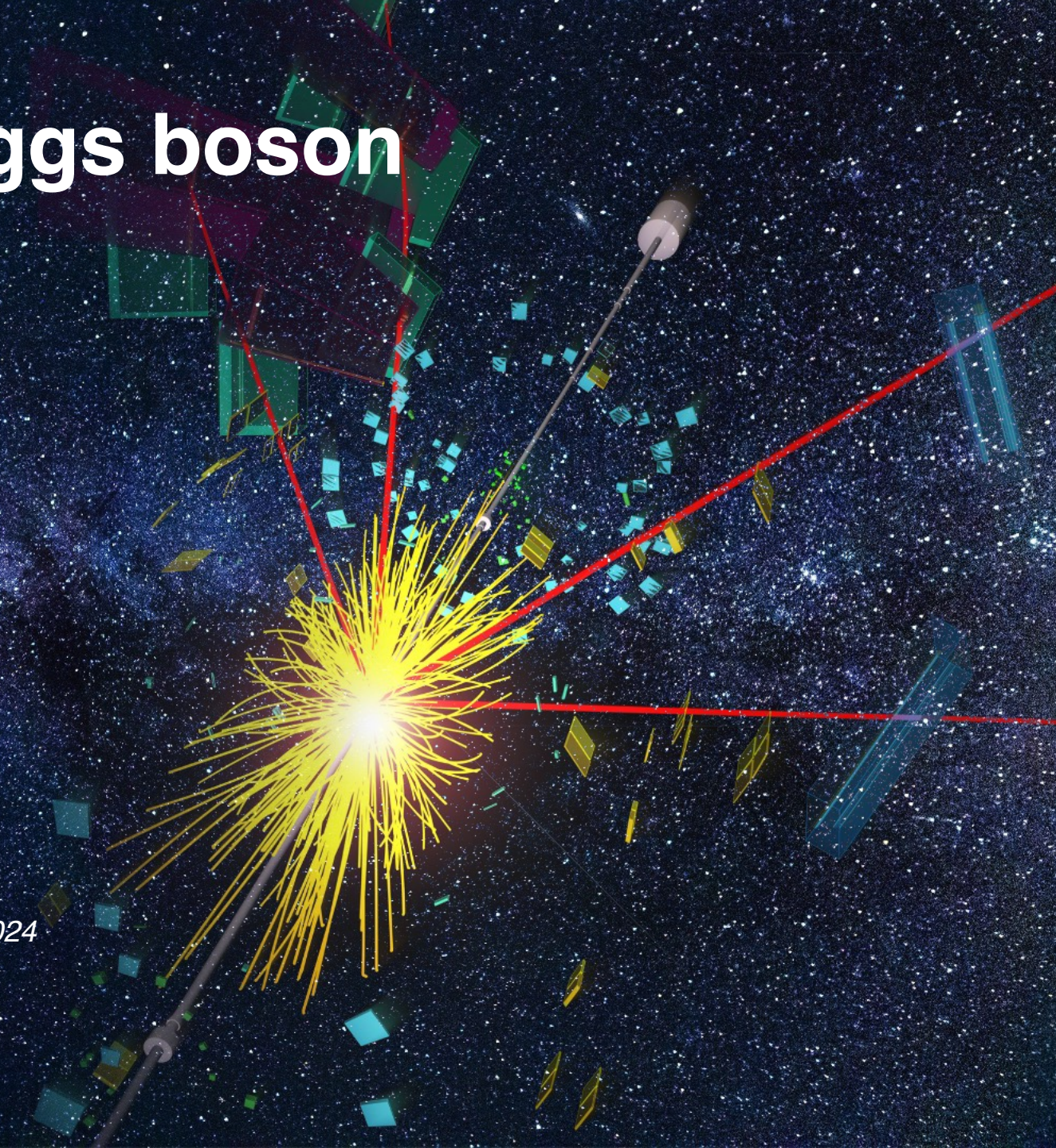


Deciphering the Higgs boson

Insights and revelations a decade after the discovery

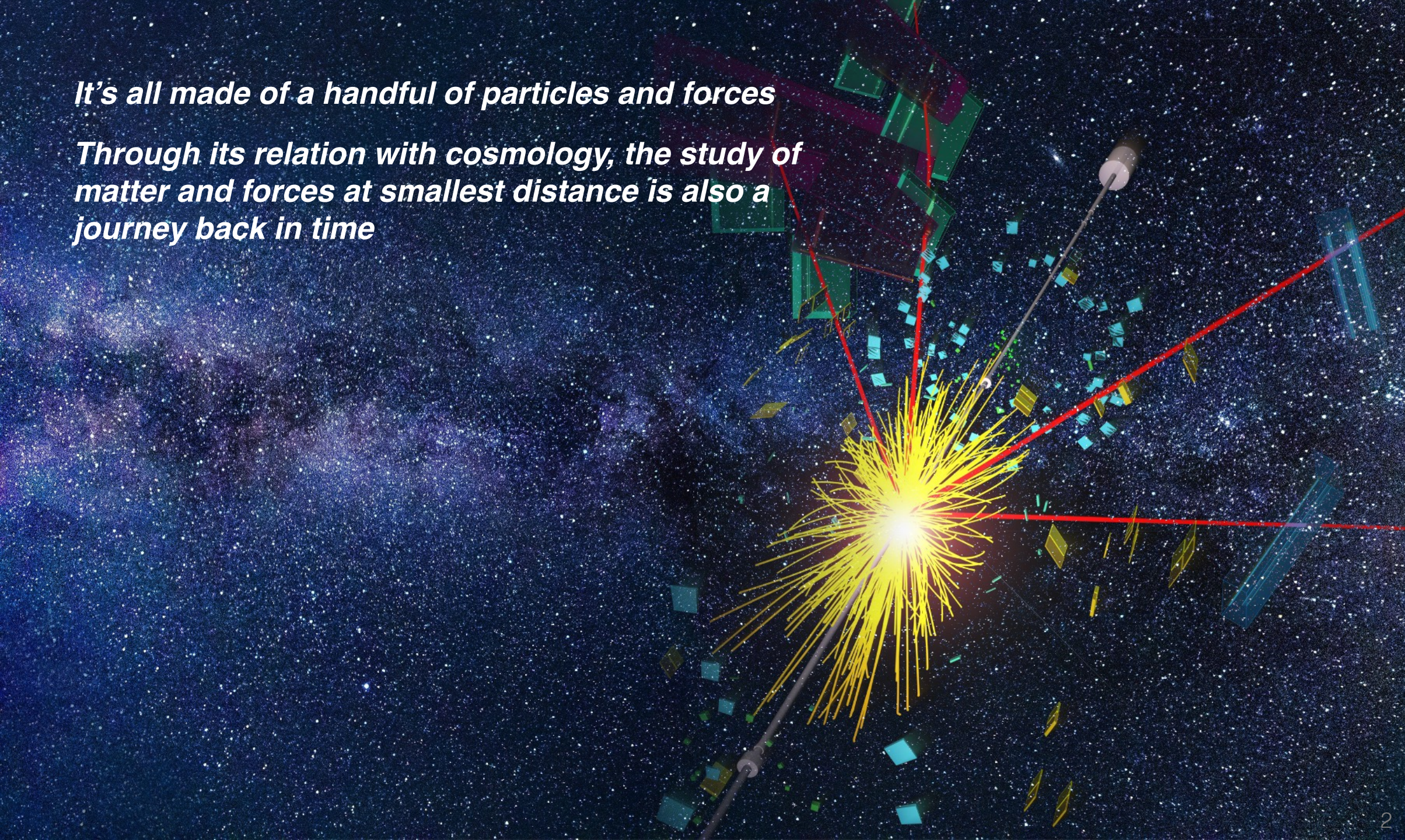
Andreas Hoecker (CERN)

Primakoff Lecture, University of Pennsylvania, 13 March 2024



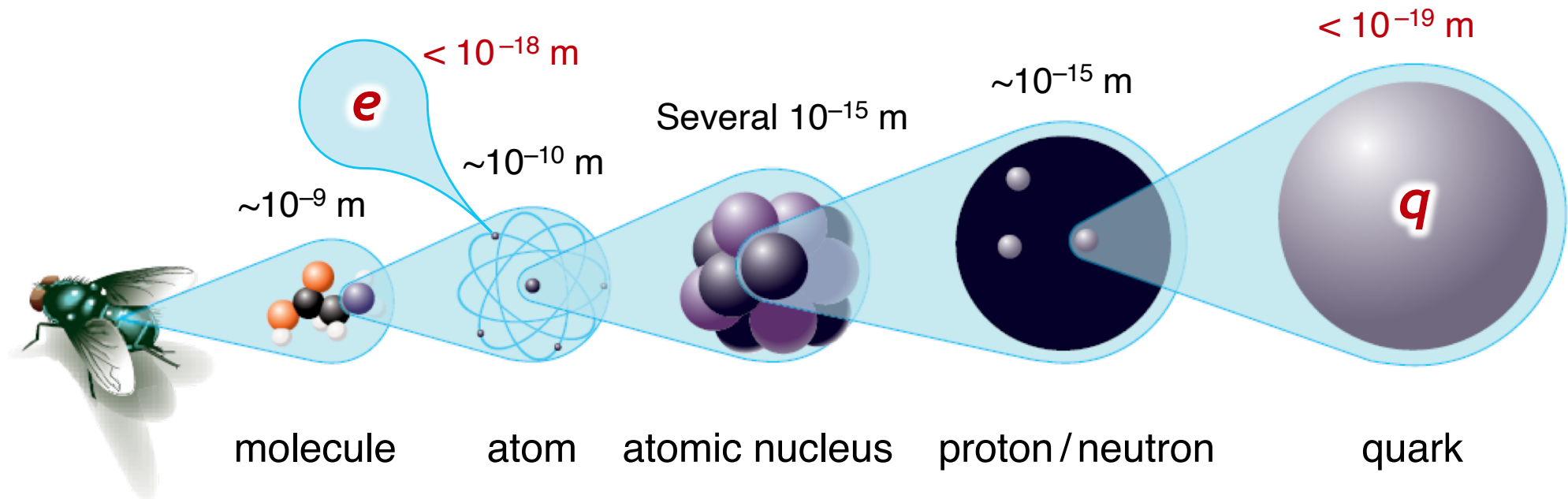
It's all made of a handful of particles and forces

Through its relation with cosmology, the study of matter and forces at smallest distance is also a journey back in time



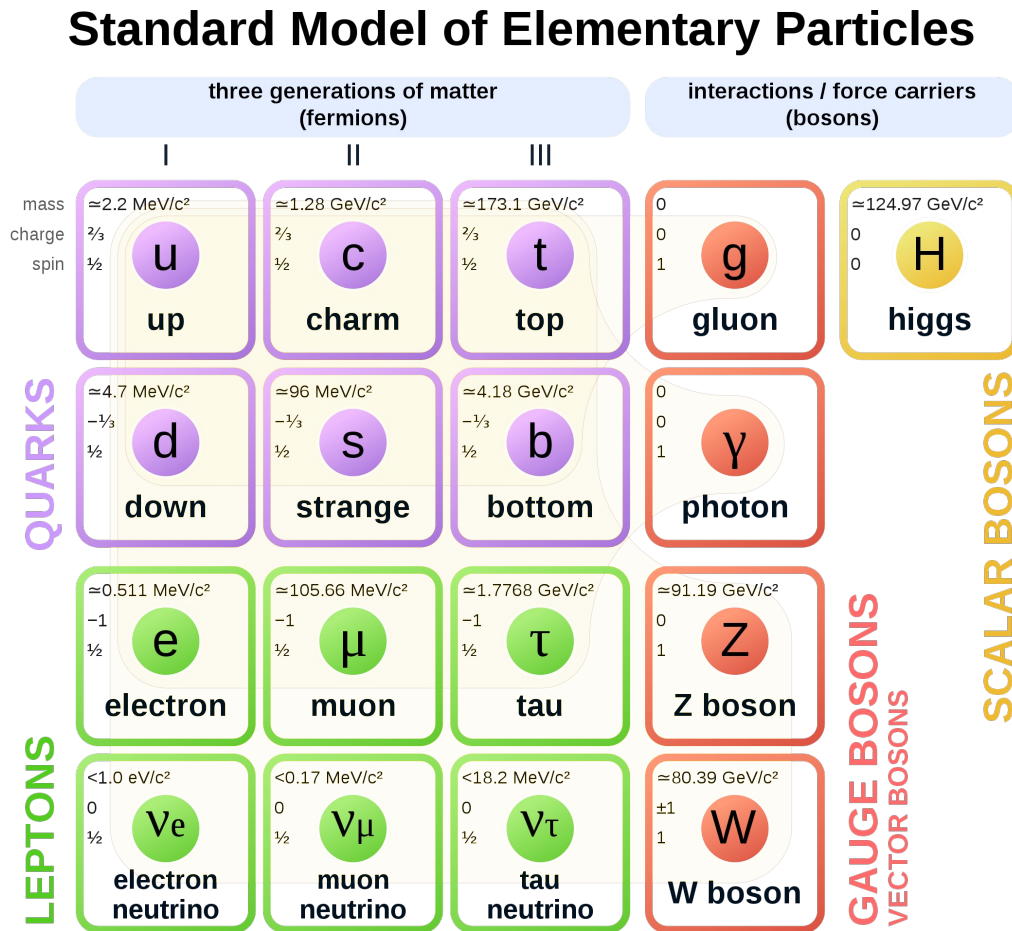
It's all made of a handful of particles and forces

The sub-atomic structure of matter



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

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

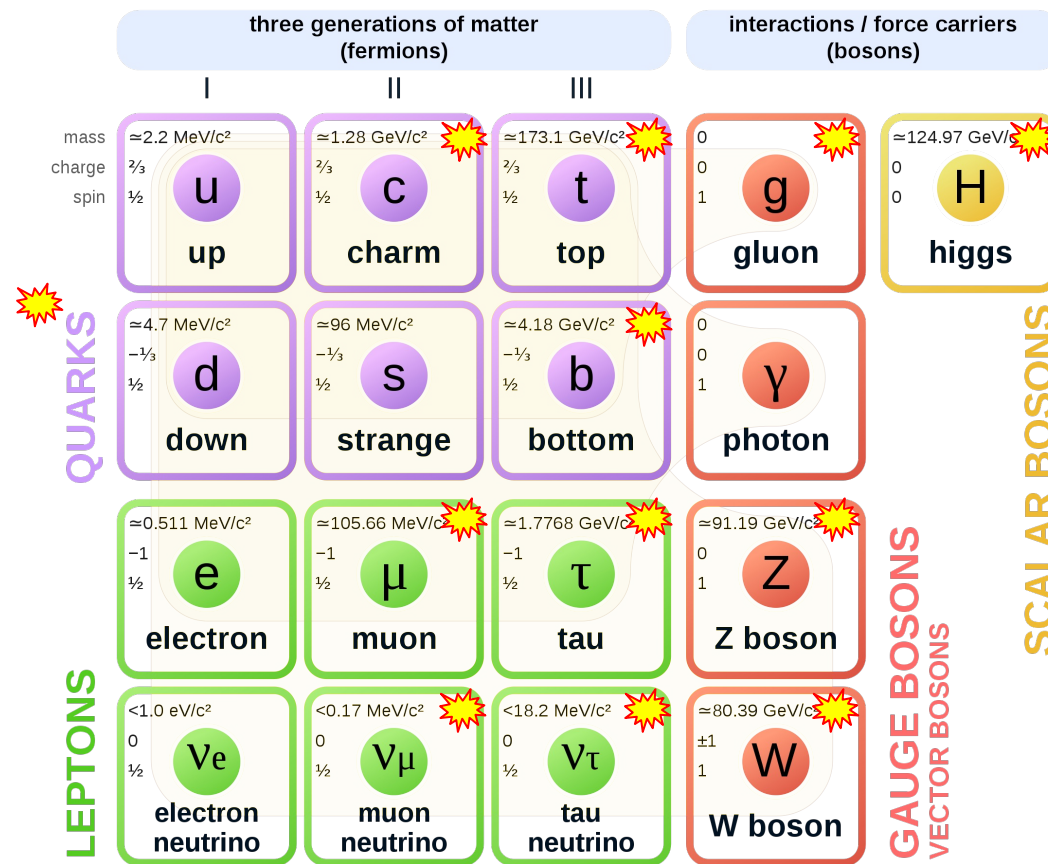


Completely new type of non-universal interactions, nothing to do with known forces

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

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

Standard Model of Elementary Particles



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

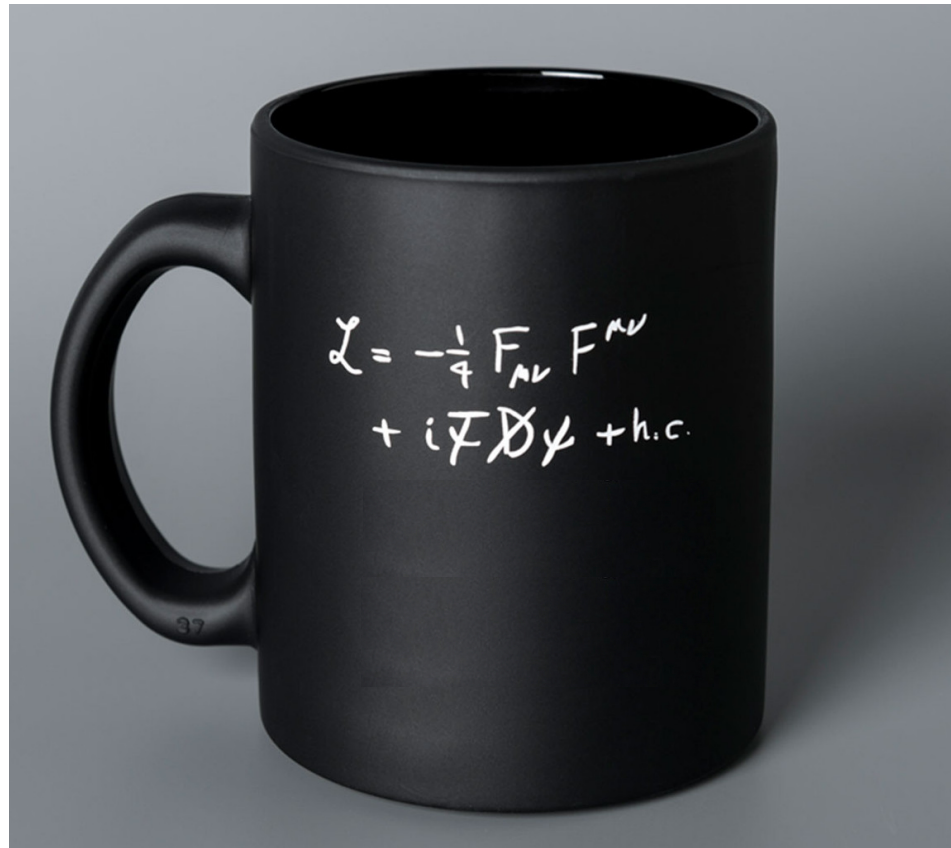
Completely new type of non-universal interactions, nothing to do with known forces

The Standard Model

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



It can be written in a very compact form so that it fits on a mug

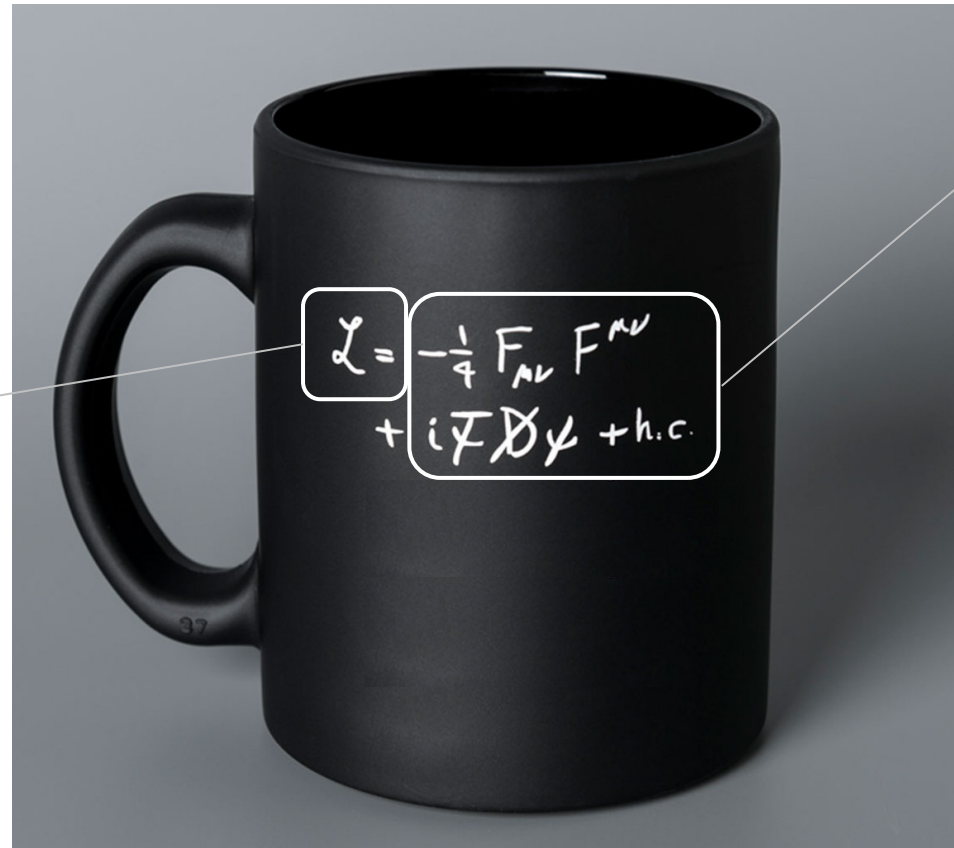
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The **Lagrangian** allows to derive the equations of motion of a system



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 $\rightarrow$ strong CP problem) parameters

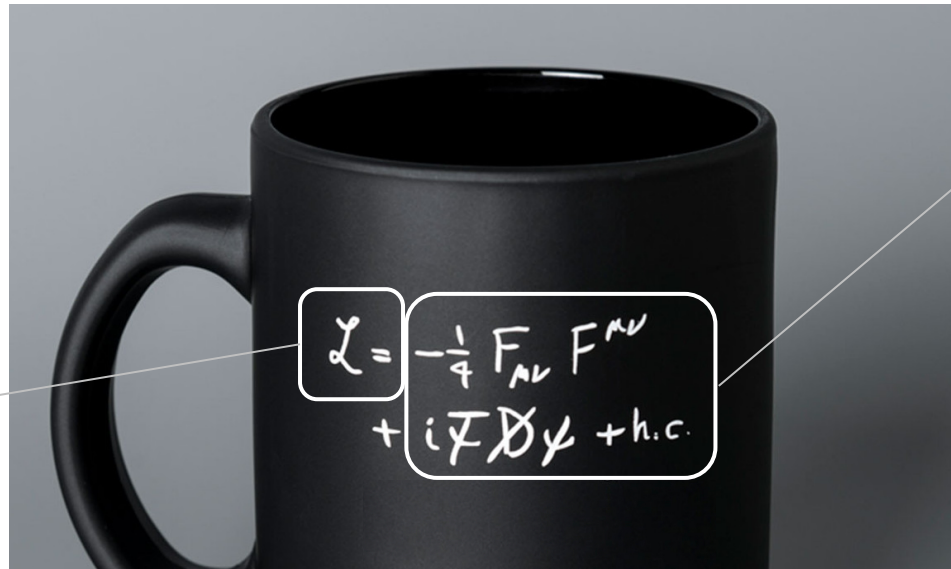
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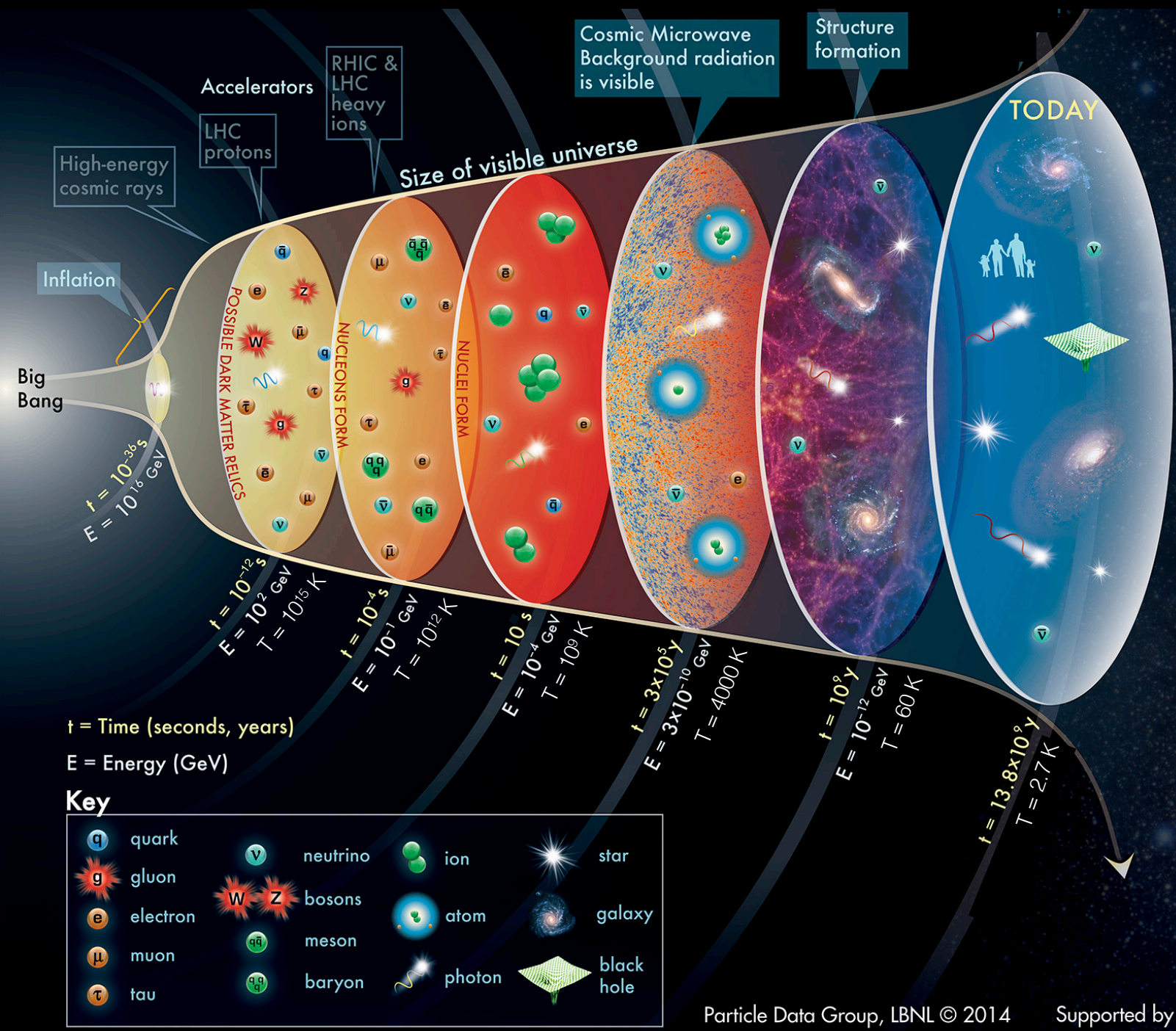
The Standard Model is a highly predictive theory

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} !

The Standard Model

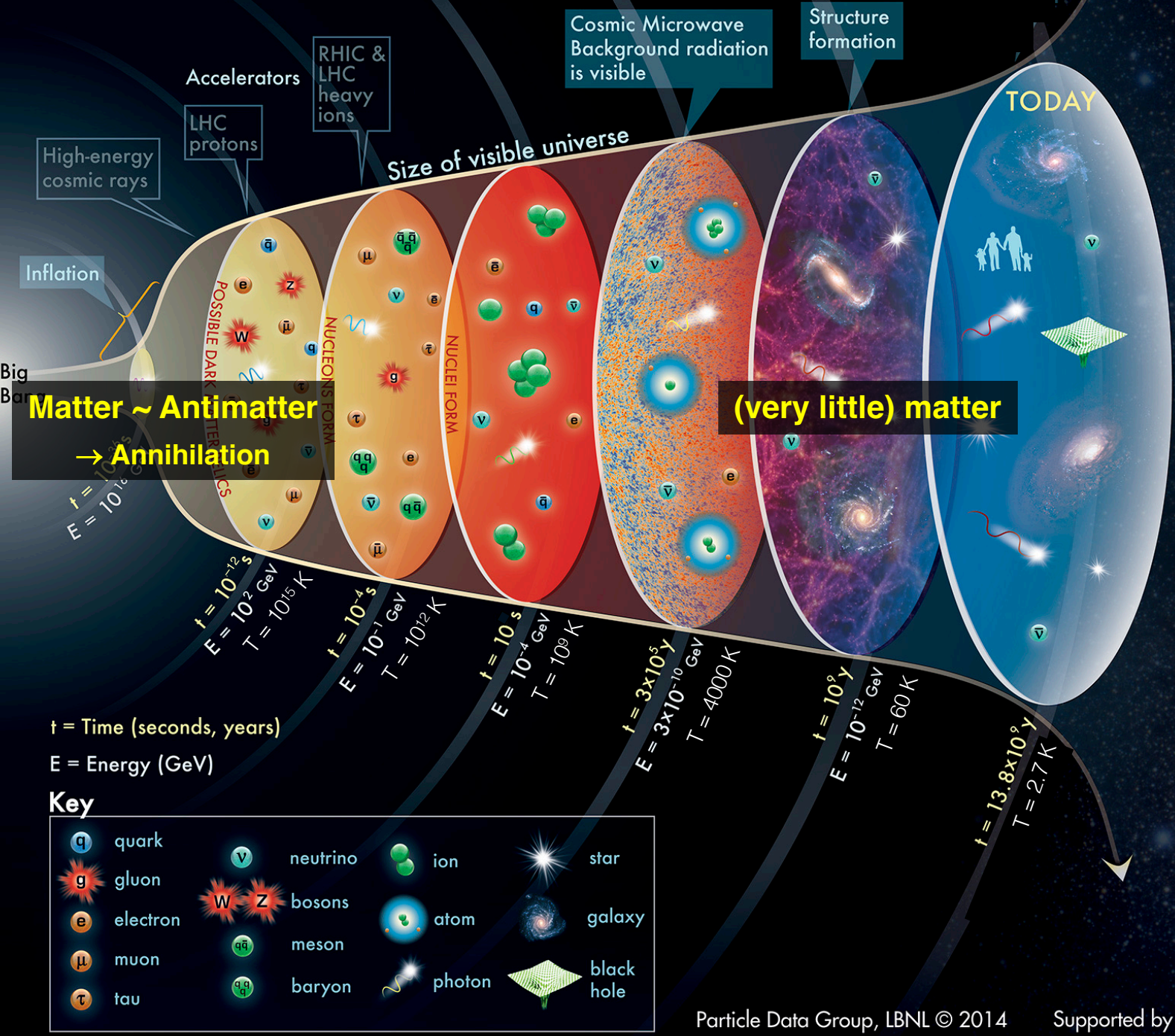
... should not only work today, but also describe the history of the universe since the Big Bang 13,8 billion years ago



The Standard Model

... should not only work today, but also describe the history of the universe since the Big Bang 13,8 billion years ago

