Naturalness at the 100 TeV scale

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FCC Week 2015

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However…

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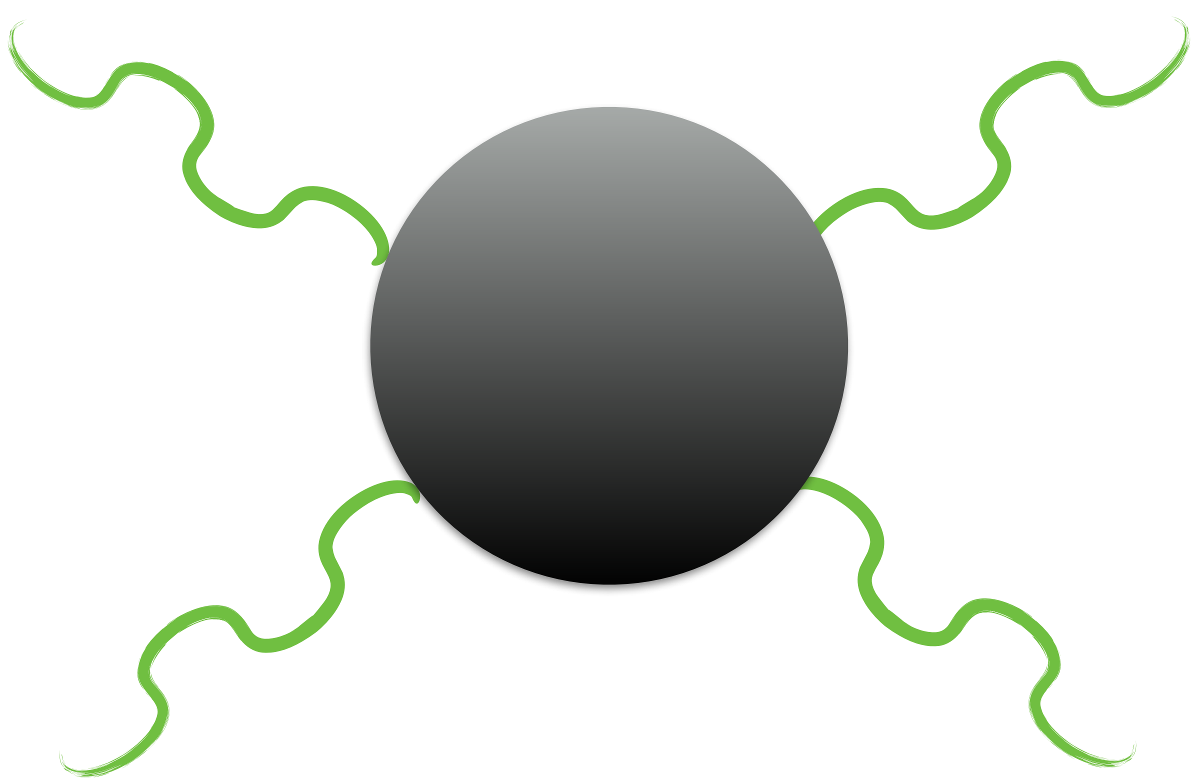
It is extremely useful to have specific motivation to shape the goals of future colliders.

Pre-Higgs Guarantee

Planning for colliders was simple following the discovery of W/Z bosons:



Consistency gave us a no-lose theorem.

Violation of unitarity in VV scattering

↓

Standard Model breaks down parametrically near weak scale

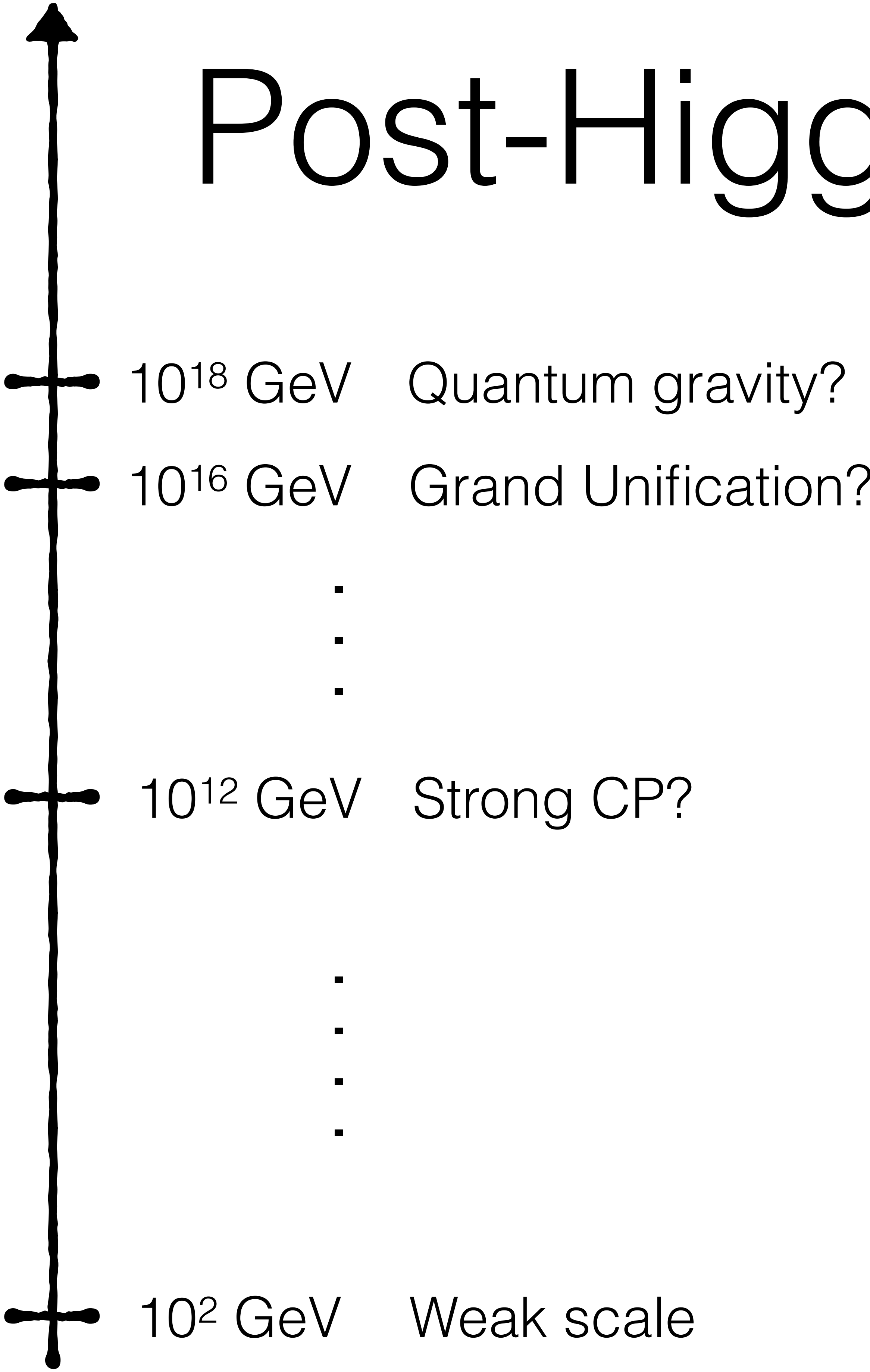
↓

Consistency demands new physics (e.g. Higgs mechanism)

↓

Higgs discovery @ LHC

Post-Higgs Ambiguity

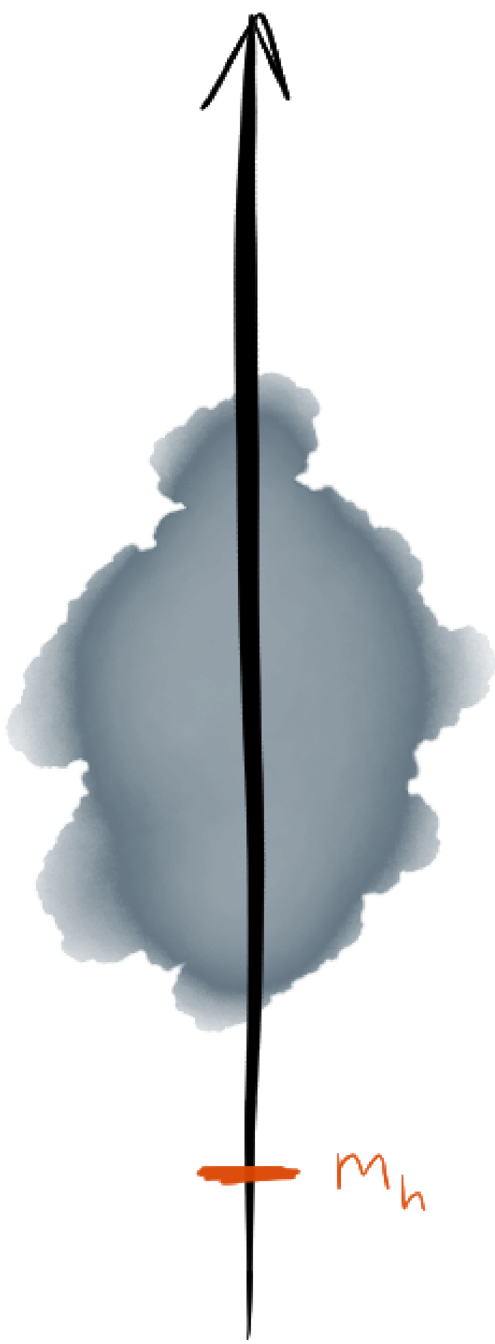


The Standard Model with an elementary Higgs boson is consistent to energies far beyond the weak scale.

There are suggestive indications of interesting physics at various scales, but these need not be accessible at colliders.

We face an absence of no-lose theorems — but in their place we have *compelling strategies*.

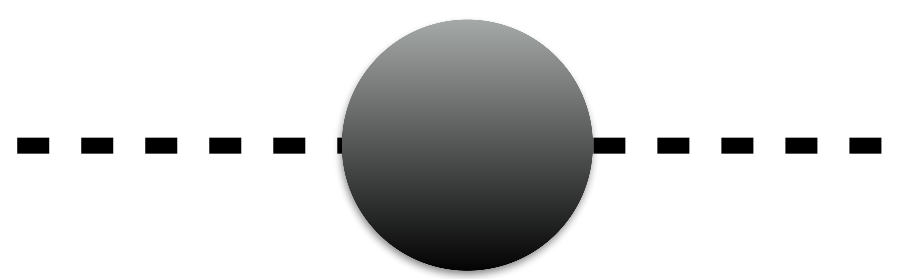
The naturalness strategy



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.



$$\delta m_h \propto \Lambda$$

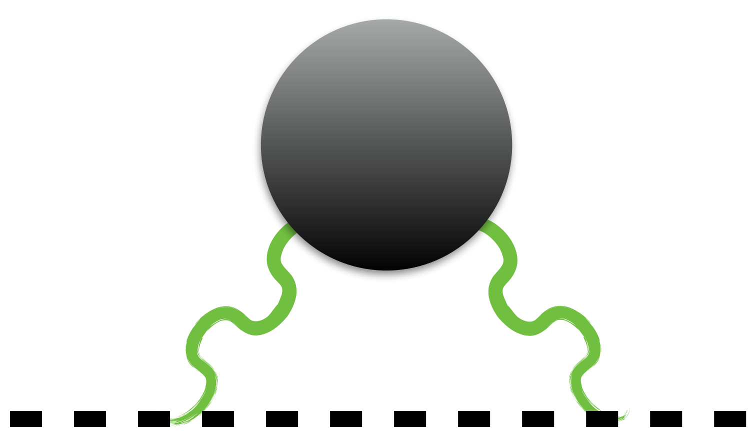
Natural if $\delta m_h \sim m_h$.
($\delta m_h \gg m_h$ unnatural or UV miracle)

