SUSY Theory After LHC Run 2 (a fairly personal perspective)

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THE STATE OF SUPERSYMMETRY

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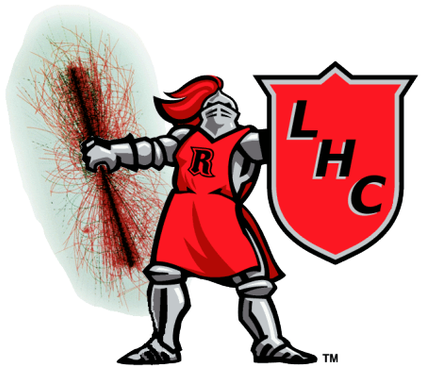

LHCP 2014

SUPERSYMMETRIC OPTIMISM AT LHC-13/14

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IFT MADRID

09.16.14

SUPERSYMMETRIC OPPORTUNITIES IN RUN 2 @ ATLAS

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The Status of Supersymmetric (Un)naturalness

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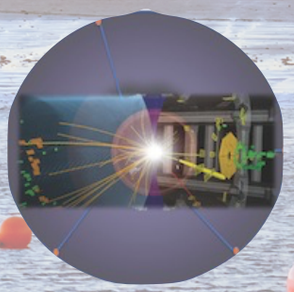
Experimental Challenges for the LHC Run II



SUSY Theory Status
& Recent Developments

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The State of SUSY

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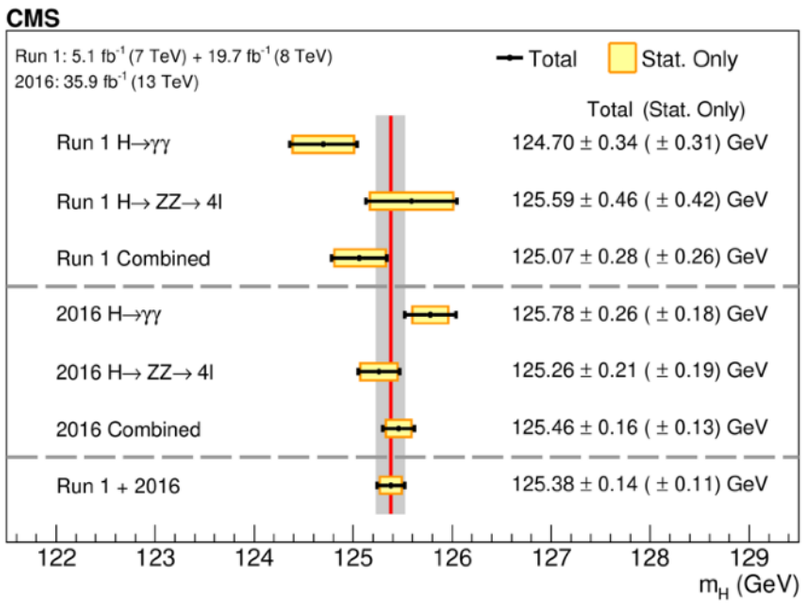
The Naturalness Strategy

Param	UV sensitivity	Natural if	NP	Scale	Natural?
"m_e"	$e^2\Lambda$	$\Lambda \lesssim$ 5 MeV	Positron	511 keV	✓
$m_{\pi^\pm}^2 - m_{\pi^0}^2$	$\frac{3\alpha}{4\pi}\Lambda^2$	$\Lambda \lesssim$ 850 MeV	Rho	770 MeV	✓
m_{K_L}-m_{K_S}	$\frac{s_c^2 f_K^2 m_{K_L^0}}{24\pi^2 v^4}\Lambda^2$	$\Lambda \lesssim$ 2 GeV	Charm	1.2 GeV	✓
m_H^2	$-\frac{6y_t^2}{16\pi^2}\Lambda^2$	$\Lambda \lesssim$ 500 GeV	?	?	?

Naturalness / "hierarchy problem" is a strategy for finding new physics

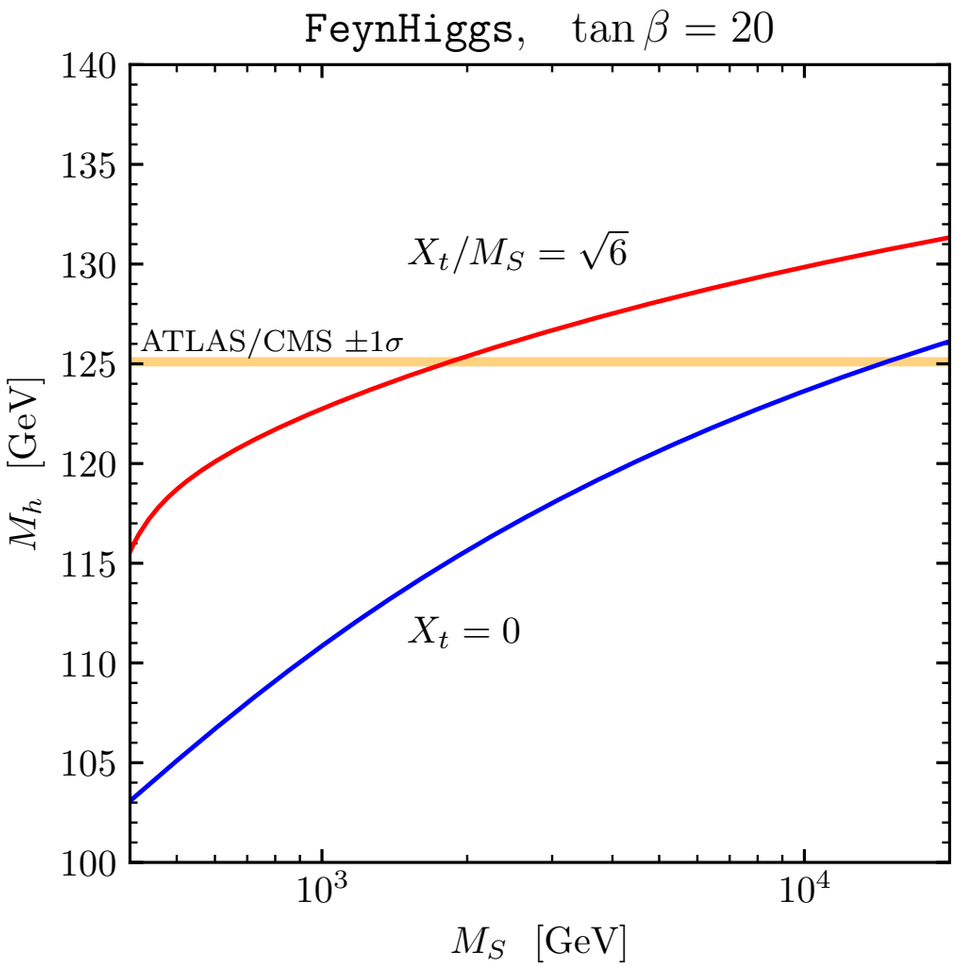
What do we know?

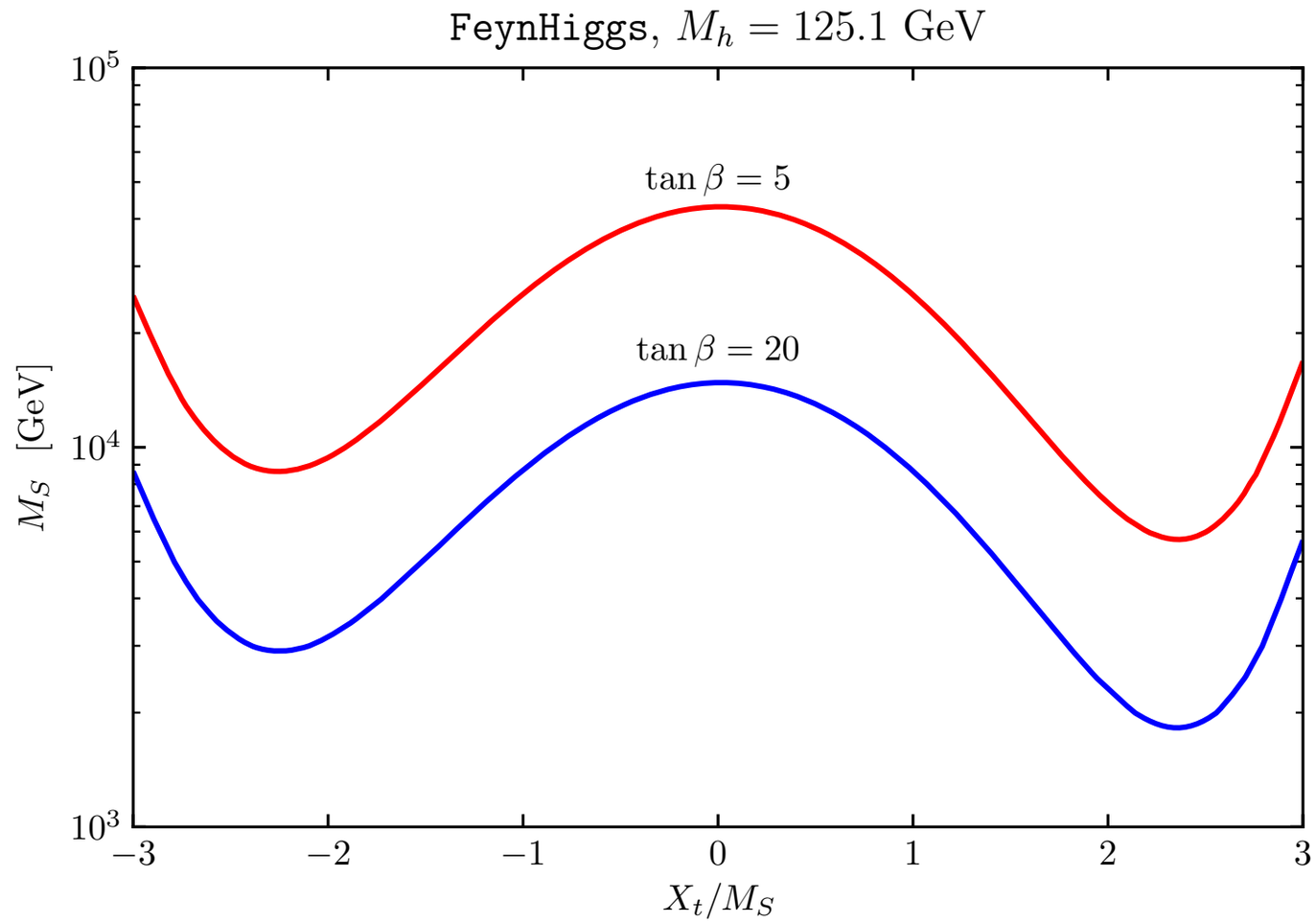
- Pre-LHC priors: naturalness, unification, DM
- Higgs mass: m_h = 125 GeV
- SM-like Higgs boson @ ~10% level
- No direct evidence for sparticles thus far
- No generic new flavor / CP violation
- Possible hints of NP in muon g-2, LFUV?



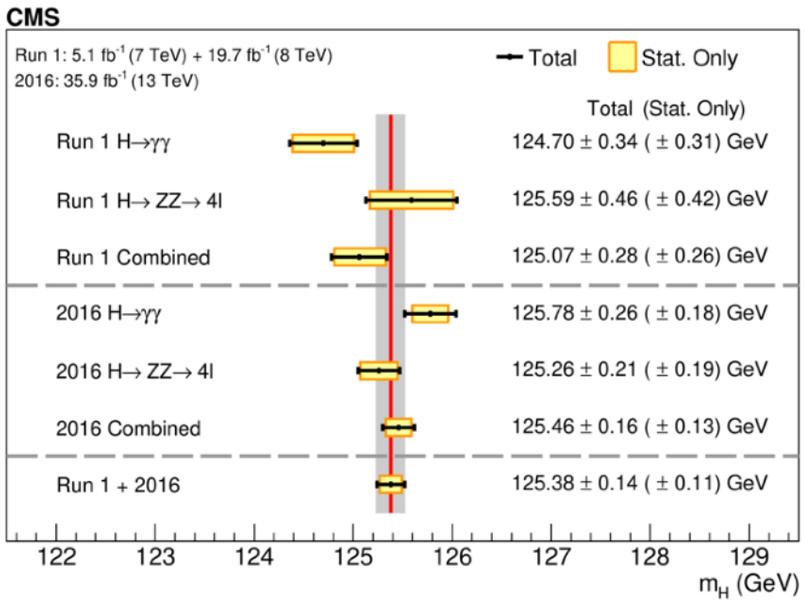
The Higgs Mass

In MSSM: tension with naturalness,
but consistent w/ current limits.





