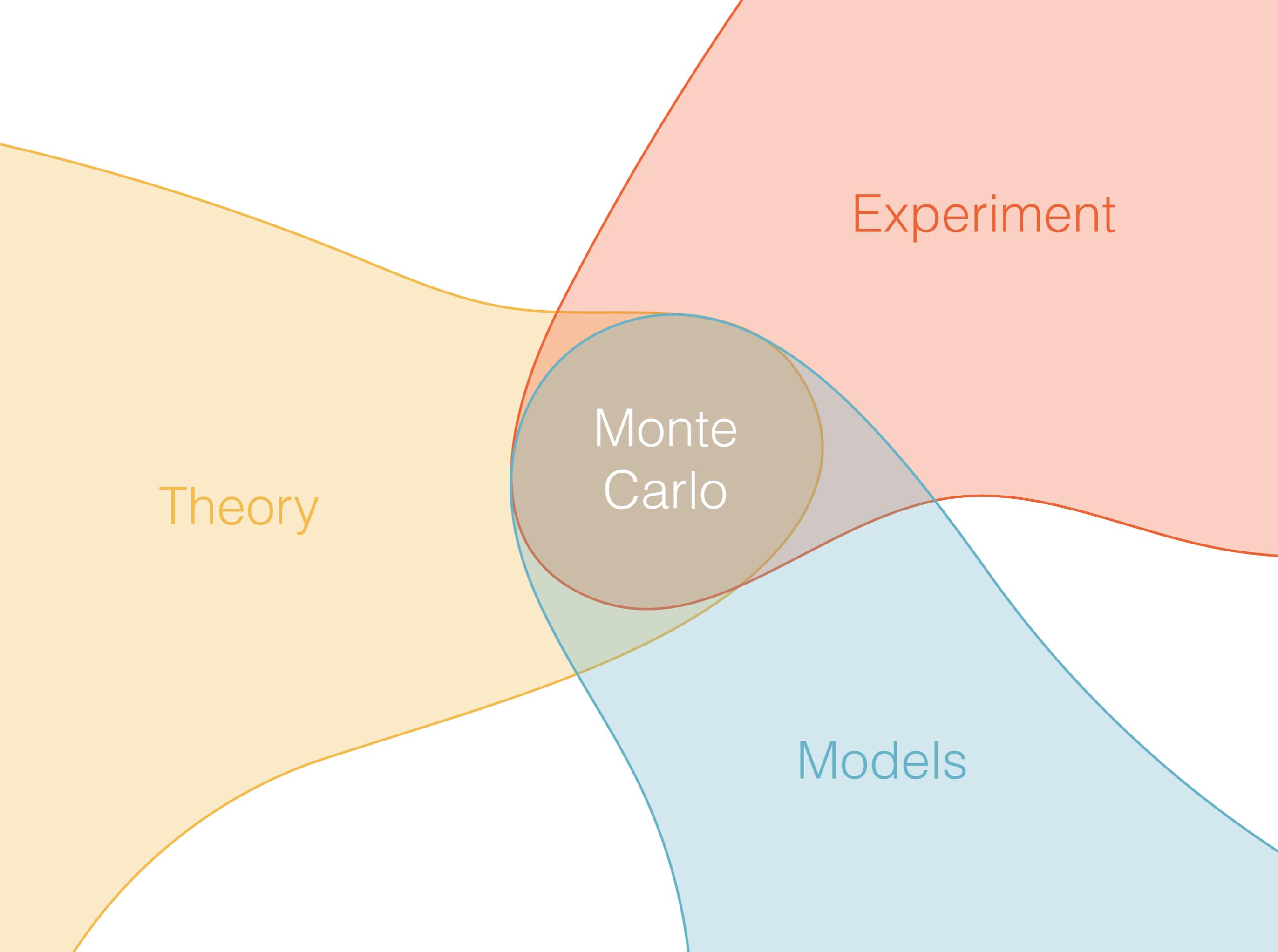


# BSM Overview

MCSM



**Nathaniel Craig**  
University of California,  
Santa Barbara



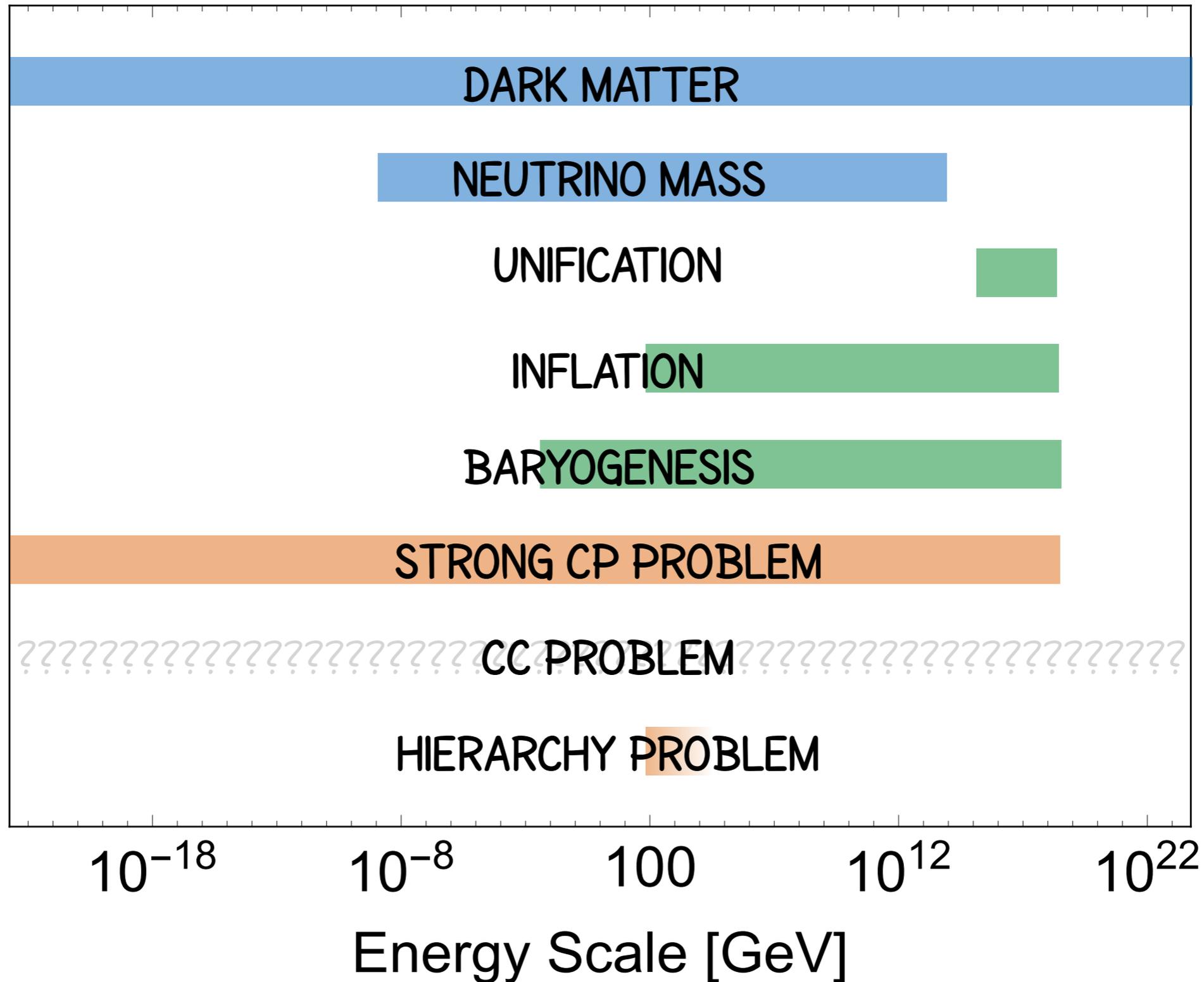
Theory

Experiment

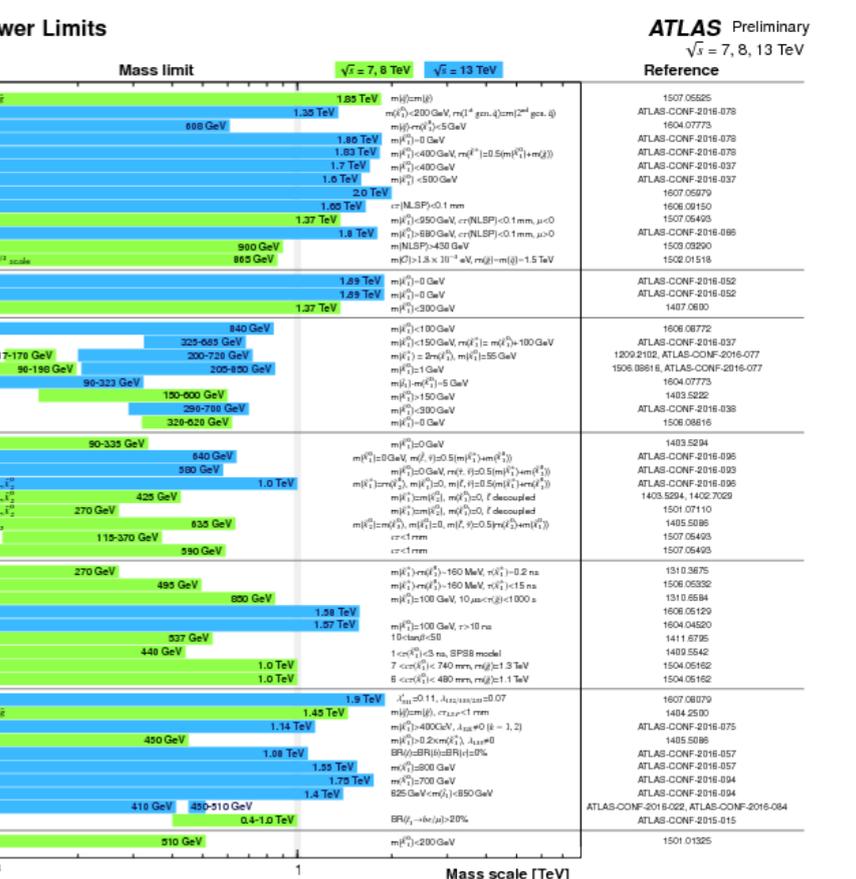
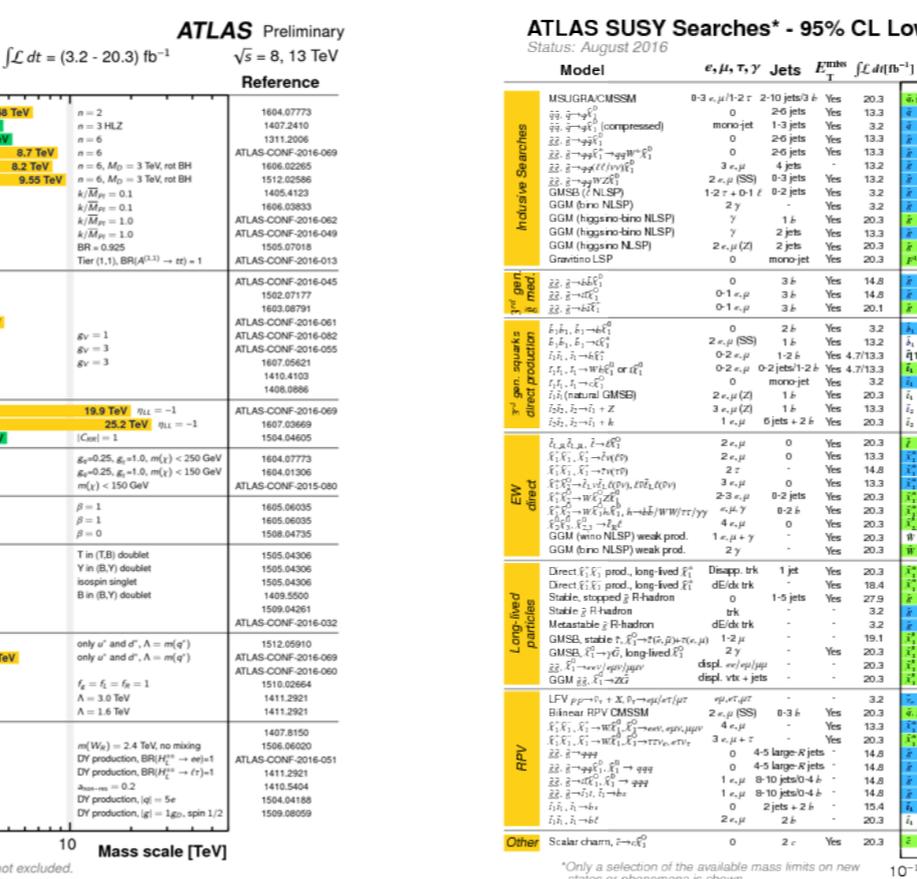
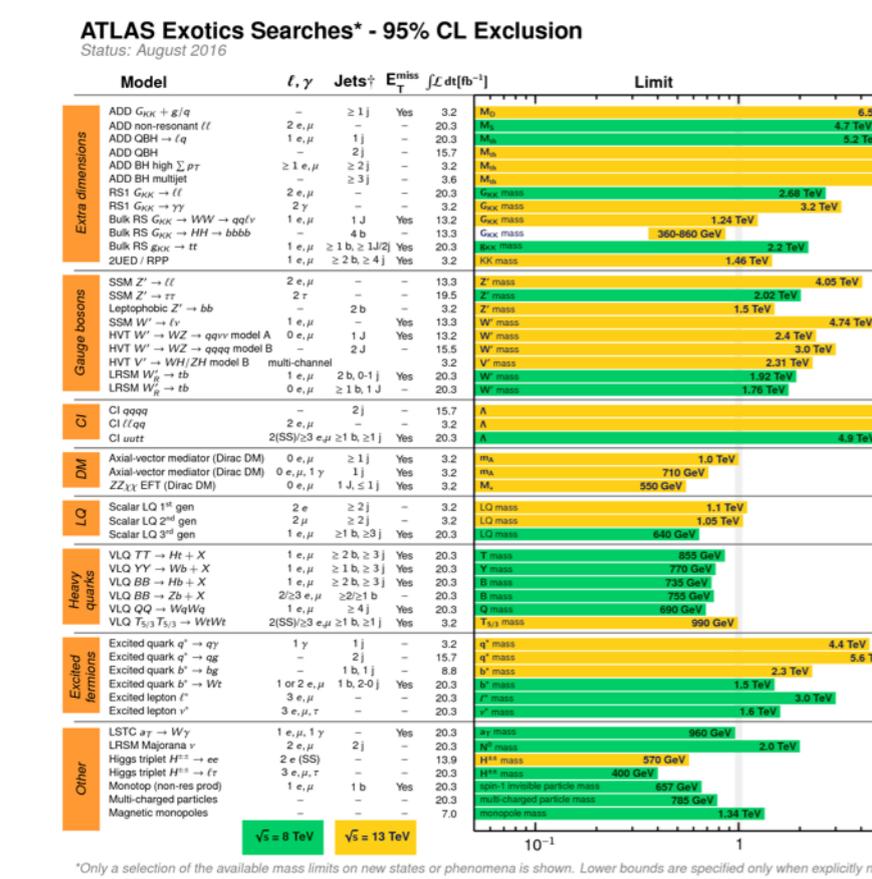
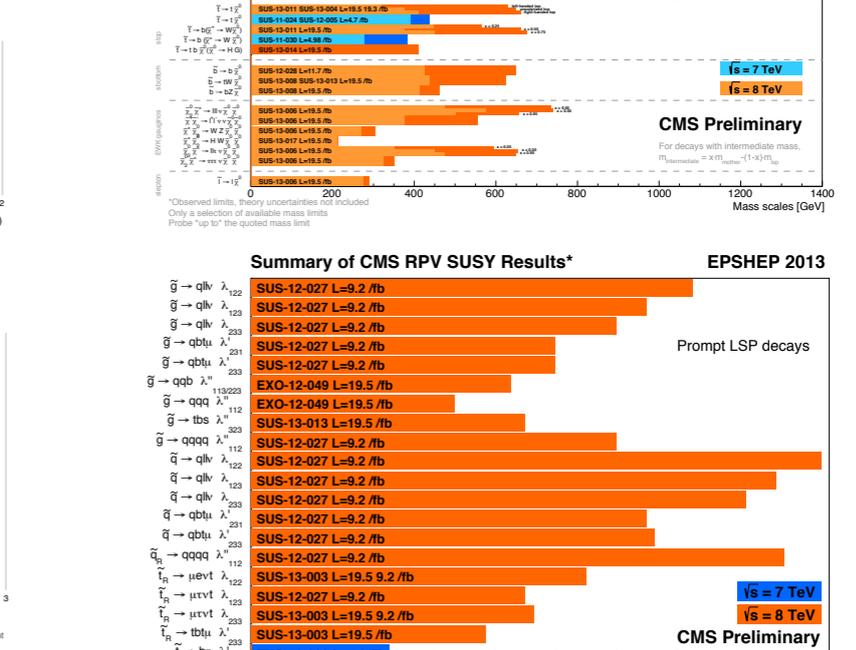
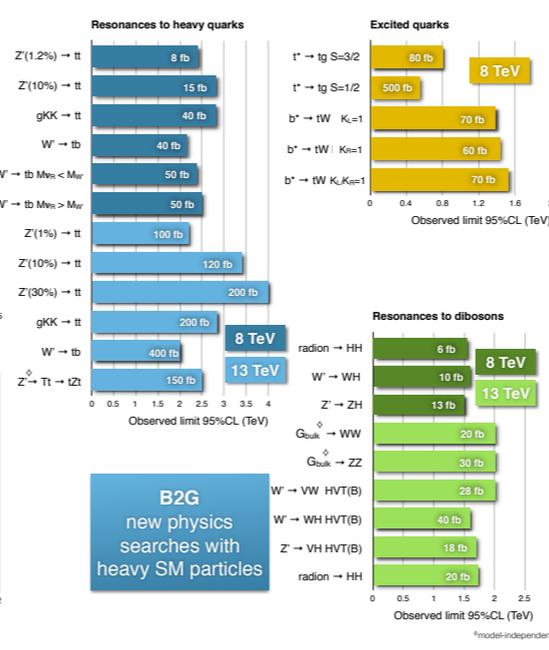
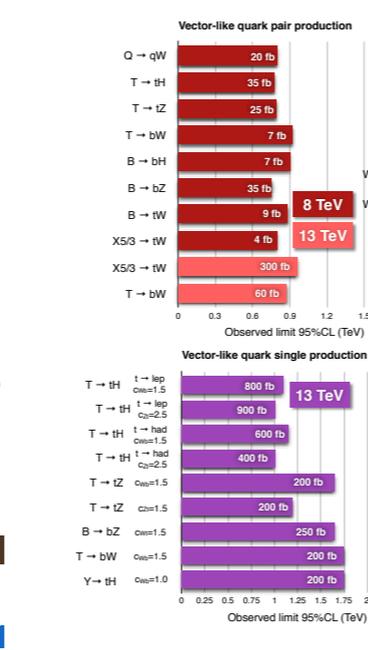
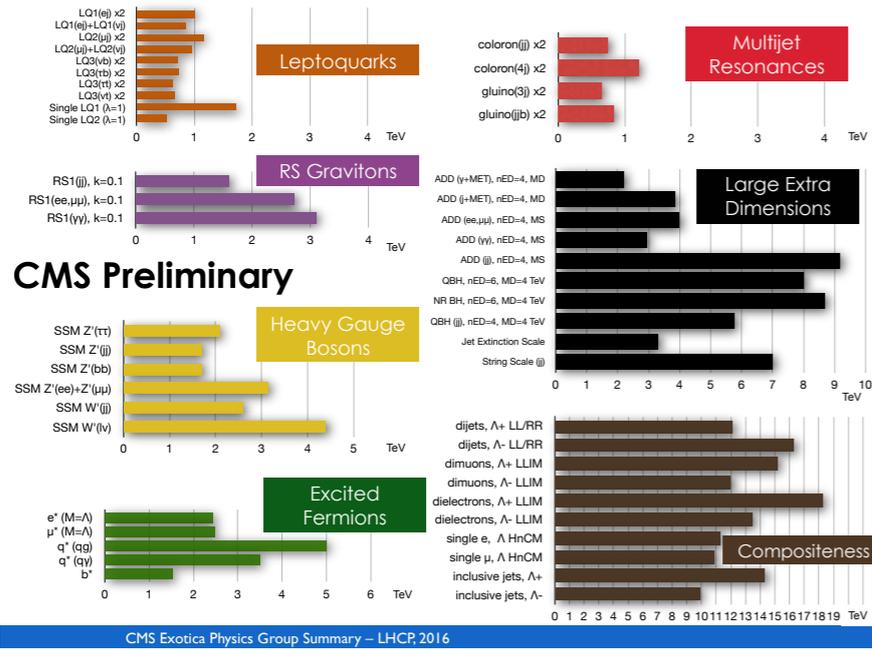
Monte Carlo

