University of Southampton, 22nd May 2015

The Unnaturally Split Composite Higgs

inc. arXiv:1409.7391

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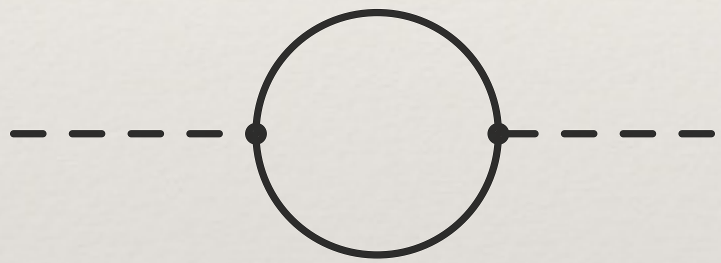
Outline

- 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) x U(1) Theory
- Collider Phenomenology
- Conclusions

Introduction

Naturalness

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



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

- To avoid large accidental cancellations, expect

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

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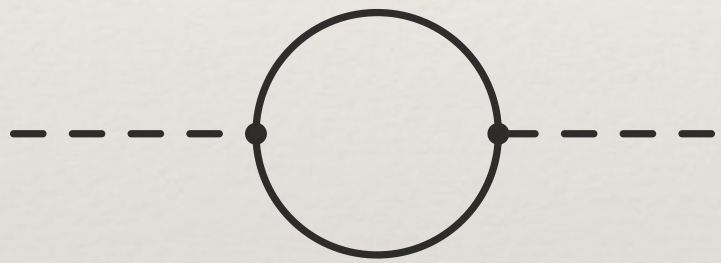

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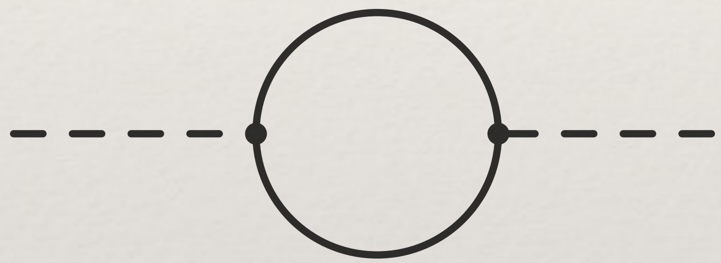

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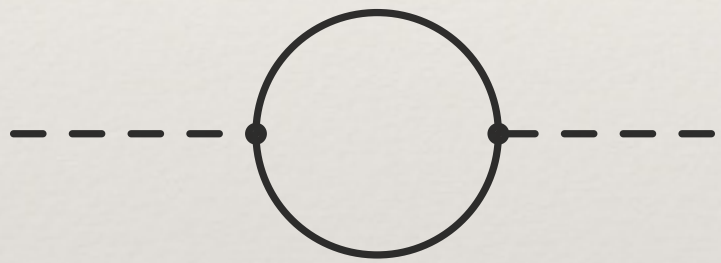

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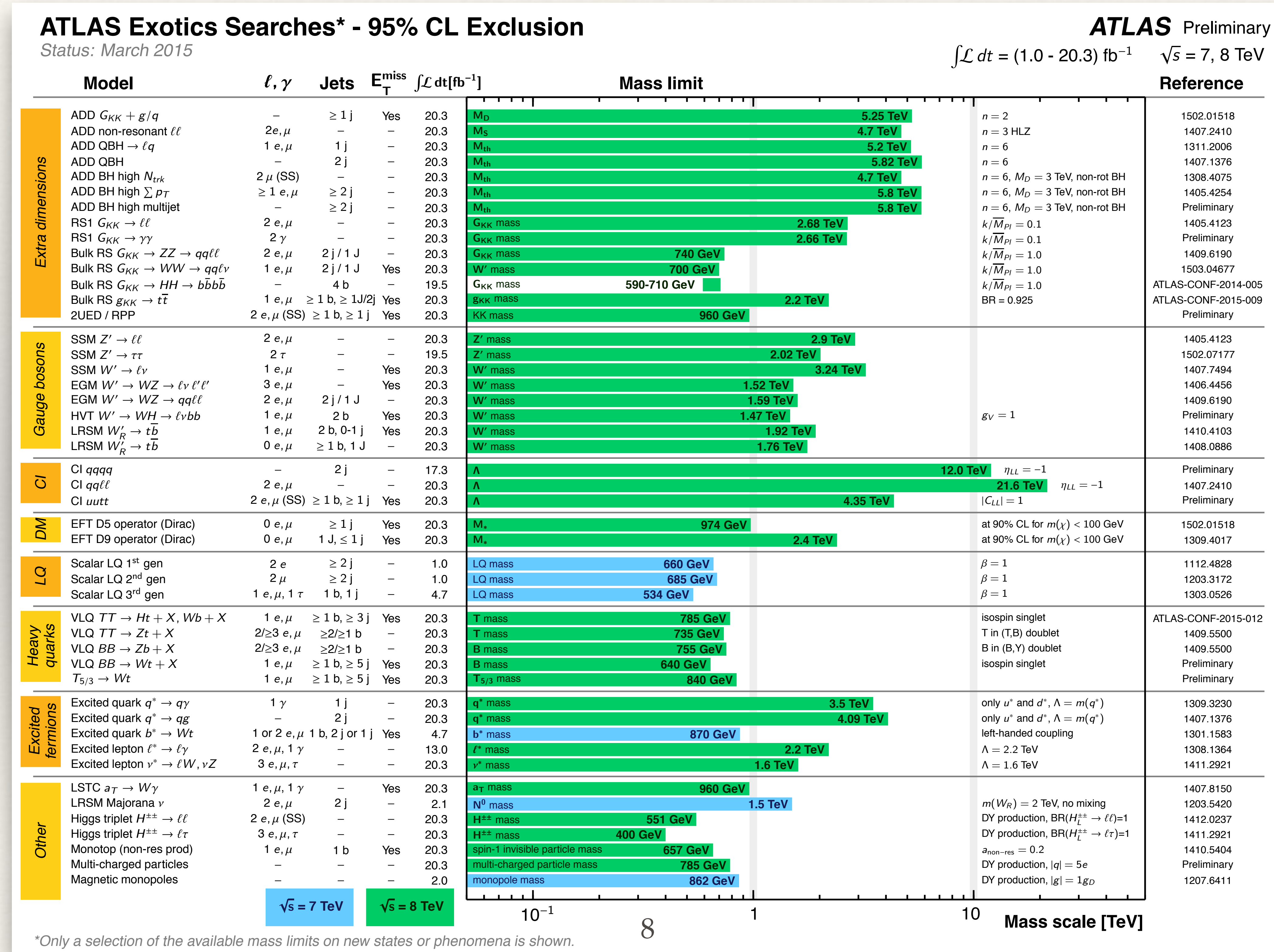
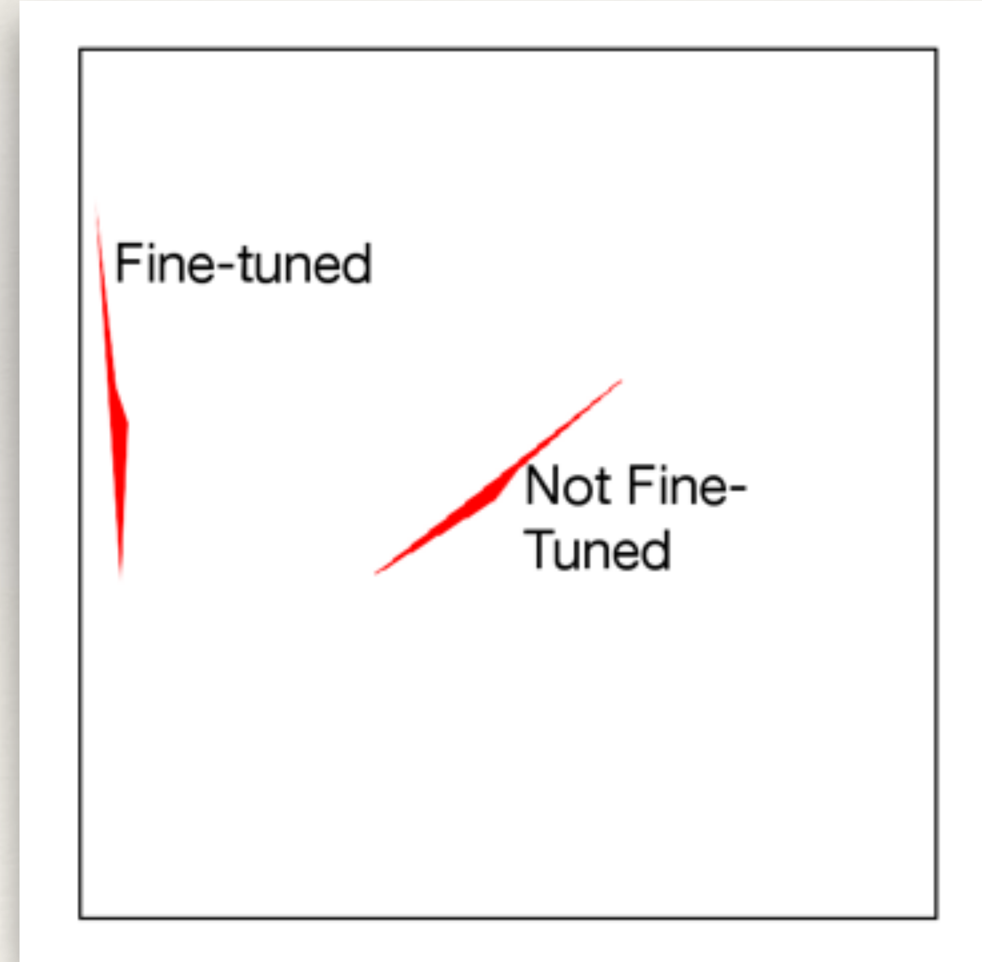
Facing the Evidence



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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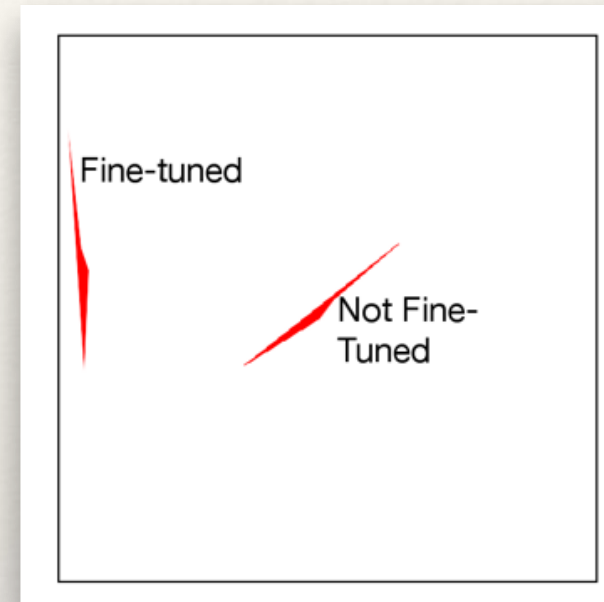
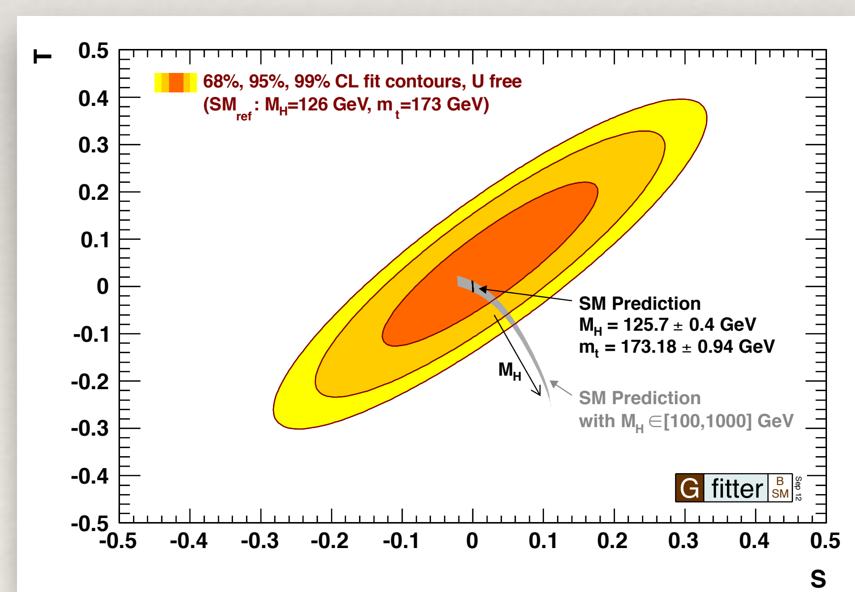
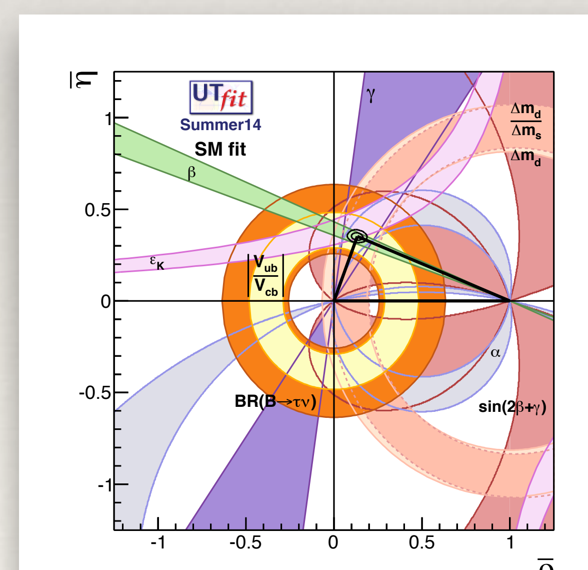


- Irrelevant Operators in the EFT?
  - T Parameter $T \sim |H^\dagger D_\mu H|^2 \Rightarrow \Lambda_{UV} > 10 \text{ TeV}$
  - Flavour-changing operators $\epsilon_K \sim (\bar{s}_R d_L)^2 \Rightarrow \Lambda_{UV} > 10^{3-4} \text{ TeV}$





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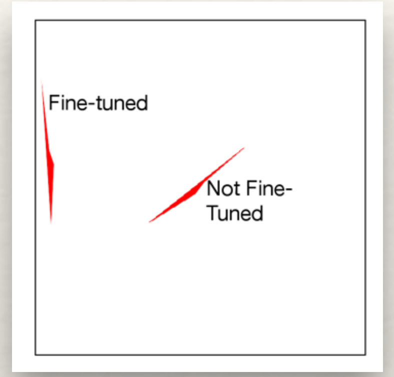

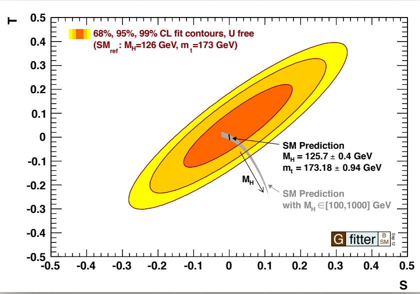

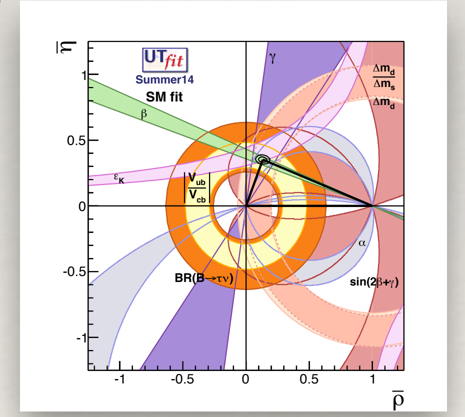

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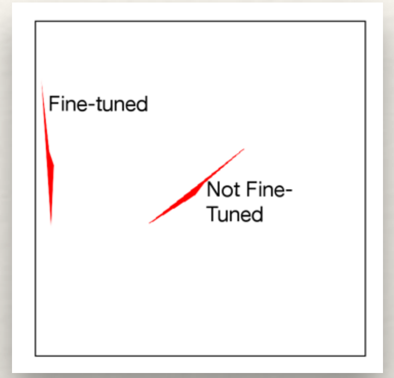
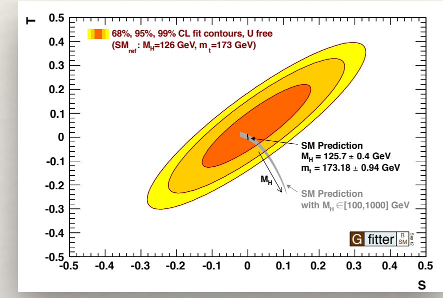
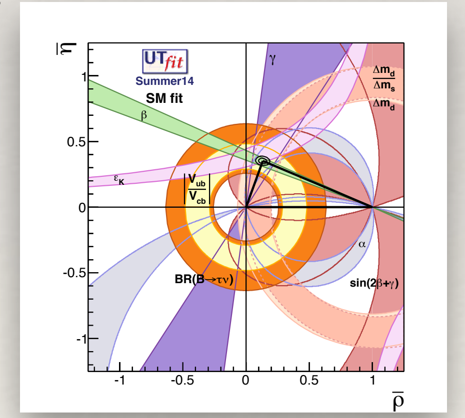


