The **Un**-Natural PNGB Higgs

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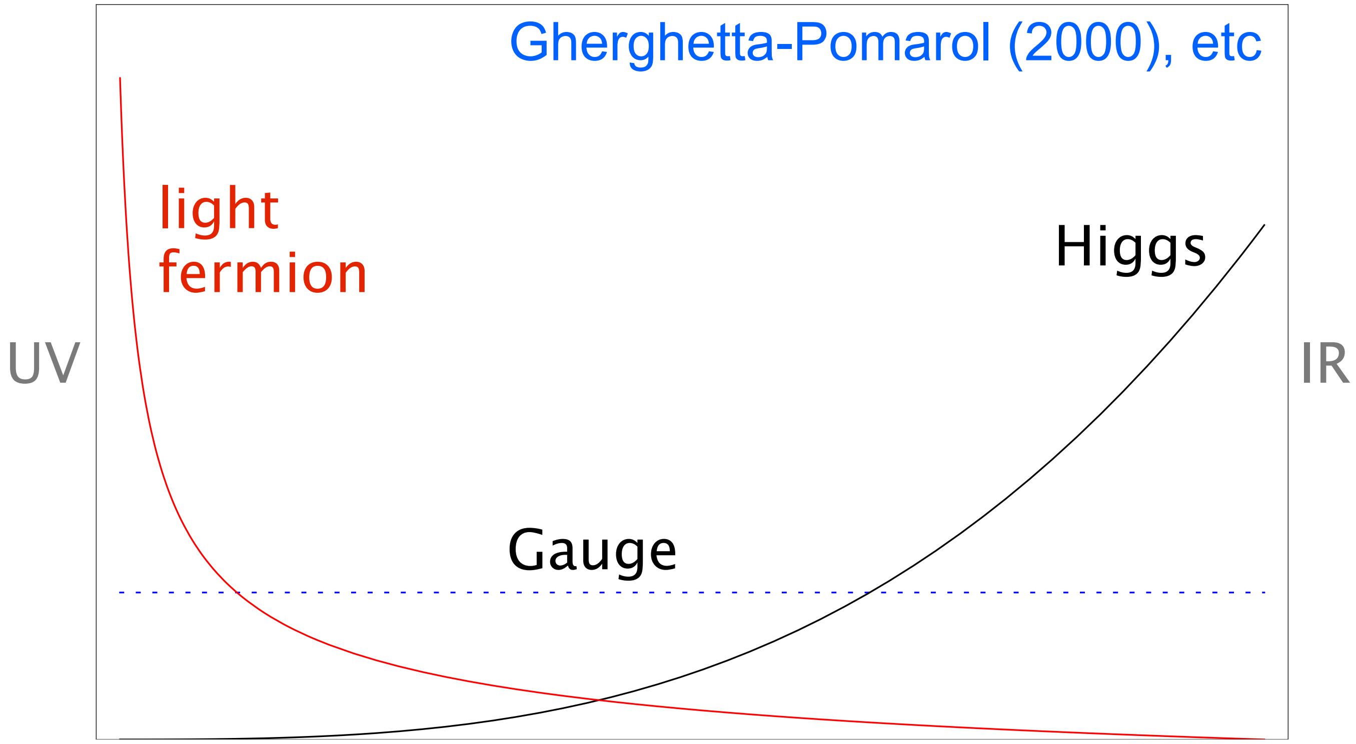
PNGB Higgs models are still a viable alternative to SUSY

a problem then $\xrightarrow{\text{Flavor}}$ a virtue now

$$\frac{\bar{q}q\mathcal{O}}{\Lambda^d}$$

$$\epsilon\bar{q}\mathcal{O} \xrightarrow[\text{hierarchy via RG}]{} y \propto \epsilon_L \epsilon_R$$



Outline:

- Status after Higgs discovery (see Matthias talk)
  ➤ mass at 125 GeV

- Natural Vs “Un-natural” PNGB Higgs:
  ➤ **Why un-naturalness?**

- Signatures of un-naturalness

The pseudo-NGB Higgs

Georgi-Kaplan ('80s)

Broad picture: NDA

Georgi et al.
Contino et al. (2006)
Giudice et al. (2007)

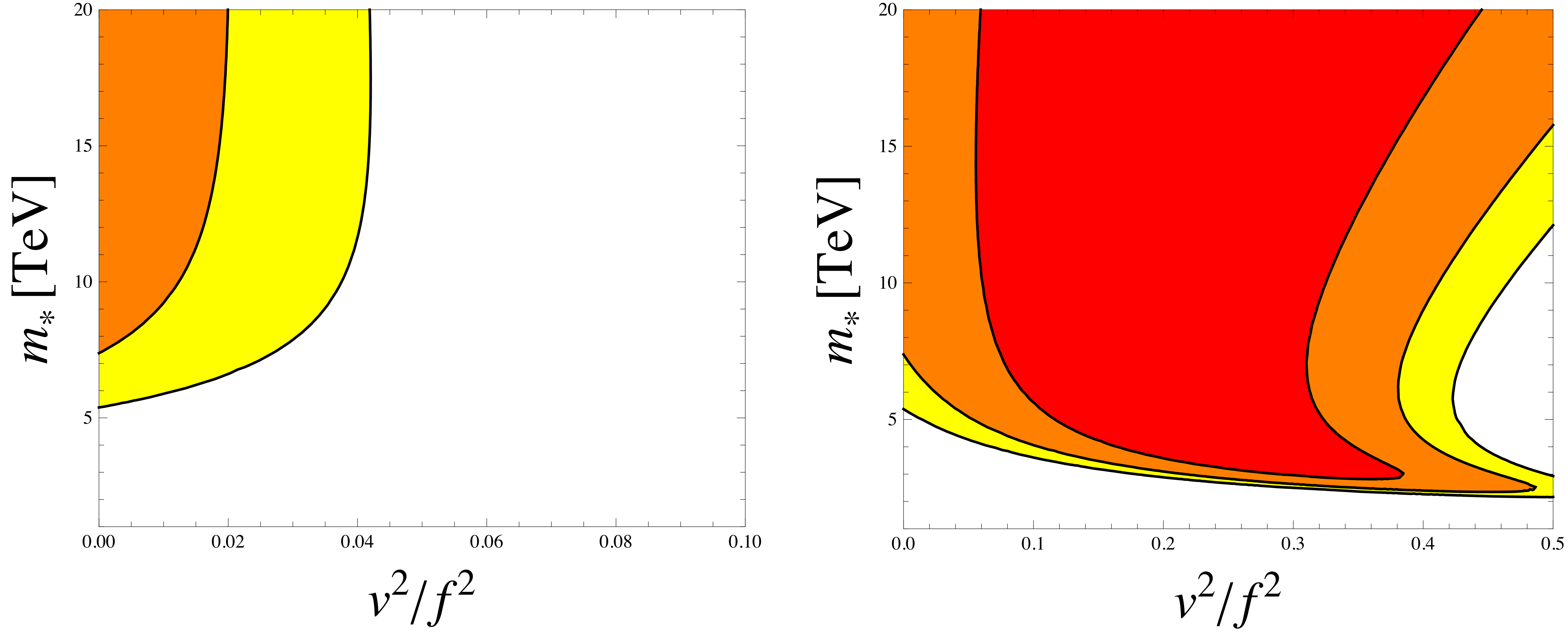
$$m_* \sim g_* f$$

one coupling,
one mass scale

EW precision data

GFitter (2014) U=0

$$\Delta T = \Delta T_h \qquad\qquad \Delta T = \Delta T_h + \frac{v^2}{f^2}$$



conservative **Vs** optimistic (Z-->bb?)

