Implications of SUSY Searches for BSM

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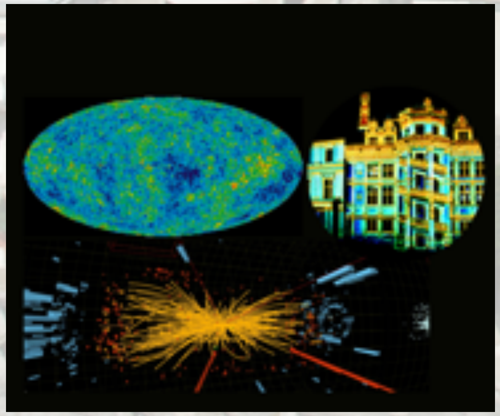
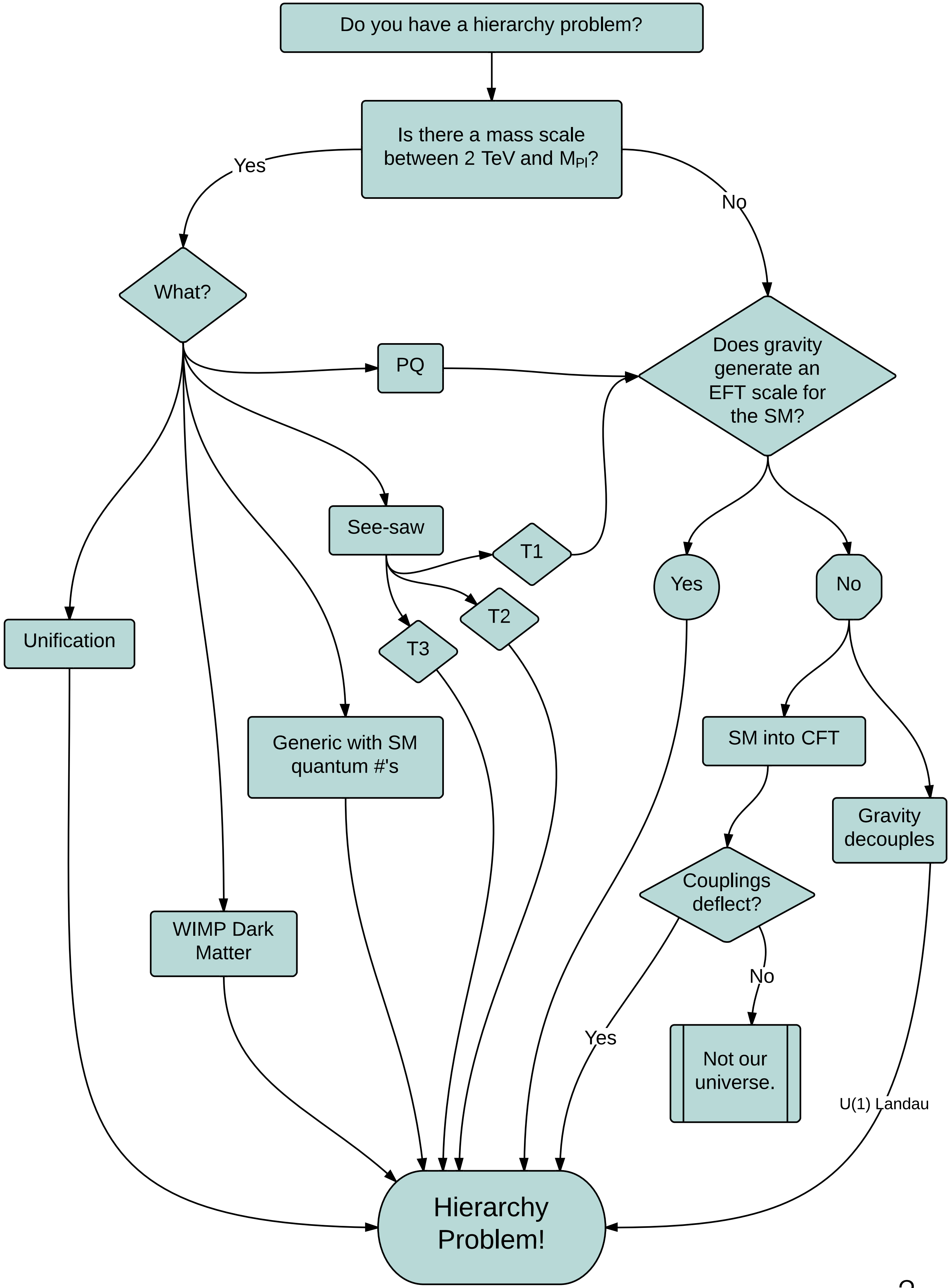


Rencontres de Blois 2015



Hierarchy Problem

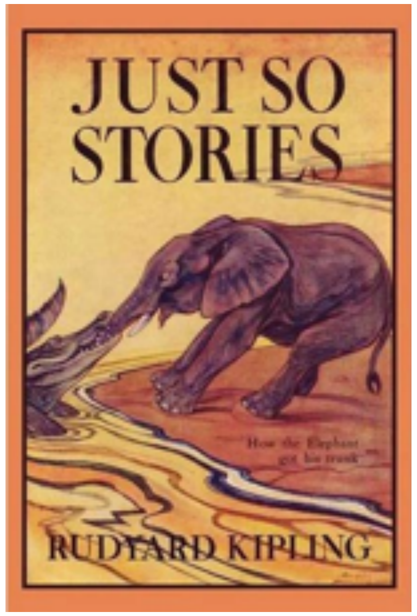
Elementary scalars are quadratically sensitive to physics at higher scales.

Independent of regularization scheme.

Model-building scales aside, gravity attests to presence of a higher scale.

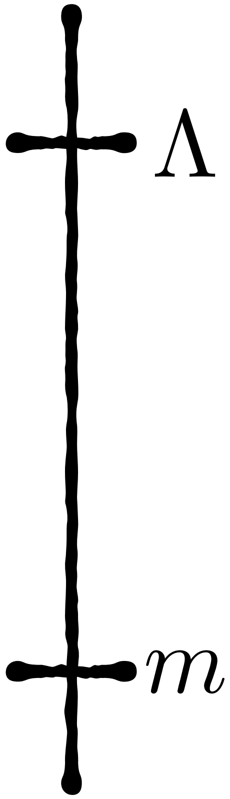
No viable proposals for mitigating sensitivity to physics @ Planck scale *without* new physics @ weak scale.

Hierarchy problem only sharpened with the discovery of an elementary SM-like Higgs (+nothing else so far).



Natural vs. unnatural

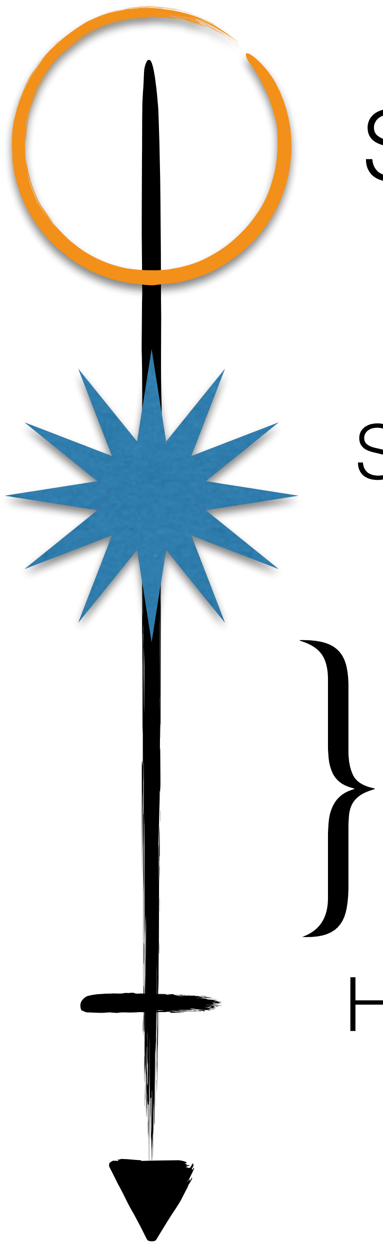
Hierarchy problem is not a “just-so story”



Field	Symmetry as $m \to 0$	Implication
Spin-1/2 $m\Psi\bar{\Psi}$	$\Psi \to e^{i\theta}\Psi$ $\bar{\Psi} \to e^{-i\theta}\bar{\Psi}$ (chiral symmetry)	$\delta m \propto m$ **Natural!**
Spin-1 $m^2 A_\mu A^\mu$	$A_\mu \to A_\mu + \partial_\mu \alpha$ (gauge invariance)	$\delta m \propto m$ **Natural!**
Spin-0 $m^2 \lvert H \rvert^2$	None	$\delta m \propto \Lambda$ **Unnatural!**

Electroweak naturalness

Make the Higgs mass technically natural by introducing symmetries



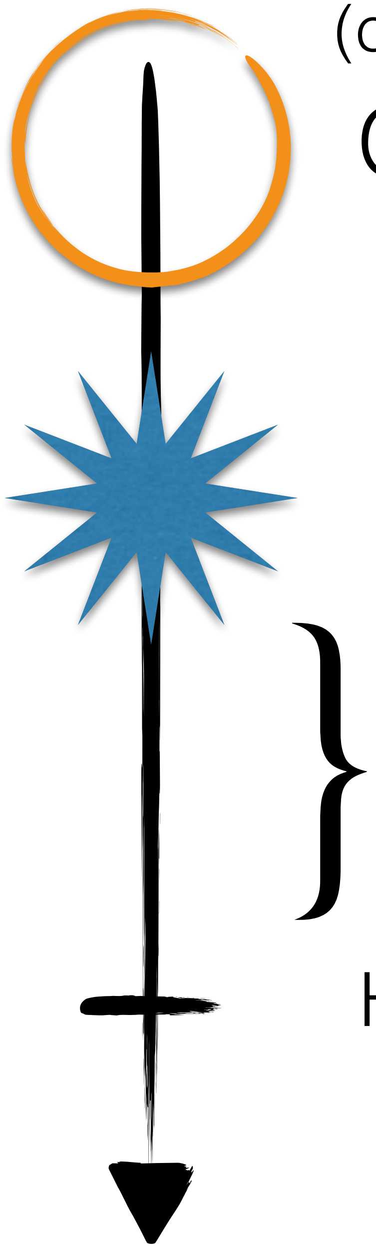
Supersymmetry

[Fayet '76; Dimopoulos & Georgi '81]

SUSY breaking
Sparticles $\tilde{m}$

$\lesssim 4\pi/G$

Higgs m_h



(compositeness, SUSY, turtles)

Global symmetry

[Georgi & Kaplan '84; Contino, Nomura, Pomarol '03]

Global symm. breaking
Partner particles $\tilde{m}$

$\lesssim 4\pi/G$

Higgs m_h

Continuous symmetries → partner states w/ SM quantum #s

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

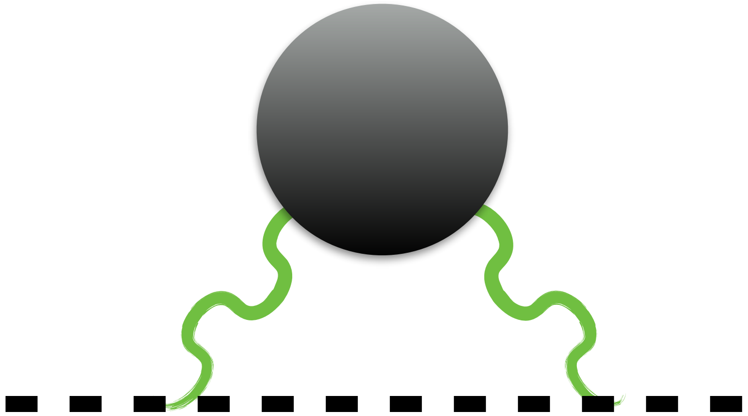
Totally natural: $\tilde{m} \lesssim 200\,\mathrm{GeV}$

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

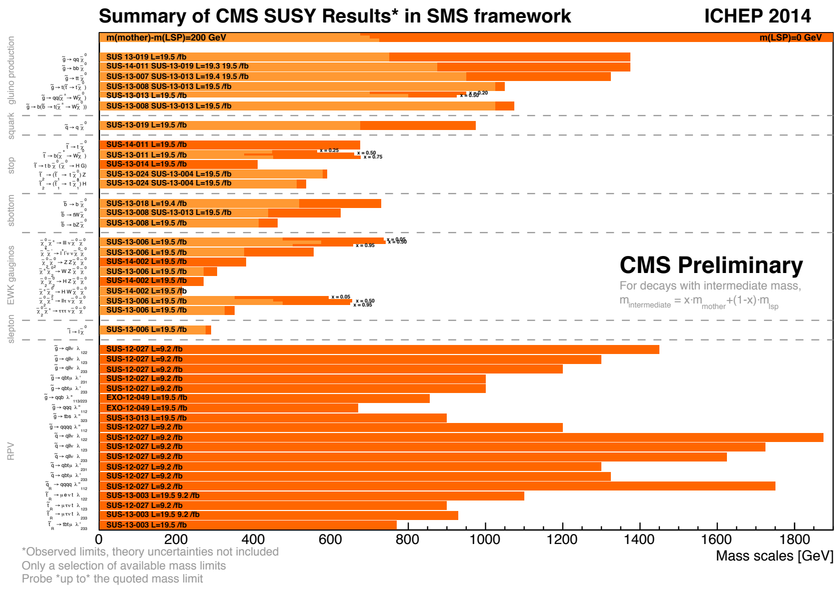


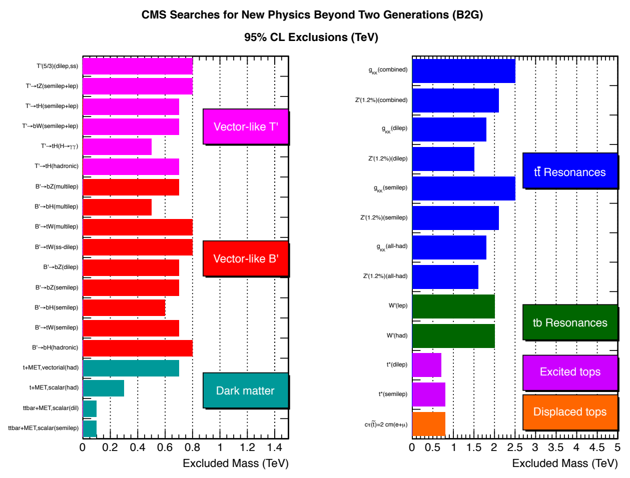
Electromagnetic contribution to the charged pion mass sensitive to the cutoff of the pion EFT.

