Flavor, Naturalness & the Tops in Composite Higgs

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Keren-Zur, Lodone, Nardecchia, Pappadopulo,RR, Vecchi [arXiv:1205.5803]
De Simone, Matsedonskyi, RR, Wulzer, to appear

The Stardard Model as an Effective Theory

with fundamental scale $\Lambda_{UV}^2 \gg 1\,\mathrm{TeV}$

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$$\mathcal{L}_{SM} \;=\; \mathcal{L}_{kin} + gA_\mu \bar{F}\gamma_\mu F + Y_{ij}\bar{F}_i H F_j + \lambda(H^\dagger H)^2$$

d=4

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$$+ \quad \frac{b_{ij}}{\Lambda_{UV}} L_i L_j H H$$

$$+ \quad \frac{c_{ijkl}}{\Lambda^2_{UV}} \bar{F}_i F_j \bar{F}_k F_\ell \; + \; \frac{c_{ij}}{\Lambda_{UV}} \bar{F}_i \sigma_{\mu\nu} F_j G^{\mu\nu} + \ldots$$

$$+ \quad \ldots$$

d>4

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$$+ \quad \ldots$$

d>4

$\Lambda_{UV} \rightarrow \infty$ (pointlike limit) nicely accounts for ‘what we see’

The Stardard Model as an Effective Theory

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$$+\, c\Lambda_{UV}^2\, H^\dagger H$$

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$$+ \quad \ldots$$

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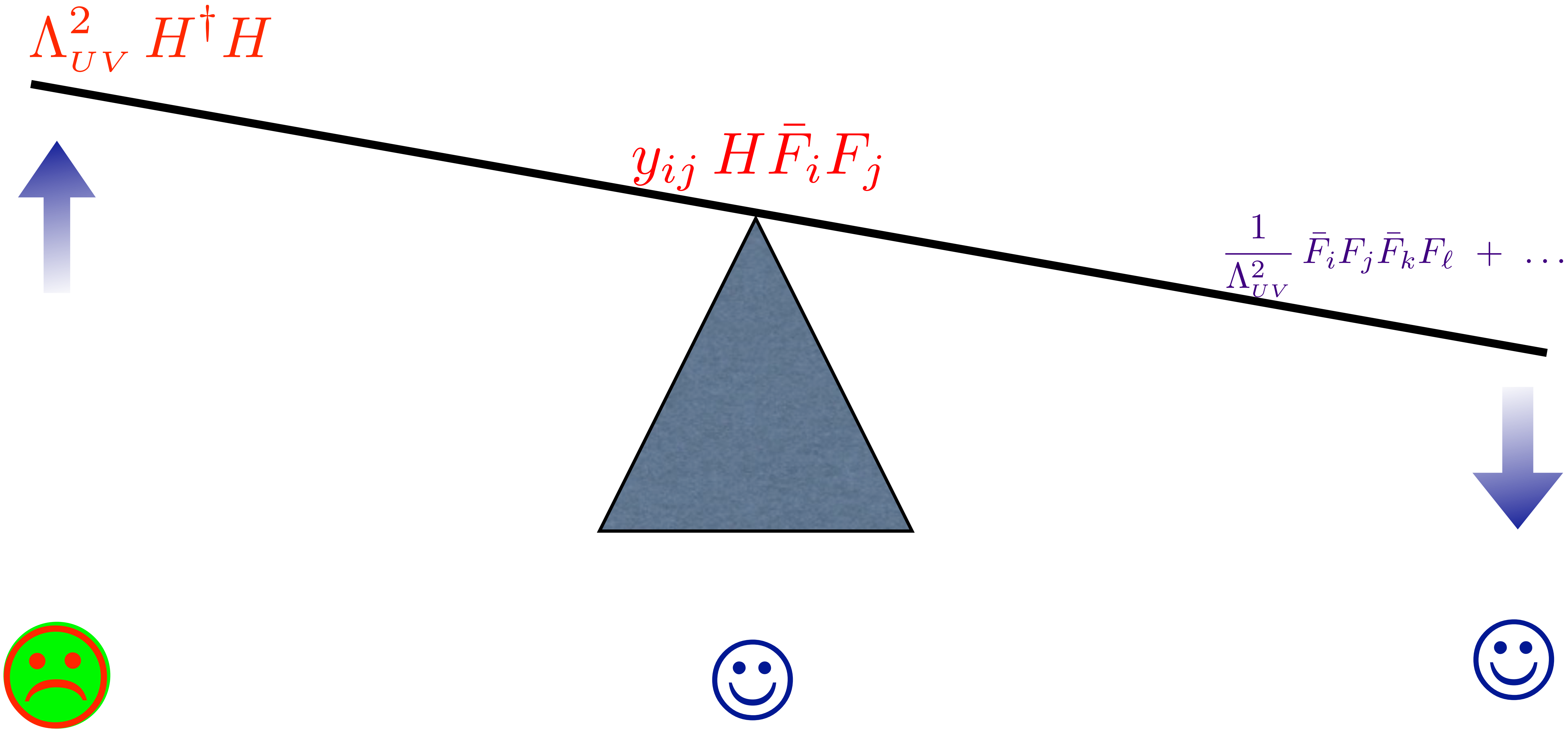
Hierarchy see-saw

Standard Model up to some $\Lambda_{UV}^2 \gg 1\,\mathrm{TeV}$



$\Lambda_{UV}^2\, H^\dagger H$

$y_{ij}\, H \bar{F}_i F_j$

$\frac{1}{\Lambda_{UV}^2} \bar{F}_i F_j \bar{F}_k F_\ell \; + \; \ldots$

☹ ☺ ☺

Hierarchy see-saw

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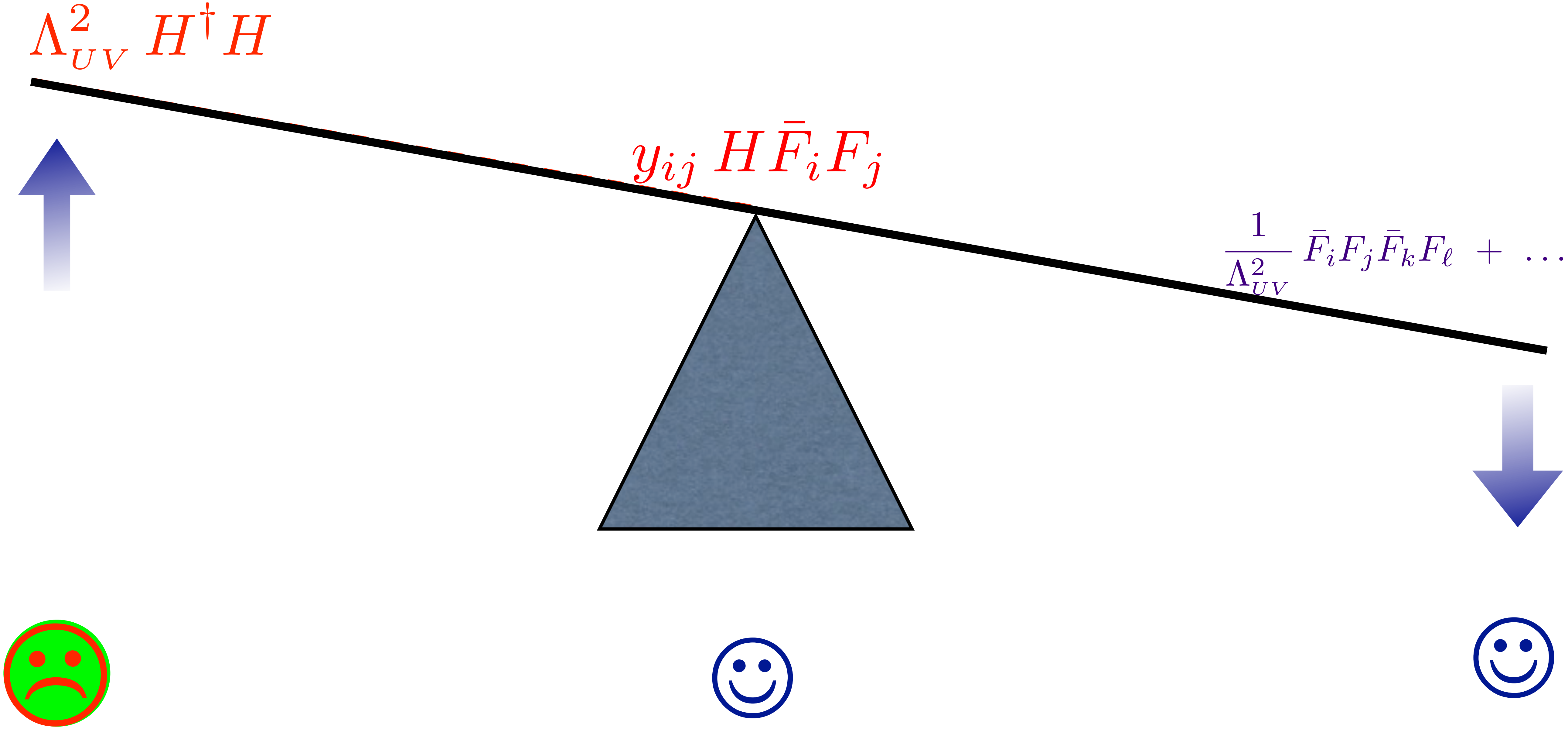

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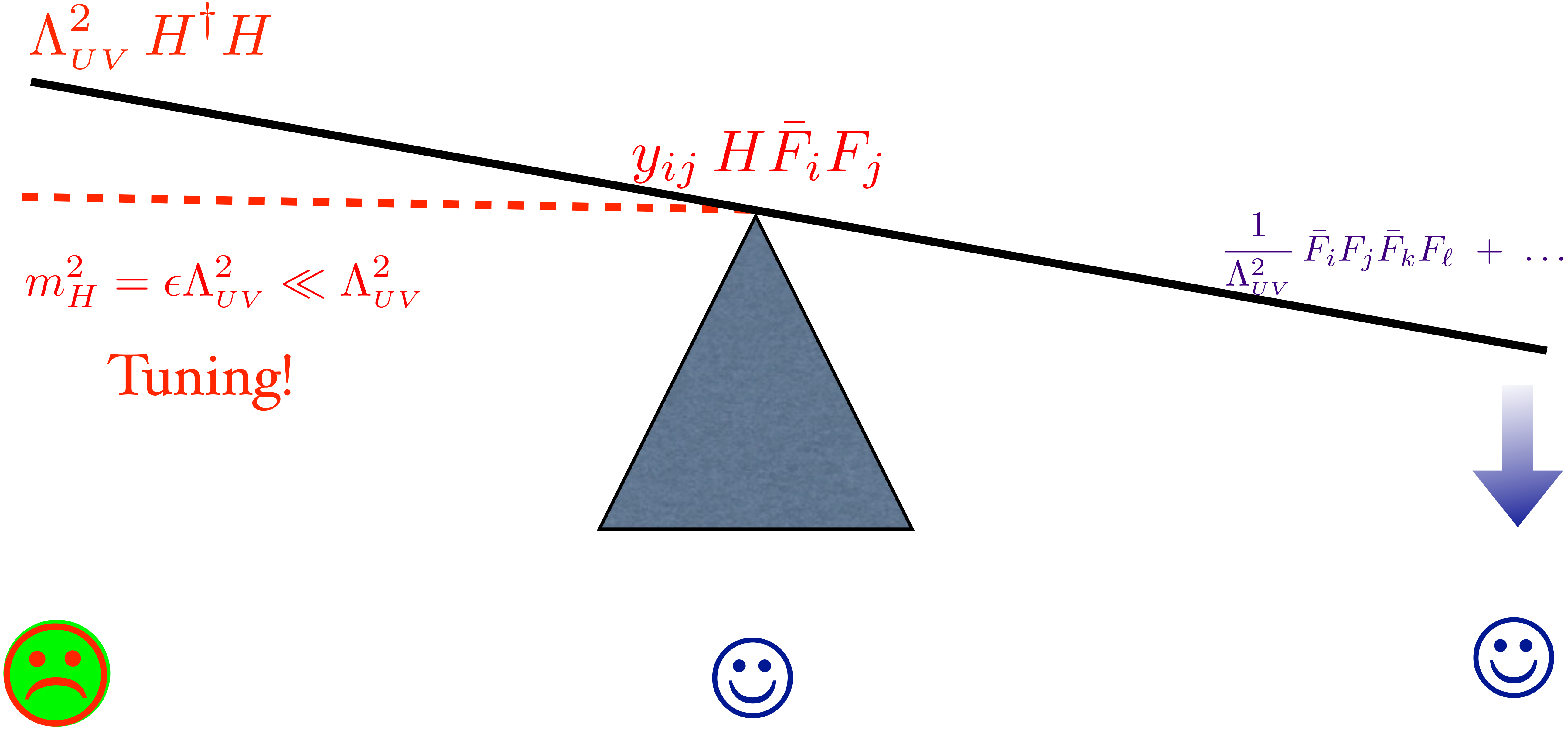


