BSM Overview

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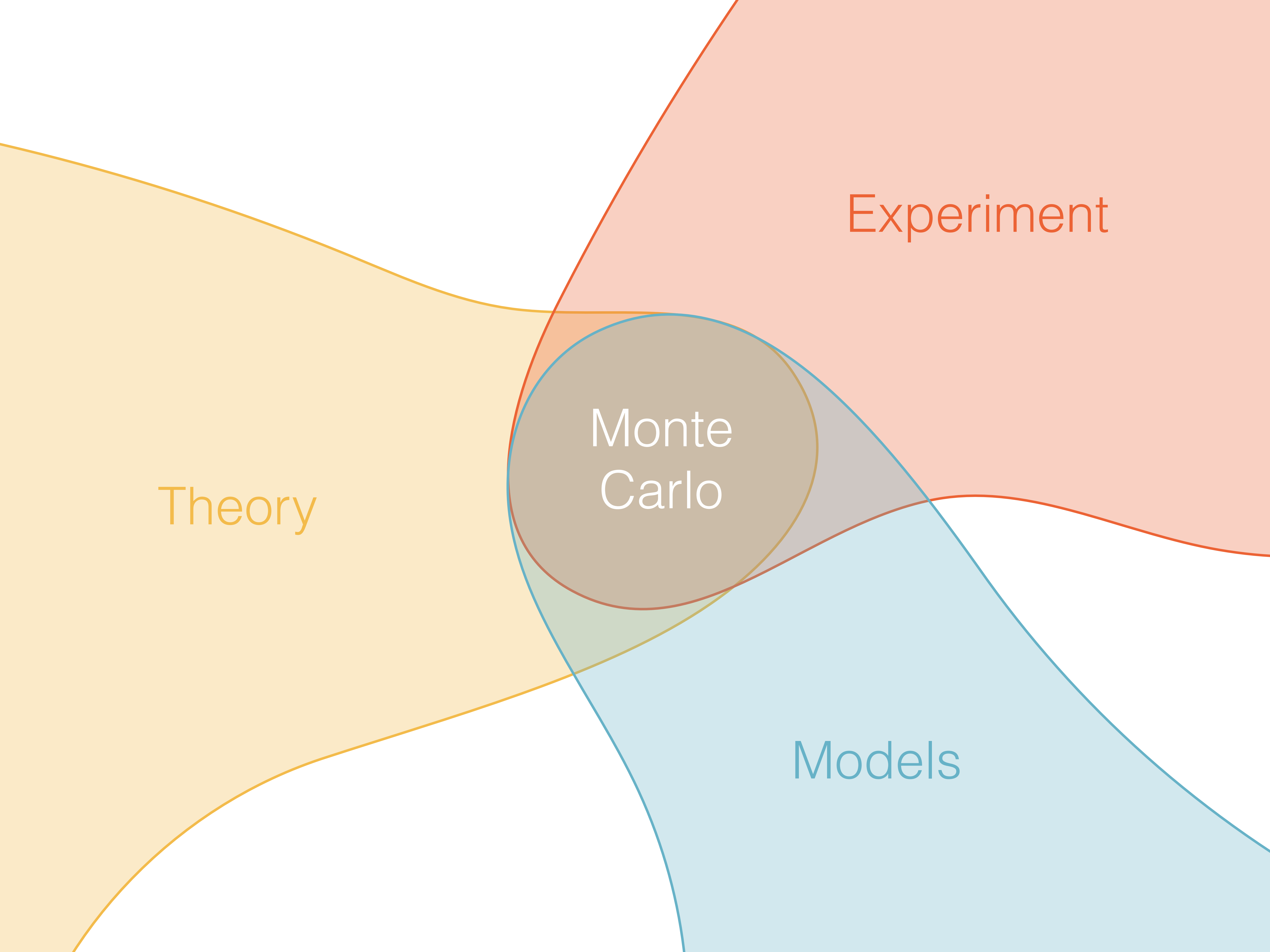
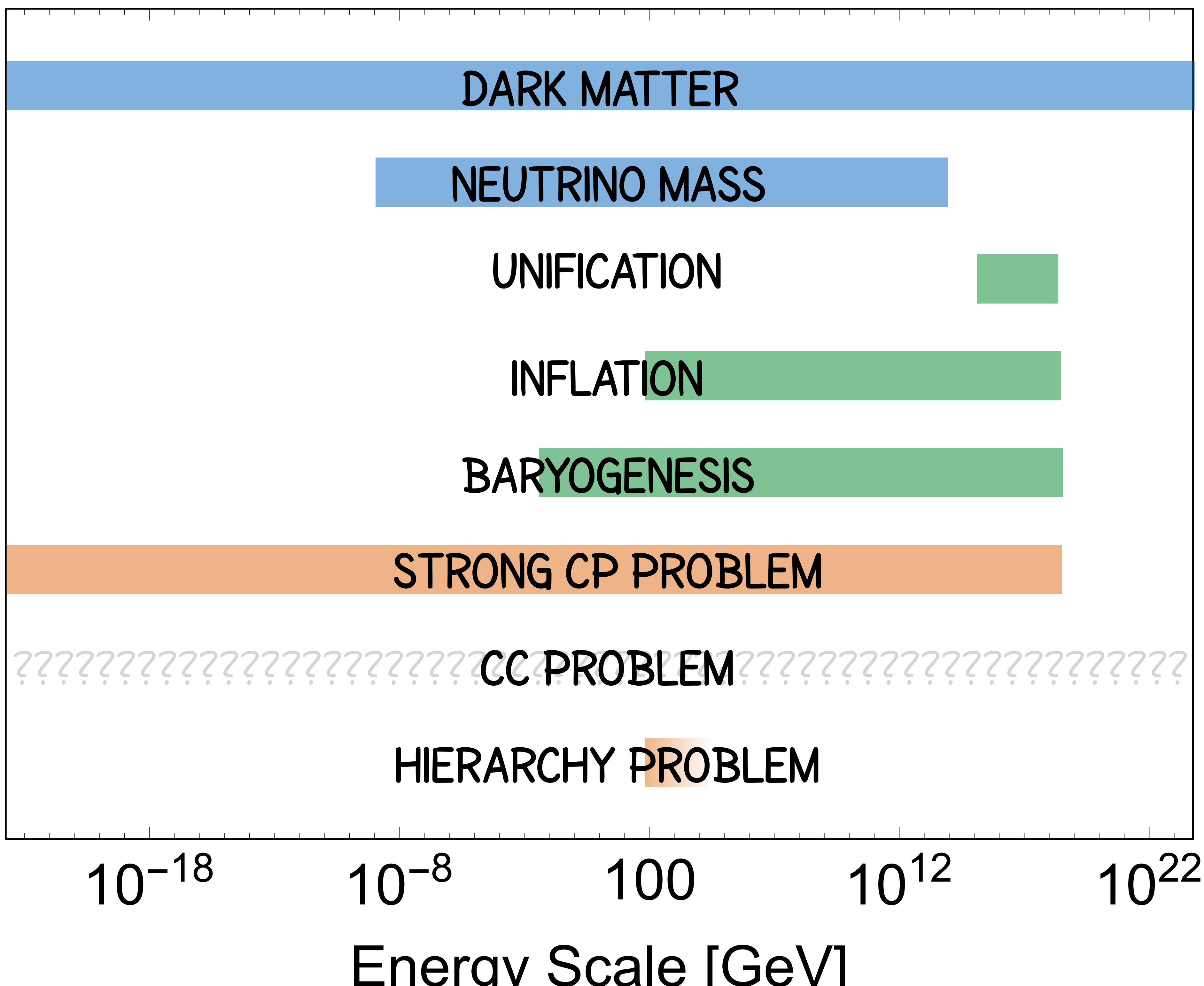
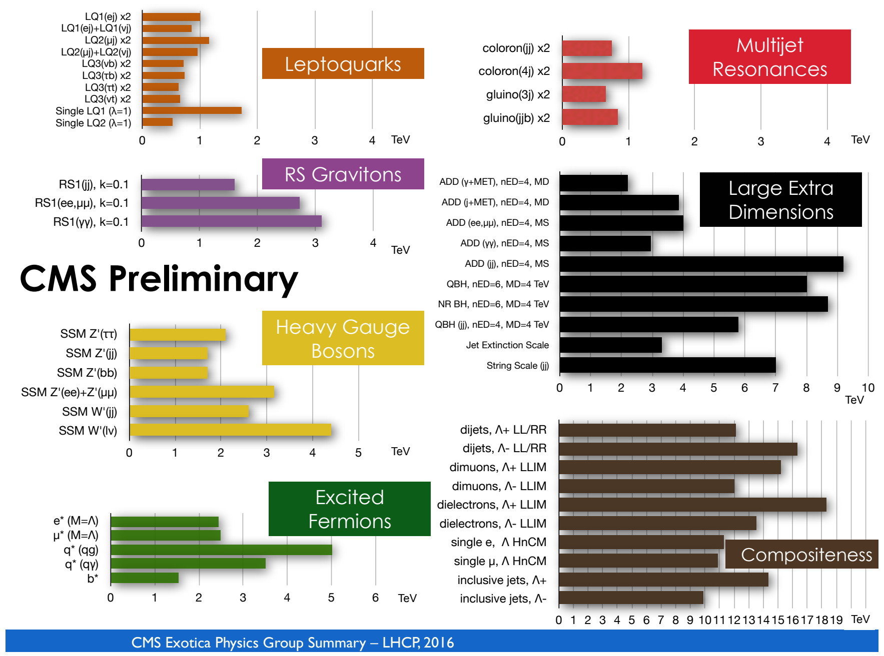
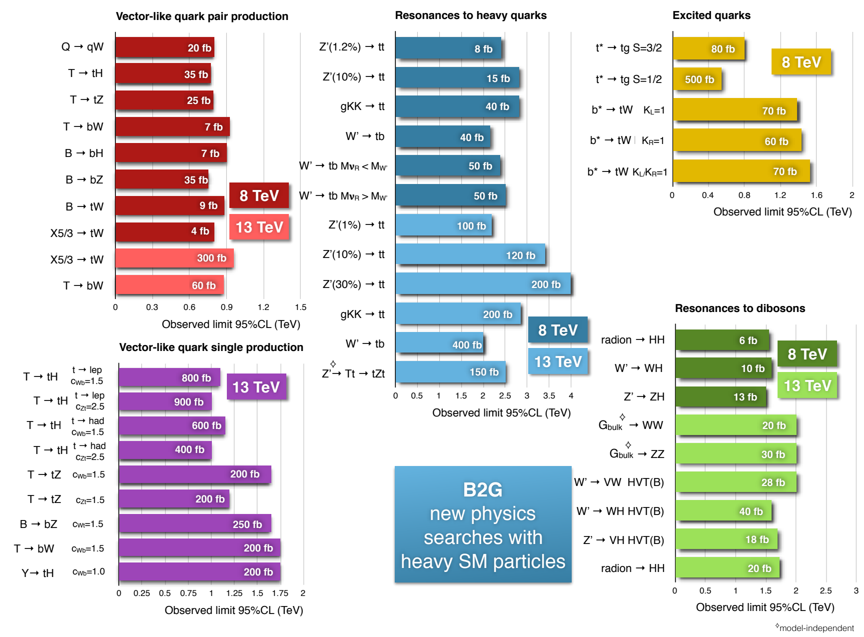

Experiment
Monte
Carlo
Theory
Models

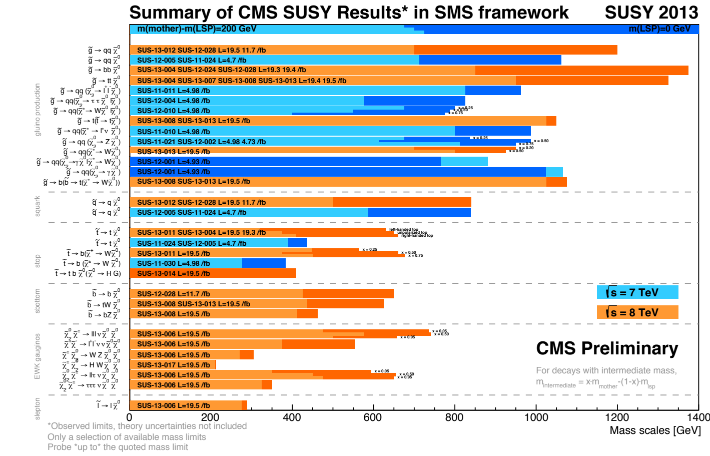
Lots of “Beyond the Standard Model”

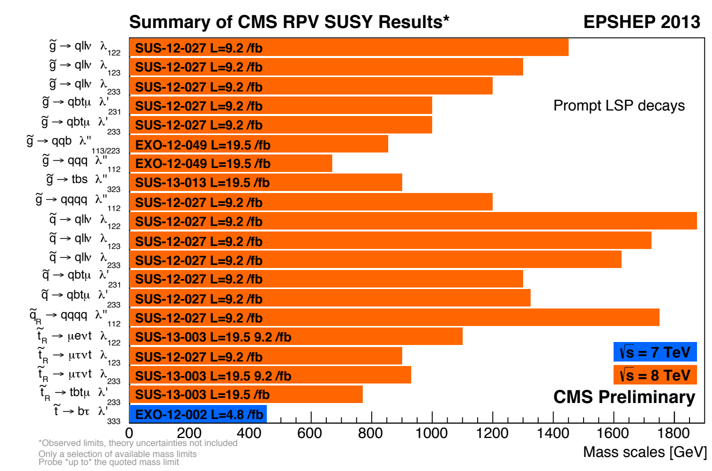


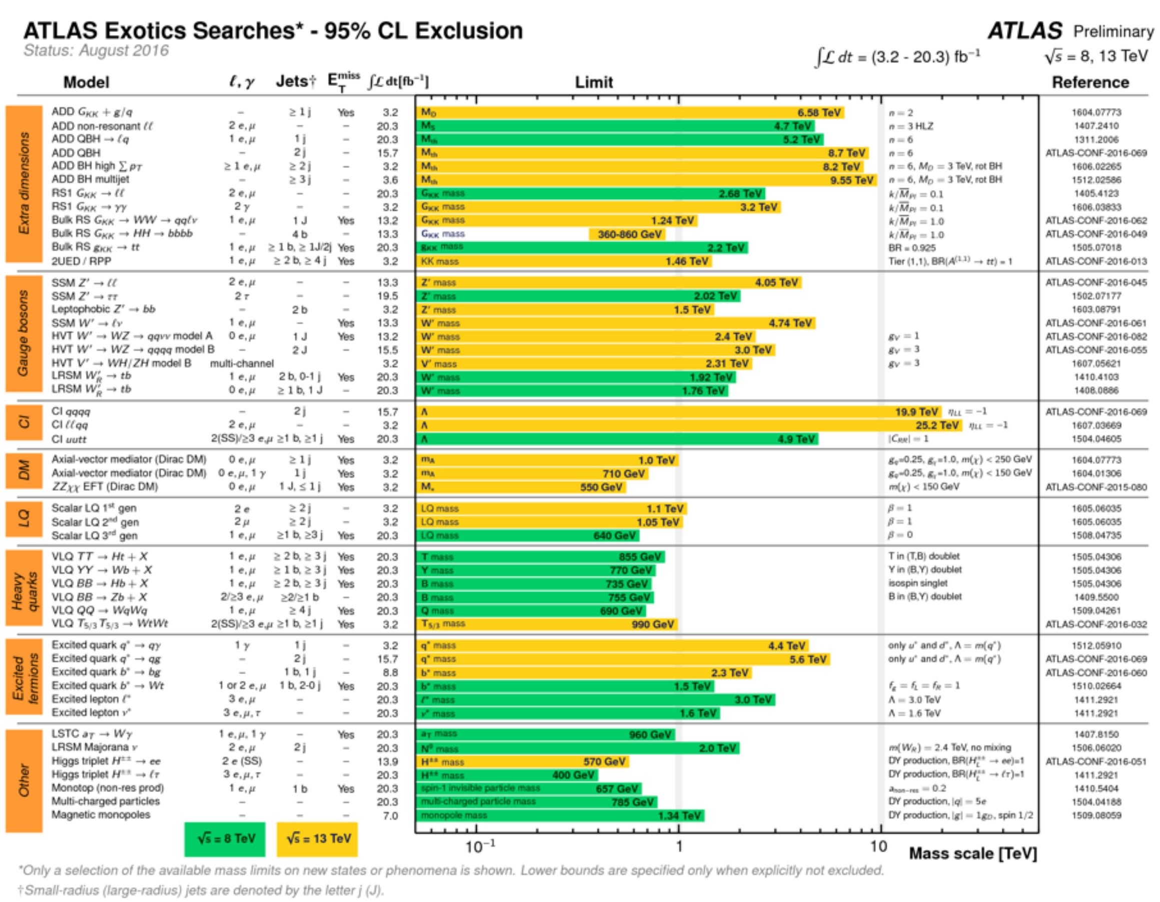
Hierarchy problem the biggest driver @ colliders

