Beyond the Standard Model with the LHC. Current status

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What is the LHC?

What did we know before the LHC start? What were our expectations?

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

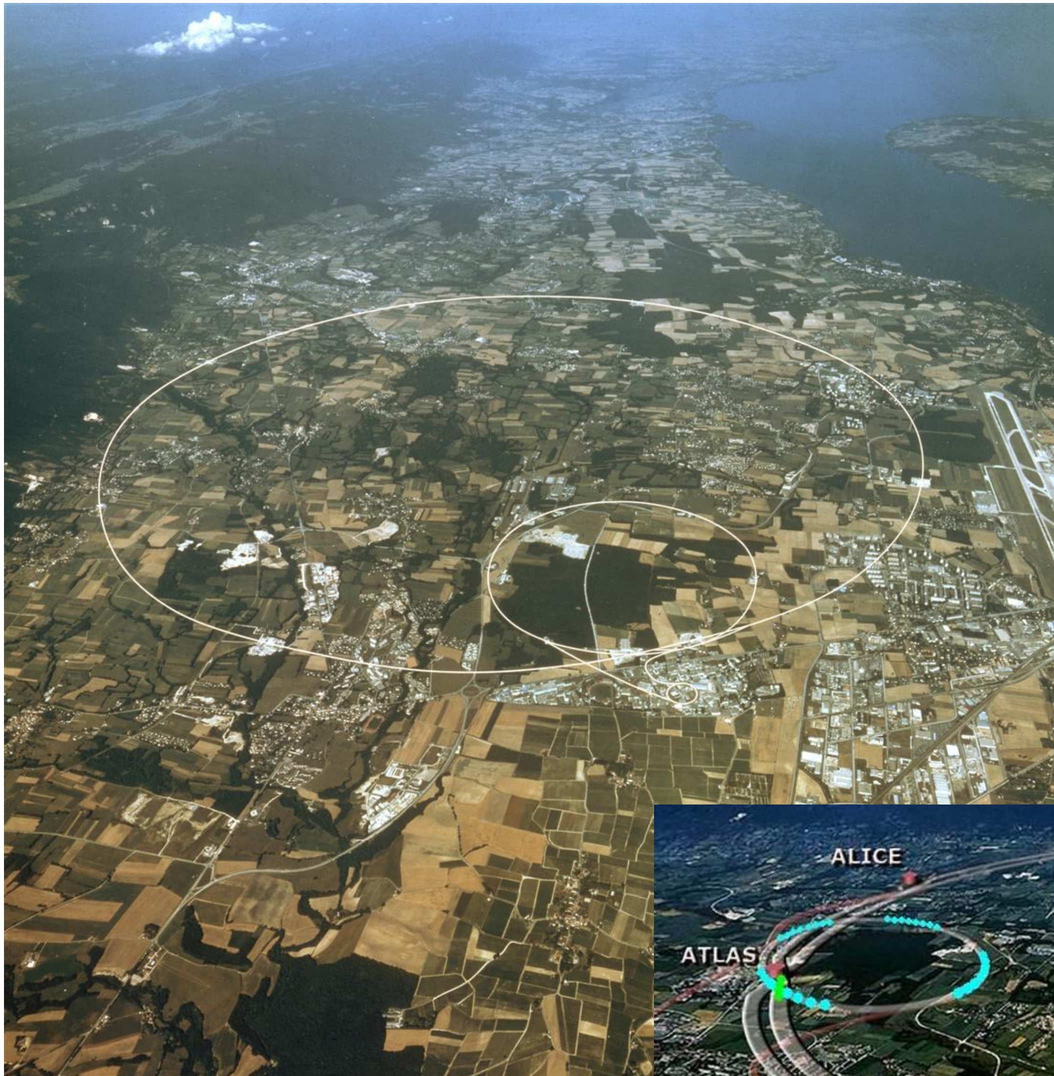
What the LHC experiments tell us?

Higgs-like boson is found.
What is found and what does it mean?

BSM searches. And where we are?

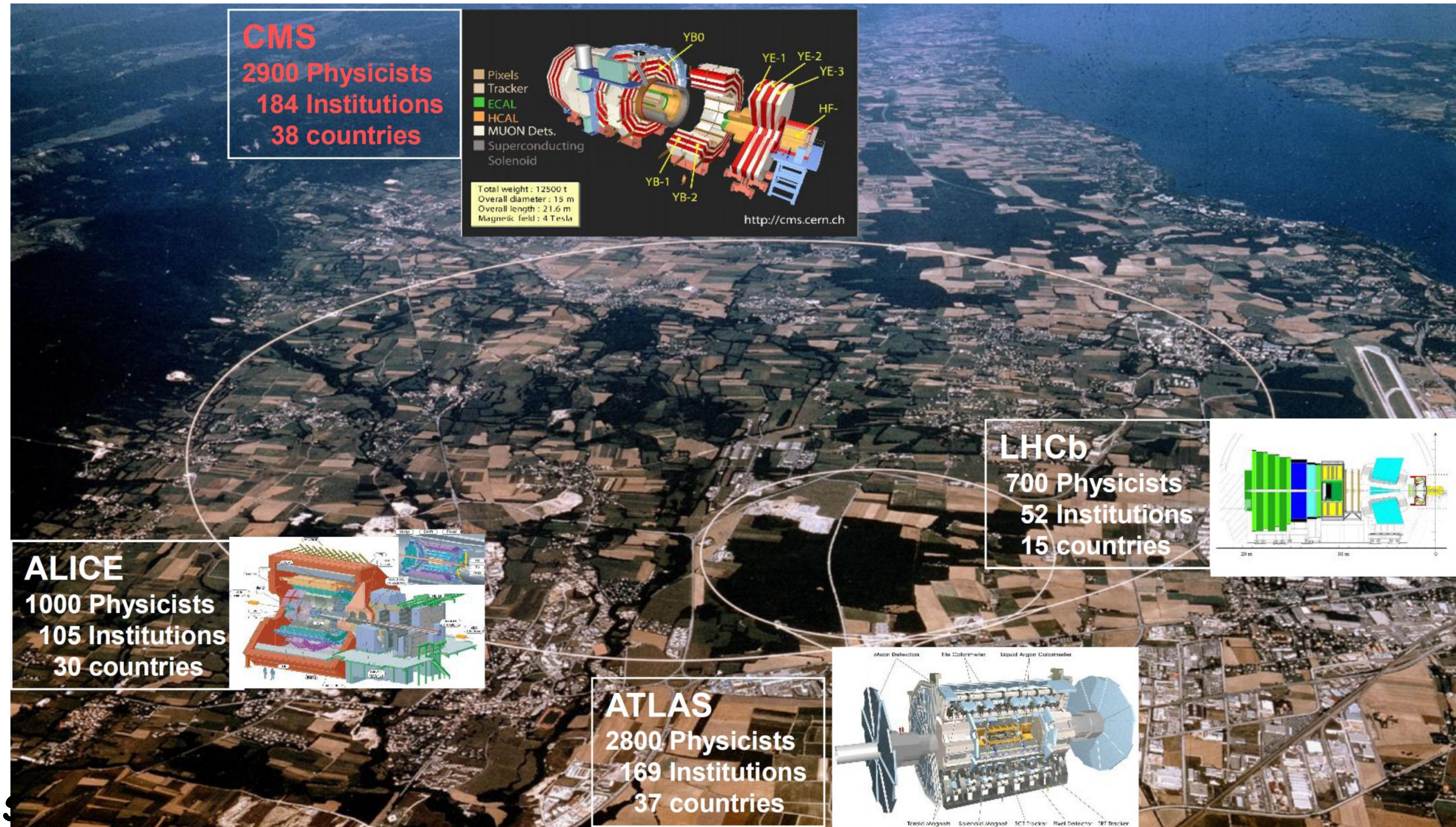
What is the LHC?

Collider LHC



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

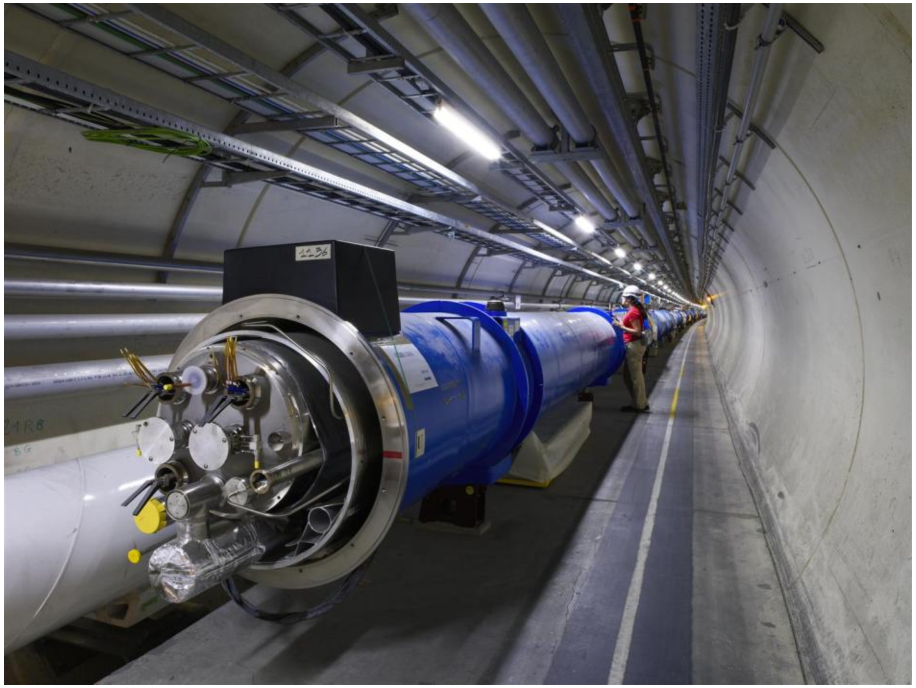
27 km circumference, about 100 m underground



September 19 (2008) – an accident

2012 – run at 8 TeV

LHC is the most complicated and expensive project in fundamental science

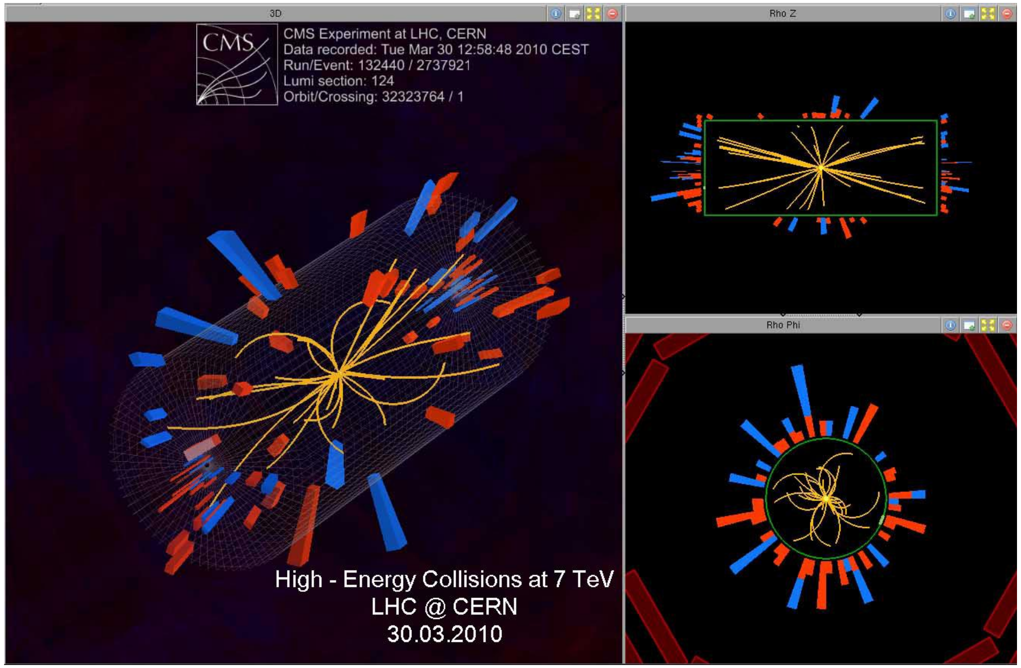


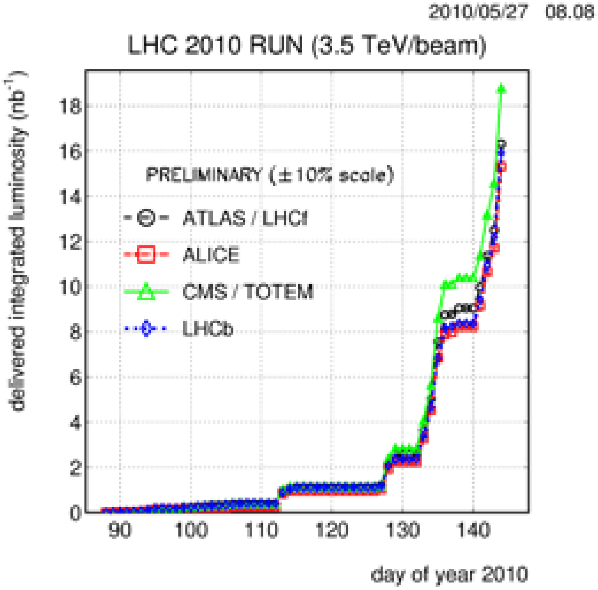
LHC vs Tevatron

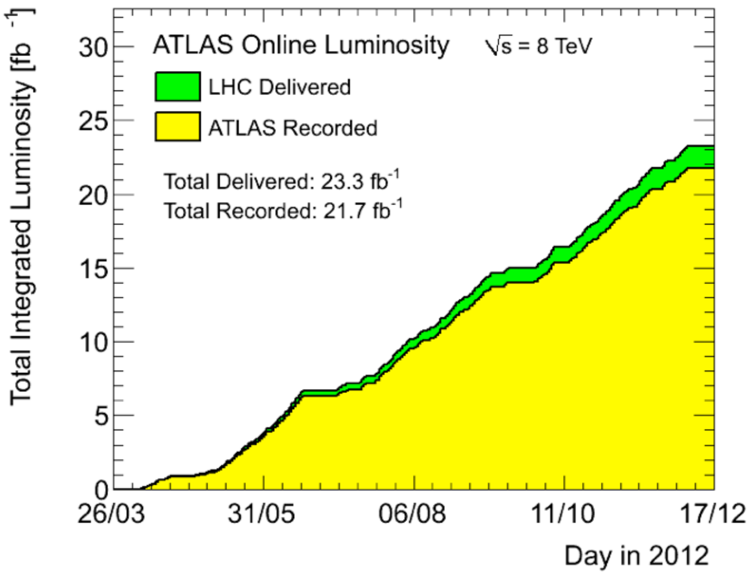
Energy: 14 TeV vs 2 TeV

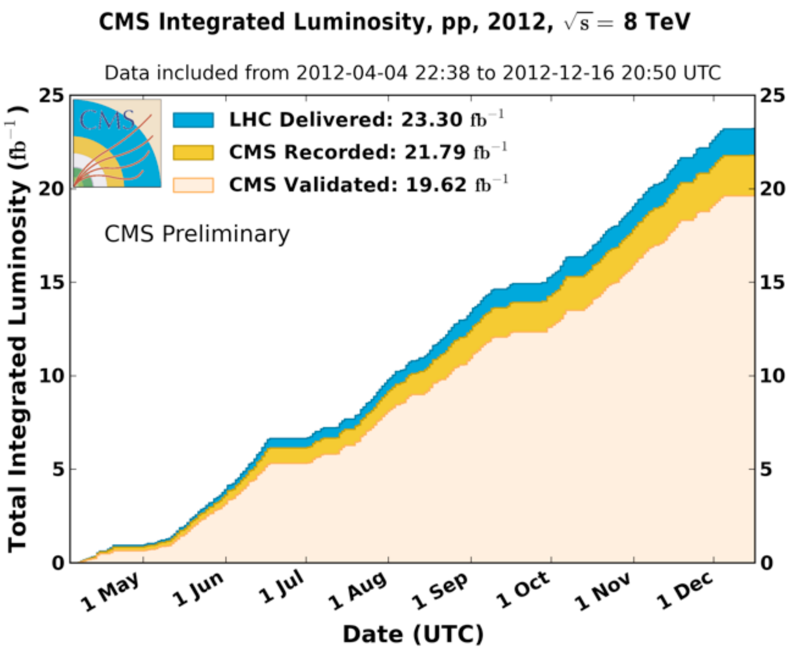
Luminosity: 10^{34} vs 10^{32} $cm^{-2}s^{-1}$

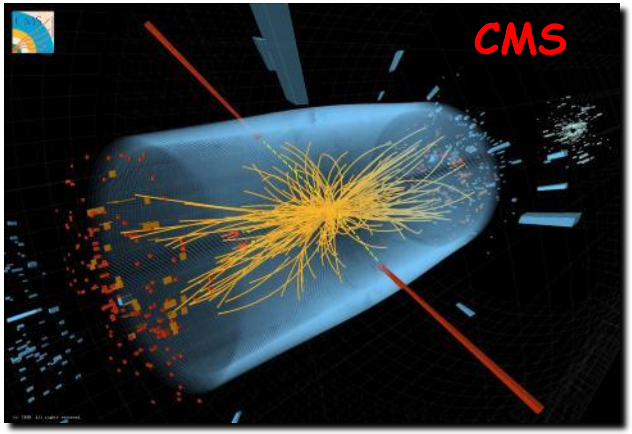
30 March 2010
LHC&7TeV
has started

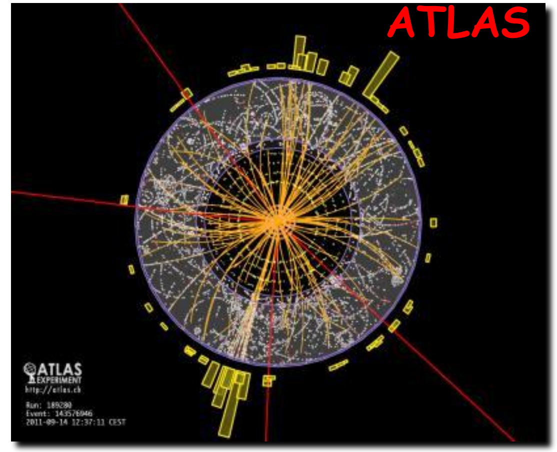


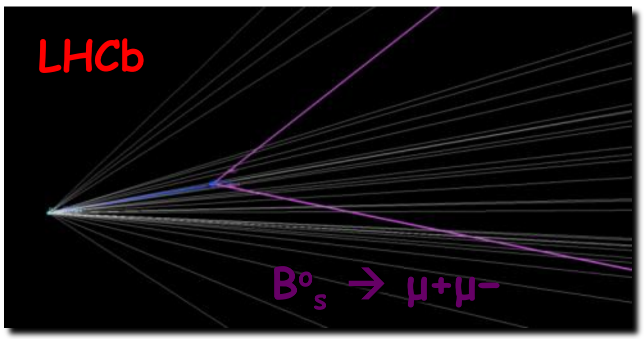



ATLAS Online Luminosity
√s = 8 TeV
LHC Delivered
ATLAS Recorded
Total Delivered: 23.3 fb-1
Total Recorded: 21.7 fb-1
Total Integrated Luminosity [fb -1]
0
5
10
15
20
25
30
26/03
31/05
06/08
11/10
17/12
Day in 2012

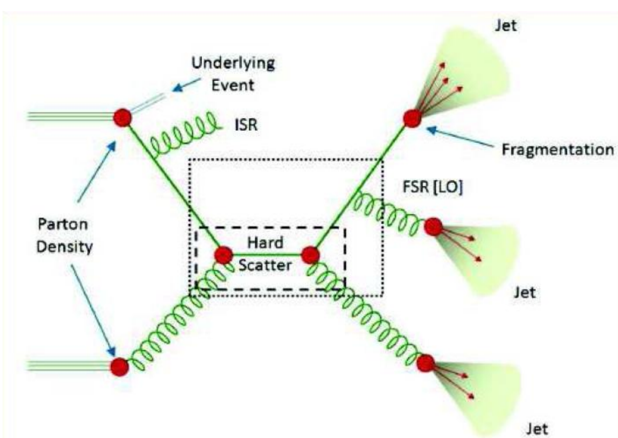

CMS Integrated Luminosity, pp, 2012, √s = 8 TeV
Data included from 2012-04-04 22:38 to 2012-12-16 20:50 UTC
LHC Delivered: 23.30 fb-1
CMS Recorded: 21.79 fb-1
CMS Validated: 19.62 fb-1
CMS Preliminary
Total Integrated Luminosity (fb-1)
0
5
10
15
20
25
1 May
1 Jun
1 Jul
1 Aug
1 Sep
1 Oct
1 Nov
1 Dec
Date (UTC)

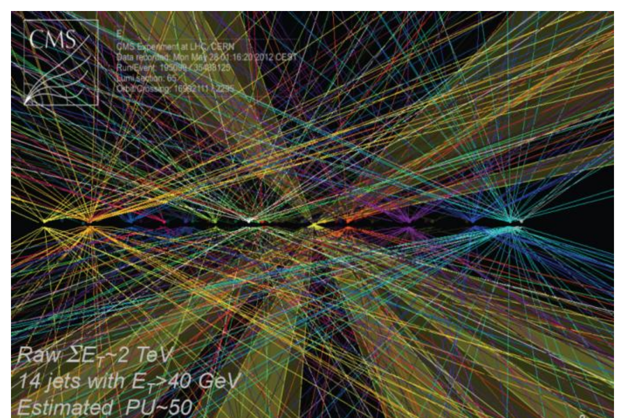

CMS


ATLAS


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

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

What did we know before the LHC start?

SM – the quantum field theory based on few principles and requirements :

- gauge invariance with lowest dimension (dimension 4) operators;
  SM gauge group: $SU(3)_c \times SU(2)_L \times U(1)_Y$

- correct electromagnetic neutral currents and (V-A) charged currents (Fermi);

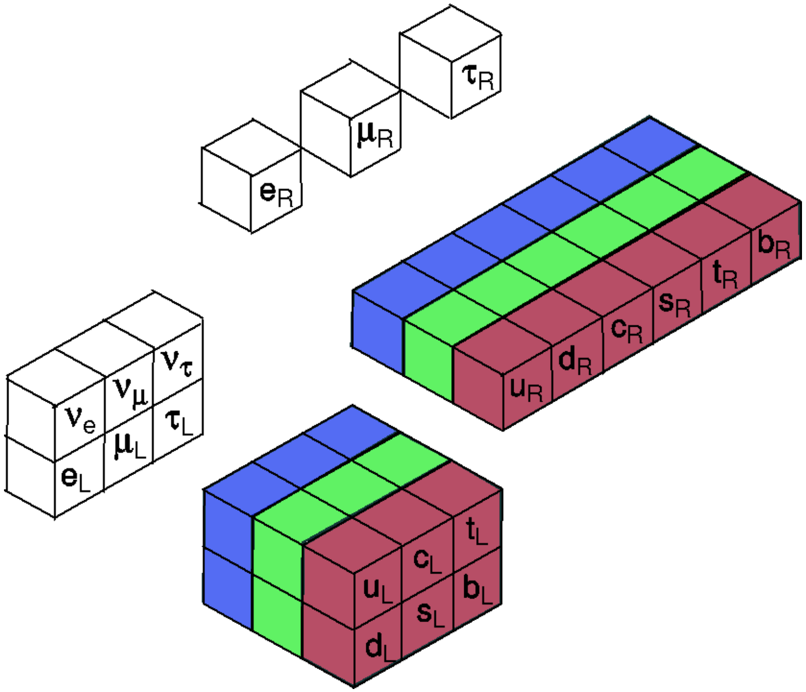
$$\frac{G_F}{\sqrt{2}} \cdot [\bar{\nu}_\mu \cdot \gamma_\alpha (1-\gamma_5) \cdot \mu] \cdot [\bar{e} \cdot \gamma_\alpha (1-\gamma_5) \cdot \nu_e] + h.c.$$

- 3 generations without chiral anomalies

- Higgs mechanism of spontaneous symmetry breaking

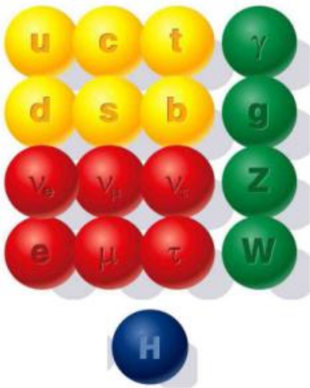
Standard Model – one of the main intellectual achievement for about last 50 years, a result of many theoretical and experimental studies

Fermions are combined into 3 generations forming left doublets and right singlets with respect to weak isospin



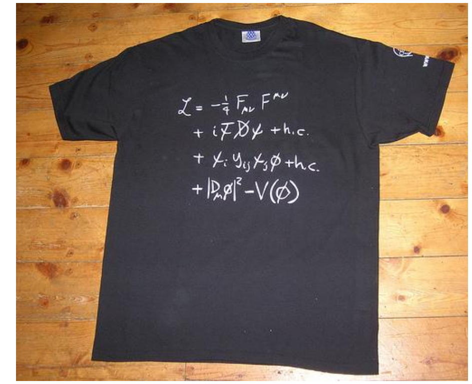
$$f_{L,R} = \frac{1}{2}(1 \mp \gamma_5) f$$

$$I_f^{3L,3R} = \pm\frac{1}{2}, 0 \;:\quad \begin{array}{l} L_1 = \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L, \; e_{R_1} = e_R^-, \; Q_1 = \begin{pmatrix} u \\ d \end{pmatrix}_L, \; u_{R_1} = u_R, \; d_{R_1} = d_R \\ L_2 = \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L, \; e_{R_2} = \mu_R^-, \; Q_2 = \begin{pmatrix} c \\ s \end{pmatrix}_L, \; u_{R_2} = c_R, \; d_{R_2} = s_R \\ L_3 = \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L, \; e_{R_3} = \tau_R^-, \; Q_3 = \begin{pmatrix} t \\ b \end{pmatrix}_L, \; u_{R_3} = t_R, \; d_{R_3} = b_R \end{array}$$



Standard Model

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



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

$$L_H = L_\Phi + L_{Yukawa}$$

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

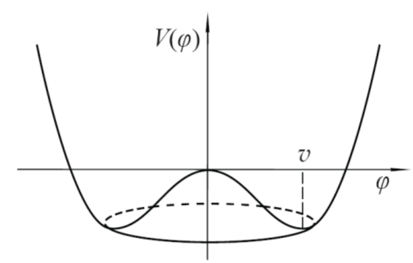
$$L_{Yukawa} = -\Gamma^{ij}_d \bar{Q'_L}^i \Phi {d'_R}^j + h.c. - \Gamma^{ij}_u \bar{Q'_L}^i \Phi^C {u'_R}^j + h.c. - \Gamma^{ij}_e \bar{L'_L}^i \Phi {e'_R}^j + h.c.$$

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

$$G^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g_S f^{abc} A^b_\mu A^c_\nu \qquad W^i_{\mu\nu} = \partial_\mu W^i_\nu - \partial_\nu W^i_\mu + g_2 \varepsilon^{ijk} W^j_\mu W^k_\nu$$

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

$$D^R_\mu = \partial_\mu - ig_1 B_\mu \left(\frac{Y^f_R}{2}\right) - ig_S A^a_\mu t^a \qquad i = 1,2,3;\ a = 1,\ldots,8,$$



$M_V,\ M_h,\ M_f \sim v$

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

A very elegant theoretical construction!

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

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

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

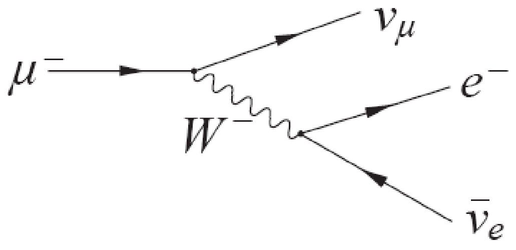
$$M_H^2 = 2\lambda v^2$$

Electroweak Standard Model

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!

$$M_W^2 = \frac{1}{4} g_2^2 v^2 \qquad g_2 s_W = e \qquad M_W = M_Z c_W$$

$$M_W^2 \left(1 - \frac{M_W^2}{M_Z^2}\right) = \frac{\pi \alpha_{em}}{\sqrt{2} G_F} \equiv A_0^2$$

$\alpha_{em} = e^2/4\pi$ is the electromagnetic fine structure constant. The low energy value follows mainly from the electron anomalous magnetic measurements

$$\alpha_{em} = (137.035\,999\,074(44))^{-1}$$

One gets A_0 very precisely from low energy measurements

$$A_0 = 37.2804 \text{ GeV}$$

From the other hand one gets A_0 from measured values for the masses of W and Z bosons

$$\begin{array}{rclll} M_W & = & 80.385 & \pm 0.015 & \text{GeV} \\ M_Z & = & 91.1876 & \pm 0.0021 & \text{GeV} \end{array} \quad \Longrightarrow \quad A_0 = 37.95 \text{ GeV}$$

Values are close. The difference is about 1%.

CC and NC interactions of SM fermions, as we know already, have the following structure

$$L_{CC} = \frac{g_2}{2\sqrt{2}} \sum_{ij} V_{ij} \bar{u}_i \gamma_\mu (1-\gamma_5) d_j = \frac{e}{2\sqrt{2} s_W} \sum_{ij} V_{ij} \bar{u}_i \gamma_\mu (1-\gamma_5) d_j,$$

$$L_{NC} = e \sum_f Q_f \bar{f} \gamma_\mu f + \frac{e}{4 s_W c_W} \sum_f \bar{f} \gamma_\mu (v_f - a_f \gamma_5) f Z^\mu,$$

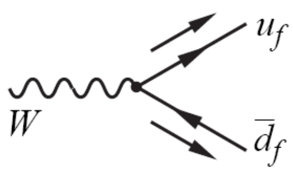
where Vij is the CKM matrix element, i, j = 1, 2, 3 - number of fermion generation

$$v_{u_i} = 1 - \frac{8}{3} s_W^2, \quad a_{u_i} = 1; \quad v_{d_i} = -1 + \frac{4}{3} s_W^2, \quad a_{d_i} = -1$$

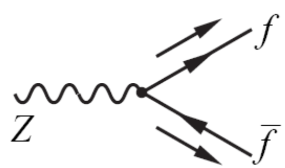
$$v_\ell = -1 + 4 s_W^2, \quad a_\ell = -1; \quad v_\nu = 1, \quad a_\nu = 1.$$

$$v_f = 2T_3^f - 4Q_f s_W^2, \quad a_f = 2T_3^f$$

The Feynman rules following from L_{CC} and L_{NC} allow to get tree level formulas for the W and Z boson widths



$$\Gamma(W \to u_f \bar{d}_f) = |V_{ij}|^2 N_c \frac{\alpha}{12 s_W^2} M_W,$$



$$\Gamma(Z \to f\bar{f}) = N_c \frac{\alpha M_Z}{12 \sin^2(2\theta_W)} [v_f^2 + a_f^2]$$

N_c = 3 for quarks, and N_c = 1 for leptons

Since CC for all fermions have the same (V – A) structure one can very easily obtain branching fractions for W decay modes

$$\sum_q \mathrm{Br}(W \to q\bar{q}) = 2N_c \cdot \frac{1}{9} = \frac{2}{3}$$
$$\sum_\ell \mathrm{Br}(W \to \ell\nu) = 3 \cdot \frac{1}{9} = \frac{1}{3}$$

Measured Br(W → ℓν) = (10.80±0.09)% is in a reasonable agreement with simple tree level result 1/9 = 11%

QCD corrections to Br(W → qq) improved the agreement

The decay width of the Z-boson to neutrinos, the invisible decay mode, allows to measure the number of light ($m_\nu < M_Z/2$) neutrinos

$$\Gamma^Z_{inv} = \Gamma^Z_{tot} - \Gamma^Z_{had} - \Gamma^Z_{\ell+\ell-}$$

$$\Gamma^Z_{tot} = 2.4952 \pm 0.0023 \text{ GeV}$$ is measured from the shape of the Z-boson resonance

$$\Gamma^Z_{\ell+\ell-} = 83.984 \pm 0.086 \text{ MeV}$$
$$\Gamma^Z_{had} = 1744.4 \pm 2.0 \text{ MeV}$$

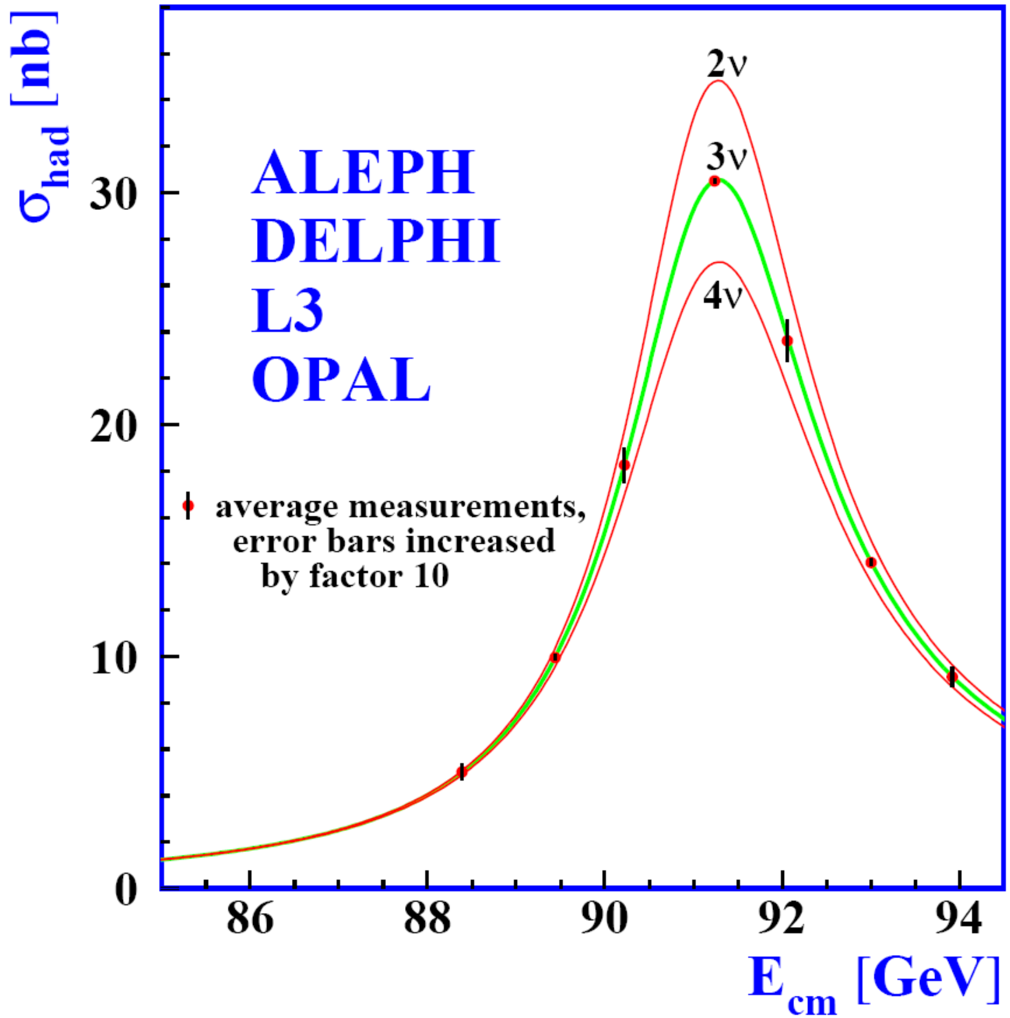
→ $$\Gamma^Z_{inv} = 499.0 \pm 1.5 \text{ MeV}$$

In SM $$\Gamma(Z \to f\bar{f}) = N_c \frac{\alpha M_Z}{12 \sin^2(2\theta_W)}[v_f^2 + a_f^2] \Longrightarrow \Gamma^Z_{inv} = \Gamma^Z_{\nu\bar{\nu}} = N_\nu \cdot \frac{\alpha M_Z}{12 \sin^2(2\theta_W)}(1+1)$$

⇓

$$2.9840 \pm 0.0082$$

Confirmation of 3 fermion generations assumed in the SM and observed in nature



σhad [nb]
30
20
10
0
86
88
90
92
94
Ecm [GeV]
ALEPH
DELPHI
L3
OPAL
2ν
3ν
4ν
average measurements,
error bars increased
by factor 10

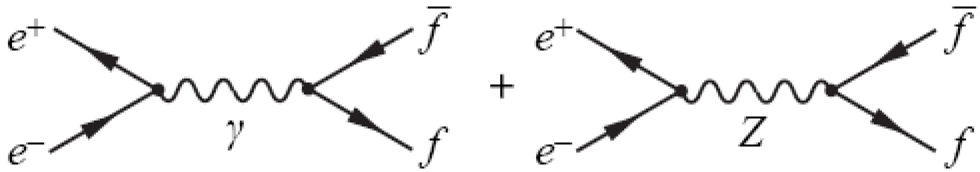
Another way to make this test

$$\frac{\Gamma^Z_{inv}}{\Gamma^Z_{e^+e^-}} = \frac{2N_\nu}{1+(1-4s^2_W)^2}$$

The experimental value 5.942 ± 0.016

$N_\nu = 3$ gives for the ratio about 5.970 in an agreement with the measured value ($s_W^2 = 0.2324$)

An important part of information about EW fermionic interactions and couplings comes from e+e− annihilation to fermion-antifermion pairs



$$\frac{d\sigma}{d\cos\theta} = \frac{2\pi\alpha^2}{4s} N_C \{(1+\cos^2\theta)\cdot \cdot\left[Q_f^2 - 2\chi_1 v_e v_f Q_f + \chi_2(a_e^2+v_e^2)(a_f^2+v_f^2)\right] + +2\cos\theta\left[-2\chi_1 a_e a_f Q_f + 4\chi_2 a_e a_f v_e v_f\right]\}$$

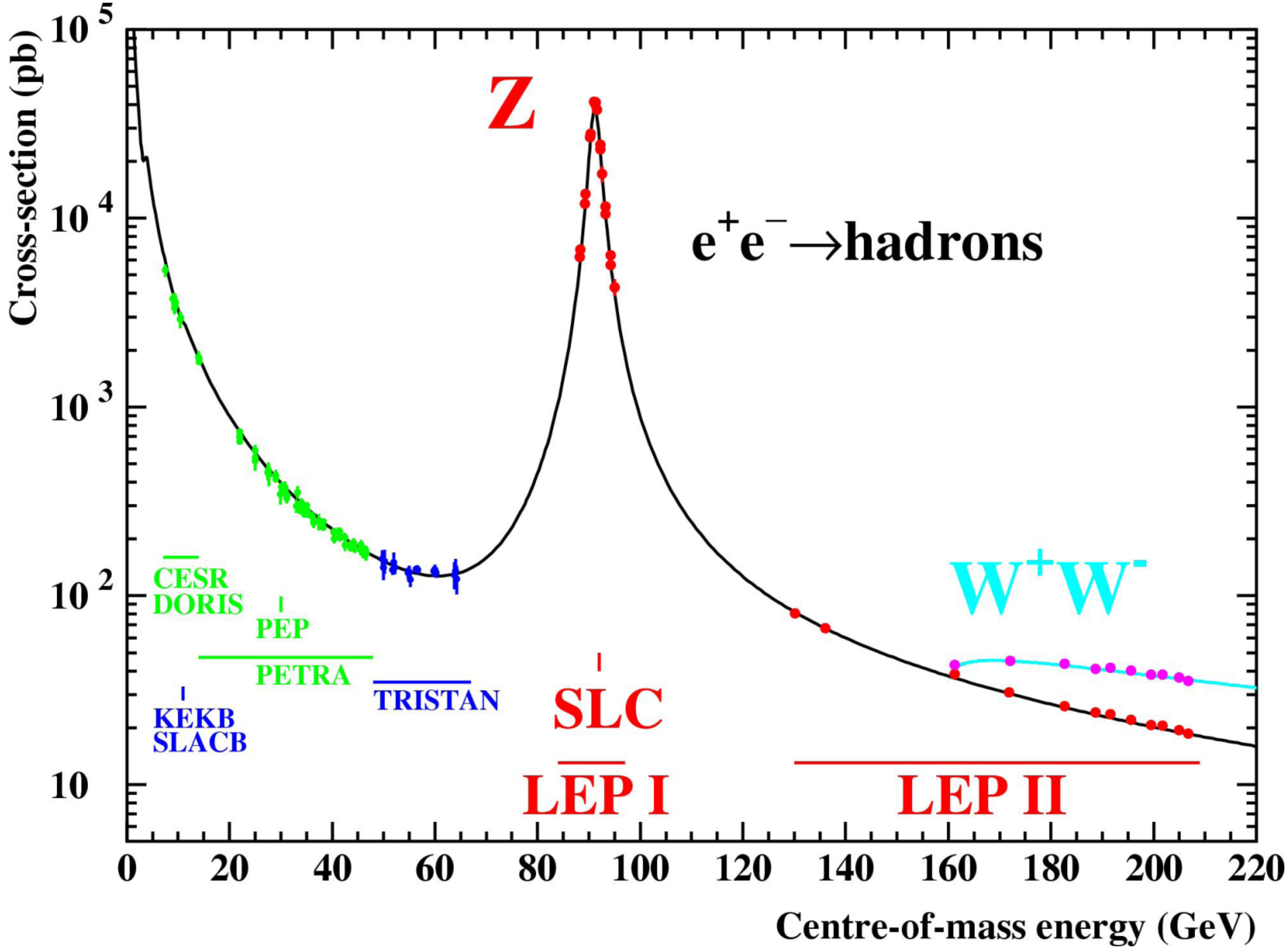
$$\chi_1 = \frac{1}{16 s_W^2 c_W^2}\frac{s(s-M_Z^2)}{(s-M_Z^2)^2 + M_Z^2\Gamma_Z^2},$$

$$\chi_2 = \frac{1}{256 s_W^2 c_W^2}\frac{s^2}{(s-M_Z^2)^2 + M_Z^2\Gamma_Z^2}.$$

In the region much below Z-boson pole one can neglect Z-boson exchange diagram and well known QED formula is restored

$$\frac{d\sigma}{d\cos\theta} = \frac{\pi\alpha^2}{2s} Q_f^2 N_C (1+\cos^2\theta), \quad \sigma = \frac{4\pi\alpha^2}{3} Q^2 N_C$$

N_c = 3 for quarks, and N_c = 1 for leptons



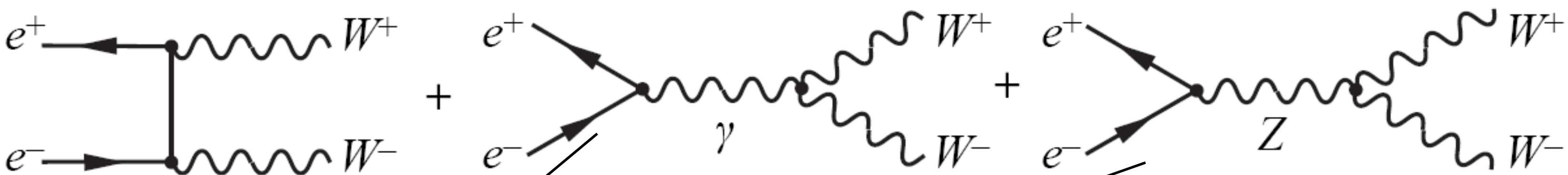
Cross-section (pb)
10 5
10 4
10 3
10 2
10
Z
e+e−→hadrons
CESR
DORIS
PEP
PETRA
KEKB
SLACB
TRISTAN
SLC
LEP I
LEP II
W+W-
0
20
40
60
80
100
120
140
160
180
200
220
Centre-of-mass energy (GeV)

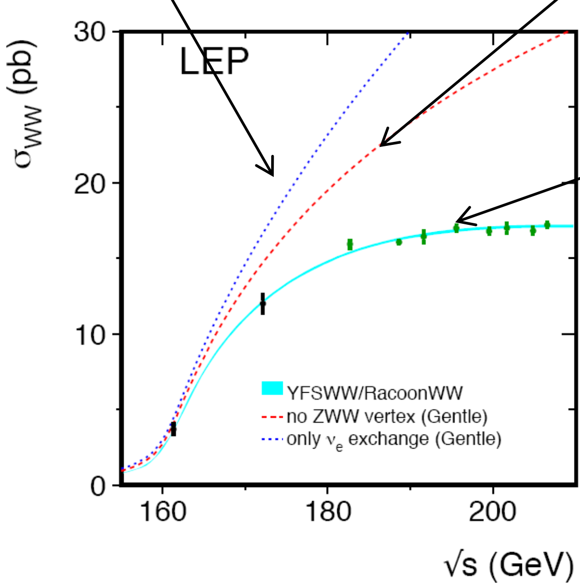
Well known example demonstrating correctness of the Yang-Mills interaction of gauge bosons is W-boson pair production. Triple gauge boson vertex WWγ and WWZ have been tested at LEP2 ($e^+e^- \to W^+W^-$) and at the Tevatron ($q\bar{q} \to W^+W^-,\ q\bar{q}' \to W\gamma,\ q\bar{q}' \to WZ$).

