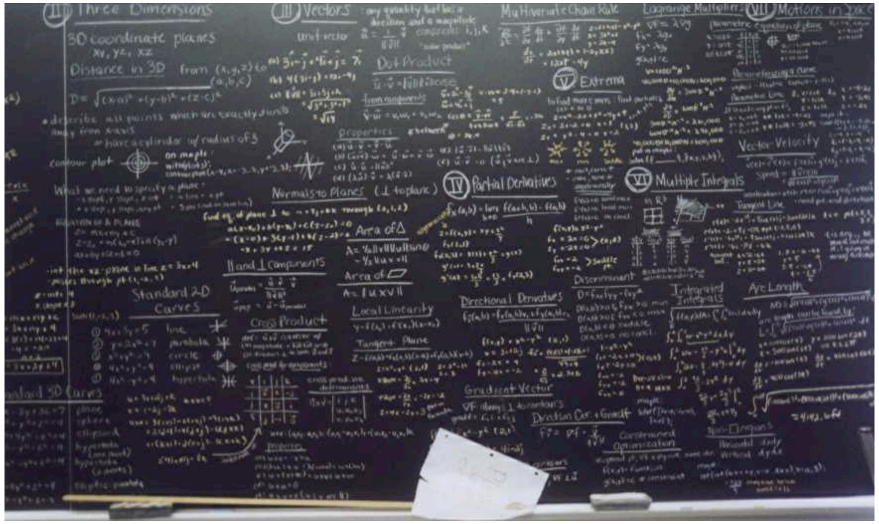
Implications of LHC Data to New Physics

Alex Pomarol (Univ. Autonoma Barcelona)

vs



Loop effects make the EW scale unnatural

$$v^2 = -(\mu^2 + m_{H_u}^2)\frac{1}{\lambda} \simeq (246\ \mathrm{GeV})^2$$

(at large tanβ)

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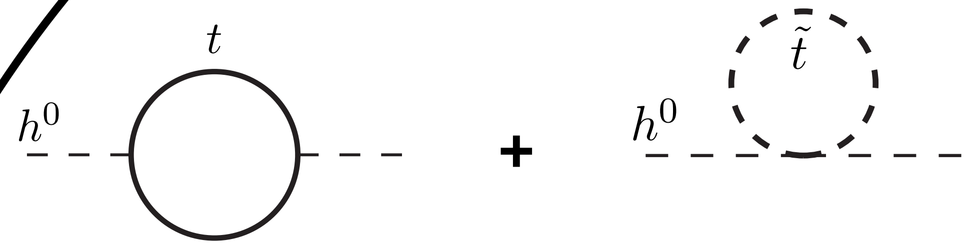
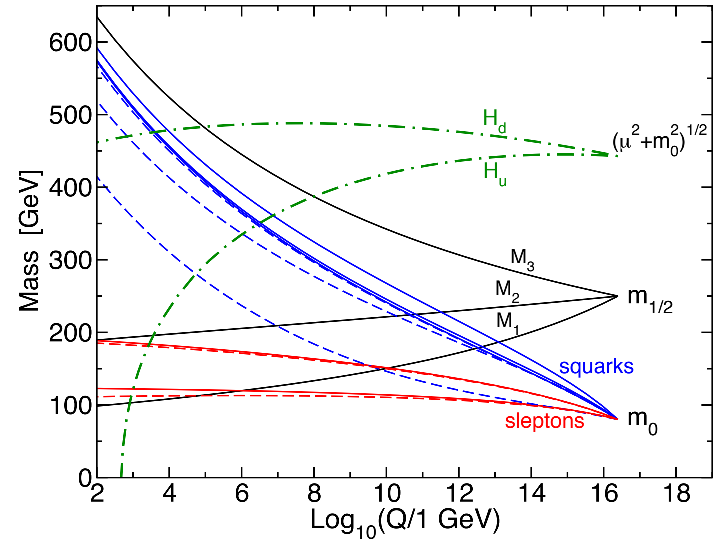


scale at which the susy-breaking terms are generated

$$\delta m^2_{H_u} = -\frac{3y_t^2}{8\pi^2}\left(m^2_{Q_3} + m^2_{u_3} + |A_t|^2\right)\ln\left(\frac{\Lambda}{m_{\tilde{t}}}\right)$$

Loop effects make the EW scale unnatural

If soft-terms generated at M_{GUT} :



$$M_1(m_{\rm weak}) = 0.41 M_1$$
$$M_2(m_{\rm weak}) = 0.82 M_2$$
$$M_3(m_{\rm weak}) = 2.91 M_3$$
$$-2\mu^2(m_{\rm weak}) = -2.18\mu^2$$
$$-2m^2_{Hu}(m_{\rm weak}) = 3.84 M_3^2 + 0.32 M_3 M_2 + 0.047 M_1 M_3 - 0.42 M_2^2 + 0.011 M_2 M_1 - 0.012 M_1^2 - 0.65 M_3 A_t - 0.15 M_2 A_t - 0.025 M_1 A_t + 0.22 A_t^2 + 0.0040 M_3 A_b - 1.27 m^2_{H_u} - 0.053 m^2_{H_d} + 0.73 m^2_{Q_3} + 0.57 m^2_{U_3} + 0.049 m^2_{D_3} - 0.052 m^2_{L_3} + 0.053 m^2_{E_3}$$

sum of both

(125 GeV)²

~(1000 GeV)²

➥ MSSM entering the unnatural territory

(we must tune parameters to keep v~246 GeV)

Directions to go to keep susy natural:

Beyond the MSSM:

- Extra states (singlets): **NMSSM**
- New sources of Susy breaking

NMSSM= MSSM+singlet

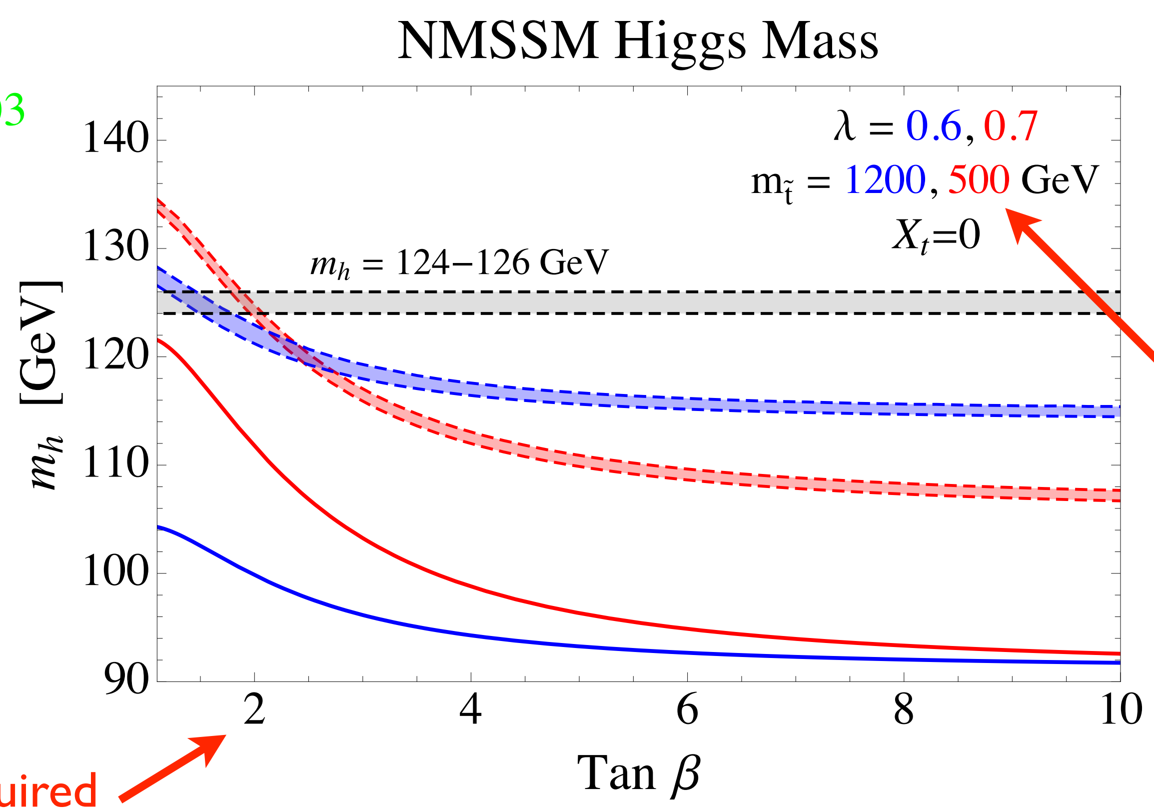
$$m_h^2 = M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta + \delta_t^2$$

new contribution:

W= λSH$_u$H$_d$

(also gives mass to the Higgsino)

arXiv:1112.2703



stops can be light accessible to LHC8:

(Remnant tuning of 10%)

small tanβ required

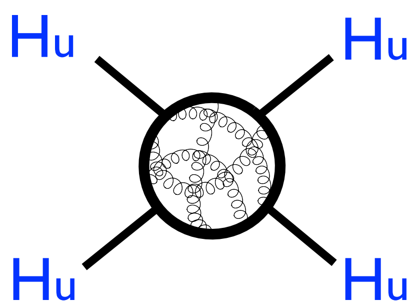
Extra contributions to the Higgs mass

➥ the end of only soft-breaking susy

- New U(1) at ~ TeV: extra D-term

$$\Delta V = \kappa \left(|H_1^0|^2 - |H_2^0|^2 \right)^2 \qquad \kappa = \frac{g_X^2}{8(1 + \frac{M_{Z'}^2}{2m_\phi^2})}.$$

- Supersymmetry breaking at the TeV:



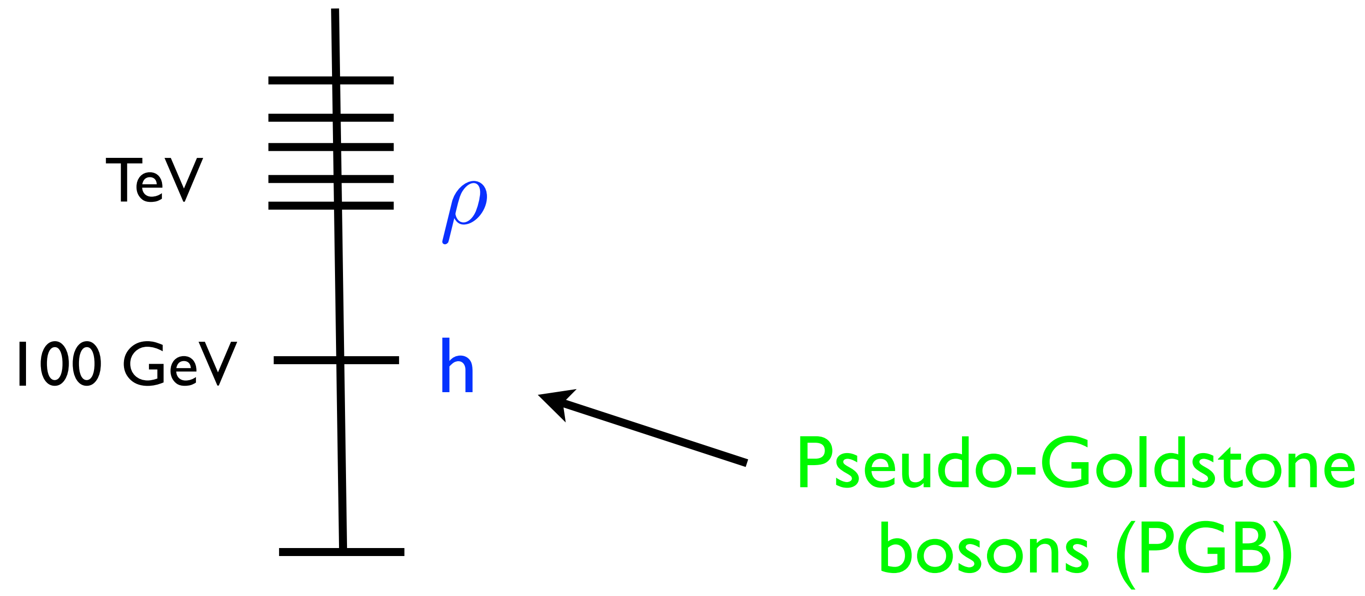
$$\Delta\lambda_i \sim \frac{g_i^4 N}{16\pi^2}$$

➥ Relax bounds on stops:

Susy back to the natural territory

125 GeV Composite Pseudo-Goldstone Higgs

New **strong sector at the TeV** with a spectrum:



Possible symmetry breaking patterns of the **strong TeV sector**:

$$G \rightarrow H$$

G	H	PGB
SO(5)	SO(4)	4=(2,2)
SO(6)	SO(5)	5=(2,2)+(1,1)
	SO(4)xSO(2)	8=(2,2)+(2,2)
SO(7)	SO(6)	6=(2,2)+(1,1)+(1,1)
	G_2	7=(1,3)+(2,2)
...	...	...

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one H doublet

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One doublet + Singlet

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Two doublets

Galloway, Evans, Luty, Tacchi 10

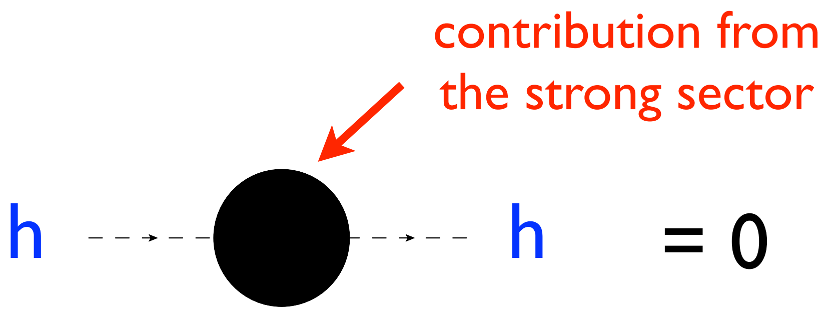
Example: Just replace in QCD **SU(3)c** by **SU(2)c**

2 flavors: ψ_L, ψ_R^c 2L + 2R = 4 of SU(4)

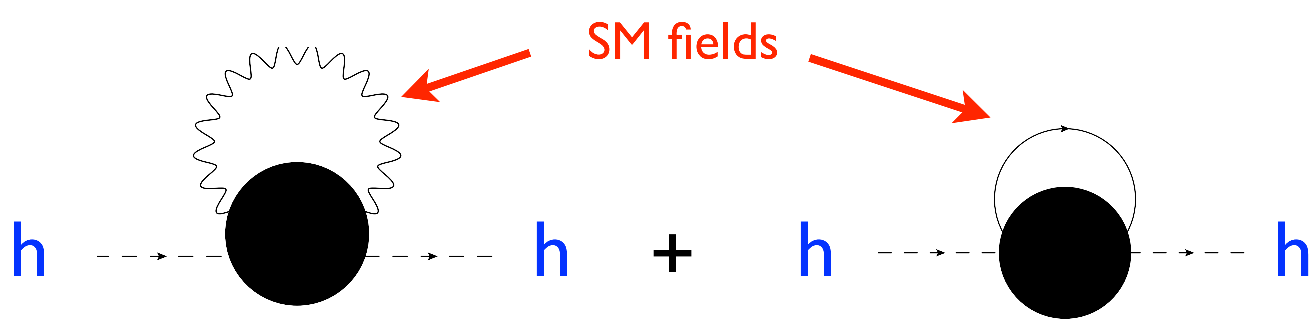
if <ΨΨ> breaks SU(4)~**SO(6)** → **SO(5)**

5 Goldstones = **Higgs doublet**
and a singlet

Light Higgs since its mass arises from one loop (explicit breaking of the global symmetry due to the SM couplings):



it's a Goldstone



$$\Rightarrow \quad V(h) = \frac{g_{SM}^2 m_\rho^2}{16\pi^2} h^2 + \cdots$$

Difficult to get predictions due to the intractable **strong** dynamics**!**

A possibility to move forward has been to use the...

AdS/CFT approach

Strongly-coupled systems
in the Large N_c
Large $\lambda \equiv g^2 N_c$

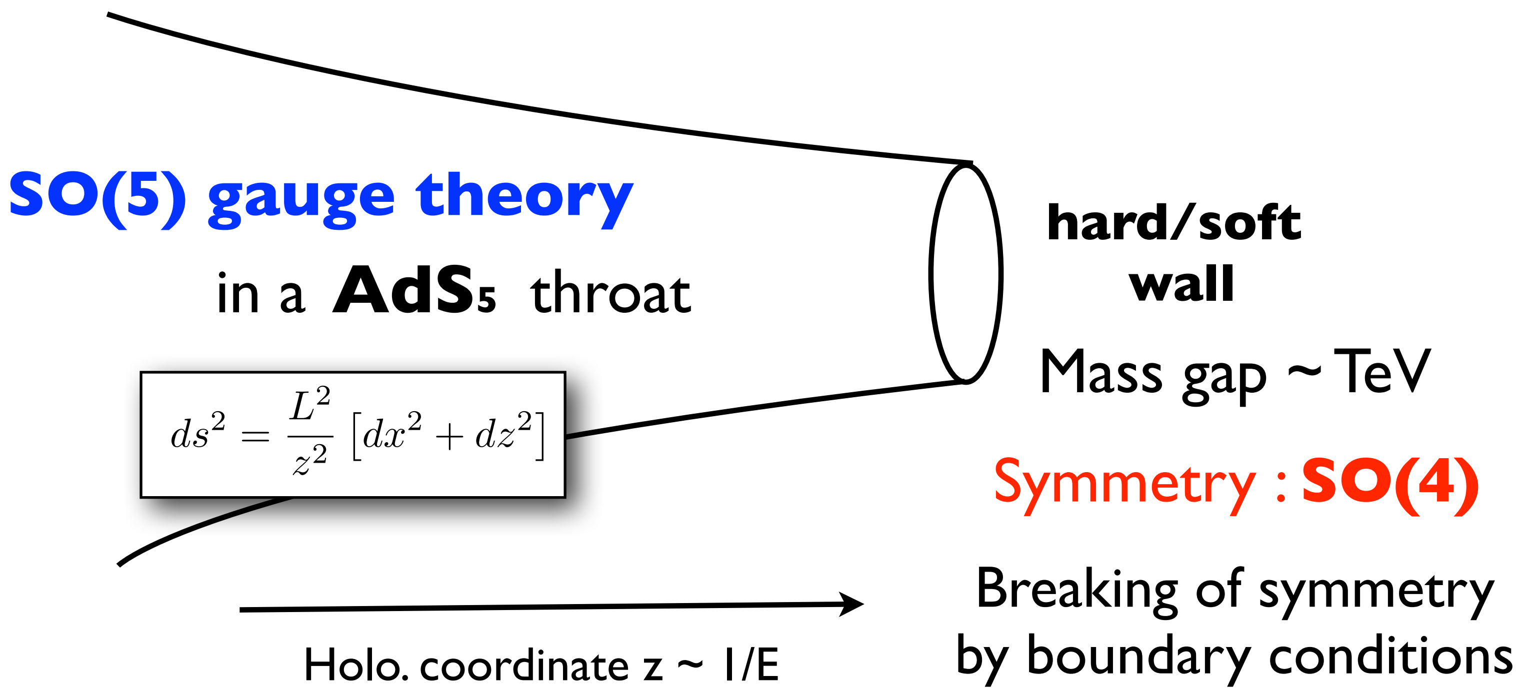
→

Weakly-coupled Gravitational systems in higher-dimensions

Very **useful** to derive properties of **composite states** from studying weakly-coupled fields in warped extra-dimensional models

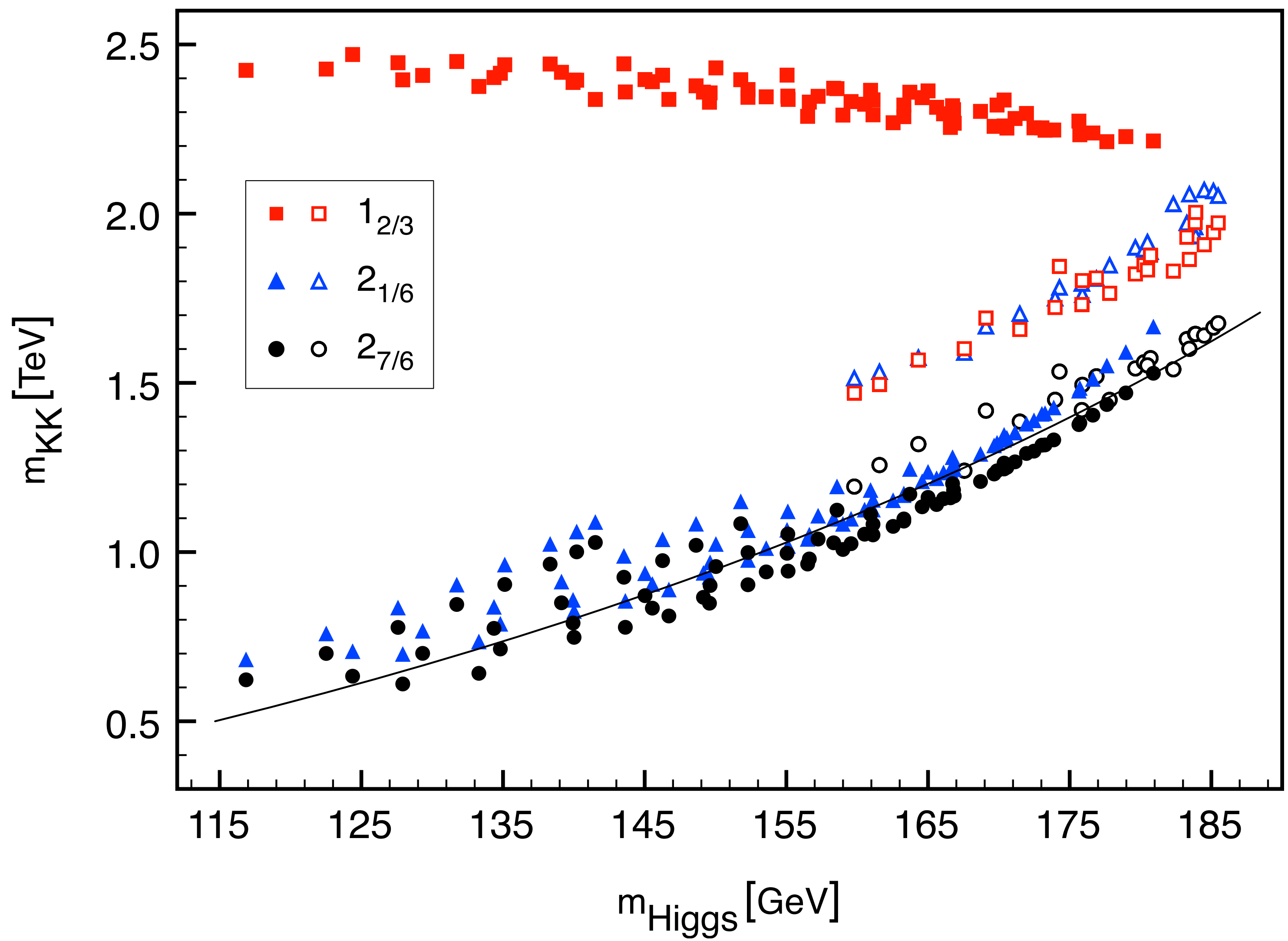
We can study the properties of this scenarios without knowing the fundamental theory behind