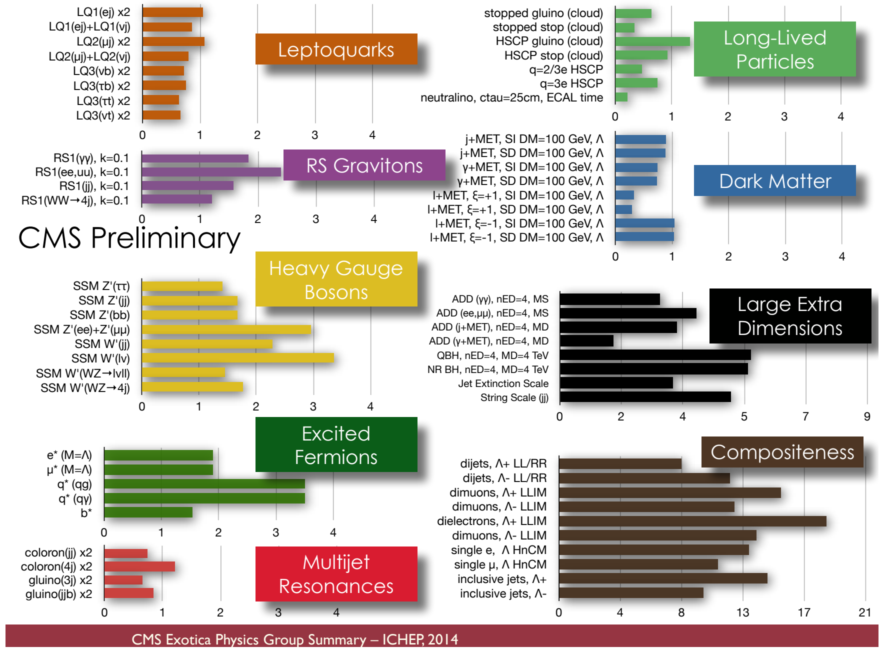
$$\delta m^2 \sim \frac{3e^2}{16\pi^2}\Lambda^2$$

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

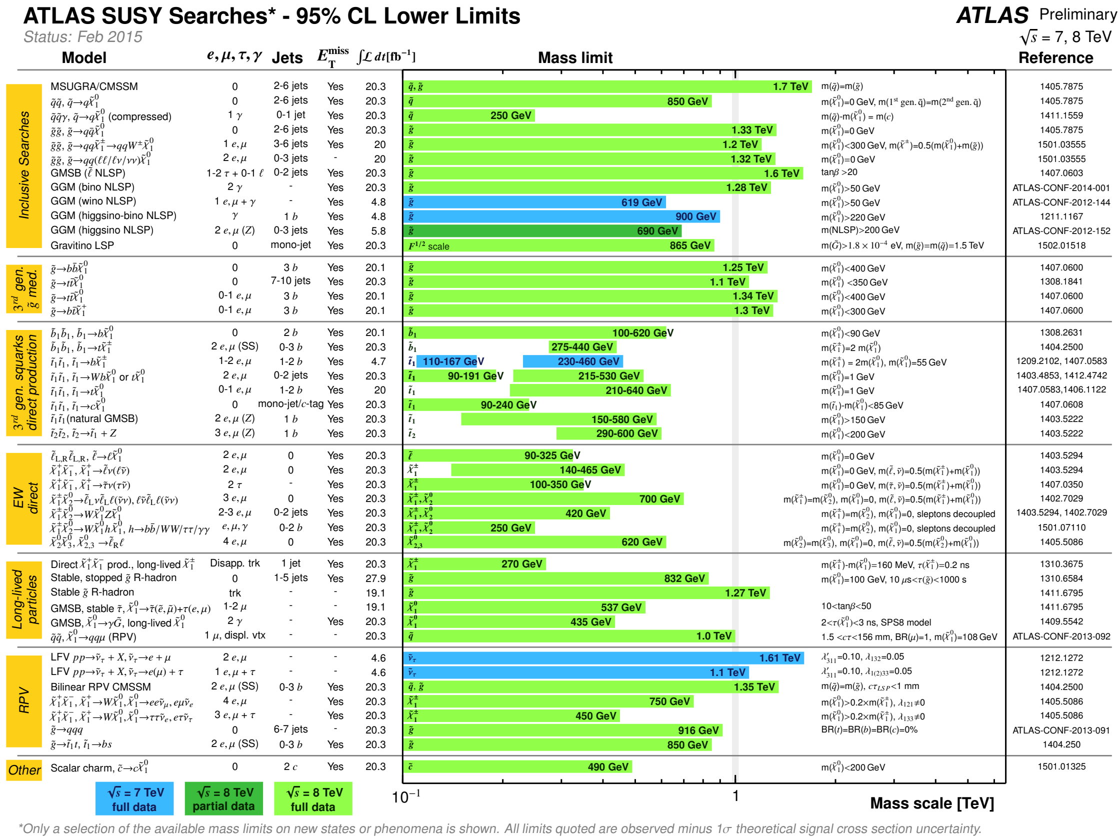
A physics driver @ LHC

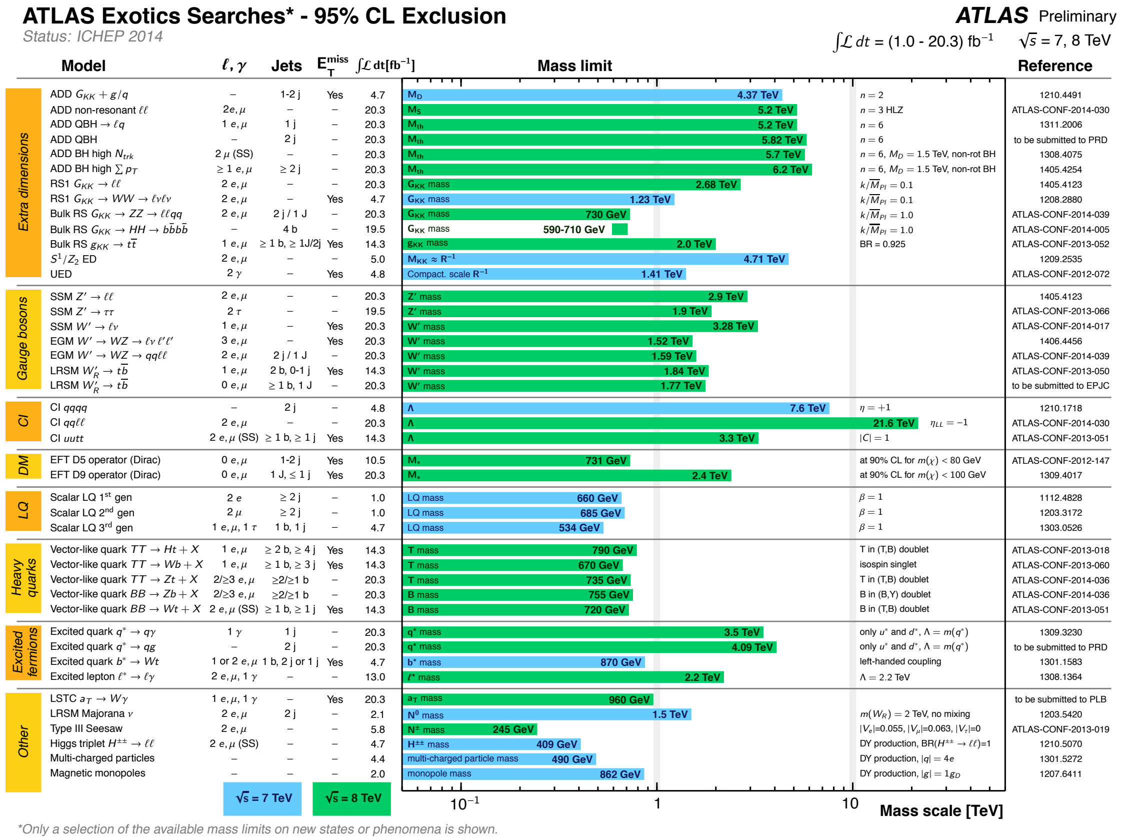






170 of these 226 channels tied to naturalness



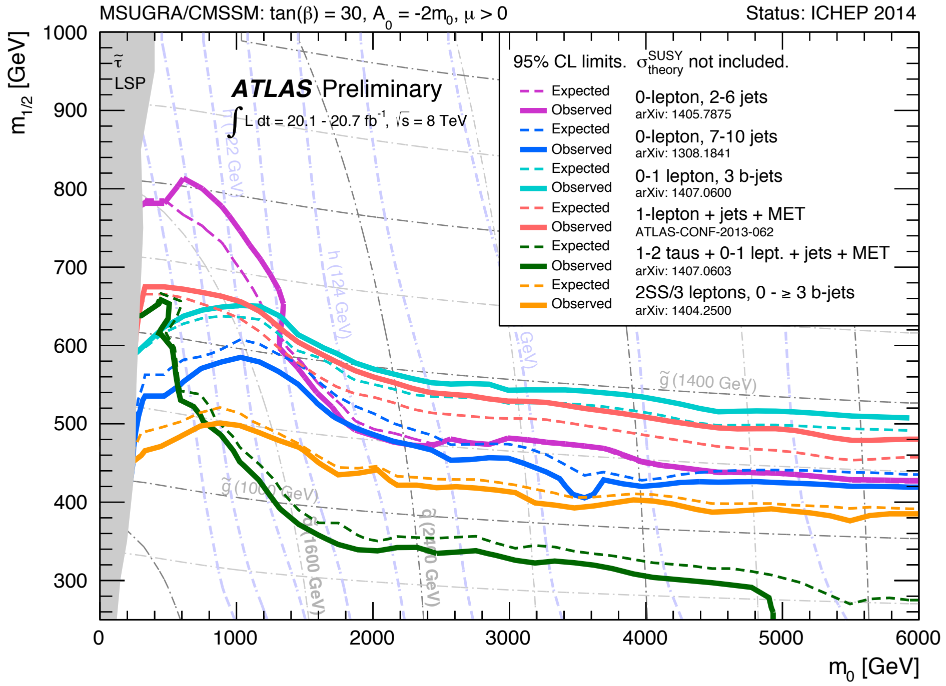


The case for SUSY

Why SUSY?