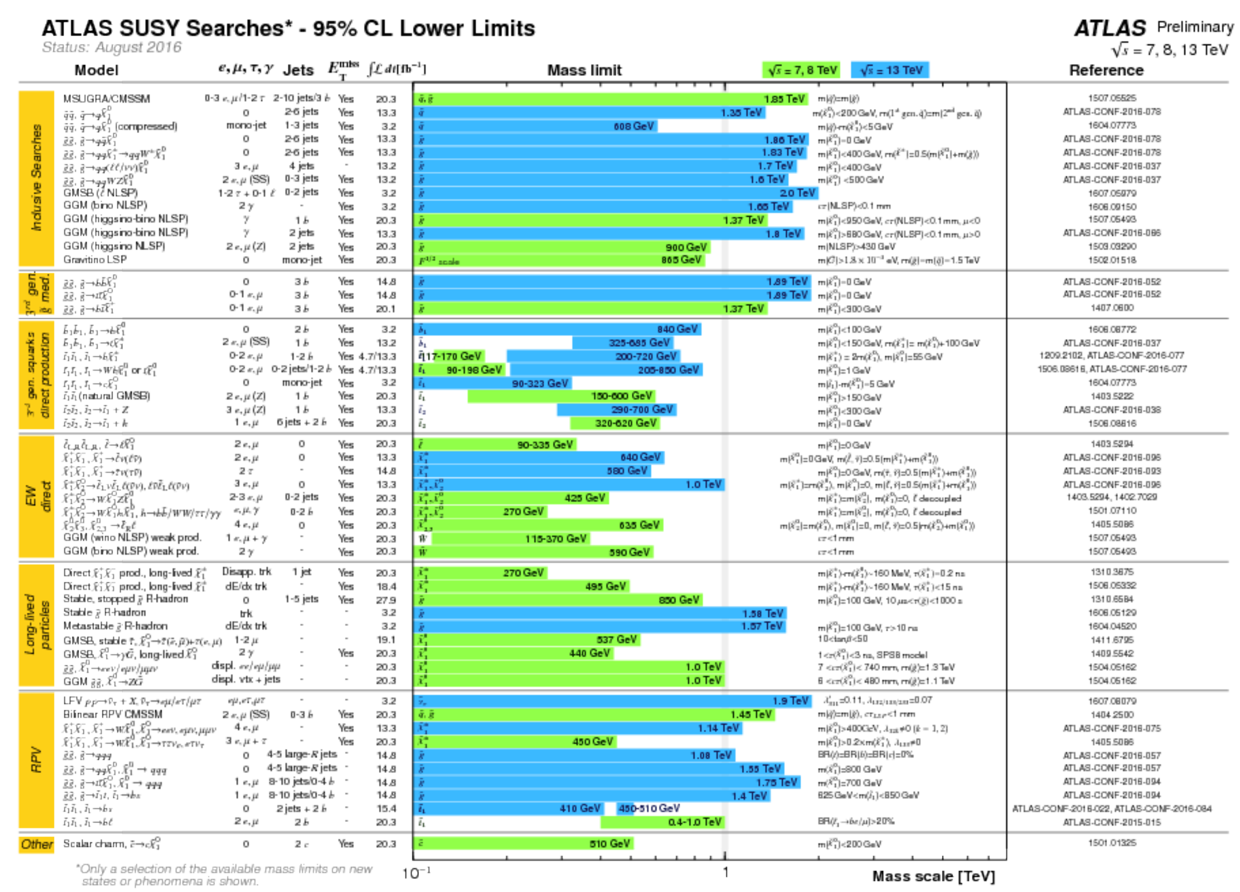






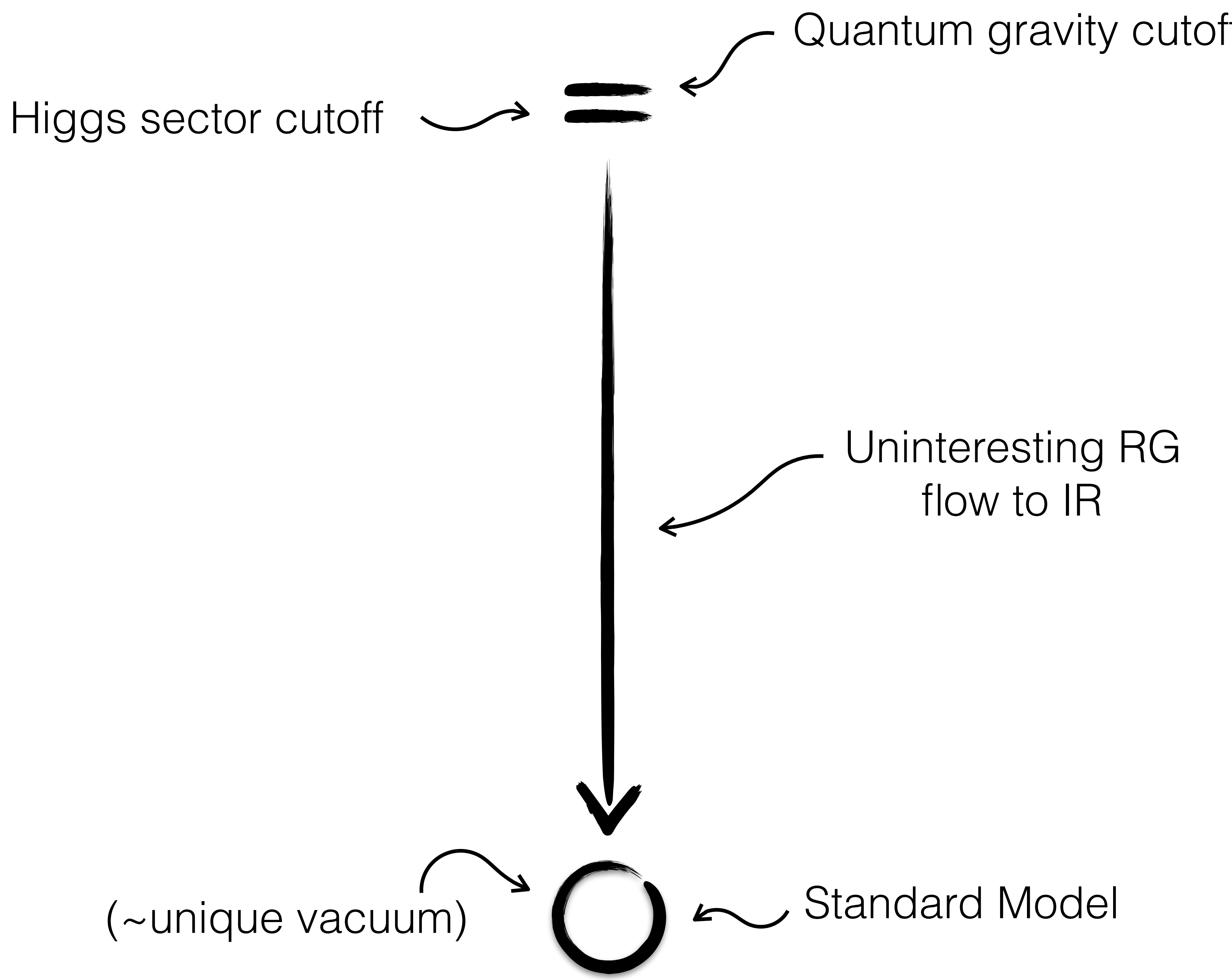






But theory motivation aside, a tremendous signal generator.

