The Status of Supersymmetric (Un)naturalness

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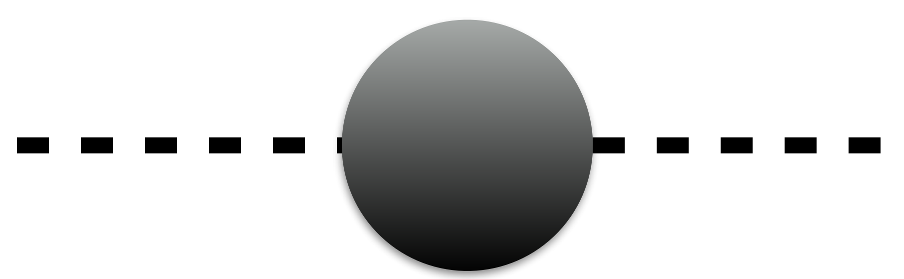
Experimental Challenges for the LHC Run II

The naturalness strategy

In the SM, m_h is a parameter: not predicted, and worse, incalculable (elementary scalars are special).

In a theory where m_h is calculable, new physics beyond the SM enters at a scale Λ.

We see a *hierarchy problem*: quantum contributions to m_h are *at least* around this scale Λ.



$$\delta m_h \propto \Lambda$$

Natural if $\delta m_h \sim m_h$.

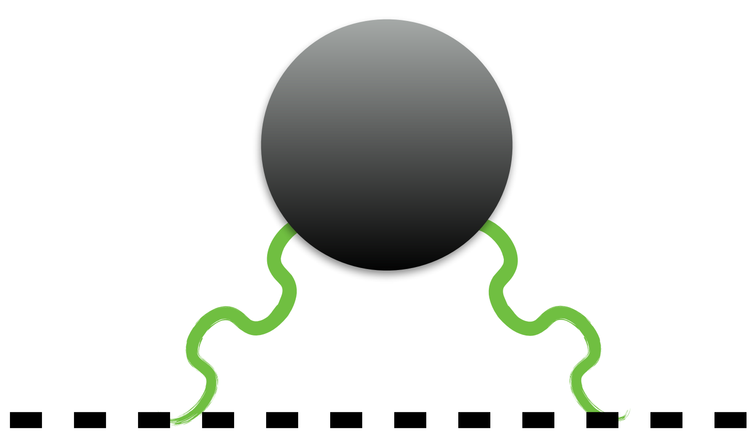
($\delta m_h \gg m_h$ unnatural or UV miracle)

The naturalness strategy

This is a *strategy* for new physics near m_h, not a *no-lose theorem*, because the theory does not break down if it is unnatural.

But naturalness has often been a very *successful* strategy.

E.g. charged pions



Electromagnetic contribution to the charged pion mass sensitive to the cutoff of the pion EFT.

$$\delta m^2 \sim \frac{3e^2}{16\pi^2}\Lambda^2$$

Naturalness suggests Λ~850 MeV.
Rho meson (new physics!) enters at 770 MeV.

The Situation in SUSY

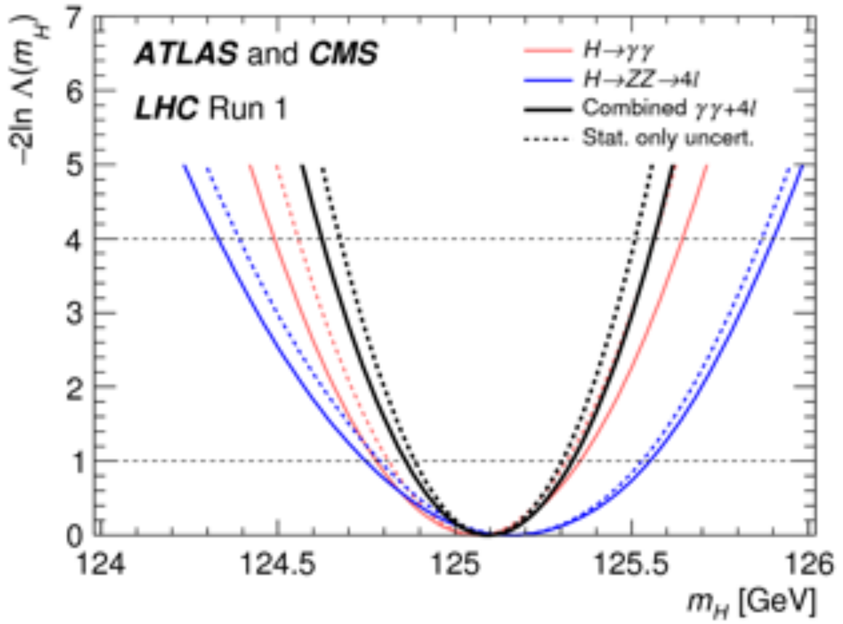
$$m_h^2 = -2m_H^2 = \lambda v^2$$

$$m_{H_u}^2 + \mu^2 + \frac{c}{16\pi^2} m_{\tilde{t}}^2 + \ldots$$

$$\left(\frac{m_Z^2}{v^2} + \frac{d}{16\pi^2}\log(m_{\tilde{t}}^2/m_t^2) + \ldots\right) v^2$$

Two problems:

- Terms quadratic in superpartner masses have to cancel to fine precision
- Physical Higgs mass prediction too low at tree level, only logarithmically sensitive to superpartner masses.

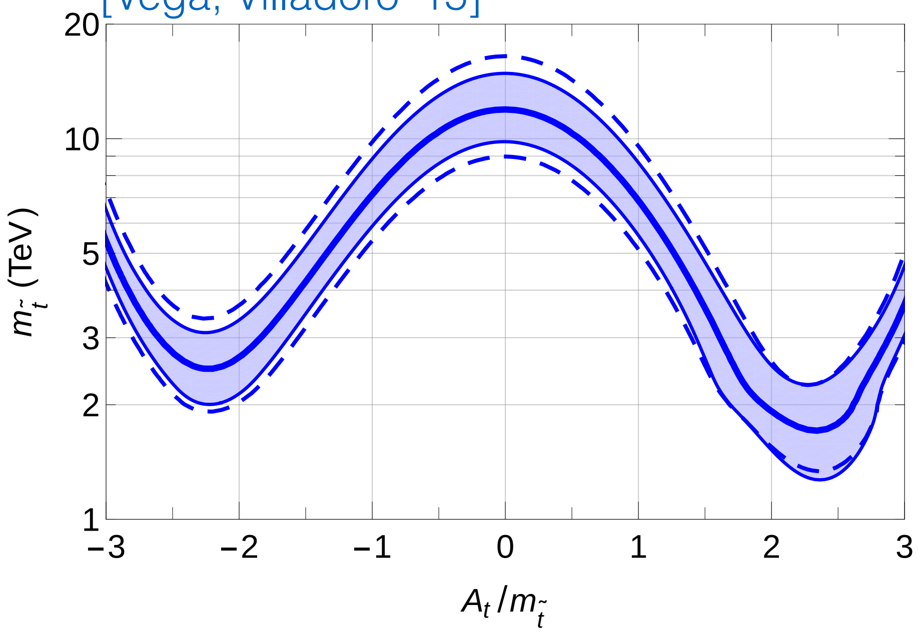


Physical Higgs mass

Challenge is to accommodate/explain m_h=125 GeV without tuning.
Expect "natural" theory must go beyond MSSM.

Mixing

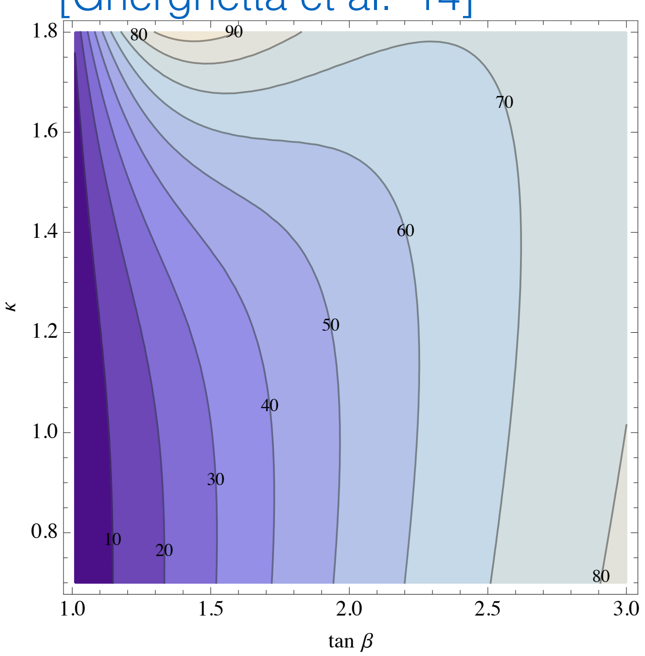
[Vega, Villadoro '15]



Not very natural; no stops at the LHC

F-term

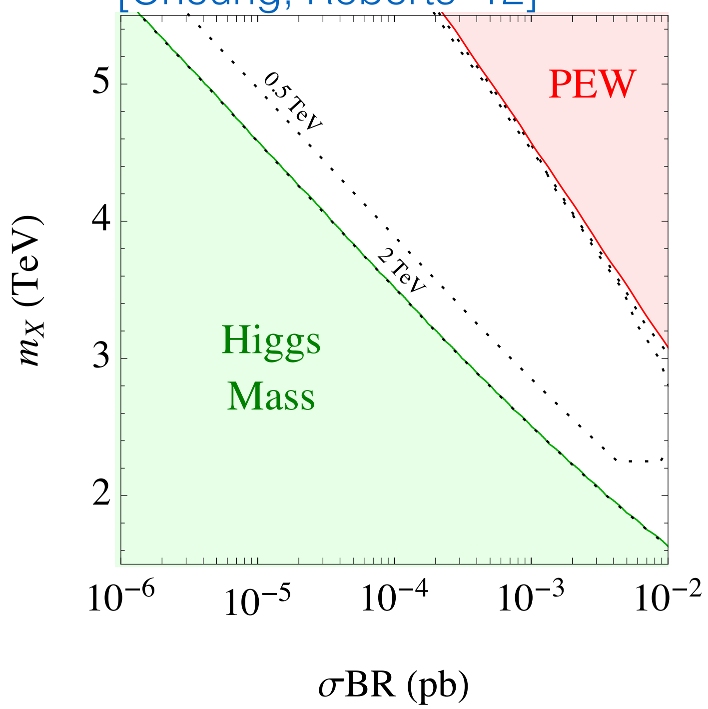
[Gherghetta et al. '14]



Finite decoupling; Higgs coupling measurements constraining.

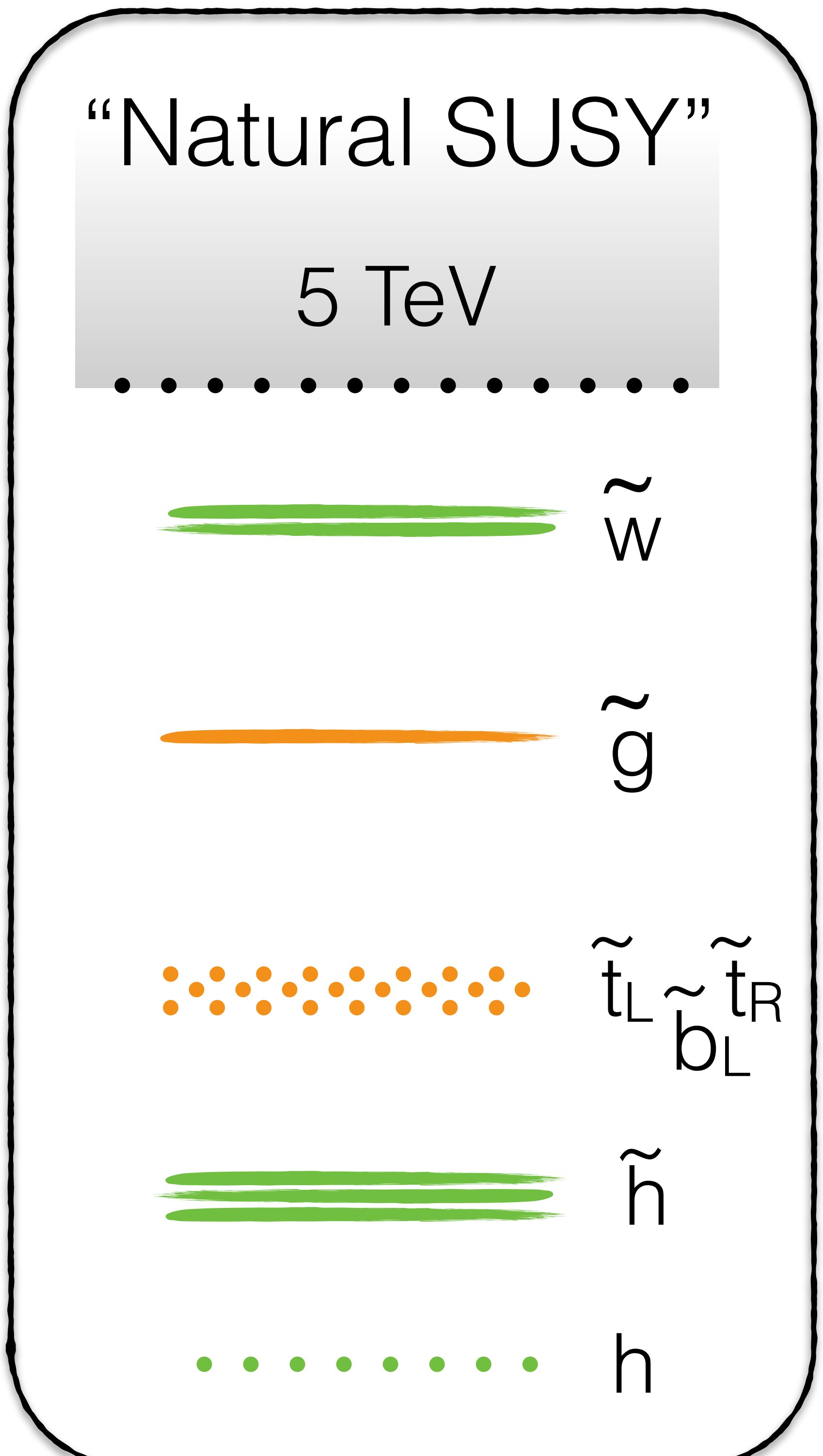
D-term

[Cheung, Roberts '12]