- ✓ Naturalness
- ✓ Dark matter
- ✓ Unification
- ✓ Higgs mass
- ✓ Decoupling

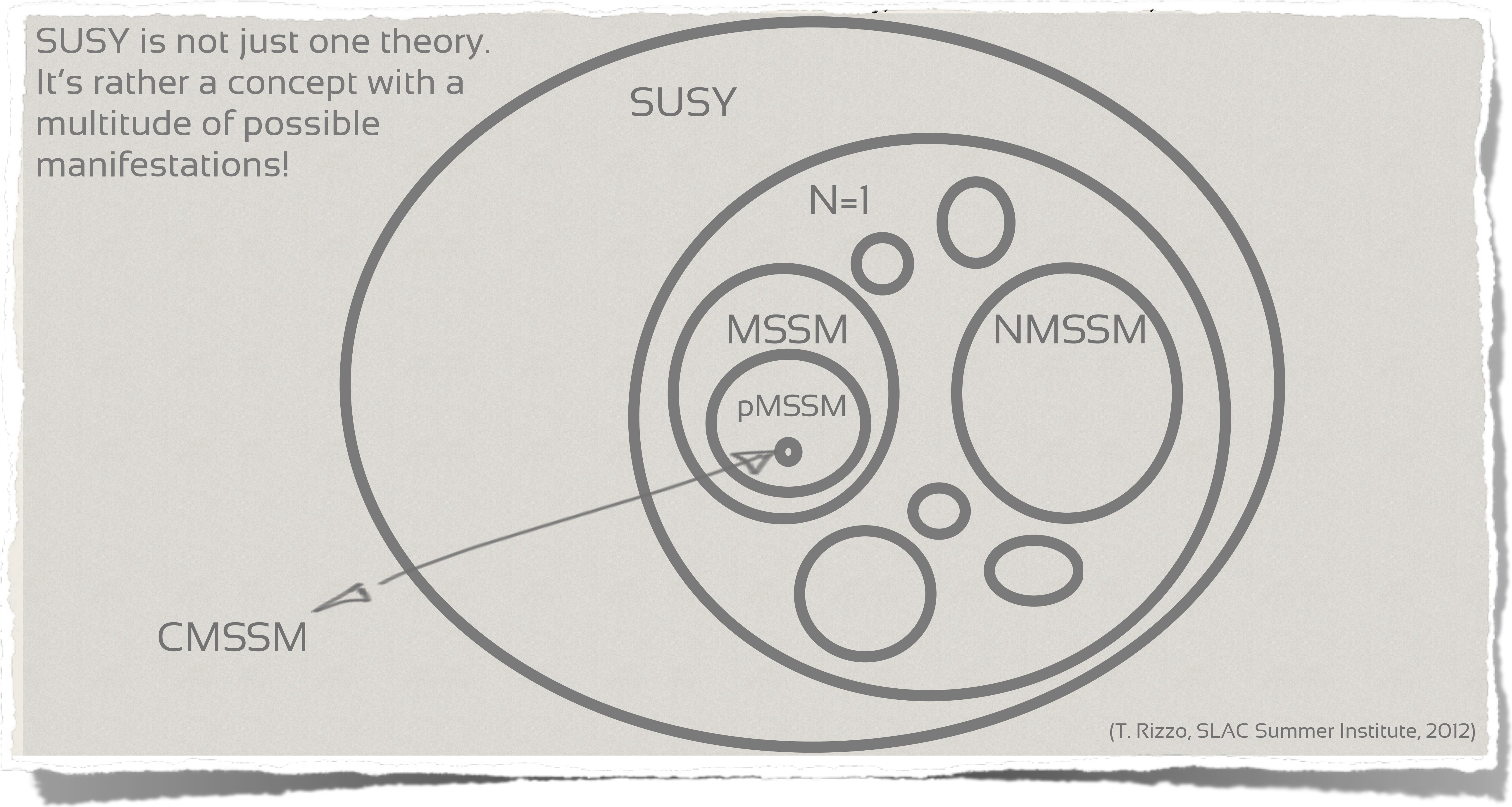
Why not?



Mass reach for simplest versions out to 1.5 TeV

~1% tuning level

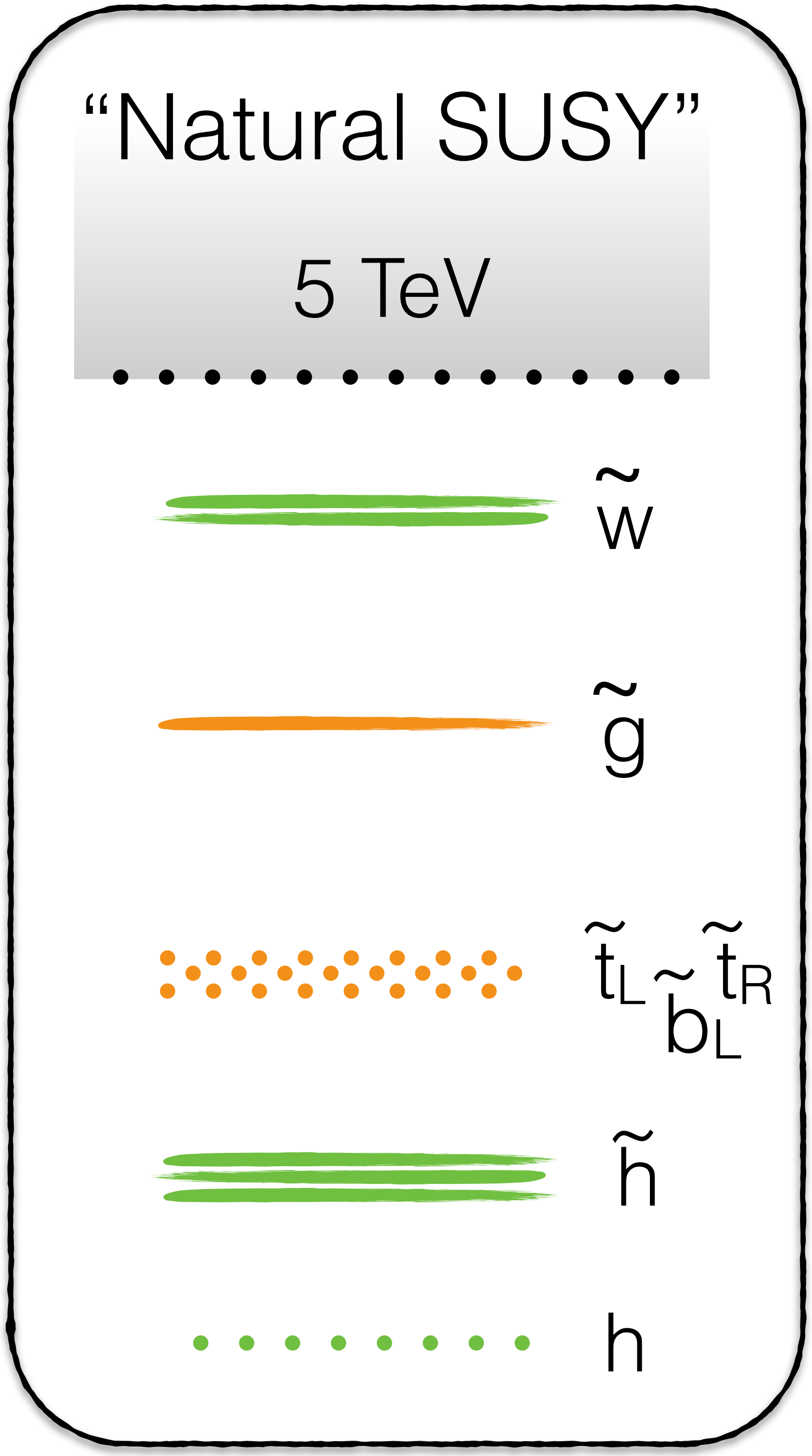
SUSY contains multitudes!



SUSY is not just one theory. It's rather a concept with a multitude of possible manifestations!

(T. Rizzo, SLAC Summer Institute, 2012)

Minimal ingredients



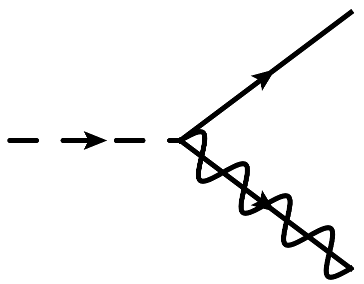
At the very least: organize minimal spectrum for naturalness by size of threshold corrections to Higgs

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

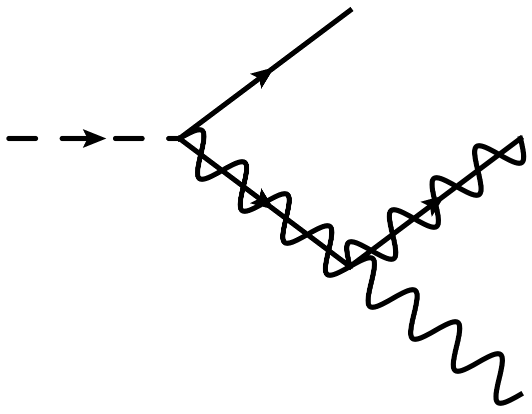
QCD production of stops, gluinos makes natural target for LHC (but also look for electroweak physics @ electroweak scale)

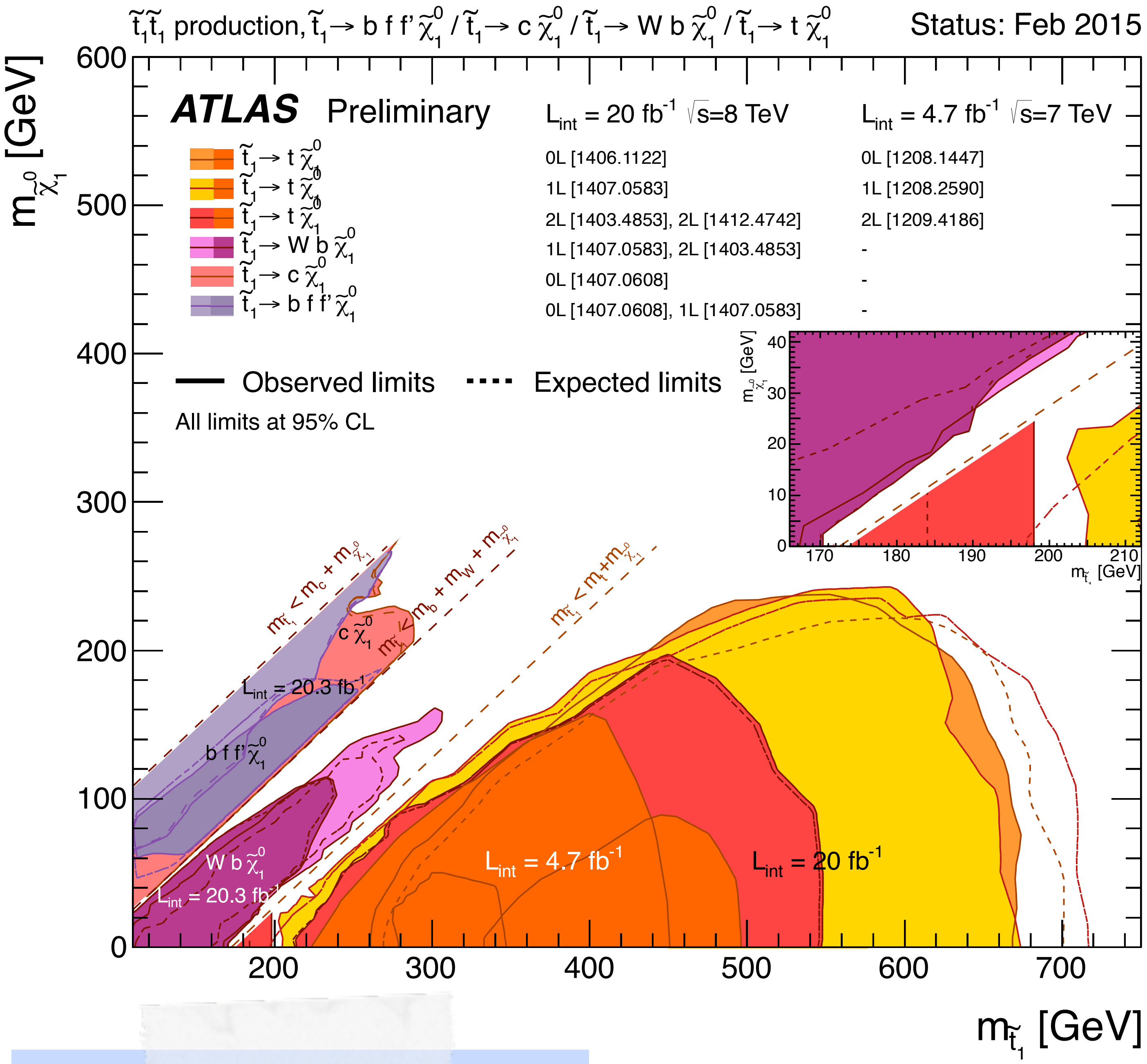
[Dimopoulos, Giudice ‘95; Cohen, Kaplan, Nelson ’96; Papucci, Ruderman, Weiler ’11; Brust, Katz, Lawrence, Sundrum ’11]

Natural SUSY was in the “Old Testament”