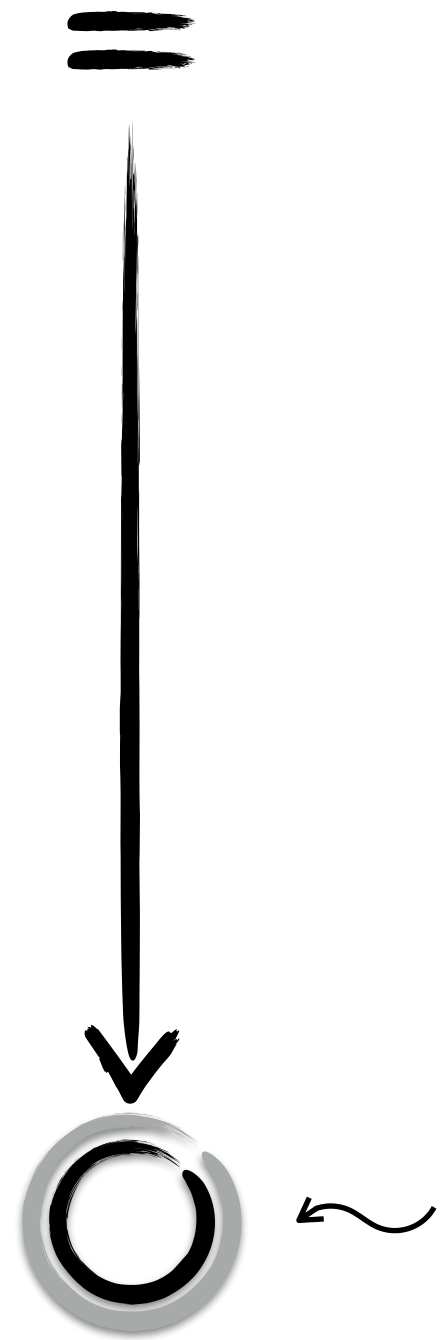
The Hierarchy Problem



m_H is not technically natural ⇒ hierarchy problem

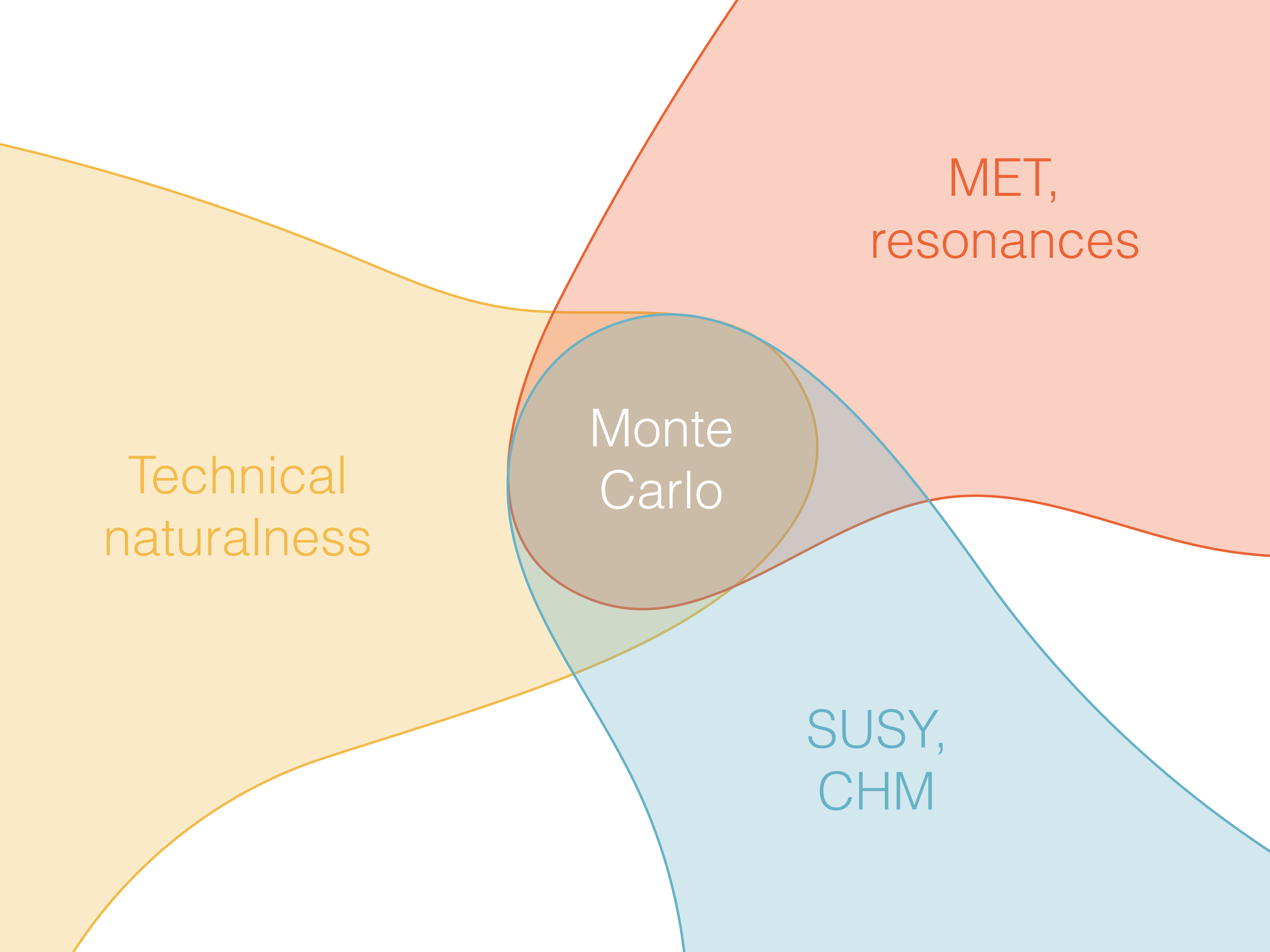
The usual approach*

*given an elementary Higgs

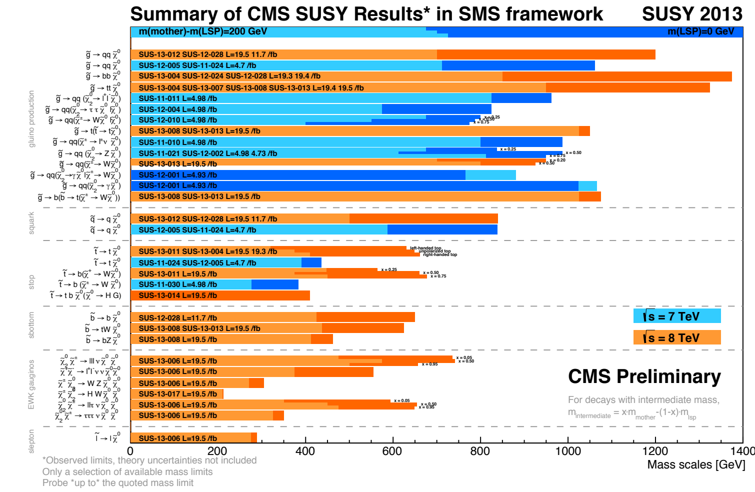


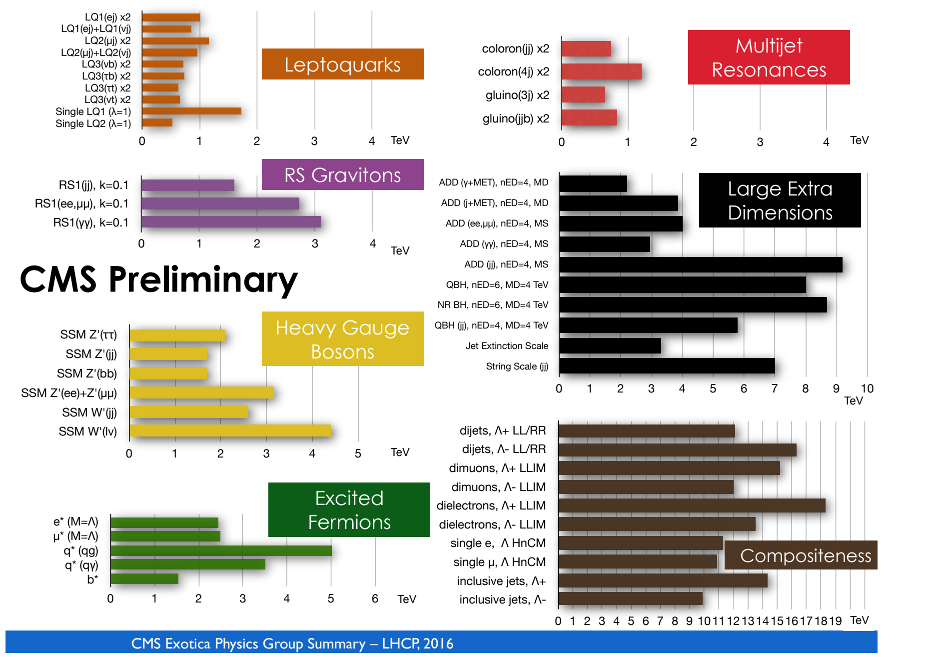
Extend SM with
a symmetry

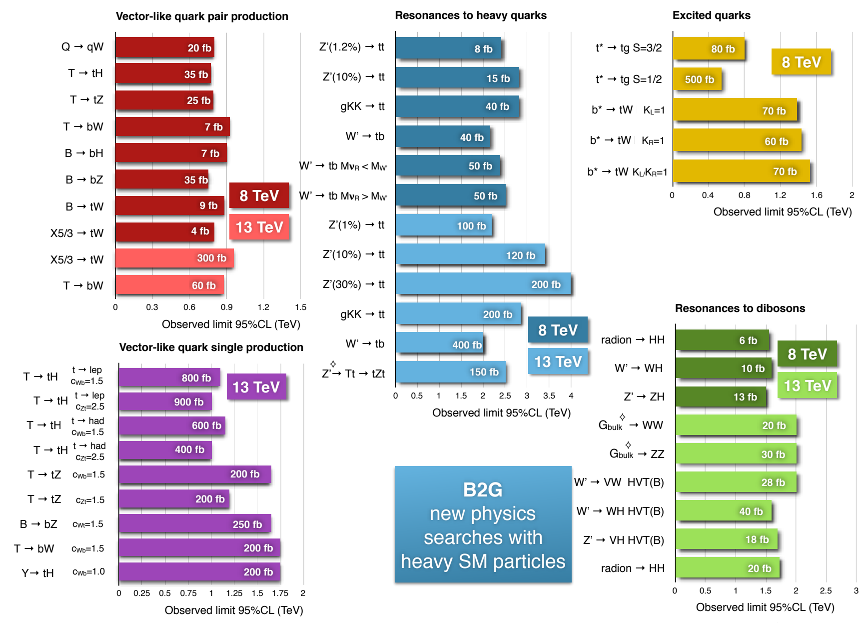
m_H is technically natural

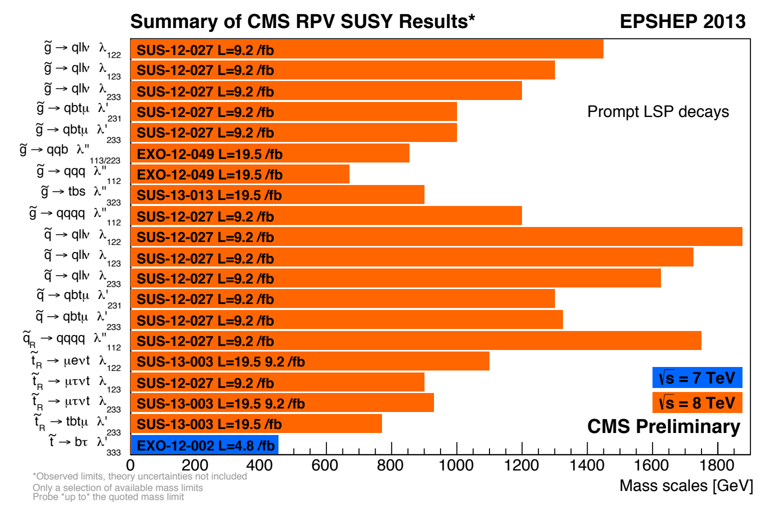

MET,
resonances
Technical
naturalness
Monte
Carlo
SUSY,
CHM

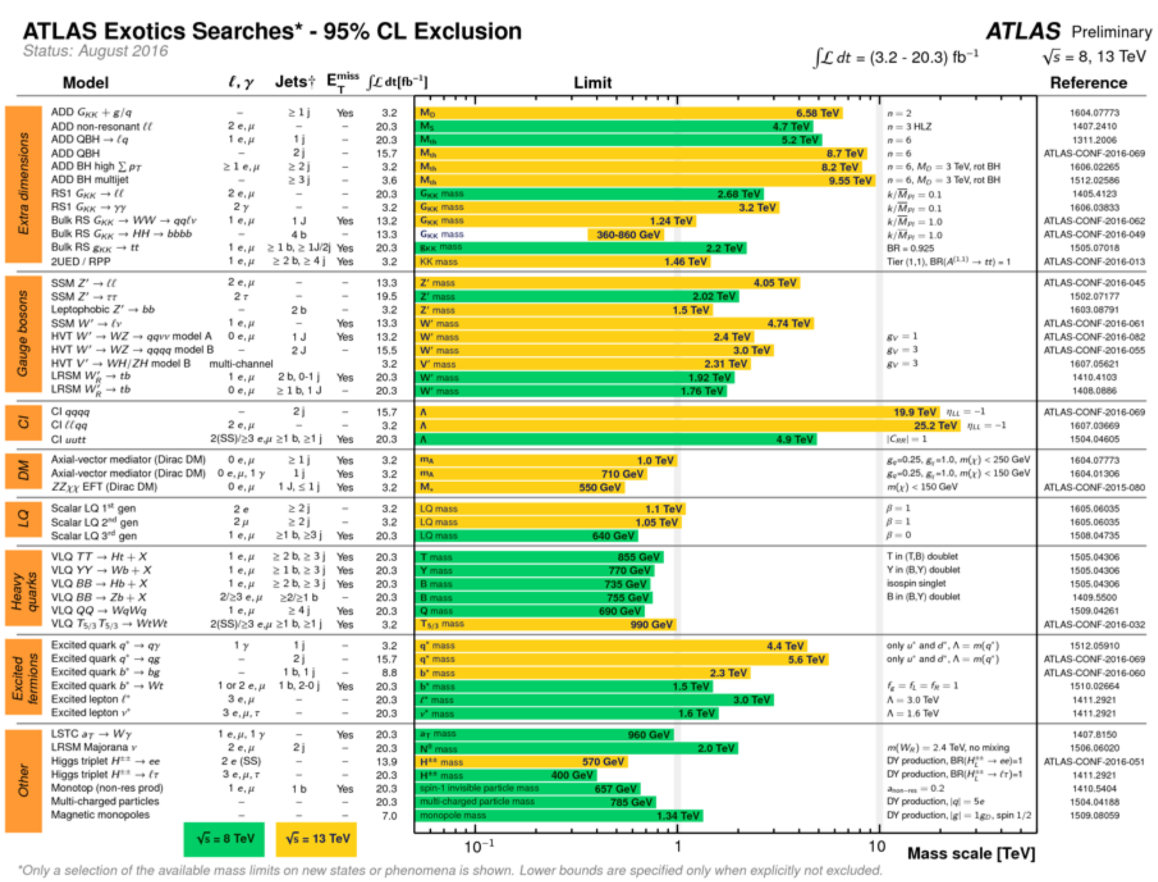
Tremendously effective! Nothing so far.

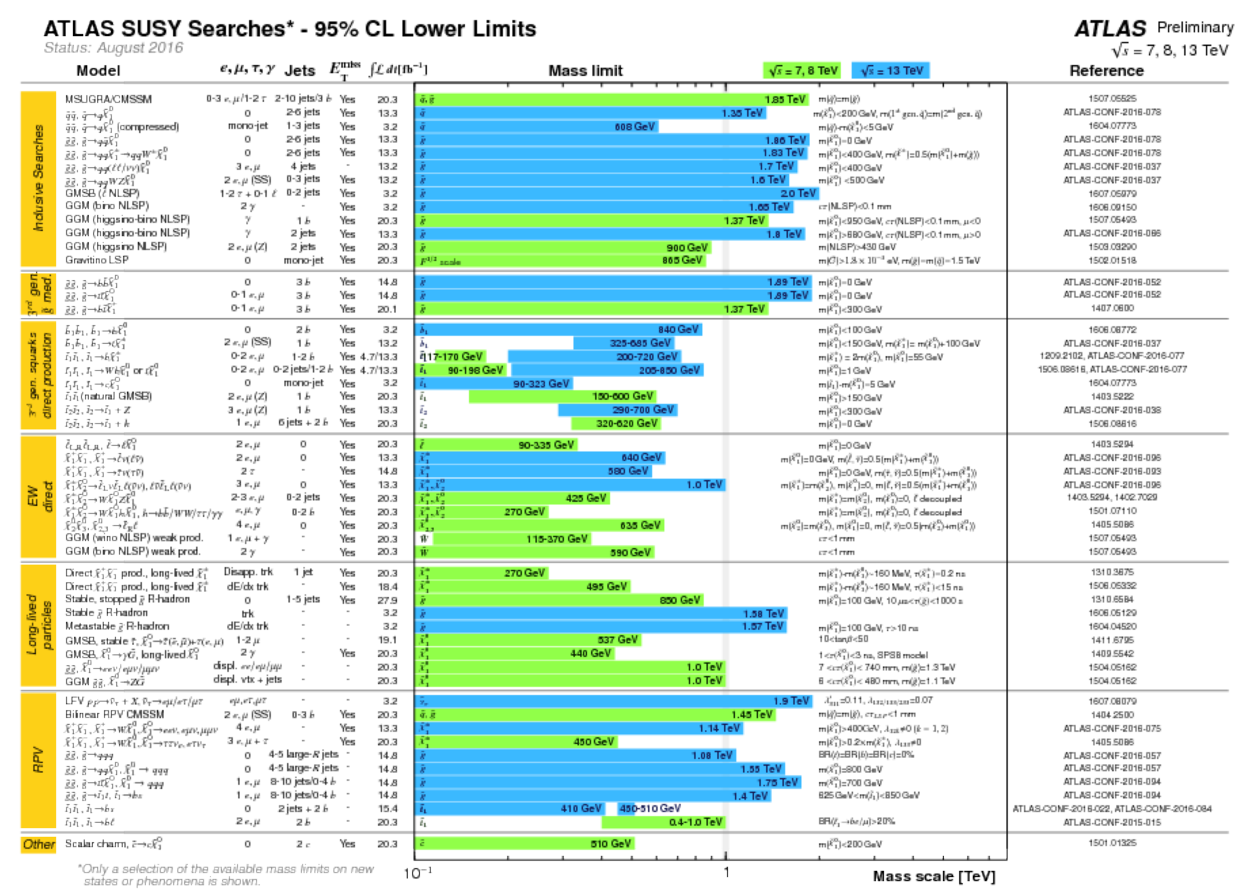


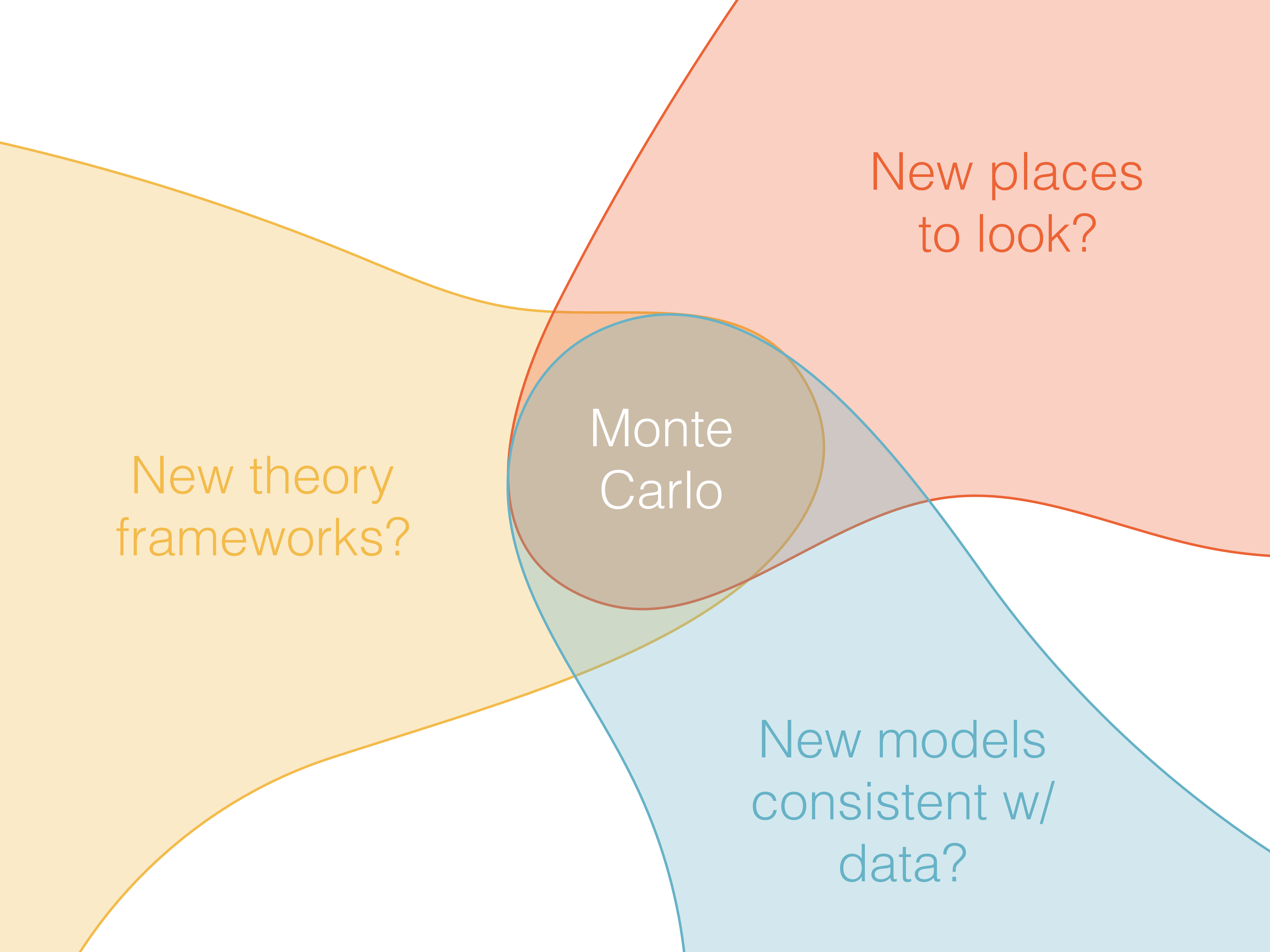




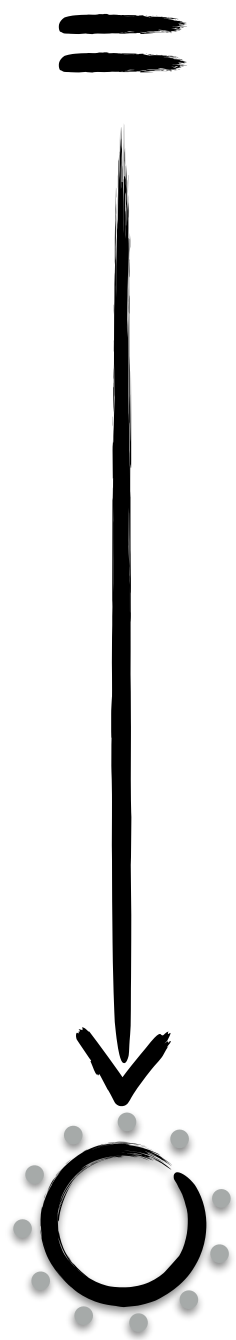







New places to look?
New theory frameworks?
Monte Carlo
New models consistent w/ data?

New theory frameworks?