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

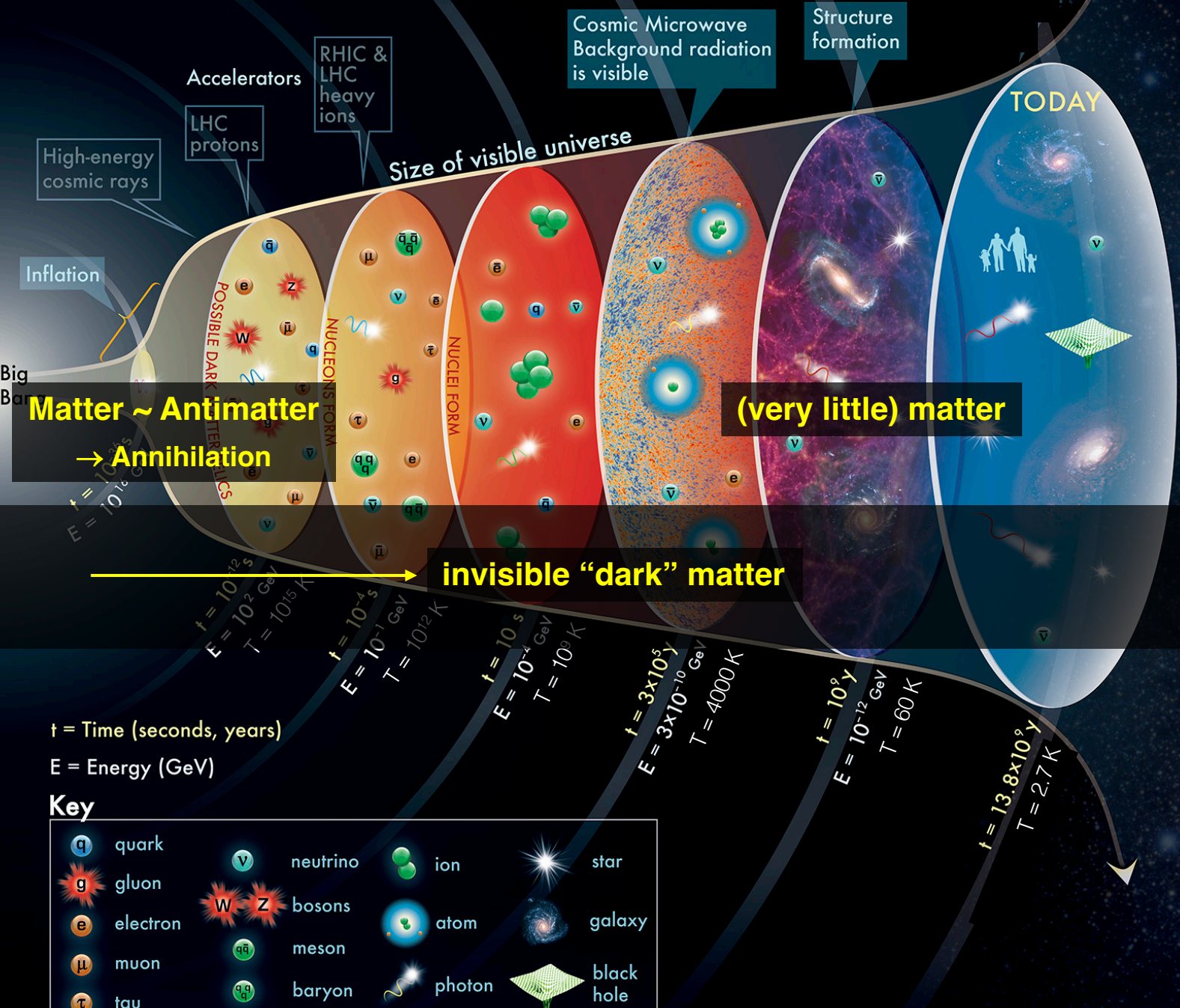


The Standard Model

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



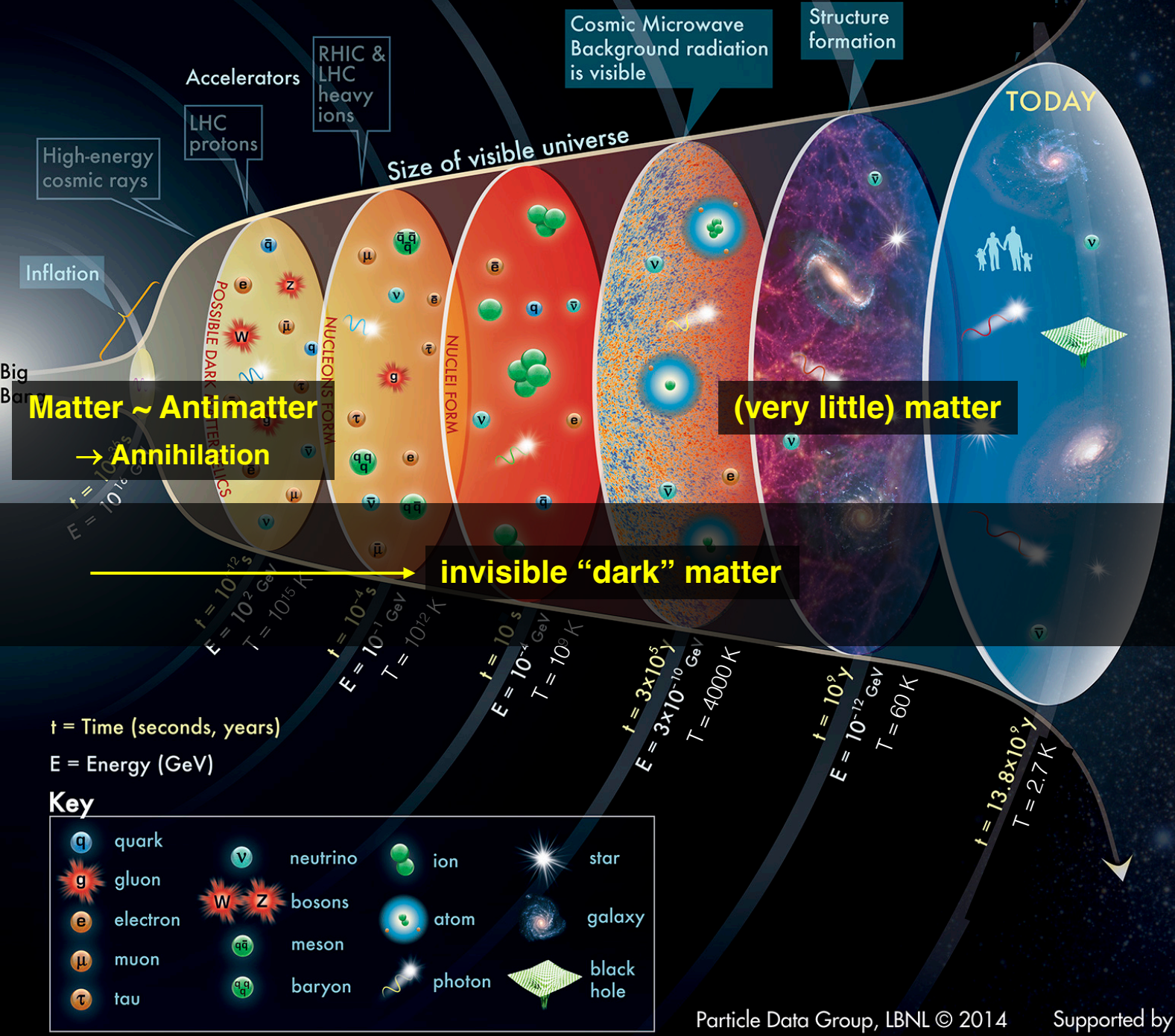
The Standard Model

... should not only work today, but also describe the history of the universe since the Big Bang 13,8 billion years ago

But 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?



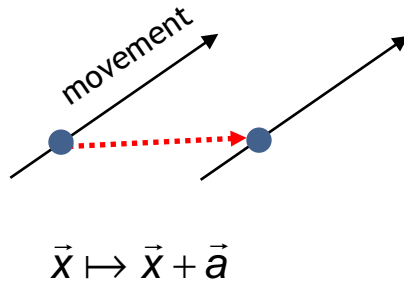
Gauge symmetry and the Higgs mechanism

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

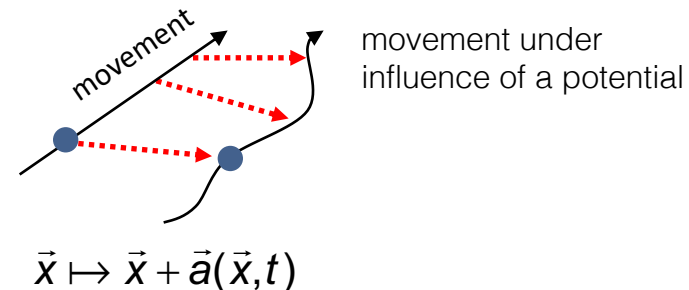
Gauge symmetry is the invariance of equations of motion with respect to a local transformation belonging to a symmetry group

Example: translation group — uniform movement of particle

Global
symmetry:



Local
symmetry:



A new trajectory is possible, if **forces** act on the particle: a potential that restores the symmetry of the dynamic under this particular gauge transformation

The dynamic found is not just any dynamic, but one of the 4 forces of nature: **gravitation**

Requiring the same local gauge invariance for a wave function gives us: **QED**

We can do so for all fundamental forces of the Standard Model, which have thus a **Geometric origin** !

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

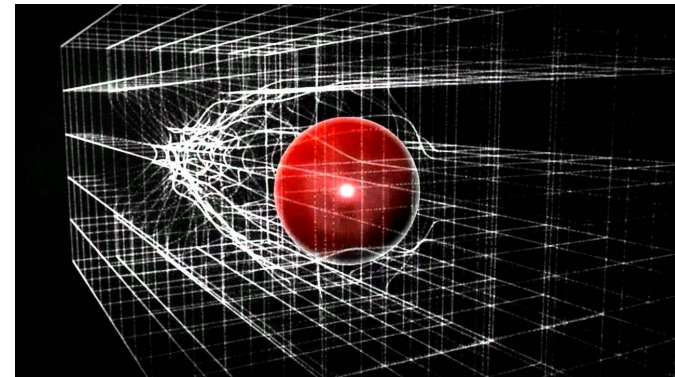
Applying an arbitrary local gauge transformation $A_\mu \rightarrow A_\mu + \partial_\mu \alpha$ on a mass term $m^2 A^\mu A_\mu$, invariance requires $m = 0$

However, the W, Z bosons are massive (= finite range of weak interaction $\sim 10^{-15}$ 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 “soaks” 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:

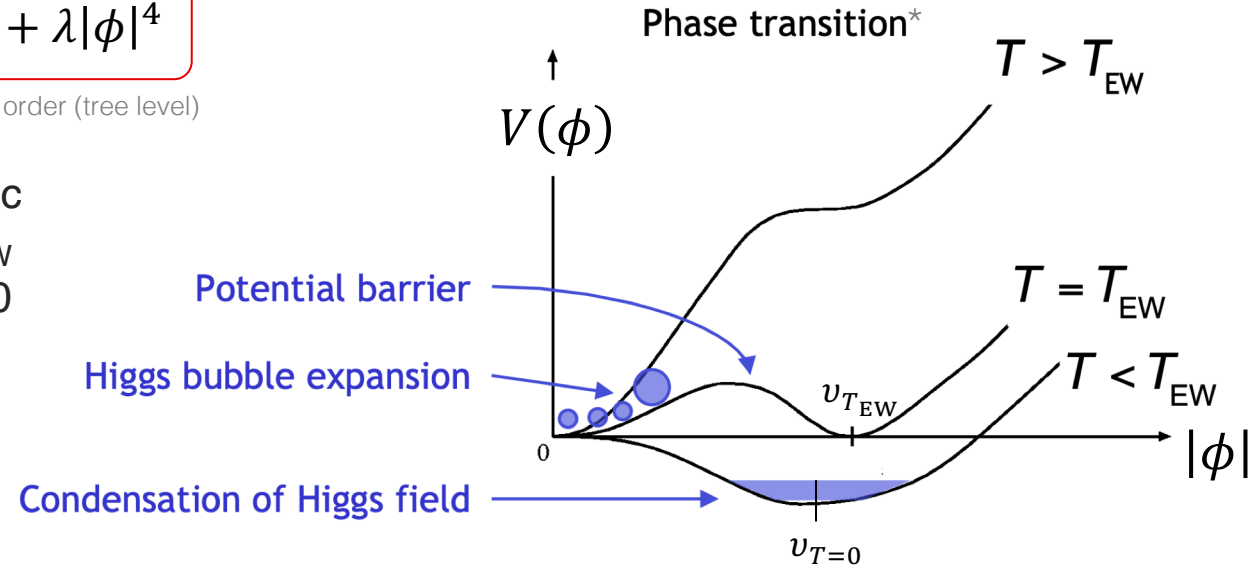
$$V(\phi) = -\mu^2 |\phi|^2 + \lambda |\phi|^4$$

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:

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

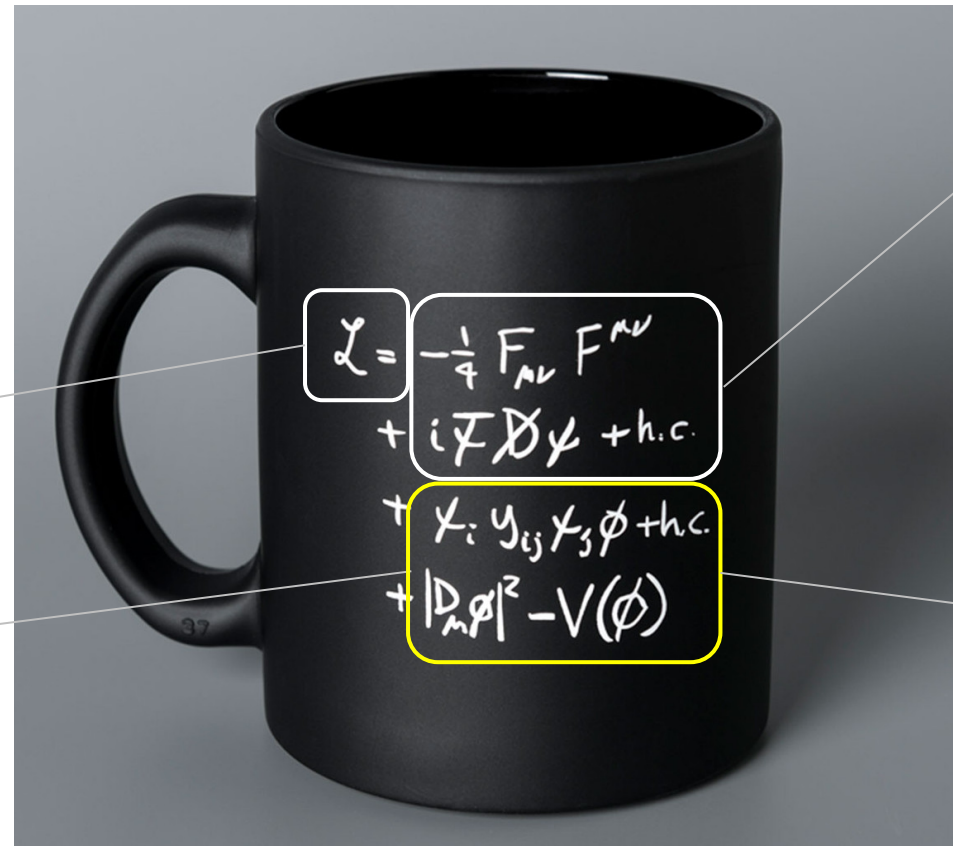


Developing $\phi(x) \propto (0, v + H(x))$ around the minimum and inserting it into the SM Lagrangian expanded by particle interactions with $\phi(x)$, determines the particle spectrum

- $m_\gamma = 0$, $m_W = \frac{1}{2} g v$, $m_Z = \frac{1}{2} \sqrt{g^2 + g'^2} \cdot v$, $m_W/m_Z = \cos \theta_W$
- $m_f = \frac{1}{\sqrt{2}} g_f v$, (g_f (Yukawa couplings) not predicted by Higgs mechanism, note that $g_{top} \approx 1$, 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 Higgs mechanism is a necessary ingredient of the Standard Model to accommodate the reality of boson and fermion masses



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

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**

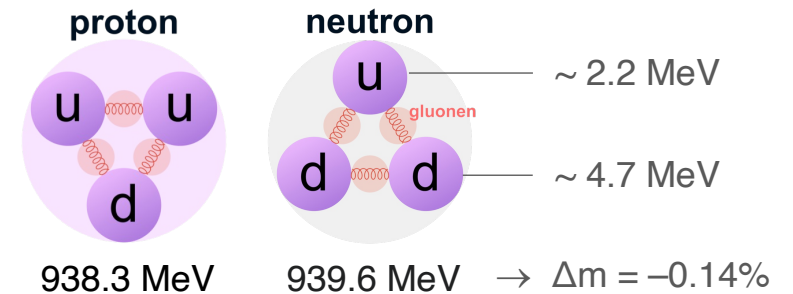
The lower left term describes the **interaction of the Higgs field with the weak-interaction bosons, which thereby obtain mass**

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

Gauge symmetry and the Higgs mechanism

A few comments:

- The Higgs mechanism is required because we assume the bosons and fermions to be elementary. It would be different had they substructure: binding energy could give mass
- The resulting mass values govern the history of the universe (incl. complex chemistry and life) → what would happen had we (or nature) a dial to change the particle masses? [see [R. Cahn](#)]
- $V(\phi)$ is the simplest scalar potential that breaks ground state symmetry. Does what we need, but bears fundamental problems → carries the seeds for new physics
- The Higgs mechanism doesn't tell us everything: there is this field which generates mass, but we do not know why some particles soak a lot of energy out of this field and others much less → this is the “flavour” problem
- The vacuum energy density of the Higgs field (among others) generates a "cosmological constant" that is 10^{56} times larger than the dark energy observed*. It would curve the universe into an object roughly the size of a football, contrary to reality → this is the “cosmological constant” (finetuning) problem



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

An analogy to the Higgs mechanism

Superconductivity

SC (BCS) theory

Cooper pair Bose condensation

Electrically charged ($2e$)

Mass of the photon

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

Higgs mechanism

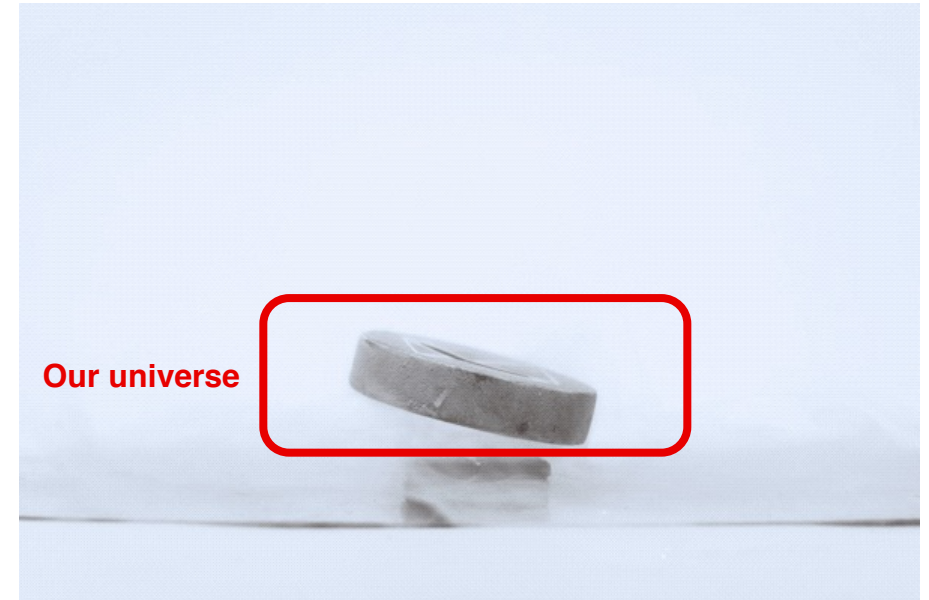
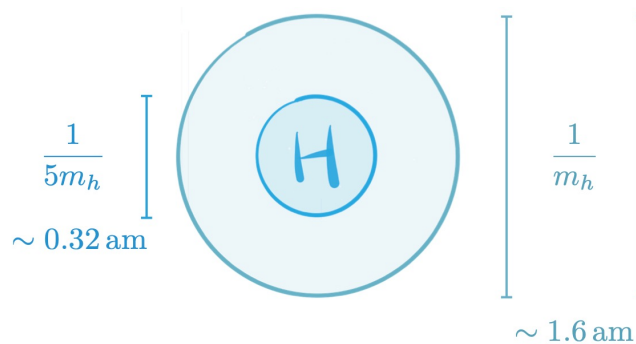
Condensed Higgs field

Weak charge

Mass of W & Z bosons

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

→ Is the Higgs boson elementary or composite?



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

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

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

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



Producing and studying the Higgs boson requires a huge machine



Particle accelerators

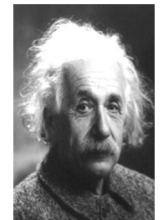
- Look deeper into matter (size $\sim 1/E$) (powerful microscope)
- Discover new heavier particles ($E = mc^2$)
- Probe conditions of the early universe ($E = kT$)



de Broglie



Boltzmann



Einstein

This machine was realized at CERN



CERN

Founded in 1954 became a role model
of international scientific cooperation

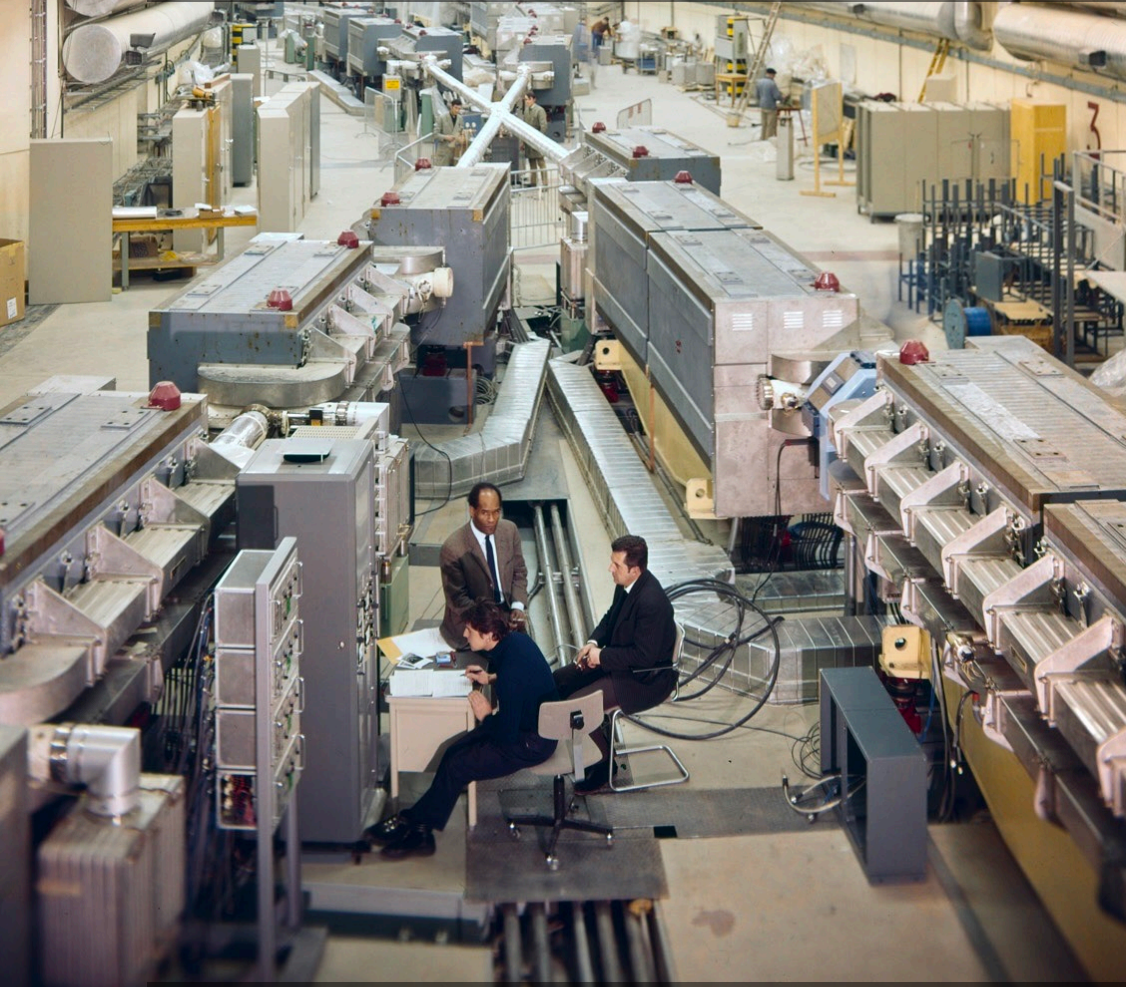


CERN — the world's largest center for fundamental research

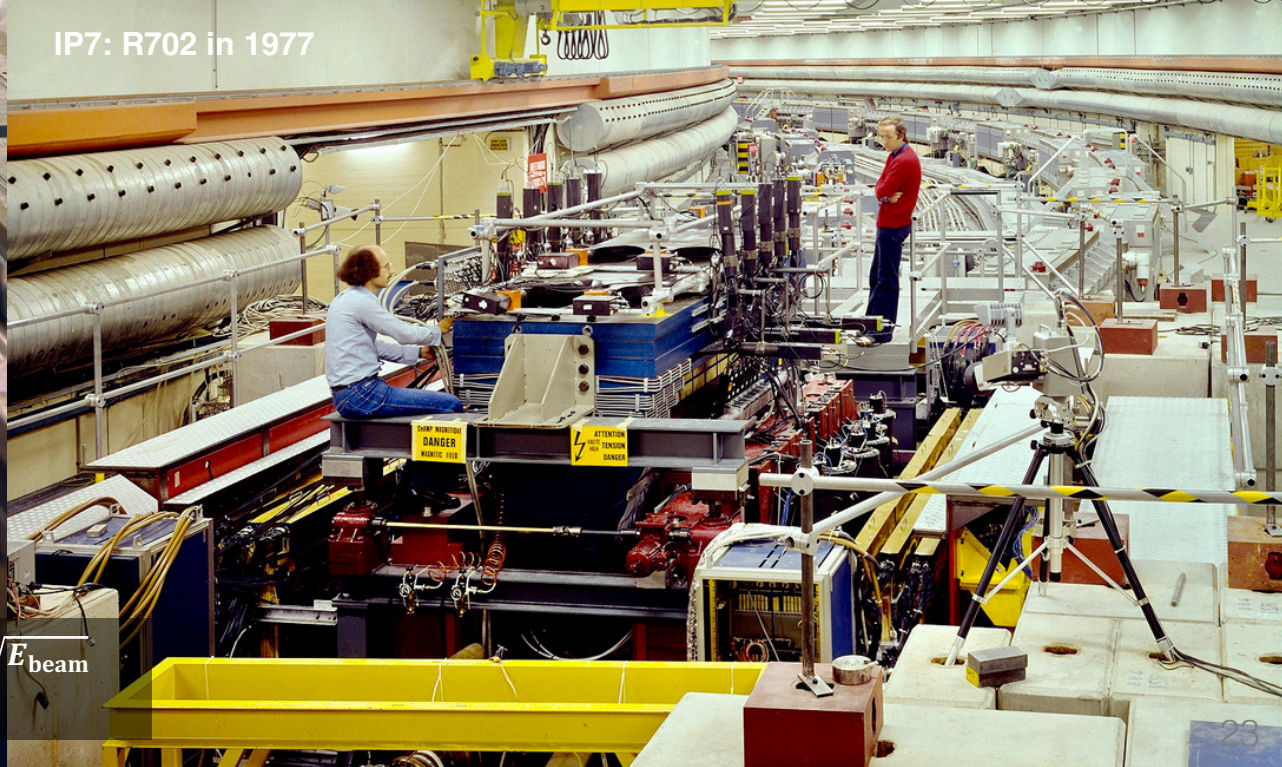


1971 — the first Hadron-Collider

Intersecting Storage Rings at CERN operated as a proton, proton-antiproton and ion collider for physics between 1971 and 1983. 943 m circumference, 1.3 T dipole field, CM energy up to 63 GeV, holding luminosity record for hadron machines until 2004



IP7: R702 in 1977



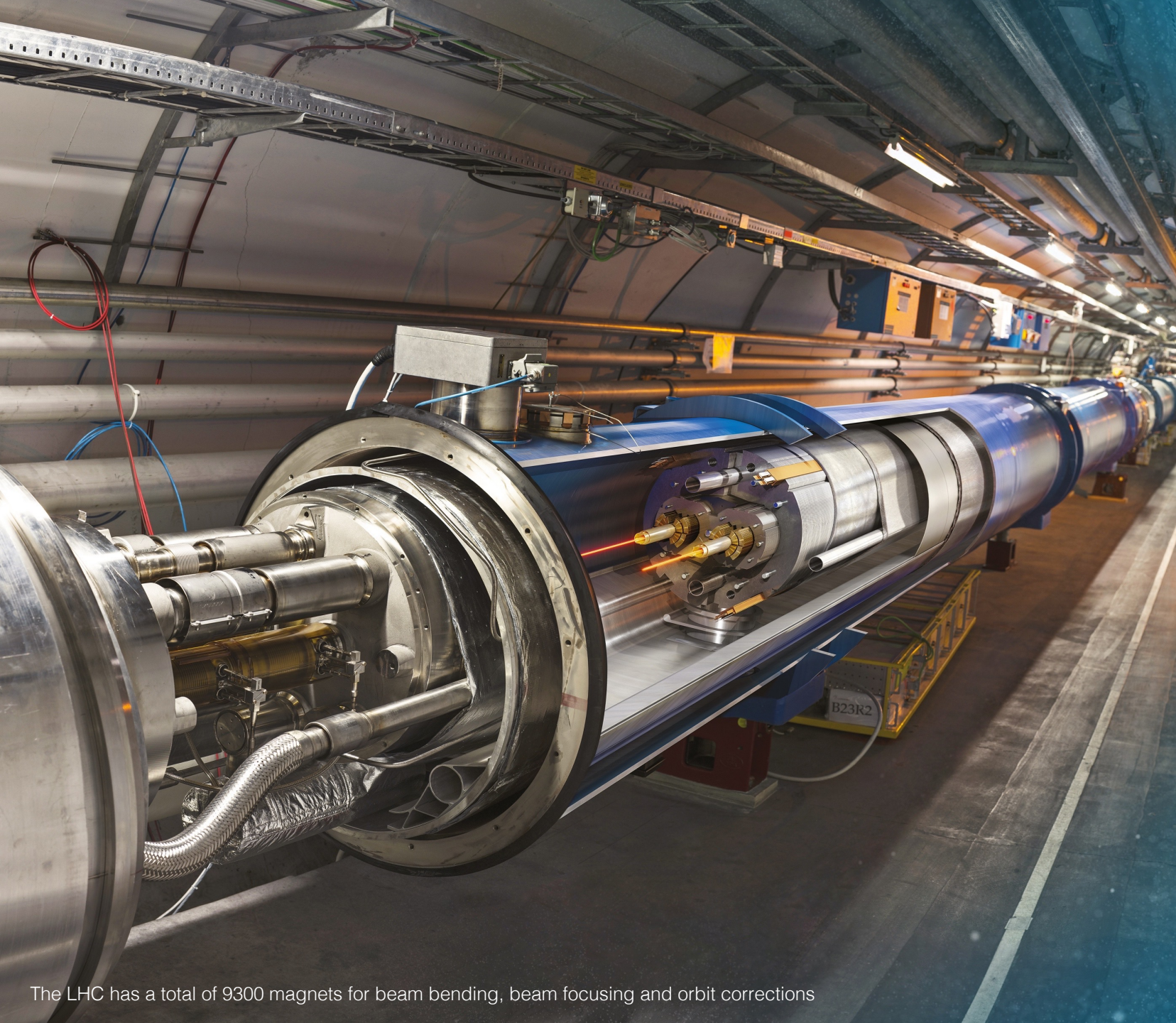
Huge advantage over fixed target; for protons: $E_{CM} = 1.4\sqrt{\text{GeV}}\sqrt{E_{beam}}$
 $\rightarrow E_{CM} = 14 \text{ TeV}$ would require a 10,000 TeV beam

ISR Control Room (early 70s)



LHC Control Room (July 2022)



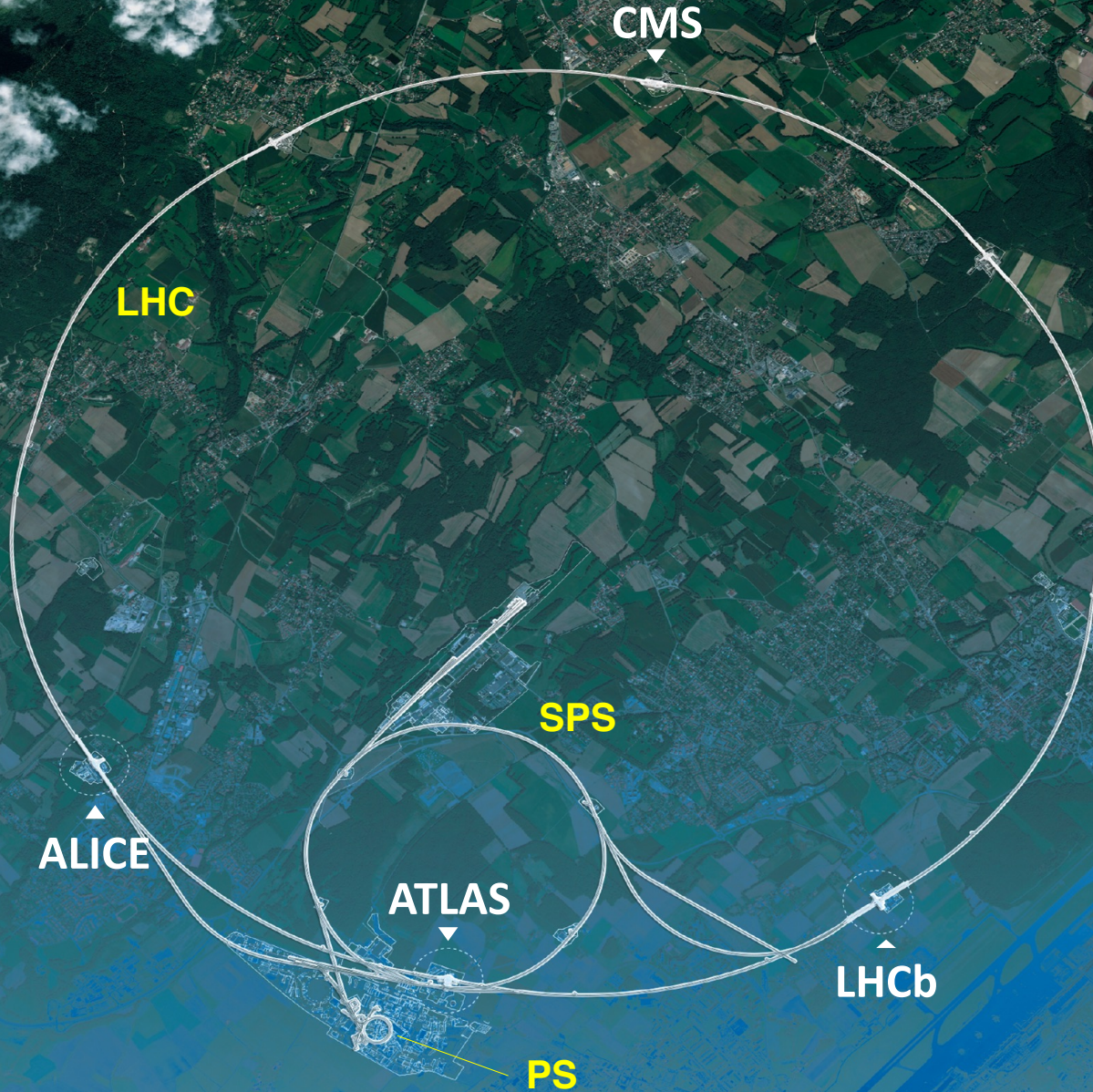


Large Hadron Collider (LHC)