[Slavich, Heinemeyer, et al. 2012.15629]

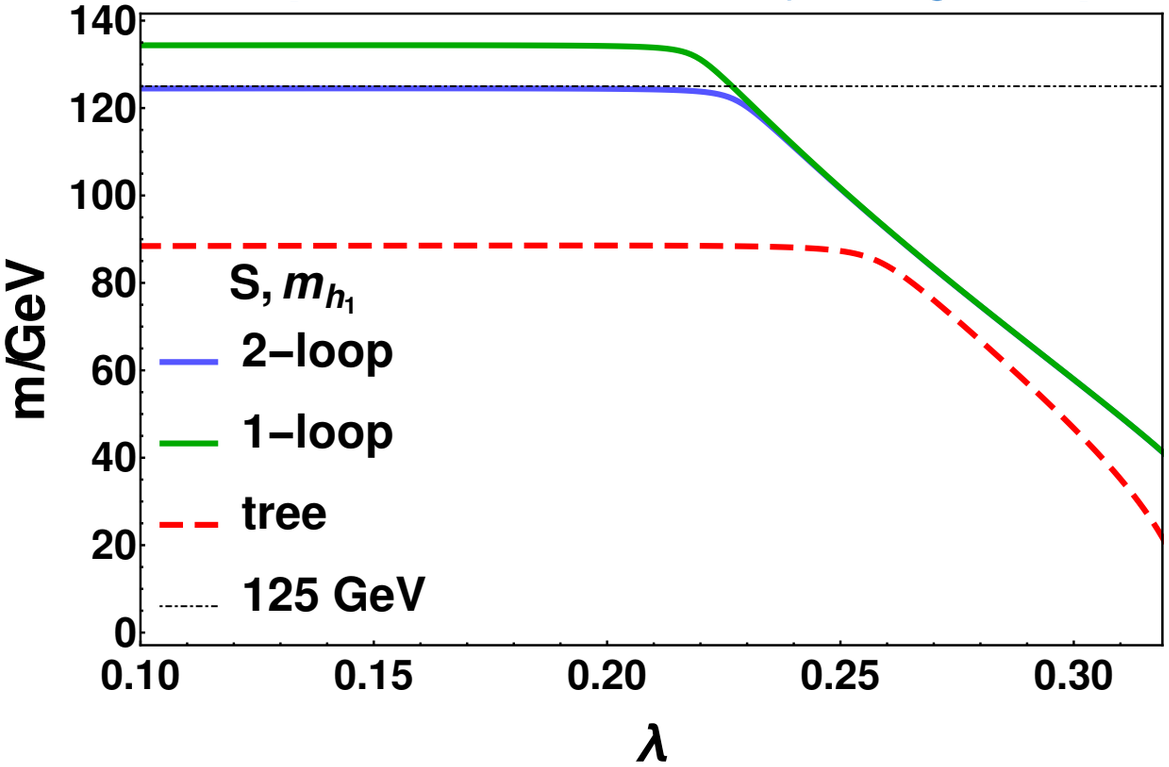


The Higgs Mass

Preserve naturalness by going beyond MSSM → Higgs properties

F-term (new singlet)

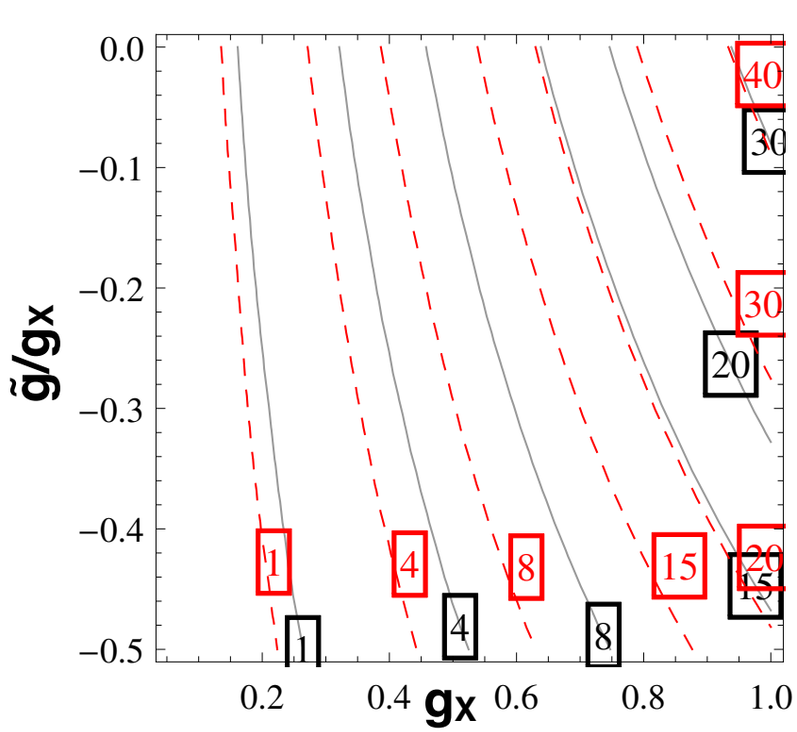
[Drechsel, Galeta, Heinemeyer, Weiglein '16]



Finite decoupling; Higgs coupling measurements constraining (or alignment → light states).

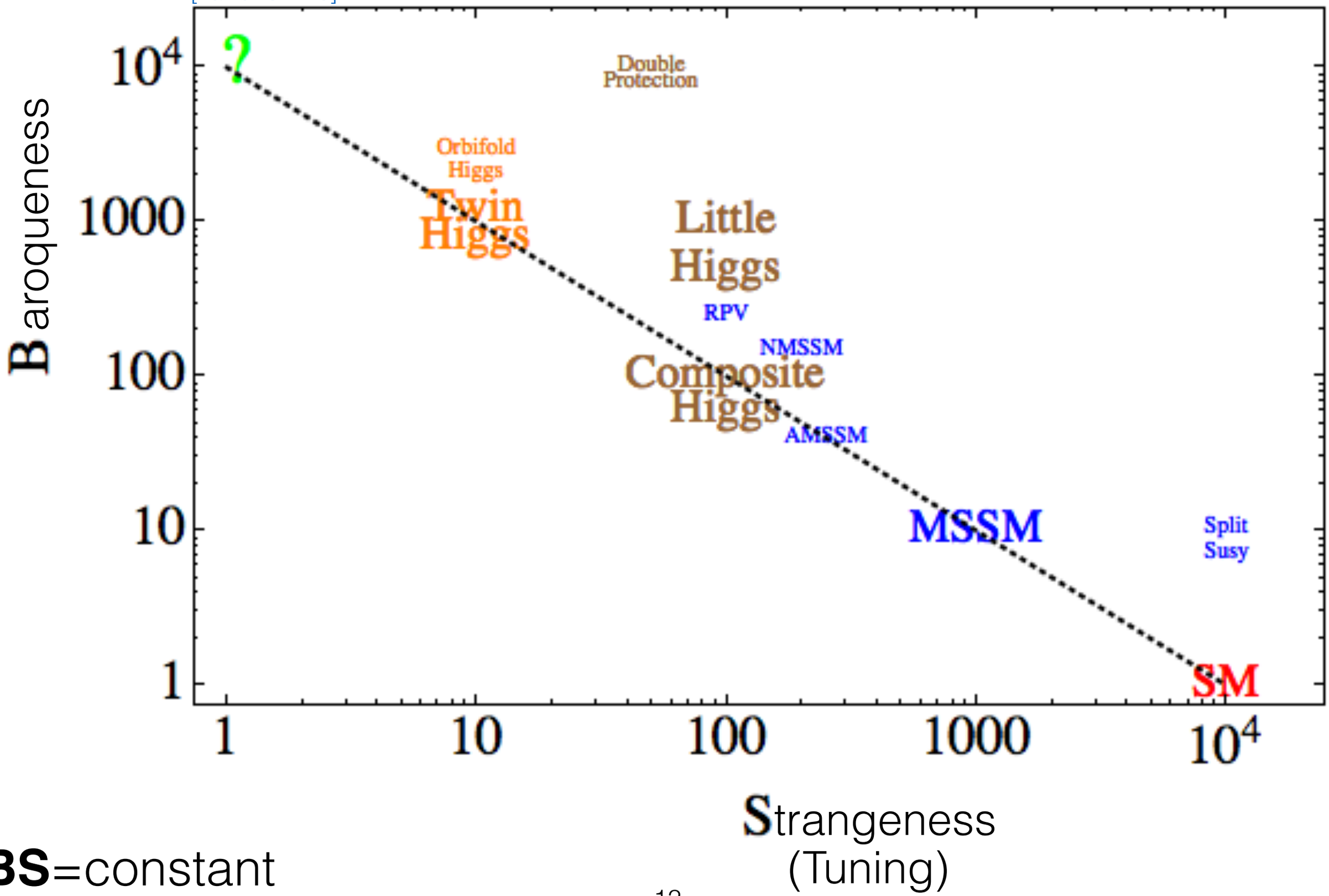
D-term (new U(1))

[Staub '16]



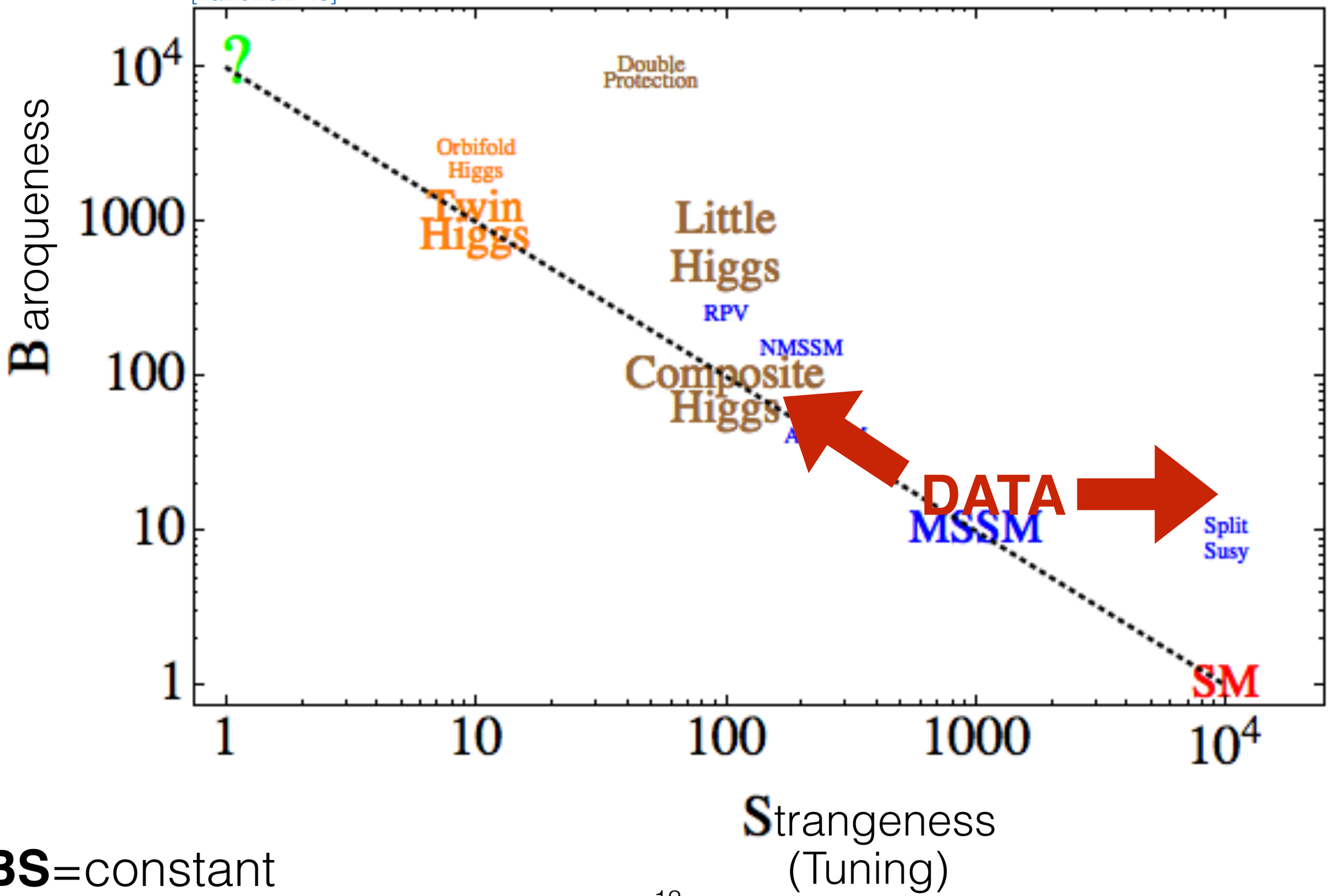
Higgs couplings; heavy vector bosons at LHC13/14

[Falkowski ‘15]



