Physics at the LHC
(Beginning of a long way)

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Outline

- Introduction. The Large Hadron Collider.
- Standard Model, Higgs boson physics and observation of the Higgs-like state
- Standard Model and top-quark physics at the LHC.
- Open questions and problems. Main BSM avenues: SUSY, extra dimensions, new strong dynamics… BSM searches at the LHC
- (EW gauge boson physics, QCD physics, b-physics, heavy ion physics… are discussed very little in the lectures)

“Theorist”

“Experimentalist”

What did we know before the LHC start?

Whether or not the LHC energy scale is an appropriate one?

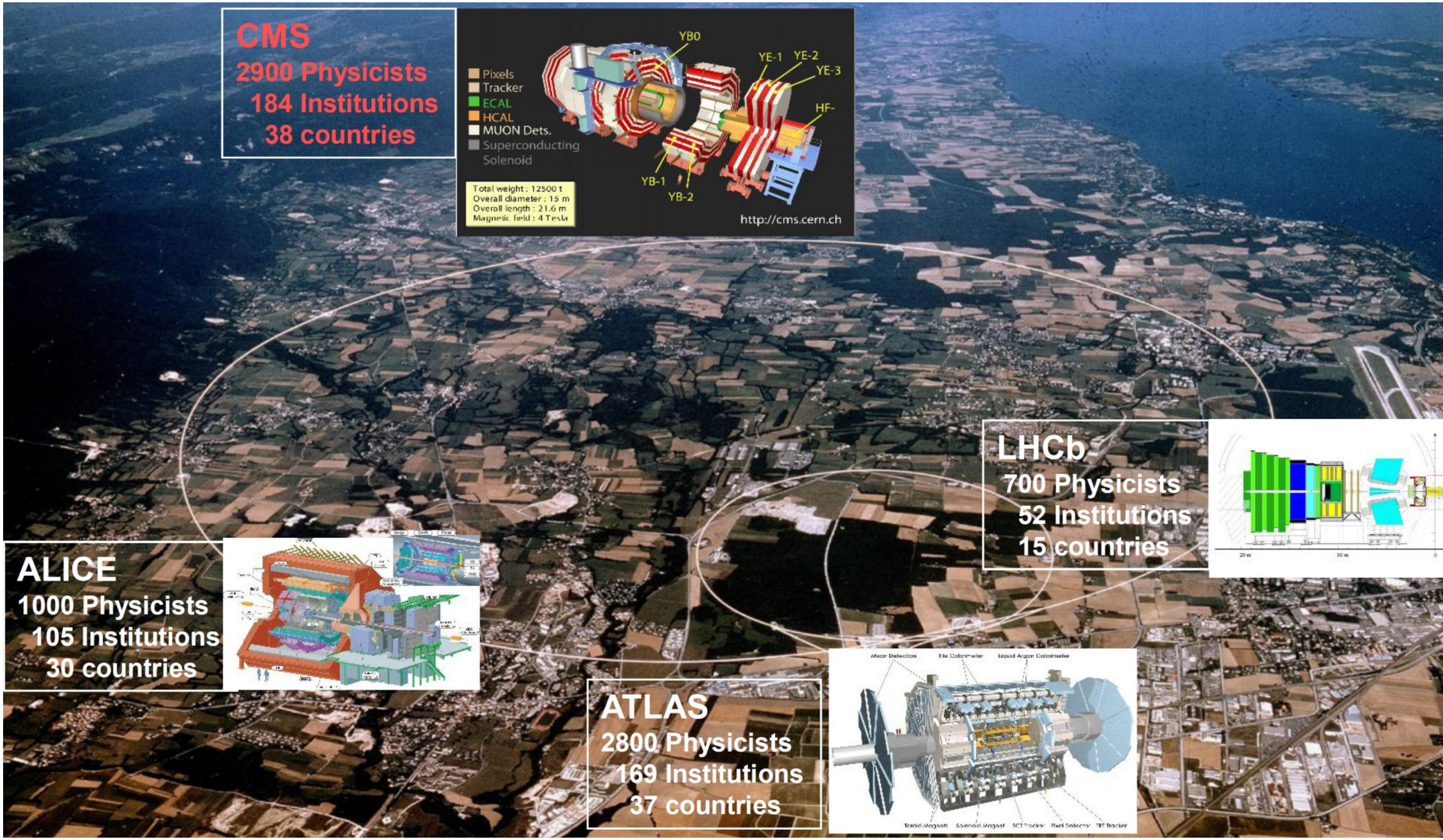
What one can say after current LHC results?

What are expectations?

Collider LHC

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

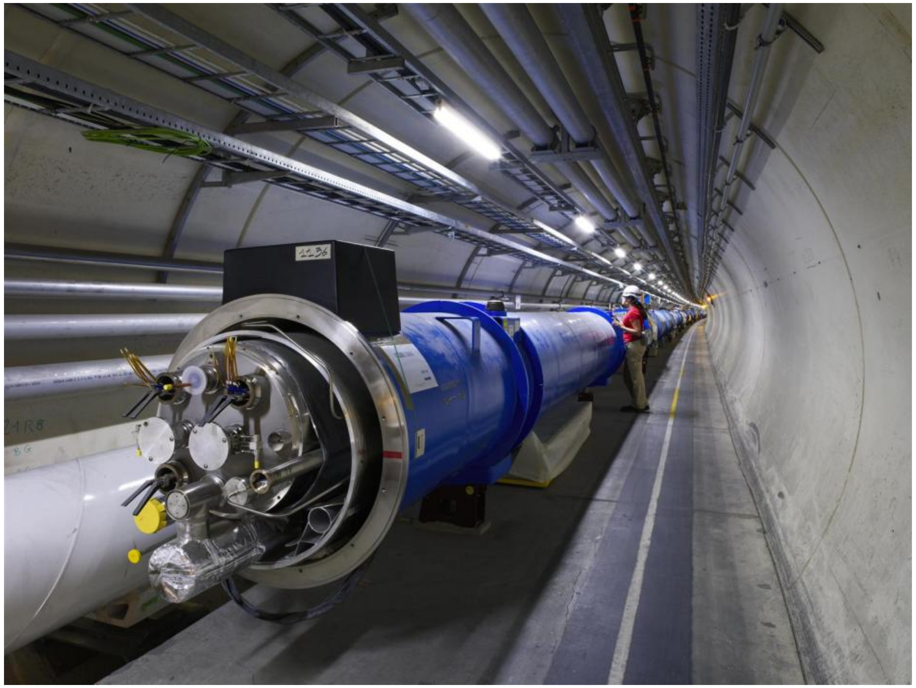
27 km circumference, about 100 m underground



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

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

LHC is the most complicated and expensive project in fundamental science

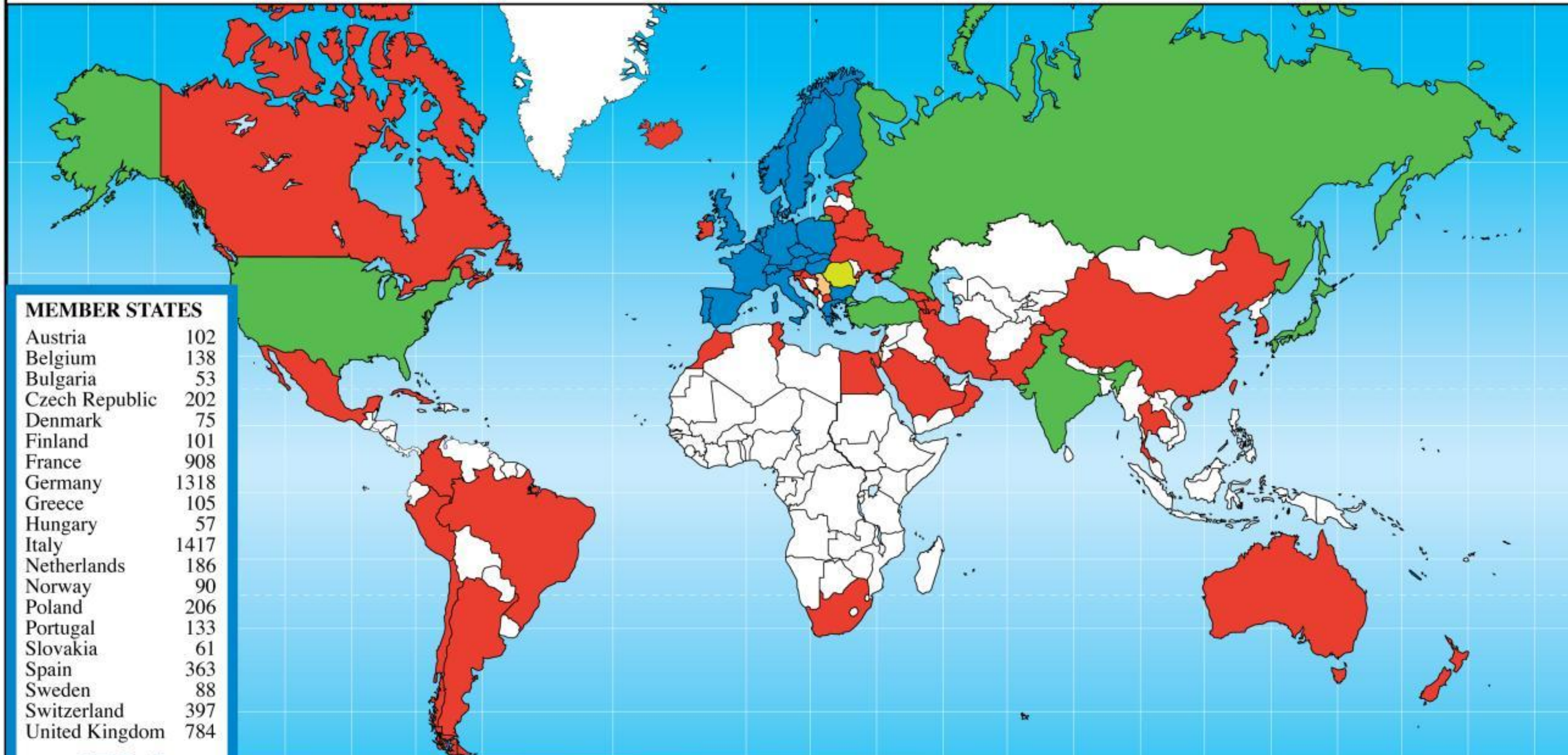


LHC vs Tevatron

Energy: 14 TeV vs 2 TeV

Luminosity: 10^{34} vs 10^{32} $cm^{-2}s^{-1}$

Distribution of All CERN Users by Nation of Institute on 4 April 2012



MEMBER STATES

Austria	102
Belgium	138
Bulgaria	53
Czech Republic	202
Denmark	75
Finland	101
France	908
Germany	1318
Greece	105
Hungary	57
Italy	1417
Netherlands	186
Norway	90
Poland	206
Portugal	133
Slovakia	61
Spain	363
Sweden	88
Switzerland	397
United Kingdom	784

6784

OBSERVERS

India	134
Japan	225
Russia	859
Turkey	83
USA	1749

3050

CANDIDATE FOR ACCESSION

Romania	78

ASSOCIATE MEMBER IN THE PRE-STAGE TO MEMBERSHIP

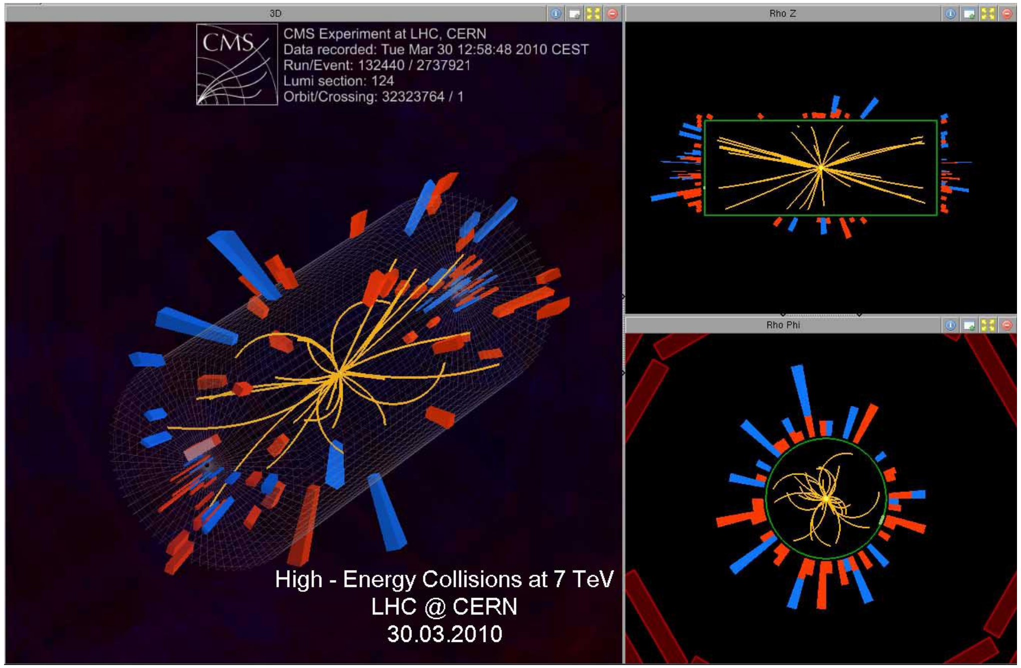
Israel	67
Serbia	26

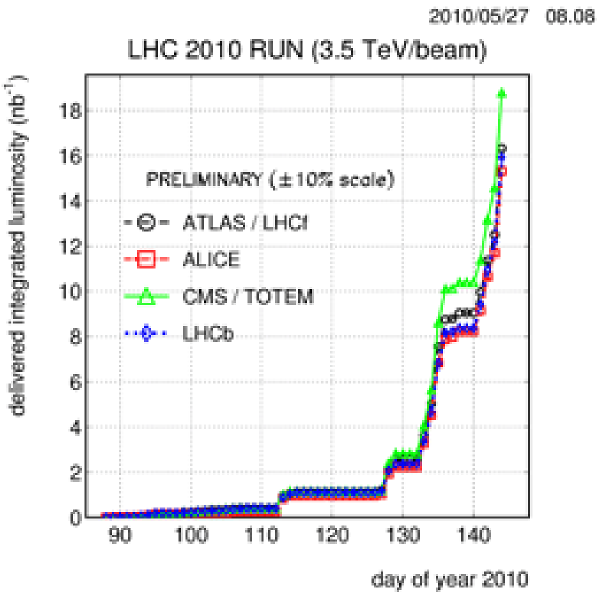
OTHERS

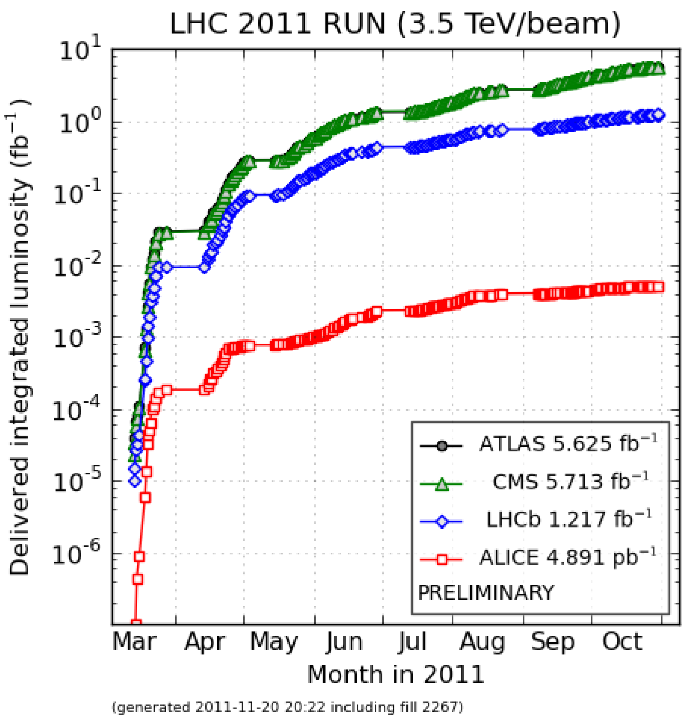
Argentina	18
Armenia	13
Australia	28
Azerbaijan	1
Belarus	22
Brazil	102
Canada	170
Chile	4
China	115
China (Taipei)	70
Colombia	10
Croatia	21
Cuba	4
Cyprus	9
Egypt	7
Estonia	17
Georgia	10
Iceland	3
Iran	16
Ireland	10
Korea	91
Lebanon	1
Lithuania	13
Malta	1
Mexico	43
Montenegro	1
Morocco	6
New Zealand	11
Oman	1
Pakistan	22
Peru	2
Qatar	1
Saudi Arabia	3
Slovenia	38
South Africa	21
Thailand	5
T.F.Y.R.O.M.	2
Tunisia	1
Ukraine	21
Uzbekistan	1

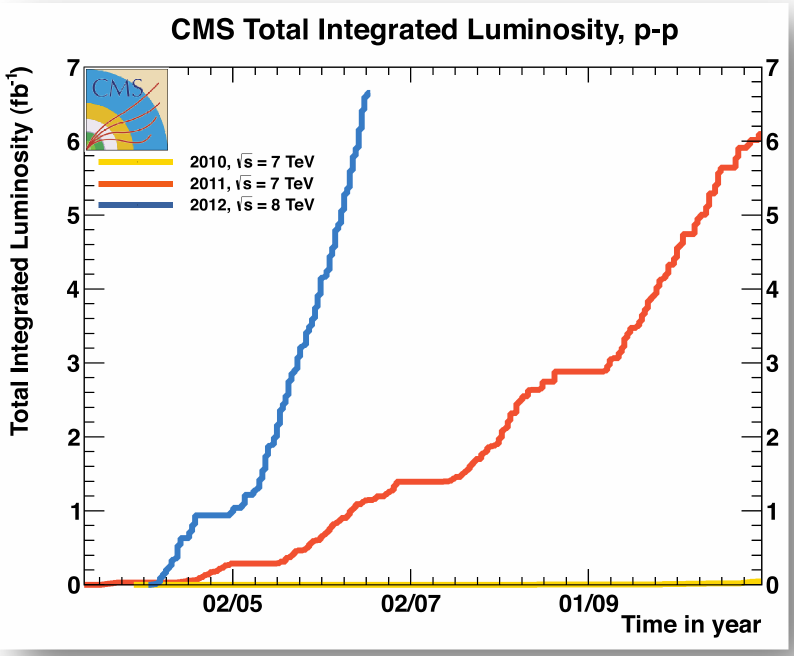
934

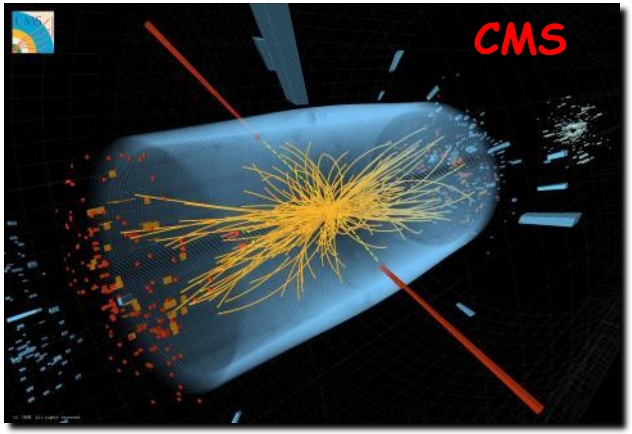
30 March 2010
LHC&7TeV
has started

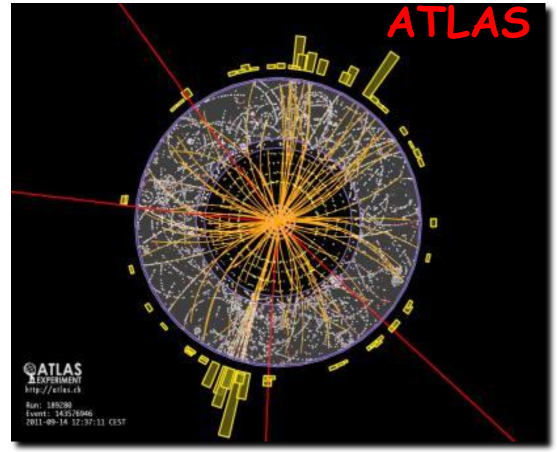


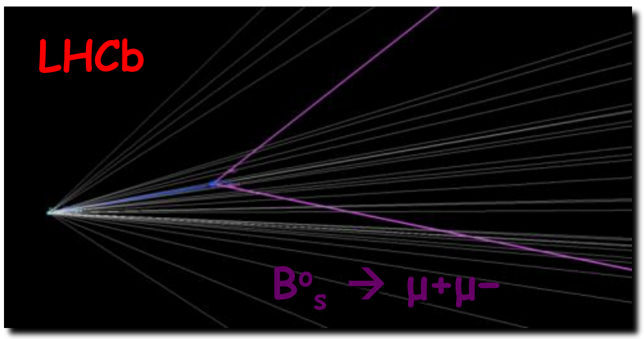



LHC 2011 RUN (3.5 TeV/beam)
Delivered integrated luminosity (fb^{-1})
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
ATLAS 5.625 fb^{-1}
CMS 5.713 fb^{-1}
LHCb 1.217 fb^{-1}
ALICE 4.891 pb^{-1}
PRELIMINARY
Mar Apr May Jun Jul Aug Sep Oct
Month in 2011
(generated 2011-11-20 20:22 including fill 2267)

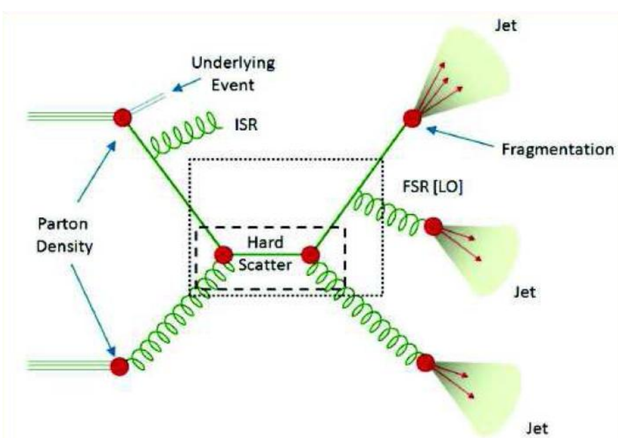

CMS Total Integrated Luminosity, p-p
Total Integrated Luminosity (fb^{-1})
0 1 2 3 4 5 6 7
2010, $\sqrt{s}$ = 7 TeV
2011, $\sqrt{s}$ = 7 TeV
2012, $\sqrt{s}$ = 8 TeV
02/05
02/07
01/09
Time in year

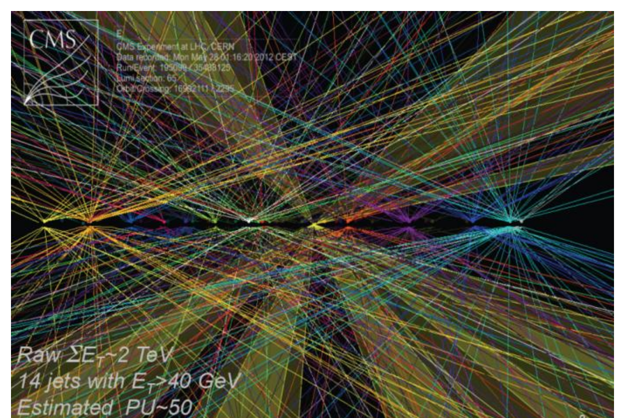

CMS


ATLAS
ATLAS EXPERIMENT


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


ALICE: Pb-Pb


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


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

Для чего нужен такой грандиозный коллайдер?

