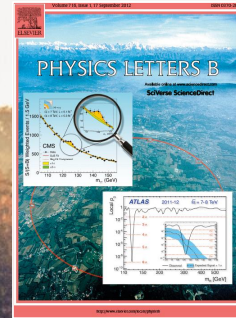


# The long road to the Higgs boson discovery

Fabiola Gianotti (CERN), ICHEP, 12 July 2022



# Initial remarks

1. Experimental verification of the Brout-Englert-Higgs mechanism through the discovery of the Higgs boson: **monumental step forward** in our understanding of fundamental physics, with **wide-ranging implications** for particle physics and beyond

2. Higgs boson discovery is the culmination of a long journey (completion of the Standard Model!) and the **beginning of a new era**:

- ❑ the Higgs boson is profoundly different from all elementary particles discovered previously (first elementary scalar?)
- ❑ brings new interactions (Yukawa, self-interaction)
- ❑ is **related to the most obscure sector of the Standard Model** and linked to some of the **deepest structural questions** (flavour, naturalness/hierarchy, vacuum, ...)



Higgs boson discovery opens new paths of exploration, provides a unique door into new physics, and calls for a compelling and broad experimental programme which will extend for decades at the LHC and beyond

3. **Nature has been kind** to us:  $m_H = 125 \text{ GeV} !!$

→ ~ all production and large number of decay modes accessible, allowing a vast, detailed and robust portrait of the new particle (although not the easiest mass range for discovery!)

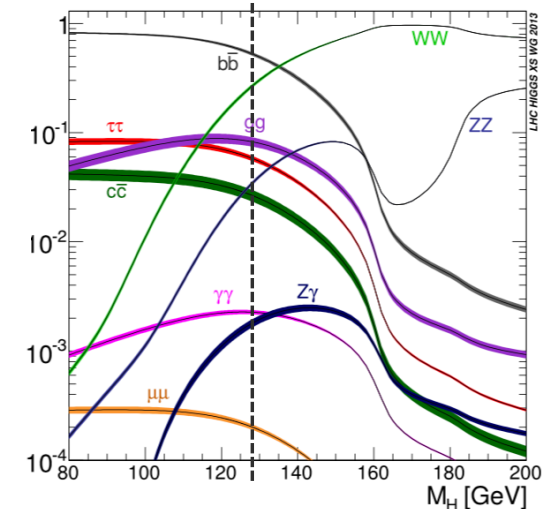
G. Giudice

Every problem of the SM originates from Higgs interactions

$$\mathcal{L} = \lambda H \psi \bar{\psi} + \mu^2 |H|^2 - \lambda |H|^4 - V_0$$

↑ flavour     ↑ naturalness     ↑ stability     ↑ C.C.

Higgs boson branching ratios





# The long road ...

# It didn't start so well ...

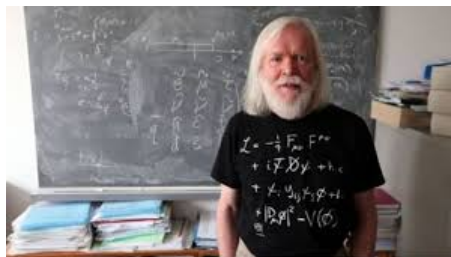
## A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John ELLIS, Mary K. GAILLARD \* and D.V. NANOPOULOS \*\*  
*CERN, Geneva*

Received 7 November 1975

A discussion is given of the production, decay and observability of the scalar Higgs boson  $H$  expected in gauge theories of the weak and electromagnetic interactions such as the Weinberg-Salam model. After reviewing previous experimental limits on the mass of

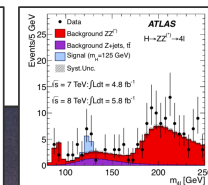
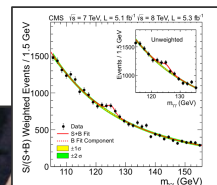
We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.





# The main milestones on the path to the discovery

- 1977 : Sir John Adams (Technical DG of CERN) argued that LEP tunnel should be made large enough to accommodate a ring of superconducting magnets to accelerate protons to at least 3 TeV
- 1979 : ECFA-LEP WG (Chair A. Zichichi): "A tunnel with a 27 circumference and a diameter of 5 m with a view to the replacement of LEP at the end of its activities by a proton-proton collider using cryogenic magnets"
- 1983 : Discovery of the W and Z bosons at CERN
- 1984 : ECFA-CERN WS on "Large Hadron Collider in the LEP tunnel", Lausanne
- 1989 : Start of SLC and LEP  $e^+e^-$  colliders
- 1992 : End of four experiments (ASCOT, EAGLE, CMS, L3P) presented at Evian WS in March  
Lol submitted by ATLAS (merging of ASCOT and EAGLE), CMS and L3P in the fall
- 1993 : SSC cancelled → US colleagues join the LHC
- 1994 : LHC approved by CERN Council (staged version initially)
- 1995 : Top-quark discovery at the Tevatron
- 1997 : ATLAS and CMS approved → construction starts
- 2000 : End of LEP2
- 2003 : Start of LHC machine and experiments installation
- 2008 : LHC commissioning interrupted by serious incident provoked by faulty electrical busbar connection
- 2009 : 23 Nov: first LHC collisions at  $\sqrt{s} = 900$  GeV
- 2010 : 30 March: first collisions at  $\sqrt{s} = 7$  TeV → inauguration of a > 30 year exploration of E-frontier
- 2012 : 1<sup>st</sup> May: first collisions at  $\sqrt{s} = 8$  TeV
- 2012 : 4 July: discovery of a Higgs-like boson announced



# The main milestones on the path to the discovery

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A challenging path that required:

- ❑ new concepts and innovative technologies for the collider (e.g. superconducting magnets), detectors, and computing
- ❑ lot of ingenuity to address daunting challenges and solve tons of (unforeseen) problems
- ❑ huge efforts of the worldwide community and the funding agencies (ideas, technology, people, money, ...)
- ❑ patience, perseverance, determination, optimism ...

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2003 : Start of LHC machine and experiments installation

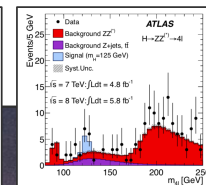
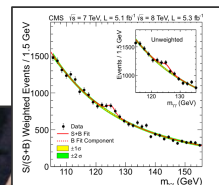
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QRL crisis 2004



## Accelerator: a bumpy path to an extraordinary success

September 2008



L. Evans

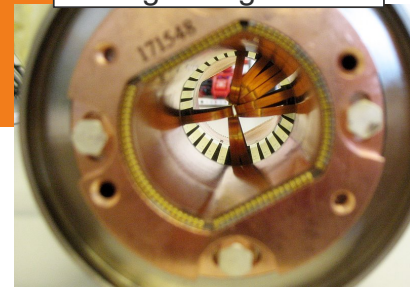
### LHC timeline

- Preliminary conceptual studies 1984
- First magnet models 1988
- Start structured R&D program 1990
- Approval by CERN Council 1994
- Industrialization of series production 1996-1999
- DUP & start civil works 1998
- Adjudication of main procurement contracts 1998-2001
- Start installation in tunnel 2003
- Cryomagnet installation in tunnel 2005-2007
- Functional test of first sector 2007
- Commissioning with beam 2008
- Operation for physics 2010-?

Inner triplet crisis 2005



Plug-in module with damaged fingers 2008



Although focus here is on experiments, the road of the LHC machine was also characterised by big challenges and great accomplishments

# ATLAS and CMS design

Higgs boson searches have guided conception, design and technological choices:

- ❑ are **one of primary LHC goals**
- ❑ are among the **most challenging processes** (especially in the low-mass region below 200 GeV where  $\Gamma_H < 1$  GeV)
  - variety of final states; stringent performance requirements for physics objects (leptons, photons, jets, b-jets, fwd jets, missing  $E_T$ ):  
**reconstruction and identification efficiency, energy/momentum resolution, rejection and control of huge backgrounds**; etc.
- excellent **benchmark** for design of general-purpose, high-performing, robust detectors

## How ideas evolved with time

From : "Report of High Luminosity Study Group to the CERN Long-Range Planning Committee", CERN 88-02, 1988.

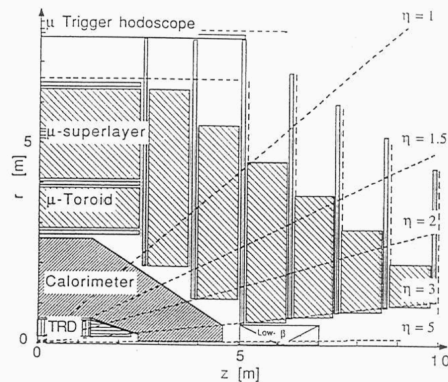


Figure 1. Conceptual design of 'non-magnetic' detector system. Calorimeter coverage for  $3 < |\eta| \leq 5$  is not essential for luminosity  $> 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ .

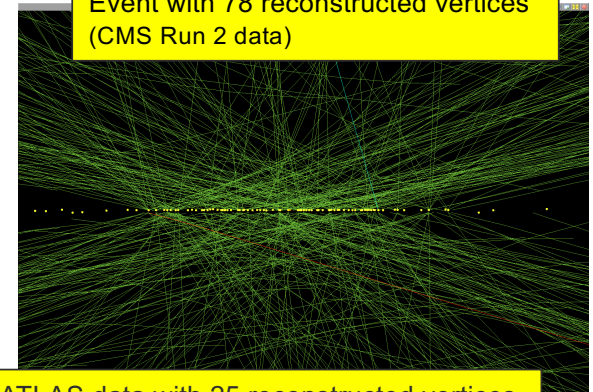
?

Missing  $E_T$ ? Forward jets and vector-boson fusion?

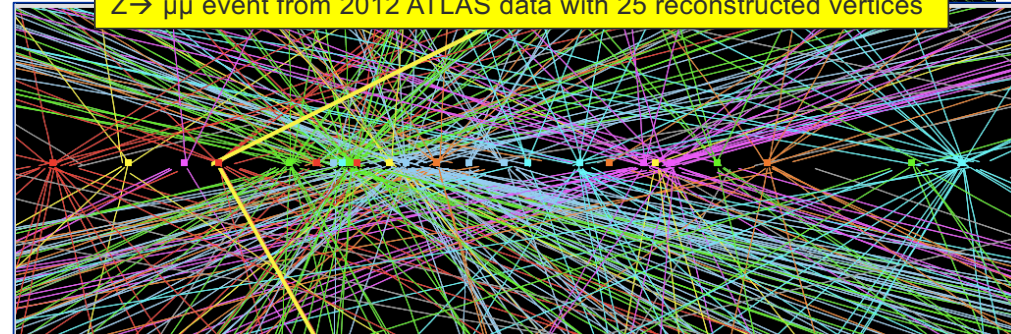
## How challenges and performance evolved with time: pile-up

- ❑ Initially, tracking at  $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$  was considered to be impossible.
- ❑ Later detectors designed for  $\sim 20$  events/xbing (expected at  $10^{34}$ )

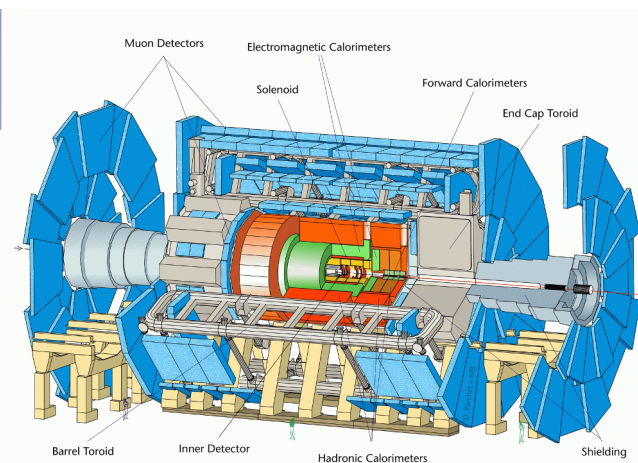
Event with 78 reconstructed vertices (CMS Run 2 data)



