SUSY and BSM Theory after LHC16

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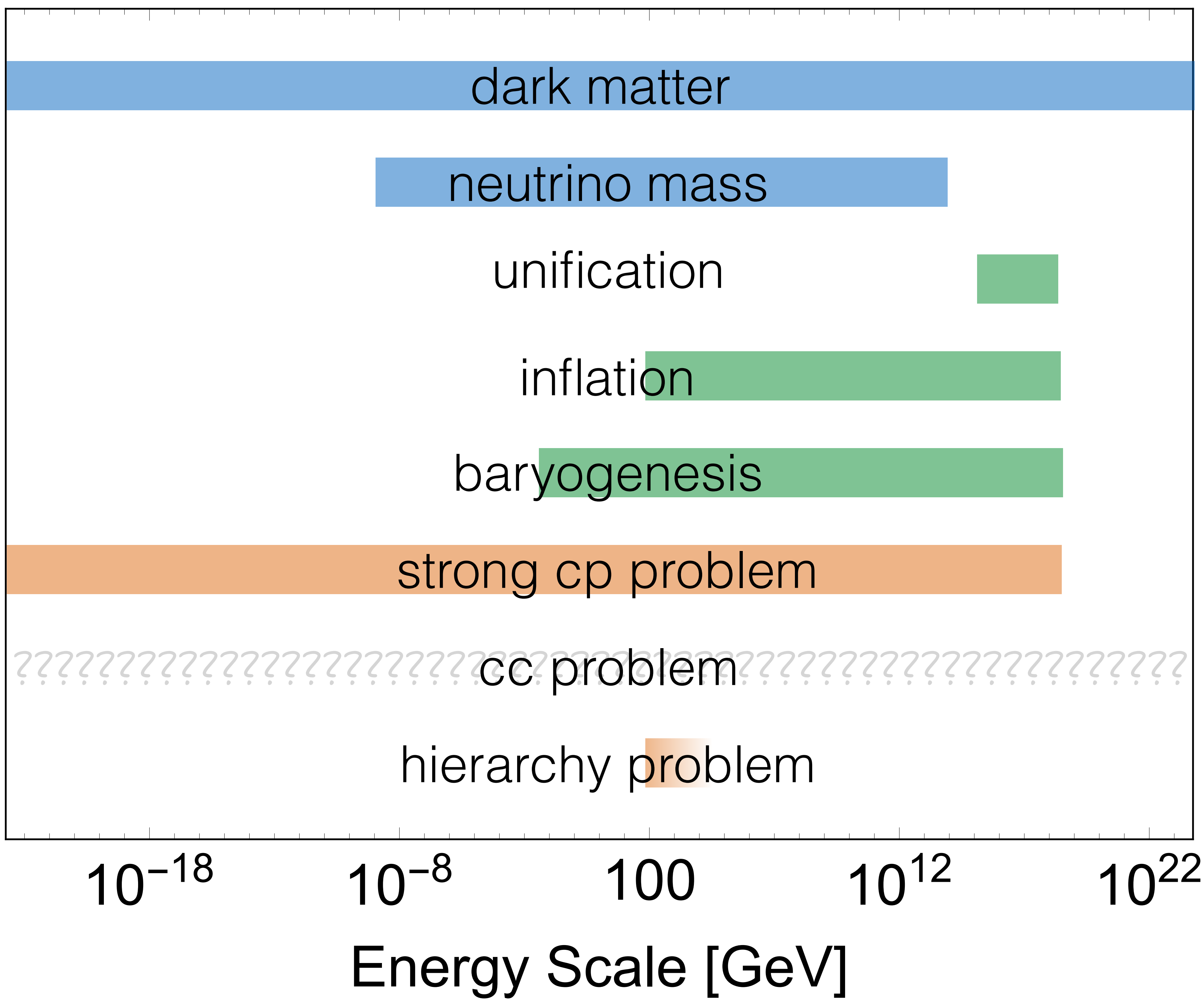
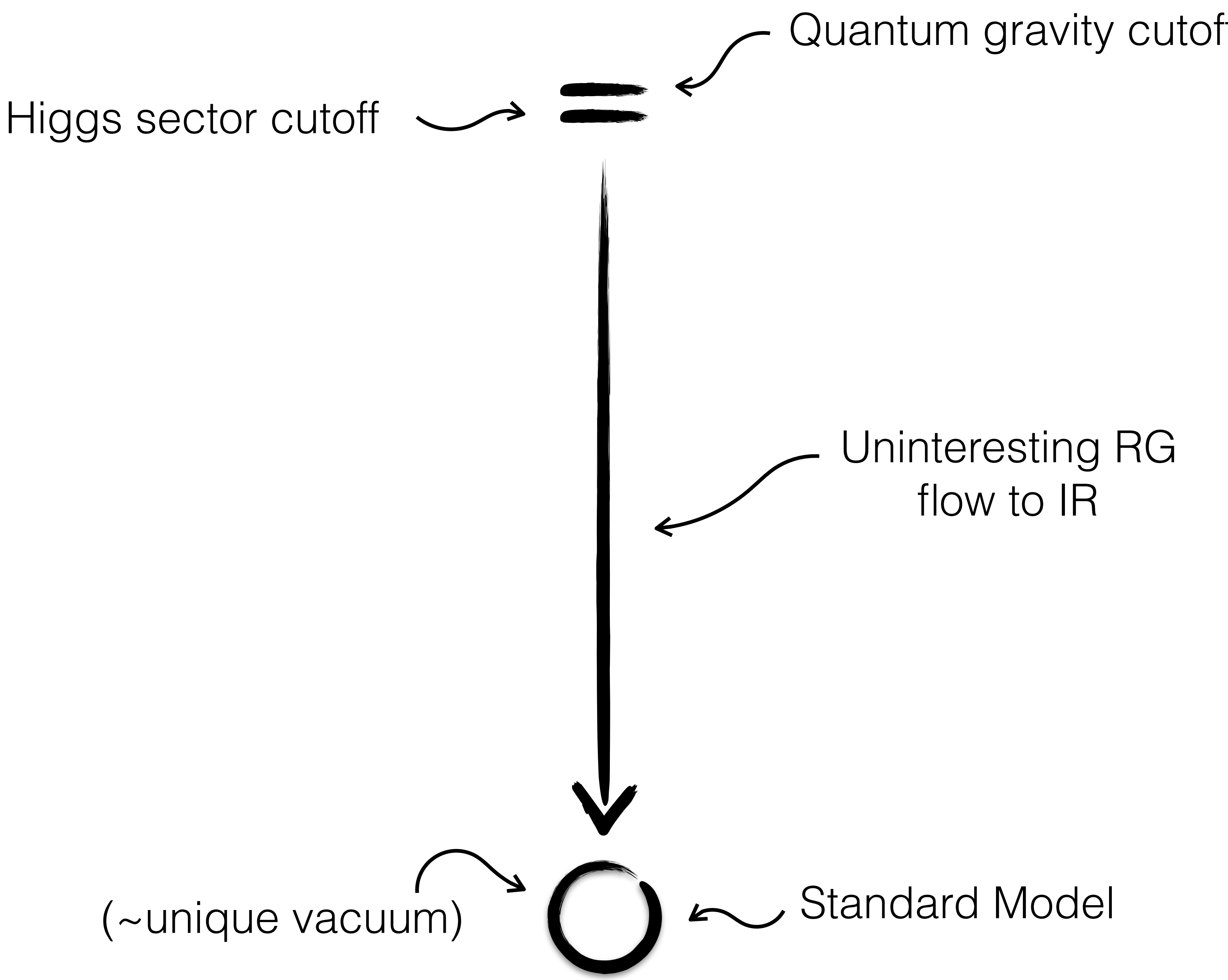
Lots of “Beyond the Standard Model”