Что мы ожидаем от LHC?
Почему интересна именно ТэВ-ая область энергий?

Найти бозон Хиггса (какой именно?) и понять природу возникновения масс

Найти возможных кандидатов в состав темной материи

Найти отклонения от предсказаний Стандартной Модели, обнаружить "новую физику" на ТэВ-ных масштабах

Понять природу CP нарушения и асимметрии Вселенной

Понять поведение адронной материи при сверхвысоких температурах и плотностях (поведение Вселенной в первые мгновения после Большого Взрыва)

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 the Higgs properties

Search for deviations from SM in top quark production (pair/single) and decays, search for anomalous top properties expected for the heaviest SM particle

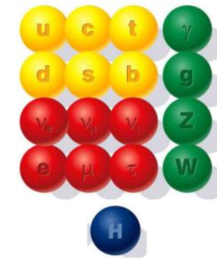
Search for best motivated BSM scenarios:
supersymmetry, extra dimensions, new strong dynamics
Model independent searches (Leptoquarks, Leptogluons, Z', W', …)

Search for any other possible exotics (unparticles, hidden vallyes…)

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

Detail studies of strongly interacting quark-gluon color medium

Standard Model



SU(3)c x SU(2)$_L$ x U(1)$_Y$

$$\mathcal{L}_{\rm SM} = -\frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a - \frac{1}{4}W^a_{\mu\nu}W^{\mu\nu}_a - \frac{1}{4}B_{\mu\nu}B^{\mu\nu}$$
$$+\bar{L}_i\, iD_\mu\gamma^\mu\, L_i + \bar{e}_{Ri}\, iD_\mu\gamma^\mu\, e_{R_i}$$
$$+\bar{Q}_i\, iD_\mu\gamma^\mu\, Q_i + \bar{u}_{Ri}\, iD_\mu\gamma^\mu\, u_{R_i} + \bar{d}_{Ri}\, iD_\mu\gamma^\mu\, d_{R_i}$$
$$+ L_H$$

$$Q^i_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix} \quad \begin{pmatrix} c_L \\ s_L \end{pmatrix} \quad \begin{pmatrix} t_L \\ b_L \end{pmatrix}$$
$$u^i_R = \quad u_R \quad c_R \quad t_R$$
$$d^i_R = \quad d_R \quad s_R \quad b_R$$

$$G^a_{\mu\nu} = \partial_\mu G^a_\nu - \partial_\nu G^a_\mu + g_s f^{abc} G^b_\mu G^c_\nu$$
$$W^a_{\mu\nu} = \partial_\mu W^a_\nu - \partial_\nu W^a_\mu + g_2\,\epsilon^{abc} W^b_\mu W^c_\nu$$
$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$$

$$D_\mu\psi = \left(\partial_\mu - ig_s T_a G^a_\mu - ig_2 T_a W^a_\mu - ig_1 \frac{Y_q}{2} B_\mu\right)\psi$$

$$Y_f = 2Q_f - 2I^3_f \;\Rightarrow\; Y_{L_i} = -1,\; Y_{e_{R_i}} = -2,\; Y_{Q_i} = \frac{1}{3},\; Y_{u_{R_i}} = \frac{4}{3},\; Y_{d_{R_i}} = -\frac{2}{3}$$

SM – quantum field theory describing strong and electroweak forces is based on few fundamental principles:

gauge invariance with lowest dimension operators;

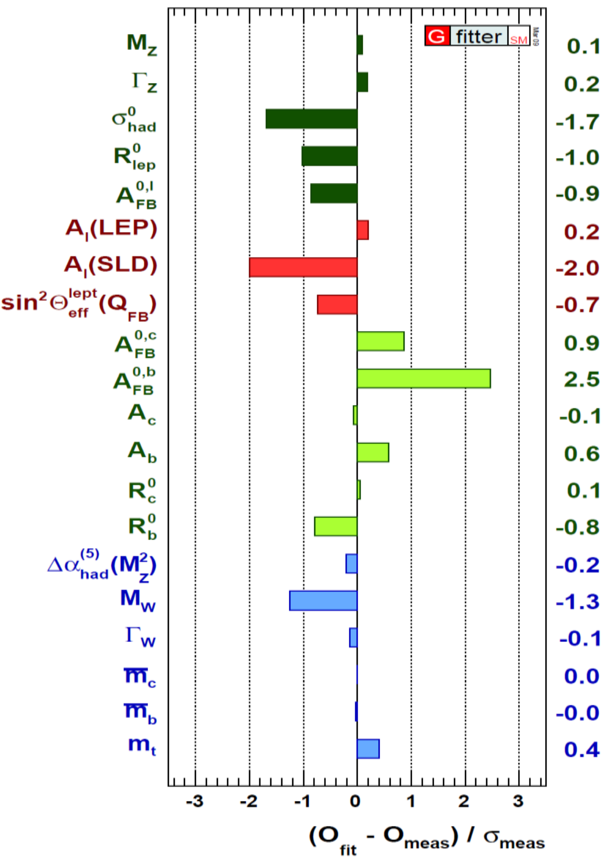
chiral structure of fermions ((V-A) charged currents);

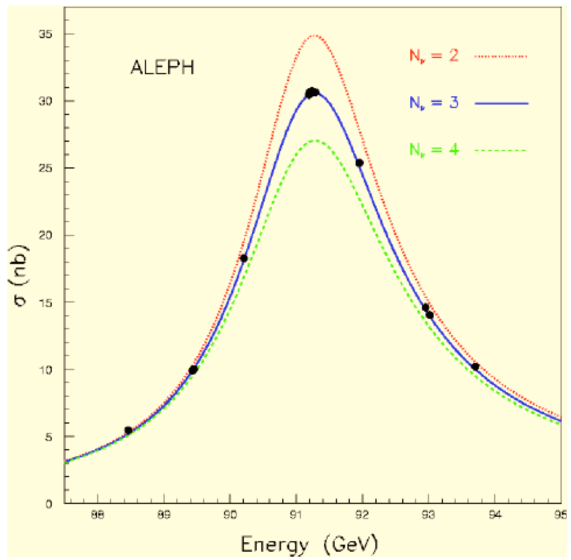
Higgs mechanism of spontaneous symmetry breaking

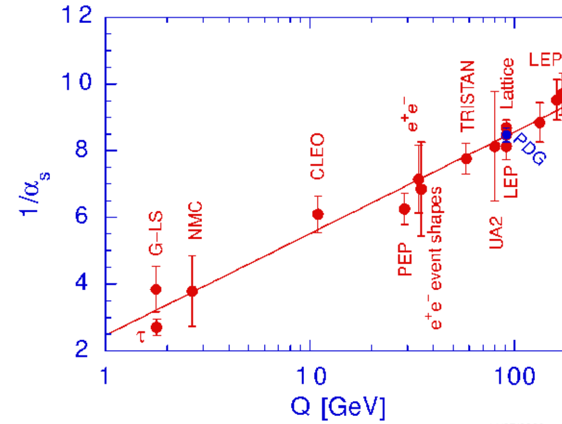
A very elegant theoretical construction! Standard Model – one of the main intellectual achievement for about last 50 years, a result of many theoretical and experimental studies

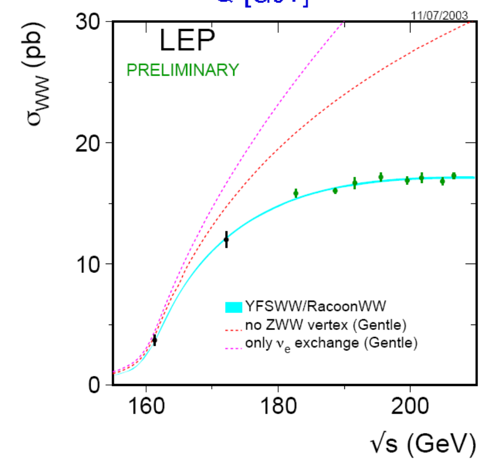
Some remarkable confirmations of the SM gauge structure

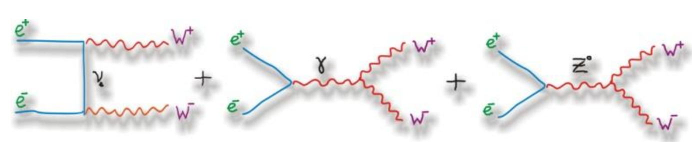
SM: $SU(3)_c \times SU(2)_L \times U(1)_Y$





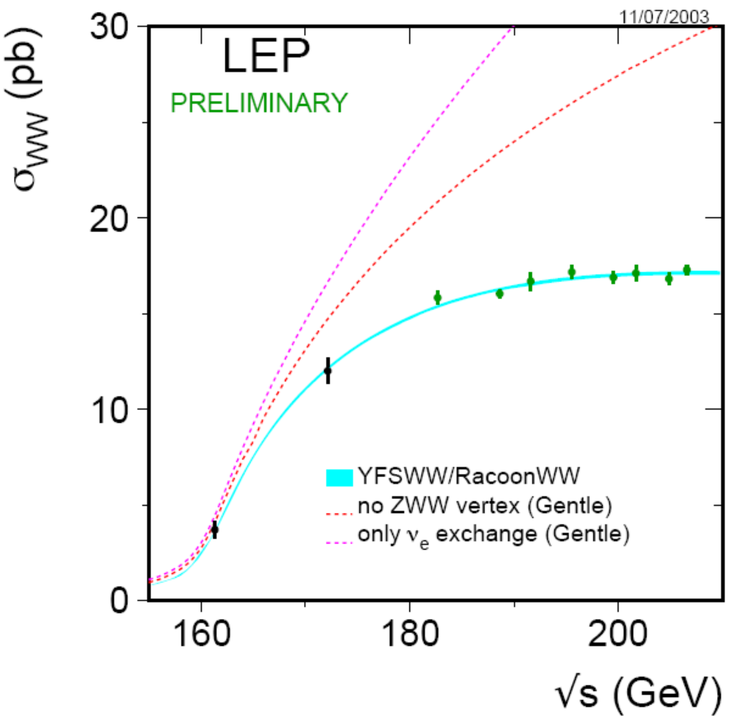


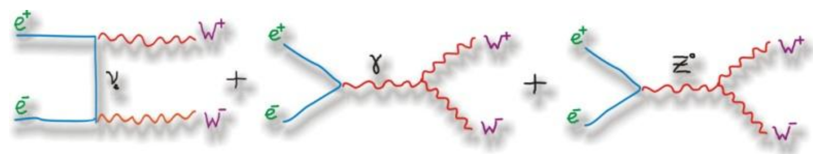




Калибровочная структура взаимодействий очень хорошо установлена

Один из примеров





Взаимодействия инвариантны, а спектр не инвариантен.
Mphoton = 0, MZ = 90 GeV

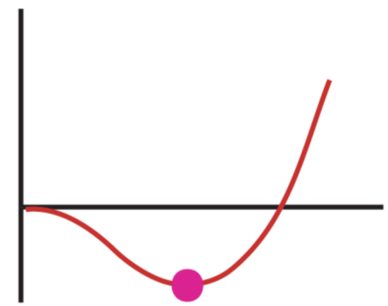
Симметрия спонтанно нарушена

SM provides an elegant solution to make massive simultaneously gauge bosons and fermions without violation of gauge invariance principle and the chiral structure of fermion interactions –
Higgs mechanism of spontaneous symmetry breaking

$$\mathcal{L} = |D_\mu \varphi|^2 - V(|\varphi|) - \frac{1}{4}(F^a_{\mu\nu})^2 - \frac{1}{4}(G_{\mu\nu})^2$$
$$-\mathrm{f_e}(\bar{\mathrm{e}}, \bar{\nu})_\mathrm{L} \Phi \mathrm{e_R} - \mathrm{f_d}(\bar{\mathrm{u}}, \bar{\mathrm{d}})_\mathrm{L} \Phi \mathrm{d_R} - \mathrm{f_u}(\bar{\mathrm{u}}, \bar{\mathrm{d}})_\mathrm{L} \tilde{\Phi} \mathrm{u_R}$$

$$V(|\varphi|) = \mu^2 |\varphi|^2 + \lambda |\varphi|^4$$
$$\varphi = \begin{pmatrix} \pi^+ \\ (v + h + i\pi^0)/\sqrt{2} \end{pmatrix}$$

$$\mu^2 < 0$$



Golstone bosons $\pi^\pm, \pi^0$ are "eaten" by the longitudinal components of becoming massive gauge bosons

$$|D_\mu \Phi)|^2 = \left| \left(\partial_\mu - i g_2 \frac{\tau_a}{2} W^a_\mu - i g_1 \frac{1}{2} B_\mu \right) \Phi \right|^2$$

$$M_W^2 W^+_\mu W^{-\mu} + \frac{1}{2} M_Z^2 Z_\mu Z^\mu + \frac{1}{2} M_A^2 A_\mu A^\mu$$

$$W^\pm = \frac{1}{\sqrt{2}}(W^1_\mu \mp i W^2_\mu) \ , \ Z_\mu = \frac{g_2 W^3_\mu - g_1 B_\mu}{\sqrt{g_2^2 + g_1^2}} \ , \ A_\mu = \frac{g_2 W^3_\mu + g_1 B_\mu}{\sqrt{g_2^2 + g_1^2}}$$

$$A \equiv B \cos\theta_W + W^3 \sin\theta_W$$
$$Z \equiv -B \sin\theta_W + W^3 \cos\theta_W$$

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

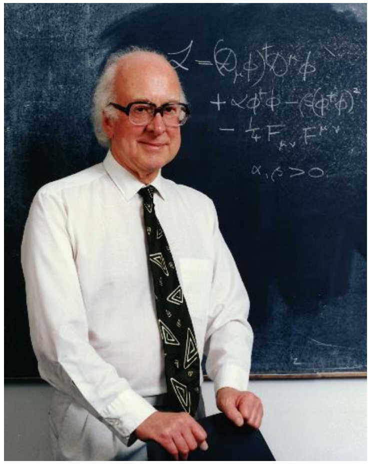
$$\frac{G_F}{\sqrt{2}} = \frac{g_2^2}{8 M_W^2}$$

$$\mathcal{L}_\mathrm{Yuk} = -\mathrm{f_e}(\bar{\mathrm{e}}, \bar{\nu})_\mathrm{L} \Phi \mathrm{e_R} - \mathrm{f_d}(\bar{\mathrm{u}}, \bar{\mathrm{d}})_\mathrm{L} \Phi \mathrm{d_R} - \mathrm{f_u}(\bar{\mathrm{u}}, \bar{\mathrm{d}})_\mathrm{L} \tilde{\Phi} \mathrm{u_R}$$

$$\Phi \to \frac{1}{\sqrt{2}} \binom{0}{\mathrm{H+v}} \Rightarrow \mathrm{m_e} = \frac{\mathrm{f_e\, v}}{\sqrt{2}}, \ \mathrm{m_u} = \frac{\mathrm{f_u\, v}}{\sqrt{2}}, \ \mathrm{m_d} = \frac{\mathrm{f_d\, v}}{\sqrt{2}}$$

v= 246 GeV

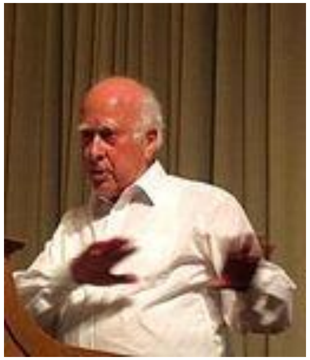
Бозон Хиггса



Массы кварков и лептонов

Массы W и Z бозонов

Унитарное поведение и перенормируемость СМ



Brout–Englert–Higgs –Hagen–Guralnik–Kibble mechanism

[4] F. Englert, R. Brout, Phys. Rev. Lett. 13 (1964) 321, doi:10.1103/PhysRevLett.13.321.

[5] P.W. Higgs, Phys. Lett. 12 (1964) 132, doi:10.1016/0031-9163(64)91136-9.

[6] P.W. Higgs, Phys. Rev. Lett. 13 (1964) 508, doi:10.1103/PhysRevLett.13.508.

[7] G. Guralnik, C. Hagen, T.W.B. Kibble, Phys. Rev. Lett. 13 (1964) 585, doi:10.1103/PhysRevLett.13.585.

[8] P.W. Higgs, Phys. Rev. 145 (1966) 1156, doi:10.1103/PhysRev.145.1156.

[9] T.W.B. Kibble, Phys. Rev. 155 (1967) 1554, doi:10.1103/PhysRev.155.1554.

Что нам известно о бозоне Хиггса СМ?

Прямые поиски

Петлевые вклады и сравнение с экпериментальными ошибками

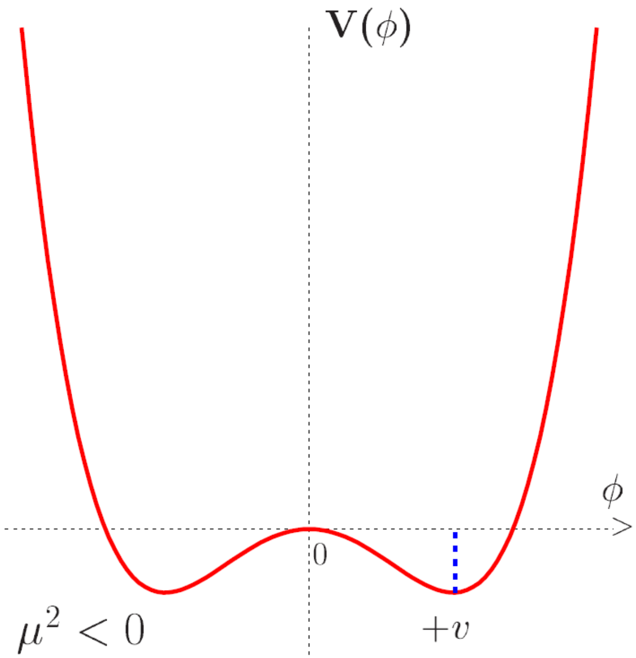
Ограничения из условия унитарности

Ограничения из самосогласованности теории

Еще раз вспомним потенциал самодействия поля Хиггса

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

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

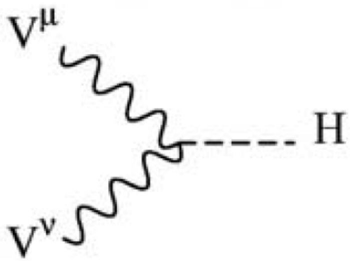


$$\mathcal{L}_{\mathrm{H}} = \frac{1}{2}(\partial_\mu \mathrm{H})(\partial^\mu \mathrm{H}) - \mathrm{V} = \frac{1}{2}(\partial^\mu \mathrm{H})^2 - \lambda \mathrm{v}^2 \mathrm{H}^2 - \lambda \mathrm{v}\, \mathrm{H}^3 - \frac{\lambda}{4} \mathrm{H}^4$$

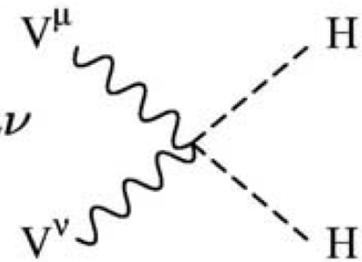
$$\mathbf{M_H^2 = 2\lambda v^2 = -2\mu^2}$$

Вершины взаимодействия бозона Хиггса в СМ

С EW бозонами:

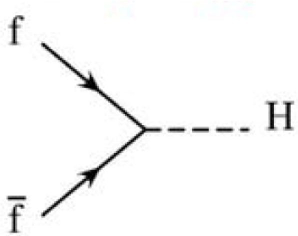


$$= 2i\frac{M_V^2}{v}g^{\mu\nu}$$



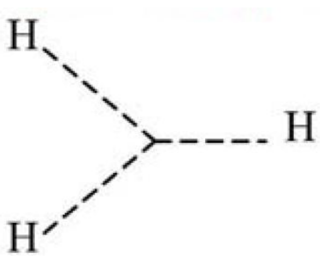
$$= 2i\frac{M_V^2}{v^2}g^{\mu\nu}$$

С фермионами:

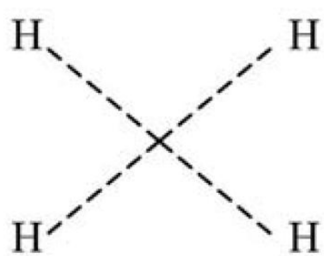


$$= -i\frac{m_f}{v}$$

Самодействие:



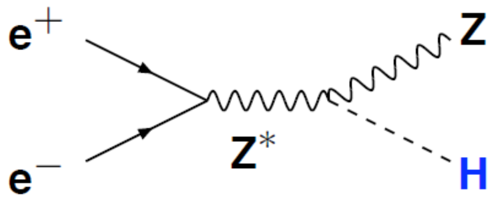
$$= -3i\frac{M_H^2}{v}$$

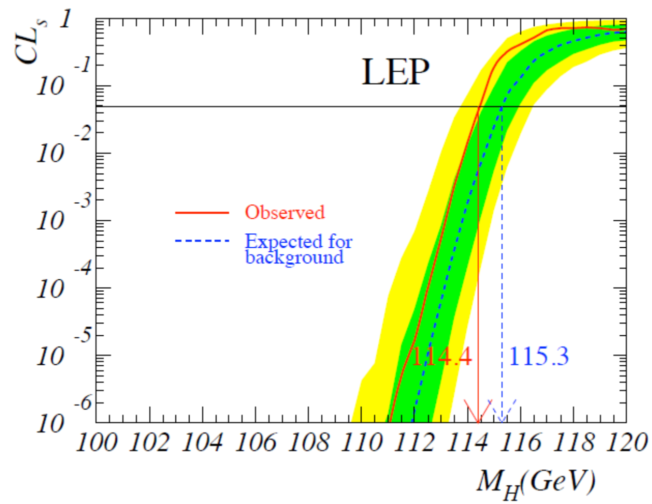


$$= -3i\frac{M_H^2}{v^2}$$

What did we know about SM Higgs boson before the LHC?