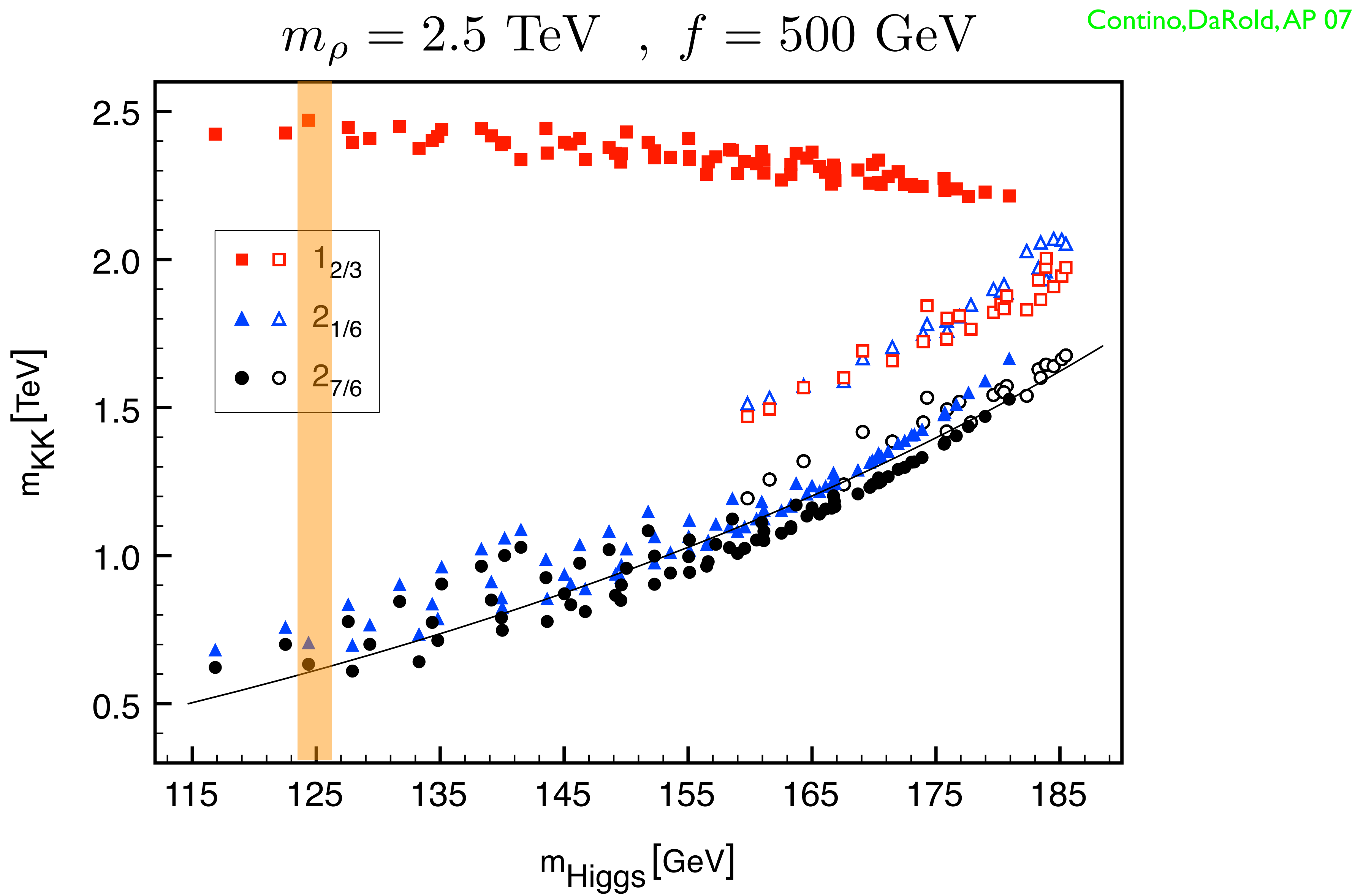
Using holography (AdS/CFT) we can relate this scenario to a weakly-coupled 5D dimensional model and get predictions:



$m_\rho = 2.5$ TeV , $f = 500$ GeV

Contino,DaRold,AP 07

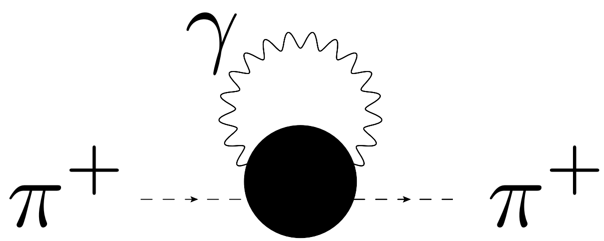




For a 125 GeV Higgs, the fermionic **resonances** of the top are light ~ 600 GeV

Simpler derivation of the connection:
Light Higgs - Light Resonance

As Das,Guralnik,Mathur,Low,Young 67 for the charged pion mass:



➥ correlator encoding the QCD contributions

Approximation: QCD correlator dominated by the minimal number of resonances giving the right convergence at high momentum

$$m^2_{\pi^+} - m^2_{\pi^0} \simeq \frac{3\alpha}{2\pi} m^2_\rho \log 2 \simeq (37 \text{ MeV})^2$$

Exp. (35 MeV)²

quite successful!

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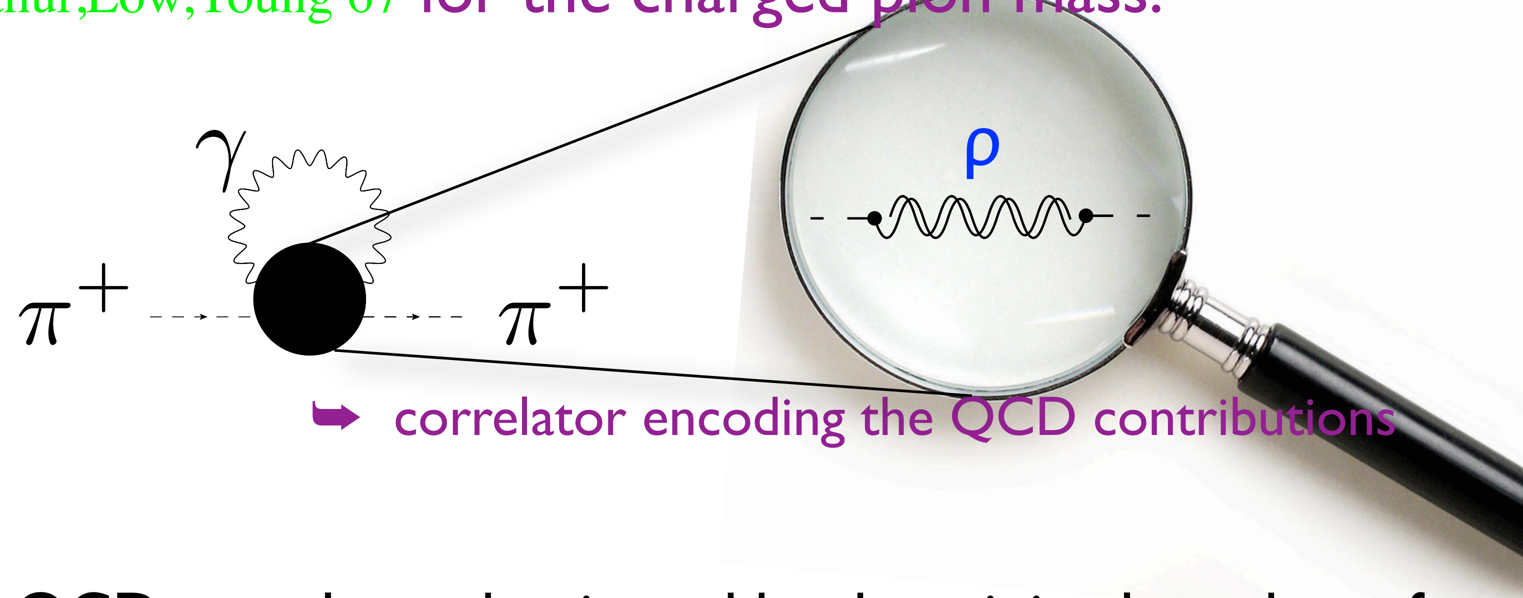

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We must only specify how the SM couples to the strong sector

$$\mathcal{L} = \mathcal{L}_{\rm strong} + \mathcal{L}_{\rm SM} + J^{\mu}_{\rm strong} W_{\mu} + \mathcal{O}_{\rm strong} \cdot \psi_{\rm SM}$$

we must specify which rep of SO(5)

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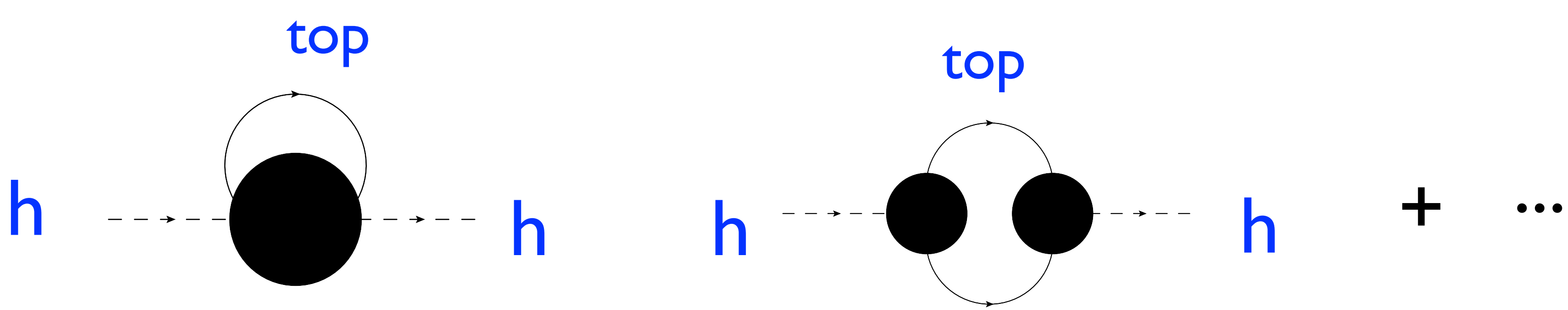
Higgs mass:



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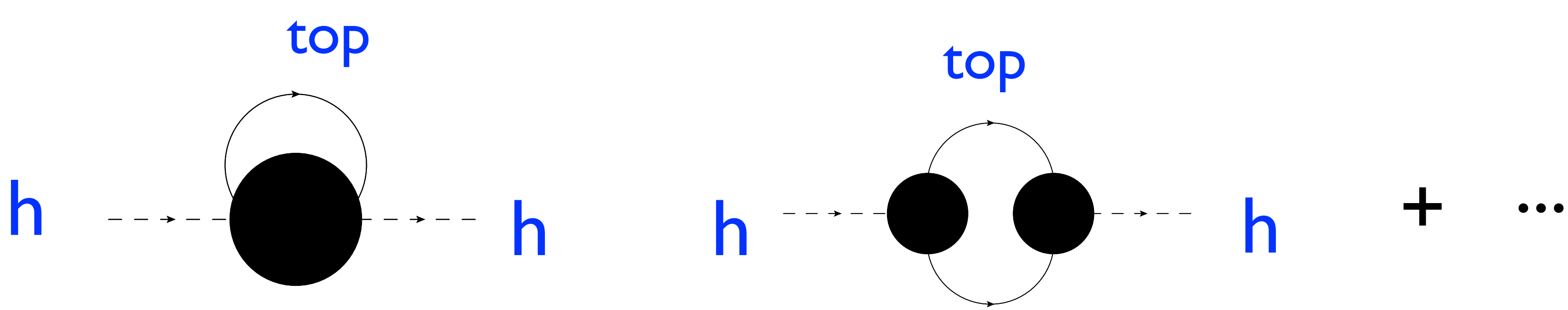


Procedure (as in the pion case):

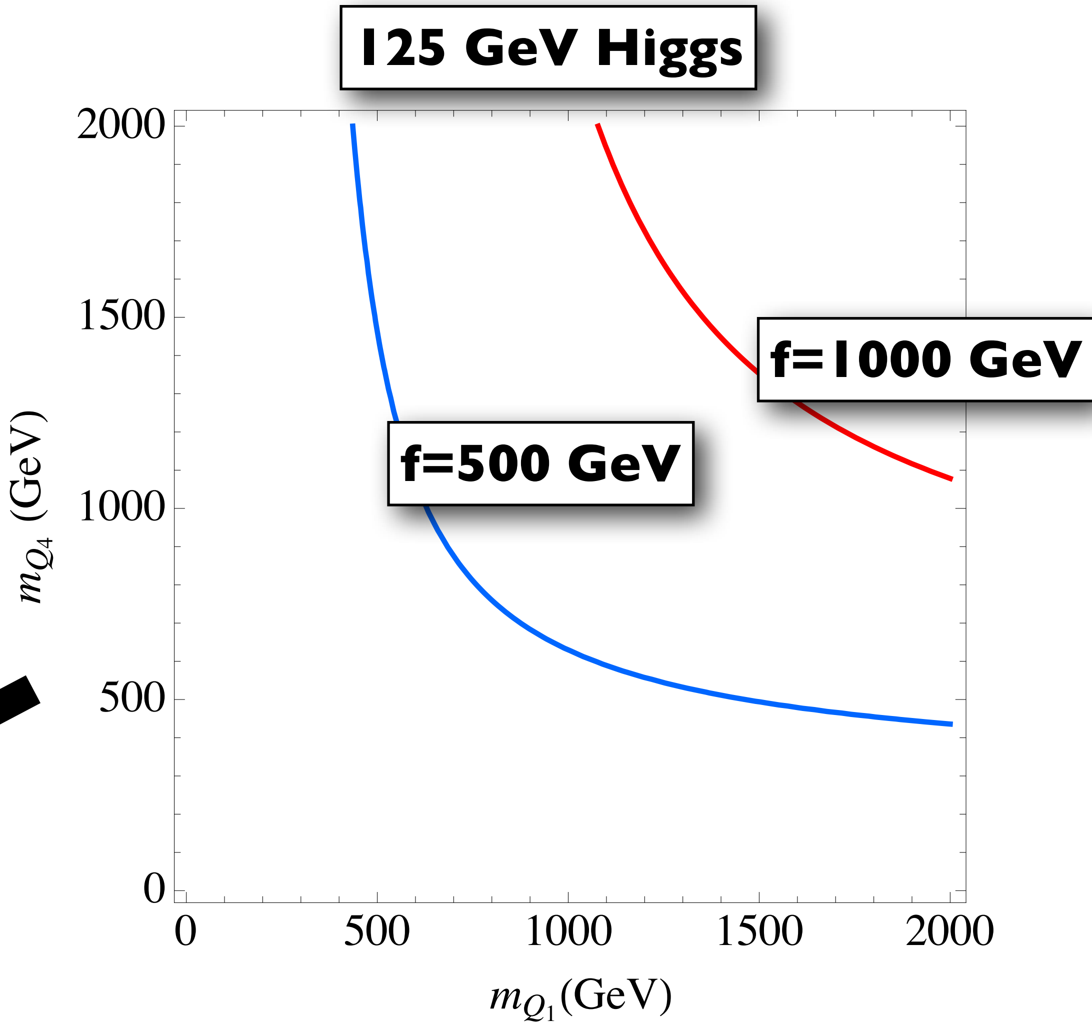
1) Demand convergence at high momentum
2) Assume correlators are dominated by the lowest resonances

For the minimal composite PGB Higgs model:

$$m_h^2 \simeq \frac{N_c}{\pi^2}\left[\frac{m_t^2}{f^2}\frac{m_{Q_4}^2 m_{Q_1}^2}{m_{Q_1}^2 - m_{Q_4}^2}\log\left(\frac{m_{Q_1}^2}{m_{Q_4}^2}\right)\right]$$

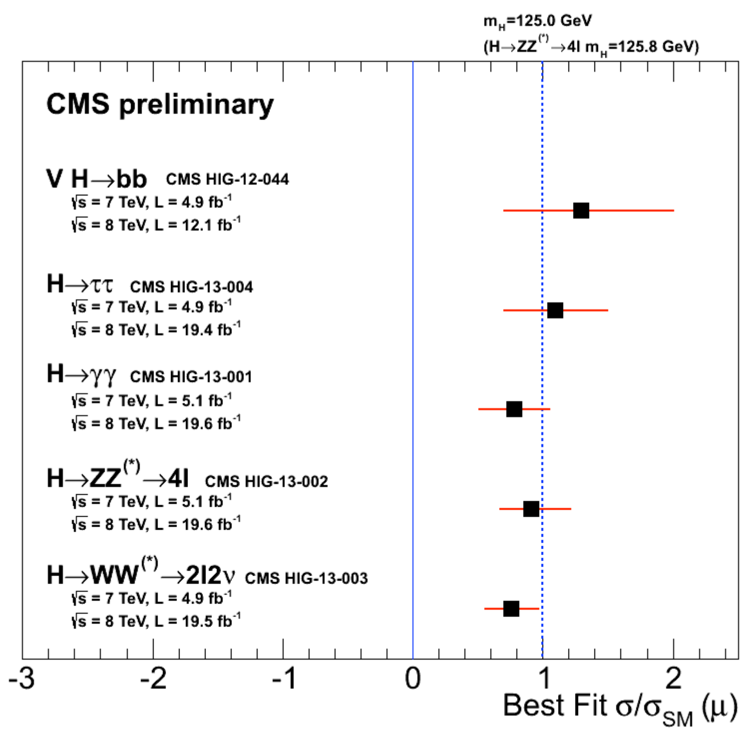
f = Decay-constant of the PGB Higgs

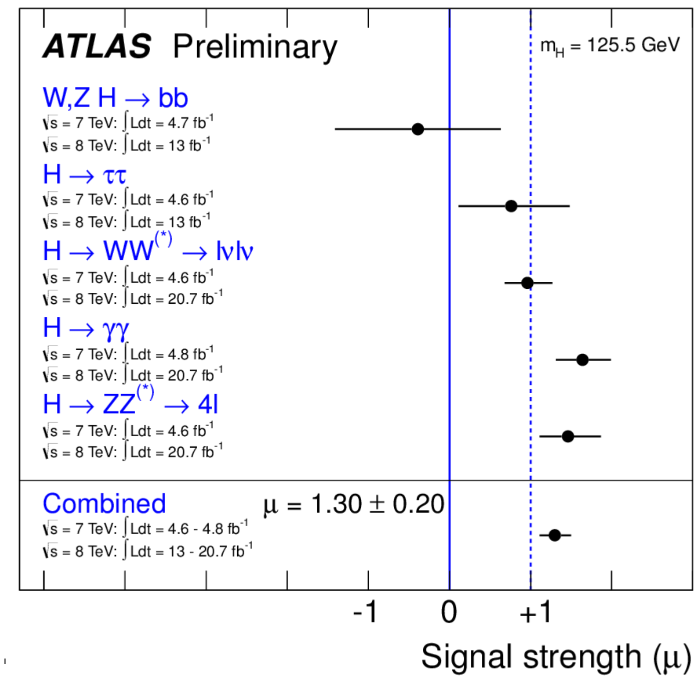
mass of color vector-like fermions with EM charges 5/3,2/3,-1/3



Fermion resonances must be below the TeV

What does the Higgs couplings tell us?

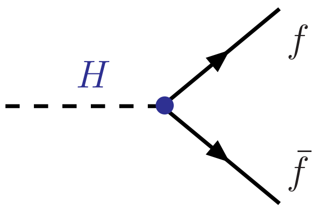




Not significant deviations from a SM Higgs !

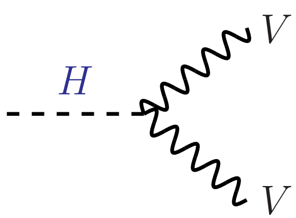
Main pieces of information extracted from data:

1)

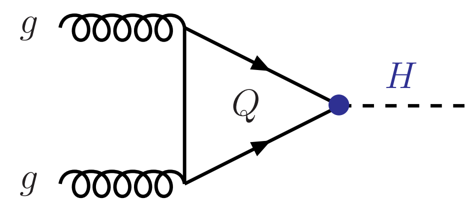


f=fermions

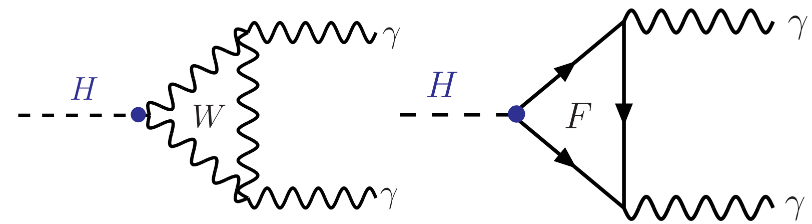
2)



3)



4)



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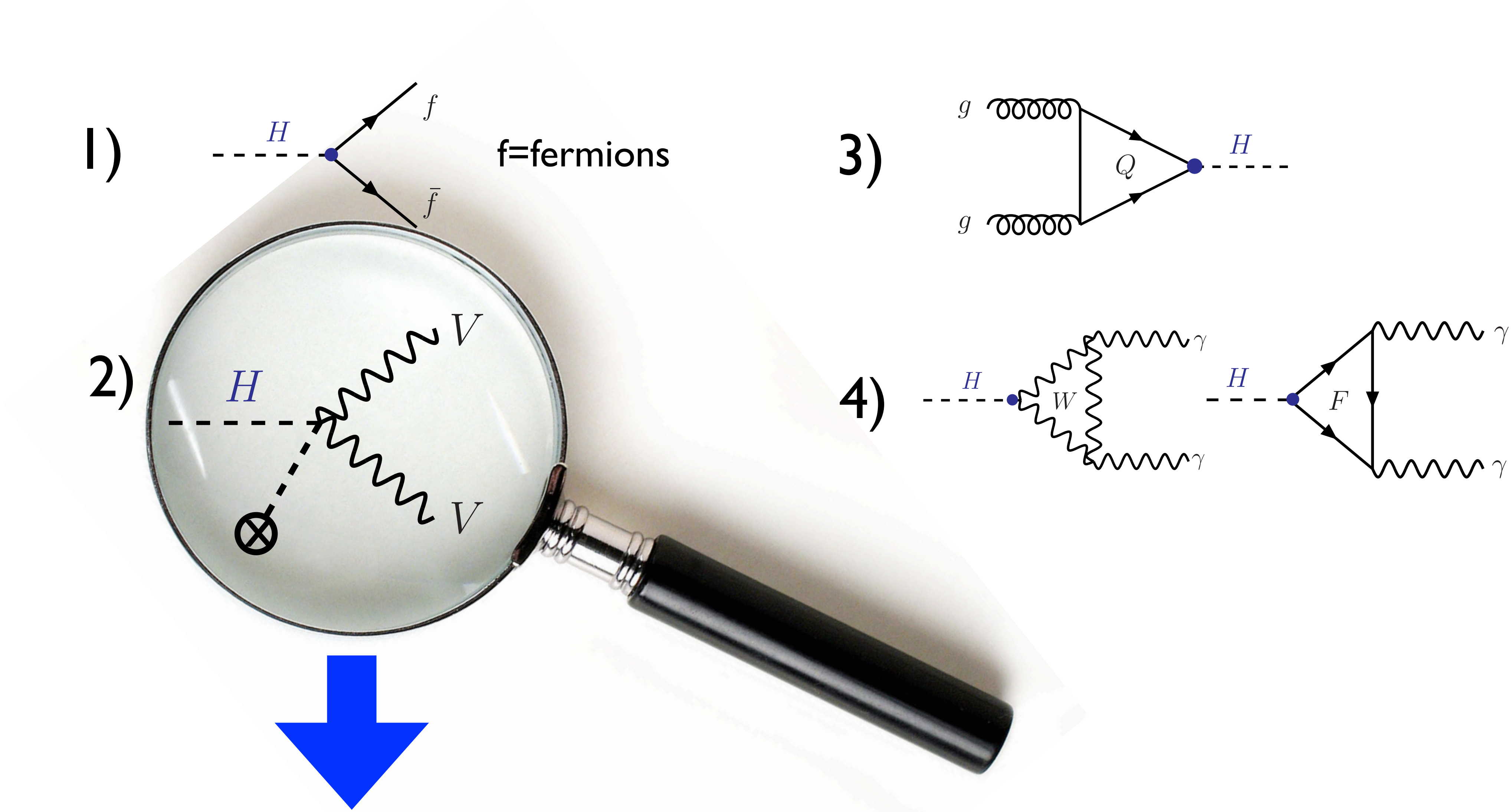
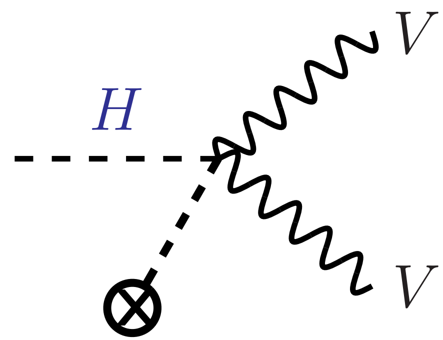


