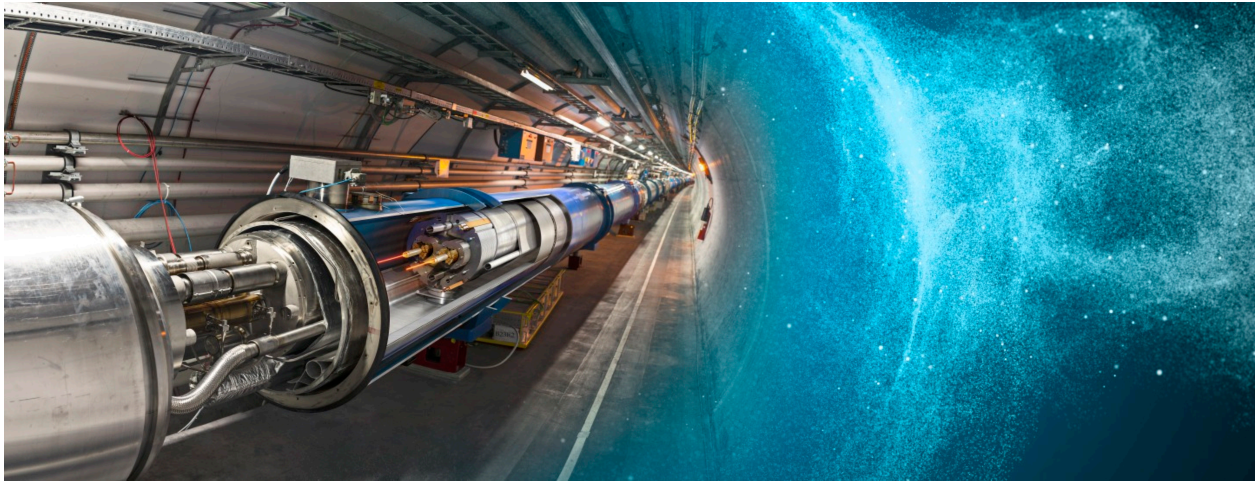
The Path to the Higgs Boson Discovery



Karl Jakobs
University of Freiburg

100 Jahre Quantenphysik, DPG
Göttingen, 10th September 2025

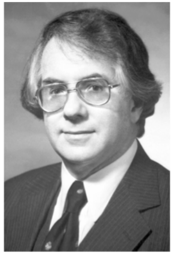
universität freiburg

4 July 2012

Nobel Prize for Physics 2013: François Englert and Peter Higgs

“ … for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of sub-atomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN’s Large Hadron Collider.”

Key milestones towards the electroweak theory



1961: Glashow develops the **SU(2)$_L$ x U(1)$_Y$ model** for weak and electromagnetic interactions*

- Isotriplet of **vector fields W_μ^i** coupled with strength g to the weak isospin current
- Single **vector field B^μ** coupled to the weak hypercharge current with strength $g'/_2$

$$W_\mu^\pm = \frac{1}{\sqrt{2}}\left(W_\mu^1 \mp W_\mu^2\right)$$

$$A_\mu = B_\mu \cos\theta_W + W_\mu^3 \sin\theta_W$$

$$Z_\mu = -B_\mu \sin\theta_W + W_\mu^3 \cos\theta_W$$

Charged bosons W^+, W^-

Photon → $g \sin\theta_W = g' \cos\theta_W = e$ (weak mixing angle θ_W)

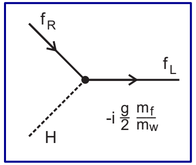
Neutral boson ("weak neutral current")

Problem: massive vector fields, without breaking the gauge invariance!

1964: Brout-Englert-Higgs mechanism

1967: Weinberg**: the same Higgs doublet which generates W and Z masses is also sufficient to give masses to leptons and quarks

→ Yukawa couplings

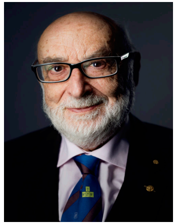


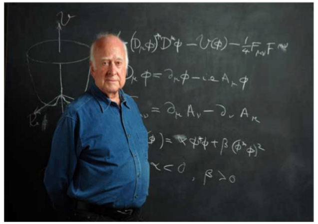
* S. Glashow, *Partial-Symmetries of Weak Interactions, Nuclear Physics B 22 (1961) 569*

** S. Weinberg, *A Model of Leptons, Phys. Rev. Lett.* 19 (1967) 1264

Key milestones towards the electroweak theory

Brout-Englert-Higgs mechanism





F. Englert and R. Brout. Phys. Rev. Lett. 13 (1964) 321;
P.W. Higgs, Phys. Lett. 12 (1964) 132, Phys. Rev. Lett. 13 (1964) 508;
G.S. Guralnik, C.R. Hagen, and T.W.B. Kibble. Phys. Rev. Lett. 13 (1964) 585.

Add complex scalar fields in an isospin doublet with potential:

$$V(\phi) = \mu^2(\phi^* \phi) + \lambda(\phi^* \phi)^2$$

For $\lambda > 0$, $\mu^2 < 0$: Potential has minimum at $|\phi|^2 = -\mu^2 / 2\lambda$

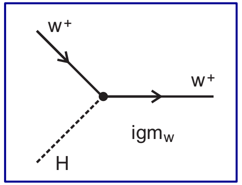
"Spontaneous symmetry breaking" choose $\phi = \frac{1}{\sqrt{2}} \binom{0}{v}$

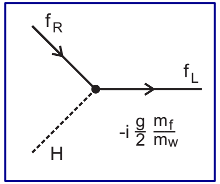
$v = (\sqrt{2}\, G_F)^{-1/2}$ = 246 GeV (vacuum expectation value)

(i) Mass terms for W and Z bosons

$$m_{W^\pm} = {}^1/_2\ v\ g, \qquad m_Z = m_{W^\pm}/\cos\theta_W$$

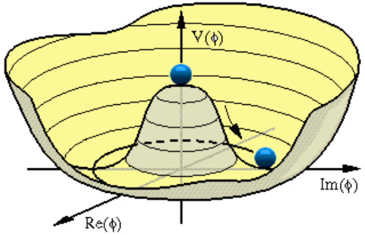
(ii) Couplings to fermions (Yukawa couplings)





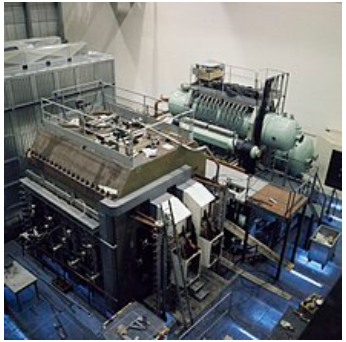
(iii) Higgs boson self coupling

$$V(\phi) = \frac{1}{2} m_H^2 h^2 + 3\,\frac{m_H^2}{v} h^3 + 3\,\frac{m_H^2}{4!\ v^2} h^4$$



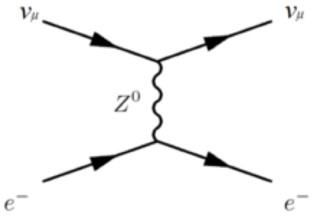
Key milestones towards the electroweak theory

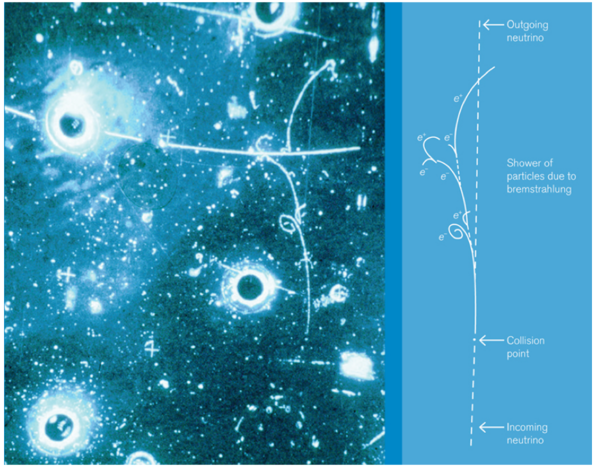
1973: **Discovery of weak neutral currents** in the Gargamelle bubble chamber at CERN



$\nu_\mu + e^- \to \nu_\mu + e^-$ observed!

This process can only be explained by exchange of a neutral boson (Z)





→ The "Glashow-Salam-Weinberg" model is taken seriously, and from there on it is considered as the **"Standard Model"**

Still missing: the direct detection of the $W^\pm$ and Z^0 bosons

PROPOSAL FOR A NEUTRINO EXPERIMENT IN GARGAMELLE

Aachen, Brussels, CERN, Ecole Polytechnique,
Milan, Orsay, University College

1. INTRODUCTION

Among the many problems posed in weak interactions, it appears that neutrino experiments in Gargamelle would be especially suitable to investigate the following : *)

i) Total cross-sections in the high energy region, for ν and $\bar{\nu}$;

ii) Inelastic continuum excitation of the hadronic amplitude-structure factors and "partons";

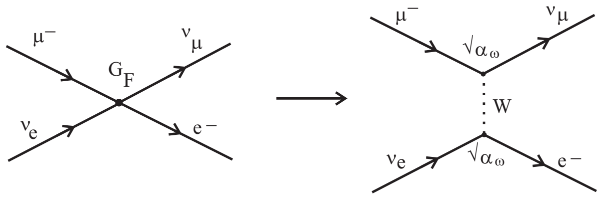
iii) Existence of the intermediate W-boson;

iv) Coupling constants for diagonal and non-diagonal weak interactions;

v) Neutral currents.