Higgs mass

$$V = \frac{y_t^2 N_c}{16\pi^2} m_*^2 f^2 \left[a \ \sin^2 \frac{h}{f} + b \ \sin^4 \frac{h}{f} + \cdots \right]$$

plus gauge and/or
exotic contributions

$$\boxed{\begin{array}{l} \dfrac{v^2}{f^2} \sim \dfrac{a}{b} < 1 \\ m_h = 100 \text{ GeV} \ \sqrt{b \dfrac{g_*^2}{y_t^2}} \end{array}}$$

$$m_h = 100 \text{ GeV} \sqrt{b \frac{g_*^2}{y_t^2}}$$

$g_* = ?, \;\; b \ll 1$

larger tuning

$g_T \ll g_*, \;\; b \sim 1$

light top partners

Ex: minimal SO(5)/SO(4) with bulk fermions in the irreps 4,5,10...

Pomarol et al. (2012)

Panico et al. (2012)

Marzocca et al. (2012)

...

tuned, but
potentially generic

Vs

split spectrum

Example:
SU(4)/Sp(4) with $\epsilon \overline{q} \mathcal{O}$, and $\mathcal{O} \sim \mathbf{4} \in SU(4)$

$$V \propto \sin^2 + \frac{y_t^2}{g_*^2} \sin^4 + \cdots \Rightarrow \begin{cases} b \sim \dfrac{y_t^2}{g_*^2} \\ \lambda = c \dfrac{N_c y_t^4}{4\pi^2} \ln \dfrac{m_*}{m_h} \end{cases}$$

Lesson:

Once tuning (v/f<<1) is swallowed $\sim \dfrac{m_*^2}{m_t^2}$

1) split spectrum is not necessary

2) coupling strength is not constrained

Flavor

typical spectrum >10 TeV with flavor anarchy

Bauer et al. (2010)
Keren-Zur et al. (2013)
...

light top partners

m_T>10 TeV ($\Delta F=2$) $\Longleftrightarrow$
tuning or symmetries

Keren-Zur et al. (2013)
Barbieri et al. (2013)
...

hierarchy from flavor anarchy **vs** flavor symmetries needed

	Natural	Vs	**Un-Natural**
Tuning	<1/10		<1/1000
EW data	with luck		generically
Flavor	non-generic		**very attractive**
Higgs mass	split spectrum		**generic spectrum**

	Natural	Vs	**Un-Natural**
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Flavor	non-generic		**very attractive**
Higgs mass	split spectrum		**generic spectrum**

Non-Generic

Tuned

natural but non-generic **?** **OR** **generic and fine-tuned**

How much tuning?
and “Why”?

WIMP “miracle”?!

$$\sigma v = \frac{g_*^4}{4\pi m_*^2} \;\Rightarrow\; m_* \sim (3-5) g_*^2 \ \mathrm{TeV}$$

light composites
annihilate into SM

mass in the 1s of TeV

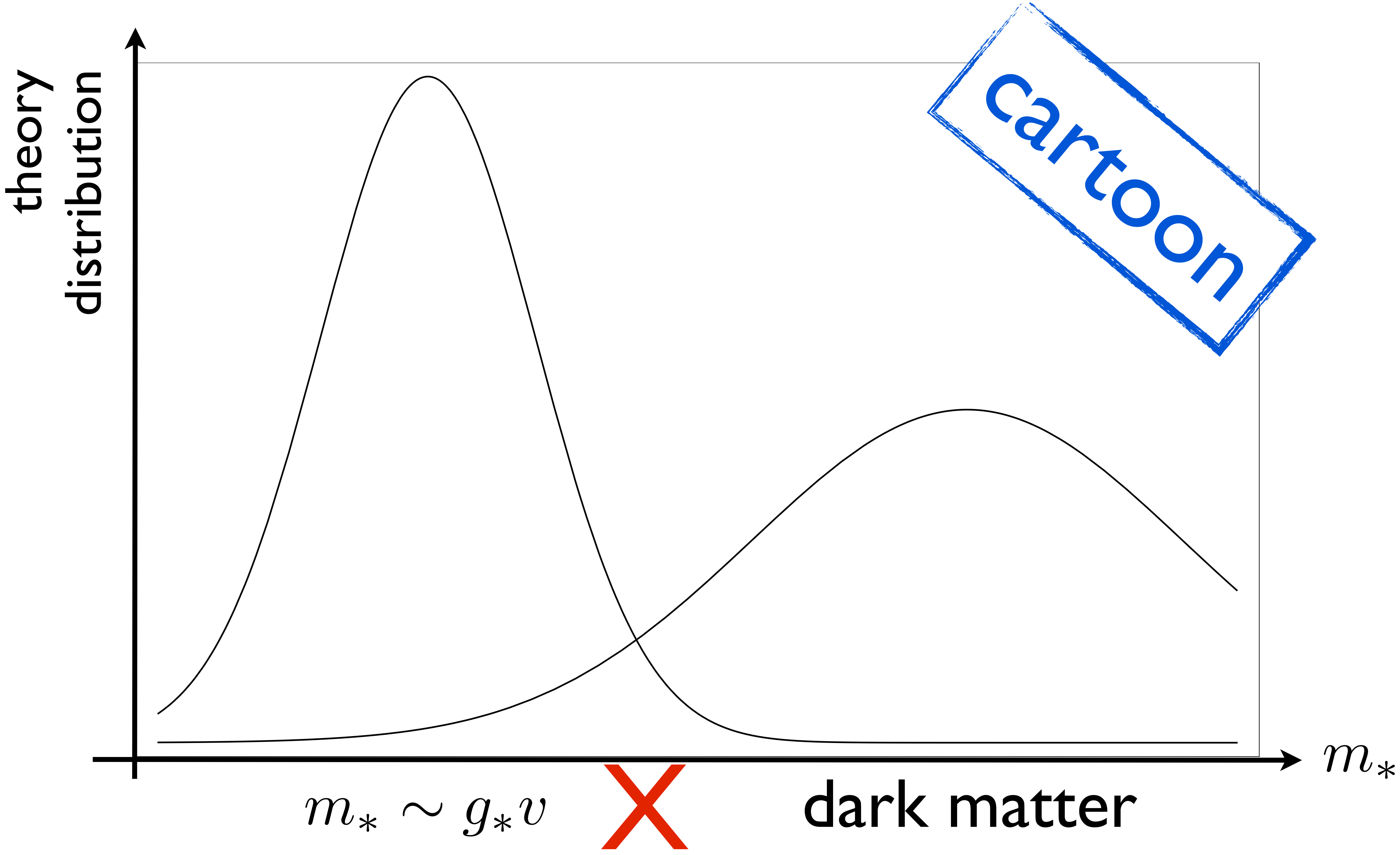
typical composites
annihilate into BSM

mass in the 10s of TeV

tuning is generic

(“natural” in a broader sense)

One parameter, **Two** observable to explain “naturally”...