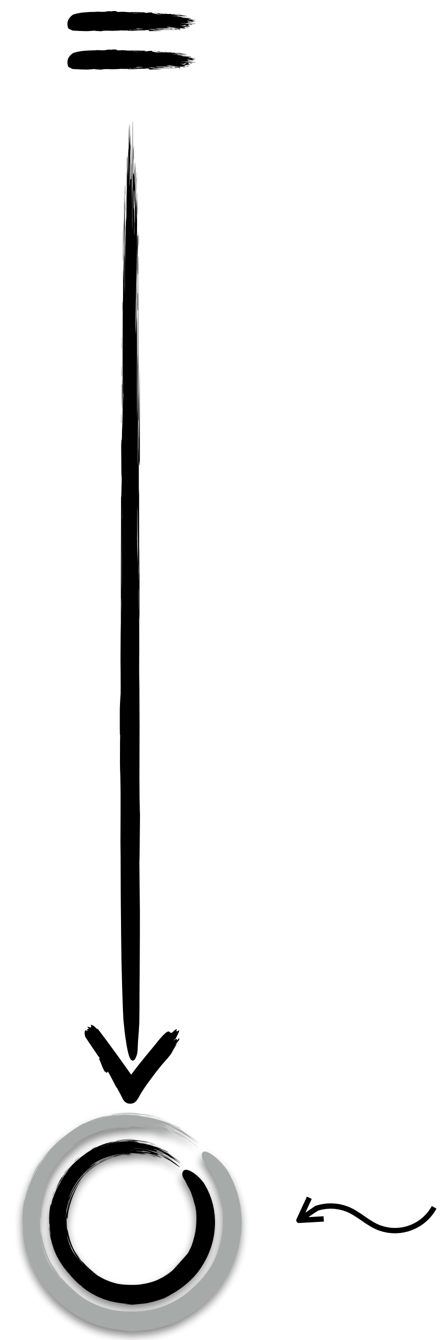
The Hierarchy Problem



m_H is not technically natural ⇒ Hierarchy problem

The usual approach*

*given an elementary Higgs

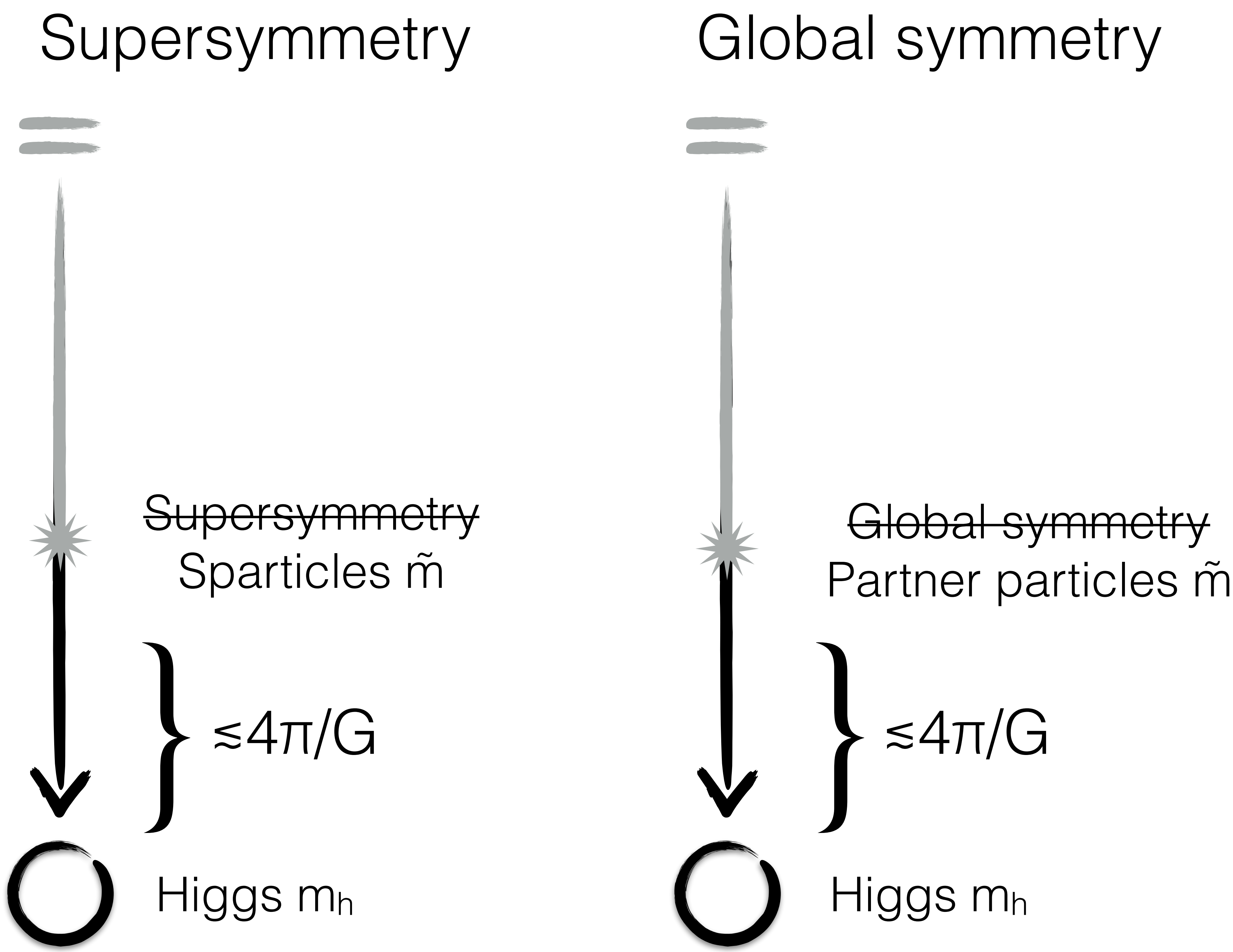


Extend SM with a symmetry

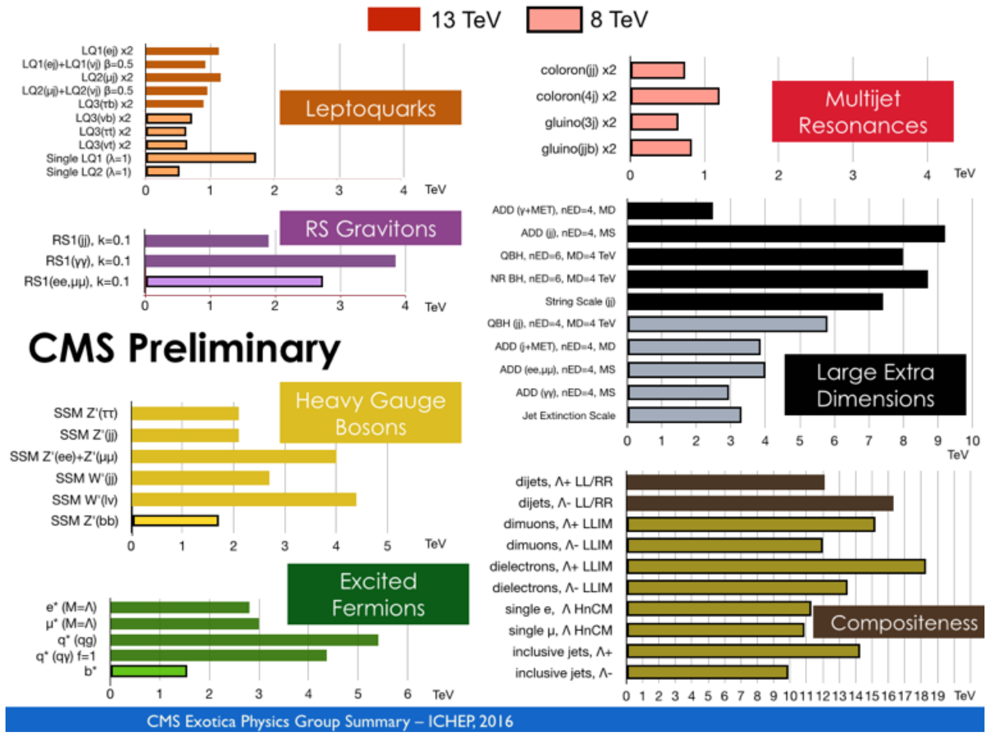
m_H is technically natural

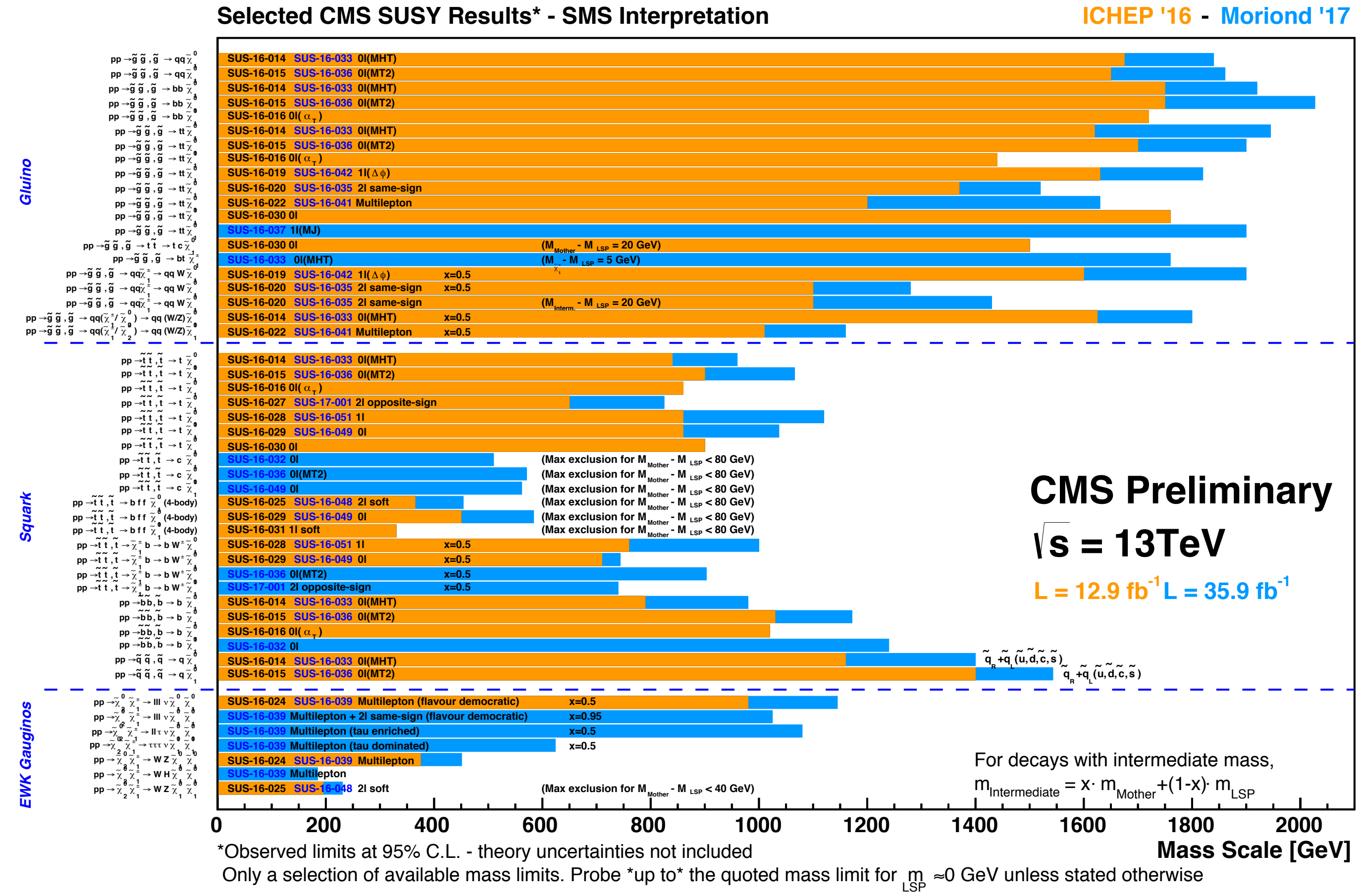
The usual approach*

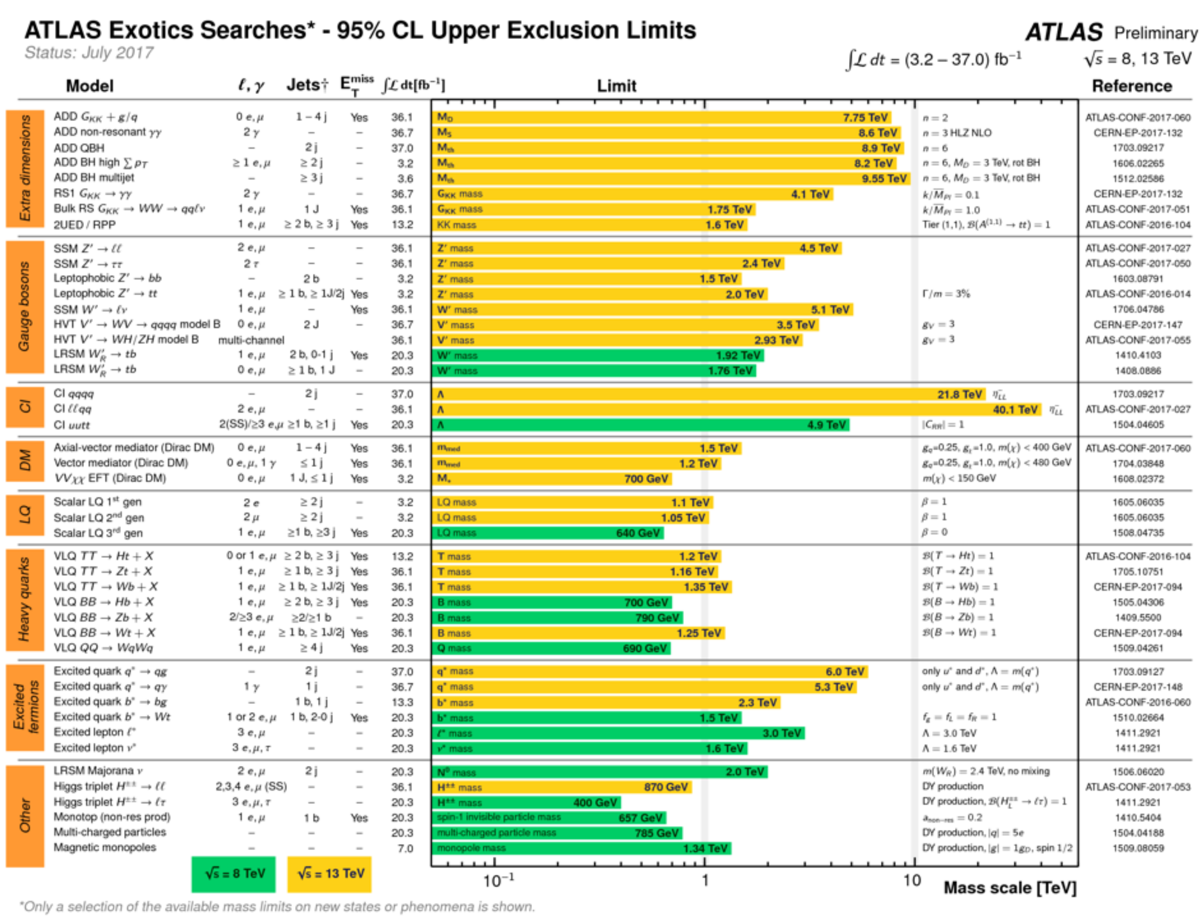
*given an elementary Higgs

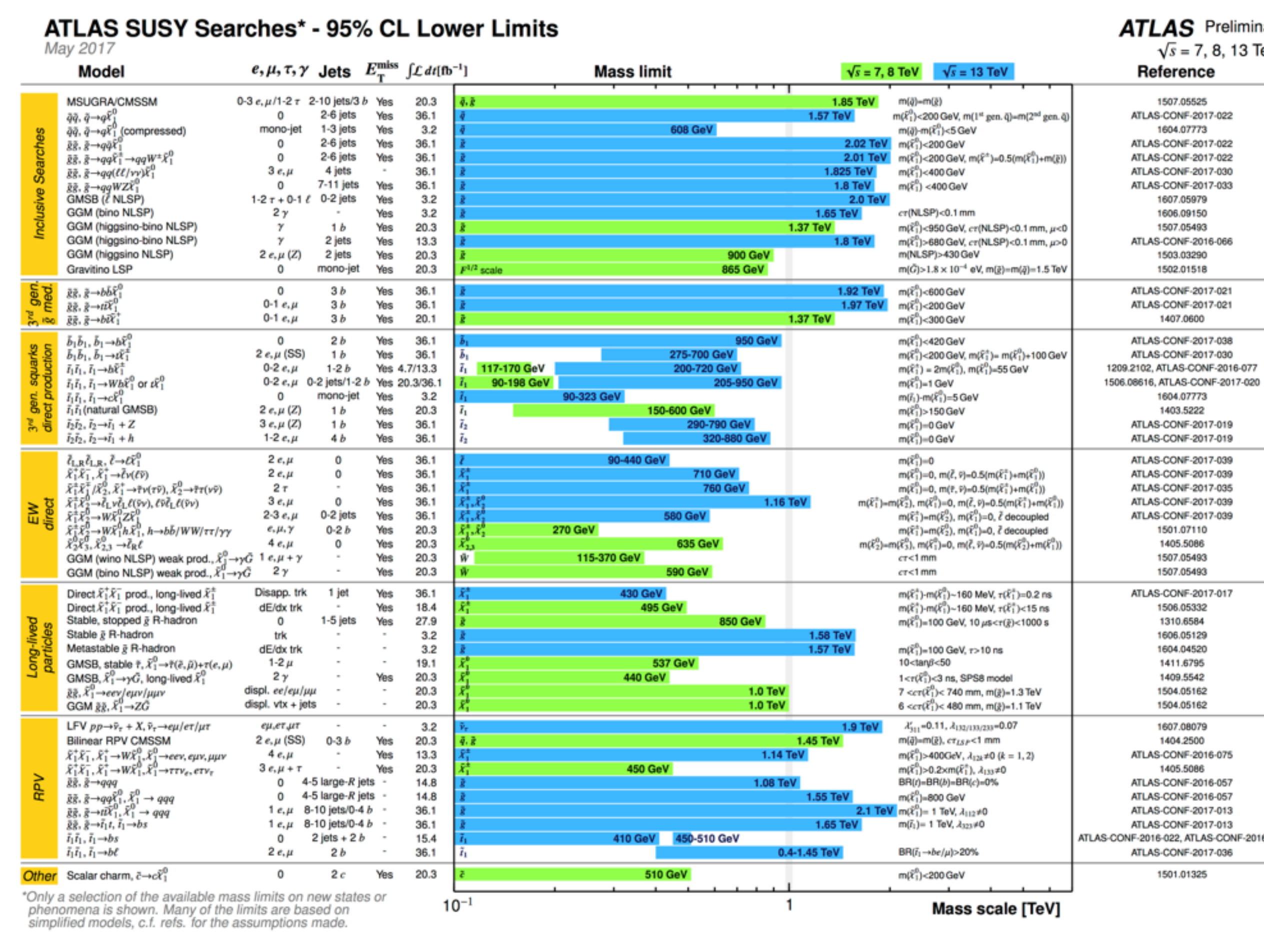


Tremendously effective!
Nothing so far.

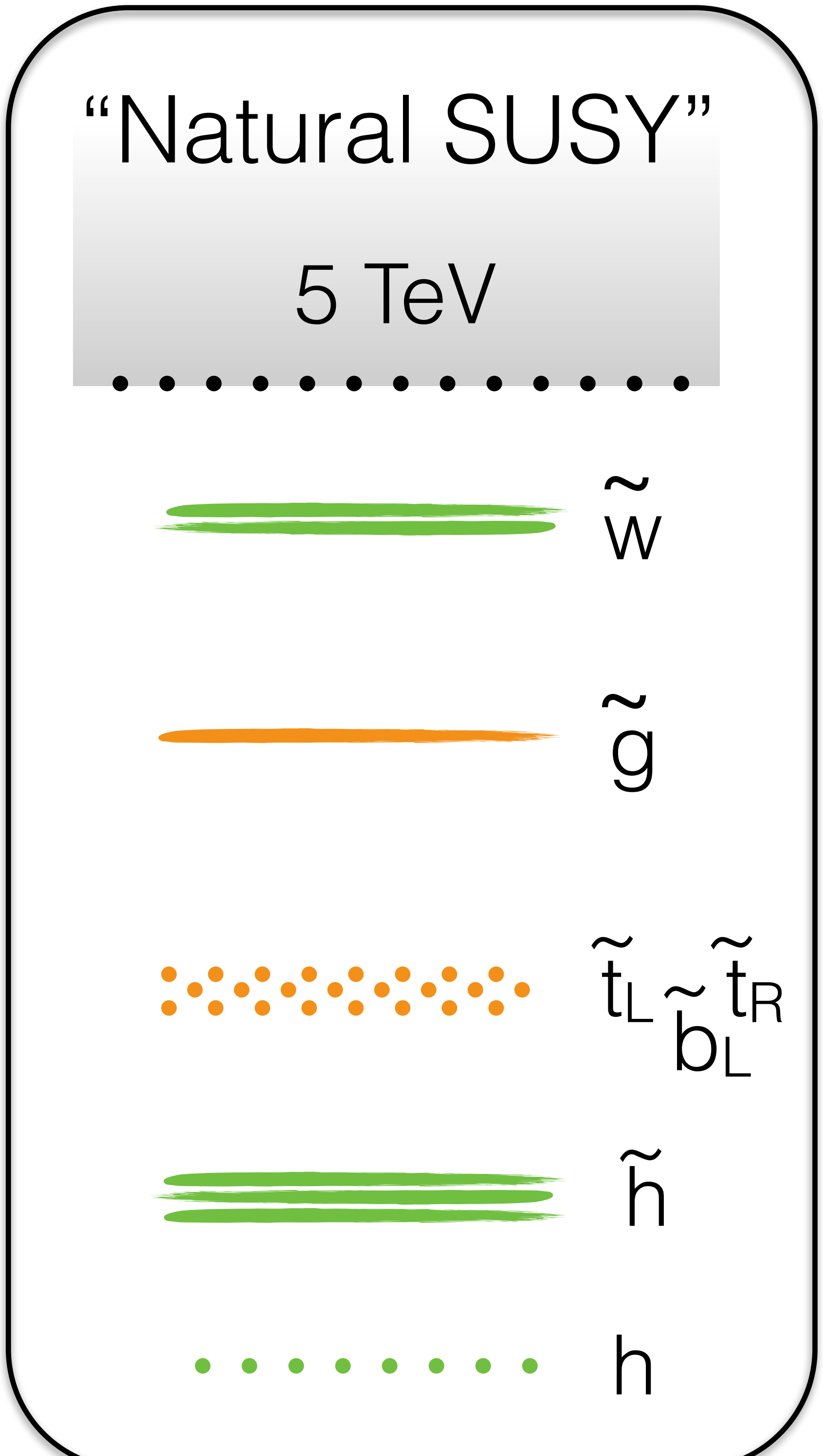








Where are we?



Best case scenario given null results: partner mass hierarchy inversely proportional to contribution to Higgs mass

Supersymmetry

$$\delta m_H^2 \propto \mu^2 \quad \text{(higgsinos)}$$

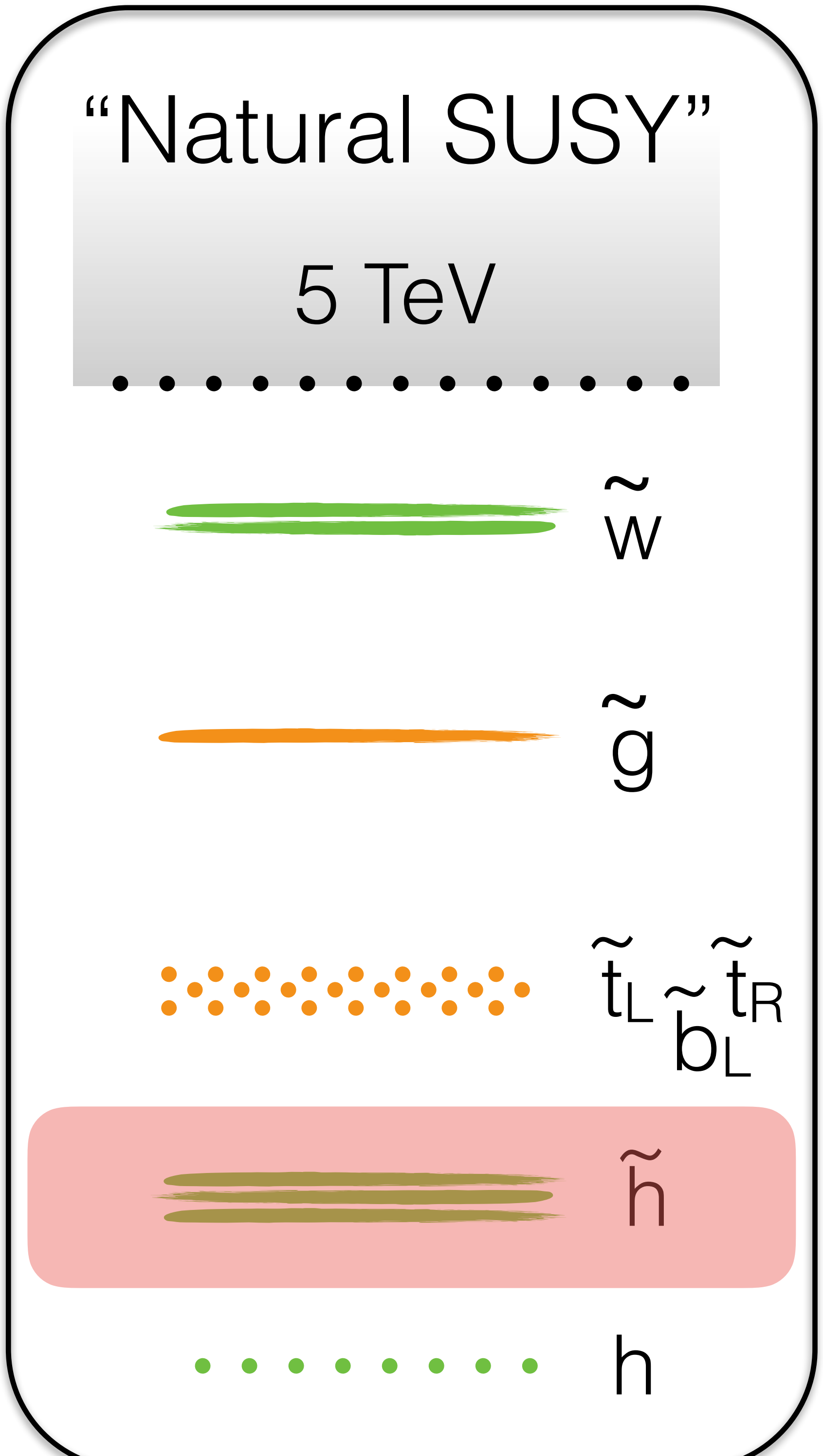
$$\delta m_H^2 \propto \frac{3y_t^2}{8\pi^2}\tilde{m}^2 \log(\Lambda/\tilde{m})$$

(stops, …)

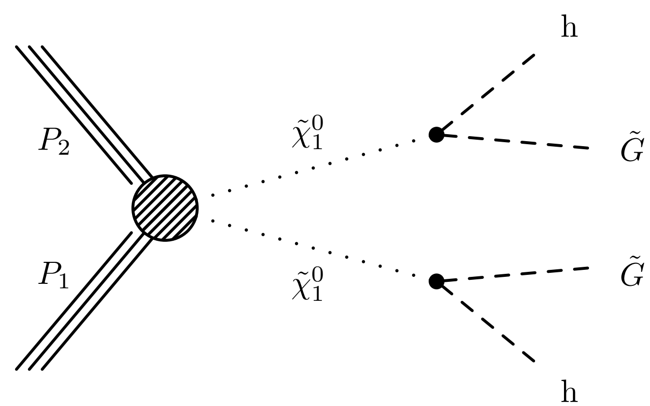
Quantify tuning (as you like) $\Delta \equiv \frac{2\delta m_H^2}{m_h^2}$ (“linearized” Barbieri-Giudice)

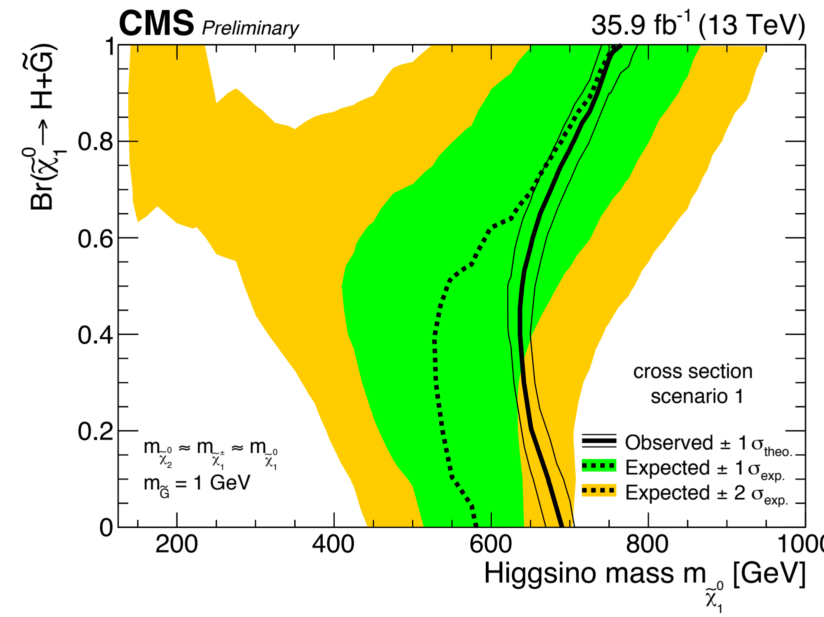
[Dimopoulos, Giudice ‘95; Cohen, Kaplan, Nelson ’96; Papucci, Ruderman, Weiler ’11; Brust, Katz, Lawrence, Sundrum ’11]