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

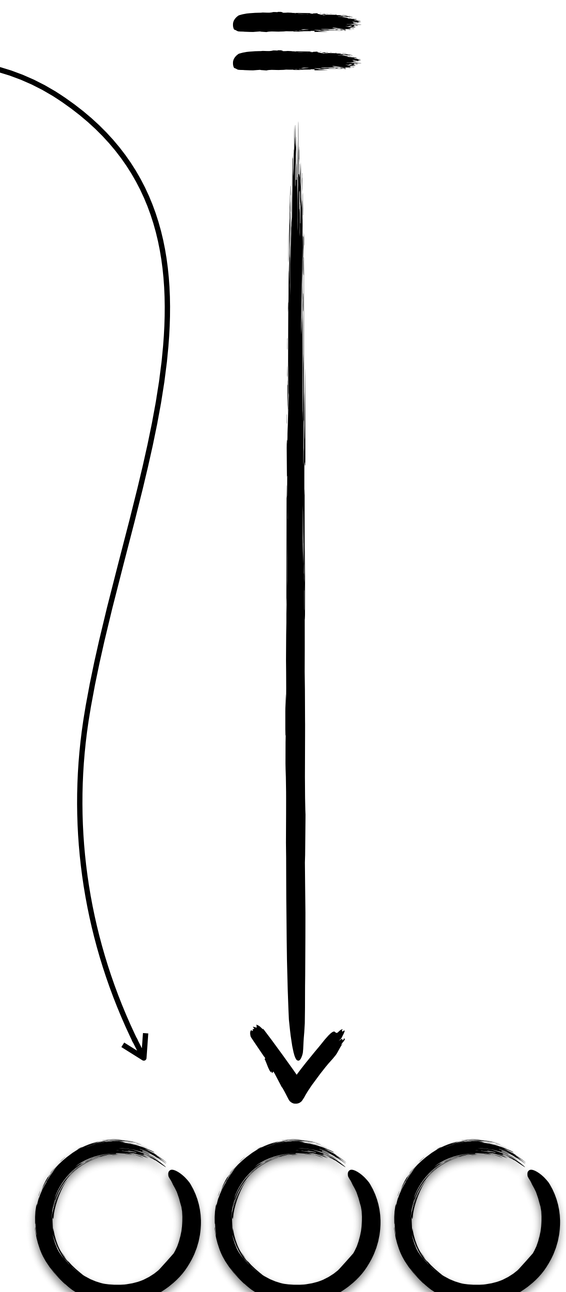
But IR symmetries discrete, not continuous

“Neutral Naturalness”

Hierarchy problem not directly controlled by symmetries, contributions large

But total Higgs mass scanned dynamically

“Relaxion”



Models consistent w/ data?

Conventional symmetries

- R-parity violation
- Compression
- Stealth SUSY
- .....

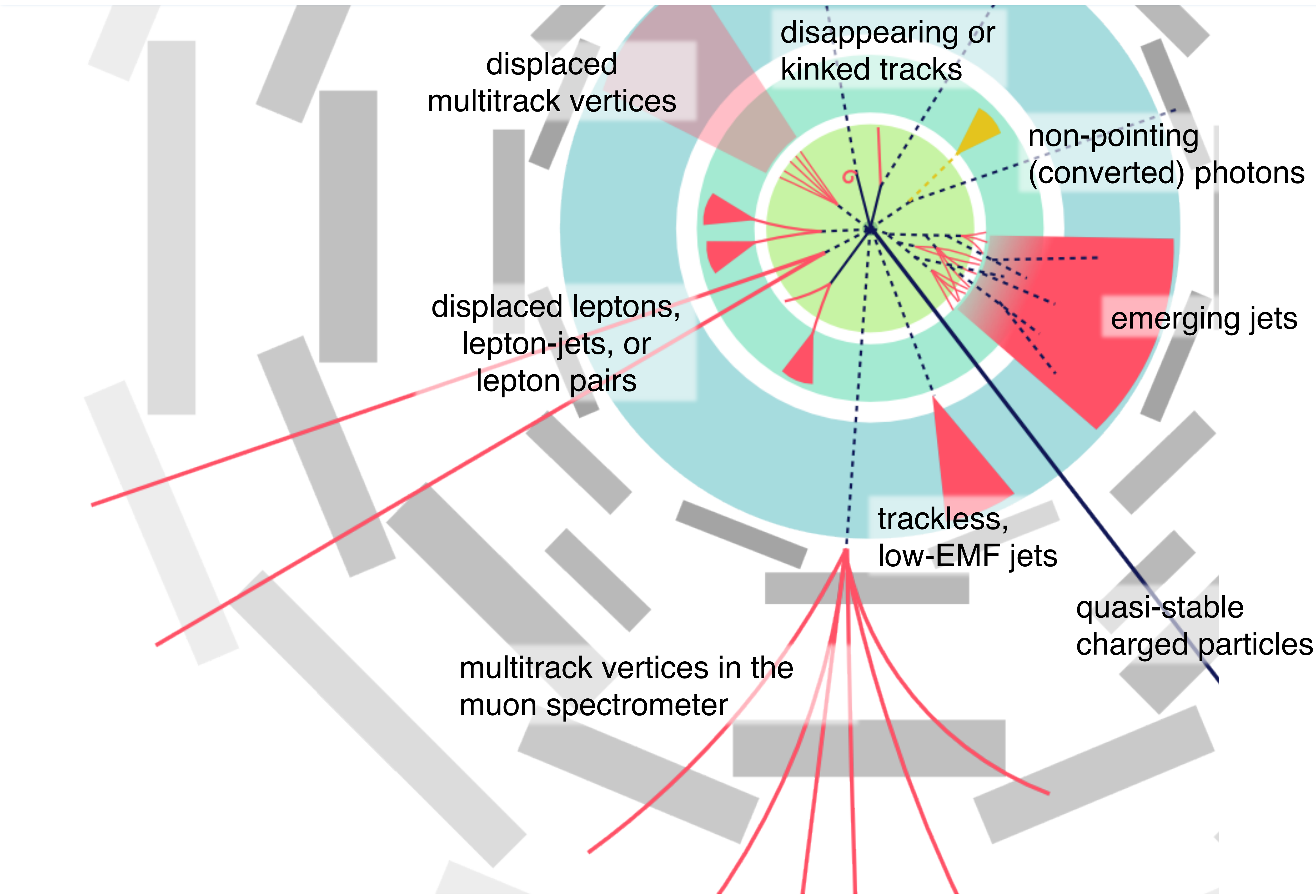
Neutral naturalness

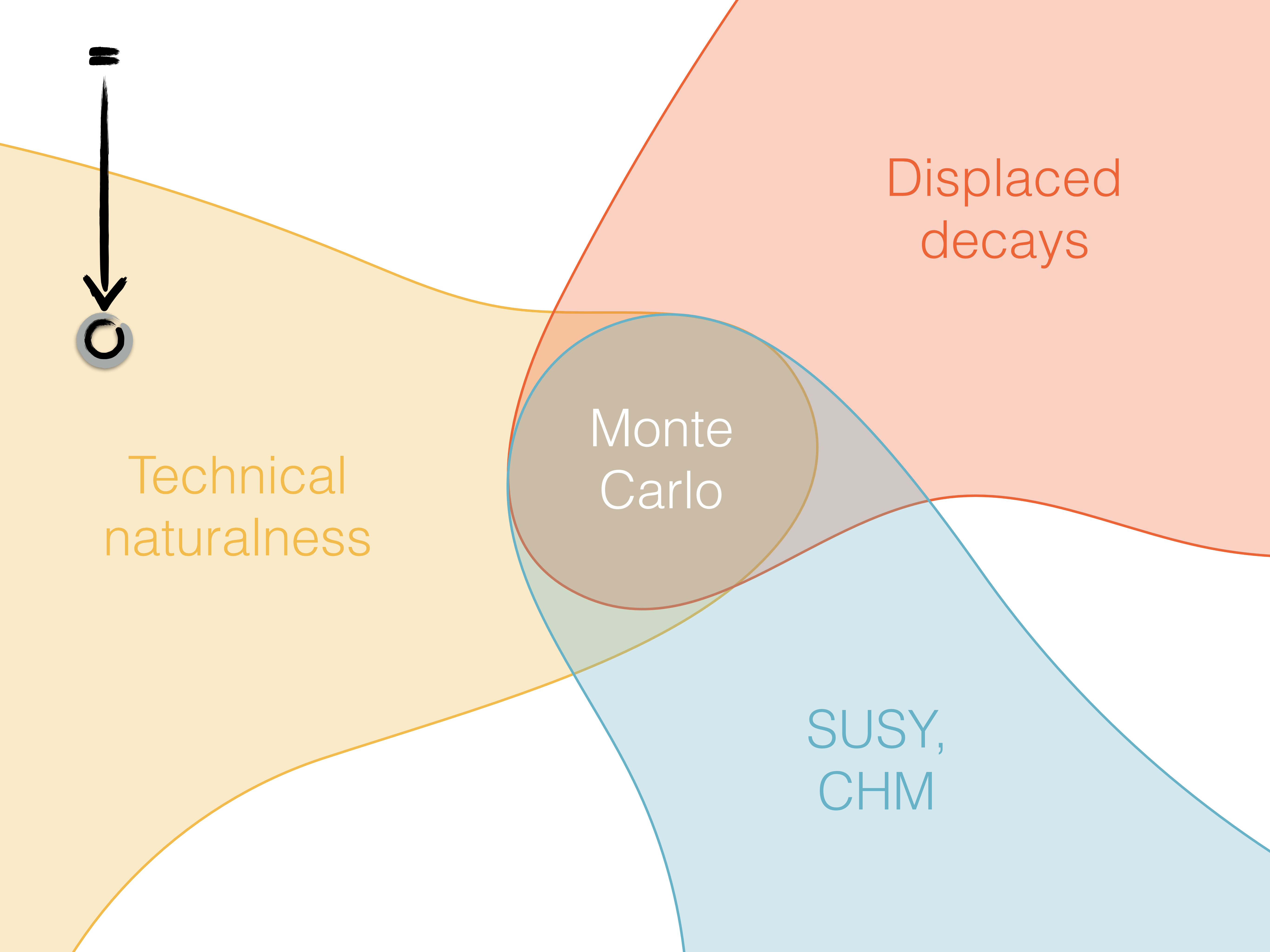
- Twin Higgs
- Orbifold Higgs
- Folded SUSY
- .....

Relaxion

- QCD relaxion
- QCD’ relaxion
- Interactive relaxion
- .....

New places to look?

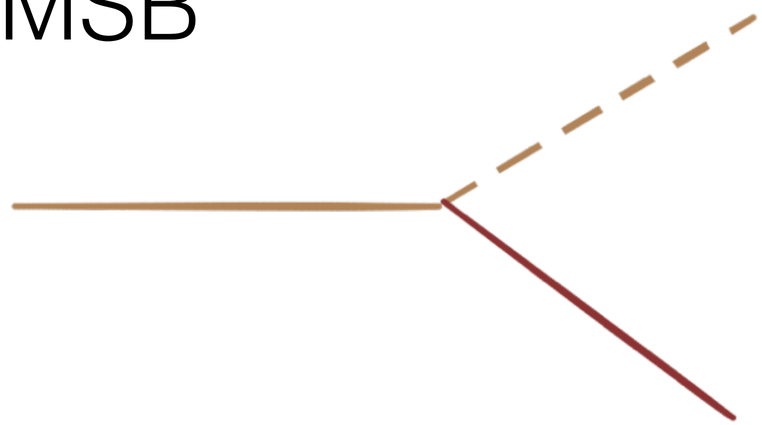



Displaced
decays
Monte
Carlo
Technical
naturalness
SUSY,
CHM

Displaced SUSY

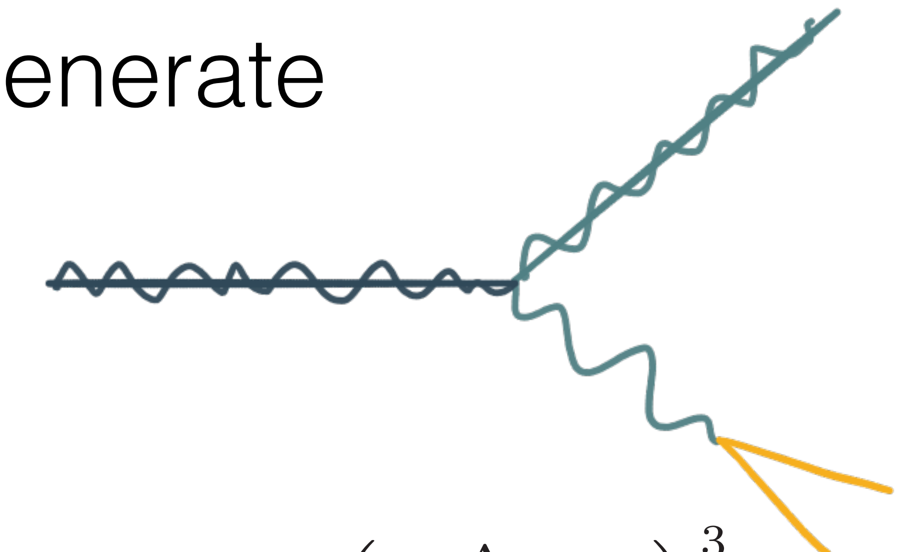
Countless avenues for SUSY decays to become non-prompt

GMSB



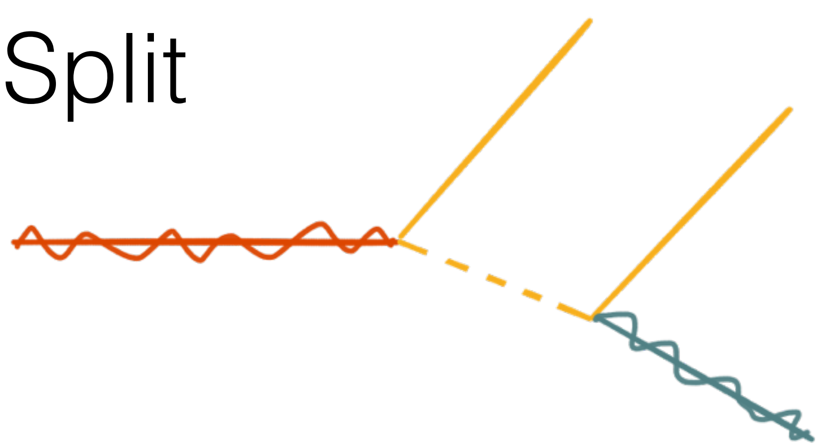
$$c\tau \approx 100\ \mu\text{m} \times \left(\frac{\sqrt{F}}{100\ \text{TeV}}\right)^4 \times \left(\frac{100\ \text{GeV}}{m_{\tilde{h}}}\right)^5$$

Degenerate



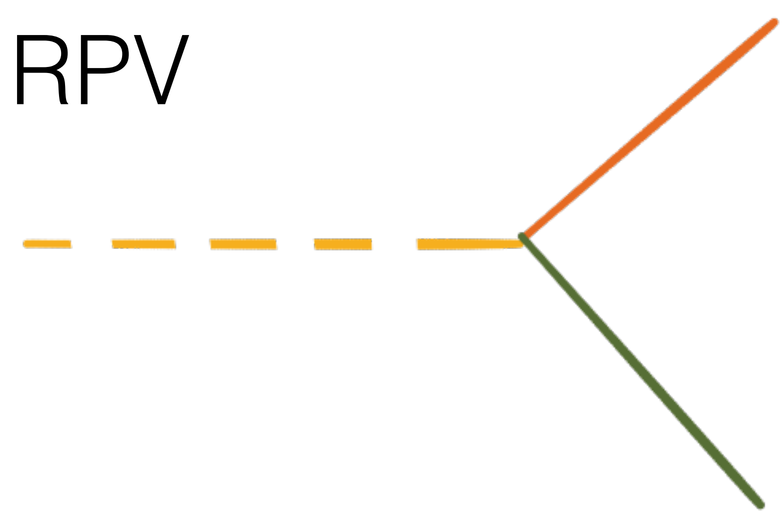
$$c\tau \approx 1\ \text{cm} \times \left(\frac{\Delta m}{340\ \text{MeV}}\right)^3$$

Split



$$c\tau \approx 100\ \mu\text{m} \times \left(\frac{m_{\tilde{q}}}{10^3\ \text{TeV}}\right)^4 \times \left(\frac{\text{TeV}}{m_{\tilde{g}}}\right)^5$$