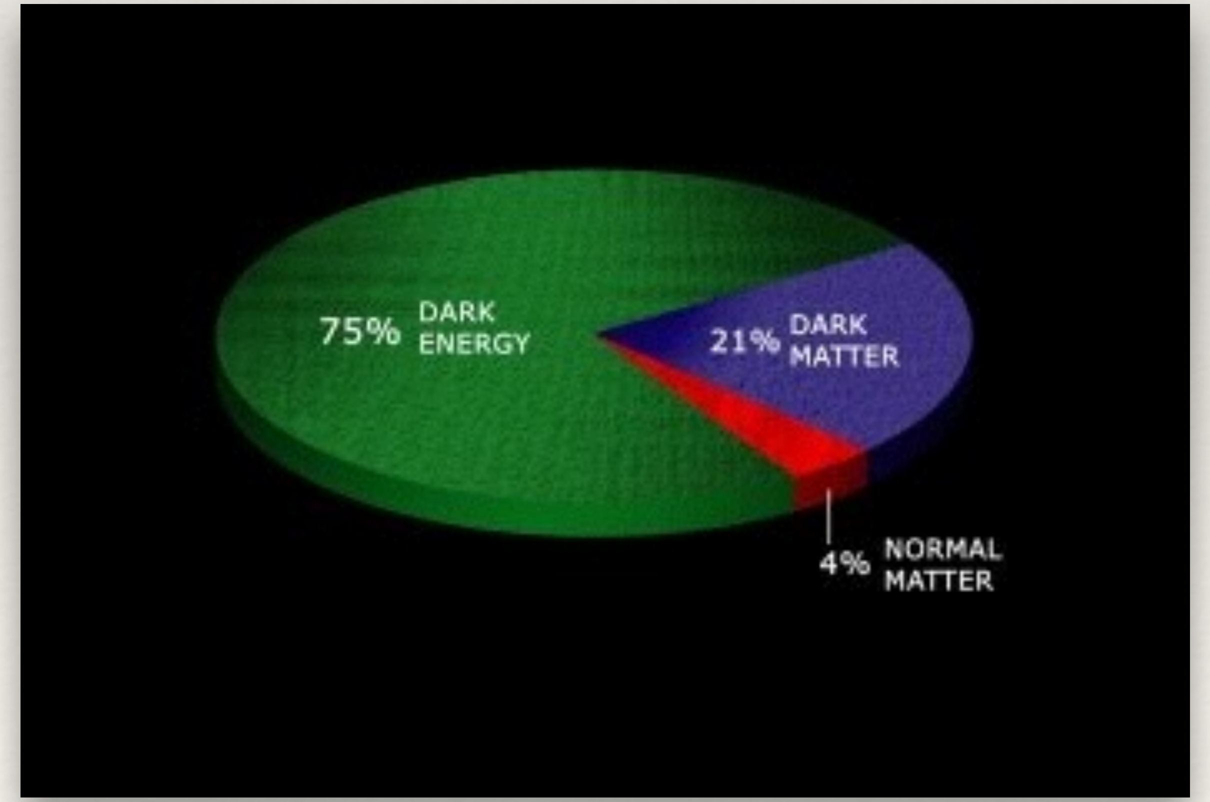




What happens without Naturalness?

Unnatural Reasons for New Physics

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



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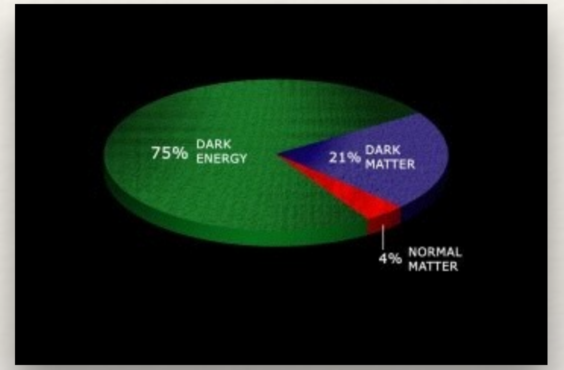

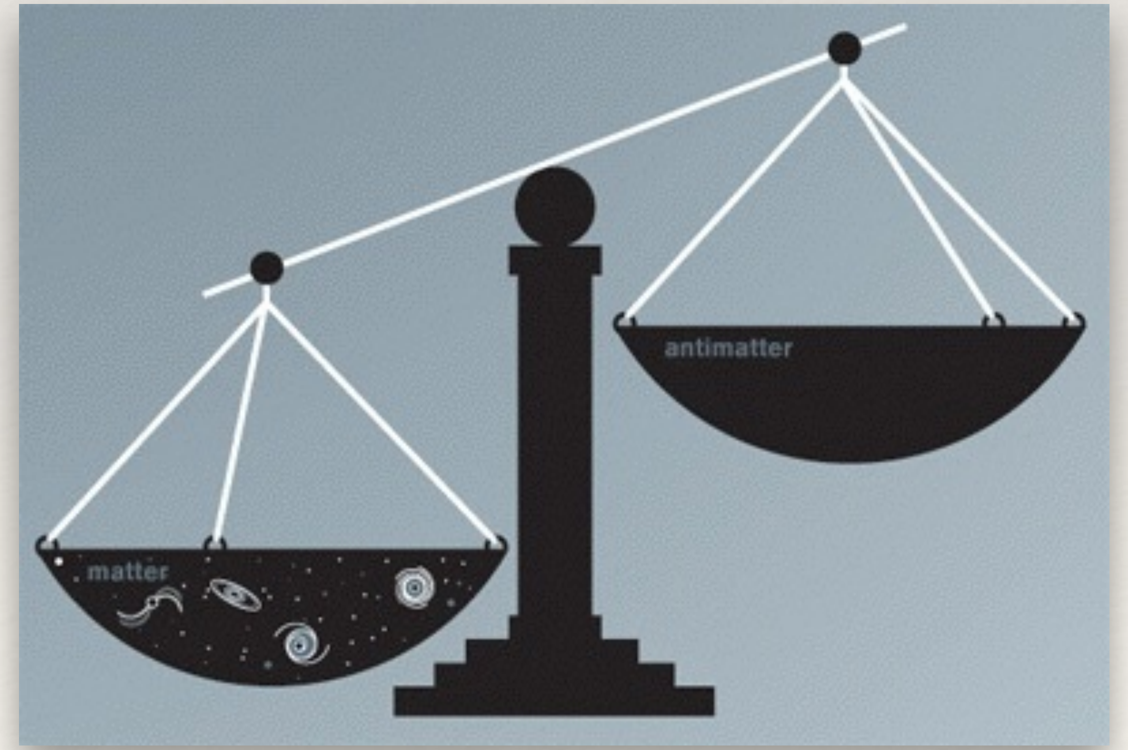

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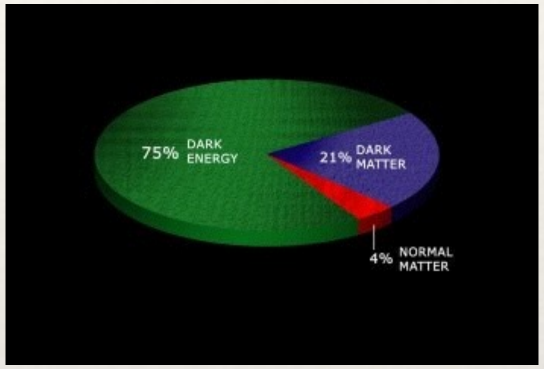

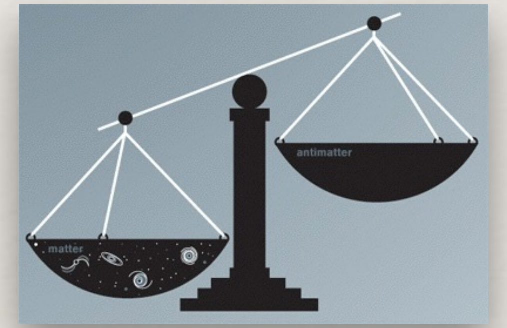

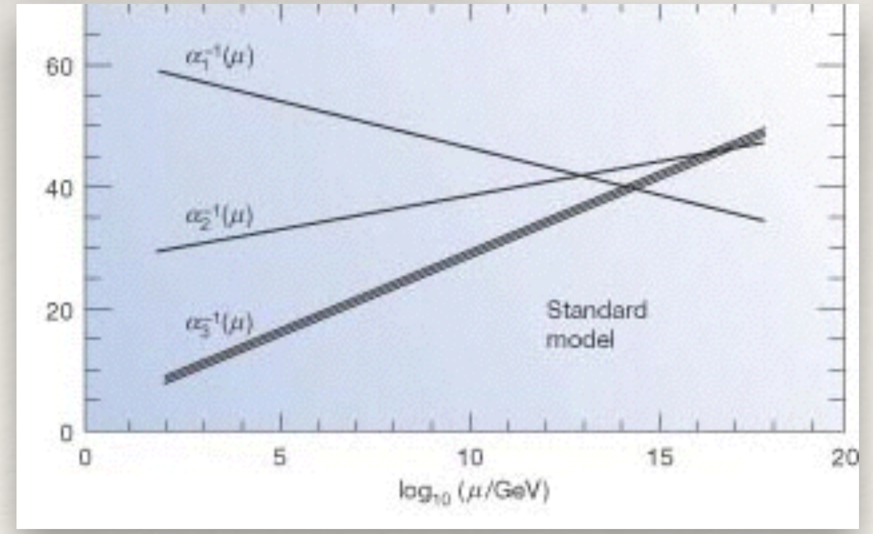

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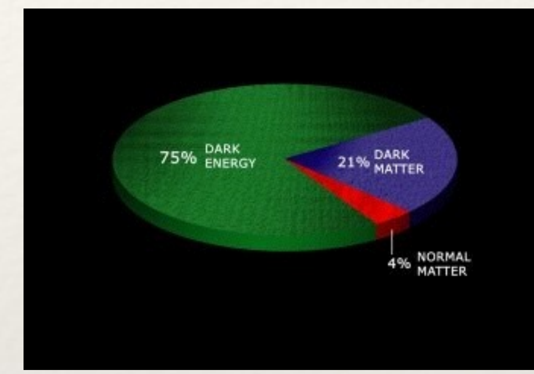

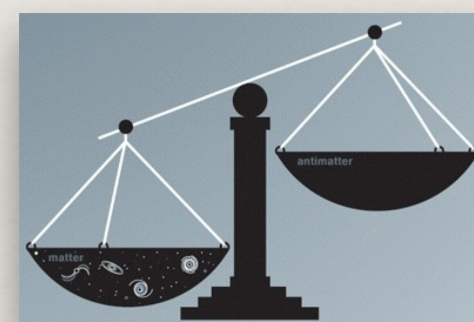

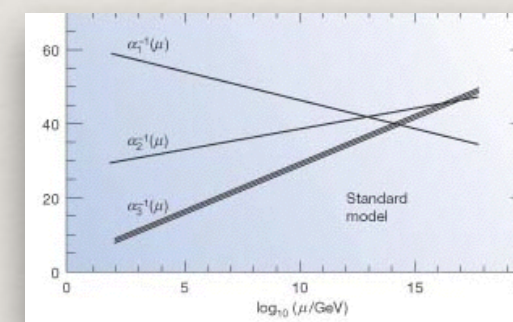

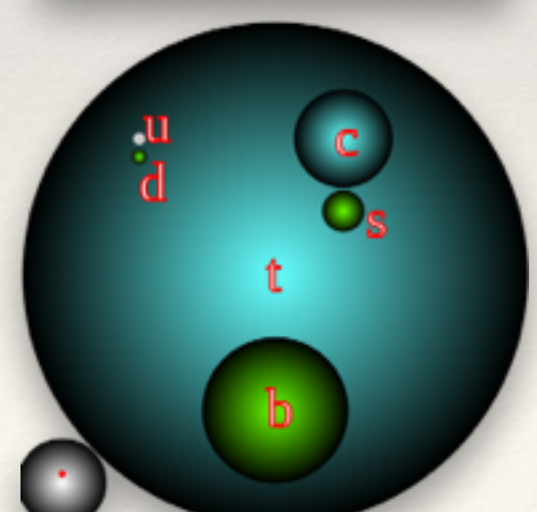

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- Dark Matter
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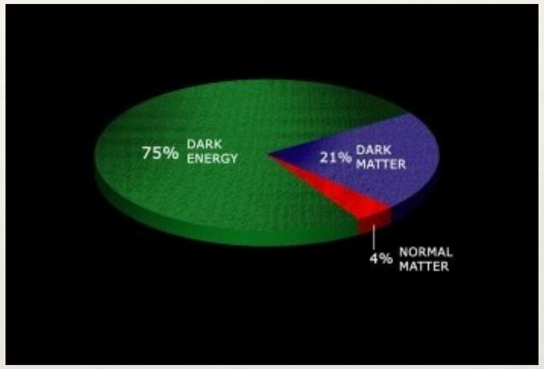
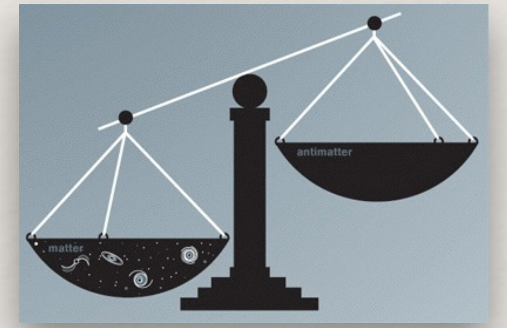
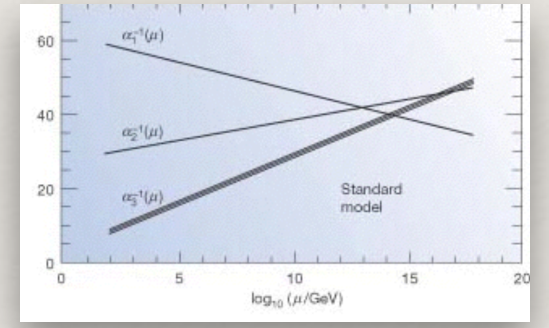
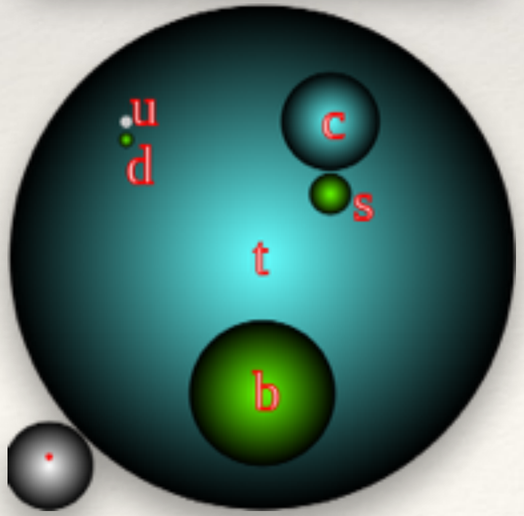
- Baryogenesis
  - Must be non-SM physics
- Gauge Unification
- Flavour Physics
- Simpler Models!