1. Direct serches:

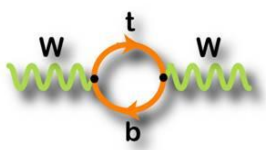


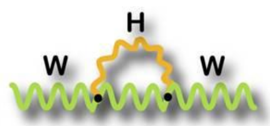


M_H > 114.4 GeV 95% C.L.

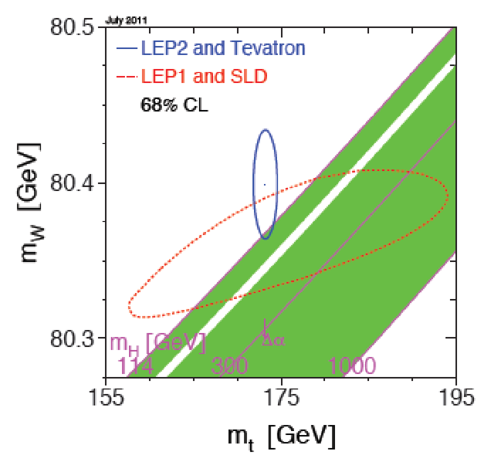
Tevatron (in gluon fusion with decay to WW):
Excluded region
M_H : 160-170 GeV

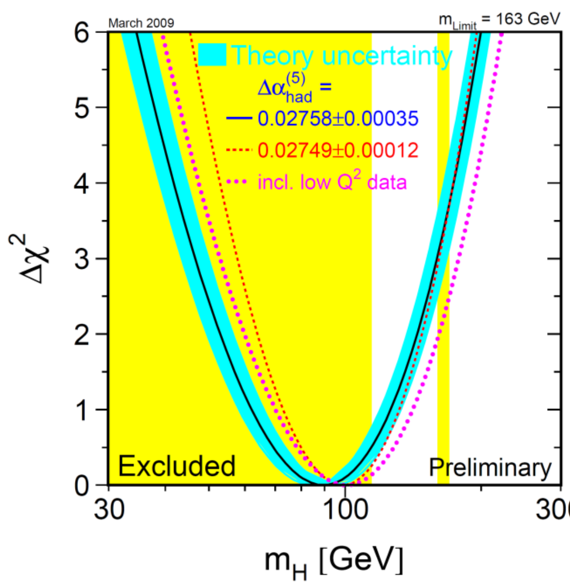
2. From loop corrections:





$$(\Delta r)_{\rm top} \approx -\frac{3G_F m_t^2}{8\sqrt{2}\pi^2}\frac{1}{t_W^2} \qquad (\Delta r)_{\rm Higgs} \approx \frac{11 G_F M_Z^2 c_W^2}{24\sqrt{2}\pi^2}\ln\frac{m_h^2}{M_Z^2}$$





M_H < 155 GeV 95% C.L.

Ограничения из унитарности

Процесс 2->2, хорошо известное из квантовой механики разложение амплитуды по полиномам Лежандра

$$\frac{d\sigma}{d\Omega} = \frac{1}{64\pi^2 s}|A|^2 \quad A = 16\pi\sum_{l=0}^{\infty}(2l+1)P_l(\cos\theta)a_l \quad \int_{-1}^{1} dx P_l(x)P_{l'}(x) = \frac{2\delta_{l,l'}}{2l+1}$$

$$\sigma = \frac{8\pi}{s}\sum_{l=0}^{\infty}(2l+1)\sum_{l'=0}^{\infty}(2l'+1)a_l a_{l'}^* \int_{-1}^{1} d\cos\theta P_l(\cos\theta)P_{l'}(\cos\theta)$$

$$= \frac{16\pi}{s}\sum_{l=0}^{\infty}(2l+1)|a_l|^2$$

выражается

Оптическая теорема:

$$\sigma = \frac{1}{s}\mathrm{Im}[A(\theta=0)] = \frac{16\pi}{s}\sum_{l=0}^{\infty}(2l+1)|a_l|^2 \qquad \mathrm{Im}(a_l) = |a_l|^2$$

$$[\mathrm{Re}(a_\ell)]^2 + [\mathrm{Im}(a_\ell) - \frac{1}{2}]^2 = \frac{1}{4} \qquad |\mathrm{Re}(a_l)| \le \frac{1}{2}$$

Рассмотрим поведение амплитуд рассеяния W и Z бозонов при энергиях много больших их масс.

Вместо прямого вычисления диаграмм WW->WW воспользуемся Электрослабой Теоремой Эквивалентности:

$$A(V^1\cdots V^n \to V^1 \cdots V^{n'}) \sim A(V_L^1\cdots V_L^n \to V_L^1 \cdots V_L^{n'}) \sim A(w^1\cdots w^n \to w^1 \cdots w^{n'})$$

$$\epsilon_L^\mu = \left(\frac{|\vec{p}|}{M_V}, 0, 0, \frac{E}{M_V}\right) \xrightarrow{E\gg M_V} \frac{p_\mu}{M_V}$$

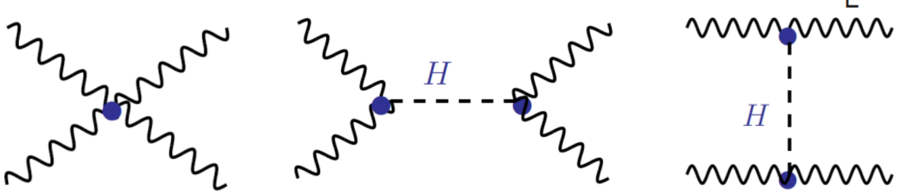
w – это Голстоуновский бозон, который в унитарной калибровке становится продольной модой W-бозона

Потенциал взаимодействия поля Хиггса с Голстоуновскими бозонами:

$$V = \frac{M_H^2}{2v}(H^2 + w_0^2 + 2w^+w^-)H + \frac{M_H^2}{8v^2}(H^2 + w_0^2 + 2w^+w^-)^2$$

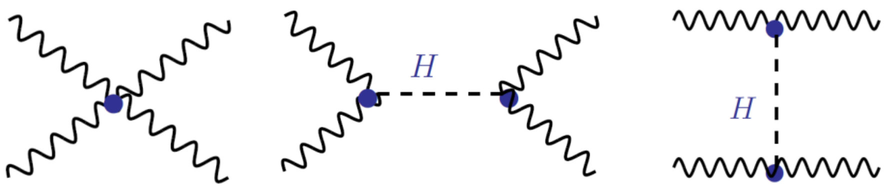
$w^+ w^- \to w^+ w^-$

$$A(w^+w^- \to w^+w^-) = -\left[2\frac{M_H^2}{v^2} + \left(\frac{M_H^2}{v}\right)^2 \frac{1}{s - M_H^2} + \left(\frac{M_H^2}{v}\right)^2 \frac{1}{t - M_H^2}\right]$$



Амплитуда рассеяния двух голстоуновских бозонов:

w+ w- -> w+ w-



$$A(w^+w^- \to w^+w^-) = -\left[2\frac{M_H^2}{v^2} + \left(\frac{M_H^2}{v}\right)^2 \frac{1}{s - M_H^2} + \left(\frac{M_H^2}{v}\right)^2 \frac{1}{t - M_H^2}\right]$$

Амплитуда для J=0:

$$a_0 = \frac{1}{16\pi s}\int_s^0 \mathrm{d}t|A| = -\frac{M_H^2}{16\pi v^2}\left[2 + \frac{M_H^2}{s - M_H^2} - \frac{M_H^2}{s}\log\left(1 + \frac{s}{M_H^2}\right)\right]$$

Два режима (либо Хиггс, либо new physics):

$$|\mathrm{Re}(a_l)| \leq \frac{1}{2}$$

С учетом всех каналов

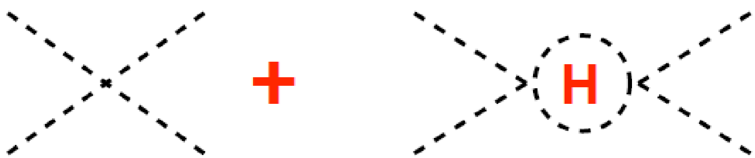
$$a_0 \xrightarrow{s \gg M_H^2} -\frac{M_H^2}{8\pi v^2} \qquad M_H \lesssim 870 \text{ GeV} \qquad (M_H \lesssim 710 \text{ GeV})$$

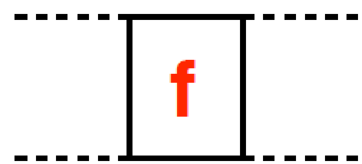
$$a_0 \xrightarrow{s \ll M_H^2} -\frac{s}{32\pi v^2} \qquad \sqrt{s} \lesssim 1.7 \text{ TeV} \qquad (\sqrt{s} \lesssim 1.2 \text{ TeV})$$

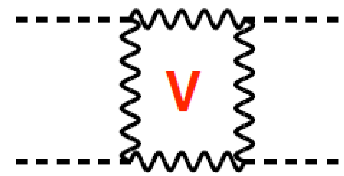
Ограничения из “тривиальности” и “стабильности”

Однопетлевое уравнение ренормгруппы:

$$\frac{\mathrm{d}\lambda}{\mathrm{d}\log Q^2} \simeq \frac{1}{16\pi^2}\left[12\lambda^2 + 6\lambda\lambda_t^2 - 3\lambda_t^4 - \frac{3}{2}\lambda(3g_2^2 + g_1^2) + \frac{3}{16}\left(2g_2^4 + (g_2^2 + g_1^2)^2\right)\right]$$







Доминирует при больших λ

$$\frac{\mathrm{d}}{\mathrm{d}Q^2}\lambda(Q^2) = \frac{3}{4\pi^2}\lambda^2(Q^2)$$

$$\lambda(Q^2) = \lambda(v^2)\left[1 - \frac{3}{4\pi^2}\lambda(v^2)\log\frac{Q^2}{v^2}\right]^{-1}$$

Полюс Ландау

$$\Lambda_C = v\,\exp\left(\frac{4\pi^2}{3\lambda}\right) = v\,\exp\left(\frac{4\pi^2 v^2}{M_H^2}\right)$$

Доминирует при малых λ

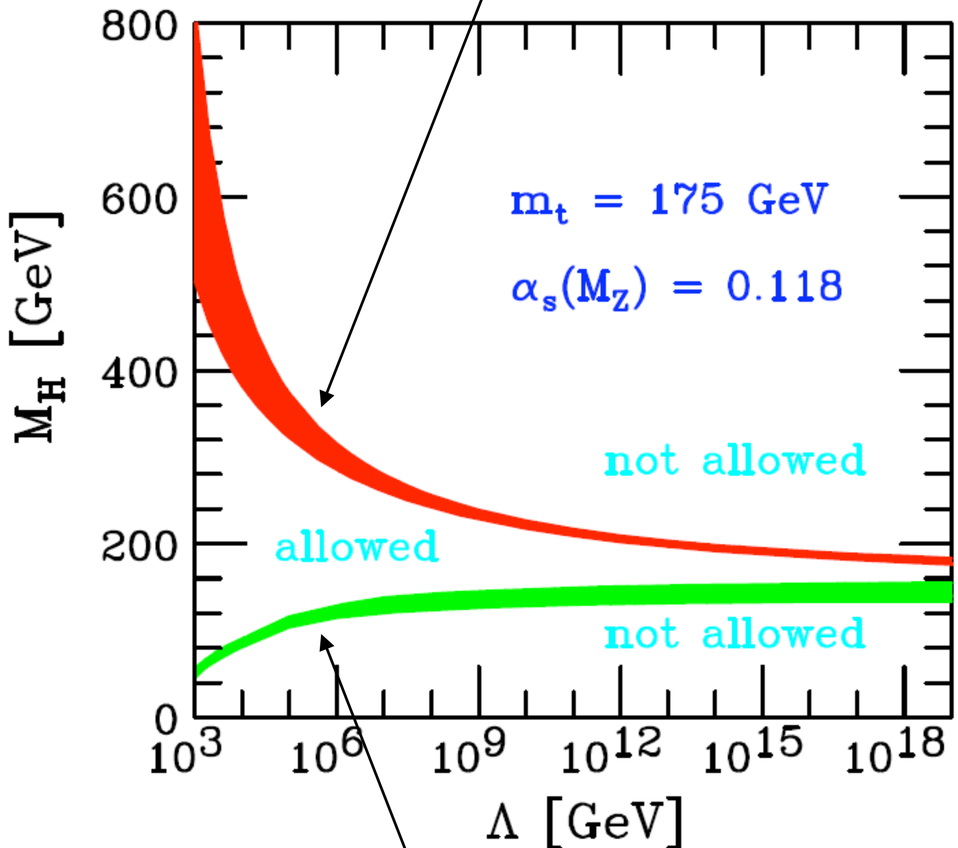
$$\lambda(Q^2) = \lambda(v^2) +$$

$$\frac{1}{16\pi^2}\left[-12\frac{m_t^4}{v^4} + \frac{3}{16}\left(2g_2^4 + (g_2^2 + g_1^2)^2\right)\right]\log\frac{Q^2}{v^2}$$

$$M_H^2 > \frac{v^2}{8\pi^2}\left[-12\frac{m_t^4}{v^4} + \right.$$

$$\left.\frac{3}{16}\left(2g_2^4 + (g_2^2 + g_1^2)^2\right)\right]\log\frac{Q^2}{v^2}$$

Не достигается полюс Ландау (тривиальность теории)



$$\Lambda_C \sim 10^3 \text{ GeV} \Rightarrow$$

$$70 \text{ GeV} \lesssim M_H \lesssim 700 \text{ GeV}$$

$$\Lambda_C \sim 10^{16} \text{ GeV} \Rightarrow$$

$$120 \text{ GeV} \lesssim M_H \lesssim 180 \text{ GeV}$$

Константа самодействия положительна (стабильность)

$$\lambda(Q^2) > 0$$

3. From the unitariry of VV->VV (V: W,Z) amplitudes:

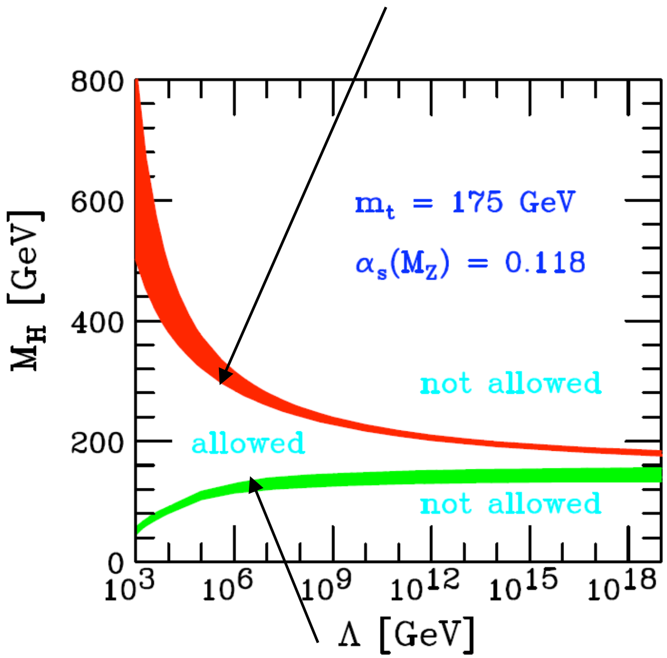
$$\mathrm{Im}(a_l) = |a_l|^2 \qquad |\mathrm{Re}(a_l)| \leq \frac{1}{2}$$

$M_H \lesssim 710$ 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:

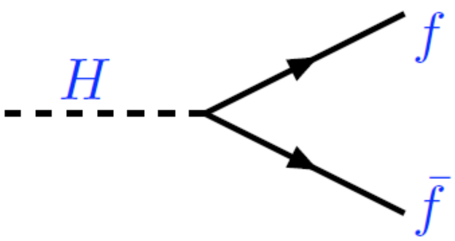
No Landau pole (triiviality)



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

Распады СМ Хиггса

В фермион-антифермионные пары



$$\Gamma_{\rm Born}(\mathrm{H} \to \mathrm{f}\bar{\mathrm{f}}) = \frac{\mathrm{G}_\mu \mathrm{N}_\mathrm{c}}{4\sqrt{2}\pi} \mathrm{M}_\mathrm{H}\, \mathrm{m}_\mathrm{f}^2\, \beta_\mathrm{f}^3$$

$$\beta_\mathrm{f} = \sqrt{1 - 4\mathrm{m}_\mathrm{f}^2/\mathrm{M}_\mathrm{H}^2}$$

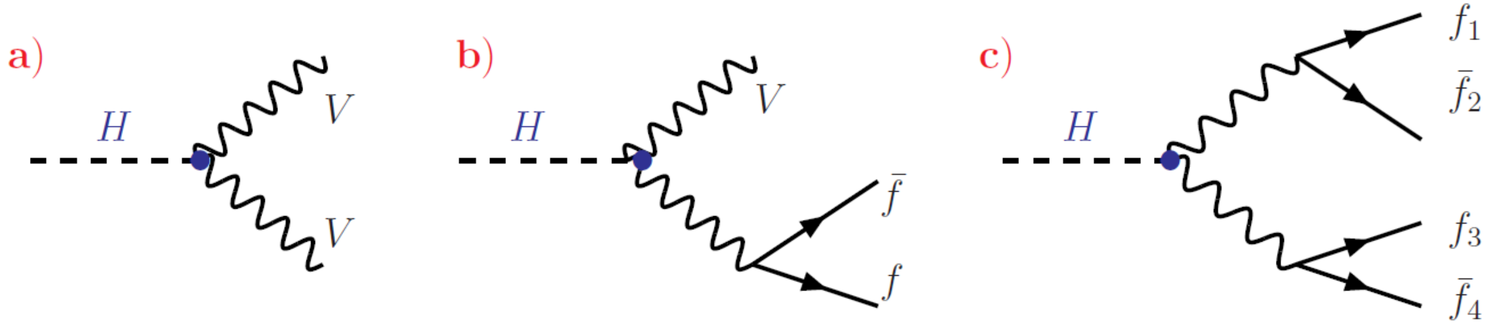
$\mathrm{b}\bar{\mathrm{b}}, \mathrm{c}\bar{\mathrm{c}}, \tau^+\tau^-, \mu^+\mu^-$ для $M_H < 2\, M_{top}$

Основная часть QCD поправки – перенормировка массы $m_f(m_f) \to m_f(M_H)$

$$\Gamma \propto \Gamma_0[1 - \frac{\alpha_s}{\pi} \log \frac{\mathrm{M}_\mathrm{H}^2}{\mathrm{m}_\mathrm{q}^2}] \qquad \mathrm{m_b}(\mathrm{M}_\mathrm{H}^2) \sim \frac{2}{3} \mathrm{m}_\mathrm{b}^{\rm pole} \sim 3\,\mathrm{GeV}$$

На сегодняшний день известны поправки: QCD – 3 loop, EW - 1 loop

Распады в калибровочные бозоны



a) 2 onshell b) 1 onshell, 1 offshell c) 2 offshell

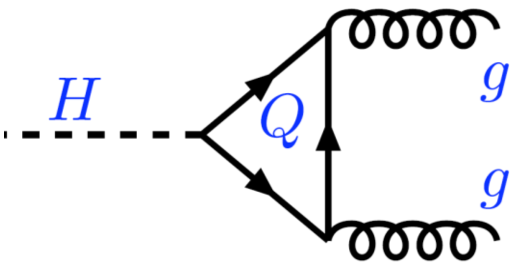
$$\Gamma(H \to VV) = \frac{G_\mu M_H^3}{16\sqrt{2}\pi} \delta_V \sqrt{1-4x}\,(1-4x+12x^2)$$

$$\mathbf{x = M_V^2/M_H^2,\ \beta_V = \sqrt{1-4x}}$$
$$\mathbf{\delta_W = 2,\ \delta_Z = 1}$$

Быстро растет как M_H^3

$$\Gamma(H \to WW + ZZ) \sim 0.5\ \text{TeV}\ [M_H/1\ \text{TeV}]^3$$

Распад в два глюона (начинается с одной петли)



$$\Gamma\left(H \to gg\right) = \frac{G_\mu\, \alpha_s^2\, M_H^3}{36\sqrt{2}\,\pi^3} \left| \frac{3}{4} \sum_Q A_{1/2}^H(\tau_Q) \right|^2$$

$$\mathbf{A^H_{1/2}}(\tau) = \mathbf{2}[\tau + (\tau - \mathbf{1})\mathbf{f}(\tau)]\,\tau^{-\mathbf{2}}$$

$$\mathbf{f}(\tau) = \arcsin^{\mathbf{2}}\sqrt{\tau}\ \mathbf{for}\ \tau = \mathbf{M_H^2/4m_Q^2} \le \mathbf{1}$$

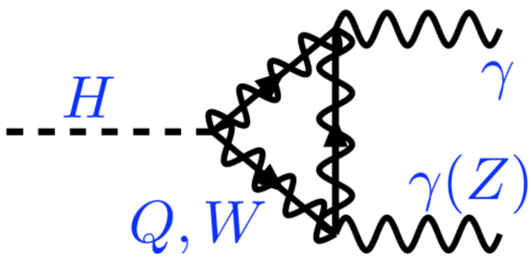
$$\mathbf{m_Q} \to \infty, \tau_\mathbf{Q} \sim \mathbf{0} \Rightarrow \mathbf{A_{1/2}} = \frac{\mathbf{4}}{\mathbf{3}} = \textbf{constant}$$

В СМ важен только вклад t-кварка (вклад b-кварка < 5 %)

Большие QCD поправки:

$$\mathbf{\Gamma = \Gamma_0[1 + 18\frac{\alpha_s}{\pi} + 156\frac{\alpha_s^2}{\pi^2}] \sim \Gamma_0[1 + 0.7 + 0.3] \sim 2\Gamma_0}$$

Распады в фотоны и Z бозон



$$\Gamma = \frac{G_\mu\, \alpha^2\, M_H^3}{128\,\sqrt{2}\,\pi^3} \left| \sum_f N_c e_f^2 A_{\frac{1}{2}}^H(\tau_f) + A_1^H(\tau_W) \right|^2$$

$$A_{1/2}^H(\tau) = 2[\tau + (\tau - 1) f(\tau)]\,\tau^{-2}$$

$$A_1^H(\tau) = -[2\tau^2 + 3\tau + 3(2\tau - 1) f(\tau)]\,\tau^{-2}$$

(Формула для распада γZ сложнее)

