A natural Fermi scale

Majorana Lectures
Naples, June 15, 2012

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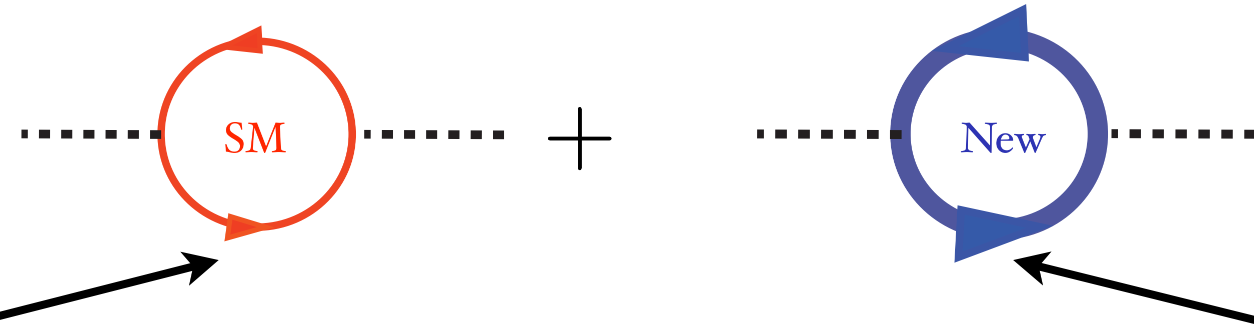
The Fine Tuning problem of the Fermi scale

$$\delta m_H^2 =$$



in isolation grows like Λ^2
where $\Lambda \equiv$ the "cutoff"
i.e. the highest scale at which the theory is valid:
a signal of the sensitivity of m_H

knows about Λ_{NP}
i.e. any higher physical scale to which the Higgs boson is possibly coupled
$M_{Pl}, M_{GUT} \ldots$ you name it

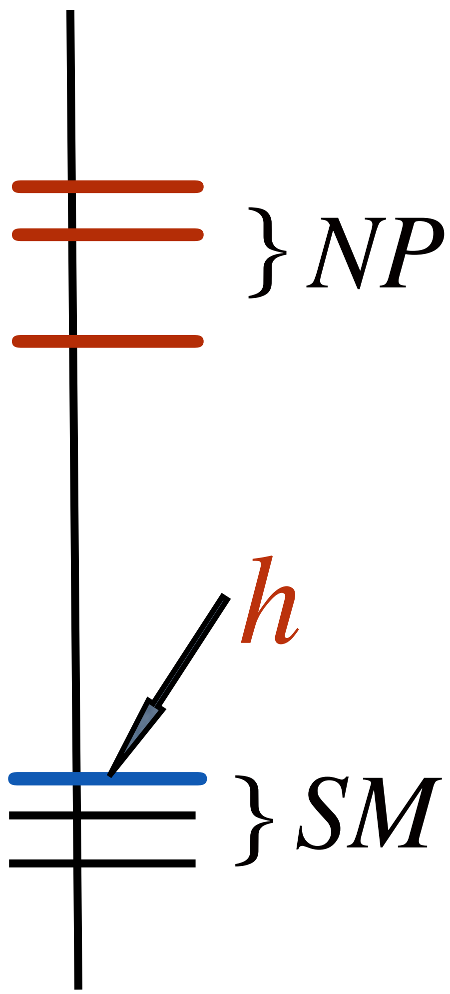
$$\delta m_H^2 \approx \frac{\lambda^2}{16\pi^2}\Lambda_{NP}^2$$

The ElectroWeak scale determined by the Higgs mass

Why $G_F^{-1/2} << \Lambda_{NP}$? Why $G_F^{-1/2} << G_N^{-1/2}$?

Another look at the FT problem

There are infinitely many theories at short distances, that give the same physics of the Standard Model, as long as their "low energy" spectrum coincides with the one of the SM



including the Higgs boson

We only know of approximate symmetries that can explain this

In all explicit examples, without unwarranted cancellations, new phenomena required at a scale Λ_{NP} not far from m_h

⇒ What are and where are they?

The (many) reactions to the FT problem

0. Ignore it and view the SM in isolation
   (if no other short distance scale, what about gravity?)

1. Cure it by symmetries: SUSY, Higgs as PGB

2. A new strong interaction nearby

3. A new strong interaction not so nearby: quasi-CFT

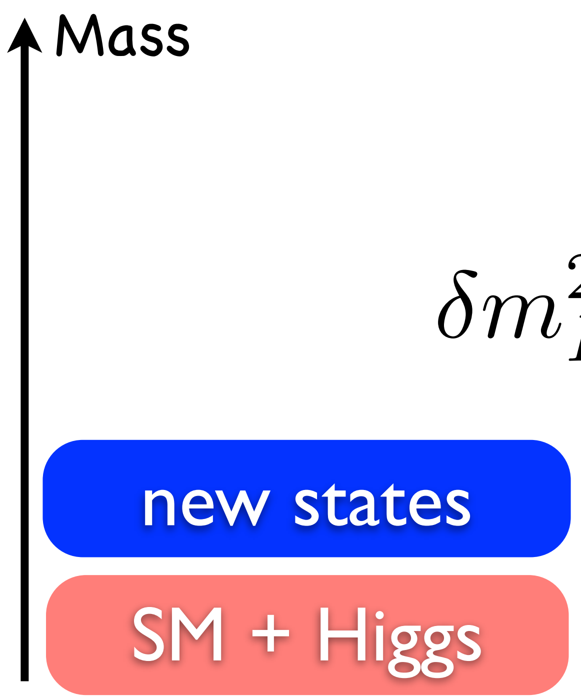
4. Saturate the UV nearby: extra-dimensions around the corner

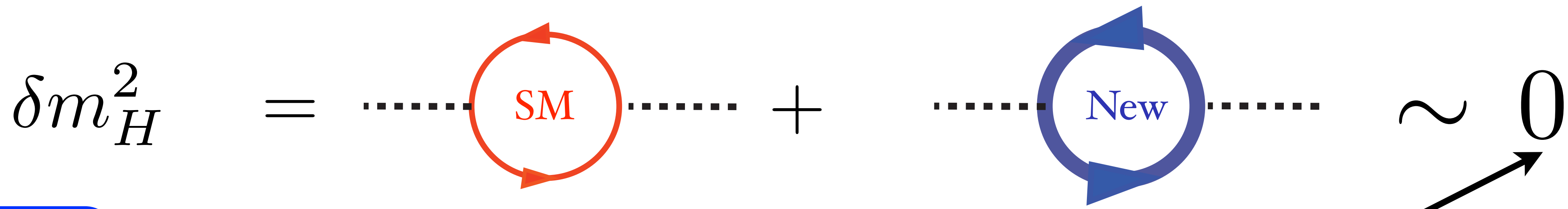
5. Warp space-time: RS

6. Accept it: anthropic selection, the multiverse, the 10^{120} vacua of string theory

Anything else?

Natural theories





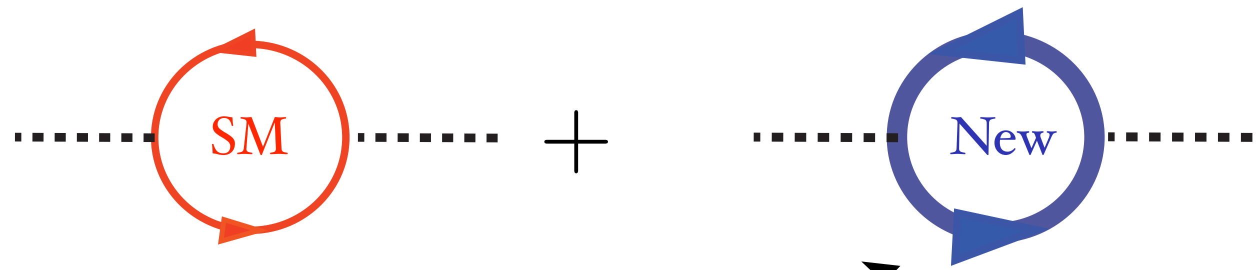
by an (approximate) symmetry

relative to any higher physical scale to which the Higgs boson is possibly coupled

Symmetries crucial to the empirical success of particle physics so far

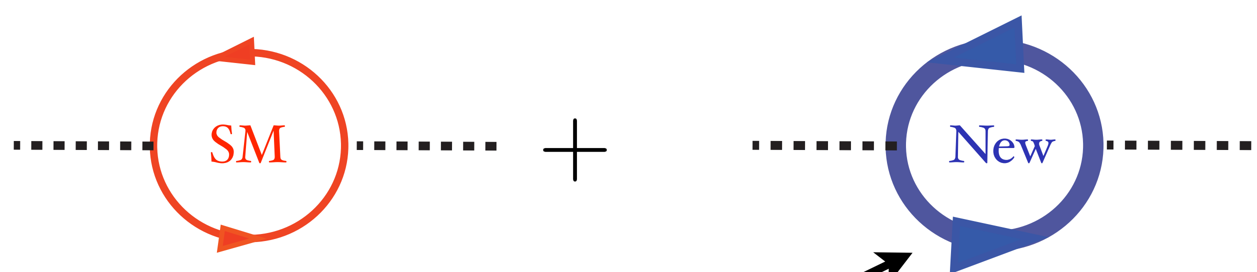
Have they exhausted their role?

Supersymmetry

$\delta m_H^2 =$  ~ 0

s-particles

The Higgs boson as a pseudoGolsdtone

$\delta m_H^2 =$  ~ 0

Heavy "composite" fermions

Question: Where and how to look for these phenomena?
(Nothing seen at the LHC so far)

Answer: No theorem but this page offers the driving criterium

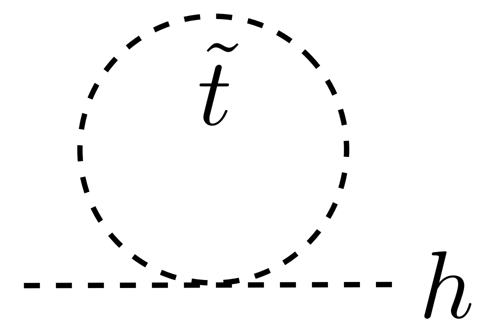
SUSY and its crucial configuration

The key equations:

$m_{\tilde{h}}$

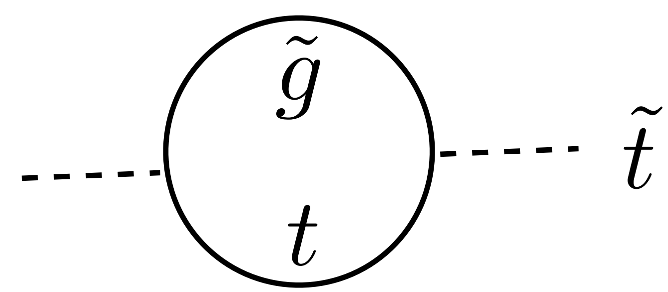
$$\frac{m_h^2}{2} \approx -|\mu|^2 + m_u^2$$

$$\delta m_u^2 \approx -\frac{3y_t^2}{8\pi^2}(m_{\tilde{t}_L}^2 + m_{\tilde{t}_R}^2 + A_t^2) \log M/m_{\tilde{t}}$$



