Tests of the SM and Higgs bozon discovery

Particles and Universe

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1. Introduction
2. $W^{\pm}$ and Z° bosons
3. Top quark
4. Higgs boson
5. Tests of the SM

Nobel Prizes

1979 - Sheldon L.Glashow, Abdus Salam i Steven Weinberg
model of electro-weak interactions, predicting $W^{\pm}$ and Z°

1984 - Carlo Rubia and Simon Van der Meer
$W^{\pm}$ and Z° discovery at CERN SPS

1999 - Gerardus 'T Hooft and Martinus J.G.Veltman
renormalization of the Standard Model

2004 - David J. Gross, H. David Politzer and Frank Wilczek
model of strong interactions

2008 - Yoichiro Nambu, Makoto Kobayashi and Toshihide Maskawa
mechanism of the sponteus symmetry breaking
description of quark mixing, predicting 3rd quark generation

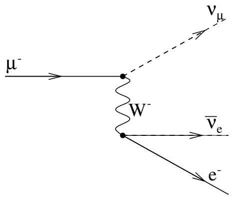
2013 - Franois Englert, Peter Higgs
for the mechanism explaining the origin of particle masses
confirmed recently by the ATLAS and CMS experiments

Standard Model: electro-weak int. + quantum chromodynamics (QCD)

Weinberg-Salam model (1968)

New model of the weak interactions
Interaction can be described by the exchange of the very massive boson: $W^{\pm}$ or Z°.

Muon decay:



"Weakness" is not due to the small coupling but results from the large boson mass:

$$G_F \sim \frac{g^2}{m_W^2}$$

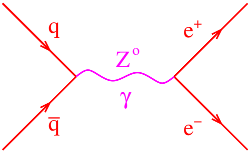
Assuming coupling g same as for the EM interactions Weinberg i Salam **predicted** masses of $W^{\pm}$ and Z°:

$$m_W \sim 80\ GeV$$
$$m_Z \sim 90\ GeV$$

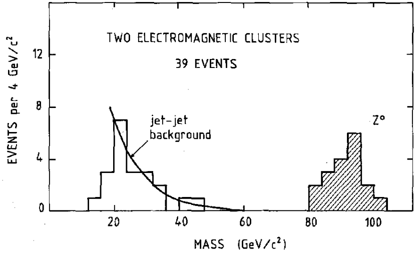
Neutrino interactions with Z^0 (neutral currents) exchange - 1973

Discovery SPS accelerator at CERN

In $p\bar{p}$ interactions, $q\bar{q}$ annihilating in virtual photon can result in lepton-pair production $(e^+e^-, \mu^+\mu^-, \tau^+\tau^-)$.
Drela-Yana process:



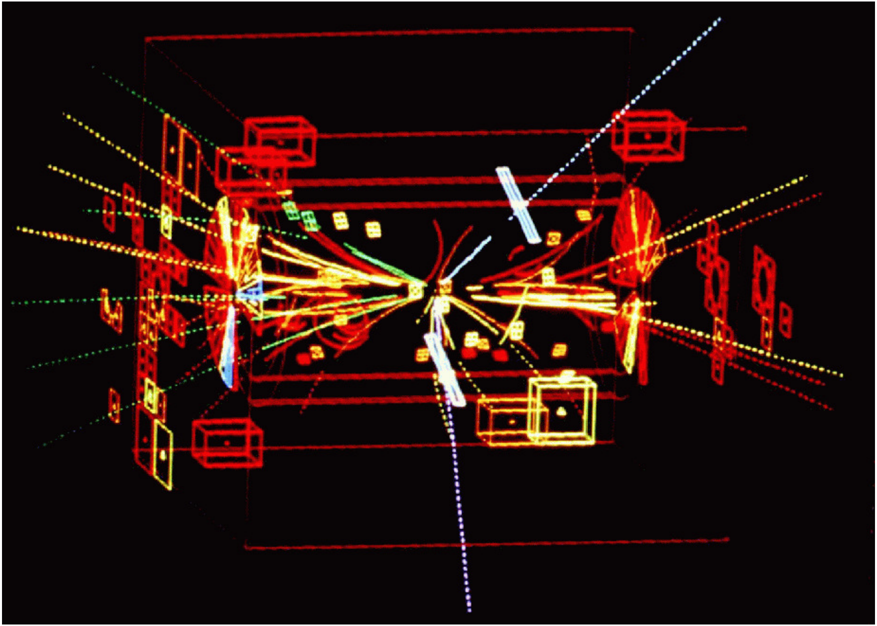
UA1 results (1983):



If the invariant mass of annihilating quarks is large, also virtual Z° can be exchanged.

Z° contribution $\Rightarrow$ maximum in the lepton invariant mass distribution

Z° event in UA1 detector (1983)



Discovery

In $p\bar{p}$ interactions, $q\bar{q}'$ annihilation can also result in production of the $W^\pm$ boson:

$$u\bar{d} \rightarrow W^+ \rightarrow e^+ \nu_e$$

Decay with neutrino production
$\Rightarrow$ transverse momentum imbalance

Longitudinal neutrino momentum unknown
$\Rightarrow$ we can not reconstruct $W^\pm$ mass directly

"Transverse mass" m_T:
reconstructed assuming $p_z^\nu = 0 \Rightarrow m_T \leq m_W$

$W^\pm$ and Z° bosons were discovered at UA1 and UA2 experiments at CERN SPS.