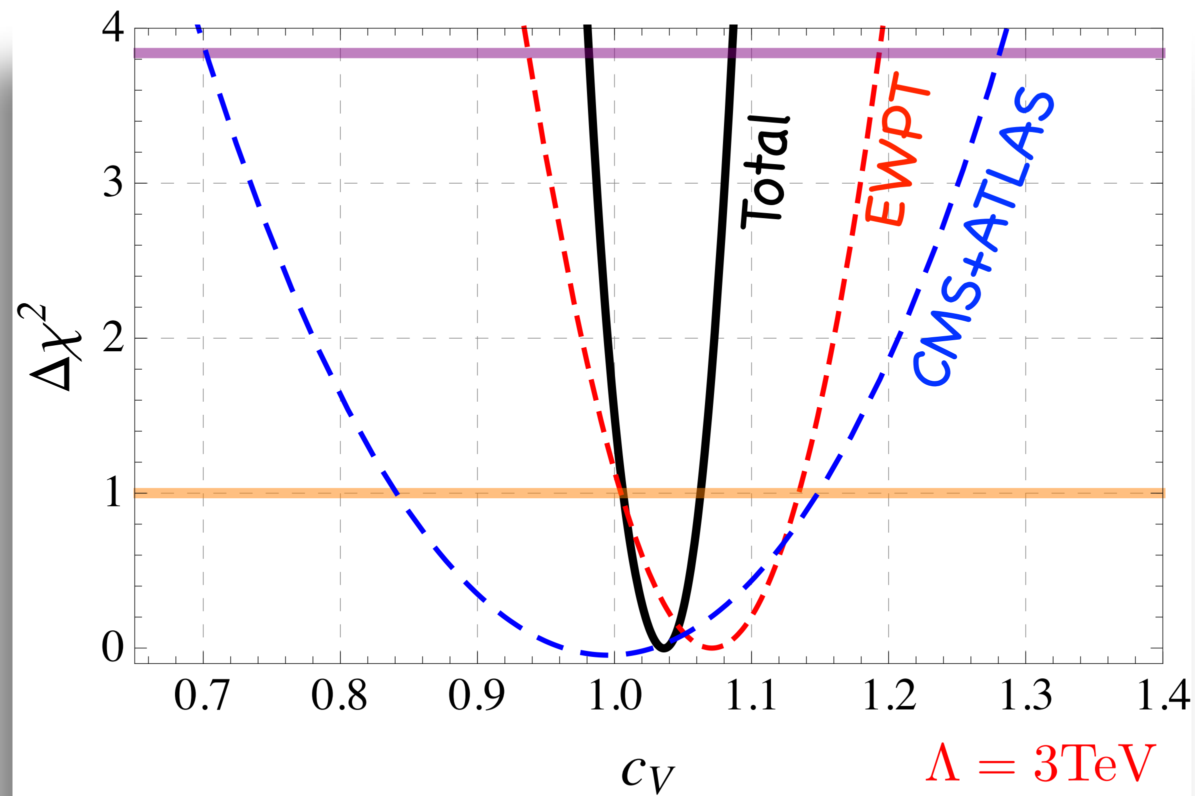
Most genuine Higgs coupling
(discloses its role in EWSB)

Present data is telling us that the 125 GeV state has to do with EWSB

Most genuine Higgs coupling:
(discloses its role in EWSB)



$$c_V = \frac{g_{hVV}}{g_{hVV}^{\text{SM}}}$$



Falkowski,Riva,Urbano 13

it behaves as a Higgs doublet!

Different origins of the Higgs mechanism
give **different predictions** for these couplings

Two examples:

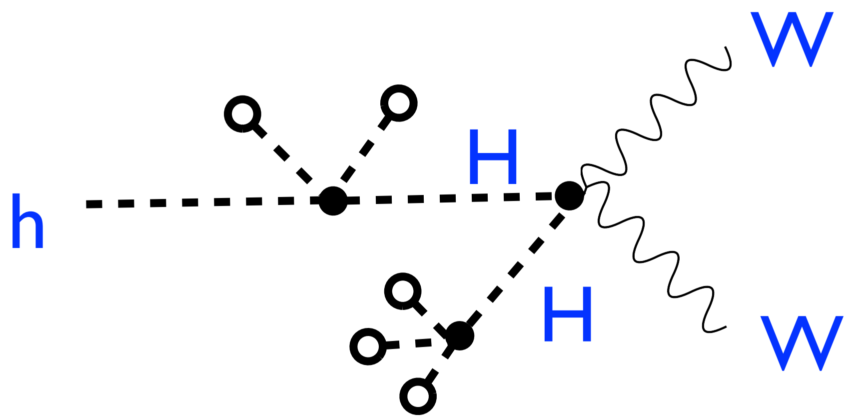
a) **Supersymmetry (MSSM)**
with a Heavy spectrum $M_{susy} \gg m_W$

b) **Composite PGB Higgs**

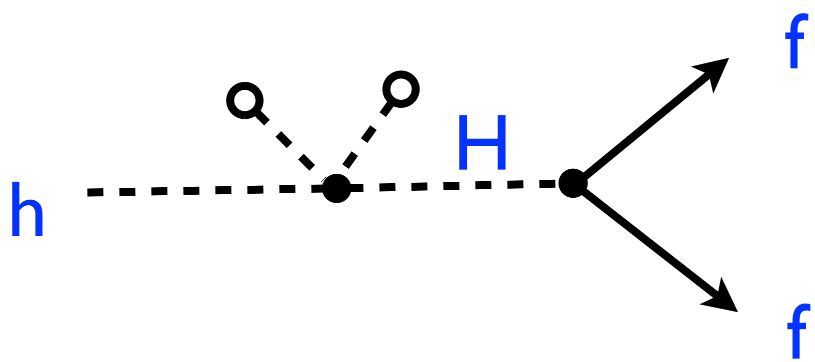
Supersymmetry

MSSM with heavy spectrum ($\gg$100 GeV)

At $\mathcal{O}(v^2/M_{susy}^2)$ main effects from the 2nd Higgs doublet on the Higgs couplings to fermions:



$\sim \frac{v^4}{M_H^4}$



$\sim \frac{v^2}{M_H^2}$ **Dominant effect!**

Superpartners can only modify Higgs couplings at the loop-level:
Only stops/sbottoms give some contribution to hgg/hγγ (not very large)

Corrections to h coupling to fermions: $c_i = \frac{g_{hii}}{g_{hii}^{\rm SM}}$

1) MSSM (no mixing):

$$c_b \approx 1 + \frac{m_h^2 - m_Z^2 \cos 2\beta}{m_H^2},$$
$$c_t \approx 1 - (\cot\beta)^2 \frac{m_h^2 - m_Z^2 \cos 2\beta}{m_H^2}$$

2) MSSM (with extra D-terms):

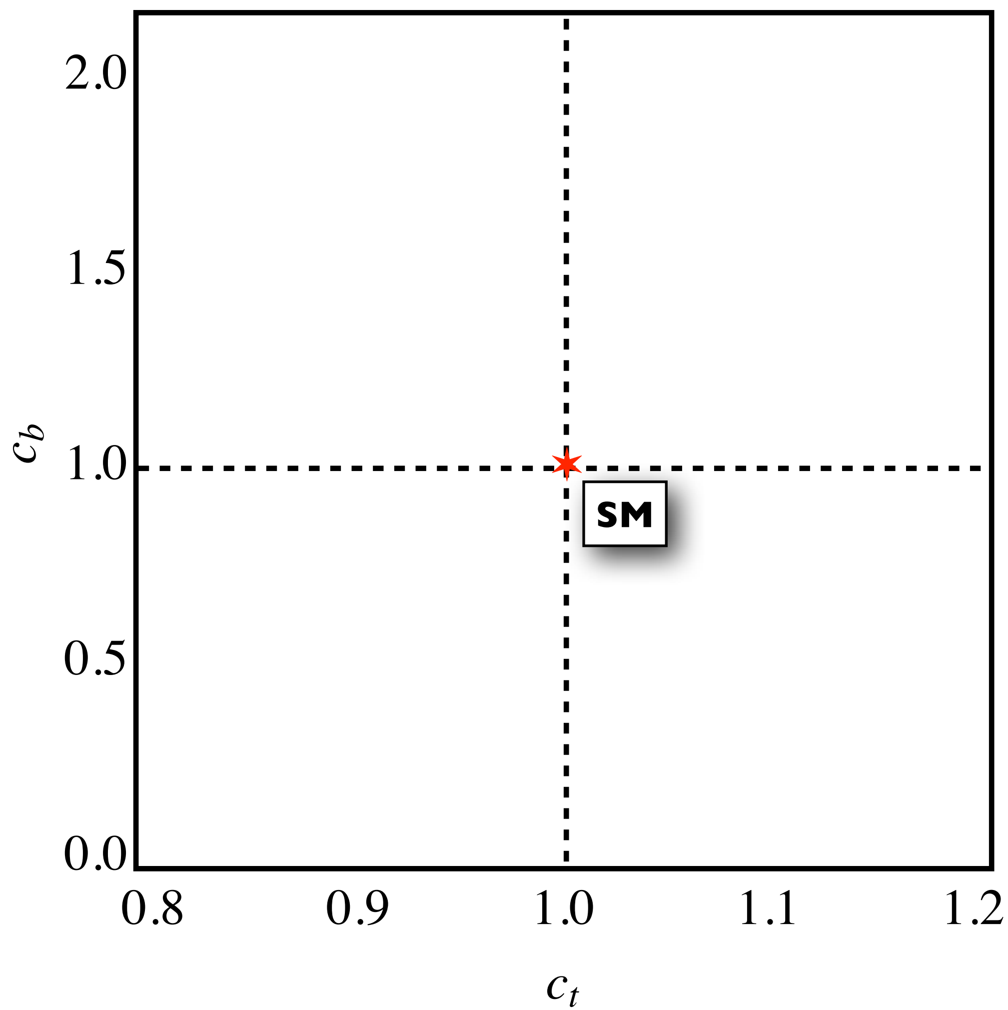
$$c_b \approx 1 + 2\frac{m_h^2}{m_H^2}\frac{t_\beta^2}{t_\beta^2 - 1}$$
$$c_t \approx 1 - 2\frac{m_h^2}{m_H^2}\frac{1}{t_\beta^2 - 1}.$$

3) NMSSM (with heavy singlet and light stops):

$$c_b \approx 1 - \frac{t_\beta^2 - 1}{2}\frac{m_h^2 - m_Z^2}{m_H^2}$$
$$c_t \approx 1 + \frac{t_\beta^2 - 1}{2t_\beta^2}\frac{m_h^2 - m_Z^2}{m_H^2}$$

from arXiv:1212.524

Relevant plane for susy Higgs couplings:



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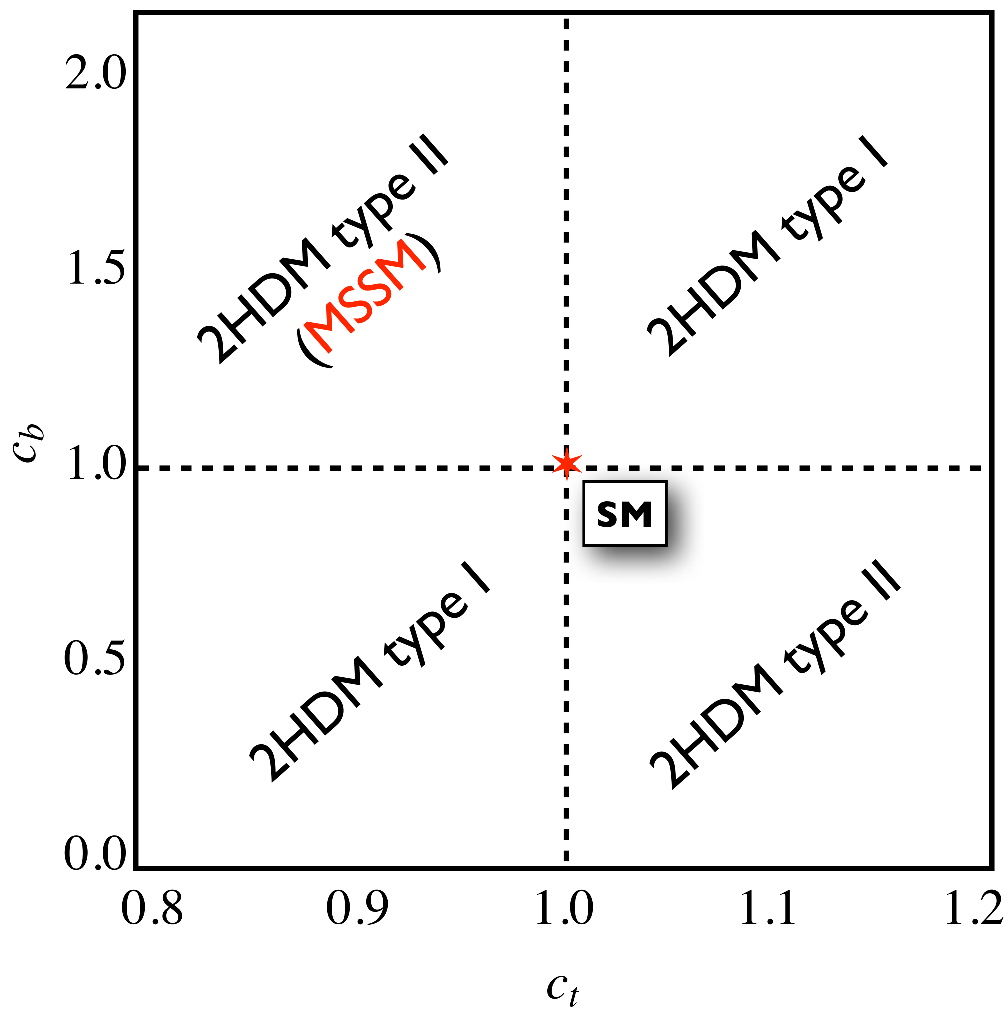
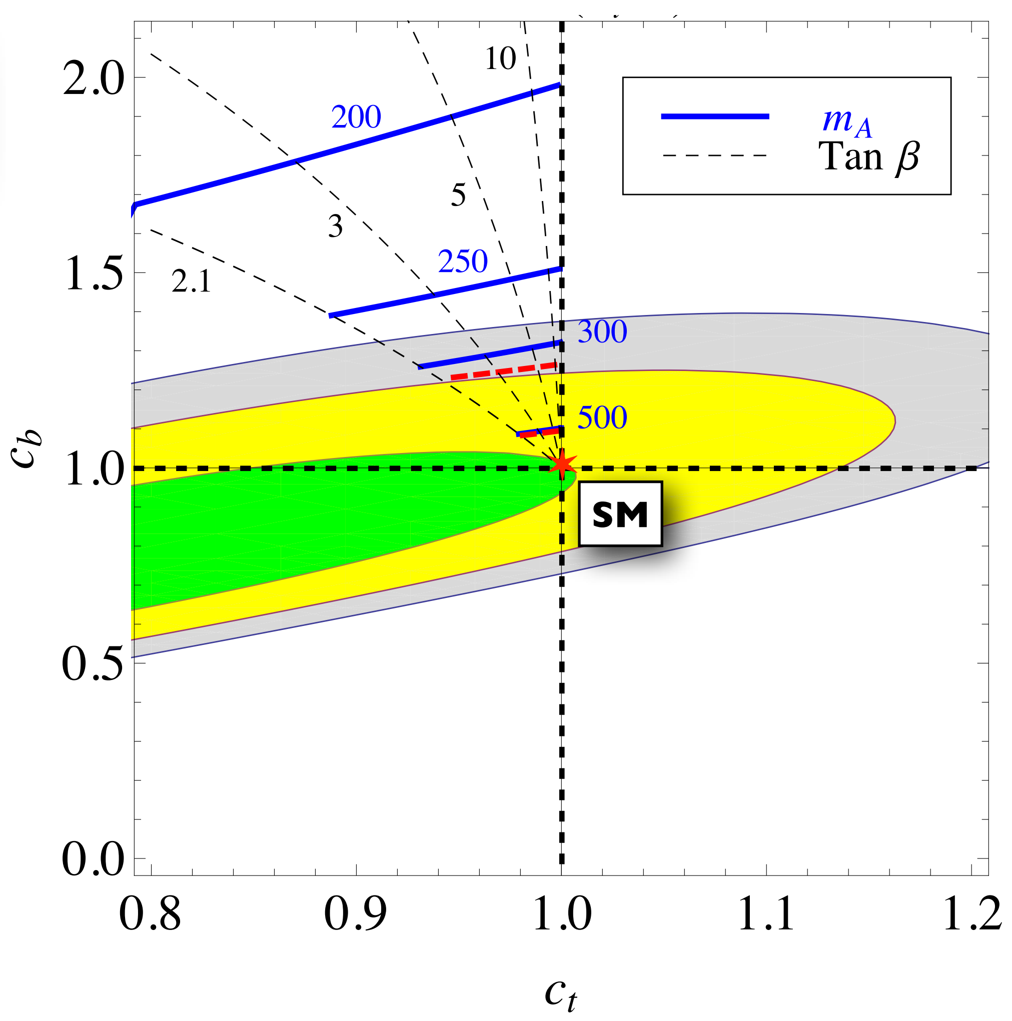


Relevant plane for susy Higgs couplings:

MSSM (X_t=0)

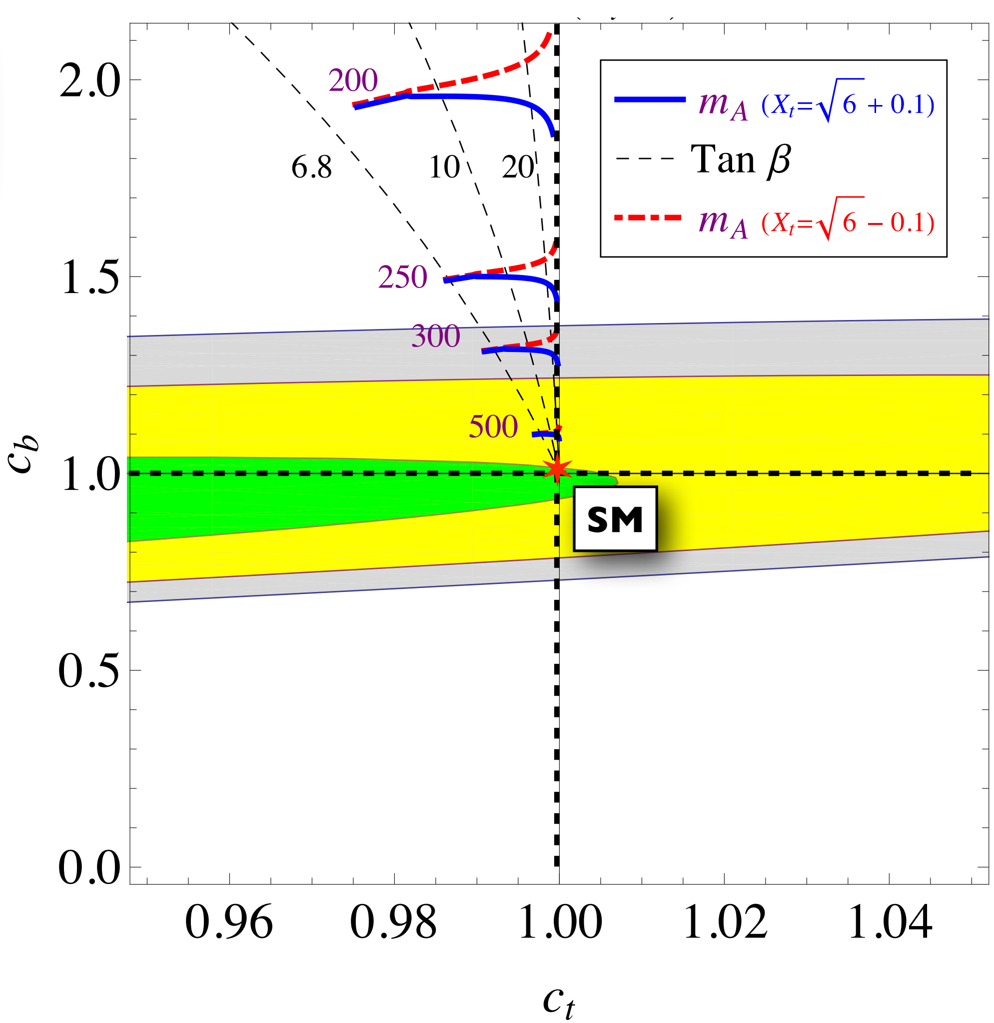


from arXiv:1212.524

(data before Moriond 13)

Relevant plane for susy Higgs couplings:

MSSM ($X_t \neq 0$)



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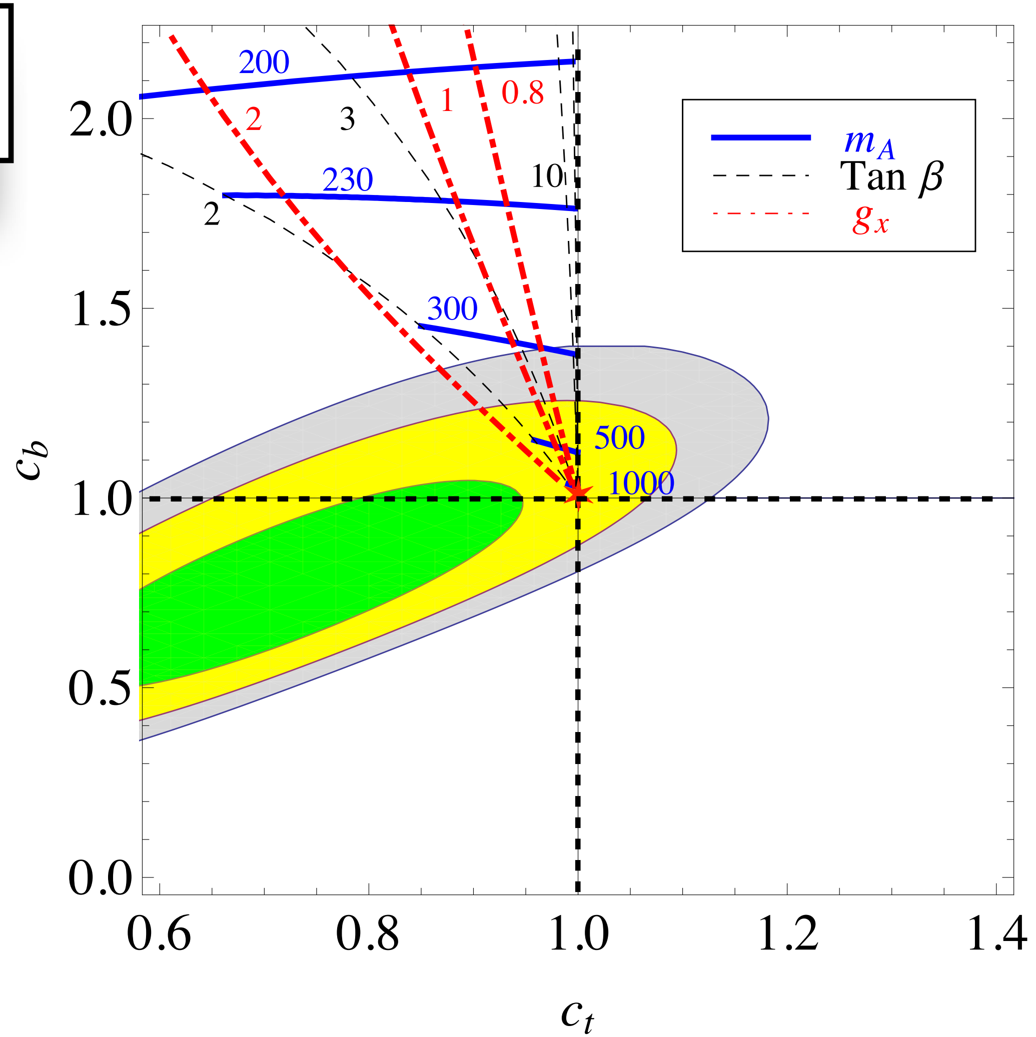
Relevant plane for susy Higgs couplings:

MSSM with extra D-terms



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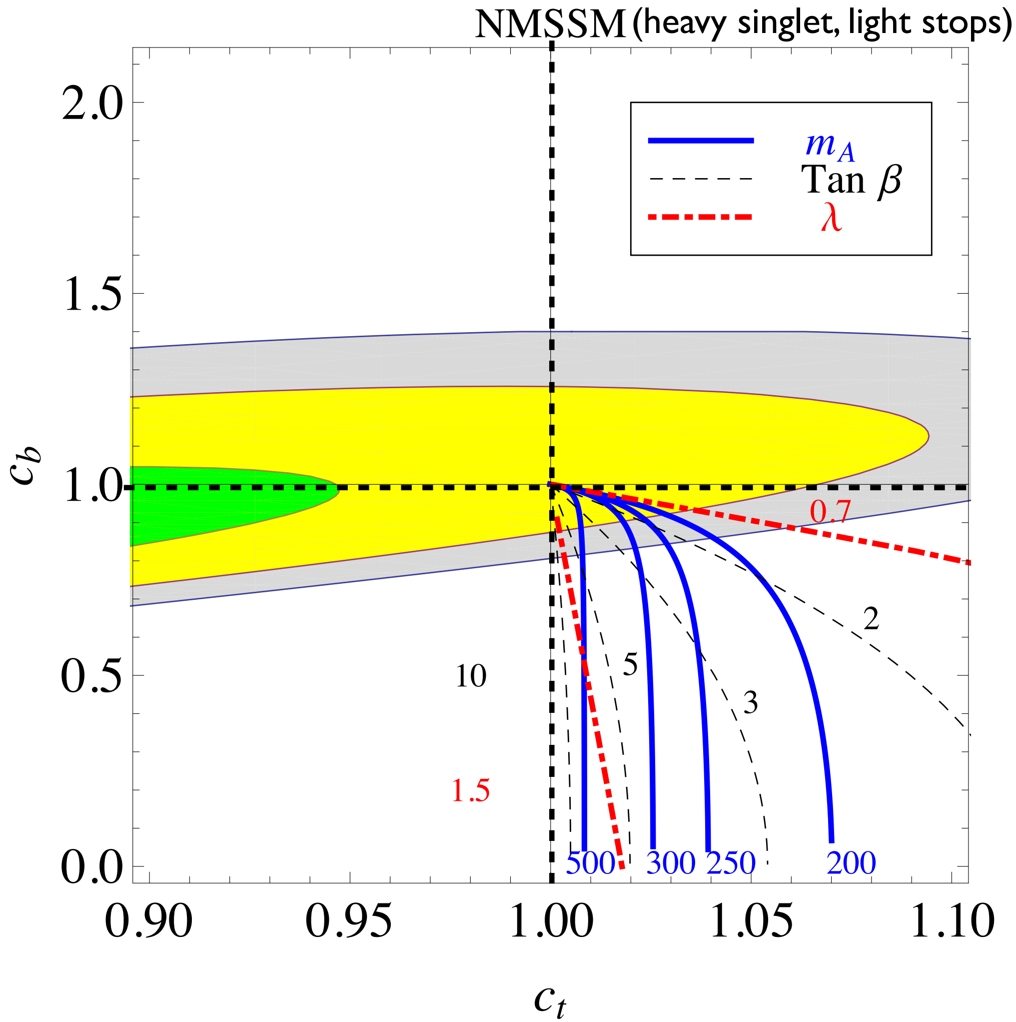
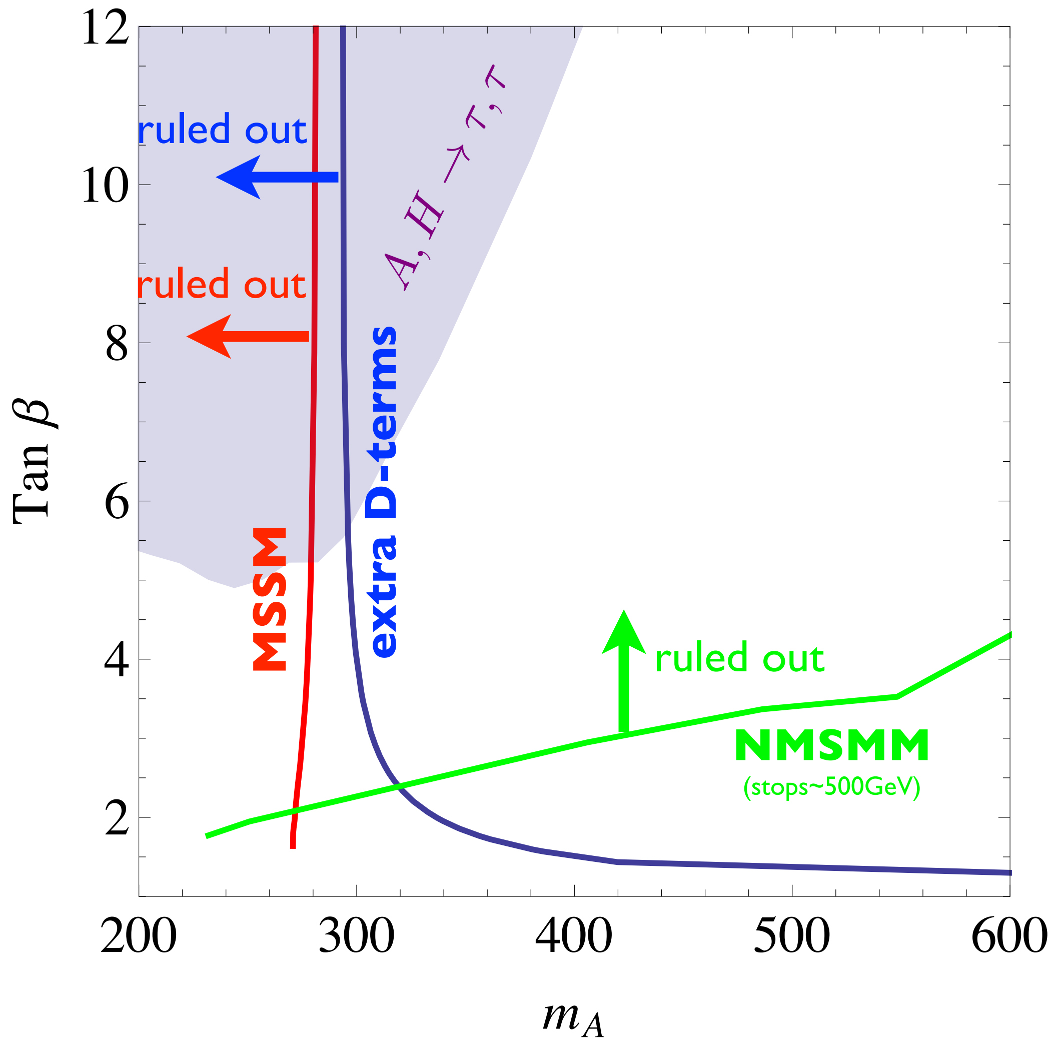


from arXiv:1212.524

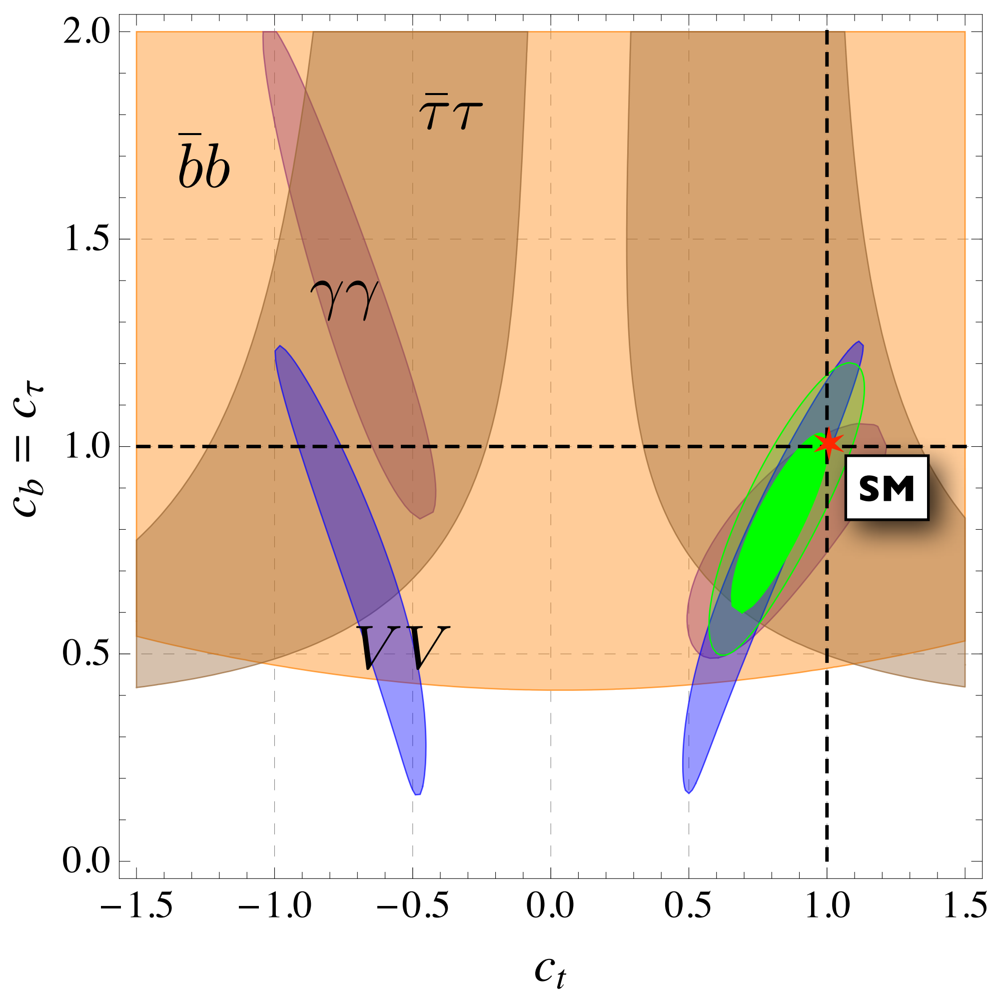
effects of a lighter singlet: reducing all rates of h due to mixing

Higgs physics is already **ruling out** susy-parameter space



arXiv:1212.524

With the most recent data, from arXiv:1303.1812



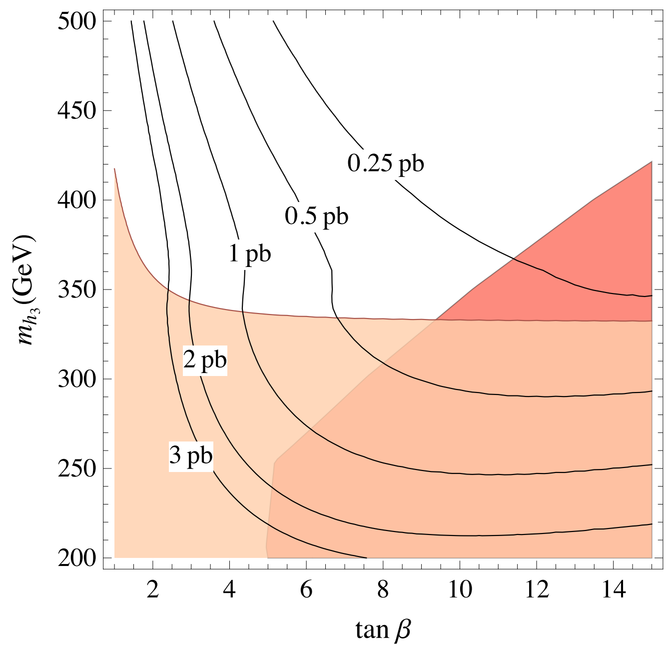
$$c_i = \frac{g_{hii}}{g_{hii}^{\rm SM}}$$

You can get predictions on where to find the other Higgses:

MSSM

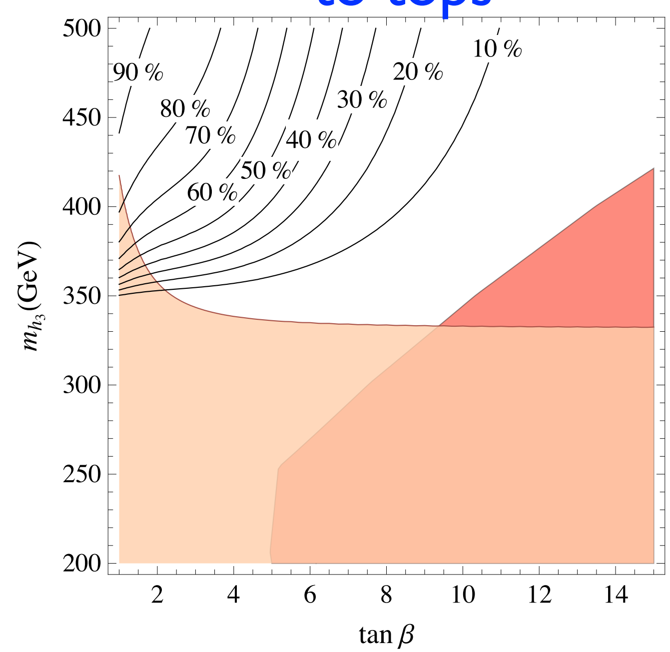
arXiv:1304.3670

production cross-section

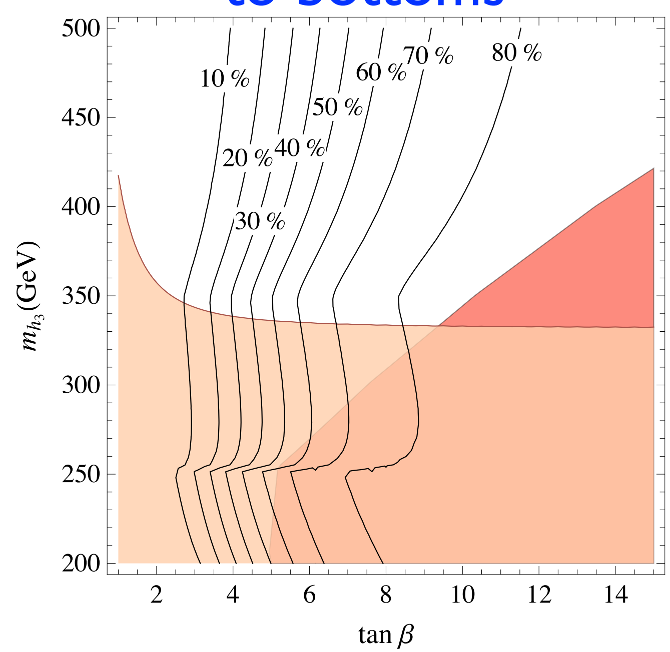


decays to tops and bottoms

to tops



to bottoms



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Singlet of NMSSM

arXiv:1304.3670

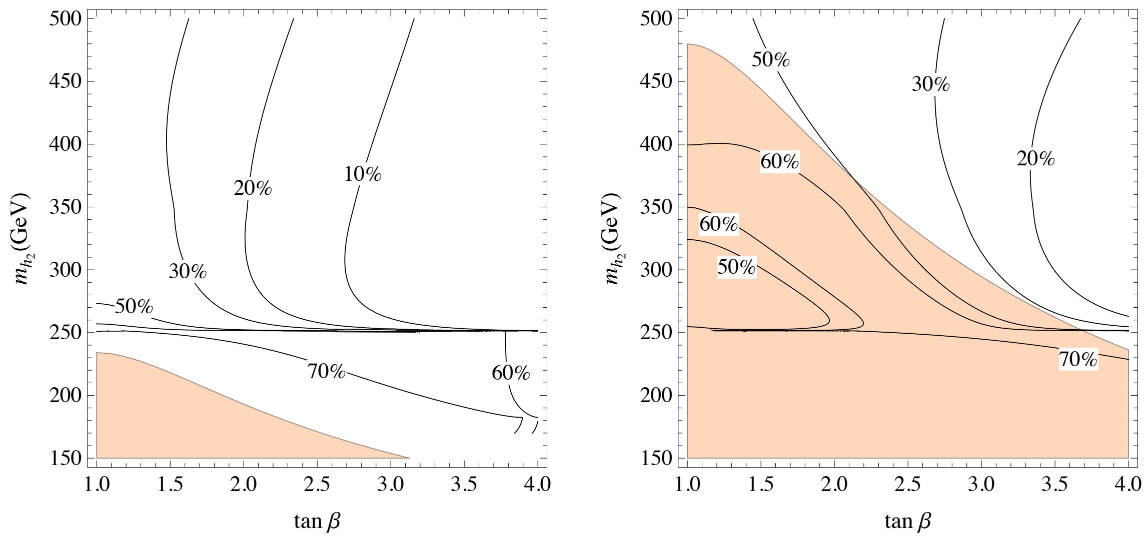


Figure 5. H decoupled. Isolines of $\mathrm{BR}(h_2 \to W^+W^-)$. Left: $\lambda = 0.8$ and $v_S = 2v$. Right: $\lambda = 1.4$ and $v_S = v$. The colored region is excluded at 95%C.L.

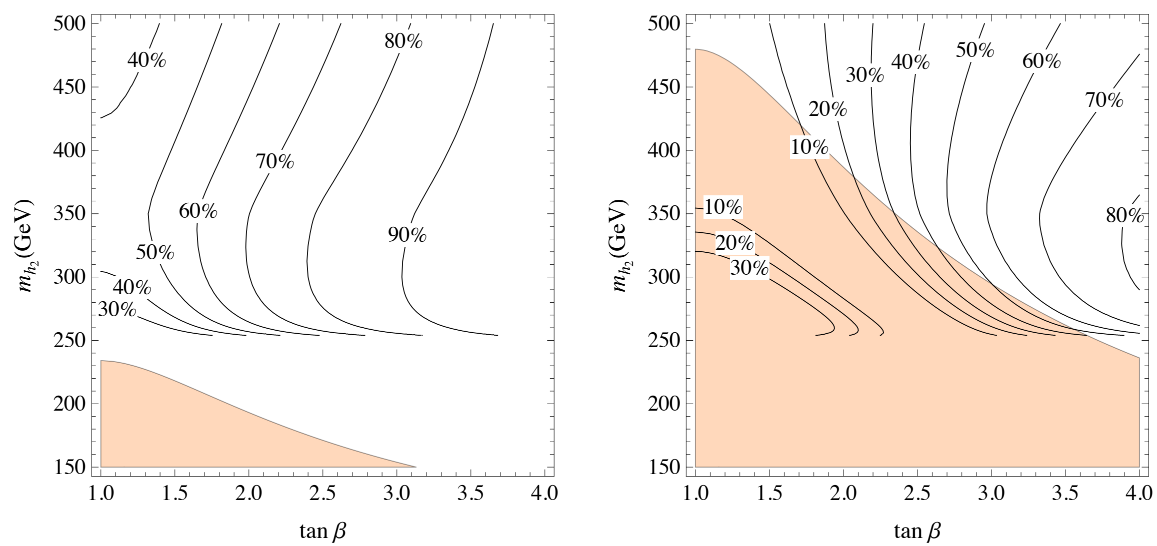


Figure 4. H decoupled. Isolines of $\mathrm{BR}(h_2 \to hh)$. Left: $\lambda = 0.8$ and $v_S = 2v$. Right: $\lambda = 1.4$ and $v_S = v$. The colored region is excluded at 95%C.L.