$Z \rightarrow \mu\mu$  event from 2012 ATLAS data with 25 reconstructed vertices





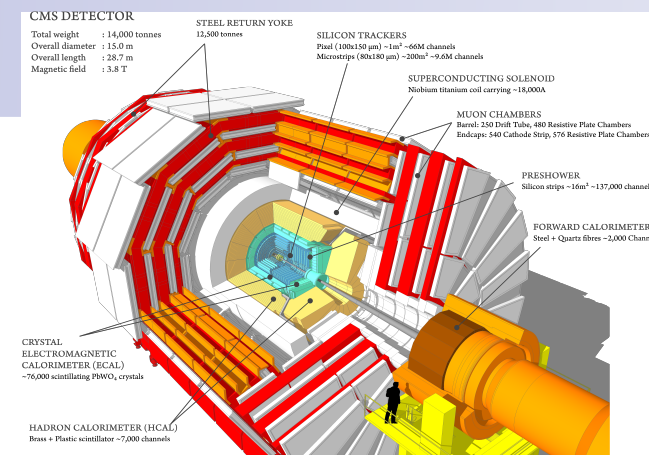


Length ~ 45 m; height ~ 25 m

- **Tracking ( $|\eta| < 2.5$ ,  $B=2T$ ):**
  - Si pixels and strips
  - Transition Radiation Detector ( $e/\pi$  separation)
- **Calorimetry ( $|\eta| < 5$ ):**
  - EM: Pb-LAr
  - HAD: Fe/scintillator (central)
  - Cu/W-LAr (end-cap/fwd)
- **Muon Spectrometer ( $|\eta| < 2.7$ ):**
  - Air-core toroids with muon chambers



## ATLAS and CMS: the complementarity

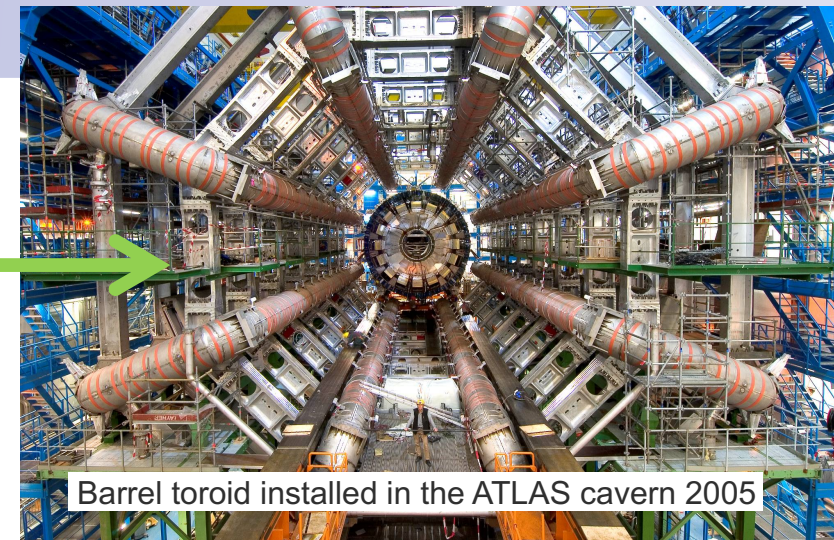
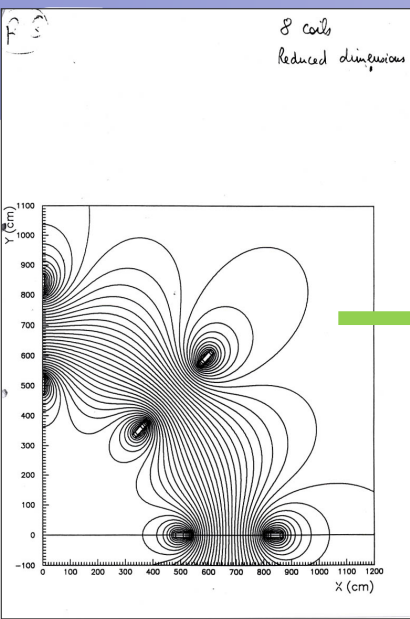


Length ~ 22 m; height ~ 15 m

- **Tracking ( $|\eta| < 2.5$ ,  $B=3.8T$ ):**
  - Si pixels and strips
- **Calorimetry ( $|\eta| < 5$ ):**
  - EM : PbWO<sub>4</sub> crystals
  - HAD: brass/scintillator (central+ end-cap)
  - Fe/Quartz (fwd)
- **Muon Spectrometer ( $|\eta| < 2.5$ ):** return yoke of solenoid instrumented with muon chambers

	ATLAS $\equiv$ A Toroidal LHC Apparatus	CMS $\equiv$ Compact Muon Solenoid
MAGNET(S)	Air-core toroids + solenoid in inner cavity 3 magnet systems Calorimeters in field-free region	Solenoid 1 magnet Calorimeters inside field
TRACKER	Si pixels + strips TRT $\rightarrow$ particle identification $B=2T$ $\sigma/p_T \sim 5 \times 10^{-4} p_T \oplus 0.01$	Si pixels + strips $B = 3.8 T$ $\sigma/p_T \sim 1.5 \times 10^{-4} p_T \oplus 0.005$
EM CALO	Pb-liquid argon $\sigma/E \sim 10\%/\sqrt{E}$ uniform longitudinal segmentation	PbWO <sub>4</sub> crystals $\sigma/E \sim 2-5\%/\sqrt{E}$ no longitudinal segmentation
HAD CALO	Fe-scint. / Cu-liquid argon ( $> 11 \lambda$ ) $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$	Brass-scint. (7-11 $\lambda$ + catcher) $\sigma/E \sim 110\%/\sqrt{E} \oplus 0.09$
MUON	Air $\rightarrow \sigma/p_T \sim 10\%$ at 1 TeV standalone (~ 7% combined with tracker)	Fe $\rightarrow \sigma/p_T \sim 15-30\%$ at 1 TeV standalone (5-10% with tracker)





## Example of technical challenge: ATLAS magnet system

### Barrel Toroid parameters

25.3 m length  
20.1 m outer diameter  
8 coils  
1.08 GJ stored energy  
370 tons cold mass  
830 tons weight  
4 T on superconductor  
56 km Al/NbTi/Cu conductor  
20.5 kA nominal current  
4.7 K working point

### End-Cap Toroid parameters

5.0 m axial length  
10.7 m outer diameter  
2 x 8 coils  
2 x 0.25 GJ stored energy  
2 x 160 tons cold mass  
2 x 240 tons weight  
4 T on superconductor  
2 x 13 km Al/NbTi/Cu conductor  
20.5 kA nominal current  
4.7 K working point