Key milestones towards the electroweak theory

Glashow-Salam-Weinberg theory provides an estimate of the boson masses via the relation to the Fermi / (V-A) theory:



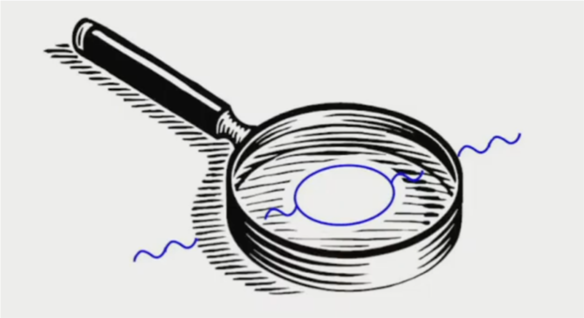
$$\mathcal{M}^{CC} = \frac{4G_F}{\sqrt{2}} (J_\mu)(J^{\mu\dagger}) \qquad \mathcal{M}^{CC} = \frac{g}{\sqrt{2}} (J_\mu) \left(\frac{1}{m_W^2}\right) \frac{g}{\sqrt{2}} (J^{\mu\dagger})$$

$$\rightarrow \frac{G_F}{\sqrt{2}} = \frac{g^2}{8\, m_W^2} \xrightarrow[g \,=\, e/\sin\theta_W,\ \alpha \,=\, e^2/4\pi]{} \boxed{m_W = \sqrt{\frac{\pi\,\alpha}{\sqrt{2}\,G_F}} \cdot \frac{1}{\sin\theta_W}}$$

Measured value of $sin^2\theta_W$ = 0.234 $\pm$ 0.013 (from ν scattering) at times $\rightarrow$ $\boldsymbol{m_W \sim 76\ \mathrm{GeV}}$, $\boldsymbol{m_Z \sim 88\ \mathrm{GeV}}$

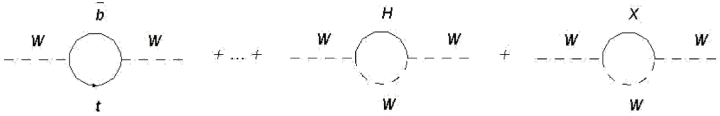
Leading order estimate, no quantum corrections included!

Quantum Corrections



Particle physics example:

Corrections to the **W boson mass**:



Sensitivity to:
- Top-quark mass
- Higgs boson mass
- Any new particle coupling to the W boson e.g. supersymmetric particles

- Corrections by known SM particles
  Well-known example: Lamb shift, vacuum polarisation

- But also sensitivity to particles beyond the energy scale of the process
  (SM particles, e.g. top quark, and particles from extensions beyond the SM (BSM))

$$m_W = \sqrt{\frac{\pi\,\alpha}{\sqrt{2}\,G_F}} \cdot \frac{1}{\sin\theta_W \cdot \sqrt{1-\Delta r}}$$

$\Delta r =$ quantum corrections $\sim f(m_{top}^2, \log m_H)$

$\mathcal{O}\,(6\%)$

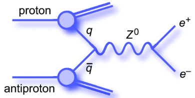
Discovery of the W and Z bosons at the CERN $p\bar{p}$ collider

1983/84: **Discovery of the W and Z bosons at the CERN $p\bar{p}$ collider**
by the UA1 and UA2 experiments
(Carlo Rubbia, Simon van der Meer (accelerator))

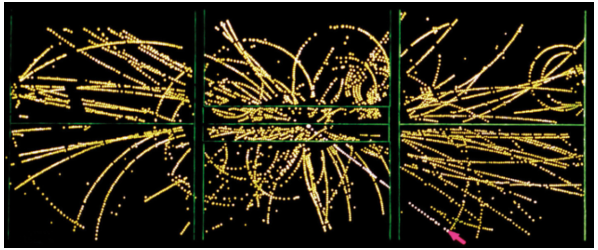
Carlo Rubbia (UA1), Herwig Schopper

Simon van der Meer

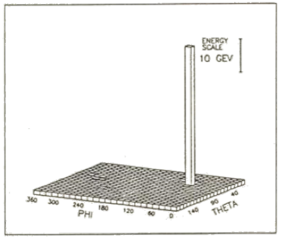
Drell-Yan production



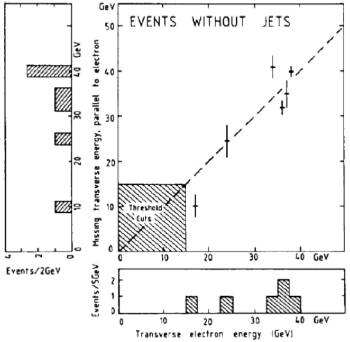
Leptonic decays: $W \to \ell\,\nu$ (large $P_T(\ell)$, large E_T^{miss})
$Z \to \ell\,\ell$



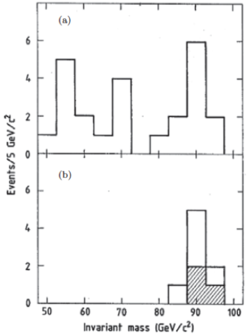
UA1 central tracking



UA2 calorimeter



UA1: Transverse momentum vs. E_t^{miss}

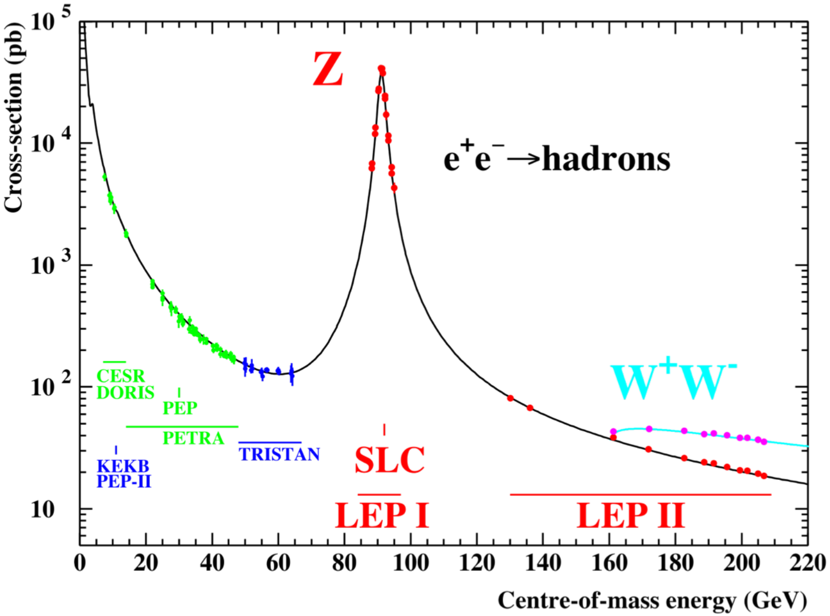


UA2: Invariant di-electron mass

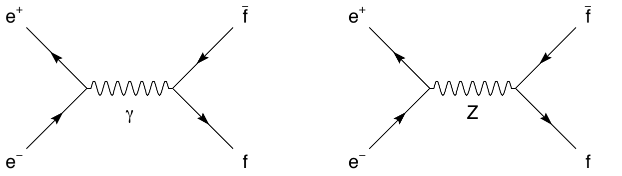
Measured mass values (1985):

$$m_W = 82.7 \pm 1.0 \pm 2.7 \text{ GeV}$$
$$m_Z = 93.1 \pm 1.0 \pm 3.1 \text{ GeV}$$

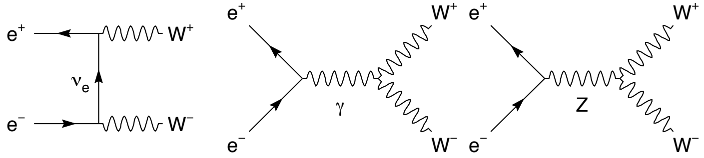
Precision measurements of Z and W⁺W⁻ bosons at LEP



Z boson production at LEP I ($\sqrt{s}$ = 91 GeV)

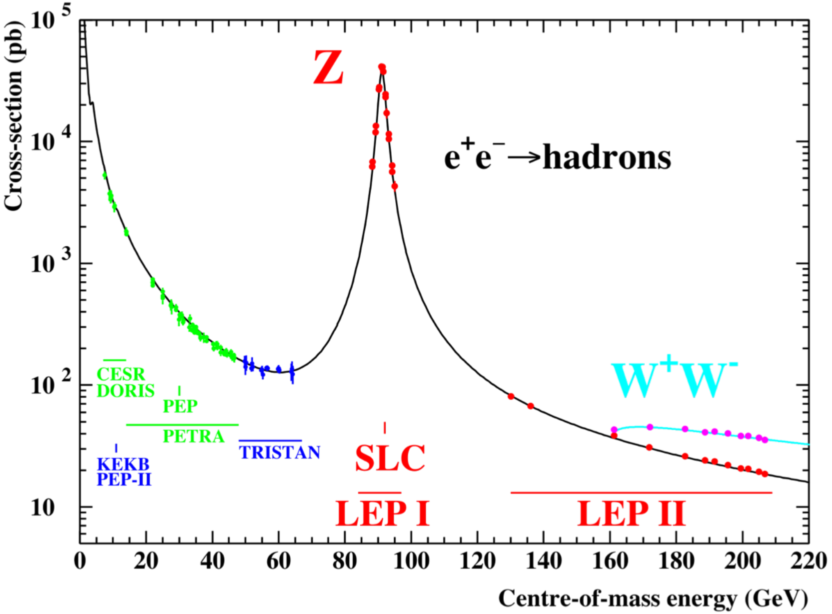


W pair production at LEP II ($\sqrt{s} \geq 2\, m_W$)