Composite Higgs scenarios

Composite PGB Higgs couplings

Couplings dictated by symmetries (as in the QCD chiral Lagrangian)

arXiv:1205.6434

$$\frac{g_{hWW}}{g_{hWW}^{\rm SM}} = \sqrt{1-\frac{v^2}{f^2}}$$

f = Decay-constant of the PGB Higgs

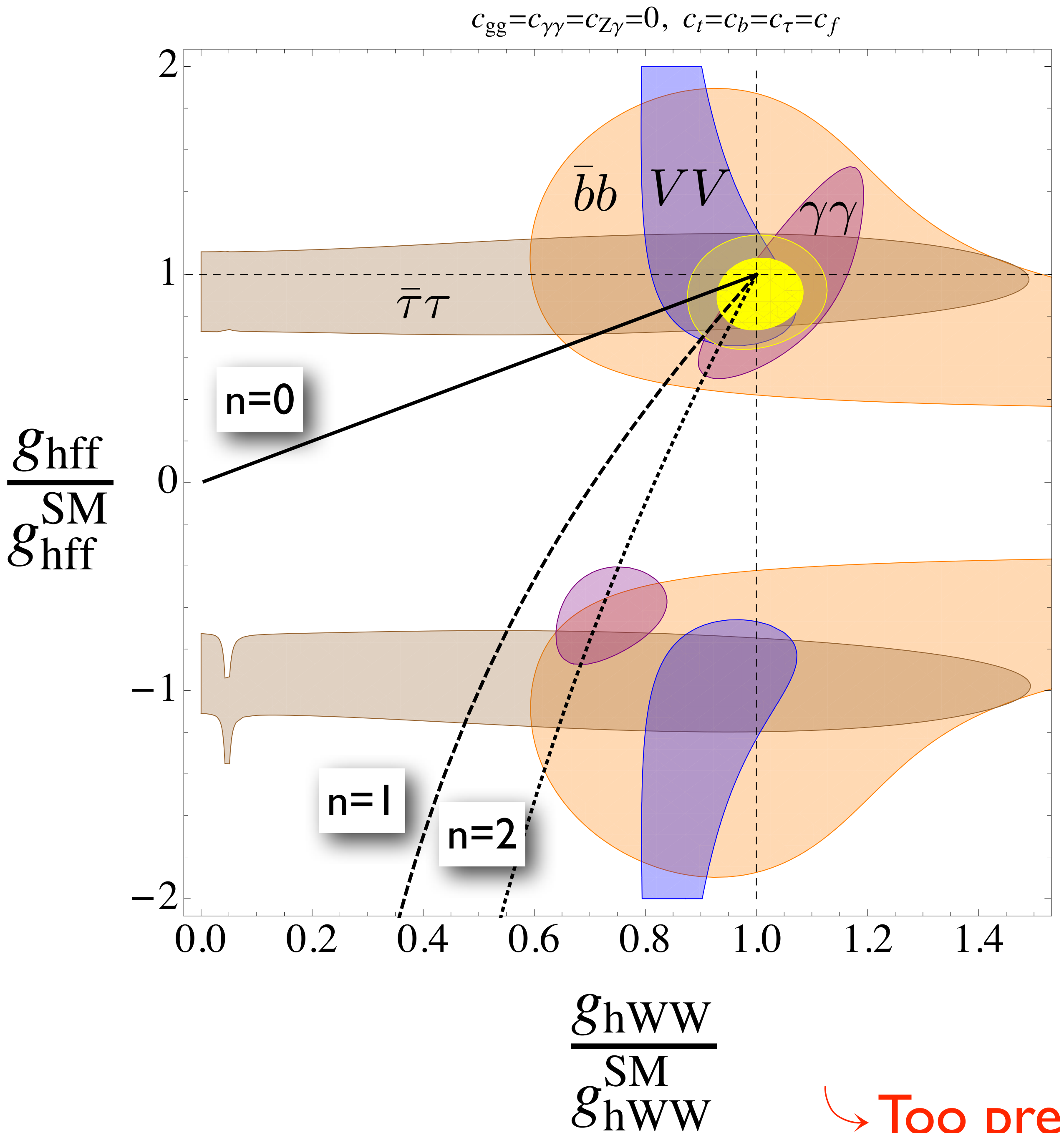
EWPT: v/f≲1/3

$$\frac{g_{hff}}{g_{hff}^{\rm SM}} = \frac{1-(1+n)\frac{v^2}{f^2}}{\sqrt{1-\frac{v^2}{f^2}}}$$

$$n = 0, 1, 2, \ldots$$

$\rm MCHM_{5,10}$ (→ $n=1$)

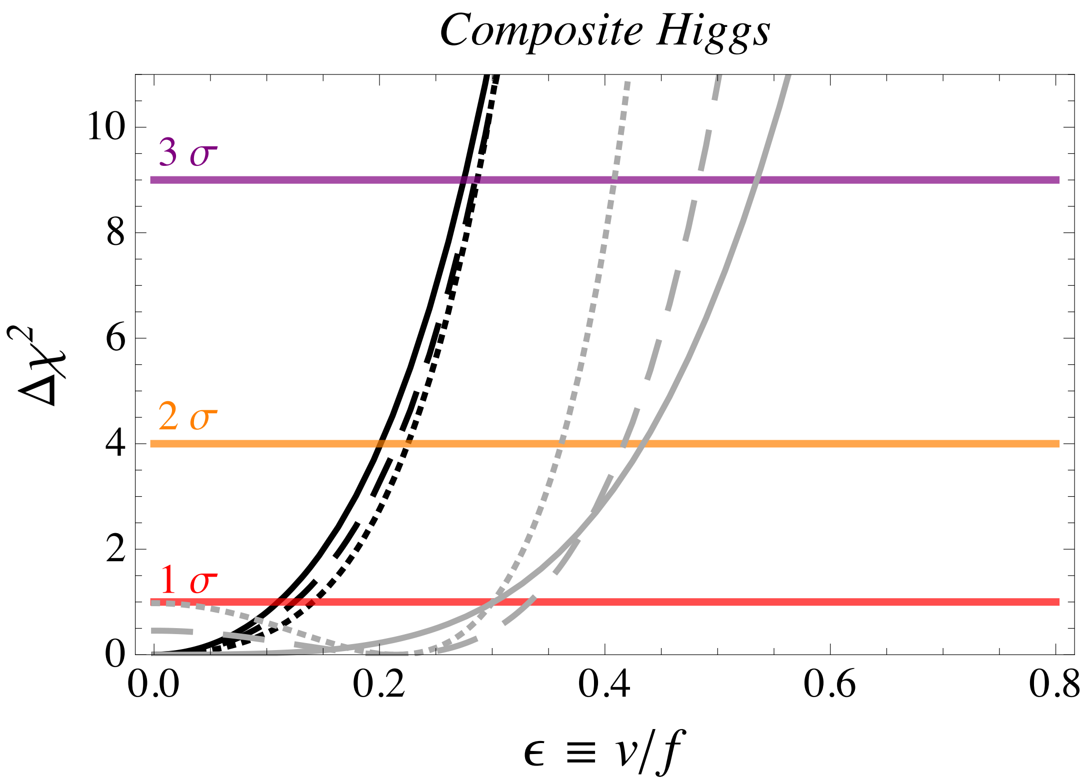
small deviations on the h$\gamma\gamma$(gg)-coupling due to the Goldstone nature of the Higgs



arXiv:1303.1812

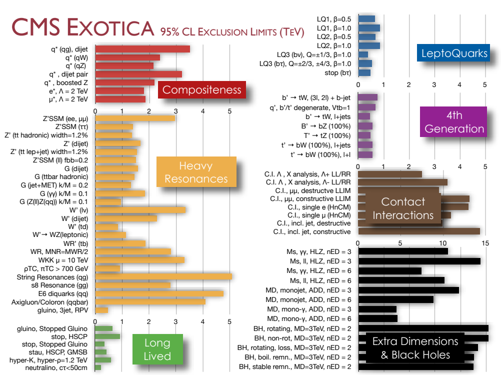
↳ Too premature to see deviations for v/f~1/3!

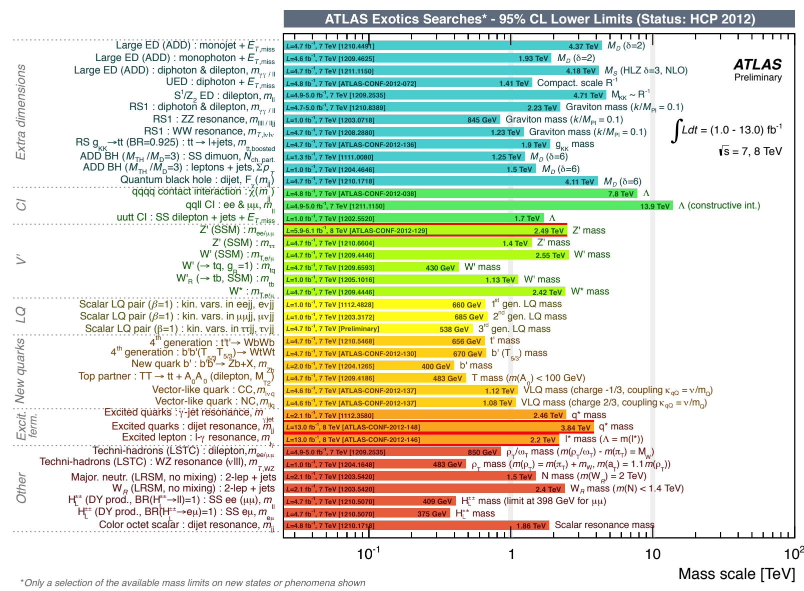
At present, just bounds on v/f:



arXiv:1303.1812

Direct LHC searches for New Physics





Supersymmetry

The MSSM in the aftermath of M_H~125 GeV

- Big chunks of the parameter space are excluded
- Main simple models: GMSB, Gravity/String mediated SB, in trouble as are forced to have a high scalar susy-spectrum

SUSY is unnatural,

but simple

SUSY is natural

but not minimal

SUSY is dead

... place your bets!

SUSY is natural but not minimal

Open to variants:

M_H~125 GeV obtained going beyond the MSSM

Stops and **Higgsinos** are the lightest sparticles:

$$\mu^2 + m_{H_u}^2 = -\frac{m_h^2}{2} \approx -(88\ \text{GeV})^2$$

$$\delta m_{H_u}^2 = -\frac{3y_t^2}{8\pi^2}\left(m_{Q_3}^2 + m_{u_3}^2 + |A_t|^2\right)\ln\left(\frac{\Lambda}{m_{\tilde{t}}}\right)$$

➥ Stop mass ~ 500 GeV

Higgisinos mass ~ 100 GeV

SUSY is natural but not minimal

Open to variants:

M_H~125 GeV obtained going beyond the MSSM

Stops and **Higgsinos** are the lightest sparticles:

➥ Look for them in all possible ways

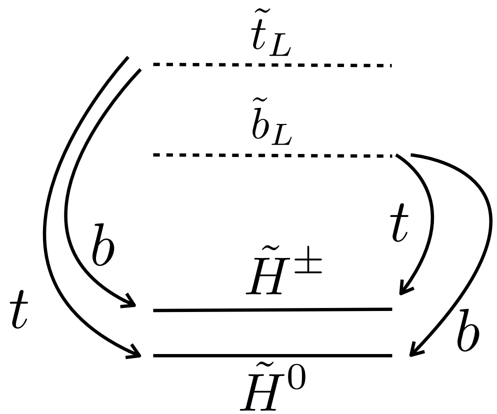
Gauginos could be heavier (TeV-regime) but since they are easy to see, the LHC searches can be competitive

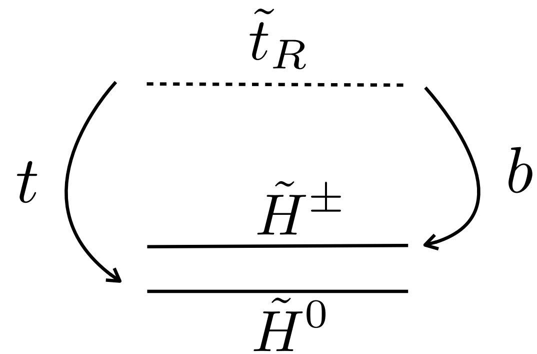
➥ Stop mass ~ 500 GeV
Higgsinos mass ~ 100 GeV

Stop/Sbottom phenomenology

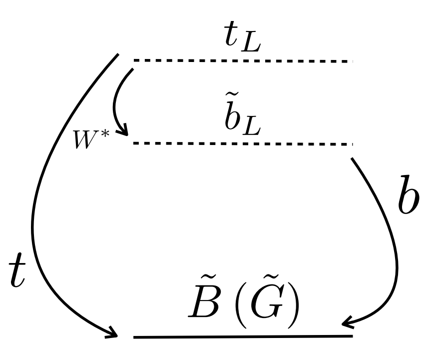
If R-parity present and Higgsino the lightest:

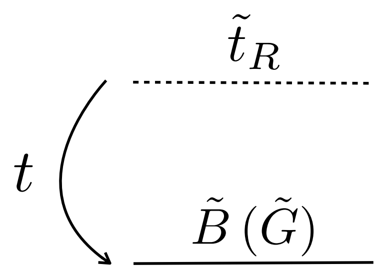
arXiv:1110.6926





But also could be the Gravitino:





Stop/Sbottom phenomenology

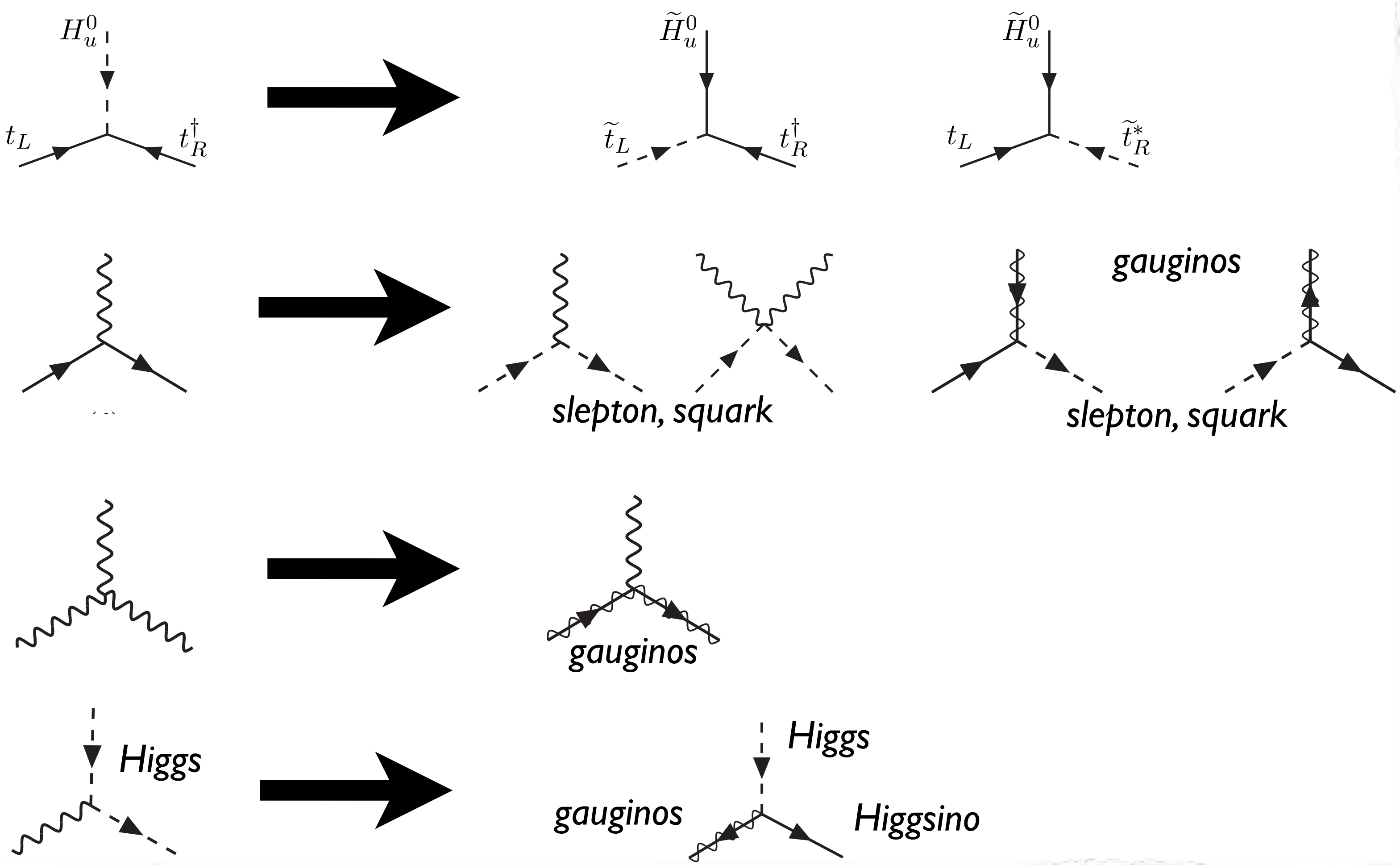
If R-

But

Type of interactions

10.6926

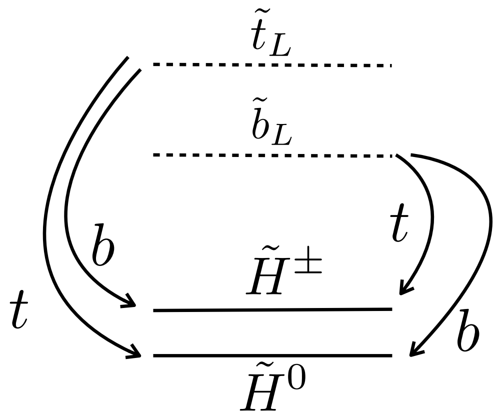
Getting them from “supersymmetrization”:

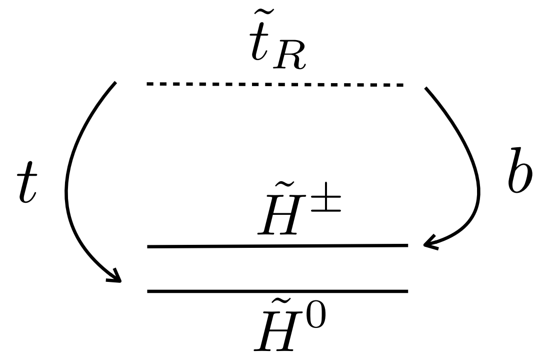


Stop/Sbottom phenomenology

If R-parity present and Higgsino the lightest:

arXiv:1110.6926





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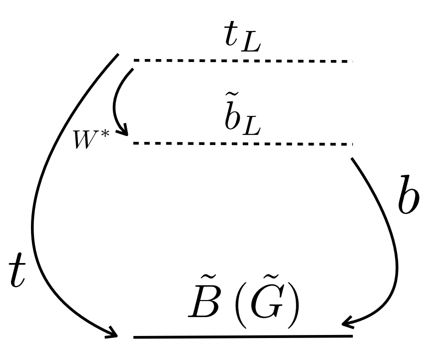
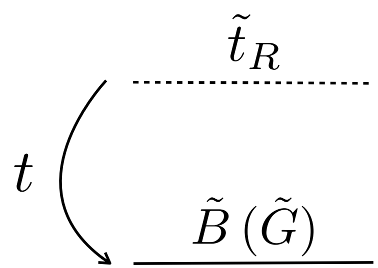
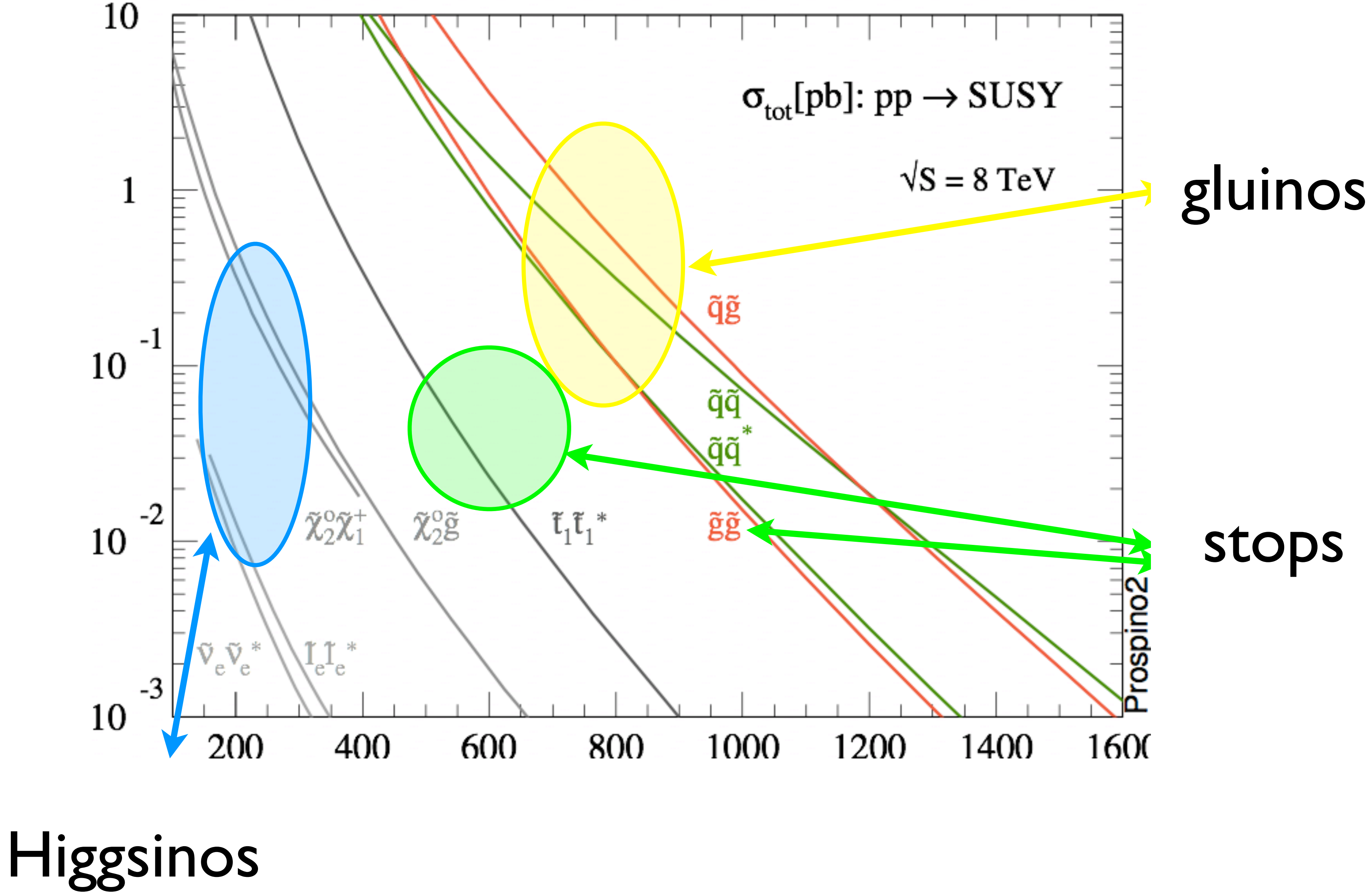




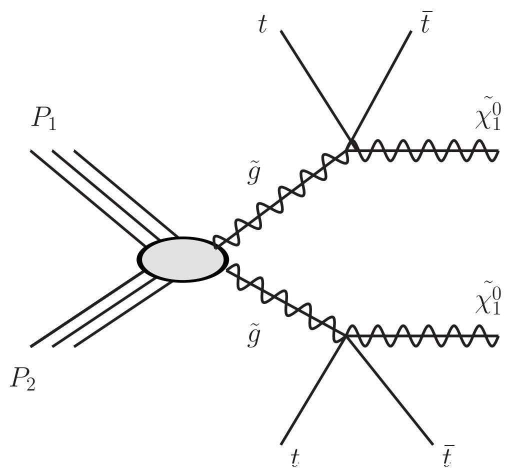
there was a lot of **hope** in these searches...

