XLII International Meeting on
Fundamental Physics
Benasque, January 27-31, 2014

Beyond the Standard Model Physics and implications from recent high-pT LHC data

José Santiago (CAFPE and U. Granada)

What is this (course)?

- The organizers asked me to give a course on BSM and implications from recent high-pT LHC data
- These are exciting times for BSM physics:
  - The LHC is probing for the first time (and quite exhaustively) the TeV scale
  - Null results so far force us to reconsider some of our assumptions/expectations
- I'll try to give an overview of how LHC data re-shape our ideas about BSM using specific examples, rather than trying to be comprehensive (either in the model-building or in the experimental side)

Outline

- The Standard Model
- New Physics searches: the effective way
- New Physics searches: model building
  - Supersymmetry
    - Simplified models
  - Composite Higgs
- Implications from recent high p_T data
  - Higgs Physics
  - Direct searches
- Some final thoughts

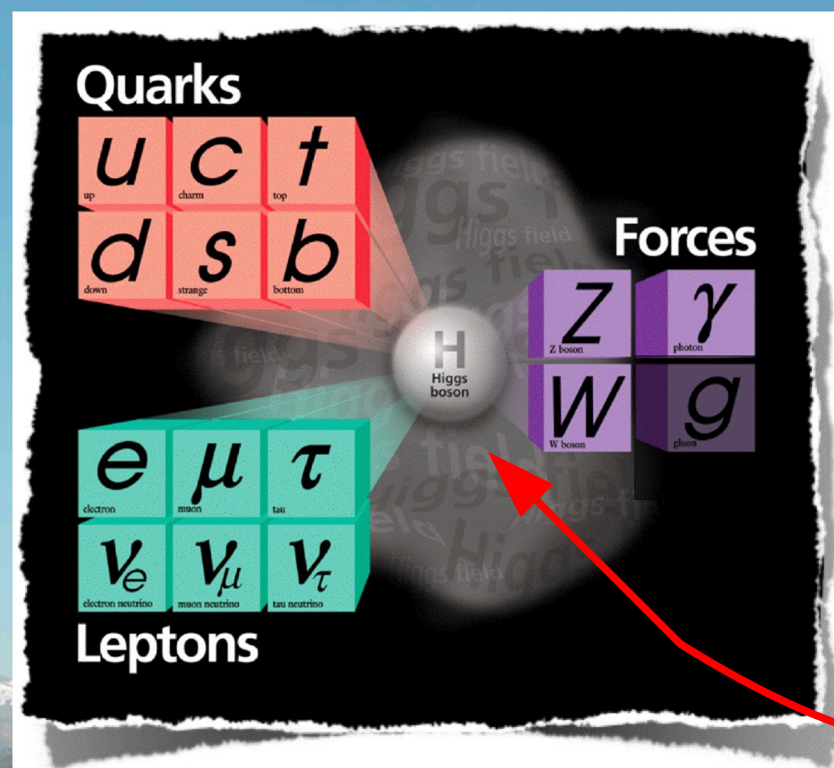
The Standard Model

- The Standard Model of particle physics
  - Defined by
    - Symmetry: local $SU(3)_C \times SU(2)_L \times U(1)_Y$

The Standard Model

- The Standard Model of particle physics
  - Defined by
    - Symmetry: local $SU(3)_C \times SU(2)_L \times U(1)_Y$
    - Particle content

$$
\begin{array}{ll}
q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix} & (3,2)_{\frac{1}{6}} \\
u_R & (3,1)_{\frac{2}{3}} \\
d_R & (3,1)_{-\frac{1}{3}} \\
l_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} & (1,2)_{-\frac{1}{2}} \\
e_R & (1,1)_{-1}
\end{array}
$$



$$\phi \quad (1,2)_{\frac{1}{2}}$$

The Standard Model

- The Standard Model of particle physics
  - Defined by
    - Symmetry: local $SU(3)_C \times SU(2)_L \times U(1)_Y$
    - Particle content
    - Renormalizable Lagrangian: only relevant or marginal operators (mass dimension ≤4)

$$
\begin{aligned}
\mathcal{L} = &-\tfrac{1}{4} F_{\mu\nu} F^{\mu\nu} + \bar{\psi} \mathrm{i} \gamma^\mu D_\mu \psi + (D_\mu \phi)^\dagger D^\mu \phi \\
&- [\bar{q}_L \lambda^u \tilde{\phi} u_R + \bar{q}_L V \lambda^d \phi d_R + \bar{l}_L \lambda^e \phi e_R + \text{h.c.}] \\
&- [\mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2] \\
&+ \theta \frac{g^3}{64\pi^2} F^a_{\mu\nu} \tilde{F}^{a\,\mu\nu}
\end{aligned}
$$

J. Redondo's talk

The Standard Model

- Some (successful) features of the SM
  - It is anomaly-free (and almost the minimal option)
  - Reproduces successfully EWSB
  - (Minimal) flavor (and CP) violation: GIM
  - Agrees with observation
- Some unsatisfactory features of the SM
  - Does not agree with all observations: dark matter (energy), baryon asymmetry, …
  - Does not explain its structure: number of families, flavor, nature of neutrino masses ...
  - The Higgs: hierarchy problem, origin of EWSB

The Standard Model

- Flavor in the SM:
  - Flavor violation absent in neutral currents and mediated by unitary CKM in charged currents with a single CP violating phase
  - Lepton and baryon number: accidental symmetries (not imposed, arise from gauge symmetries and particle content)
    - They are both anomalous but B-L is not
- Tested experimentally to an extreme precision

S. Descontes-Genon course

The Standard Model

- EWSB in the SM: $V(\phi) = \mu^2 \phi^\dagger \phi + \lambda(\phi^\dagger \phi)^2$
  - $SU(2)_L \times U(1)_Y \to U(1)_Q$ if $\mu^2 < 0$

$$\langle \phi^\dagger \phi \rangle = \frac{v^2}{2} = \frac{-\mu^2}{2\lambda} \qquad \phi = \begin{pmatrix} \pi^+ \\ \frac{v+h+\mathrm{i}\pi^0}{\sqrt{2}} \end{pmatrix}$$

$\pi^\pm,\ \pi^0,$ would-be GB, eaten by $\mathrm{W}^\pm, Z$

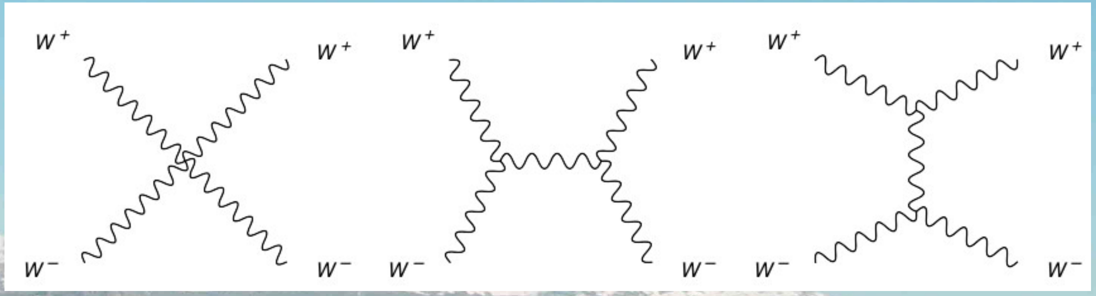
$h,$ physical scalar Higgs boson

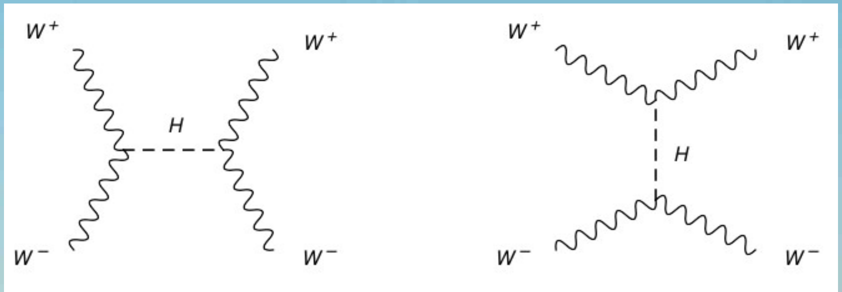
$$V(h) = \lambda v^2 h^2 + \lambda v h^3 + \frac{\lambda}{4} h^4 \Rightarrow m_h^2 = 2\lambda v^2$$

The Standard Model

- EWSB in the SM: $V(\phi) = \mu^2 \phi^\dagger \phi + \lambda(\phi^\dagger \phi)^2$
  - $SU(2)_L \times U(1)_Y \to U(1)_Q$ if $\mu^2 < 0$
    - h provides the right degree of freedom to unitarize longitudinal gauge boson scattering

$$\begin{aligned}\mathcal{M}(W_L^+ W_L^- \to W_L^+ W_L^-) &= \frac{g^2}{4m_W^2}\left[s + t - \frac{s^2}{s - m_H^2} - \frac{t^2}{t - m_H^2}\right] \\ &= -\frac{g^2}{4m_W^2} m_H^2 \left[\frac{s}{s - m_H^2} + \frac{t}{t - m_H^2}\right].\end{aligned}$$





The Standard Model

- EWSB in the SM: $V(\phi) = \mu^2 \phi^\dagger \phi + \lambda(\phi^\dagger \phi)^2$
  - $SU(2)_L \times U(1)_Y \to U(1)_Q$ if $\mu^2 < 0$
    - h provides the right degree of freedom to unitarize longitudinal gauge boson scattering
    - Has approximate custodial symmetry

$$\Sigma = (\tilde{\phi}\,\phi) = \begin{pmatrix} \phi_0^* & \phi^+ \\ -\phi^- & \phi_0 \end{pmatrix} \to U_L \Sigma U_R^\dagger$$

$$\langle \Sigma \rangle = \begin{pmatrix} v & 0 \\ 0 & v \end{pmatrix}$$ breaks $SU(2)_L \times SU(2)_R \to SU(2)_{L+R}$

$$W_\mu^I \text{ triplet under } SU(2)_{L+R} \Rightarrow \rho \equiv \frac{m_W^2}{m_Z^2 c_W^2} = 1$$

The Standard Model

- EWSB in the SM: $V(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$
  - $SU(2)_L \times U(1)_Y \to U(1)_Q$ if $\mu^2 < 0$
    - h provides the right degree of freedom to unitarize longitudinal gauge boson scattering
    - Has approximate custodial symmetry (explicitly broken by the top/bottom mass difference and hypercharge interactions)

$$\begin{pmatrix} t_L \\ b_L \end{pmatrix} \Sigma \begin{pmatrix} \lambda_t t_R \\ \lambda_b b_R \end{pmatrix}$$

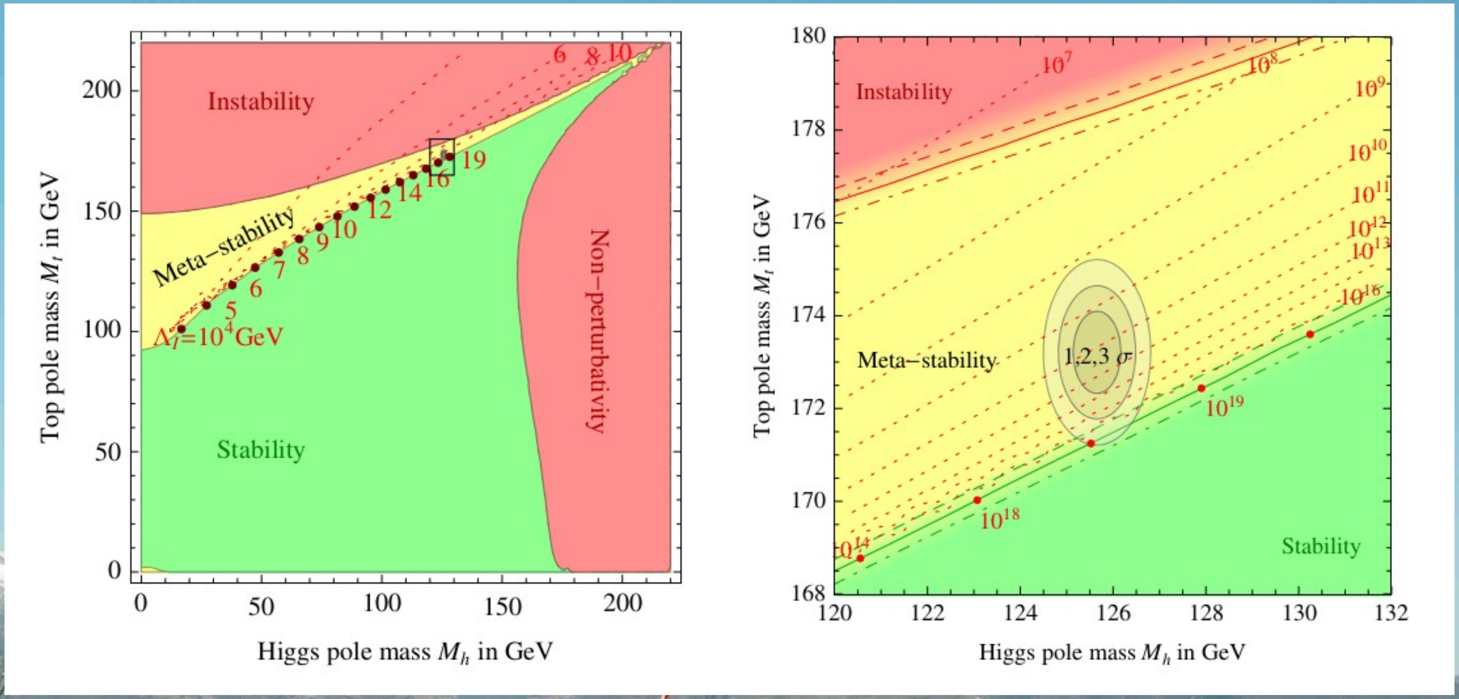
$$\delta\rho = \frac{3 G_F m_t^2}{8\sqrt{2}\pi}$$

$$Y = T_R^3 + Q_{B-L}$$

$$\delta_\rho = -\frac{3 g'^2 G_F m_W^2}{4\sqrt{2}\pi^2 g^2} \ln\left(\frac{m_h^2}{m_{h,\mathrm{ref}}^2}\right)$$

The Standard Model

- Tests of the SM
  - Higgs discovery at the LHC: last remaining coupling measured in the SM $(\lambda \approx 0.13)$
  - With interesting implications

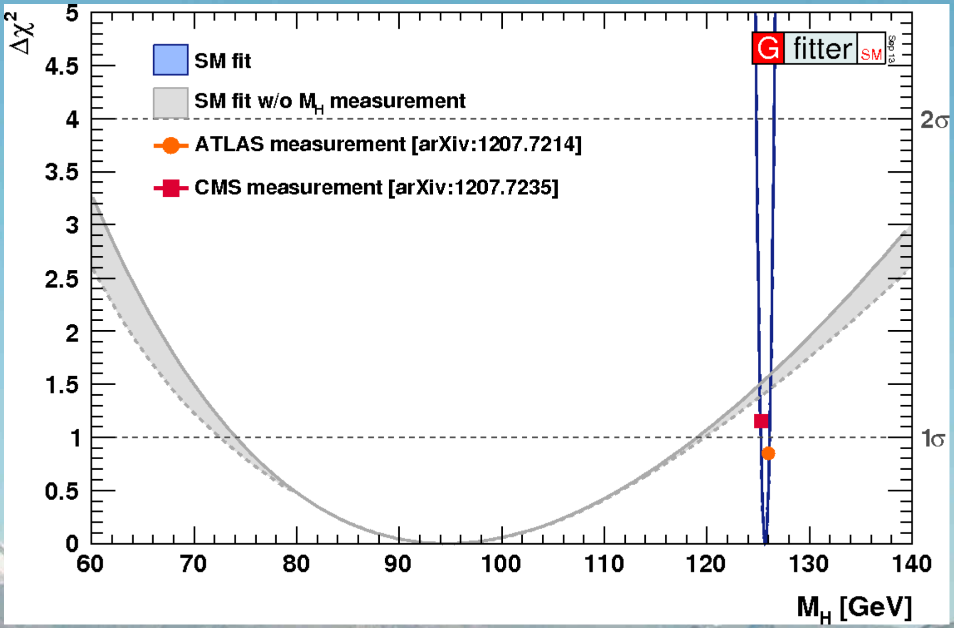


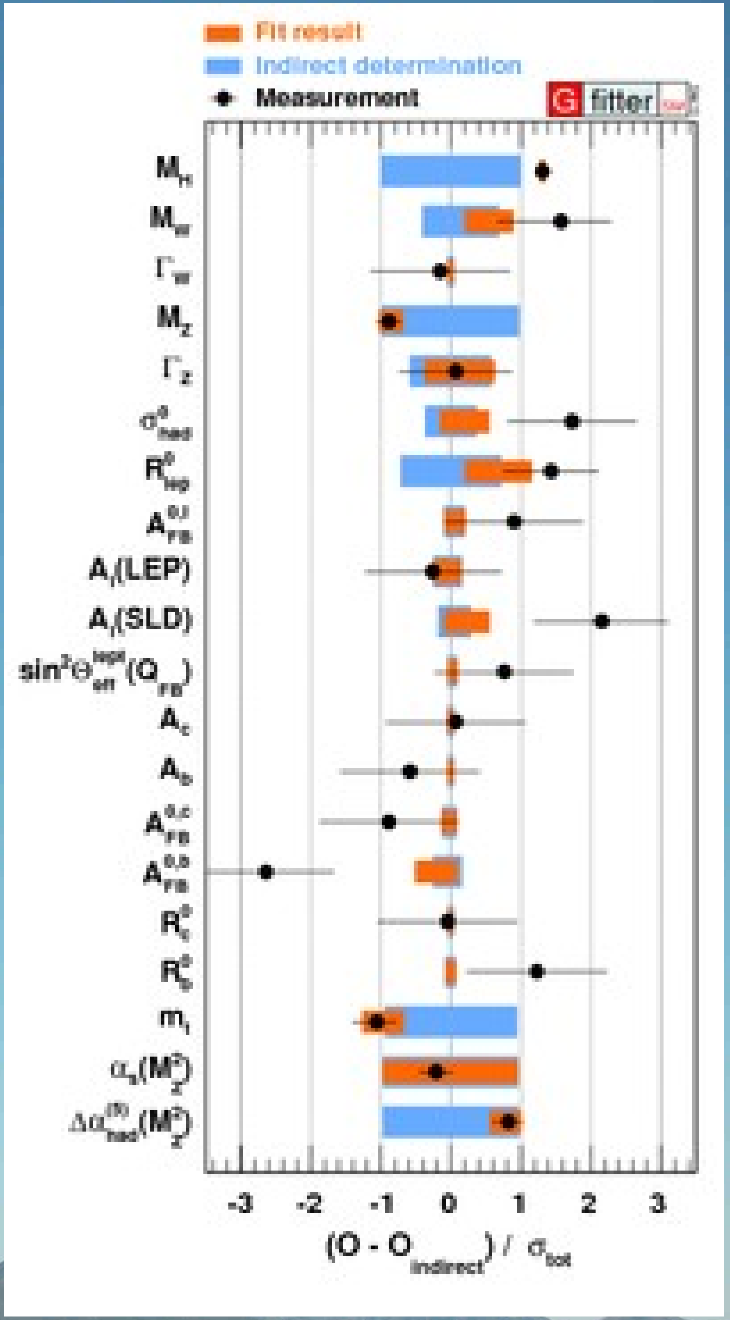
Buttazzo et al '13;
See also:
Degrassi et al '12;
Bezrukov et al '12