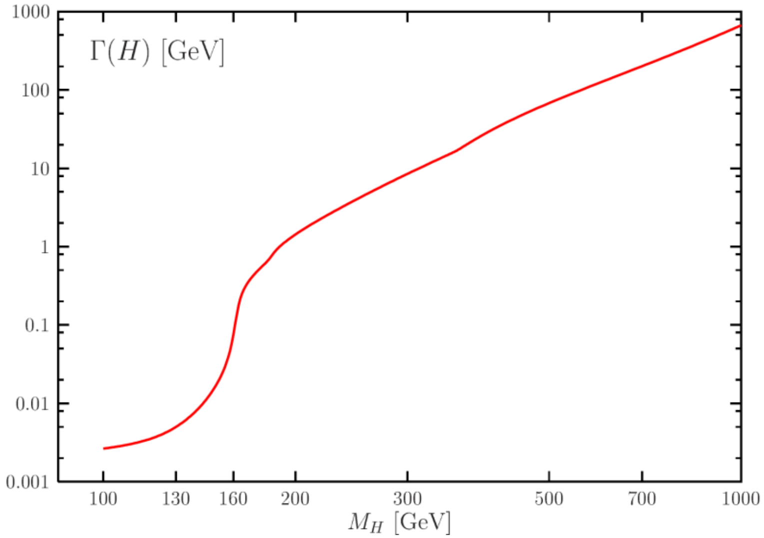
Дают вклад петли t-кварка и W-бозона. В пределе:

$$m_i \to \infty \Rightarrow A_{1/2} = \frac{4}{3} \text{ and } A_1 = -7$$

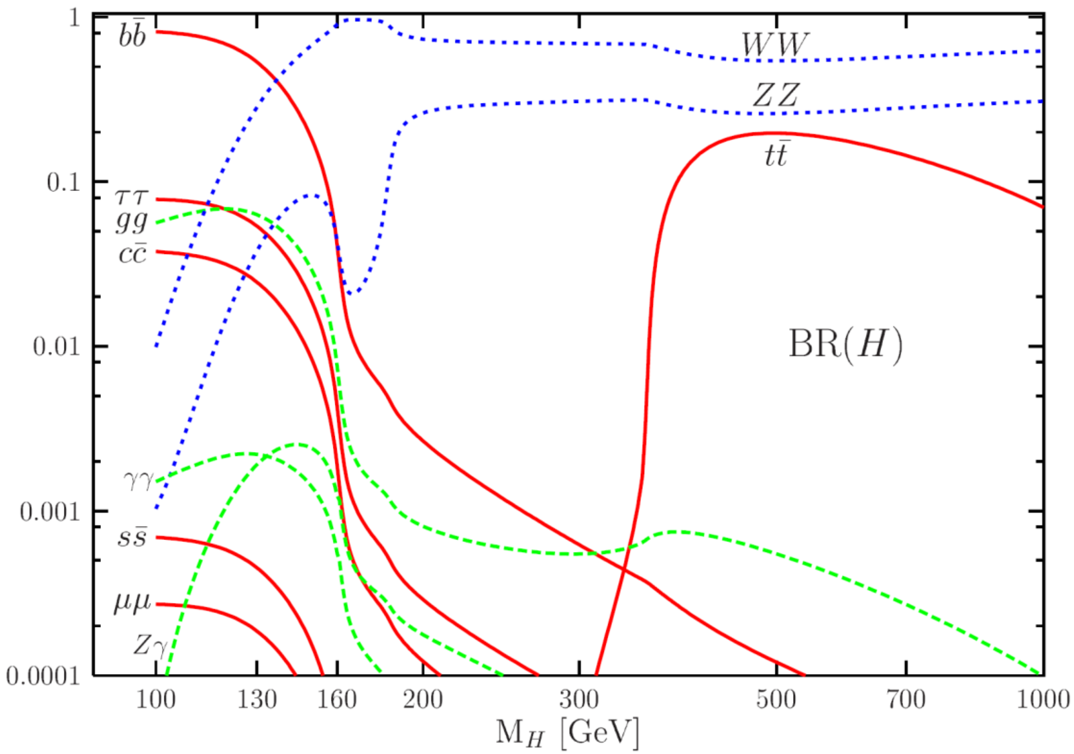
QCD поправки достаточно малы: $\frac{\alpha_s}{\pi} \sim 5\%$

Ширина распада H->γγ “подсчитывает” тяжелые заряженные частицы, взаимодействующие с бозоном Хиггса

Распад исключительно важен для поисков на LHC



Полная ширина мала для легкого бозона Хиггса и велика для тяжелого



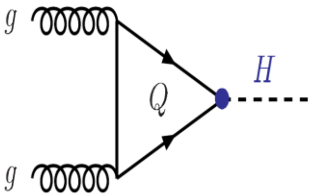
$M_H \lesssim 130$ GeV:

- $H \to b\bar{b}$ dominant, BR = 60–90%
- $H \to \tau^+\tau^-, c\bar{c}, gg$ BR= a few %
- $H \to \gamma\gamma, \gamma Z$, BR = a few permille.

$M_H \gtrsim 130$ GeV:

- $H \to WW^*, ZZ^*$ up to $\gtrsim 2M_W$
- $H \to WW, ZZ$ above (BR $\to \frac{2}{3}, \frac{1}{3}$)
- $H \to t\bar{t}$ for high M_H; BR $\lesssim 20\%$.

gg - fusion

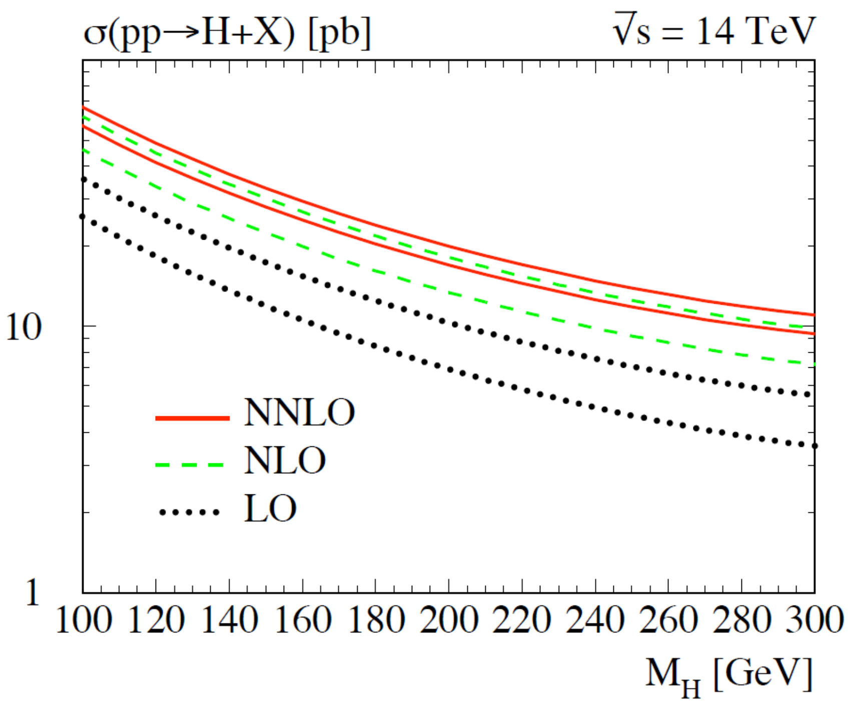


$$\hat{\sigma}(gg \to H) = \int \frac{1}{2\hat{s}} \times \frac{1}{2\cdot 8} \times \frac{1}{2\cdot 8} |\mathcal{M}_{Hgg}|^2 \frac{d^3 p_H}{(2\pi)^3 2E_H} (2\pi^4)\delta^4(q - p_H)$$

$$\hat{\sigma}_{LO}(gg \to H) = \frac{\pi^2}{8M_H} \Gamma_{LO}(H \to gg)\delta(\hat{s} - M_H^2)$$

$$\sigma_0^H = \frac{G_\mu \alpha_s^2(\mu_R^2)}{288\sqrt{2}\pi} \left| \frac{3}{4} \sum_q A_{1/2}^H(\tau_Q) \right|^2$$

Ведущий механизм рождения

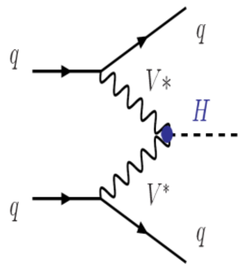


Результат стабилизируется по отношению к варированию factirization and normalization scales

$$\sigma = \int_0^1 dx_1 \int_0^1 dx_2$$
$$\frac{\pi^2 M_H}{8\hat{s}} \Gamma(H \to gg) g(x_1) g(x_2) \delta(\hat{s} - M_H^2)$$

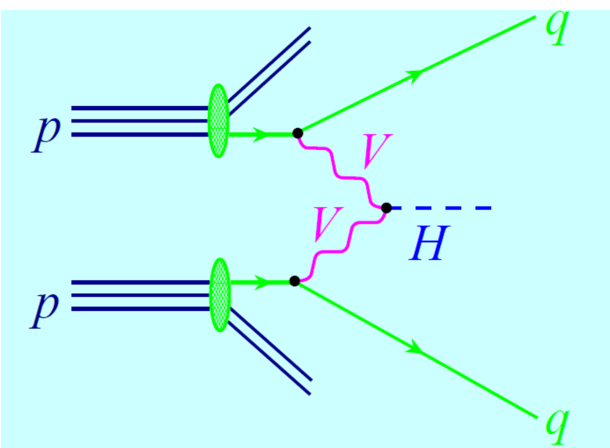
Vector boson fusion

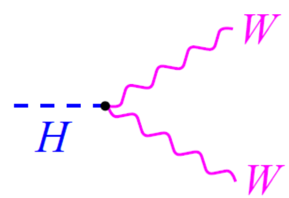
В приближении эффективных бозонов:



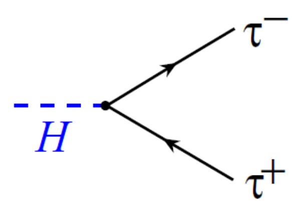
$$\hat{\sigma}_{\mathrm{LO}} = \frac{16\pi^2}{M_H^3}\Gamma(H \to V_L V_L)\frac{d\mathcal{L}}{d\tau}\Big|_{V_L V_L/qq}$$

$$\frac{d\mathcal{L}}{d\tau}\Big|_{V_L V_L/qq} \sim \frac{\alpha}{4\pi^3}(v_q^2 + a_q^2)^2 \log\left(\frac{\hat{s}}{M_H^2}\right)$$

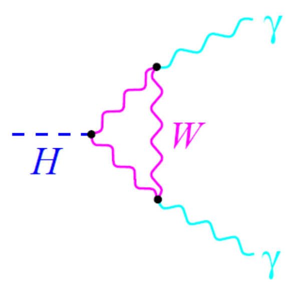




$m_H > 120$ GeV

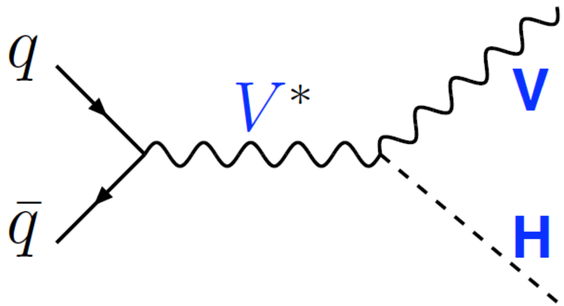


$m_H < 140$ GeV



$m_H < 150$ GeV

The associated HV production:



$$\hat{\sigma}_{\rm LO}(\mathbf{q\bar{q}} \to \mathbf{VH}) = \frac{\mathbf{G}_\mu^2 \mathbf{M_V^4}}{\mathbf{288}\pi\hat{\mathbf{s}}}$$

$$\times(\hat{\mathbf{v}}_\mathbf{q}^2 + \hat{\mathbf{a}}_\mathbf{q}^2)\lambda^{1/2}\frac{\lambda + \mathbf{12M_V^2}/\hat{\mathbf{s}}}{(\mathbf{1} - \mathbf{M_V^2}/\hat{\mathbf{s}})^2}$$

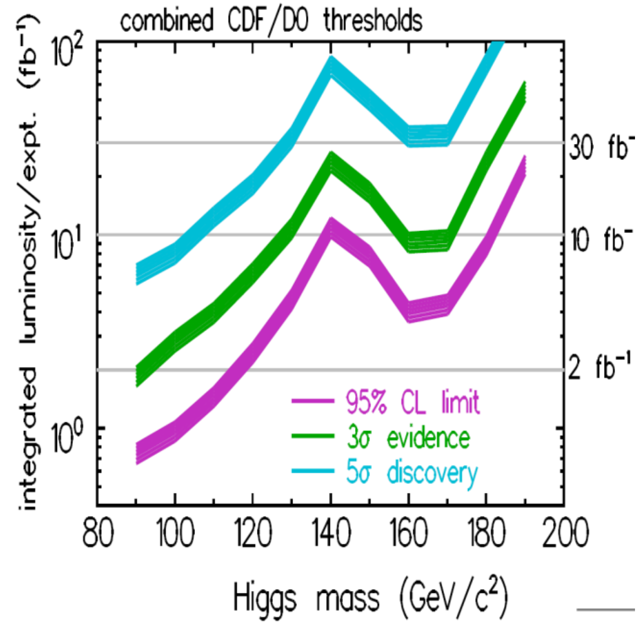
Основной канал поиска Tevatron

$M_H \lesssim 130$ **GeV: H⟶ bb**

$\Rightarrow \ell\nu b\bar{b},\ \nu\bar{\nu}b\bar{b},\ \ell^+\ell^- b\bar{b}$

$M_H \gtrsim 130$ **GeV: H⟶ WW***

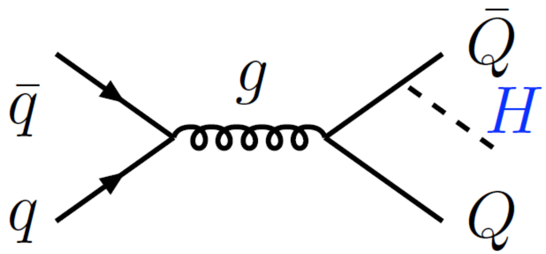
$\Rightarrow \ell^\pm\ell^\pm jj,\ 3\ell^\pm$

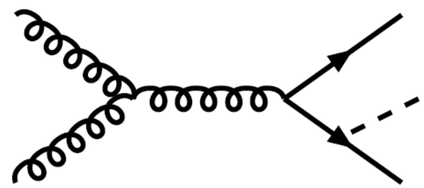


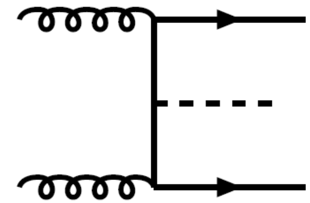
D0/CDF: область 160-170 GeV исключена

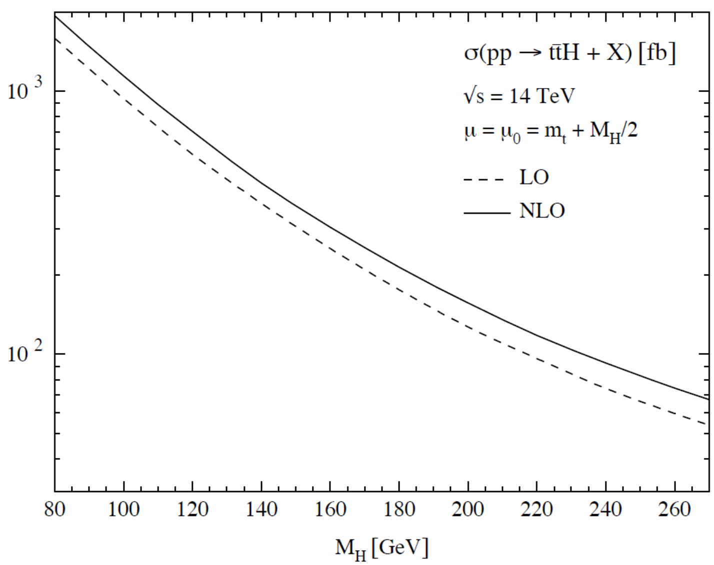
Lot of studies at LHC in $\gamma\gamma$, bb, WW*, $\tau^+\tau^-$ modes

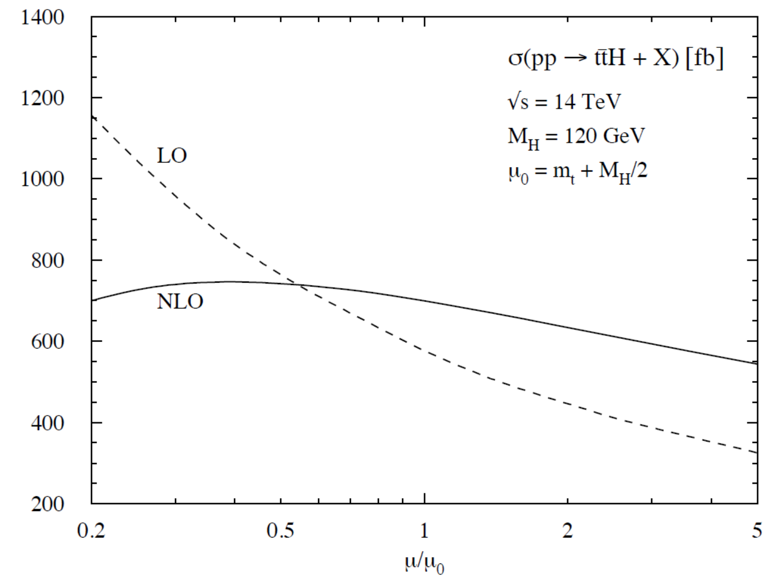
ttH production









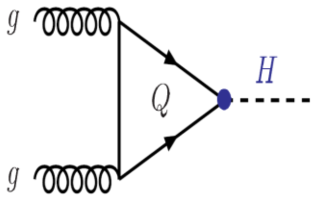


K-factor ~ 1.2

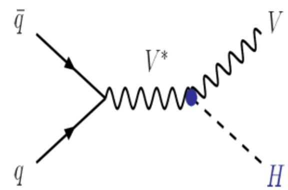
Less scale dependence

Top Yukawa coupling could be measured with 16% accuracy at low lumi and 11% at high lumi regime

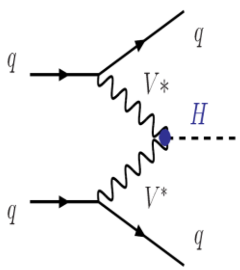
4 main SM Higgs production modes at LHC



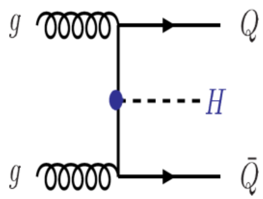
Gluon-gluon fusion



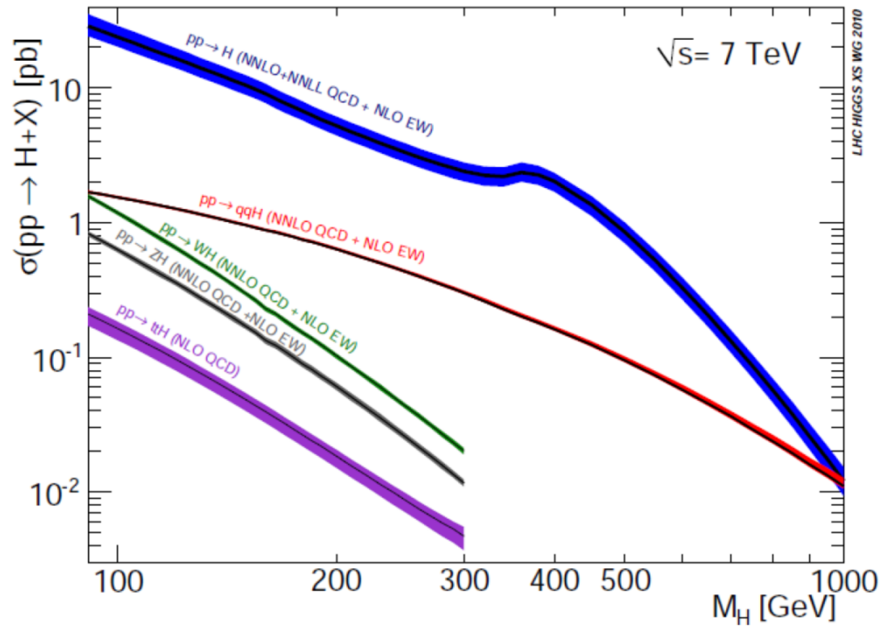
W/Z-Higgs associated



Vector boson fusion



t t-bar Higgs associated



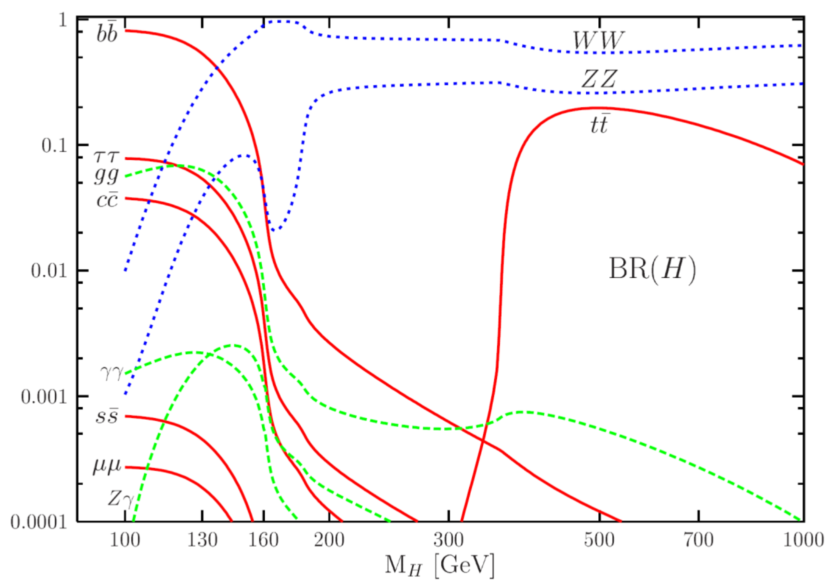
Main decay modes

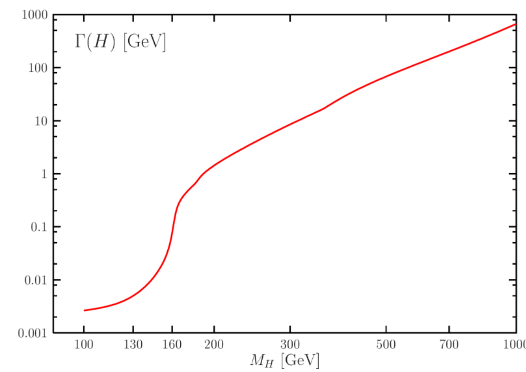
$\mathrm{M_H} \lesssim 130$ **GeV:**

- $\mathrm{H} \to \mathrm{b\bar{b}}$ **dominant, BR = 60–90%**
- $\mathrm{H} \to \tau^+\tau^-, \mathrm{c\bar{c}}, \mathrm{gg}$ **BR= a few %**
- $\mathrm{H} \to \gamma\gamma, \gamma\mathrm{Z}$, **BR = a few permille.**

$\mathrm{M_H} \gtrsim 130$ **GeV:**

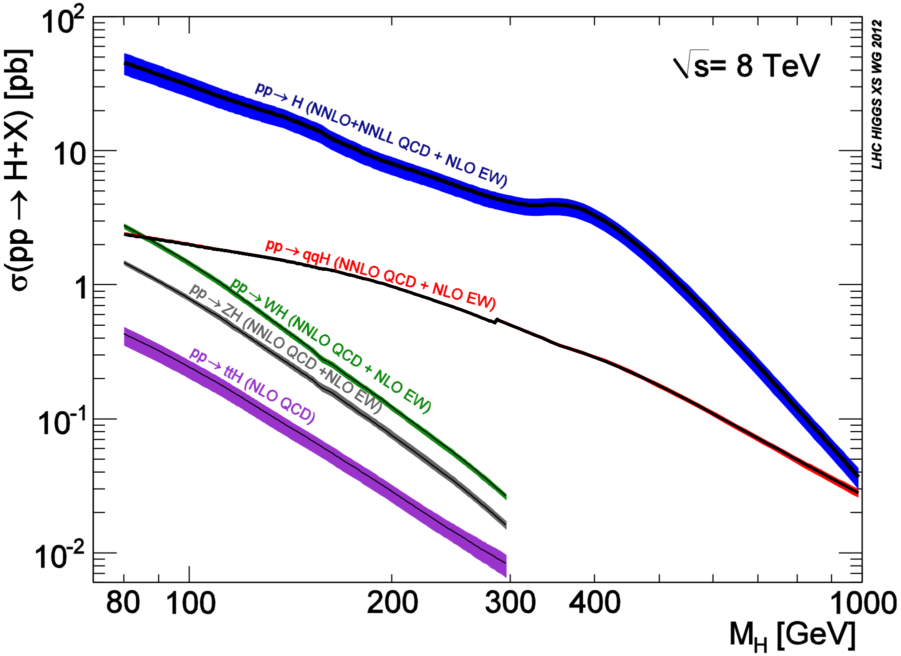
- $\mathrm{H} \to \mathrm{WW}^*, \mathrm{ZZ}^*$ **up to** $\gtrsim 2\mathrm{M_W}$
- $\mathrm{H} \to \mathrm{WW}, \mathrm{ZZ}$ **above (BR** $\to \frac{2}{3}, \frac{1}{3}$**)**
- $\mathrm{H} \to \mathrm{t\bar{t}}$ **for high** $\mathrm{M_H}$**; BR** $\lesssim 20\%$.

