

*University of Southampton, 22nd May 2015*

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# The Unnaturally Split Composite Higgs

inc. arXiv:1409.7391  
J. Barnard, P. Cox,  
T. Gherghetta,  
T. Sankar Ray, A. Spray

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# Outline

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- ❖ **Introduction**

- ❖ Naturalness, Unnatural Models and SUSY
- ❖ Composite Higgses

- ❖ **General Features of Split Composite Higgs Models**

- ❖ Flavour and Precision Electroweak Constraints
- ❖ Gauge Unification
- ❖ Proton Stability and Dark Matter

- ❖ **An Explicit Model**

- ❖ The  $SU(7)/SU(6) \times U(1)$  Theory

- ❖ **Collider Phenomenology**

- ❖ **Conclusions**

# Introduction

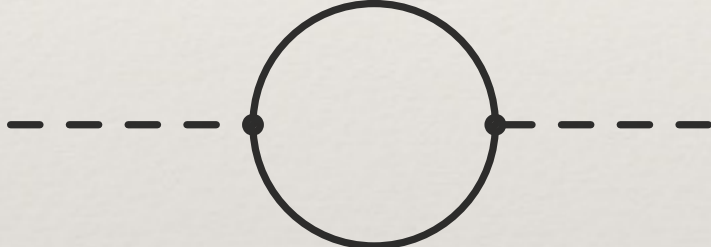


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# Naturalness

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- ❖ Standard Model is an Effective Theory with Cut-Off  $\Lambda_{UV}$
- ❖ Integrating out physics at  $\Lambda_{UV}$  contributes to SM terms:



A Feynman diagram showing a dashed line entering from the left, connecting to a solid circular loop, which then connects to another dashed line exiting to the right. The loop is attached to the dashed lines at two vertices, each marked with a small black dot.

$$\sim \frac{\Lambda_{UV}^2}{(4\pi)^2}$$

- ❖ To avoid large accidental cancellations, expect

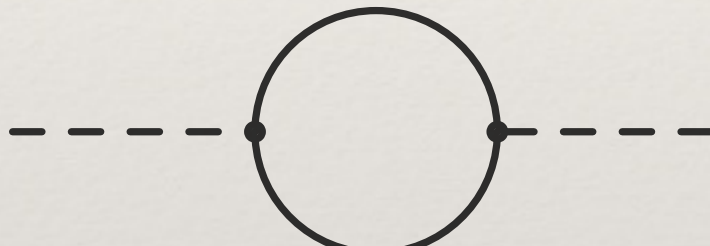
$$\Lambda_{UV} \lesssim 4\pi m_H \sim 1 \text{ TeV}$$

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A Feynman diagram showing a tadpole loop. It consists of a central circle with two vertices on its horizontal diameter. From each vertex, a dashed line extends outwards to the left and right respectively. To the right of the diagram is an approximation symbol followed by the expression  $\frac{\Lambda_{UV}^2}{(4\pi)^2}$ .
$$\text{---} \circ \text{---} \sim \frac{\Lambda_{UV}^2}{(4\pi)^2}$$

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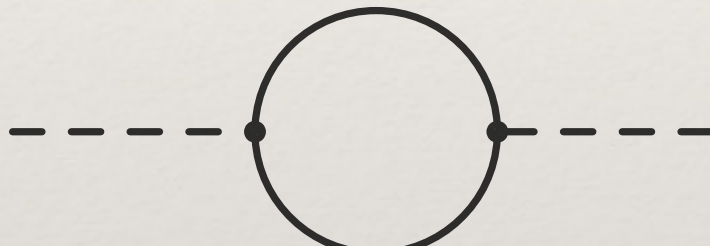
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A Feynman diagram showing a tadpole loop. It consists of a central circle with two vertices. From each vertex, a dashed line extends outwards to the left and right respectively. The diagram is followed by an approximation symbol and a fraction.

$$\sim \frac{\Lambda_{UV}^2}{(4\pi)^2}$$

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$$\Lambda_{UV} \lesssim 4\pi m_H \sim 1 \text{ TeV}$$

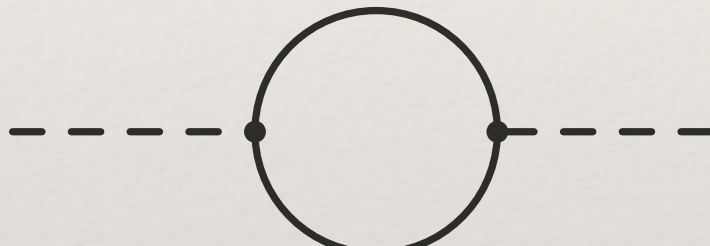


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$$\sim \frac{\Lambda_{UV}^2}{(4\pi)^2}$$

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# Facing the Evidence

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

Status: March 2015

ATLAS Preliminary

$\int \mathcal{L} dt = (1.0 - 20.3) \text{ fb}^{-1}$   $\sqrt{s} = 7, 8 \text{ TeV}$

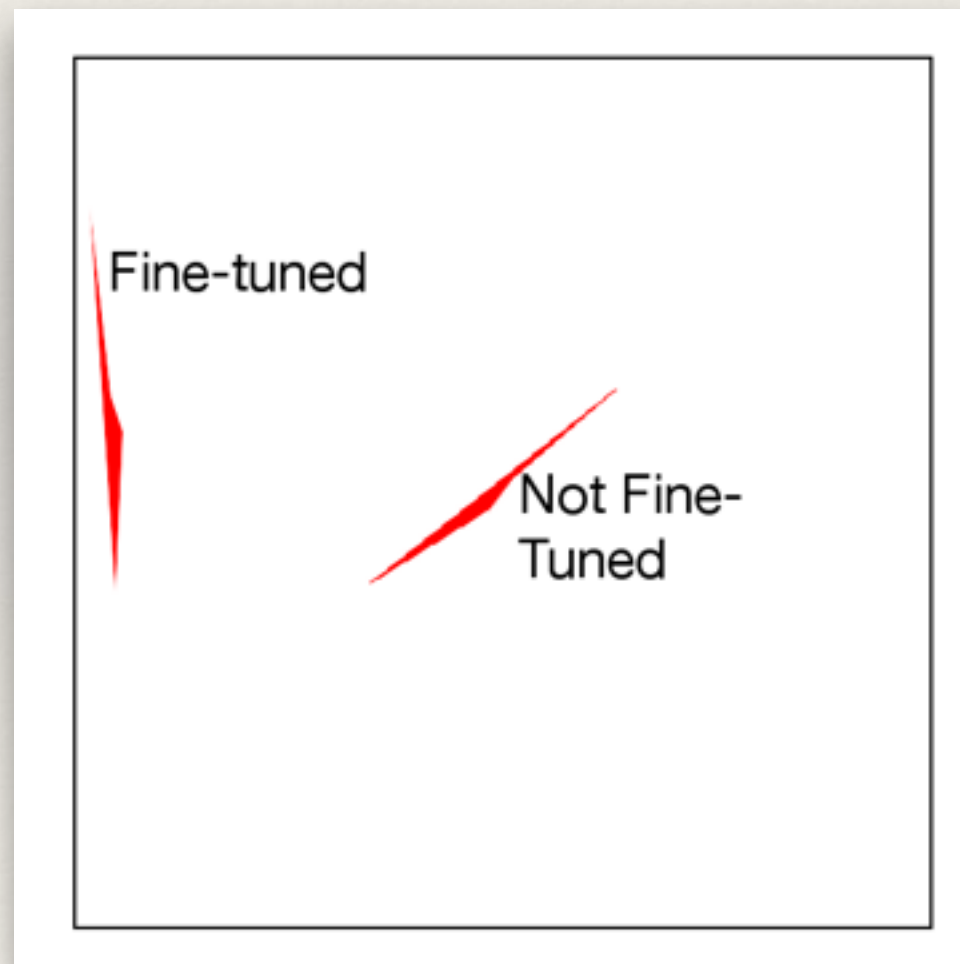
Model	$\ell, \gamma$	Jets	$E_T^{\text{miss}}$	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Mass limit	Reference
Extra dimensions	ADD $G_{KK} + g/q$	$\geq 1 \text{ j}$	Yes	20.3	$M_D$ 5.25 TeV	$n = 2$ 1502.01518
	ADD non-resonant $\ell\ell$	$2 e, \mu$	-	20.3	$M_S$ 4.7 TeV	$n = 3 \text{ HLZ}$ 1407.2410
	ADD QBH $\rightarrow \ell q$	$1 e, \mu$	$1 \text{ j}$	-	$M_{\text{th}}$ 5.2 TeV	$n = 6$ 1311.2006
	ADD QBH	-	$2 \text{ j}$	-	$M_{\text{th}}$ 5.82 TeV	$n = 6$ 1407.1376
	ADD BH high $N_{\text{trk}}$	$2 \mu \text{ (SS)}$	-	-	$M_{\text{th}}$ 4.7 TeV	$n = 6, M_D = 3 \text{ TeV, non-rot BH}$ 1308.4075
	ADD BH high $\sum p_T$	$\geq 1 e, \mu$	$\geq 2 \text{ j}$	-	$M_{\text{th}}$ 5.8 TeV	$n = 6, M_D = 3 \text{ TeV, non-rot BH}$ 1405.4254
	ADD BH high multijet	-	$\geq 2 \text{ j}$	-	$M_{\text{th}}$ 5.8 TeV	$n = 6, M_D = 3 \text{ TeV, non-rot BH}$ Preliminary
	RS1 $G_{KK} \rightarrow \ell\ell$	$2 e, \mu$	-	-	$G_{KK} \text{ mass}$ 2.68 TeV	$k/\overline{M}_{Pl} = 0.1$ 1405.4123
	RS1 $G_{KK} \rightarrow \gamma\gamma$	$2 \gamma$	-	-	$G_{KK} \text{ mass}$ 2.66 TeV	$k/\overline{M}_{Pl} = 0.1$ Preliminary
	Bulk RS $G_{KK} \rightarrow ZZ \rightarrow qq\ell\ell$	$2 e, \mu$	$2 \text{ j} / 1 \text{ J}$	-	$G_{KK} \text{ mass}$ 740 GeV	$k/\overline{M}_{Pl} = 1.0$ 1409.6190
	Bulk RS $G_{KK} \rightarrow WW \rightarrow qq\ell\nu$	$1 e, \mu$	$2 \text{ j} / 1 \text{ J}$	Yes	$W' \text{ mass}$ 700 GeV	$k/\overline{M}_{Pl} = 1.0$ 1503.04677
	Bulk RS $G_{KK} \rightarrow HH \rightarrow b\bar{b}b\bar{b}$	-	$4 \text{ b}$	-	$G_{KK} \text{ mass}$ 590-710 GeV	$k/\overline{M}_{Pl} = 1.0$ ATLAS-CONF-2014-005
	Bulk RS $g_{KK} \rightarrow t\bar{t}$	$1 e, \mu$	$\geq 1 \text{ b}, \geq 1 \text{ J} / 2 \text{ j}$	Yes	$g_{KK} \text{ mass}$ 2.2 TeV	BR = 0.925 ATLAS-CONF-2015-009
	2UED / RPP	$2 e, \mu \text{ (SS)}$	$\geq 1 \text{ b}, \geq 1 \text{ j}$	Yes	$KK \text{ mass}$ 960 GeV	Preliminary
Gauge bosons	SSM $Z' \rightarrow \ell\ell$	$2 e, \mu$	-	20.3	$Z' \text{ mass}$ 2.9 TeV	1405.4123
	SSM $Z' \rightarrow \tau\tau$	$2 \tau$	-	19.5	$Z' \text{ mass}$ 2.02 TeV	1502.07177
	SSM $W' \rightarrow \ell\nu$	$1 e, \mu$	-	Yes	$W' \text{ mass}$ 3.24 TeV	1407.7494
	EGM $W' \rightarrow WZ \rightarrow \ell\nu\ell'\ell'$	$3 e, \mu$	-	Yes	$W' \text{ mass}$ 1.52 TeV	1406.4456
	EGM $W' \rightarrow WZ \rightarrow qq\ell\ell$	$2 e, \mu$	$2 \text{ j} / 1 \text{ J}$	-	$W' \text{ mass}$ 1.59 TeV	1409.6190
	HVT $W' \rightarrow WH \rightarrow \ell\nu b\bar{b}$	$1 e, \mu$	$2 \text{ b}$	Yes	$W' \text{ mass}$ 1.47 TeV	Preliminary
	LRSM $W'_R \rightarrow t\bar{b}$	$1 e, \mu$	$2 \text{ b}, 0-1 \text{ j}$	Yes	$W' \text{ mass}$ 1.92 TeV	1410.4103
	LRSM $W'_R \rightarrow t\bar{t}$	$0 e, \mu$	$\geq 1 \text{ b}, 1 \text{ J}$	-	$W' \text{ mass}$ 1.76 TeV	1408.0886
CI	CI $qqqq$	-	$2 \text{ j}$	-	$\Lambda$ 12.0 TeV	$\eta_{LL} = -1$ Preliminary
	CI $qq\ell\ell$	$2 e, \mu$	-	20.3	$\Lambda$ 21.6 TeV	$\eta_{LL} = -1$ 1407.2410
	CI $uutt$	$2 e, \mu \text{ (SS)}$	$\geq 1 \text{ b}, \geq 1 \text{ j}$	Yes	$\Lambda$ 4.35 TeV	$ C_{LL}  = 1$ Preliminary
DM	EFT D5 operator (Dirac)	$0 e, \mu$	$\geq 1 \text{ j}$	Yes	$M_\chi$ 974 GeV	at 90% CL for $m(\chi) < 100 \text{ GeV}$ 1502.01518
	EFT D9 operator (Dirac)	$0 e, \mu$	$1 \text{ J}, \leq 1 \text{ j}$	Yes	$M_\chi$ 2.4 TeV	at 90% CL for $m(\chi) < 100 \text{ GeV}$ 1309.4017
LQ	Scalar LQ 1 <sup>st</sup> gen	$2 e$	$\geq 2 \text{ j}$	-	$LQ \text{ mass}$ 660 GeV	$\beta = 1$ 1112.4828
	Scalar LQ 2 <sup>nd</sup> gen	$2 \mu$	$\geq 2 \text{ j}$	-	$LQ \text{ mass}$ 685 GeV	$\beta = 1$ 1203.3172
	Scalar LQ 3 <sup>rd</sup> gen	$1 e, \mu, 1 \tau$	$1 \text{ b}, 1 \text{ j}$	-	$LQ \text{ mass}$ 534 GeV	$\beta = 1$ 1303.0526
Heavy quarks	VLQ $TT \rightarrow Ht + X, Wb + X$	$1 e, \mu$	$\geq 1 \text{ b}, \geq 3 \text{ j}$	Yes	$T \text{ mass}$ 785 GeV	isospin singlet T in (T,B) doublet 1409.5500
	VLQ $TT \rightarrow Zt + X$	$2/\geq 3 e, \mu$	$\geq 2/\geq 1 \text{ b}$	-	$T \text{ mass}$ 735 GeV	B in (B,Y) doublet 1409.5500
	VLQ $BB \rightarrow Zb + X$	$2/\geq 3 e, \mu$	$\geq 2/\geq 1 \text{ b}$	-	$B \text{ mass}$ 755 GeV	isospin singlet Preliminary
	VLQ $BB \rightarrow Wt + X$	$1 e, \mu$	$\geq 1 \text{ b}, \geq 5 \text{ j}$	Yes	$B \text{ mass}$ 640 GeV	Preliminary
	$T_{5/3} \rightarrow Wt$	$1 e, \mu$	$\geq 1 \text{ b}, \geq 5 \text{ j}$	Yes	$T_{5/3} \text{ mass}$ 840 GeV	Preliminary
Excited fermions	Excited quark $q^* \rightarrow q\gamma$	$1 \gamma$	$1 \text{ j}$	-	$q^* \text{ mass}$ 3.5 TeV	only $u^*$ and $d^*$ , $\Lambda = m(q^*)$ 1309.3230
	Excited quark $q^* \rightarrow qg$	-	$2 \text{ j}$	-	$q^* \text{ mass}$ 4.09 TeV	only $u^*$ and $d^*$ , $\Lambda = m(q^*)$ 1407.1376
	Excited quark $b^* \rightarrow Wt$	$1 \text{ or } 2 e, \mu$	$1 \text{ b}, 2 \text{ j or } 1 \text{ j}$	Yes	$b^* \text{ mass}$ 870 GeV	left-handed coupling 1301.1583
	Excited lepton $\ell^* \rightarrow \ell\gamma$	$2 e, \mu, 1 \gamma$	-	-	$\ell^* \text{ mass}$ 2.2 TeV	$\Lambda = 2.2 \text{ TeV}$ 1308.1364
	Excited lepton $\nu^* \rightarrow \ell W, \nu Z$	$3 e, \mu, \tau$	-	-	$\nu^* \text{ mass}$ 1.6 TeV	$\Lambda = 1.6 \text{ TeV}$ 1411.2921
Other	LSTC $a_T \rightarrow W\gamma$	$1 e, \mu, 1 \gamma$	-	Yes	$a_T \text{ mass}$ 960 GeV	1407.8150
	LRSM Majorana $\nu$	$2 e, \mu$	$2 \text{ j}$	-	$N^0 \text{ mass}$ 1.5 TeV	$m(W_R) = 2 \text{ TeV, no mixing}$ 1203.5420
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	$2 e, \mu \text{ (SS)}$	-	-	$H^{\pm\pm} \text{ mass}$ 551 GeV	DY production, $\text{BR}(H_L^{\pm\pm} \rightarrow \ell\ell)=1$ 1412.0237
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\tau$	$3 e, \mu, \tau$	-	-	$H^{\pm\pm} \text{ mass}$ 400 GeV	DY production, $\text{BR}(H_L^{\pm\pm} \rightarrow \ell\tau)=1$ 1411.2921
	Monotop (non-res prod)	$1 e, \mu$	$1 \text{ b}$	Yes	spin-1 invisible particle mass 657 GeV	$a_{\text{non-res}} = 0.2$ 1410.5404
	Multi-charged particles	-	-	-	multi-charged particle mass 785 GeV	DY production, $ q  = 5e$ Preliminary
Magnetic monopoles	-	-	-	monopole mass 862 GeV	DY production, $ g  = 1g_D$ 1207.6411	

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



# Rethinking Naturalness

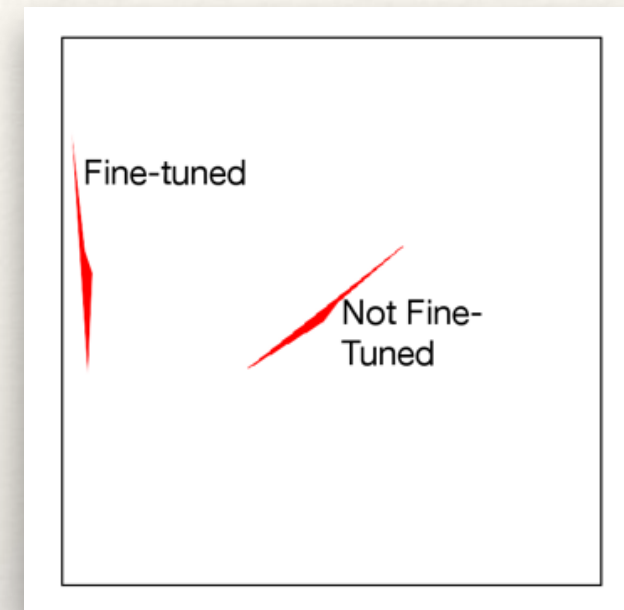
- ❖ Naturalness is an Argument from Aesthetics
  - ❖ Fine-tuned theories are consistent, unlike breaking gauge invariance/unitarity
  - ❖ How much fine-tuning is too much? 1%? 0.001%?  $v_{EW}/M_{Pl}$ ?



