IBS CTPU, 29th October 2015

The Unnaturally Split Composite Higgs

`arXiv:1409.7391, 1510.06405`

J. Barnard, P. Cox, T. Gherghetta, T. Sankar Ray, A. Spray

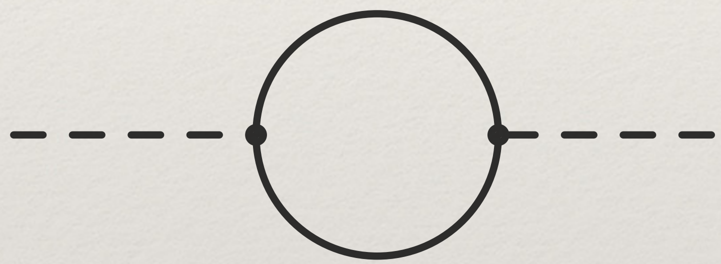
Outline

- Introduction
  - Naturalness, Unnatural Models and SUSY
  - Composite Higgses
- General Features of Split Composite Higgses
  - Flavour and Precision Electroweak Constraints
  - Gauge Unification
  - Proton Stability and Dark Matter
- A Specific Model: SU(7)/SU(6) x U(1)
- Collider Phenomenology of Long-Lived Scalar Triplets
- Conclusions

Introduction

Naturalness

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



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- To avoid large accidental cancellations, expect

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

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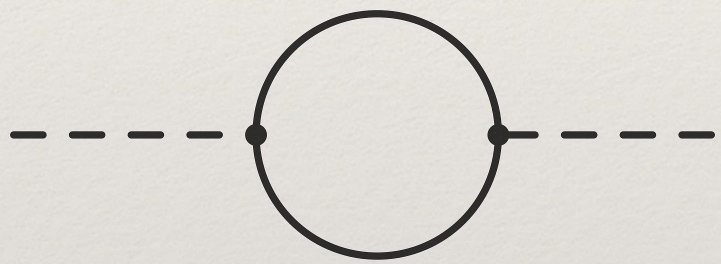

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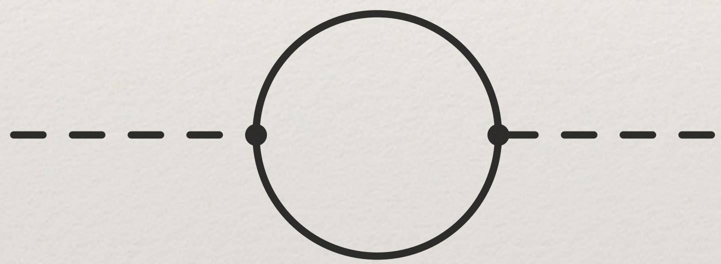

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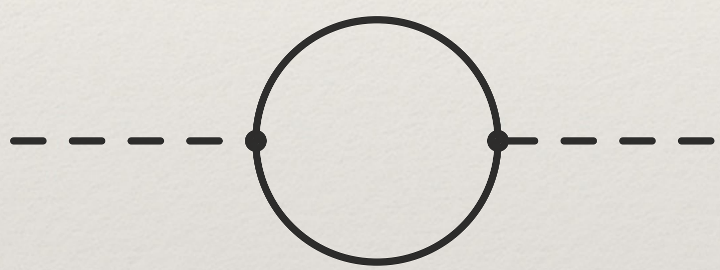

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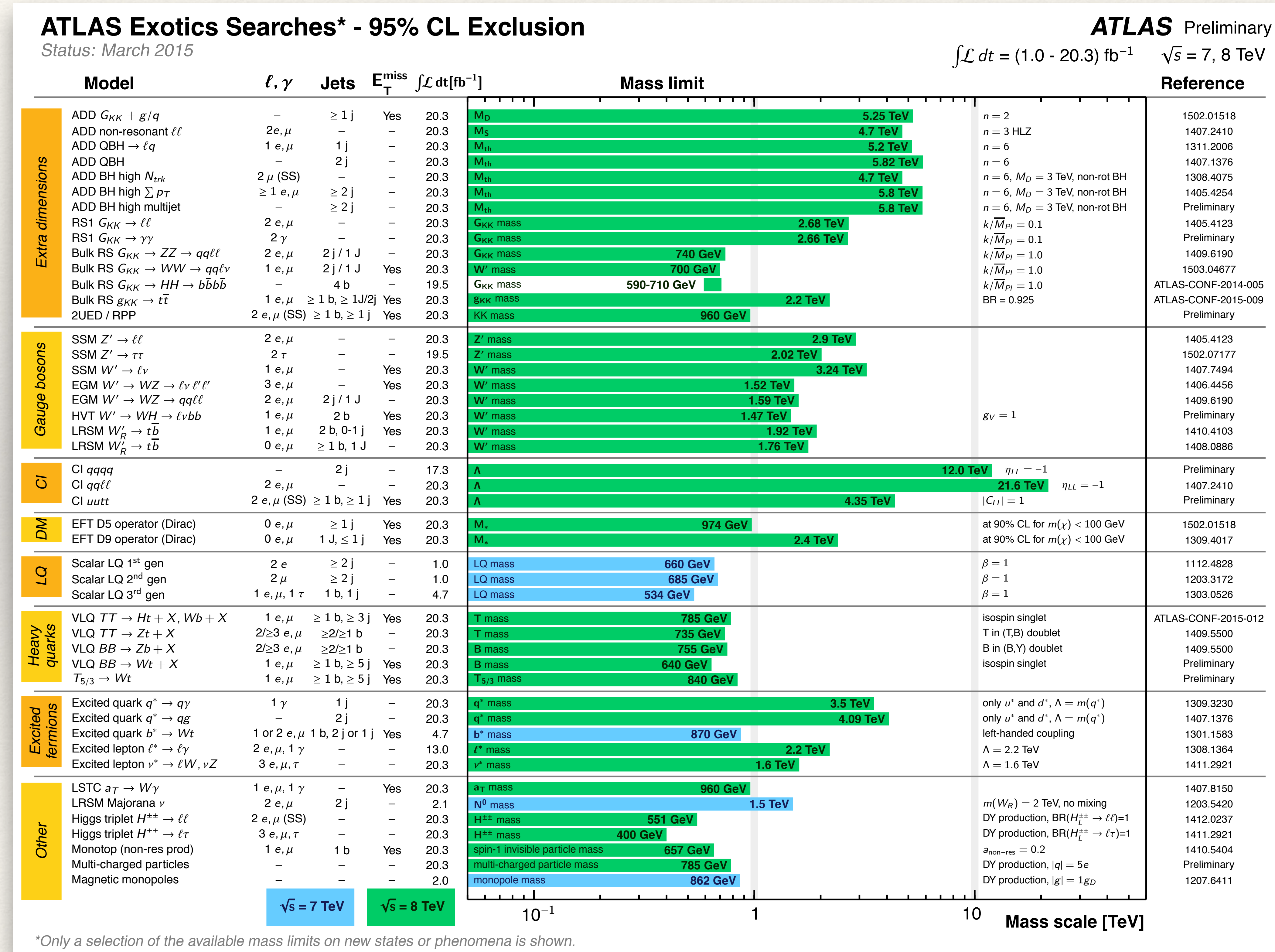
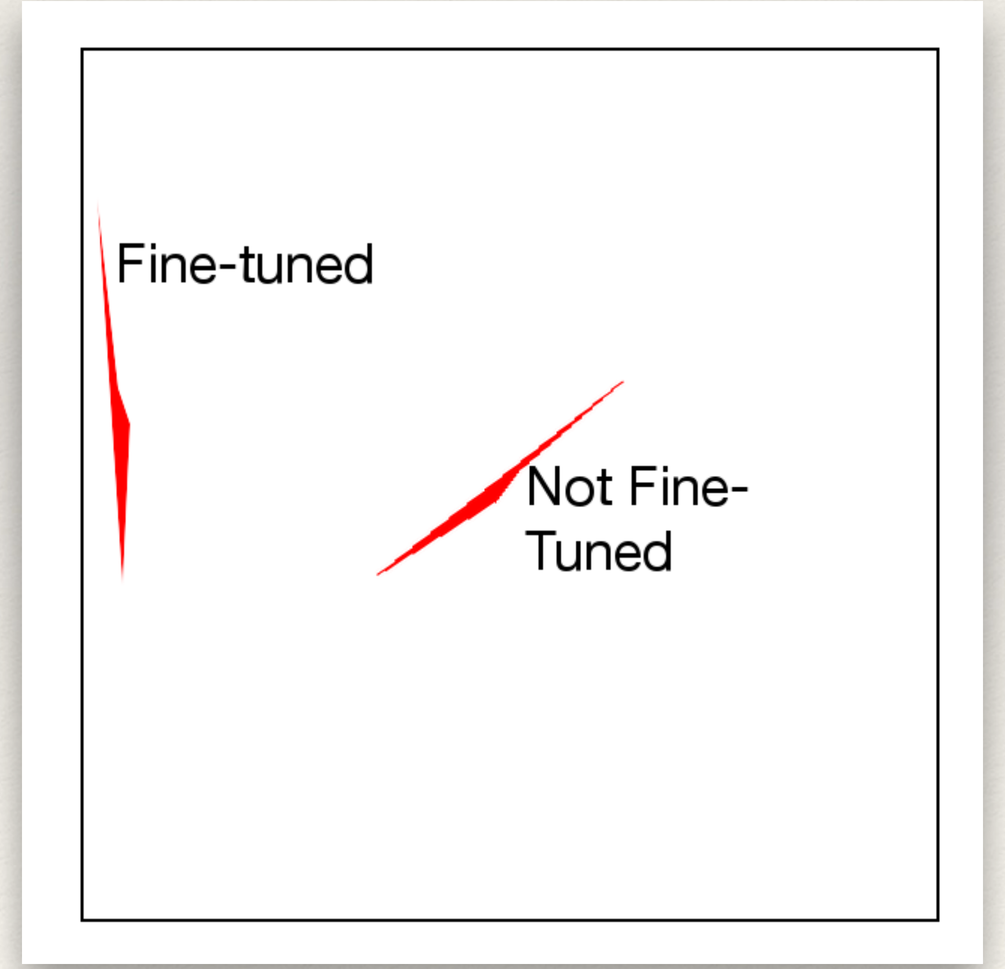
Facing the Evidence



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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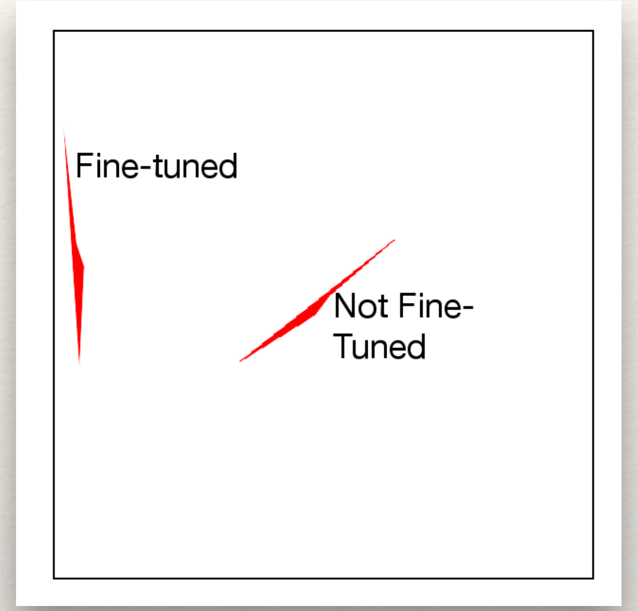

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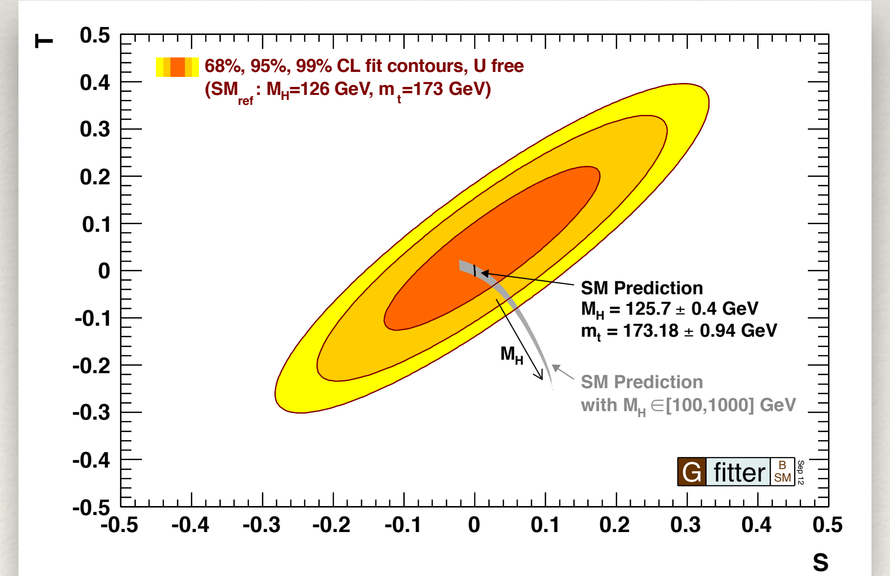
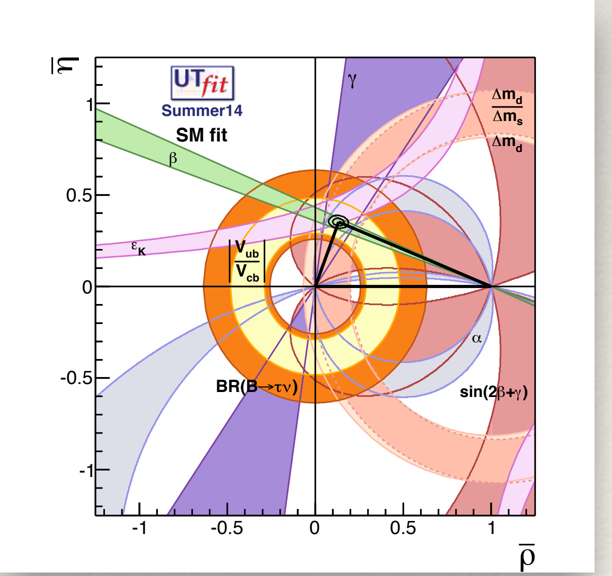
  - T Parameter $T \sim |H^\dagger D_\mu H|^2 \Rightarrow \Lambda_{UV} > 10\ \text{TeV}$
  - Flavour-changing operators $\epsilon_K \sim (\bar{s}_R d_L)^2 \Rightarrow \Lambda_{UV} > 10^{3-4}\ \text{TeV}$





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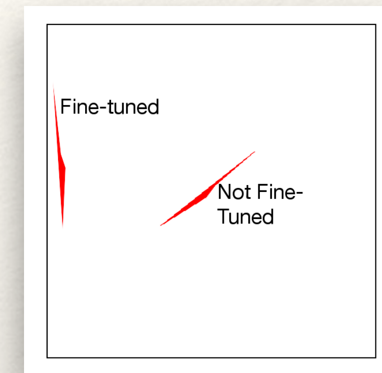

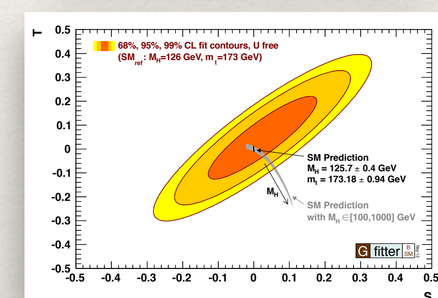

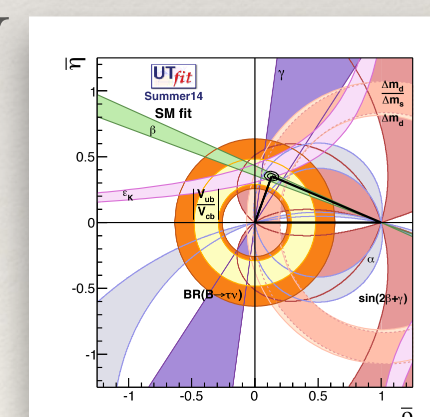

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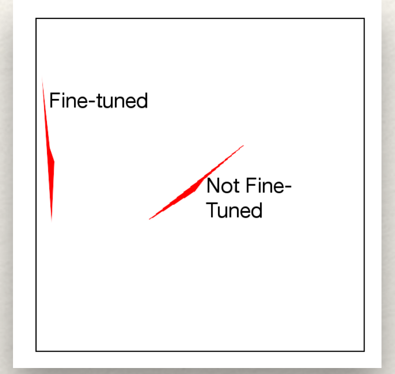
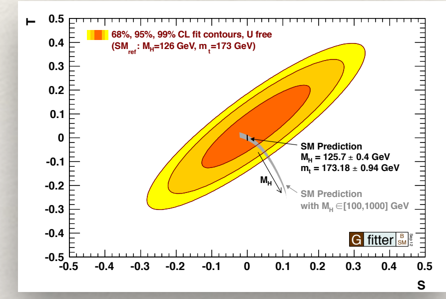
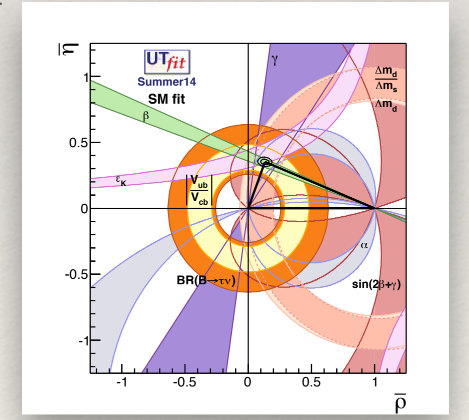


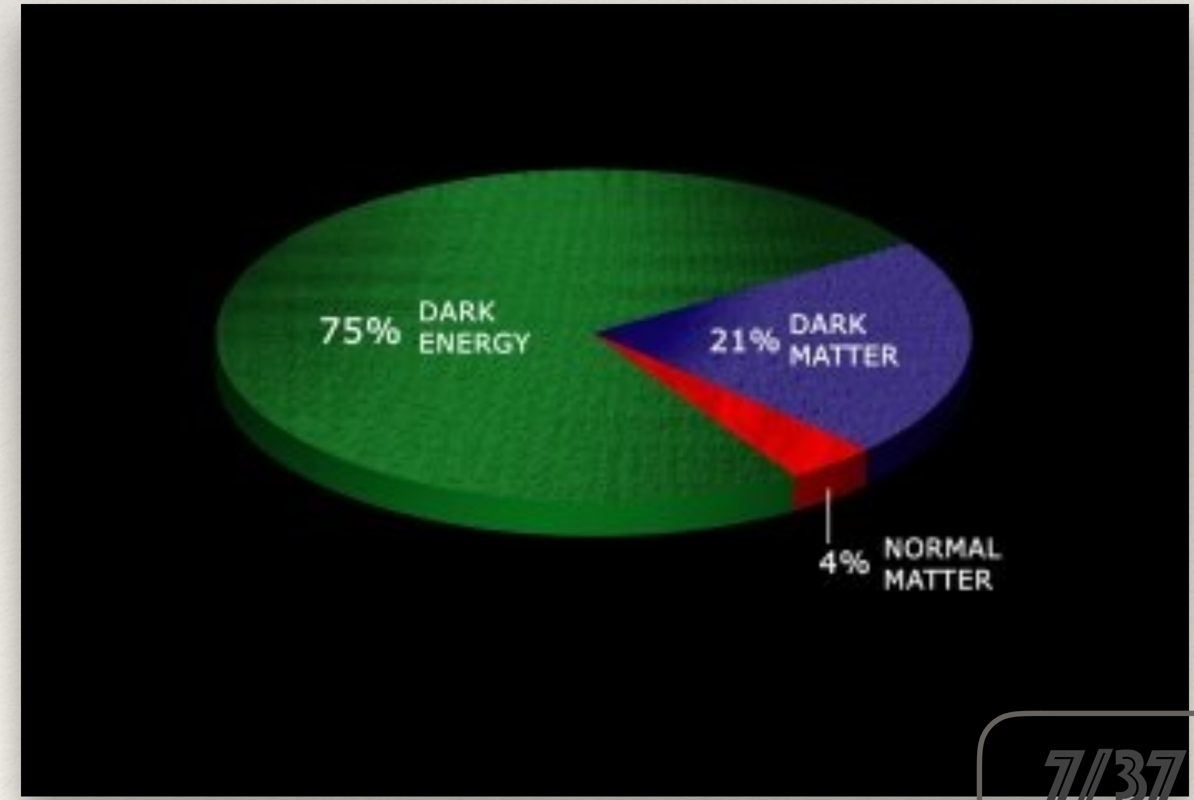




What happens without Naturalness?