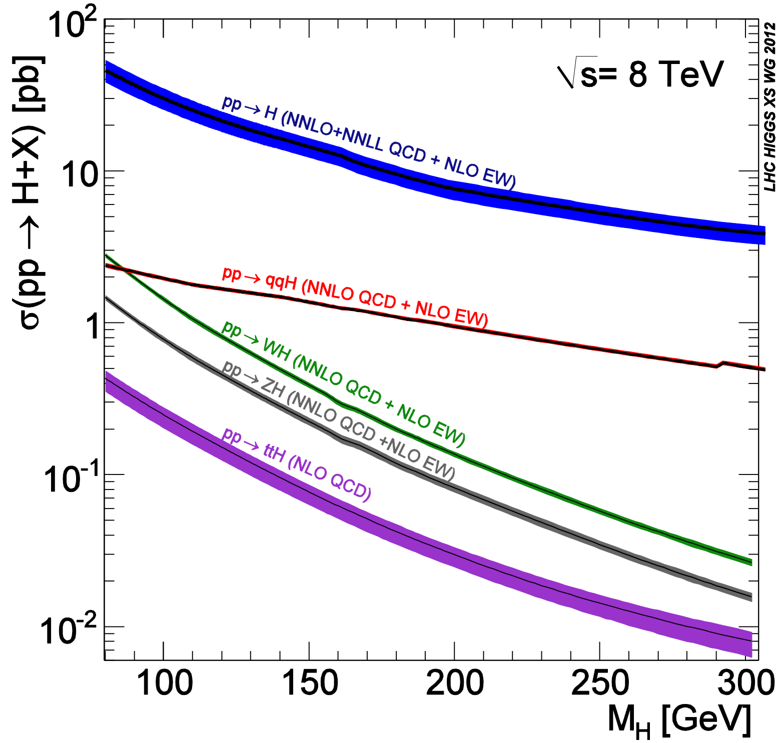




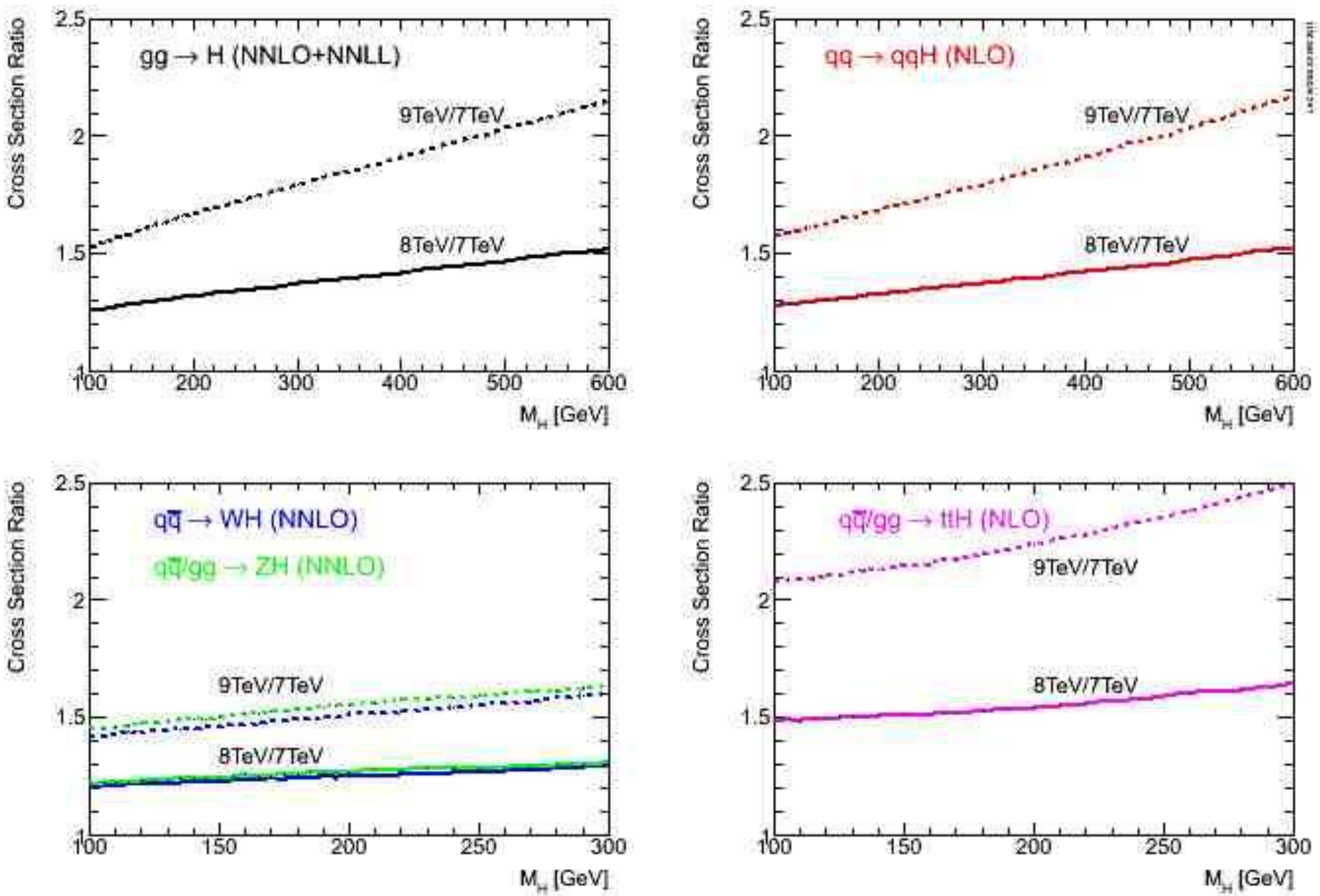
Total width is small for light and large for heavy Higgs

Сечения рождения бозона Хиггса при энергии 8 ТэВ

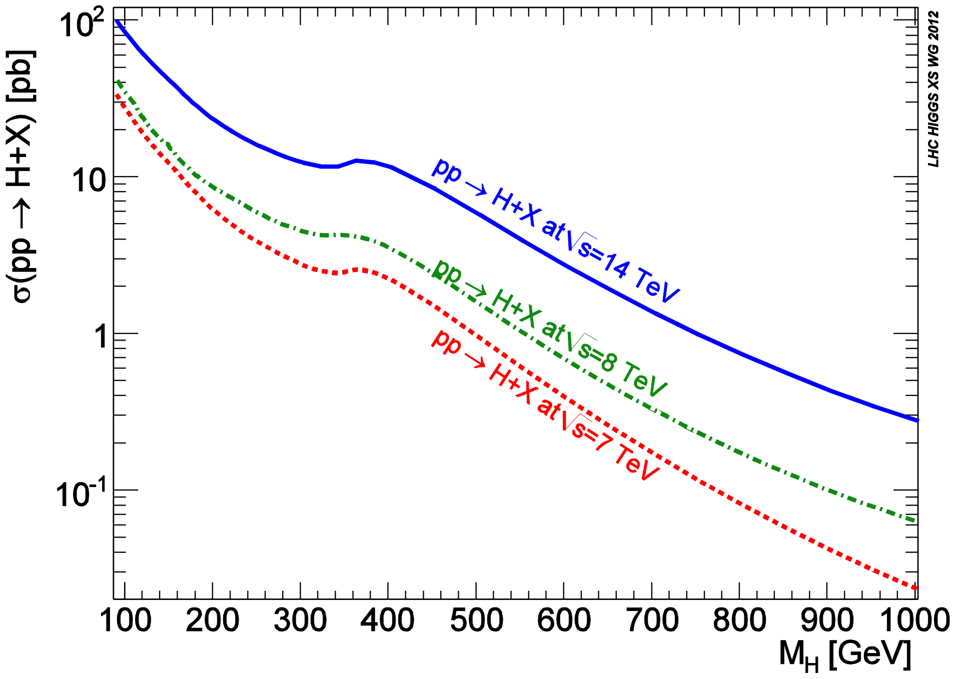


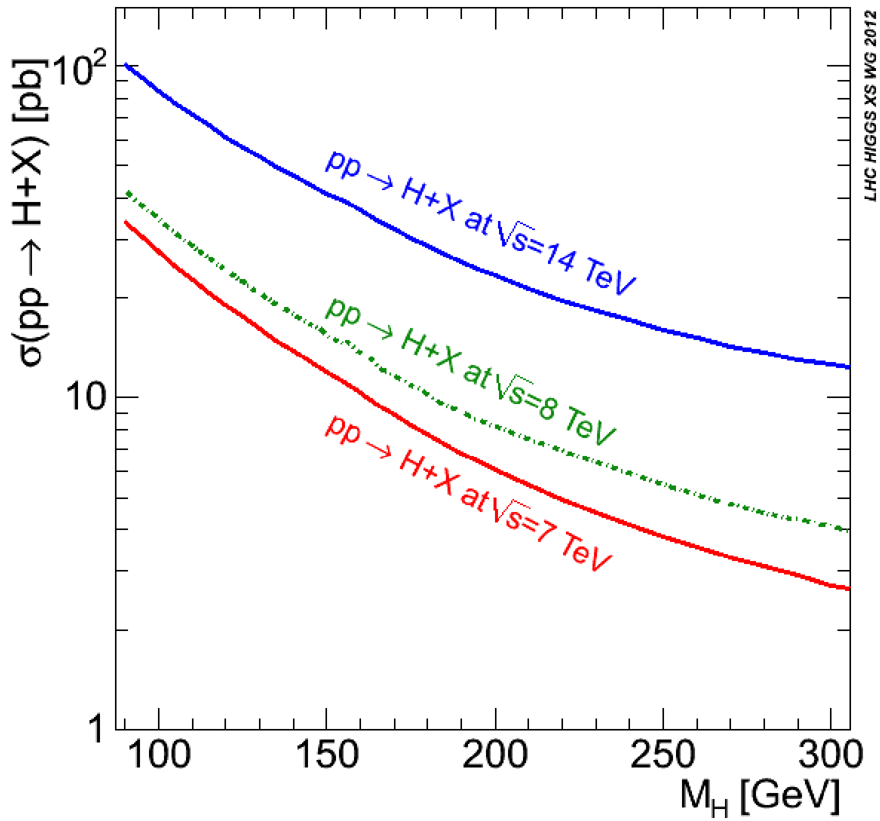


Отношение сечений рождения бозона Хиггса при разных энергиях

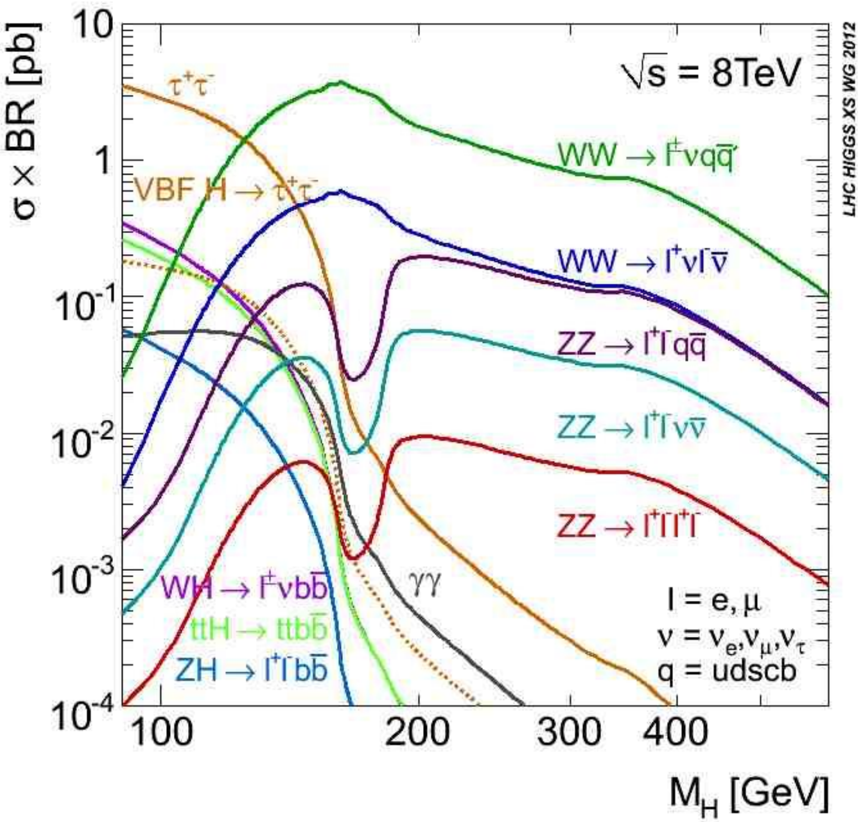


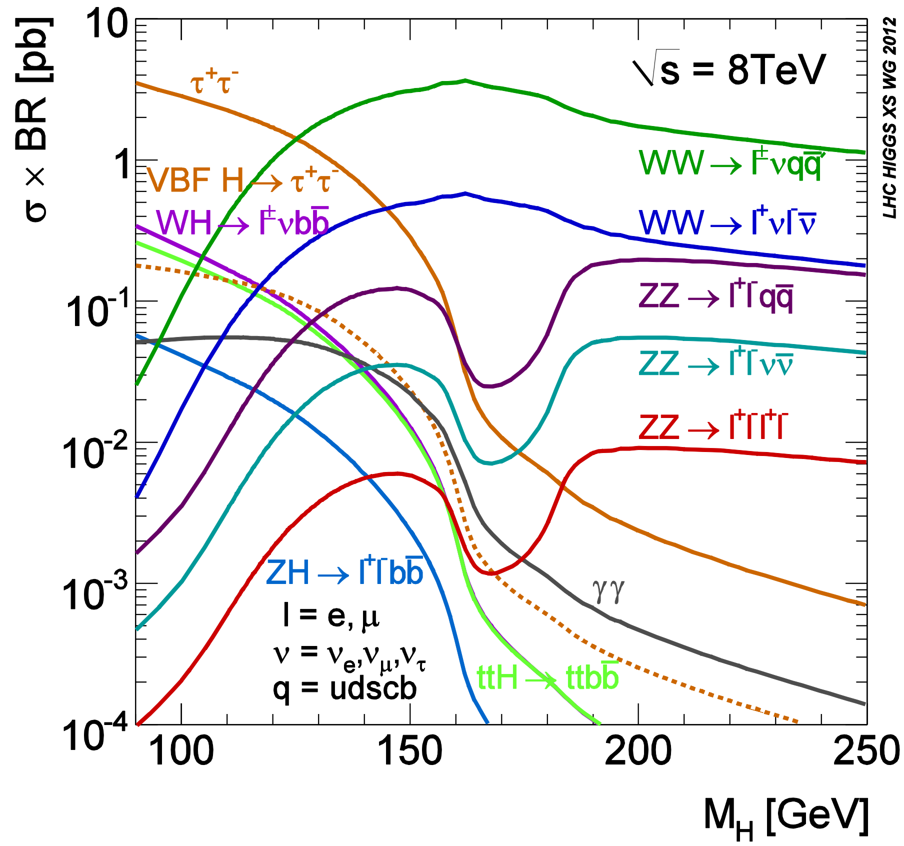
Увеличение сечения рождения бозона Хиггса с ростом энергии



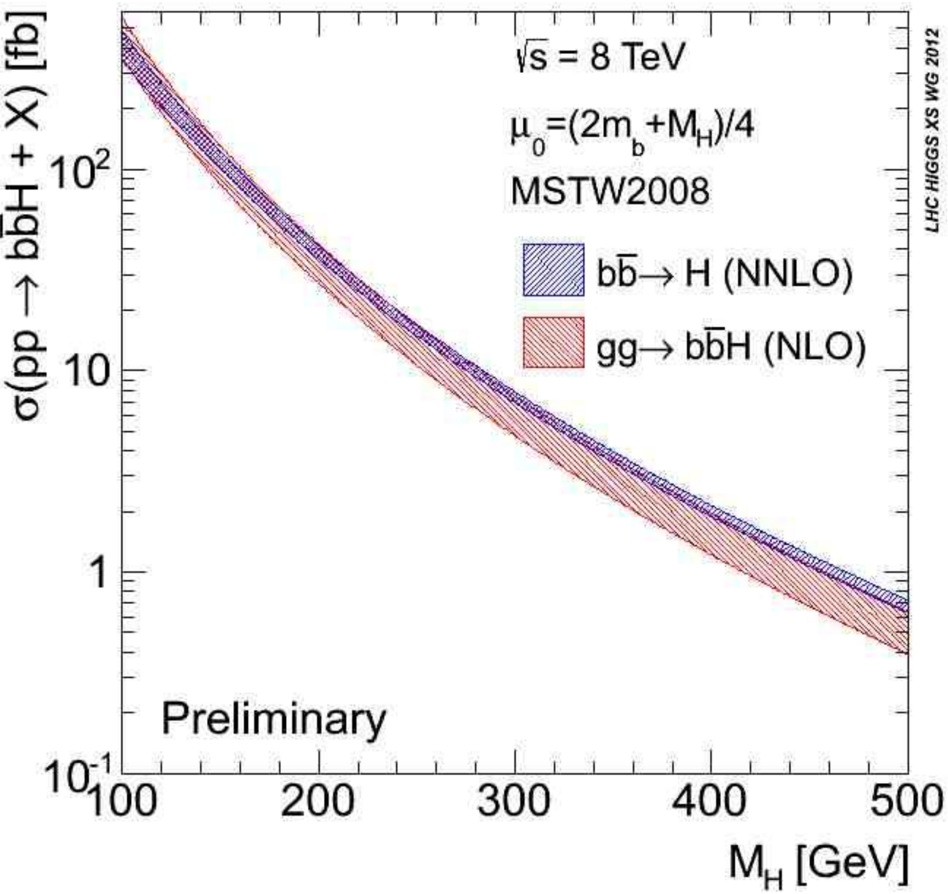


Сечения различных мод (сигнатур) образования бозона Хиггса при энергии 8 ТэВ





Сечение рождения бозона Хиггса в сопровождении b-кварков в так называемых 4-flavor (NLO) and 5-flavor (NNLO) схемах вычислений



NLO (NNLO) computations, corresponding event generators – an important part of the LHC physics program

- more correct rate (K-factors)
- more correct distribution shapes
- much weaker dependence on renormalization and factorization scales
- more reliable Monte-Carlo modeling

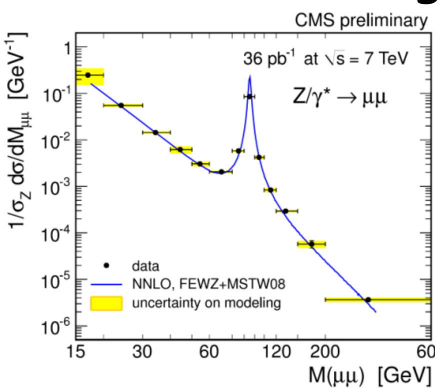
All these are needed for experimental analysis
- to optimize signal extraction from backgrounds
- to improve accuracies of measured quantities

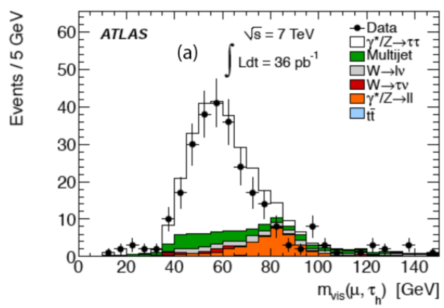
Recent single top quark observation (5 sigma, March 2009) at the Tevatron is a remarkable example

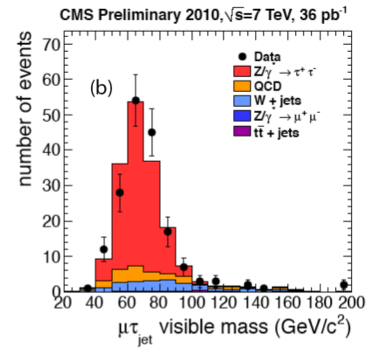
What the LHC experiments tell us?