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

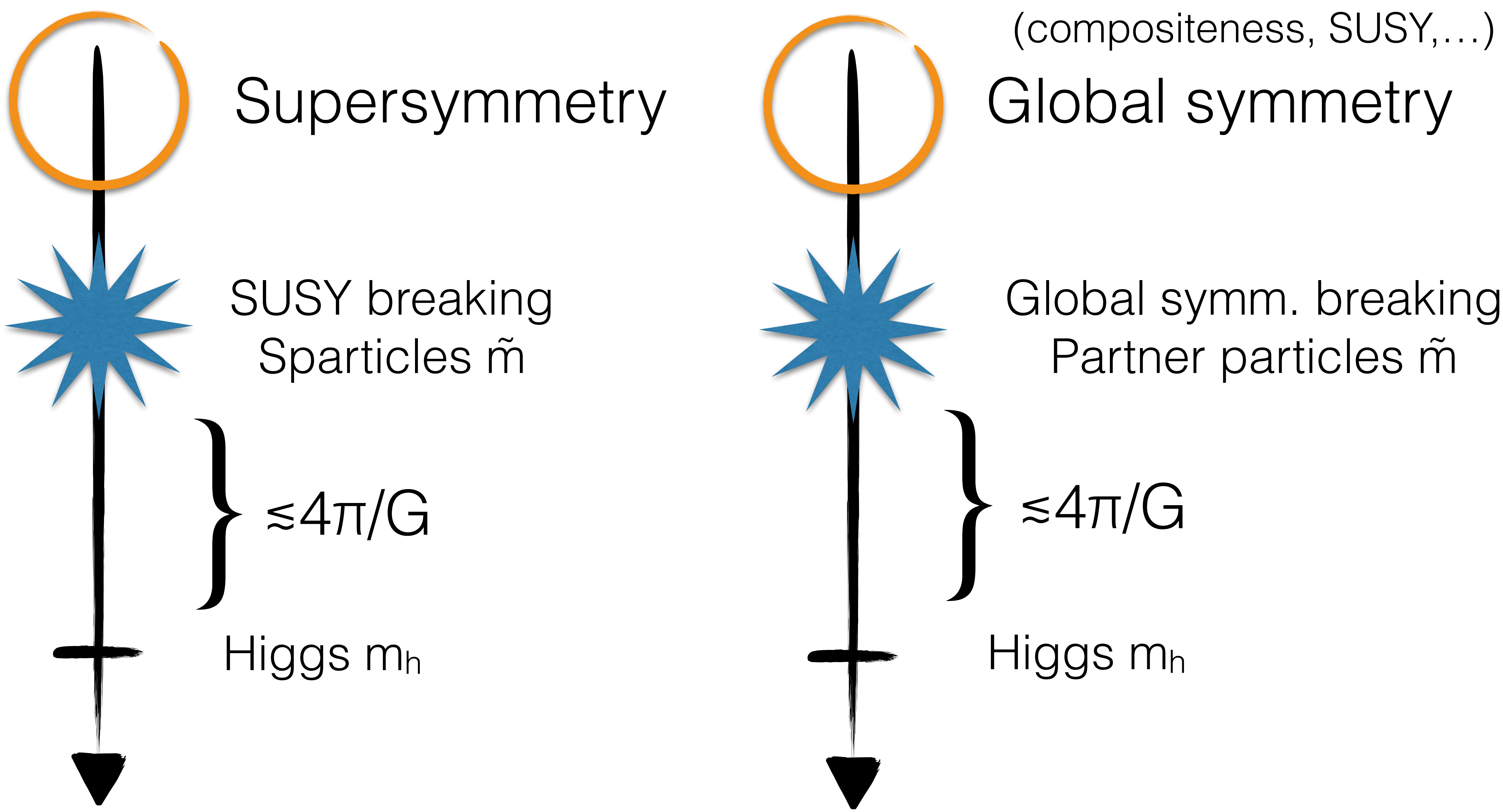


Electromagnetic contribution to the charged pion mass sensitive to the cutoff of the pion EFT.

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

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

Electroweak naturalness

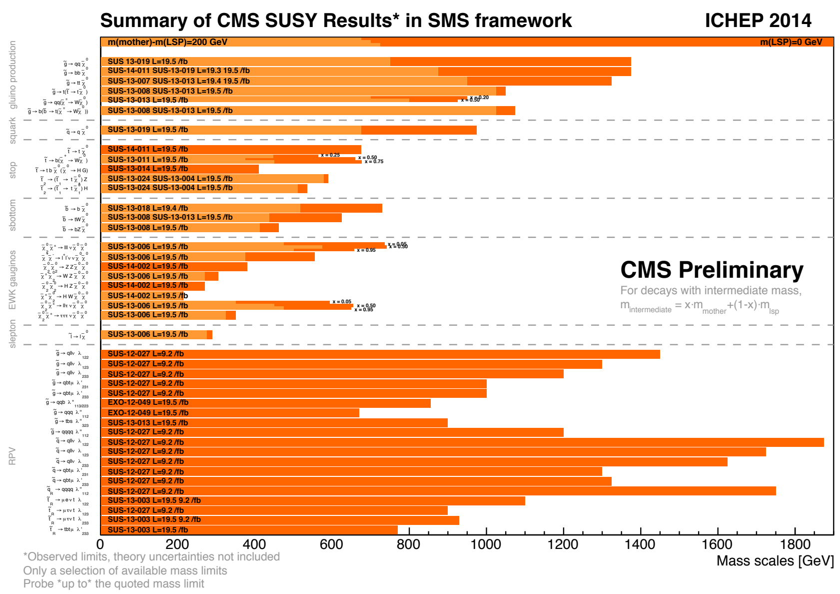


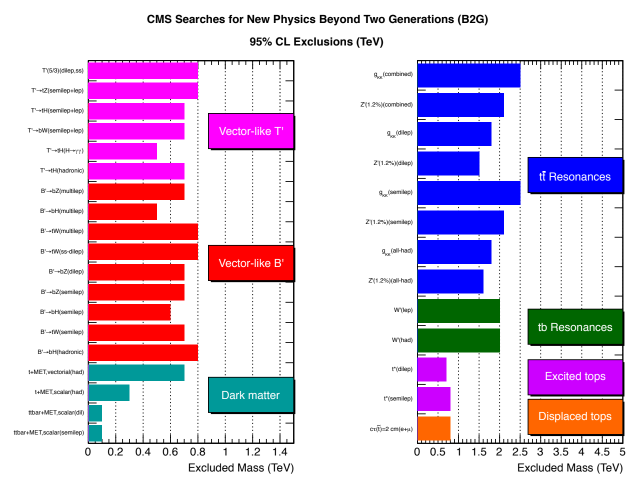
Continuous symmetries → partner states w/ SM quantum #s

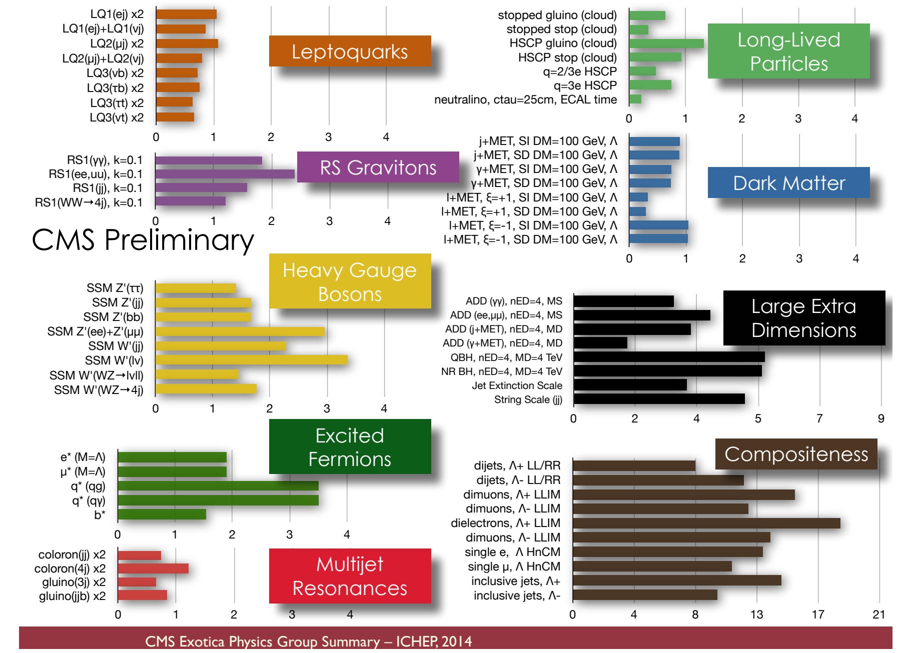
$$m_h^2 \sim \frac{3y_t^2}{4\pi^2}\tilde{m}^2 \log(\Lambda^2/\tilde{m}^2)$$