Unnatural Reasons for New Physics

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



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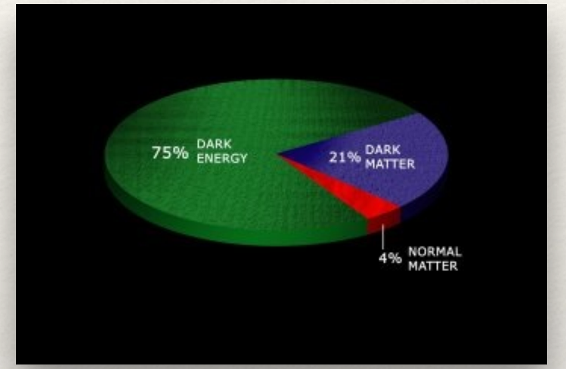

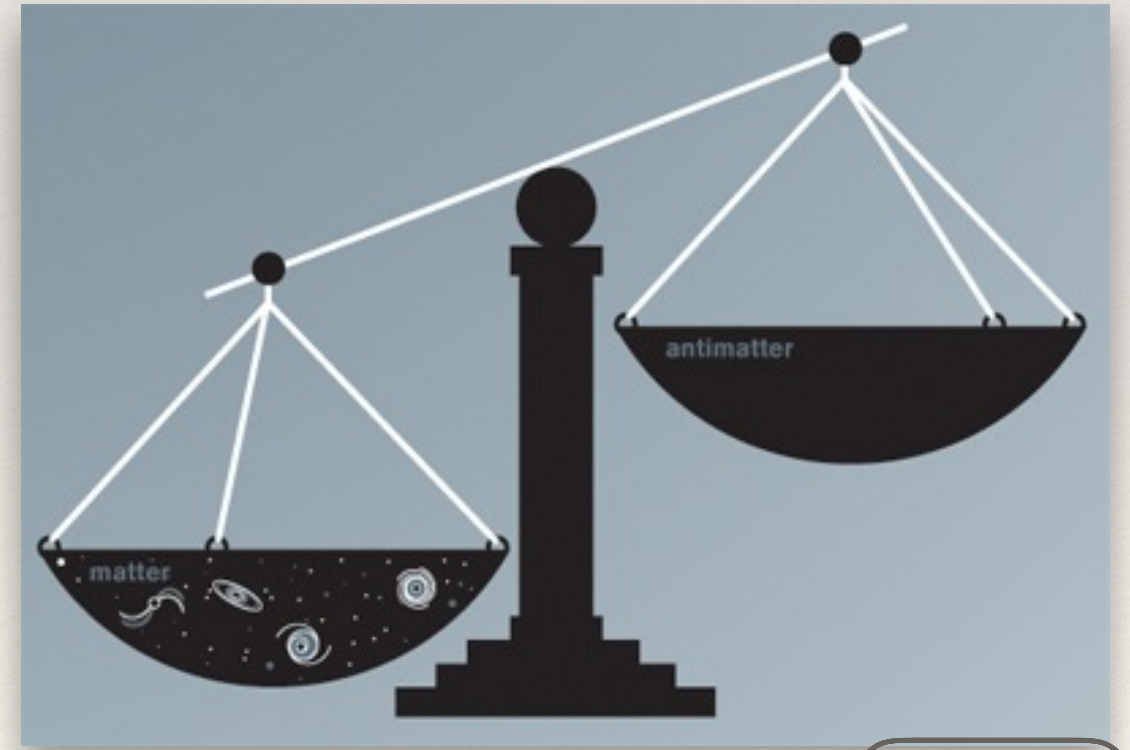

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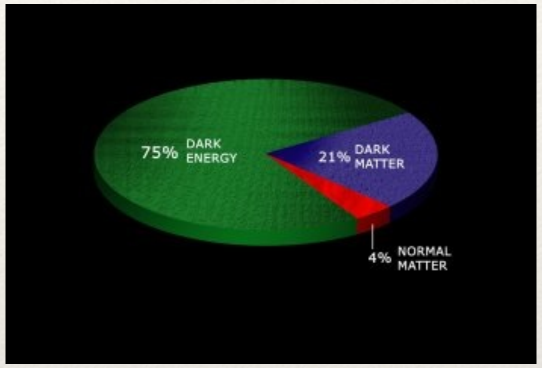

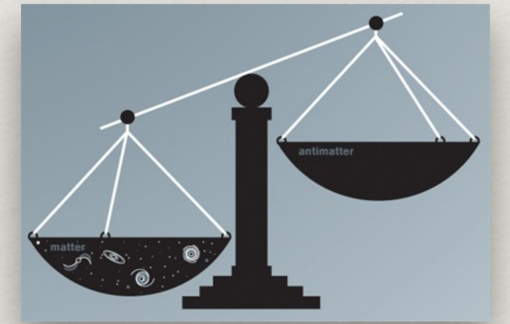

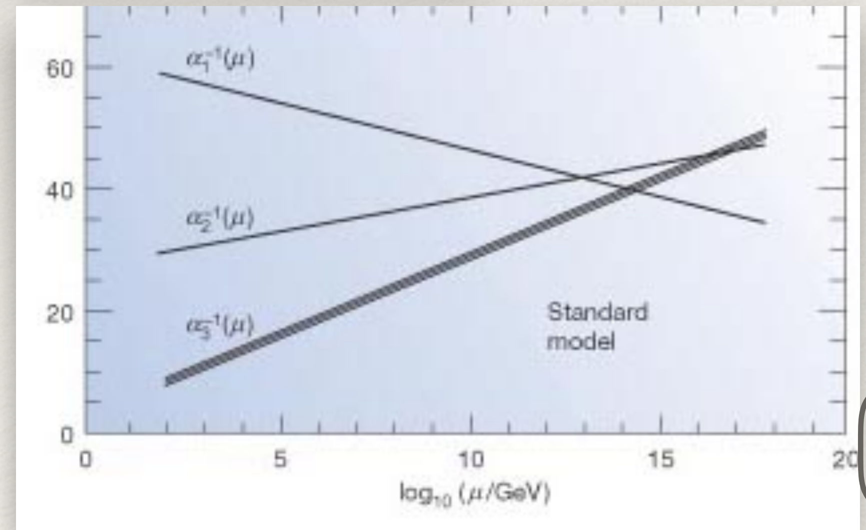

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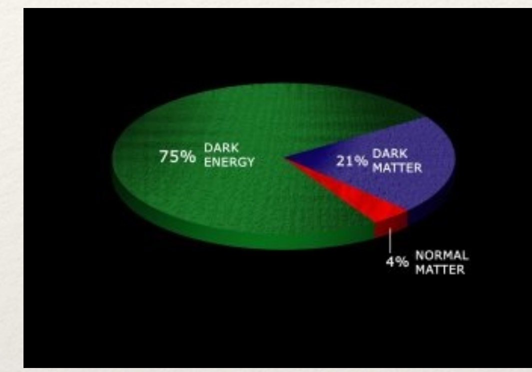

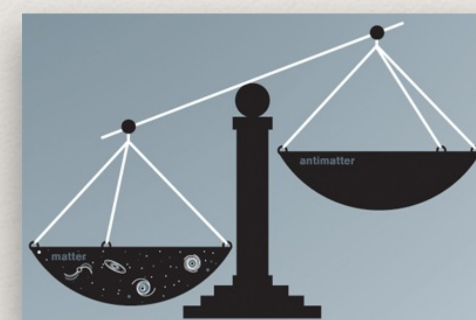

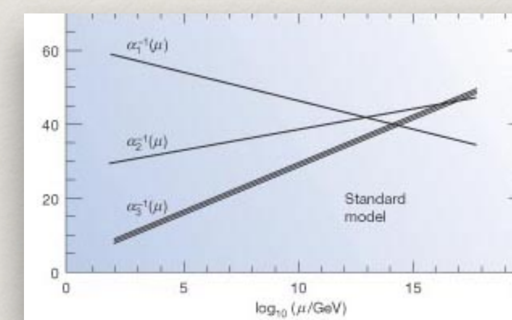

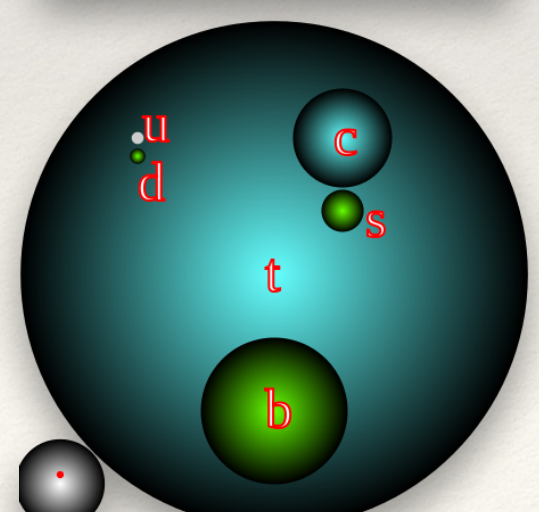

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- Dark Matter
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- Baryogenesis
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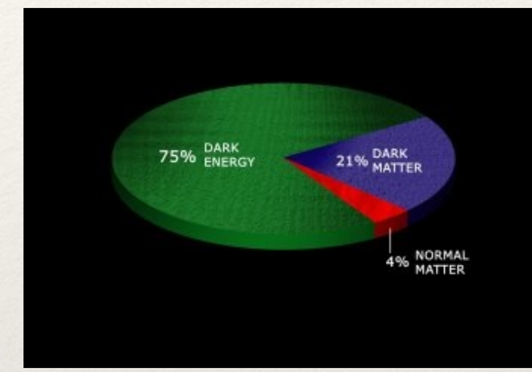
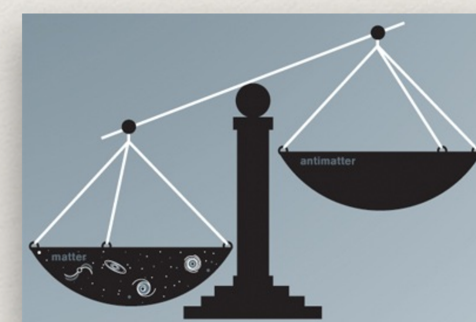
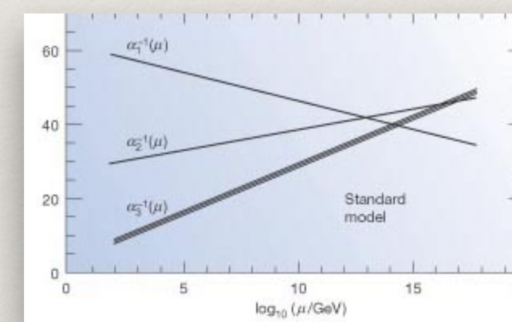
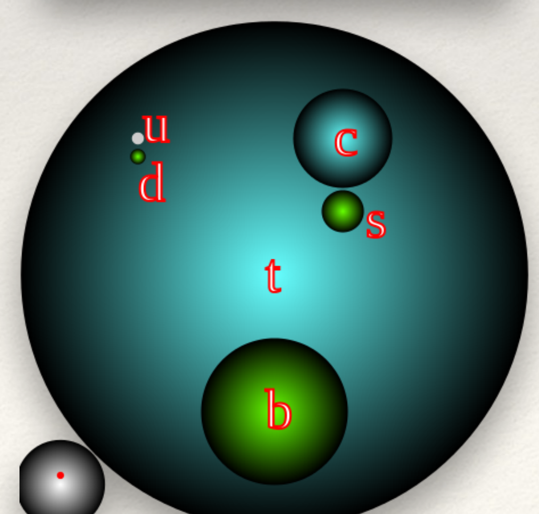
- Gauge Unification
- Flavour Physics
- Simpler Models!



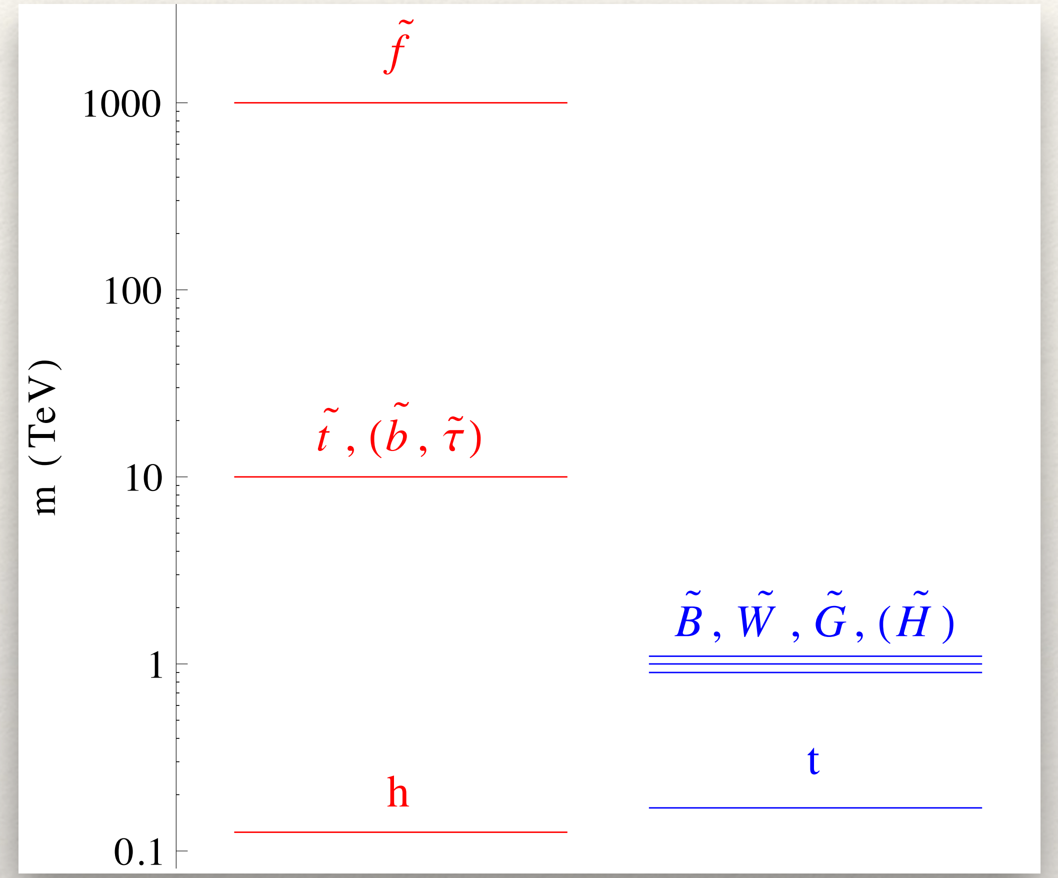






Mini-Split Supersymmetry

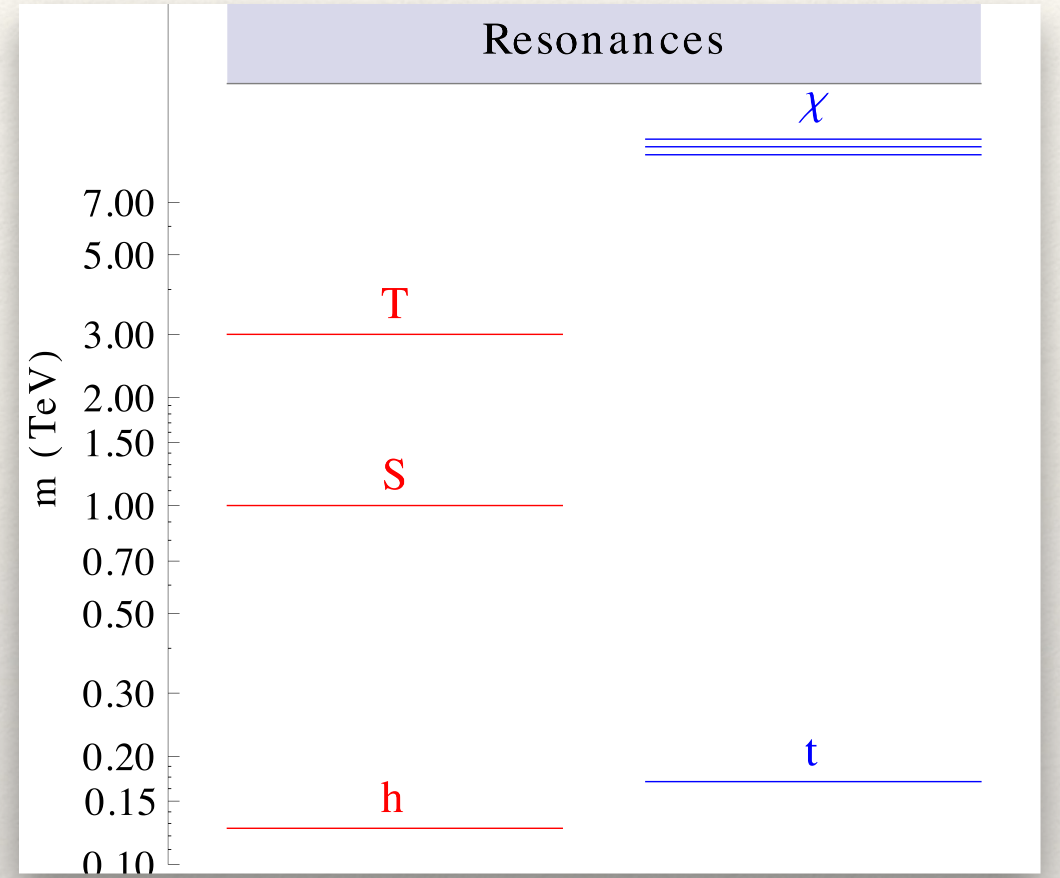
- Without Naturalness, SUSY still has:
  - Dark Matter (R-Parity)
  - Consistent with Leptogenesis
  - Improved Unification (Gauginos)
- Gauginos light by R-symmetry
- Split Spectrum avoids Flavour, LHC problems
- Long-lived gluino signal