→ Test of the gauge structure / gauge couplings of the electroweak interaction

Precision measurements of W^+W^- and Z bosons at LEP



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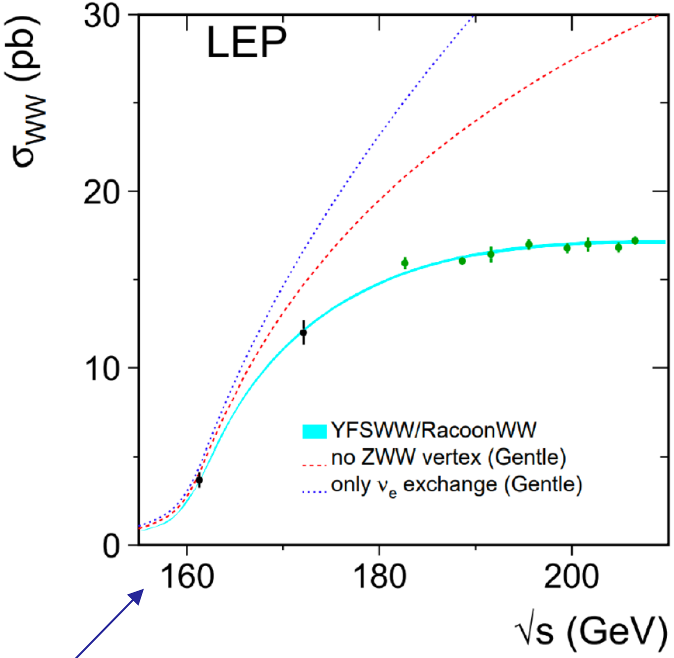
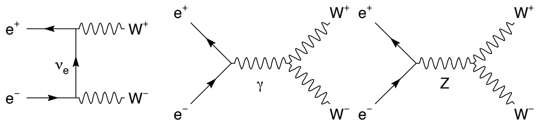
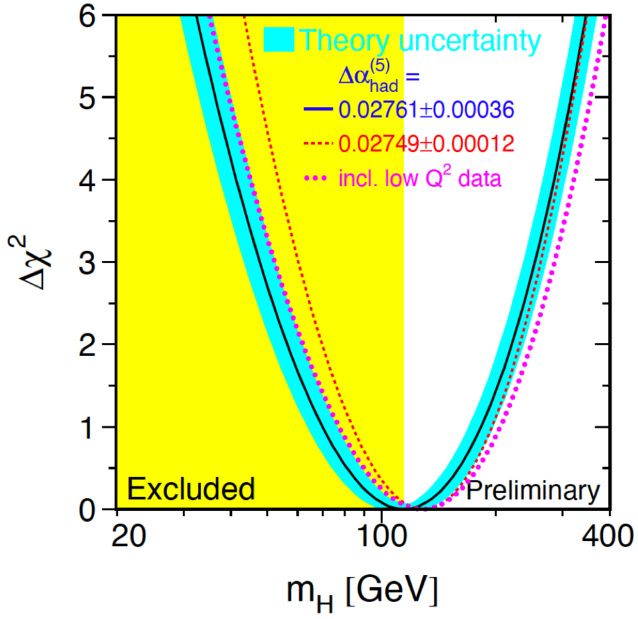


Milestone result in the experimental test of el.weak interactions → convincing proof of gauge-boson self coupling



Where is the Higgs boson?



- No Higgs boson observed at LEP, limit from LEP searches: m_H > 114.4 GeV (95% C.L.)
- Electroweak precision data favour a light Higgs boson (quantum corrections, m_t known, SM assumed)

Towards the Large Hadron Collider

"The real belief that a 'dirty' hadron collider can actually do great discovery physics came from the UA1 and UA2 experiments with their W and Z boson discoveries at CERN (1983)"

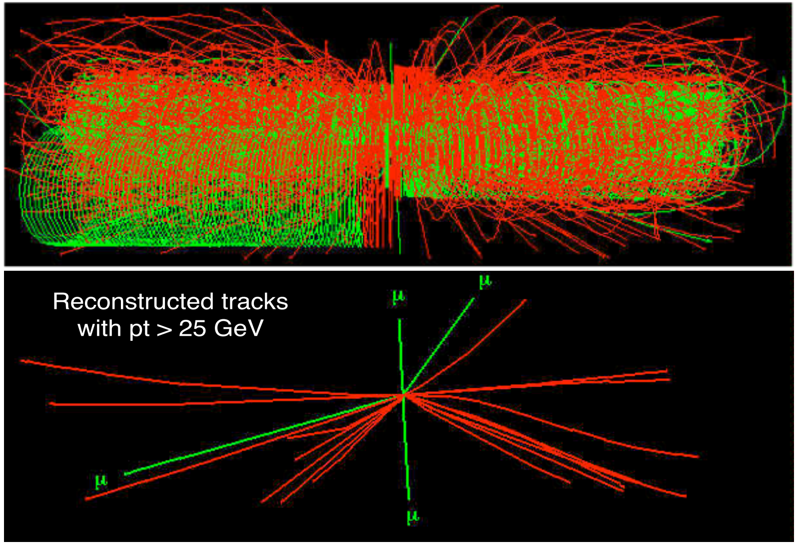
- The Large Hadron Collider was designed to be capable to discover the Higgs boson over the entire mass range, up to the TeV mass scale

- Given the low production cross section, this was a formidable charge, calling for a very high luminosity of 10^{34} cm^{-2} s^{-1}

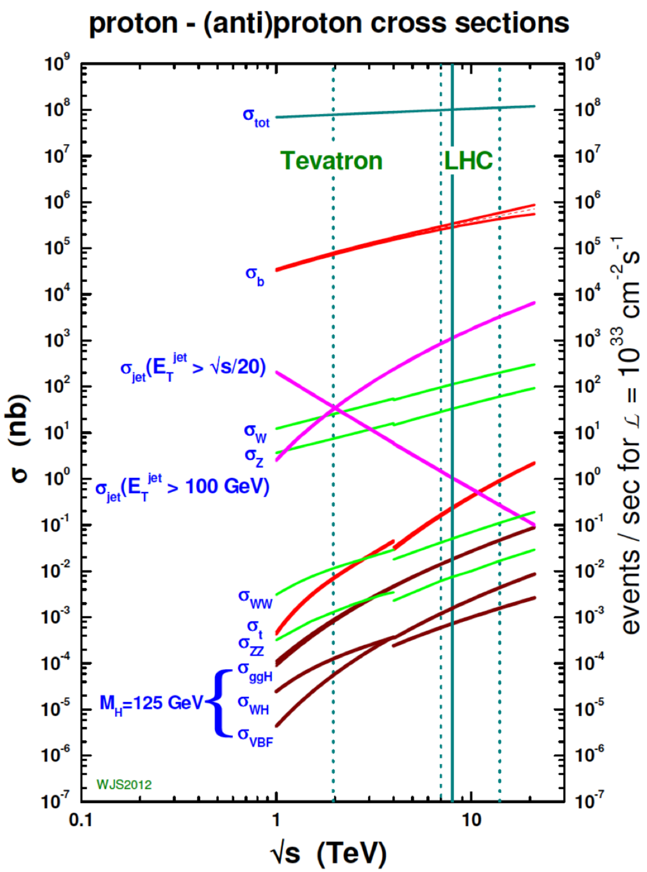
  → huge experimental challenges
  (overlapping events, very high track density, small signal-to-background ratio)

  At the beginning of the 1990s it was e.g. not clear, how central tracking detectors could be built

  → Large Detector R&D programme initiated at CERN



Arguing about LHC detector designs in the early 1990s …



Peter Jenni
(Spokesperson ATLAS experiment)

A very simplified summary:

detector signature		accessible physics process
$\mu^\pm$		$H \to ZZ \to 4\mu^\pm$ $Z' \to \mu^+\mu^-$ (σ_m ?)
$\mu^\pm$, jets, $p\!\!\!/_T$	add:	$H \to ZZ \to \mu^+\mu^-\nu\bar\nu$ $W' \to \mu^\pm\nu$ compositeness $\tilde q, \tilde g$ (direct decays) jet spectroscopy
e, $\mu^\pm$, jets, $p\!\!\!/_T$ (non-)magnetic central part (reduced tracking)	add:	4× rate $H \to ZZ \to 4\ell^\pm$ 2× rate $H \to ZZ \to \ell^+\ell^-\nu\bar\nu$ 2× rate Z', W' $\tilde q, \tilde g$ (also cascade decays) mass resolution eμ heavy Q, L $H \to \gamma\gamma$
$e^\pm$, $\mu^\pm$, $\tau^\pm$, jets, $p\!\!\!/_T$ full momentum and tracking	add:	more redundancy and cross-checks on above, H^+, SUSY-H, heavy flavour tags

Lepton detection at LHC is crucial. Small rates are expected for many potential signals

⇒ detection of e and μ

Muons are relatively easy to identify but hard to measure well

(precise μ measurements may mean hundreds of MCHF)

