Physics at the LHC. Status and Perspectives

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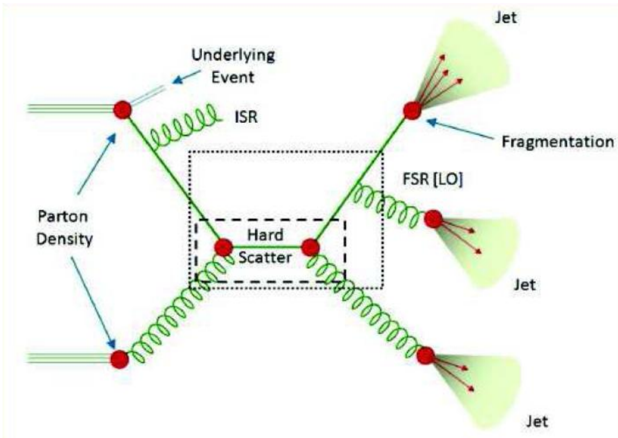
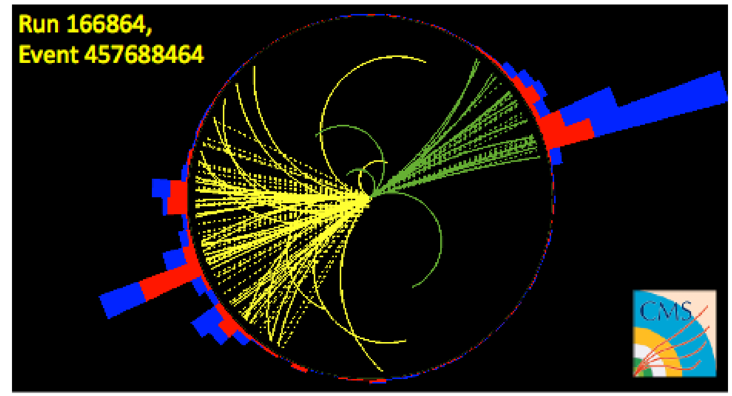
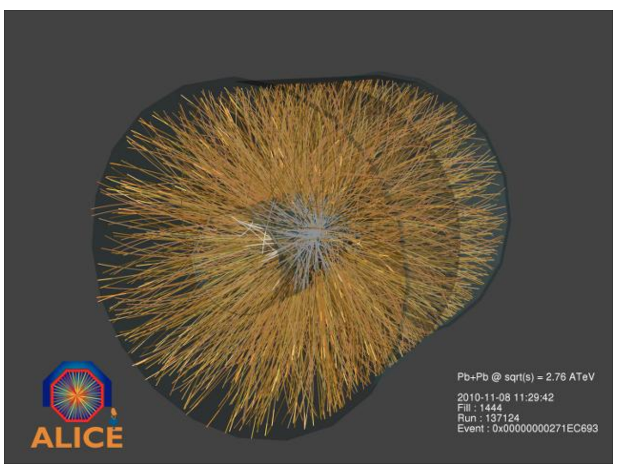
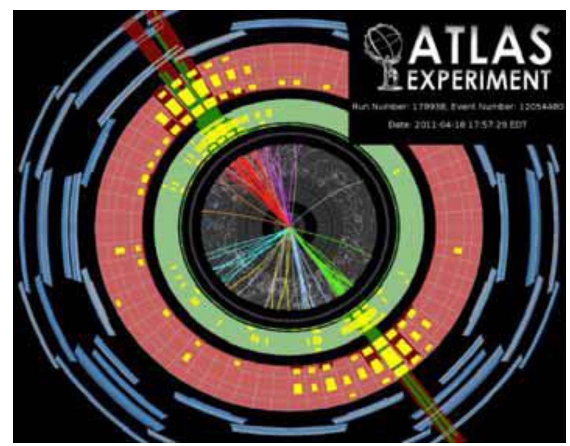
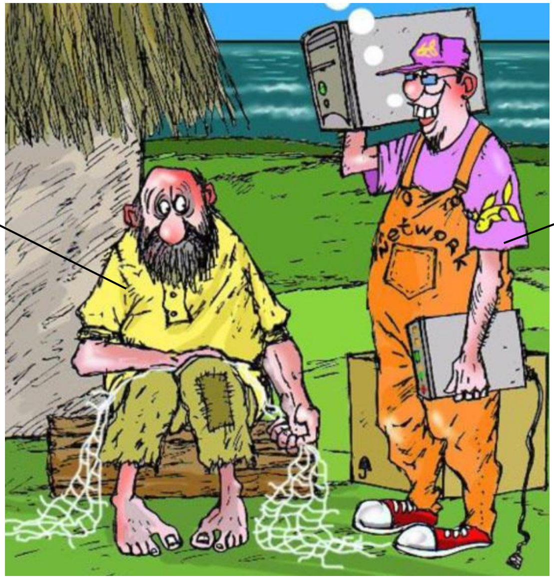








"Theorist"



"Experimentalist"

What did we know before the LHC start?
Whether or not the LHC energy scale is an appropriate one?

What one can say after first LHC results?

What are expectations?

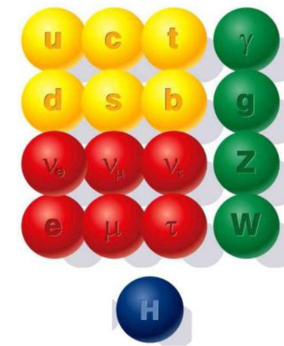
SU(3)c x SU(2)$_L$ x U(1)$_Y$

$$\mathcal{L}_{SM} = -\frac{1}{4}G^a_{\mu\nu}G_a^{\mu\nu} - \frac{1}{4}W^a_{\mu\nu}W_a^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu}$$

$$+\bar{L}_i\, iD_\mu\gamma^\mu\, L_i + \bar{e}_{Ri}\, iD_\mu\gamma^\mu\, e_{R_i}$$

$$+\bar{Q}_i\, iD_\mu\gamma^\mu\, Q_i + \bar{u}_{Ri}\, iD_\mu\gamma^\mu\, u_{R_i} + \bar{d}_{Ri}\, iD_\mu\gamma^\mu\, d_{R_i}$$

$$+ L_H$$



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

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

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

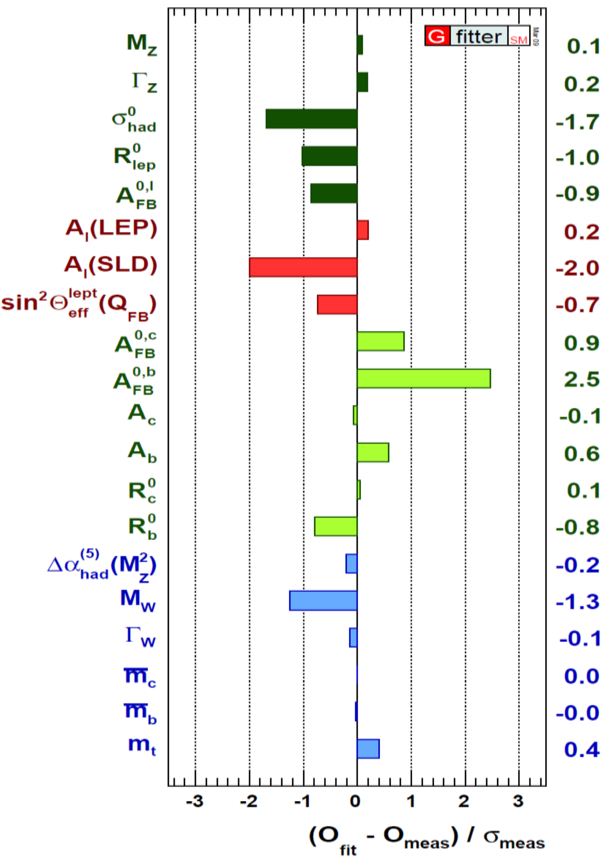
SM – quantum field theory describing strong and electroweak forces is based on few fundamental principles:
gauge invariance with lowest dimension operators;
chiral structure of fermions ((V-A) charged currents);
Higgs mechanism of spontaneous symmetry breaking

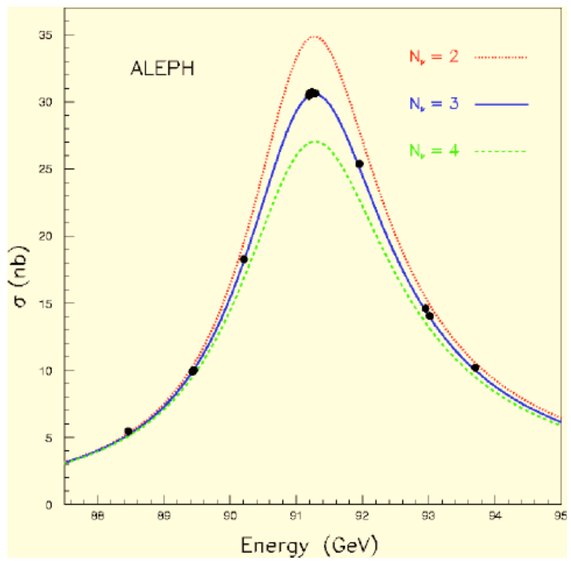
A very elegant theoretical construction!

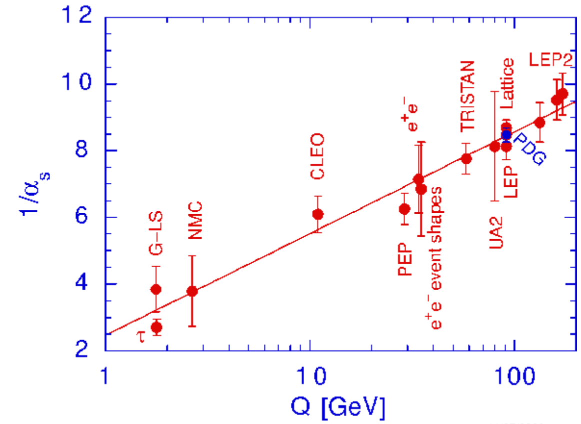
Why not just find the Higgs particle, for completeness, and declare that particle physics is closed?