- 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

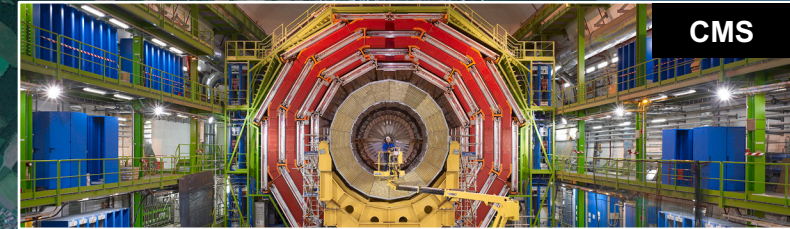
The Large Hadron Collider



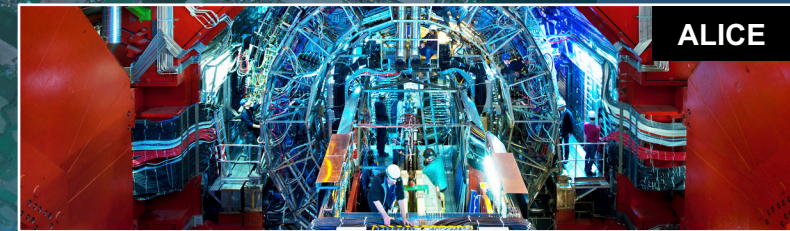
Areal view



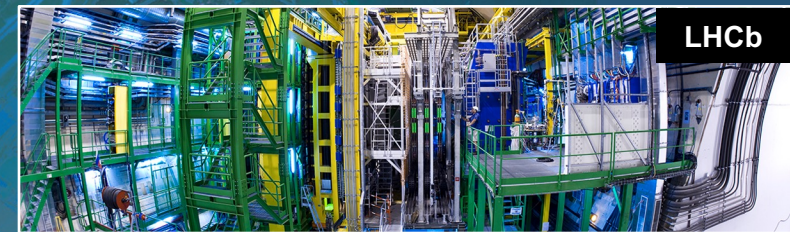
ATLAS



CMS



ALICE



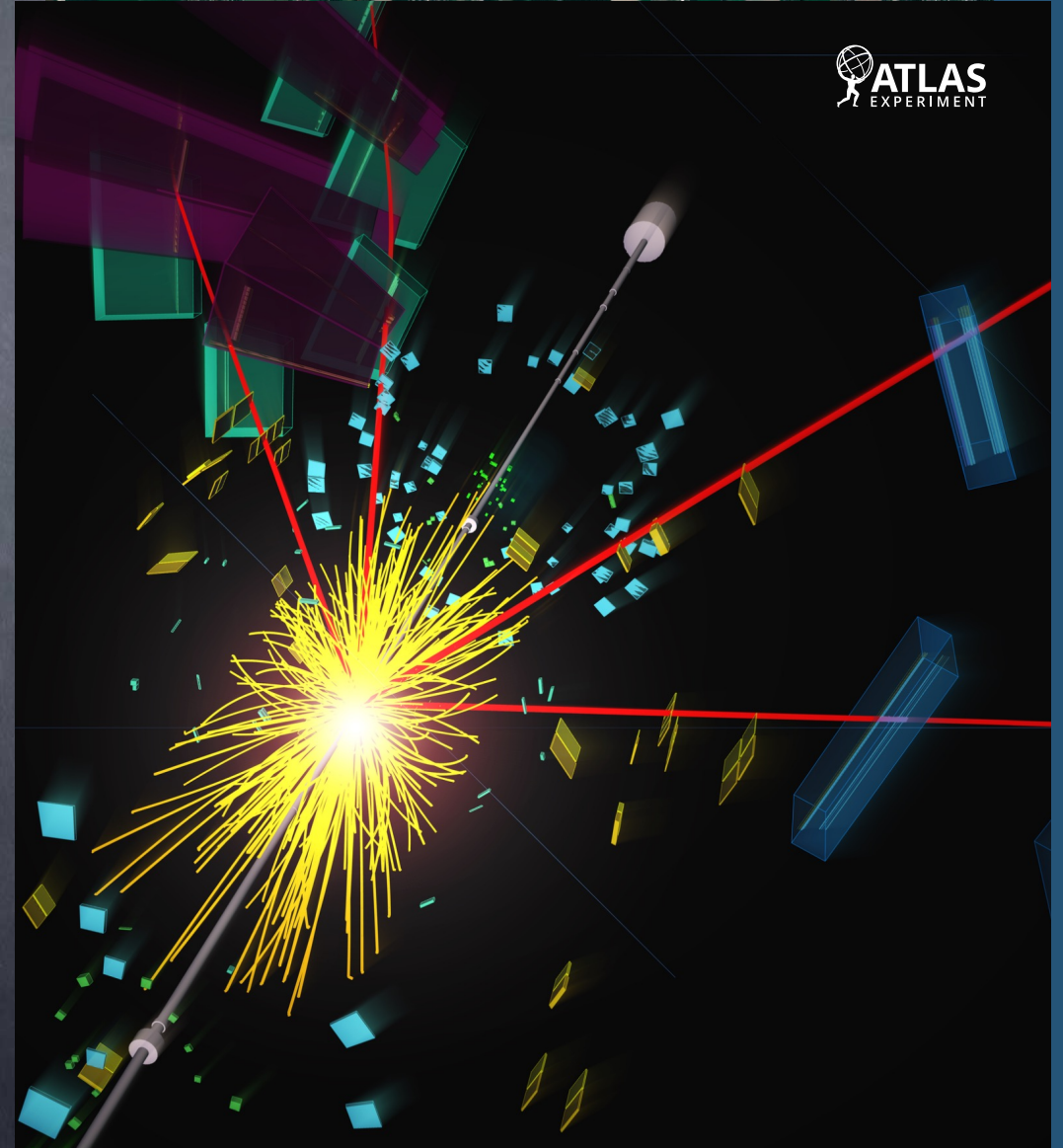
LHCb



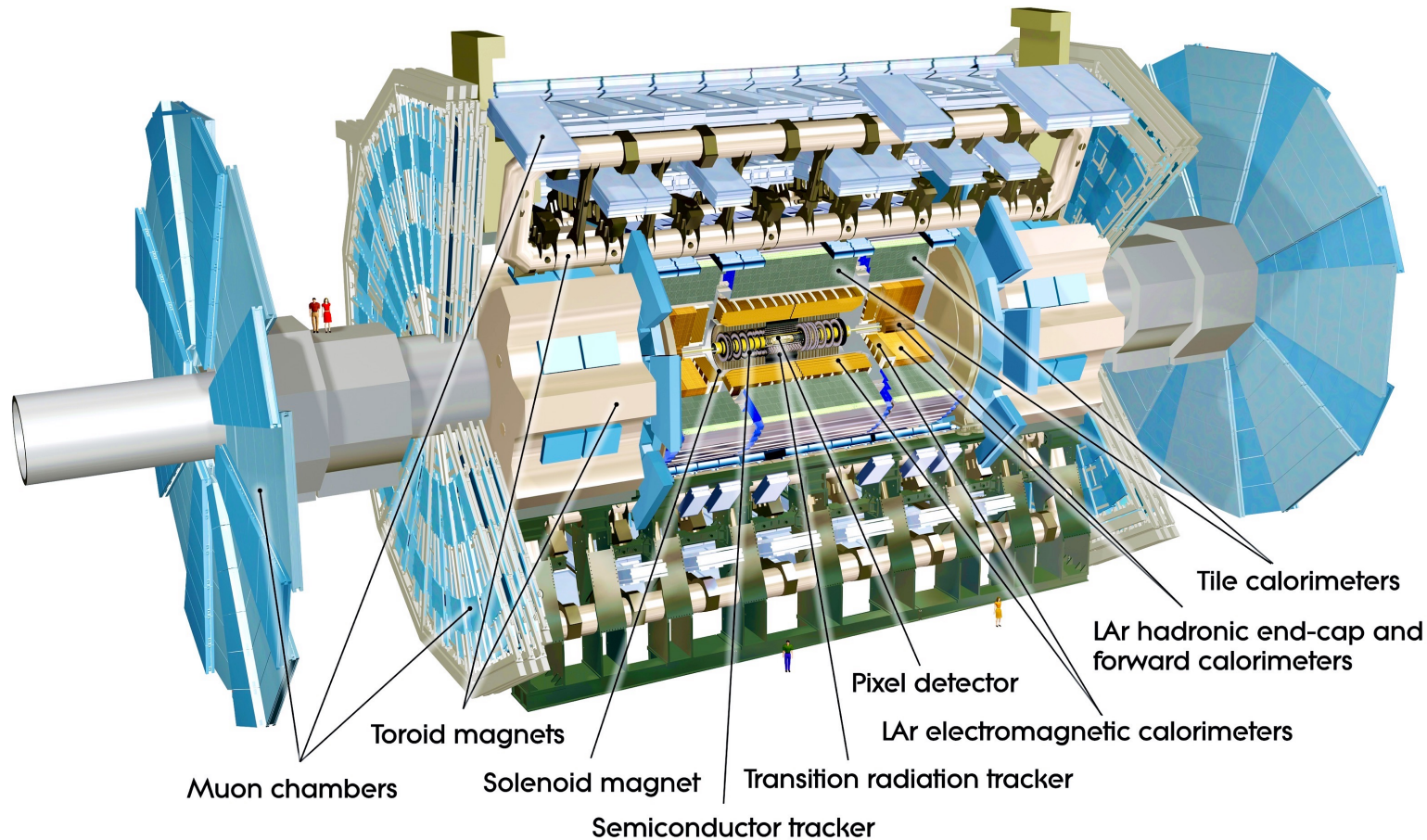
What happens in a high-energy proton–proton collision?

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

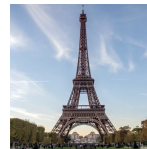
- Light quarks, gluons (“jets”) $\gg$ W, Z $\gg$ top quark $\gg$ Higgs boson
- Heavy particles decay instantaneously to light, stable particles (quarks/hadrons, leptons, photons)
- A particle detector precisely measures these decay particles, which allows to deduce the properties of the mother particle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



The ATLAS Detector



25 m diameter, 46 m long, 7000 tons weight ~



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

High resolution silicon **detectors**:

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

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

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

Independent **muon spectrometer** (superconducting 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 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](#)

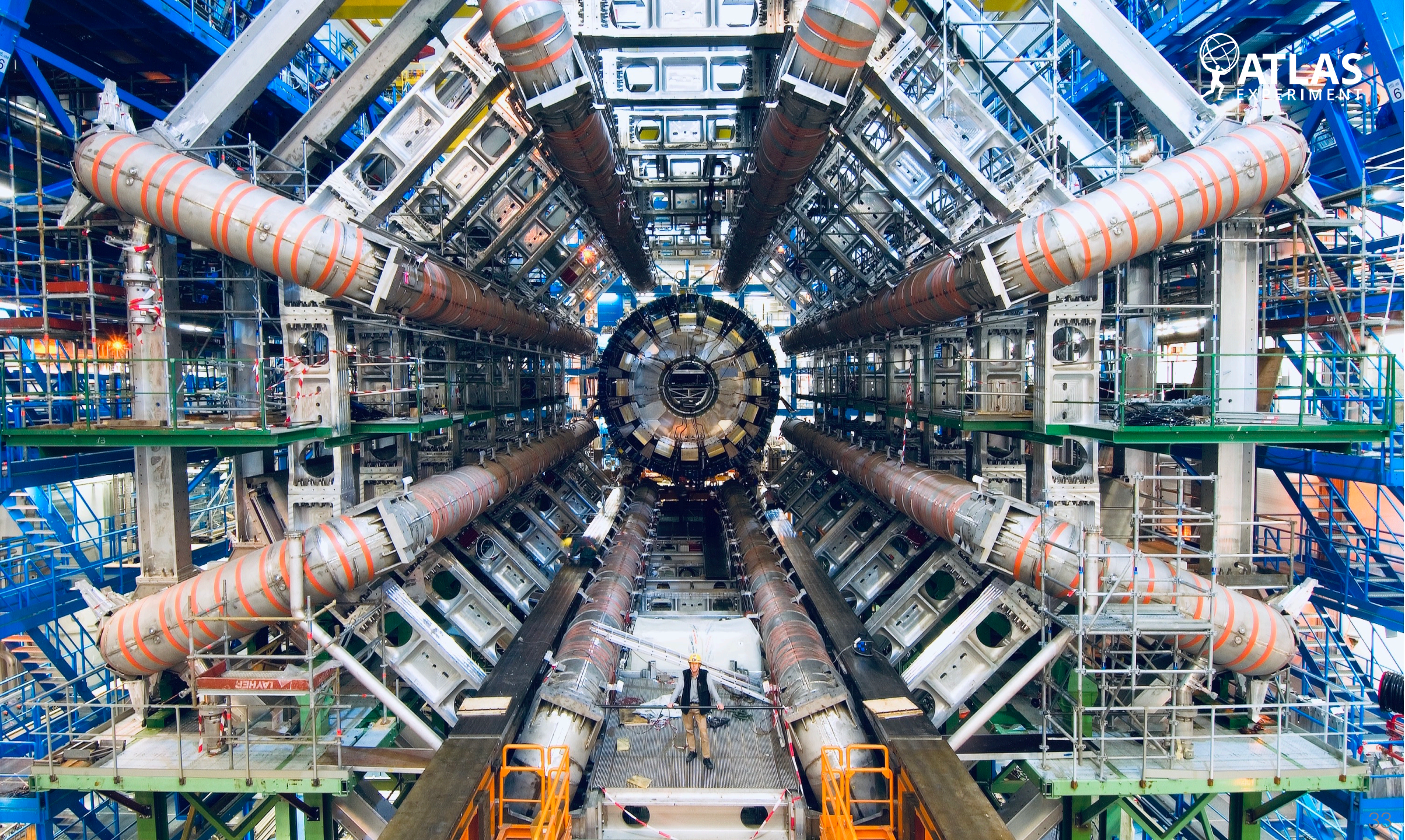


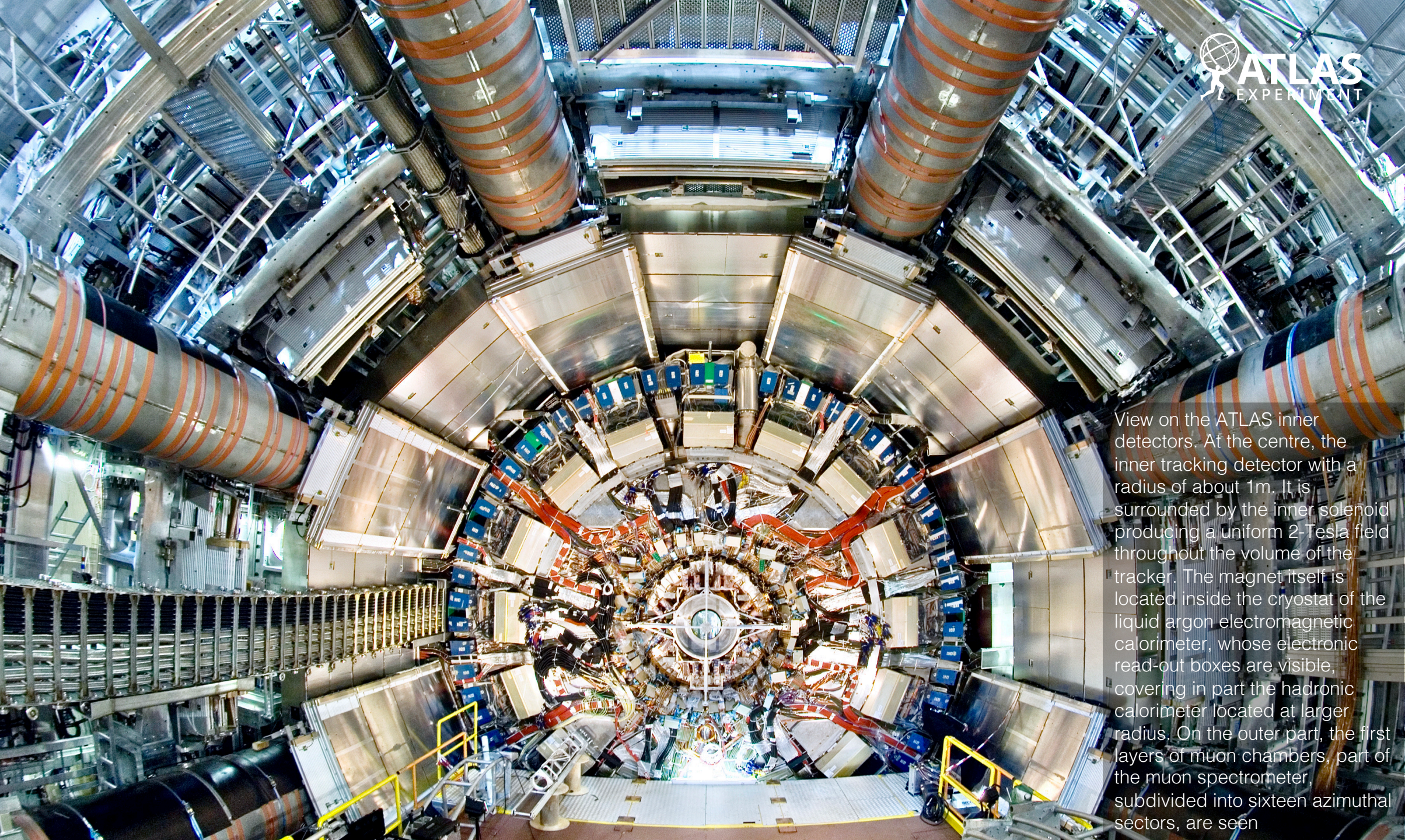
ATLAS Detector construction and installation



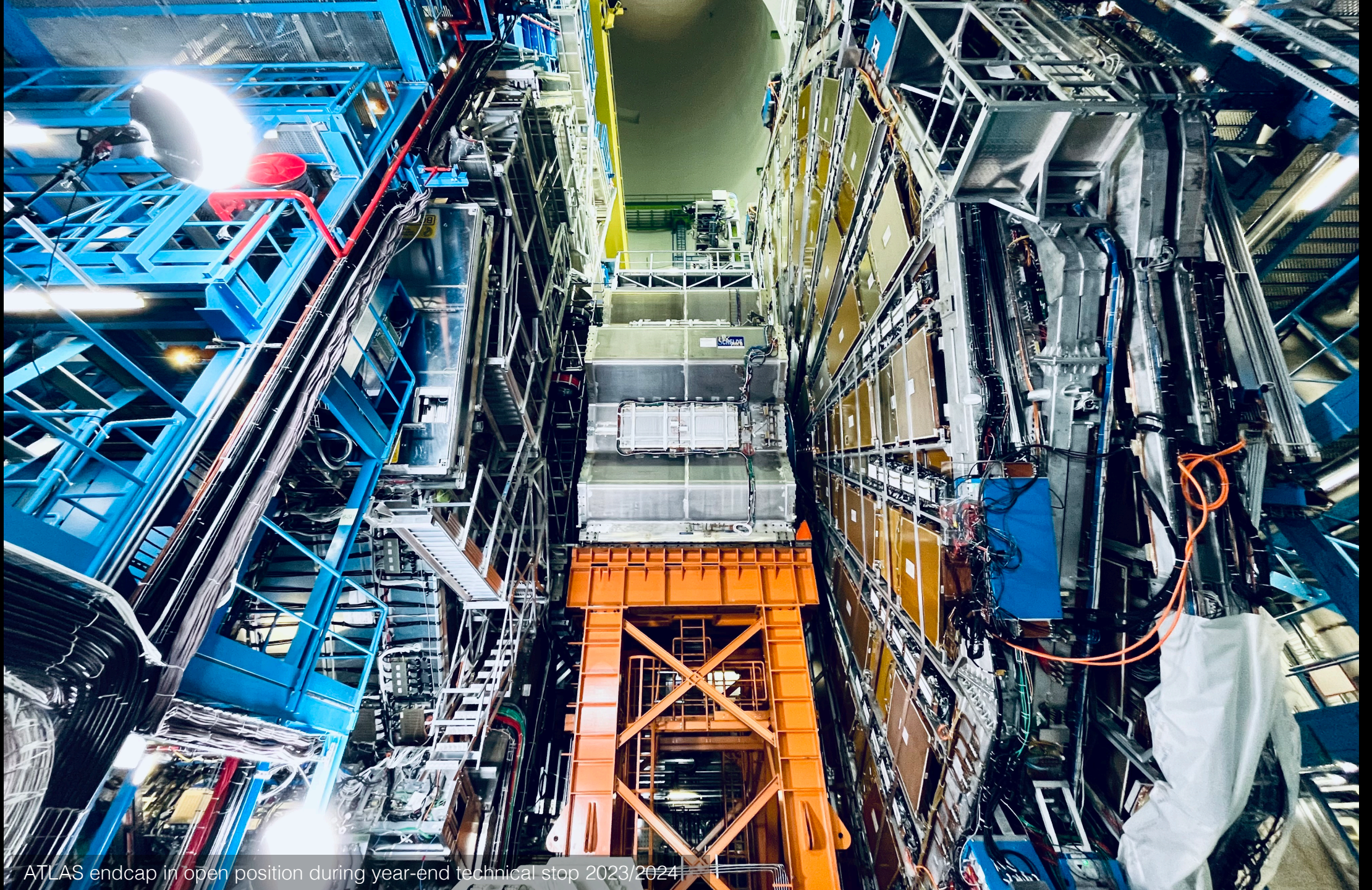
ATLAS cavern after excavation in July 2002

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





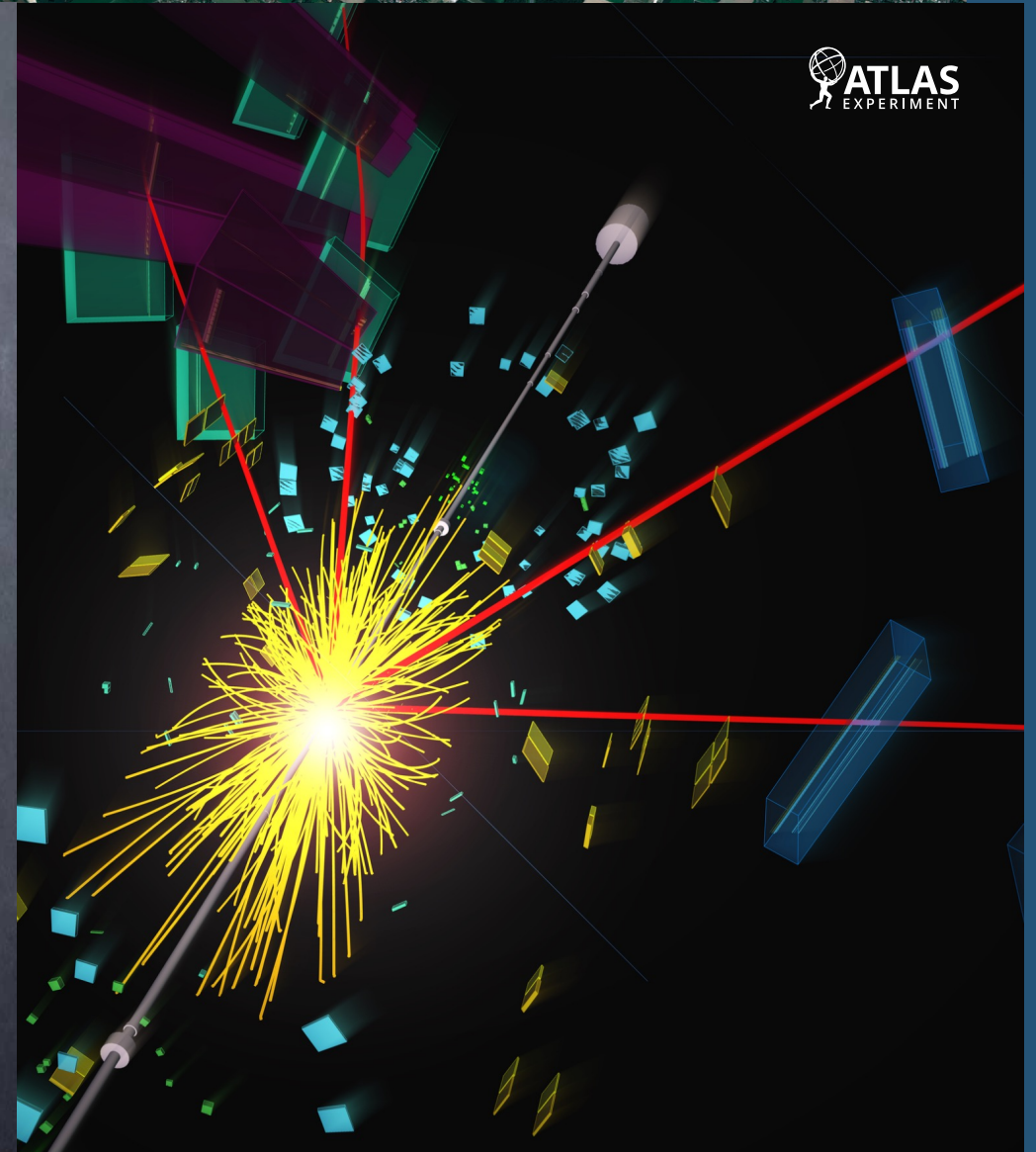
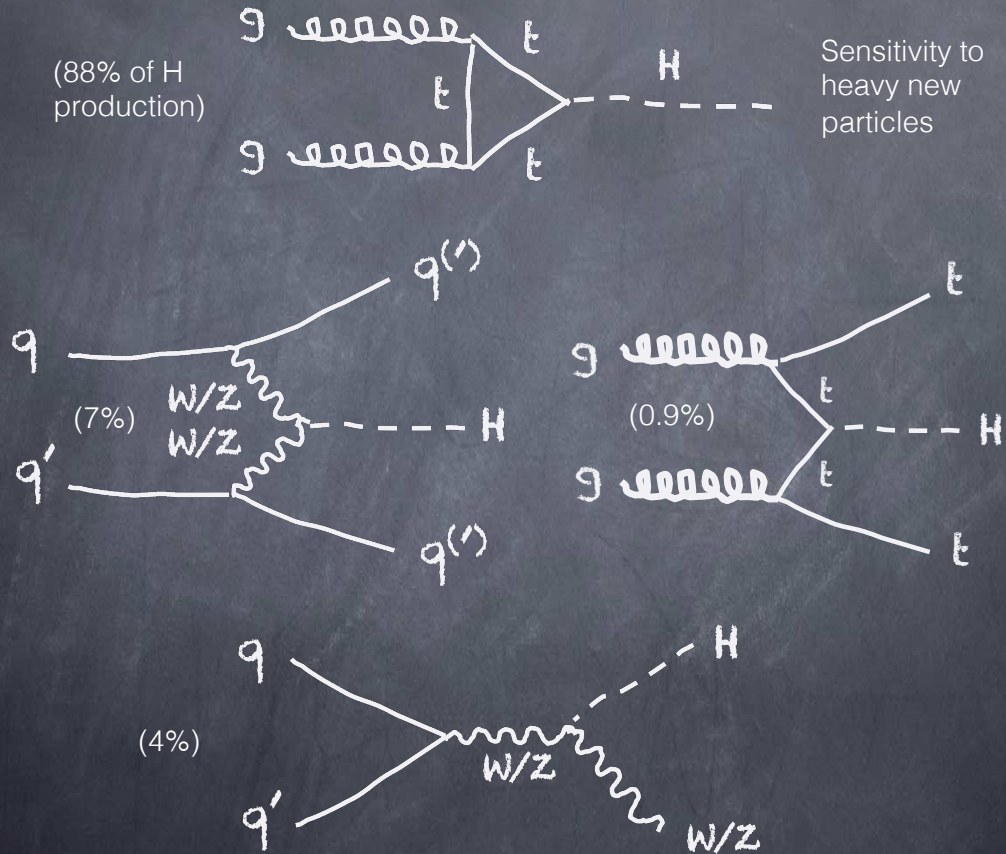
View on the ATLAS inner detectors. At the centre, the inner tracking detector with a radius of about 1m. It is surrounded by the inner solenoid producing a uniform 2-Tesla field throughout the volume of the tracker. The magnet itself is located inside the cryostat of the liquid argon electromagnetic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

Higgs boson production in the Standard Model

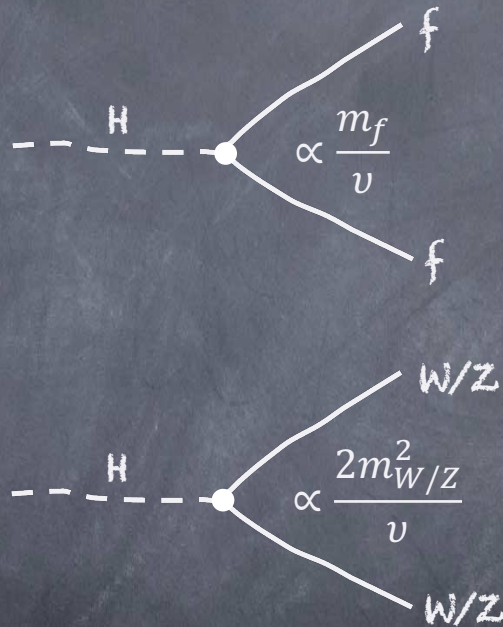
About 1 Higgs boson per second is produced in ATLAS at the LHC (about 12M total by today)



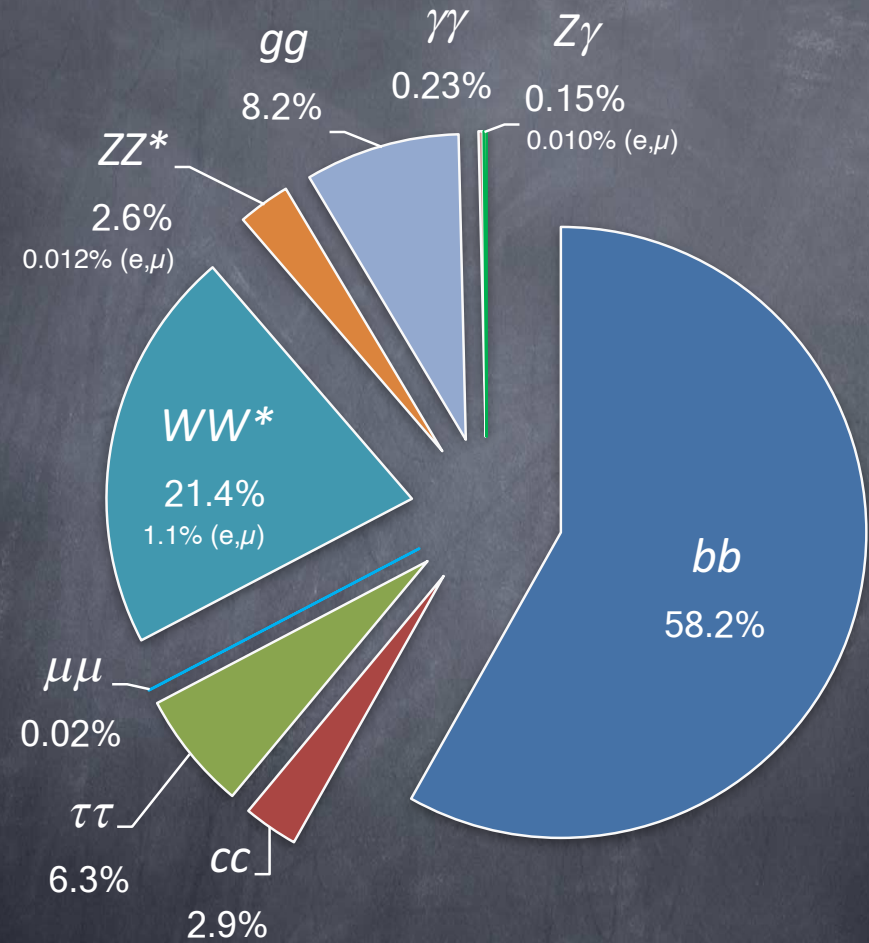
Higgs boson production in the Standard Model