Models

# Lots of “Beyond the Standard Model”

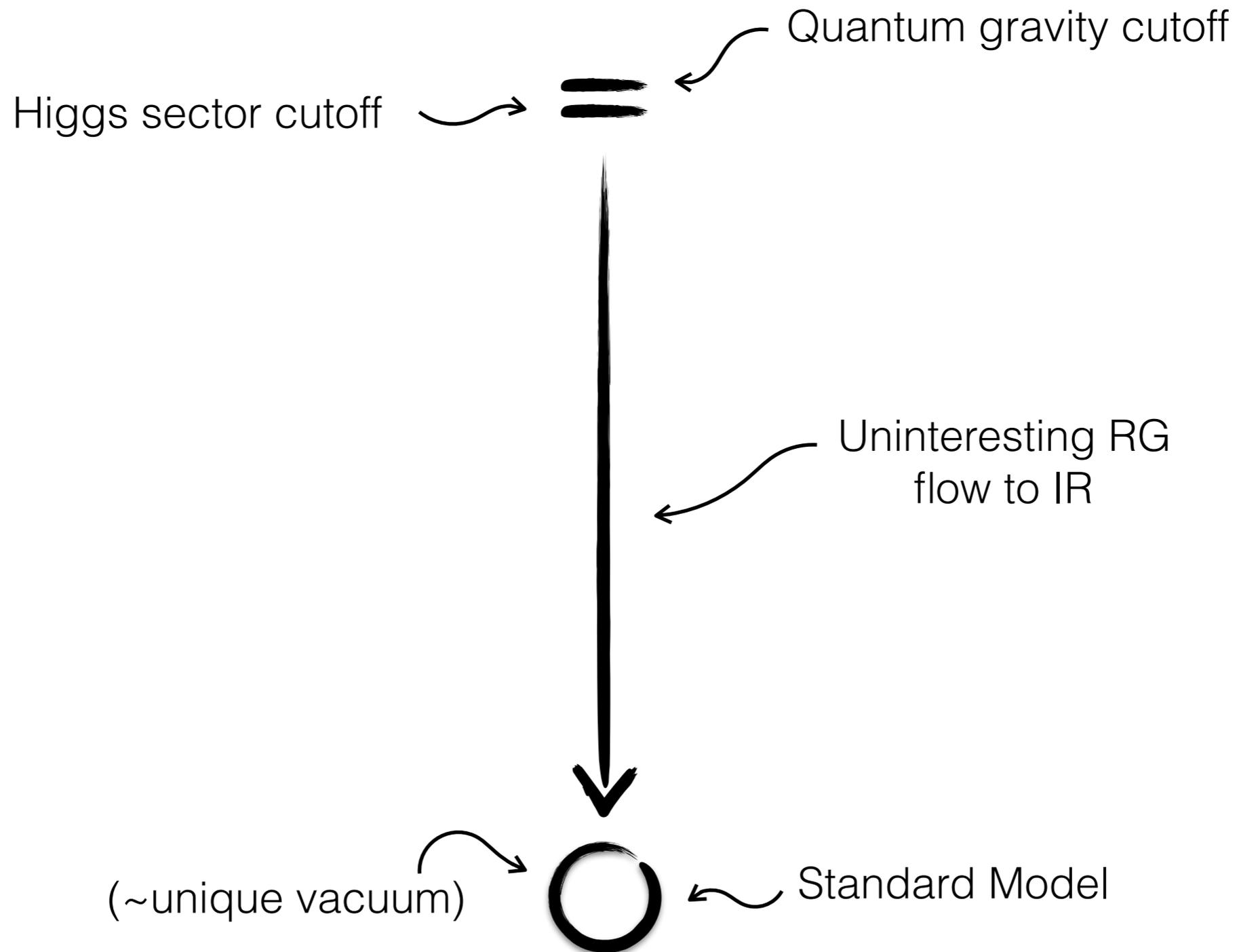


# Hierarchy problem the biggest driver @ colliders



But theory motivation aside, a tremendous signal generator.