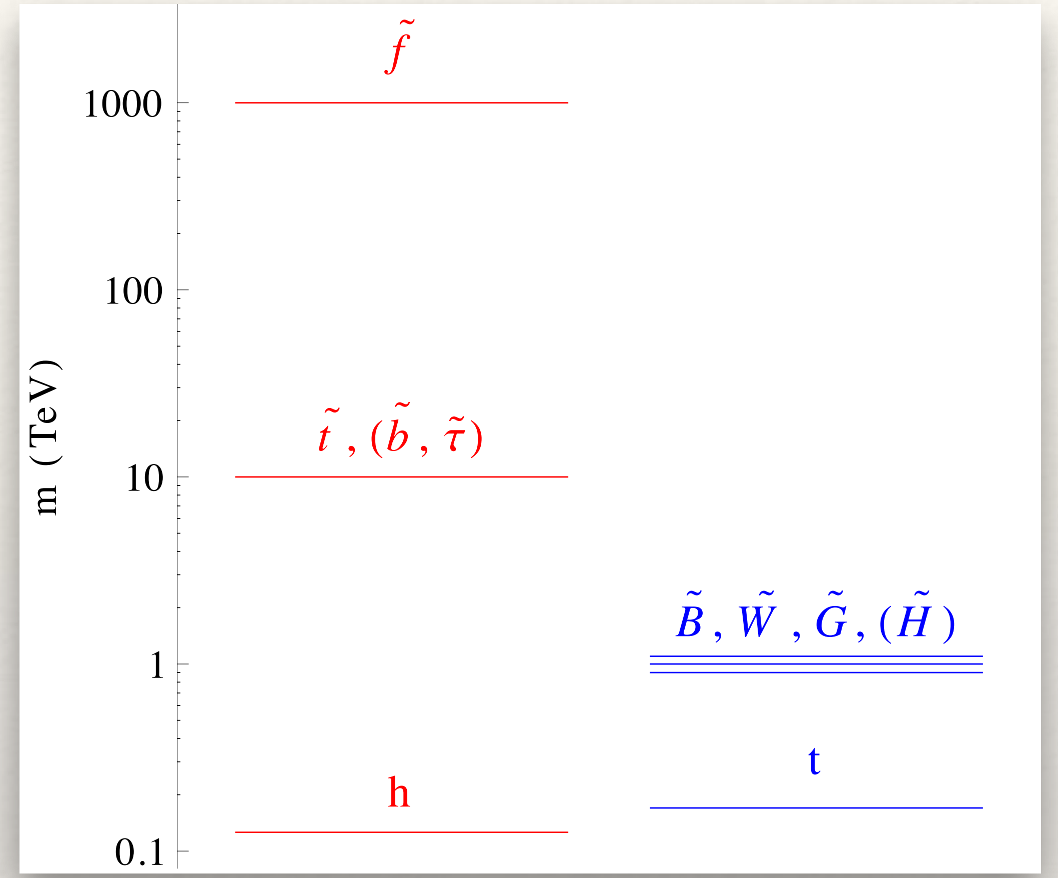






Mini-Split Supersymmetry

- Without Naturalness, SUSY still has:
  - Dark Matter (R-Parity)
  - Consistent with Leptogenesis
  - Improved Unification (Gauginos)

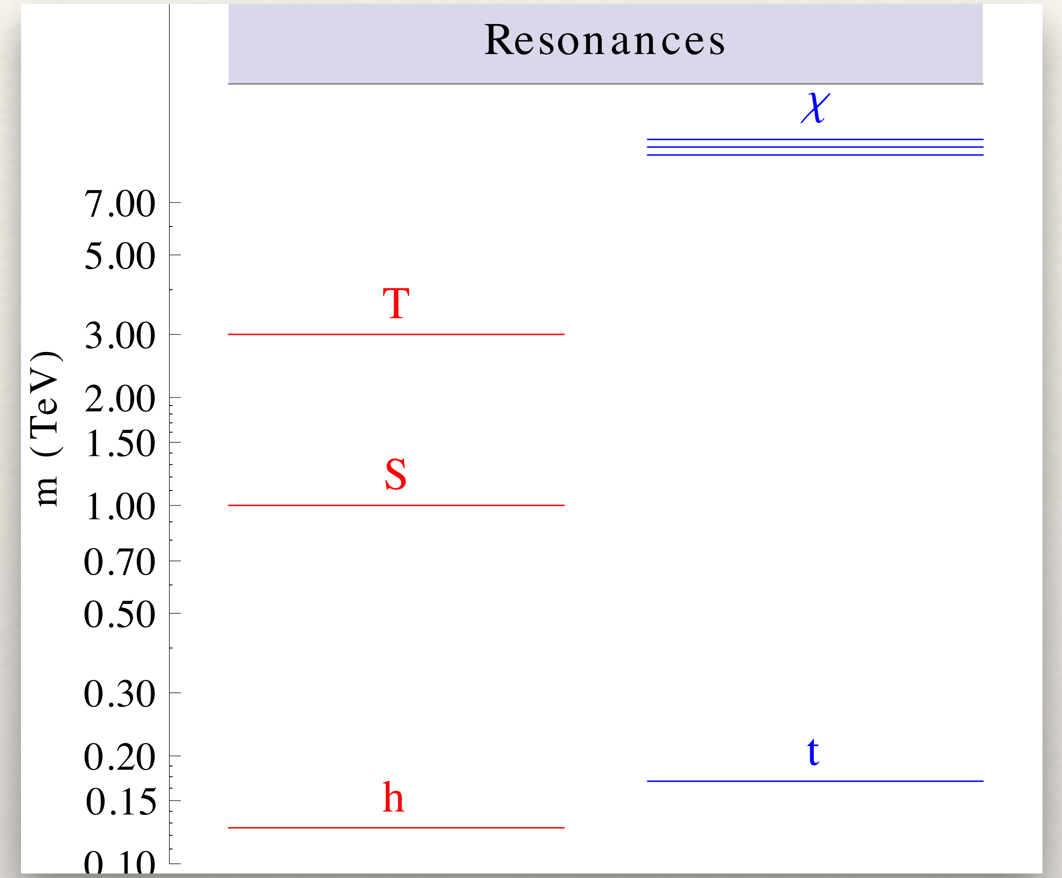


- Gauginos light by R-symmetry
- Split Spectrum avoids Flavour, LHC problems
- Long-lived gluino signal

- 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

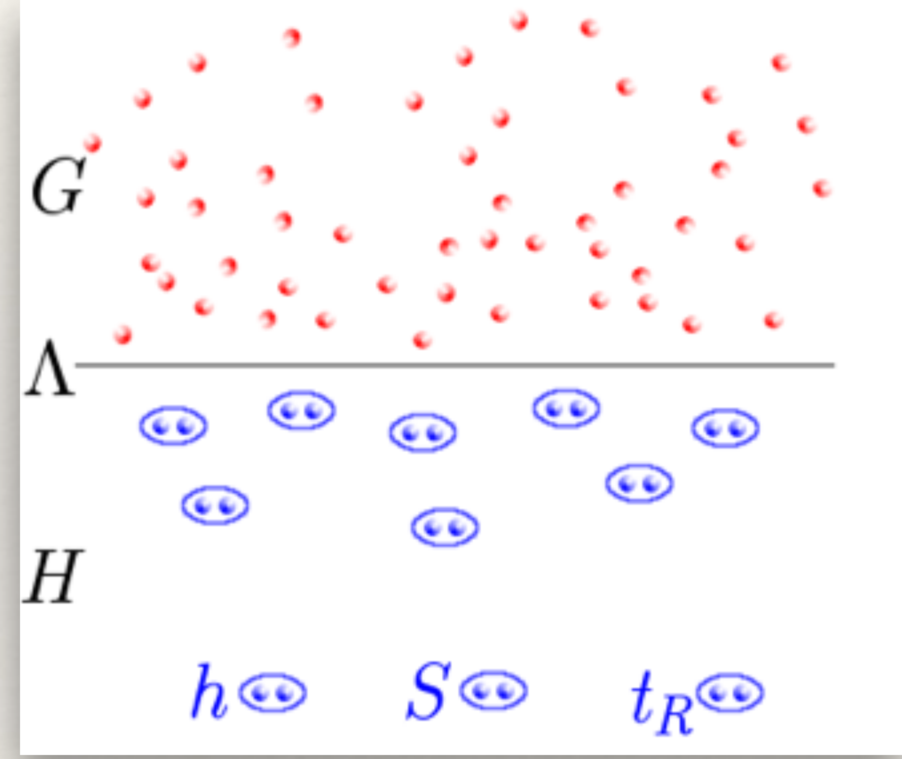
- Without Naturalness, still have:
  - Dark Matter (Baryon Triality)
  - Consistent with Leptogenesis
  - Improved Unification (Top Exotics)
  - Theory of Flavour
- Goldstones light by shift symmetry
- Split Spectrum avoids Flavour, LHC problems
- Long-lived SU(3) triplet signal



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 $\Lambda \approx g_\varrho f$
- Symmetry breaking $G \to H \supset G_{SM}$
- Higgs is among associated pseudo-Goldstones

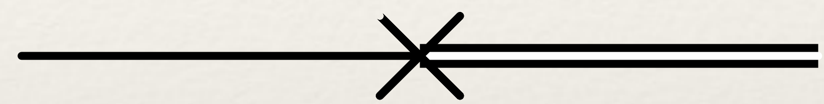


Fermion Masses

D. Kaplan, Nucl. Phys. **B365** 259

- Fermions mix with confining sector (Partial Compositeness)

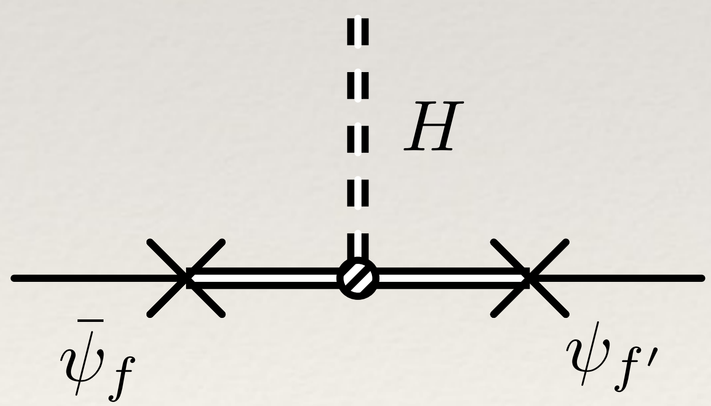
$$\mathcal{L} \supset \frac{c_f}{\Lambda^D} \psi_f \mathcal{O}^f \sim \psi_f$$



$$\mathcal{O}^f$$

- Strong coupling $\rightarrow$ Large anomalous dimensions D

- Mixings generate Yukawa couplings:

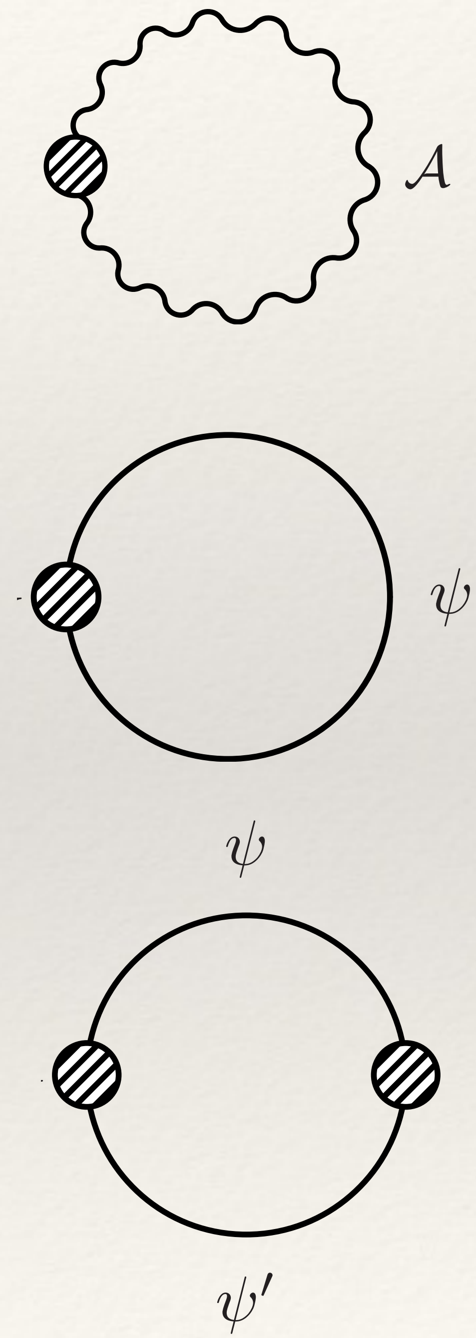


$$\sim \frac{c_f c'_f}{g_\rho} \left(\frac{f}{\Lambda}\right)^{D_f + D_{f'}}$$

- $\mathcal{O}(1)$ parameter variation generates Yukawa hierarchy

Higgs Potential

- When SM couplings vanish:
  - PNGBs $\rightarrow$ Goldstones
  - Goldstone potential vanishes
- So Higgs potential $V = V(g, \lambda)$
  - "Calculable"
  - Loop-level: $v_{EW} \sim \frac{\Lambda}{4\pi} \sim f$
  - Intrinsic Fine-Tuning (gauge vs fermion loops) $\Delta \sim \frac{v_{EW}^2}{f^2}$

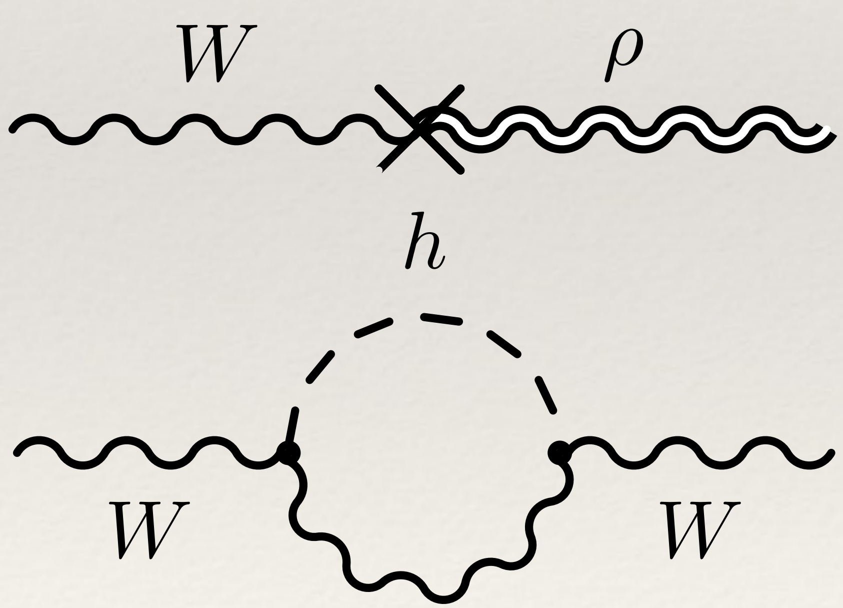


General Features of
Split Composite Higgs

EW Precision Observables

- Peskin-Takeuchi parameters (Peskin & Takeuchi, PRL **65** 964)
  - S: new neutral current physics (Contino, `1005.4269`)
    - Vector boson mixing
    - Higgs coupling shifts

$\Delta S \sim$



$$\sim \frac{m_W^2}{m_\rho^2}$$

$+\,\Delta$

$$\sim \frac{\alpha}{4\pi}\,\frac{v^2}{f^2}$$

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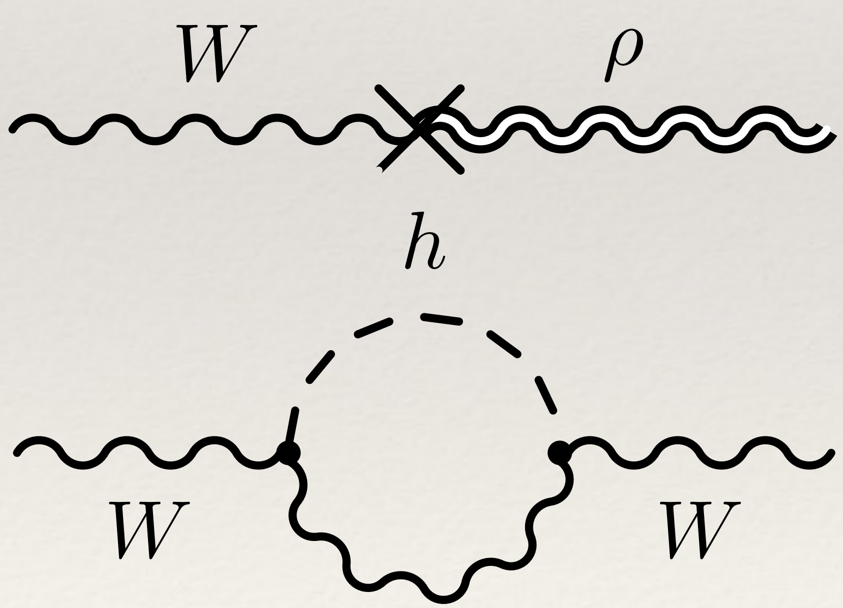
$$f \gtrsim 0.8 \text{ TeV}$$



$$\Delta S \sim [W\text{–}\rho \text{ mixing}] \sim \frac{m_W^2}{m_\rho^2}$$

$$+\,\Delta [W\text{–}W \text{ loop with } h] \sim \frac{\alpha}{4\pi}\,\frac{v^2}{f^2}$$

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

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  (Though problem still exists in non-flat cosets H, Bertuzzo *et al* `1206.2623`)

