Physics at the LHC

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"Cosmology, Strings, New Physics"
BLTP, JINR , 28 Aug – 10 Sept, 2016

1. What is the LHC?

LHC physics programme

2. What did we know before the LHC start?

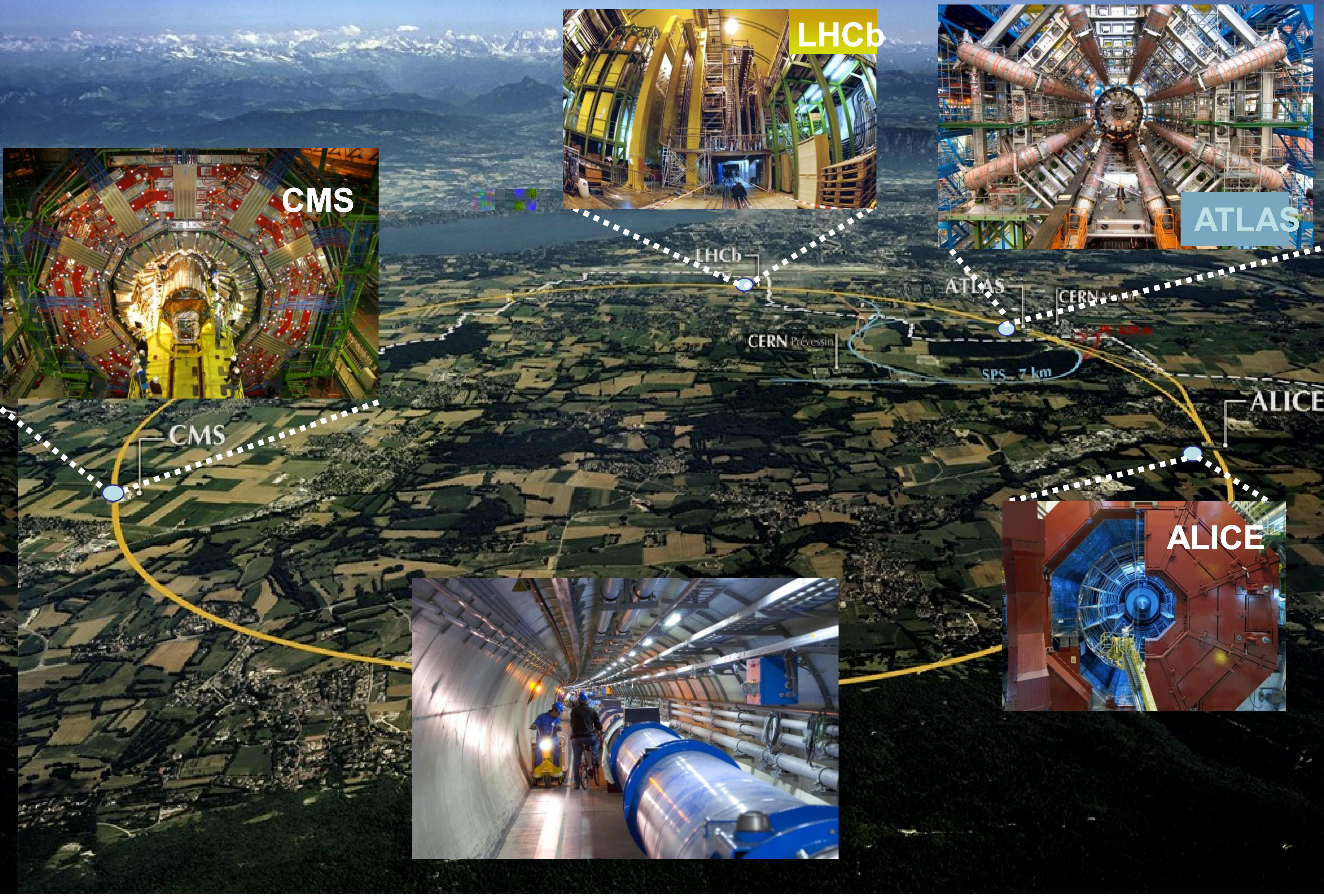
Introduction to the Standard Model

3. What the LHC experiments tell us?

Confirmation of SM, Higgs discovery, BSM searches in RUN1 and RUN2

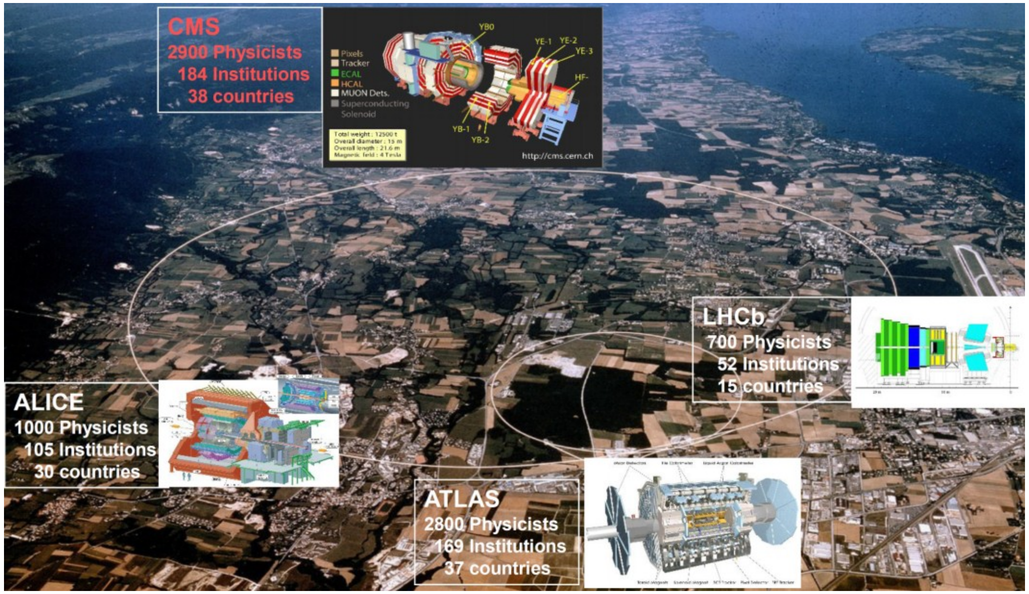
What is the LHC?

LHC is one the most complicated and expensive project in fundamental science (4 detectors: ATLAS, CMS, LHCb, ALICE)



LHC collider (4 detectors: ATLAS, CMS, LHCb, ALICE)

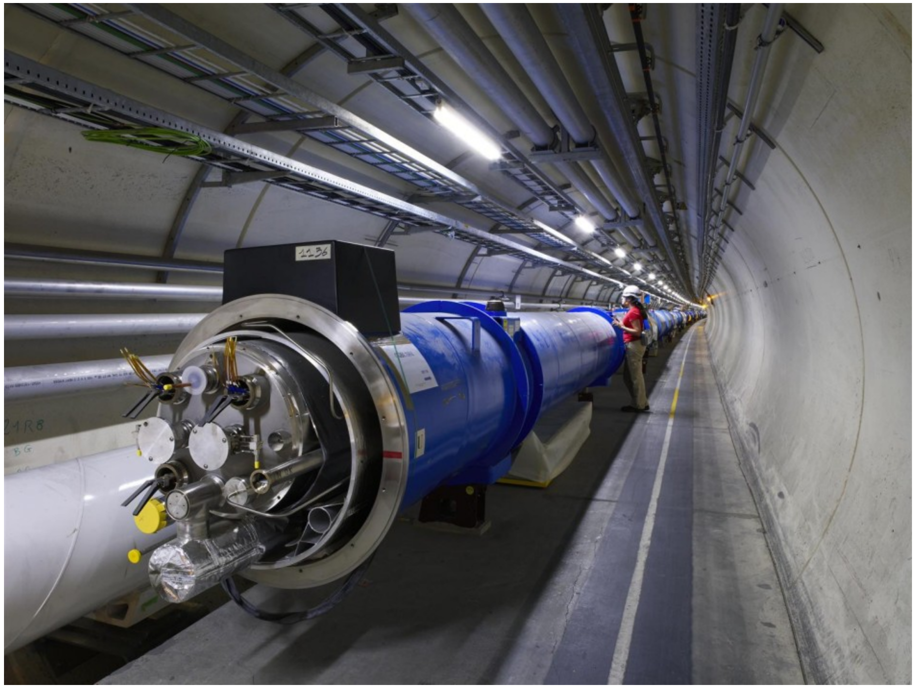
27 km circumference, about 100 m underground



September 10 (2008) – first beams at 400 GeV
September 19 (2008) – an accident

2010 – 2011 run at 7 TeV }
2012 – run at 8 TeV } RUN1

2015 – RUN2 starts at 13 TeV => Latest results at ICHEP'2016



In units ħ=c=1

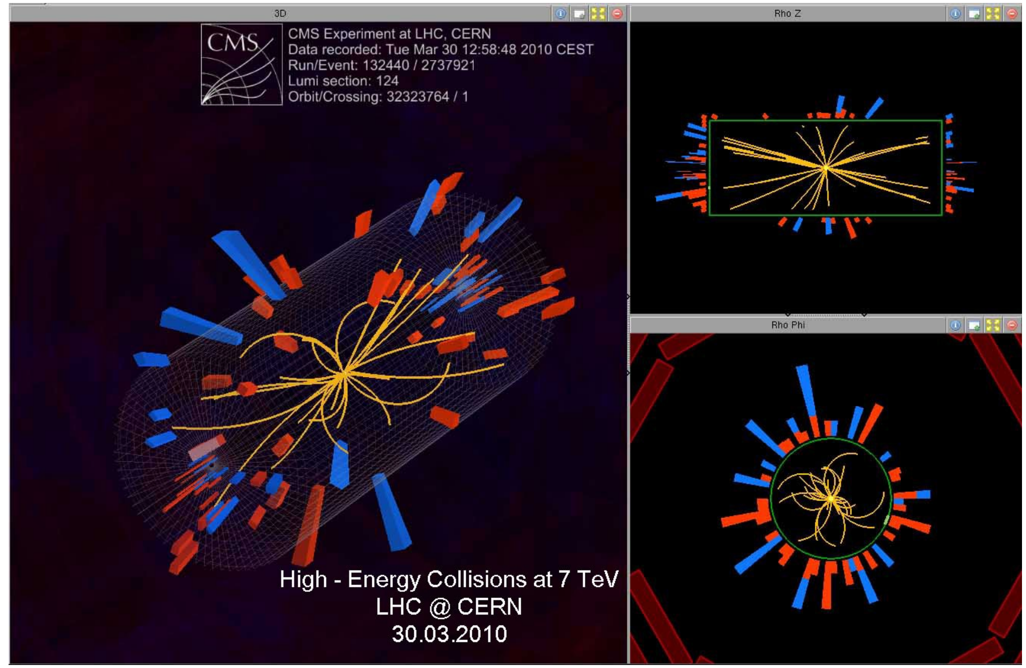
1/GeV ≈ 2*10^{-14} cm

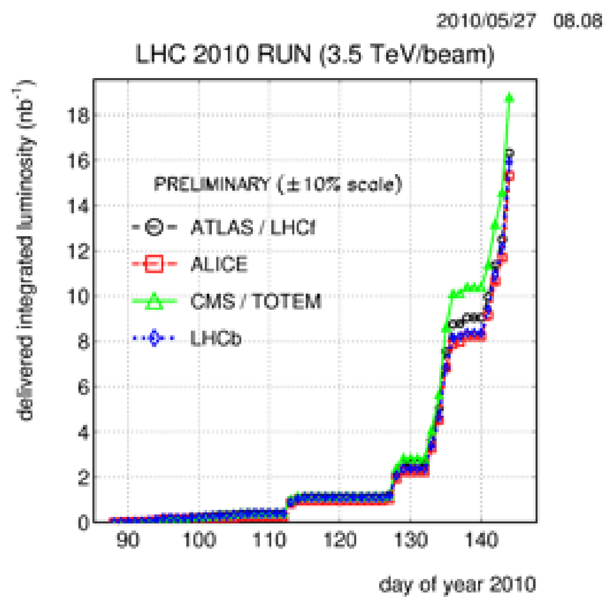
More energy one transfers smaller distances one can probe

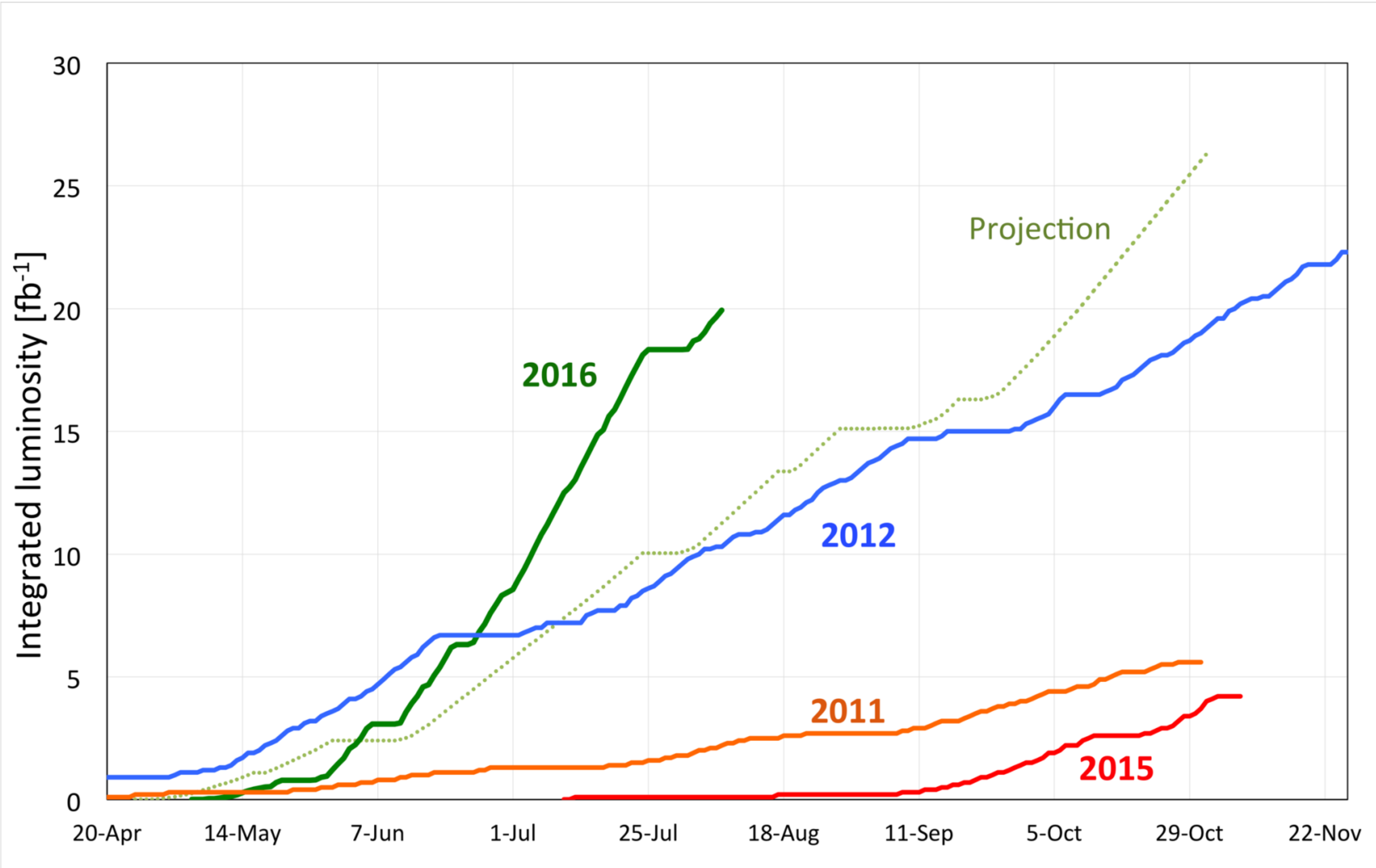
$\Delta X * \Delta P \geq 1/2$

100 GeV -> 10^{-16} cm
1 TeV -> 10^{-17} cm
10 TeV -> 10^{-18}cm
LHC -> 10^{-17} - 10^{-18}cm

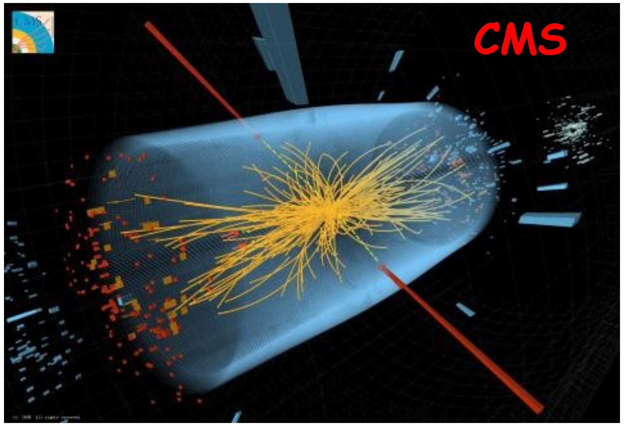
30 March 2010
LHC&7TeV
has started

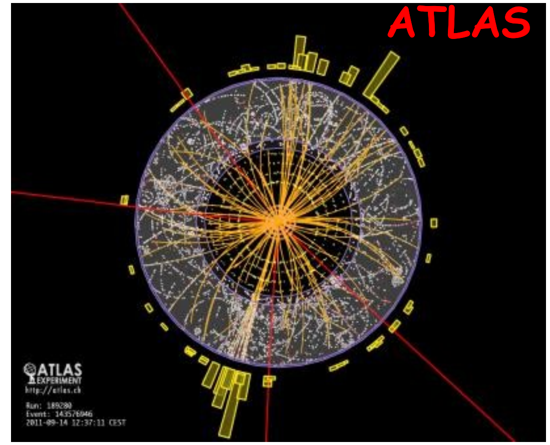


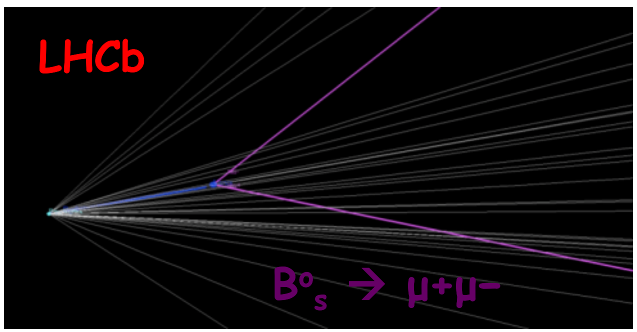


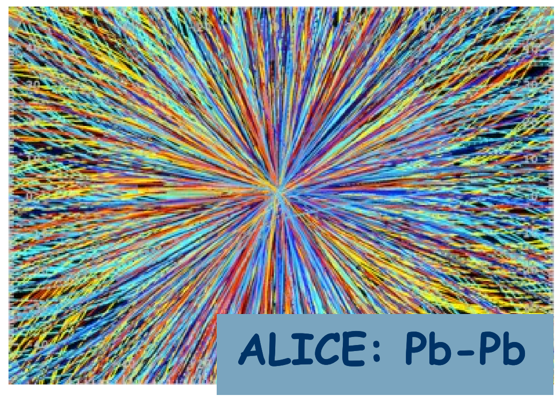


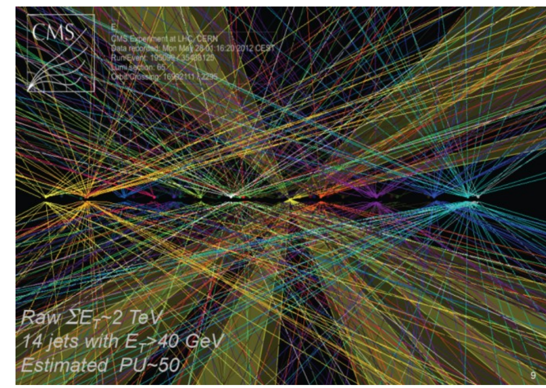
Integrated luminosity [fb-1]
30
25
20
15
10
5
0
20-Apr
14-May
7-Jun
1-Jul
25-Jul
18-Aug
11-Sep
5-Oct
29-Oct
22-Nov
Projection
2016
2012
2011
2015

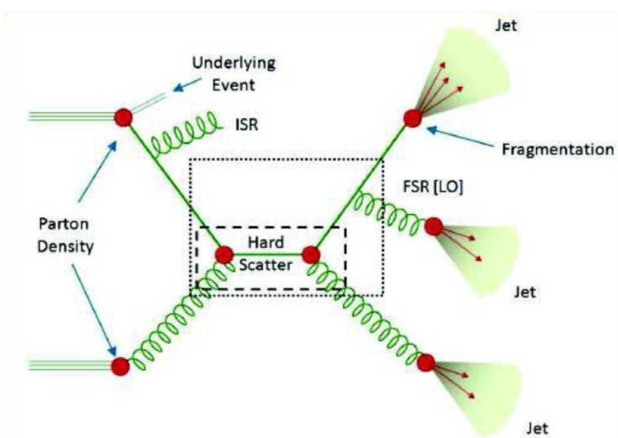

CMS

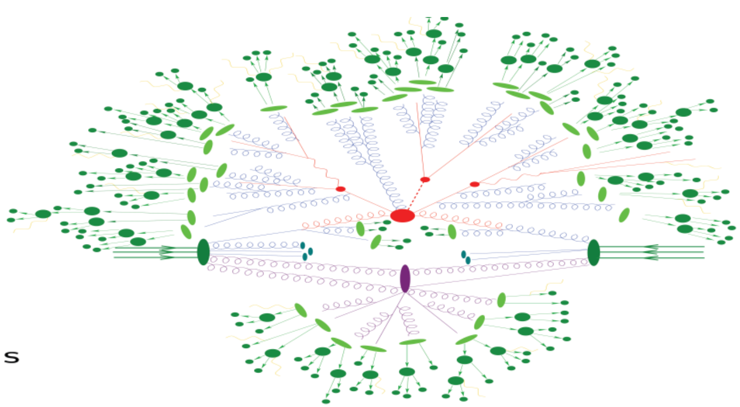

ATLAS
ATLAS EXPERIMENT


LHCb
$B^0_s \rightarrow \mu^+\mu^-$


ALICE: Pb-Pb


CMS
Raw ΣE_T~2 TeV
14 jets with E_T>40 GeV
Estimated PU~50


Jet
Underlying Event
ISR
Fragmentation
FSR [LO]
Parton Density
Hard Scatter
Jet
Jet



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LHC is supposed to give answers on very fundamental questions

What is an origin of the EW symmetry breaking? Does the Higgs boson exist?
What is a possible content of DM? What is a next "step" after SM? …

LHC physics programme

ATLAS and CMS (multipurpose detectors), ALICE and LHCb (dedicated detectors)

Detail studies of various SM processes (including diffraction) and comparisons to NLO (Next to Leading Order), NNLO computations

Search for the Higgs boson in various production and decay modes, measurements of Higgs properties

Search for various deviations from the SM and possible BSM manifestations

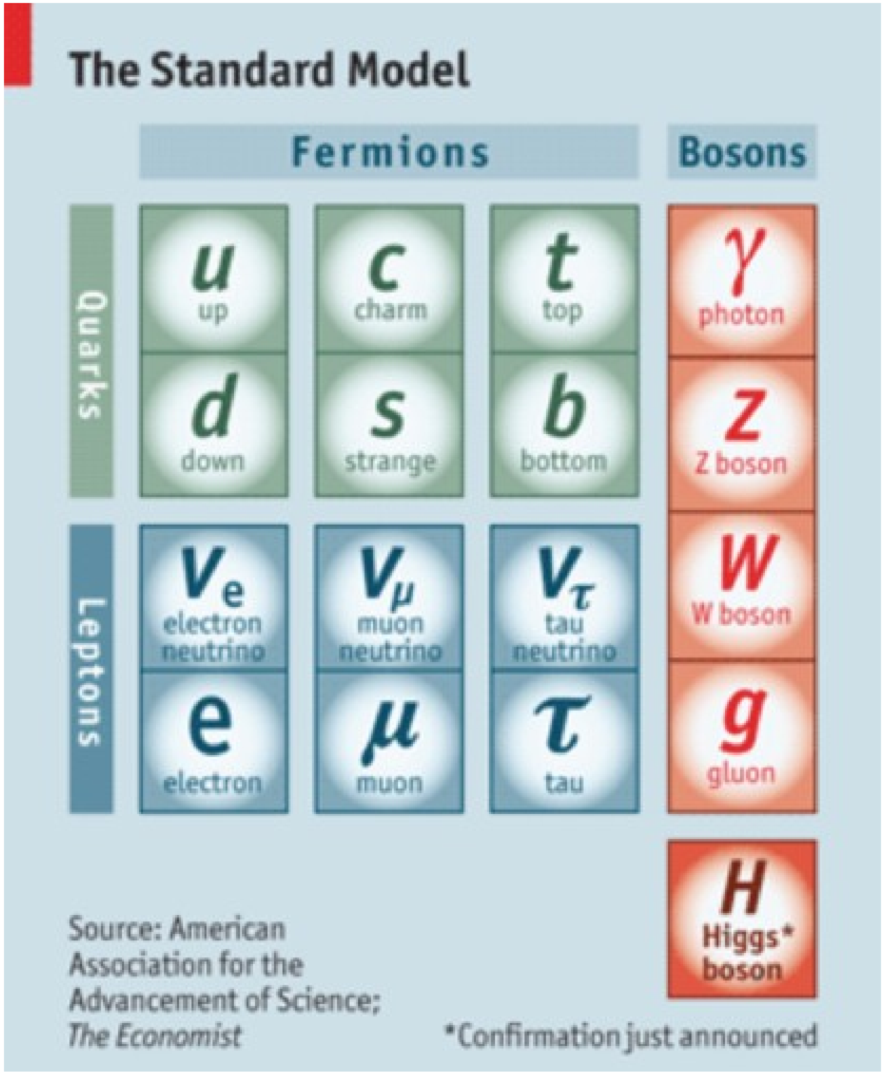
Detail studies of b-physics, b-meson oscillations,CP violation, rear decays, BSM in loops

Detail studies of strongly interacting quark-gluon color medium (quark-gluon plasma)

Study properties of medium (energy density, temperature, pressure, entropy, viscosity, sound velocity…)
in order to understand better nonperturbative QCD and our Universe much closer to the Big Bang

What did we know before the LHC start?