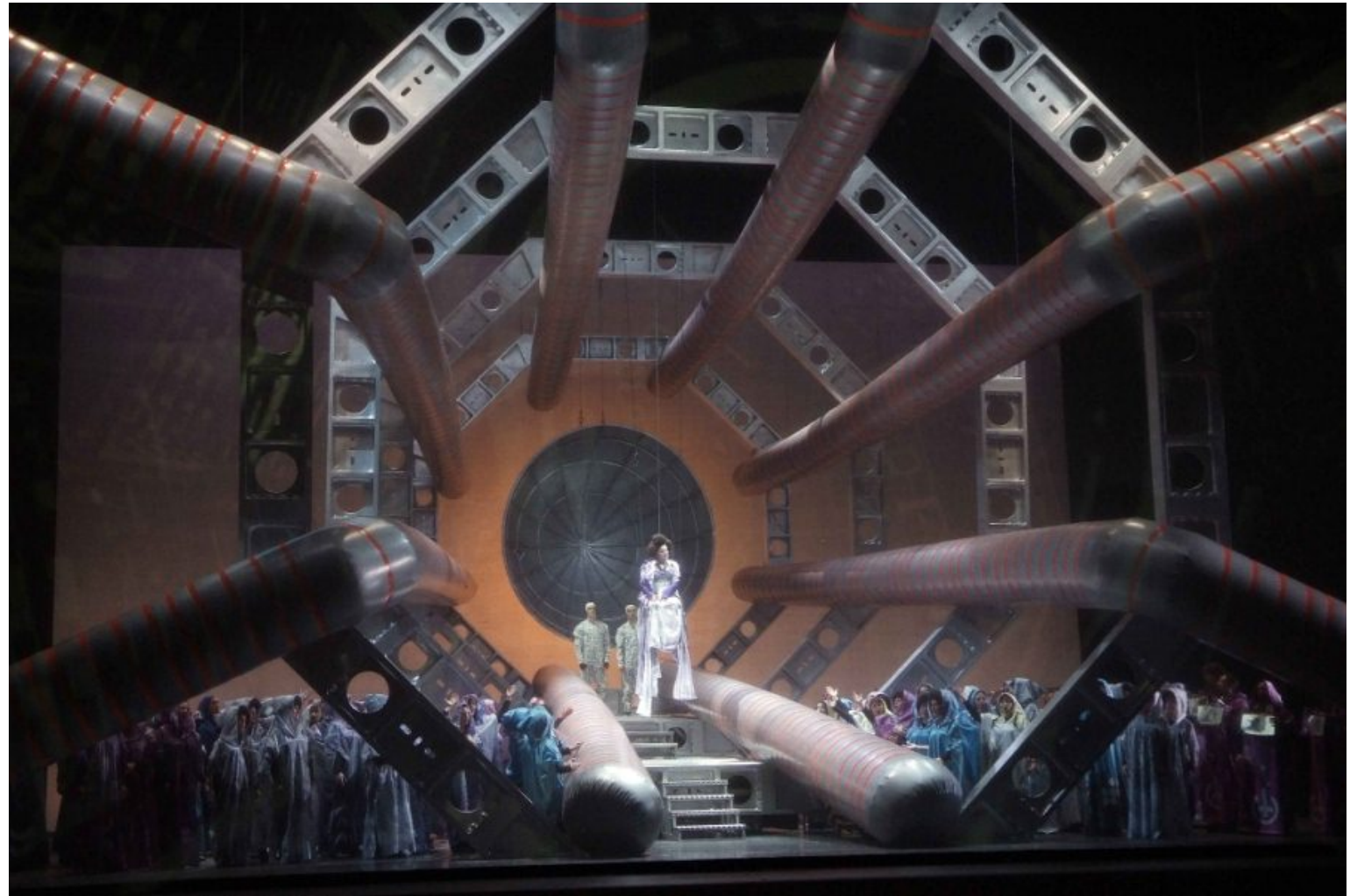




Hector Berlioz, “Les Troyens”, opera in five acts

Valencia, Palau de les Arts Reina Sofia, 31 October -12 November 2009

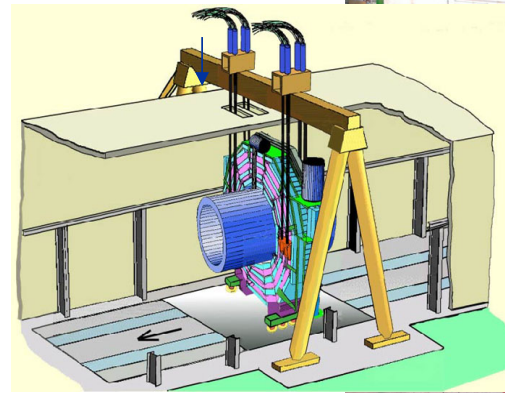
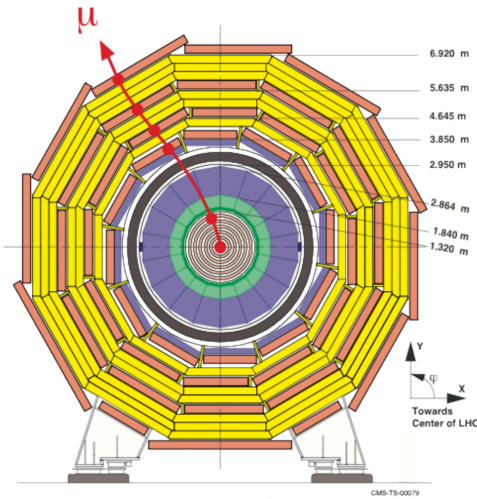
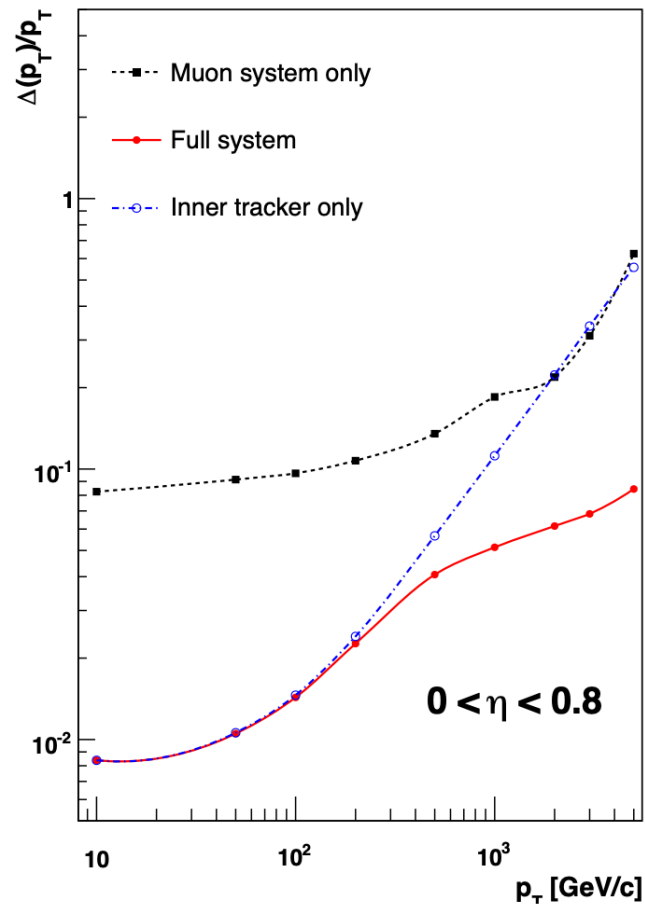
ATLAS is really a  
general-purpose  
detector!



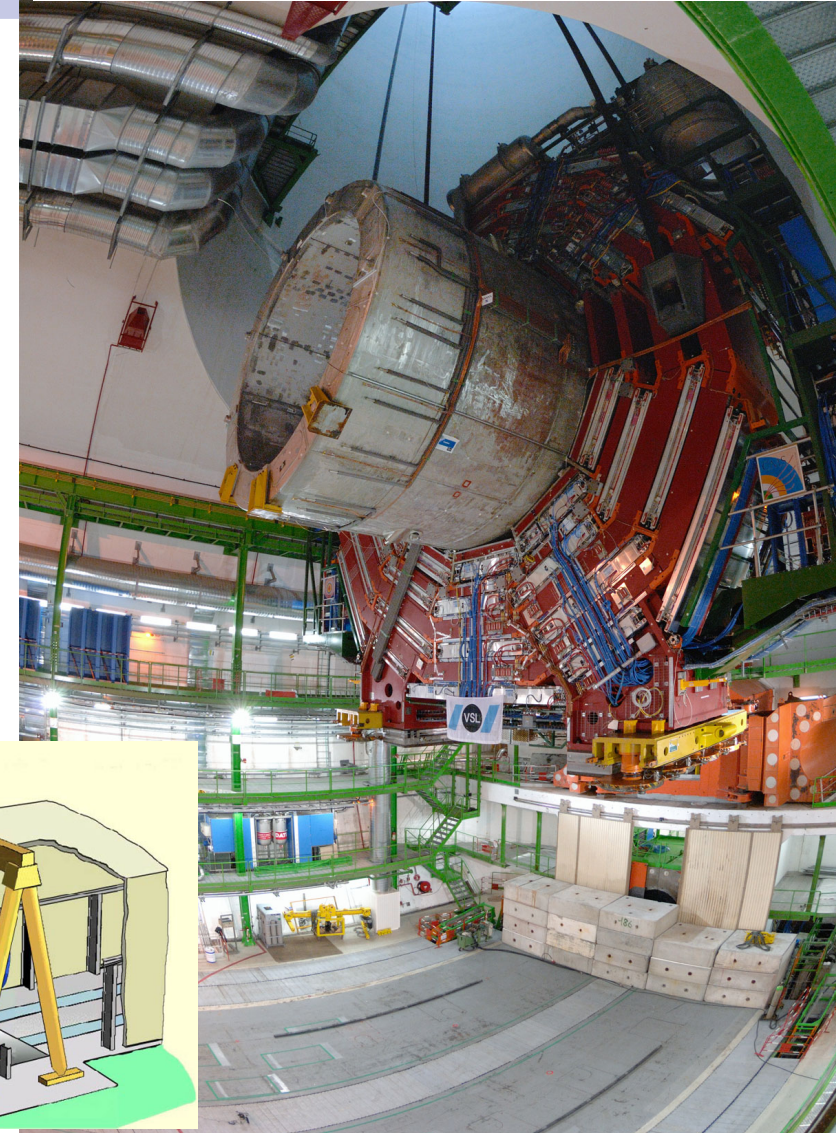
### CMS solenoid:

Magnetic length	12.5 m
Inner radius	2.9 m
Magnetic field	3.8 T
Nominal current	~20 kA
Stored energy	2.7 GJ
Operation temperature	4.5 K

Example of technical  
challenge:  
CMS solenoid

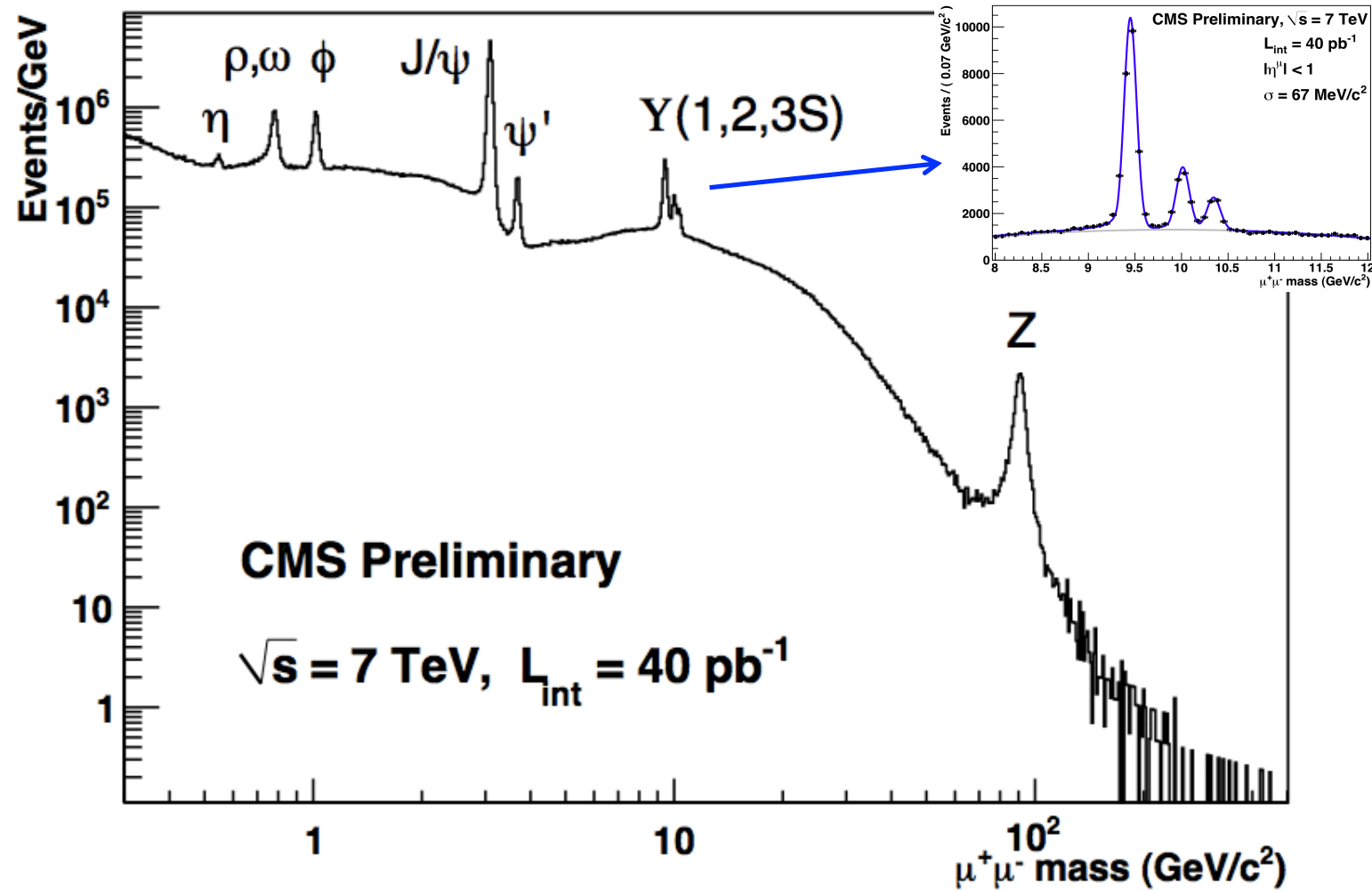


Lowering of the central wheel (2000 tons!) of the CMS detector in the underground cavern in Feb 2007



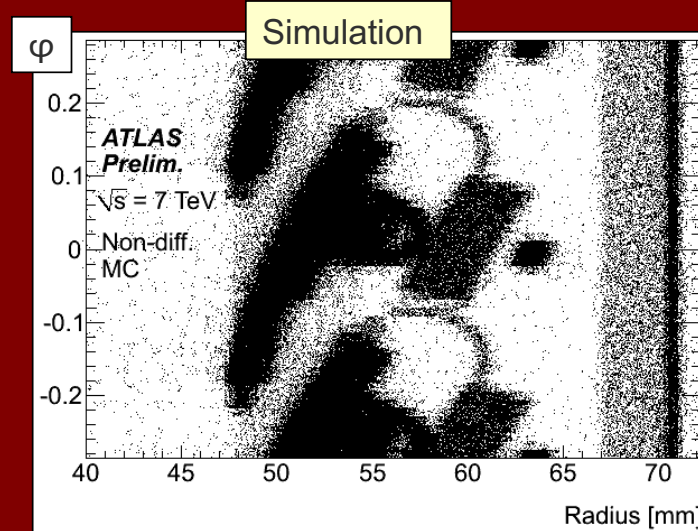
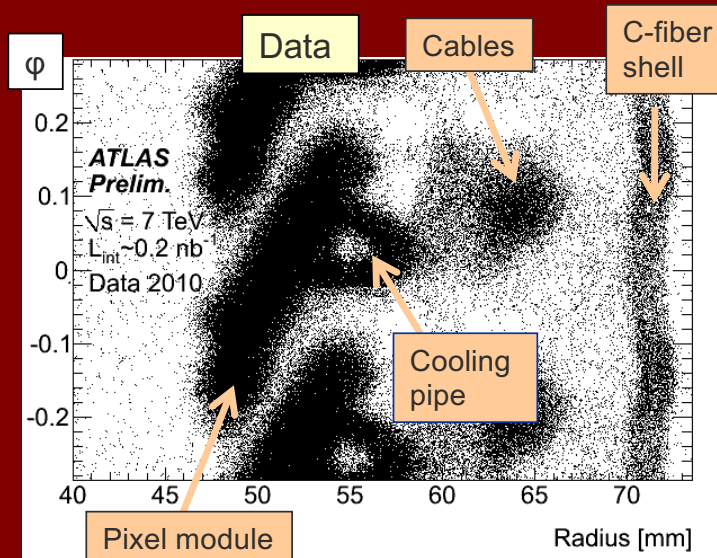