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

It decays within 10^{-22} s



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



Higgs boson production in the Standard Model

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

It decays within 10^{-22} s

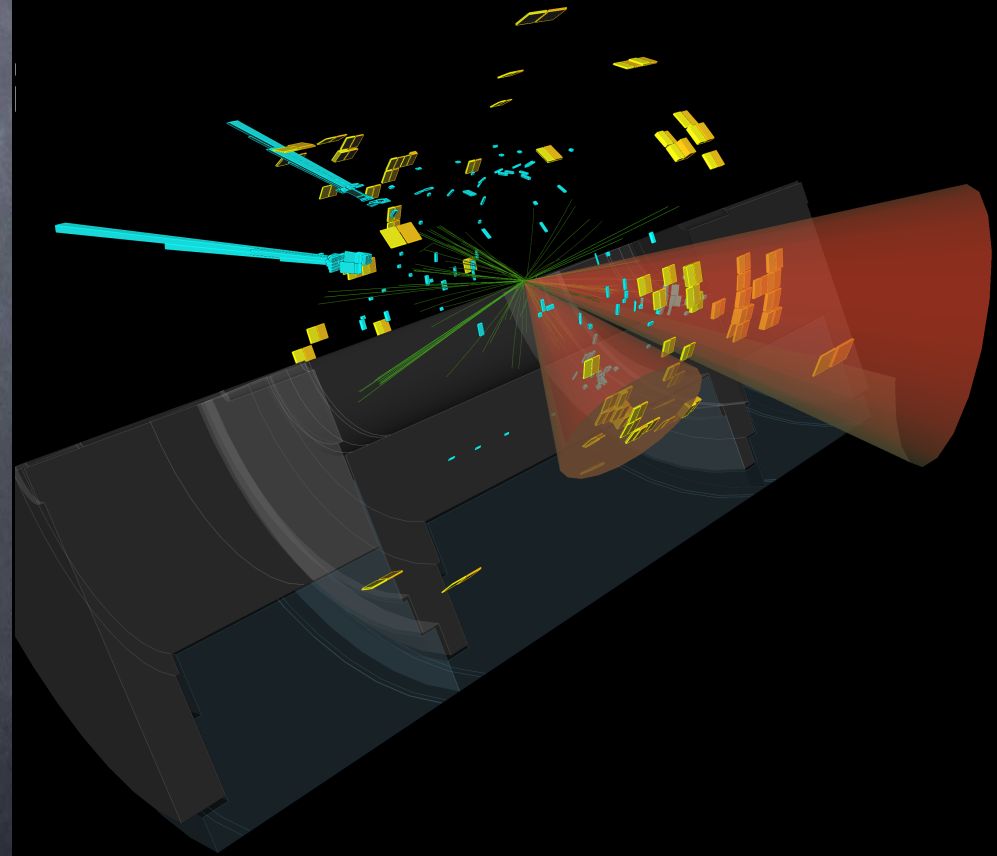
It should also interact with itself



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

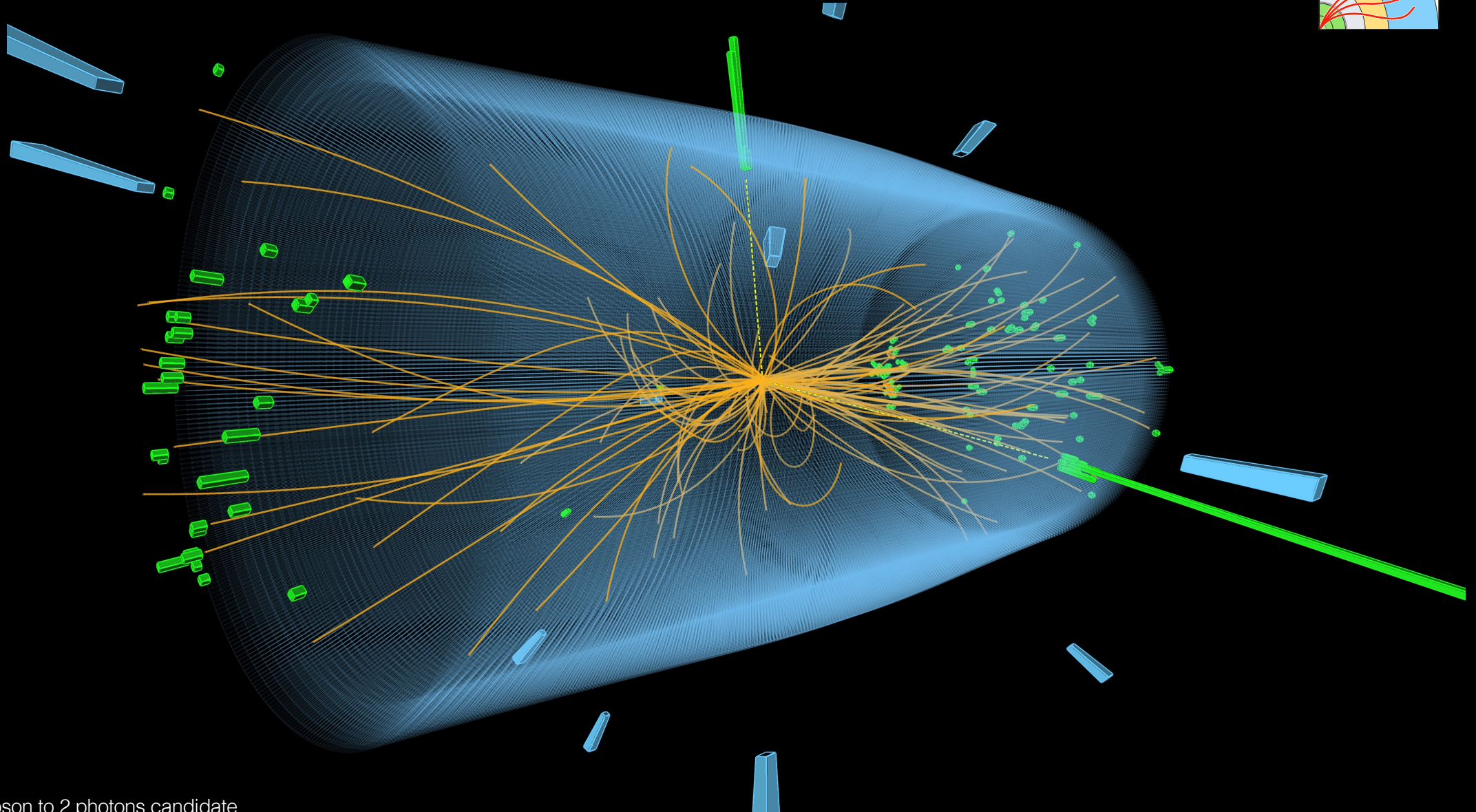
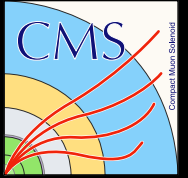
$$V(\phi) = -\mu^2|\phi|^2 + \lambda|\phi|^4$$

HH production > 1000 times rarer than H!



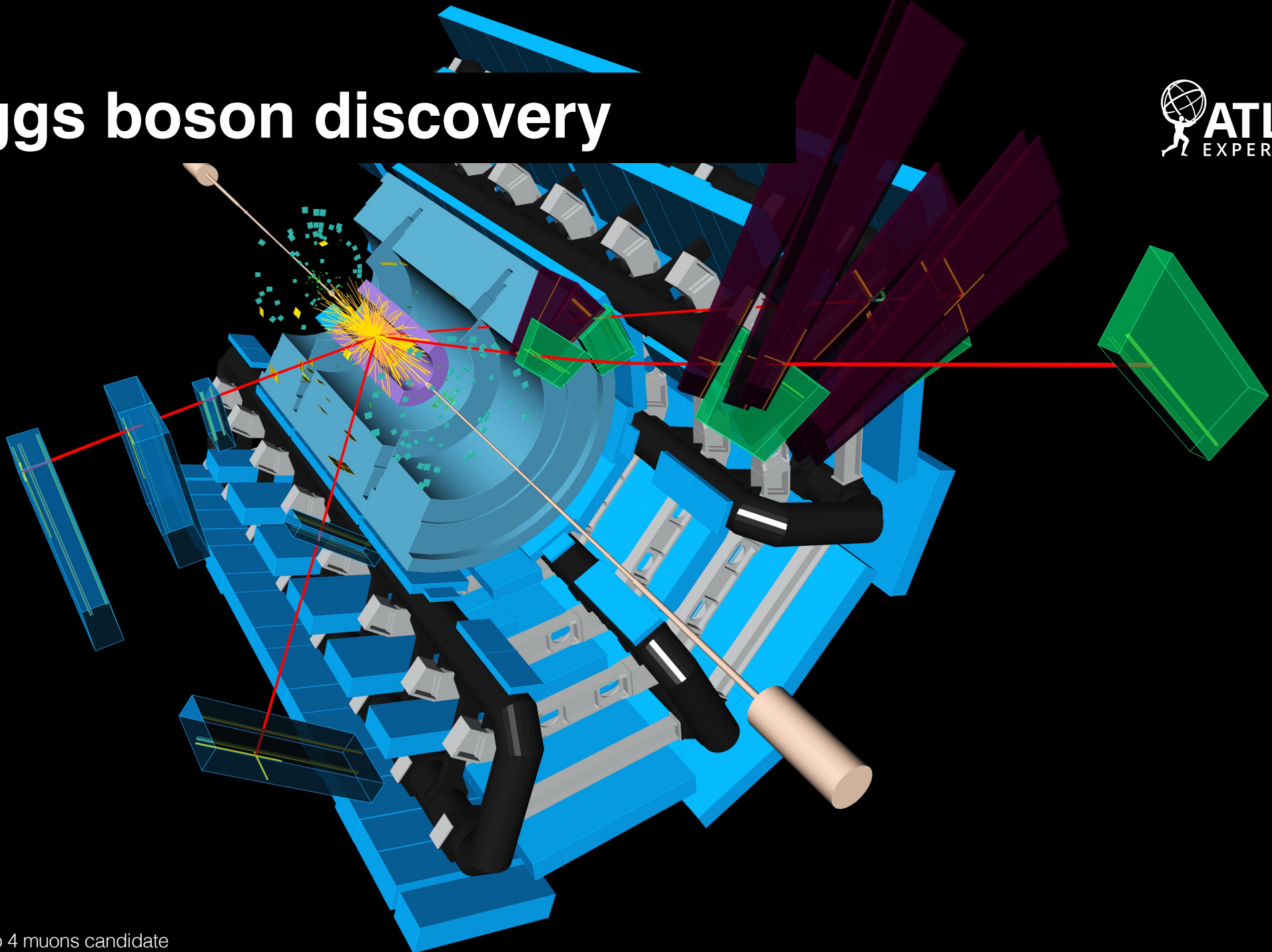
HH $\rightarrow$ bb $\tau\tau$ candidate event recorded in 2017

Higgs boson discovery



A Higgs boson to 2 photons candidate

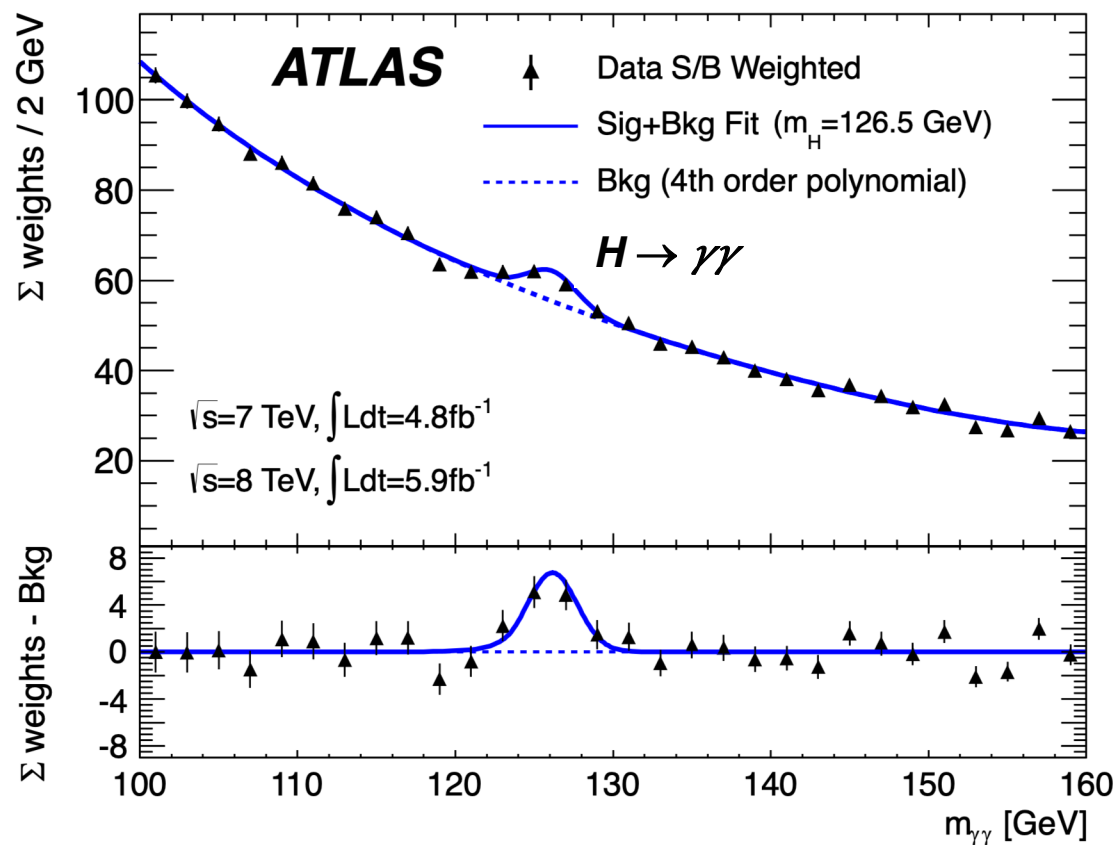
Higgs boson discovery



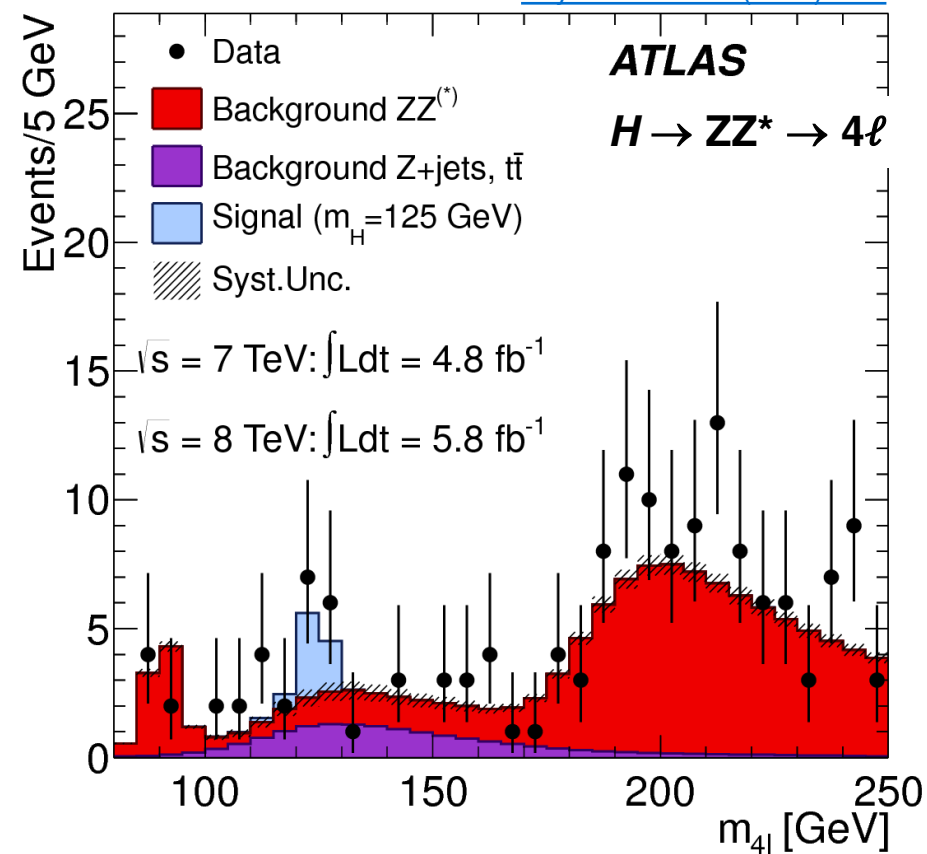
A Higgs boson to 4 muons candidate

Higgs boson discovery

2012



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



Higgs boson discovery

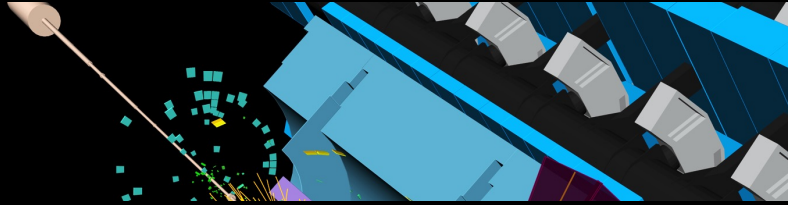


Fabiola Gianotti (ATLAS Spokesperson) and Peter Higgs, 4 July 2012



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

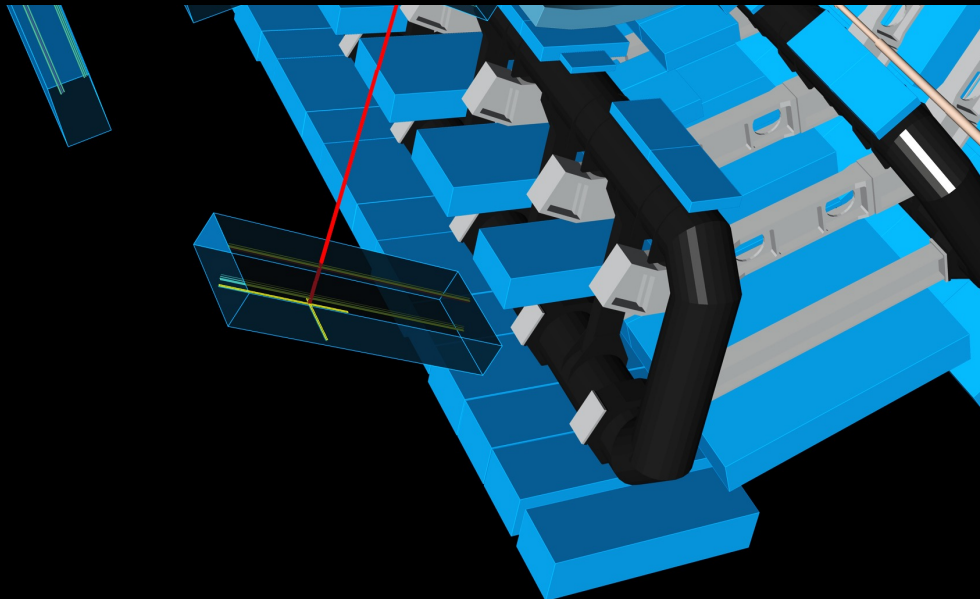
The Higgs boson



The LHC's magnum opus

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

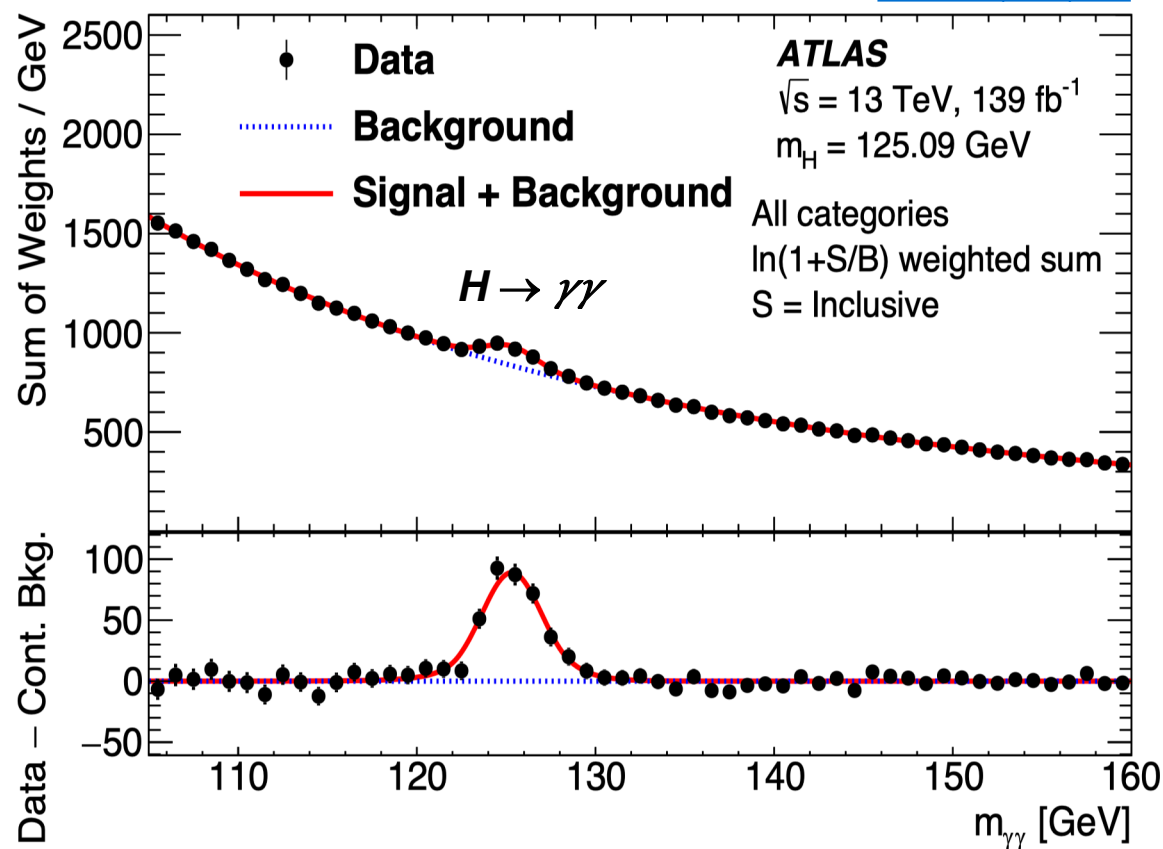
Spin-parity of 0^+ was quickly confirmed using angular analyses. Deeper studies required much more data



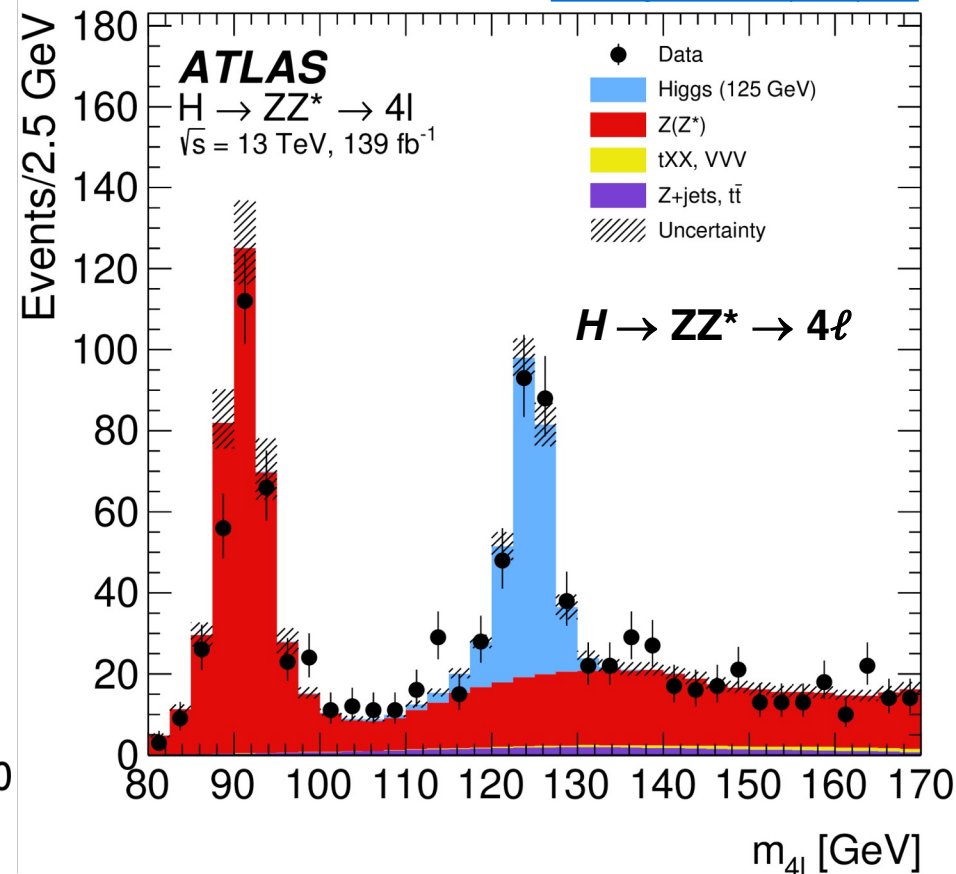
The Higgs boson — At 10

2020

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



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

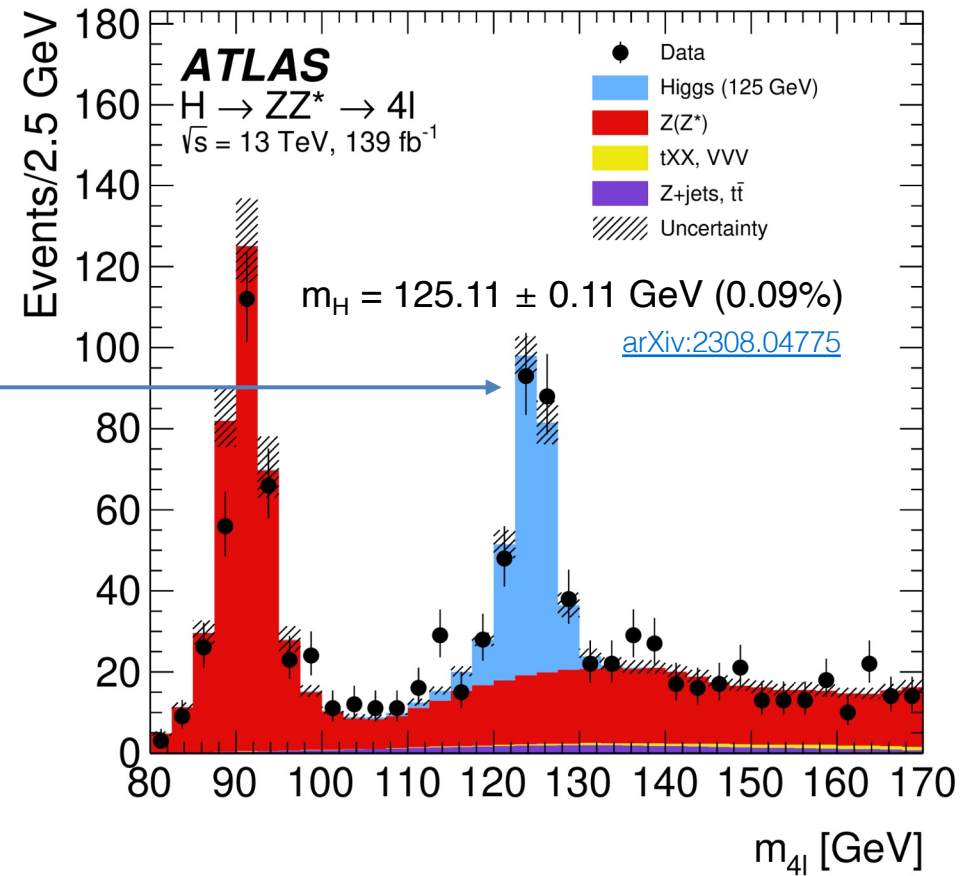


Higgs boson mass

The Higgs mass is peculiar

2020

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

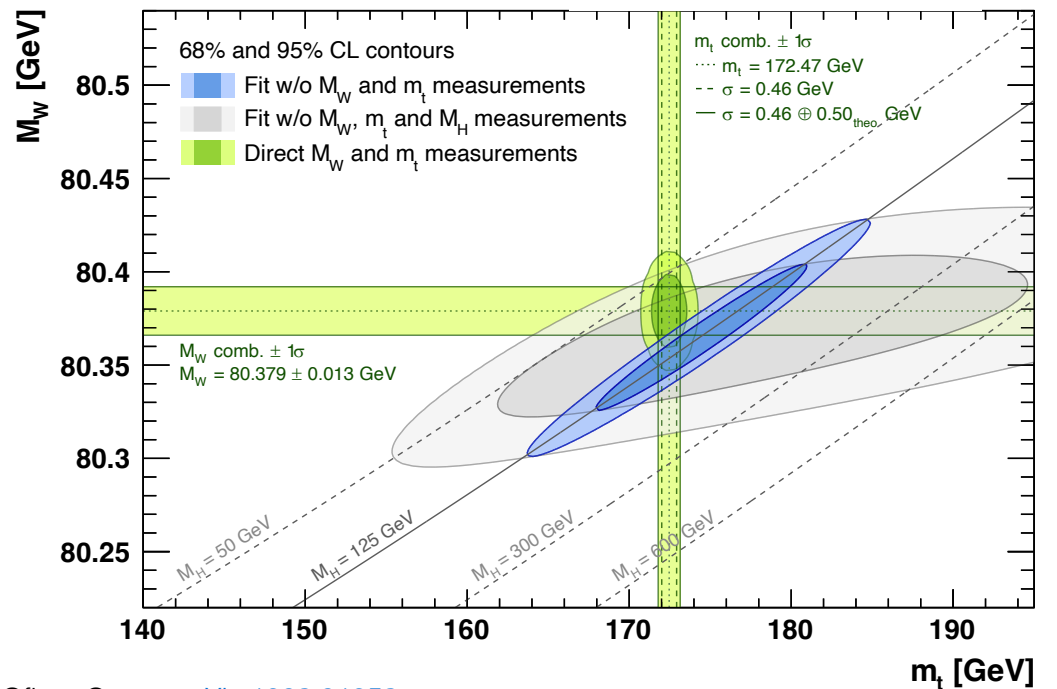
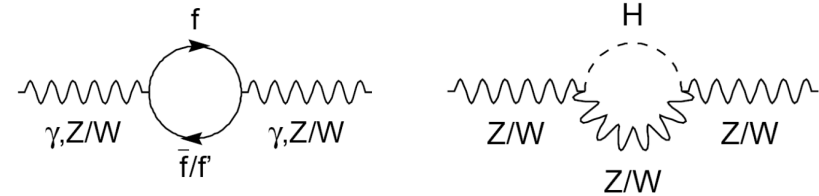


Higgs boson mass

The Higgs mass is peculiar

- It is consistent with the global electroweak fit

Radiative corrections sensitive to heavy particles in loop



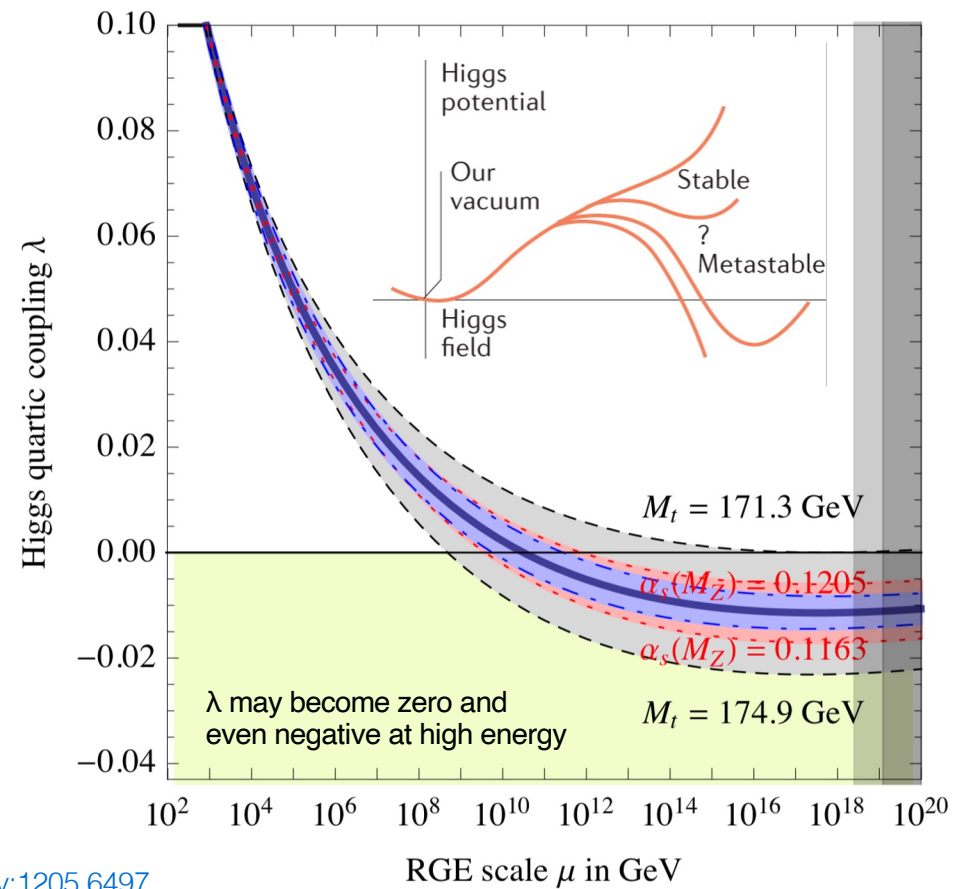
Gfitter Group: [arXiv:1803.01853](https://arxiv.org/abs/1803.01853)

Higgs boson mass

The Higgs mass is peculiar

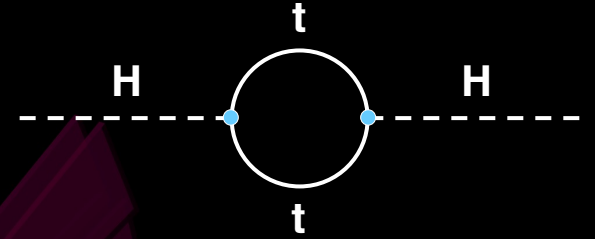
- It is consistent with the global electroweak fit
- But the electroweak vacuum seems to be metastable