# The Hierarchy Problem



$m_H$  is not technically natural

$\Rightarrow$  hierarchy problem

# The usual approach\*

\*given an elementary Higgs

=



Extend SM with  
a symmetry



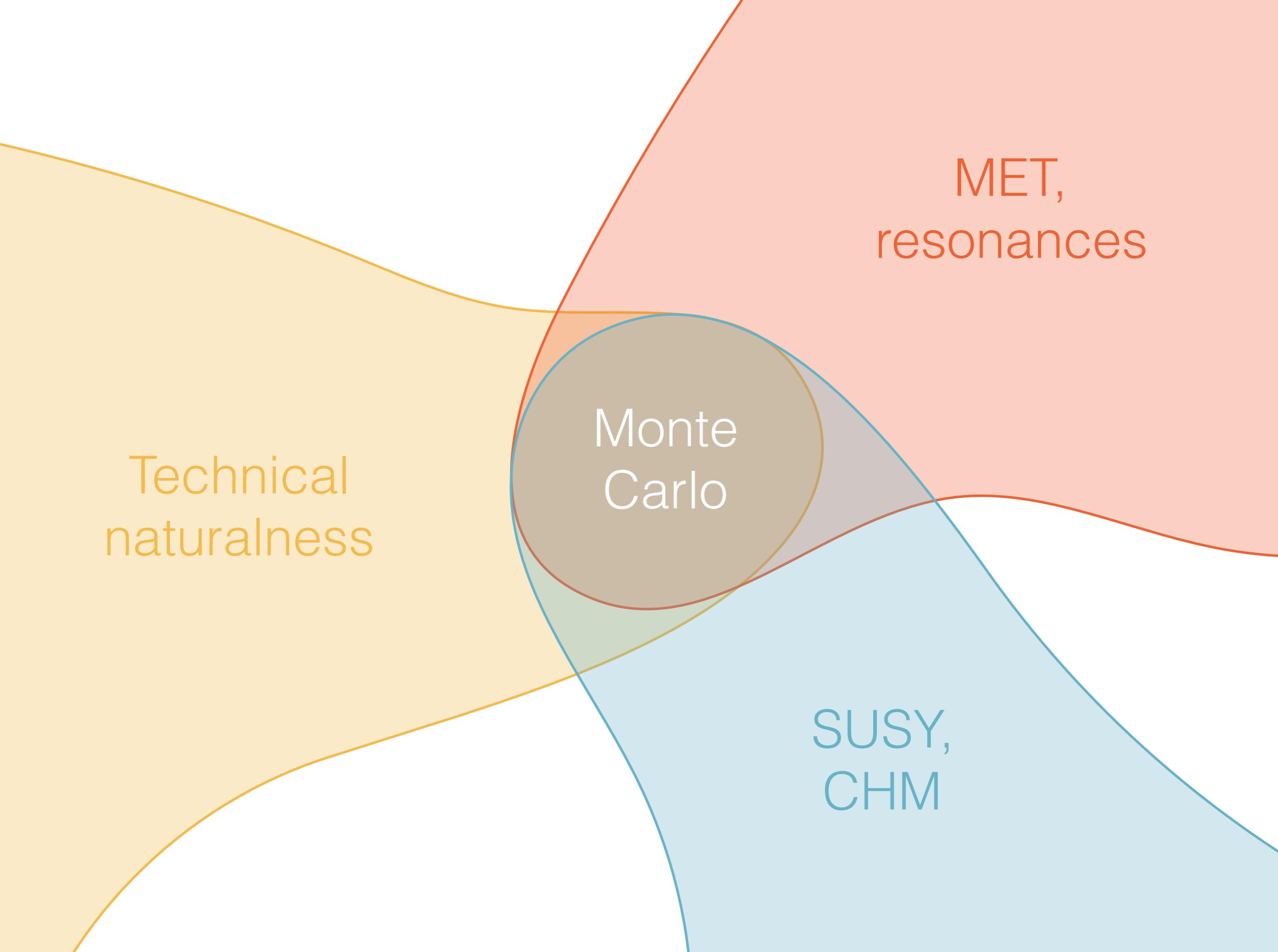
$m_H$  is technically natural

Technical  
naturalness

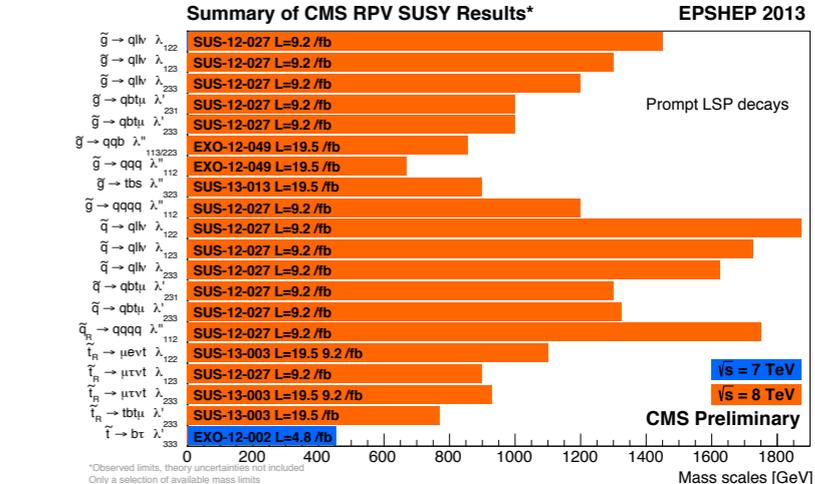
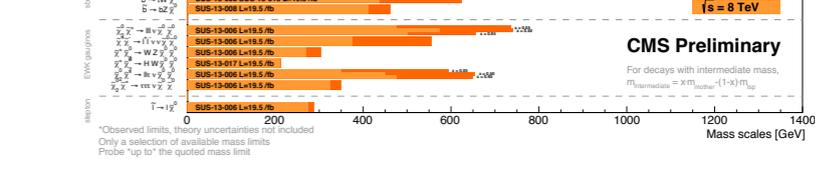
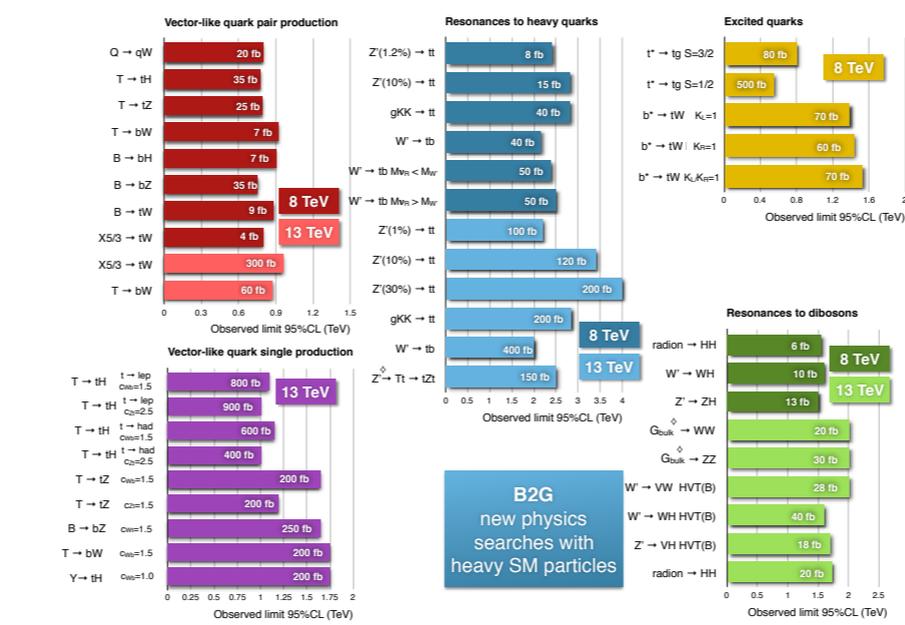
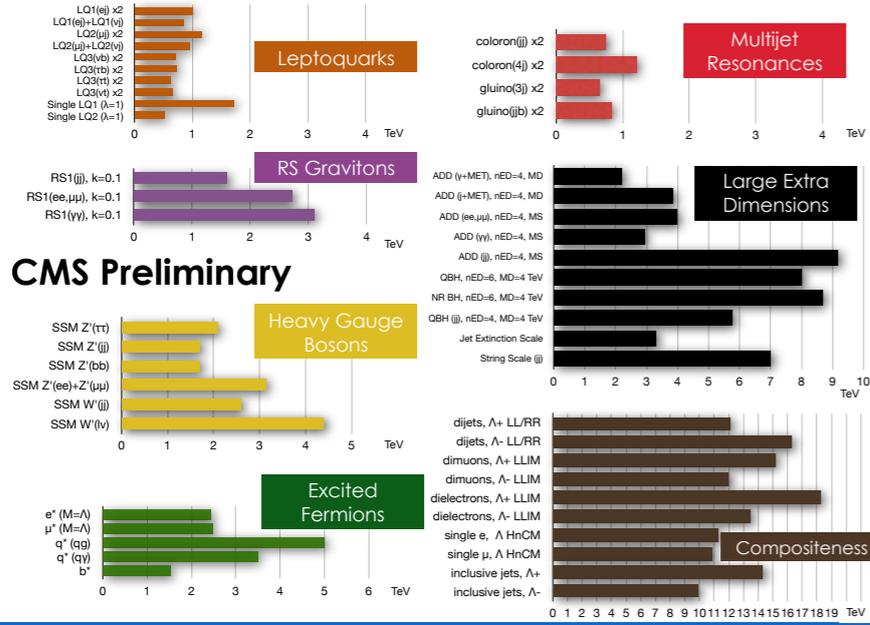
Monte  
Carlo

MET,  
resonances

SUSY,  
CHM



# Tremendously effective! Nothing so far.



## ATLAS Exotics Searches\* - 95% CL Exclusion

Status: August 2016

Model	$\ell, \gamma$	Jets <sup>†</sup>	$E_{T}^{miss}$	$\int \mathcal{L} dt [fb^{-1}]$	Limit	Reference	
Extra dimensions	ADD $G_{KK} + g/q$	$\geq 1j$	Yes	3.2	$M_{KK}$	1604.07773	
	ADD non-resonant $\ell\ell$	$2e, \mu$	-	20.3	$M_{KK}$	1407.2410	
	ADD QBH $\rightarrow \ell q$	$1e, \mu$	$1j$	-	$M_{KK}$	1311.2006	
	ADD QBH	$2j$	-	15.7	$M_{KK}$	1604.07773	
	ADD BH high $\Sigma p_T$	$\geq 1e, \mu$	$\geq 2j$	-	$M_{KK}$	1604.07773	
	ADD BH multijet	$2e, \mu$	$\geq 3j$	-	$M_{KK}$	1604.07773	
	RS1 $G_{KK} \rightarrow \ell\ell$	$2e, \mu$	-	20.3	$k/M_{KK}$	1405.4123	
	RS1 $G_{KK} \rightarrow \ell\gamma$	$2e, \mu$	-	3.2	$k/M_{KK}$	1606.03933	
	Bulk RS $G_{KK} \rightarrow WW \rightarrow qq/\nu$	$1e, \mu$	$1j$	Yes	13.2	$k/M_{KK}$	1606.03933
	Bulk RS $G_{KK} \rightarrow HH \rightarrow bbbb$	$1e, \mu$	$\geq 1b, \geq 1j/2j$	Yes	20.3	$k/M_{KK}$	1606.03933
Bulk RS $G_{KK} \rightarrow t\bar{t}$	$1e, \mu$	$\geq 2b, \geq 4j$	Yes	3.2	$k/M_{KK}$	1606.03933	
Gauge bosons	SSM $Z' \rightarrow \ell\ell$	$2e, \mu$	-	13.2	$Z'$ mass	1606.03933	
	SSM $Z' \rightarrow \tau\tau$	$2\tau$	-	19.5	$Z'$ mass	1606.03933	
	Leptophobic $Z' \rightarrow bb$	$2b$	-	3.2	$Z'$ mass	1606.03933	
	SSM $W' \rightarrow \ell\nu$	$1e, \mu$	$1j$	Yes	13.2	$W'$ mass	1606.03933
	HVT $W' \rightarrow WZ \rightarrow qq\nu$ model A	$0e, \mu$	$1j$	Yes	13.2	$W'$ mass	1606.03933
	HVT $W' \rightarrow WZ \rightarrow qq\nu$ model B	$0e, \mu$	$2j$	Yes	15.5	$W'$ mass	1606.03933
	HVT $V' \rightarrow WH/ZH$ model B	multi-channel	-	3.2	$V'$ mass	1606.03933	
	LRSM $W'_\mu \rightarrow t\bar{b}$	$1e, \mu$	$2b, 0-1j$	Yes	20.3	$W'$ mass	1606.03933
	LRSM $W'_\mu \rightarrow t\bar{b}$	$0e, \mu$	$\geq 1b, 1j$	-	20.3	$W'$ mass	1606.03933
	CI	CI $qqqq$	$2j$	-	15.7	$A$	1606.03933
CI $\ell\ell qq$		$2e, \mu$	-	3.2	$A$	1606.03933	
CI $uutt$		$2(SS)/23e, \mu \geq 1b, \geq 1j$	Yes	20.3	$A$	1504.04605	
DM	Axial-vector mediator (Dirac DM)	$0e, \mu$	$\geq 1j$	Yes	3.2	$m_A$	1604.07773
	Axial-vector mediator (Dirac DM)	$0e, \mu, 1\gamma$	$1j$	Yes	3.2	$m_A$	1604.07773
	$ZZ\gamma$ EFT (Dirac DM)	$0e, \mu$	$1j, \leq 1j$	Yes	3.2	$M$	1604.07773
LO	Scalar LQ 1 <sup>st</sup> gen	$2e, \mu$	$\geq 2j$	-	3.2	$LQ$ mass	1606.03933
	Scalar LQ 2 <sup>nd</sup> gen	$2e, \mu$	$\geq 2j$	-	3.2	$LQ$ mass	1606.03933
	Scalar LQ 3 <sup>rd</sup> gen	$1e, \mu$	$\geq 1b, \geq 3j$	Yes	20.3	$LQ$ mass	1606.03933
Heavy quarks	VLO $TT \rightarrow Ht + X$	$1e, \mu$	$\geq 2b, \geq 3j$	Yes	20.3	$T$ mass	1505.04306
	VLO $YY \rightarrow Wb + X$	$1e, \mu$	$\geq 1b, \geq 3j$	Yes	20.3	$Y$ mass	1505.04306
	VLO $BB \rightarrow Hb + X$	$1e, \mu$	$\geq 2b, \geq 3j$	Yes	20.3	$B$ mass	1505.04306
	VLO $BB \rightarrow Zb + X$	$2/3e, \mu$	$\geq 2/3b$	-	20.3	$B$ mass	1409.5500
	VLO $QQ \rightarrow WqWq$	$1e, \mu$	$\geq 4j$	Yes	20.3	$Q$ mass	1509.04061
	VLO $T_{3/3} T_{3/3} \rightarrow WW$	$2(SS)/23e, \mu \geq 1b, \geq 1j$	Yes	3.2	$T_{3/3}$ mass	1606.03933	
Excited fermions	Excited quark $q^* \rightarrow q\gamma$	$1\gamma$	$1j$	-	3.2	$q^*$ mass	1606.03933
	Excited quark $q^* \rightarrow qg$	$1g$	$1j$	-	15.7	$q^*$ mass	1606.03933
	Excited quark $b^* \rightarrow b\gamma$	$1\gamma$	$1j$	-	8.8	$b^*$ mass	1606.03933
	Excited quark $b^* \rightarrow Wt$	$1e, \mu$	$1b, 2-0j$	Yes	20.3	$b^*$ mass	1606.03933
	Excited lepton $\ell^*$	$3e, \mu, \tau$	-	-	20.3	$\ell^*$ mass	1411.2921
	Excited lepton $\ell^*$	$3e, \mu, \tau$	-	-	20.3	$\ell^*$ mass	1411.2921
Other	LSTC $\Delta\gamma \rightarrow W\gamma$	$1e, \mu, 1\gamma$	-	Yes	20.3	$\Delta\gamma$ mass	1407.8150
	LRSM Majorana $\nu$	$2e, \mu$	$2j$	-	20.3	$\tilde{\chi}^0$ mass	1506.06020
	Higgs triplet $H^{\pm\pm} \rightarrow ee$	$2e$ (SS)	-	-	13.9	$H^{\pm\pm}$ mass	1411.2921
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\tau$	$3e, \mu, \tau$	-	-	20.3	$H^{\pm\pm}$ mass	1411.2921
	Monopole (non-res prod)	$1e, \mu$	$1b$	Yes	20.3	$A_{mon}$ mass	1410.5404
	Multi-charged particles	-	-	-	20.3	DY production, $ q  = 5e$	1504.04188
Magnetic monopoles	-	-	-	7.0	DY production, $ q  = 1/2e, \text{spin } 1/2$	1508.08059	

\*Only a selection of the available mass limits on new states or phenomena is shown. Lower bounds are specified only when explicitly not excluded. <sup>†</sup>Small-radius (large-radius) jets are denoted by the letter j (J).

