Beyond the Standard Model: The aftermath of a momentous achievement

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Beyond the Standard Model

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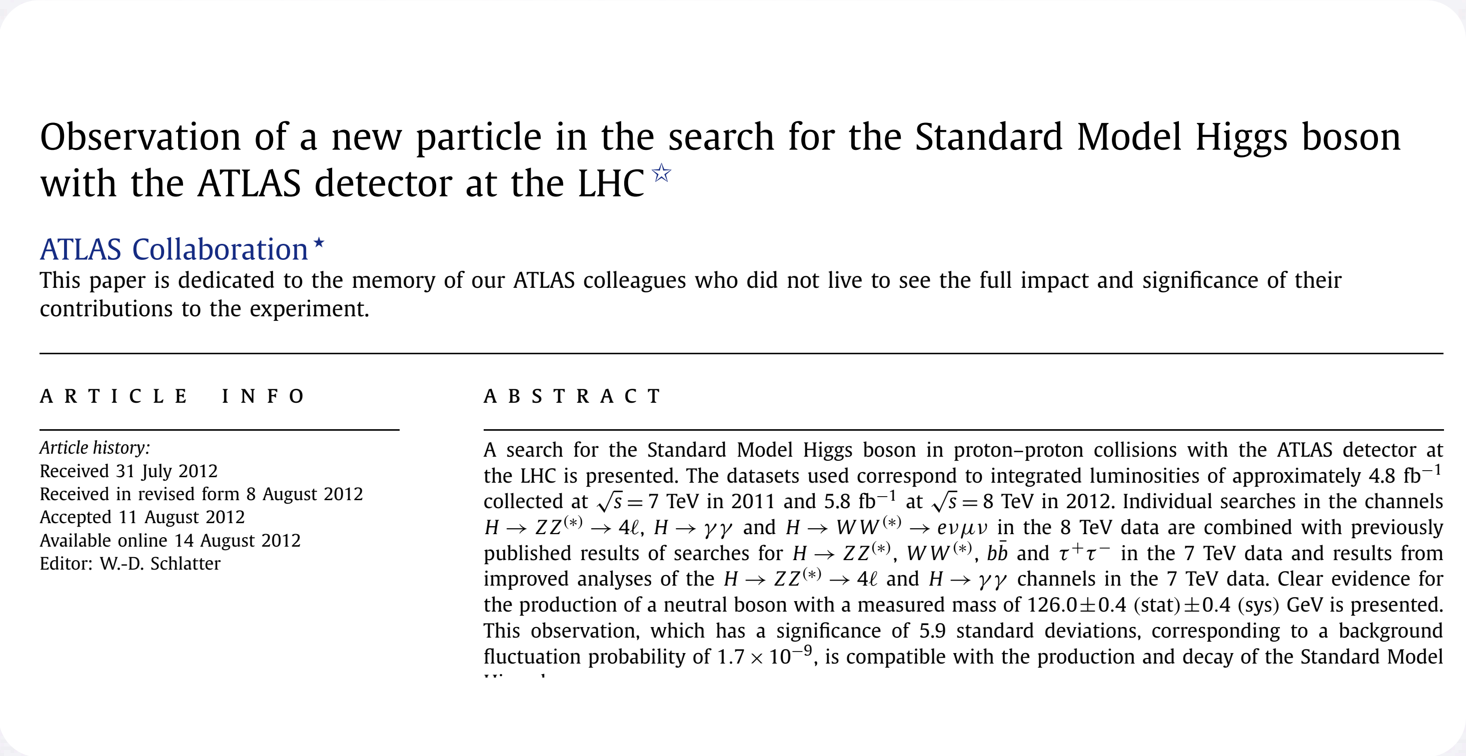
Any manifestation not described (at least in principle) by the SM with a **Higgs doublet**

Open questions

- Neutrino masses
- Non-baryonic Dark Matter
- Matter-antimatter asymmetry
- *Mechanism* of EW symmetry breaking

The Resonance at ~126 GeV



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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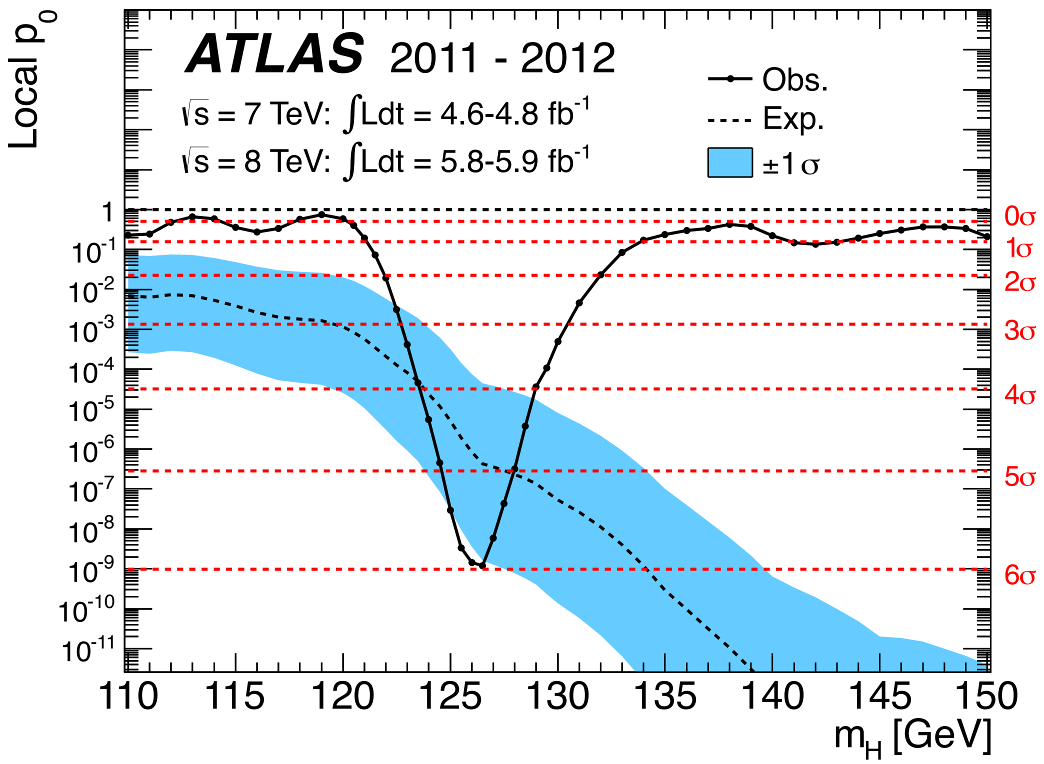
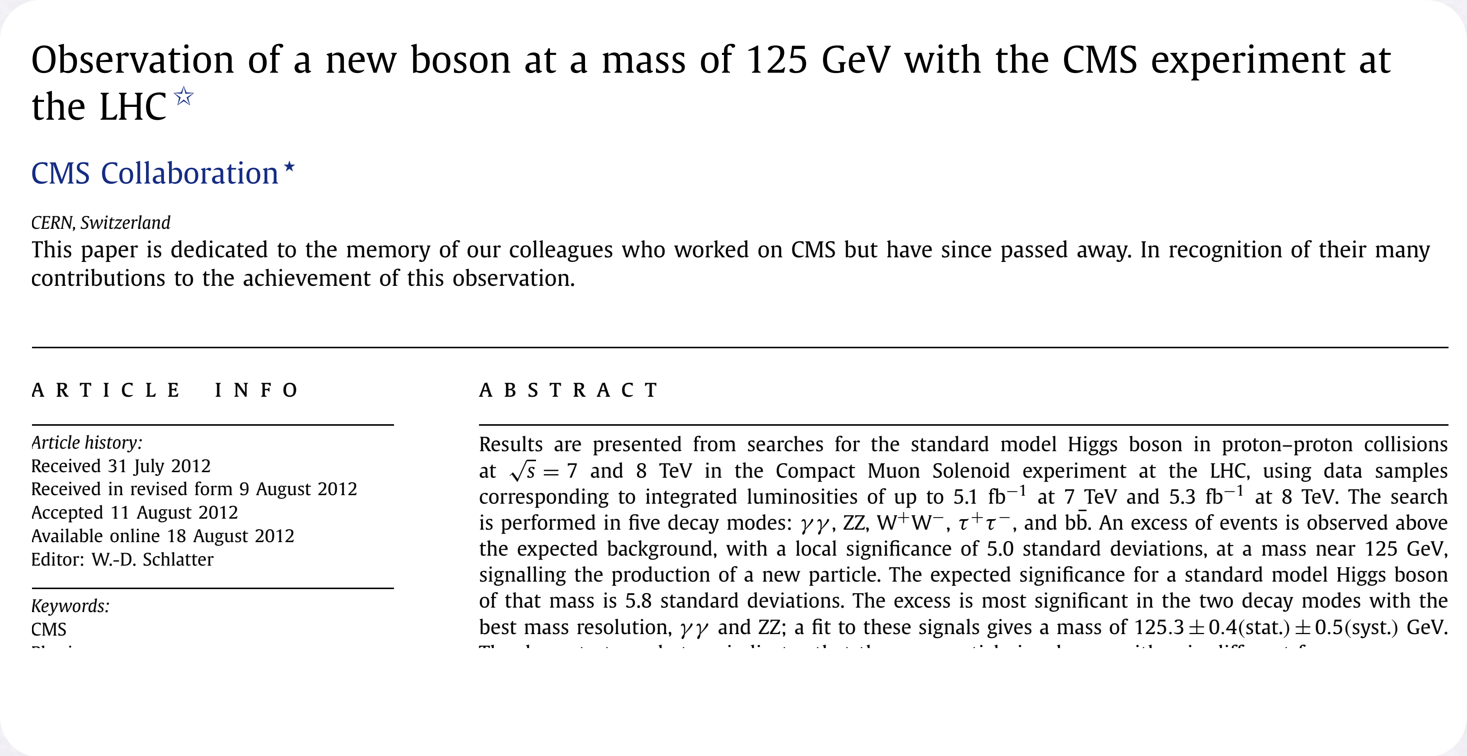
ABSTRACT

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





Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC ☆

CMS Collaboration *

CERN, Switzerland

This paper is dedicated to the memory of our colleagues who worked on CMS but have since passed away. In recognition of their many contributions to the achievement of this observation.

ARTICLE INFO

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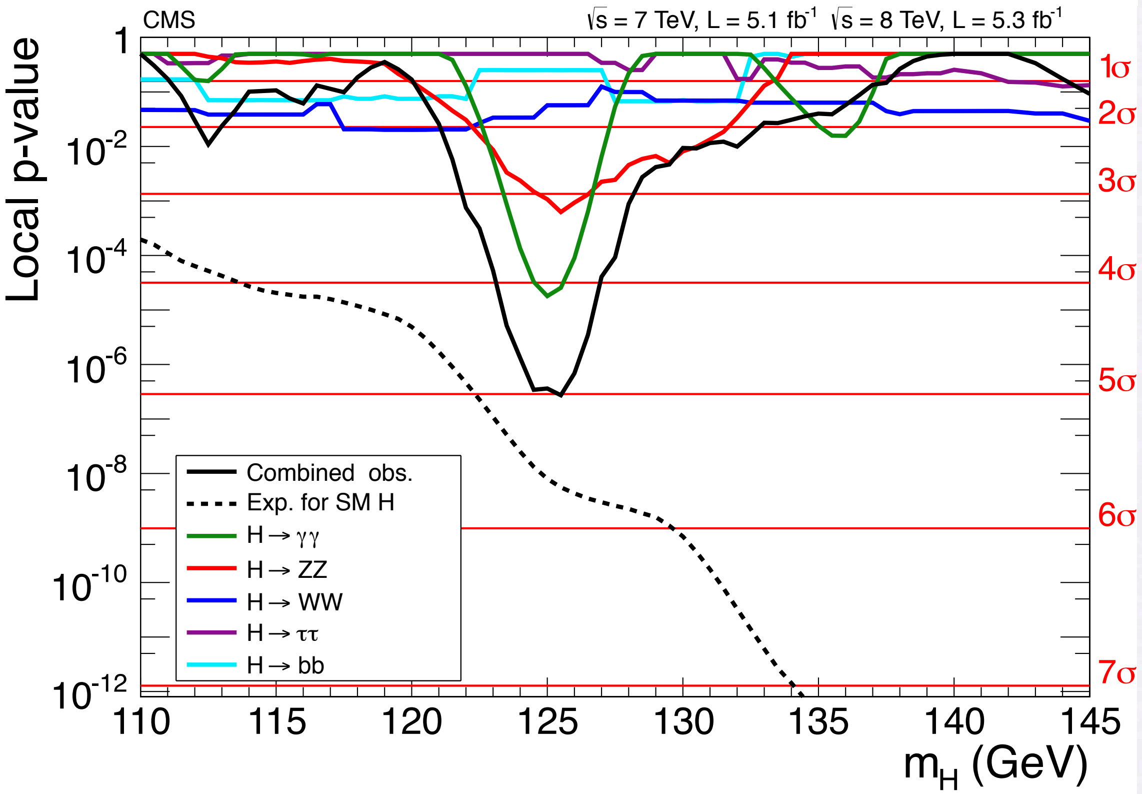
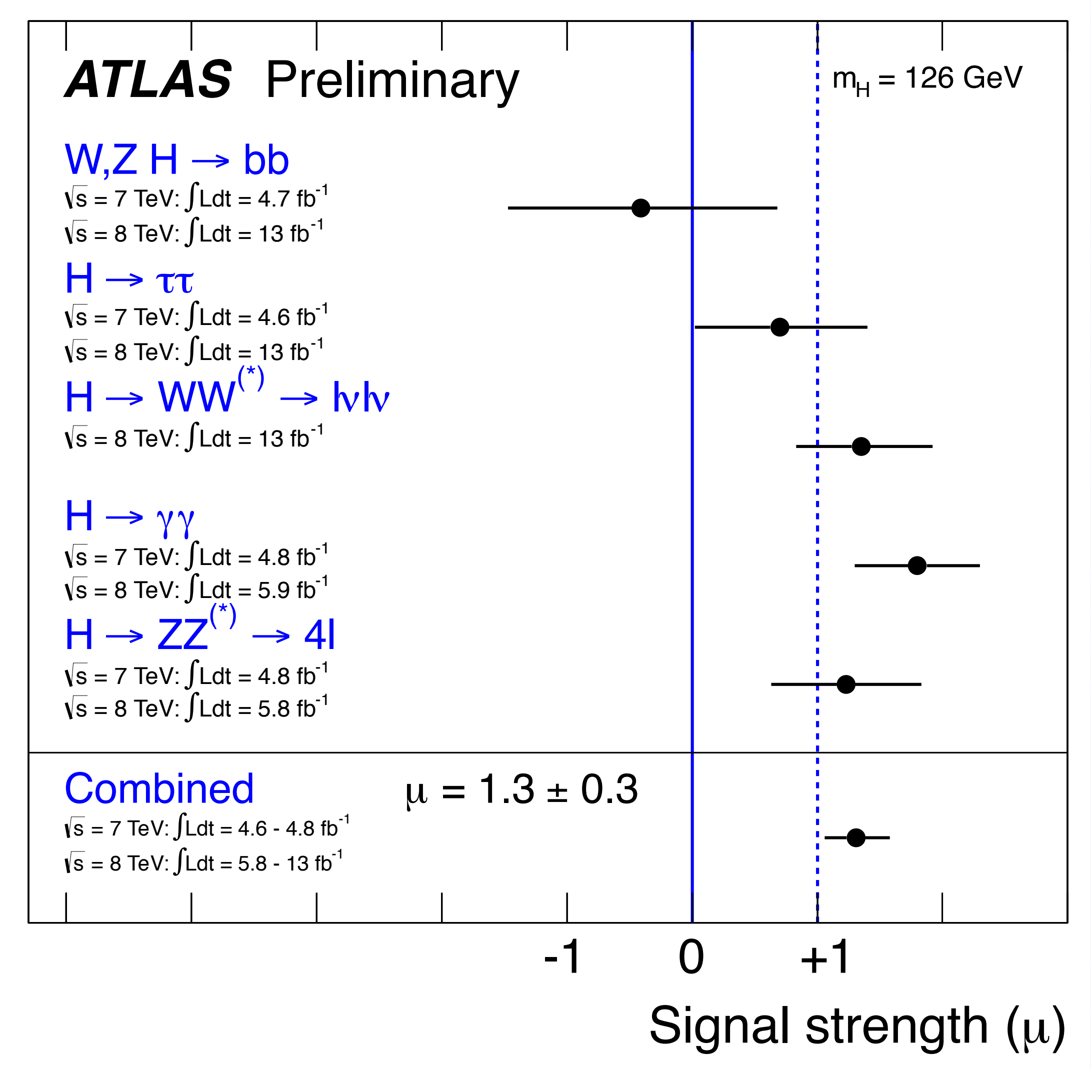
ABSTRACT