Direct limits





See also S. Asai's talk

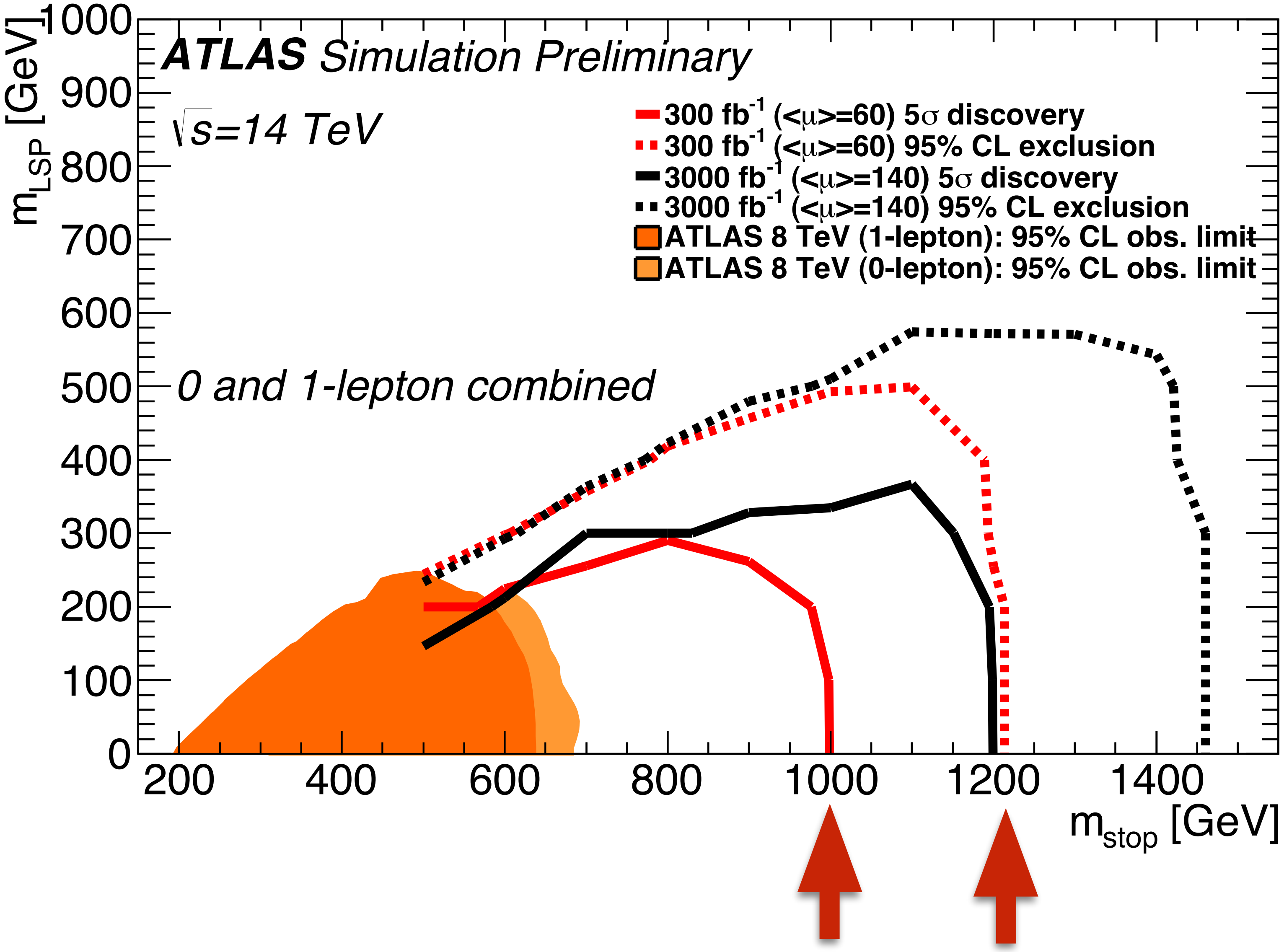
Scalar top searches: greatest reach for SUSY naturalness

Where we are: "generically"

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

~7% tuning level

Looking forward



Reach doubles by 300/fb

Where we'll be @ end of LHC:

"generically"

~1% tuning level

If stops are just outside our current reach, an abundance of new physics awaits in Run 2. If not…

Implications

SUSY searches

Natural SUSY

Unnatural SUSY

Global symmetry

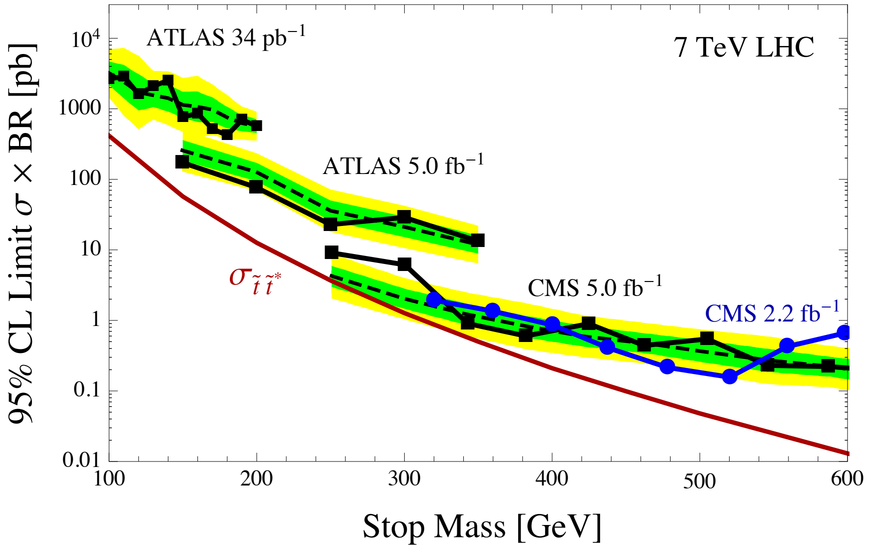
Radical symmetry

Not symmetry

1. Natural SUSY?

Or: UDD RPV

[Bai, Katz, Tweedie '13]

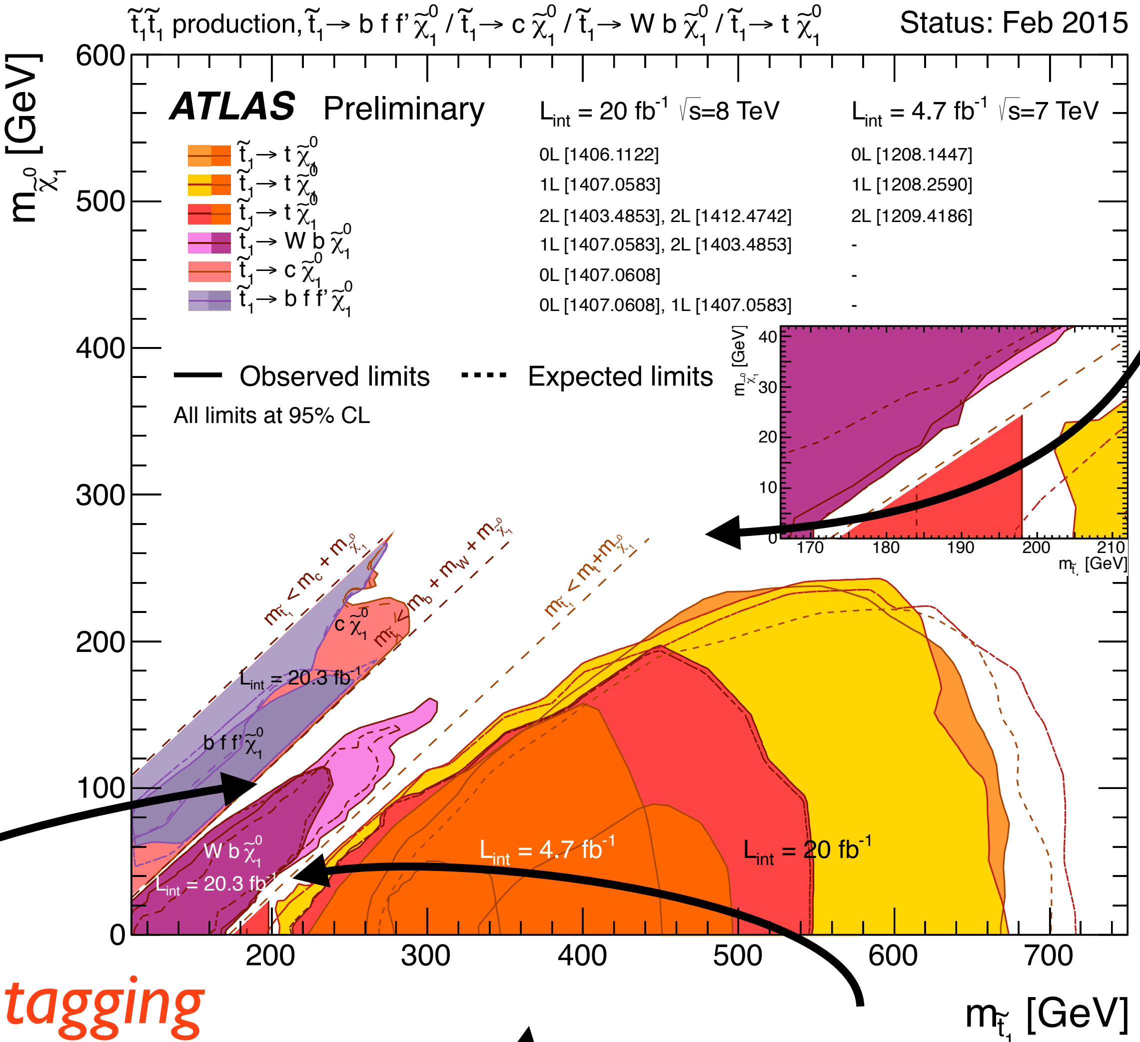


Exclusions assume R parity is conserved; no sensitivity to stops with baryonic RPV

Be compressed

coverage improving with shape-based searches

[Martin '07; LeCompte & Martin '11]



Mix your flavors

improving charm+MET with charm tagging

[Mahbubani, Perez, Papucci, Ruderman, Weiler '12]

Be stealthy

cascades; tt spin correlations; tt cross section limit

[Shelton '08; Fan, Reece, Ruderman '11; Han, Katz, Krohn, Reece '12; Czakon, Mitov, Papucci, Ruderman, Weiler '14]

Mix your decay modes

use topness & other dedicated variables

[Grasser, Shelton '12]

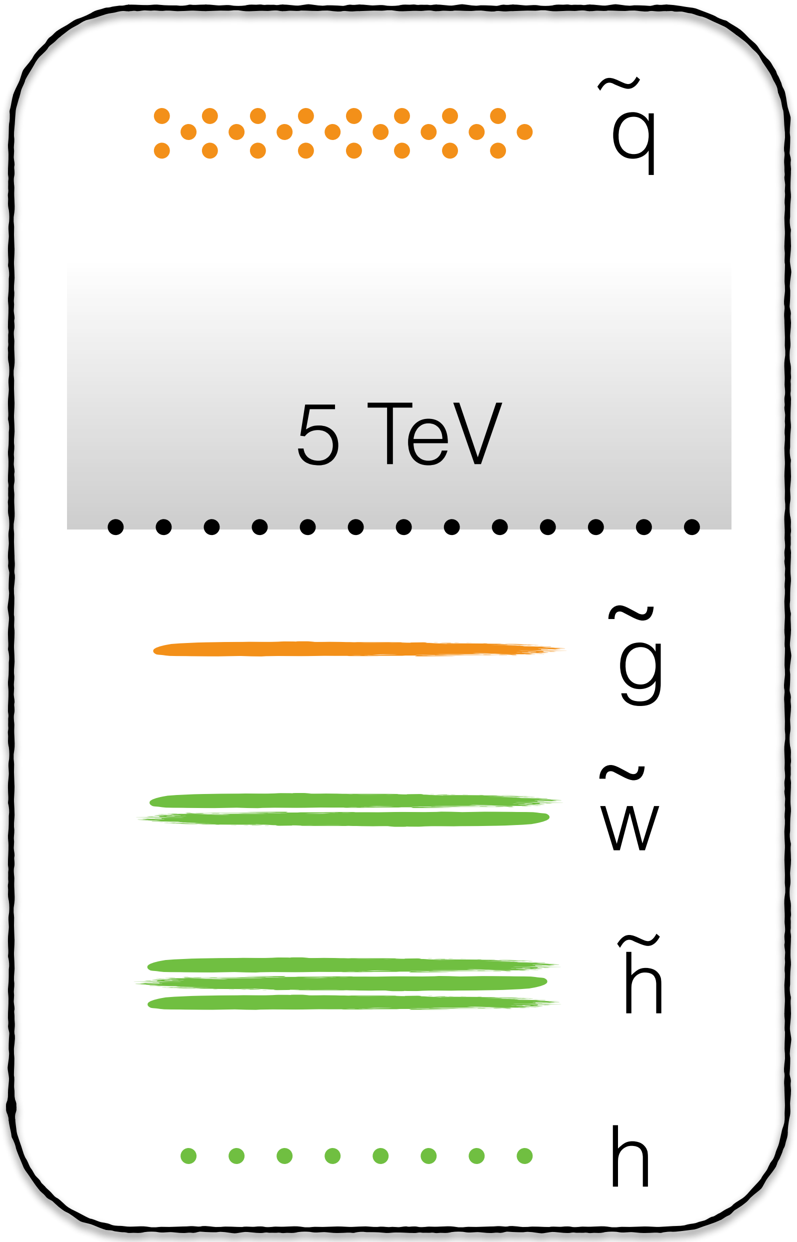
[Wells ‘03; Giudice & Romanino ‘04; Arkani-Hamed & Dimopoulos ‘04]