UA1 results (1983):

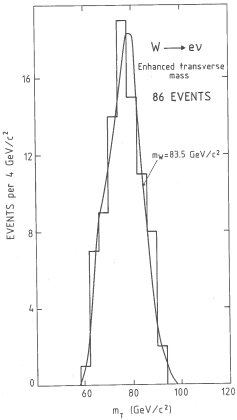


Fig. 3b

W^- event in UA1 detector (1983)

LEP, CERN, Geneva

1989 - 2000: precise tests of the Standard Model

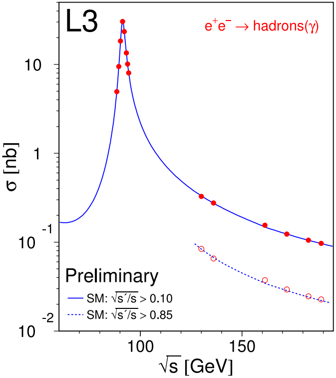
$e^+e^- \to Z^{\circ}$

High precision tests of the Standard Model were possible in e^+e^- interactions at LEP and SLC (millions of events).

Clear maximum in the hadron production cross section corresponds to the real Z° production (on mass shell).

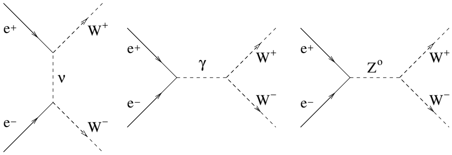
Width of the maximum corresponds to the finite Z° width (Heisenberg's uncertainty principle)

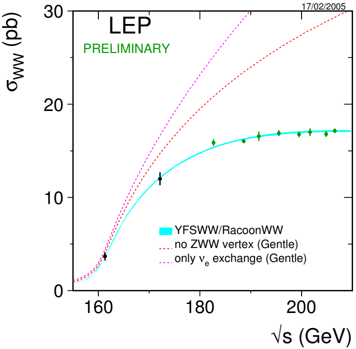
As the Z° lifetime is extremely short, its mass is not fixed - and can vary from event to event. Resonance width $\Gamma_Z \approx 2.5$ GeV



$e^+e^- \rightarrow W^+W^-$

At LEP $W^{\pm}$ can only be produced in pairs.
Three diagrams contribute:





Couplings are uniquely given by the structure of the Standard Model
⇒ strict theoretical prediction

Cancellation of divergences confirmed by LEP experiments

Top quark

Short history

- 1964 - Gell-Mann and Zweig, quark model with 3 quarks: u, d, s
- 1970 - Glashow, Iliopoulos and Maiani (GIM) - 2 doublets: u, d, s, c
- 1973 - Kobayashi and Maskawa add 3rd doublet (t and b),
  to allow for CP violation
- 1974 - Ting, Richter: charm discovery (c quark)
- 1977 - Lederman (Fermilab): b quark discovery

b quark properties (charge, isospin, gauge boson couplings) in agreement with expectation for "down" member of quark doublet

$\Rightarrow$ "up" partner needed: **top**

First prediction (rule of "3"):

$$m_s = 0.5\ GeV \quad m_c = 1.5\ GeV \quad m_b = 4.5\ GeV \quad \Rightarrow \quad m_t \sim 15\ GeV$$

First "discovery": CERN SPS, 1984, $m_t \sim 40\ GeV$ (revoked)
Searches at LEP and HERA, without success...

Comparison

Many different observables measured with high precision at LEP.

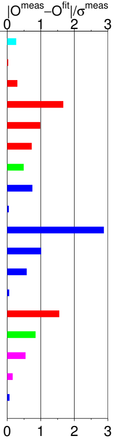
Only three free parameters describing Standard Model interactions (+ fermion and Higgs masses).

Possible choice: α_{em}, G_F, M_Z can be fitted to precise data.

All other electroweak measurements should be then uniquely predicted

Level of agreement: pull $\equiv \frac{|X_{meas} - X_{SM}|}{\sigma_X} \Rightarrow$

	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02750 ± 0.00033	0.02759
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]	80.385 ± 0.015	80.377
Γ_W [GeV]	2.085 ± 0.042	2.092
m_t [GeV]	173.20 ± 0.90	173.26



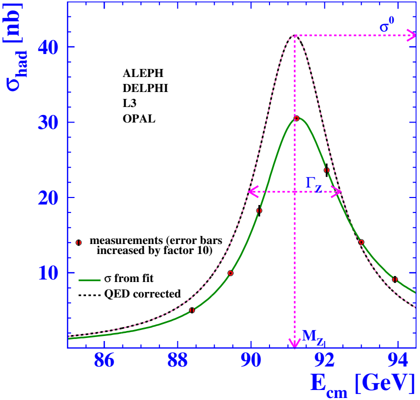
March 2012

Corrections

Measurements at LEP turn out to be very sensitive to "higher order" corrections.

In particular, sizable corrections are due to diagrams including exchange of heavy virtual particles: $W^{\pm}$ boson, top quark, Higgs boson or new exotic states...

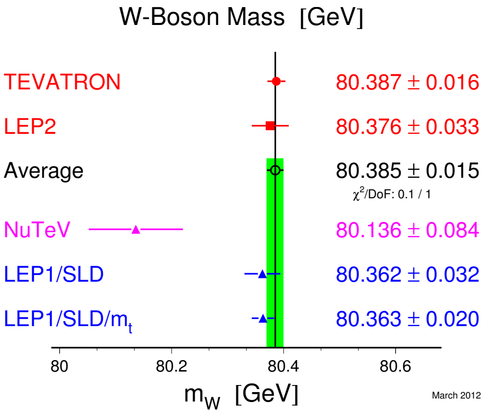
Precise measurements at LEP and other experiments allow us to infer about masses of these heavy states, even if we do not observe them directly!



Corrections

We can extract masses of heavy particles from the precision measurements at lower energies.