# Superb performance of ATLAS and CMS since the beginning (2009-2010 data)





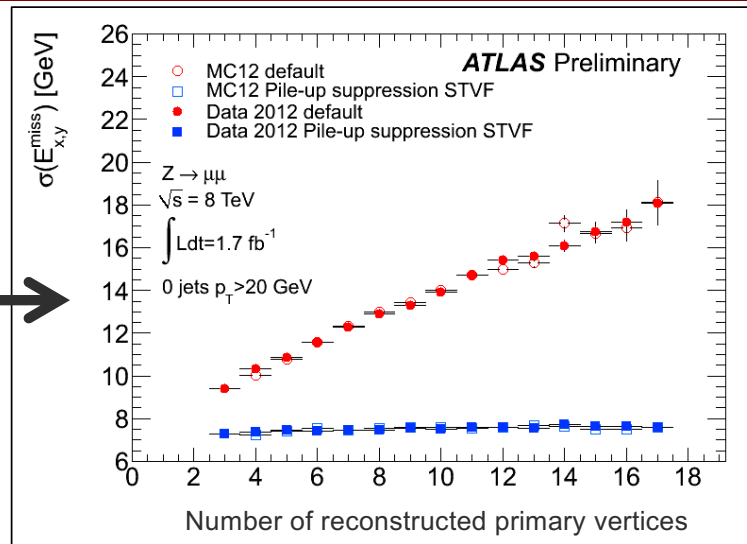
# Superb performance of ATLAS and CMS since the beginning (2009-2010 data)



Reconstructed secondary vertices from hadronic interactions in minimum-bias events in first pixel layer  
 → allow improvement of material description in MC simulation

Missing transverse energy resolution vs pile-up in  $Z \rightarrow \mu\mu$  events **before** and **after** pile-up suppression using tracking information

Note: number of reconstructed primary vertices was  $\sim 60\%$  number of interactions per crossings



# The discovery

Announcement at CERN seminar on 4 July 2012, followed by publications submitted on 31 July 2012:

ATLAS Collaboration, Phys. Lett. B 716 (2012) 1

<https://www.sciencedirect.com/science/article/pii/S037026931200857X>

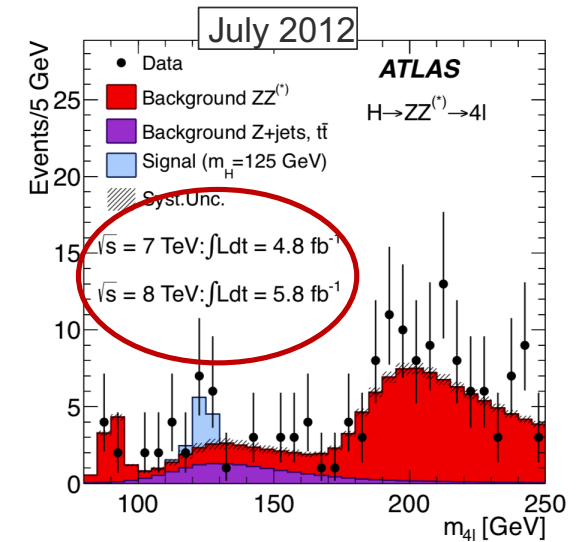
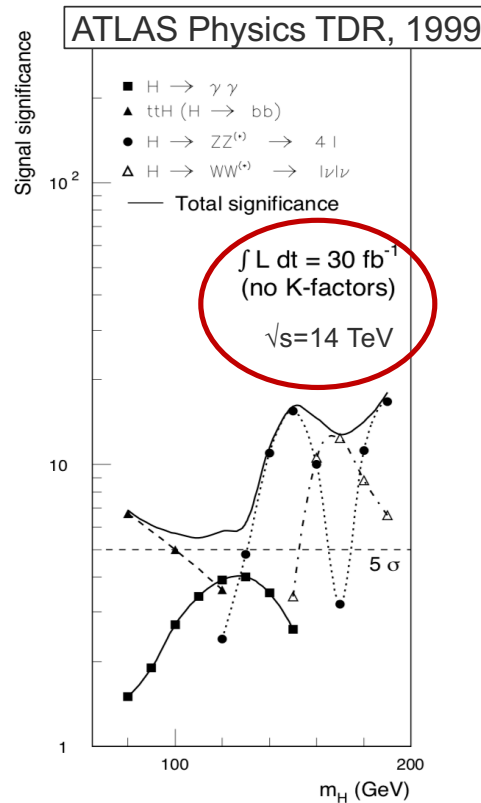
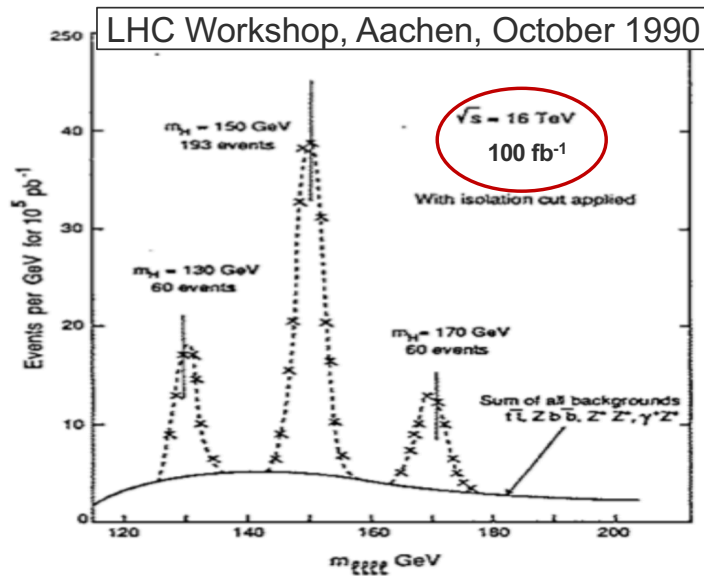
CMS Collaboration, Phys. Lett. B 716 (2012) 30

<https://www.sciencedirect.com/science/article/pii/S0370269312008581>

Results shown here are mainly based on the publications

## It came relatively quickly ...

- ❑ Fast ramp up of the LHC achieving  $\sim 7 \times 10^{33}$  in 2012 and excellent availability in Spring/Summer 2012
- ❑ Detector performance close to (or better than) target; fast development of methods to mitigate the impact of pile-up
- ❑ Excellent performance of the WLCG  $\rightarrow$  data processed and distributed quickly to the worldwide community for analysis
- ❑ Nature: actual Higgs production cross-section (N3LO) is  $\sim 3$  larger than predictions used in the past (LO)



2.5-3 times larger cross-sections at 14-16 TeV than at 8 TeV  $\sim$  offset by cross-section increase from LO to N3LO



# Discovery mainly based on 2 channels

$H \rightarrow \gamma\gamma$ : cross-section  $\sim 50$  fb at 8 TeV

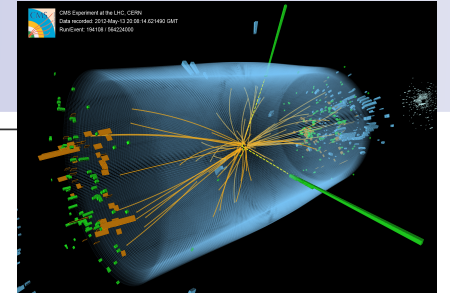
❑ Simple topology: **two high- $p_T$  isolated photons**

❑ Main background:  $\gamma\gamma$  (irreducible)

❑ Crucial experimental requirements:

-- **excellent  $\gamma\gamma$  mass resolution** to observe narrow signal peak above irreducible background (S/B $\sim$ 5% after selection)

--  **$\gamma$ /jet separation** to suppress  $\gamma$ -jet and jet-jet background with jet  $\rightarrow \pi^0 \rightarrow$  fake- $\gamma$  ( $10^4$ - $10^7$  larger cross-sections than  $\gamma\gamma$  background)



$H \rightarrow ZZ^* \rightarrow 4l$  ( $l = e, \mu$ ): cross-section  $\sim 2.5$  fb at 8 TeV

❑ **Tiny rate** but S/B  $\sim 1$

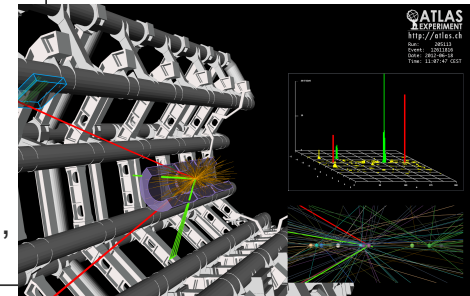
❑ Main backgrounds:  $ZZ^*$  (irreducible),  $Zbb$ ,  $Z$ +jets,  $tt$  with two leptons from b/q-jets

❑ Crucial experimental requirements:

-- **lepton reconstruction and identification efficiency down to lowest  $p_T$**

-- **lepton energy/momentum resolution**

-- **good control of reducible backgrounds** ( $Zbb$ ,  $Z$ +jets and  $tt$ ) using isolation and impact parameter requirements, Monte Carlo and control regions in data



**High-level of analysis sophistication already at this early stage:**

- ❑ quick improvement of physics objects reconstruction and identification and analysis optimisation based on growing experience with data
- ❑ effective methods to mitigate pile-up in the 2012 data ( $\sim 20$  events/xing)
- ❑ events divided in categories targeting different production processes (e.g. VBF), converted/unconverted photons, etc., to increase sensitivity
- ❑ multivariate techniques (BDT, kinematic discriminants, NN, etc.) deployed
- ❑ large and poorly-known reducible backgrounds estimated mostly with data-driven techniques using background-enriched, signal-depleted control regions to validate the MC

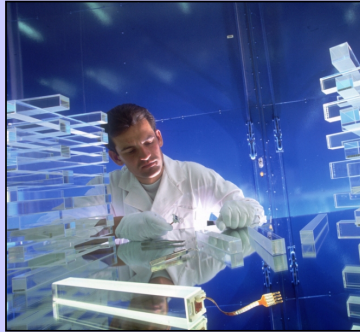
**Analyses frozen before looking at signal region in the data**  $\rightarrow$  unblinding in June 2012

ATLAS 2012:  $H \rightarrow \gamma\gamma$  and  $H \rightarrow 4l$  on 4 July;  $H \rightarrow WW$ ,  $bb$ ,  $\tau\tau$  added for the publication

CMS 2012:  $H \rightarrow \gamma\gamma$ ,  $4l$ ,  $WW$ ,  $bb$ ,  $\tau\tau$  on 4 July and the publication

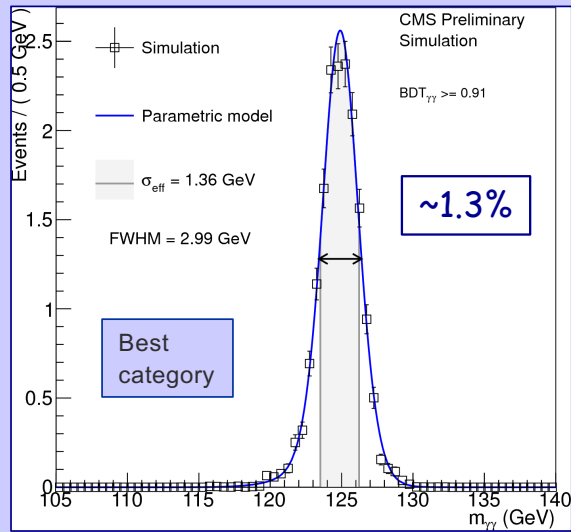
# ATLAS and CMS EM calorimeter complementarity

CMS



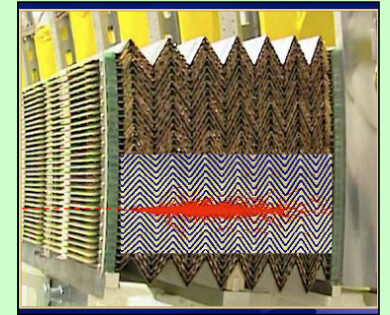
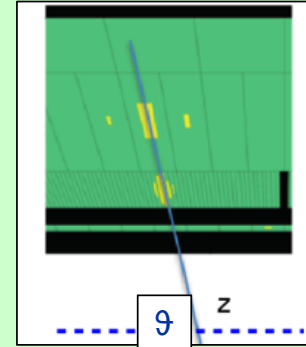
Lead-tungstate crystals (homogeneous):