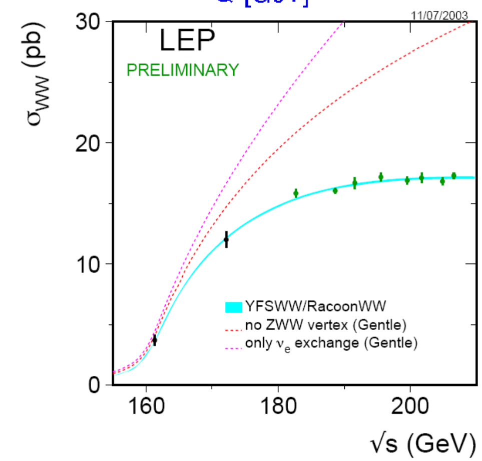
Standard Model – the main intellectual achievement for about last 50 years, a result of many theoretical and experimental studies

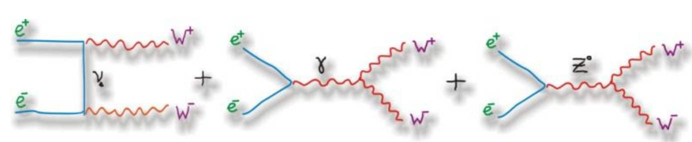
SM: $SU(3)_c \times SU(2)_L \times U(1)_Y$



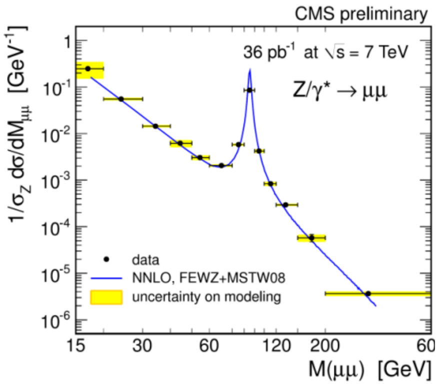


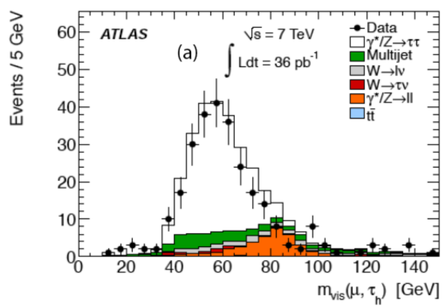


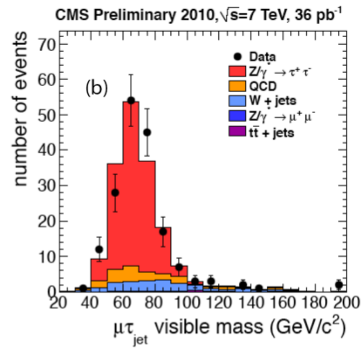


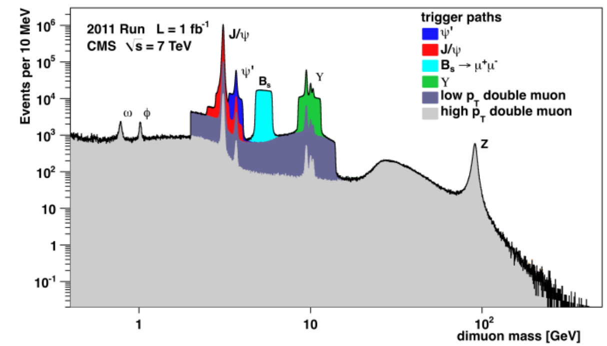


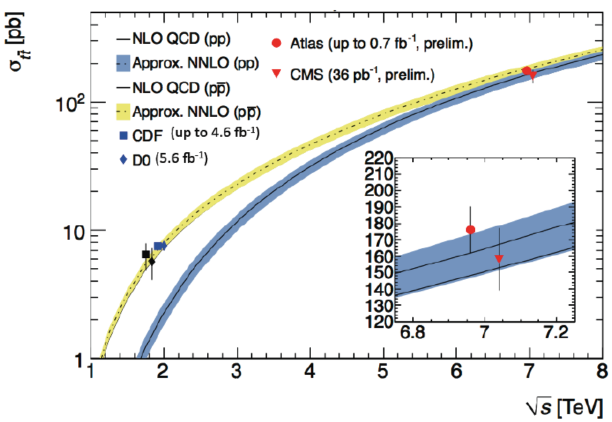
Rediscovery of the SM: W, Z, Top …. are found
WZ, Wgamma, ZZ, Top pair, single Top … are measured

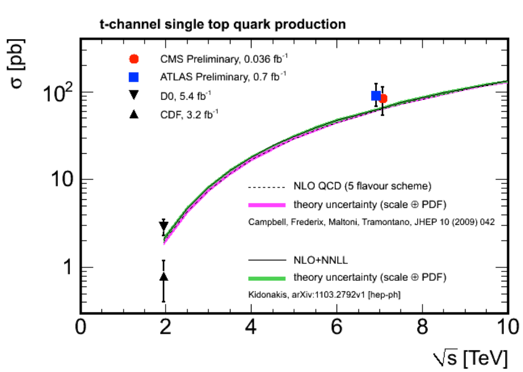


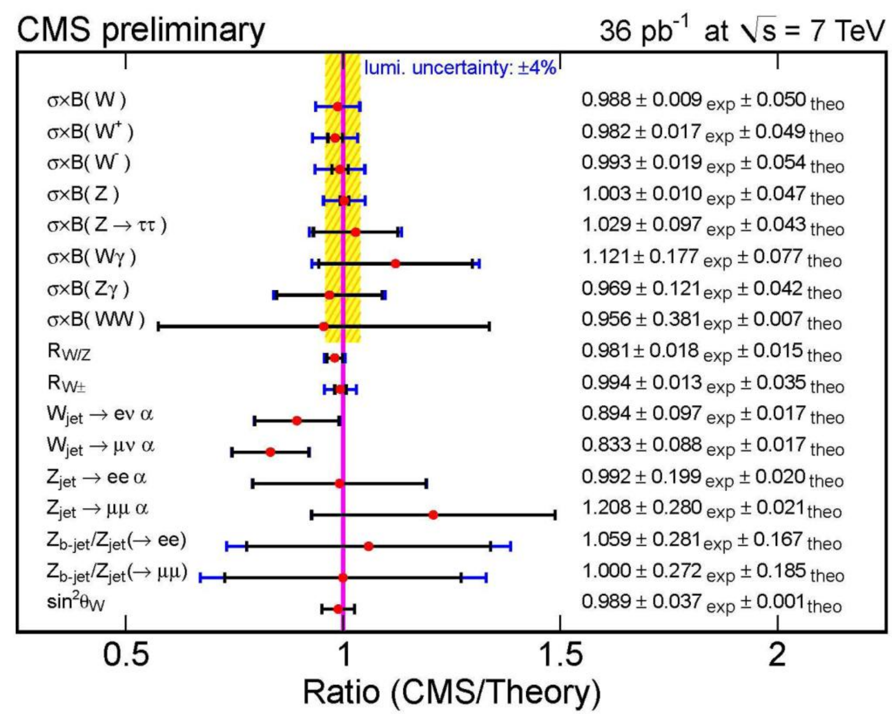








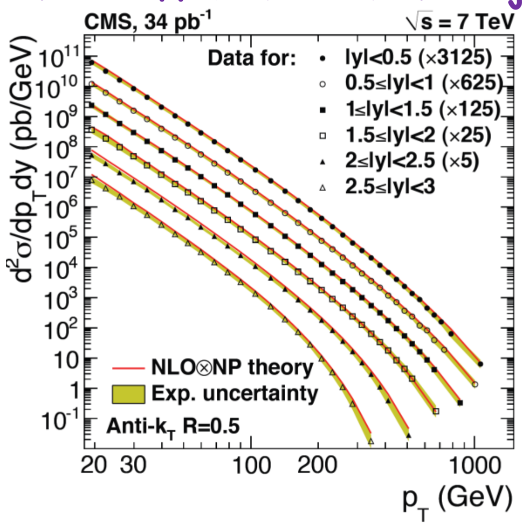




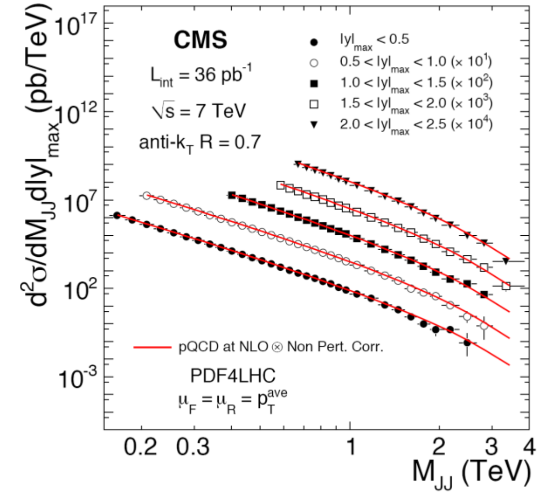
All in an agreement with the SM

New remarkable QCD results in various kinematical regions

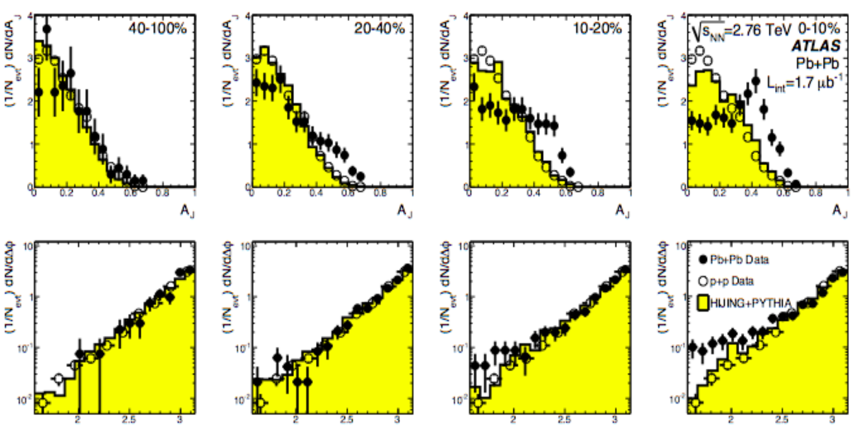
Double-differential inclusive jet production