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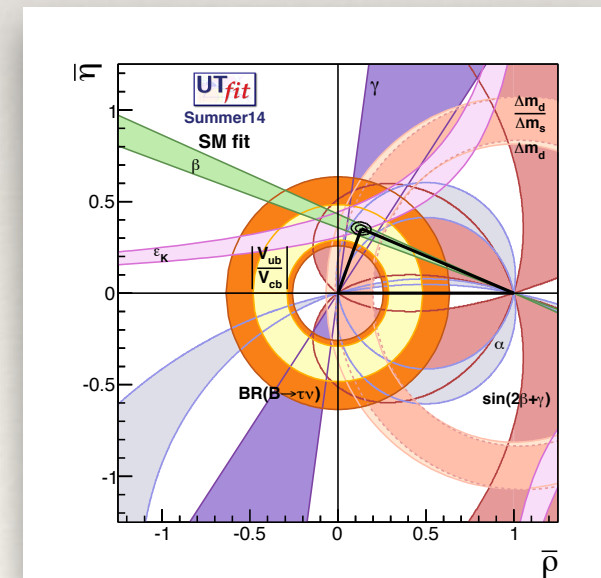
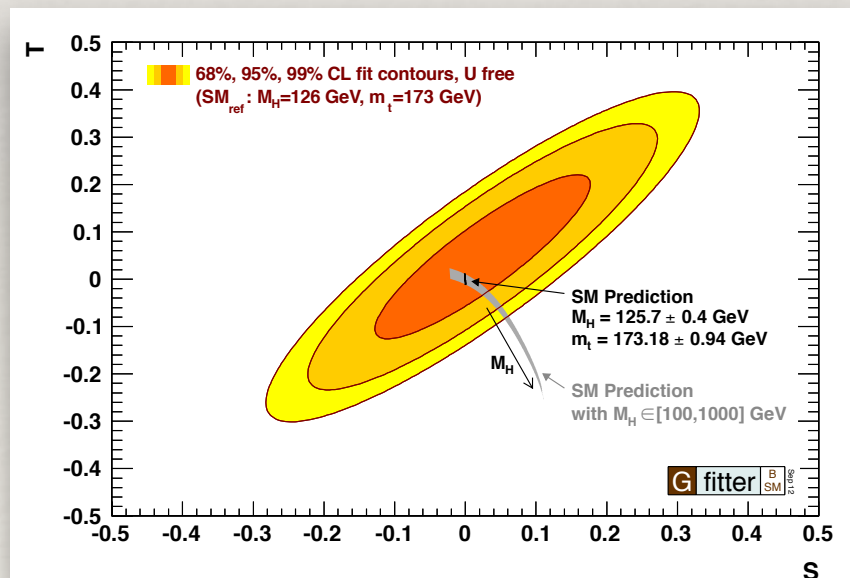
- ❖ Irrelevant Operators in the EFT?

- ❖ T Parameter

$$T \sim |H^\dagger D_\mu H|^2 \Rightarrow \Lambda_{UV} > 10 \text{ TeV}$$

- ❖ Flavour-changing operators

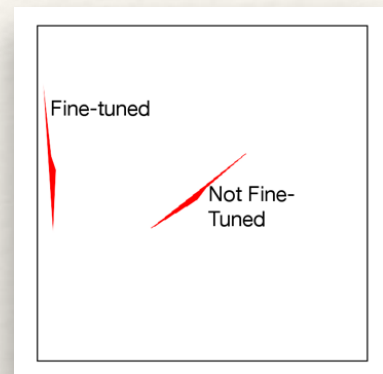
$$\epsilon_K \sim (\bar{s}_R d_L)^2 \Rightarrow \Lambda_{UV} > 10^{3-4} \text{ TeV}$$



# Rethinking Naturalness

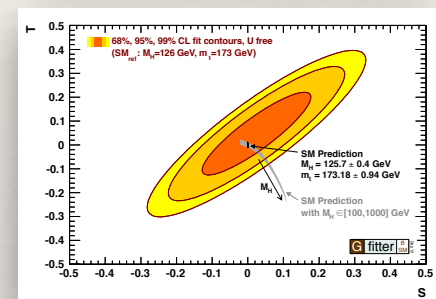
## ❖ Naturalness is an Argument from Aesthetics

- ❖ Fine-tuned theories are consistent
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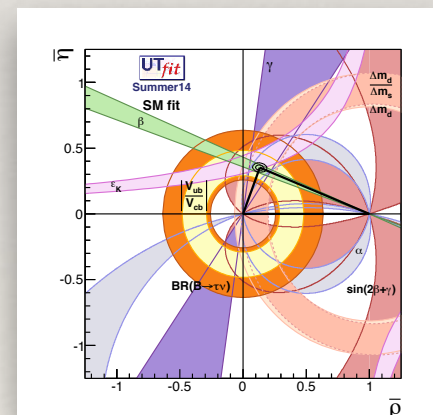
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## ❖ Multiverse arguments for Electroweak Scale

- ❖ Anthropic selection of  $v_{EW}$

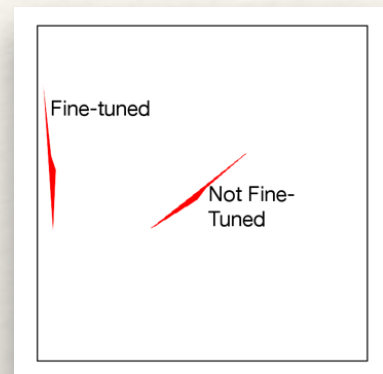




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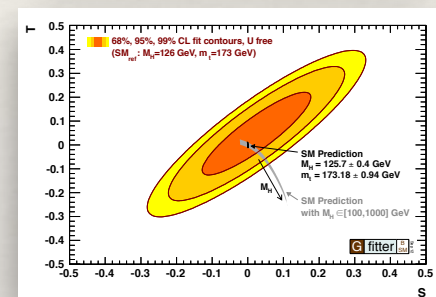
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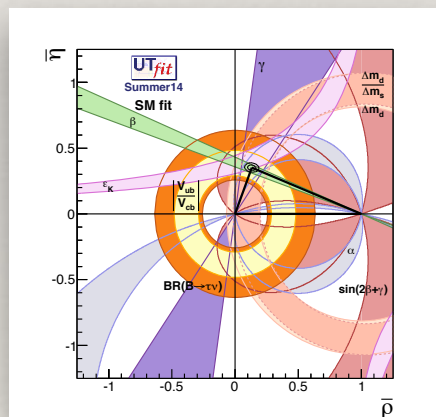
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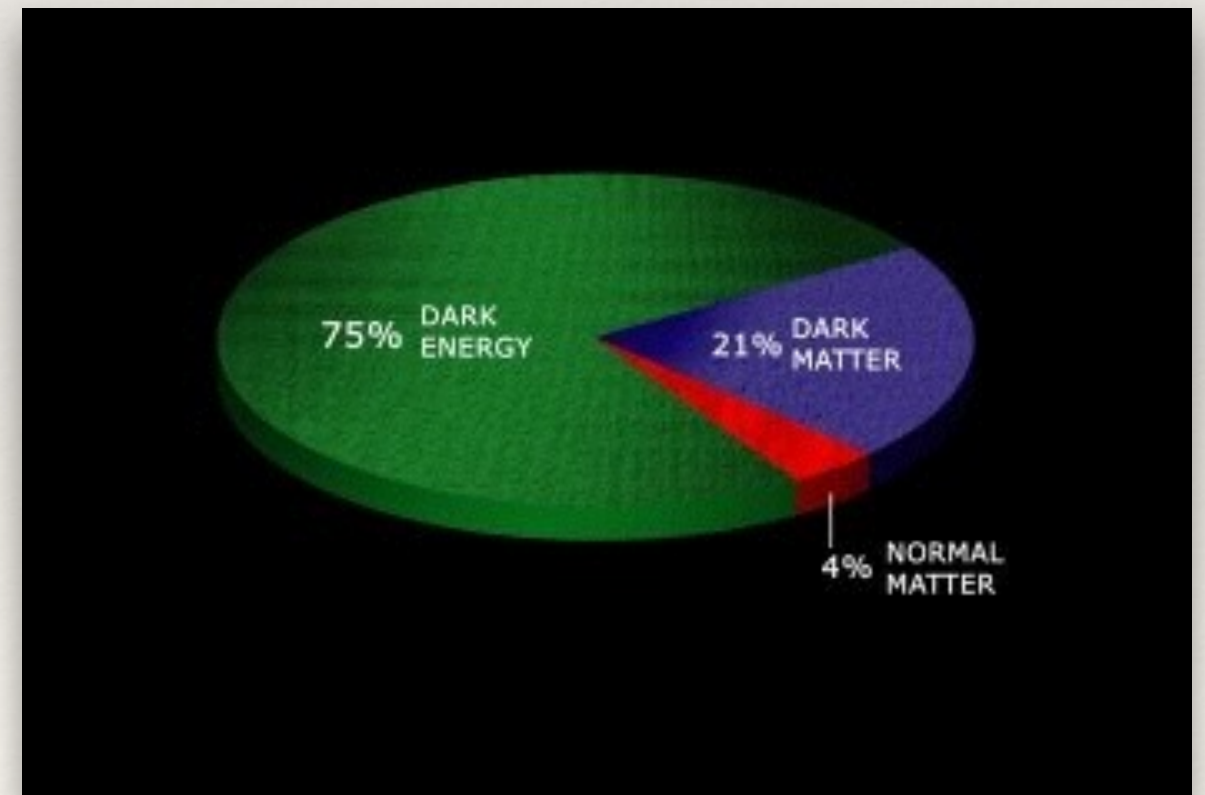
What happens without Naturalness?

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# Unnatural Reasons for New Physics

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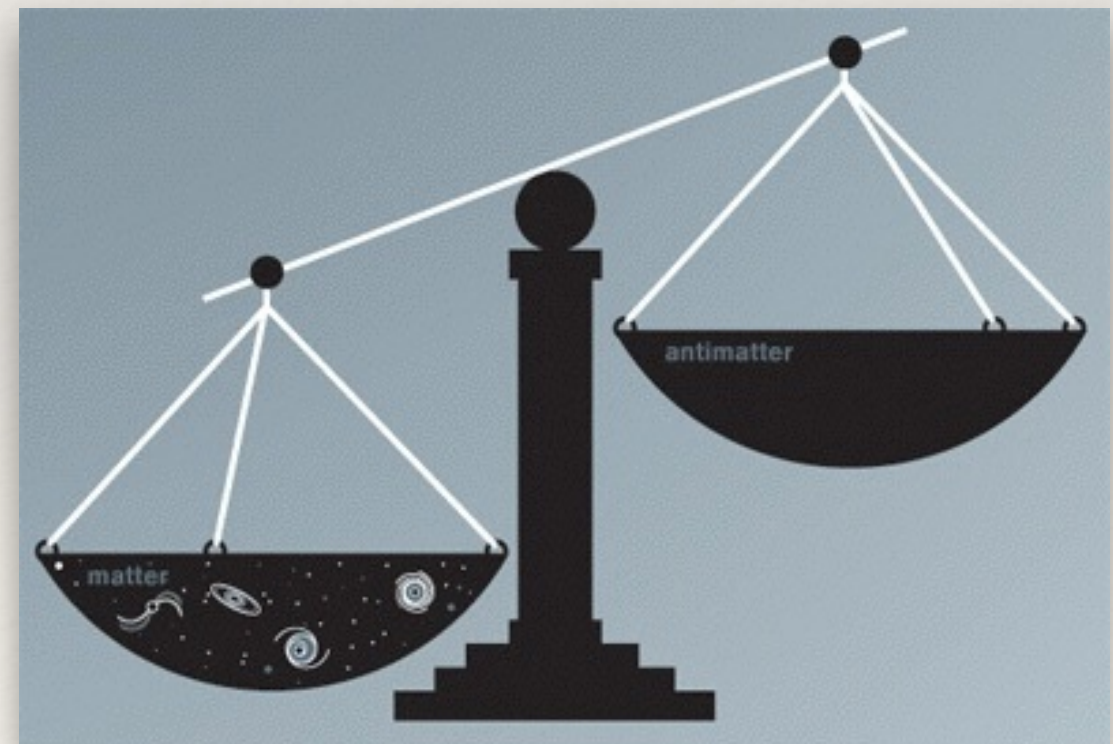
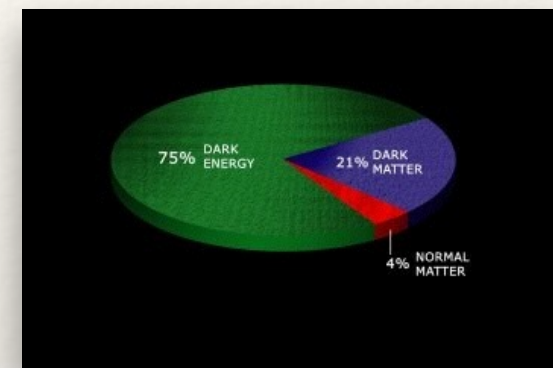
- ❖ Dark Matter
  - ❖ Must be non-SM physics
  - ❖ The WIMP miracle still holds





# Unnatural Reasons for New Physics

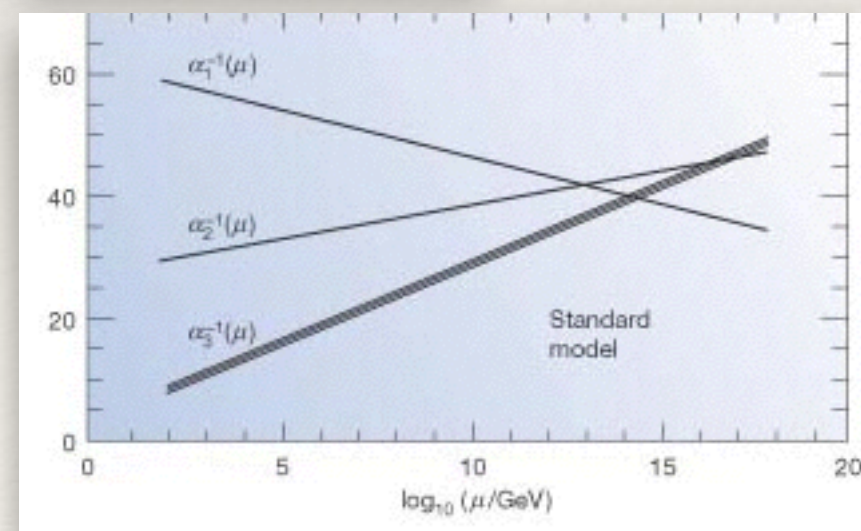
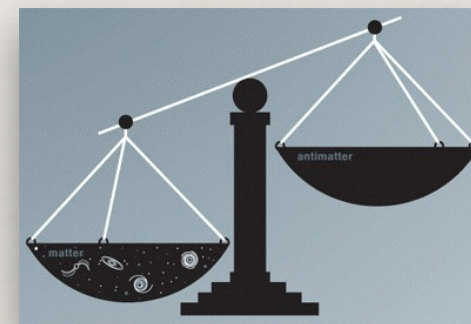
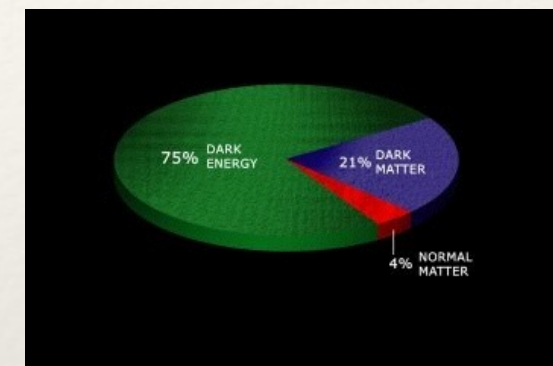
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  - ❖ The WIMP miracle still holds
- ❖ Baryogenesis
  - ❖ Must be non-SM physics