G. Degrassi's talk

The Standard Model

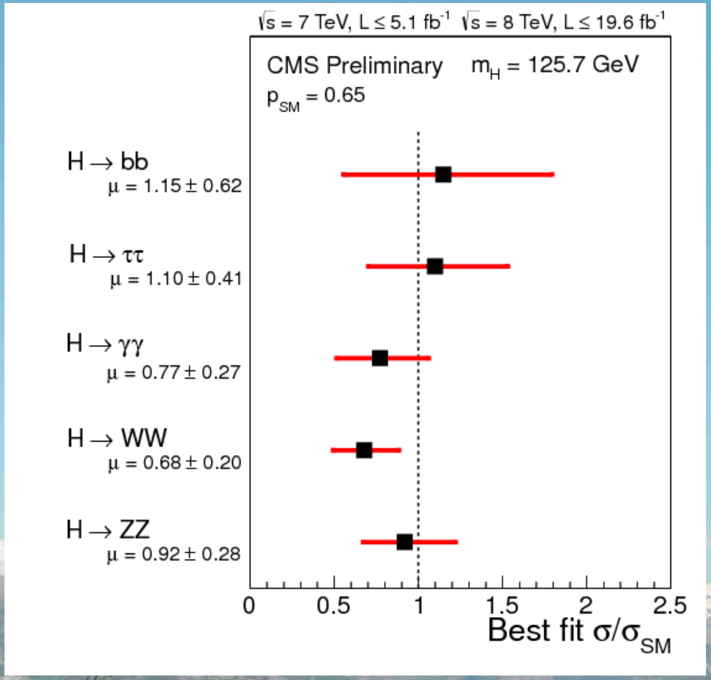
- Tests of the SM
  - Higgs discovery at the LHC: last remaining coupling measured in the SM $(\lambda \approx 0.13)$
  - Excellent agreement with data

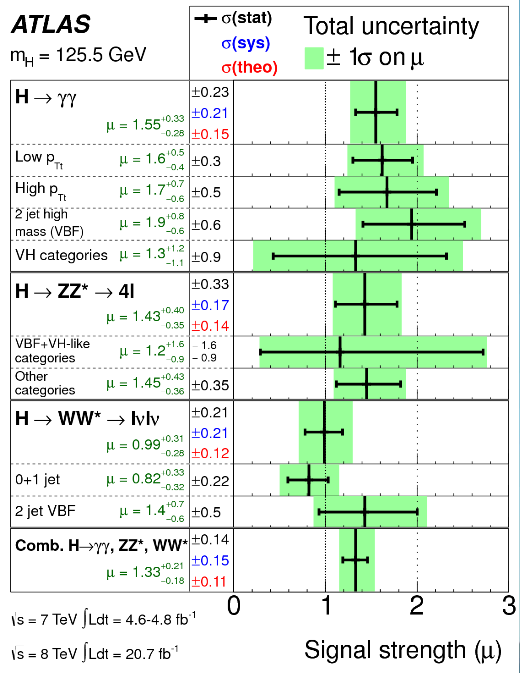


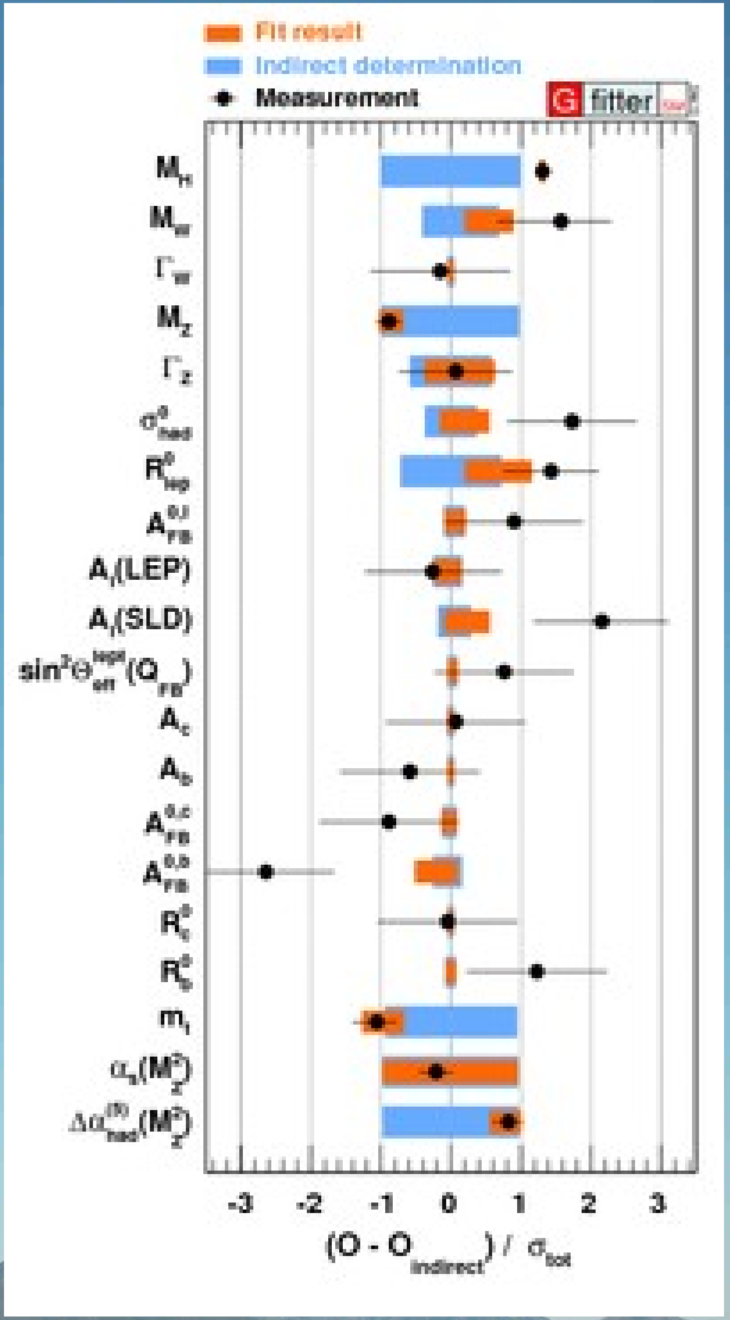


The Standard Model

- Tests of the SM
  - Higgs discovery at the LHC: last remaining coupling measured in the SM $(\lambda \approx 0.13)$
  - Excellent agreement with data







The Standard Model

- But:
  - The SM does not explain dynamically the values of the different parameters (Why $\mu^2 < 0$? Why 3 families? Why $\lambda_e/\lambda_t \sim 10^{-6}$? …)
  - Does not address many questions: dark energy, dark matter, baryon asymmetry, origin of neutrino masses, strong CP problem, …
  - And … the Higgs
    - It would be the first time an elementary scalar is observed in nature (not the first time for spontaneous symmetry breaking, though)
    - It suffers from the hierarchy problem

The Standard Model

- The Hierarchy (or naturalness) problem:
  - The mass of an elementary scalar is a relevant operator not (obviously) protected by any symmetry
  - Any new scale in the UV will induce a correction to the Higgs mass proportional to the new scale

$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 + \frac{1}{2}(\partial\Phi)^2 + \bar{\psi} i \not{\partial}\psi - \frac{1}{2}m_\phi^2\phi^2 - \frac{1}{2}m_\Phi^2\Phi^2 - m_\psi\bar{\psi}\psi - \frac{\lambda}{4}\phi^2\Phi^2 - \lambda_\phi\phi\bar{\psi}\psi - \lambda_\Phi\Phi\bar{\psi}\psi$$

1 loop mass shift in $\overline{\text{MS}}$ scheme

$$\delta m_\phi^2 = m_\psi^2\frac{\lambda_\phi^2}{4\pi^2}\left[1 - 2\ln\frac{m_\psi^2}{\mu^2} + \mathcal{O}(m_\phi^2/m_\psi^2)\right] - m_\Phi^2\frac{\lambda}{32\pi^2}\left[1 - \ln\frac{m_\Phi^2}{\mu^2}\right]$$

$$\delta m_\psi = m_\psi\frac{\lambda_\phi^2}{16\pi^2}\left[\frac{5}{4} - \frac{3}{2}\ln\frac{m_\phi^2}{\mu^2} + \mathcal{O}(m_\psi^2/m_\phi^2)\right] + (\phi \to \Phi)$$

The Standard Model

- The Hierarchy (or naturalness) problem:
  - The mass of an elementary scalar is a relevant operator not (obviously) protected by any symmetry
  - Any new scale in the UV will induce a correction to the Higgs mass proportional to the new scale
  - It is difficult to understand the scale of EWSB unless some new structure appears around the TeV scale

The Standard Model

- The Hierarchy (or naturalness) problem:
  - The mass of an elementary scalar is a relevant operator not (obviously) protected by any symmetry
  - Any new scale in the UV will induce a correction to the Higgs mass proportional to the new scale
  - It is difficult to understand the scale of EWSB unless some new structure appears around the TeV scale
  - Currently tested tuning is not yet dramatic

Crude estimate

$$\frac{\delta m_H^2}{m_H^2} \sim \frac{\Lambda^2}{4\pi^2 m_H^2} \leq \Delta \Rightarrow \Lambda \lesssim \text{few } \sqrt{\Delta} m_H \sim \text{ few } \begin{cases} 1 \text{ TeV, } 0.01 \text{ tuning} \\ 3 \text{ TeV, } 0.001 \text{ tuning} \end{cases}$$

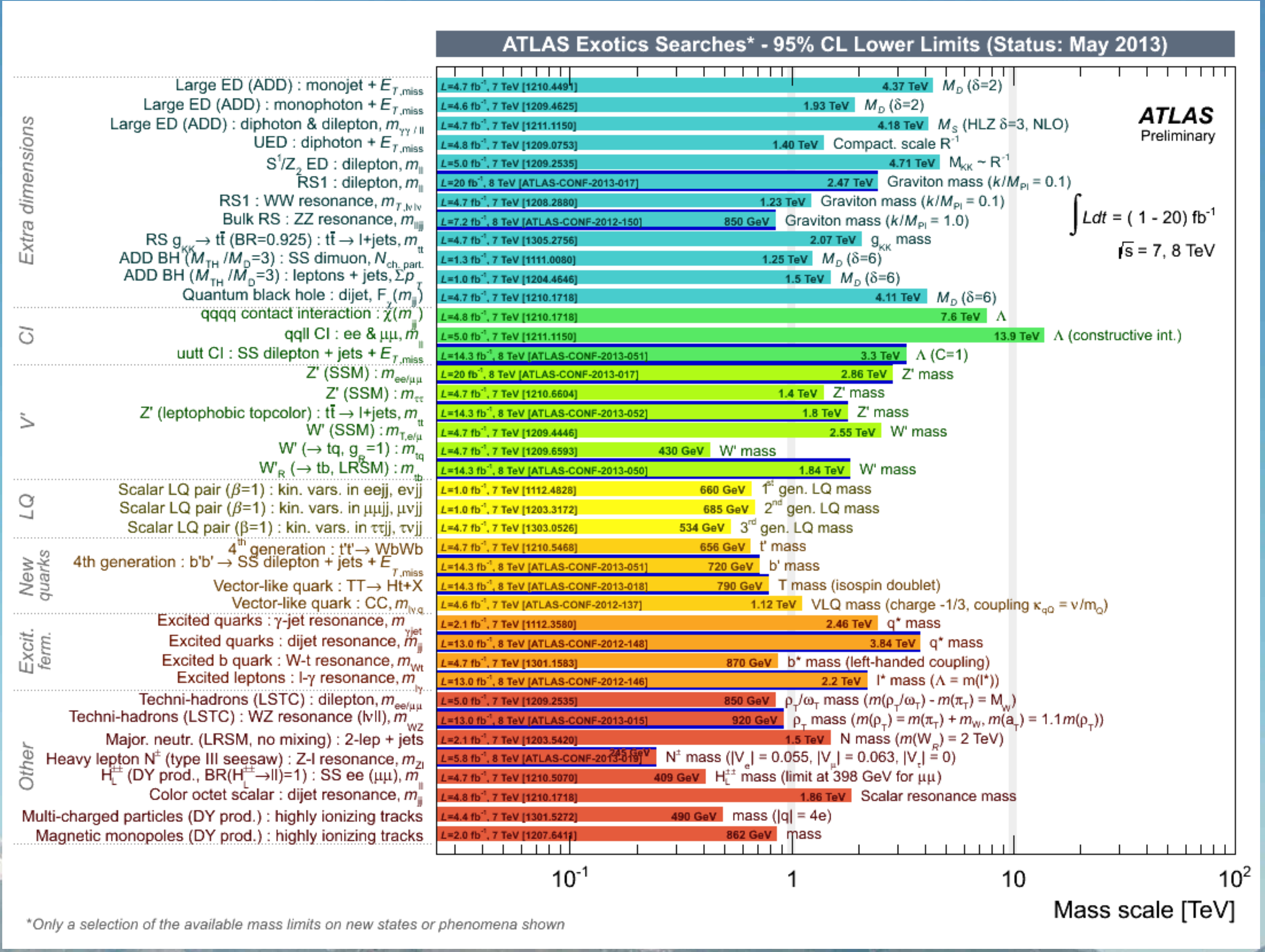
The Standard Model

- Searches for New Physics at the LHC

If the SM is not satisfactory and the hierarchy problem suggests that there should be new physics at the TeV scale … we should find it at the LHC!

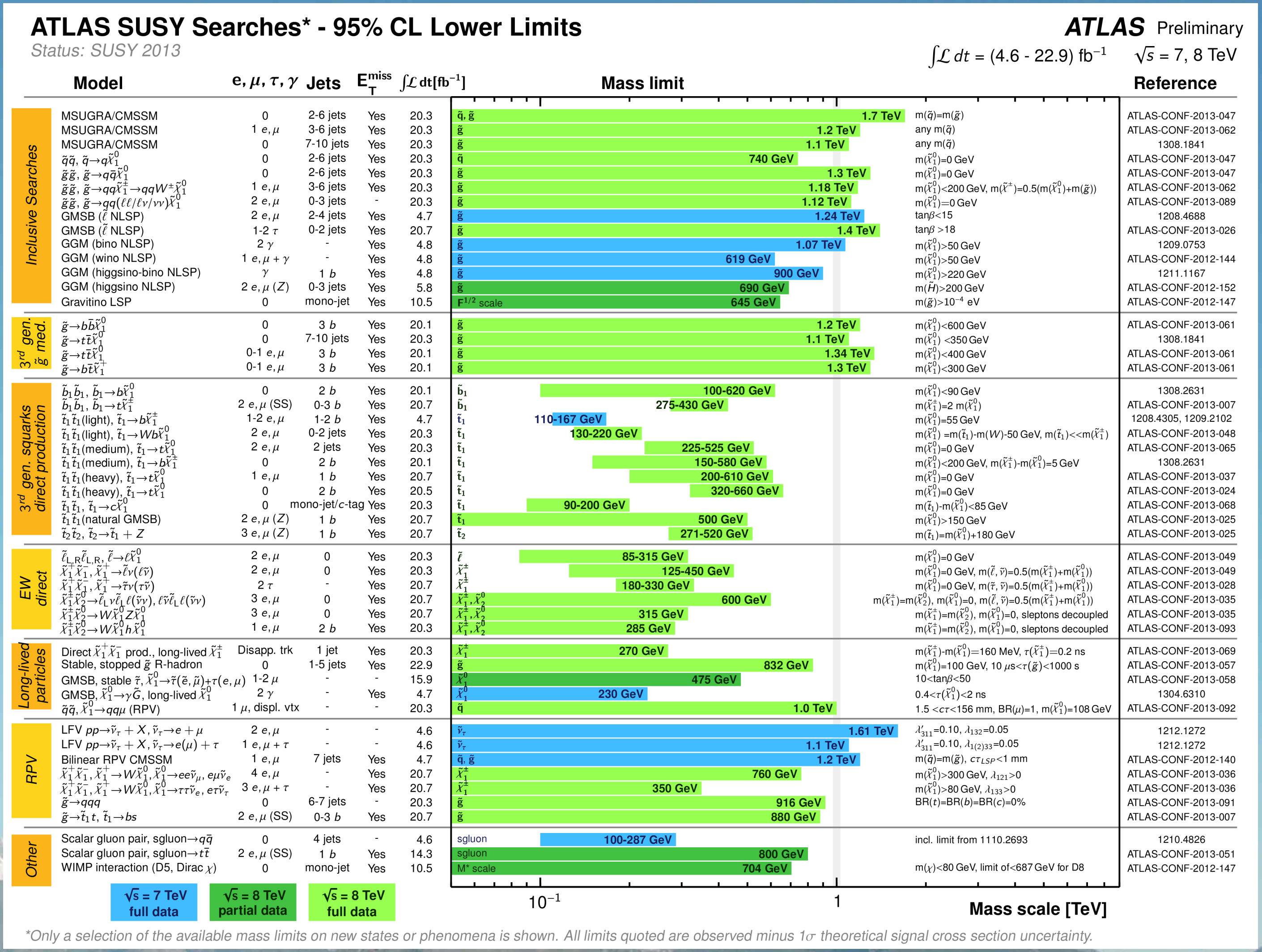
The Standard Model

- Searches for New Physics at the LHC



The Standard Model

- Searches for New Physics at the LHC



Where do we stand?