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 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	3%	✓	✓	✓	✓	✓
WW	22%	✓	✓	✓	✓	✓
$\tau\tau$	6.3 %	✓	✓	✓	✓	✓
bb	55%	✓	✓	✓	✓	✓
$Z\gamma$ (& $\gamma\gamma^*$)	0.2 %	✓	✓	✓	✓	✓
$\mu\mu$	0.02 %	✓	✓	✓	✓	✓

In grey: evidence for decays, but not observed yet

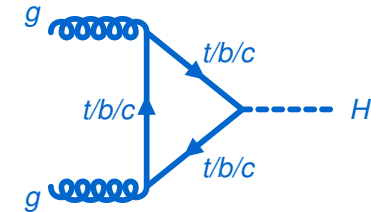
Theory predictions

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

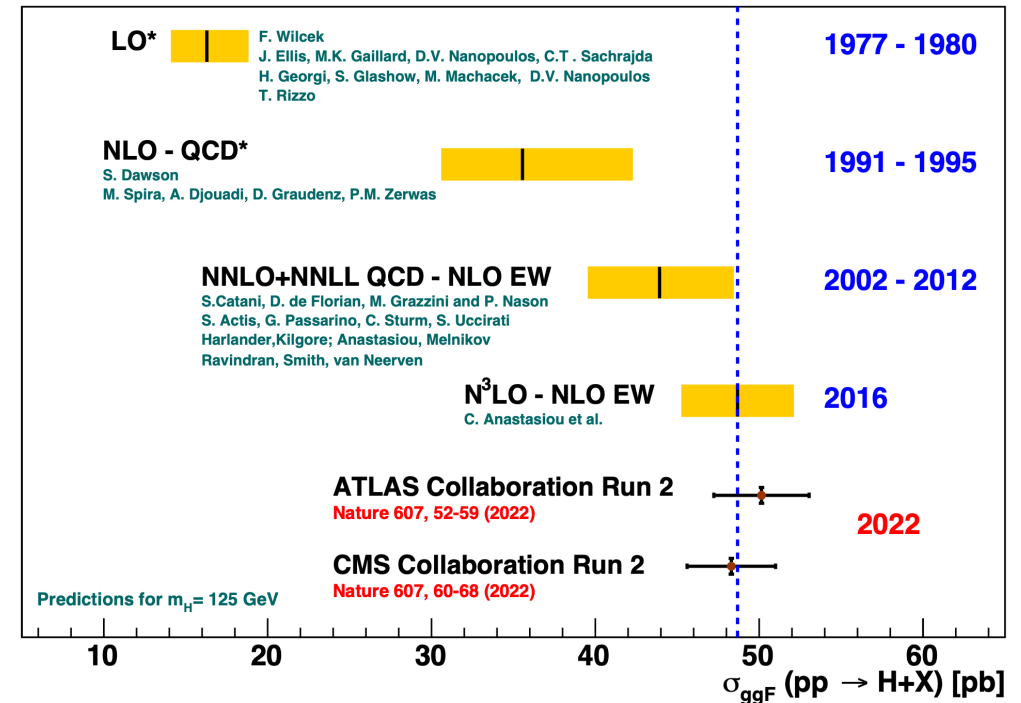
The LHC has become a precision measurements machine, this would not have been possible without the huge efforts of the theory community

Calculations of Higgs boson production via gluon fusion versus time

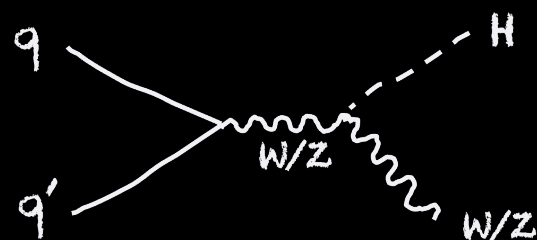
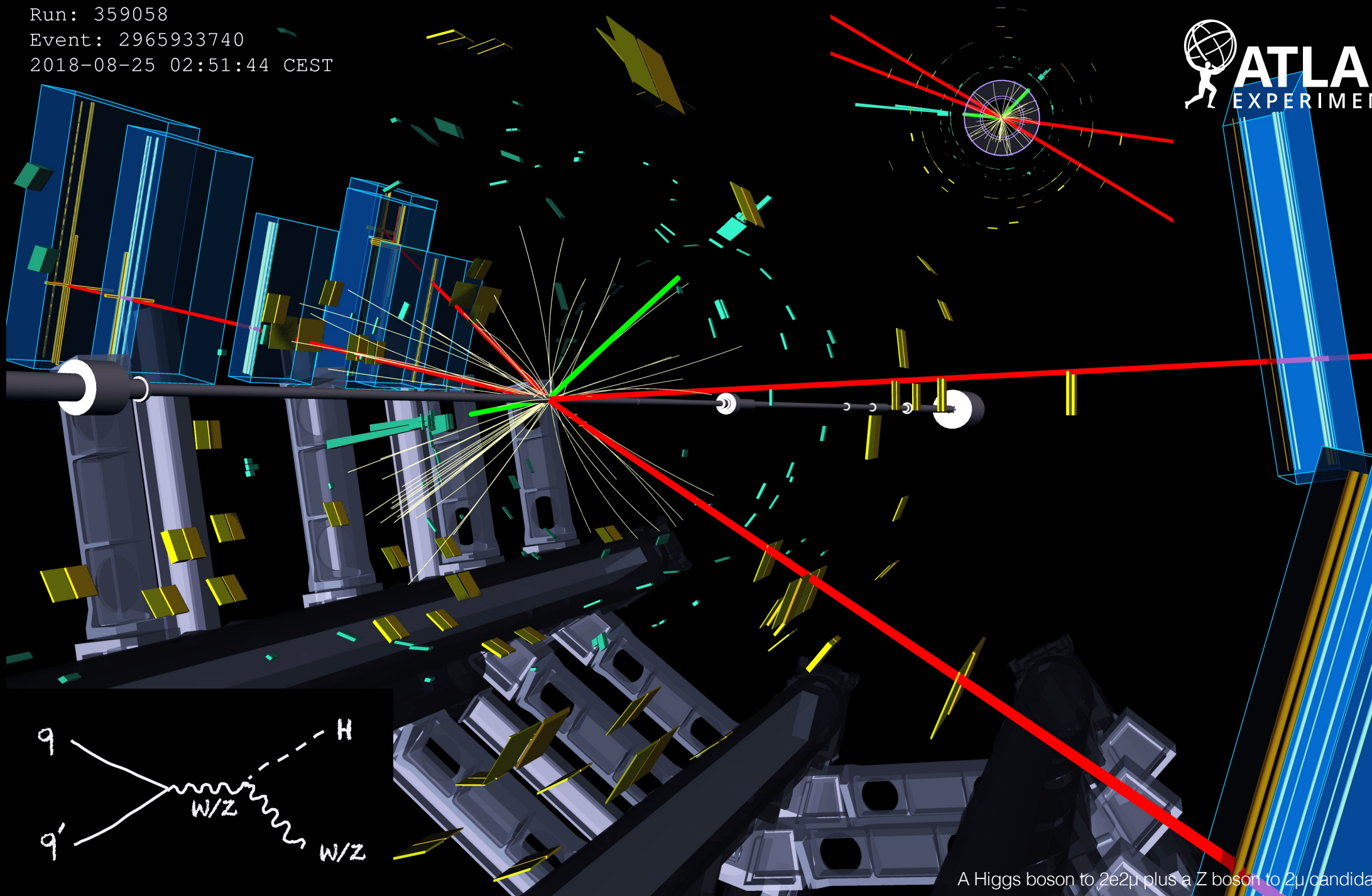


$\sqrt{s} = 13 \text{ TeV}$

* From iHixs

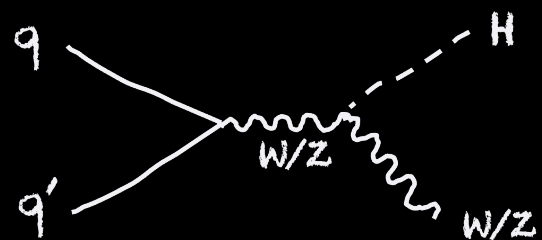


Run: 359058
Event: 2965933740
2018-08-25 02:51:44 CEST



A Higgs boson to 2γ plus a Z boson to 2μ candidate event

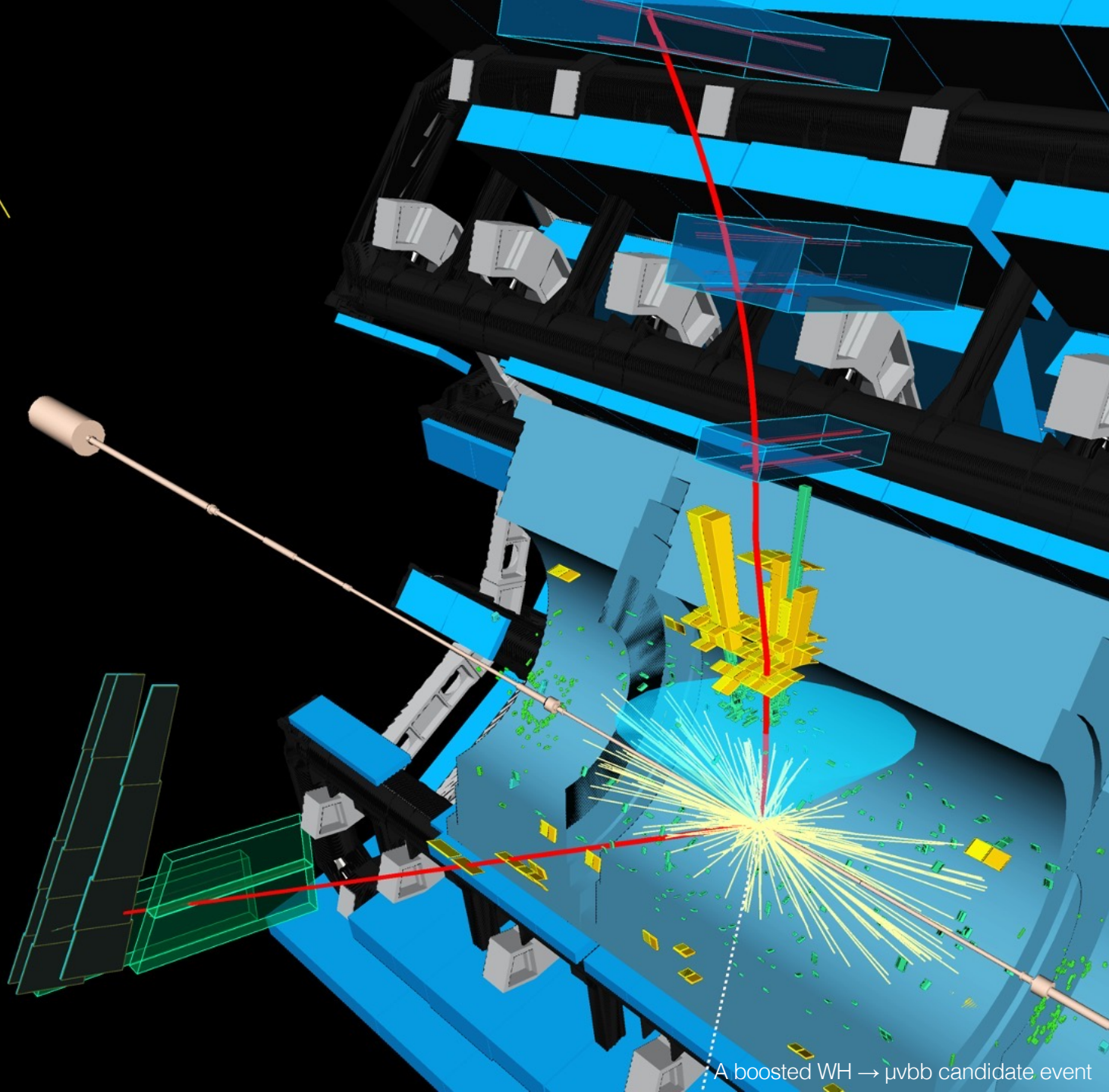
$H \rightarrow bb$



Run: 338349

Event: 616525246

2017-10-16 20:24:46 CEST

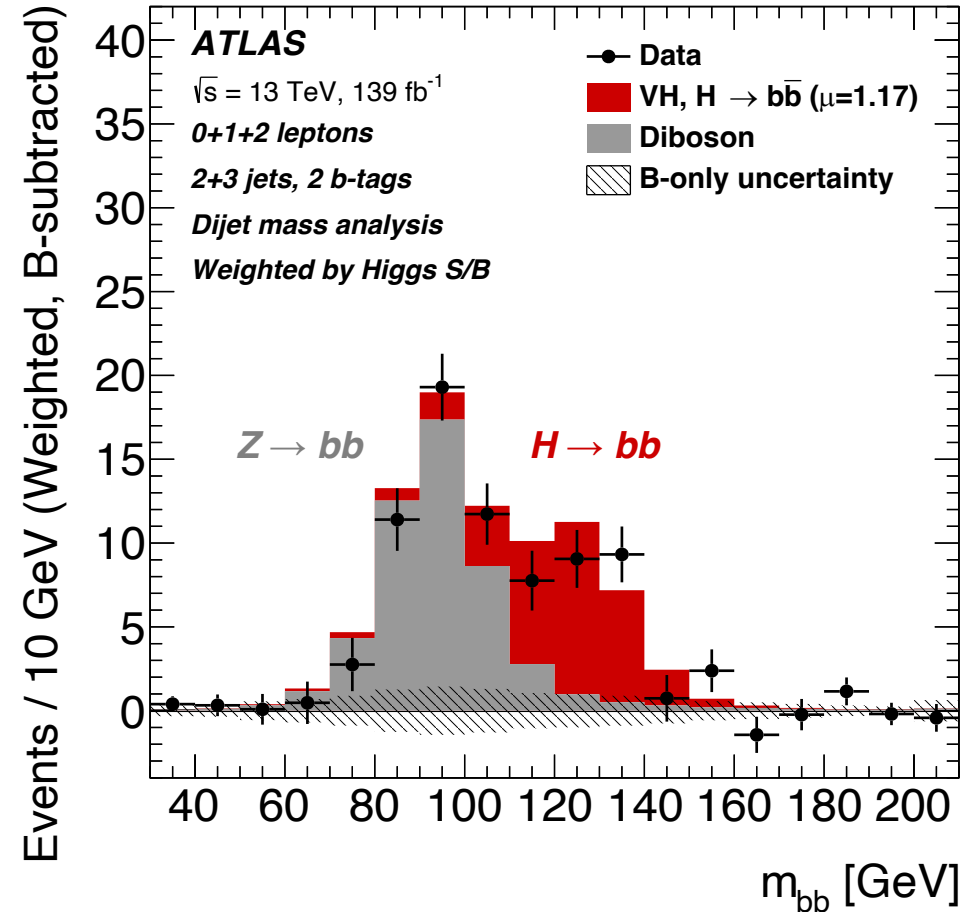
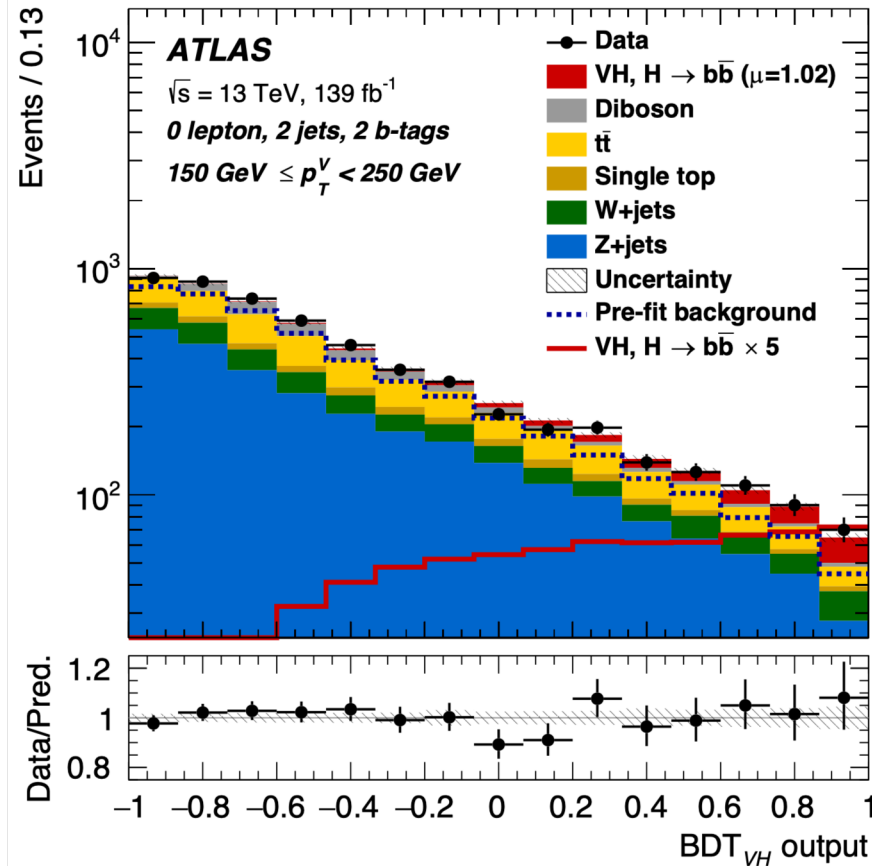


A boosted $WH \rightarrow \mu b b$ candidate event

$H \rightarrow b\bar{b}$

Measurement of $H \rightarrow b\bar{b}$ via associated production $pp \rightarrow W/Z + H$ and leptonic W/Z decays

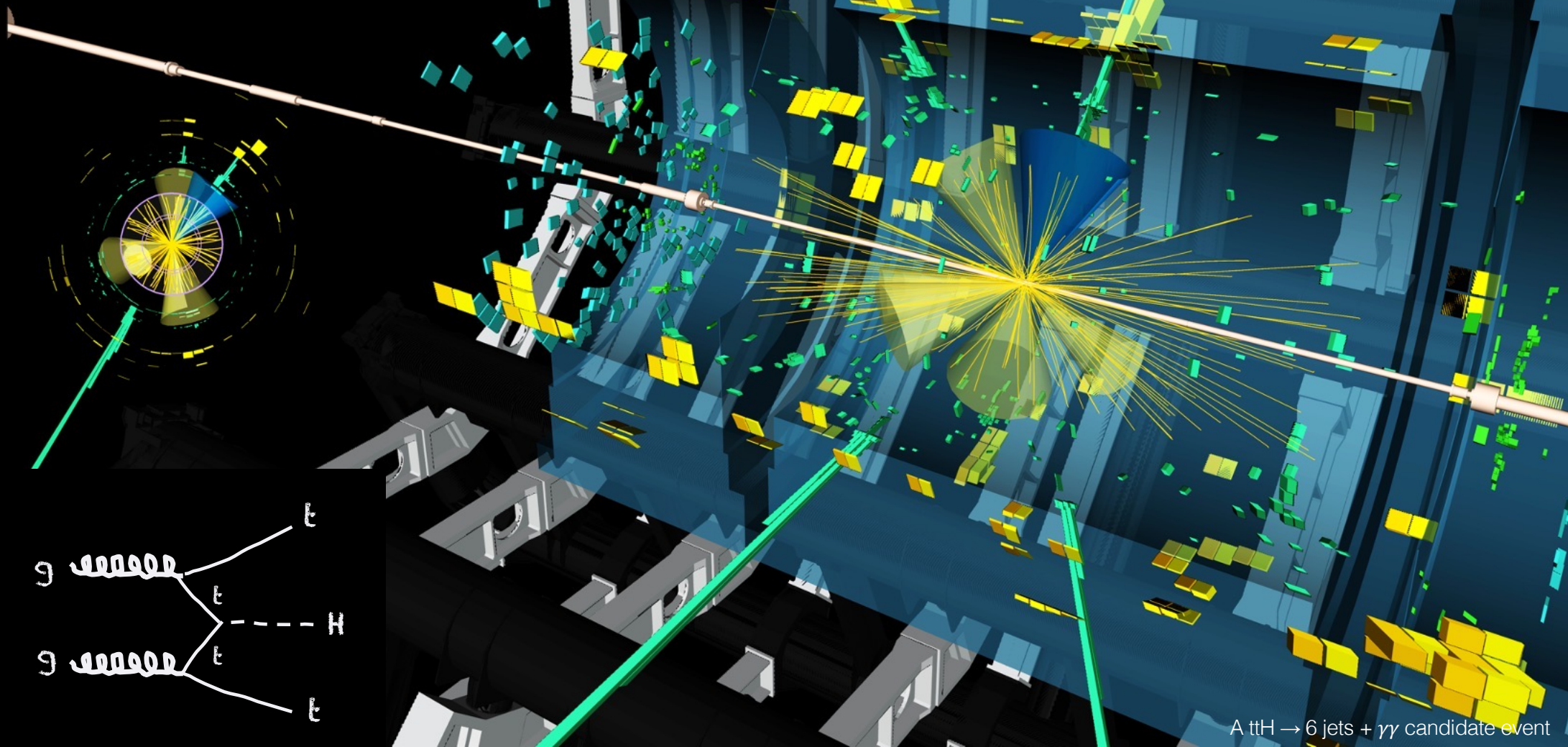
Highly complex analyses requiring excellent control of background processes and signal purification with machine learning



ttH



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

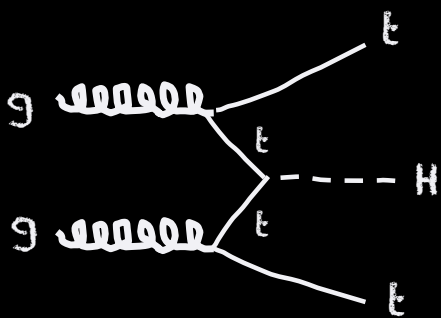
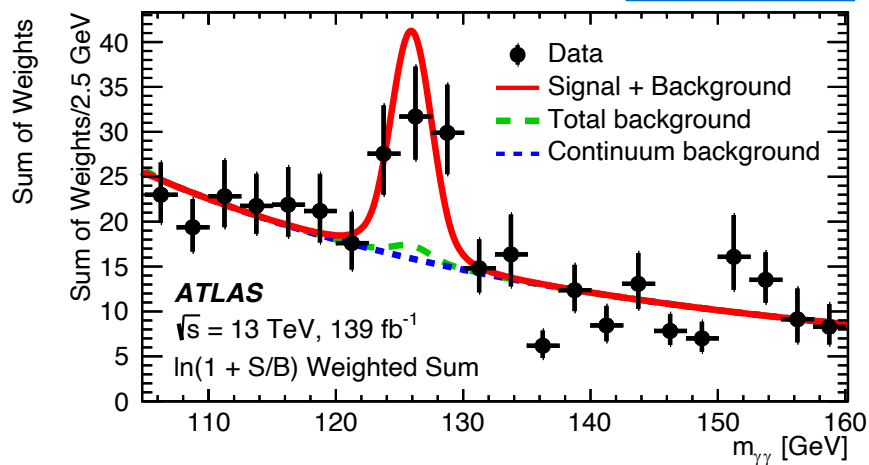


A $ttH \rightarrow 6 \text{ jets} + \gamma\gamma$ candidate event

$t\bar{t}H$

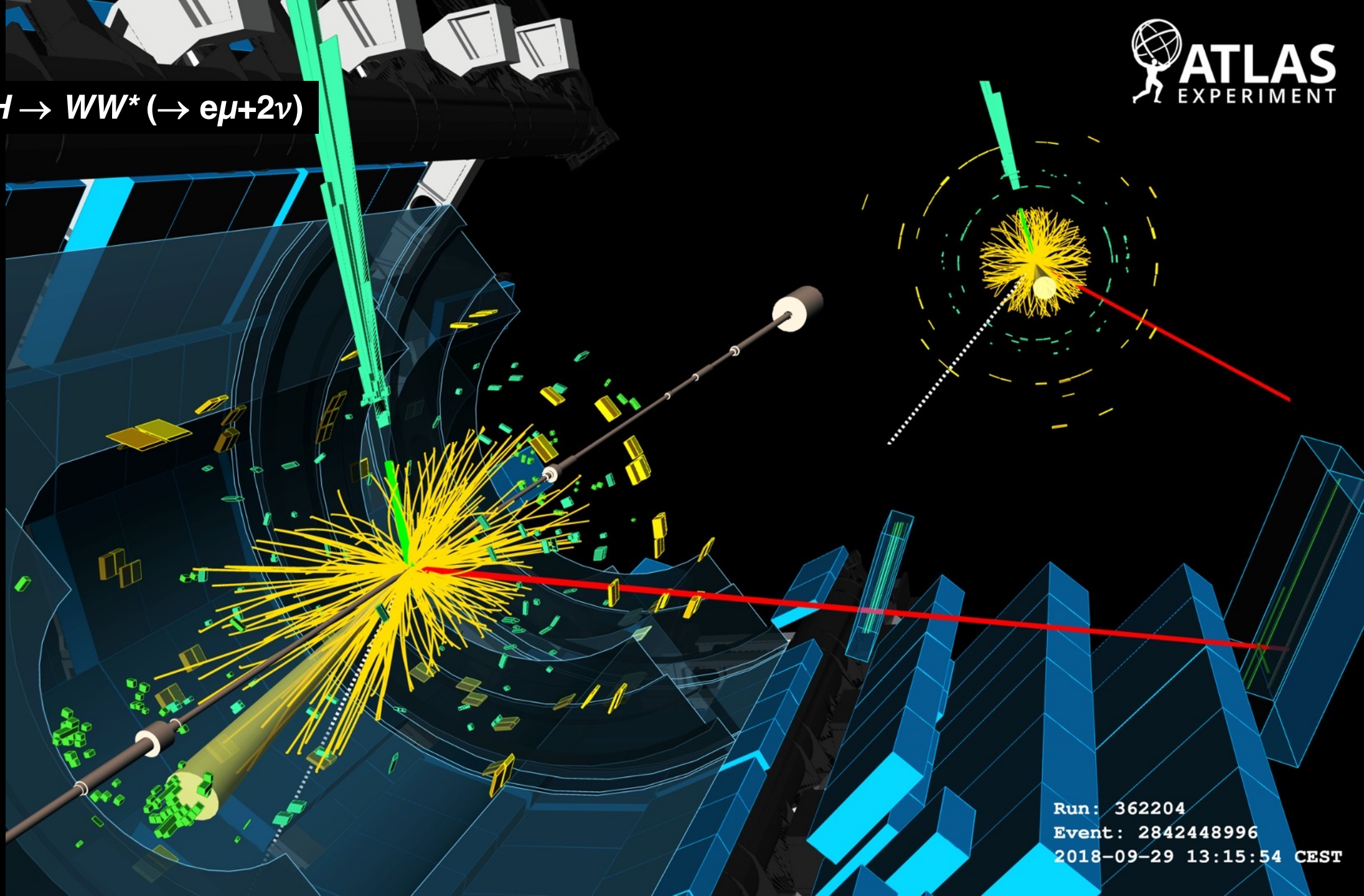
$t\bar{t}H$ production features rich events,
 $H \rightarrow \gamma\gamma$ channel most powerful

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



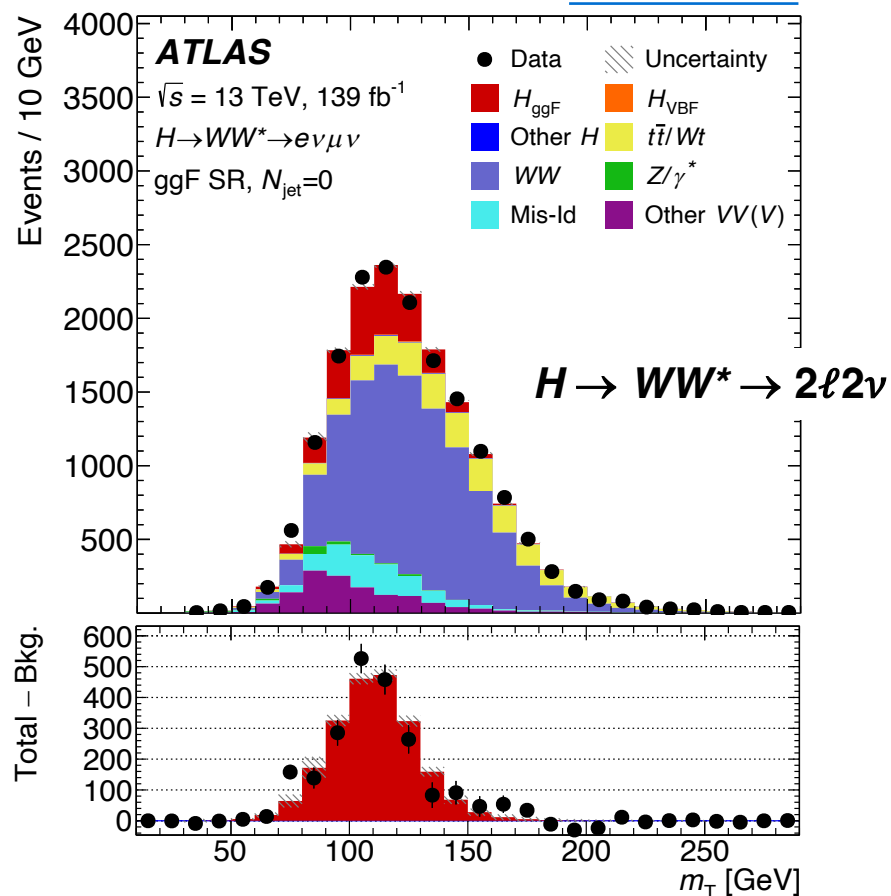
A $t\bar{t}H \rightarrow 6 \text{ jets} + \gamma\gamma$ candidate event

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

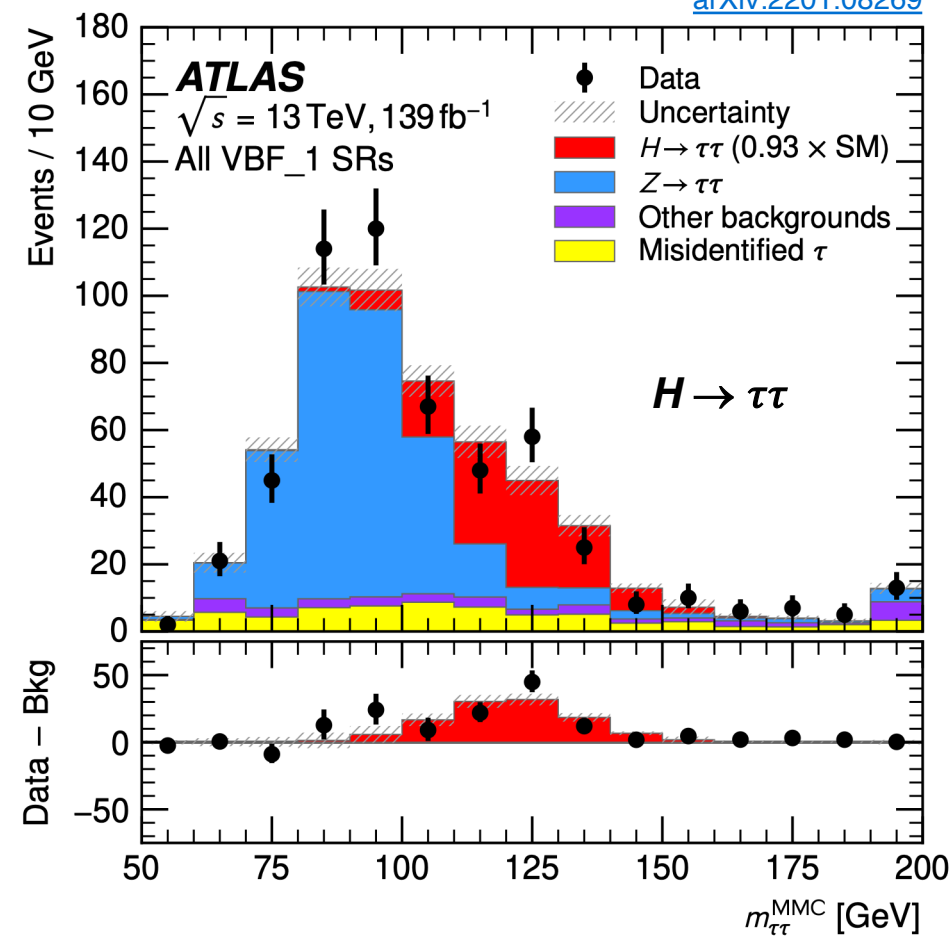


Run : 362204
Event : 2842448996
2018-09-29 13:15:54 CEST

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

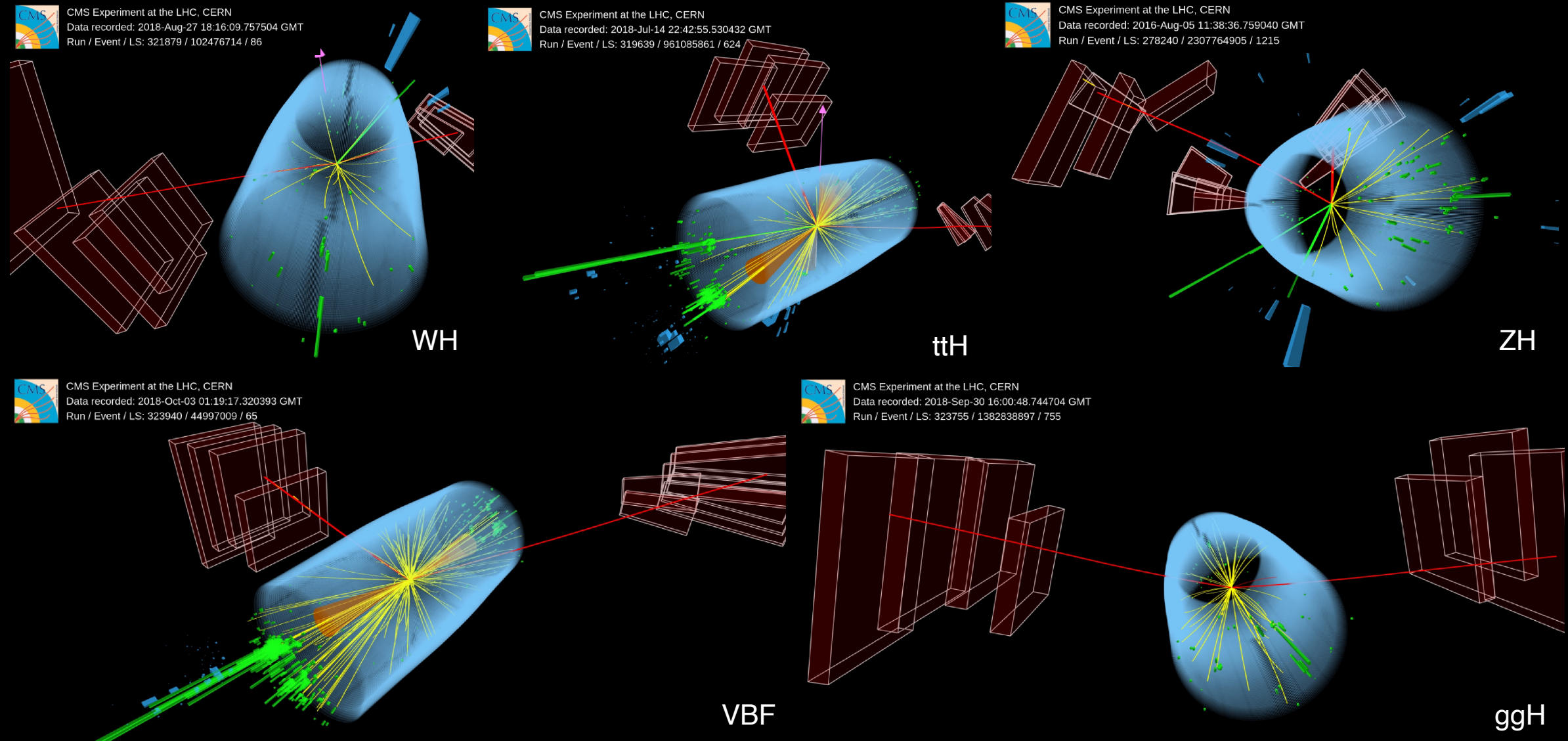


[arXiv:2201.08269](https://arxiv.org/abs/2201.08269)