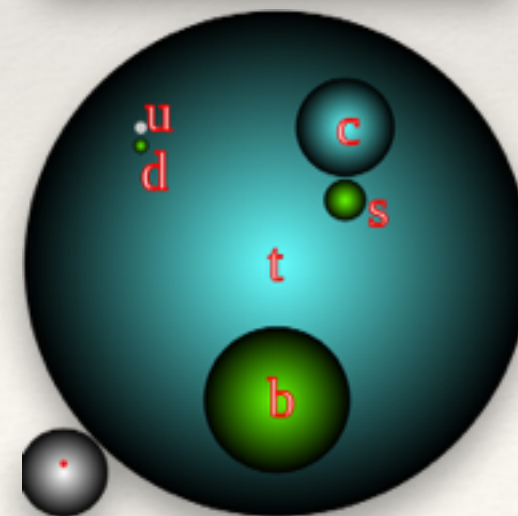
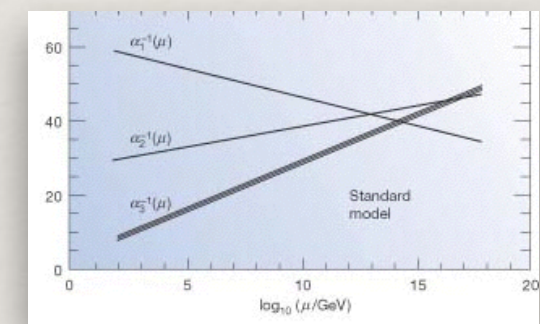
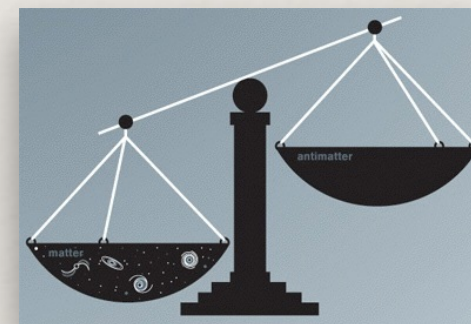
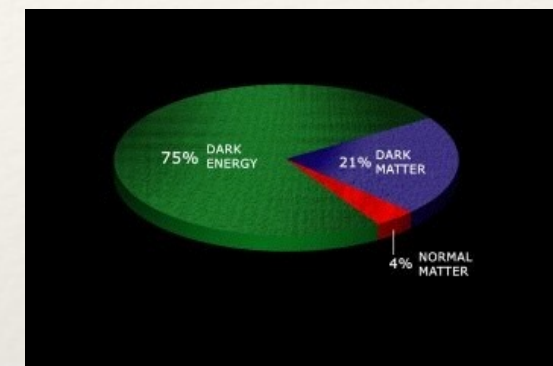
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- ❖ Dark Matter
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- ❖ Gauge Unification



# Unnatural Reasons for New Physics

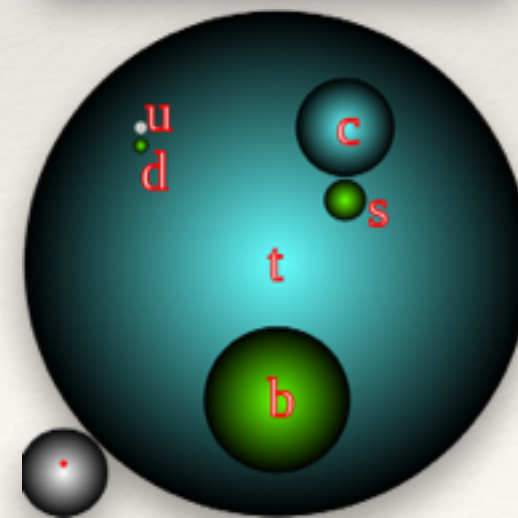
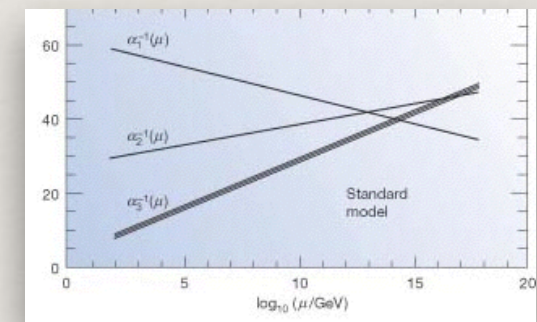
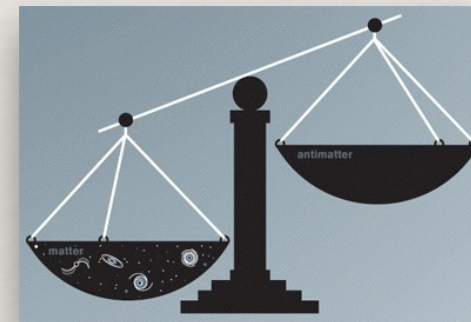
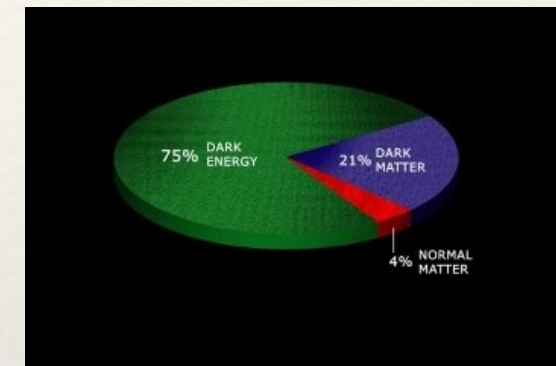
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  - ❖ Must be non-SM physics
- ❖ Gauge Unification
- ❖ Flavour Physics





# Reasons for Unnatural New Physics

- ❖ Dark Matter
  - ❖ Must be non-SM physics
  - ❖ The WIMP miracle still holds
- ❖ Baryogenesis
  - ❖ Must be non-SM physics
- ❖ Gauge Unification
- ❖ Flavour Physics
- ❖ **Simpler Models!**

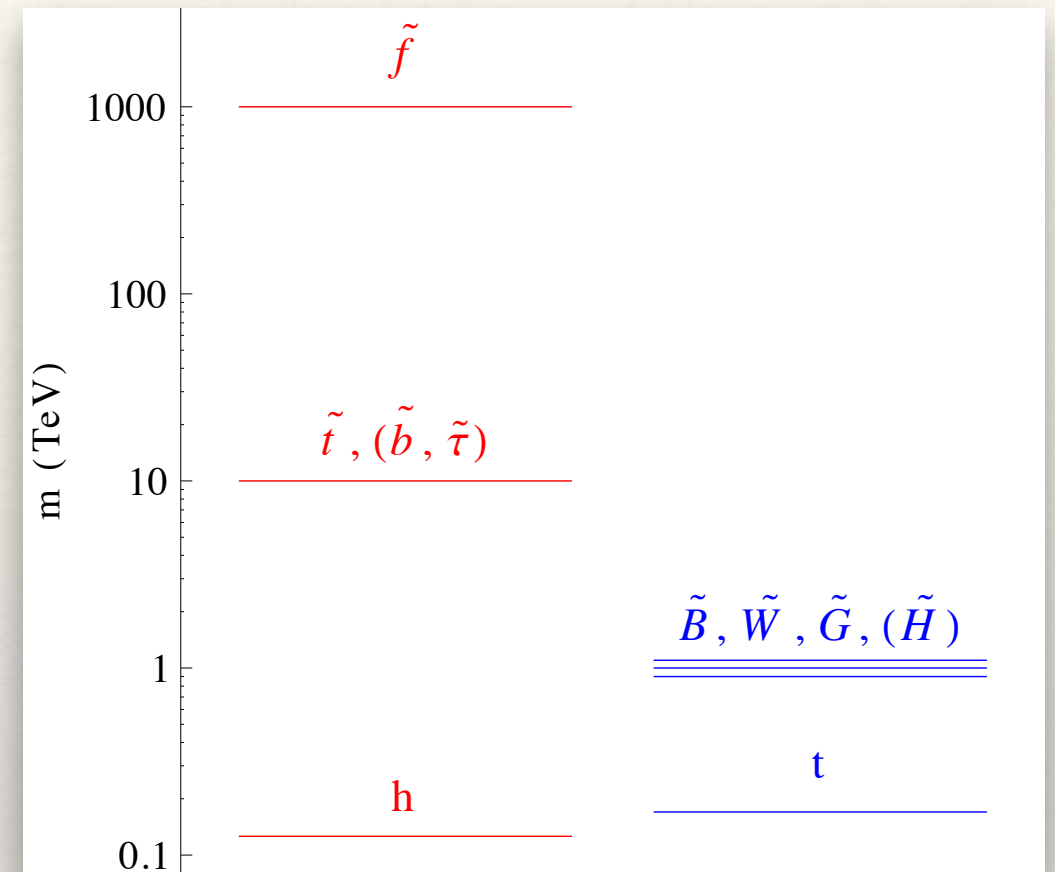




# Mini-Split Supersymmetry

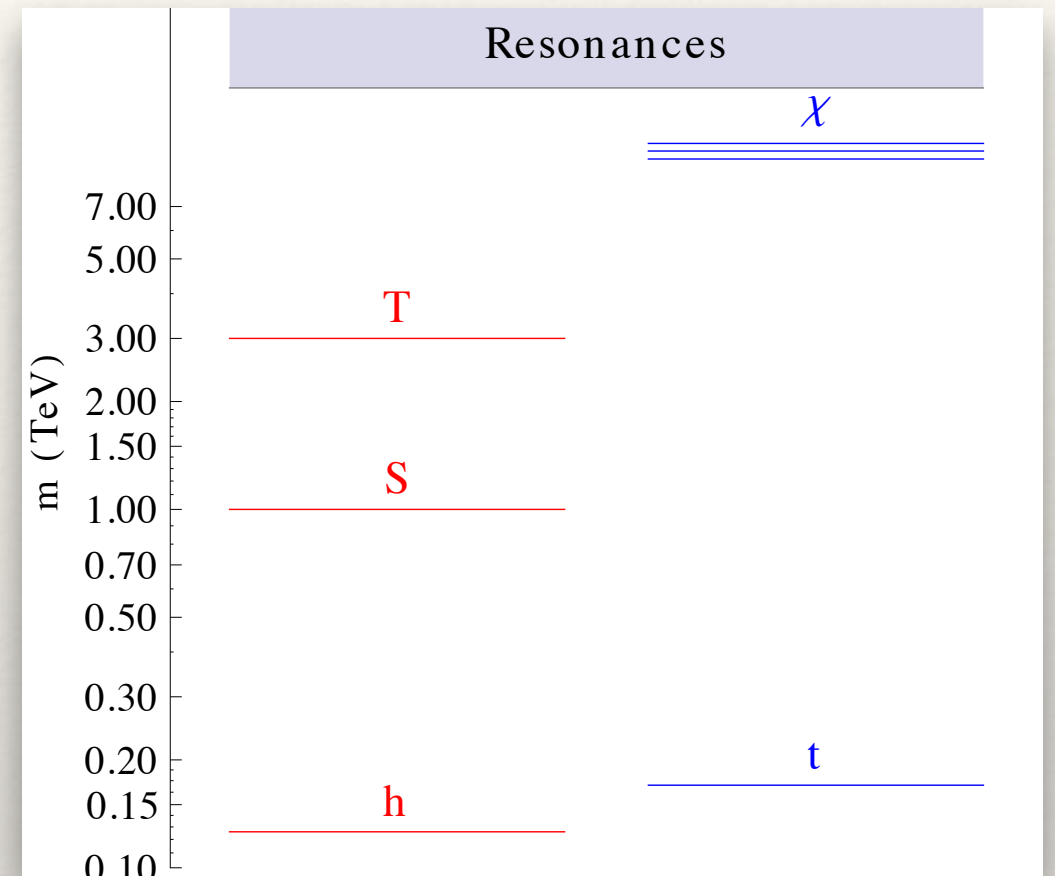
- ❖ Without Naturalness, SUSY still has:
  - ❖ Dark Matter (R-Parity)
  - ❖ Consistent with Leptogenesis
  - ❖ Improved Unification (Gauginos)
- ❖ Gauginos light by R-symmetry
- ❖ Split Spectrum avoids Flavour, LHC problems
- ❖ Long-lived gluino signal

- ❖ Arvatanki *et al* 1210.0555, Feldstein *et al* 1210.7578, Arganda *et al* 1211.0163, Arkani-Hamed *et al* 1212.6971, Arganda *et al* 1301.0708, Hisano *et al* 1304.3651, Eliaz *et al* 1306.2956, Kim *et al* 1405.3700, Nomura *et al* 1407.3785, D'Eramo *et al* 1409.5123, Cheung *et al* 1411.7329, Wang *et al* 1501.02906



# Split Composite Higgses

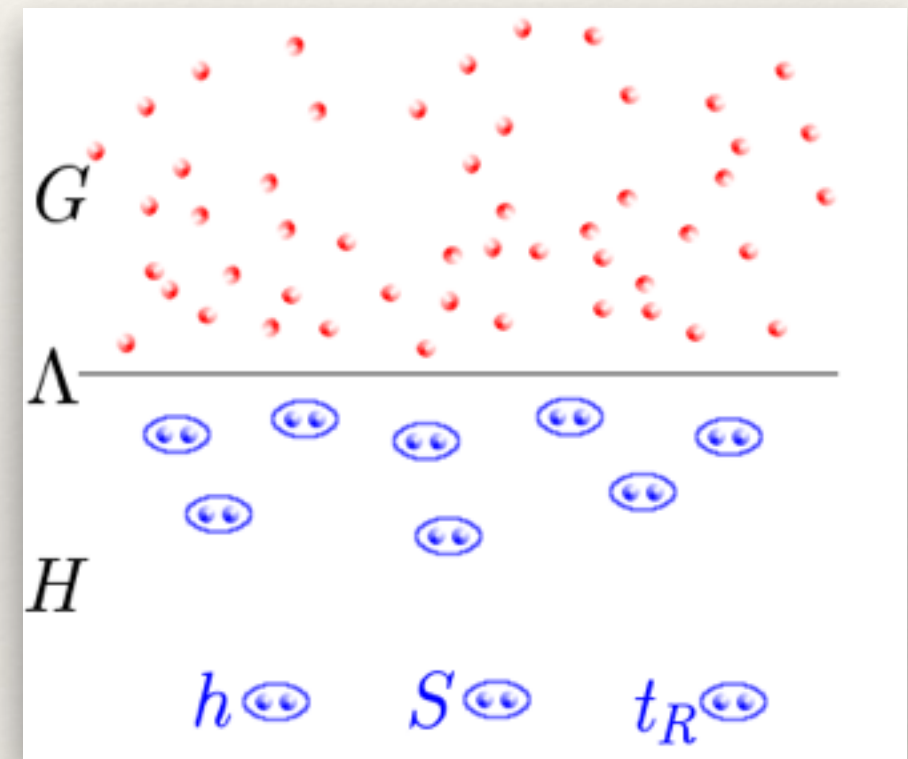
- ❖ Without Naturalness, still have:
  - ❖ Dark Matter (Baryon Triality)
  - ❖ Consistent with Leptogenesis
  - ❖ Improved Unification (Top Exotics)
  - ❖ Theory of Flavour
- ❖ Goldstones light by shift symmetry
- ❖ Split Spectrum avoids Flavour, LHC problems
- ❖ Long-lived SU(3) triplet signal



# Composite PNGB Higgs

Kaplan *et al*, Phys. Lett. **B136** 183; Kaplan *et al*, Phys. Lett. **B136** 187; Dugan *et al*, Nucl. Phys. **B254** 299; Contino *et al*, hep-ph/0306259; Agashe *et al* hep-ph/0412089

- ❖ New, strongly-coupled sector
- ❖ Global Symmetry  $G \supsetneq G_{SM}$
- ❖ Confines at  $\Lambda \approx g_{\rho} f$
- ❖ Symmetry breaking  $G \rightarrow H \supset G_{SM}$
- ❖ Higgs is among associated **pseudo-Goldstones**





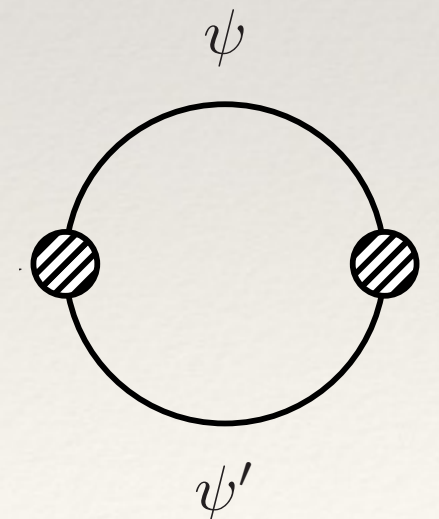
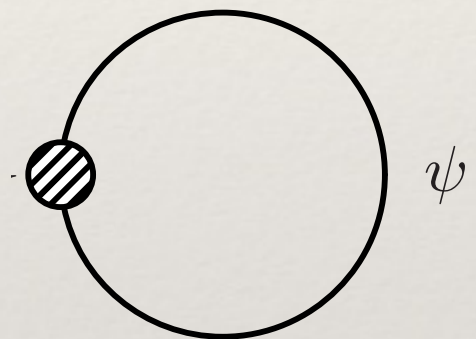
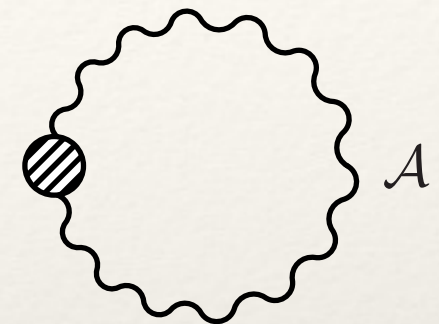


# Higgs Potential

- ❖ When SM couplings vanish:
  - ❖ PNGBs  $\rightarrow$  Goldstones
  - ❖ Goldstone potential vanishes
- ❖ So Higgs potential  $V = V(g, \lambda)$ 
  - ❖ “Calculable”
  - ❖ Loop-level:
  - ❖ Intrinsic Fine-Tuning (gauge vs fermion loops)

$$v_{EW} \sim \frac{\Lambda}{4\pi} \sim f$$

$$\Delta \sim \frac{v_{EW}^2}{f^2}$$



# General Features of Split Composite Higgs





# EW Precision Observables

❖ Peskin-Takeuchi parameters (Peskin & Takeuchi, PRL **65** 964)

❖ S: new neutral current physics (Contino, 1005.4269)

❖ Vector boson mixing

$$f \gtrsim 0.8 \text{ TeV}$$

❖ Higgs coupling shifts

$$\Delta S \sim \begin{array}{c} \text{Diagram 1: } W \text{ and } \rho \text{ mixing via } h \\ \text{Diagram 2: } W \text{ loop via } h \end{array} \sim \frac{m_W^2}{m_\rho^2} + \Delta \sim \frac{\alpha}{4\pi} \frac{v^2}{f^2}$$

---

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$$\mathcal{L}_{eff} \supset \frac{c_T}{2f^2} |H^\dagger D_\mu H|^2 \quad \Rightarrow \quad \Delta T \sim c_T \frac{v^2}{f^2} \quad \Rightarrow \quad f \gtrsim 6 \text{ TeV}$$

