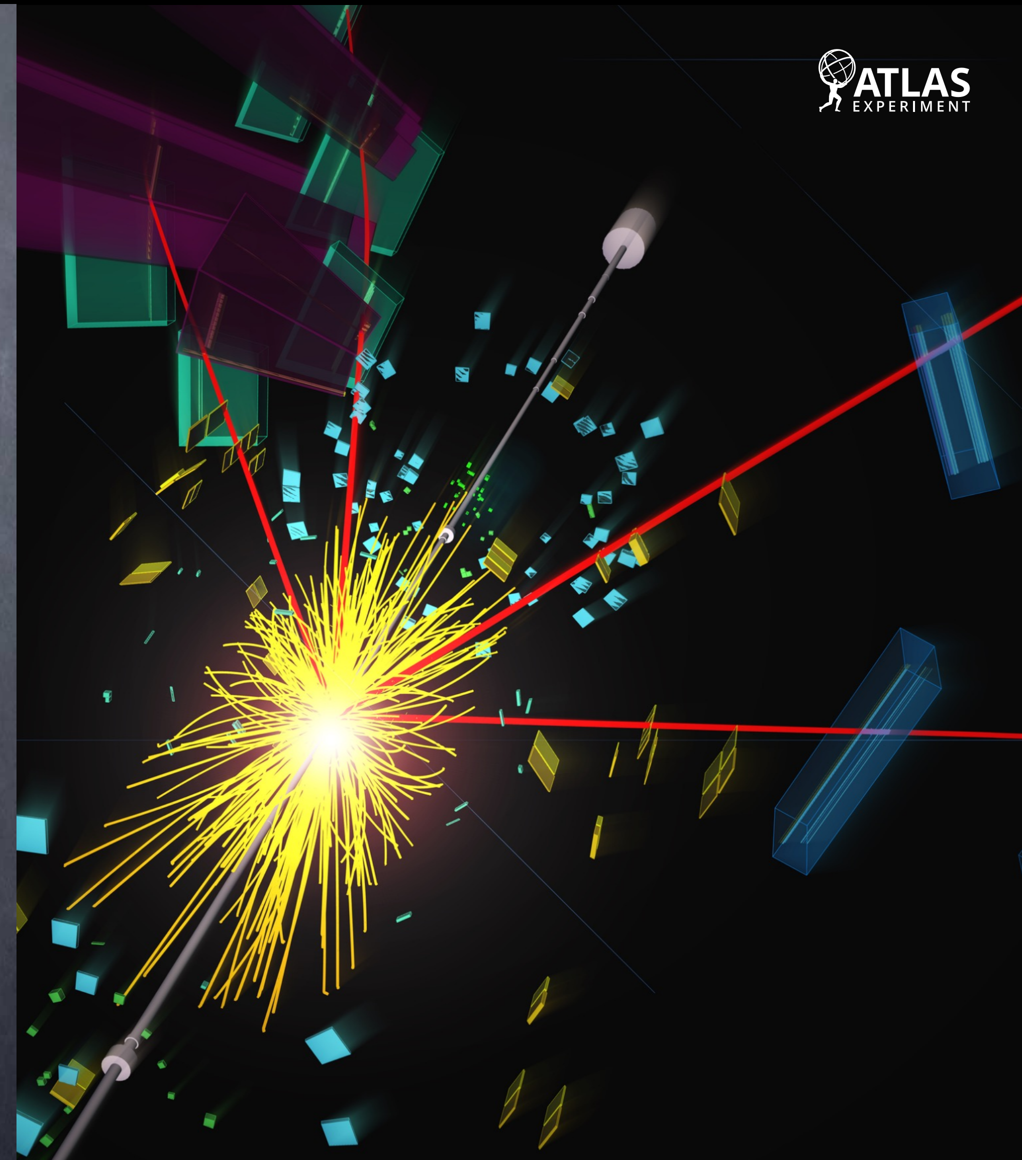
ATLAS endcap in open position during year-end technical stop 2023/2024

The LHC timeline

The Higgs boson at the LHC

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

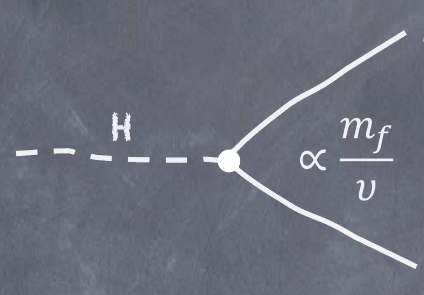


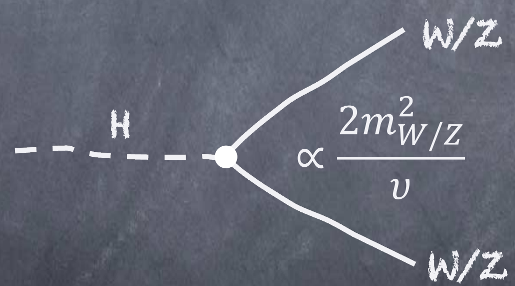


The Higgs boson at the LHC

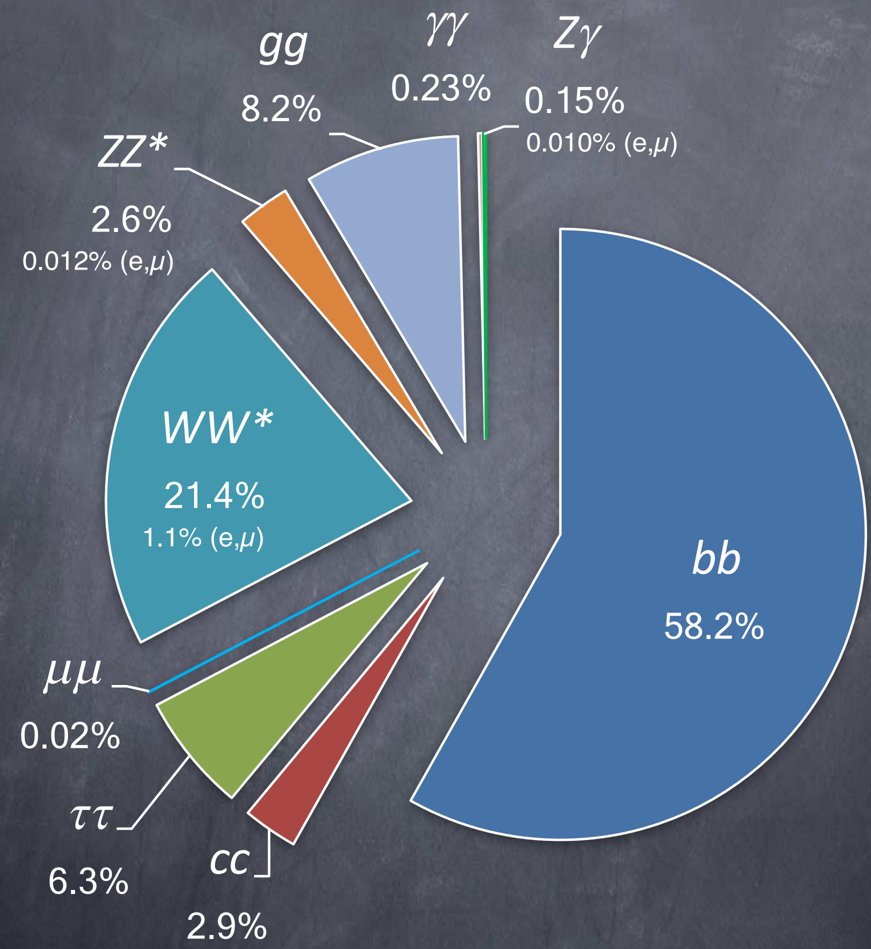
About 1 Higgs boson per second is produced in ATLAS at the LHC (about 12M total by today)

It decays within 10^{-22} s

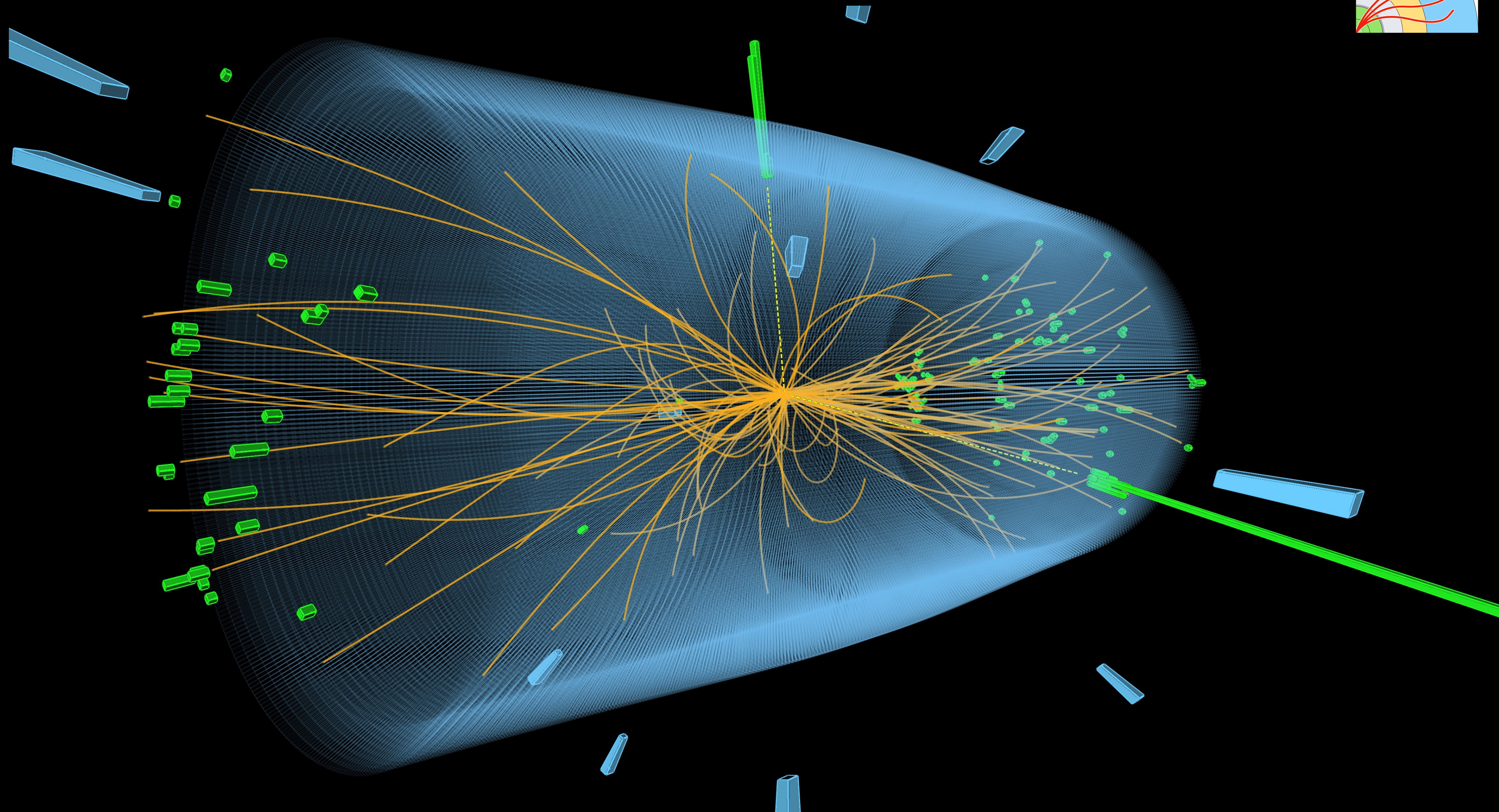




$H \to \gamma\gamma$, $Z\gamma$ occur through virtual top or W loops (no direct Higgs coupling to massless particles)



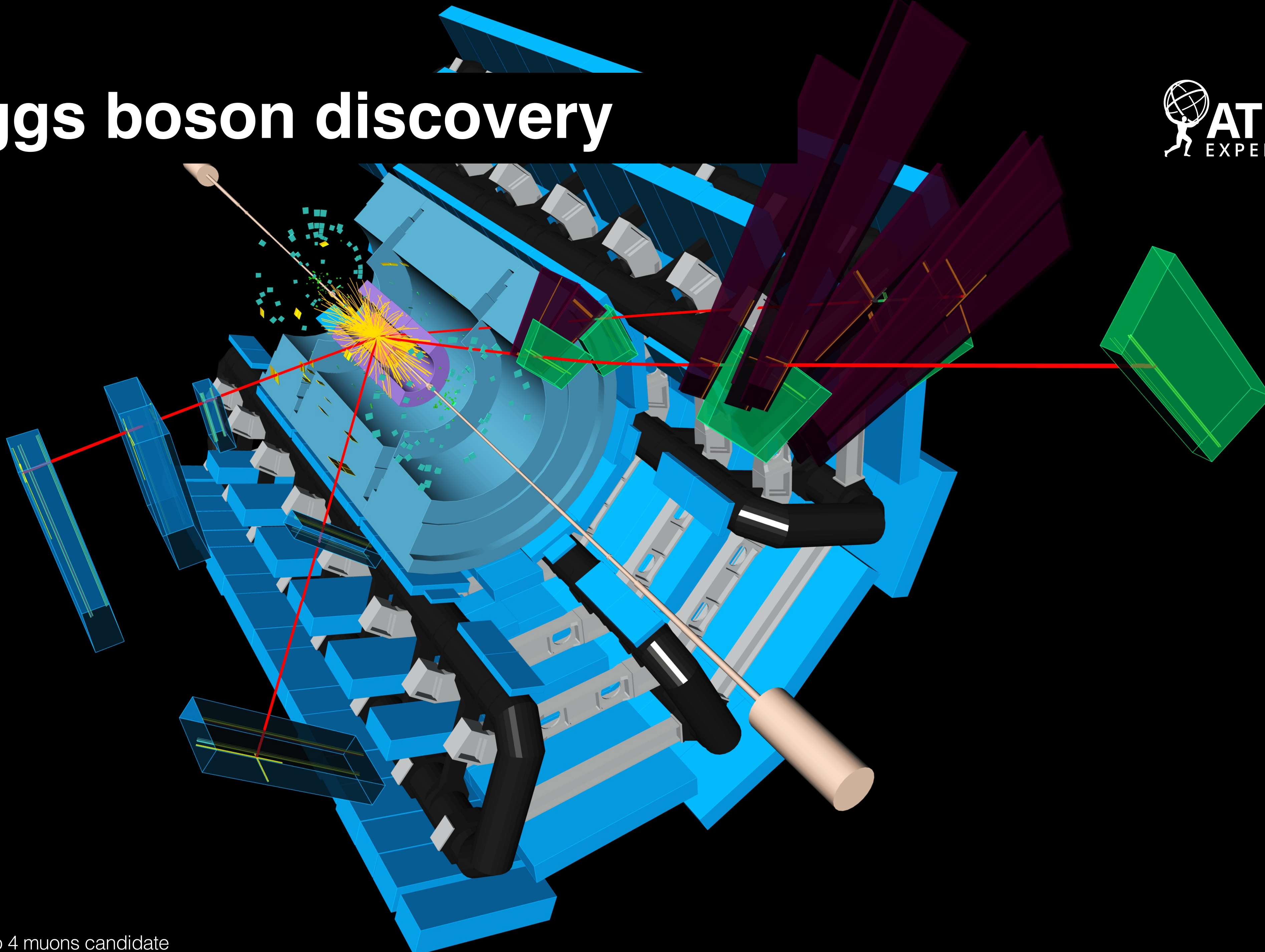
Higgs boson discovery



A Higgs boson to 2 photons candidate

Higgs boson discovery

ATLAS EXPERIMENT

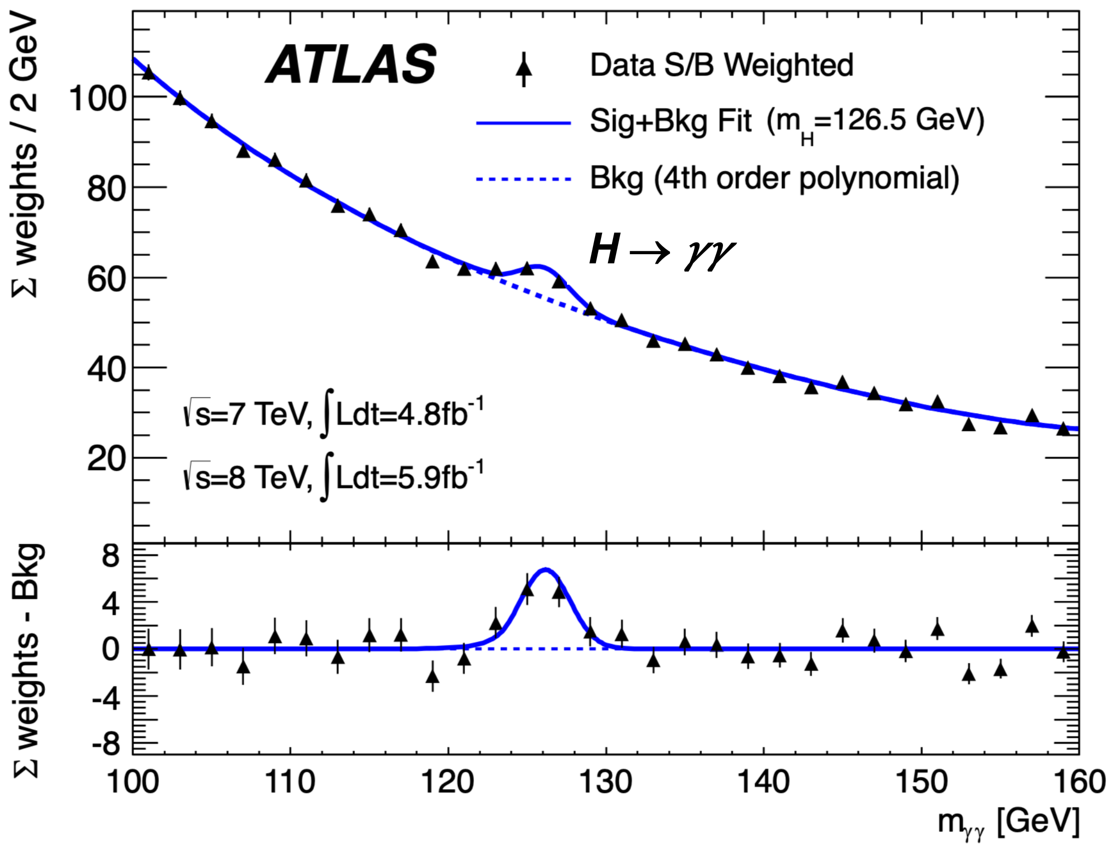


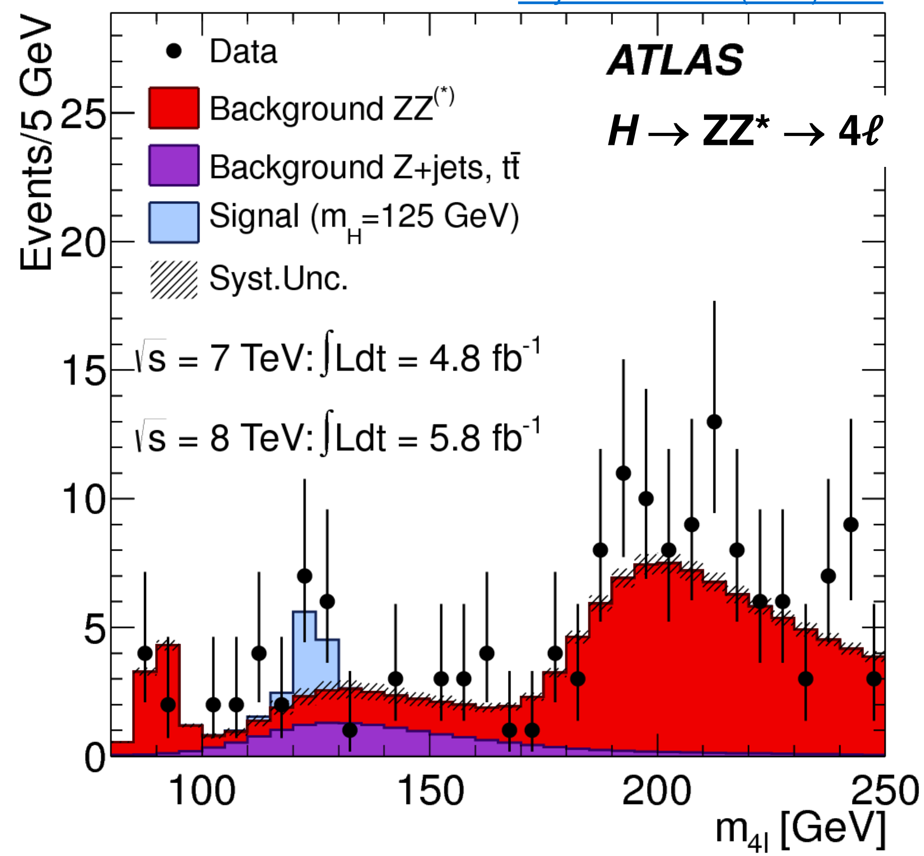
A Higgs boson to 4 muons candidate

Higgs boson discovery

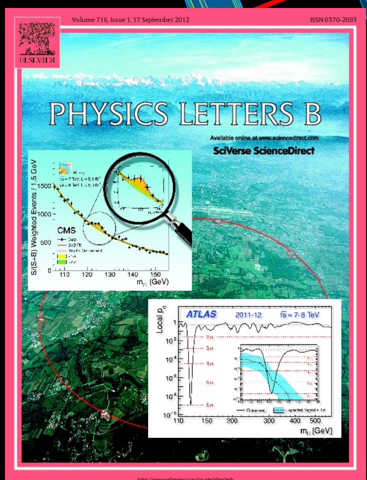
2012

Phys. Lett. B 716 (2012) 1-29



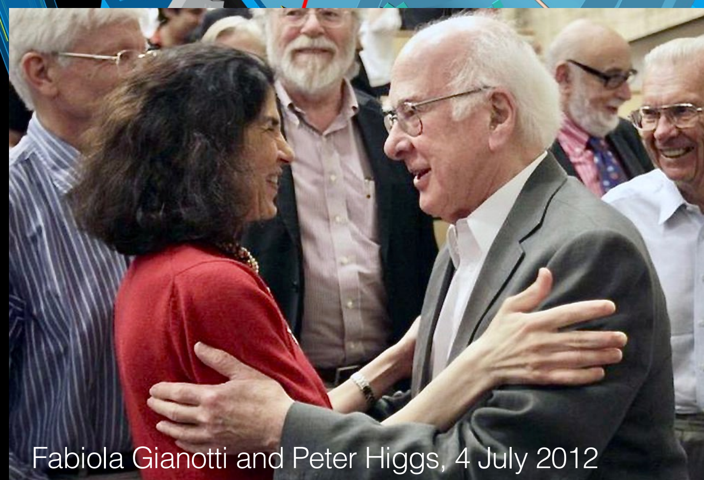


Higgs boson discovery



Phys. Lett.B 716 (2012)

Cited almost 15,000 times (today)



Fabiola Gianotti and Peter Higgs, 4 July 2012

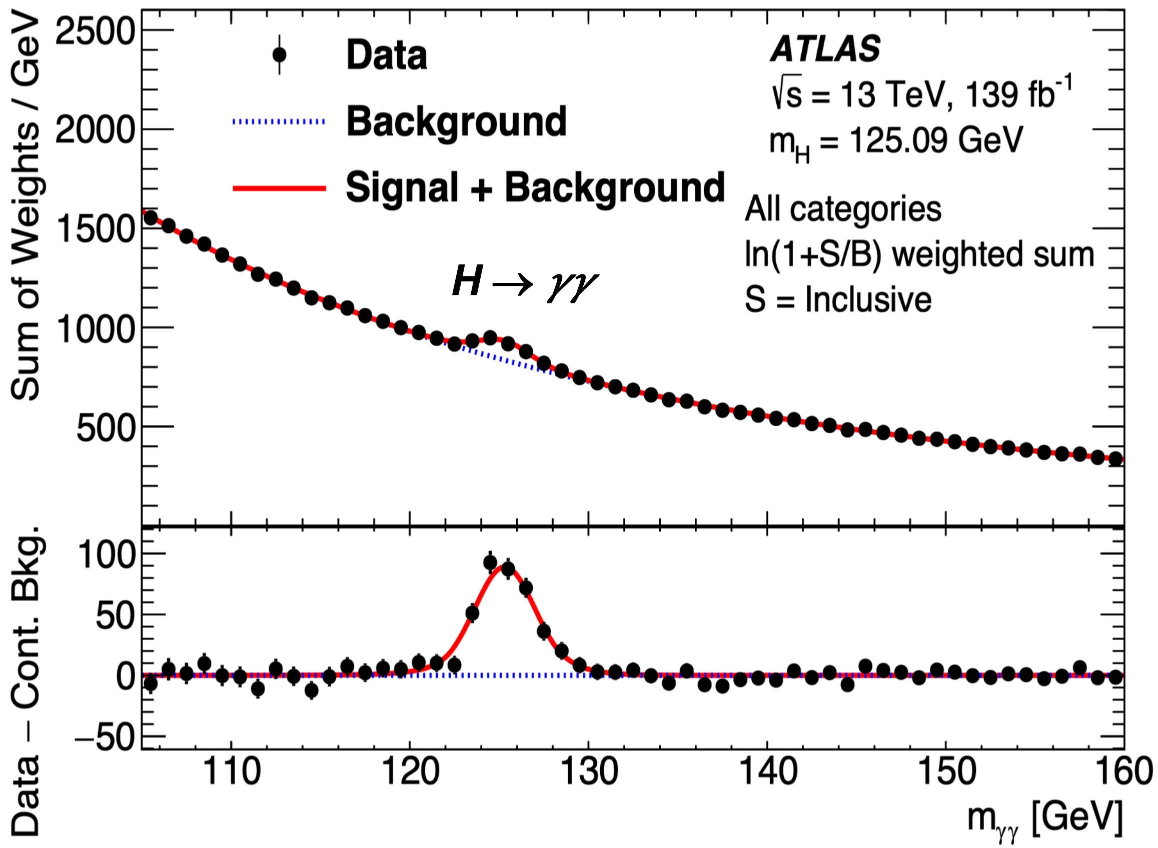
4 July 2012: ATLAS (Fabiola Gianotti) und CMS (Joseph Incandela) announce the Higgs boson discovery before a packed auditorium