$m_{\tilde{b}_L}$

$$\delta m_{\tilde{t}}^2 \approx \frac{8\alpha_s}{3\pi} m_{\tilde{g}}^2 \log M/m_{\tilde{t}}$$



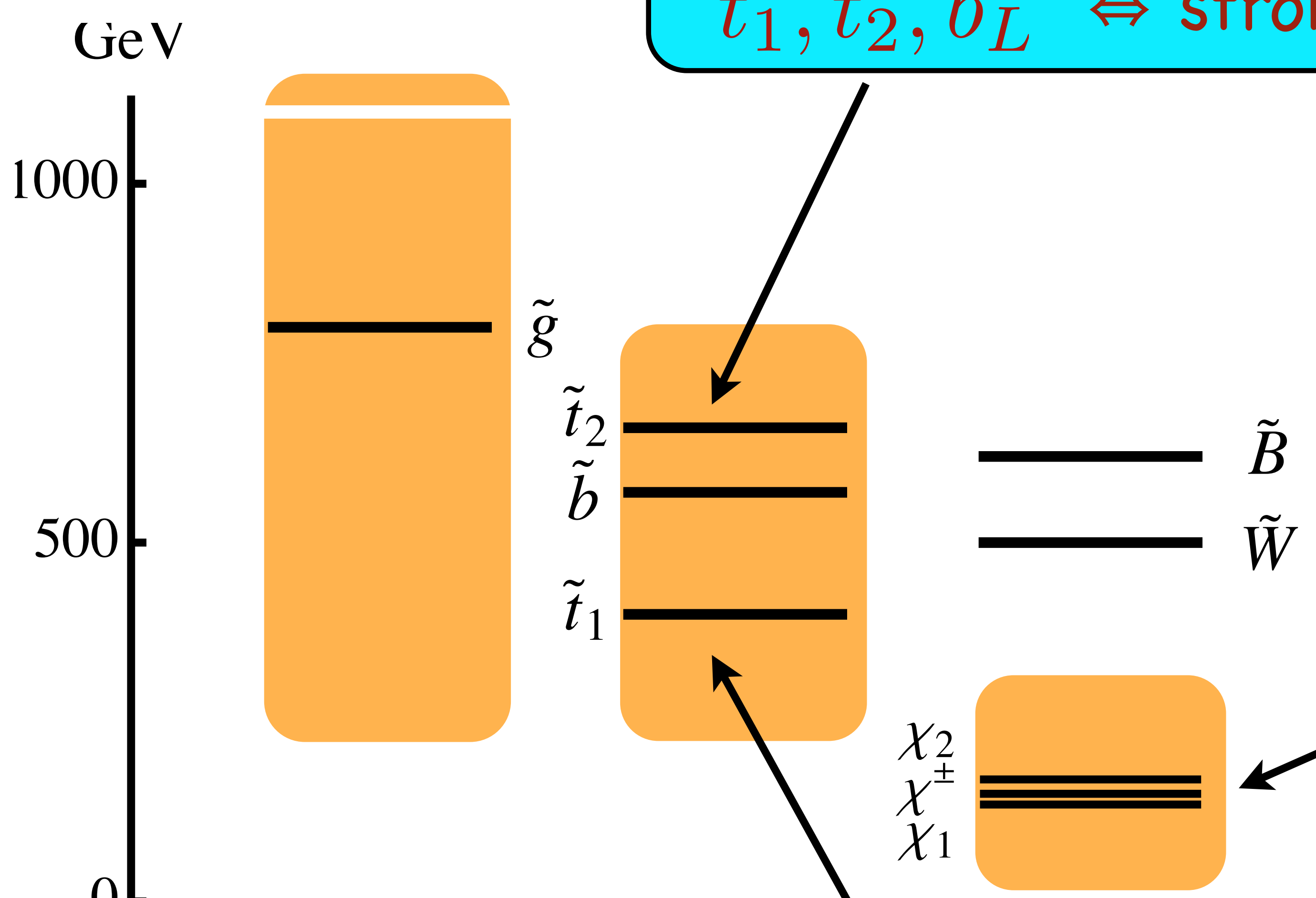
(to be made more precise in any given SB-mediation scheme)

All s-particles other than $\tilde{g}, \tilde{t}_L, \tilde{t}_R, \tilde{b}_L, \tilde{h}$ weakly constrained

The crucial configuration

"s-particles at their naturalness limit"

$\tilde{t}_1, \tilde{t}_2, \tilde{b}_L$ ⇔ strongest coupling to the Higgs system



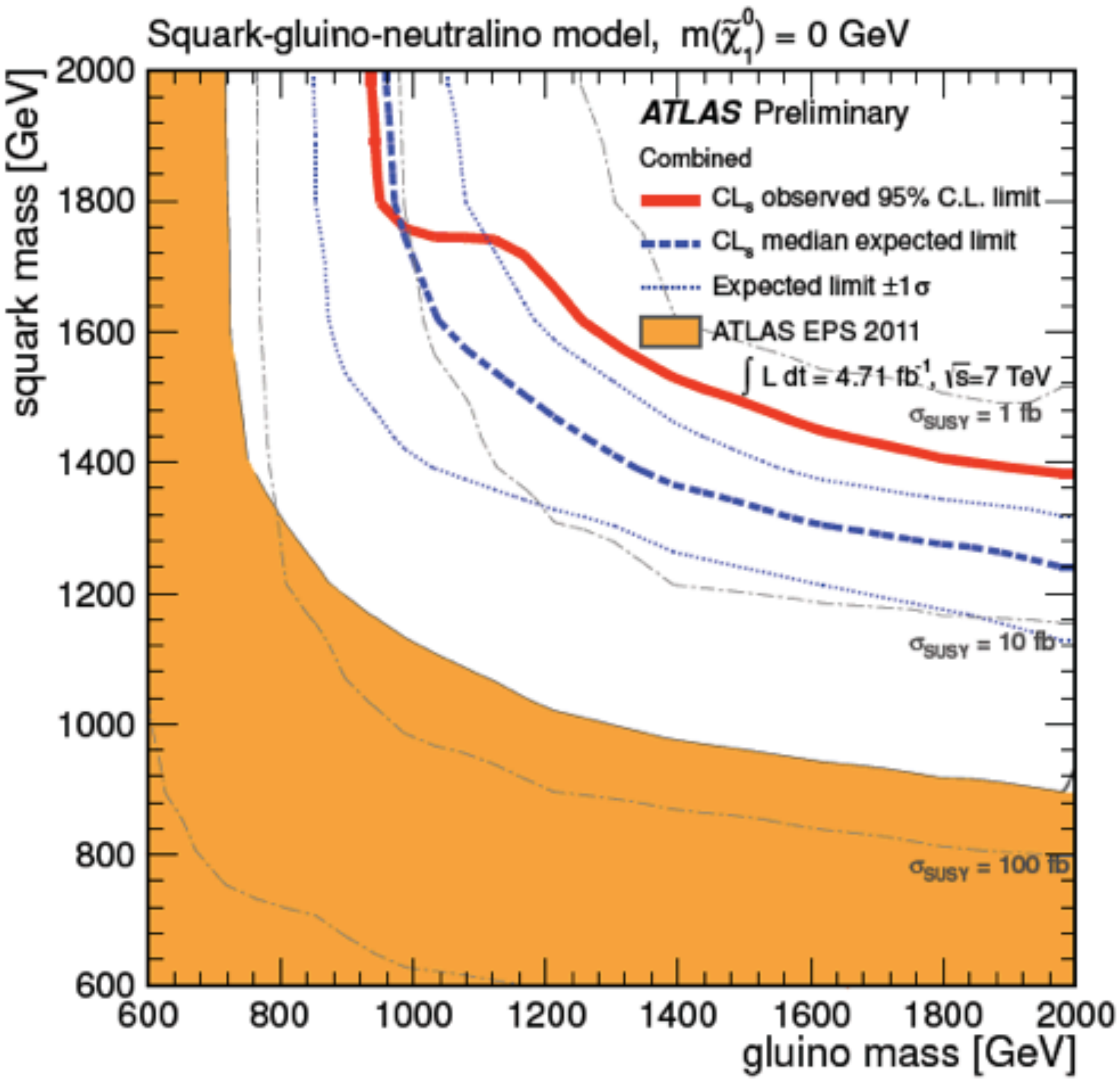
(μ ⇔ M_Z at tree level)

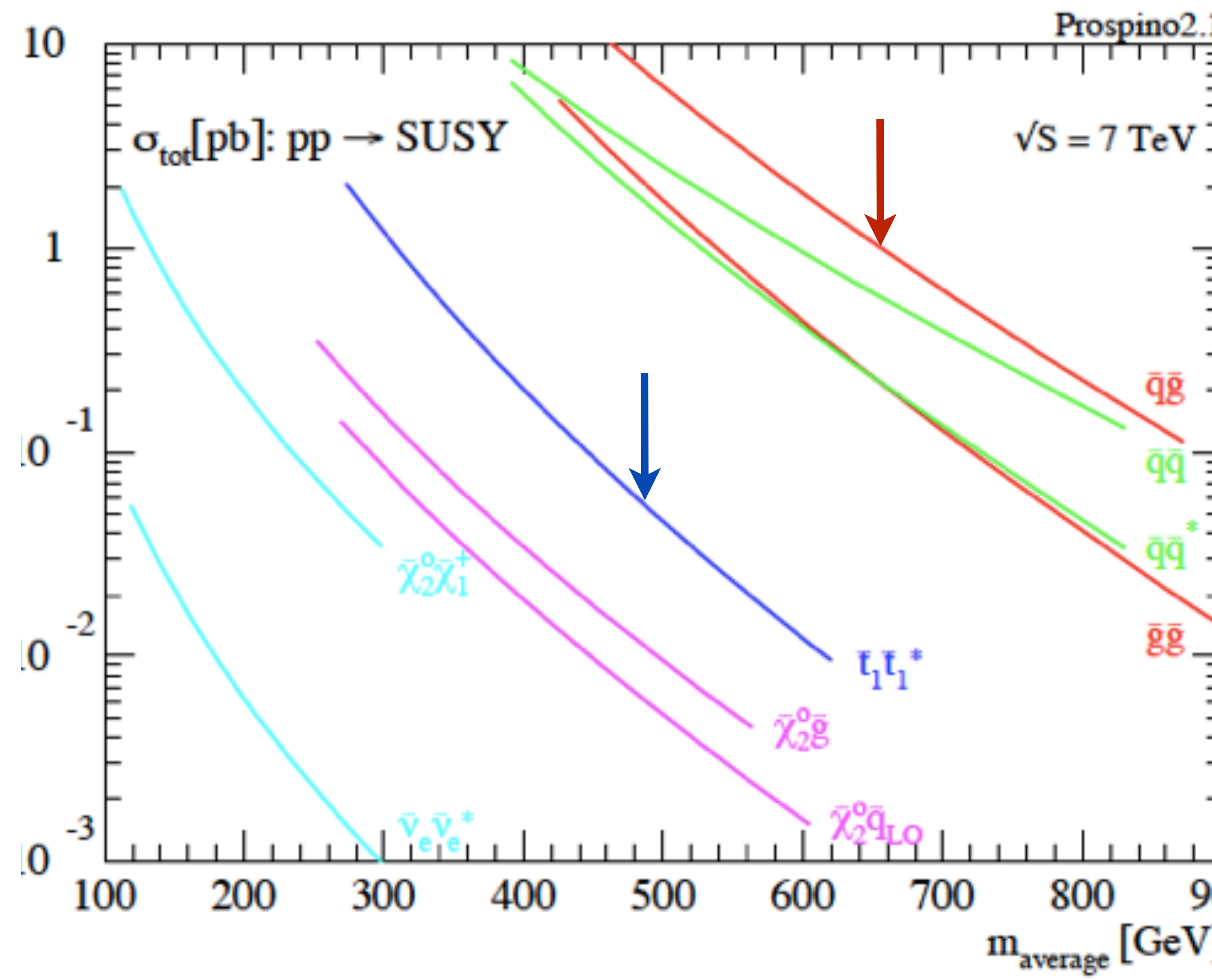
$\tilde{q}_1, \tilde{q}_2, \tilde{b}_R$ heavy enough (≥ $\tilde{g}$) to be ~ irrelevant

