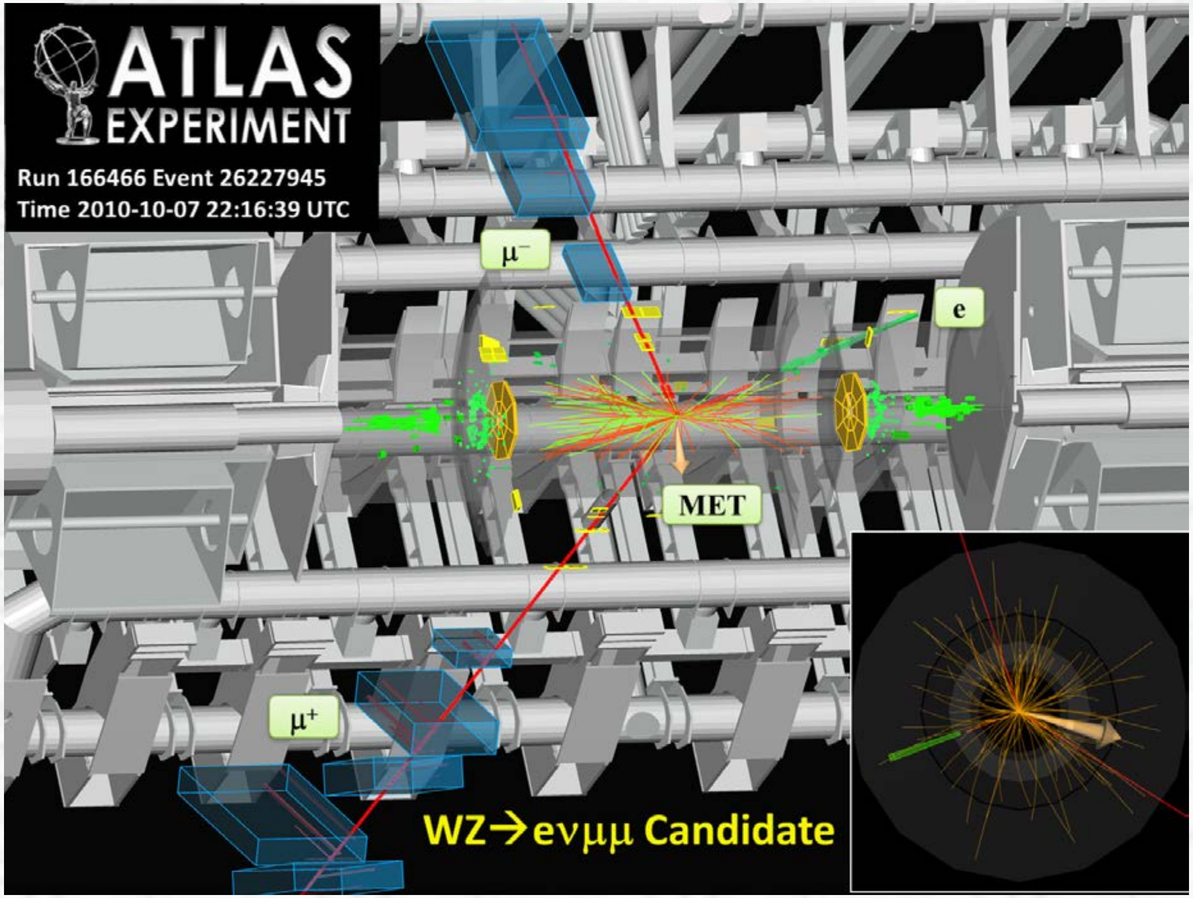
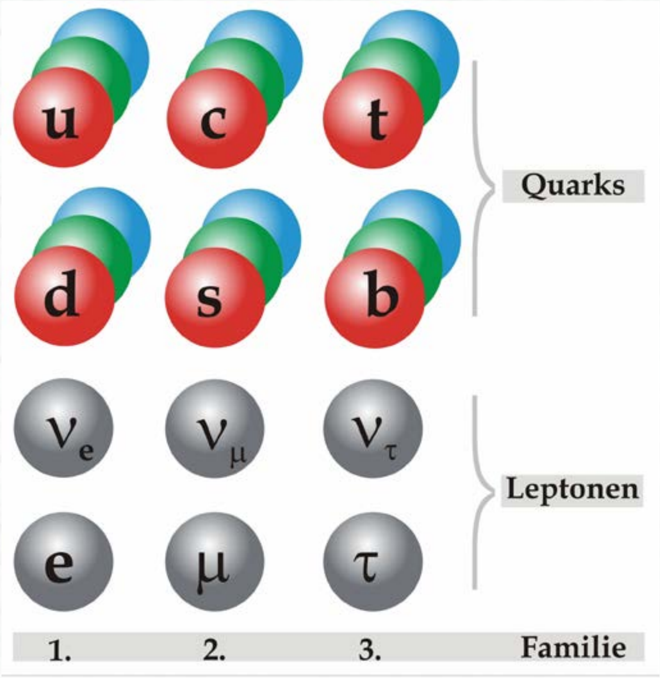
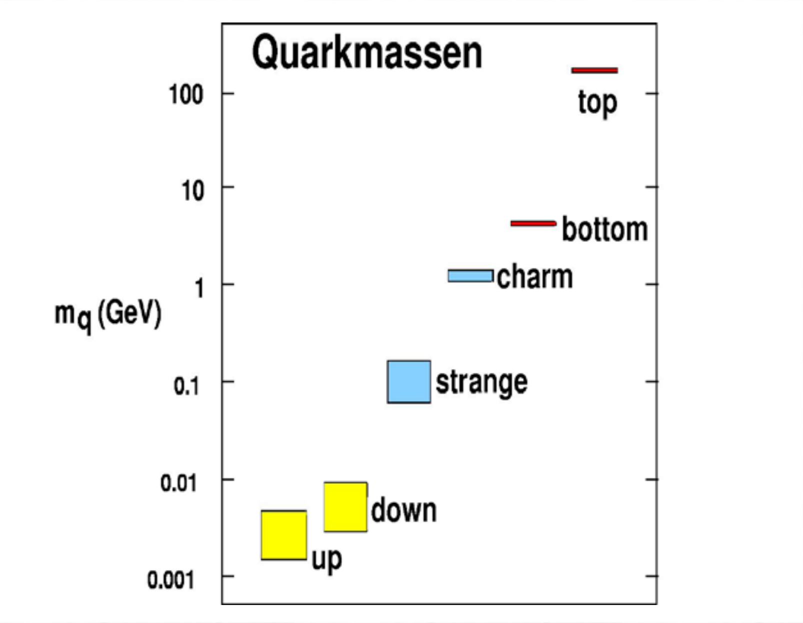
Advanced Particle Physics



The Standard Model of Particle Physics

(i) The building blocks of matter: Quarks and Leptons





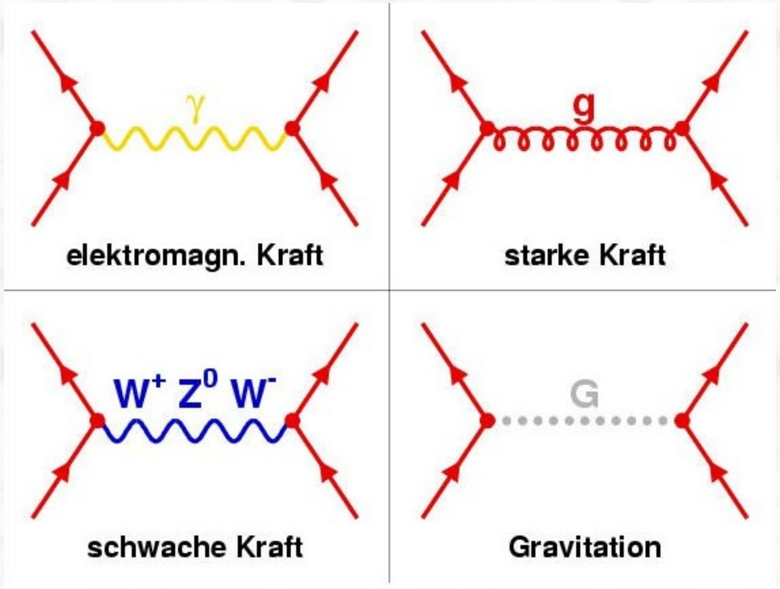
m (e) = 0,000511 GeV/c^2
m (τ) = 1,8 GeV/c^2

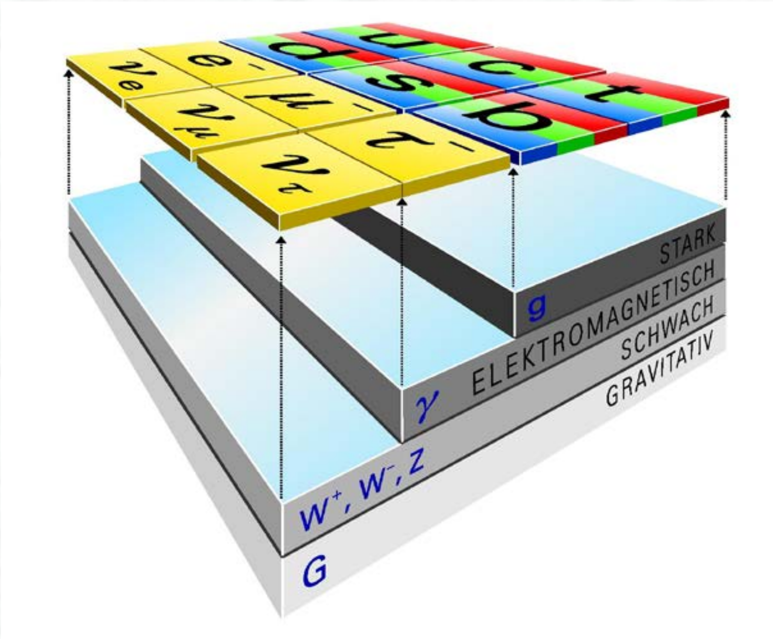
m (u) = 0,005 GeV/c^2
m (t) = 178 GeV/c^2