Standard Model of strong and electroweak interactions is the basis for understanding of nature at extremely small distances



SM is the quantum field theory

basic requirements:

1. Well known $U(1)_{em}$ electromagnetic interactions of leptons and quarks with charges $Q_e= -1$, $Q_\nu =0$, $Q_u = 2/3$, $Q_d = -1/3$

2. (V-A) structure of charged currents (Fermi interation)

$$L = \frac{G_F}{\sqrt{2}}\bar{\mu}\gamma_\sigma(1-\gamma_5)\nu_\mu\bar{e}\gamma_\sigma(1-\gamma_5)\nu_e + h.e. \Longrightarrow J_\ell \sim \bar{\ell}\gamma_\mu(1-\gamma_5)\nu_\ell$$

Only left components $\Psi = \frac{1-\gamma_5}{2}\Psi + \frac{1+\gamma_5}{2}\Psi = \Psi_L + \Psi_R$

3. Independence of the Lagrangian on the arbitrary field phase

   ⟹ the gauge character of interactions

4. Renormalizability and unitarity

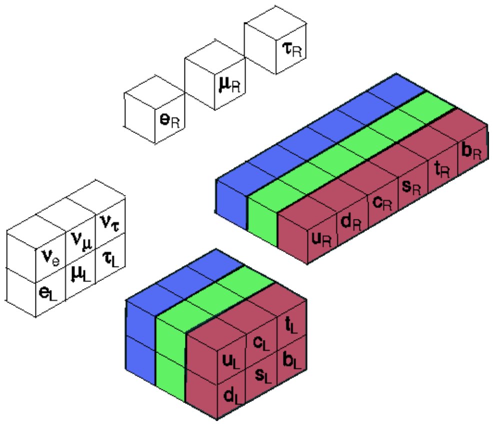
   ⟹ The dimension of the terms (operators) in the SM Lagrangian should not be more than 4

5. Absence of chiral anomalies

6. Three generations of leptons and quarks

7. Masses ⟹ Spontaneous symmetry breaking (BEH mechanism)

Fermions in each generation are combined to Left doublets and Right singlets with respect to the weak isospin



$$f_{L,R} = \frac{1}{2}(1 \mp \gamma_5) f$$

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$$
$$e_R \quad \mu_R \quad \tau_R$$

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \quad \begin{pmatrix} c \\ s \end{pmatrix}_L \quad \begin{pmatrix} t \\ b \end{pmatrix}_L$$
$$u_R, d_R \quad c_R, s_R \quad t_R, b_R.$$

Both left and right charged leptons have electric charge -1,
Neutrinos are only left and neutral,
u-type quarks have electric charge +2/3 and d-type -1/3
All quarks are left triplets

$$SU_L(2) \otimes U_Y(1)$$

Weak isospin group $SU_L(2)$
Weak hypercharge group $U_Y(1)$

SM Gauge group $SU(2)_L \times U(1)_Y \times SU(3)_c$

$$L = -\frac{1}{4}W^i_{\mu\nu}(W^{\mu\nu})^i - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}G^a_{\mu\nu}(G^{\mu\nu})^a + \\ + \sum_{f=\ell,q}\bar{\Psi}^f_L(iD^L_\mu\gamma^\mu)\Psi^f_L + \sum_{f=\ell,q}\bar{\Psi}^f_R(iD^R_\mu\gamma^\mu)\Psi^f_R$$

$$W^i_{\mu\nu} = \partial_\mu W^i_\nu - \partial_\nu W^i_\mu + g_2\varepsilon^{ijk}W^j_\mu W^k_\nu \qquad i = 1,2,3;\ a = 1,\ldots,8,$$

$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$$

$$G^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g_S f^{abc}A^b_\mu A^c_\nu$$

$$D^L_\mu = \partial_\mu - ig_2 W^i_\mu\tau^i - ig_1 B_\mu\left(\frac{Y^f_L}{2}\right) - ig_S A^a_\mu t^a$$

$$D^R_\mu = \partial_\mu - ig_1 B_\mu\left(\frac{Y^f_R}{2}\right) - ig_S A^a_\mu t^a$$

$Y_{L,R}^f$ - weak hypercharge

g_S coupling constant is 0 for leptons

Gauge and fermion fields are chosen to be in adjoined and in fundamental representations respectively

Interactions of charged gauge bosons with fermions have (V-A) stucture

$$W^{\pm}_{\mu} = \left(W^1_{\mu} \mp i W^2_{\mu}\right)/\sqrt{2}$$

$$L^{\ell}_{CC} = \frac{g_2}{\sqrt{2}} \bar{\nu}_{e_L} \gamma_\mu W^+_\mu e_L + h.c. = \frac{g_2}{2\sqrt{2}} \bar{\nu}_e \gamma_\mu (1-\gamma_5) W^+_\mu e + h.c.$$

$$L^{q}_{CC} = \frac{g_2}{2\sqrt{2}} \bar{u} \gamma_\mu (1-\gamma_5) W^+_\mu d + \frac{g_2}{2\sqrt{2}} \bar{d} \gamma_\mu (1-\gamma_5) W^-_\mu u$$

Neutral EW gauge bosons are mixed such that one on the component A has well known electromagnetic interations with fermions. Another component Z – is a neutral vector field predicted by the theory

$$W^3_\mu = Z_\mu \cos\theta_W + A_\mu \sin\theta_W$$
$$B_\mu = -Z_\mu \sin\theta_W + A_\mu \cos\theta_W$$

$$L_{NC} = e \sum_f Q_f J^{em}_{f\mu} A^\mu + \frac{e}{4 \sin\theta_W \cos\theta_W} \cdot \sum_f J^Z_{f\mu} Z^\mu$$

$$J^{em}_{f\mu} = \bar{f} \gamma_\mu f,\ Q_\nu = 0,\ Q_e = -1,\ Q_u = 2/3,\ Q_d = -1/3,$$

$$J^Z_{f\mu} = \bar{f} \gamma_\mu [v_f - a_f \gamma_5] f$$

$$v_{u_i} = 1 - \tfrac{8}{3} s^2_W, \quad a_{u_i} = 1; \quad v_{d_i} = -1 + \tfrac{4}{3} s^2_W, \quad a_{d_i} = -1$$
$$v_\ell = -1 + 4 s^2_W, \quad a_\ell = -1; \quad v_\nu = 1, \quad a_\nu = 1.$$

$$Y^\ell_R = 2 Y^\ell_L$$
$$Y^\ell_L = -3 Y^q_L$$
$$Y^u_R + Y^d_R = 2 Y^q_L$$
$$Y^u_R = -\frac{4}{3} Y^\ell_L$$

$v_f = 2T_3^f - 4Q_f s_W^2$, a_f = $g_2 \sin\Theta_W = -g_1 Y^\ell_L \cos\Theta_W$

Good properties of the theory:

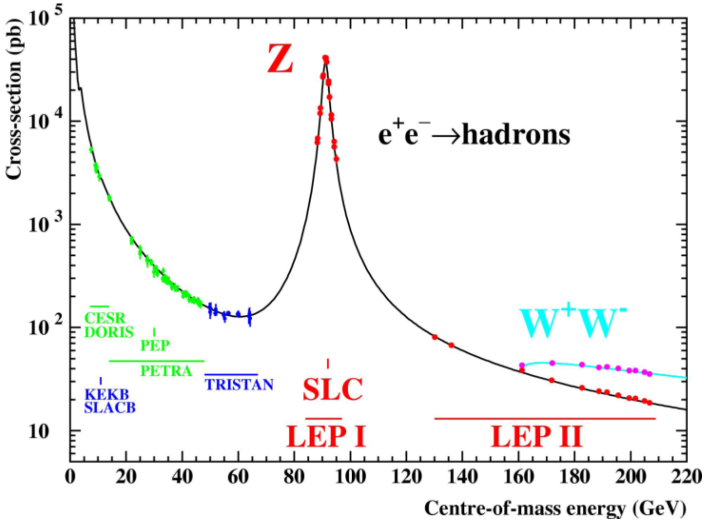
1. Correct charged current interactions (V-A)
2. Correct electromagnetic interations
3. Chiral anomalies cancellation (N_C = 3)
4. Prediction on new neutral currents confirmed experimentally

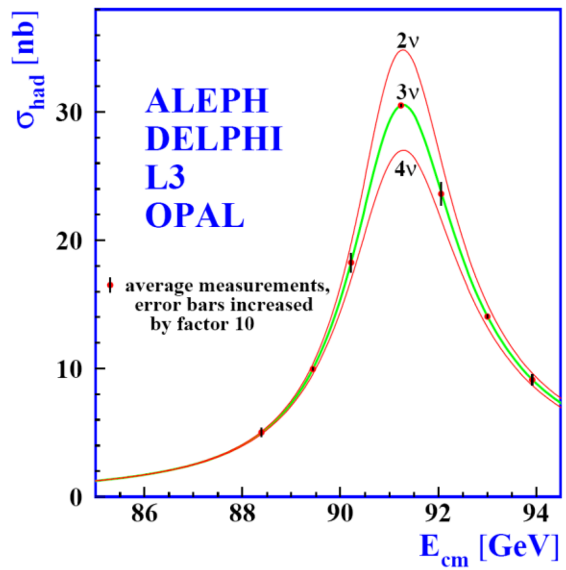
But in this theory all fields are massless

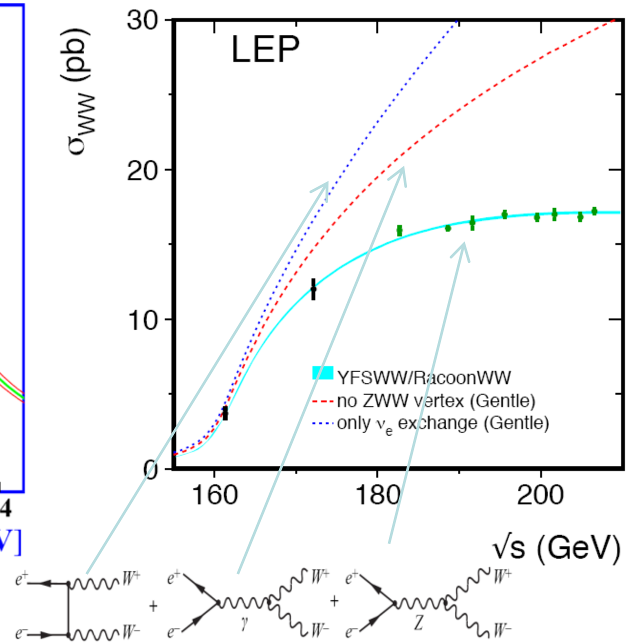
and

it can not describe Nature correctly

Interaction structure follows from the gauge invariance and well established experimentally







But the gauge invariance forbids mass terms

$$M_W^2 W_\mu^+ W^{\mu-} \qquad \frac{1}{2} M_Z^2 Z_\mu Z^\mu \qquad m\bar{\Psi}\Psi = m\left(\bar{\Psi}_L \Psi_R + \bar{\Psi}_R \Psi_L\right)$$

$$V_\mu \to V_\mu + \partial_\mu \alpha$$

doublet singlet

But all particles (except photon and gluon) have masses

Interactions respect the gauge invariance, but the spectrum does not

$M_\gamma = 0$, $M_Z = 90$ GeV

=> Symmetry is broken spontaneously

⇓

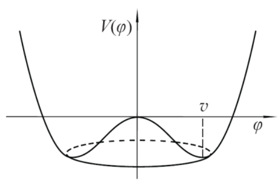
Higgs scalar field with non-zero vacuum expectation value

To the Lagrangian

$$L = -\tfrac{1}{4}W^i_{\mu\nu}(W^{\mu\nu})^i - \tfrac{1}{4}B_{\mu\nu}B^{\mu\nu} - \tfrac{1}{4}G^a_{\mu\nu}(G^{\mu\nu})^a + \\ + \sum_{f=\ell,q}\bar{\Psi}^f_L(iD^L_\mu\gamma^\mu)\Psi^f_L + \sum_{f=\ell,q}\bar{\Psi}^f_R(iD^R_\mu\gamma^\mu)\Psi^f_R$$

one adds a complex scalar field, $SU_L(2)$ doublet and $U_Y(1)$ singlet

$$L_\Phi = D_\mu\Phi^\dagger D^\mu\Phi - \mu^2\Phi^\dagger\Phi - \lambda(\Phi^\dagger\Phi)^4$$



Covariant derivative
$$D_\mu = \partial_\mu - ig_2 W^3_\mu \tau^i - ig_1\frac{Y_H}{2}B_\mu$$

$SU_L(2)$ transformation
$$\Phi(x) \to \Phi'(x) = \exp\left(ig_2\alpha^i t^i\right)\Phi(x)$$

Complex scalar field is parametrised by four real scalar fields
$$\Phi(x) = \exp\left(-i\frac{\xi^i(x)t^i}{v}\right)\begin{pmatrix} 0 \\ (v+h)/\sqrt{2} \end{pmatrix}$$

In unitary gauge
$$g_2\alpha^i(x) = \xi^i(x)/v$$
$$\Phi = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v+h(x) \end{pmatrix}$$

Вакуум $\Phi_{vac} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v \end{pmatrix}$ violates $SU_L(2)$ and $U_Y(1)$ symmetries but $U_{em}(1)$ remains unbroken

The Lagrangian $$L_\Phi = D_\mu \Phi^\dagger D^\mu \Phi - \mu^2 \Phi^\dagger \Phi - \lambda(\Phi^\dagger \Phi)^4$$

in terms of the fields: $$W^\pm_\mu = \left(W^1_\mu \mp i W^2_\mu\right)/\sqrt{2}$$

$$W^3_\mu = Z_\mu \cos\theta_W + A_\mu \sin\theta_W$$
$$B_\mu = -Z_\mu \sin\theta_W + A_\mu \cos\theta_W$$

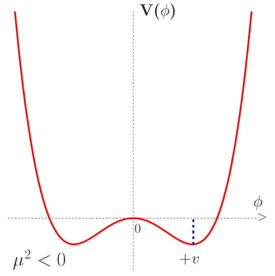
$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$$

The diagonal mass matrix -> physics states with definite masses

$$Y_H = 1 \qquad M_W = M_Z \cos\theta_W \qquad M_W = \frac{1}{2} v g_2\ ,\ M_Z = \frac{1}{2} v \sqrt{g_2^2 + g_1^2}\ ,\ M_A = 0$$

$$L_H = \frac{1}{2}(\partial^\mu h)(\partial_\mu h) + \frac{M_h^2}{2} h^2 - \frac{M_h^2}{2v} h^3 - \frac{M_h^2}{8v^2} h^4 + \left(M_W^2 W_\mu^+ W^{-\mu} + \tfrac{1}{2} M_Z^2 Z_\mu Z^\mu\right)\left(1 + \frac{h}{v}\right)^2 - \sum_f m_f \bar{f} f \left(1 + \frac{h}{v}\right)$$

$$\mathbf{M_H^2 = 2\lambda v^2 = -2\mu^2}$$



How the Higgs mechanism of spontaneous symmetry breaking works in case of fermion fields?

There are only two gauge invariant dimension 4 operators preserving the SM gauge invariance – the Yukawa type operators:

$$\bar{Q}_L \Phi d_R \quad \text{and} \quad \bar{Q}_L \Phi^C u_R \qquad\qquad Q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$$

$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v+h \end{pmatrix} \quad \text{and} \quad \Phi^C = i\sigma^2 \Phi^\dagger = \frac{1}{\sqrt{2}} \begin{pmatrix} v+h \\ 0 \end{pmatrix}$$

Charge conjugated operators:

$$\left(\bar{Q}_L \Phi d_R\right)^\dagger = d_R^\dagger \Phi^\dagger \left(\bar{Q}_L\right)^\dagger = d_R^\dagger \gamma^0 \gamma^0 \Phi^\dagger \gamma^0 Q_L = \bar{d}_R \Phi^\dagger Q_L$$

After spontaneous symmetry breaking such operators generate needed fermion masses of Dirac type:

$$(\bar{u}_L \bar{d}_L) \begin{pmatrix} 0 \\ v \end{pmatrix} d_R + \bar{d}_R (0 \;\; v) \begin{pmatrix} u_L \\ d_L \end{pmatrix} = \bar{d}_L d_R + v \bar{d}_R d_L = v\left(\bar{d}_L d_R + \bar{d}_R d_L\right) = v \bar{d} d$$

and similar for the up-type quarks with the field Φ^C

$$\left(\bar{Q}_L \Phi^C u_R\right)^\dagger = \bar{u}_R \left(\Phi^C\right)^\dagger Q_L$$

Most general gauge invariant Lagrangian with possible mixing of Yukawa type operators:

$$L_{Yukawa} = -\Gamma_d^{ij}\bar{Q'_L}^i \Phi {d'_R}^j + h.c. - \Gamma_u^{ij}\bar{Q'_L}^i \Phi^C {u'_R}^j + h.c. - \Gamma_e^{ij}\bar{L'_L}^i \Phi {e'_R}^j + h.c.$$

$$\Phi = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v+h \end{pmatrix} \text{ and } \Phi^C = i\sigma^2\Phi^\dagger = \frac{1}{\sqrt{2}}\begin{pmatrix} v+h \\ 0 \end{pmatrix}$$

In the unitary gauge one can rewrite the Lagrangian as follows

$$L_{Yukawa} = -\left[M_d^{ij}\bar{d'_L}^i {d'_R}^j + M_u^{ij}\bar{u'_L}^i {u'_R}^j + M_e^{ij}\bar{e'_L}^i {e'_R}^j + h.c.\right]\cdot\left(1+\frac{h}{v}\right)$$

$$M^{ij} = \Gamma^{ij}v/\sqrt{2}$$

The physics states are the states with definite mass. One should diagonalize matrices in order to get the physical states for quark and leptons

$$d'_{Li} = (U_L^d)_{ij}d_{Lj}; \quad d'_{Ri} = (U_R^d)_{ij}d_{Rj}; \quad u'_{Li} = (U_L^u)_{ij}u_{Lj}; \quad u'_{Ri} = (U_R^u)_{ij}u_{Rj}$$

$$\ell'_L = (U_L^\ell)\ell_L; \quad \ell'_R = (U_R^\ell)\ell_R$$

$$U_L U_L^\dagger = 1, \quad U_R U_R^\dagger = 1, \quad U_L^\dagger U_L = 1.$$

The matrices U are chosen such:

$$(U_L^u)^\dagger M_u U_R^u = \begin{pmatrix} m_u & 0 & 0 \\ 0 & m_c & 0 \\ 0 & 0 & m_t \end{pmatrix}; \quad (U_L^d)^\dagger M_d U_R^d = \begin{pmatrix} m_d & 0 & 0 \\ 0 & m_s & 0 \\ 0 & 0 & m_b \end{pmatrix} \quad (U_L^\ell)^\dagger M_\ell U_R^\ell = \begin{pmatrix} m_e & 0 & 0 \\ 0 & m_\mu & 0 \\ 0 & 0 & m_\tau \end{pmatrix}$$

The Yukawa Lagrangian after diagonalization

$$\Longrightarrow L_{Yukawa} = -\left[m_d^i \bar{d}^i d^i + m_u^i \bar{u}^i u^i + m_\ell^i \bar{\ell}^i \ell^i\right] \cdot \left(1 + \frac{h}{v}\right)$$

contains masses of particles and the interaction of the fermions with the Higgs boson

Neutral currents have the same structure with respect to flavors as the mass terms. And they become diagonal simultaneously with the mass terms

$$\Psi' \rightarrow U\Psi \qquad \bar{\Psi}'\hat{O}_N\Psi' \rightarrow \bar{\Psi}\hat{O}\Psi$$

But charge currents contain fermions rotated by different matrices

$$J_C \sim \bar{u}_L \hat{O}_{ch} d_L \qquad u' \rightarrow (U_L^u)u,\ d' \rightarrow (U_L^d)d$$

$$J_C \sim (U_L^u)^\dagger U_L^d \bar{u}_L \hat{Q} d_L \qquad V_{CKM} = (U_L^u)^\dagger U_L^d$$

The unitary matrix is called the Cabbibo-Kobayashi-Moskawa mixing matrix (3 real parameters + 1 phase)