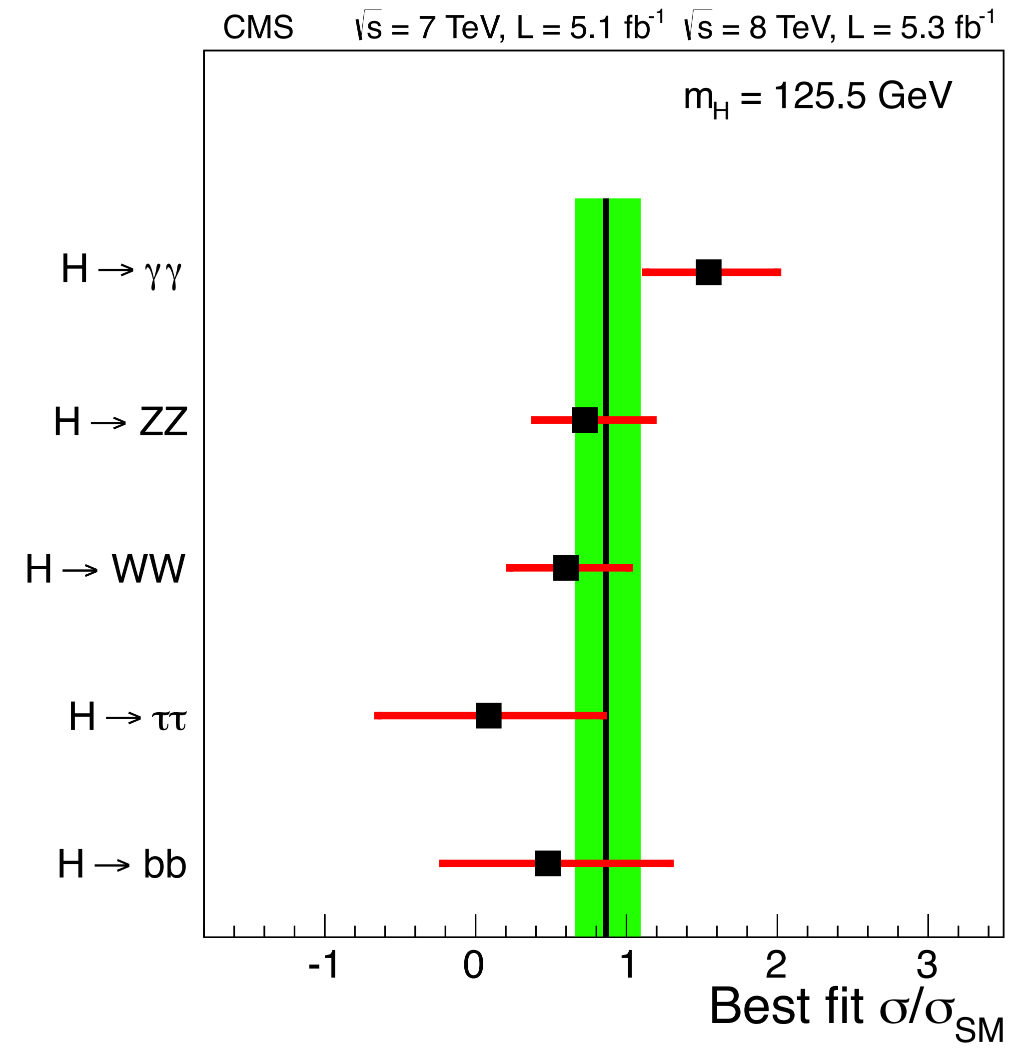
Results are presented from searches for the standard model Higgs boson in proton–proton collisions at $\sqrt{s} = 7$ and 8 TeV in the Compact Muon Solenoid experiment at the LHC, using data samples corresponding to integrated luminosities of up to 5.1 fb^{-1} at 7 TeV and 5.3 fb^{-1} at 8 TeV. The search is performed in five decay modes: $\gamma\gamma$, ZZ, W^+W^-, $\tau^+\tau^-$, and $b\bar{b}$. An excess of events is observed above the expected background, with a local significance of 5.0 standard deviations, at a mass near 125 GeV, signalling the production of a new particle. The expected significance for a standard model Higgs boson of that mass is 5.8 standard deviations. The excess is most significant in the two decay modes with the best mass resolution, $\gamma\gamma$ and ZZ; a fit to these signals gives a mass of $125.3 \pm 0.4(\text{stat.}) \pm 0.5(\text{syst.})$ GeV.



SM-Higgs Interpretation

- Signal in $VV = WW, ZZ, \gamma\gamma$, also searched for in $f\bar{f} = b\bar{b}, \tau^+\tau^-$
- Good agreement with a SM-Higgs interpretation





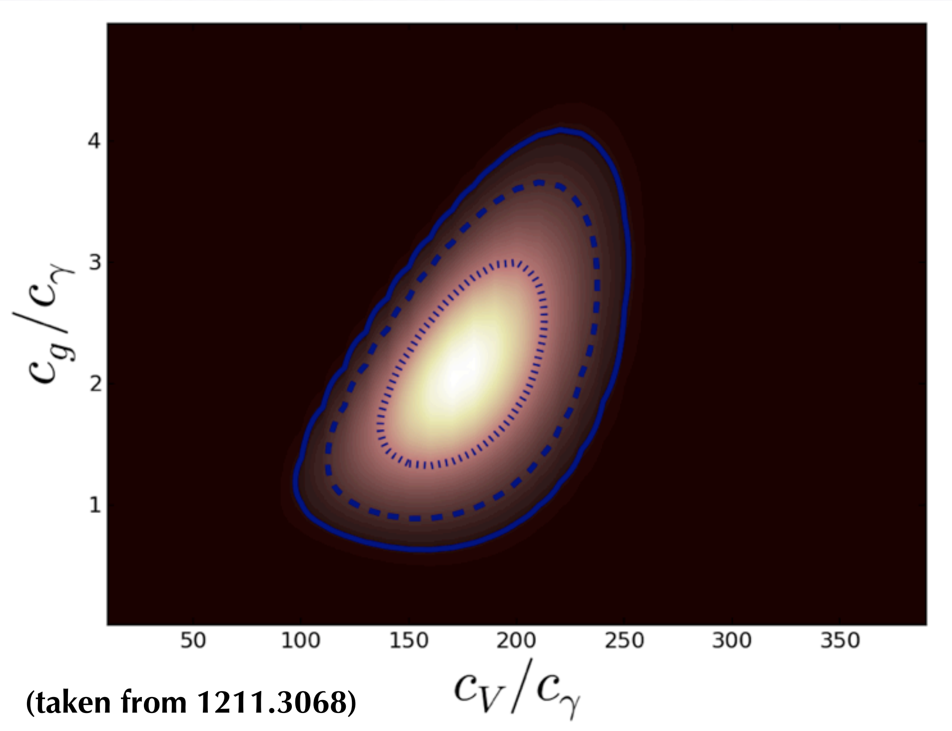
Compatibility with SM hypothesis $\approx 23\%$ (ATLAS)

Agnostic Interpretation: Spin

- We know it is a bosonic resonance from the observed final states
- $S = 1$ excluded by observation of $\gamma\gamma$ channel (Landau-Yang theorem)
- Possible $S = 2$ interpretation considered recently by Ellis, Sanz and You (1211.3068)

Parametrize couplings of massive $h_{\mu\nu}$ (need not be related to EWSB)

$$\frac{c_i}{M} h_{\mu\nu} T_i^{\mu\nu} \qquad \text{for} \qquad c_W, c_Z, c_\gamma, c_g, c_f \left\{ \begin{array}{l} \text{gauge inv.: } c_g = c_\gamma \\ \text{custodial: } c_W = c_Z \equiv c_V \end{array} \right.$$



(taken from 1211.3068)

Observed rates imply

$$c_g = (1.97 \pm 0.59) \times c_\gamma$$

$$c_V = (175 \pm 25) \times c_\gamma$$

- Tension with expected $\Gamma(gg) = 8\,\Gamma(\gamma\gamma)$
- If some connection to EWSB, may expect enhancement to $W_L W_L / Z_L Z_L$ over $\gamma\gamma$, but not as large as loop factor
- (Known realization would face other pheno. hurdles)

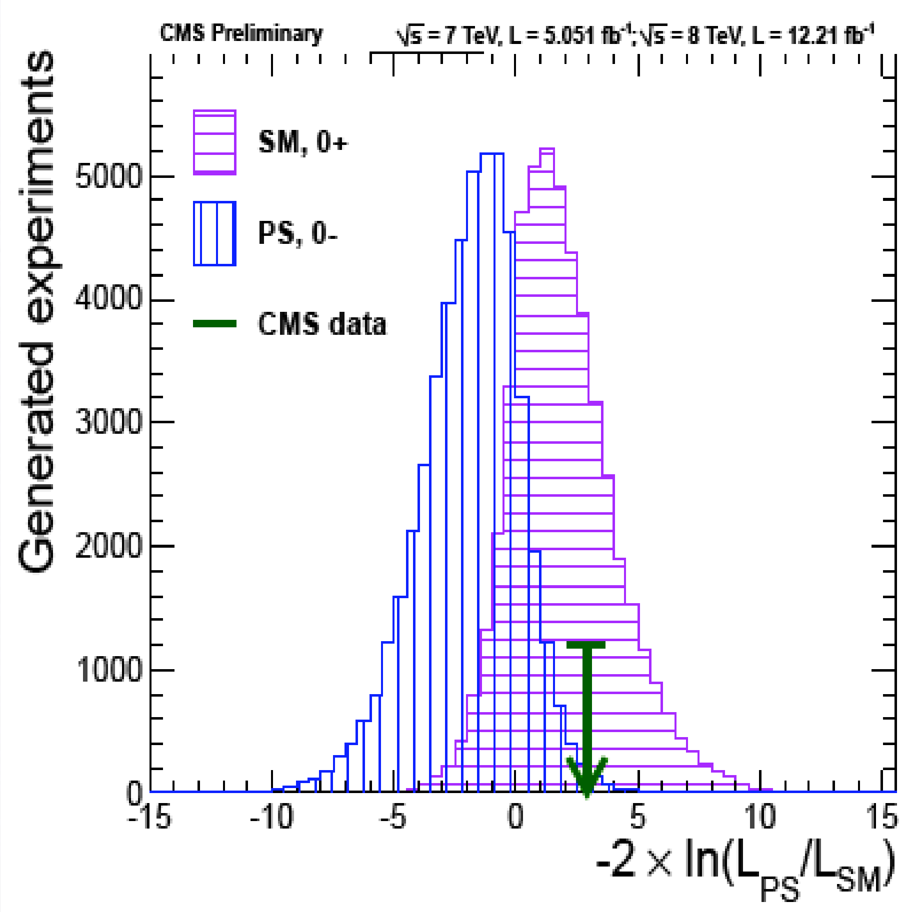
$S = 2$ currently disfavored

Agnostic Interpretation: Parity

Focus on $S = 0$ resonance: what about its parity?

At the Nov. HCP meeting, CMS presented first analysis to distinguish between

$$\text{Scalar:} \begin{cases} hF_{\mu\nu}F^{\mu\nu} \\ h\bar{\psi}\psi \end{cases} \qquad \textit{versus} \qquad \text{Pseudoscalar:} \begin{cases} hF_{\mu\nu}\tilde{F}^{\mu\nu} \\ h\bar{\psi}\gamma_5\psi \end{cases}$$



- Data consistent with 0^+ (at $0.6\,\sigma$)
- Pseudoscalar, 0^-, excluded at $2.5\,\sigma$

Mounting evidence for scalar case...