$\Lambda^2_{UV}\, H^\dagger H$

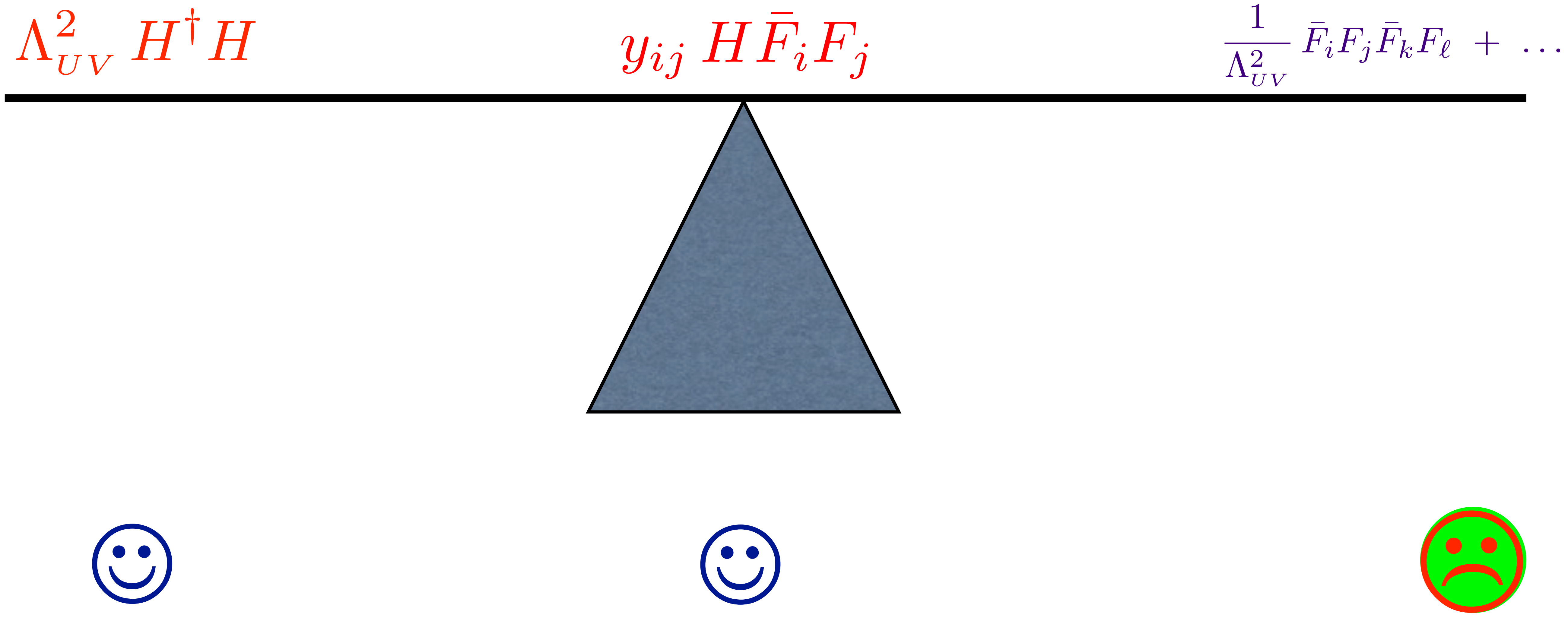
$y_{ij}\, H \bar{F}_i F_j$

$\frac{1}{\Lambda^2_{UV}} \bar{F}_i F_j \bar{F}_k F_\ell \; + \; \dots$

$m^2_H = \epsilon \Lambda^2_{UV} \ll \Lambda^2_{UV}$

Tuning!

Natural SM : $\Lambda^2_{UV} \lesssim 1\,\mathrm{TeV}$



$\Lambda^2_{UV}\, H^\dagger H$

$y_{ij}\, H \bar{F}_i F_j$

$\frac{1}{\Lambda^2_{UV}}\, \bar{F}_i F_j \bar{F}_k F_\ell \,+\, \ldots$

☺ ☺ ☹

Focus on composite Higgs

✦ Flavor

✦ Naturalness and the search for top partners


Λ_{UV}^{II}
TeV$\equiv \Lambda_{UV}^{I}$

Λ_{UV}^{II}

~ scale invariance

TeV$\equiv \Lambda_{UV}^{I}$

Λ_{UV}^{II}

~ scale invariance

TeV $\equiv \Lambda_{UV}^{I}$

Use $\Lambda_{UV}^{II} \gg$ TeV to filter out unwanted effects and produce a realistic Flavor story

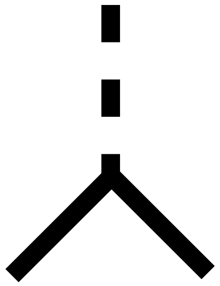
Scale (conformal) invariant theories are thus an essential ingredient of model building

Composite sector is *broadly* described by:

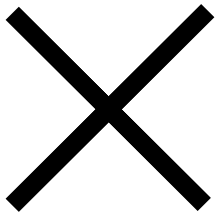
Giudice, Grojean, Pomarol, RR, 2007

✦ one mass scale m_ρ (of order TeV)

✦ one coupling g_ρ $g_\rho \sim g_{KK}$ $g_\rho \sim \frac{4\pi}{\sqrt{N}}$



$$= g_\rho \, \bar\Psi \Psi \Phi$$

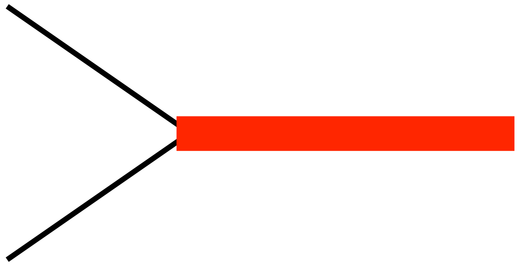


$$= \frac{g_\rho^2}{m_\rho^2} \, \bar\Psi \Psi \bar\Psi \Psi$$

Three Ways to Flavor

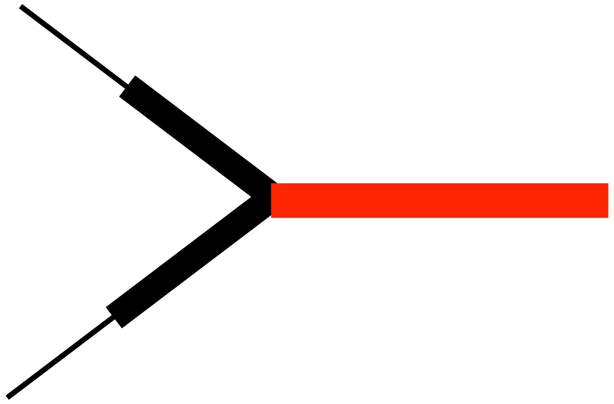
Bilinear: ETC, conformalTC

Dimopoulos, Susskind
Holdom
....
Luty, Okui



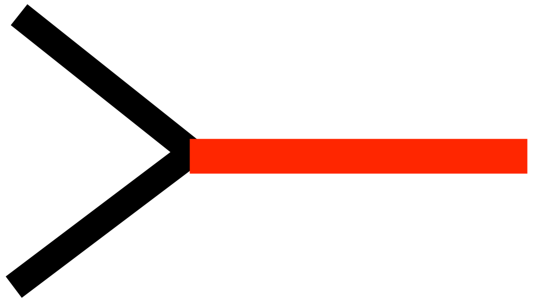
Linear: partial compositeness

D.B. Kaplan
....
Huber
RS with bulk fermions



Total compositeness

ex: minimal RS
Rattazzi-Zaffaroni



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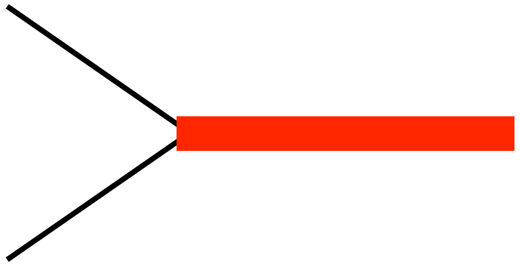

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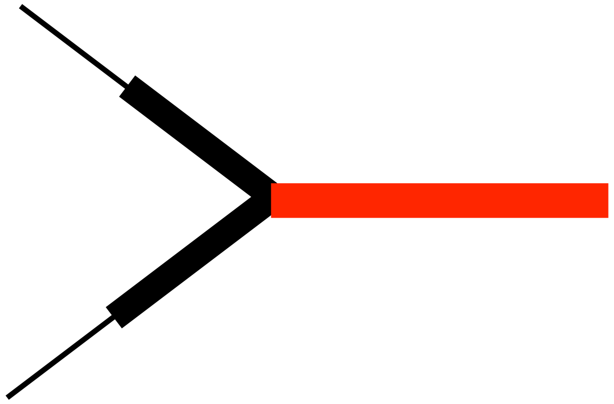

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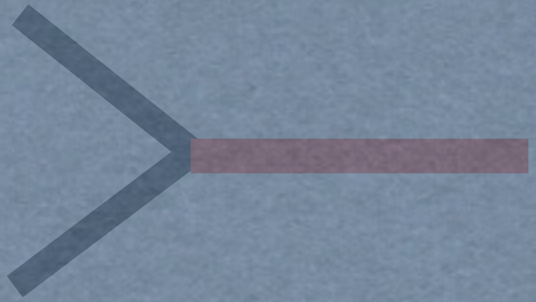

~ ruled out by LEP bounds on lepton compositeness

Three Ways to Flavor

Bilinear: ETC, conformal TC

Dimopoulos, Susskind
Holdom
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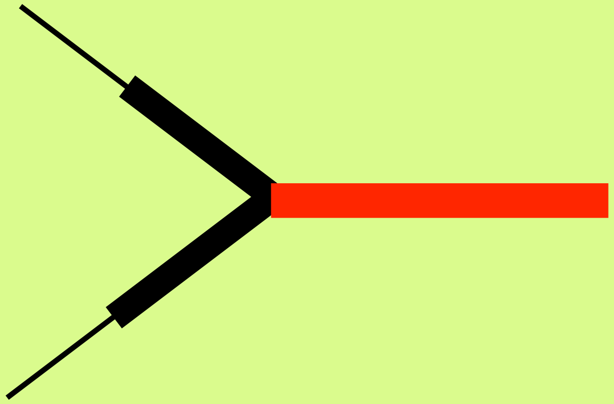
Luty, Okui

disfavored by CFT ‘theorems’
Rychkov, Rattazzi, Tonni, Vichi 2008
Poland, Simmons-Duffin, Vichi 2011



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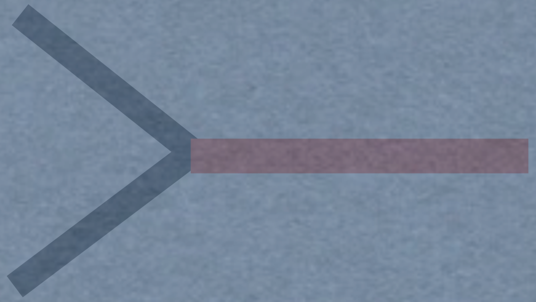