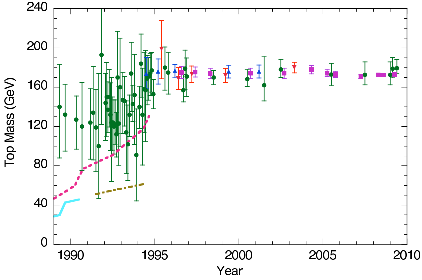
It worked very well for $W^{\pm}$ $\Rightarrow$



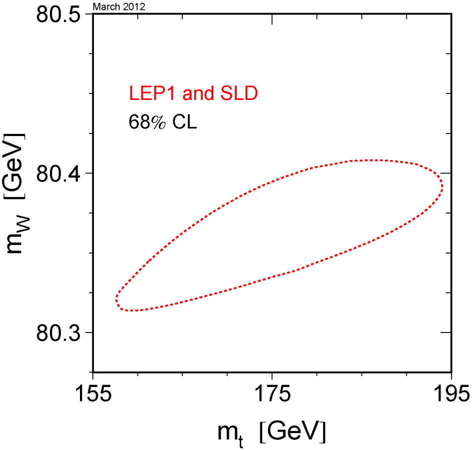
Direct measurement in agreement (to 0.03%) with theoretical predictions based on lower energy measurements.

Prediction

Based on the LEP1/SLD measurements, we expected that mass of the top quark should be about 120-180 GeV.

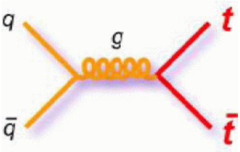


Final LEP1+SLD constraints:

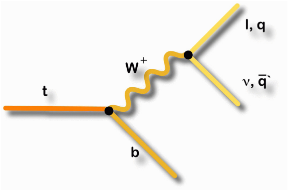


Tevatron $p\bar{p}$ interactions at $\sqrt{s} \sim 2$ TeV

Top quark pairs produced mainly in quark-antiquark annihilation:



Top decays almost immediately, (no bound state is formed):



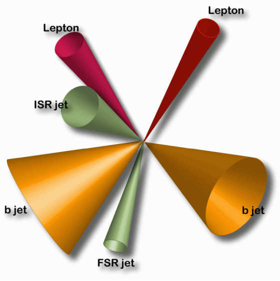
We expect to observe a *b* quark jet plus lepton and neutrino (missing transverse momentum) or pair of jets with invariant mass of W

Top quark

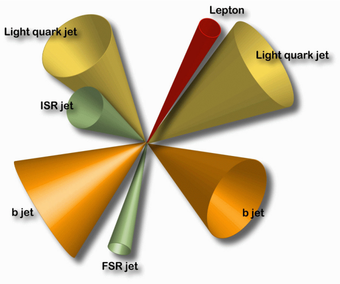
Tevatron

As top is produced in pairs ($t\bar{t}$), 3 event topologies are possible:

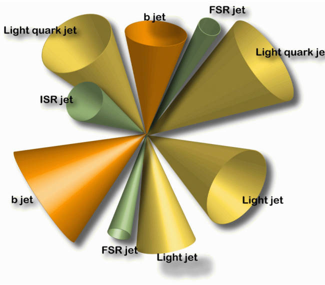
leptonic



semi-leptonic



hadronic



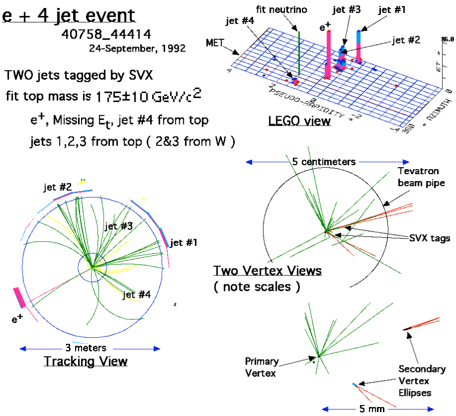
"gold sample" but only $\sim$4% of events (e^+e^-, $\mu^+\mu^-$ i $e^\pm\mu^\pm$)

$\sim$30% of events ($e^\pm$ and $\mu^\pm$ only)
small background

$\sim$46% of events
huge background
difficult identification

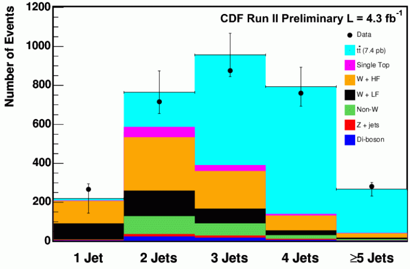
Tevatron

One of the first events



⇒ actual discovery in 1995

Number of jets reconstructed in events with isolated lepton ($e^{\pm}$, $\mu^{\pm}$)



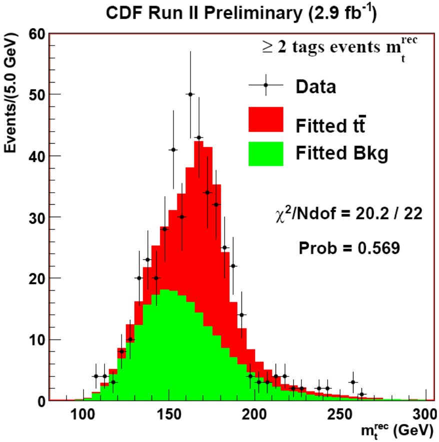
Events with lepton and $\geq$ 3 jets

⇒ mostly $t\bar{t}$

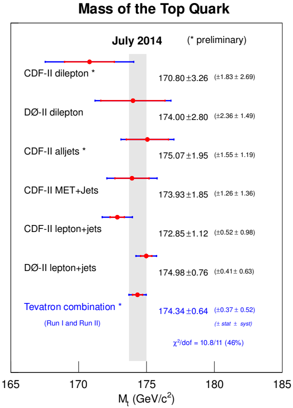
Thousands of events collected...