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

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

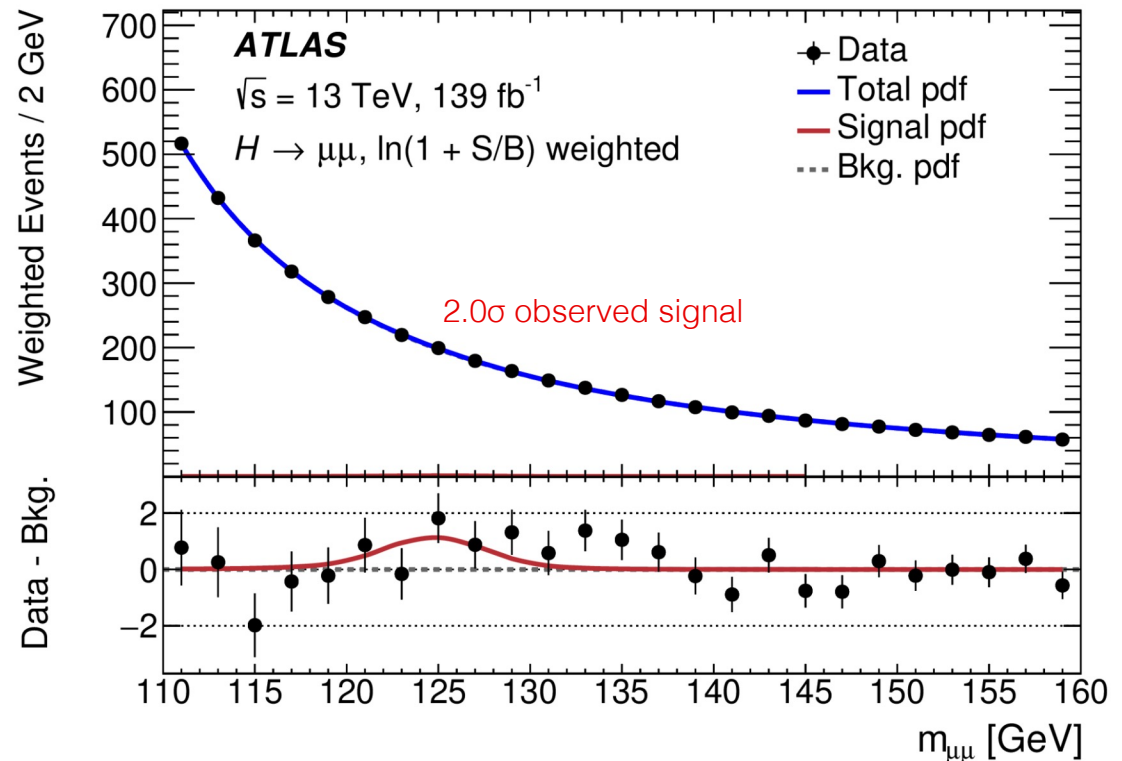
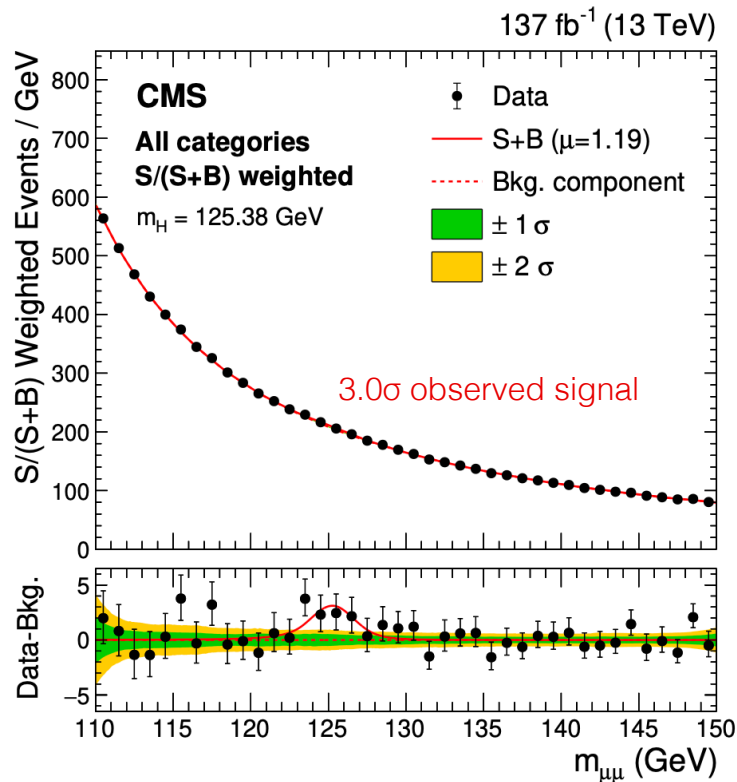


$H \rightarrow \mu\mu$ candidate events

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

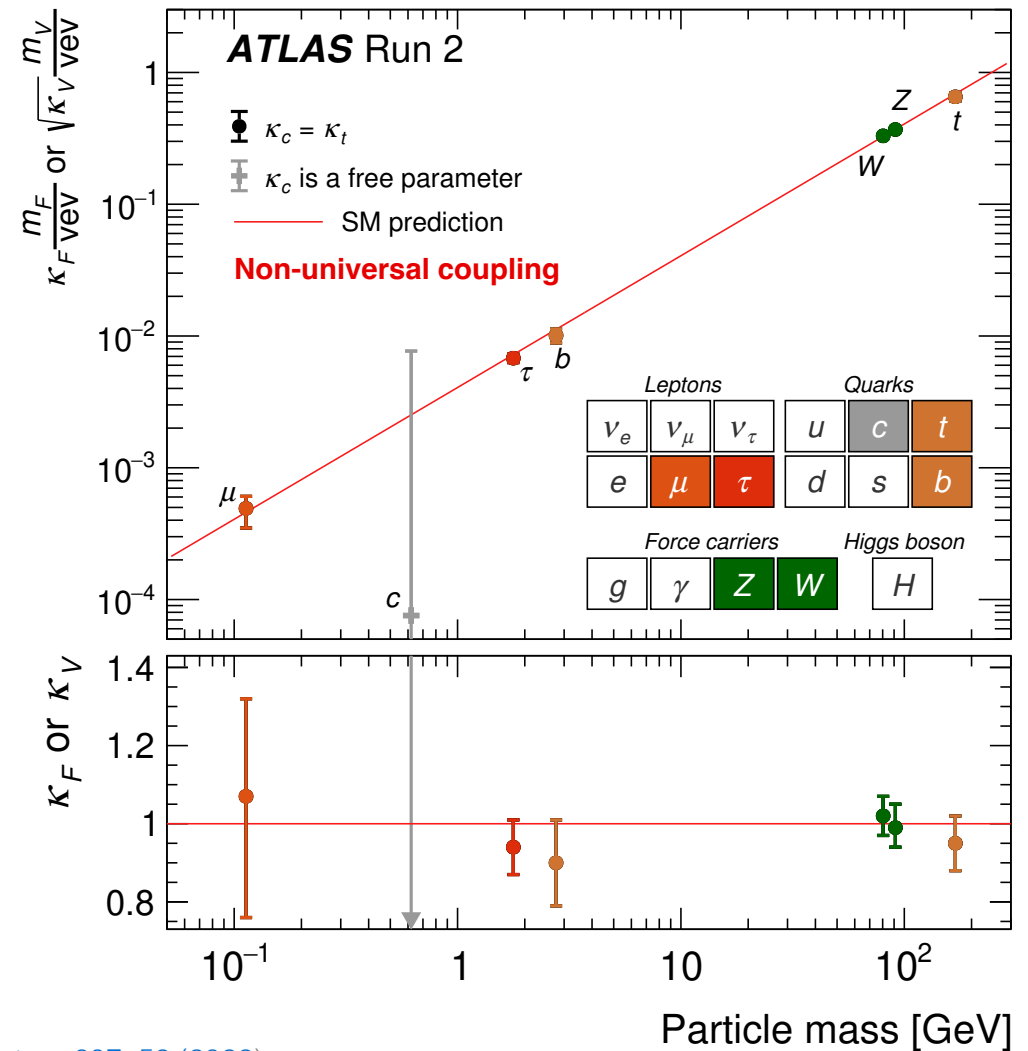
$H \rightarrow \mu\mu$, very challenging channel (0.02% branching fraction)

- 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



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

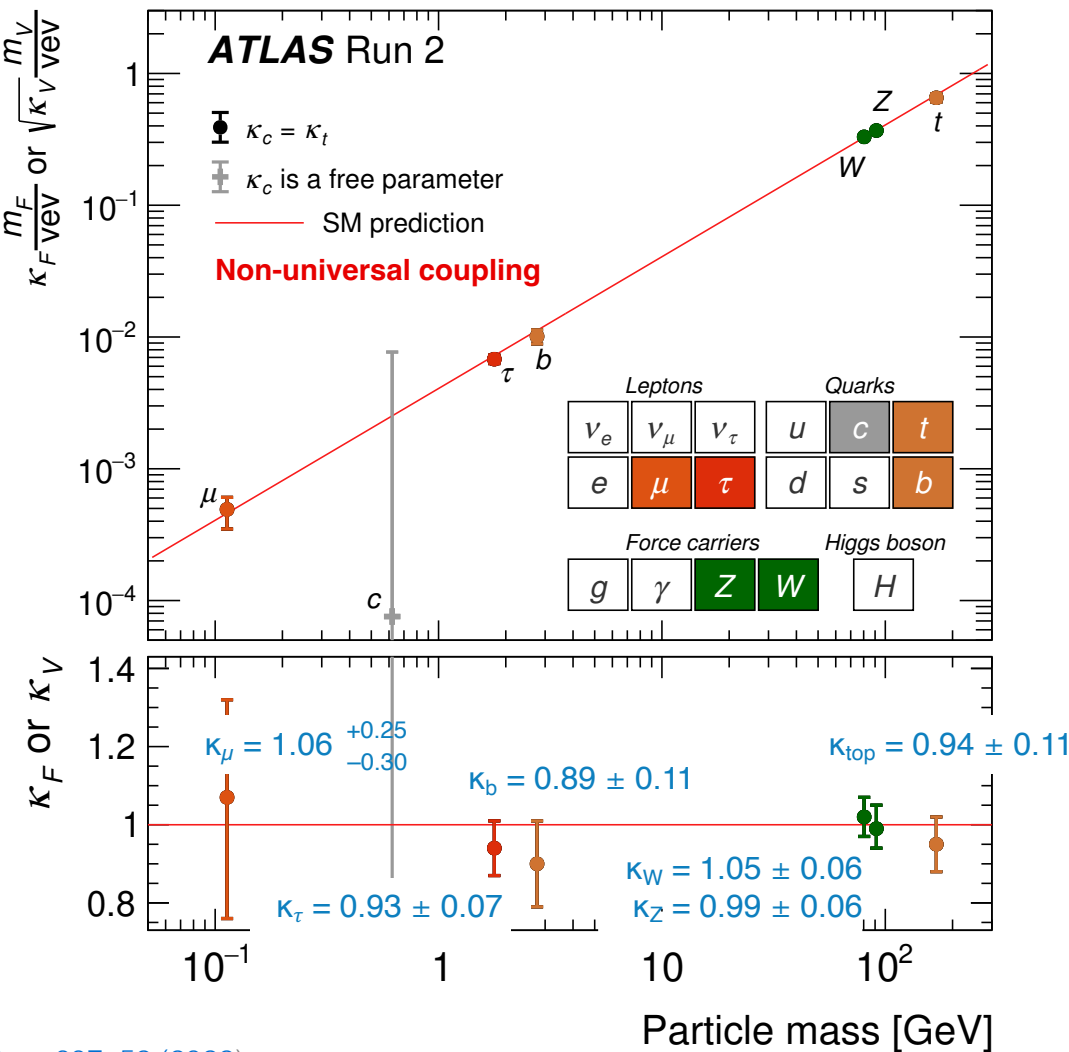


[Nature 607, 52 \(2022\)](#)

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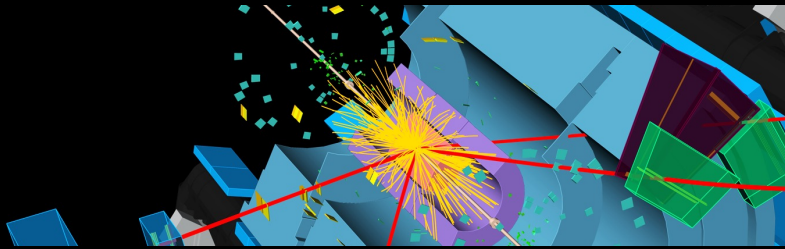
Measurements by ATLAS and CMS have confirmed the non-universal, mass-dependent coupling strengths of the Higgs boson to the SM particles

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



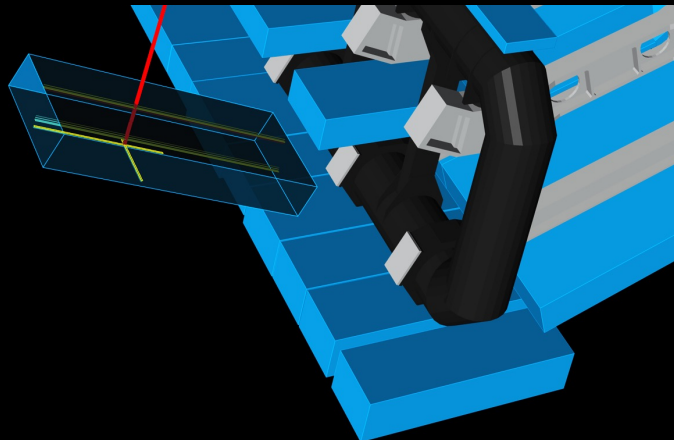
[Nature 607, 52 \(2022\)](#)

The Higgs mechanism is real !



The new sector opens a variety of possibilities and questions

The discovery of an (apparently) fundamental scalar particle, resulting from spontaneous symmetry breaking, fuels renewed interest in other fundamental (pseudo)scalars, such as the **axion**...
(which can be detected from the sun via inverse Primakoff effect!)

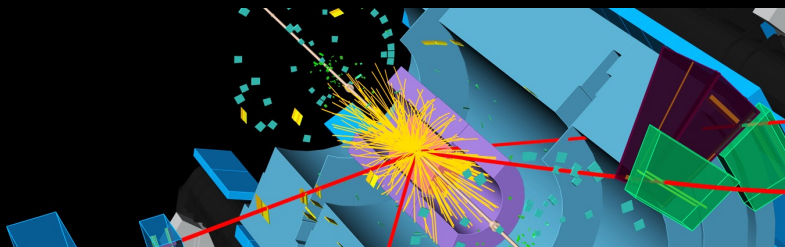


Possible relations between the Higgs boson and open questions in particle physics and cosmology

- 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?

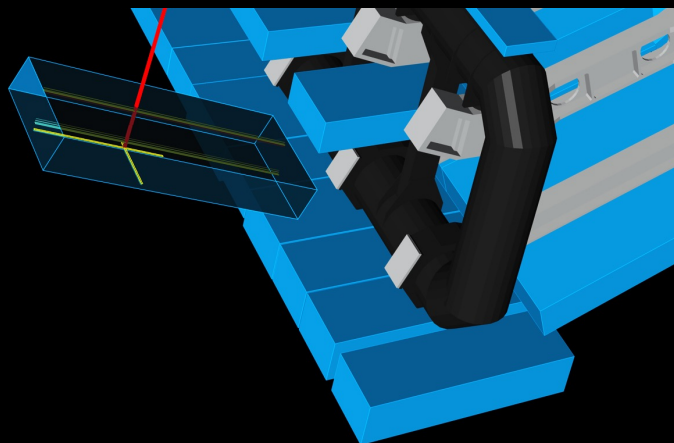
[Salam, Wang, Zanderighi: Nature 607, 41 \(2022\)](#)

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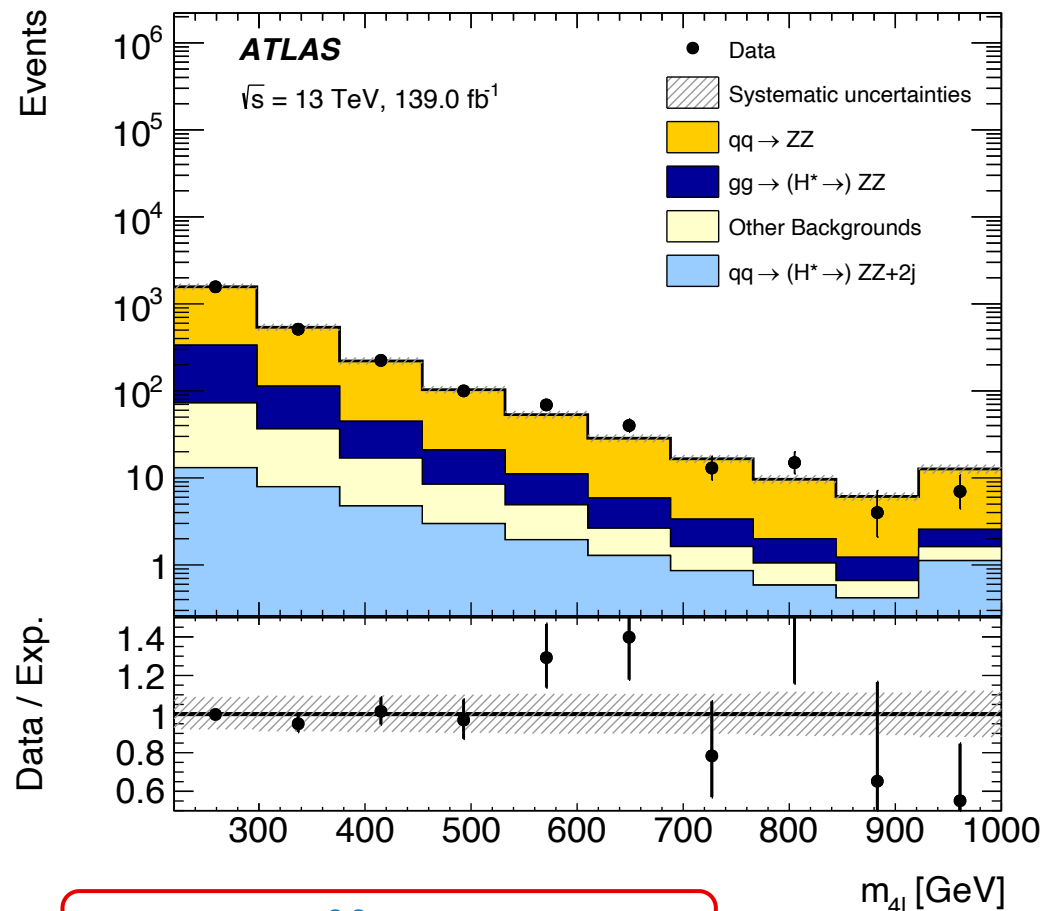
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[Salam, Wang, Zanderighi: Nature 607, 41 \(2022\)](#)

Higgs boson width

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

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

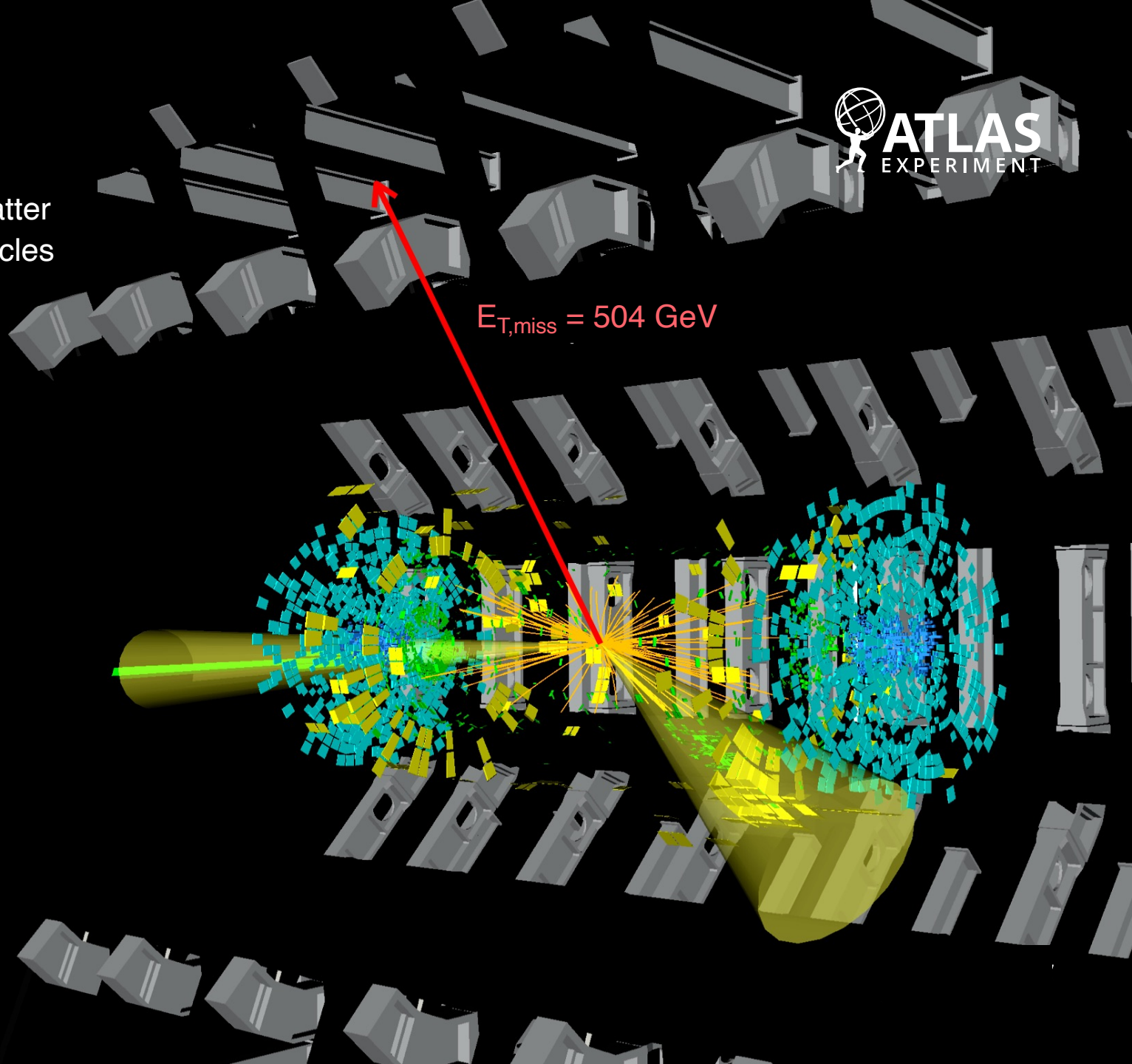
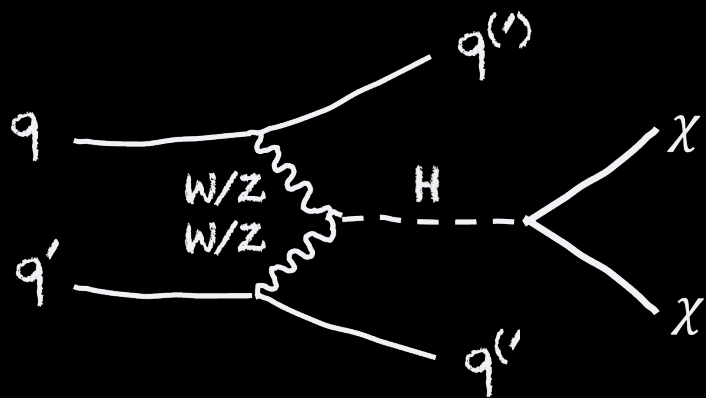


$$\Rightarrow \Gamma_H = 4.5^{+3.3}_{-2.5} \text{ MeV (SM: 4.1 MeV)}$$

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

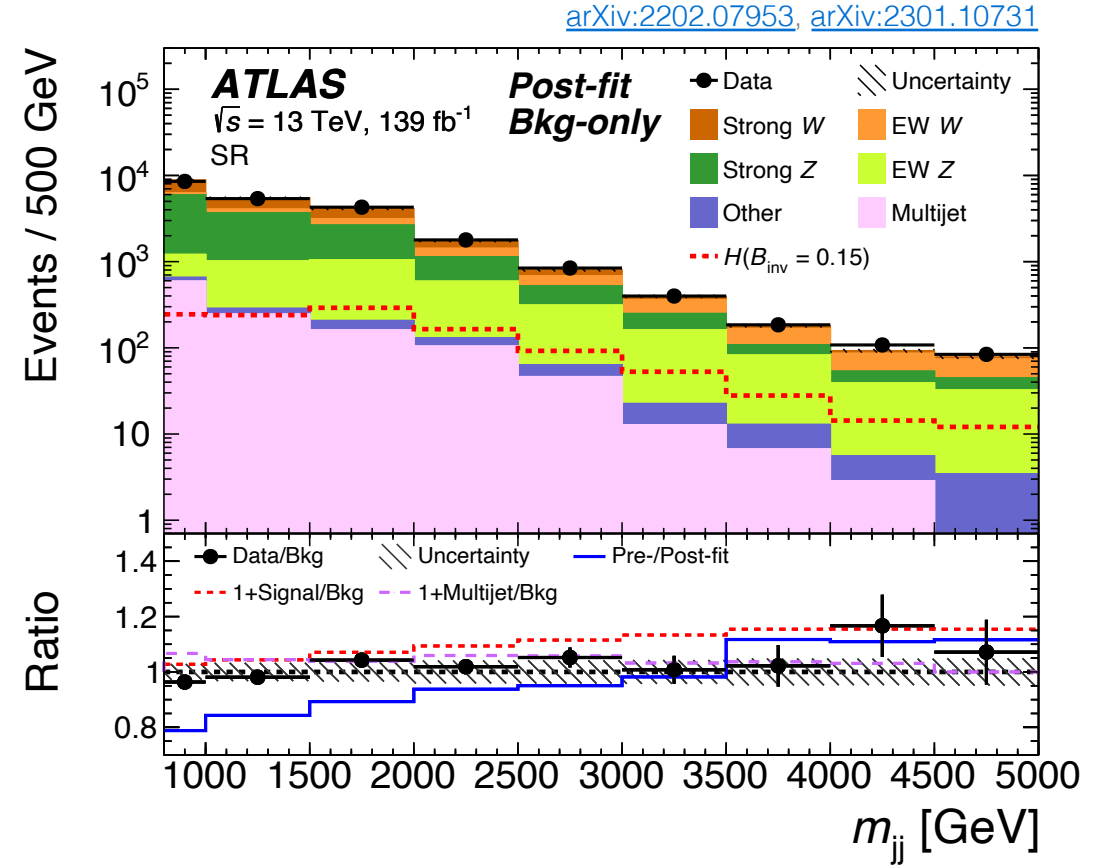
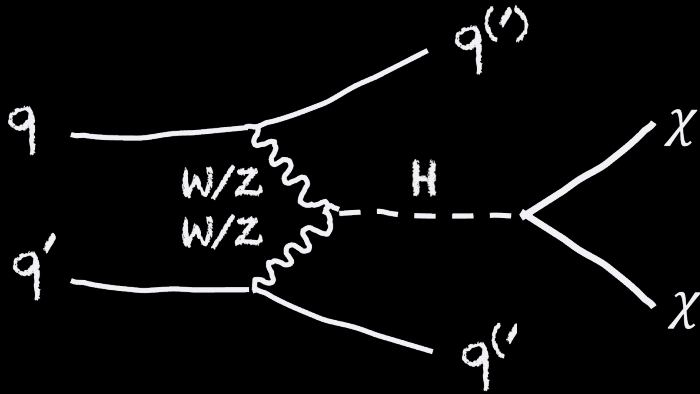
Dark matter

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



Dark matter

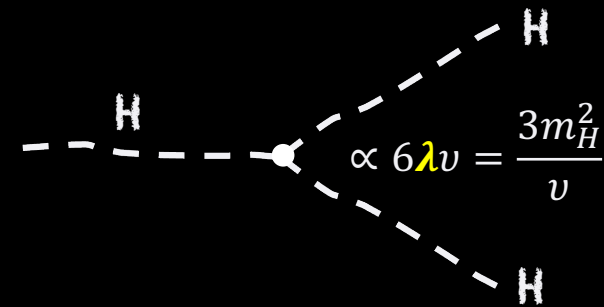
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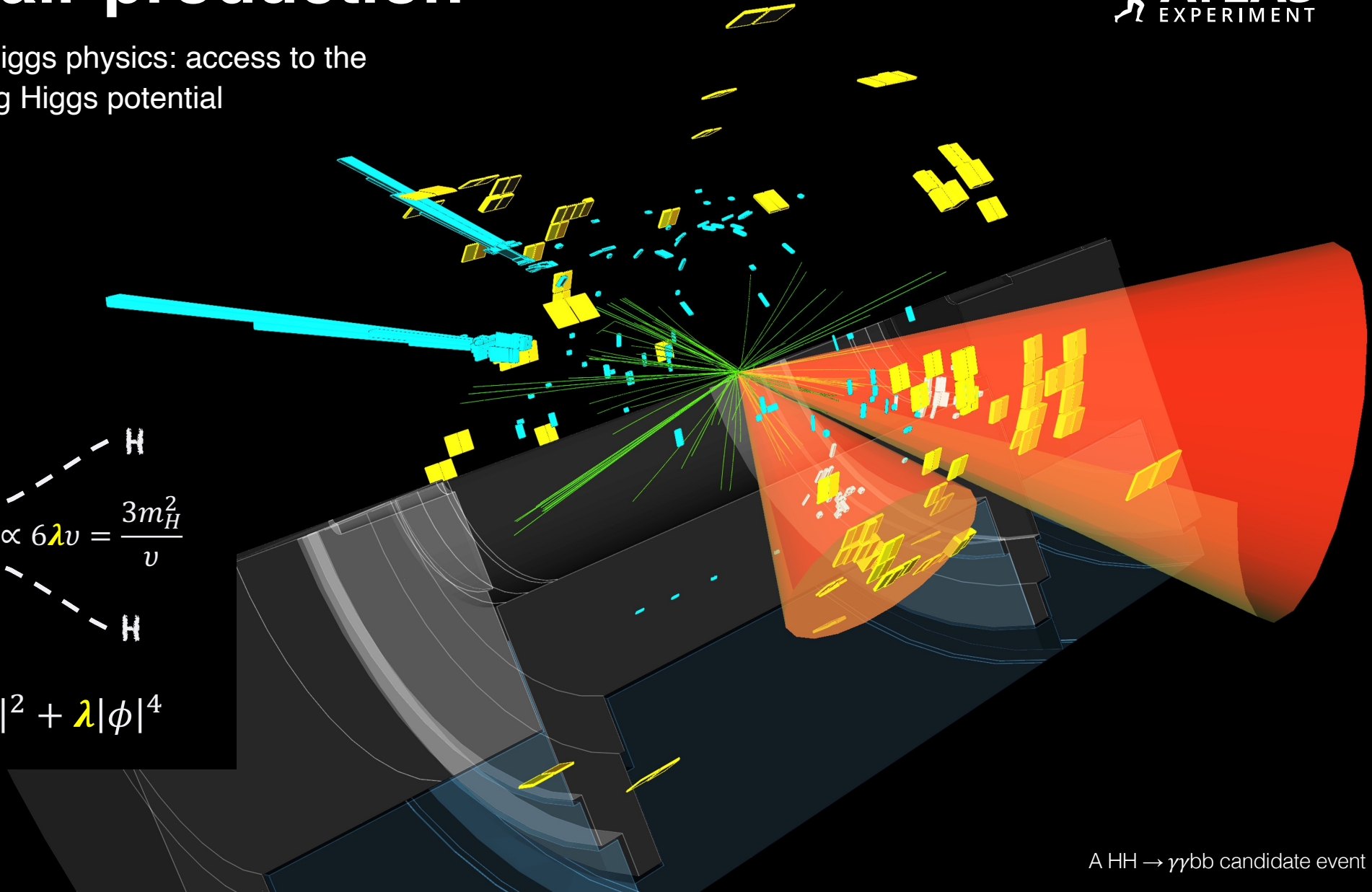
⇒ $\text{BR}(H \rightarrow \text{invisible}) < 0.107 \text{ (0.077) at 95\% CL}$