orange areas indicative and dependent on the Higgs mass

$\tilde{B}, \tilde{W}$ not much constrained but expected below $m_{\tilde{g}}$

A first look at the LHC





$$g\ q \to \tilde{g}\ \tilde{q}$$
$$q\ q \to \tilde{q}\ \tilde{q}$$
$$q\ \bar{q} \to \tilde{q}\ \tilde{q}^*$$

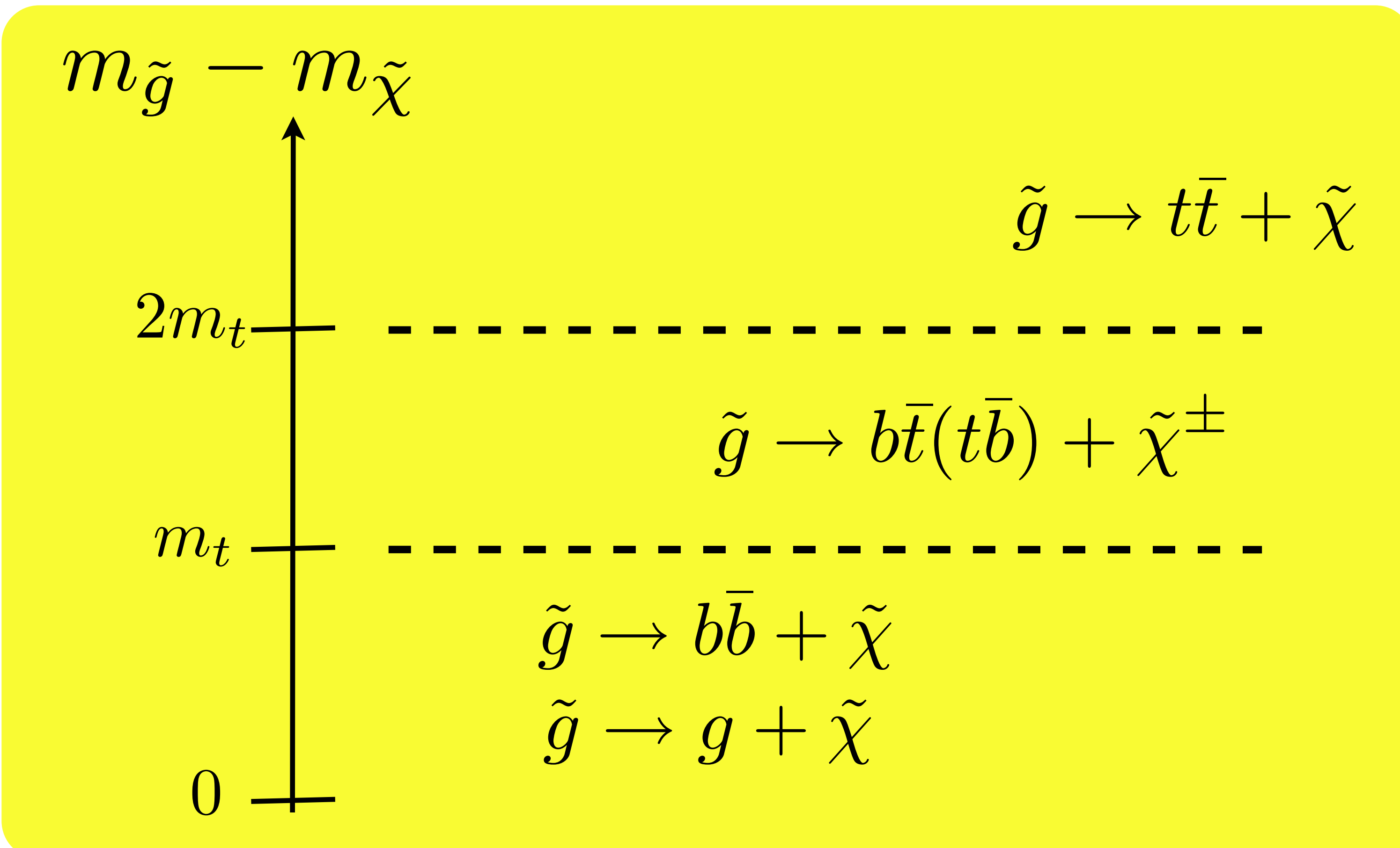
$\Rightarrow m_{\tilde{g}}, m_{\tilde{q}_{1,2}} > 1 \div 1.5\ TeV$

(for $\chi^0, \tilde{g}$ not too close in mass)

$\tilde{t}, \tilde{b}$ unconstrained

A synthetic description of the LHC phenomenology

$pp \longrightarrow \tilde{g}\tilde{g}$ dominant over $pp \longrightarrow \tilde{t}\tilde{t}^* \ (\tilde{b}\tilde{b}^*)$



$$pp \longrightarrow \tilde{g}\tilde{g} \longrightarrow tt\bar{t}\bar{t} + \chi\chi$$
$$pp \longrightarrow \tilde{g}\tilde{g} \longrightarrow tt\bar{t}\bar{b}(\bar{t}\bar{t}tb) + \chi\chi$$
$$pp \longrightarrow \tilde{g}\tilde{g} \longrightarrow tt\bar{b}\bar{b}(\bar{t}\bar{t}bb) + \chi\chi$$
$$pp \longrightarrow \tilde{g}\tilde{g} \longrightarrow t\bar{t}b\bar{b} + \chi\chi$$

$$\chi = \chi^{\pm}, \chi_1, \chi_2$$

3 body final states either by cascade or direct
($m_{\tilde{t}}, m_{\tilde{b}}$ almost don't matter)

When phase space opens up, $\tilde{g} \longrightarrow b\bar{b}\chi$ suppressed

If $\mu < M_1, M_2$ then $\chi^{\pm}, \chi^0$ close in mass

current bounds on $\tilde{g}, \tilde{t}, \tilde{b}$

ATLAS, ∫Ldt≈2 fb^{-1}

$\tilde{b}_1\tilde{b}_1^*$ (MSSM)	$\tilde{b}_1 \to b\tilde{\chi}_1^0$	$m_{\tilde{b}_1} = 390$ GeV ($m_{\tilde{\chi}_1^0} = 0$)	2 b-jets
$\tilde{b}_1\tilde{b}_1^*$ (MSSM)	$\tilde{b}_1 \to b\tilde{\chi}_1^0$	$m_{\tilde{b}_1} = 350$ GeV ($m_{\tilde{\chi}_1^0} = 120$ GeV)	2 b-jets
$\tilde{g}\tilde{g}$, $\tilde{b}_1\tilde{b}_1^*$ (MSSM)	$\tilde{g} \to \tilde{b}_1 b$, $\tilde{b}_1 \to b\tilde{\chi}_1^0$	$m_{\tilde{g}} = 920$ GeV ($m_{\tilde{b}_1} < 800$ GeV)	0ℓ + b-jets
$\tilde{g}\tilde{g}$ (simpl. model)	$\tilde{g} \to \bar{b}\tilde{\chi}_1^0$	$m_{\tilde{g}} = 900$ GeV ($m_{\tilde{\chi}_1^0} < 300$ GeV)	0ℓ + b-jets
$\tilde{g}\tilde{g}$, $\tilde{t}_1\tilde{t}_1^*$ (MSSM)	$\tilde{g} \to \tilde{t}_1 t$, $\tilde{t}_1 \to t\tilde{\chi}_1^0$	$m_{\tilde{g}} = 620$ GeV ($m_{\tilde{t}_1} < 440$ GeV)	1ℓ + b-jets
$\tilde{g}\tilde{g}$, $\tilde{t}_1\tilde{t}_1^*$ (MSSM)	$\tilde{g} \to \tilde{t}_1 t$, $\tilde{t}_1 \to t\tilde{\chi}_1^0$	$m_{\tilde{g}} = 650$ GeV ($m_{\tilde{t}_1} < 450$ GeV)	2ℓSS
$\tilde{g}\tilde{g}$ (simpl. model)	$\tilde{g} \to t\bar{t}\tilde{\chi}_1^0$	$m_{\tilde{g}} = 700$ GeV ($m_{\tilde{\chi}_1^0} < 100$ GeV)	1ℓ + b-jets
$\tilde{g}\tilde{g}$ (simpl. model)	$\tilde{g} \to t\bar{t}\tilde{\chi}_1^0$	$m_{\tilde{g}} = 650$ GeV ($m_{\tilde{\chi}_1^0} < 215$ GeV)	2ℓSS
$\tilde{g}\tilde{g}$ (simpl. model)	$\tilde{g} \to tb + \tilde{\chi}_1^0$	$m_{\tilde{g}} = 710$ GeV ($m_{\tilde{\chi}_1^0} < 100$ GeV)	1ℓ + b-jets

My rough summary:

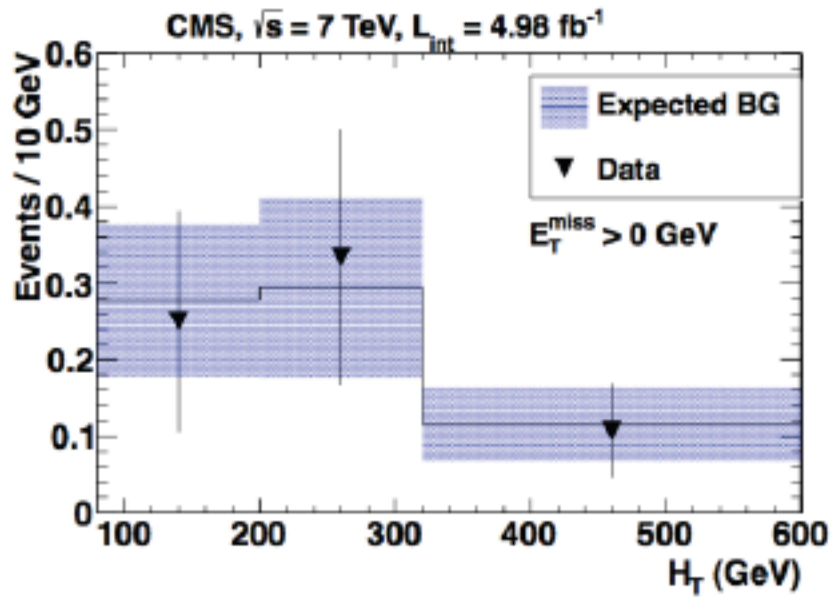
$m_{\tilde{g}} \gtrsim 700\ GeV$ $\quad m_{\tilde{b}} \gtrsim 350\ GeV$ $\quad m_{\tilde{t}} \gtrsim 200\ GeV$

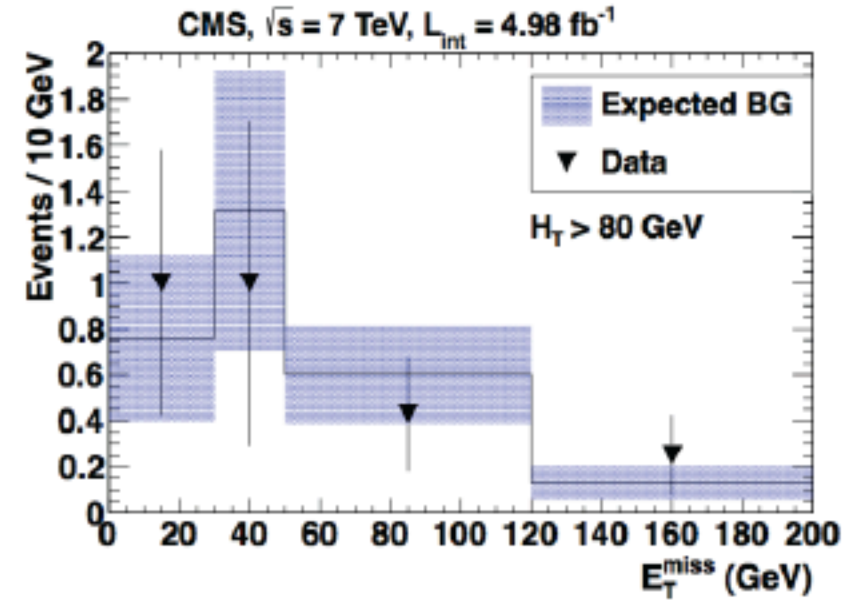
(from Tevatron searches)

CMS in progress on 3d generation squarks

Kovalskyi

Same-sign leptons + MET + b-jets

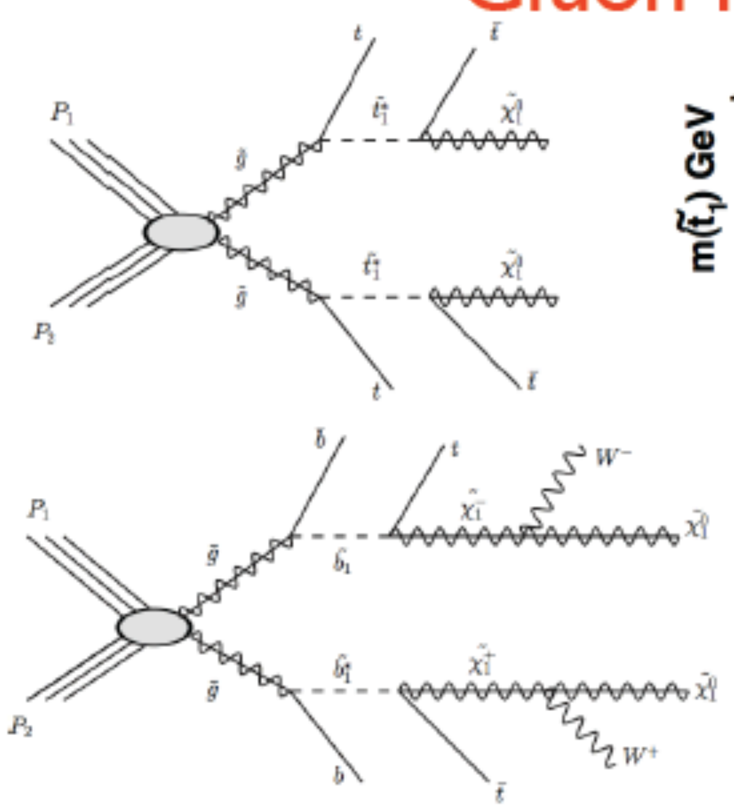


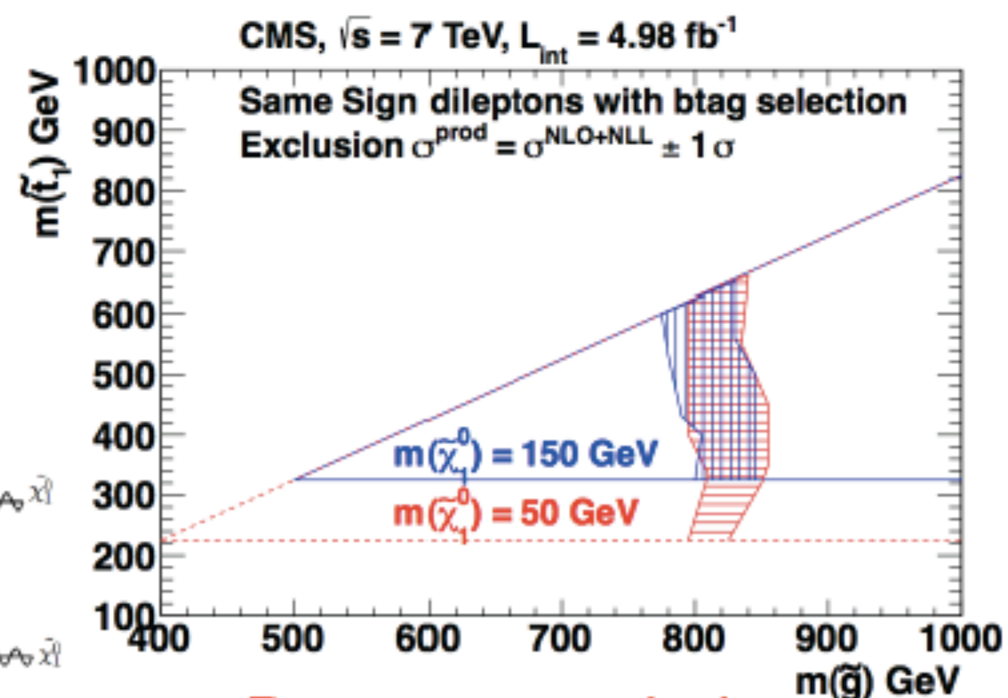


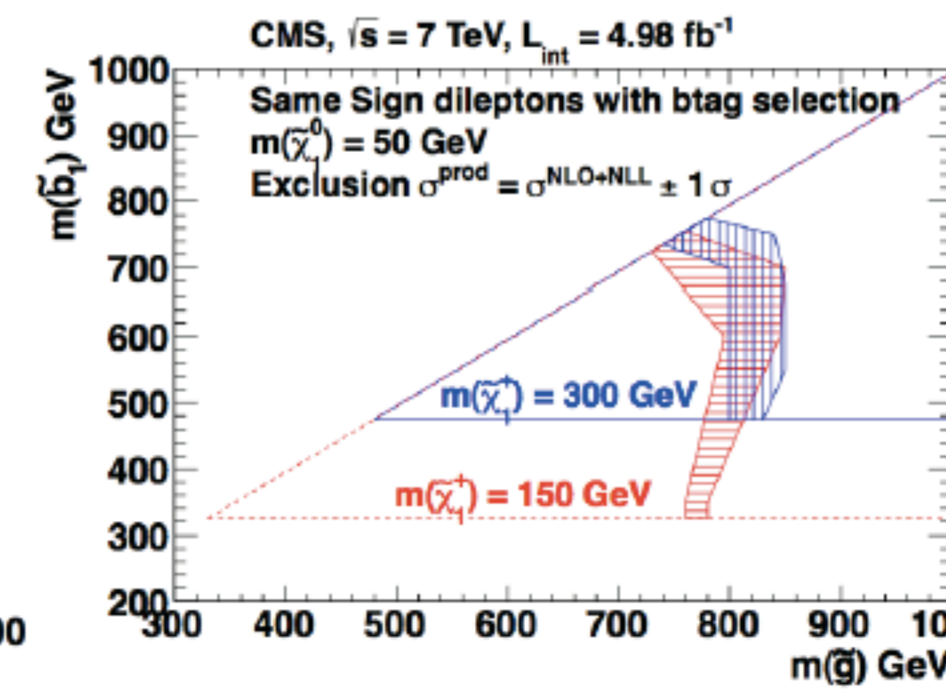
For SUSY to remain natural with Higgs ~ 120GeV