The triple vertex of Yang-Mills interaction

$$\Gamma^{WW\gamma/Z}_{m_1m_2m_3}(p_1p_2p_3) = g_{\gamma,Z}\left[(p_1-p_2)_{m_3}g_{m_1m_2} + (p_3-p_1)_{m_2}g_{m_1m_3} + (p_2-p_3)_{m_1}g_{m_2m_3}\right]$$

$$g_\gamma = e,\ g_Z = g_2 c_W = e\frac{c_W}{s_W}$$





Three SM diagrams

The quartic gauge couplings WWγγ, WWγZ, WWZZ have not been tested yet. This is challenging task for the LHC. It will require high luminosity regime at a linear collider

All terms of the SM Lagrangian have dimension 4, and all the coupling constants are dimensionless. So, the SM is the renormalizable theory in the same manner as QED.

The perturbation theory expansion EW parameters α/π with $\alpha_{em} \sim 1/129$ and $\alpha_{weak} \sim 1/30$ are very small

Naively - the EW higher order corrections are not that important

However, the experimental accuracies are in some cases so high, that even 1-loop EW corrections might not be sufficient

$$\begin{array}{lllllll} M_Z & = & 91.1875 & \pm & 0.0021 & \text{GeV} & 0.002\% \\ \Gamma_Z & = & 2.4952 & \pm & 0.0023 & \text{GeV} & 0.09\% \\ M_W & = & 80.385 & \pm & 0.015 & \text{GeV} & 0.02\% \\ M_{top} & = & 173.2 & \pm & 0.9 & \text{GeV} & 0.52\% \end{array}$$

$$\rho_0 = \frac{m_W^2}{m_Z^2 \cos^2\theta_W}$$

$$\rho_\ell = 1.0050 \pm 0.0010$$

$$\sin^2\theta_{\text{eff}}^{\text{lept}} = 0.23153 \pm 0.00016$$

Most important corretions:

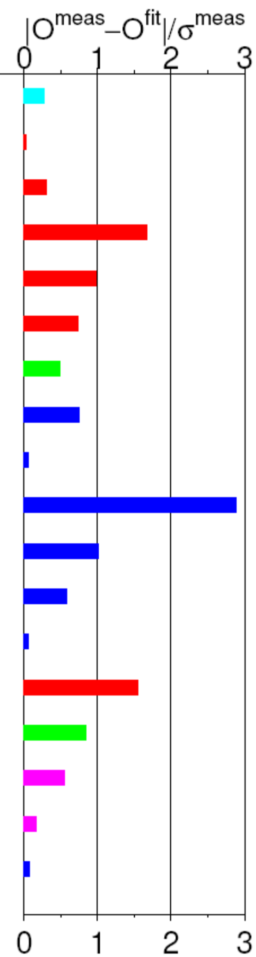
Resummation of large logs - $\log(M_{top}^2/m_e^2) \approx 24.2$;

Corrections proportional to M_{top}^2/M_W^2 coming from longitudinal modes

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

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02750 ± 0.00033	0.02759
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ_{had}^0 [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.385 ± 0.015	80.377
Γ_W [GeV]	2.085 ± 0.042	2.092
m_t [GeV]	173.20 ± 0.90	173.26



March 2012

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

CDF ($\int L dt$ = 2.2 fb^{-1})

Electron and Muon

M_W = 80387 ± 19 MeV

Dzero ($\int L dt$ = 5.2 fb^{-1})

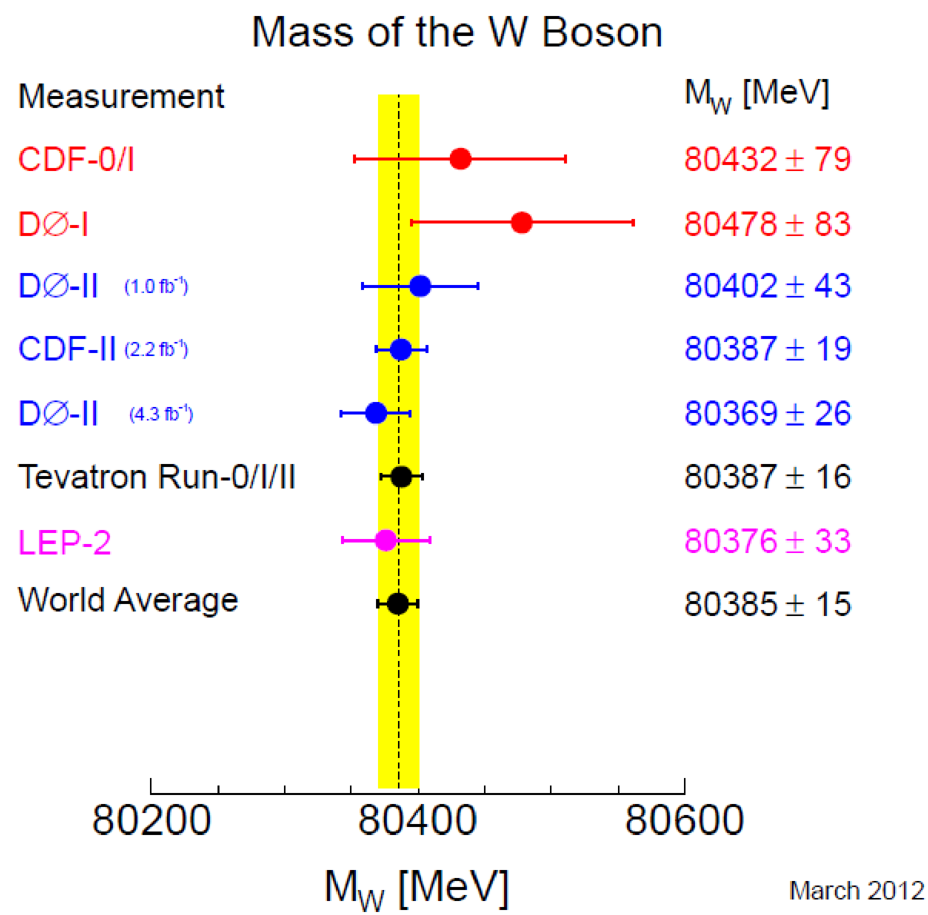
Electron only

M_W = 80369 ± 26 MeV

difficult analysis

Calibration / alignment

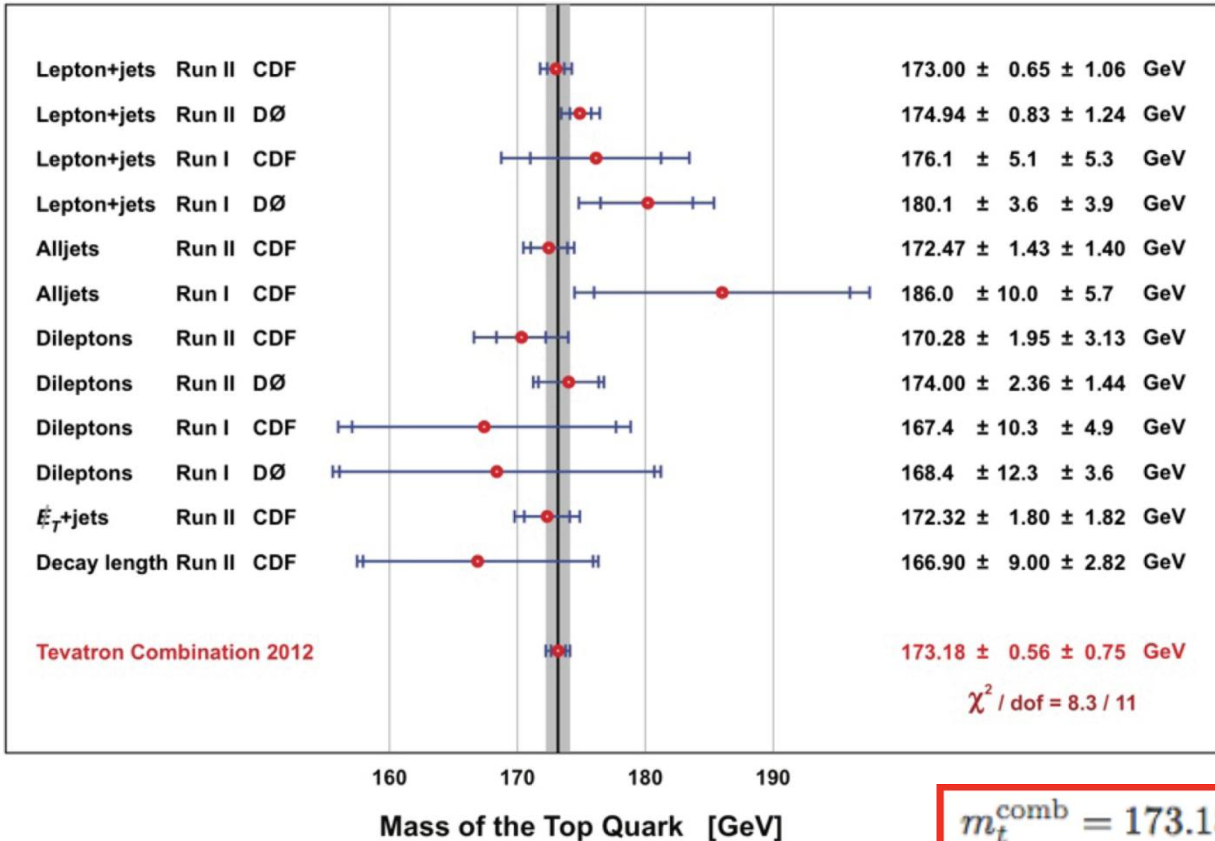
Understanding of recoil



Combination : M_W = 80385 ± 15 MeV

0.02%

Top quark mass measurements



Most precisely measured quark mass !

$$m_t^{comb} = 173.18 \pm 0.56\,(\mathrm{stat}) \pm 0.75\,(\mathrm{syst})\ \ \mathrm{GeV}$$
$$= 173.18 \pm 0.94\ \mathrm{GeV}$$

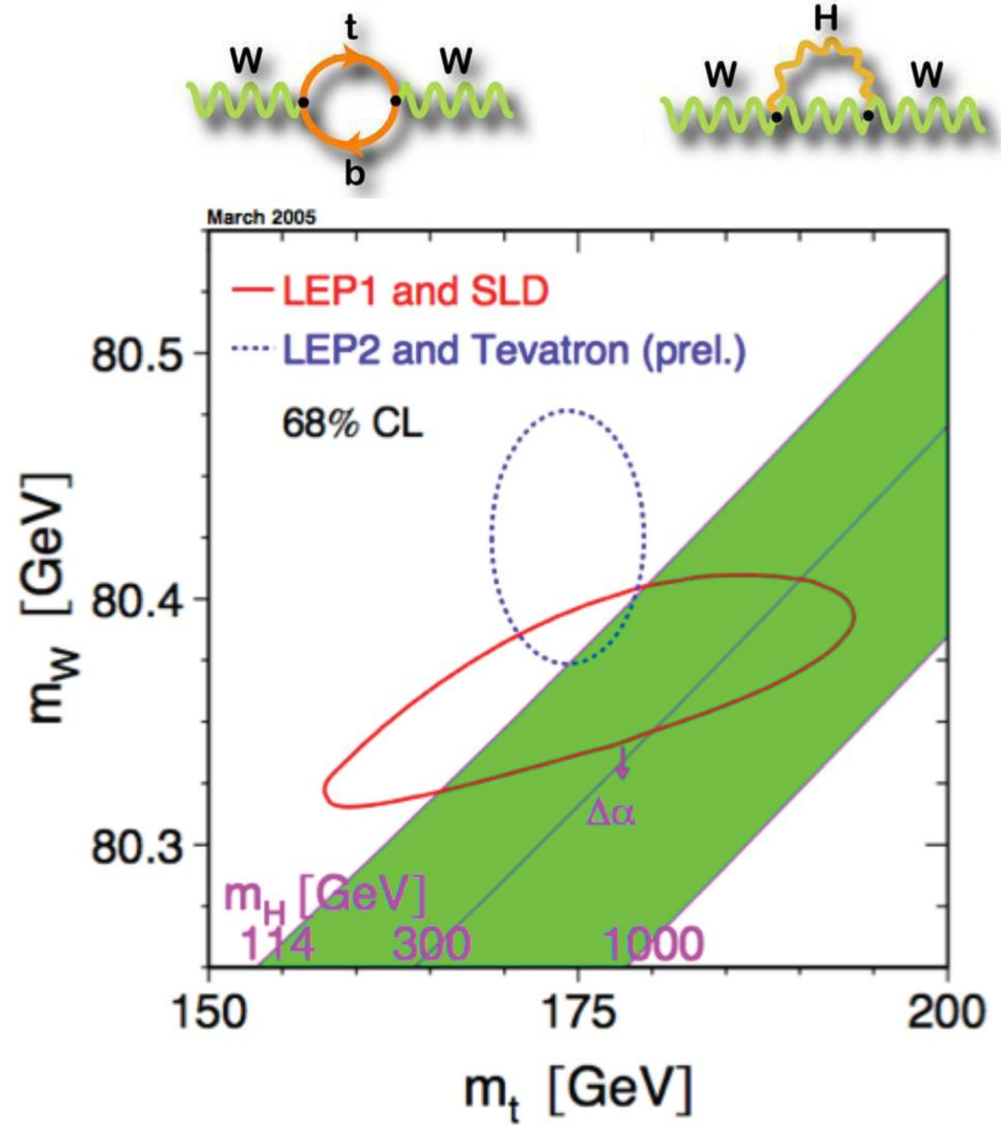
LHC: m_t=173.3±0.5(stat.)±1.3(sist.) GeV

Measurement of top and anti-top mass difference – check of CPT theorem

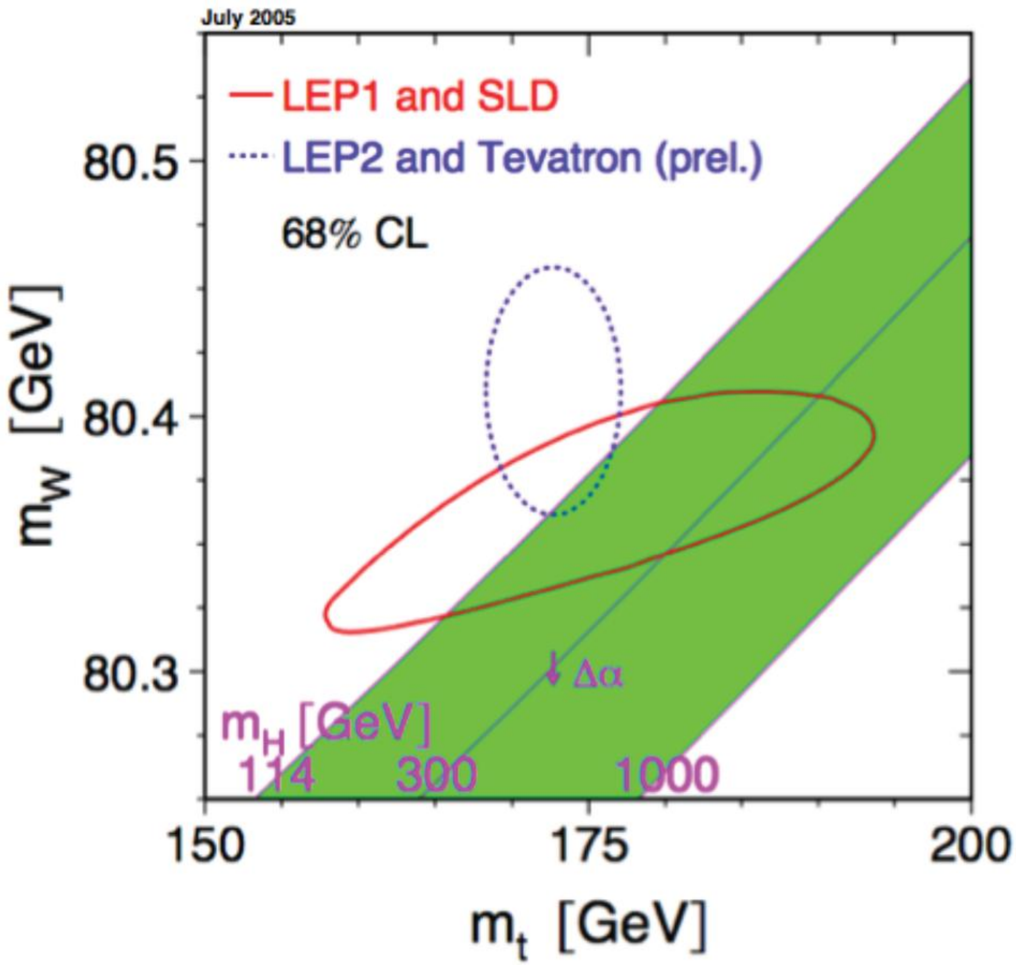
D0 : = 0.84±1.87 GeV
CDF : = -3.3±1.7 GeV

For comparisonCMS : = -0.44±0.53 GeV/c^2

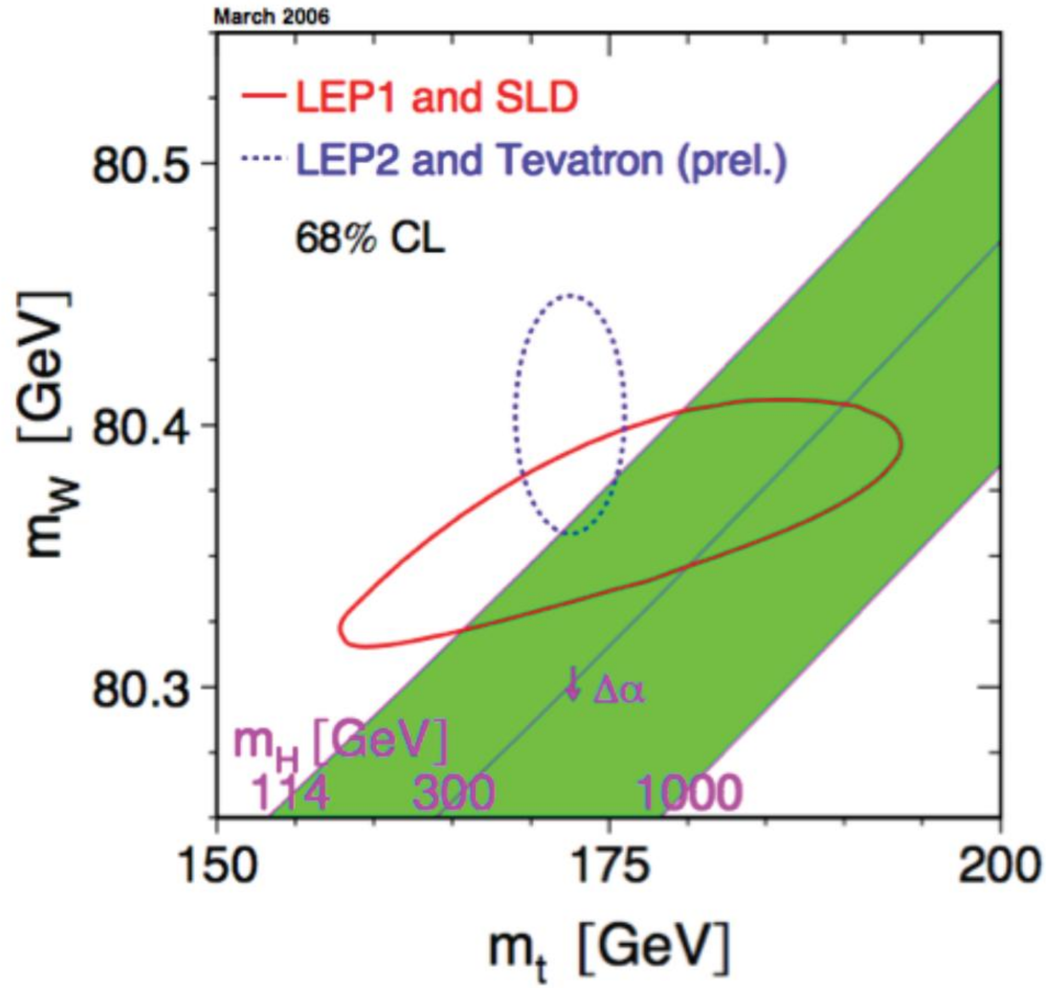
M_W is a function of M_{top} and M_H in SM as the quantum field theory (history)



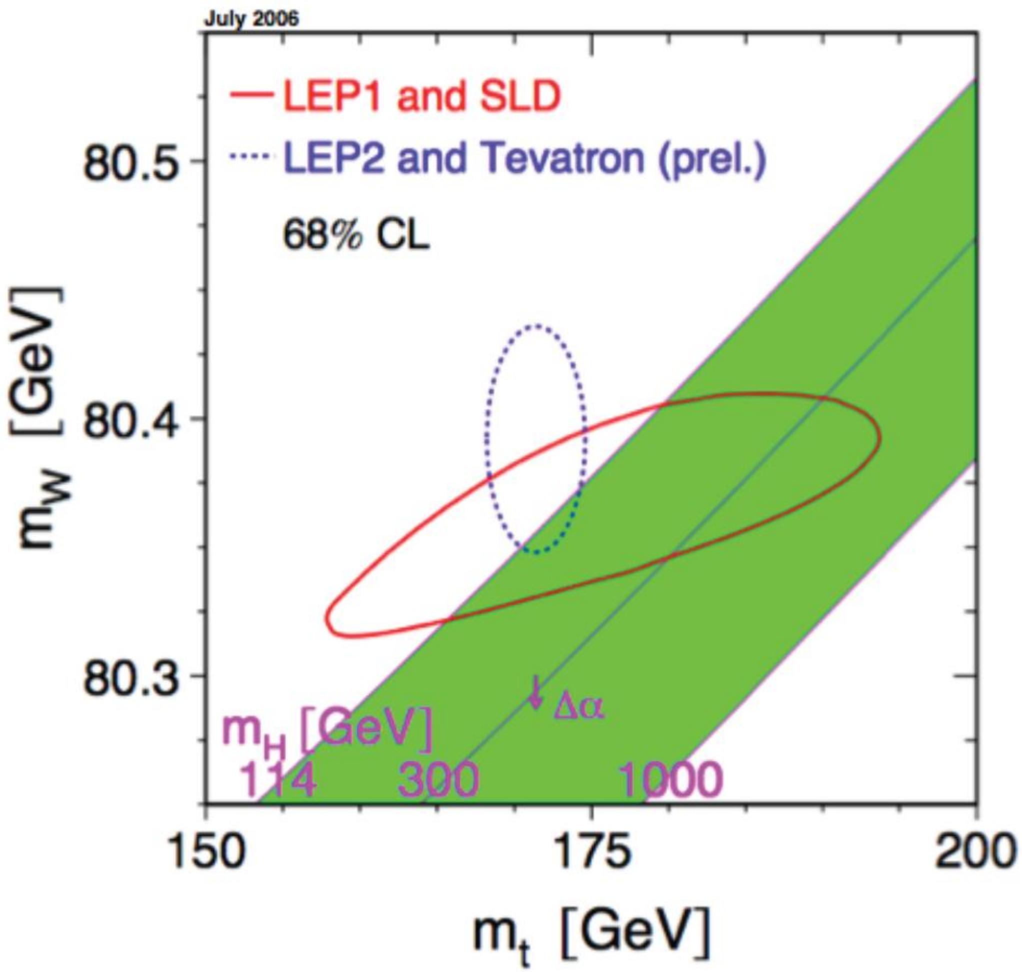
Schwanenberger 2012



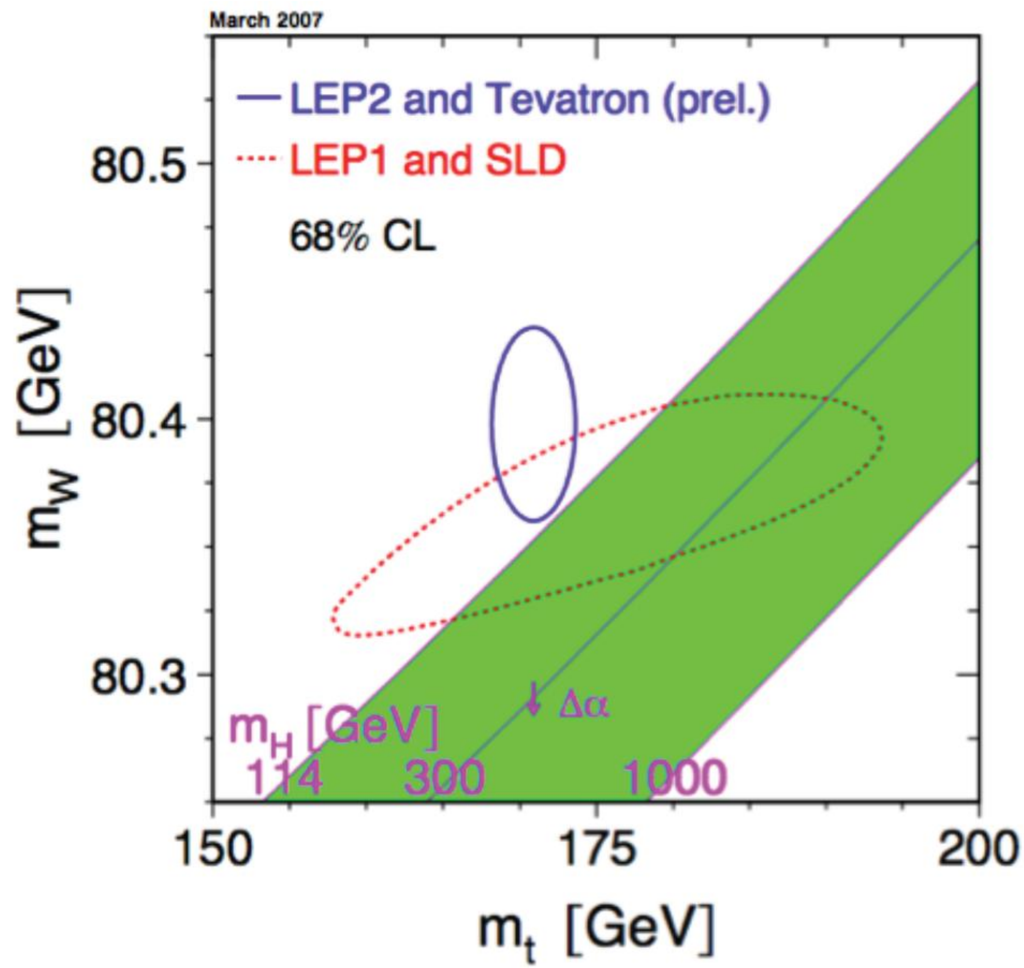
July 2005
LEP1 and SLD
LEP2 and Tevatron (prel.)
68% CL
80.5
80.4
80.3
m_W [GeV]
Δα
m_H [GeV]
114
300
1000
150
175
200
m_t [GeV]



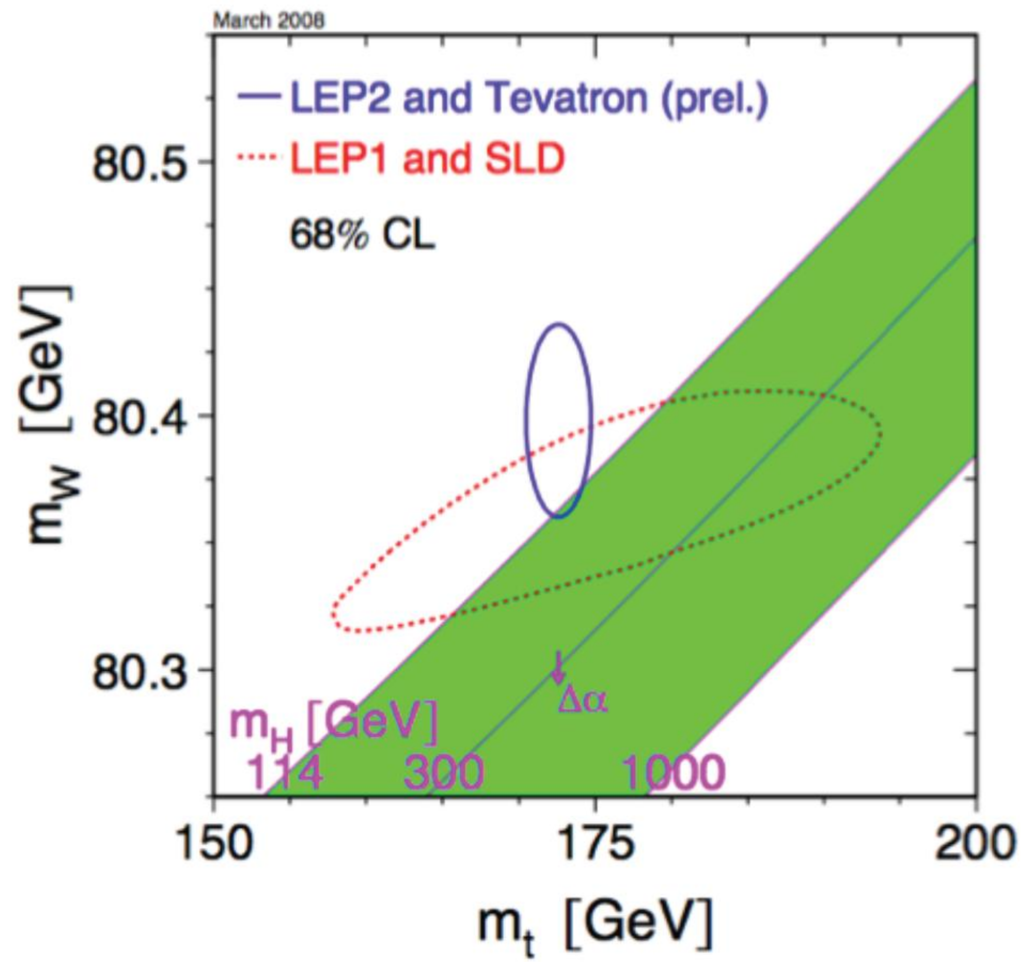
March 2006
LEP1 and SLD
LEP2 and Tevatron (prel.)
68% CL
m_W [GeV]
80.5
80.4
80.3
$\Delta\alpha$
m_H [GeV]
114
300
1000
150
175
200
m_t [GeV]



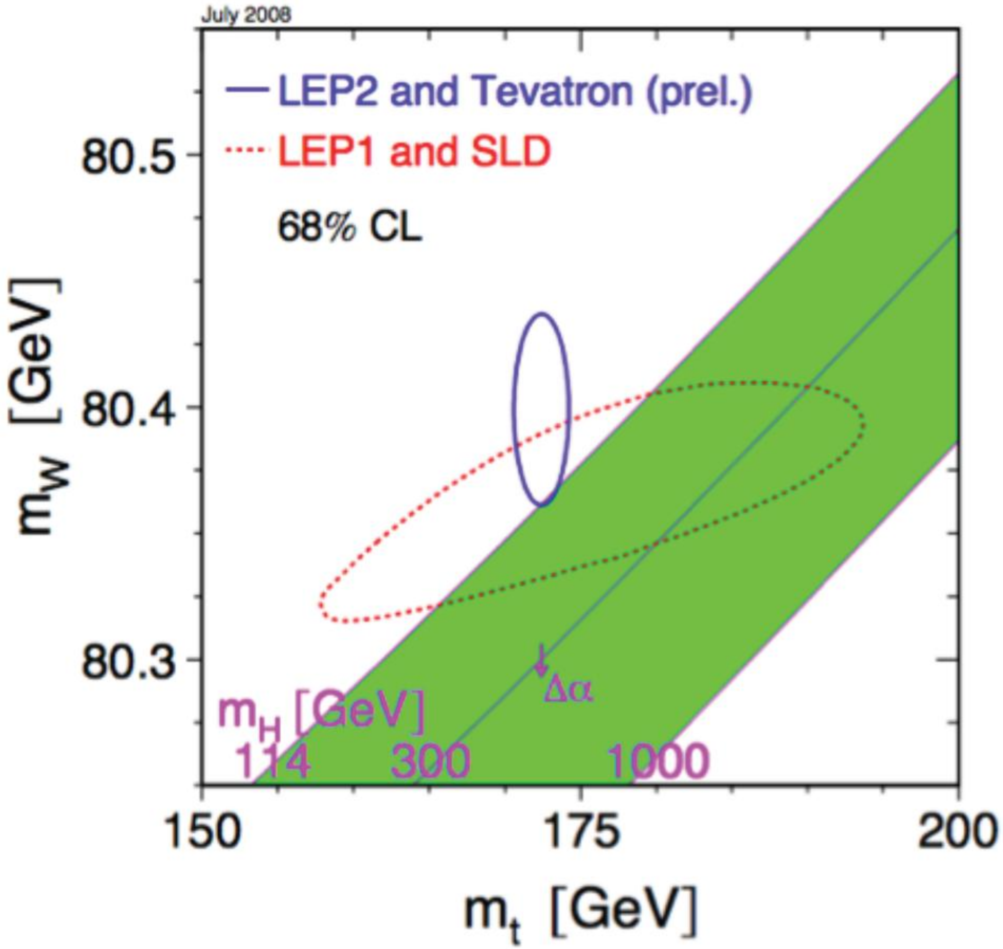
July 2006
LEP1 and SLD
LEP2 and Tevatron (prel.)
68% CL
80.5
80.4
80.3
m_W [GeV]
m_H [GeV]
114
300
1000
Δα
150
175
200
m_t [GeV]



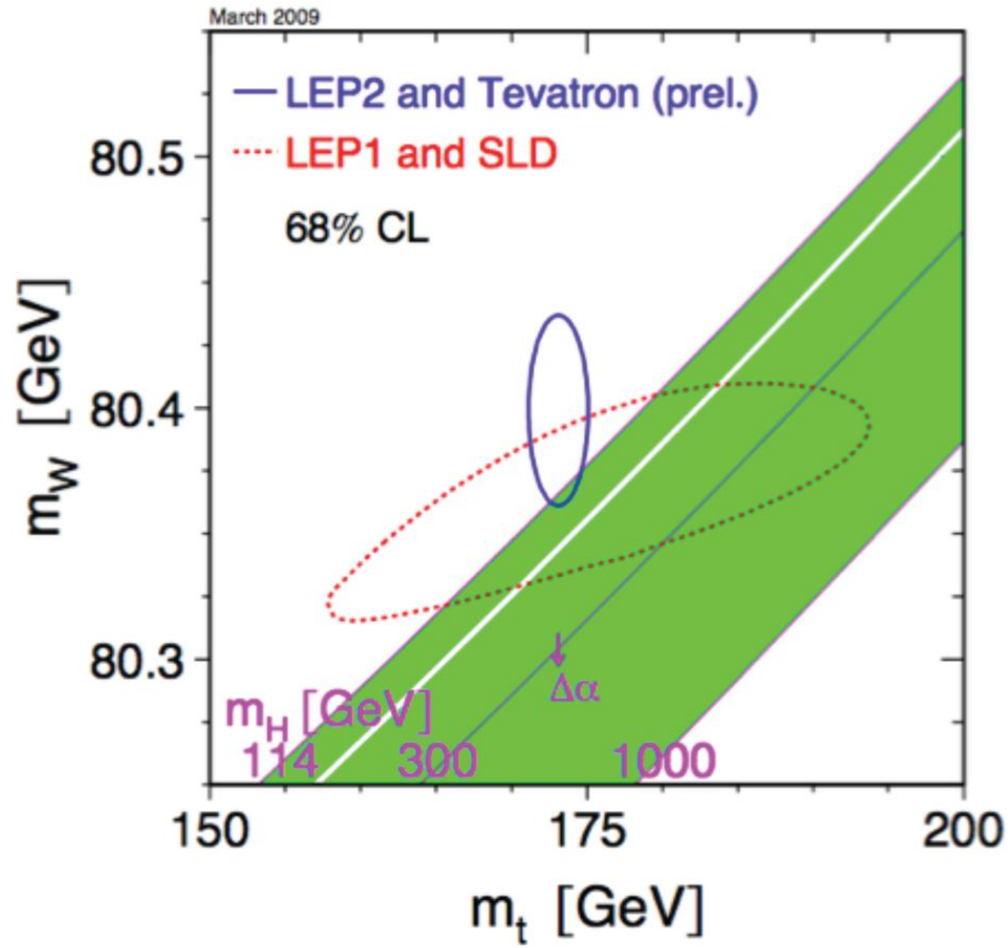
March 2007
LEP2 and Tevatron (prel.)
LEP1 and SLD
68% CL
80.5
80.4
80.3
m_W [GeV]
Δα
m_H [GeV]
114
300
1000
150
175
200
m_t [GeV]



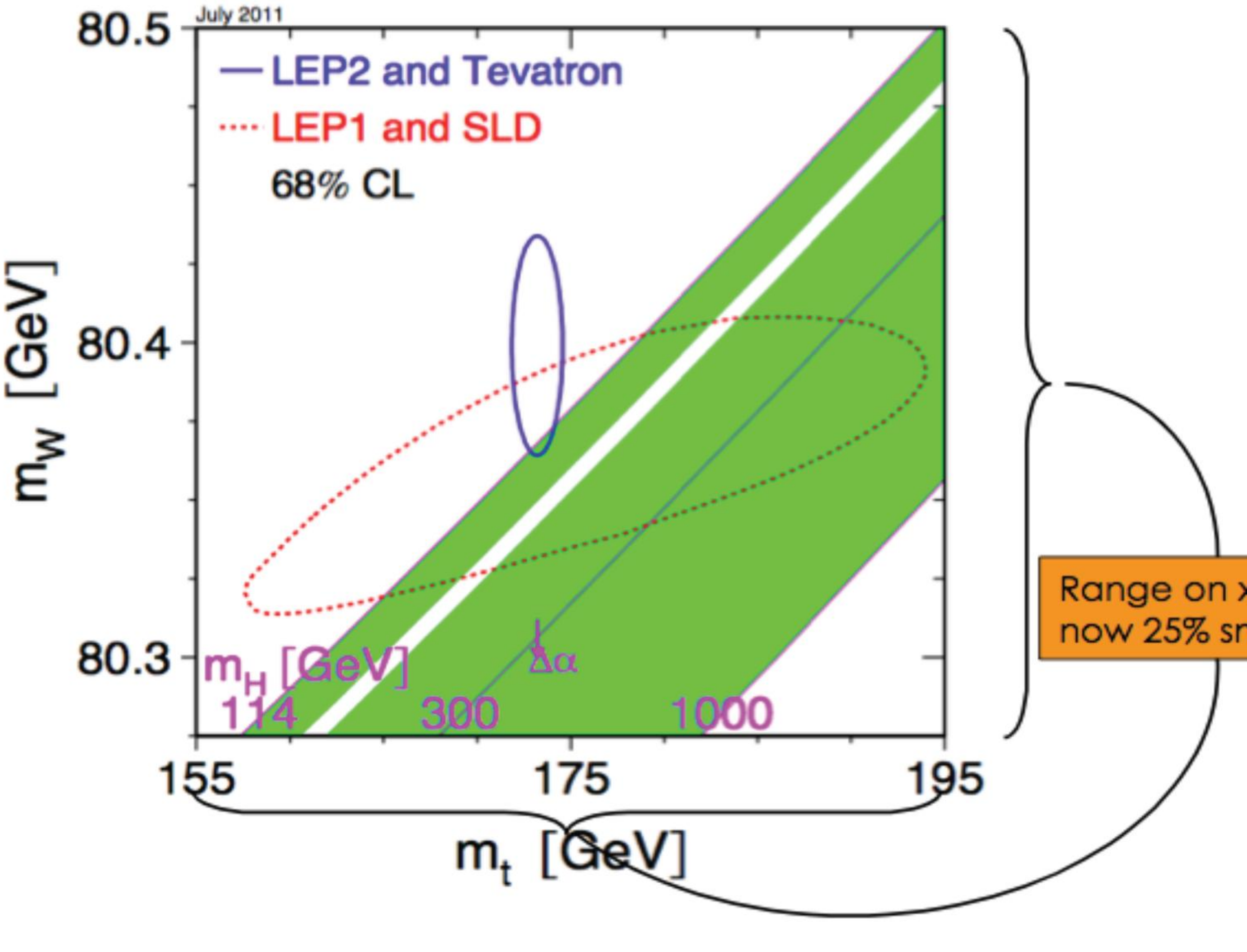
March 2008
LEP2 and Tevatron (prel.)
LEP1 and SLD
68% CL
80.5
80.4
80.3
m_W [GeV]
$\Delta\alpha$
m_H [GeV]
114
300
1000
150
175
200
m_t [GeV]