“Naturally Un-natural”

WIMPs in
warped extra dimensions?

Baryon DM Nussinov (1985)

(soliton in 5D)

pp-->pi's has $\sigma_{p\overline{p}}v \sim \text{few} \times 10 \text{ mb}$

$$\sigma_{X\overline{X}}v \sim \sigma_{p\overline{p}}v \left(\frac{\text{GeV}}{m_X}\right)^2 \sim \text{few pb} \left(\frac{100\text{ TeV}}{m_X}\right)^2$$ "upper bound"

Heavy WIMPs in warped extra dimensions are **generic**

Stability ✔

B&L is typically enough to have stable particles (SUSY)

$$(-)^{B+L+2s}$$

Ex: Majorana fermion, boson with non-even B, etc.

in warped 5D B&L are spontaneously
broken gauge symmetries.
Some "hadron" carries B&L: $\lambda\bar{q}\mathcal{O}$

Annihilation into BSM ✔ $m_* \sim (3-5) g_*^2 \text{ TeV}$

Majorana DM

U(1)_X broken in the bulk by 5D Majorana mass (i.e. no chiral symmetry)
$\Longrightarrow$ <u>heavy DM</u>
XX-->KK-fermions, Goldberger-Wise, etc. dominates

Baryonic (Leptonic) DM

Ex: scalar with non-even B (L)
$\Longrightarrow$ **XX-->U(1)_B gauge fields is generic**

A testable picture:
Signatures of Un-Naturalness

Dark matter
Colliders

...

WIMP detection

Indirect detection and colliders: model-dependent $q^2 \sim m_X^2$

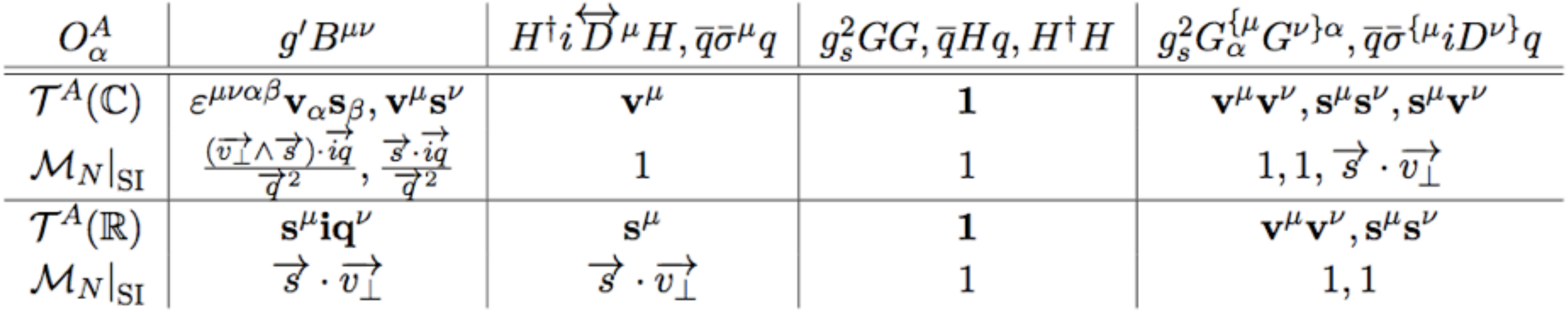
Direct detection: model-independent $q^2 \ll m_X^2$

“heavy” WIMPs ⇛ determine only sigma/m

no “standard pNGB model” ⇛ EFT approach Bagnasco et al. (1994), LV (2013)

SM operator!

$$\frac{d\sigma}{dE_R} \sim \left(\frac{\mu}{m_*}\right)^{2d-4} \frac{1}{m_*^2 E_R}$$



O^A_α	$g' B^{\mu\nu}$	$H^\dagger i \overleftrightarrow{D}^\mu H, \bar{q}\bar{\sigma}^\mu q$	$g_s^2 GG, \bar{q}Hq, H^\dagger H$	$g_s^2 G_\alpha^{\{\mu} G^{\nu\}\alpha}, \bar{q}\bar{\sigma}^{\{\mu} i D^{\nu\}} q$
$\mathcal{T}^A(\mathbb{C})$	$\varepsilon^{\mu\nu\alpha\beta}\mathbf{v}_\alpha \mathbf{s}_\beta, \mathbf{v}^\mu \mathbf{s}^\nu$	$\mathbf{v}^\mu$	$\mathbf{1}$	$\mathbf{v}^\mu\mathbf{v}^\nu, \mathbf{s}^\mu\mathbf{s}^\nu, \mathbf{s}^\mu\mathbf{v}^\nu$
$\mathcal{M}_N\vert_{\rm SI}$	$\frac{(\vec{v}_\perp \wedge \vec{s})\cdot \vec{iq}}{\vec{q}^{\,2}}, \frac{\vec{s}\cdot\vec{iq}}{\vec{q}^{\,2}}$	1	1	$1, 1, \vec{s}\cdot\vec{v}_\perp$
$\mathcal{T}^A(\mathbb{R})$	$\mathbf{s}^\mu \mathbf{iq}^\nu$	$\mathbf{s}^\mu$	$\mathbf{1}$	$\mathbf{v}^\mu\mathbf{v}^\nu, \mathbf{s}^\mu\mathbf{s}^\nu$
$\mathcal{M}_N\vert_{\rm SI}$	$\vec{s}\cdot\vec{v}_\perp$	$\vec{s}\cdot\vec{v}_\perp$	1	$1, 1$