- s-top/bottom < 400 GeV
- gluino < 1500 GeV

Gluon mitigated s-top and s-bottom production





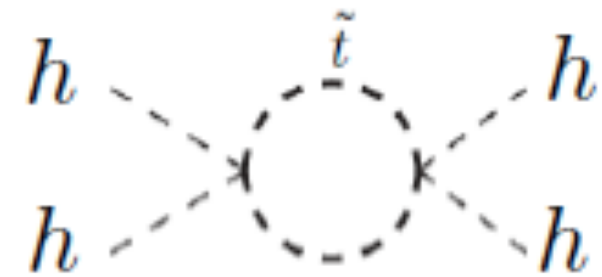


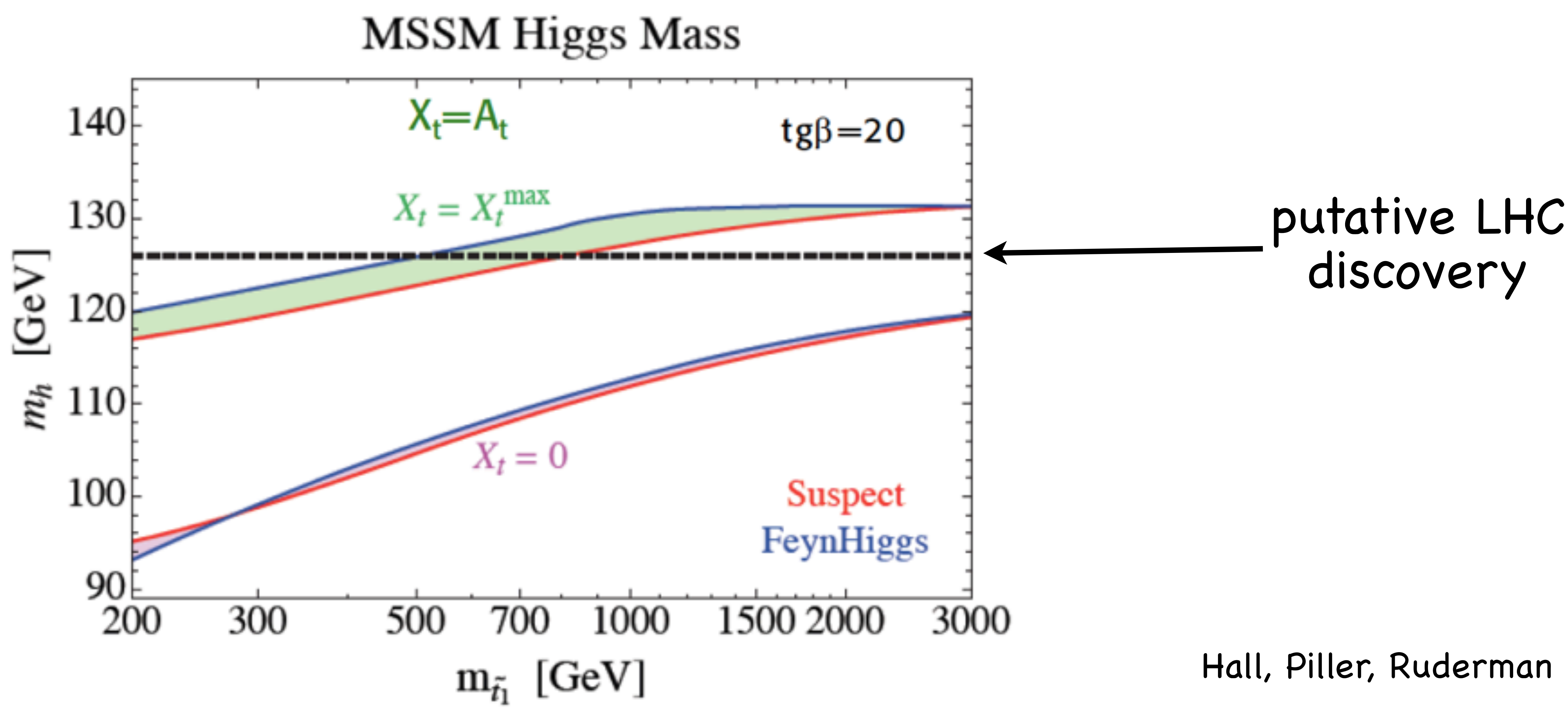
Direct s-top and s-bottom production searches are in the pipeline

Where is the supersymmetric Higgs boson?

MSSM

$$m_h^2 \approx m_Z^2 \cos^2 2\beta + \frac{3}{(4\pi)^2}\frac{m_t^4}{v^2}\left[\ln\frac{m_{\tilde{t}}^2}{m_t^2} + \frac{X_t^2}{m_{\tilde{t}}^2}\left(1 - \frac{X_t^2}{12 m_{\tilde{t}}^2}\right)\right]$$





Hall, Piller, Ruderman 2011

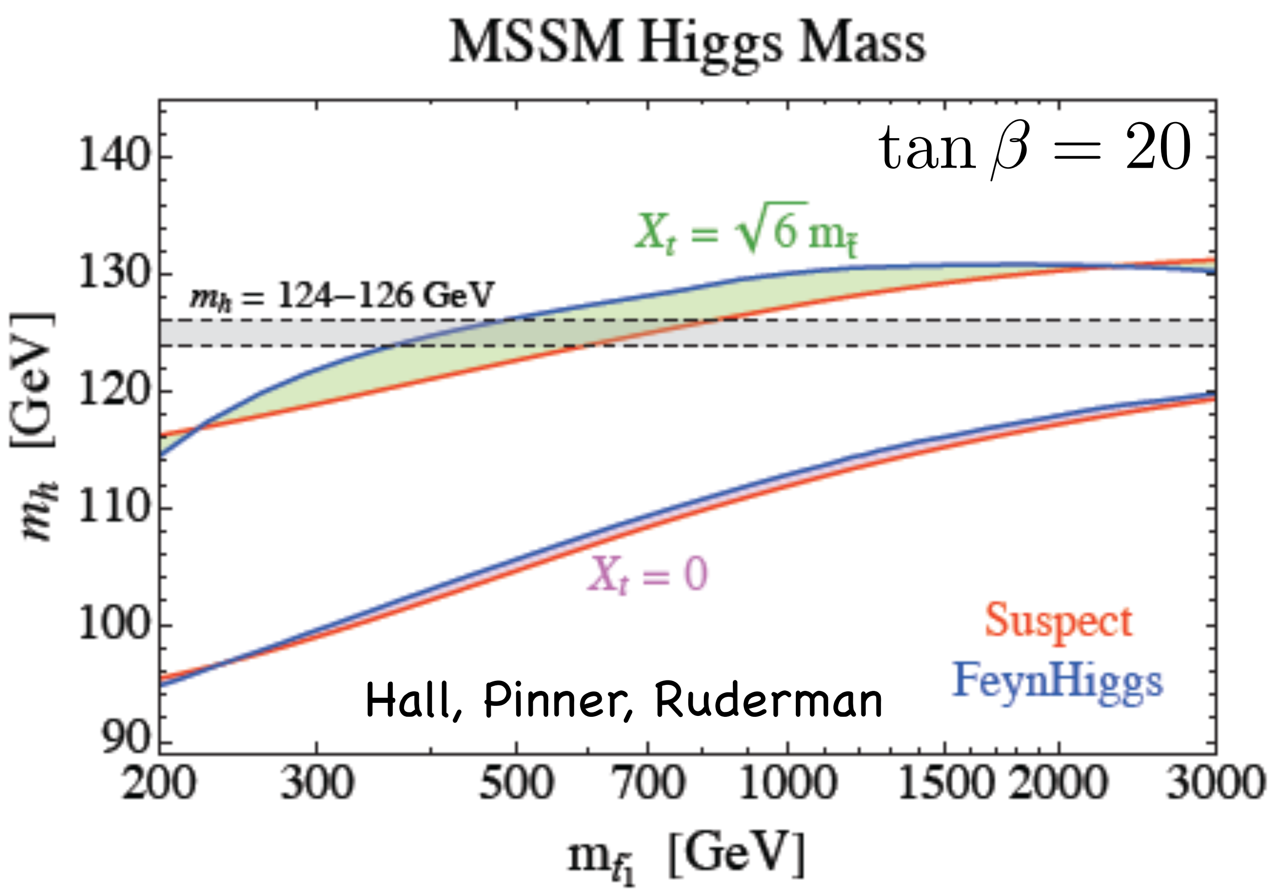
MSSM expectation well OK with current allowed "SM range"
but 125 GeV too high for naturally light stops

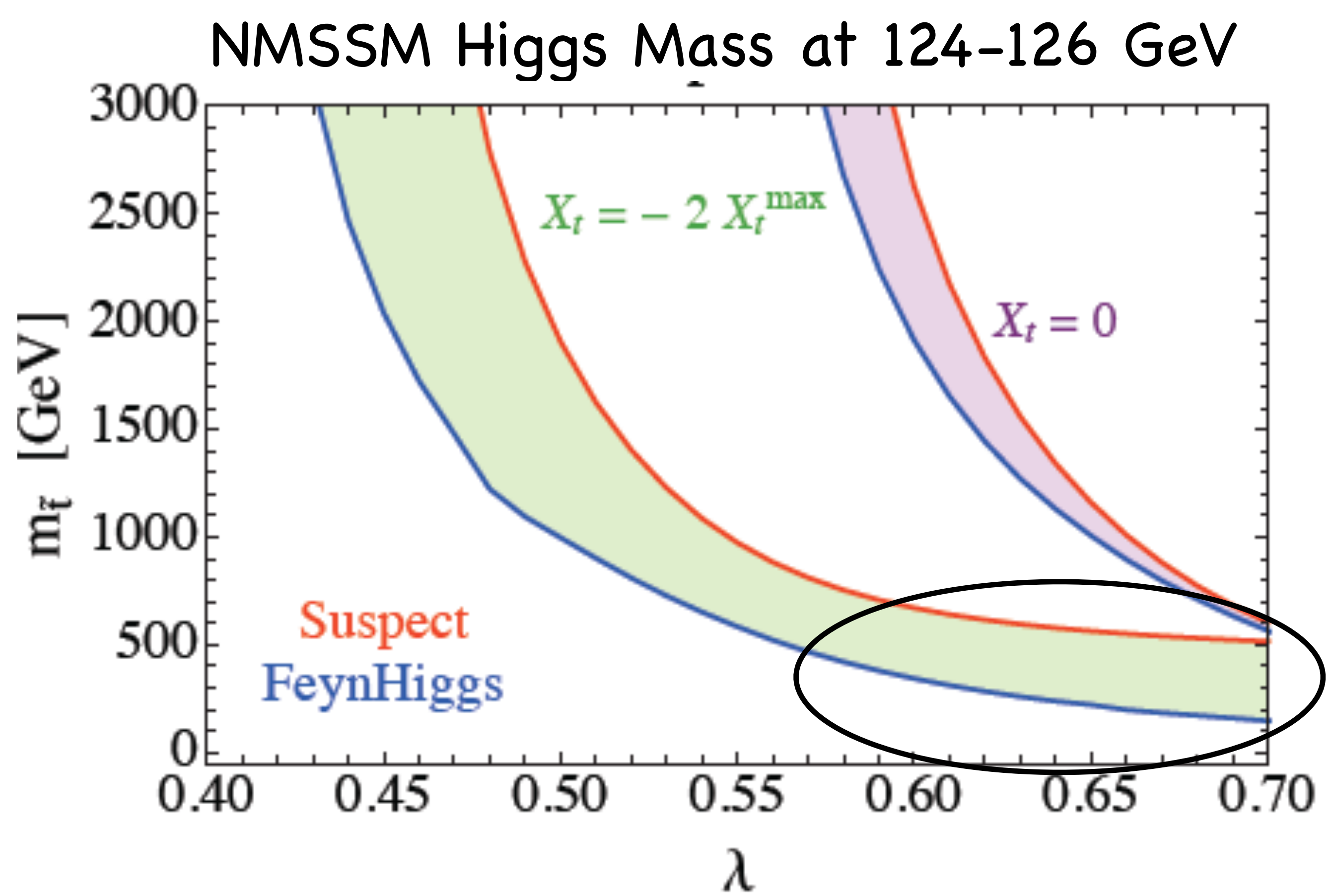
What about the Higgs mass?