## ATLAS SUSY Searches\* - 95% CL Lower Limits

Status: August 2016

Model	$e, \mu, \tau, \gamma$	Jets	$E_{T}^{miss}$	$\int \mathcal{L} dt [fb^{-1}]$	Mass limit	Reference
Inclusive Searches	MSJGRACMSM	$0-3e, \mu, 1-2\tau$	$2-10$ jets/0-3	Yes	20.3	1507.05525
	$\tilde{g} \rightarrow q\bar{q}$	0	$2-6$ jets	Yes	13.2	1604.07773
	$\tilde{g} \rightarrow q\bar{q}$ (compressed)	0	$1-3$ jets	Yes	3.2	1311.2006
	$\tilde{g} \rightarrow q\bar{q}$	0	$2-6$ jets	Yes	13.2	1604.07773
	$\tilde{g} \rightarrow q\bar{q}$	0	$2-6$ jets	Yes	13.2	1604.07773
	$\tilde{g} \rightarrow q\bar{q}$	$3e, \mu$	$4$ jets	-	13.2	1604.07773
	$\tilde{g} \rightarrow q\bar{q}$	$2e, \mu$ (SS)	$0-3$ jets	Yes	13.2	1604.07773
	GMSJ NLSFP	$1-2e, \mu, 0-1\tau$	$0-2$ jets/1-2	Yes	3.2	1606.03933
	GGM (bino NLSFP)	$2\gamma$	$0$	Yes	3.2	1606.03933
	GGM (higgsino-bino NLSFP)	$1e, \mu$	$1j$	Yes	20.3	1606.03933
GGM (higgsino-bino NLSFP)	$2e, \mu$	$2$ jets	Yes	13.2	1606.03933	
GGM (higgsino NLSFP)	$2e, \mu$ (Z)	$2$ jets	Yes	20.3	1606.03933	
Gravitino LSP	0	monojet	Yes	20.3	1606.03933	
1 <sup>st</sup> gen squarks direct production	$\tilde{q}\tilde{q} \rightarrow q\bar{q}$	0	$3$ jets	Yes	14.8	1606.03933
	$\tilde{q}\tilde{q} \rightarrow q\bar{q}$	$0-1e, \mu$	$3$ jets	Yes	14.8	1606.03933
	$\tilde{q}\tilde{q} \rightarrow q\bar{q}$	$0-1e, \mu$	$3$ jets	Yes	20.1	1606.03933
	$\tilde{q}\tilde{q} \rightarrow q\bar{q}$	0	$2$ jets	Yes	3.2	1606.03933
	$\tilde{q}\tilde{q} \rightarrow q\bar{q}$	$2e, \mu$ (SS)	$1$ jet	Yes	13.2	1606.03933
	$\tilde{q}\tilde{q} \rightarrow q\bar{q}$	$0-2e, \mu$	$1-2$ jets	Yes	4.7/13.3	1606.03933
	$\tilde{q}\tilde{q} \rightarrow q\bar{q}$	$0-2e, \mu$	$0-2$ jets/1-2	Yes	4.7/13.3	1606.03933
	$\tilde{q}\tilde{q} \rightarrow q\bar{q}$	0	monojet	Yes	3.2	1606.03933
	$\tilde{q}\tilde{q} \rightarrow q\bar{q}$ (natural GMSJ)	$2e, \mu$ (Z)	$1$ jet	Yes	20.3	1606.03933
	$\tilde{q}\tilde{q} \rightarrow q\bar{q}$	$3e, \mu$ (Z)	$1$ jet	Yes	13.2	1606.03933
EW correct	$\tilde{g}\tilde{g} \rightarrow q\bar{q}$	$2e, \mu$	0	Yes	20.3	1606.03933
	$\tilde{g}\tilde{g} \rightarrow q\bar{q}$	$2e, \mu$	0	Yes	13.2	1606.03933
	$\tilde{g}\tilde{g} \rightarrow q\bar{q}$	$2e, \mu$	0	Yes	14.8	1606.03933
	$\tilde{g}\tilde{g} \rightarrow q\bar{q}$	$2e, \mu$	0	Yes	13.2	1606.03933
	$\tilde{g}\tilde{g} \rightarrow q\bar{q}$	$2e, \mu$	0	Yes	13.2	1606.03933
	$\tilde{g}\tilde{g} \rightarrow q\bar{q}$	$2e, \mu$	0	Yes	13.2	1606.03933
	$\tilde{g}\tilde{g} \rightarrow q\bar{q}$	$2e, \mu$	0	Yes	13.2	1606.03933
	$\tilde{g}\tilde{g} \rightarrow q\bar{q}$	$2e, \mu$	0	Yes	13.2	1606.03933
	$\tilde{g}\tilde{g} \rightarrow q\bar{q}$	$2e, \mu$	0	Yes	20.3	1606.03933
	$\tilde{g}\tilde{g} \rightarrow q\bar{q}$	$2e, \mu$	0	Yes	20.3	1606.03933
Long-lived particles	Direct $\tilde{g}\tilde{g}$ prod, long-lived $\tilde{g}$	Disapp. trk	$1$ jet	Yes	20.3	1606.03933
	Direct $\tilde{g}\tilde{g}$ prod, long-lived $\tilde{g}$	dE/dx trk	-	Yes	18.4	1606.03933
	Stable, stopped $\tilde{g}$ R-hadron	0	$1-5$ jets	Yes	27.9	1606.03933
	Stable $\tilde{g}$ R-hadron	dE/dx	-	-	3.2	1606.03933
	Measurable $\tilde{g}$ R-hadron	$1-2\mu$	-	-	3.2	1606.03933
	GMSJ, stable $\tilde{g}$ R-hadron	$1-2\mu$	-	-	18.1	1606.03933
	GMSJ, stable $\tilde{g}$ R-hadron	$2\gamma$	-	-	20.3	1606.03933
	GMSJ, stable $\tilde{g}$ R-hadron	displ. $e\ell/\mu\mu$	-	-	20.3	1606.03933
	GMSJ, stable $\tilde{g}$ R-hadron	displ. $\nu\ell/\mu\mu$	-	-	20.3	1606.03933
	GMSJ, stable $\tilde{g}$ R-hadron	displ. $\nu\ell/\mu\mu$	-	-	20.3	1606.03933
RPV	LFV $\mu\mu \rightarrow e\gamma$	$2e, \mu$	0	-	3.2	1606.03933
	Bilinear RPV CMSSM	$2e, \mu$ (SS)	$0-3$ jets	Yes	20.3	1606.03933
	DY production, BR( $H^{\pm\pm} \rightarrow ee$ )=1	$4e, \mu$	-	Yes	13.2	1606.03933
	DY production, BR( $H^{\pm\pm} \rightarrow ee$ )=1	$3e, \mu, \tau$	-	Yes	20.3	1606.03933
	$\tilde{g}\tilde{g} \rightarrow q\bar{q}$	0	$4-5$ large- $R$ jets	-	14.8	1606.03933
	$\tilde{g}\tilde{g} \rightarrow q\bar{q}$	0	$4-5$ large- $R$ jets	-	14.8	1606.03933
	$\tilde{g}\tilde{g} \rightarrow q\bar{q}$	$1e, \mu$	$8-10$ jets/0-4- $b$	-	14.8	1606.03933
	$\tilde{g}\tilde{g} \rightarrow q\bar{q}$	$1e, \mu$	$8-10$ jets/0-4- $b$	-	14.8	1606.03933
	$\tilde{g}\tilde{g} \rightarrow q\bar{q}$	$2e, \mu$	$2$ jets + $2b$	-	15.4	1606.03933
	$\tilde{g}\tilde{g} \rightarrow q\bar{q}$	$2e, \mu$	$2$ jets + $2b$	-	20.3	1606.03933
Other	Scalar charm, $\tilde{c} \rightarrow c\bar{c}$	0	$2e$	Yes	20.3	1606.03933

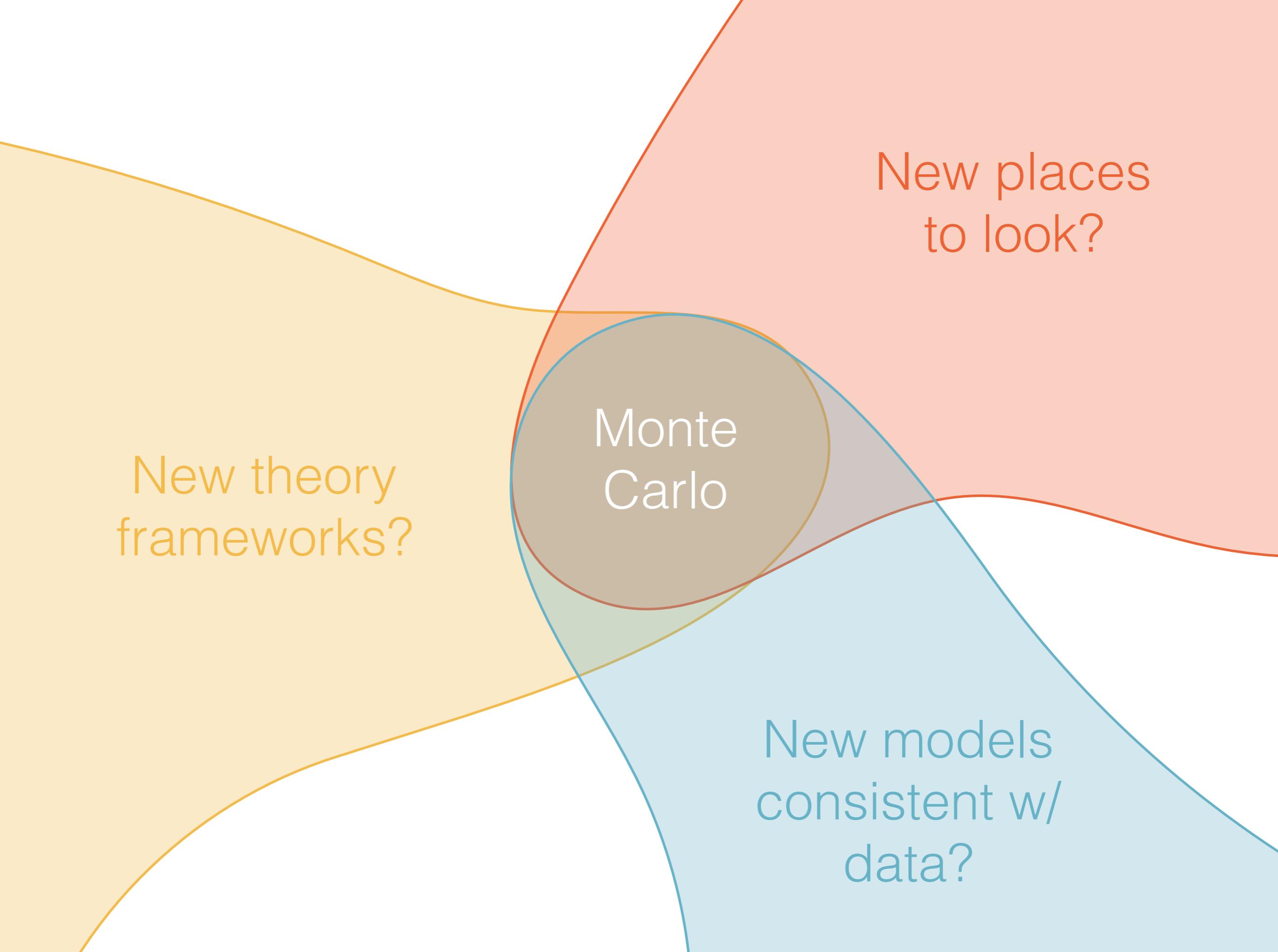
\*Only a selection of the available mass limits on new states or phenomena is shown.

New theory  
frameworks?

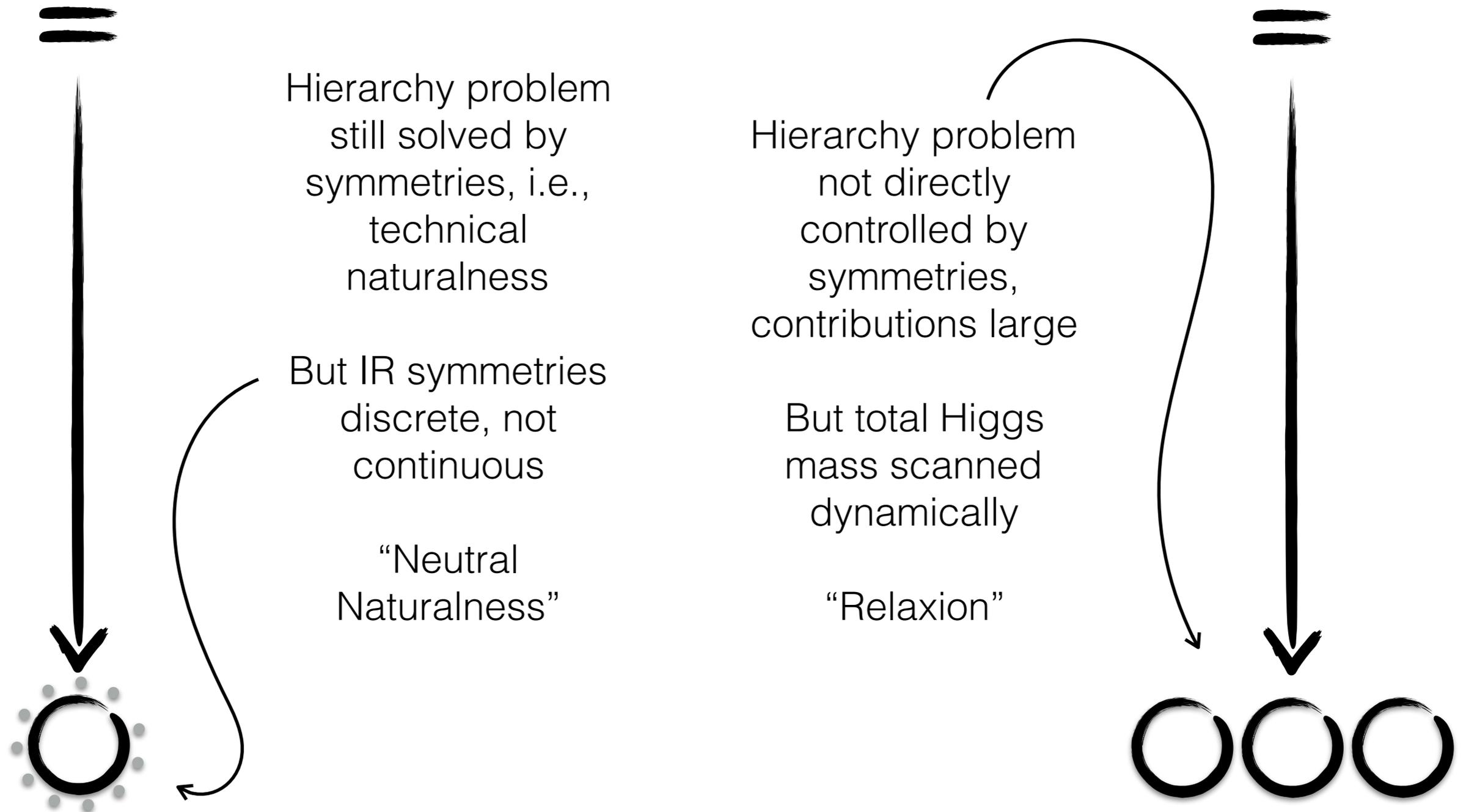
Monte  
Carlo

New places  
to look?

New models  
consistent w/  
data?



# New theory frameworks?



# Models consistent w/ data?

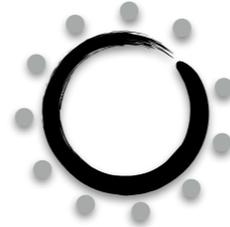
**=** Conventional symmetries

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



**=** Neutral naturalness

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

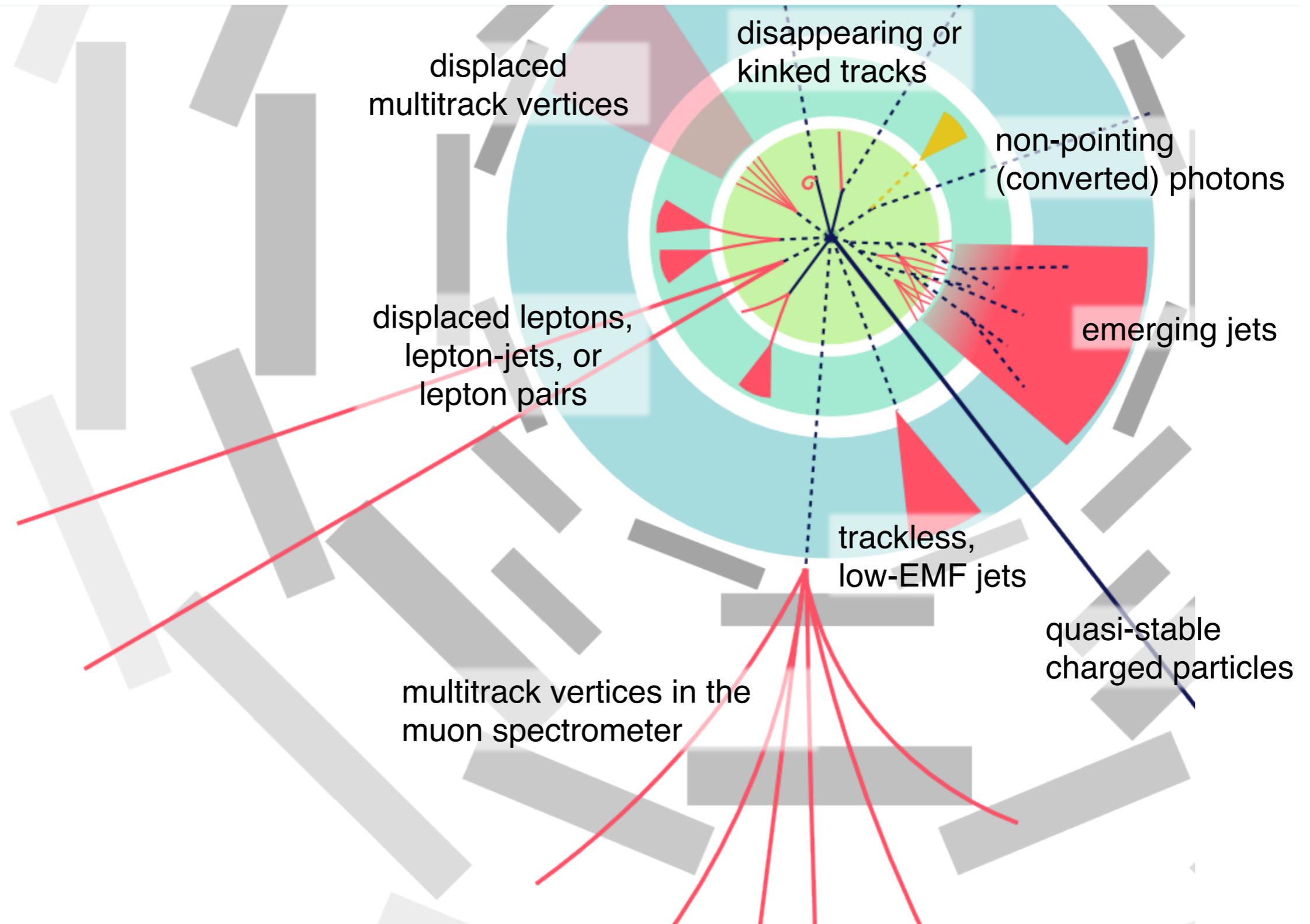


**=** Relaxion

- QCD relaxion
- QCD' relaxion
- Interactive relaxion
- .....