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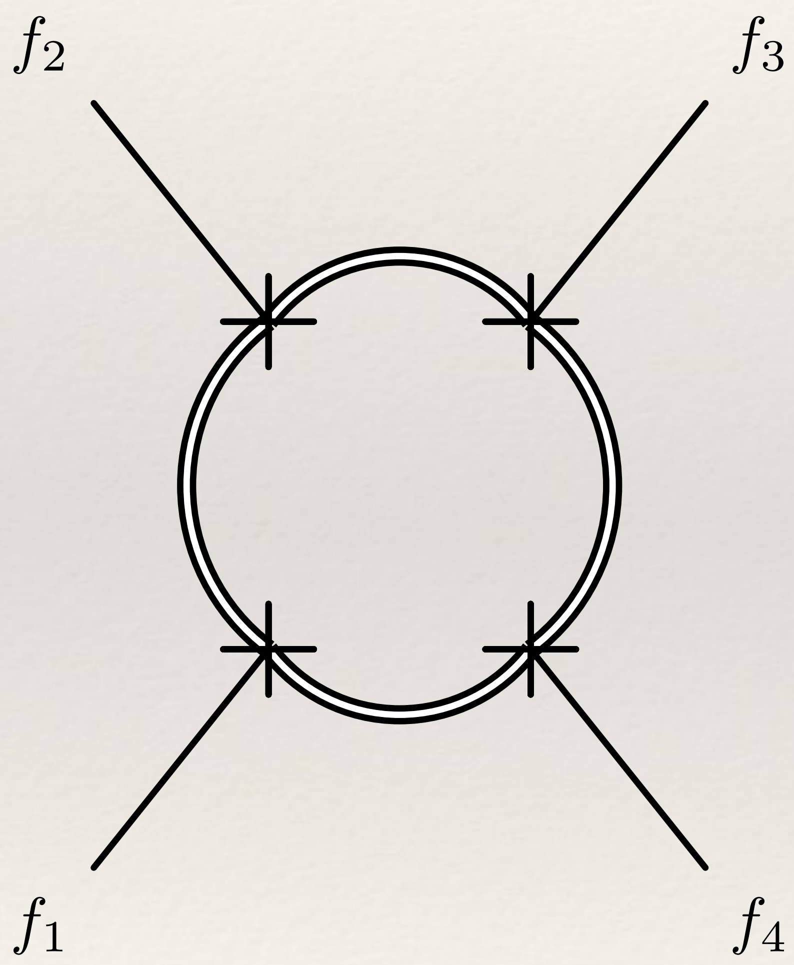
- Unnatural models can avoid this: SIMPLER

Flavour Observables

- Partial Compositeness generates 4-fermion operators:



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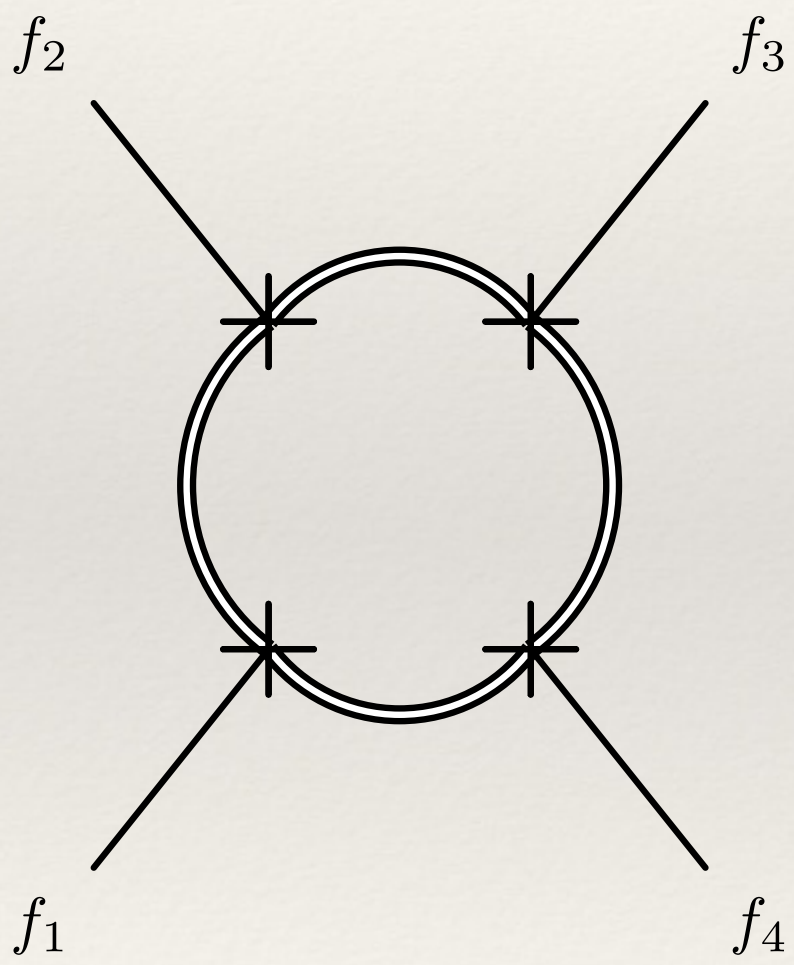

$$\propto \frac{\sqrt{y_1 y_2 y_3 y_3}}{\Lambda^2}$$

- BUT! result $\propto$ Yukawas

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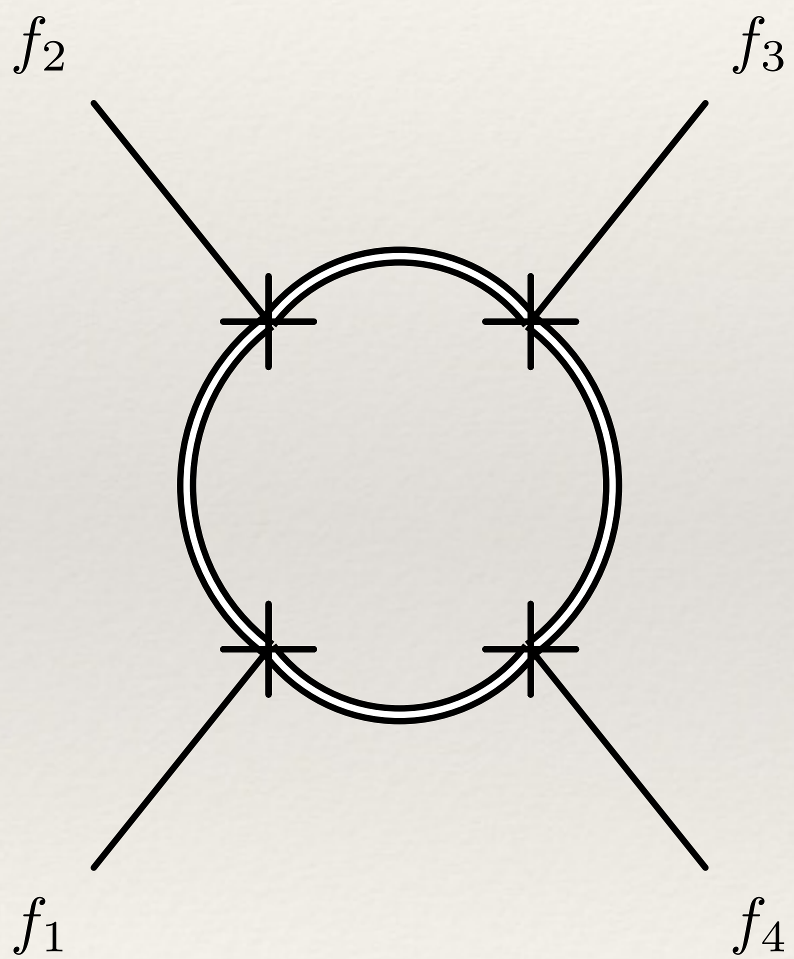

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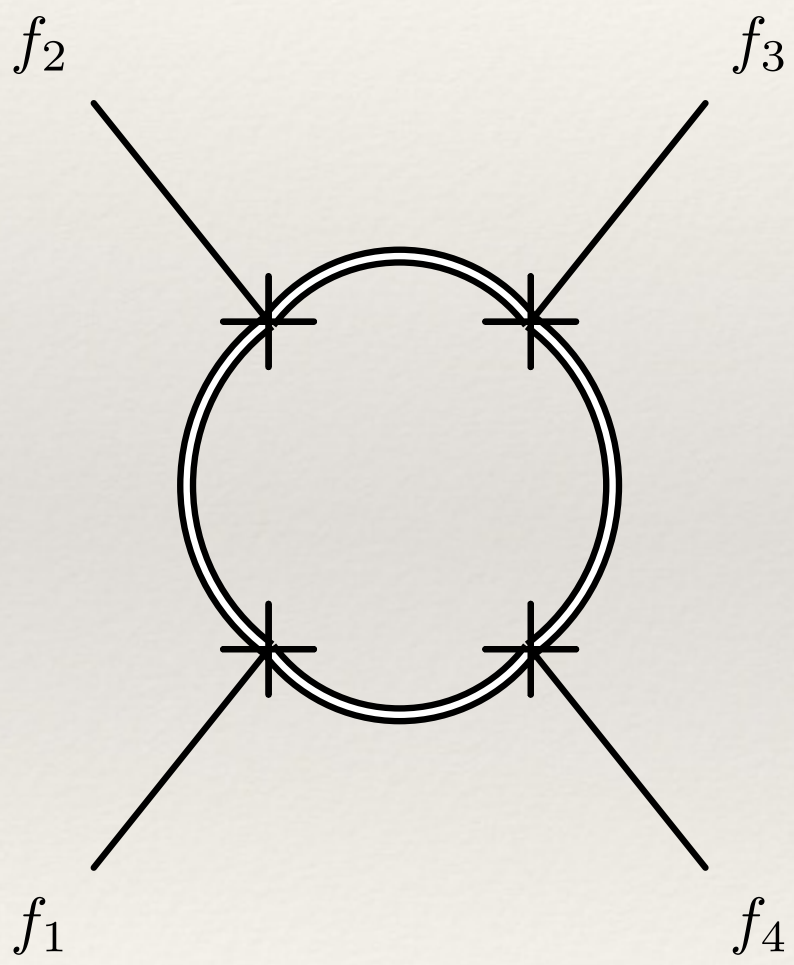

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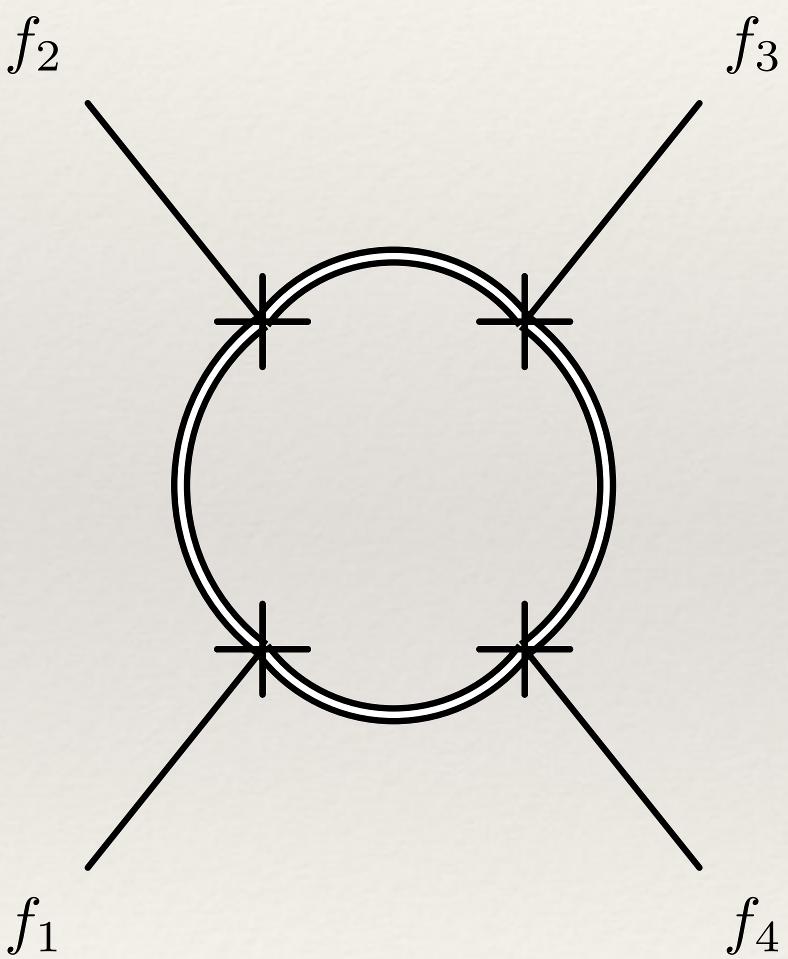

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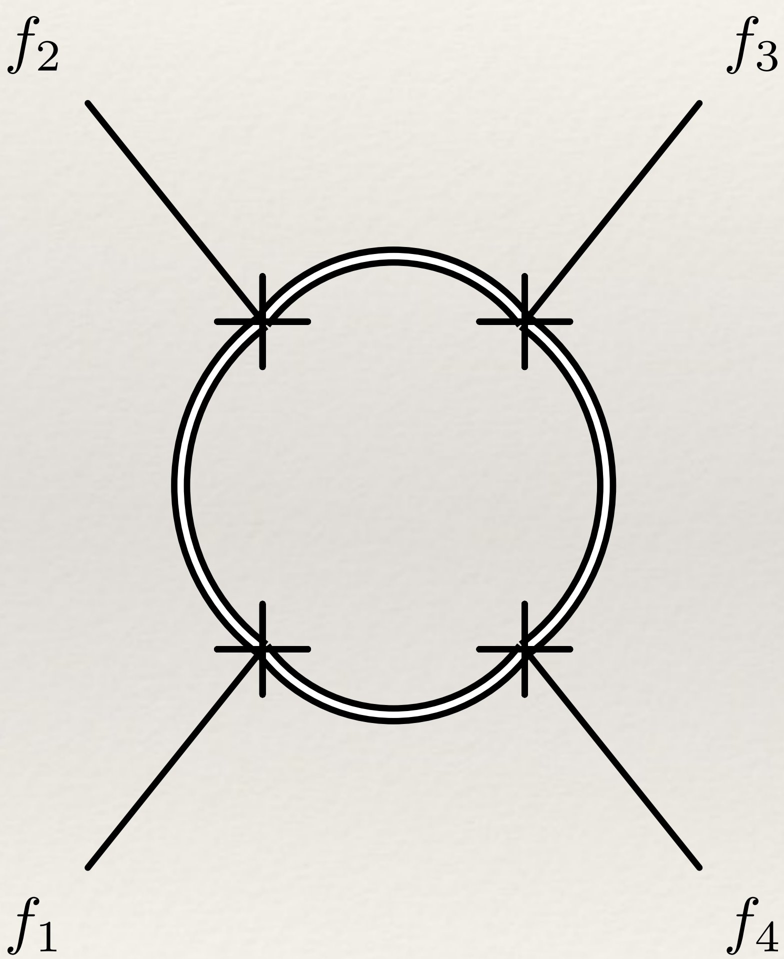

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Keren *et al* `1205.5803`, Csaki *et al* `1401.2457`

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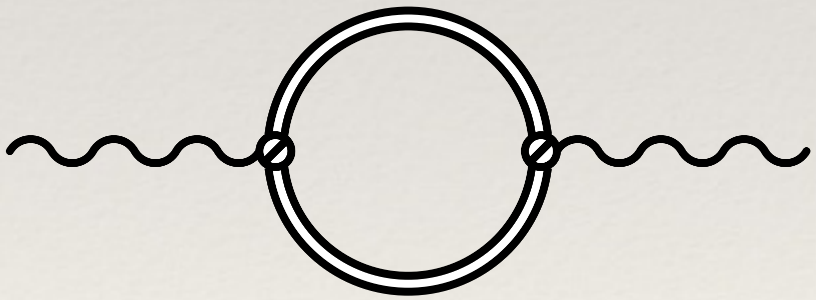
- Or unnatural $\rightarrow$ SIMPLER

Calculable Gauge Unification

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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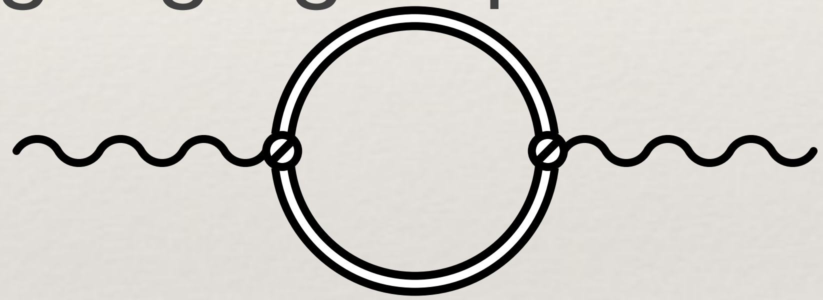
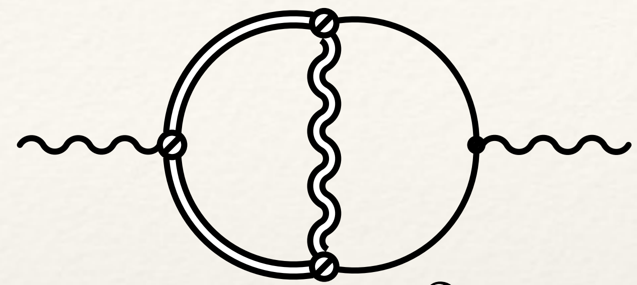