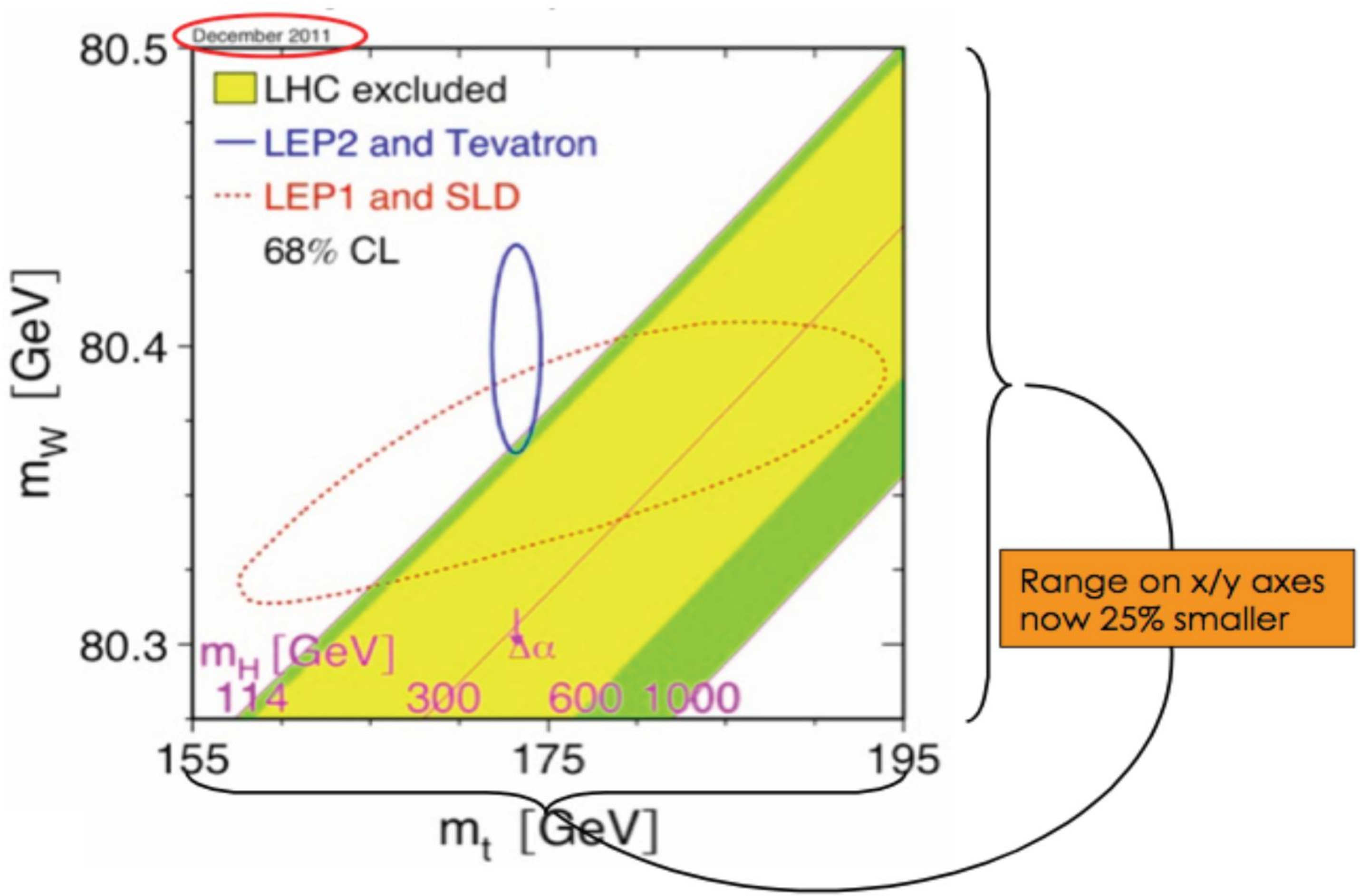
July 2008
LEP2 and Tevatron (prel.)
LEP1 and SLD
68% CL
80.5
80.4
80.3
m_W [GeV]
m_H [GeV]
114
300
1000
Δα
150
175
200
m_t [GeV]

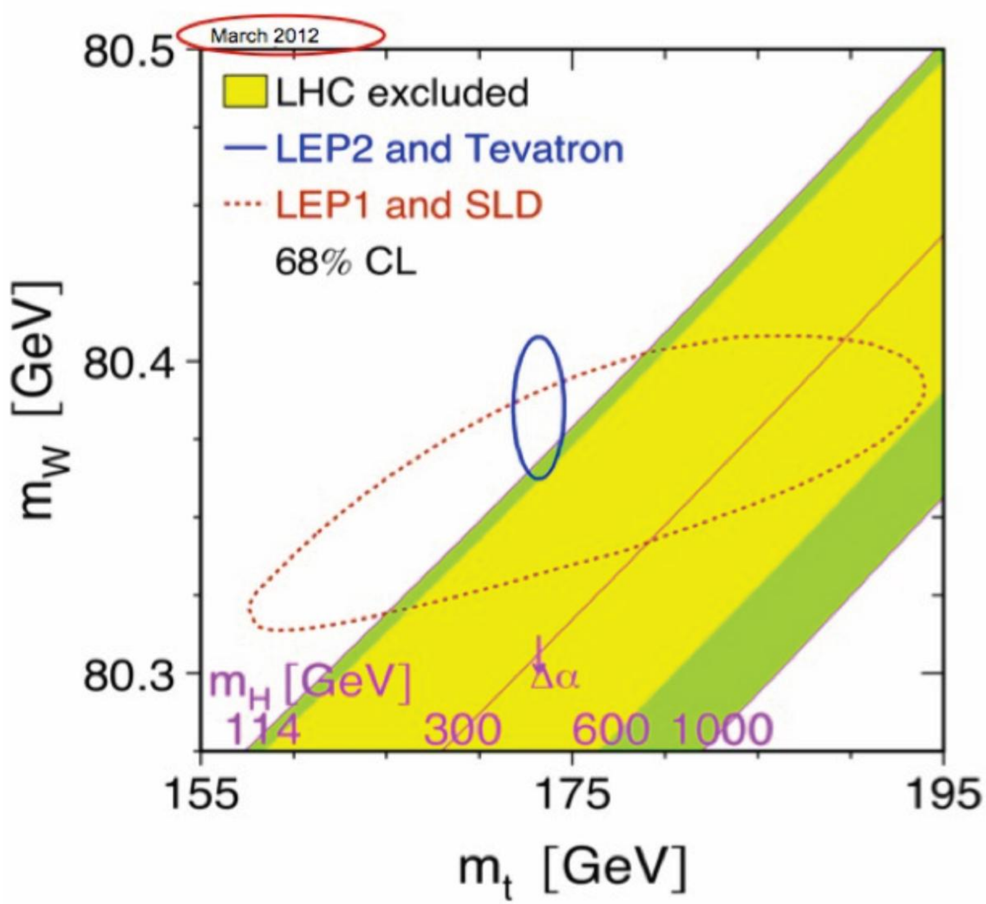


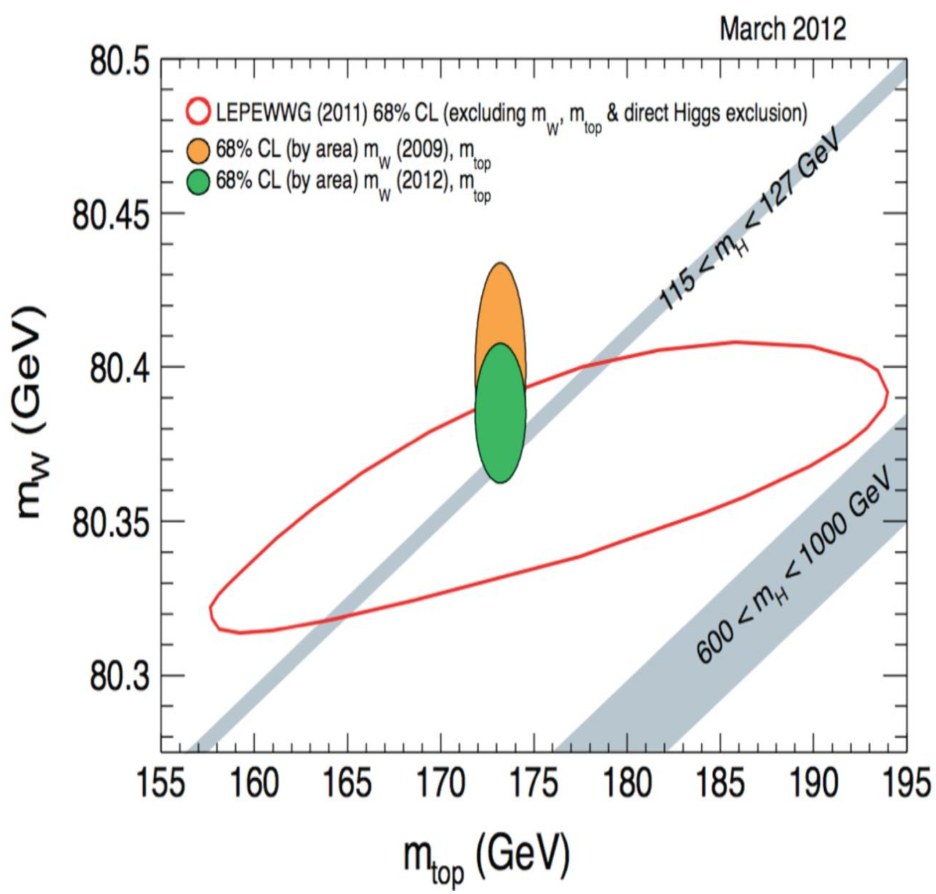
March 2009
LEP2 and Tevatron (prel.)
LEP1 and SLD
68% CL
80.5
80.4
80.3
m_W [GeV]
m_H [GeV]
114
300
1000
Δα
150
175
200
m_t [GeV]



Range on x/y axes now 25% smaller

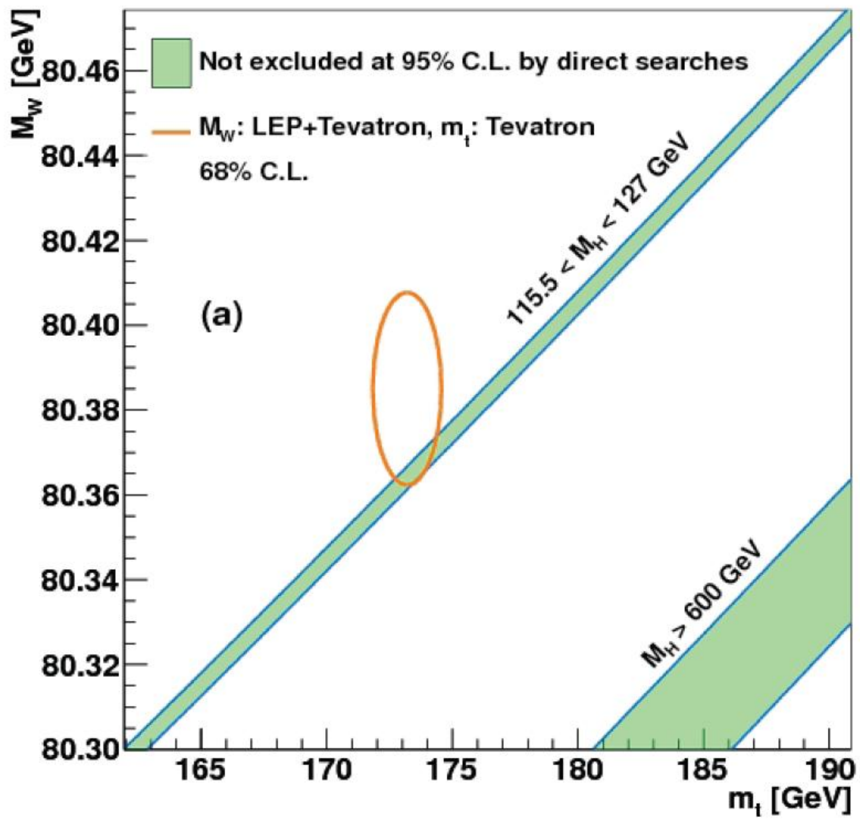

December 2011
LHC excluded
LEP2 and Tevatron
LEP1 and SLD
68% CL
m_W [GeV]
80.5
80.4
80.3
m_H [GeV]
114
300
600
1000
Δα
155
175
195
m_t [GeV]
Range on x/y axes now 25% smaller


March 2012
LHC excluded
LEP2 and Tevatron
LEP1 and SLD
68% CL
m_W [GeV]
80.5
80.4
80.3
m_H [GeV]
114
300
600
1000
Δα
155
175
195
m_t [GeV]



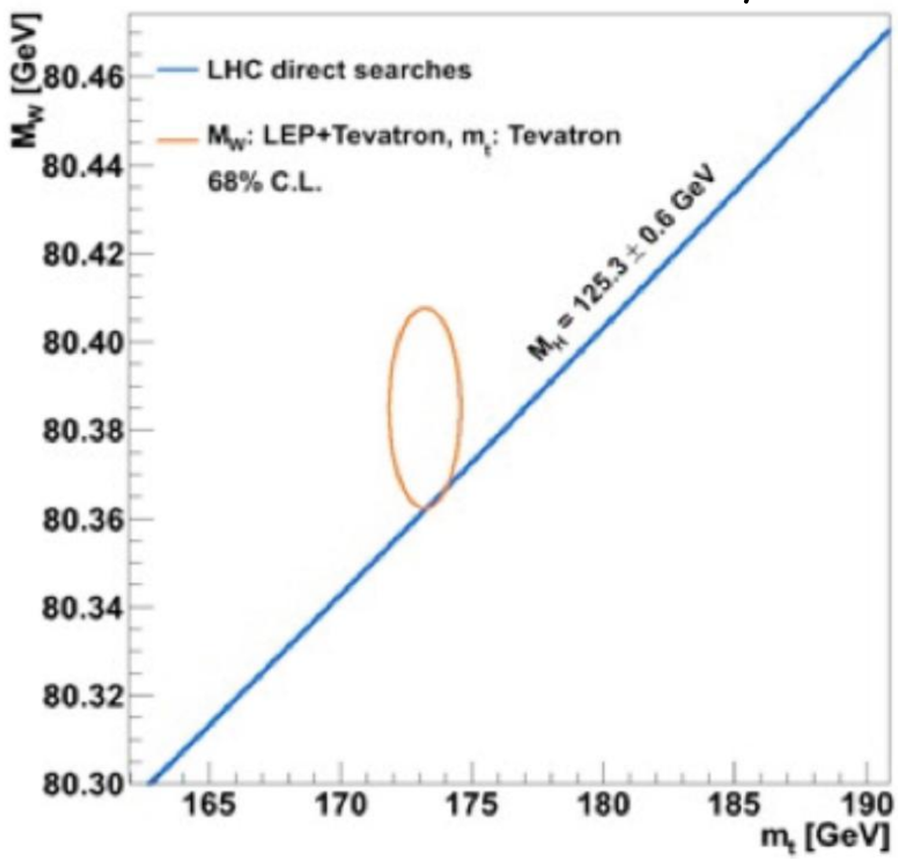
March 2012
LEPEWWG (2011) 68% CL (excluding m_W, m_{top} & direct Higgs exclusion)
68% CL (by area) m_W (2009), m_{top}
68% CL (by area) m_W (2012), m_{top}
$115 < m_H < 127$ GeV
$600 < m_H < 1000$ GeV
80.5
80.45
80.4
80.35
80.3
m_W (GeV)
155
160
165
170
175
180
185
190
195
m_{top} (GeV)

April 2012



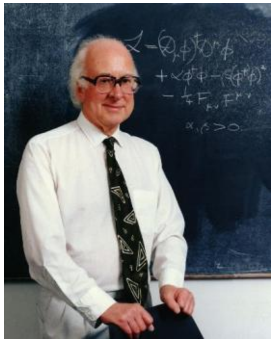
Not excluded at 95% C.L. by direct searches
M_W: LEP+Tevatron, m_t: Tevatron
68% C.L.
(a)
115.5 < M_H < 127 GeV
M_H > 600 GeV
M_W [GeV]
80.46
80.44
80.42
80.40
80.38
80.36
80.34
80.32
80.30
165
170
175
180
185
190
m_t [GeV]

July 2012



LHC direct searches
M_W: LEP+Tevatron, m_t: Tevatron
68% C.L.
M_H = 125.3 ± 0.6 GeV
M_W [GeV]
80.46
80.44
80.42
80.40
80.38
80.36
80.34
80.32
80.30
165
170
175
180
185
190
m_t [GeV]

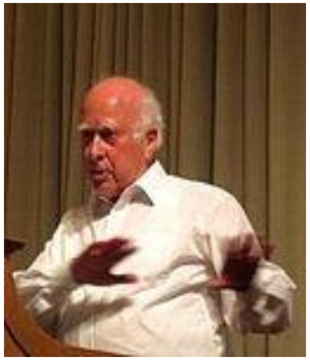
Higgs Boson



Masses of quarks and leptons (except neutrinos)

Masses of W and Z bosons

Unitarity and renormalizability of the SM



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.

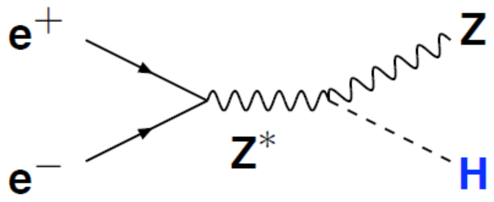
[7] G. Guralnik, C. Hagen, T.W.B. Kibble, Phys. Rev. Lett. 13 (1964) 585, doi:10.1103/PhysRevLett.13.585.

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

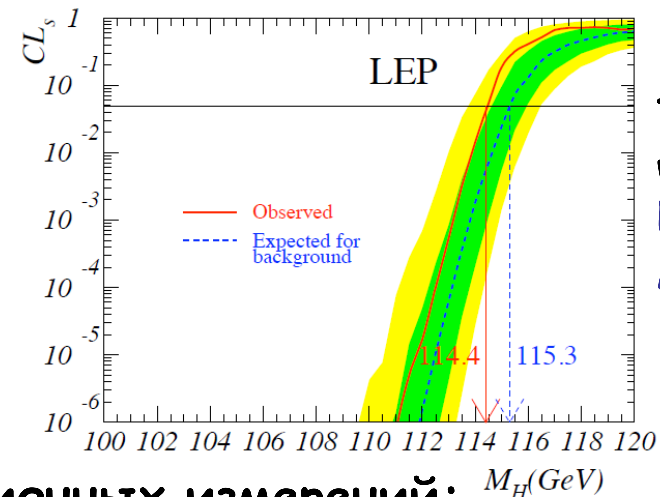
[9] T.W.B. Kibble, Phys. Rev. 155 (1967) 1554, doi:10.1103/PhysRev.155.1554.

Что нам было известно о бозоне Хиггса до БАК?

1. Ограничения из прямых поисков:

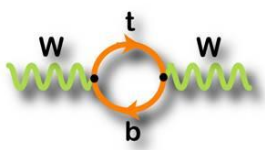


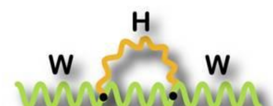
M_H > 114.4 GeV 95% C.L.



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

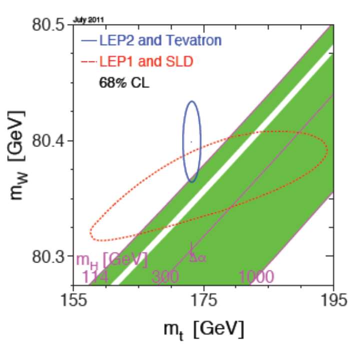
2. Ограничения из прецизионных измерений:

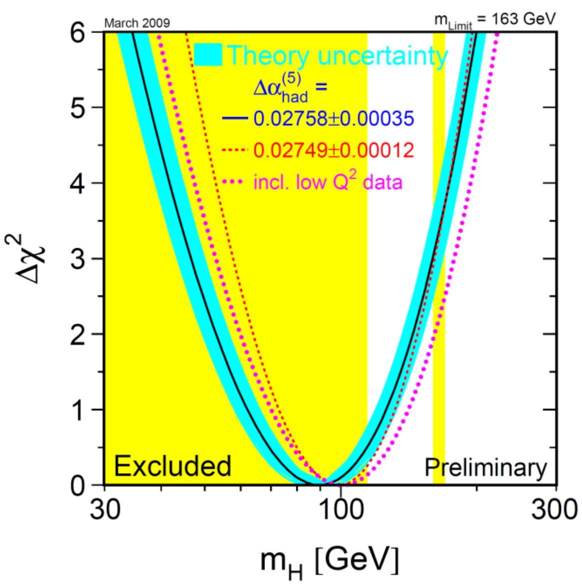




$$(\Delta r)_{\text{top}} \approx -\frac{3G_F m_t^2}{8\sqrt{2}\pi^2}\frac{1}{t_W^2} \qquad (\Delta r)_{\text{Higgs}} \approx \frac{11 G_F M_Z^2 c_W^2}{24\sqrt{2}\pi^2}\ln\frac{m_h^2}{M_Z^2}$$

M_H < 155 GeV 95% C.L.





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

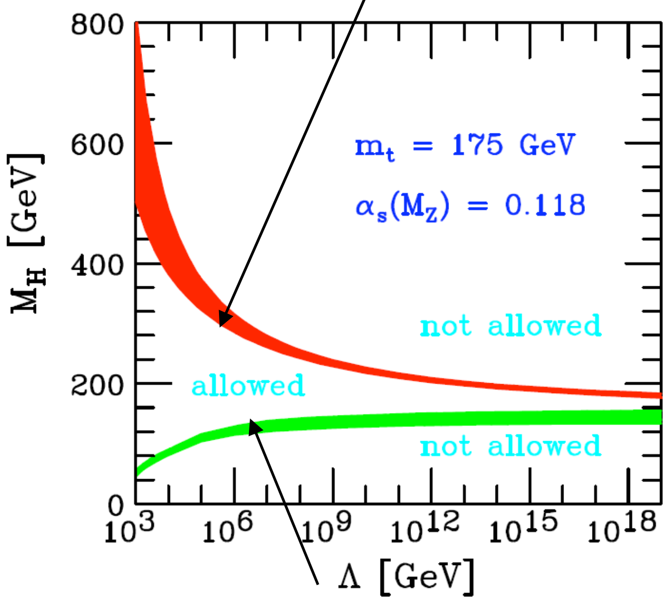
$$\mathrm{Im}(a_l) = |a_l|^2 \qquad |\mathrm{Re}(a_l)| \leq \frac{1}{2}$$

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

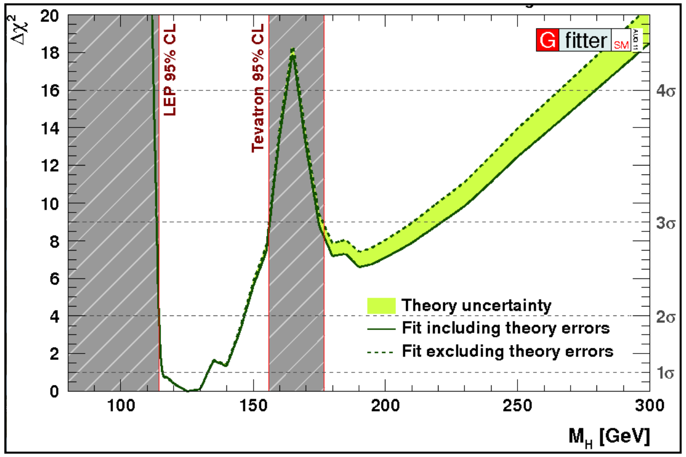
$\sqrt{s} \lesssim 1.2$ TeV if $\sqrt{s} \ll M_H$

4. From self-consistency of quantum theory:

No Landau pole (triiviality)



Combining all direct and indirect constraints:



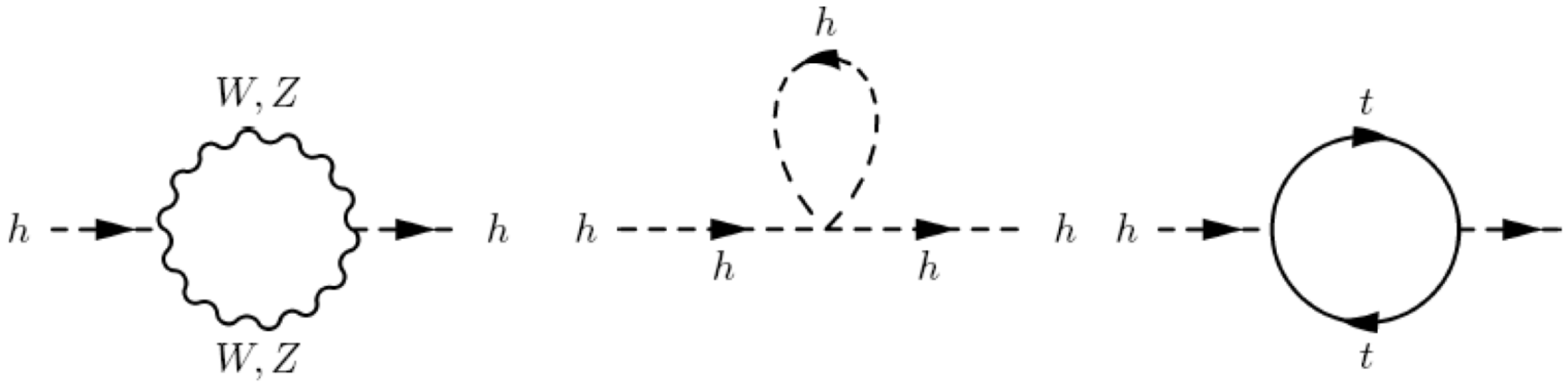
GFitter collaboration, Aug. 2011

M_H = 125 ± 10 GeV

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

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

Loop corrections to the Higgs mass



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

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

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

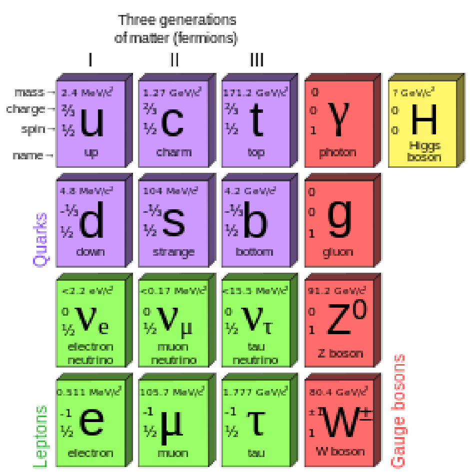
Something is needed in addition to SM…

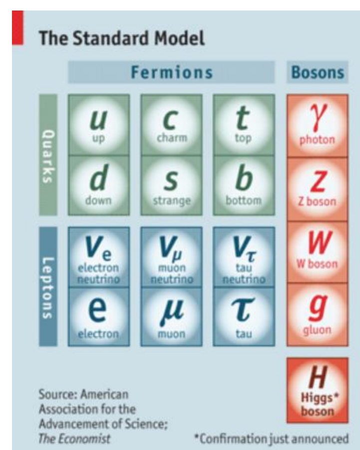
* Standard Model is the renormalizable anomaly free gauge quantum field theory with spontaneously broken electroweak symmetry. Remarkable agreement with many experimental measurements.

* The EW SM has 17 parameters (from experiments)
  gauge-Higgs sector contains 4 parameters:
  g_1, g_2, μ^2, λ $\longrightarrow$ 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} $\Longrightarrow$ 18 SM parameters
  (+ may be masses and mixing parameters from neutrino sector)



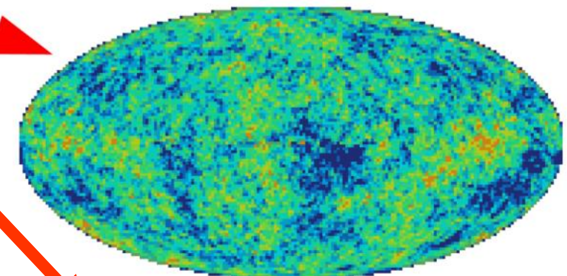


Facts which can not be explained in SM

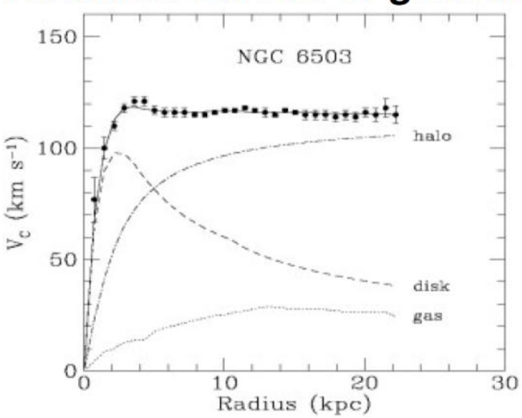
- EW symmetry is broken – photon is massless, W and Z are massive prticles
Fermions have very much different masses
(Mtop ≈ 172 GeV, Me ≈ 0.5 MeV, $\Delta M\nu \approx 10^{-3}$ eV)

- Dark Matter exists in the Universe

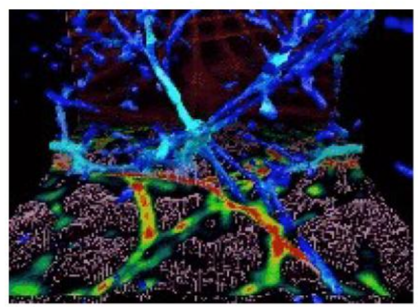
CMB



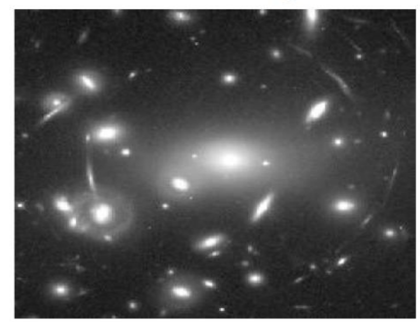
Rotation curves of galaxies

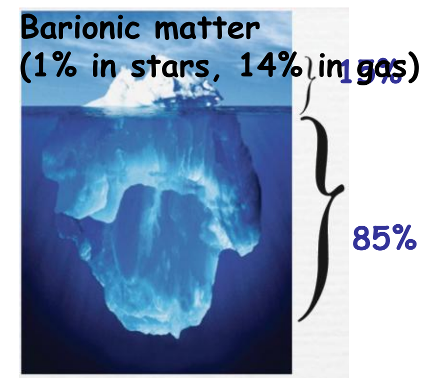


Large Scale Structure



Lensing





Dark unknown matter

- (g-2)μ (about 3.5 σ)
- Neutrino masses, mixing, oscillations

- Particle – antiparticle asymmetry in the Universe,
CP violation

baryon asymmetry: $\frac{n_B - n_{\bar{B}}}{n_B + n_{\bar{B}}} \sim 10^{-10}$

CKM phase – too small efect

In addition to mentioned problems (naturalness/hierarchy, dark matter content, CP violation) SM does not give answers to many questions

What is a generation? Why there are only 3 generations?

How quarks and leptons related to each other, what is a nature of quark-lepton analogy?

What is responsible for gauge symmetries, why charges are quantize? Are there additional gauge symmetries?

What is responsible for a formation of the Higgs potential?

To which accuracy the CPT symmetry is exact?

Why gravity is so weak comparing to other interactions?

....

LHC – Why Terascale?

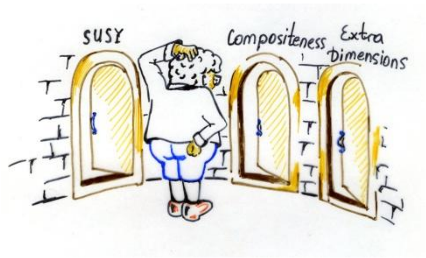
Stabilization of the Higgs mechanism
→ $\Lambda \sim 1$ TeV

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

Main options beyond SM



1. Fundamental Higgs:
- Supersymmetric models
  (MSSM, NMSSM…)

2. Composite Higgs:
- Models with new strong dynamics
  (Chiral Lagrangians from holography, latest technicolor variants, Little Higgs…)

3. Mixed cases:
- Models with extra space dimensions
- Partially composite models…

4. Many more (hidden valleys, landscape ….)

Supersymmetry is one of the most favorite BSM ideas, relating spin $\frac{1}{2}$ fermions with spin 0,1 bosons

$$Q|\text{Boson}\rangle = |\text{Fermion}\rangle \qquad Q^\dagger|\text{Boson}\rangle = |\text{Fermion}\rangle$$

Fermion degrees of freedom ←→ boson degrees of freedom

Minimal particle content

❑ Gauge / Gaugino Sector

Standard Bosons	Supersymmetric Partners
$W^\pm$ $H^\pm$	Charginos $\chi_1^\pm$ $\chi_2^\pm$
g Z h H A	Neutralinos χ_1^0 χ_2^0 χ_3^0 χ_4^0
g_i	Gluinos $\tilde{g}_i$

[Two Higgs doublets] [All fermions]

And also ...

Graviton G	Gravitino $\tilde{G}$

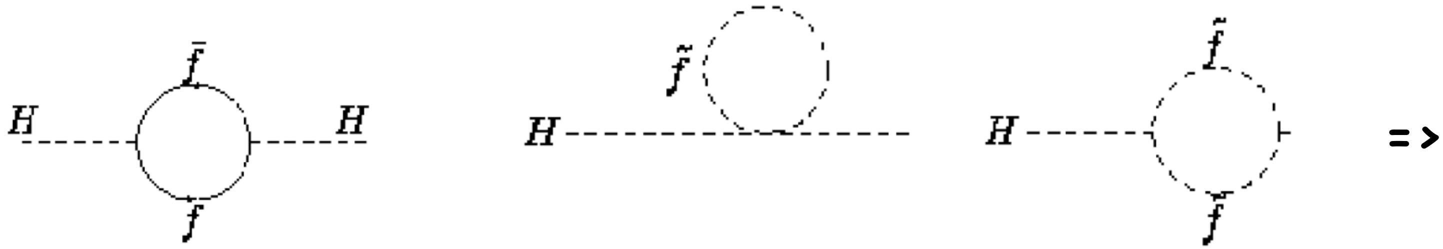
❑ Particle / Sparticle Sector

Standard Particles	Supersymmetric Partners
Leptons ℓ	Sleptons $\tilde{\ell}_{R,L}$
Neutrinos ν_ℓ	Sneutrinos $\tilde{\nu}_\ell$
Quarks q	Squarks $\tilde{q}_{R,L}$

[All scalars]

SUSY

1. Cancellation of Λ^2 dependence

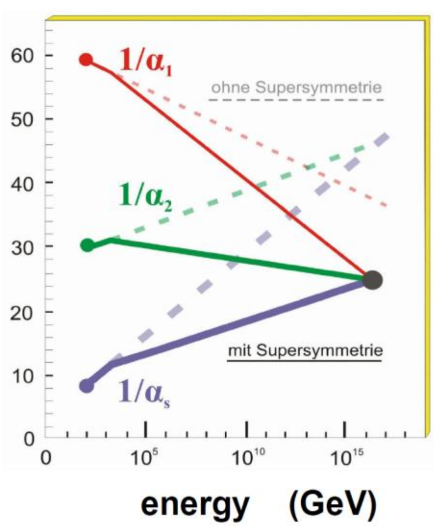


$$\Delta M_H^2|^{tot} = \frac{\lambda_f^2 N_f}{4\pi^2}\left[(m_f^2 - m_S^2)\log\left(\frac{\Lambda}{m_S}\right) + 3m_f^2\log\left(\frac{m_S}{m_f}\right)\right]$$

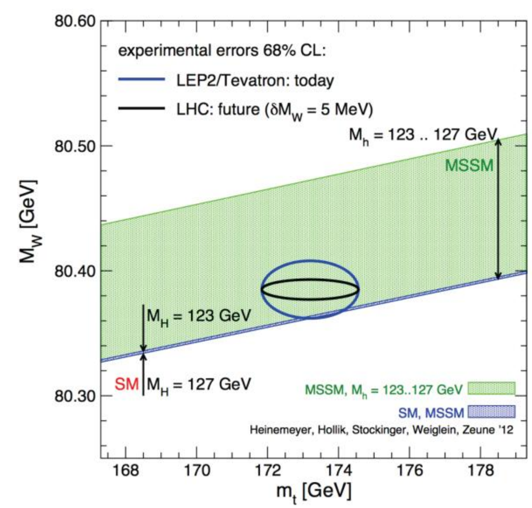
M_H is protected!

2. Lightest SUSY particle is stable (if R-parity) – very good Dark Matter candidate

3. Unification of couplings in contrast to SM



4. Fit of EW precision data



SUSY is one of the most attractive idea for BSM physics

SUSY, if exists, is broken, and there are many possibilities:

Gravity mediation
Gauge madiation
Gaugino mediation
Anomaly mediation
Hidden sector mediation
…

Many models:
MSSM
CMSSM
mSUGRA
mGMSB
mAMSB
Split SUSY
…
NMSSM
Natural SUSY
…

In general the unconstrained MSSM has 105 parameters
(22 with reasonable assumptions)
(many parameter space points of mSUGRA scenario are rulled out already)

Concrete predictions depend strongly on MSSM breaking scenario.
There are no theory arguments to prefer some of them.

Many nice SUSY feaches are due to additional global symmetry- R-parity. Tiny deviations of R-parity possible leading to processes with FCNC, lepton/barion number violation, proton decay…
But what is an origin of R-parity?...

Models with new strong dynamics

Most of composite models are based on symmetry breaking by nontrivial Top condensate

For example (assisted technicolor with top-seesaw):

$$SU(3)_1 \times SU(3)_2 \times U(1)_1 \times U(1)_2 \stackrel{\langle\Phi\rangle}{\rightarrow} SU(3)_{\rm QCD} \times U(1)_Y$$

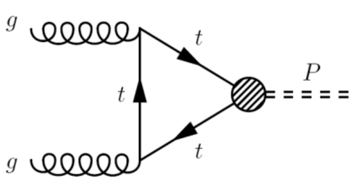
$$\langle\Phi\rangle \text{ is the condensation of } \langle t\bar{t}\rangle = f_\pi$$

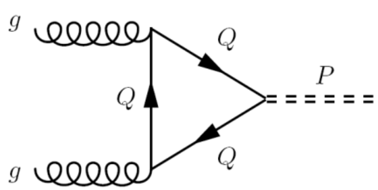
3d generation quarks and 1st,2d generation quarks are charged under two different SU(3)

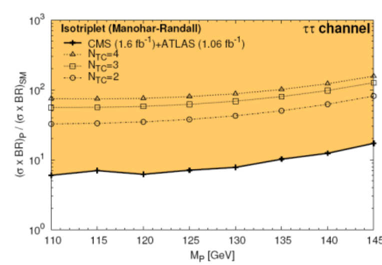
One should avoid FCNC, too large top mass, constrains from s,t,u parameters

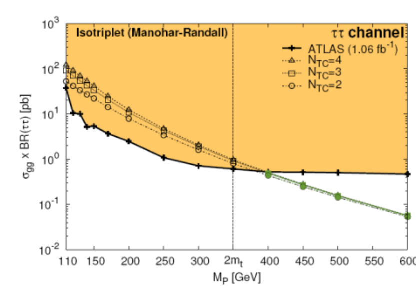
In general, there are: techni-pions, techin-rhos, composite Higgs(es), vector-like top-quark partners

R.Chivikula, P.Ittisamai, E.Simmons





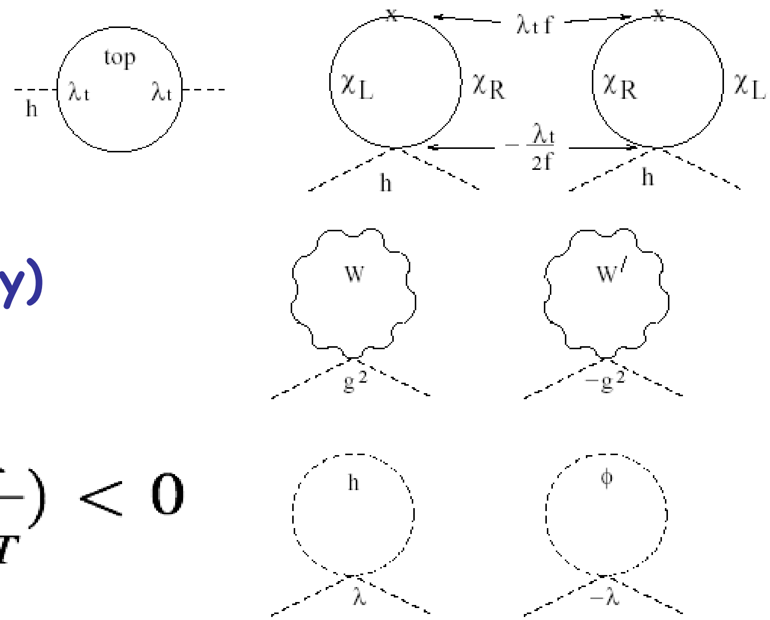




CMS and ATLAS searches for the Higgs in gamma-gamma and tau-tau modes exclude techni-(pseudo)scalars upto 2Mtop

New strong dynamics (Little Higgs, Technicolor like models ...)