Higgs pair production

The holy grail of Higgs physics: access to the symmetry breaking Higgs potential



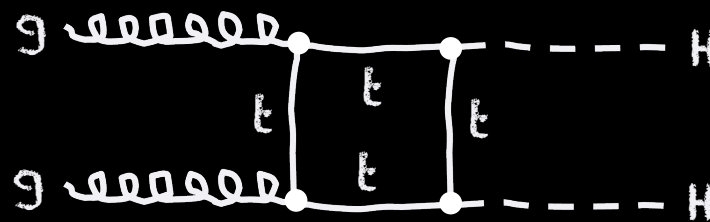
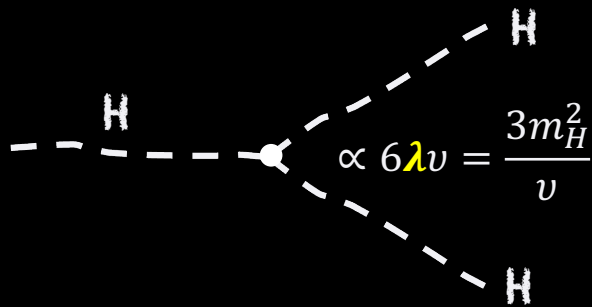
$$V(\phi) = -\mu^2|\phi|^2 + \lambda|\phi|^4$$



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

Higgs pair production

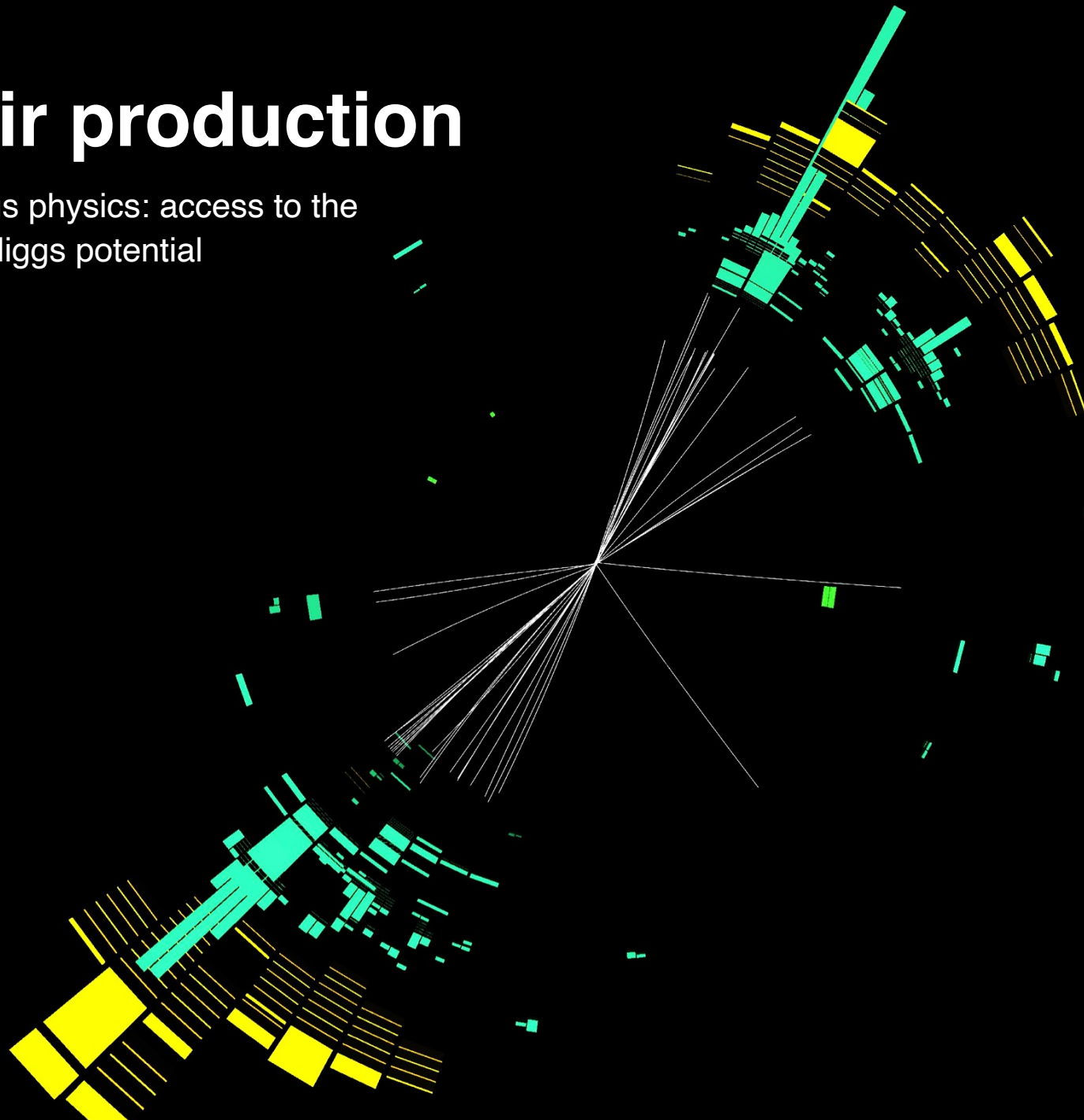
The holy grail of Higgs physics: access to the symmetry-breaking Higgs potential



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The holy grail of Higgs physics: access to the symmetry-breaking Higgs potential

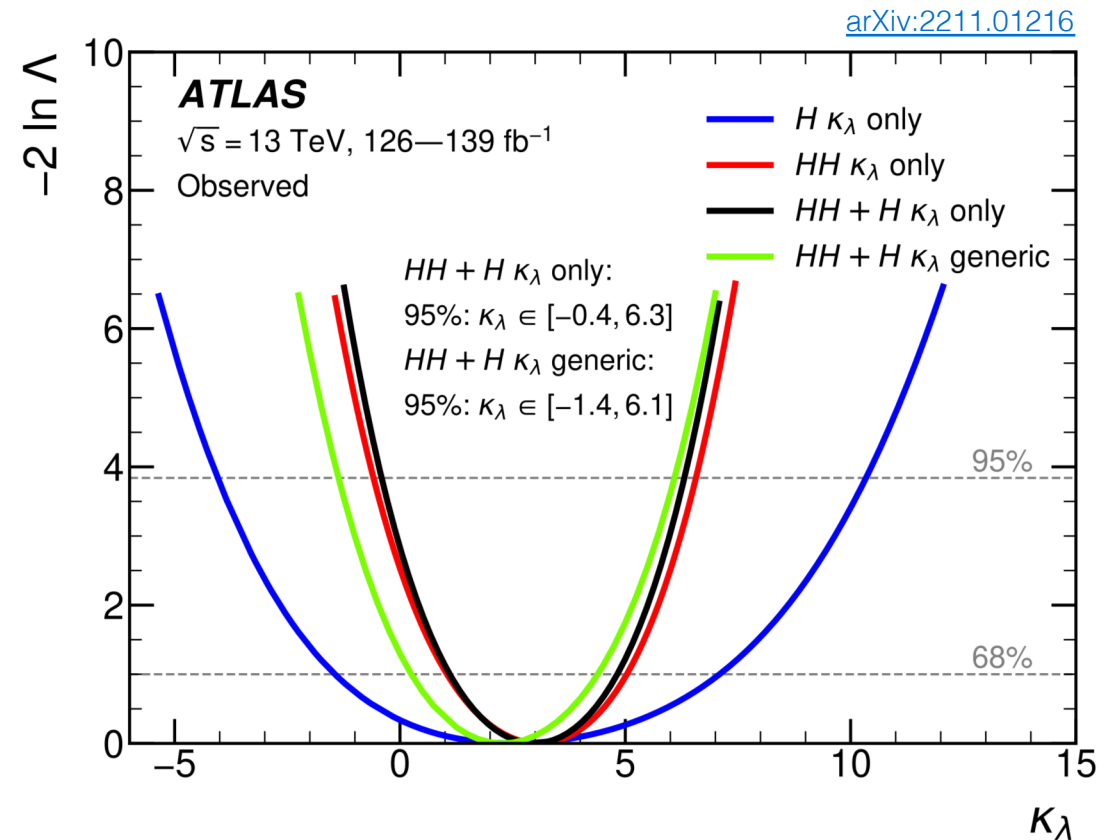
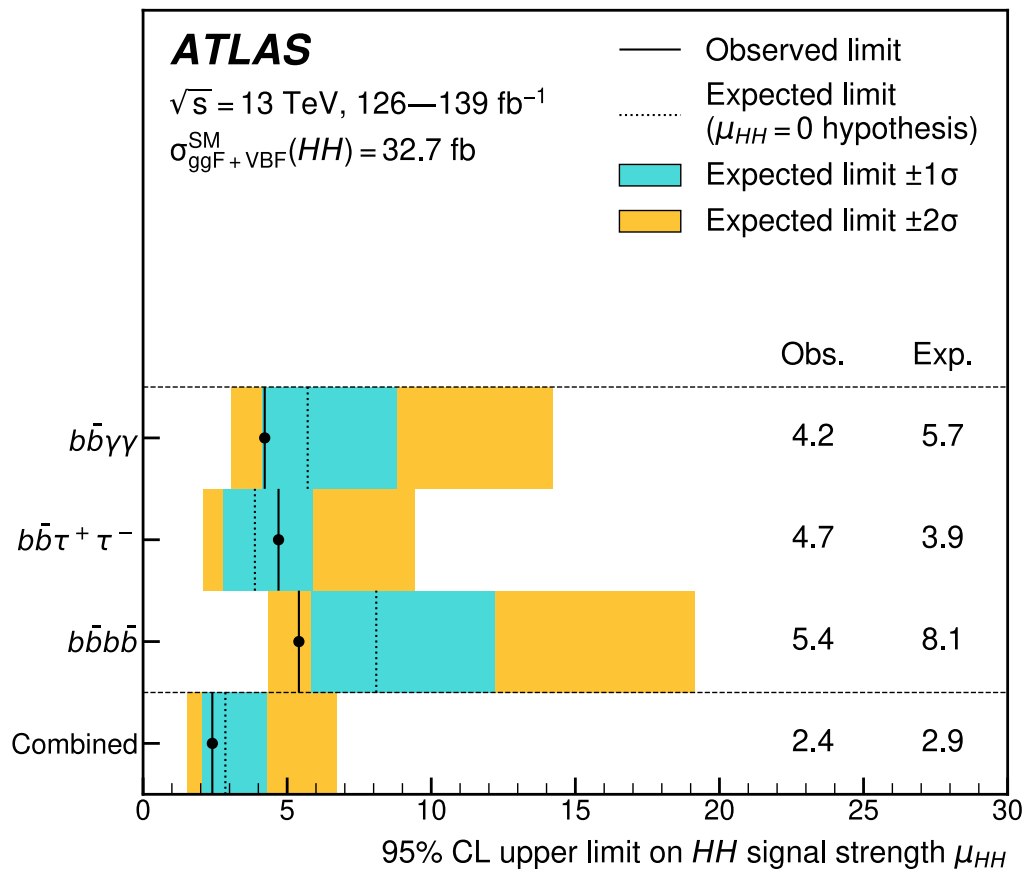


A $HH \rightarrow bbbb$ candidate event

Higgs pair production

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

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



The next steps

LHC

CMS

SPS

ALICE

ATLAS

LHCb

PS

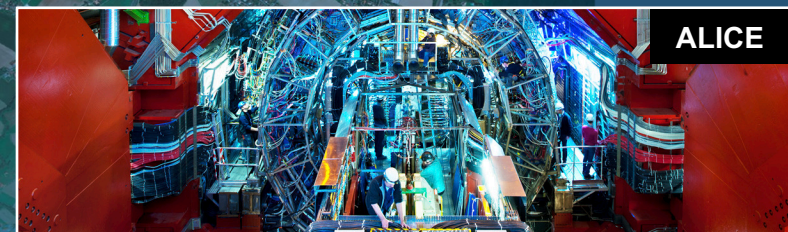
Areal view



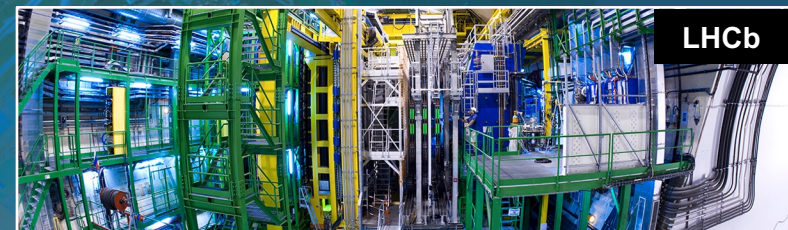
ATLAS



CMS



ALICE

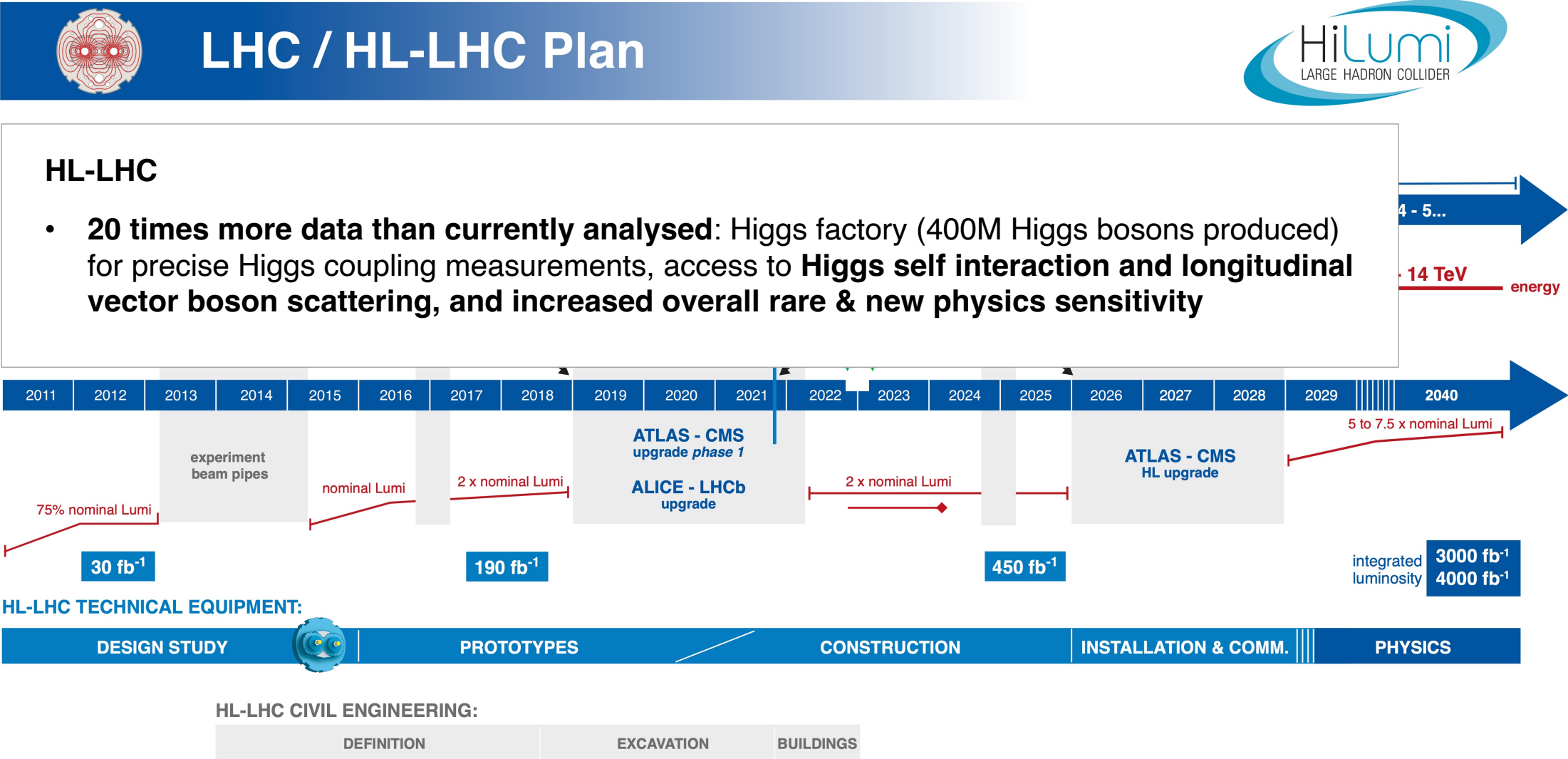


LHCb

Preparing the future — the grand plan of the LHC



Preparing the future — the grand plan

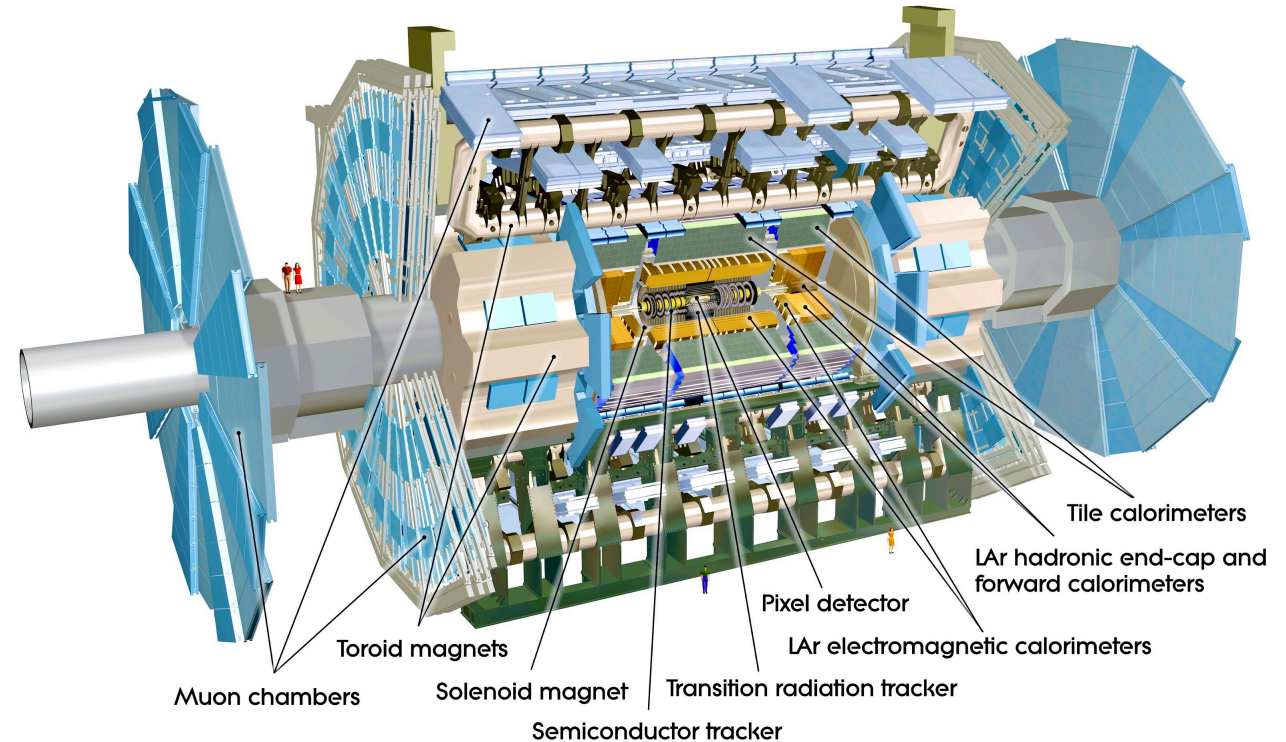


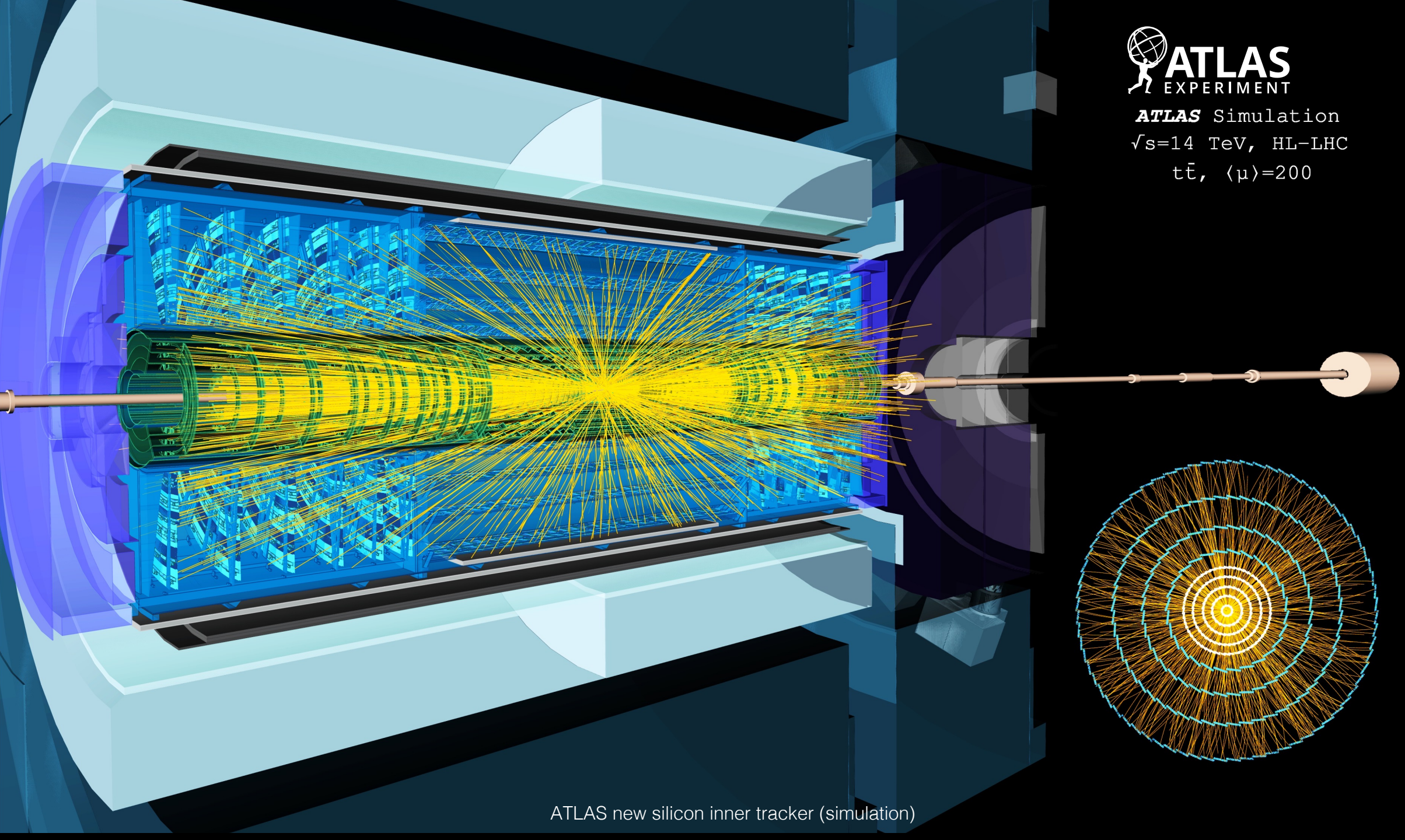
High-Luminosity LHC (HL-LHC)



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

- Radiation hardness
- High detection granularity and resolution
- Precise timing detectors
- More powerful online filtering
- Machine learning & data science
- High-performance software & computing





ATLAS new silicon inner tracker (simulation)

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

First 13.6 TeV collisions on 5 July 2022



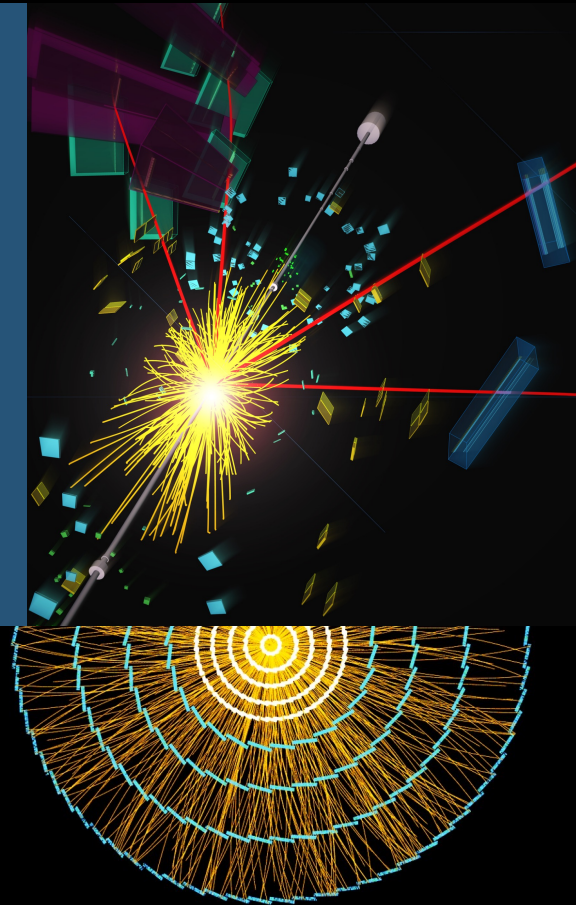
Conclusions

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

The Higgs sector is directly connected with very profound questions: naturalness, vacuum stability and energy, flavour, dark matter and other new physics

Their study requires a broad experimental programme that will extend over decades

Thank you for your attention !





Extra slides

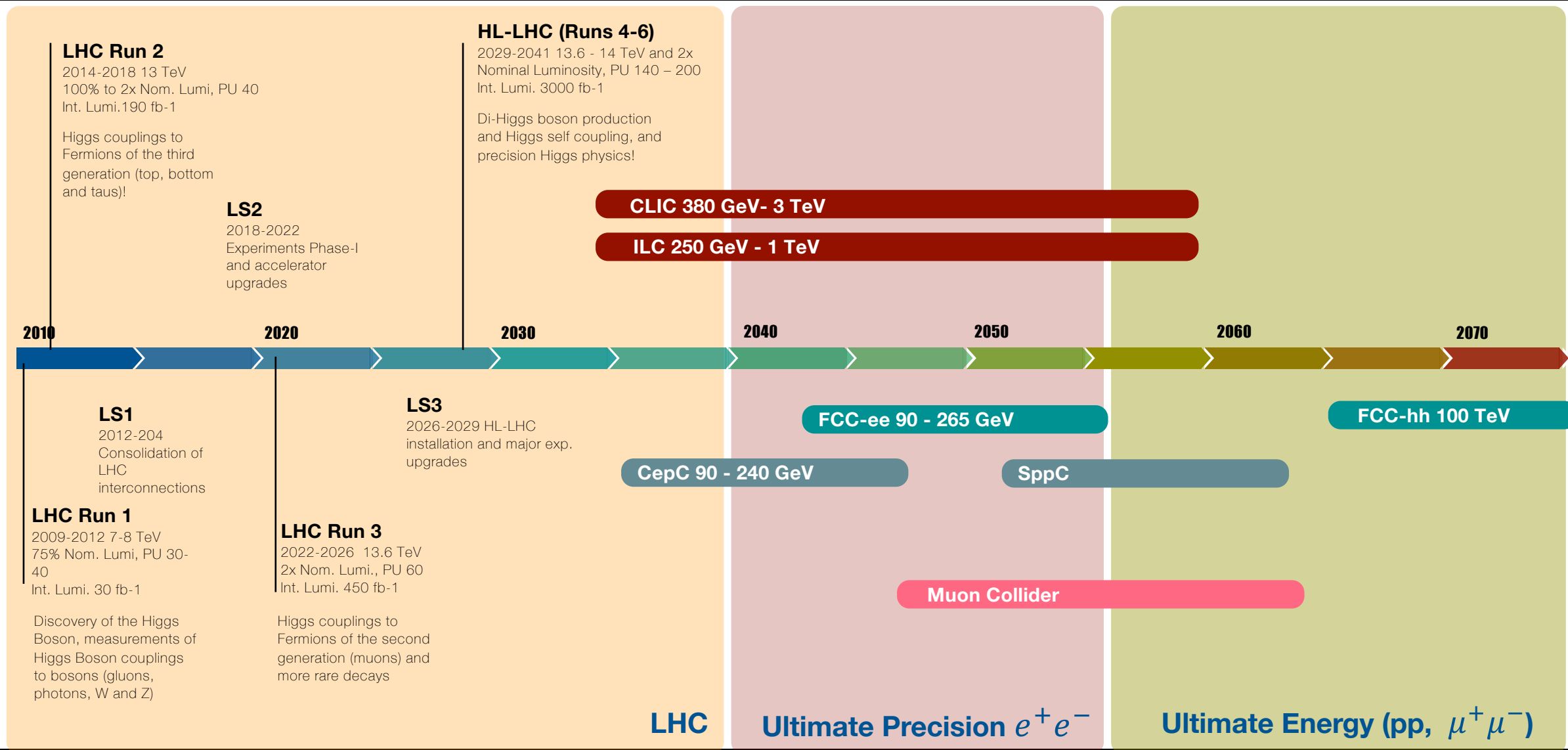
Scientific priorities for future energy- frontier projects



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

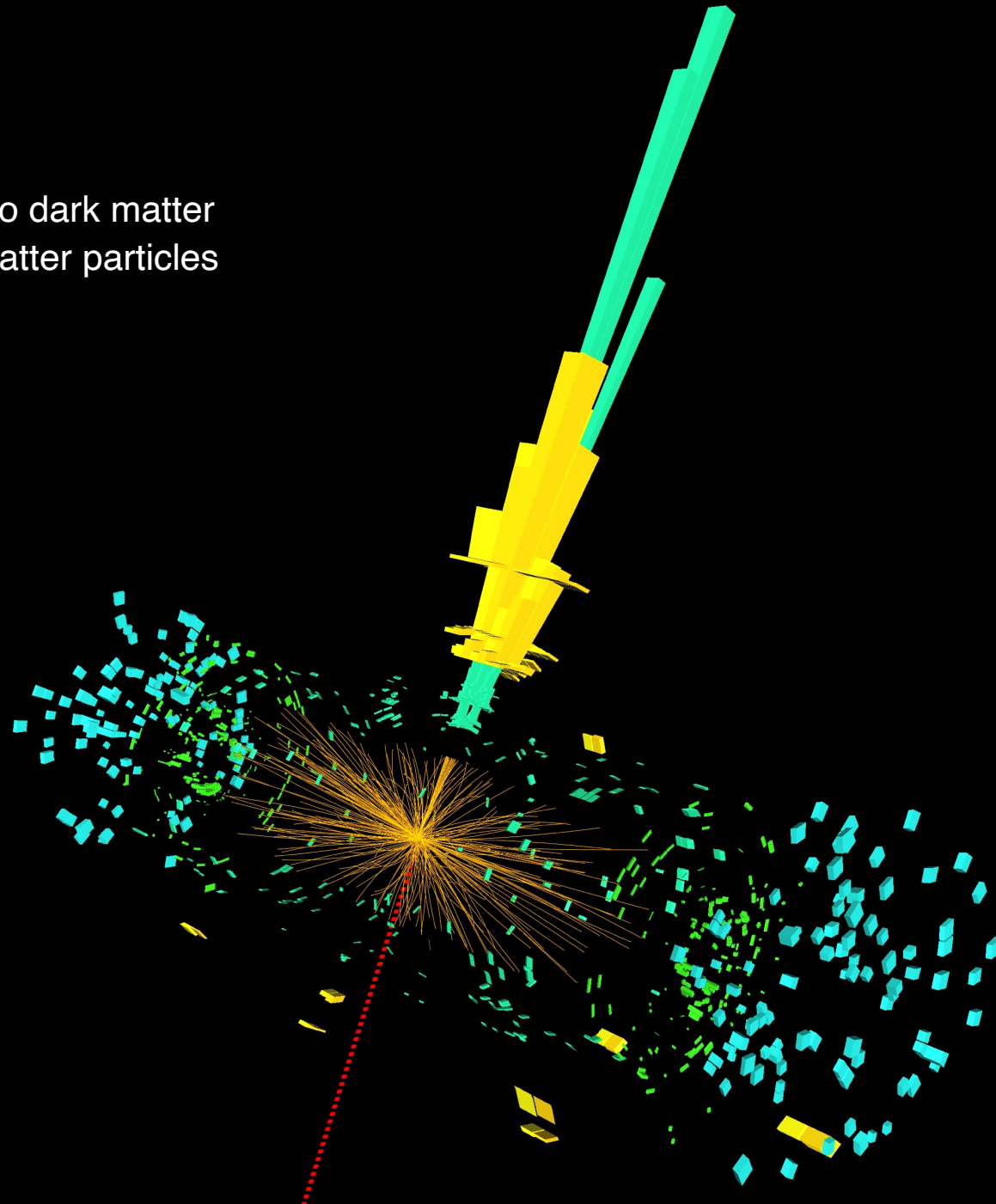
- Fully exploit the HL-LHC
- Build an e^+e^- Higgs factory for high-precision studies of this unique particle
- Investigate the technical and financial feasibility of a future 100 TeV energy-frontier collider at CERN
- Ramp up the relevant R&D