- Let $G \supseteq G_{GUT}$
  - Strong sector states come in complete representations of SU(5)
  - One-loop differential running unaffected (away from Landau poles)
  - Two-loop diagrams with SM, confining sector states, do affect running

The Top Problem

- Generic two-loop running:



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

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

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

- 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 Λ, top within confining sector; gauge running under control

Composite Unification

- In a general theory,

$$\alpha(\mu) = \alpha_{\rm GUT} + {\rm SM} + {\rm NP} + M_{\rm GUT}\text{-physics}$$

Composite Unification

- In a composite Higgs theory above Λ,

$$\alpha(\mu) = \alpha_{\mathrm{GUT}} + \mathrm{SM} - \{\mathrm{h},\ldots\} + \mathrm{NP}^{\mathrm{comp}} + \mathrm{NP}^{\mathrm{elem}}$$

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$$\alpha^{\mathrm{i}}(\mu) - \alpha^{\mathrm{j}}(\mu) = \mathrm{SM} - \{\mathrm{h},\ldots\} + \mathrm{NP}^{\mathrm{elem}}$$

- Simple metric for differential running

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

- $R(\mathrm{SM}) = 0.53 \quad R(\mathrm{MSSM}) = 0.71 \quad R(\mathrm{SM{-}h{-}t_R}) = 0.59$

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- Higgs in **5** of $\mathrm{SU}(5)$: expect Goldstone $\mathrm{SU}(3)$ triplet T
- $\mathrm{t_R}$ in **10** of $\mathrm{SU}(5)$: 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) $\begin{pmatrix} 0 & \tilde{Q}^c \\ \tilde{Q}^{cT} & \tilde{e}^c \end{pmatrix}$

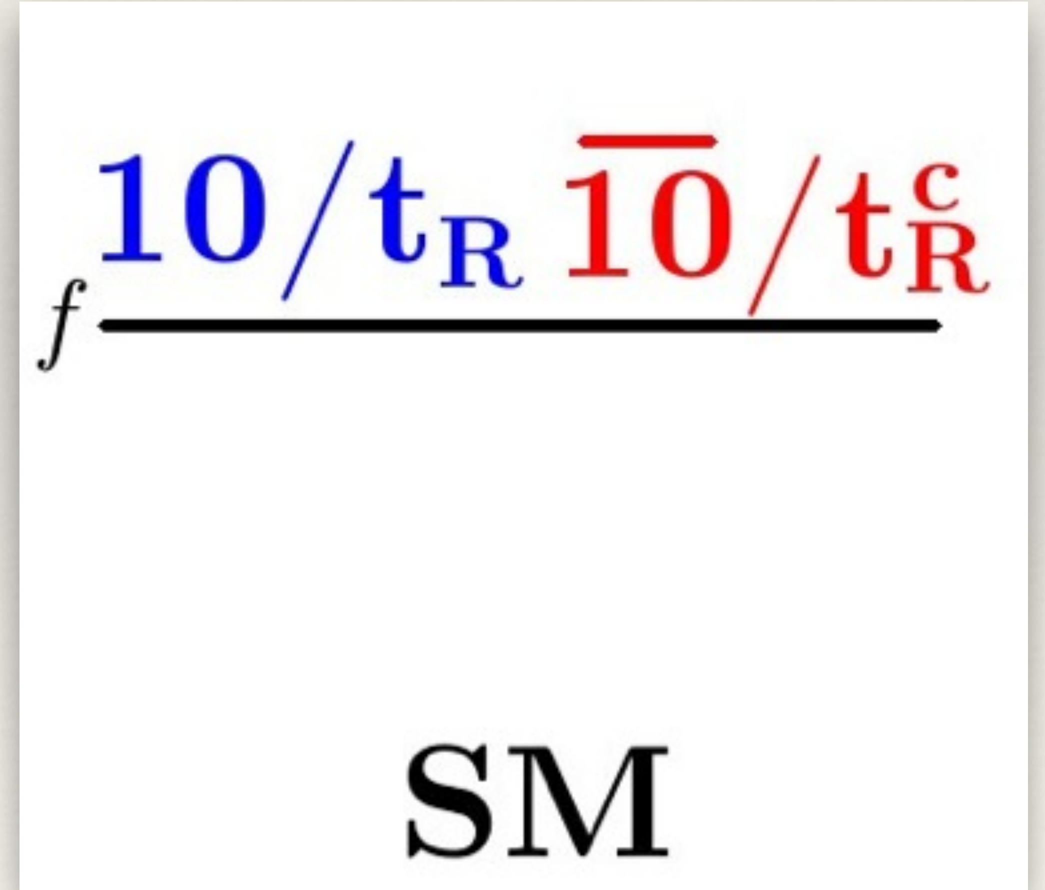
Precision Unification

- Exotic fermion masses similar to top Yukawa

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

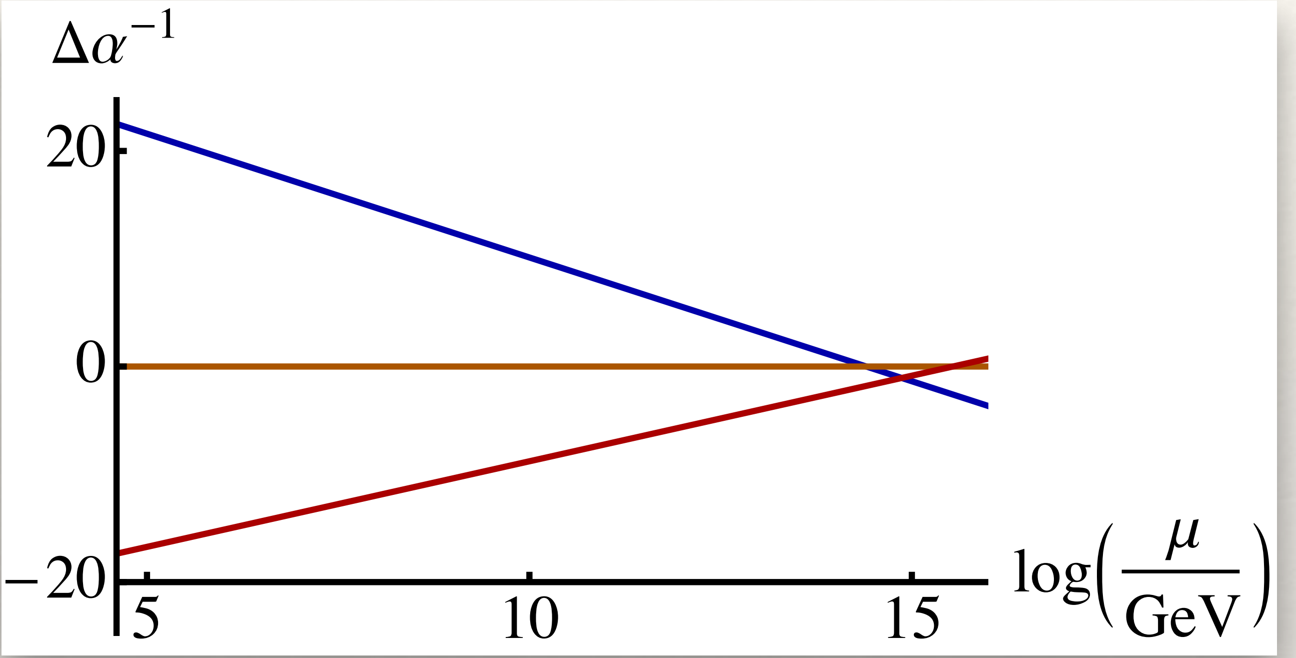
- At scale $m_\chi \sim f$, add nearly-complete GUT multiplet
- Effect on running equivalent to subtracting $\mathrm{t_R}^\mathrm{c}$

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



An Upper Limit on f

- One-Loop Unification



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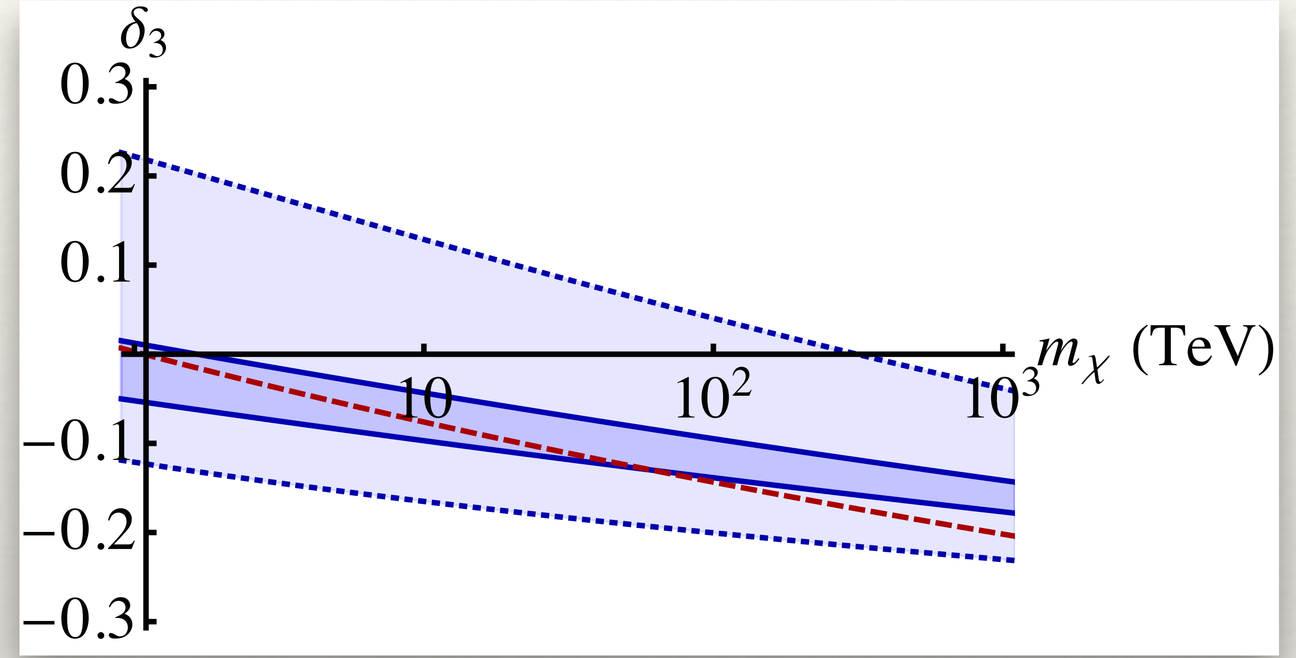

- m_χ = 20 TeV
- Red: 5D Calculation
  Choi & Kim, `hep-th/0411090`
- Blue: 4D Estimate

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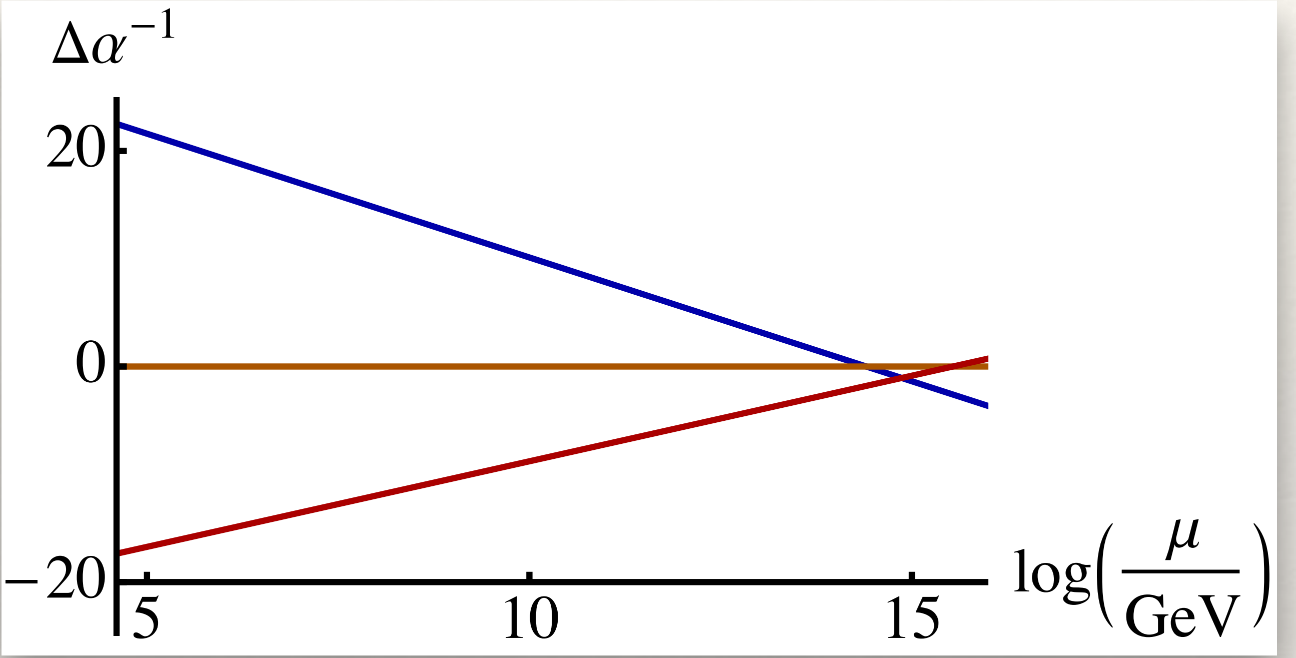

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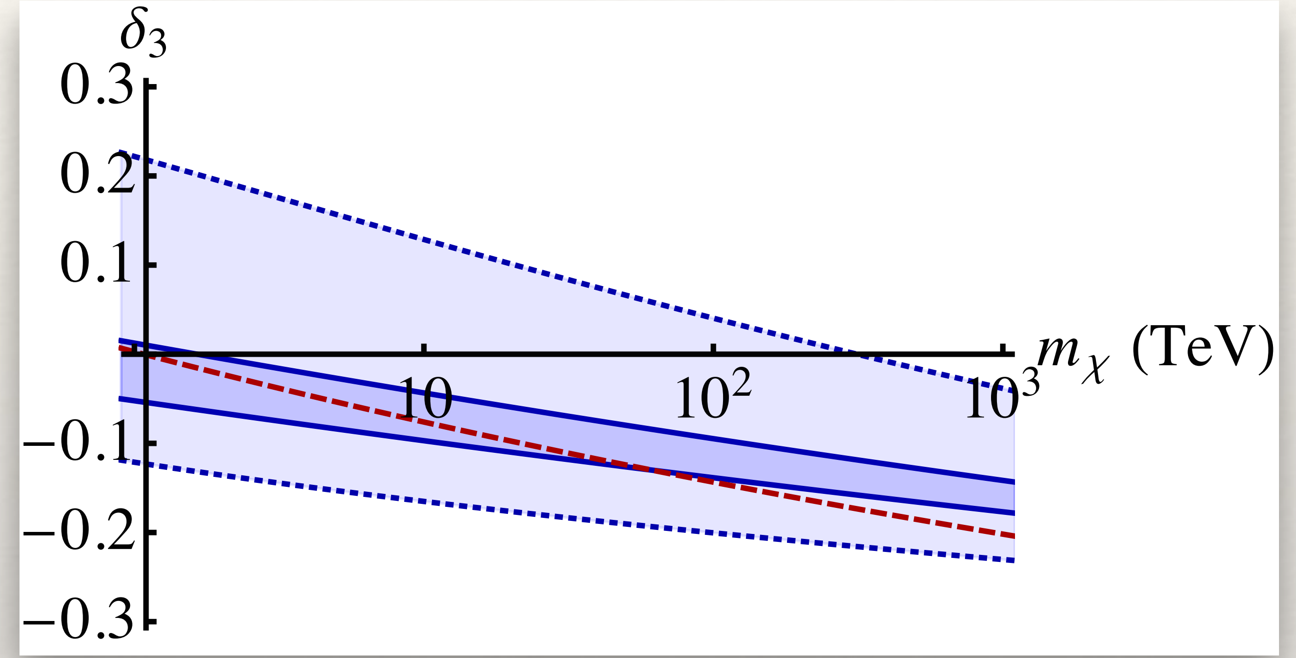