- The lack of new physics signals plus the good health of the SM has put some pressure on BSM practitioners
- Naturalness remains a good guiding principle:
  - Still at the ~ few per cent level
  - It is The One argument that points to the TeV scale (dark matter, baryon asymmetry, origin of flavor, …, could be related to the TeV scale or to any other)
  - Discoveries perfectly possible at 13/14 TeV
- The Higgs can play a fundamental role in the discovery of new physics.

How do we proceed?

- Experimental collaborations are massive beasts
  - They have a lot of man-power but also a lot of inertia (plus politics, internal competition, ...)
- How do we search for new physics?
  - Use an effective Lagrangian description: general but assumes new particles are virtual
  - Guide searches by “well motivated” models: very efficient but suffers from theory bias
  - Use “simplified models”: easy to reinterpret
  - Search for arbitrary new particles: general but highly inefficient (limited in practice by manpower)

NP searches: the effective way

- Facts:
  - SM agrees very well with data
  - Direct NP searches unsuccessful so far
- Effective Lagrangians. Model-independent description of NP with the following ingredients:
  - Low energy symmetries and degrees of freedom
  - Mass gap between experiment and NP scale
- Caveats:
  - No “light” new physics

NP searches: the effective way

- The Effective Lagrangian for the SM
  - Choose how to incorporate the Higgs (linear vs non-linear realization)

L. Merlo's talk

  - Write all possible operators with the SM fields, respecting the SM symmetries

$$\mathcal{L}_{eff} = \mathcal{L}_{\rm SM} + \sum_{d\geq 6} \sum_{i} \frac{\alpha_d^{(i)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

Neglecting L violation

    - General parameterization: incorporates all physics
    - New terms are all "irrelevant" operators: Physics effect of $\mathcal{O}_i^{(d)}$ suppressed by $(E/\Lambda)^{d-4}$
    - Renormalizability not an issue

NP searches: the effective way

- The Effective Lagrangian for the SM: practical issues
  - We can focus on d=6
  - There is a large number of ops at d=6
    - We can assume L and B conservation
    - Operators can be eliminated by field redefinitions or by use of SM equations of motion (redundant operators)
      - First attempt: 81 operators (x flavor)

        Buchmüller, Wyler '86
      - First non-redundant basis: 59 operators (x flavor)

        Grzadkowski et al '10

NP searches: the effective way

- Basis choice (which 59 independent operators to use)
  - Physics is independent of the choice but some bases are more convenient than others:
    - Choice based on classification Grzadkowski et al '10
    - Choice based on physics arguments (relation to experiment and to models) Contino et al '13; Elias-Miró et al '13
      - Classify operators according to how they can be generated (tree-level vs non-tree level) Artz al '93
      - Correlate them with experimental data
- Interpretation of LHC results in terms of Eff. Lags. should be done with caution: ensure the gap

NP searches: the effective way

- Sample use of effective Lagrangians at the LHC
  - Higgs physics

Elias-Miró et al '13
Pomarol, Riva '13

See also:
Corbett et al '12-'13
Alonso et al '13
Contino et al '13
Brivio et al '13
...

NP searches: the effective way

- Sample use of effective Lagrangians at the LHC
  - Higgs physics

Elias-Miró et al '13
Pomarol, Riva '13

$$\mathcal{O}_H = \frac{1}{2}(\partial^\mu |H|^2)^2$$
$$\mathcal{O}_T = \frac{1}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$$
$$\mathcal{O}_6 = \lambda |H|^6$$

$$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H\right) D^\nu W^a_{\mu\nu}$$
$$\mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right) \partial^\nu B_{\mu\nu}$$

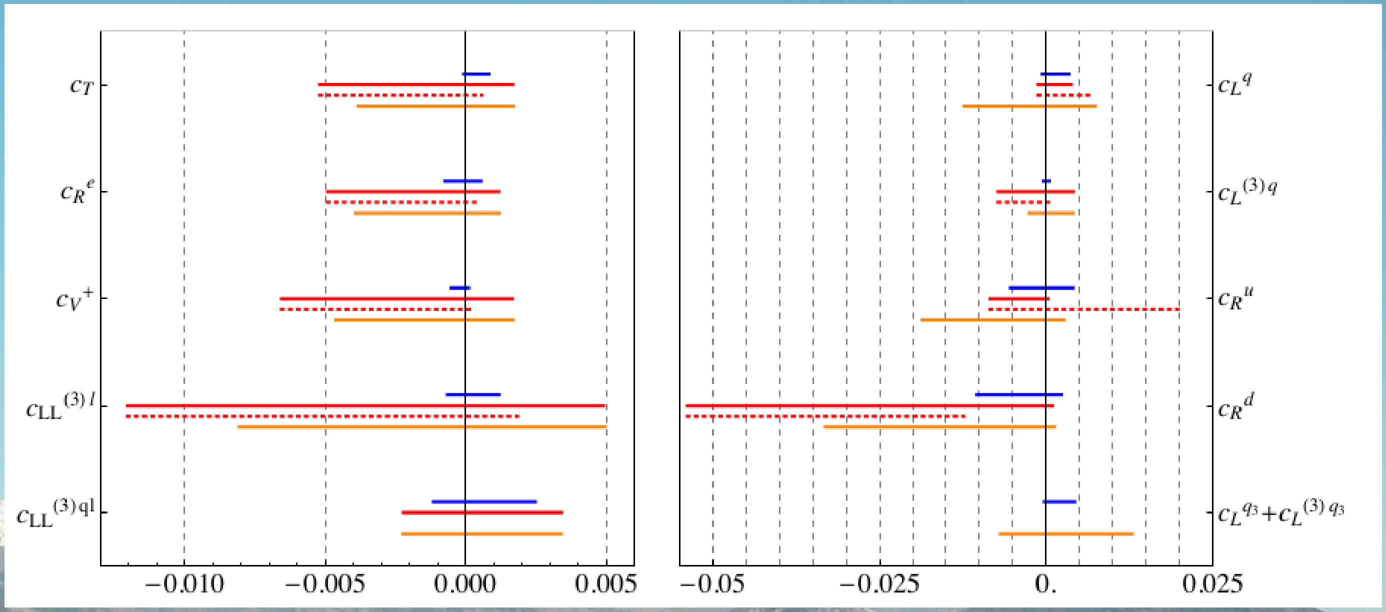
$$\mathcal{O}_{BB} = g'^2 |H|^2 B_{\mu\nu} B^{\mu\nu}$$
$$\mathcal{O}_{GG} = g_s^2 |H|^2 G^A_{\mu\nu} G^{A\mu\nu}$$
$$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$$
$$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$
$$\mathcal{O}_{3W} = \frac{1}{3!} g \epsilon_{abc} W^{a\,\nu}_{\mu} W^b_{\nu\rho} W^{c\,\rho\mu}$$

$\mathcal{O}_{y_u} = y_u |H|^2 \bar{Q}_L \widetilde{H} u_R$	$\mathcal{O}_{y_d} = y_d |H|^2 \bar{Q}_L H d_R$	$\mathcal{O}_{y_e} = y_e |H|^2 \bar{L}_L H e_R$
$\mathcal{O}^u_R = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}_R \gamma^\mu u_R)$ $\mathcal{O}^q_L = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{Q}_L \gamma^\mu Q_L)$ $\mathcal{O}^{(3)\,q}_L = (iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\bar{Q}_L \sigma^a \gamma^\mu Q_L)$	$\mathcal{O}^d_R = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{d}_R \gamma^\mu d_R)$	$\mathcal{O}^e_R = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}_R \gamma^\mu e_R)$
$\mathcal{O}^{(3)\,ql}_{LL} = (\bar{Q}_L \sigma^a \gamma_\mu Q_L)(\bar{L}_L \sigma^a \gamma^\mu L_L)$		$\mathcal{O}^{(3)\,l}_{LL} = (\bar{L}_L \sigma^a \gamma^\mu L_L)(\bar{L}_L \sigma^a \gamma_\mu L_L)$

NP searches: the effective way

- Sample use of effective Lagrangians at the LHC
  - Higgs physics

    Elias-Miró et al '13
    Pomarol, Riva '13
  - Relevant operators can be classified in three groups:
    - Ops constrained by EWPT



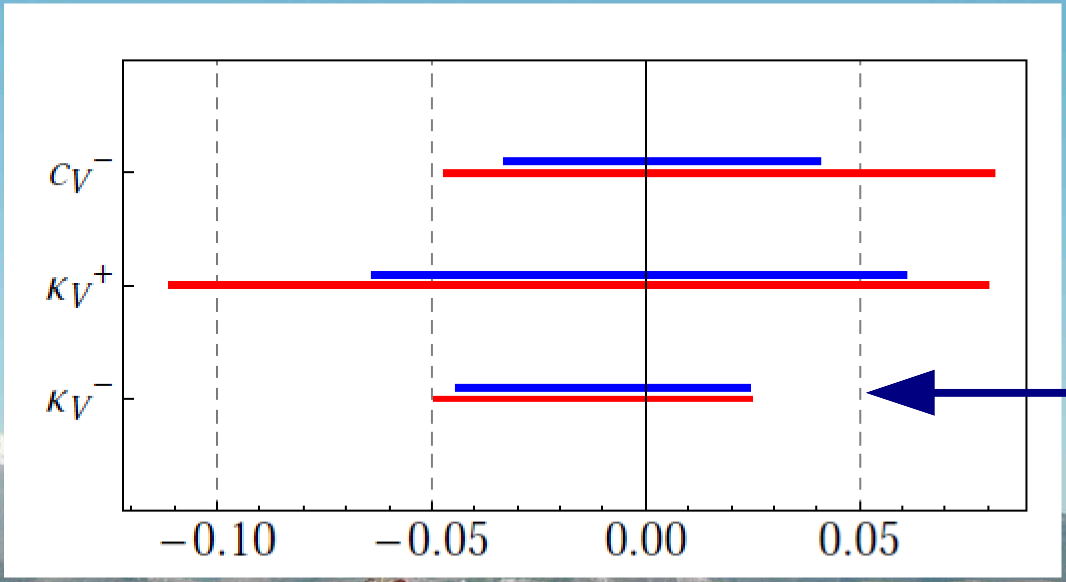
Correlations very important!

NP searches: the effective way

- Sample use of effective Lagrangians at the LHC
  - Higgs physics

Elias-Miró et al '13
Pomarol, Riva '13

  - Relevant operators can be classified in three groups:
    - Ops constrained by EWPT
    - Ops constrained by triple gauge boson couplings



$BR(h->Z\gamma)$

NP searches: the effective way

- Sample use of effective Lagrangians at the LHC
  - Higgs physics

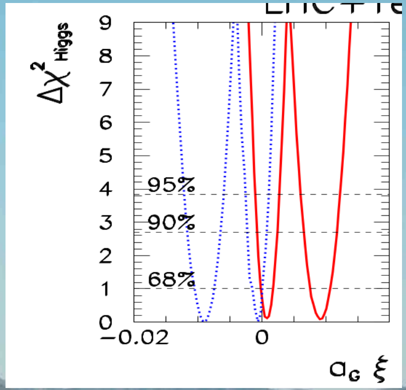
    Elias-Miró et al '13
    Pomarol, Riva '13
  - Relevant operators can be classified in three groups:
    - Ops constrained by EWPT
    - Ops constrained by triple gauge boson couplings
    - Ops only constrained by Higgs physics (strong for loop-mediated processes in the SM)

$$\kappa_{GG} \in [-0.8, 0.8] \times 10^{-3}\,,$$

$$\kappa_{BB} \in [-1.3, 1.8] \times 10^{-3}\,,$$

$$\kappa_{Z\gamma} \in [-6, 12] \times 10^{-3}$$

Interference effects can be relevant
Brivio et al '13



NP searches: the effective way

- Sample use of effective Lagrangians at the LHC
  - Higgs physics

    Elias-Miró et al '13
    Pomarol, Riva '13
  - Relevant operators can be classified in three groups:
    - Ops constrained by EWPT
    - Ops constrained by triple gauge boson couplings
    - Ops only constrained by Higgs physics (strong for loop-mediated processes in the SM)
  - Deviations in $h \to Z f \bar{f}$ are likely to be seen/constrained earlier in TGB coupling measurements

NP searches: model building

- We can instead explore ideas that solve the SM naturalness problem and use them to motivate LHC searches:
- Two main contenders (but many more proposed)
  - Supersymmetry
    - Weakly coupled (can be extrapolated to MP)
    - Many extras “for free” (unification, DM, dynamical EWSB, string completions, …)
  - Compositeness
    - Already seen in Nature (in other examples)
    - Flavor realization, dynamical EWSB, new phase at TeV

Theorist-experimentalist interaction

- The story usually goes like this …
  - Theorists have a great idea

EUREKA!

Theorist-experimentalist interaction

- The story usually goes like this …
  - Theorists have a great idea
  - Run to tell their experimental friends

It's a beautiful idea, it has to be right,
it solves all our (my) problems!

Ok, how do we look for it?

You'll find it immediately.
My model predicts this amazing
bump here and enormous
departures from the background.
It's impossible to miss!
We'll be both famous!

Theorist-experimentalist interaction

- The story usually goes like this …
  - Theorists have a great idea
  - Run to tell their experimental friends
  - Experimentalists go back to their experiment and find nothing … and tell their theory friends

No significant departures observed, we exclude your model

Nah! That's 'cause you were looking only at the simplest possible realization of the model. You are just starting to explore the relevant parameter space of my model

But it is what you told me to look for!

Yep, I know, but what you should be really looking for is ...

Theorist-experimentalist interaction

- The story usually goes like this …
  - Theorists have a great idea
  - Run to tell their experimental friends
  - Experimentalists go back to their experiment and find nothing … and tell their theory friends
  - Theorists refine their predictions to comply with the minimal distance (to discovery) principle
  - It is the natural procedure in science:
    - Explore first the most dramatic signatures, if nothing is found try to figure out what more elusive signatures might look like

Model building: SUSY

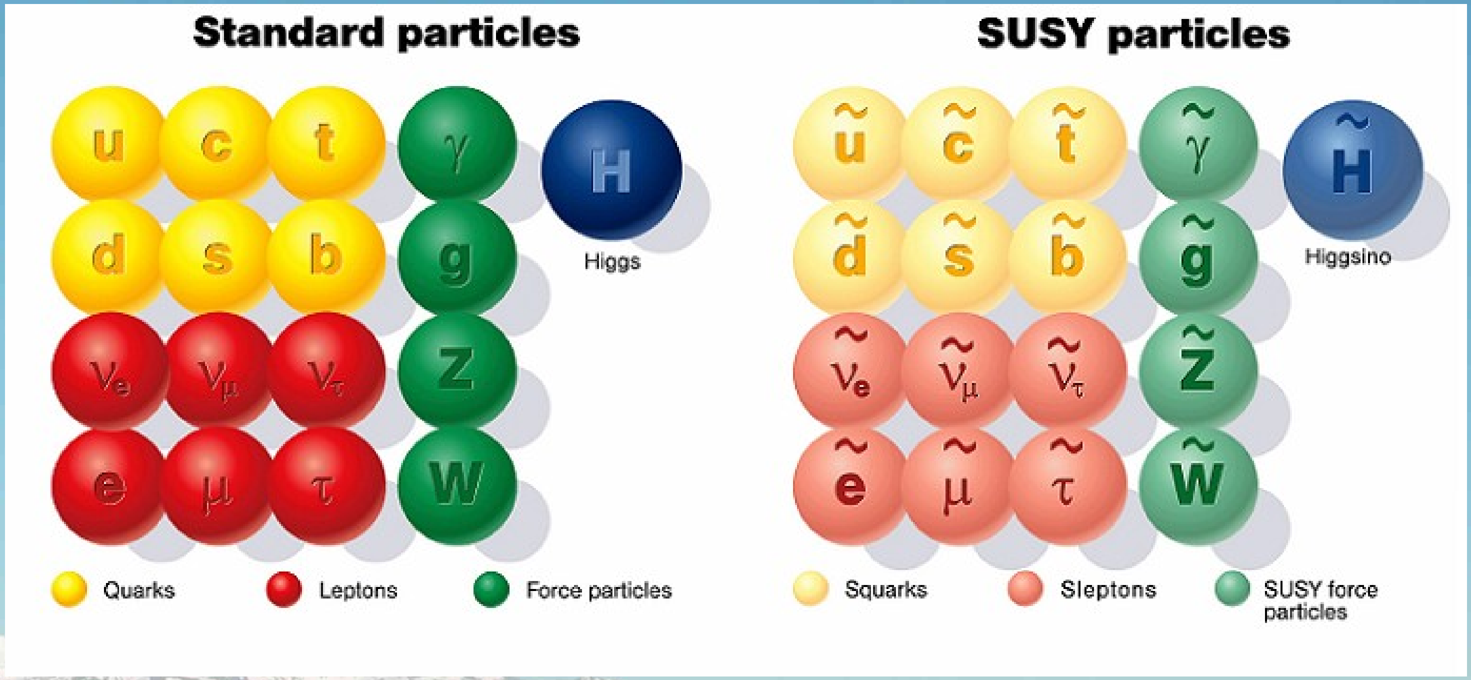
- SUSY: symmetry between particles with different spin

$$\delta B \sim \epsilon F, \quad \delta F \sim \epsilon B$$

Not a new idea!