For comparison: m (p) = 0,938 GeV/c^2

(ii) Forces / Interactions:

are transmitted via exchange of field quanta / bosons





$m_\gamma = 0$, $m_g = 0$

$M_W = 80.399 \pm 0.025$ GeV / c^2

$M_Z = 91.1875 \pm 0.0021$ GeV / c^2

The structure of the Standard Model

Fundamental principle: Local gauge invariance
Prototype: Quantum Electrodynamics (QED)

Free Dirac equation: $i\gamma^{\mu}\partial_{\mu}\psi - m\psi = 0$

Lagrangian formalism: $L = i\bar{\psi}\gamma^{\mu}\partial_{\mu}\psi - m\bar{\psi}\psi$

Local gauge transformation: $\psi(x) \rightarrow e^{i\alpha(x)}\psi(x)$

(derivative: $\partial_{\mu}\psi \rightarrow e^{i\alpha(x)}\partial_{\mu}\psi + ie^{i\alpha(x)}\psi\partial_{\mu}\alpha$,
$\delta_{\mu}\alpha$ term breaks the invariance of L)

Invariance of L under local gauge transformations can be accomplished by introducing a gauge field A_{μ}, which transforms as:

$$A_{\mu} \rightarrow A_{\mu} + \frac{1}{e}\partial_{\mu}\alpha$$

where $e = g_e/4\pi$ = coupling strength

Can be formally achieved by the construction of a “modified” derivative

$$\partial_{\mu} \rightarrow D_{\mu} = \partial_{\mu} - ieA_{\mu}$$

(covariant derivative)

→ Lagrangian of QED:

$$L = i\overline{\psi}\gamma^{\mu}\partial_{\mu}\psi - m\overline{\psi}\psi + e\overline{\psi}\gamma^{\mu}A_{\mu}\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

interaction term

where $F_{\mu\nu}$ is the usual field strength tensor: $F_{\mu\nu} = \partial_{\mu}A_{\nu} - \partial_{\nu}A_{\mu}$

Note:

(i) Imposing local gauge invariance leads to the interacting field theory of QED

(ii) A mass term ($\frac{1}{2}m^2 A_{\mu}A^{\mu}$) for the gauge field A_{μ} would violate gauge invariance

Similar for the other Standard Model interactions:

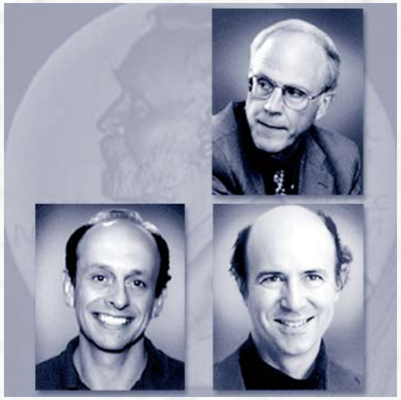
Quantum Chromodynamics (QCD):

$$D_\mu = \partial_\mu + igT_a G_\mu^a$$

$$G_\mu^a \to G_\mu^a - \frac{1}{g}\partial_\mu \alpha_a - f_{abc}\alpha_b G_\mu^c$$

SU(3) transformations, 8 gauge fields,
8 massless gluons, gluon self-coupling

- T_a (a = 1,…,8) generators of the SU(3) group (independent traceless 3x3 matrices)
- G_μ gluon fields
- g = coupling constant



Electroweak Interaction (Glashow, Salam, Weinberg):
$SU(2)_L \times U(1)_Y$ transformations,
4 gauge fields, (W_μ^1, W_μ^2, W_μ^3, B_μ)

Physical states:

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

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

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

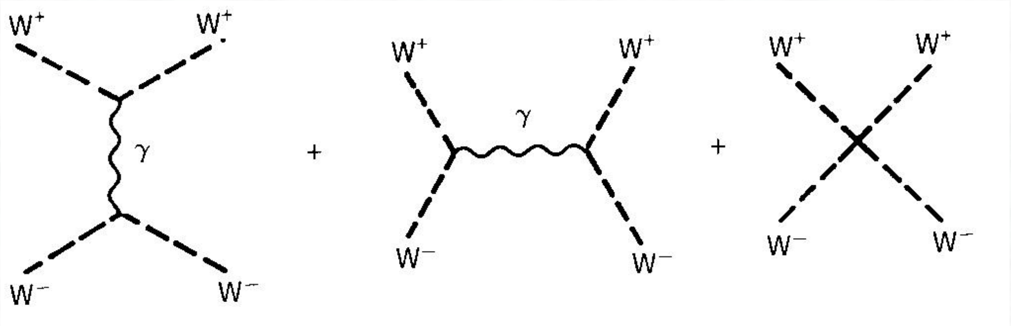
Problems at that stage:

- **Masses of the vector bosons W and Z:**

Experimental results: $M_W = 80.399 \pm 0.023$ GeV / c^2
$M_Z = 91.1875 \pm 0.0021$ GeV / c^2

A local gauge invariant theory requires massless gauge fields

- **Divergences in the theory (scattering of W bosons)**



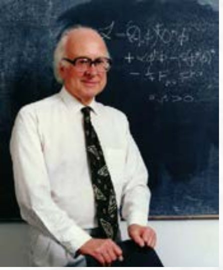
$$-iM(W^+W^- \rightarrow W^+W^-) \sim \frac{s}{M_W^2} \quad \text{for} \quad s \rightarrow \infty$$

Solution to **both** problems:

- create mass via spontaneous breaking of electroweak symmetry

- introduce a scalar particle that regulates the WW scattering amplitude

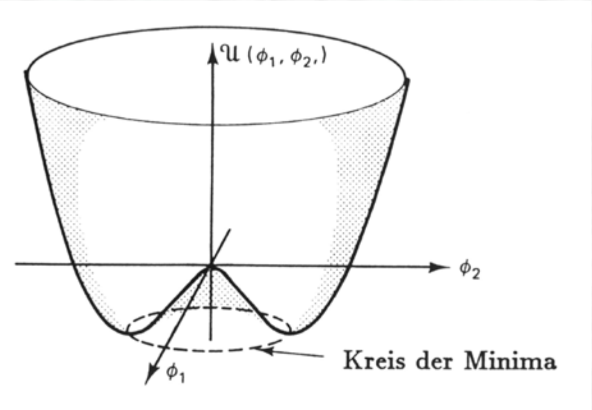
➔ Higgs mechanism



The Higgs mechanism

- Add scalar fields: $$\phi = \frac{1}{\sqrt{2}}\begin{pmatrix}\phi_1 + i\phi_2 \\ \phi_3 + i\phi_4\end{pmatrix} = \begin{pmatrix}\phi^+ \\ \phi^0\end{pmatrix}$$

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



- For $\mu^2 < 0$, $\lambda > 0$, minimum of potential: $\phi_1^2 + \phi_2^2 + \phi_3^2 + \phi_4^2 = v^2$ $\quad v^2 = -\mu^2/\lambda$

  v = vacuum expectation value $v = \frac{1}{\sqrt{\sqrt{2}G_F}} = 246\ \text{GeV}$

- Perturbation theory around ground state:

$$\phi_0(x) = \frac{1}{\sqrt{2}}\begin{pmatrix}0 \\ v + h(x)\end{pmatrix} \Rightarrow$$

3 massive vector fields: $m_{W^\pm} = \frac{1}{2}vg$ $\quad m_Z = \frac{m_W}{\cos\theta_W}$

(g = coupling constant, well measured in experiments)

1 massless vector field: $m_\gamma = 0$

1 massive scalar field: The Higgs boson H $\quad m_H = \sqrt{\lambda v^2}$

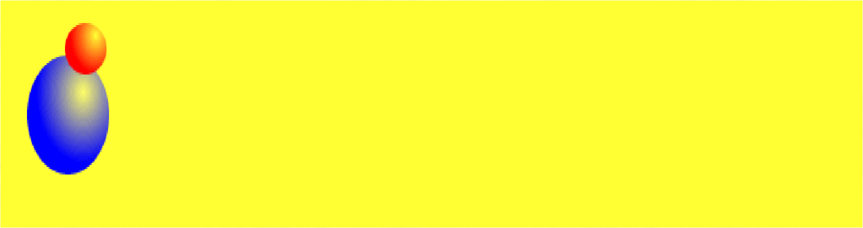
(mass not predicted, < ~1 TeV/c²)

F. Englert and R. Brout. Phys Rev. Lett. 13: 321-323 (1964)
P.W. Higgs, Phys. Rev. Lett. 13: 508-509 (1964)
G.S. Guralnik, C.R. Hagen, and T.W.B. Kibble. Phys. Rev. Lett. 13: 585-587 (1964)

Principle of mass generation

Empty vacuum:

All particles are massless,
move with the speed of light

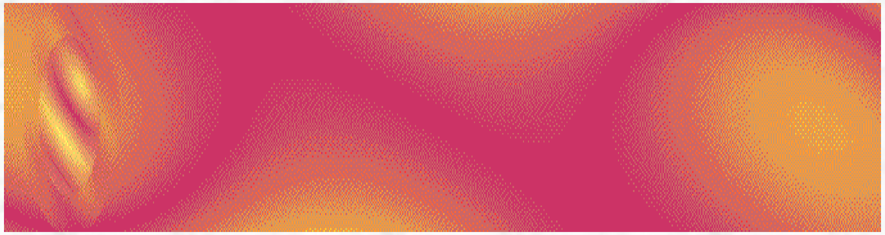


Higgs “background” field:

Particles interact with the Higgs field, v<c,
interpreted as mass,
mass depends on the interaction strength