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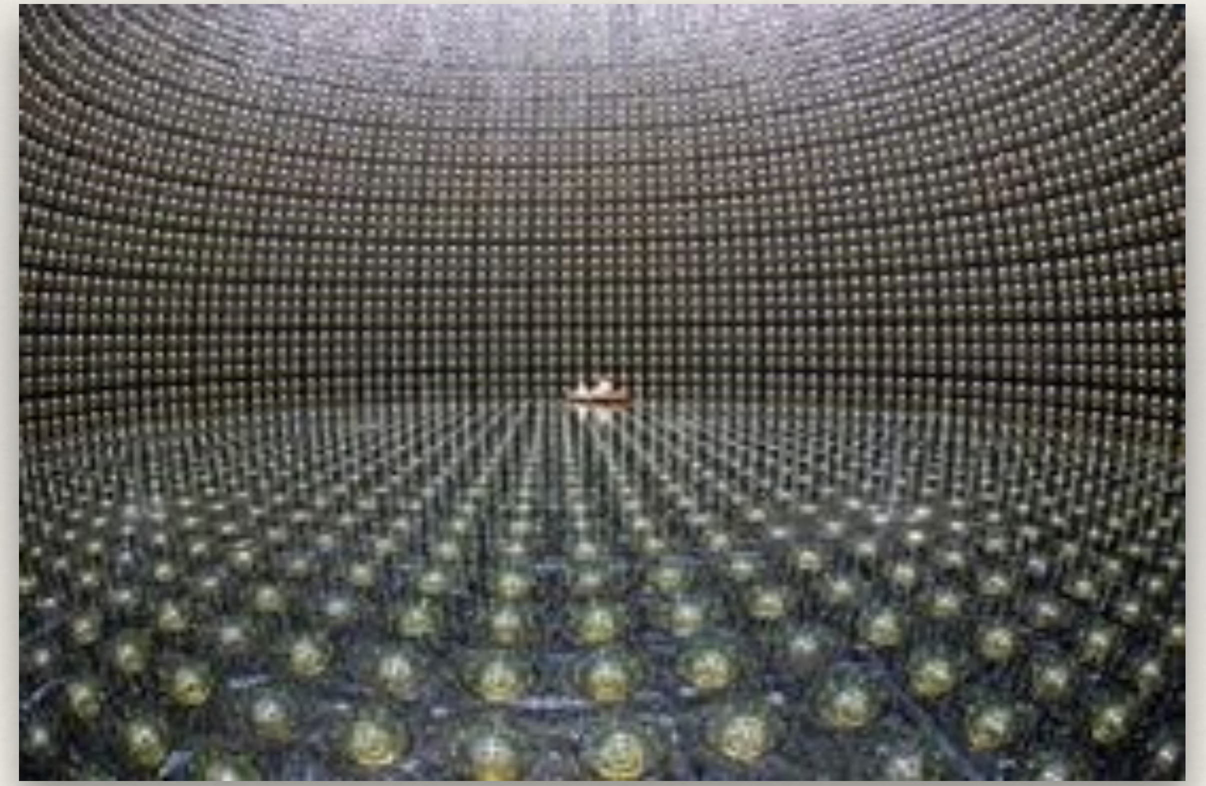
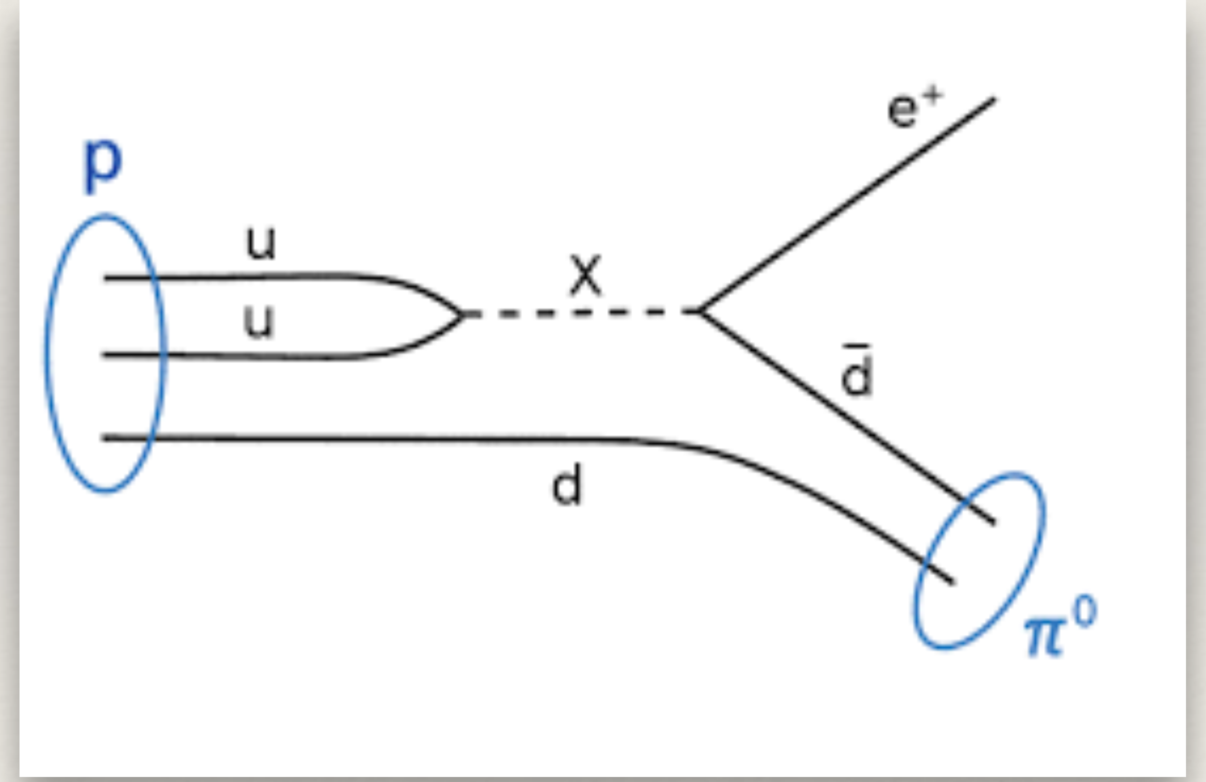
$$f < 1000\ \text{TeV}$$

Proton Decay and Dark Matter

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

- GUT multiplets at very low scale Λ: Proton Decay?





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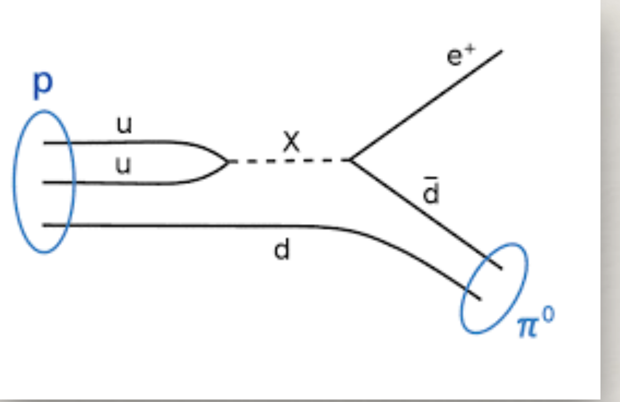
- Promote $\mathrm{U(1)_B}$ to global symmetry of strong sector
- Interesting subgroup: Baryon Triality

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



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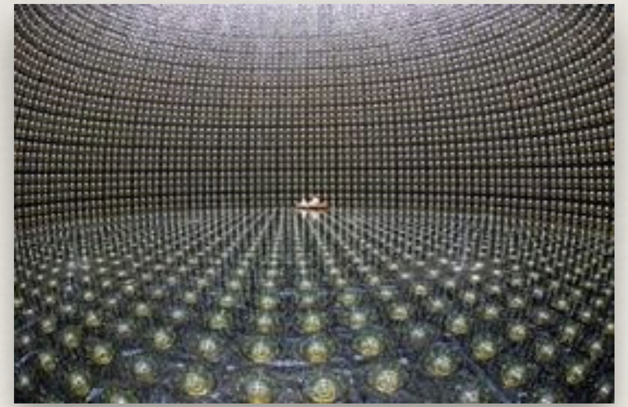
- Goldstone triplet has $\mathbb{Z}_B$ charge!



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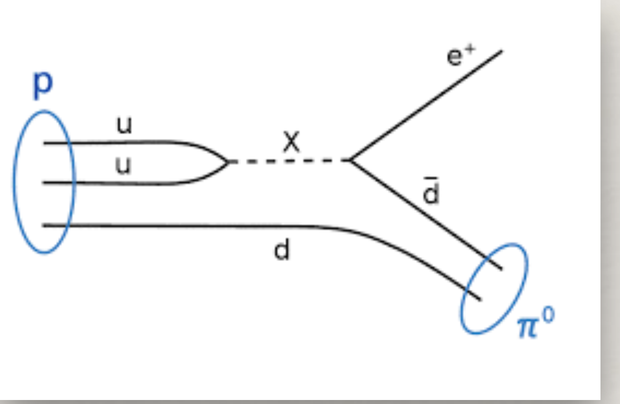

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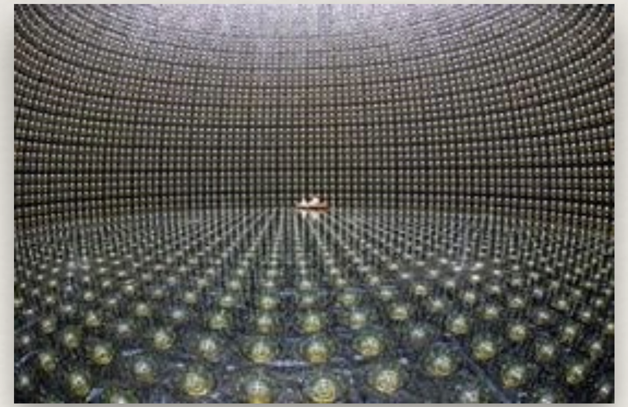

Dark Matter

- Two possible dark matter candidates:
  - Top Companion Fermion Frigerio *et al* `1103.2997`
  - Goldstone scalar Frigerio *et al*, `1204.2808`
- Two possible annihilation channels:
  - Non-Renormalisable operators mediated by composite sector

$$\frac{1}{f^2}(\bar{\tilde{l}} Q_{3L})\,(\bar{Q}_{3L}\tilde{l}) \qquad \frac{1}{f}(H^\dagger \tilde{l})^2$$

  - Renormalisable interactions

$$T(\bar{Q}_{3L}\tilde{q}) \qquad H^\dagger H\, S^\dagger S$$

- Phenomenological details more model-dependent

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An Explicit Model

Symmetry Breaking

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

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

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- So consider $\mathrm{SU}(7)/\mathrm{SU}(6)\times\mathrm{U}(1)$

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

Dark Matter Stability: U(1)s

- Gauging breaks $\mathrm{SU}(6)\times\mathrm{U}(1) \to \mathrm{SU}(5)\times\mathrm{U}(1)\times\mathrm{U}(1)$

$$SU(7) \to \begin{pmatrix} SU(5) & 0 & 0 \\ 0 & U(1)_6 & 0 \\ 0 & 0 & U(1)_7 \end{pmatrix}$$

- Linear combination of $\mathrm{U}(1)$s stabilises S

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

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- However, fermion couplings complicate things

Dark Matter Stability: Z_B

- Fermion couplings break $\mathrm{U(1)_S}$
- Enlarge symmetry: $\mathrm{U(7)\times U(1)_{B0}/U(6)\times U(1)\times U(1)_{B0}}$
  - Expect $\mathrm{U(N)}$ global flavour symmetries
  - Need to add Baryon number anyway
- Fermion, gauge couplings break $H \to \mathrm{G_{SM}\times U(1)_B}$

$$U(1)_B \equiv \frac{1}{126}\left(6U(1)_E + U(1)_7 - 7U(1)_6 + 126U(1)_{B0}\right)$$

- Goldstones have different charge under true $\mathrm{U(1)_B}$

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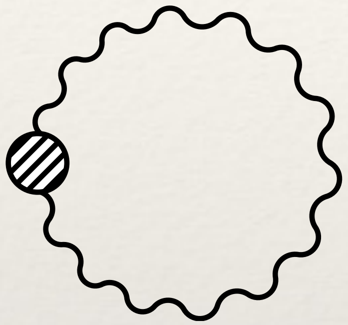
Matter Embeddings

- t_R (& hence top companions) in **15** of $\mathrm{SU}(6)$ = **10** + **5** of $\mathrm{SU}(5)$
- All SM Yukawas generated
  - Quarks couple to **35**
  - Leptons couple to **21**
  - Doublets couple to two operators
- Right-handed neutrinos $\mathrm{N^c}$:
  - Needed for Majorana ν 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	$\frac{1}{3}$
$(\tilde{d}^c, \tilde{l})$			$\overline{\mathbf{5}}$	0	0

Scalar Potential

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



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

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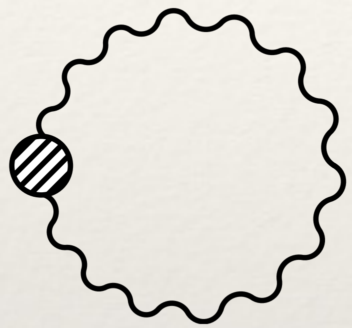

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- Triplet, Singlet masses typically

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

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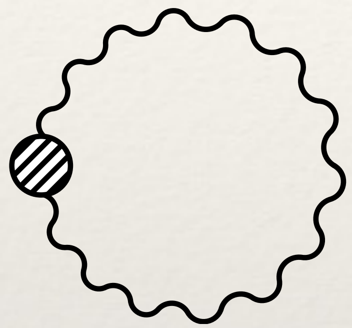

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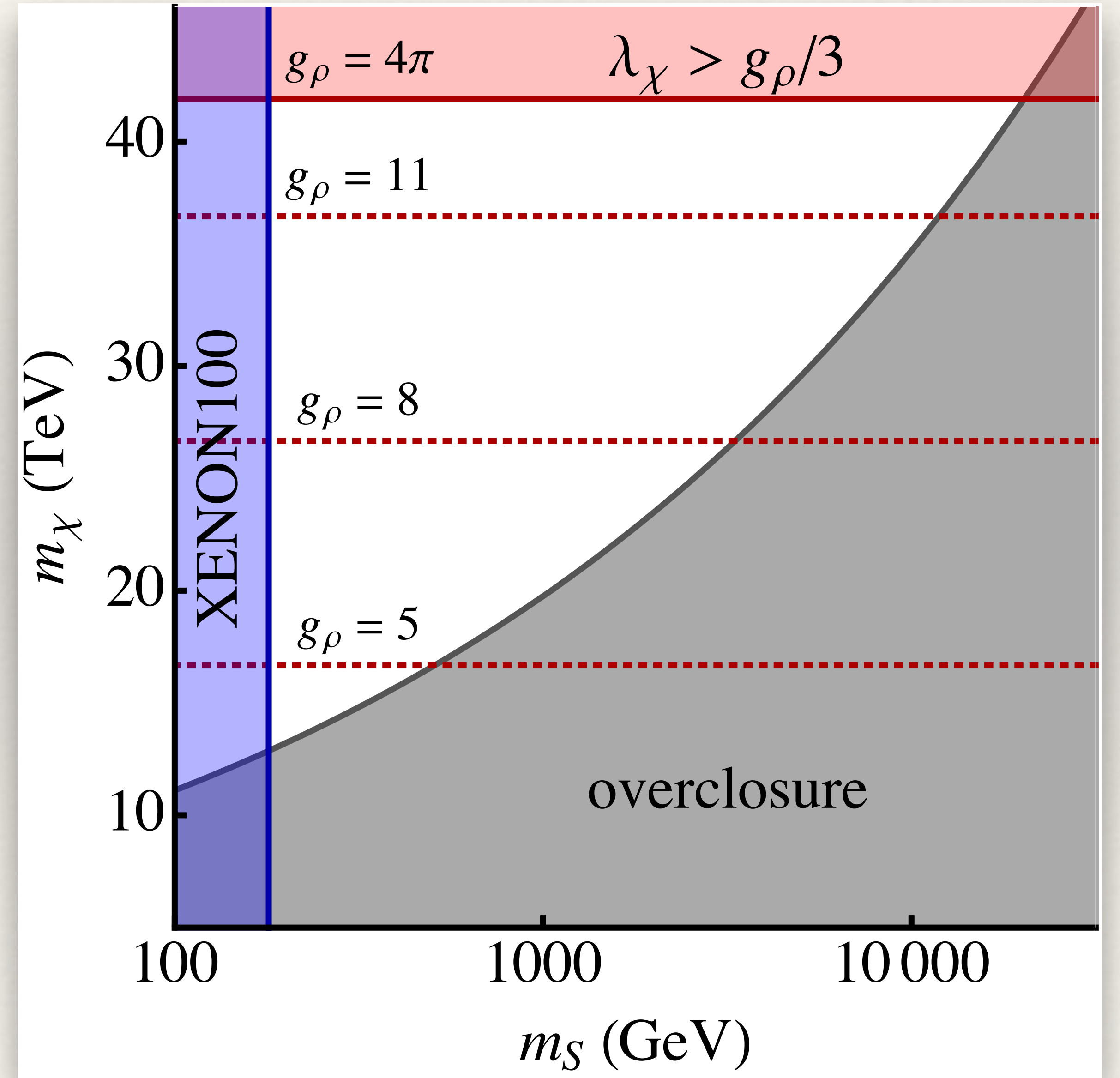
- Singlet can be tuned lighter; needed to fit relic density
  - For f ~ 10 TeV, only ~ few to 25 percent tuning