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \approx \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

$$\lambda = 0.2257^{+0.0009}_{-0.0010}, \qquad A = 0.814^{+0.021}_{-0.022}$$

$$\bar{\rho} = 0.135^{+0.031}_{-0.016}, \qquad \bar{\eta} = 0.349^{+0.015}_{-0.017}$$

Brout-Englert-Higgs (BEH) mechanism

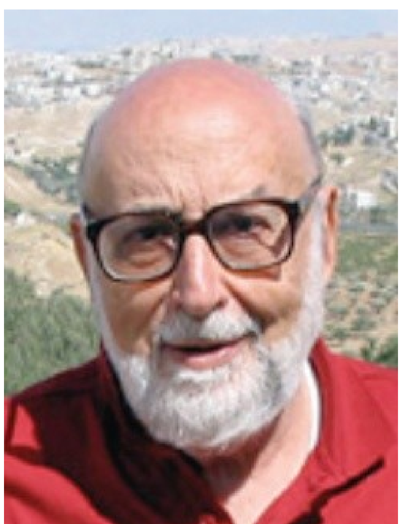
Masses of quarks and leptons (except neutrinos)

Masses of W and Z bosons

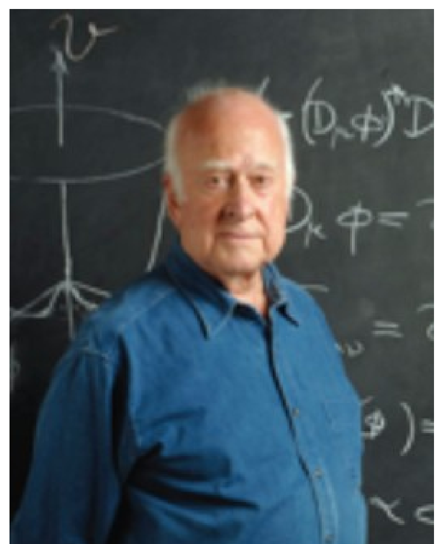
Unitarity and renormalizability of the SM

Higgs Boson

Francios Englert



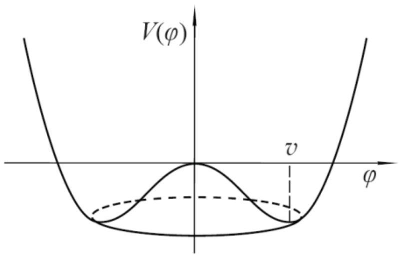
Peter Higgs

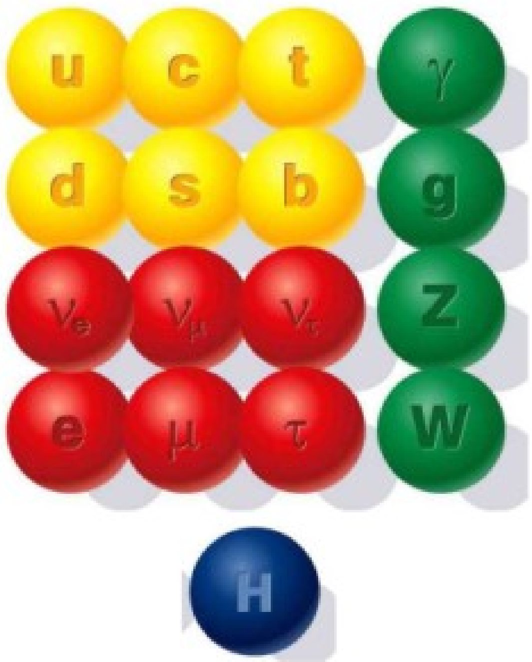


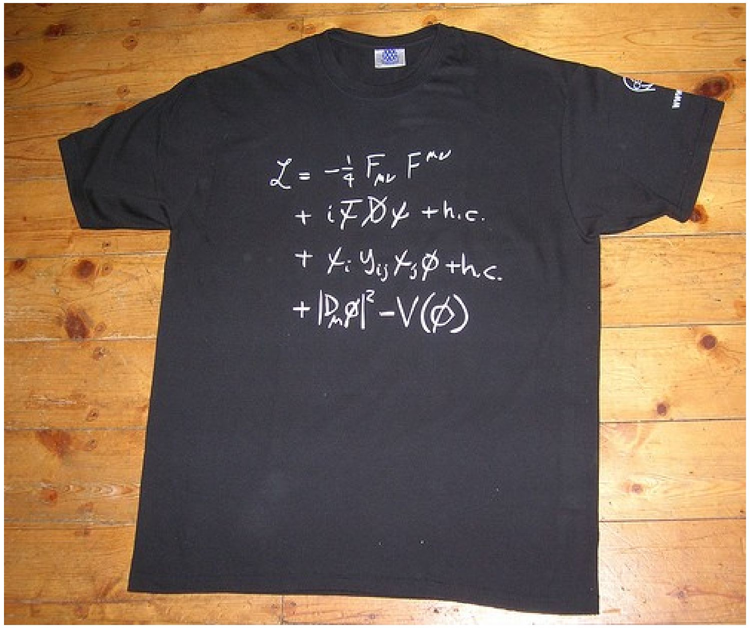
Nobel Prize in physics 2013

Standard Model

$SU(2)_L \times U(1)_Y \times SU(3)_c$







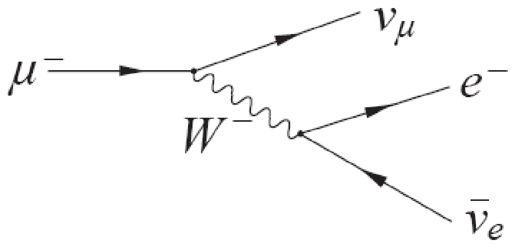
A very elegant theoretical construction!

Vacuum expectation value v

The Fermi constant G_F is measured with high precision from muon life time

$$G_F = 1.166\,378\,7(6) \times 10^{-5}\ \mathrm{GeV}^{-2}$$

Since the muon mass $m_\mu \ll M_W$ one can neglect the W-boson mass in the propagator and immediately get the following relation



$$\frac{g_2^2}{8M_W^2} = \frac{G_F}{\sqrt{2}}$$

As we have seen the W boson mass is obtained in SM due to the Higgs mechanism and proportional to the Higgs vacuum expectation value v

$$M_W^2 = \frac{1}{4} g_2^2 v^2$$

From these two relations we obtain

$$v = \frac{1}{\sqrt{\sqrt{2} G_F}} = 246.22\ \mathrm{GeV}$$

At this point one can see the power of gauge invariance principle, g_2 is the same gauge coupling

The Higgs field expectation value v is determined by the Fermi constant G_F introduced long before the Higgs mechanism appeared!

$$L_{SM} = L_{Gauge} + L_{FG} + L_H$$

Kinetic terms for the gauge fields;
Interaction terms of the gauge fields

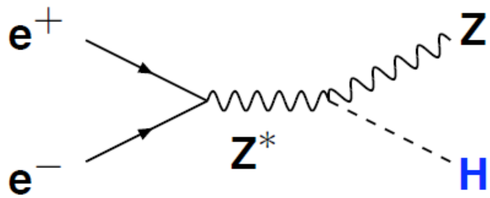
Kinetic terms for fermions;
Interactions of fermions with the gauge fields
(NC and CC currents)

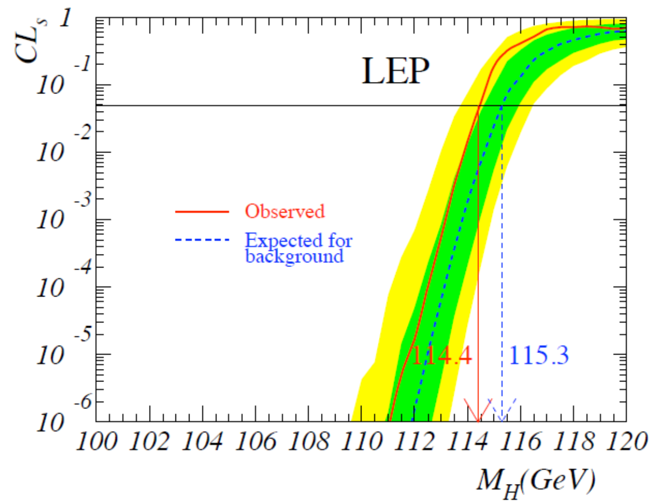
Kinetic and self-interaction terms for the higgs boson fields;
Higgs – gauge boson interaction terms;
Higgs-fermion interaction terms;
Mass terms for the gauge bosons and fermions;
+ Goldstone bosons and ghosts interactions

$$\begin{aligned} L_H &= \frac{1}{2}(\partial^\mu h)(\partial_\mu h) + \frac{M_h^2}{2}h^2 - \frac{M_h^2}{2v}h^3 - \frac{M_h^2}{8v^2}h^4 + \\ &+ \left(M_W^2 W_\mu^+ W^{-\mu} + \tfrac{1}{2}M_Z^2 Z_\mu Z^\mu\right)\left(1+\frac{h}{v}\right)^2 - \textstyle\sum_f m_f \bar{f} f \left(1+\frac{h}{v}\right) \end{aligned}$$

$$M_H^2 = 2\lambda v^2$$

1. Direct serches :



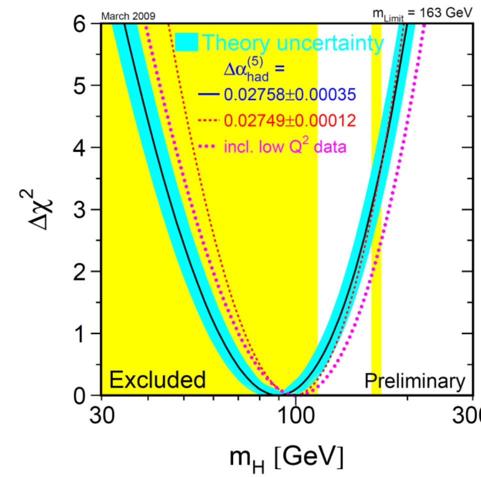


$M_H > 114.4$ GeV 95% C.L.

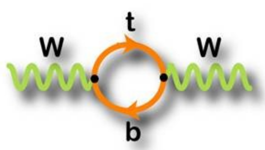
Tevatron (in gluon fusion with decay to WW):

Excluded region

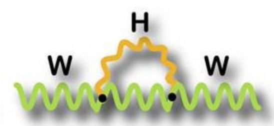
M_H : 160-170 GeV



2. From loop corrections :



$\sim M_{top}^2$



$\sim \log(M_H^2/M_W^2)$

Best fit $M_H = 94^{+29}_{-24}$ GeV

Combination (LEP + Tevatron):

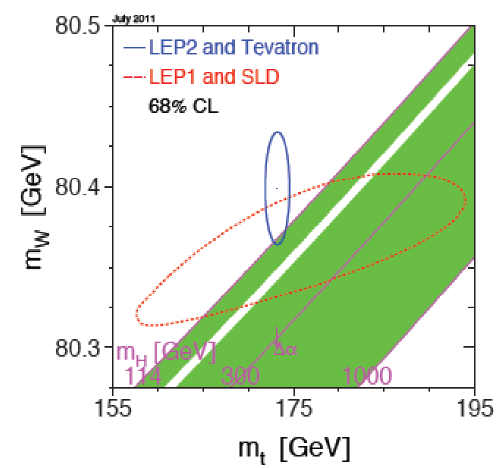
$M_W = 80385 \pm 15$ MeV 0.02%

Tevatron

$M_{top} = 173.18 \pm 0.56(stat) \pm 0.75$ (syst) GeV

LHC

$M_{top} = 173.3 \pm 0.5(stat.) \pm 1.3(syst.)$ GeV



$M_H < 155$ GeV 95% C.L.

3. From the unitariry of VV->VV (V: W,Z) amplitudes: No loose theorem!

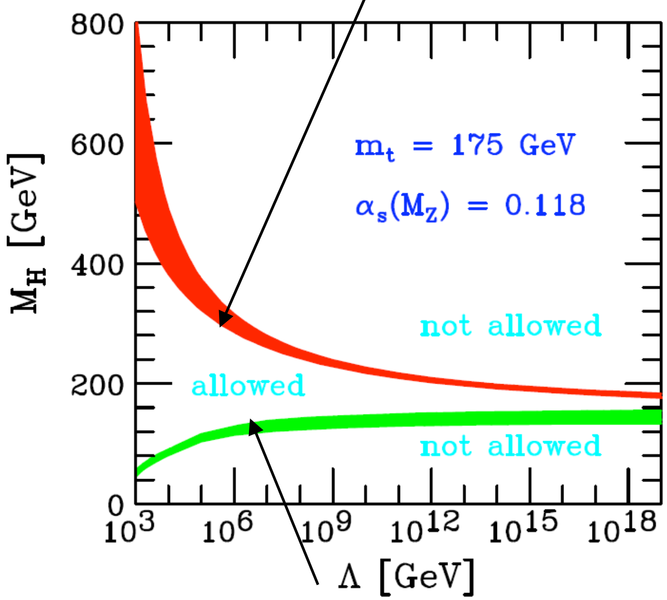
$$\mathrm{Im}(a_l) = |a_l|^2 \qquad |\mathrm{Re}(a_l)| \le \frac{1}{2}$$

$M_H \lesssim 710$ GeV if $\sqrt{s} \gg M_H$

$\sqrt{s} \lesssim 1.2$ TeV if $\sqrt{s} \ll M_H$

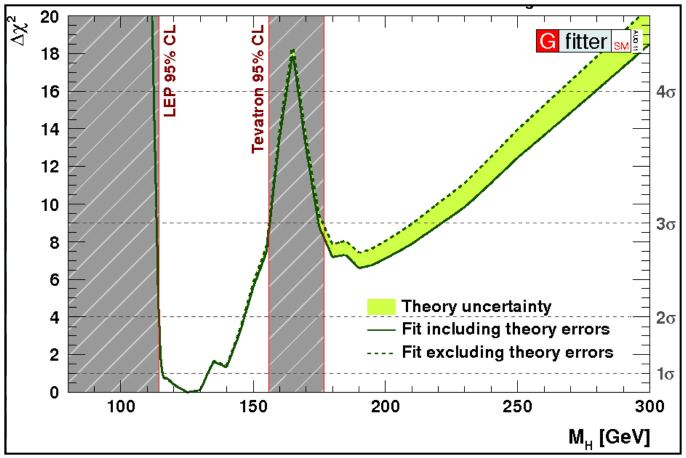
4. From self-consistency of quantum theory:

No Landau pole (triiviality)



Positive self coupling (vacuum stability) $\lambda(Q^2) > 0$

Combining all direct and indirect constraints:

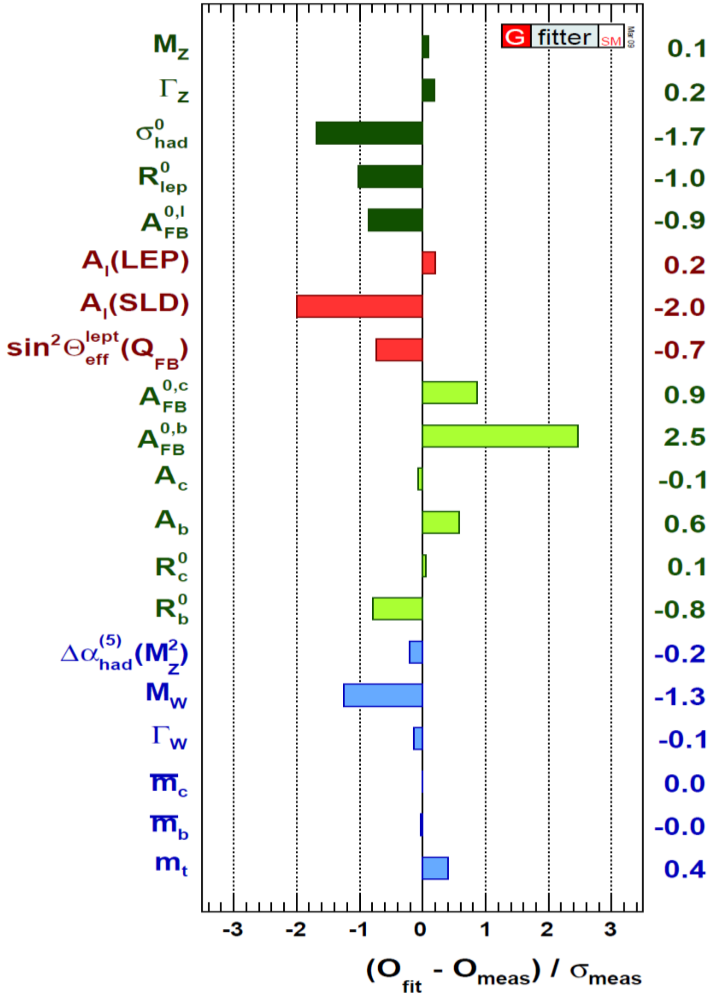


GFitter collaboration, Aug. 2011

M_H = 125 ± 10 GeV

Loop corrections lead to the fact that SM parameters (coupling constants, masses, widths) are the running parameters, and **they are nontrivial functions of each other.**

Summary of comparisons of the EW precision measurements at LEP1, LEP2, SLD, and the Tevatron and a global parameter fit



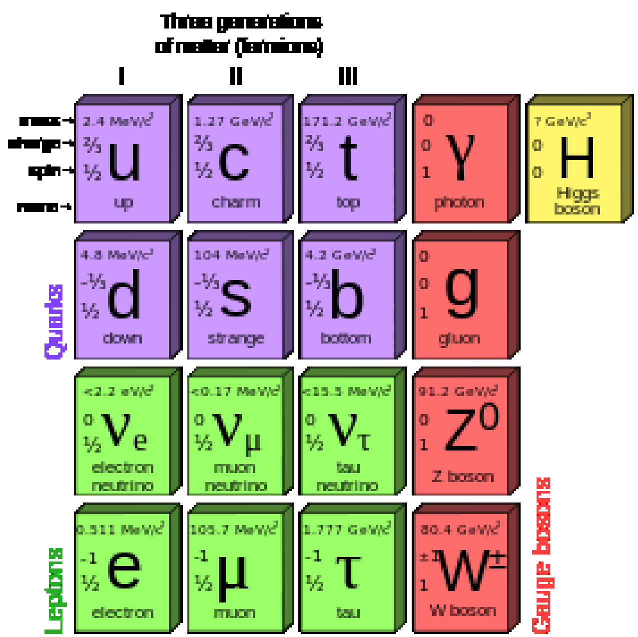
$$\sin^2\theta^{lept}_{eff} \equiv \frac{1}{4}\left(1 - \frac{v_l}{a_l}\right)$$

* Standard Model is the renormalizable anomaly free gauge quantum field theory with spontaneously broken electroweak symmetry. Remarkable agreement with many experimental measurements.

* The EW SM has 17 parameters (from experiments)
  gauge-Higgs sector contains 4 parameters:
  g_1, g_2, μ^2, λ → best measured α_{em}, G_F, M_Z (or α_{em}, s_W, M_W) plus M_H

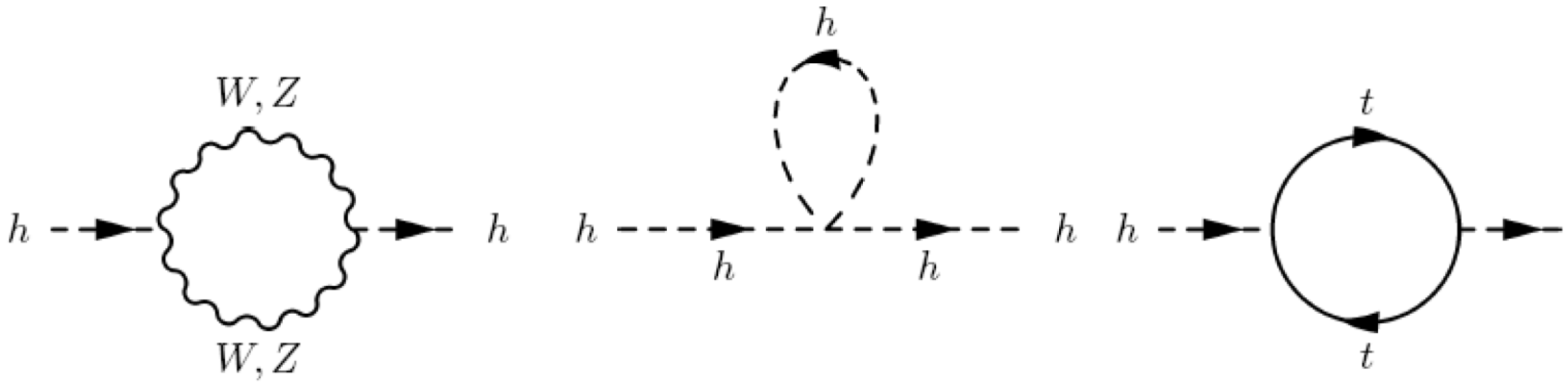
  In addition, 6 quarks masses, 3 lepton masses,
  3 mixing angles and one phase of the CKM matrix

  plus α_{QCD} → **18** SM parameters
  (+ may be masses and mixing parameters from neutrino sector)



The simplest Higgs mechanism SM is not stable with respect to quantum corrections (naturalness problem)

Loop corrections to the Higgs mass



$$\delta m_H^2 = \frac{3G_F}{4\sqrt{2}\pi^2}\left(2m_W^2 + m_Z^2 + m_H^2 - 4m_t^2\right)\Lambda^2 \approx -(0.2\,\Lambda)^2$$

$\delta m_H < m_H$ $\quad\quad$ $\Lambda < 1$ TeV

In SM there is no symmetry which protects a strong dependence of Higgs mass on a possible new scale

Something is needed in addition to SM…

LHC – Why Terascale?

Stabilization of the Higgs mechanism
→ $\Lambda \sim 1$ TeV

Unitarization of EW vector boson and heavy quark amplitudes
→ $\Lambda \sim 1$ TeV

If Mh ~ 1 TeV → SM Higgs width ~ 0.5 TeV, strong coupling regime

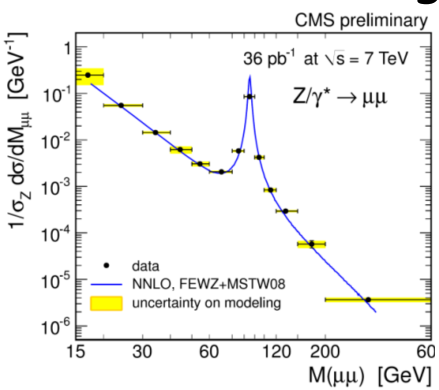
Dark Matter density: in most popular scenarios masses of DM candidates are less than 1 TeV

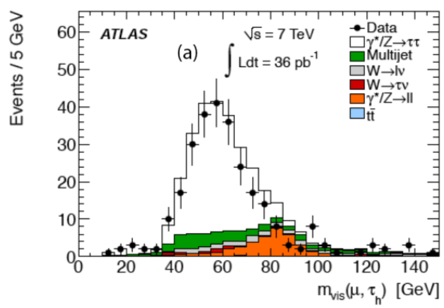
$$\Omega_{\rm WIMP} \sim 0.2 \left(\frac{m_\chi}{200\,{\rm GeV}}\right)^2 \left(\frac{0.1}{g^2}\right)^2$$

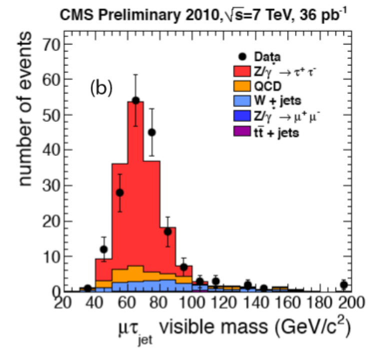
What the LHC experiments tell us?