EW Quantum Numbers

Well-established evidence for custodial symmetry $SU(2)_C \subset SU(2)_L^{\text{gauge}} \times SU(2)_R^{\text{global}}$

$\longrightarrow$ Dominant source of EWSB from vev of $SU(2)_C$ singlet

- The SM provides a simple realization

$$H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix} \quad \longrightarrow \quad \Phi = \begin{pmatrix} H^{0*} & H^+ \\ -H^- & H^0 \end{pmatrix} \quad \text{with} \quad \langle \Phi \rangle = v \times \mathbb{1}_{2\times 2}$$

- But there are other possibilities, e.g. three $SU(2)_L$ triplets with $Y = 0, \pm 1$ **(Gunion, Vega & Wudka, 1990)**

$$\Phi = \begin{pmatrix} \chi^0 & t^+ & \xi^{++} \\ \chi^- & t^0 & \xi^+ \\ \chi^{--} & t^- & \xi^0 \end{pmatrix} \quad \text{with} \quad \langle \Phi \rangle = v \times \mathbb{1}_{3\times 3}$$

These are consistent with EW precision measurements (more generally could use (N_L, N_R) reps.)

(e.g. Low & Lykken, 1005.0872)

CP-even, neutral excitations: singlet, i.e. $\Phi = (v + h) \times \mathbb{1}$, versus 5-plet of $SU(2)_C$

EW Quantum Numbers

Low, Lykken & Shaughnessy, 1207.1093

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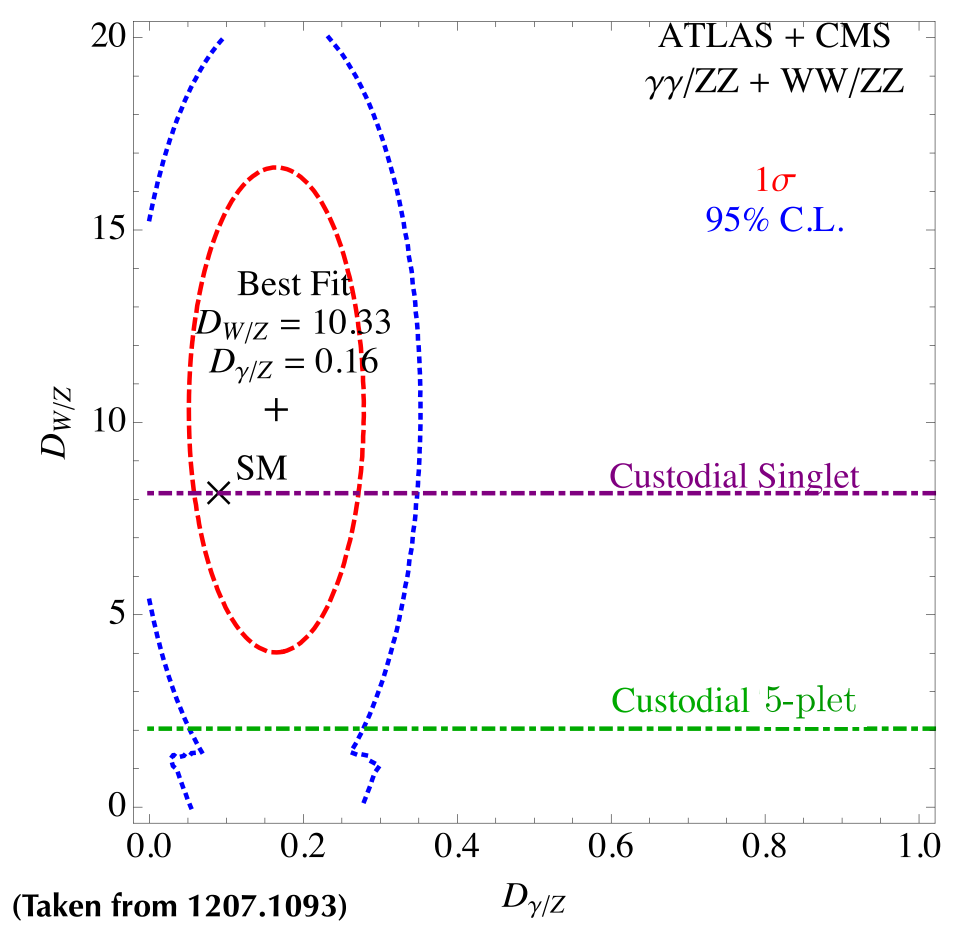
Current LHC data has some discriminating power



(Taken from 1207.1093)

- Couplings to gg or $\gamma\gamma$ parameterized by higher-dimension operators

- Consider ratios with identical production

$$D_{W/Z} \equiv \frac{\sigma_{gg}(h \to WW)}{\sigma_{gg}(h \to ZZ)} \qquad D_{\gamma/Z} \equiv \frac{\sigma_{gg}(h \to \gamma\gamma)}{\sigma_{gg}(h \to ZZ)}$$

- The difference arises from

$$\frac{g_{hWW}}{g_{hZZ}} = \frac{m_W^2}{m_Z^2} = c_w^2 \qquad \text{versus} \qquad \frac{g_{h_5WW}}{g_{h_5ZZ}} = \frac{m_W^2}{2m_Z^2} = -\frac{c_w^2}{2}$$

Since 5-plet does not have renormalizable couplings to fermion pairs, an unambiguous non-vanishing rate in such channels will rule this option out

More Exotic Interpretations

SM-Higgs couplings proportional to mass... also a natural feature for a *dilaton* !

Picture: (approximately) scale invariant theory, spontaneously broken at a scale f

Relation between f and EWSB scale not specified

Perhaps the actual ``Higgs boson" is heavy and what we are seeing is a dilaton?

- Dilaton couplings to W and Z: $\frac{\sigma}{f}\left(2m_W^2 W_\mu^+ W^{-\mu} + m_Z^2 Z_\mu Z^\mu\right)$

- Couplings to gg and $\gamma\gamma$: fixed by beta functions of composite states

Case 1: The SM degrees of freedom are composite remnants of the conformal breaking

$\longrightarrow$ Couplings to gluons significantly enhanced compared to SM-Higgs: **disfavored**

Case 2: ``Partial compositeness": most of SM remains *elementary*, gauge bosons (e.g. gluons) have small mixing with CFT composites, (RH) top and NGB's are CFT composites

More Exotic Interpretations

Two groups have recently studied the ~125 GeV signal as a possible dilaton in partial compos. case.

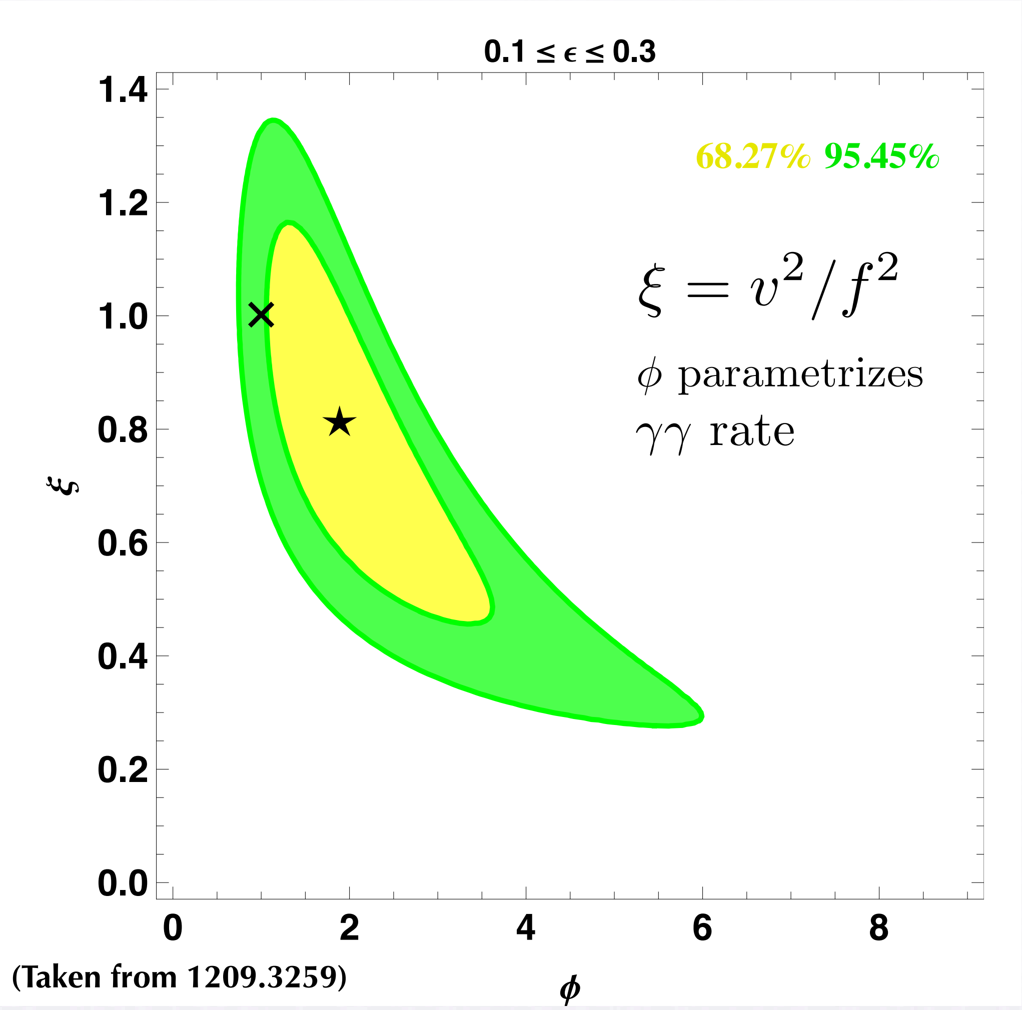
Chacko, Franceschini & Mishra, 1209.3259

Bellazini, Csáki, Hubisz, Serra & Terning, 1209.3299

see also: Goldberger, Grinstein & Skiba, 0708.1463

Low, Lykken & Shaughnessy, 1207.1093

- May accommodate rates for $f \approx v$
- A number of coincidences necessary to mimic SM rates...



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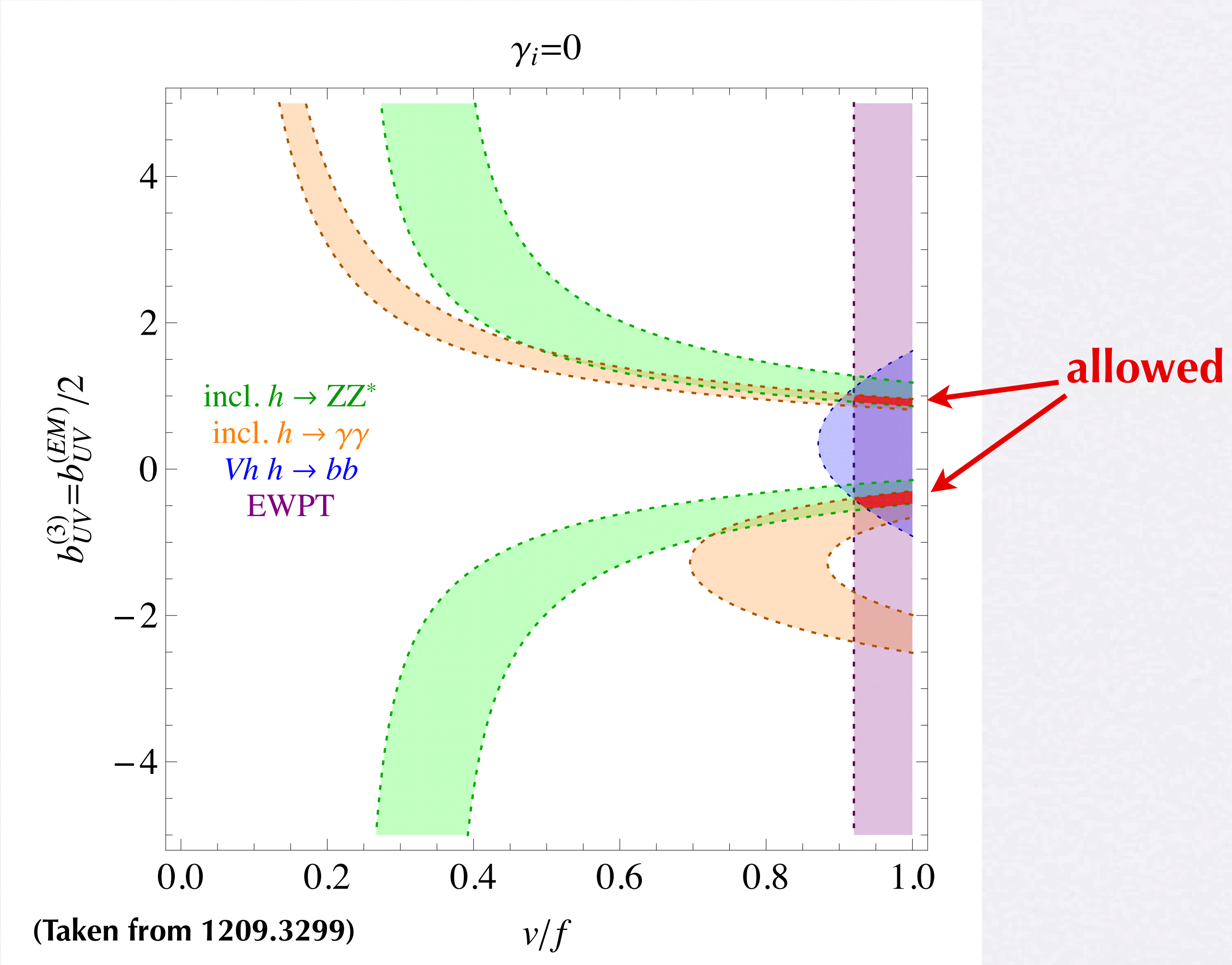