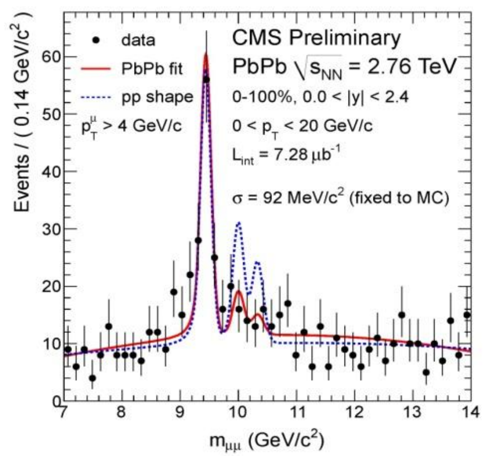


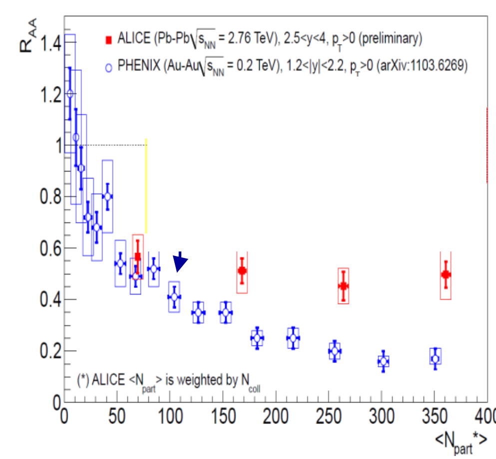
Double-differential inclusive dijet production



First LHC exiting heavy ion run results:
elliptic flow, ridge-effect, J/Ψ and high-pT hadron suppression; direct observation of jet quenching, suppression of exited Y-states



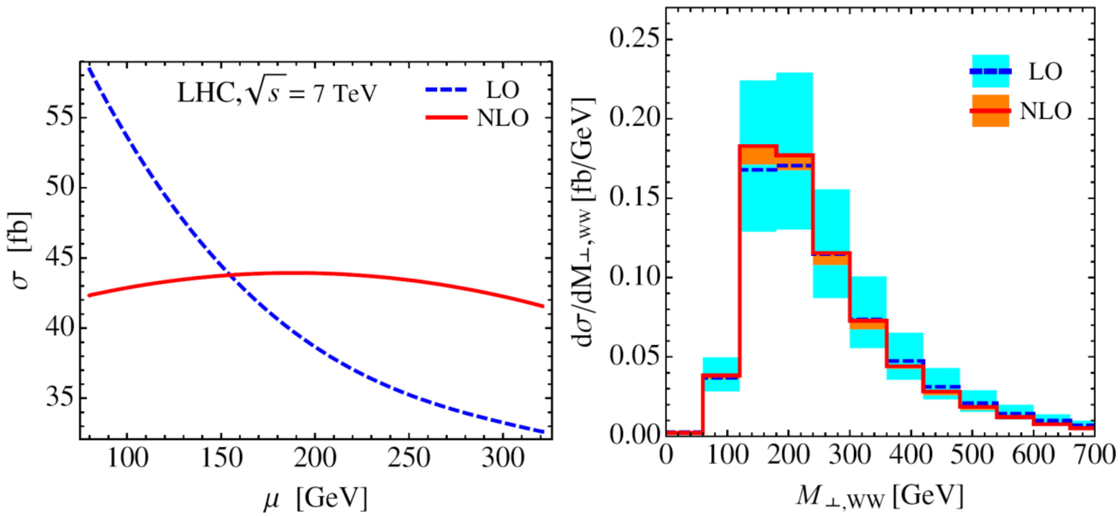




Significant theoretical progress in NLO and NNLO computations:
much less scale dependence
much better control of distribution shapes

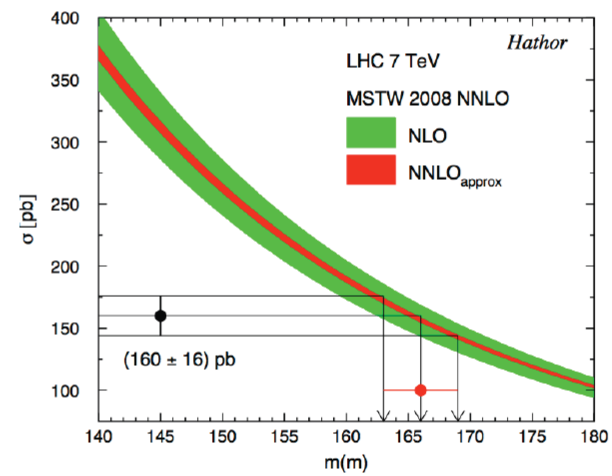
$W^+W^- + jj$

Melia, Melnikov, Rontsch, Zanderighi



Top pair

Kidonakis



$$pp \to t\bar{t}b\bar{b} \qquad pp \to W(Z) + 3j$$

$$pp \to t\bar{t}jj \qquad pp \to W^+W^-b\bar{b}$$

$$pp \to W(Z) + 4j \quad pp \to W^+W^+jj$$

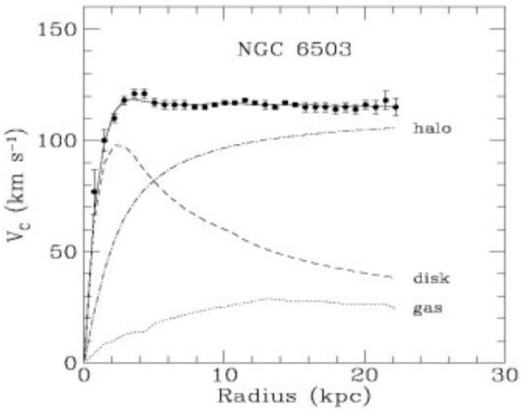
Bern, Dixon, Kosower, Berger, Forde, Maitre, Febres-Cordero, Gleisberg, Papadopoulos, Ossola, Pittau, Czakon, Worek, Melnikov, Bevilacqua, Ellis, Kunszt, Giele, Zanderighi, Melia, Rountsh, Denner, Dittmaier, Pozzorini, Kallweit ….

There is a number of facts which needs to be explained

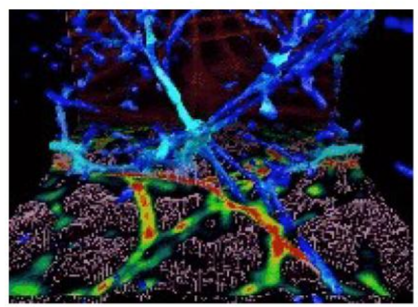
1. EW symmetry is broken – photon is massless, W and Z are massive particles
Fermions have very much different masses
(Mtop ≈ 172 GeV, Me ≈ 0.5 MeV, $\Delta M\nu \approx 10^{-3}$ eV)

2. Dark Matter exists in the Universe

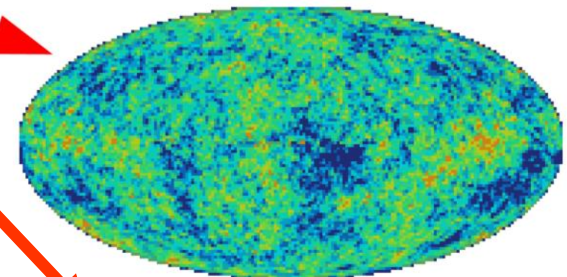
Rotation curves of galaxies



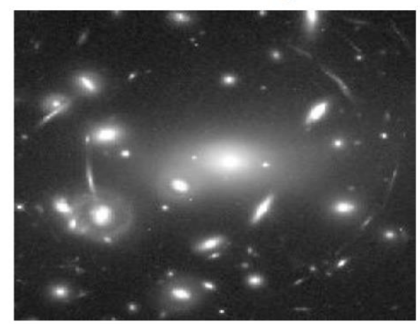
Large Scale Structure



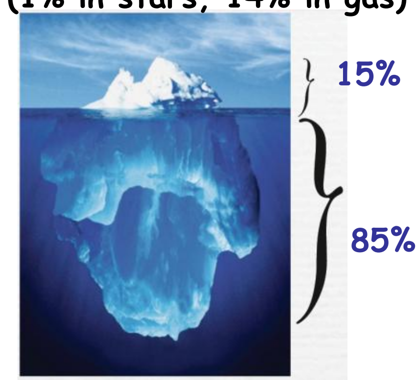
CMB



Lensing



Barionic matter
(1% in stars, 14% in gas)



Dark unknown matter

3. (g-2)μ (about 3.5 σ)   4. Neutrino oscillations

5. Particle – antiparticle asymmetry in the Universe,
CP violation

6. Gravity (no connection to EW?). Why gravity is so weak?
What is dark energy? Why Λ is so small?

In addition 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?

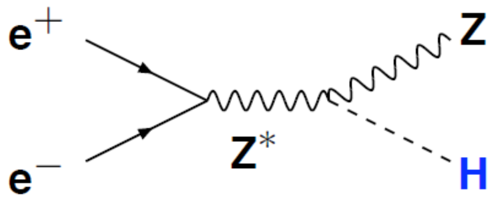
To which accuracy the CPT symmetry is exact?

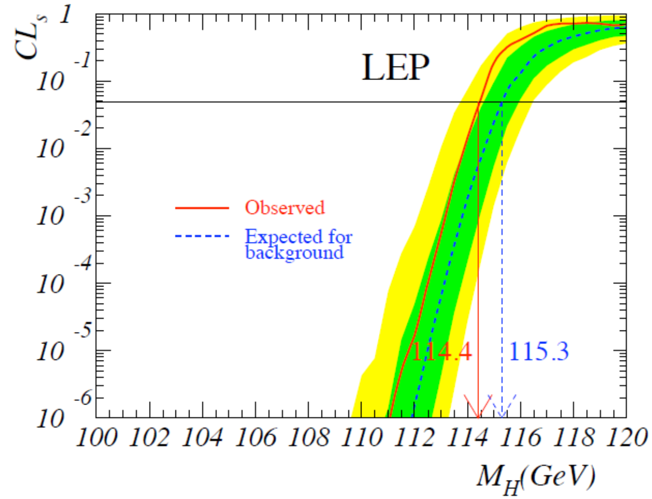
....