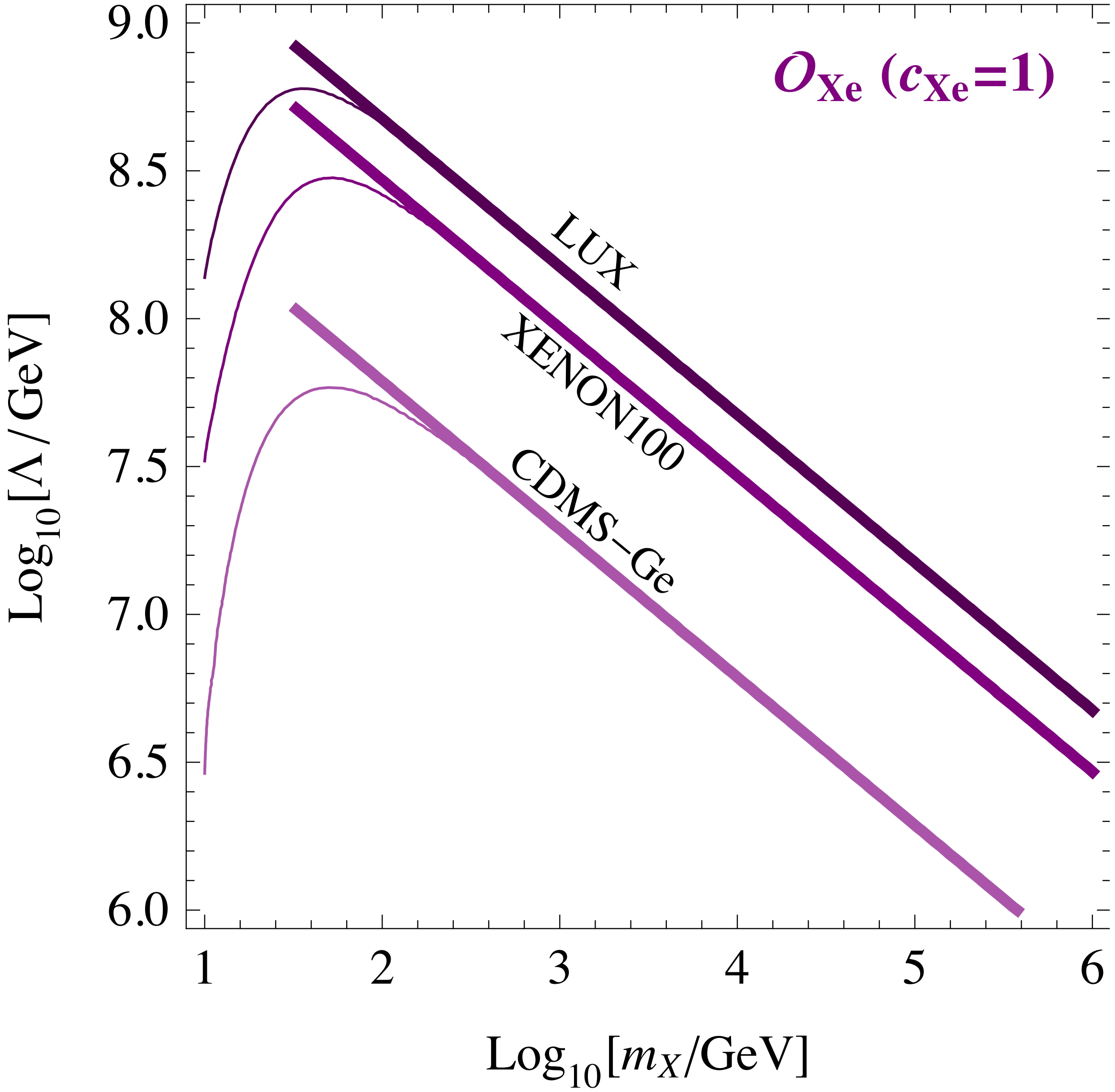
$\vec{v}^{\,2}, (\vec{s}\cdot\vec{v})^2, \cdots$ **subleading** (advantage of relativistic formulation)

d=2 (dipole)

complex WIMPs with spin & generic CPV

$$\frac{c_{Xe}}{\Lambda}\overline{X}i\sigma^{\mu\nu}\gamma^5 X e F_{\mu\nu}$$

>1000 TeV!!!



$$c_{Xe} \sim \frac{g_*^2}{16\pi^2} \;\Rightarrow\; m_* \gtrsim 100\ \mathrm{TeV}\ g_*^{4/3}$$

d=2 (dipole)

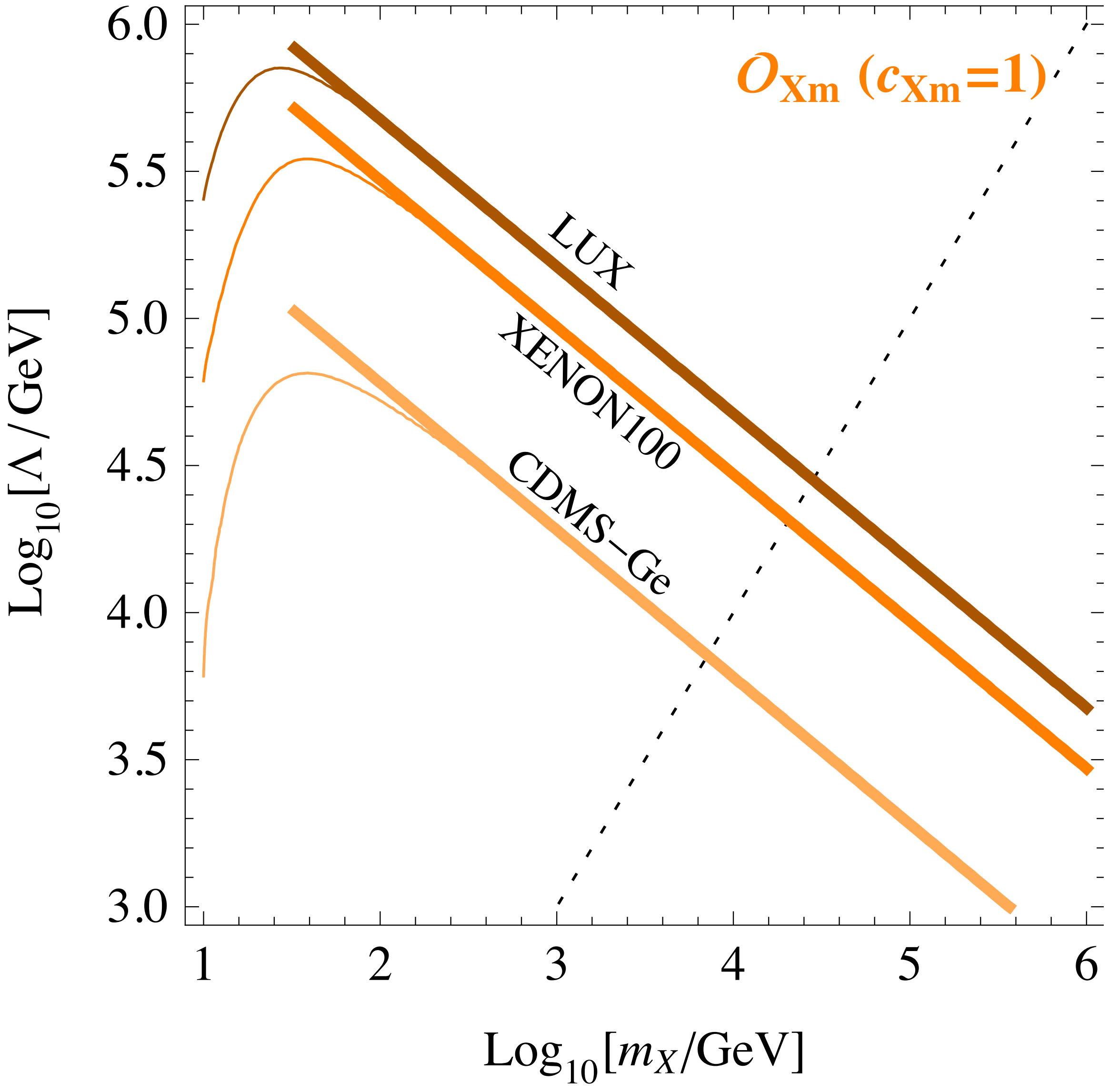
complex WIMPs with spin & ~~generic CPV~~

non-generic CPV is welcome (n-EDM)

$$\frac{c_{Xm}}{\Lambda}\overline{X}\sigma^{\mu\nu}XeF_{\mu\nu}$$

>30 TeV

(>130 TeV XENON1T)



$$c_{Xm} \sim \frac{g_*^2}{16\pi^2} \;\Rightarrow m_* \gtrsim 4.5\ \mathrm{TeV}\ g_*^{4/3}$$ XENON1T

d=2 (Higgs)