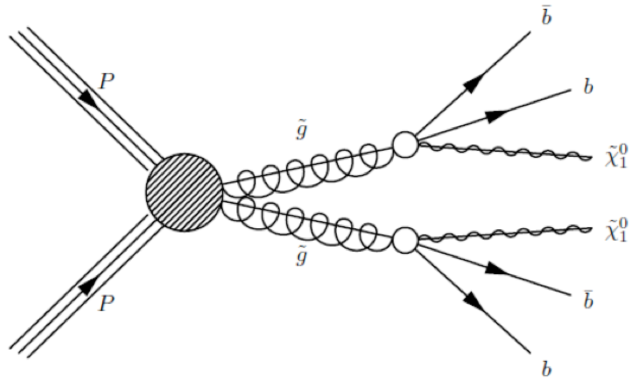
but didn't give positive results

Production cross-sections

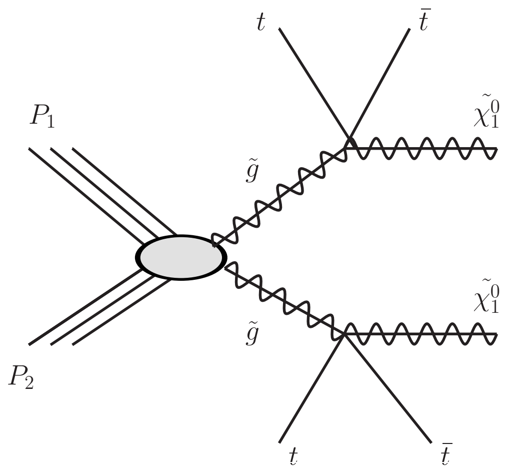


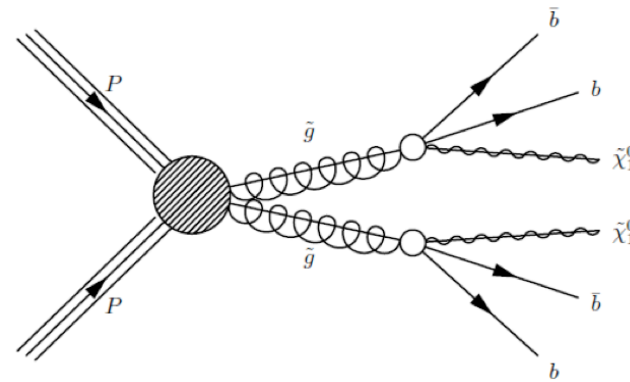
Gluino-mediated stop/sbottoms

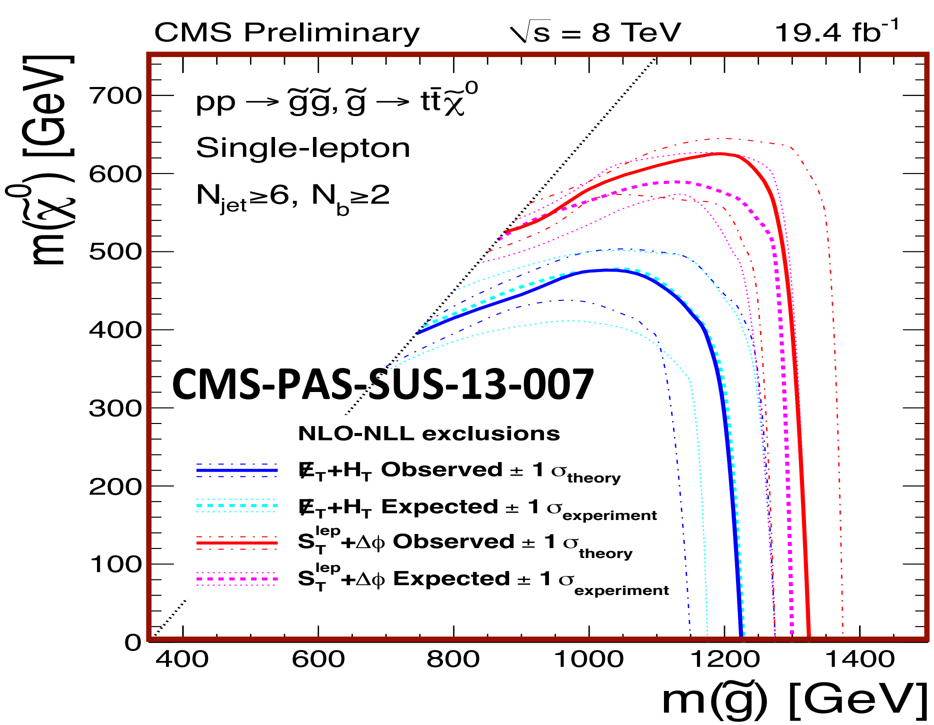


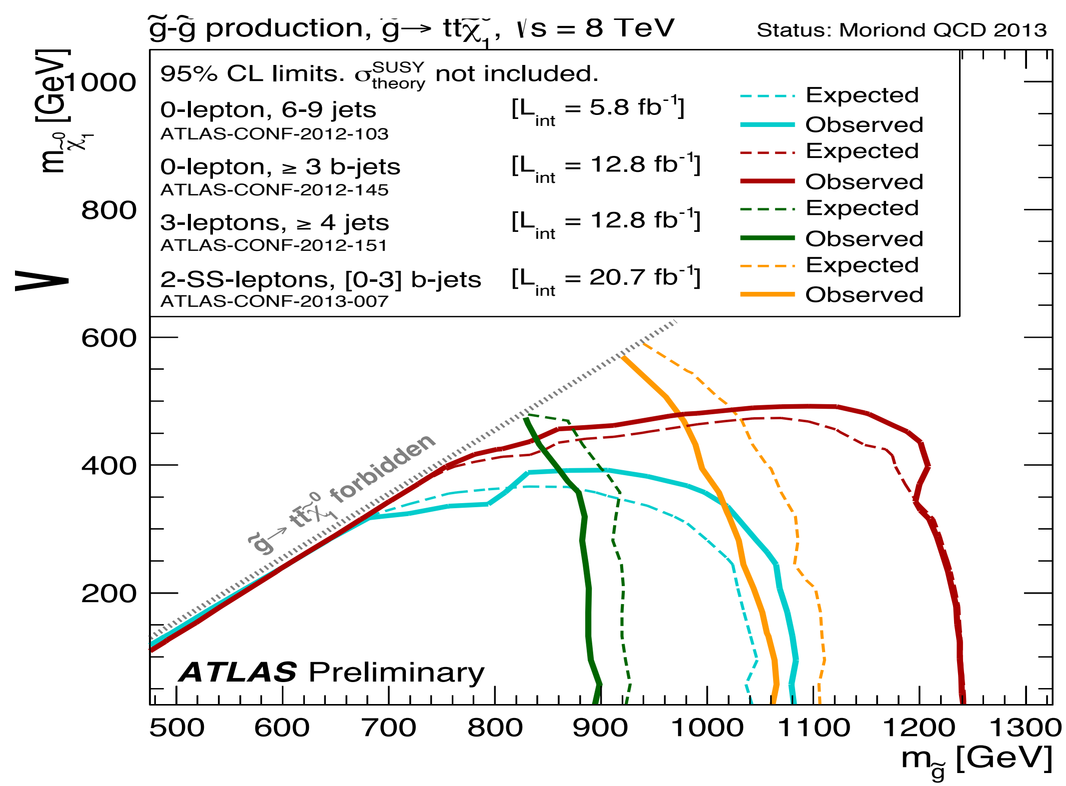


Gluino-mediated stop/sbottoms

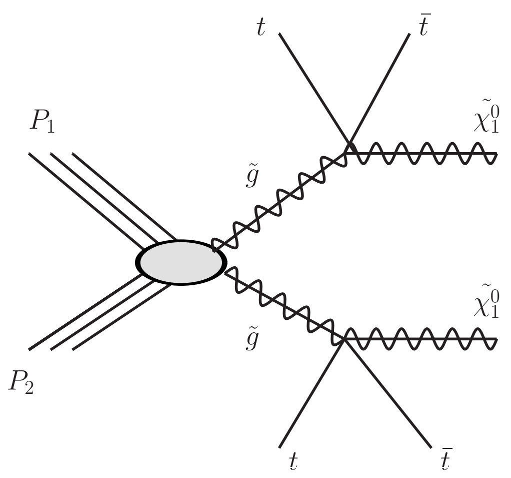


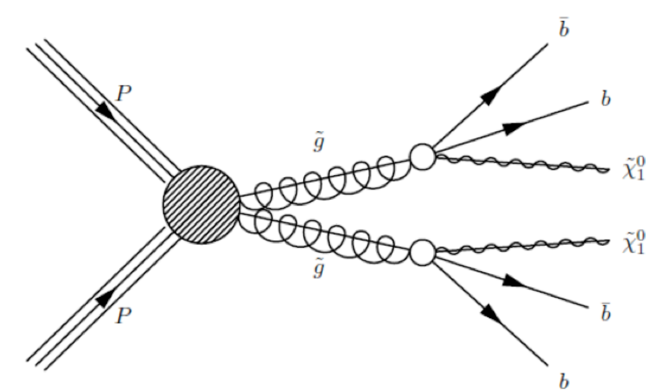


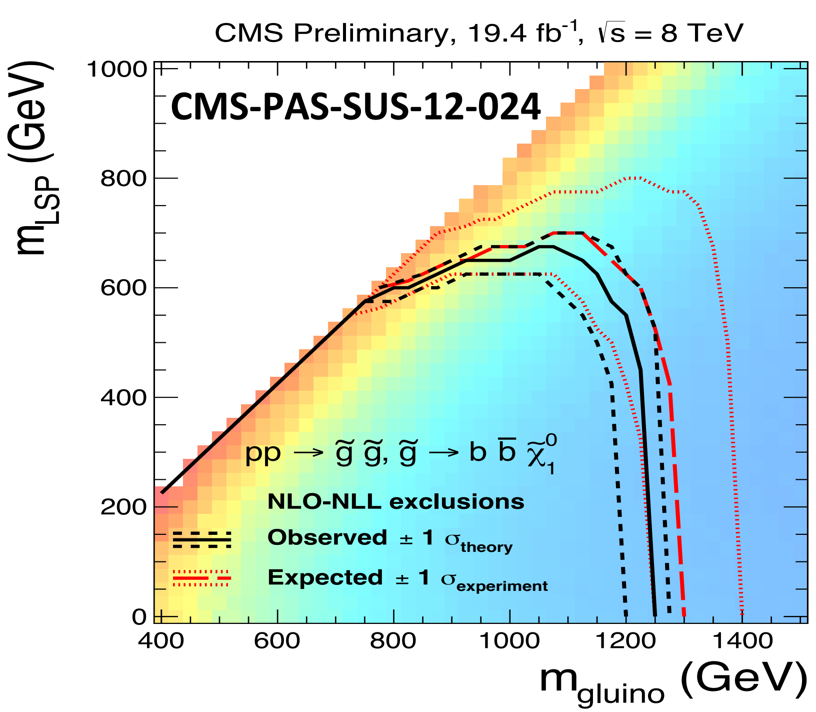


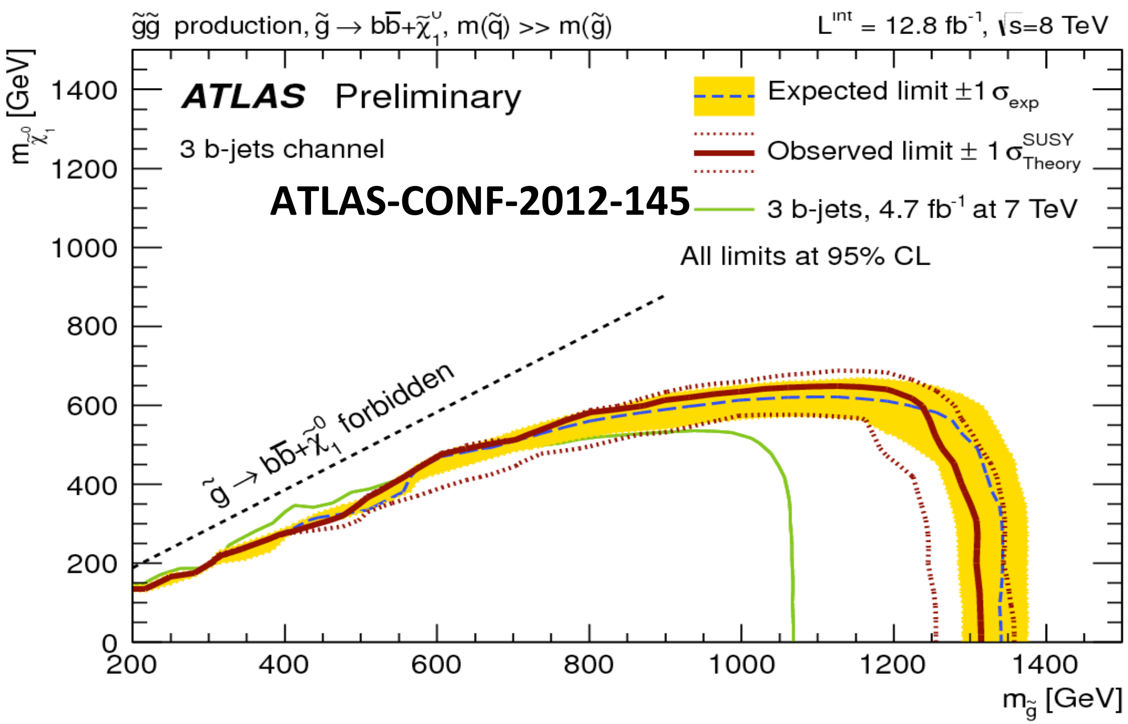


Gluino-mediated stop/sbottoms

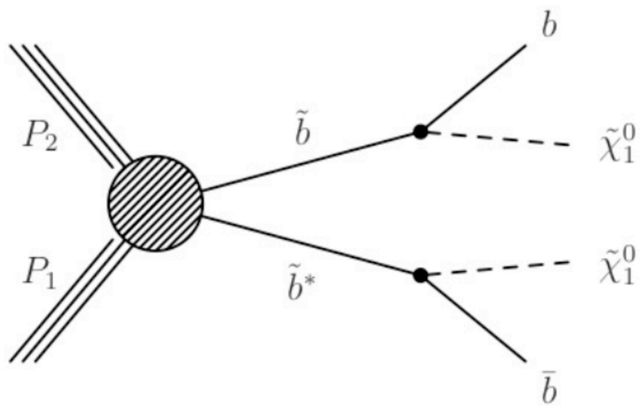




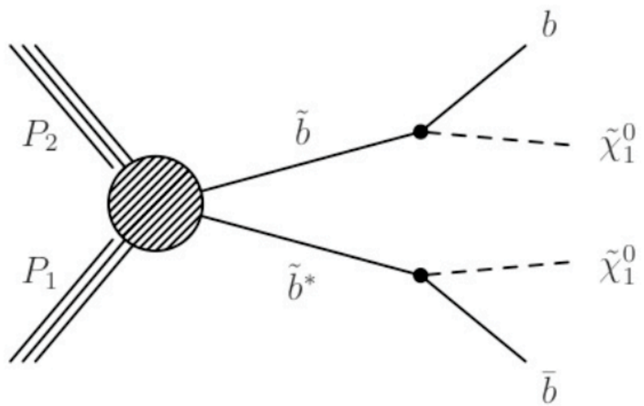


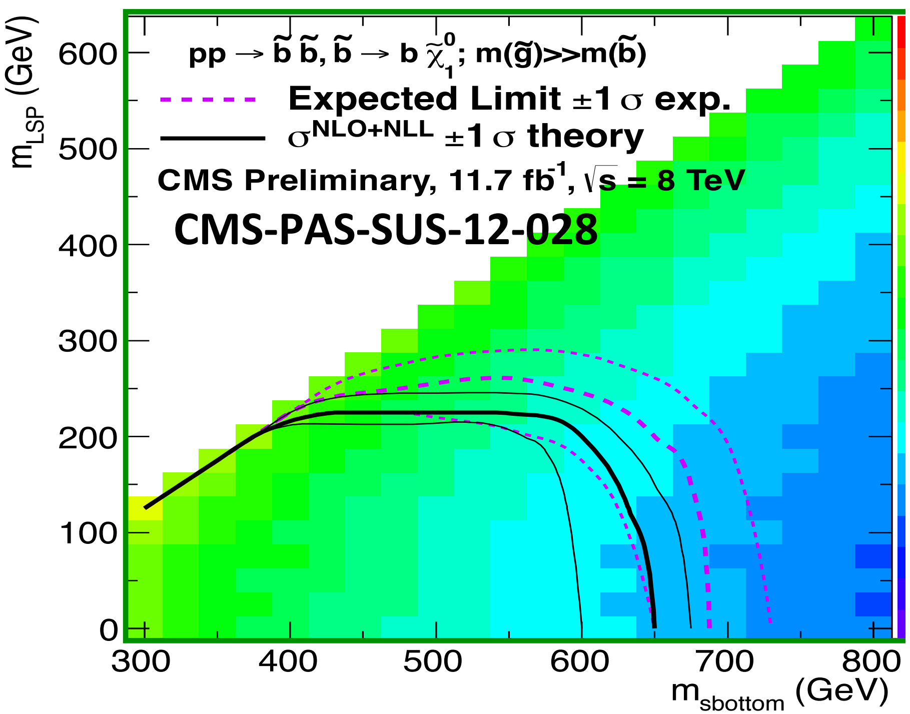


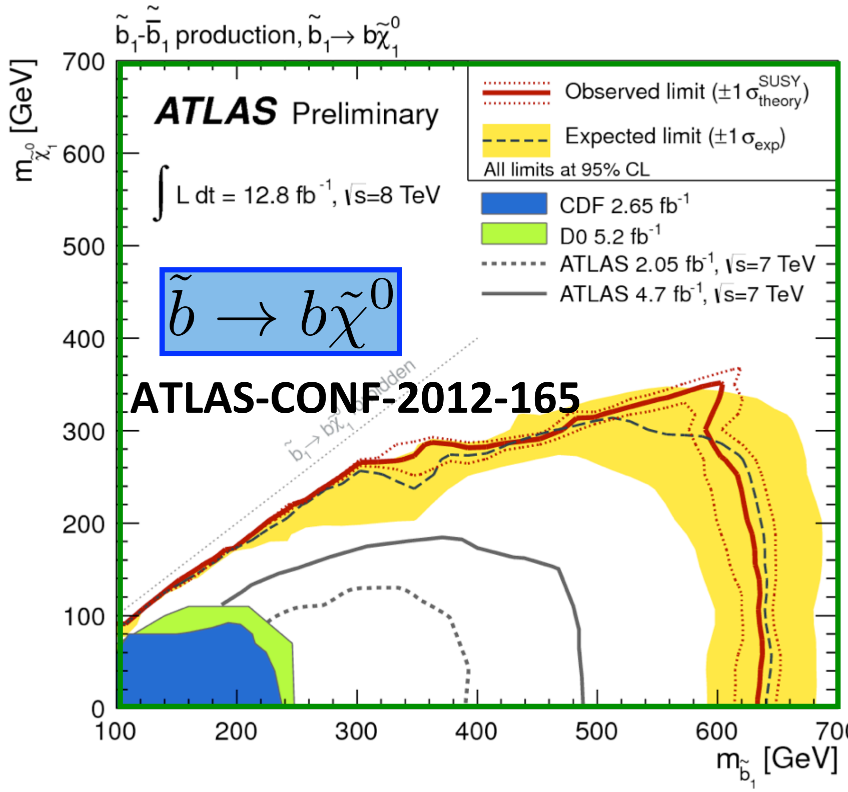
Sbottom production



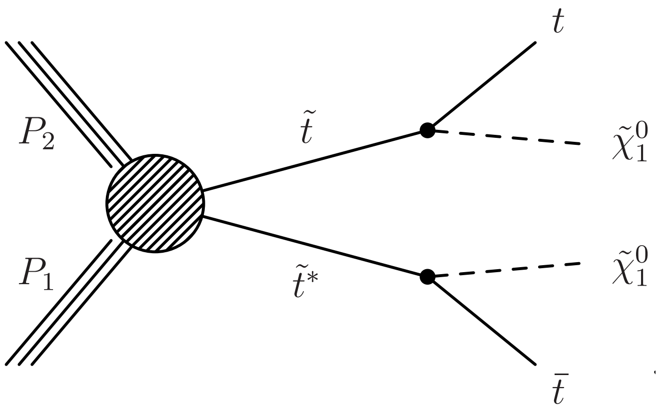
Sbottom production



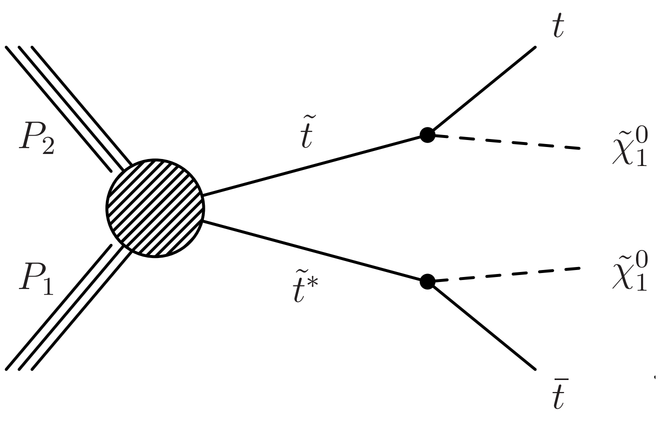


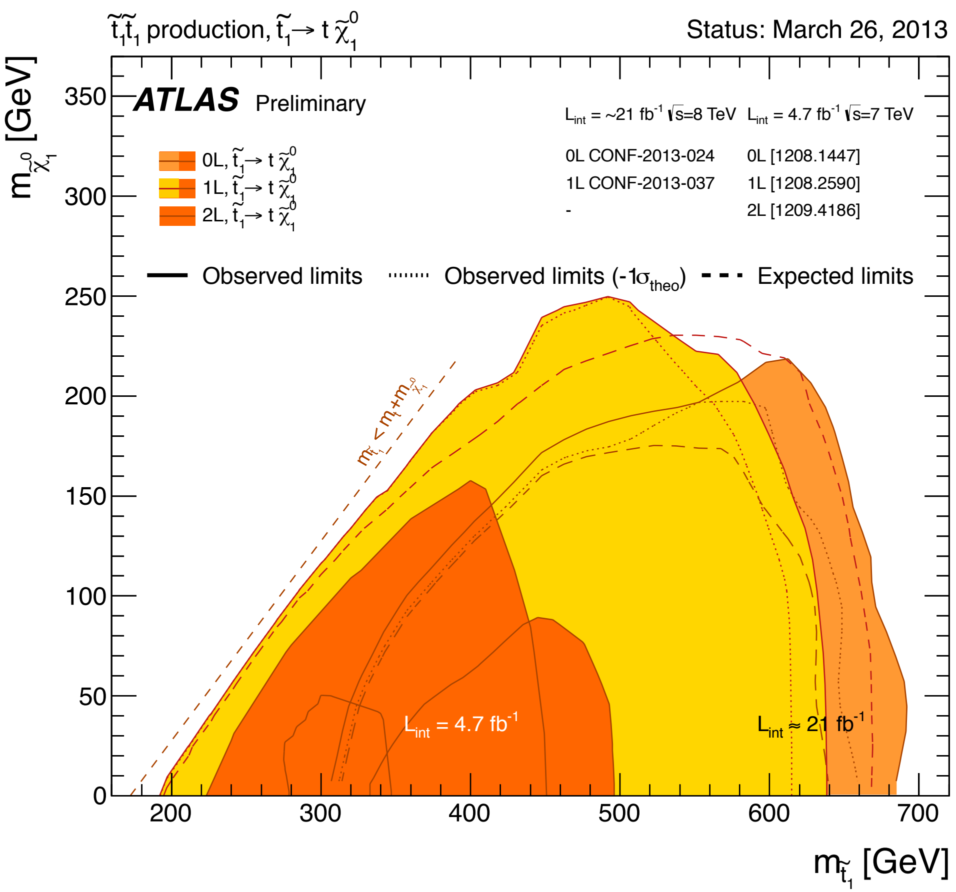


Stop production

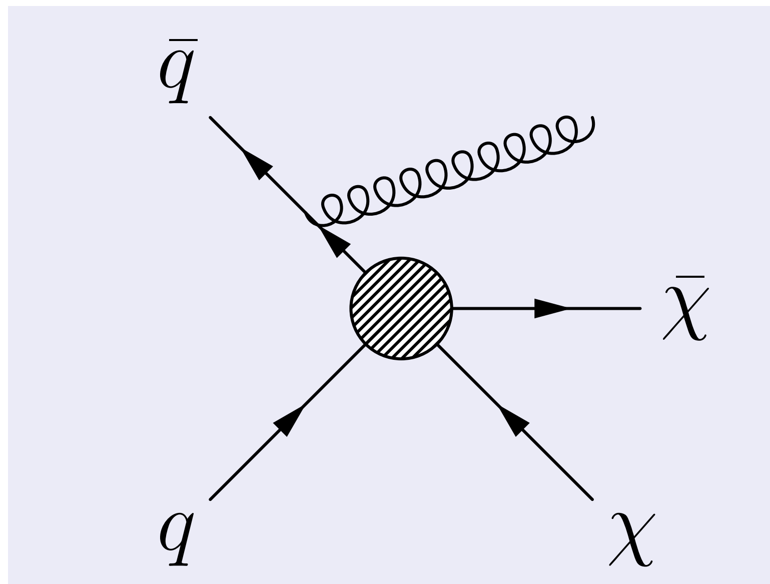


Stop production



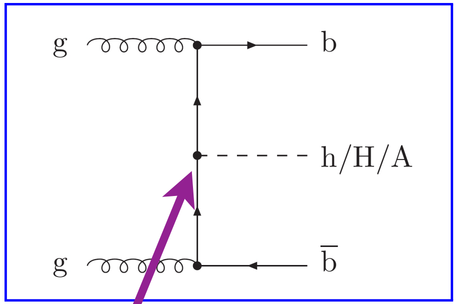


Higgsinos double-production, ,even if they are light,
very difficult to be seen
since one needs monojets/monophoton searches + missing E_T