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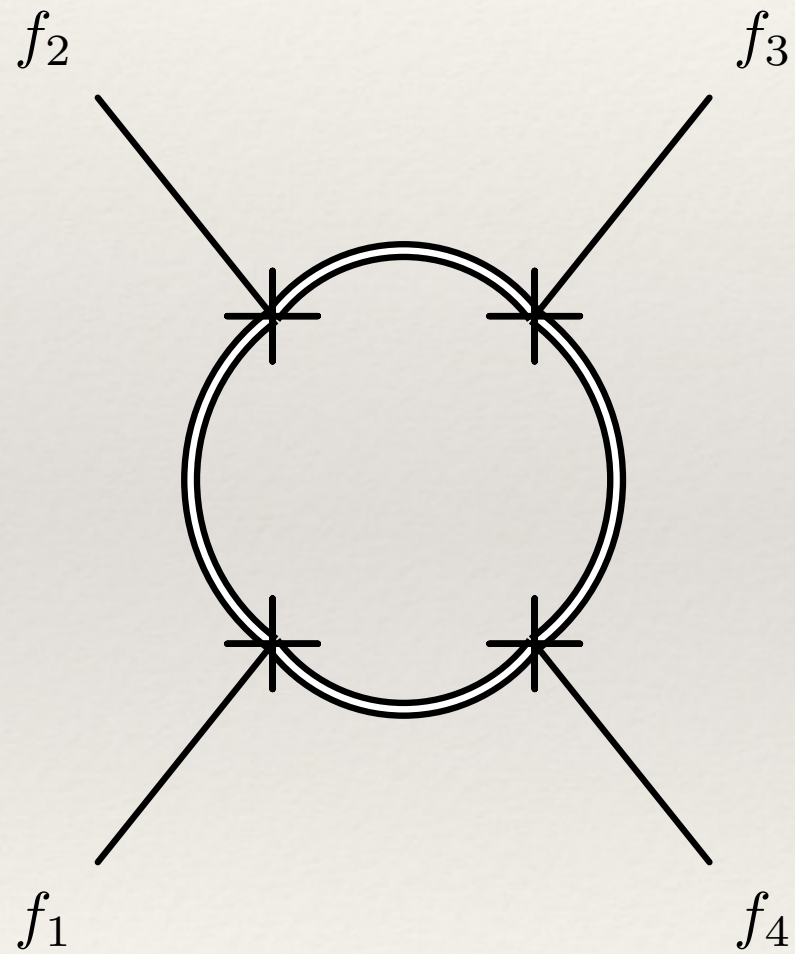
- ❖ Nearly all modern models use custodial SU(2)  
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- ❖ Unnatural models can avoid this: **SIMPLER**

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# Flavour Observables

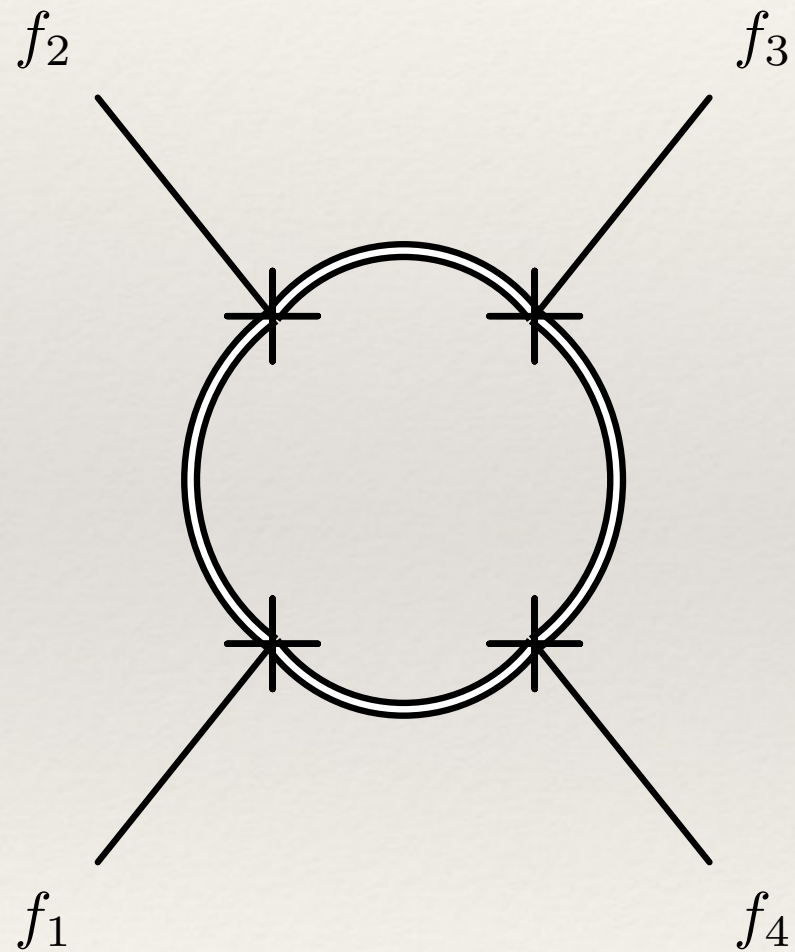
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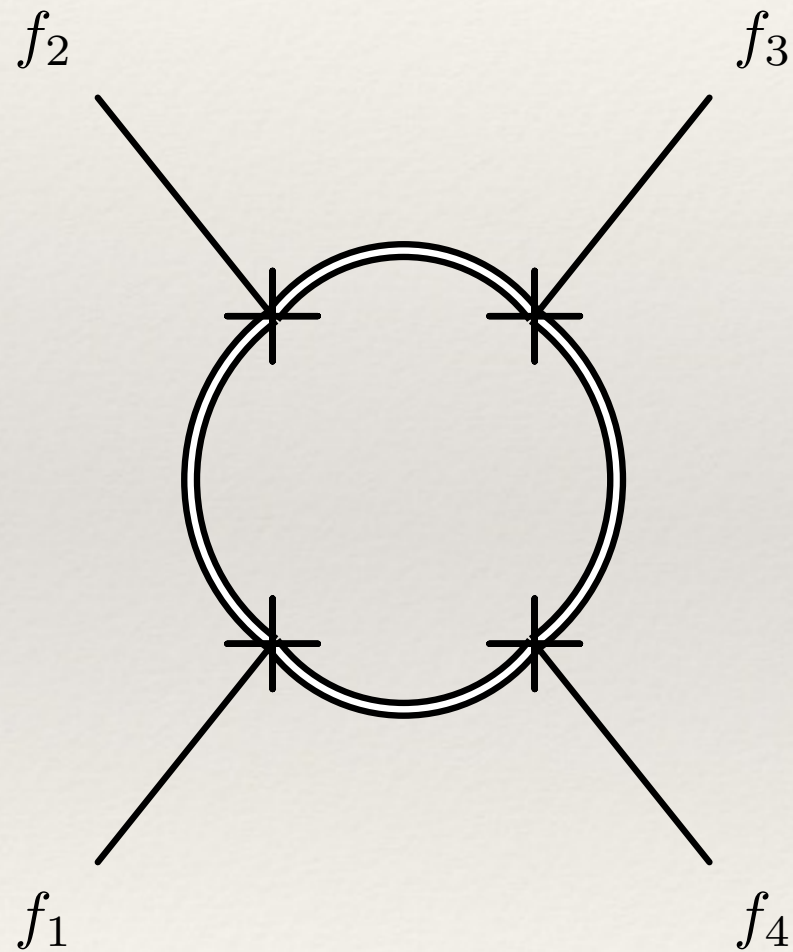
- ❖ **BUT!** result  $\propto$  Yukawas

$$\propto \frac{\sqrt{y_1 y_2 y_3 y_3}}{\Lambda^2}$$



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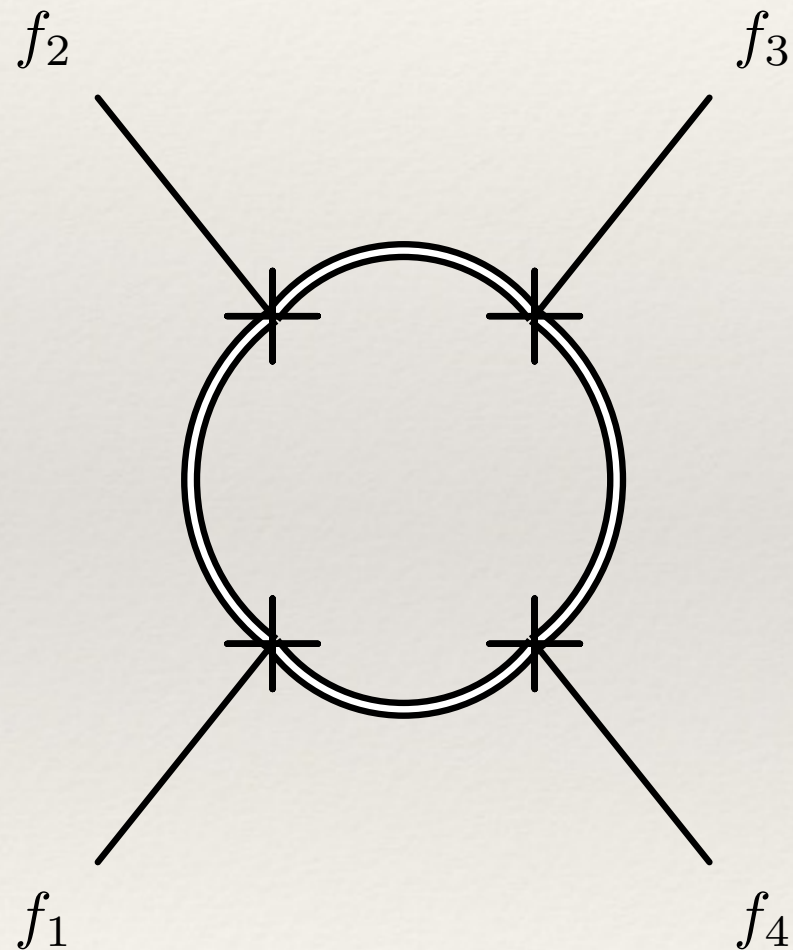
- ❖ RS-GIM mechanism

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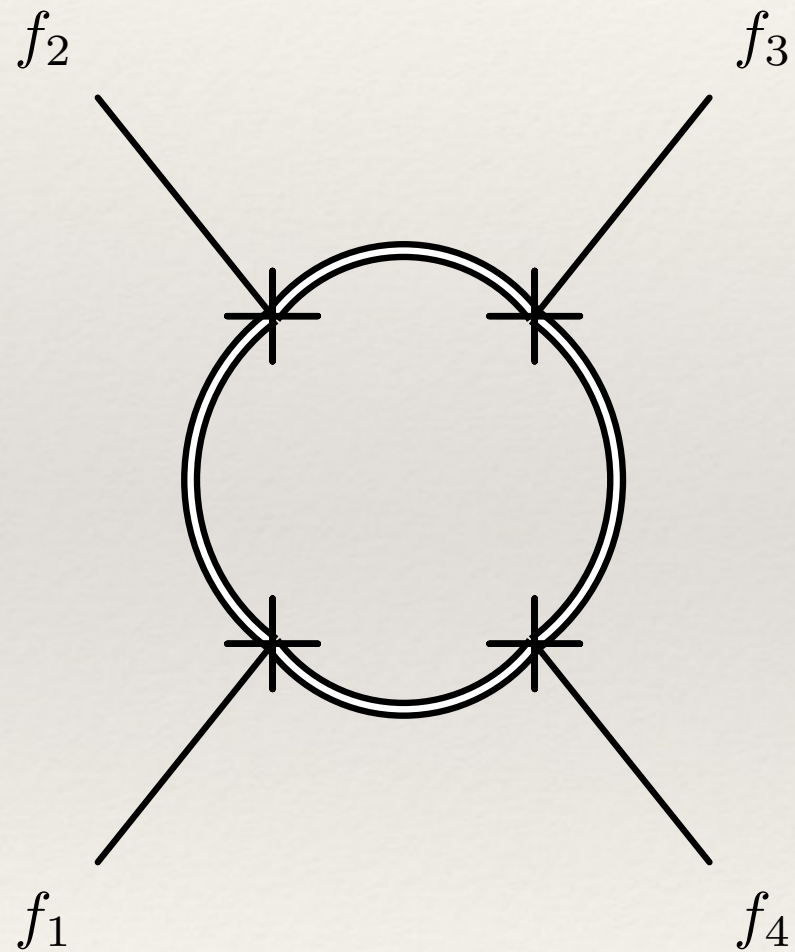
- ❖ Strongest Constraint ( $\epsilon_K$ ):

$$f \gtrsim 12 \text{ TeV}$$

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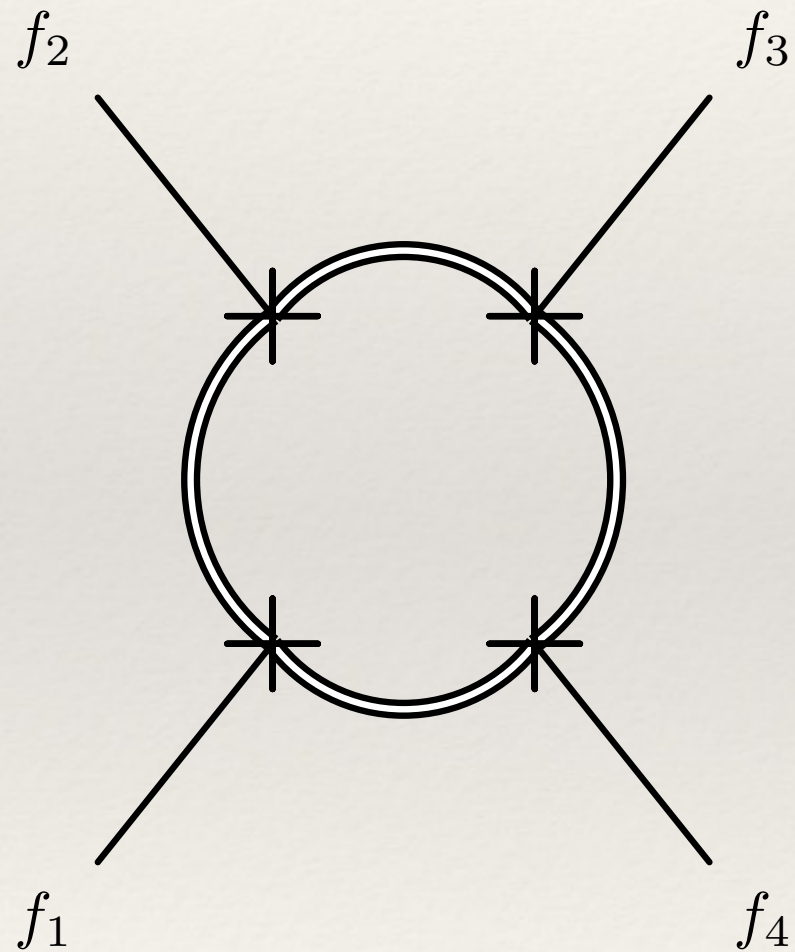
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- ❖ Or unnatural  $\rightarrow$  **SIMPLER**

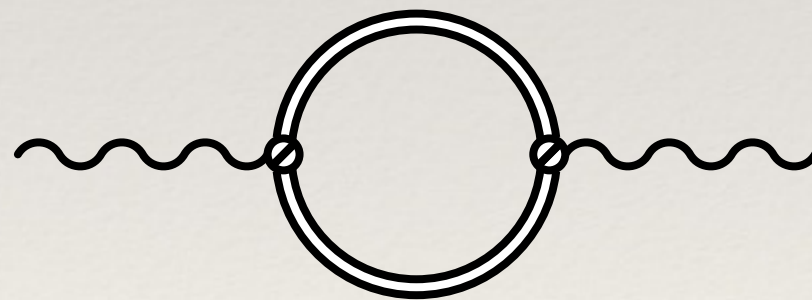
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# Calculable Gauge Unification

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Agashe *et al*, hep-ph/0212028, hep-ph/0403143, hep-ph/050222

- ❖ Unification scale  $M_{GUT} \gg f, \Lambda$
- ❖ Confining sector charged under SM gauge groups
- ❖ How to avoid **ruining** unification?



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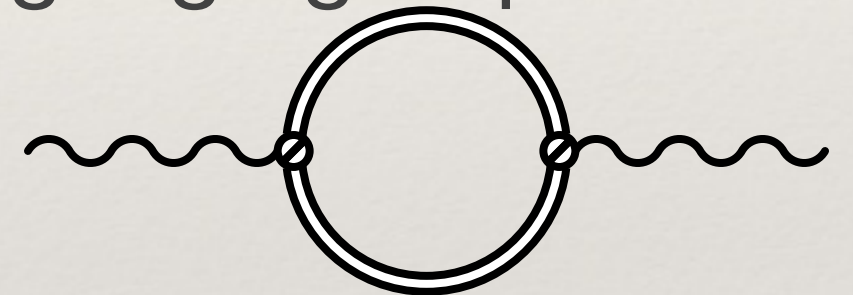
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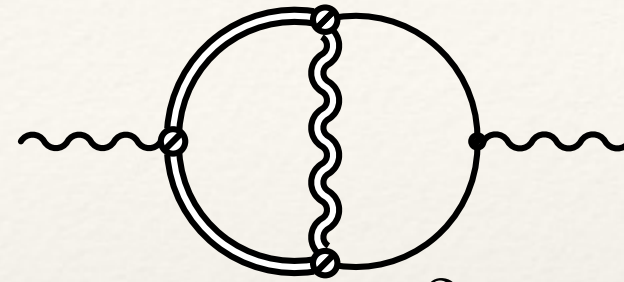
❖ Let  $G \supseteq G_{GUT}$

- ❖ Strong sector states come in **complete representations of SU(5)**
- ❖ **One-loop differential running unaffected** (away from Landau poles)
- ❖ Two-loop diagrams with SM, confining sector states, **do** affect running



# The Top Problem

- ❖ Generic two-loop running:



$$\frac{d}{d \ln \mu} \left( \frac{1}{\alpha_a} \right) = \frac{b_a}{2\pi} + \frac{B_{ab} \alpha_b}{2\pi 4\pi} + \frac{C_{af} c_f^2}{2\pi 16\pi^2} \left( \frac{f}{\Lambda} \right)^{2D_f}$$

- ❖ Largest effect involves  $t_R$ :  $D_t \approx 0$ ,  $c_t \approx g_\rho$

$$\frac{C_{at} c_t^2}{2\pi 16\pi^2} \left( \frac{f}{\Lambda} \right)^{2D_t} \sim \frac{\mathcal{O}(1)}{2\pi}$$

- ❖ Too large to be under control!