All WIMPs, Ex: fermion

$$\frac{g_*^2}{\Lambda}\frac{\delta m_h^2}{\Lambda^2}\overline{X}XH^\dagger H \implies \mathcal{M}\sim g_*^2\frac{\delta m_h^2}{\Lambda^2}\frac{m_*}{\Lambda}\langle T'|H^\dagger H|T\rangle$$

no dependence on NP scale

- suppressed in PNGB Higgs typically O(0.1-0.01)
- enhanced by a light dilaton

$$m_* \gtrsim (0.5-2)\ \text{TeV}\ g_*^{4/3}$$

XENON1T

d=3

complex WIMPs of any spin:

DD complementary to EW precision tests!

$$\frac{m_X}{\Lambda^2} X^\dagger v_\mu X e \partial_\nu B^{\mu\nu}$$

$$\Big\downarrow$$

>2 TeV (LUX)
>5 TeV (XENON1T)

$$\frac{m_X}{f^2} X^\dagger v_\mu X \;\; H^\dagger i \overrightarrow{D}^\mu H$$

$$\Big\downarrow \;\text{“T-parameter”}$$

$\frac{v^2}{f^2} \lesssim 10^{-3}$ (LUX)

“Un-naturalness” at colliders

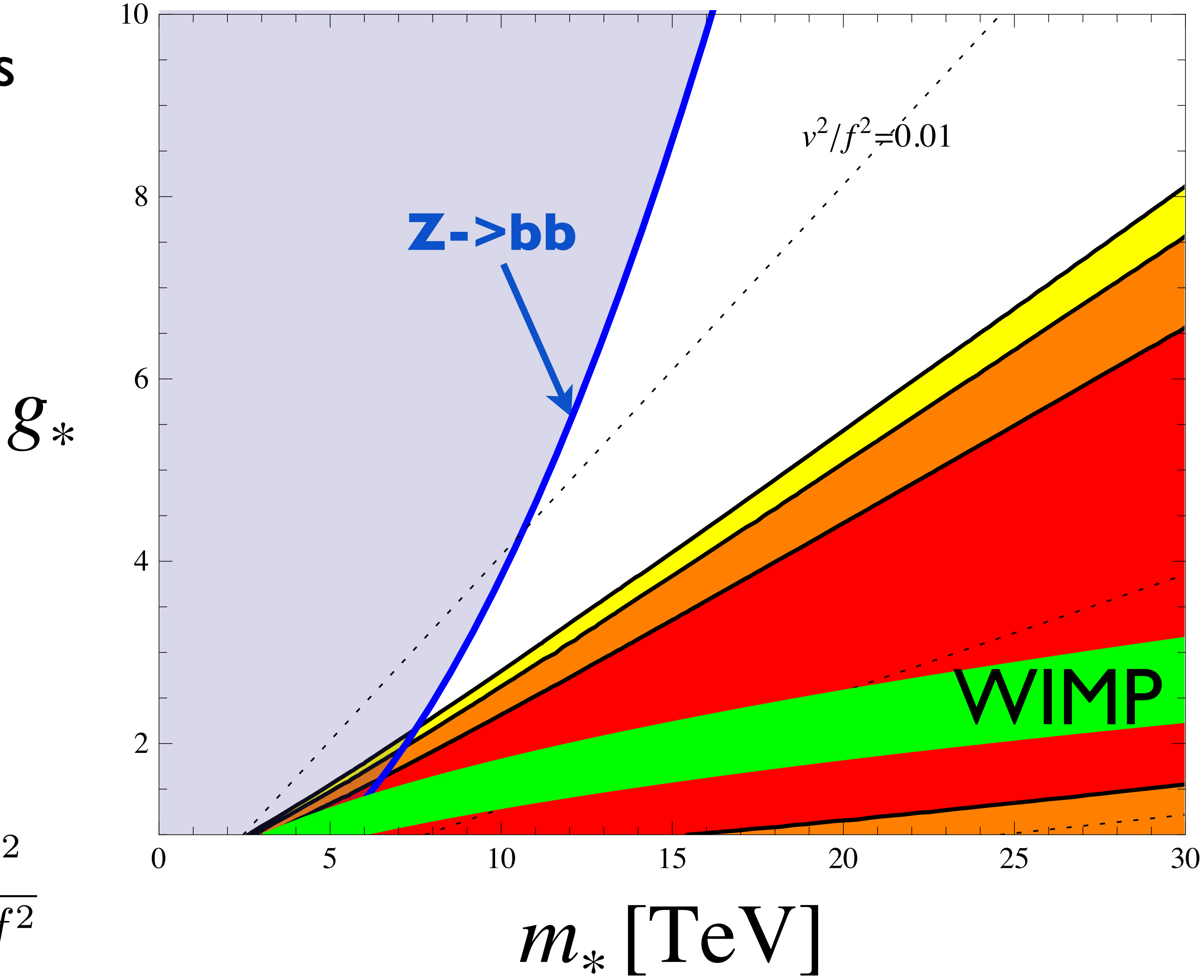
$$m_* \sim (3-5)g_*^2\ \mathrm{TeV} \Longrightarrow \frac{v^2}{f^2} \sim 5\times 10^{-3}\frac{1}{g_*^2}$$

⁕ **no custodial SU(2)** -- truly accidental
more models, ex. minimal SU(3)/SU(2)xU(1)

⁕ **no protection for Z-->bb**:
generic embedding of SM fermions

⁕ **Future linear collider?**
Higgs couplings >0.001

Abramowicz et al. (2013)



fit with $\alpha_{\rm em}\Delta T_{\rm UV} = +\frac{v^2}{4f^2}$

pp collider, resonant production

- Light dilaton? Davoudiasl et al. (2012)