SUSY after LHC16: Higgsinos



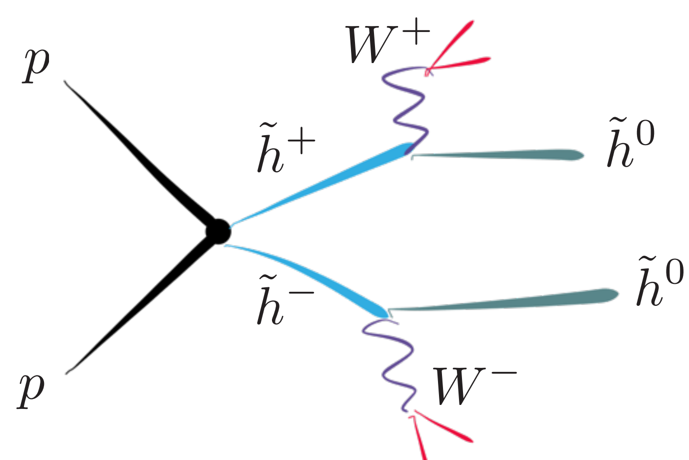
Lots of searches…

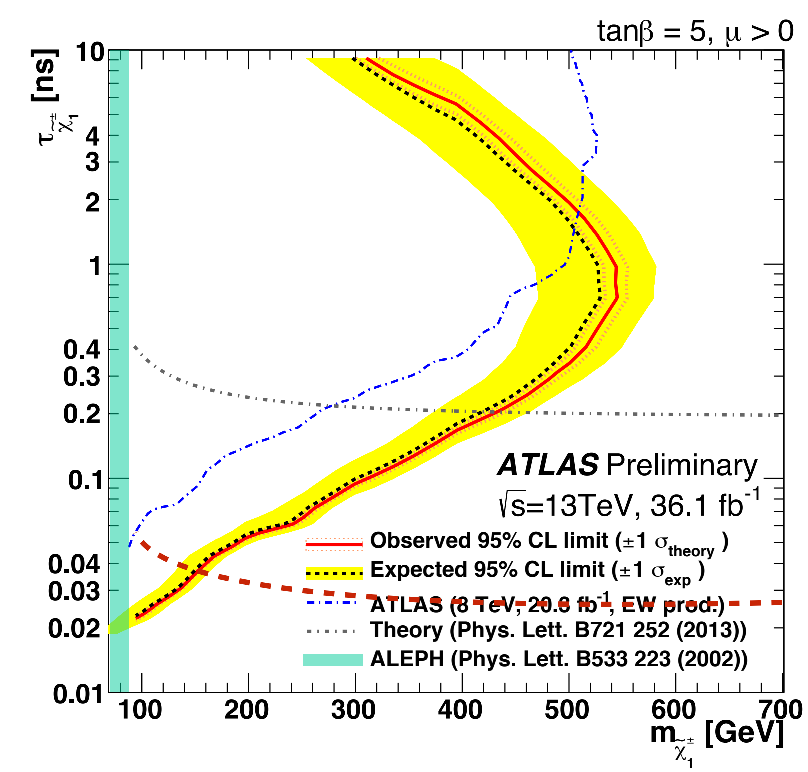




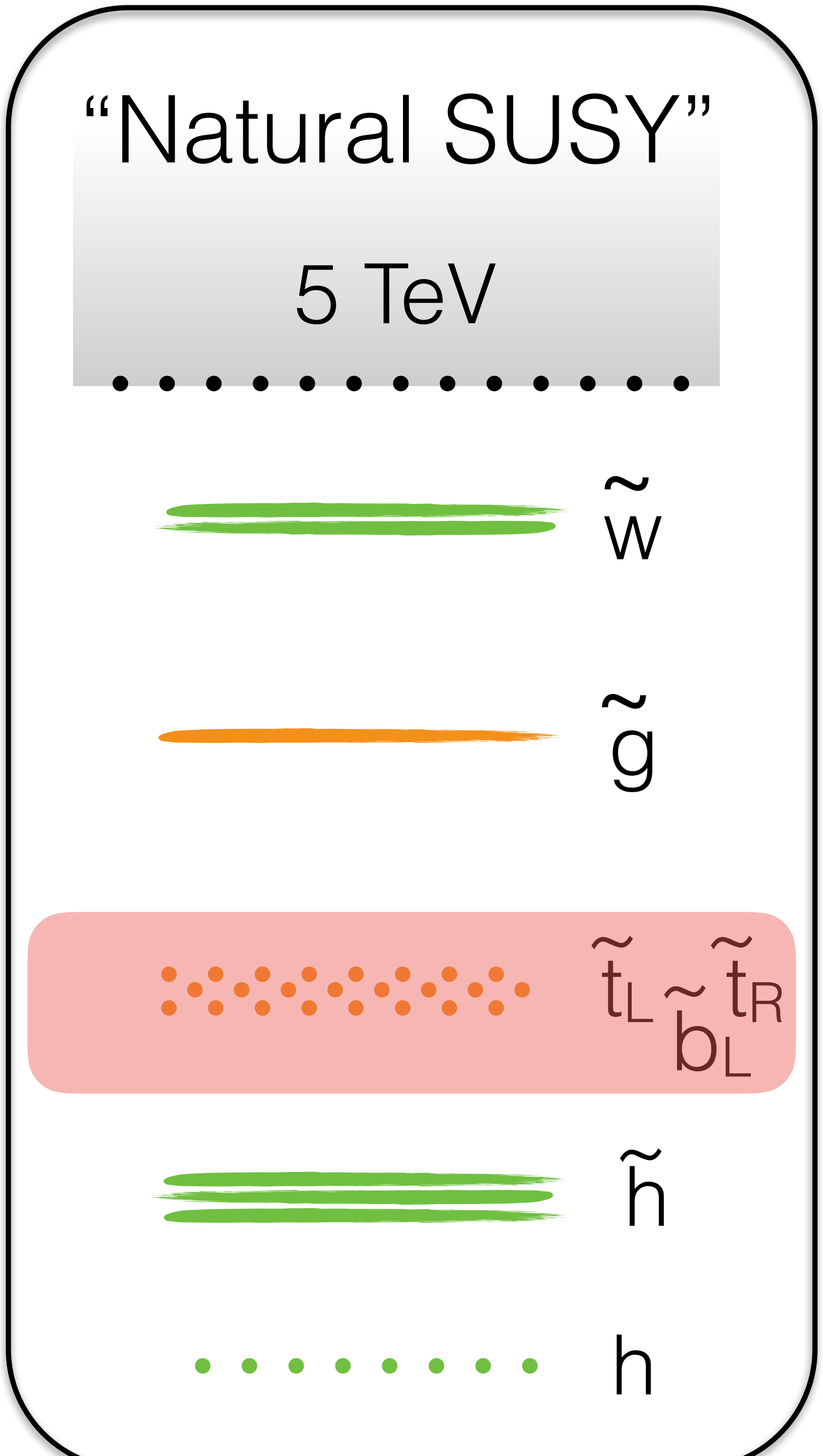
…no irreducible limits, but getting there?

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

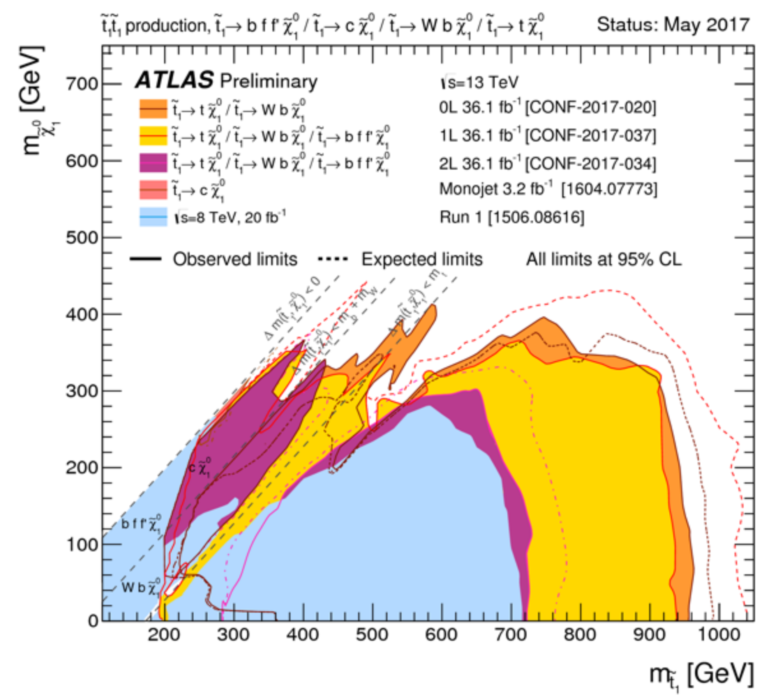


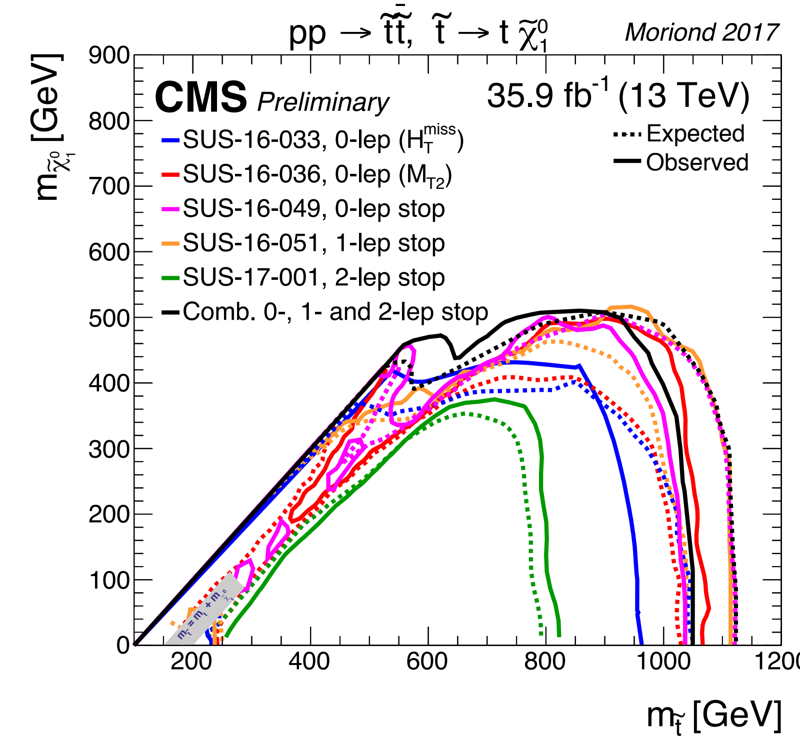


SUSY after LHC16: Stops



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

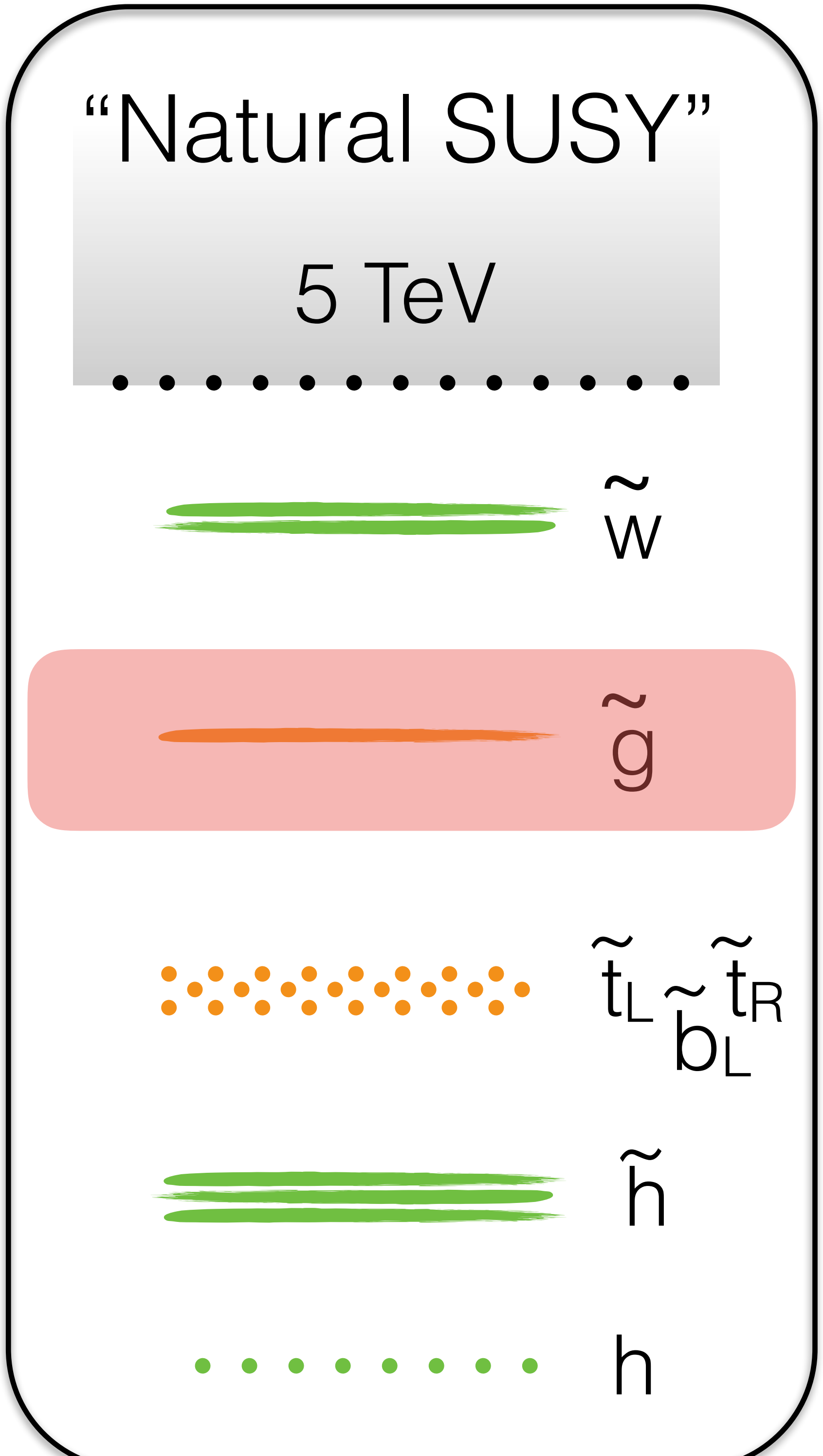




Generic limit > 1.1 TeV
→ **Δ~50 (2% tuning)**
(2 stops, Λ = 100 TeV)

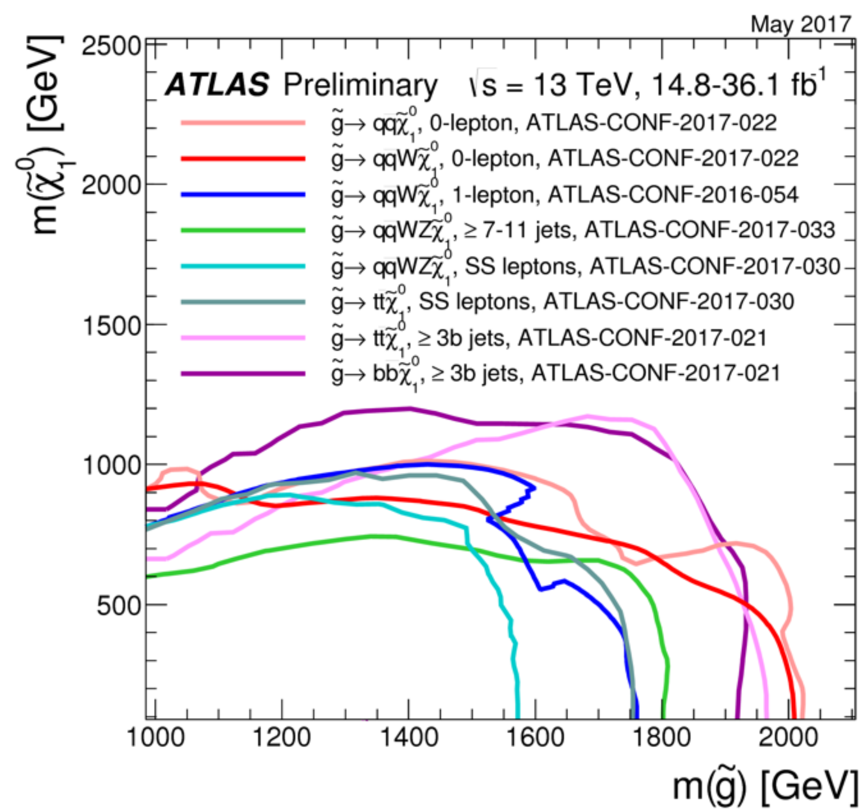
Compressed limit
> (600 GeV, 500 GeV)
→ **Δ~32 (3% tuning)**

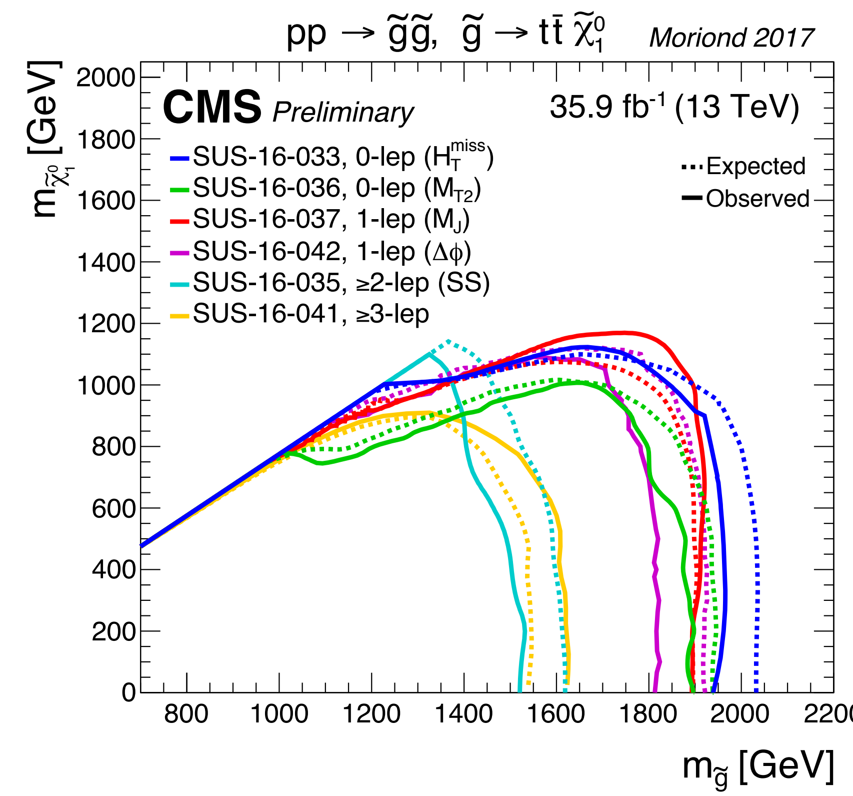
SUSY after LHC16: Gluinos



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

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





Generic limit > 2 TeV
→ **Δ~30 (3% tuning)**
(Λ = 100 TeV)

Compressed limit
> (1 TeV, 1 TeV)
→ **Δ~130 (1% 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)