- 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

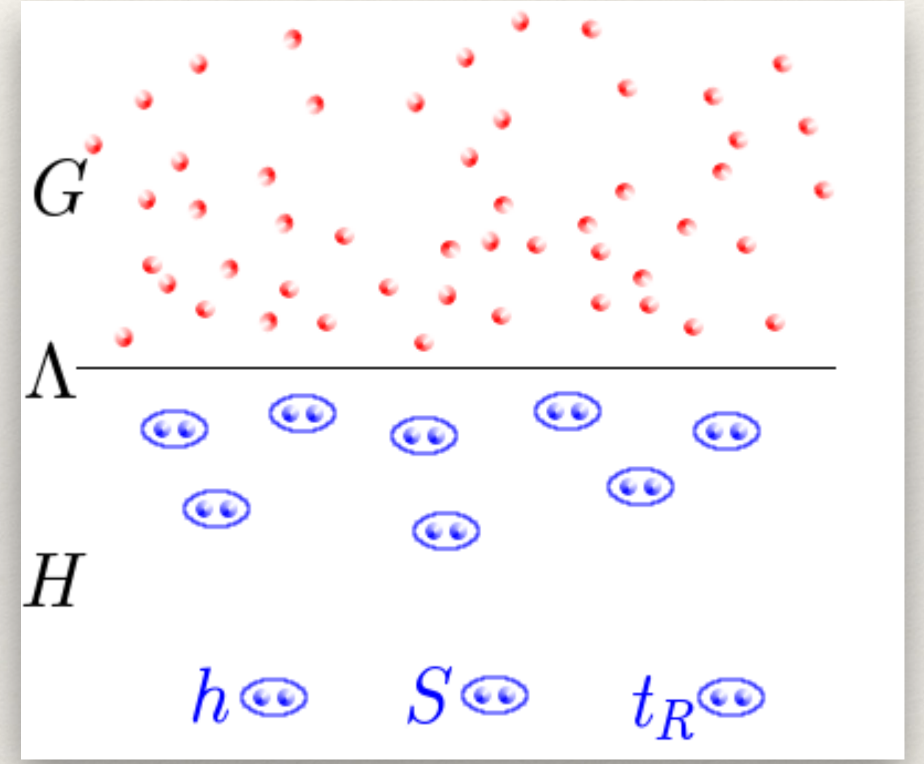
- Without Naturalness, still have:
  - Dark Matter (Baryon Triality)
  - Consistent with Leptogenesis
  - Improved Unification (Top Exotics)
  - Theory of Flavour
- Goldstones light by shift symmetry
- Split Spectrum avoids Flavour, LHC problems
- Long-lived SU(3) triplet signal



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

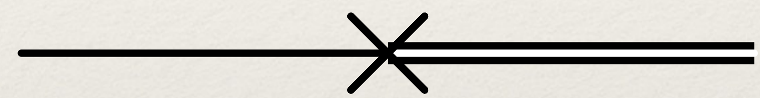


Fermion Masses

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

- Fermions mix with confining sector at high scale Λ_{UV} (Partial Compositeness)

$$\mathcal{L} \supset \frac{c_f}{\Lambda_{UV}^{D_f}} \psi_f \mathcal{O}^f \sim \psi_f$$

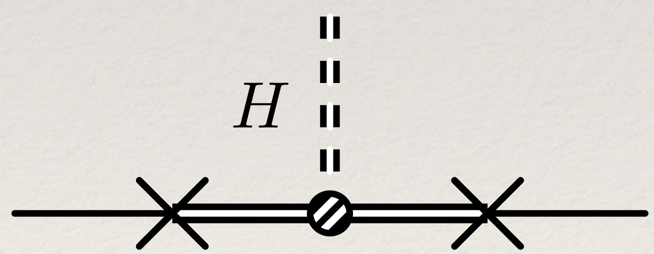


$$\mathcal{O}^f$$

Flavour-dependent dimensions D_f

Mixings generate Yukawa couplings:

$$\bar{\psi}_f$$

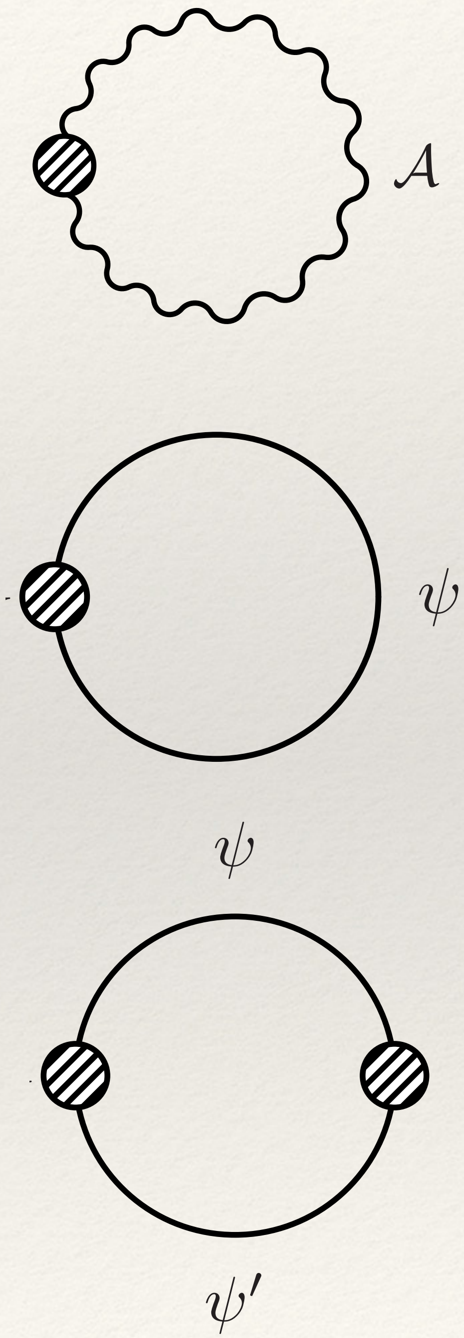


$$\psi_{f'} \sim c_f c_{f'} \left(\frac{f}{\Lambda_{UV}} \right)^{D_f + D_{f'}}$$

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

Higgs Potential

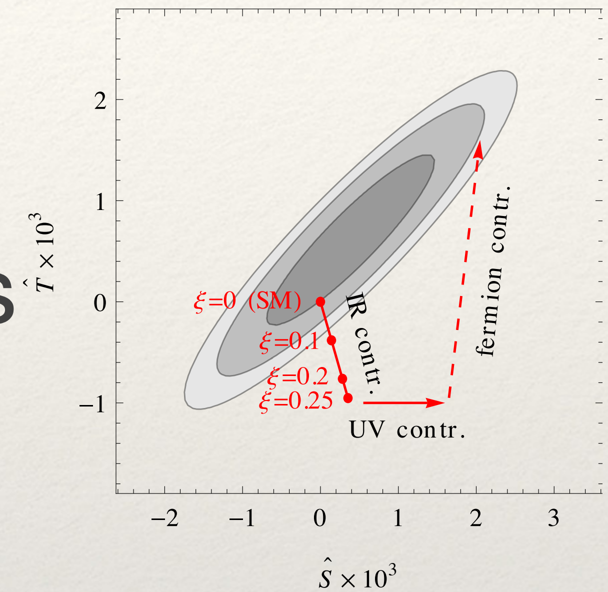
- When SM couplings vanish:
  - PNGBs $\rightarrow$ Goldstones
  - Goldstone potential vanishes
- So Higgs potential $V = V(g, \lambda)$
  - "Calculable"
  - Loop-level: $v_{EW} \sim \frac{\Lambda}{4\pi} \sim f$
  - Intrinsic Fine-Tuning (gauge vs fermion loops) $\Delta \sim \frac{v_{EW}^2}{f^2}$



General Features of Split Composite Higgses

Lower Bound 1: EWPT

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

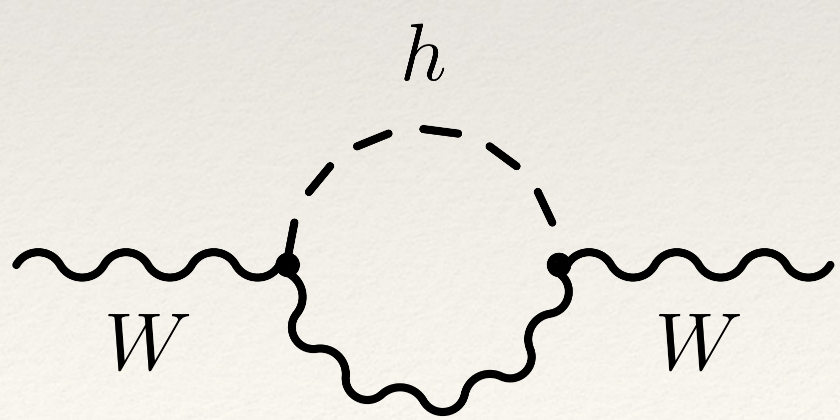


Grojean *et al*, `1306.4655`

$\Delta S \sim$

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

$+\,\Delta$



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

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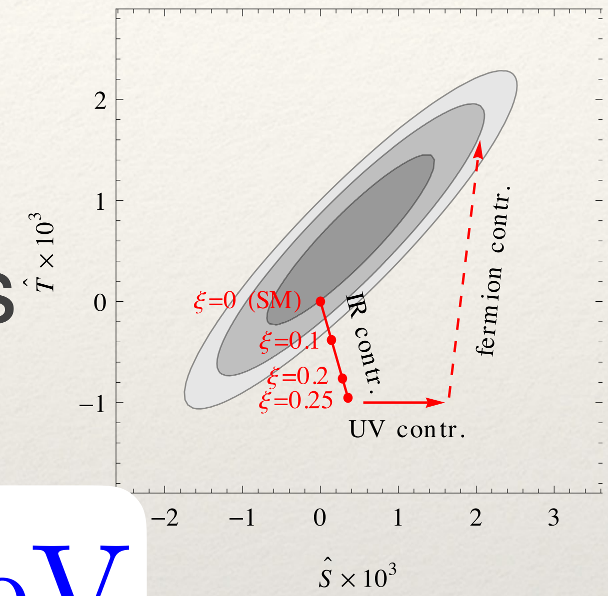

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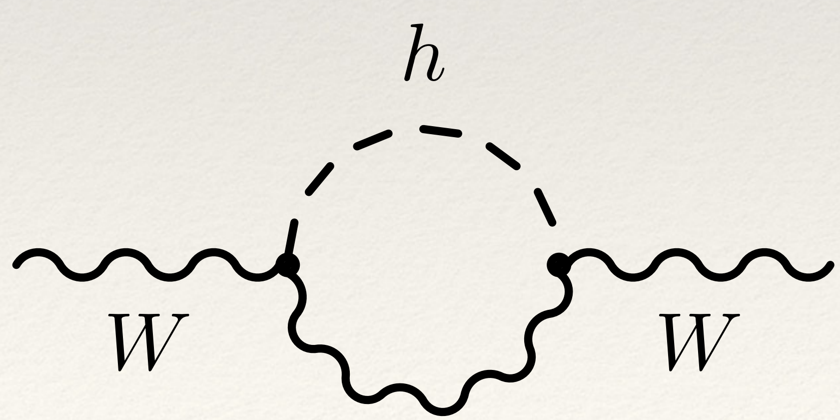

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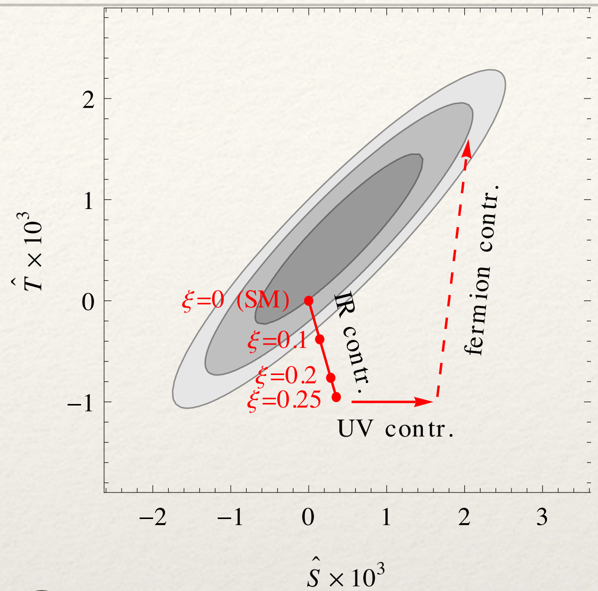

Grojean *et al*, 1306.4655

  - T: new isospin violation (Kaplan & Georgi, Phys. Lett. **B136** 183, Csaki et al hep-ph/0303236, Agashe et al hep-ph/0308036, Giudice et al hep-ph/0703164, Bertuzzo *et al* 1206.2623)

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

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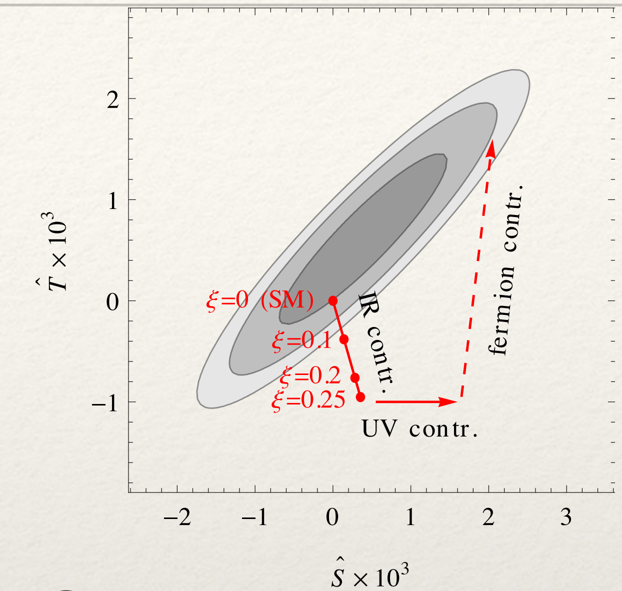

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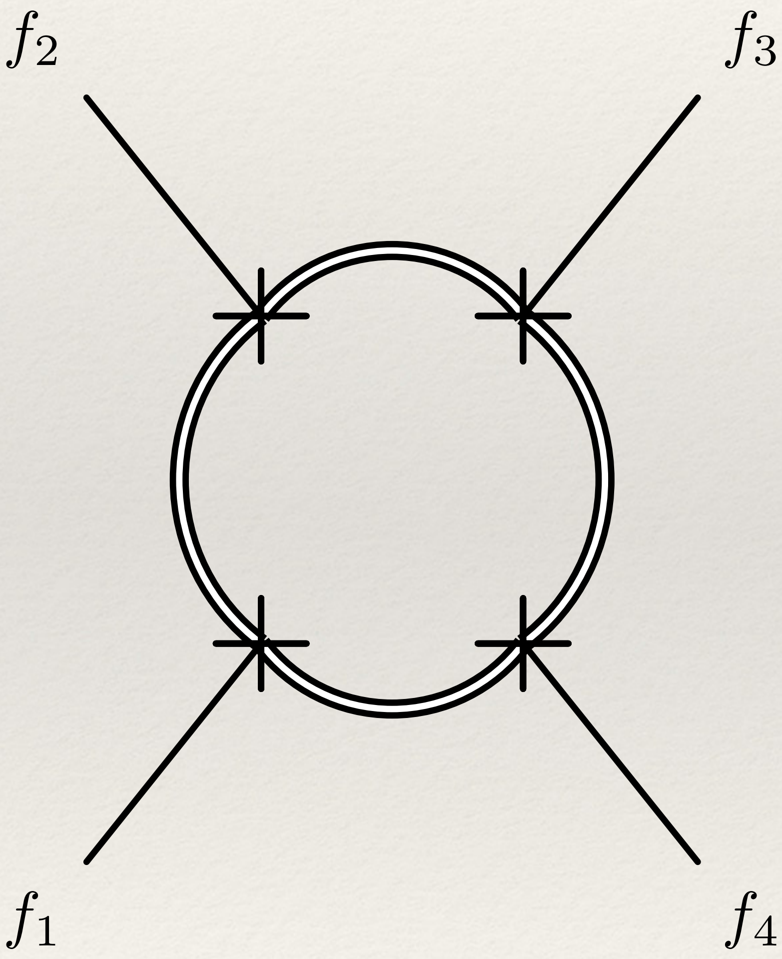
- Nearly all modern models use custodial SU(2)
  (Though problem still exists in non-flat cosets H, Bertuzzo *et al* `1206.2623`)
- Unnatural models can avoid this: SIMPLER

Lower Bound 2: Flavour

- Partial Compositeness generates 4-fermion operators:



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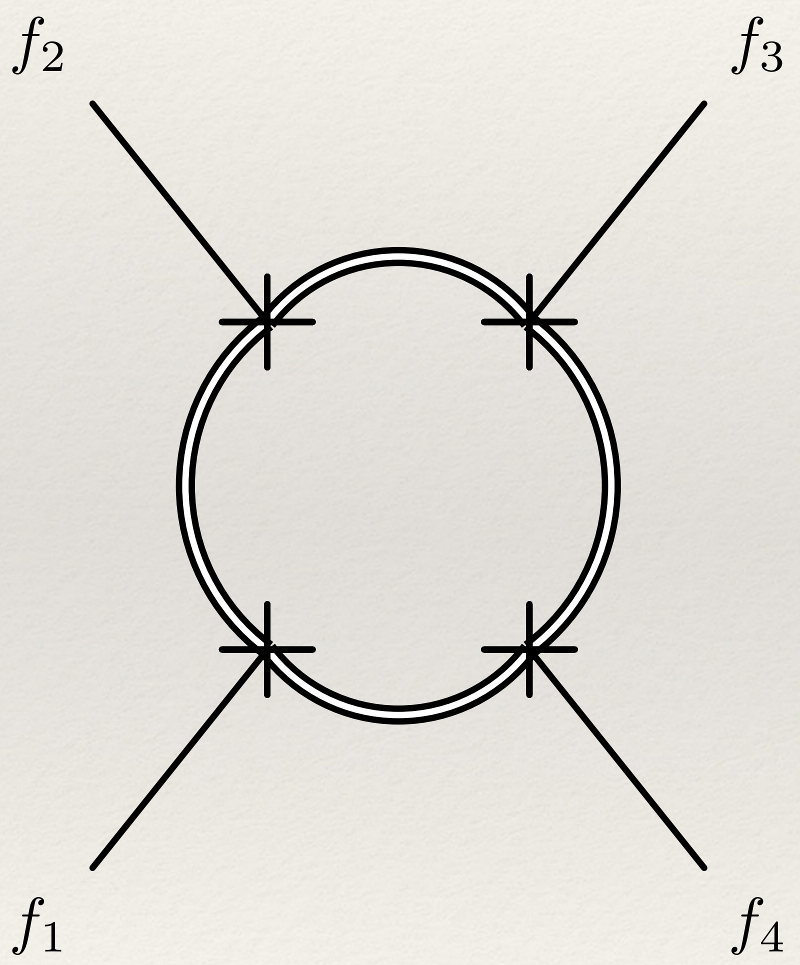

$$\propto \frac{\sqrt{y_1 y_2 y_3 y_3}}{\Lambda^2}$$

- BUT! result $\propto$ Yukawas

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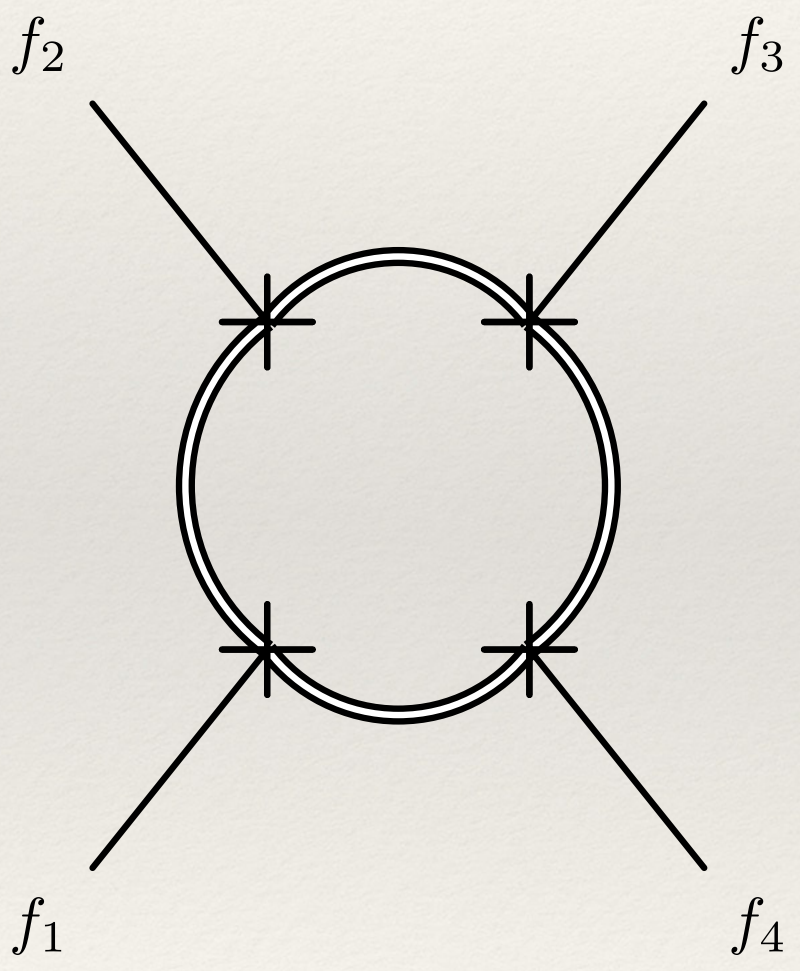

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  - RS-GIM mechanism

(Gherghetta & Pomarol `hep-ph/0003129`, Huber `hep-ph/0303183`, Agashe *et al* `hep-ph/0408134`)

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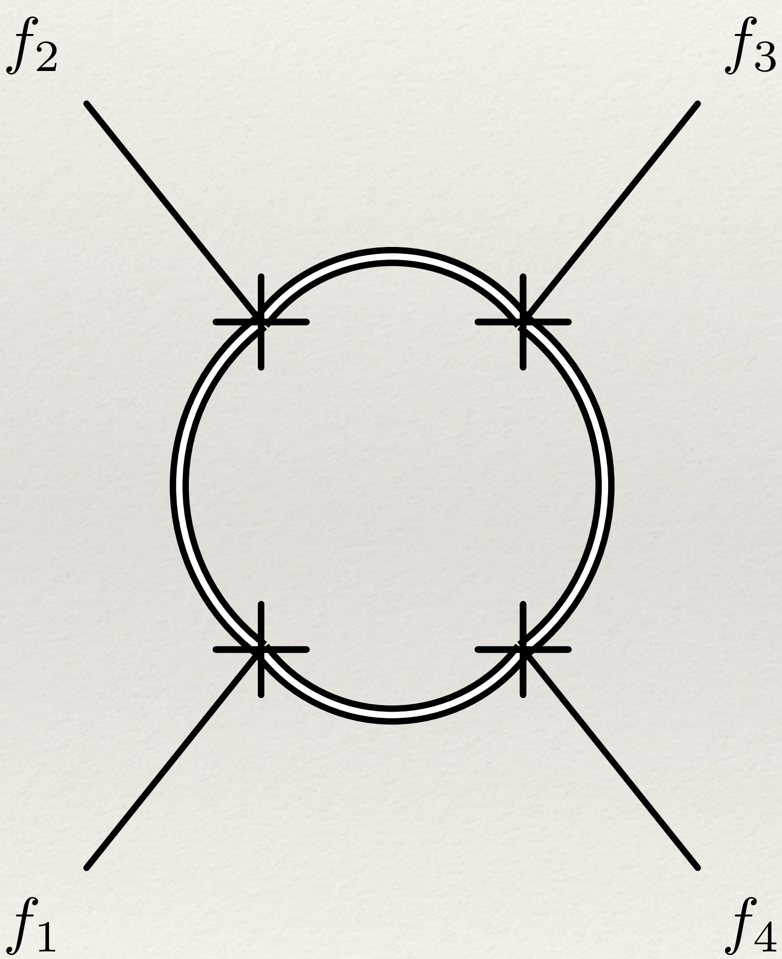

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- Strongest Constraint (ε_K): $f \gtrsim 12$ TeV

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

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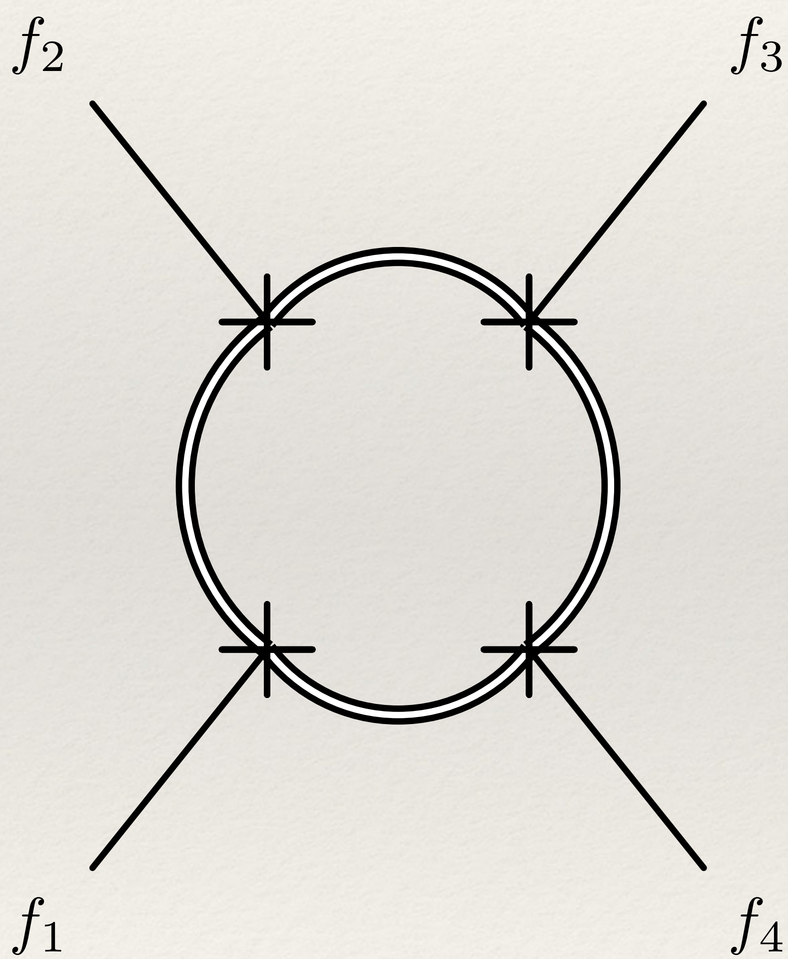

$$\propto \frac{\sqrt{y_1 y_2 y_3 y_3}}{\Lambda^2}$$

- BUT! result ∝ Yukawas
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(Gherghetta & Pomarol hep-ph/0003129, Huber hep-ph/0303183, Agashe *et al* hep-ph/0408134)

- Strongest Constraint (ε_K): $f \gtrsim$ 12 TeV

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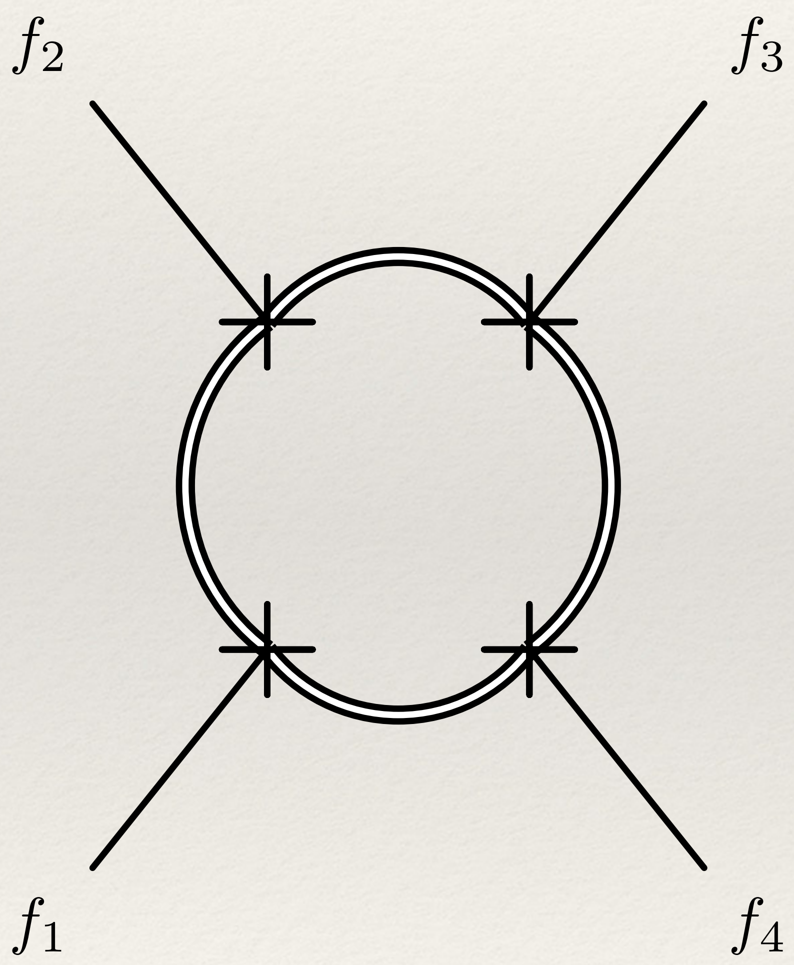

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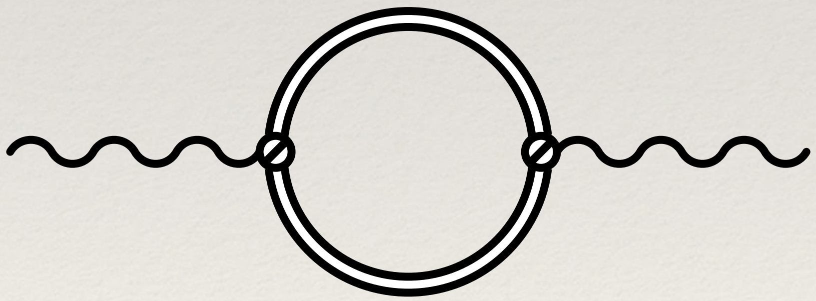
- Or unnatural $\longrightarrow$ SIMPLER

Calculable 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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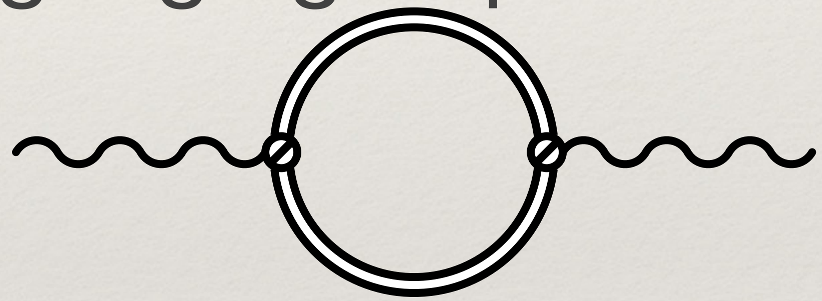
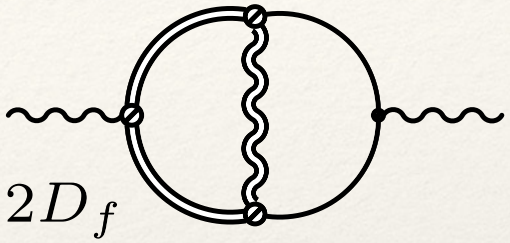


- Let $G \supseteq\ G_{GUT}$
  - Strong sector states come in complete representations of SU(5)
  - One-loop differential running unaffected (away from Landau poles)
  - Two-loop diagrams with SM, confining sector states, do affect running

The Top Problem

- Two-loop elementary-composite running:



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

- Contribution from t_R ($D_t \approx 0$, $c_t \approx g_\rho$) out of control!

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

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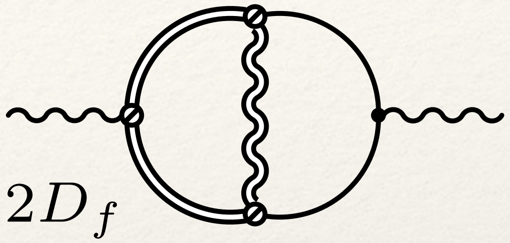

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- Solution: make $\mathrm{t_R}$ fully composite
  - Nearly composite anyway
  - Chiral, so massless despite being composite
- Top may have companions from representation of H…

Top Companions & Goldstones

- If $G_{\rm GUT} \subset H$, then $\rm h$, $\rm t_R$ NOT only light composites!
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- Higgs in **5** of $\rm SU(5)$: expect Goldstone $\rm SU(3)$ triplet T $\begin{pmatrix} T \\ H \end{pmatrix}$
- $\rm t_R$ in **10** of $\rm SU(5)$: 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) $\begin{pmatrix} 0 & \tilde{Q}^c \\ \tilde{Q}^{cT} & \tilde{e}^c \end{pmatrix}$
- Related to top: expect $\rm m_\chi \sim y_t\ \mathit{f}$

An Upper Limit on f

- Above Λ, Composite SM states “dissolve” into $\mathrm{NP}^{\mathrm{comp}}$

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

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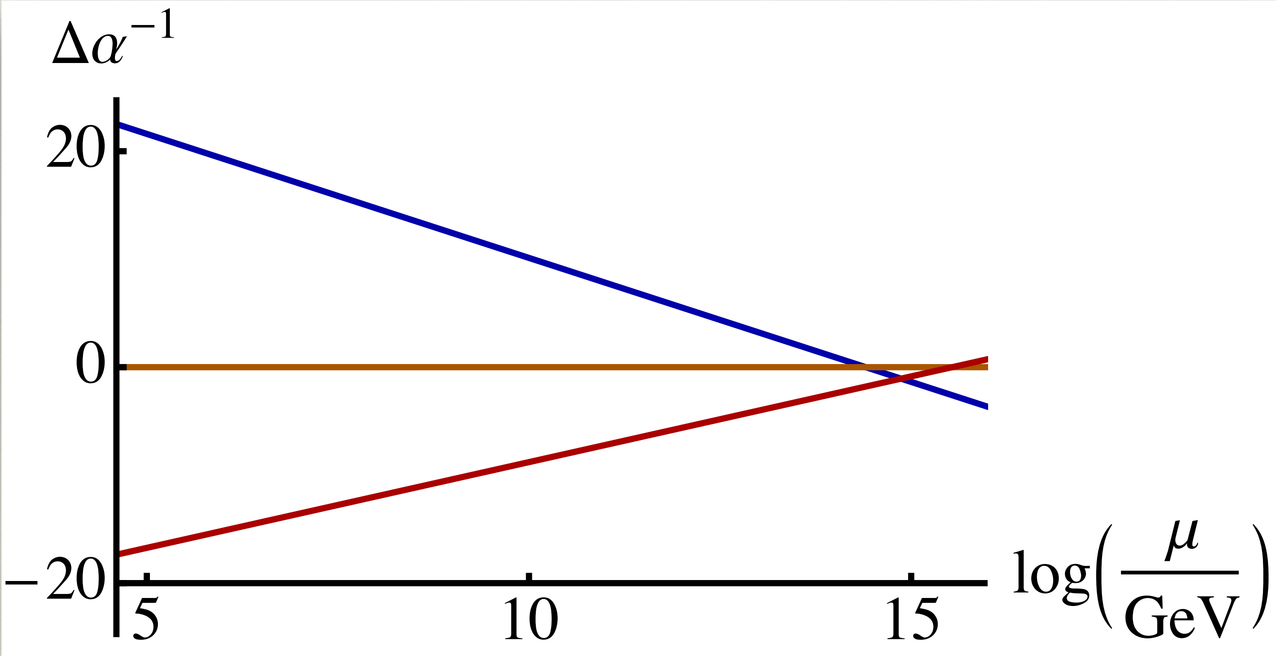
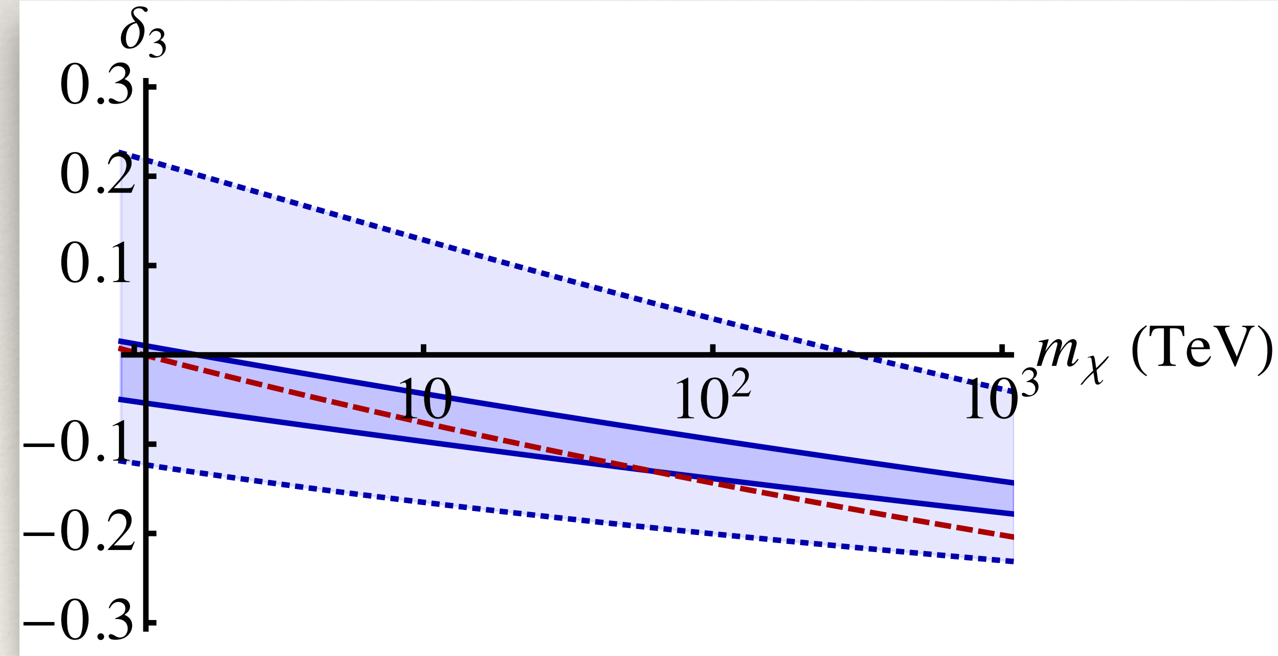