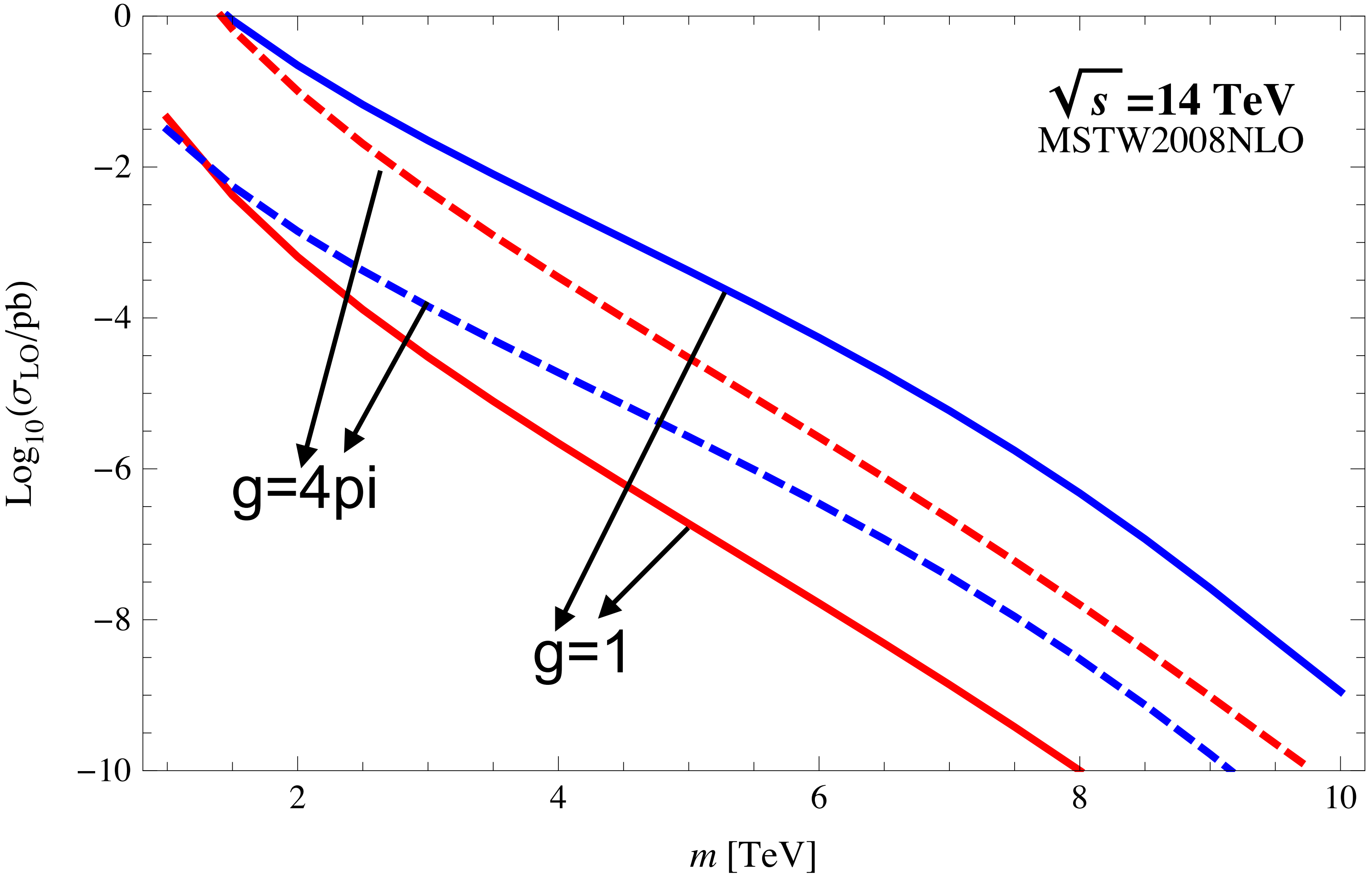
$$\frac{\alpha_s}{4\pi} G G \frac{\sigma}{f}$$

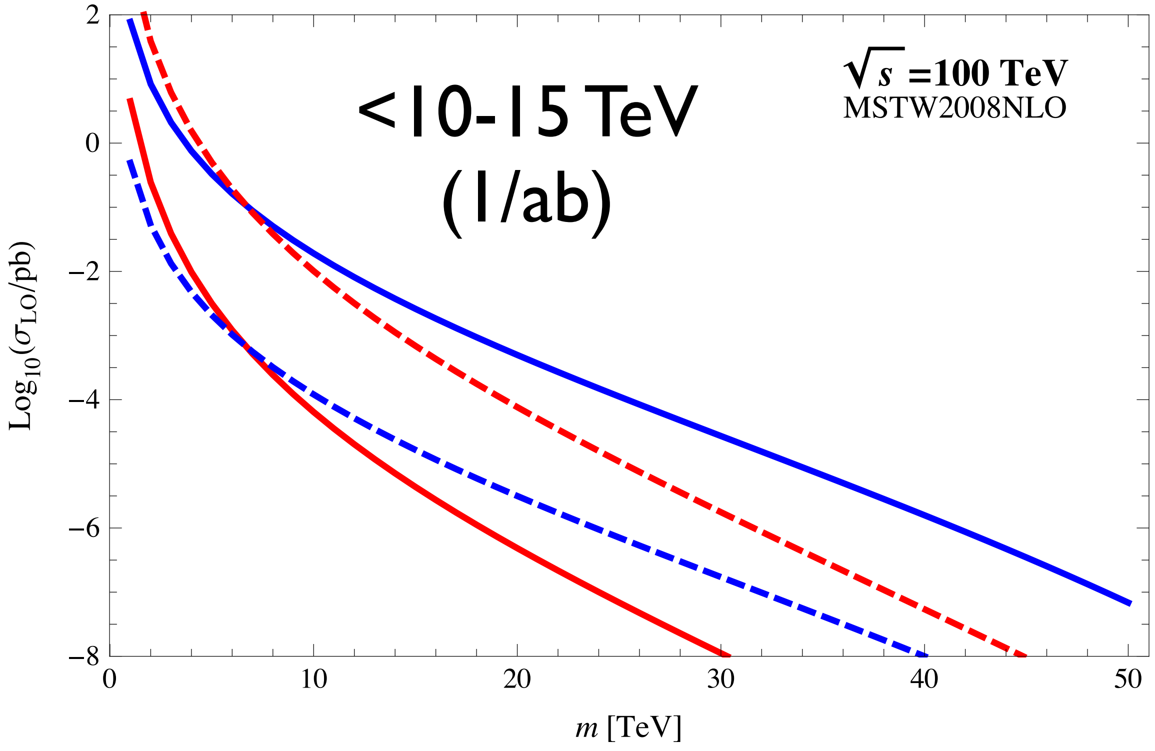
rough estimate:
m=f<5 TeV, for100 TeV and 1/ab

- Light axions? $\frac{\alpha_s}{4\pi} F \tilde{F} \frac{a}{f}$ (non-minimal models)

vector or scalar ?