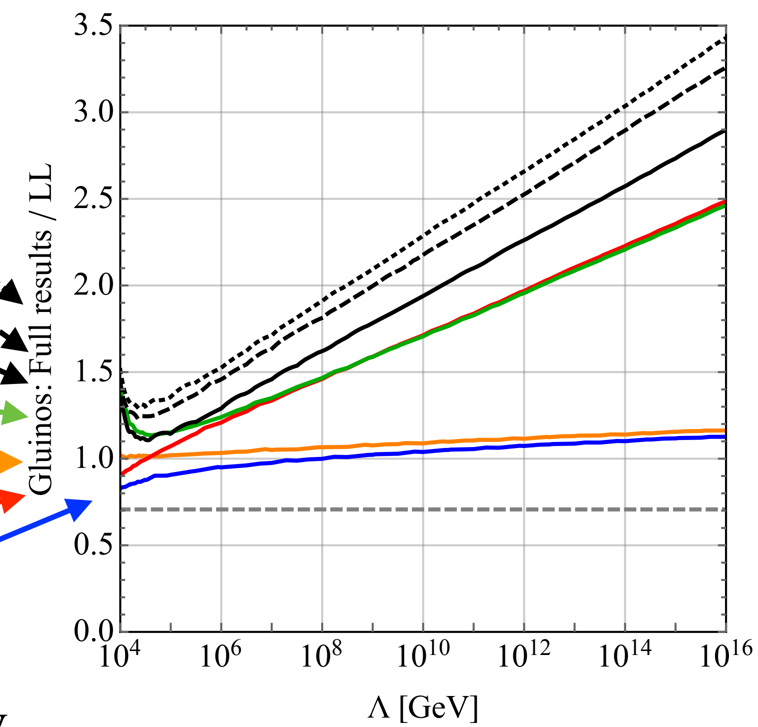
5. Pole masses (1G,2G=3G)

4. Two-loop thresholds

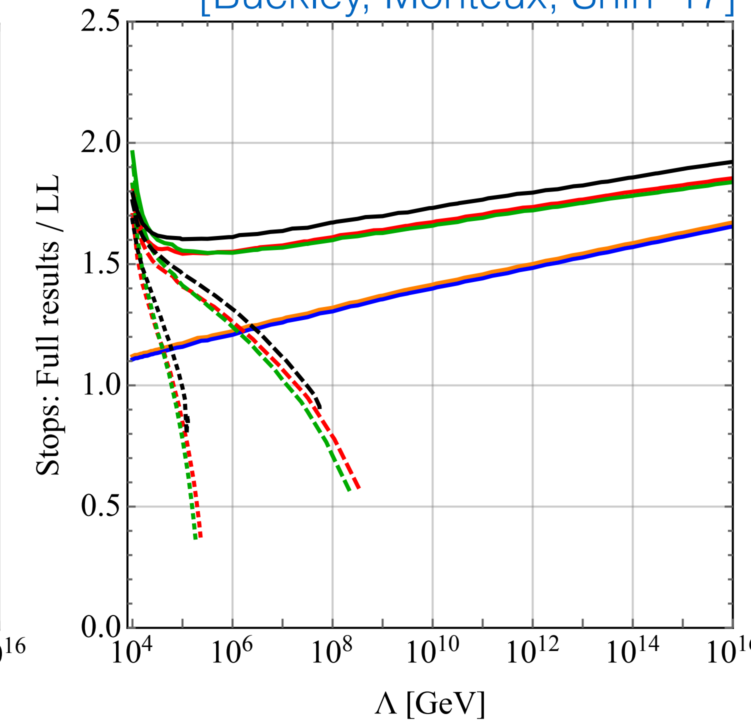
1. Resummed one-loop RGE

3. IR Running masses

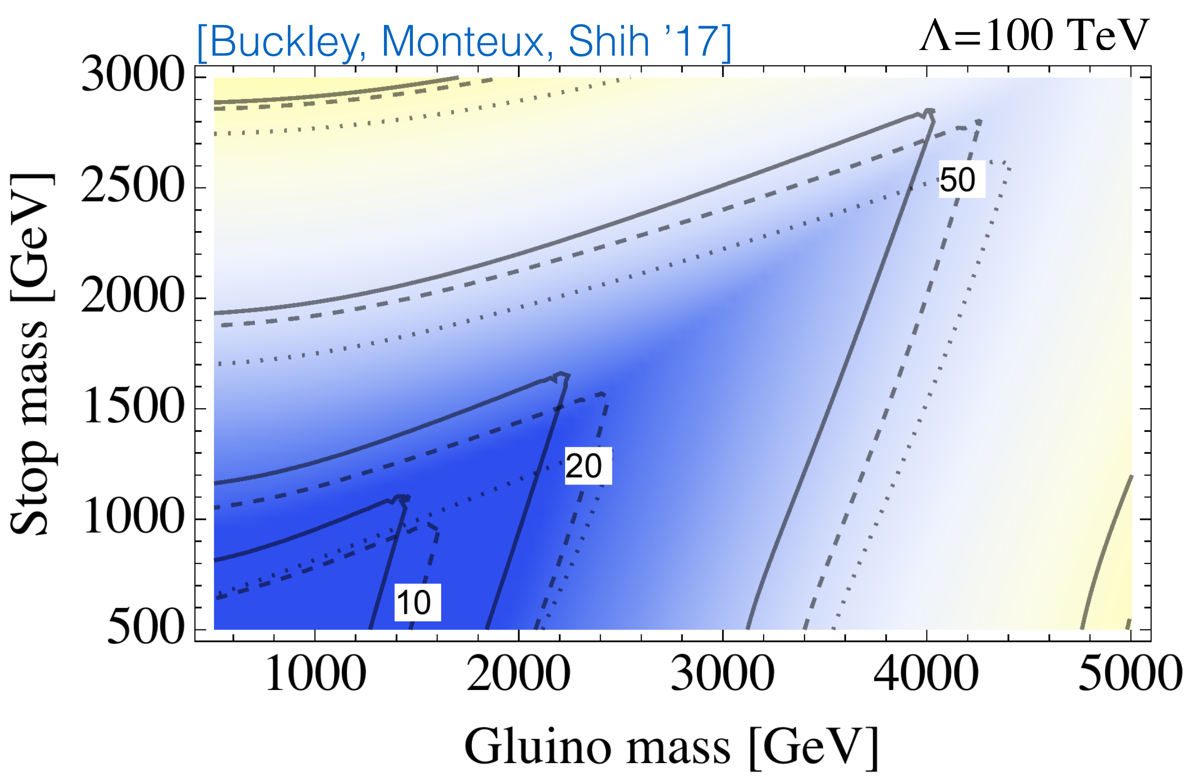
2. Resummed two-loop RGE



[Buckley, Monteux, Shih '17]



[Buckley, Monteux, Shih '17]

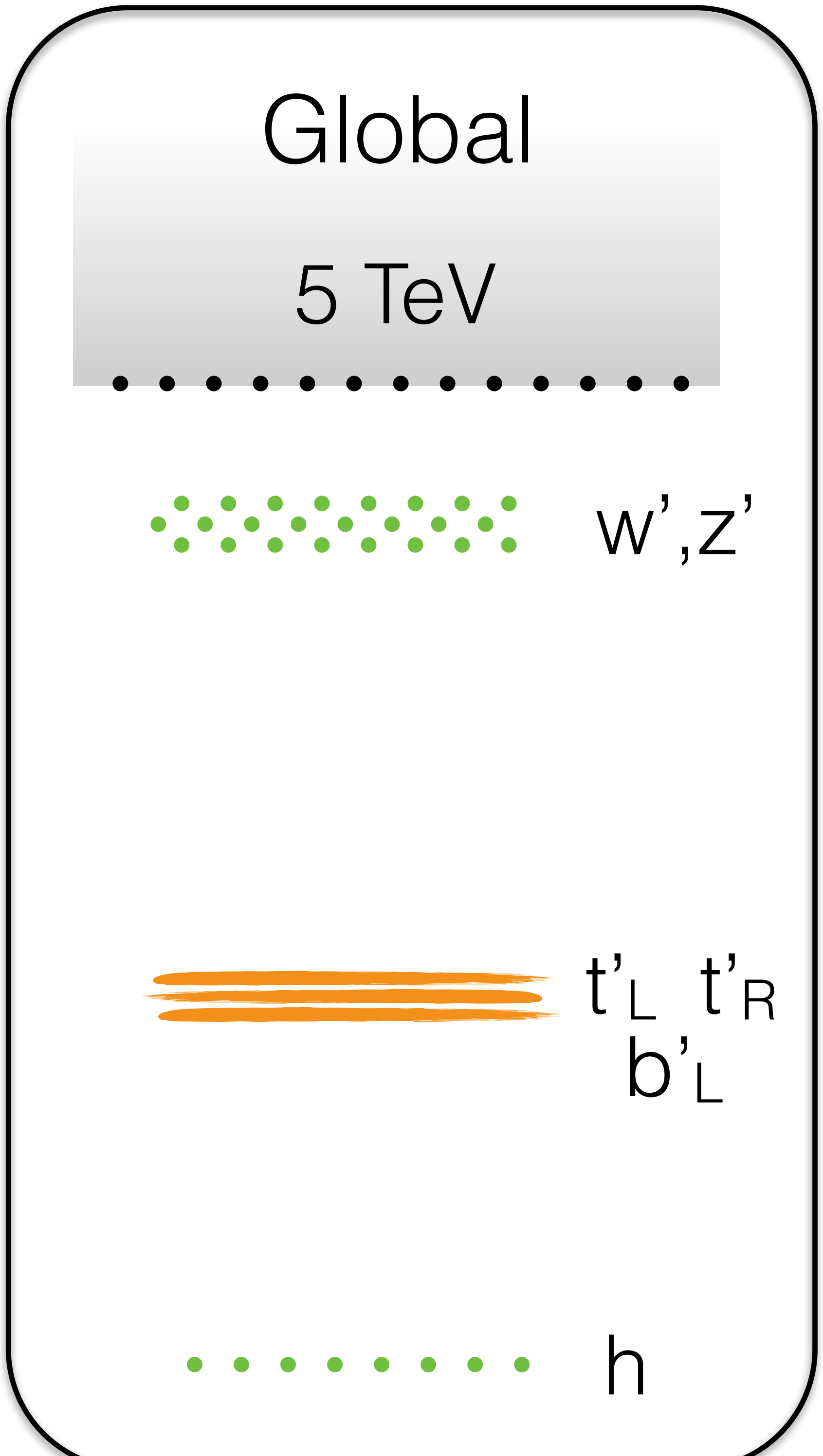


Accounting for all these effects gives factor-of-2 improvement. UV correlations could give further improvement*

Of course, fine-tuning not quantitative, just a measure of relative discomfort

*See also talk by R. Dermisek

Global expectations



Story essentially same as SUSY, but now w/ light fermionic top partners & Higgs tuning

$$\delta m_H^2 \propto \frac{3y_t^2}{8\pi^2} m_T^2 \log(\Lambda/m_T) \qquad \text{(top partners)}$$

Radiative Higgs potential from partners

$$V(h) \sim \frac{N_c}{16\pi^2} m_\psi^4 \epsilon^2 \left[c_1 \frac{h^2}{f^2} + c_2 \frac{h^4}{f^4} \right]$$

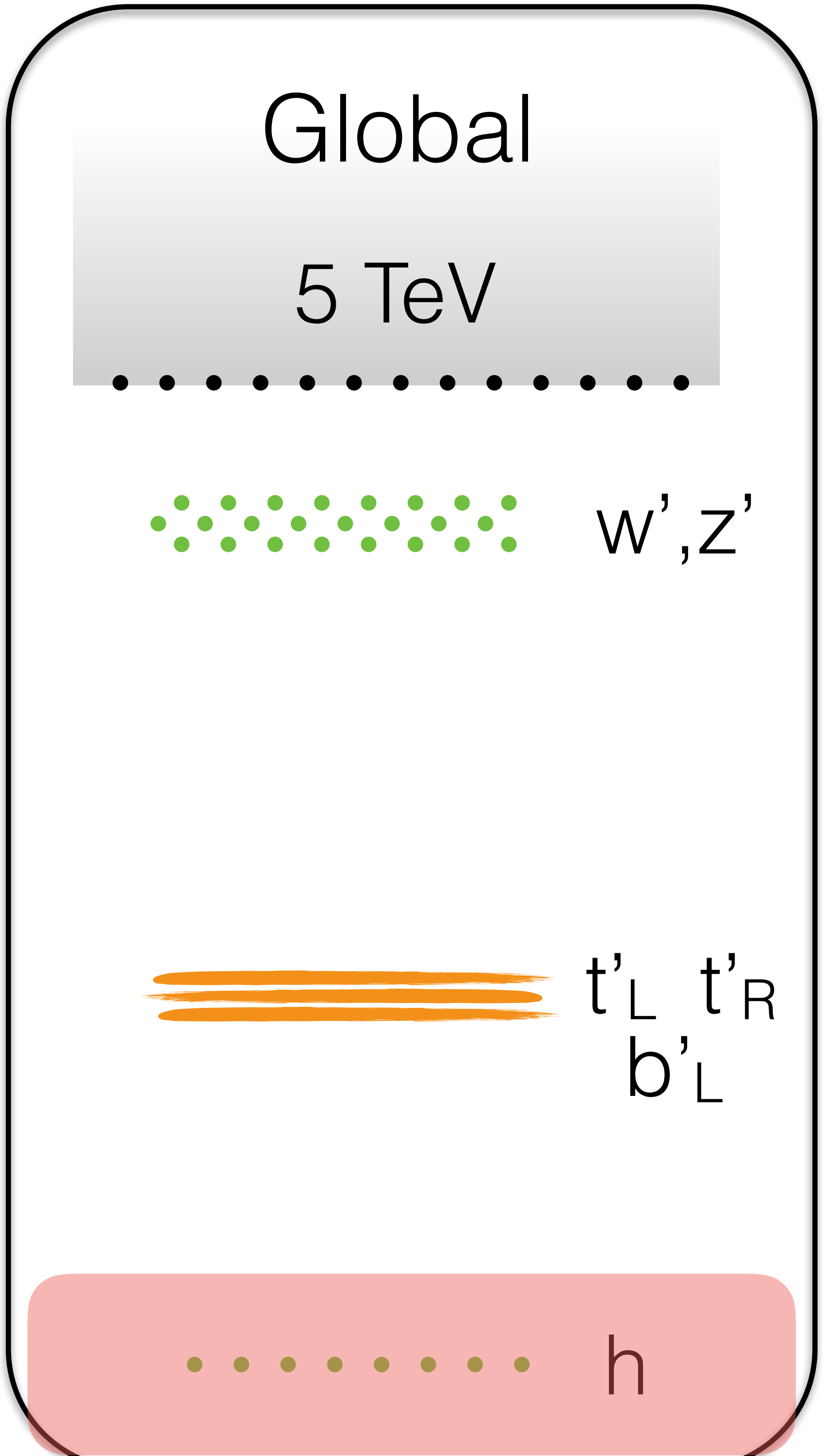
Quartic & m^2 at same loop order, expect **v~f**

i.e., no separation between weak scale & global breaking

Making **v < f** requires tree-level tuning of terms in the potential $\Delta \sim f^2/v^2$

For more detail & subtlety, see talk by A. Azatov

GLSY after LHC16: Higgs



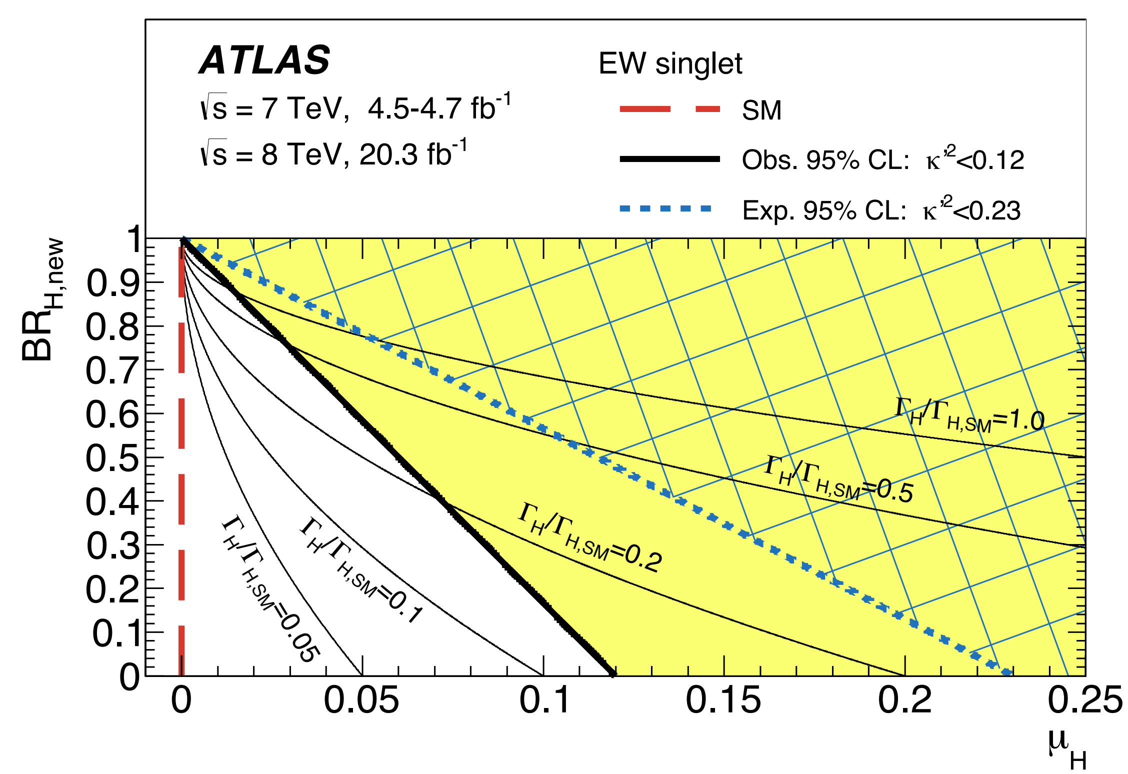
$$|\partial_\mu H|^2 + \frac{H^\dagger H}{f^2}|\partial_\mu H|^2 \to \left(1+\frac{v^2}{f^2}\right)\frac{1}{2}(\partial_\mu h)^2$$

Canonically normalize $h \to (1 - v^2/2f^2)h$

shifts higgs couplings uniformly, e.g.