A Scientific Mission for the 21st Century

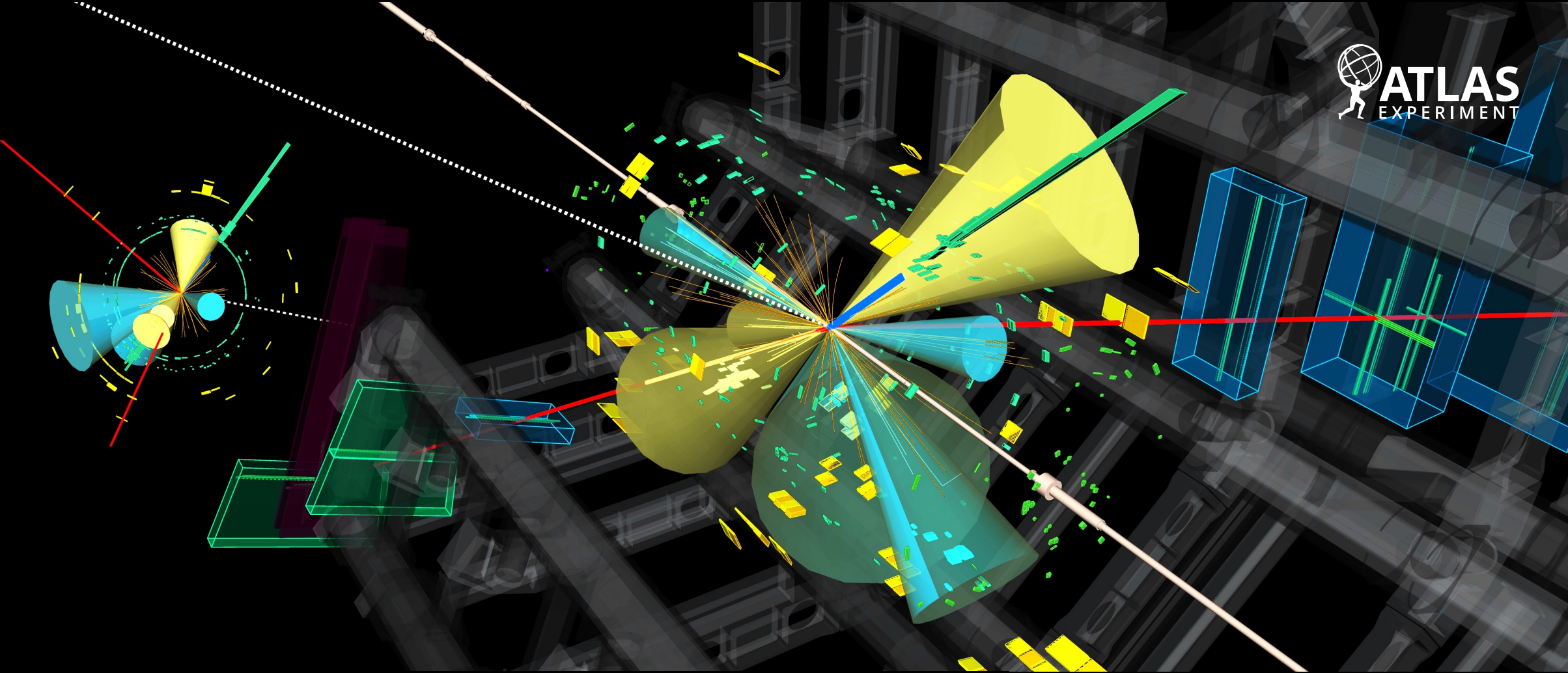


Dark matter

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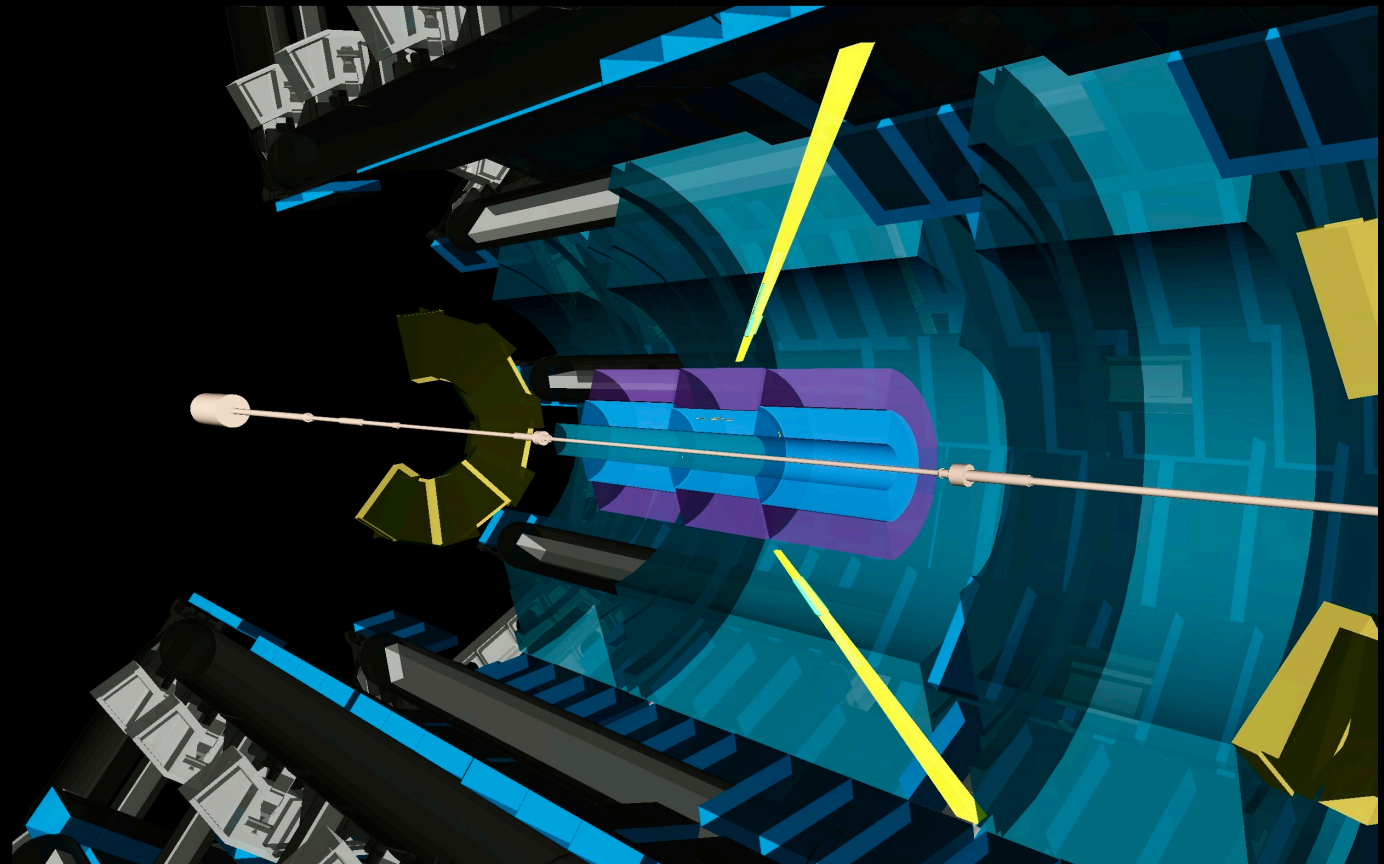
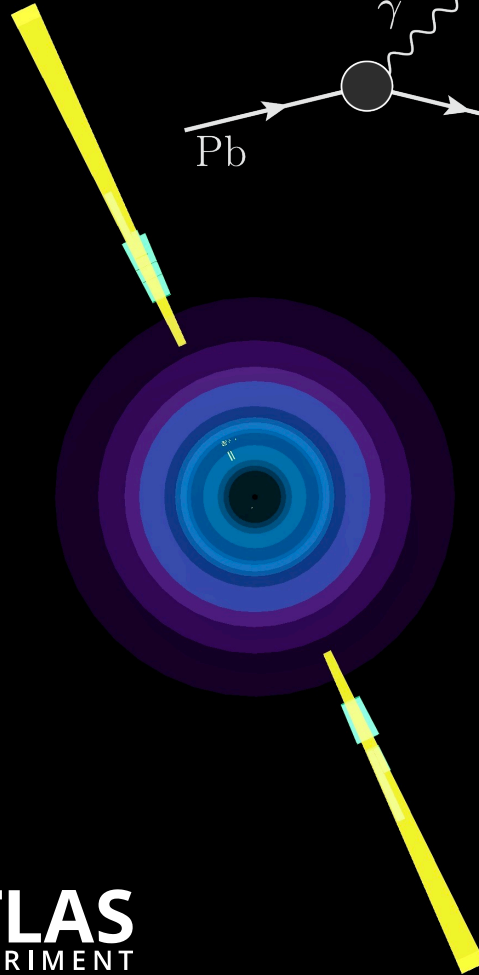
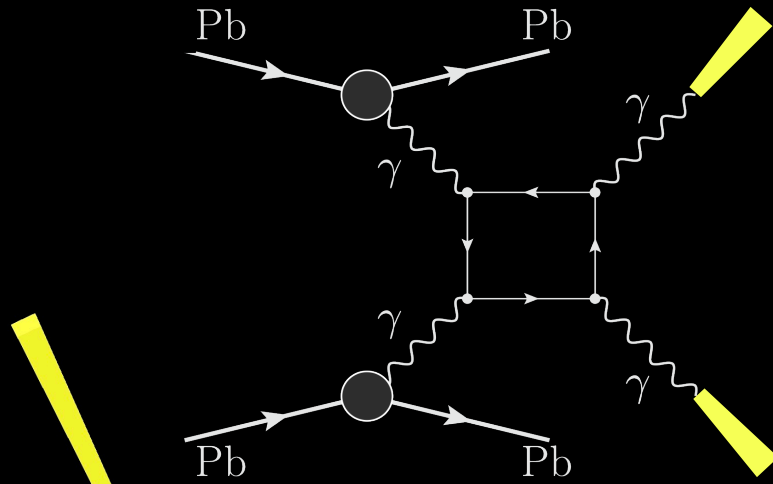
The LHC also provided a new understanding of hadron collider processes: the observation of numerous very rare channels testing the Standard Model



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)

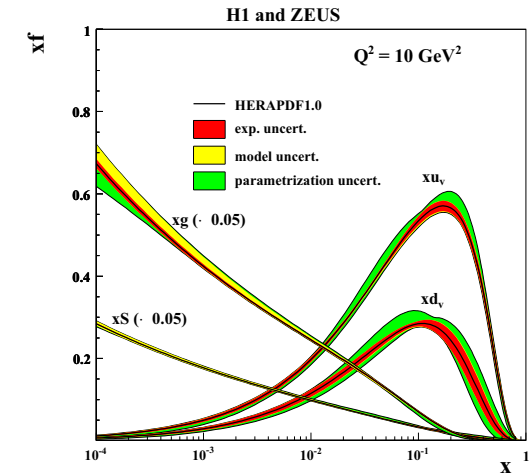
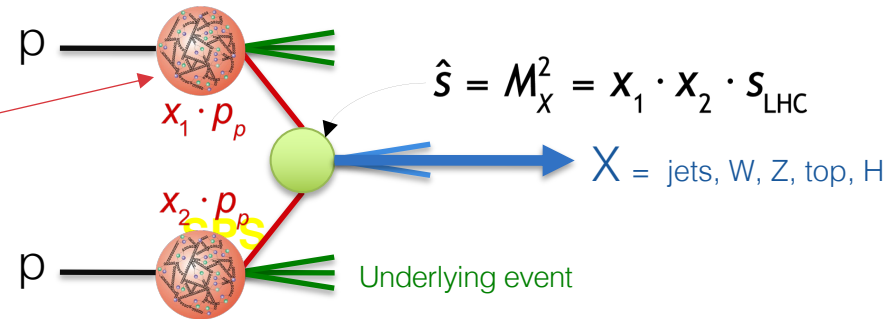
Studies of physics in extreme electromagnetic fields



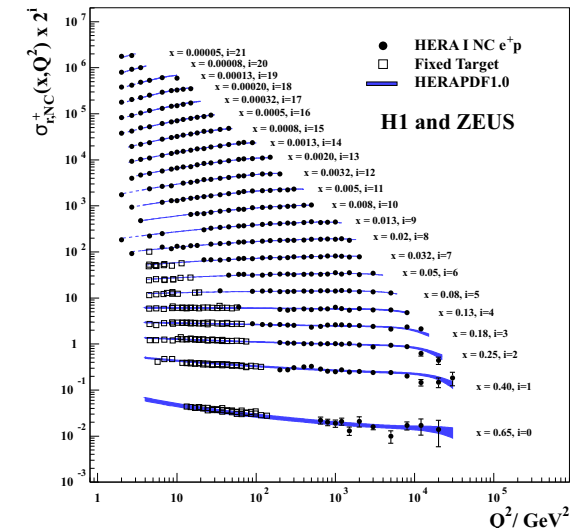
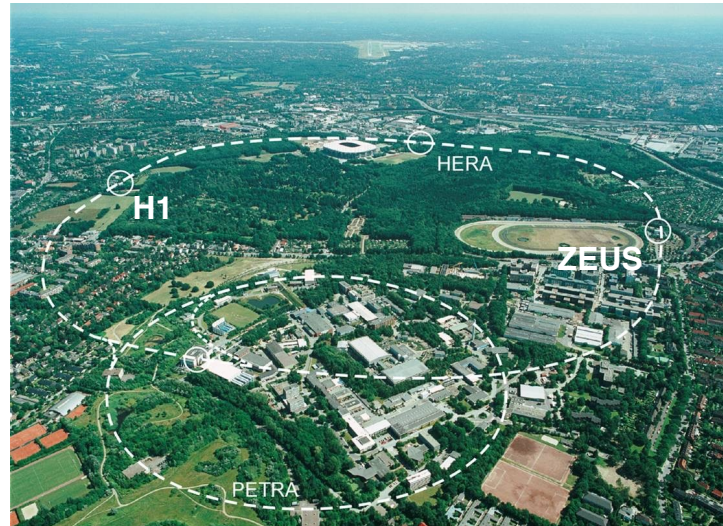
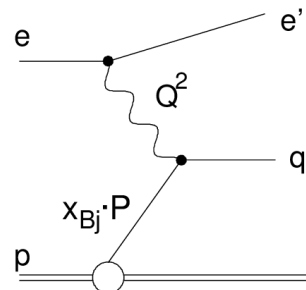
A major ingredient

In proton–proton collisions, cross section is convolution of parton distribution functions (PDF) with parton scattering matrix element

Parton distribution functions
Representing structure of proton,
extracted using experimental
data and QCD properties

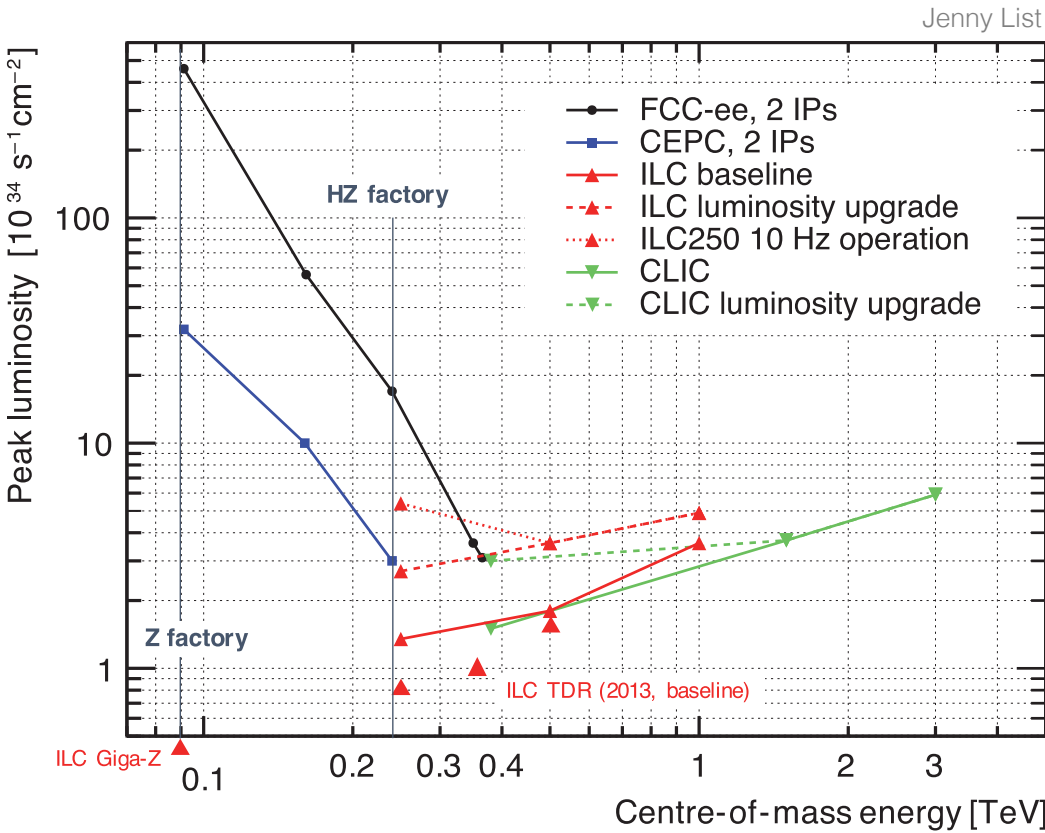


PDFs were measured precisely
at the 6.3 km superconducting
ep collider HERA at DESY
(1992–2007)



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)

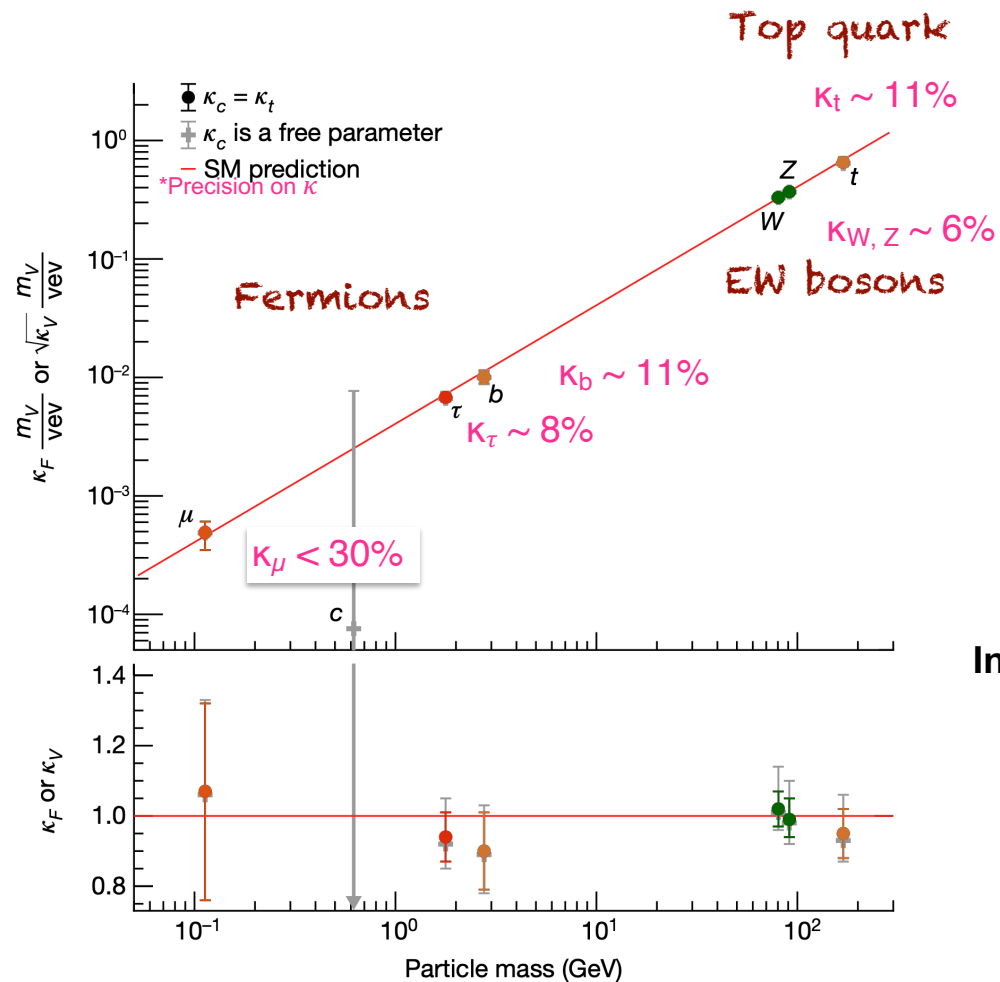
1) Higgs self-coupling: expected precision on λ_3

- 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

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

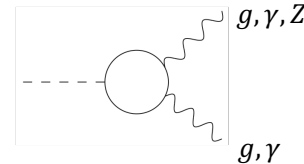
Electron–positron Higgs factories

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

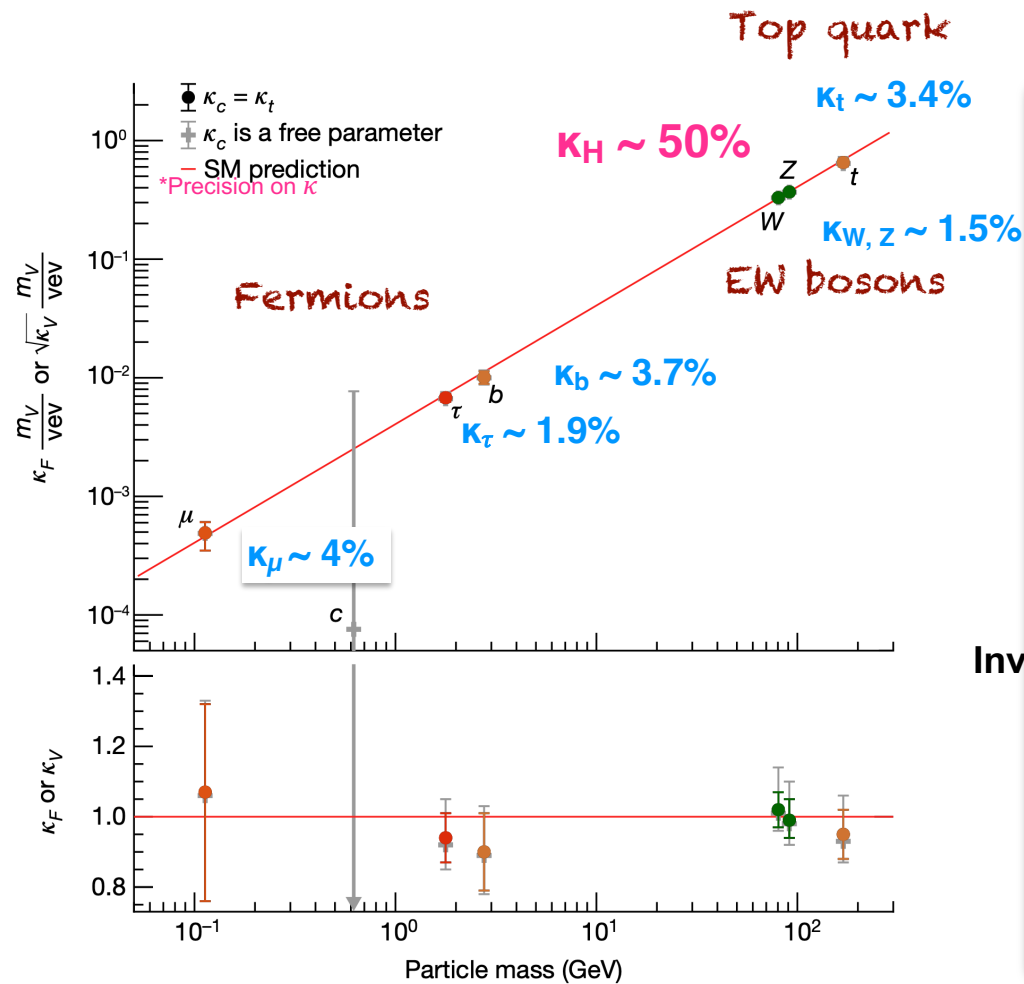
$\text{Br}_{\text{inv}} < 11\%$ **DM?**

Higgs width

$\Gamma_H \sim 100\%$

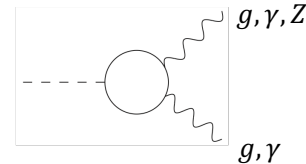
Electron–positron Higgs factories

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

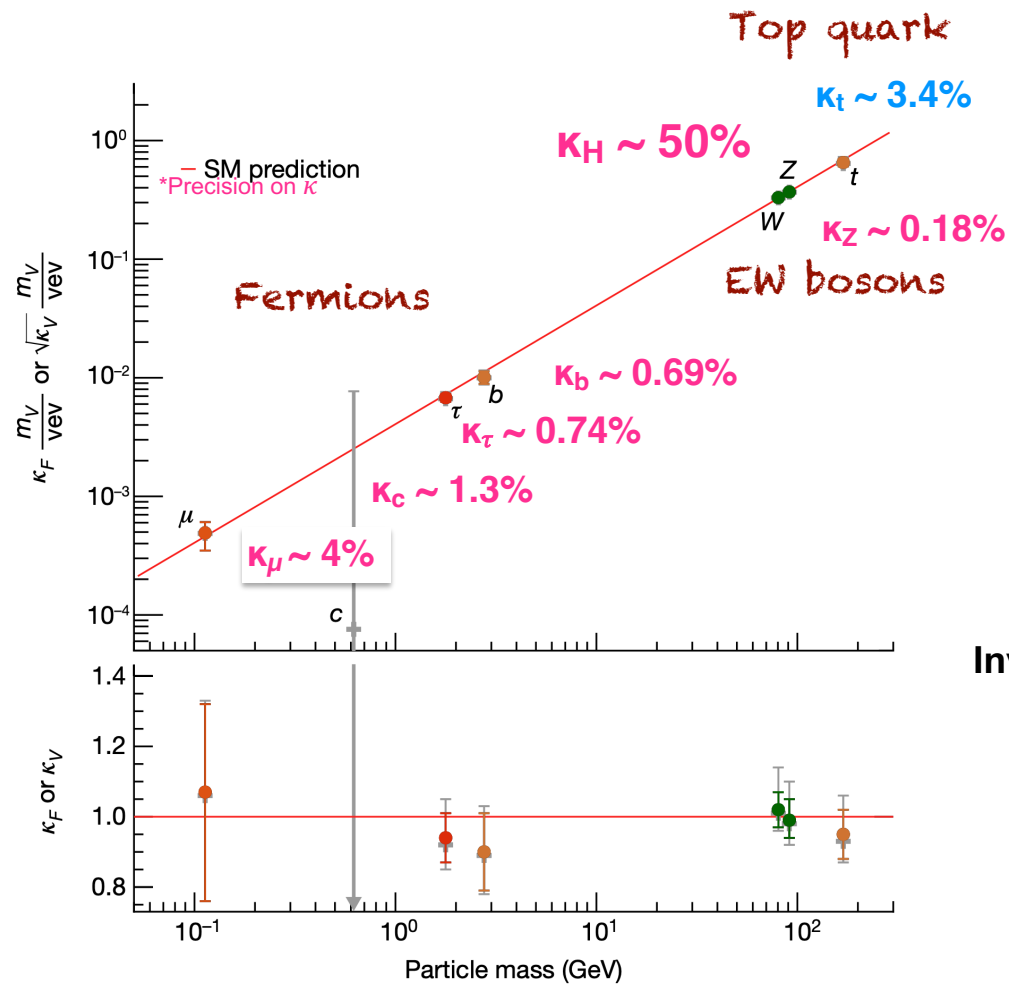
$\text{Br}_{\text{inv}} < 2.5\%$ DM?

Higgs width

$\Gamma_H \sim 20\%$

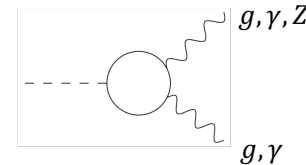
Electron–positron Higgs factories

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



Nature 607, 52-59 (2022)

Effective loop



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

$\kappa_g \sim 1.0\%$

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

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:

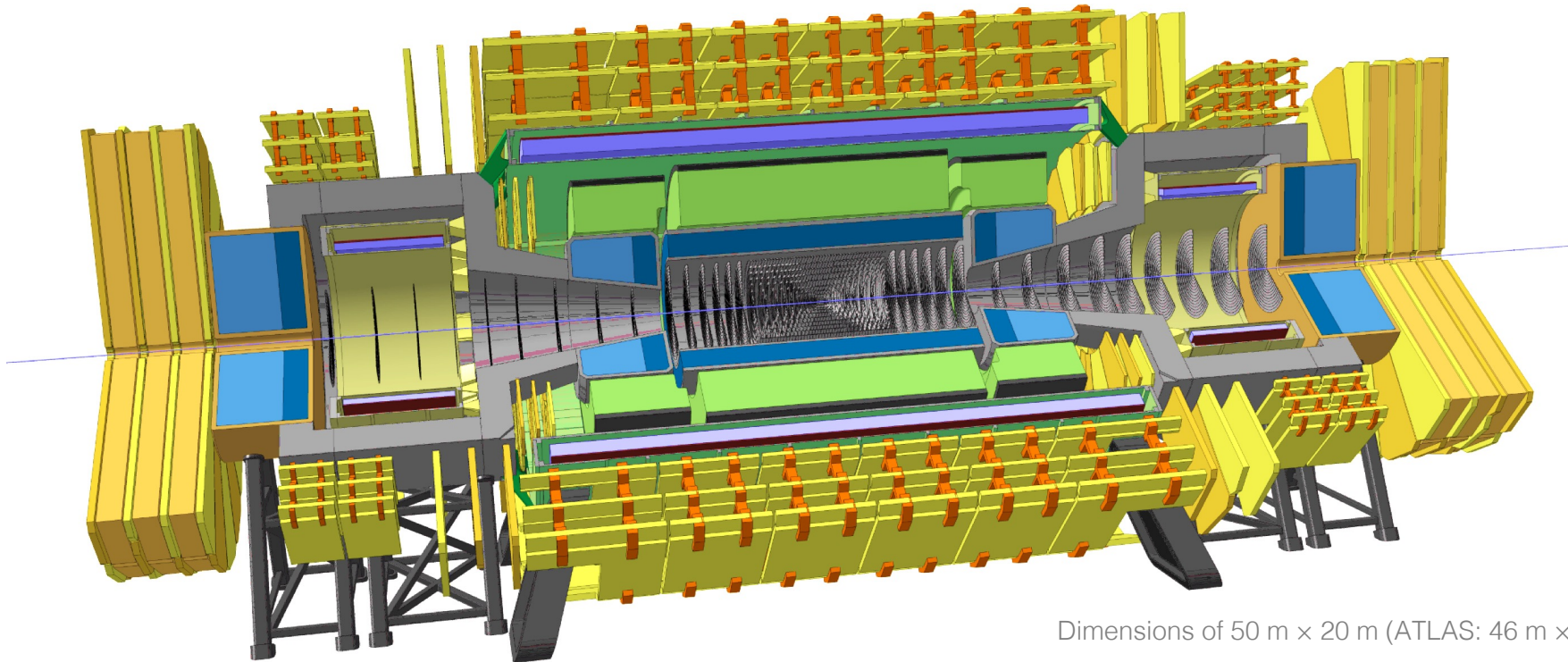
$$m_Z \sim 10^{-6}, m_W \sim 10^{-5}, m_{\text{top}} \sim 10^{-4}$$

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

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

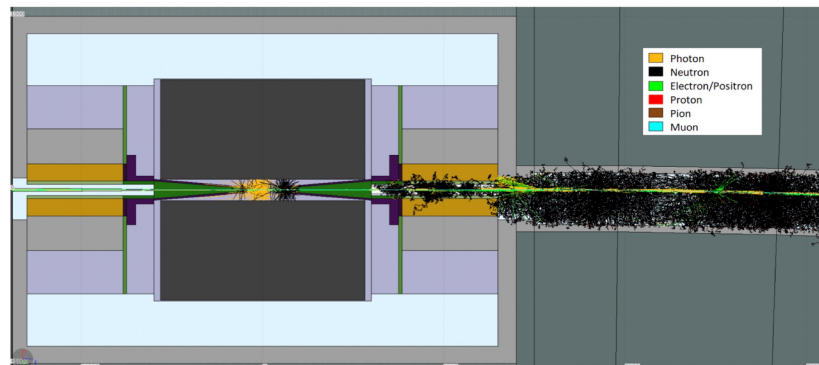
Best of all worlds?

- 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