The Higgs boson — At 10

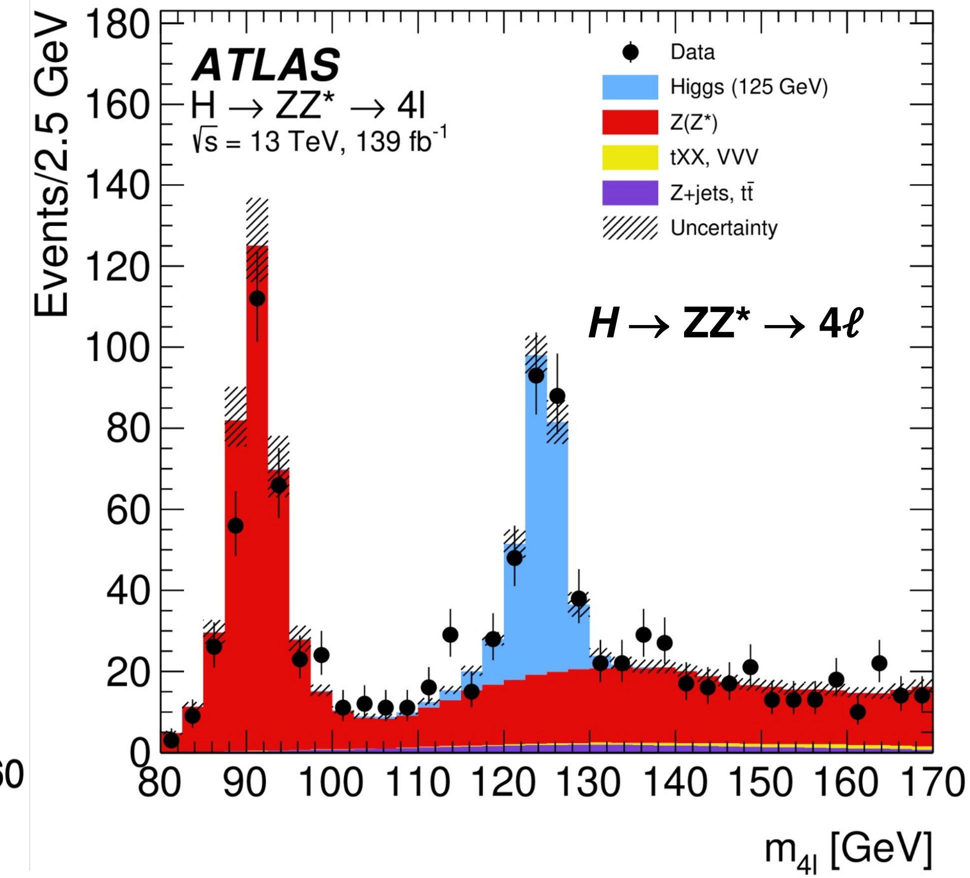
ATLAS EXPERIMENT

2020

JHEP 07 (2023) 088

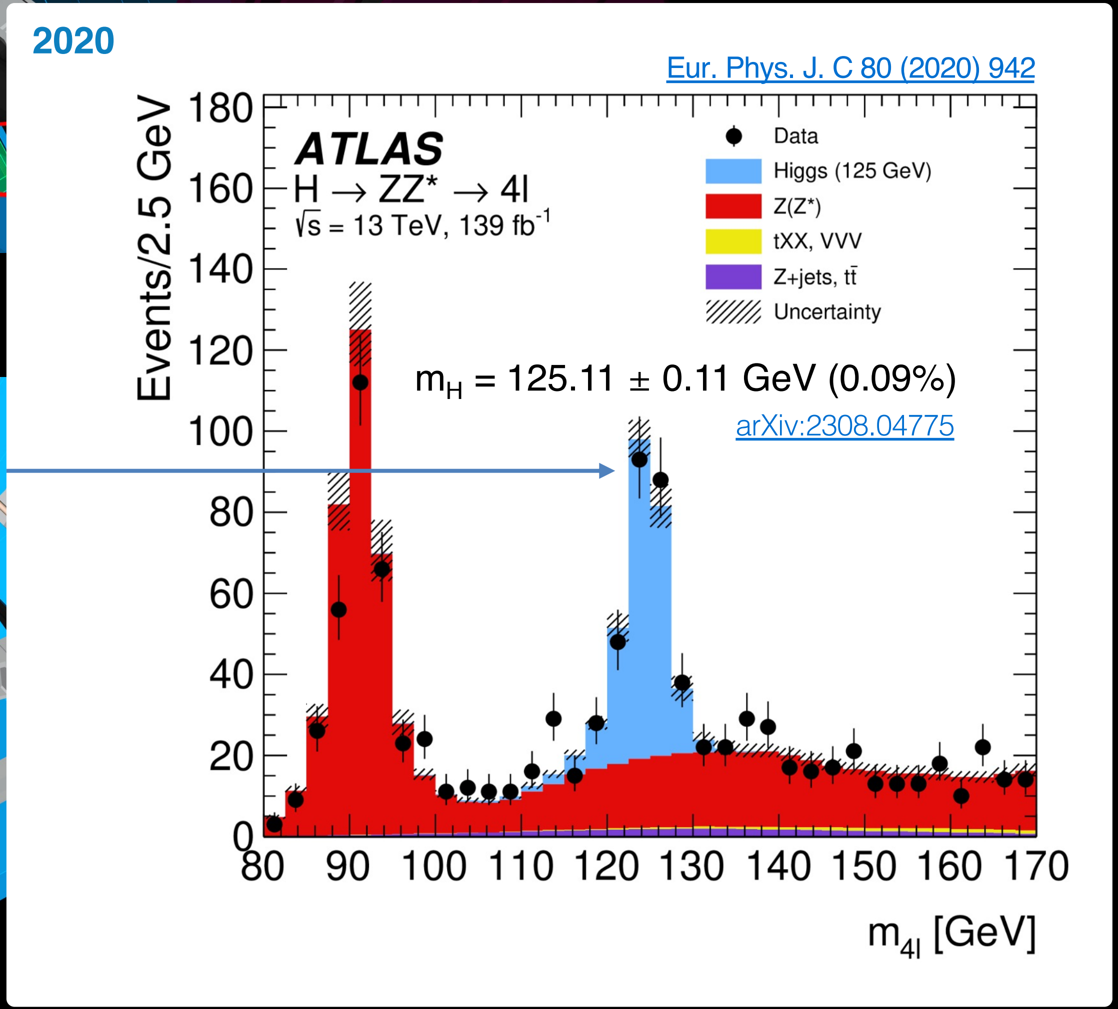


Eur. Phys. J. C 80 (2020) 942

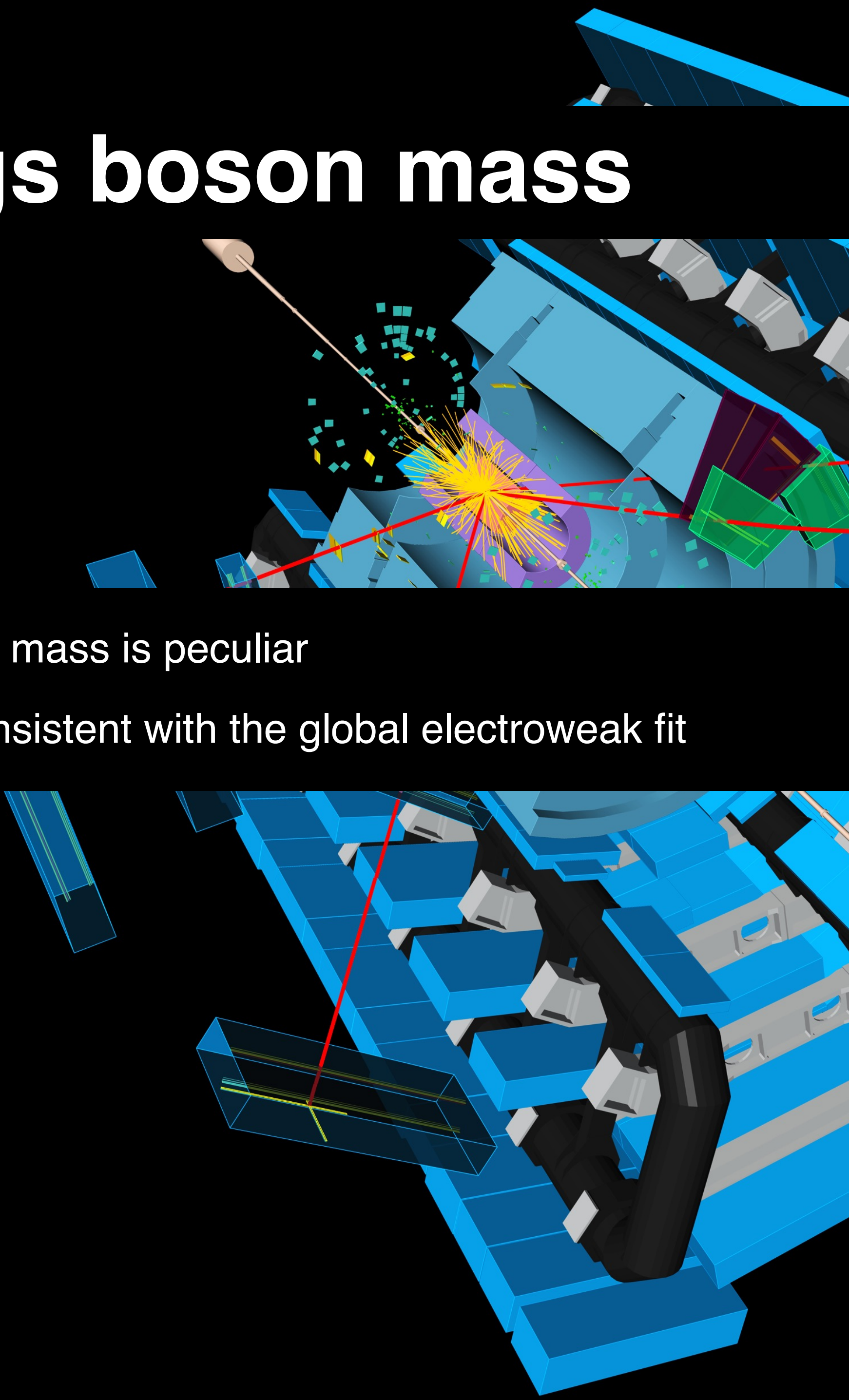


Higgs boson mass

The Higgs mass is peculiar



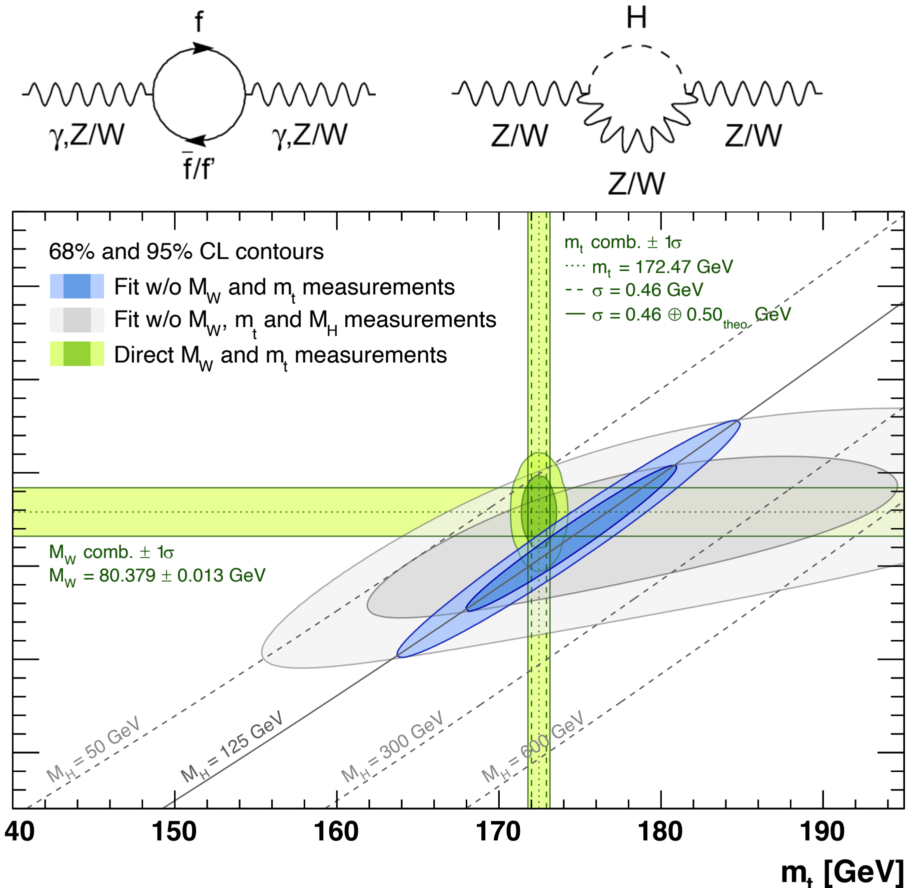
Higgs boson mass



The Higgs mass is peculiar

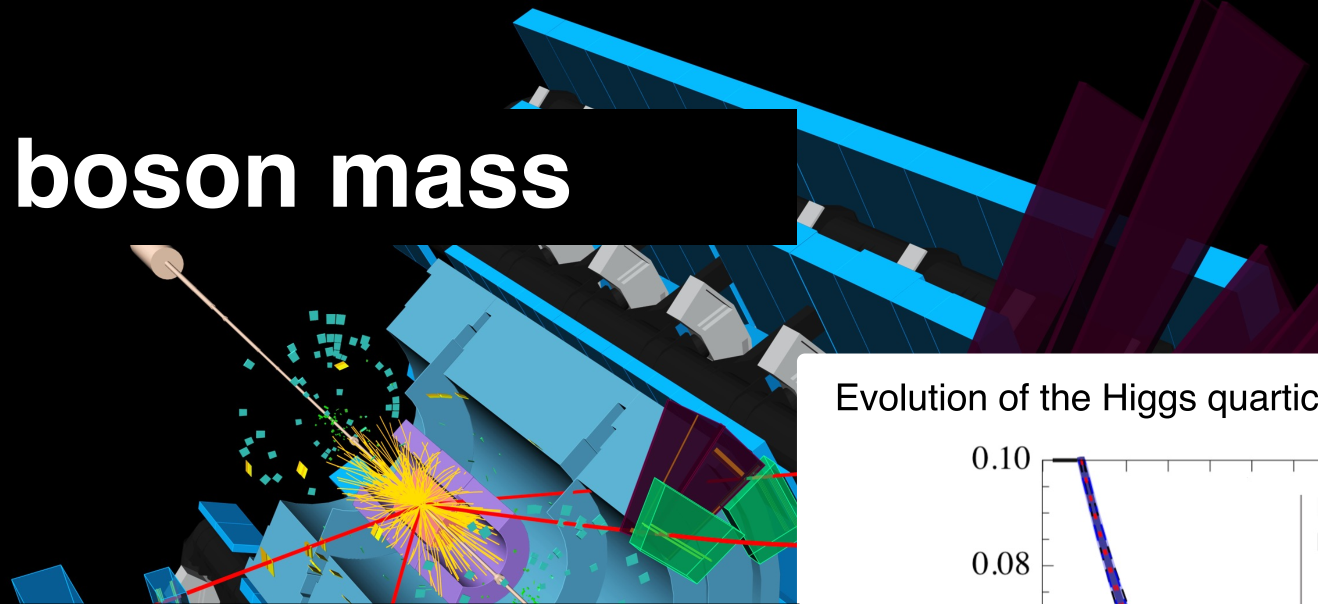
- It is consistent with the global electroweak fit

Radiative corections sensitive to heavy particles in loop



Gfitter Group: arXiv:1803.01853

Higgs boson mass



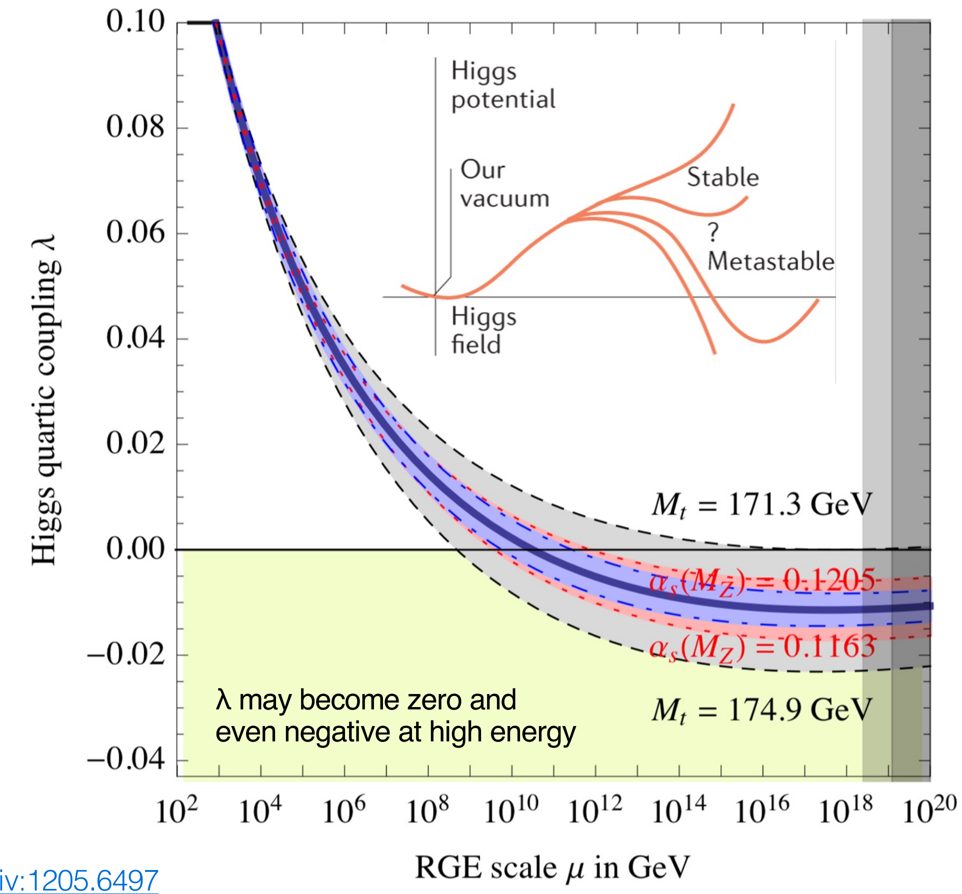
$$V(\phi) = -\mu^2|\phi|^2 + \lambda|\phi|^4$$

At lowest order (tree level)

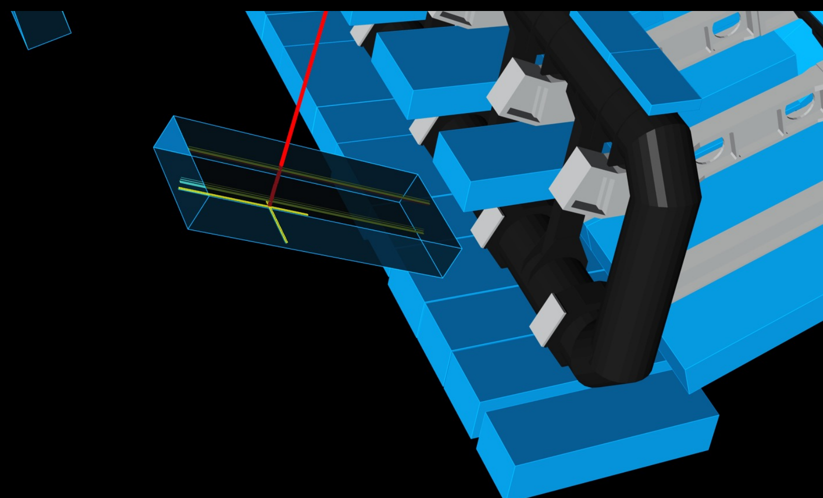
The Higgs mass is peculiar

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

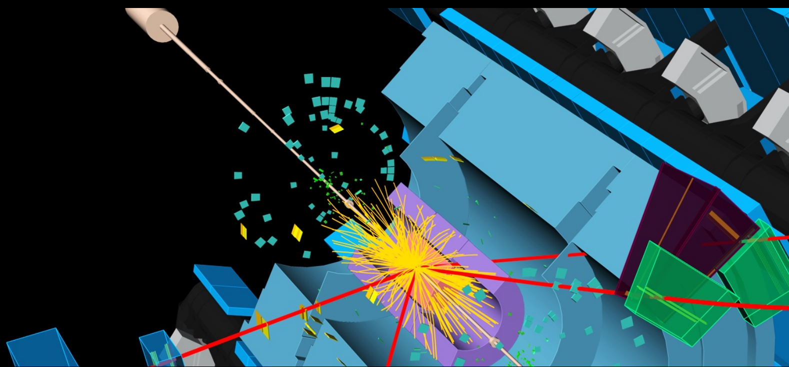
Evolution of the Higgs quartic coupling, assuming SM (only)

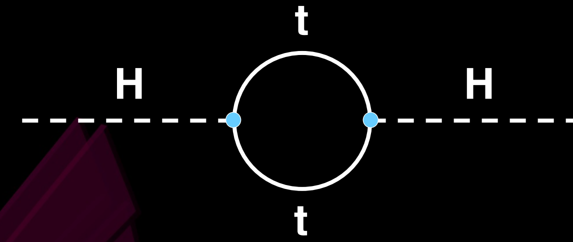


arXiv:1205.6497



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}):

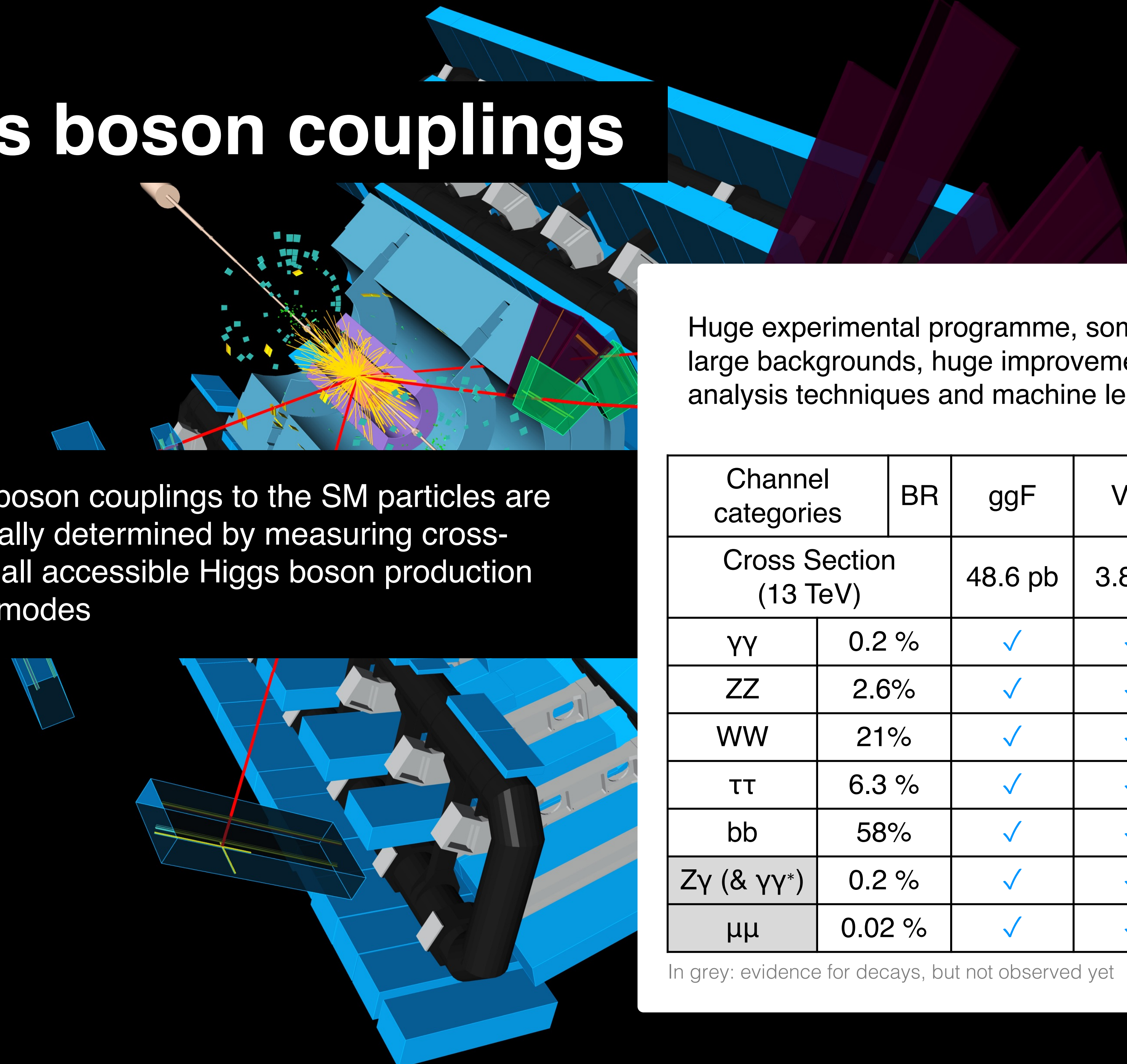
$$m_H^2 = m_{\mathrm{bare}}^2 + \delta m_H^2$$

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

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

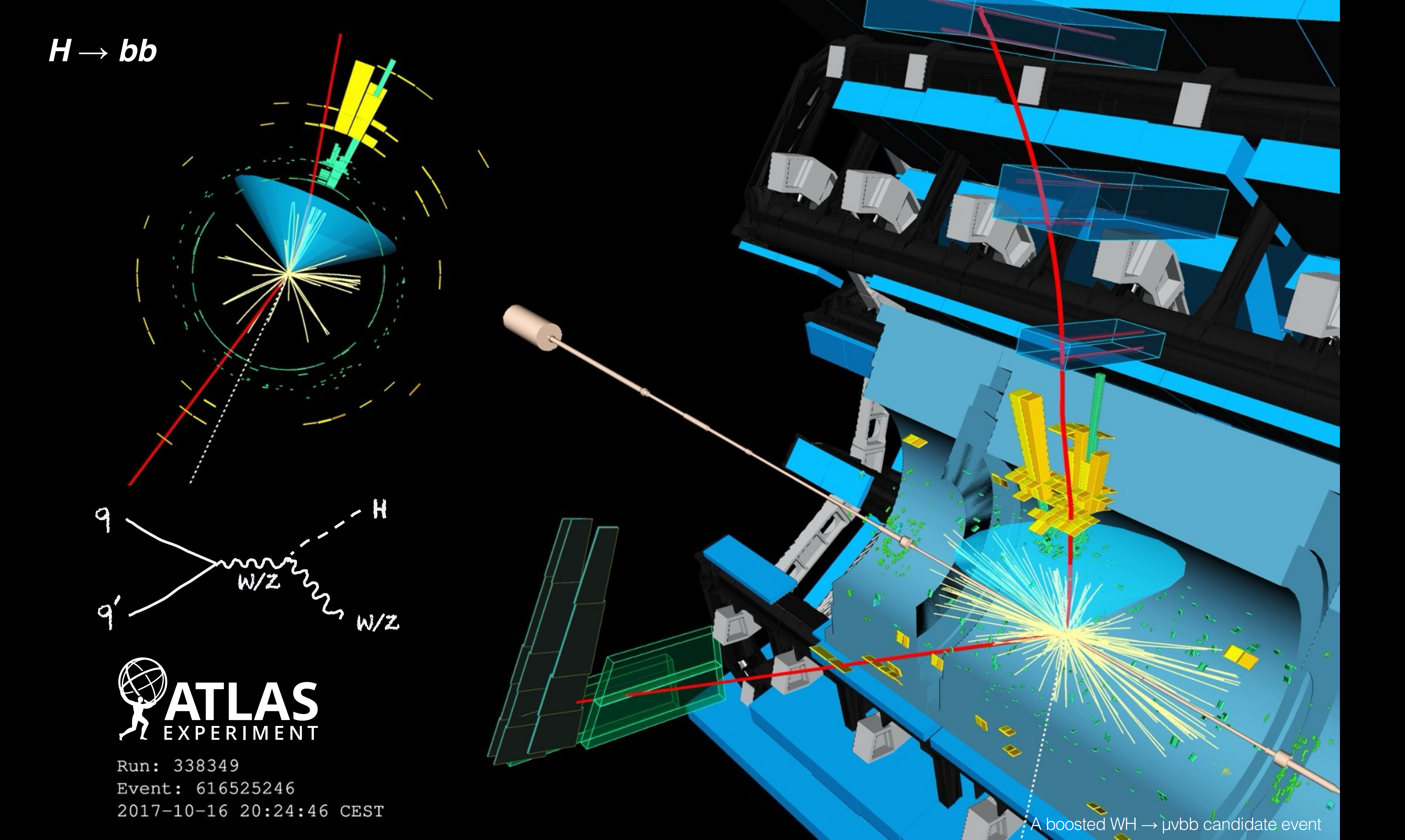


The Higgs boson couplings to the SM particles are experimentally determined by measuring cross-sections of all accessible Higgs boson production and decay modes

