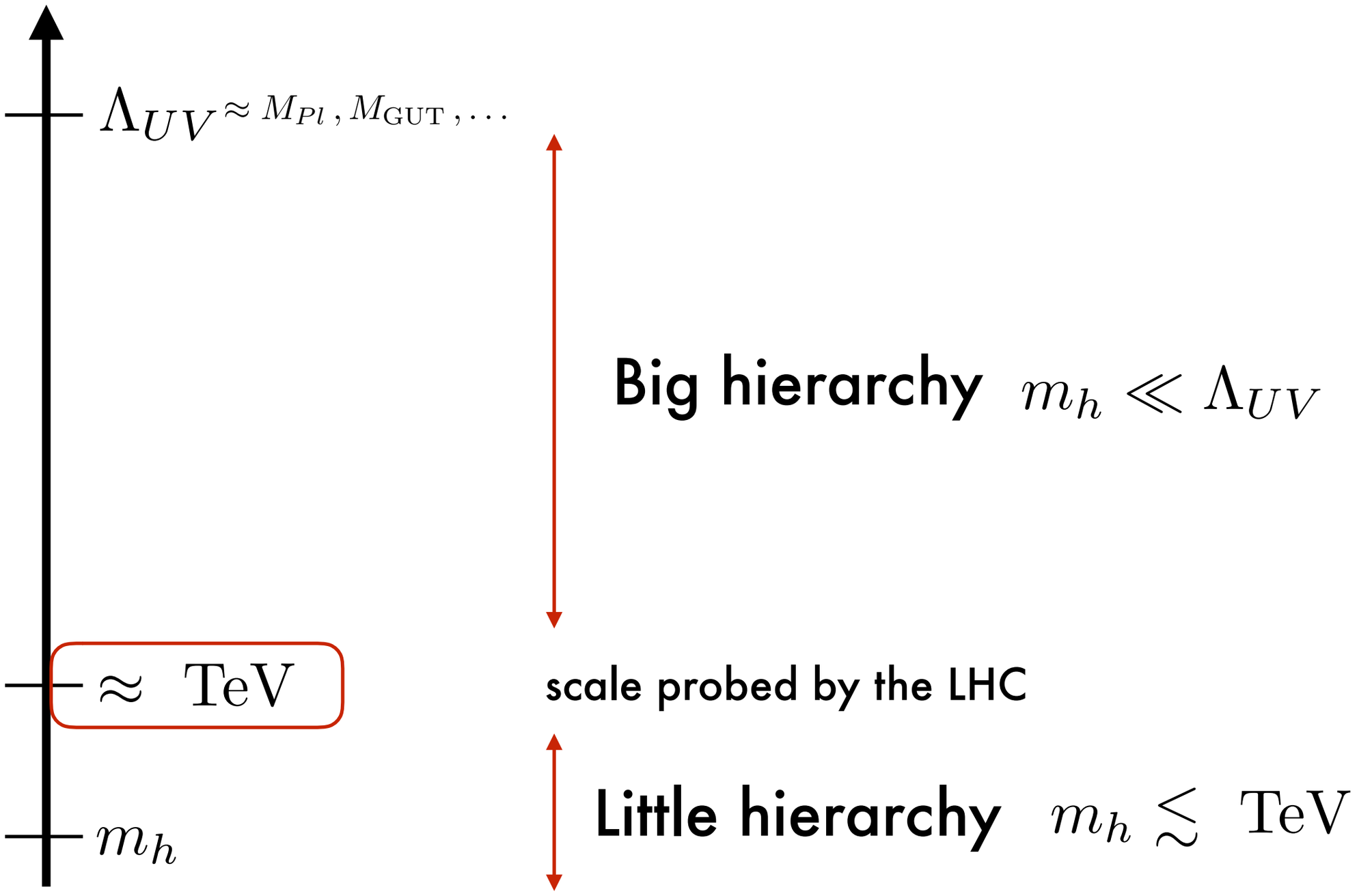
Neutral Naturalness

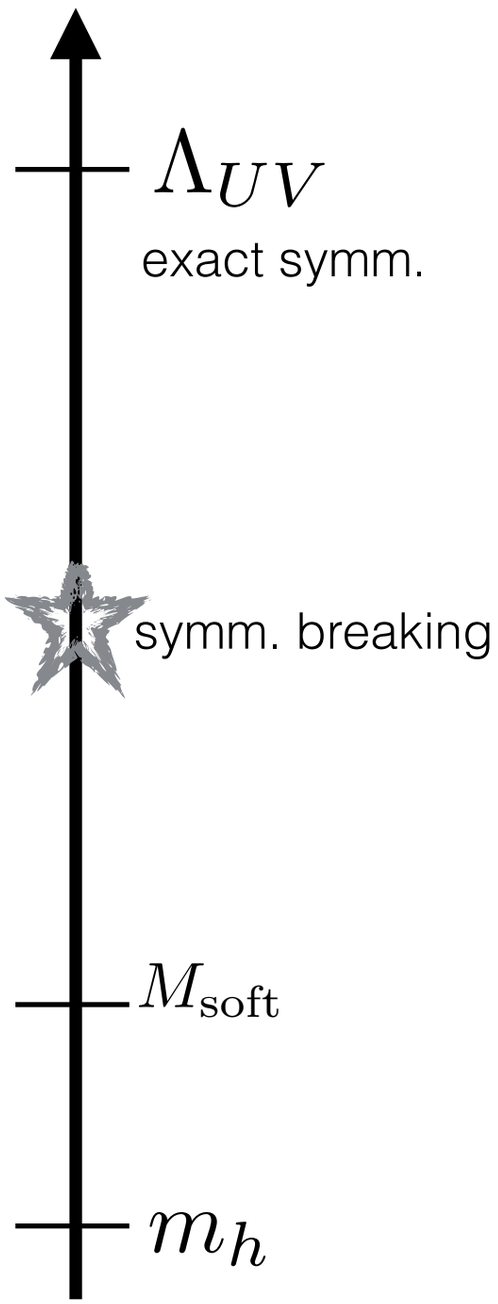
Diego Redigolo

@ VUB 12/06/2017

What do we mean by Neutral Naturalness?