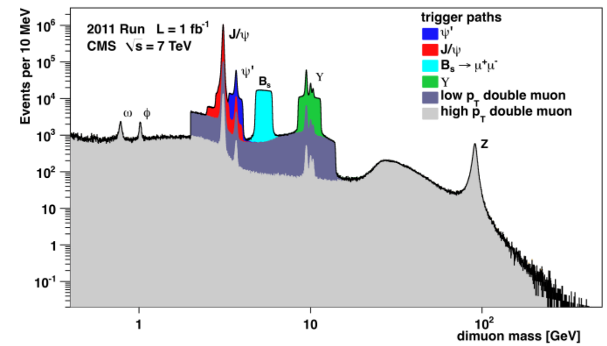
First LHC results confirm the Standard Model

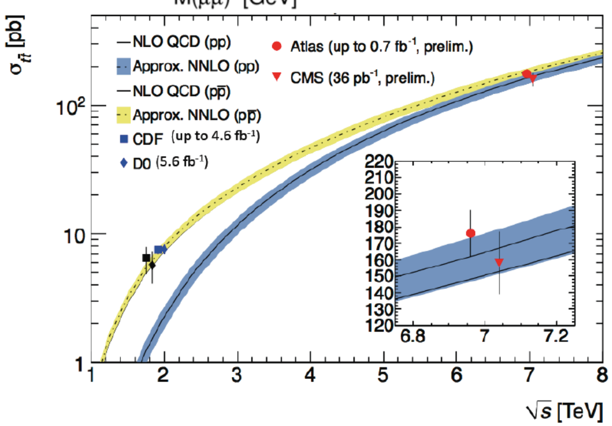
Rediscovery of the SM: W, Z, Top …. are found
WZ, Wgamma, ZZ, Top pair, single Top … are measured

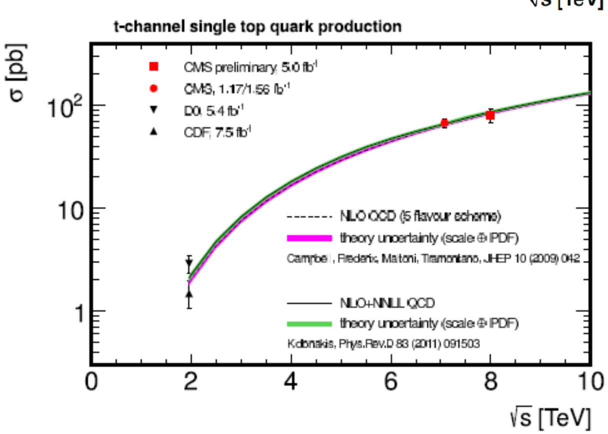


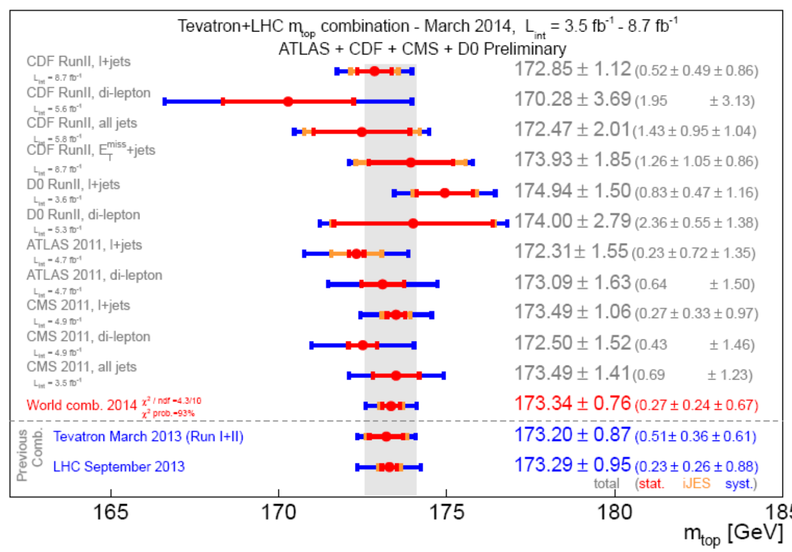






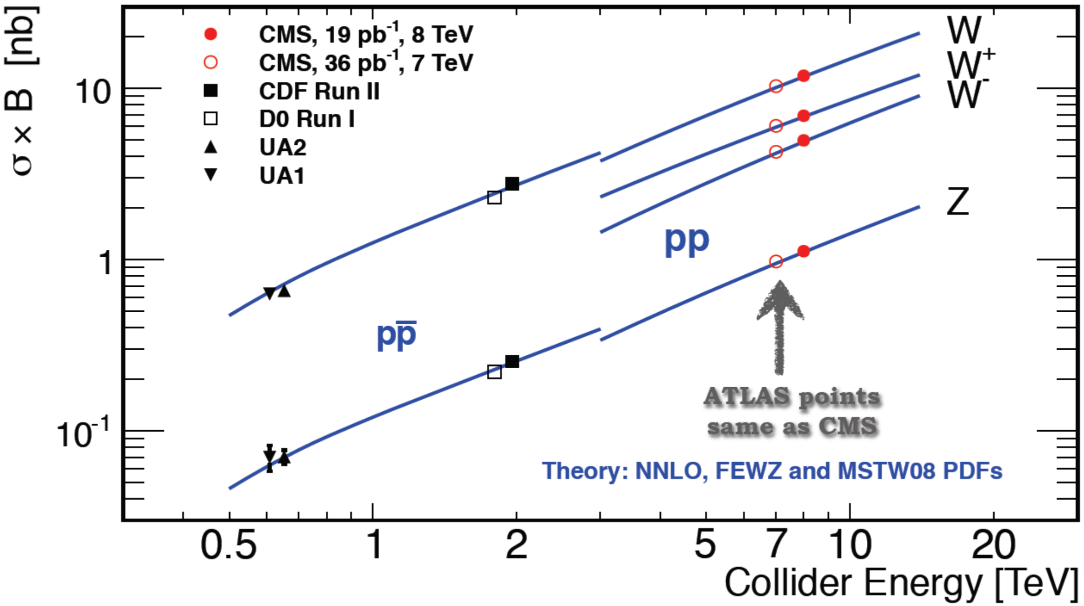


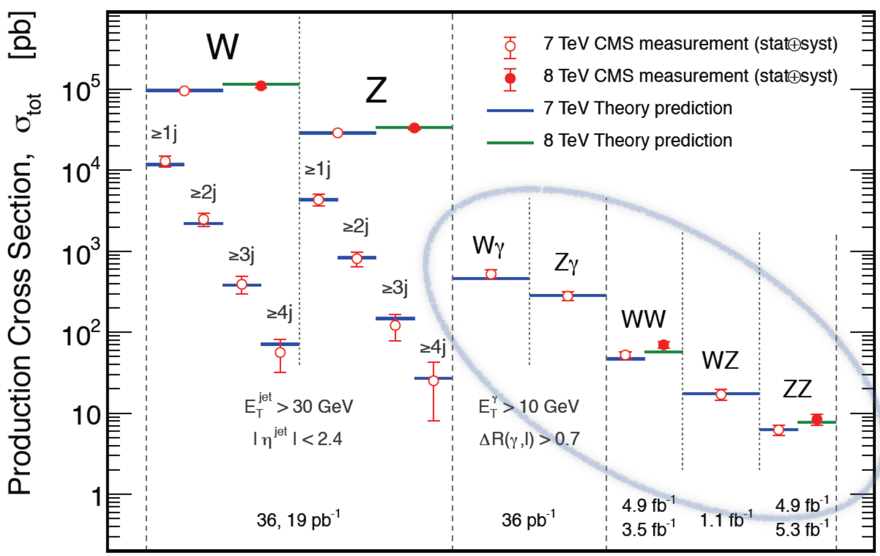


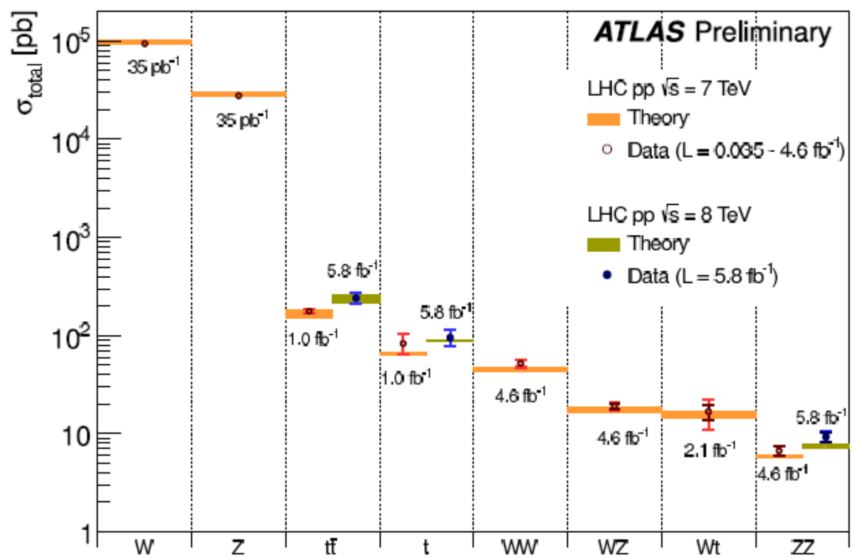


M_{top} = 173.34 ± 0.76 (0.27 ± 0.24 ± 0.67) GeV

Tevatron/LHC



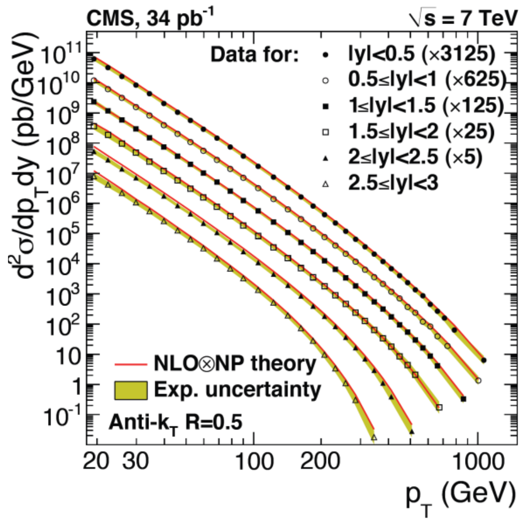


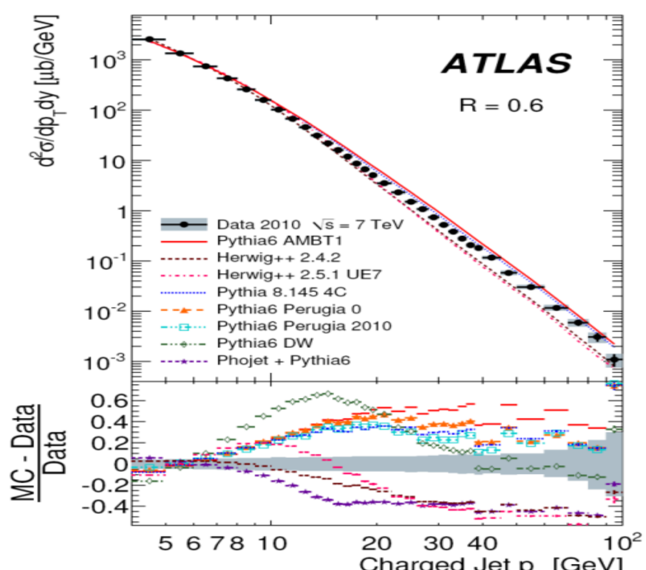


All in an agreement with the SM

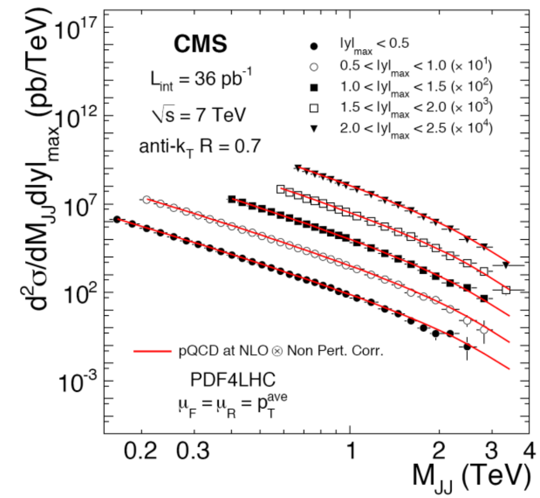
New remarkable QCD results in various kinematical regions

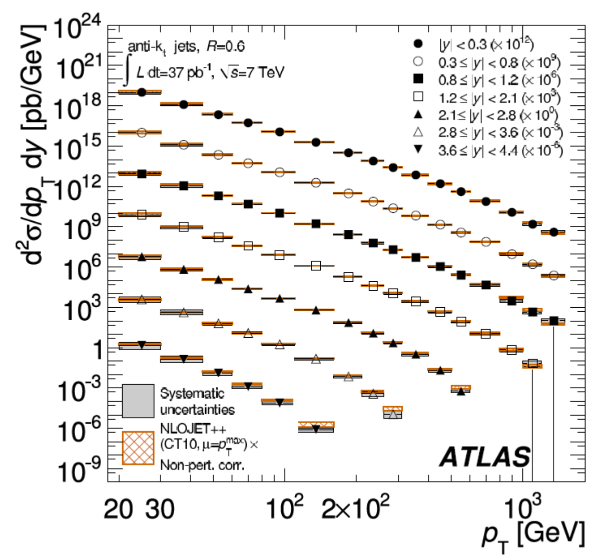
Double-differential inclusive jet production



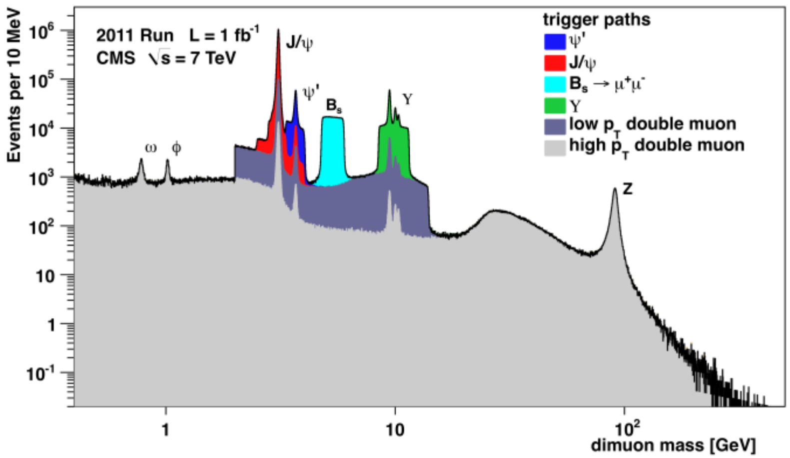


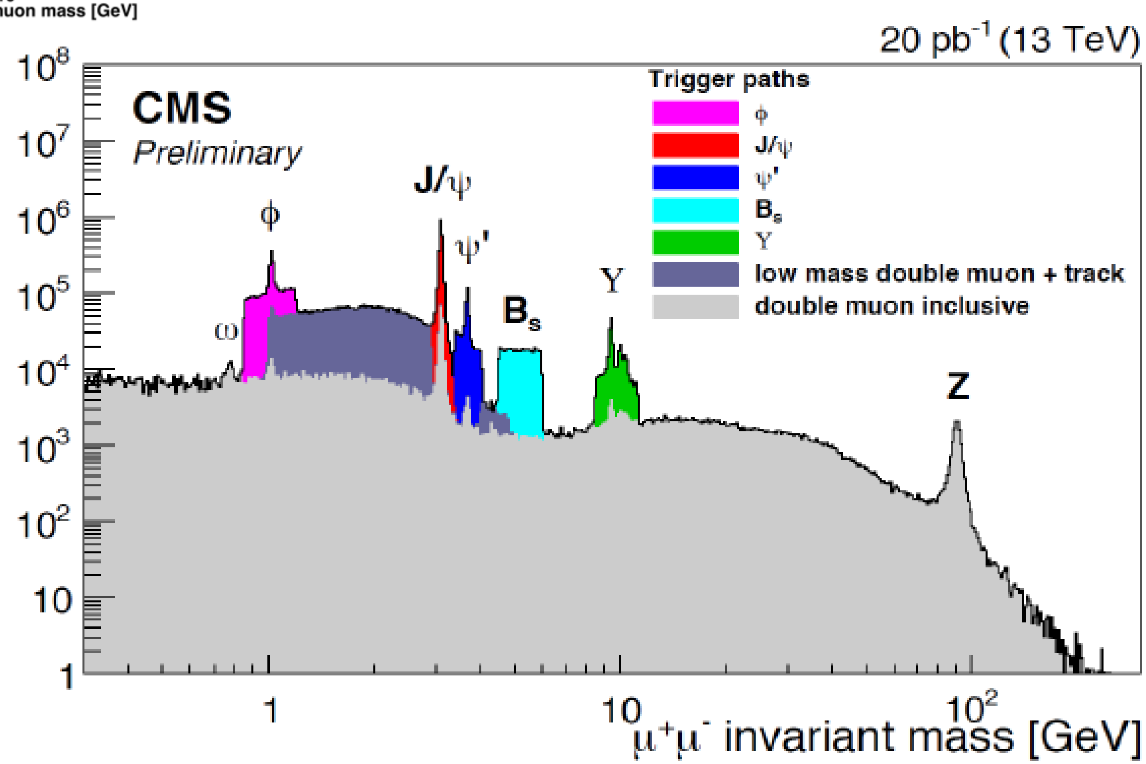
Double-differential inclusive dijet production



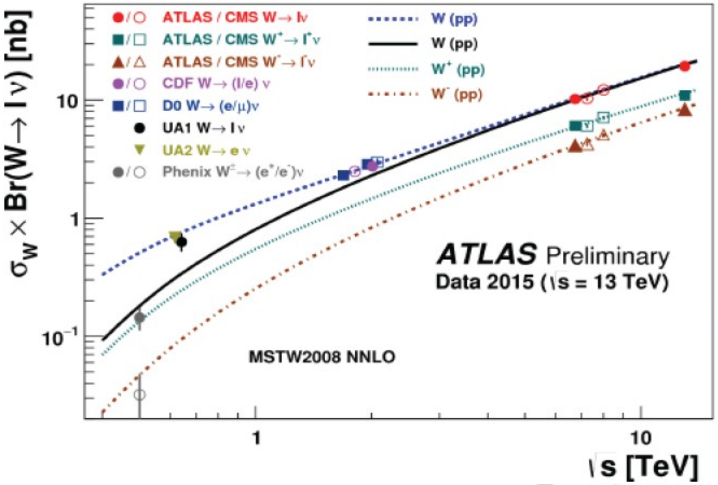


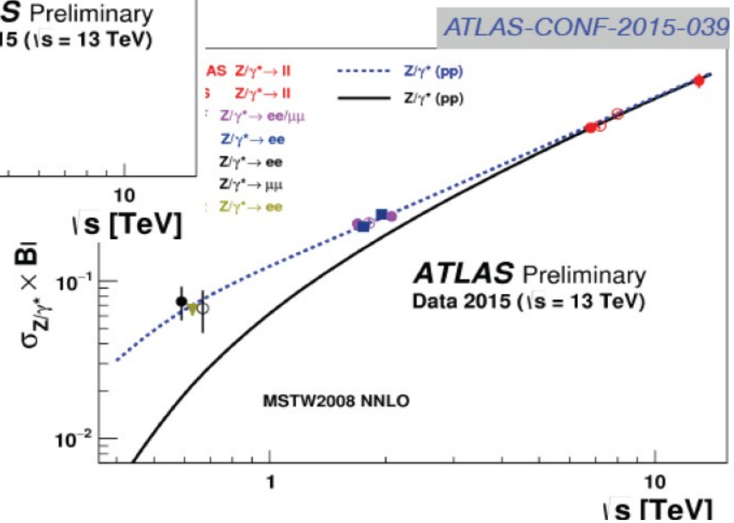
After few days of RUN2

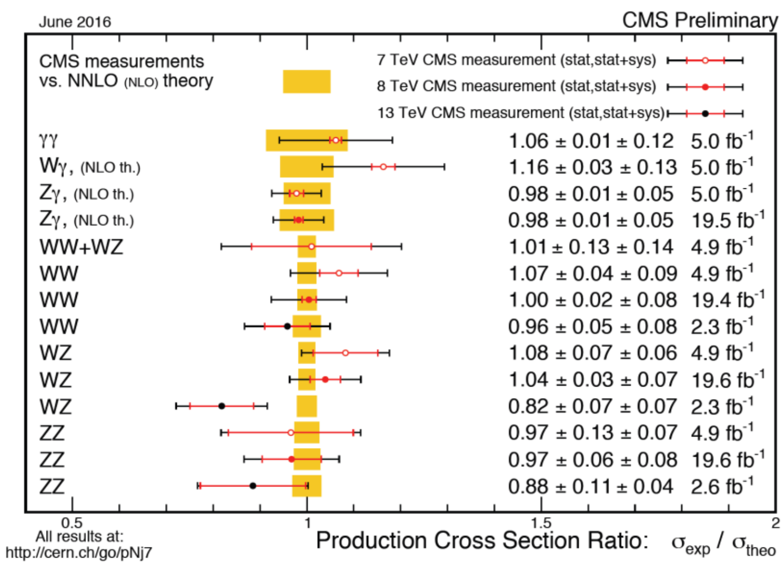


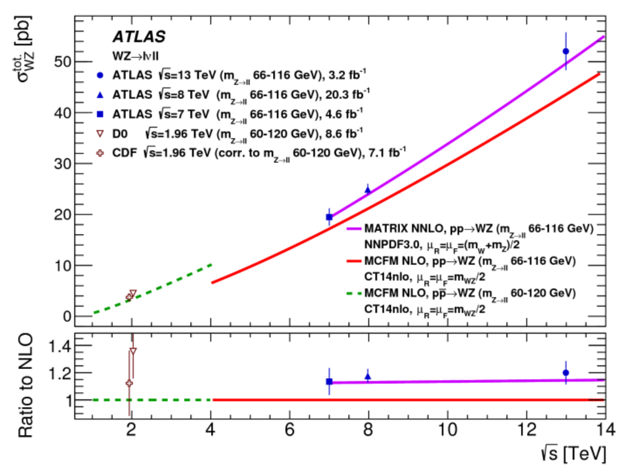


Perfect agreement with the SM predictions
W/Z – bosons (first results at 13 TeV)