In Little Higgs models
new particle loops cancel
same spin SM particle loops
(cancellation at 1-loop level only)

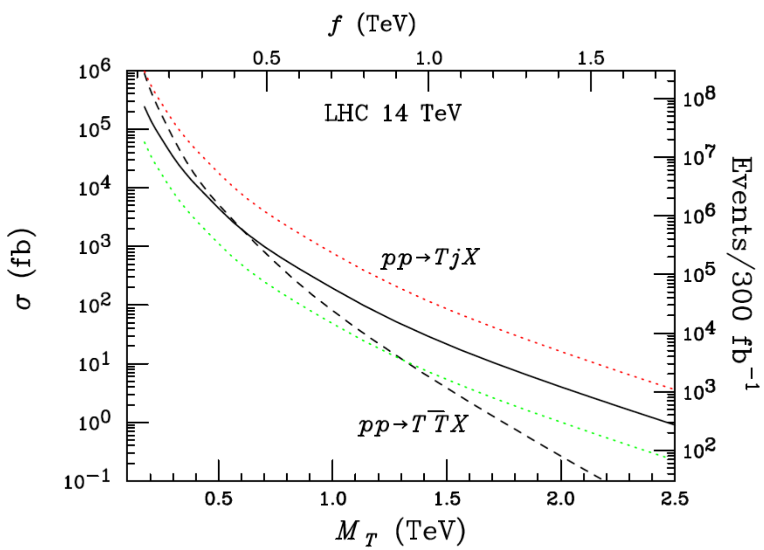


$$\delta m_H^2 = -\frac{3}{8\pi^2}\lambda_t^2 m_T^2 \ln\left(\frac{\Lambda}{m_T}\right) < 0$$

(similar to SUSY)

If T-parity is assumed there is a DM candidate

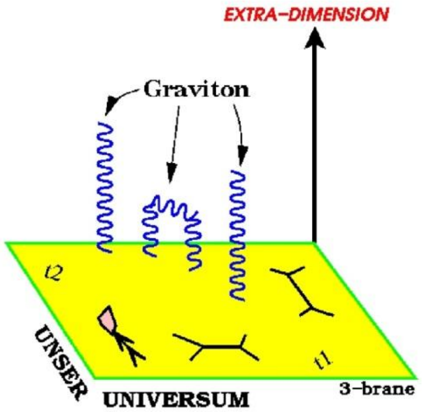
top-qaurk partner T can be found at the LHC in few TeV mass range



Models with extra space dimensions

we are confined on some 4-dim. brane imbedded into higher dim. bulk

ADD type models

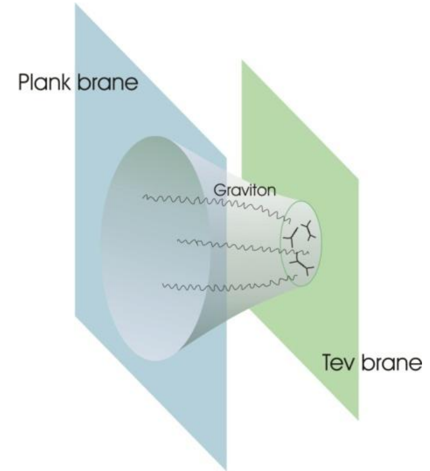


UED type scenarios

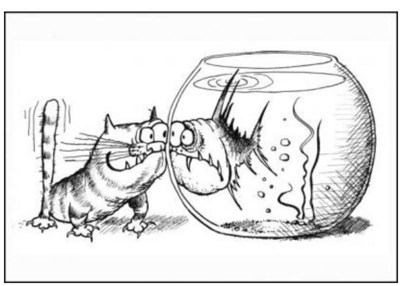
with SM fields in ADD or RS bulk

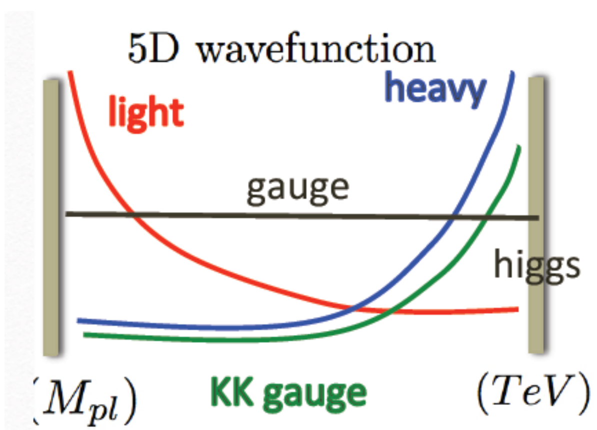
KK-parity ->
LKKP is a good DM candidate

RS type models



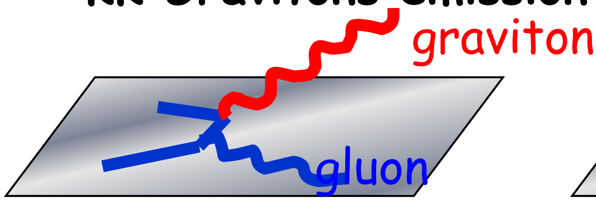
Can unify the forces
Can explain why gravity is weak (solve hierarchy problem)
Contain Dark Matter Candidates
Can generate neutrino masses

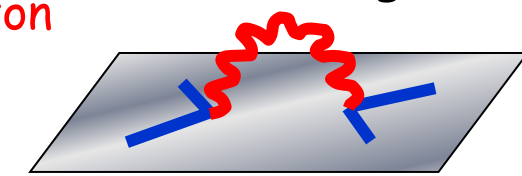


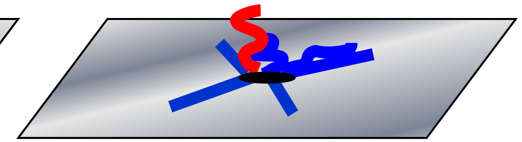


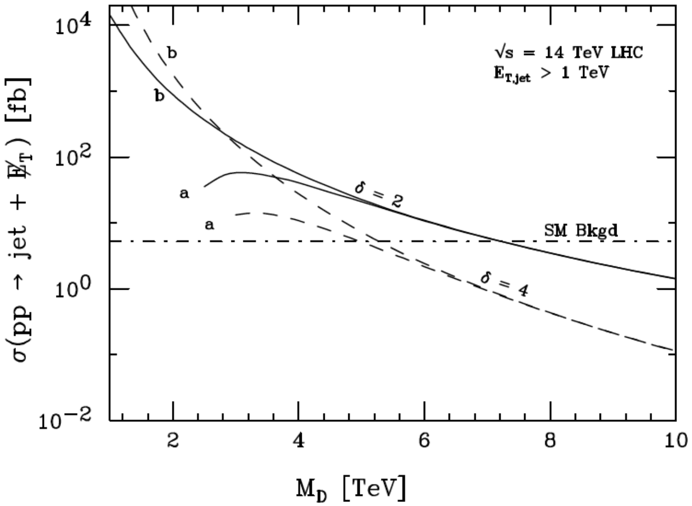
In ADD scenario typical processes:

KK Gravitons emission | **Virtual KK gravitons** | **TeV black holes**

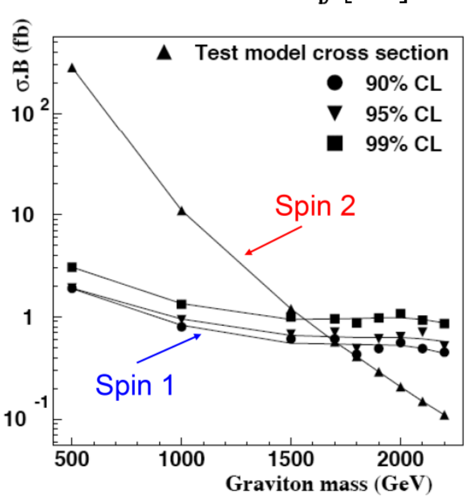






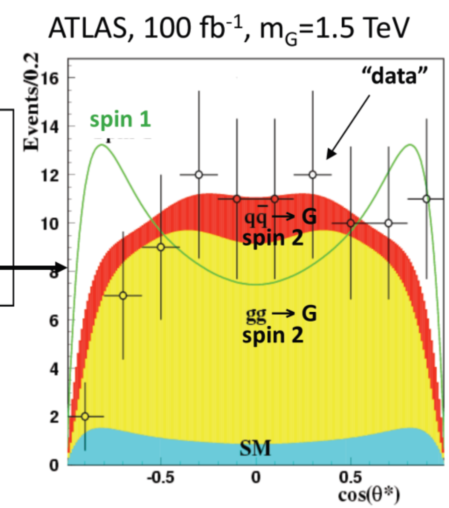


δ	Max M_D sensitivity $\mathcal{L} = 100$ fb^{-1}	Max M_D sensitivity $\mathcal{L} = 10$ fb^{-1}	Min M_D perturbativity
2	8.5 TeV	7.9 TeV	3.8 TeV
3	6.8	6.3	4.3
4	5.8	5.5	4.8
5	5.0	4.6	5.4



In RS scenario typical processes: Spin 2 resonances or virtual KK gravitons below thersholds

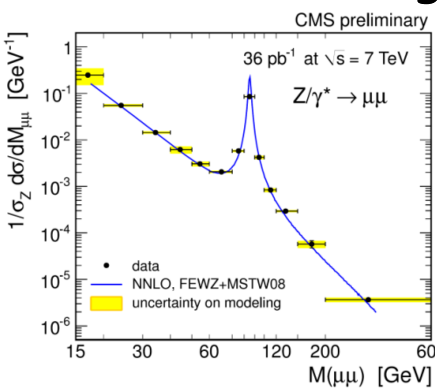
Graviton (s=2) or Z' (s=1) ?
→ look at e± angular distributions

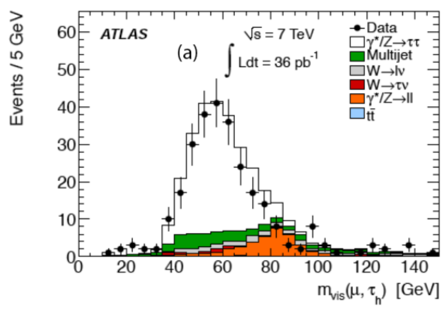


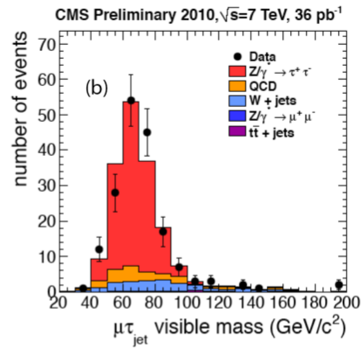
What the LHC experiments tell us?

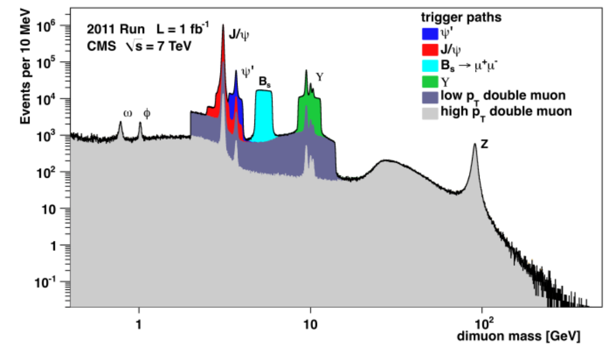
First LHC results also confirm Standard Model

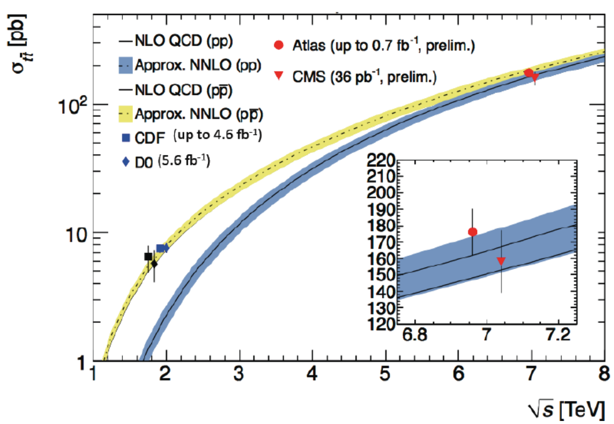
Rediscovery of the SM: W, Z, Top …. are found
WZ, Wgamma, ZZ, Top pair, single Top … are measured

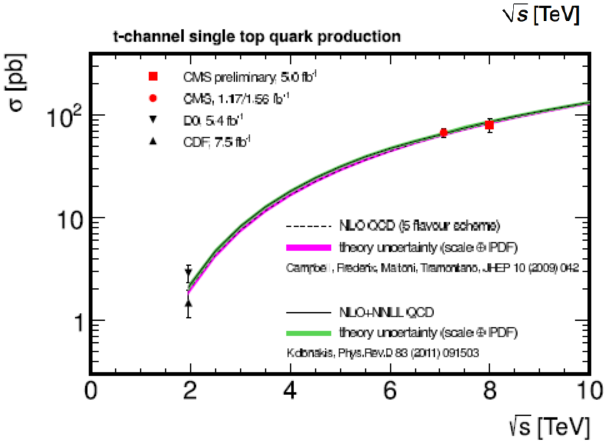


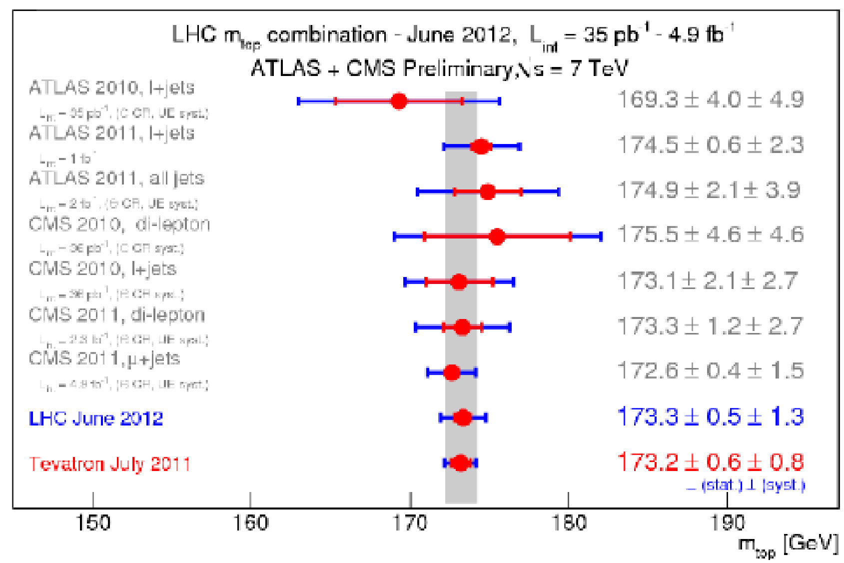




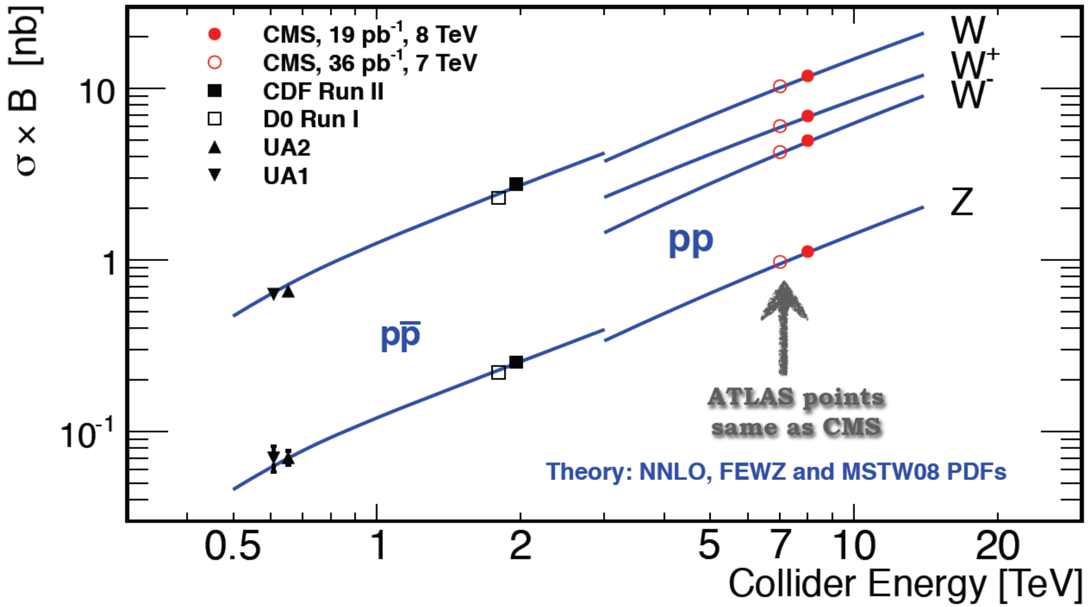




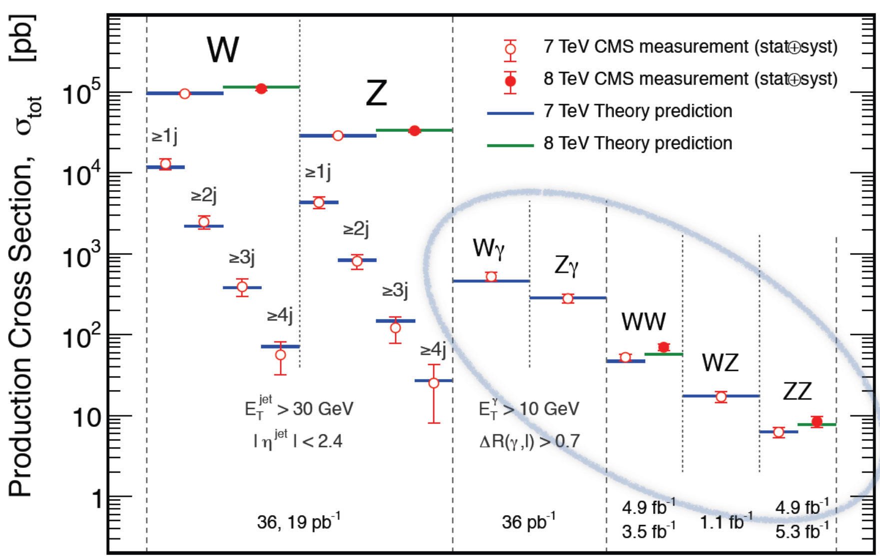




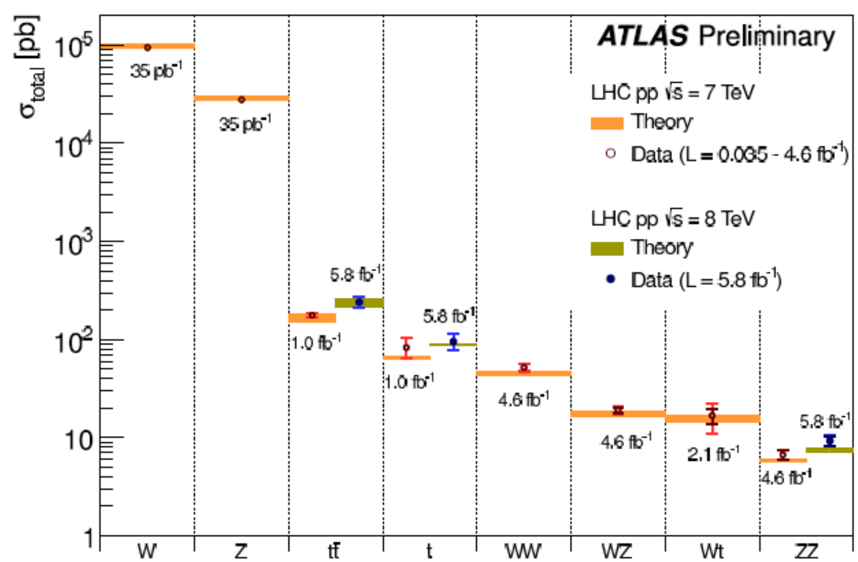
All in an agreement with the SM



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



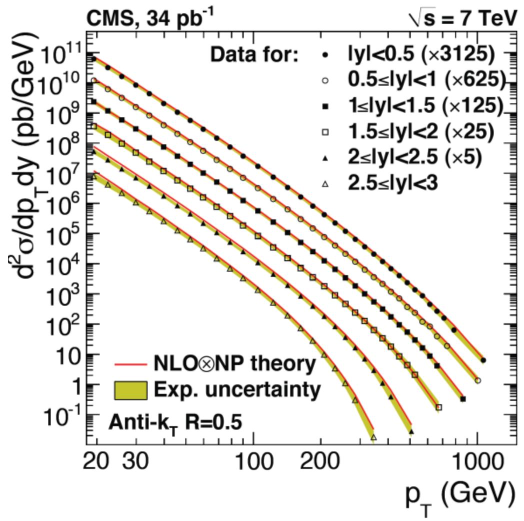
W
Z
7 TeV CMS measurement (stat⊕syst)
8 TeV CMS measurement (stat⊕syst)
7 TeV Theory prediction
8 TeV Theory prediction
≥1j
≥2j
≥3j
≥4j
Wγ
Zγ
WW
WZ
ZZ
E_T^jet > 30 GeV
| η^jet | < 2.4
E_T^γ > 10 GeV
ΔR(γ,l) > 0.7
36, 19 pb-1
36 pb-1
4.9 fb-1
3.5 fb-1
1.1 fb-1
4.9 fb-1
5.3 fb-1
Production Cross Section,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

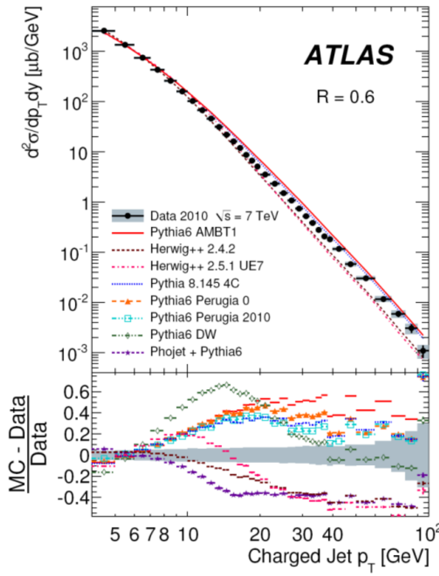


ATLAS Preliminary
LHC pp √s = 7 TeV
Theory
Data (L = 0.035 - 4.6 fb-1)
LHC pp √s = 8 TeV
Theory
Data (L = 5.8 fb-1)
35 pb-1
35 pb-1
1.0 fb-1
5.8 fb-1
1.0 fb-1
5.8 fb-1
4.6 fb-1
4.6 fb-1
2.1 fb-1
4.6 fb-1
5.8 fb-1
σ_total [pb]
W
Z
tt̄
t
WW
WZ
Wt
ZZ

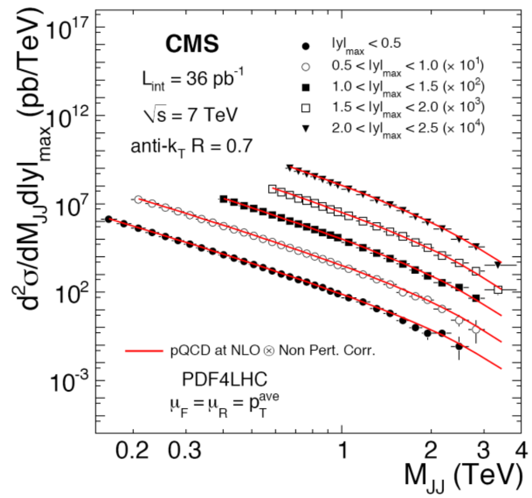
New remarkable QCD results in various kinematical regions

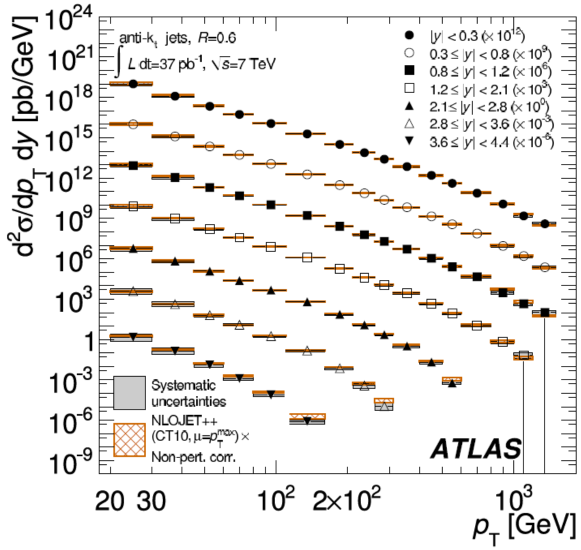
Double-differential inclusive jet production



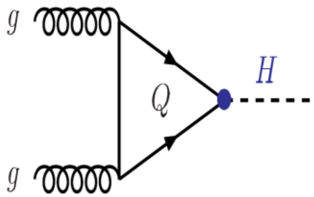


Double-differential inclusive dijet production

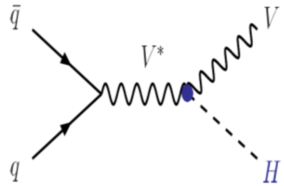




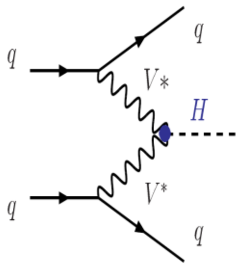
Higgs production modes, decays and signatures at LHC



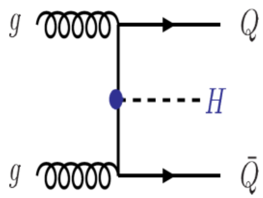
Gluon-gluon fusion



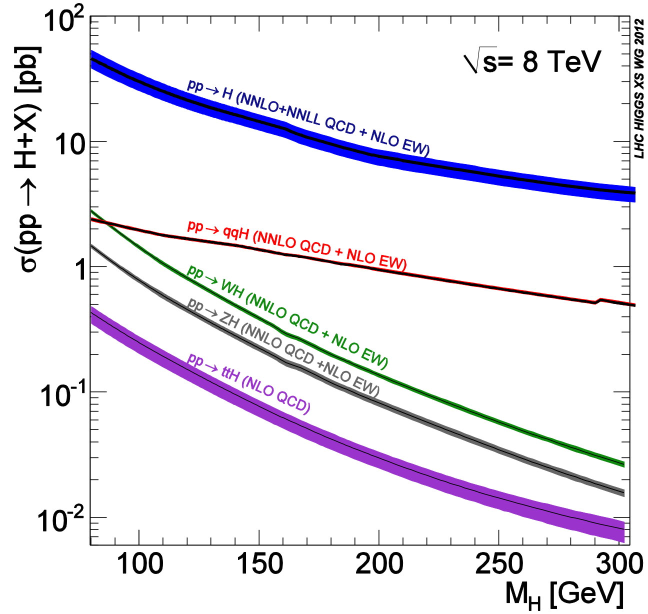
W/Z-Higgs associated

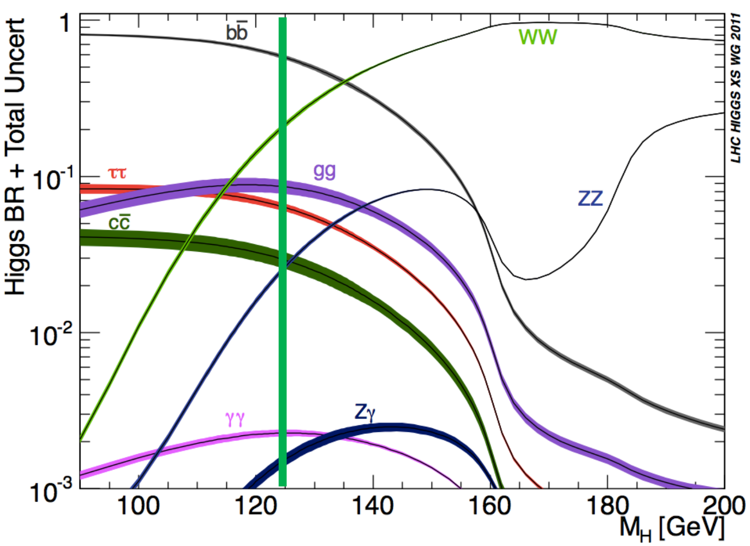


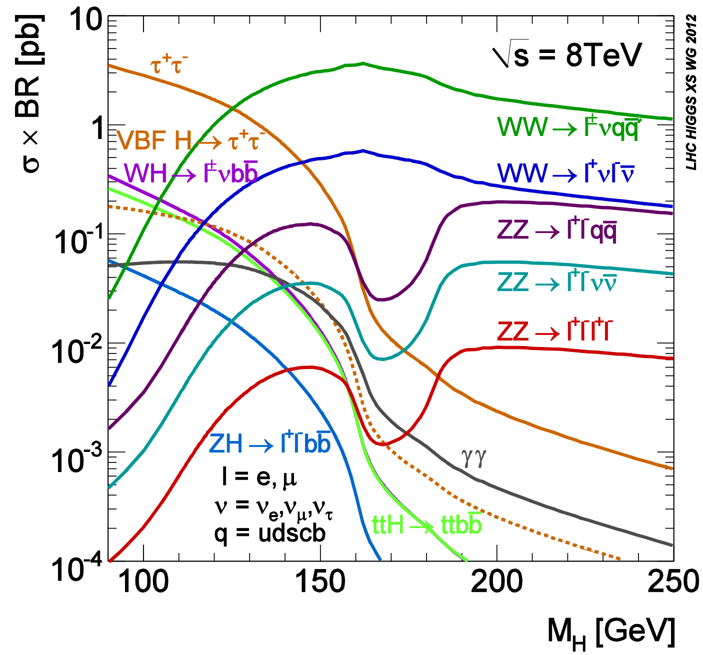
Vector boson fusion



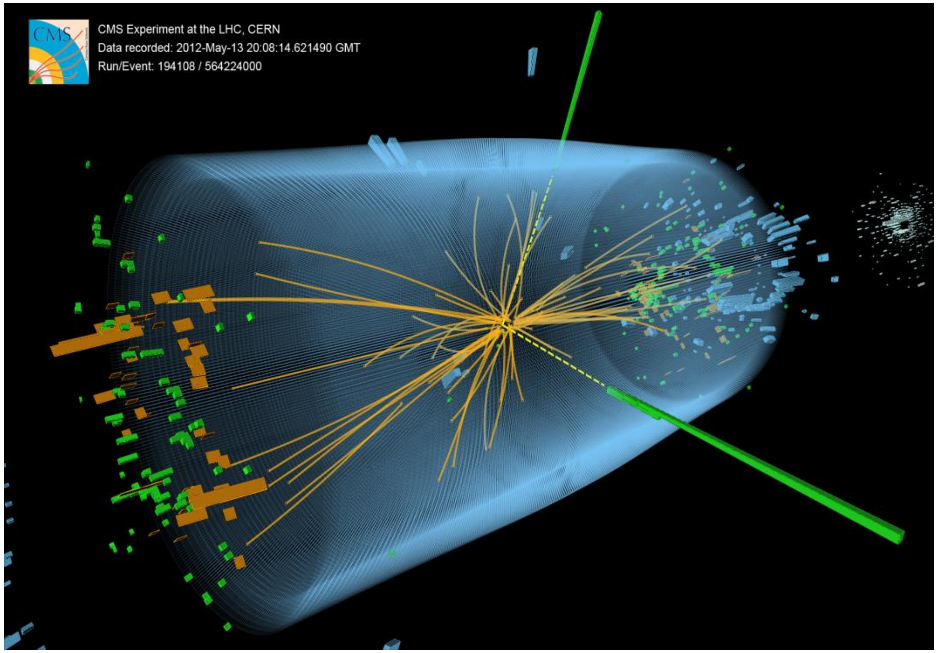
t t-bar Higgs associated

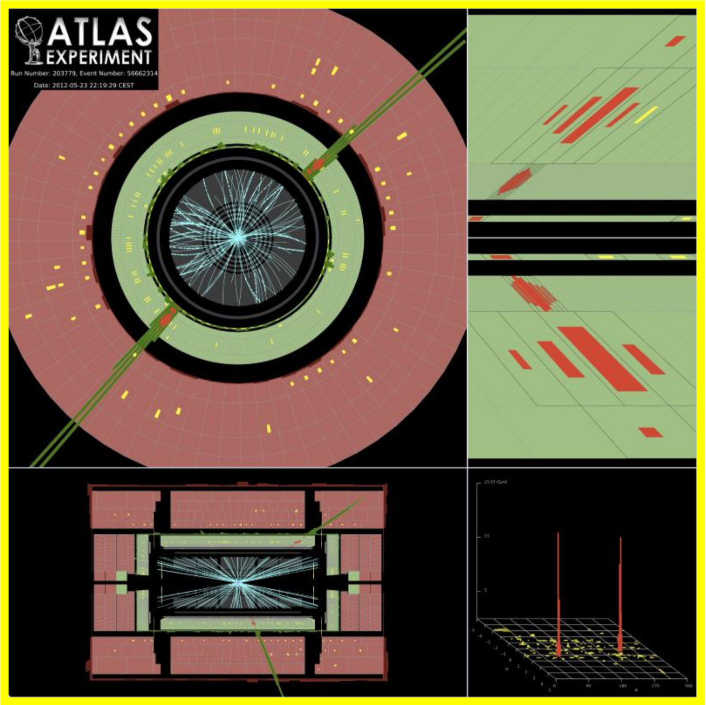




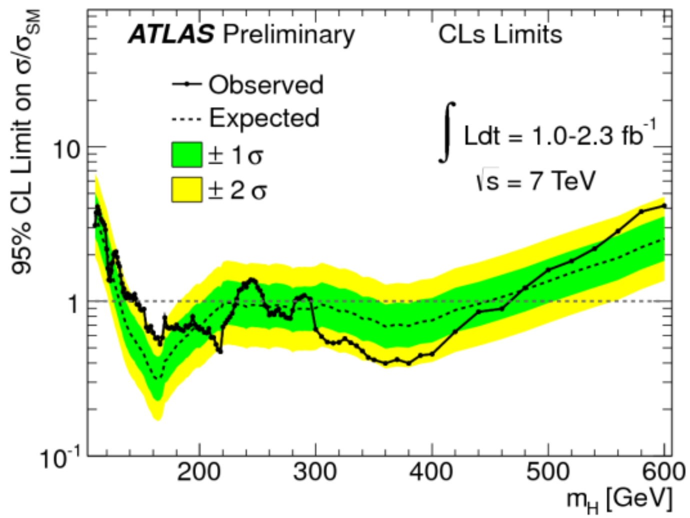


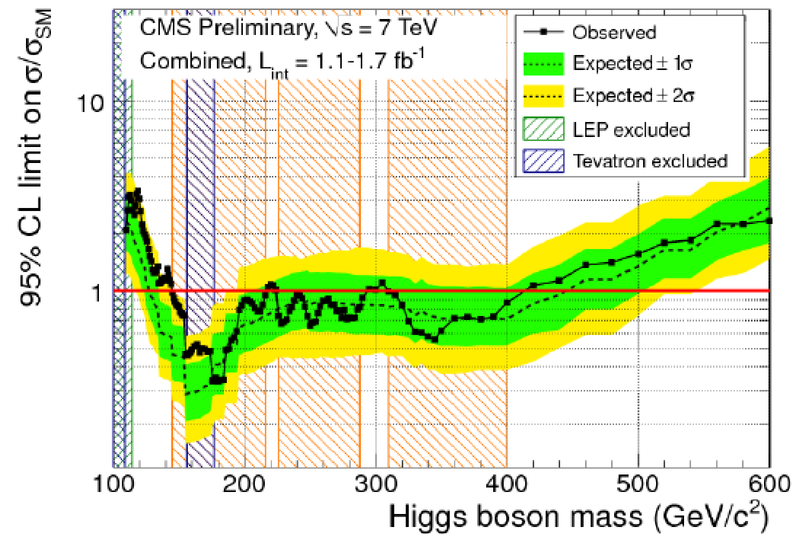
Examples of the CMS and ATLAS events with two photons (Higgs candidates)



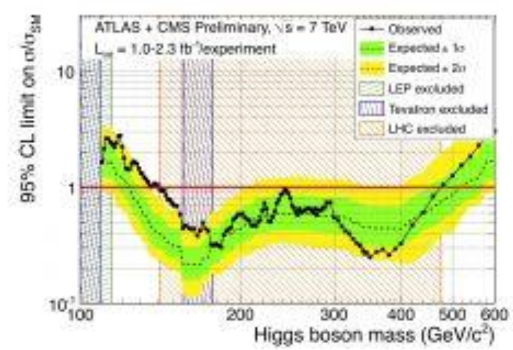


LHC limits on Higgs mass



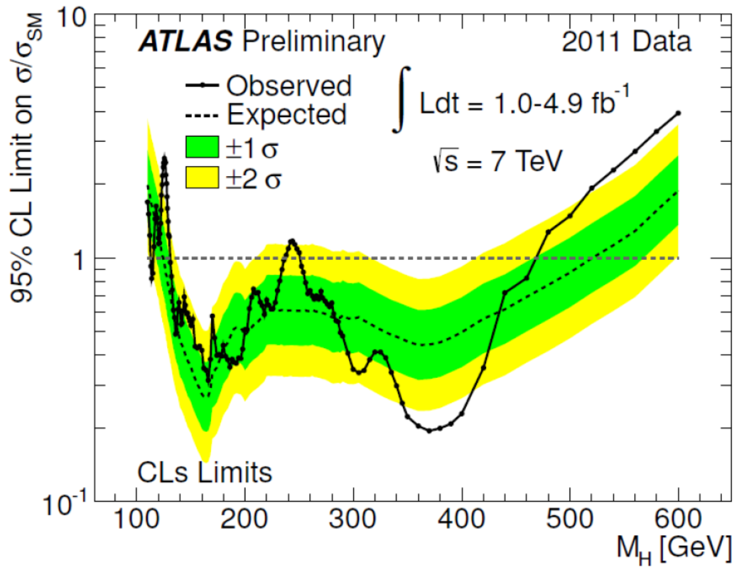


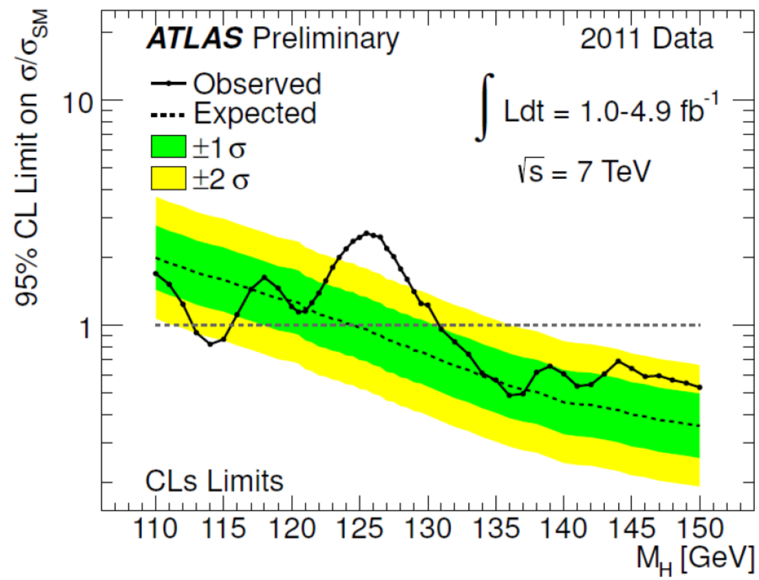
Excluded either by ATLAS or CMS 145-466 GeV (except 288-296 GeV) 95%CL



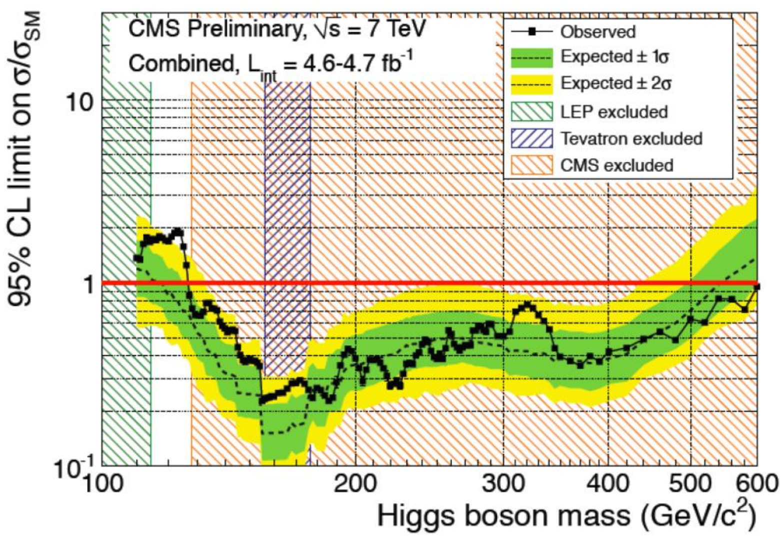
CMS and ATLAS combined result for MH : 141-476 GeV is excluded

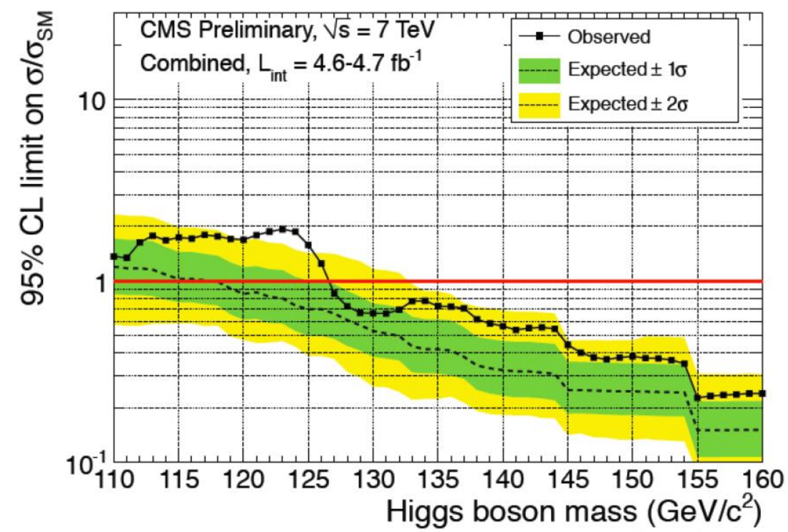
With roughly 10 1/fb per experiment at the LHC one expects to reach for SM Higgs combined 5σ sensitivity in the interval 114 < MH < 600 GeV