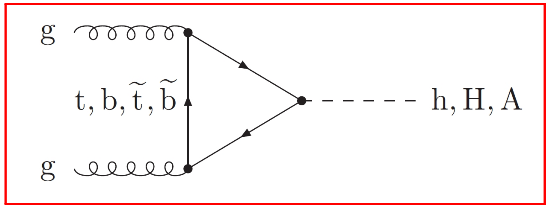


still bounds from LEP1 (>100 GeV) remain

Other **searches** that kill a lot of parameter space:

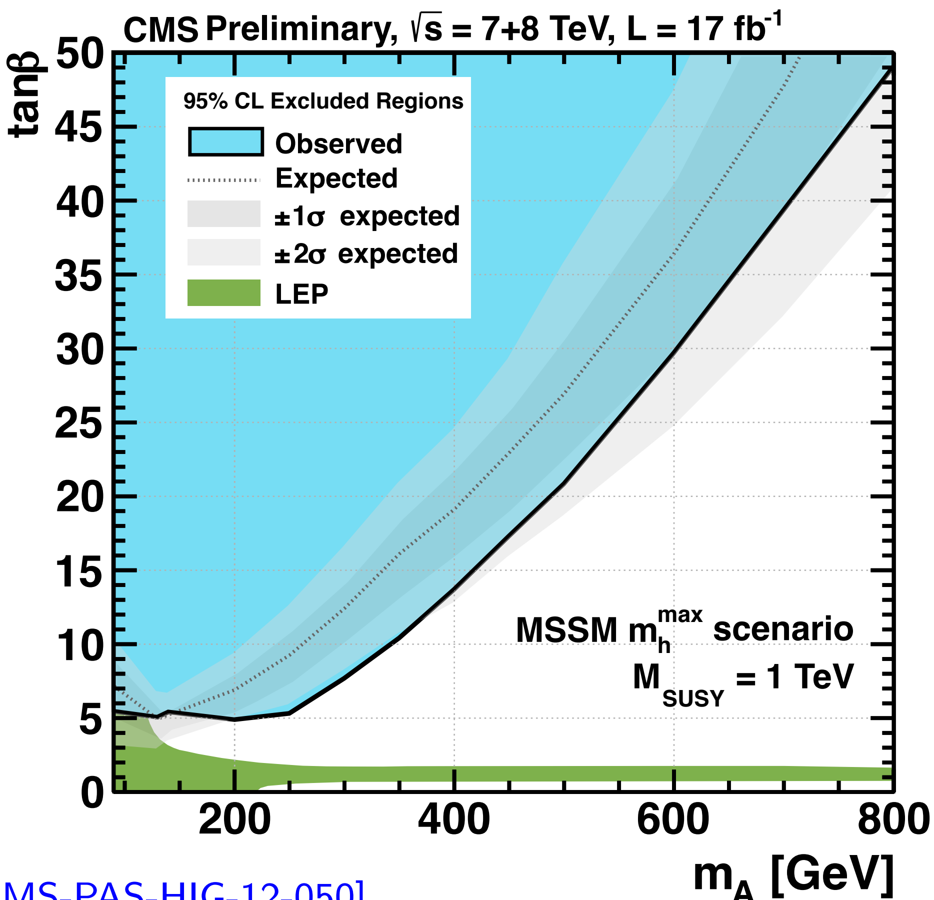


$\propto \tan\beta$



and **H,A→ττ**

$\propto \tan\beta$



[CMS-PAS-HIG-12-050]

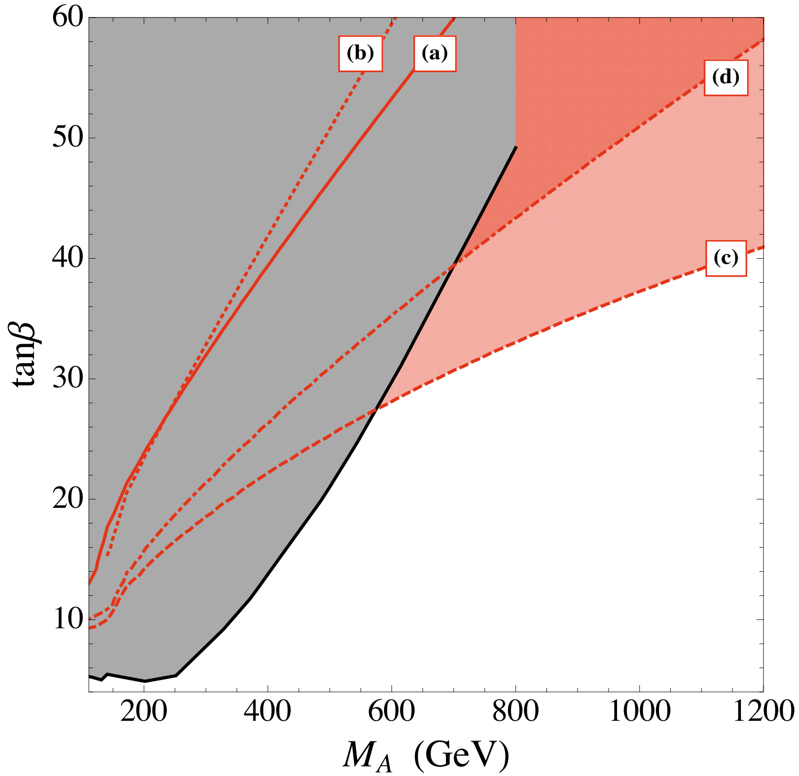
Other **searches** that kill a lot of parameter space:

$B_s \to \mu^+\mu^-$ measurement

$$\mathrm{BR}(B_s \to \mu^+\mu^-)_{\mathrm{exp}} = (3.2\ ^{+1.4}_{-1.2}\ ^{+0.5}_{-0.3}) \times 10^{-9}\ ,$$

and gives the following two sided 95% C.L. bound

$$1.1 \times 10^{-9} < \mathrm{BR}(B_s \to \mu^+\mu^-)_{\mathrm{exp}} < 6.4 \times 10^{-9}\ .$$



$m_{\tilde{f}} = 2$ TeV

(a) $\mu = 1$ TeV, $A_t > 0$

(b) $\mu = 4$ TeV, $A_t > 0$

(c) $\mu = -1.5$ TeV, $A_t > 0$

(d) $\mu = 1$ TeV, $A_t < 0$

gray: $A, H \to \tau^+\tau^-$

[Altmannshofer et al. 1211.1976]

Interesting directions still to go:

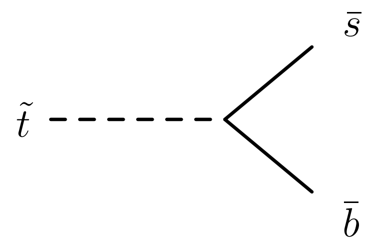
We must look for light stops in all possible scenarios:

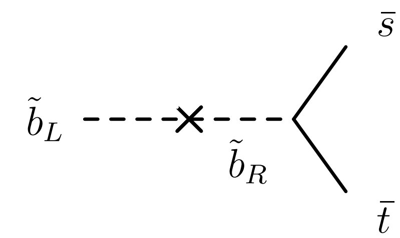
1) R-parity breaking:

$$W_{\rm BNV} = \frac{1}{2}\lambda''_{ijk}\epsilon^{abc}\bar{u}^i_a\bar{d}^j_b\bar{d}^k_c\,,$$

arXiv:1111.1239

stop/sbottom decay to quarks:





$$\tau_{\tilde{t}} \sim (2\ \mu{\rm m})\left(\frac{10}{\tan\beta}\right)^4\left(\frac{300\ {\rm GeV}}{m_{\tilde{t}}}\right)\left(\frac{1}{2\sin^2\theta_{\tilde{t}}}\right)$$

Difficult to disentangle from QCD backgrounds at the LHC!

2) No Higgsino (SM lepton superpartner of the Higgs):

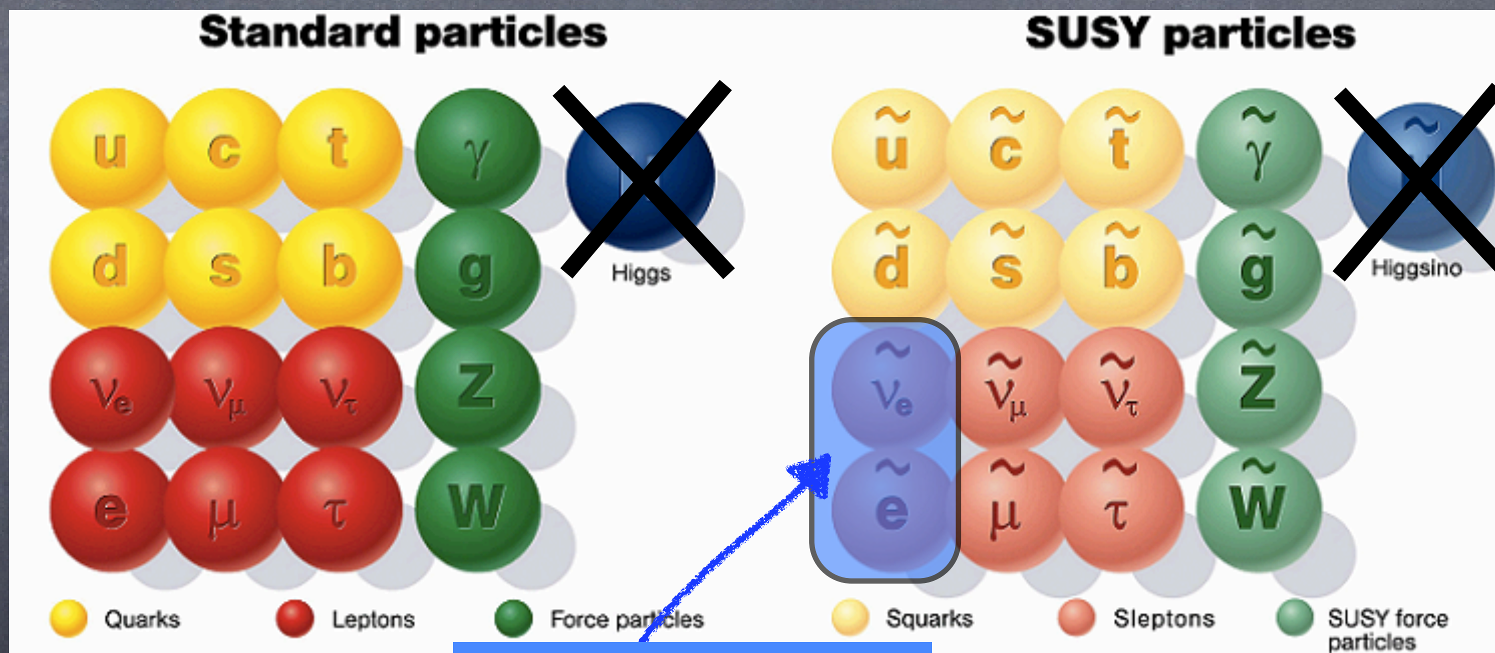
Can the Higgs be superpartner of a neutrino?

Yes: same quantum numbers

$$L = \begin{pmatrix} \nu \\ l_L^- \end{pmatrix} = (1,2)_{1/2} \quad \overset{\text{SUSY}}{\longleftrightarrow} \quad H = \begin{pmatrix} h^0 \\ h^- \end{pmatrix} = (1,2)_{1/2}$$

MSSM

Possibility here:

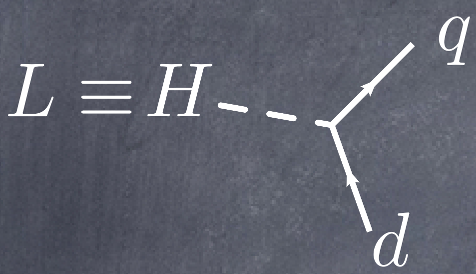


Higgs doublet

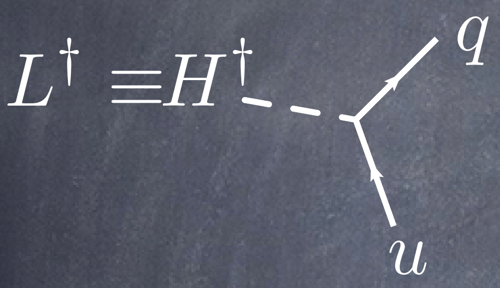
from F. Riva

Fayet,'76; Pomarol,FR,Biggio'12

Yukawa Couplings



✓ Can be supersymmetrized



✗ Cannot be supersymmetrized:
Up-sector Yukawa must come from ~~SUSY~~

Different stop/sbottom decays

arXiv:1211.4526

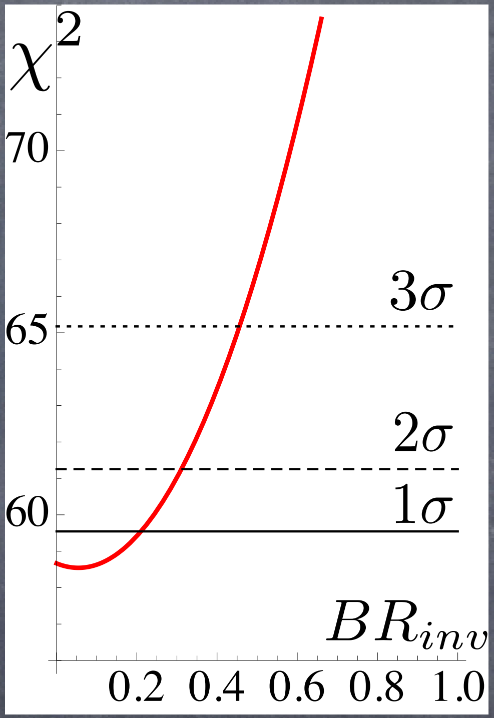
Decay	Interaction
$\tilde{t}_L \longrightarrow b_R \bar{l}_L^-$	$Y_d\, HQD\|_{\theta^2}$
$\tilde{t}_L \longrightarrow t_R \bar{\nu}_L$	$\frac{1}{\Lambda^2}\|H\|^2\|Q\|^2\|_{\theta^4}$
$\tilde{t}_L \longrightarrow t_L \tilde{G}$	$\frac{m_t^2 - m_{\tilde{t}_L}^2}{F}\, \tilde{t}_L^* \tilde{G}\, t_L$
$\tilde{b}_L \longrightarrow b_R \bar{\nu}_L$	$Y_d\, QHD\|_{\theta^2}$
$\tilde{b}_L \longrightarrow b_L \tilde{G}$	$\frac{m_b^2 - m_{\tilde{b}_L}^2}{F}\, \tilde{b}_L^* \tilde{G}\, b_L$

Decay	Interaction
$\tilde{t}_R \longrightarrow t_L \nu_L$	$\frac{1}{\Lambda^2}\|H\|^2\|U\|^2\|_{\theta^4}$
$\tilde{t}_R \longrightarrow t_R \bar{\tilde{G}}$	$\frac{m_t^2 - m_{\tilde{t}_R}^2}{F}\, \tilde{t}_R^* \bar{\tilde{G}}\, \bar{t}_L$
$\tilde{b}_R \longrightarrow b_L \nu_L$	$Y_d\, QHD\|_{\theta^2}$
$\tilde{b}_R \longrightarrow t_L\, l_L^-$	$Y_d\, QHD\|_{\theta^2}$
$\tilde{b}_R \longrightarrow b_R \bar{\tilde{G}}$	$\frac{m_b^2 - m_{\tilde{b}_R}^2}{F}\, \tilde{b}_R^* \bar{\tilde{G}}\, \bar{b}_L$

Table 2: *Decay modes for the (third family) squarks with the corresponding Lagrangian interaction.*

Signatures: Higgs sector

Higgs sector: Invisible decay $h \to \nu + \tilde{G}$ with $BR_{inv} \lesssim 10\%$

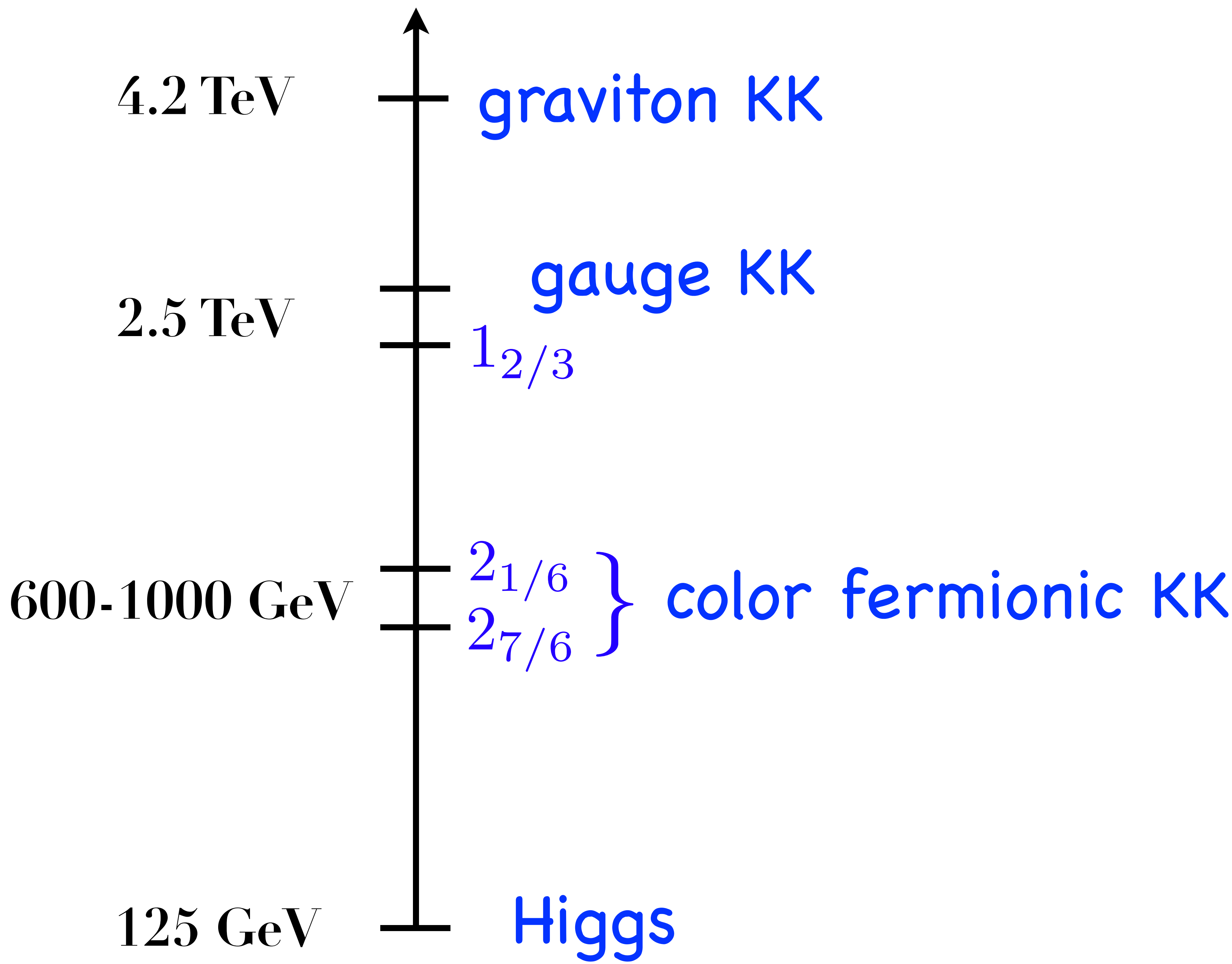


Montull,FR '12

Composite Higgs scenarios

MASS SPECTRUM

the higher the spin,
the higher the mass



MASS SPECTRUM

the higher the spin,
the higher the mass

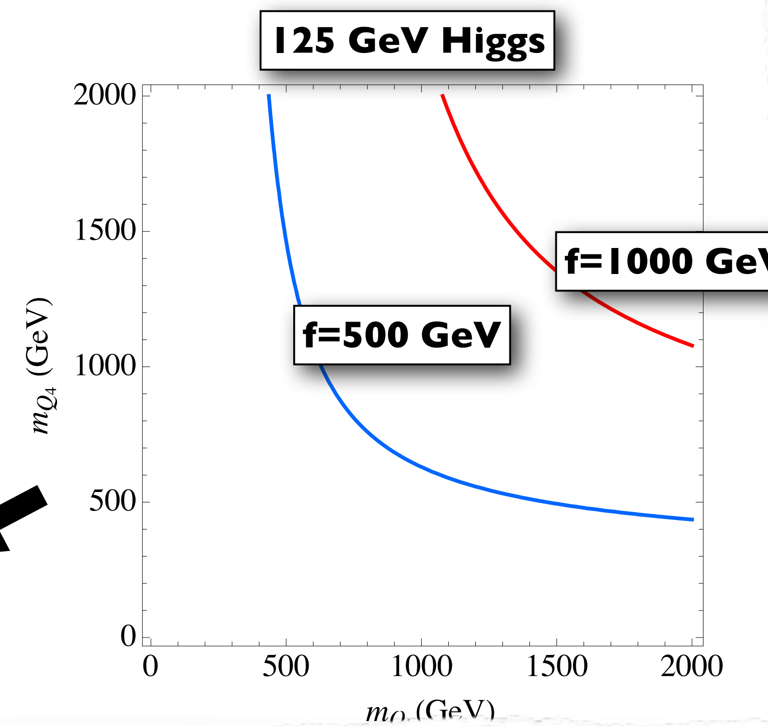
4.2

For the minimal composite PGB Higgs model:

$$m_h^2 \simeq \frac{N_c}{\pi^2}\left[\frac{m_t^2}{f^2}\frac{m_{Q_4}^2 m_{Q_1}^2}{m_{Q_1}^2 - m_{Q_4}^2}\log\left(\frac{m_{Q_1}^2}{m_{Q_4}^2}\right)\right]$$

2.5

mass of color vector-like fermions
with EM charges 5/3,2/3,-1/3



600-100

Fermion resonances must
be below the TeV

125 GeV

Higgs

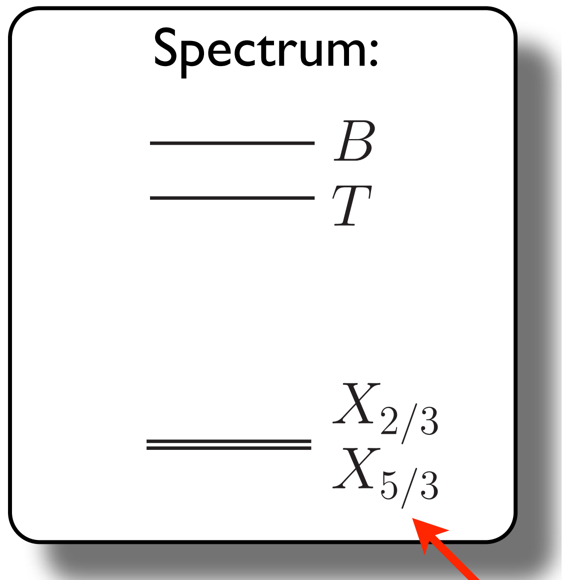
Colored fermion resonances

Lightest: a $(\mathbf{2},\mathbf{2})_{2/3}$ of $SU(2)_L \otimes SU(2)_R \otimes U(1)_X$:

$Y = T_R^3 + X$:

$2_{1/6}$

$2_{7/6}$

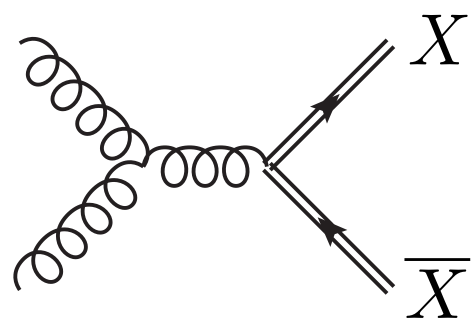


from A.Wulzer (arXiv: 1211.5663)

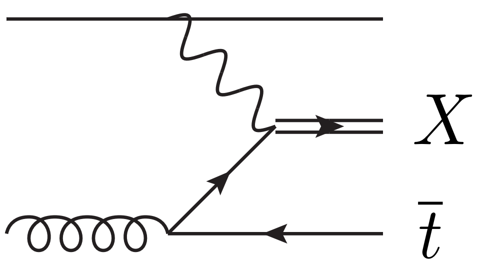
Lightest fermion $Q_{EM}=5/3$!