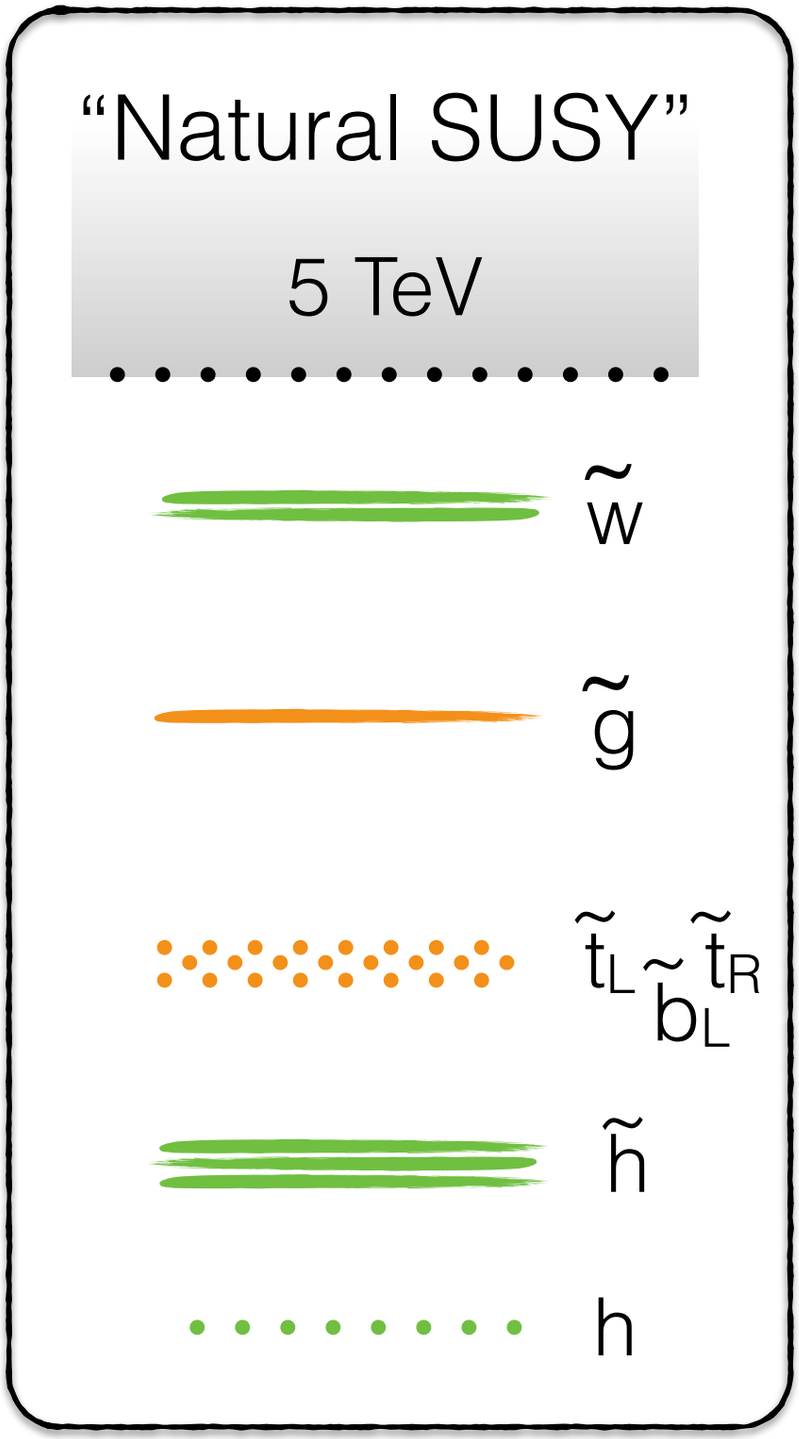
BS=constant

[Falkowski '15]



BS=constant

Embracing Naturalness



Assume Higgs mass given by non-decoupling effects, superpartner mass hierarchy inversely proportional to contribution to Higgs potential

$$\delta m_h^2 \propto \mu^2 \qquad \text{(higgsinos)}$$

$$m_h^2 \sim \frac{3y_t^2}{4\pi^2}\tilde{m}^2 \log(\Lambda^2/\tilde{m}^2)$$

(everything else)

Quantify tuning (as you like)

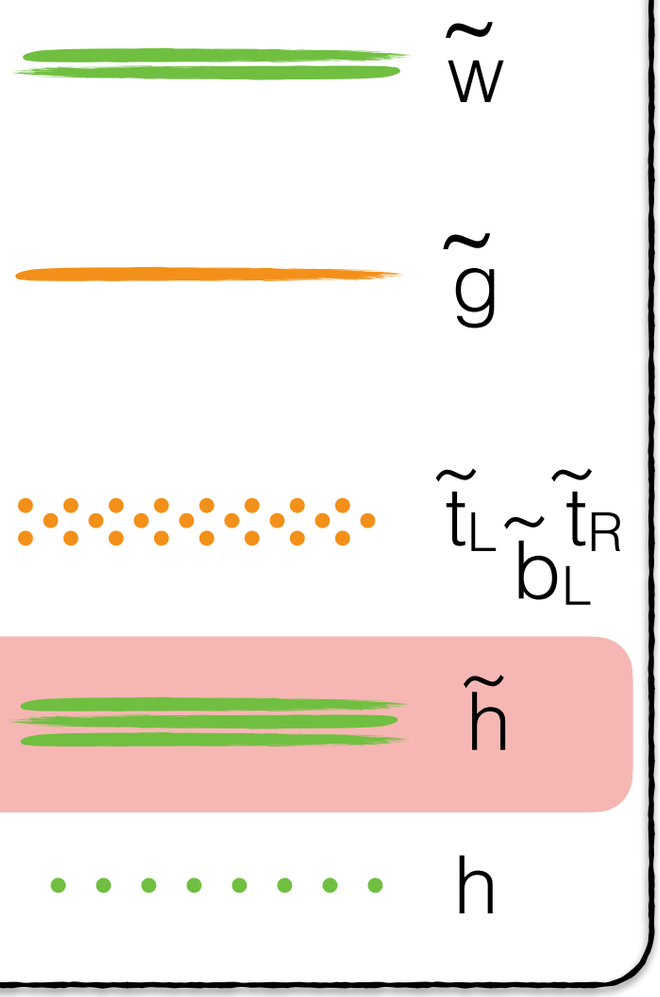
$$\Delta \equiv \frac{2\delta m_H^2}{m_h^2}$$

[Dimopoulos, Giudice '95; Cohen, Kaplan, Nelson '96; Papucci, Ruderman, Weiler '11; Brust, Katz, Lawrence, Sundrum '11]

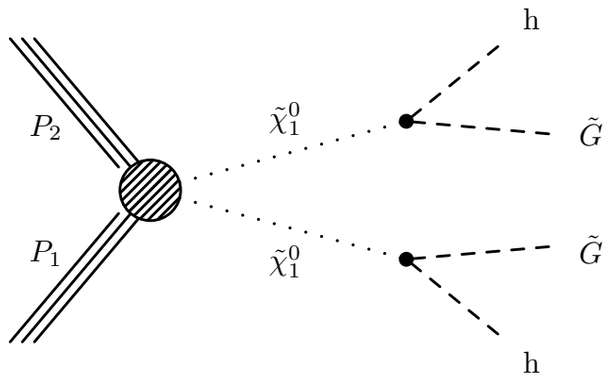
Where we are now: Higgsinos

"Natural SUSY"

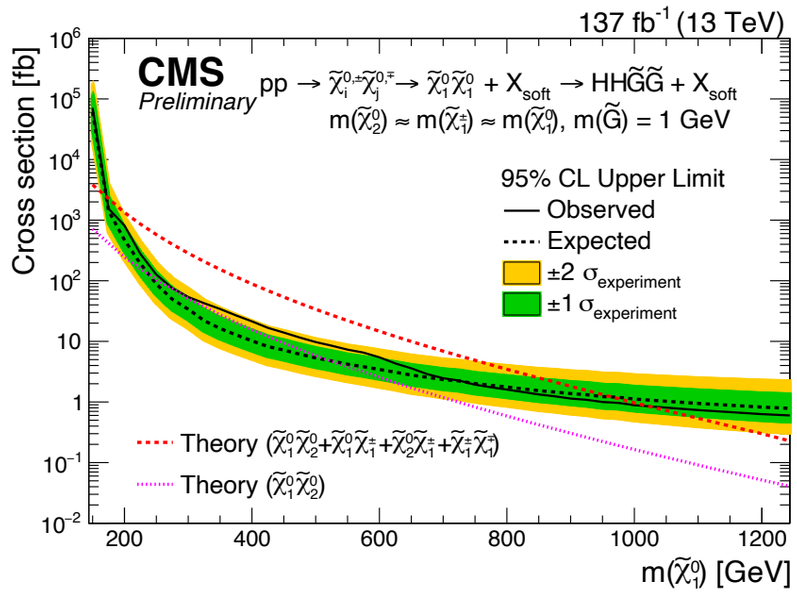
5 TeV



Lots of searches…

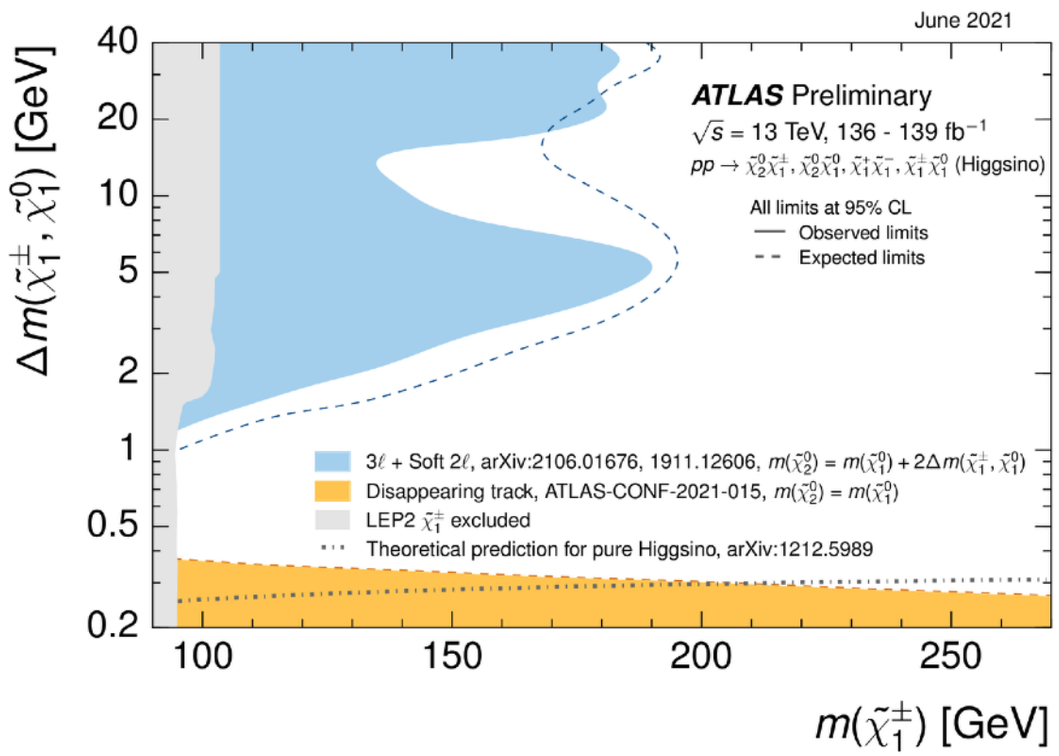


See talk by Shah



…and finally "irreducible" limits

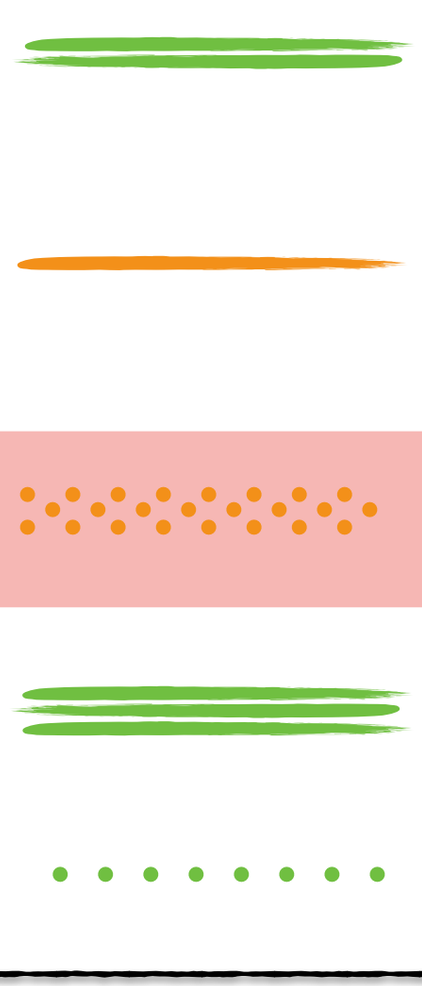
Chargino-neutralino splitting in pure higgsino multiplet: 355 MeV [Thomas, Wells '98]