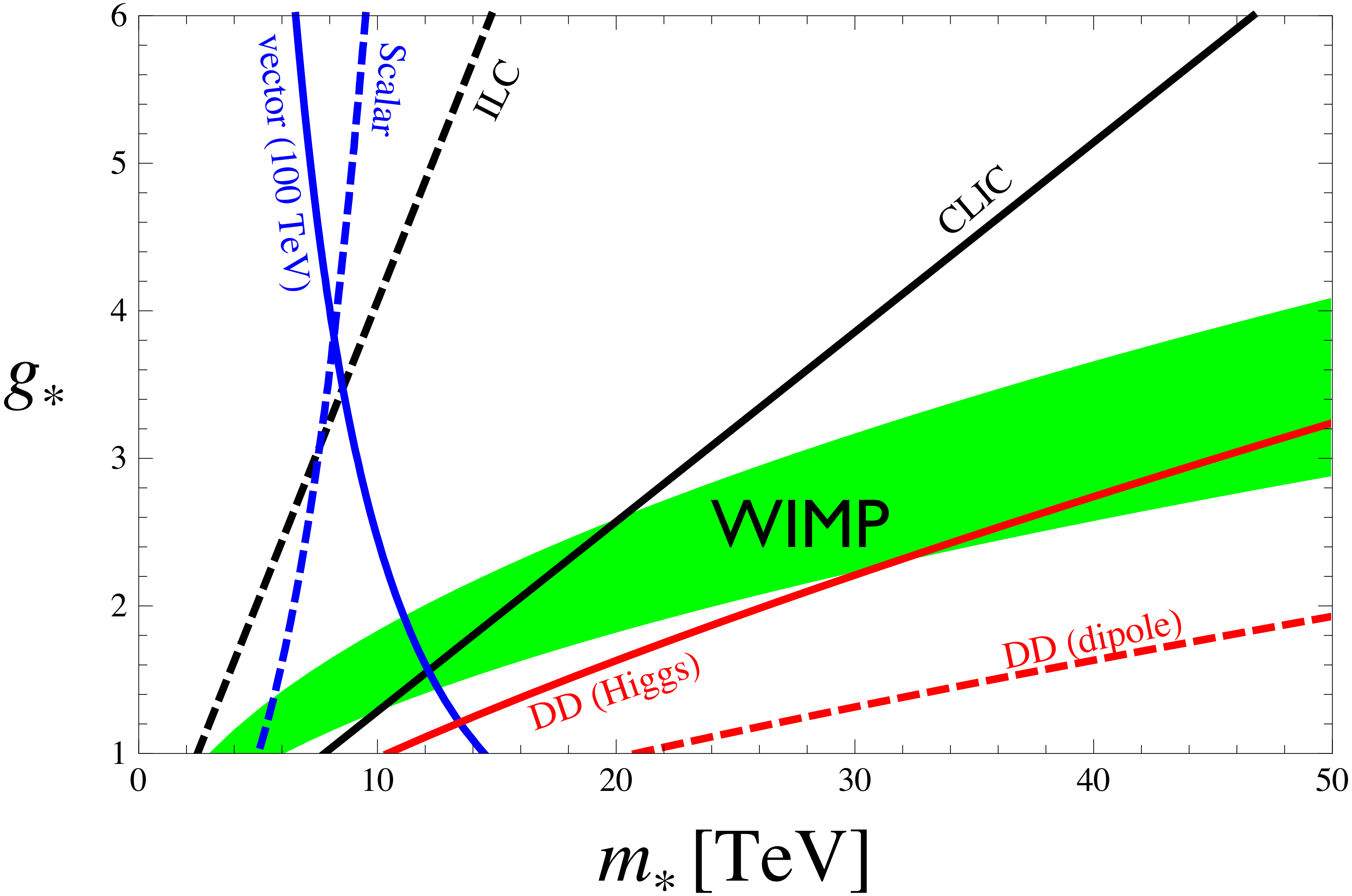
$$\frac{g^2}{g_*}\bar{q}\gamma^\mu q\rho_\mu \qquad \frac{\alpha_s}{4\pi}GG\frac{\sigma}{f}$$





vectors:

Dobrescu, Yu (2013), Pappadopulo et al. (2014), etc.


6
5
4
3
2
1
0
10
20
30
40
50
g_*
m_* [TeV]
vector (100 TeV)
Scalar
ILC
CLIC
WIMP
DD (Higgs)
DD (dipole)

Conclusion

- **Tuning can be natural:** profound connection Dark Matter ↔ Weak Scale
- **Tuning can be predictive:** Dark matter is a key signature
  Direct detection is a complementary (and very efficient) probe of un-naturalness
- **Tuning can be attractive:**
  pNGB Higgs ⇛ simple theory of Weak scale (& Higgs mass), Flavor, and DM

Back-up slides

EWPT

- S-parameter: m>3-5 TeV

$$\Delta S = 8\pi \frac{v^2}{m_\rho^2}$$

- T-parameter (model-dependent)

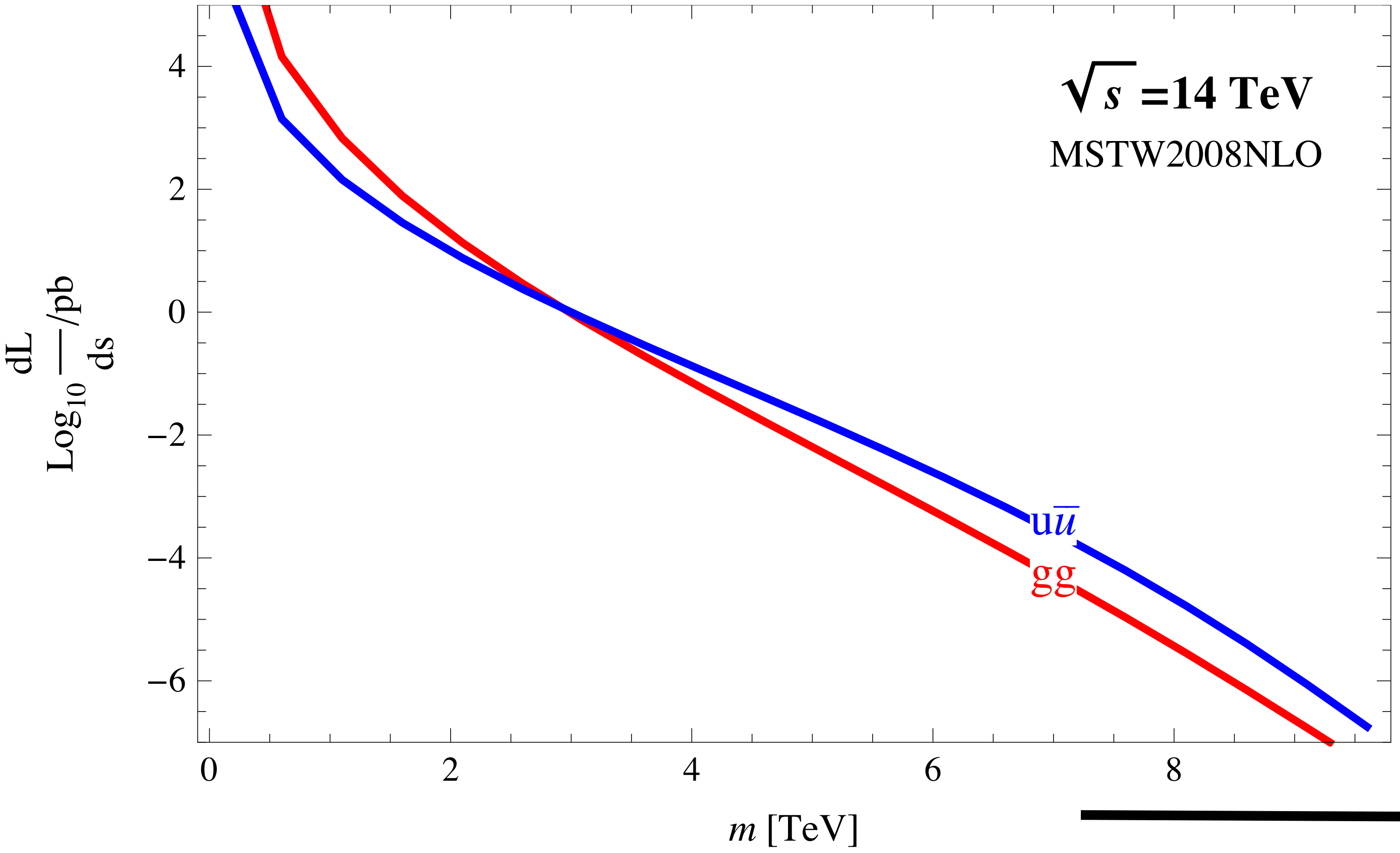
$$\Delta T = -\frac{3}{8\pi c_w^2}\frac{v^2}{f^2}\ln\frac{m_\rho}{m_h} + \Delta T_{\rm UV}$$