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`
- κ 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 $\kappa \to m_\chi$
- DD best hope for signal

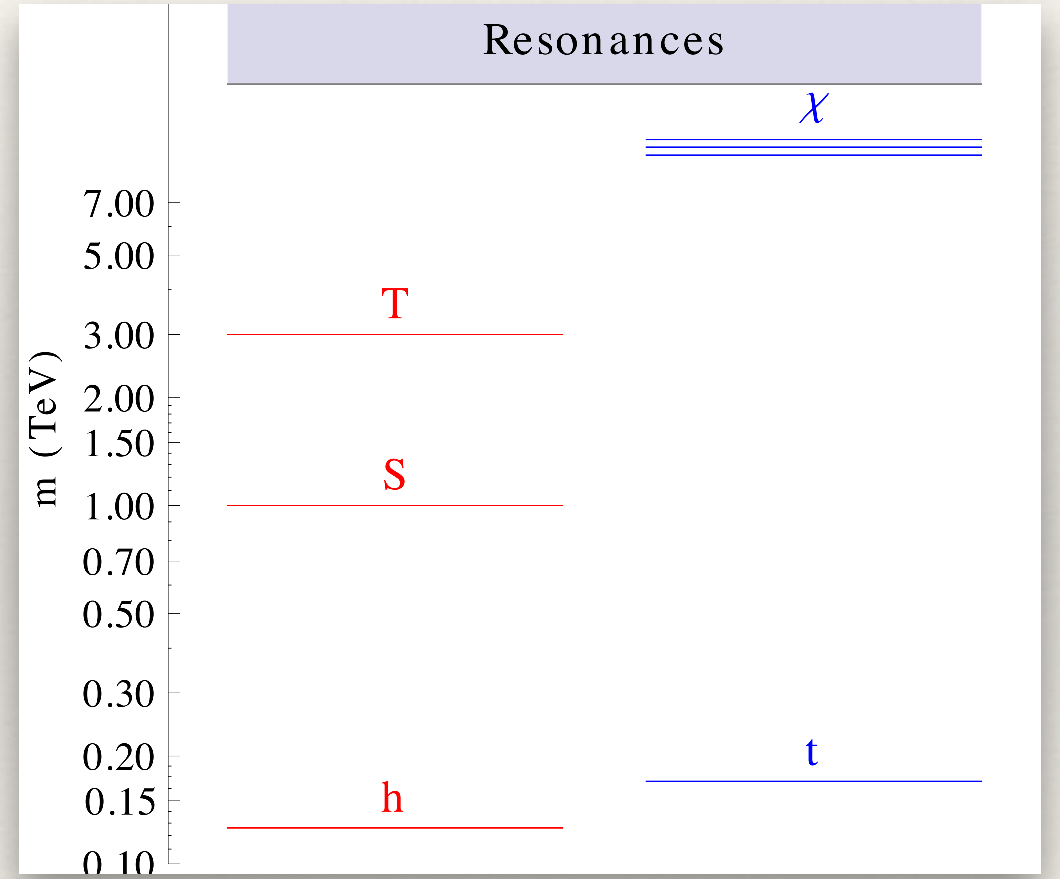


Collider Phenomenology

General Features

- Higgs deviations from SM ~ v^2/f^2
  - Unnatural models untestable this way
- Typical Spectrum

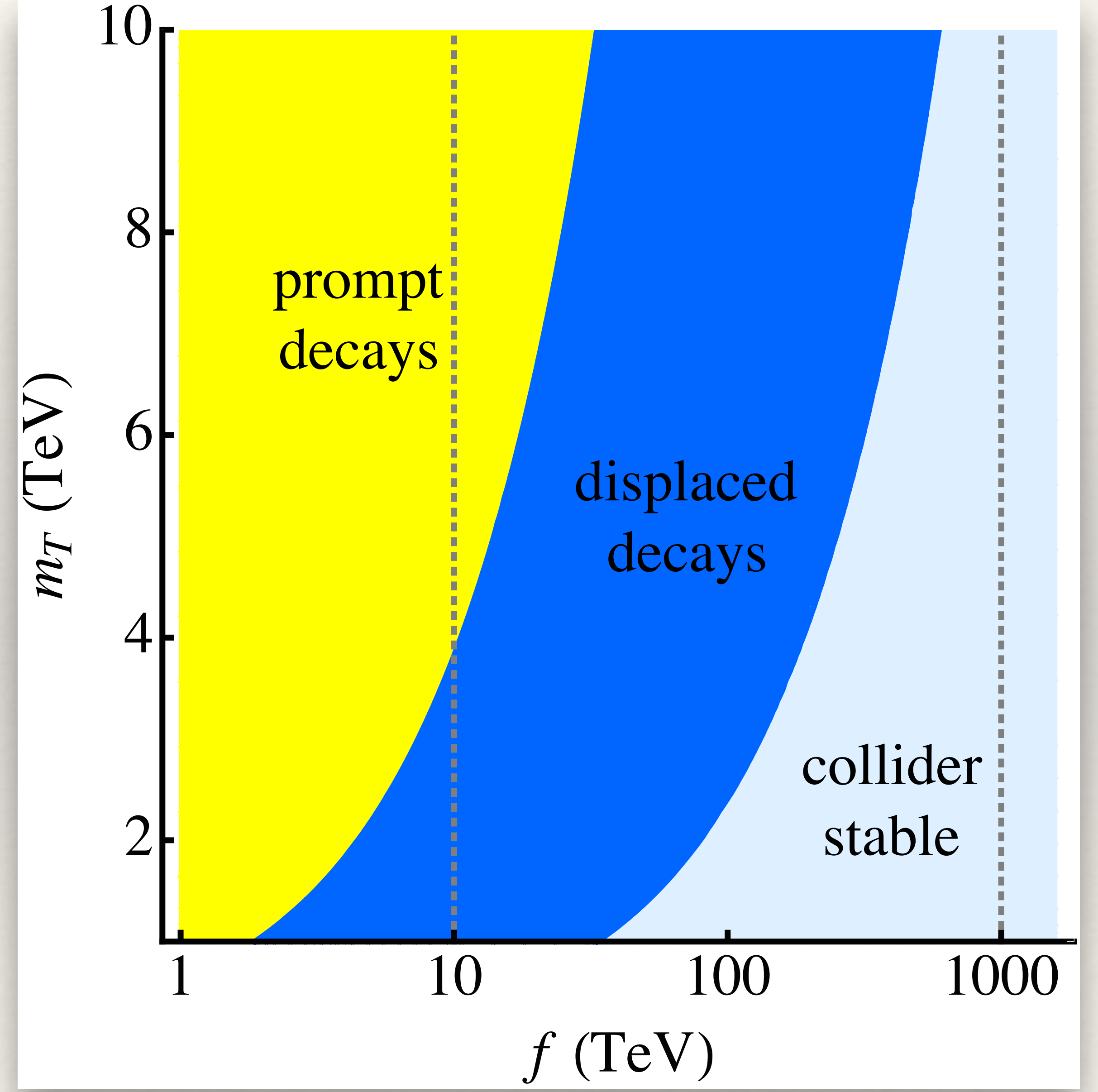
$$m_\chi \sim (1\text{–}2)\,f \quad m_T \sim \frac{(1\text{–}2)}{\pi} f \quad m_{DM} \sim 1\ \text{TeV}$$



- Top Companions decay promptly
- Triplet decays to $\mathrm{t\ b\ DM\ DM}$
  - 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



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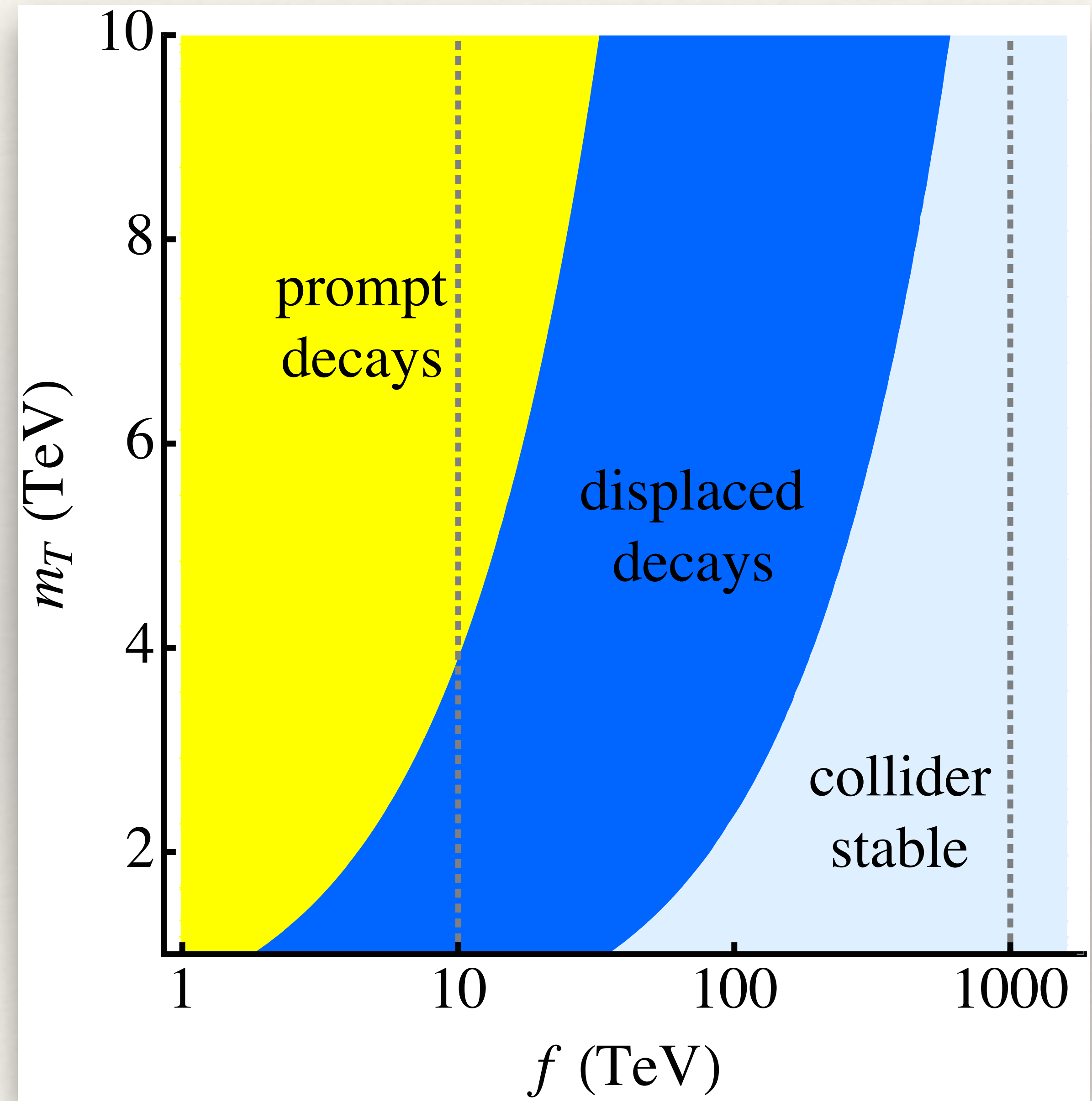
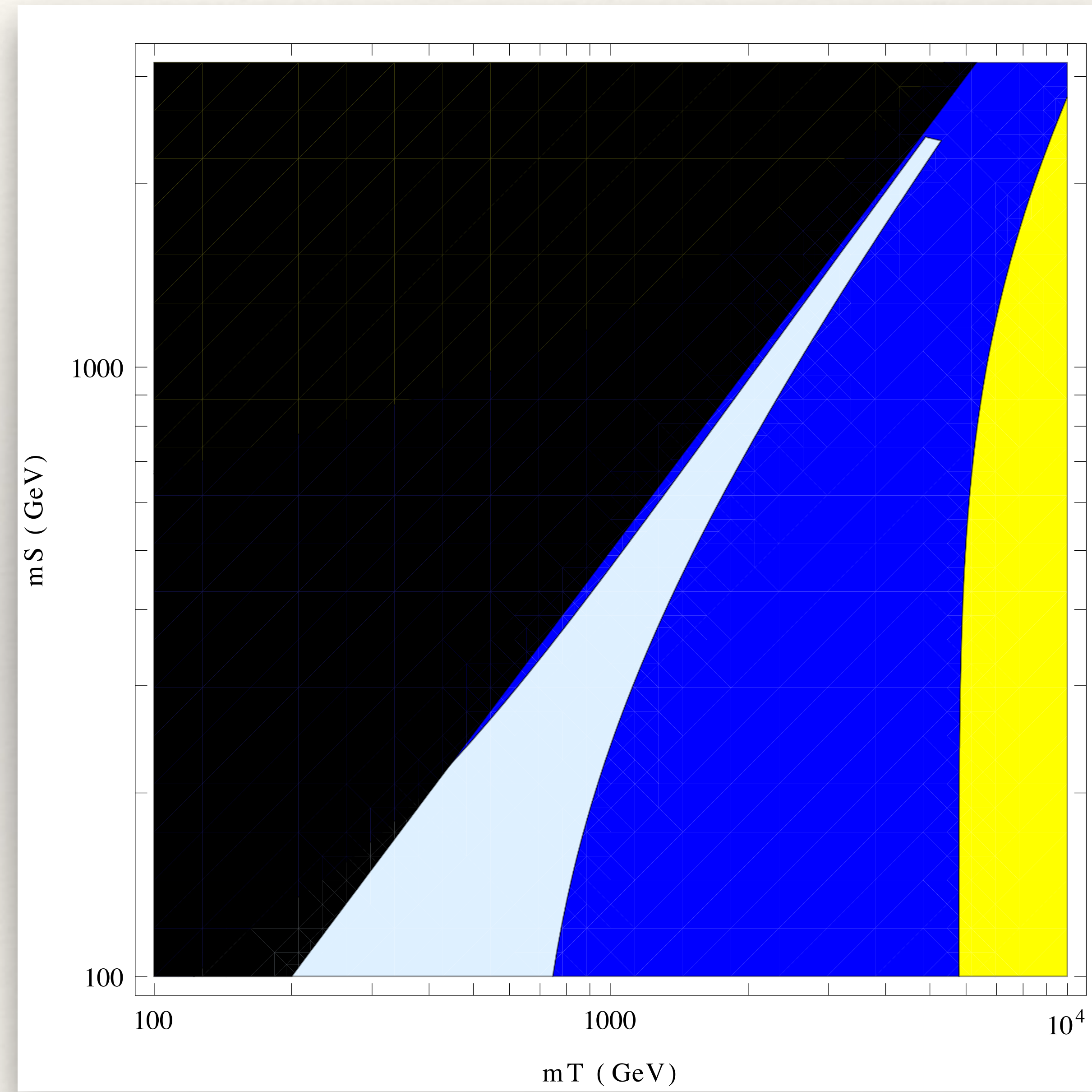
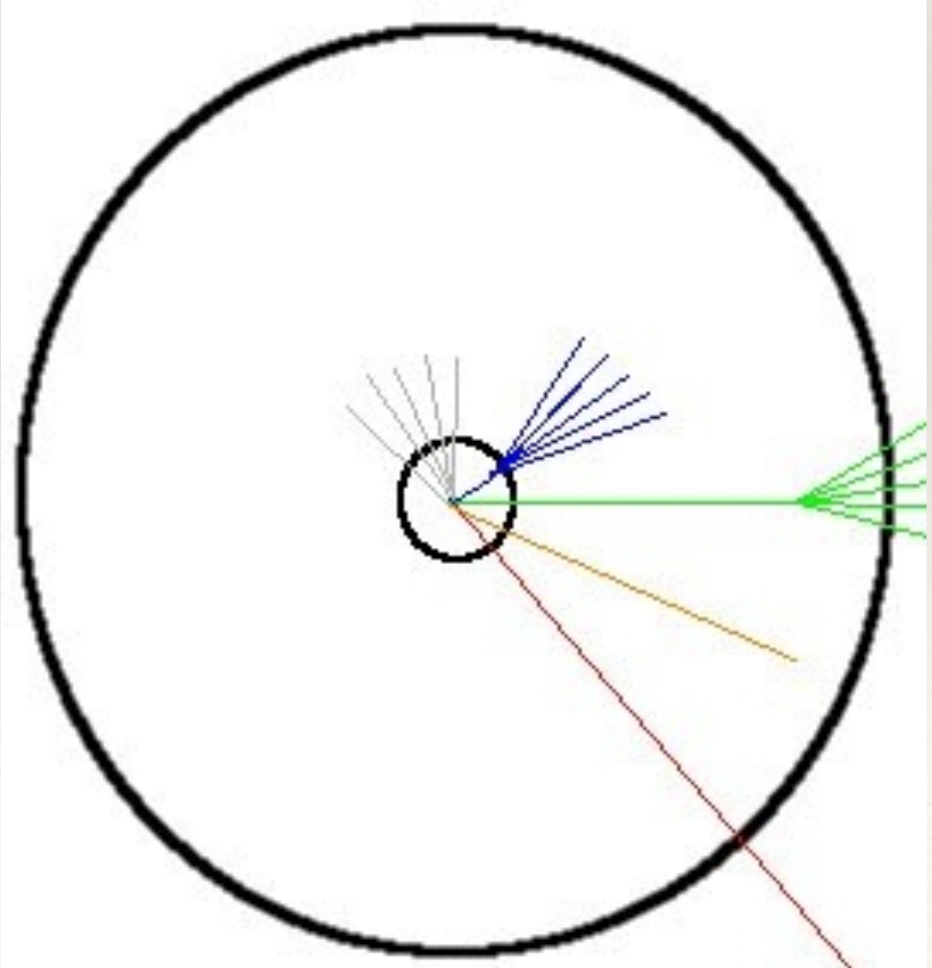