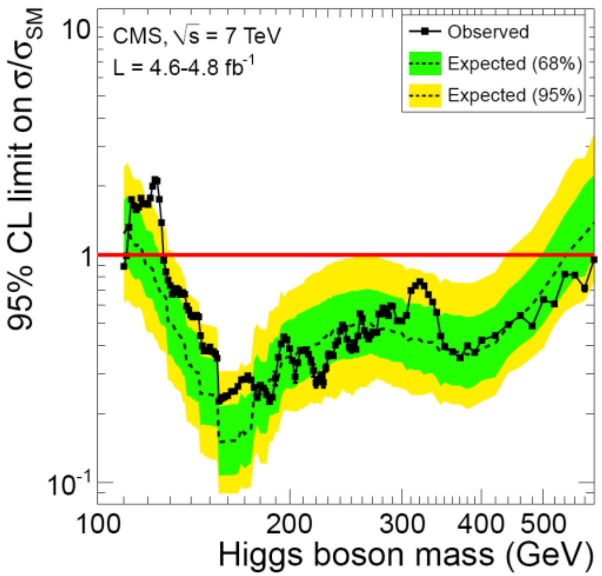


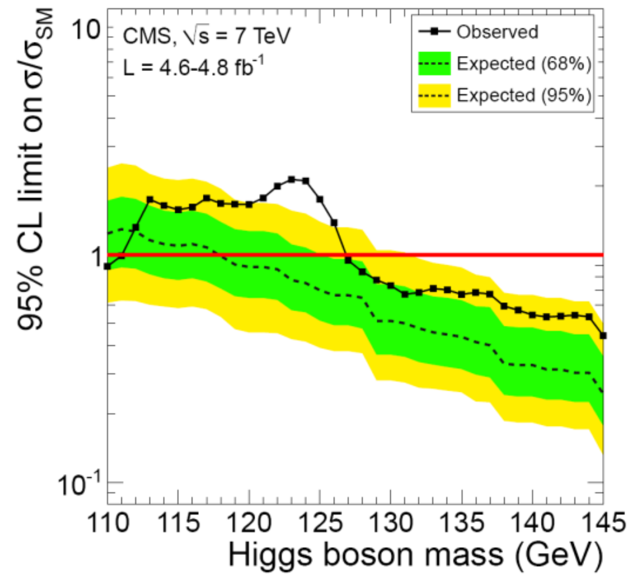
Combining only $\gamma\gamma$ and 4l: 3.6σ

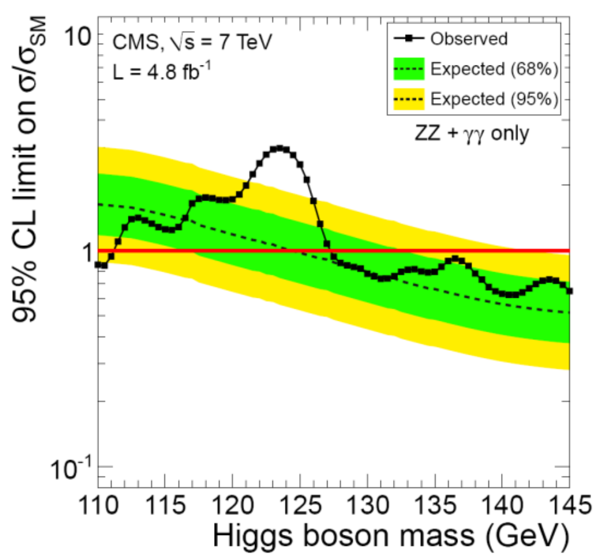


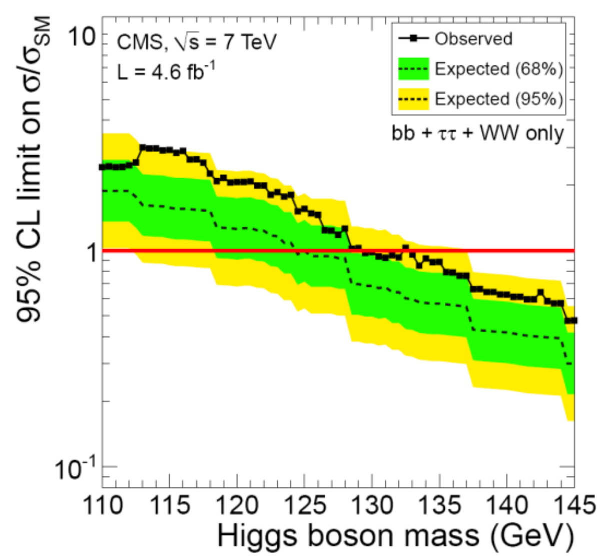


Small window from 115 GeV to 127 GeV is remaining with a small access at about 125 GeV


CMS, $\sqrt{s}$ = 7 TeV
L = 4.6-4.8 fb^{-1}
Observed
Expected (68%)
Expected (95%)
95% CL limit on σ/σ_{SM}
10
1
10^{-1}
100
200
300
400
500
Higgs boson mass (GeV)


CMS, $\sqrt{s}$ = 7 TeV
L = 4.6-4.8 fb^{-1}
Observed
Expected (68%)
Expected (95%)
95% CL limit on σ/σ_{SM}
10
1
10^{-1}
110
115
120
125
130
135
140
145
Higgs boson mass (GeV)


CMS, $\sqrt{s}$ = 7 TeV
L = 4.8 fb^{-1}
Observed
Expected (68%)
Expected (95%)
ZZ + γγ only
95% CL limit on σ/σ_{SM}
10
1
10^{-1}
110
115
120
125
130
135
140
145
Higgs boson mass (GeV)


CMS, $\sqrt{s}$ = 7 TeV
L = 4.6 fb^{-1}
Observed
Expected (68%)
Expected (95%)
bb + ττ + WW only
95% CL limit on σ/σ_{SM}
10
1
10^{-1}
110
115
120
125
130
135
140
145
Higgs boson mass (GeV)

Observation of the Higgs-like boson in 2012 at the LHC

Physics Letters B 710 (2012) 26–48

Contents lists available at SciVerse ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Combined results of searches for the standard model Higgs boson in pp collisions at $\sqrt{s} = 7$ TeV ☆

CMS Collaboration *

CERN, Switzerland

ARTICLE INFO

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Editor: W.-D. Schlatter

Keywords:
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Higgs
Physics
Statistics

ABSTRACT

Combined results are reported from searches for the standard model Higgs boson in proton–proton collisions at $\sqrt{s} = 7$ TeV in five Higgs boson decay modes: $\gamma\gamma$, bb, $\tau\tau$, WW, and ZZ. The explored Higgs boson mass range is 110–600 GeV. The analysed data correspond to an integrated luminosity of 4.6–4.8 fb^{-1}. The expected excluded mass range in the absence of the standard model Higgs boson is 118–543 GeV at 95% CL. The observed results exclude the standard model Higgs boson in the mass range 127–600 GeV at 95% CL, and in the mass range 129–525 GeV at 99% CL. An excess of events above the expected standard model background is observed at the low end of the explored mass range making the observed limits weaker than expected in the absence of a signal. The largest excess, with a local significance of 3.1σ, is observed for a Higgs boson mass hypothesis of 124 GeV. The global significance of observing an excess with a local significance $\geqslant 3.1\sigma$ anywhere in the search range 110–600 (110–145) GeV is estimated to be 1.5σ (2.1σ). More data are required to ascertain the origin of the observed excess.

Physics Letters B 716 (2012) 1–29

Contents lists available at SciVerse ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

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

ATLAS Collaboration *

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

ARTICLE INFO

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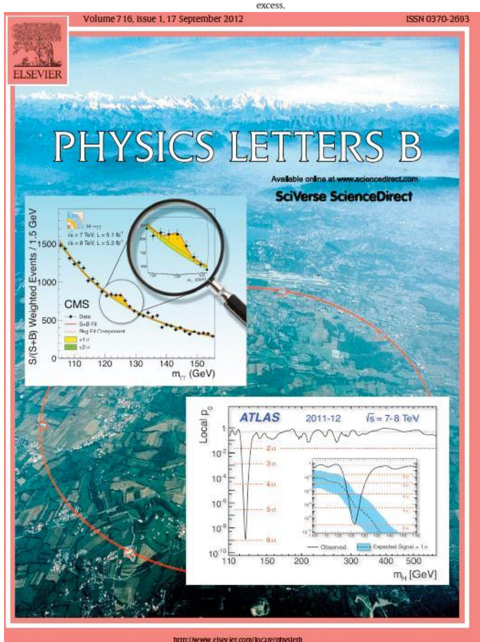
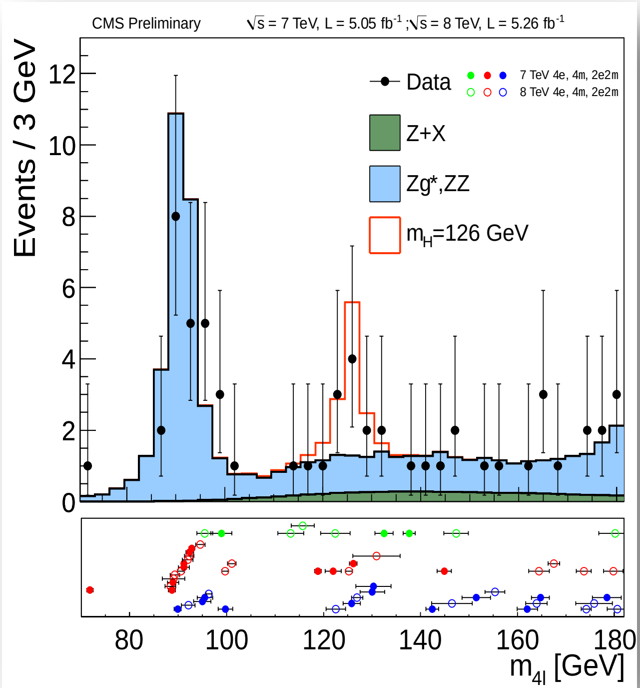
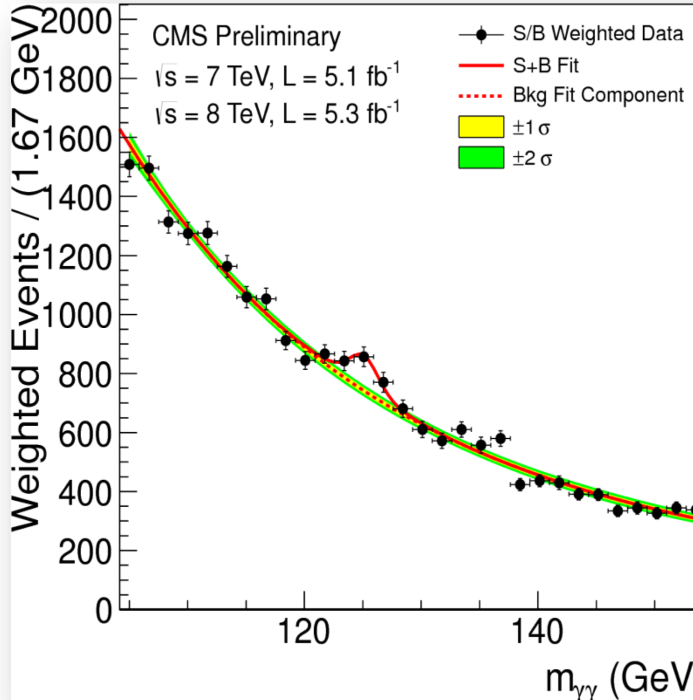
ABSTRACT

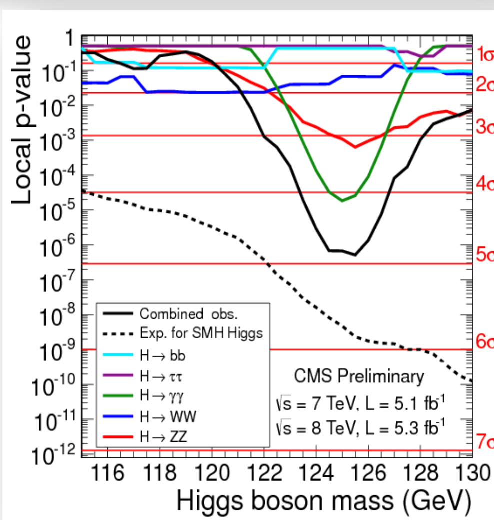
A search for the Standard Model Higgs boson in proton–proton collisions with the ATLAS detector at the LHC is presented. The datasets used correspond to integrated luminosities of approximately 4.8 fb^{-1} collected at $\sqrt{s} = 7$ TeV in 2011 and 5.8 fb^{-1} at $\sqrt{s} = 8$ TeV in 2012. Individual searches in the channels $H \to ZZ^{(*)} \to 4\ell$, $H \to \gamma\gamma$ and $H \to WW^{(*)} \to e\nu\mu\nu$ in the 8 TeV data are combined with previously published results of searches for $H \to ZZ^{(*)}$, $WW^{(*)}$, $b\bar{b}$ and $\tau^+\tau^-$ in the 7 TeV data and results from improved analyses of the $H \to ZZ^{(*)} \to 4\ell$ and $H \to \gamma\gamma$ channels in the 7 TeV data. Clear evidence for the production of a neutral boson with a measured mass of 126.0 ± 0.4 (stat) ± 0.4 (sys) GeV is presented. This observation, which has a significance of 5.9 standard deviations, corresponding to a background fluctuation probability of 1.7×10^{-9}, is compatible with the production and decay of the Standard Model Higgs boson.



Результаты CMS на ICHEP2012







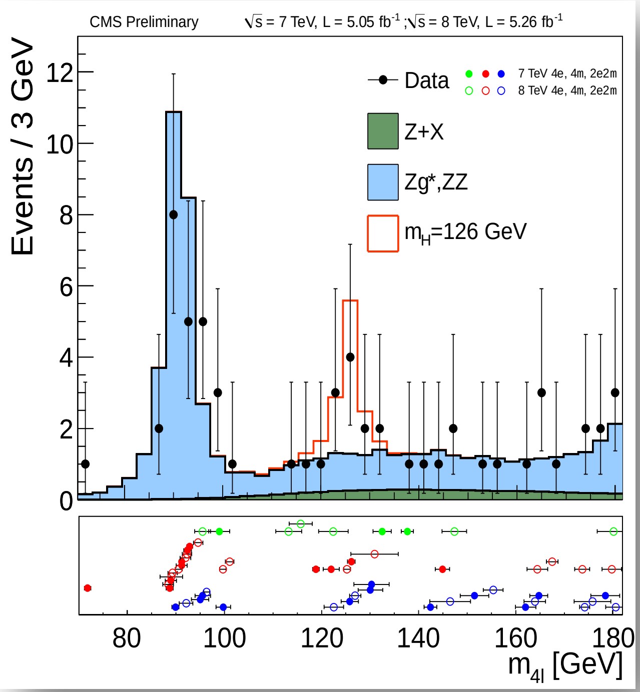
Зарегестрирован новый бозон с массой

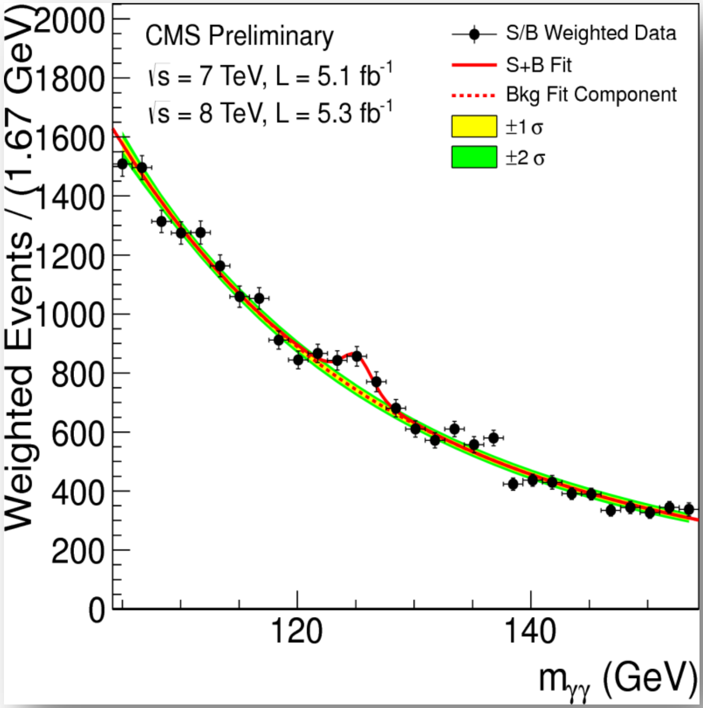
125.3 ± 0.6 GeV

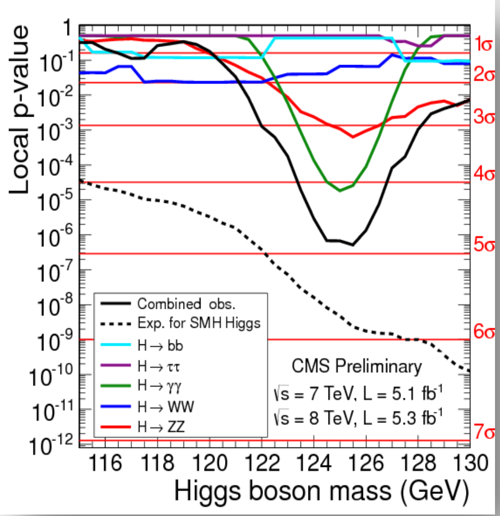
Достоверность результата

4.9 σ !

Результаты CMS на ICHEP2012







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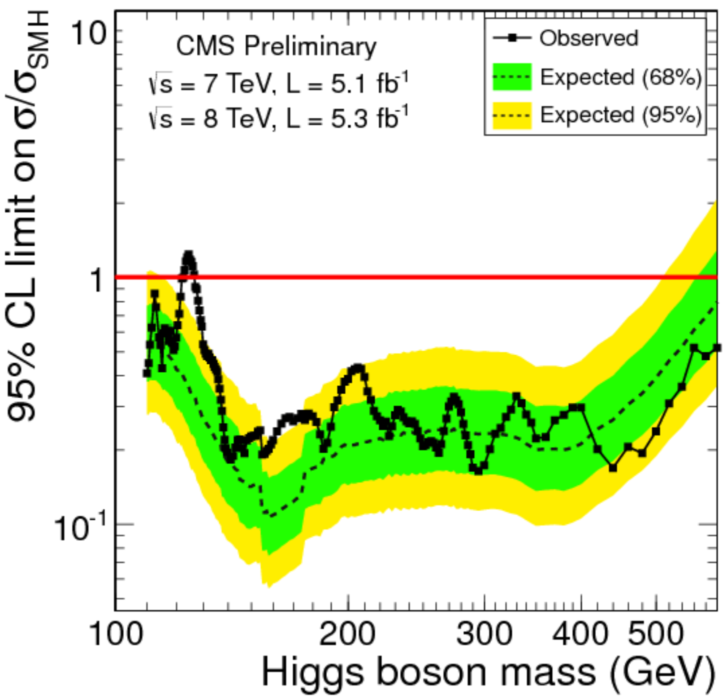
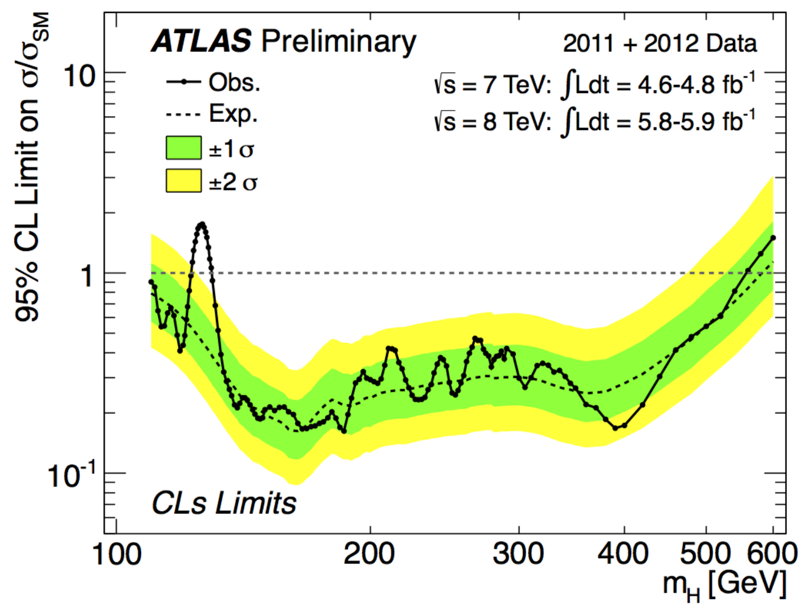
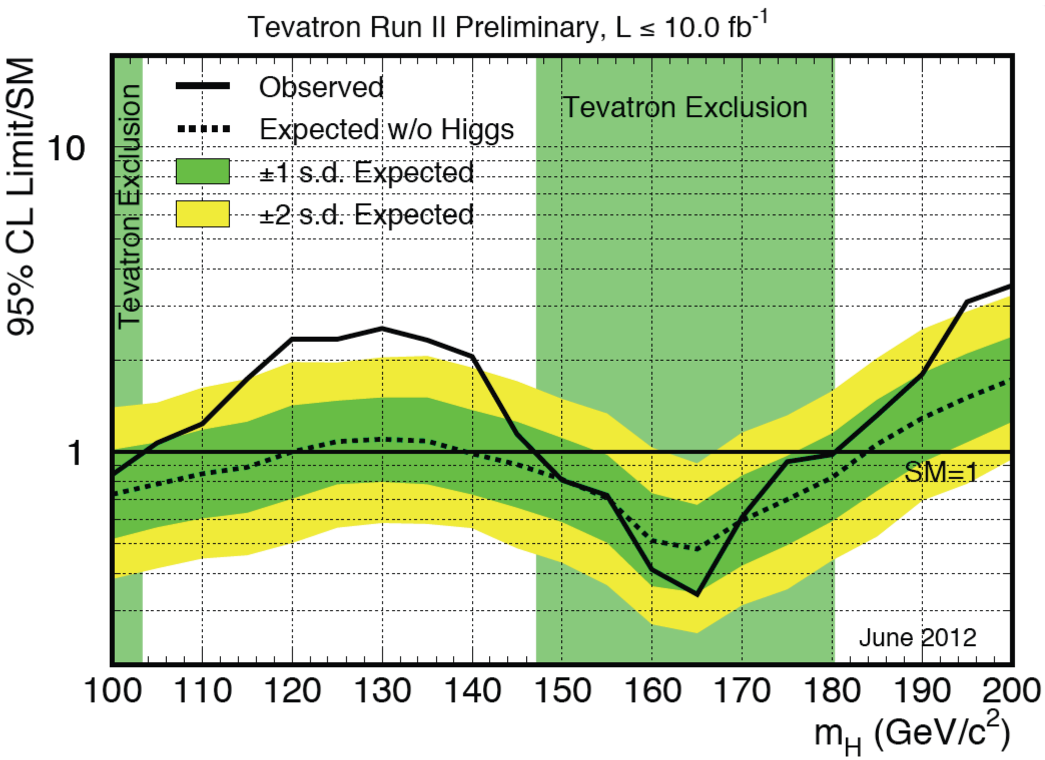
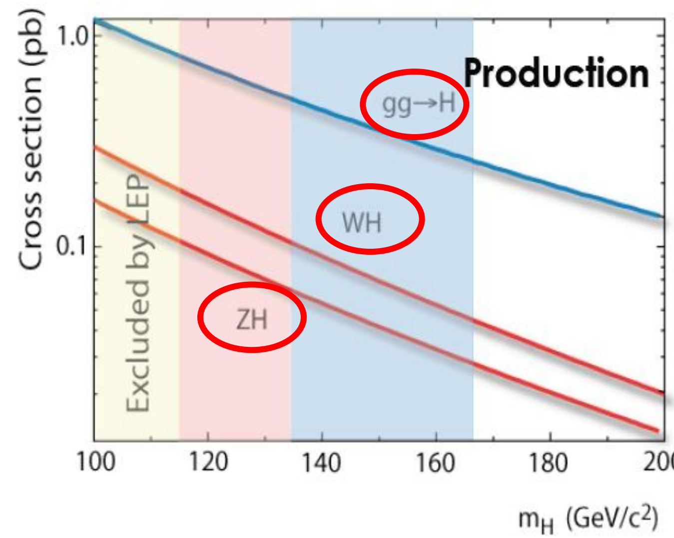




Both CMS and ATLAS have excluded SM Higgs in the mass interval upto about 560 GeV except small interval where the signal was observed

Summer 2012 Tevatron Combination





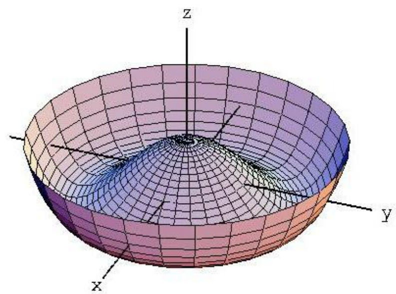
Significant excess:
~3σ for 115→140 GeV

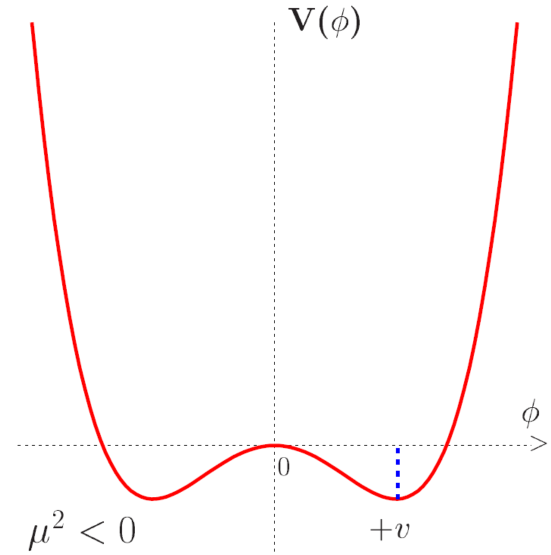
Not only discovery and mass measurement

but also

Very good precision of the mass measurement

Exclusion of large range of higher masses





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

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

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

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

$$\lambda \cong 0.12$$

Origin of the EWSB potential → a weakly-coupled theory

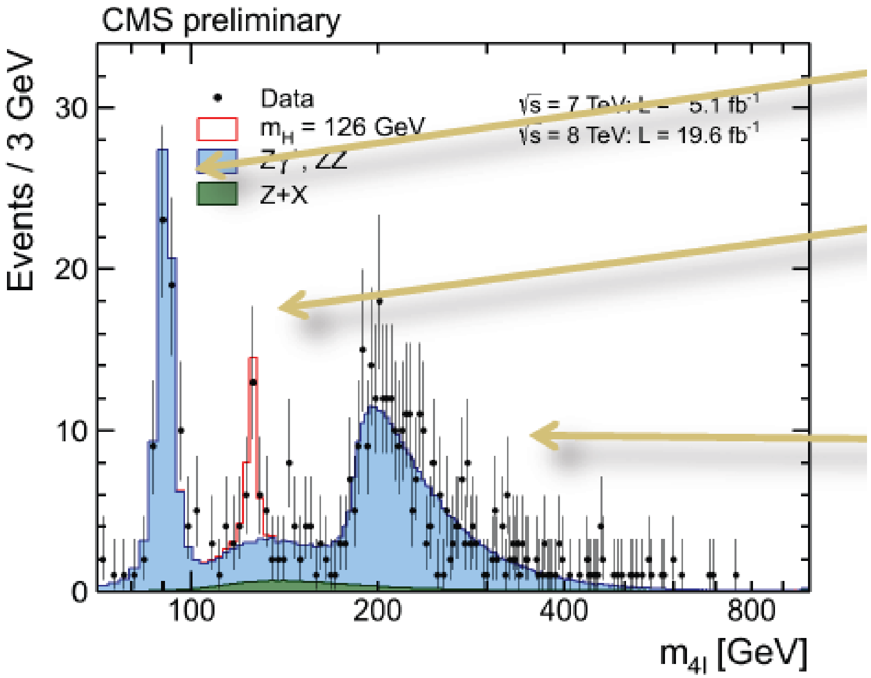
Is observed state the Standard Model Higgs?

Production and decay modes?

Spin and parity?

→ More precise measurements are needed

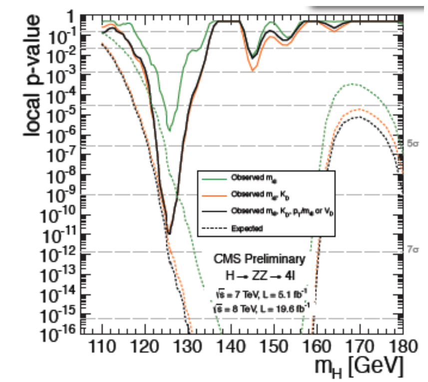
ZZ*-channel CMS



Zγ -> 4l

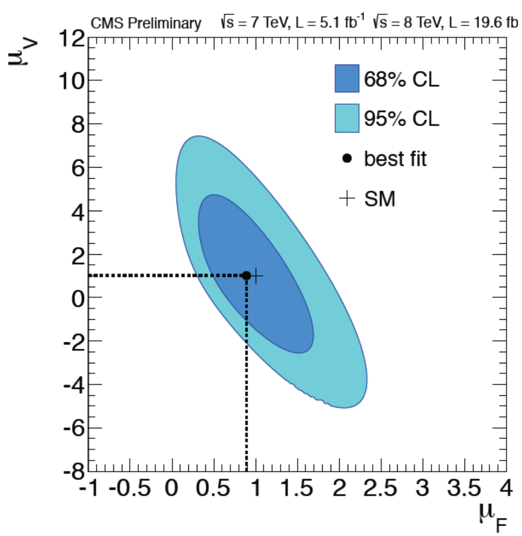
H->ZZ*->4l

ZZ->4l



p-value:
Expected: 7.1σ
Observed: 6.7σ

$\mu = 0.92^{+0.30}_{-0.24}$



$M_H = 125.8 \pm 0.5(\text{stat}) \pm 0.2(\text{syst})$ GeV

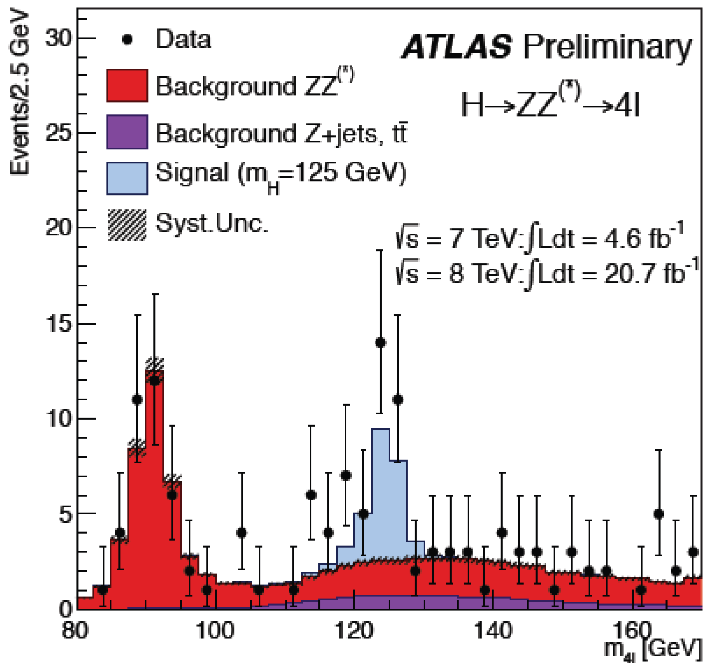
Signal strength

$$\mu_V\ (qqH,\ ZH,\ WH) = 1.0^{+2.4}_{-2.3}$$

$$\mu_F\ (gg \to H,\ t\bar{t}H) = 0.9^{+0.5}_{-0.4}$$

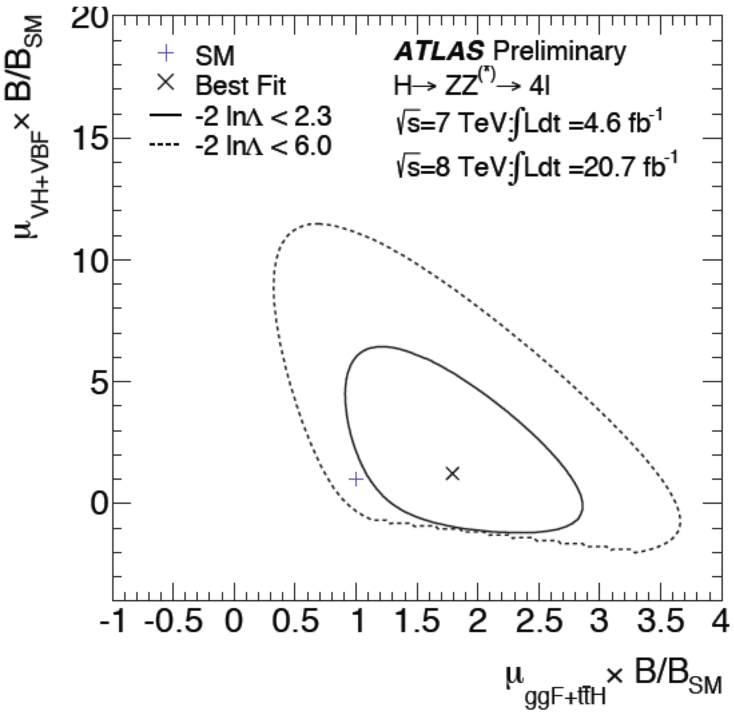
$$\mu = \frac{\sigma \times BR}{(\sigma \times BR)_{SM}}$$

ZZ*-channel ATLAS



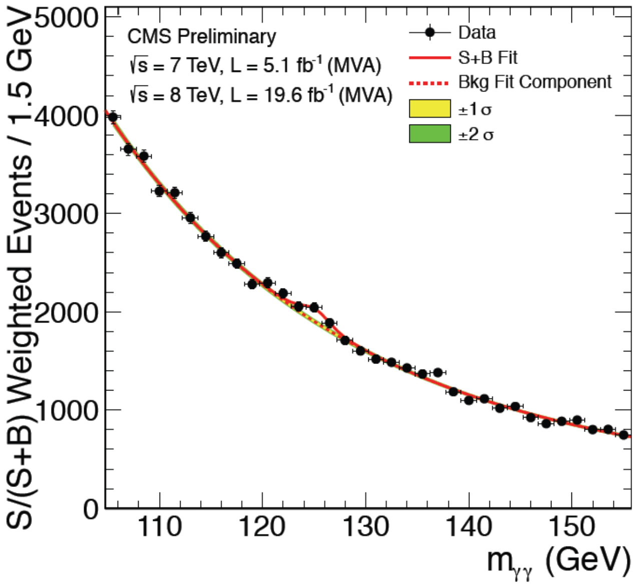
$M_H = 124.3^{+0.6}_{-0.5}(\text{stat})^{+0.5}_{-0.3}(\text{syst})$ GeV

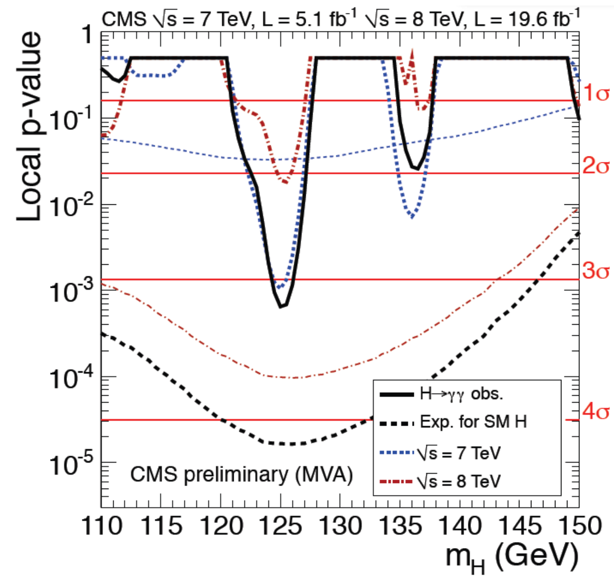
Signal strength $\mu = 1.7^{+0.5}_{-0.4}$



$\mu_{VBF+VH}/\mu_{ggF+ttH} = 0.7^{+2.4}_{-1.0}$

γγ-channel CMS





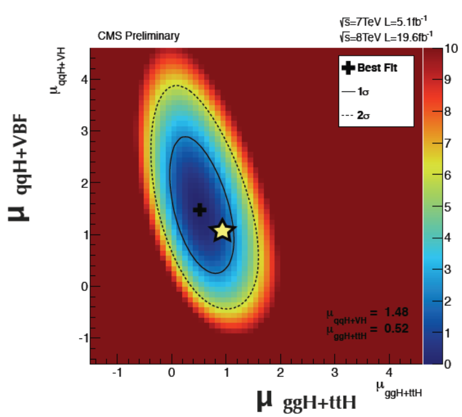
Boosted decision trees:

$$\sigma/\sigma_{SM} = 0.78^{+0.28}_{-0.26}$$

Cut based:

$$\sigma/\sigma_{SM} = 1.11^{+0.32}_{-0.30}$$

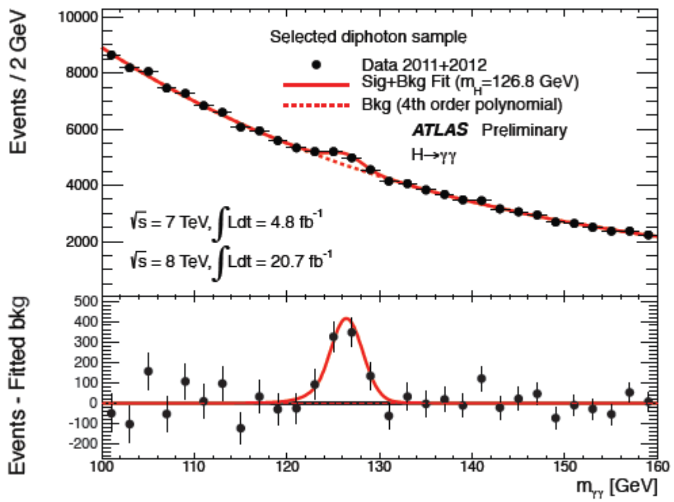
$$M_H = 125.4 \pm 0.5(\text{stat.}) \pm 0.6(\text{syst.})\ \text{GeV}$$

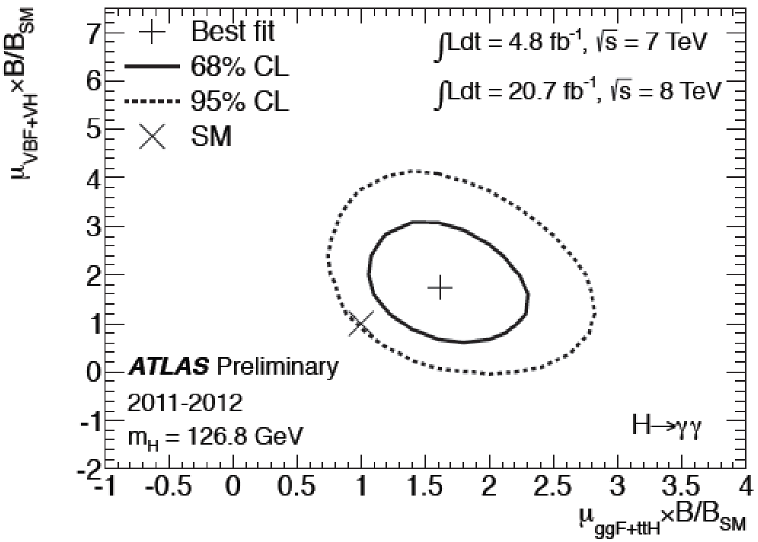


$$\mu_{qqH+VBF} = 1.48$$

$$\mu_{ggH+ttH} = 0.52$$

$\gamma\gamma$-channel ATLAS



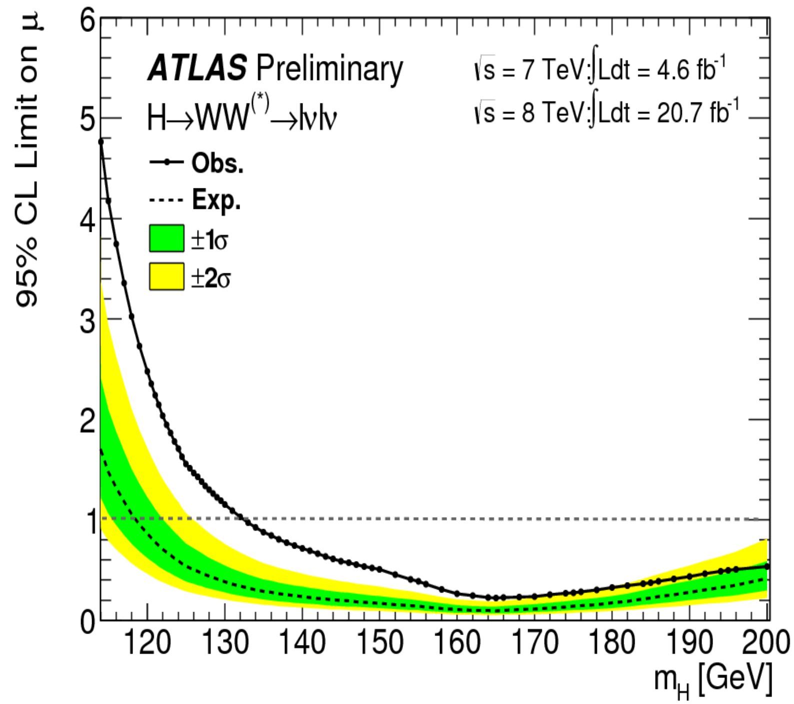


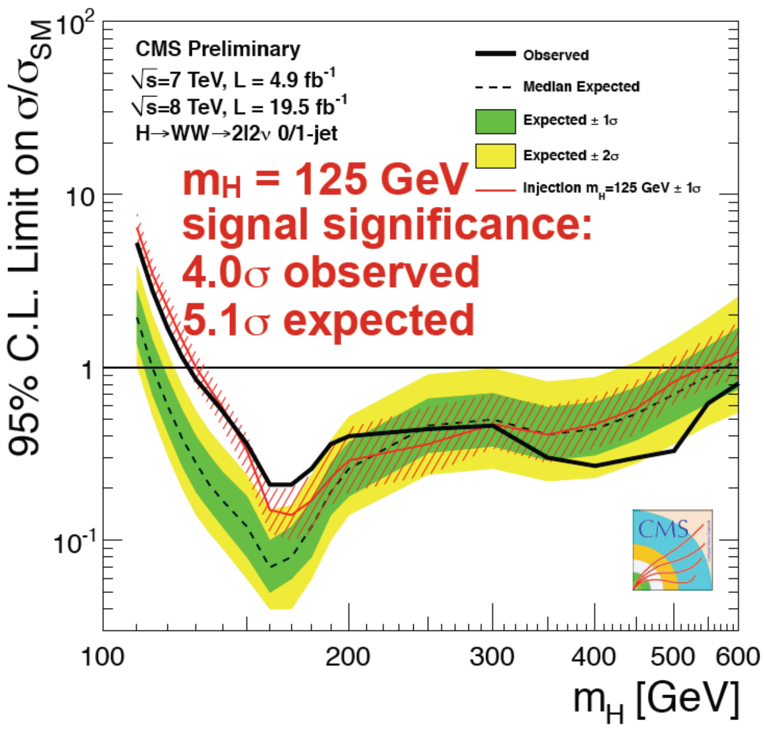
M_H = 126.8±0.2(stat)±0.7(syst) GeV

Signal strength μ = $1.65 \pm 0.24(stat)^{+0.25}_{-0.18}(syst)$

2.3σ from the SM hypothesis

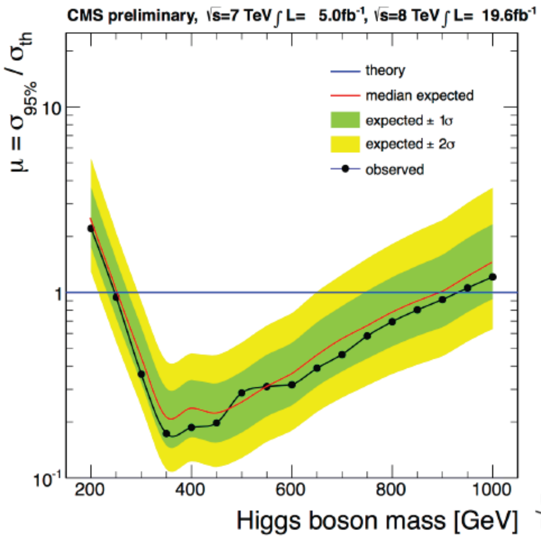
H -> WW*





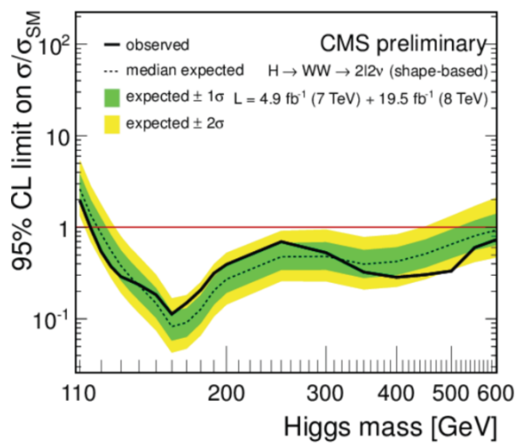
bb and $\tau\tau$ modes are not yet visible individually