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



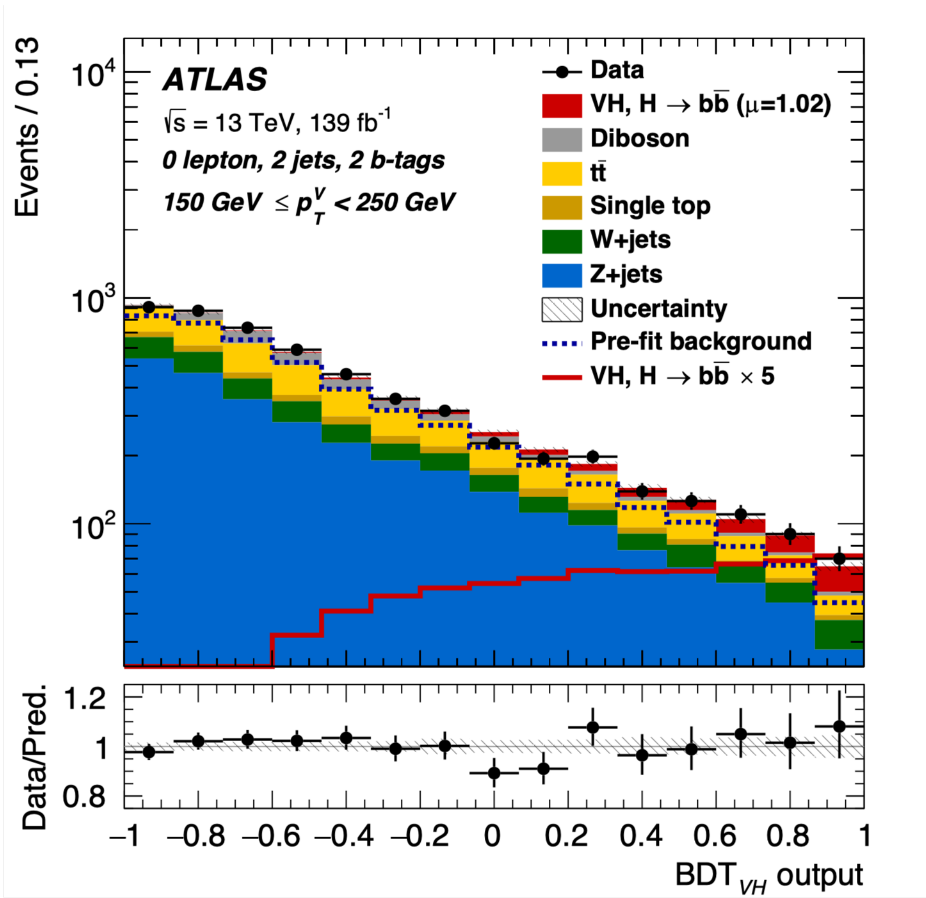
H → bb
q
q'
H
W/Z
W/Z
ATLAS
EXPERIMENT
Run: 338349
Event: 616525246
2017-10-16 20:24:46 CEST
A boosted WH → μνbb candidate event

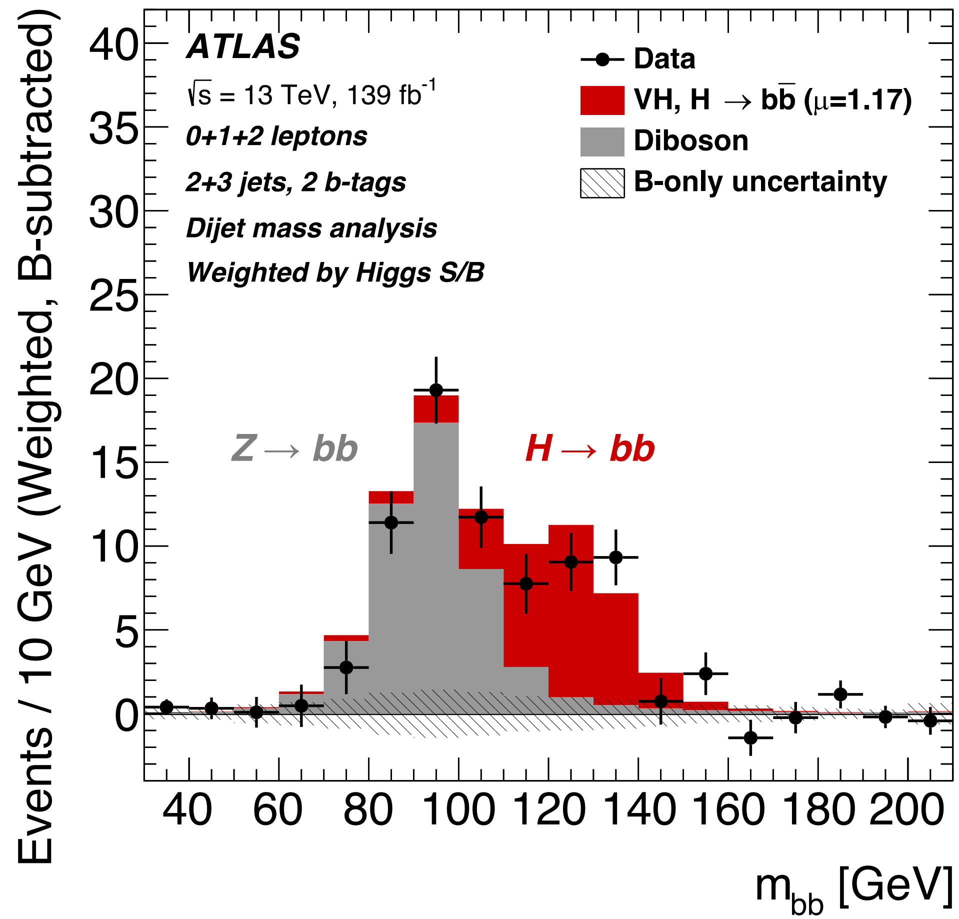
$H \to bb$

Measurement of H → bb via associated production pp → 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

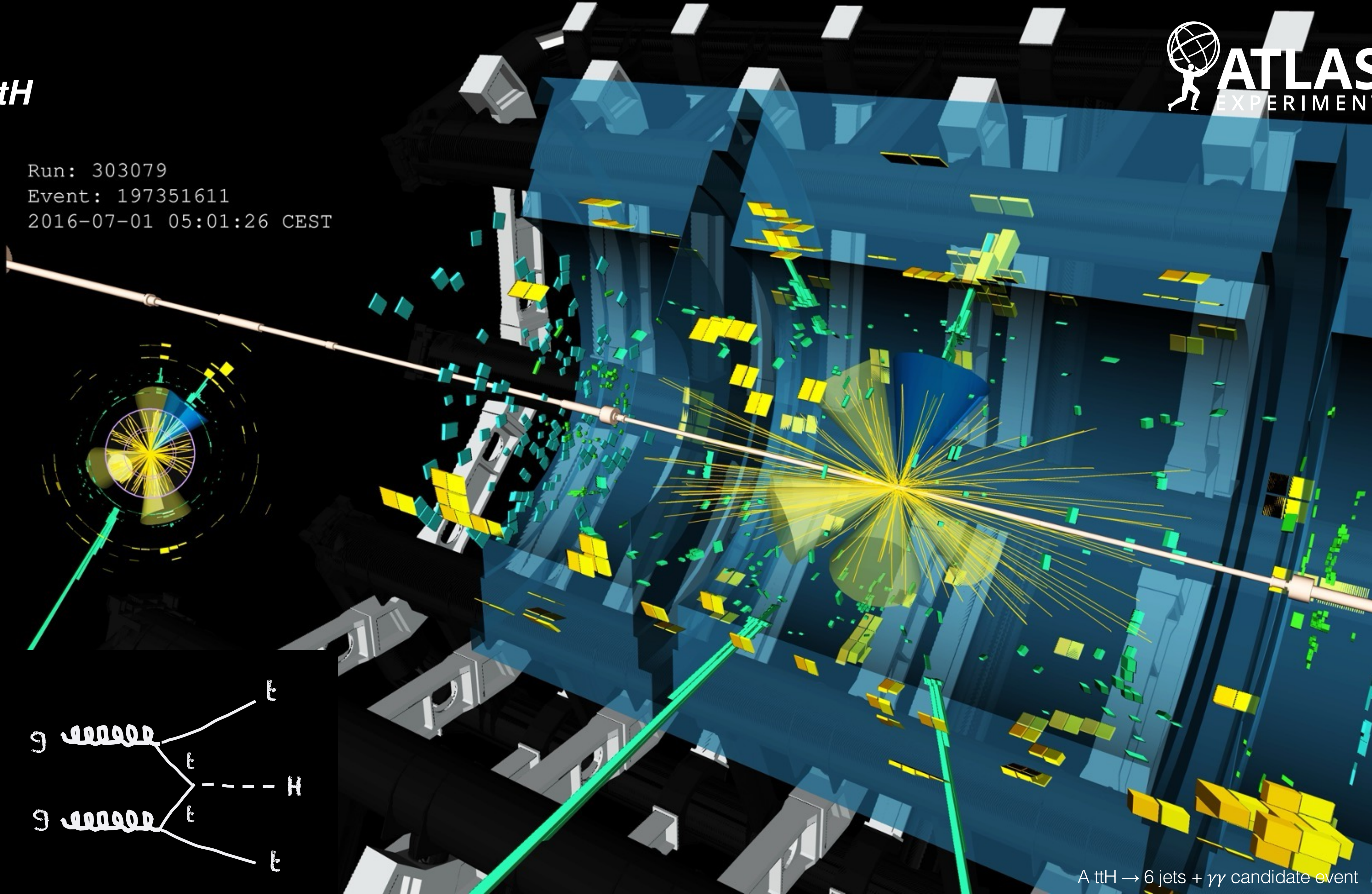




Event: 616525246
2017-10-16 20:24:46 CEST

A boosted WH → μνbb candidate event

ttH

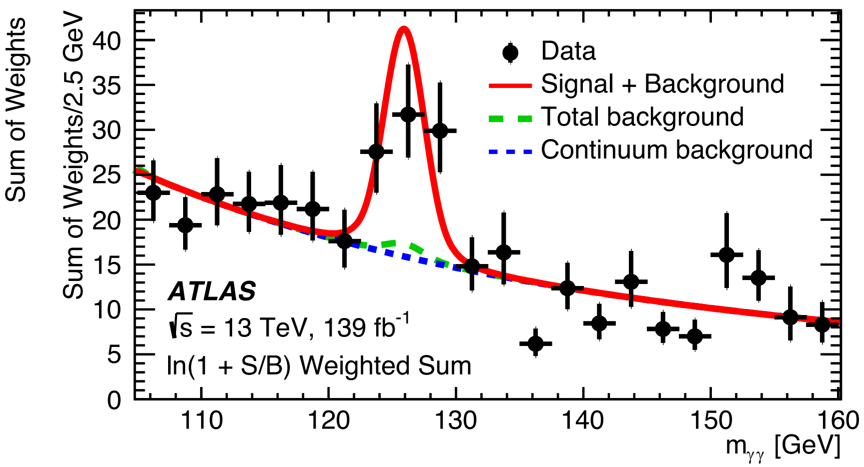


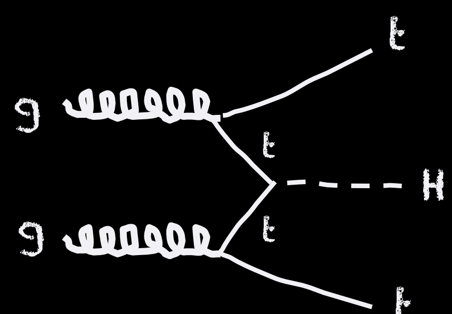
A ttH → 6 jets + $\gamma\gamma$ candidate event

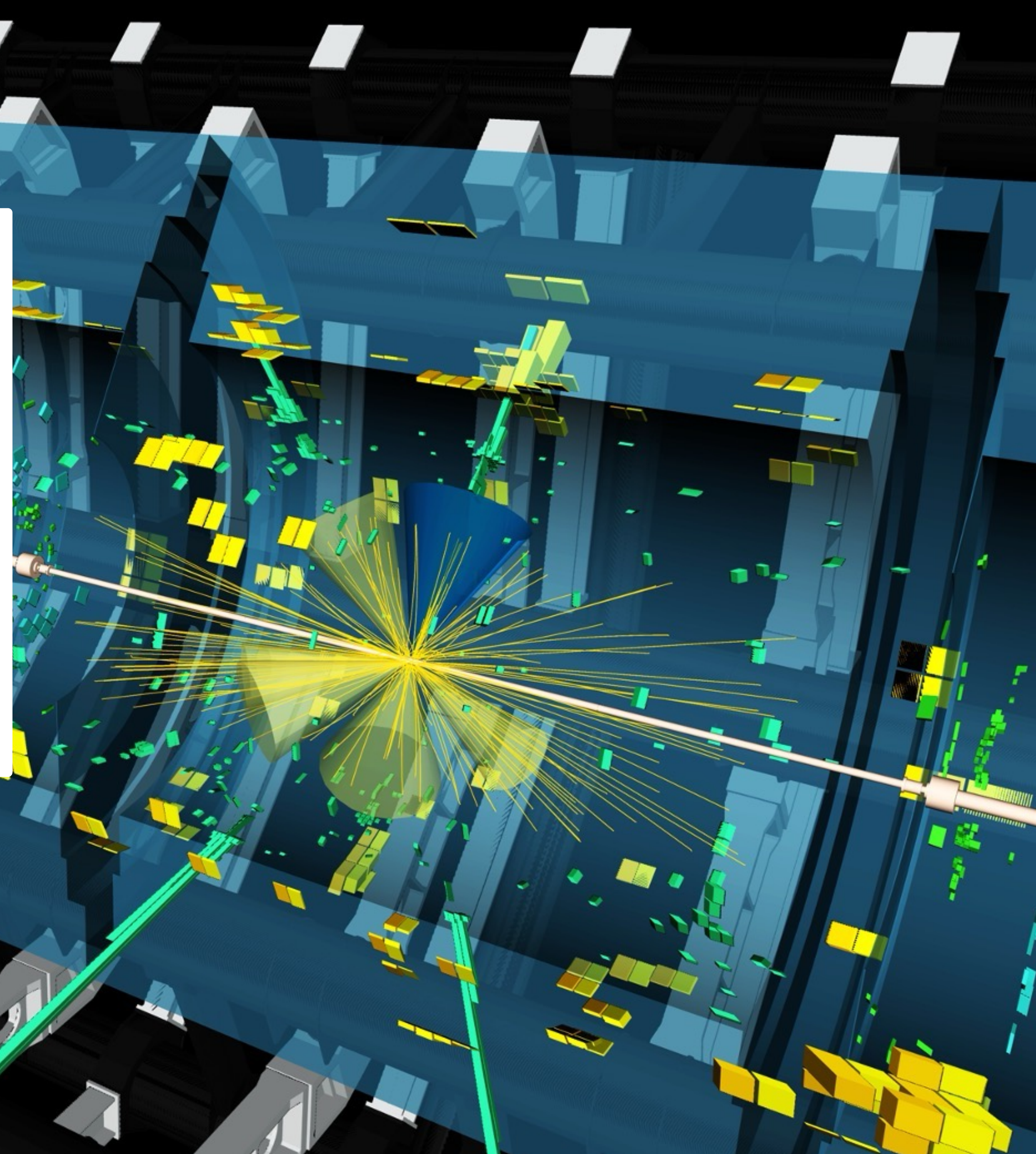
ttH

ttH production features rich events,
H → $\gamma\gamma$ channel most powerful

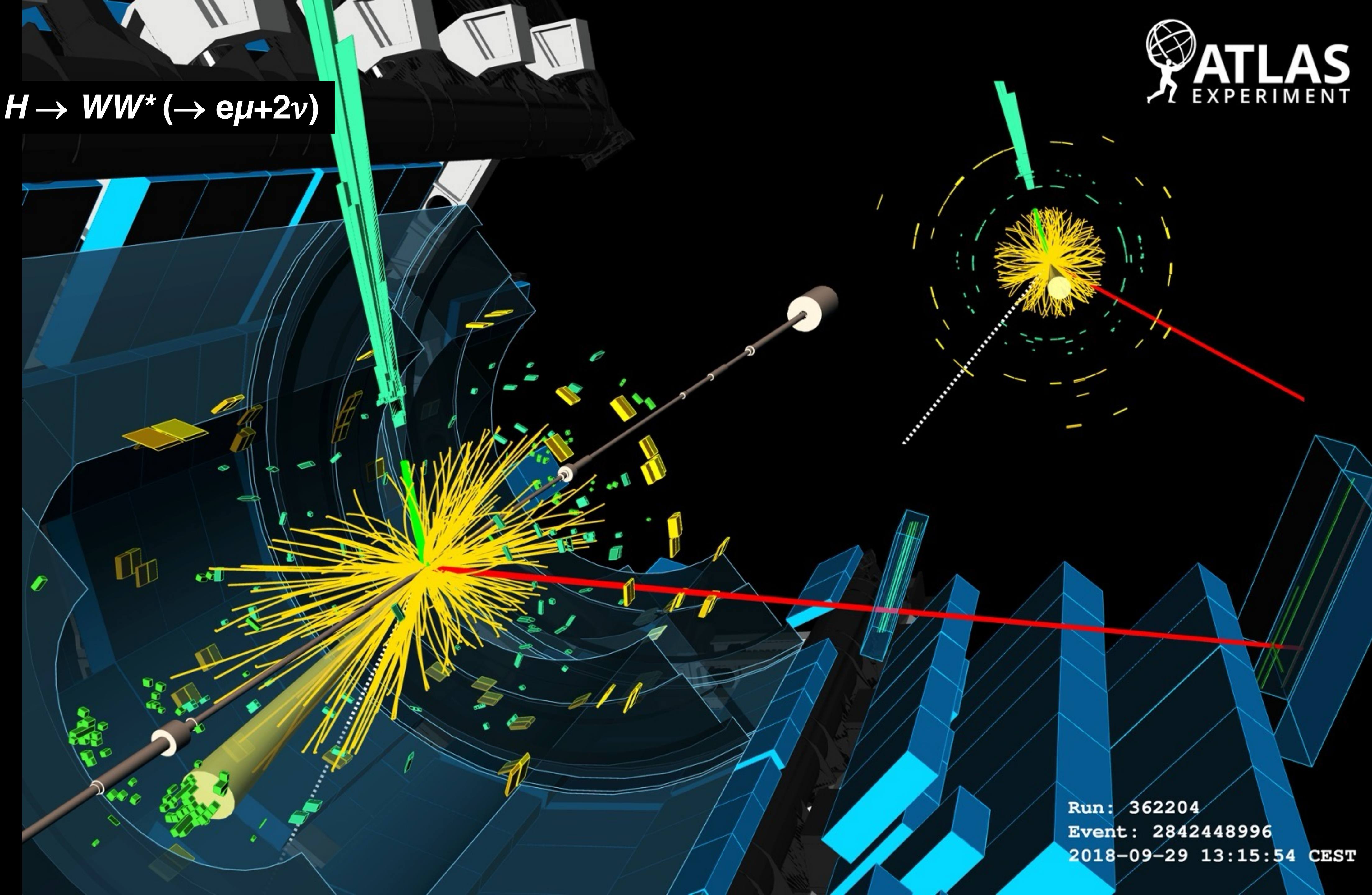
arXiv:2004.04545



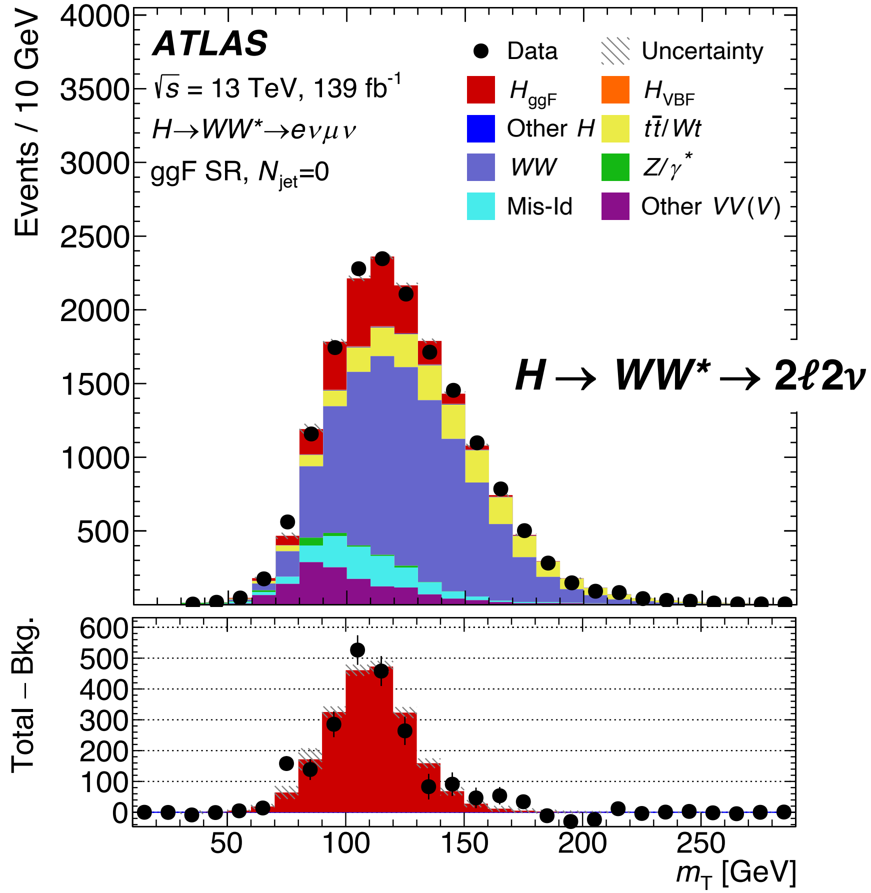




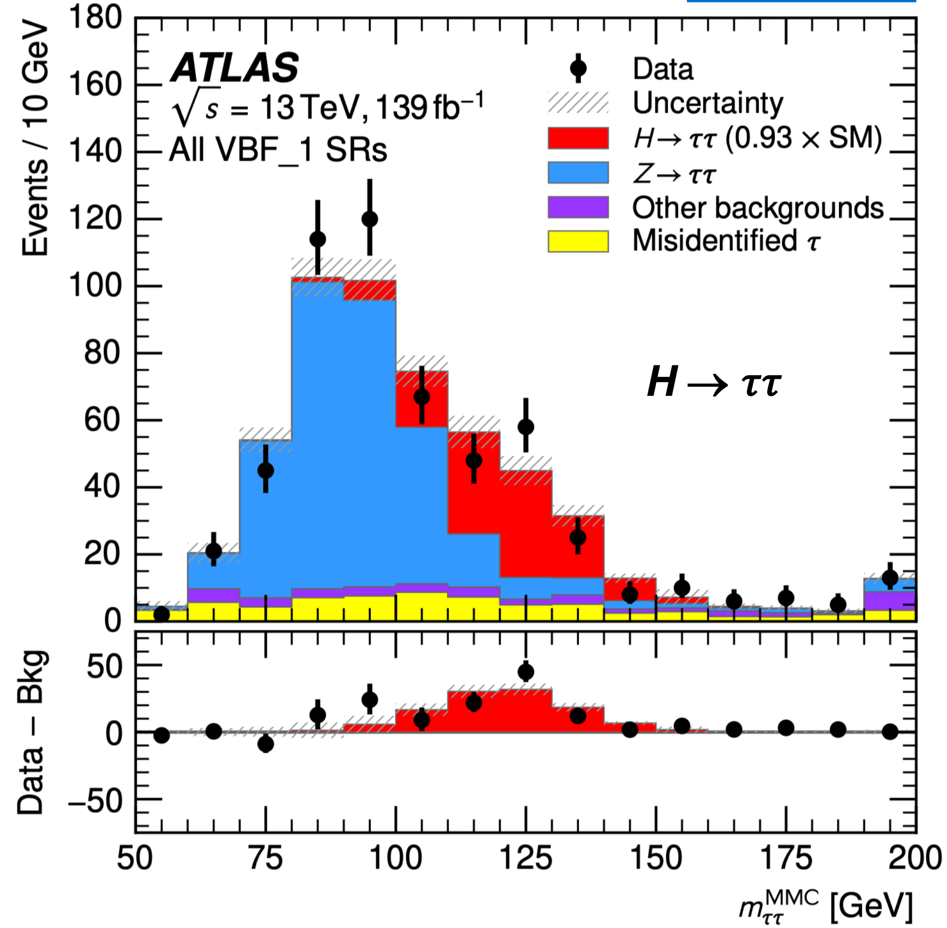
A ttH → 6 jets + $\gamma\gamma$ candidate event


$H \to WW^* (\to e\mu+2\nu)$
ATLAS
EXPERIMENT
Run: 362204
Event: 2842448996
2018-09-29 13:15:54 CEST

arXiv:2207.00338



arXiv:2201.08269



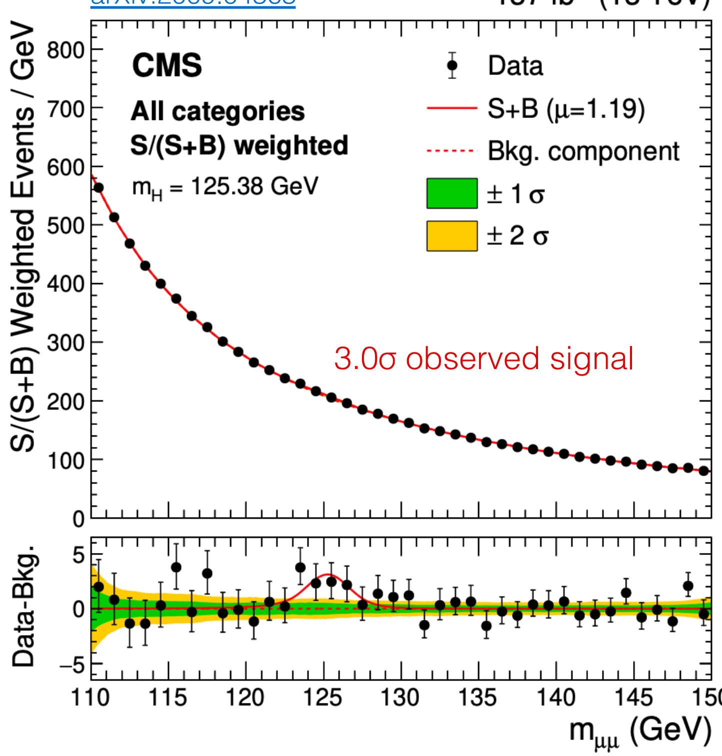
Run: 362204
Event: 2842448996
2018-09-29 13:15:54 CEST