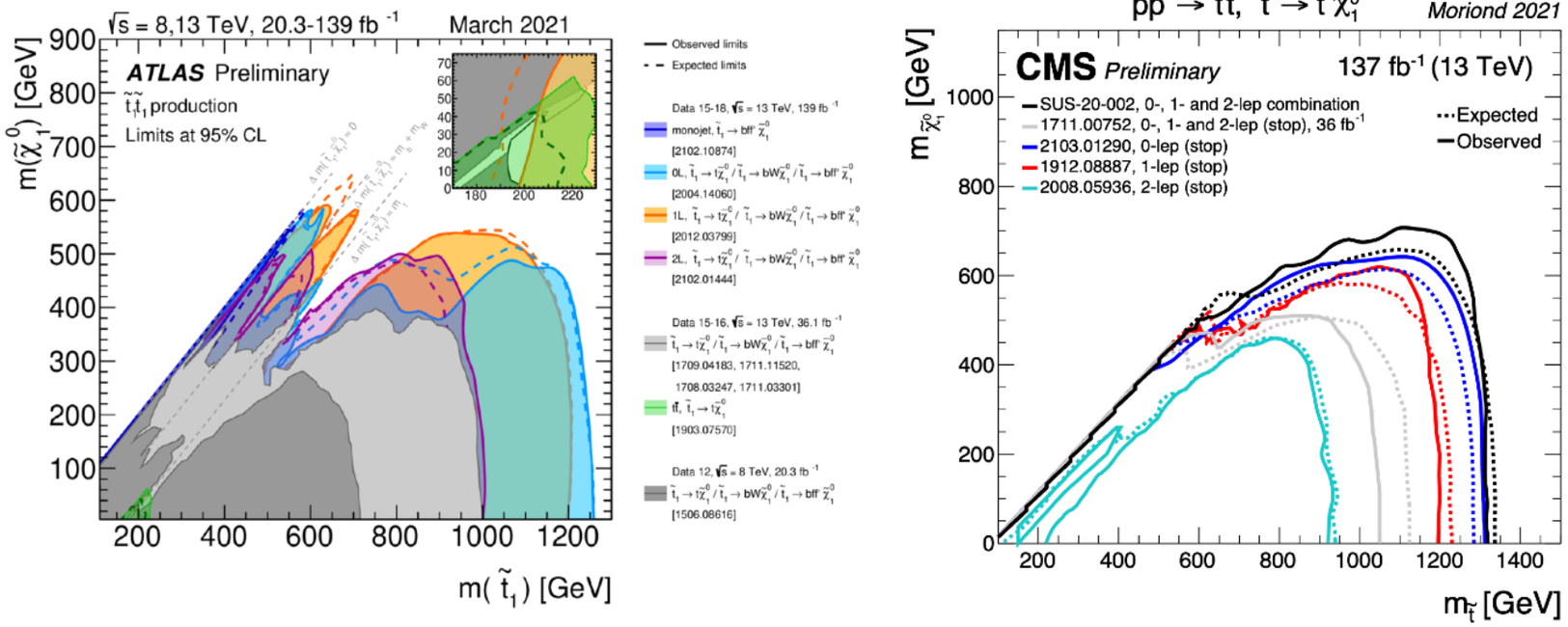
Where we are now: Stops

"Natural SUSY"

5 TeV



$$\delta m_H^2 \sim -\frac{3}{8\pi^2} y_t^2 (m_{Q_3}^2 + m_{u_3}^2 + |A_t|^2) \log(\Lambda/\mathrm{TeV})$$



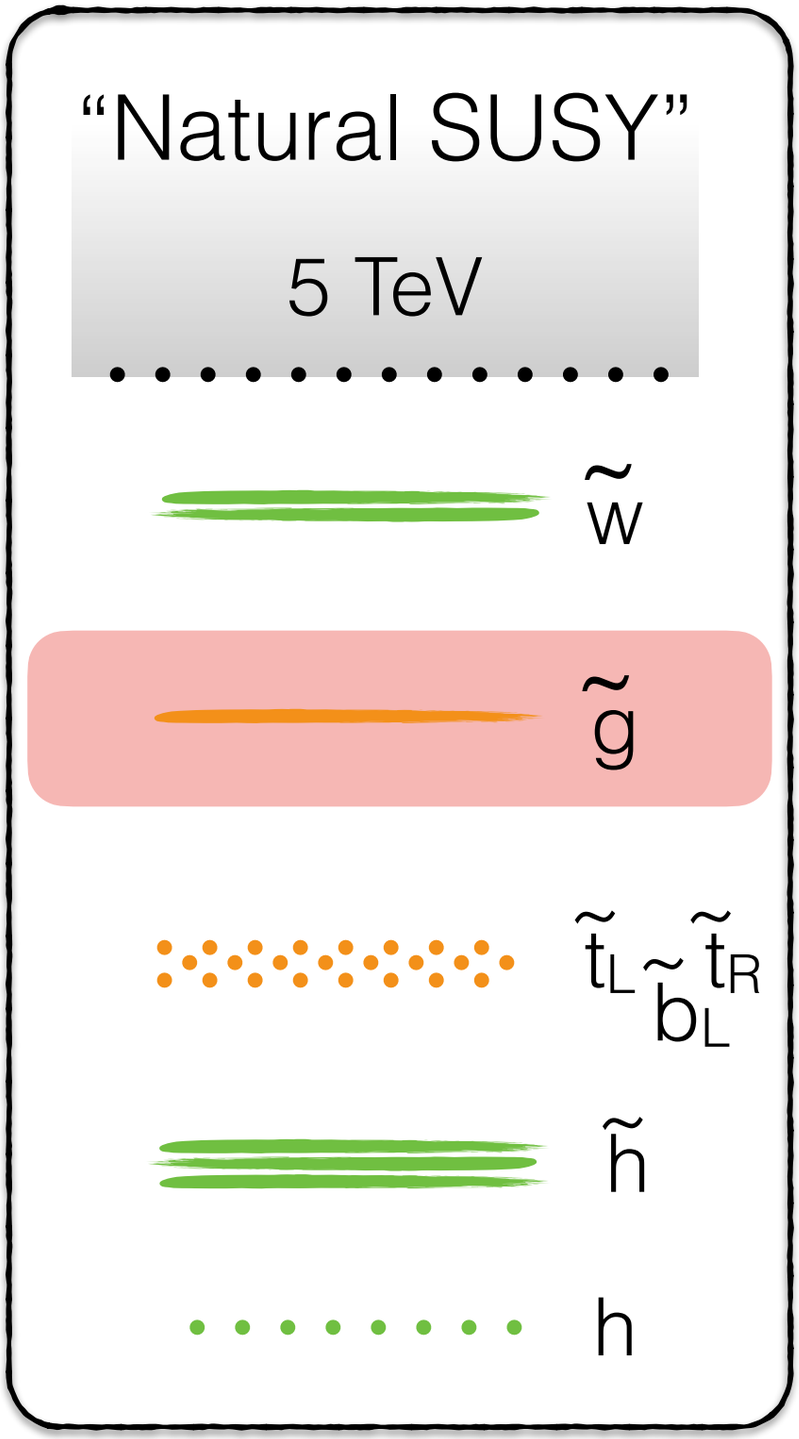
Generic limit > 1.3 TeV
→ **Δ~70 (1-2% tuning)**
(2 stops, Λ = 100 TeV)

Compressed limit
> (600 GeV, 500 GeV)
→ **Δ~32 (3% tuning)**

Where we are now: Gluinos

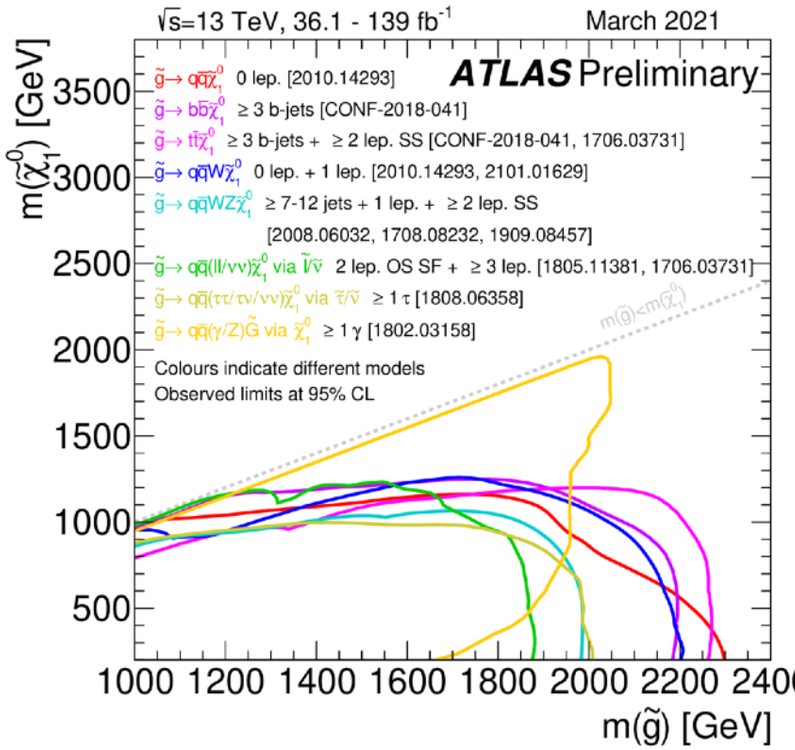
"Natural SUSY"

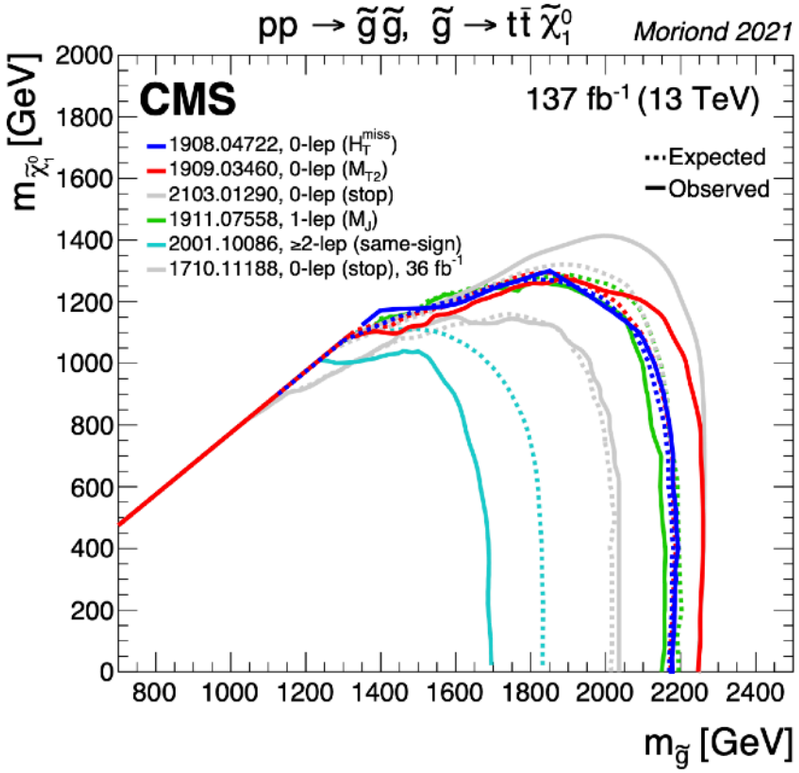
5 TeV



$$\delta m_H^2 \sim -\frac{\alpha_s y_t^2}{\pi^3}|M_3|^2 \log^2(\Lambda/\mathrm{TeV})$$

Leads to $\text{“}m_{\tilde{t}} \gtrsim M_3/2\text{”}$





Generic limit > 2.2 TeV

→ **Δ~35 (3% tuning)**

(Λ = 100 TeV)

Compressed limit

> (1.3 TeV, 1.3 TeV)

→ **Δ~220 (0.5% tuning)**

Fine Print

Fine-tuning estimates are leading-logarithm

[Casas, Moreno, Robles, Rolbieki, Zaldivar '14]
[Buckley, Monteux, Shih '17]

5. Pole masses (1G,2G=10TeV)

5. Pole masses (1G,2G=5TeV)

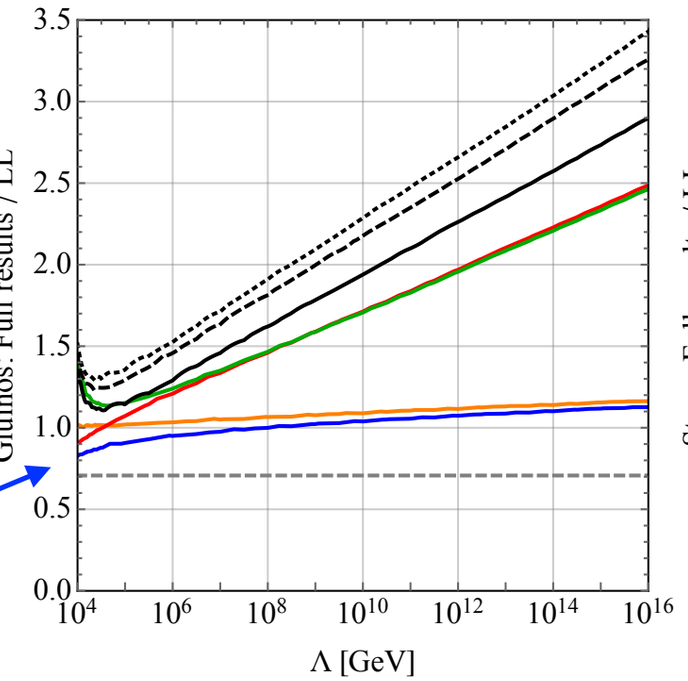
5. Pole masses (1G,2G=3G)