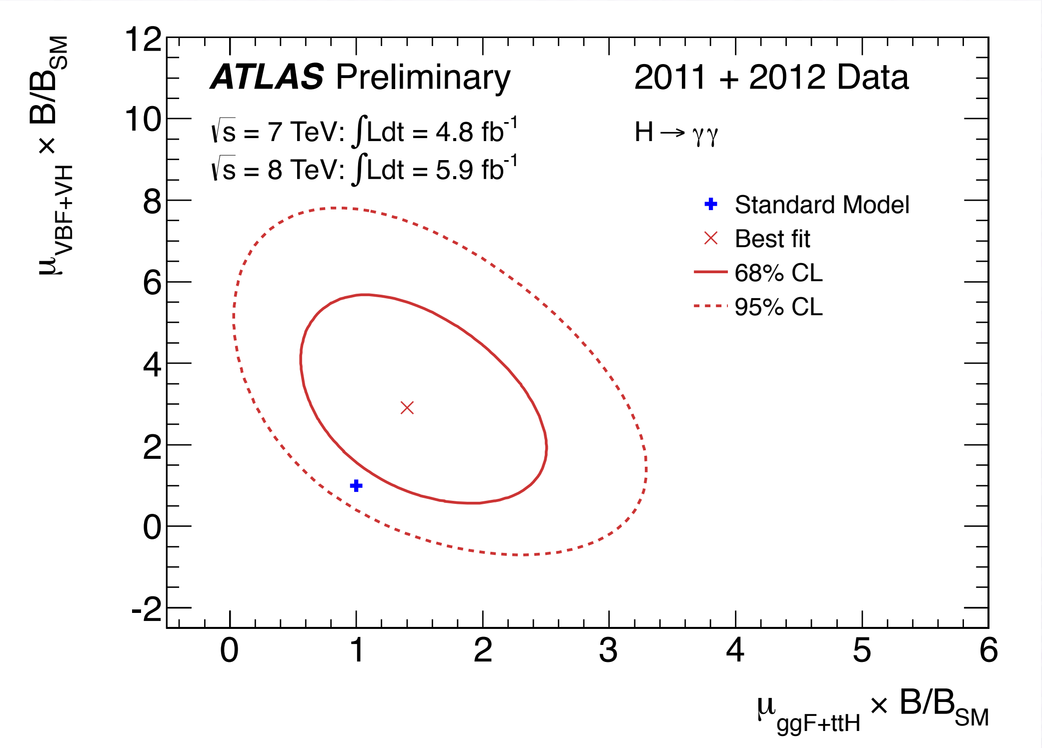
(Taken from 1209.3299)

SM-Higgs Interpretation

So the new resonance looks like a SM Higgs...

... though detailed properties might still contain crucial information

For instance, a *potential* enhancement in the diphoton signal compared to a SM-Higgs has recently caused much excitement: *loop-level process sensitive to new physics*



Need constructive interference with dominant W-loop

Enhancement due to BSM state, with $\tau_i = 4m_i^2/m_h^2$

$$R_{\gamma\gamma} \simeq \left| 1 - Q_i^2 \underbrace{\frac{F_i(\tau_i)}{F_{\rm SM}}}_{\text{loop functions}} \frac{\partial \ln m_i}{\partial \ln v} \right|^2 ,$$

coupling to Higgs

New scalars or fermions getting mass mainly from EWSB tend to cause a *suppression*...

But vector-like particles can produce an enhancement!

Vector-like particles

To the extent that Higgs production is dominated by gluon-fusion, the presence of colored states would induce an (unobserved) overall enhancement in all channels

→ suggests weakly interacting new physics (new electrically charged particles)

- A scalar example might be provided by staus in SUSY

Carena, Gori, Shah & Wagner, 1112.3336
Carena, Low & Wagner, 1207.1093

- Vector-like ``leptons" can be even more effective

Arkani-Hamed, Blum, D'Agnolo & Fan, 1207.4482

Consider $(\psi, \psi^c) \sim (1,2)_{\pm\frac{1}{2}}$, $(\chi, \chi^c) \sim (1,1)_{\mp 1}$,

$$M = \begin{pmatrix} m_\psi & \frac{1}{\sqrt{2}} y v \\ \frac{1}{\sqrt{2}} y_c v & m_\chi \end{pmatrix}$$

EWSB mass mixing pushes lightest eigenvalue down: $\frac{\partial \ln m_1}{\partial \ln v} < 0$

Sizeable enhancement needs light states and couplings $\gtrsim 1$

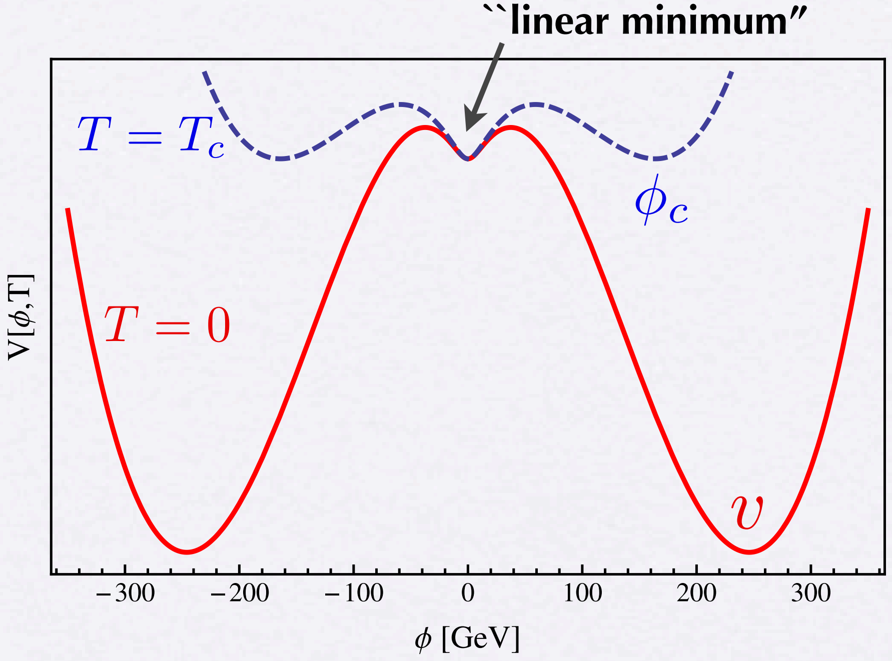
Unlike *generic* scalars, fermions can be light without tuning.

The EW Phase Transition

Davoudiasl, Lewis & EP, 1211.3449

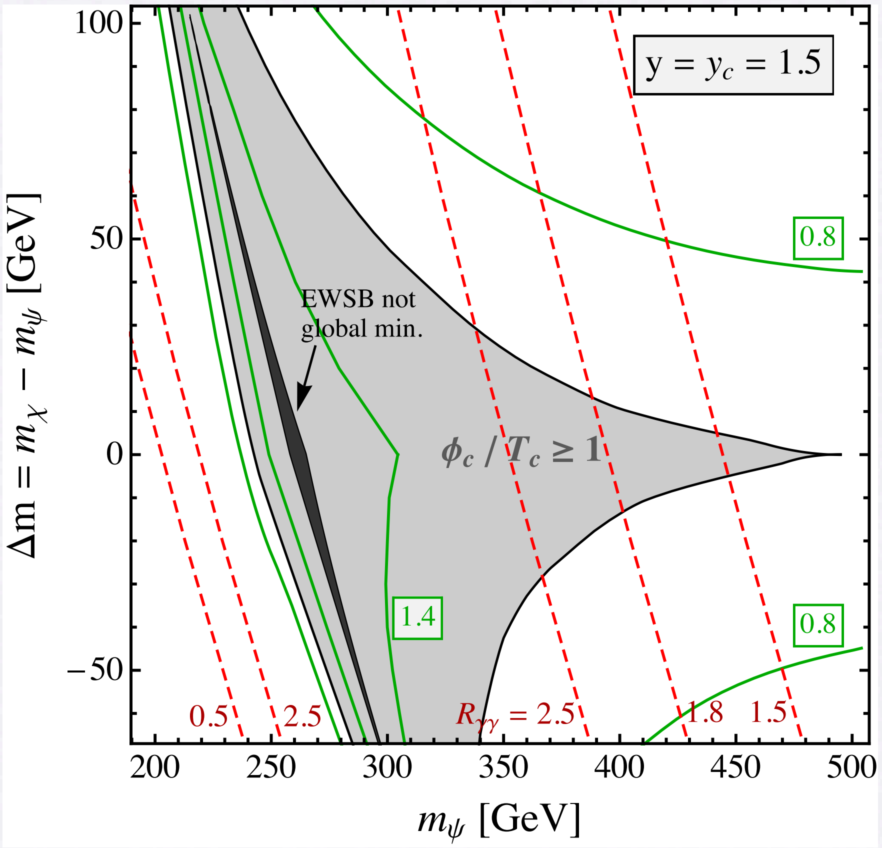
Such a setup could have interesting implications in the early universe...

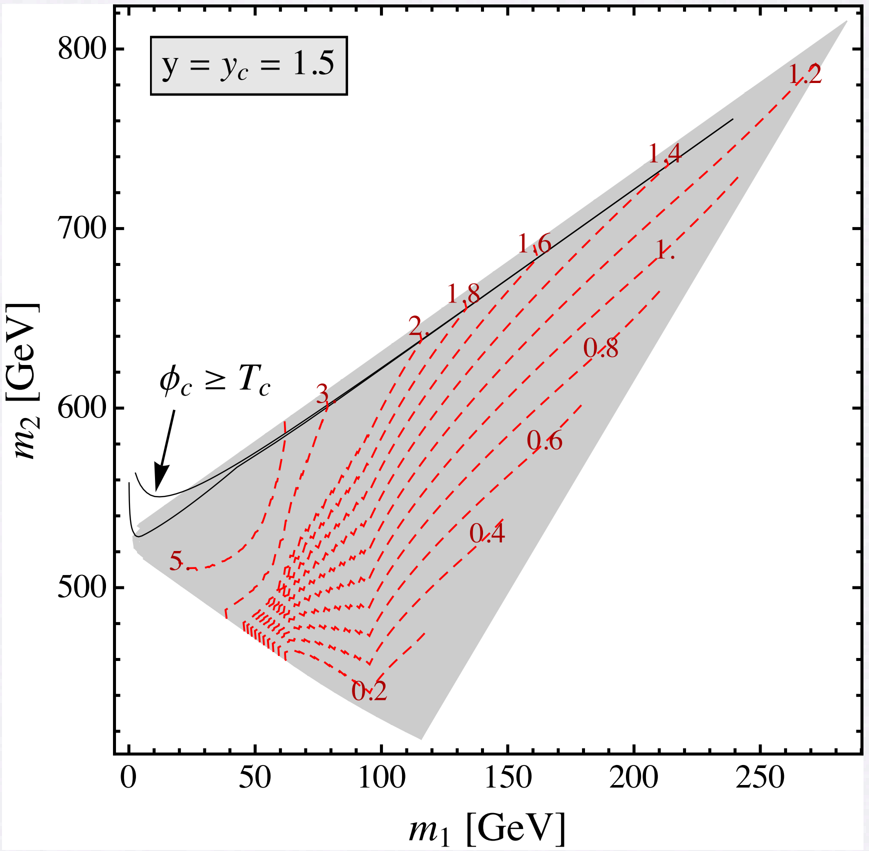
Fermionic contribution induces a local minimum at the origin, even at T = 0, provided $m_\psi \sim m_\chi$



A connection between diphoton enhancement and EW baryogenesis? Strongly first-order EWPhT!

Higgs instability would require additional new phys. close to the TeV scale (bosons?)





Of course, the current excess in diphotons over SM expectation may just be a fluke...

Would a SM-like Higgs (within LHC precision) be a ``surprise" in any way?

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Would a SM-like Higgs (within LHC precision) be a ``surprise″ in any way?

Most certainly NOT!

Decoupling

- Excellent agreement of SM predictions and observations has long suggested that any new physics must be decoupling, i.e. it must be possible to make it heavy without leaving large effects behind

- Witness: a fourth generation ⟶ - large effects on EW precision observables

  (albeit indirect, so could have been canceled by ``something else")

  - large impact on Higgs production via gluon fusion, and significant suppression of diphoton rate

  (now clearly ruled out)

- Expect new physics to be ``vector-like", i.e. masses not mainly from EWSB

- Complicated Higgs sectors often have a natural decoupling limit, with the lightest state having properties close to those of a SM-Higgs

  e.g. the ``large" m_A limit of 2HDM (such as in the MSSM)

  Thus, scenarios with several Higgs doublets, singlets, triplets (with small vevs) still allowed.

Understanding EWSB

Spontaneous breaking of the EW symmetry a well-established experimental fact...

... Higgs boson discovery a crucial step towards a full understanding of this phenomenon

Experimental determination of the Higgs boson properties very important...

in particular, eventually measure the (trilinear, ...) Higgs self-interactions

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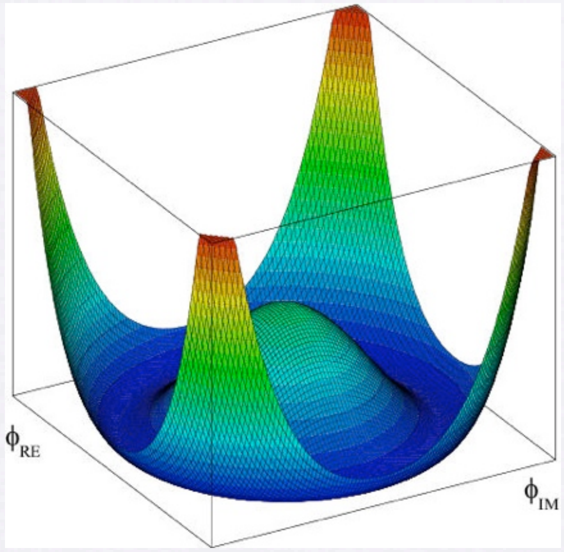
Nobody should be particularly surprised if the ``wine bottle'' potential:

$$V(\Phi) = -m^2\Phi^\dagger\Phi + \frac{\lambda}{4}(\Phi^\dagger\Phi)^2$$

is in fact an excellent *description* of the phenomenon of EWSB.