Model building: SUSY

- SUSY: symmetry between particles with different spin
  - Many profound implications:
    - Spectrum gets doubled



Model building: SUSY

- SUSY: symmetry between particles with different spin
  - Many profound implications:
    - Spectrum gets doubled, except for an extended Higgs sector: we need 2 different Higgs doublets (hint: Higgsinos are chiral fermions)

8 real components: 3 would be Goldstones plus 5 physical scalars

$$\phi_d = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_d^0 + \mathrm{i} a_d^0 \\ \sqrt{2}\phi_d^- \end{pmatrix}$$

$$\phi_u = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}\phi_u^+ \\ \phi_u^0 + \mathrm{i} a_u^0 \end{pmatrix}$$

$$\begin{aligned} h &= -s_\alpha(\phi_d^0 - v_d) + c_\alpha(\phi_u^0 - v_u) \\ H &= c_\alpha(\phi_d^0 - v_d) + s_\alpha(\phi_u^0 - v_u) \\ A &= s_\beta a_d^0 + c_\beta a_u^0 \\ H^\pm &= s_\beta \phi_d^\pm + c_\beta \phi_u^\pm \end{aligned}$$

$$\tan\beta = \frac{\langle \phi_u^0 \rangle}{\langle \phi_d^0 \rangle} = \frac{v_u}{v_d}$$

$$v_u^2 + v_d^2 = v^2$$

Large tan β: enhanced bottom/tau Yukawa couplings (α also relevant)

Model building: SUSY

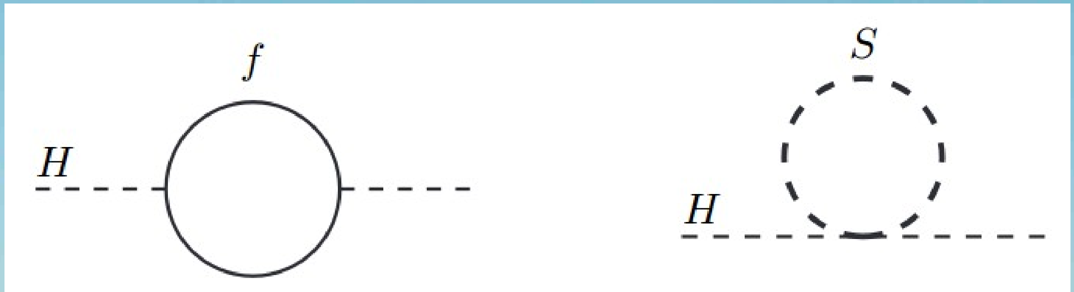
- SUSY: symmetry between particles with different spin
  - Many profound implications:
    - Spectrum gets doubled, except for an extended Higgs sector: we need 2 different Higgs doublets (hint: Higgsinos are chiral fermions)
    - Higgs potential strongly constrained by SUSY
      - Quartic coupling fixed by gauge interactions

$$m_h \leq m_Z \text{ at tree level (in MSSM)}$$

        - Loop corrections improve the situation but introduce tension in minimal models: very sensitive to stop mass and mixing

Model building: SUSY

- SUSY: symmetry between particles with different spin
  - Many profound implications:
    - Spectrum gets doubled, except for an extended Higgs sector: we need 2 different Higgs doublets (hint: Higgsinos are chiral fermions)
    - Higgs potential strongly constrained by SUSY
    - UV sensitivity of Higgs mass cancels:



Model building: SUSY

- SUSY: symmetry between particles with different spin
  - Many profound implications:
    - Spectrum gets doubled, except for an extended Higgs sector: we need 2 different Higgs doublets (hint: Higgsinos are chiral fermions)
    - Higgs potential strongly constrained by SUSY
    - UV sensitivity of Higgs mass cancels:
    - SUSY partners degenerate:
      - Introduce soft (relevant operators) SUSY breaking terms: lifts mass degeneracy but preserves cancellations in H mass

Model building: SUSY

- SUSY: symmetry between particles with different spin
  - Many profound implications:
    - Spectrum gets doubled, except for an extended Higgs sector: we need 2 different Higgs doublets (hint: Higgsinos are chiral fermions)
    - Higgs potential strongly constrained by SUSY
    - UV sensitivity of Higgs mass cancels:
    - SUSY partners degenerate:

$$\begin{aligned}
\mathcal{L}_{\rm soft}^{\rm MSSM} &= -\frac{1}{2}\left(M_3\widetilde{g}\widetilde{g} + M_2\widetilde{W}\widetilde{W} + M_1\widetilde{B}\widetilde{B} + \text{c.c.}\right) \\
&\quad -\left(\widetilde{\overline{u}}\,\mathbf{a_u}\,\widetilde{Q}H_u - \widetilde{\overline{d}}\,\mathbf{a_d}\,\widetilde{Q}H_d - \widetilde{\overline{e}}\,\mathbf{a_e}\,\widetilde{L}H_d + \text{c.c.}\right) \\
&\quad -\widetilde{Q}^\dagger\,\mathbf{m^2_Q}\,\widetilde{Q} - \widetilde{L}^\dagger\,\mathbf{m^2_L}\,\widetilde{L} - \widetilde{\overline{u}}\,\mathbf{m^2_{\overline{u}}}\,\widetilde{\overline{u}}^\dagger - \widetilde{\overline{d}}\,\mathbf{m^2_{\overline{d}}}\,\widetilde{\overline{d}}^\dagger - \widetilde{\overline{e}}\,\mathbf{m^2_{\overline{e}}}\,\widetilde{\overline{e}}^\dagger \\
&\quad - m^2_{H_u}H_u^*H_u - m^2_{H_d}H_d^*H_d - (bH_uH_d + \text{c.c.})\,.
\end{aligned}$$

Many new parameters:

- A lot of freedom
- Difficult to parameterize

Model building: SUSY

- SUSY: symmetry between particles with different spin
  - Many profound implications:
    - Spectrum gets doubled, except for an extended Higgs sector: we need 2 different Higgs doublets (hint: Higgsinos are chiral fermions)
    - Higgs potential strongly constrained by SUSY
    - UV sensitivity of Higgs mass cancels:
    - SUSY partners degenerate:
    - R-parity naturally implemented: Discrete symmetry, SM=even, Partners=odd
      - DM candidate, missing energy at colliders
      - New particles produced in pairs

Model building: SUSY

- SUSY: symmetry between particles with different spin
  - Generic features:
    - New light, colored particles (squarks, gluinos)
      - Large cross sections
      - Cascade decays (many particles in the final state) with missing energy
      - Tops commonly among intermediate produced particles (bottoms and leptons in final state)
    - Extended Higgs sector
      - New neutral (CP even and CP odd) Higgses
      - New charged Higgses

Model building: SUSY

- SUSY: symmetry between particles with different spin
  - Generic features … but how generic?
    - The huge number of parameters makes it difficult to consider (classify) all relevant options. Even worse if we consider non-minimal models.
      - Constrained models: take simplifying assumptions (mSUGRA: 5 parameters)
      - Phenomenological approach: pMSSM
      - Choose your favorite model and region of parameter space
      - Use simplified models

Simplified Models

Alwall, Schuster, Toro '09; Alves et al '12

- Simplified models: what are they (useful for)?
  - Simple models based on a few assumptions
    - Only a small number of particles and parameters involved in the process of interest
  - Useful first characterization of NP
  - Easy to interpret results in different models
  - Already adopted by experimental collaborations
    - But many realistic models are not simple

The Higgs as a composite pNGB

- If the Higgs we have discovered is the SM Higgs, it would be the first time an elementary scalar has been observed in nature
- Known examples of SSB and/or light scalars involve composite scalars:
  - Superconductivity: electron (Cooper) pairs condense due to their interactions with the phonons in a crystal
  - The pions are composite pNGB of chiral symmetry breaking
- Maybe the Higgs is also a composite state of a new strongly interacting theory?

The Higgs as a composite pNGB

- The QCD lesson: in the limit $m_u = m_d = 0$ QCD has an $SU(2)_L \times SU(2)_R$ invariance, broken spontaneously to $SU(2)_{L+R}$
- The pions are the three associated NG bosons
- QED breaks $SU(2)_{L+R}$ explicitly. It weakly gauges a U(1) subgroup making the pions pseudo-NGB (they acquire mass at loop level)

$$m_{\pi^\pm}^2 - m_0^2 \approx \frac{3\alpha_{em}}{4\pi} \frac{m_\rho^2 m_{a_1}^2}{m_{a_1}^2 - m_\rho^2} \log\left(\frac{m_{a_1}^2}{m_\rho^2}\right)$$

Using vector-meson dominance and Weinberg sum rules

The Higgs as a composite pNGB

- A naturally light composite Higgs: Ingredients
  - H as a pNGB: Georgi, Kaplan '80, ...
    - A new strongly coupled sector condenses at a scale f~TeV spontaneously breaking a global symmetry: H is the NGB of the breaking
  - Partial compositeness: Kaplan '91
    - The global symmetry is explicitly broken by a weakly coupled elementary sector that mixes linearly with the strong sector

$$\mathcal{L}_{\rm mix} = g A_\mu J^\mu + \left[\lambda_L \bar{q}_L \mathcal{O}_L + \lambda_R \bar{q}_R \mathcal{O}_R + \text{h.c.}\right]$$

$$\psi_{SM} = \cos\theta\ \psi_e + \sin\theta\ \psi_c$$
$$\psi_{\rm heavy} = -\sin\theta\ \psi_e + \cos\theta\ \psi_c$$

$$\tan\theta = \frac{\lambda f}{M}$$

Degree of compositeness

The Higgs as a composite pNGB

- A naturally light composite Higgs: Ingredients
  - H as a pNGB: Georgi, Kaplan '80, ...
    - A new strongly coupled sector condenses at a scale f~TeV spontaneously breaking a global symmetry: H is the NGB of the breaking
  - Partial compositeness: Kaplan '91
    - The global symmetry is explicitly broken by a weakly coupled elementary sector that mixes linearly with the strong sector
    - Flavor violation is proportional to the degree of compositeness (softens flavor constraints although some structure might be needed)

Csaki et al '08-'09; J.S. '08; Keren-Zur et al '13; ...

The Higgs as a composite pNGB

- The revival of composite Higgs models
  - Composite Higgs models have received a huge attention only in the last few years

The Minimal composite Higgs model
Kaustubh Agashe, Roberto Contino (Johns Hopkins U.), Alex Pomarol (Barcelona, IFAE). Dec 2004. 27 pp.
Published in **Nucl.Phys. B719 (2005) 165-187**
UAB-FT-567
DOI: 10.1016/j.nuclphysb.2005.04.035
e-Print: **hep-ph/0412089 | PDF**

References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service

Detailed record - Cited by 534 records 500+

The Higgs as a composite pNGB

- The revival of composite Higgs models
  - Composite Higgs models have received a huge attention only in the last few years
  - Thanks to the AdS/CFT correspondence it was understood that CHM were duals to weakly coupled (calculable) models with warped extra dimensions
  - Higgs as a pNGB corresponds to gauge-Higgs unification models ($H \sim A_5$)
  - Partial compositeness is automatically realized
    - Pro: makes models calculable
    - Con: easy to keep prejudices from models with Xdims

The Higgs as a composite pNGB

- Realistic composite Higgs models
  - Need custodial symmetry — Agashe, Contino, Pomarol '05
  - Need to protect $Zb_L\bar{b}_L$ coupling — Agashe, Contino, Da Rold, Pomarol '06
- Can be minimal — Agashe, Contino, Pomarol '05

$$SO(5)/SO(4) \times P_{LR}$$

Has 4 NGB transforming as a 4 of SO(4): just like the SM Higgs!

- Or have an extended Higgs sector
  - Singlets: $SO(6)/SO(5)$ — Gripaios, Pomarol, Riva, Serra '09
  - Doublets: $SO(7)/G_2$ — Chala '13
    $SO(6)/SO(4) \times SO(2)$ — Mrazek, Pomarol, Rattazzi, Redi, Serra, Wulzer '11
  - ...

The Higgs as a composite pNGB

- General features at the LHC?
  - Higgs physics:
    - Higgs potential is dynamically generated and calculable: the observed Higgs mass has implications on the spectrum (from naturalness arguments)
    - Higgs couplings are modified (by v^2/f^2 terms)
  - Extended structures:
    - new resonances with ~TeV masses (fermions and bosons). Generically small couplings to light SM particles and large couplings to heavy SM particles and other massive resonances
    - New vector-like quarks, some with exotic charges (-4/3, -1/3, 2/3, 5/3, 8/3, …), also possibly leptons

The Higgs as a composite pNGB

- How do we build Composite Higgs Models?
  - Higgs is the NGB or G/H symmetry breaking pattern: non-linear realization (Callan), Coleman, Wess, Zumino '69
  - Sometimes it is easier to use the Goldstone matrix to write directly a G-invariant effective Lagrangian

Explicit example: SO(5)/SO(4)

$$\Sigma_0 = (0,0,0,0,1)^{\mathrm{T}}$$ SO(4) preserving vacuum (H singlet)

$$\Sigma = e^{\mathrm{i}\sqrt{2}\pi^{\hat{a}}T^{\hat{a}}}\Sigma_0 = (0,0,0,\sin(h/f),\cos(h/f))^{\mathrm{T}}$$ Transforms as a 5 of SO(5)

Explicit breaking through spurions: embed SM fields in full SO(5) multiplets

$$\Psi_L = \left[\begin{array}{c} \begin{pmatrix} q' \\ q \end{pmatrix} \\ u' \end{array}\right], \quad \Psi_R = \left[\begin{array}{c} \begin{pmatrix} \tilde{q}' \\ \tilde{q} \end{pmatrix} \\ u \end{array}\right]$$

A_μ adjoint of $SO(5)$

The Higgs as a composite pNGB

- How do we build Composite Higgs Models?
  - Higgs is the NGB or G/H symmetry breaking pattern: non-linear realization (Callan), Coleman, Wess, Zumino '69
  - Sometimes it is easier to use the Goldstone matrix to write directly a G-invariant effective Lagrangian

Explicit example: SO(5)/SO(4)

Most general SO(5) invariant Lagrangian at quadratic level

$$\begin{aligned}\mathcal{L} = {} & \tfrac{1}{2}(P_T)^{\mu\nu}\big[\Pi_0^X(q^2)X_\mu X_\nu + \Pi_0(q^2)\mathrm{Tr}(A_\mu A_\nu) + \Pi_1(q^2)\Sigma^T A_\mu A_\mu \Sigma\big] \\ & + \textstyle\sum_{r=L,R} \bar{\Psi}_r \not{q}\left[\Pi_0^r(q^2) + \Pi_1^r(q^2)\Sigma\Sigma^{\mathrm{T}}\right]\Psi_r \\ & + \left\{\bar{\Psi}_L\left[M_0(q^2) + M_1(q^2)\Sigma\Sigma^{\mathrm{T}}\right]\Psi_R + \mathrm{h.c.}\right\}\end{aligned}$$

Many relevant properties can be computed in terms of the form factors (that can in turn be computed in 5D models, large N limit, etc.): Gauge boson masses and couplings, fermion masses and couplings, Higgs potential, ...

The Higgs as a composite pNGB

- How do we build Composite Higgs Models?

Explicit example: SO(5)/SO(4)

$$\mathcal{L} = (P_T)^{\mu\nu}\Big\{\frac{1}{2}\left(\frac{f^2\sin^2(\langle h\rangle/f)}{4}\right)\left(B_\mu B_\nu + W^3_\mu W^3_\nu - 2W^3_\mu B_\nu\right) + \left(\frac{f^2\sin^2(\langle h\rangle/f)}{4}\right) W^+_\mu W^-_\nu + \frac{q^2}{2}\Big[\Pi'_0(0)\, W^{a_L}_\mu W^{a_L}_\nu + \left(\Pi'_0(0) + \Pi^{X}_0{}'(0)\right) B_\mu B_\nu\Big] + \ldots\Big\}$$