4. Two-loop thresholds

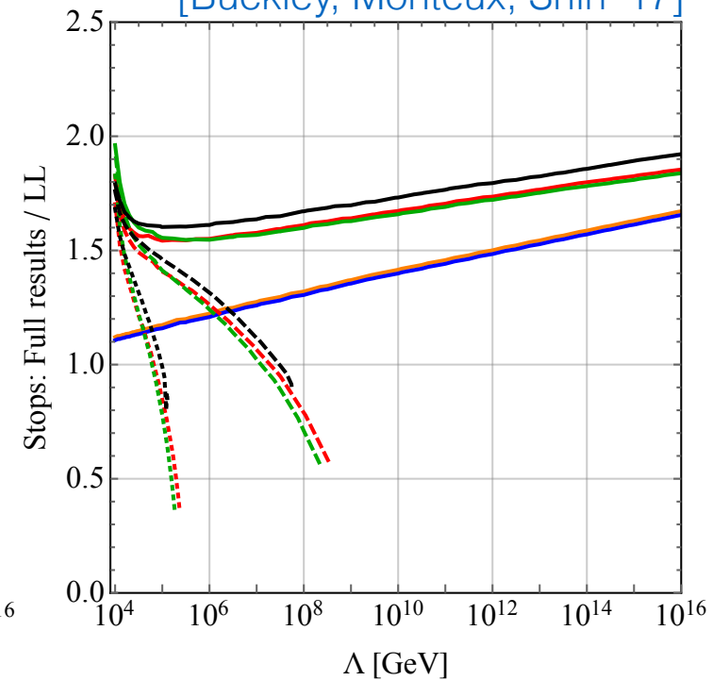
1. Resummed one-loop RGE

3. IR Running masses

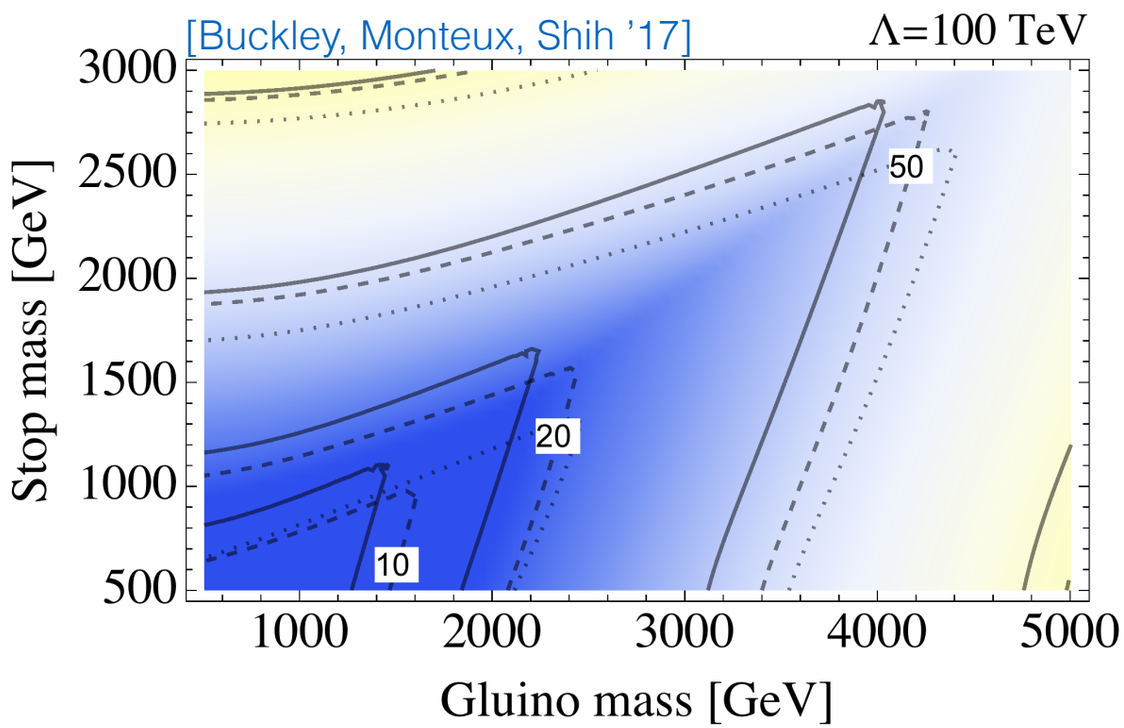
2. Resummed two-loop RGE



[Buckley, Monteux, Shih '17]



[Buckley, Monteux, Shih '17]



Accounting for all these effects gives factor-of-2 improvement. UV correlations could give further improvement

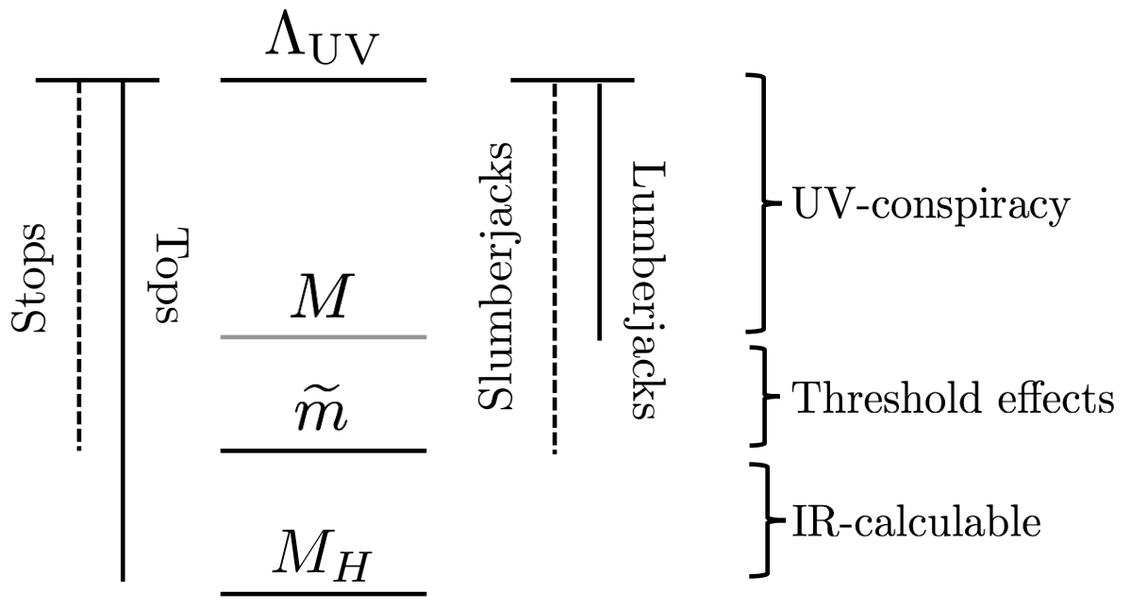
Of course, fine-tuning not quantitative

Removing the Logs

Logarithms from the UV play a key role in tuning (~factor of 5 for stops)
Situation more favorable if only IR contributions considered
(e.g. [Baer, Barger, Mickelson 1309.2984] et seq.)

See talk by Baer

A simple model: [Cohen, NC, Koren, McCullough, Tooby-Smith 2002.12630]
(see also [Dermisek 1606.09031]). Sharp prediction: **more stops.**

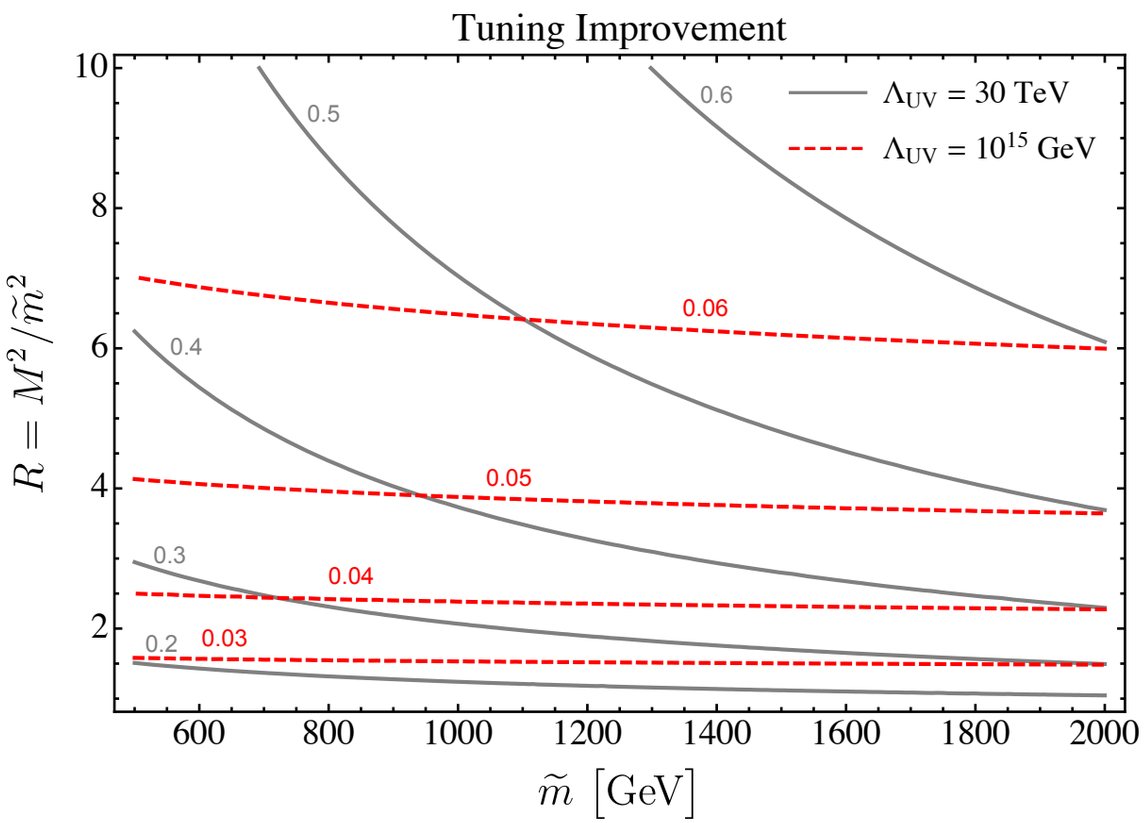


$$\boldsymbol{W_\lambda} = \lambda_t\, \boldsymbol{H_u}\, \boldsymbol{Q}\, \boldsymbol{U^c} + \lambda_t\, \boldsymbol{H_u}\, \boldsymbol{Q'}\, \boldsymbol{U'^c}$$

$$\boldsymbol{W_M} = M\left(\boldsymbol{Q'}\,\overline{\boldsymbol{Q}}' + \boldsymbol{U'^c}\,\overline{\boldsymbol{U}}'^{\boldsymbol{c}}\right)$$

$$V_{\rm Soft} \simeq \widetilde{m}^2\left(\left|\widetilde{Q}\right|^2 + \left|\widetilde{U}^c\right|^2 - \left|\widetilde{Q}'\right|^2 - \left|\widetilde{U}'^c\right|^2\right)$$

$$\delta M_{H_u}^2 \simeq -\frac{3\,\lambda_t^2}{8\pi^2}\,\widetilde{m}^2\left[\frac{3}{2} + \log\left(\frac{M^2}{\widetilde{m}^2}\right)\right]$$



Breaking the Spectrum

Bring in new charged states at the TeV scale.

Supersoft Dirac gauginos

[Fox, Nelson, Weiner '02]

$$m_{\tilde{t}} \neq M_3/2$$

SUSY broken by a D-term

$$\mathcal{D} \equiv \frac{1}{8}\langle D^2\bar{D}^2 V'\rangle > 0$$

$$W \supset \frac{W'_\alpha W_j^\alpha A_j}{M} \rightarrow \mathcal{L} \supset \frac{\mathcal{D}}{M}\lambda\tilde{a}$$

Scalar masses radiative

$$\tilde{m}_i^2 \sim \frac{\alpha_i}{\pi} m_D^2 \log\left(m_a^2/m_D^2\right)$$

Minimally $m_a \sim 2m_D$

so $m_{\tilde{t}} \sim M_3/5$

Decouple gluinos! Predict new adjoint scalars

Global symmetry for Higgsinos

[Birkedal, Chacko, Gaillard '04; Chankowski, Falkowski, Pokorski, Wagner '04]

$$m_H^2 \neq \mu^2$$

SUSY Higgs is a pNGB associated w/ spontaneously broken global symmetry

$$\mathcal{G} \rightarrow \mathcal{H}$$

μ term an invariant of

$$\mathcal{G}$$

doesn't contribute to Higgs potential

No problem w/ higgsinos @ TeV, but predict new states associated w/ global symmetry.