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

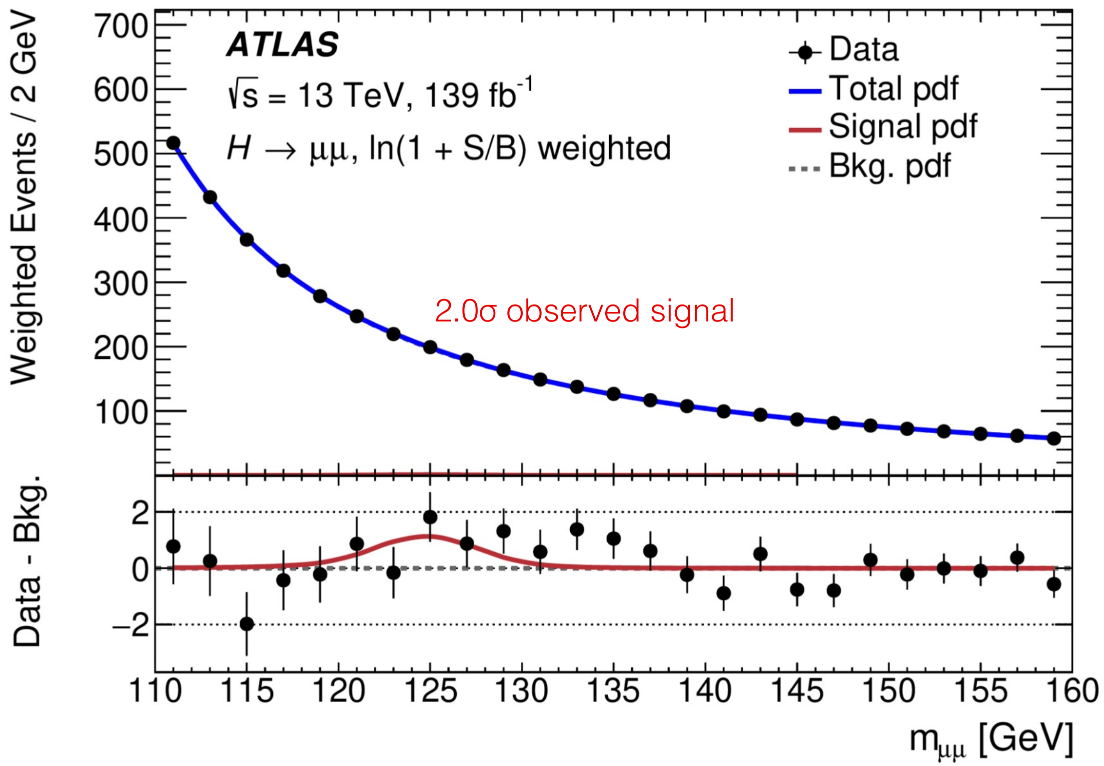
H → μμ, very challenging channel (0.02% branching fraction)

- 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

arXiv:2009.04363

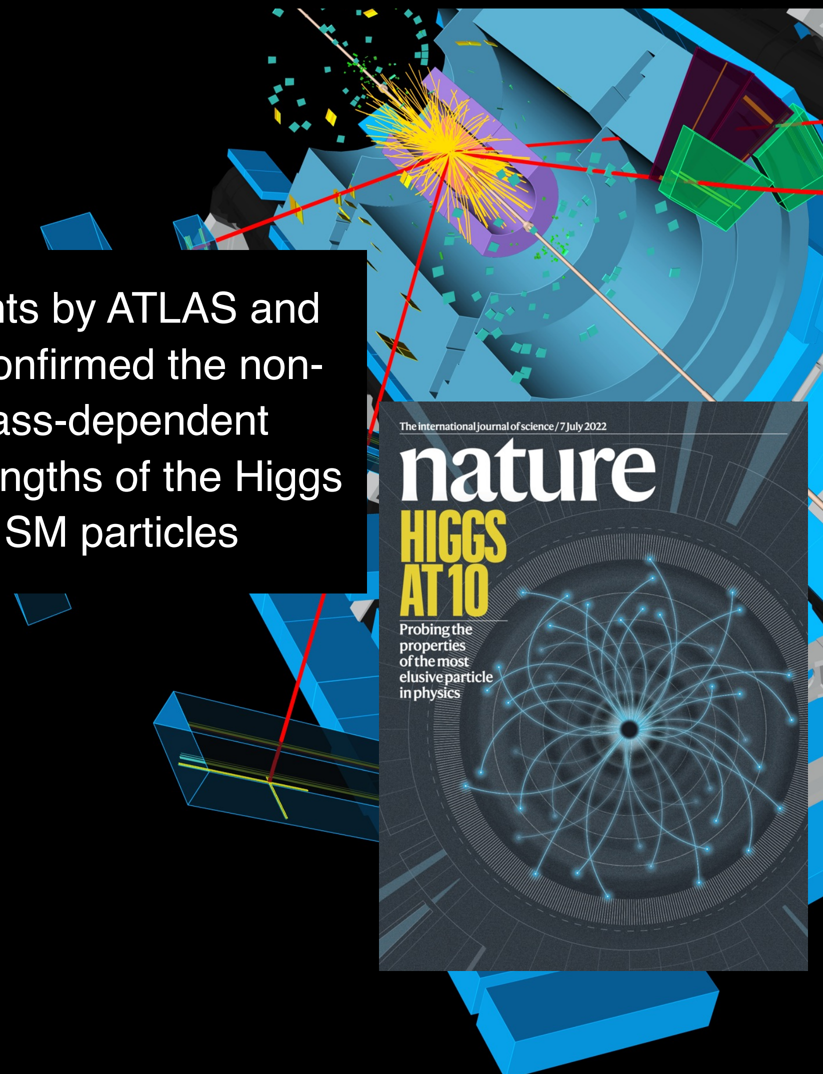


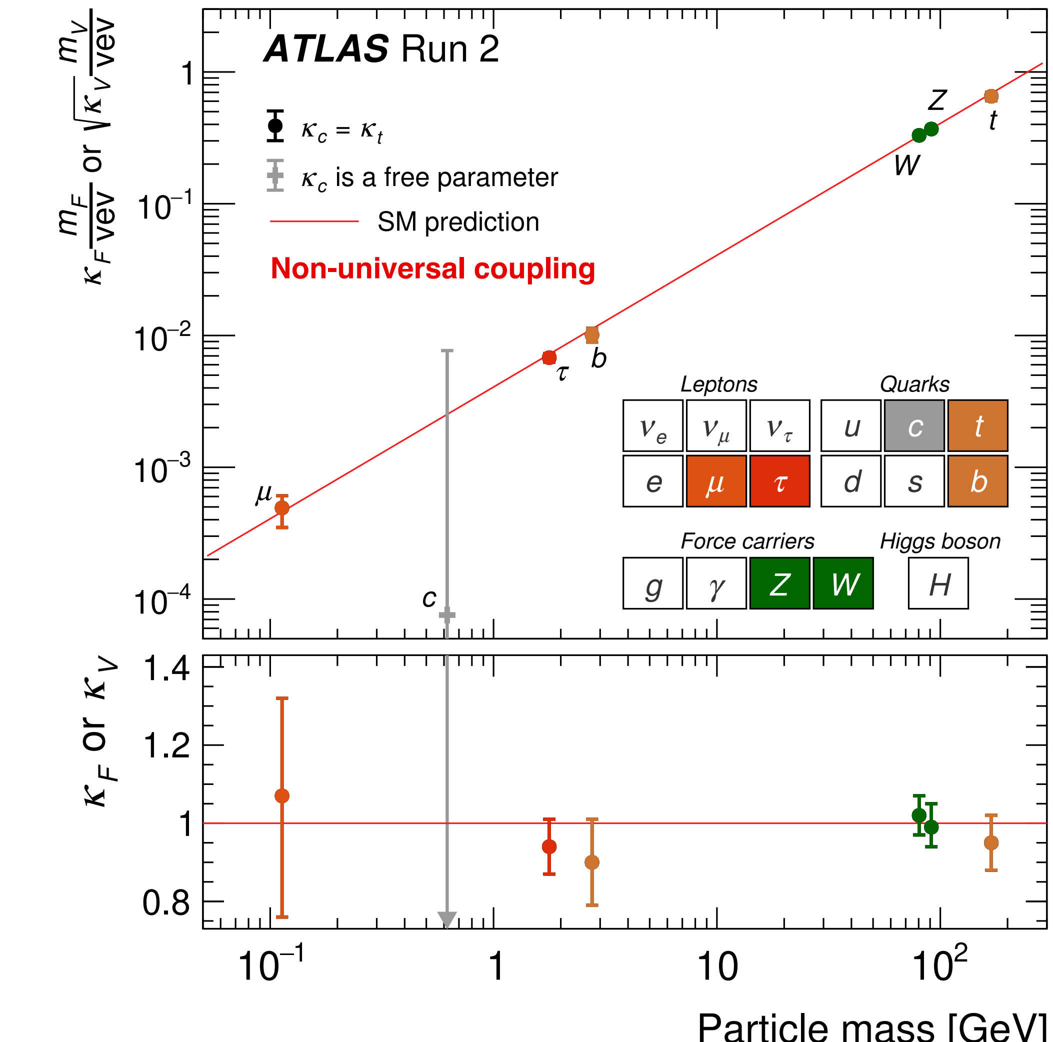
arXiv:2007.07830



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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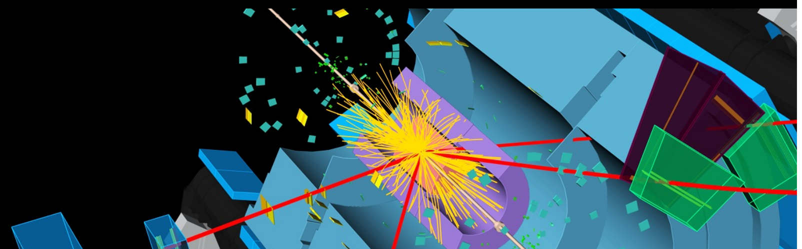
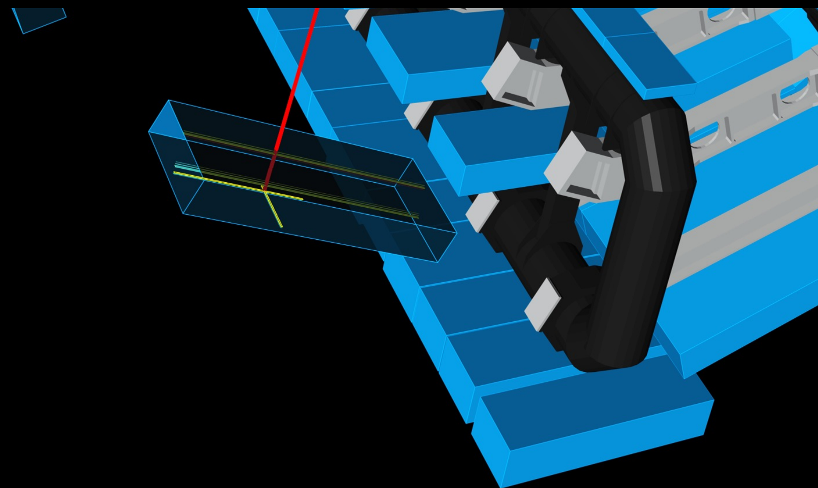


The new sector opens a variety of possibilities and questions

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

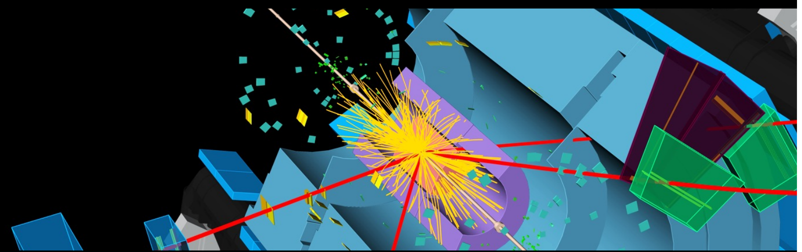


Possible relations between the Higgs boson and open questions in particle physics and cosmology

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

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

The Higgs mechanism is real !



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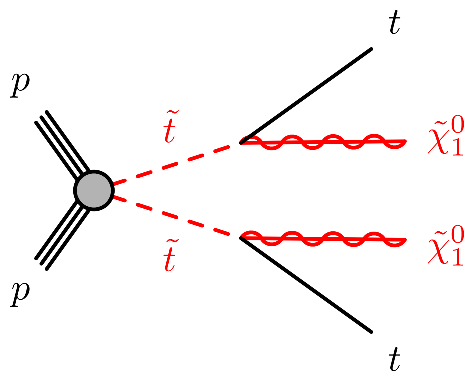
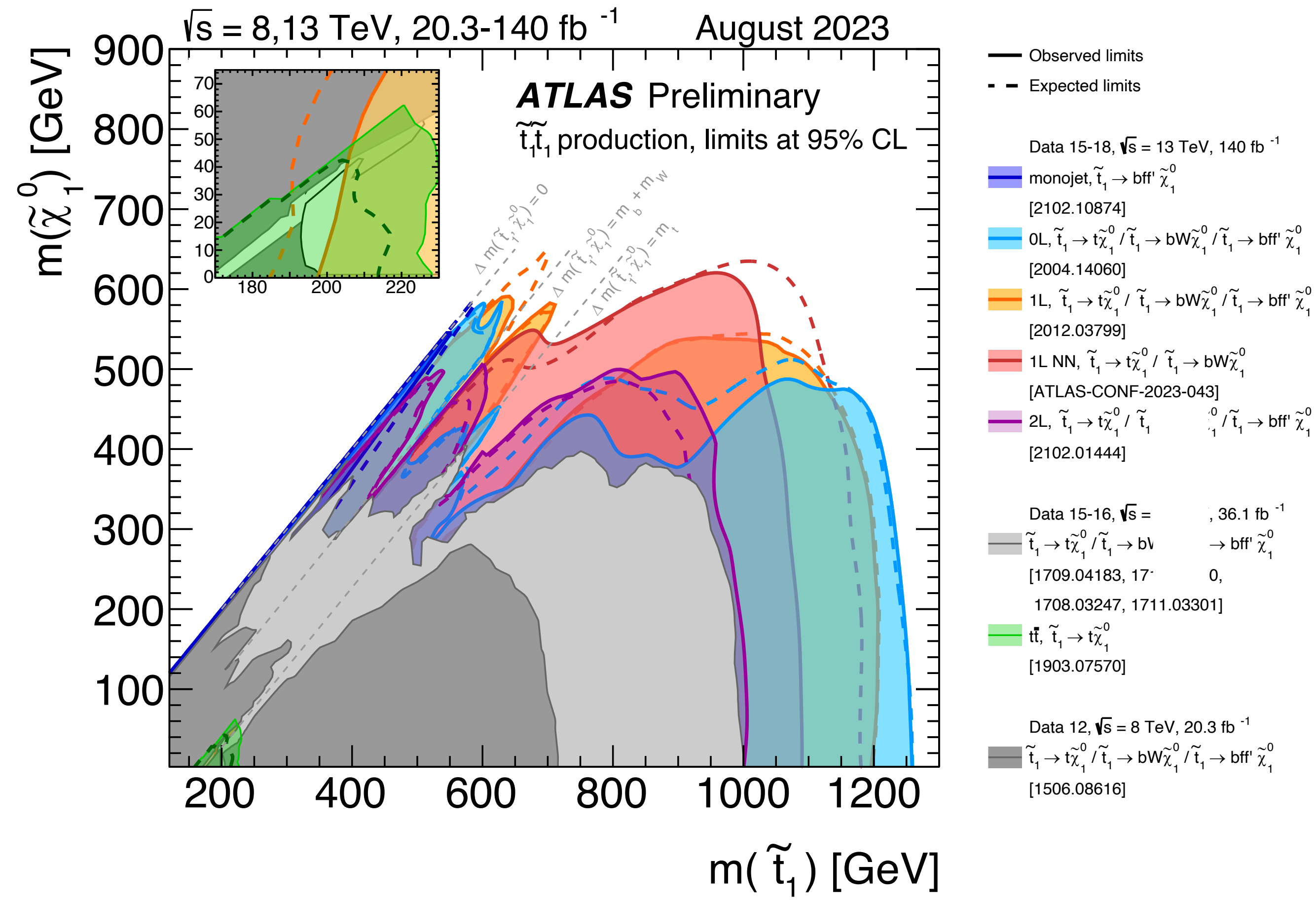
Salam, Wang, Zanderighi: Nature 607, 41 (2022)

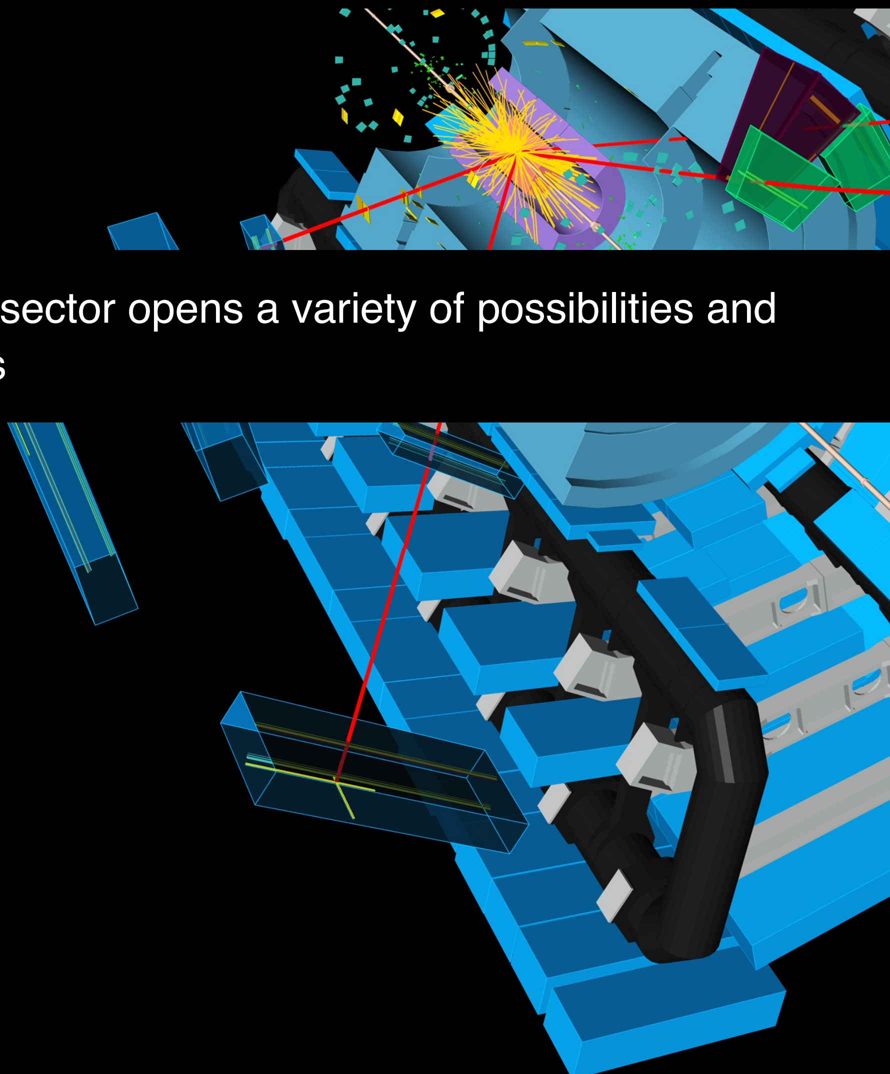
Supersymmetry?





arXiv:2403.02455

The Higgs mechanism is real !



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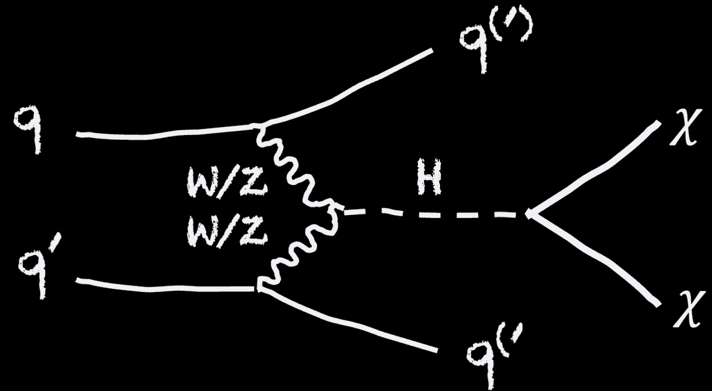
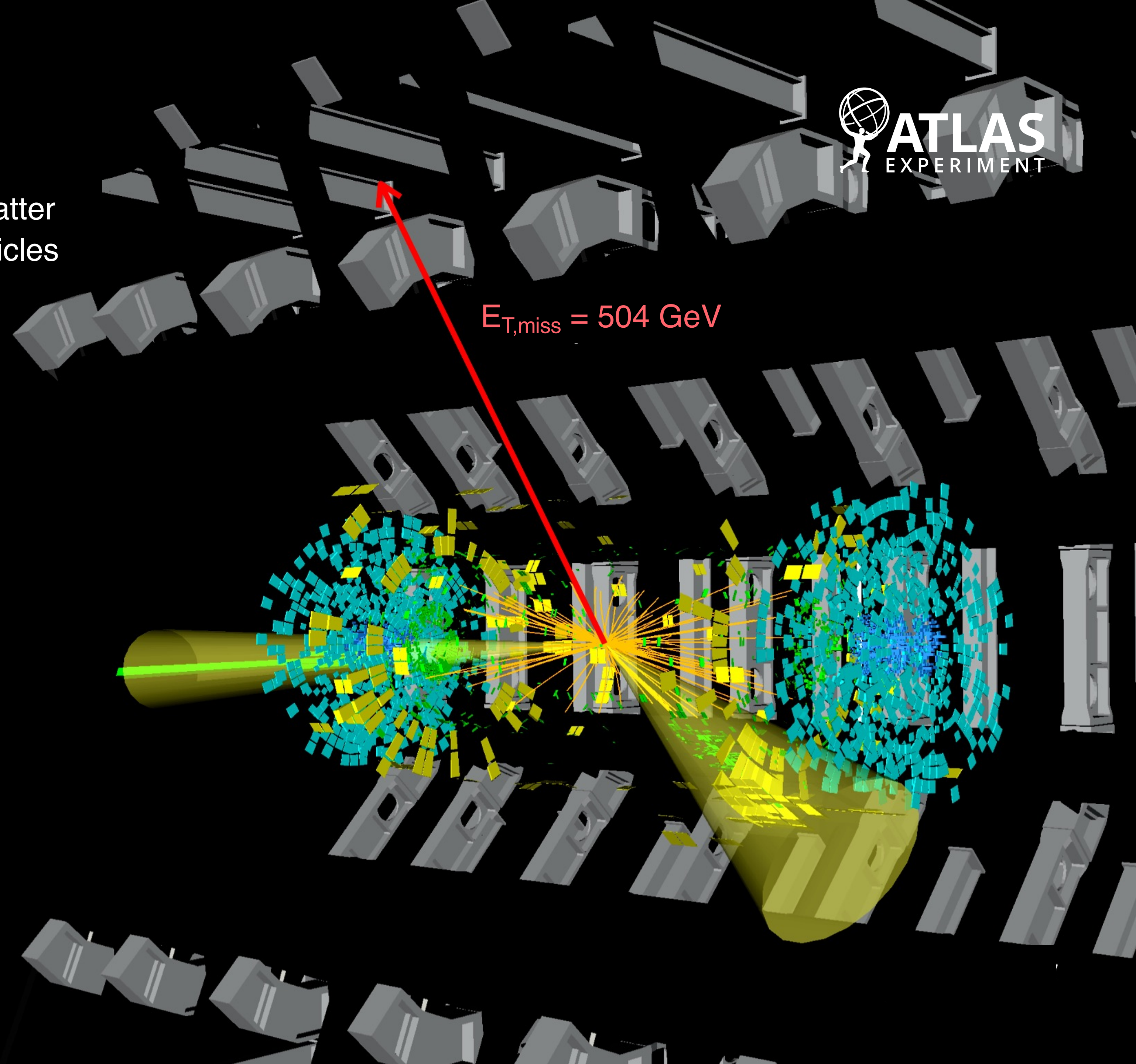
Salam, Wang, Zanderighi: Nature 607, 41 (2022)