First evidence 3.4 σ for combination of bb and $\tau\tau$ is given by CMS



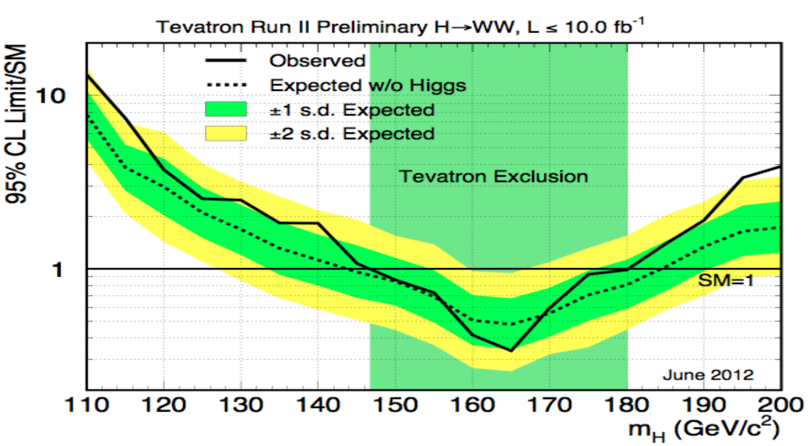
ZZ->2l+2ν

Excluded region 248-930 GeV



WW->2l+2ν

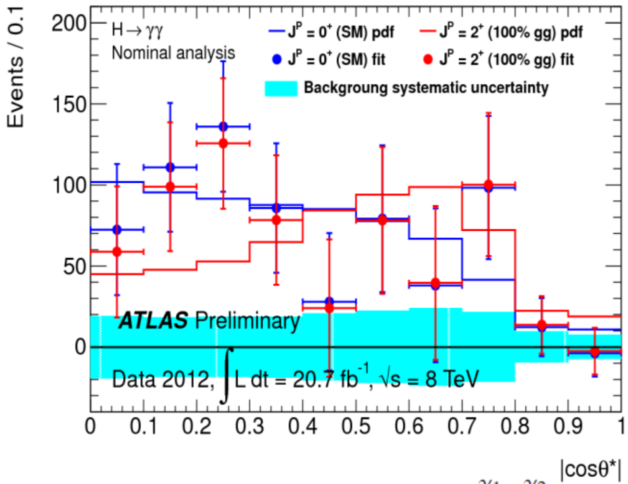
Excluded region 140-590 GeV

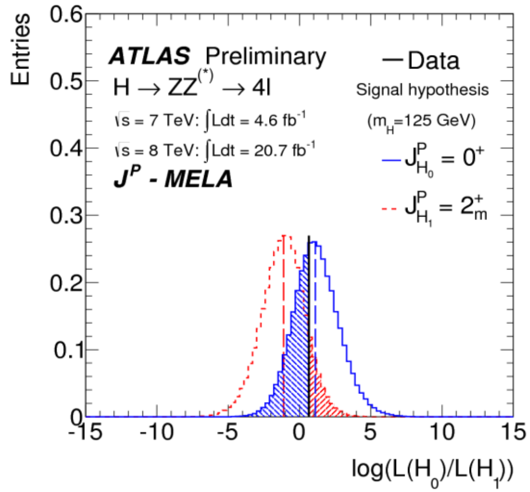


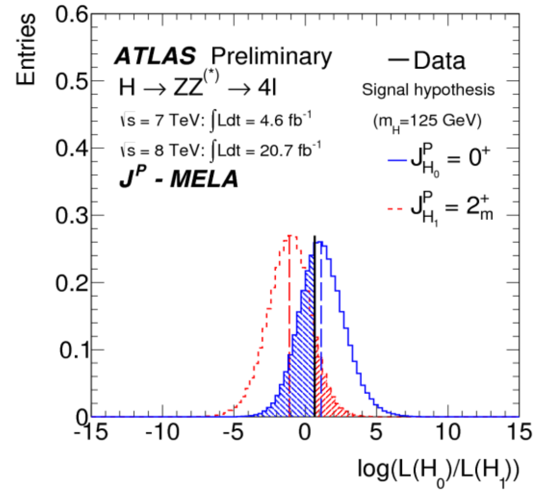
Tevatron combination: Excluded region
147< M_H < 180 GeV at 95% CL

Spin, Parity ?

H decays to $\gamma\gamma$, can not have spin 1 – Landay,Yang theorem





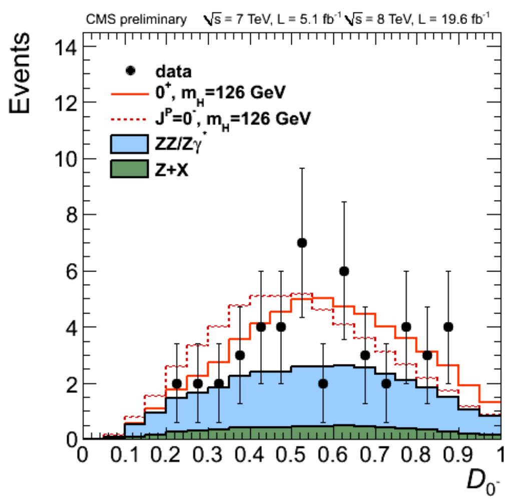


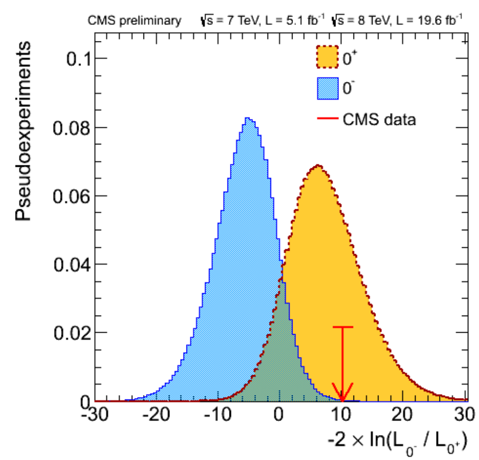
$$\cos\theta^* = \frac{\sinh(\eta_{\gamma_1} - \eta_{\gamma_2})}{\sqrt{1 + \left(p_T^{\gamma\gamma}/m_{\gamma\gamma}\right)^2}} \cdot \frac{2 p_T^{\gamma_1} p_T^{\gamma_2}}{m_{\gamma\gamma}^2}$$

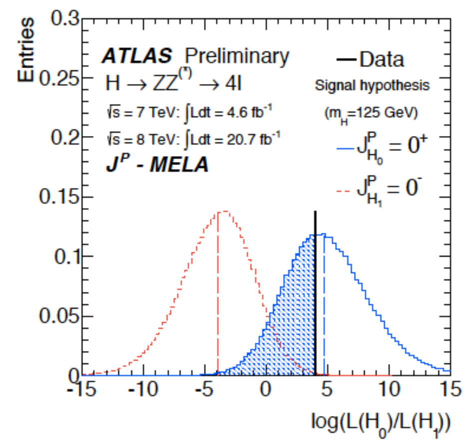
Graviton-like spin-2^+ disfavoured at 99.9% CL

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

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



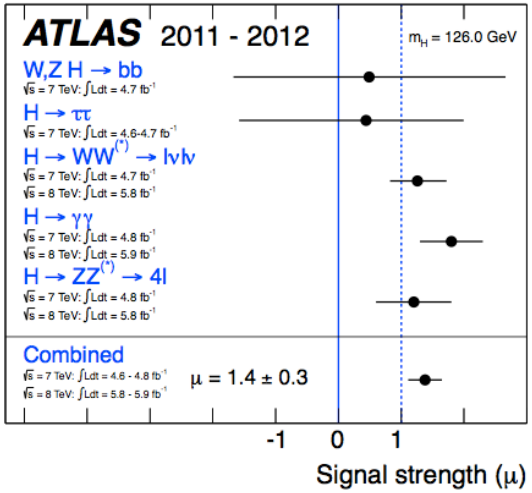


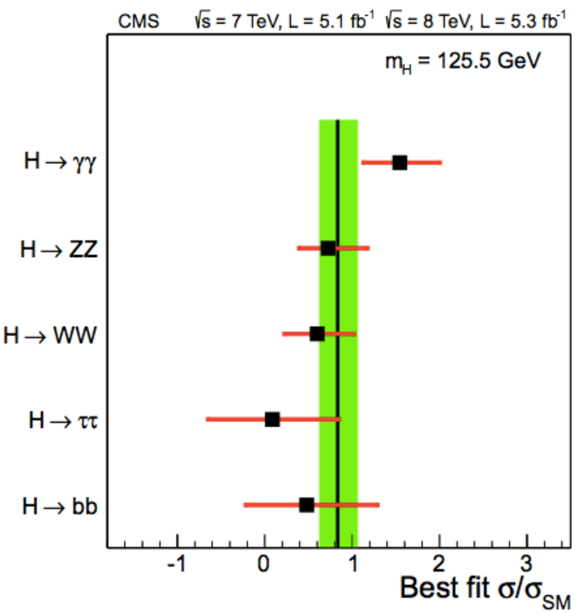


Pseudoscalar 0^- disfavoured at > 99% CL

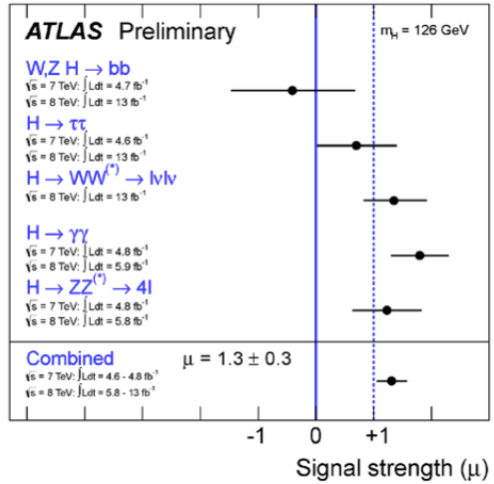
Signal strength μ

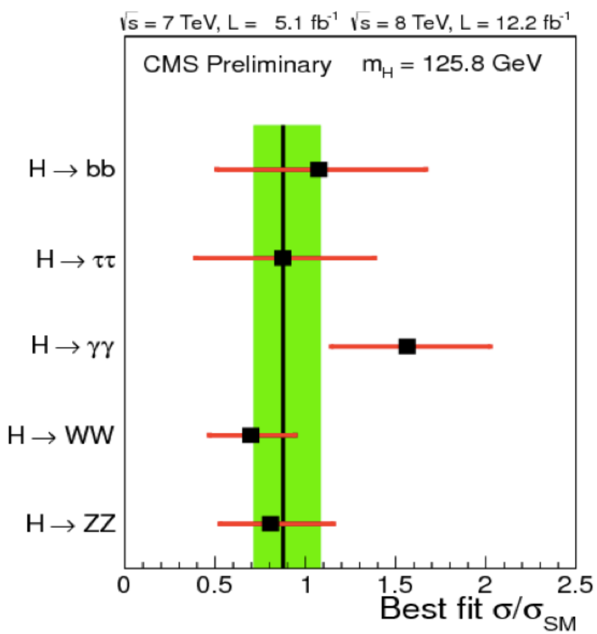
July 2012



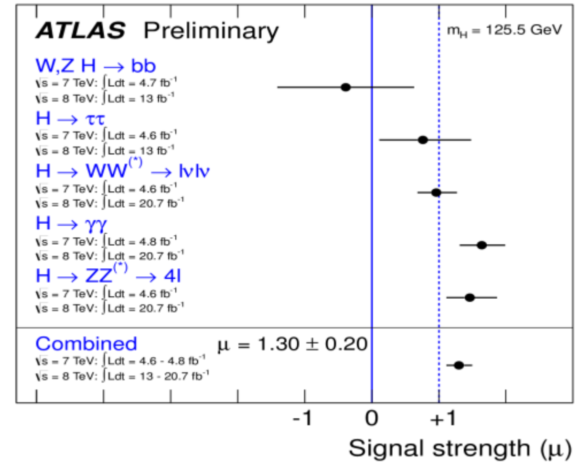


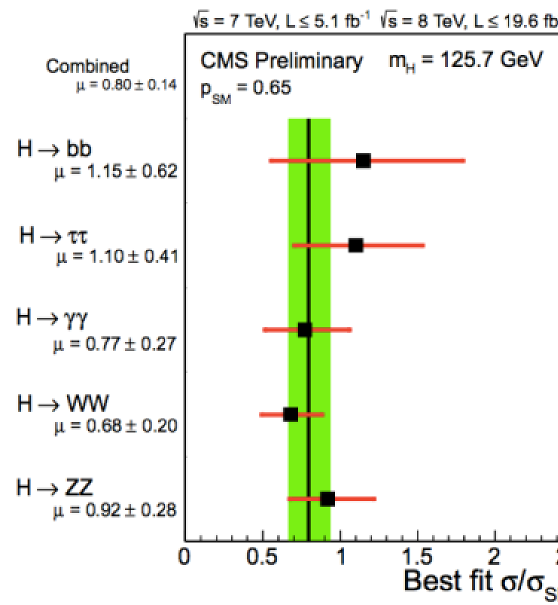
November 2012



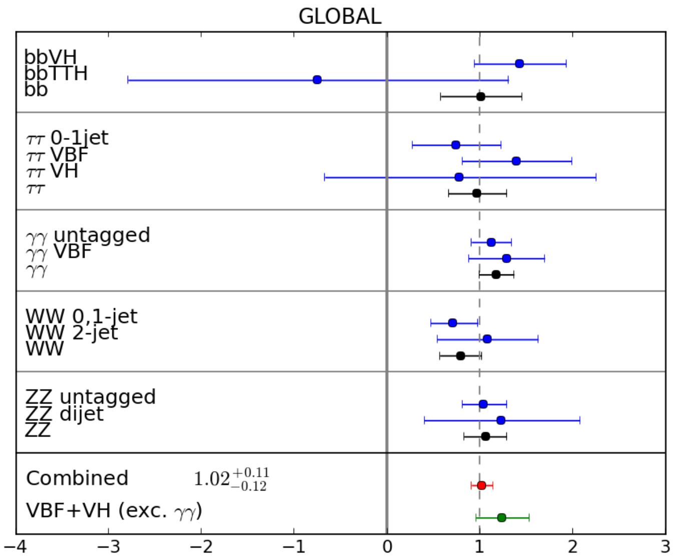


July 2013





Does the resonance couple to particle masses?



John Ellis et al 2013

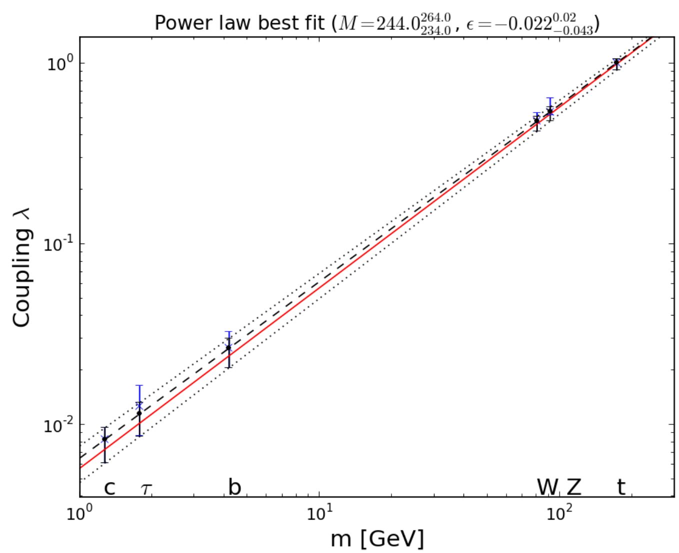
$$\lambda_f = \sqrt{2}\left(\frac{m_f}{M}\right)^{1+\epsilon}, \quad g_V = 2\left(\frac{m_V^{2(1+\epsilon)}}{M^{1+2\epsilon}}\right)$$

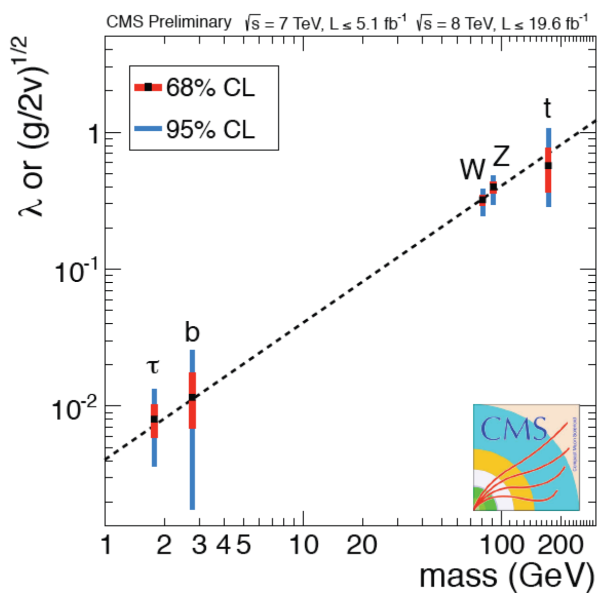
In SM ε=0, M=v

Best fit:

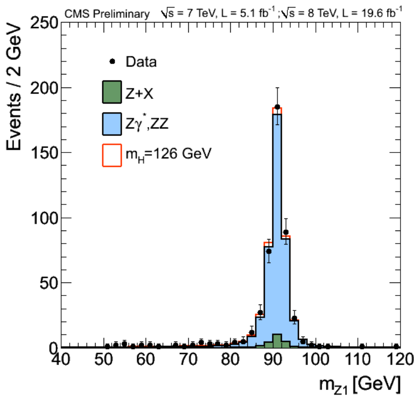
$\varepsilon = -0.022^{+0.042}_{-0.021}$

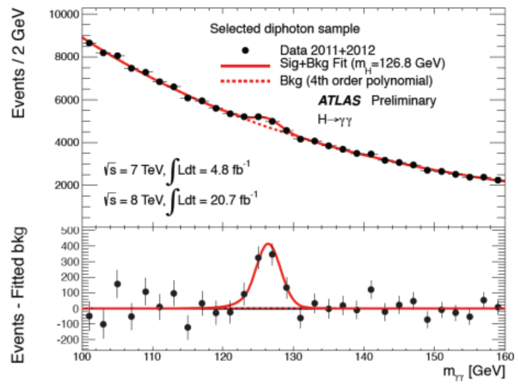
$M = 244^{+20}_{-10}$ GeV

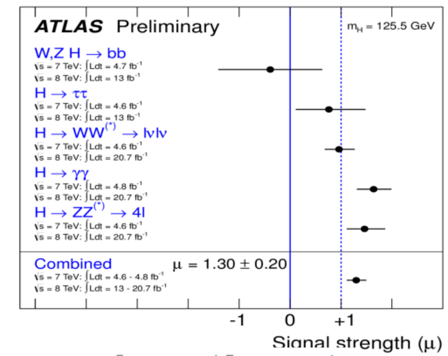


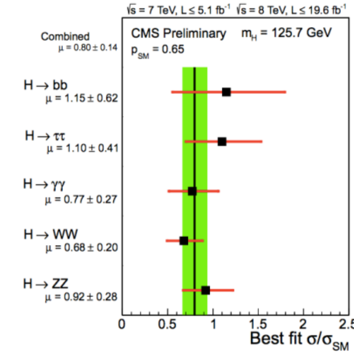


- Higgs boson is found. Confirmation in 2013 with more statistics









- 0^+ state is confirmed

- Signal strengths coincide with SM predictions

- But accuracy is not good enough. Not all modes observed. Lot of room for extensions

Limits on invisible mode are still very weak

ATLAS (4.7+13.0 fb^{-1}):
$Br(H \to \chi\chi) < 65\%$ @ 95% CL,
$M_H = 125$ GeV

CMS (5+20 fb^{-1}):
$Br(H \to \chi\chi) < 75\%$ @ 95% CL,
$M_H = 125$ GeV

$$\mathbf{M_h^2 \leq M_Z^2 + \Delta m^2}$$

susy breaking term (at one-loop)

$$(125\ \mathrm{GeV})^2 \qquad (91\ \mathrm{GeV})^2 \qquad (86\ \mathrm{GeV})^2$$

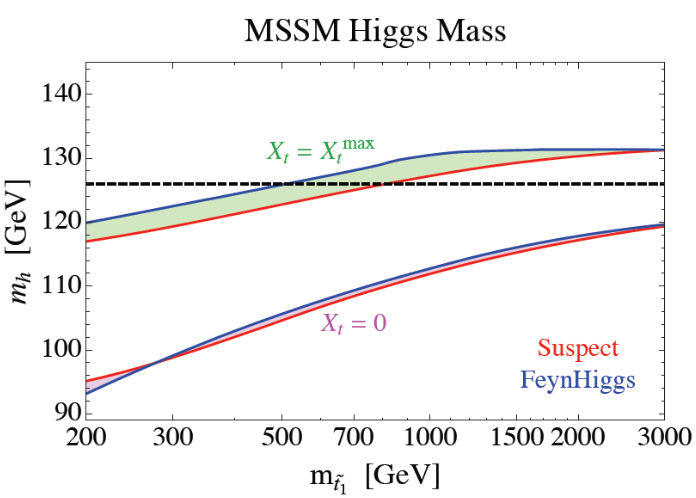
$$\Delta m_h^2 = \frac{3m_t^4}{4\pi^2 v^2}\left[\ln\left(\frac{M_{\mathrm{SUSY}}^2}{m_t^2}\right) + \frac{X_t^2}{M_{\mathrm{SUSY}}^2}\left(1 - \frac{X_t^2}{12 M_{\mathrm{SUSY}}^2}\right)\right]$$

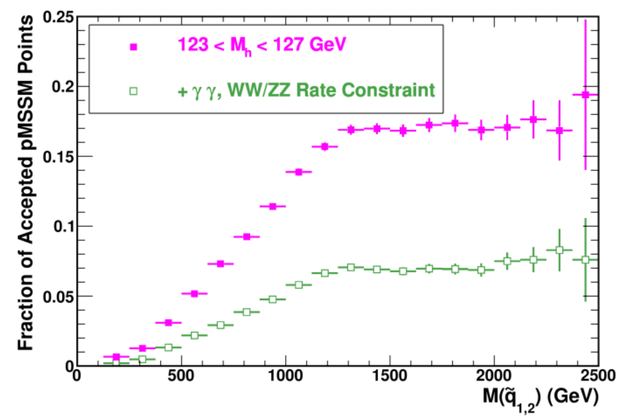
$$M_{\mathrm{SUSY}} \equiv \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$$

Heavy stop is needed

Fine tuning:

$$-\frac{m_Z^2}{2} = |\mu|^2 + m_{H_u}^2$$





Mahmoudi et al 2012

Many options for observed state in the NMSSM

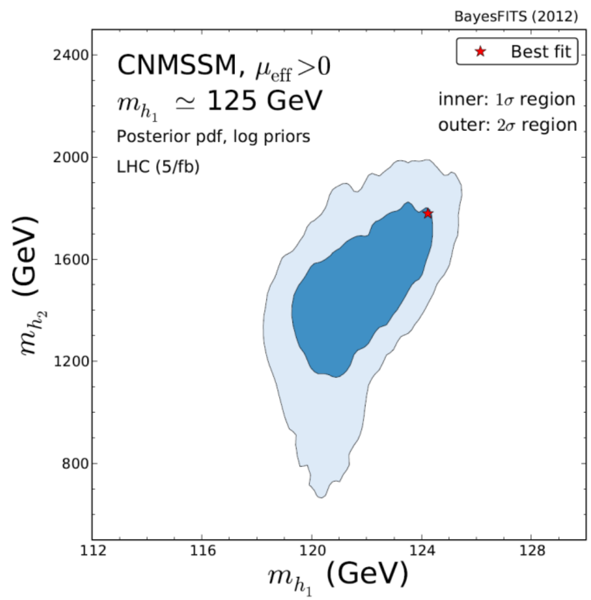
Kazakov et al

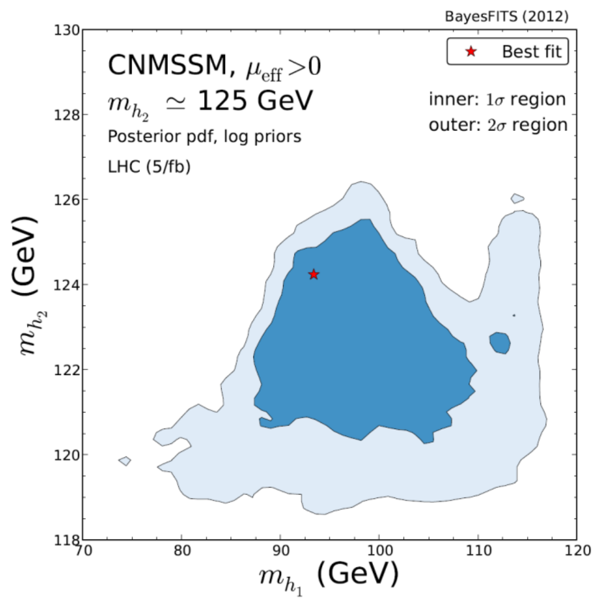
Lightest Higgs Mh 125 GeV (most of studies)

Heavy Higgs Mh 98 GeV, MH 125 GeV (Drees , Belanger et al)

Denenerate Higgses (Gunion et al)

The aim is to make better overall χ^2 fit…





(Kowalska et al)

One of the motivation – Effective chiral Lagrangian from golografic viewpoint

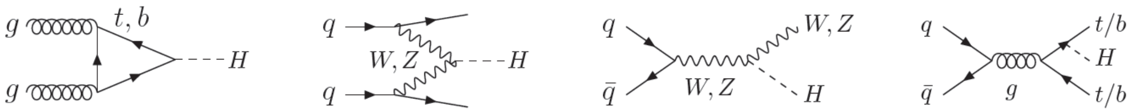
Crojean et al 2012

$$\mathcal{L} = \frac{1}{2}(\partial_\mu h)^2 + \frac{v^2}{4}\mathrm{Tr}(D_\mu \Sigma^\dagger D^\mu \Sigma)\left[1 + 2\,a\,\frac{h}{v}\right]$$
$$-\frac{v}{\sqrt{2}}(\bar{u}_L^i \bar{d}_L^i)\,\Sigma\left[1 + c\,\frac{h}{v}\right]\begin{pmatrix} y_{ij}^u\, u_R^j \\ y_{ij}^d\, d_R^j \end{pmatrix} + h.c. + \cdots$$

$$\mathcal{L} = \frac{1}{2}(\partial_\mu h)^2 - \frac{1}{2}m_h^2 h^2 - \frac{d_3}{6}\left(\frac{3m_h^2}{v}\right)h^3 - \frac{d_4}{24}\left(\frac{3m_h^2}{v^2}\right)h^4 \ldots$$
$$-\left(m_W^2\, W_\mu W_\mu + \frac{1}{2}m_Z^2\, Z_\mu Z_\mu\right)\left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + \ldots\right)$$
$$-\sum_{\psi=u,d,l} m_{\psi^{(i)}}\,\bar{\psi}^{(i)}\psi^{(i)}\left(1 + c_\psi\frac{h}{v} + c_{2\psi}\frac{h^2}{v^2} + \ldots\right)$$
$$+\frac{g^2}{16\pi^2}\left(c_{WW}\, W_{\mu\nu}^+ W_{\mu\nu}^- + c_{ZZ}\, Z_{\mu\nu}^2 + c_{Z\gamma}\, Z_{\mu\nu}\gamma_{\mu\nu}\right)\frac{h}{v} + \ldots$$
$$+\frac{g^2}{16\pi^2}\left[\gamma_{\mu\nu}^2\left(c_{\gamma\gamma}\frac{h}{v} + \ldots\right) + G_{\mu\nu}^2\left(c_{gg}\frac{h}{v} + c_{2gg}\frac{h^2}{v^2}\ldots\right)\right]$$
$$+\frac{g^2}{16\pi^2}\left[\frac{c_{hhgg}}{\Lambda^2}G_{\mu\nu}^2\frac{(\partial_\rho h)^2}{v^2} + \frac{c'_{hhgg}}{\Lambda^2}G_{\mu\rho}G_{\rho\nu}\frac{\partial_\mu h\partial_\nu h}{v^2} + \ldots\right]$$
$$+\ \ldots$$

$$\mathcal{L} = \mathcal{L}_h - (M_W^2 W_\mu^+ W^{\mu -} + \frac{1}{2} M_Z^2 Z_\mu Z^\mu)[1 + 2a\frac{h}{v} + \mathcal{O}(h^2)] - m_{\psi_i}\bar{\psi}_i\psi_i[1 + c\frac{h}{v} + \mathcal{O}(h^2)] + \ldots$$

Contino et al 2012,
….
Espinosa et al 2012



$\frac{\sigma_{NLO}}{\sigma^{SM}_{NLO}}$ c^2 a^2 a^2 c^2

$$\Gamma(H \to f\bar{f}) = c^2\, \Gamma^{SM}(H \to f\bar{f}),$$
$$\Gamma(H \to VV) = a^2\, \Gamma^{SM}(H \to VV),$$
$$\Gamma(H \to gg) = c^2\, \Gamma^{SM}(H \to gg),$$
$$\Gamma(H \to \gamma\gamma) = \frac{(cI_\gamma + aJ_\gamma)^2}{(I_\gamma + J_\gamma)^2}\Gamma^{SM}(H \to \gamma\gamma)$$

In SM a=1 and c=1

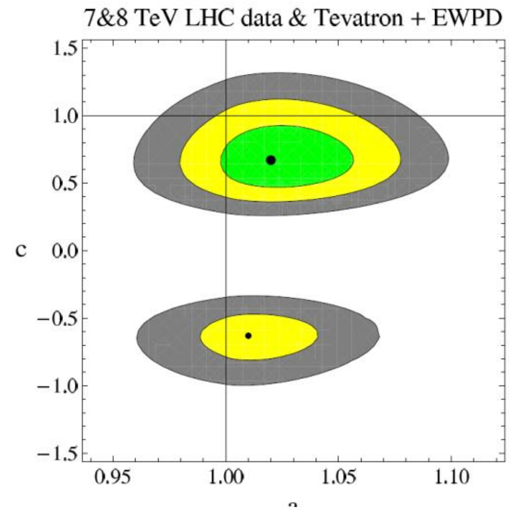
Higgs signal strength parameter:

$$\mu_i = \frac{[\sigma_{j\to h} \times \mathrm{Br}(h \to i)]_{observed}}{[\sigma_{j\to h} \times \mathrm{Br}(h \to i)]_{SM}}$$

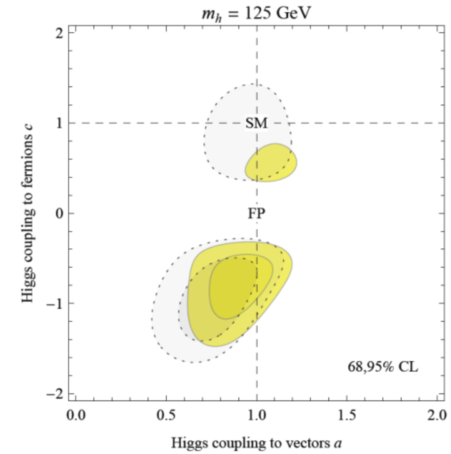
Global χ^2 fit

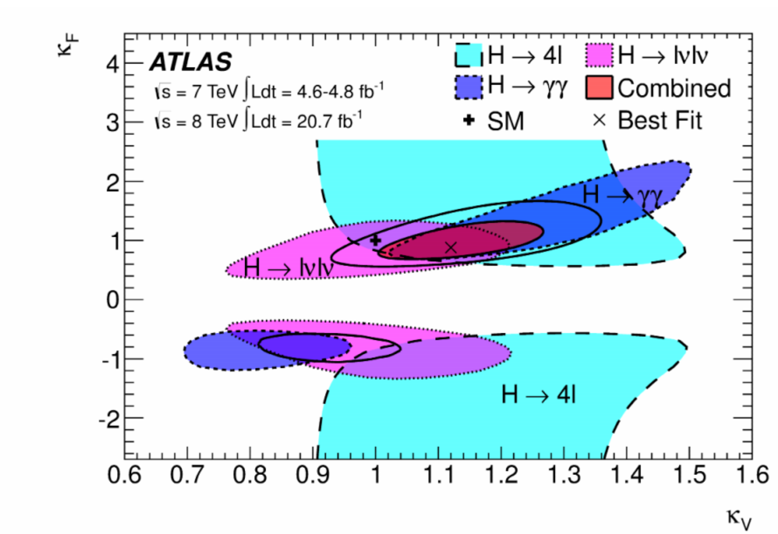
D0, CDF, CMS, ATLAS data

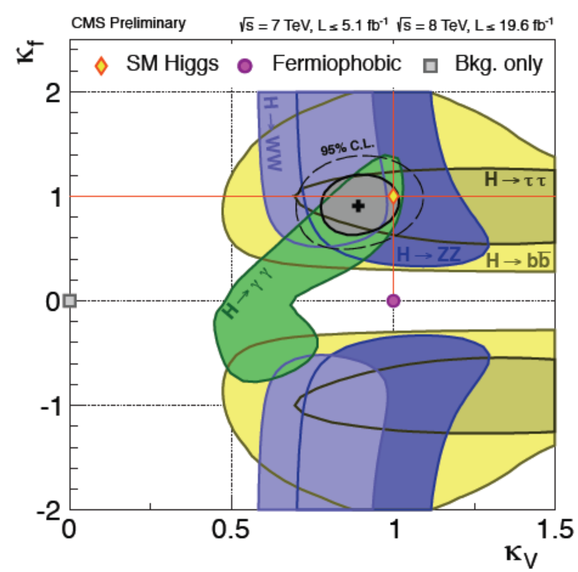
Espinosa et al 2012



Giardino et al 2012







All experiments compatible with SM predictions: accuracy ~10---20%

- ATLAS: κ_v [1.05,1.22] at 68% CL --- κ_f [0.76,1.18] at 68% CL

- CMS: κ_v [0.74,1.06] at 95% CL ---κ_f [0.61,1.33] at 95% CL

Gerutti EPS 2013

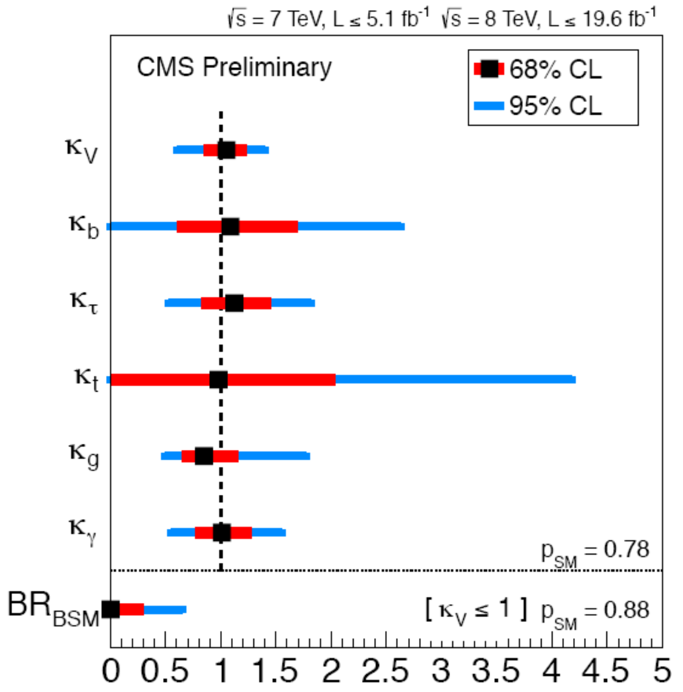
$\Gamma_H = \Gamma_{SM} + \Gamma_{BSM}$ $\qquad$ $BR_{BSM} = \Gamma_{BSM}/\Gamma_H$

ATLAS: $BR_{BSM} < 0.60$ @ 95%CL (0.67exp.)

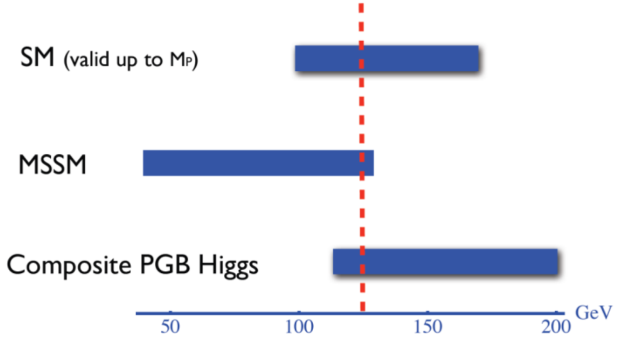
$\kappa_b = \kappa_W .. = 1$ and 3 Fitted Parameters.: κ_γ κ_g BR_{BSM}

CMS: $BR_{BSM} < 0.64$ @ 95%CL (0.66exp.)