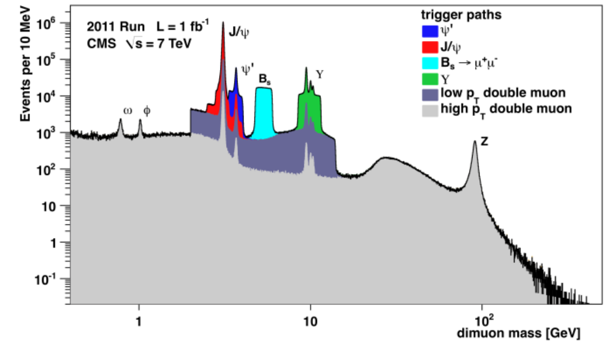
First LHC results also confirm Standard Model

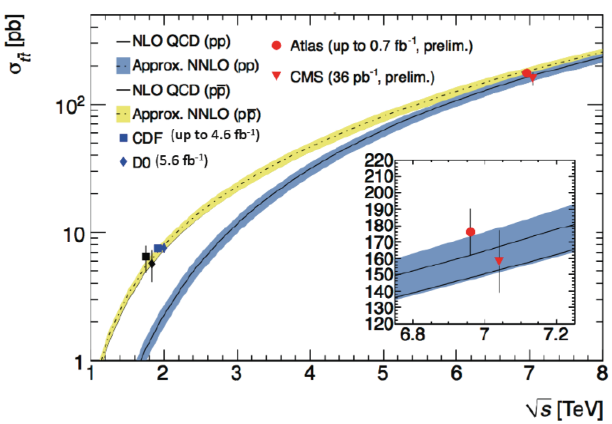
Rediscovery of the SM: W, Z, Top …. are found
WZ, Wgamma, ZZ, Top pair, single Top … are measured

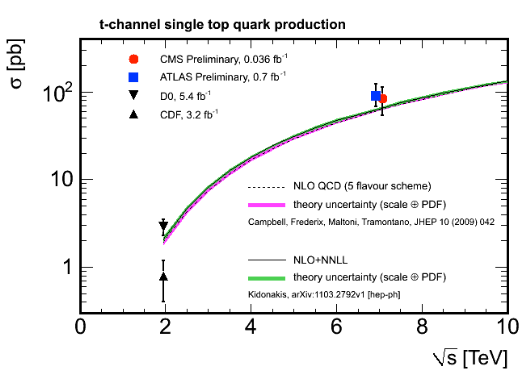


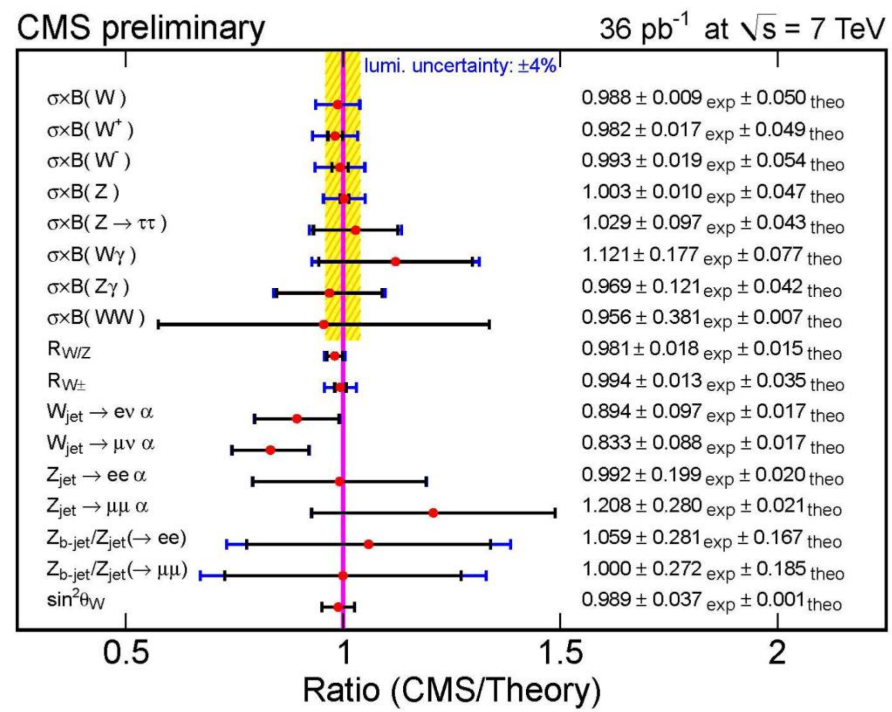




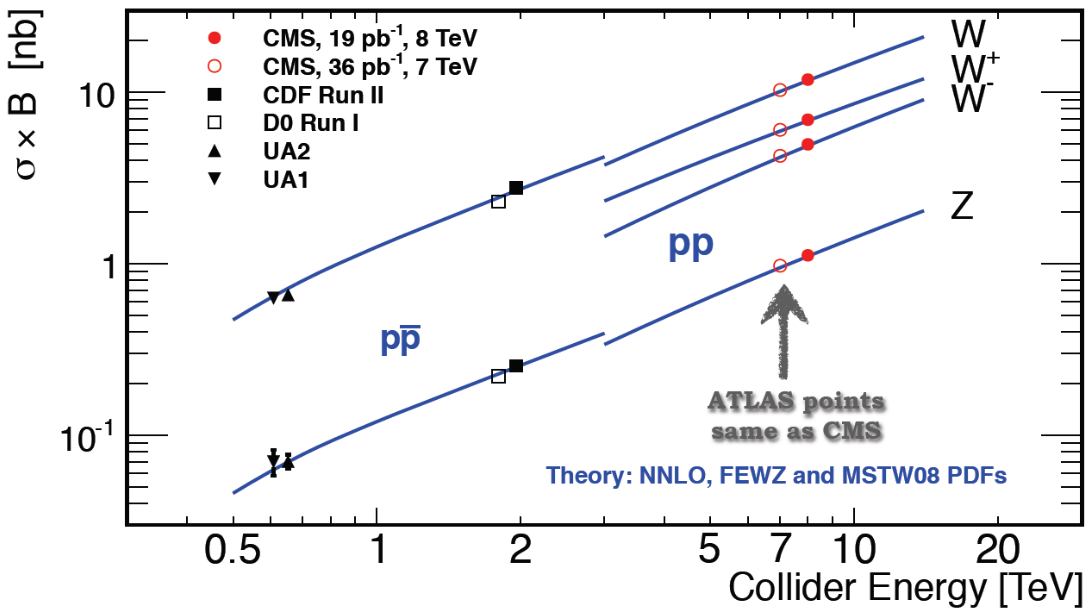


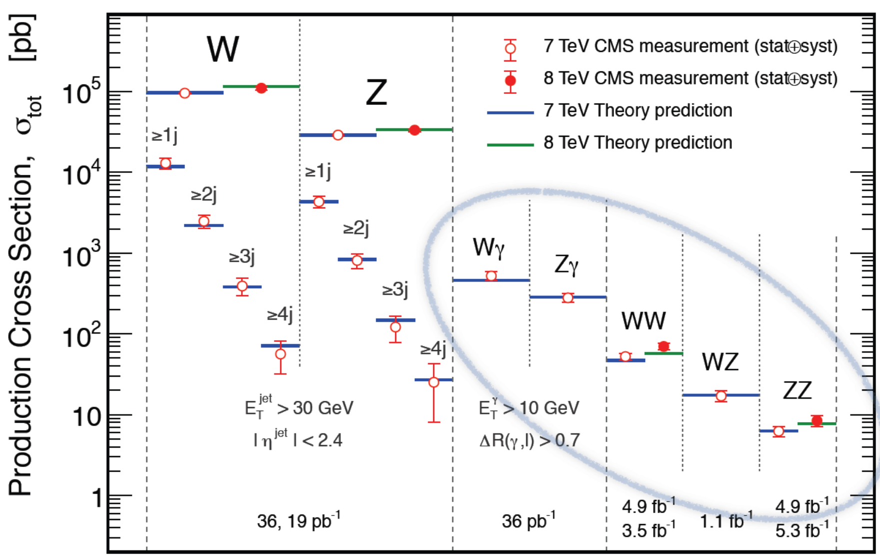


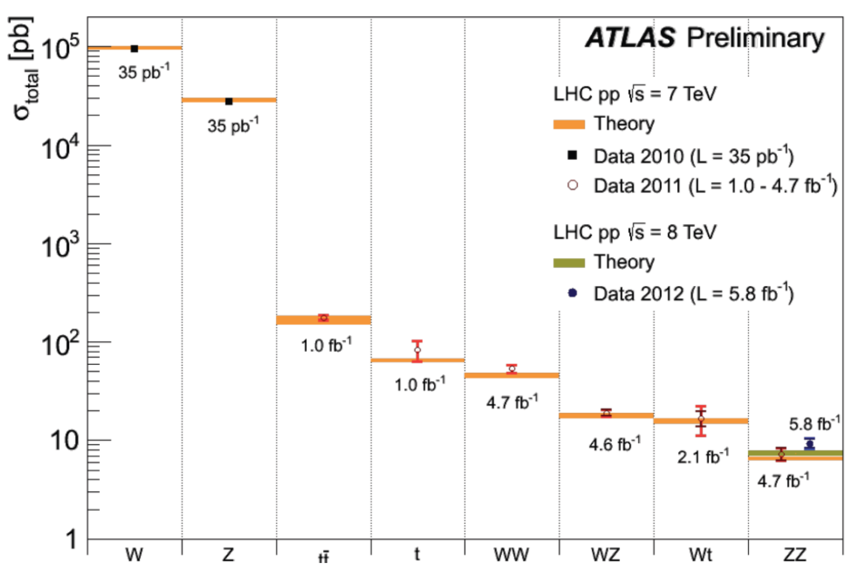




All in an agreement with the SM

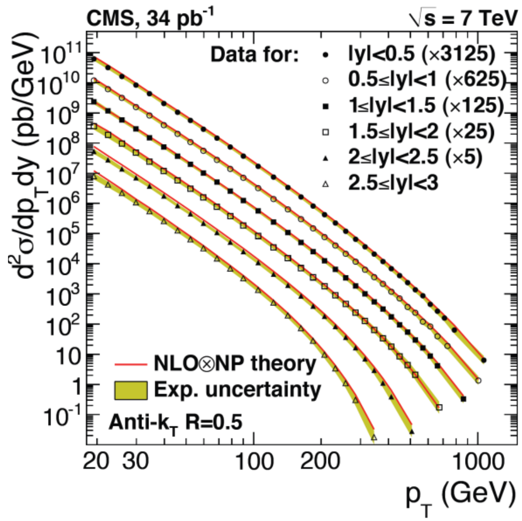

CMS, 19 pb-1, 8 TeV
CMS, 36 pb-1, 7 TeV
CDF Run II
D0 Run I
UA2
UA1
σ × B [nb]
W
W+
W-
Z
pp
pp̄
ATLAS points same as CMS
Theory: NNLO, FEWZ and MSTW08 PDFs
Collider Energy [TeV]

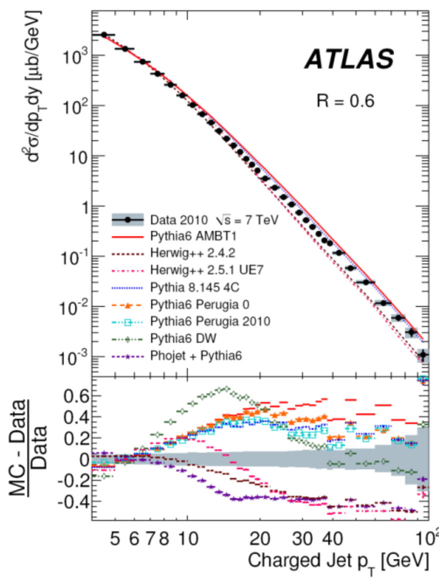

Production Cross Section, σtot [pb]
W
Z
7 TeV CMS measurement (stat⊕syst)
8 TeV CMS measurement (stat⊕syst)
7 TeV Theory prediction
8 TeV Theory prediction
≥1j
≥2j
≥3j
≥4j
Wγ
Zγ
WW
WZ
ZZ
E_T^jet > 30 GeV
|η^jet| < 2.4
E_T^γ > 10 GeV
ΔR(γ,l) > 0.7
36, 19 pb-1
36 pb-1
4.9 fb-1
3.5 fb-1
1.1 fb-1
4.9 fb-1
5.3 fb-1


ATLAS Preliminary
σtotal [pb]
LHC pp √s = 7 TeV
Theory
Data 2010 (L = 35 pb-1)
Data 2011 (L = 1.0 - 4.7 fb-1)
LHC pp √s = 8 TeV
Theory
Data 2012 (L = 5.8 fb-1)
35 pb-1
35 pb-1
1.0 fb-1
1.0 fb-1
4.7 fb-1
4.6 fb-1
2.1 fb-1
5.8 fb-1
4.7 fb-1
W
Z
tt̄
t
WW
WZ
Wt
ZZ

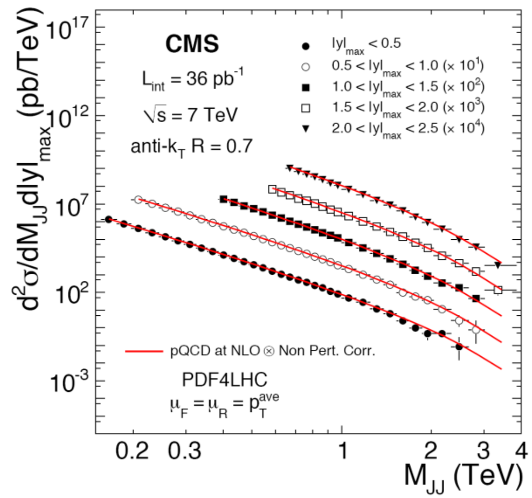
New remarkable QCD results in various kinematical regions

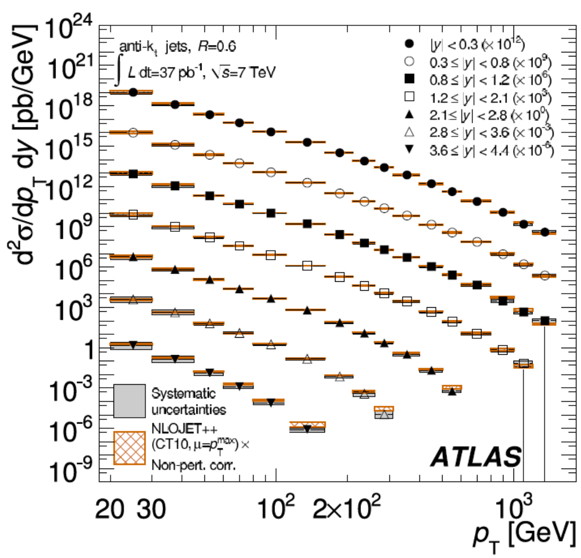
Double-differential inclusive jet production



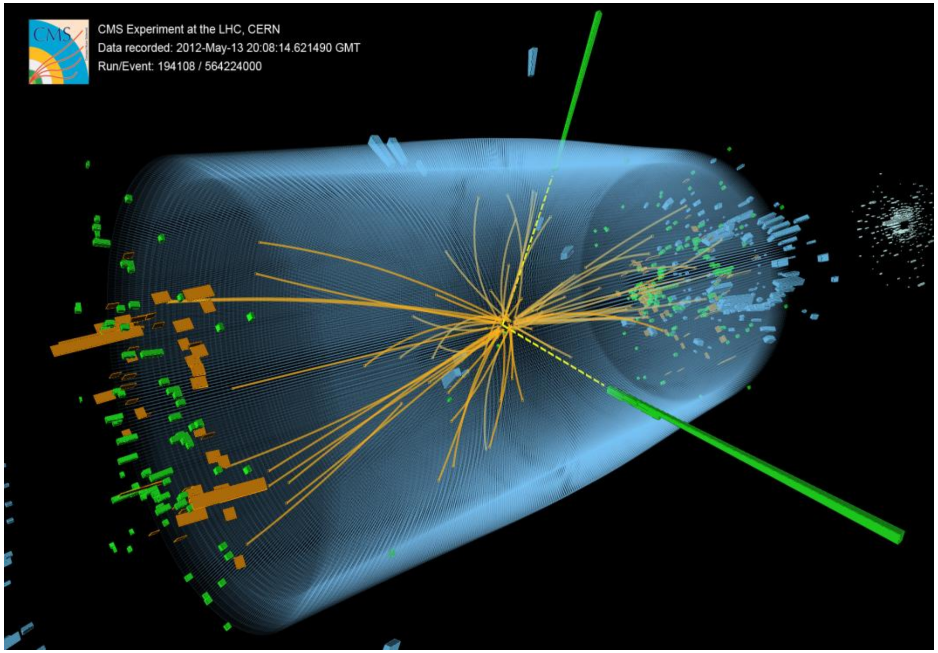


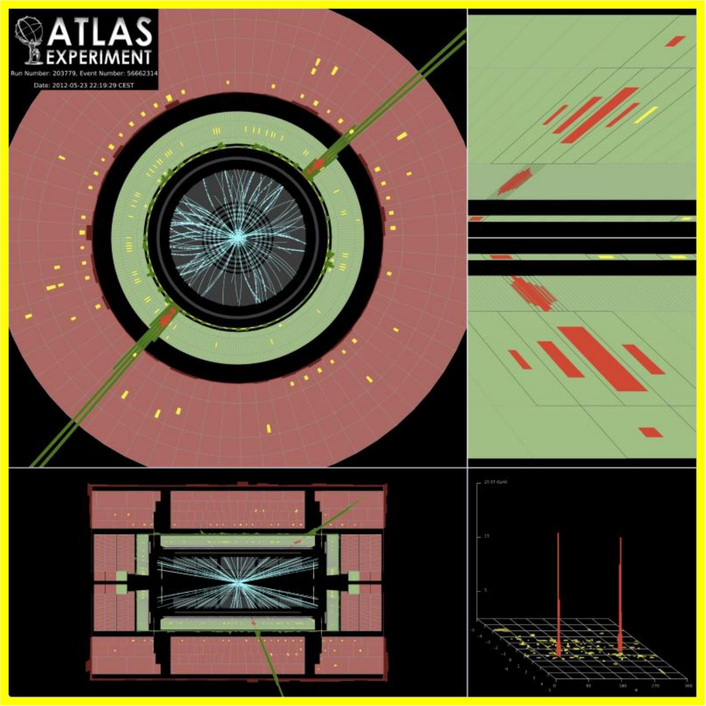
Double-differential inclusive dijet production



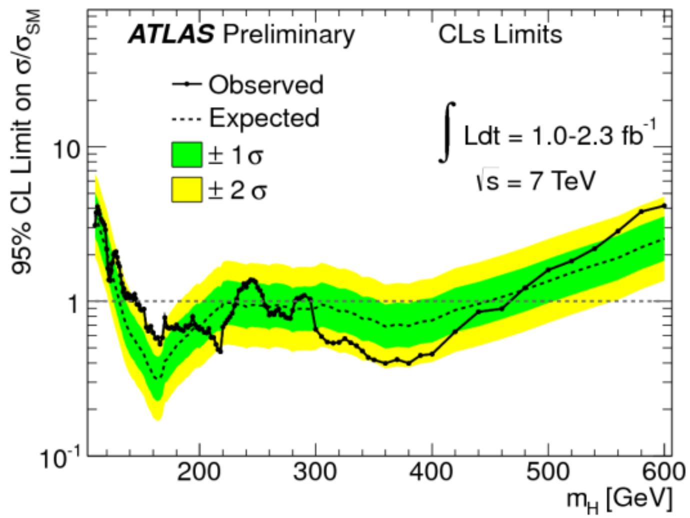


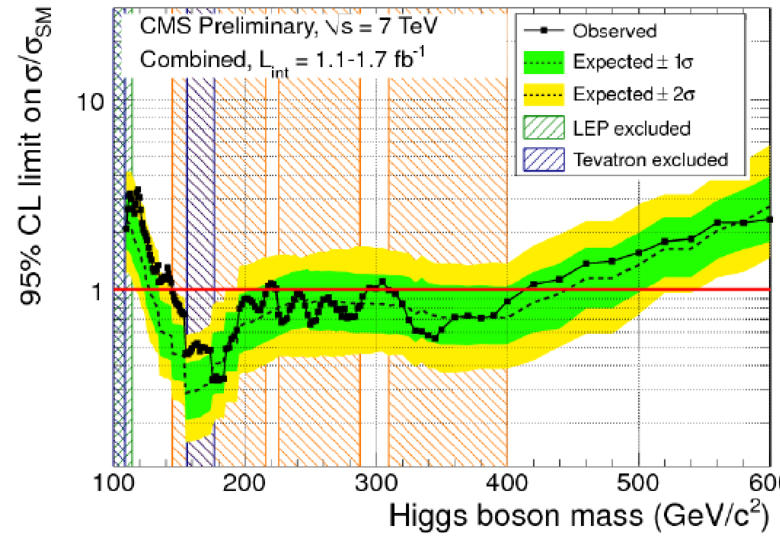
Examples of the CMS and ATLAS events with two photons (Higgs candidates)



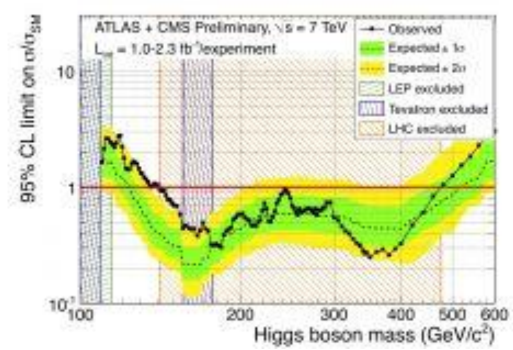


LHC limits on Higgs mass



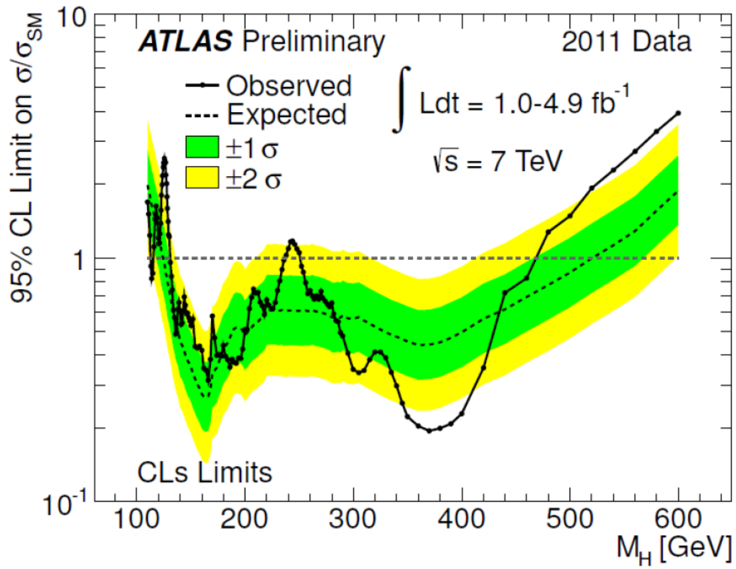


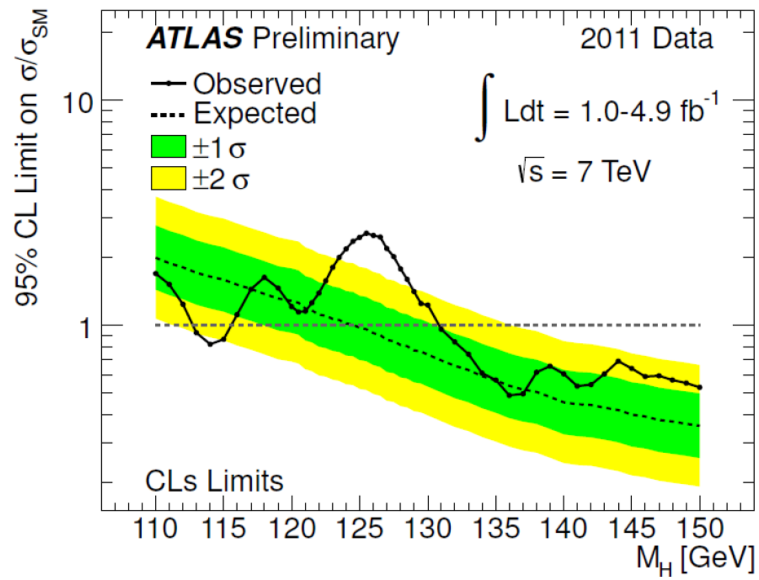
Excluded either by ATLAS or CMS 145-466 GeV (except 288-296 GeV) 95%CL