Tevatron

Distribution of the reconstructed top mass
in one of the considered channels



Comparison of results

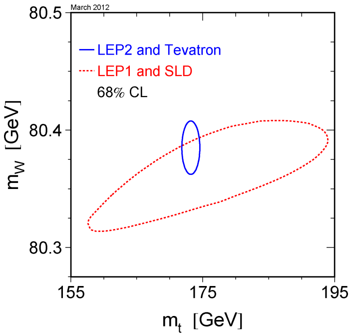


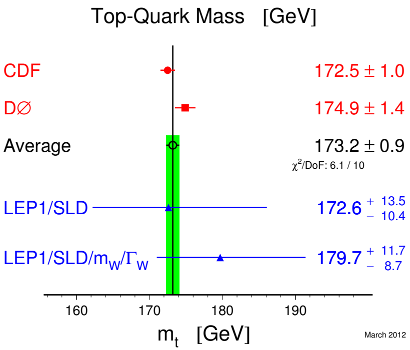
CDF + D0:

$$m_t = 174.34 \pm 0.64 \ GeV$$

Comparison

Direct measurements compared with constraints obtained with precise measurements at lower energies.

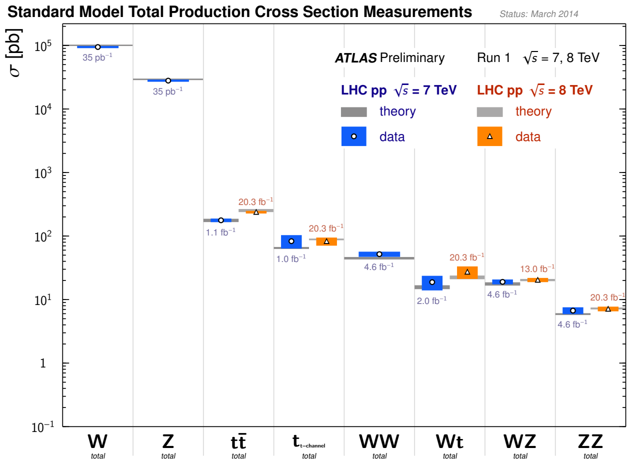




Direct measurement in agreement with theory predictions based on precise measurements at lower energies.

LHC experiments

High precision studies of processes with $W^{\pm}$, Z^0 and top quark production.
All results with perfect agreement with SM predictions. March 2014:



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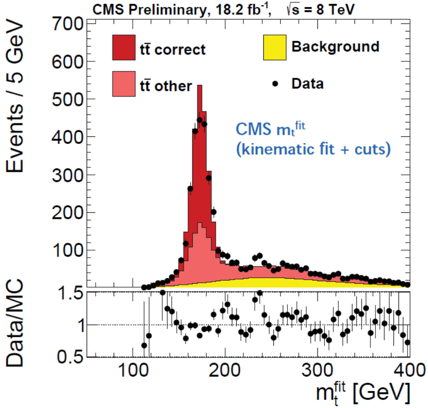
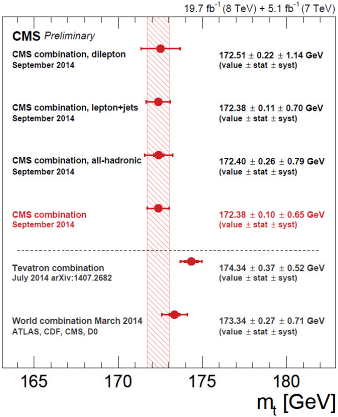




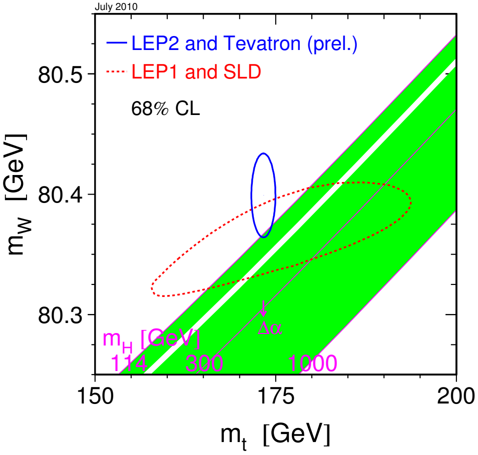
Number of t produced at LHC is already much higher than at Tevatron...

Corrections

We can extract masses of heavy particles from the precision measurements at lower energies.

For $W^{\pm}$ and t direct measurements in perfect agreement with expectation

$\Rightarrow$ we can make another step and try to estimate mass of the yet unobserved particle - Higgs



Higgs mass

Analysis of all available data indicated, that the Higgs mass should be about 100 – 200 GeV

2010 fit result:

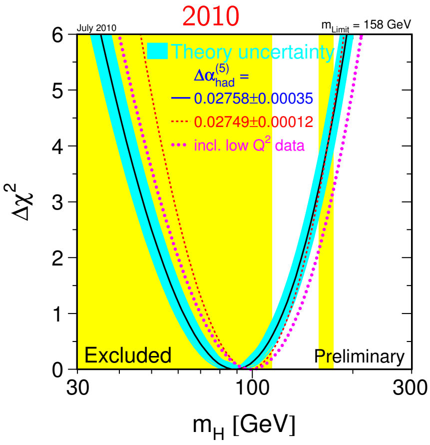
$$m_h = 89^{+35}_{-26}\ \text{GeV}$$

or: $m_h < 158$ GeV (95% CL)

Limit from direct search:

$$m_h > 114.4\ \text{GeV (95\% CL)}$$

all LEP data:
ALEPH + DELPHI + L3 + OPAL

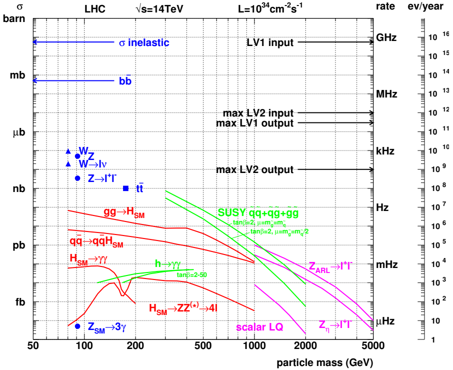


LHC, CERN, Genewa

Run I: 2009-2012 Run II: 2015-2018(?)

Higgs at LHC

Higgsa boson is a key element of the Standard Model, with very special properties. Search for the Higgs boson and measurement of its properties were the main goals of LHC experiments.