$f = 10$ TeV

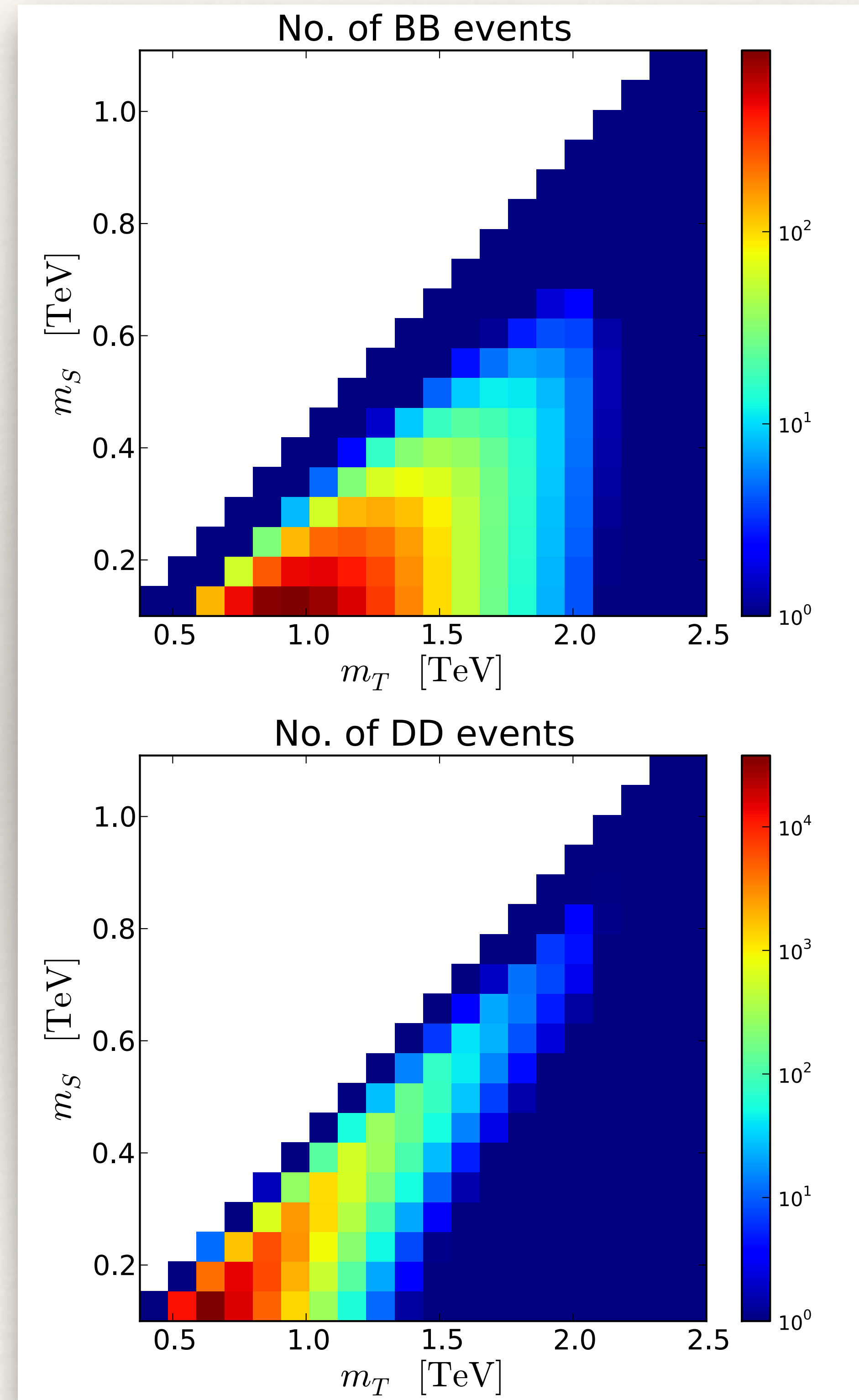


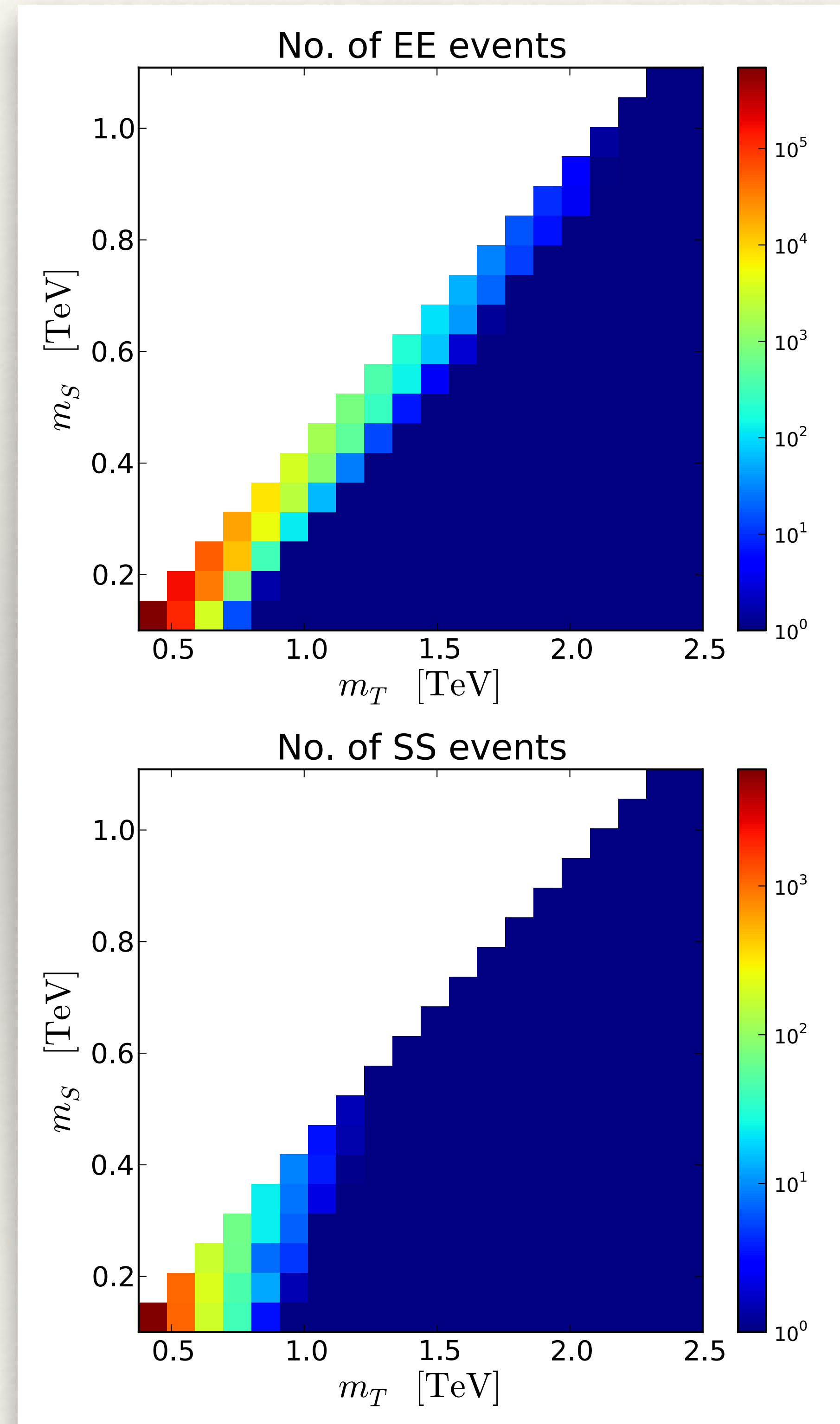
Qualitative Collider Events

- Top companions too heavy even for 100 TeV collider
- Strongest collider signals: $\mathrm{T}^\dagger\mathrm{T}$ 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

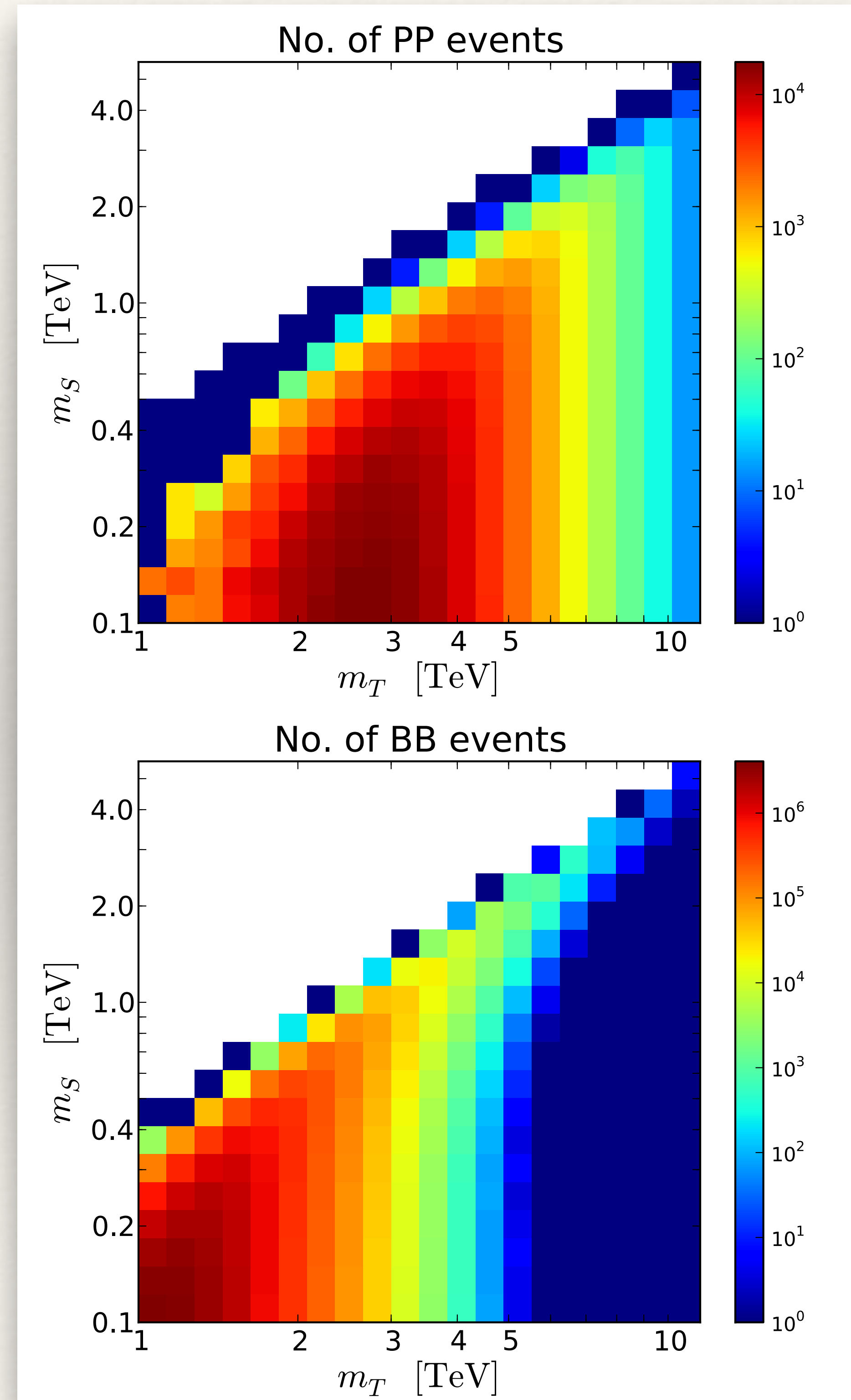


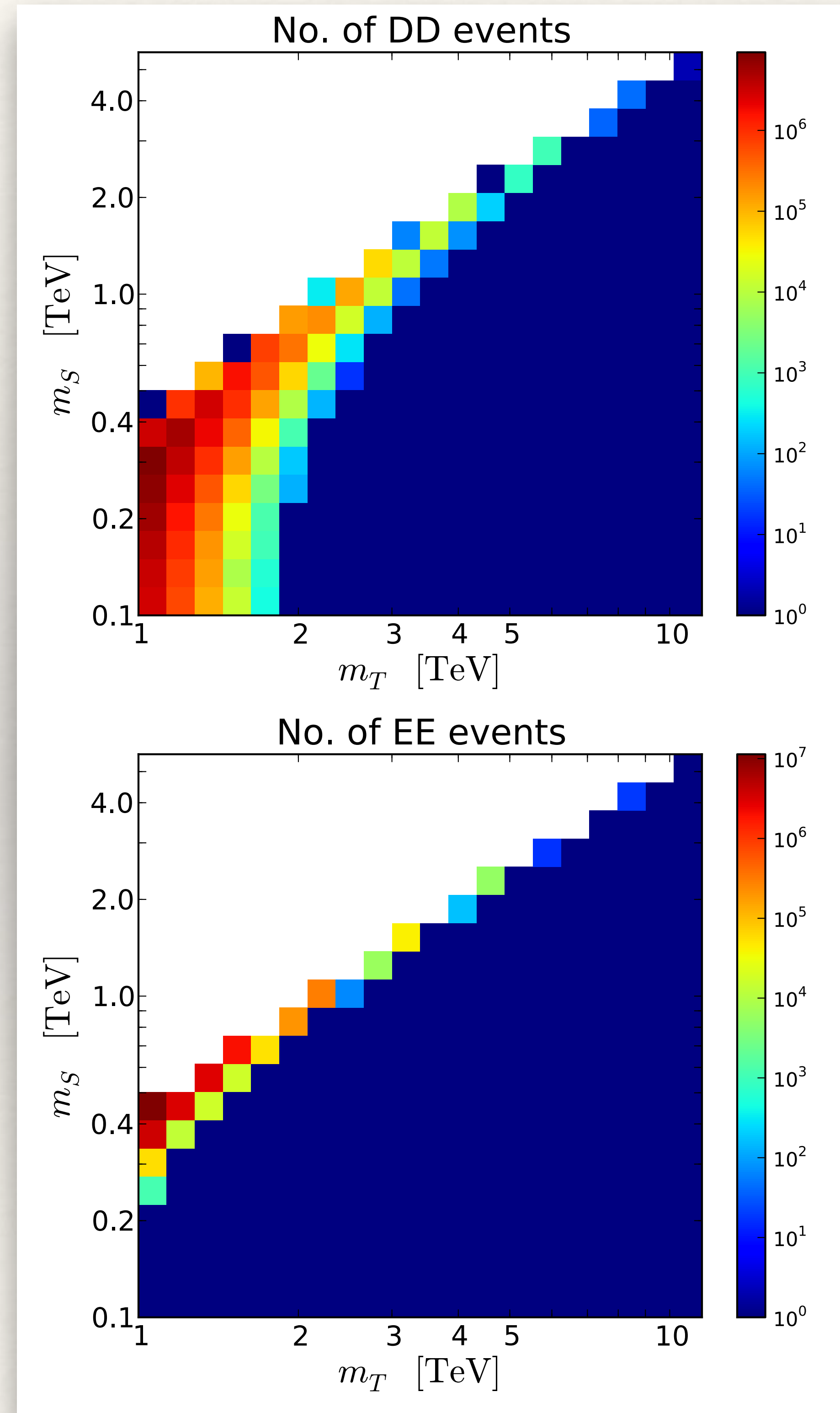
LHC Events (13 TeV)





100 TeV Events (3ab^{-1})





Conclusions

Conclusions

- 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 $\mathrm{SU}(5)$ model with scalar dark matter given
- Future directions: Collider phenomenology, Baryogenesis, Other Cosets

Back-up Slides

Neutrino Masses

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

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

- This is forbidden: $m_\nu \sim 0.06 - 6\ \mathrm{GeV}$
  - We must impose $\mathrm{U(1)_L}$ as a symmetry of strong sector
  - So neutrino masses require $\mathrm{N_R}$
- Majorana $\mathrm{N_R}$ lead to ν_L masses via controlled L violation

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

Incomplete Generations and Baryon Number

- 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	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$