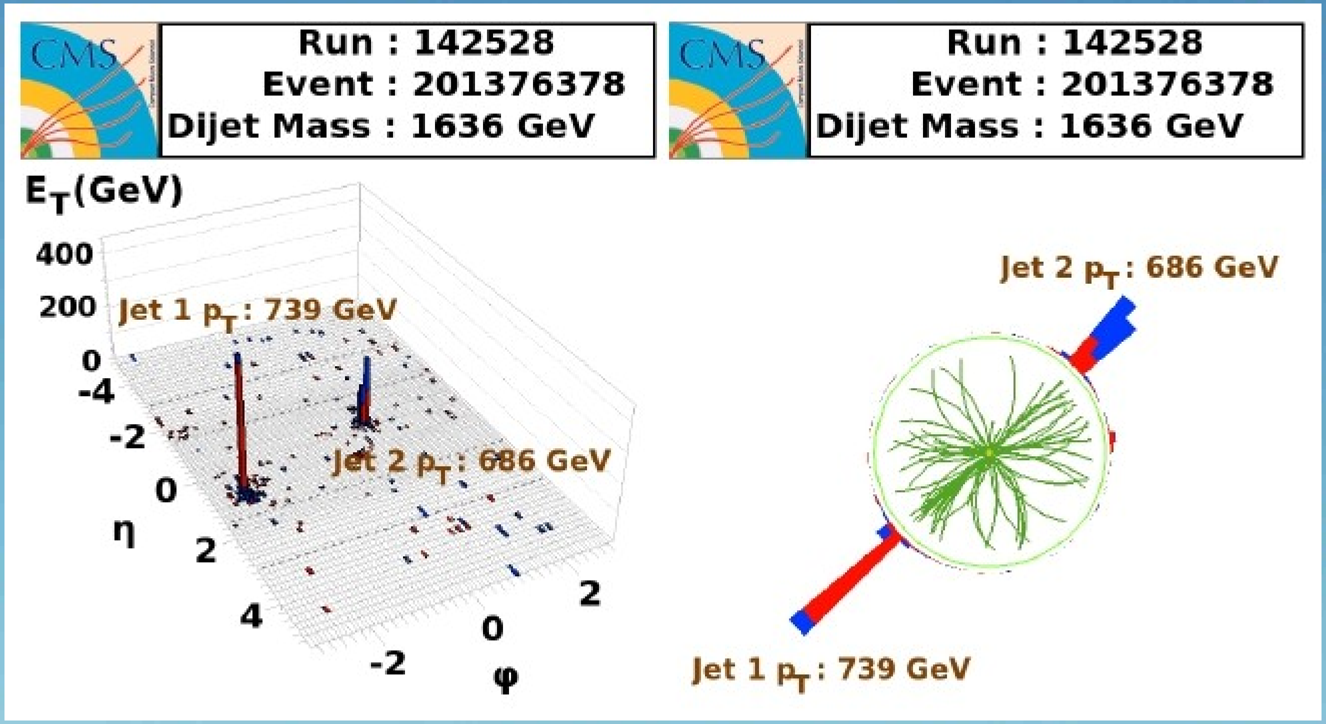
$$v = f\sin(\langle h\rangle/f)$$

$$\mathcal{L} = \sum_{r=L,R} \bar{t}_r\, \not{q}\left[\Pi^r_0 + \frac{s_h^2}{2}\Pi^r_1\right] t_r + \frac{s_h c_h}{\sqrt{2}}\left[\bar{t}_L M_1 t_R + \text{h.c.}\right] + \ldots$$

$$m_t \approx \frac{s_h c_h}{\sqrt{2}}\frac{M_1(0)}{\sqrt{Z_L Z_R}}$$

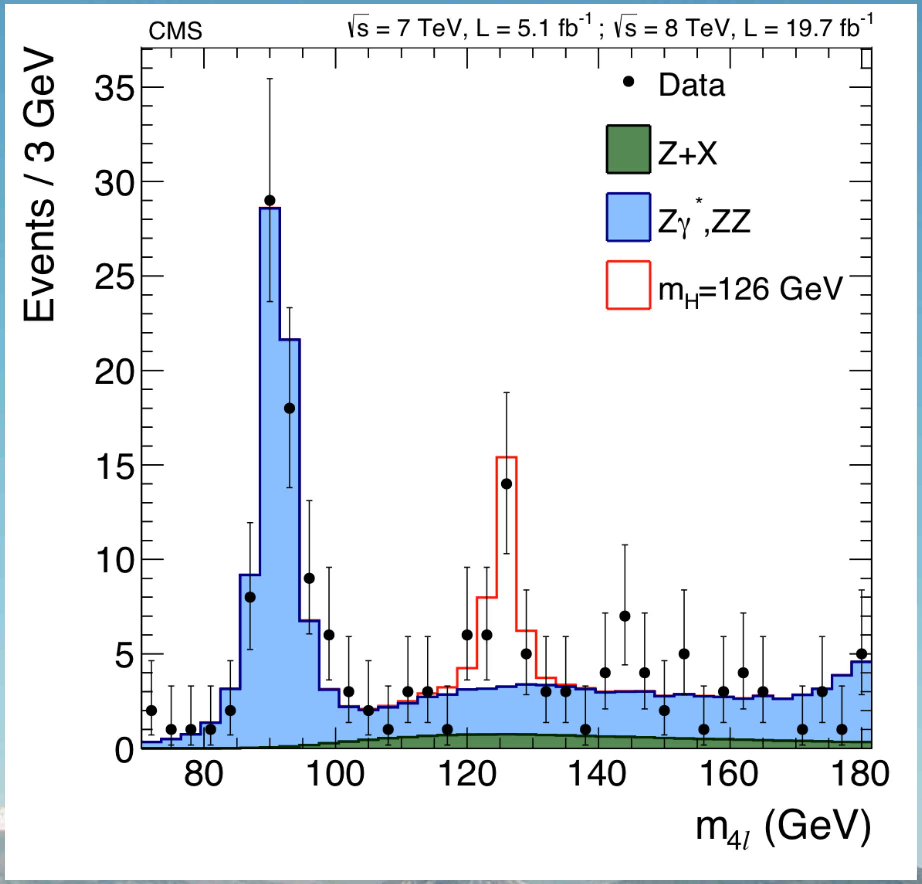
$$V(h) = \frac{9}{2}\int\frac{d^4Q}{(2\pi)^4}\ln\left(\Pi_0 + \frac{s_h^2}{2}\Pi_1\right) - 6\int\frac{d^4Q}{(2\pi)^4}\Big\{\ln\left[\Pi^L_0 + \frac{s_h^2}{2}\Pi^L_1\right] + \ln\left[Q^2\left(\Pi^L_0 + \frac{s_h^2}{2}\Pi^L_1\right)\left(\Pi^R_0 + \frac{s_h^2}{2}\Pi^R_1\right) - \frac{s_h^2 c_h^2}{2}M_1^2\right]\Big\}$$

Implications from recent high p_T data



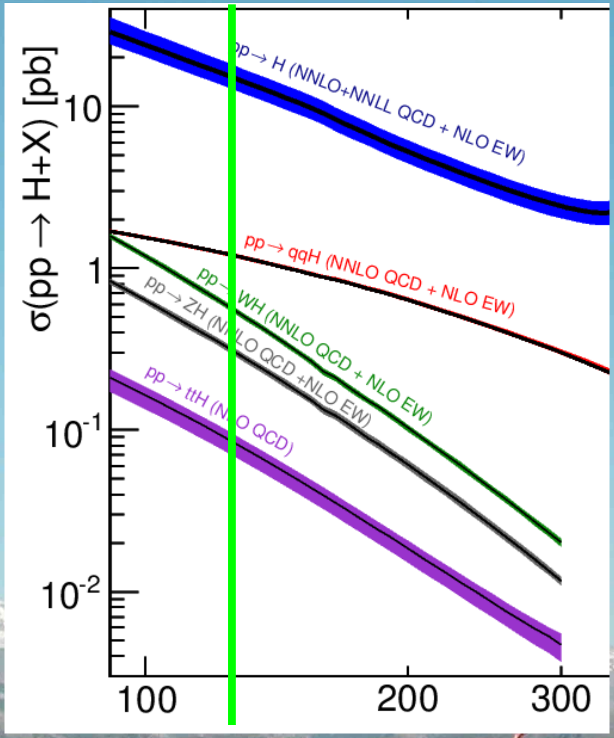
Implications from recent high p_T data

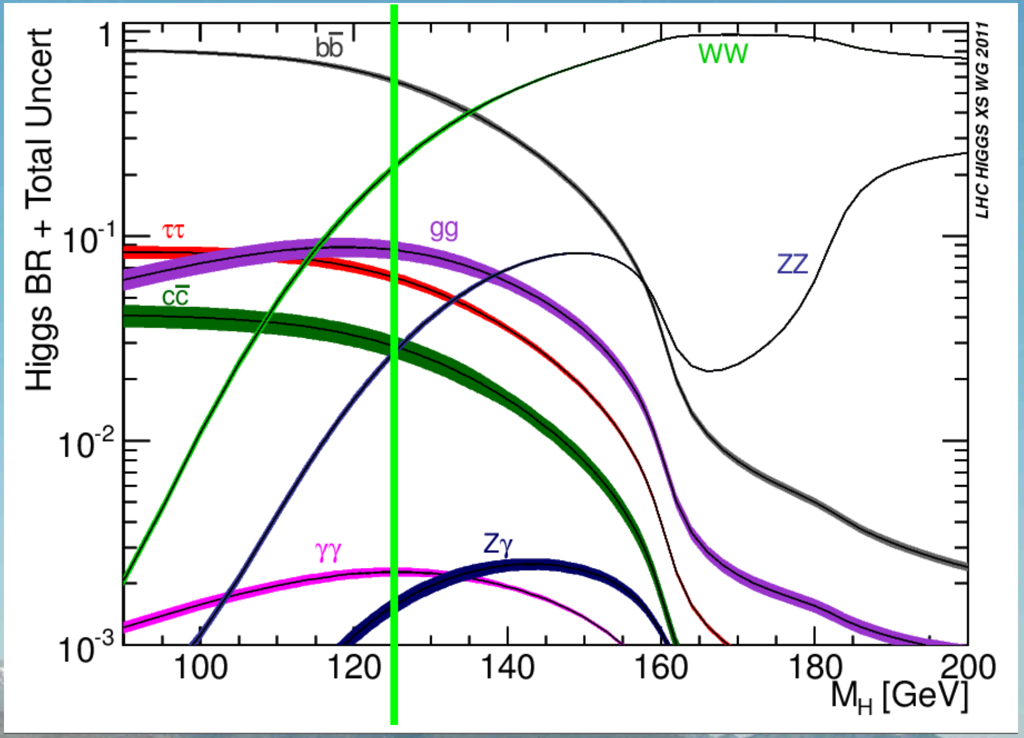
- Higgs searches @ LHC and constraints on new physics
- A Higgs boson has been discovered with m ~125 GeV



Implications from recent high p_T data

- Higgs searches @ LHC and constraints on new physics
- A Higgs boson has been discovered with m ~125 GeV
- 125 GeV is a very special value
  - In the SM

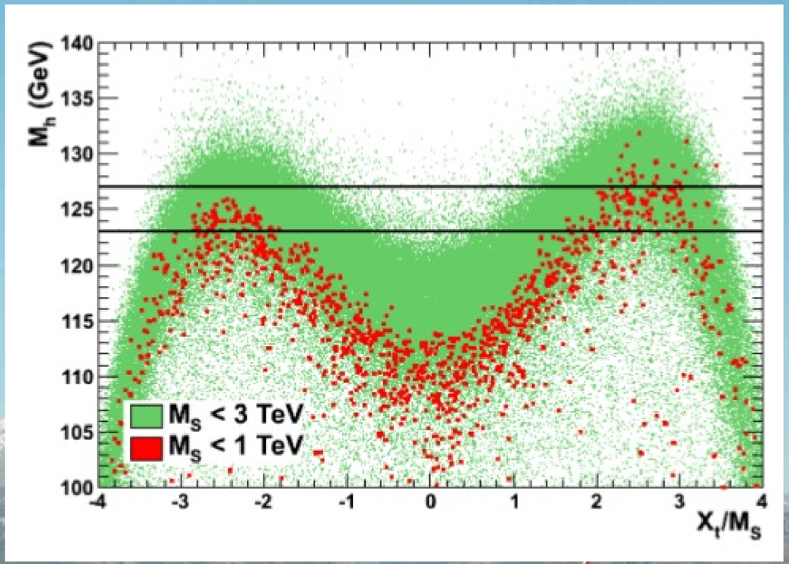




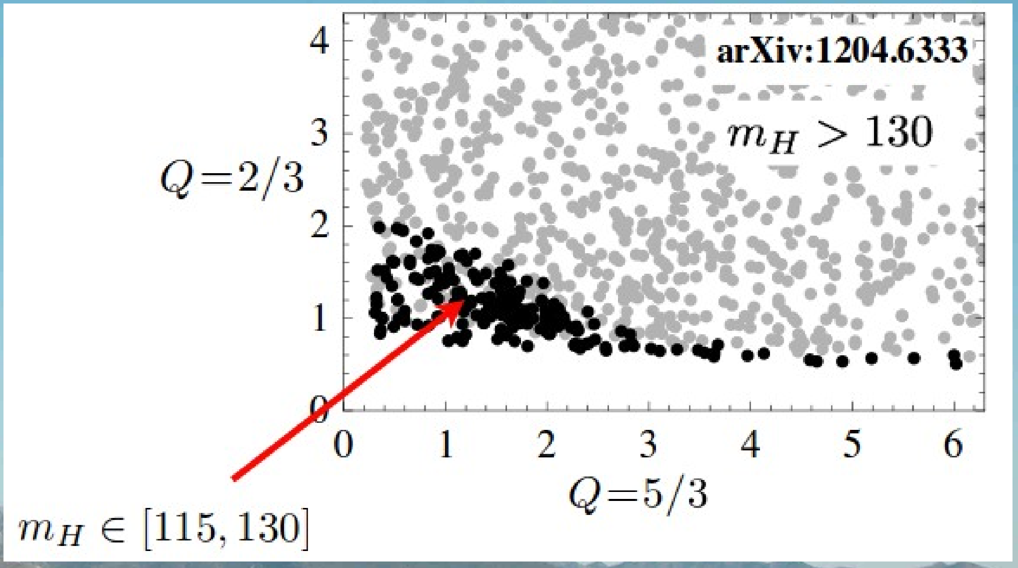
Implications from recent high p_T data

- Higgs searches @ LHC and constraints on new physics
- A Higgs boson has been discovered with m ~125 GeV
- 125 GeV is a very special value
  - In the SM
  - And in BSM

pMSSM



MCHM



Implications from Higgs mass

Implications from recent high p_T data

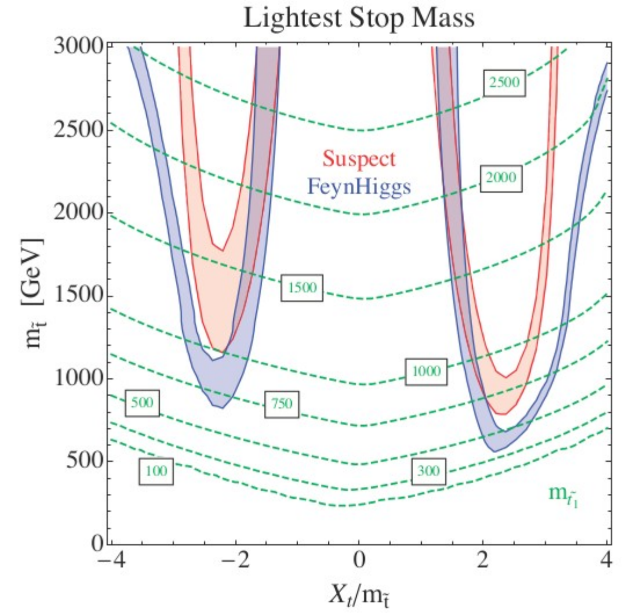
- Implications of the Higgs mass for SUSY (MSSM)

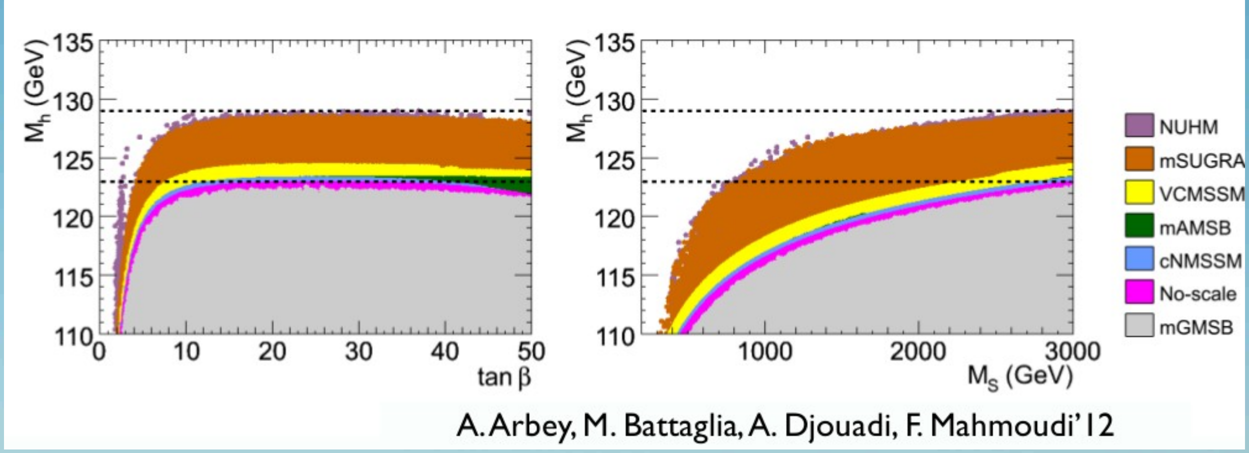
$$m_h^2 \cong M_Z^2 \cos^2 2\beta + \frac{3}{4\pi^2}\frac{m_t^4}{v^2}\left[\frac{1}{2}\tilde{X}_t + t + \frac{1}{16\pi^2}\left(\frac{3}{2}\frac{m_t^2}{v^2} - 32\pi\alpha_3\right)\left(\tilde{X}_t t + t^2\right)\right]$$

$$t = \log(M_{SUSY}^2/m_t^2) \qquad \tilde{X}_t = \frac{2X_t^2}{M_{SUSY}^2}\left(1 - \frac{X_t^2}{12M_{SUSY}^2}\right)$$

Carena et al '95, ...

Very sensitive to the stop mixing parameter X_t





Models that predict a low X_t are strongly constrained

Implications from recent high p_T data

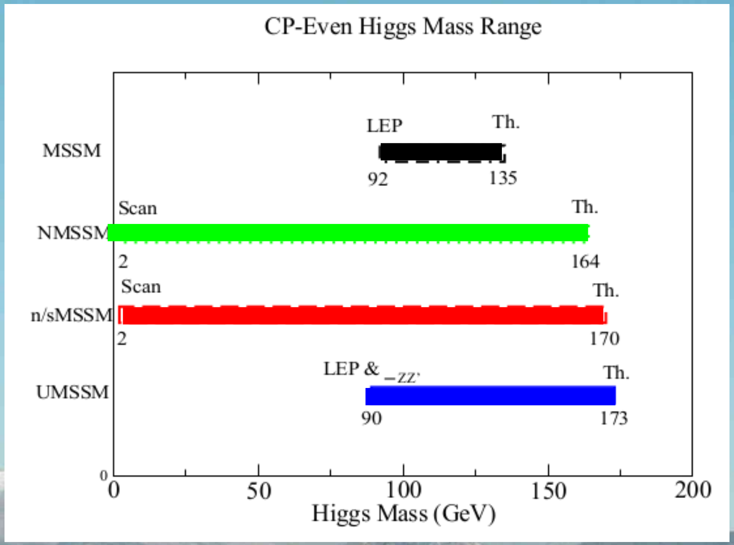
- Implications of the Higgs mass for SUSY (MSSM)

$$\boxed{m_h^2 \cong M_Z^2\cos^2 2\beta + \frac{3}{4\pi^2}\frac{m_t^4}{v^2}\left[\frac{1}{2}\tilde{X}_t + t + \frac{1}{16\pi^2}\left(\frac{3}{2}\frac{m_t^2}{v^2} - 32\pi\alpha_3\right)\left(\tilde{X}_t t + t^2\right)\right]}$$

$$t = \log(M_{SUSY}^2/m_t^2) \qquad \tilde{X}_t = \frac{2X_t^2}{M_{SUSY}^2}\left(1-\frac{X_t^2}{12M_{SUSY}^2}\right)$$

Carena et al '95, ...