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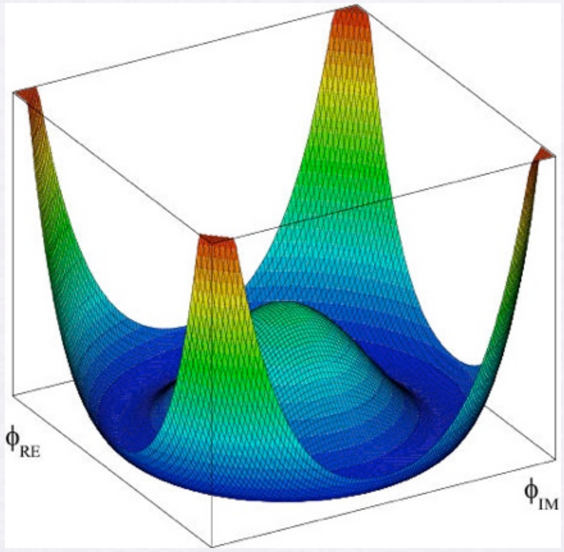

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But this much knowledge still would not amount to a proper understanding of EWSB!

Compare superconductivity: should a (theoretical) physicist be satisfied with the Ginzburg-Landau Theory?

What we are really after is the underlying ``BCS theory” of EWSB!

Understanding EWSB

Under my ``uncontroversial" definition, the case for BSM physics is as strong as ever...

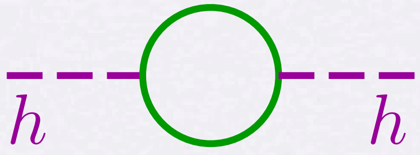
... in fact stronger

- To the extent that we know that the 125 resonance is the Higgs boson, we have ruled out technicolor-type models for EWSB, i.e. models that *do not* give rise to a *light scalar*, besides the Nambu-Goldstone bosons of the symmetry breaking.

But note: this does not mean that the *origin* of EWSB is weakly coupled

(Higgs could still be composite, e.g. a pseudo-NGB of strong dynamics)

- The quantum excitations of the Higgs field, however, are weakly coupled, and we are faced with the relevant operator $\frac{1}{2}m_h^2 h^2$



$$\sim \frac{\lambda^2}{16\pi^2}\Lambda^2$$

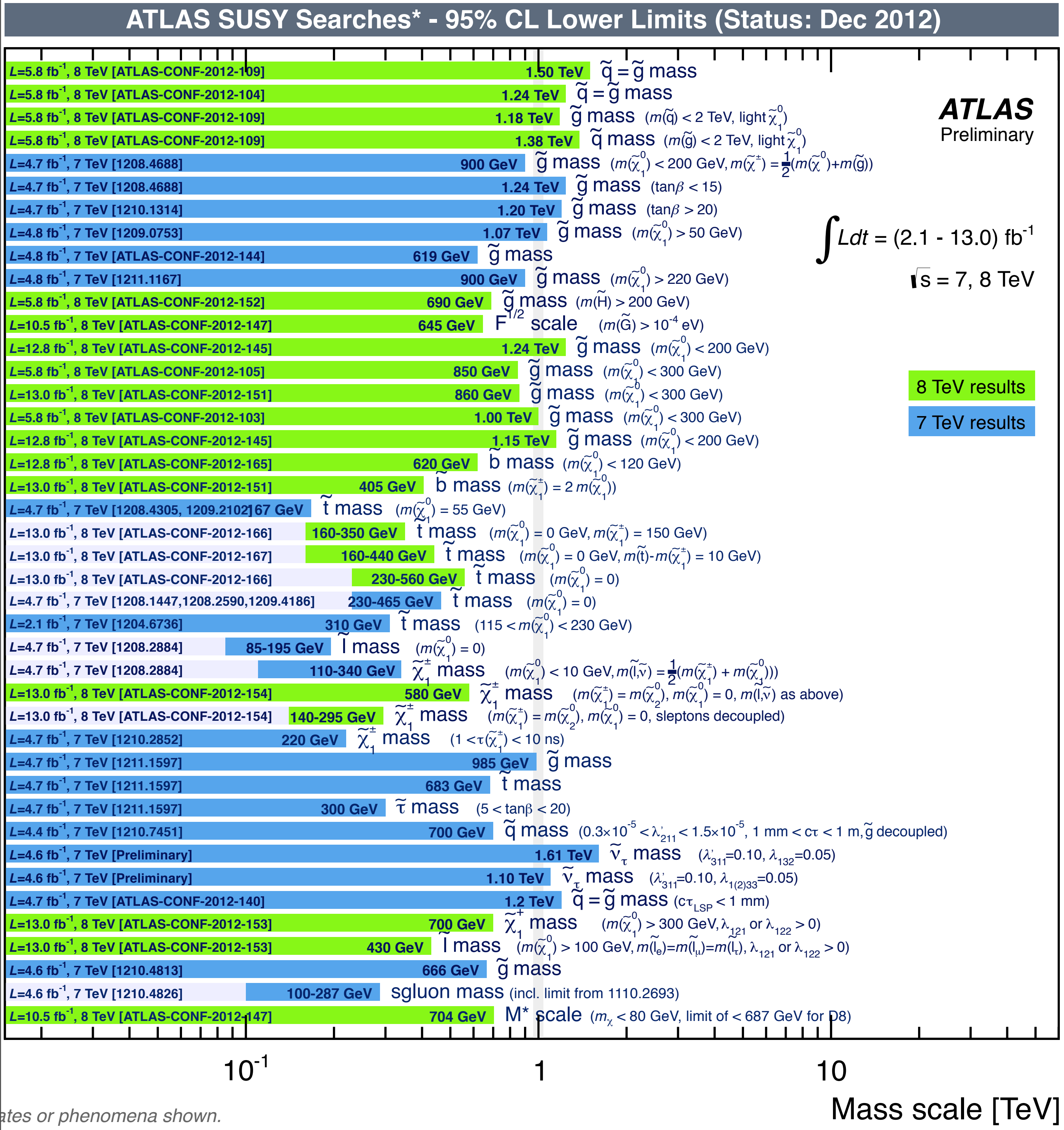
The ``hierarchy problem" is the *sharp* QFT formulation of the intuition that whatever generates dynamically the weak scale *should* have characteristic length scales of that order

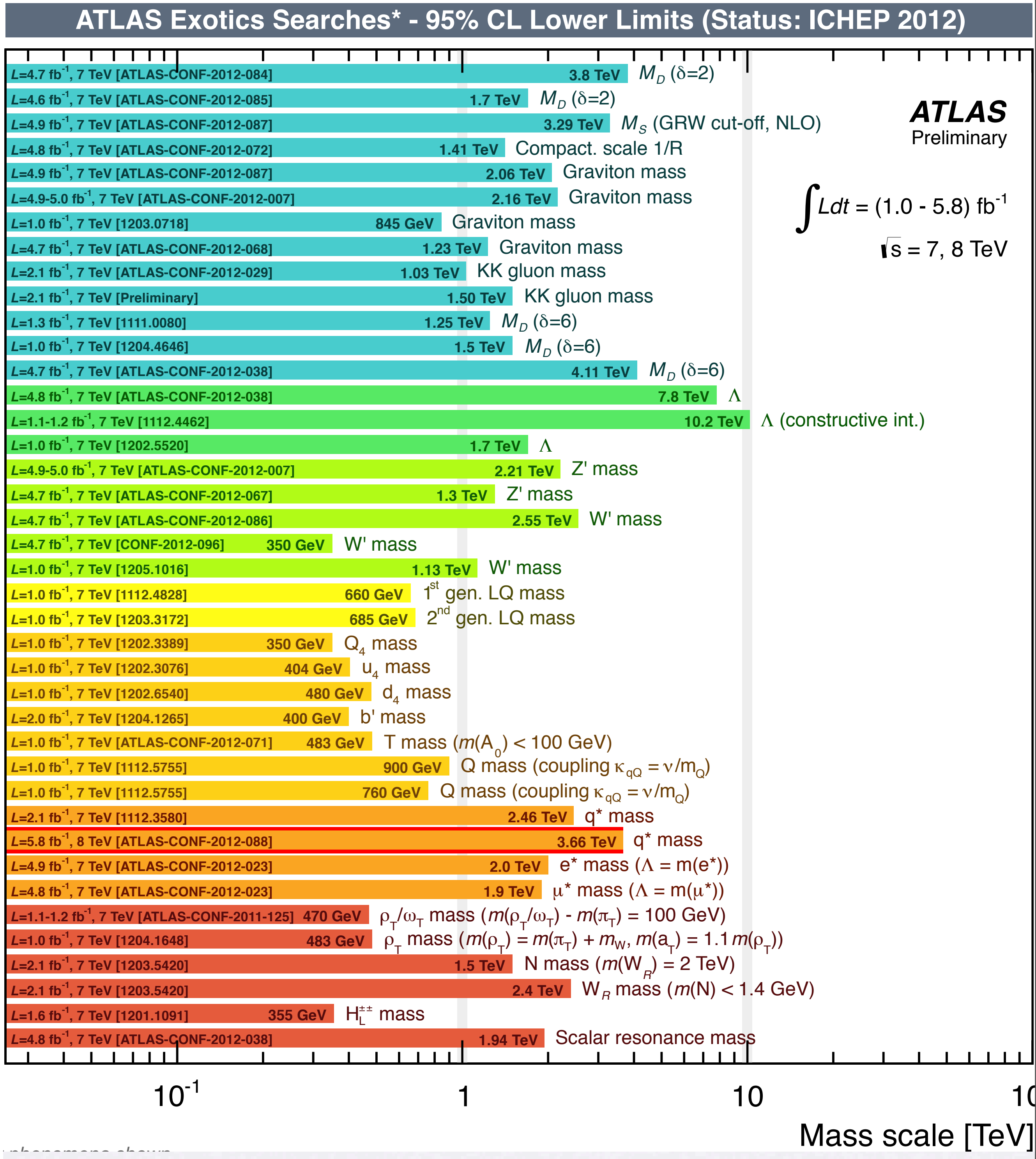
Naturalness: not simply ``esthetic", but a test of Quantum Field Theory thinking!

Yet…

No signs of NP below 1 TeV?

A taste of ATLAS bounds on SUSY and ``Exotics'' searches:

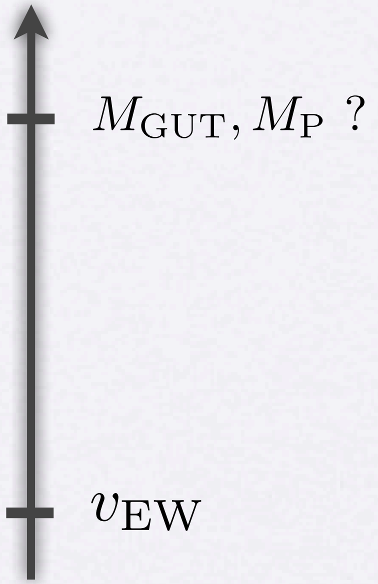




Two distinct paths...

Weakly coupled extensions

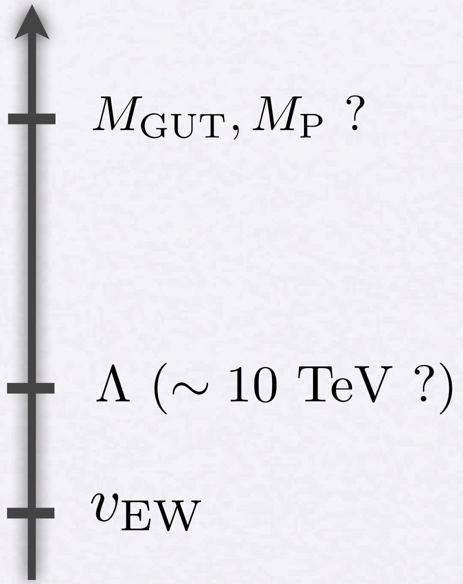
(e.g. ``standard'' SUSY)



- EW scale generated radiatively?,
- A desert above few TeV?,...
- Gauge coupling unification?

Strongly coupled extensions

(e.g. XDim, Little Higgs, Non-standard SUSY, ...)



- Nature of physics above Λ? Defer.
- Need a scalar that is light compared to Λ
  (generically , a ``little hierarchy'' problem)

Extra Dimensional Scenarios

Extra dimensional theories non-renormalizable: necessarily have a cutoff Λ not far above compact. scale

→ want compactification scale close to the EW scale

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Several varieties:

Flat extra dimensions

- Minimal implementations (SM in D-dim)
  - Pair production, single prod. at loop
  - Relatively mild indirect constraints
  - DM candidate (``KK photon”)
- Other variations such as ``Split-UED” → more visible, hence more constrained
- Large XDim (ADD) → ``Fundamental” scale being steadily constrained (e.g. $M_D \gtrsim 4.5$ TeV for $\delta = 2$)

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Significant curvature (``warped scenarios")

- Original RS I proposal: only gravity in bulk
  - spin-2 KK in diphoton above $1\ (2.2)\ \text{TeV}$ for $k/M_P = 0.01\ (0.1)$
- Bulk RS model:
  - spin-2 KK in ZZ above 850 GeV
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  - KK Z in ttbar above 1.3 TeV

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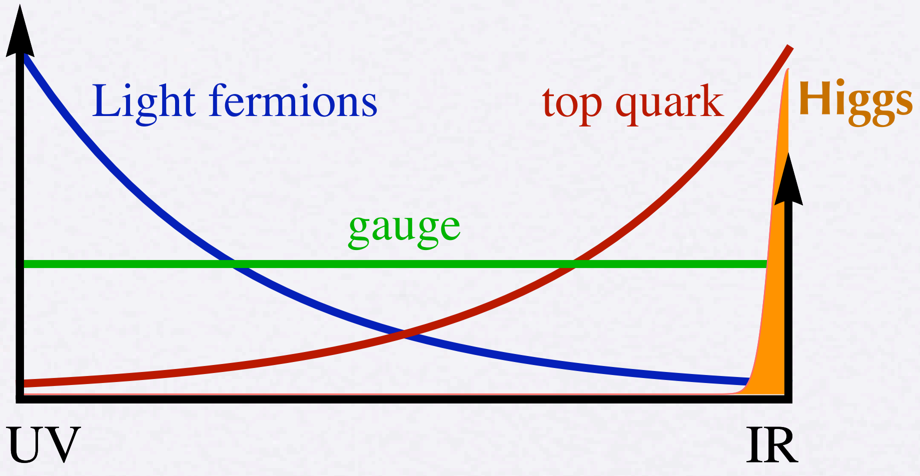
LHC making headway in constraining such scenarios...