The NMSSM as a possible way out

(since the 70's, Fayet, etc)

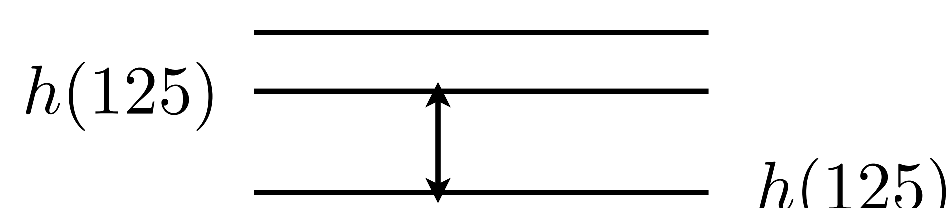
$$f = \mu H_1 H_2 \Rightarrow f = \lambda S H_1 H_2 \qquad m_h^2 \leq m_Z^2 (\cos^2 2\beta + \frac{2\lambda^2}{g^2 + g'^2} \sin^2 2\beta) + \delta_t(m_{\tilde{t}_1}, X_t)$$





before mixing with the other 2 scalars

⇒ 2 options:



A pessimistic reaction

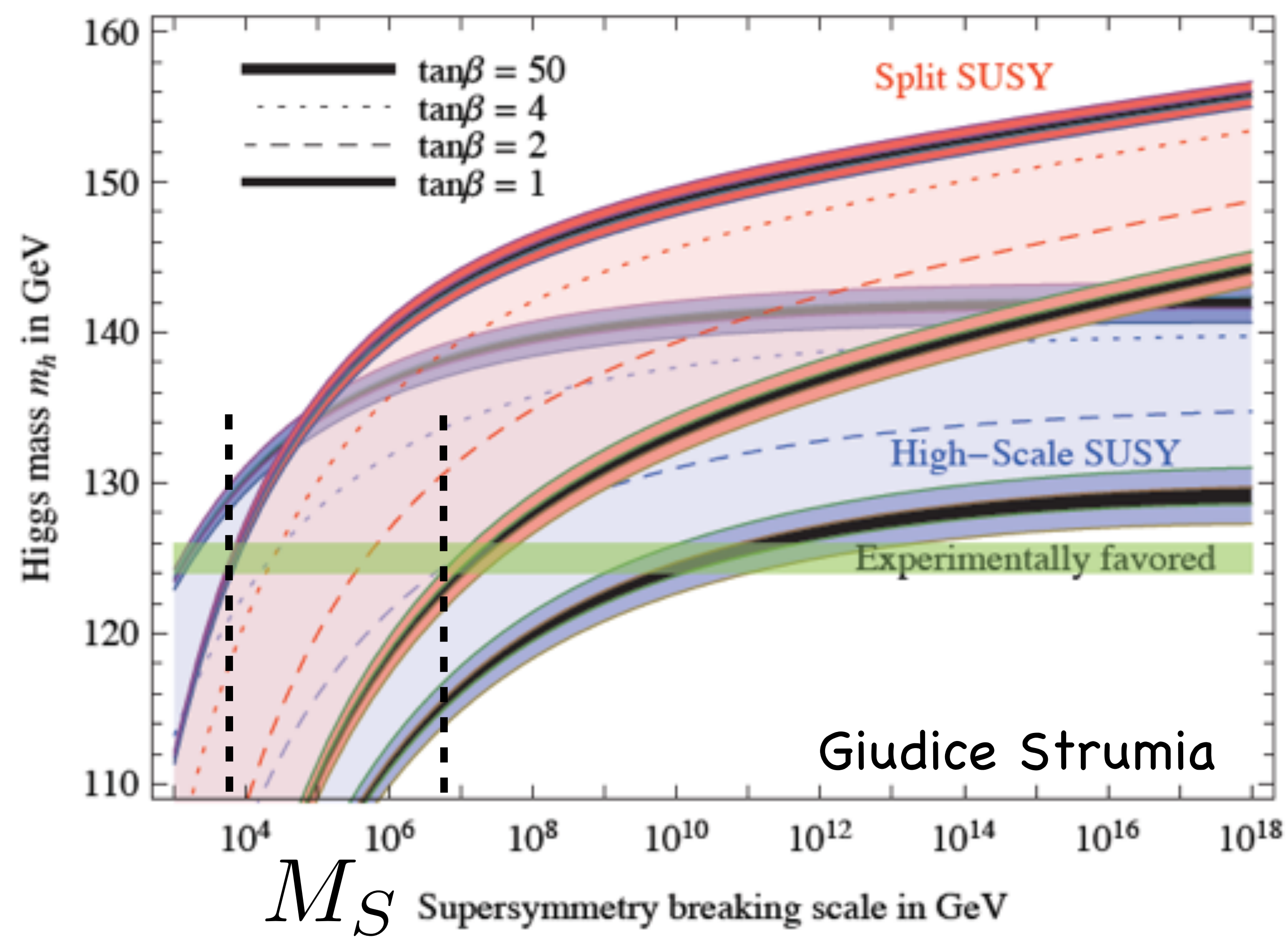
The SUSY scale, M_S, and the Fermi scale, $G_F^{-1/2}$, not so tied together as we thought

$\Rightarrow$ flavour physics, CPV as in SM
$\Rightarrow$ no SUSY at LHC so far

An "extreme" example:

Split-SUSY $\equiv$
SUSY scalars at $\sim M_S$
SUSY fermions at $\sim G_F^{-1/}$

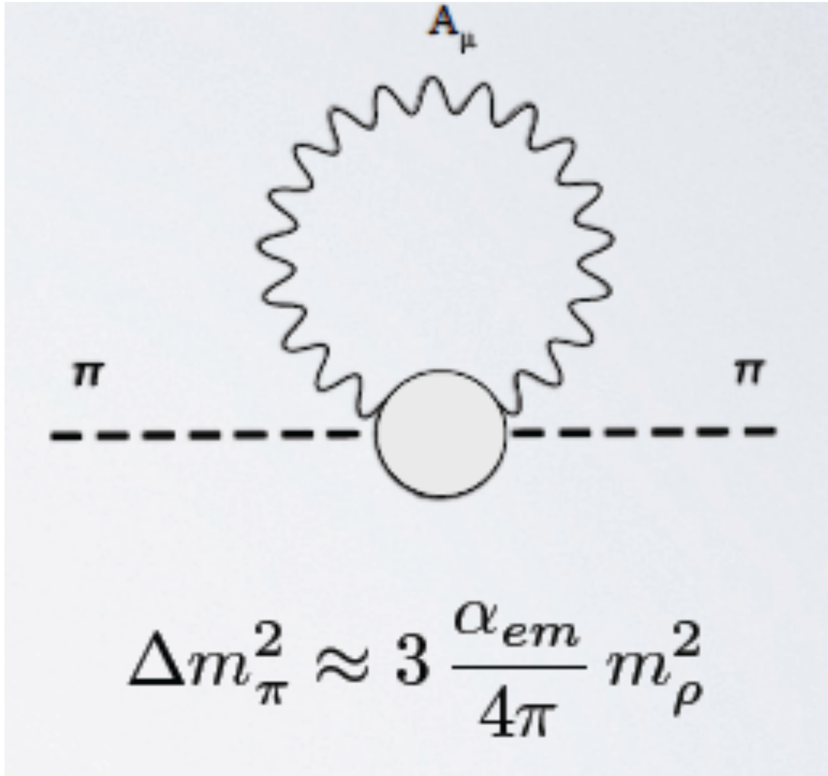
("High-scale" SUSY $\equiv$
all s-particles at M_S)



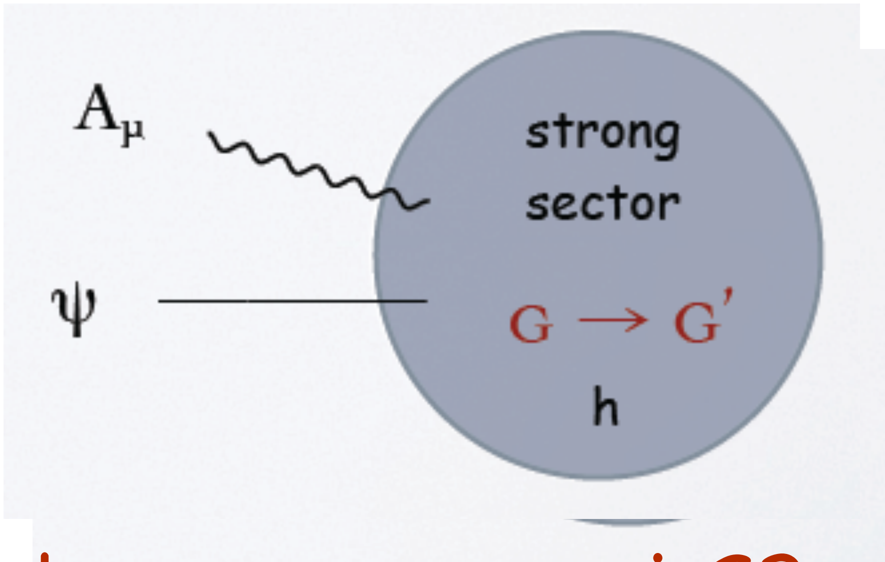
The Higgs boson as a PGB

The pion as an analogy:

$$SU(2)_L \times SU(2)_R \Rightarrow SU(2)_I$$
$$\Delta m_\pi^2 = m_{\pi^+}^2 - m_{\pi^0}^2$$

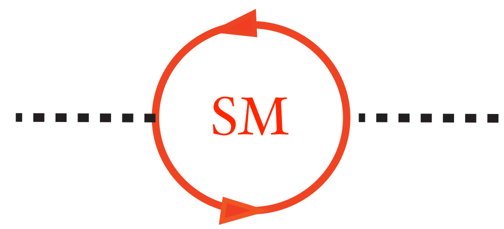
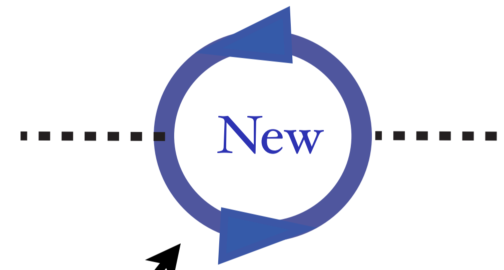


A new strong sector
at the TeV scale

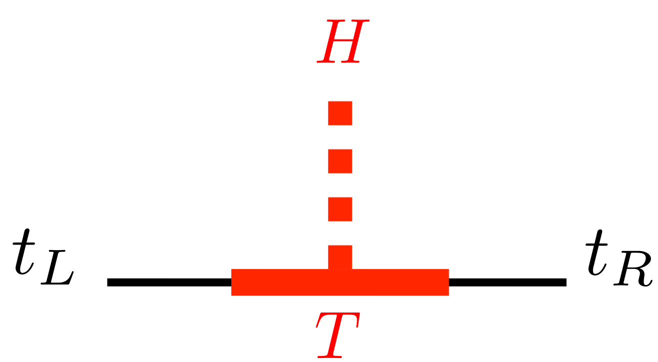


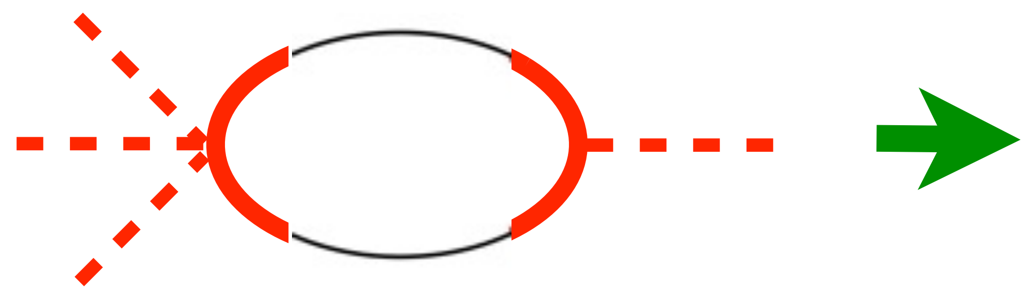
Like the pion in QCD, the Higgs boson as a quasi GB
of a spontaneously broken global symmetry