No local 4D SUSY

[Antoniadis, Dimopoulos, Pomarol, Quiros '98; Delgado, Pomarol, Quiros '98]

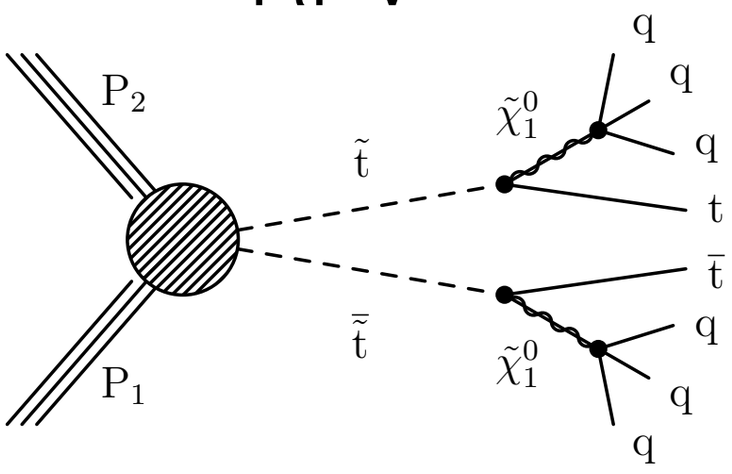
- E.g. 5D SUSY on S_1/Z_2, SUSY broken by BCs.
- Spectrum finite, no large logs. (Often) dirac gauginos.
- Geography/localization can distinguish generations.
- Zero modes not supersymmetric ("hard breaking" for higgsino).
- Scale is 1/R ~ 5 TeV
- Analogous models in 4D

Look for the new stuff. Often large cross sections or resonantly produced.

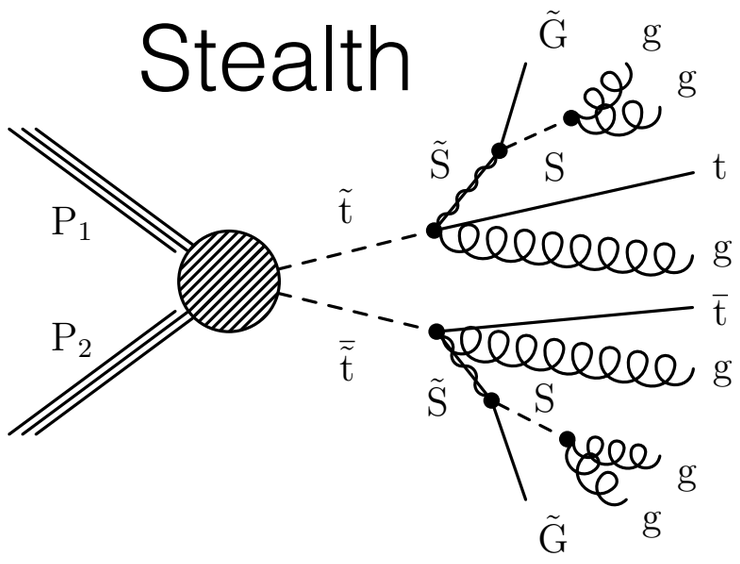
Breaking the Signal

Erase MET by RPV *or* stealth (new sector with small non-SUSY splitting, [Fan, Reece, Ruderman '11; Fan, Krall, Pinner, Reece, Ruderman '15])

RPV



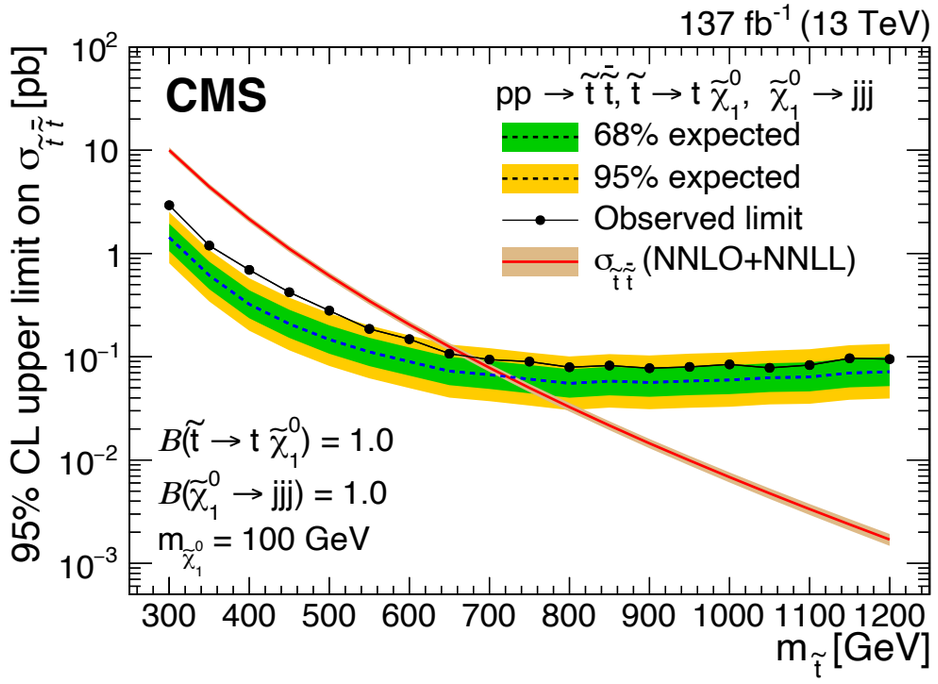
Stealth

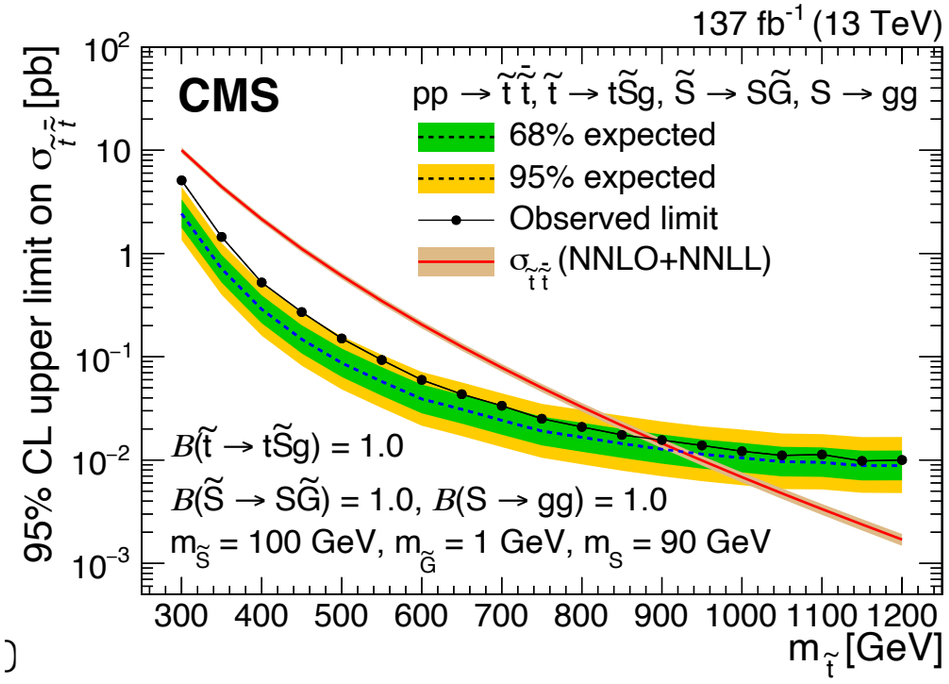


Trade MET for additional soft event activity, migrate signals to exotics; *sometimes you win, sometimes you lose*.