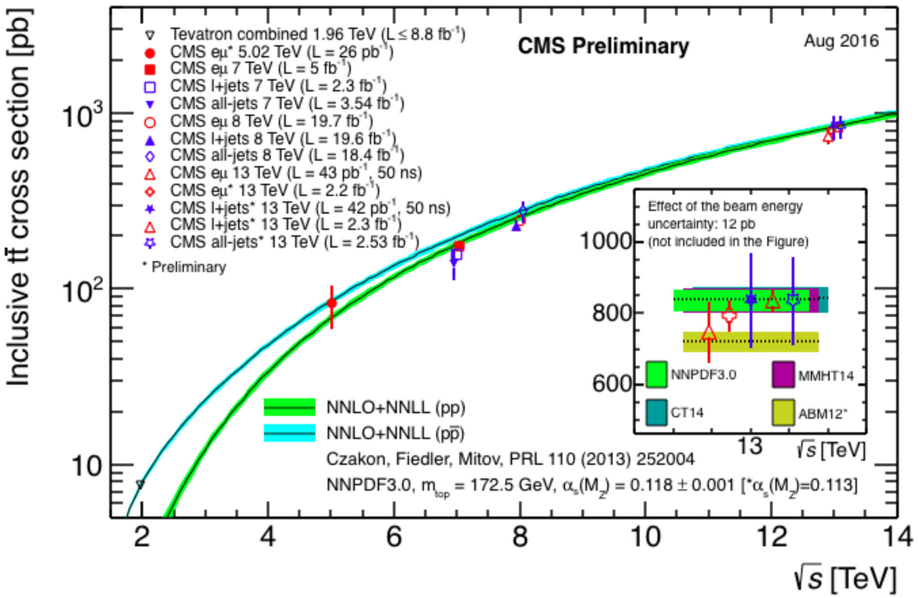


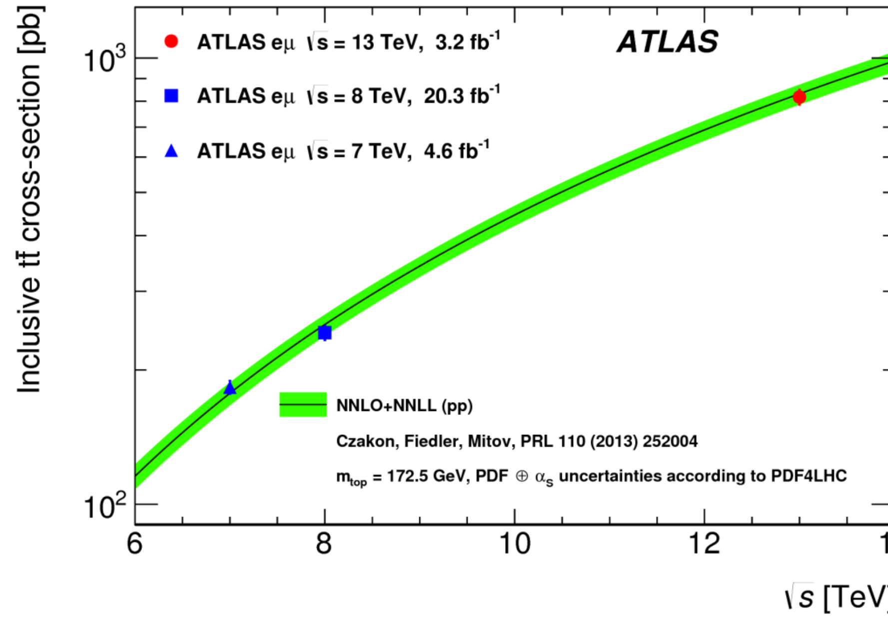




Top quark (RUN2)

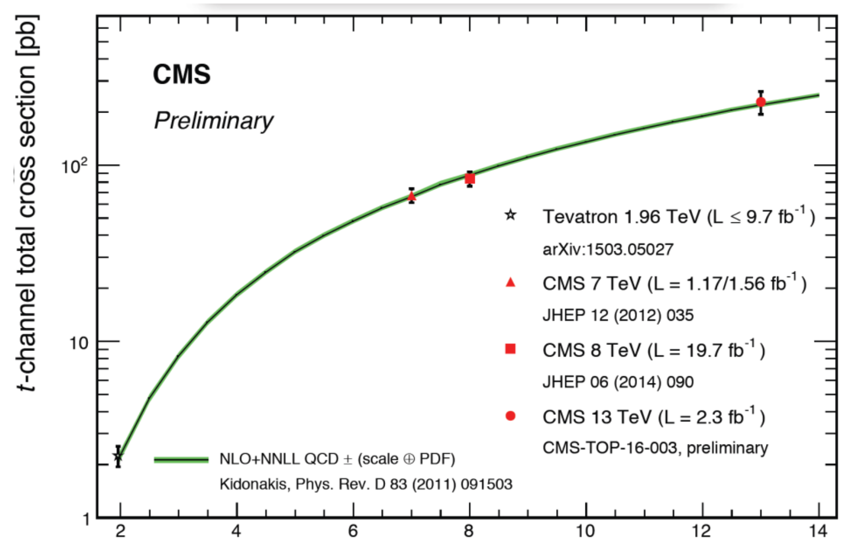
Top pair production



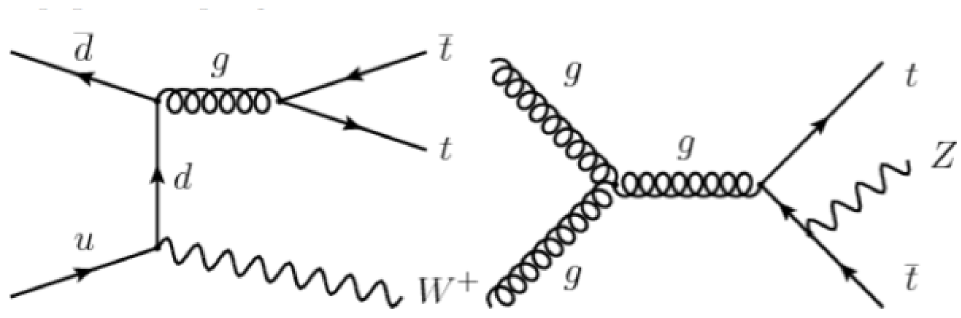


Single top production

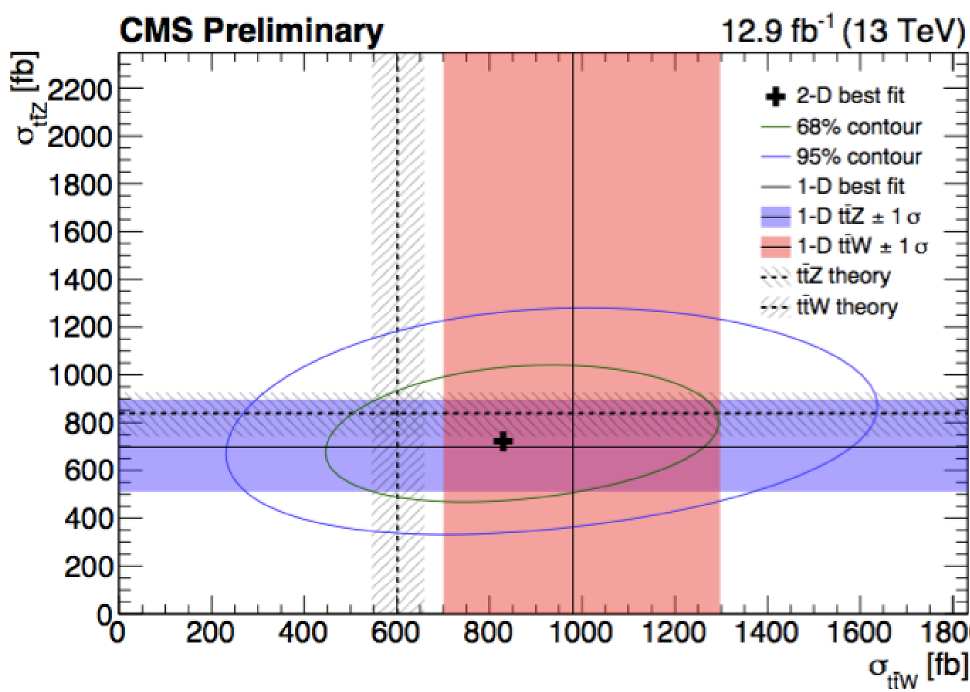
|Vtb| =1.12 ± 0.24(exp.) ± 0.02(th.)

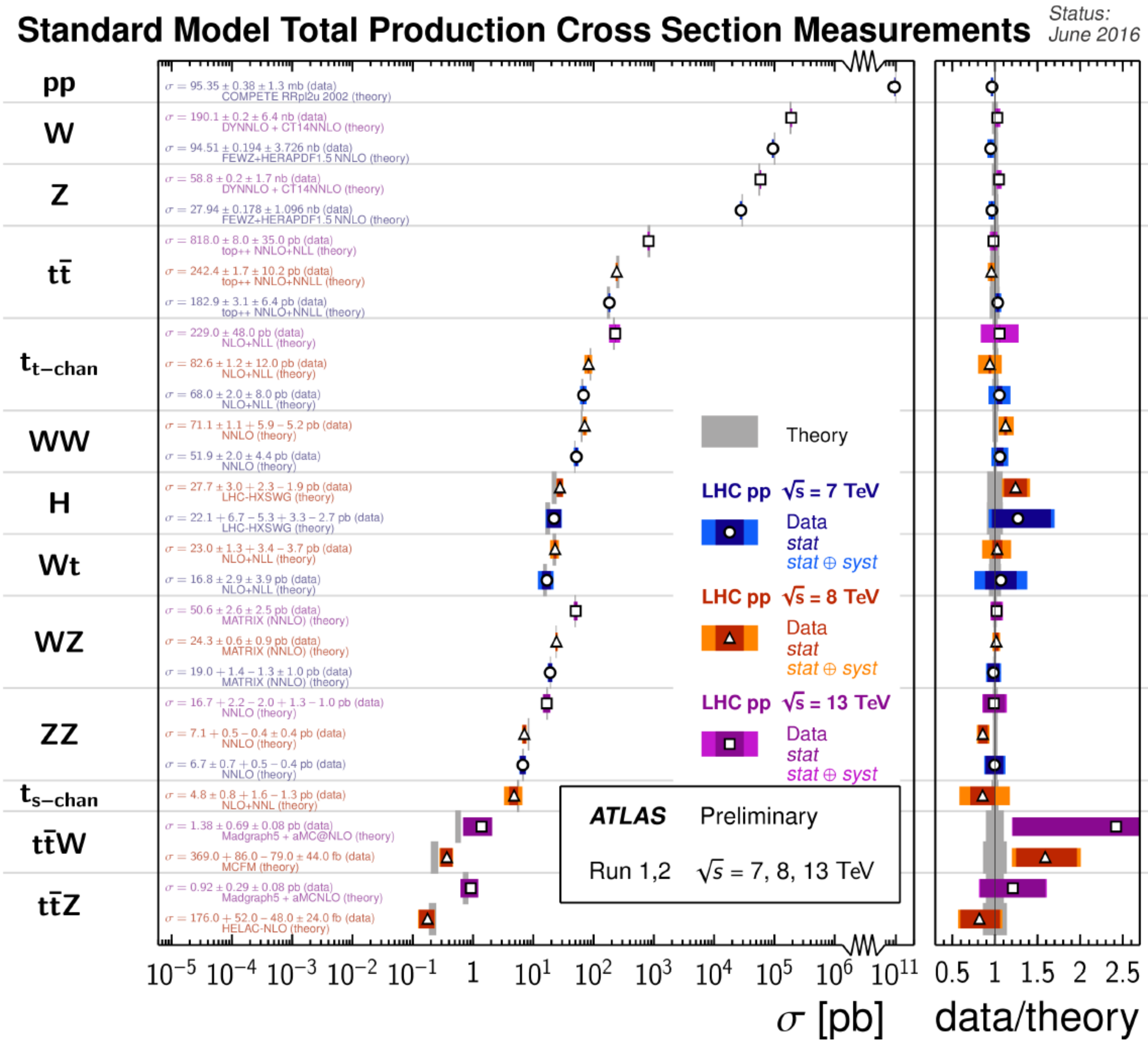


First measurements ttV



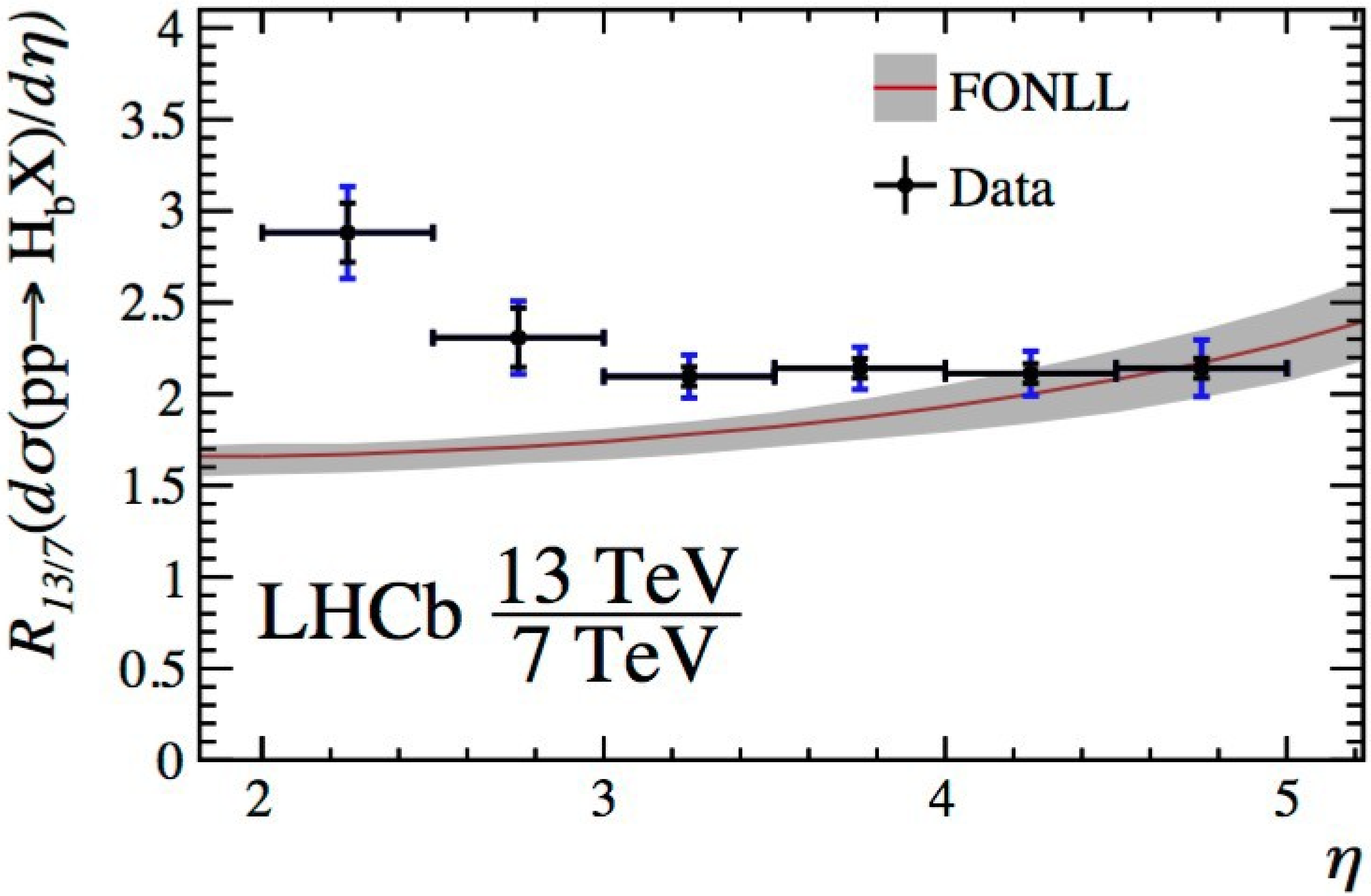
$$\sigma(\mathrm{t\bar{t}W}) = 0.98\,^{+0.23}_{-0.22}(\mathrm{stat.})\,^{+0.22}_{-0.18}(\mathrm{sys.})\,\mathrm{pb} \qquad \sigma(\mathrm{t\bar{t}Z}) = 0.70^{+0.16}_{-0.15}(\mathrm{stat.})^{+0.14}_{-0.12}(\mathrm{sys.})\,\mathrm{pb}$$



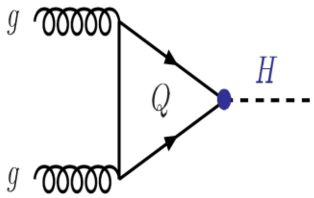


Standard Model Total Production Cross Section Measurements
Status: June 2016
pp
σ = 95.35 ± 0.38 ± 1.3 mb (data)
COMPETE RRpl2u 2002 (theory)
W
σ = 190.1 ± 0.2 ± 6.4 nb (data)
DYNNLO + CT14NNLO (theory)
σ = 94.51 ± 0.194 ± 3.726 nb (data)
FEWZ+HERAPDF1.5 NNLO (theory)
Z
σ = 58.8 ± 0.2 ± 1.7 nb (data)
DYNNLO + CT14NNLO (theory)
σ = 27.94 ± 0.178 ± 1.096 nb (data)
FEWZ+HERAPDF1.5 NNLO (theory)
tt̄
σ = 818.0 ± 8.0 ± 35.0 pb (data)
top++ NNLO+NLL (theory)
σ = 242.4 ± 1.7 ± 10.2 pb (data)
top++ NNLO+NNLL (theory)
σ = 182.9 ± 3.1 ± 6.4 pb (data)
top++ NNLO+NNLL (theory)
t_{t-chan}
σ = 229.0 ± 48.0 pb (data)
NLO+NLL (theory)
σ = 82.6 ± 1.2 ± 12.0 pb (data)
NLO+NLL (theory)
σ = 68.0 ± 2.0 ± 8.0 pb (data)
NLO+NLL (theory)
WW
σ = 71.1 ± 1.1 + 5.9 − 5.2 pb (data)
NNLO (theory)
σ = 51.9 ± 2.0 ± 4.4 pb (data)
NNLO (theory)
H
σ = 27.7 ± 3.0 + 2.3 − 1.9 pb (data)
LHC-HXSWG (theory)
σ = 22.1 + 6.7 − 5.3 + 3.3 − 2.7 pb (data)
LHC-HXSWG (theory)
Wt
σ = 23.0 ± 1.3 + 3.4 − 3.7 pb (data)
NLO+NLL (theory)
σ = 16.8 ± 2.9 ± 3.9 pb (data)
NLO+NLL (theory)
WZ
σ = 50.6 ± 2.6 ± 2.5 pb (data)
MATRIX (NNLO) (theory)
σ = 24.3 ± 0.6 ± 0.9 pb (data)
MATRIX (NNLO) (theory)
σ = 19.0 + 1.4 − 1.3 ± 1.0 pb (data)
MATRIX (NNLO) (theory)
ZZ
σ = 16.7 + 2.2 − 2.0 + 1.3 − 1.0 pb (data)
NNLO (theory)
σ = 7.1 + 0.5 − 0.4 ± 0.4 pb (data)
NNLO (theory)
σ = 6.7 ± 0.7 + 0.5 − 0.4 pb (data)
NNLO (theory)
t_{s-chan}
σ = 4.8 ± 0.8 + 1.6 − 1.3 pb (data)
NLO+NNL (theory)
tt̄W
σ = 1.38 ± 0.69 ± 0.08 pb (data)
Madgraph5 + aMC@NLO (theory)
σ = 369.0 + 86.0 − 79.0 ± 44.0 fb (data)
MCFM (theory)
tt̄Z
σ = 0.92 ± 0.29 ± 0.08 pb (data)
Madgraph5 + aMCNLO (theory)
σ = 176.0 + 52.0 − 48.0 ± 24.0 fb (data)
HELAC-NLO (theory)
Theory
LHC pp √s = 7 TeV
Data
stat
stat ⊕ syst
LHC pp √s = 8 TeV
Data
stat
stat ⊕ syst
LHC pp √s = 13 TeV
Data
stat
stat ⊕ syst
ATLAS Preliminary
Run 1,2 √s = 7, 8, 13 TeV
10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 10^{1} 10^{2} 10^{3} 10^{4} 10^{5} 10^{6} 10^{11}
σ [pb]
0.5 1 1.5 2 2.5
data/theory

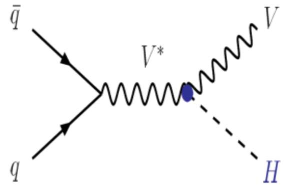
LHCb has measured the cross-section for the process pp→bbX at both 7 and 13



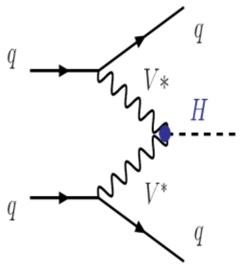
Higgs production modes, decays and signatures at LHC