Dark matter

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





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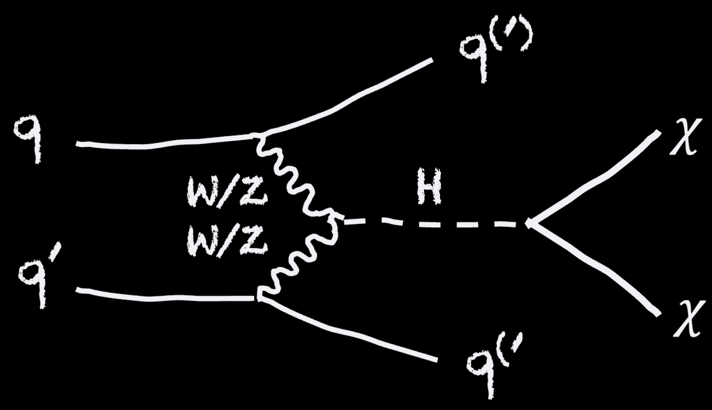
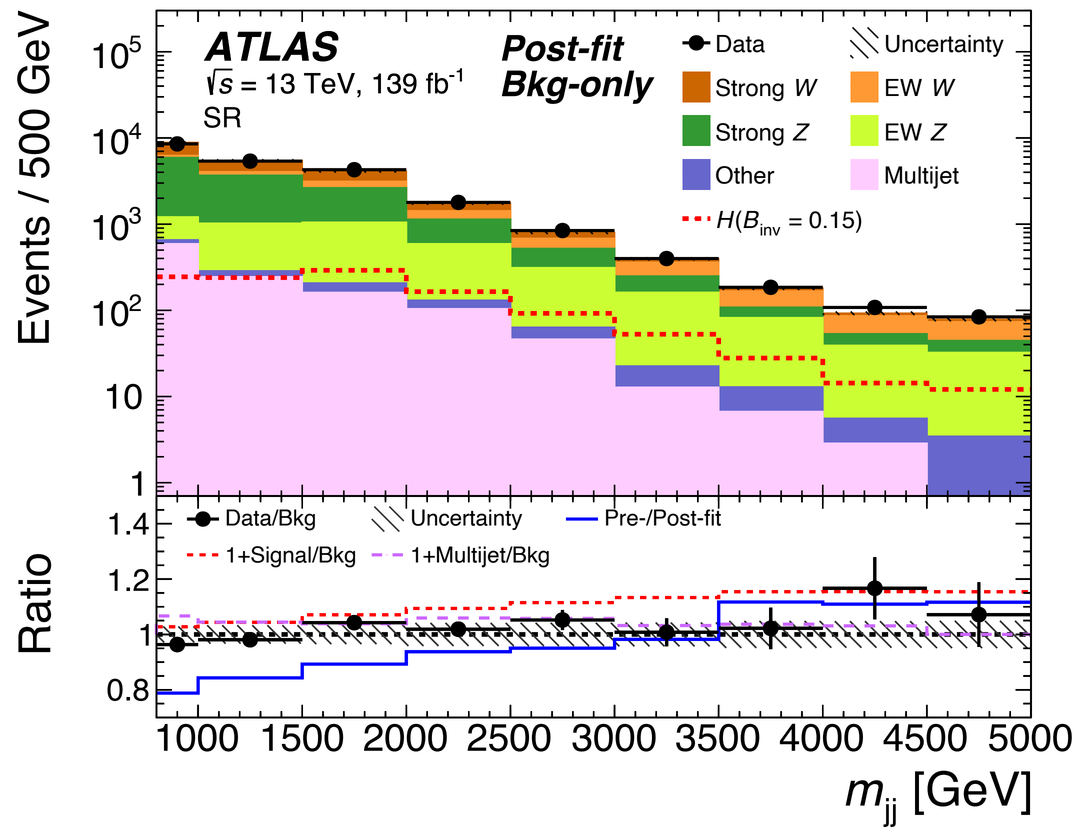
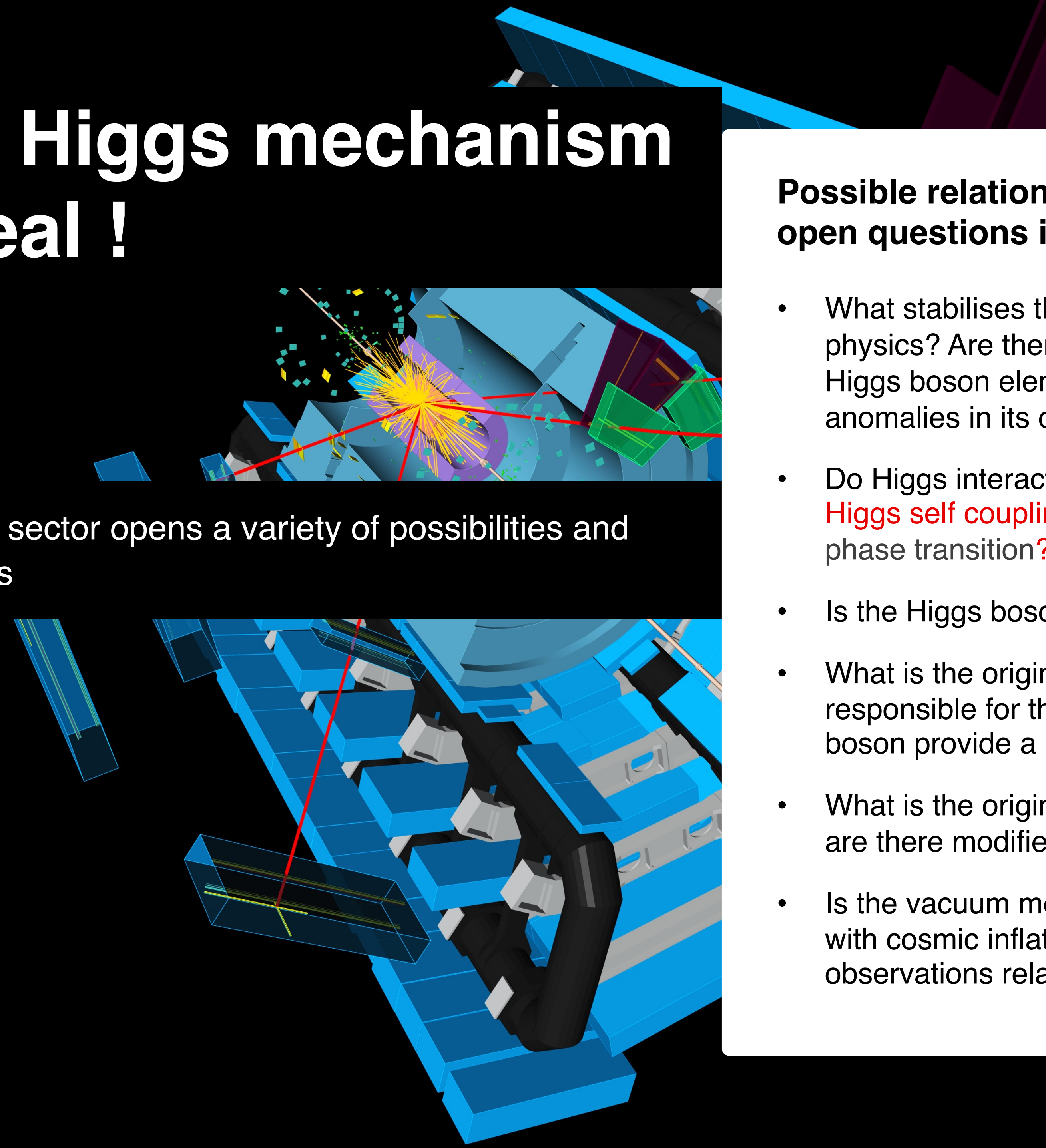


arXiv:2202.07953, arXiv:2301.10731



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

The Higgs mechanism is real !



The new sector opens a variety of possibilities and questions

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

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

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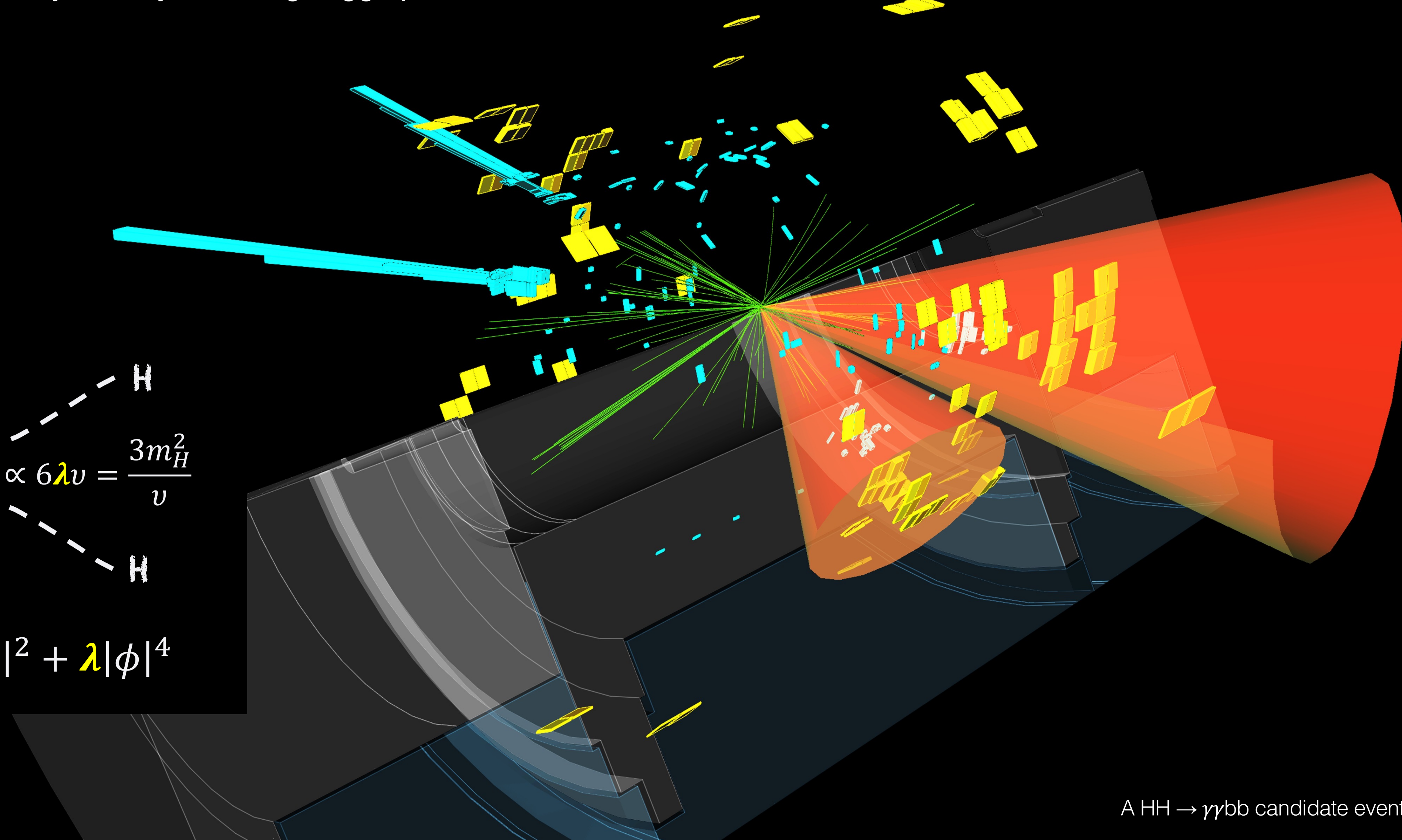
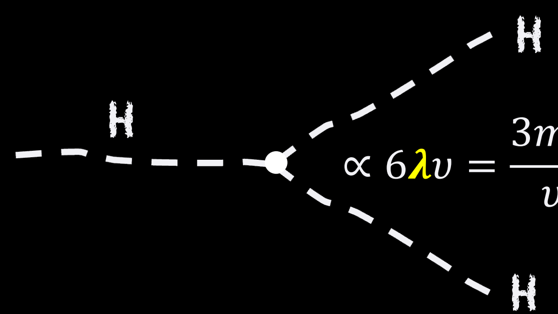
Salam, Wang, Zanderighi: Nature 607, 41 (2022)

Higgs pair production

Direct access to the symmetry breaking Higgs potential





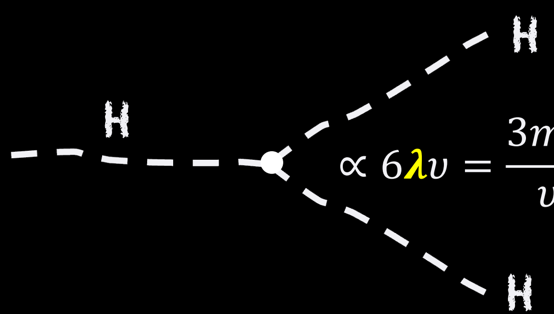
$$\propto 6\lambda v = \frac{3m_H^2}{v}$$

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

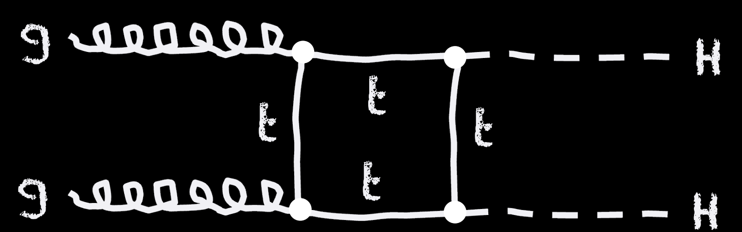
A HH → $\gamma\gamma$bb candidate event

Higgs pair production

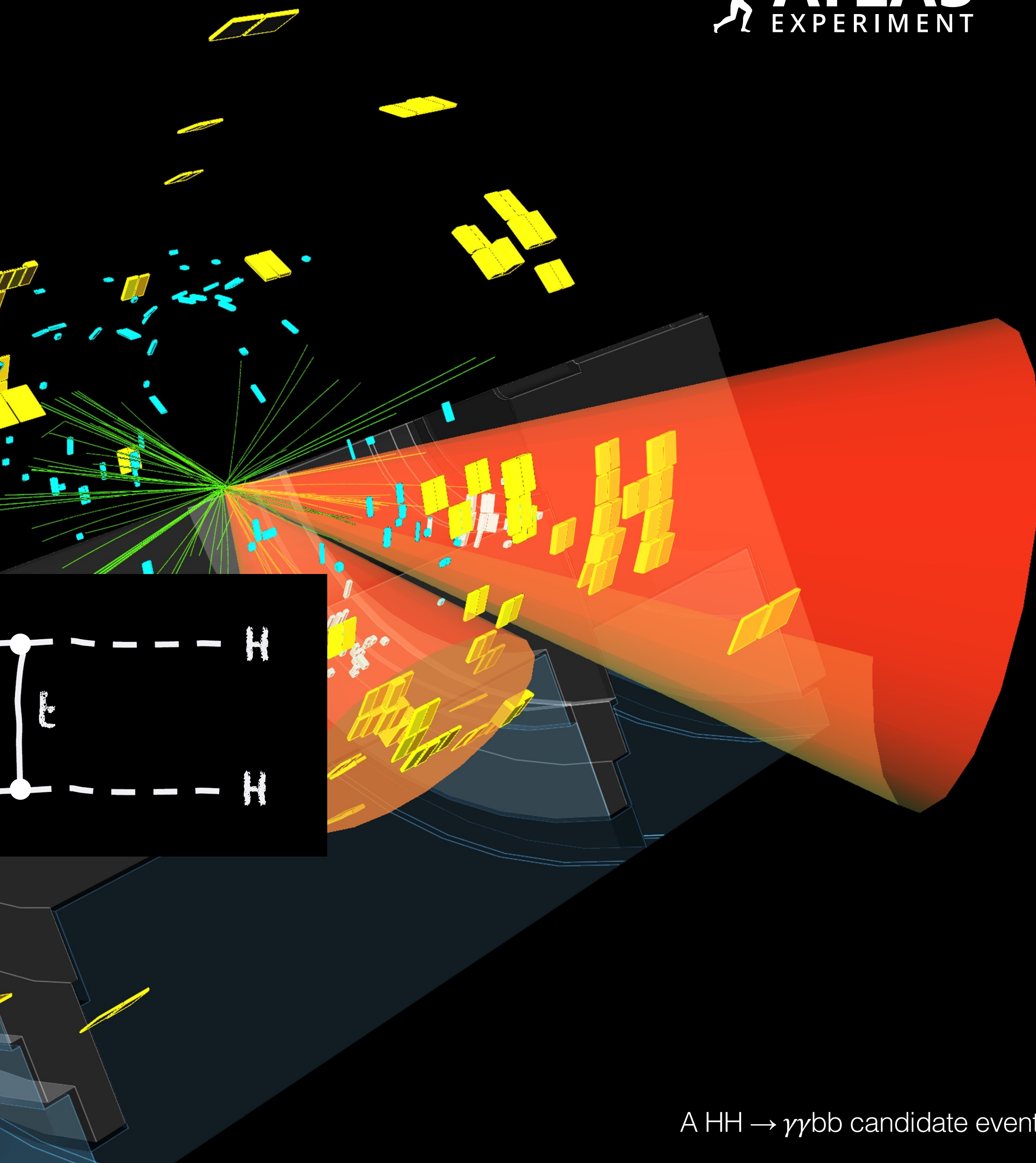
Direct access to the symmetry breaking Higgs potential



$\propto 6\lambda v = \frac{3m_H^2}{v}$



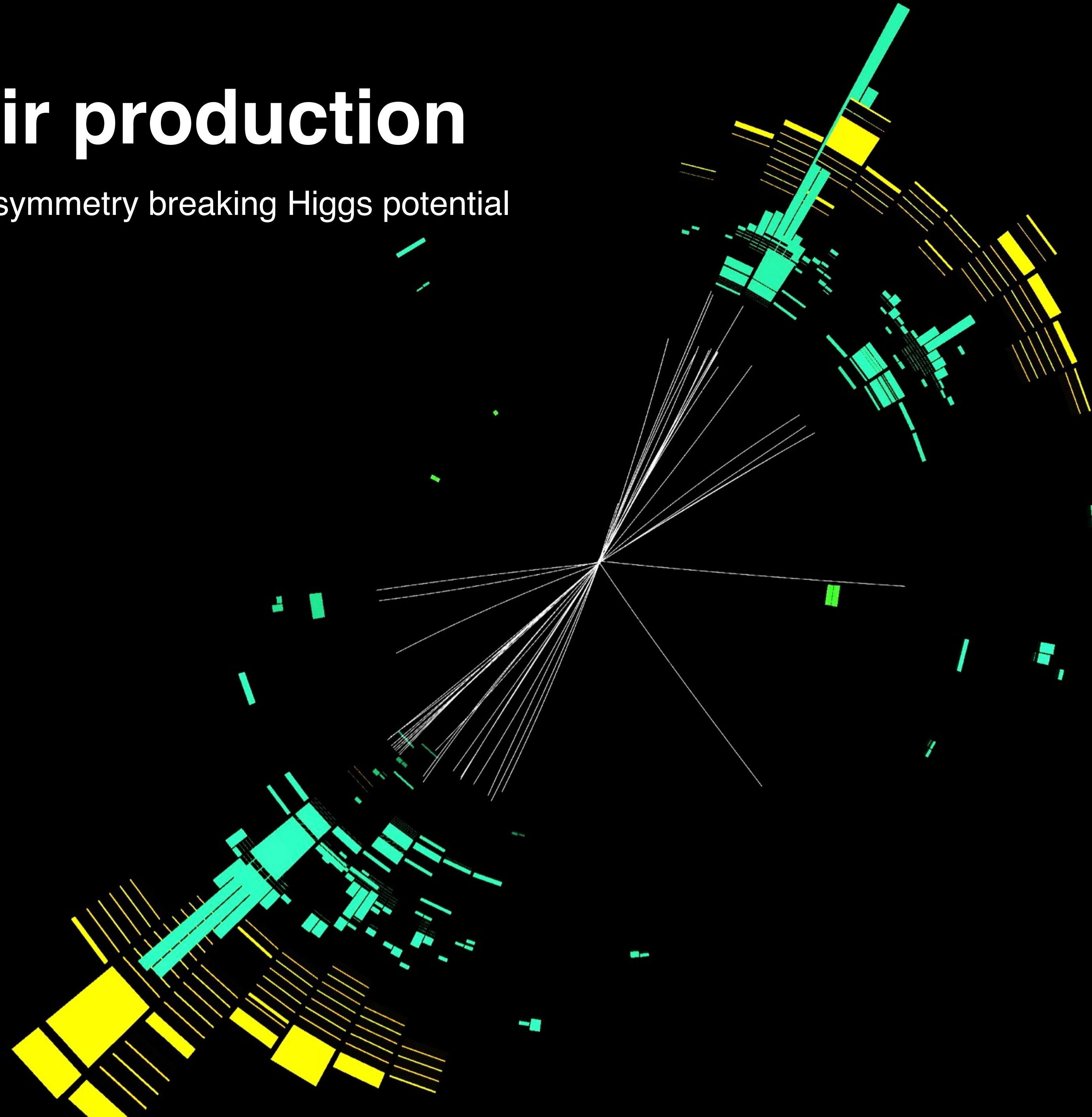
$$V(\phi) = -\mu^2|\phi|^2 + \lambda|\phi|^4$$



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

Higgs pair production

Direct access to the symmetry breaking Higgs potential

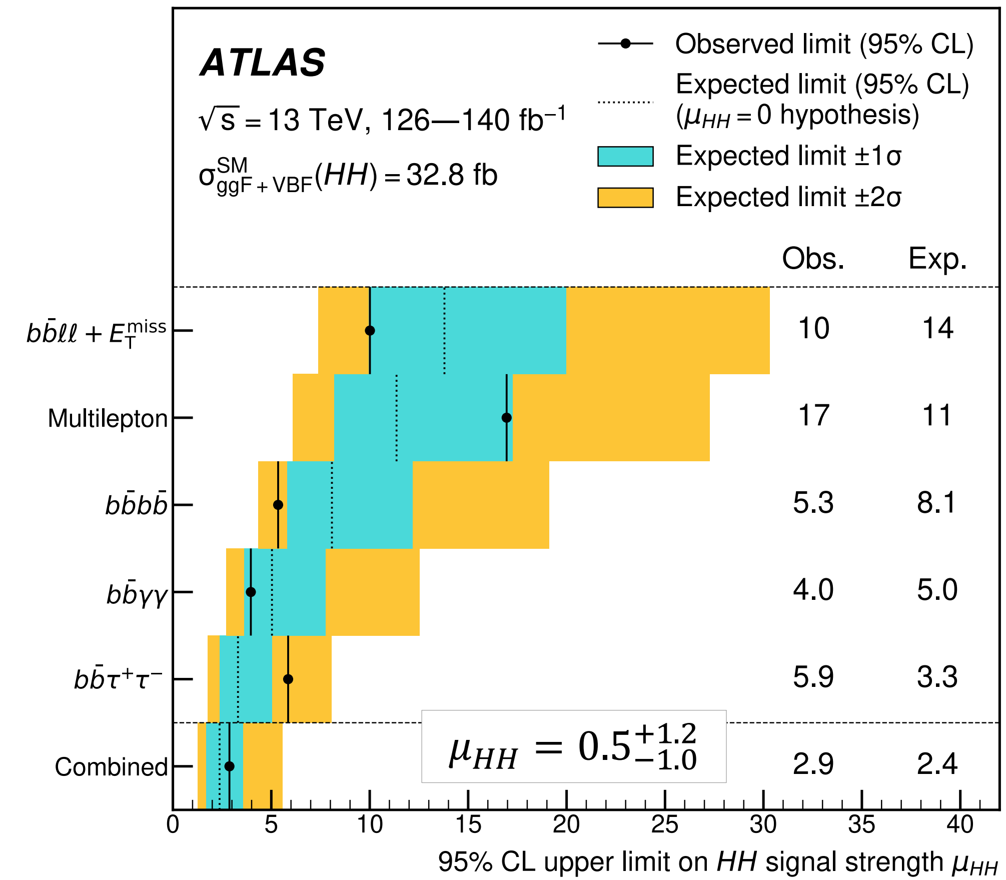


A HH → bbbb candidate event

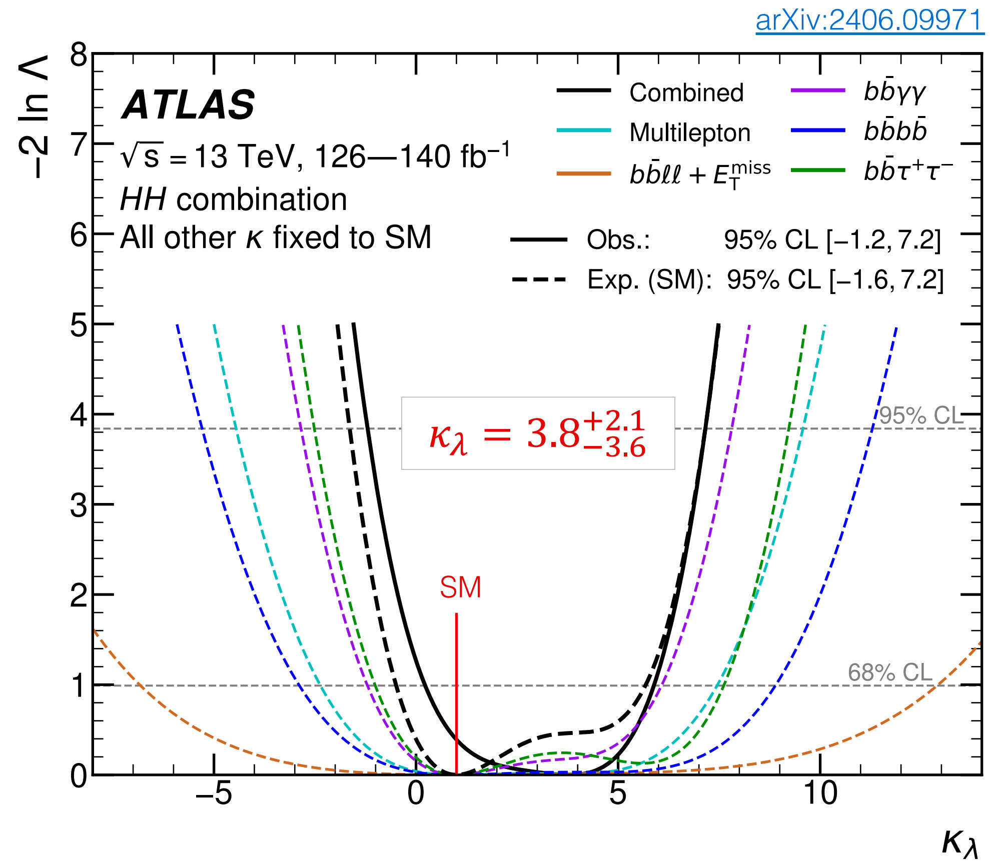
Higgs pair production

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

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



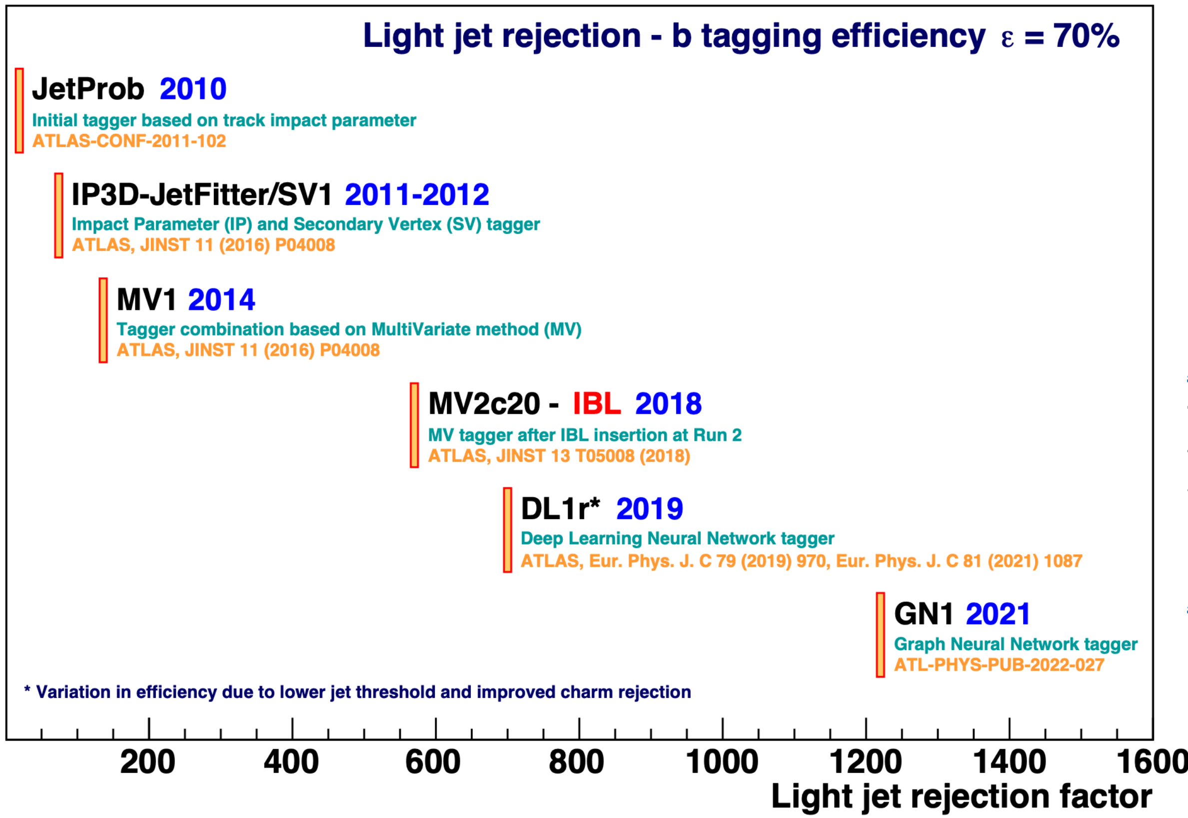
Constraint on $\kappa_\lambda = \lambda/\lambda_{SM}$, $\lambda_{SM}\sim0.13$ also benefits from single-Higgs coupling measurements via quantum loop