# Top Compositeness

- ❖ Solution: make  $t_R$  fully composite
  - ❖ Nearly composite anyway
- ❖ Chiral, so massless despite being composite
- ❖ Top Yukawa comes from  $Q_{3L}$  mixing term (only)

$$\frac{c_{Q3}}{\Lambda^{D_{Q3}}} \bar{Q}_{3L} \mathcal{O}^t \Rightarrow c_{Q3} \left( \frac{f}{\Lambda} \right)^{D_{Q3}} \bar{Q}_{3L} t_R H$$

- ❖ Above  $\Lambda$ , top within confining sector;  
gauge running **under control**



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# Composite Unification

---

❖ In a general theory,

$$\alpha(\mu) = \alpha_{\text{GUT}} + \text{SM} + \text{NP} + \text{M}_{\text{GUT-physic}}$$



---

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---

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- ❖ Simple metric for differential running

$$R \equiv \frac{b_2 - b_3}{b_1 - b_2}$$

- ❖  $R(\text{SM}) = 0.53$      $R(\text{MSSM}) = 0.71$      $R(\text{SM-h-t}_R) = 0.59$



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---

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- ❖ Higgs in **5** of  $\text{SU}(5)$ : expect Goldstone  **$\text{SU}(3)$  triplet  $T$**

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- ❖ If  $G_{\text{GUT}} \subset H$ , then  $h, t_R$  **NOT** only light composites!  $\begin{pmatrix} T \\ H \end{pmatrix}$
- ❖ Higgs in **5** of  $SU(5)$ : expect Goldstone  $SU(3)$  triplet  $T$
- ❖  $t_R$  in **10** of  $SU(5)$ : expect **other chiral fermions!**  $\begin{pmatrix} t_R & Q' \\ Q'^T & e' \end{pmatrix}$
- ❖ Need **elementary exotics** for vector-like masses
- ❖ Call these **Top Companions** (not partners)  $\begin{pmatrix} 0 & \tilde{Q}^c \\ \tilde{Q}^{cT} & \tilde{e}^c \end{pmatrix}$

# Precision Unification

- ❖ Exotic fermion masses similar to top Yukawa

$$c_\chi \bar{\chi}_L \mathcal{O}^t \Rightarrow c_\chi f \bar{\chi}_L \chi_R \quad m_\chi \sim f$$

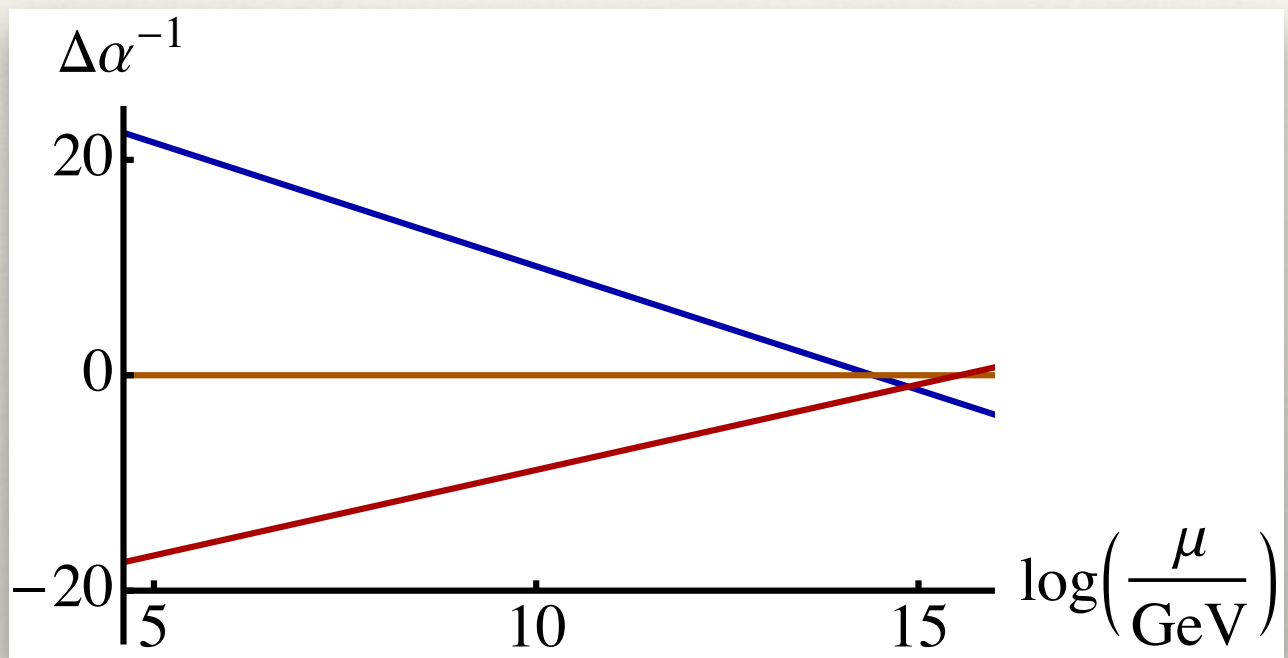
- ❖ At scale  $m_\chi \sim f$ , add nearly-complete GUT multiplet
- ❖ Effect on running equivalent to subtracting  $t_R^c$

$$R(\text{SM}-h-t_R-t_R^c) = 0.69$$

$$f \frac{\mathbf{10}/t_R \bar{\mathbf{10}}/t_R^c}{\text{SM}}$$

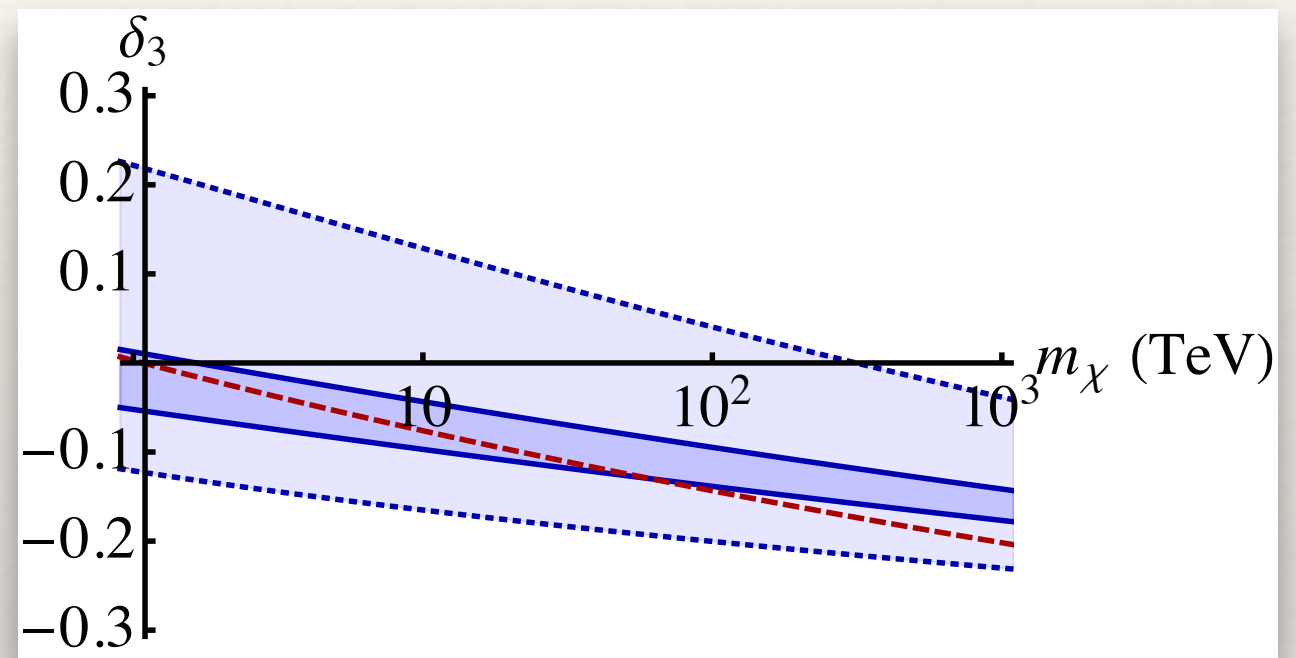
# An Upper Limit on $f$

## ❖ One-Loop Unification



## ❖ $m_\chi = 20$ TeV

## ❖ Two-Loop Unification



## ❖ Red: 5D Calculation

Choi & Kim, hep-th/0411090

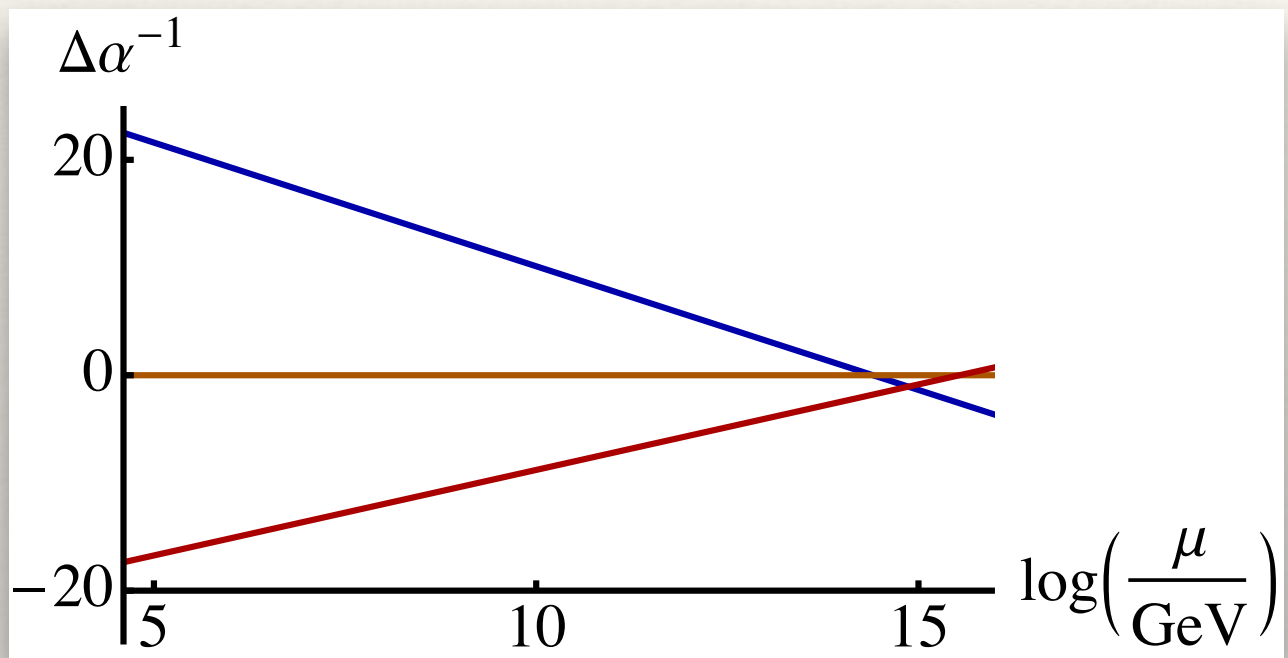
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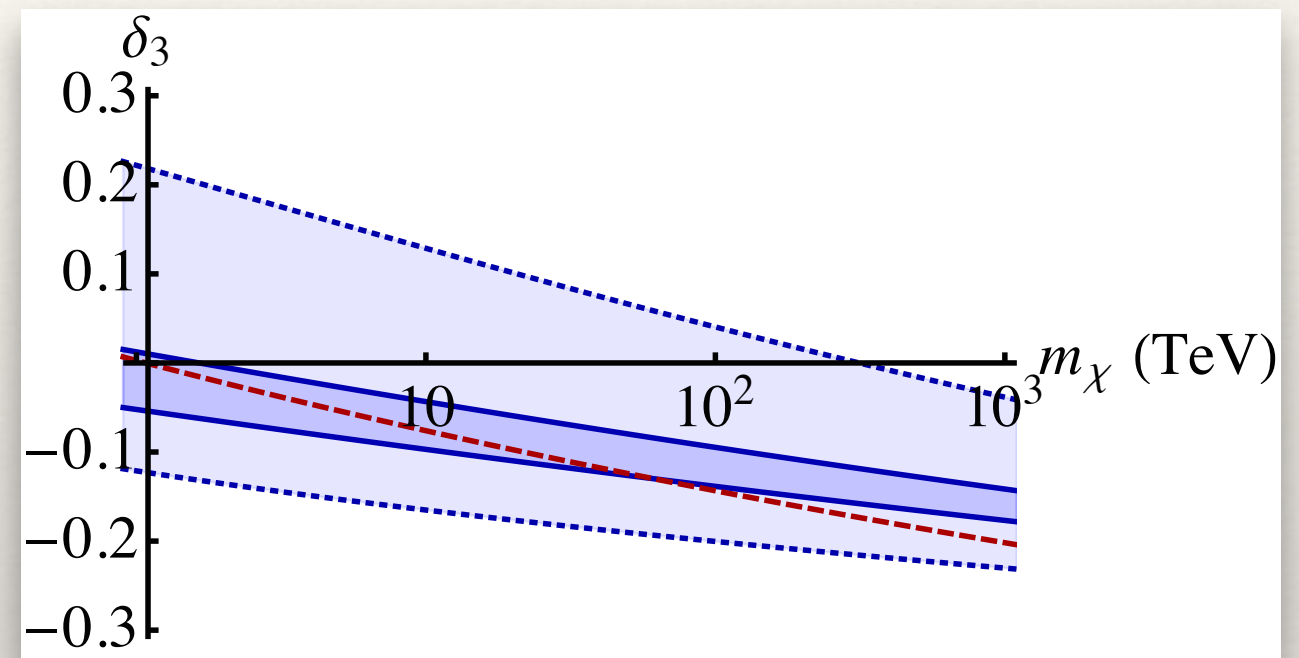
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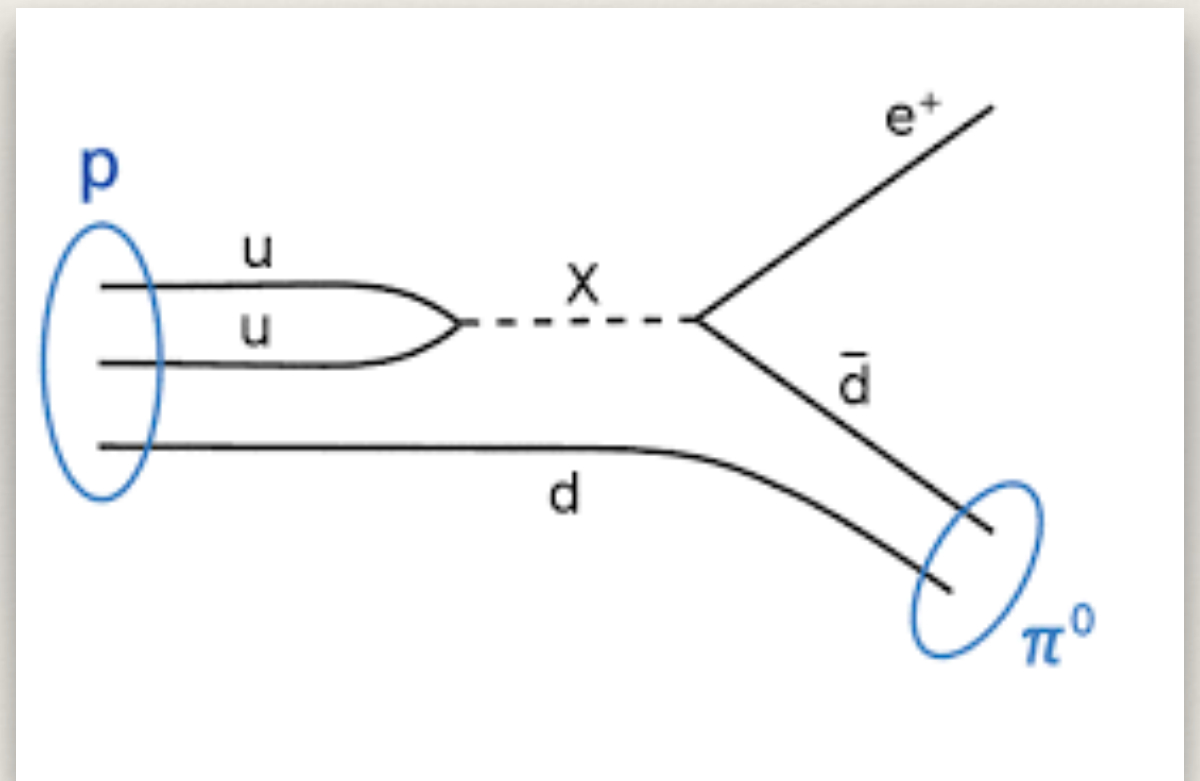
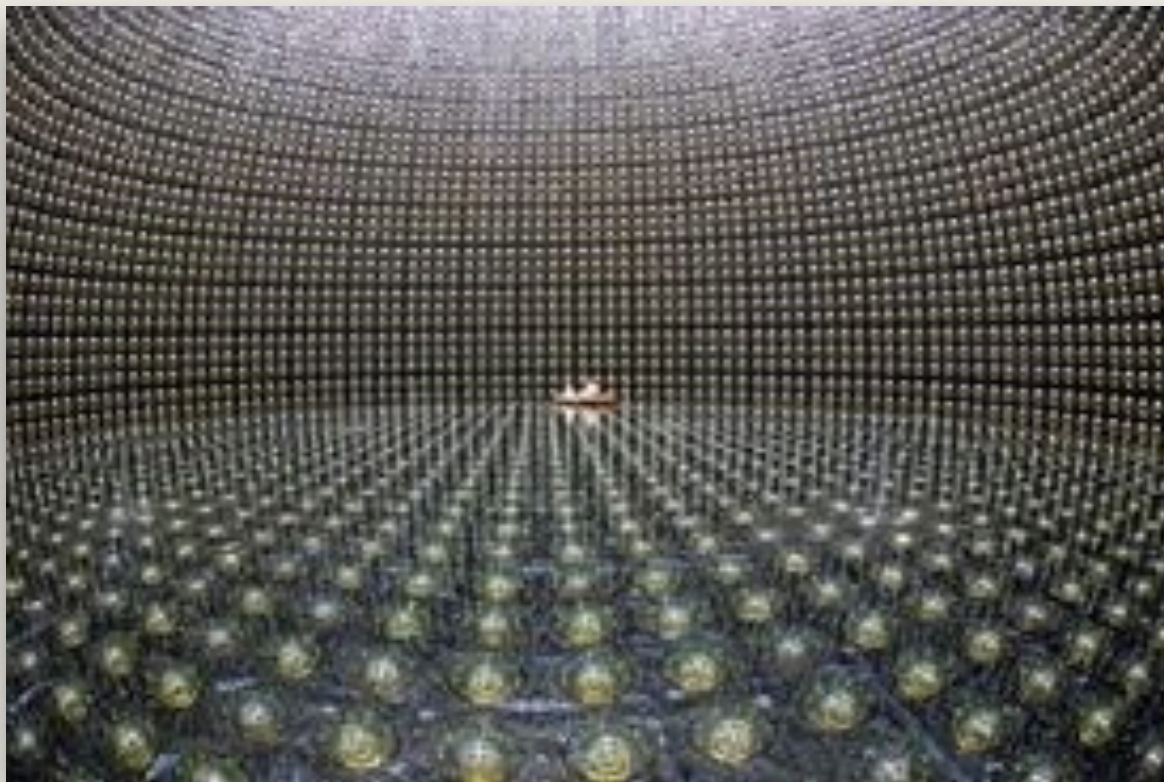
❖ Blue: 4D Estimate

$$f < 1000 \text{ TeV}$$

# Proton Decay and Dark Matter

Agashe & Servant hep-ph/0403143, hep-ph/0411254, Frigerio *et al* 1103.2997

- ❖ GUT multiplets at very low scale  $\Lambda$ : Proton Decay?