Heavy vector bosons at LHC13/14

Minimize the damage



Best case scenario given nonobservation: superpartner mass hierarchy inversely proportional to contribution to Higgs mass

$$\delta m_h^2 \propto \mu^2 \quad (\text{“higgsinos”})$$

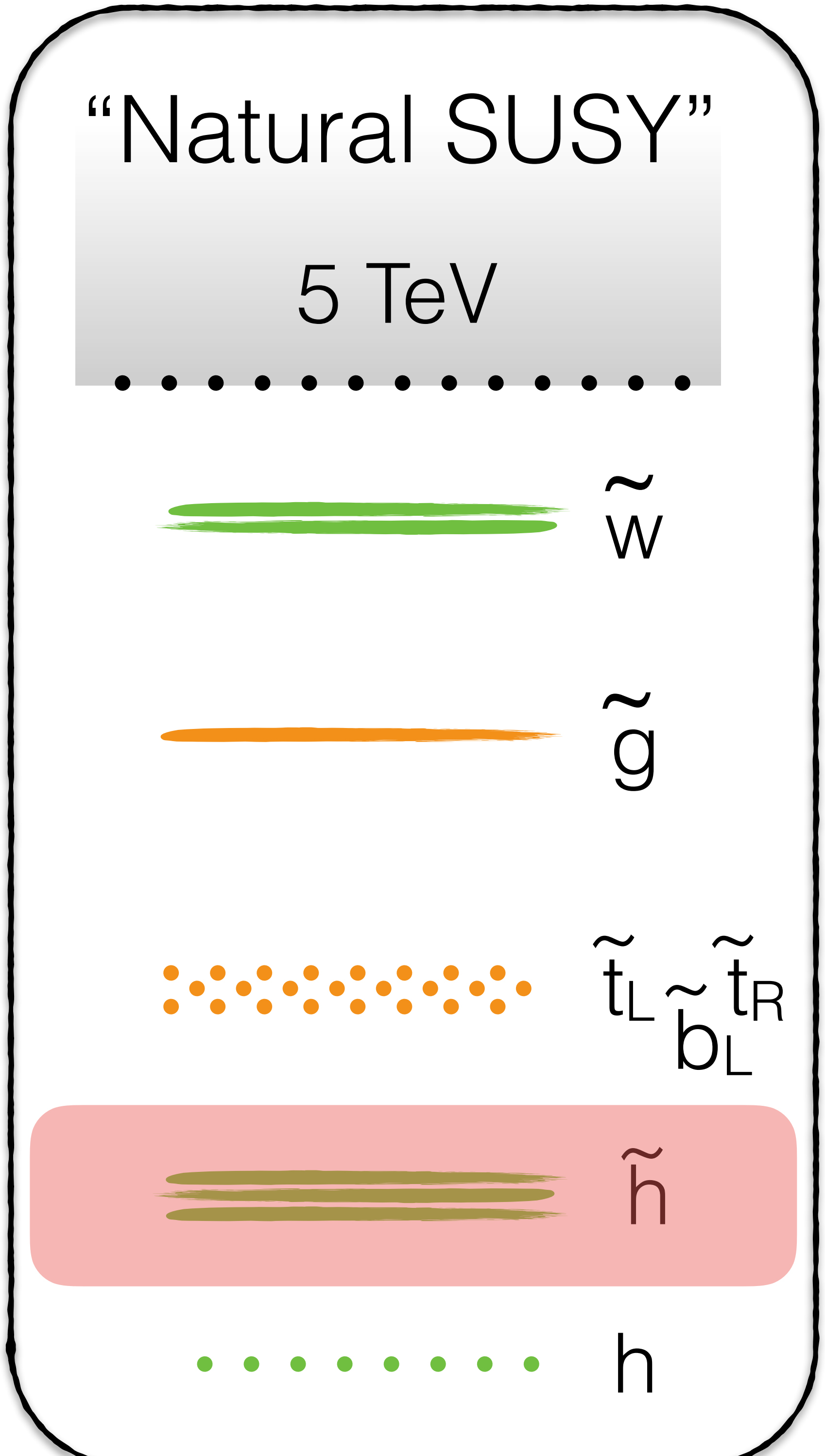
$$m_h^2 \sim \frac{3y_t^2}{4\pi^2} \tilde{m}^2 \log(\Lambda^2/\tilde{m}^2)$$

(everything else)

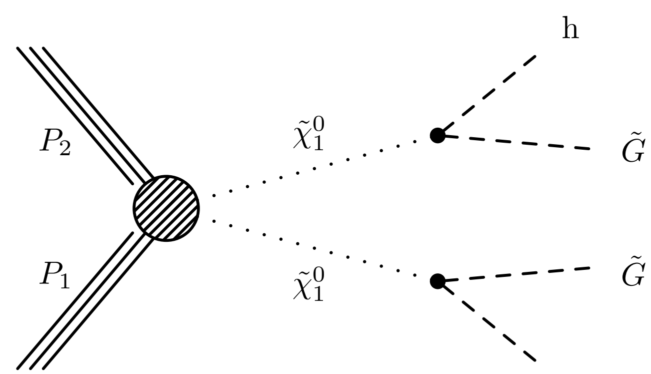
QCD production of stops, gluinos leads to strongest constraints

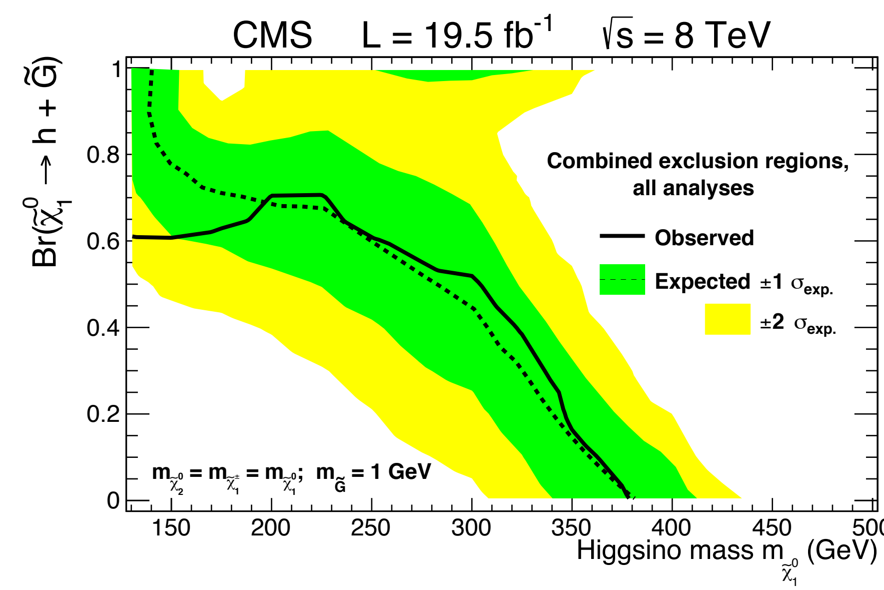
[Dimopoulos, Giudice ‘95; Cohen, Kaplan, Nelson ’96; Papucci, Ruderman, Weiler ’11; Brust, Katz, Lawrence, Sundrum ’11]

Where we are now: Higgsinos



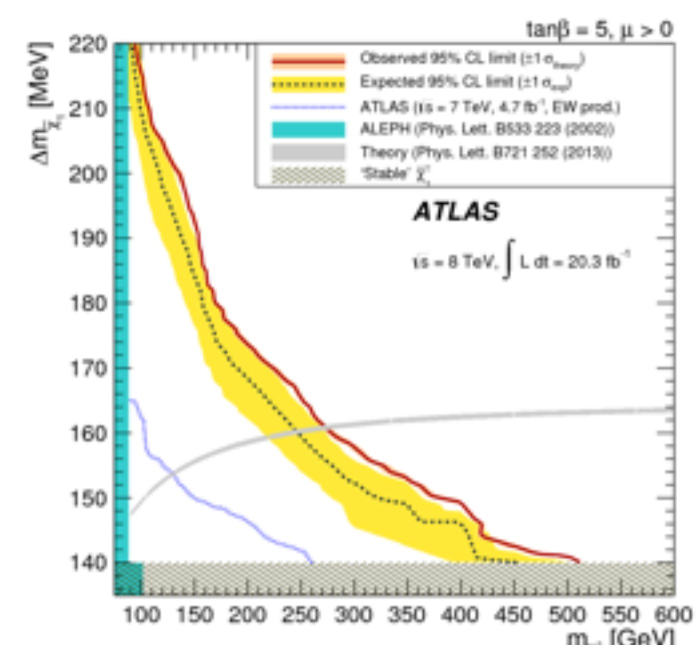
Lots of searches…



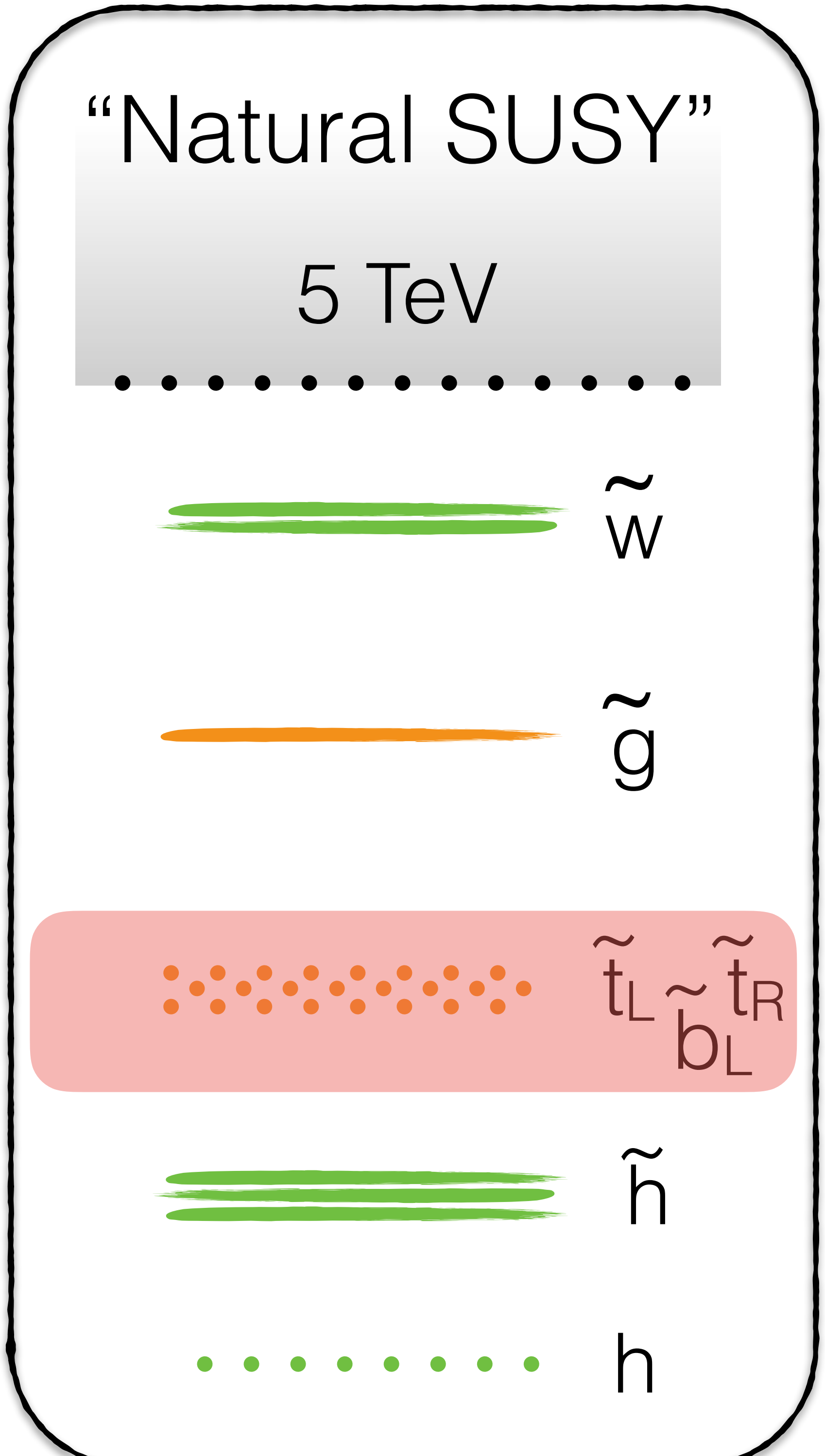


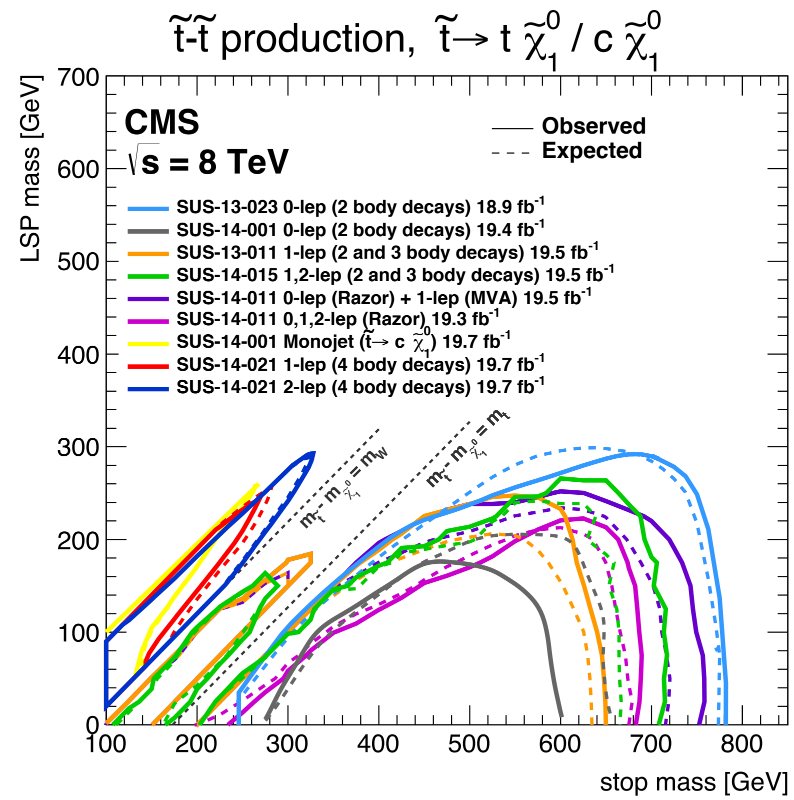
…but no irreducible limits

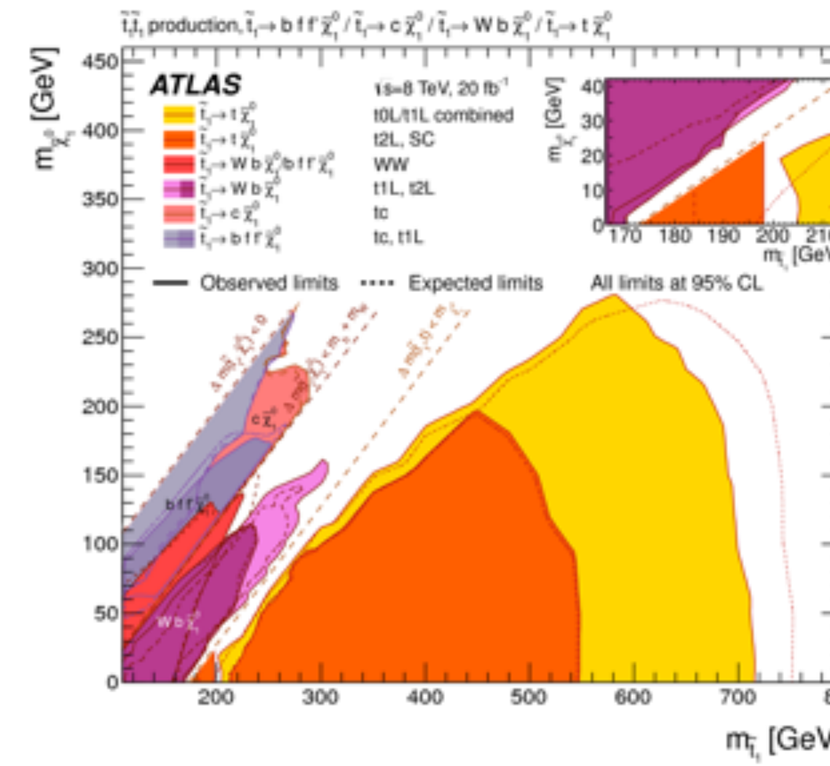
Chargino-neutralino splitting in pure higgsino multiplet: 355 MeV [Thomas, Wells '98]