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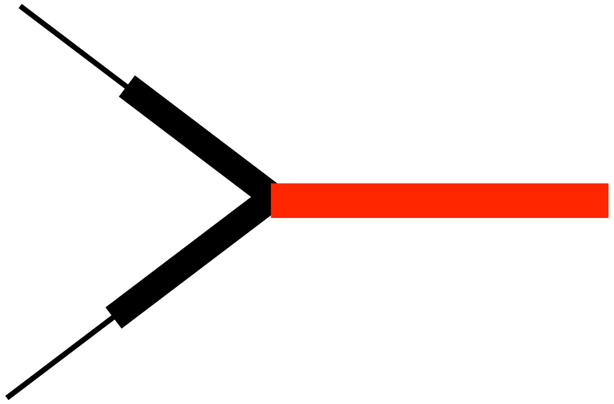


$$\mathcal{L}_{Yukawa} = \epsilon_q^i q_L^i \mathcal{O}_q^i + \epsilon_u^i u_L^i \mathcal{O}_u^i + \epsilon_d^i d_L^i \mathcal{O}_d^i$$

Hypothesis

∃ at least 3 families of composite fermionic operators with same gauge quantum numbers as elementary ones

$\dim \mathcal{O}^i \simeq \frac{5}{2}$ to ensure couplings slowly run

Hypothesis seems a bit wishful to me, but I see no other option

Yukawas

$$Y_u^{ij} \sim \epsilon_q^i \epsilon_u^j g_\rho$$

$$Y_d^{ij} \sim \epsilon_q^i \epsilon_d^j g_\rho$$

Flavor transitions controlled by selection rules

(accidental non-compact $U(1)^9$ flavor symmetry)

ΔF=1 $\epsilon_q^i \epsilon_u^j g_\rho \times \frac{v}{m_\rho^2} \times \frac{g_\rho^2}{16\pi^2} \quad \bar{q}^i \sigma_{\mu\nu} u^j G_{\mu\nu}$

ΔF=2 $\epsilon_q^i \epsilon_d^j \epsilon_q^k \epsilon_d^\ell \times \frac{g_\rho^2}{m_\rho^2} \quad (\bar{q}^i \gamma^\mu d^j)(\bar{q}^l \gamma_\mu d^\ell)$

Bounds & an intriguing hint

Davidson, Isidori, Uhlig '07

Keren-Zur, Lodone, Nardecchia, Pappadopulo, RR, Vecchi '12

ϵ_k	$m_\rho \gtrsim 10\ \text{TeV}$
$\epsilon'/\epsilon, \quad b \to s\gamma$	$m_\rho \gtrsim \frac{g_\rho}{4\pi} \times (10-15)\ \text{TeV}$
d_n	$m_\rho \gtrsim \frac{g_\rho}{4\pi} \times (20-40)\ \text{TeV}$
CP violation in D decays $\Delta a_{CP} = a_{KK} - a_{\pi\pi} = -(0.67 \pm 0.16)\%$	$m_\rho \simeq \frac{g_\rho}{4\pi} \times 10\ \text{TeV}$

- Not crazy at all to see deviation in D's first !
- d_n should be next
- connection with weak scale not perfect

tuning

$$0.1\% \left(\frac{m_h}{125\,\text{GeV}}\right)^2 \left(\frac{10\,\text{TeV}}{m_\rho}\right)^2$$

$$\mu \to e\gamma \qquad \frac{\sqrt{m_\mu m_e}}{m_\rho^2}\,\bar{\mu}\sigma_{\alpha\beta}e\,F^{\alpha\beta}$$

MEG: Br($\mu \to e\ \gamma$) < 2.4 x 10^{-12} $\qquad m_\rho \gtrsim 150\ \mathrm{TeV}$

Partial compositeness clearly cannot be the full story

Must assume strong sector possesses some flavor symmetry

Range of possibilities

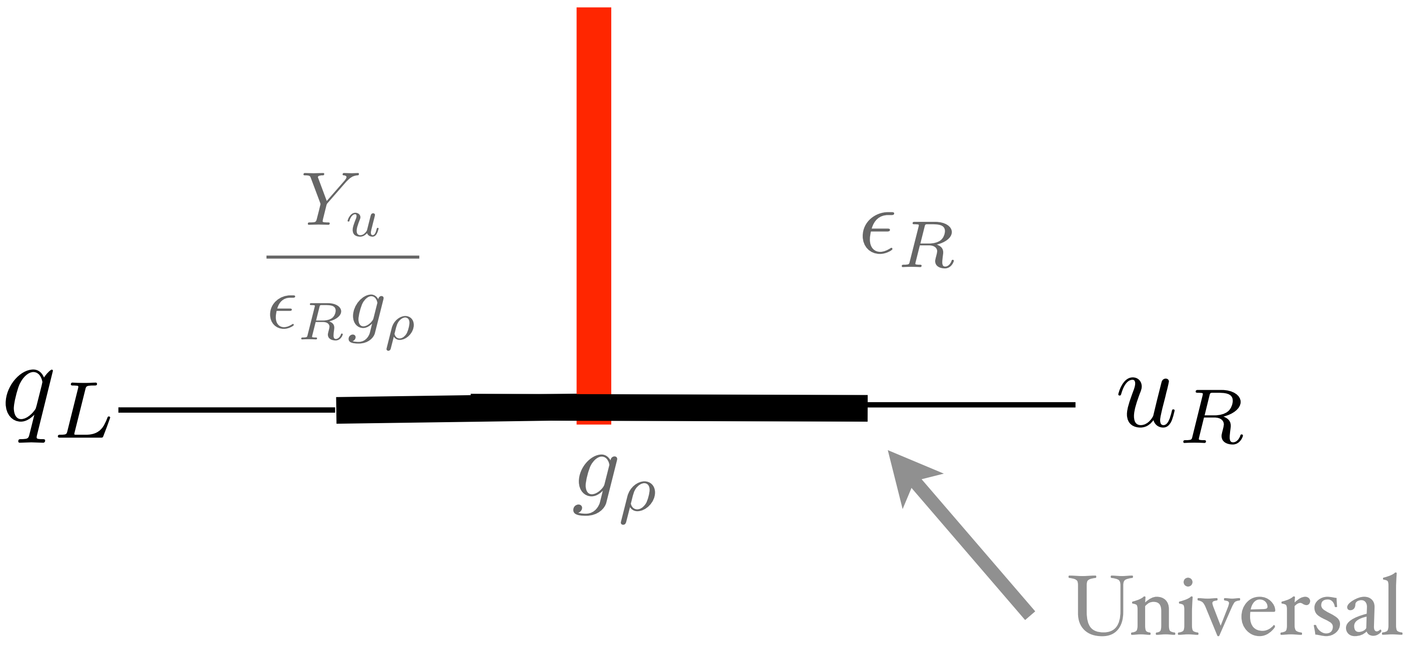
$U(1)_e$ x $U(1)_\mu$ x $(1)_\tau$

. . . .

SU(3) x SU(3) x ...

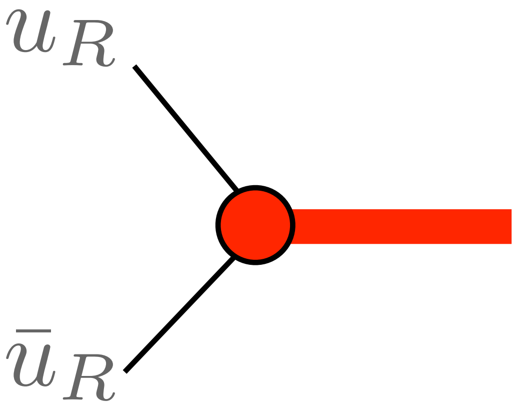
Basically the only case where it makes sense to invoke MFV

Redi, Weiler '11



Observed m_t → $\epsilon_R \gtrsim \frac{1}{g_\rho} > 0.1$

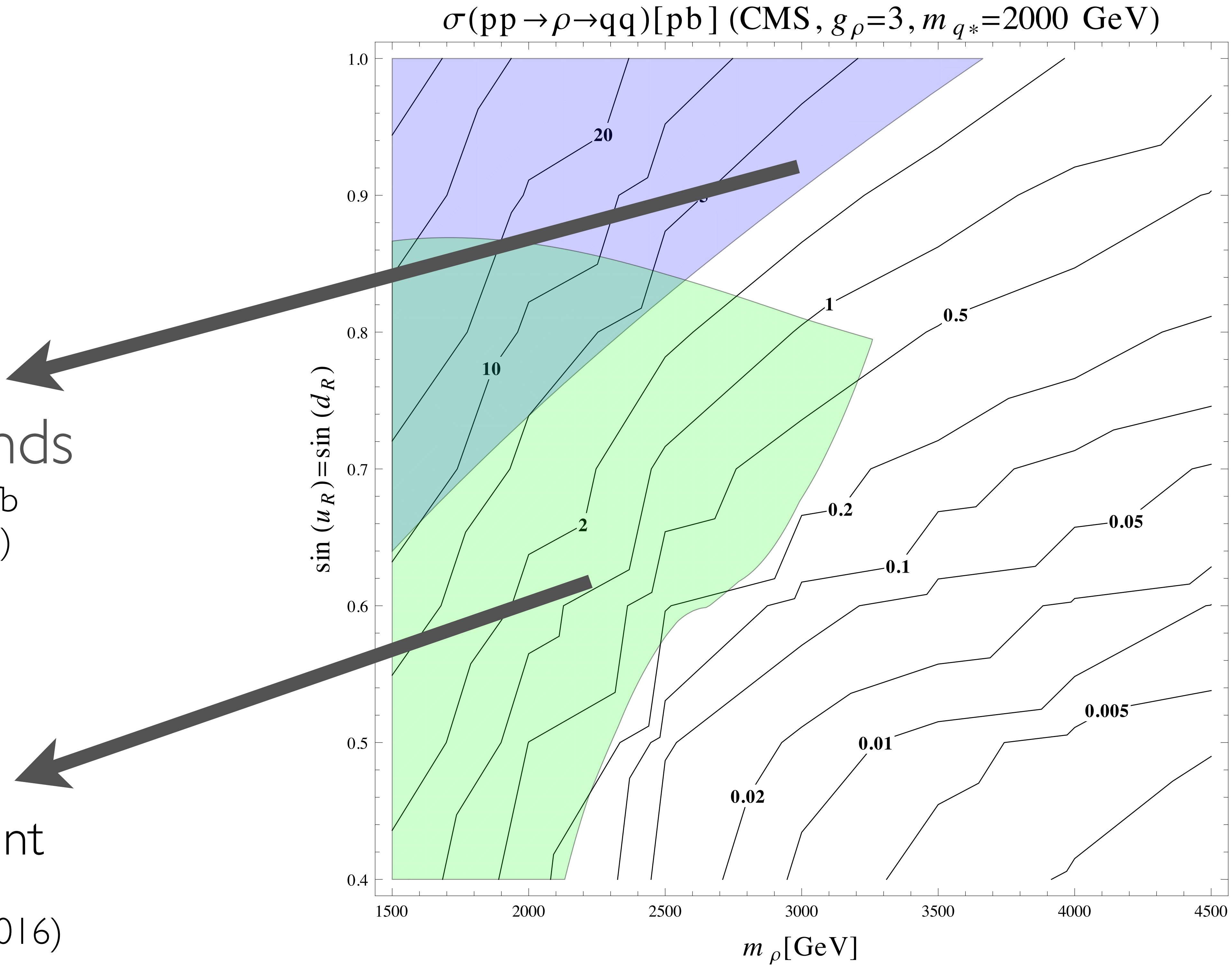
Predict sizeable effects in right handed quarks



all possible resonances (Ex. massive gluon)

LHC bounds:

de Vries, Redi, Weiler: to appear



Di-jet bounds

CMS 7 TeV 2.2 inv fb
(CMS-EXO-11-017)

Di-jet Bump hunt

CMS 8 TeV 4 inv fb
(CMS PAS EXO-12-016)

$$g_\rho = 3$$

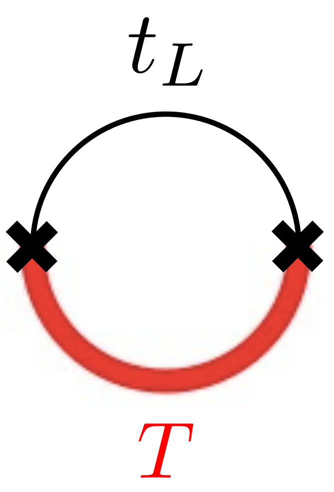
Expected signals in di-jet.