# New places to look?





Technical  
naturalness

Monte  
Carlo

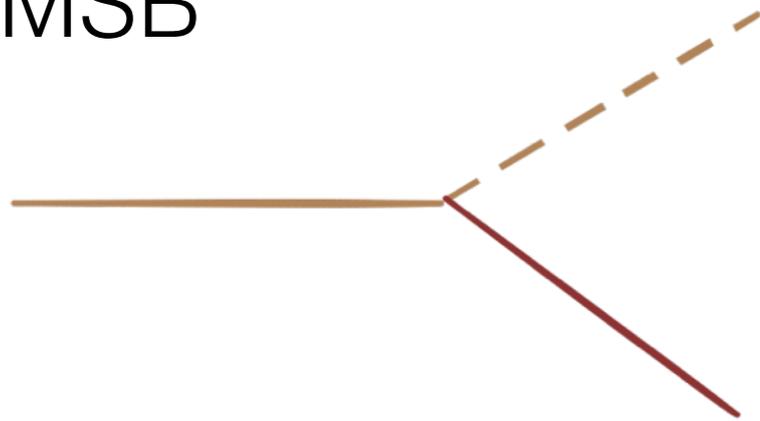
Displaced  
decays

SUSY,  
CHM

# Displaced SUSY

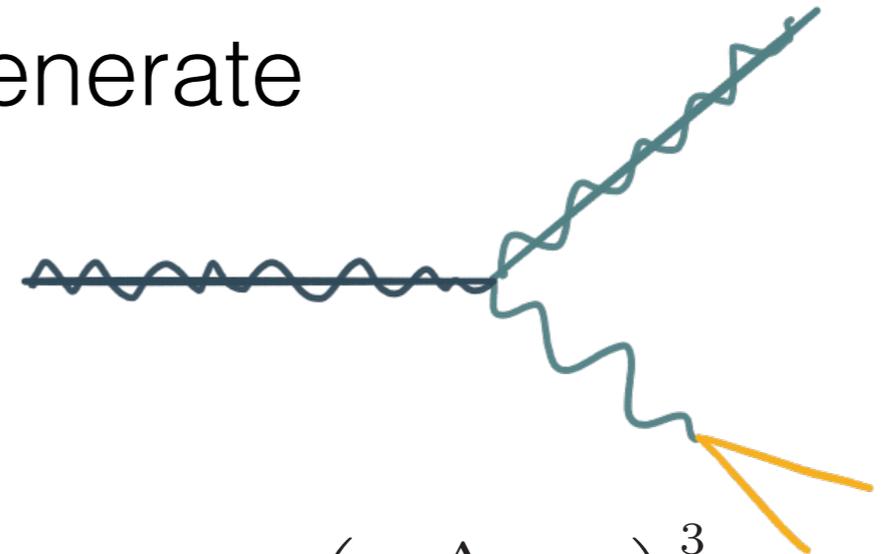
Countless avenues for SUSY decays to become non-prompt

GMSB



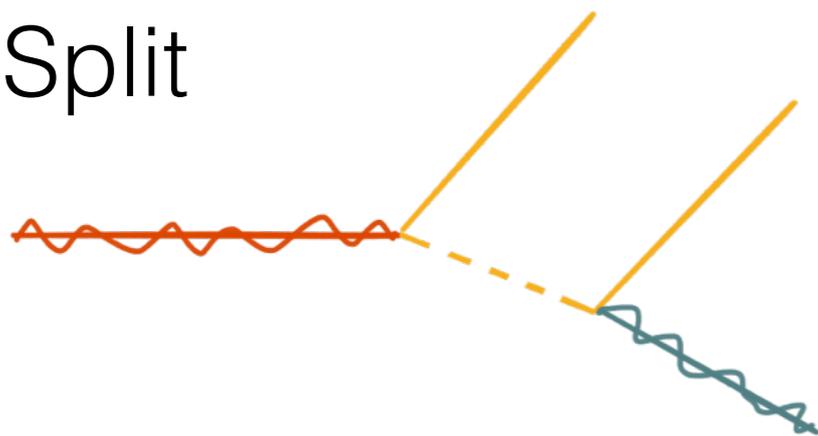
$$c\tau \approx 100 \mu\text{m} \times \left( \frac{\sqrt{F}}{100 \text{ TeV}} \right)^4 \times \left( \frac{100 \text{ GeV}}{m_{\tilde{h}}} \right)^5$$

Degenerate



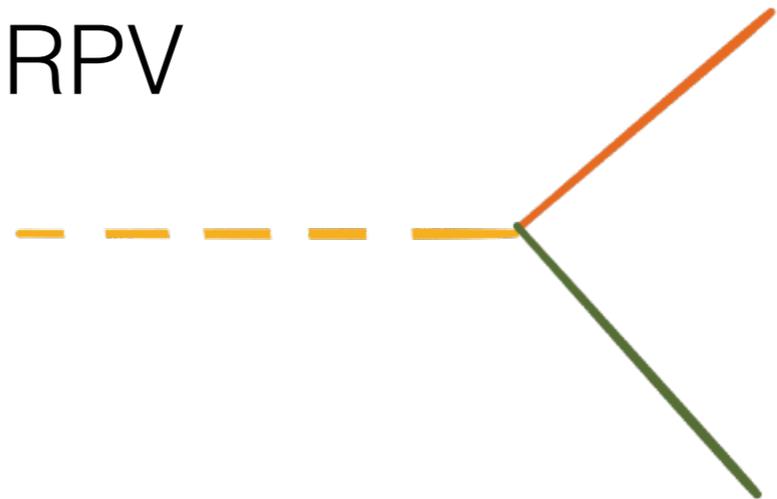
$$c\tau \approx 1 \text{ cm} \times \left( \frac{\Delta m}{340 \text{ MeV}} \right)^3$$

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

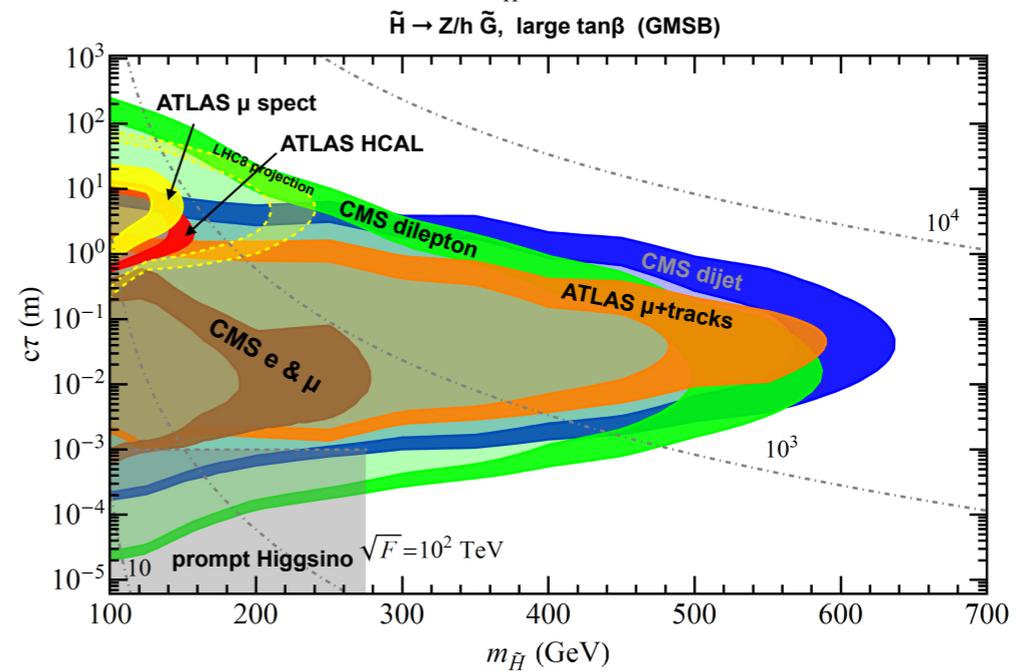
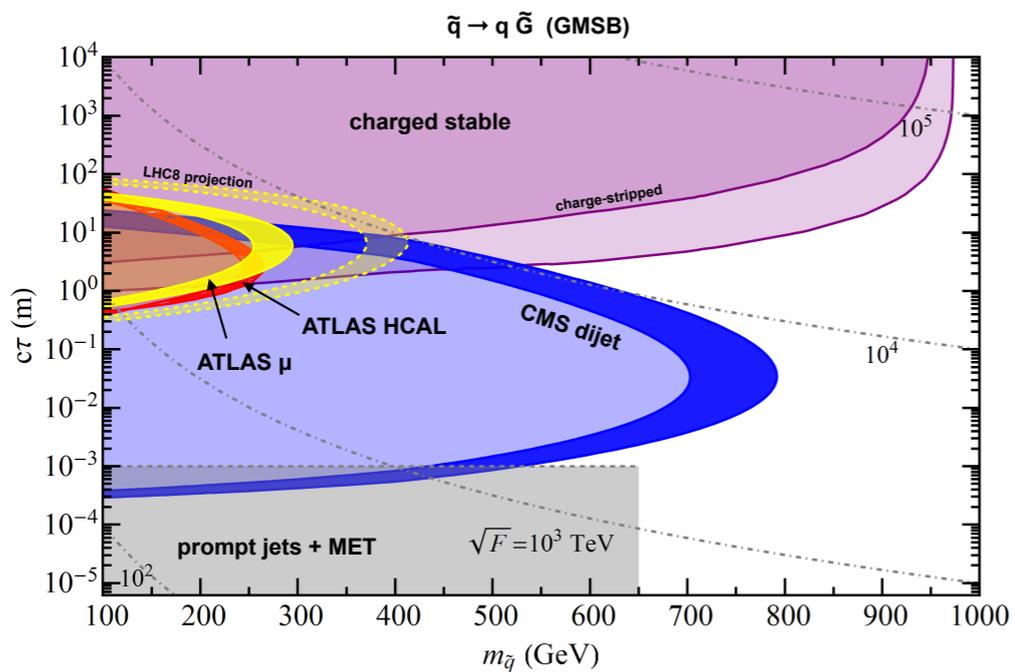
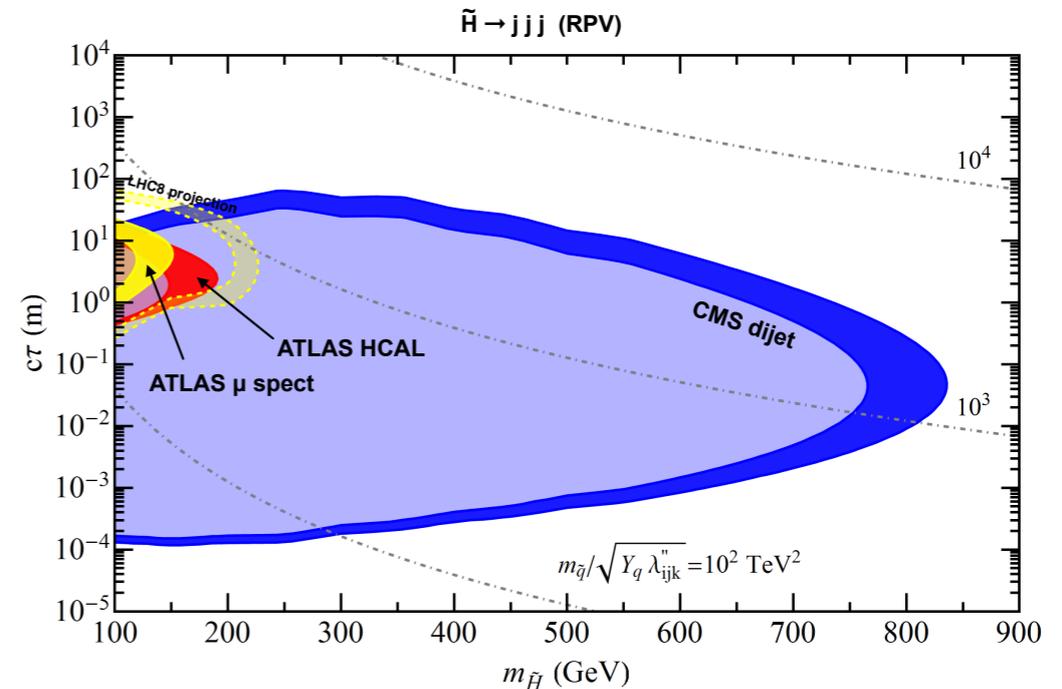
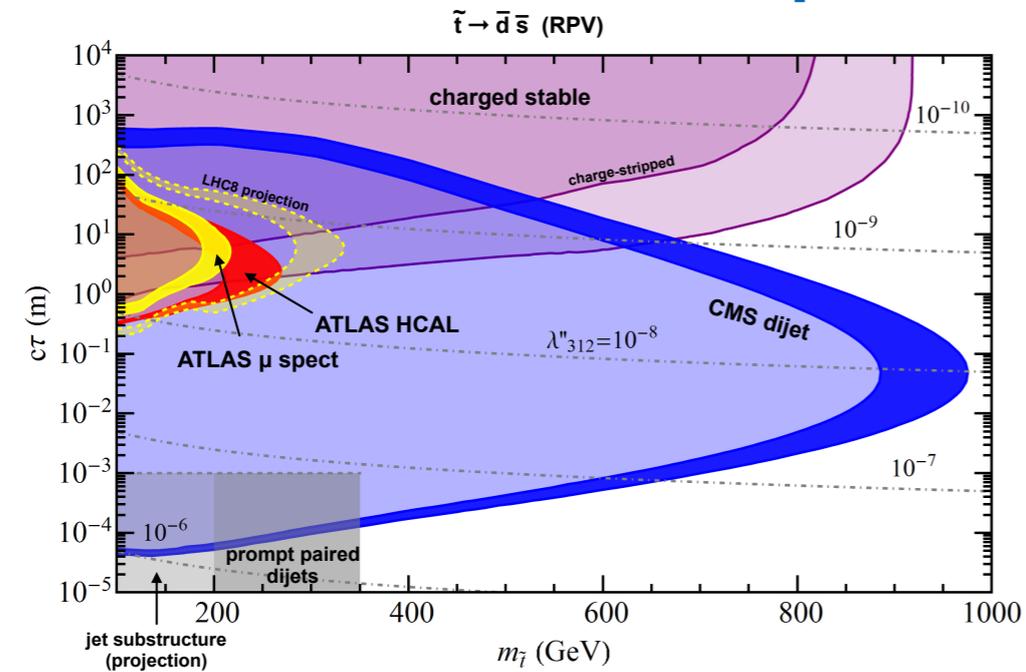


$$c\tau \approx 500 \mu\text{m} \times \left( \frac{10^{-7}}{\lambda} \right)^2 \left( \frac{\text{TeV}}{m_{\tilde{q}}} \right)^1$$