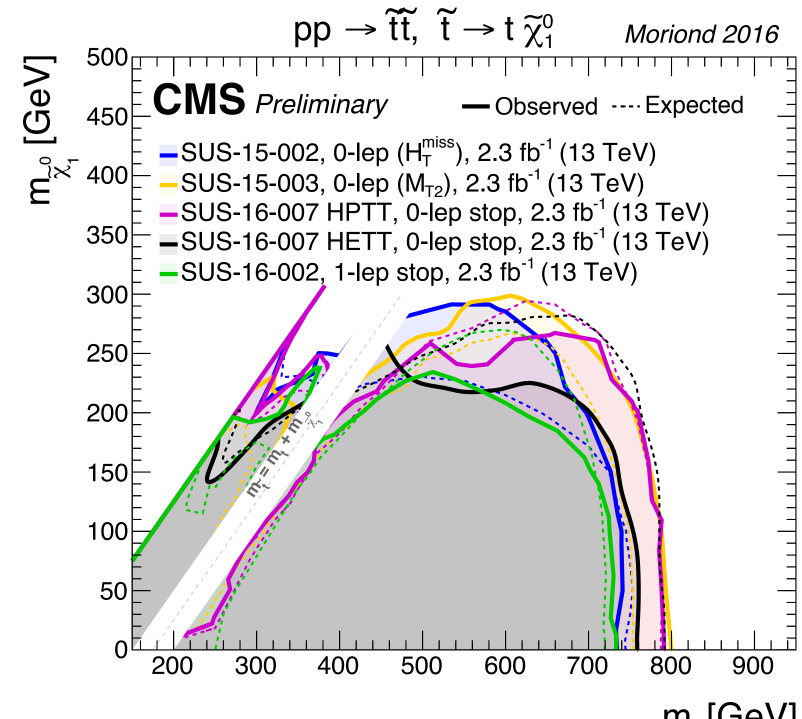


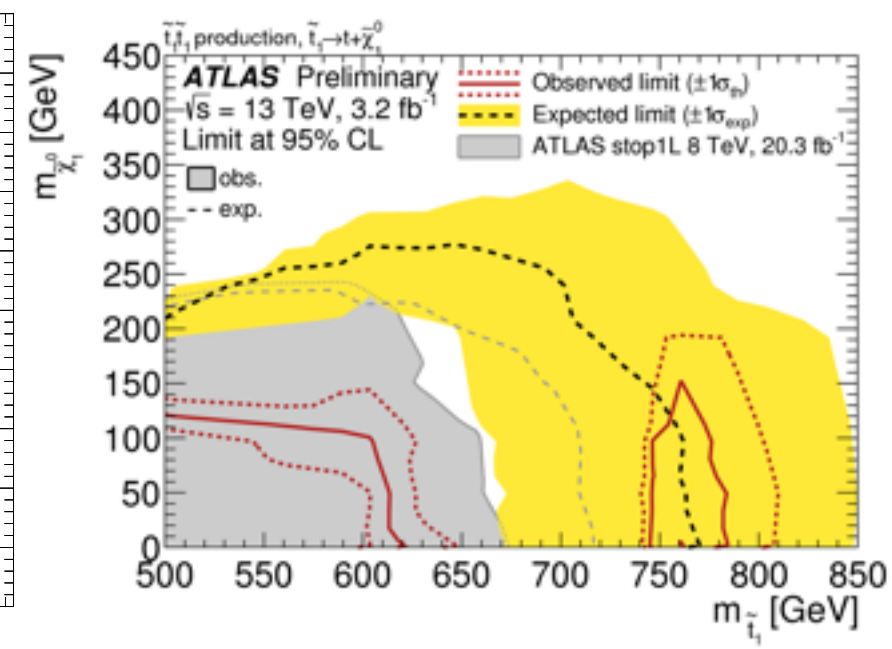
Where we are now: Stops



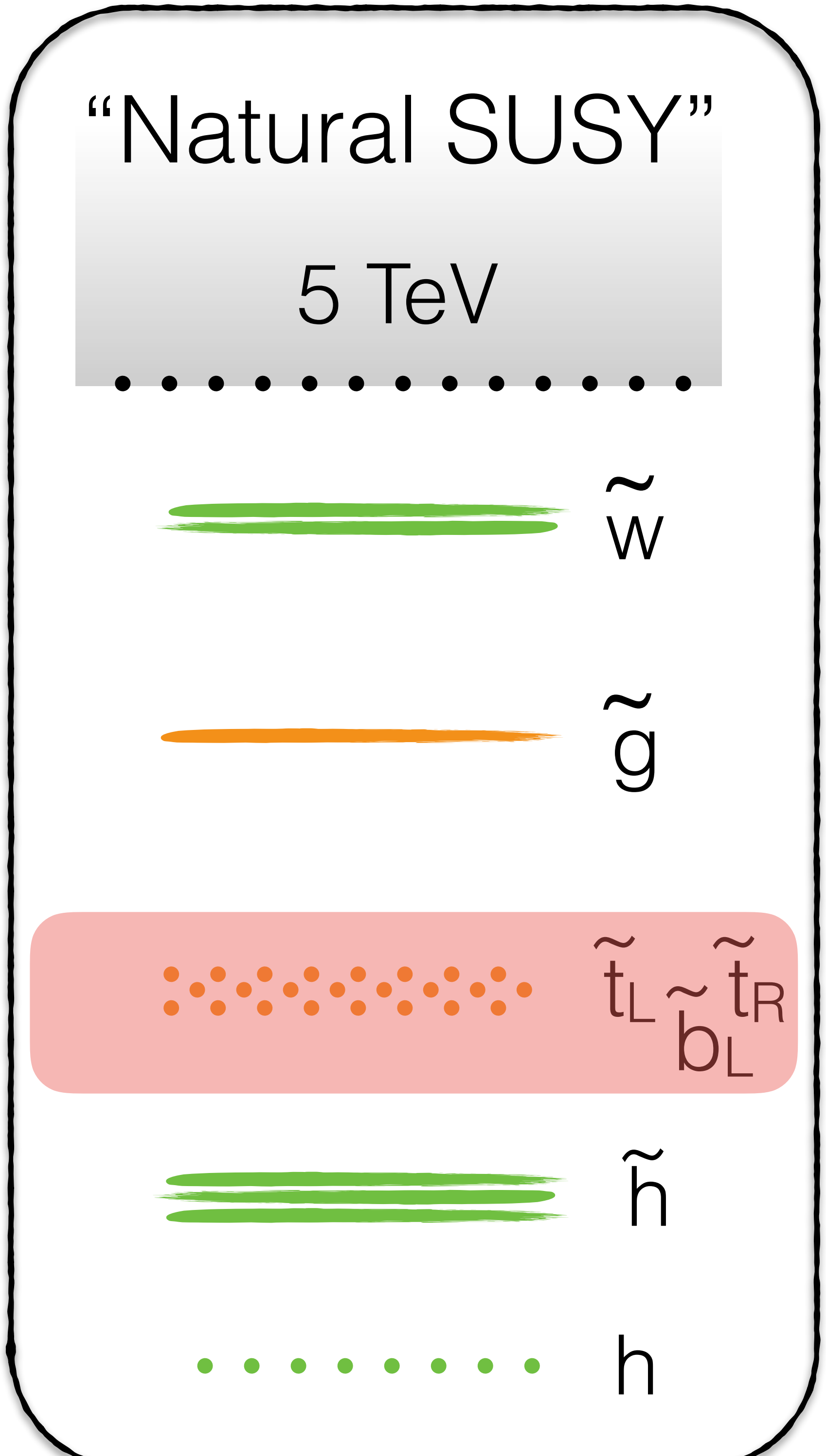




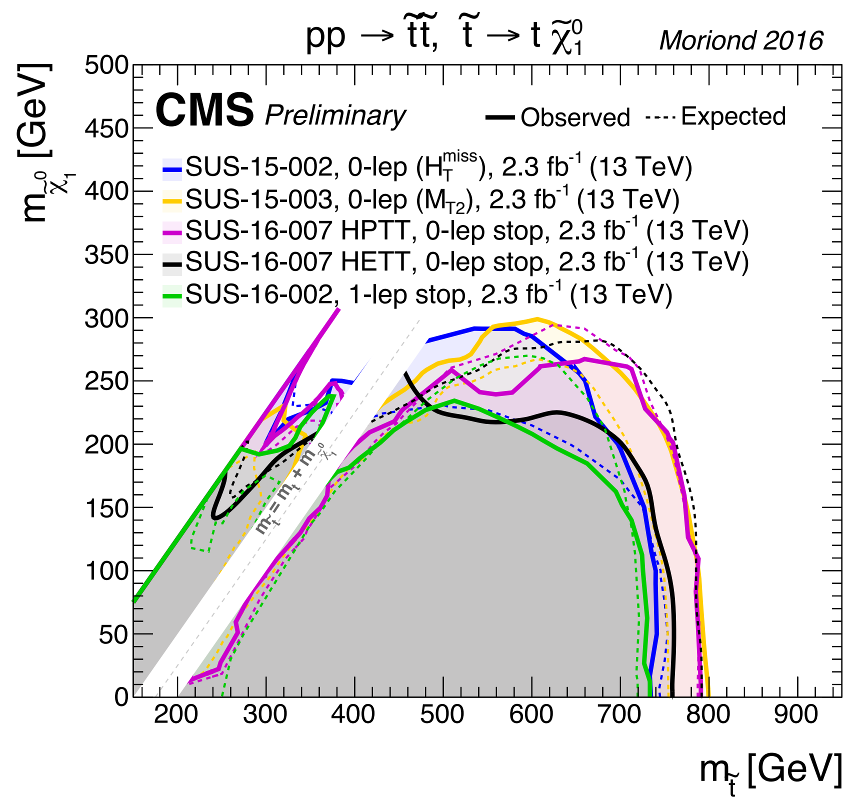




Where we are now: Stops



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



Quantify tuning
(as you like)

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

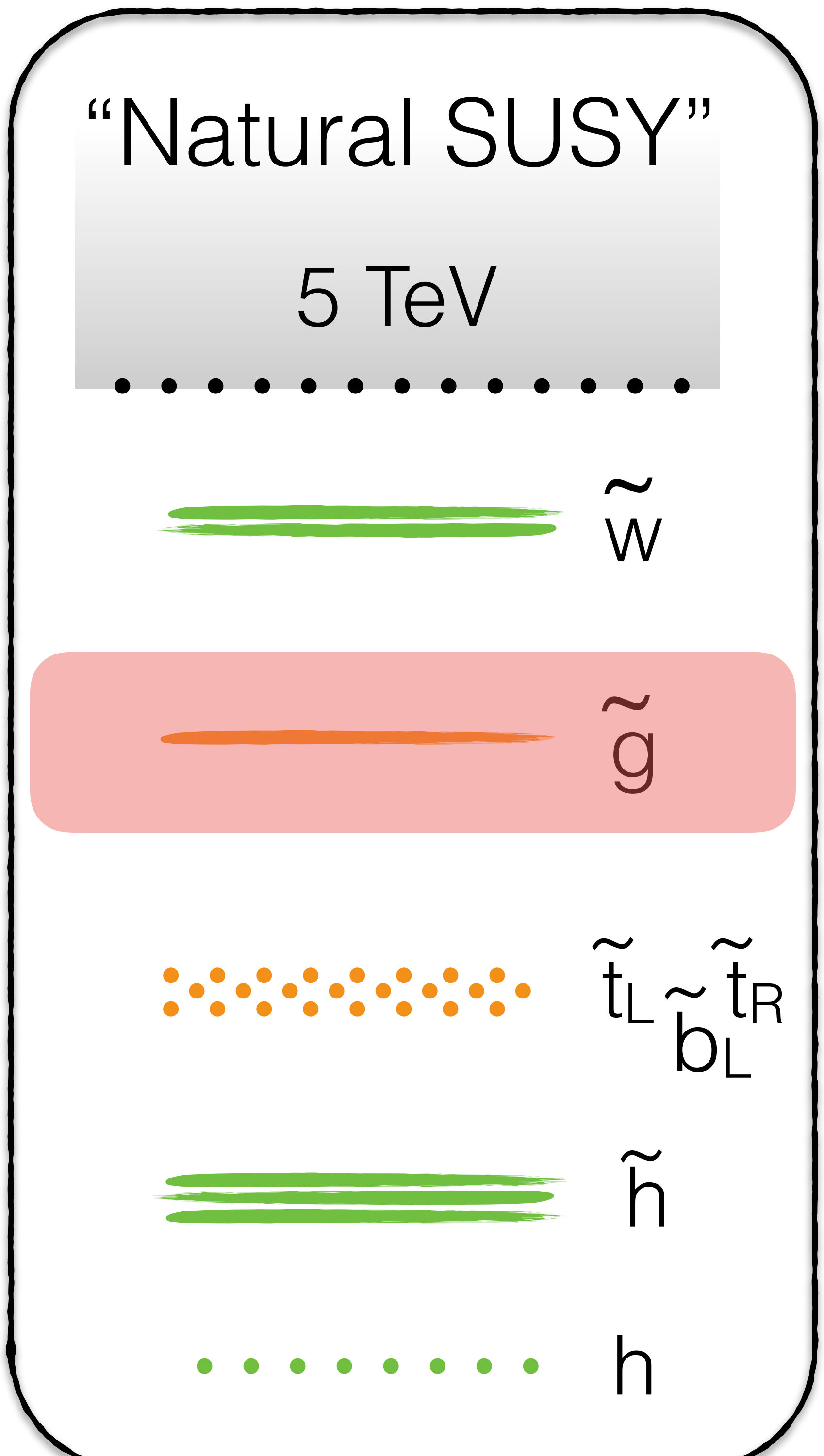
Generic limit* > 800 GeV (both stops)