What is a scale for possible “new physics” ?

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

1. Direct serches:

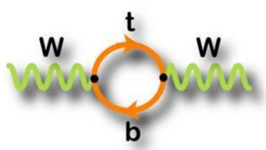


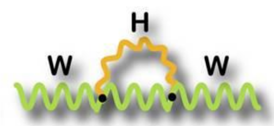


M_H > 114.4 GeV 95% C.L.

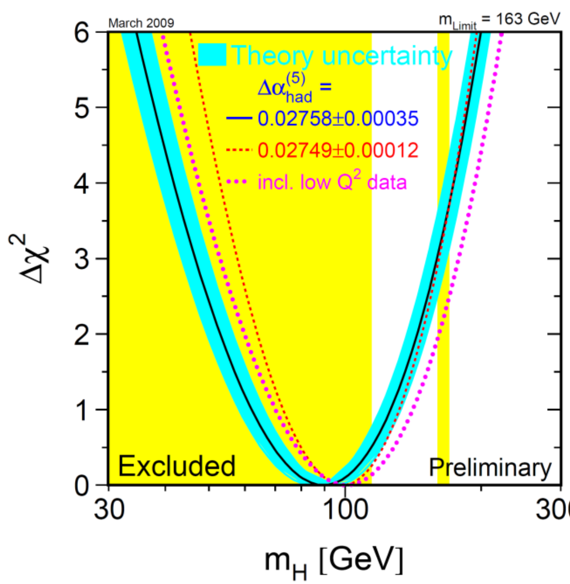
Tevatron (in gluon fusion with decay to WW):
Excluded region
M_H : 160-170 GeV

2. From loop corrections:

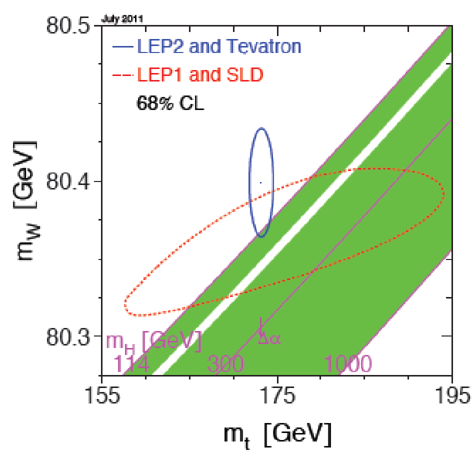




$$(\Delta r)_{\text{top}} \approx -\frac{3G_F m_t^2}{8\sqrt{2}\pi^2}\frac{1}{t_W^2} \qquad (\Delta r)_{\text{Higgs}} \approx \frac{11 G_F M_Z^2 c_W^2}{24\sqrt{2}\pi^2} \ln\frac{m_h^2}{M_Z^2}$$



M_H < 158 GeV 95% C.L.



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

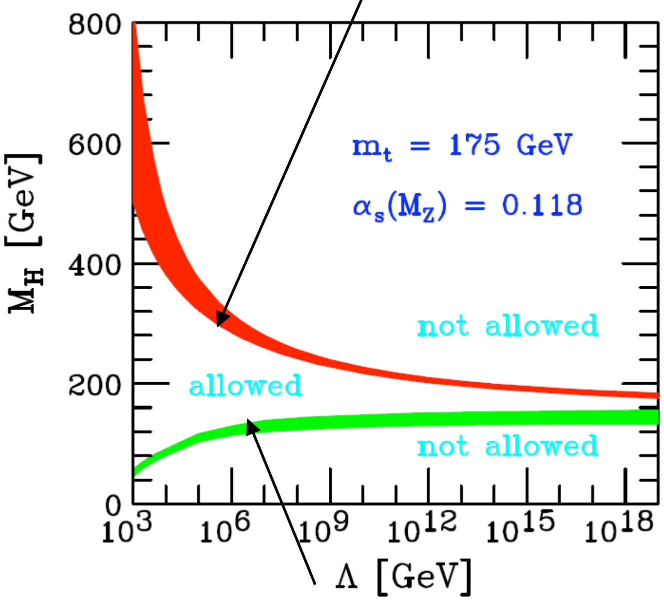
$\mathrm{Im}(a_l) = |a_l|^2$ $\qquad |\mathrm{Re}(a_l)| \leq \frac{1}{2}$

$M_H \lesssim 710$ 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)



$\Lambda_C \sim 10^3$ GeV $\Rightarrow$

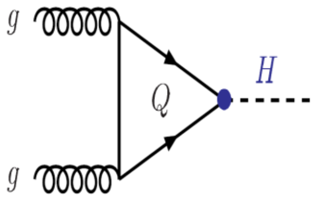
70 GeV $\lesssim$ M_H $\lesssim$ 700 GeV

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

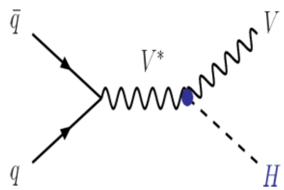
130 GeV $\lesssim$ M_H $\lesssim$ 180 GeV

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

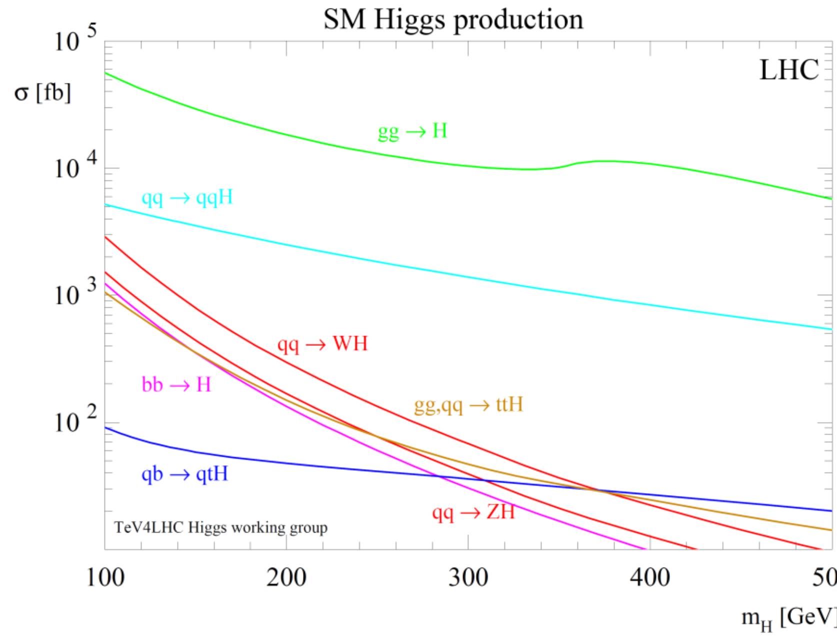
4 main SM Higgs production modes at LHC

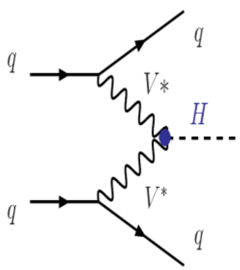


Gluon-gluon fusion

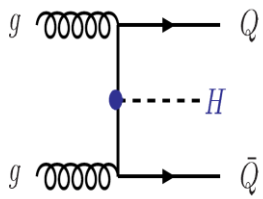


W/Z-Higgs associated





Vector boson fusion



t t-bar Higgs associated

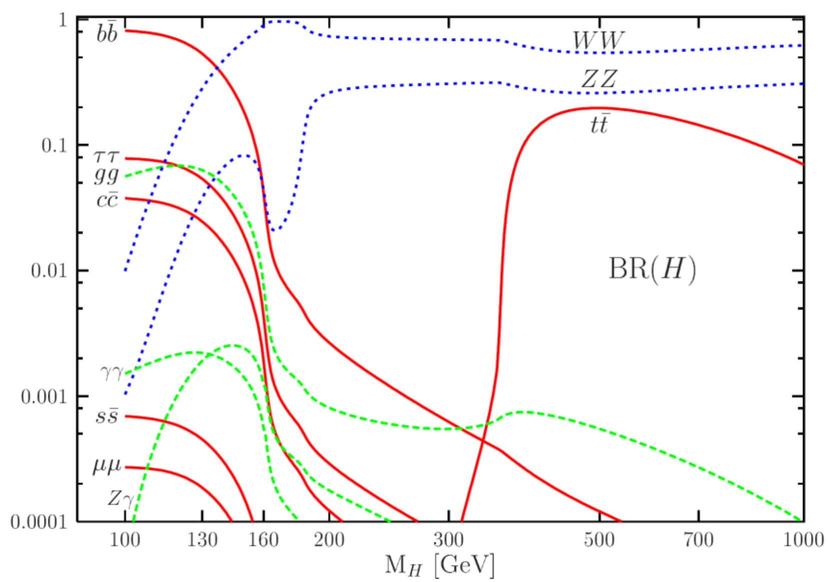
Main decay modes

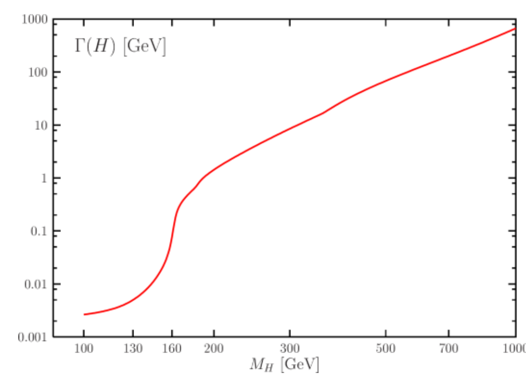
$M_H \lesssim 130$ GeV:

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

$M_H \gtrsim 130$ GeV:

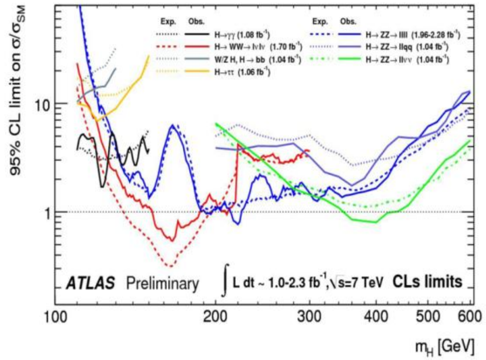
- $H \to WW^*, ZZ^*$ up to $\gtrsim 2M_W$
- $H \to WW, ZZ$ above (BR $\to \frac{2}{3}, \frac{1}{3}$)
- $H \to t\bar{t}$ for high M_H; BR $\lesssim 20\%$.