# Displaced SUSY

*Not that many places to hide once the searches catch up*

[Liu, Tweedie 1503.05923]



*Not totally hermetic, some holes remain.*



Technical  
naturalness

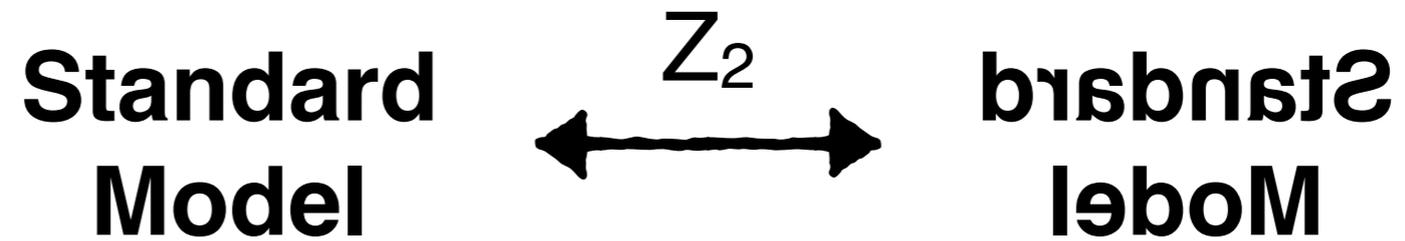
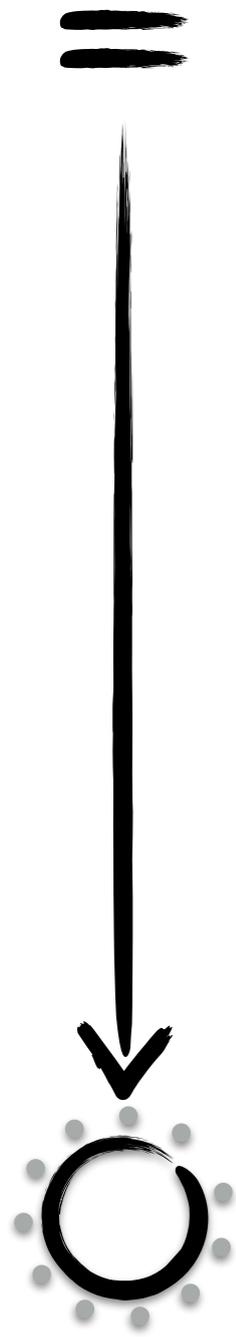
Monte  
Carlo

Displaced  
decays

Neutral  
naturalness

# Example 1: Twin Higgs

[Chacko, Goh, Harnik '05]



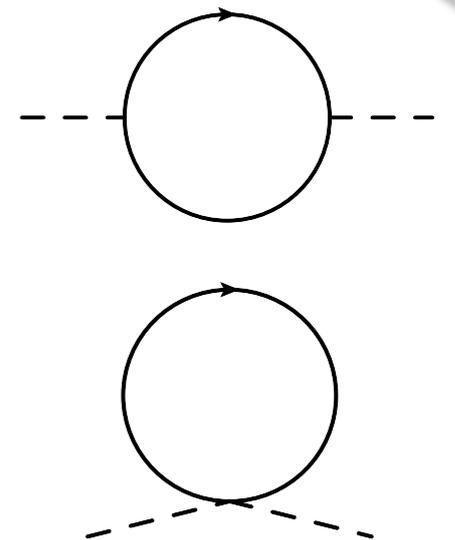
Radiative corrections to the Higgs mass are SU(4) symmetric thanks to  $Z_2$ :

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

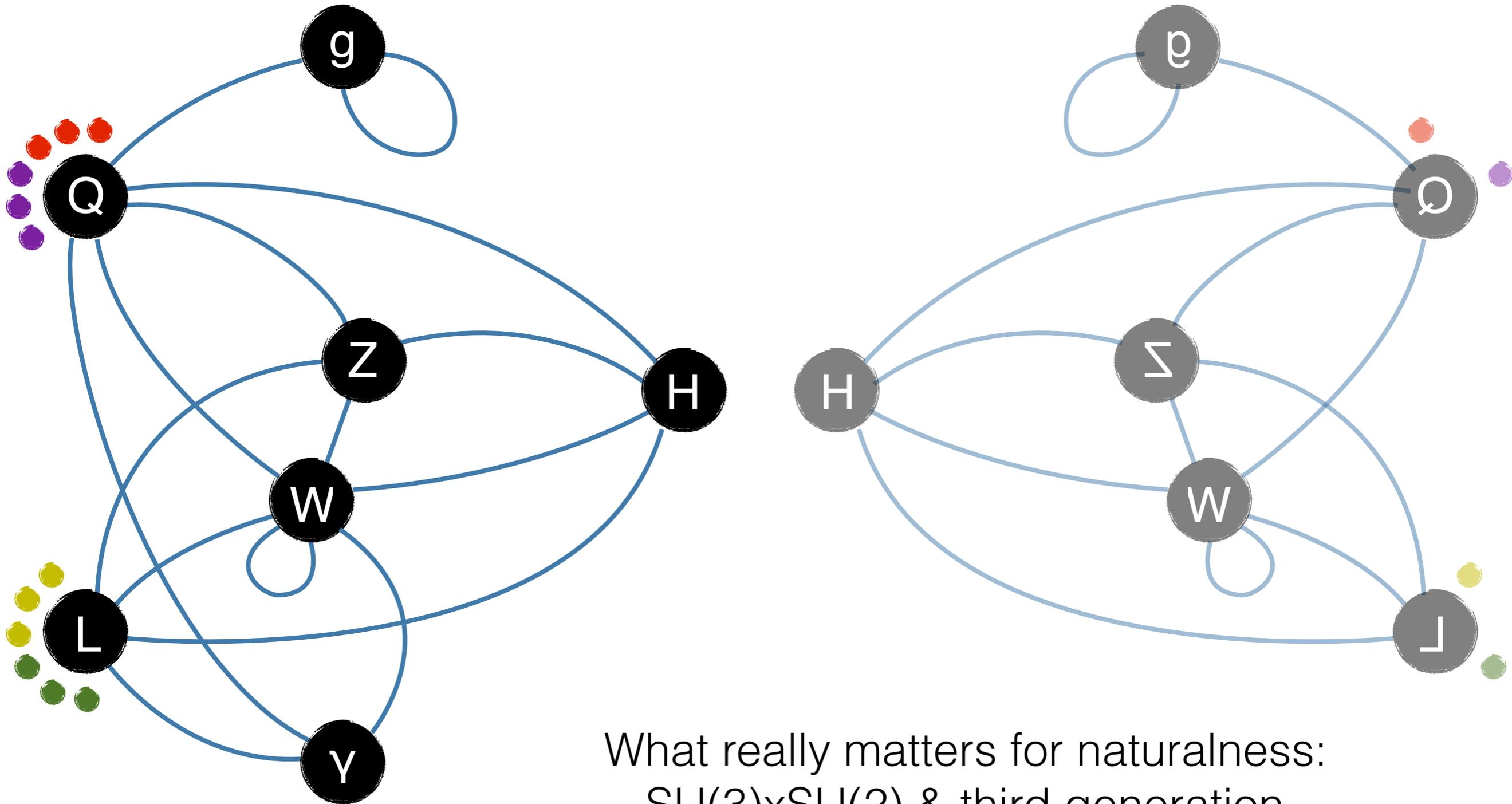
Higgs is a PNGB of  $\sim$ SU(4), but partner states neutral under SM.

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

$\downarrow$   $\downarrow$   
 $h + \dots$   $f - \frac{h^2}{2f} + \dots$



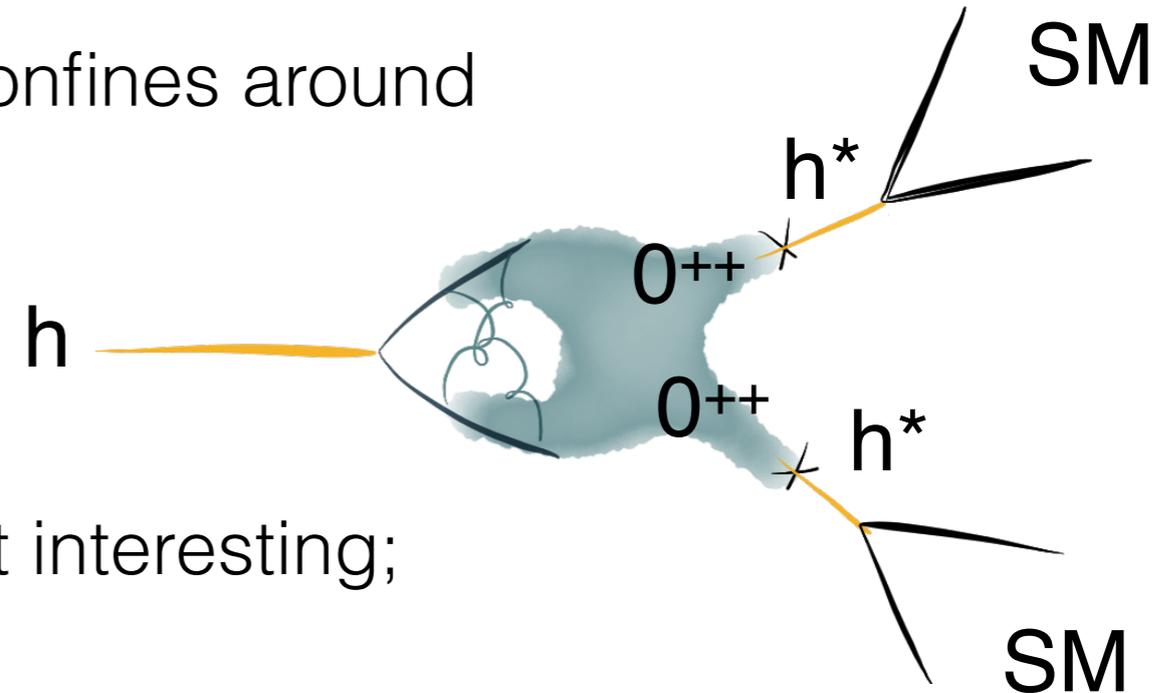
# Fraternal twins



What really matters for naturalness:  
 $SU(3) \times SU(2)$  & third generation  
 $\Rightarrow$  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



$$\mathcal{L} \supset -\frac{\alpha'_3}{6\pi} \frac{v}{f} \frac{h}{f} G'_{\mu\nu a} G'^{\mu\nu}_a$$

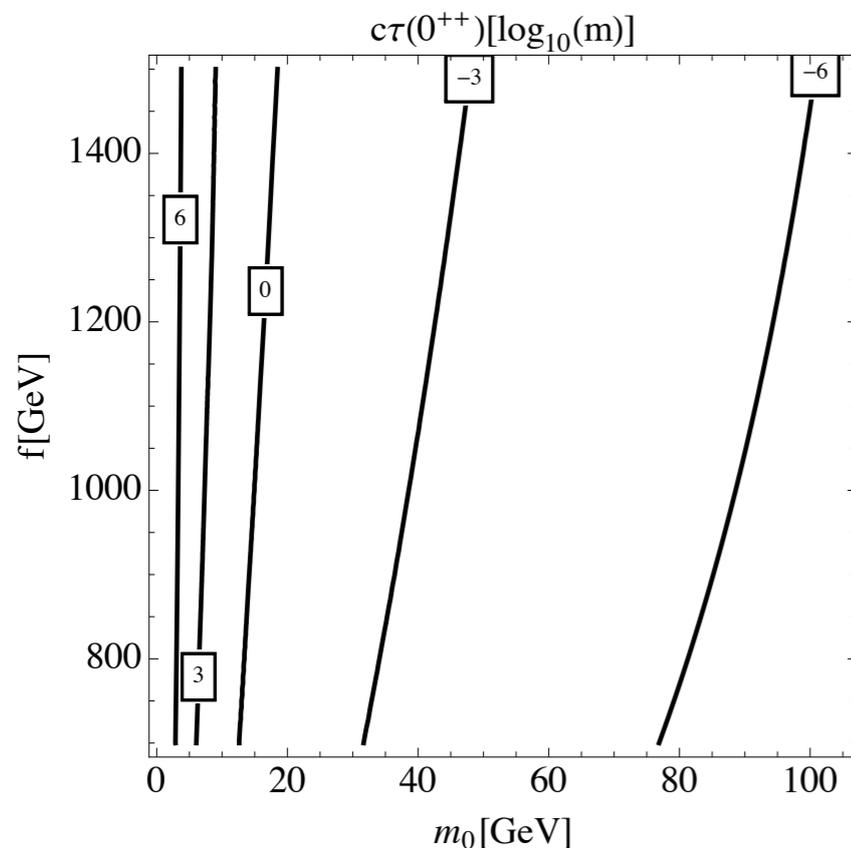
Produce in rare Higgs decays (BR  $\sim 10^{-3}$ - $10^{-4}$ )