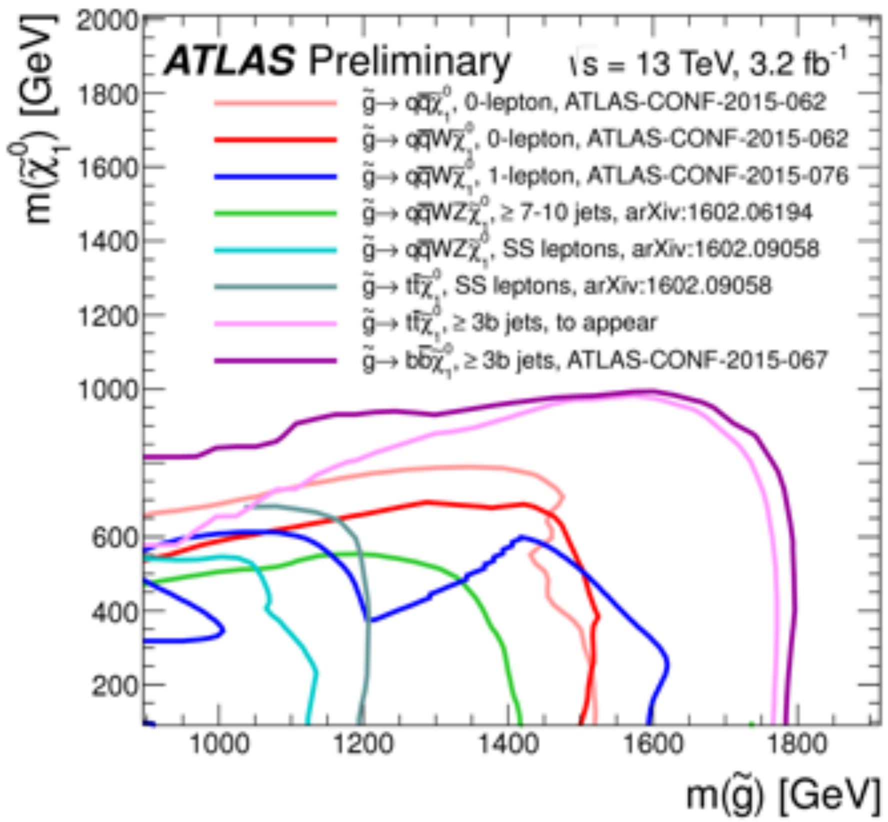
→ **Δ~90 (1% tuning)**

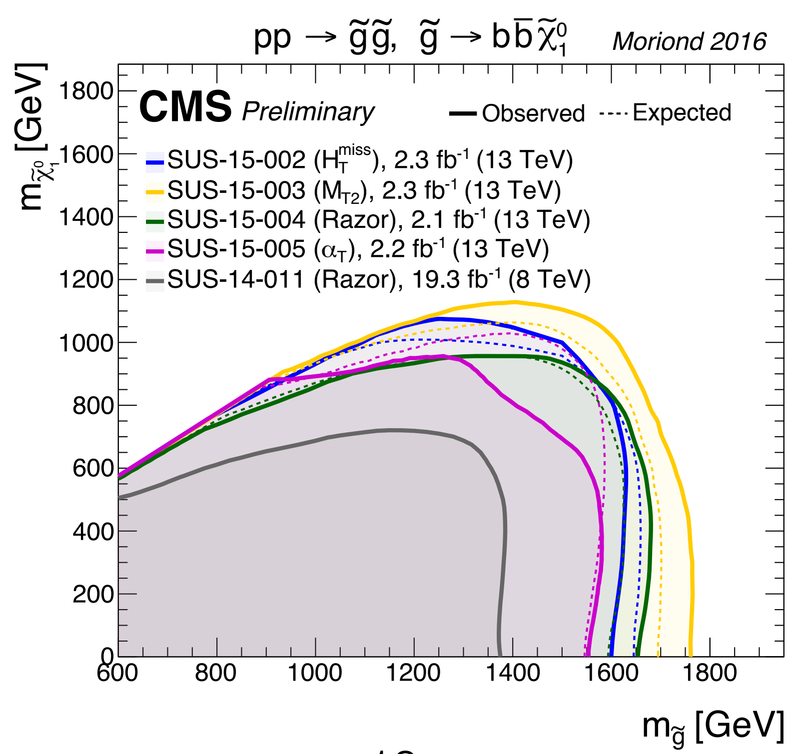
(Λ = 100 TeV)*

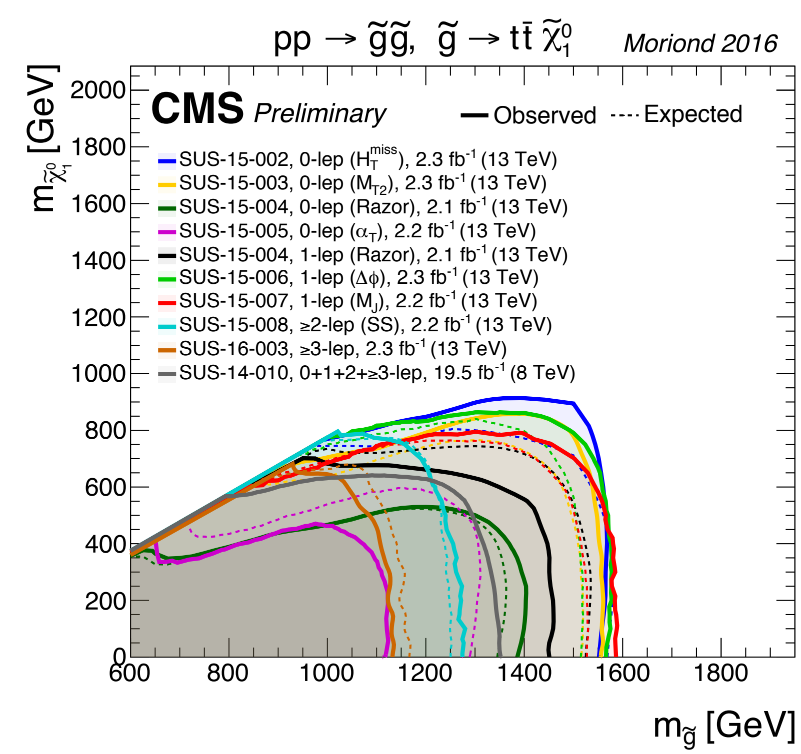
* We'll come back to all this.

Where we are now: Gluinos

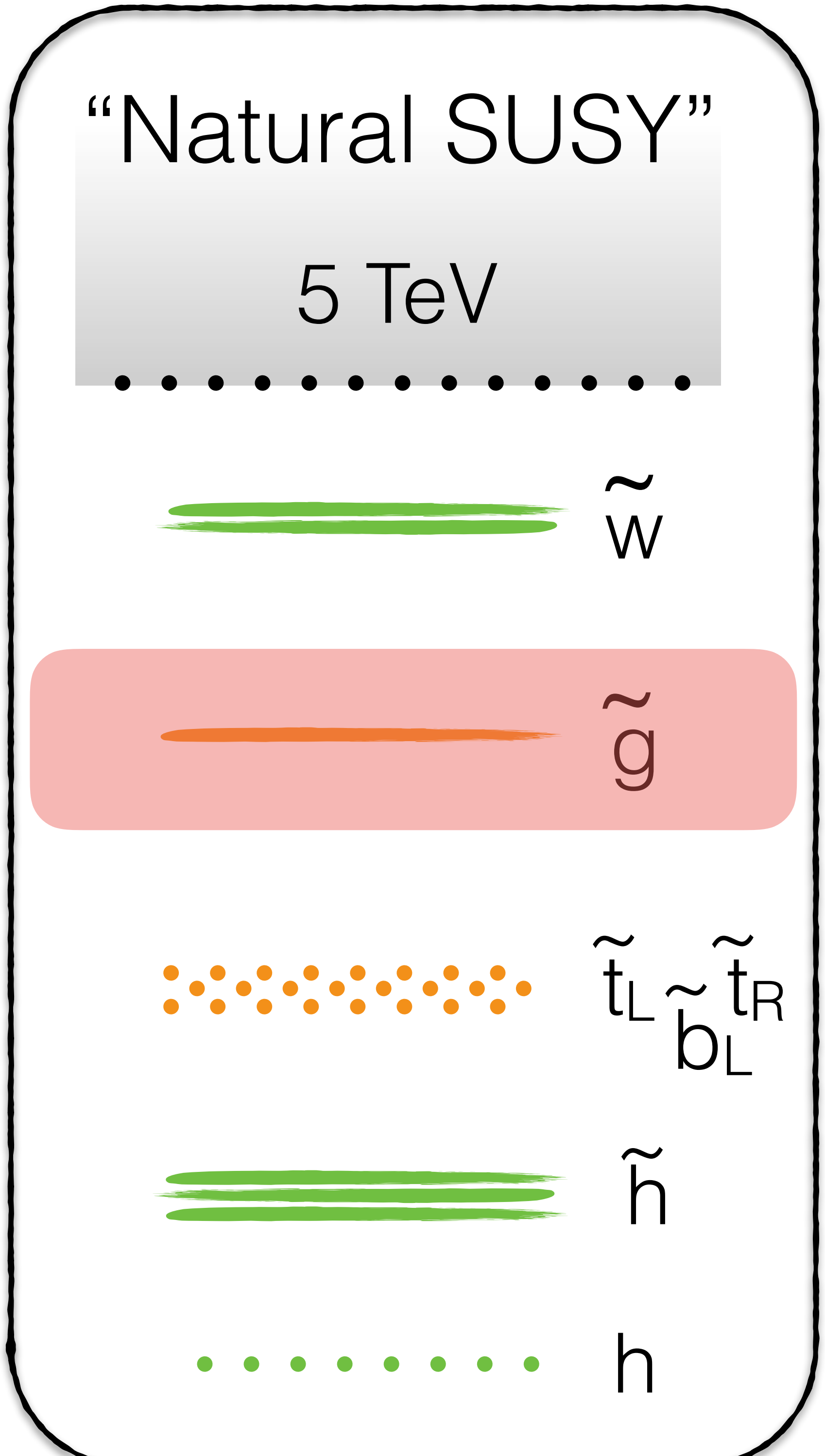






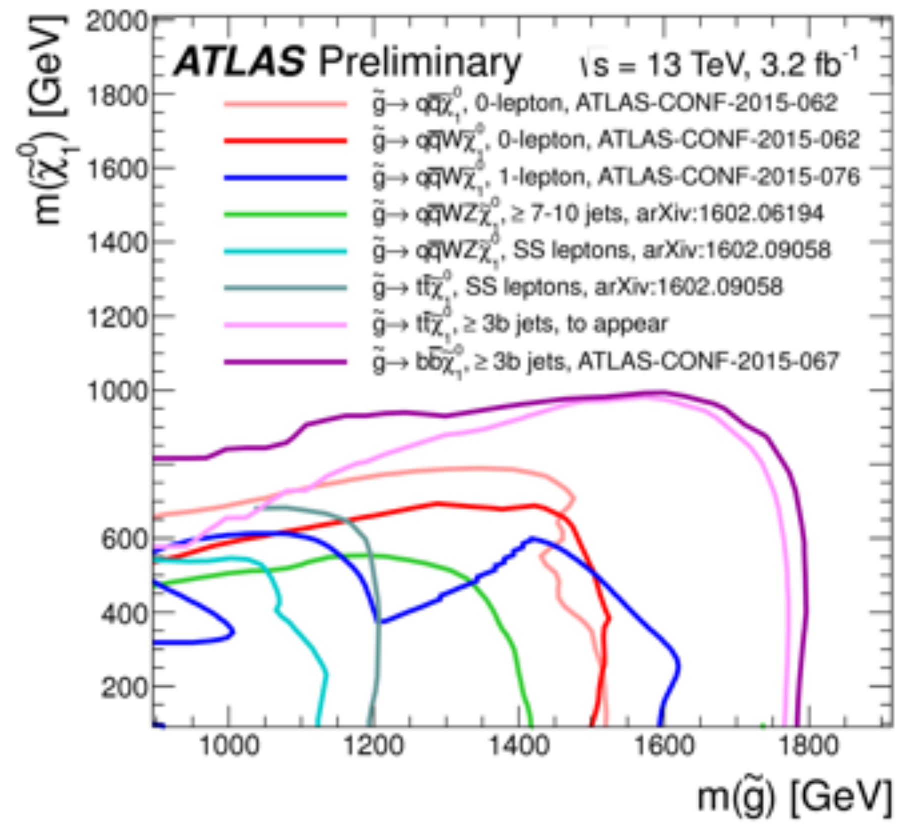


Where we are now: Gluinos



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

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



Generic limit* > 1800 GeV

→ **Δ~57 (2% tuning)**

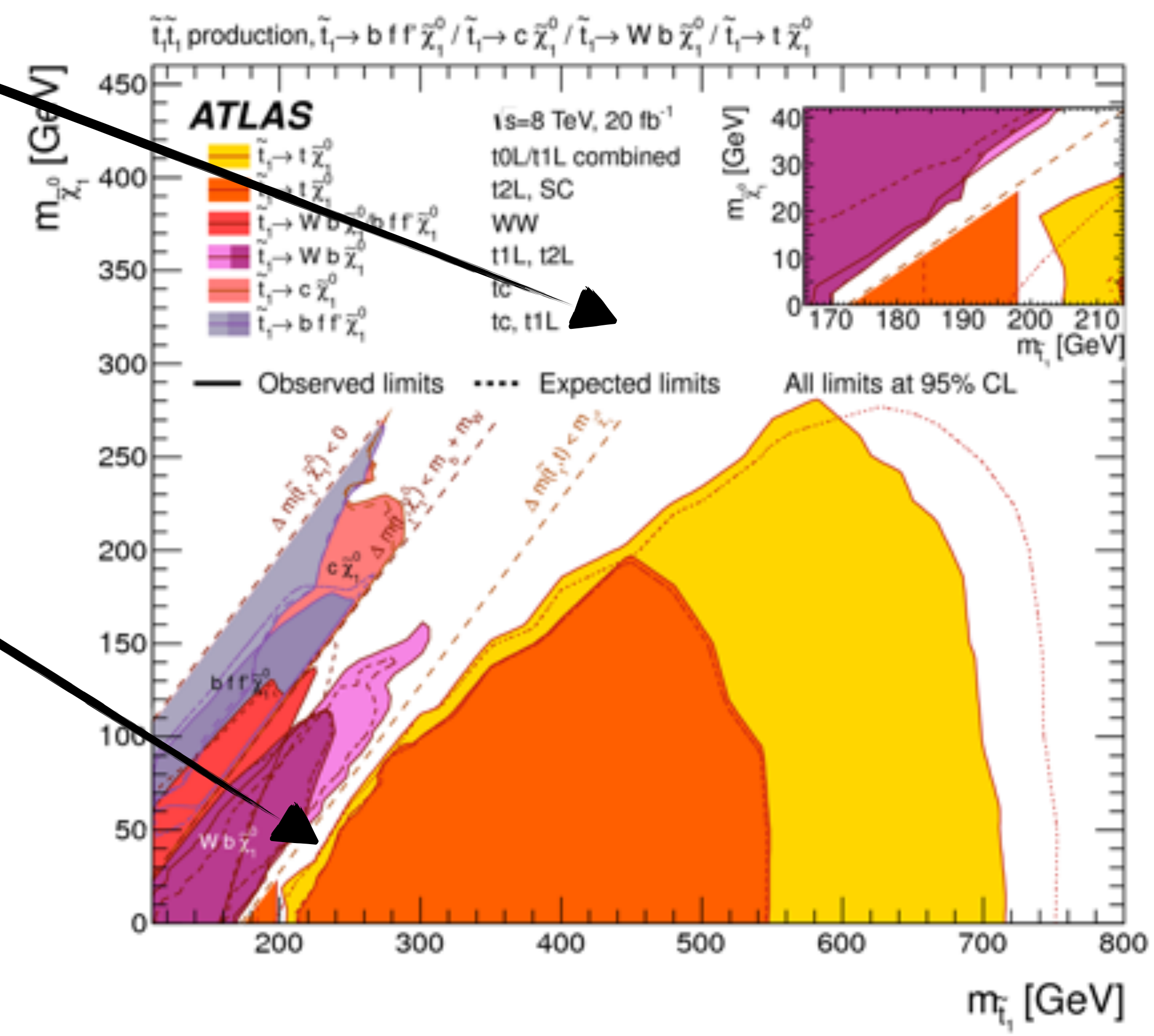
(Λ = 100 TeV)*

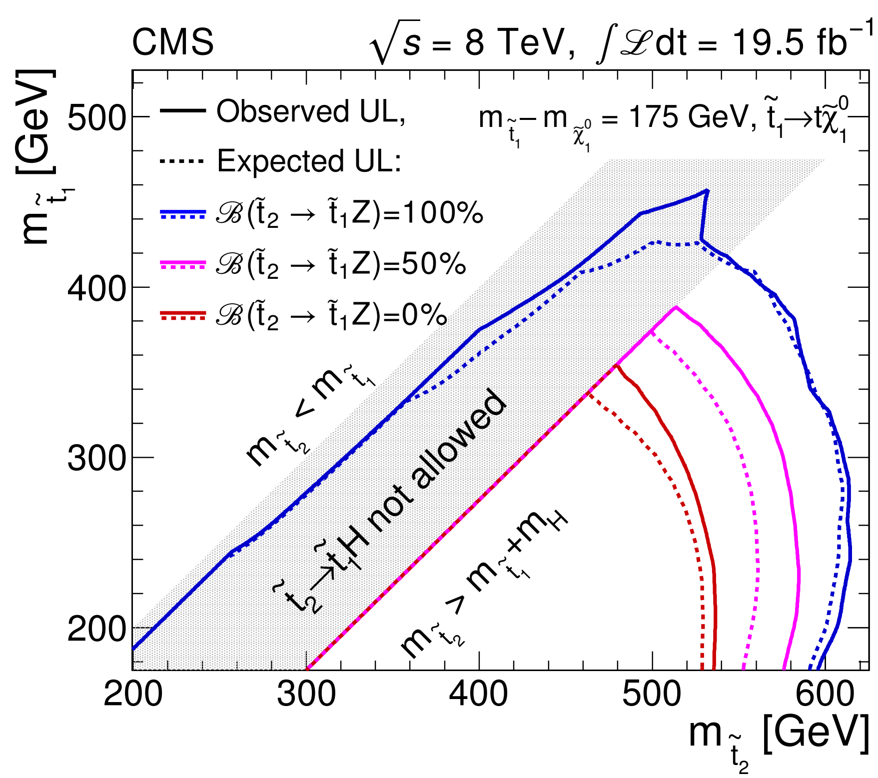
What about…

…ameliorating things by living in gaps?