RPV

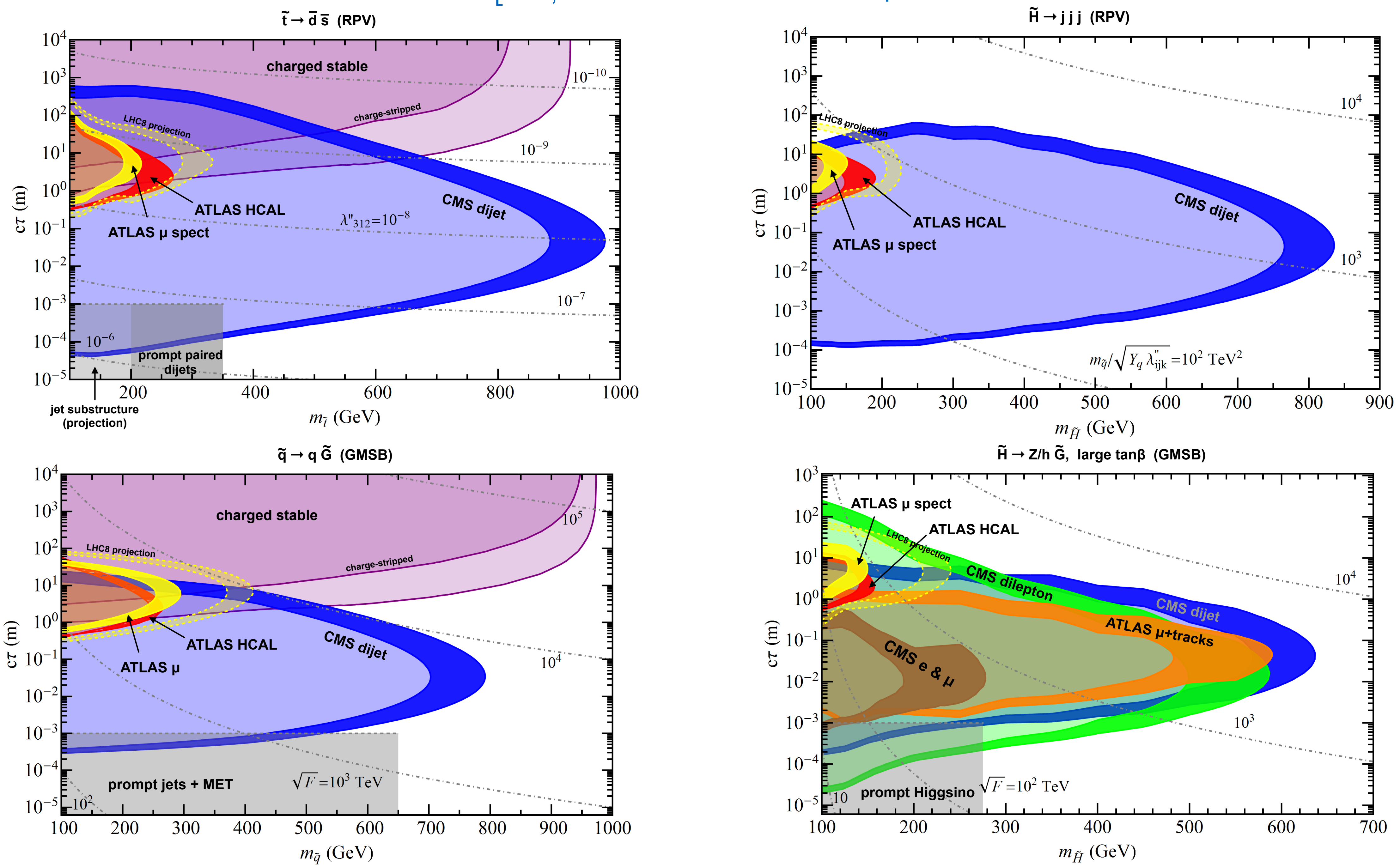


$$c\tau \approx 500\ \mu\text{m} \times \left(\frac{10^{-7}}{\lambda}\right)^2 \left(\frac{\text{TeV}}{m_{\tilde{q}}}\right)^1$$

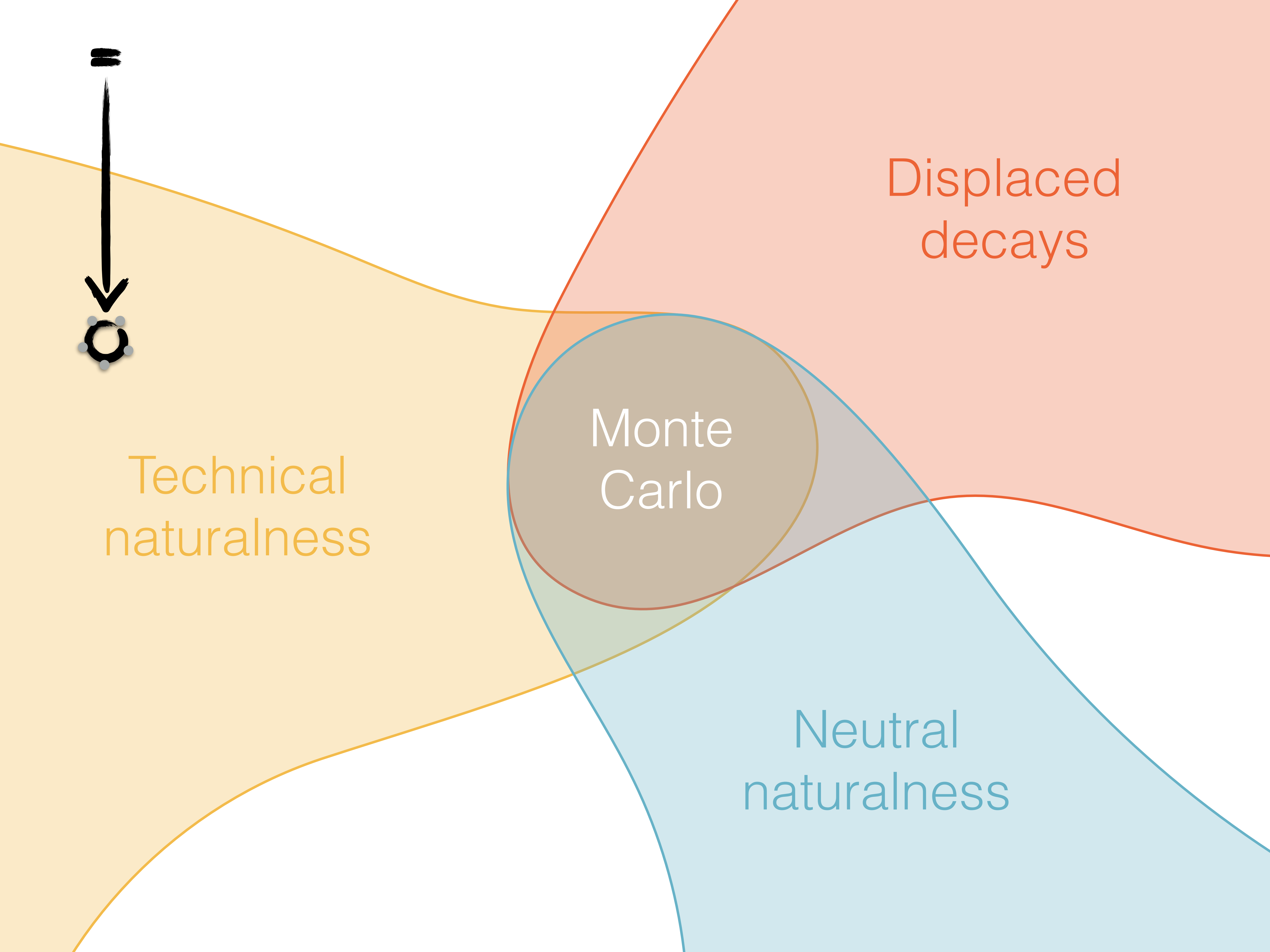
Displaced SUSY

Not that many places to hide once the searches catch up

[Liu, Tweedie 1503.05923]

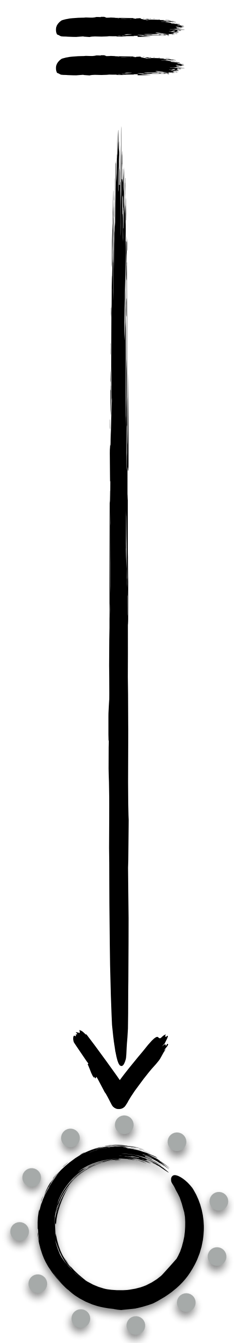


Not totally hermetic, some holes remain.


Displaced decays
Technical naturalness
Monte Carlo
Neutral naturalness

Example 1: Twin Higgs

[Chacko, Goh, Harnik ‘05]



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

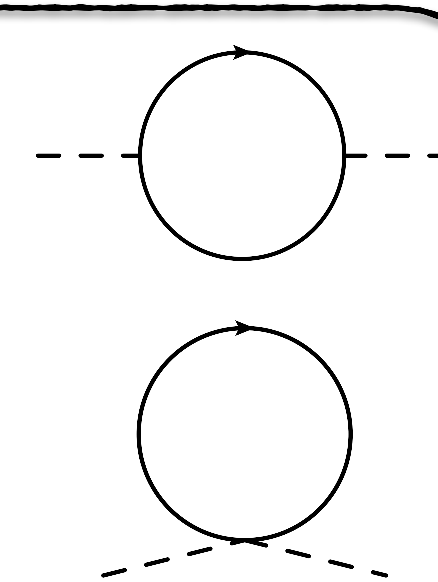
Radiative corrections to the Higgs mass are SU(4) symmetric thanks to Z_2:

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

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

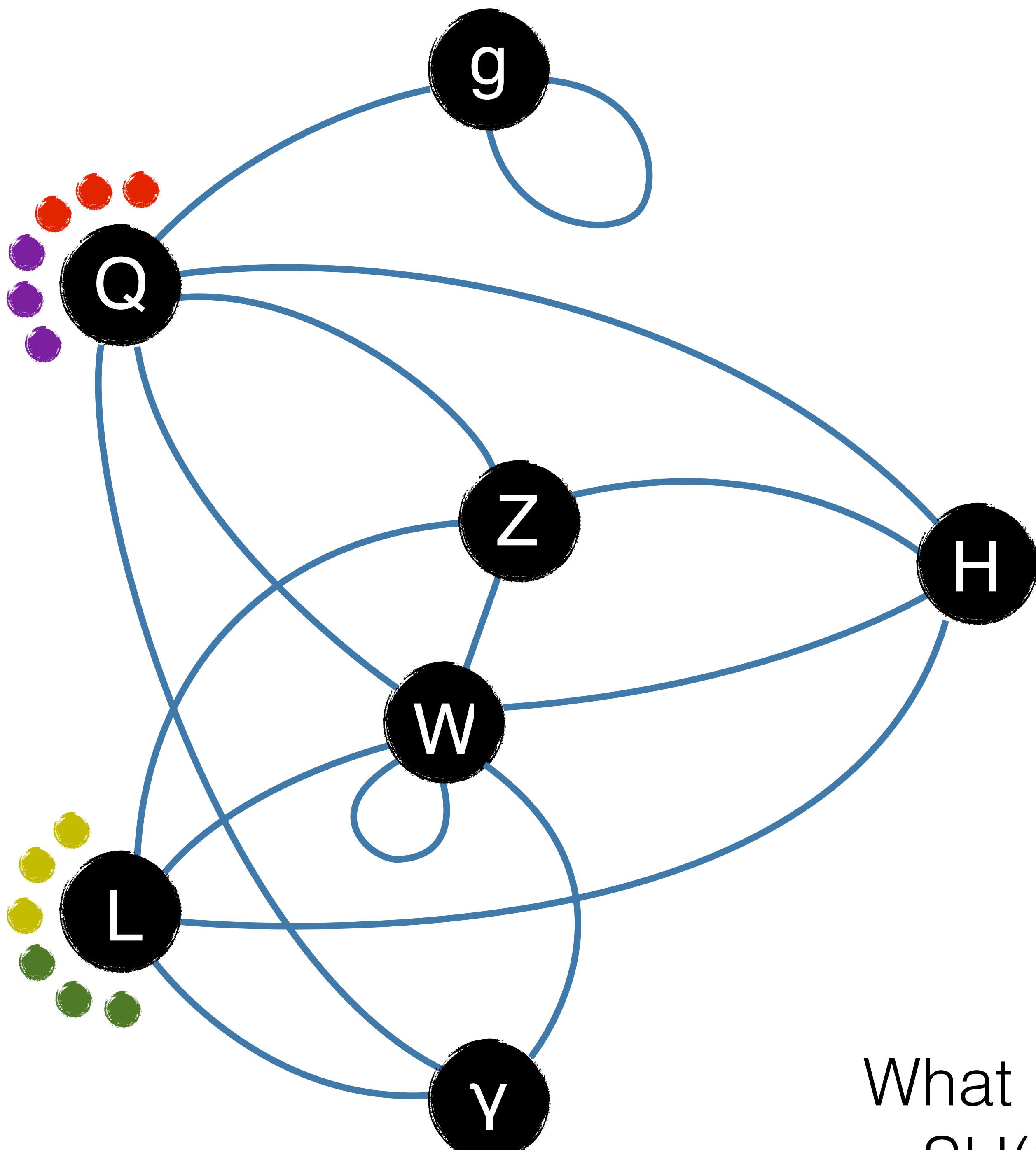
$$\mathcal{L} \supset -y_t H_A Q_3^A \bar{u}_3^A - y_t H_B Q_3^B \bar{u}_3^B$$

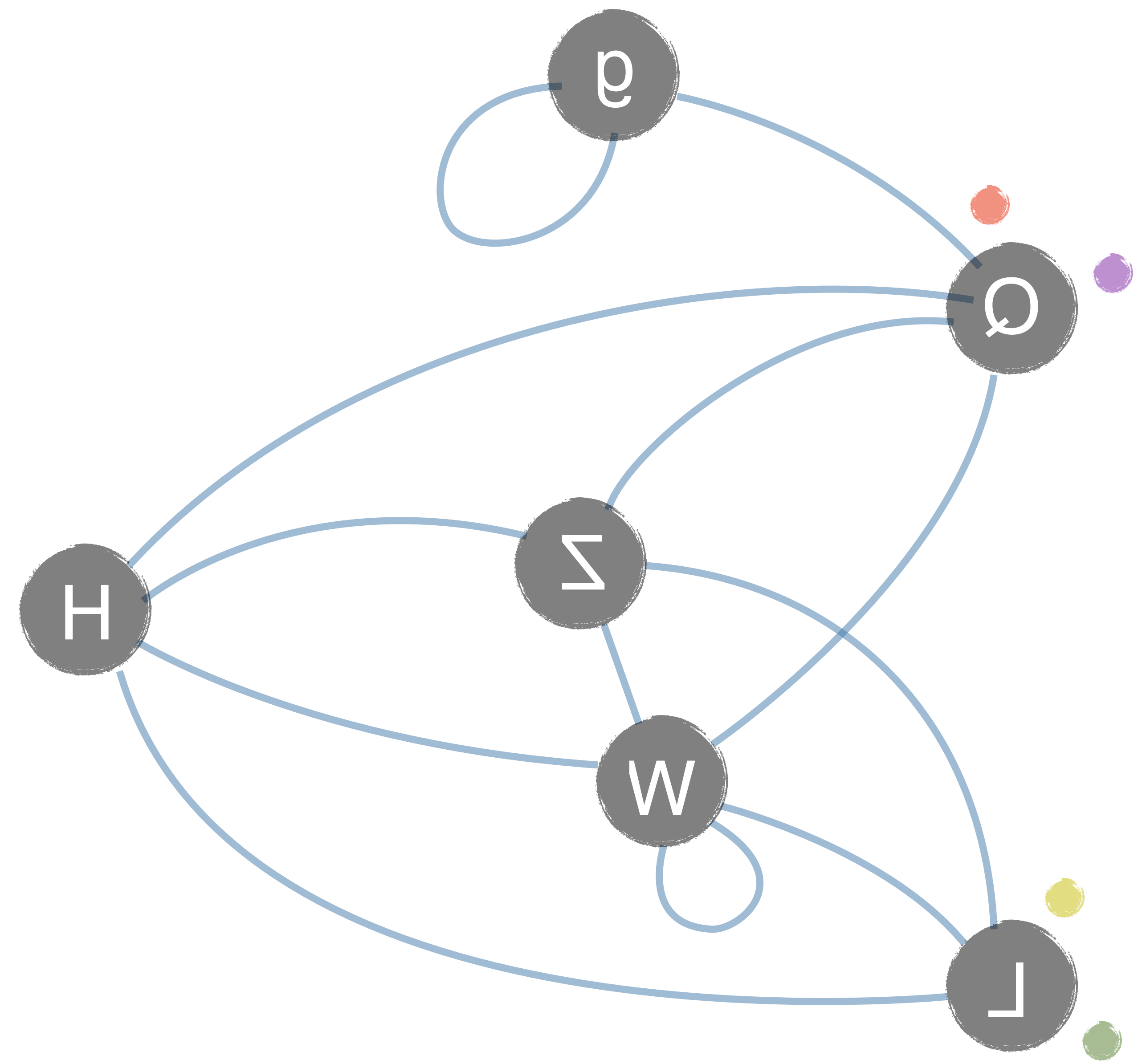
$$h + \ldots \qquad\qquad f - \frac{h^2}{2f} + \ldots$$