✦ Flavor

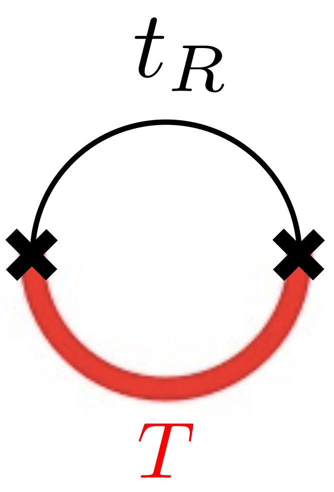
✦ Naturalness and the search for top partners

Higgs's mass versus top-partners'

$V(h) =$



$+$



$+ \ldots$

$O(\lambda_L^2)$ $O(\lambda_R^2)$

$$\boxed{\lambda_L \lambda_R \sim \lambda_t g_T}$$

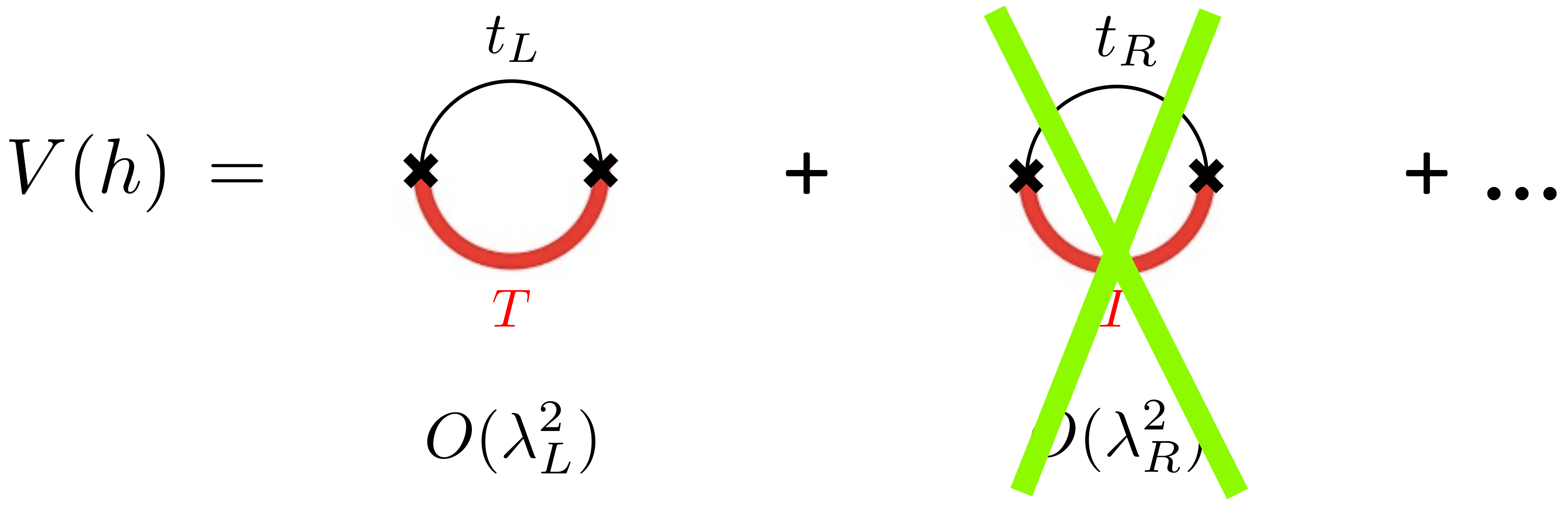
$\lambda_L \sim \lambda_t$

best option t_R is fully composite SO(5) singlet

$\lambda_R \sim g_T$

$$\boxed{V(h) = \frac{m_T^4}{g_T^2} \times \frac{\lambda_t^2}{16\pi^2} \times F(h/f)}$$

Higgs's mass versus top-partners'



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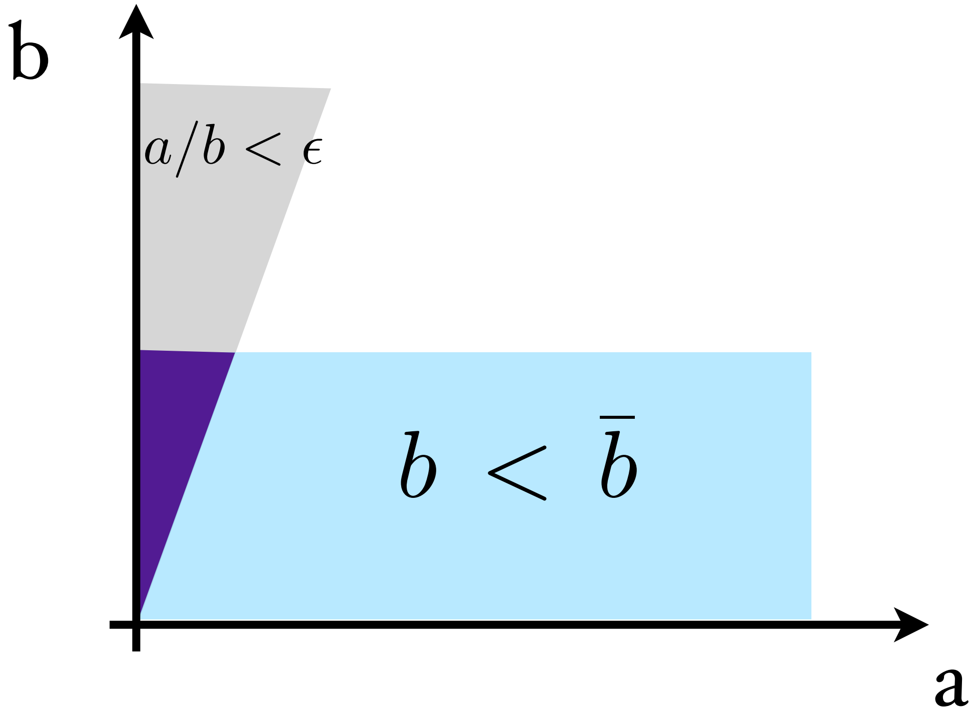
Mrazek et al, '11
Pomarol, Riva '12

$$\boxed{V(h) = \frac{m_T^4}{g_T^2} \times \frac{\lambda_t^2}{16\pi^2} \times F(h/f)}$$

$$V = \frac{3\lambda_t^2 m_T^2}{16\pi^2}\left(ah^2 + bh^4/f^2 + \ldots\right)$$

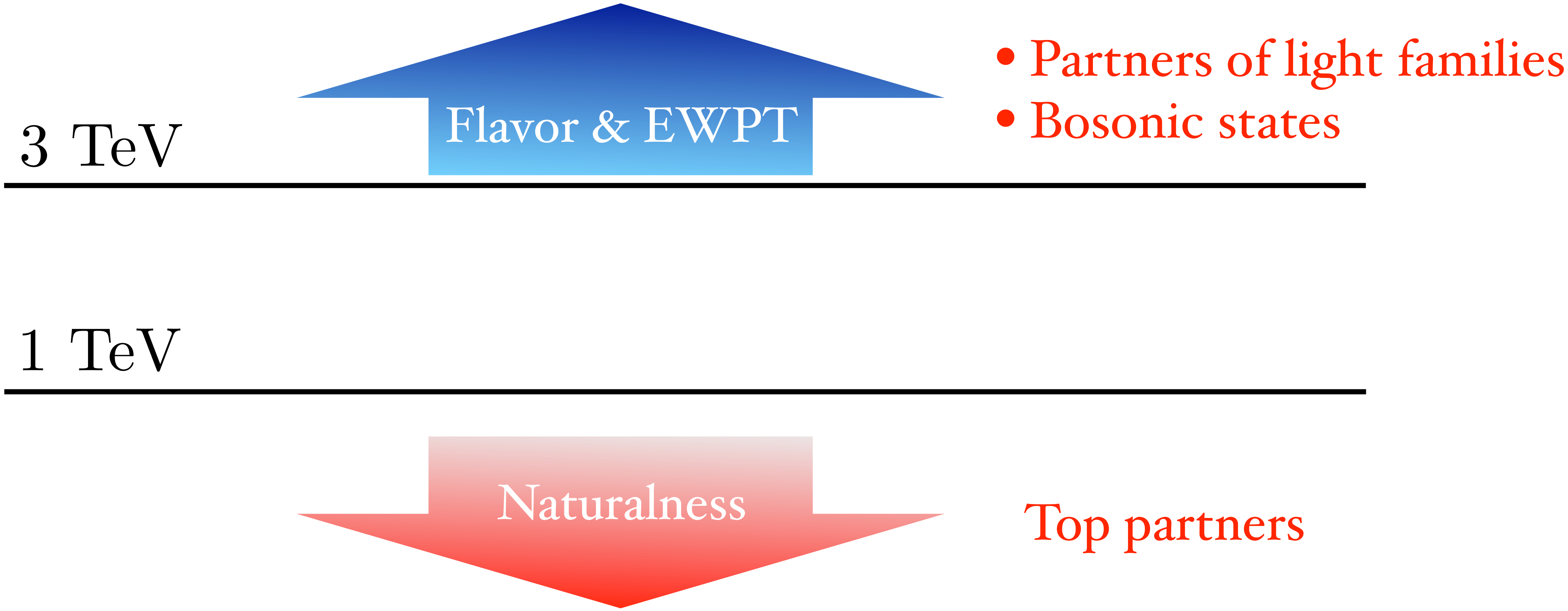


tunings

VEV $v^2/f^2 < \epsilon$ $a/b < \epsilon$

quartic $$b = \bar{b} \equiv \frac{m_h^2}{m_t^2}\frac{2\pi^2}{3g_T^2} \sim \frac{4}{g_T^2}$$

Total tuning ~ area = $$\epsilon\,\bar{b}^2 = \left(\frac{430\,\mathrm{GeV}}{m_T}\right)^2 \times \frac{4}{g_T^2}$$



- Partners of light families
- Bosonic states

Flavor & EWPT

3 TeV

1 TeV

Naturalness

Top partners

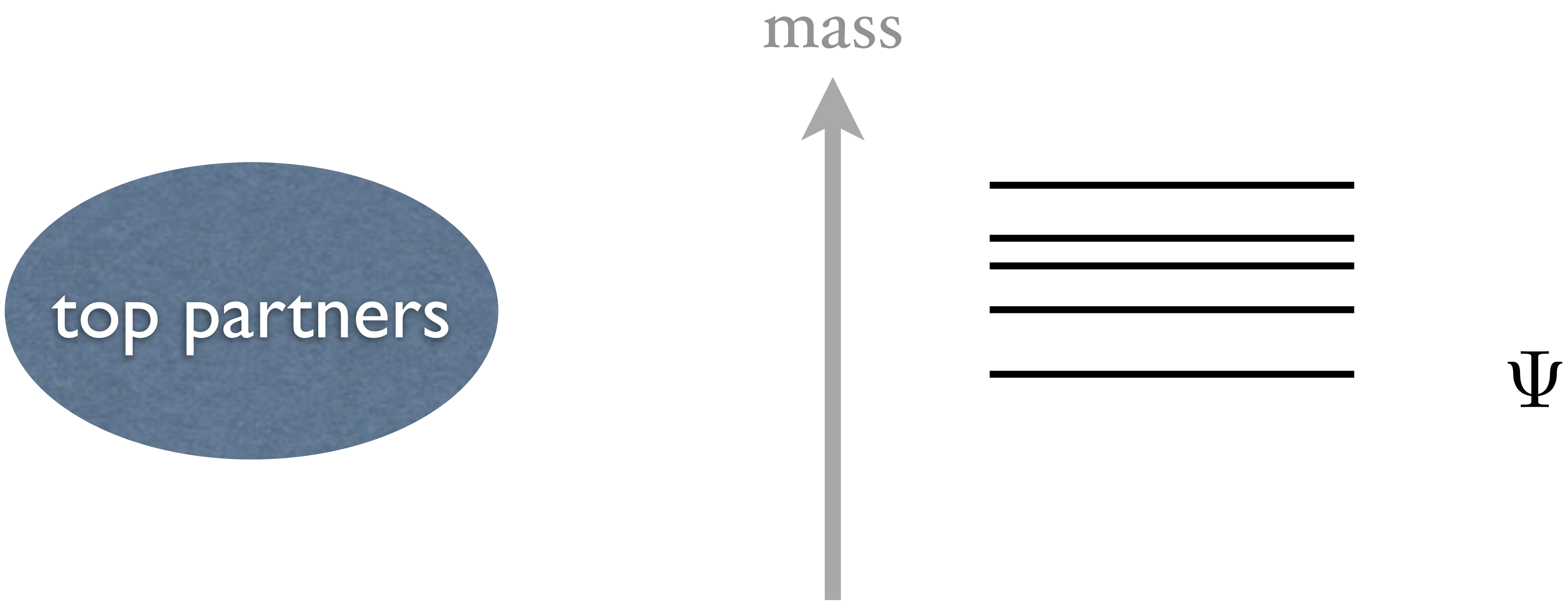
The main test of naturalness is the search for fermionic top partners

but how to proceed? given we do not have in our hand
a truly compelling and calculable model

how to help our experimental colleagues to express the
results of their searches in the light of more interesting
scenarios than, say, a fourth family