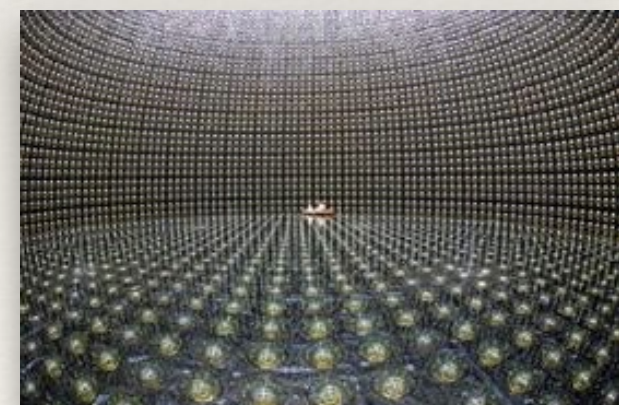
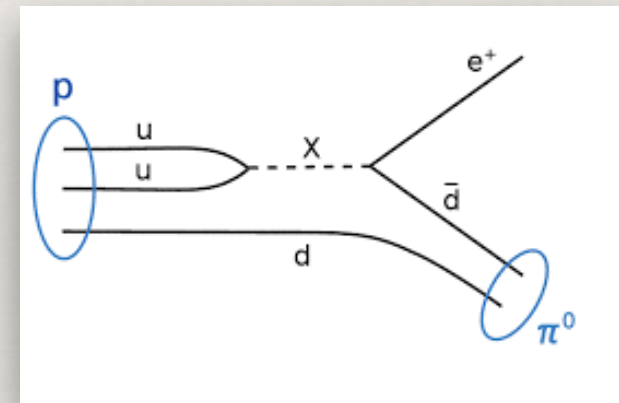
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- ❖ Promote  $U(1)_B$  to **global symmetry** of strong sector
- ❖ Interesting subgroup: Baryon Triality

$$\mathbb{Z}_B \equiv 3B - n_c \pmod{3}$$

- ❖ All SM states  $\mathbb{Z}_B$ -neutral: can stabilise DM
- ❖ Goldstone triplet has  $\mathbb{Z}_B$  charge!





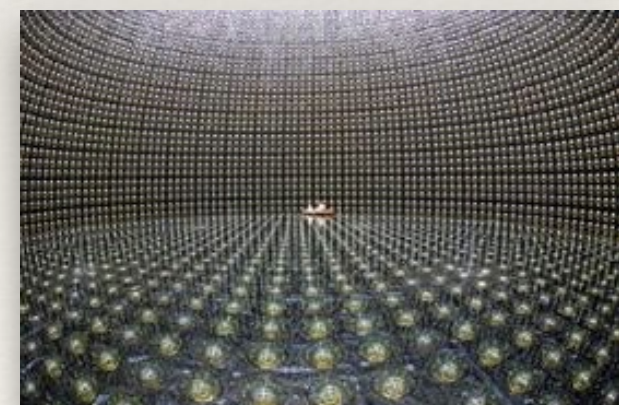
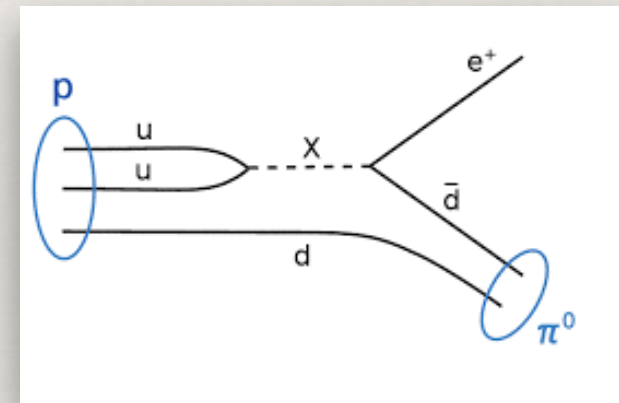
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  - ❖ Non-Renormalisable operators mediated by composite sector
$$\frac{1}{f^2} (\bar{\tilde{l}} Q_{3L}) (\bar{Q}_{3L} \tilde{l}) \quad \frac{1}{f} (H^\dagger \tilde{l})^2$$
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# An Explicit Model

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# Symmetry Breaking

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- ❖ Consider model **without custodial  $SU(2)$** , based on  $SU(5)$ 
  - ❖ For  $SO(10)$  (natural) model, see Frigerio *et al* 1103.2997
- ❖  $SU(5)$  models struggle to have top companion DM
  - ❖ Lack of neutral fermion outside electroweak doublet
- ❖ **Smallest groups:  $SU(6)/SU(5)$ ,  $U(6)/U(5)$ : DM unstable**

$$SU(6) \rightarrow \begin{pmatrix} SU(5) & 0 \\ 0 & 0 \end{pmatrix} \quad \Pi \sim \begin{pmatrix} T \\ H \\ e^{i\eta} \end{pmatrix}$$



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- ❖ So consider  $SU(7)/SU(6) \times U(1)$

$$SU(7) \rightarrow \begin{pmatrix} SU(6) & 0 \\ 0 & U(1)_7 \end{pmatrix} \quad \Pi \sim \begin{pmatrix} T \\ H \\ S \\ 0 \end{pmatrix}$$

# Dark Matter Stability: U(1)s

- ❖ Gauging breaks  $SU(6) \times U(1) \rightarrow SU(5) \times U(1) \times U(1)$

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- ❖ Linear combination of U(1)s stabilises S

$$U(1)_7 - 7U(1)_6 \sim \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -1 \end{pmatrix} \quad \Pi \sim \begin{pmatrix} T \\ H \\ S \\ 0 \end{pmatrix}$$



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- ❖ However, **fermion couplings** complicate things

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- ❖ Enlarge symmetry:  $U(7) \times U(1)_{B0} / U(6) \times U(1) \times U(1)_{B0}$ 
  - ❖ Expect  $U(N)$  global flavour symmetries
  - ❖ Need to add Baryon number anyway
- ❖ Fermion, gauge couplings break  $H \rightarrow G_{SM} \times U(1)_B$ 
$$U(1)_B \equiv \frac{1}{126} (6U(1)_E + U(1)_7 - 7U(1)_6 + 126U(1)_{B0})$$
- ❖ Goldstones have different charge under true  $U(1)_B$

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- ❖ Fermion, gauge couplings break  $H \rightarrow G_{SM} \times U(1)_B$ 
$$U(1)_B \equiv \frac{1}{126} (6U(1)_E + U(1)_7 - 7U(1)_6 + 126U(1)_{B0})$$
- ❖ Goldstones have different charge under true  $U(1)_B$



# Matter Embeddings

- ❖  $t_R$  (& hence top companions) in **15** of  $SU(6) = \mathbf{10} + \mathbf{5}$  of  $SU(5)$
- ❖ All SM Yukawas generated
  - ❖ Quarks couple to **35**
  - ❖ Leptons couple to **21**
  - ❖ Doublets couple to two operators
- ❖ Right-handed neutrinos  $N^c$ :
  - ❖ Needed for Majorana  $\nu$  masses
  - ❖ Allow leptogenesis

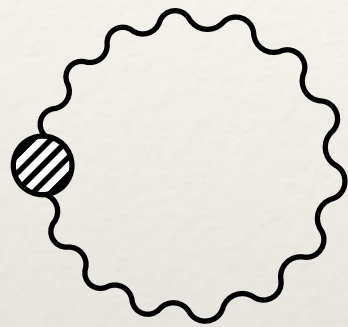
	$SU(7)$	$SU(6)$	$SU(5)$	$U(1)_L$	$U(1)_B$
$q(u)$	$\overline{\mathbf{35}}$	$\mathbf{20}$	$\mathbf{10}$	0	$\frac{1}{3}$
$q(d)$	$\mathbf{35}$	$\mathbf{20}$	$\mathbf{10}$	0	$\frac{1}{3}$
$u^c$	$\mathbf{35}$	$\mathbf{15}$	$\mathbf{10}$	0	$-\frac{1}{3}$
$d^c$	$\overline{\mathbf{35}}$	$\overline{\mathbf{15}}$	$\overline{\mathbf{5}}$	0	$-\frac{1}{3}$
$l(\nu)$	$\overline{\mathbf{21}}$	$\overline{\mathbf{15}}$	$\overline{\mathbf{5}}$	1	0
$l(e)$	$\overline{\mathbf{21}}$	$\overline{\mathbf{6}}$	$\overline{\mathbf{5}}$	1	0
$N^c$	$\mathbf{21}$	$\mathbf{6}$	$\mathbf{1}$	-1	0
$e^c$	$\mathbf{21}$	$\mathbf{15}$	$\mathbf{10}$	-1	0
$(\tilde{q}^c, \tilde{e})$	$\overline{\mathbf{35}}$	$\overline{\mathbf{15}}$	$\overline{\mathbf{10}}$	0	$\frac{1}{3}$
$(\tilde{d}^c, \tilde{l})$	$\mathbf{35}$	$\mathbf{15}$	$\overline{\mathbf{5}}$	0	0

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# Scalar Potential

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- ❖ Higgs VEV tuned; Higgs Mass set by **gauge loops**:



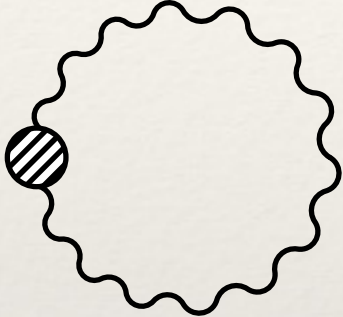
A Feynman diagram showing a scalar loop (represented by a scalloped circle) with a Higgs boson (represented by a shaded circle) attached to the left side. The diagram is associated with the equation  $\mathcal{A} = \frac{c_2^A f^4}{16\pi^2}$ .

$$\mathcal{A} = \frac{c_2^A f^4}{16\pi^2}$$

$$m_h^2 = \frac{3c_2^A g_\rho^2}{8\pi^2} M_W^2$$

# Scalar Potential

- ❖ Higgs VEV tuned; Higgs Mass set by gauge loops:



A Feynman diagram showing a scalar loop (represented by a wavy line) with a Higgs insertion (represented by a shaded circle) on the left side. The diagram is associated with the equation  $\mathcal{A} = \frac{c_2^A f^4}{16\pi^2}$ .

$$\mathcal{A} = \frac{c_2^A f^4}{16\pi^2} \qquad m_h^2 = \frac{3c_2^A g_\rho^2}{8\pi^2} M_W^2$$

- ❖ Triplet, Singlet masses typically

$$m_T \sim \frac{g_\rho f}{4\pi} \max[g_3, \lambda_\psi] \sim (1-2) \frac{f}{\pi} \qquad m_S \sim \frac{g_\rho f}{4\pi} \max[\lambda_\chi, \lambda_b] \sim \frac{f}{\pi}$$

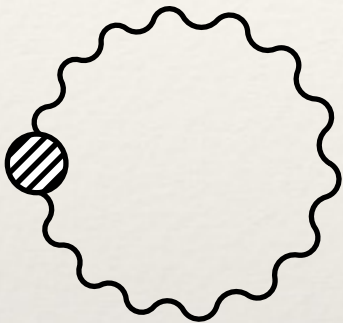


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# Scalar Potential

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- ❖ Higgs VEV tuned; Higgs Mass set by gauge loops:


$$A = \frac{c_2^A f^4}{16\pi^2} \qquad m_h^2 = \frac{3c_2^A g_\rho^2}{8\pi^2} M_W^2$$

- ❖ Triplet, Singlet masses typically

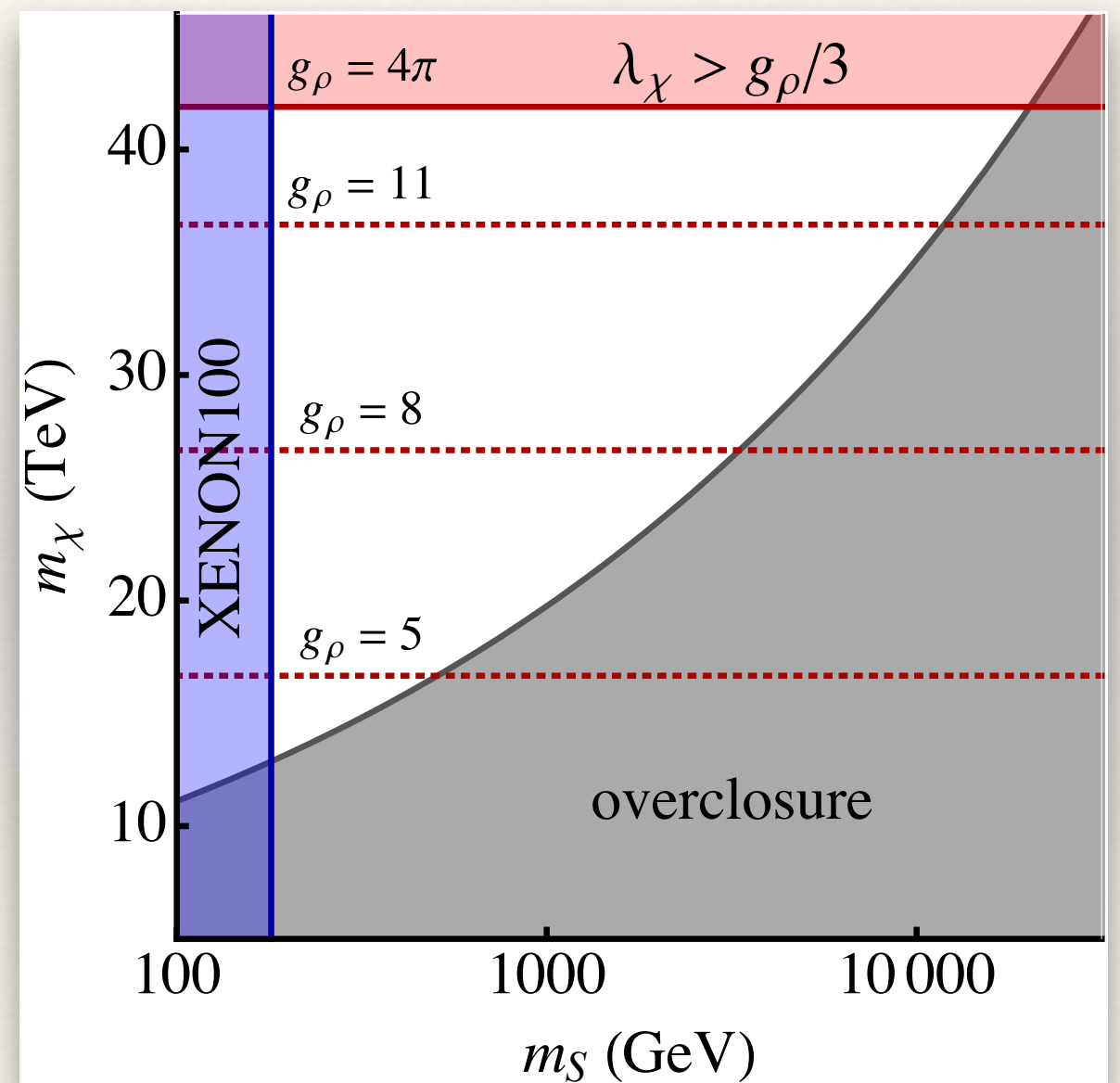
$$m_T \sim \frac{g_\rho f}{4\pi} \max[g_3, \lambda_\psi] \sim (1-2) \frac{f}{\pi} \qquad m_S \sim \frac{g_\rho f}{4\pi} \max[\lambda_\chi, \lambda_b] \sim \frac{f}{\pi}$$

- ❖ **Singlet** can be tuned **lighter**; needed to fit relic density
  - ❖ For  $f \sim 10$  TeV, only  $\sim$  **few to 25 percent tuning**

# Dark Matter Phenomenology

$$V \supset -\mu^2 H^\dagger H + m_S^2 S^\dagger S + \lambda (H^\dagger H)^2 + \kappa (H^\dagger H) (S^\dagger S)$$

- ❖ Higgs portal singlet  
Cline *et al*, 1306.4710
- ❖  $\kappa$  set by top companion loops:  
 $\kappa \sim 0.02 (m_\chi/f)^4$
- ❖ Limits:
  - ❖ Direct Detection  $m_S > 300$  GeV
  - ❖ Calculability  $\lambda_\chi < g_\rho/3$
  - ❖ Relic Density bounds  $\kappa \rightarrow m_\chi$
- ❖ DD best hope for signal