Higgs boson decays primarily to the heaviest available states: for mass m_h <135 GeV decay to $b\bar{b}$ dominates.

However, there is a huge background of other pp collisions with $b\bar{b}$ production.

We need to look for decay channels with less background...

Higgs at LHC

For small Higgs masses the best channel is

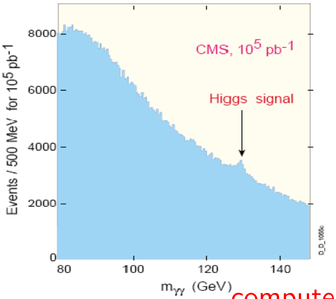
$$H \rightarrow \gamma\gamma$$

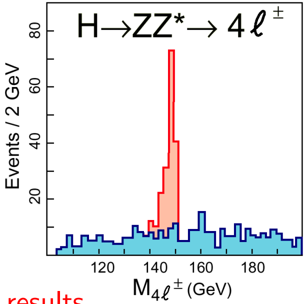
Background is high, but we should see a clear Higgs peak

For large masses we should look for:

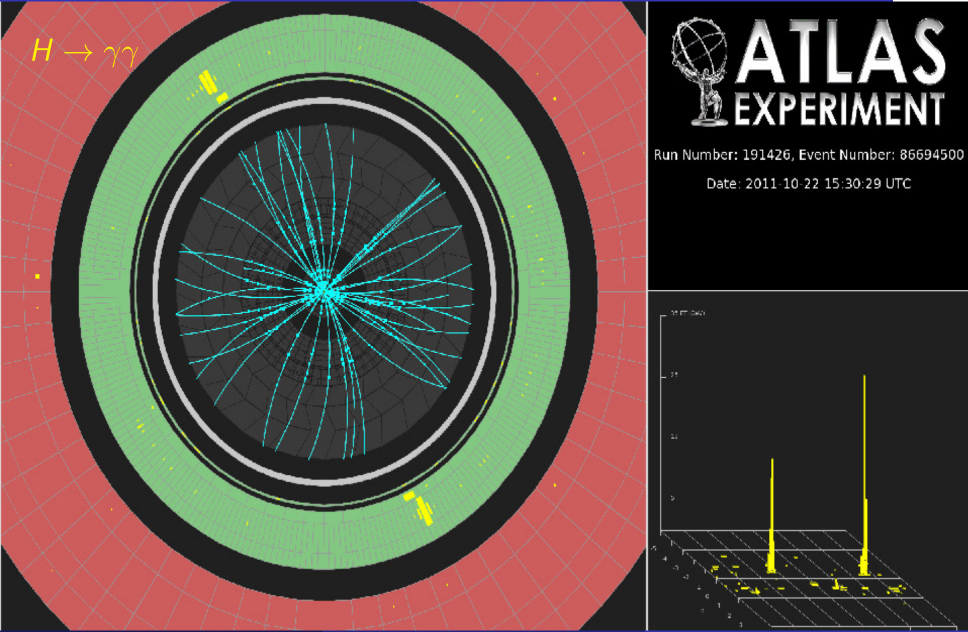
$$H \rightarrow Z^\circ Z^\circ \rightarrow l^+ l^- l^+ l^-$$

as the charged leptons ($e^\pm$ i $\mu^\pm$) are very easy to identify.
But the events are rare...

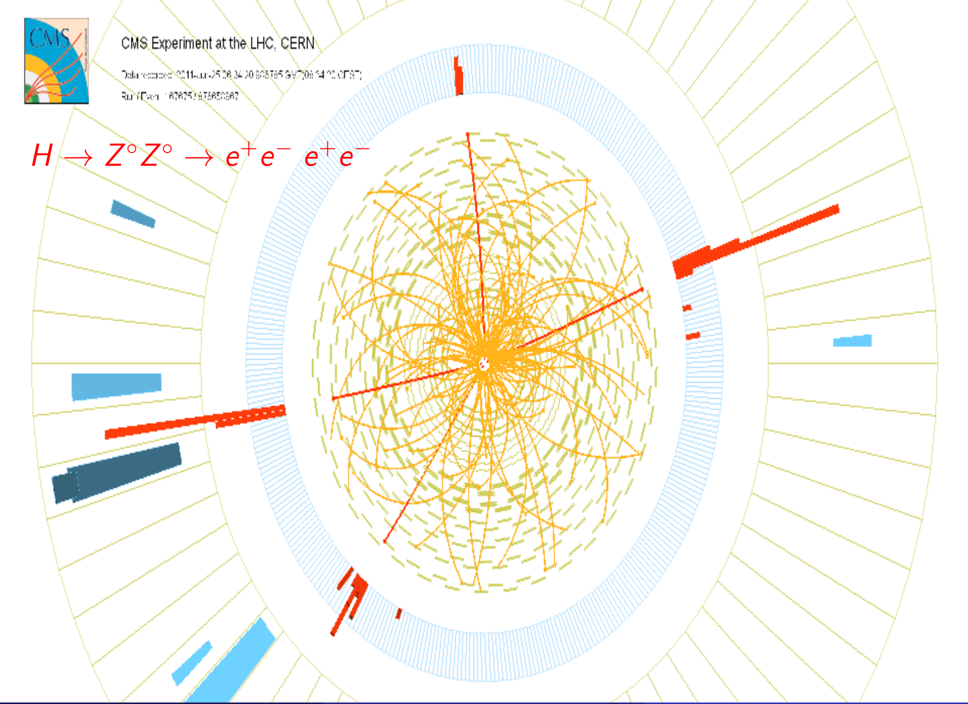




computer simulation results

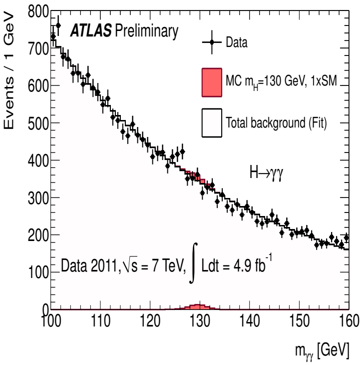

$H \to \gamma\gamma$
ATLAS
EXPERIMENT
Run Number: 191426, Event Number: 86694500
Date: 2011-10-22 15:30:29 UTC