Electrons are relatively easy to measure but hard to identify at 10^{34}

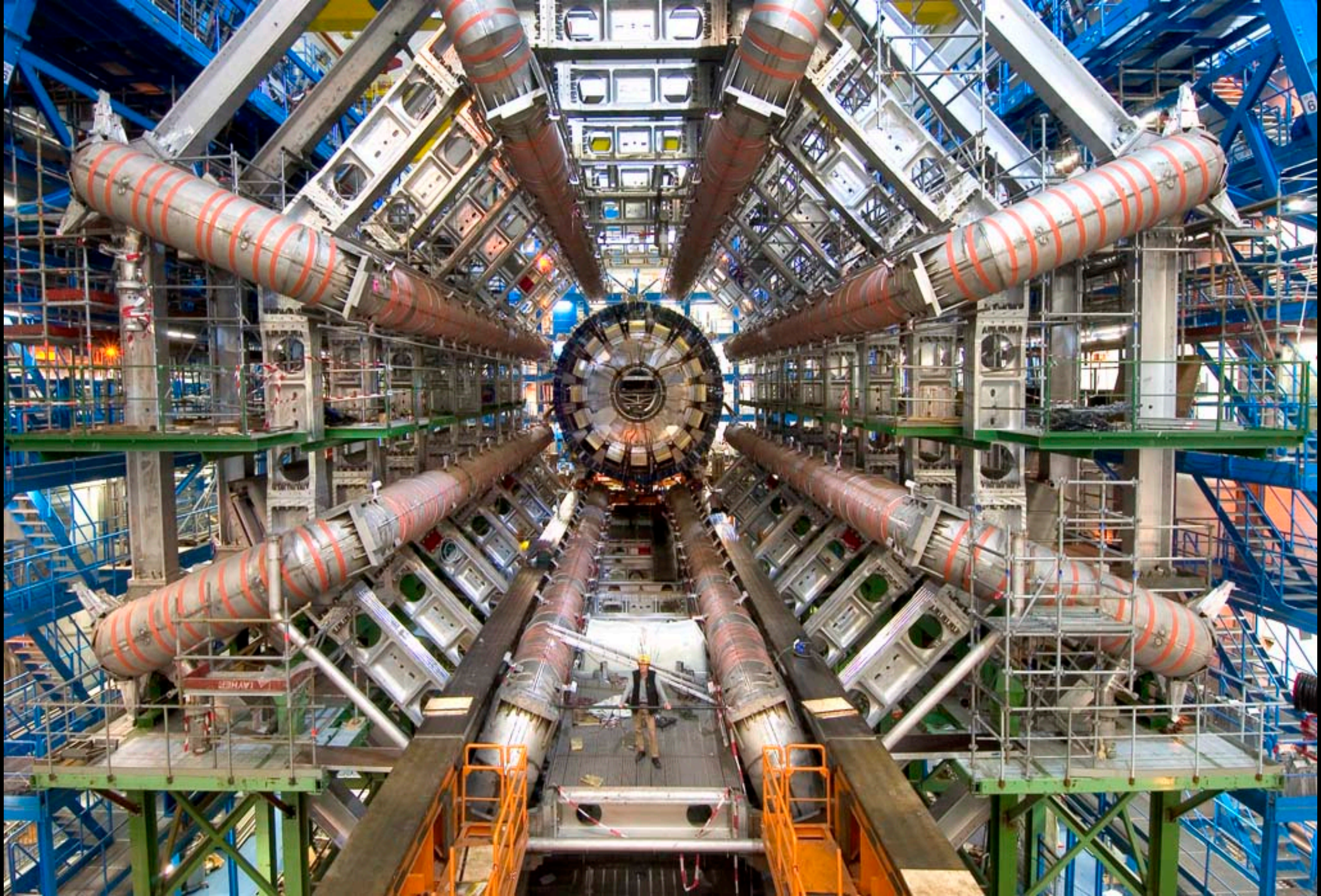
(radiation-hard inner detector)

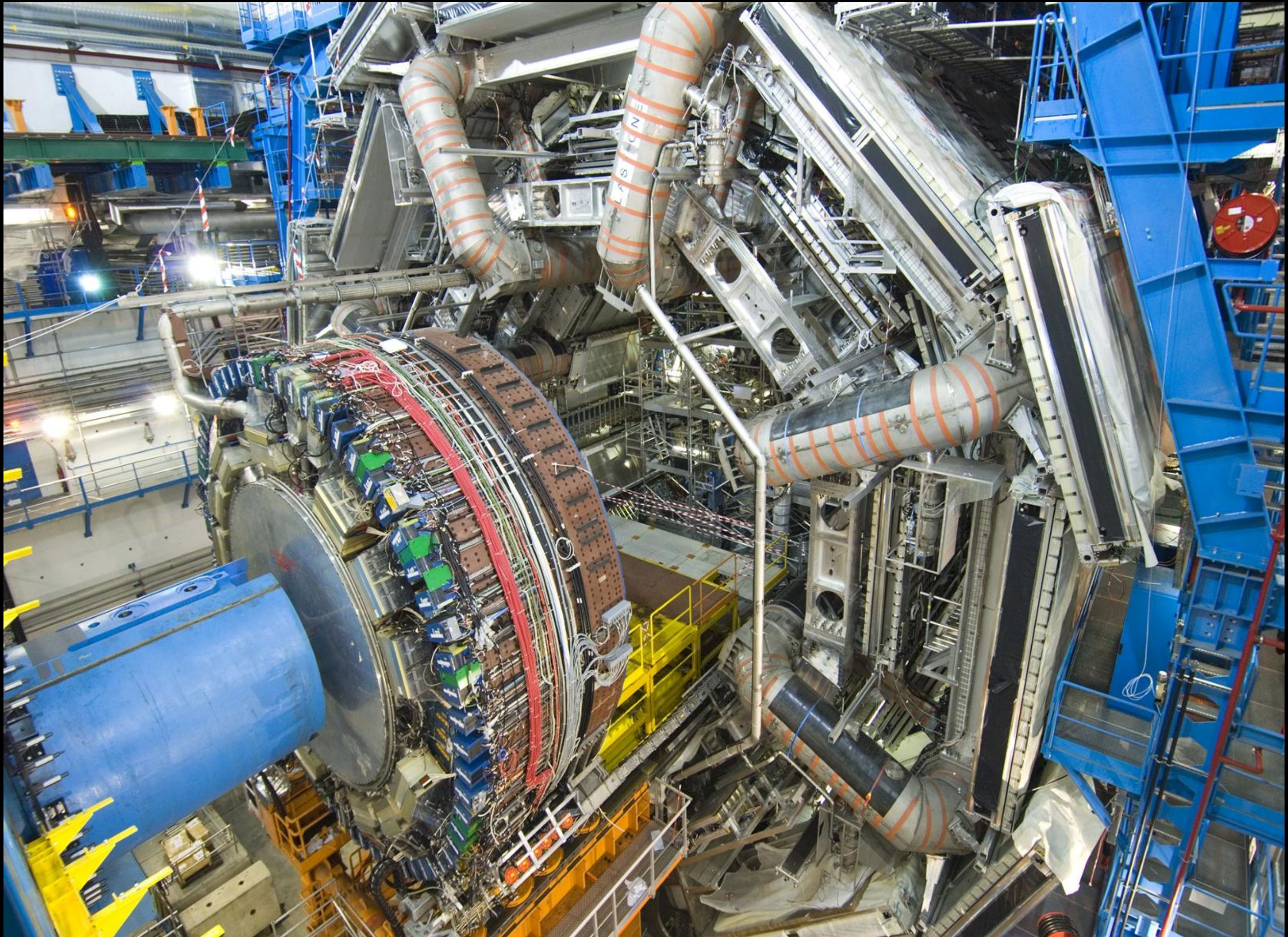
Lepton isolation criteria are also important to reject backgrounds from heavy flavour decays

Towards the Large Hadron Collider (cont.)

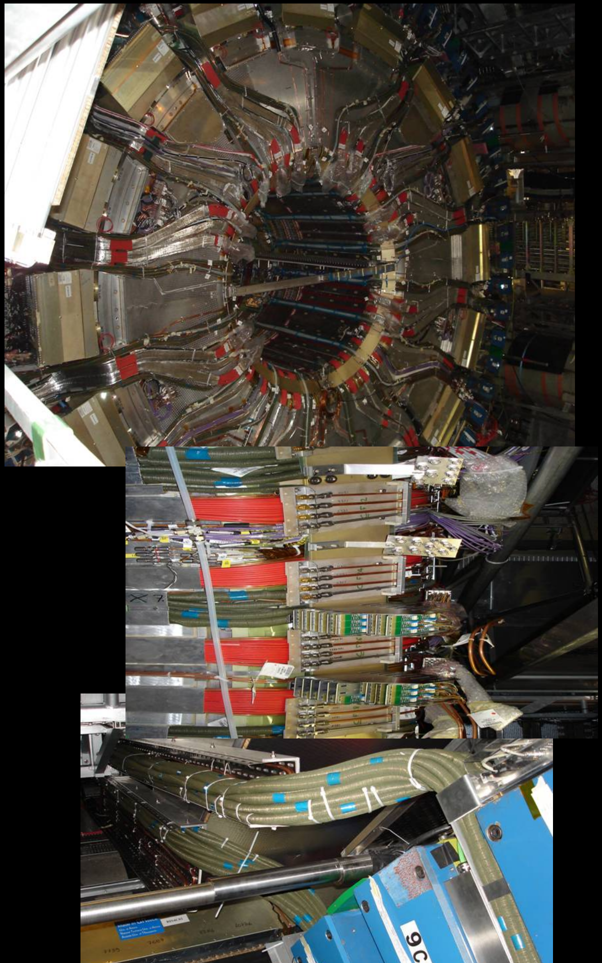
- 1984: First official discussions on the feasibility of a hadron collider in the LEP tunnel at an CERN-ECFA* workshop in Lausanne
- 1990: ECFA* workshop in Aachen - Important community workshop -
- 1992: ECFA workshop in Evian: presentation of Detector Expressions of Interest: ASCOT, EAGLE, CMS, L3* → ATLAS + CMS
- >1990: Massive detector R&D programme, RD collaborations at CERN
- 1996: Approval of the LHC as 14 TeV collider
- >1996: Technical Design Reports of the subdetector systems
- > 1998: Detector construction