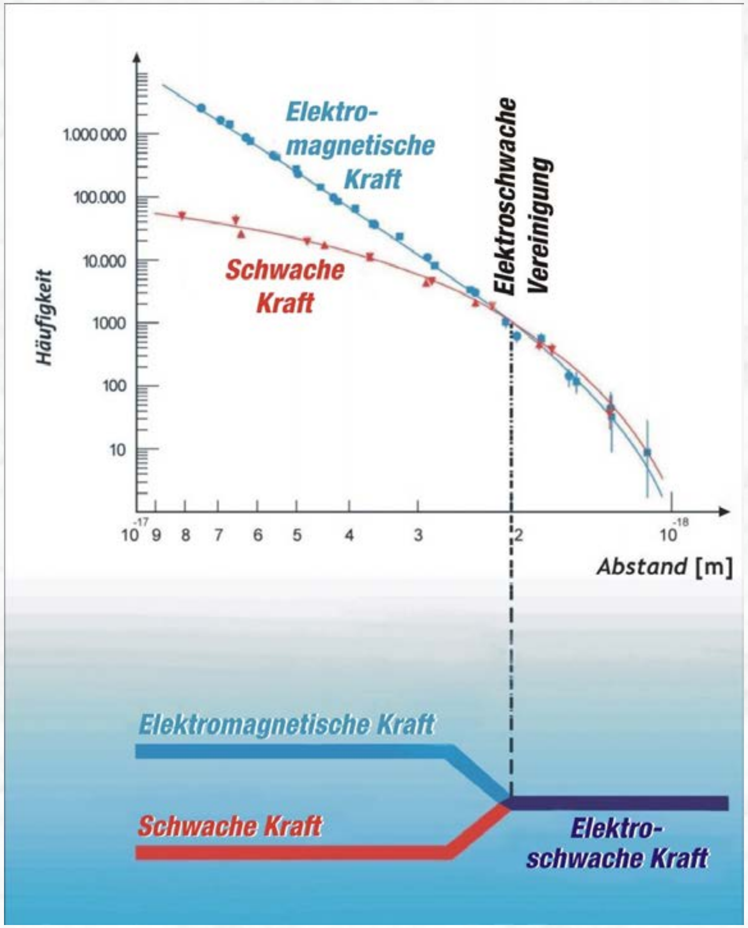
Higgs particle:

Excitation of the field

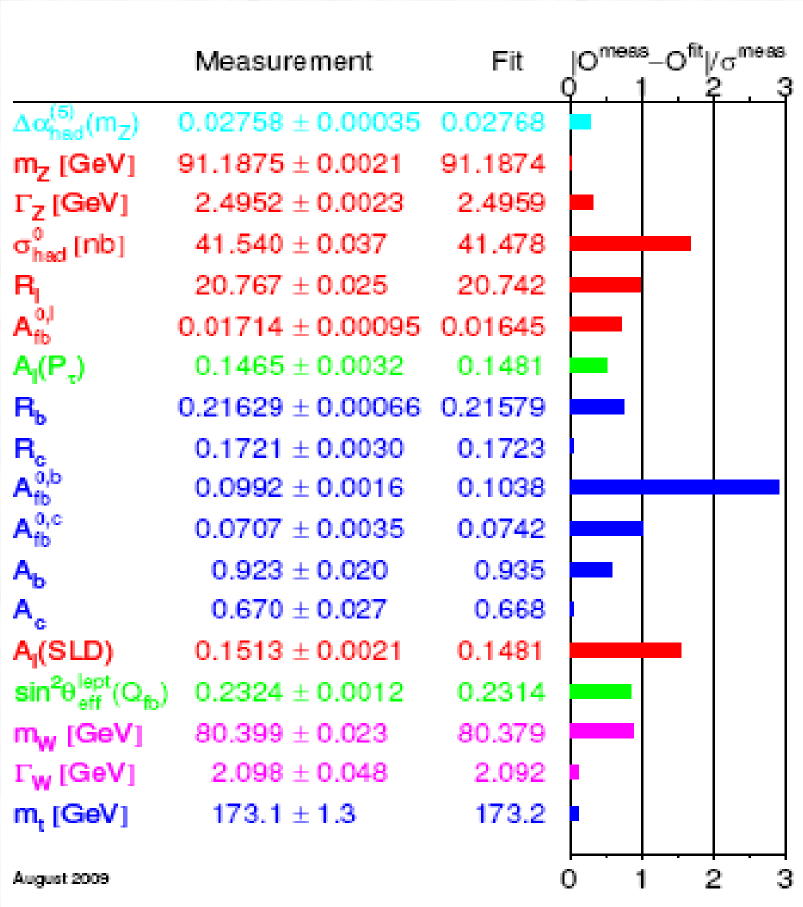


Wo standen wir vor dem LHC ?

Die e^+e^- Beschleuniger LEP am CERN und SLC am SLAC
p p Beschleuniger Tevatron am Fermilab/USA
$e^{\pm}p$ Beschleuniger HERA am DESY ….. + Fixed-Target-Experimente
haben den Energiebereich bis **~100 GeV** mit unglaublicher Präzision erforscht



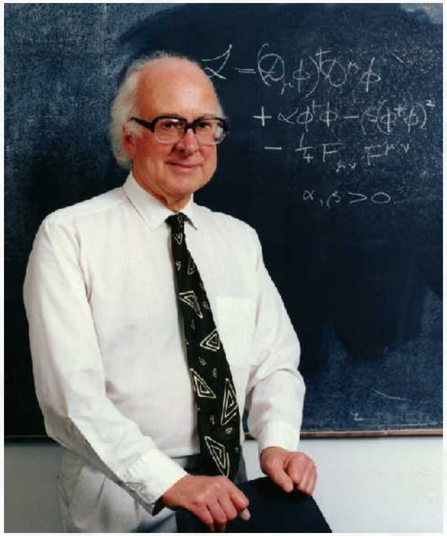
Sommer 2009



	Measurement	Fit	$\lvert O^{meas}-O^{fit}\rvert/\sigma^{meas}$
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02768	
m_Z [GeV]	91.1875 ± 0.0021	91.1874	
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959	
σ^0_{had} [nb]	41.540 ± 0.037	41.478	
R_l	20.767 ± 0.025	20.742	
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01645	
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481	
R_b	0.21629 ± 0.00066	0.21579	
R_c	0.1721 ± 0.0030	0.1723	
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1038	
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0742	
A_b	0.923 ± 0.020	0.935	
A_c	0.670 ± 0.027	0.668	
A_l(SLD)	0.1513 ± 0.0021	0.1481	
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314	
m_W [GeV]	80.399 ± 0.023	80.379	
Γ_W [GeV]	2.098 ± 0.048	2.092	
m_t [GeV]	173.1 ± 1.3	173.2	

Where is the Higgs boson ?

- The Standard Model is consistent with all experimental data !
- No Physics Beyond the SM observed
  (except clear evidence for neutrino masses)
- No Higgs seen (yet) before LHC

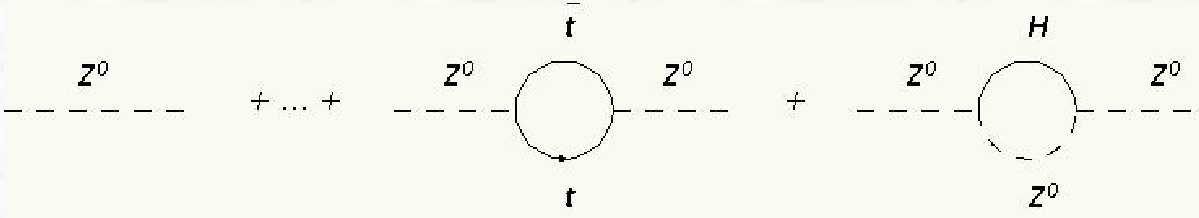


Only unambiguous example of observed Higgs before LHC

(P. Higgs, Univ. Edinburgh)

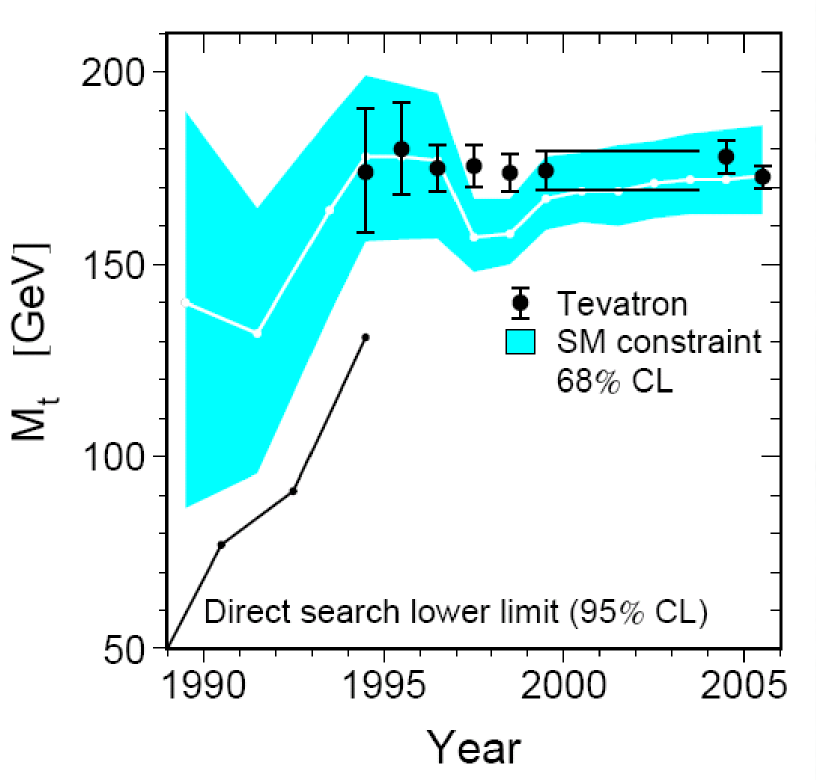
Direct searches: (95% CL limits)
$m_H > 114.4$ GeV/c^2
$m_H < 156$ GeV/c^2 or $m_H > 177$ GeV/c^2