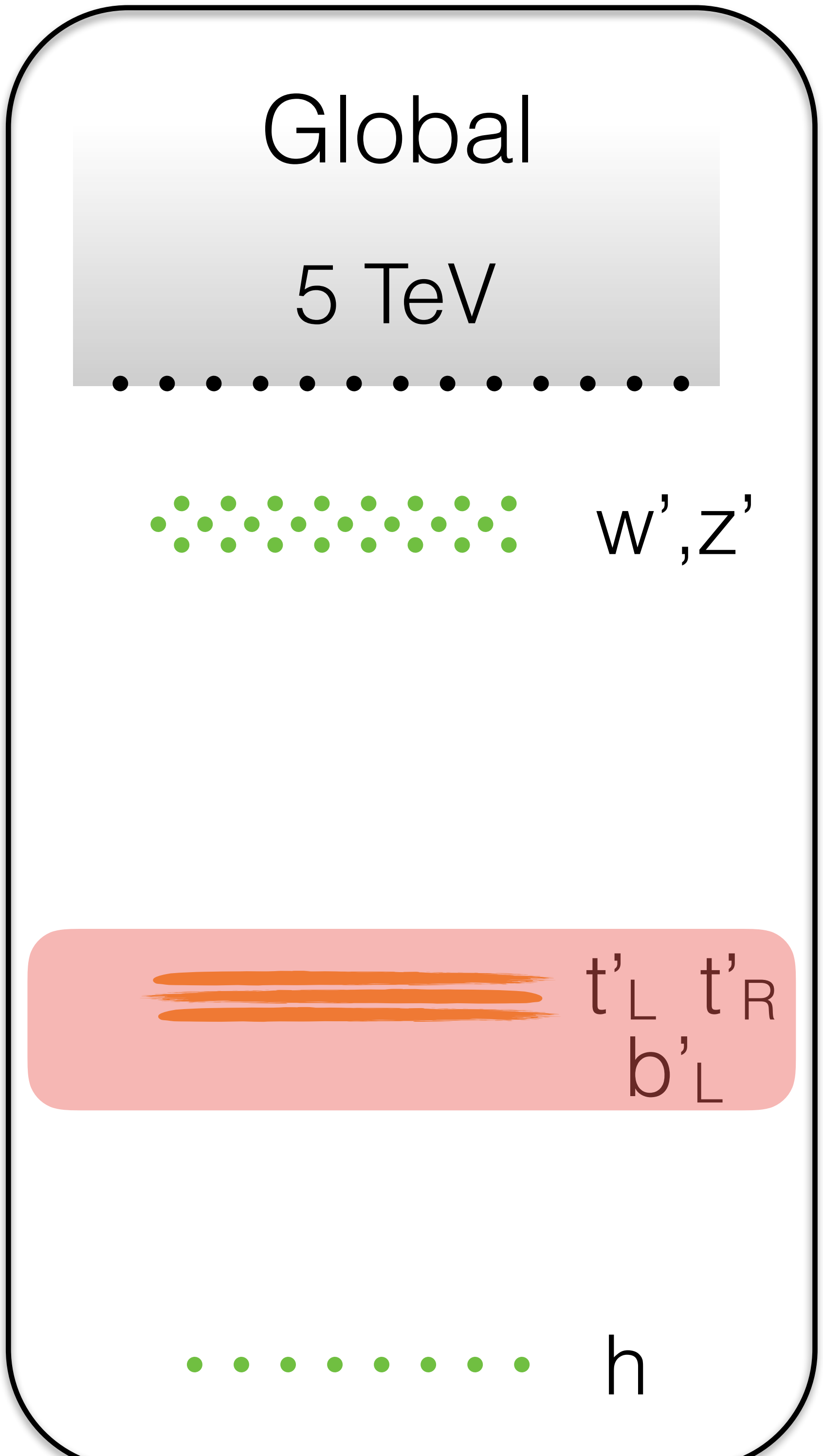
$$\frac{m_Z^2}{v} h Z_\mu Z^\mu \to \frac{m_Z^2}{v}(1 - v^2/2f^2) h Z_\mu Z^\mu$$

+additional model- & species-dependent changes

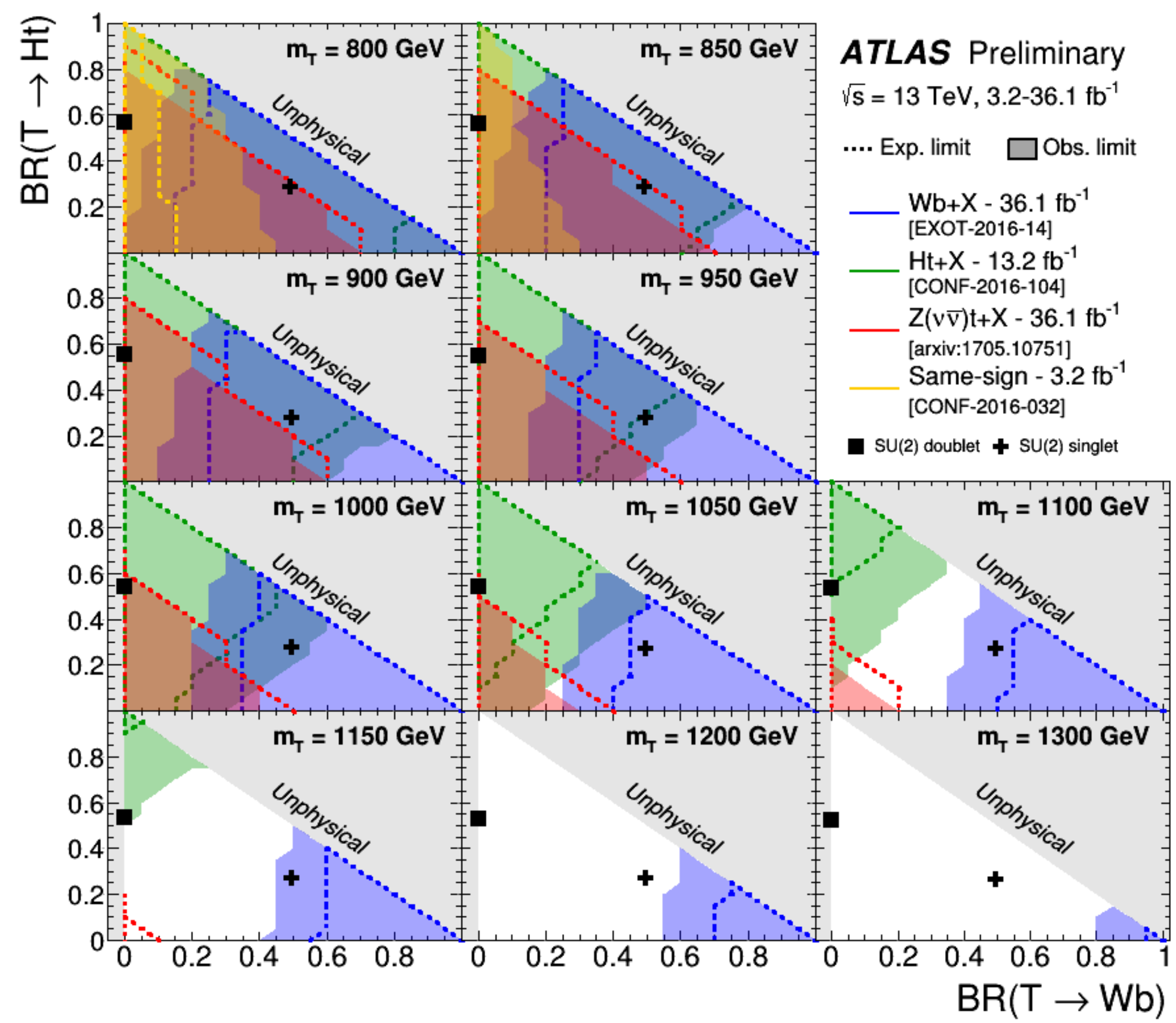


Limit
$v^2/f^2 < 0.1$
→ **Δ~10 (10% tuning)**

GLSY after LHC16: Top'



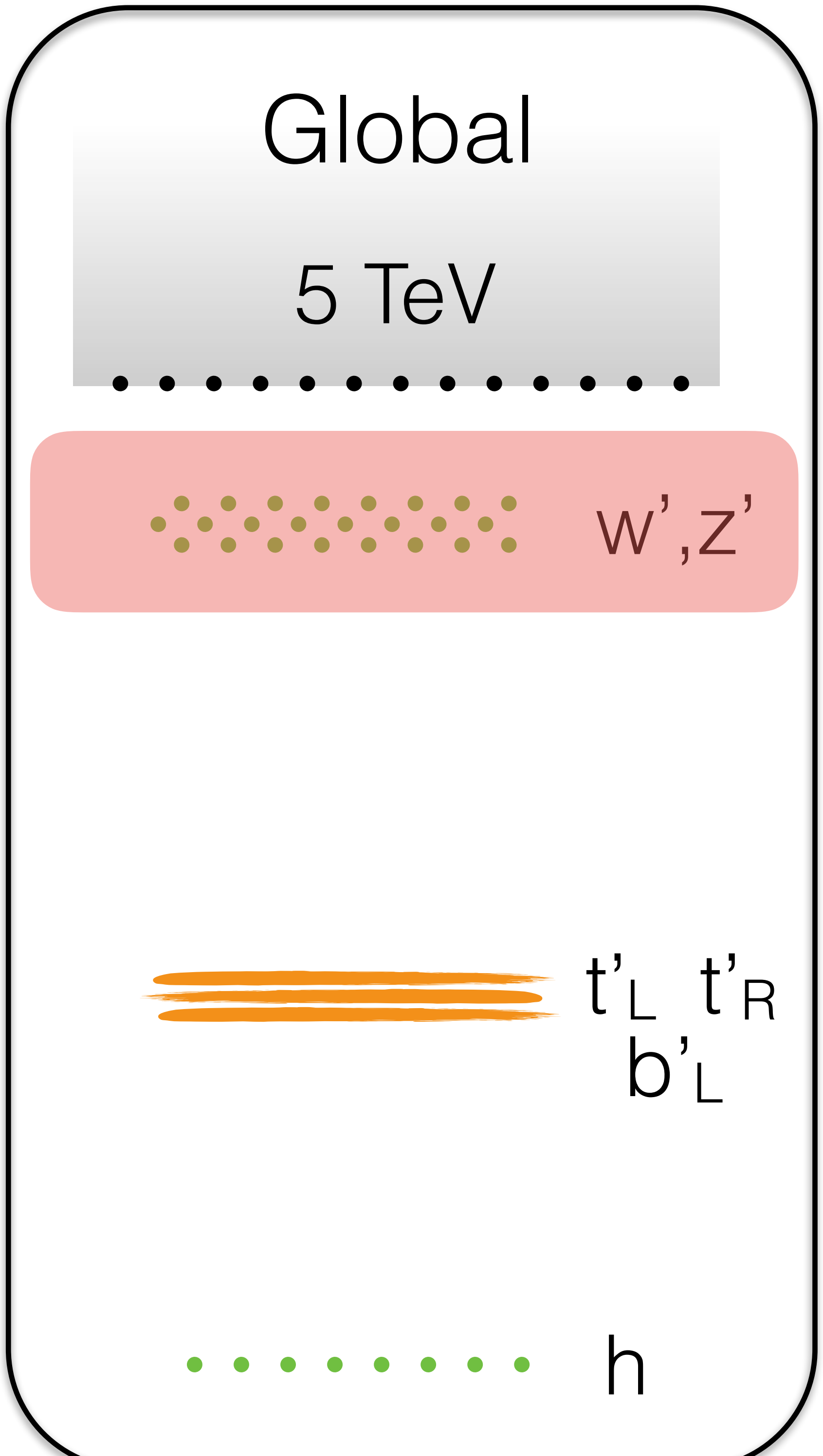
3rd-generation vector-like quarks. Relative to SUSY: larger xsec, no missing energy



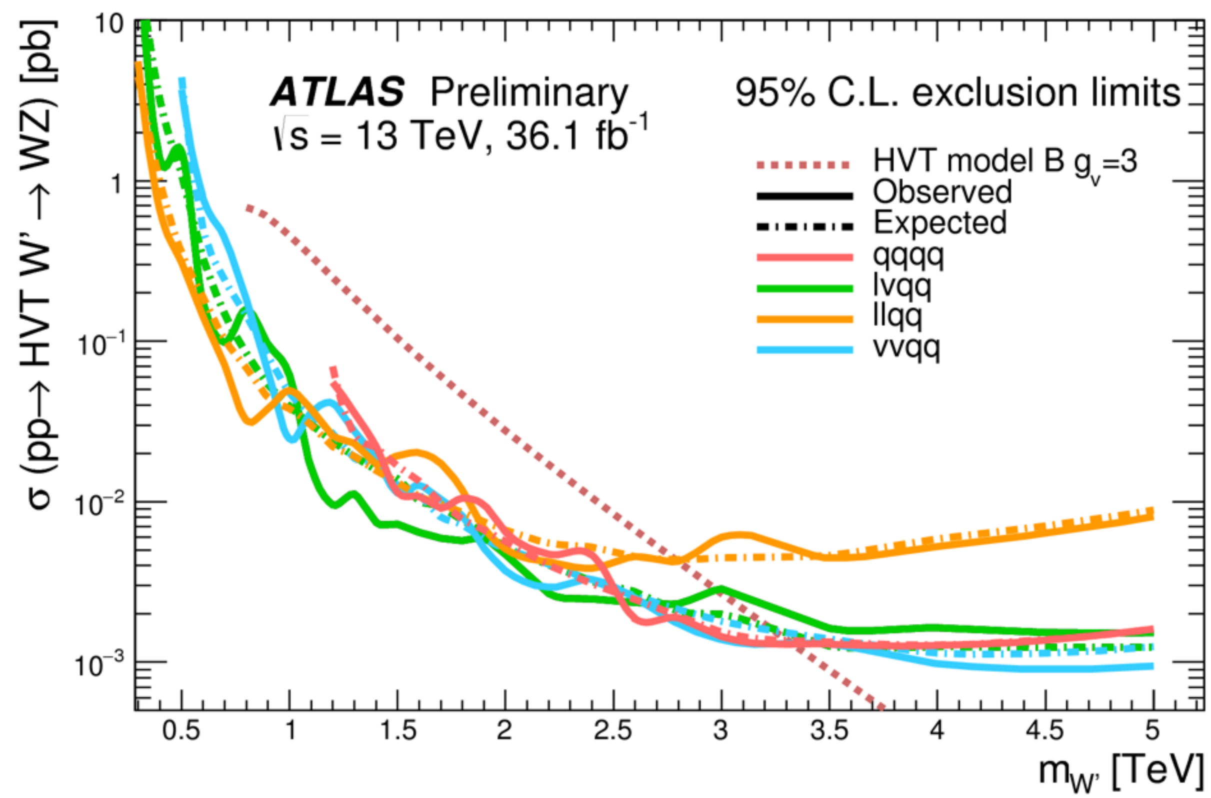
Generic limits >1 TeV (both t')

→ **Δ~10 (10% tuning)** (Λ = 3 TeV)

GLSY after LHC16: Resonances



Wide variety of possible resonances & signals



Comparable to precision electroweak limits

$$S = 4\pi(1.36)\left(\frac{v}{m_\rho}\right)^2 \rightarrow m_\rho \gtrsim 3 \text{ TeV}$$

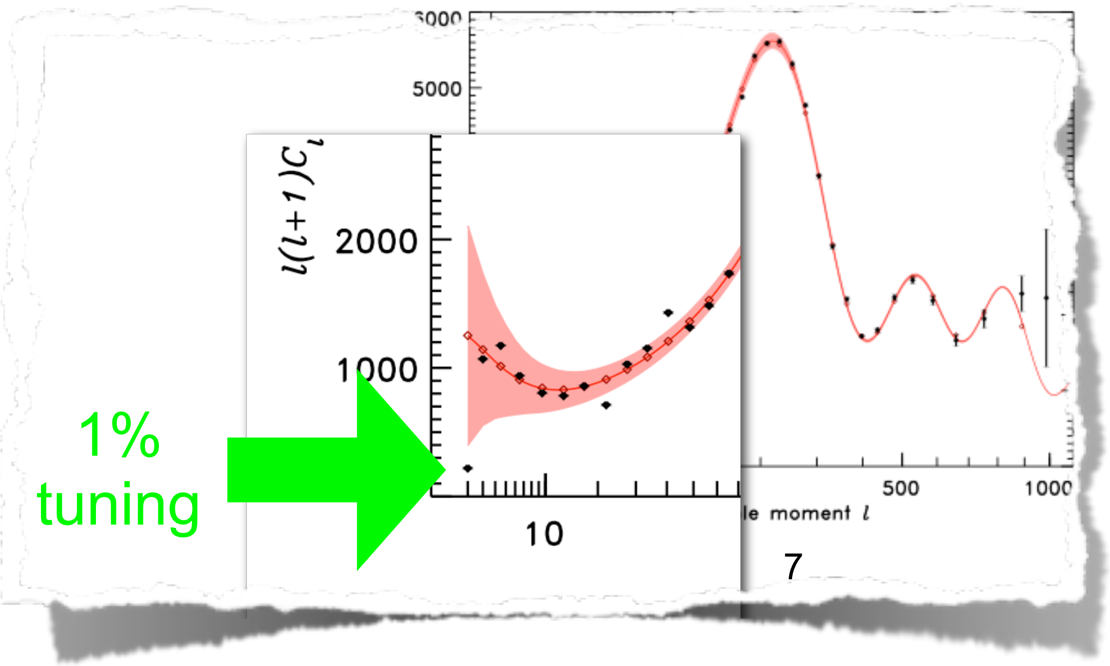
Generic limit > 3 TeV

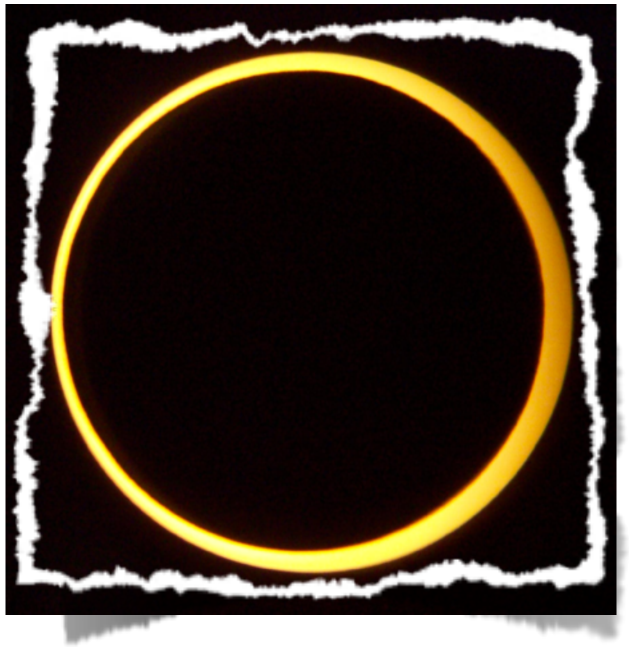
→ **Δ~1 (no tuning** *on top of v/f tuning)*

Bad luck?