Colored fermion resonance pheno

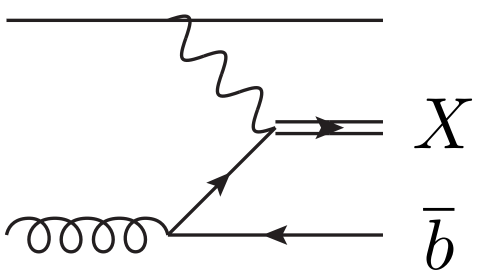
Three possible production mechanisms



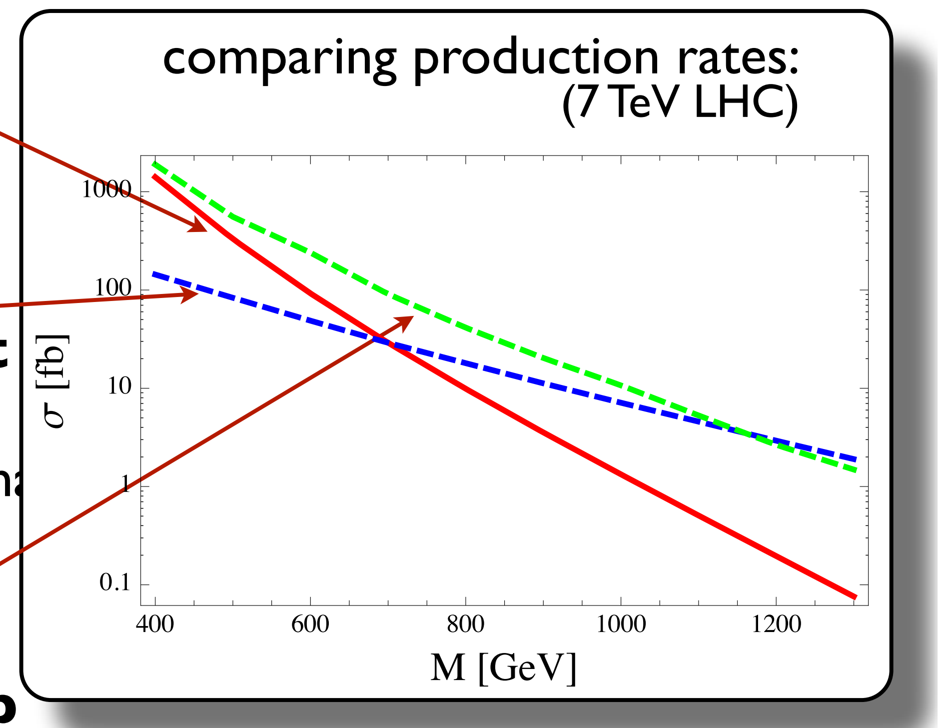
QCD **pair prod**.
model indep.,
relevant at low mass



single prod. with **t**
model dep. coupling
pdf-favored at high ma



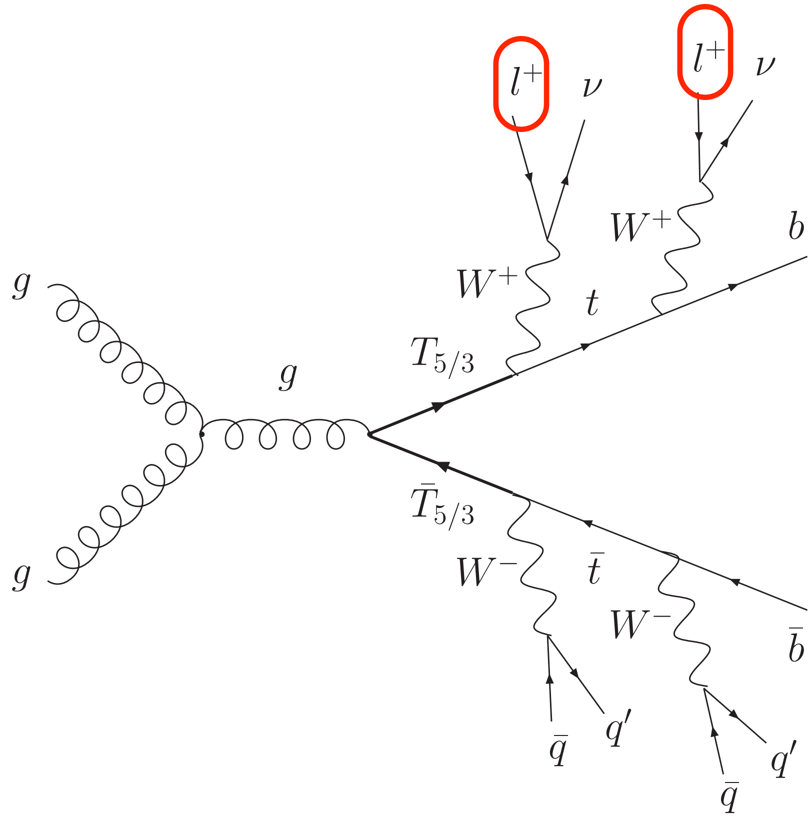
single prod. with **b**
favored by small b mass
dominant when allowed



from A.Wulzer (arXiv: 1211.5663)

Color vector-like fermions with charge 5/3:

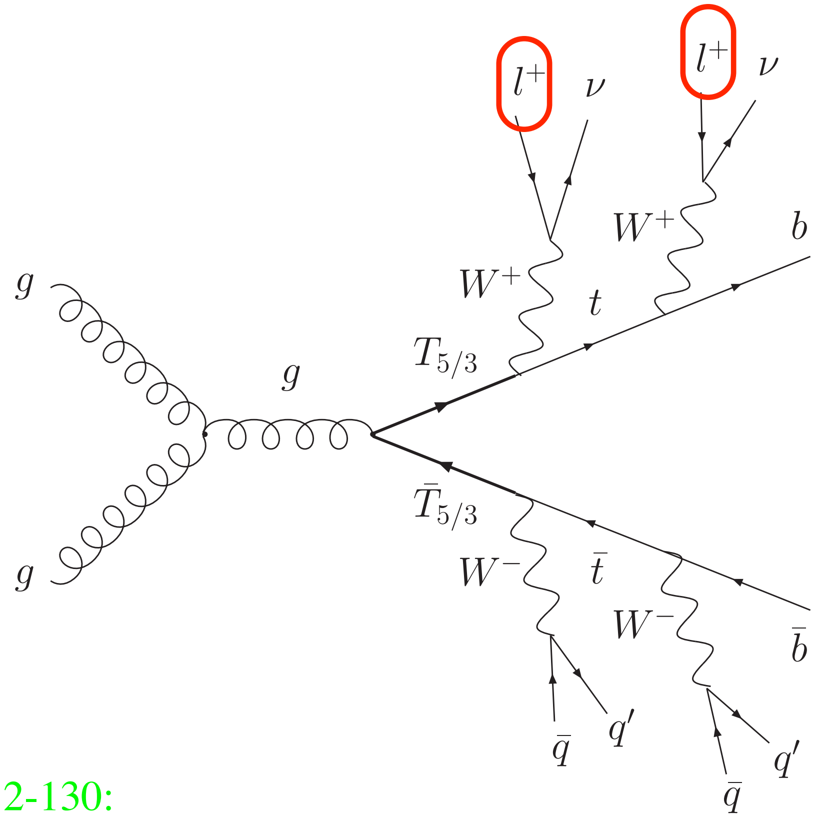
If this fermion is light, it can be double produced:



same-sign di-leptons

Color vector-like fermions with charge 5/3:

If this fermion is light, it can be double produced:



same-sign di-leptons

ATLAS-CONF-2012-130:

$$M_{T_{5/3}} \gtrsim 700 \text{ GeV}$$

CMS PAS B2G-12-003:

$$M_{T_{5/3}} \gtrsim 645 \text{ GeV}$$

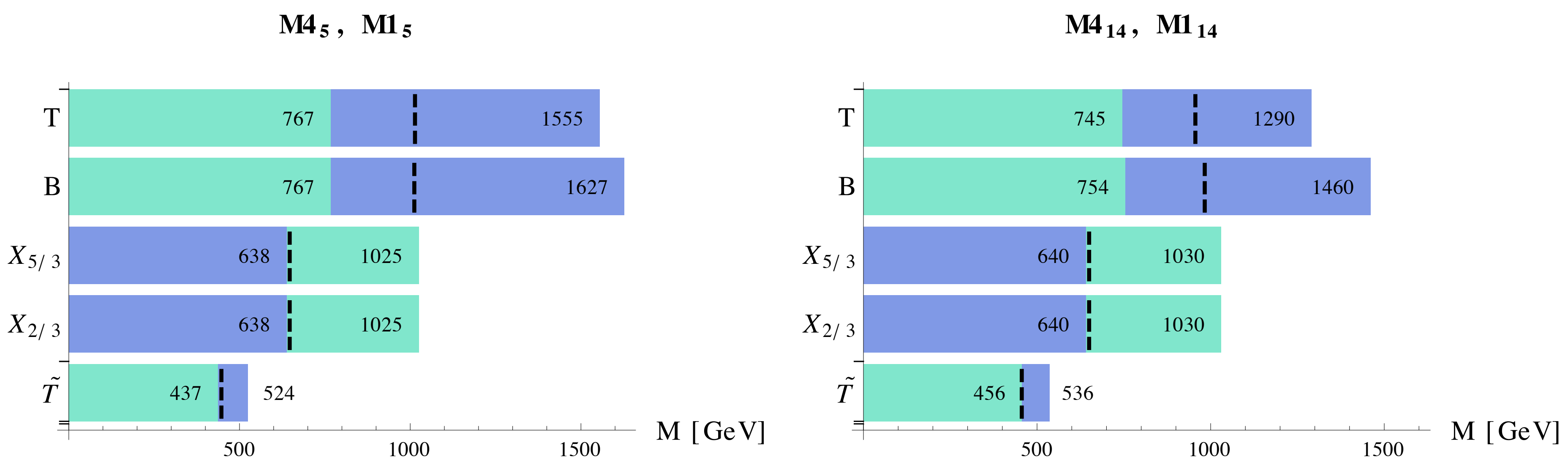
☛ sensitive to predictions from Higgs mass!

but could can be improved using single production

arXiv: 1211.5663

After LHC8:

arXiv: 1211.5663



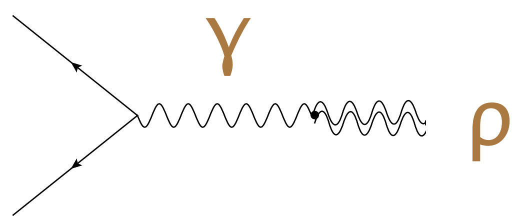
(model dependence pictured by the elongation of the bar in different color)

Scratching the interesting areas of the models...

Spin=1 resonances

☛ Expected mass ~ **3 TeV** from EWPT

Searches difficult since, as the ρ in QCD, couples to SM fermion through mixing with gauge bosons



$$\sim \frac{g}{g_{\rm strong}}$$

Suppressed production cross-section

Decay into Goldstones (also strong resonances): **W_L , Z_L**
or, when possible, into a pair of tops: **t_R**

➥ Not sensitive at LHC8!

Searching for them?

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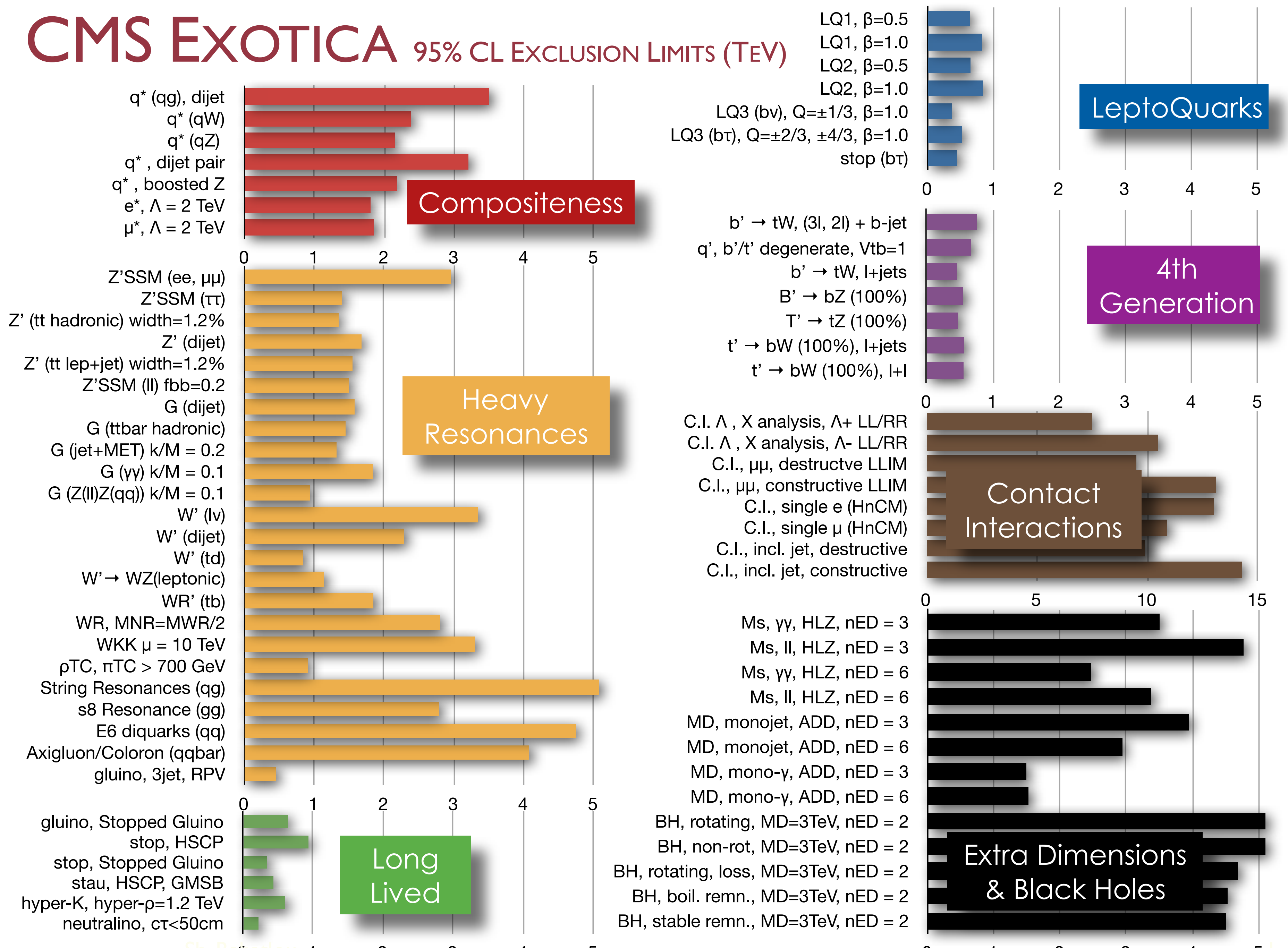
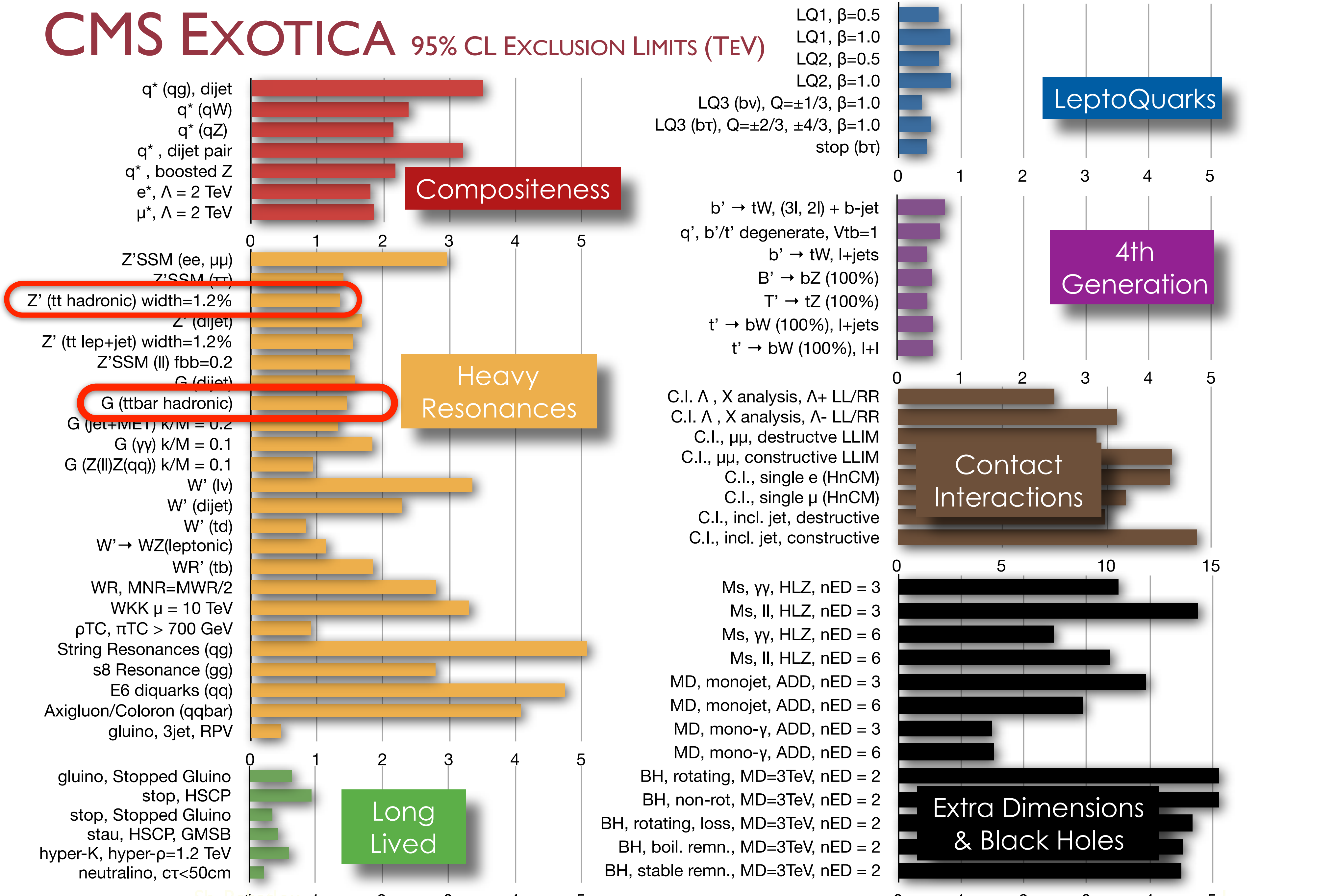
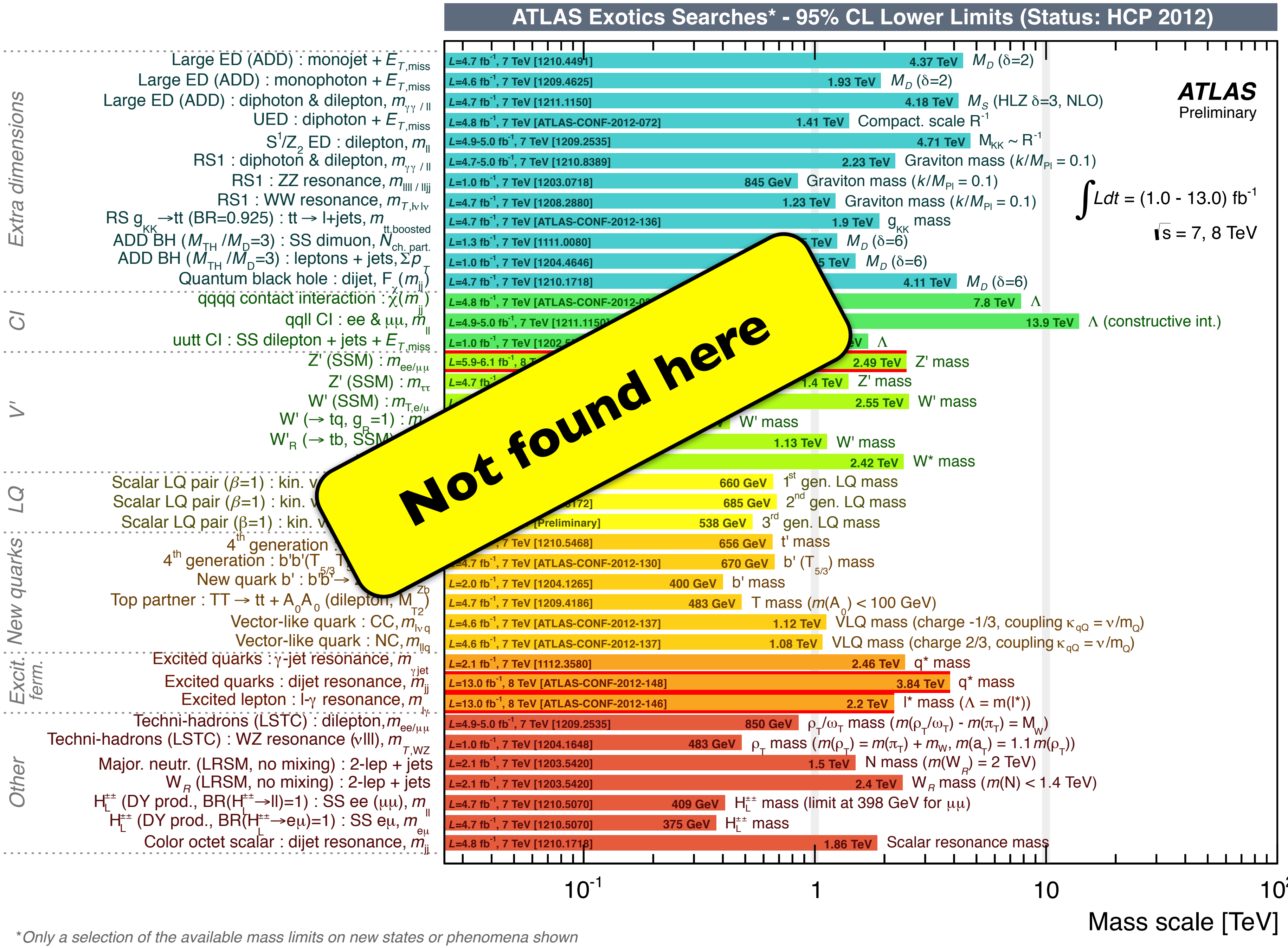


Searching for them?



Searching for them?



Conclusions

<u>LHC data has had an important but not determinant impact on BSM</u>

The most important: M_H~125 GeV

- We have a plan (well-motivated) and we must go for it with the LHC at 14 TeV

- **Advise**: Be open to all version of **<u>natural</u>** susy (e.g. R-parity breaking, ...), composite Higgs models that we just started to explore through **fermionic colored resonances**, and variants

- Sorry, but no plan B!!!

- If at the end we crash with the SM, we crash!

➥ We will be definitely also learning something

(in a bloody way though)