Präzisionsmessungen ↔ Sensitivität auf Quantenkorrekturen



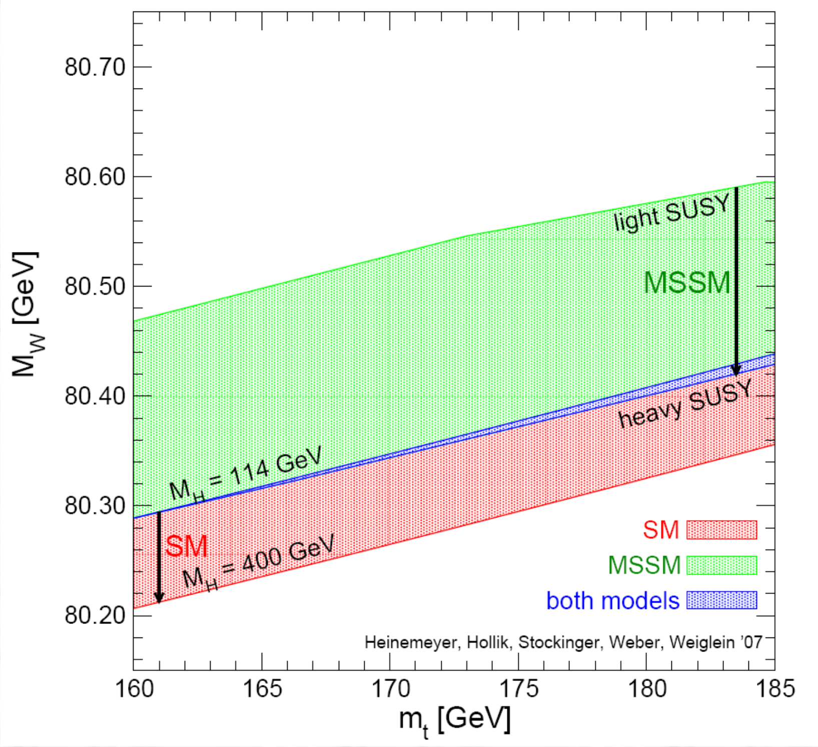
$$m_Z^2 = m_Z^2(0.) \cdot (1 + \Delta(m_t, m_H, ...))$$

$$\Delta = ... + c_1 \cdot m_t^2 + ... + c_2 \cdot \ln m_H + ...$$



Präzisionsmessungen von m_W und m_t $\rightarrow m_H$

Relation zwischen m_W, m_t und m_H



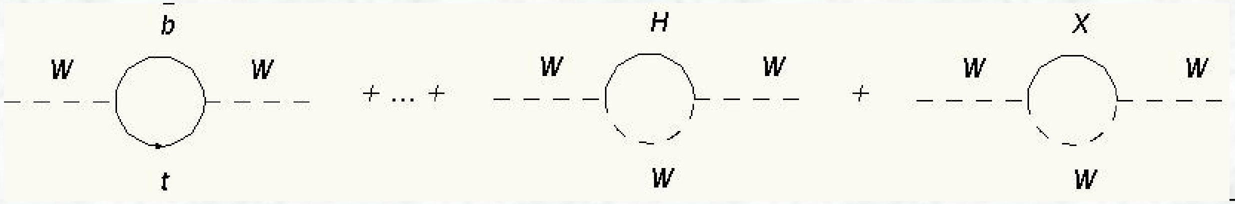
Feinstrukturkonstante
Atomphysik,
e^+e^- Beschleuniger, etc.

$$m_W = \left(\frac{\pi \, \alpha_{EM}}{\sqrt{2} \, G_F} \right)^{1/2} \frac{1}{\sin \theta_W \sqrt{1 - \Delta r}}$$

Fermi-Konstante
Myon-Zerfall

Schwacher
Mischungswinkel
LEP/SLC

Strahlungs-
korrekturen
$\Delta r \sim f\,(m_{top}^2, \log m_H, \ldots)$



Constraints on the Higgs boson mass (before LHC)

- $m_H > 114.4$ GeV/c^2 from direct searches at LEP
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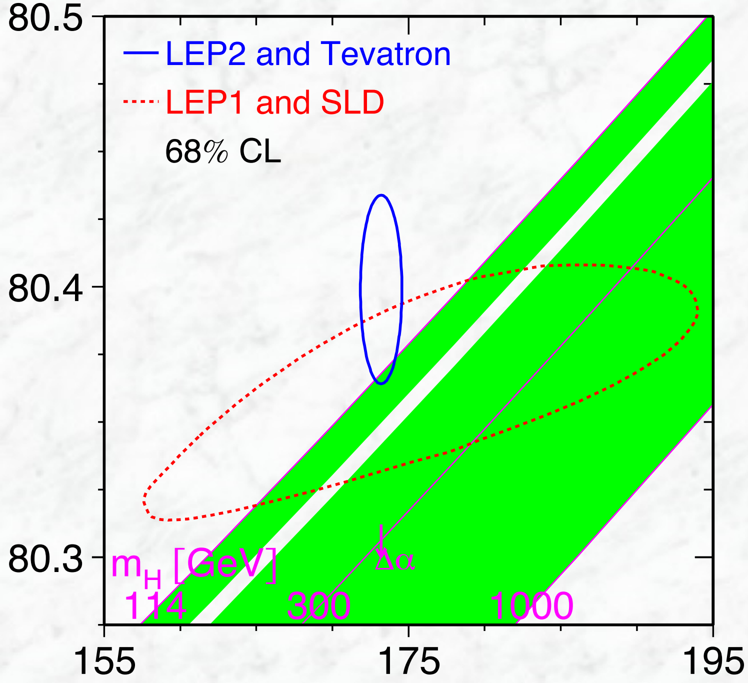
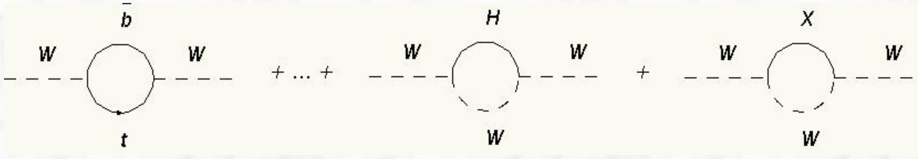


July 2011



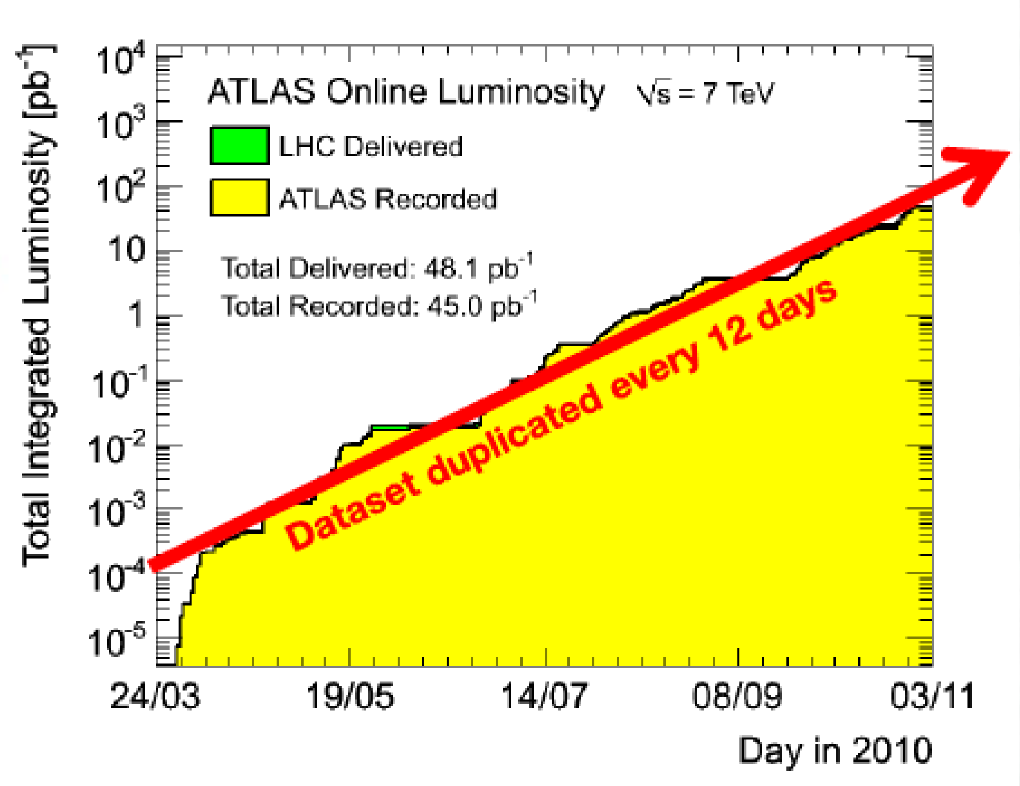
m_H = 92 $^{+34}_{-26}$ GeV/c^2
m_H < 161 GeV/c^2 (95 % C.L.)

- Indirect constraints from precision measurements (quantum corrections)

Begin of a new era in particle physics

Data collected in 2010:

~40 pb^{-1} recorded
~36 pb^{-1} used in analysis
(good quality)