More in detail

$\delta m_H^2 =$  $+$  ~ 0

Heavy "composite" fermions





Heavy "composite" fermion mass

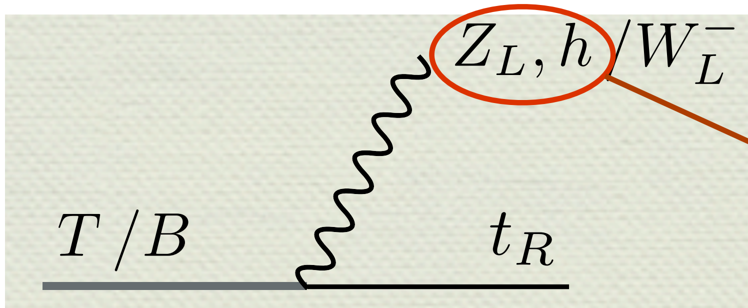
$$m_h \sim m_t \frac{M_T}{\pi f}$$

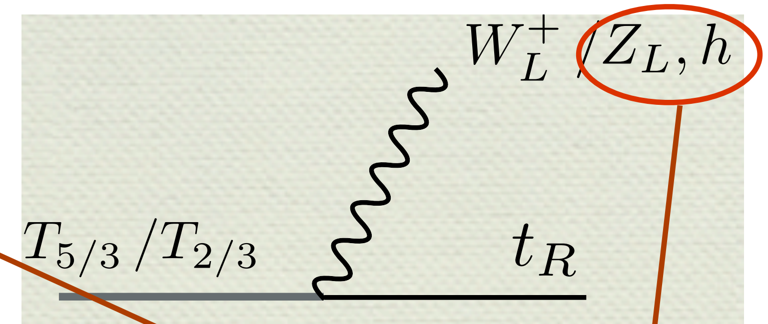
symmetry breaking scale

Most common: $(2,2)_{2/3} = \left[Q = \begin{pmatrix} T \\ B \end{pmatrix} \quad Q' = \begin{pmatrix} T_{5/3} \\ T_{2/3} \end{pmatrix} \right]$

Phenomenology of the "composite" fermions

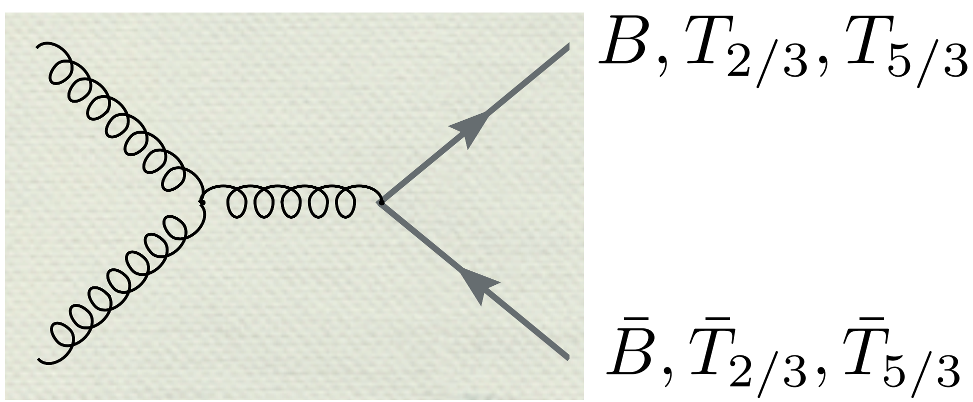
Heavy-light couplings



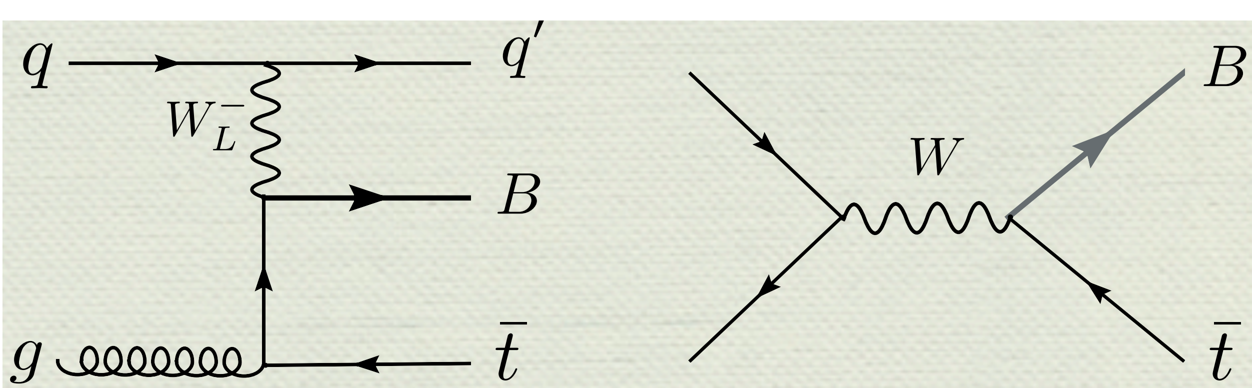


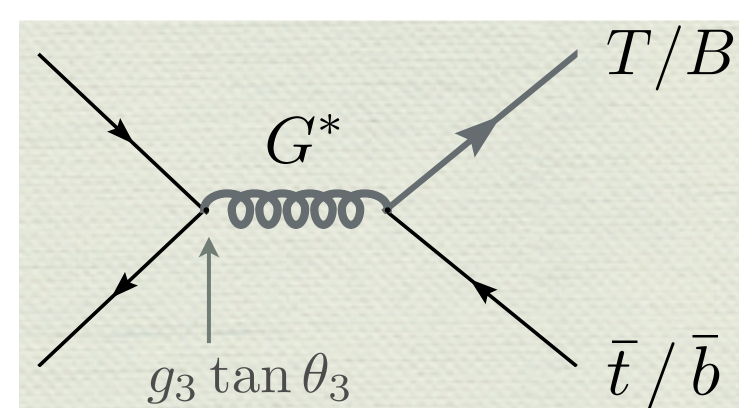
Not like a sequential family

Pair production



Single production





(Some of) the existing limits

Contino, Servant 2008

Pair production

[CMS L=1.14 fb^{-1}] $T\bar{T} \to WbW\bar{b} \to b\bar{b}\, l^+ l^- \not{E}_T$ $m_T > 422\,\text{GeV}$

PAS-EXO-11-050

[CMS L=0.80 fb^{-1}] $T\bar{T} \to WbW\bar{b} \to b\,3j\, l^{\pm} \not{E}_T$ $m_T > 450\,\text{GeV}$

PAS-EXO-11-051

[CMS L=191 pb^{-1}] $T\bar{T} \to tZ\bar{t}Z \to (l^+l^-)l^{\pm}\, jj$ $m_T > 417\,\text{GeV}$

PAS-EXO-11-005

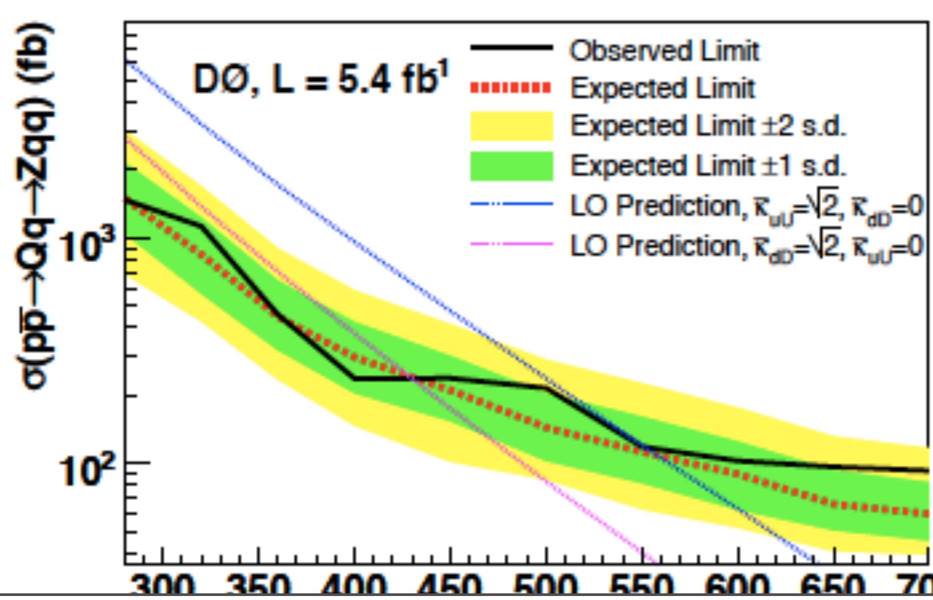
[CMS L=1.14 fb^{-1}] $B\bar{B} \to WtW\bar{t} \to l^{\pm}l^{\pm}\, b\,3j\, \not{E}_T$ $m_B > 495\,\text{GeV}$