- excellent E-resolution:  $2\text{-}5\%/\sqrt{E}$
- no longitudinal segmentation  $\rightarrow$  event vertex from tracks (more sensitive to pile-up)



Similar expected sensitivity  
for  $H \rightarrow \gamma\gamma$ ,  $m_H \sim 125$  GeV  
in 2012:  $2.4\text{-}2.8 \sigma$

ATLAS

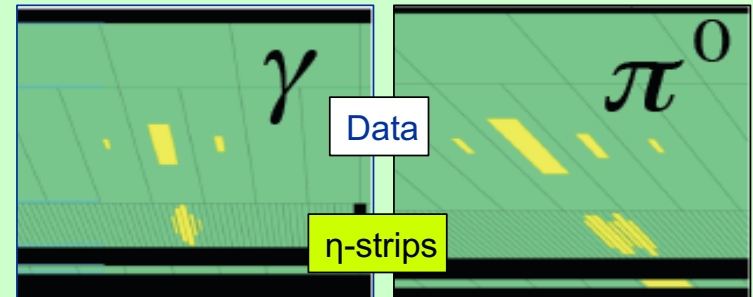


Lead/liquid-argon (sampling):

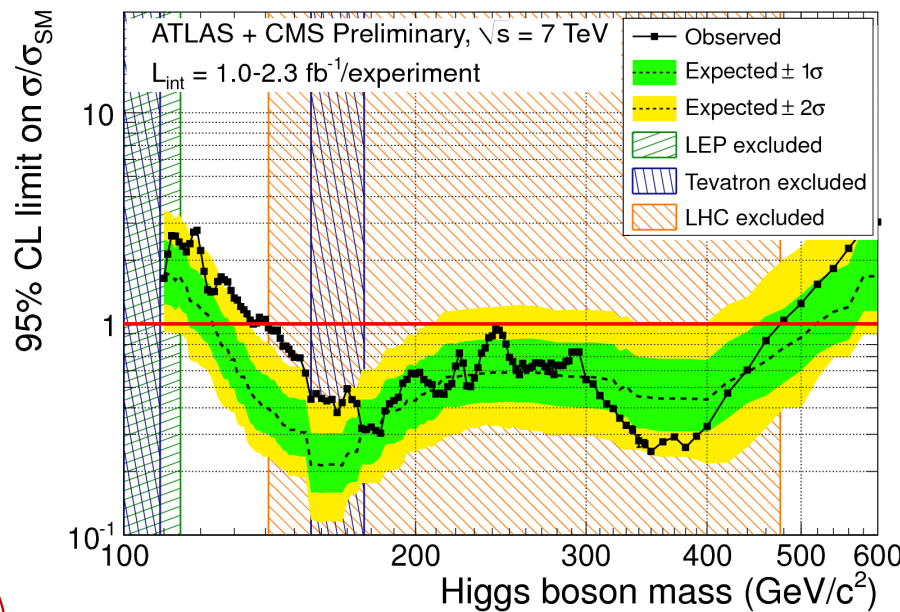
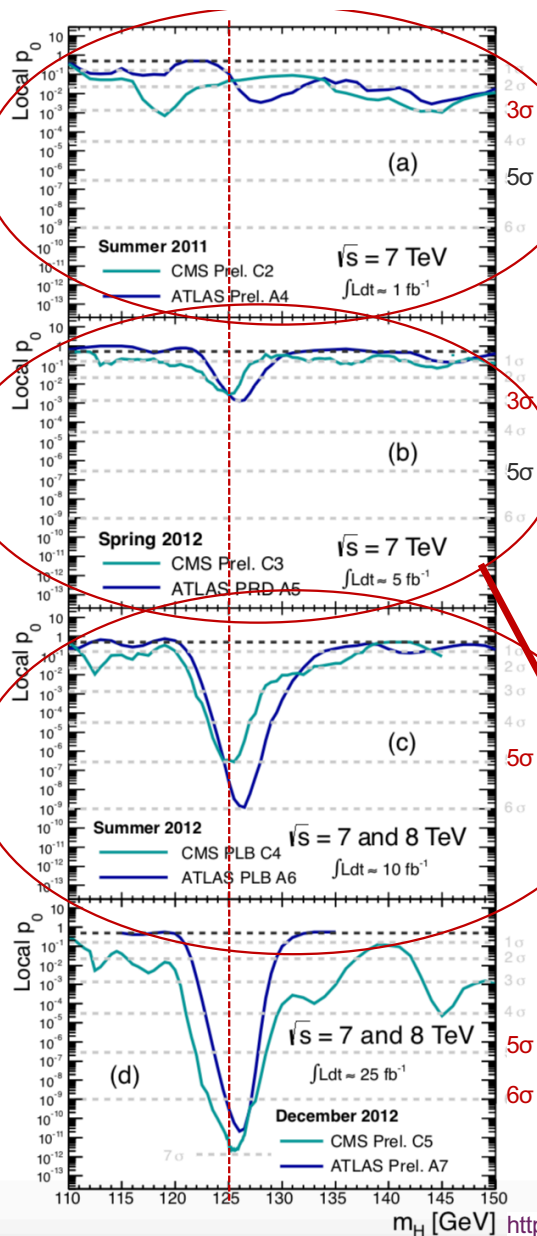
- good E-resolution:  $\sim 10\%/\sqrt{E}$
- longitudinal segmentation  $\rightarrow$  primary vertex from  $\gamma$  direction  $\rightarrow$  maintains good mass resolution in high pile-up conditions

Fine lateral segmentation

$\rightarrow \gamma/\pi^0$  separation (background rejection)



# Signal evolution with time



November 2011 (exclusions, 95% C.L.):

LEP:  $m_H > 114.4$  GeV

Tevatron:  $156 < m_H < 177$  GeV

ATLAS and CMS combined:  
 $141 < m_H < 476$  GeV

Expected exclusion if no signal:  
124-520 GeV

Light Higgs predicted by EW fits

December 2011 (CERN seminar) and Spring 2012:  $\sim 5$  fb $^{-1}$  of 7 TeV data:

- ATLAS:  $2.9 \sigma$  local significance for  $m_H \sim 126$  GeV  
Excluded (95% C.L.): 111.4-116.6 GeV, 119.4-122.1, 129.2-541 GeV (exp. if no signal: 120-560 GeV)
- CMS:  $2.8 \sigma$  local significance in the region  $m_H \sim 125$  GeV  
Excluded (95% C.L.): 127.5-600 GeV (exp. if no signal: 114.5-543)

Note: ALEPH excess at 115 GeV excluded at 95% C.L. (former CERN DG is happy!)

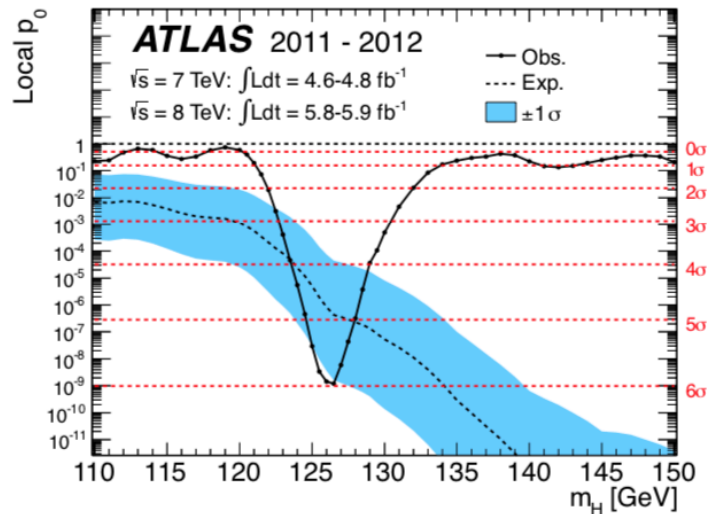
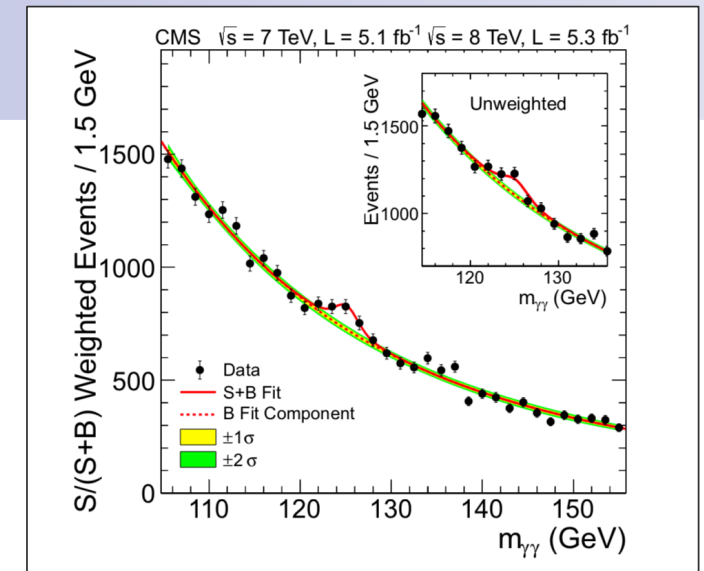
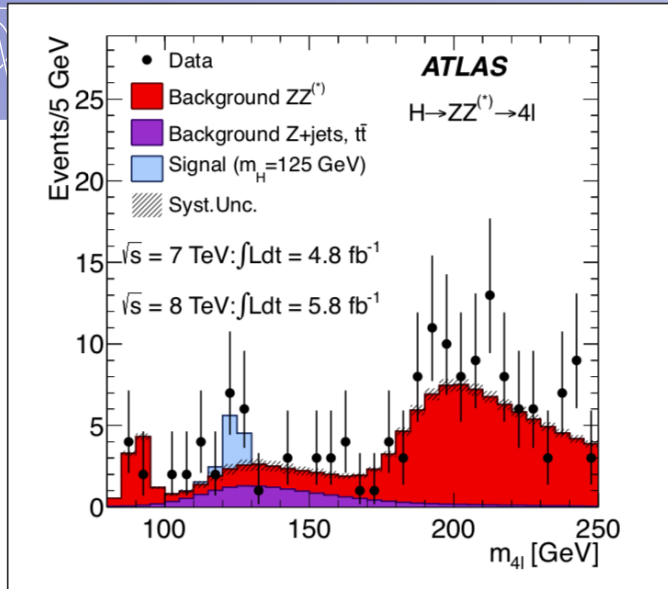
July 2012 (CERN seminar and PLB publications): “We have it!” (R. Heuer, CERN DG)



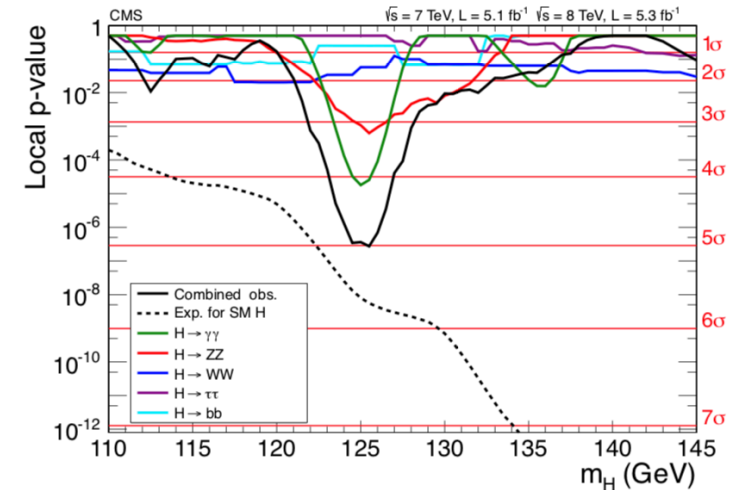
<https://pdg.lbl.gov/2013/reviews/rpp2013-rev-higgs-boson.pdf>