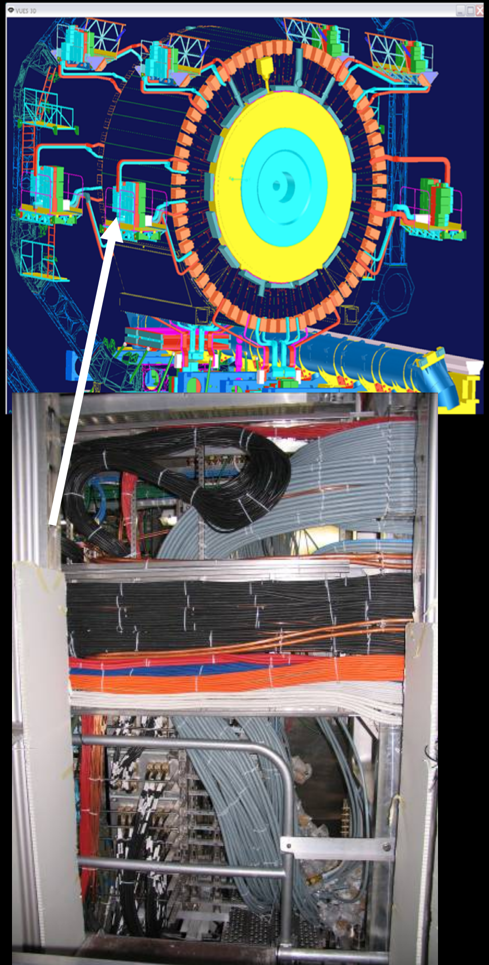
* ECFA: European Committee for Future Accelerators





Installation of cables and supply lines





Example:

Tracking detector in the central area

~ 800 person months over a period of 18 month (45 persons daily)

~ 12900 cable bundles

~ 30100 additional cables

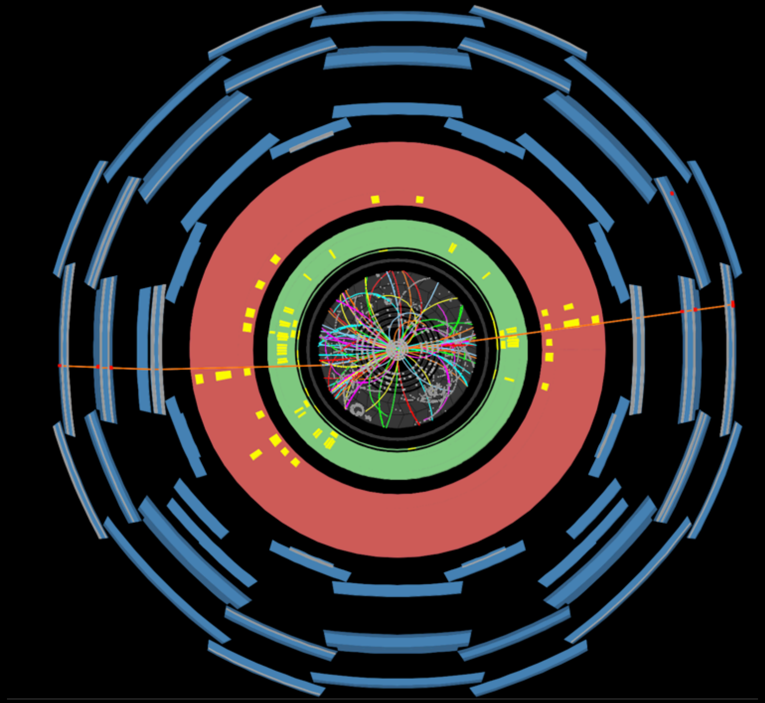
~ 2800 cooling and gas supply lines

All tested and qualified

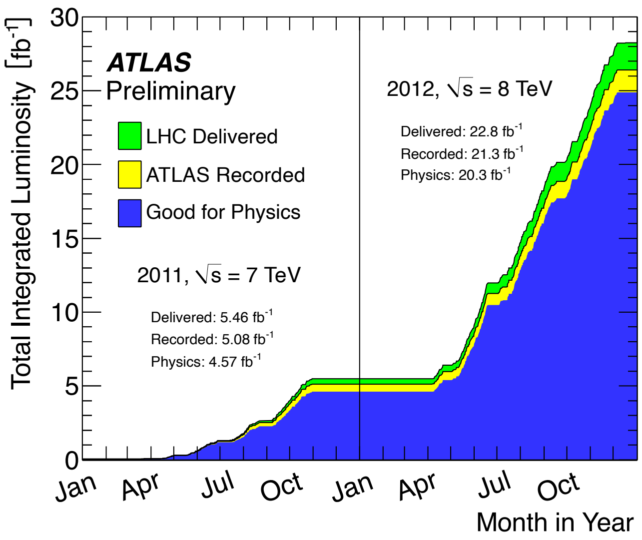
The Large Hadron Collider (LHC)

30 March 2010: first collisions at 7 TeV

- the highest energies ever reached until then -



Data Taking in the Years 2011 and 2012

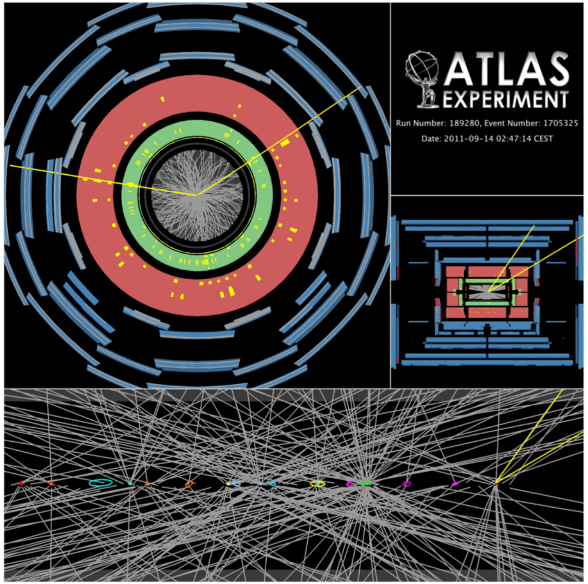


Until July 2012:

> 10^{15} pp collisions

~ 10^{10} pp collisions recorded

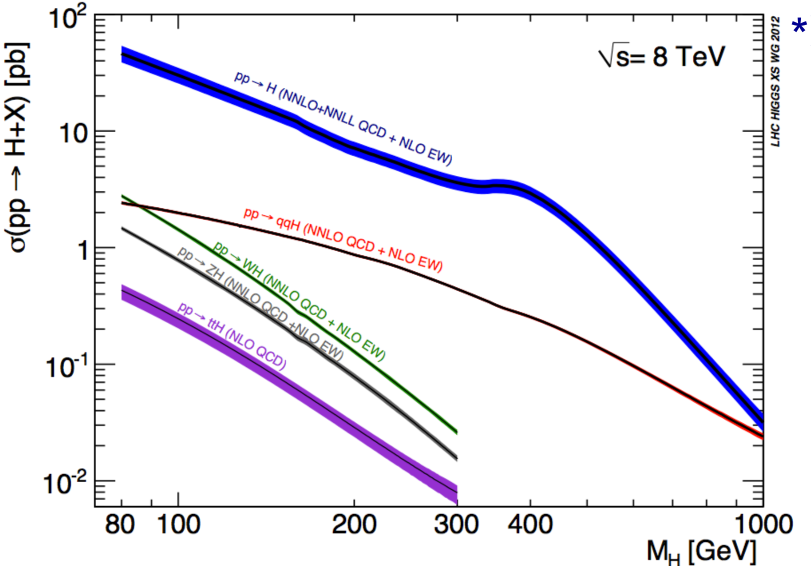
$25 \cdot 10^{6}$ $Z \rightarrow \mu\mu$ decays produced



Z → $\mu^{+} \mu^{-}$ event with 20 superimposed pp collisions

- *The LHC operation has produced sensational performance, well beyond the expectations.*
- *The combination of the performance of the **LHC machine**, the **detectors** and the **GRID computing** have proven to be a terrific success story.*

Higgs Boson Production



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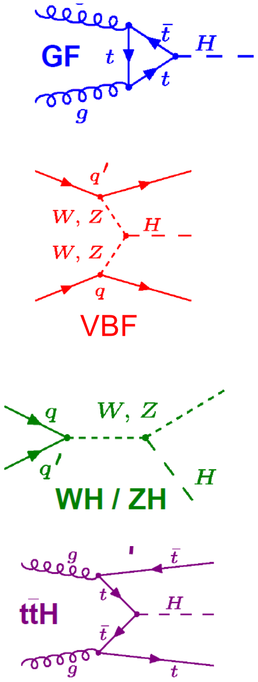