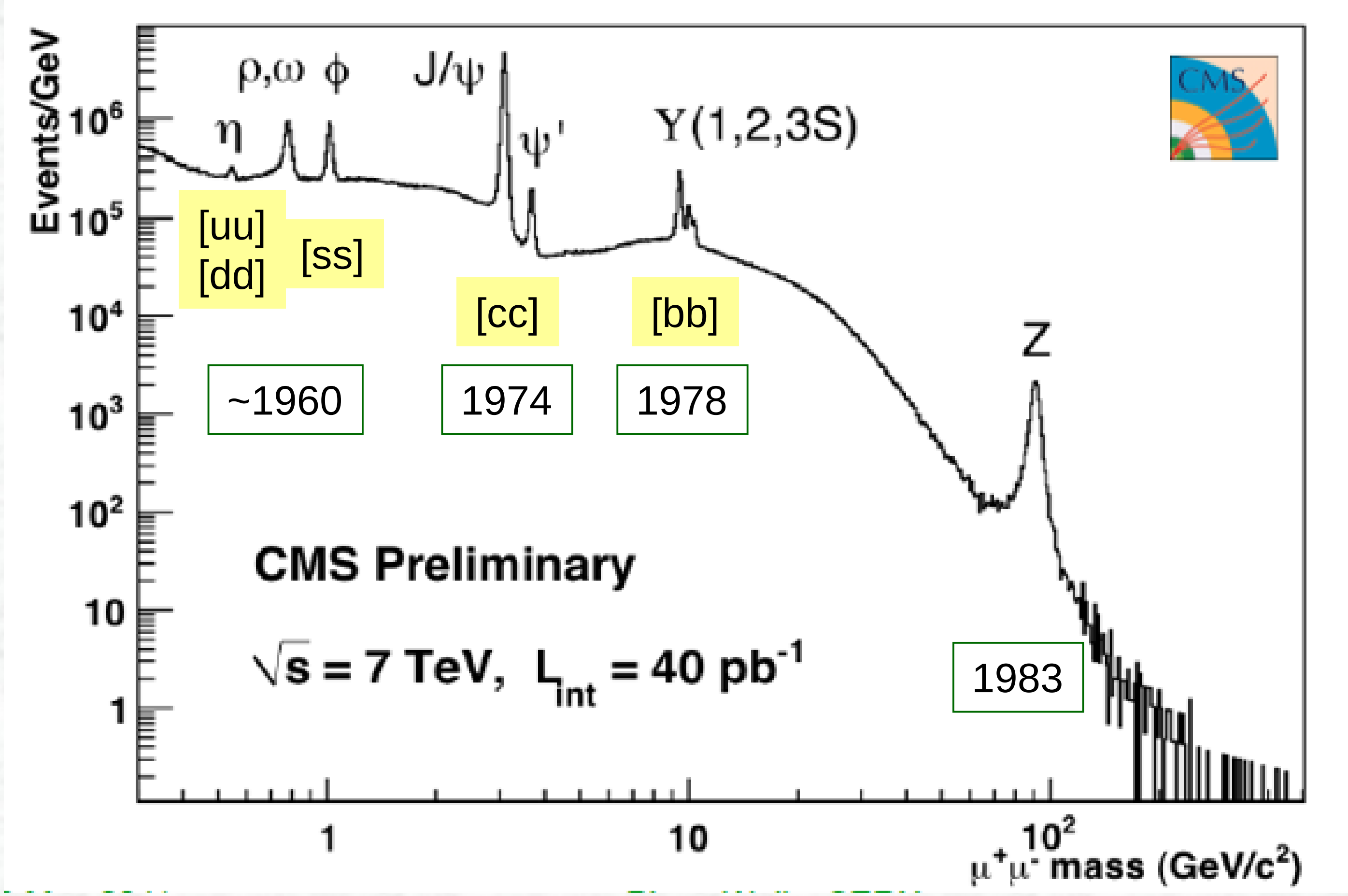
Running again since a few weeks

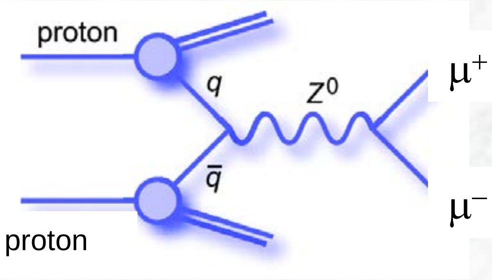
collected so far: > 100 pb^{-1}
expected for 2011: 1 – 2 fb^{-1}

World record in instantaneous luminosity on 22. April 2011: $4.67\ 10^{32}\ cm^{-2}\ s^{-1}$
so far: Tevatron record: $4.02\ 10^{32}\ cm^{-2}\ s^{-1}$

2010

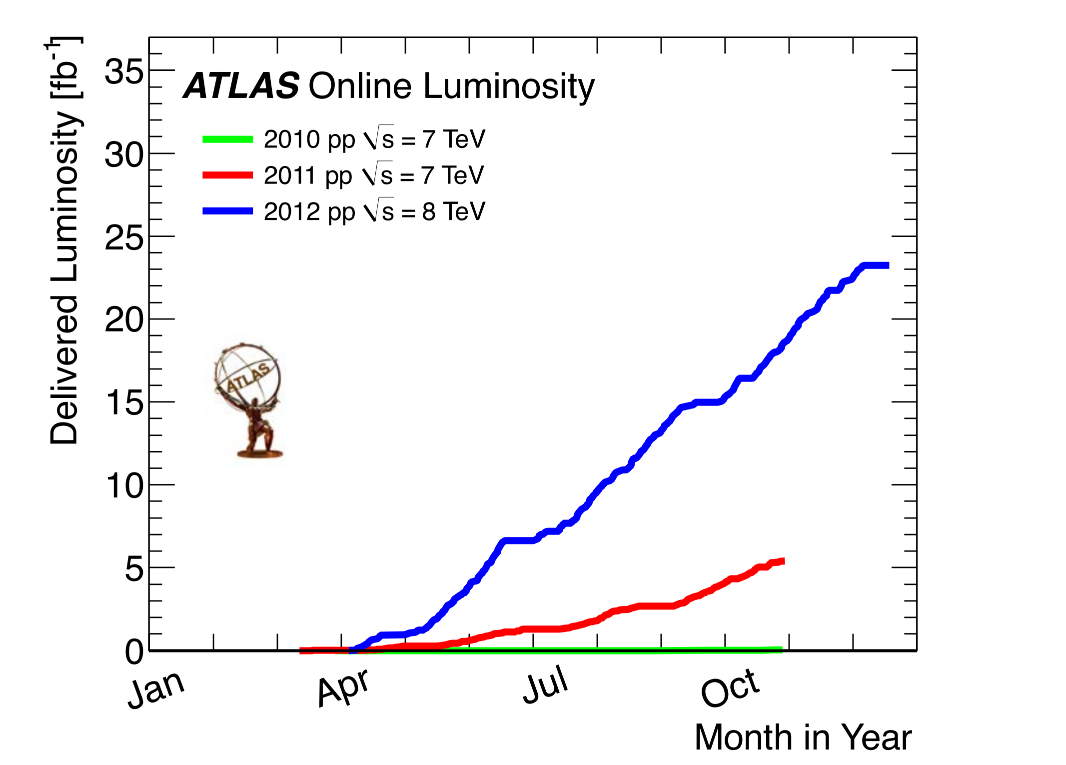
Data corresponding to ~40 pb^{-1} collected
→ re-discovery of the Standard Model





Well known quark-antiquark resonances (bound states) appeared "online"

Data taking in 2011/ 2012



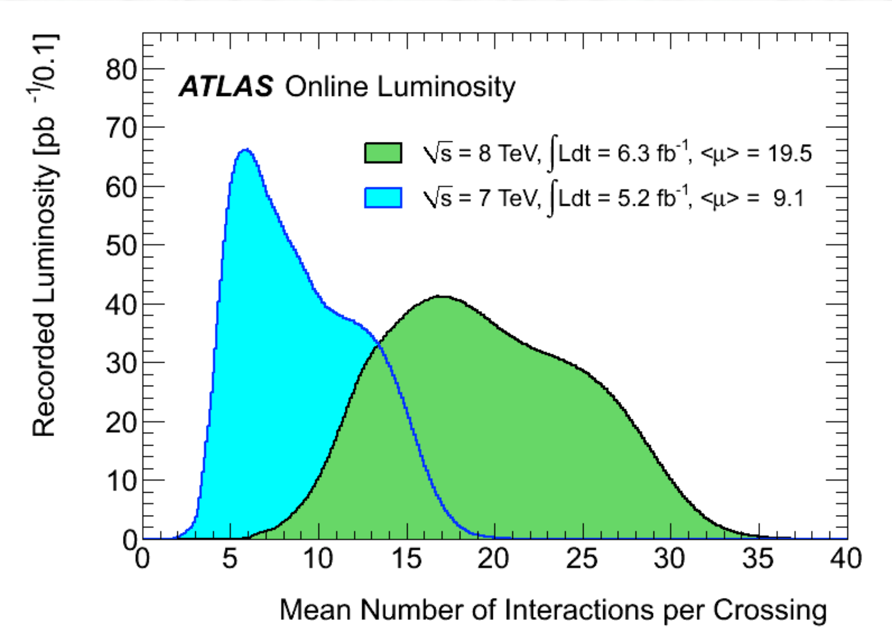
Until end 2012:

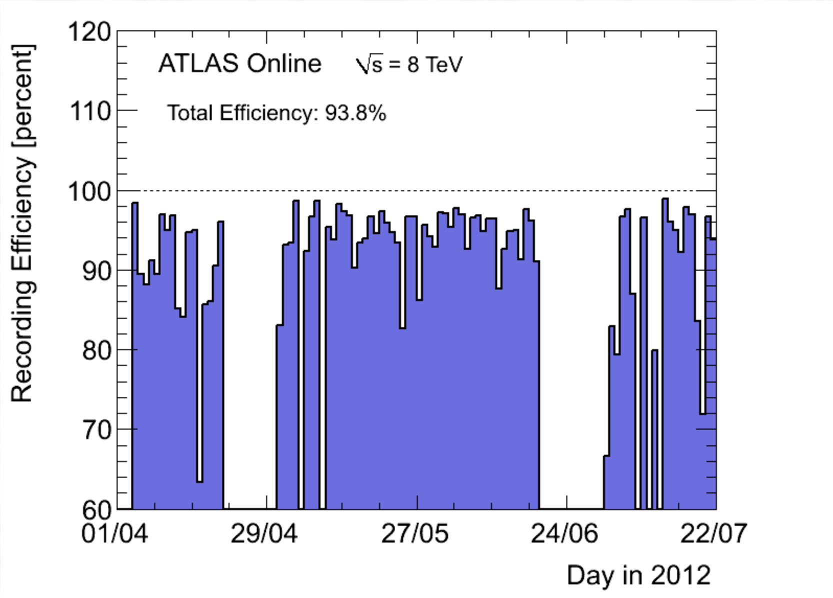
> 10^{15} pp collisions

~10^{10} pp collisions recorded

25 ·10^6 Z → μμ decays produced

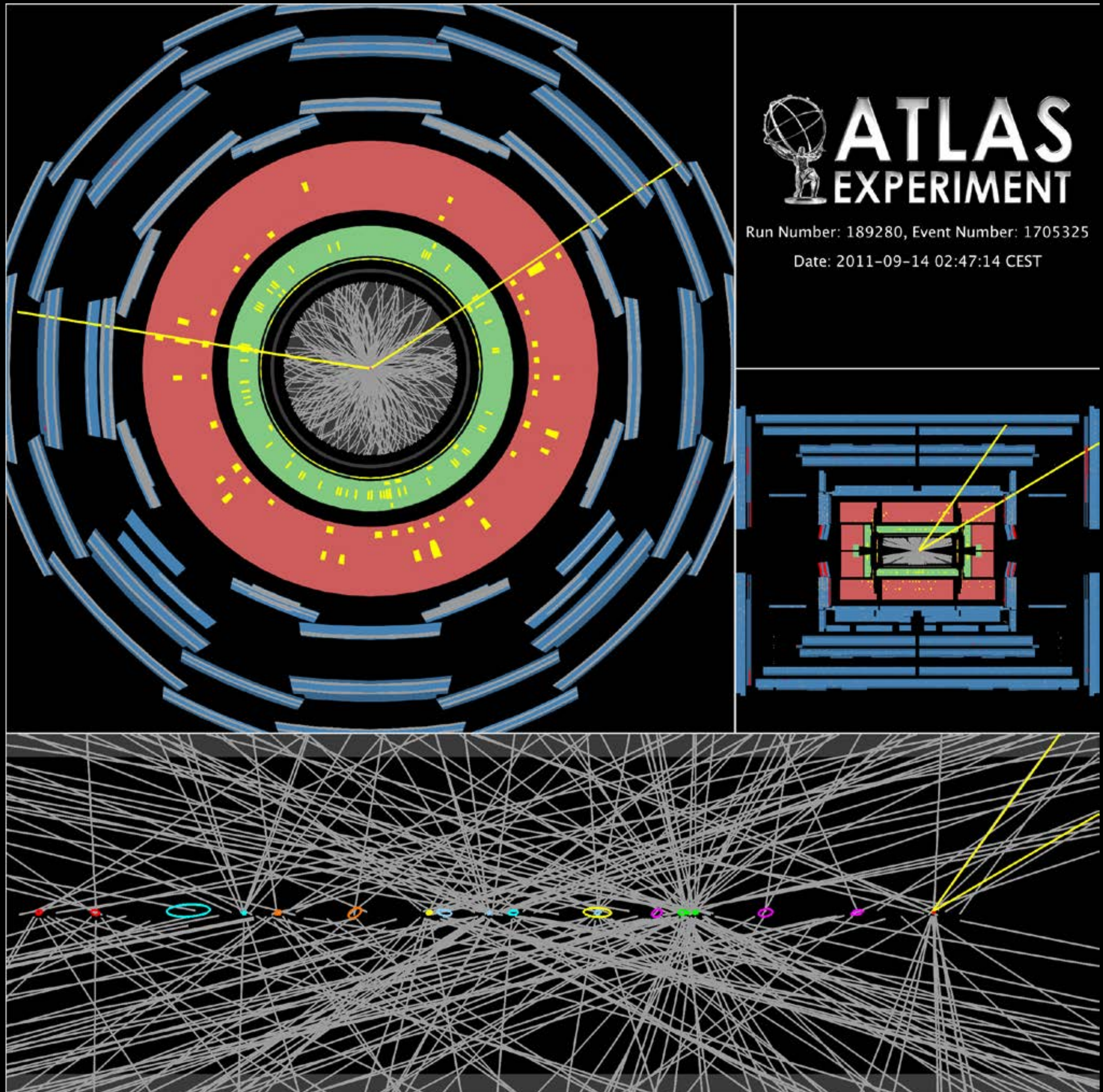
- Excellent LHC performance in 2011and 2012 (far beyond expectations)
- Peak luminosity seen by ATLAS: 7.7 10^{33} cm^{-2} s^{-1} (world record, 2012)
- Excellent performance of the experiments in recording the data (efficiency ~93.5%, working detector channels >99%, speed of data analysis,…)





- High efficiencies of the ATLAS and CMS experiments to collect and analyze the data

$Z \rightarrow \mu^+ \mu^-$ with 20 superimposed events



Constraints on the Higgs boson mass (before LHC)

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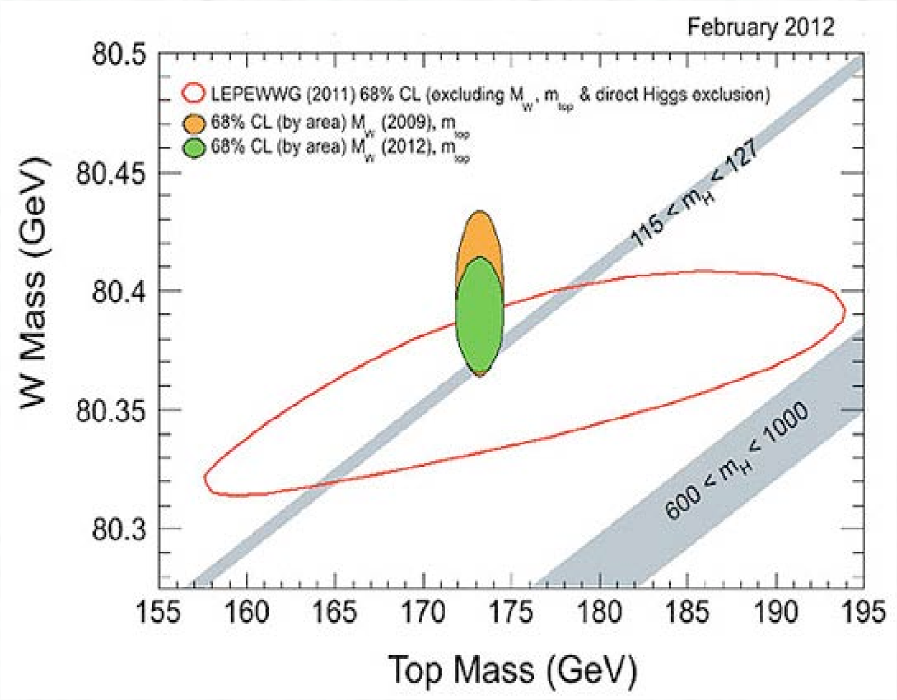
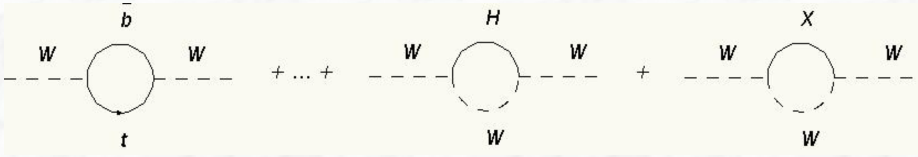


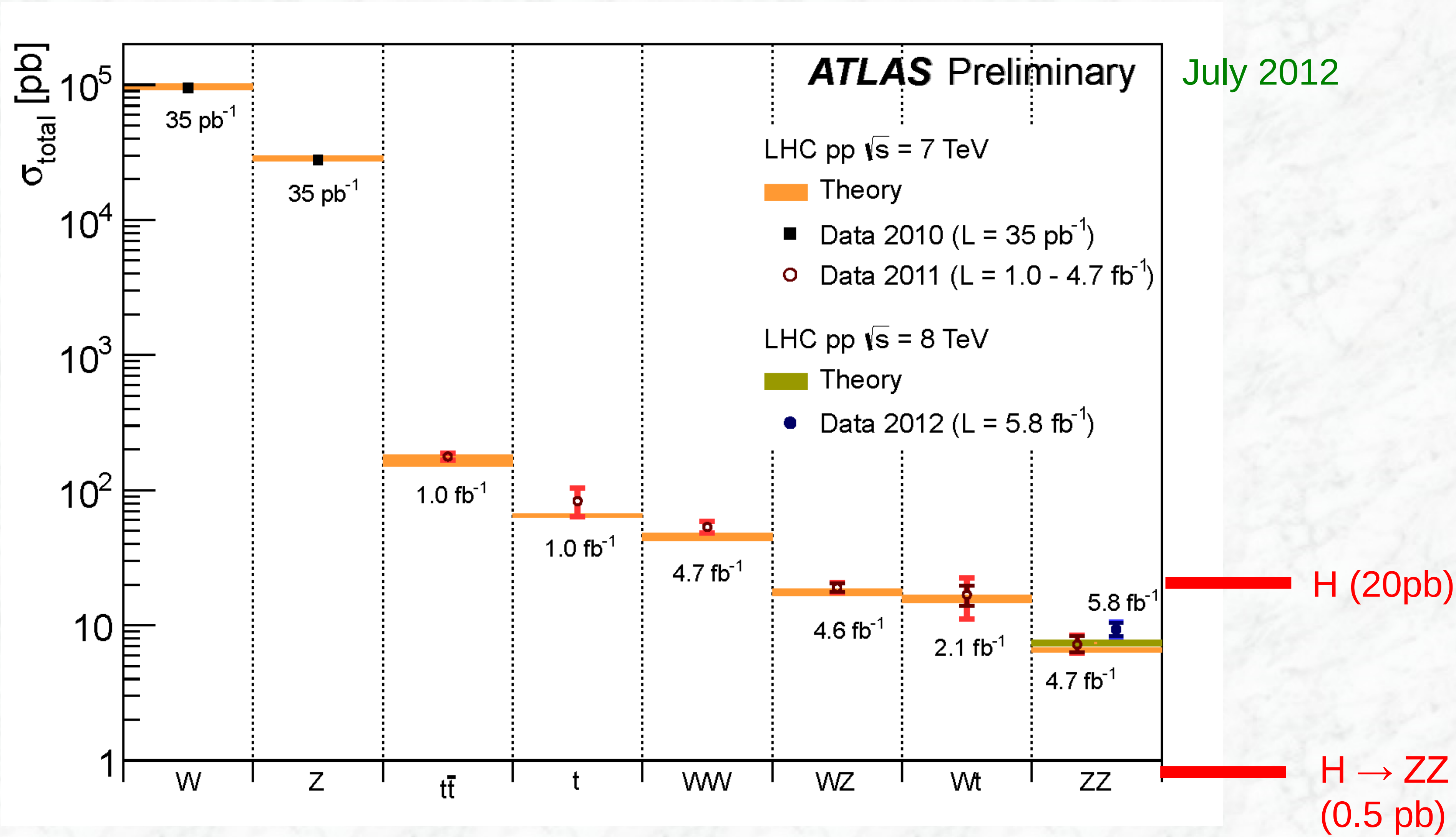
February 2012



$m_H = 92^{+34}_{-26}$ GeV/c^2
$m_H < 161$ GeV/c^2 (95 % C.L.)