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

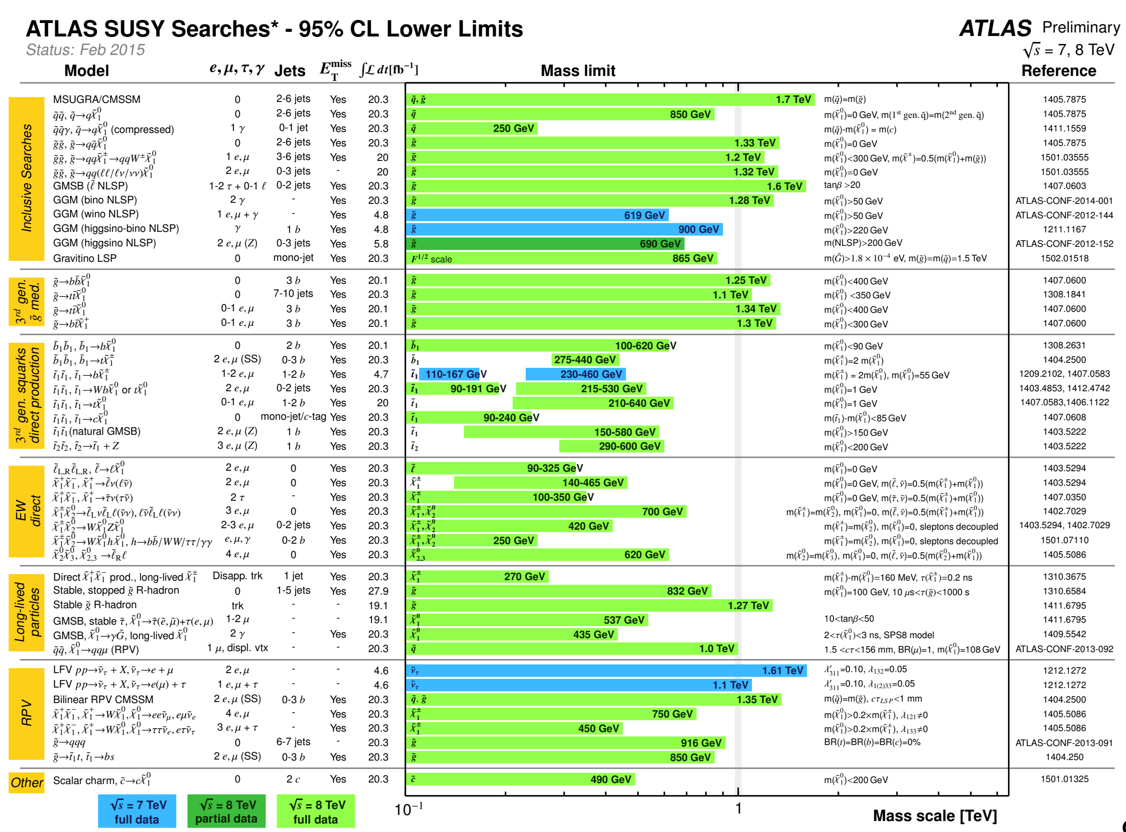
A physics driver @ LHC

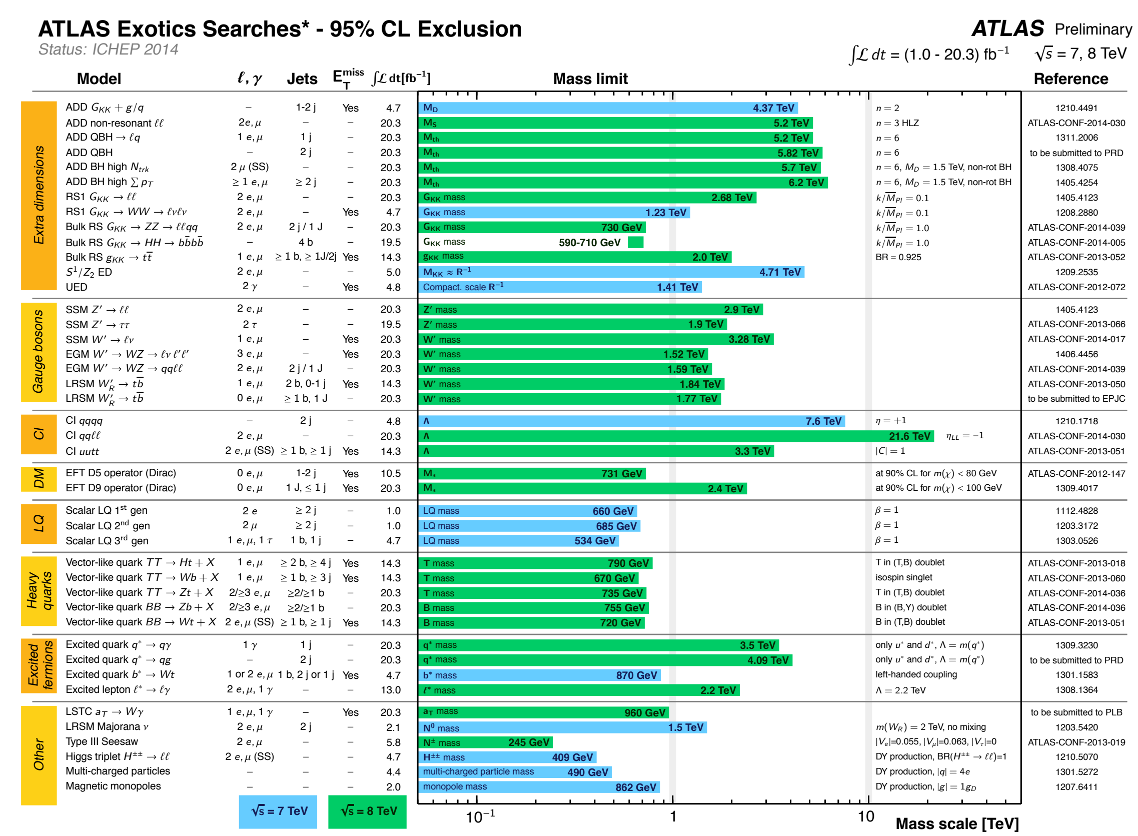






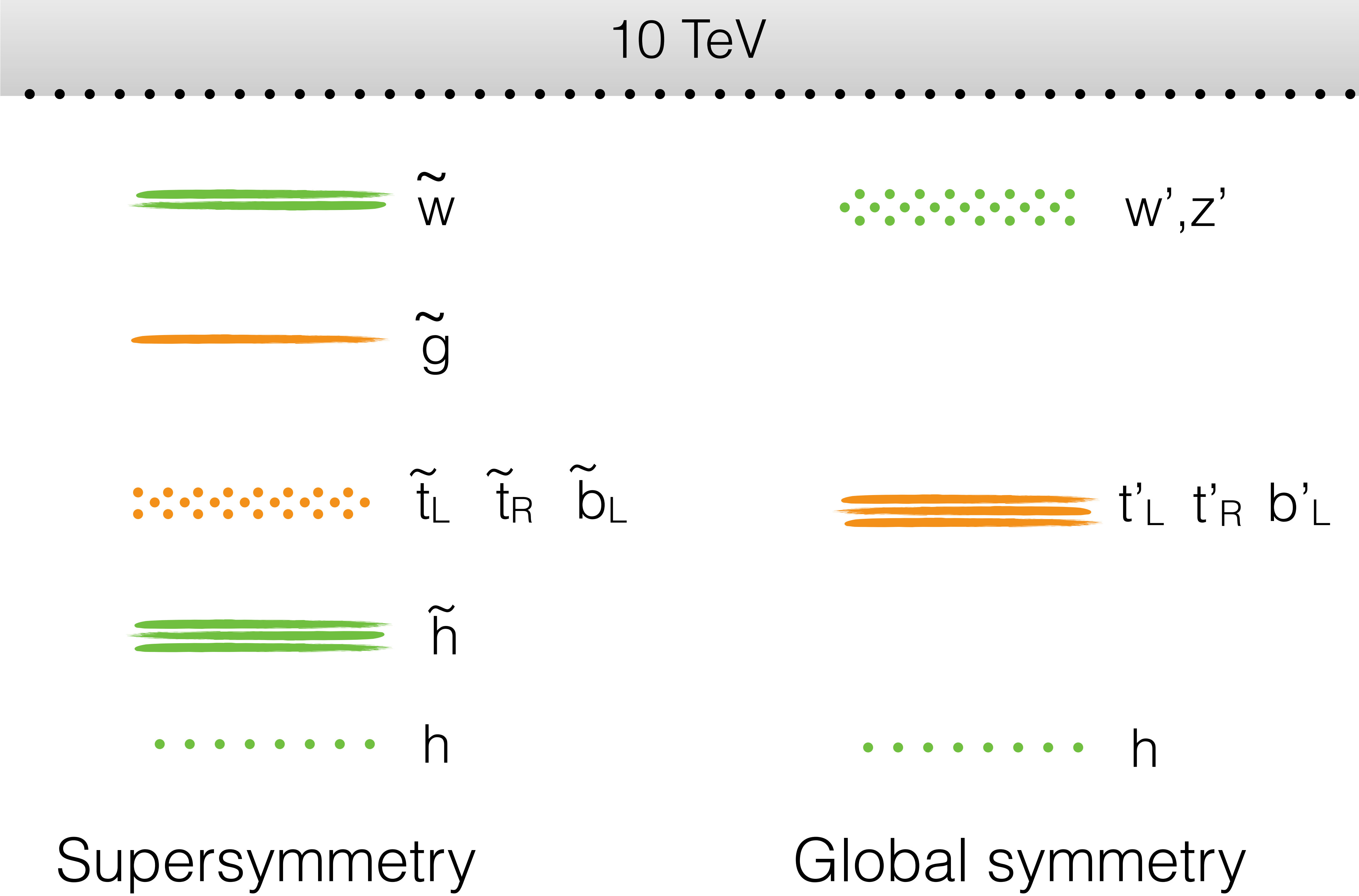
170 of these 226 channels tied to naturalness



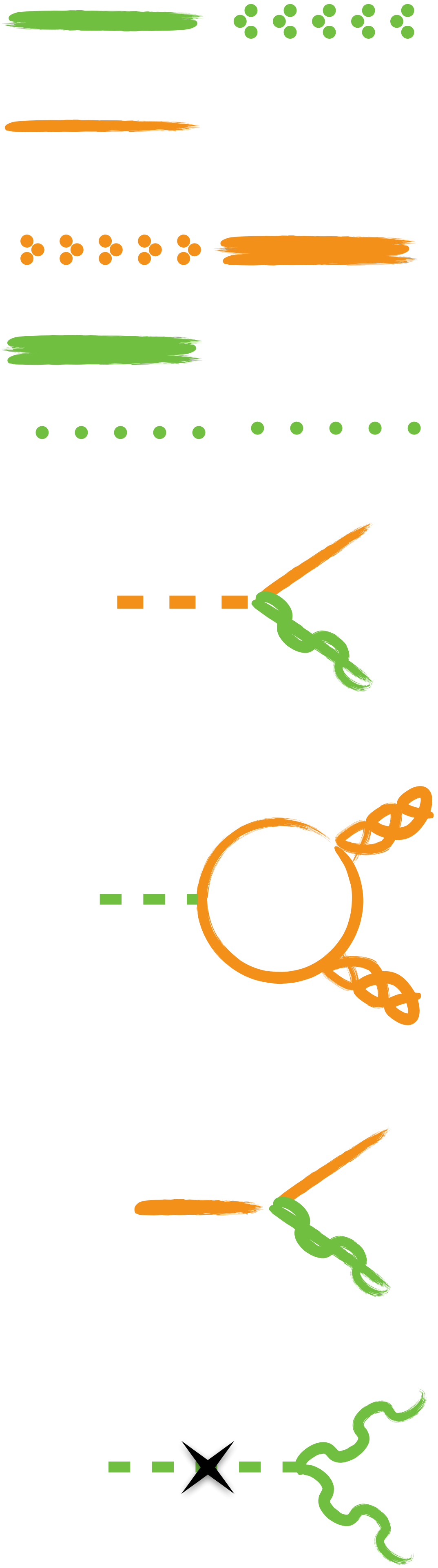


Signs of naturalness

“Colorful” naturalness



Simple game for LHC: look for QCD-charged partners.



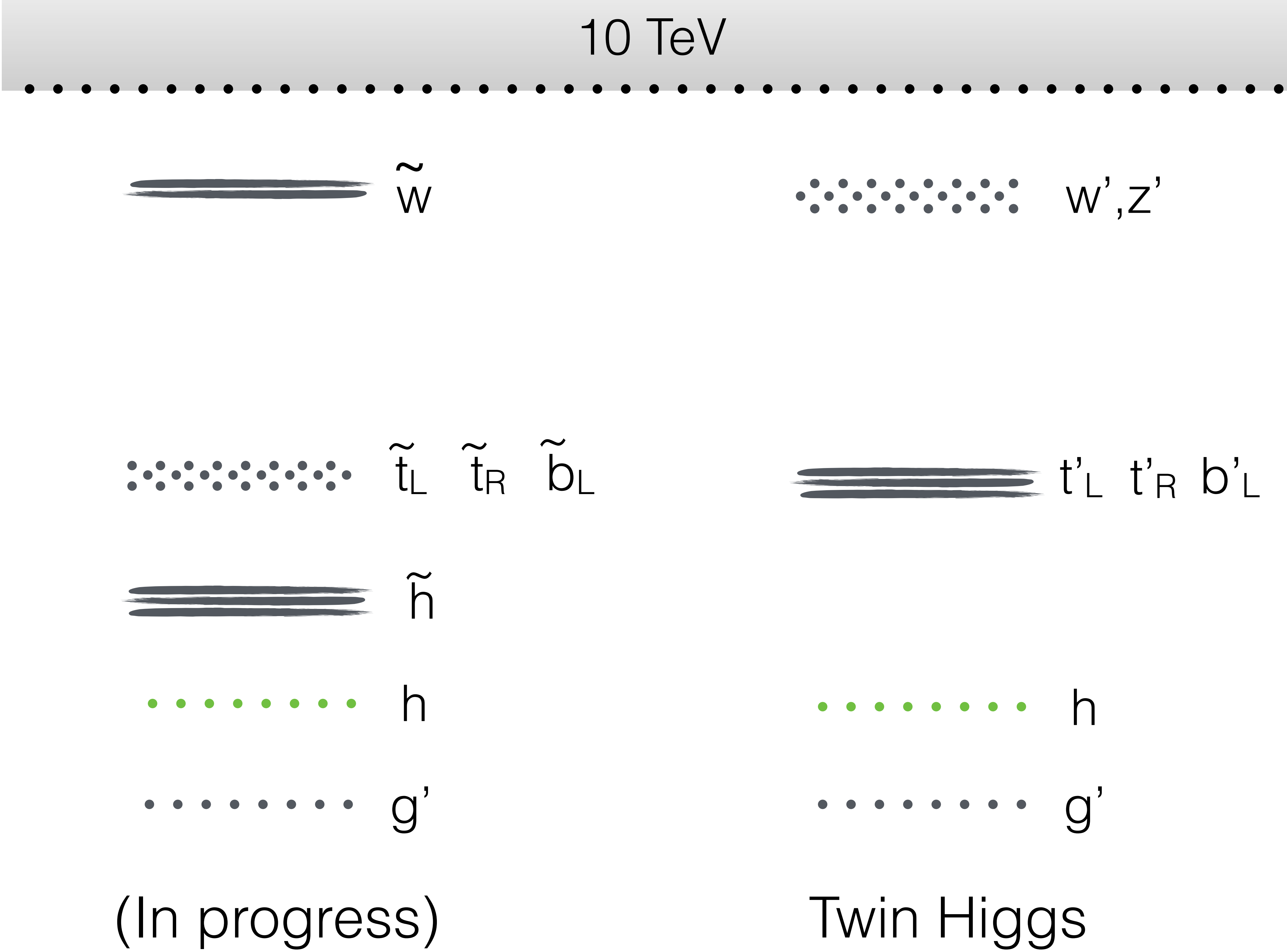
Colorful naturalness

Experimental handles

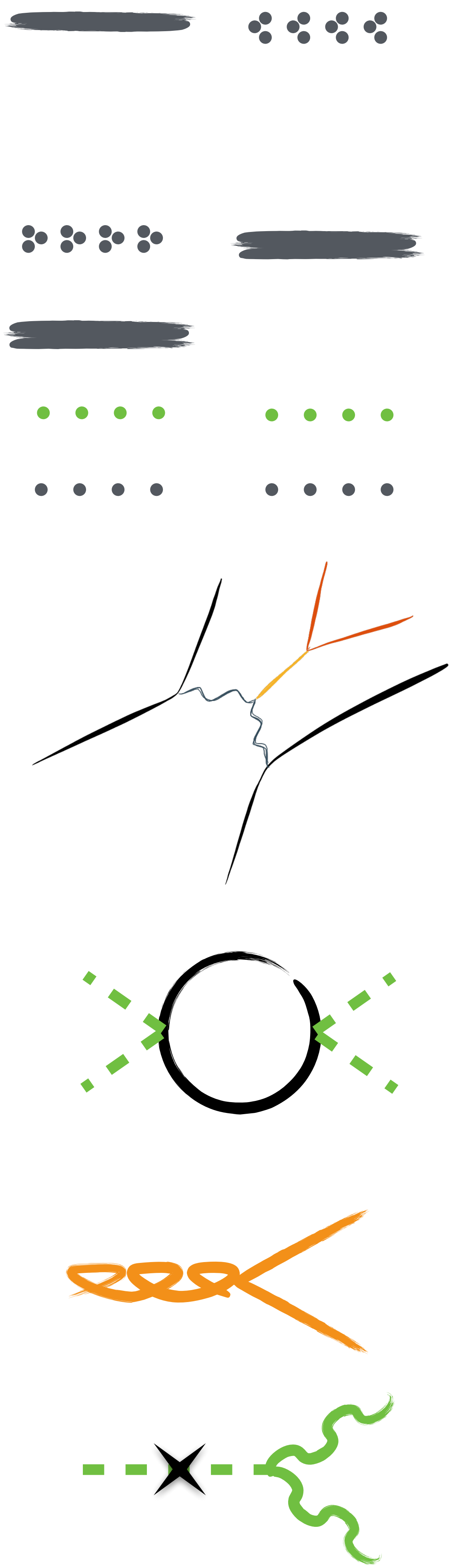
- SUSY: Direct searches (and indirect searches).
  - Look for colored partner states (stops, gluinos)
  - Look for O(loop*v/m) Higgs coupling deviations.
- Global: Direct and indirect searches.
  - Look for colored partner states (vector-like t')
  - Look for O(v/f) Higgs coupling deviations.