125 GeV Higgs & Tuning

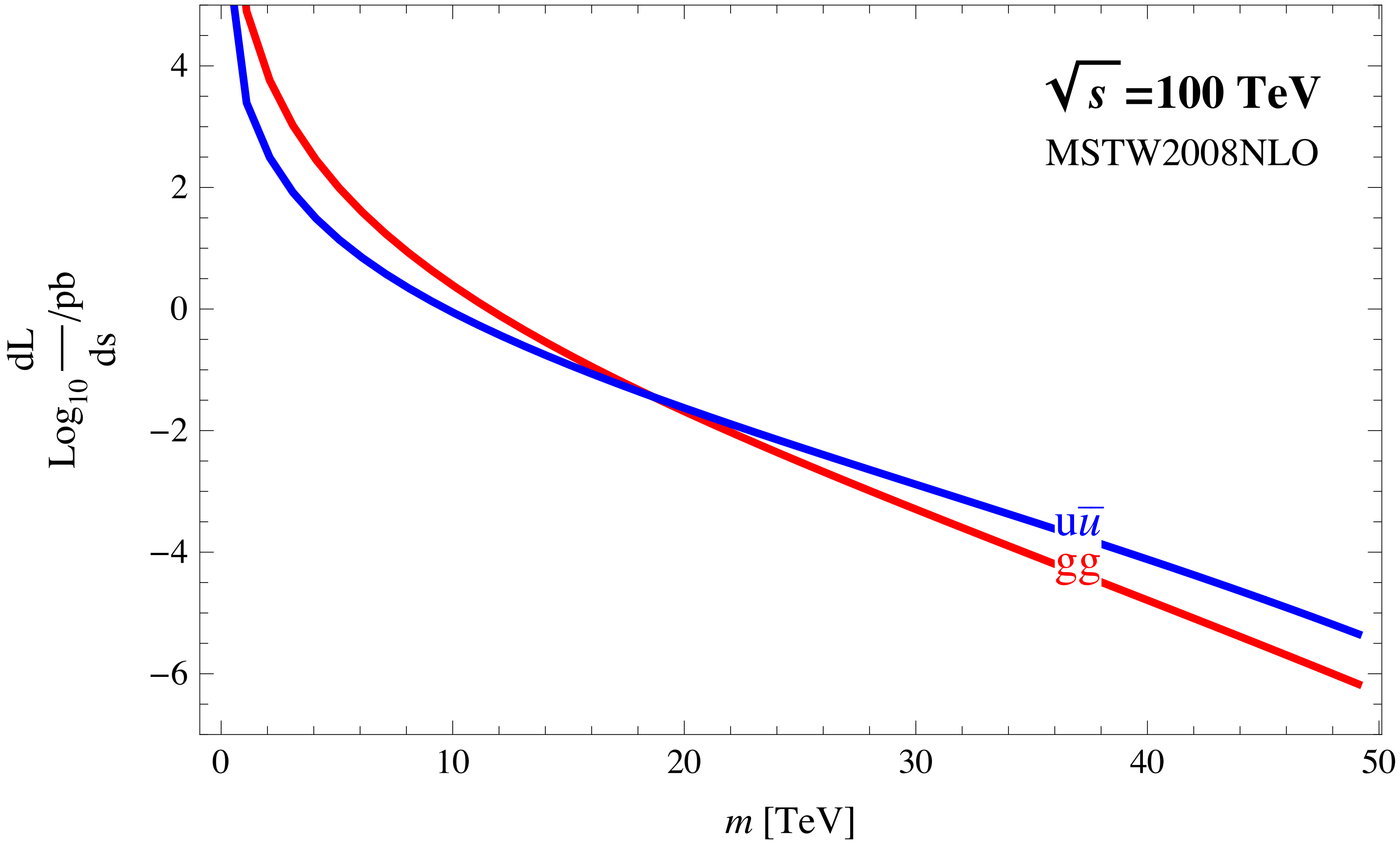
$$V = \frac{y_t^2 N_c}{16\pi^2} m_*^2 f^2 \left[a\ \sin^2 \frac{h}{f} + b\ \sin^4 \frac{h}{f} + \cdots \right]$$

plus gauge and/or
exotic contributions

$$\text{total tuning} \sim \frac{\delta m_h^2}{m_h^2}\,\frac{\delta \lambda}{\lambda} \sim \frac{\overset{\overset{\sim 1}{\uparrow}}{\delta a}}{\underset{\underset{\text{v/f}}{\downarrow}}{a}}\,\frac{\delta b}{\underset{\underset{\text{Higgs mass}}{\searrow}}{b}} \sim \frac{m_*^2}{m_t^2}\left(\delta b \frac{g_*^2}{y_t^2}\right)$$


$\sqrt{s}$ =14 TeV
MSTW2008NLO
$\mathrm{Log}_{10}\frac{dL}{ds}$/pb
4
2
0
−2
−4
−6
0
2
4
6
8
m [TeV]
$u\bar{u}$
gg

x (pdf)


$\sqrt{s}$ =100 TeV
MSTW2008NLO
$\mathrm{Log}_{10}\frac{dL}{ds}$/pb
4
2
0
−2
−4
−6
0
10
20
30
40
50
m [TeV]
$u\bar{u}$
gg

Flavor and CP violation

$$m_* \sim (3-5)g_*^2 \ \mathrm{TeV}$$

$$\Downarrow$$

- **FV in the quark sector is under control for couplings >1-2**
- **neutron EDM requires couplings >2-3 or non-generic CPV**
- **mu--->e gamma and e-EDM, three options:**

1) maximal coupling
2) non-generic FV, CPV
3) just luck at % level