7 Fitted Parameters : κ_V κ_γ κ_g k_t k_τ κ_b BR_{BSM}



Different assumptions but similar limits



Pomarol 2012

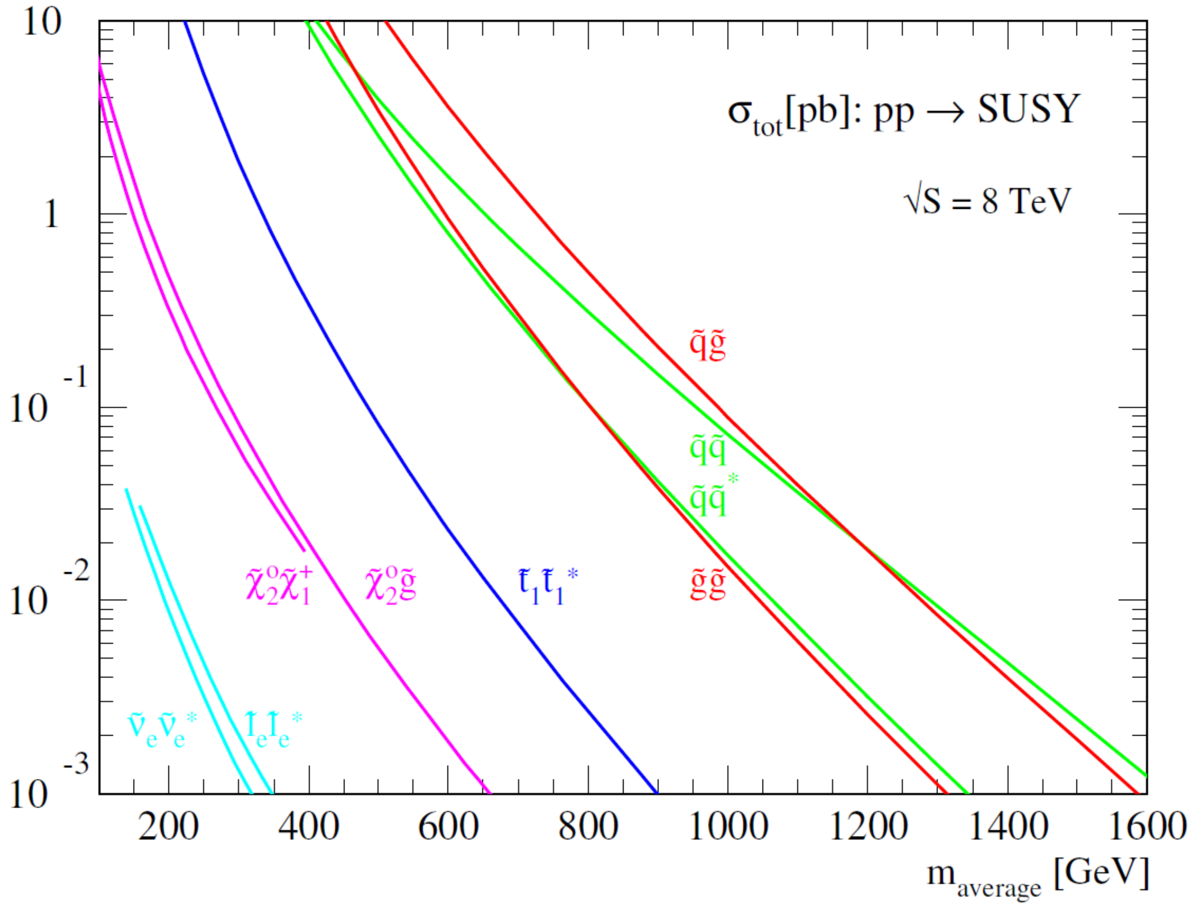
BSM searches

Collision energy > particle production threshold

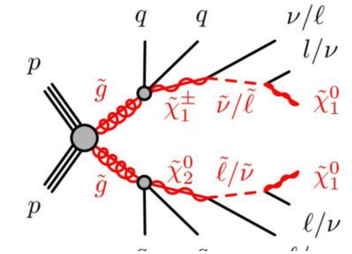
-Searches for new particles
strongly interacting new particles with large cross sections (squarks, gluinos…)
top partners motivated by naturalness (stop, sbottom, vector like quarks, t* …)
new resonances predicted by many BSM extensions (Z', W', π_T, ρ_T , KK states, ..)
extended Higgs sector (new neutral Higgses, charged Higgs)

Collision energy < particle production threshold

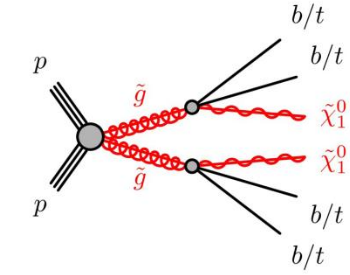
-Anomalous/new interactions of SM particles
(anom. gauge boson couplings, anom. Wtb couplings, FCNC …)
-New particle contributions via quantum loops



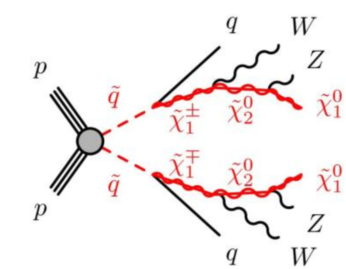
σ_{tot}[pb]: pp → SUSY
$\sqrt{S}$ = 8 TeV
$\tilde{q}\tilde{g}$
$\tilde{q}\tilde{q}$
$\tilde{q}\tilde{q}^*$
$\tilde{g}\tilde{g}$
$\tilde{t}_1\tilde{t}_1^*$
$\tilde{\chi}_2^o\tilde{\chi}_1^+$
$\tilde{\chi}_2^o\tilde{g}$
$\tilde{\nu}_e\tilde{\nu}_e^*$
$\tilde{l}_e\tilde{l}_e^*$
10
1
10^{-1}
10^{-2}
10^{-3}
200 400 600 800 1000 1200 1400 1600
$m_{average}$ [GeV]



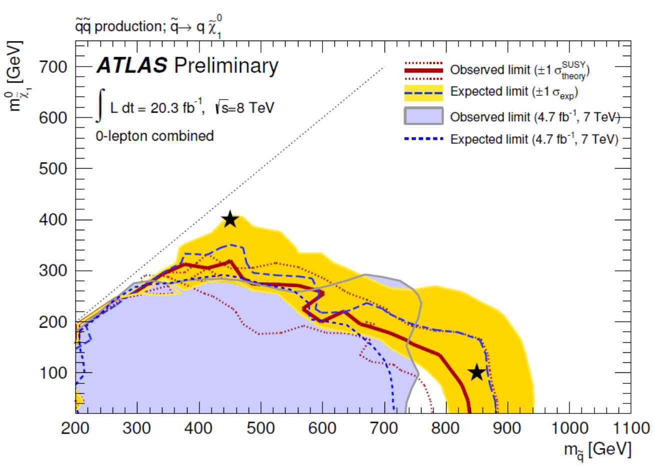
p
p
q
q
ν/ℓ
l/ν
ℓ/ν
$\tilde{g}$
$\tilde{g}$
$\tilde{\chi}_1^\pm$
$\tilde{\nu}/\tilde{\ell}$
$\tilde{\chi}_2^0$
$\tilde{\ell}/\tilde{\nu}$
$\tilde{\chi}_1^0$
$\tilde{\chi}_1^0$



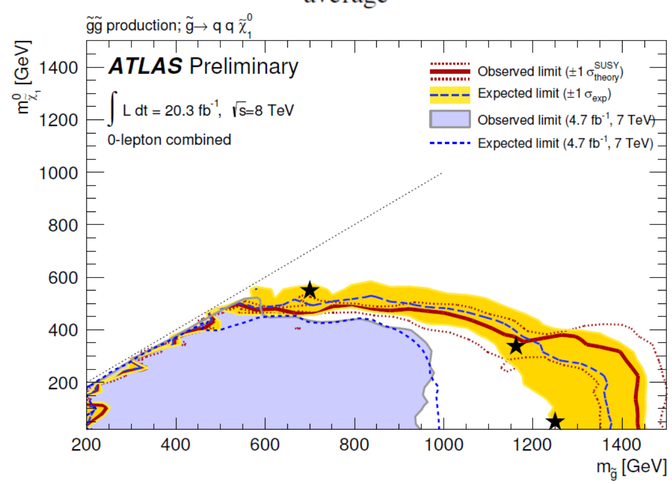
p
p
$\tilde{g}$
$\tilde{g}$
b/t
b/t
b/t
b/t
$\tilde{\chi}_1^0$
$\tilde{\chi}_1^0$



p
p
$\tilde{q}$
$\tilde{q}$
q
W
Z
$\tilde{\chi}_1^\pm$
$\tilde{\chi}_2^0$
$\tilde{\chi}_1^0$
$\tilde{\chi}_1^\mp$
$\tilde{\chi}_2^0$
$\tilde{\chi}_1^0$
Z
q
W

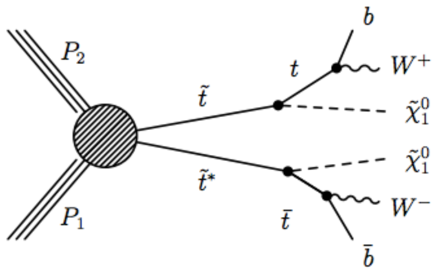


$\tilde{q}\tilde{q}$ production; $\tilde{q}\to q\,\tilde{\chi}_1^0$
ATLAS Preliminary
$\int L\,dt$ = 20.3 fb^{-1}, $\sqrt{s}$=8 TeV
0-lepton combined
Observed limit ($\pm1\,\sigma_{theory}^{SUSY}$)
Expected limit ($\pm1\,\sigma_{exp}$)
Observed limit (4.7 fb^{-1}, 7 TeV)
Expected limit (4.7 fb^{-1}, 7 TeV)
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{q}}$ [GeV]

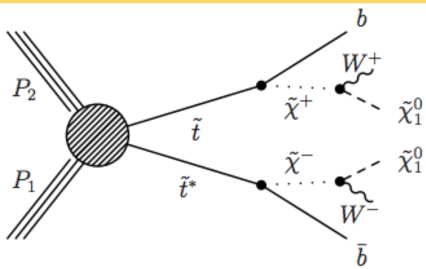


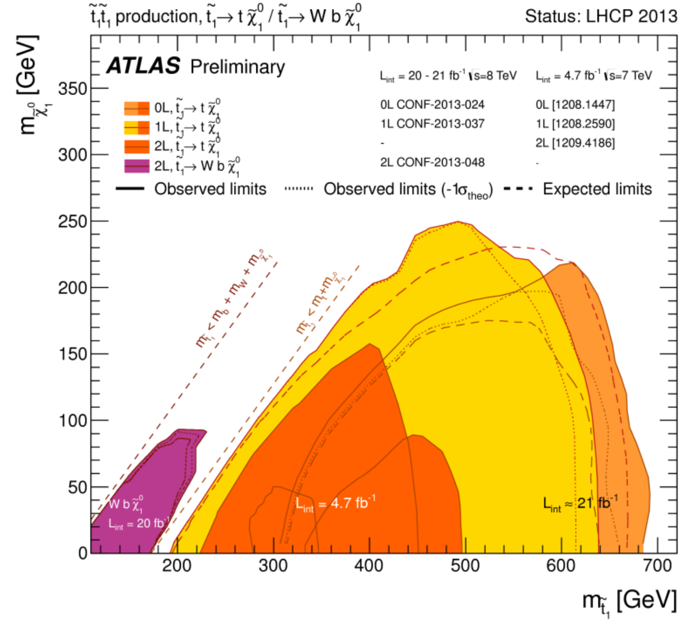
$\tilde{g}\tilde{g}$ production; $\tilde{g}\to q\,q\,\tilde{\chi}_1^0$
ATLAS Preliminary
$\int L\,dt$ = 20.3 fb^{-1}, $\sqrt{s}$=8 TeV
0-lepton combined
Observed limit ($\pm1\,\sigma_{theory}^{SUSY}$)
Expected limit ($\pm1\,\sigma_{exp}$)
Observed limit (4.7 fb^{-1}, 7 TeV)
Expected limit (4.7 fb^{-1}, 7 TeV)
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{g}}$ [GeV]

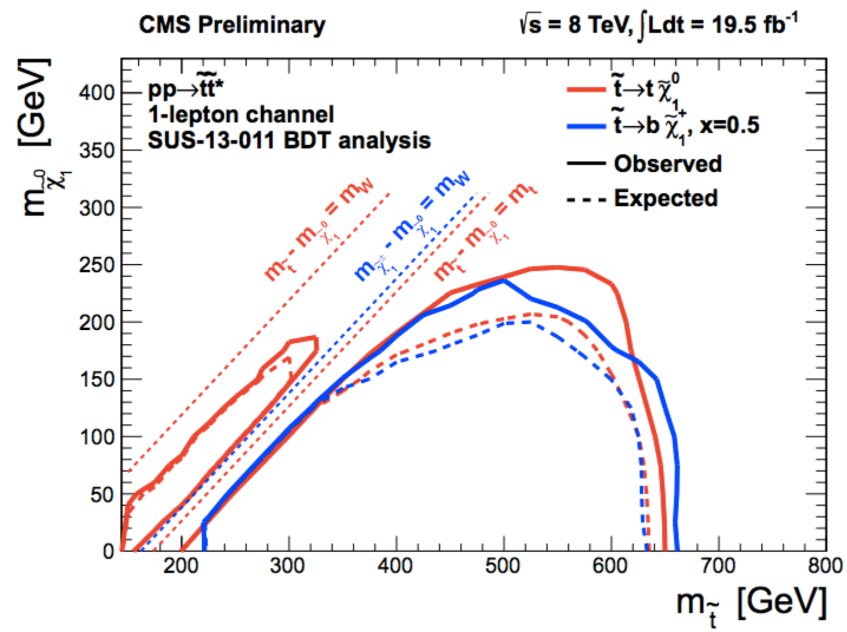
$$\tilde{t}\tilde{t} \rightarrow t\bar{t}\tilde{\chi}_1^0\tilde{\chi}_1^0$$



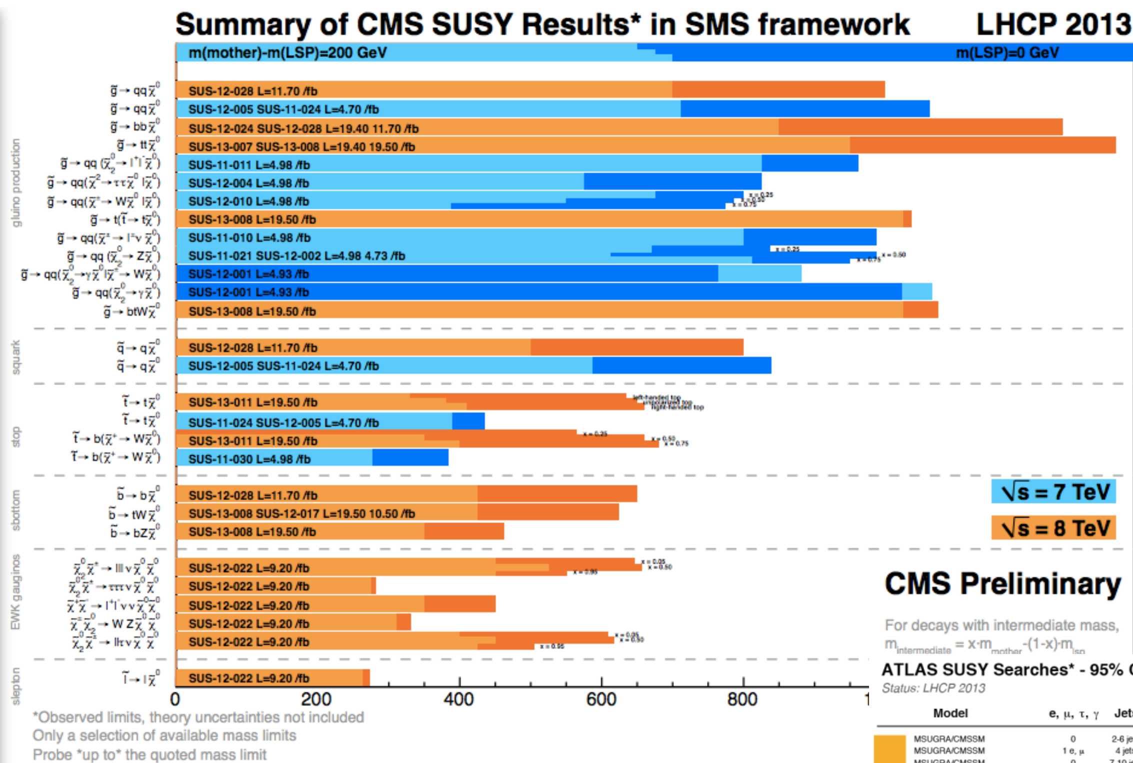
$$\tilde{t}\tilde{t} \rightarrow b\bar{b}\tilde{\chi}_1^+\tilde{\chi}_1^- \rightarrow b\bar{b}W^+W^-\tilde{\chi}_1^0\tilde{\chi}_1^0$$

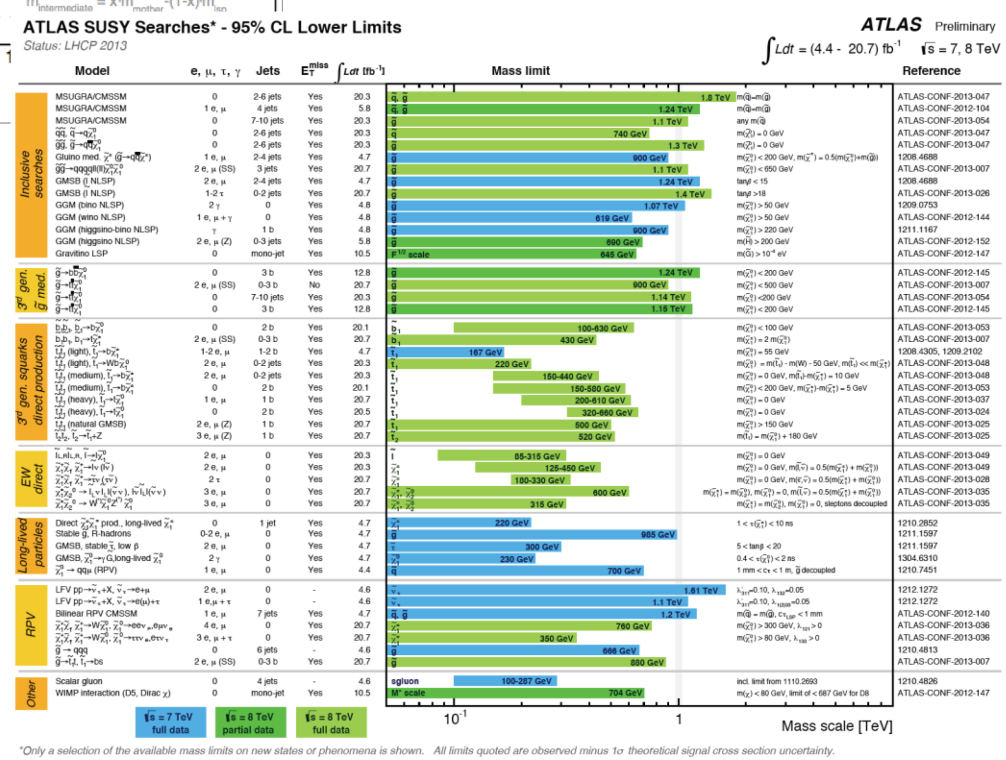




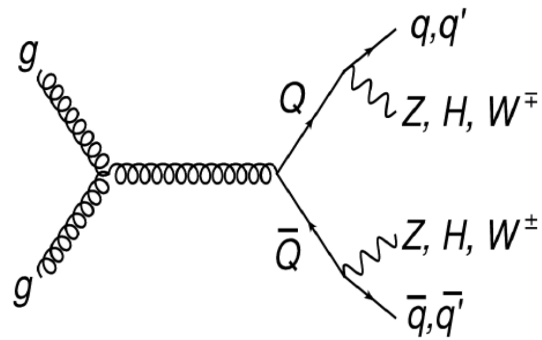


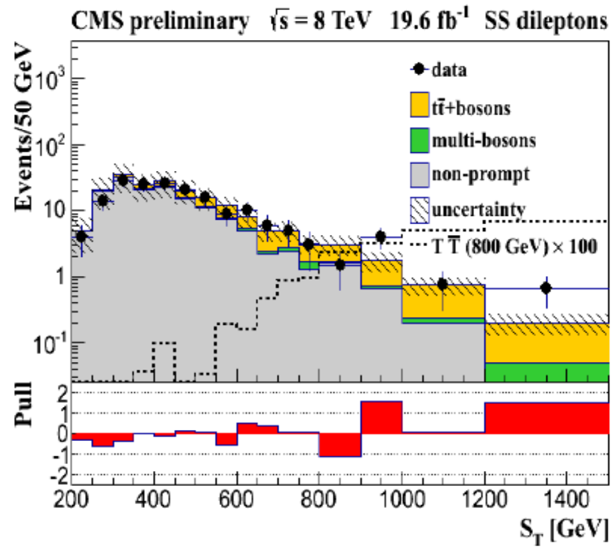
Mass exclusion limits:
Mstop ~660 GeV and
Msbottom ~630 GeV


Summary of CMS SUSY Results* in SMS framework
LHCP 2013
m(mother)-m(LSP)=200 GeV
m(LSP)=0 GeV
gluino production
squark
stop
sbottom
EWK gauginos
slepton
SUS-12-028 L=11.70 /fb
SUS-12-005 SUS-11-024 L=4.70 /fb
SUS-12-024 SUS-12-028 L=19.40 11.70 /fb
SUS-13-007 SUS-13-008 L=19.40 19.50 /fb
SUS-11-011 L=4.98 /fb
SUS-12-004 L=4.98 /fb
SUS-12-010 L=4.98 /fb
SUS-13-008 L=19.50 /fb
SUS-11-010 L=4.98 /fb
SUS-11-021 SUS-12-002 L=4.98 4.73 /fb
SUS-12-001 L=4.93 /fb
SUS-12-001 L=4.93 /fb
SUS-13-008 L=19.50 /fb
SUS-12-028 L=11.70 /fb
SUS-12-005 SUS-11-024 L=4.70 /fb
SUS-13-011 L=19.50 /fb
SUS-11-024 SUS-12-005 L=4.70 /fb
SUS-13-011 L=19.50 /fb
SUS-11-030 L=4.98 /fb
SUS-12-028 L=11.70 /fb
SUS-13-008 SUS-12-017 L=19.50 10.50 /fb
SUS-13-008 L=19.50 /fb
SUS-12-022 L=9.20 /fb
SUS-12-022 L=9.20 /fb
SUS-12-022 L=9.20 /fb
SUS-12-022 L=9.20 /fb
SUS-12-022 L=9.20 /fb
SUS-12-022 L=9.20 /fb
√s = 7 TeV
√s = 8 TeV
CMS Preliminary
For decays with intermediate mass,
0
200
400
600
800
*Observed limits, theory uncertainties not included
Only a selection of available mass limits
Probe *up to* the quoted mass limit

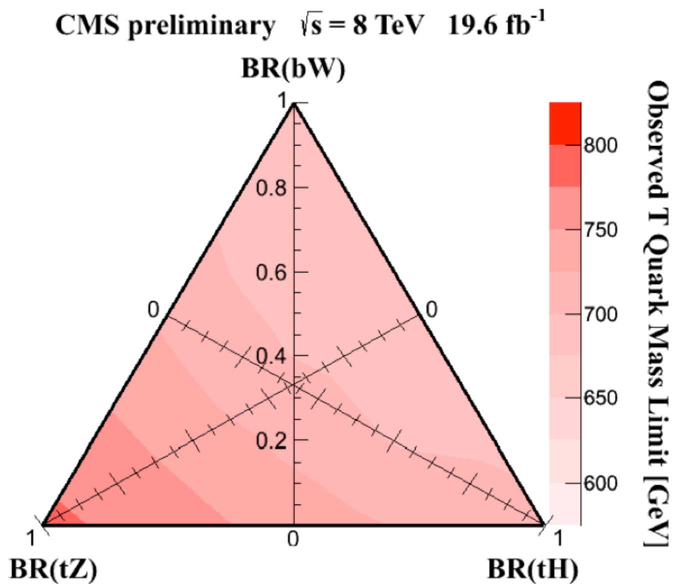

ATLAS SUSY Searches* - 95% CL Lower Limits
Status: LHCP 2013
ATLAS Preliminary
∫Ldt = (4.4 - 20.7) fb⁻¹
√s = 7, 8 TeV
Model
e, μ, τ, γ
Jets
Mass limit
Reference
Inclusive searches
3rd gen. g̃ med.
3rd gen. squarks direct production
EW direct
Long-lived particles
RPV
Other
√s = 7 TeV full data
√s = 8 TeV partial data
√s = 8 TeV full data
Mass scale [TeV]
*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

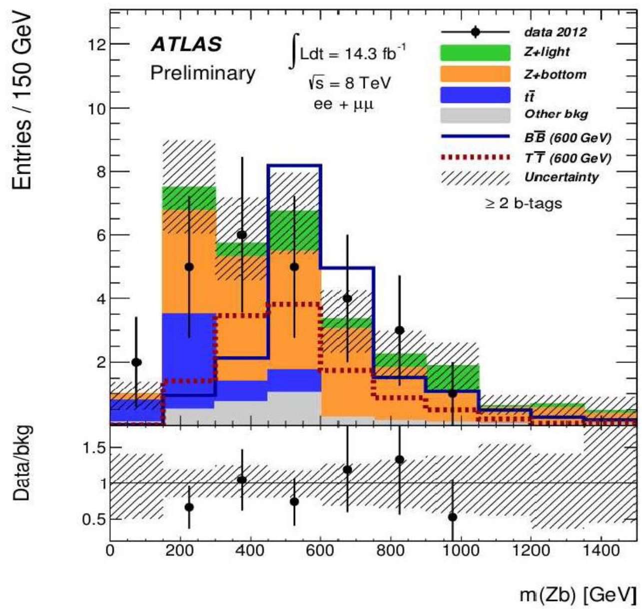
Vector like top partners



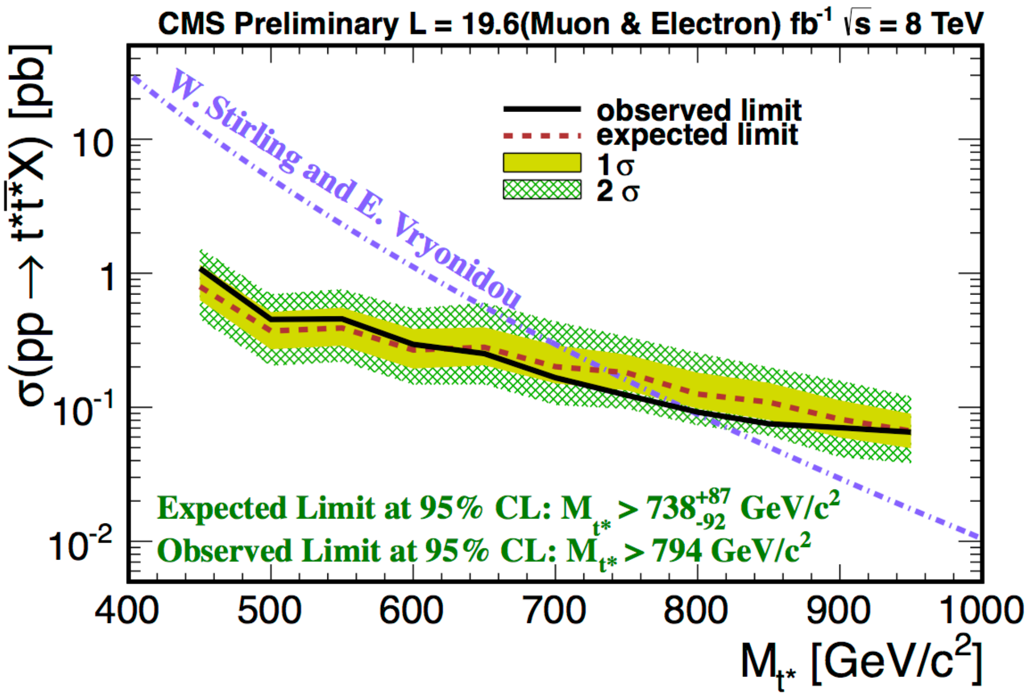


Mass limits ~ 700 GeV
(T → Zt, T → Wb, T → Ht)

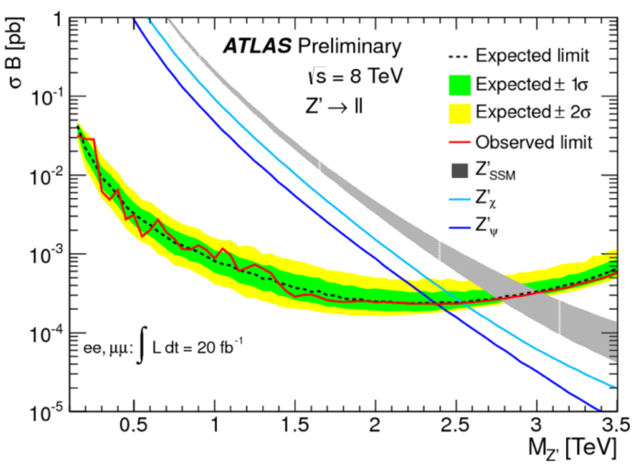


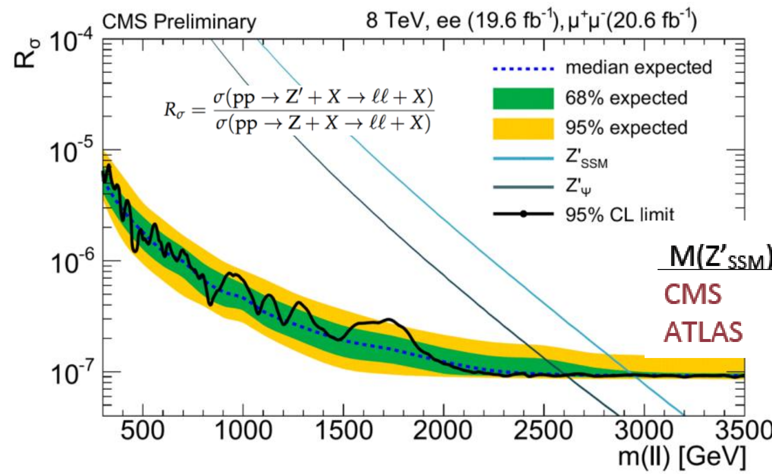


Searches for excited Top in top+jet



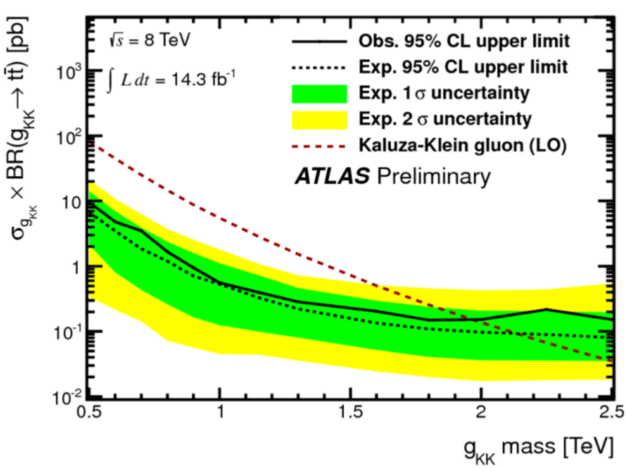
Searches for Z' in dileptons

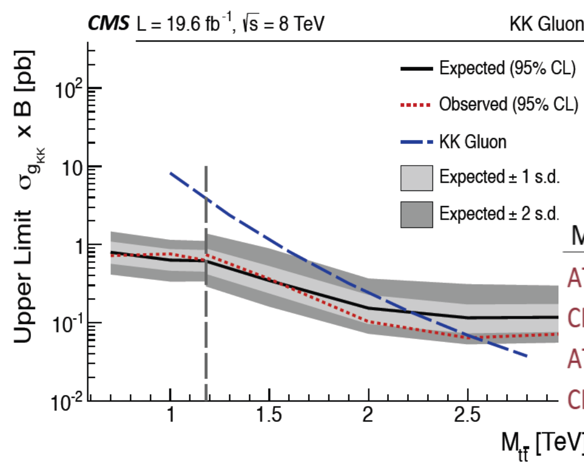




$M(Z'_{SSM})$	expected	observed
CMS	> 2.96 TeV	> 2.96 TeV
ATLAS	> 2.85 TeV	> 2.86 TeV

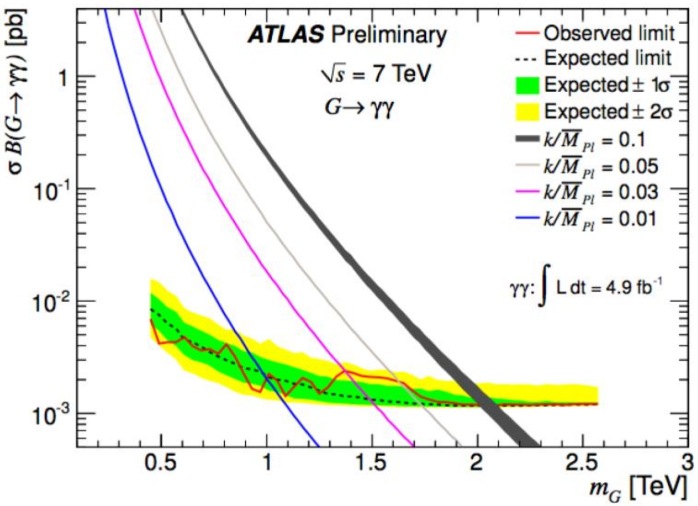
Searches for Z' and KK resonances in top pair

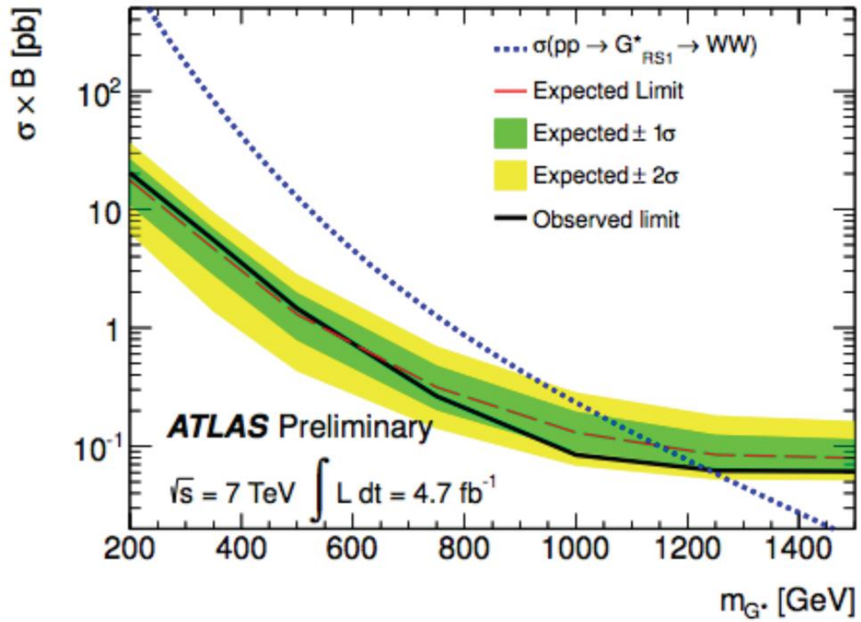


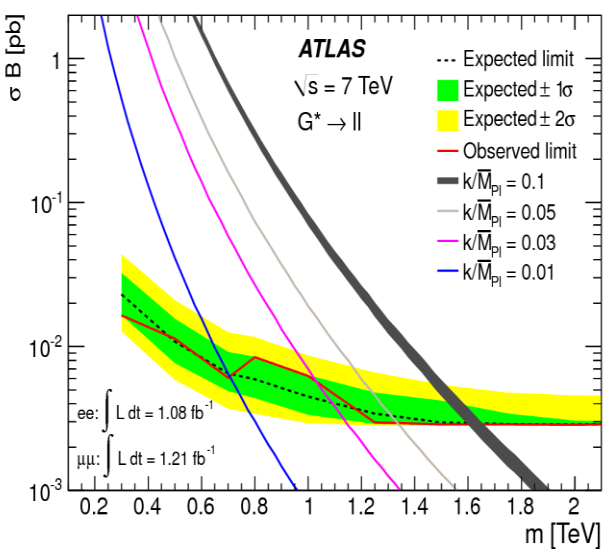


M(Z' or g_{KK}) 95%	Luminosity	Expected	Observed
ATLAS Z'	14.3	> 1.9 TeV	> 1.8 TeV
CMS Z'	19.6	> 2.0 TeV	> 2.1 TeV
ATLAS g_{KK}	14.3	> 2.1 TeV	> 2.0 TeV
CMS g_{KK}	19.6	> 2.2 TeV	> 2.5 TeV

Searches for RS gravitons

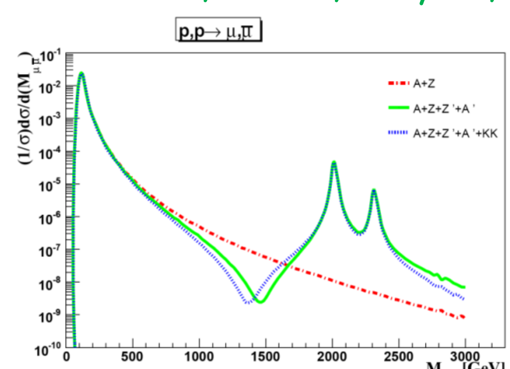




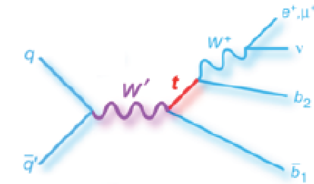


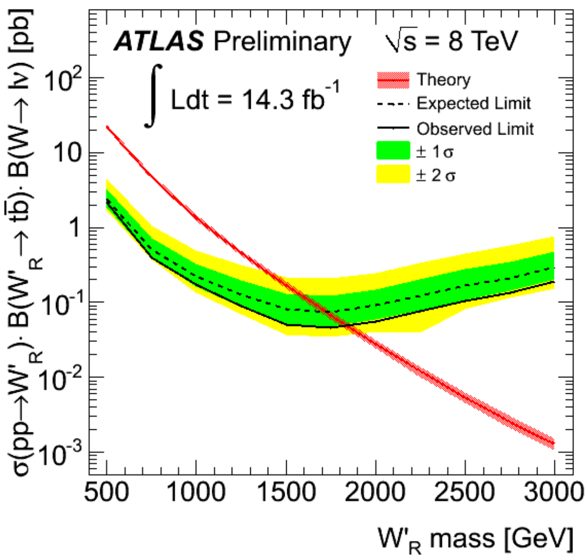
No interferences yet
The interferences
should be included

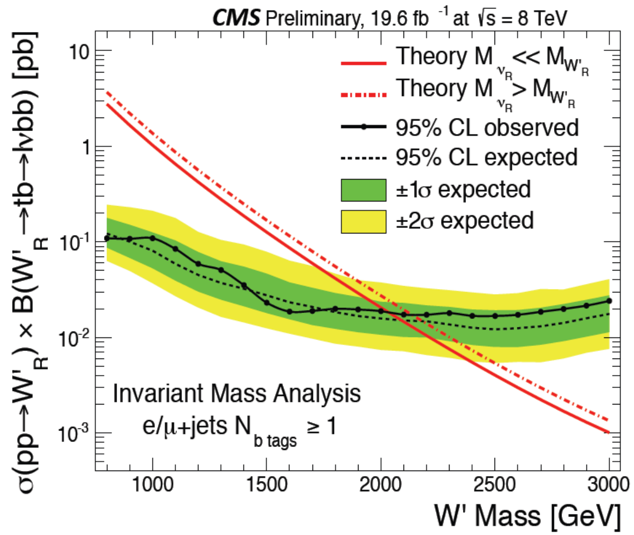
Boos, Bunichev, Smolyakov, Volobuev



Searches for W' in top+b



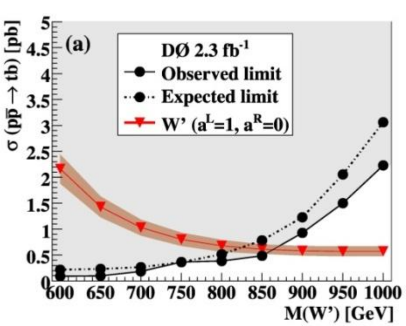


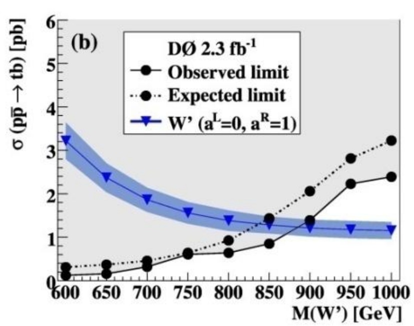


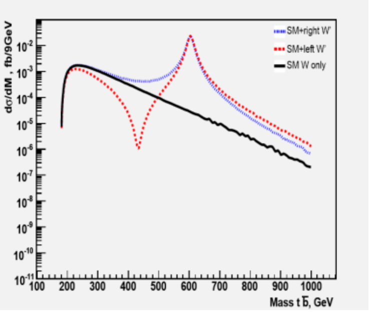
$M_{W'_R(tb)}$ 95% CL	Luminosity	Expected	Observed
ATLAS W'$_R$	14.3	> 1.72 TeV	> 1.84 TeV
CMS W'$_R$	19.6	> 2.09 TeV	> 2.03 TeV

D0 limits: $M_{W'}$ > 830 (860) GeV L(R)

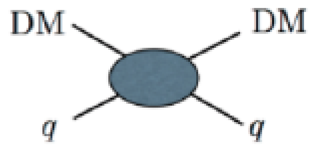
Boos, Bunichev, Dudko, Perfilov



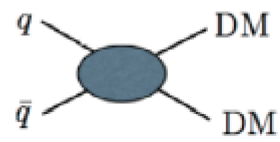




Negative interference

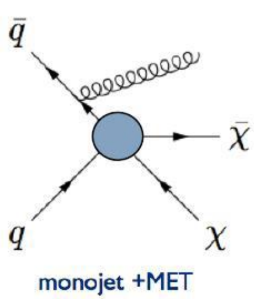


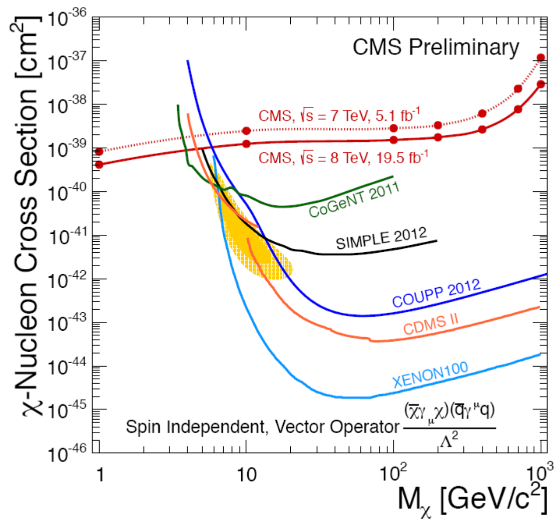
Direct Detection (t-channel)

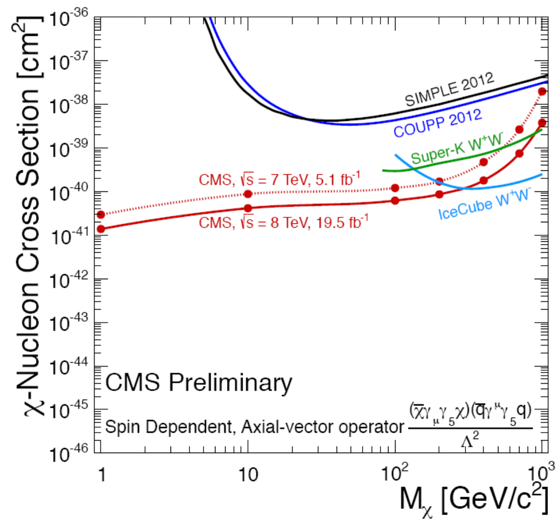


Collider Searches (s-channel)