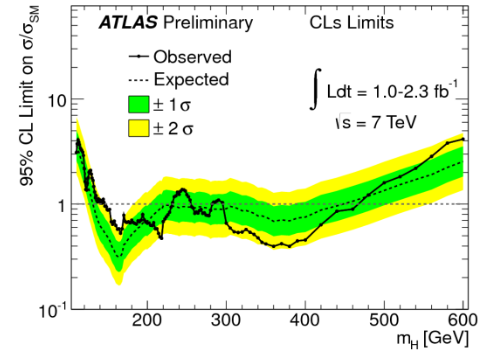


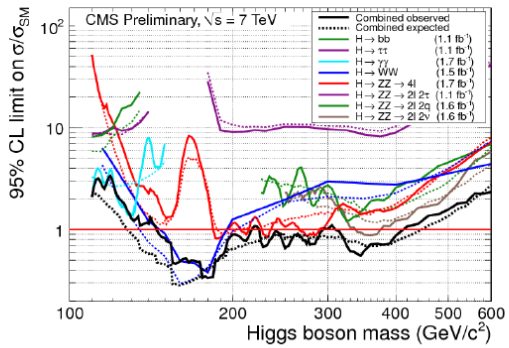


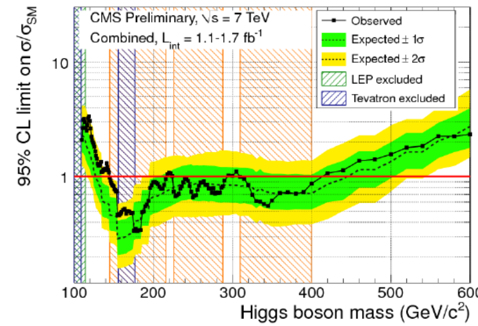
Total width is small for light and large for heavy Higgs

LHC limits on Higgs mass

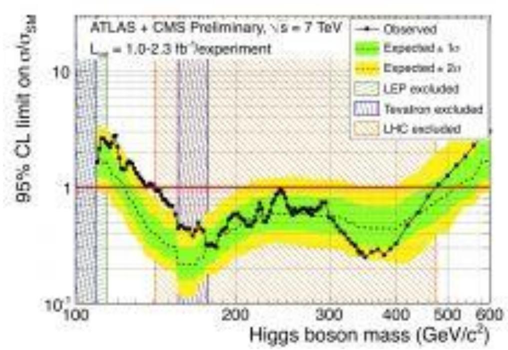








Excluded either by ATLAS or CMS 145-466 GeV (except 288-296 GeV) 95%CL

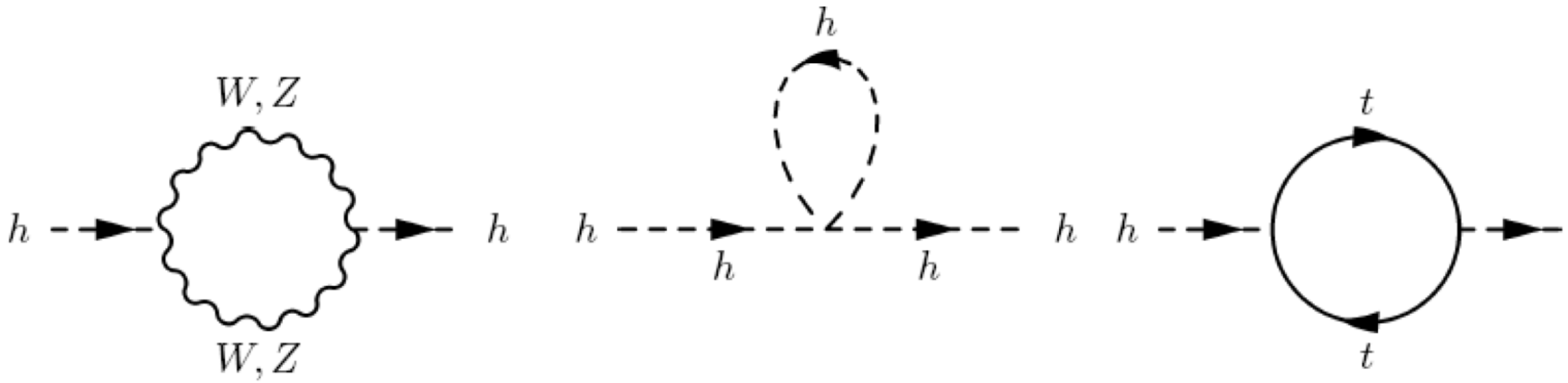


CMS and ATLAS combined result for MH :
141-476 GeV is excluded

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

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

Loop corrections to the Higgs mass



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

δm_H < 160 GeV (95% CL limit on SM Higgs) $\Lambda \sim 1$ 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…

Higgs-like state is found

But which Higgs?-
Fundamental or composite?
SM Higgs, or SUSY Higgses, or Pseudo-Goldstone boson of an enlarged symmetry, or fifth component of a gauge boson on a brane in models with extra dimensions, or …?
One doublet, two doublets, many doublets?

Only SM Higgs – possible but rather unlikely
(what to do with a little hierarchy problem?)

No Higgs-like state is found

Does not exist at all
Invisible in SM decay modes

We are in a very beginning of a long story !

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

Mostly discussed BSM models pretend to provide

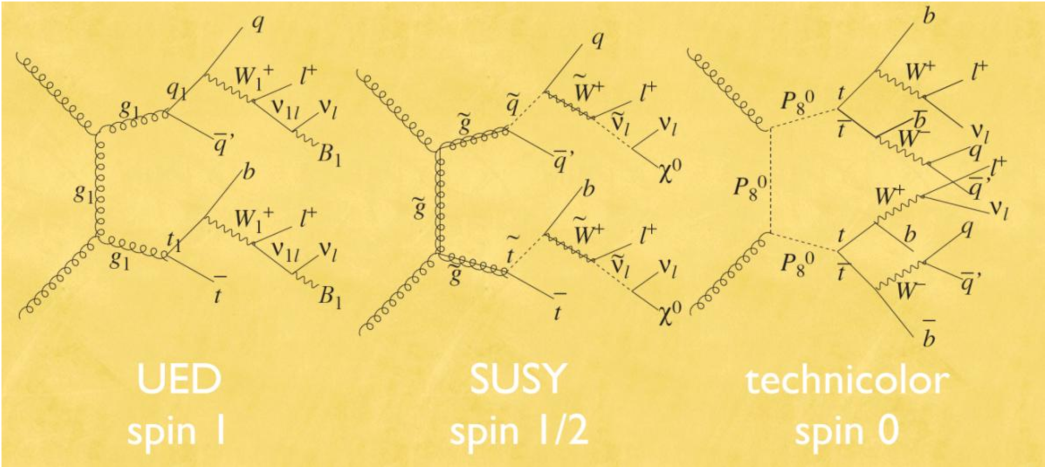
(at least partly)

- a stable with respect to quantum corrections EWSB mechanism
- a candidate for Dark Matter
- a source for amount of CP violation to be enough for bariogenesis

and

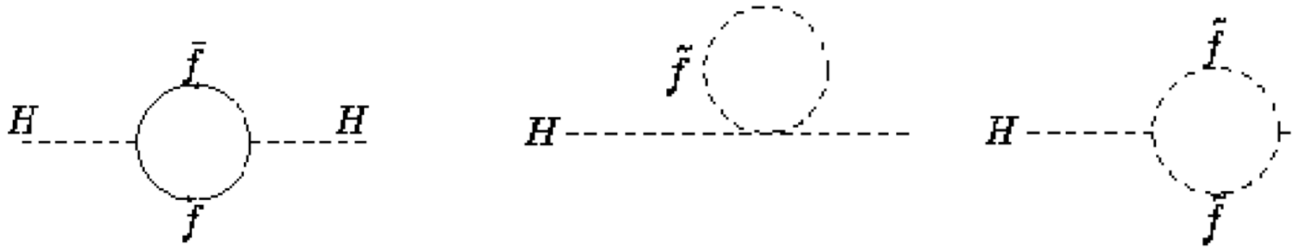
- include gravity if possible

Supersymmetric models
(MSSM, NMSSM…)
Models with extra space dimensions
(ADD, RS, UED …)
Models with new strong dynamics
(latest technicolor variants, Little Higgs…)



SUSY Fermion degrees of freedom ←→ boson degrees of freedom

1. Cancellation of Λ^2 dependence



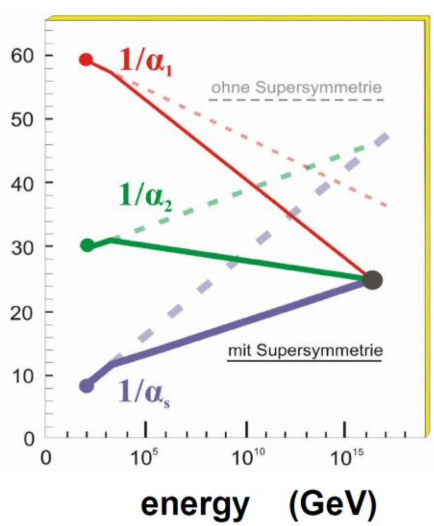
=>

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

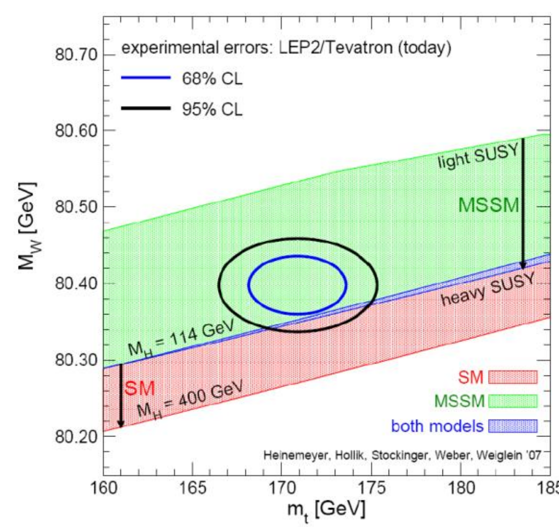
M_H is protected!