PAS-EXO-11-036 $\to lll\, b\, 1j\, \not{E}_T$

Single production

[D0 L=5.4 fb^{-1}] $Q\bar{q} \to Wq\bar{q} \to l^{\pm} jj \not{E}_T$

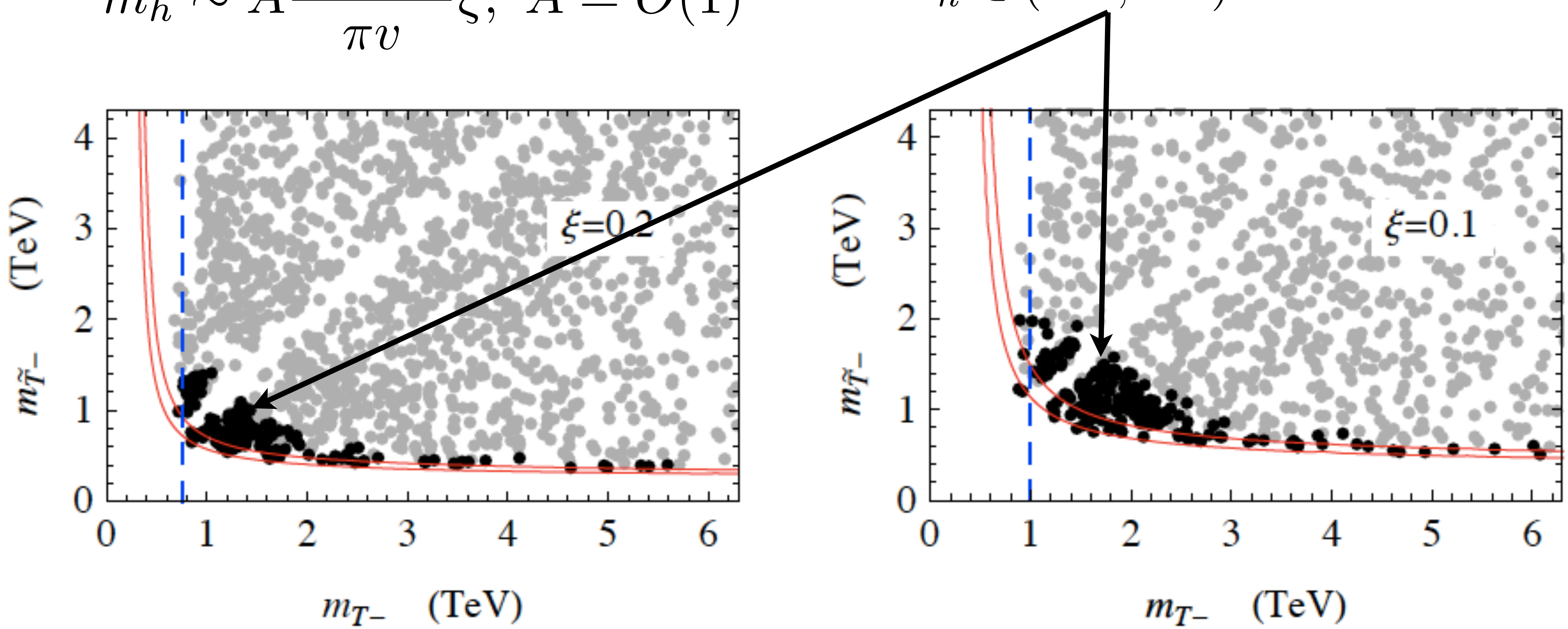
arXiv:1010.1466 $\to Zq\bar{q} \to (l^+l^-)jj$



Relatively light composite fermions preferred by currently "allowed" SM range for m_H

$$m_h \sim A \frac{m_T m_{\tilde{T}}}{\pi v} \xi, \;\; A = O(1)$$

$$m_h \in (115, 130) GeV$$



Matsedonskyi, Panico, Wulzer, 2012

$T, \; \tilde{T}$ lightest fermionic partners of $t_L, \; t_R$

$\xi = \frac{v^2}{f^2}$ made small by fine tuning

Higgs boson branching ratios

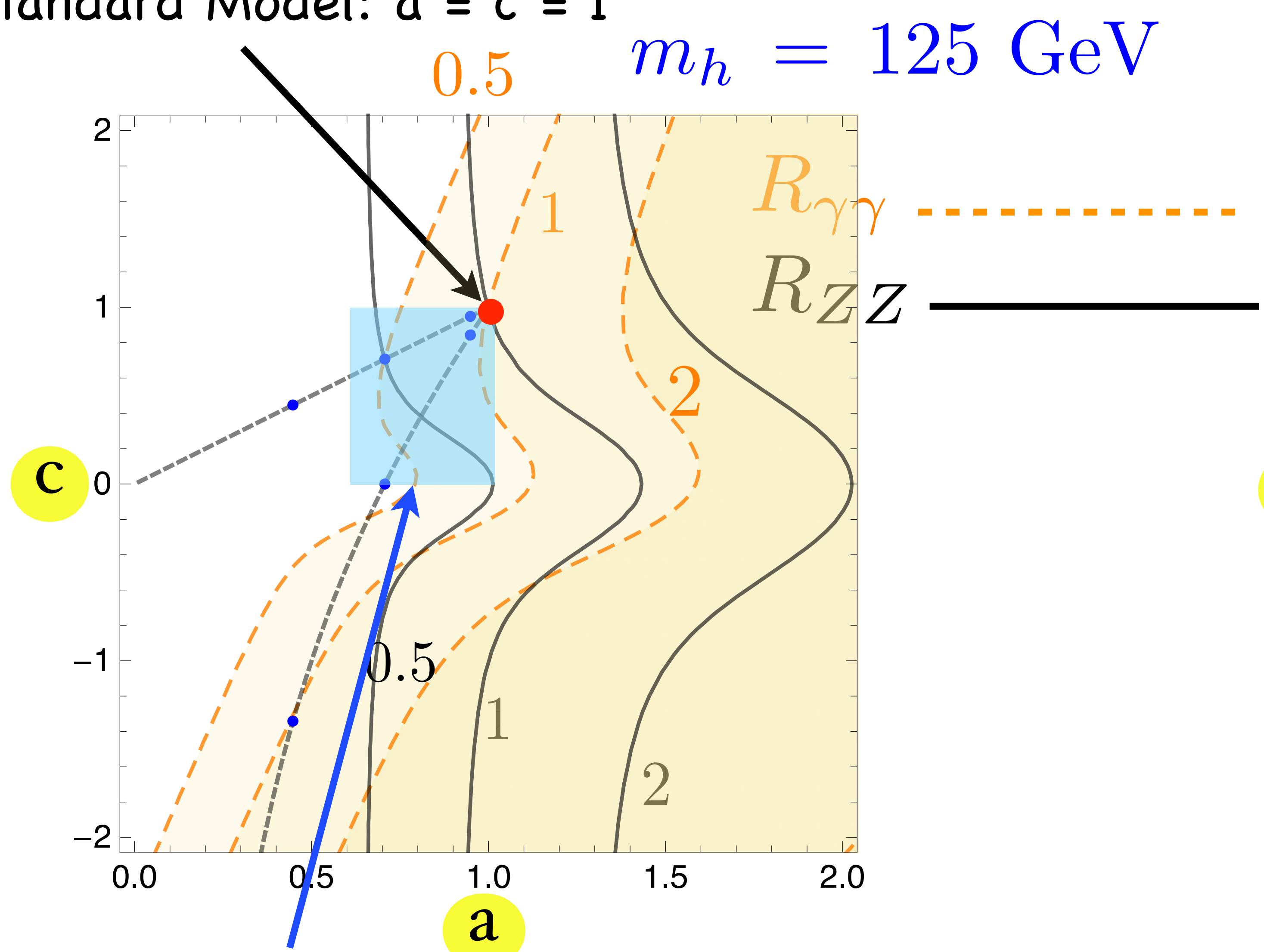
$$\mathcal{L} = \mathcal{L}^{SM}_{gauge} + \frac{v^2}{4} < (D_\mu U)^+ (D_\mu U) > (1 + a\frac{h}{v}) + \frac{v}{\sqrt{2}} \bar{Q}_{Li} U Q_{Ri} (1 + c\frac{h}{v})$$

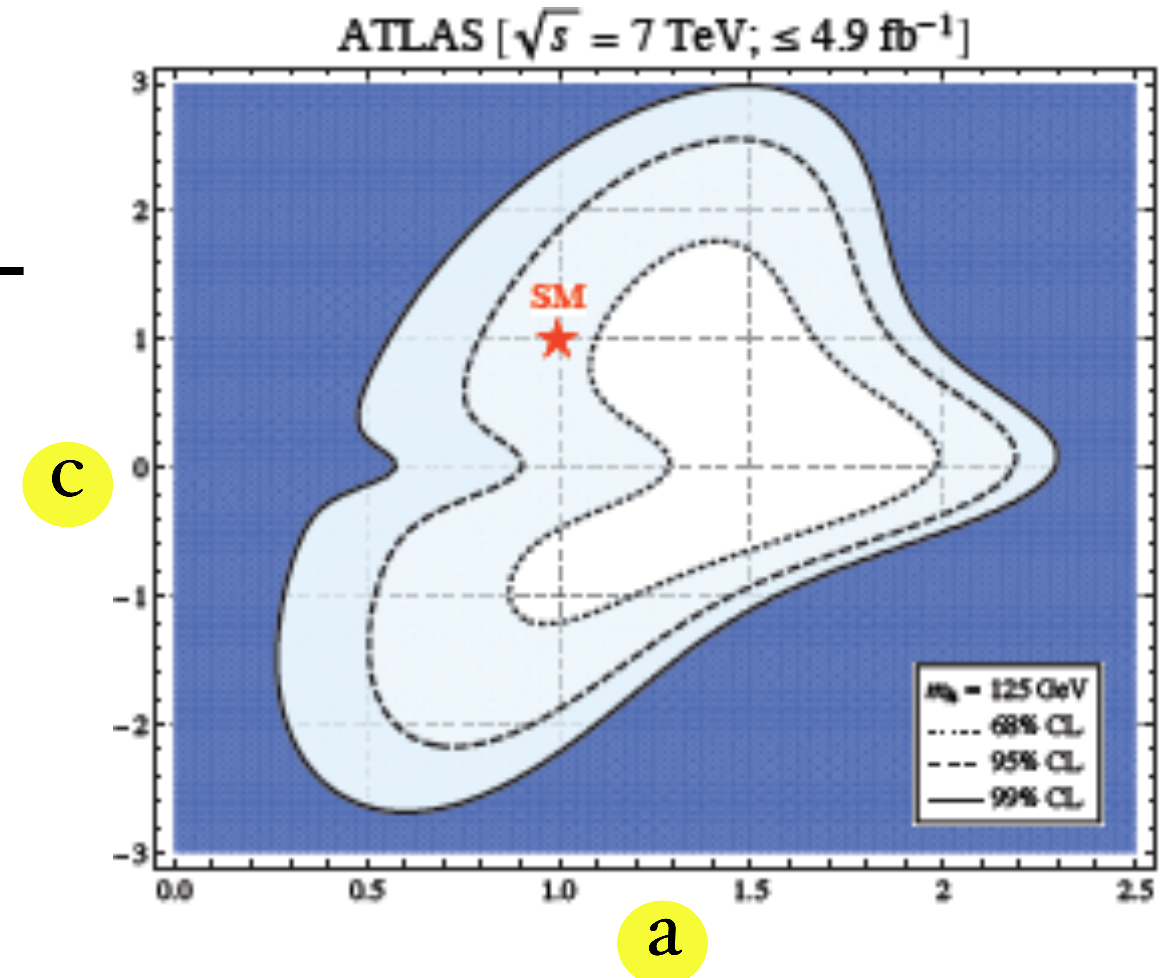
$$U(x) = e^{i\hat{\pi}(x)/v}, \qquad \hat{\pi}(x) = \tau^a \pi^a \qquad Q_{Ri} = \begin{pmatrix} \lambda^u_{ij} u_{Rj} \\ \lambda^d_{ij} d_{Rj} \end{pmatrix}$$

"π" = longitudinal W,Z

Standard Model: a = c = 1

Azatov, Contino, Galloway 2012





blu area preferred by EWPT

Summary

1. What underlies EWSB still unknown, as is the solution of the "little hierarchy" problem

2. To discover the Higgs boson and to know (some of) its properties has such far reaching implications that it pays to be patient a bit more to draw any conclusion

3. To discover (or to exclude natural) supersymmetry important to focus on $m_{\tilde{g}}, m_{\tilde{t}}, m_{\tilde{b}}, m_{\tilde{h}}$

4. Among "Exotica" the searches for the heavy fermions of the Higgs=PGB picture stand up