See talk by Dreiner

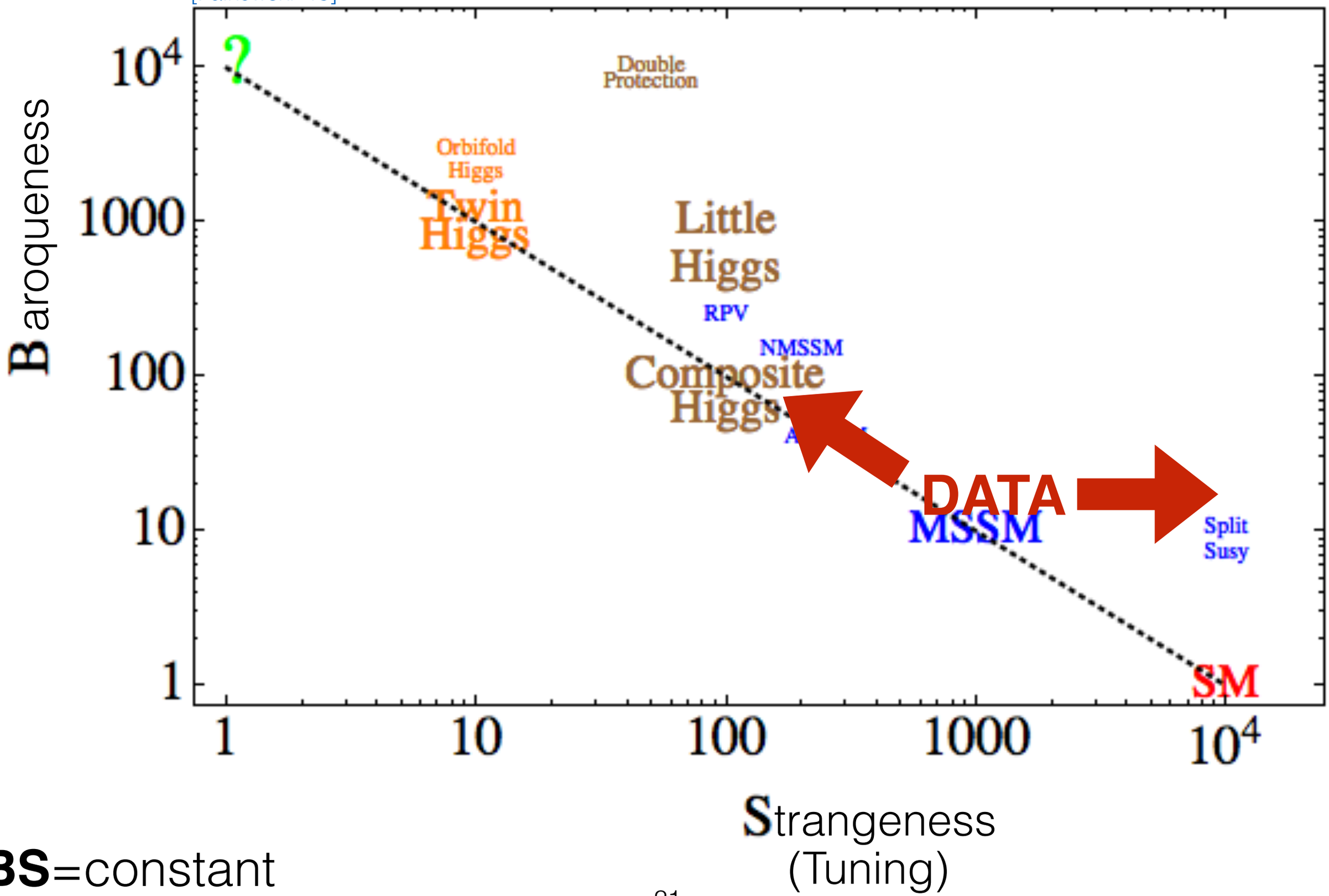
RPV





Stealth

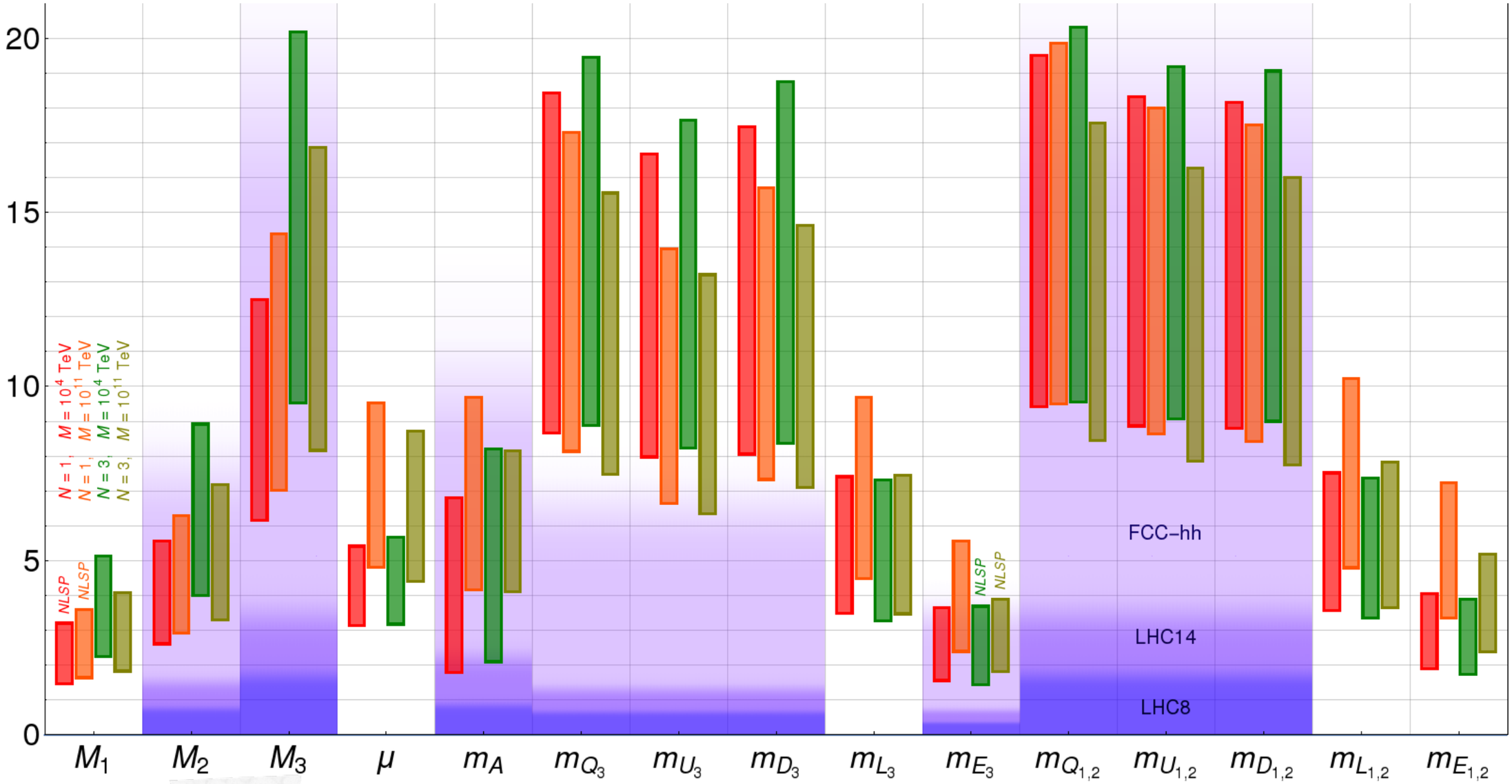
[Falkowski '15]



BS=constant

Simple Frameworks

e.g. minimal gauge mediation

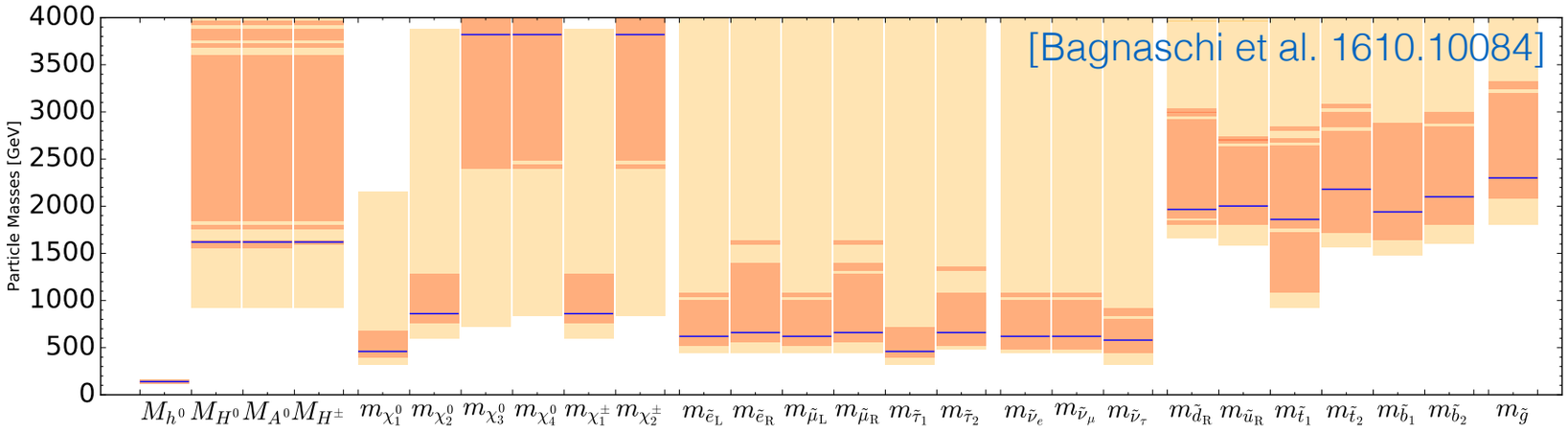


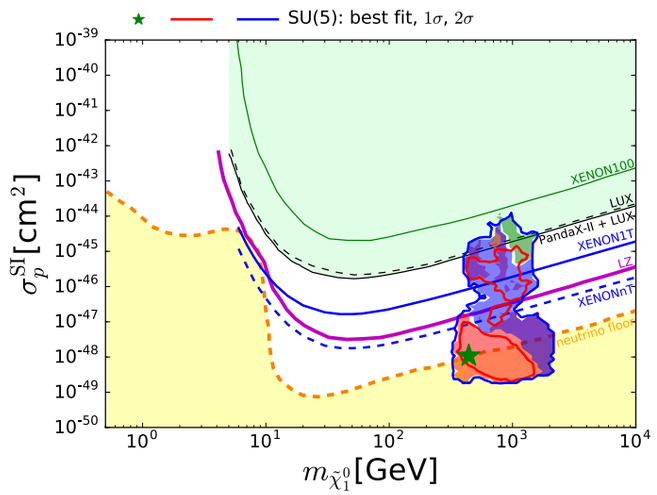
See talk by Shah

[Pardo Vega, Villadoro 1504.05200]

Simple Frameworks

SUSY SU(5) GUT

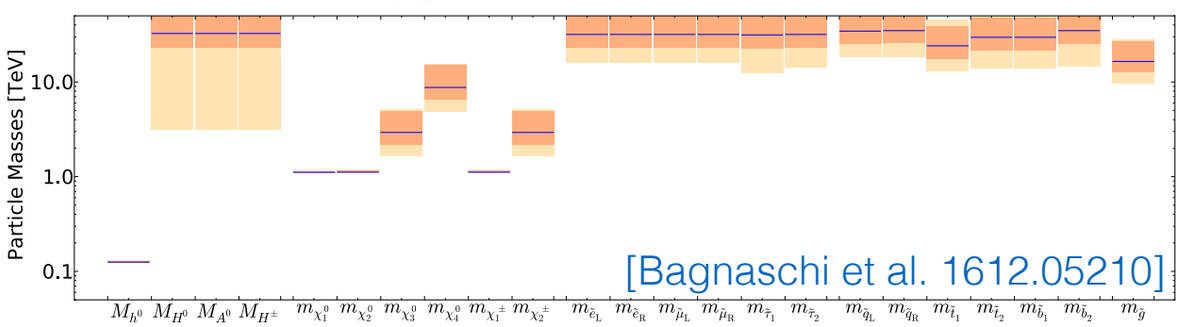




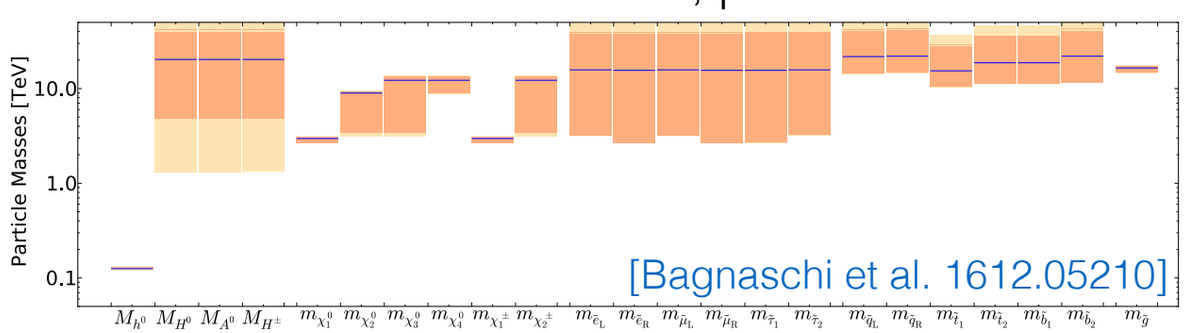
Minimal Anomaly Mediation

Narrow region of viable thermal cosmology w/ higgsino or wino LSP

Higgsino LSP DM, μ>0



Wino LSP DM, μ>0

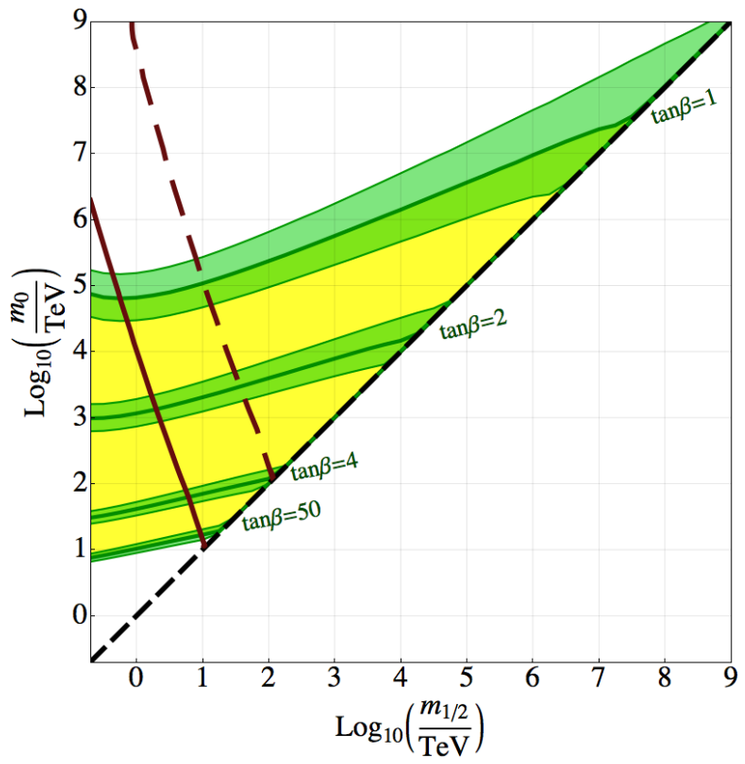


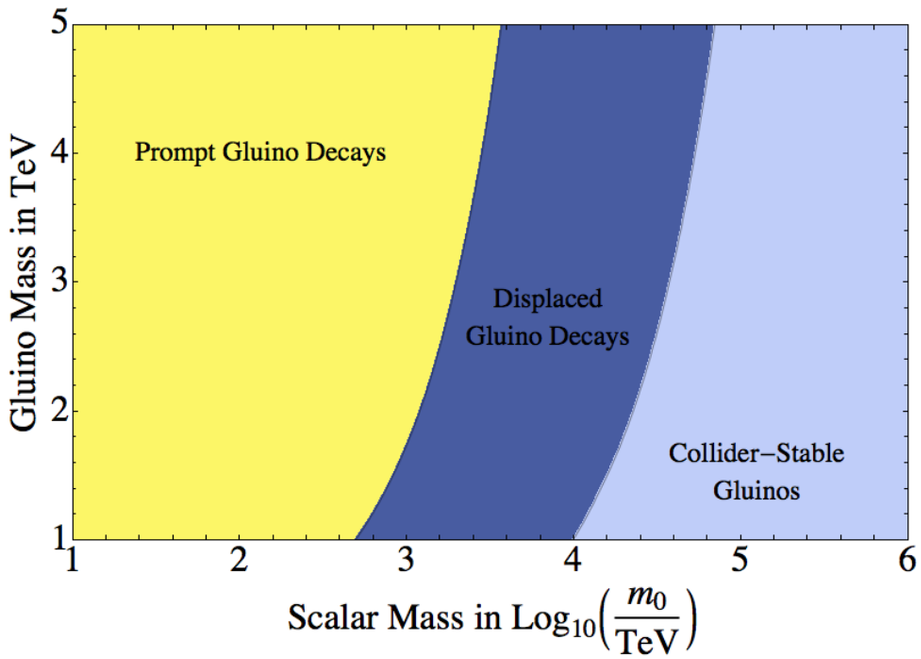
Largely inaccessible to LHC, better for indirect detection

More on DM: see talk by Godbole

Unification & Dark Matter

[Arvanitaki, NC, Dimopoulos, Villadoro '12]