2. Unnatural SUSY?

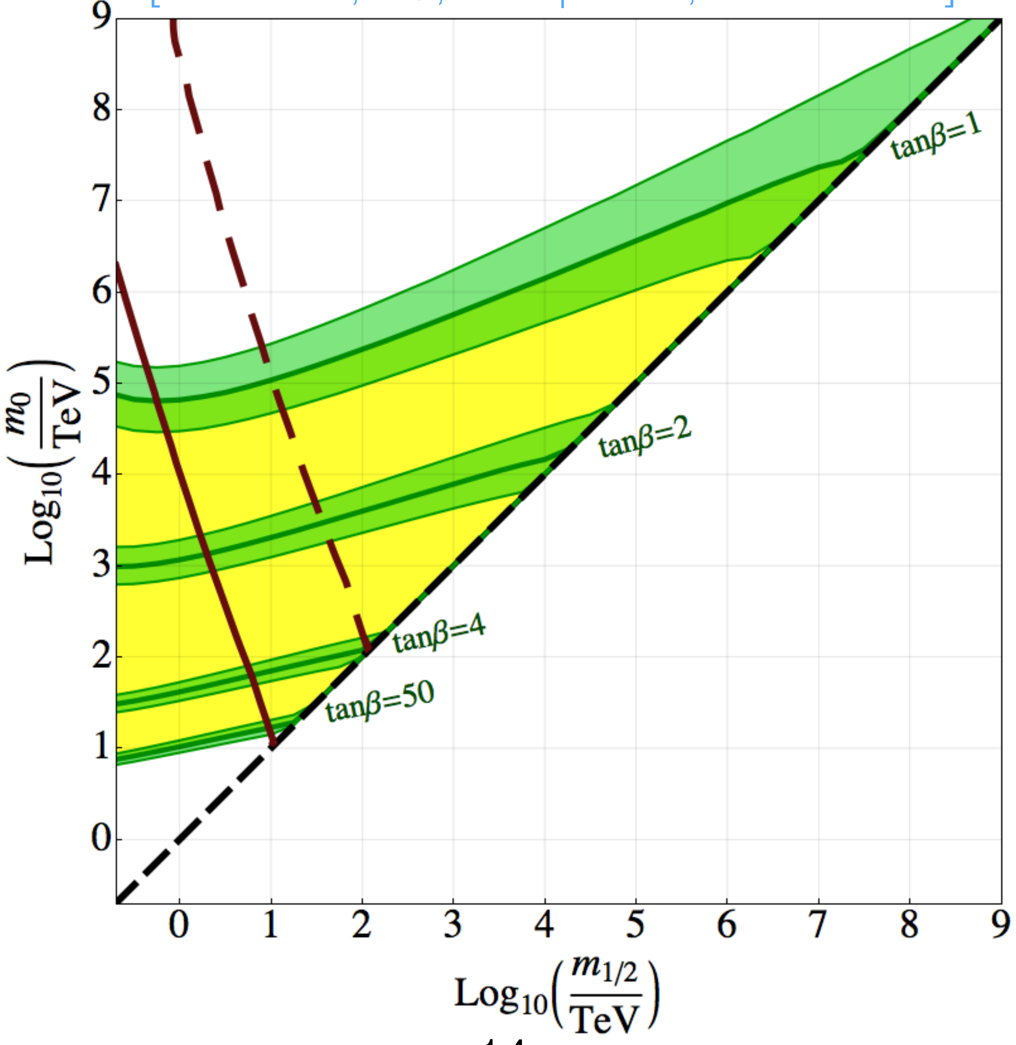
What if SUSY has nothing to do with stabilizing the weak scale?

“(mini-)Split SUSY”

- X Naturalness
- ✓ Dark matter
- ✓ Unification



[Arvanitaki, NC, Dimopoulos, Villadoro ‘12]



Scalars decouple, fermions are light (unification/DM)

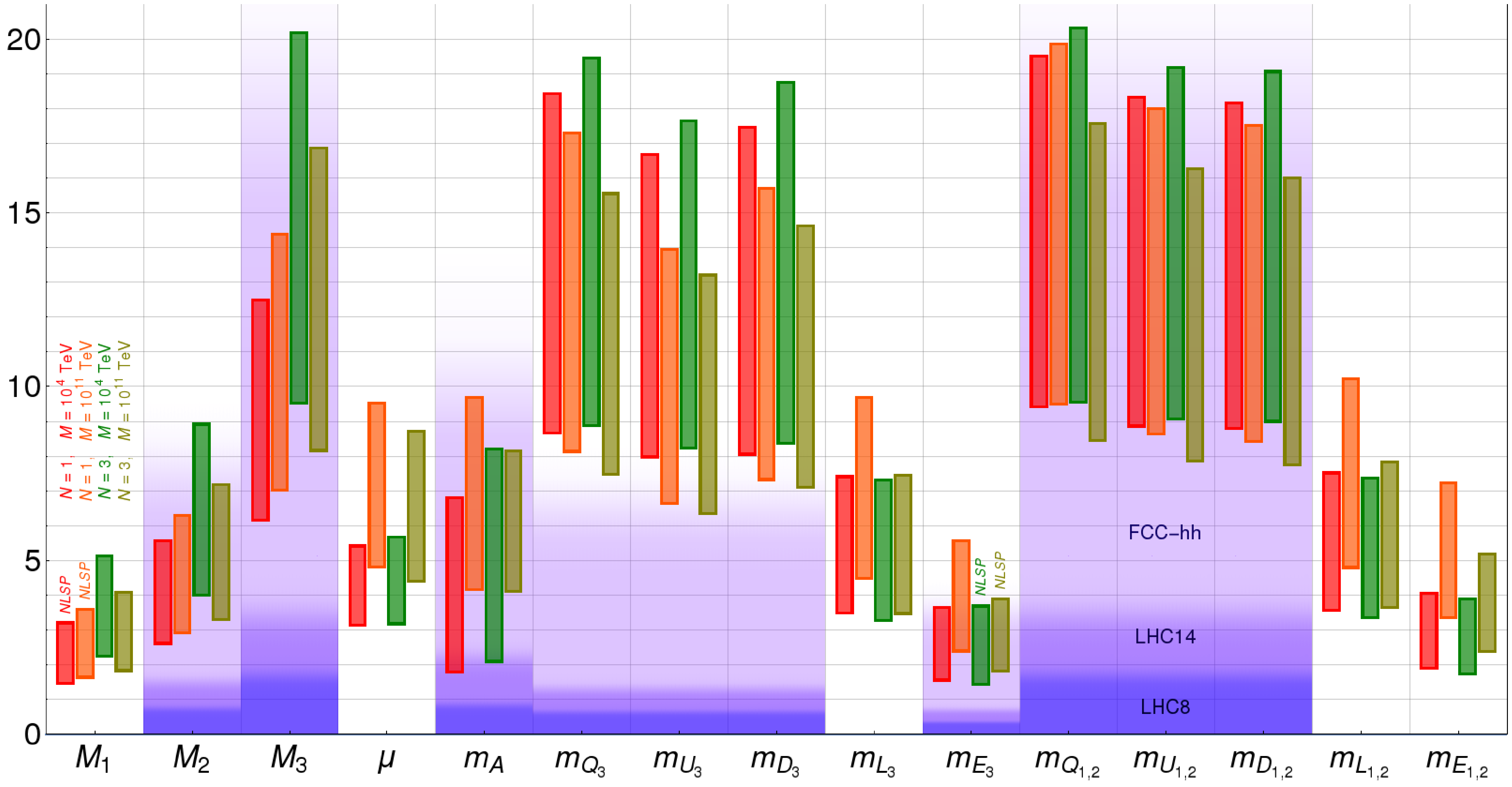
Gluino, higgsino signals @ LHC

Gluino decays prompt or displaced

Unnatural but simple

And still 28 orders of magnitude more natural than SM

[Vega, Villadoro '15]



E.g., spectrum of minimal gauge mediation entirely fixed.

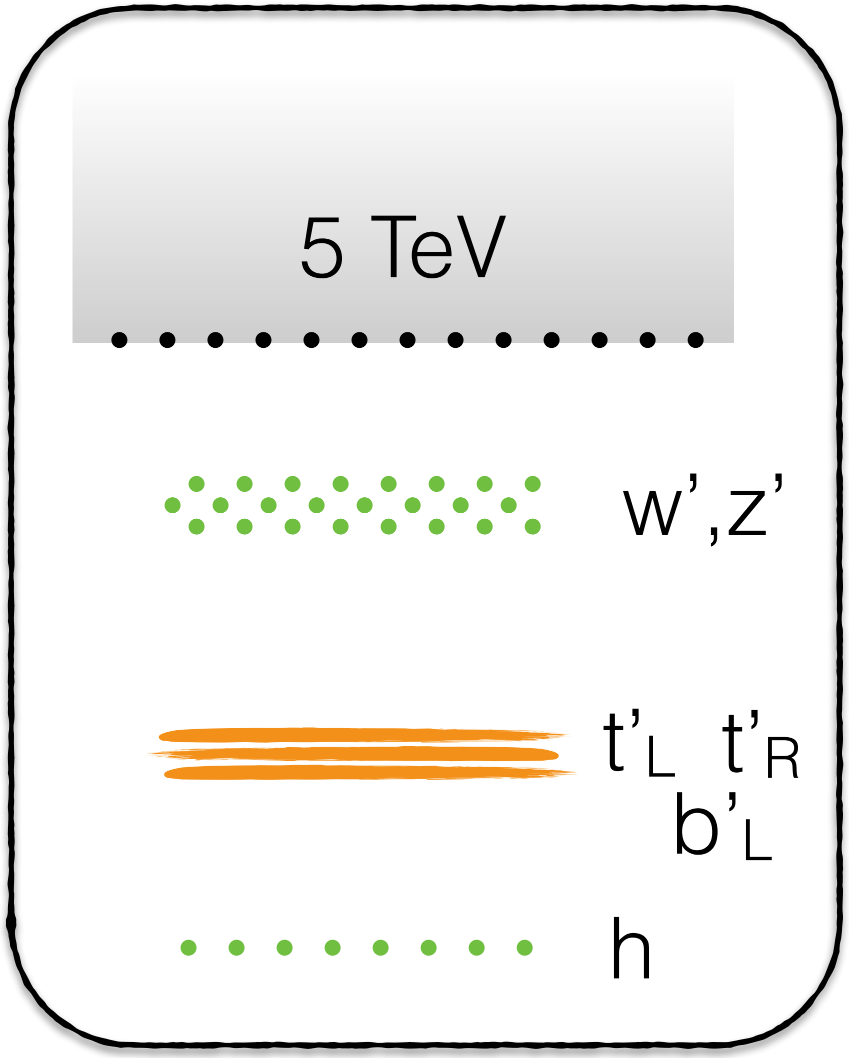
[Georgi & Kaplan ’84; Arkani-Hamed, Cohen, Katz, Nelson, Gregoire ’02; Contino, Nomura, Pomarol ’03]

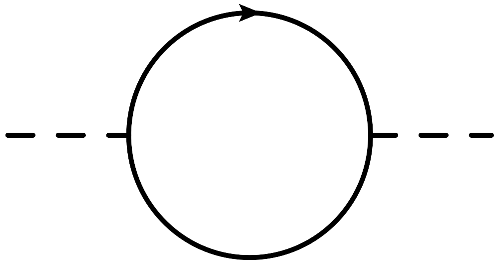
3. Global symmetries?

What about the “other” symmetry (global) for the Higgs mass?

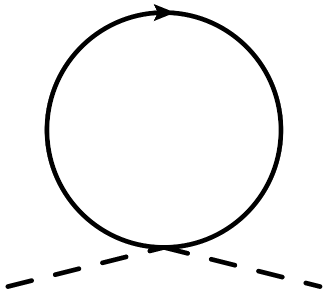
- ✓ Naturalness
- ✓ Dark matter
- X Unification

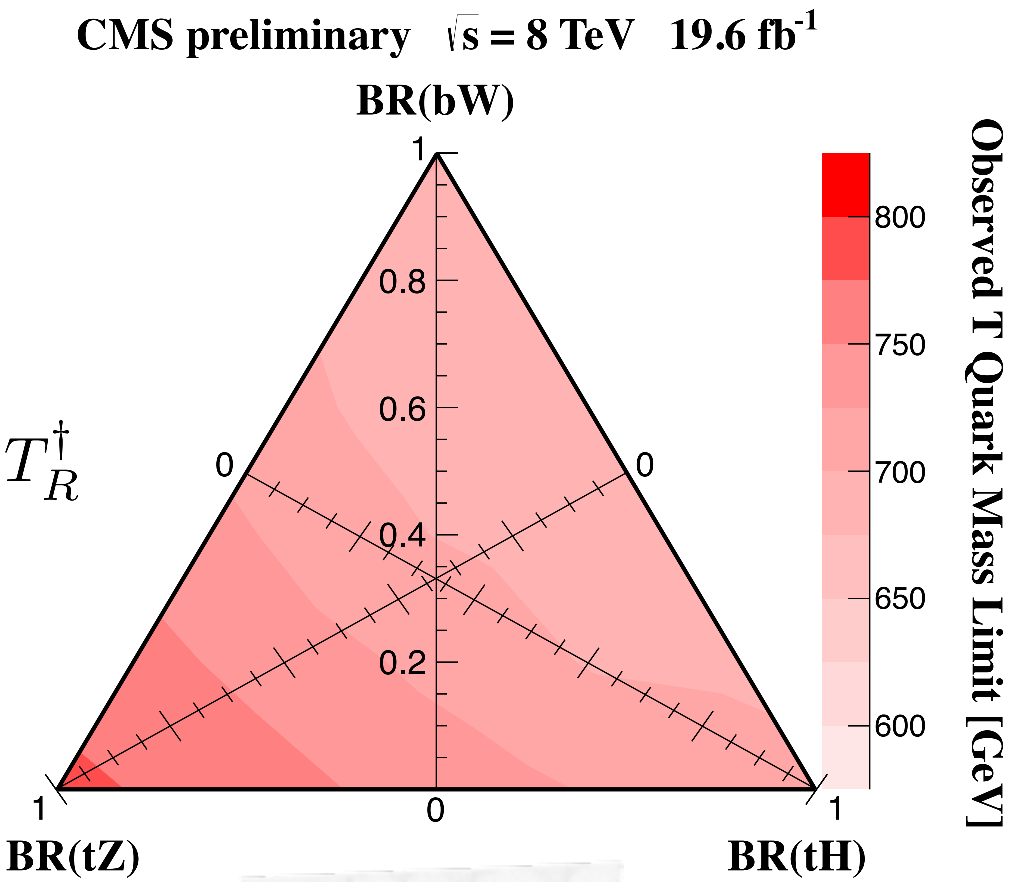
“Composite Higgs/Little Higgs”