Gluon fusion

Vector boson fusion

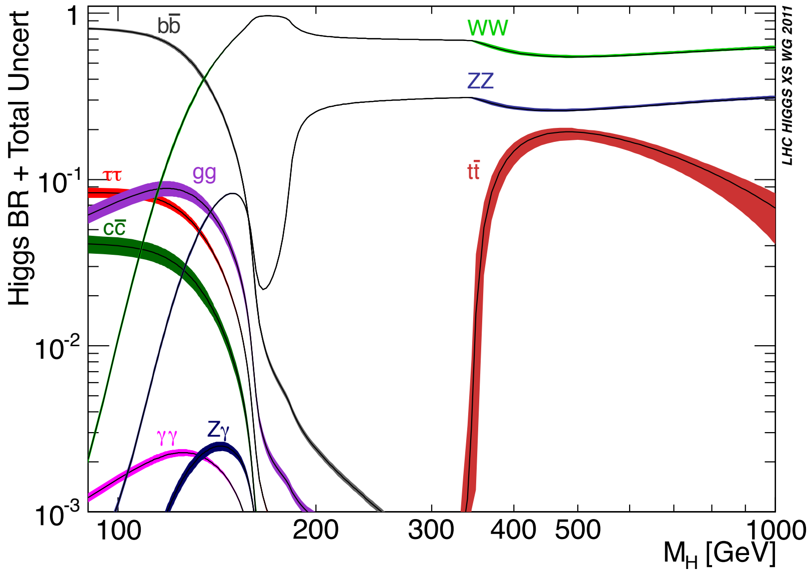
WH/ZH associated production

tt associated production

*) LHC Higgs cross-section working group
Large theory effort

Meanwhile also the NNNLO = N^{3}LO calculation for the gluon-fusion process exists; B. Anastasiou et al. (2015)

Higgs Boson Decays



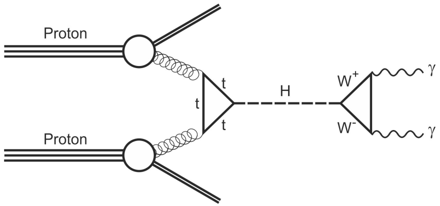
Useful decays at a hadron collider:

- Final states with leptons via WW and ZZ decays
- $\gamma\gamma$ final states (despite small branching ratio)
- $\tau\tau$ final states (more difficult)
- In addition: H → bb decays via associated lepton signatures (VBF, VH or ttH production)

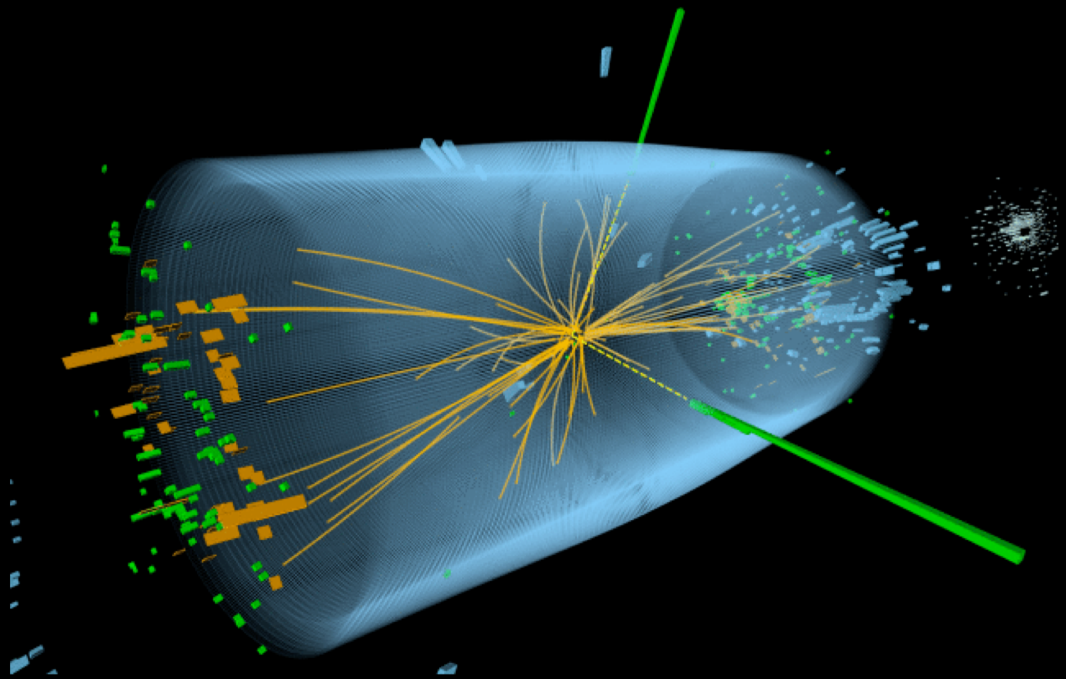
SM predictions (m_H = 125 GeV):

BR (H → WW) = 22.3%	BR (H → bb) = 56.9%
BR (H → ZZ) = 2.8%	BR (H → $\tau\tau$) = 6.2%
BR (H → $\gamma\gamma$) = 0.24%	BR (H → $\mu\mu$) = 0.022%

→ at 125 GeV: only ~11% of decays not observable (gg, cc)



Candidate event for a H → $\gamma\gamma$ decay

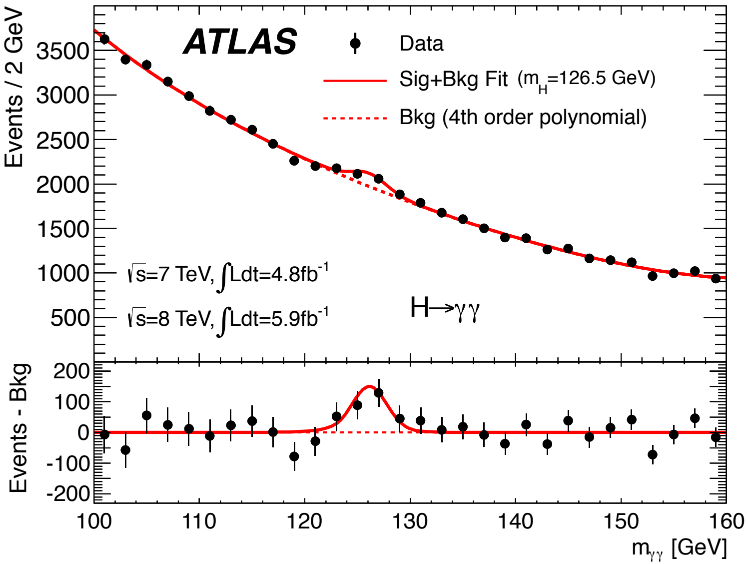


Expected number of Higgs boson decays in the data:
m_H = 125 GeV

~ 480 H → $\gamma\gamma$
~ 30 H → ZZ* → 4ℓ
~ 4400 H → WW* → ℓν ℓν

Results of the H → γγ search

Phys. Lett. B 716 (2012) 1



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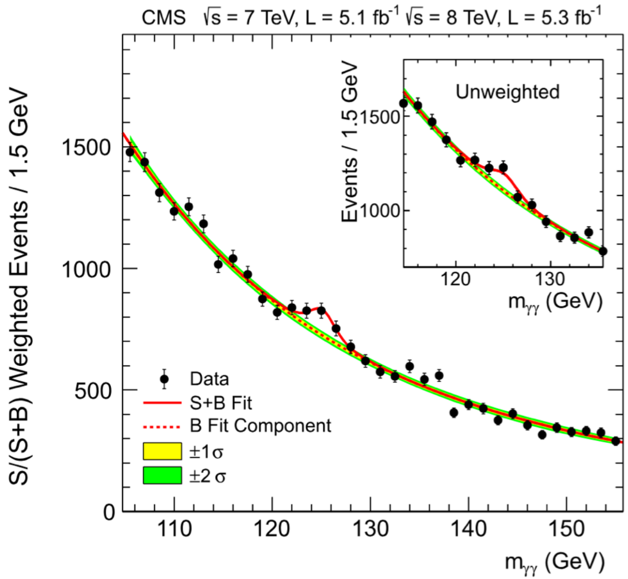
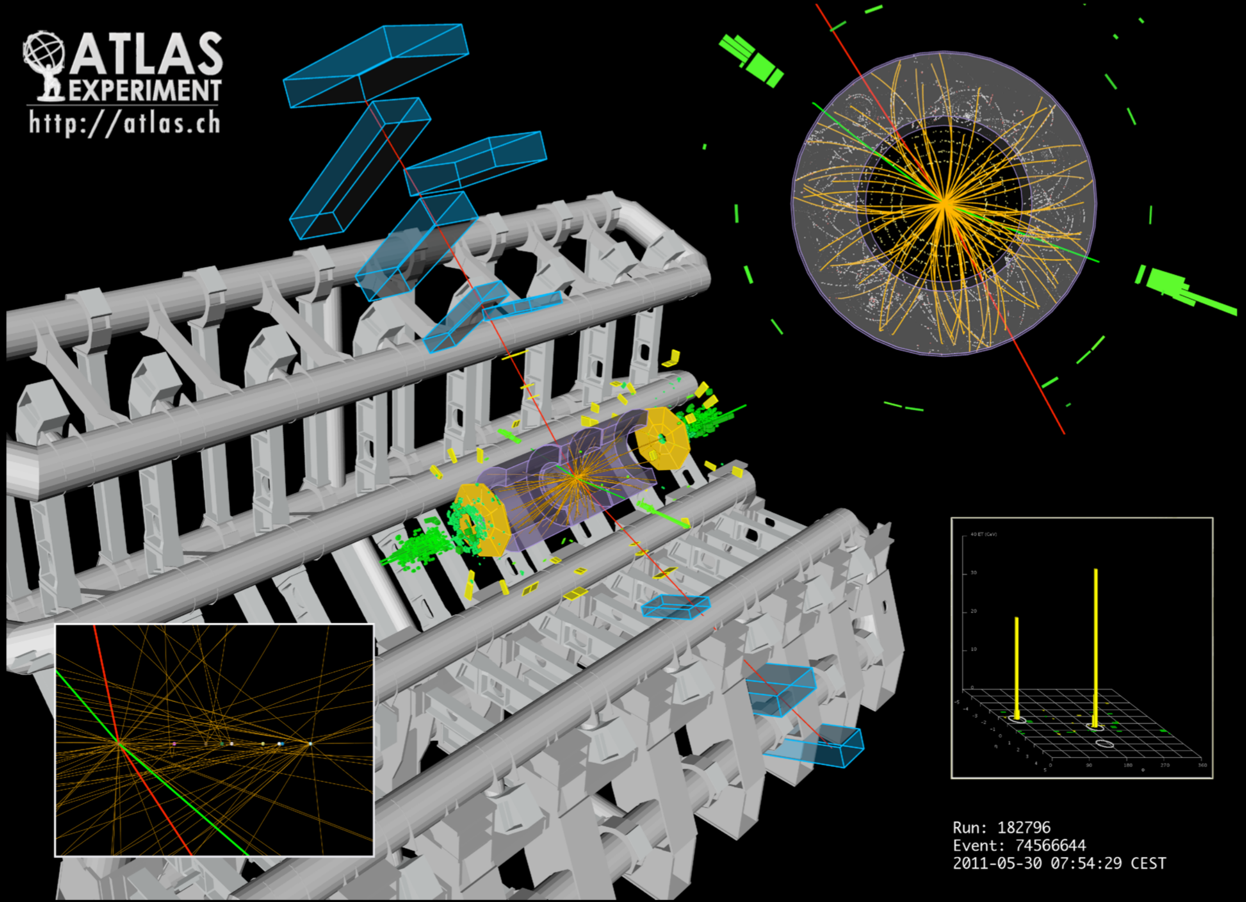