Simplified Model Ideology

in the end model builders mistrust full fledged models



top partners

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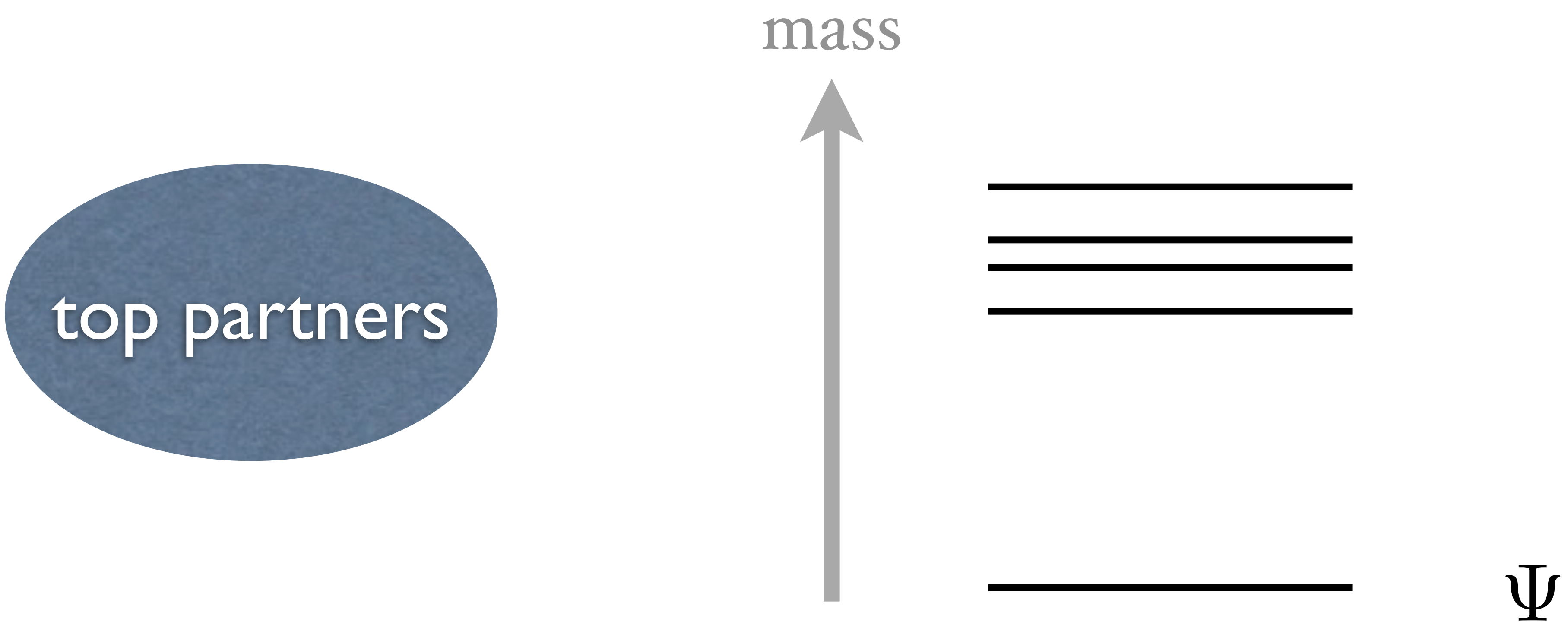

mass

top partners

Ψ

Focus on
on just Ψ

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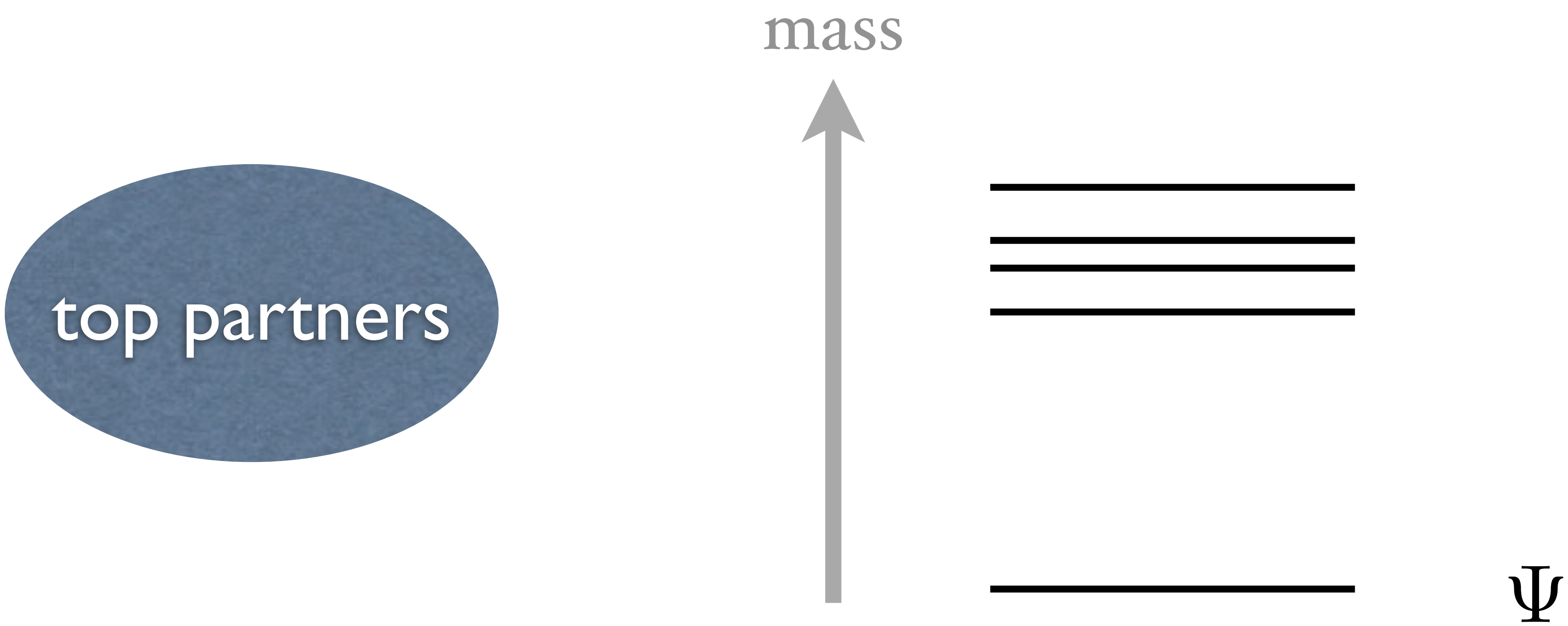

Focus on
on just ψ

simplest: ψ = Dirac spinor in irrep of SO(4)

next-to-simplest: ψ = makes up a *generalized* two- or three-site model

next-to-next: ψ = whole KK-tower from extra-dimension

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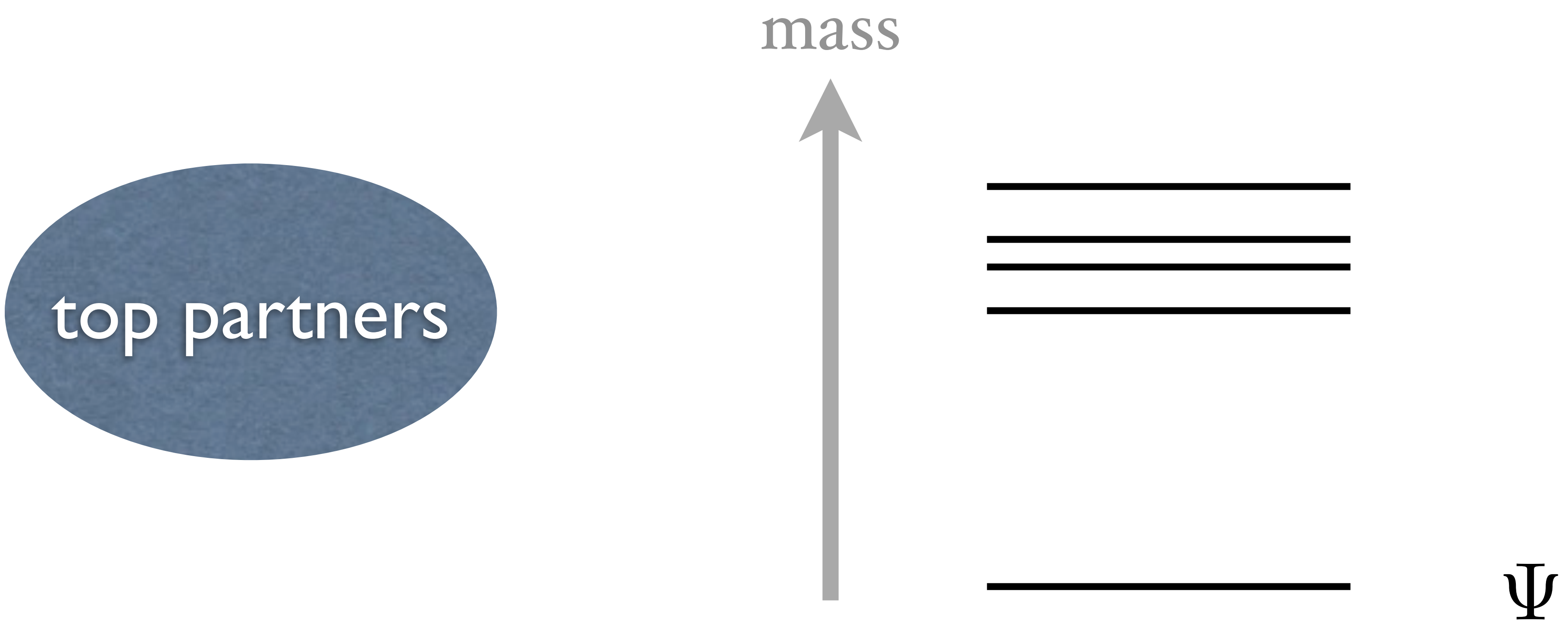

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calculable contribution to V(h)