This is our current search program for naturalness. But…

“Neutral” naturalness



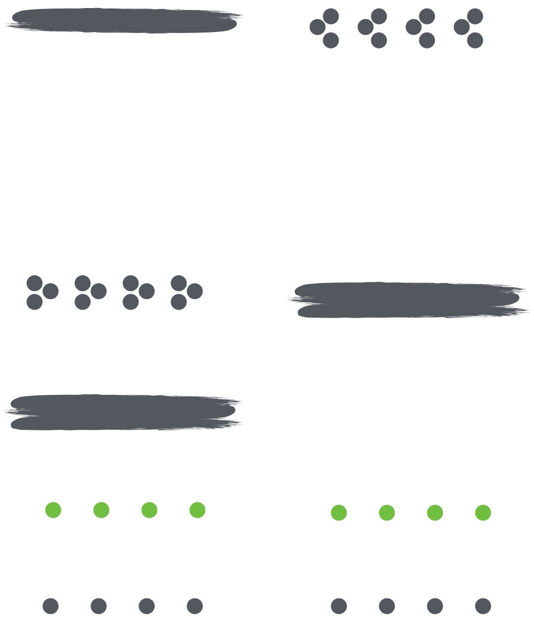
[Chacko, Goh, Harnik]



Neutral naturalness

Experimental handles

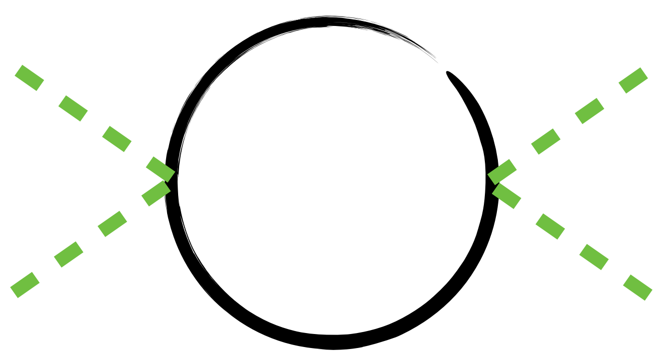
- SUSY: Direct searches (and indirect searches).
  - Look for off-shell Higgs portal.
  - Look for O(loop*v/m) Higgs coupling deviations.
  - *Look for the UV completion.*
- Global: Direct and indirect searches.
  - Look for O(v/f) Higgs coupling deviations.
  - Look for displaced decays [NC, Katz, Strassler, Sundrum]
  - *Look for the UV completion.*



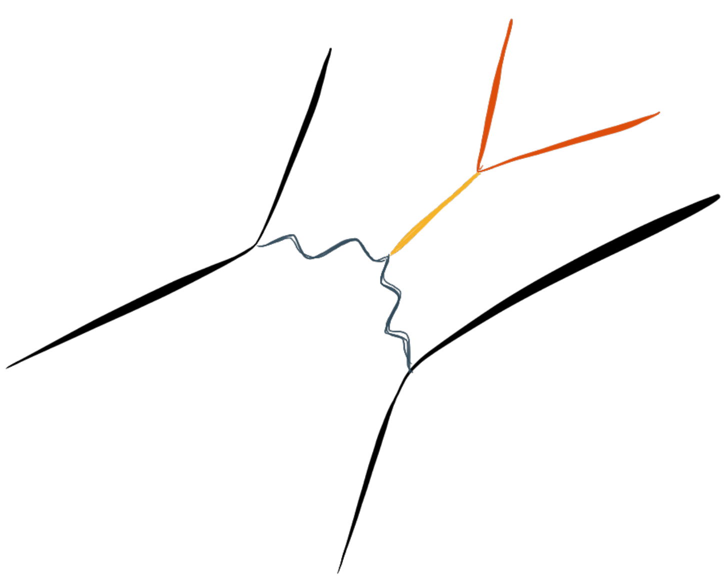
Neutral naturalness

Higgs couplings: accustomed to looking for corrections to loop-level couplings ($h \to \gamma\gamma$, gg), but even loops of neutral states can be seen.

[NC, Englert, McCullough; Henning, Lu, Murayama; NC, Farina, McCullough, Perelstein]



$$\frac{c_H}{m_\phi^2}\left(\partial_\mu|H|^2\right)^2 \to \delta\sigma_{Zh} = -2c_H\frac{v^2}{m_\phi^2}$$



Direct searches: states lighter than $m_h/2$ easily constrained by Higgs width; if heavier than $m_h/2$, can still produce via an off-shell Higgs. Look for associated production + invisible.

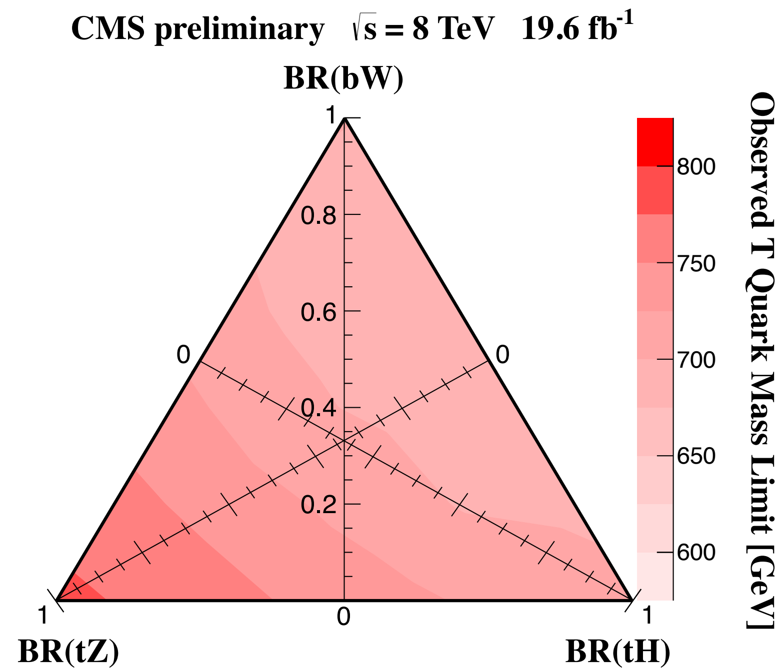
[Curtin, Meade, Yu; NC, Lou, McCullough, Thalapillil]

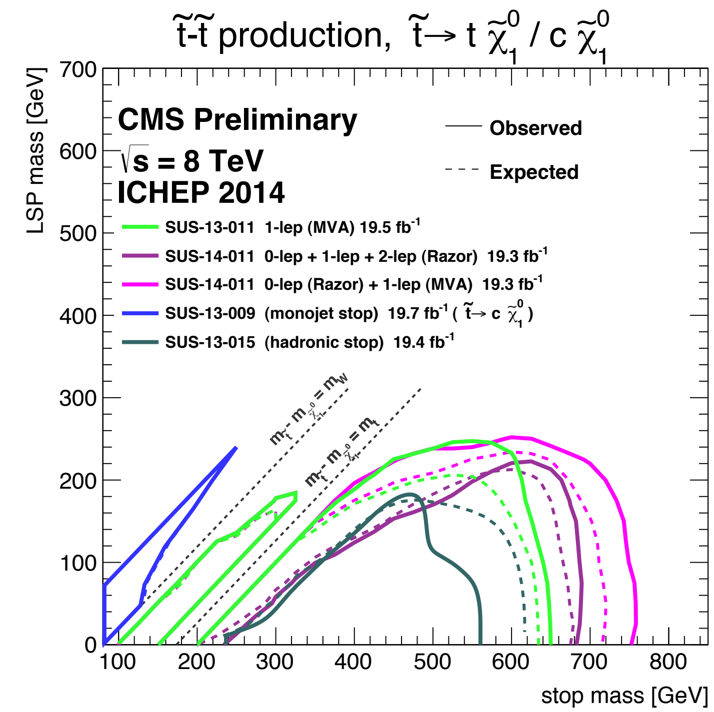
Colorful naturalness

@LHC

Where we are: “generically”

~7% tuning level

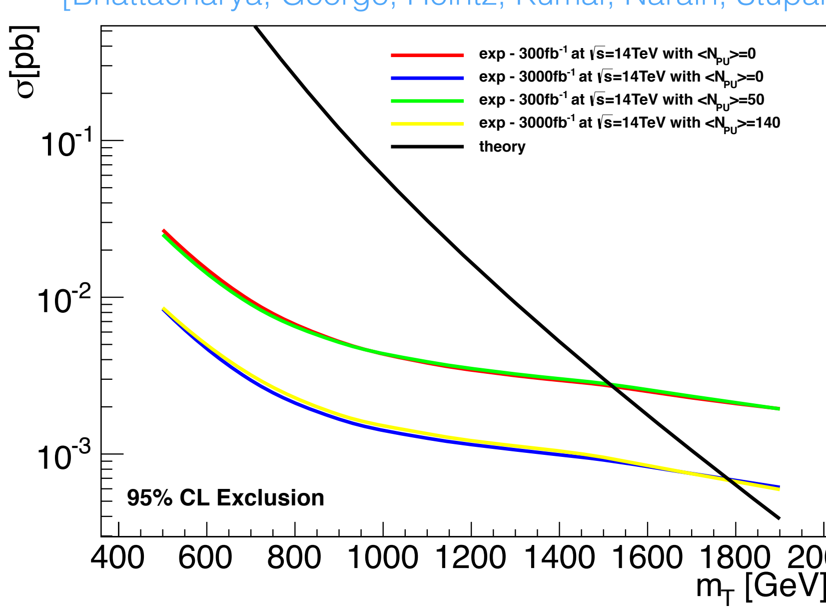


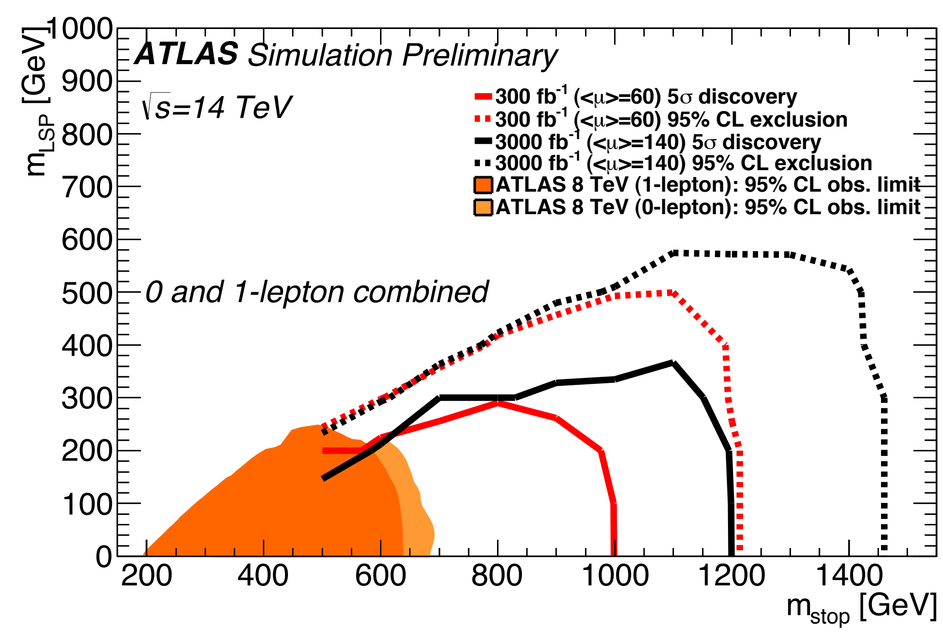


Where we’ll be @ end of LHC: “generically”