$$y_t H Q_3 t_R^\dagger - \frac{y_t^2}{2m_T}(H^\dagger H) T_L T_R^\dagger$$





See also P. Azzi’s talk

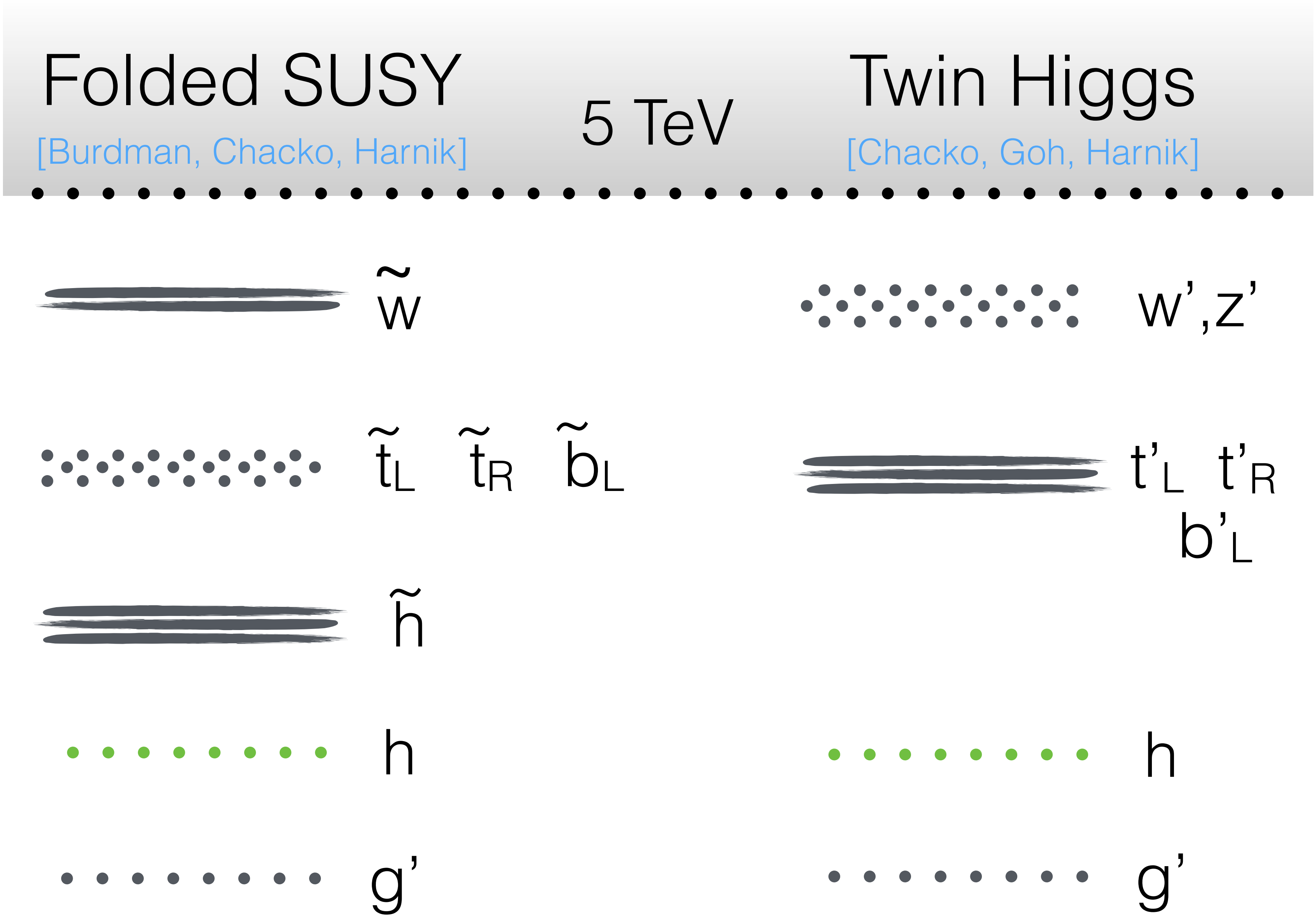
Need light QCD-charged top partners; bounds and tuning comparable to SUSY.

4. Radical symmetries?

What if the weak scale is natural,
but the new states are SM neutral?

“Neutral naturalness”

- ✓ Naturalness
- ✓ Dark matter
- ✓ Unification



Strong SUSY bounds have nothing to do with couplings to Higgs.

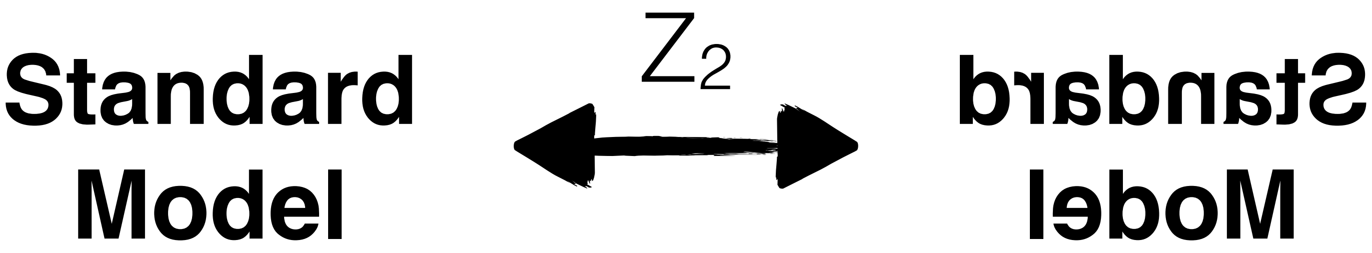
Reach comes from QCD quantum #’s

Can we have natural theories without colored partner states?

Yes

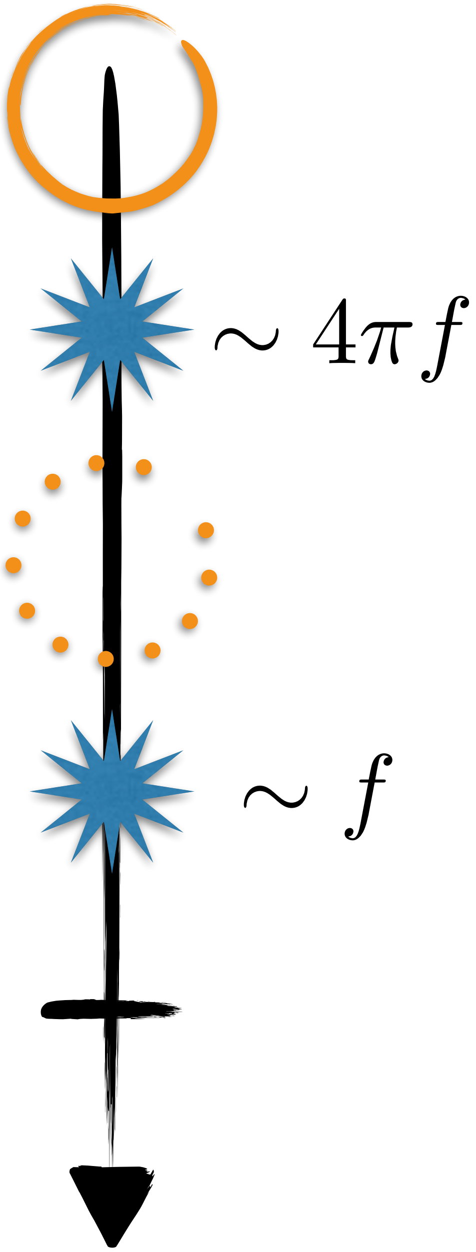
[Chacko, Goh, Harnik '05]

An example: Twin Higgs


Standard Model

Z_2

Standard Model



E.g., weak gauge symmetry is SU(2)$_{\text{us}}$ x SU(2)$_{\text{twin}}$

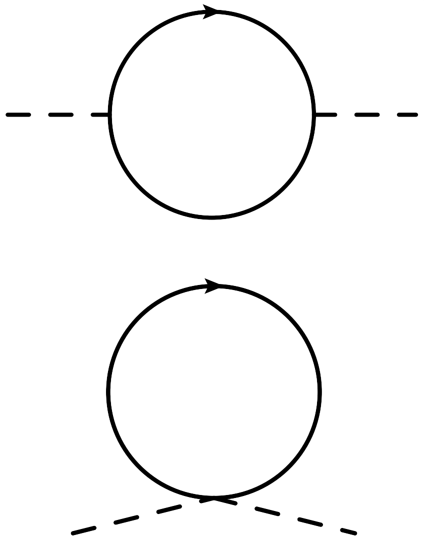
Thanks to Z_2, radiative corrections to the Higgs mass are SU(4) symmetric:

$$V(H) \supset \frac{9}{64\pi^2} g^2 \Lambda^2 \left(|H_A|^2 + |H_B|^2\right)$$

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

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

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



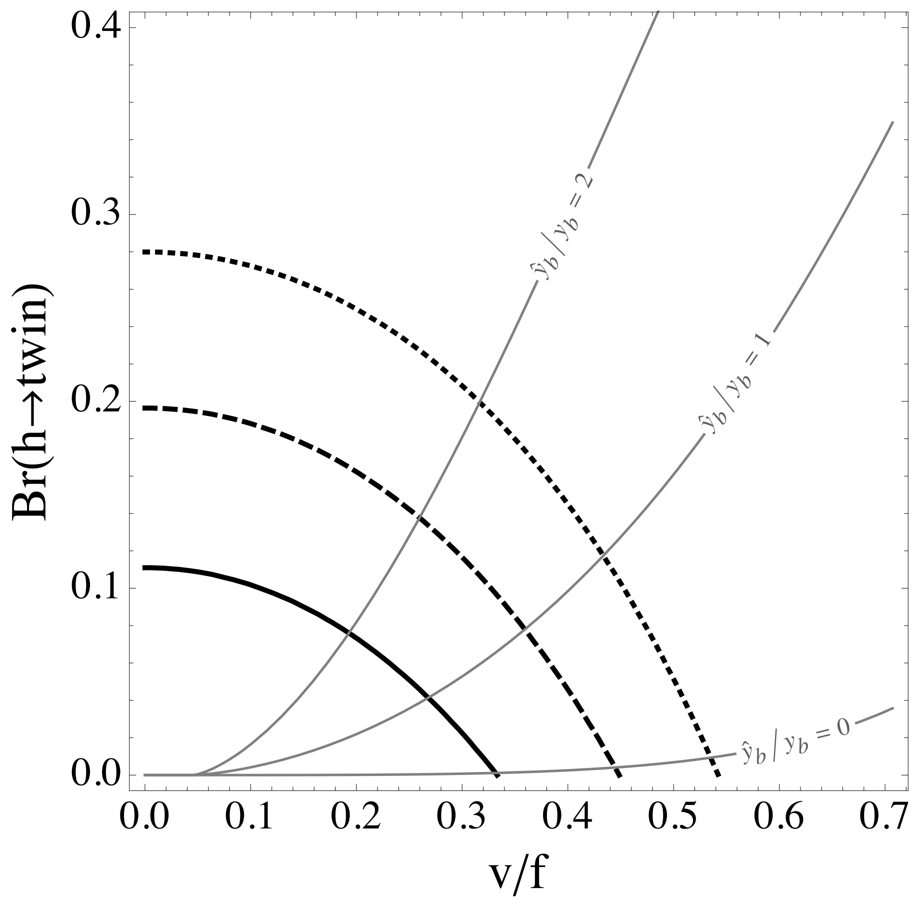
There are many more theories of this kind [NC, S Knapen, P Longhi '14]