# Collider Phenomenology



# General Features

❖ Higgs deviations from SM  $\sim v^2/f^2$

❖ Unnatural models untestable this way

❖ Typical Spectrum

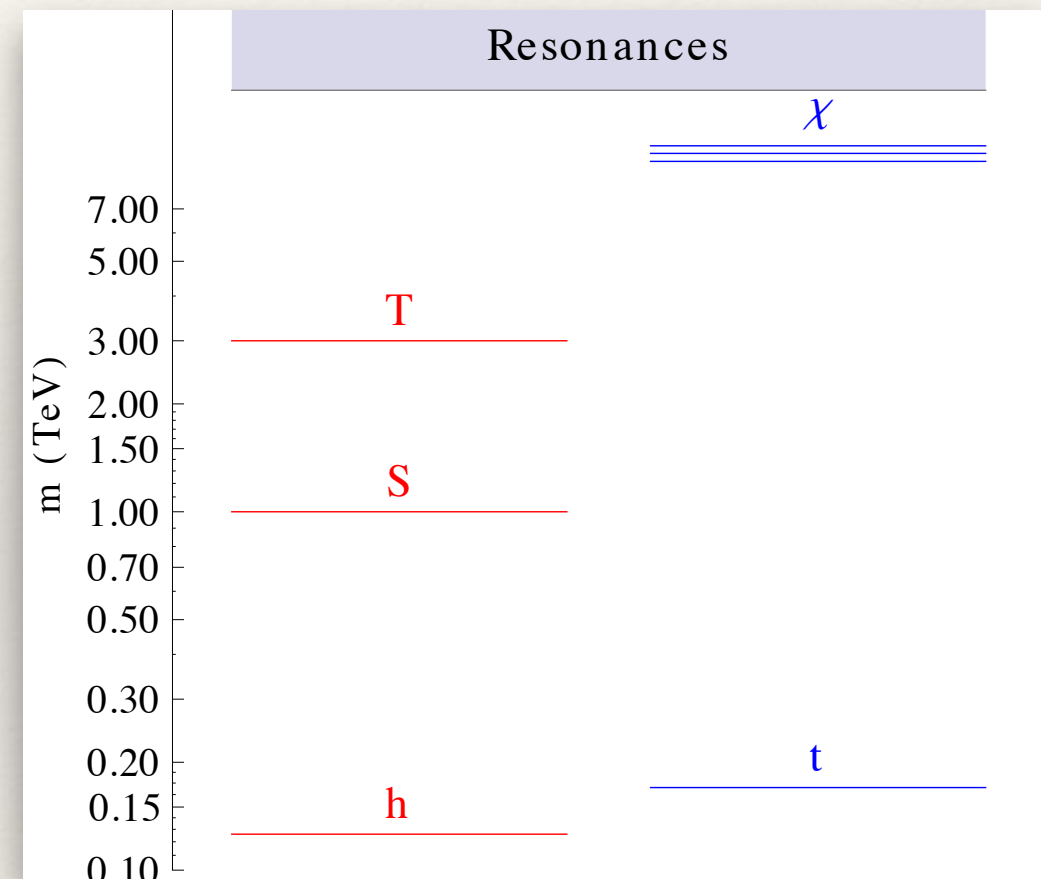
$$m_\chi \sim (1-2)f \quad m_T \sim \frac{(1-2)}{\pi}f \quad m_{DM} \sim 1 \text{ TeV}$$

❖ Top Companions decay promptly

❖ Triplet decays to  $t$   $b$  DM DM

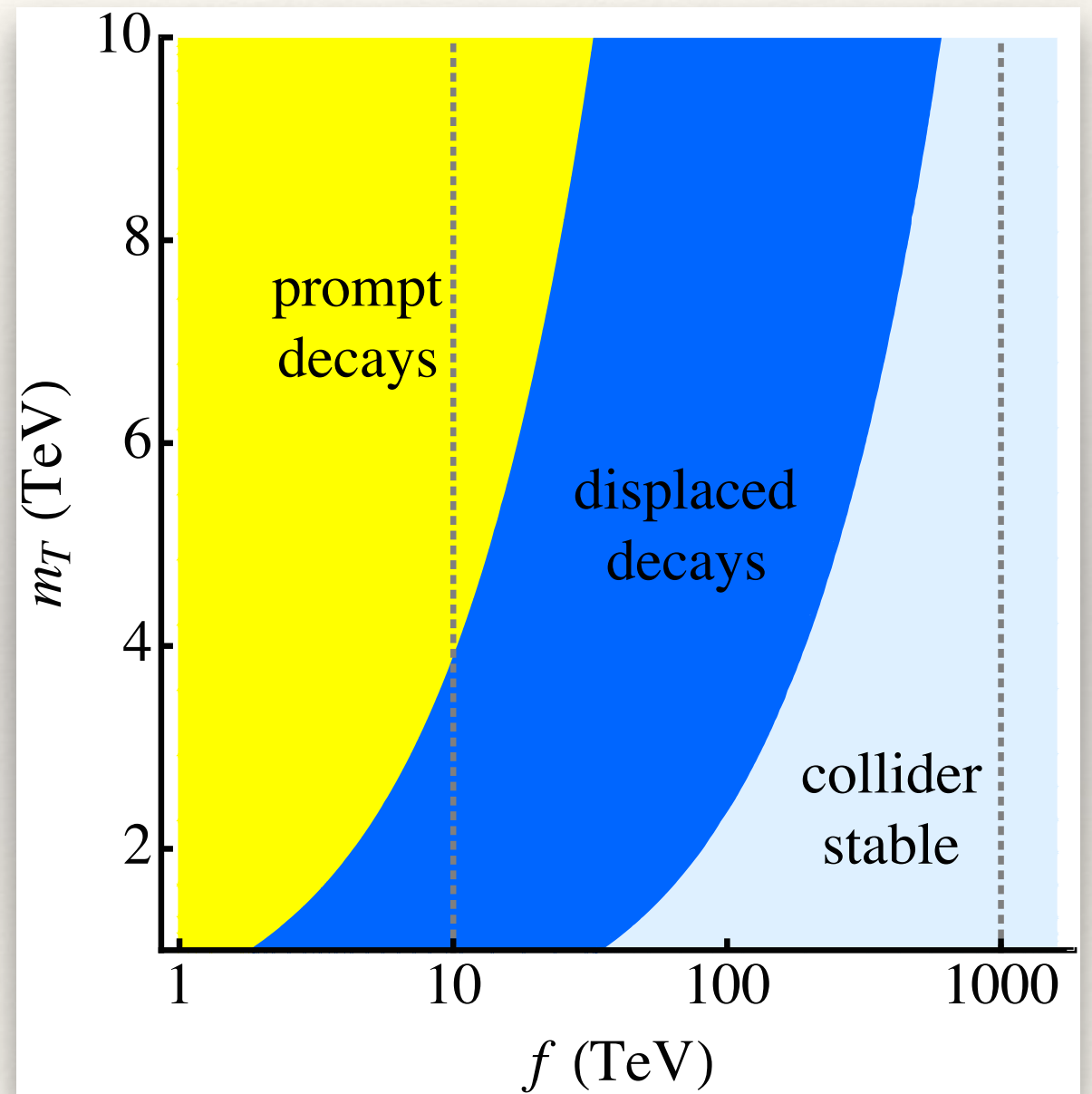
❖ Top companion DM: fermion number

❖ Goldstone DM: accidental  $Z_2$



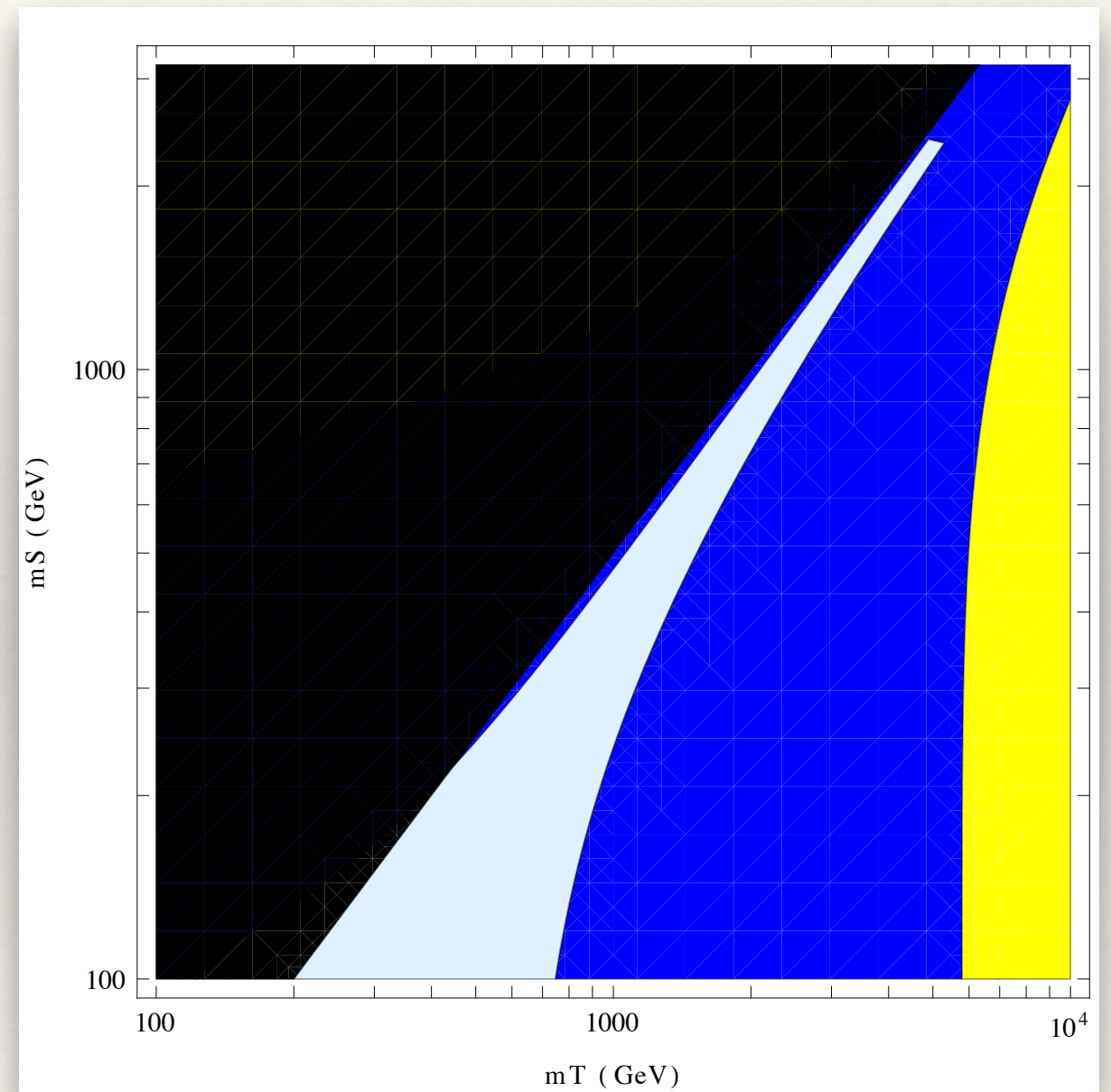
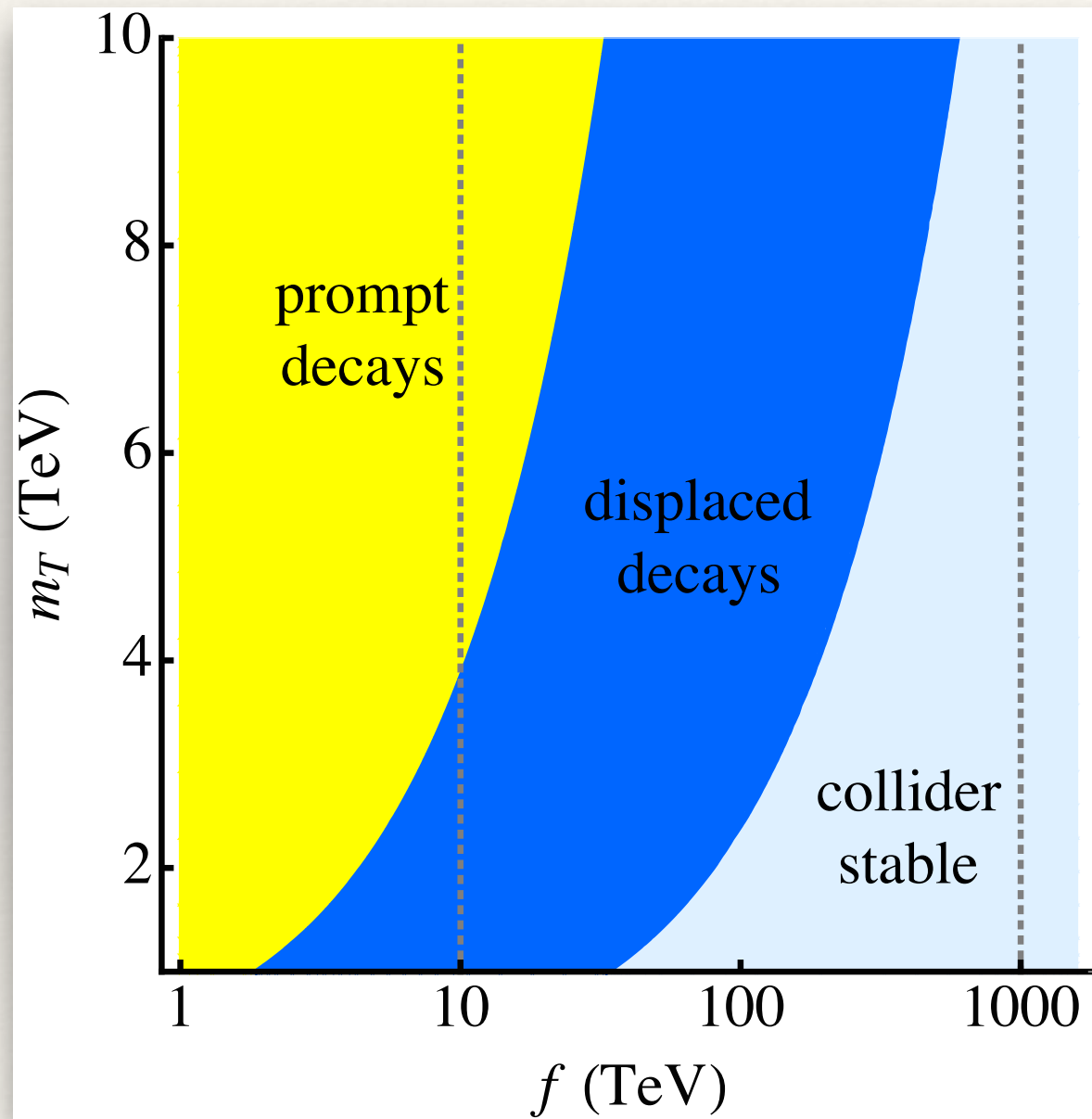
# Scalar Triplet Decays

- ❖ Triplet decay suppressed: phase space,  $m_T/f$
- ❖ Triplet can decay promptly/displaced/collider stable
- ❖ Long-lived state marker for split spectrum
  - ❖ Compare gluino in split-SUSY