- Two-Loop 4D/5D
(Choi & Kim, `hep-th/0411090`)



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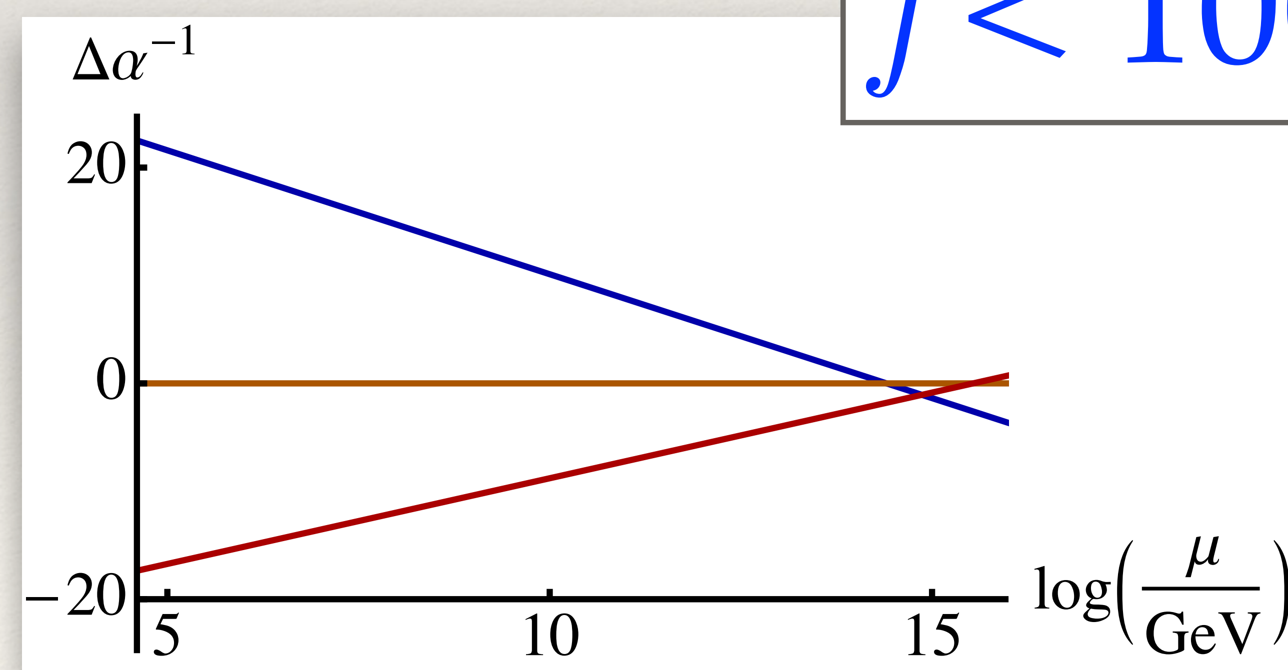
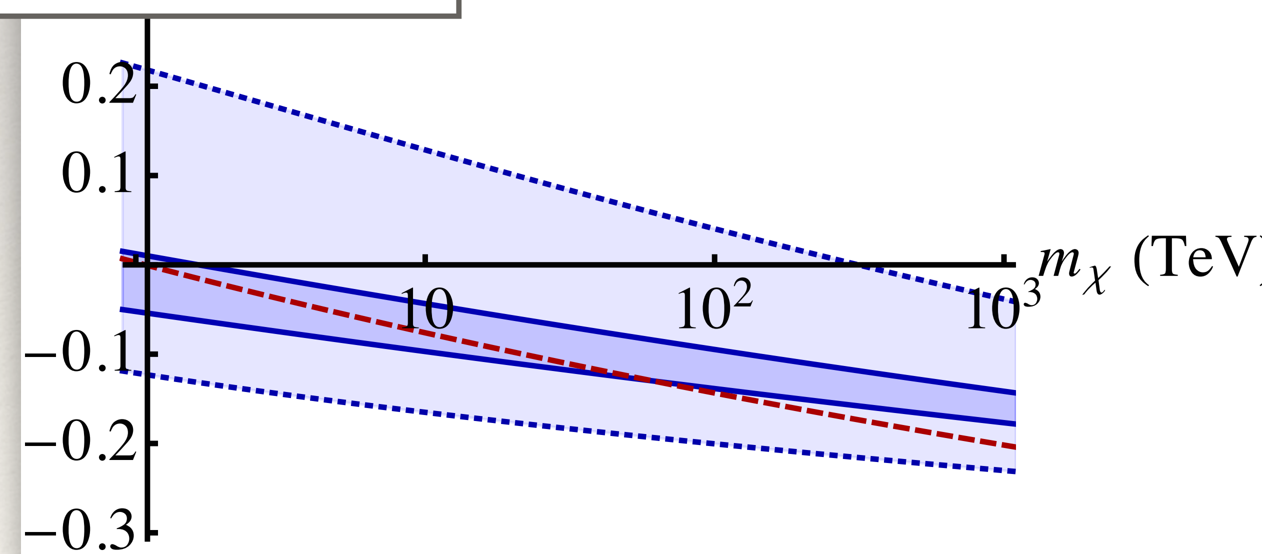
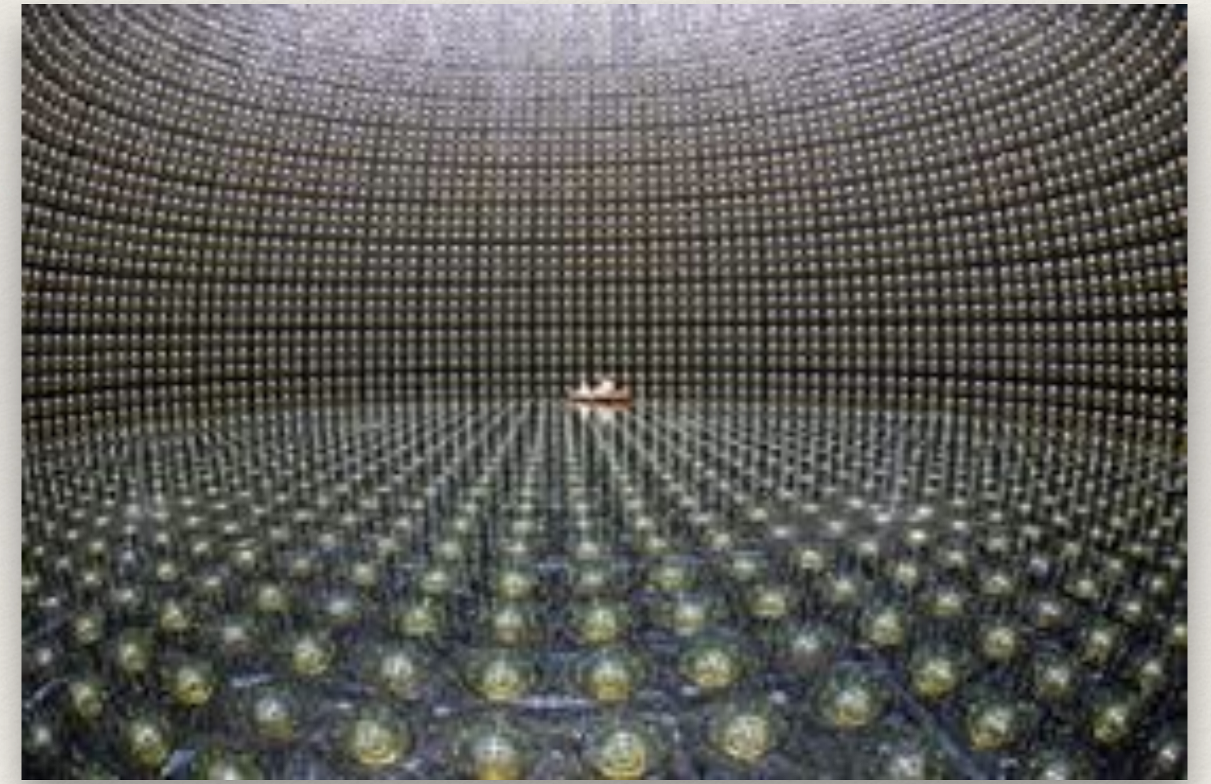


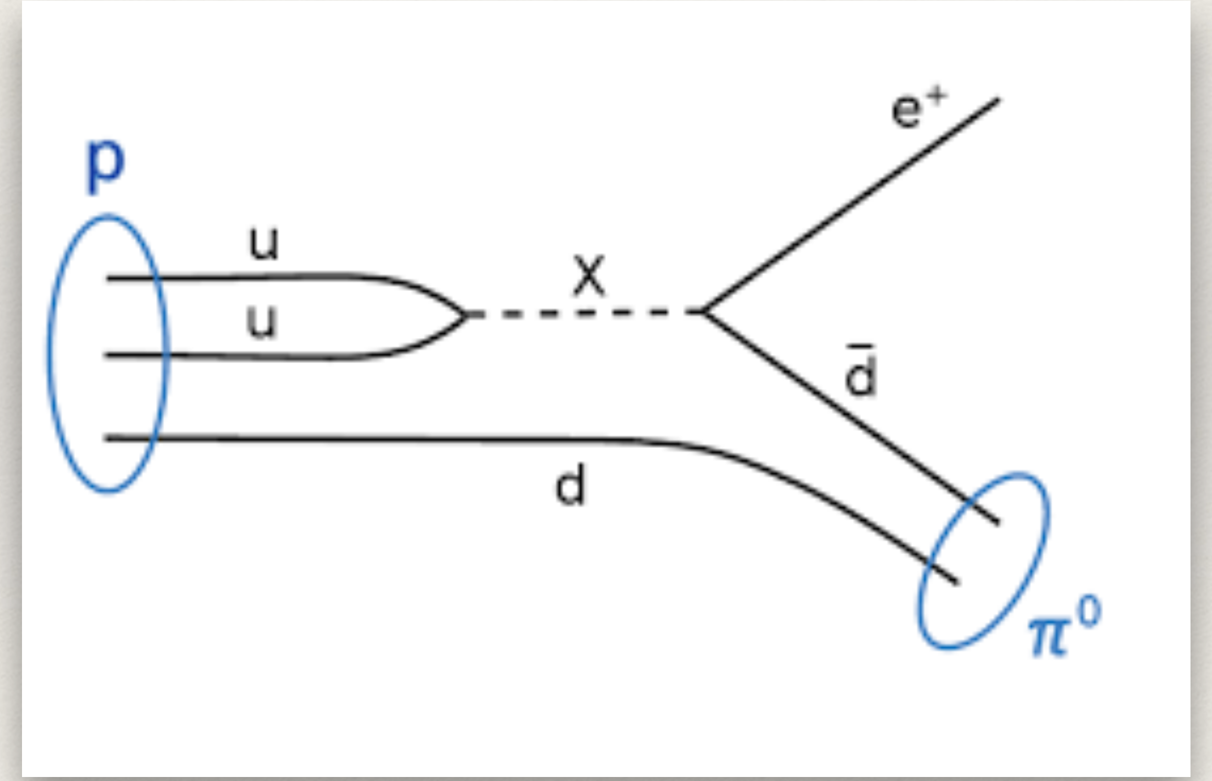


Proton Decay and Dark Matter

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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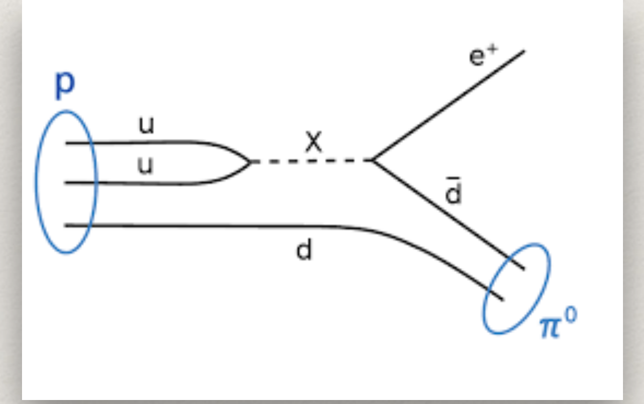

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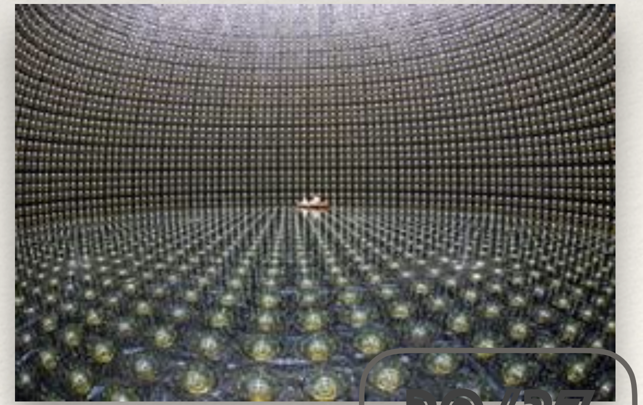

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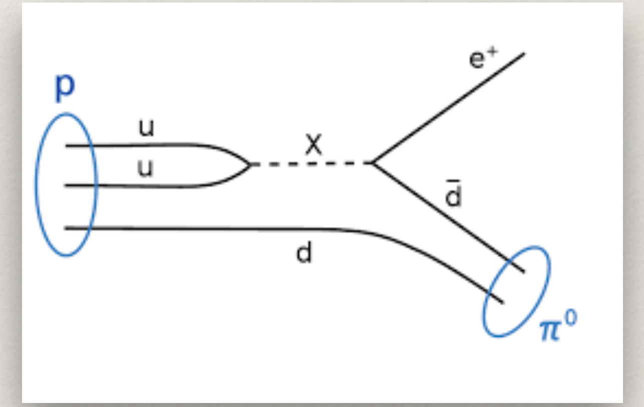

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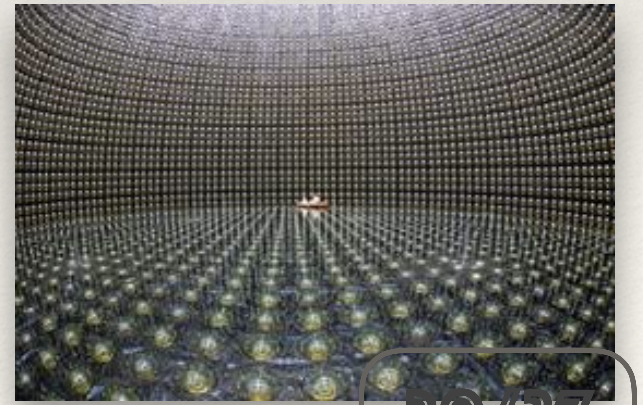

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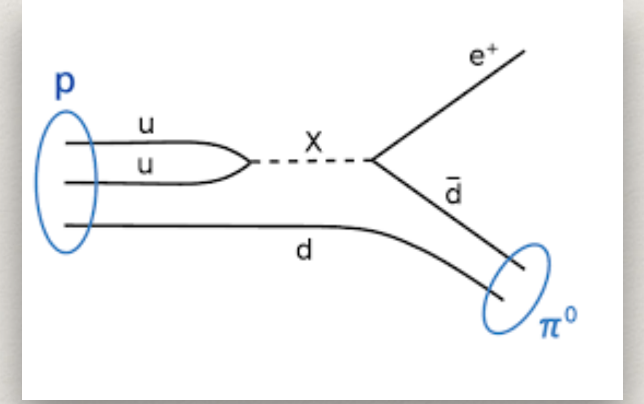

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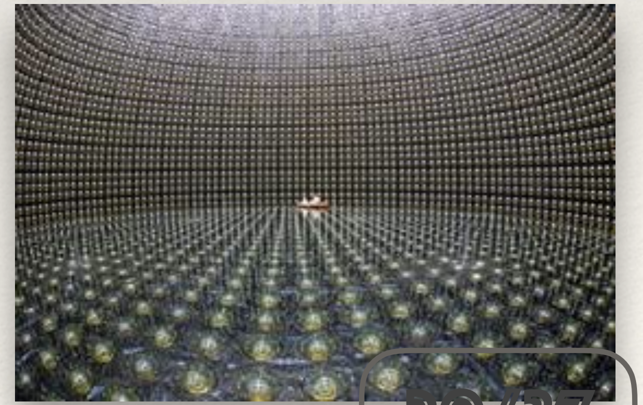

But all Model-Dependent

An Explicit Model:
SU(7)/SU(6) x U(1)

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`
- No singlet top companion in $\mathrm{SU}(5)$ models
- Goldstone dark matter: constrains minimal coset
  - Need **5** of $\mathrm{SU}(5)$ plus singlet
  - $\mathrm{SU}(6)/\mathrm{SU}(5)$, $\mathrm{U}(6)/\mathrm{U}(5)$: **5** ⊕ **1**, real singlet unstable
  - $\mathrm{SU}(7)/\mathrm{SU}(6)$ x $\mathrm{U}(1)$: **5** ⊕ **1**, complex singlet

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- Must have $\mathrm{B(H)} = 0$ and $\mathrm{B(S)} \neq 0$
  - B internal to $\mathrm{SU(6)}$ x $\mathrm{U(1)}$
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$$U(1)_7 - 7\,U(1)_6 \sim \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -1 \end{pmatrix} \qquad \Pi \sim \begin{pmatrix} T \\ H \\ S \\ 0 \end{pmatrix}$$

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- However, fermion couplings complicate things
  - Extend symmetry to $\mathrm{U(7)\times U(1)_{B0}/U(6)\times U(1)\times U(1)_{B0}}$
  - Expect $\mathrm{U(N)}$ global symmetries anyway