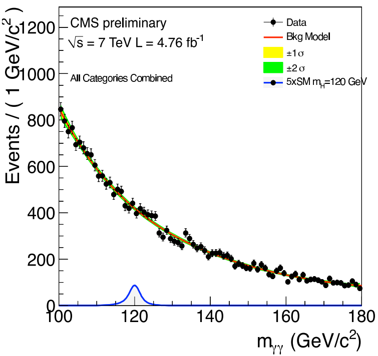
$H \to Z^{\circ}Z^{\circ} \to e^{+}e^{-}\ e^{+}e^{-}$



In December 2011, ATLAS and CMS experiments presented first results of the Higgs boson search, based on the data sample collected in 2010-2011.
Event statistics still very low

$$H \rightarrow \gamma\gamma$$





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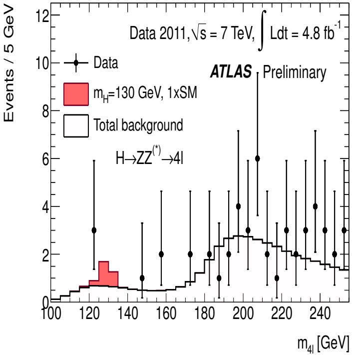
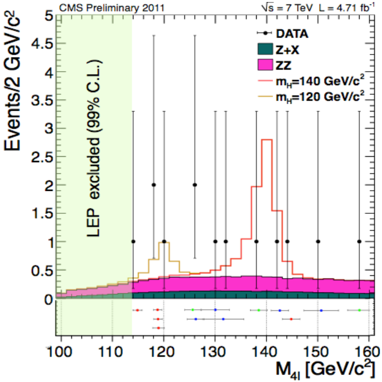
$$H \rightarrow Z^{\circ}Z^{\circ} \rightarrow l^{+}l^{-}l^{+}l^{-}$$





Precise measurements at LEP

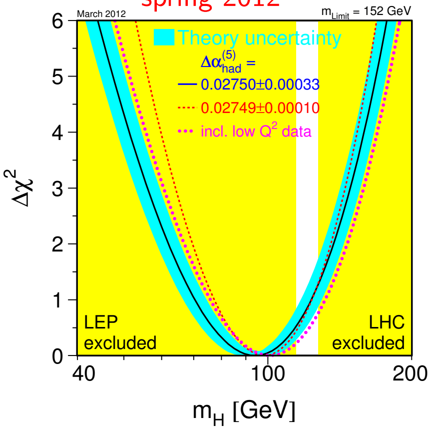
Higgs mass

Analysis of all available data from LEP, Tevatron and the first data from LHC (!).

In spring 2012 only a small gap remained were the Higgs mass could be in agreement with the Standard Model predictions:

$$114.7\,GeV \; < \; m_H \; < \; 127\,GeV$$

spring 2012

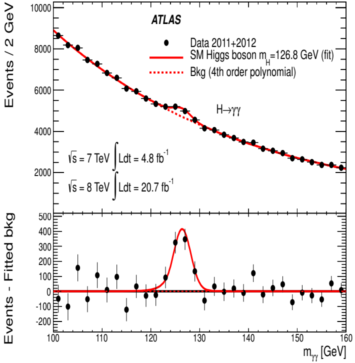


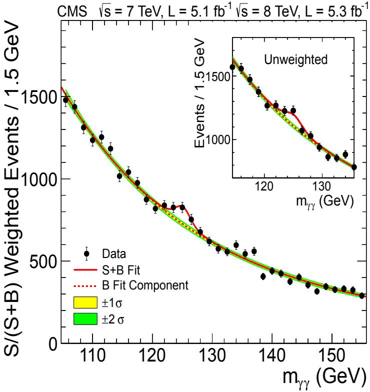
If this “window” is closed,
it would mean that the Standard Model is excluded!
But the measurement most difficult for mass of about 120 GeV...
Intermediate mass region, between “light” and “heavy” Higgs

Results of ATLAS and CMS, after including data collected in 2012.

Fivefold increase in event sample! Signal clearly visible

$$H \rightarrow \gamma\gamma$$





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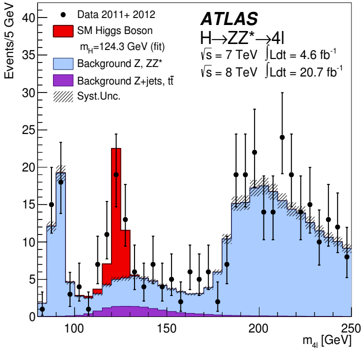
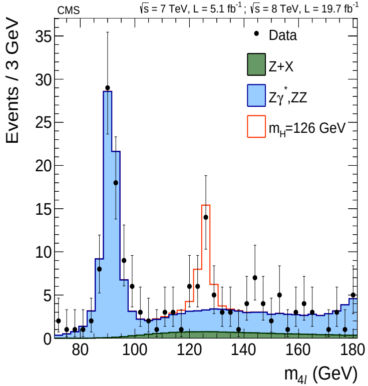


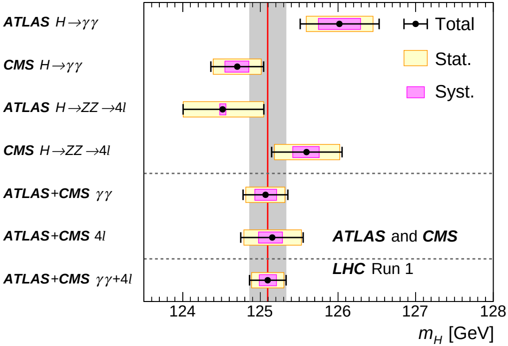


Results of ATLAS and CMS, after including data collected in 2012.