~1% level (global)
~2% level (SUSY)

[Bhattacharya, George, Heintz, Kumar, Narain, Stupak]

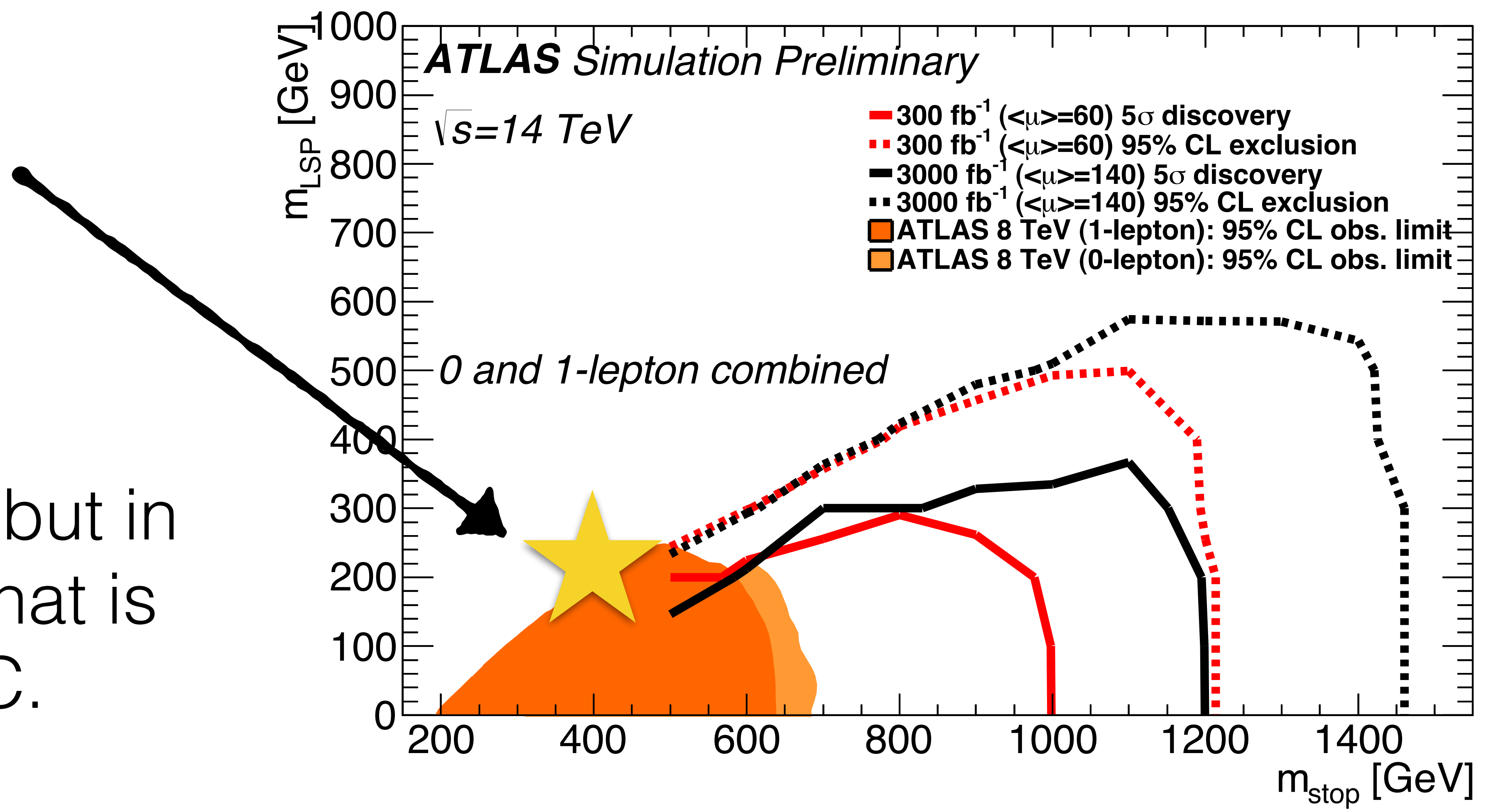




And yet…

We could live right here

Completely natural, but in a kinematic region that is hard to cover @ LHC.



…or the conventional collider signals could be eroded or reduced by modest complications of the theory (RPV, stealth, etc.)

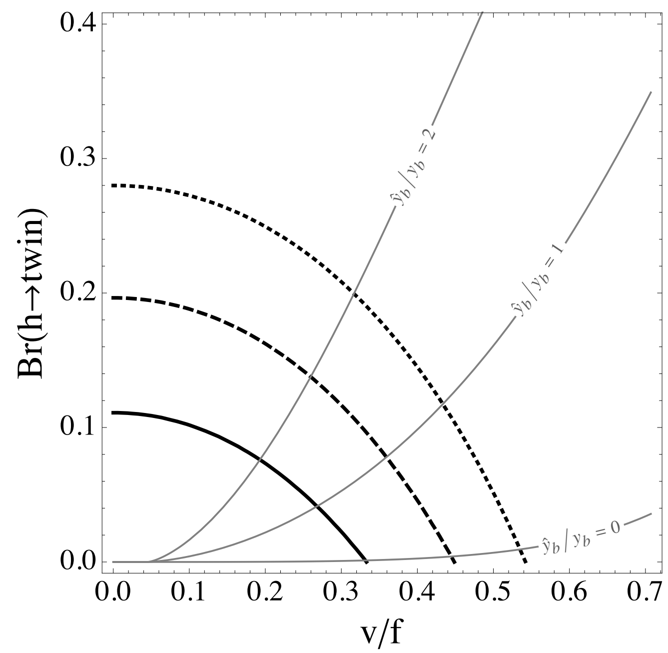
Neutral naturalness

@LHC

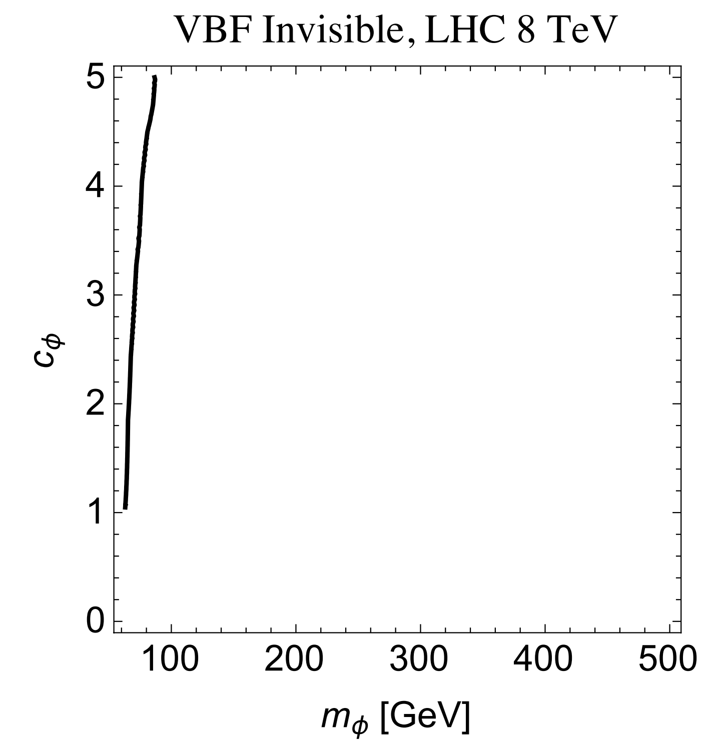
Where we are:

natural (at worst 30% for global)

[NC, Katz, Strassler, Sundrum]



[NC, Lou, McCullough, Thalapillil]



Where we'll be @ end of LHC:

natural (at worst 20% for global)

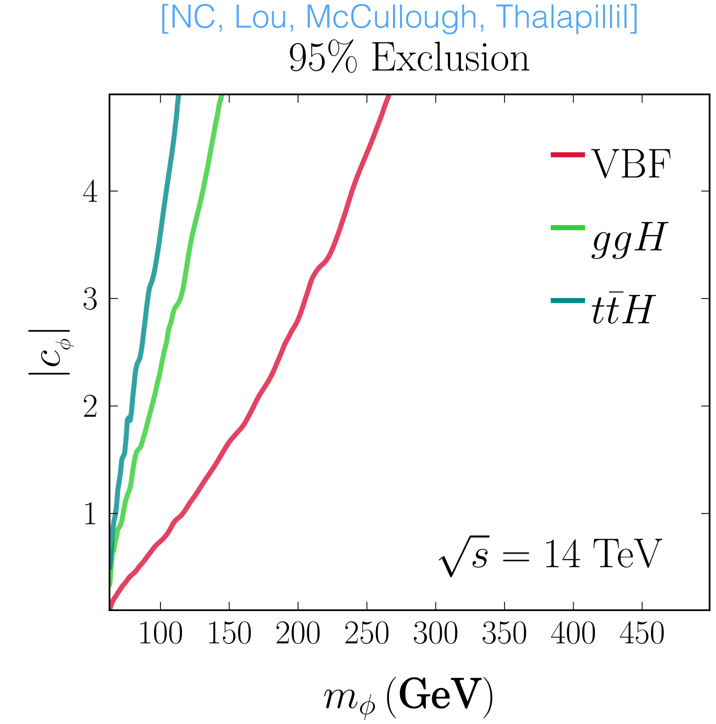
95% CL bounds

$$v/f \lesssim 0.31\,(0.25)$$

(ATLAS)

$$\mathrm{Br(inv.)} \lesssim 10\%$$

[NC, Lou, McCullough, Thalapillil]

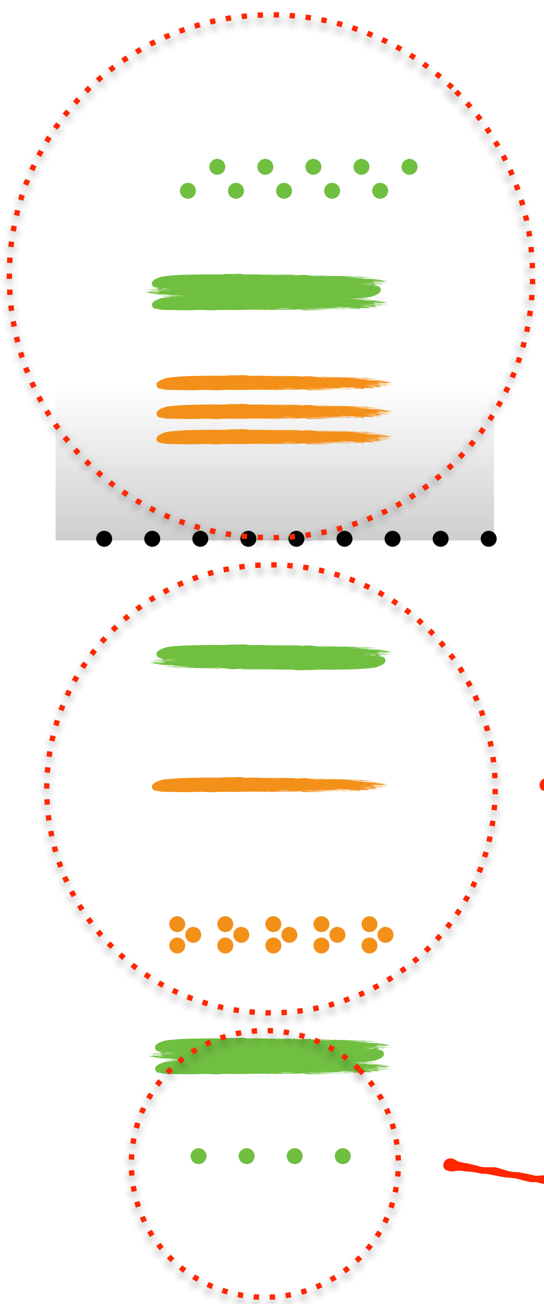


The question of electroweak naturalness *cannot be settled at the LHC.*

Settling the question of naturalness is a compelling strategy for future colliders.