Dark Matter searches in monojets





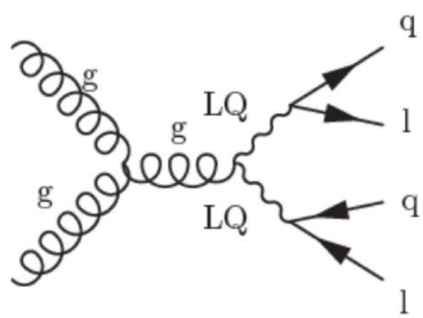


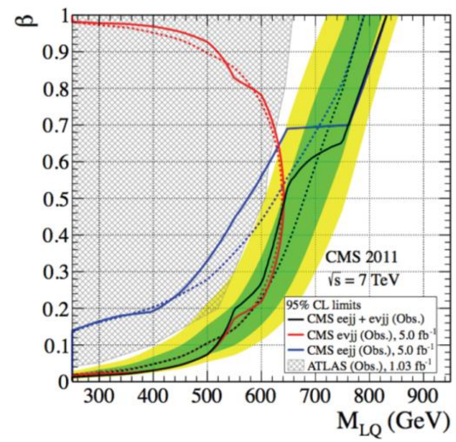
Leptoquark searches

LQs are predicted by composite models, GUT …

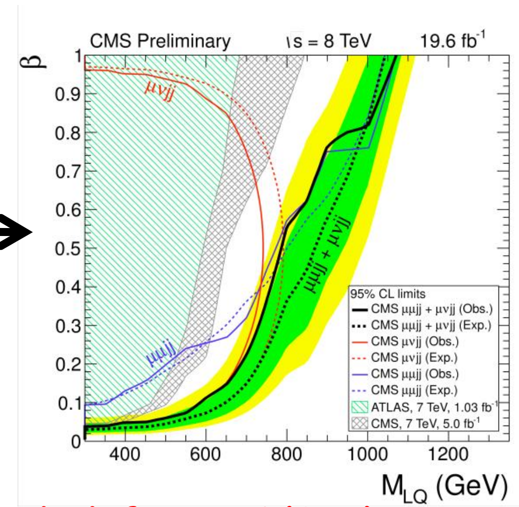
$\beta = BR(LQ \to lq)$

1st and 2d generation LQs





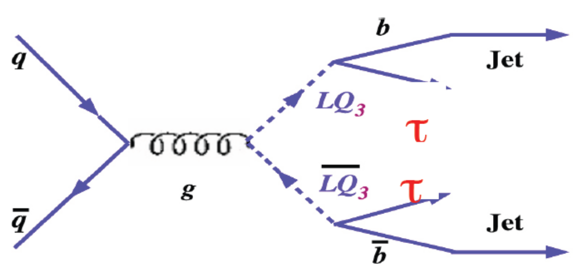
→

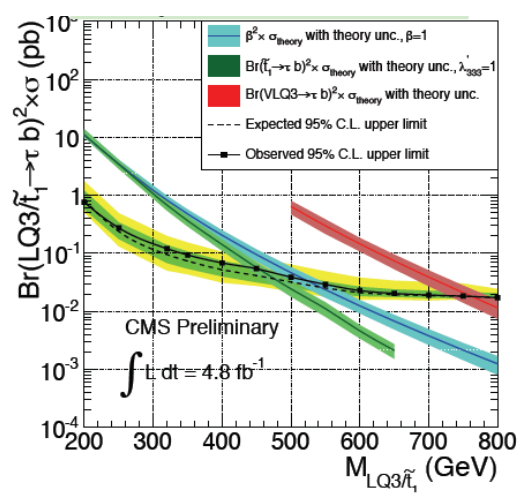


M_{LQ1}> 830 (640) GeV for β=1 (0.5)
M_{LQ2}> 840 (650) GeV for β=1 (0.5)

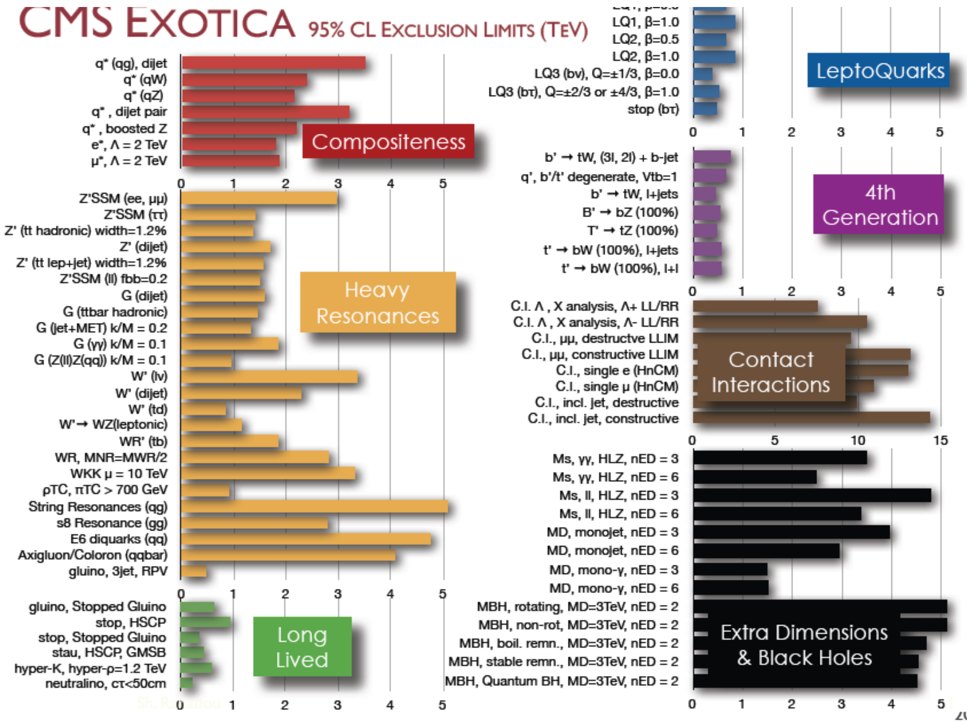
→ **1070 (785) GeV excluded for β=1(0.5)**

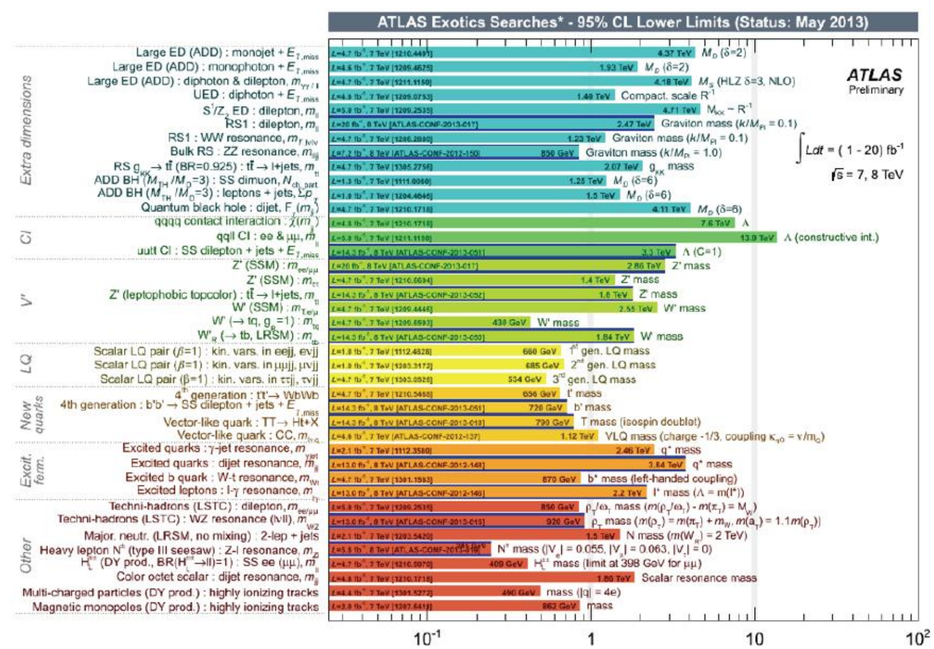
3d generation LQs





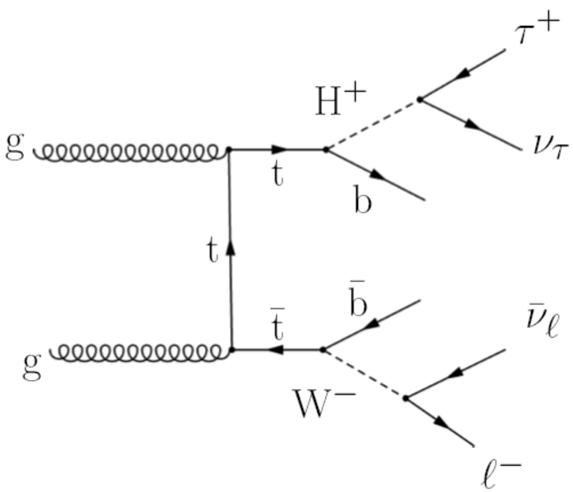
M_{SLQ3}> 525 GeV for β=1
M_{VLQ3}> 763 GeV for β=1



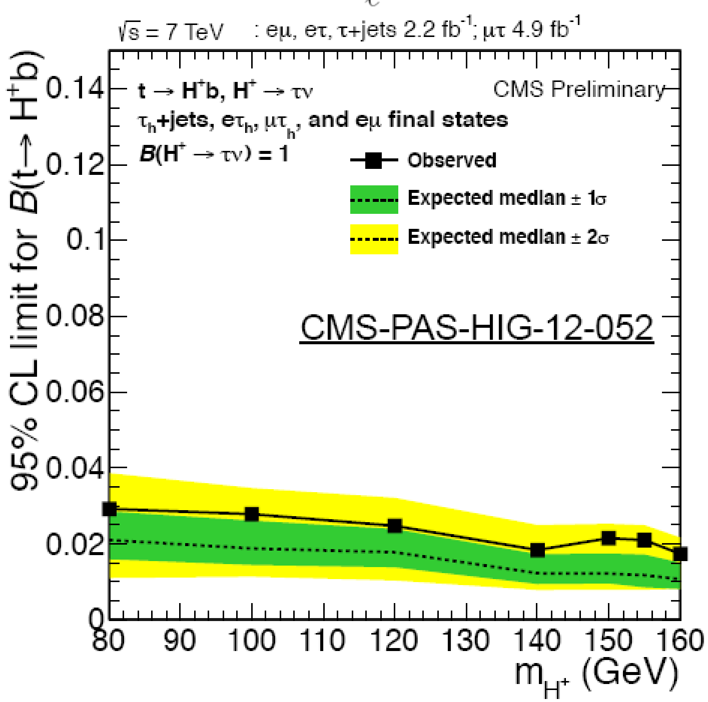


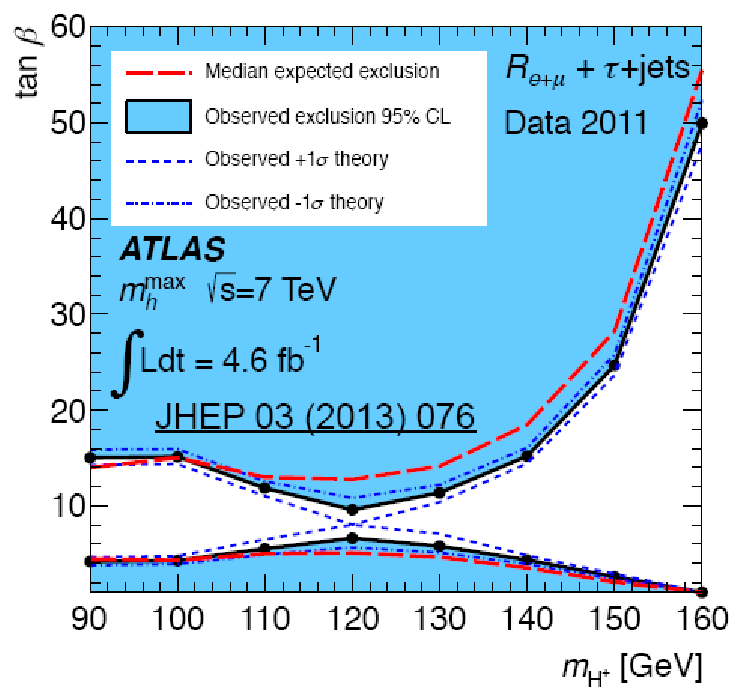
"There are more things in heaven and earth, Horatio, than are dreamt of in your philosophy." -- Hamlet

Charged Higgs searches



For m(H+) < m(t) - m(b)
the decay t→H+b is allowed,
H+→τν dominates

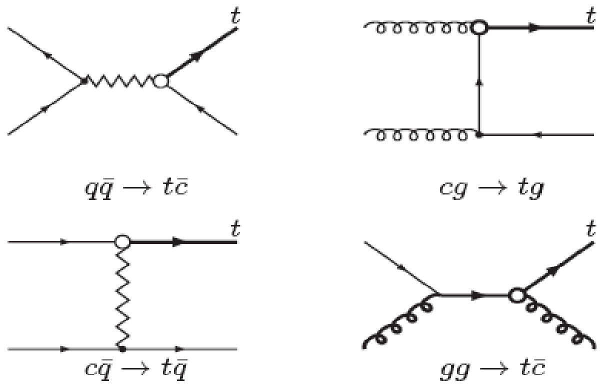


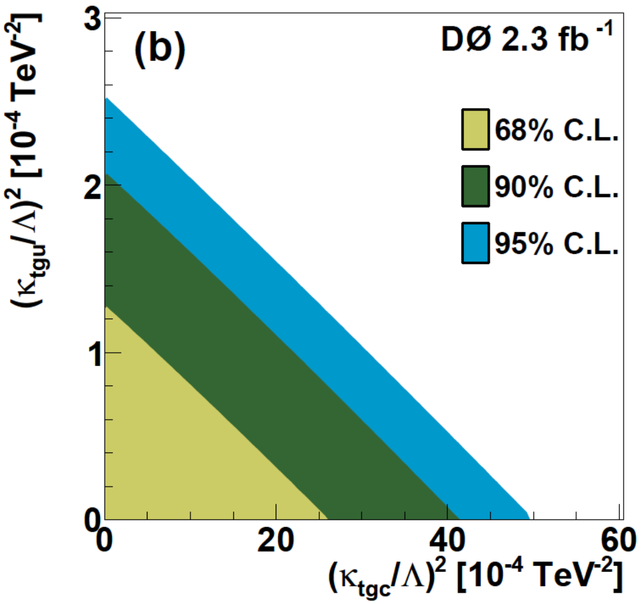


FCNC anomalous top couplings

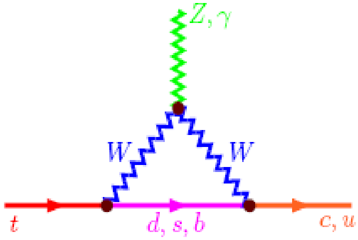
- Couplings: tqg, $tq\gamma$, tqZ, where $q = u, c$

$$\Delta\mathcal{L}^{eff} = \frac{1}{\Lambda}\left[\kappa_{tq}^{\gamma,Z} e\bar{t}\sigma_{\mu\nu}qF^{\mu\nu}_{\gamma,Z} + \kappa_{tq}^{g} g_s\bar{t}\sigma_{\mu\nu}\frac{\lambda^i}{2}qG^{i\mu\nu}\right] + h.c.$$





W' boson and FCNC MC event samples from SingleTop (CompHEP) generator



	SM	two-Higgs	SUSY
$\mathrm{BR}(t \to cg)$	$5 \cdot 10^{-11}$	10^{-6}	10^{-3}
$\mathrm{BR}(t \to c\gamma)$	$5 \cdot 10^{-13}$	10^{-6}	10^{-5}
$\mathrm{BR}(t \to cZ)$	$\sim 10^{-13}$	10^{-9}	10^{-4}

FCNC decays are highly suppressed in SM $t \to qg$, $t \to q\gamma$, $t \to qZ$

To compare FCNC limits from top decays and top production one can express limits on FCNC couplings in term of Br fractions

$$\Gamma(t \to qg) = \left(\frac{\kappa_{tq}^{g}}{\Lambda}\right)^2 \frac{8}{3}\alpha_s m_t^3 \quad , \quad \Gamma(t \to q\gamma) = \left(\frac{\kappa_{tq}^{\gamma}}{\Lambda}\right)^2 2\alpha m_t^3 ,$$

$$\Gamma(t \to qZ)_{\gamma} = \left(|v_{tq}^{Z}|^2 + |a_{tq}^{Z}|^2\right) \alpha\, m_t^3 \frac{1}{4M_Z^2 \sin^2 2\theta_W}\left(1 - \frac{M_Z^2}{m_t^2}\right)^2 \left(1 + 2\frac{M_Z^2}{m_t^2}\right),$$

$$\Gamma(t \to qZ)_{\sigma} = \left(\frac{\kappa_{tq}^{Z}}{\Lambda}\right)^2 \alpha\, m_t^3 \frac{1}{\sin^2 2\theta_W}\left(1 - \frac{M_Z^2}{m_t^2}\right)^2 \left(2 + \frac{M_Z^2}{m_t^2}\right)$$

Expectations:

$t \to$	Tevatron Run II	LHC decay	LHC production	ILC
$g\,q$	0.06%	1.6×10^{-3}	1×10^{-5}	–
$\gamma\,q$	0.28%	2.5×10^{-5}	3×10^{-6}	4×10^{-6}
$Z\,q$	1.3%	1.6×10^{-4}	1×10^{-4}	2×10^{-4}

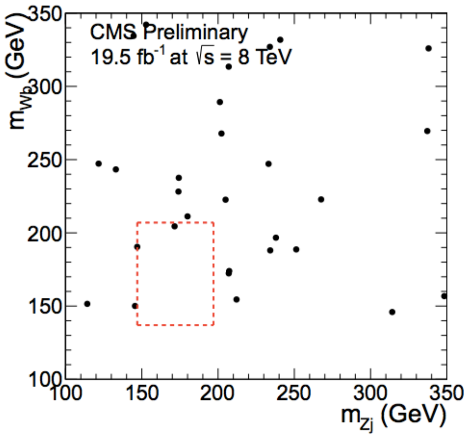
CDF:

$$\mathcal{B}(t \to u + g) < 3.9 \cdot 10^{-4}$$
$$\mathcal{B}(t \to c + g) < 5.7 \cdot 10^{-3}$$

D0:

LHC limits are about to come!

	tgu	tgc
Cross section	0.20 pb	0.27 pb
κ_{tgf}/Λ	0.013 TeV^{-1}	0.057 TeV^{-1}
$\mathcal{B}(t \to qg)$	2.0×10^{-4}	3.9×10^{-3}



CMS limit: B(t -> Zq) < 0.07% @ 95%C.L.

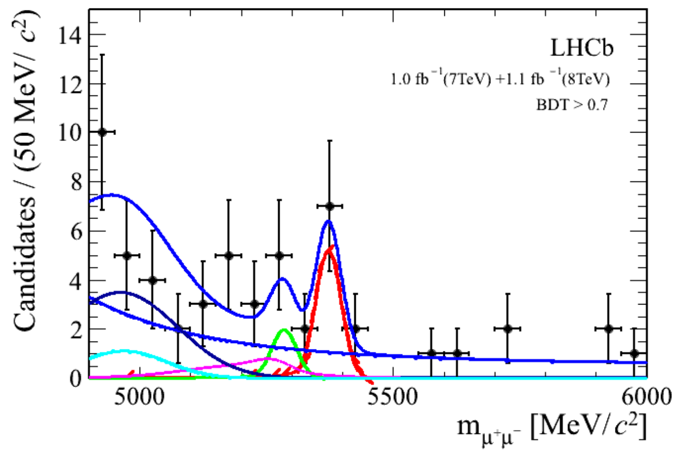
Many interesting new results

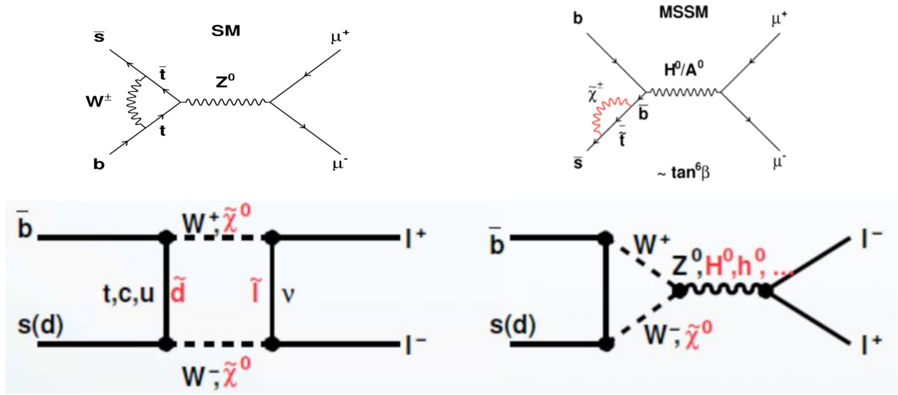
Indirect search for BSM physics – the main goal of the LHCb experiment.

Rare $B_s \to \mu\mu$ decay

LHCb:

$$Br(B_s^0 \to \mu\mu) = (3.2^{+1.4}_{-1.2}(\text{stat})^{+0.5}_{-0.3}(syst)) \times 10^{-9}$$





$B_s^0 \to \mu\mu$ | $B^0_{(s)} \to h^+h^-$ | $B^{0(+)} \to \pi^{0(+)}\mu^+\mu^-$

$B^0 \to \mu\mu$ | $B^0 \to \pi^-\mu^+\nu_\mu$ | combinatorial background

CMS:

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.0^{+1.0}_{-0.9}) \times 10^{-9}$$

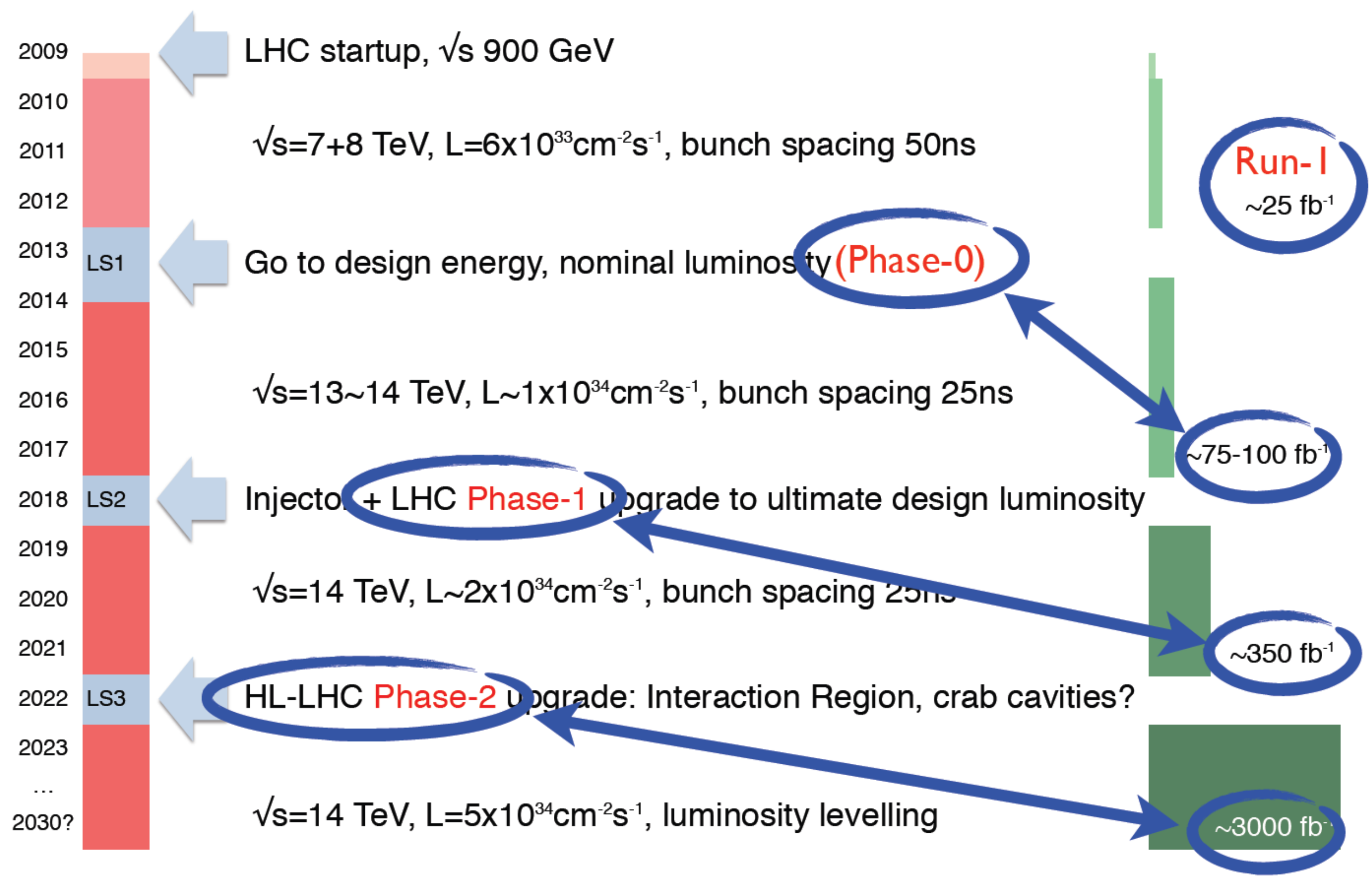
Observed decay rate is compatible with the SM expectation:

$$\text{Br}(B_s \to \mu\mu) = (3.53 \pm 0.38) \times 10^{-9}$$

“It doesn't matter how beautiful your theory is, it doesn't matter how smart you are. If it doesn't agree with experiment, it's wrong”.

Richard P. Feynman

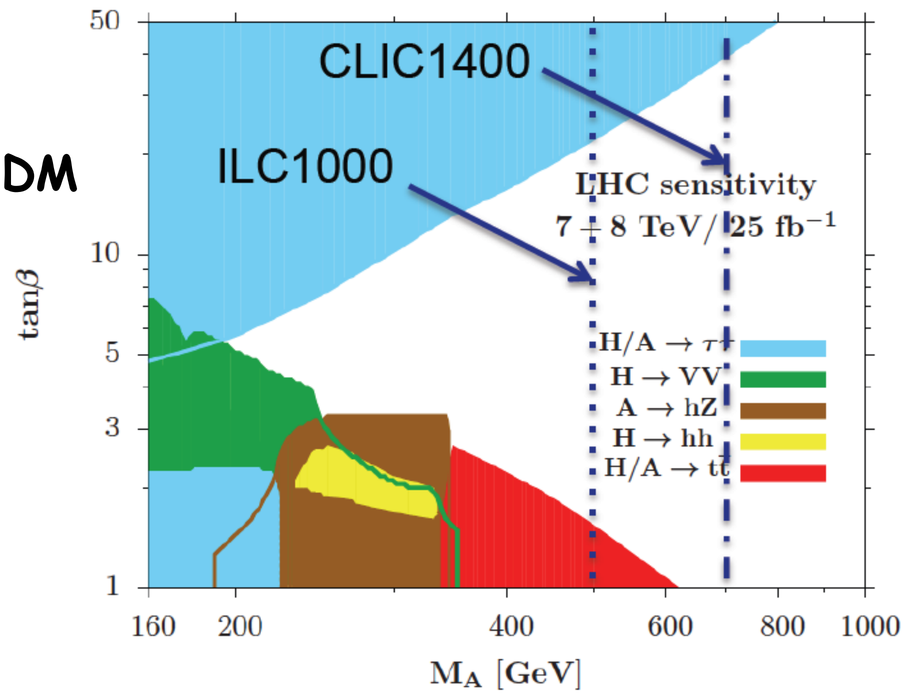
R.Heuer 2013

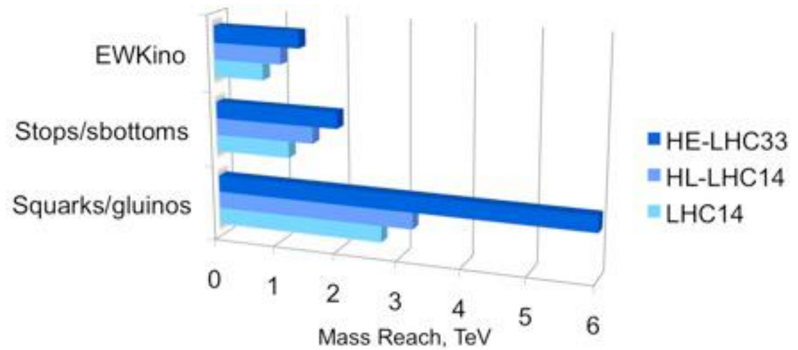

2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
...
2030?
LS1
LS2
LS3
LHC startup, √s 900 GeV
√s=7+8 TeV, L=6x10^33 cm^-2 s^-1, bunch spacing 50ns
Go to design energy, nominal luminosity (Phase-0)
√s=13~14 TeV, L~1x10^34 cm^-2 s^-1, bunch spacing 25ns
Injector + LHC Phase-1 upgrade to ultimate design luminosity
√s=14 TeV, L~2x10^34 cm^-2 s^-1, bunch spacing 25ns
HL-LHC Phase-2 upgrade: Interaction Region, crab cavities?
√s=14 TeV, L=5x10^34 cm^-2 s^-1, luminosity levelling
Run-I
~25 fb^-1
~75-100 fb^-1
~350 fb^-1
~3000 fb^-1

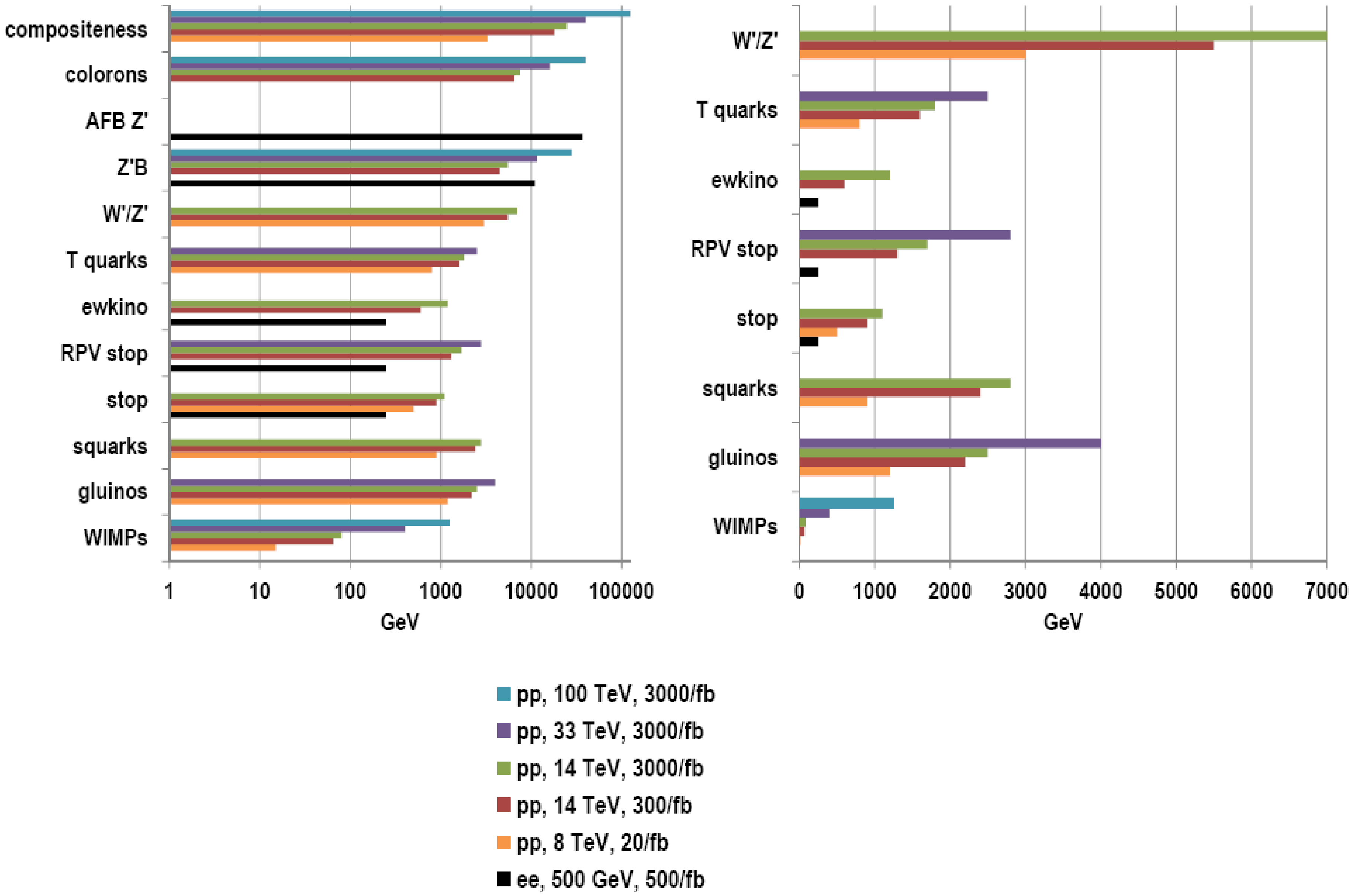
Expected precisions for Higgs couplings

Facility	LHC	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC	TLEP (4 IPs)
$\sqrt{s}$ (GeV)	14,000	14,000	250/500	250/500	250/500/1000	250/500/1000	350/1400/3000	240/350
$\int \mathcal{L}dt$ (fb^{-1})	300/expt	3000/expt	250+500	1150+1600	250+500+1000	1150+1600+2500	500+1500+2000	10,000+2600
κ_γ	5 − 7%	2 − 5%	8.3%	4.4%	3.8%	2.3%	−/5.5/<5.5%	1.45%
κ_g	6 − 8%	3 − 5%	2.0%	1.1%	1.1%	0.67%	3.6/0.79/0.56%	0.79%
κ_W	4 − 6%	2 − 5%	0.39%	0.21%	0.21%	0.13%	1.5/0.15/0.11%	0.10%
κ_Z	4 − 6%	2 − 4%	0.49%	0.24%	0.44%	0.22%	0.49/0.33/0.24%	0.05%
κ_ℓ	6 − 8%	2 − 5%	1.9%	0.98%	1.3%	0.72%	3.5/1.4/<1.3%	0.51%
κ_d	10 − 13%	4 − 7%	0.93%	0.51%	0.51%	0.31%	1.7/0.32/0.19%	0.39%
κ_u	14 − 15%	7 − 10%	2.5%	1.3%	1.3%	0.76%	3.1/1.0/0.7%	0.69%

2HDM







Very simplified plot does not show holes in searches

Discovering of new Higgs-like state

"Theorist"

"Experimentalist"

Not discovering anything else → ???????

New phases of the LHC and new colliders !!!!!

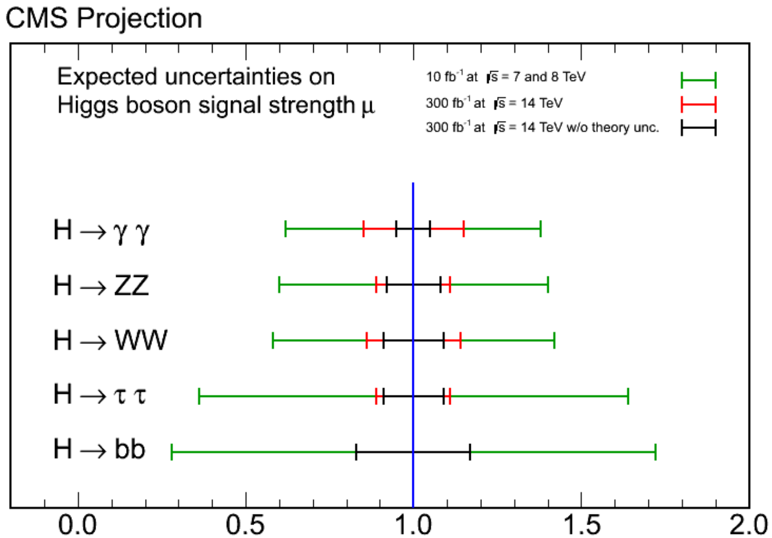
LHC (phase 0,1), HL-LHC (phase 2), HE-LHC, VLHC, ILC, CLIC

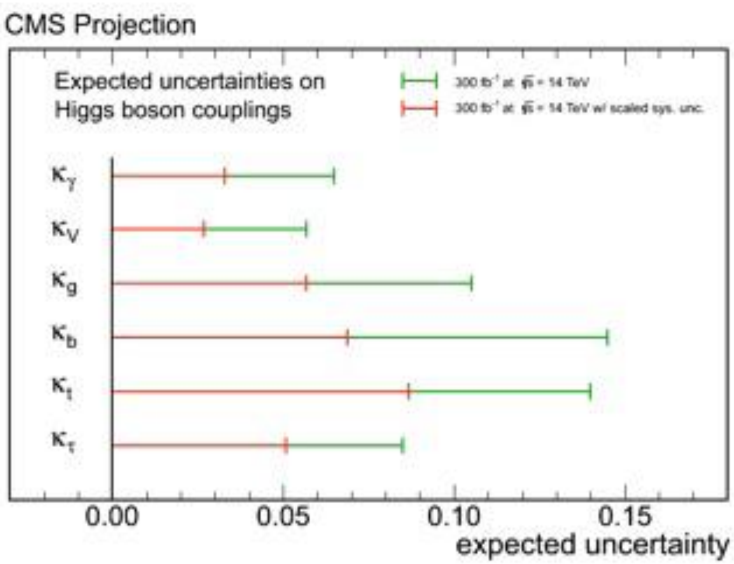
We are in a very beginning of exploration of the Terascale !

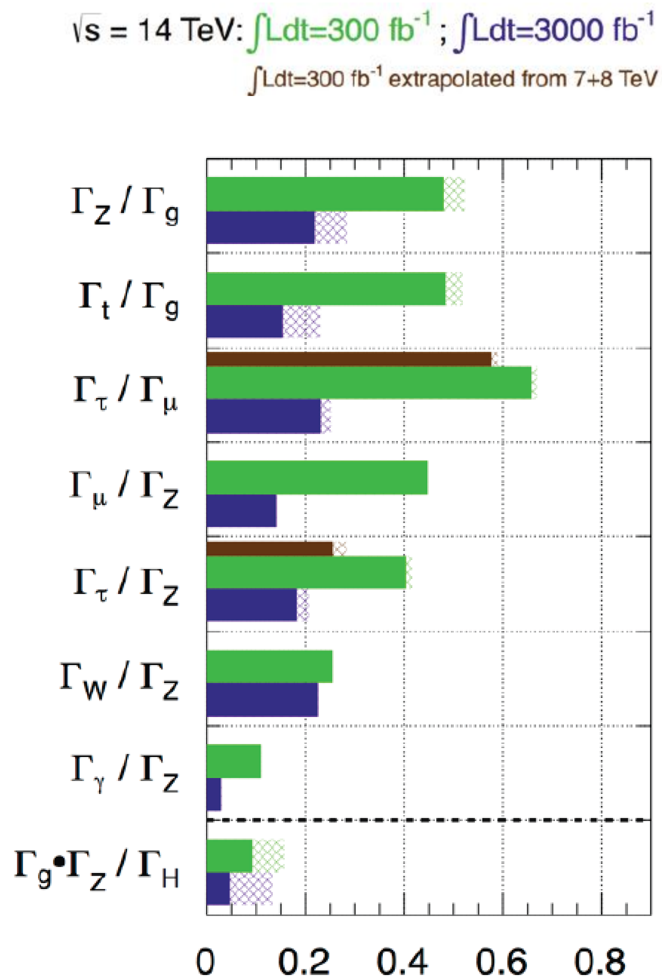
BACKUP SLIDES

Expected uncertaities in CMS

ATLAS





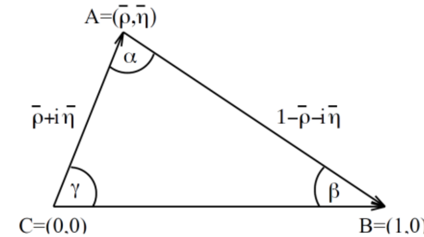


Indirect search for BSM physics – the main goal of the LHCb experiment.

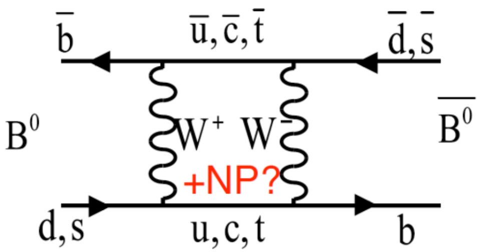
Flavor & CP in CKM matrix

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

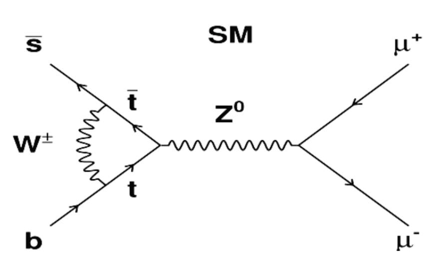
One of unitarity triangles $V_{ub}V_{ud}^* + V_{cb}V_{cd}^* + V_{tb}V_{td}^* = 0$

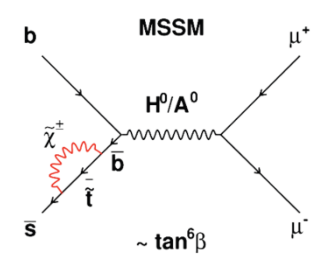


Two body B-meson hadronic decays (B_d->J/Ψ K^0_S...) and phase of B0 oscillations for CP violation studies



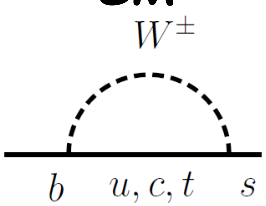
Deviations in Br fractions in rare b-decays



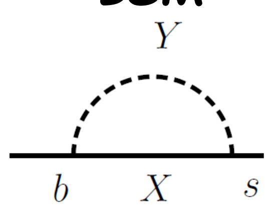


A-penguin, where A is added in all places radiative boson, A=γ,Z,g,h^0

SM



BSM



Key measurements: rare B-meson decays (B_S->μμ, B_S->K^*μμ, B_d->K^*ee, B_S->φγ)