[NC, Katz, Strassler, Sundrum ’15]

Fraternal twins

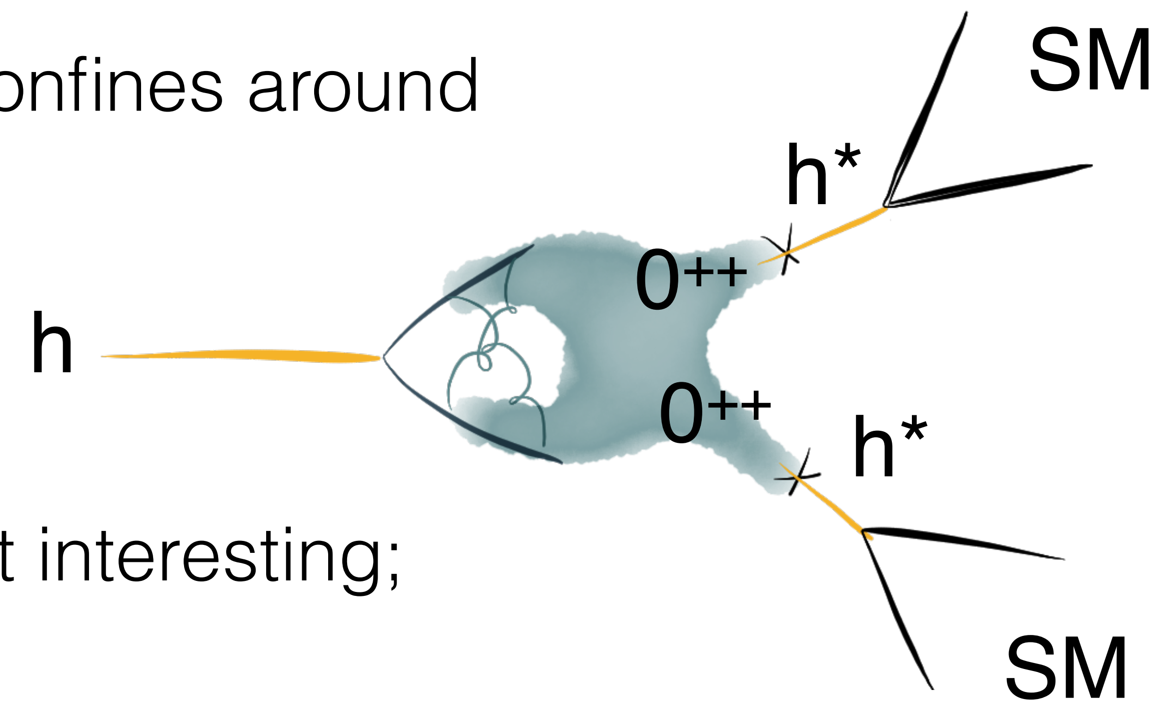


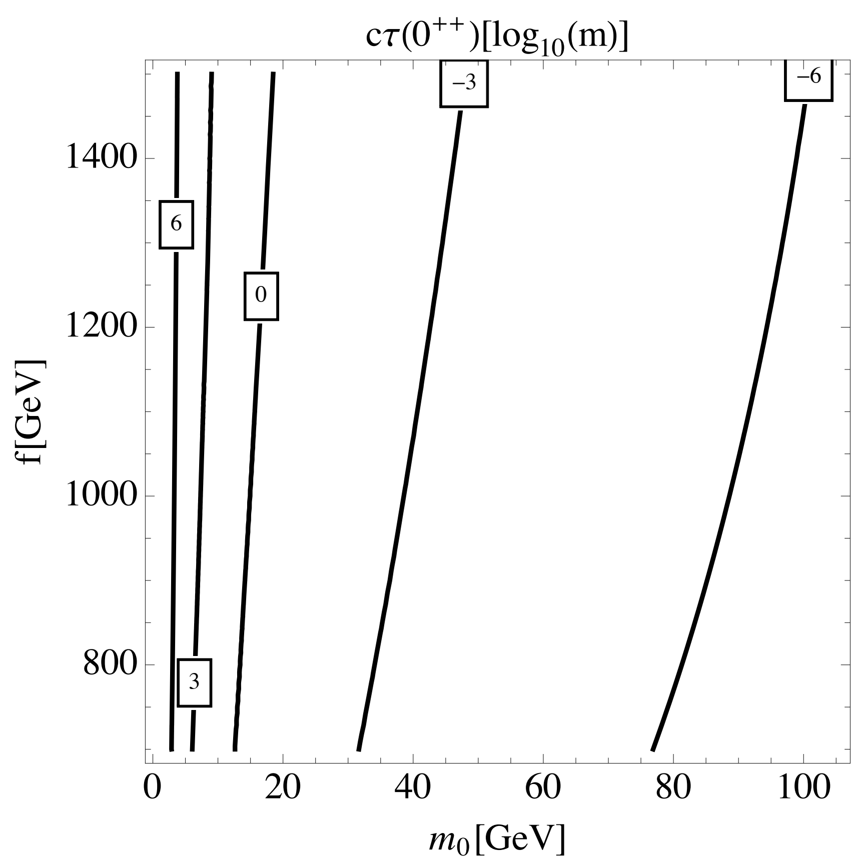


What really matters for naturalness:
SU(3)xSU(2) & third generation
⇒ Dark QCD

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; 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

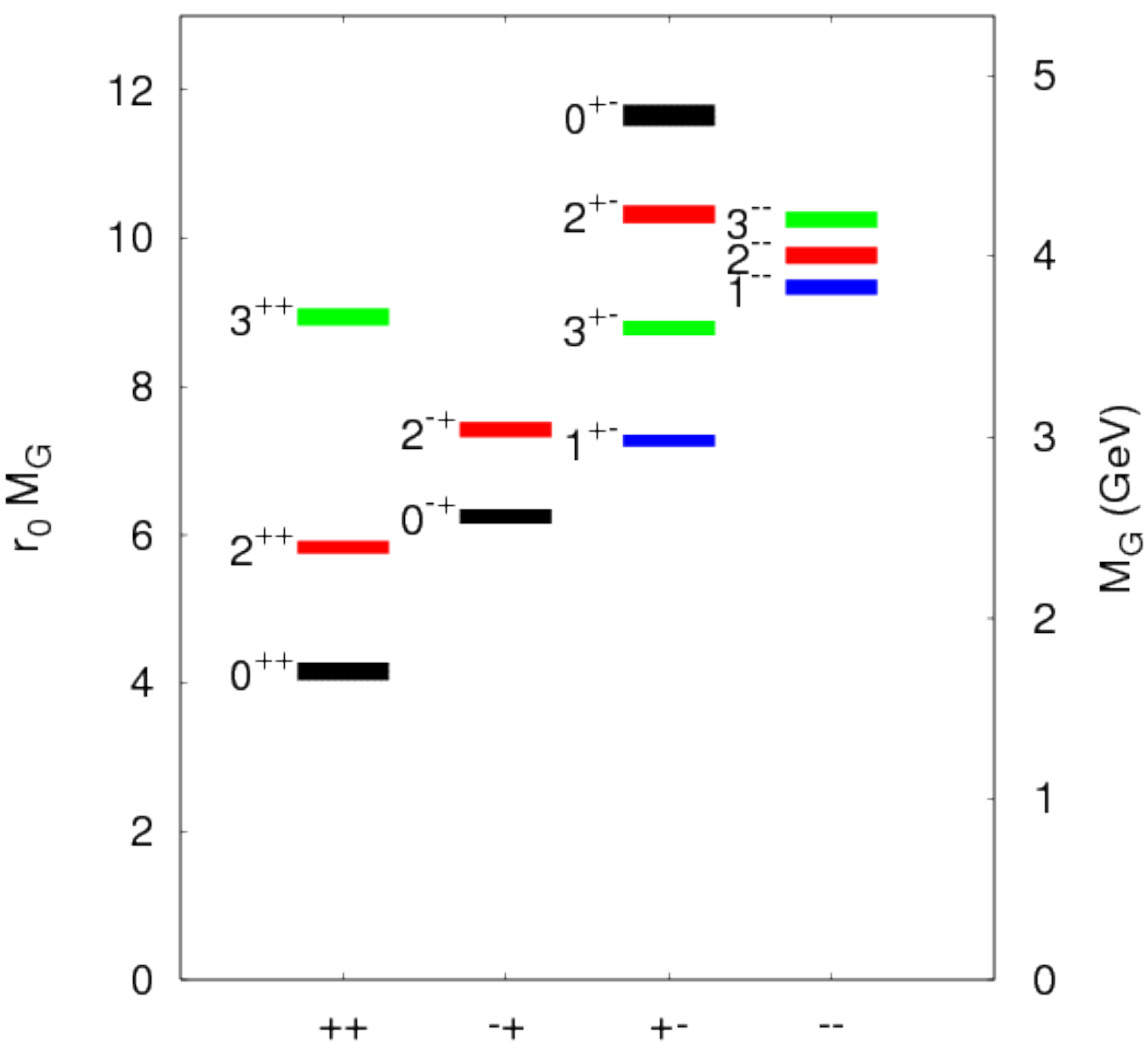
$$0^{++} \to h^* \to f\bar{f}$$

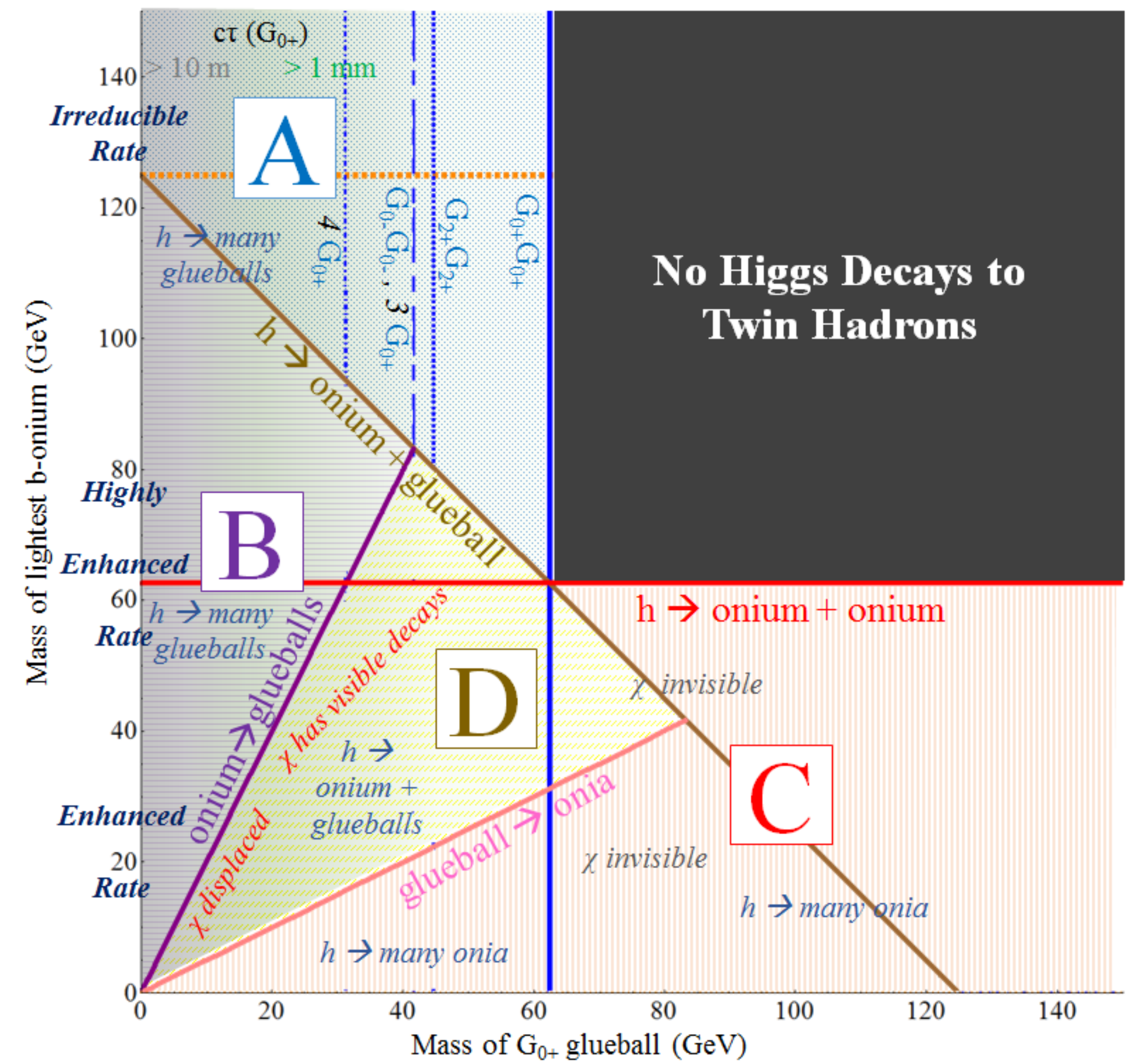
Long-lived, decay length is macroscopic; length scale ~ LHC detectors

Complexities

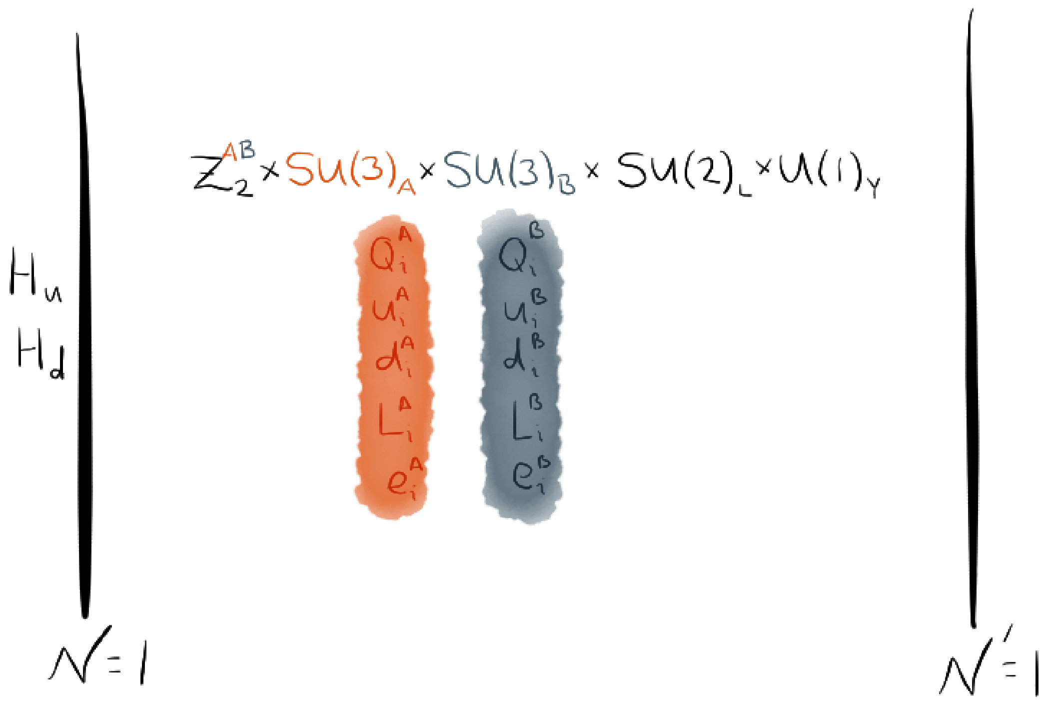
Naive picture is simple, reality is more complicated