# July 2012: the signal



ATLAS: Local significance:  $5.9 \sigma$  (exp.  $4.9 \sigma$ ) at  $m_H = 126.5 \text{ GeV}$   
 Global significance (including LEE):  $5.1 \sigma$



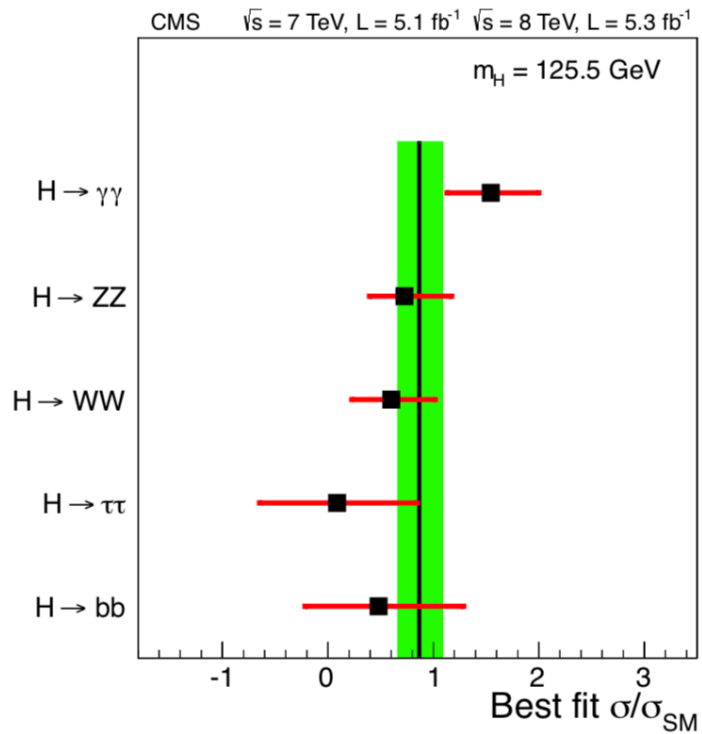
CMS: Local significance:  $5 \sigma$  (exp.  $5.8 \sigma$ ) at  $m_H = 125.5 \text{ GeV}$   
 Global significance (including LEE):  $4.6 \sigma$

# July 2012: first characterisation of the new particle

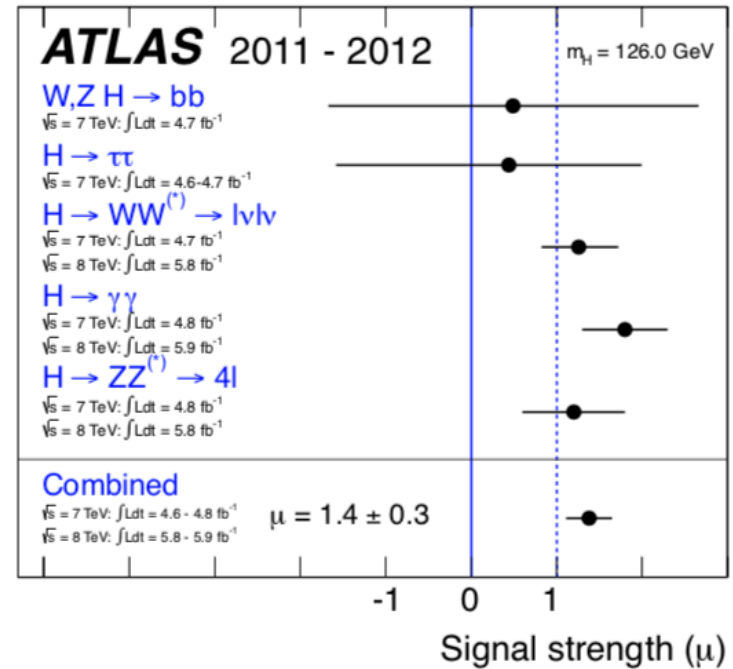
$m_H = 126.0 \pm 0.4 \pm 0.4$  GeV ATLAS

$m_H = 125.3 \pm 0.4 \pm 0.5$  GeV CMS

Measured signal strength normalised to the SM expectation ( $\mu$ )



CMS :  $\mu = 0.87 \pm 0.23$



ATLAS :  $\mu = 1.4 \pm 0.3$

Since then ...



## Immense progress on all fronts

- ❑ Superb **performance of the accelerator complex** → > 30 times more Higgs bosons available than in 2012
- ❑ Superb (understanding of) **performance of ATLAS and CMS detectors** (despite aging, huge pile-up, ...)
- ❑ Superb **performance of WLCG** in handling floods of data (storage, simulation, reconstruction, distribution, analysis, ...)
- ❑ Much improved **analysis methods** (machine learning, statistical treatment, etc.) boosting detector performance and physics sensitivity
- ❑ Very **fruitful theory-experiments collaboration** (e.g. in the framework of LHC Higgs XS WG and LPCC)
- ❑ Lots of **new ideas have made “impossible at hadron colliders” channels become accessible**

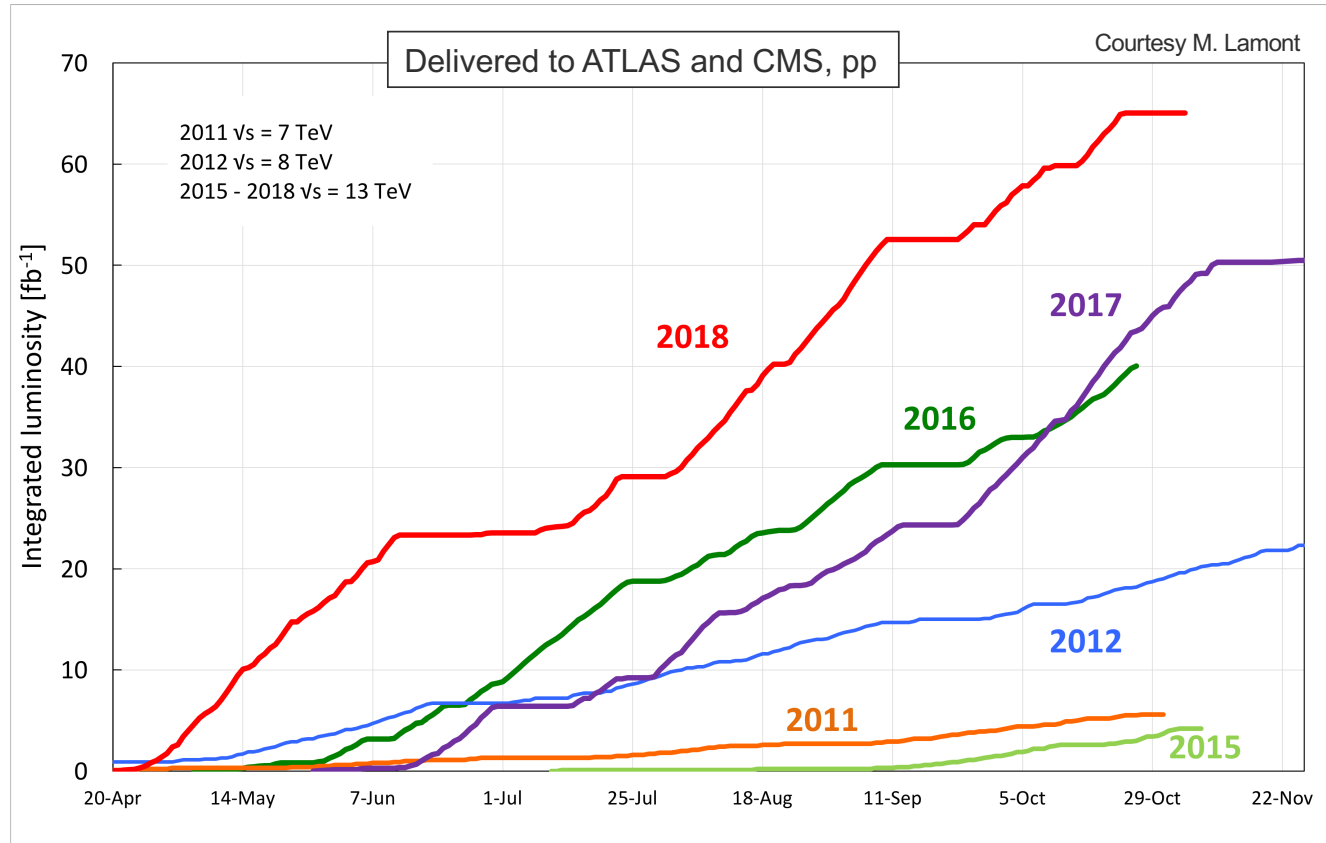
TODAY (numbers below are per experiment):

→ see C. Mariotti's talk

- ❑ All main **Higgs boson production modes** (ggF, VBF, VH, ttH+tH) established at **> 5 $\sigma$**
- ❑ **Couplings to gauge bosons** (established in Run 1) measured to **6-8%**  
**Couplings to 3<sup>rd</sup> generation fermions** (established in Run 2) measured to **7-11%**  
**Couplings to 2<sup>nd</sup> generation fermions: 3 $\sigma$  evidence for  $H \rightarrow \mu\mu$ ; first constraints on  $H \rightarrow cc$**
- ❑ **Rare decays** (e.g.  $H \rightarrow Z\gamma$ ;  $H \rightarrow l\gamma$  at  $\sim 3\sigma$  level)  
Limits on **invisible and exotic decays**
- ❑ **HH production: sensitivity x 3 SM cross-section**
- ❑ **Mass** measured to  **$\sim 0.1\%$**
- ❑ **Width measurement from off-shell/on-shell production** demonstrated (3.6 $\sigma$  evidence for H off-shell production)
- ❑ **J<sup>CP</sup>=0<sup>++</sup>** (large number of alternative hypotheses excluded > 99.9% C.L.)
- ❑ Inclusive studies complemented by **increasing variety of differential/exclusive measurements** (useful to constrain theory; provide additional constraints on couplings; sensitive to new physics in quantum loops affecting kinematic distributions)
- ❑ Searches for **additional Higgs bosons** (no sign yet ...)
- ❑ Etc. etc.