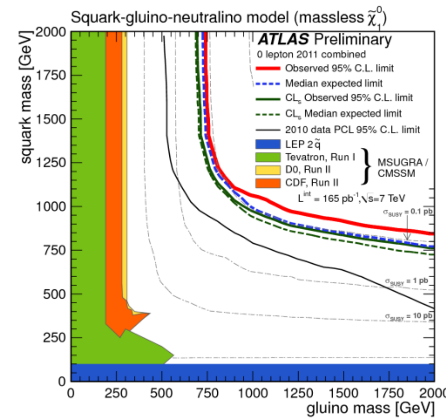
2. Lightest SUSY particle is stable (if R-parity) – very good Dark Matter candidate

3. Unification of couplings in contrast to SM



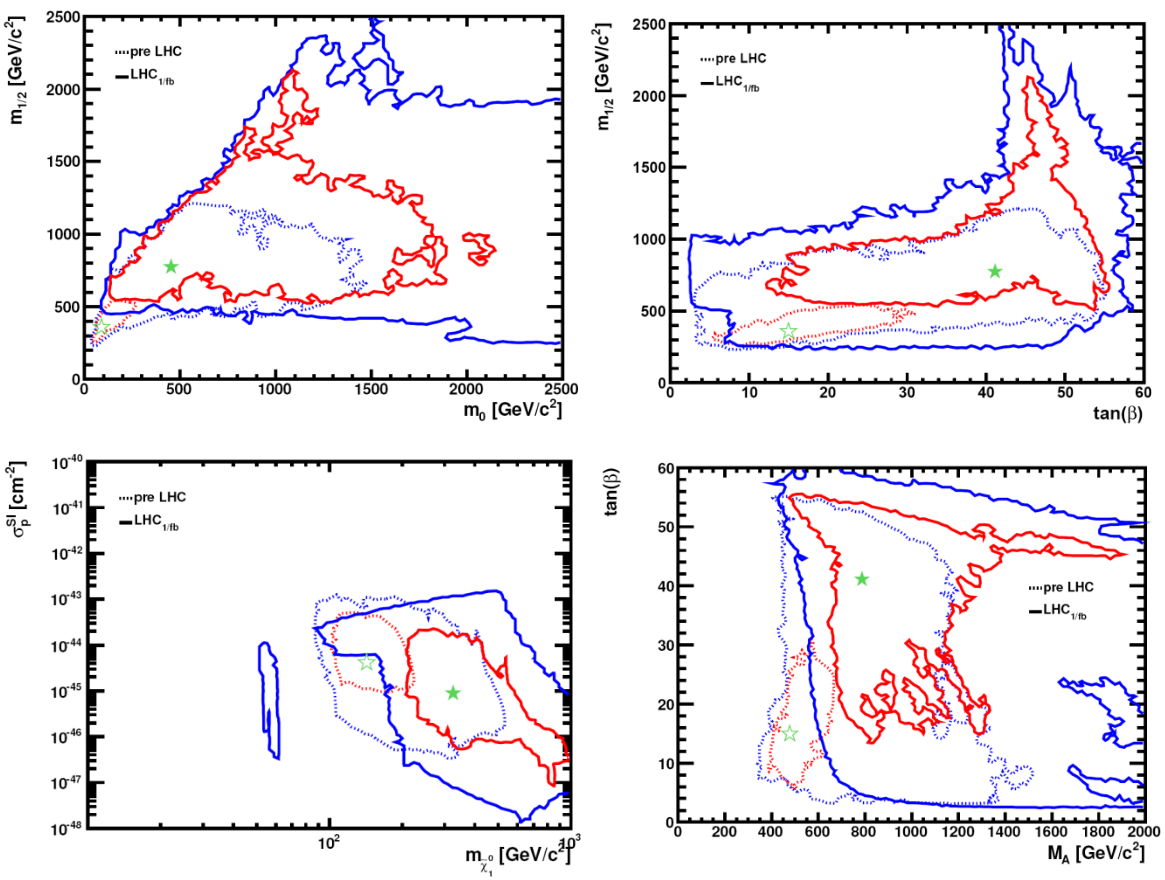
4. Good fit of EW precision data

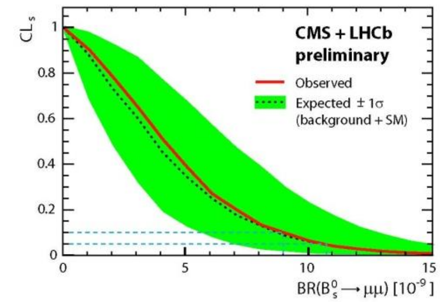




The LHC data set includes ATLAS and CMS searches for jets + / ET events and for the heavier MSSM Higgs bosons, and the upper limits on BR(Bs → μ+μ−) from LHCb and CMS.

O.Buchmueller, R.Cavanaugh, A.DeRoeck, M.J.Dolan ,
J.R.Ellis, H.Flacher, S.Heinemeyer, G.Isidori, D.Martınez Santos,
K.A.Olive, S.Rogerson, F.J.Ronga, G.Weiglein

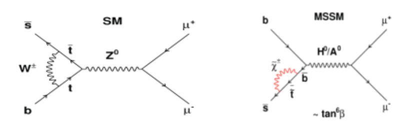




SM Prediction

$Br(B_s \to \mu\mu) = (3.2 \pm 0.2) \times 10^{-9}$

$Br(B_s \to \mu\mu) < 1.1 \times 10^{-8}$ at 95% CL



CMSSM

Parameter space is significantly moved

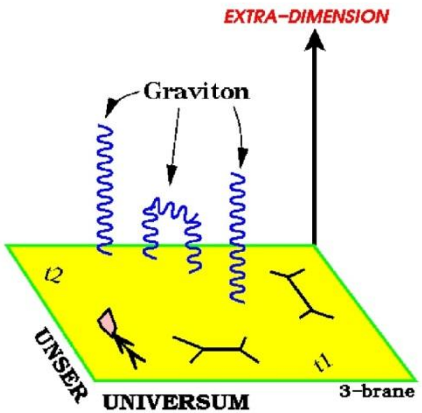
☆ Best fit before LHC

★ Best fit LHC 1/fb

Models with extra space dimensions

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

ADD type models

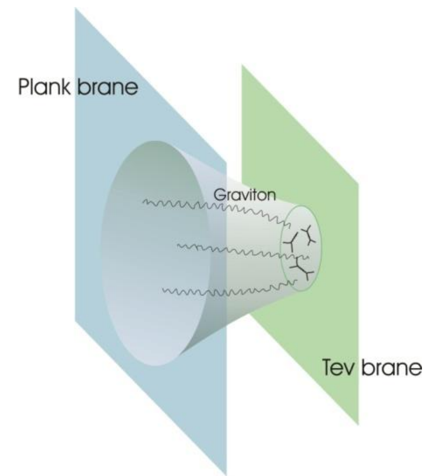


UED type scenarios

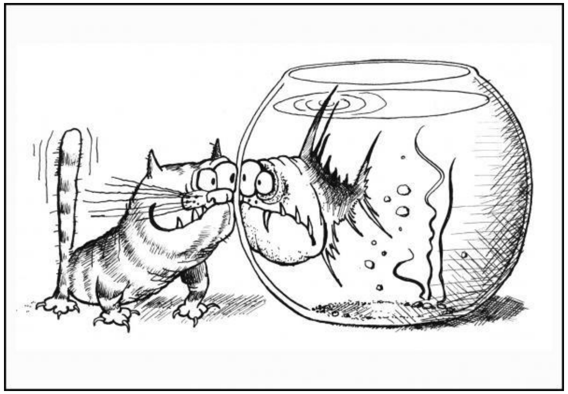
with SM fields in ADD or RS bulk

KK-parity ->
LKKP is a good DM candidate

RS type models

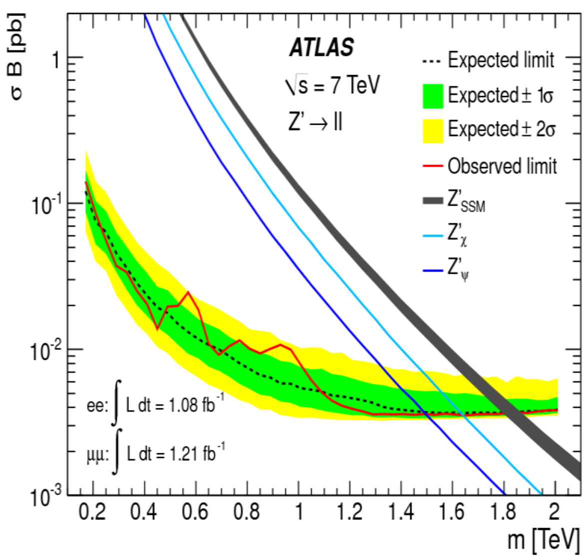


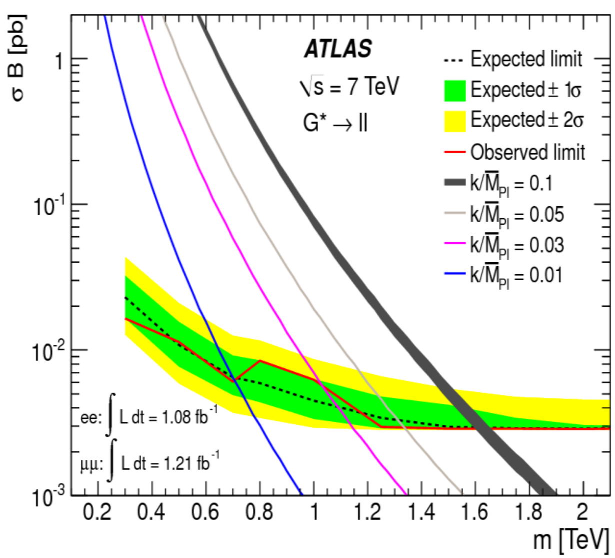
Can unify the forces
Can explain why gravity is weak (solve hierarchy problem)
Contain Dark Matter Candidates
Can generate neutrino masses



Limits on the Z' and RS graviton masses

Latest limits exclude:
->1.83 TeV on m(Z') in the Sequential Standard Model.
->1.63 TeV for a Randall-Sundrum graviton (k=mPl = 0:1).