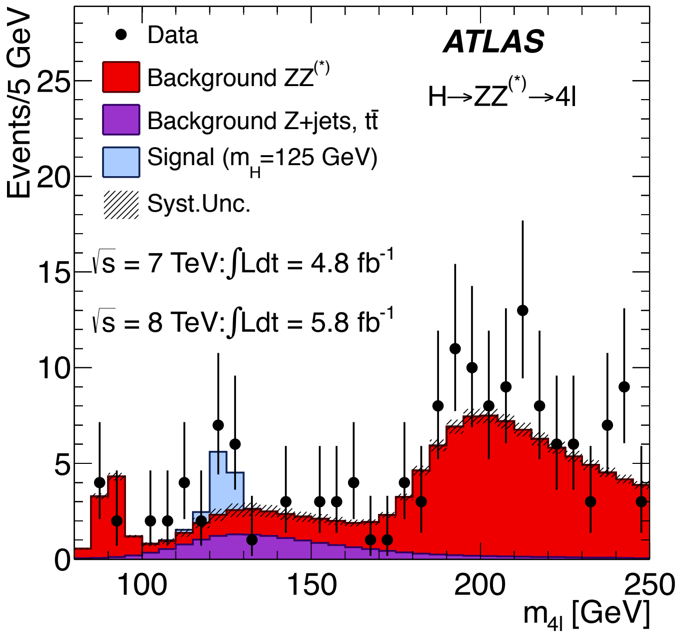
- Background interpolation in the region of the excess (obtained from sidebands)
- Reducible γ-jet and jet-jet background at the level of 25%

Candidate event for a decay $H \rightarrow ZZ^* \rightarrow e^+e^- \mu^+\mu^-$

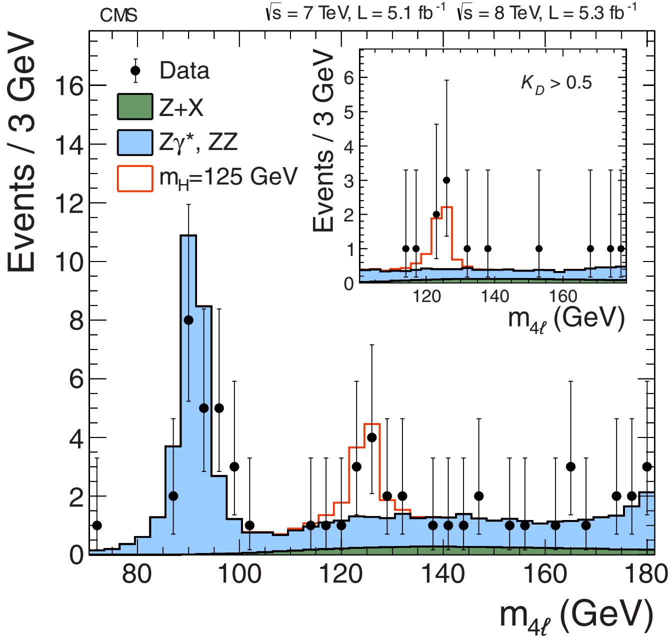


Results of the H → ZZ* → 4ℓ search

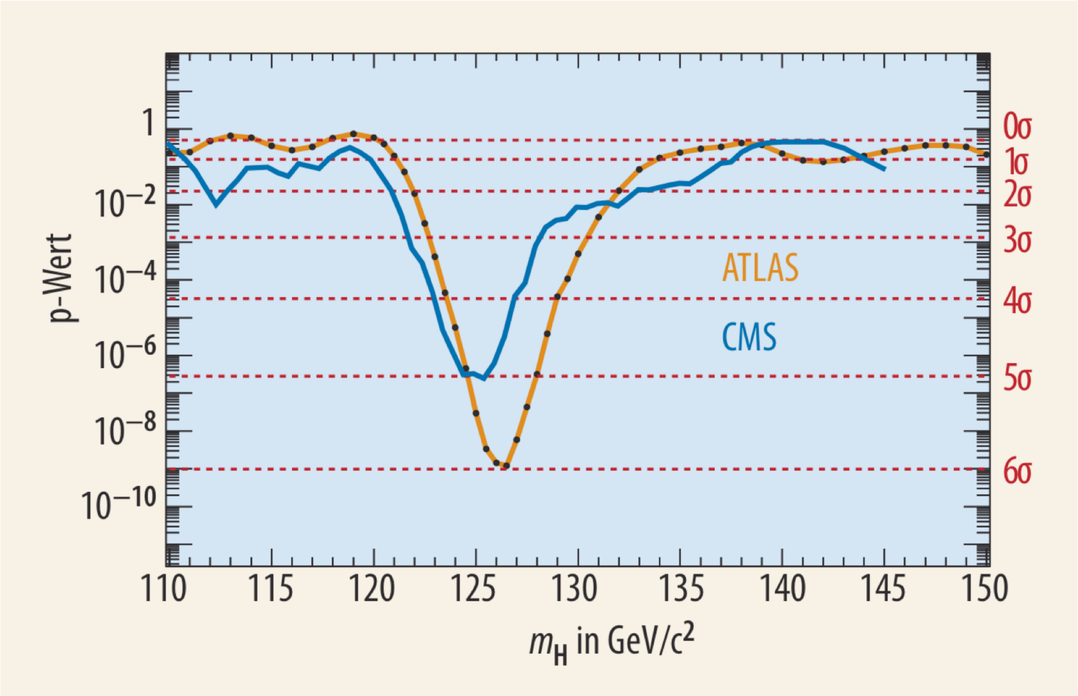
Phys. Lett. B 716 (2012) 1



Phys. Lett. B 716 (2012) 30



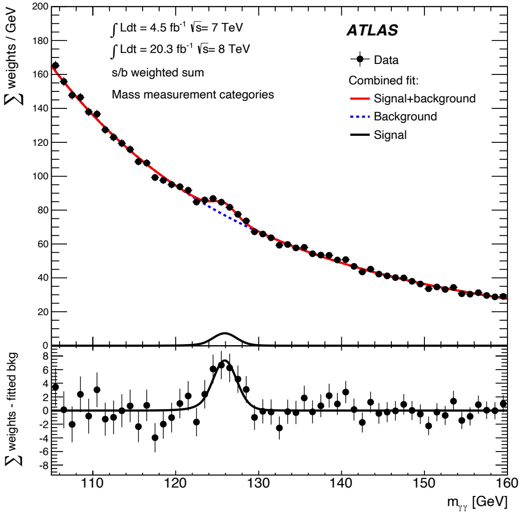
Significance of the signals
- Combination of channels -