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

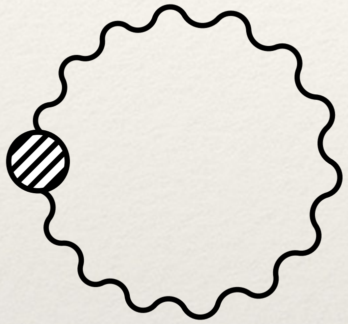
Matter Embeddings

- 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:



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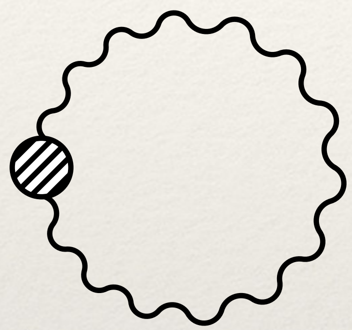

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- Triplet, Singlet masses typically

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

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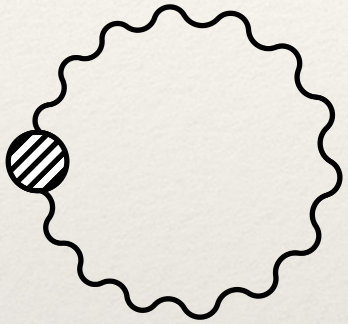

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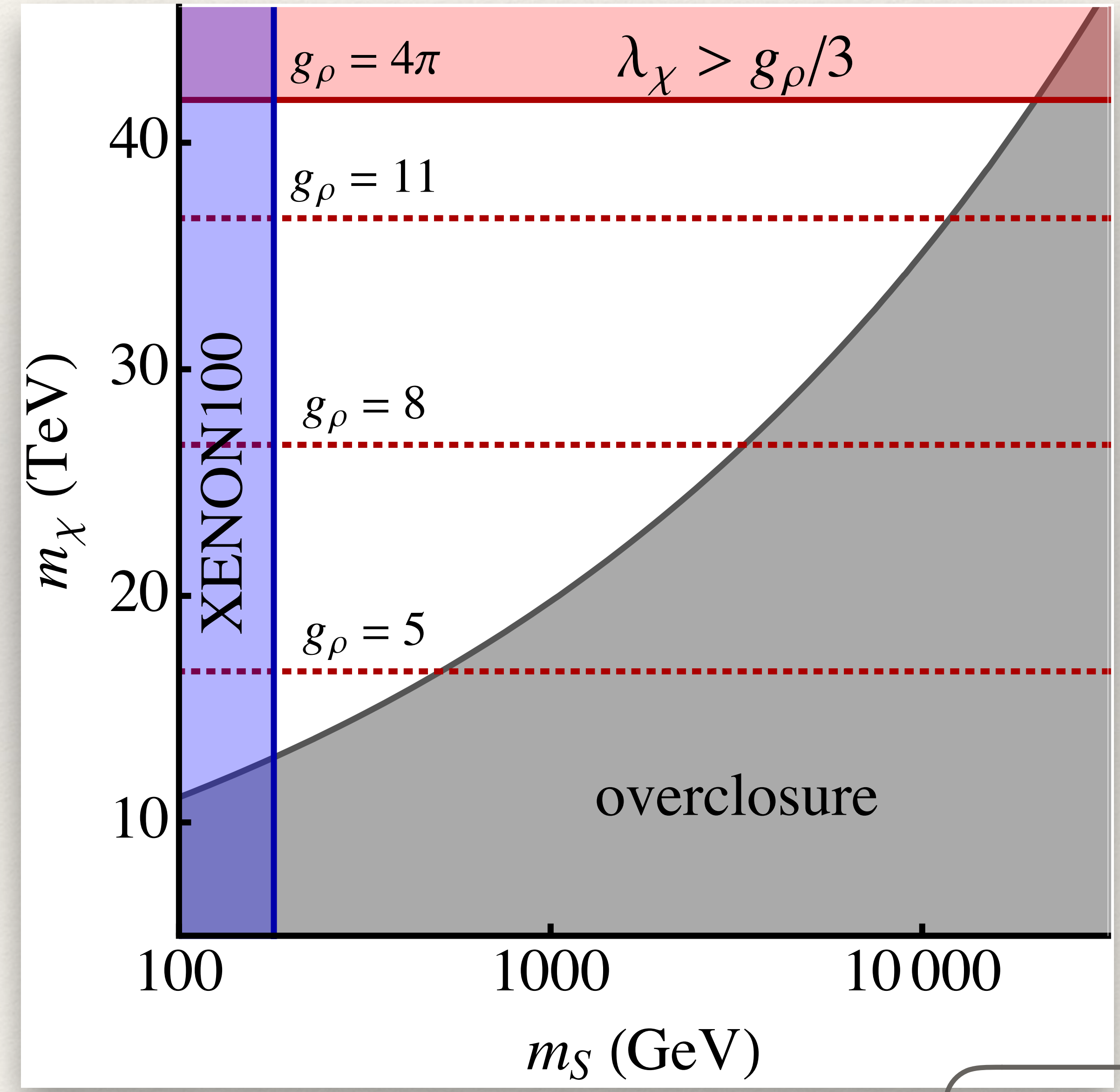
- Singlet can be tuned lighter; needed to fit relic density
  - For f ~ 10 TeV, only ~ few to 25 percent tuning

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:

  $\kappa \sim 0.02\ (\mathrm{m}_\chi/\mathrm{f})^4$
- Limits:
  - Direct Detection $m_S > 150\ \mathrm{GeV}$
  - Calculability $\lambda_\chi < g_\rho/3$
  - Relic Density bounds $\kappa \to m_\chi$
- DD best hope for signal



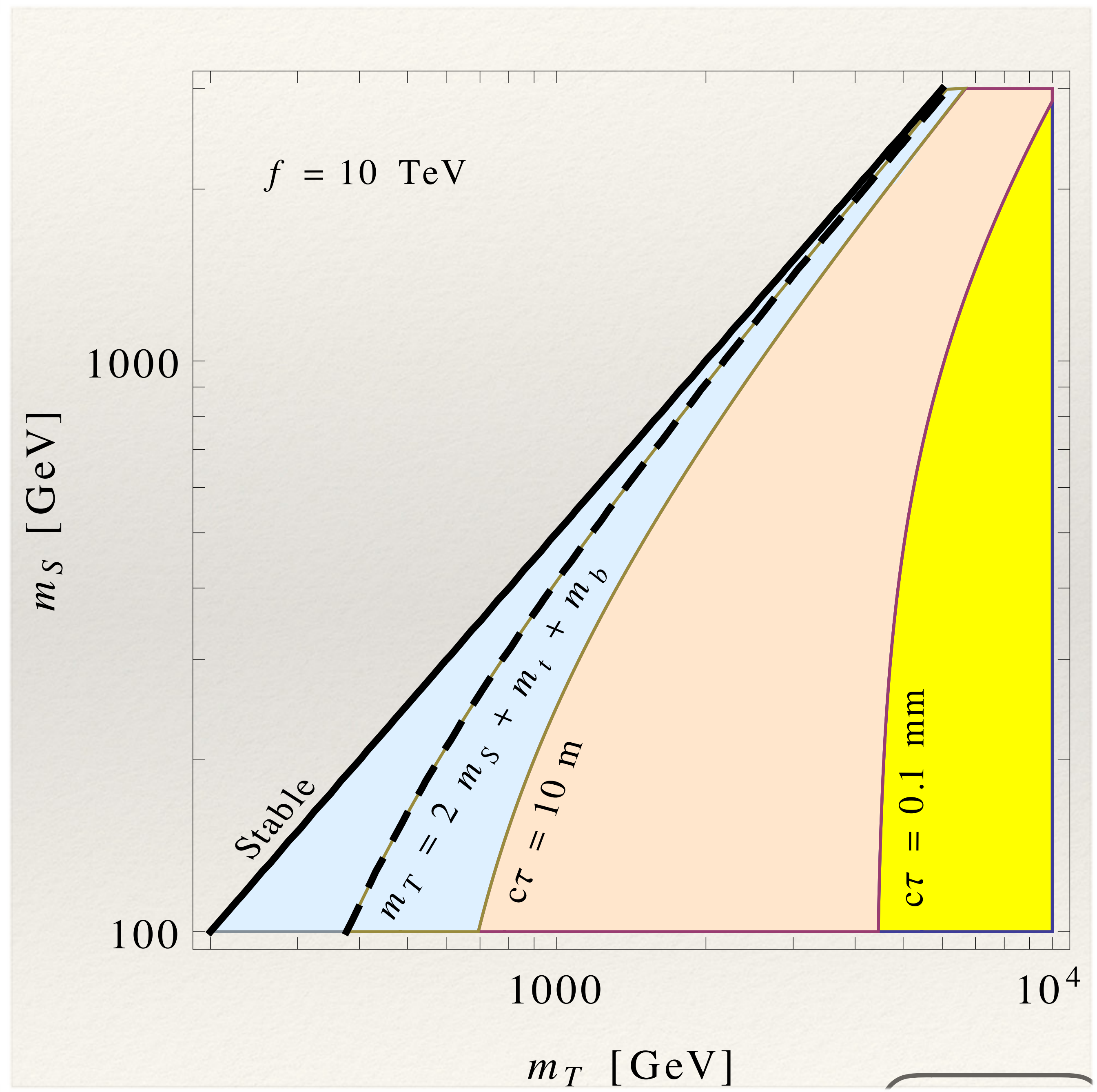
Collider Phenomenology of Long-Lived Scalar Triplets

Triplets and Unnaturalness

- All composite Higgs GUTs have scalar triplet Goldstone
- Minimal decay: t b S S
  - $B(T) = 0, \; B(S) = ⅓,$ $Z_B(T) = 2, \; Z_B(S) = 1$
- Triplet long-lived for large f

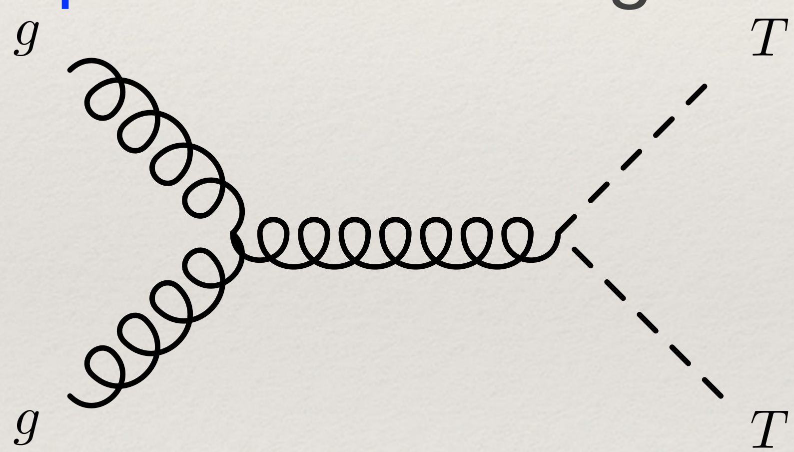
$$c\tau \sim 0.6 \text{ mm} \left(\frac{3 \text{ TeV}}{m_T}\right)^5 \left(\frac{f}{10 \text{ TeV}}\right)^4$$

- Generic signal of unnatural composite Higgs!

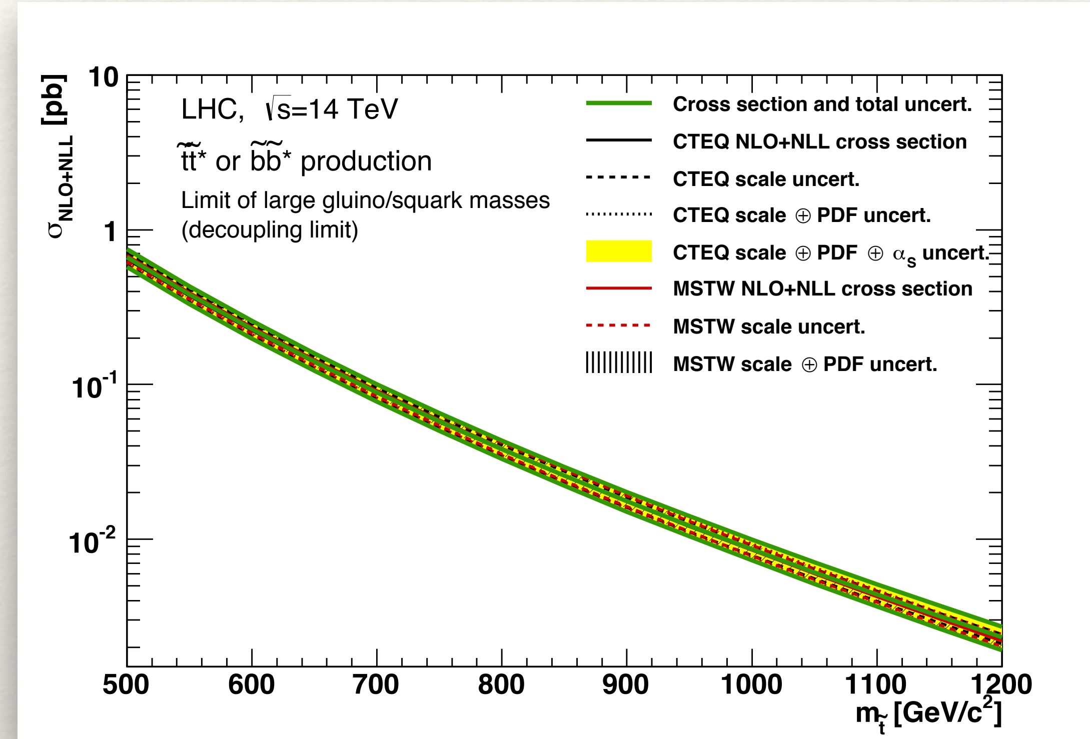


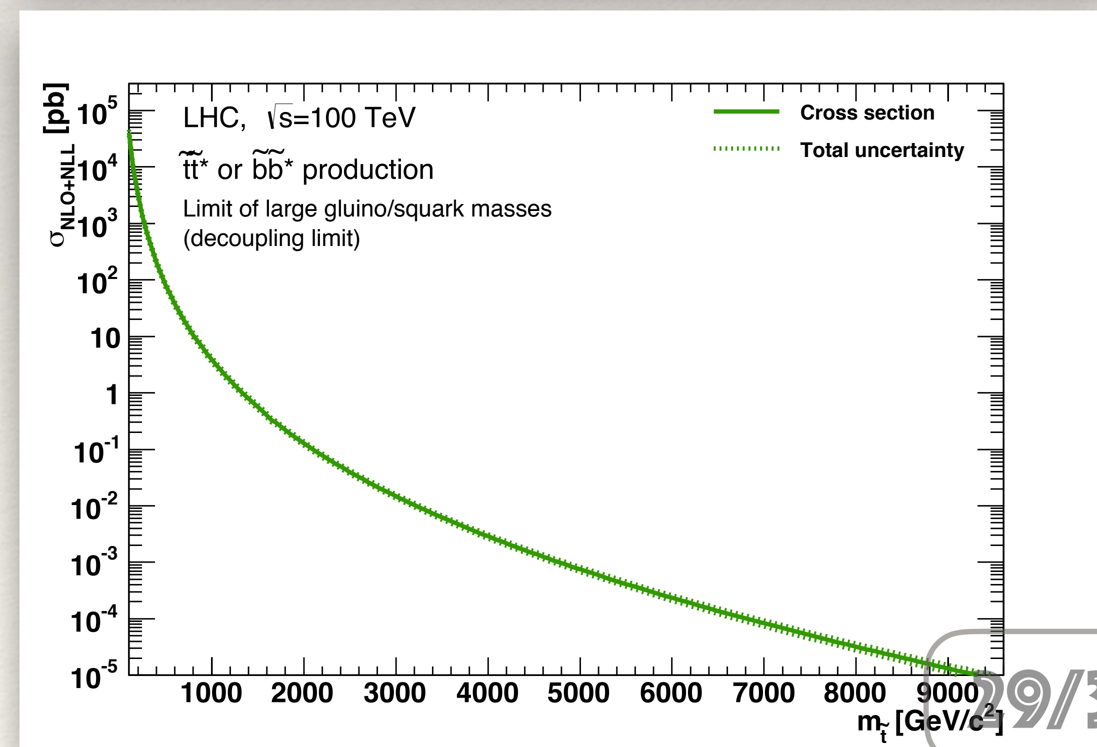
Triplet Production

- Triplet charged under Z_B
- Pair produced through QCD



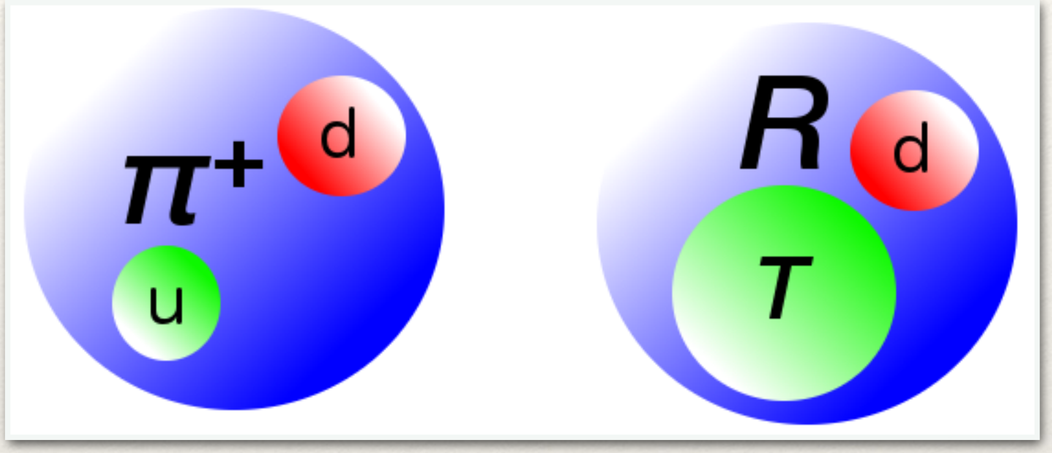
- Cross section same as $\tilde{b}$:
  Borschensky *et al*, `1407.5066`