Two considered "discovery channels" also give the most precise mass determination for new particle.

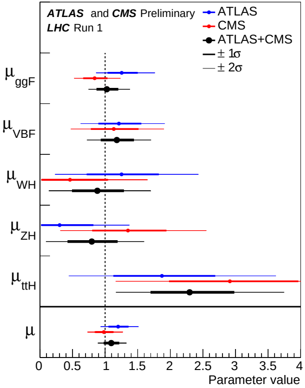
Results based on the full 2009-2012 LHC data sample (Run I):

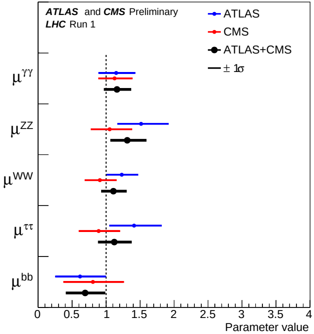
$$M_H = 125.09 \pm 0.24\ GeV$$



Large sample of collected events allowed searching for other decay channels

Number of events for all identified production and decay channels in good agreement with SM





Only 2/3 of measurements expected to agree with predictions within $\pm 1\sigma$

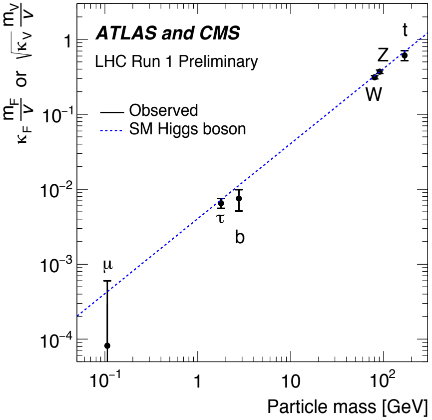
Higgs couplings

Key prediction of the model can now be verified:
Higgs boson coupling should be proportional to the particle mass

Errors are still very large!

Much higher precision possible after more data collected at $\sqrt{s}$=13TeV.

Tenfold increase in data sample expected until 2020.

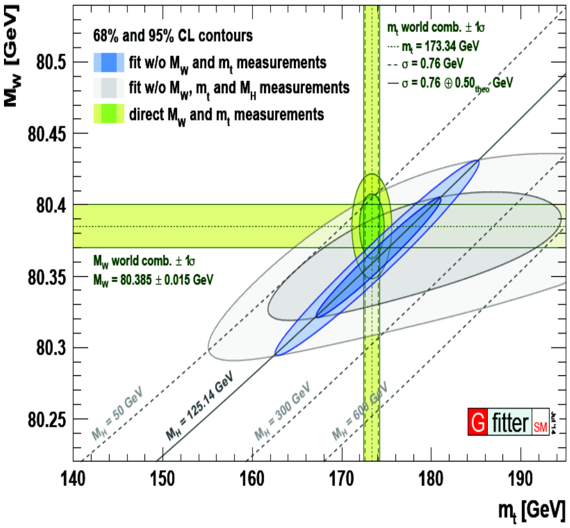


Standard Model

Within the Standard Model, Higgs boson mass is related to W and t masses via loop corrections.

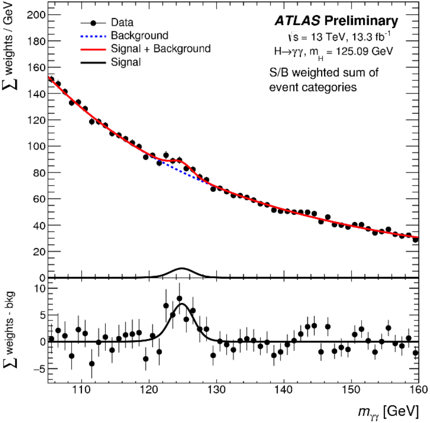
Higgs boson mass measurement at LHC in agreement with direct measurements of W and t masses, and LEP results.

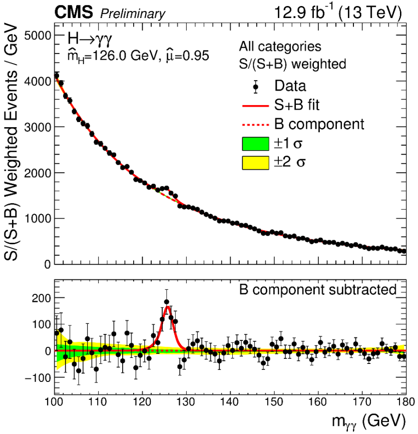
Everything looks fine...



Higgs at LHC

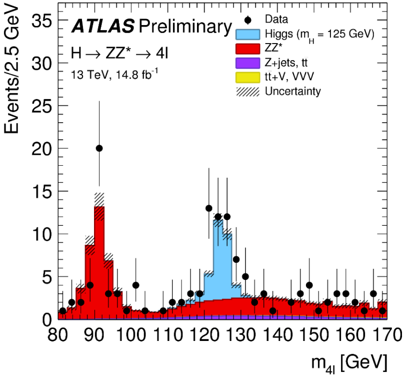
Run 2 results (2015+2016) $H \to \gamma\gamma$

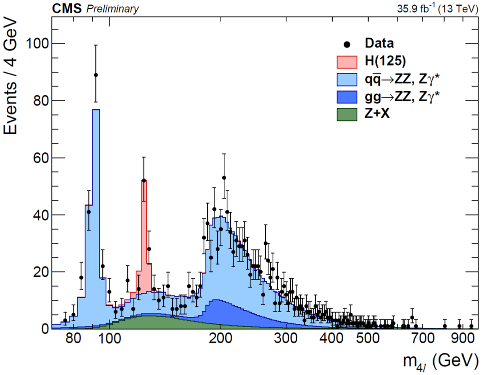




Observations consistent with Run I.