- Indirect constraints from precision measurements (quantum corrections)

The Standard Model at the LHC

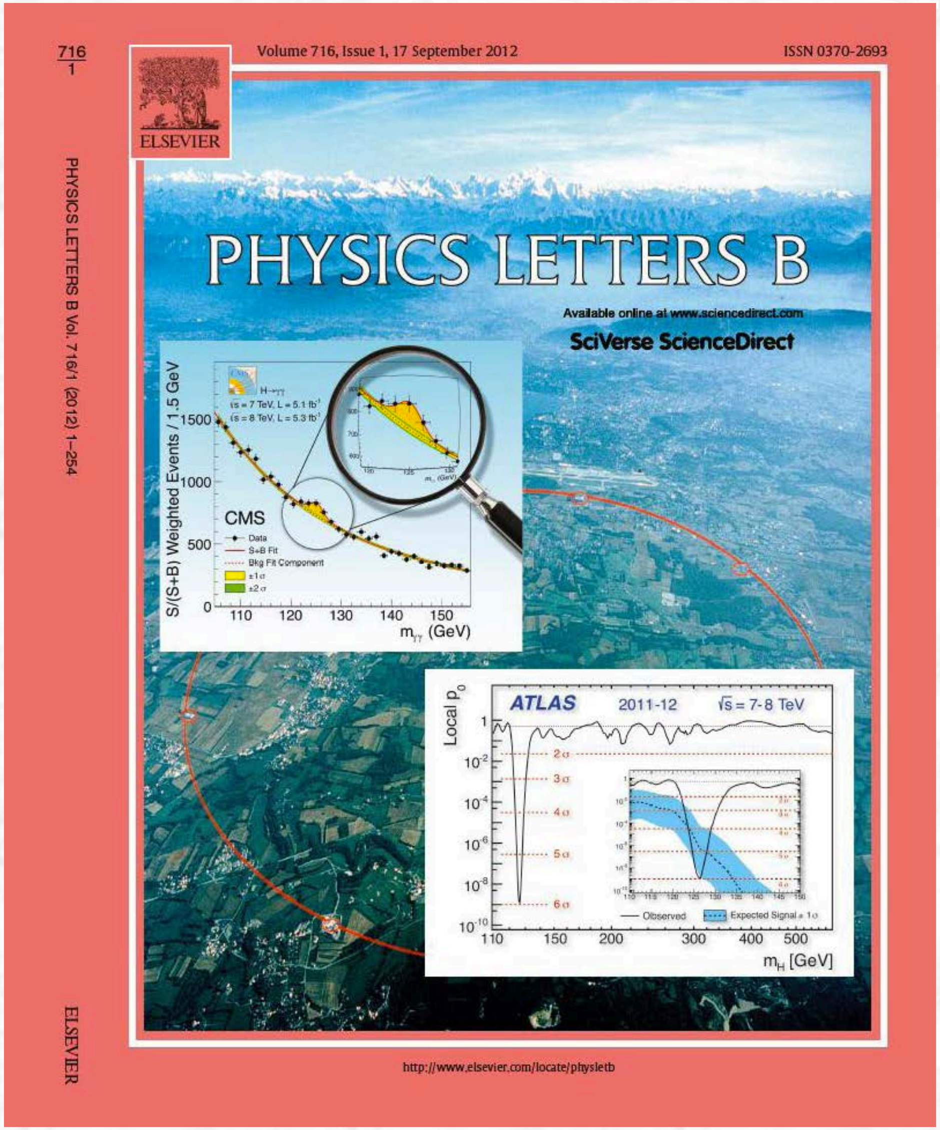


4th July 2012

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

Observation of a New Particle



Submission to PLB on 31st July 20

Contents lists available at SciVerse ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC ☆

ATLAS Collaboration *

This paper is dedicated to the memory of our ATLAS colleagues who did not live to see the full impact and significance of their contributions to the experiment.

Contents lists available at SciVerse ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC ☆

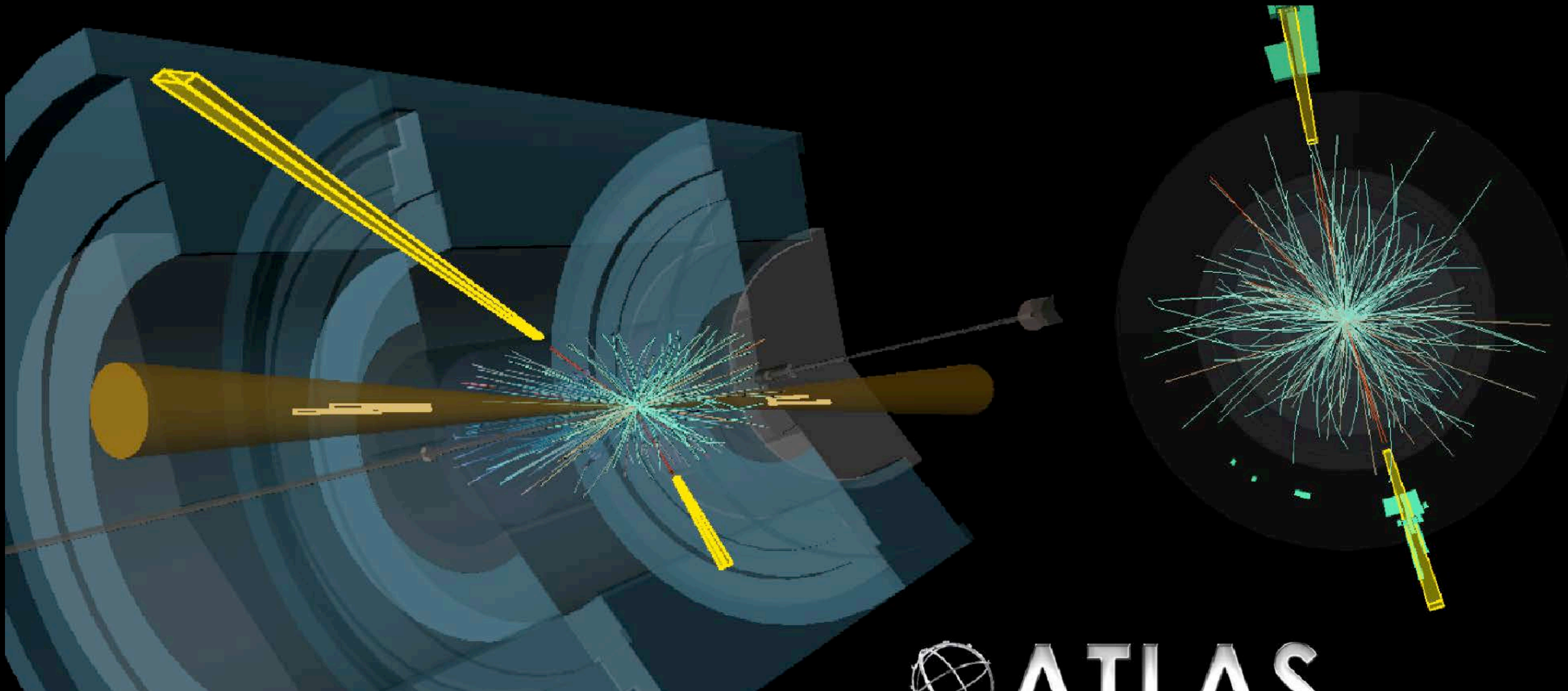
CMS Collaboration *

CERN, Switzerland

This paper is dedicated to the memory of our colleagues who worked on CMS but have since passed away. In recognition of their many contributions to the achievement of this observation.

Decay observed into particles with same spin and electric charge sum = 0
→ a new neutral boson has been discovered

$H \rightarrow \gamma\gamma$ VBF candidate event



$E_T(\gamma_1)$ = 80.1 GeV, η = 1.01
$E_T(\gamma_2)$ = 36.2 GeV, η = 0.17
$m_{\gamma\gamma}$ = 126.9 GeV

$E_T(jet_1)$ = 121.6 GeV, η = -2.90
$E_T(jet_2)$ = 82.8 GeV, η = 2.72
m_{jj} = 1.67 TeV