- Constraints are significantly relaxed in extensions of the MSSM



Implications from recent high p_T data

- Implications of the Higgs mass for Composite Higgs
  - EWSB triggered by the top (gauge contribution aligned with zero vev)
  - Quartic coupling (therefore mass) typically too large
  - H mass compatible with 125 if top partners are light

$$m_h^2 \approx \frac{6}{\pi^2}\frac{m_t^2}{f^2}\frac{m_4^2 m_1^2}{m_1^2 - m_4^2}\log\left(\frac{m_1}{m_4}\right), \quad (\text{in } SO(5)/SO(4))$$

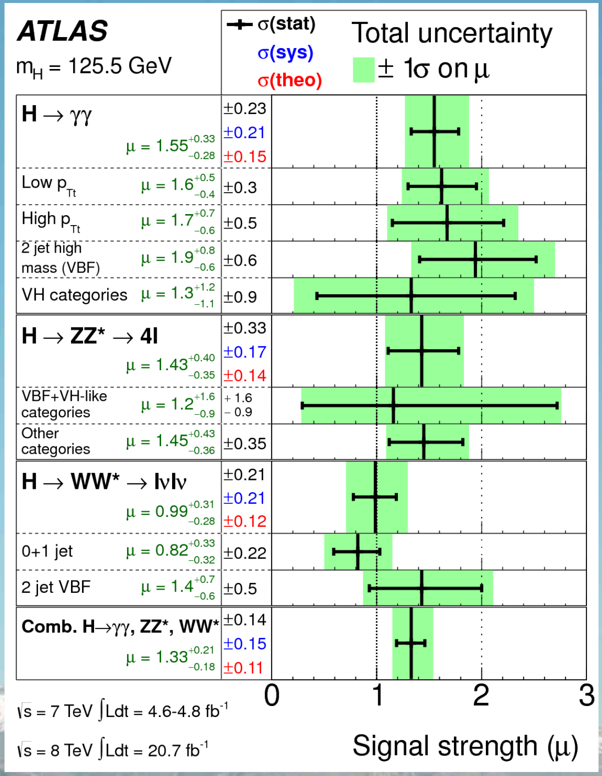
  - Quite generic in Composite Higgs models

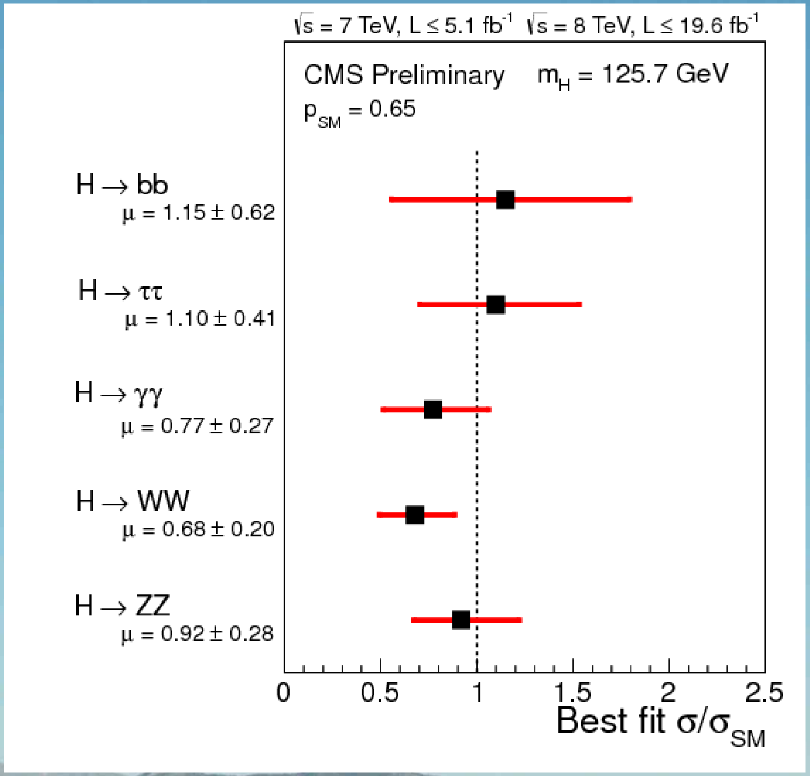
Matsedonskyi, Panico, Wulzer '13; Redi, Tesi '12; Marzocca, Serone, Shu '12; Pomarol, Riva '12; Panico et al '13, De Simone et al '13

Implications from Higgs couplings

Implications from recent high p_T data

- Higgs searches @ LHC and constraints on new physics
- Its production cross section times BR are quite compatible with the SM Higgs ones (with large errors)



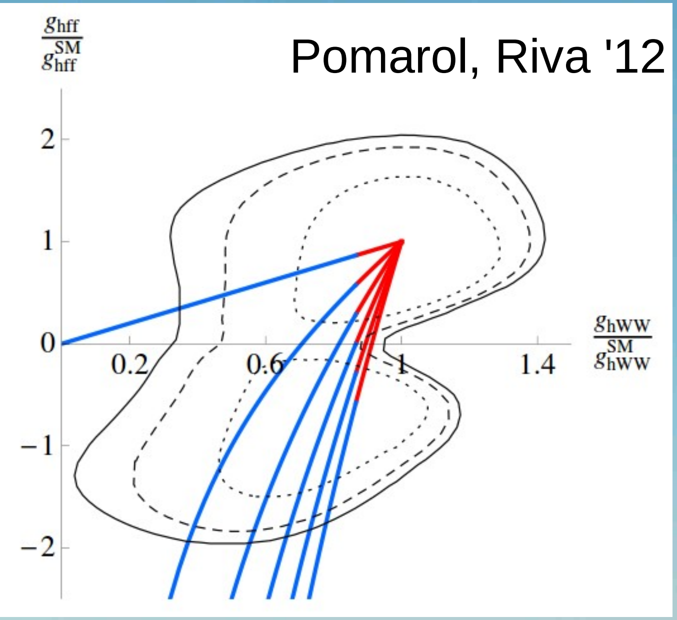


Implications from recent high p_T data

- Higgs searches @ LHC and constraints on new physics
- Its production cross section times BR are quite compatible with the SM Higgs ones (with large errors)
  - Constraints on new contributions are relatively mild:
    - SUSY:
      - Decoupling limit (mH, mA, mH+ heavy, h is SM-like)
      - Other constraints tend to make stop, bottom contributions to gg->H, … small

Implications from recent high p_T data

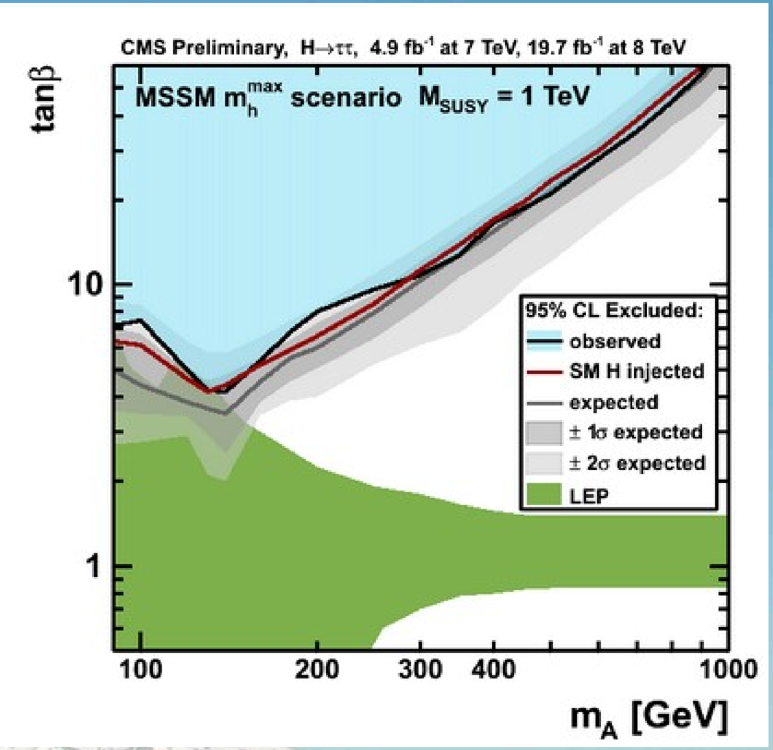
- Higgs searches @ LHC and constraints on new physics
- Its production cross section times BR are quite compatible with the SM Higgs ones (with large errors)
  - Constraints on new contributions are relatively mild:
    - Composite Higgs Models:
      - Higgs couplings modified by v^2/f^2 effects.
      - Current constraints are weaker than EWPT
      - Contribution from top partners in loop-mediated processes tend to cancel due to symmetries



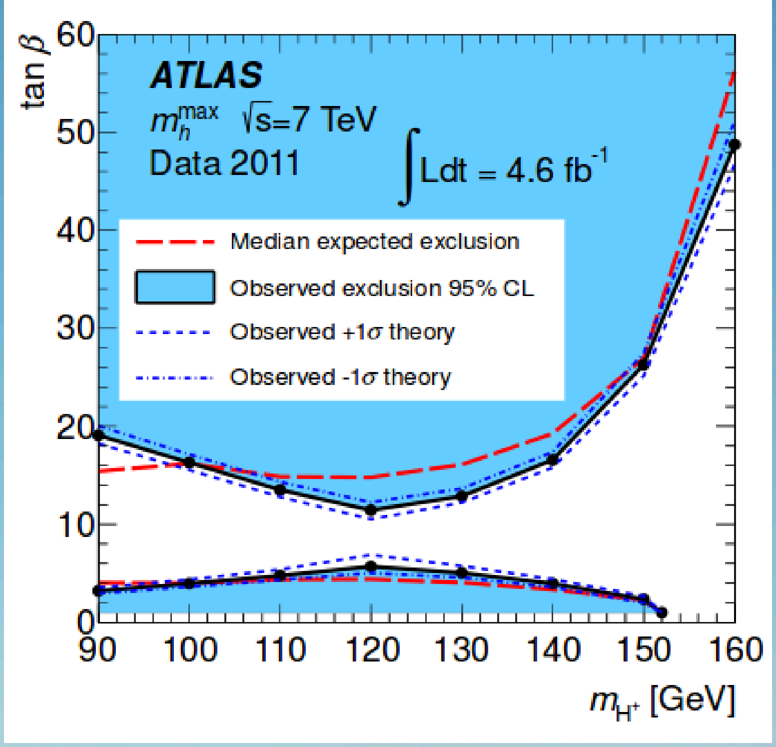
Implications from exotic Higgs searches

Implications from recent high p_T data

- Higgs searches @ LHC and constraints on new physics
- Searches for extra Higgses impose further constraints
  - But again they are not dramatic



$\Phi \to \tau\tau$



$t \to H^+ b$

Implications from direct searches

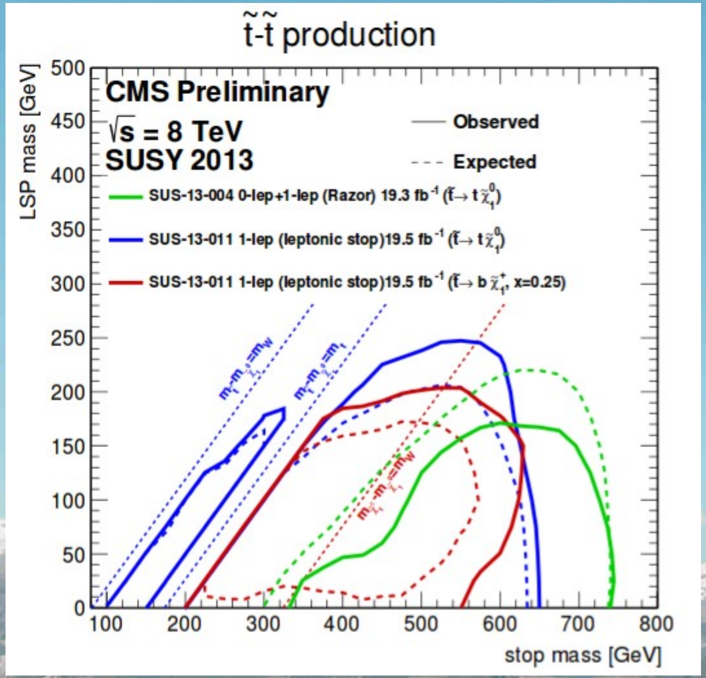
Implications from recent high p_T data

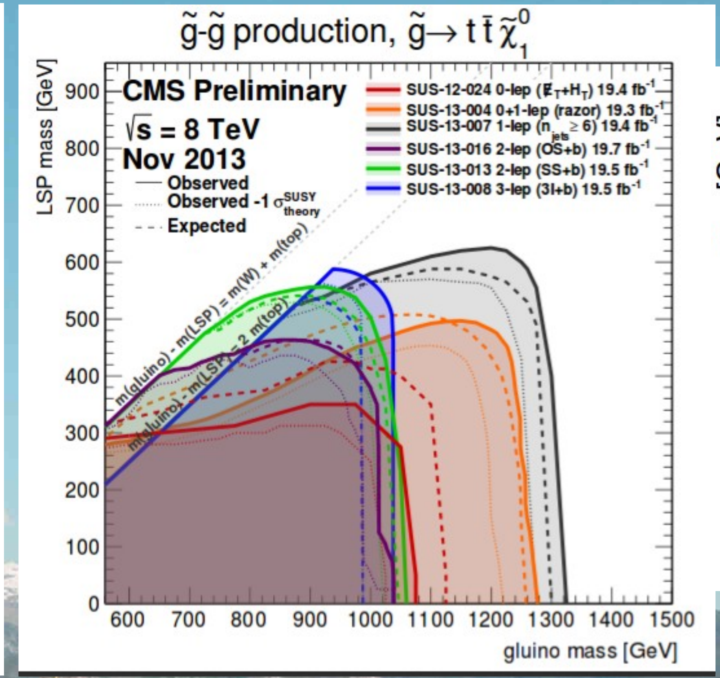
- Implications of direct searches for SUSY:
  - SUSY has been "non-exotic" for quite some time
  - Huge list of different analyses targeting all imaginable signatures

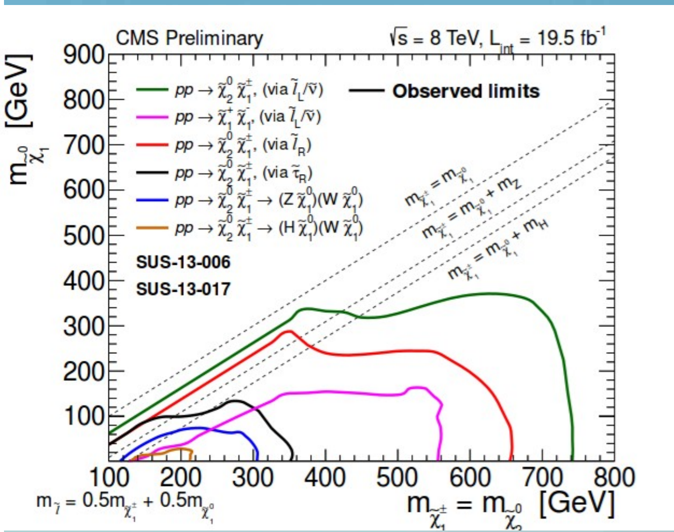
Short Title of preliminary conference note	*Date*	*√s (TeV)*	*L (fb^{-1})*
2 photons + Etmiss [GGM] NEW	01/2014	8	20.3
1 lepton + bb(H) + Etmiss [EW production]	08/2013	8	20.3
Muon + displaced vertex [RPV]	08/2013	8	20.3
Multijets [RPV]	08/2013	8	20.3
2 leptons + jets + Etmiss [incl. squarks & gluinos]	08/2013	8	20.3
0 leptons + mono-jet/c-jets + Etmiss [Stop in charm+LSP]	07/2013	8	20.3
2 leptons + (b)jets + Etmiss [Medium stop, MVA]	07/2013	8	20.3
1-2 leptons + 3-6 jets + Etmiss [Incl. squarks & gluinos, mUED]	06/2013	8	20.3
0-1 leptons + >=3 b-jets + Etmiss [3rd gen. squarks]	06/2013	8	20.1
Long-lived sleptons	06/2013	8	15.9
2 leptons + Etmiss [EW production]	05/2013	8	20.3
0 leptons + 2-6 jets + Etmiss [Incl. squarks & gluinos]	05/2013	8	20.3
2 leptons (+ jets) + Etmiss [Medium stop]	05/2013	8	20.3
1 lepton + 4(1 b-)jets + Etmiss [Medium / heavy stop]	03/2013	8	20.7
3 leptons + Etmiss [EW production]	03/2013	8	20.7
4 leptons + Etmiss [EW production, RPV]	03/2013	8	20.7

Implications from recent high p_T data

- Implications of direct searches for SUSY:
  - SUSY has been “non-exotic” for quite some time
  - Huge list of different analyses targeting all imaginable signatures
  - Difficult to grasp all this information in terms of global impact on specific models







Implications from recent high p_T data

- Implications of direct searches for SUSY:
  - SUSY has been “non-exotic” for quite some time
  - Huge list of different analyses targeting all imaginable signatures
  - Difficult to grasp all this information in terms of global impact on specific models
  - Several options:
    - Choose one model and study all constraints
    - Use a phenomenological/statistical approach
    - Use general arguments based on naturalness and generic features

Implications from recent high p_T data

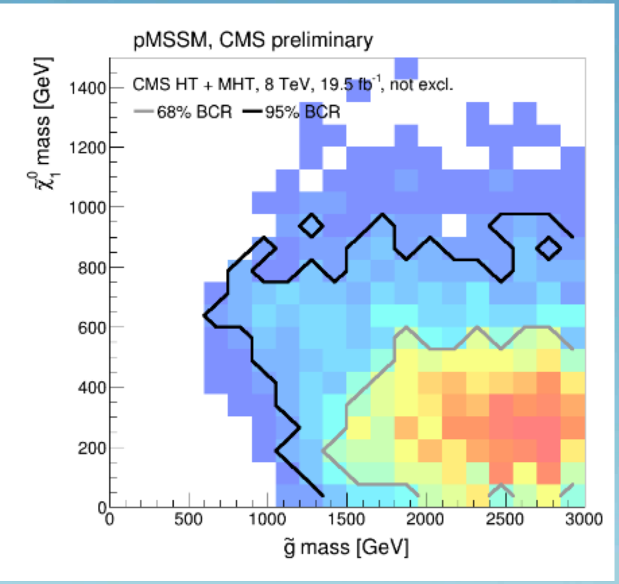
- Implications of direct searches for SUSY:
  - Choose one model and study all constraints
    - CMSSM: Universal soft terms at the GUT scale
      - Strongly constrained by direct searches but also by Higgs mass, DM and flavor

Buchmueller et al '13

Sparticle	CMSSM $\mu > 0$	CMSSM $\mu < 0$	NUHM $\mu > 0$
$\tilde{g}$	1810	(2100) (3200) 3540	1920
$\tilde{q}_R$	1620	(1900) 6300	1710
$\tilde{t}_1$	750	(950) 4100	(650) 1120
$\tilde{\tau}_1$	340	(400) 4930	380
M_A	690	(1900) 3930	450

Implications from recent high p_T data

- Implications of direct searches for SUSY:
  - Use a phenomenological/statistical approach
    - pMSSM: Reduce a bit the number of parameters and scan over them



- CMS data (and ATLAS also) is significantly impacting the pMSSM parameter space, excluding most, but certainly not all, of the high σ models.
- In the case of unexcluded high-σ models, small mass splittings are primarily to blame for lack of sensitivity. $\Rightarrow$ might gain sensitivity using more refined analyses of current data.