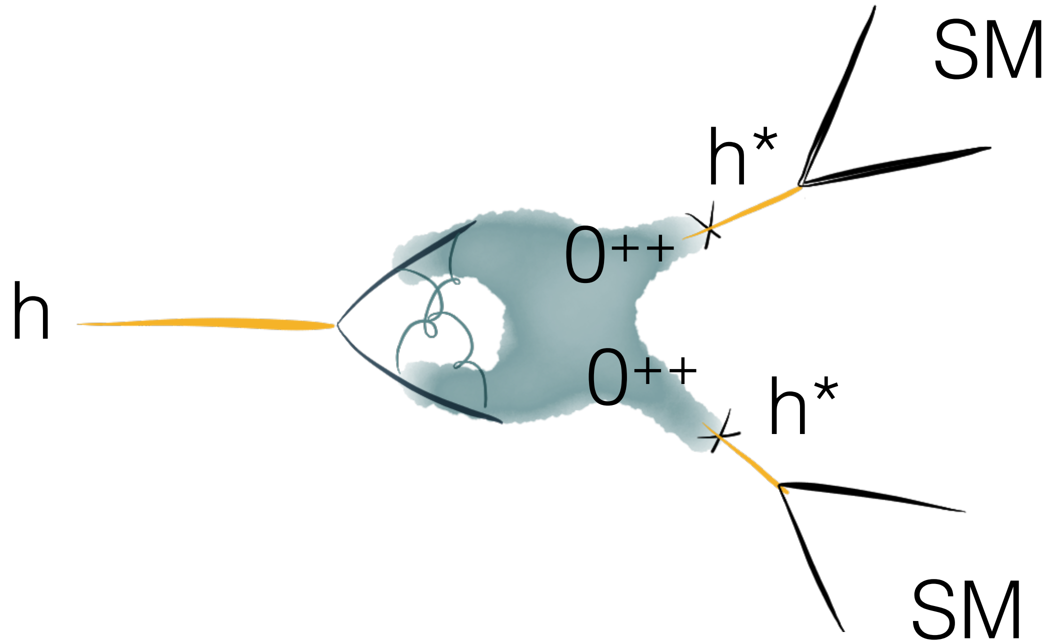
See also J. Shelton's talk

[NC, Katz, Strassler, Sundrum '15]

Twin Signals

- Modest Higgs coupling deviations and invisible branching ratio (~5-10%).
- Displaced decays: Higgs into hidden sector, hidden sector confines (must have twin QCD!), displaced decays via off-shell Higgs.
- Singlet-like heavy Higgs decaying to hh, WW, ZZ, invisible.
- Abundant dark matter candidates (thermal, asymmetric, SIMP, …)





Not yet meaningfully constrained; naturalness potentially probed to ~20% level by end of LHC

See also E. Masso's talk

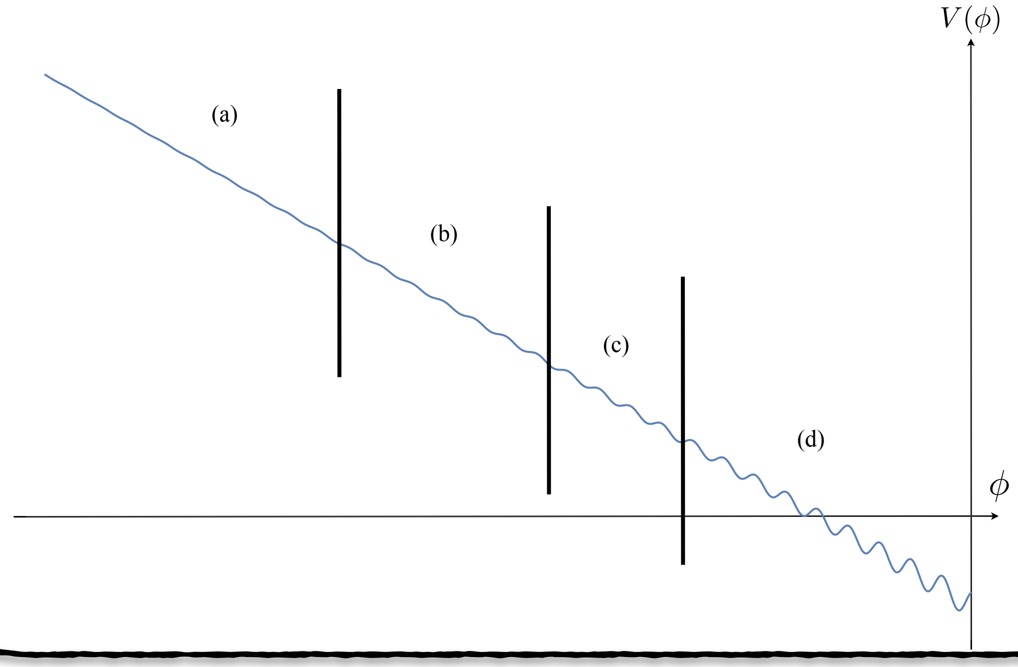
[Graham, Kaplan, Rajendran '15]

5. Not symmetries?

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

- ? Naturalness
- ✓ Dark matter
- ✓ Unification

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



GKR solution: what turns on when m_H^2 goes negative?
Vev gives **quark masses** which give **axion potential**!

"Relaxion"

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

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

Just need Higgs + non-compact axion + inflation w/

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

Minimal model: cutoff is $M < \left(\frac{\Lambda^4 M_P^3}{f}\right)^{1/6} \theta^{1/4} \sim 30\ \mathrm{TeV}\ \times \left(\frac{10^9\ \mathrm{GeV}}{f}\right)^{1/6} \left(\frac{\theta}{10^{-10}}\right)^{1/4}$

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

Just need Higgs + non-compact axion + inflation w/

- Very low Hubble scale (≪$\Lambda_{\rm QCD}$)
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☠ *In vacuum, axion gives O(1) contribution to θ_{QCD}* ☠

Fix: make it someone else's 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

1. New quarks must get most of mass from Higgs:

$$\mathcal{L} \supset m_L L L^c + m_N N N^c + y H L N^c + y' H^\dagger L^c N$$

2. Must confine, but with light flavor $\Lambda^4 \simeq 4\pi f_{\pi'}^3 m_N$

…still new physics @ weak scale

Now $m_N \geq yy'v^2/m_L$ (smallest see-saw mass from EWSB if L heavy)

But also
$$\begin{cases} m_N \geq \frac{yy'}{16\pi^2} m_L \log(M/m_L) & \text{(Radiative Dirac mass)} \\ m_N \geq yy' f_{\pi'}^2/m_L & \text{(Higgs wiggles biggest)} \end{cases}$$

These bounds imply $f_{\pi'} < v$ and $m_L < \dfrac{4\pi v}{\sqrt{\log(M/m_L)}}$

Can't decouple new degrees of freedom.
New confining physics near weak scale!

Couples to Higgs; hidden valley signatures

$$M < \left(\frac{\Lambda^4 M_P^3}{f}\right)^{1/6} \sim 3\times 10^5 \text{ TeV } \times \left(\frac{10^9 \text{ GeV}}{f}\right)^{1/6} \left(\frac{f_{\pi'}}{30 \text{ GeV}}\right)^{1/2} \left(\frac{yy'}{10^{-2}}\right)^{1/6} \left(\frac{300 \text{ GeV}}{m_L}\right)^{1/6}$$

Conclusions

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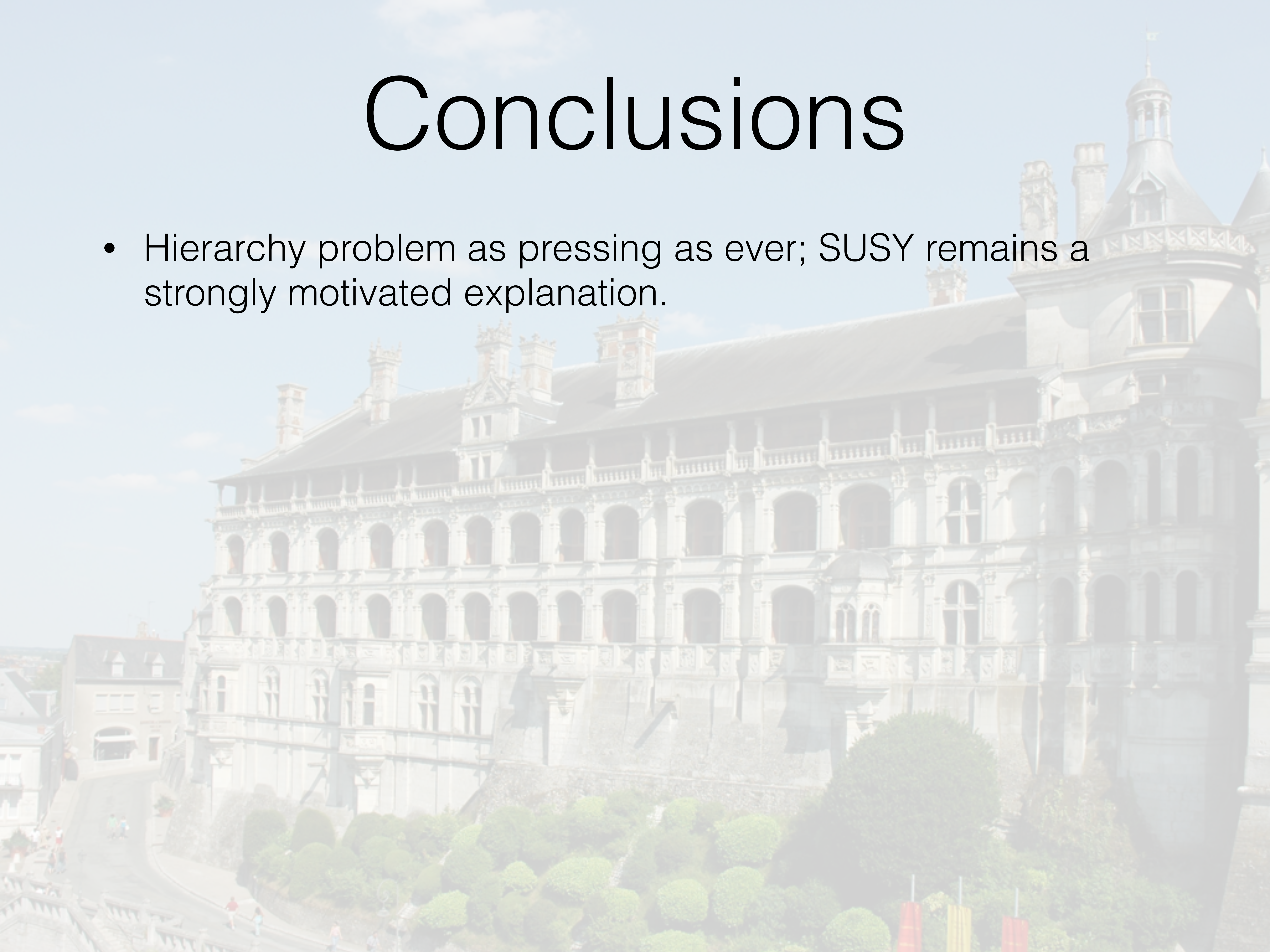
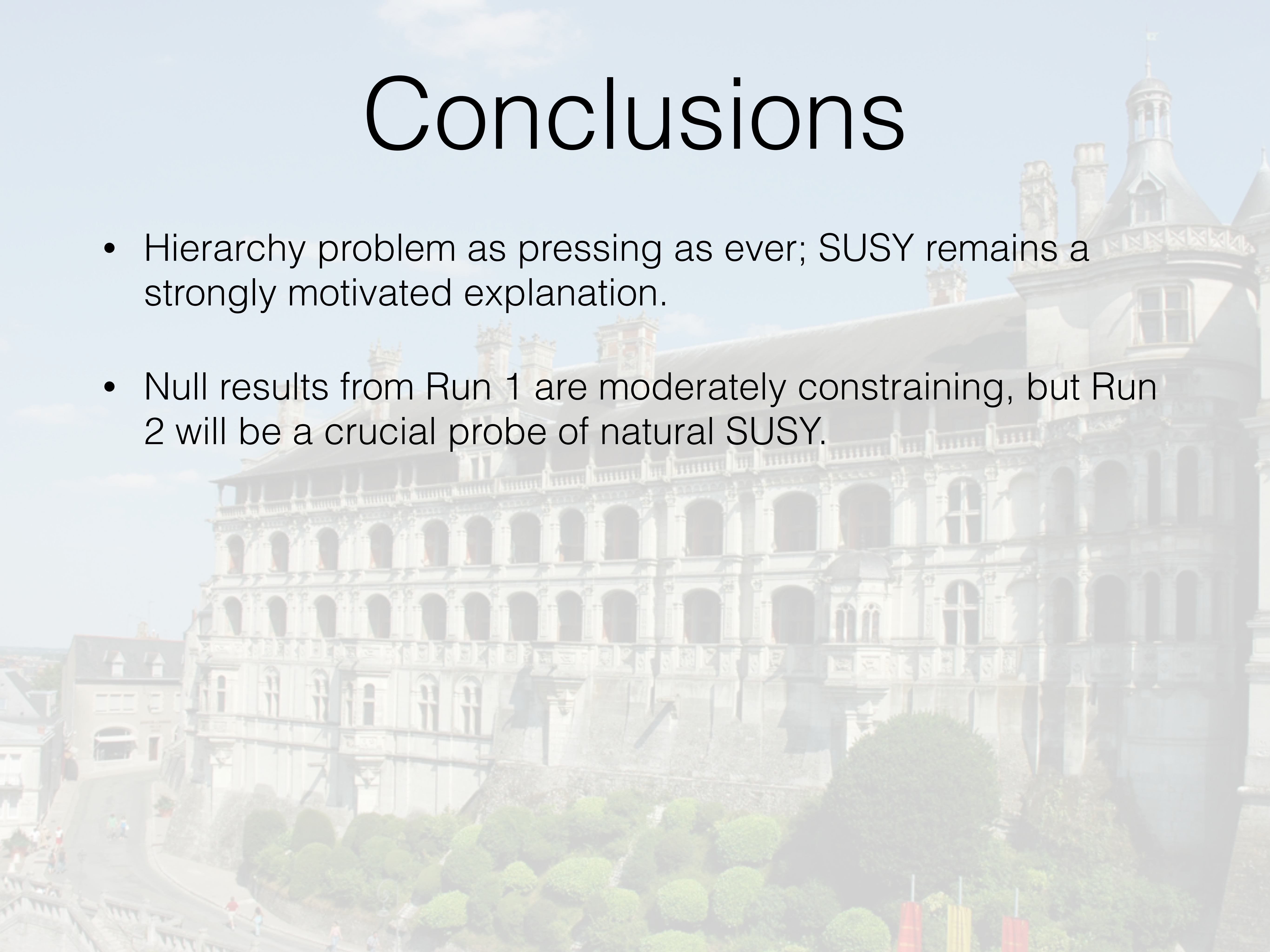
- Hierarchy problem as pressing as ever; SUSY remains a strongly motivated explanation.