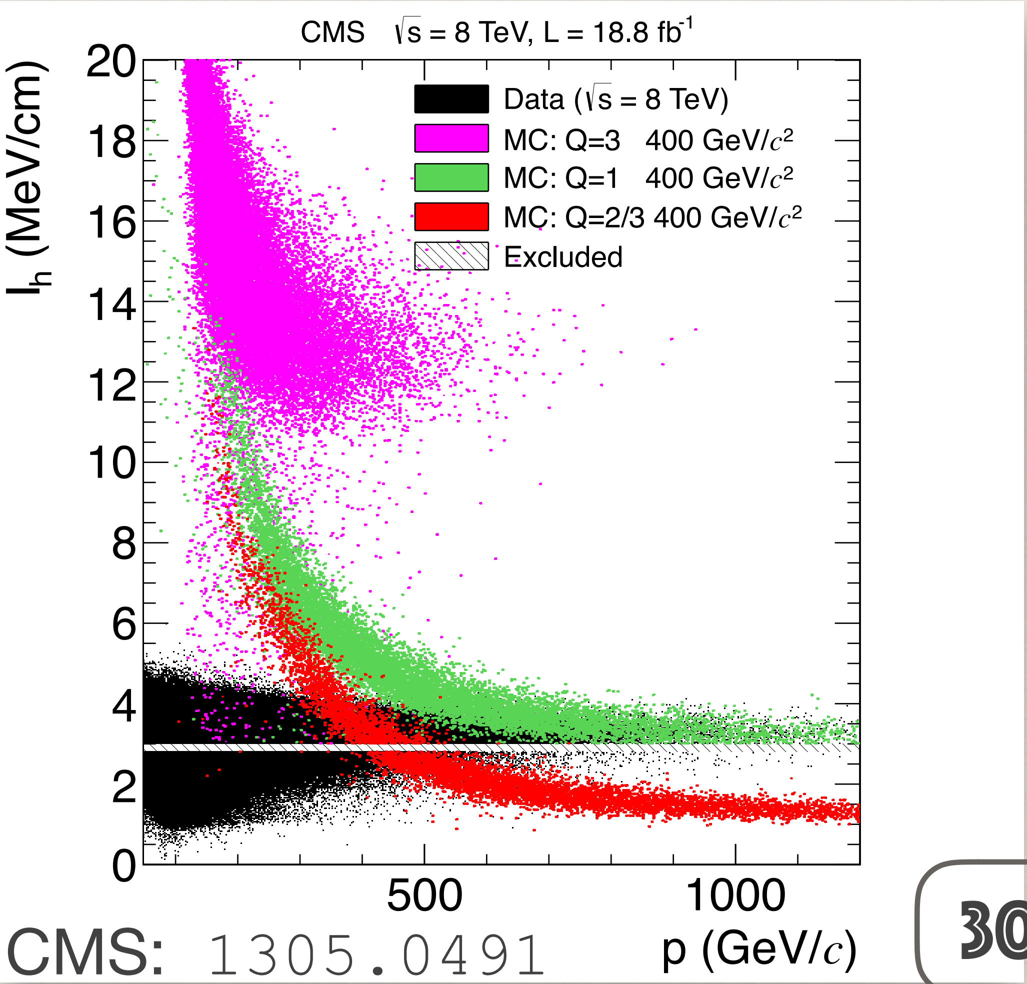




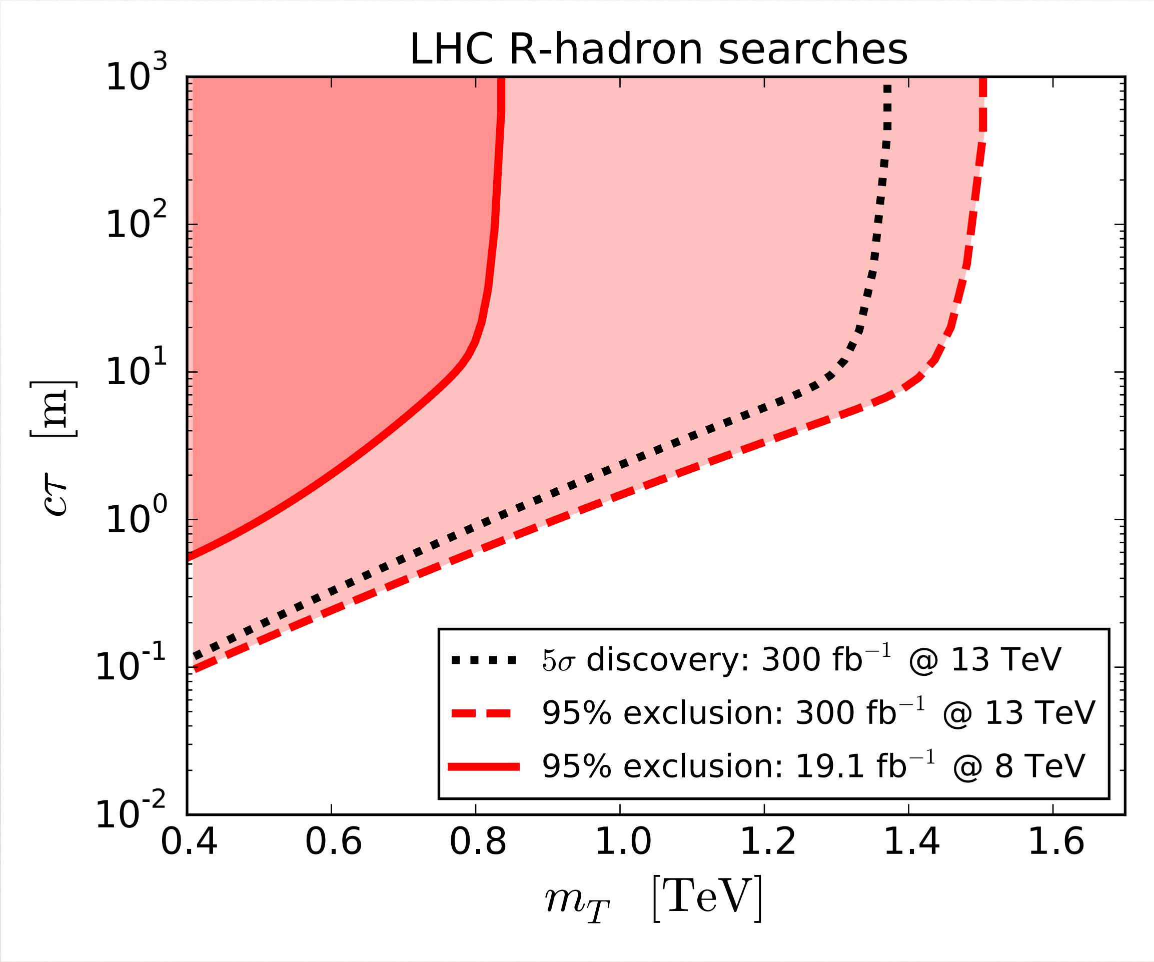
R-Hadrons

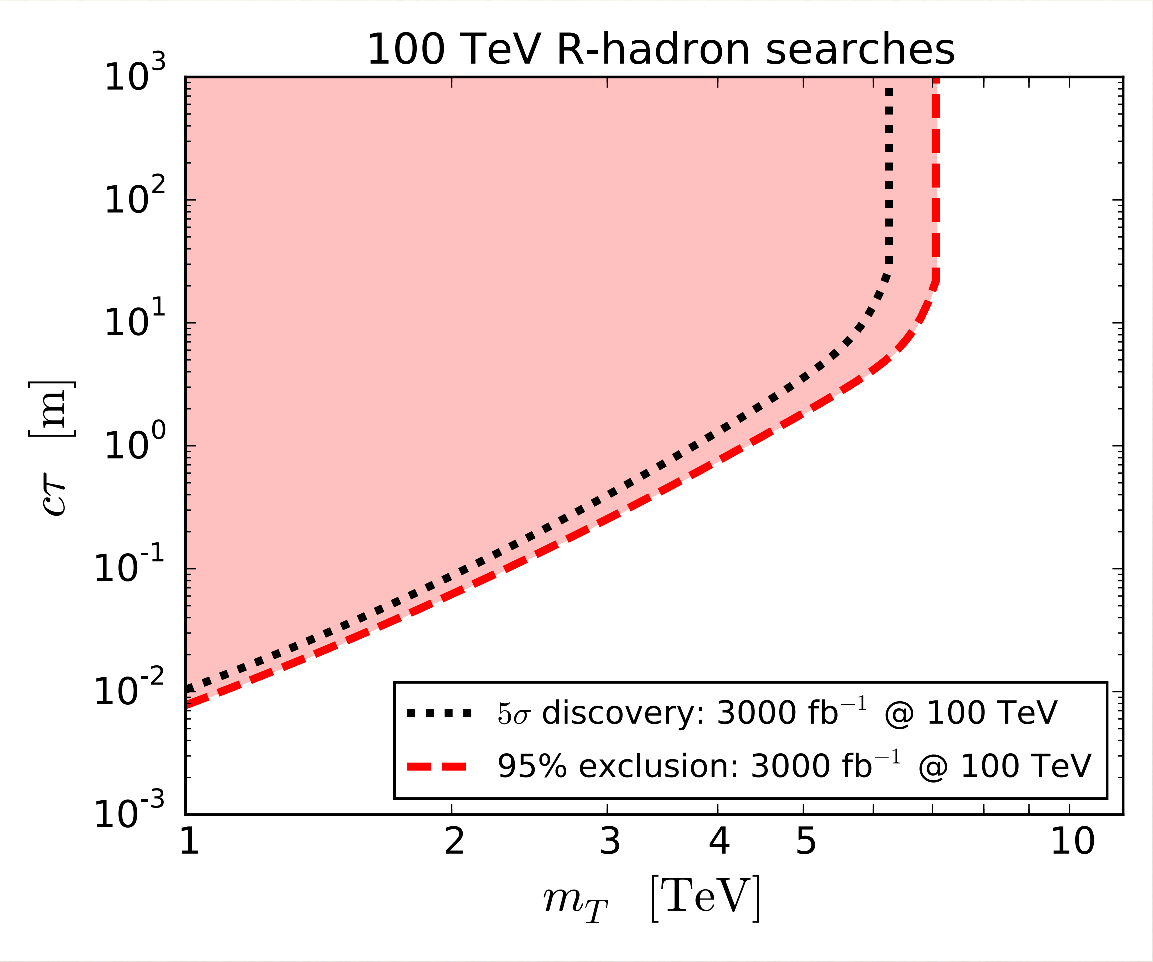
- Collider-stable coloured states form "R-hadrons"
- T forms meson-like states
- 50% Charged: heavy muons
- 50% Neutral: out of time decays
- Very low background, 10% signal efficiency
- Only current LHC constraints
- Easy to scale up to 100 TeV





R Hadron Results

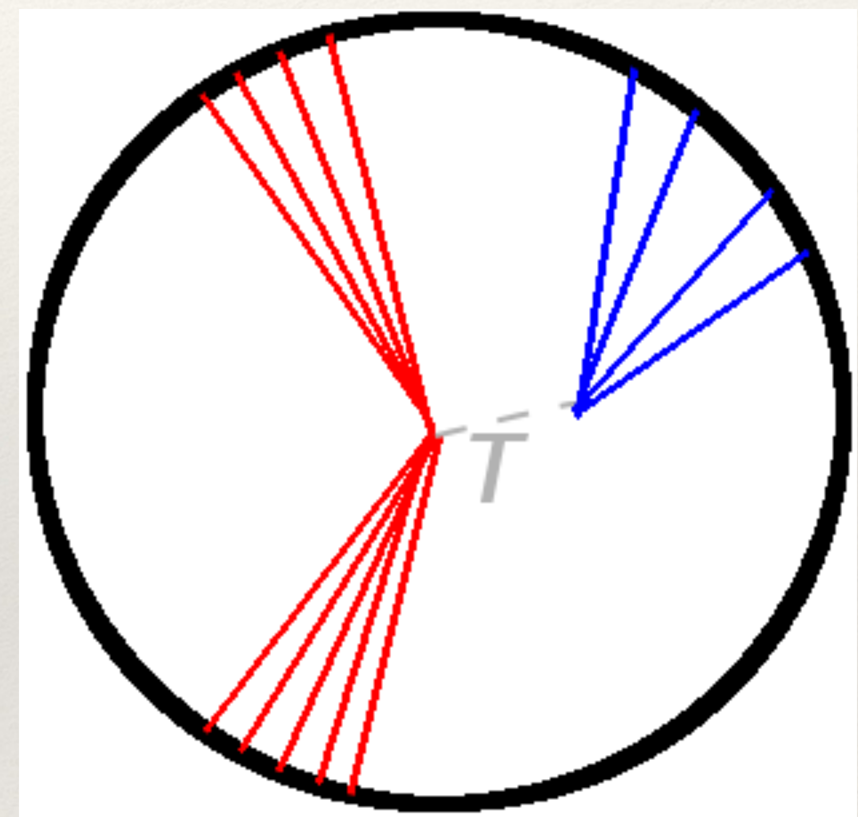




- Model-independent limits
  (depend only on mass and lifetime)

Displaced Vertexes

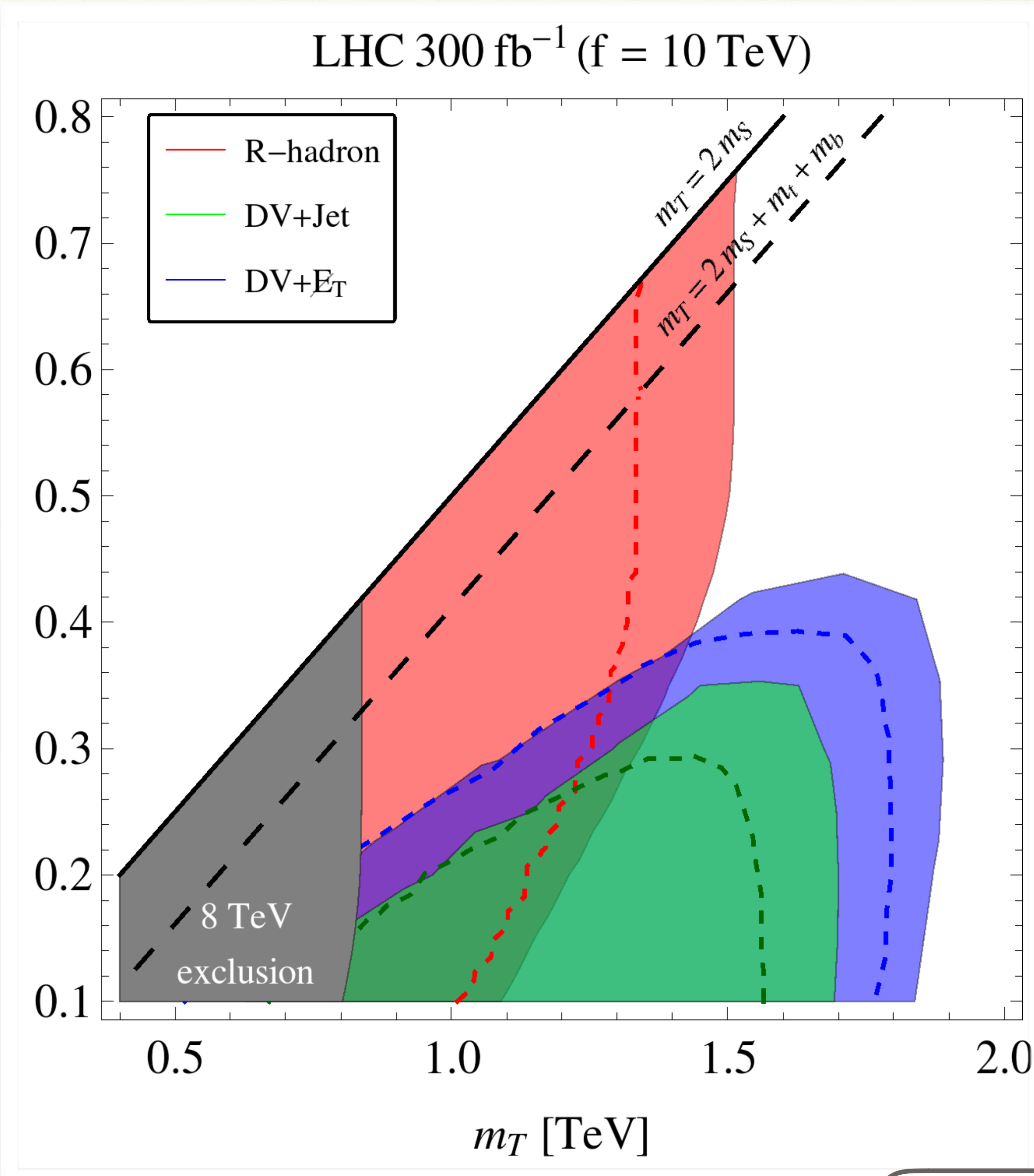
- R-hadron searches weaken as T lifetime decreases
- Displaced Vertex search:
  - Tracks meet far from interaction point



- LHC Studies (ATLAS, `1504.05162`):
  - 2 mm to 30 cm from primary vertex
  - Tag on high-p_T lepton plus E_T or 4+ jets
- Low backgrounds, 60-70% signal efficiency
- Scale up to 100 TeV using LHC cuts and SUSY studies