Improving performance

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

Marumi Kado

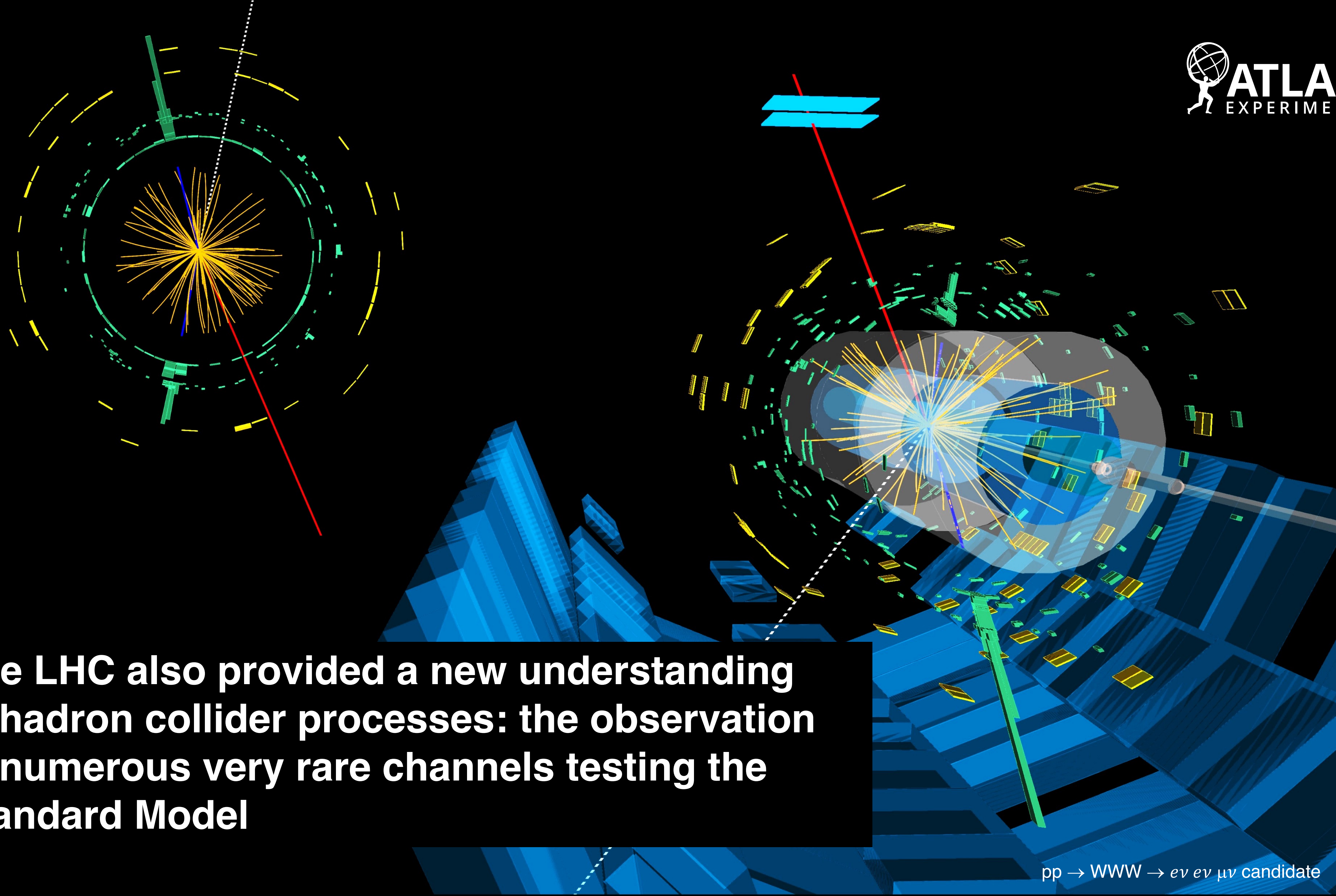


ATL-PHYS-PUB-2022-027 (2022)

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

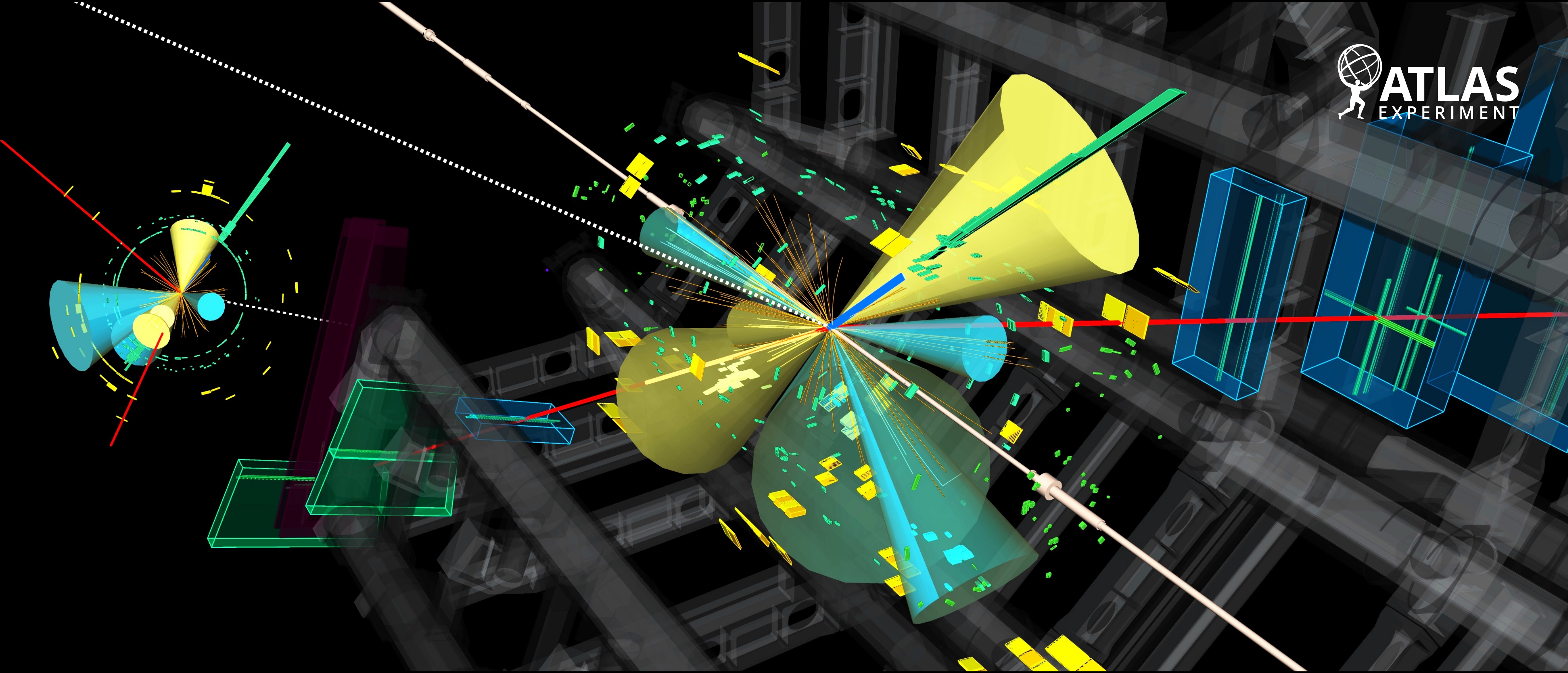
ATL-PHYS-PUB-2022-040 (2022)

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

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



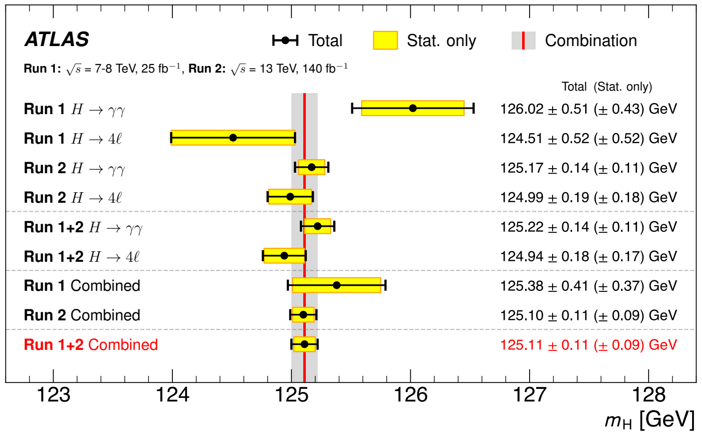
The LHC also provided a new understanding of hadron collider processes: the observation of numerous very rare channels testing the Standard Model

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

High-precision physics at the LHC

ATLAS EXPERIMENT

Most precise Higgs mass to date



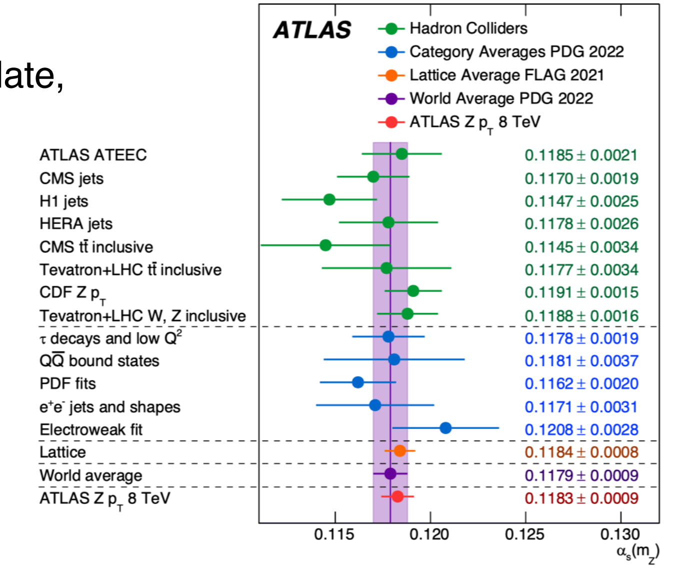
arXiv:2308.07216, arXiv:2308.04775, arXiv:2309.05471, CERN press update, Physics briefing

$\sigma(m_H)$ = 110 MeV (0.09%)

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

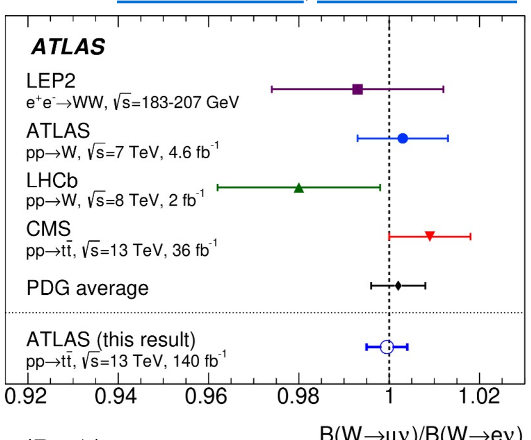
$\sigma(\alpha_s(mZ))$ = 0.0009

arXiv:2309.12986, CERN press update, Briefing



Precise test of lepton universality in W decays

arXiv:2403.02133, CERN news article

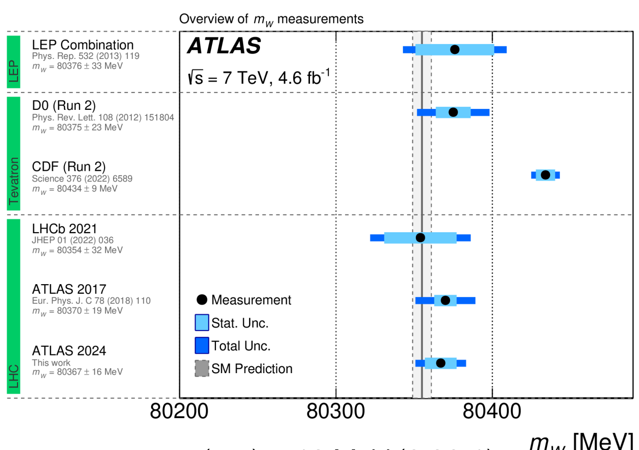


$\sigma(R_W^{\mu/e})$ = 0.45%

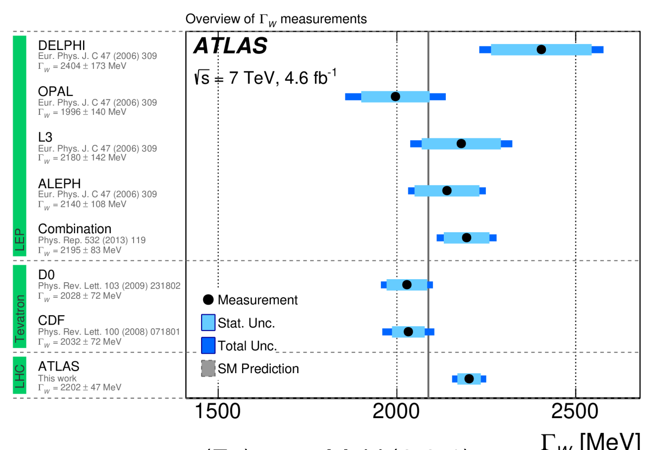
Precise measurements of W p_T, mass & width, as well as top mass (Run-1 combination with CMS)

arXiv:2403.15085, CERN news article, ATLAS briefing

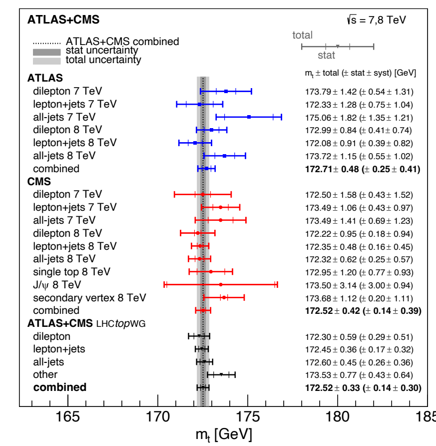
arXiv:2402.08713, Physics briefing



$\sigma(m_W)$ = 16 MeV (0.02%)



$\sigma(\Gamma_W)$ = 47 MeV (2.2%)



$\sigma(m_t)$ = 330 MeV (0.2%)

The next steps

Preparing the future — the grand plan of the LHC

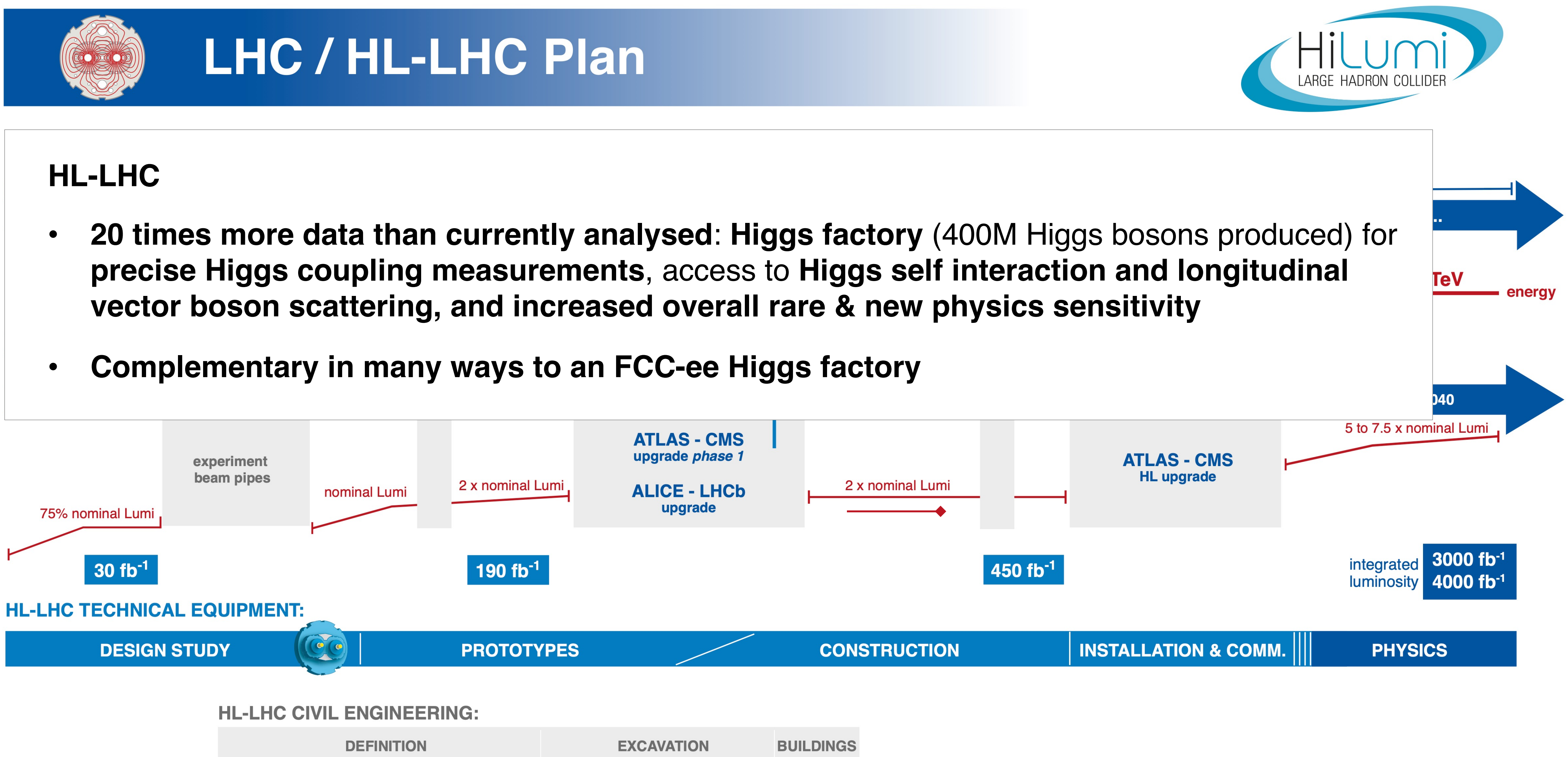
Preparing the future — the grand plan of the LHC

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

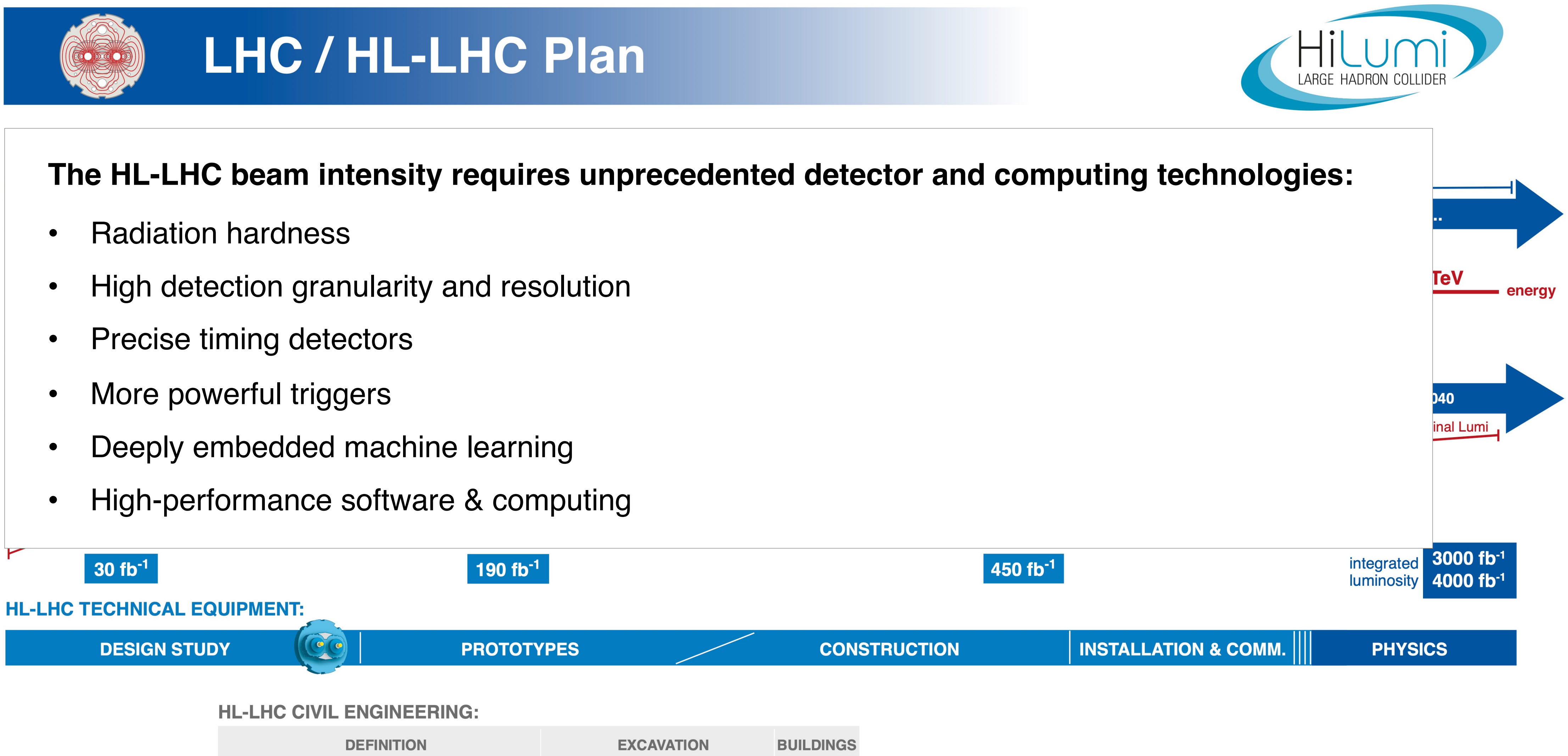
Preparing the future



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**

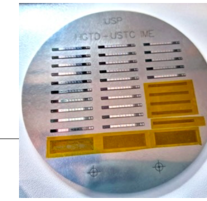
Preparing the future



The HL-LHC beam intensity 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

Detector upgrades for the HL-LHC



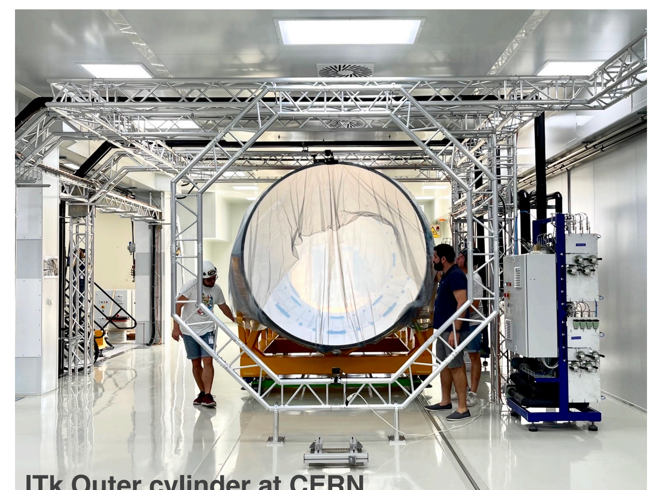
SR1 ITk surface assembly cleanroom at CERN

HGTD sensor test facility at USP

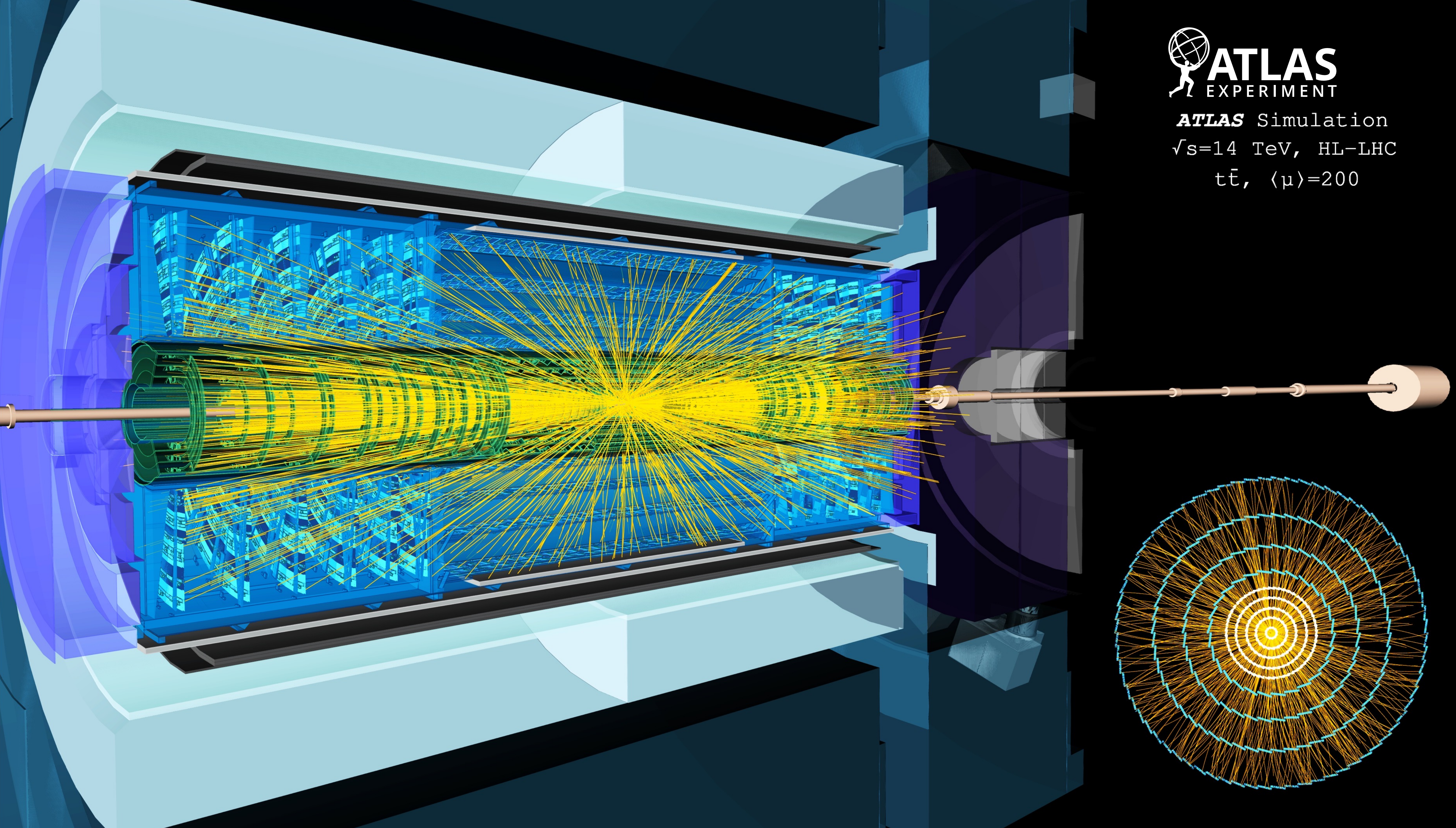
HGTD PEB prototypes

Cleanroom at Santa Cruz UC

ITk Strip endcap petal



ITk Outer cylinder at CERN



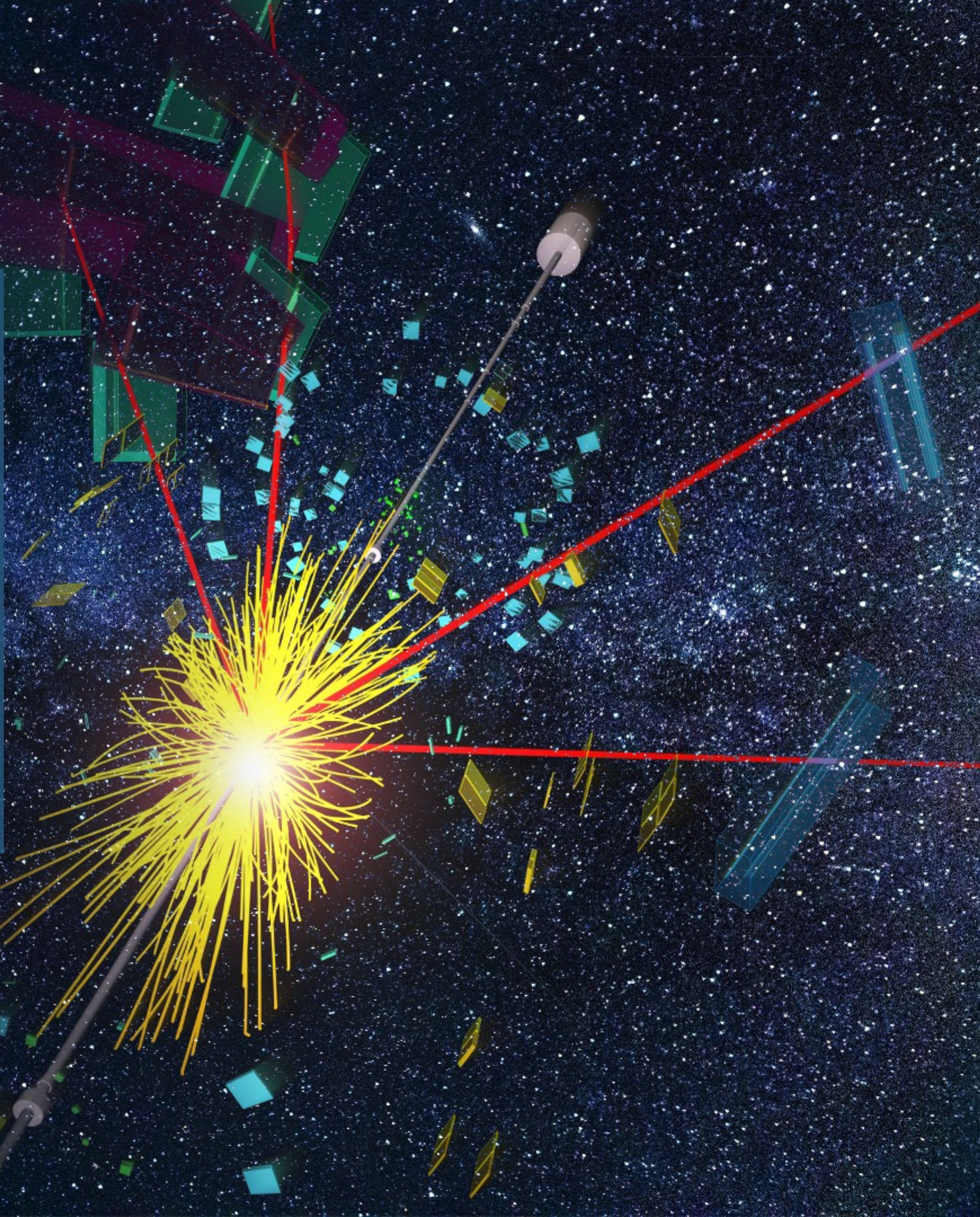
ATLAS new silicon inner tracker (simulation)