Theoretical Filtering

Low cutoff (strong dynamics) is dangerous from the point of view of flavor/CP violation

An interesting solution arises from the possibility to localize fields along the XDim

This further allows to understand hierarchies such as the SM fermion masses (based on ``anarchy")



Identification of Higgs as the extra-dimensional polarizations of appropriate 5D gauge fields (not the SM ones)

⟶ Hard to make the idea realistic in flat space, but viable in warped space.

May address ``little hierarchy" problem. Higgs loops cut at $M_{\rm KK}$, not Λ

Warped constructions, via AdS/CFT correspondence concepts, can be reinterpreted as 4D theory:

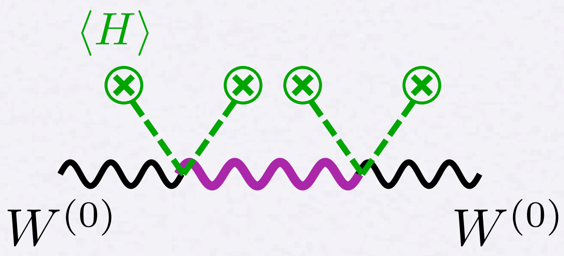
Strongly coupled (approximately) conformal field theory. Conformality spontaneously broken at TeV scale.

Localization ⟷ realization of partial compositeness

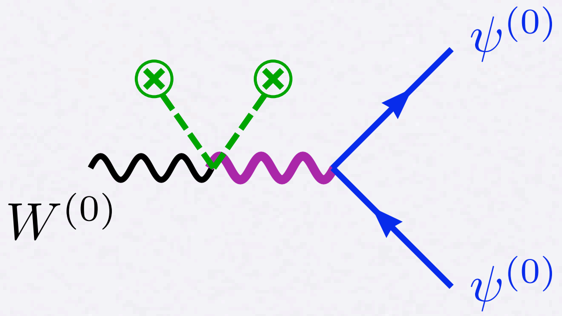
D.B. Kaplan, (1991)
Contino, Kramer, Son & Sundrum (hep-ph/0612180)

Low-energy constraints

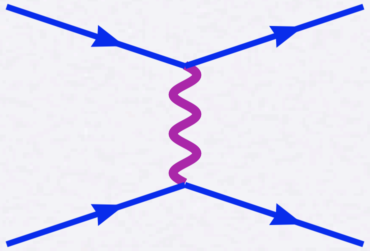
To put the LHC bounds (1-2 TeV) in context, recall low-energy constraints from EW precision tests:



T-parameter



S-parameter



Fermi constant

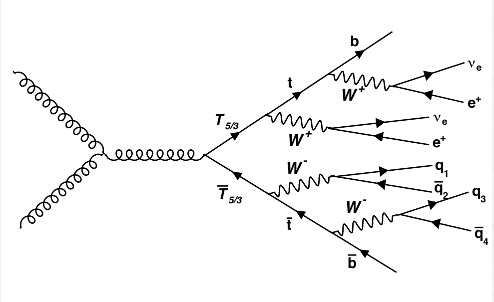
With significant model building, can get $M_{\mathrm{KK}} > 3-4\ \mathrm{TeV}$

Producing such resonances is a high luminosity proposition...

Agashe, Belyaev, Krupovnickas, Perez & Virzi (hep-ph/0612015)
Agashe, et. al. (0709.0007)

However, some fermionic KK resonances (``top partners”) can be significantly lighter...

ATLAS has performed a search for a $Q = 5/3$ quark: lower bound at $670\ \mathrm{GeV}$



What about SUSY?

Previous Expectations: SUSY

Largest radiative contribution to Higgs mass parameter from a colored object (the top quark)

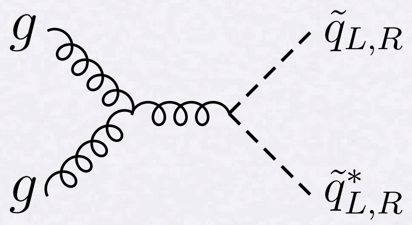
→ Suggests that mechanism of EWSB ``knows” something about QCD

Hadron machines: apart from other considerations, ideal to exploit such a handle

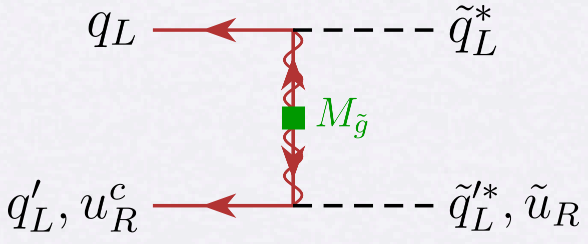
In fact, many BSM proposals involve plenty of strongly interacting new particles...

A case in point: SUSY and production of squarks and gluinos

But our expectations for early discovery of SUSY particles relied not just on QCD production, but on SUSY QCD contributions. For instance



but also



$$\propto \frac{M_{\tilde{g}}}{m^2_{\tilde{g}}}$$

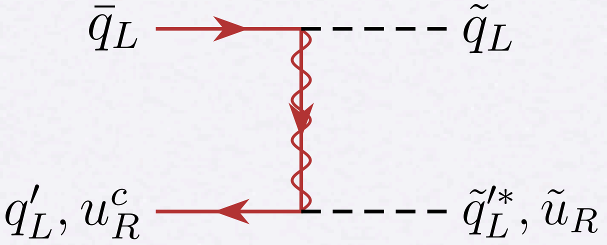
The t-channel gluino contributions are very significant, and decouple slowly with gluino mass!

This depends on ``gluino-number” violation, i.e. its Majorana nature (an interesting point on its own)

Dirac Gluinos at the LHC

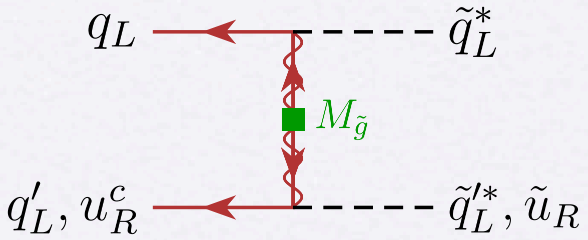
See also: **Choi et. al. 0808.2410; 0911.1951; 1005.0818; 1012.2688**
Heikinheimo, Kellerstein & Sanz, 1111.4322
Kribs & Martin, 1203.4821
Espinosa, Grojean, Sanz & Trott, 1207.7355

But what if gluinos carry a conserved quantum number?



$$\propto \frac{1}{m_{\tilde{g}}^2}$$

vs

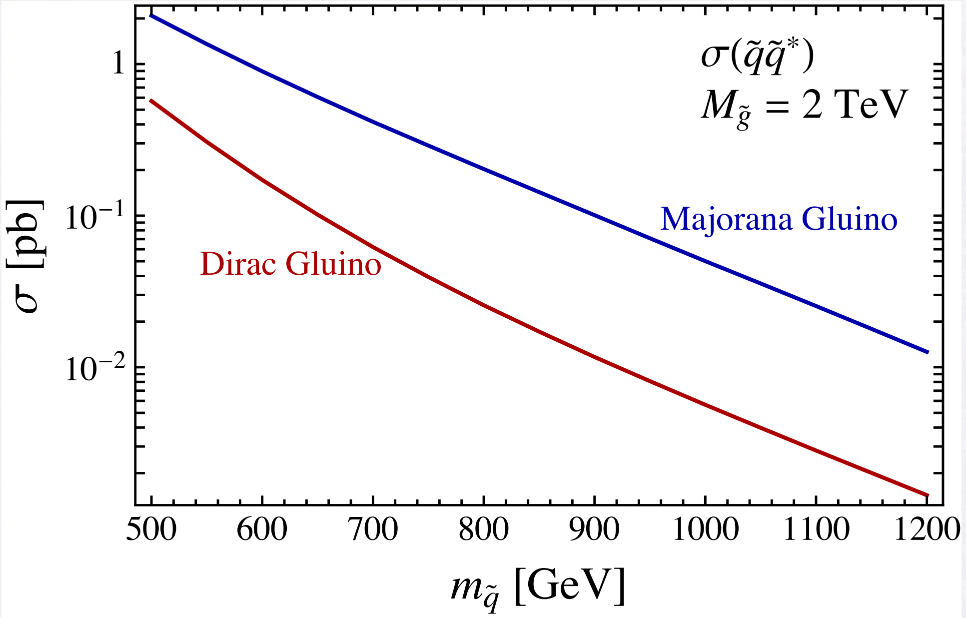


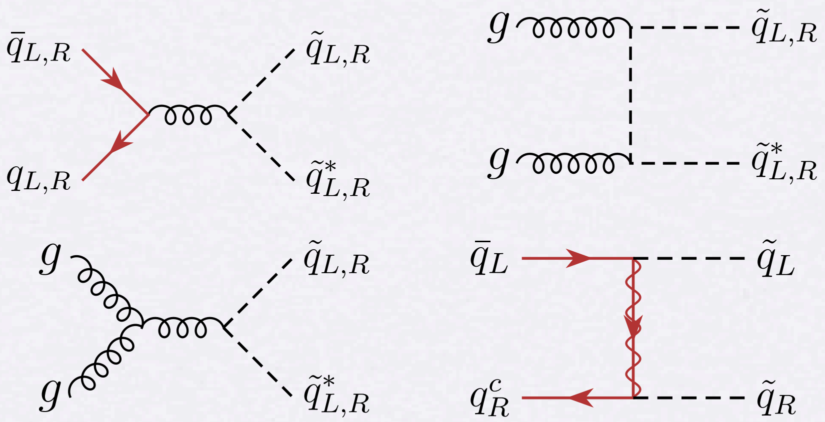
$$\propto \frac{M_{\tilde{g}}}{m_{\tilde{g}}^2}$$

(Pseudo) Dirac Nature: $\sigma\left(qq' \to \tilde{q}_L\tilde{q}'_L\right) = \sigma\left(qq' \to \tilde{q}_R\tilde{q}'_R\right) = 0 \quad \& \quad \sigma\left(q\bar{q}' \to \tilde{q}_L\tilde{q}'^*_R\right) = 0$

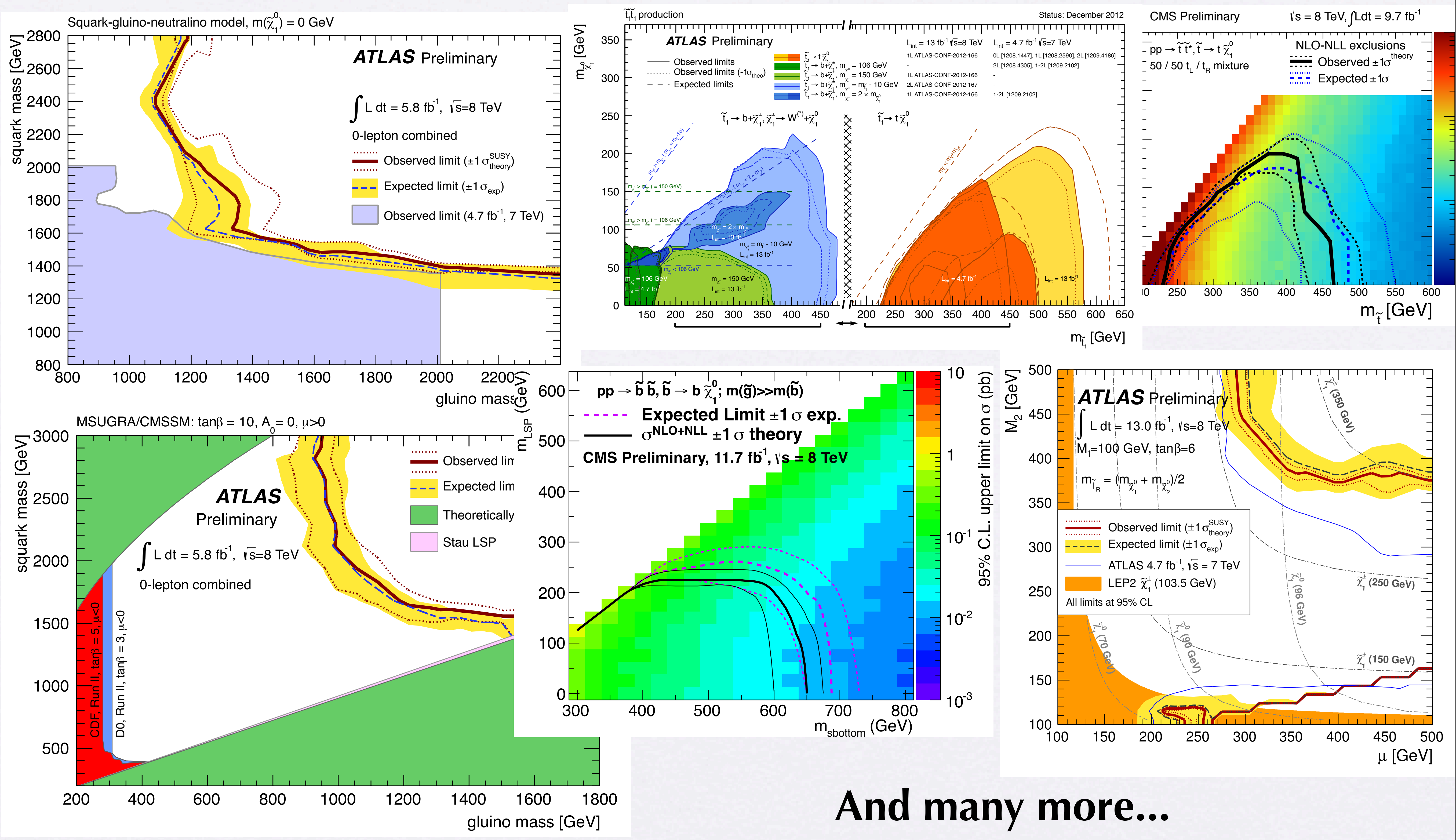
$$\sigma^{\rm Tot}_{\rm Dirac}\left(\tilde{q}\tilde{g}\right) = \sigma^{\rm Tot}_{\rm Majorana}\left(\tilde{q}\tilde{g}\right)$$

$$\sigma^{\rm Tot}_{\rm Dirac}\left(gg \to \tilde{g}\tilde{g}\right) = \mathbf{2}\,\sigma^{\rm Tot}_{\rm Majorana}\left(gg \to \tilde{g}\tilde{g}\right)$$





A Sample of SUSY Constraints



And many more...