Rates, multiplicities, signals all approximate





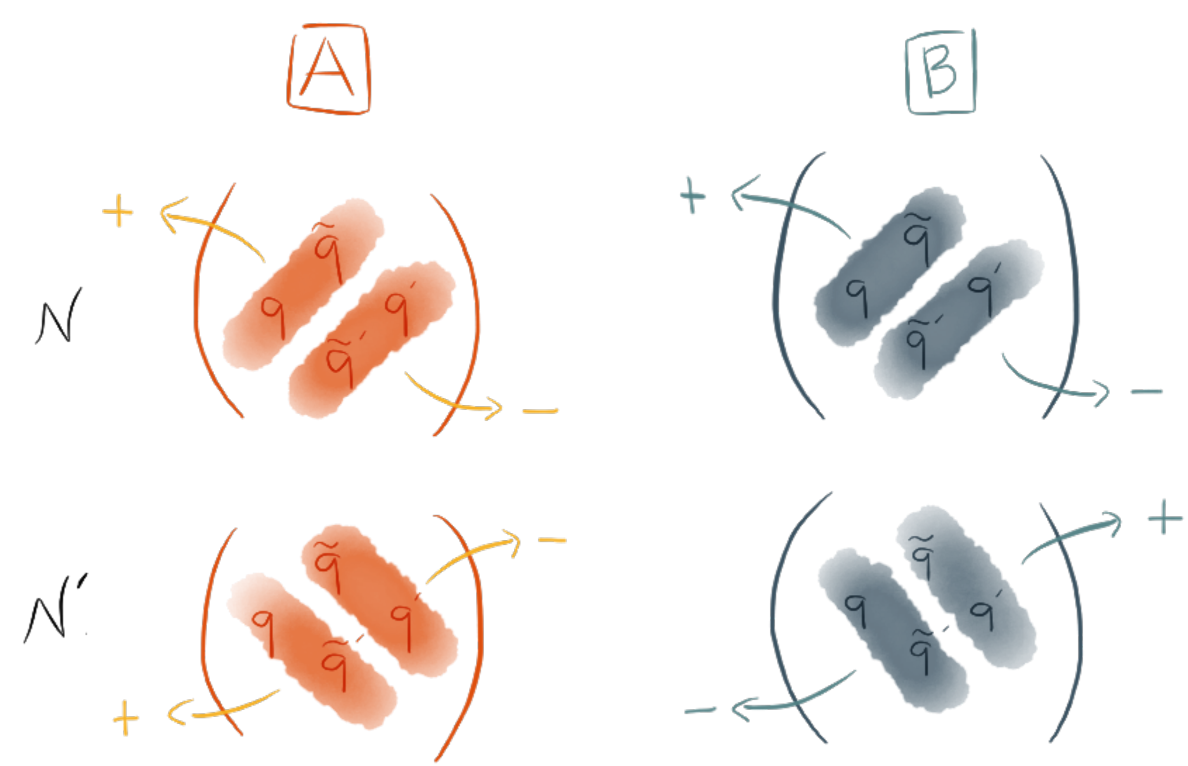
Example 2: Folded SUSY



[Burdman, Chacko, Goh, Harnik ‘06]

SUSY-like theory with uncolored sparticles. Start with a discrete symmetry + 5D SUSY.

Reduce symmetries & SUSY at the boundaries

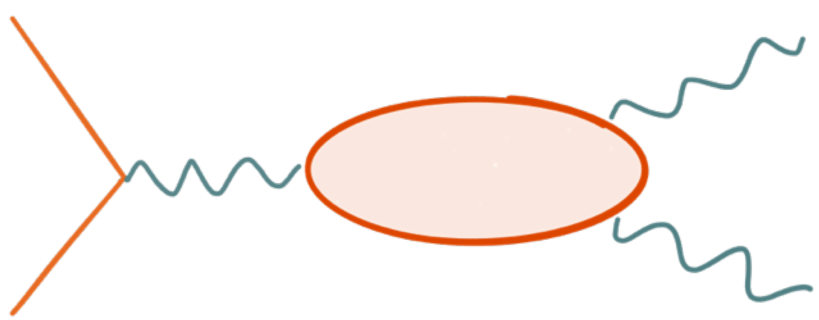


Sparticles carry standard EWK quantum #’s, but QCD charges replaced with QCD’ charges

Once again…Dark QCD

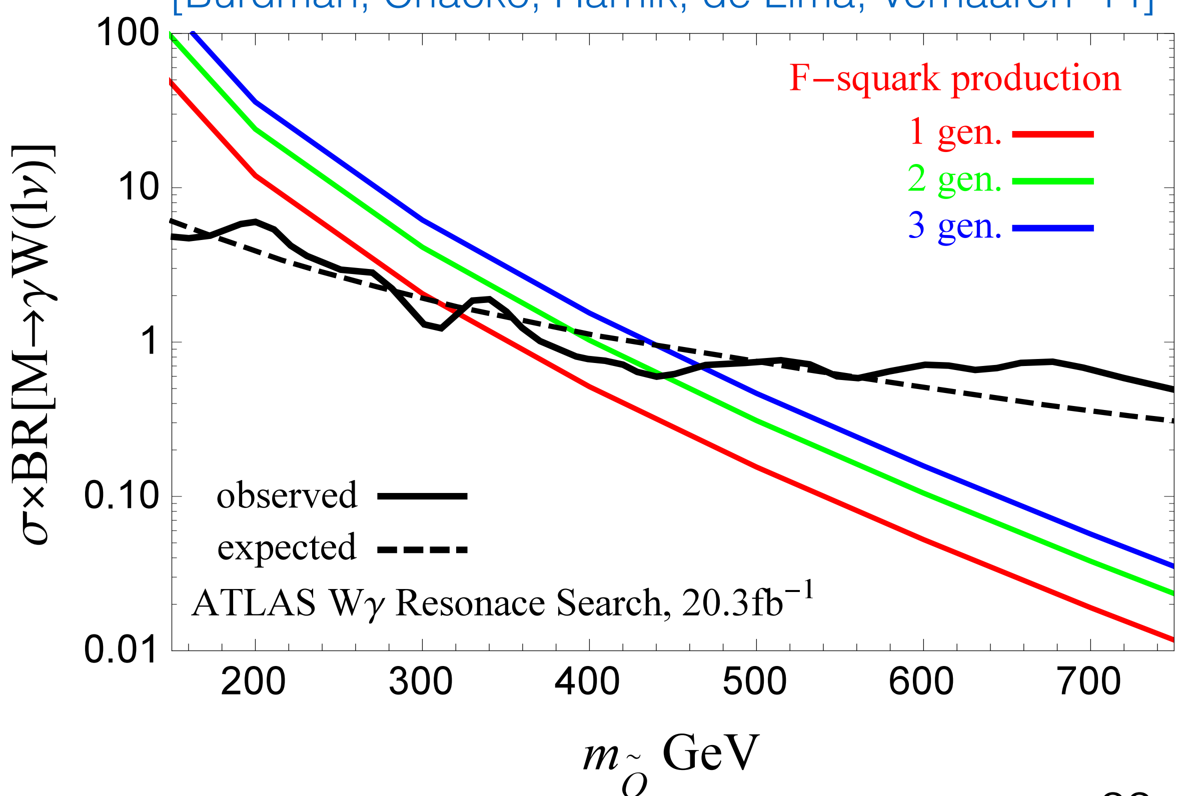
Colorless Signals

F-squarks carry electroweak quantum numbers.

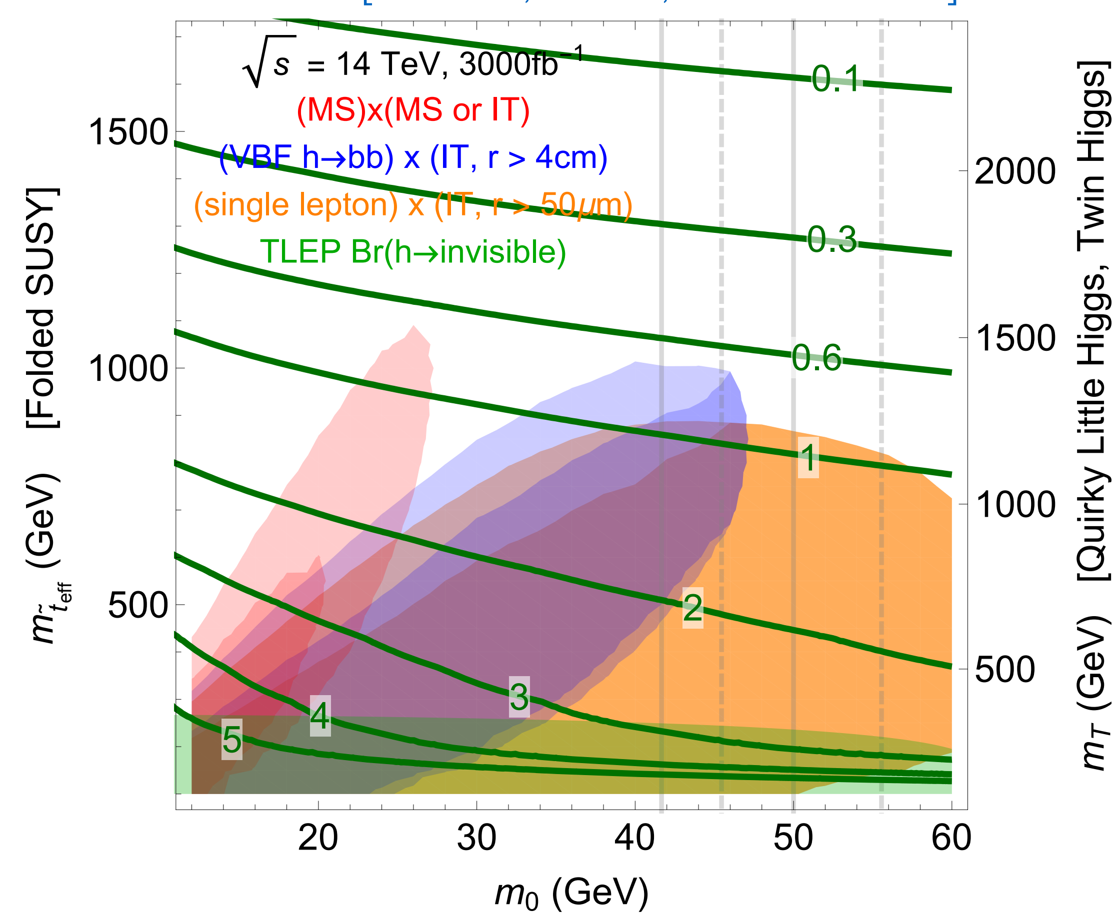


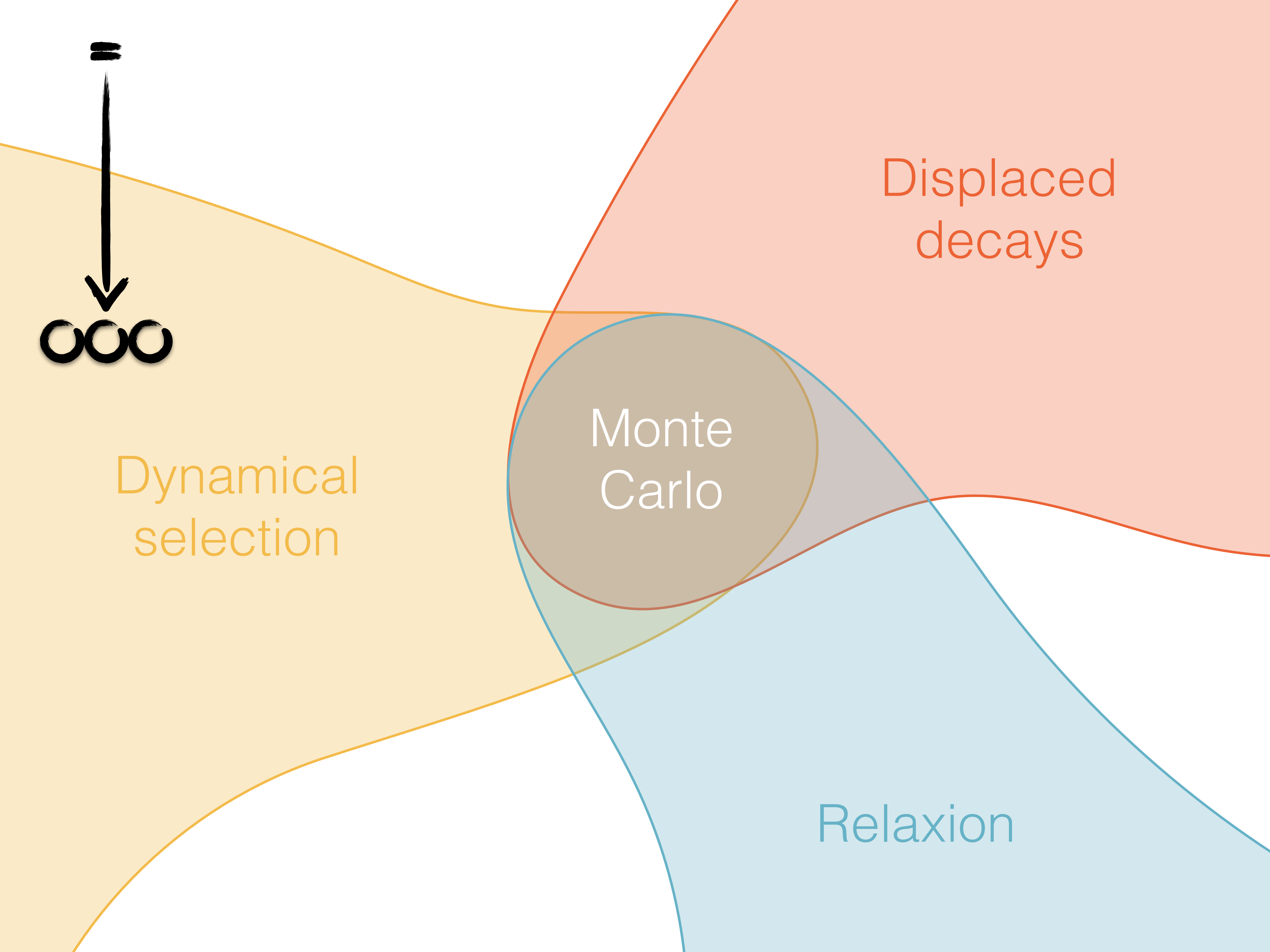
- Produced via a *Z*, annihilate into hidden glueballs, which decay back to SM via Higgs; displaced decays @ LHC length scales. [Curtin, Verhaaren '15]
- Produced via a *W*, annihilate back into the SM to shed their charge.
- (Also leave their mark indirectly, correcting Higgs decays to photons.)