$$gg \rightarrow h \rightarrow 0^{++} + 0^{++} + \dots$$

Decay back to SM via Higgs

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

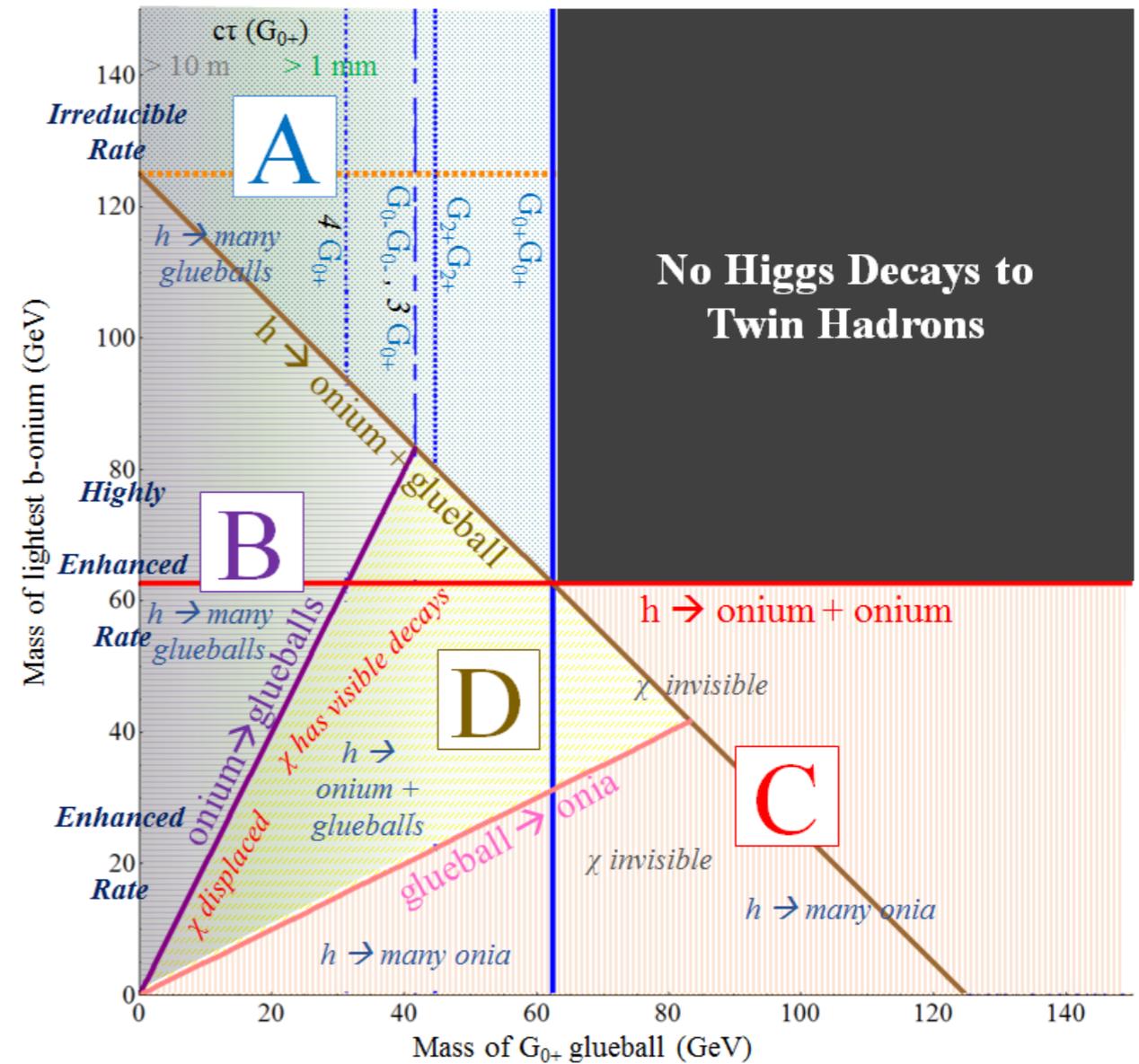
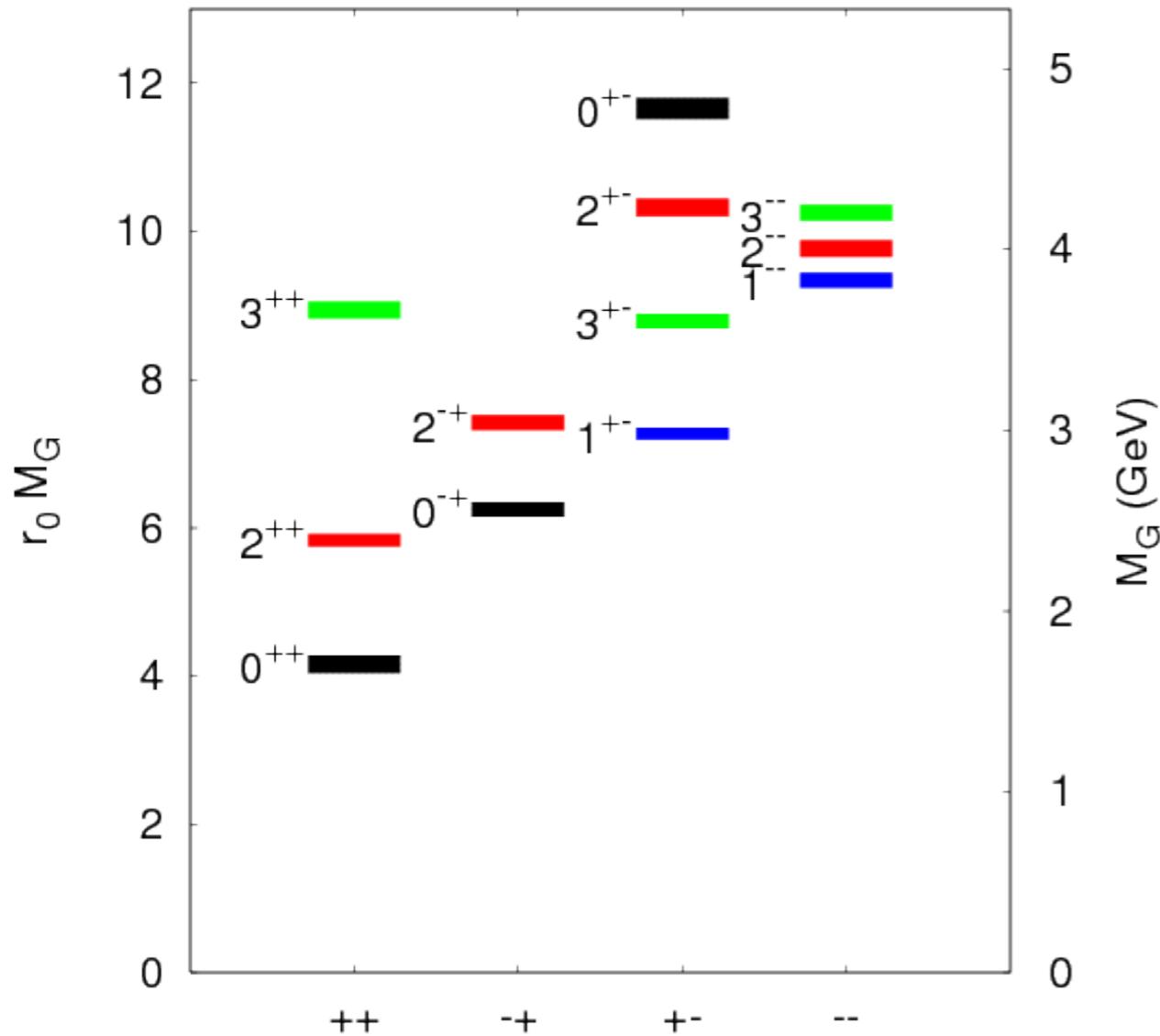
Long-lived, decay length is macroscopic;  
length scale  $\sim$  LHC detectors



# Complexities

Naive picture is simple, reality is more complicated

Rates, multiplicities, signals all approximate

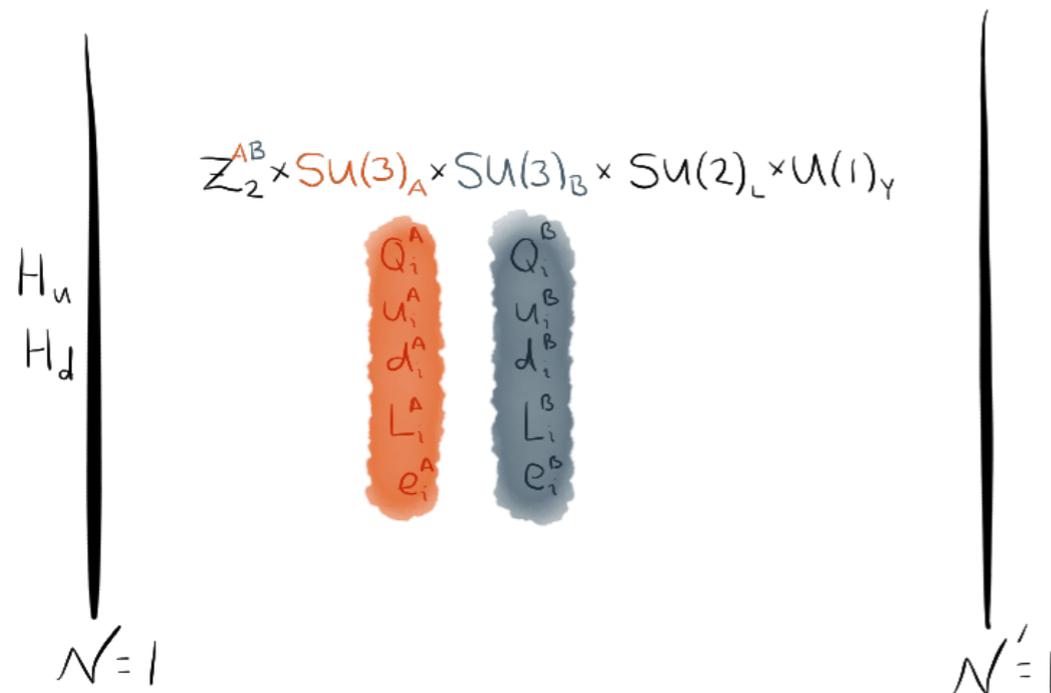


# Example 2: Folded SUSY

[Burdman, Chacko, Goh, Harnik '06]

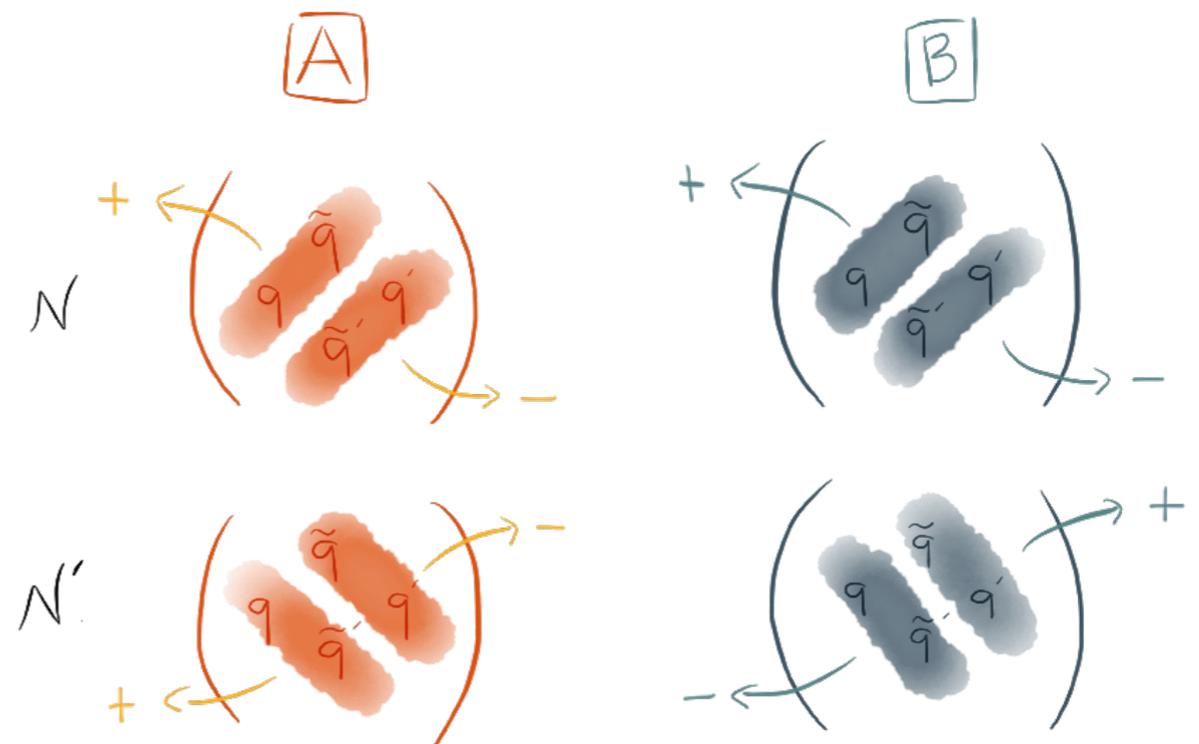
SUSY-like theory with uncolored sparticles. Start with a discrete symmetry + 5D SUSY.

Reduce symmetries & SUSY at the boundaries



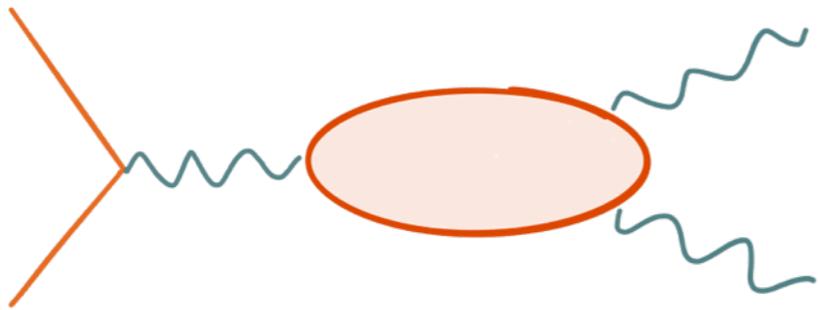
Sparticles carry standard EWK quantum #'s, but QCD charges replaced with QCD' charges