Approaching %-level tunings on all generic, conventional fronts
Certainly not time to give up, e.g. other %-level coincidences:

- Low CMB quadrupole





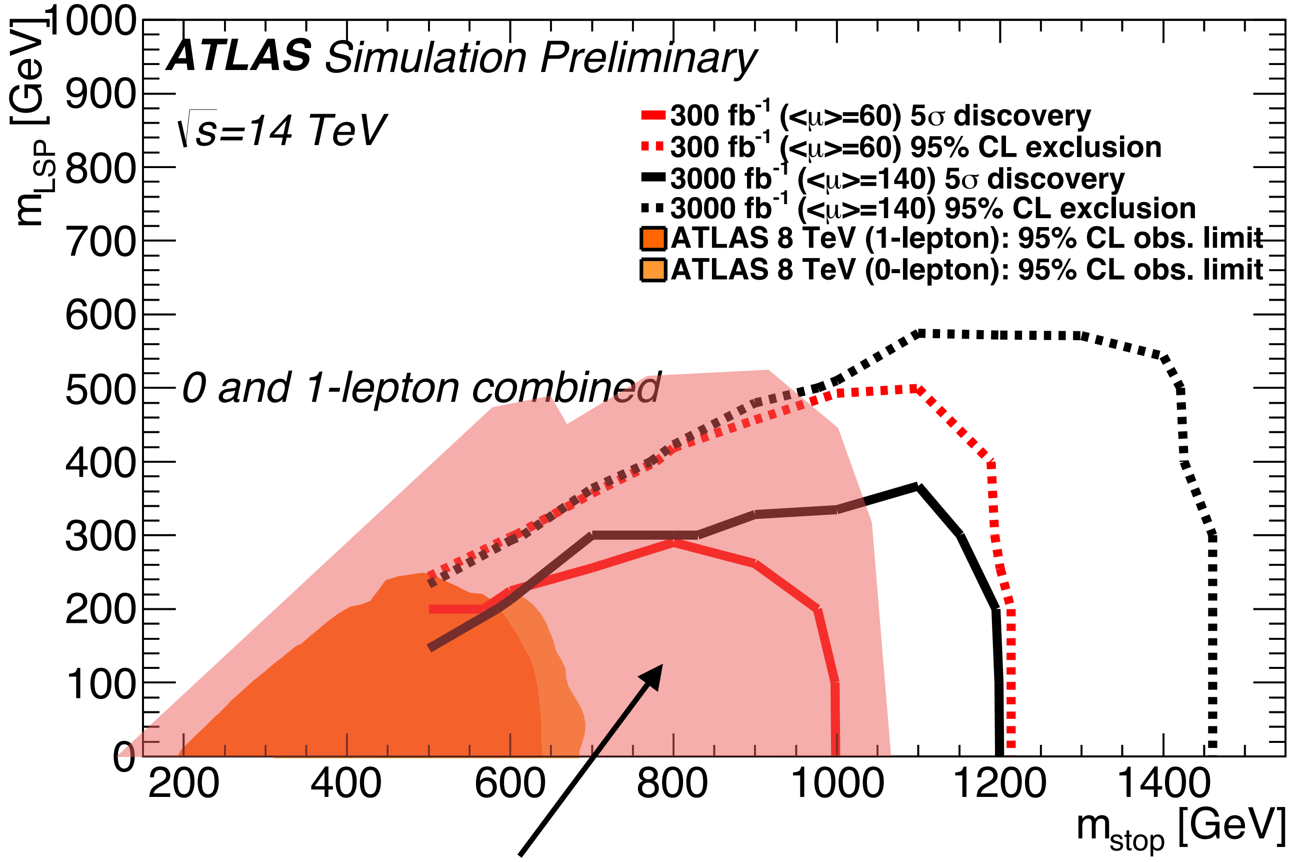
- Moon & sun ~0.5^0 of arc

- Neutrons fail to bind by 60 keV

Nature has given us 1% tunings, some as substantive as this.

…but this should still be cause for serious reflection.

Where we are going



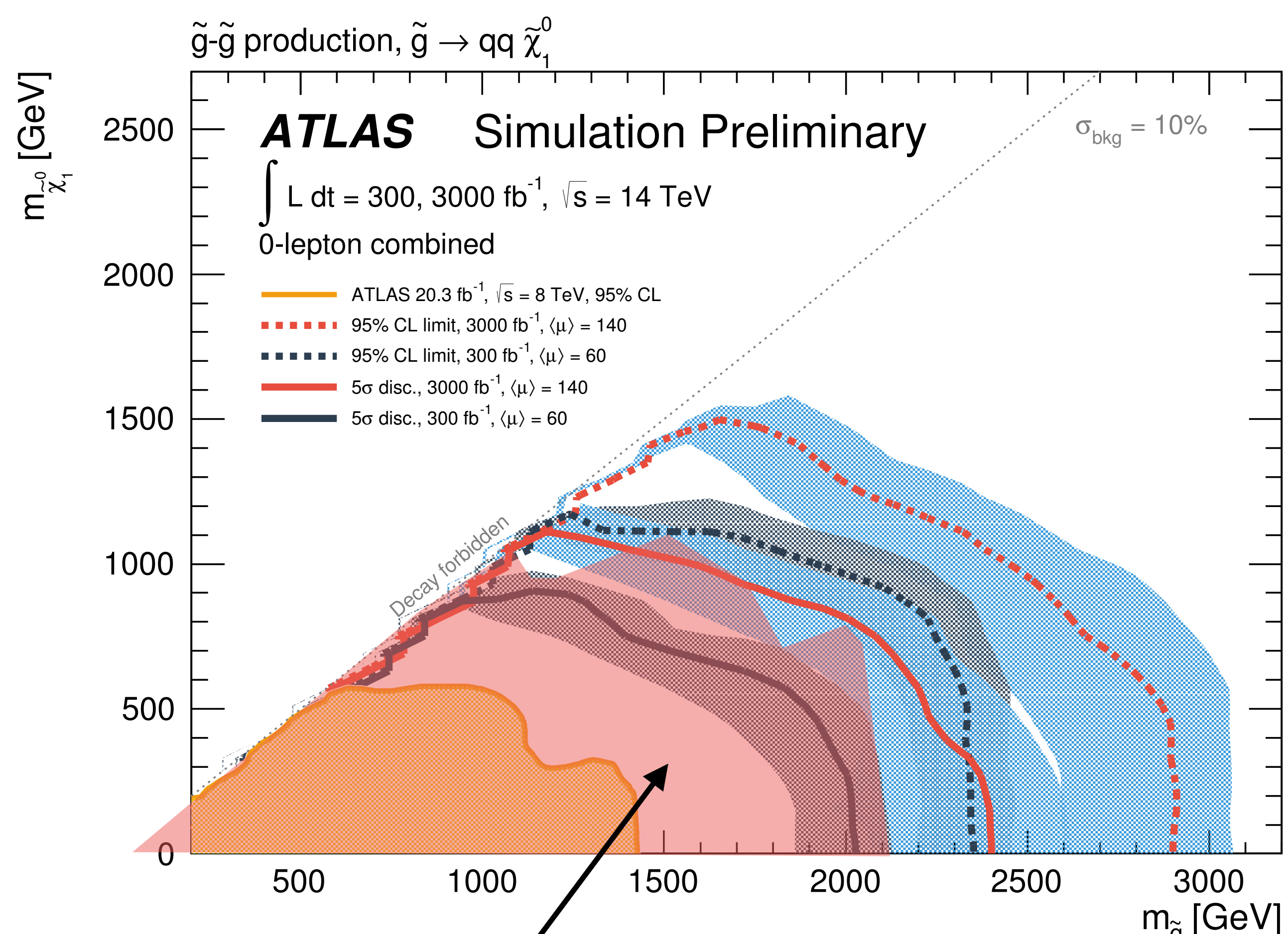
Current CMS 36/fb 0+1+2 lepton limit

Discovery potential for generic QCD-charged states is shrinking

(Many caveats: e.g. current search reach suggests HL-LHC forecasts are conservative.)

DON'T PANIC

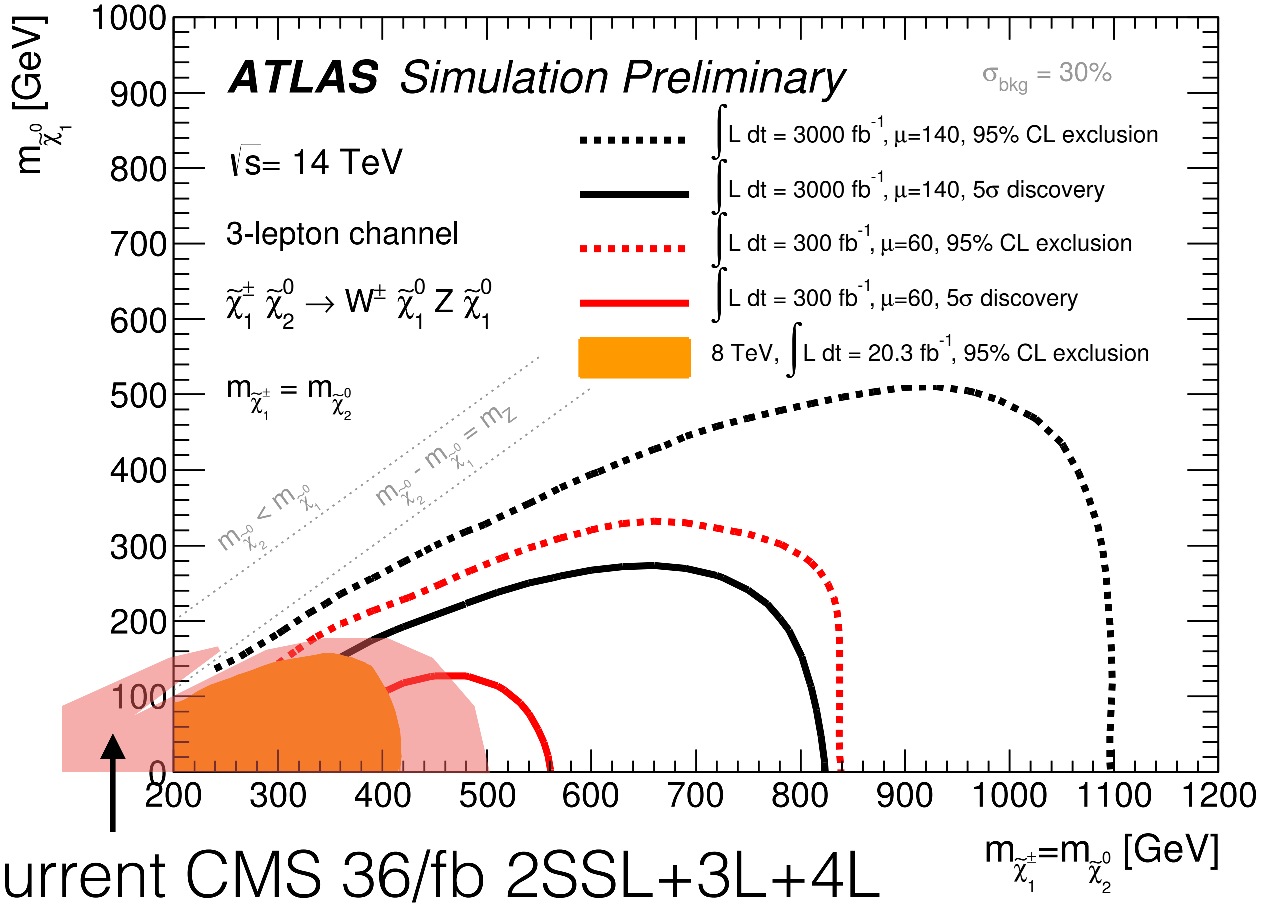
Not a sign that discovery is out of reach, but a sign that the biggest potential now lies in other channels.



Current ATLAS 36/fb 0l, 2-6j limit

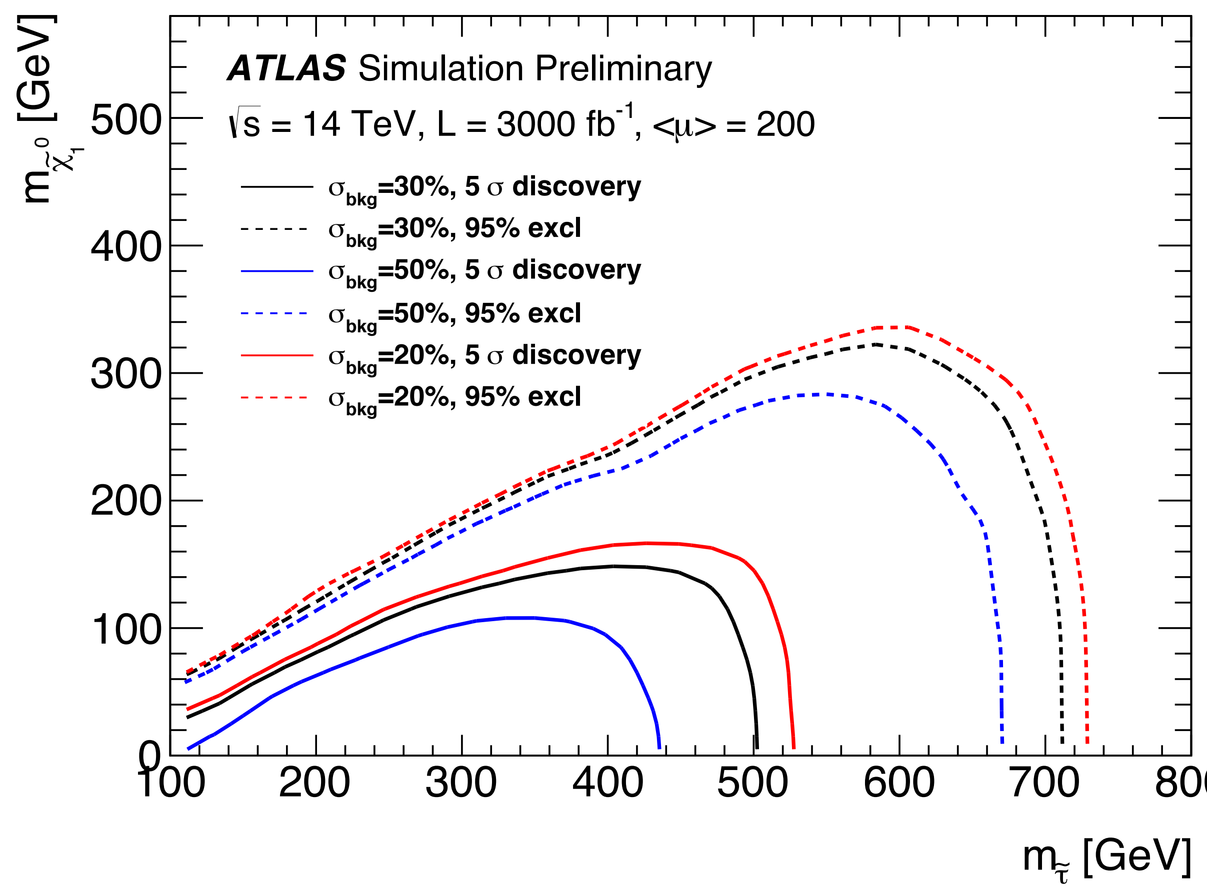
New opportunities in familiar places

Focus on opportunities



Current CMS 36/fb 2SSL+3L+4L

(*OSL has greater reach in parent mass)

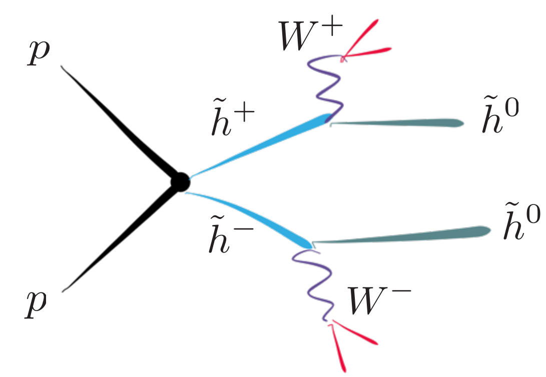


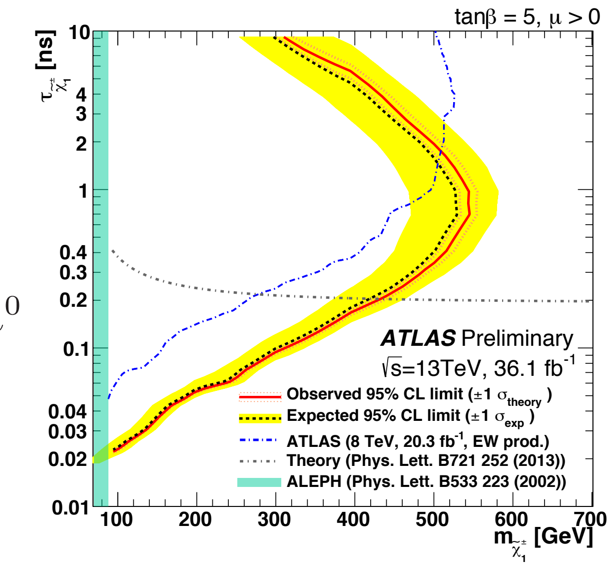
- Limits on electroweak superpartners still well below TeV scale & statistics limited.
- Significant improvement expected over the lifetime of the LHC.
- “Let’s discover electroweak physics at the electroweak scale.”

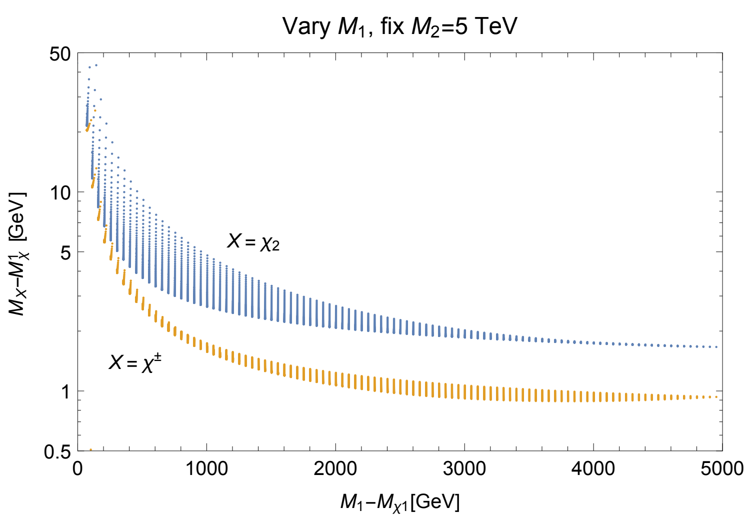
E.g. light Higgsinos

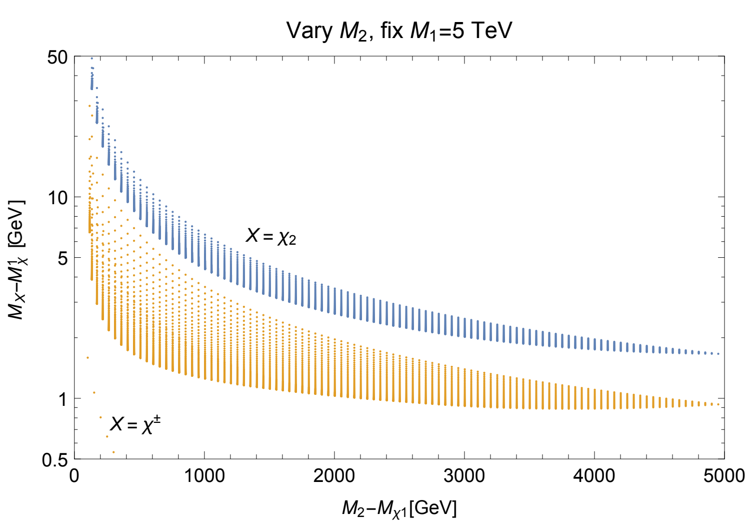
"Pure Higgsino" challenging: splitting neither big enough to see decay products nor small enough to see long charged stub.