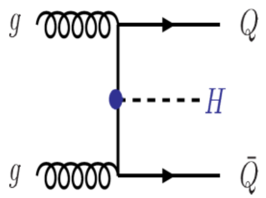
Gluon-gluon fusion



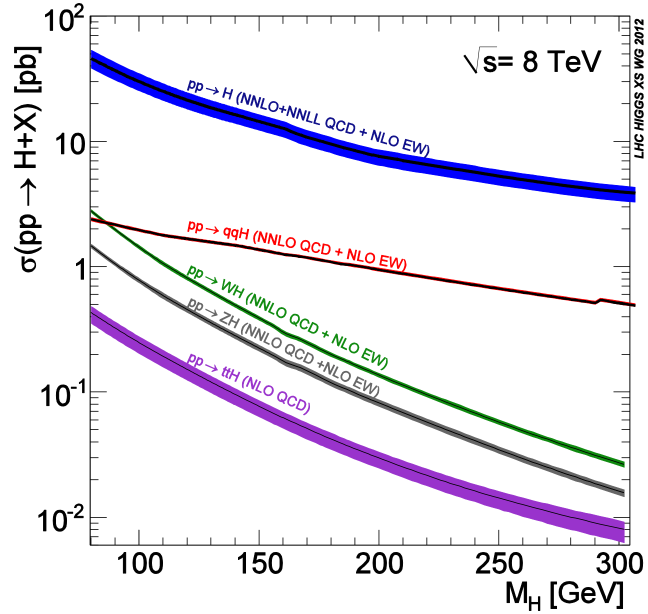
W/Z-Higgs associated

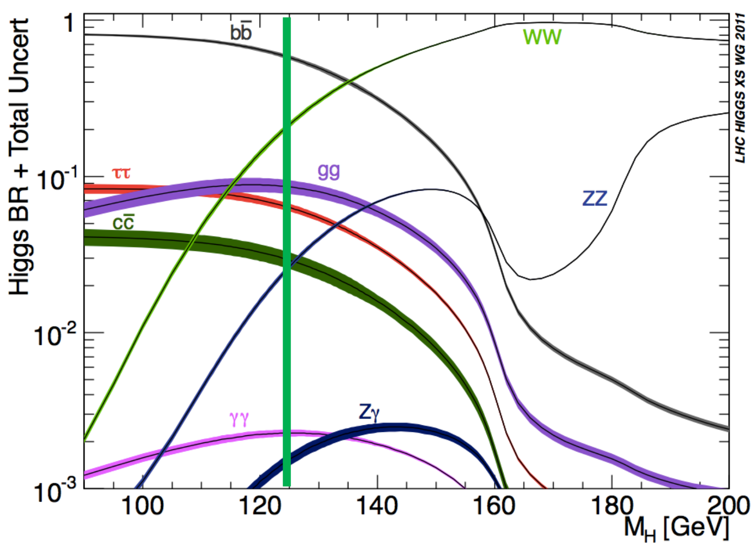


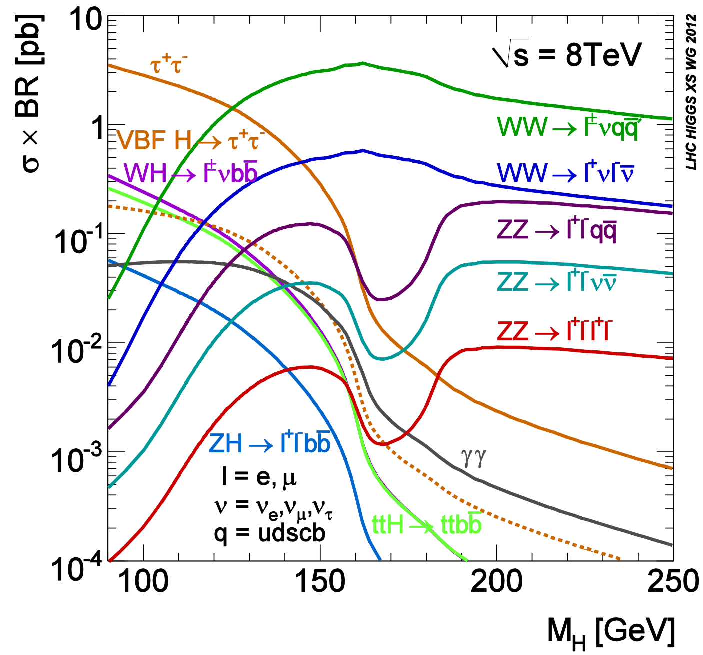
Vector boson fusion



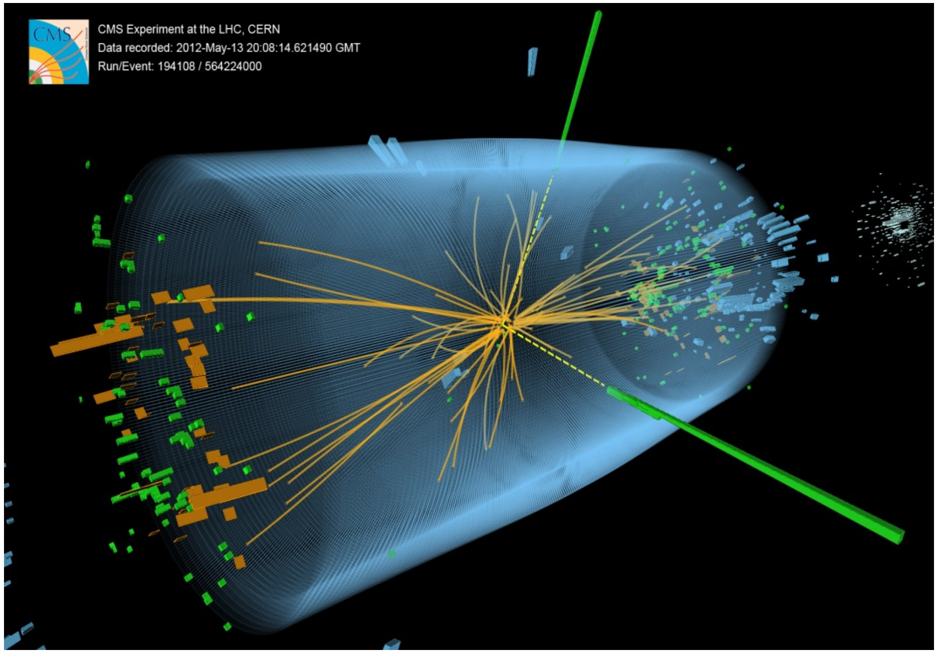
t t-bar Higgs associated

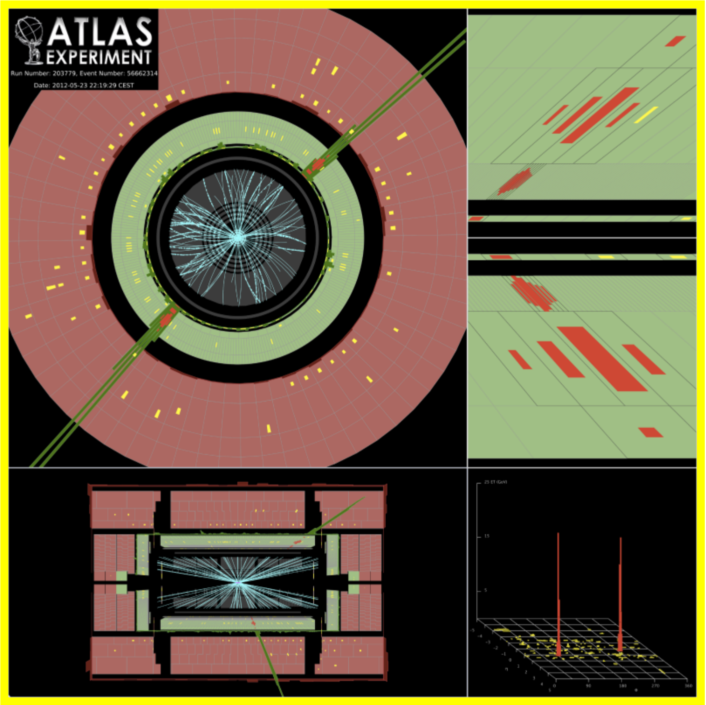




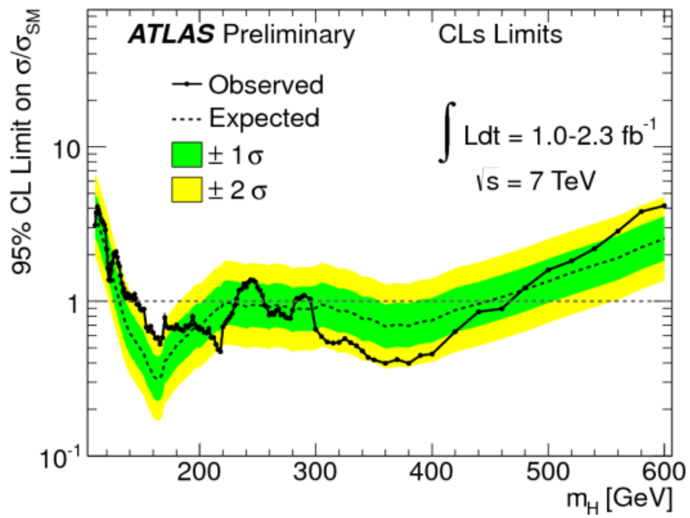


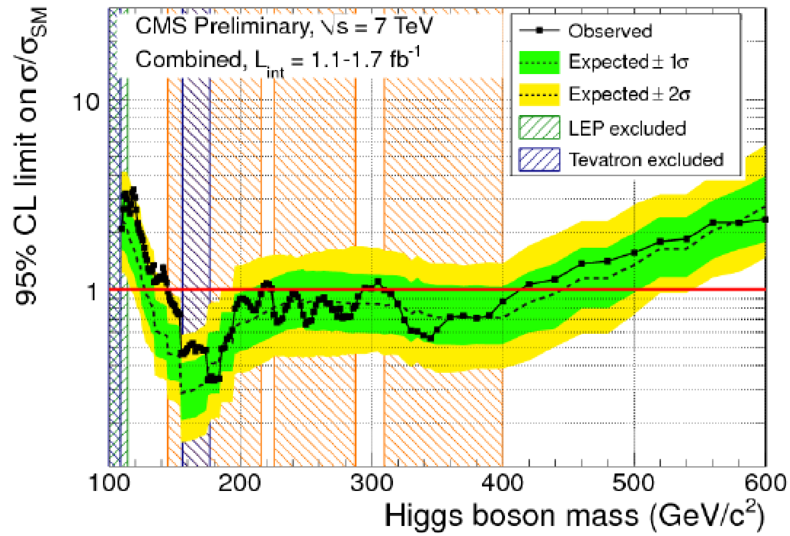
Examples of the CMS and ATLAS events with two photons (Higgs candidates)



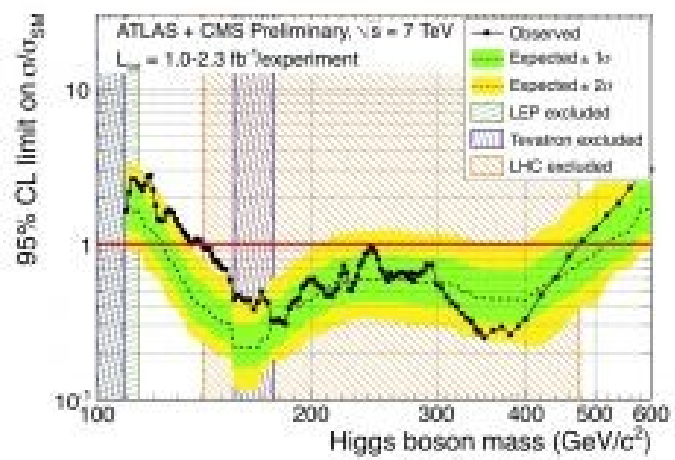


LHC begins with limits on the Higgs mass

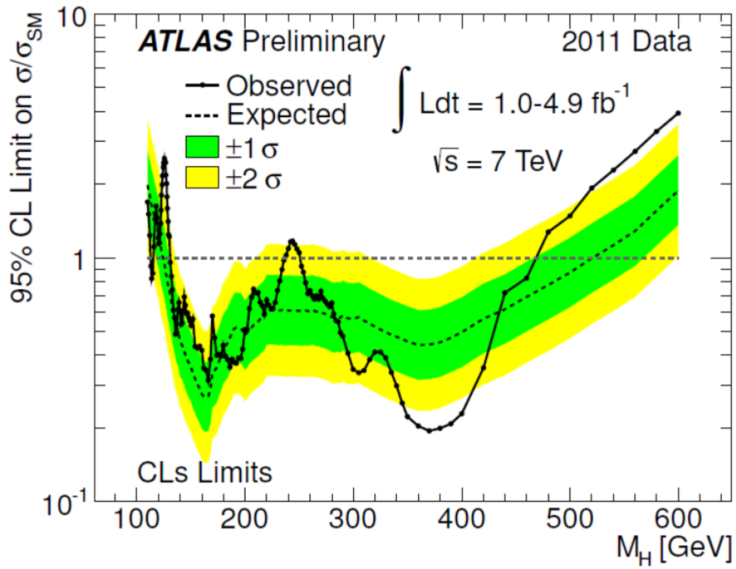


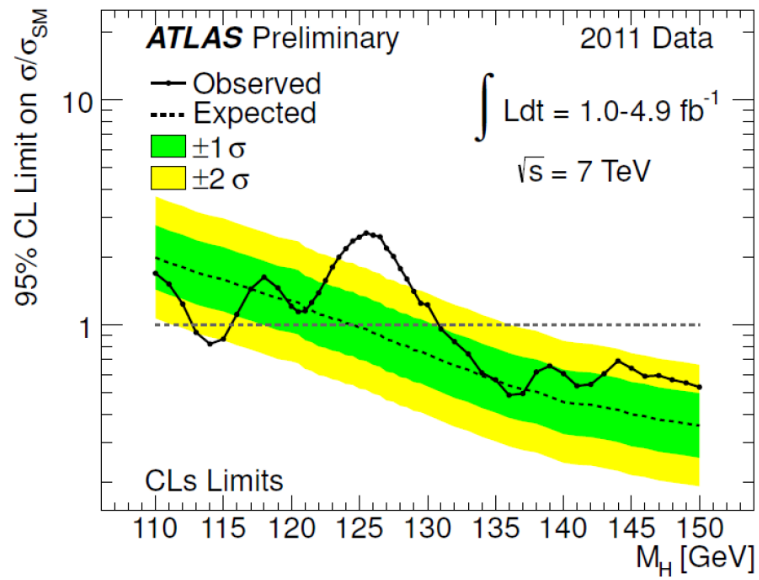


Excluded either by ATLAS or CMS 145-466 GeV (except 288-296 GeV) 95%CL

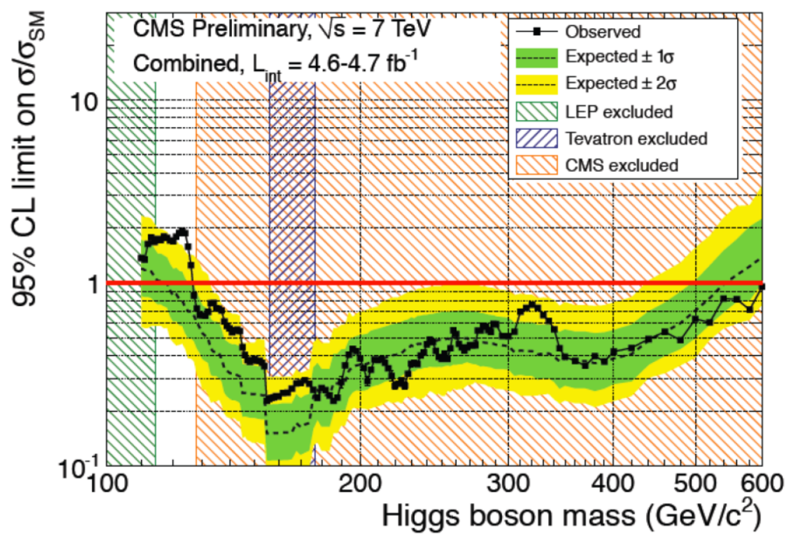


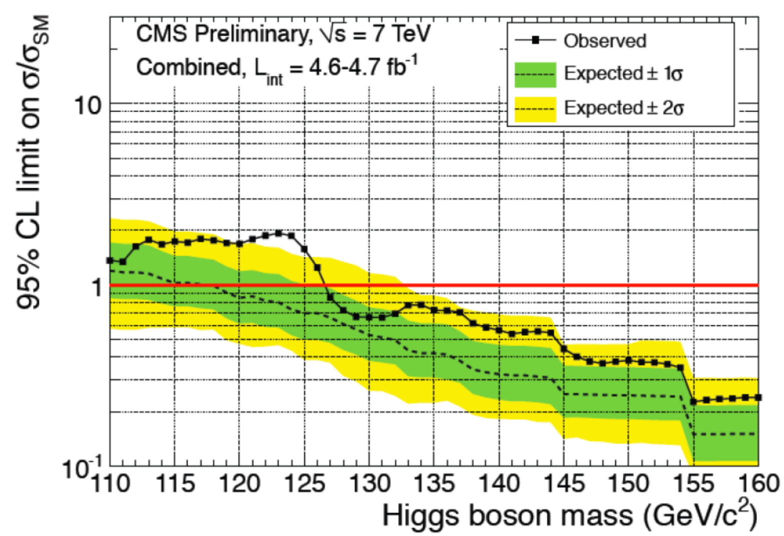
CMS and ATLAS combined result for MH : 141-476 GeV is excluded





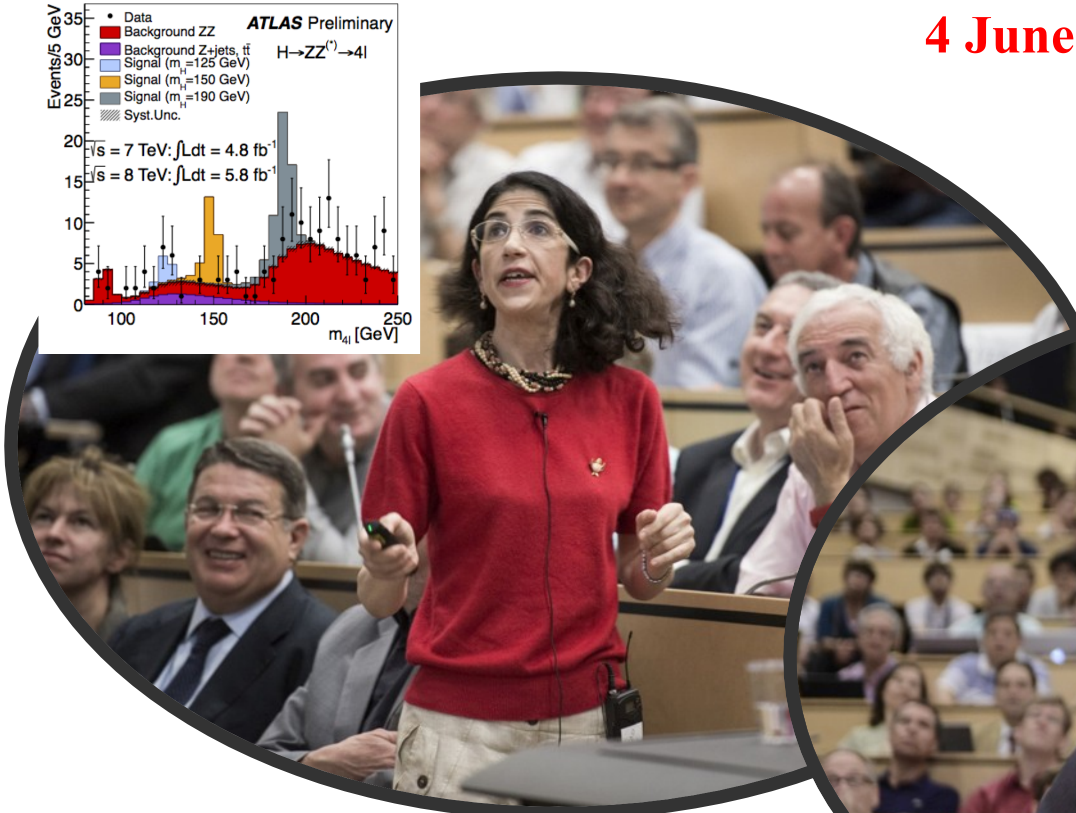
Combining only γγ and 4l: 3.6σ



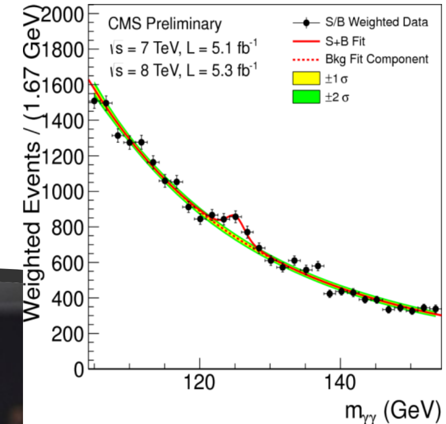


Small window from 115 GeV to 127 GeV is remaining with a small access at about 125 GeV

Presentations at CERN seminar



4 June 2012



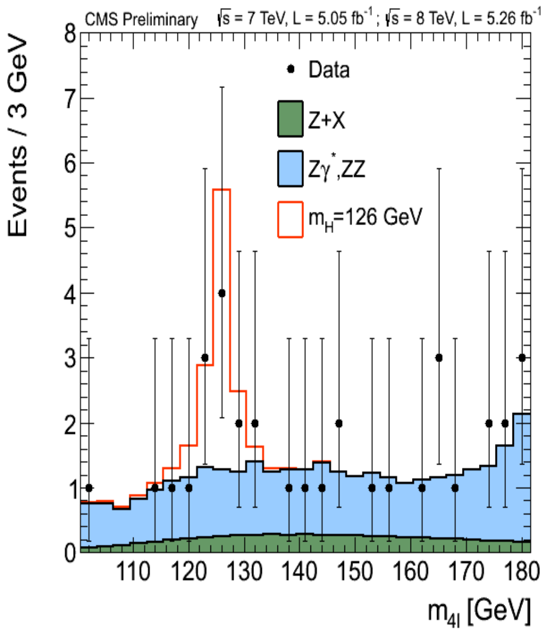
Fabiola Gianotti
ATLAS Spokesperson 2010-2012

Joe Incandela
CMS Spokesperson 2012-2013

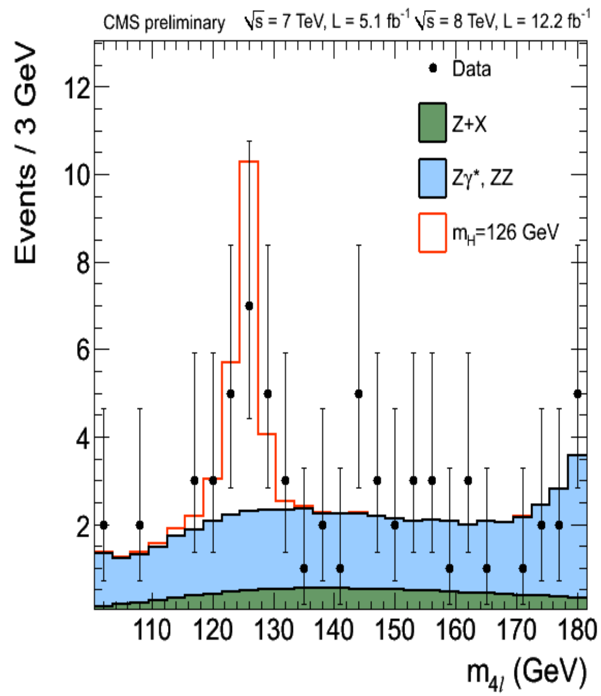
Remarkable day for worldwide physics community