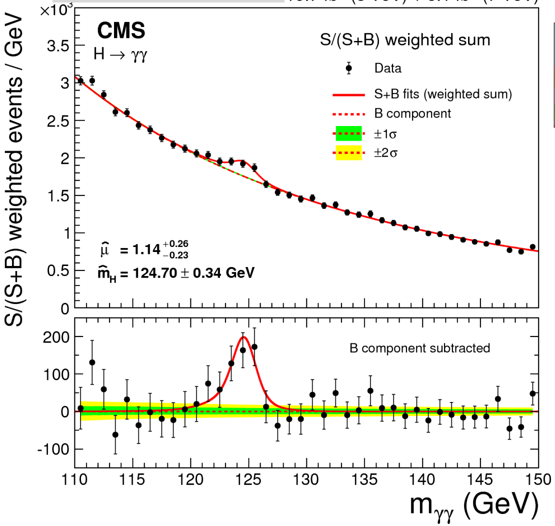
Physik Journal 11 (2012) Nr. 8/9, based on Phys. Lett. B 716 (2012) 1-29, and 30-61

Final Run-1 results for H → γγ

Phys. Rev. D90 (2014) 112015



EPJ C74 (2014) 3076



Signal strength

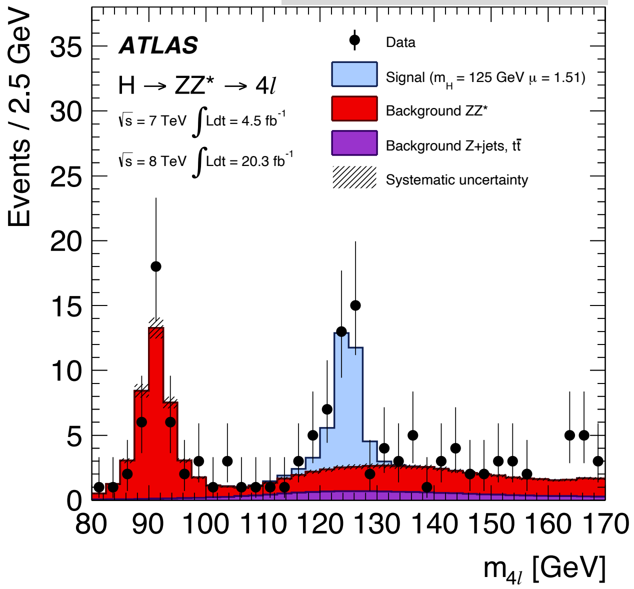
- High signal significance in both experiments: ATLAS: 5.2σ (4.6σ expected) $\mu = 1.17 \pm 0.27$

  CMS: 5.7σ (5.2σ expected) $\mu = 1.14 \pm 0.26$

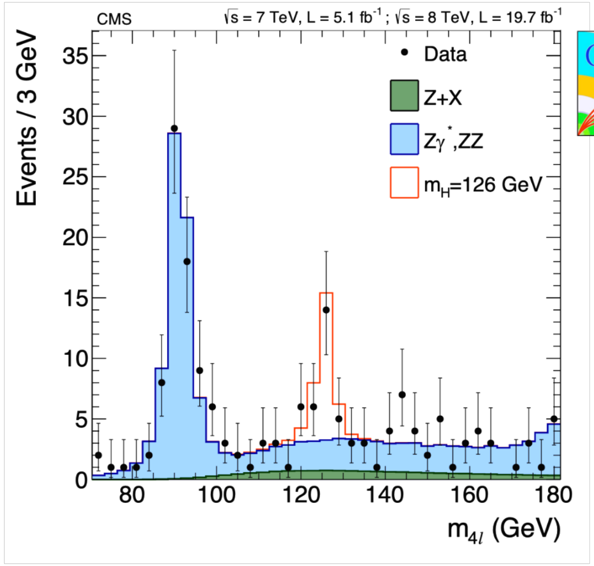
- Establishes the discovery in this channel alone

Final Run-1 results for H → ZZ* → 4ℓ

Phys. Rev. D91 (2014) 012006



Phys. Rev. D89 (2014) 092007



Significance in each experiment > 6σ

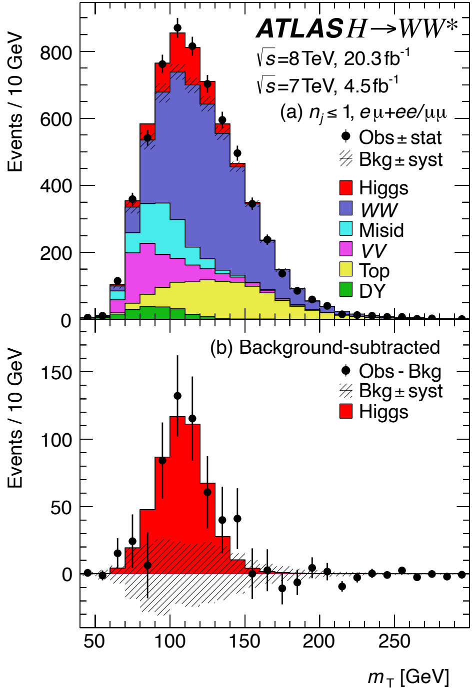
Measured signal strengths:

ATLAS: $\mu = 1.44\ ^{+0.40}_{-0.33}$

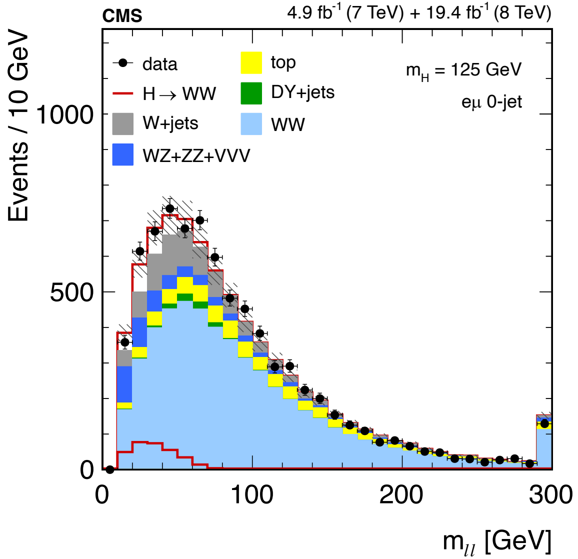
CMS: $\mu = 0.93\ ^{+0.29}_{-0.23}$

Final Run-1 results for $H \rightarrow WW^* \rightarrow \ell\nu\,\ell\nu$

Phys. Rev. D92 (2015) 012006



JHEP 01 (2014) 096



Measured signal strengths:

ATLAS: $\mu = 1.09\,^{+0.23}_{-0.21}$

CMS: $\mu = 0.72\,^{+0.20}_{-0.18}$

Very significant excesses visible in the “transverse mass” (ATLAS: 6.1σ) and $m_{\ell\ell}$ distributions (CMS: 4.5σ)

Higgs boson parameters

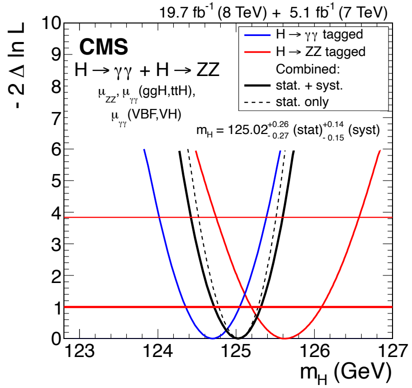
EPJ C75 (2015) 5, 212

- Mass: measured in $\gamma\gamma$ and $ZZ^* \rightarrow 4l$ channels

ATLAS: $m_H = 125.36 \pm 0.37\ (\text{stat}) \pm 0.18\ (\text{syst})$ GeV

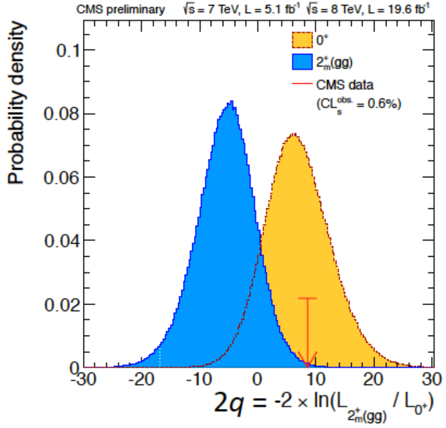
CMS: $m_H = 125.02\ ^{+0.26}_{-0.27}\ (\text{stat})\ ^{+0.14}_{-0.15}\ (\text{syst})$ GeV

Impressive accuracy reached ~ 0.25 %



- Spin / CP : data strongly favour the spin-0 hypothesis of the Standard Model

  (Alternatives (0^-, 1^-, 1^+, 2^-, 2^+) can be excluded with confidence levels > 99%)



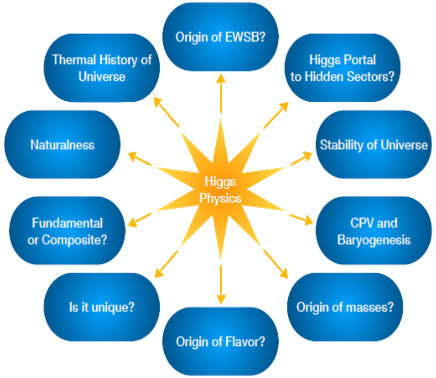
Conclusions

- *After a long path, a milestone discovery announced in July 2012*

  The ATLAS and CMS data are consistent with the expectations for the Standard Model Higgs boson

- *Excellent experimental achievements (accelerators, detectors, computing)*

- *A new era in the exploration of key questions in particle physics opened; the Higgs boson has a central role* (talk be Margarete Mühlleitner)



→ Talks by Karsten Köneke and Markus Klute

From the editorial: *"The top Breakthrough of the Year – the discovery of the Higgs boson – was an unusually easy choice, representing both a triumph of the human intellect and the culmination of decades of work by many thousands of physicists and engineers."*