But charged stub possibly accessible, & well-decoupled gauginos give O(few GeV) splittings



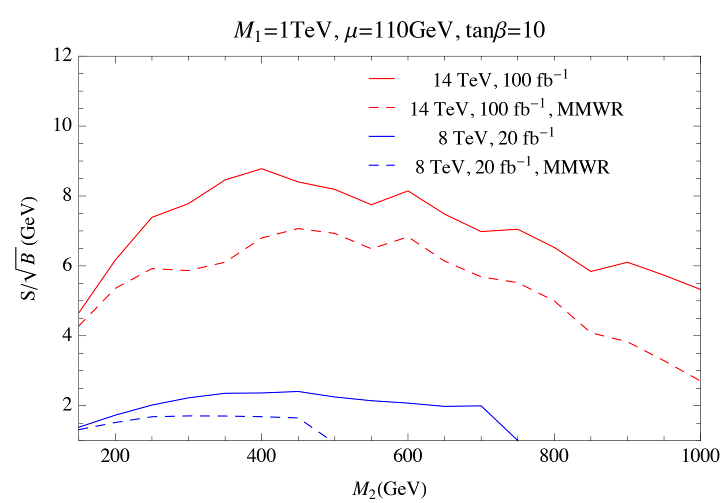






$$pp \to j + \not{E}_T + \ell\ell$$

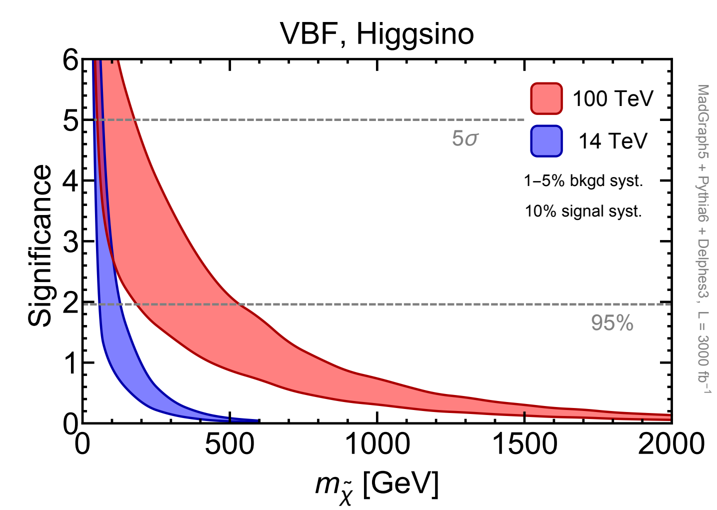
[Han, Kribs, Martin, Menon '14]



Sensitivity to few GeV splitting

$$pp \to jj_{VBF} + \not{E}_T$$

[Berlin, Lin, Low, Wang '15]



Reach LEP limit w/ SM splitting

Take naturalness to its limits

E.g., extend familiar SUSY theories w/ new 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

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

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

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

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

μ term an invariant of

$$\mathcal{G}$$

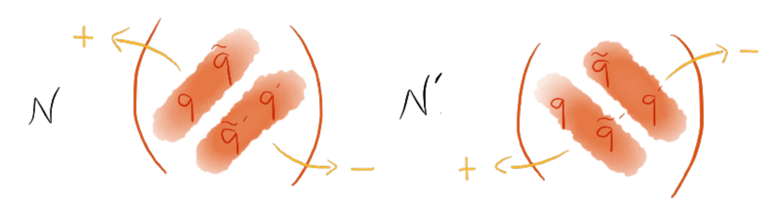
doesn't contribute to Higgs potential

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]

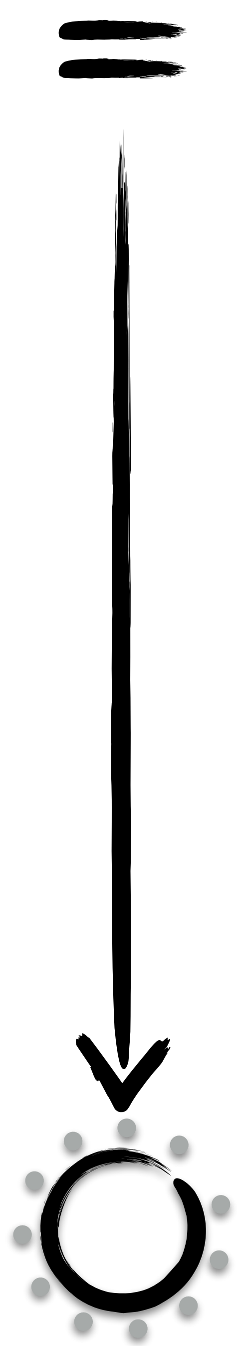
- E.g. 5D SUSY on S_1/Z_2, SUSY broken by BCs.



- Spectrum finite, no large logs. (Often) dirac gauginos.
- Zero modes not supersymmetric ("hard breaking" for higgsino).
- Scale is 1/R ~ 5 TeV

New opportunities in unfamiliar places

New theory frameworks?



Hierarchy problem still solved by symmetries, i.e., technical naturalness

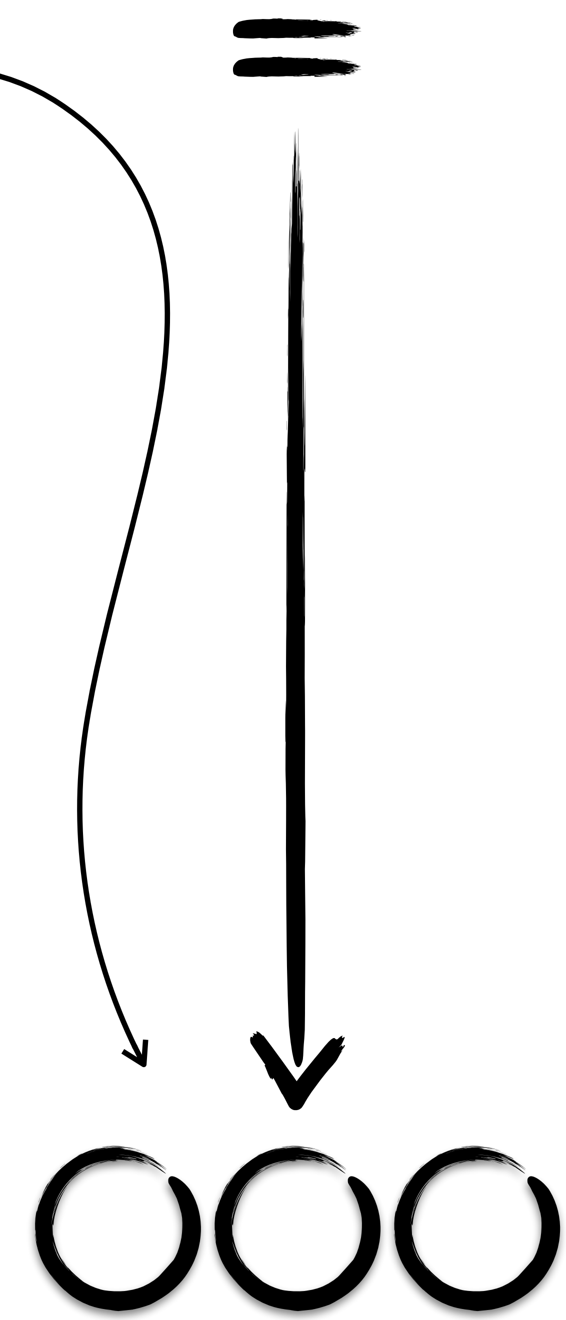
But IR symmetries discrete, not continuous

“Neutral Naturalness”

Hierarchy problem not directly controlled by symmetries, contributions large

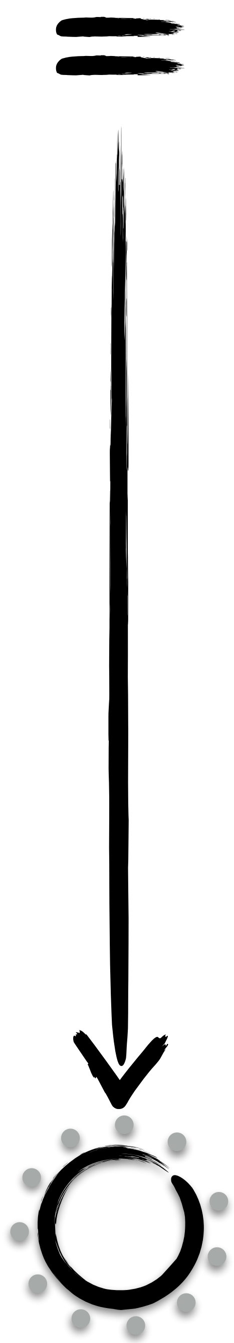
But total Higgs mass scanned dynamically

“Relaxion”



Example 1: Twin Higgs

[Chacko, Goh, Harnik '05]



Standard Model $\xleftrightarrow{Z_2}$ **Standard Model**

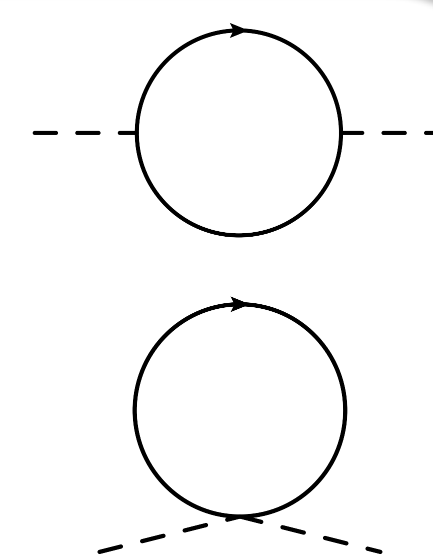
Radiative corrections to the Higgs mass are SU(4) symmetric thanks to Z_2:

$$V(H) \supset \frac{\Lambda^2}{16\pi^2}\left(-6y_t^2 + \frac{9}{4}g^2 + \dots\right)\left(|H_A|^2 + |H_B|^2\right)$$

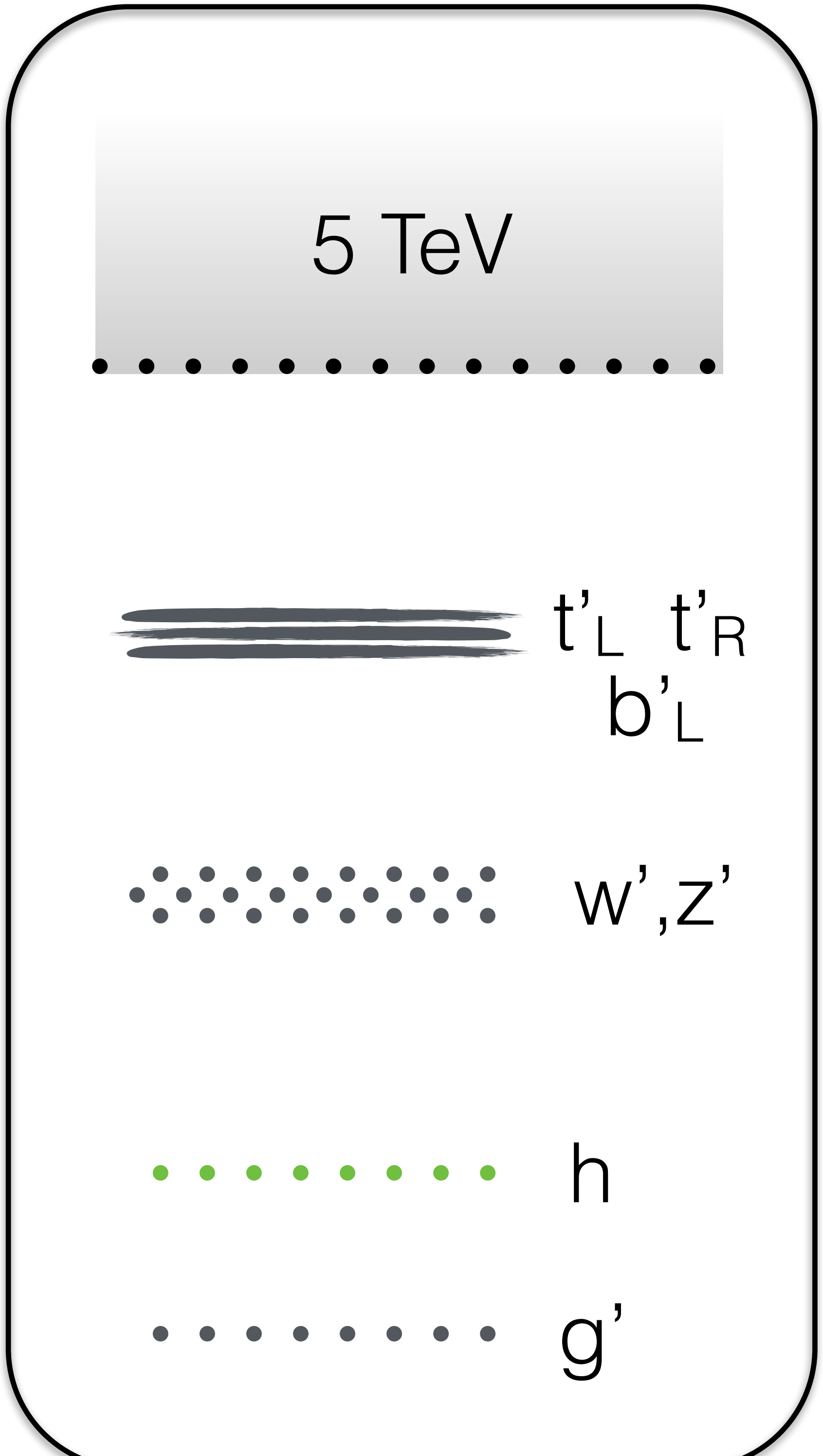
Higgs is a PNGB of ~SU(4), but partner states neutral under SM.

$$\mathcal{L} \supset -y_t H_A Q_3^A \bar{u}_3^A - y_t H_B Q_3^B \bar{u}_3^B$$

$H_A \to h + \dots$ $\qquad$ $H_B \to f - \frac{h^2}{2f} + \dots$



“Neutral” naturalness



Simplest theory: exact mirror copy of SM

[Chacko, Goh, Harnik ’05]

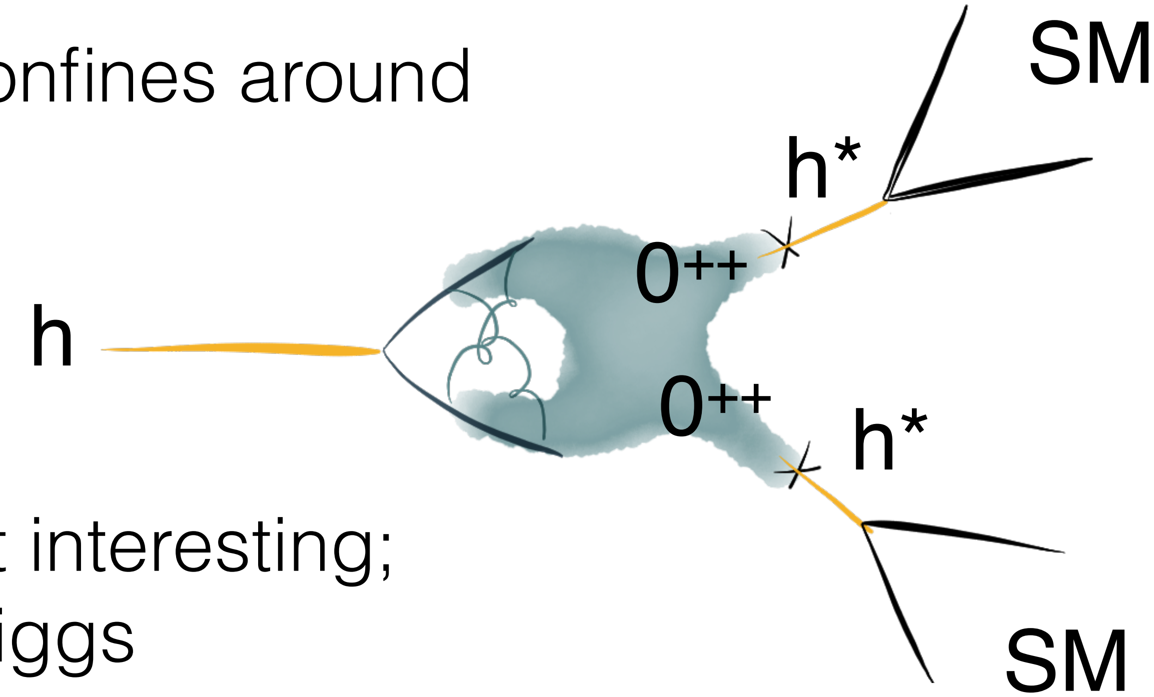
But this is more than you need, and mirror 1st, 2nd gens lead to cosmological challenges

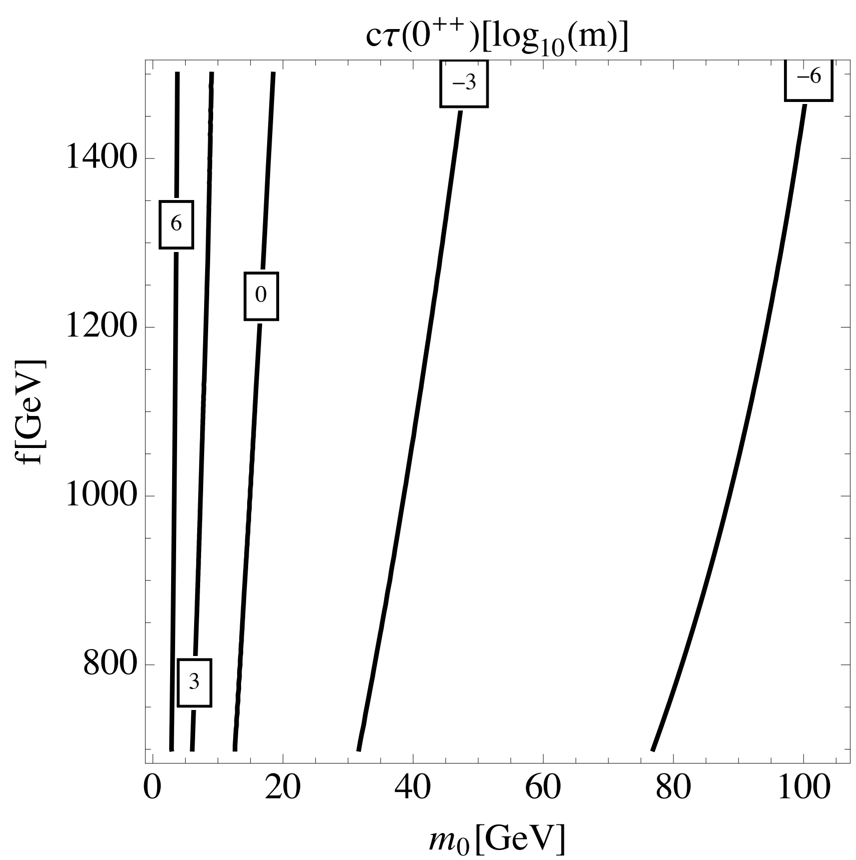
Many more options where symmetry is approximate, e.g. a good symmetry for heaviest SM particles.