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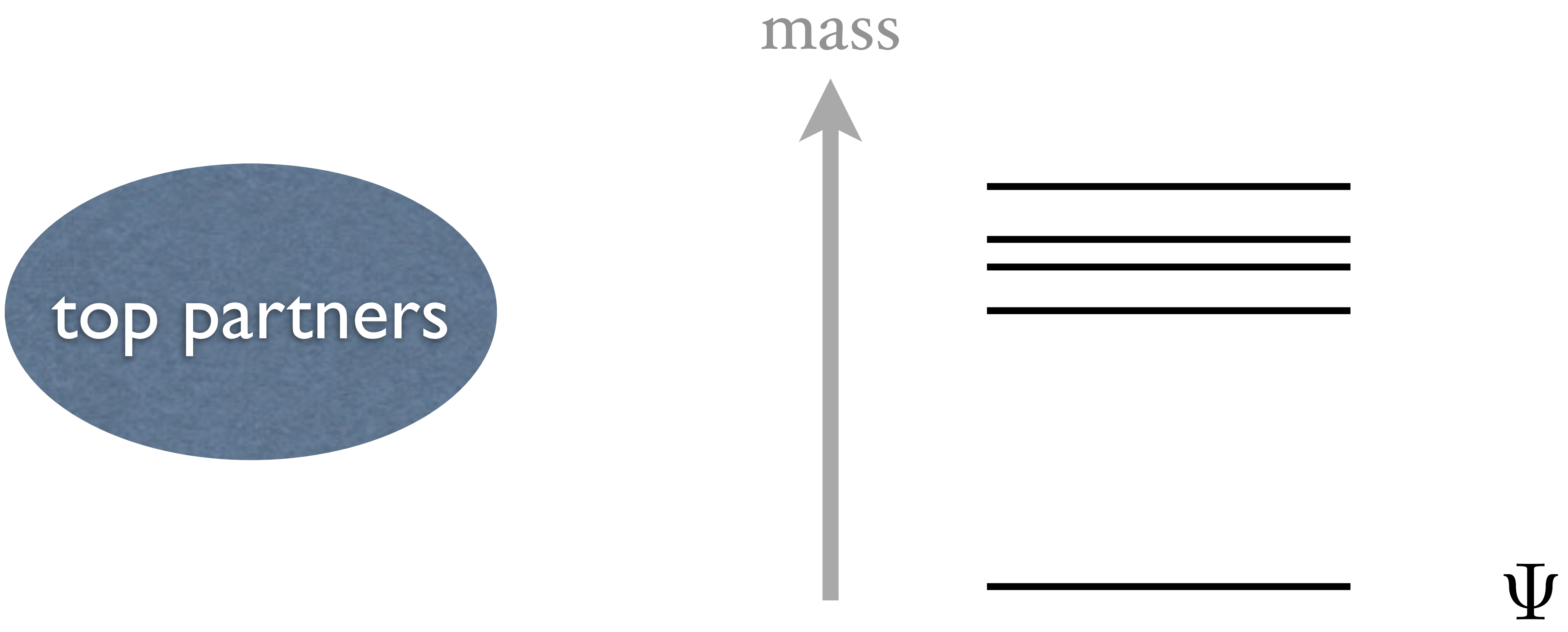

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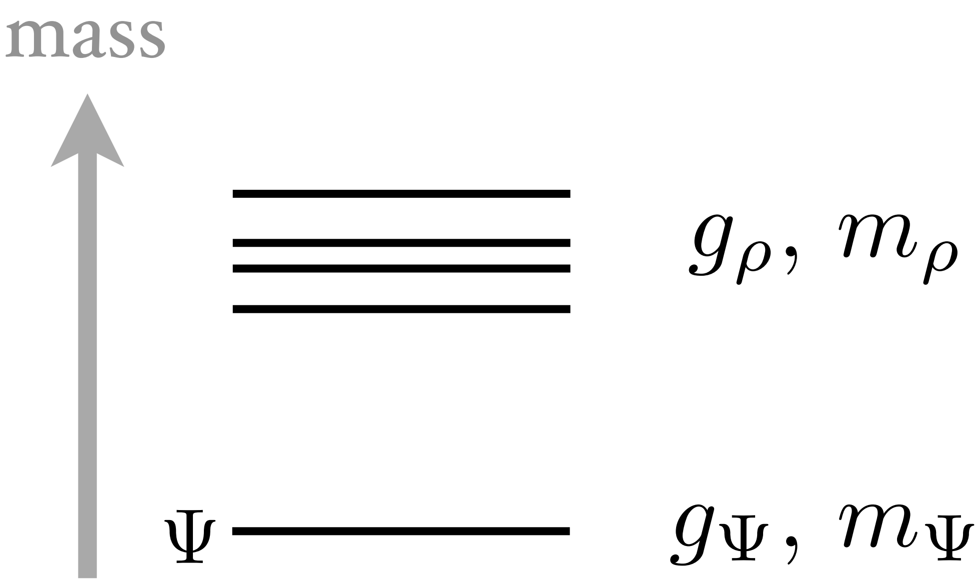
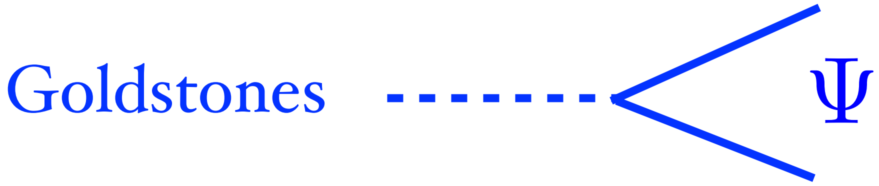




$$g_\Psi \sim \frac{m_\Psi}{f} \ll \frac{m_\rho}{f} \sim g_\rho \lesssim 4\pi$$

In formal limit $m_\Psi \ll m_\rho$ can consistently take Ψ weakly coupled
describe by effective lagrangian

already discussed for bosonic resonances in: Contino, Marzocca, Pappadopulo, RR, 2011

Expect results to semi-quantitatively remain the same even in more realistic case $m_\rho - m_\Psi = O(m_\Psi)$

Focus on SO(5)/SO(4) with totally composite t_R

Which irrep could ψ be ?

$$\mathcal{L}_{top} = \lambda_L q_L \bar{\mathcal{O}}_R + \text{h.}c.$$

simplest options $\mathcal{O}_R$

$$\mathbf{5} = \mathbf{4} \oplus \mathbf{1}$$

$$\mathbf{14} = \mathbf{9} \oplus \mathbf{4} \oplus \mathbf{1}$$

$\mathbf{4}$ and $\mathbf{1}$ are interpolated by $\mathcal{O}_R$ in both options

	$\mathcal{O}_R = \mathbf{5}$	$\mathcal{O}_R = \mathbf{14}$
$\Psi = \mathbf{1}$	$M1_5$	$M1_{14}$
$\Psi = \mathbf{4}$	$M4_5$	$M4_{14}$

$\mathcal{L}_\Psi$ based on

- symmetry (SO(5)/SO(4) **σ**-model)
- selection rules (λ_L dependence)
- naive power counting

Ex. $M4_5$

$$\mathcal{L}_\Psi = i\,\bar{q}_L \not{D}\, q_L + i\,\bar{t}_R \not{D}\, t_R + i\,\bar{\Psi}(\not{D} + i\not{e})\Psi - M_\Psi \bar{\Psi}\Psi$$

$$+ \left[i\, c_1 \left(\bar{\Psi}_R\right)_i \gamma^\mu d^i_\mu\, t_R + \lambda_L f \,(\bar{q}^{\mathbf{5}}_L)^I U_{I\,i}\, \Psi^i_R + \lambda_L\, c_2 f\, (\bar{q}^{\mathbf{5}}_L)^I U_{I\,5}\, t_R + \text{ h.c.} \right]$$

$$\Big\downarrow$$

$$\sim \partial_\mu H \quad \equiv h, W^i_L$$

in unitary gauge

$$U = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & \cos\frac{h}{f} & \sin\frac{h}{f} \\ 0 & 0 & 0 & -\sin\frac{h}{f} & \cos\frac{h}{f} \end{pmatrix}$$

4 free parameters $(\lambda_L, c_1, c_2, M_\Psi, f) \; - \; m_t$

expect $\lambda_L \sim \lambda_t$ $\qquad c_{1,2} = O(1)$

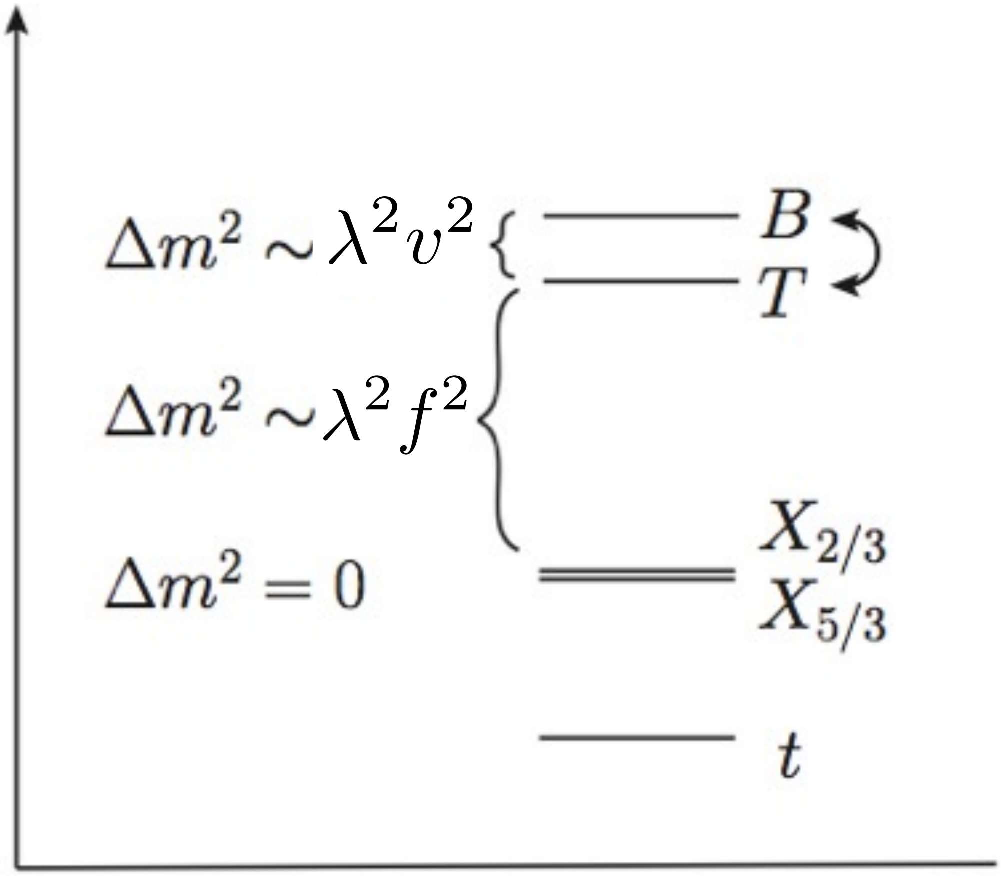
Ex. $M1_5$

$$\mathcal{L}_\Psi = i\,\bar{q}_L \not{D}\, q_L + i\,\bar{t}_R \not{D}\, t_R + i\,\bar{\Psi}(\not{D} + i\not{e})\Psi - M_\Psi \bar{\Psi}\Psi$$

$$+ \left[\lambda_L f\, (\bar{q}_L^{\mathbf{5}})^I U_{I\,5}\,\Psi_R + \lambda_L\, c_2 f\, (\bar{q}_L^{\mathbf{5}})^I U_{I\,5}\, t_R + \text{ h.c.}\right]$$