Note: some of the above measurements were not expected to be possible in Run 2

# Accelerator complex and luminosity



~ 90% of delivered luminosity  
used by the experiments  
(high data-taking efficiency  
and excellent data quality)

July 2012

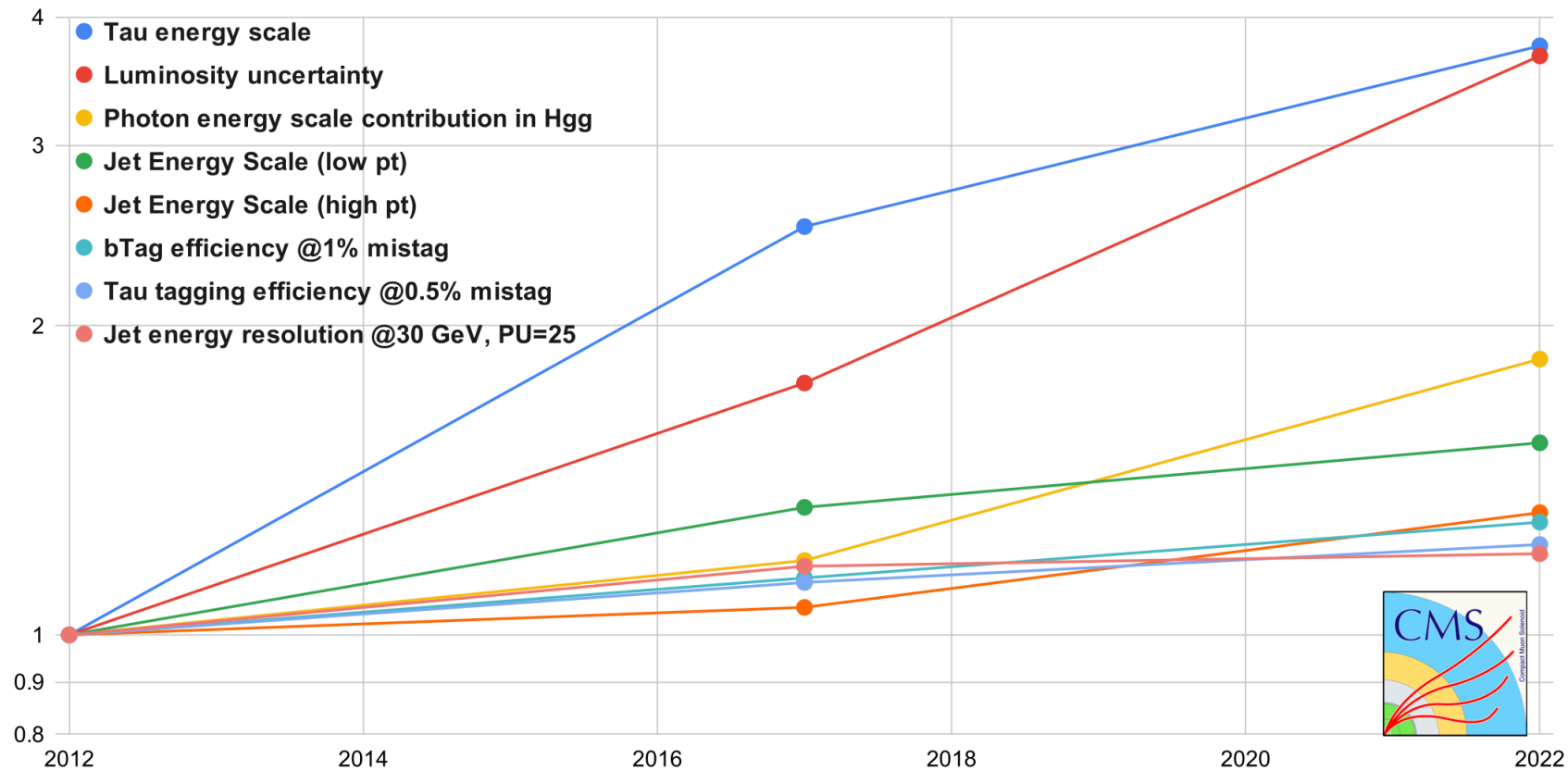
Today

Peak  $L \sim 7 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$   
~ **12  $\text{fb}^{-1}$**  at  $\sqrt{s} = 7\text{-}8$  TeV  
~ **250 000 Higgs** bosons produced per experiment

Peak  $L \sim 2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$   
~ **189  $\text{fb}^{-1}$**  (~160  $\text{fb}^{-1}$  at  $\sqrt{s} = 13$  TeV)  
~ **9 M Higgs** bosons produced per experiment

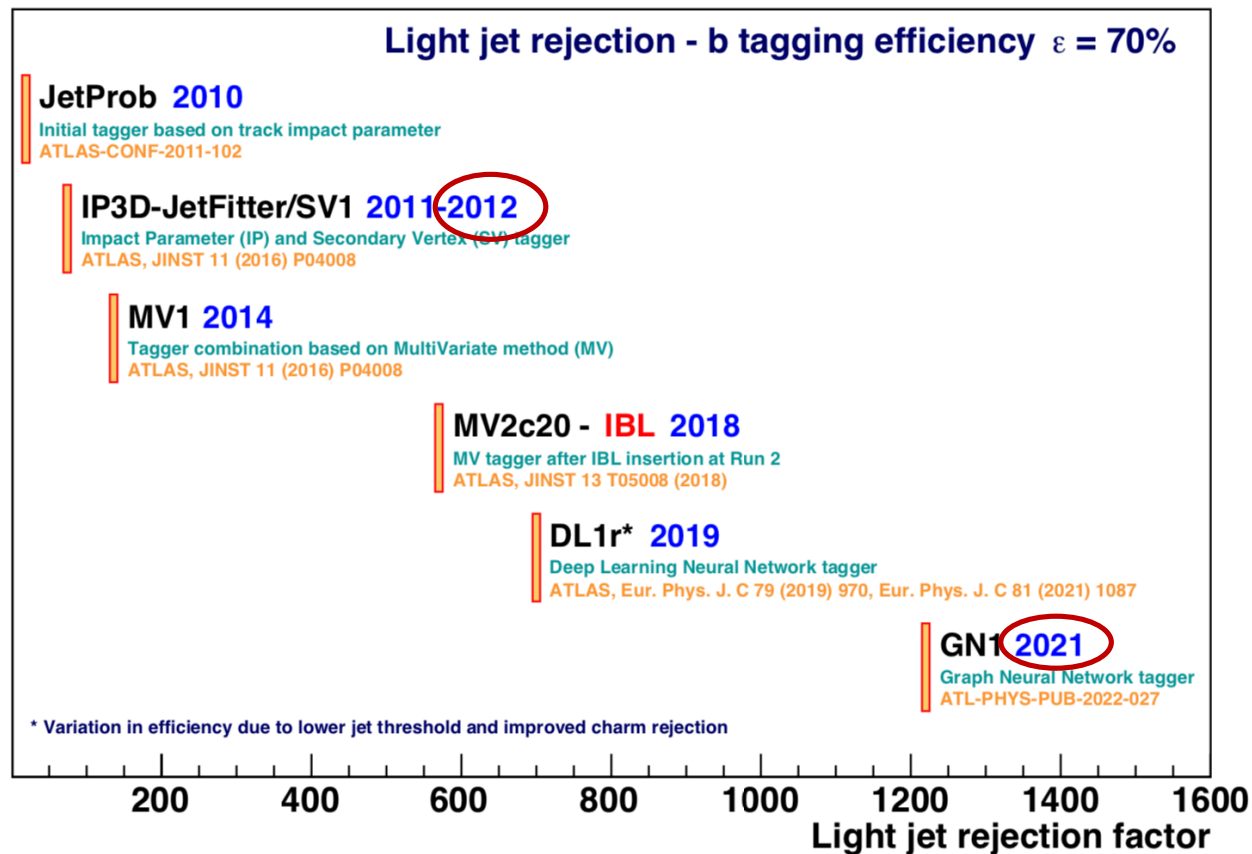
# Detector performance

Evolution of the performance for several objects in CMS from 2012 to 2022



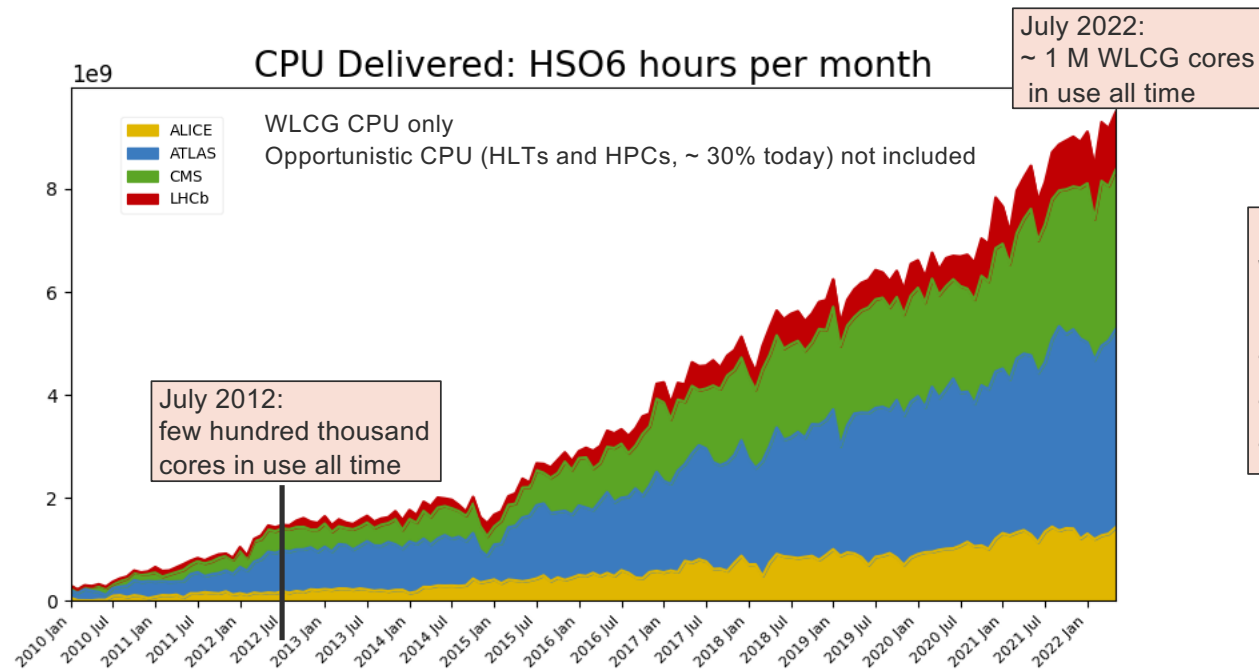


# Detector performance

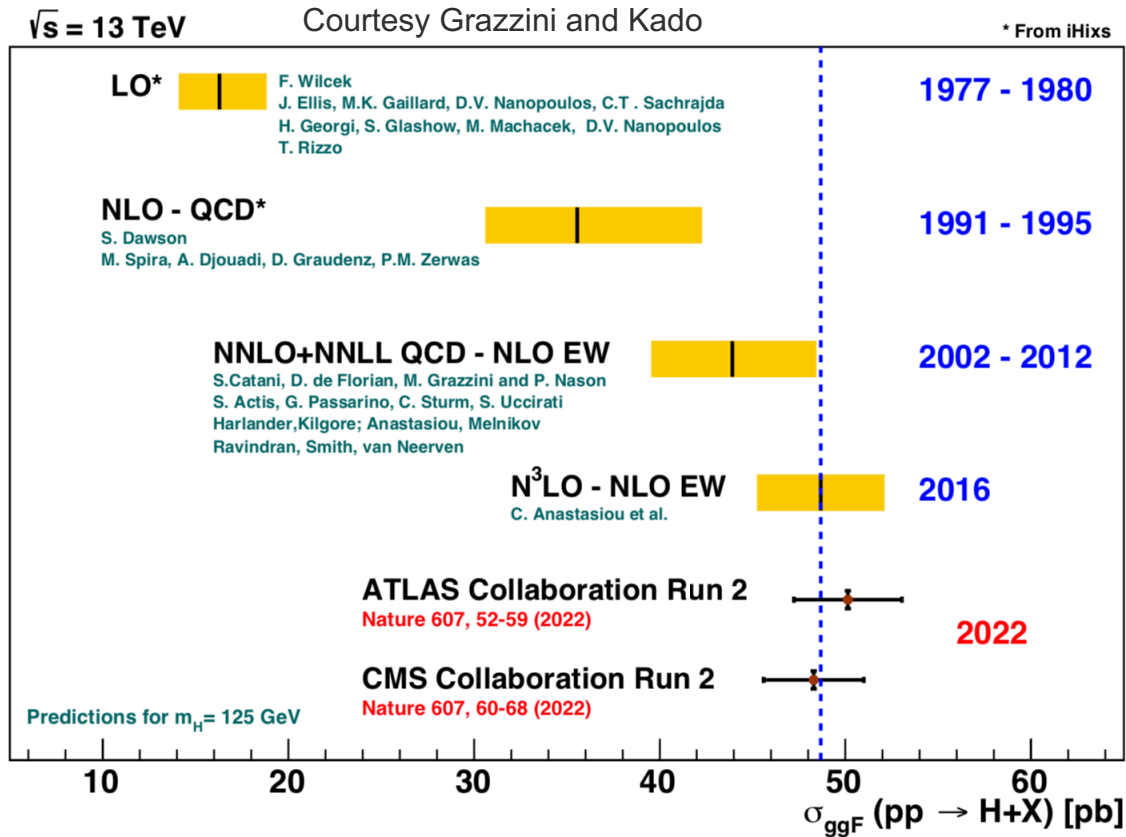


# Computing - WLCG

	2012	2022
T0 → T1 transfer rate (GB/s, peak)	5.7	33.4
Global WLCG transfer rate (GB/s, peak)	15	80 (during data challenges)
Total processing power (HS06 hours/month)	1.6 B	9.1 B
Number of cores in use (WLCG only)	~ 250 k	~ 1 M
Total disk space (PB)	170	750
Total tape (PB)	170	1200