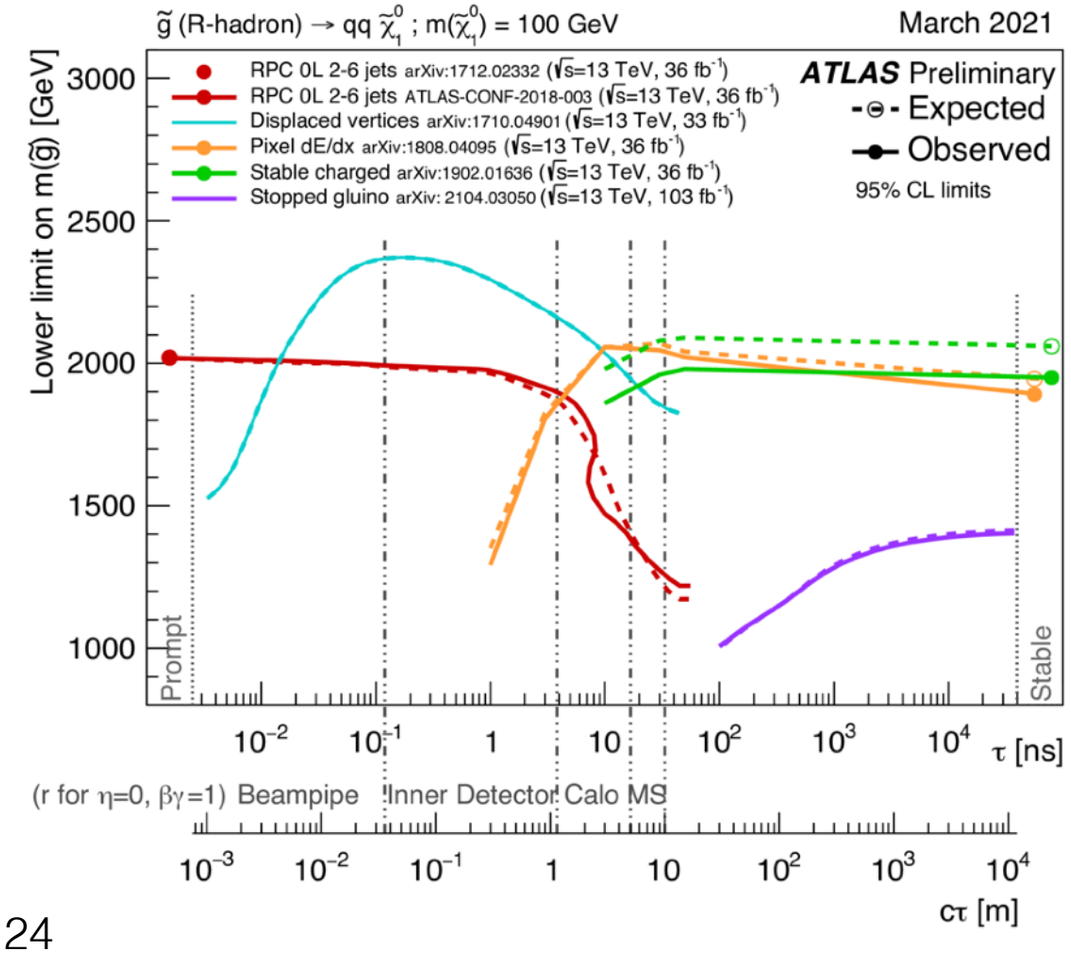




Relaxing naturalness pressure on scalars, still pressure from unification & DM to keep higgsinos & gauginos beneath ~10 TeV

"Split / mini-split"

Discovery opportunity: search for long-lived gluinos.

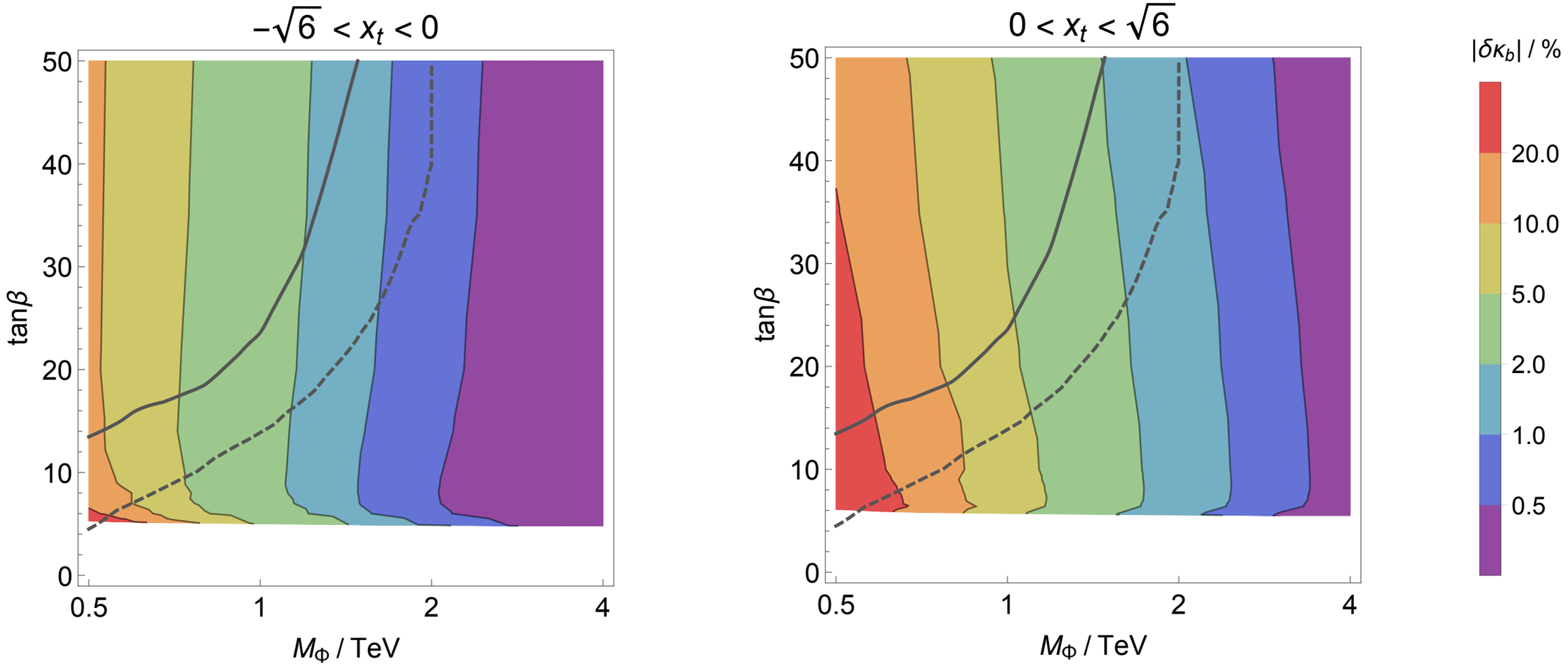


Higgs still plays a role

E.g. [Wells, Zhang 1711.04774]

$\delta\kappa_b$ enforcing $b - \tau$ unification

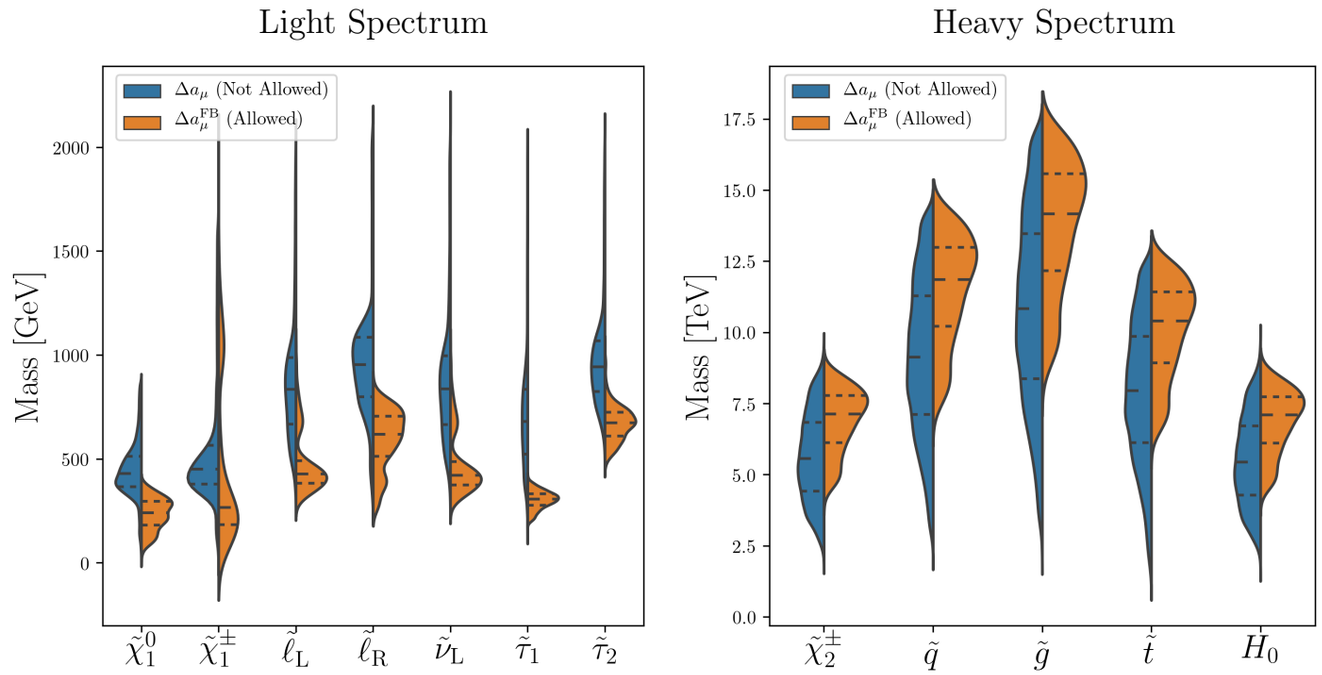
$|M_3| = 5\,\mathrm{TeV}$ $\qquad$ $|M_s| = 10\,\mathrm{TeV}$

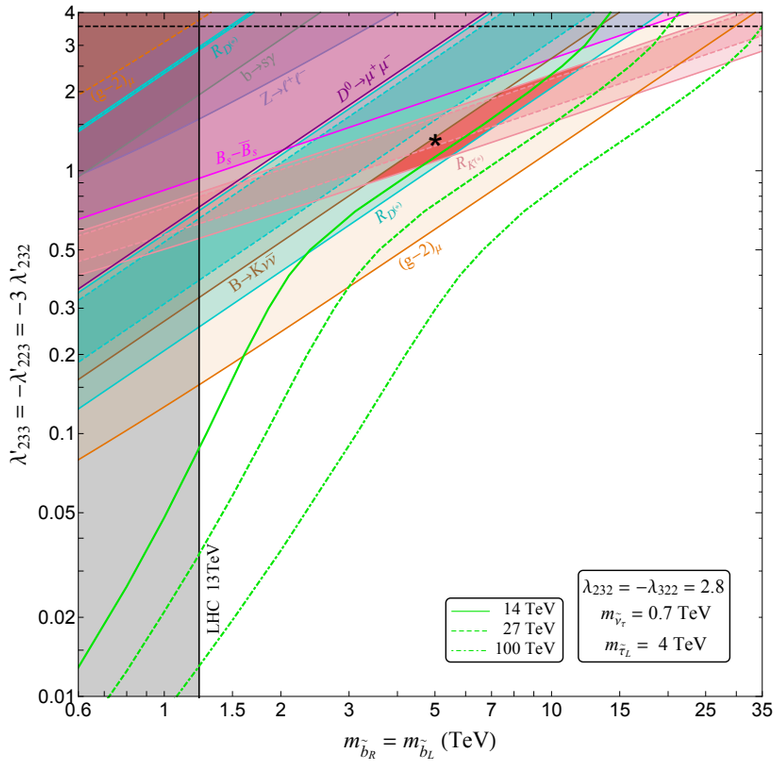


Hints from g-2 / LFUV?

Very long history of SUSY explanations for possible muon g-2 discrepancy

See talks, refs by Ellis, Heinemeyer





[Dev, Soni, Xu 2106.15647]

[Aboubrahim, Klasen, Nath, Syed 2107.06021]

Recent suggestions of lepton flavor universality violation not well-fit by vanilla supersymmetry, but RPV explanations plausible. E.g. 2nd & 3rd-generation QLD + LLE RPV [Dev, Soni, Xu 2106.15647, …]

See talk by Altmannshofer

Where does this leave us?

(a fairly personal perspective)

- Naturalness is a strategy for finding new physics (as are unification and dark matter, of course). I still very much believe in this strategy, broadly.
- But it no longer seems to me that the “most natural” versions of SUSY fulfill the naturalness strategy, in the sense of providing compelling guidance based on the evidence at hand.
- SUSY still a compelling framework for naturalness, unification, and dark matter. But Higgs mass, null results, and lack of generic flavor/CP violation suggest colored sparticles are decoupled. My eyes, at least, are mainly on electroweak physics in Run 3.
- This leaves many interesting directions (especially if anomalies persist), though perhaps not the ones most emphasized over the last decade.
- For me, the main lesson of the decade has been that experimentalists are extraordinary.

Thank you!