Grand conclusions should be drawn with care!

Suppressed Production

Frugiule, Grégoire, Kumar & EP, 1210.0541 & 1210.5257

An illustration within a specific model:

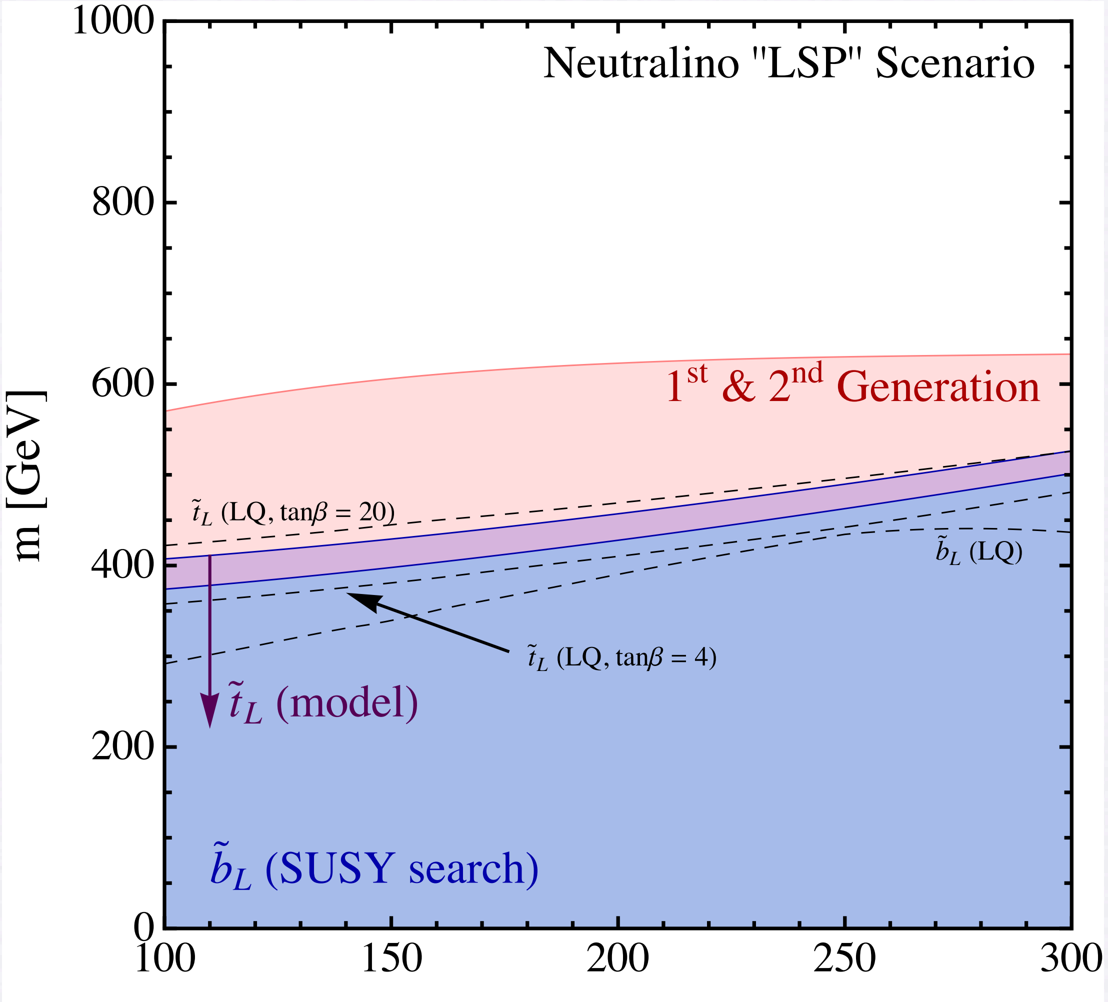
- Suppressed production allows for lighter new physics
- Experimental analyses optimized to push the ``energy frontier”. Currently, poor efficiencies at moderate scales, hence even weaker constraints!

Generic SUSY searches (ATLAS and CMS)

- jets + $\not{E}_T$
- 1, 2 or more leptons + jets + $\not{E}_T$
- Z(ll) + jets + $\not{E}_T$
- SS dilepton searches

More dedicated searches

- Searches with 1, 2 or more b-tags
- Searches involving $\tau's$
- Searches involving tops in final state



Updated from 1210.5257

Symmetries at work at the TeV

A conserved ``gluino number" can naturally arise from an (approximate) R-symmetry, which forbids Majorana masses ⟶ *Dirac* gauginos require additional degrees of freedom

Further implications:

$$\xcancel{m^2_{\rm LR} = m_u(A_u - \mu\cot\beta)}$$

LH and RH sfermions have opposite charges:

No LR mixing (*A*-terms and μ-term vanish)

$$\begin{pmatrix} u_L^* & u_R^* \end{pmatrix} \begin{pmatrix} m^2_{\tilde{U}_L} & 0 \\ 0 & m^2_{\tilde{U}_R} \end{pmatrix} \begin{pmatrix} u_L \\ u_R \end{pmatrix}$$

Turns out that this structure suppresses significantly SUSY flavor violation!

Kribs, Poppitz & Weiner, 0712.2039
see also Fok & Kribs, 1004.0556

Could the $U(1)_R$ symmetry play the moral analogue of the GIM mechanism?

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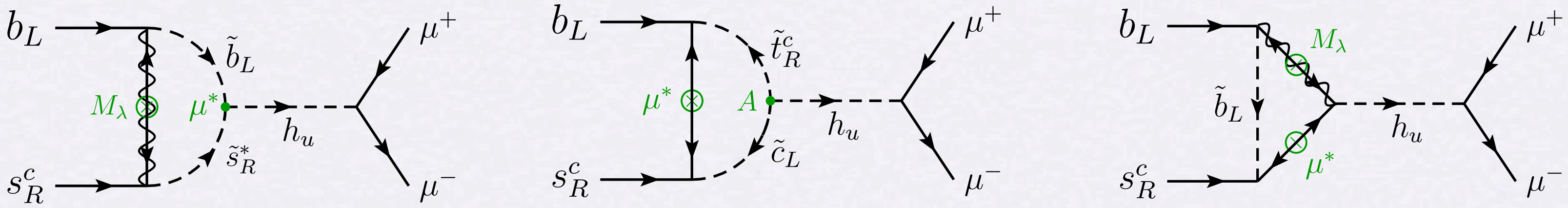
An example of current interest: $\boxed{B_s \to \mu^+\mu^-}$

tan β enhanced diagrams in the MSSM:



All proportional to M_λ, μ or A-terms ⟶ vanish in the R-symmetric limit

In the MSSM: $(\tan\beta)^6$ enhancement simply indicates that tan β cannot be too large

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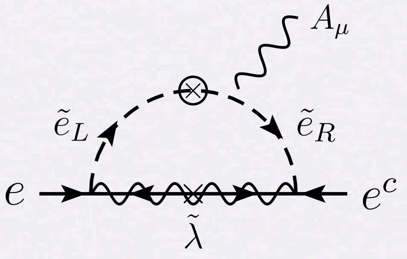
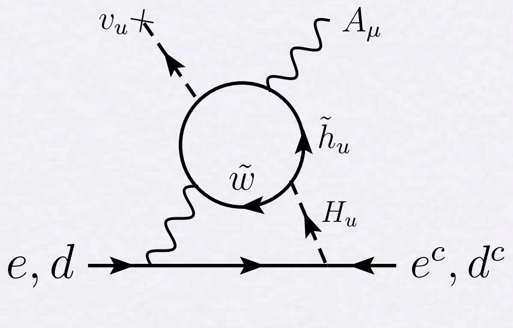
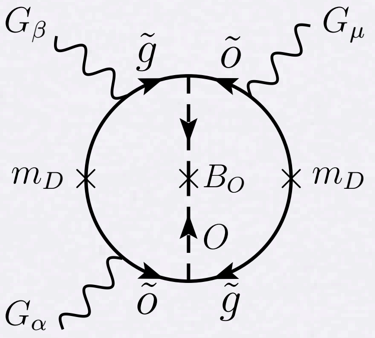
Electric dipole moments also naturally suppressed, e.g.



Suppressed,
no LR mixing



No $\tan\beta$ enhancement

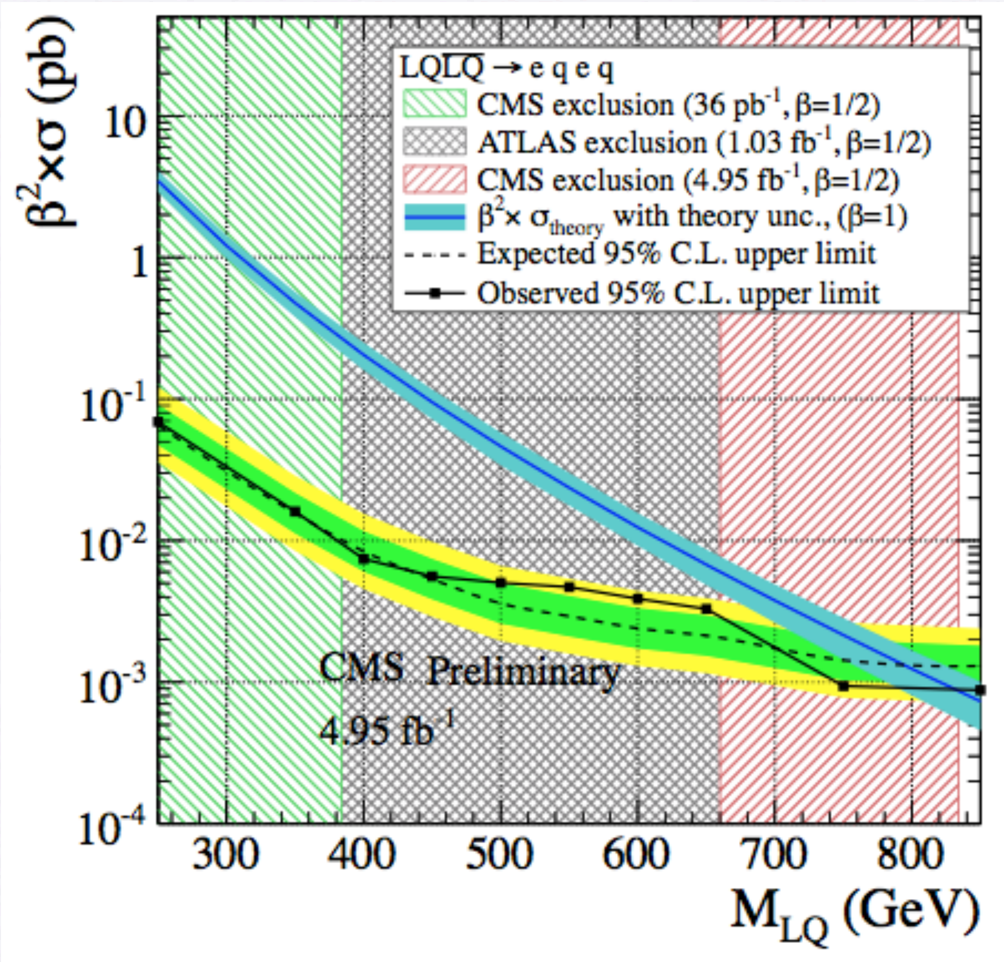


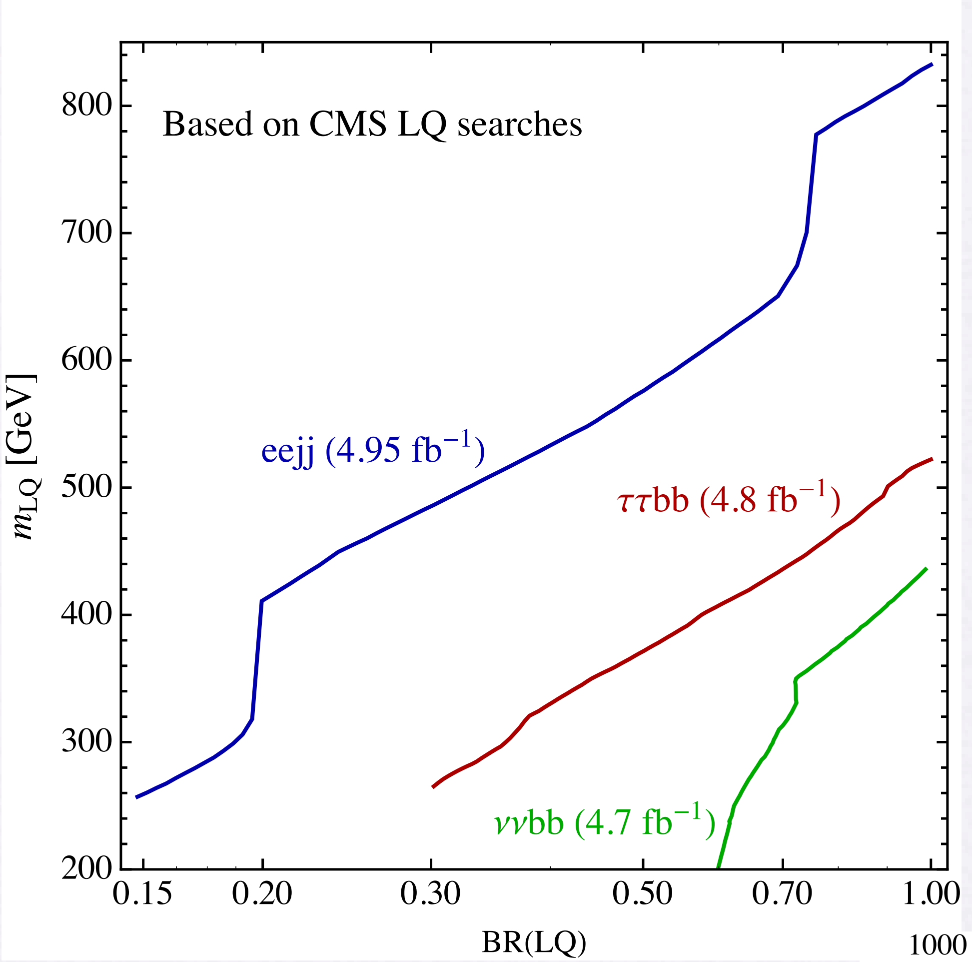
Perhaps interesting!