  But, there are many low-σ models that can only be explored with more energy and luminosity at the LHC. $\Rightarrow$ both are coming!

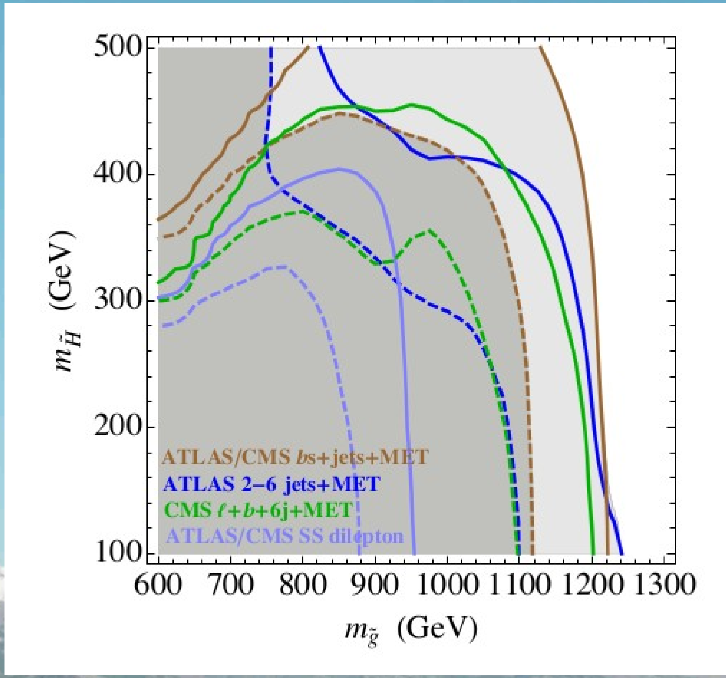
Taken from: J. Gunion, SUSY at the Near Energy Frontier, November 10, 2013 1

Implications from recent high p_T data

- Implications of direct searches for SUSY:
  - Use general arguments based on naturalness
    - What are the most likely features of a natural supersymmetric theory? Evans, Kats, Shih, Strassler '13
      - Large missing ET
      - Tops
      - Large particle multiplicity
      - … and other things that are much easier to find
    - Not all models of natural SUSY have all three features but very few have none of them
    - Assuming gauginos are within LHC8 reach (~1.4 TeV), Higgsinos are natural (≤400 GeV), what is the impact of LHC searches?

Implications from recent high p_T data

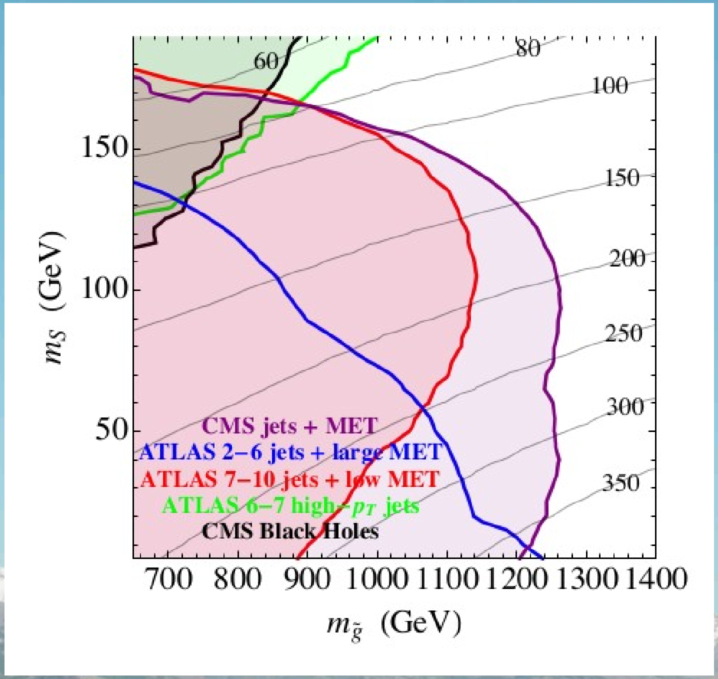
- Implications of direct searches for SUSY:
  - Use general arguments based on naturalness
    - Assuming gauginos are within LHC8 reach (~1.4 TeV), Higgsinos are natural (≤400 GeV), what is the impact of LHC searches? Evans, Kats, Shih, Strassler '13



Vanilla spectrum with tops and missing ET strongly constrained

Implications from recent high p_T data

- Implications of direct searches for SUSY:
  - Use general arguments based on naturalness
    - Assuming gauginos are within LHC8 reach (~1.4 TeV), Higgsinos are natural (≤400 GeV), what is the impact of LHC searches? Evans, Kats, Shih, Strassler '13

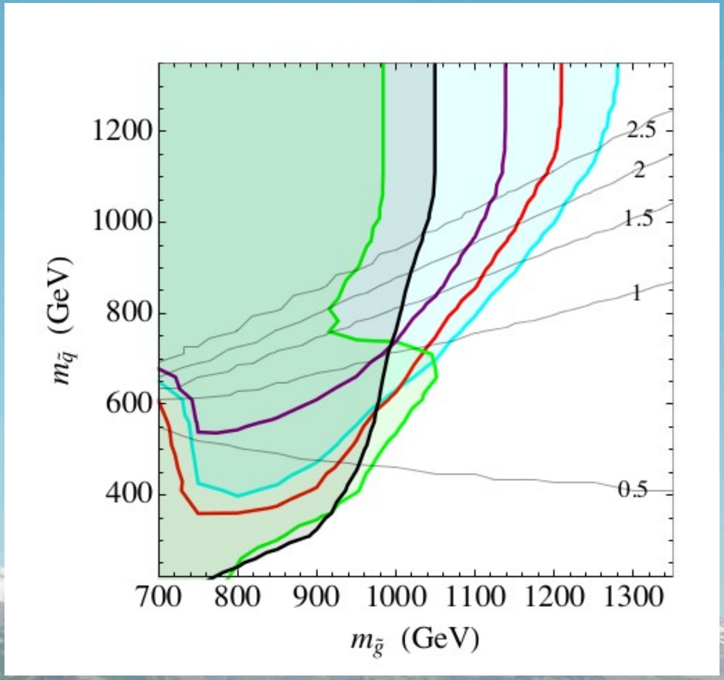


Vanilla spectrum with tops and missing ET strongly constrained

Reducing missing ET can soften the constraints (only in small corners)

Implications from recent high p_T data

- Implications of direct searches for SUSY:
  - Use general arguments based on naturalness
    - Assuming gauginos are within LHC8 reach (~1.4 TeV), Higgsinos are natural (≤400 GeV), what is the impact of LHC searches? Evans, Kats, Shih, Strassler '13



Vanilla spectrum with tops and missing ET strongly constrained

Reducing missing ET can soften the constraints (only in small corners)

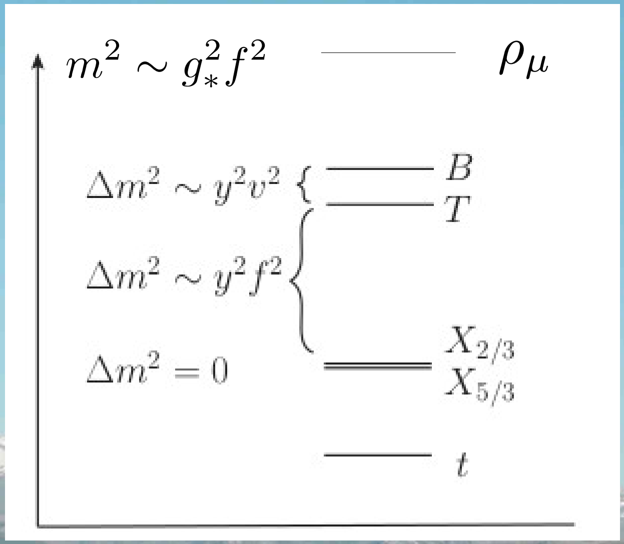
Reducing tops and missing ET provides another difficult to explore corner

Implications from recent high p_T data

- Implications of direct searches for SUSY:
  - Use general arguments based on naturalness
    - Assuming gauginos are within LHC8 reach (~1.4 TeV), Higgsinos are natural (≤400 GeV), what is the impact of LHC searches? Evans, Kats, Shih, Strassler '13
    - It is not easy to avoid all three features: missing ET, tops and high multiplicities
    - Natural SUSY not excluded but extensively probed by LHC 8
    - High-multiplicity searches (BH motivated) help closing difficult corners of parameter space

Implications from recent high p_T data

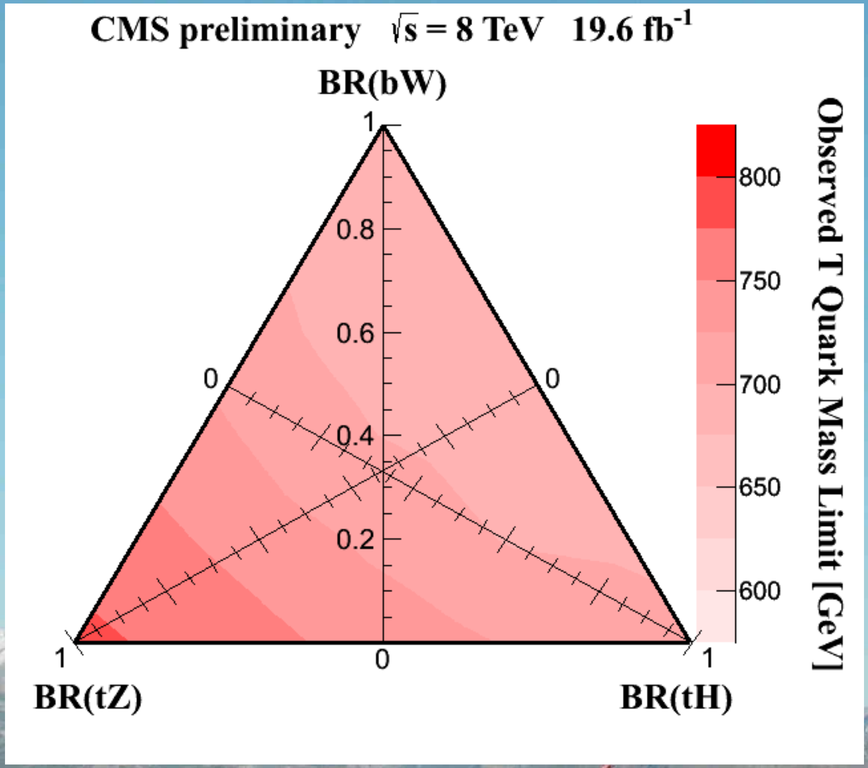
- Implications of direct searches for CHM:
  - CHM predict:
    - Light (-ish) vector-like quarks, possibly with exotic charges (top partners) and sizeable couplings to t,b and W, Z
    - Relatively heavy (~few TeV) vector resonances with small couplings to light SM fermions

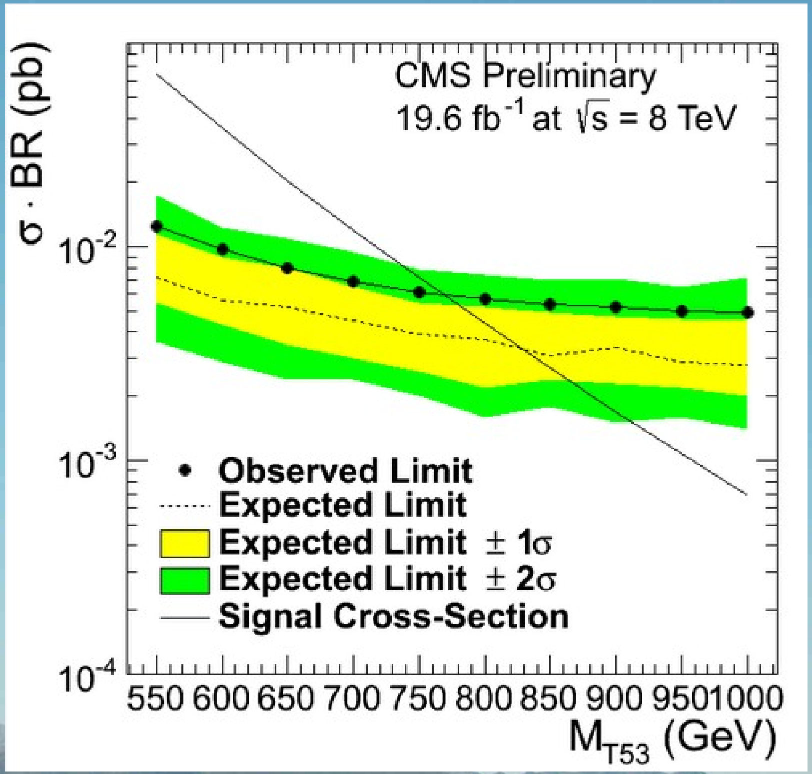


De Simone, Matsedonskyi, Rattazzi, Wulzer '13

Implications from recent high p_T data

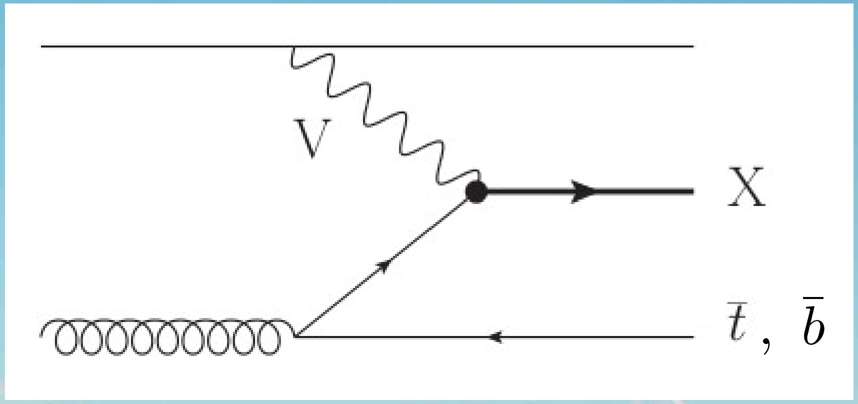
- Implications of direct searches for CHM:
  - New quark searches and impact on CHM
    - Current bounds on top partners consider pair production (but are quite general on decays)

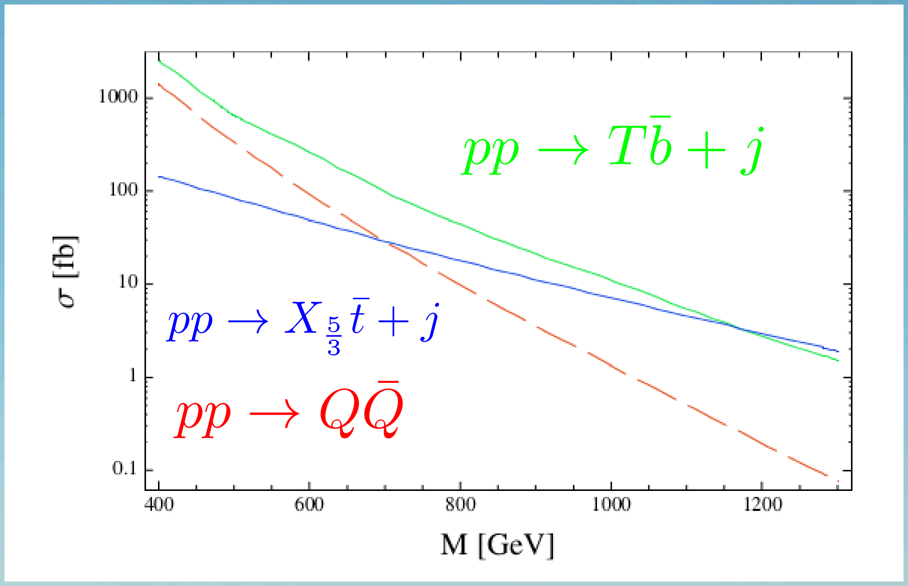




Implications from recent high p_T data

- Implications of direct searches for CHM:
  - New quark searches and impact on CHM
    - Current bounds on top partners consider pair production (but are quite general on decays)
    - Large EW couplings: single production relevant