3 free parameters $(\lambda_L, c_2, M_\Psi, f) \; - \; m_t$

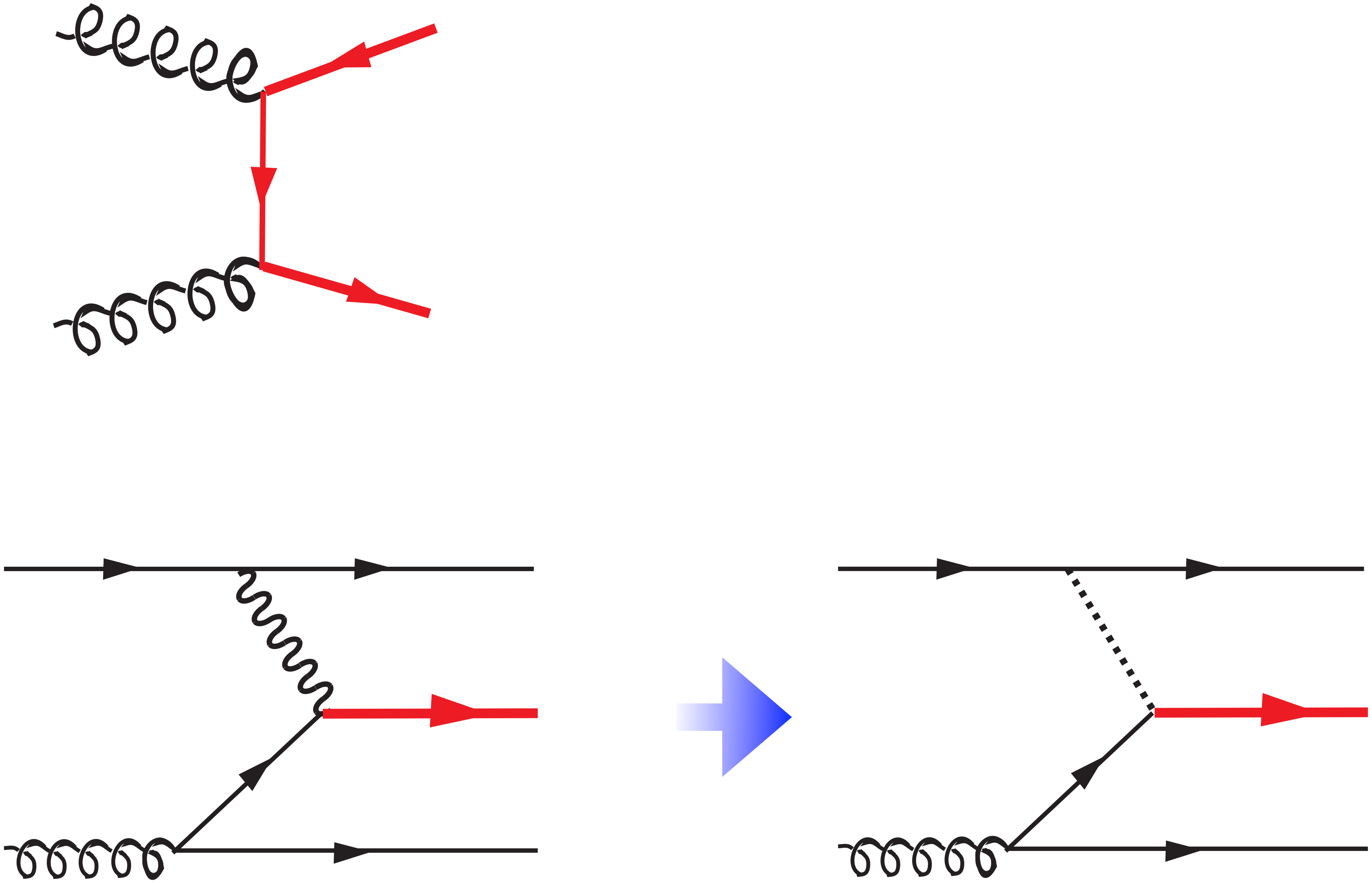
spectrum



$$\begin{pmatrix} \bar{t}_L \\ \bar{T}_L \\ {X_{2/3}}_L \end{pmatrix}^T \begin{pmatrix} -\frac{c_2 \lambda\, f}{\sqrt{2}} \sin\epsilon & \lambda\, f \cos^2\frac{\epsilon}{2} & \lambda\, f \sin^2\frac{\epsilon}{2} \\ 0 & -M_\psi & 0 \\ 0 & 0 & -M_\psi \end{pmatrix} \begin{pmatrix} t_R \\ T_R \\ {X_{2/3}}_R \end{pmatrix}$$

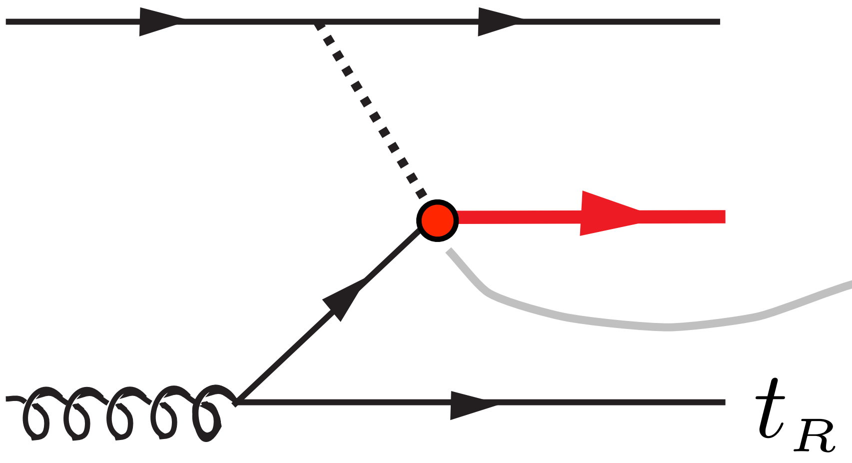
σ-model zeroes protect splitting between $X_{2/3}$ and $X_{5/3}$

Production



Contino, Servant 2008

Ex. $M4_5$



$$g_\Psi \simeq c_1 \frac{m_\Psi}{f} > \lambda_t$$

$$pp \to \Psi,\, t_R + j$$

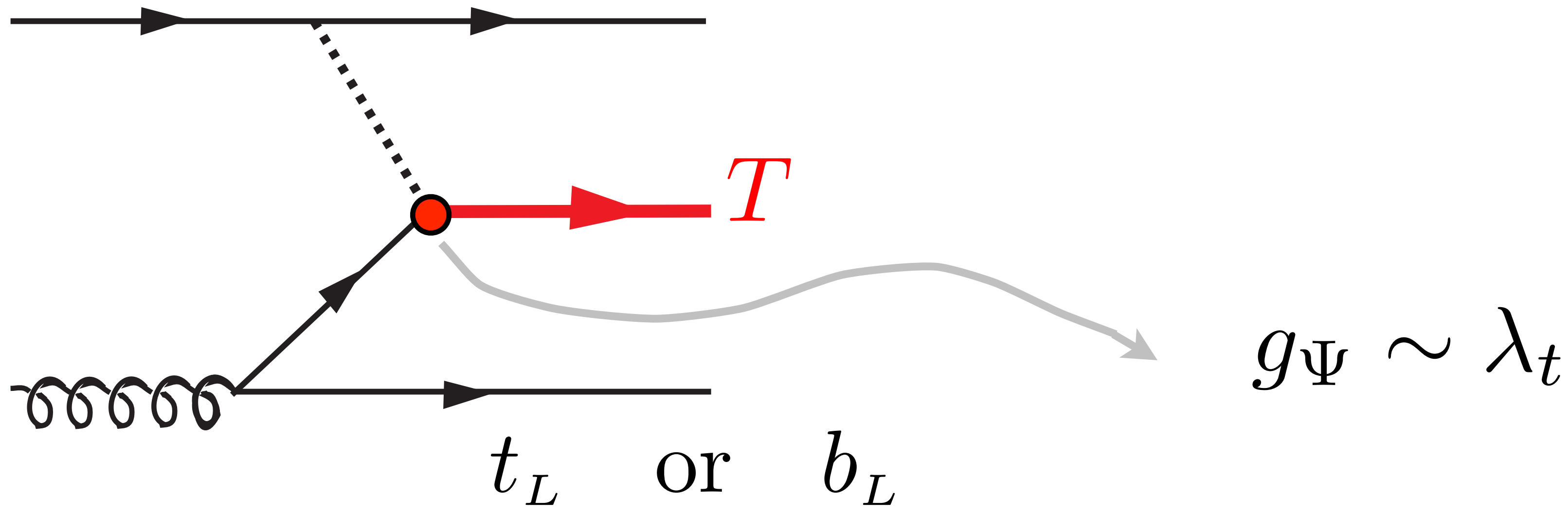
forward jet
not presently exploited in searches

$$Br(X_{5/3} \to W t_R) = 1$$

$$Br(X_{2/3} \to h t_R) \simeq Br(X_{2/3} \to Z t_R) \simeq 0.5$$

$$Br(B \to W t_R) \simeq 1$$

Ex. $M1_5$



$$Br(T \to Zt_L) \simeq Br(T \to ht_L) \simeq \frac{1}{2} Br(T \to Wb_L) \simeq 0.25$$

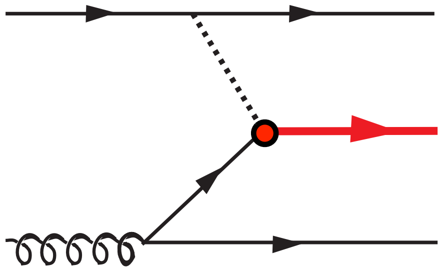
available searches tailored on 4th family double production
not very sensitive to single production in this model

We have employed CMS searches for 4th family quarks to bound the simplified top models for top partners

Our own estimate of the efficiencie of signal:

including trigger and b-tagging efficiencies reported by CMS papers
not including showering, hadronization & detector
checking our estimates are at most 30% off for the 4th family signal