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, and much more is to come

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



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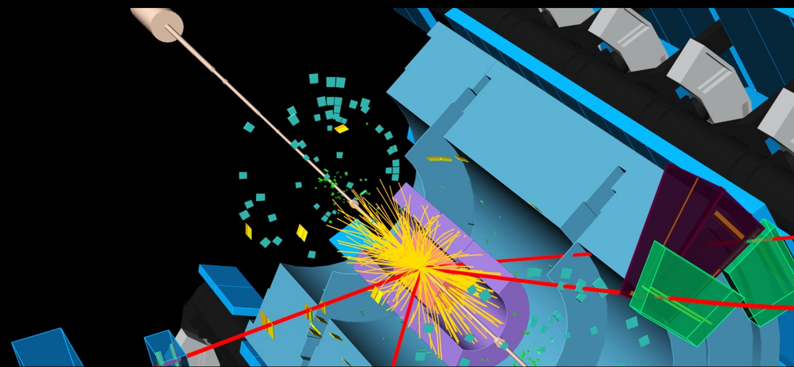
The LHC's voyage of discovery continues at pace!

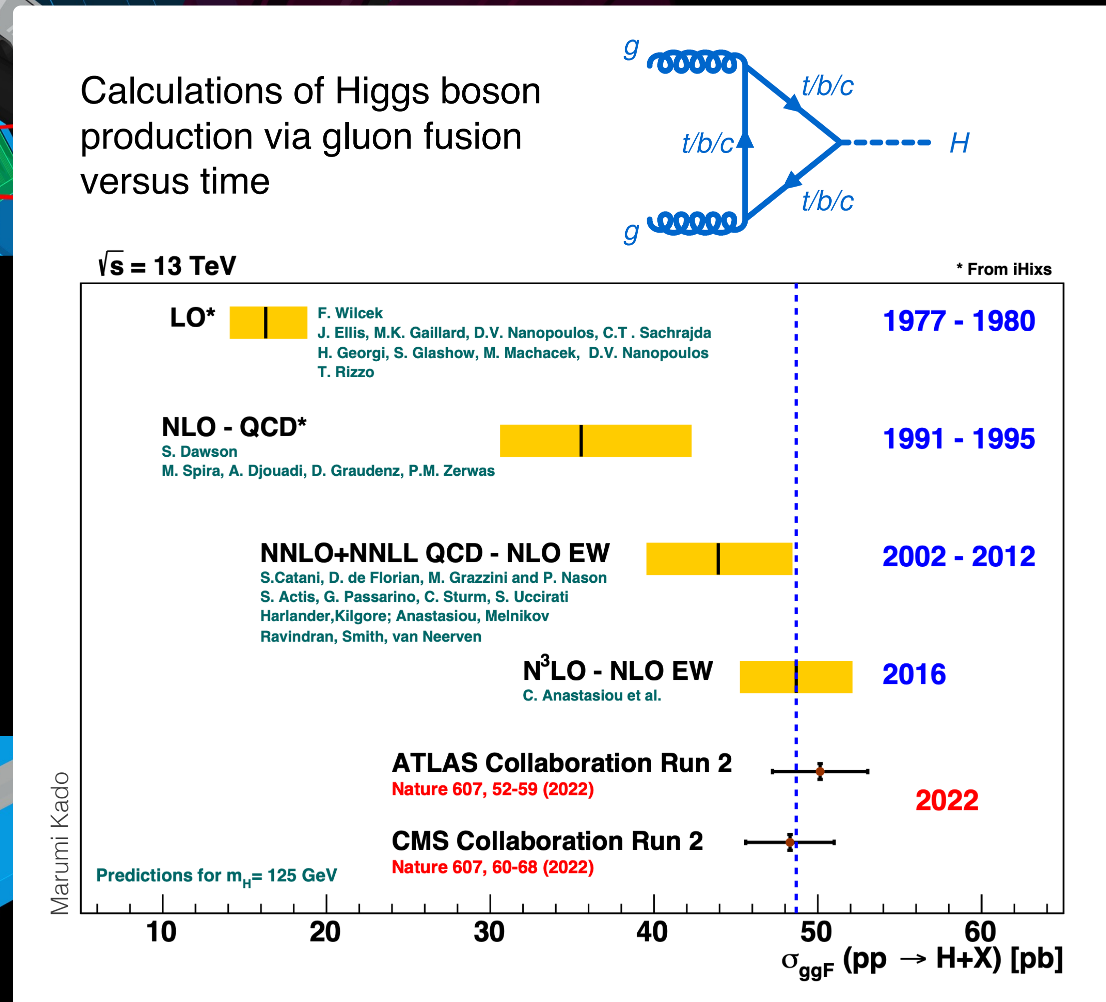
Extra slides

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…)

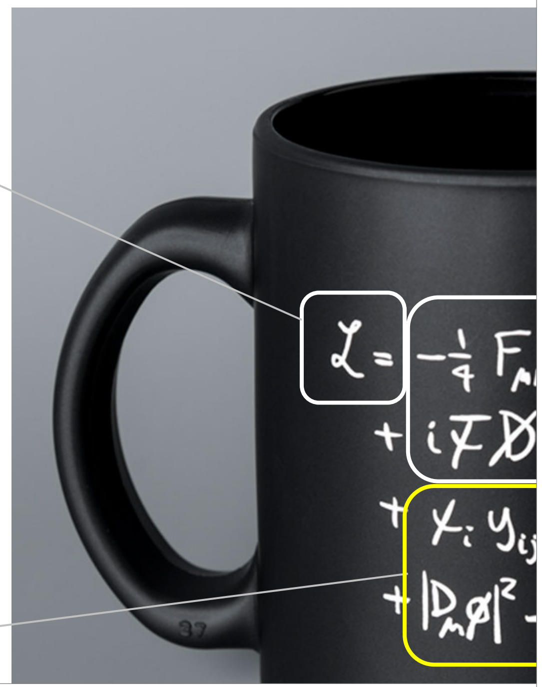
The interpretability of our results relies on our ability to compute accurate and precise predictions



Completing the Standard Model

The scalar Higgs sector completes the Standard M

The **SM Lagrangian**



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

Latest predictions of the muon g–2 and experiment:

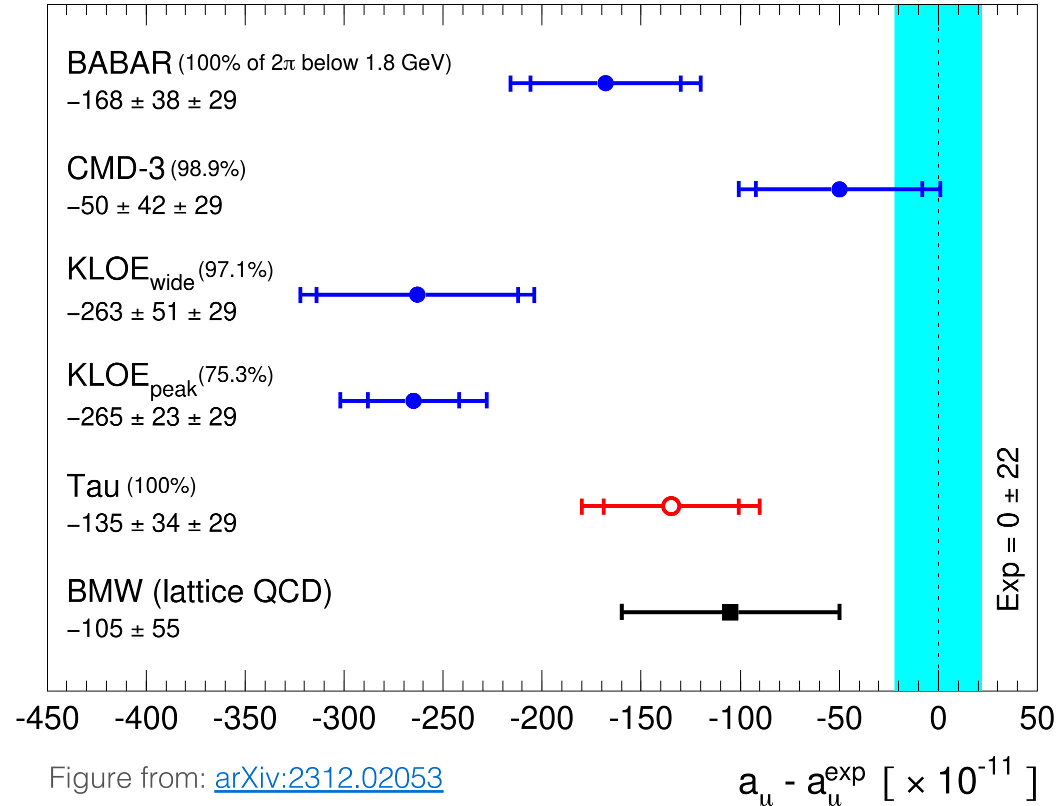


Figure from: [arXiv:2312.02053](https://arxiv.org/abs/2312.02053)

Combining BABAR, CMD-3, Tau: 2.5σ with exp.

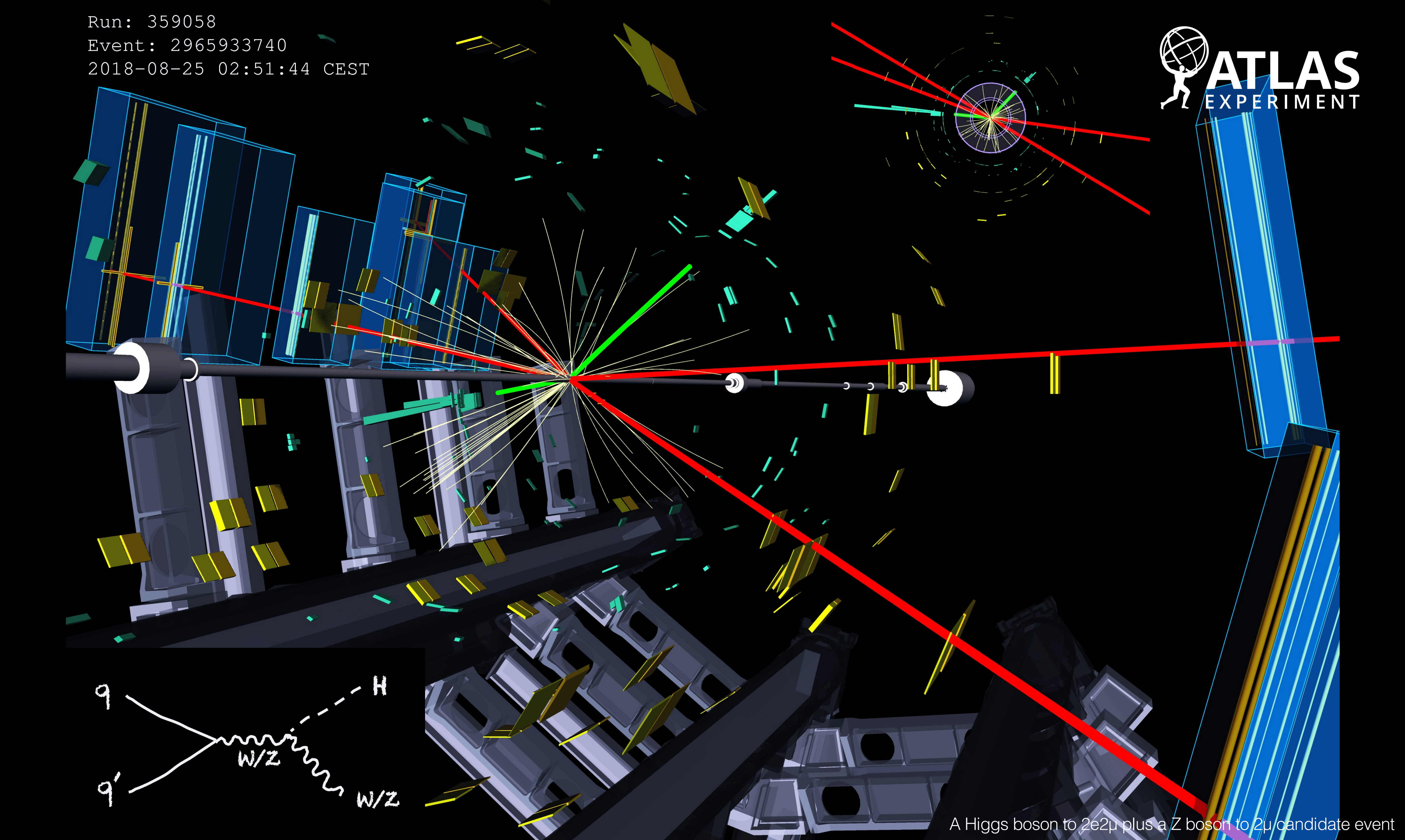
Unpleasan
symmetries, 2
large hierarc

describes the
) **with non-zero**

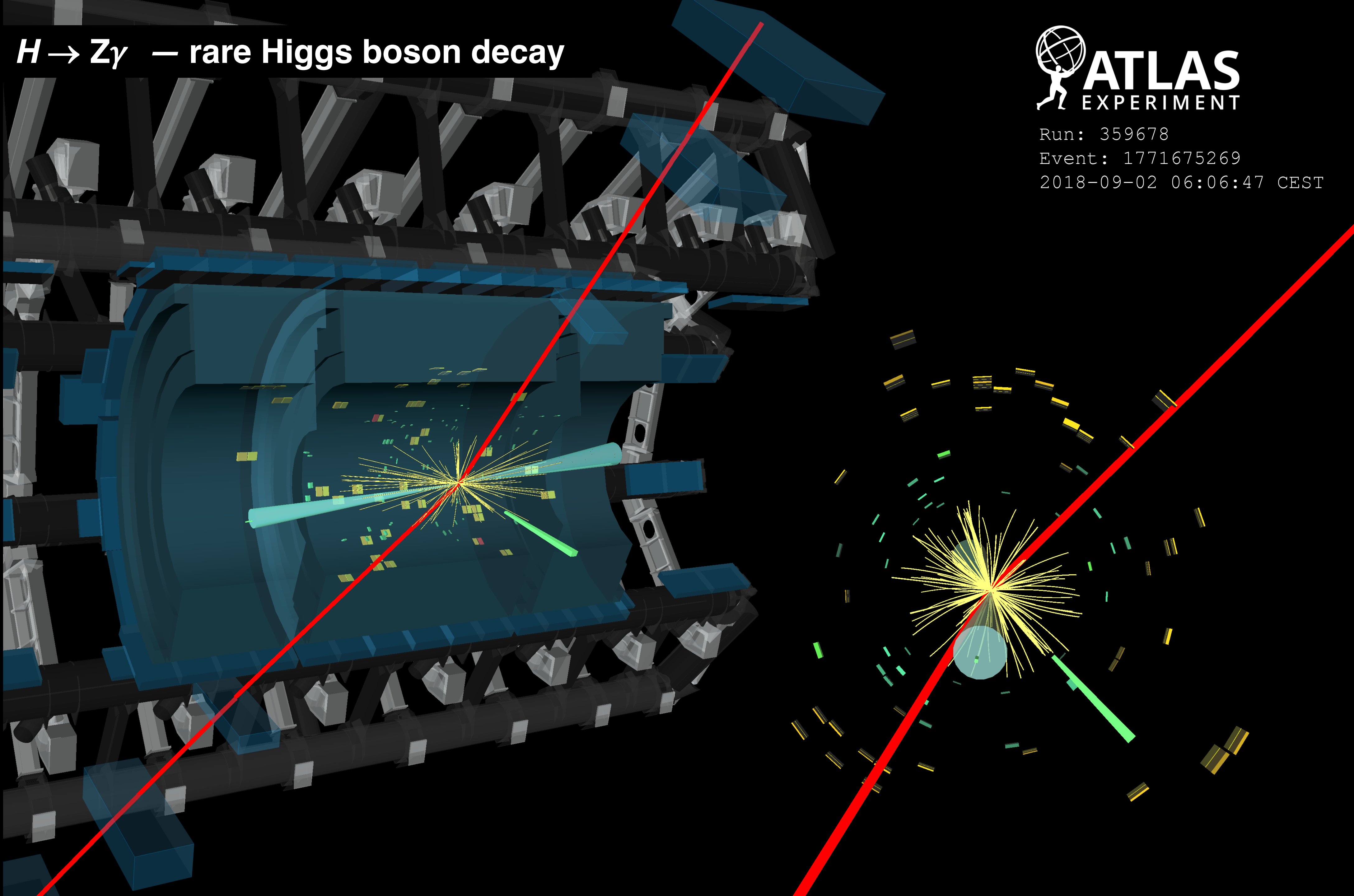
The Standard Model is a highly predictive theory

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} !


Run: 359058
Event: 2965933740
2018-08-25 02:51:44 CEST
ATLAS
EXPERIMENT
q
q'
W/Z
H
W/Z
A Higgs boson to 2e2μ plus a Z boson to 2μ candidate event

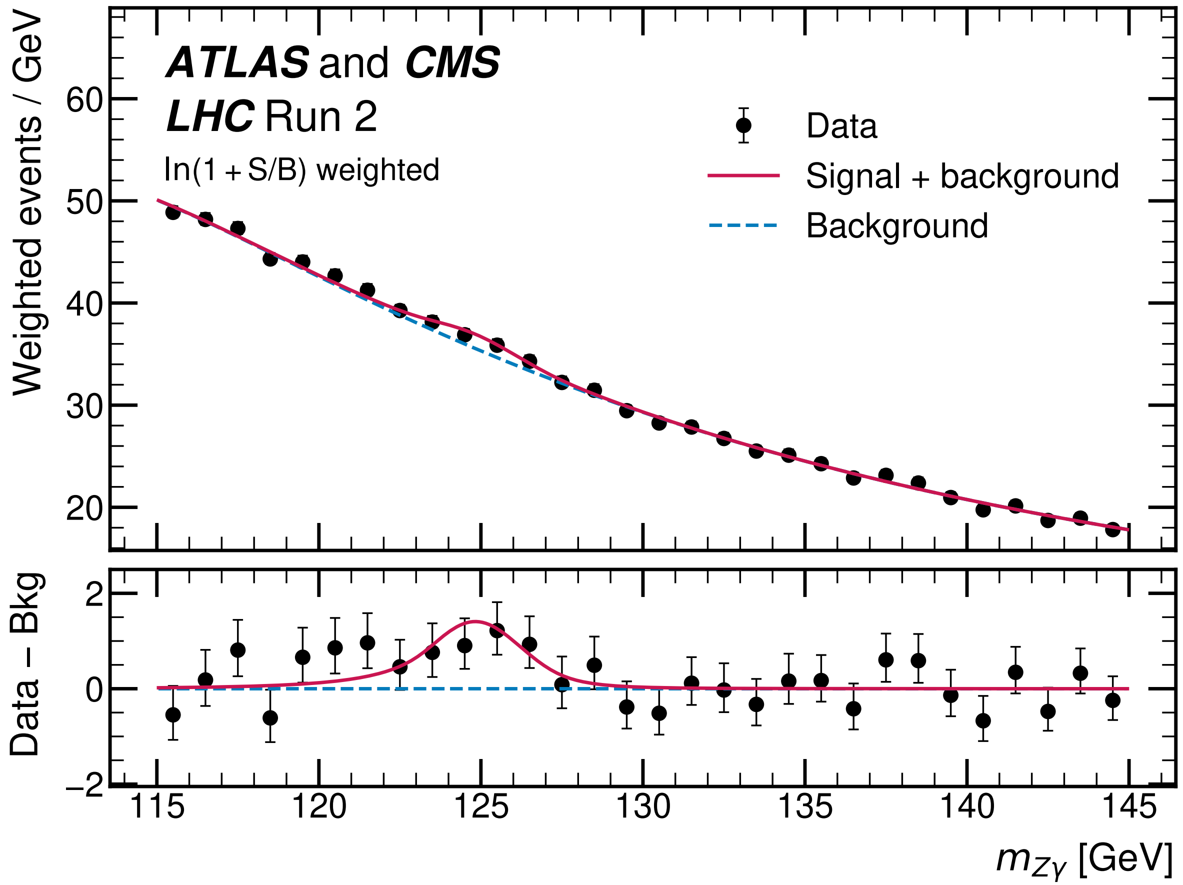
$H \rightarrow Z\gamma$ — rare Higgs boson decay

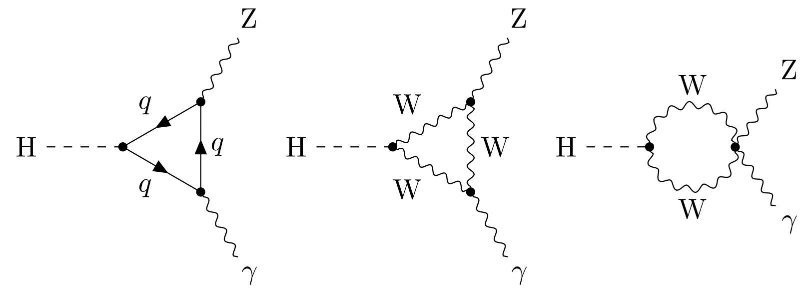


$H \to Z\gamma$ — rare Higgs boson decay

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

arXiv:2309.03501, CERN press update, Physics briefing



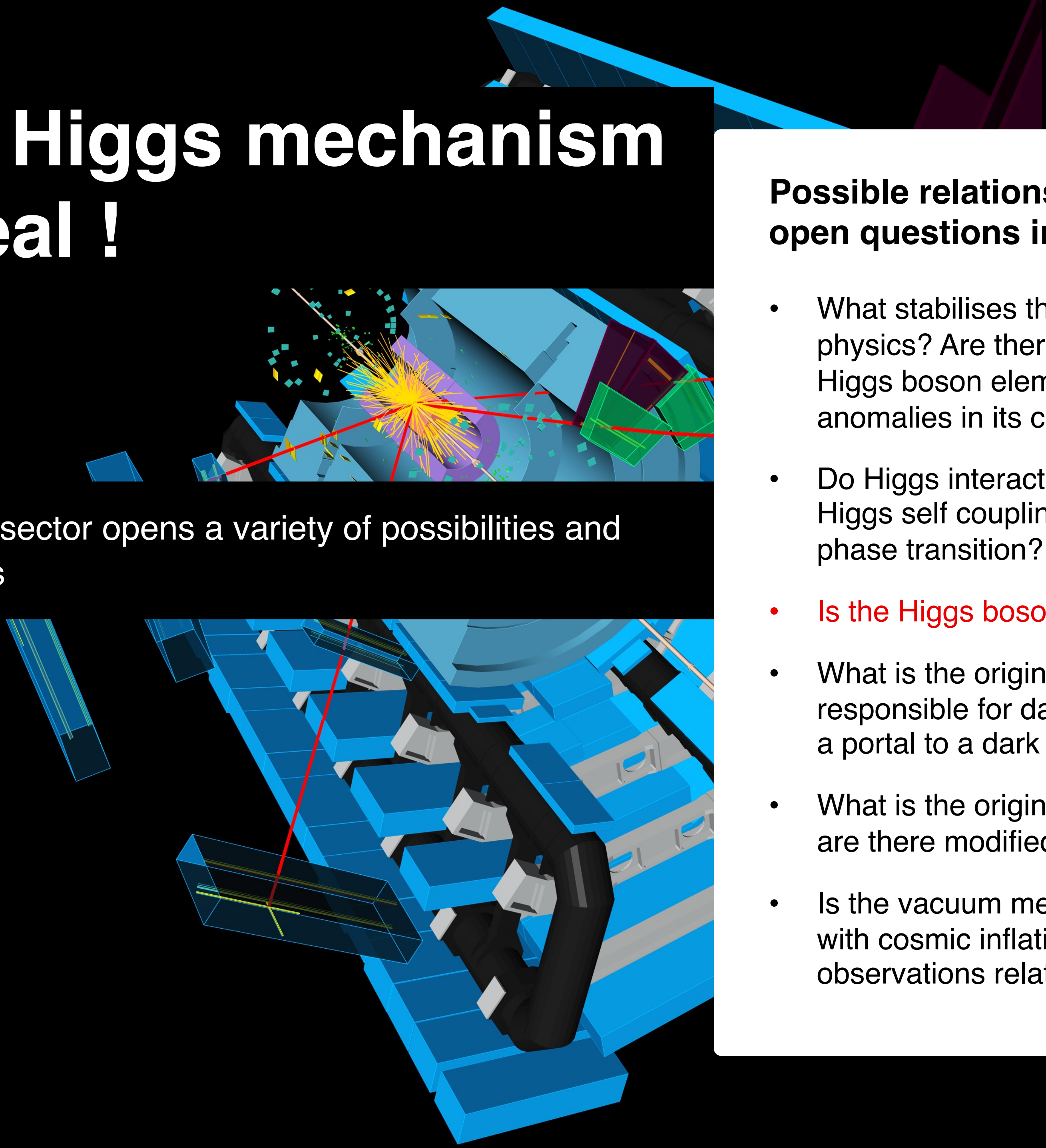


Field tensor not measured yet: $|H^2|A_{\mu\nu}Z^{\mu\nu}$

(Visible) branching fractions:

- $H \to \gamma\gamma$: 0.23%
- $H \to \mu\mu$: 0.022%
- $H \to ZZ^* \to 4\ell$: 0.012% (4e + 4μ + 2e2μ)
- **$H \to Z\gamma$: 0.010% (for $Z \to ee, \mu\mu$)**

The Higgs mechanism is real !