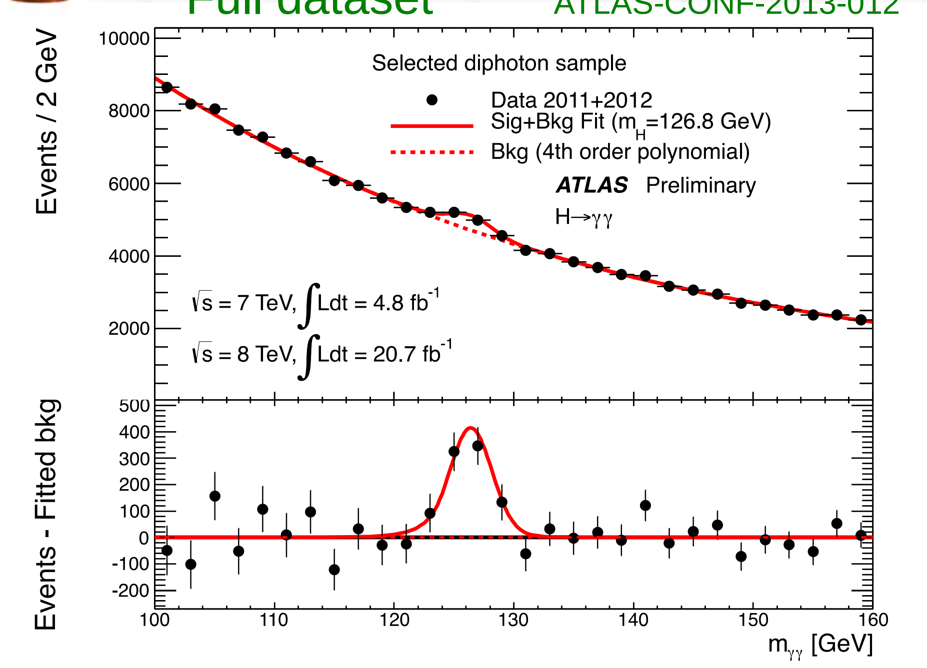
ATLAS EXPERIMENT

Run Number: 204769, Event Number: 24947130

Date: 2012-06-10 08:17:12 UTC

Result of the ATLAS search for H → $\gamma\gamma$

Full dataset ATLAS-CONF-2013-012



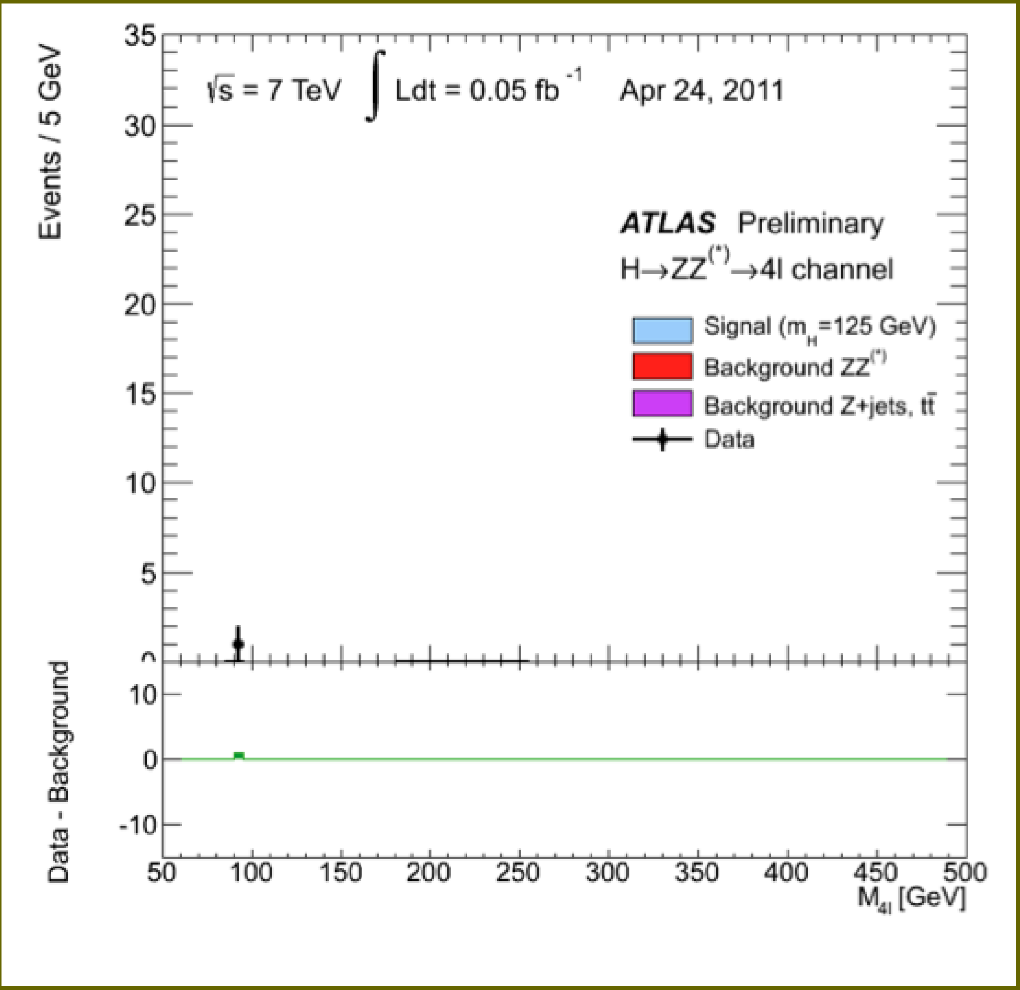
100 GeV < $m_{\gamma\gamma}$ < 160 GeV:

$\sqrt{s}$ = 7 TeV 23 788 events

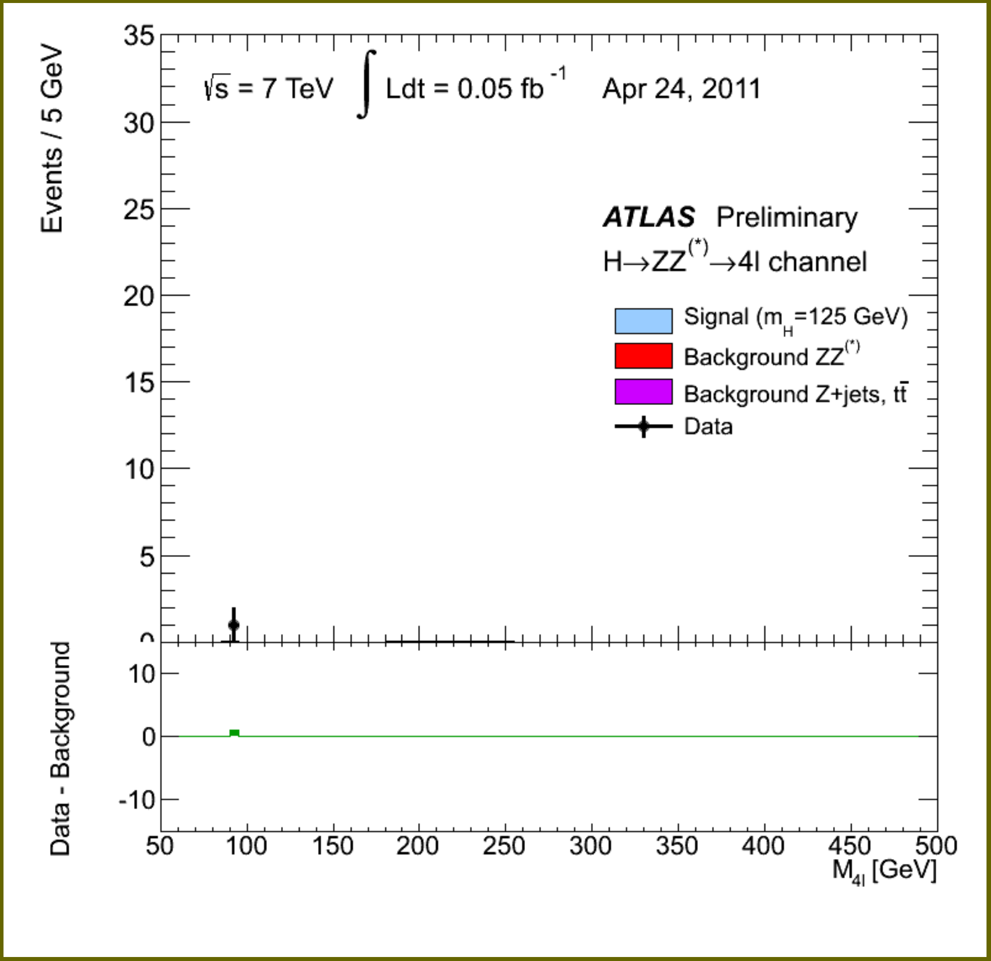
$\sqrt{s}$ = 8 TeV 118 893 events

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

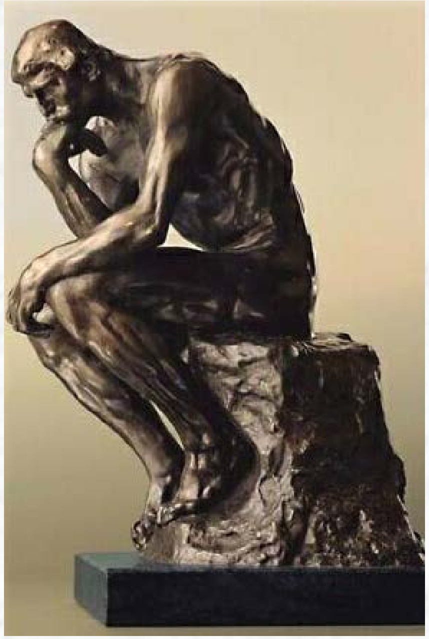
Time evolution of the H → ZZ → 4ℓ signal



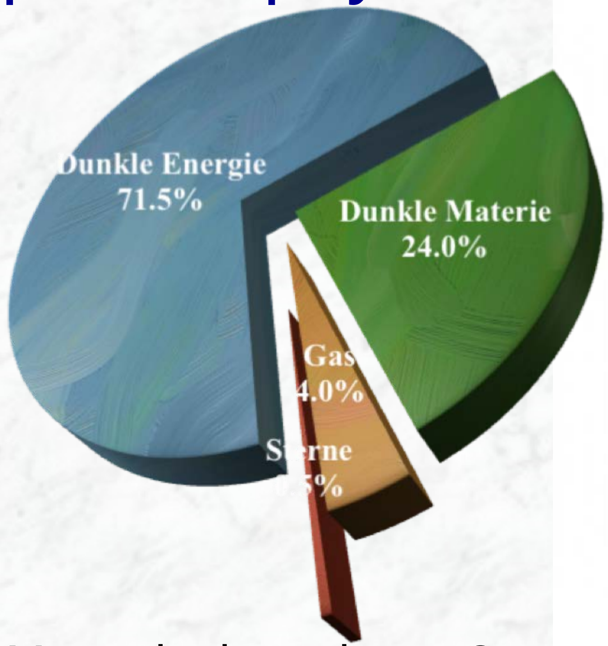
Time evolution of the H → ZZ → 4ℓ signal



Today's open questions
in particle physics



Key questions of particle physics



1. Mass

What is the origin of mass?

The Higgs particle seems to exist !

2. Unification

- Can the interactions be unified?
- Are there new types of matter, e.g. supersymmetric particles ?
  Are they responsible for the Dark Matter in the universe?

3. Flavour

- Why are there three generations of particles?
- What is the origin of the matter-antimatter asymmetry (Origin of CP violation)

Answers to some of these questions are expected on the TeV energy scale, i.e. at the LHC