No need of full simulation point by point in parameter space

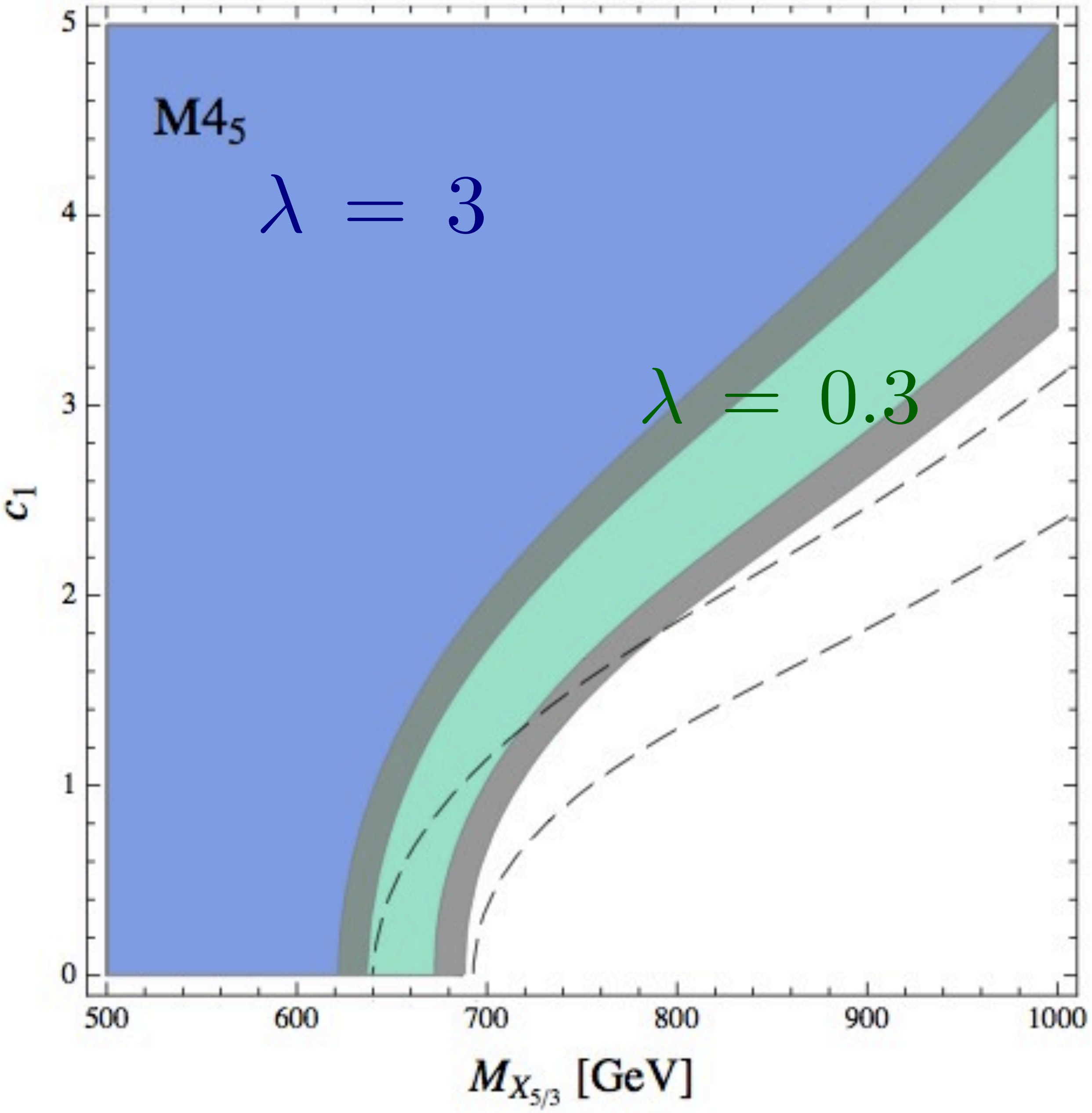


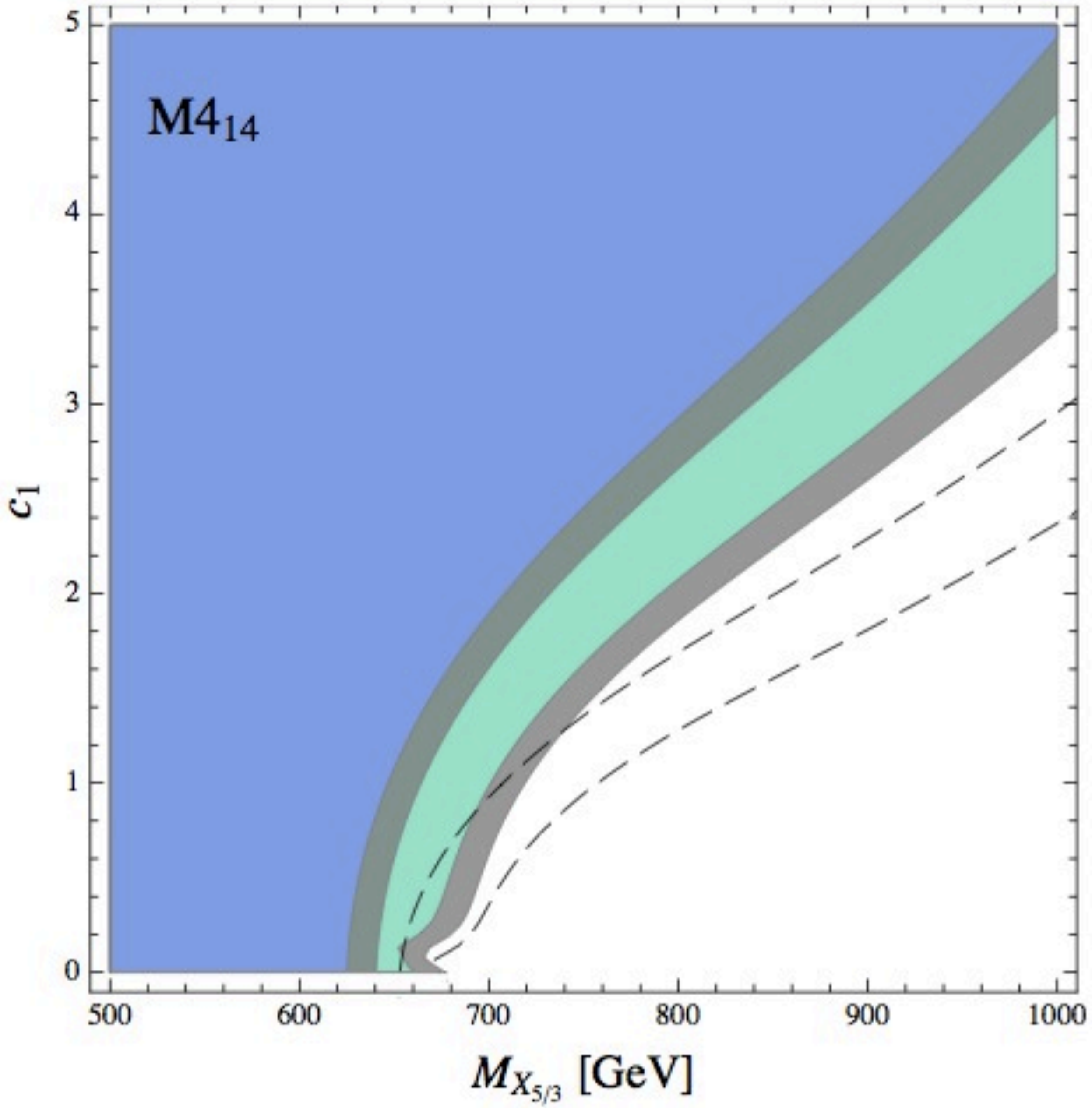
$$\sigma(\Psi t) = \underbrace{g^2_{\Psi t}}_{\text{analytic dependence on parameters}} \times \underbrace{\bar{\sigma}(\Psi t)}_{\text{simulated numerically once for all}}$$

$X_{5/3}$ and B production constrained by 4th family search $b' \to Wt$

same sign dileptons (trileptons) + b + 3 (2) jets

$$\xi \equiv \frac{v^2}{f^2} = 0.2$$

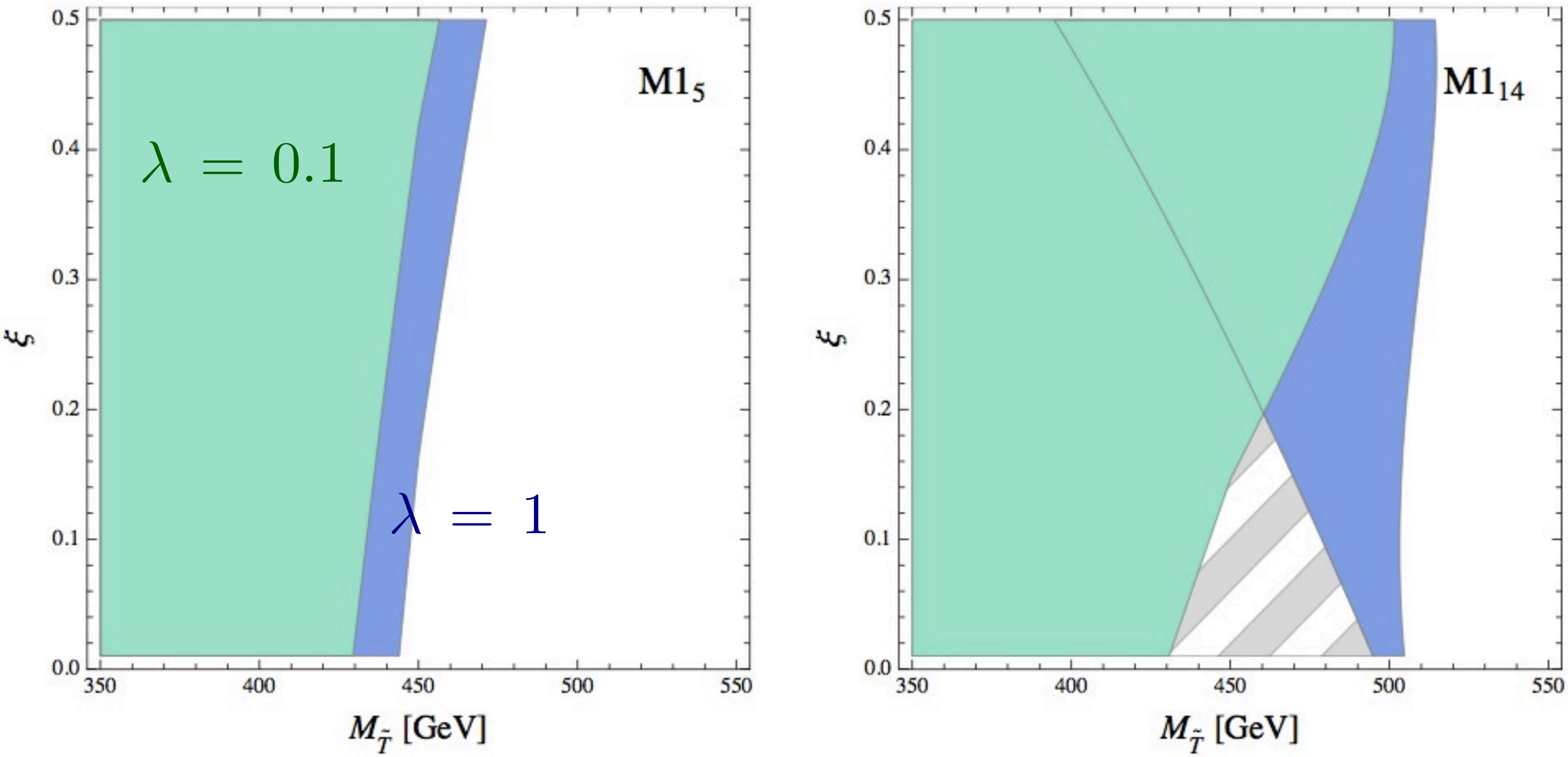




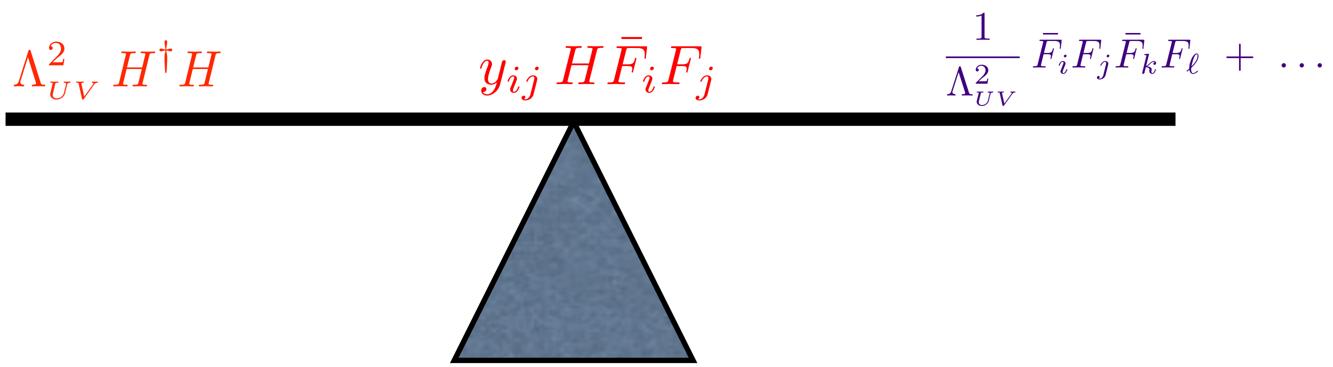
T production constrained by 4th family search

same sign dileptons (trileptons) + b + 3 (2) jets

$$t' \to Wb$$



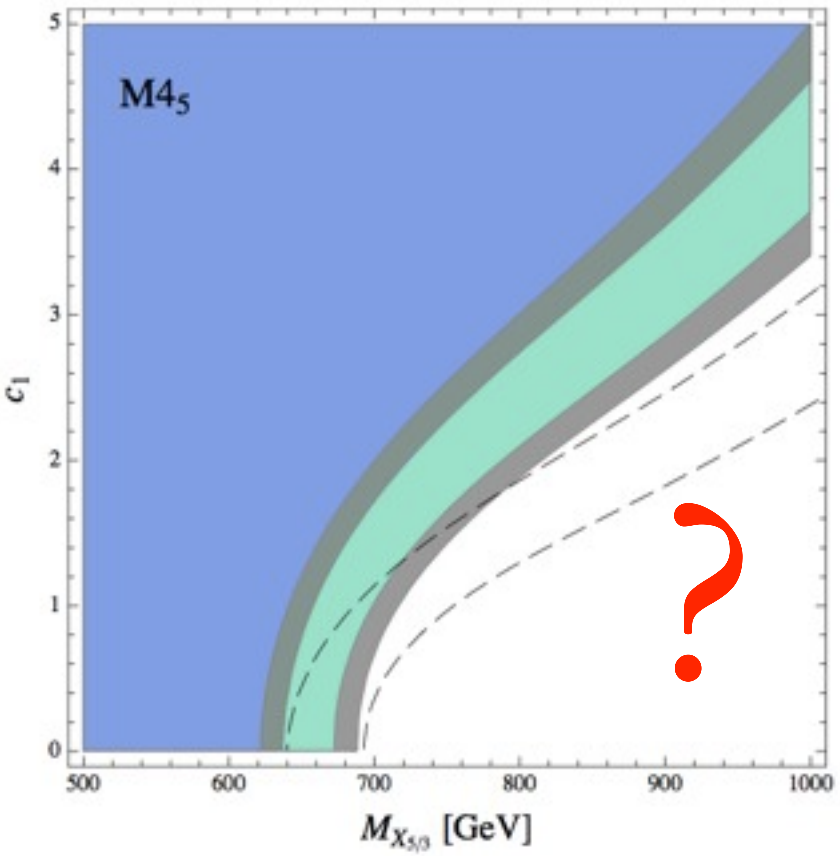
I.



$\Lambda_{UV}^2 \, H^\dagger H$ $\quad$ $y_{ij} \, H \bar{F}_i F_j$ $\quad$ $\frac{1}{\Lambda_{UV}^2} \bar{F}_i F_j \bar{F}_k F_\ell \; + \; \dots$

Flavor remains crucial
to assess
the riddle of the weak scale

II.



$$\text{tuning} \quad \lesssim \left(\frac{400\,\text{GeV}}{m_T} \right)^2$$

III. $m_h \;\simeq\; 125\ \text{GeV}$ → strong sector is not so strong