Naturalness at future colliders

Three major opportunities



Uncover UV structure well beyond LHC reach

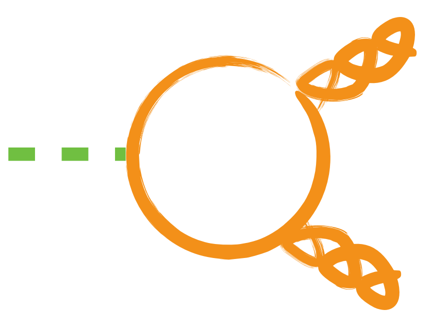
Extend reach of LHC for new particles important for naturalness

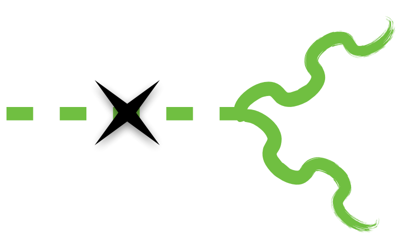
Cover holes from LHC with precision Higgs measurements

Colorful naturalness

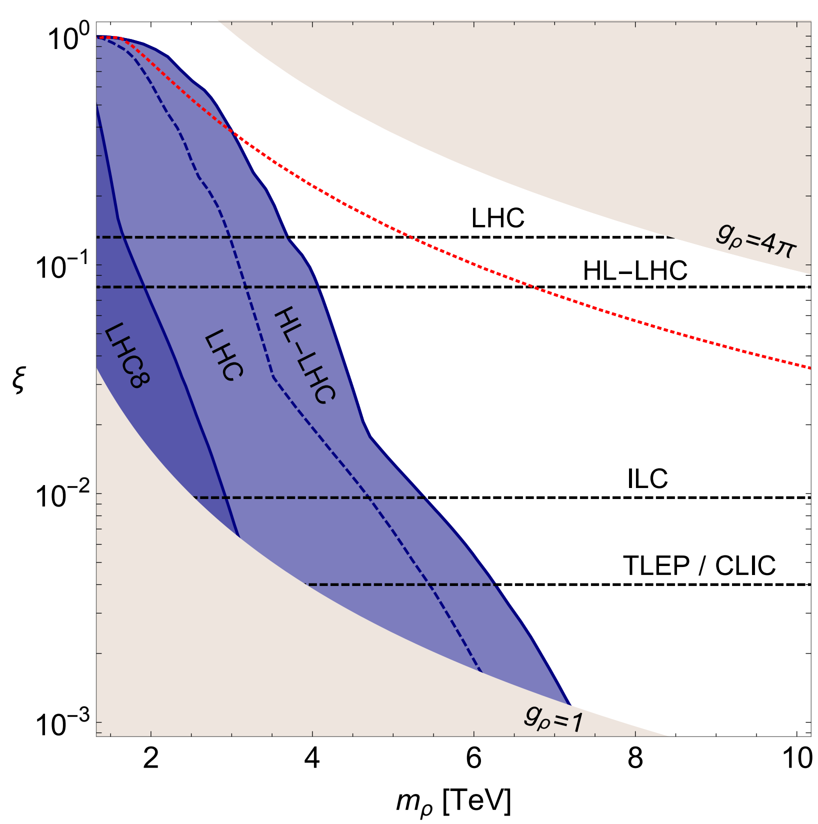
Probing at a Higgs factory:

Look for **O**(loop*v/m) [SUSY] or **O**(v/f) [global] Higgs coupling deviations; precision electroweak corrections.

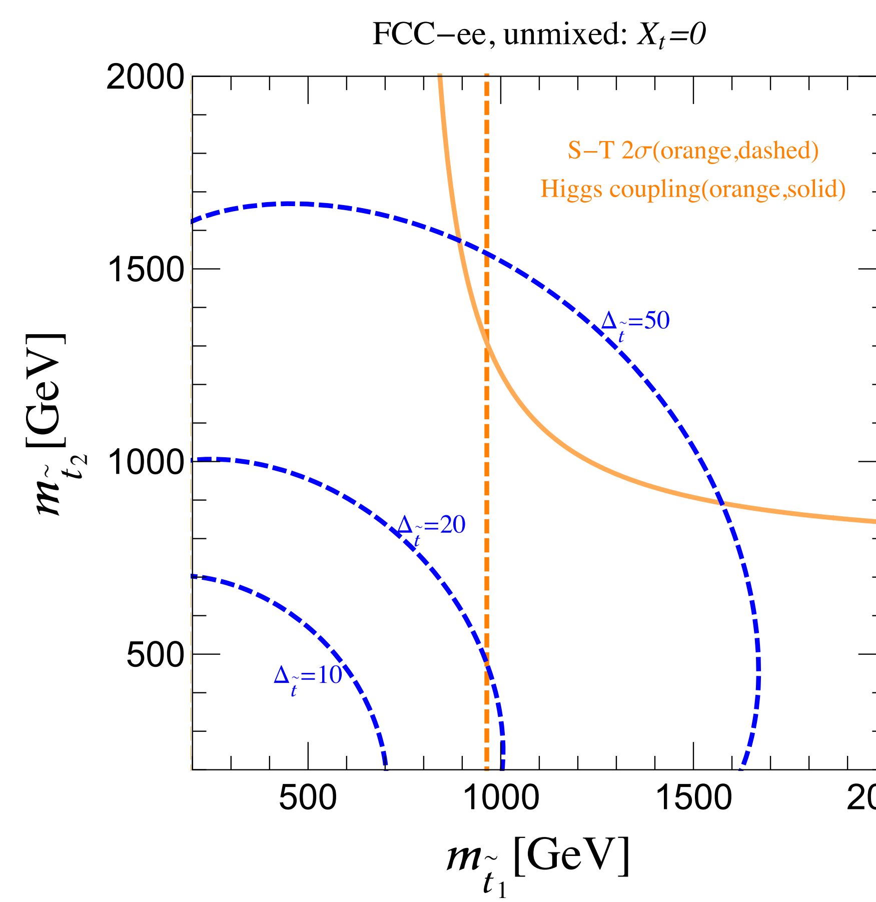




[Thamm, Torre, Wulzer]



[Fan, Reece, Wang]



Where we'll be @ Higgs factory:

Sensitive to kinematic holes at LHC.

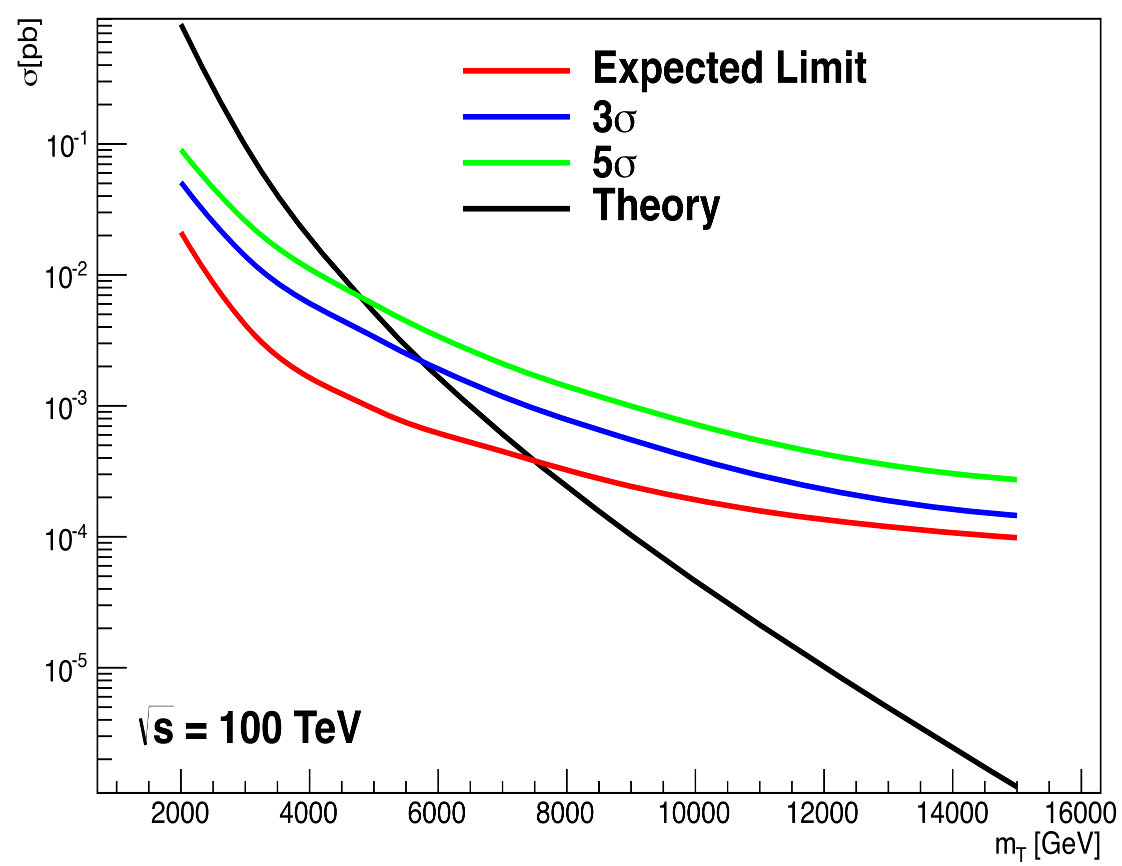
~1-2% level

Colorful naturalness

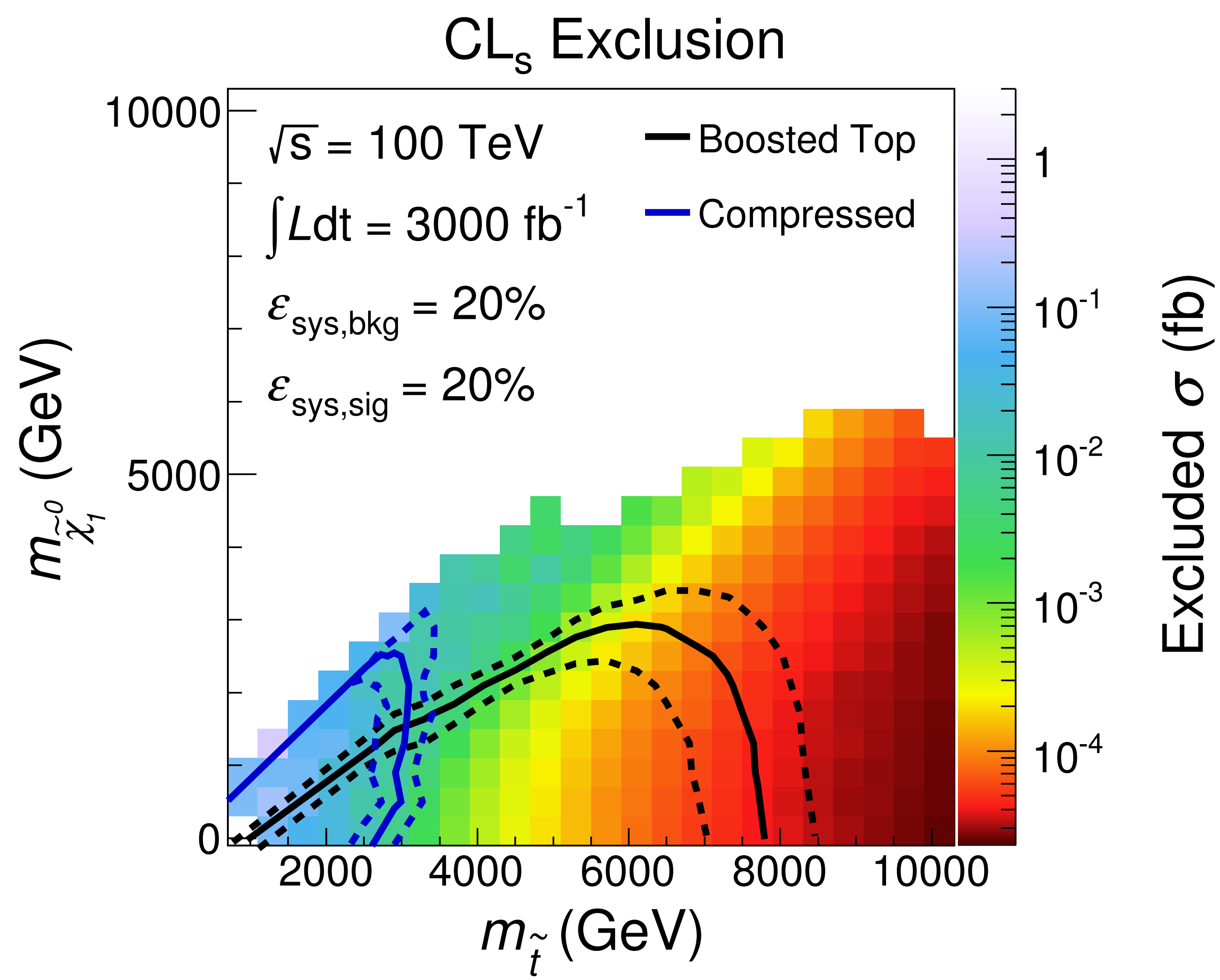
Probing at 100 TeV:

Look for the light partner states

[Ahuja, Black]



[Cohen, D'Agnolo, Hance, Lou, Wacker]