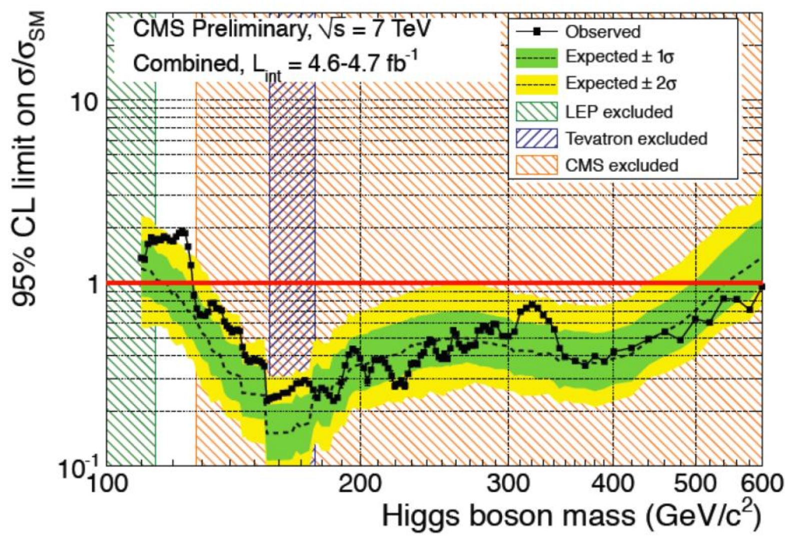
CMS and ATLAS combined result for MH :
141-476 GeV is excluded

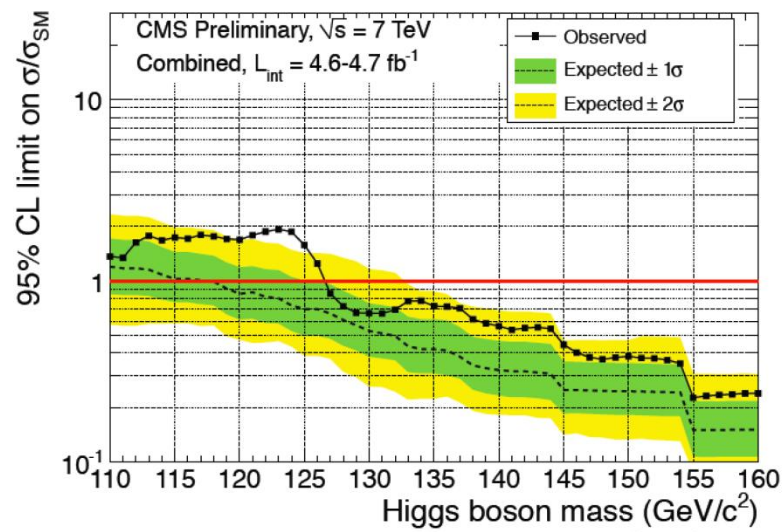
With roughly 10 1/fb per experiment at the LHC one expects to reach for SM Higgs combined 5σ sensitivity in the interval
114 < MH < 600 GeV



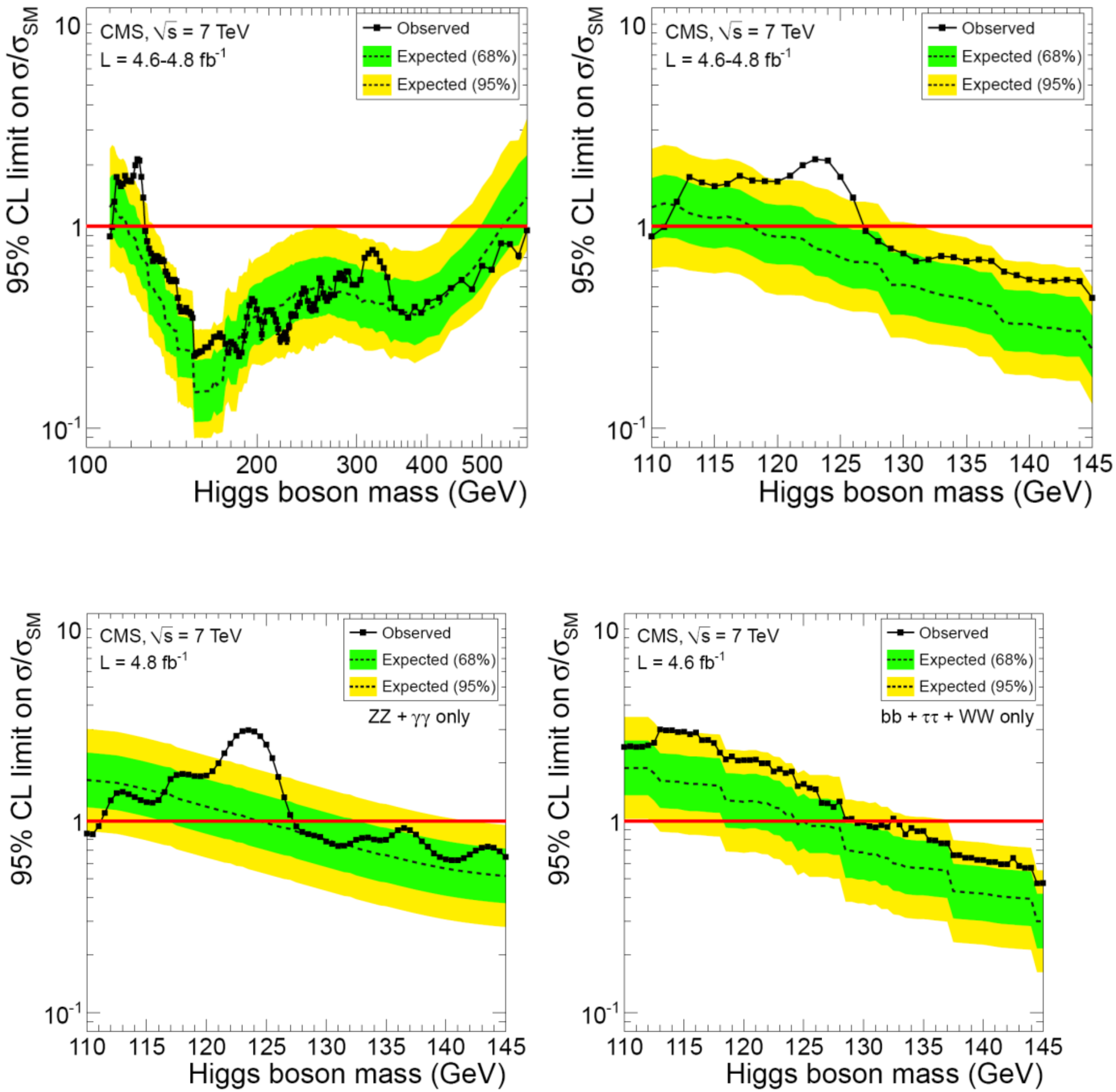


Combining only γγ and 4l: 3.6σ

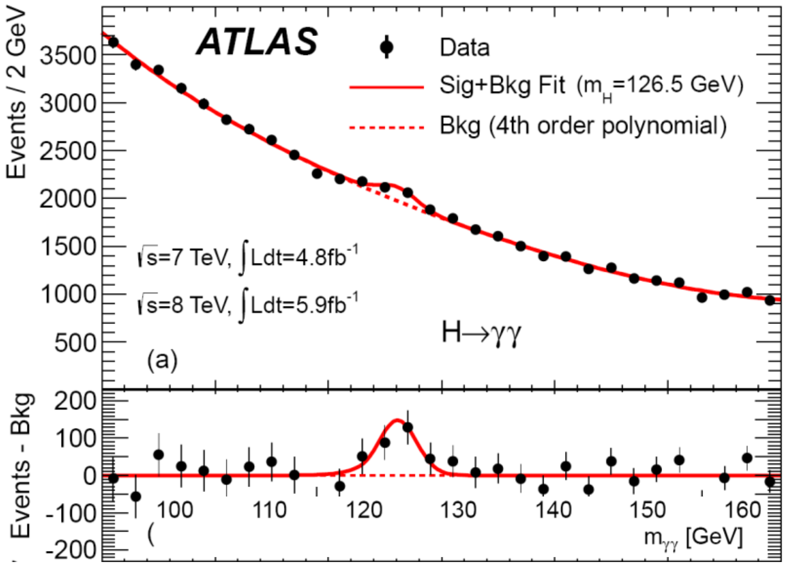


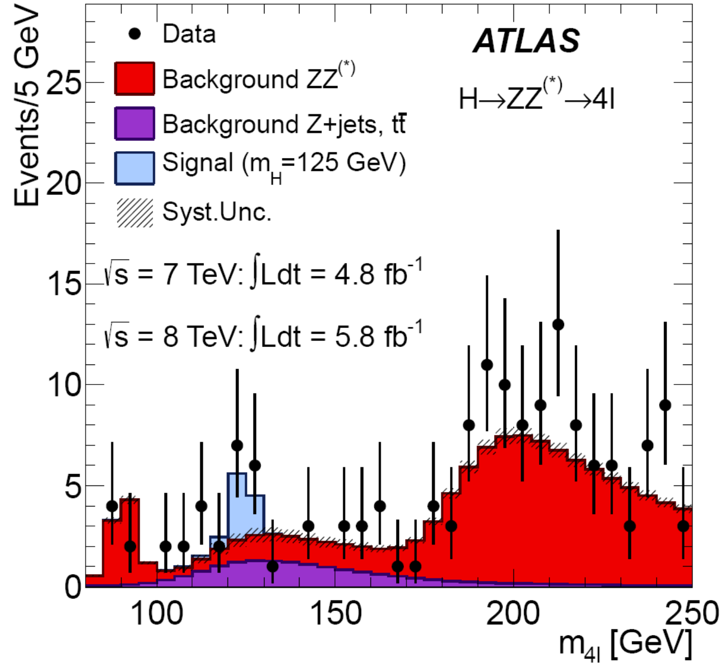


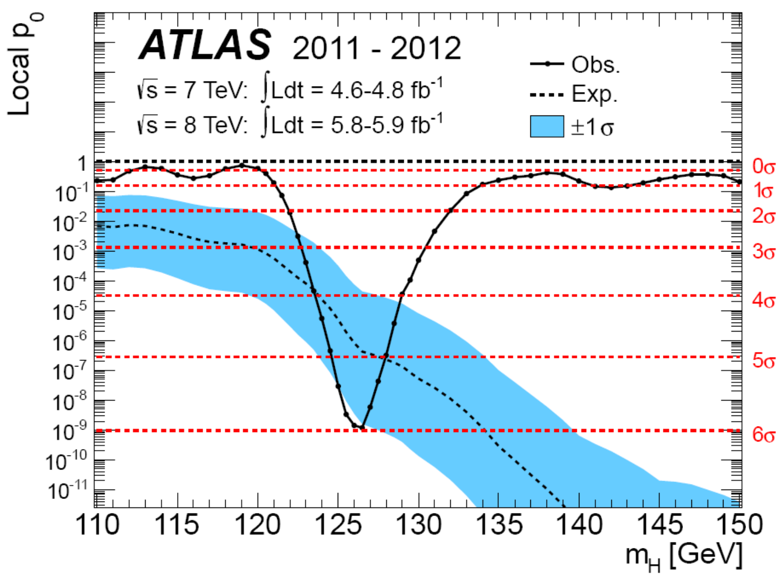
Small window from 115 GeV to 127 GeV is remaining with a small access at about 125 GeV

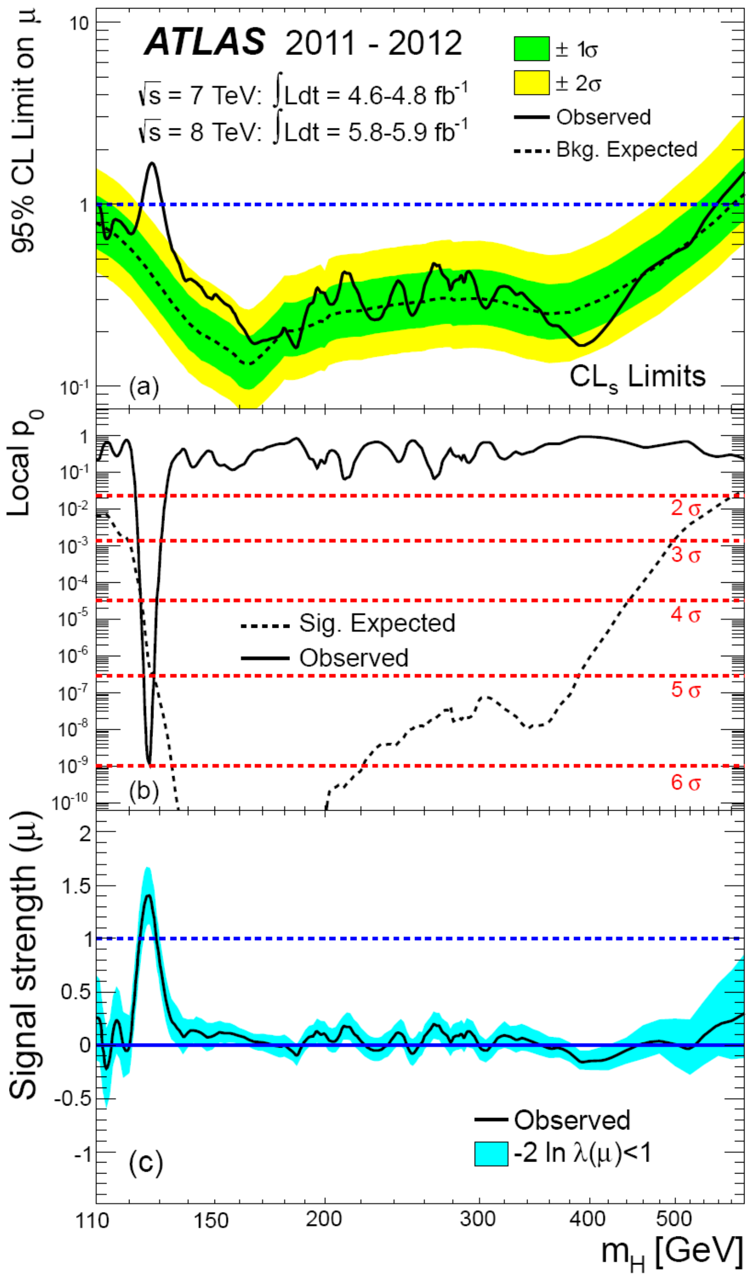

CMS, √s = 7 TeV
L = 4.6-4.8 fb-1
Observed
Expected (68%)
Expected (95%)
95% CL limit on σ/σSM
Higgs boson mass (GeV)
10
1
10-1
100
200
300
400
500
CMS, √s = 7 TeV
L = 4.6-4.8 fb-1
Observed
Expected (68%)
Expected (95%)
95% CL limit on σ/σSM
Higgs boson mass (GeV)
110
115
120
125
130
135
140
145
CMS, √s = 7 TeV
L = 4.8 fb-1
Observed
Expected (68%)
Expected (95%)
ZZ + γγ only
95% CL limit on σ/σSM
Higgs boson mass (GeV)
CMS, √s = 7 TeV
L = 4.6 fb-1
Observed
Expected (68%)
Expected (95%)
bb + ττ + WW only
95% CL limit on σ/σSM
Higgs boson mass (GeV)

ATLAS results





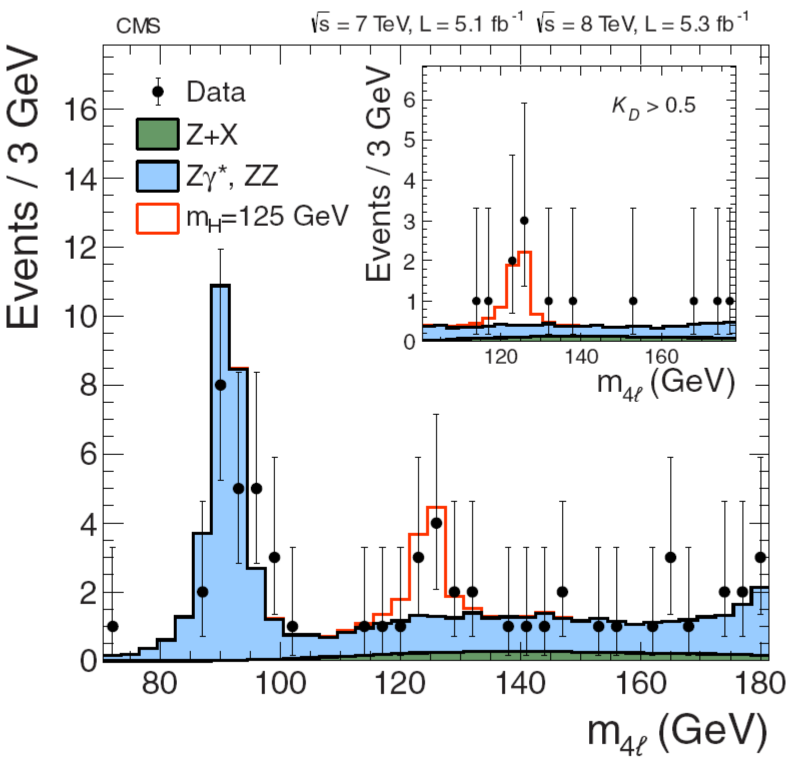


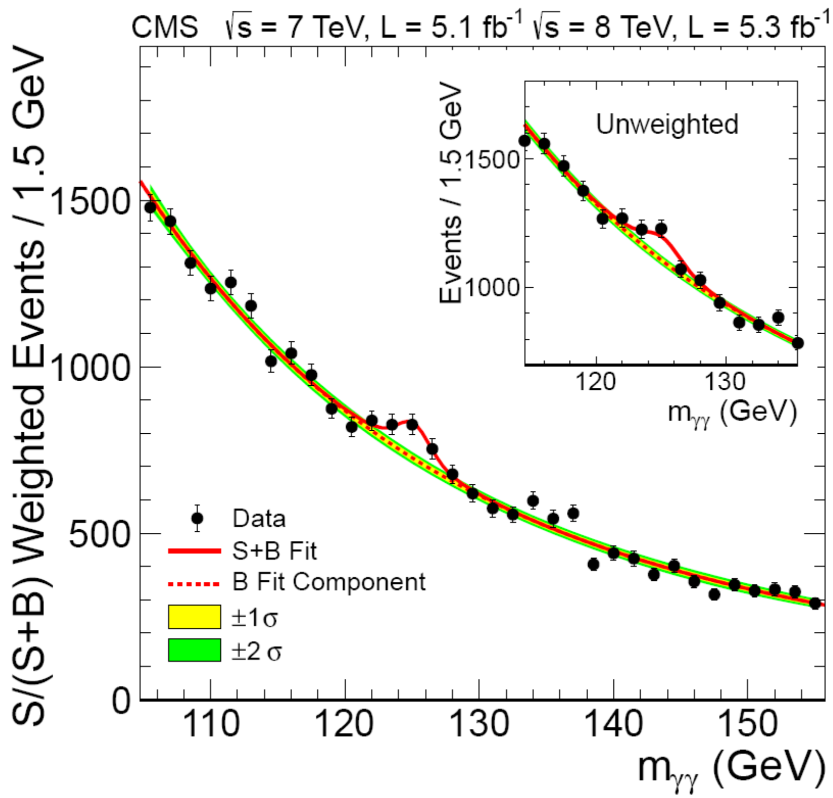


5.9 σ excess at M_H =

126.0 ± 0.4 (stat) ± 0.4 (sys)