More and more clear peak

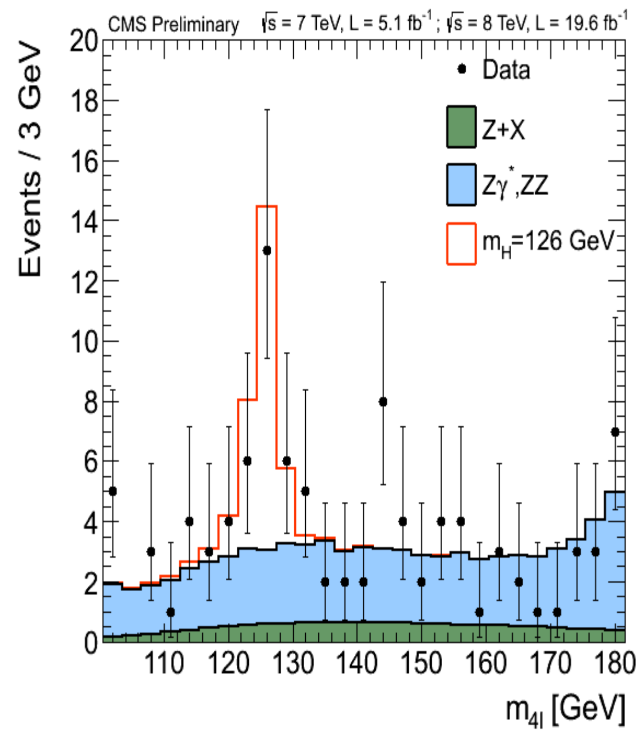
4 July



Nov 2012

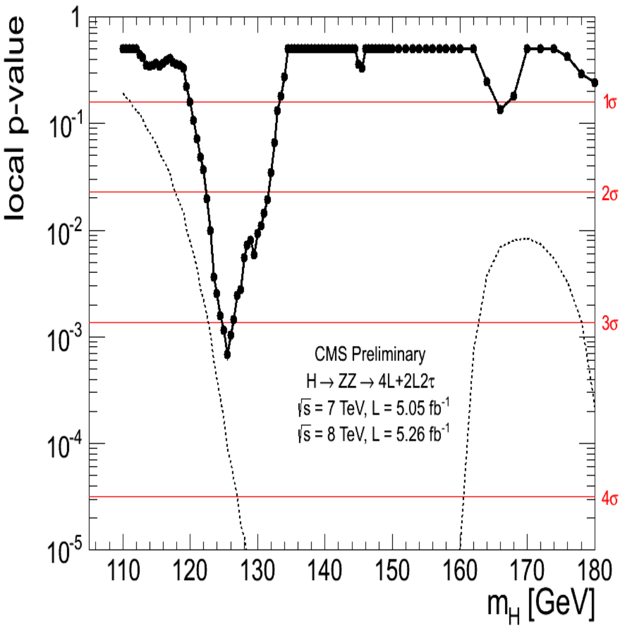


End of RUN 1

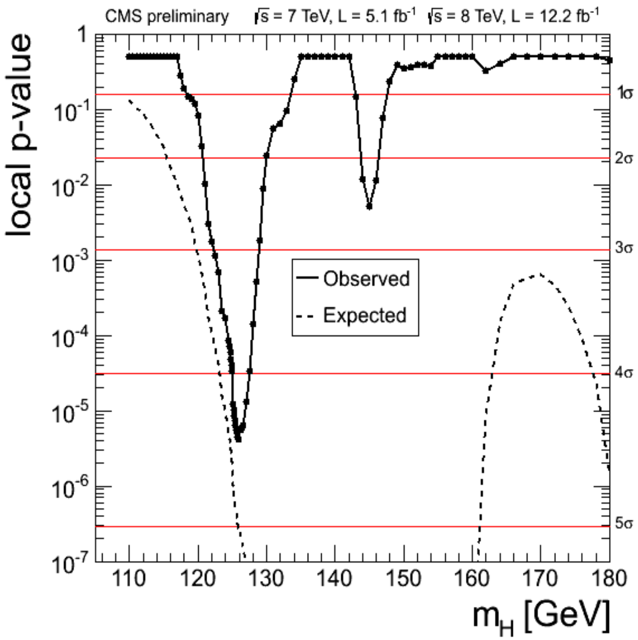


Probability to explain the peak by the background fluctuation

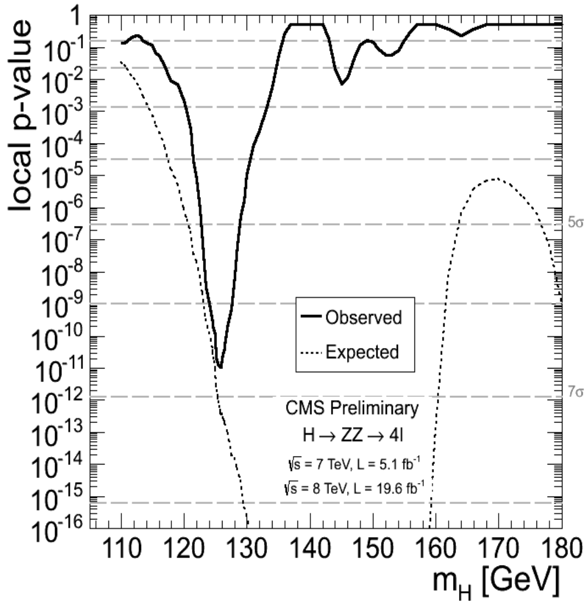
4 July



Nov 2012

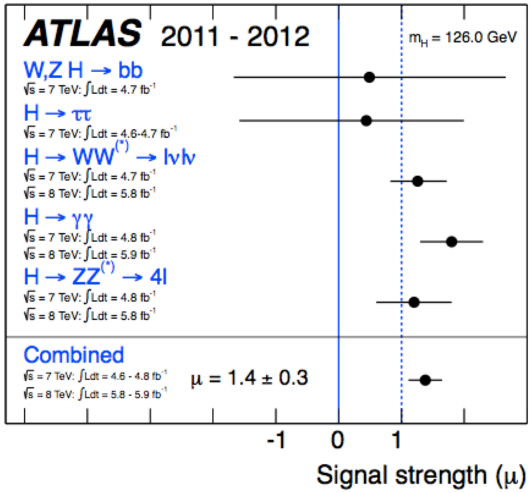


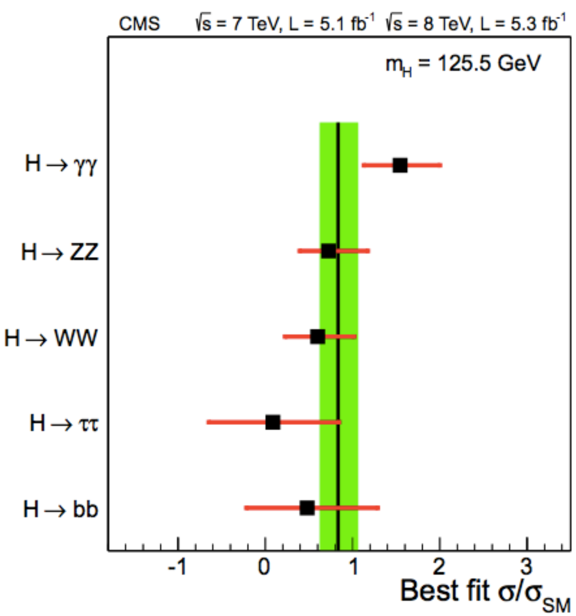
End of RUN 1



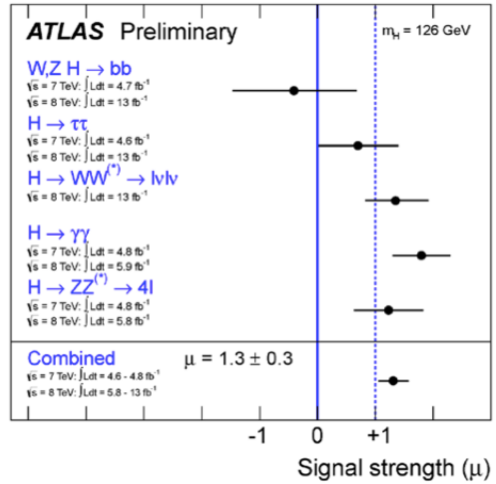
Signal strength μ

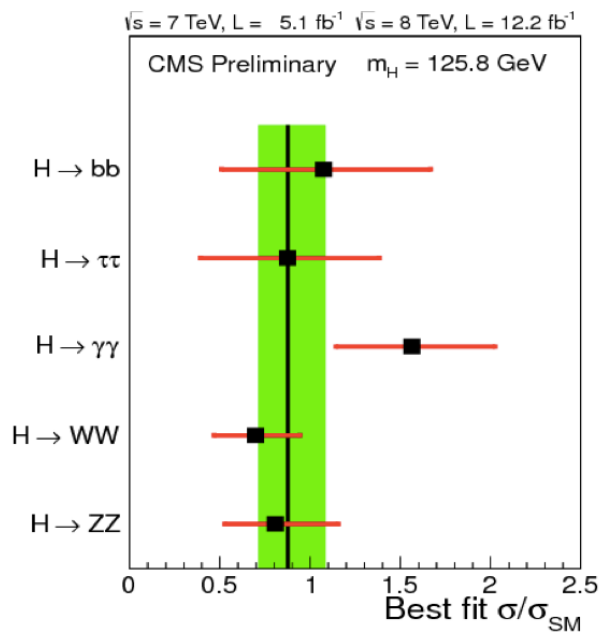
July 2012



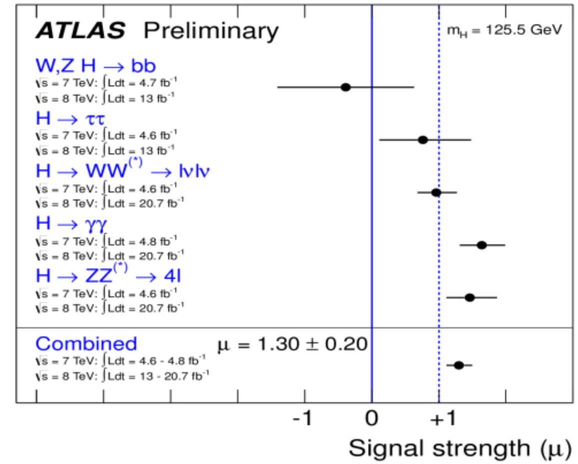


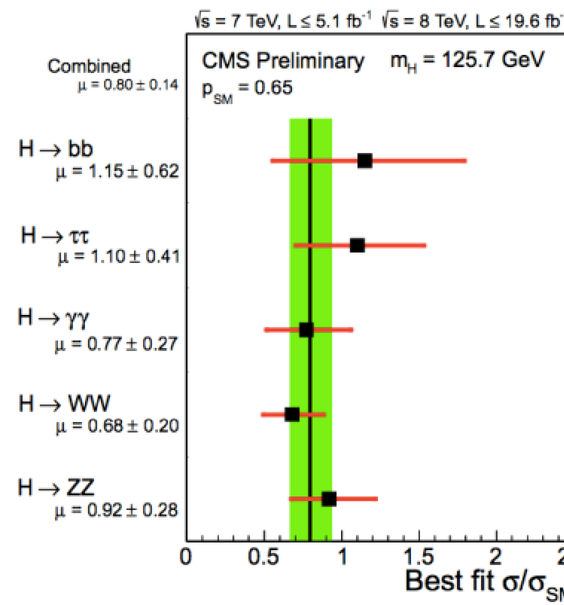
November 2012



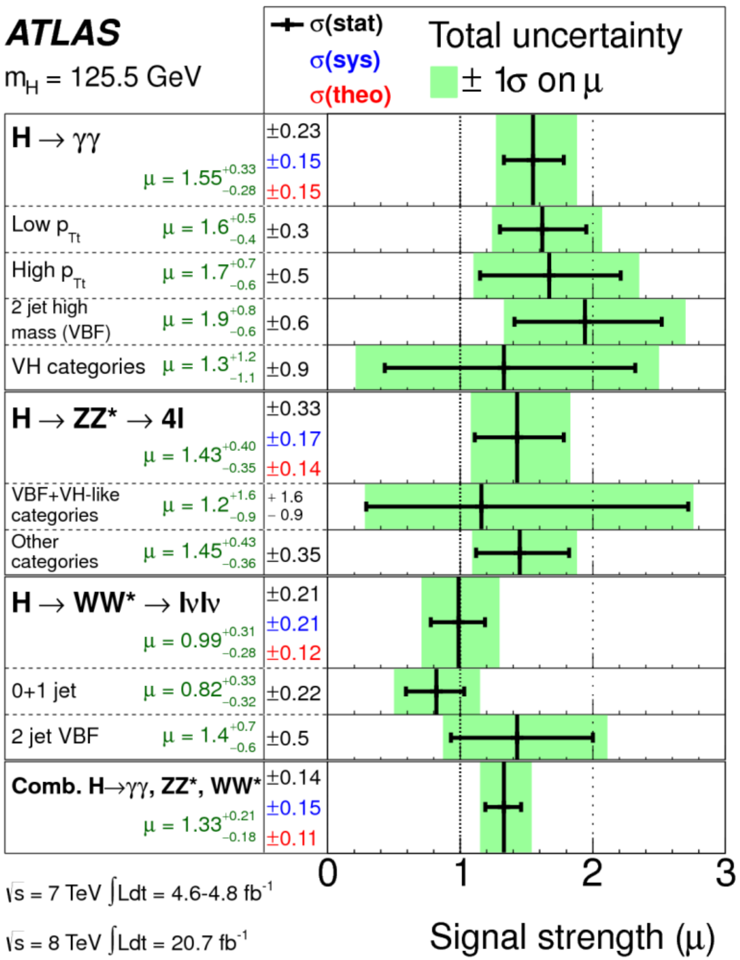


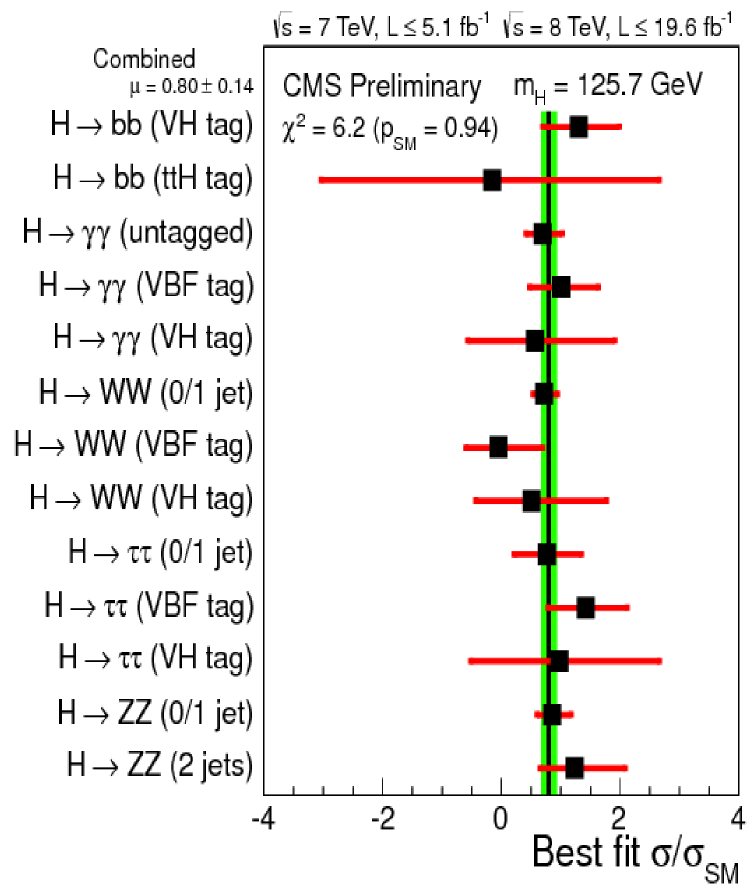
July 2013





RUN1 results in an agreement with the SM

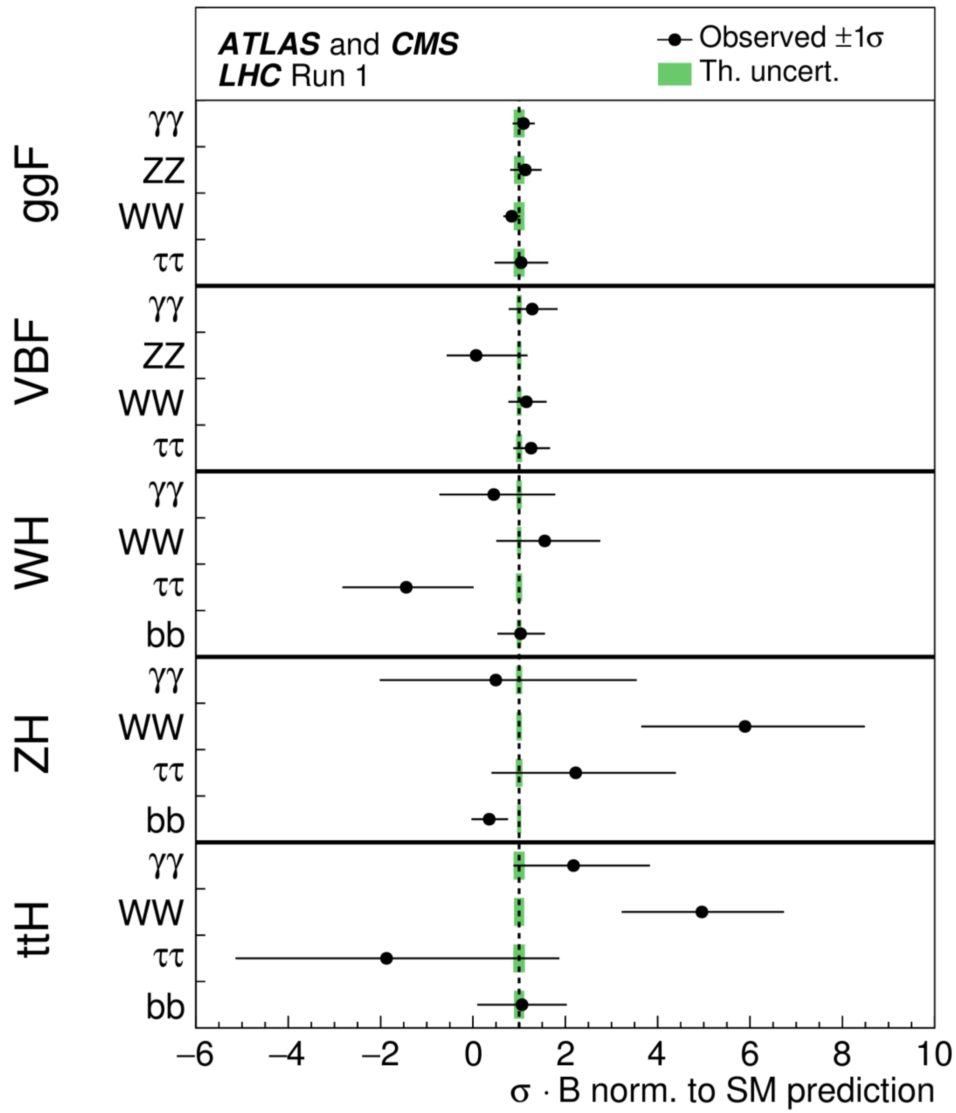


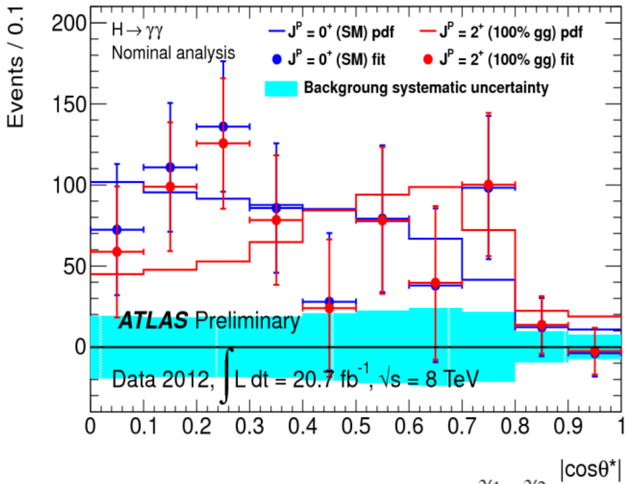


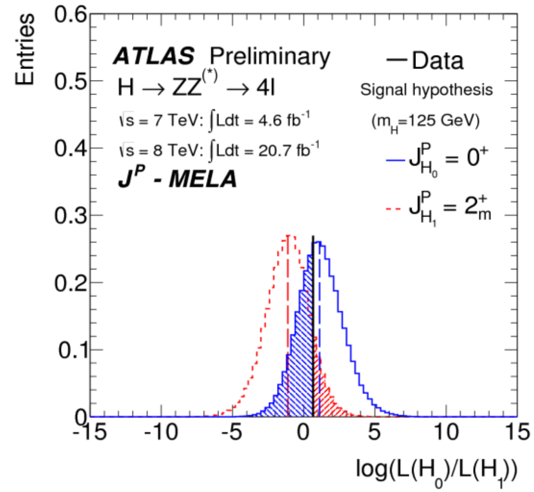
μ=1.30±0.20

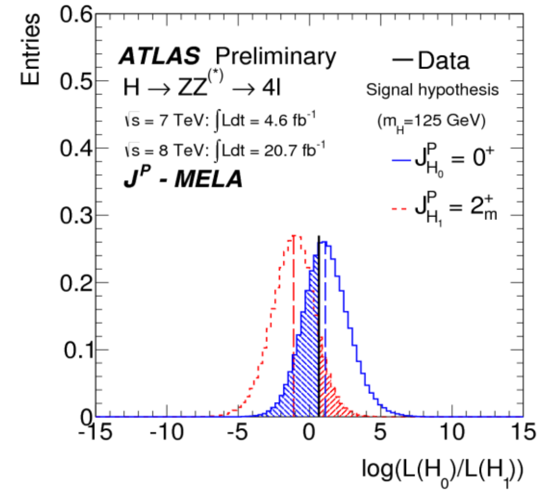
μ=0.80±0.14

Signal strength at various production channels and decay modes







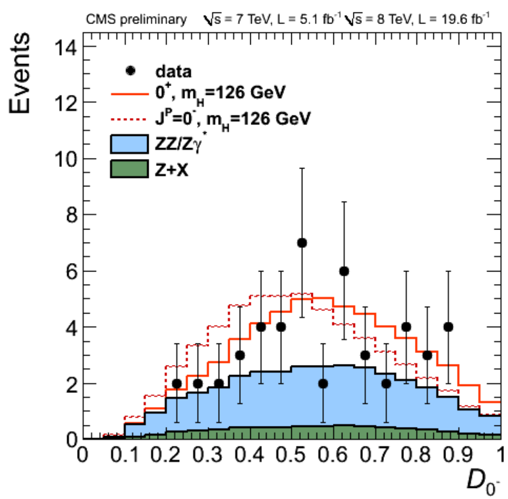


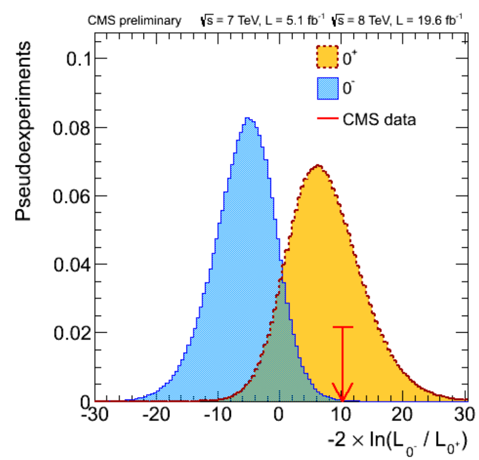
$$\cos\theta^* = \frac{\sinh(\eta_{\gamma_1} - \eta_{\gamma_2})}{\sqrt{1 + \left(p_T^{\gamma\gamma}/m_{\gamma\gamma}\right)^2}} \cdot \frac{2 p_T^{\gamma_1} p_T^{\gamma_2}}{m_{\gamma\gamma}^2}$$

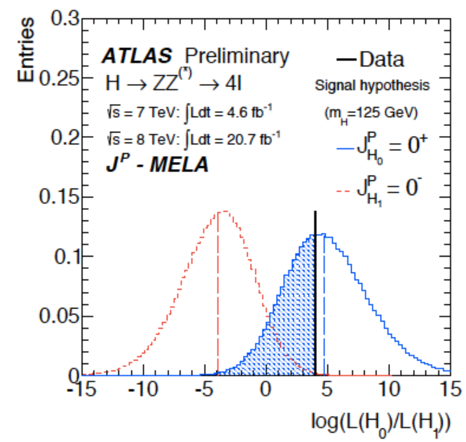
Graviton-like spin-2⁺ disfavoured at 99.9% CL

$$\mathcal{D}_{J^P} = \frac{\mathcal{P}_{SM}}{\mathcal{P}_{SM} + \mathcal{P}_{J^P}} = \left[1 + \frac{\mathcal{P}_{J^P}(m_{Z_1}, m_{Z_2}, \vec{\Omega}|m_{4\ell})}{\mathcal{P}_{SM}(m_{Z_1}, m_{Z_2}, \vec{\Omega}|m_{4\ell})}\right]^{-1}$$