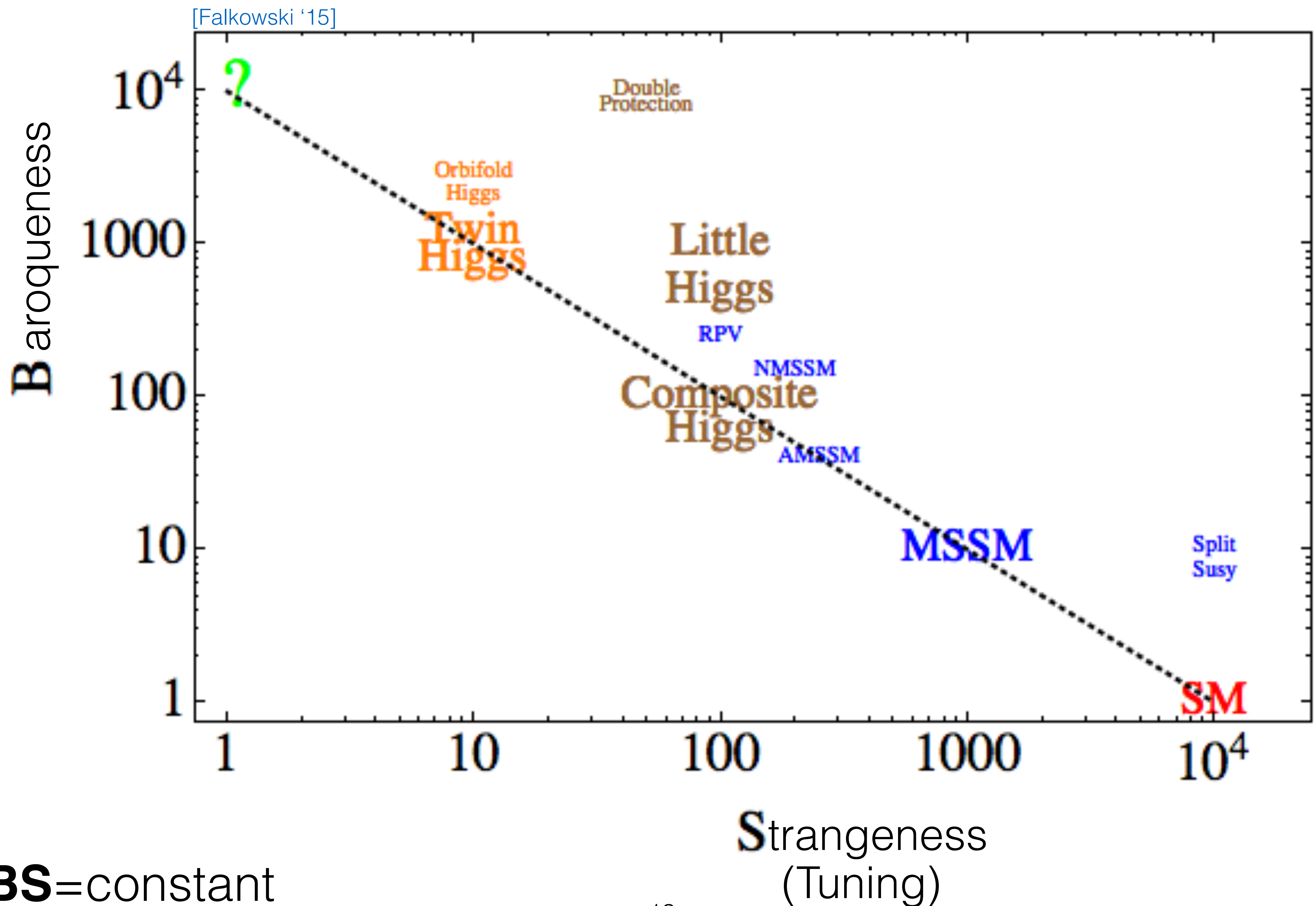
Living here? *LSP mass implies higgsino tuning (~10%)*

Living here? *Have to contend with stop$_1$-stop$_2$ limits*

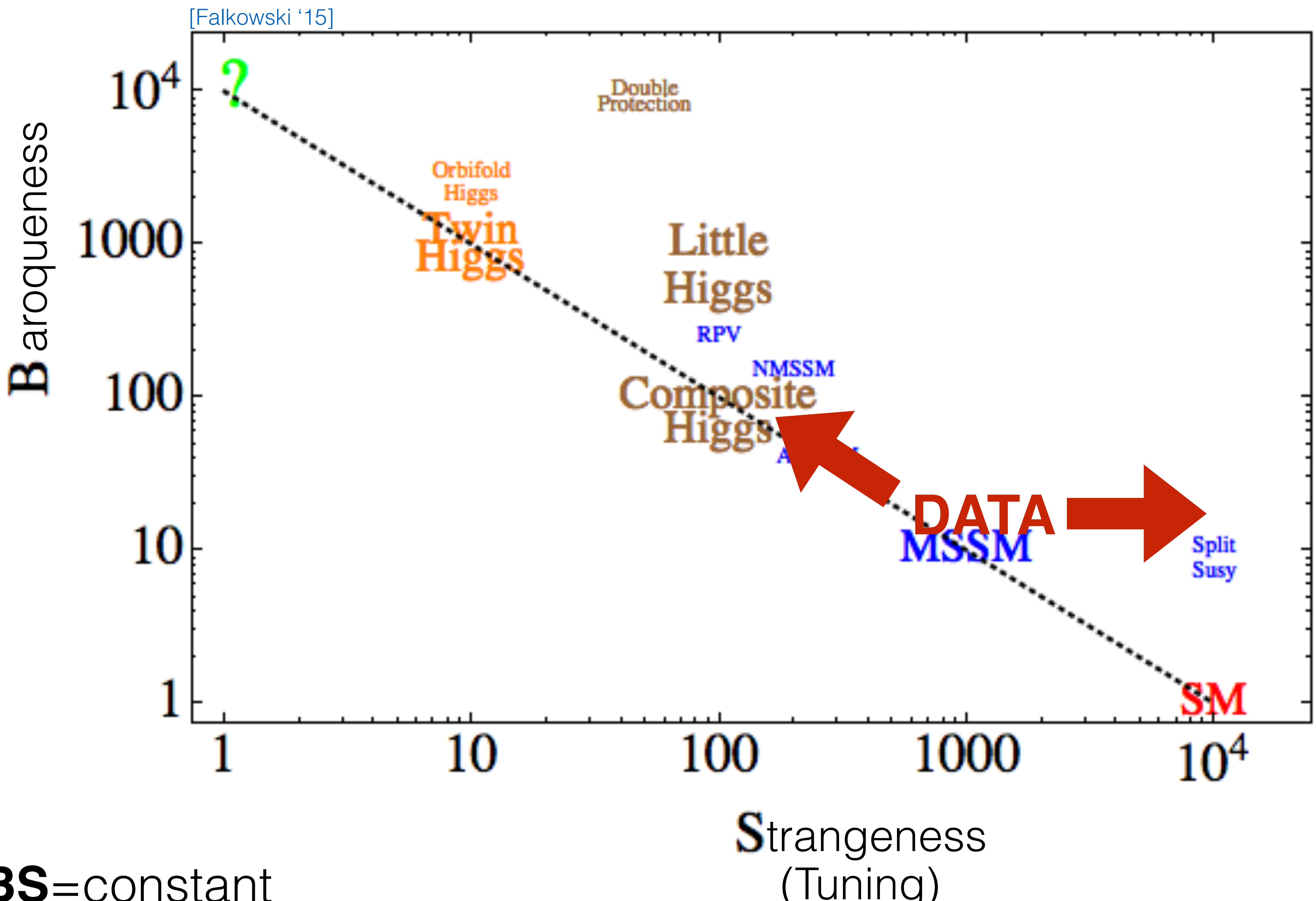




Hard to make O(1) changes in tuning in the framework of the MSSM.


[Falkowski '15]
Baroqueness
Strangeness
(Tuning)
10^4
1000
100
10
1
1
10
100
1000
10^4
?
Double
Protection
Orbifold
Higgs
Twin
Higgs
Little
Higgs
RPV
NMSSM
Composite
Higgs
AMSSM
MSSM
Split
Susy
SM

BS=constant



[Falkowski '15]
Baroqueness
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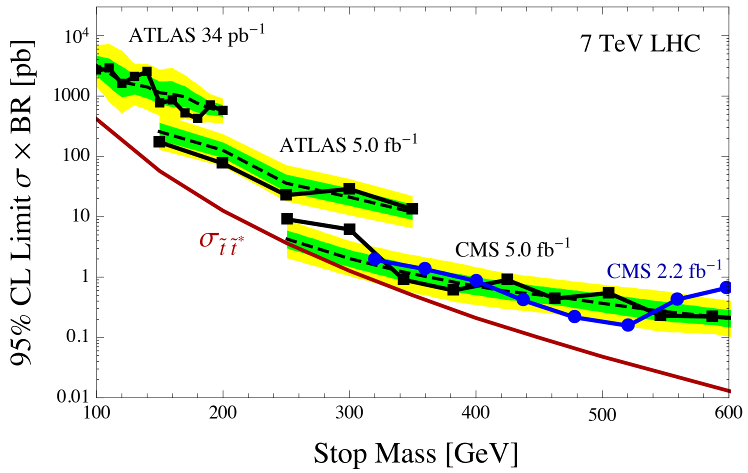
(Tuning)
?
Double Protection
Orbifold Higgs
Twin Higgs
Little Higgs
RPV
NMSSM
Composite Higgs
DATA
MSSM
Split Susy
SM
1
10
100
1000
10^4

BS=constant

Use data as a guide: find theories compatible with the data, use them to develop new signals and searches.

Break the Signal 1

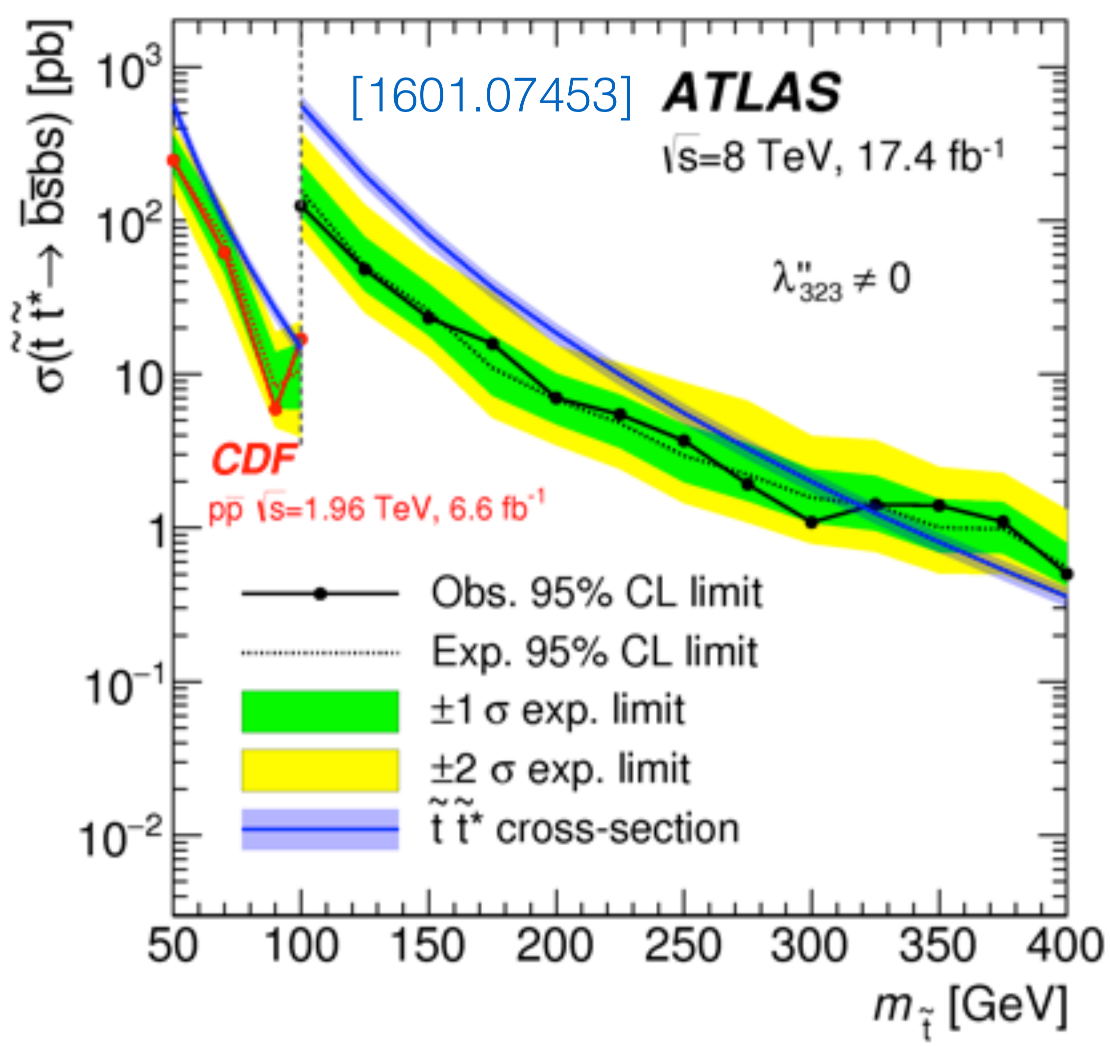
[Bai, Katz, Tweedie '13]



Exclusions assume R parity is conserved. RPV can help provided no leptons → baryonic RPV.

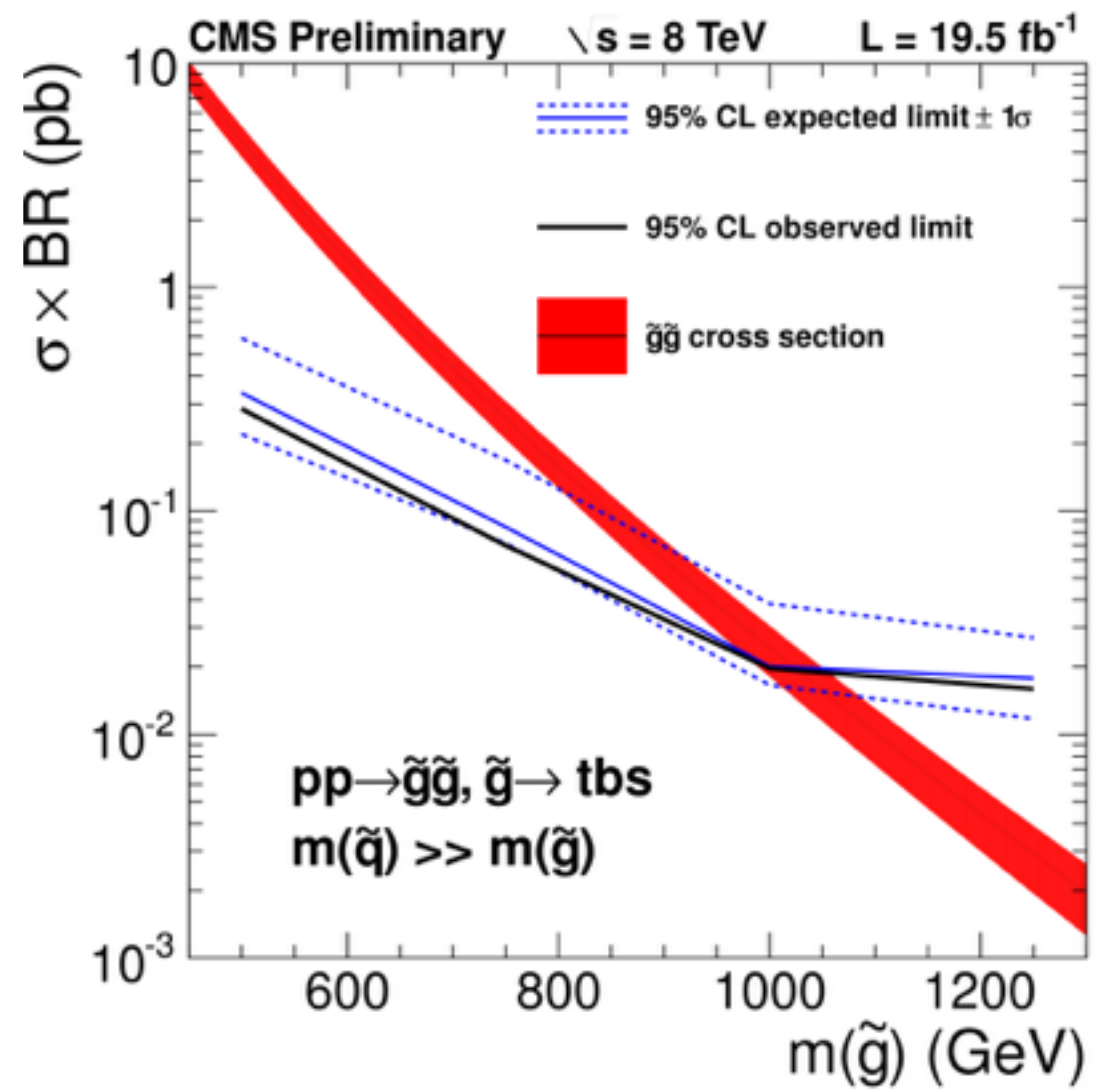
Prompt, because displaced searches powerful.