No interference with the rest of KK tower yet.
The interference should be included

Boos, Bunichev, Smolyakov, Volobuev

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):

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

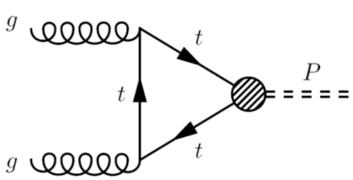
$$\langle\Phi\rangle \text{ is the condensation of } \langle t\bar{t}\rangle = f_\pi$$

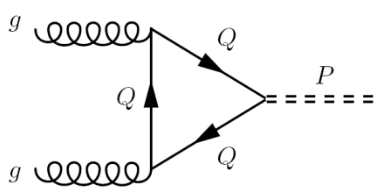
3d generation quarks and 1st,2d generation quarks are charged under two different SU(3)

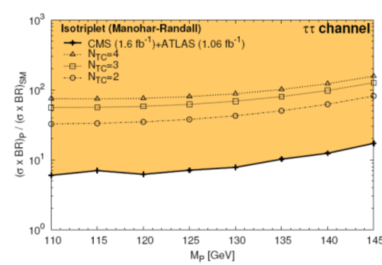
One should avoid FCNC, too large top mass, constrains from s,t,u parameters

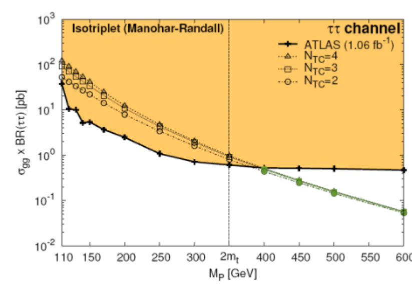
In general, there are: techni-pions, techin-rhos, composite Higgs(es), vector-like top-quark partners

R.Chivikula, P.Ittisamai, E.Simmons

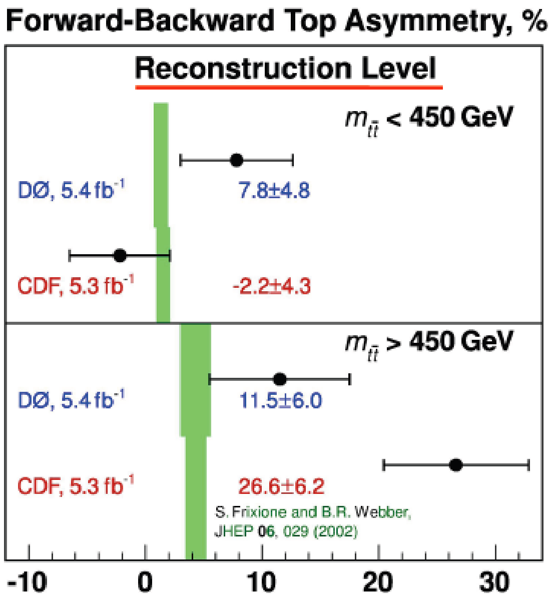








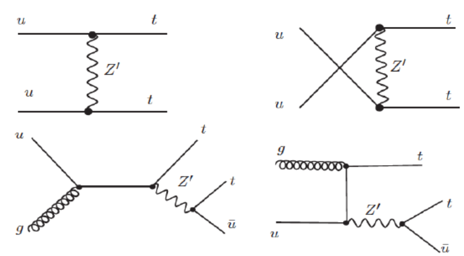
CMS and ATLAS searches for the Higgs in gamma-gamma and tau-tau modes exclude techni-(pseudo)scalars upto 2Mtop

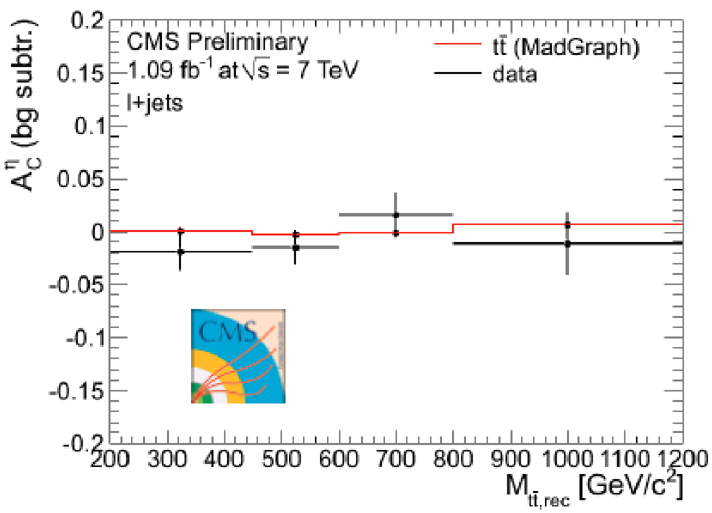


$$A_{fb} = \frac{N(-Q_l \cdot y_{\rm had} > 0) - N(-Q_l \cdot y_{\rm had} < 0)}{N(-Q_l \cdot y_{\rm had} > 0) + N(-Q_l \cdot y_{\rm had} < 0)}$$

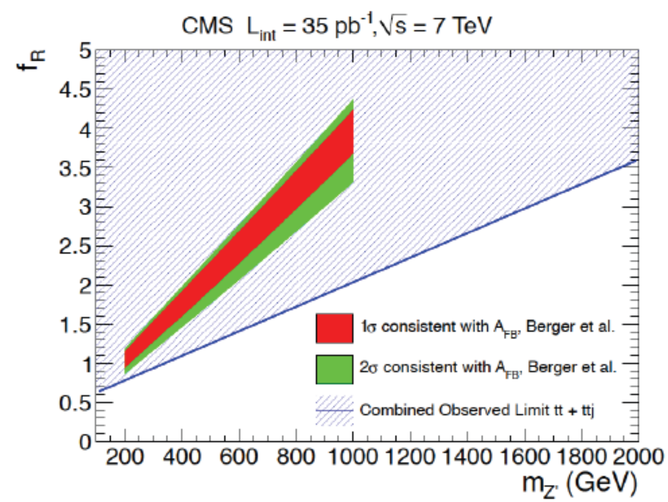
Assuming CP conservation $N_{\bar{t}}(p) = N_t(\bar{p})$