Run 2 results (2015+2016) $H \to ZZ^{\star} \to 4l$

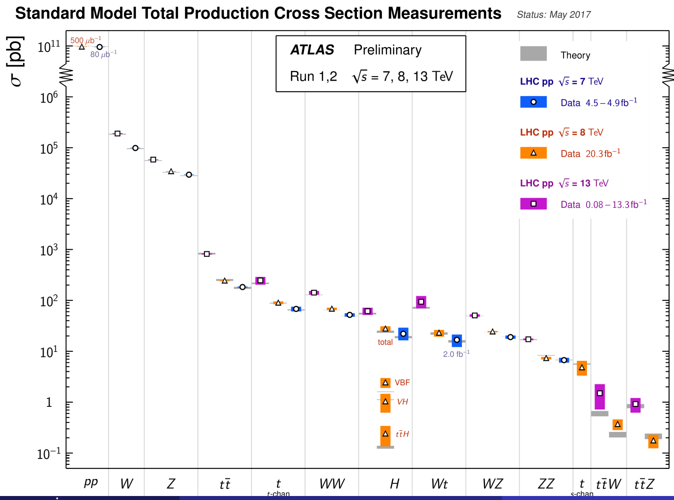




Observations consistent with Run I. Waiting for more data...

LHC results

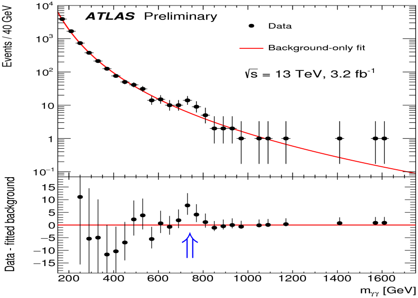
High precision studies of processes with $W^{\pm}$, Z^{0}, H boson, and top quark production. Good agreement with SM predictions. May 2017:

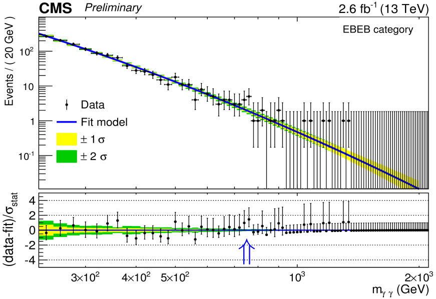


SM tests

LHC results

In 2015 LHC was running at $\sqrt{s} = 13$ TeV, little data collected.
Small excess observed in two photon production $pp \rightarrow \gamma\gamma + X$:



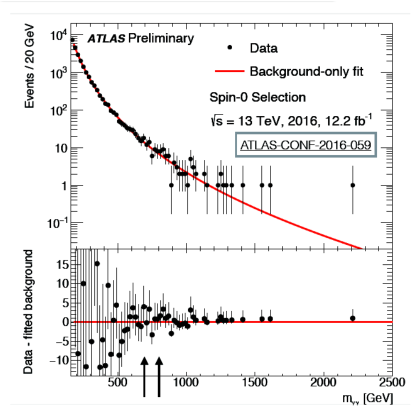


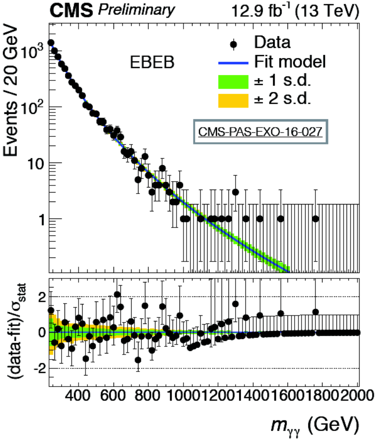
$m_{\gamma\gamma} = 750$ GeV $\Rightarrow 3.6\ \sigma\ (2.0\sigma)$ $\qquad$ $m_{\gamma\gamma} = 760$ GeV $\Rightarrow 2.6\ \sigma\ (1.2\sigma)$

Not very convincing, but started many discussions. Large expectations...

LHC results

Unfortunately, signal not confirmed with 2016 data...





Significance in 2015+2016:

m=710 GeV (Γ/M=10%)
2.3σ(local)/<1σ (global)

m=760 GeV (Γ/M=1.4x10^{-4})
<1σ(local)

LHC timeline

LHC project spans over many decades

- 1984: first LHC project draft 1989: LEP started
- 1992: proposals for ATLAS and CMS experiments
- 1994: LHC construction approved, 1997: ATLAS and CMS approved
- 2008: LHC fails to start - magnet explosion
- 2009: successful start of LHC
- 2010-2012: *pp* collisions at $\sqrt{s}$=7–8 TeV (Run 1, $\sim 25 fb^{-1}$)

  2013-2014: Long Shutdown 1 (LS1) - magnet protection upgrade
- 2015-2018: *pp* collisions at $\sqrt{s}$=13–14 TeV (Run 2, $\sim 100 fb^{-1}$)

  2019-2020: Long Shutdown 2 (LS2) - LHC/experiment upgrades
- 2021-2023: *pp* collisions at $\sqrt{s}$=14 TeV (Run 3, $\sim 200 fb^{-1}$)

  2024-2026: Long Shutdown 3 (LS2) - LHC/experiment upgrades
- 2026-2035: *pp* collisions at $\sqrt{s}$=14 TeV (HL-LHC, $\sim 3000 fb^{-1}$)

Summary

A new era in particle physics started in 2012.

ATLAS and CMS experiment discovered new particle, with properties consistent with that of the Higgs boson (50 year after its prediction)

Great success of the Standard Model!
and thousands of researchers, engineers, technicians and students involved for over 20 years in preparations of the LHC experiments.
All LHC results in good agreement with SM so far!

But we also face new challenges now:

- we need to precisely measure properties of the new particle
- we have to keep looking for other new objects
  eg. "dark matter" particles

We do believe there is "something" beyond the Standard Model.
Higgs is just the begining...