Stops > 325 GeV (**20%**)



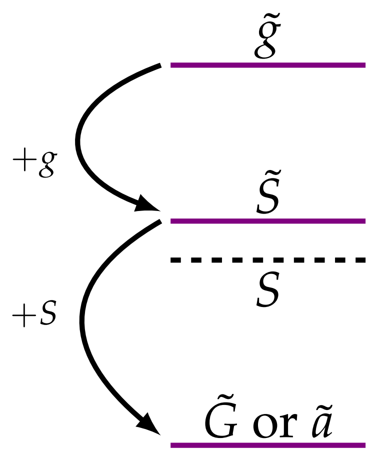
Trigger H_T>500 GeV+p_{T1}>145 GeV

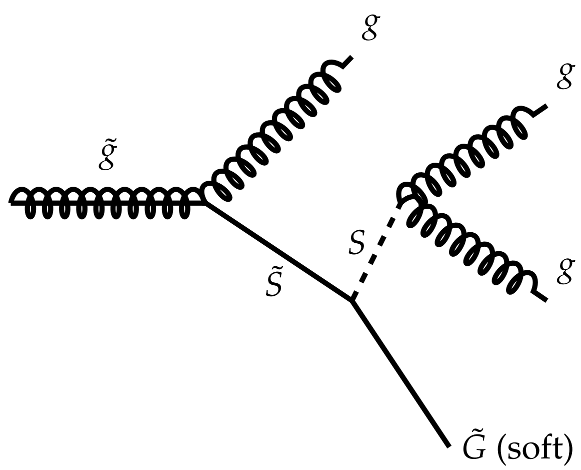
Gluinos > 1 TeV (**5%**)

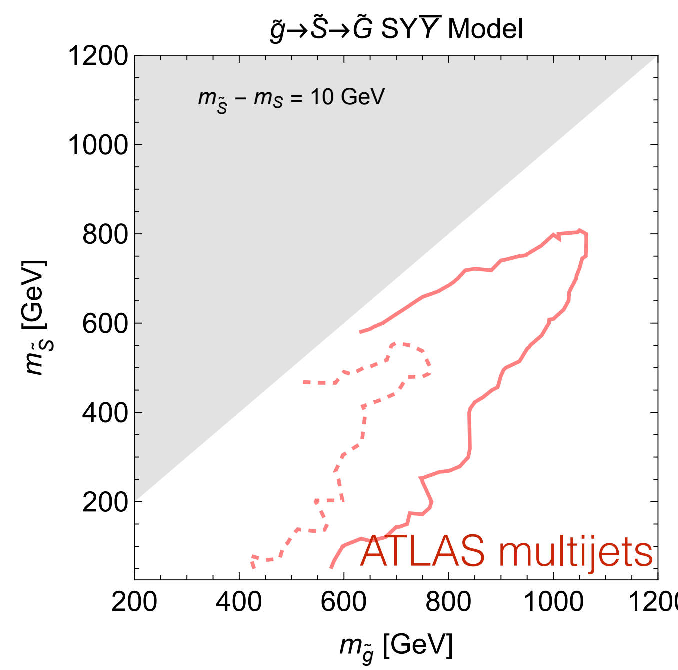


Break the Signal 2

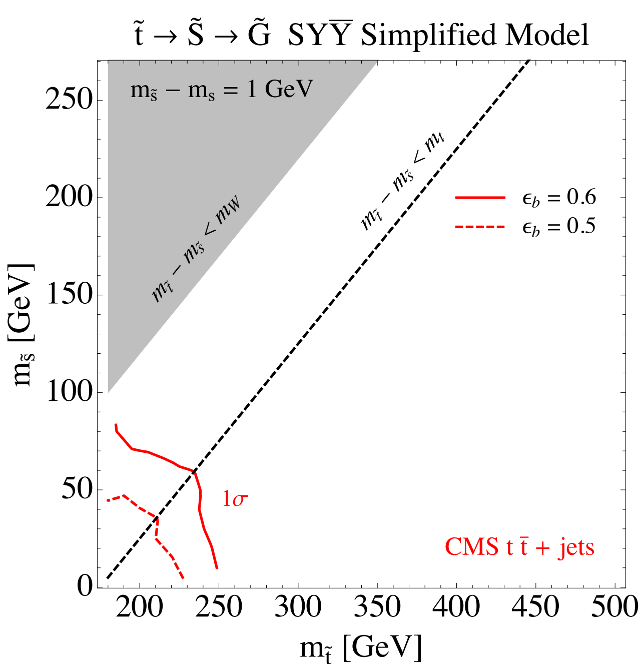
Stealth SUSY: erase MET by decaying into sector with small non-SUSY splitting
Motivates addition of hidden sectors to the MSSM.

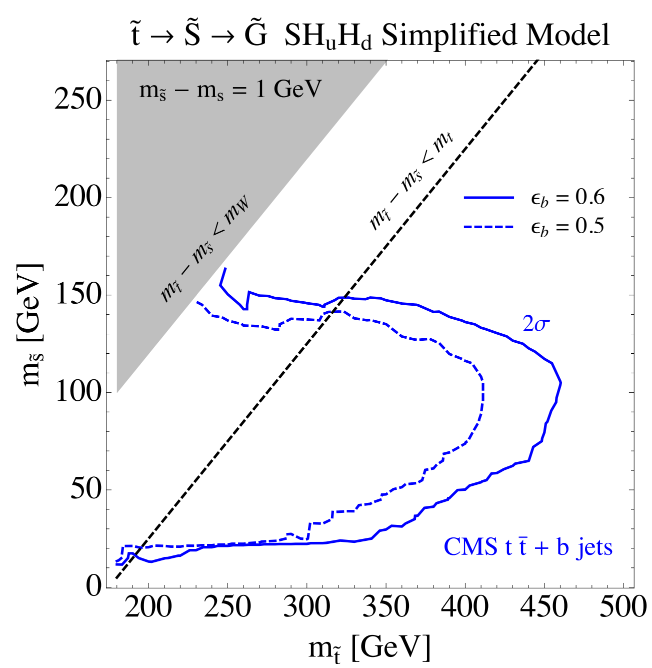


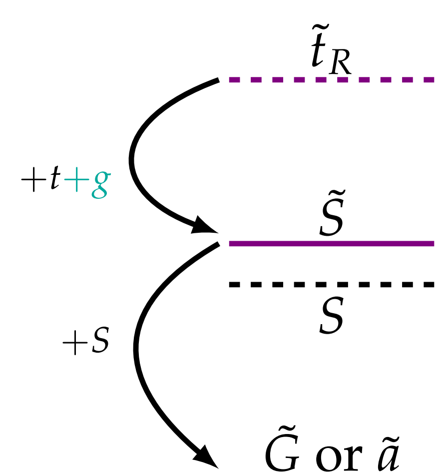


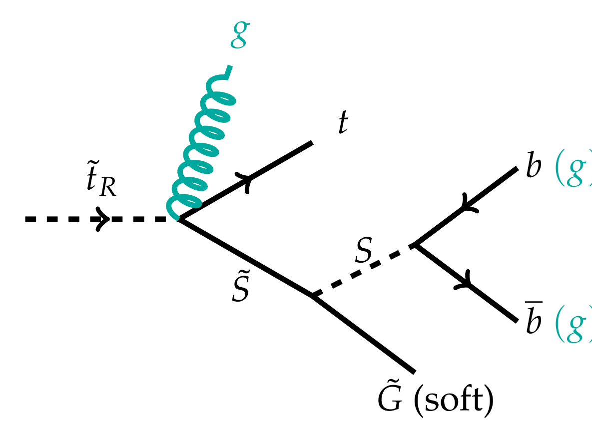


Trade MET for additional event activity, migrate signals to exotics; *sometimes you win, sometimes you lose.*









[Fan, Reece, Ruderman; Fan, Krall, Pinner, Reece, Ruderman]

Break the Spectrum 1

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

New supersoft operators

[Nelson, Roy]

SUSY broken by a D-term

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

Given an operator

$$\int d^2\theta \frac{\bar{D}^2(D^\alpha V' D_\alpha H_u)}{M} H_d$$

Effectively 2 mu parameters

$$\frac{1}{2}(\mu_u + \mu_d)\psi_u\psi_d$$
$$+|\mu_u|^2|H_u|^2 + |\mu_d|^2|H_d|^2$$

Global symmetry

[NC, Howe; Cohen, Kearney, Luty]

SUSY Higgs is a pNGB associated with spontaneously broken global symmetry

$$\mathcal{G} \to \mathcal{H}$$

mu term an invariant of

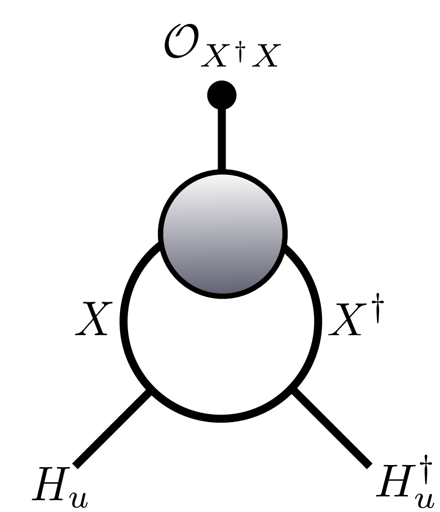
$$\mathcal{G}$$

doesn't contribute to Higgs potential

Exotic hidden sector dynamics?

[Roy, Schmaltz; NC, Green; NC, Knapen, Shih]

$$X^\dagger(z)X(0) \sim \mathcal{C}|z|^{\Delta_{X^\dagger X}-2\Delta_X}\mathcal{O}_{X^\dagger X}(0) + \ldots$$



$$m_H^2 + \mu^2 \to 0$$

Best limits:
conformal bootstrap!

No local 4D SUSY *(e.g. SUSY extra dimensions)*

Break the Spectrum 2

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

Induce Dirac gaugino mass from D-term $\quad W \supset \frac{W'_\alpha W_j^\alpha A_j}{M} \longrightarrow \mathcal{L} \supset \frac{D}{M}\lambda\tilde{a}$

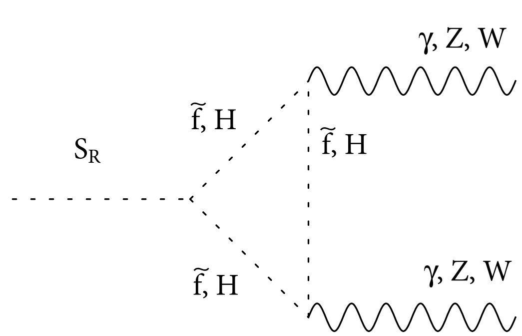
$$K \supset \frac{(W'^\alpha W'_\alpha)^\dagger W'^\beta W'_\beta}{M^6} Q^\dagger Q$$

This operator alone does not induce large scalar masses

Renders contribution to scalar masses finite, log of sgaugino/gaugino masses. $\quad \tilde{m}_i^2 \sim \frac{\alpha_i}{\pi} m_D^2 \log\left(m_a^2/m_D^2\right)$

Minimally $\; m_a \sim 2m_D \;$ so $\; m_{\tilde{t}} \sim M_3/5 \;$ Decouple gluinos!

Problem: also induce operator giving large sgaugino mass, makes log large. Much blood spilled to mitigate. $\quad W \supset \frac{W'_\alpha W'^\alpha}{M^2} A_j^2$



Experimental opportunity: new SU(3)xSU(2)xU(1) scalar adjoints

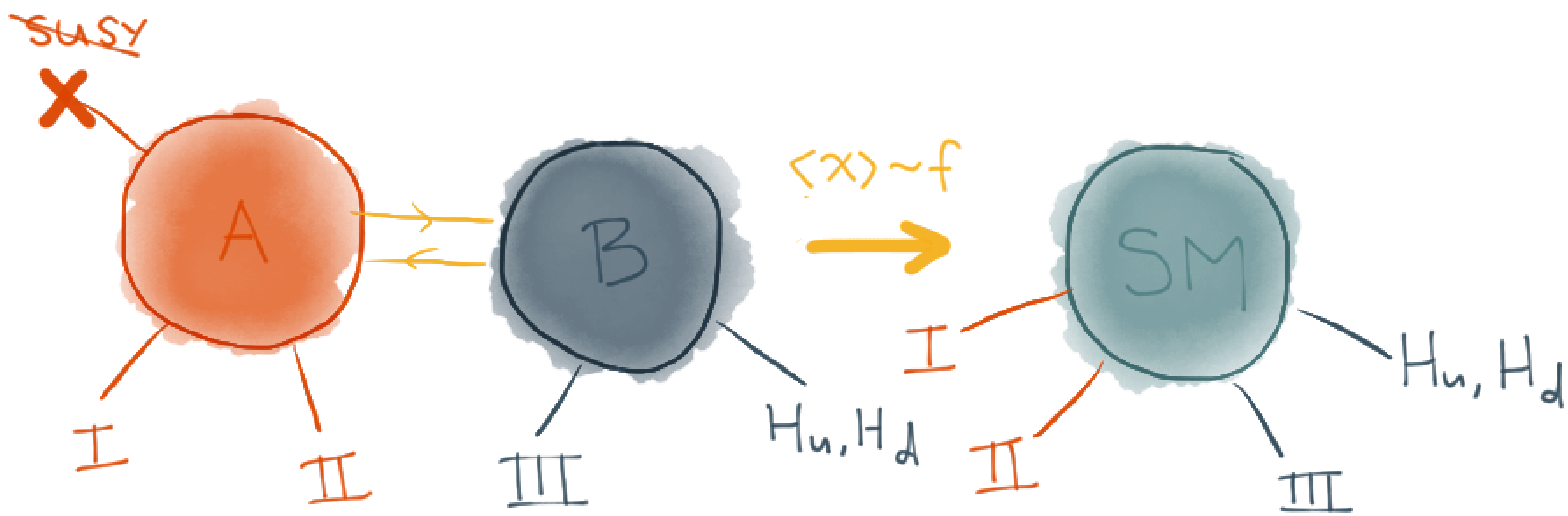
…and yes, you can have a 750 GeV sbino

[Carpenter, Colburn, Goodman]

Break the Spectrum 3

$$\Lambda \neq 100\,\mathrm{TeV}$$

(Λ = 100 TeV ~lowest practical scale for mediation of SUSY breaking, e.g. low-scale GMSB)



$$\tilde{m}_i^2 \sim \left(\frac{\alpha_i}{4\pi}\right)^2 \left(\frac{F}{M}\right)^2 \gg \tilde{m}_3^2 \sim \left(\frac{\alpha_i}{4\pi}\right)^2 \left(\frac{f}{M}\right)^2 \left(\frac{F}{M}\right)^2$$

Gives you a "natural SUSY" spectrum

Higgsing scale cuts off logarithms, e.g. $\delta m_{\tilde{t}}^2 = \frac{2g_s^2}{3\pi^2} m_{\tilde{g}}^2 \ln\left(f/m_{\tilde{g}}\right)$ where f~5-10 TeV

Experimental opportunity: new states in 1-10 TeV range associated with extended gauge structure

Is there a set of theories where this is accommodated naturally?