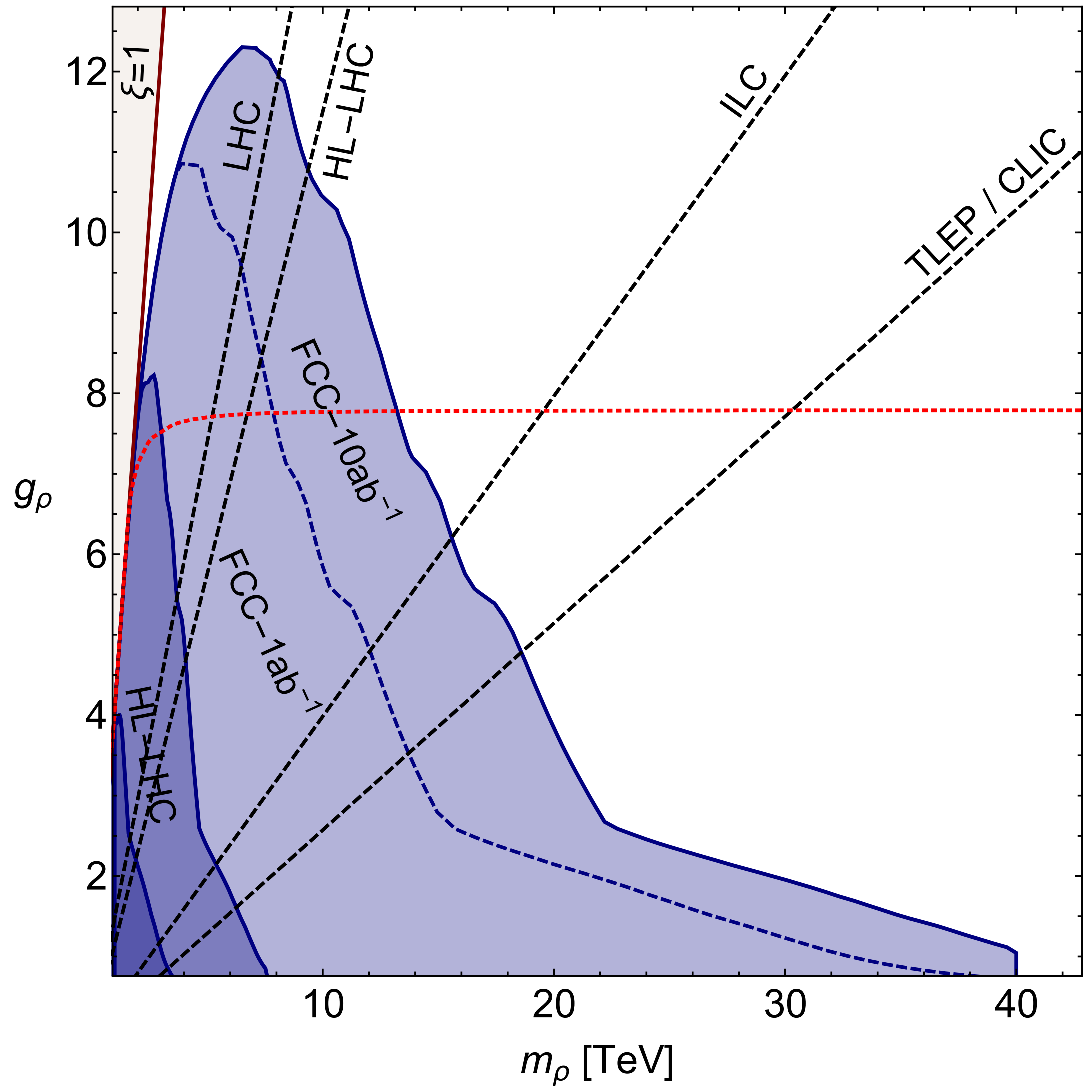
Where we'll be @ 100 TeV: "generically" ***~.05% level***

Colorful naturalness

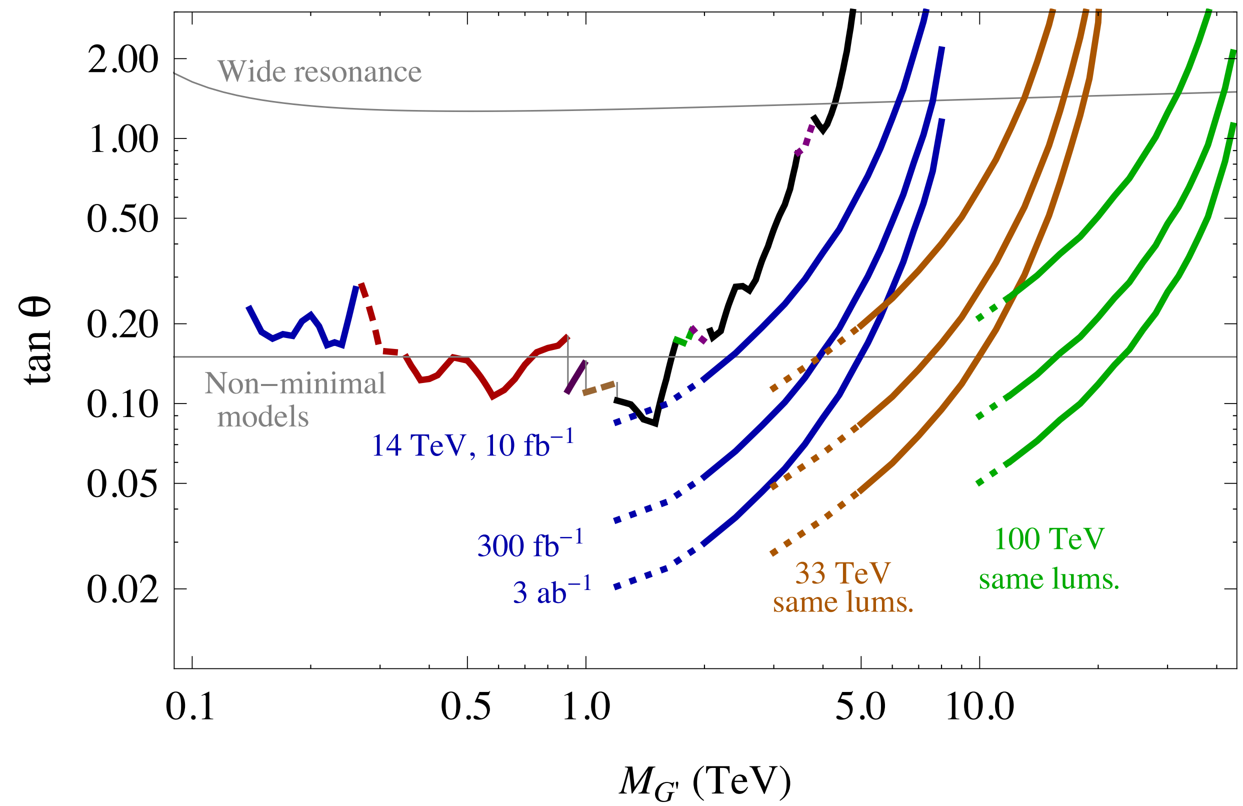
Probing at 100 TeV:

…or for the UV physics

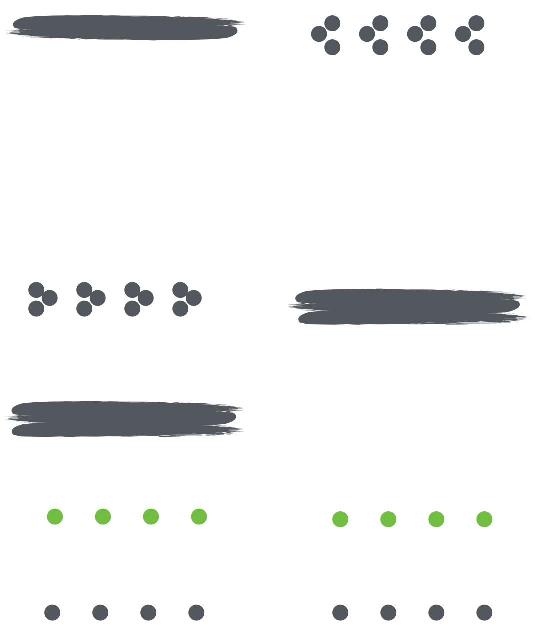
[Thamm, Torre, Wulzer]



[Felix Yu]



Even if light states are hard to find, can directly access heavy resonances



Neutral naturalness

Probing at a Higgs factory:

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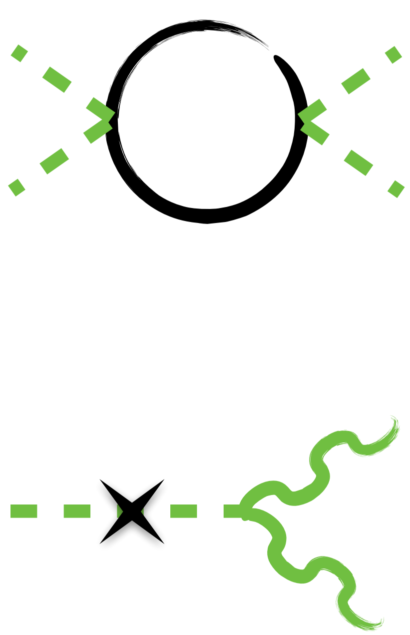
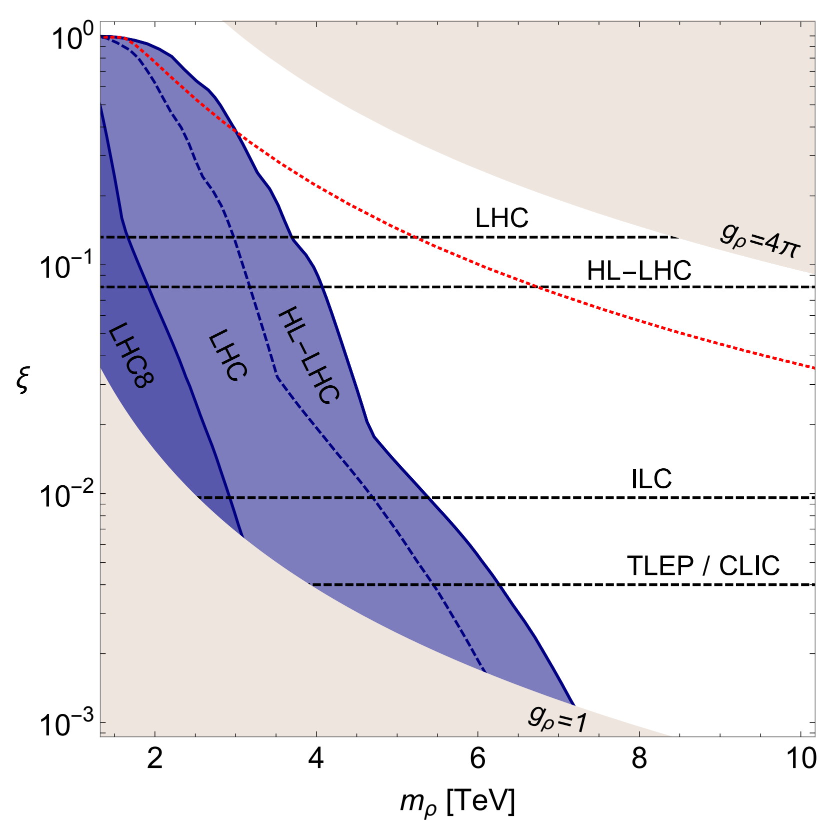
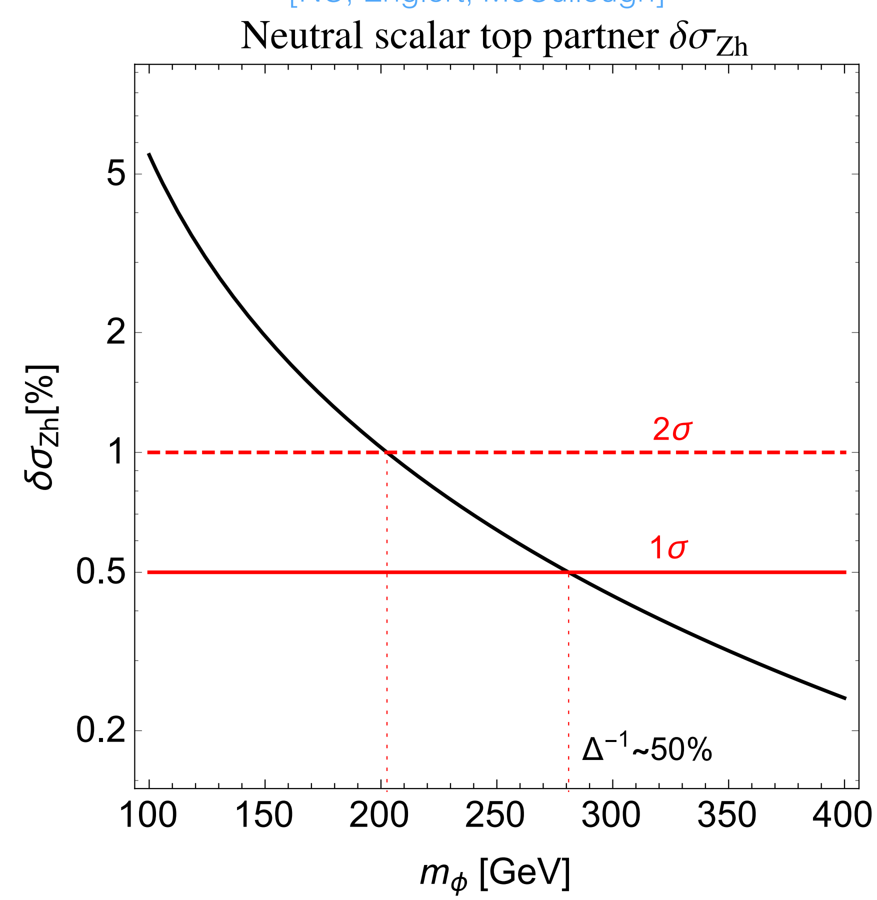