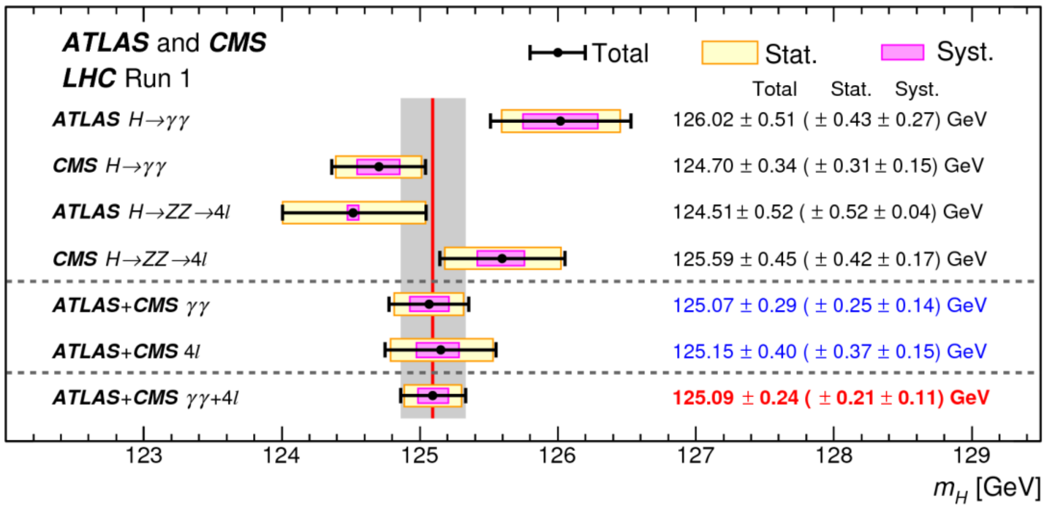
$$\text{MELA} = \left[1 + \frac{\mathcal{P}_{bkg}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1|m_{4\ell})}{\mathcal{P}_{sig}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1|m_{4\ell})}\right]^{-1}$$

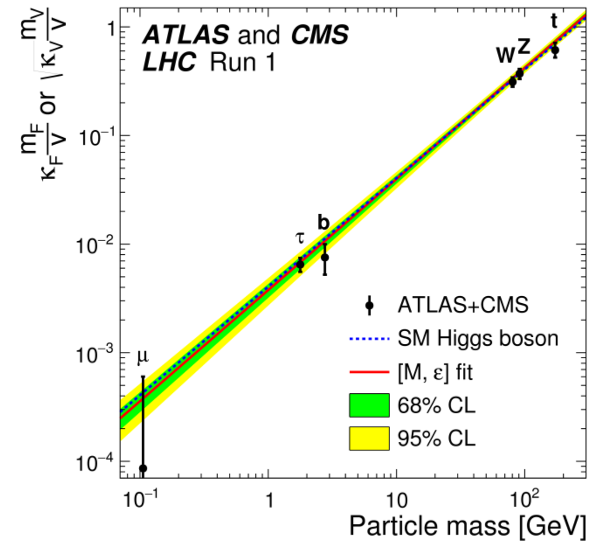






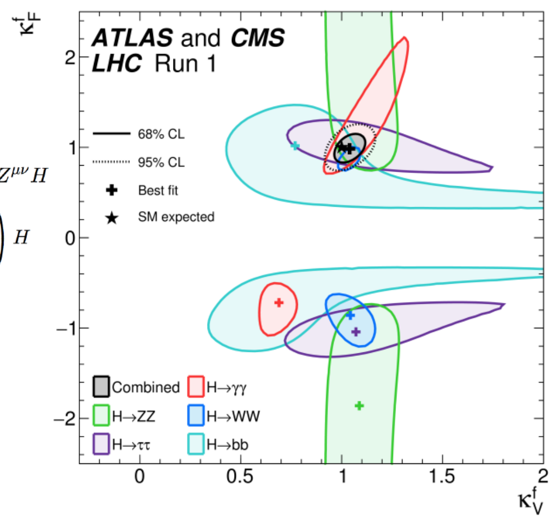
Pseudoscalar 0⁻ disfavoured at > 99% CL





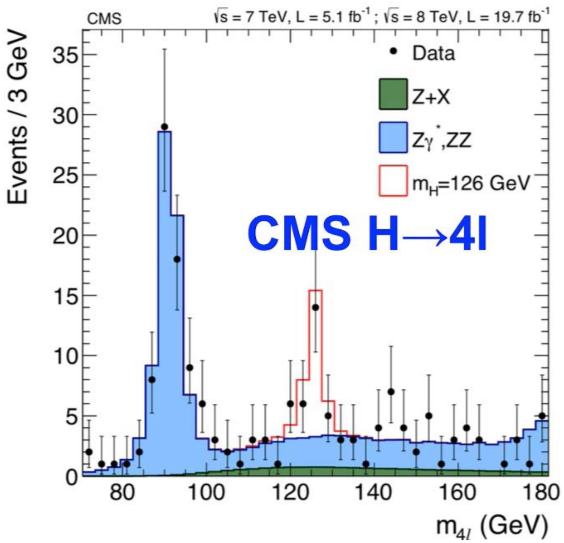
Quantum numbers 0⁺, interaction constants are proportional to masses , the Higgs mass is measured with good precision

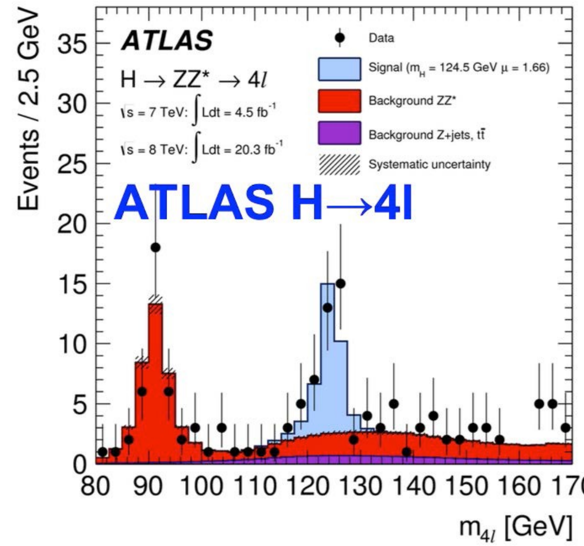
$$\mathcal{L} = \kappa_3 \frac{m_H^2}{2v} H^3 + \kappa_Z \frac{m_Z^2}{v} Z_\mu Z^\mu H + \kappa_W \frac{2m_W^2}{v} W_\mu^+ W^{-\mu} H + \kappa_g \frac{\alpha_s}{12\pi v} G^a_{\mu\nu} G^{a\mu\nu} H + \kappa_\gamma \frac{\alpha}{2\pi v} A_{\mu\nu} A^{\mu\nu} H + \kappa_{Z\gamma} \frac{\alpha}{\pi v} A_{\mu\nu} Z^{\mu\nu} H - \left(\kappa_t \sum_{f=u,c,t} \frac{m_f}{v} f\bar{f} + \kappa_b \sum_{f=d,s,b} \frac{m_f}{v} f\bar{f} + \kappa_\tau \sum_{f=e,\mu,\tau} \frac{m_f}{v} f\bar{f} \right) H$$

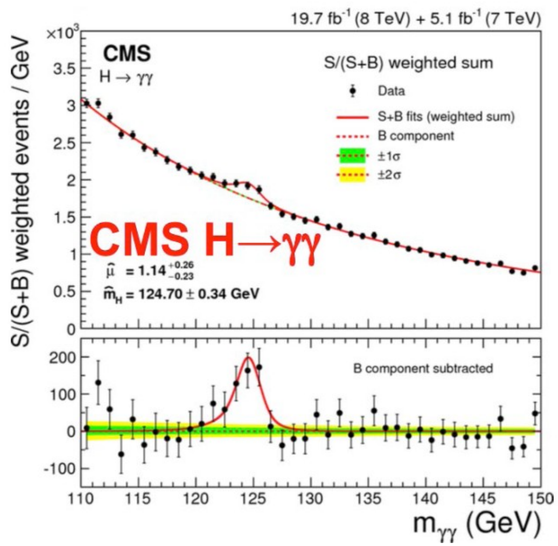


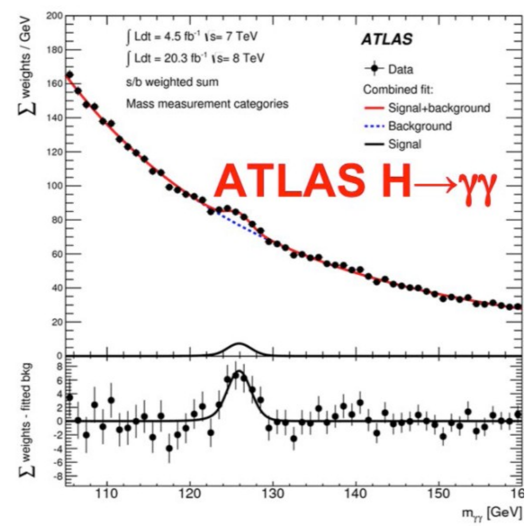
Negative Yukawa is disfavored

SM-like Higgs (scalar 0⁺) is discovered





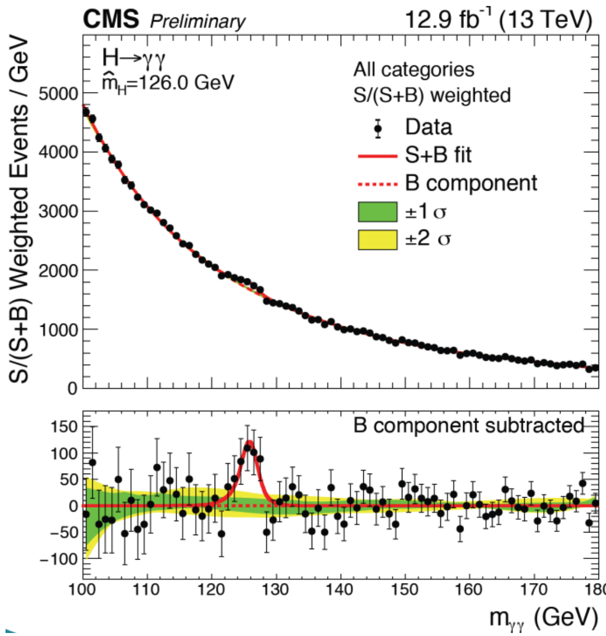


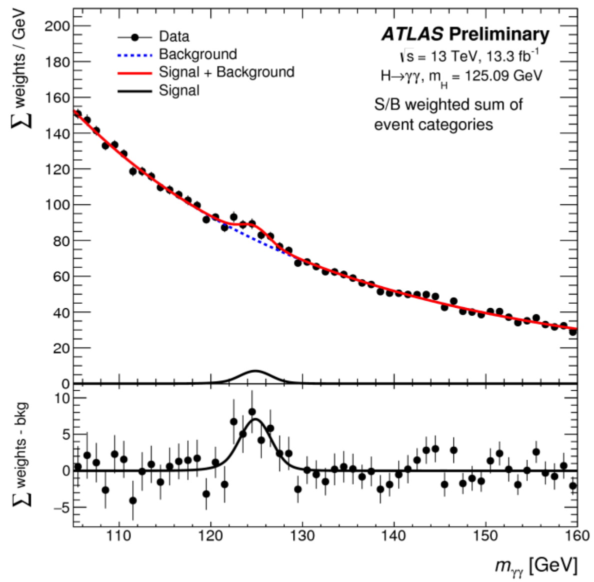


m_H = 125.09±0.21(stat.)±0.11(syst.) GeV

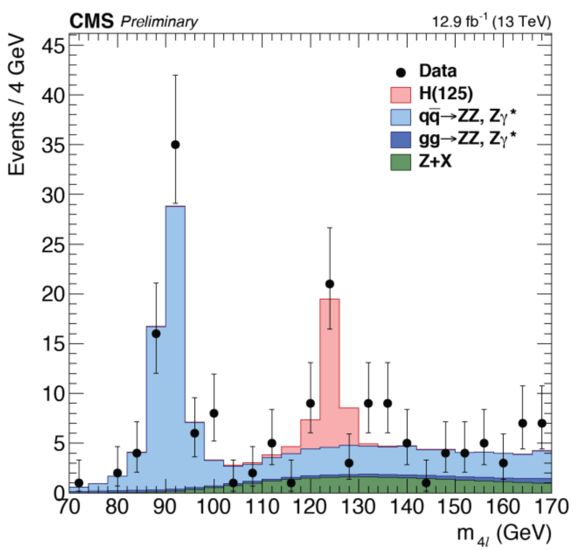
Higgs rediscovery at 13 TeV and 13 fb^{-1}

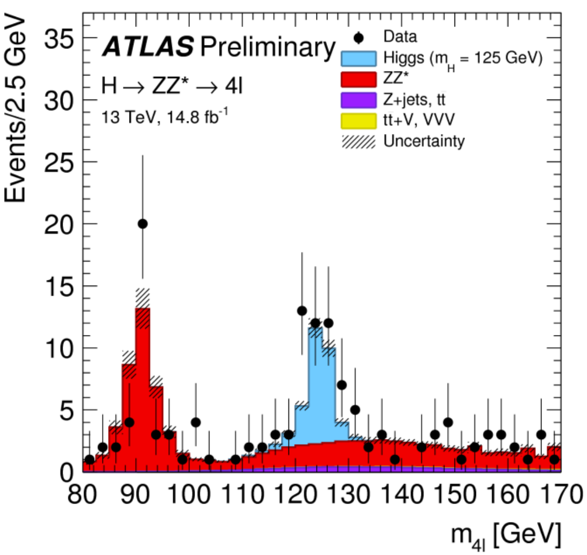
H→γγ



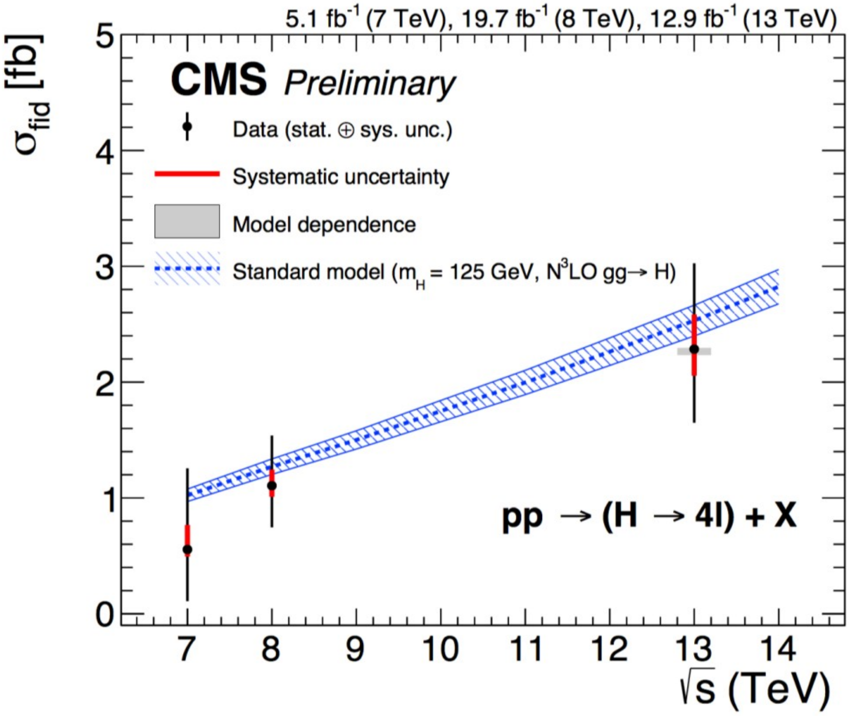


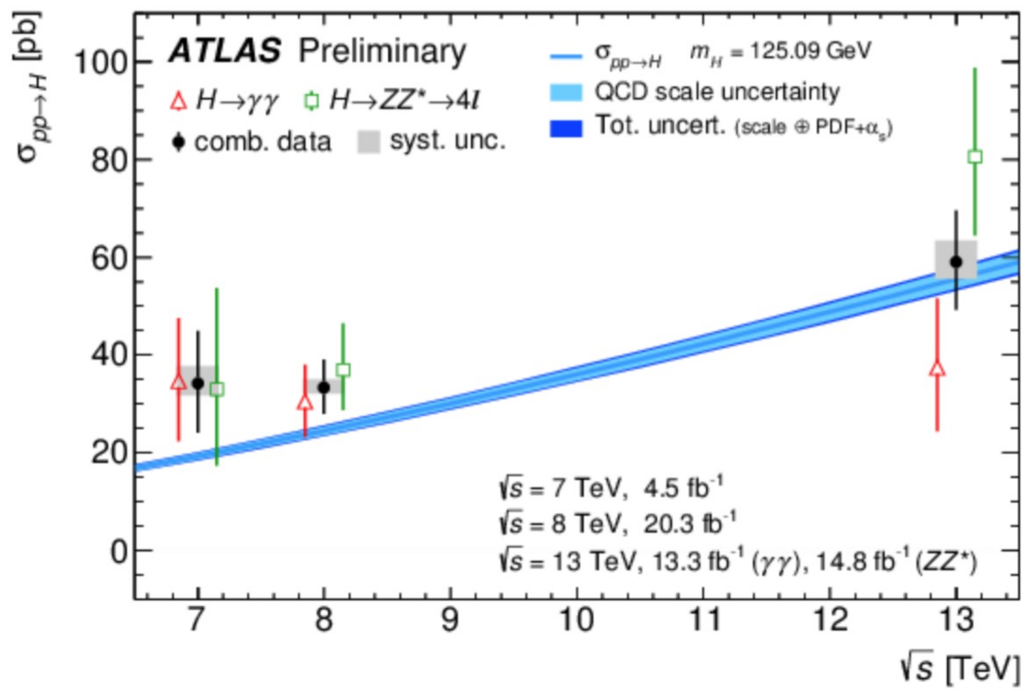
H → ZZ*

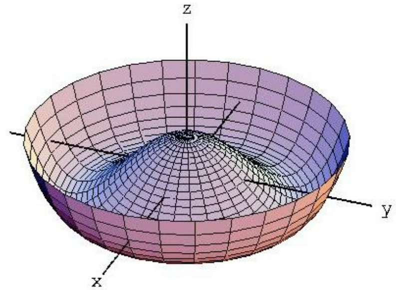


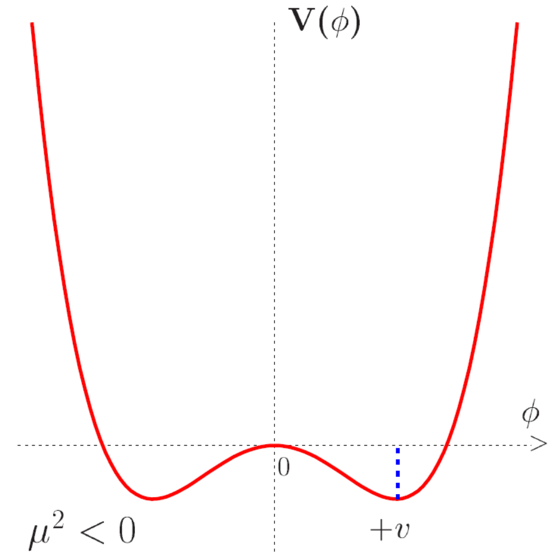


Fiducial and total cross sections









$$\mathbf{V(\Phi) = \mu^2 \Phi^\dagger \Phi + \lambda(\Phi^\dagger \Phi)^2}$$

$$\mathbf{\Phi \rightarrow \frac{1}{\sqrt{2}} \binom{0}{H+v}}$$

$$\mathcal{L}_{\mathrm{H}} = \frac{1}{2}(\partial_\mu \mathrm{H})(\partial^\mu \mathrm{H}) - \mathrm{V} = \frac{1}{2}(\partial^\mu \mathrm{H})^2 - \lambda \mathrm{v}^2 \mathrm{H}^2 - \lambda \mathrm{v}\, \mathrm{H}^3 - \frac{\lambda}{4} \mathrm{H}^4$$

$$\mathbf{M_H^2 = 2\lambda v^2 = -2\mu^2}$$

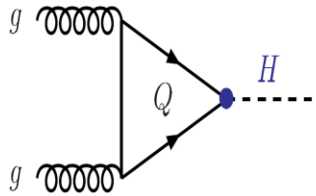
$$\lambda \cong 0.13$$

weakly-coupled theory

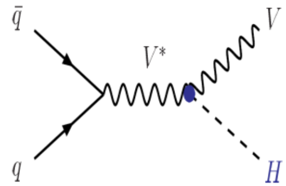
BACKUP SLIDES

Основные механизмы рождения на Tevatron

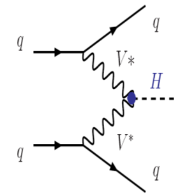
Недостижимые моды на Tevatron



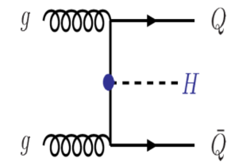
Gluon-gluon fusion



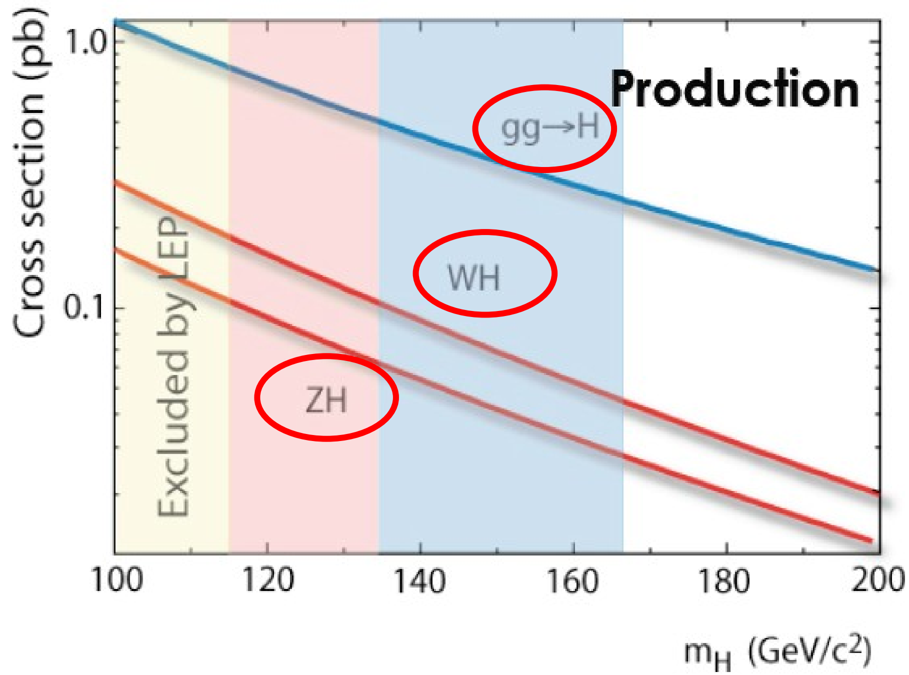
W/Z-Higgs associated



Vector boson fusion



t t-bar Higgs associated



Search strategy:

M_H <135 GeV associated production and bb decay W(Z)H → lν(ll/νν) bb

Main backgrounds: W/Zjj, top, Wbb, Zbb

M_H >135 GeV gg → H production with decay to WW*, WW

Main background: electroweak WW production, W/Zjj