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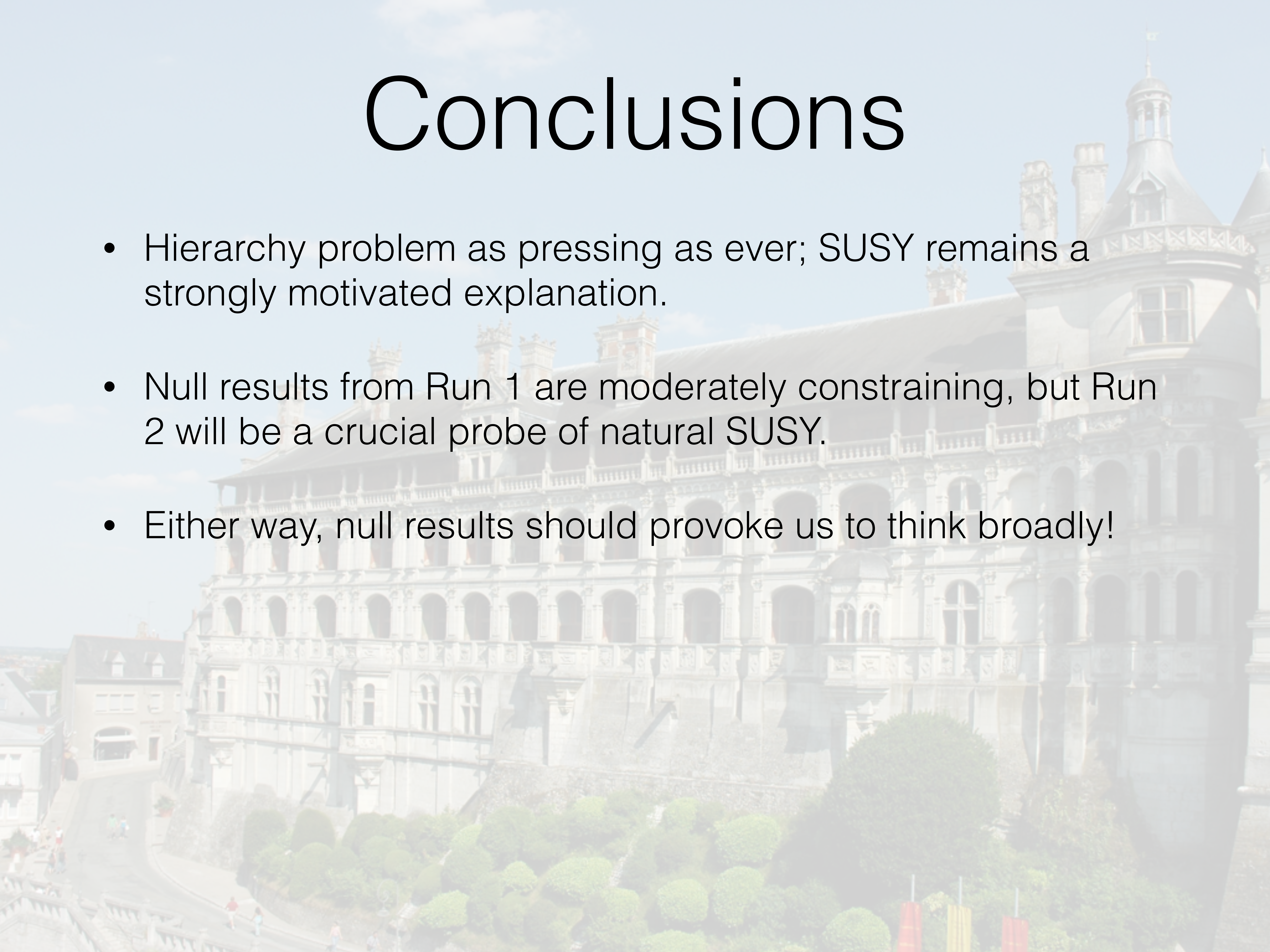

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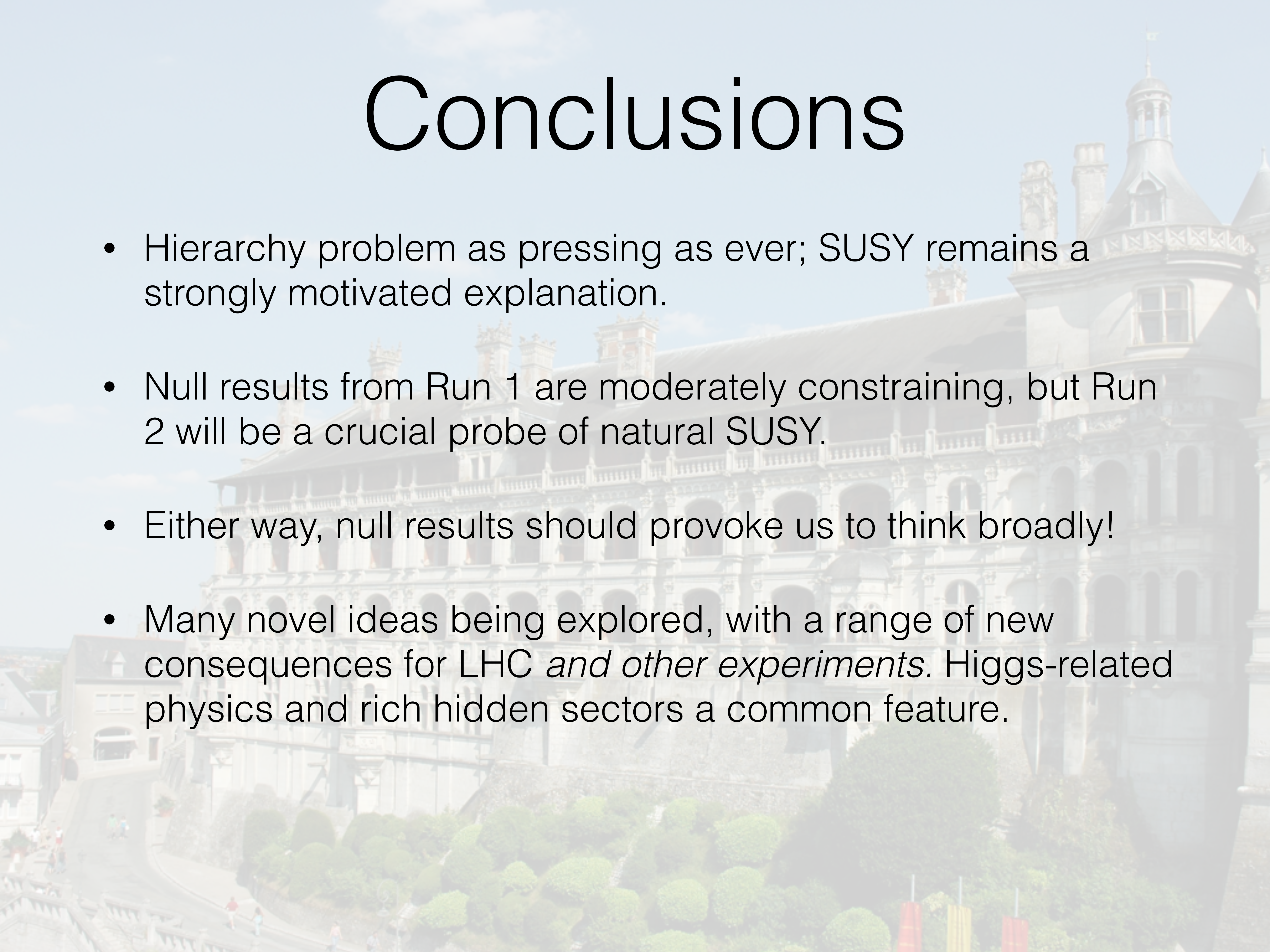

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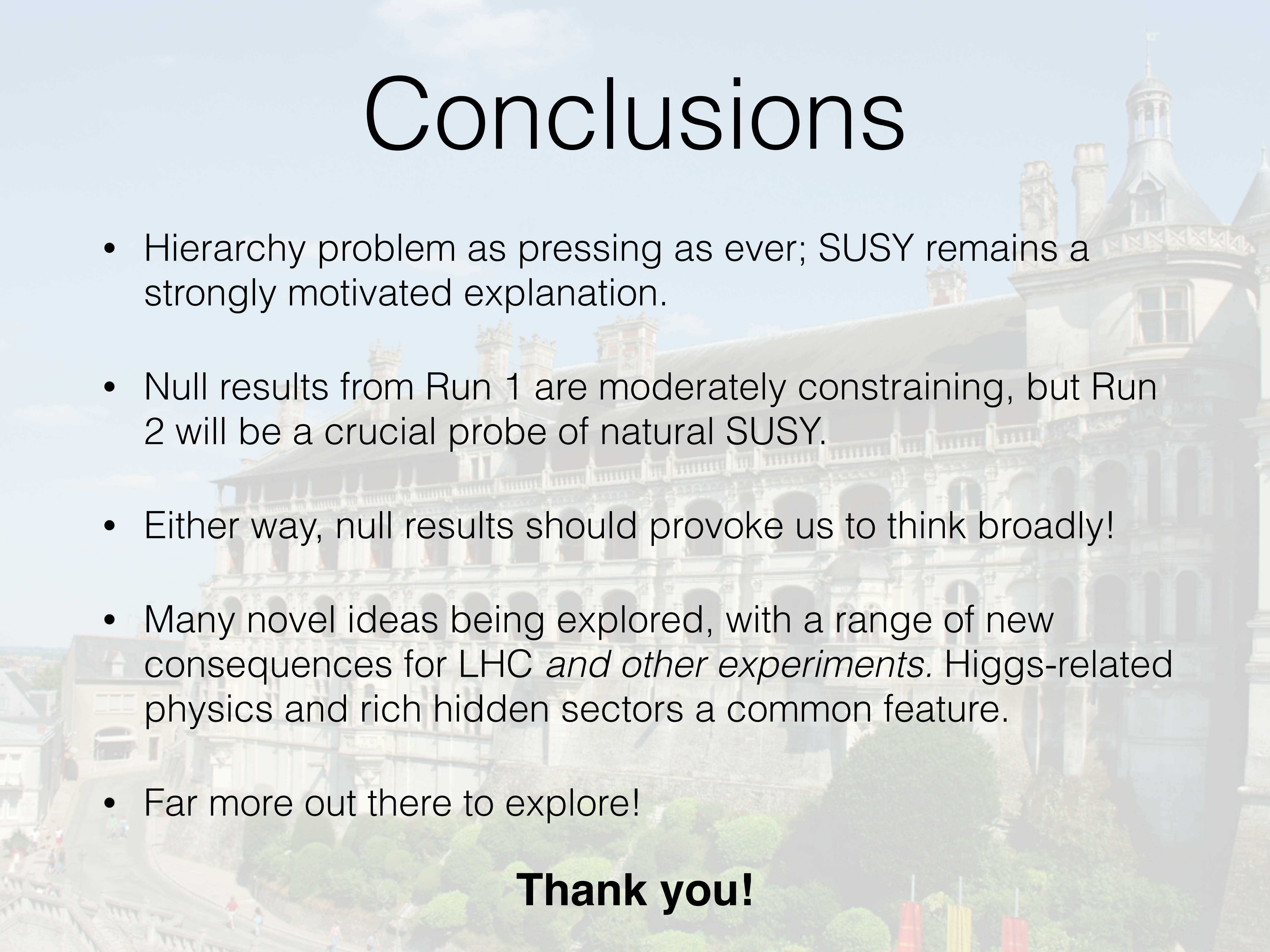
- Null results from Run 1 are moderately constraining, but Run 2 will be a crucial probe of natural SUSY.

- Either way, null results should provoke us to think broadly!

- Many novel ideas being explored, with a range of new consequences for LHC *and other experiments.* Higgs-related physics and rich hidden sectors a common feature.



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- Hierarchy problem as pressing as ever; SUSY remains a strongly motivated explanation.
- Null results from Run 1 are moderately constraining, but Run 2 will be a crucial probe of natural SUSY.
- Either way, null results should provoke us to think broadly!
- Many novel ideas being explored, with a range of new consequences for LHC *and other experiments.* Higgs-related physics and rich hidden sectors a common feature.
- Far more out there to explore!

Thank you!