Therefore $A_c = A_{fb}$

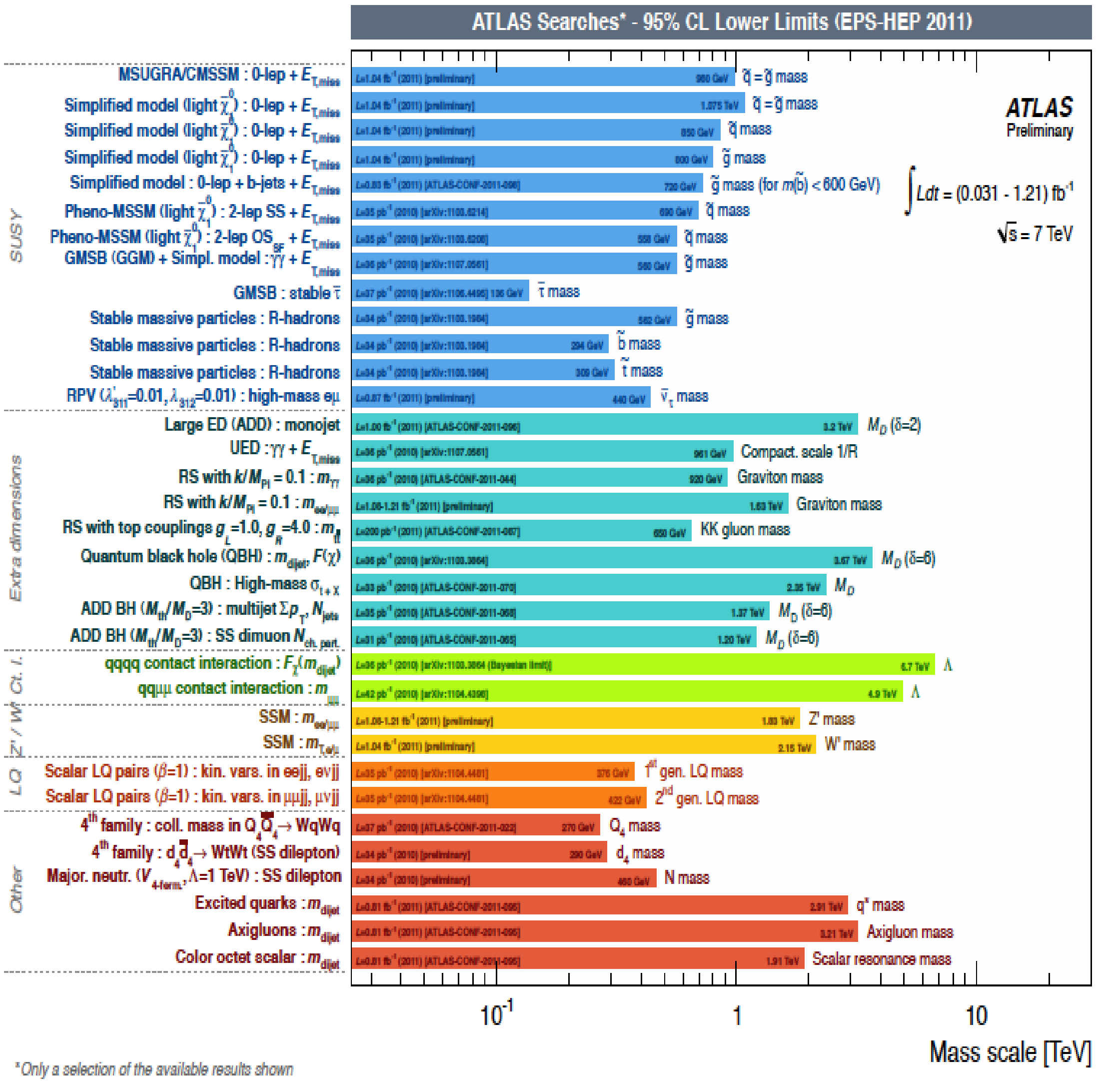




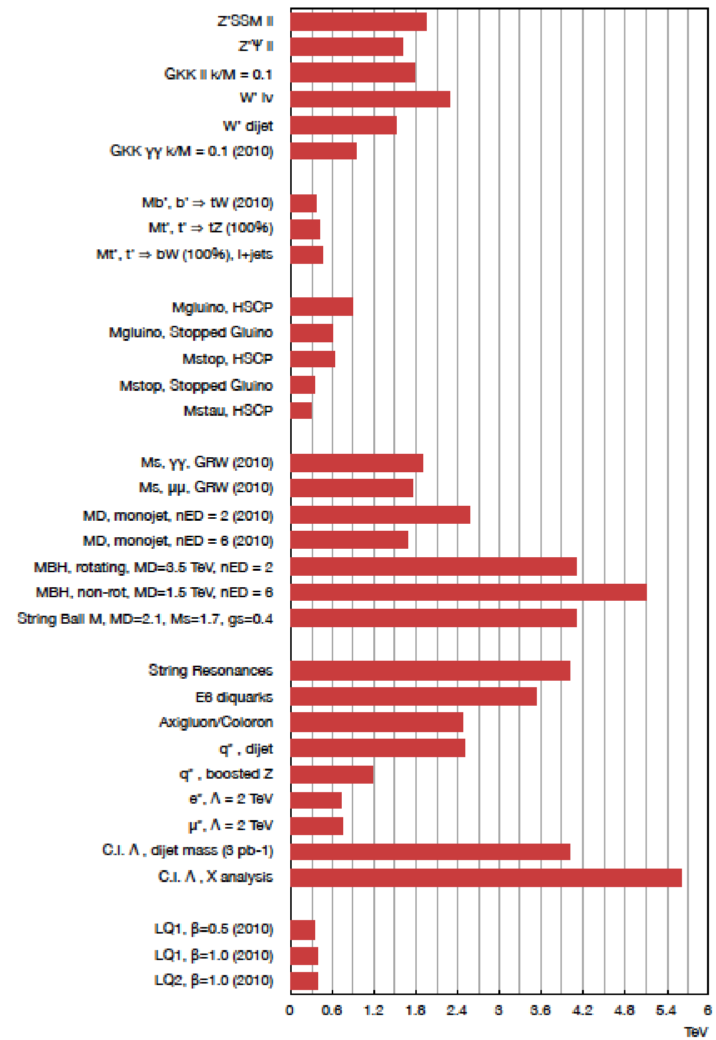
LHC rulled out most interesting t-channel possibilities



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



CMS



Concluding remarks

1. With about 10 1/fb the mass interval (114 < MH < 600 GeV) for SM-like Higgs boson is expected to be covered at 5 sigma level
   if found - more studies will be needed to clarify
   if not found - more studies will be needed at higher energies and lumi

2. If SM-like Higgs boson will be found with the mass MH > 135 GeV the MSSM will be ruled out

3. New strong bounds on masses of gluino and squarks of first two generations. Part of the SUSY spectrum with no reason to be light is excluded. Bounds on stops (sbottoms) are still weak

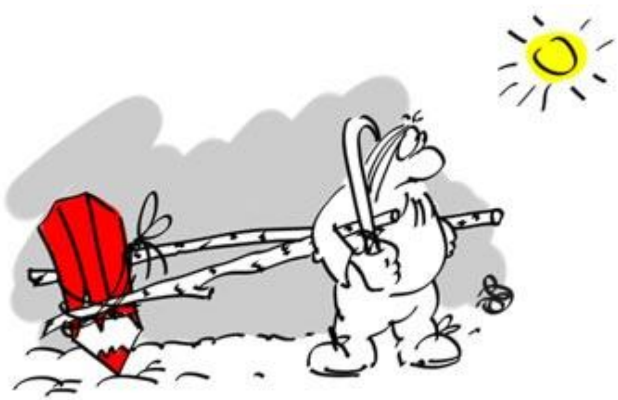
4. Many new BSM limits in the range 1-4 TeV. Many more are expected (for example, on top quark partners) for various SUSY and non-SUSY scenarios

5. Many very interesting results on QCD in various regions and regimes in pp and PbPb (hard, soft, high density, high temperature…)

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

LHC is moving into prime regions of expected Higgs and BSM physics.

Not just stay tuned but work hard



Possible results

BACKUP SLIDES

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

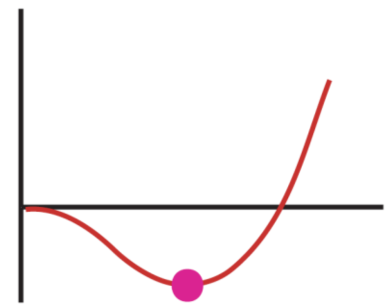
$$\mathcal{L} = |D_\mu \varphi|^2 - V(|\varphi|) - \frac{1}{4}(F^a_{\mu\nu})^2 - \frac{1}{4}(G_{\mu\nu})^2$$

$$-\lambda_e \bar{e}_R \varphi^\dagger \cdot L - \lambda_d \bar{d}_R \varphi^\dagger \cdot Q - \lambda_e \bar{u}_R \varphi_\alpha \epsilon_{\alpha\beta} Q_\beta$$

$$V(|\varphi|) = \mu^2 |\varphi|^2 + \lambda |\varphi|^4$$

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

$$\mu^2 < 0$$



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

$$|D_\mu \Phi)|^2 = \left| \left(\partial_\mu - i g_2 \frac{\tau_a}{2} W^a_\mu - i g_1 \frac{1}{2} B_\mu \right) \Phi \right|^2 \quad M_W^2 W^+_\mu W^{-\mu} + \frac{1}{2} M_Z^2 Z_\mu Z^\mu + \frac{1}{2} M_A^2 A_\mu A^\mu$$

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

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

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

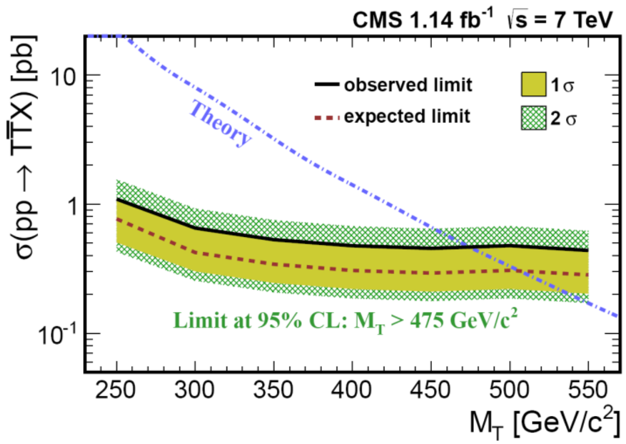
$$\frac{G_F}{\sqrt{2}} = \frac{g_2^2}{8 M_W^2}$$

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

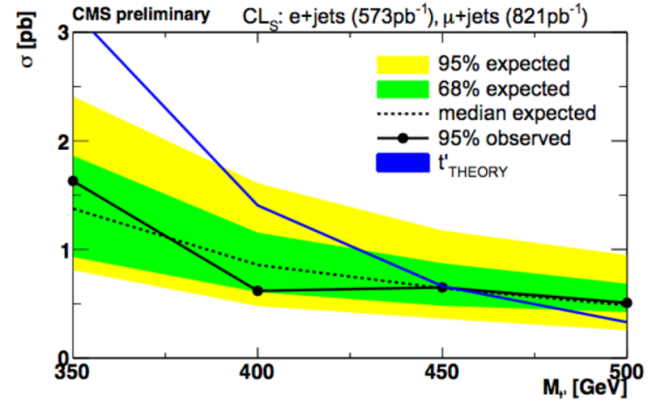
$$\Phi \to \frac{1}{\sqrt{2}} \binom{0}{H + v} \Rightarrow m_e = \frac{f_e v}{\sqrt{2}},\ m_u = \frac{f_u v}{\sqrt{2}},\ m_d = \frac{f_d v}{\sqrt{2}}$$

v= 246 GeV

Limits on vector-like top partner in T->tZ decay mode

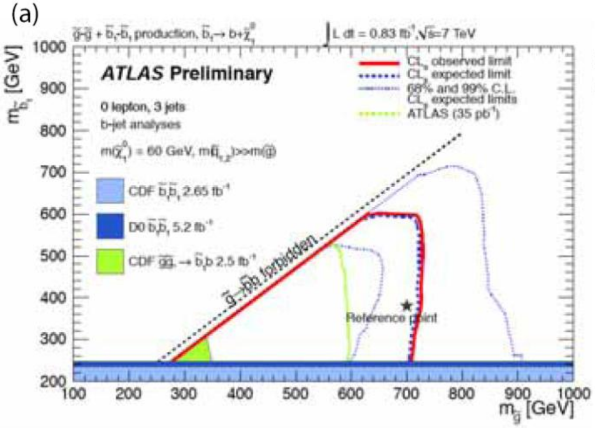


Limits on t' $t'\bar{t}' \to WbW\bar{b}$

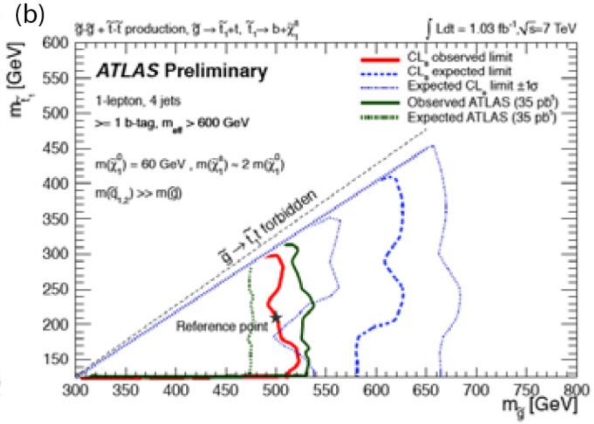


Limits on sbottoms and stops

(a)



(b)



Best spin correlation variable in searches for single top