The new sector opens a variety of possibilities and questions

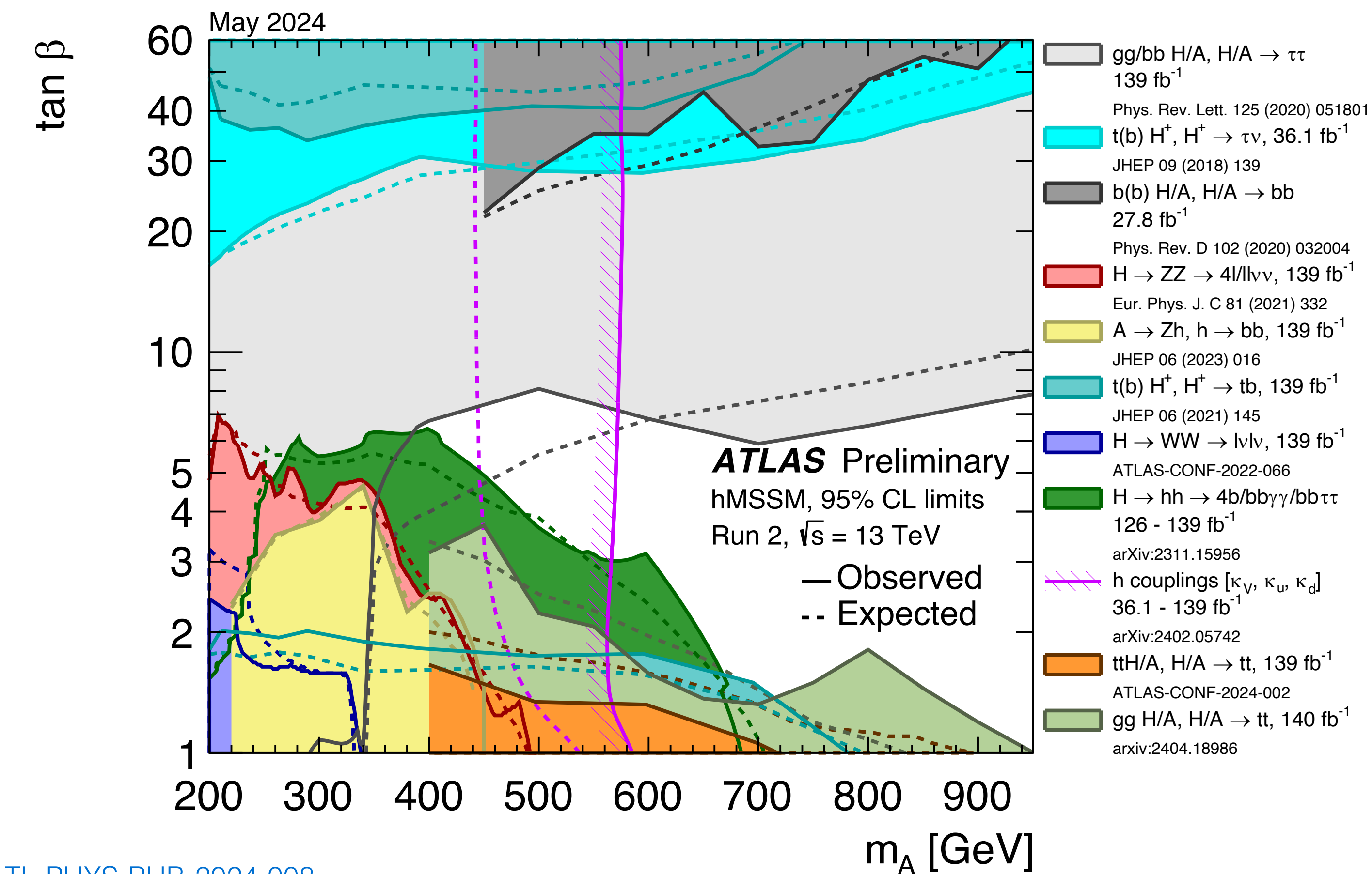
Possible relations between the Higgs boson and open questions in particle physics and cosmology

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

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

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



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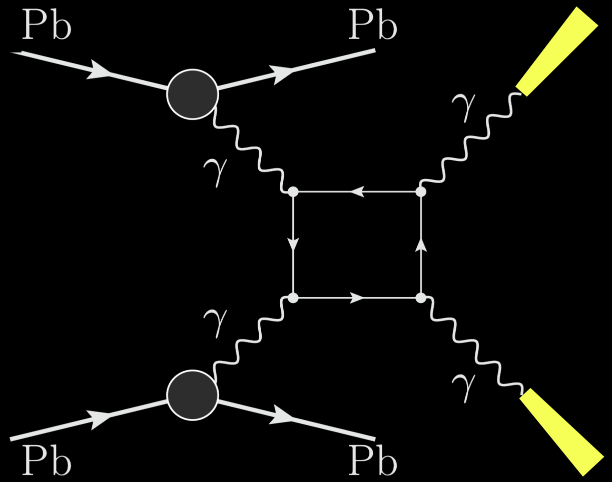
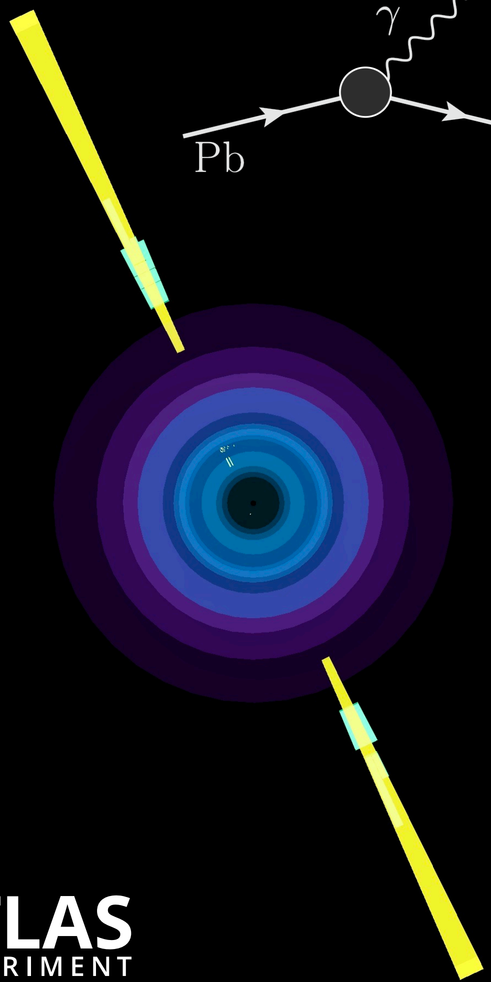
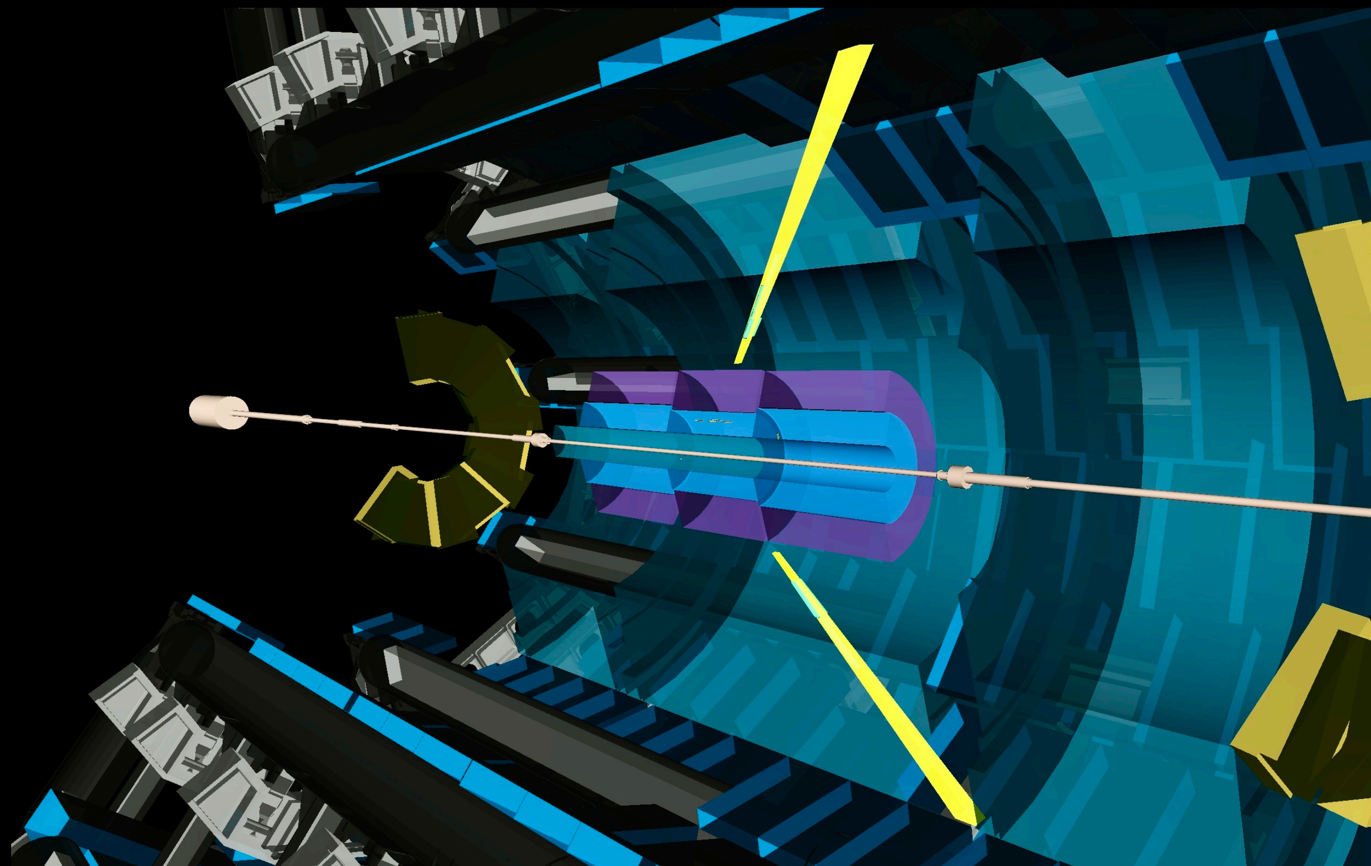
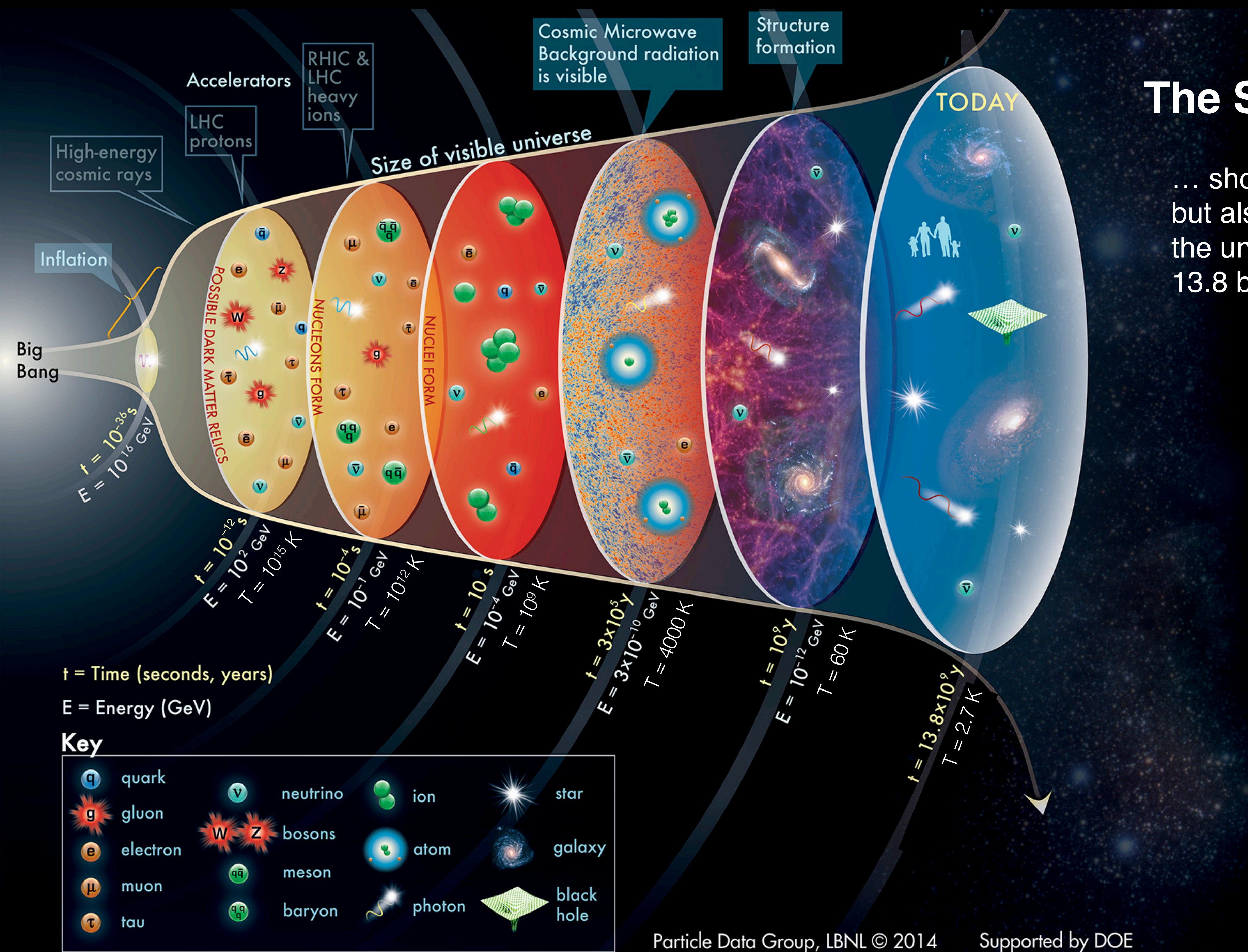
Studies of physics in extreme electromagnetic fields





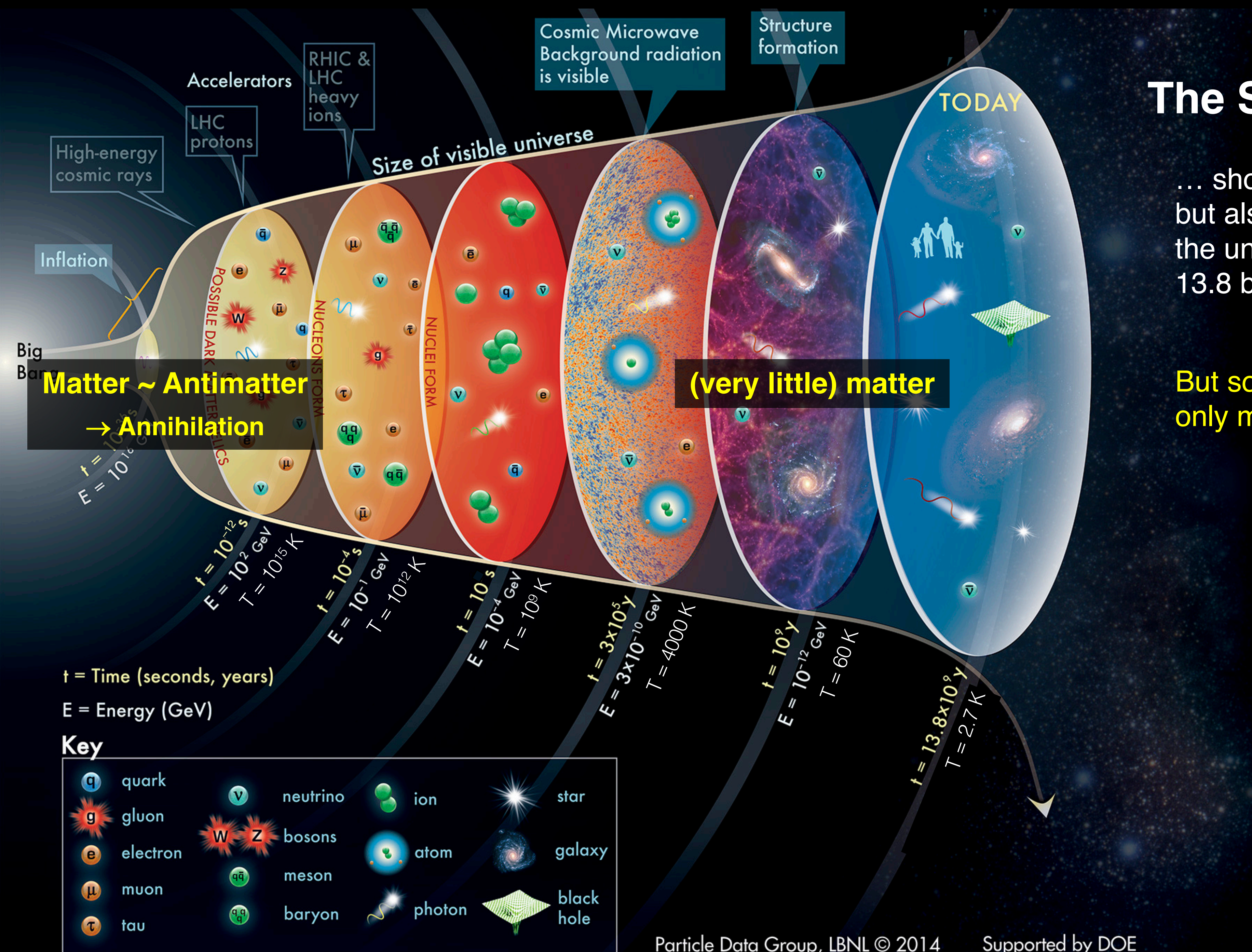


ATLAS EXPERIMENT



The Standard Model

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



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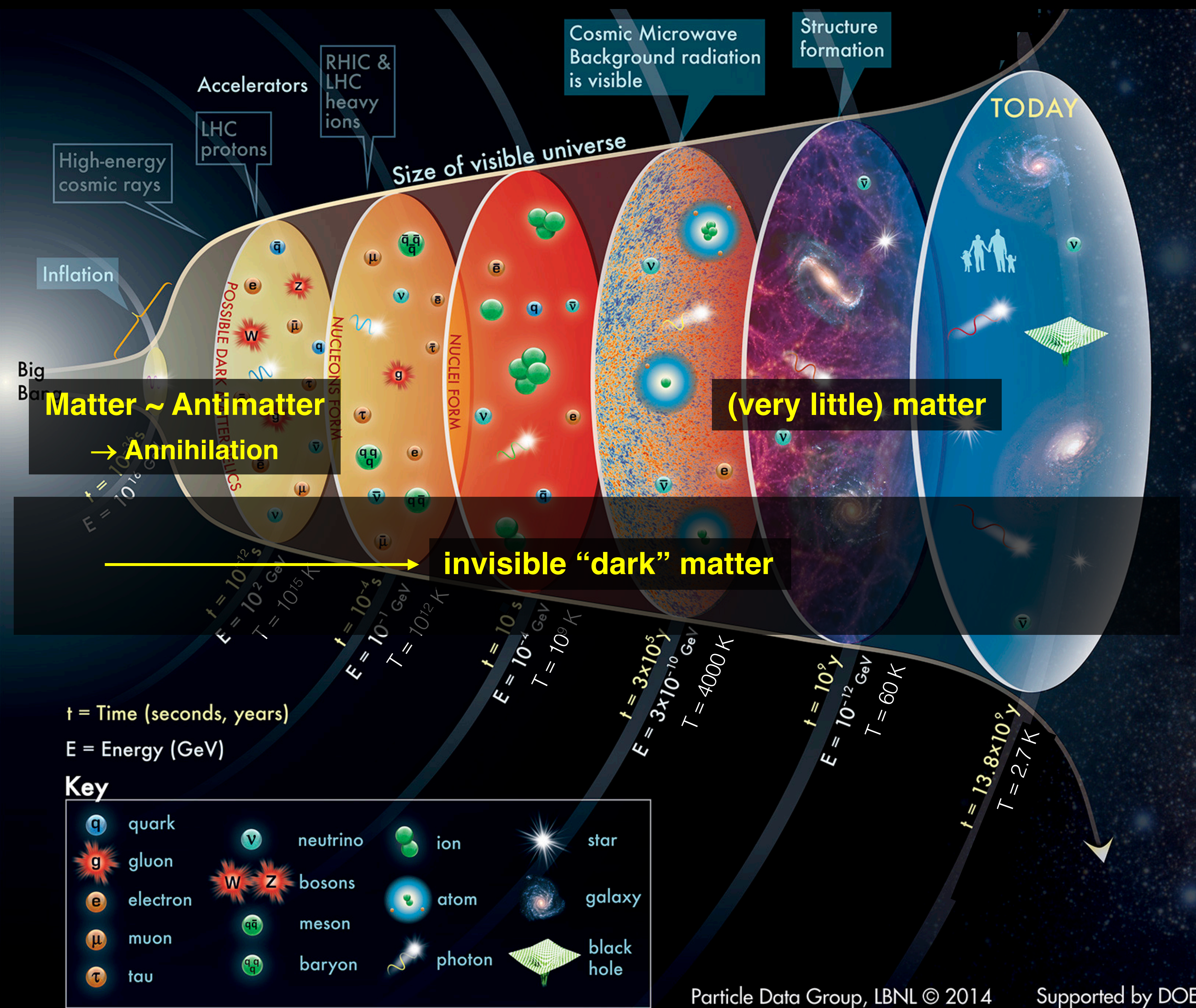
But something is odd: why is there only matter left in the universe?



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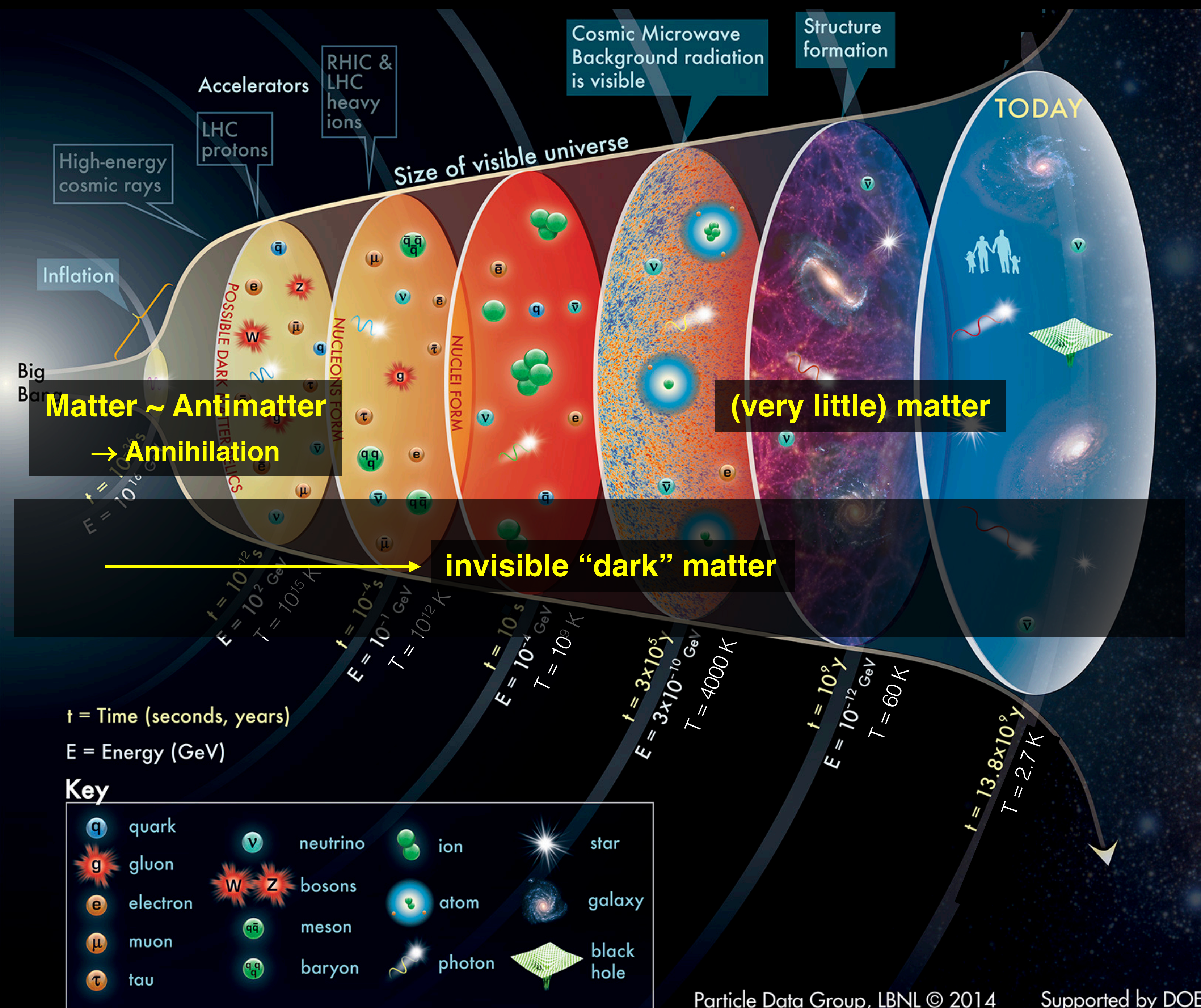

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But something is odd: why is there only matter left in the universe?

And what is the origin of the huge quantity of *dark matter*?

And why do elementary particles have mass at all? How and when did this occur?