The big success of the **Worldwide LHC Computing Grid**: outstanding performance right from the beginning of the LHC operation, thanks also to the strong support of the Funding Agencies



**Huge theoretical progress** (N3LO-QCD, NNLO Monte Carlos with PS matching, N3LL resummations matched to fixed order, etc.)  
**Challenge:** **theoretical uncertainties** on signal and backgrounds already important today, **will become dominant in many cases** with increased Run 3 and High-Luminosity LHC statistics

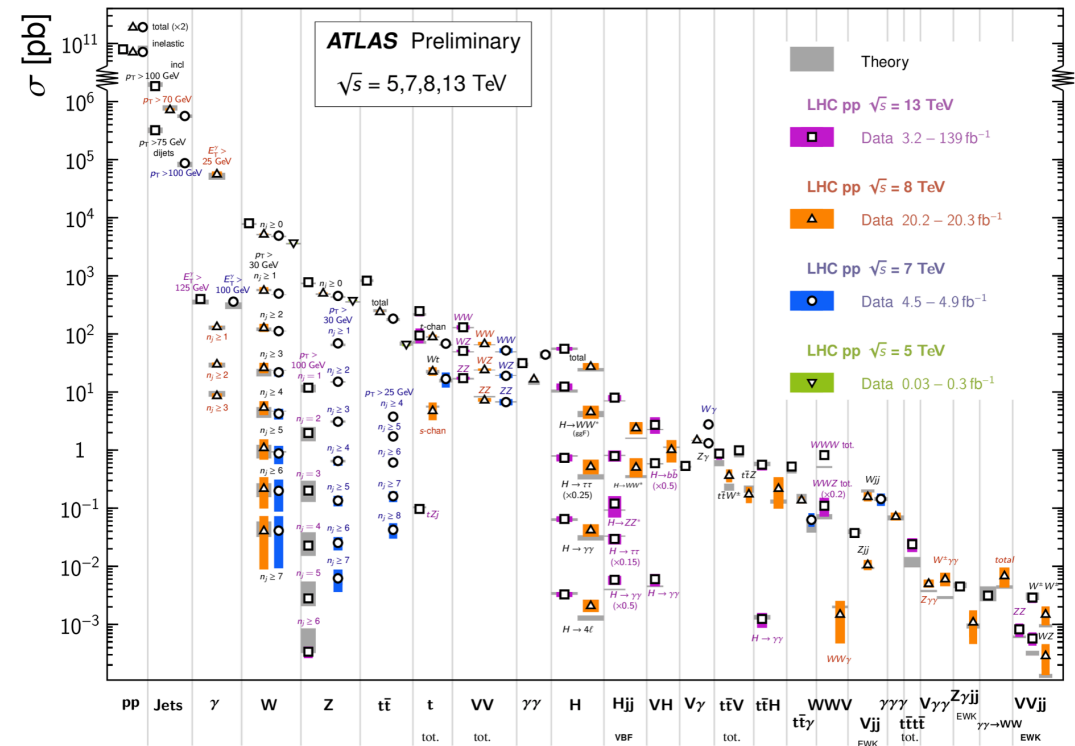
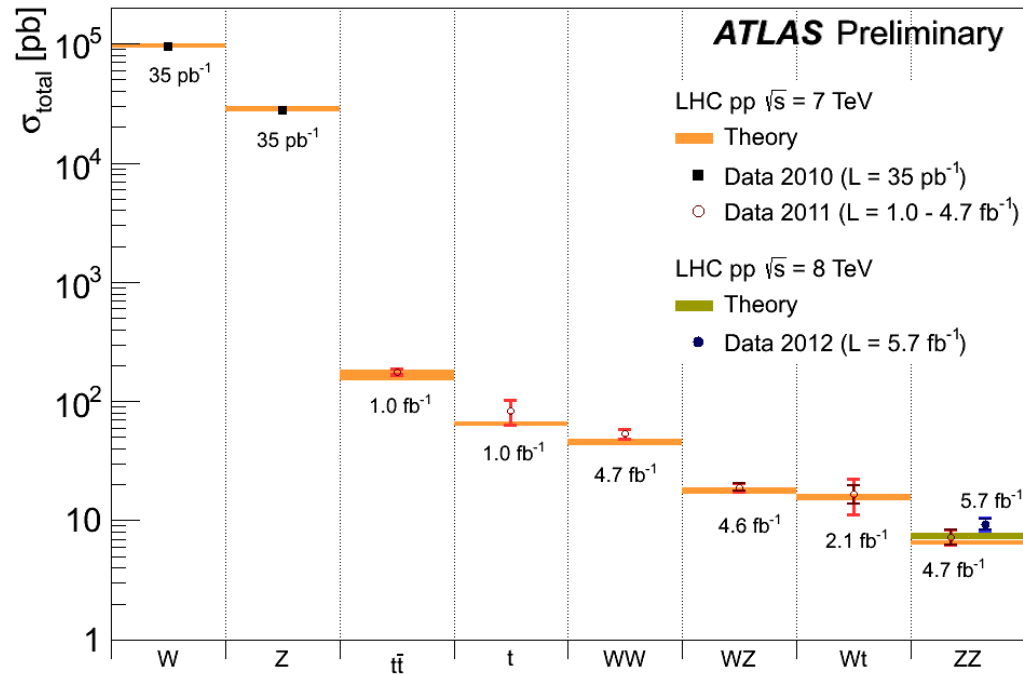


# Standard Model cross-sections

4 July 2012

Today

Status: February 2022



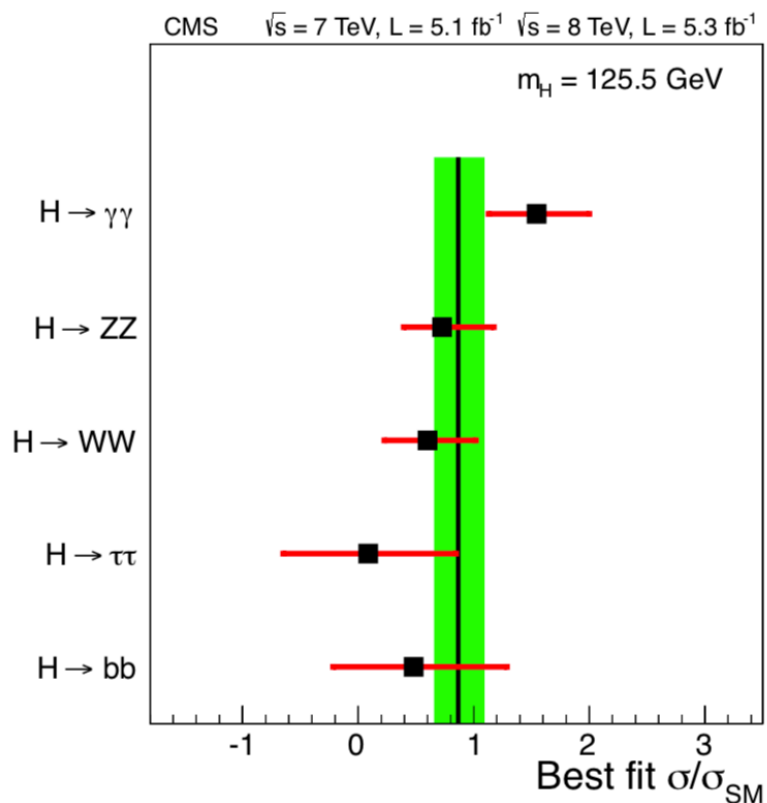
Current precision on inclusive cross-sections: typically few percent over almost 14 orders of magnitude!

# Higgs boson production and decay measurements

July 2012

Today

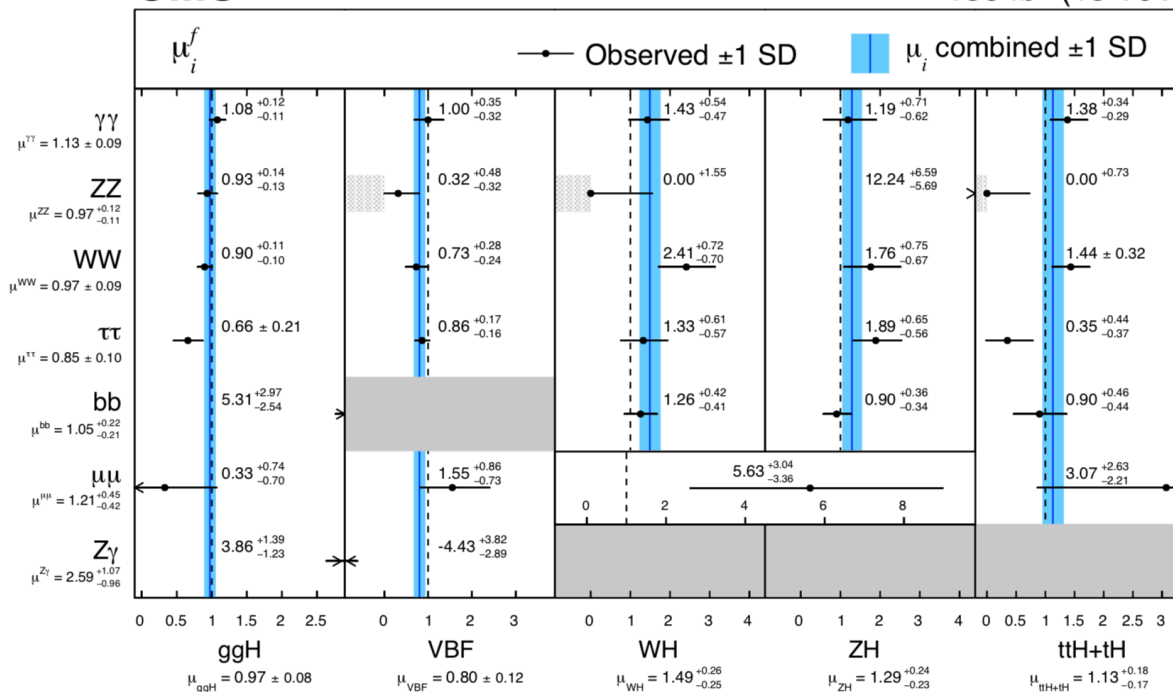
→ see C. Mariotti's talk



Overall signal strength normalised to SM expectation:  
 $\mu = 0.87 \pm 0.23$

CMS

138  $\text{fb}^{-1}$  (13 TeV)



Overall signal strength normalised to SM expectation:  
 $\mu = 1.002 \pm 0.057$



# Conclusions

The Higgs boson discovery in 2012 opened **a new era of exploration** at the LHC, HL-LHC and future colliders.

**The fundamental questions surrounding the Higgs boson** (naturalness, origin of flavor and masses, CP-violation and baryogenesis, vacuum stability, existence of additional Higgs bosons, portal to dark sector, etc.) **make it an extraordinary discovery tool and motivate a broad and extensive programme of investigations** (couplings to as many generations as possible, Higgs potential, rare decays, BSM decays, differential measurements, searches for extended Higgs sectors, etc.).

**Progress in accelerator, detector and computing technologies, theory, and analysis techniques, as well as lots of ingenuity, will be needed to fully exploit the discovery power of this special particle at current and future colliders.**

**A bright future ahead for generations of scientists!**

**The Higgs boson discovery, and the many beautiful accomplishments at the LHC since then, demonstrate the talent, competence, perseverance and determination of the worldwide high-energy physics community, and its ability to deliver beyond expectation.** These are crucial assets for future, even more ambitious projects





# Many thanks to

CERN's Member States and Associate Member States for their continued, strong support over the decades and to non-Member States for their essential contributions to the LHC.

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