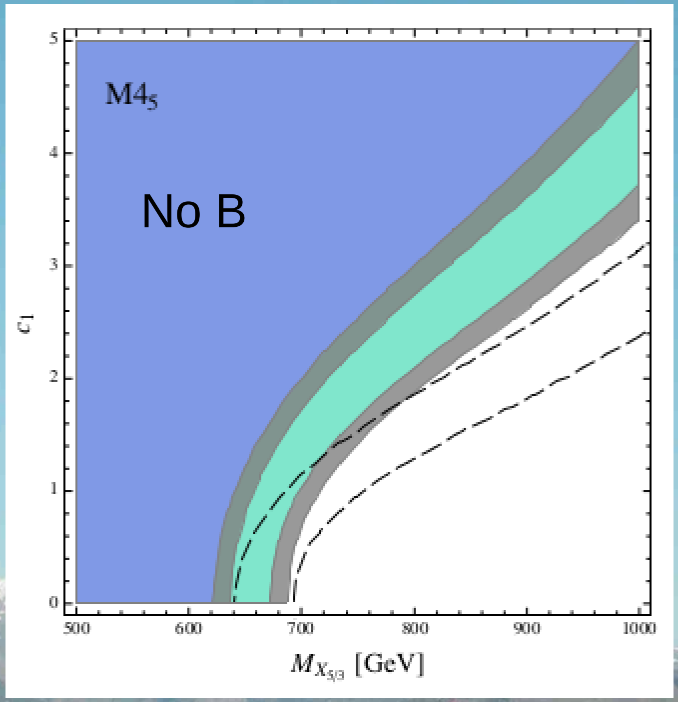


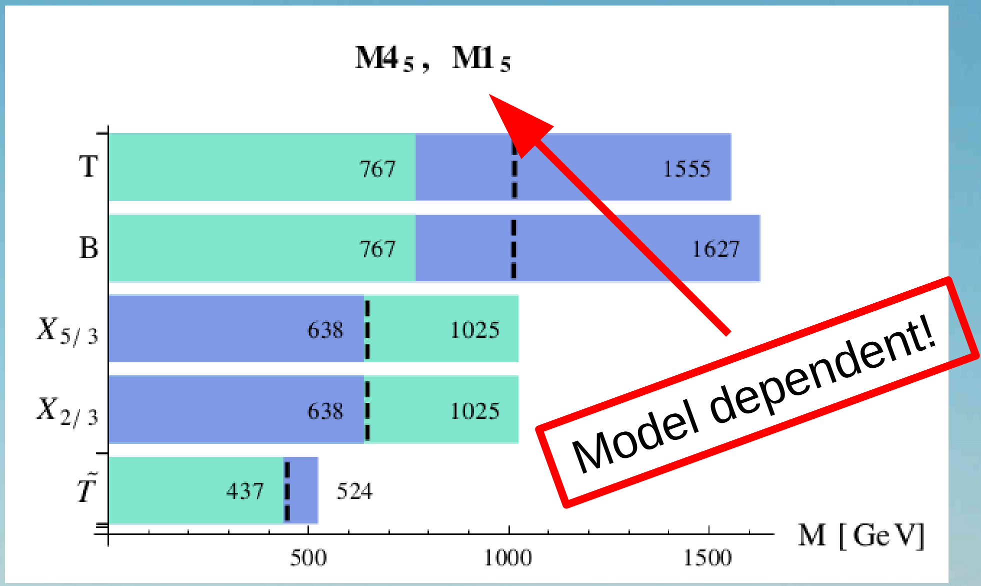


Implications from recent high p_T data

- Implications of direct searches for CHM:
  - New quark searches and impact on CHM
    - Current bounds on top partners consider pair production (but are quite general on decays)
    - Large EW couplings: single production relevant

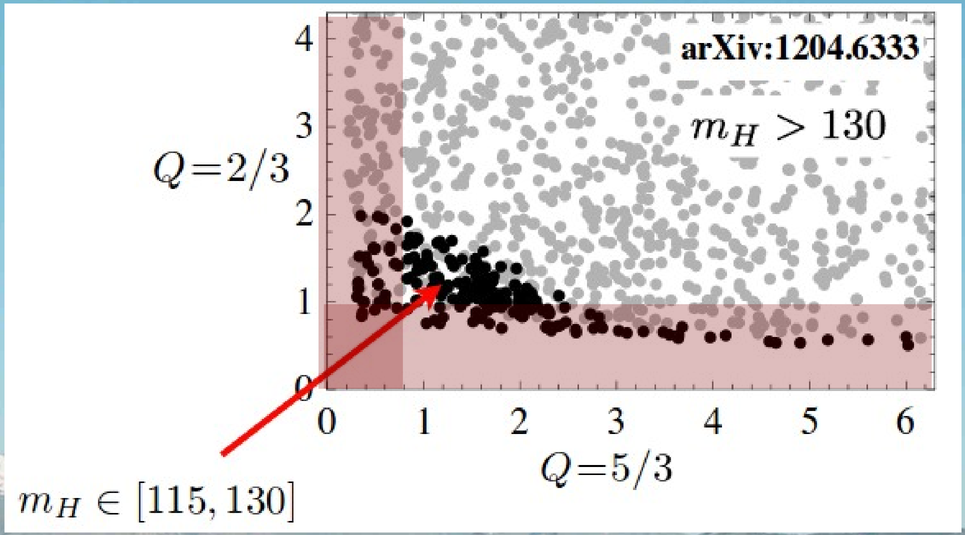
Single production relevant





Implications from recent high p_T data

- Implications of direct searches for CHM:
  - New quark searches and impact on CHM
    - Current bounds on top partners consider pair production (but are quite general on decays)
    - Large EW couplings: single production relevant
    - Current bounds ~ TeV: natural region non-trivially probed



Implications from recent high p_T data

- Implications of direct searches for CHM:
  - New vector searches and impact on CHM
    - Vector resonances in CHM are not your average Z':
      - Small coupling to light fermions (DY suppressed)
      - Large BR into heavy particles (W, Z, t, Q if open)
      - Several models, not yet adopted by experimental collaborations, beyond the old RS one

        Matsedonskyi, Panico, Wulzer '13; Redi, Tesi '12; Marzocca, Serone, Shu '12; Pomarol, Riva '12; Panico et al '13, De Simone et al '13

      - EW resonances difficult to find (even more so in unitarization of longitudinal gauge boson scattering), heavy gluon more likely

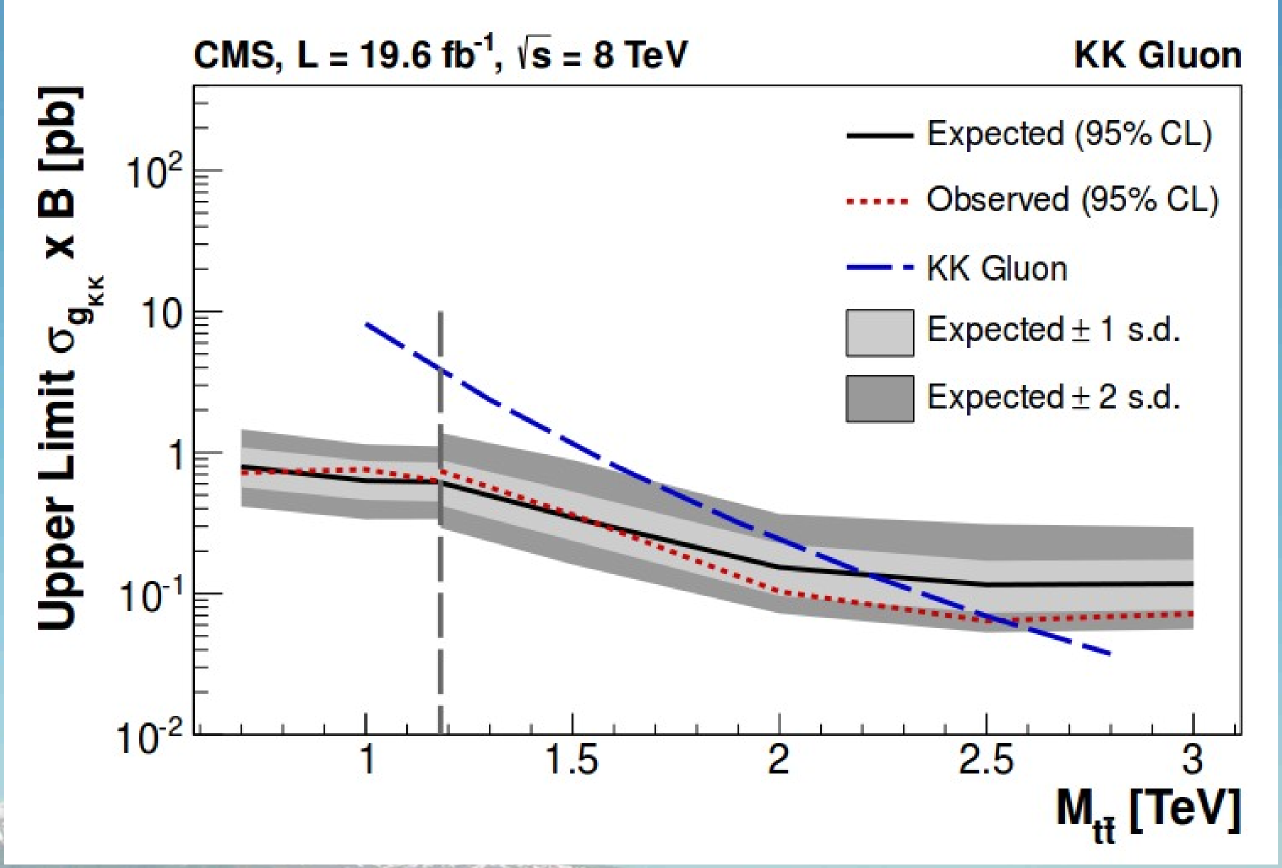
        Contino et al. '10-11 but see also Espriu, Yencho '13

Implications from recent high p_T data

- Implications of direct searches for CHM:
  - Heavy gluon searches at the LHC
    - First benchmark (IR_SM_RS):
      - Same coupling to all SM fermions: narrow dijet resonances
    - Second benchmark (UV_lightSM_RS):
      - Couplings to light SM particles suppressed, couplings to top quite large: not so narrow ttbar resonances
    - Third benchmark (partialcompositeness_toppartners):
      - Decay to top partners open, very large width unless strong coupling not so strong, non-trivial decays (not only to tops), dijets relevant again

Implications from recent high p_T data

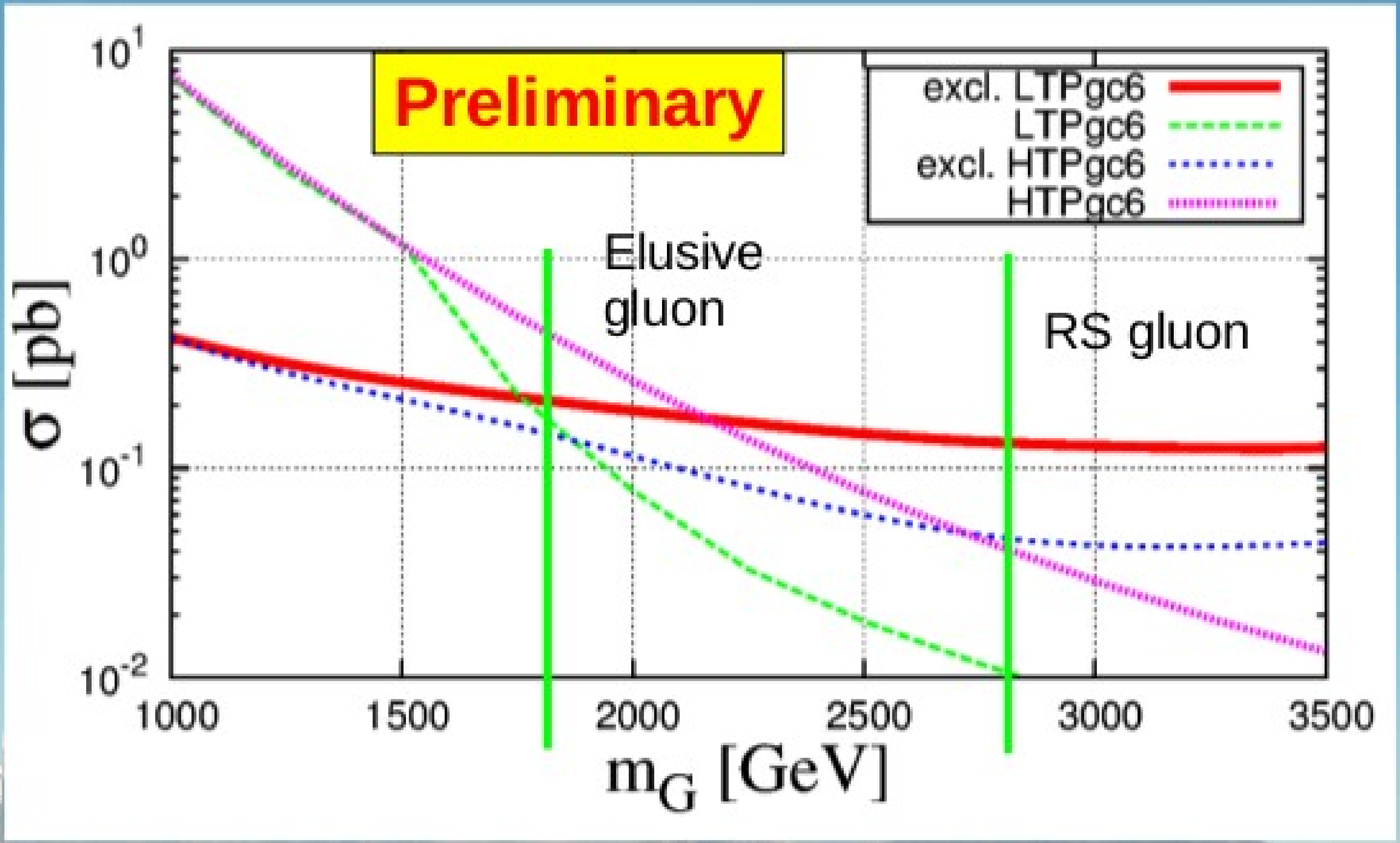
- Implications of direct searches for CHM:
  - Heavy gluon searches at the LHC



Implications from recent high p_T data

- Implications of direct searches for CHM:
  - Heavy gluon searches at the LHC

Chala, Juknevich, Perez, J.S. in progress



Final Thoughts

- I've tried to argue that naturalness is a good guiding principle
- The lack of experimental evidence of BSM physics forces us to re-consider our assumptions

No significant departures observed, we exclude your model

Nah! That's 'cause you were looking only at the simplest possible realization of the model. You are just starting to explore the relevant parameter space of my model

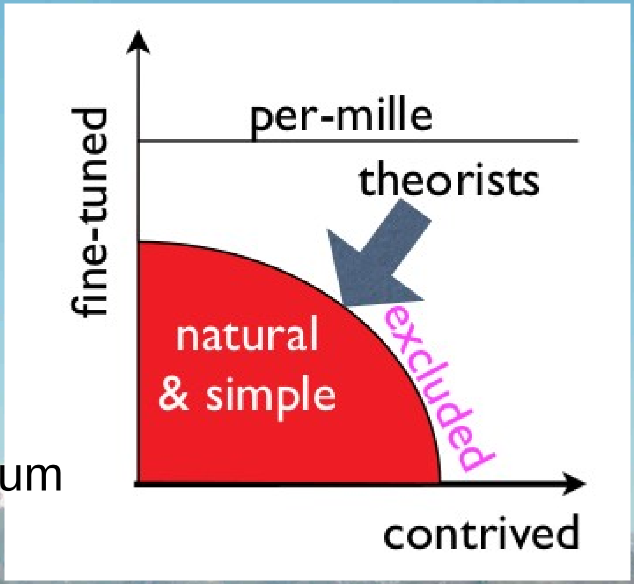
But it is what you told me to look for!

Yep, I know, but what you should be really looking for is ...

Final Thoughts

- I've tried to argue that naturalness is a good guiding principle
- The lack of experimental evidence of BSM physics forces us to re-consider our assumptions
- Models that survive experimental scrutiny are typically “not so simple”

But it is important to realize that good “more contrived” models produce cancellations via new symmetries



H. Murayama, Nobel Symposium on LHC results

Final Thoughts

- I've tried to argue that naturalness is a good guiding principle
- The lack of experimental evidence of BSM physics forces us to re-consider our assumptions
- Models that survive experimental scrutiny are typically "not so simple"

But it is important to realize that good "more contrived" models produce cancellations via new symmetries

- Example:
  - Light vector-like quarks mixing strongly with first generation SM quarks were thought to be experimentally excluded.
  - Custodial symmetry can provide the required protection to make them compatible with experiment

Carena, Pontón, J.S., Wagner '06-'07; Atre, Carena, Han, J.S. '09;
Atre et al '11; Atre, Chala, J.S. '13

Conclusions

- We have good arguments to expect new physics at the TeV scale
- The LHC is consistently probing it (and finding nothing so far)
- LHC7/8 is starting to explore the interesting region of parameter space in the simplest/most natural models
- There is still plenty of room for discovery at the LHC13
  - Realistic models can easily be beyond run I reach
  - Realistic models are likely to be somewhat elusive
- If someone asks me in 20 years: “Why did you do BSM?”


FUN RIDE
Original
The SENSATIONAL
Classic Trolley Ride
for ages 5 years and up.
Maximum weight limit 100 lbs.
Up to
35 foot
Cable Ride!
Made in U.S.A.
Printed in Israel
Includes all hardware and parts, super-durable trolley unit, and easy-assembly directions.

Thank you!