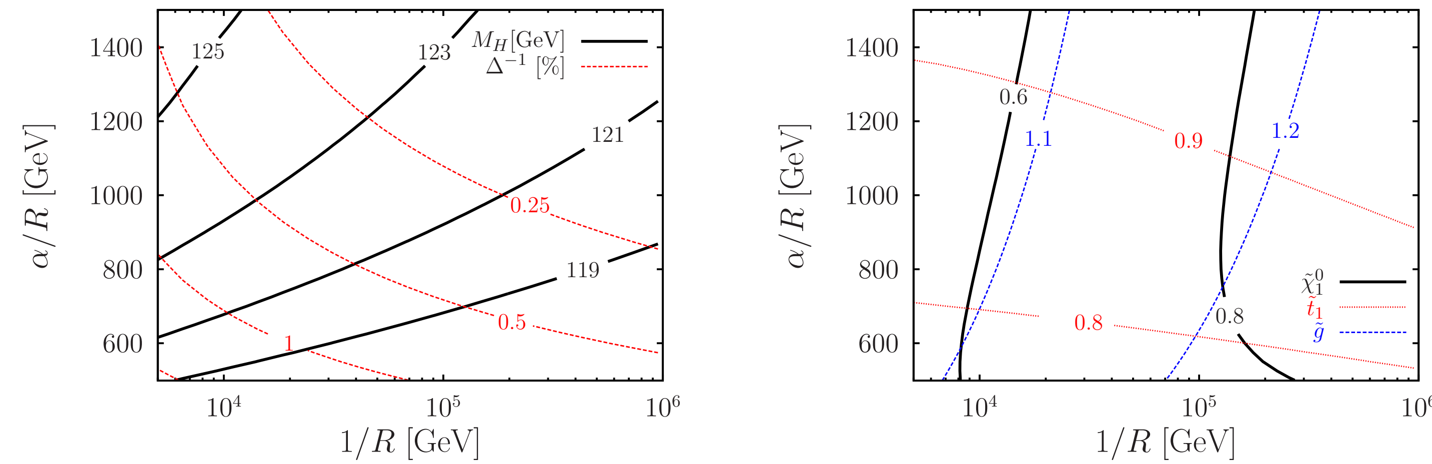
SUSY in 5D

- 5D SUSY theory, compactified on S_1/Z_2, SUSY broken by boundary conditions.
- Spectrum finite (not local in 4D) no large logarithms.
- "Universal" bulk spectrum, generically compressed.
- Geography/localization can distinguish generations.
- (Often) dirac gauginos.
- Zero modes not totally supersymmetric ("hard breaking" for higgsino).
- Higher KK modes can contribute to Higgs mass.
- Similar physics possible purely in 4D

[Quiros, Pomarol '98 et al.]

[Arkani-Hamed, Cohen, Georgi '01 et al.]

[Murayama, Nomura, Shirai, Tobioka '12]



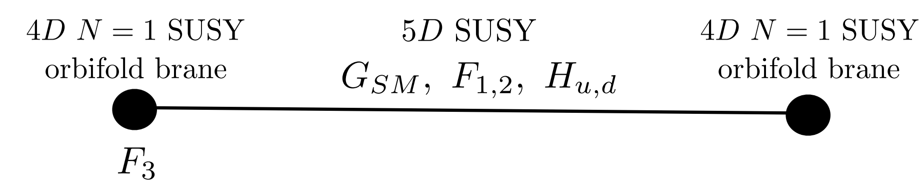


Fig. 1a

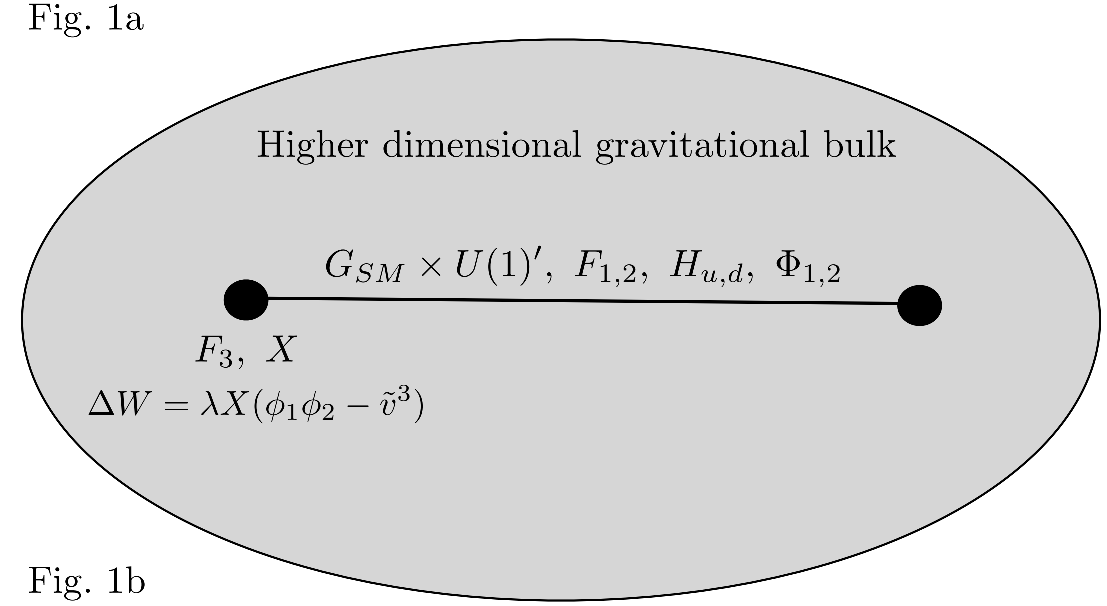
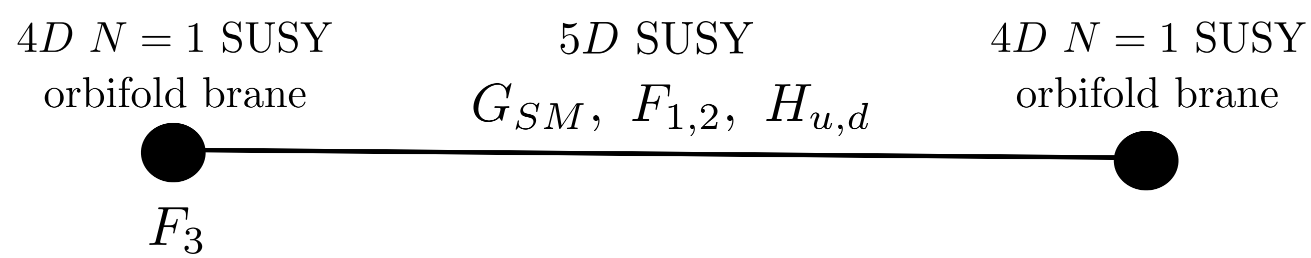
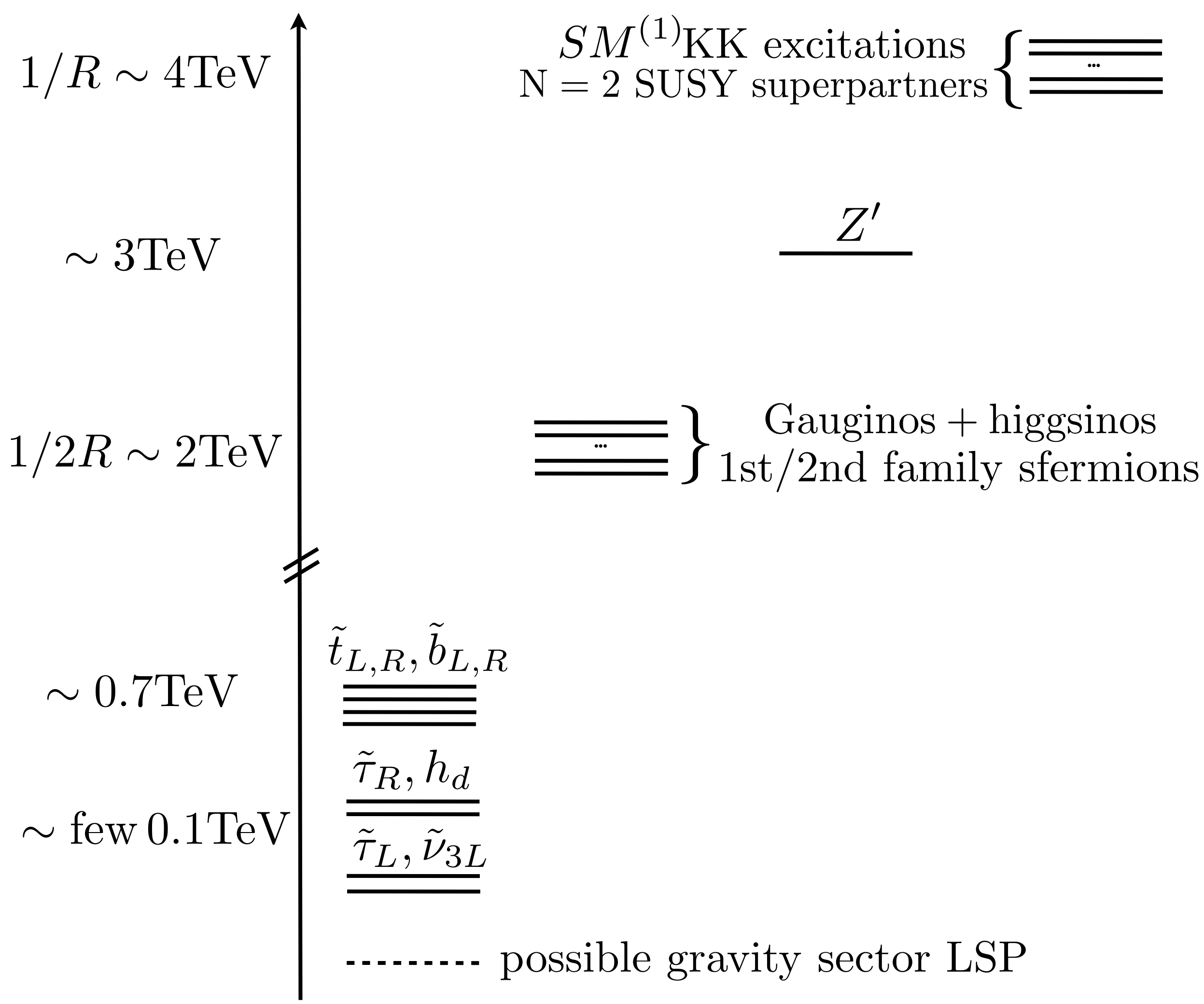


Fig. 1b

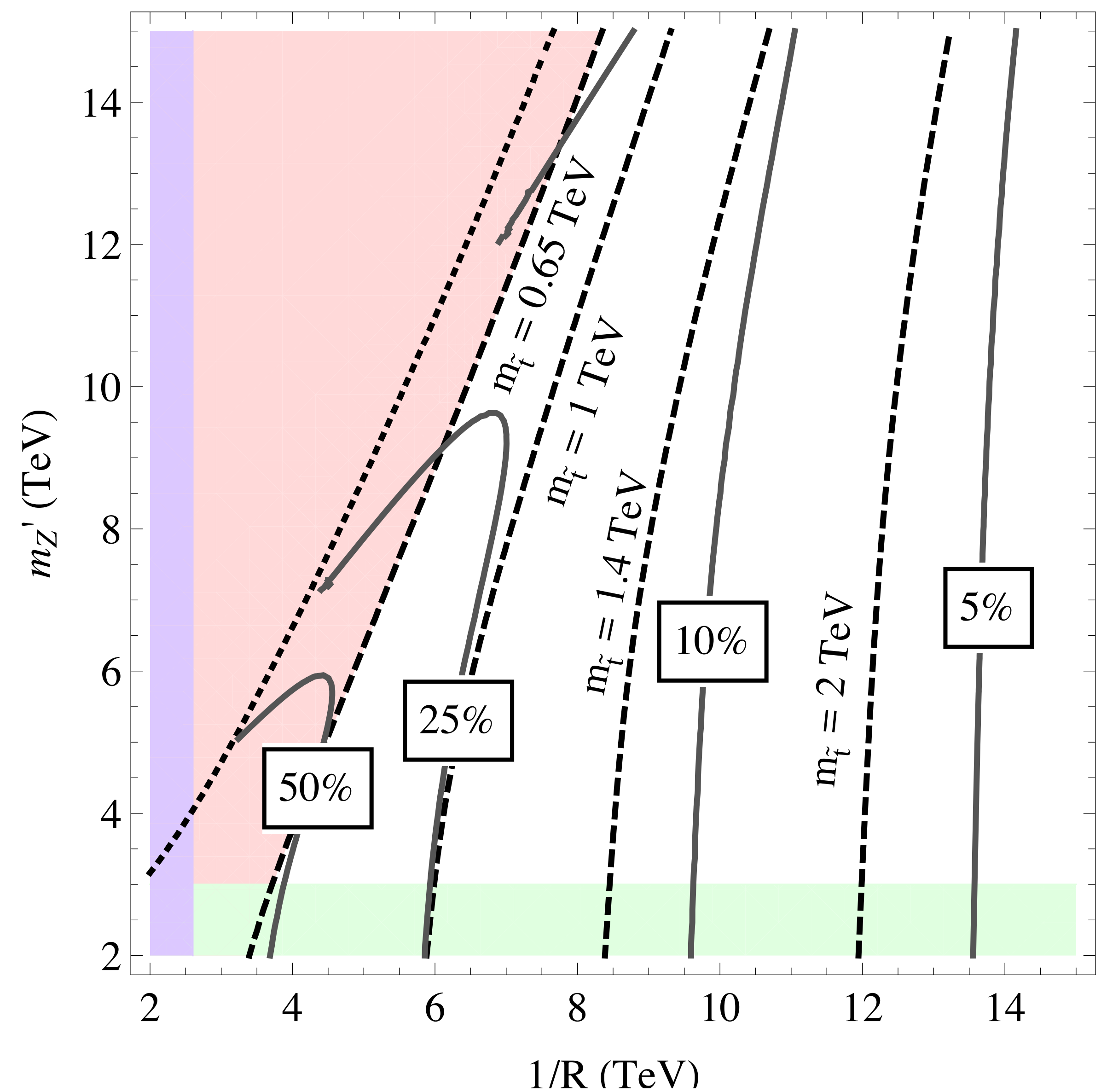
[Dimopoulos, Howe, March-Russell '14]

Maximally natural?