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



[Chacko, Curtin, Verhaaren '15]



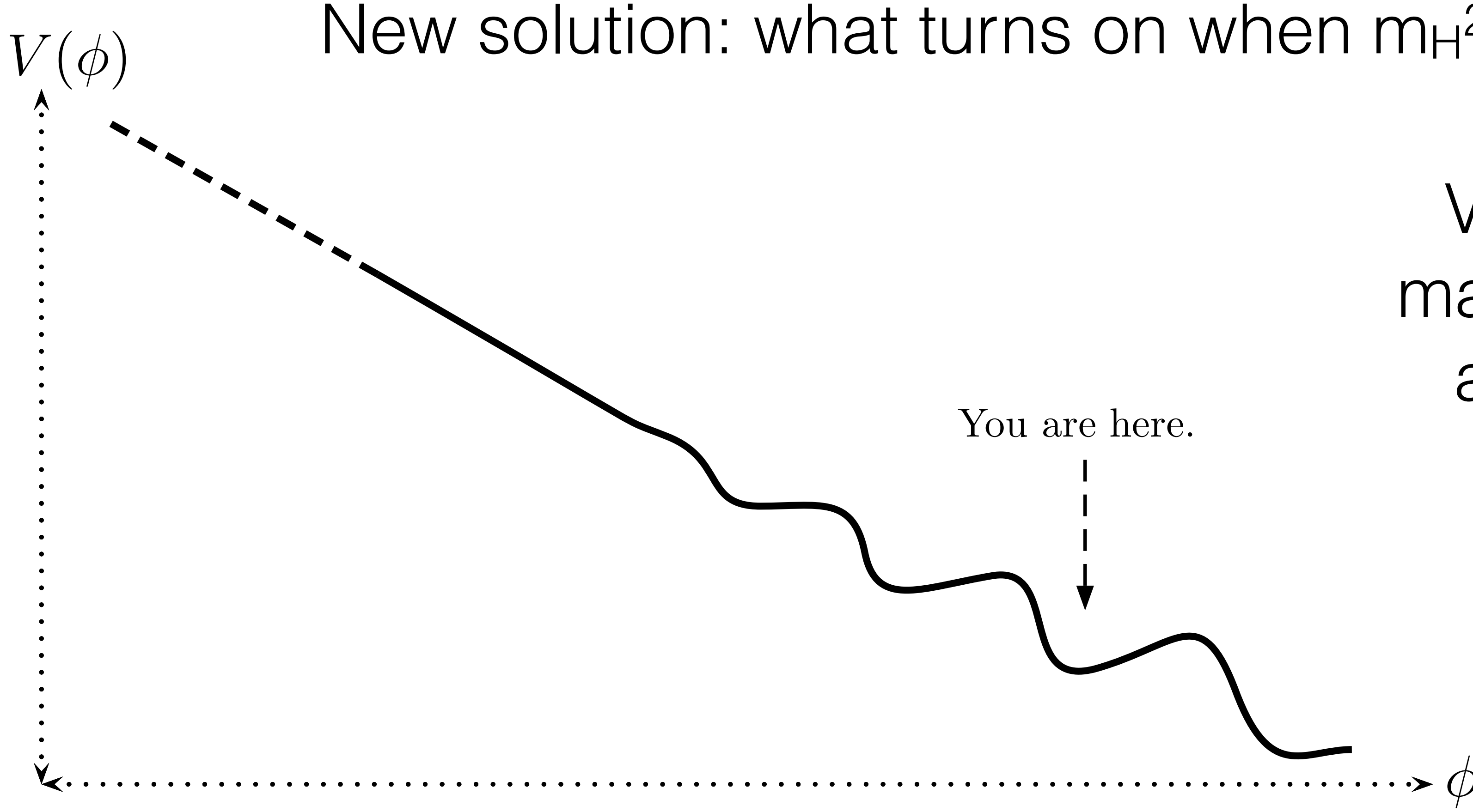

Displaced decays
Monte Carlo
Dynamical selection
Relaxion

Dynamical selection

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

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?

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



Vev gives quark masses which give axion potential!

"Relaxion"

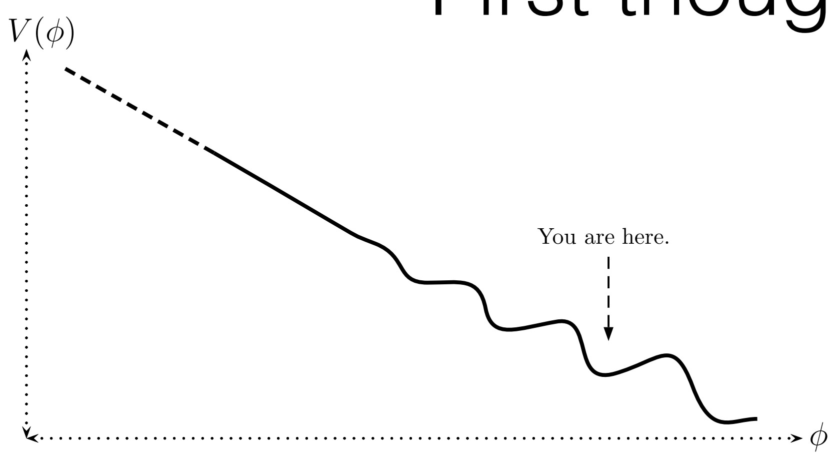
[Graham, Kaplan, Rajendran '15]

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

[Graham, Kaplan, Rajendran ‘15]

Ex.1: QCD/QCD’ relaxion

First thought: use an axion coupled to QCD.



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

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

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

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

Care required to avoid transferring fine-tuning to inflationary sector.

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

[Graham, Kaplan, Rajendran '15]

QCD' Relaxion

Fix: make it someone else's QCD + axion
Again…Dark QCD.

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 $\Lambda^4 \simeq 4\pi f_\pi^3 m_N$

Decouple from LHC?

QCD' Relaxion

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

New confining physics near weak scale!

Couples to Higgs, electroweak bosons; hidden valley signatures.
Various possibilities (N_f=1, pions not light)

To my knowledge, no systematic study to date.

[Hook, Marques-Tavares '16]

Ex. 2: Interactive relaxion

Alternative possibility:

Instead of

$$\frac{\phi}{f} G\tilde{G}$$

+ inflation

$\Rightarrow$

Use coupling to EWK gauge bosons:

$$\frac{\phi}{f}(g^2 W\tilde{W} - g'^2 B\tilde{B}) + \Lambda^4 \cos\frac{\phi}{f'}$$

Exponential production of EWK gauge bosons around h~v slows evolution

Important subtlety: can't couple to pairs of photons!

For dissipation to become efficient at h~v, can only couple to bosons acquiring mass from EWSB.

(Not a tuning, can be made natural with symmetries, e.g., $SU(2)_L$ x $SU(2)_R$)

We've done away with Dark QCD, so no interesting signals?

[NC, Kasko, Hook, *in progress*]

Interactive relaxion

Couples to all pairs of EWK bosons save photons:

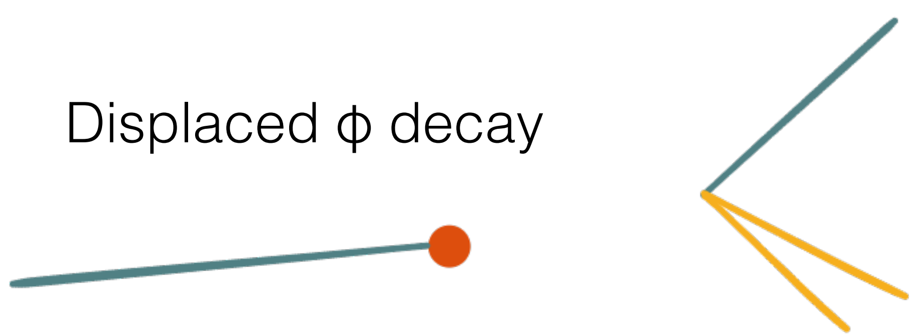
$$\frac{\phi}{f}\left(c_1 A_{\mu\nu}\tilde{Z}^{\mu\nu} + c_2 Z_{\mu\nu}\tilde{Z}^{\mu\nu} + c_3 W^{+}_{\mu\nu}\tilde{W}^{-\mu\nu}\right)$$

For $m_\phi < m_Z$, new mode for exotic Z decay: $Z \to \gamma\phi$

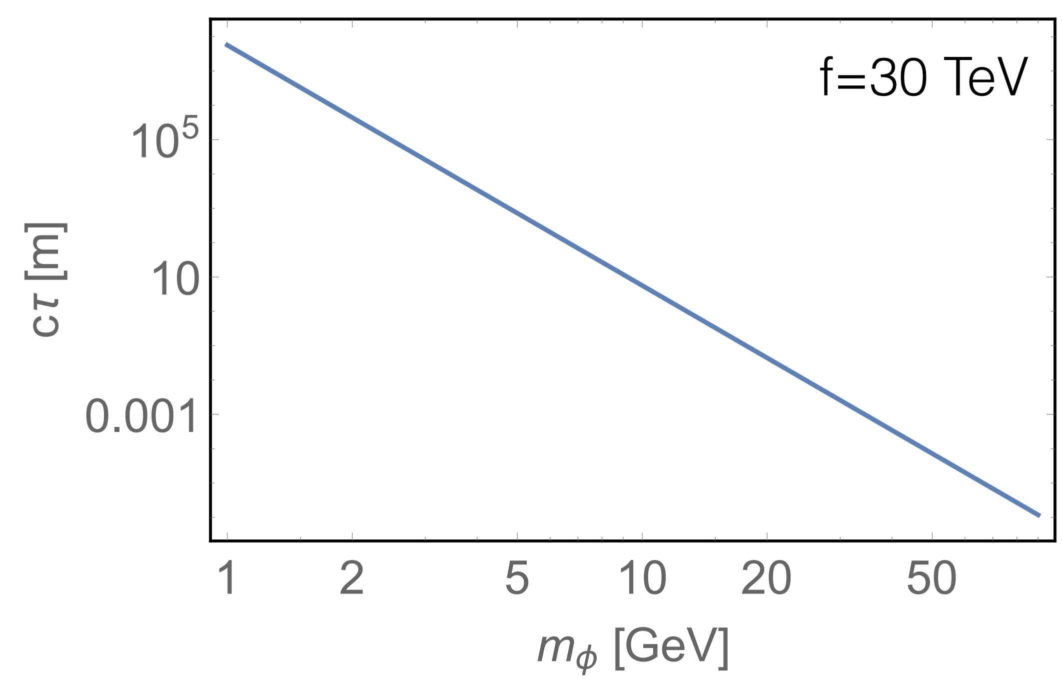
LEP bounds on exotic Z decays ⇒ f≳10 TeV ⇒ ϕ long-lived

LHC will produce more than 10^4 times the number of Z's!

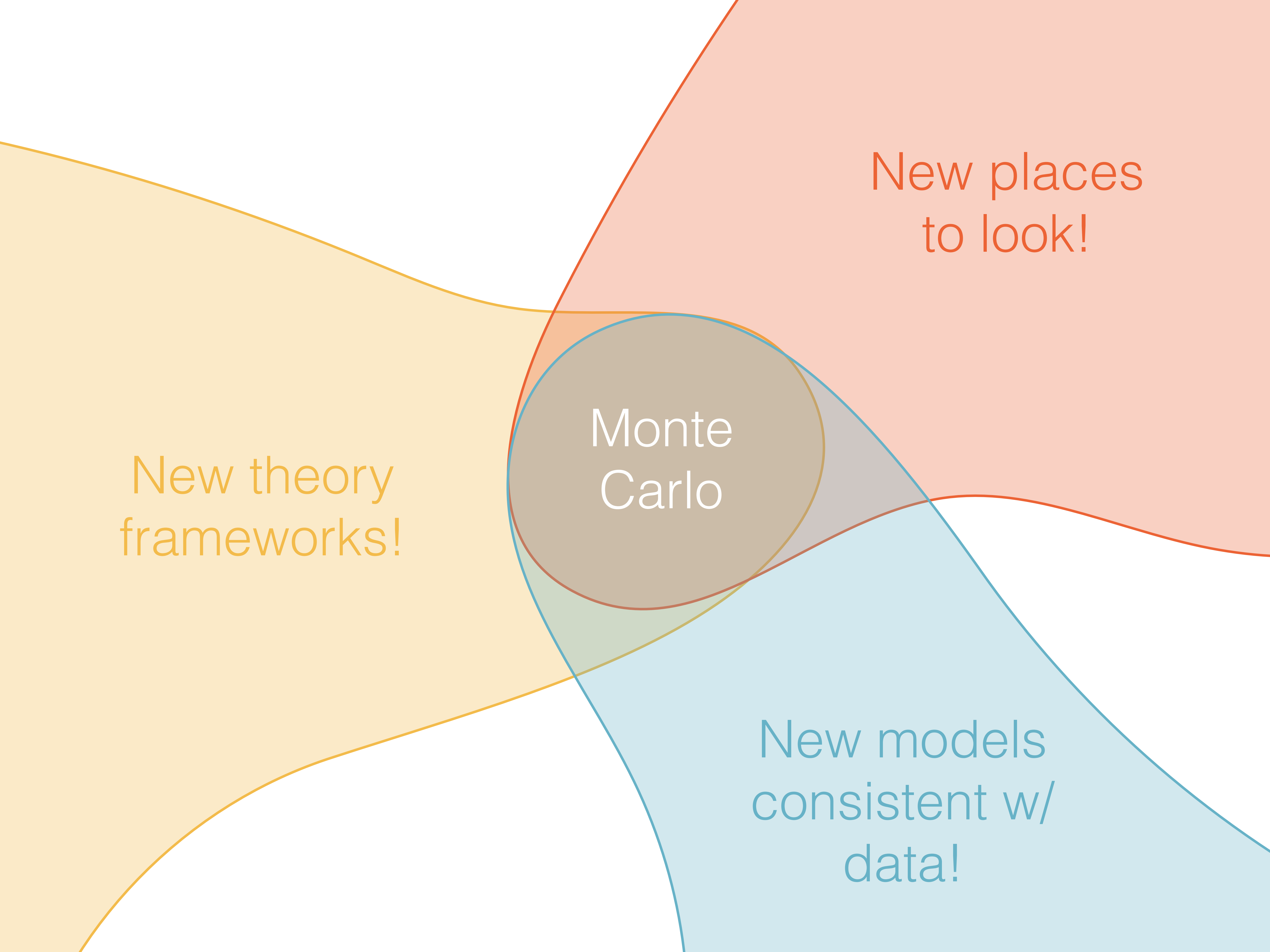
Displaced ϕ decay



$$Z \to \gamma + \phi \to \gamma + (\gamma + f\bar{f})$$



Novel displaced decay, not currently searched for meaningfully.


New places to look!
New theory frameworks!
Monte Carlo
New models consistent w/ data!

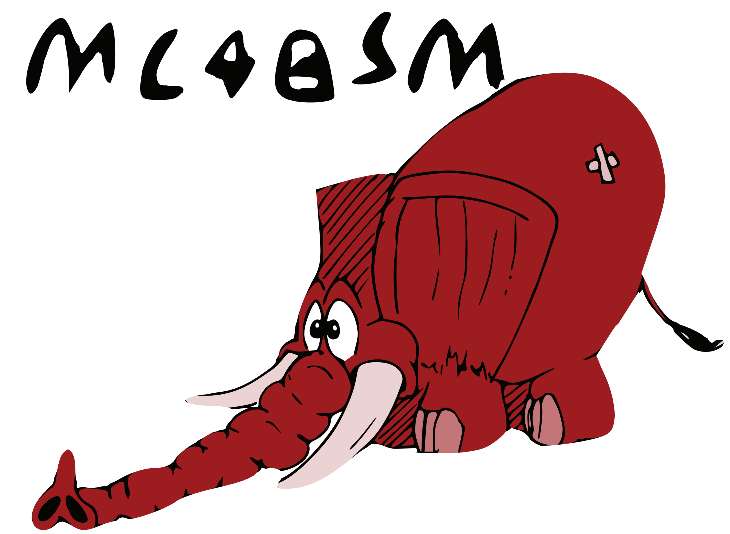
The common thread:
Hidden Valleys

[Strassler, Zurek '06]

Challenges for MC

Signal generation

- Many new directions feature versions of dark QCD, but signals vary widely (displaced jets, emerging jets, soft bombs,…).
- Need a handle on multiplicities & distributions even if ultimate goal is simplified models.
- Currently: some functionality in Pythia (thanks!), but (as far as I am aware) no glueballs, no massless quarks, etc.



Detector simulation

- Simulating detector response to LLPs obviously a challenging task and needs vast experimental input. But…
- …it's the future of BSM searches.

Conclusions

- In the midst of a paradigm shift for BSM physics.
- Null results in conventional channels are pushing us into new territory for theory & experiment.
- Many new directions have exotic signals involving displacement and/or hidden sector confinement. Numerous examples, more surely to come.
- Further progress hinges on new simulation tools.

Great time to be doing MC4BSM!