# Scalar Triplet Decays

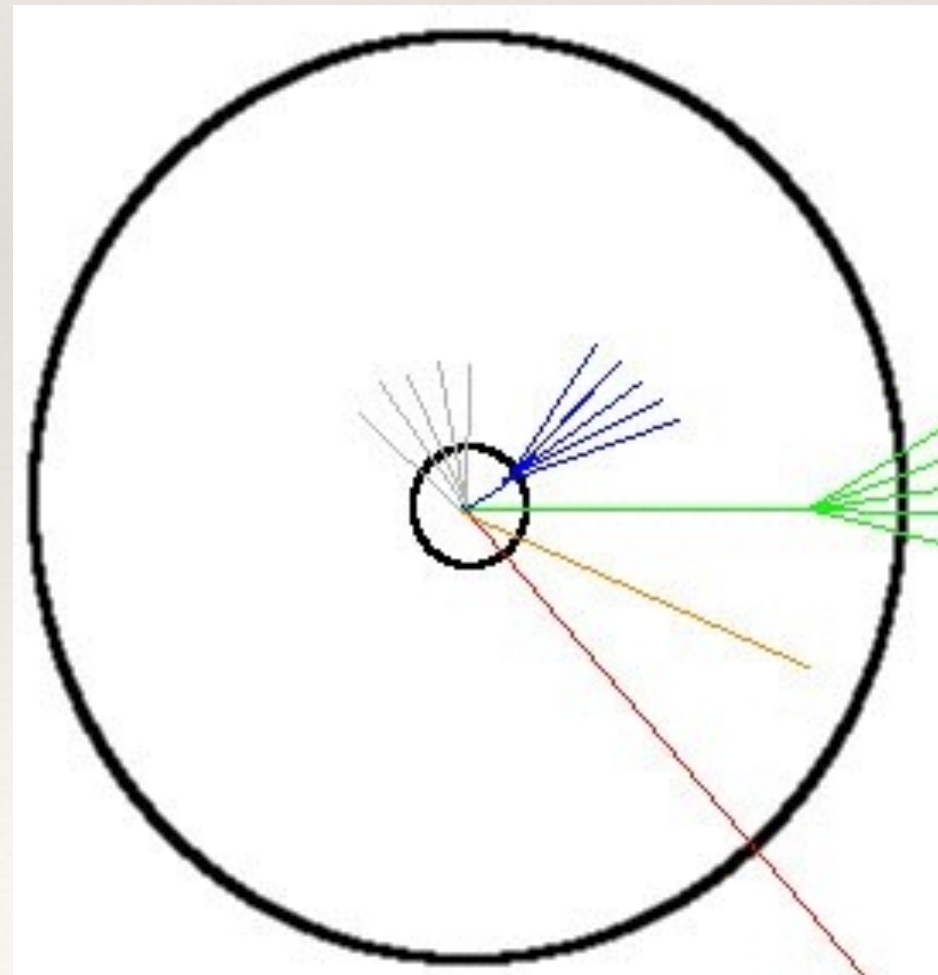
$$f = 10 \text{ TeV}$$



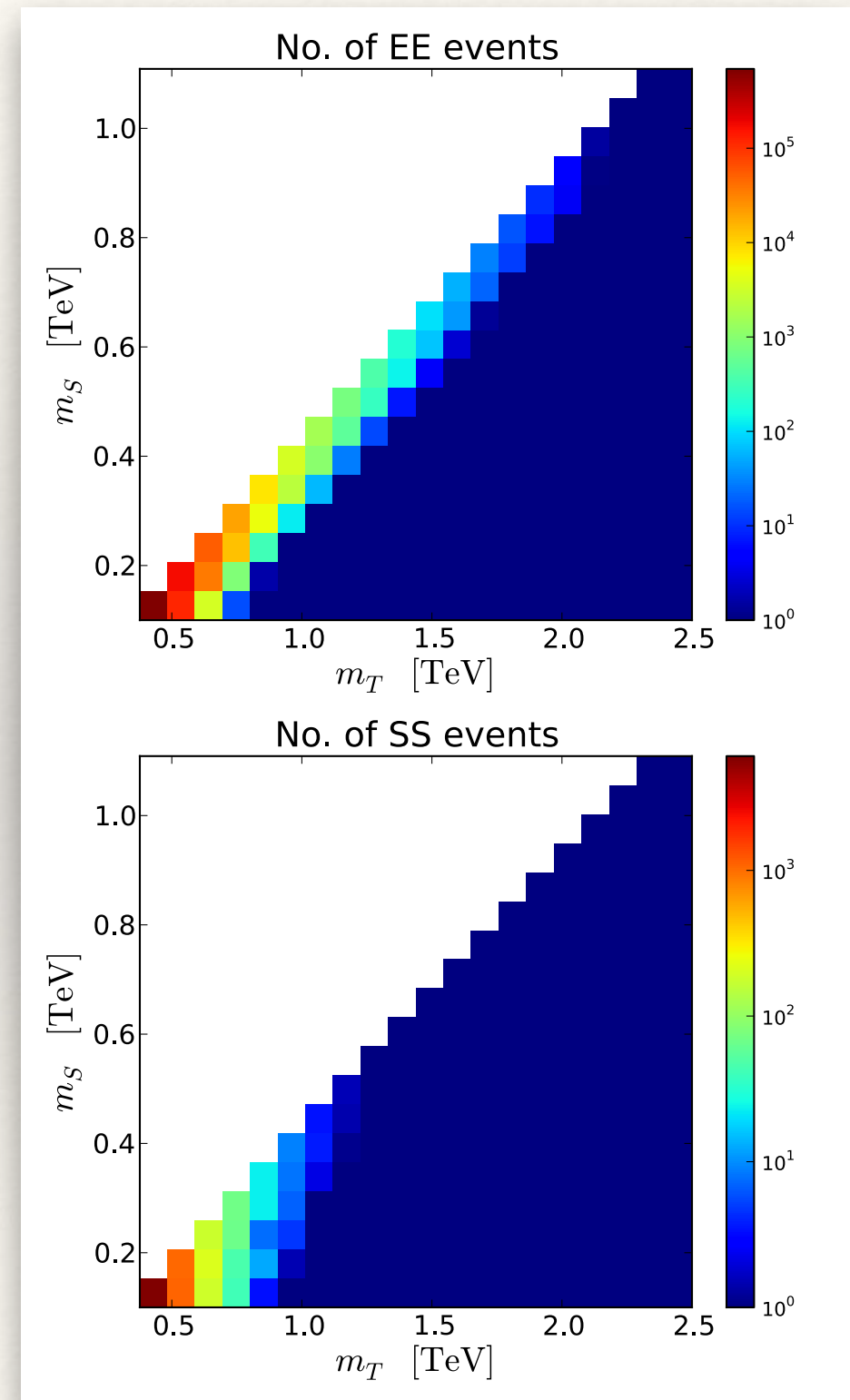
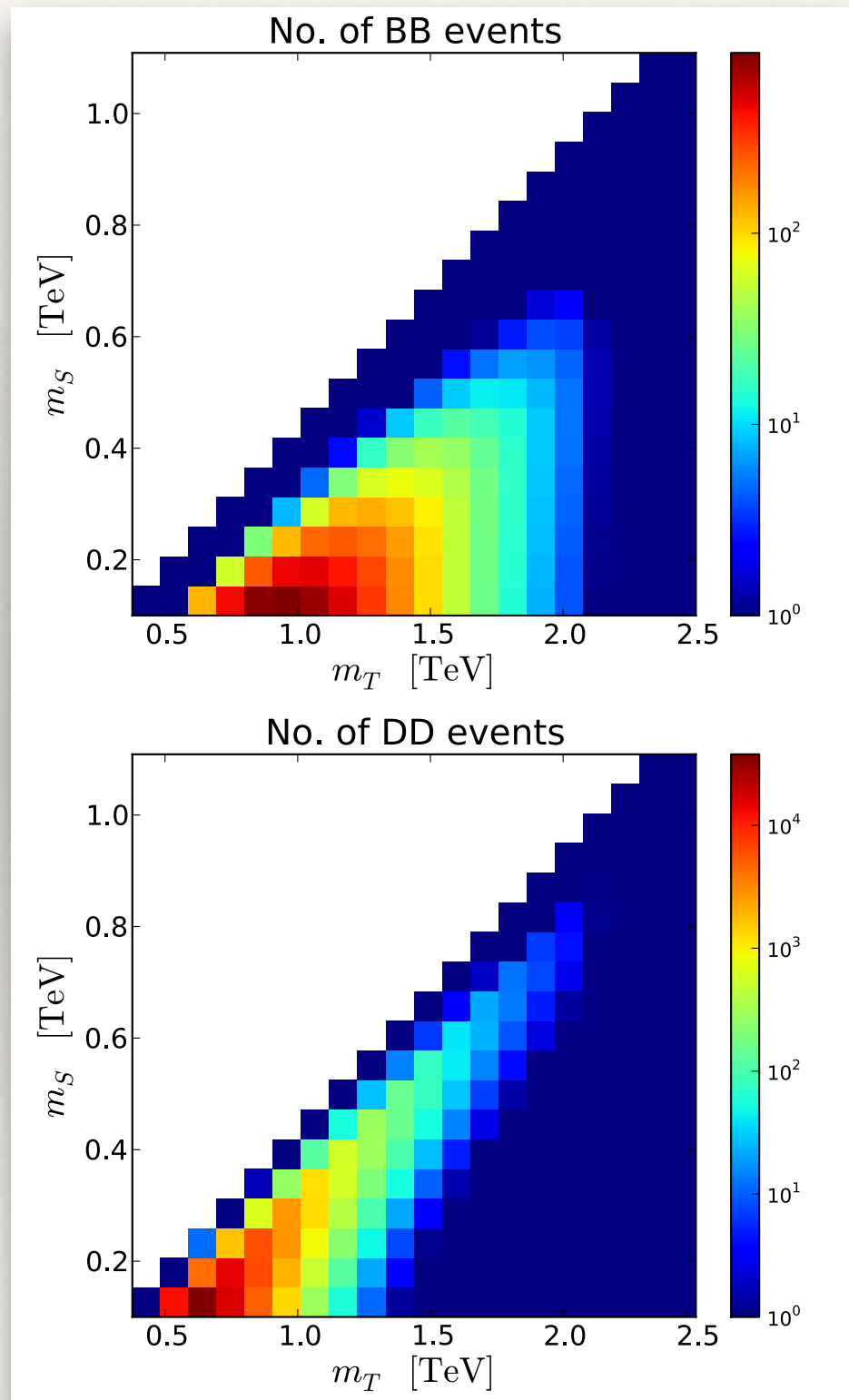


# Qualitative Collider Events

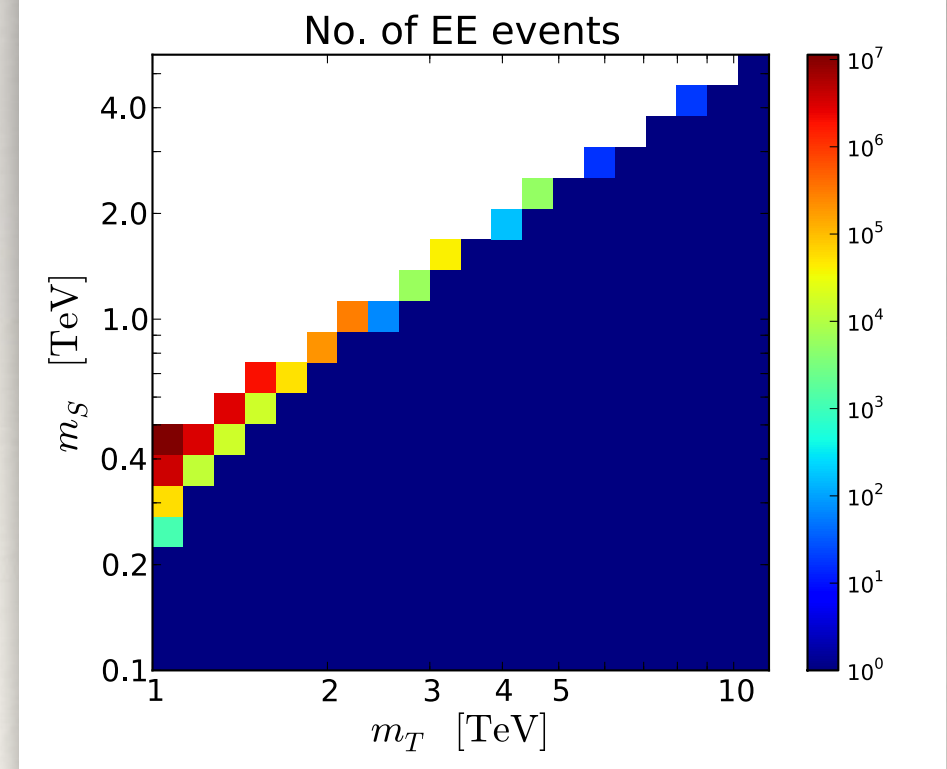
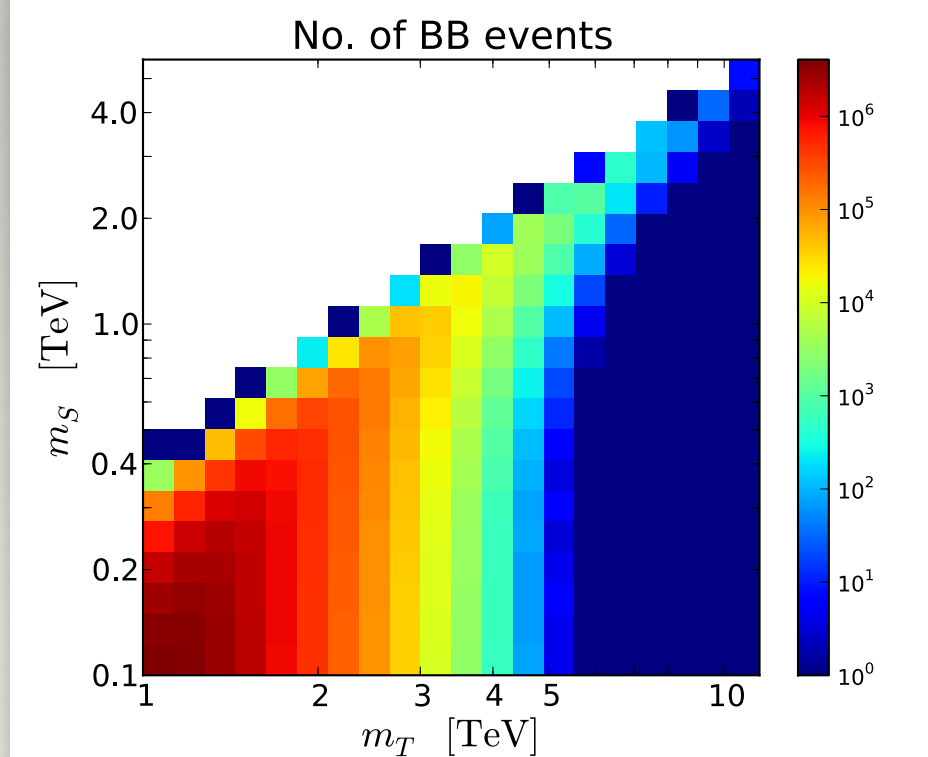
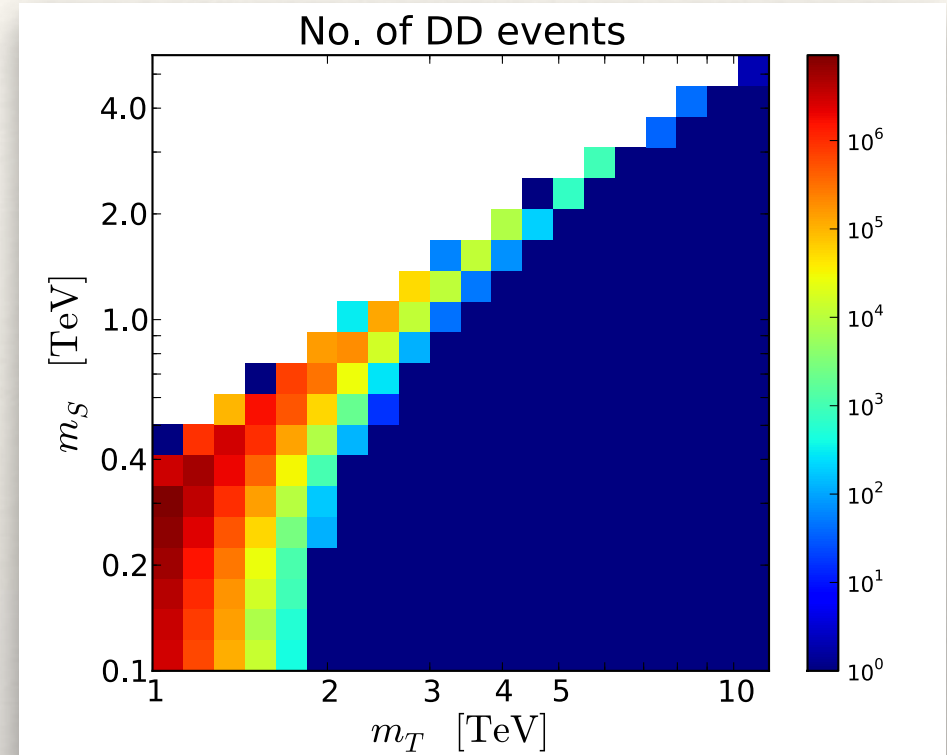
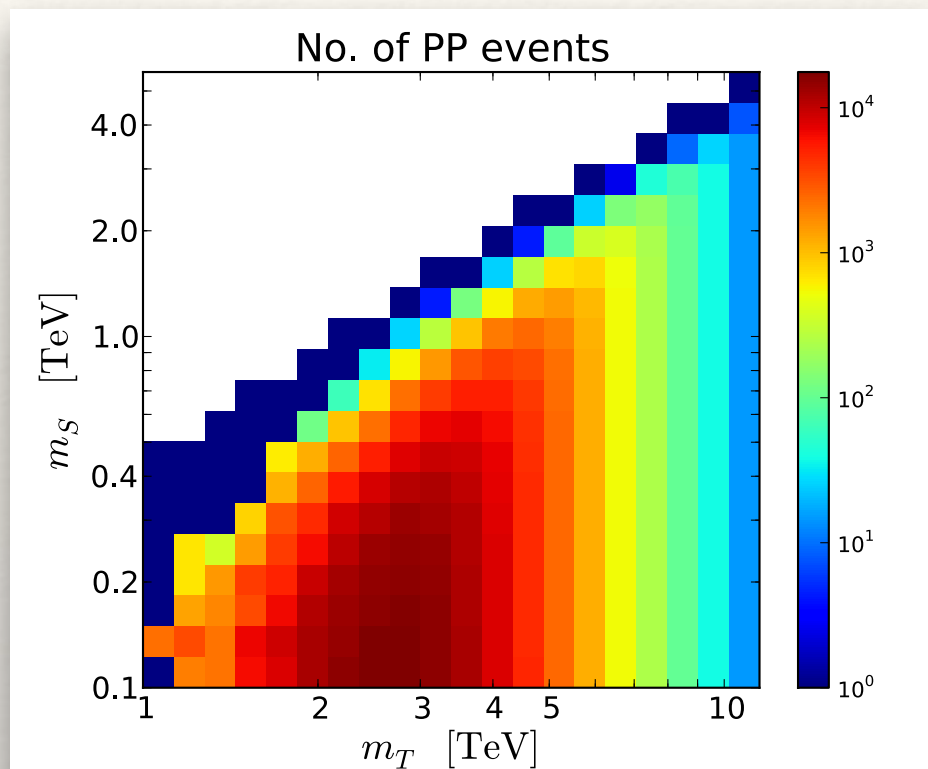
- ❖ Top companions too heavy even for 100 TeV collider
- ❖ Strongest collider signals:  $T^{\dagger}T$  production
- ❖ Classify events by decay lengths on either side
  - ❖ P: Prompt Decay
  - ❖ B: Beam-pipe Decay
  - ❖ D: Detector Decay
  - ❖ S: Stopped in Detector
  - ❖ E: Escape Detector



# LHC Events (13 TeV)



# 100 TeV Events ( $3\text{ab}^{-1}$ )





# Conclusions

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# Conclusions

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- ❖ Unnatural models worthy due to flavour, EWPO, LHC
- ❖ Unnatural Composite Higgs valid alternative to SUSY
- ❖ Gauge Unification, dark matter give bound  $f < 1000$  TeV
- ❖ Light scalar triplet is generic and long-lived
- ❖ Explicit  $SU(5)$  model with scalar dark matter given
- ❖ Future directions: Collider phenomenology, Baryogenesis, Other Cosets

# Back-up Slides



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# Neutrino Masses

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- ❖ If new sector violates  $L$ , will generate Weinberg term:

$$\mathcal{L} \supset \frac{1}{f} |L H|^2$$

- ❖ This is forbidden:  $m_\nu \sim 0.06 - 6 \text{ GeV}$

- ❖ We must impose  $U(1)_L$  as a symmetry of strong sector

- ❖ So neutrino masses require  $N_R$

- ❖ Majorana  $N_R$  lead to  $\nu_L$  masses via controlled  $L$  violation

$$\mathcal{L} \supset N_R \mathcal{O}^N + L \mathcal{O}^L \quad \Rightarrow \quad \frac{f}{m_N^2} |LH|^2$$

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# Incomplete Generations and Baryon Number

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- ❖ Three generations of chiral fermions:

$L$	$\bar{d}_R$	$\bar{e}_R$	$Q_L$	$\bar{t}'$
0	$-\frac{1}{3}$	0	$\frac{1}{3}$	$-\frac{1}{3}$
$\tilde{l}$	$\tilde{d}^c$	$\tilde{e}^c$	$\tilde{q}^c$	$t''$
0	0	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$
$l'$	$e'$	$d'^c$	$q'$	$\bar{t}_R$
0	0	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$