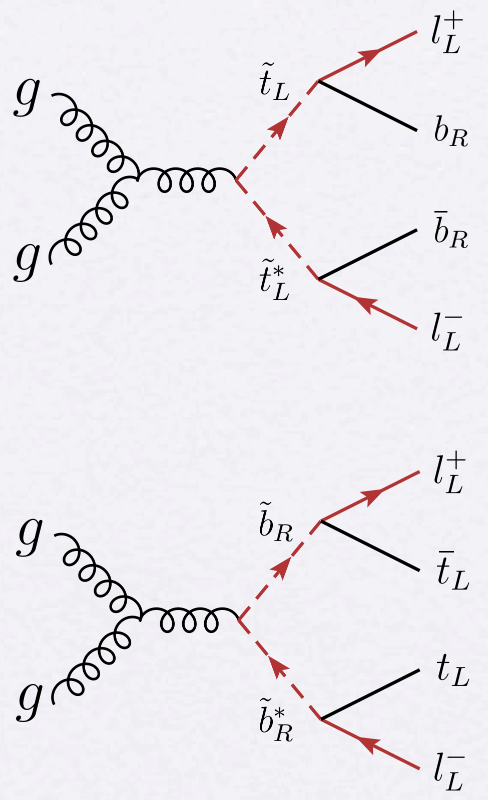
Can play a role in making EWBG viable!

Kumar and EP, 1107.1719

Lepto-quark Searches



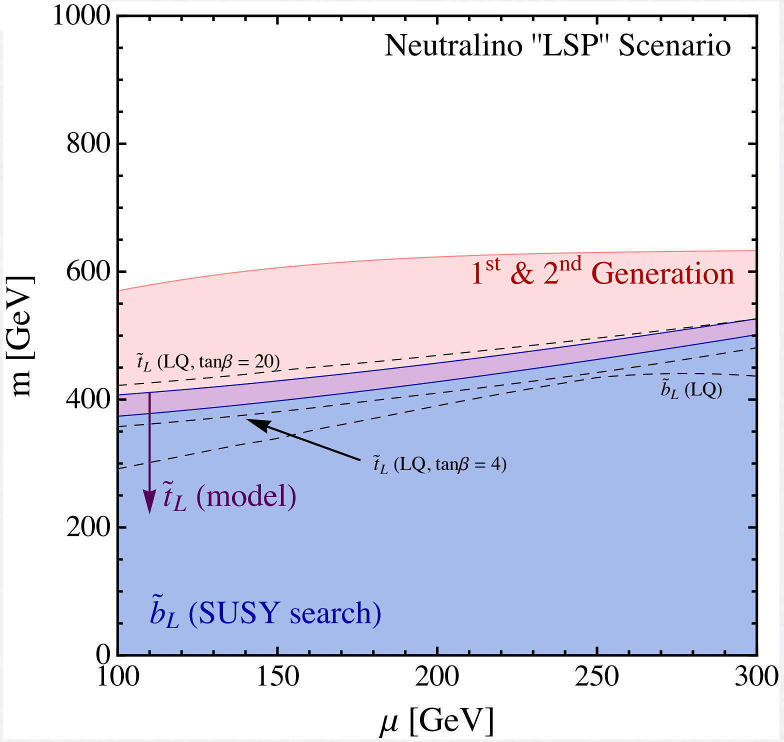




- Strong motivation to look for 3rd generation squarks in LQ modes

$$\tilde{t}_L \rightarrow b_R l_L^+ \text{ with } \tilde{b}_L \rightarrow b_R \bar{\nu} \quad ; \quad \tilde{b}_R \rightarrow t_R l_L^- \text{ with } \tilde{b}_R \rightarrow b_L \nu$$

- Or even some second generation squarks



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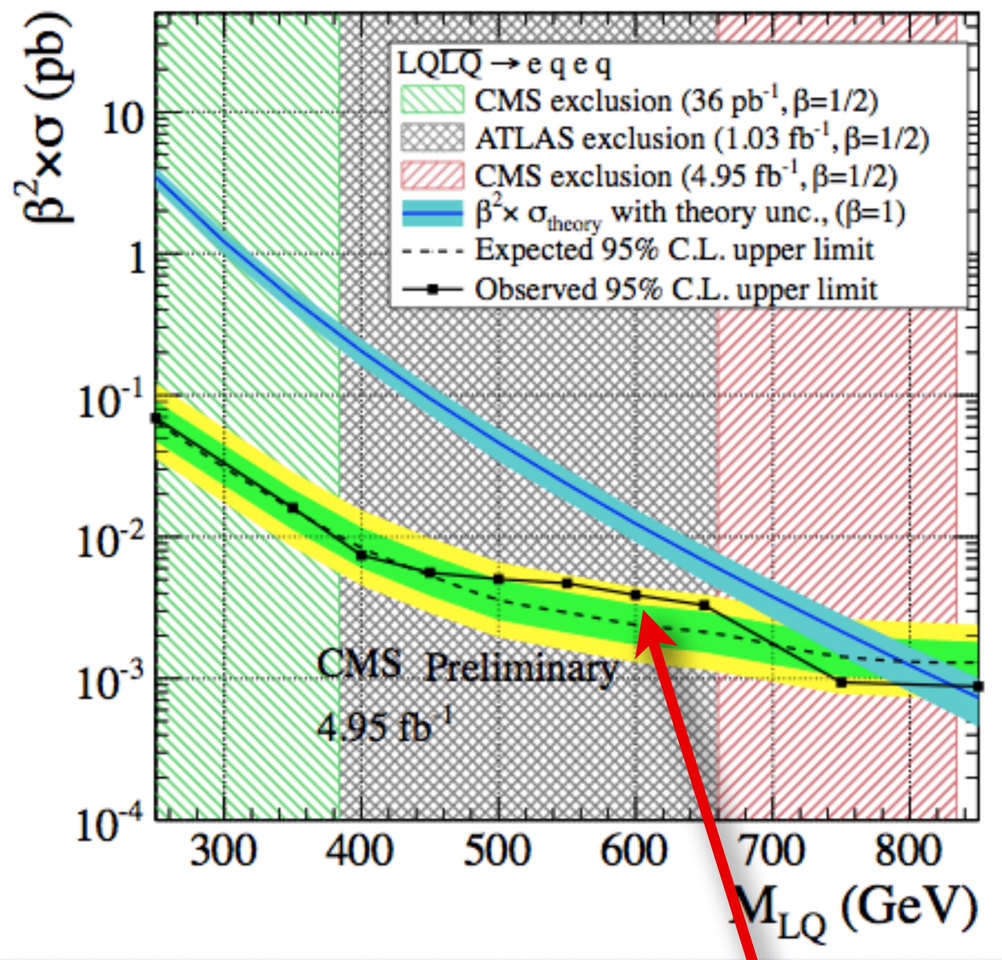

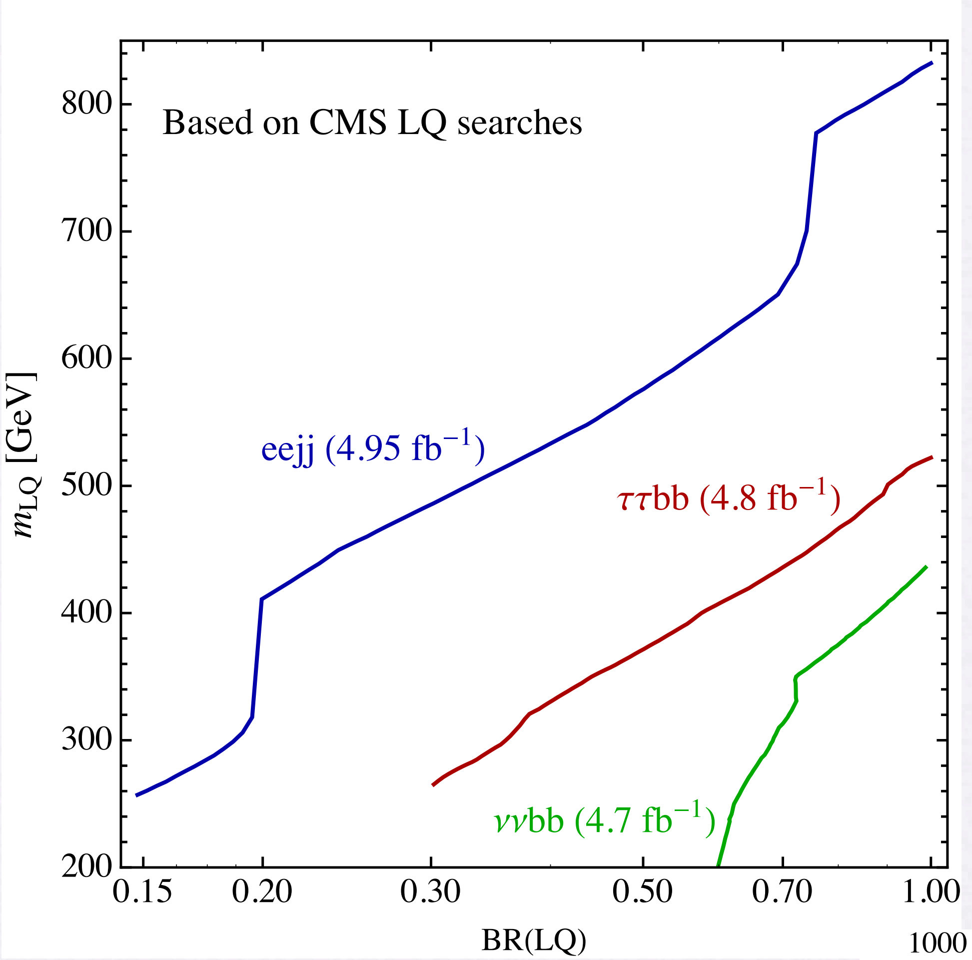

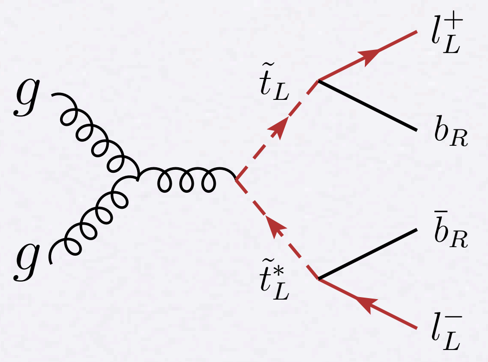

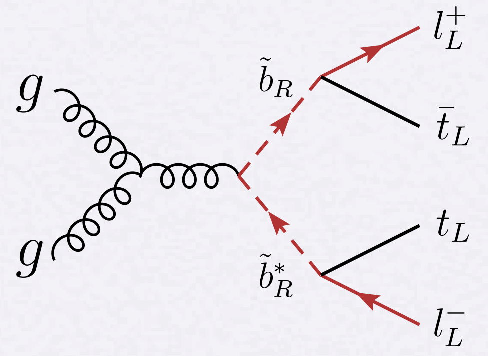

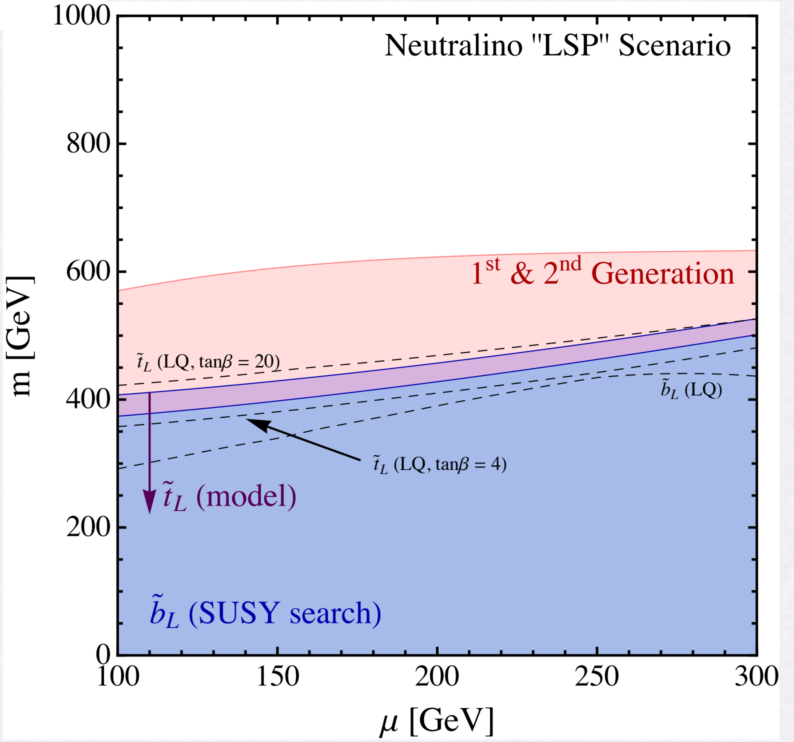

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- Or even some second generation squarks

Something cooking?

Conclusions

- We are still far from establishing a fully satisfactory answer to the question of how the breaking of the EW symmetry comes about

(The Higgs boson: a crucial step in this direction, apart from a remarkable experimental and theoretical achievement)

- The question of ``naturalness of the weak scale'' is conceptually important. Theoretical ideas have been strongly inspired by it... the LHC is just starting the journey to a possible answer.

- Important to *look* for ``light'' physics with suppressed production cross sections...

... not just to push the ``energy frontier boundary''

- Should look forward to the LHC shutdown, when the collaborations will have the time to explore more fully the recorded data... and of course to the 14 TeV run!