CMS results



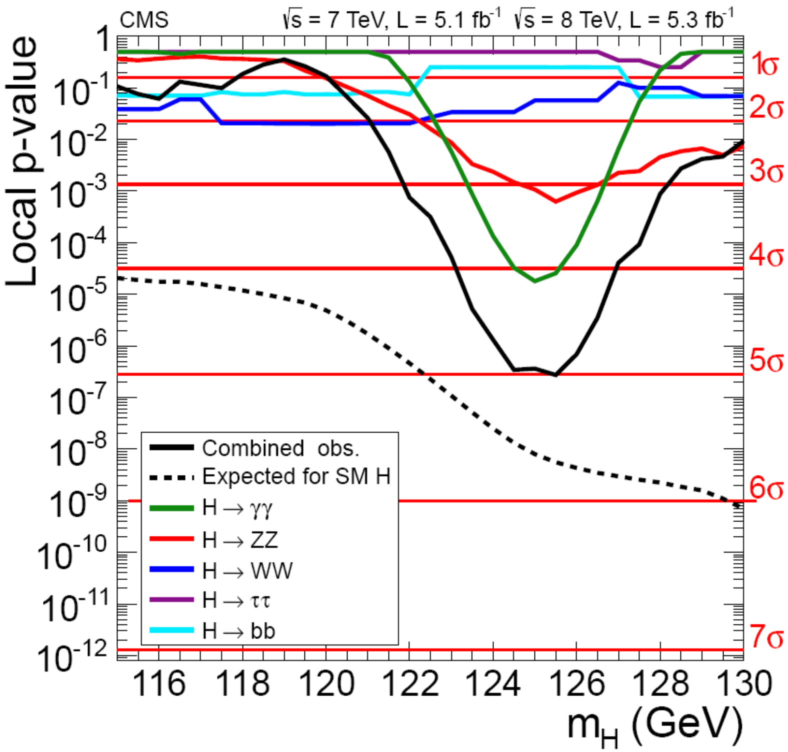


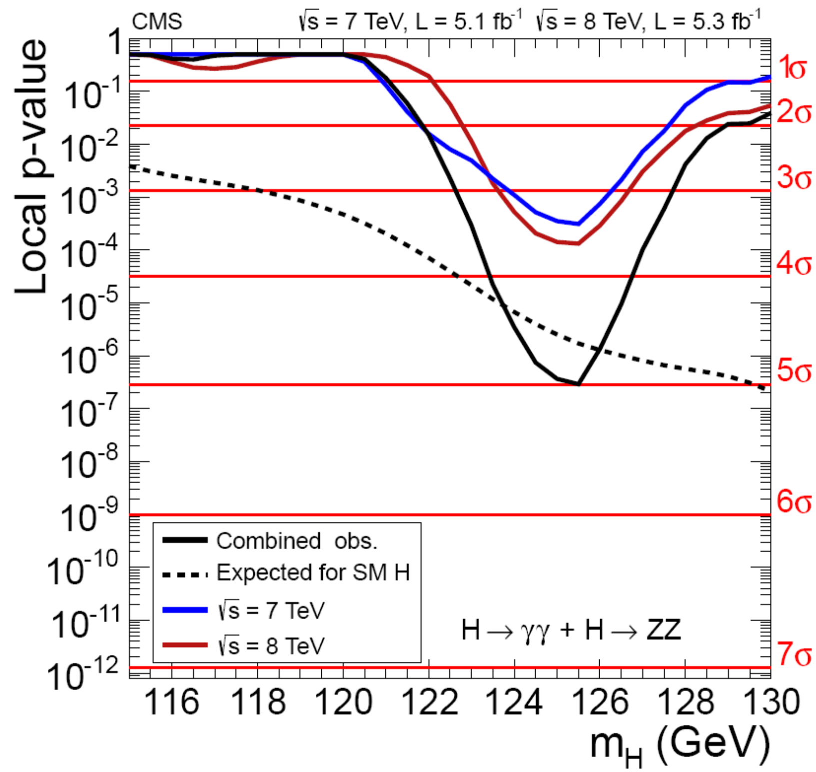
A new boson is observed with a mass of

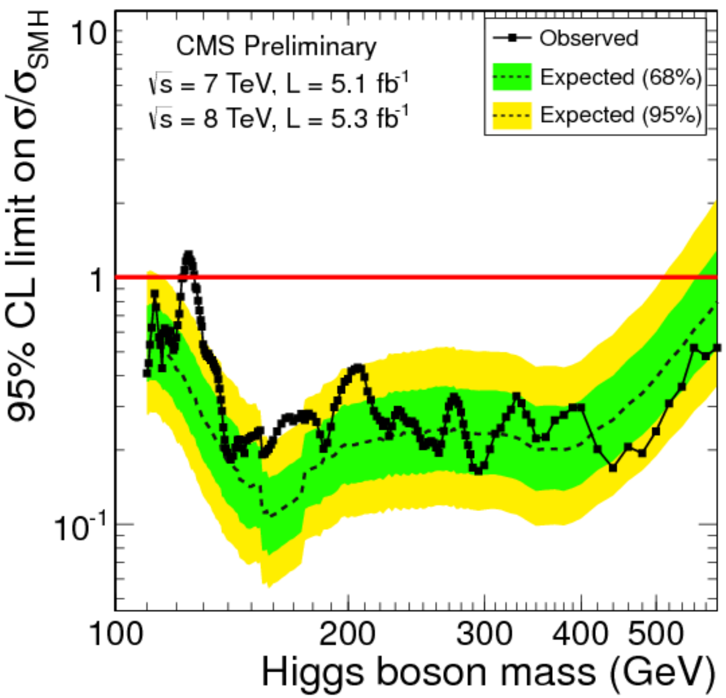
125.3 ± 0.4 (stat.) ± 0.5 (syst.) GeV

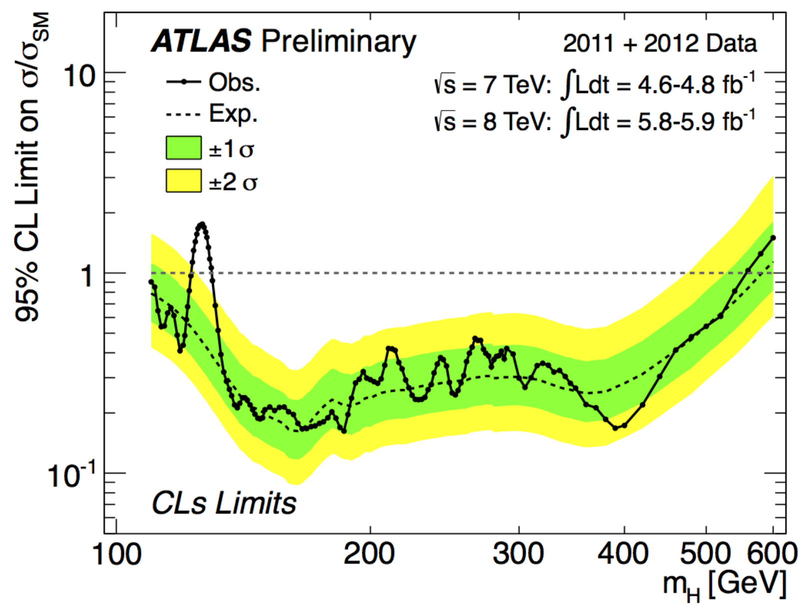
at

5.0 σ significance !


CMS
√s = 7 TeV, L = 5.1 fb-1 √s = 8 TeV, L = 5.3 fb-1
Local p-value
mH (GeV)
Combined obs.
Expected for SM H
H → γγ
H → ZZ
H → WW
H → ττ
H → bb
1σ
2σ
3σ
4σ
5σ
6σ
7σ


CMS
√s = 7 TeV, L = 5.1 fb-1 √s = 8 TeV, L = 5.3 fb-1
Local p-value
mH (GeV)
Combined obs.
Expected for SM H
√s = 7 TeV
√s = 8 TeV
H → γγ + H → ZZ
1σ
2σ
3σ
4σ
5σ
6σ
7σ

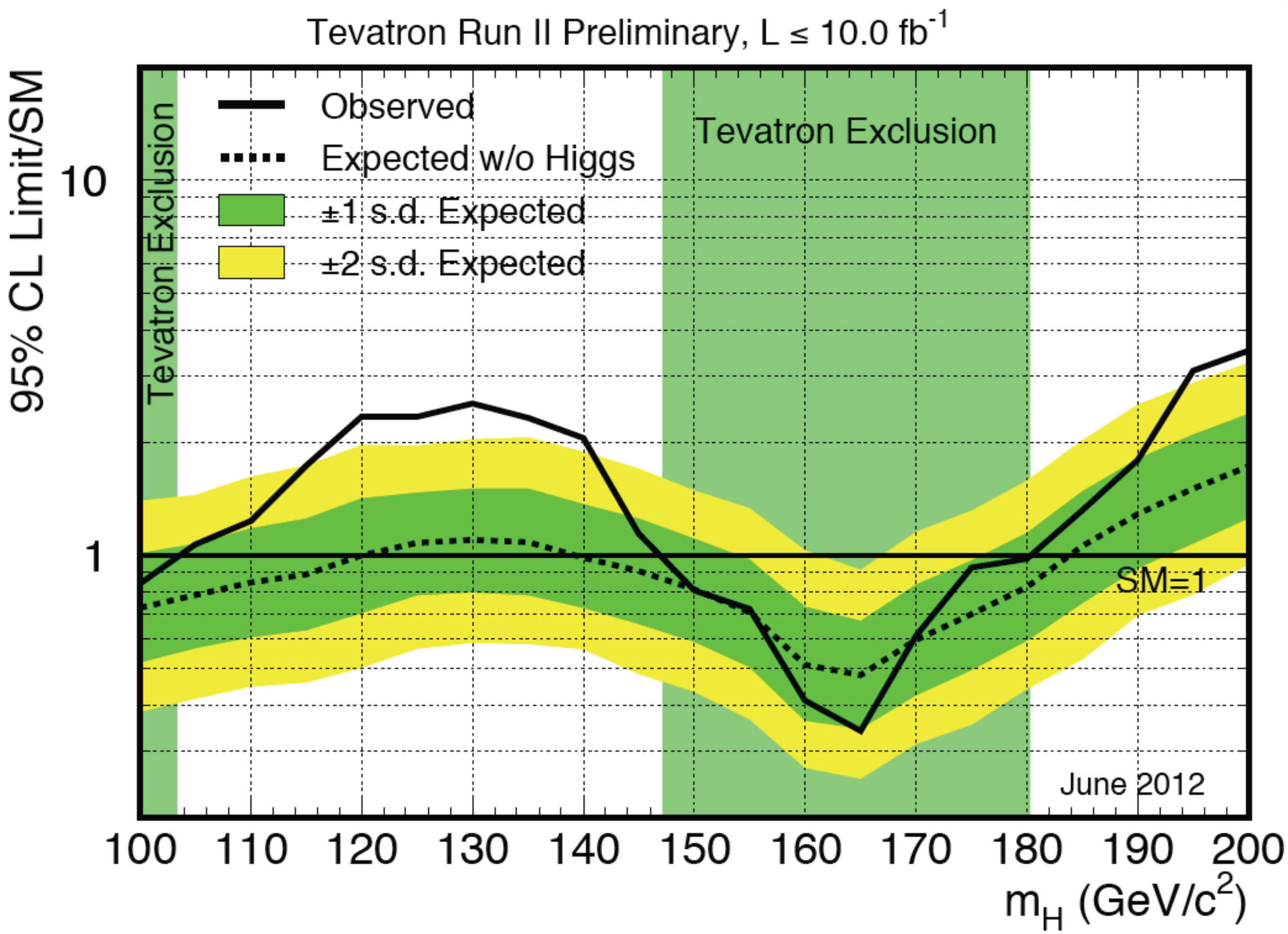


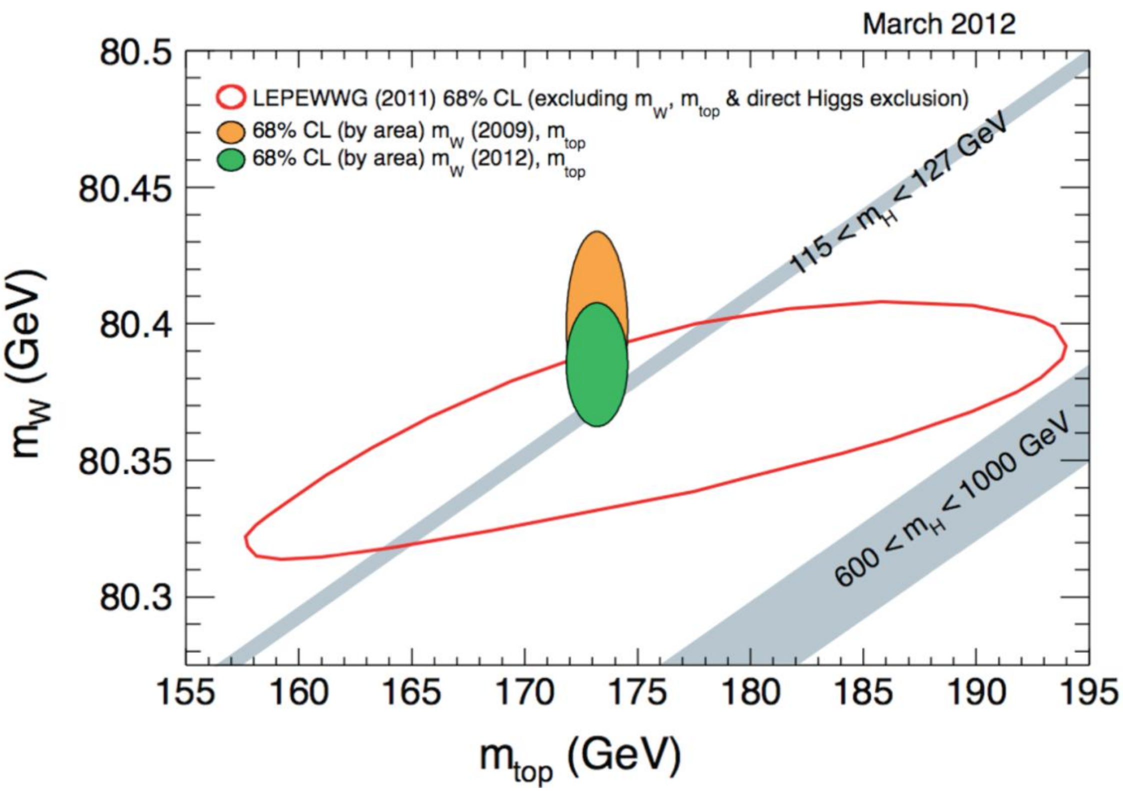


Both CMS and ATLAS have excluded SM Higgs in the mass interval upto about 560 GeV except small interval where the signal was observed

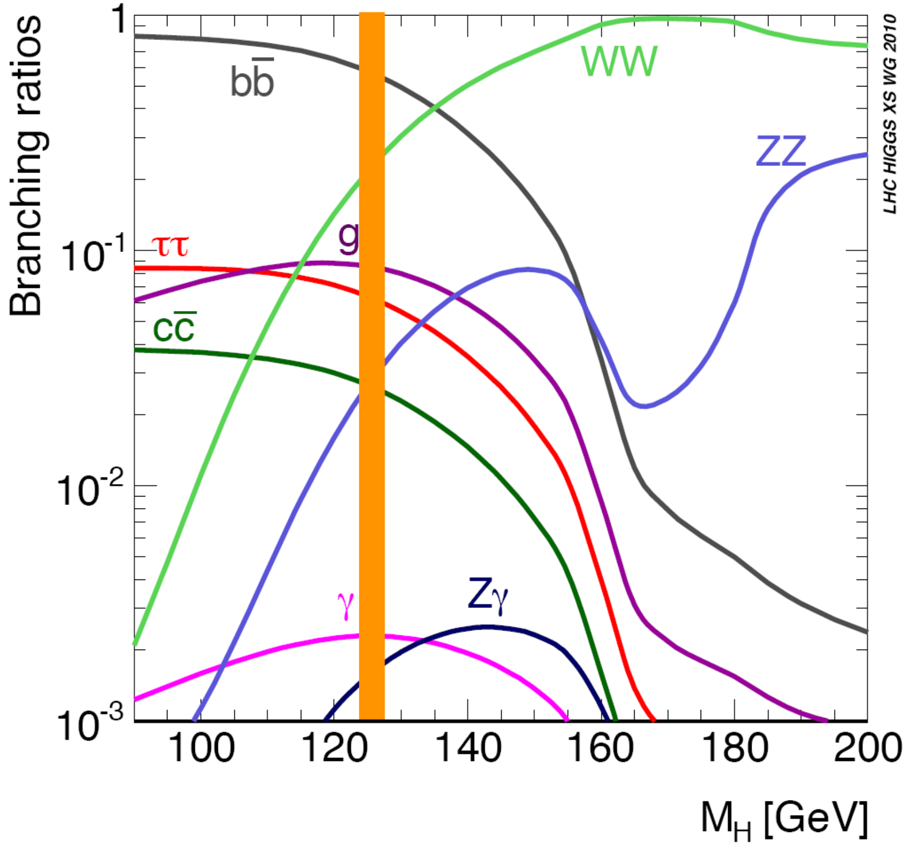
Последние результаты Tevatron

превышение над фоном на уровне 3σ в интевале 117-135 ГэВ

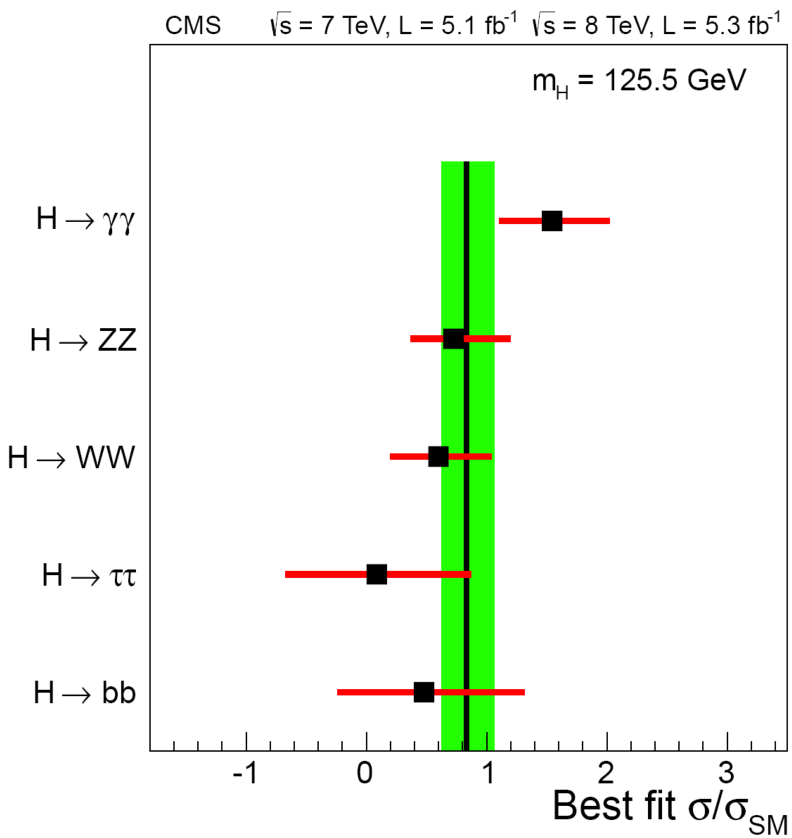




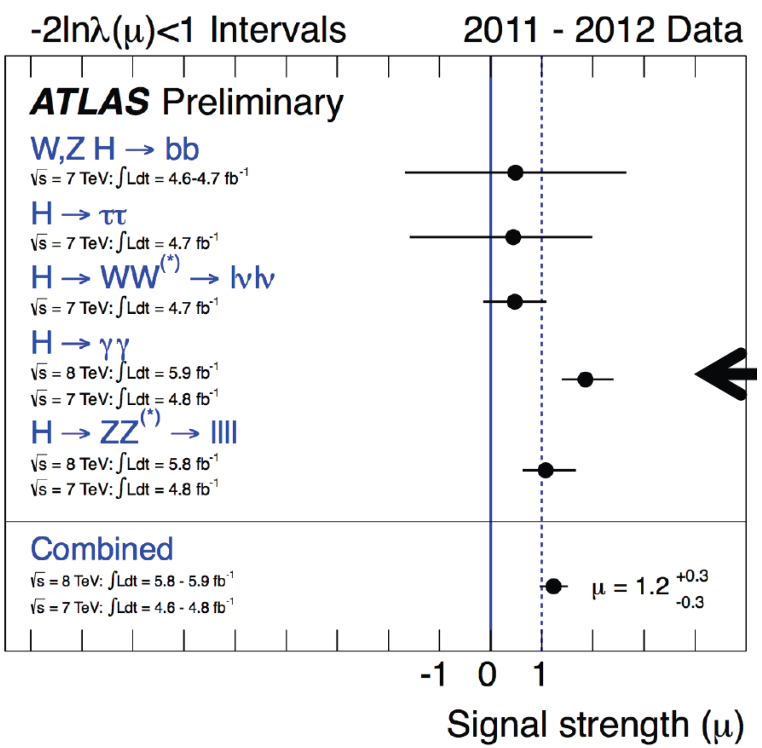
March 2012
LEPEWWG (2011) 68% CL (excluding m_W, m_{top} & direct Higgs exclusion)
68% CL (by area) m_W (2009), m_{top}
68% CL (by area) m_W (2012), m_{top}
$115 < m_H < 127$ GeV
$600 < m_H < 1000$ GeV
80.5
80.45
80.4
80.35
80.3
m_W (GeV)
155
160
165
170
175
180
185
190
195
m_{top} (GeV)



Branching ratios
1
10-1
10-2
10-3
100
120
140
160
180
200
MH [GeV]
bb̄
WW
ZZ
ττ
g
cc̄
γ
Zγ
LHC HIGGS XS WG 2010



CMS √s = 7 TeV, L = 5.1 fb-1 √s = 8 TeV, L = 5.3 fb-1
m_H = 125.5 GeV
H → γγ
H → ZZ
H → WW
H → ττ
H → bb
-1 0 1 2 3
Best fit σ/σ_SM



-2lnλ(μ)<1 Intervals
2011 - 2012 Data
ATLAS Preliminary
W,Z H → bb
√s = 7 TeV: ∫Ldt = 4.6-4.7 fb-1
H → ττ
√s = 7 TeV: ∫Ldt = 4.7 fb-1
H → WW(*) → lνlν
√s = 7 TeV: ∫Ldt = 4.7 fb-1
H → γγ
√s = 8 TeV: ∫Ldt = 5.9 fb-1
√s = 7 TeV: ∫Ldt = 4.8 fb-1
H → ZZ(*) → llll
√s = 8 TeV: ∫Ldt = 5.8 fb-1
√s = 7 TeV: ∫Ldt = 4.8 fb-1
Combined
√s = 8 TeV: ∫Ldt = 5.8 - 5.9 fb-1
√s = 7 TeV: ∫Ldt = 4.6 - 4.8 fb-1
μ = 1.2 +0.3 -0.3
-1 0 1
Signal strength (μ)

How much the boson observed corresponds to the SM Higgs boson ?

Gunion et al.

$$R_Y^h(X) = \frac{\sigma(pp \to Y \to h)\mathrm{BR}(h \to X)}{\sigma(pp \to Y \to h_{SM})\mathrm{BR}(h_{SM} \to X)}, \quad R^h(X) = \sum_Y R_Y^h,$$

where $Y = gg$ or WW.

$R(X)$, $X =$	$\gamma\gamma$	4ℓ	$\ell\nu\ell\nu$	$b\bar{b}$	$\tau^+\tau^-$
ATLAS	$\sim 1.9 \pm 0.5$	$\sim 1.1 \pm 0.6$	0.5 ± 0.6	0.5 ± 2.3	0.4 ± 2.0
CMS	$\sim 1.6 \pm 0.6$	$\sim 0.7 \pm 0.3$	0.6 ± 0.5	0.1 ± 0.7	$\sim 0 \pm 0.8$

$$R_{WW}^{\mathrm{ATLAS}}(\gamma\gamma) = 2.5 \pm 1.2 \quad R_{WW}^{\mathrm{CMS}}(\gamma\gamma) = 2.3 \pm 1.3$$

$$R_{Vh}^{\mathrm{CMS}}(b\bar{b}) = 0.5 \pm 0.6, \quad R_{Vh}^{\mathrm{ATLAS}}(b\bar{b}) \sim 0.5 \pm 2.0, \quad R_{Vh}^{\mathrm{Tev}}(b\bar{b}) \sim 1.8 \pm 1$$

In the nearest future

Detail studies and measurements of properties of the resonance observed

> 100 papers recently on theory-phenomenology side

BACKUP SLIDES