[Thamm, Torre, Wulzer]



[NC, Englert, McCullough]

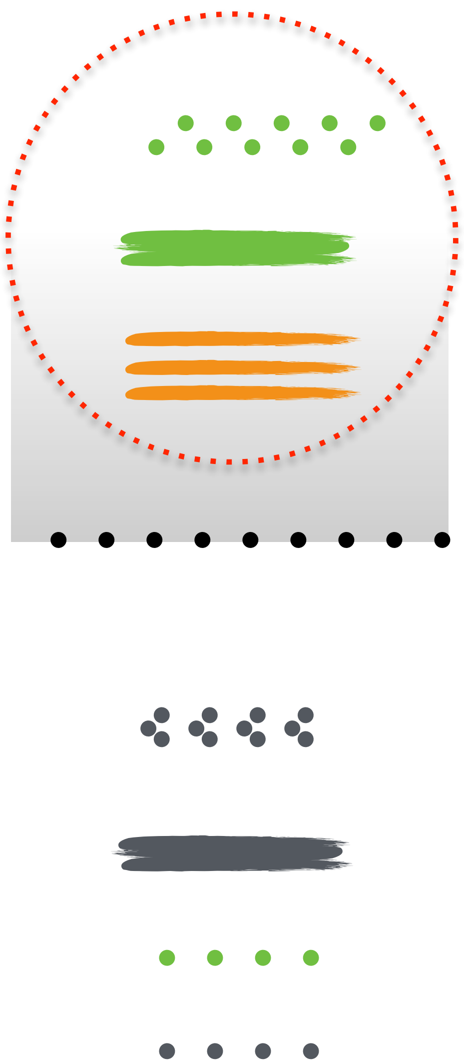


Where we'll be @ Higgs factory:

~1% level (global)
~50% level (SUSY)

Neutral naturalness

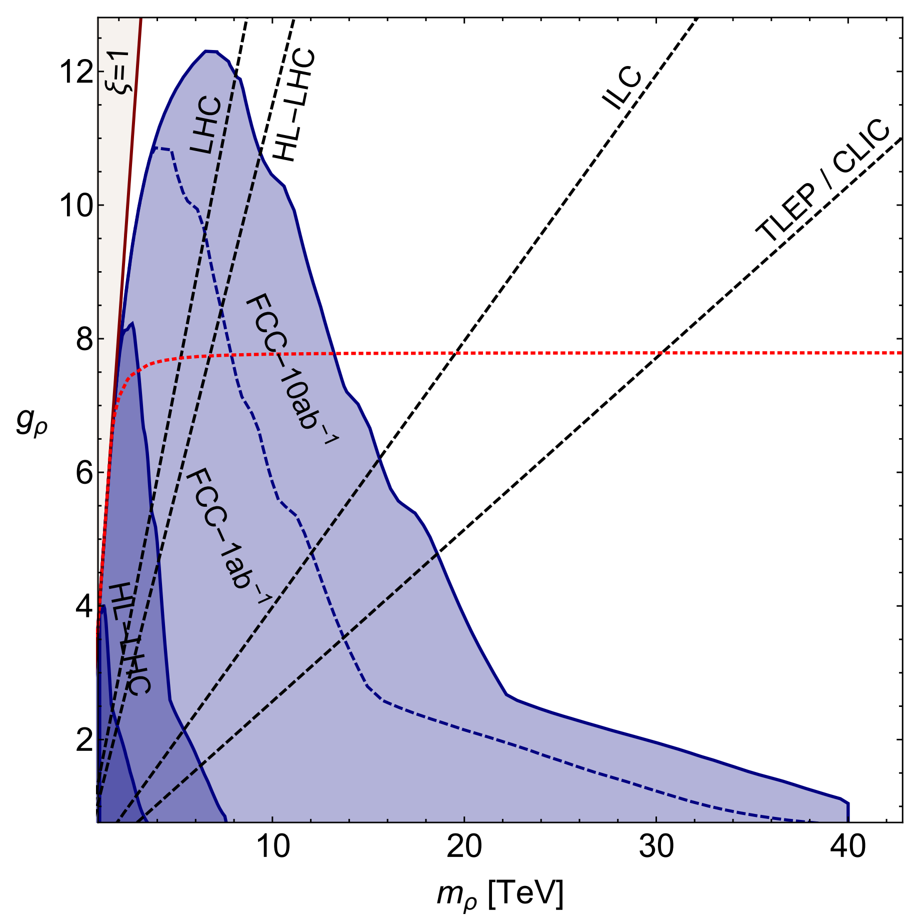
Even if the light natural states are neutral, there are heavier states with SM charges



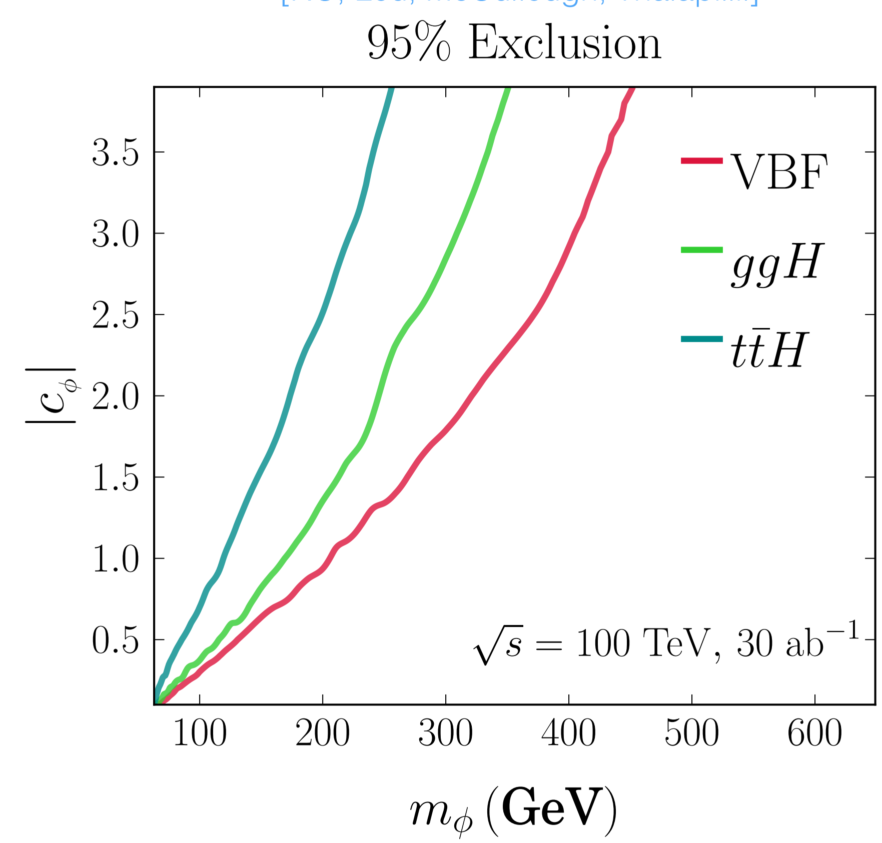
Probing at 100 TeV

Look for the UV completion, or probe light states via the Higgs portal.

[Thamm, Torre, Wulzer]

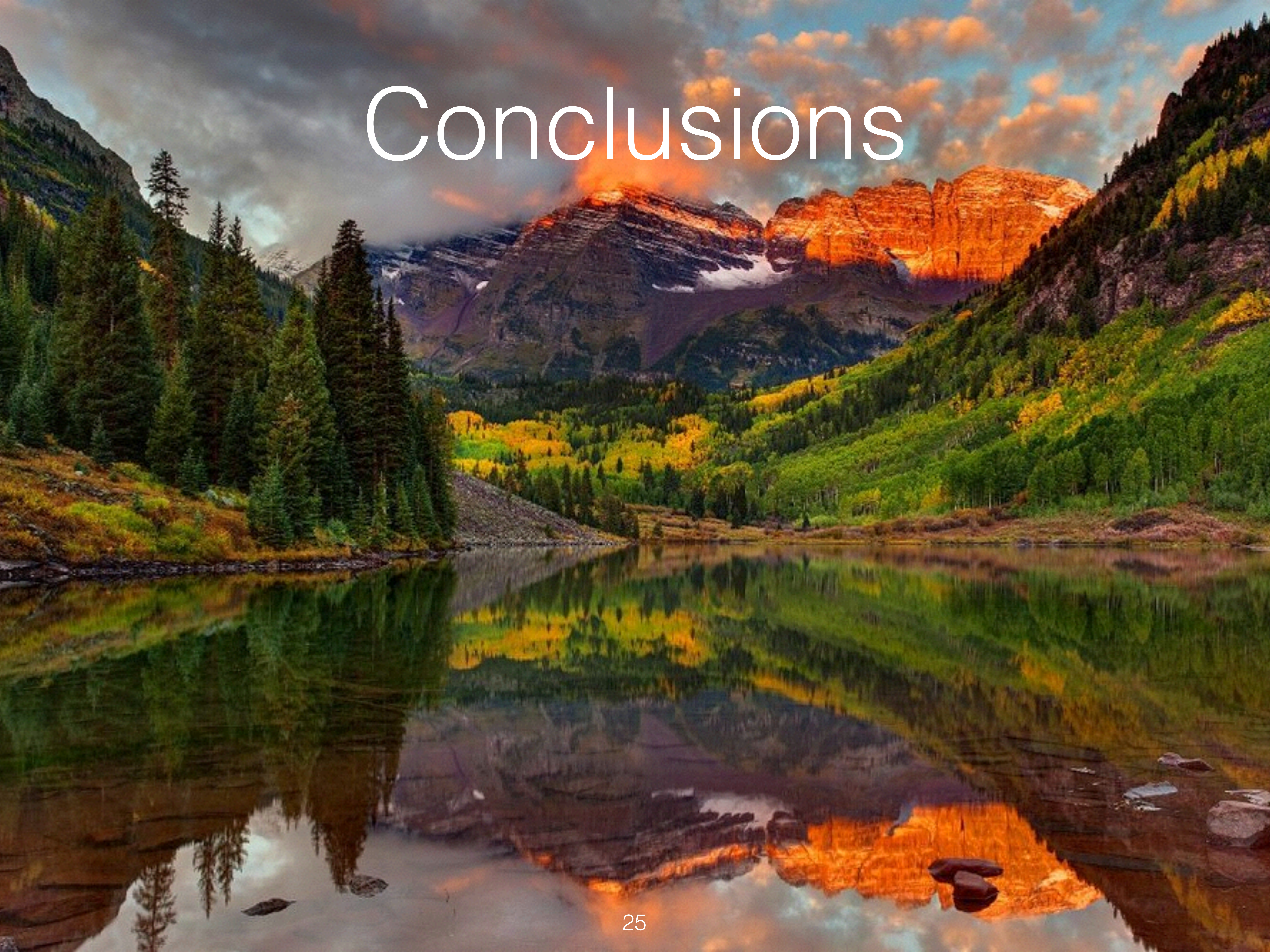


[NC, Lou, McCullough, Thalapillil]



Where we'll be @ 100 TeV: ***~1% level***

Conclusions



Conclusions

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Conclusions

- Naturalness is one of the most compelling motivations for new physics near the weak scale.
- The LHC will eventually probe conventional “colorful” theories to (at best) the ~1% level.
- But it will leave kinematic regions in conventional theories — and all regions of more novel theories — essentially untested, and the status of naturalness truly unresolved.
- A Higgs factory & 100 TeV collider can uniformly probe natural symmetry-based theories to the ~1% level with powerful complementarity.