Once again...Dark QCD

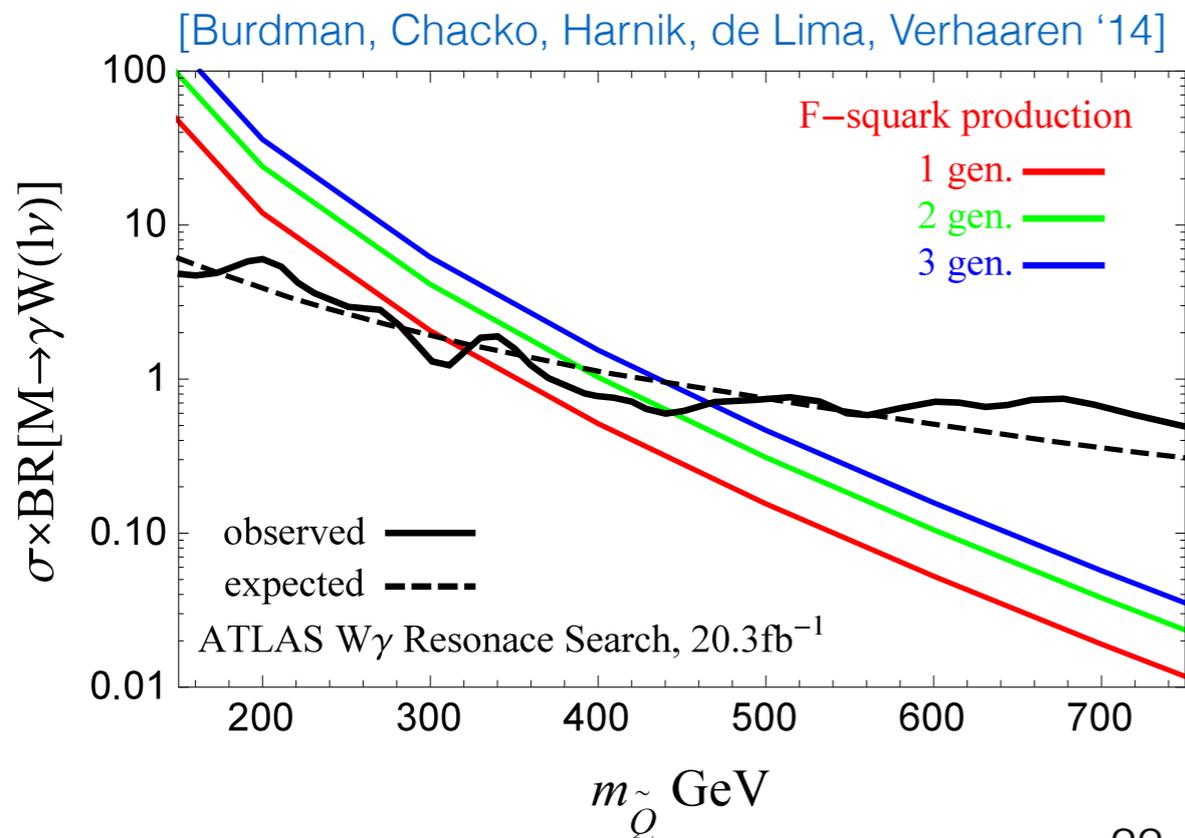


# Colorless Signals

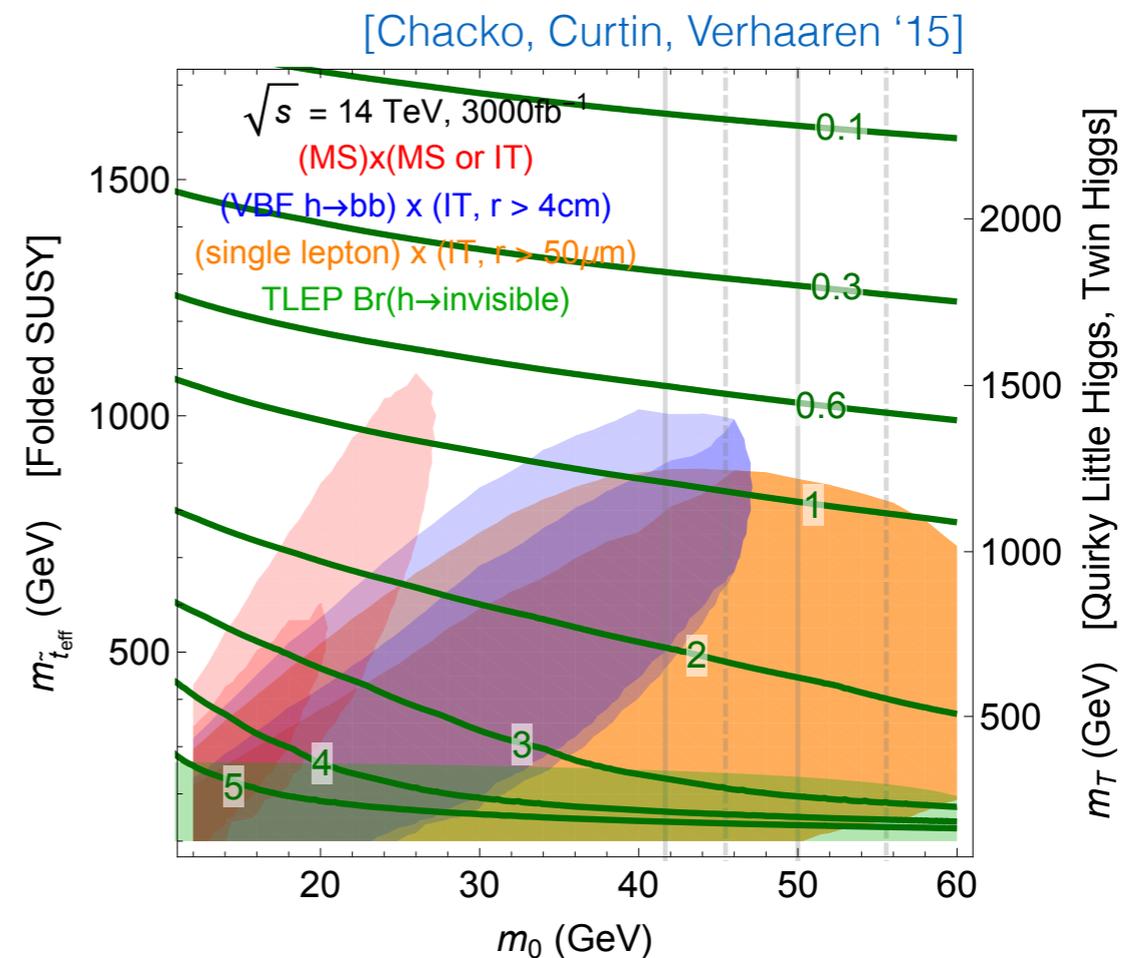
*F-squarks carry electroweak quantum numbers.*

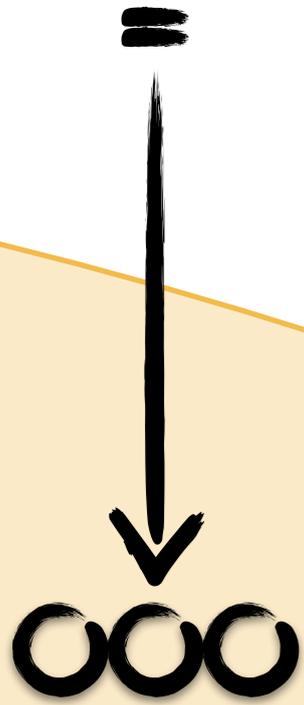


- Produced via a  $Z$ , annihilate into hidden glueballs, which decay back to SM via Higgs; displaced decays @ LHC length scales. [Curtin, Verhaaren '15]
- Produced via a  $W$ , annihilate back into the SM to shed their charge.
- (Also leave their mark indirectly, correcting Higgs decays to photons.)



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Dynamical  
selection

Monte  
Carlo

Displaced  
decays

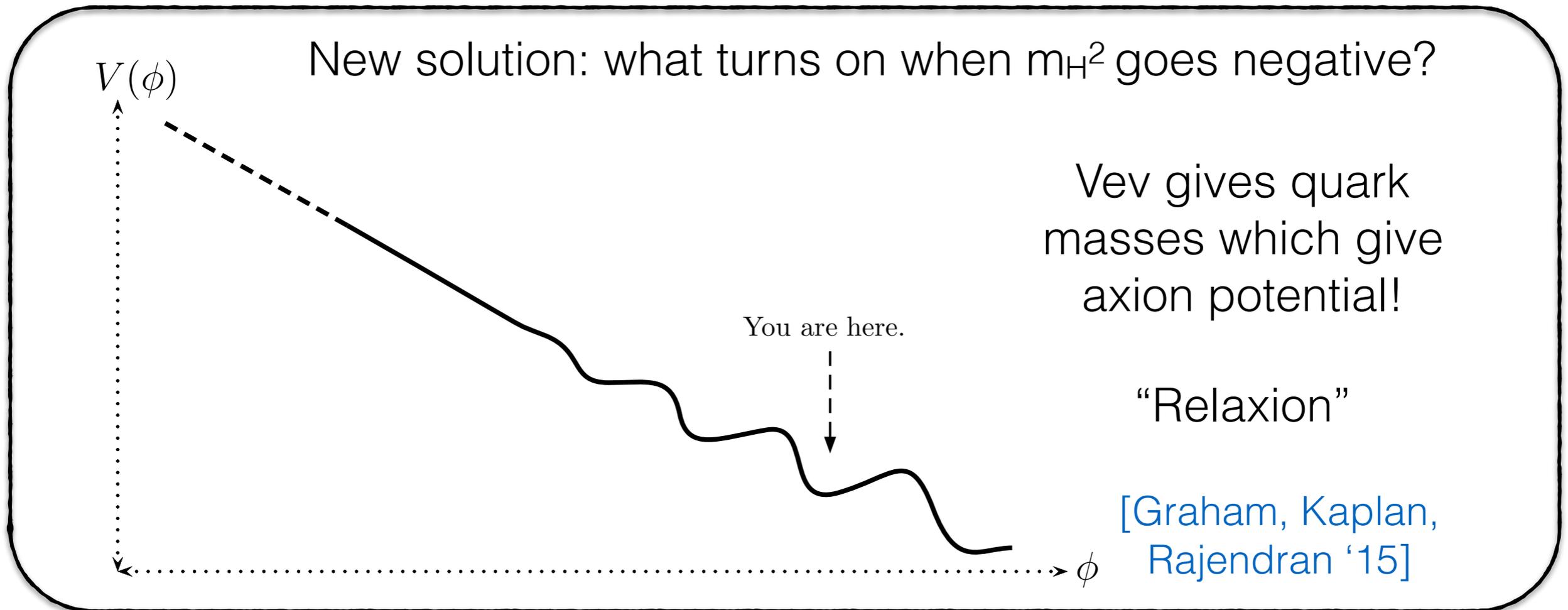
Relaxion

# Dynamical selection

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

Old idea: couple Higgs to field whose minimum sets  $m_H=0$

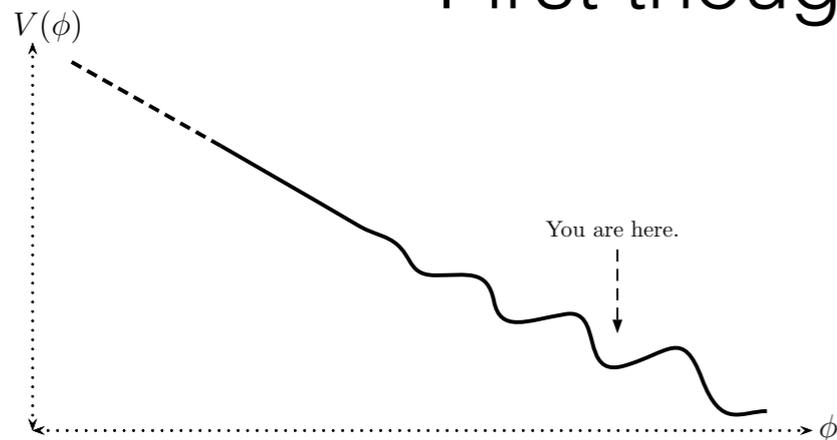
Old problem: How to make  $m_H=0$  a special point of potential?



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

# 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 ( $\ll \Lambda_{\text{QCD}}$ )
- 10 Giga-years of inflation

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



In vacuum, axion gives  $O(1)$   
contribution to  $\theta_{\text{QCD}}$



# QCD' Relaxion

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

Field	$SU(3)_N$	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	I.e. axion of a different $SU(3)$ ; need to tie in Higgs vev
$L$	$\square$	—	$\square$	$-1/2$	
$L^c$	$\bar{\square}$	—	$\square$	$+1/2$	
$N$	$\square$	—	—	$0$	
$N^c$	$\bar{\square}$	—	—	$0$	

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

*New confining physics near weak scale!*

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

*To my knowledge, no systematic study to date.*

# Ex. 2: Interactive relaxion

Alternative possibility:

Instead of

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

+ inflation



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  $h \sim v$  slows evolution

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

*For dissipation to become efficient at  $h \sim v$ , can only couple to bosons acquiring mass from EWSB.*

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

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

# Interactive relaxion

Couples to all pairs of EWK bosons save photons:

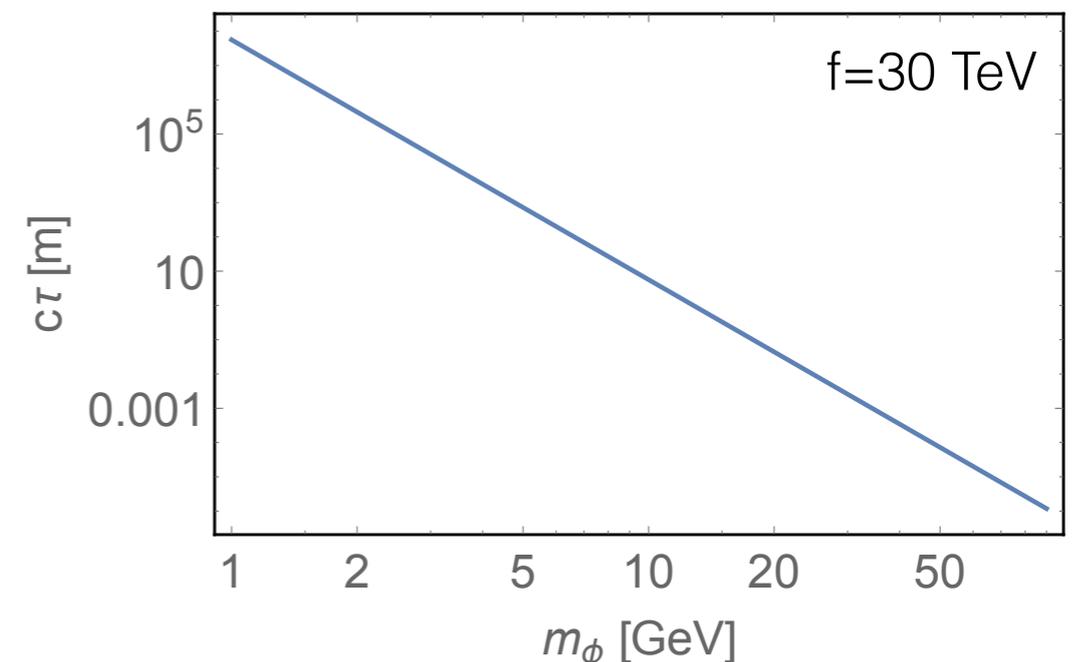
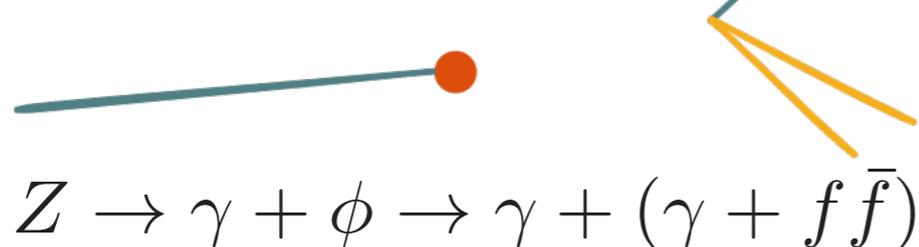
$$\frac{\phi}{f} \left( c_1 A_{\mu\nu} \tilde{Z}^{\mu\nu} + c_2 Z_{\mu\nu} \tilde{Z}^{\mu\nu} + c_3 W_{\mu\nu}^+ \tilde{W}^{-\mu\nu} \right)$$

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

LEP bounds on exotic Z decays  $\Rightarrow f \gtrsim 10$  TeV  $\Rightarrow \phi$  long-lived

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

Displaced  $\phi$  decay



Novel displaced decay, not currently searched for meaningfully.

New theory frameworks!

Monte Carlo

New places to look!

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.

MC  $\leftrightarrow$  BSM



## 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!**