[NC, Knapen, Longhi ’14; Geller, Telem ’14; NC, Katz, Strassler, Sundrum ’15; Barbieri, Greco, Rattazzi, Wulzer ’15; Low, Tesi, Wang ’15, NC, Knapen, Longhi, Strassler ‘16]

Exotic Higgs Decays

- Twin sector must have twin QCD, confines around QCD scale
- Higgs boson couples to bound states of twin QCD
- Various possibilities. Glueballs most interesting; lightest have same quantum # as Higgs





$$\mathcal{L} \supset -\frac{\alpha_3'}{6\pi}\frac{v}{f}\frac{h}{f}G'^{a}_{\mu\nu}G'^{\mu\nu}_{a}$$

Produce in rare Higgs decays (BR~10^{-3}-10^{-4})

$$gg \to h \to 0^{++} + 0^{++} + \ldots$$

Decay back to SM via Higgs

$$0^{++} \to h^* \to f\bar{f}$$

Long-lived, length scale ~ LHC detectors

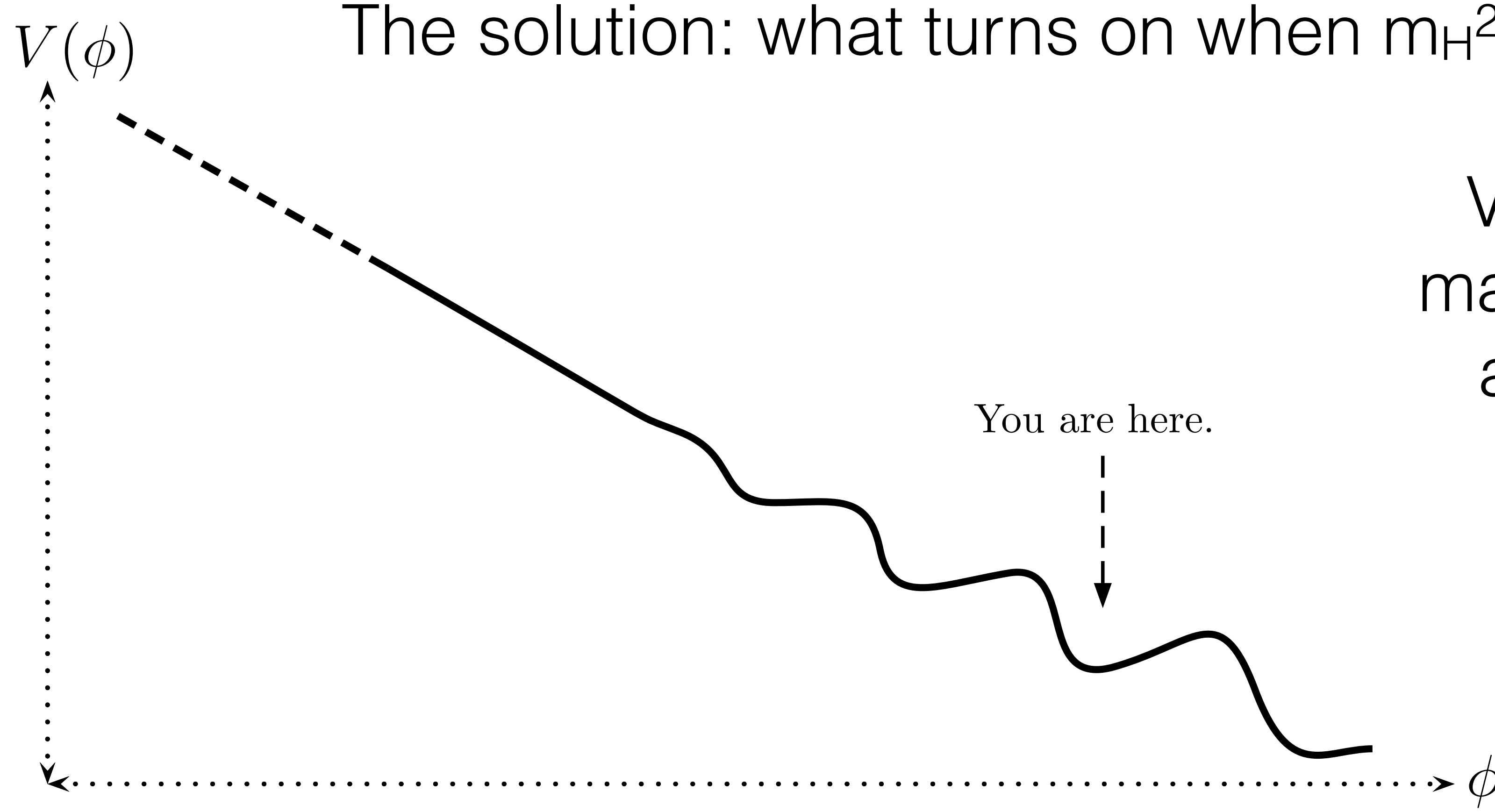
See also talk by D. Stolarski

Example 2: Relaxion

What if the weak scale is selected by dynamics, not symmetries?

The idea: couple Higgs to field whose minimum sets m_H=0
The problem: How to make m_H=0 a special point of potential?

The solution: what turns on when m_H^2 goes negative?



Vev gives quark masses which give axion potential.

“Relaxion”

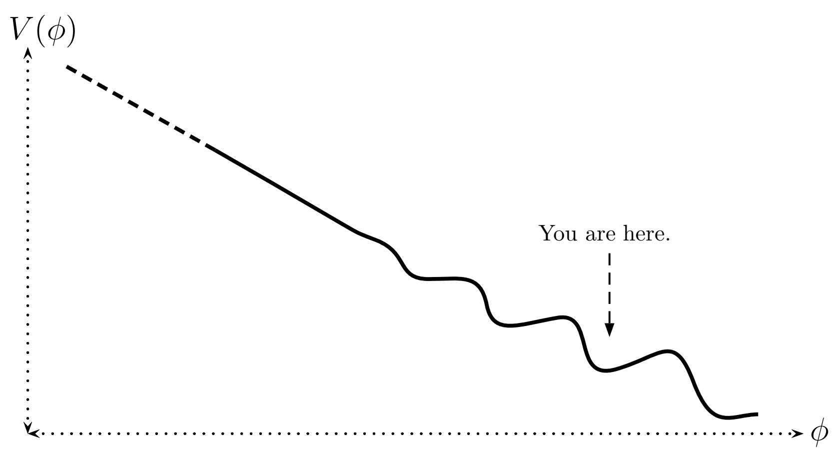
[Graham, Kaplan, Rajendran ‘15]

But: immense energy stored in evolving field, need dissipation.

[Graham, Kaplan, Rajendran '15]

QCD/QCD' relaxion

First thought: use an axion coupled to QCD during inflation.



$$(-M^2 + g\phi)|H|^2 + V(g\phi) + \frac{1}{32\pi^2}\frac{\phi}{f}\tilde{G}^{\mu\nu}G_{\mu\nu}$$

$$\Rightarrow \quad (-M^2 + g\phi)|H|^2 + V(g\phi) + \Lambda^4 \cos(\phi/f)$$

Viable for Higgs + non-compact axion + inflation w/

- Very low Hubble scale ($\ll \Lambda_{QCD}$)
- 10 Giga-years of inflation

Various other subtleties regarding technical naturalness, CC; care required to avoid transferring fine-tuning to inflationary sector.

In vacuum, axion gives O(1) contribution to θ_{QCD}

QCD’ Relaxion

Viable alternative: dark QCD + axion

Field	$SU(3)_N$	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
L	$\square$	–	$\square$	$-1/2$
L^c	$\overline{\square}$	–	$\square$	$+1/2$
N	$\square$	–	–	0
N^c	$\overline{\square}$	–	–	0

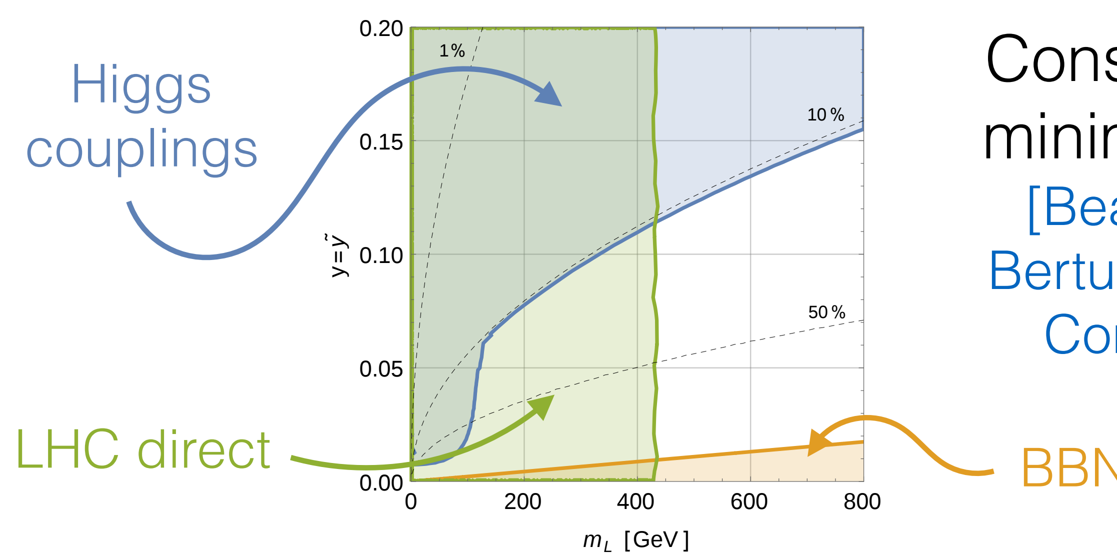
I.e. axion of a different SU(3); need to tie in Higgs vev

Bounds on mechanism imply

$$f_{\pi'} < v \quad \text{and} \quad m_L < \frac{4\pi v}{\sqrt{\log(M/m_L)}}$$

New confining physics near weak scale!

Couples to Higgs, electroweak bosons; hidden valley signatures. Various possibilities.



Constraints on minimal model [Beauchesne, Bertuzzo, Grilli di Cortona ’17]

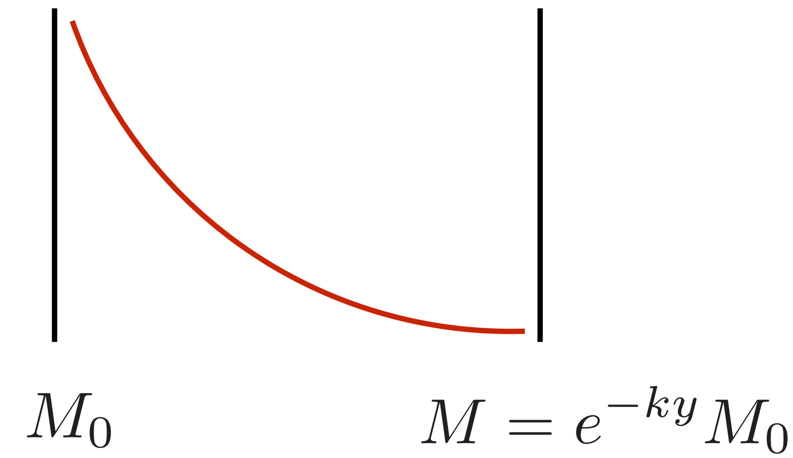
Rich hidden valley physics [Strassler, Zurek ’06], many signatures to explore

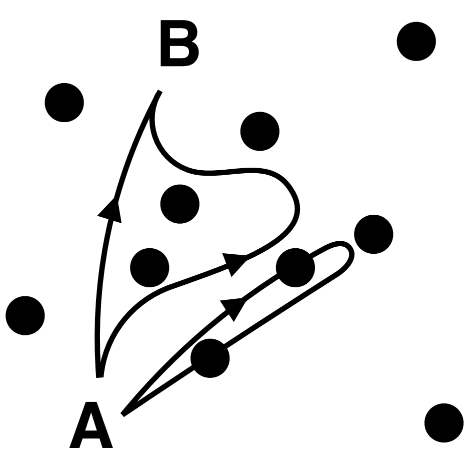
New opportunities at the edge of BSM theory

Hierarchy from disorder

How does RS [Randall, Sundrum '97] solve hierarchy problem? *Curvature localizes the graviton zero mode.*

→ Fields localized at different points in 5th dimension see different fundamental scales



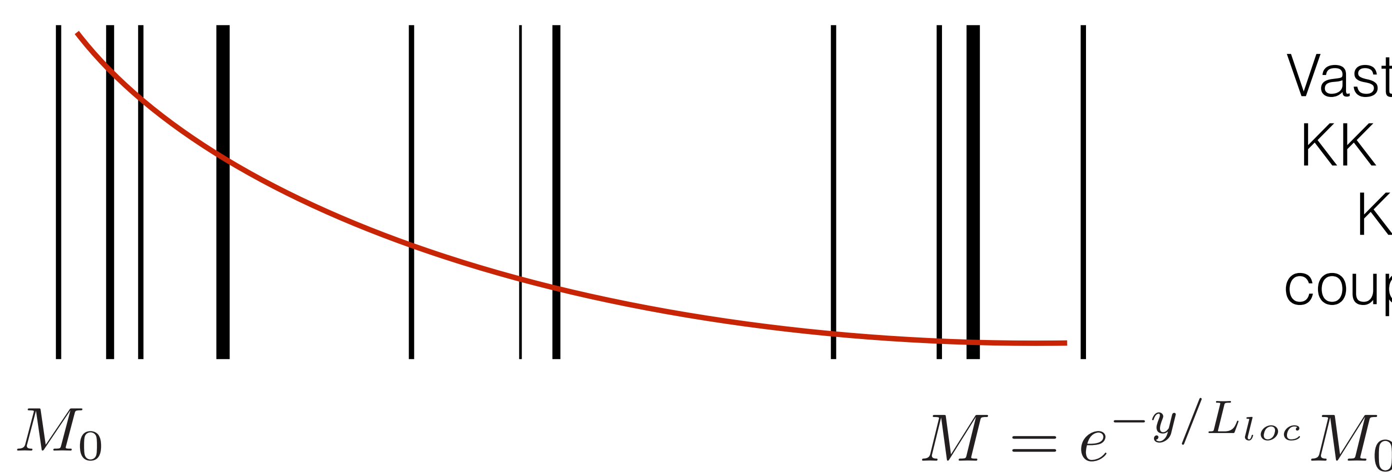


Recall (weak) Anderson localization: random phases for A → B, while A → A paths have time-reversed counterparts w/ identical phases

[Rothstein '12]: Can achieve the same outcome in a flat fifth dimension by localizing graviton w/ disorder

In this case disorder = randomly spaced & tensioned branes

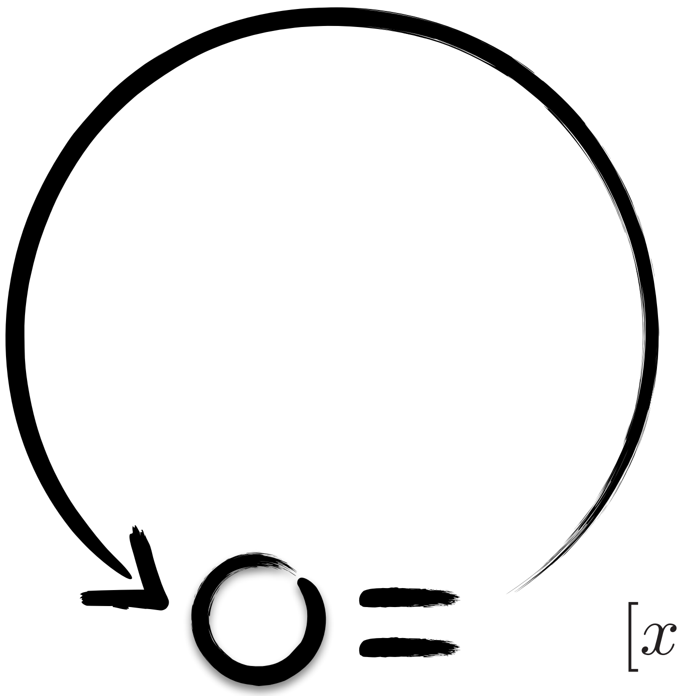
$$S = -\int d^5x\sqrt{G}(M_\star^3\mathcal{R}) + \sum_{\langle ij\rangle} M_\star^4 V(|X_i - X_j|) - \sum_i \int d^4x\sqrt{g} f_i$$



Vastly different KK spectrum, KK mode couplings, etc.

Undoubtedly more to learn from condensed matter systems

Connecting UV & IR



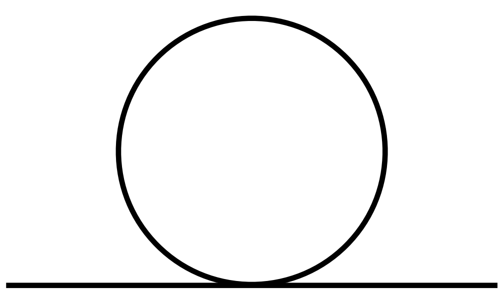
Essential feature of the hierarchy problem: the UV doesn't know about the IR…unless it does?

Two examples of UV/IR mixing: Quantum gravity & non-commutative field theory

For example, [Minwalla, Seiberg, Van Raamsdonk '99]

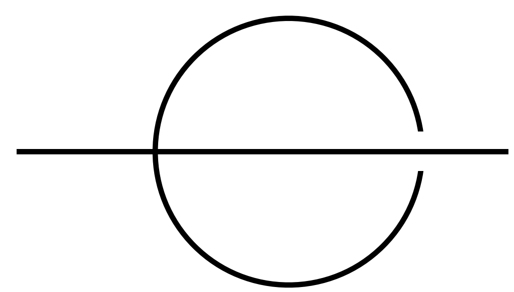
$$[x^\mu, x^\nu] = i\Theta^{\mu\nu} \Leftrightarrow \; (\phi_1 \star \phi_2)(0) = e^{i\Theta^{\mu\nu}\partial^y_\mu \partial^z_\nu} \phi_1(y)\phi_2(z)\Big|_{y=z=0}$$

Now there are "planar" and "non-planar" diagrams. E.g. ϕ^4 at one loop:



$$\sim \int \frac{d^4k}{k^2}$$

UV divergent as usual



$$\sim \int \frac{d^4k}{k^2} e^{ip\Theta k} \sim \frac{1}{\Theta^2 p^2}$$

IR divergence!

Extensively studied, but not systematically explored for hierarchy problem.

Definite frameworks for UV/IR mixing represent an entirely new frontier.

Conclusions

- LHC16 null results push generic conventional solutions to the hierarchy problem to the % level or below.
- Conventional ideas still worth pursuing, but BSM theory for the hierarchy problem is approaching a paradigm shift.

Null results an invitation for exploration:

- Data motivates new ideas in old theory frameworks…
- …and pursuing entirely new theory frameworks.
- Invariably leads to new experimental signatures & directions.
- New ideas emerging, many ambitious directions to explore…

Grazie mille!