50% tuning for stops at 650 GeV, gluinos at 2 TeV (D-term for Higgs mass)



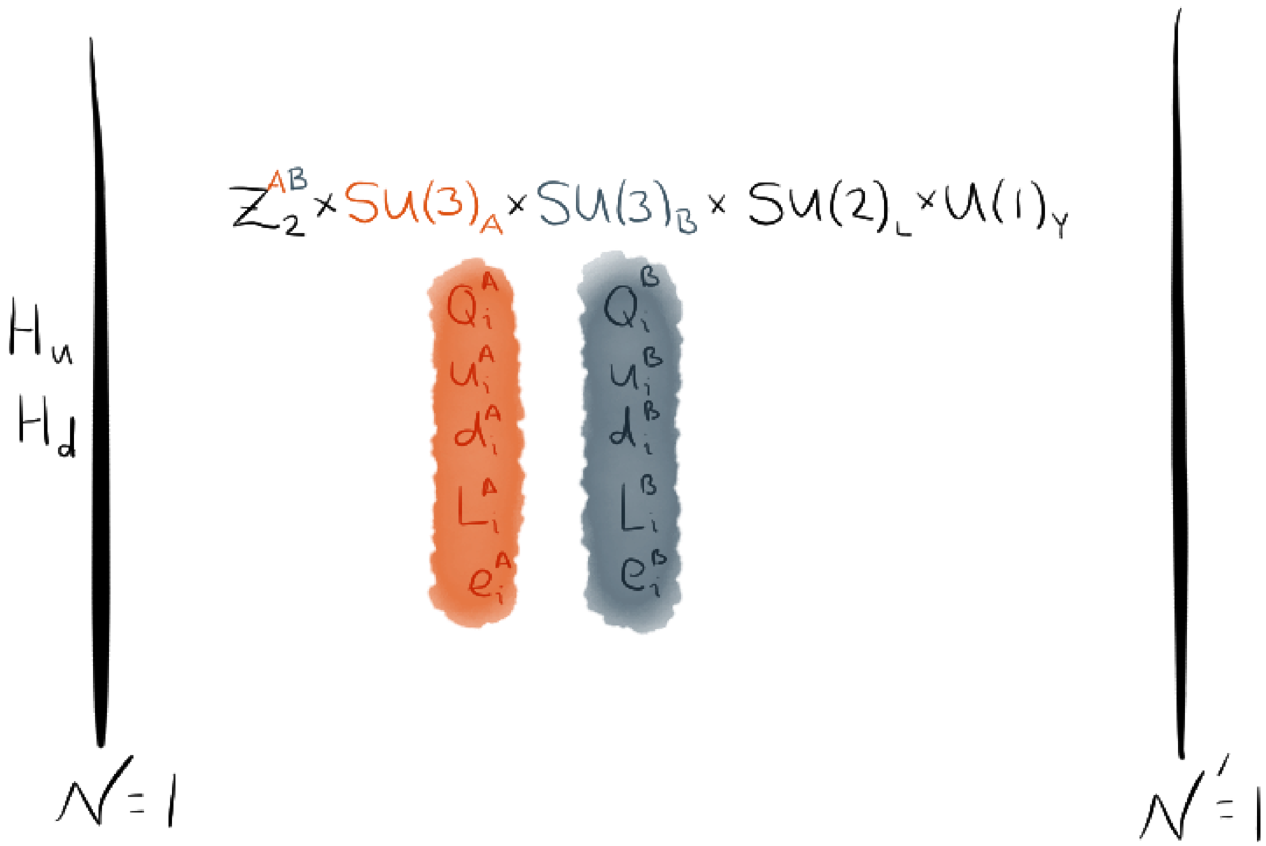
[Dimopoulos, Howe, March-Russell '14]

5D SUSY signals

- SUSY spectrum can have ideal properties consistent with current limits: light stops; heavy gluinos; heavy higgsinos, low cutoff (small logarithms).
- *Sleptons are interesting;* light stau NLSPs.
- Other models: less “natural SUSY,” more compressed spectrum.
- In all cases, KK excitations of SM states + higher-dimensional supersymmetry at ~few TeV. Can be singly produced — potentially most striking signature.
- Flavor observables interesting if geography is non-trivial; signals in lepton flavor violation and B-meson mixing.

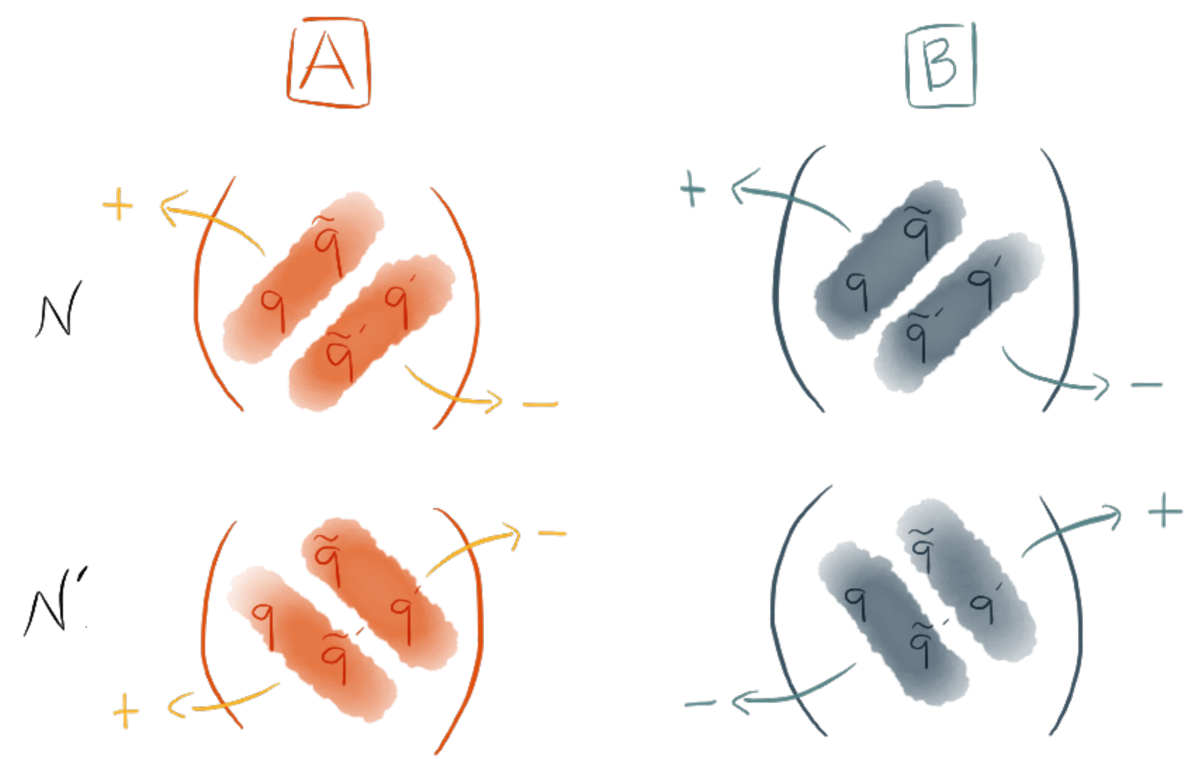
Could “natural” SUSY take an altogether different form?

SUSY without color?



Go one step past symmetry reduction with boundary conditions: increase bulk gauge symmetries beyond those of SM

Reduce symmetries & SUSY at the boundaries



Can lead to light superpartners with different gauge quantum numbers from SM counterparts

Folded SUSY

[Burdman, Chacko, Goh, Harnik '06; Cohen, NC, Lou, Pinner '15]

Colorless Stops

Zero mode spectrum: SM fermions, folded sfermions

Couplings related by SUSY

$$\mathcal{L} \supset \lambda_t H_u q_3^A u_3^A + \lambda_t^2 |H_u \cdot \tilde{q}_3^B|^2 + \lambda_t^2 |H_u|^2 |\tilde{u}_3^B|^2$$

Normal top quarks

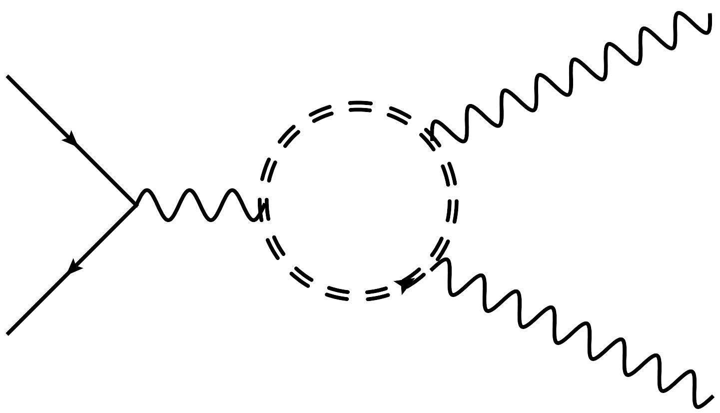
Charged under a hidden SU(3); only carry electroweak SM quantum #'s.

...Plus towers of KK states

Probably not the theory of nature, but a proof of principle for the wide scope of SUSY phenomena.

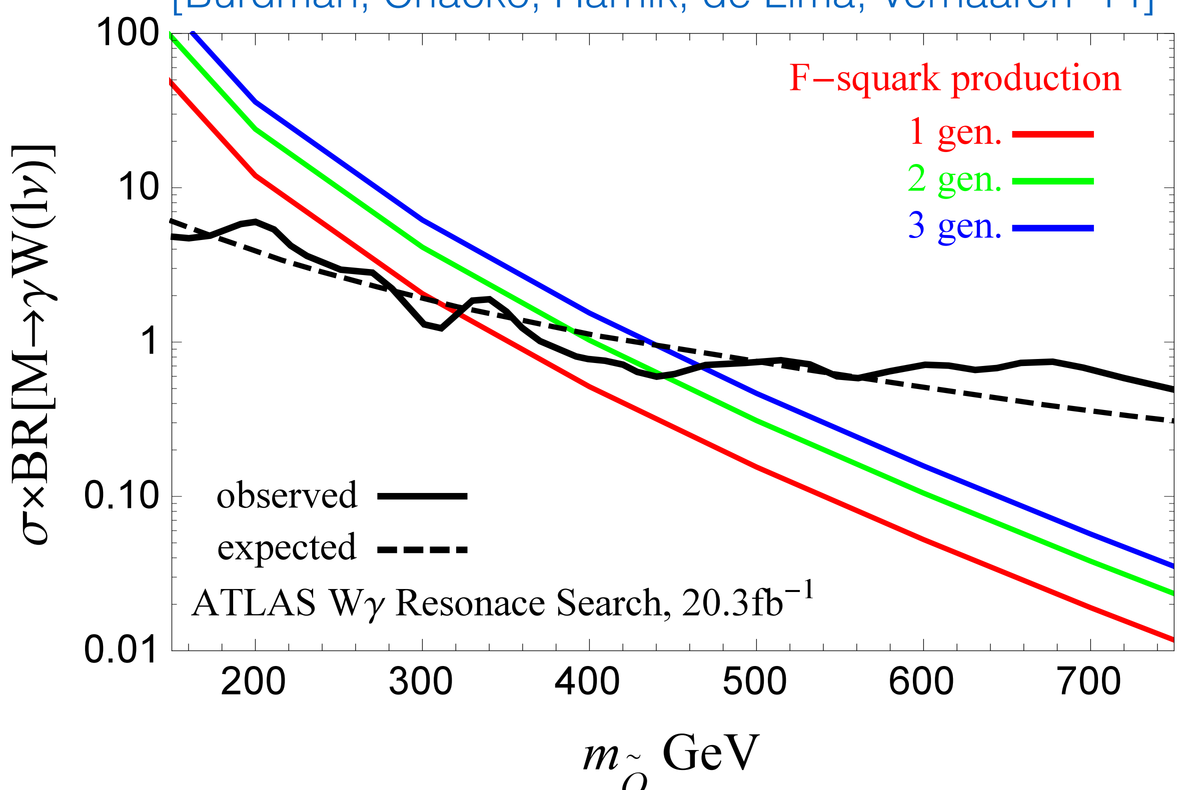
Colorless Signals

F-squarks carry electroweak quantum numbers.

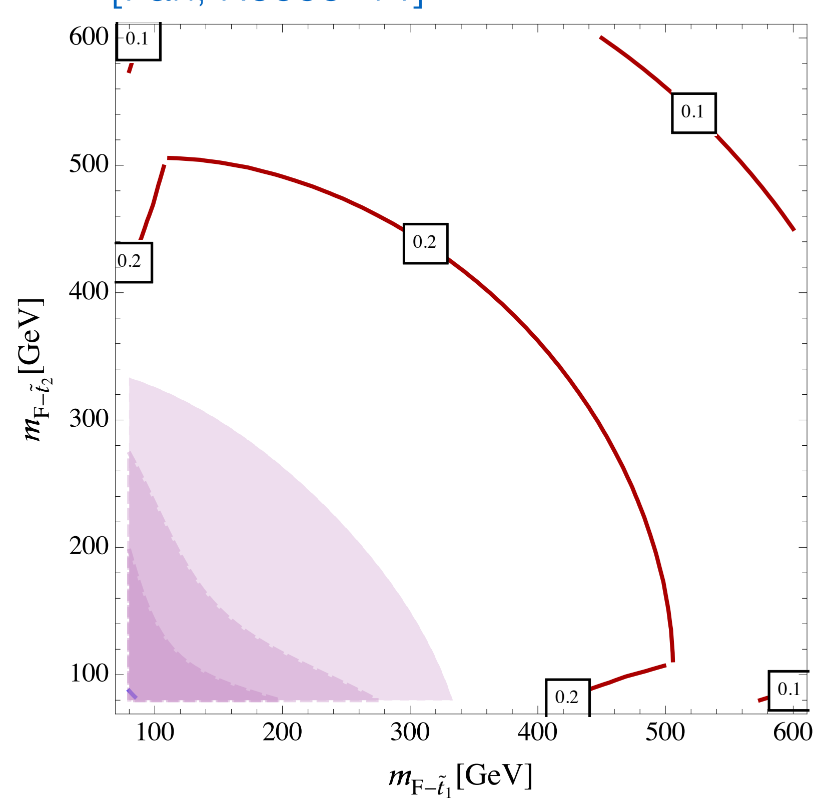


- Produced via a *Z*, typically annihilate into hidden glueballs. Glueballs decay back to SM via Higgs; displaced decays @ LHC length scales!
- Produced via a *W*, annihilate back into the SM to shed their charge.
- Also leave their mark in correcting Higgs decays to photons

[Burdman, Chacko, Harnik, de Lima, Verhaaren '14]



[Fan, Reece '14]



Could SUSY enter naturally at higher scales?

SUSY in the UV

Perhaps SUSY just solves the "big" hierarchy problem; only some residual shows up near the weak scale.

(Mini) Split SUSY

[Wells '03; Giudice & Romanino '04; Arkani-Hamed & Dimopoulos '04]

SUSY

$\tilde{m} \sim 10\text{–}10^9$ TeV

Relaxion?

[Graham, Kaplan, Rajendran; Batell, Giudice, McCullough]

$m_\lambda \sim$ TeV

Light gauginos. Stopped/displaced gluinos? Higgs production in Higgsino decays

Little Higgs

[Arkani-Hamed, Cohen, Georgi '01]

SUSY

$\tilde{m} \sim 10$ TeV

Global

$f \sim \tilde{m}/4\pi$

Light gauginos? Additional higgses. Light fermionic top partners w/ SM quantum #'s

Twin Higgs

[Chacko, Goh, Harnik '05]

SUSY

$\tilde{m} \sim 10$ TeV

Discrete

$f \sim \tilde{m}/4\pi$

Light gauginos? Additional higgses. Light fermionic top partners w/out SM quantum #'s

Conclusion

- "Vanilla" SUSY looking tuned at the percent level (even having explained the Higgs mass)
- More natural theories possible at price of minimality; generically leads to more (and more diverse) signatures.
- Blurring of SUSY & exotic signals (heavy resonances, hidden valleys, displaced decays, etc.)
- Models not "beautiful", but serve as examples of parametric phenomena that nature might prefer.