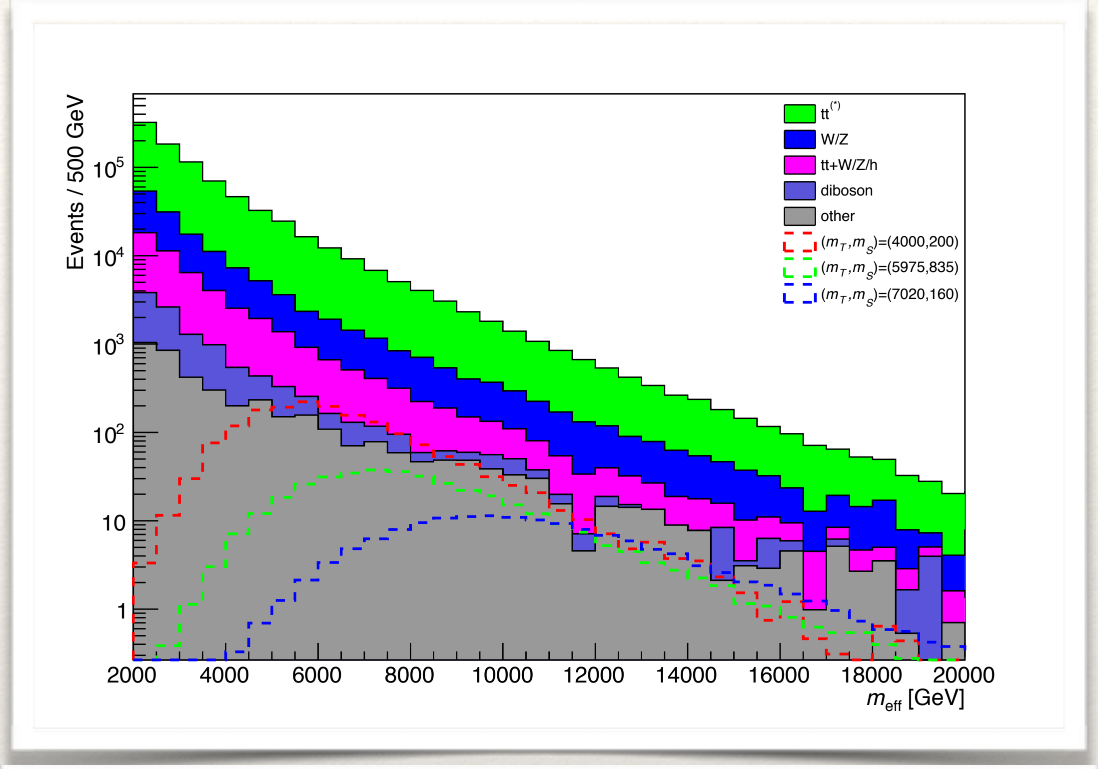
LHC Limits

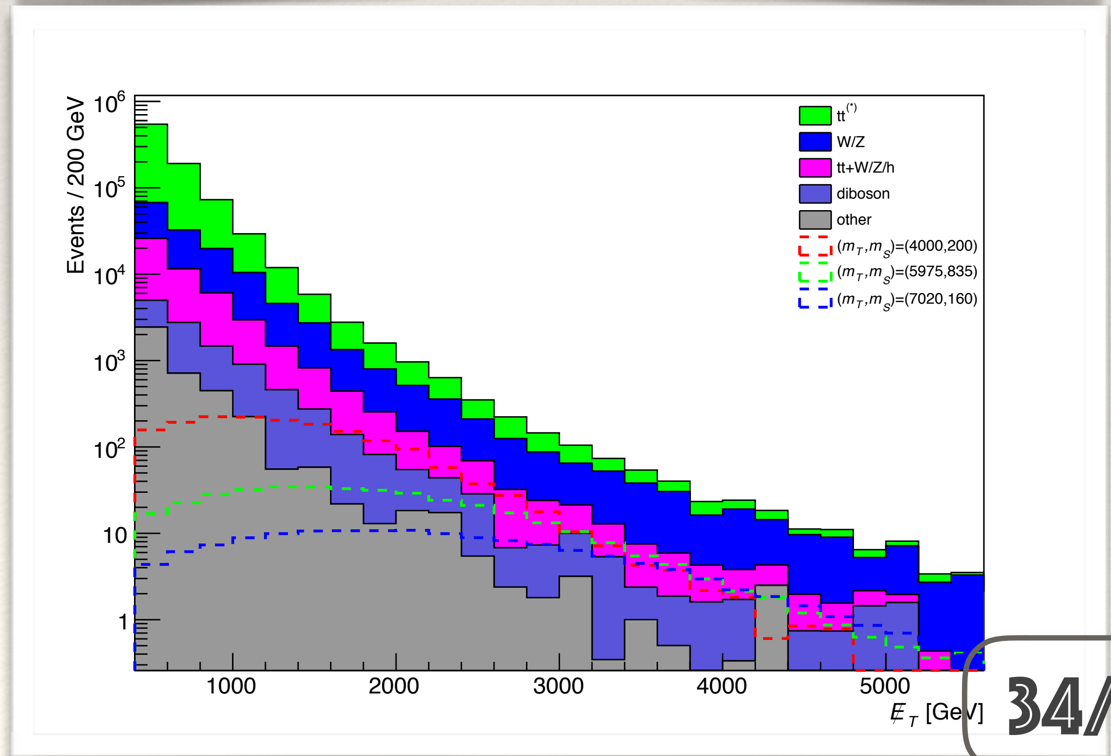
- Only current limits from R-hadrons at low masses
- R-hadron and DV searches probe up to 1.5 - 1.8 TeV
- R-hadrons better when decay kinematically suppressed
- Limits weak compared to expected triplet mass ≳ 3 TeV



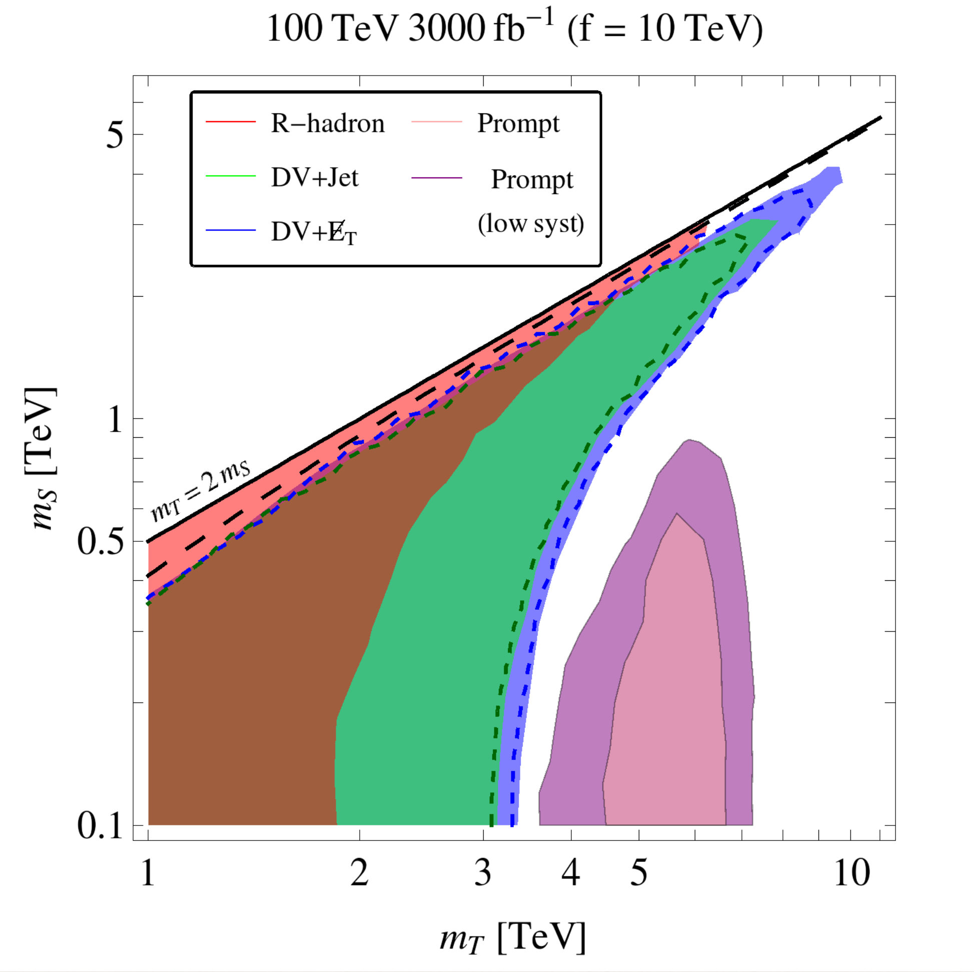
Prompt Decays

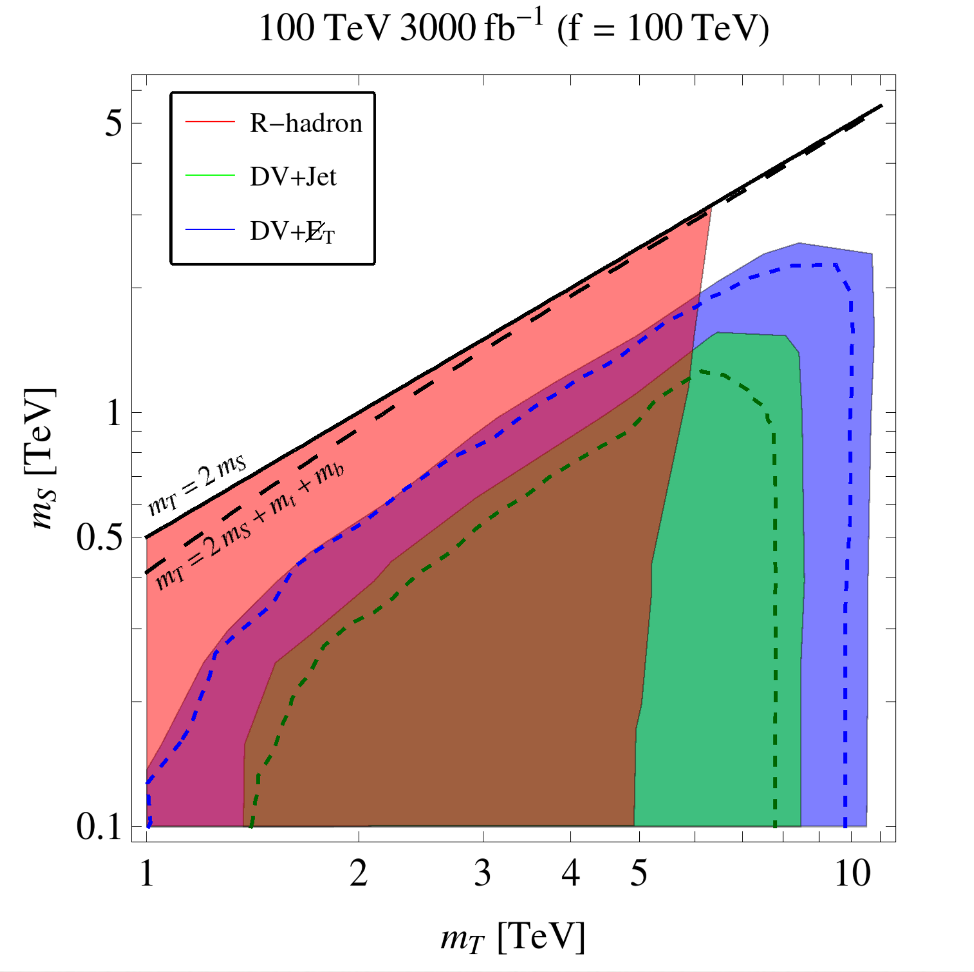
- At LHC, T always long-lived; not so at 100 TeV
- Final state $t\bar{t}b\bar{b} + \not{E}_T$
- Sizable tt + jets background
- Demand 4 b jets, $\not{E}_T$ > 2.5 TeV and m_{eff} (H_T) > 10 TeV
- Crucial dependence on b-tagging efficiency
  - Conservative 3% fake rate (Snowmass, `1309.1057`)





100 TeV Limits





- Exclusions up to $\mathrm{m_T}$ = 8 (10) TeV for f = 10 (100) TeV
- Gap at f = 10 TeV between prompt and displaced searches
- Prompt searches exclusion only (no discovery region)

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
- LHC limits $\mathrm{m_T} < 800$ GeV from R-hadron searches
- LHC (100 TeV collider) can probe $\mathrm{m_T} < 1.8$ (10) TeV

Back-up Slides

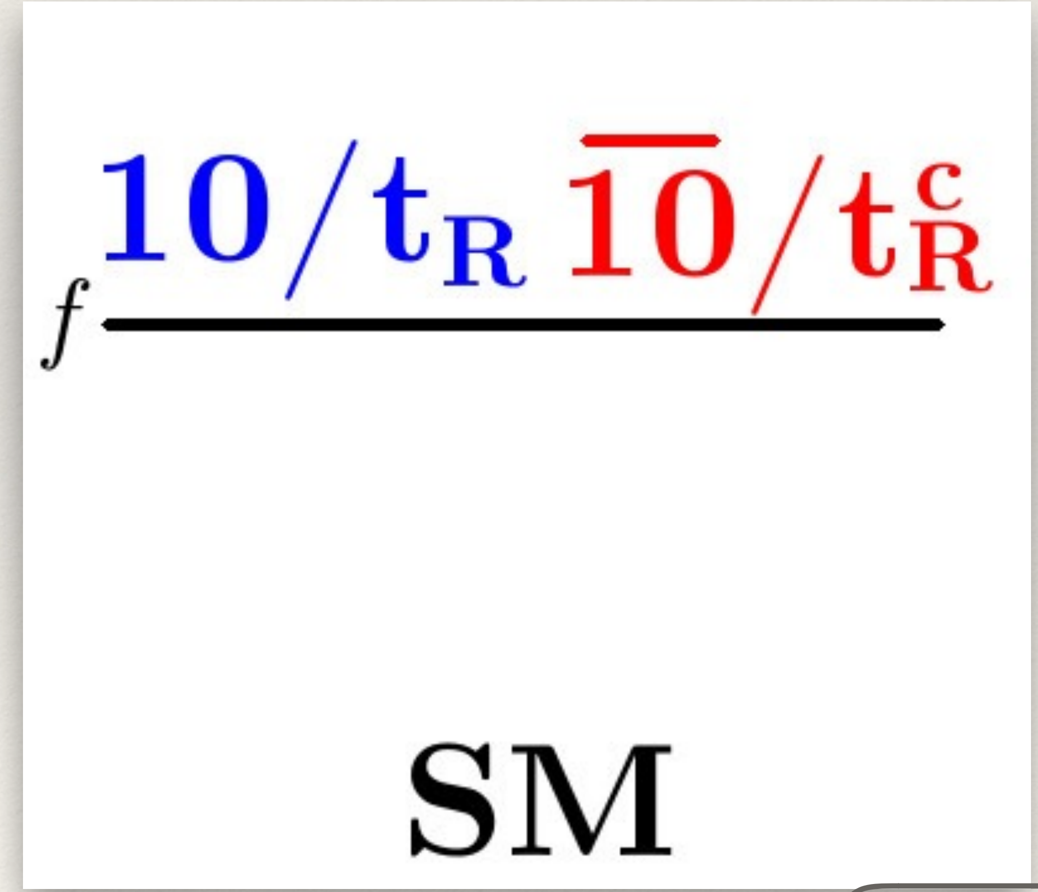
Precision Unification

- 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_χ ~ f, add nearly-complete GUT multiplet
- Effect on running equivalent to subtracting $\mathrm{t_R}^c$

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



Precision Unification

- In a composite Higgs theory above Λ,

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

- Composite SM states “dissolve”, counted in $\mathrm{NP}^{\mathrm{comp}}$

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

- 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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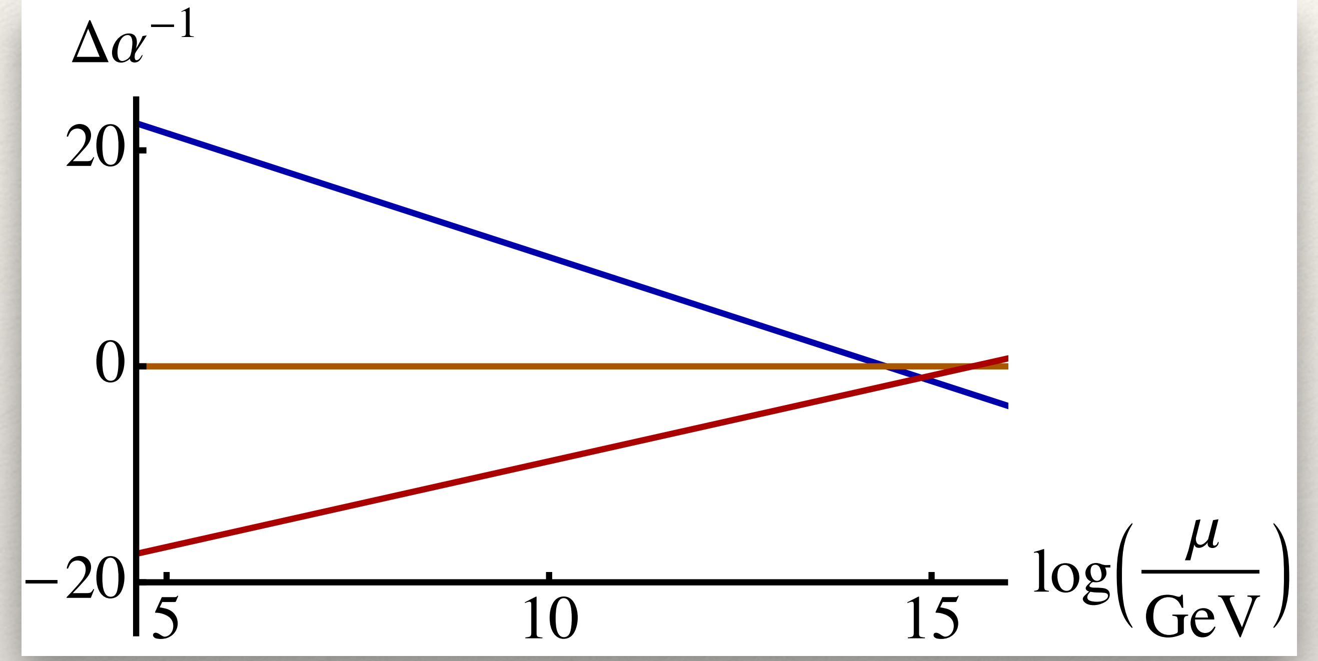
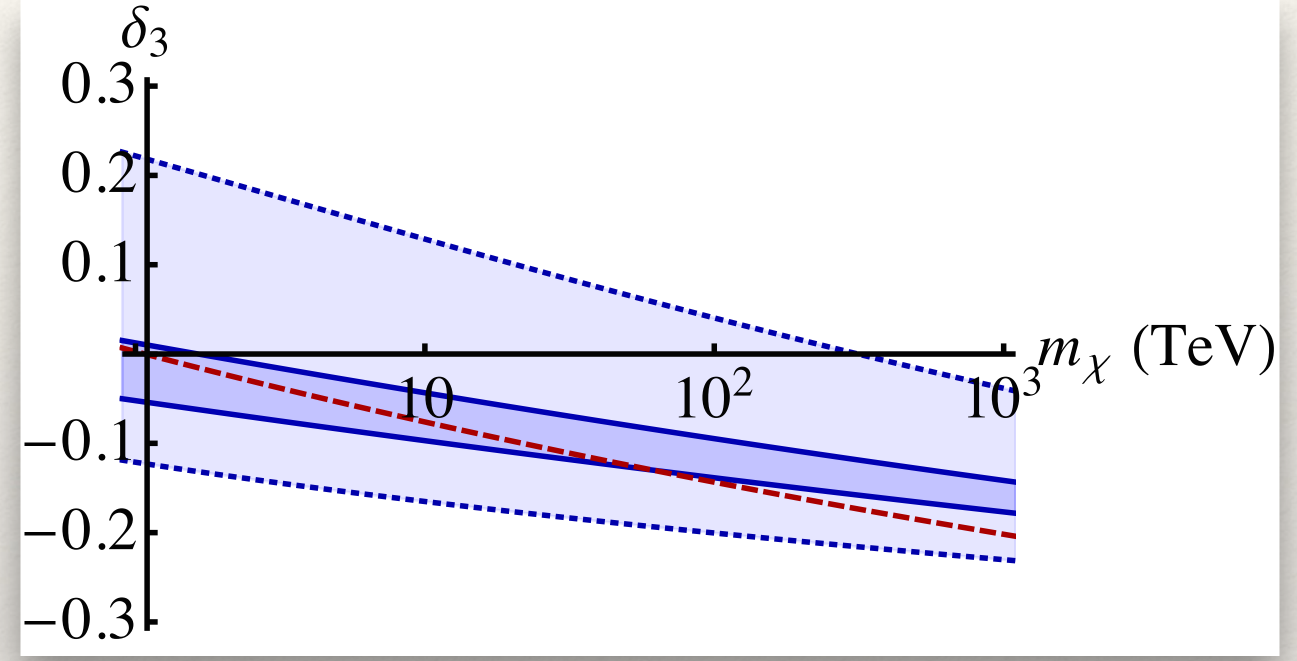
An Upper Limit on f

- One-Loop Unification



- m_χ = 20 TeV

- Two-Loop Unification



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

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

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

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