Symmetries ⟷ Colored top-partners



$$m_h \ll \Lambda_{UV}$$

the Higgs potential is generated
after the *soft breaking* of an EXACT symmetry
of the Lagrangian

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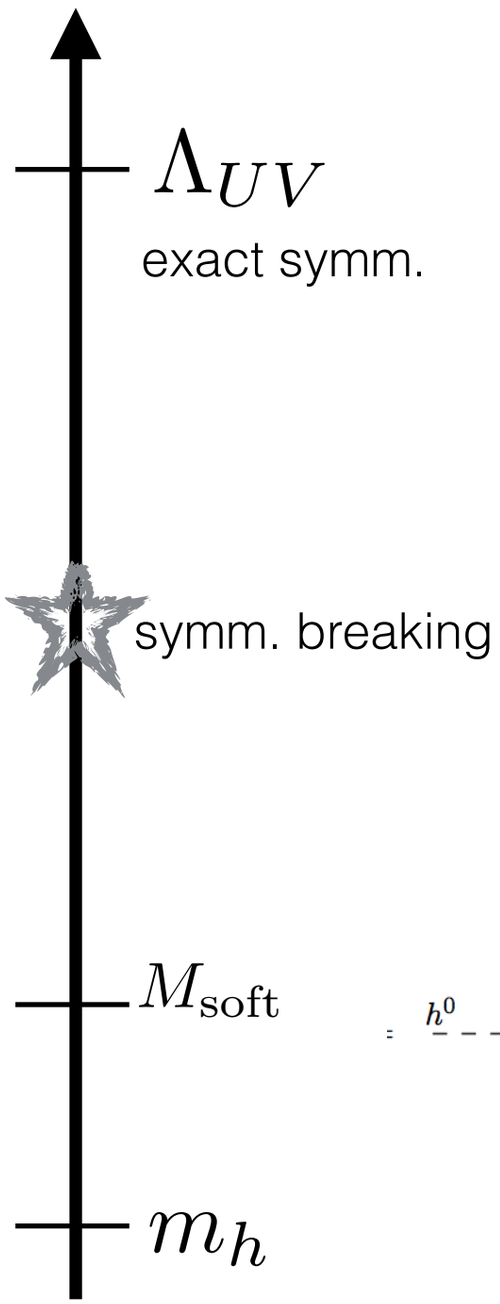

$$m_h \ll \Lambda_{UV}$$

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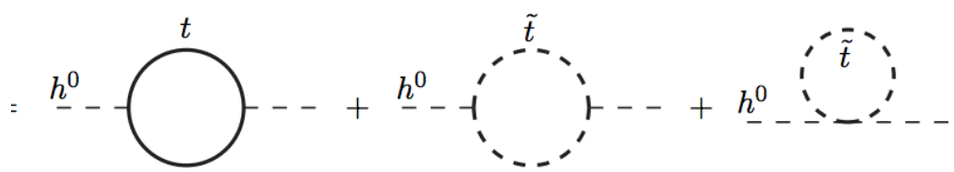
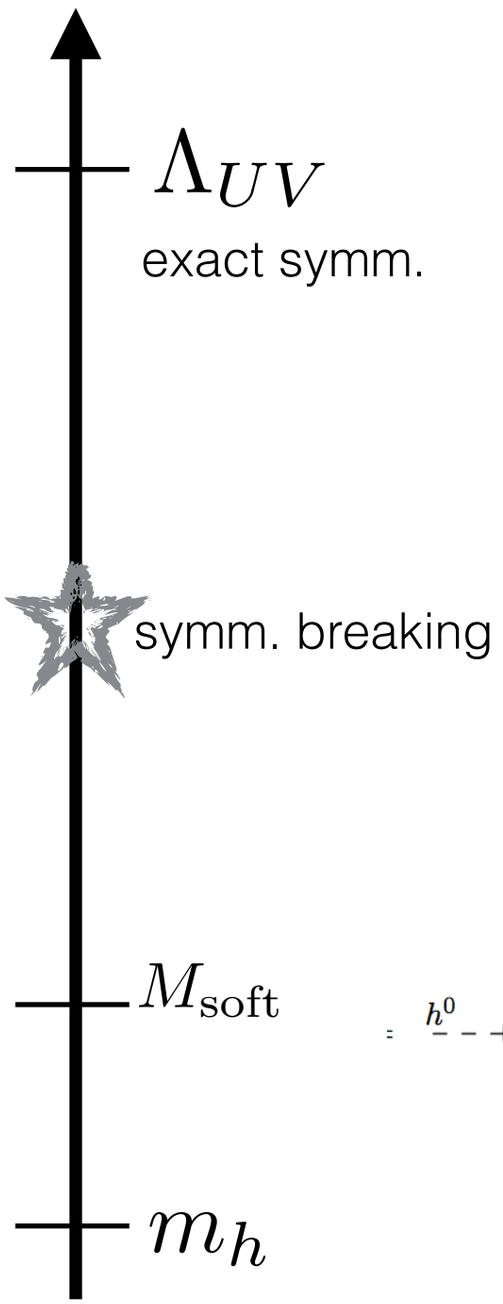
SUSY



stops enter @ 1-loop

Symmetries ⟷ Colored top-partners



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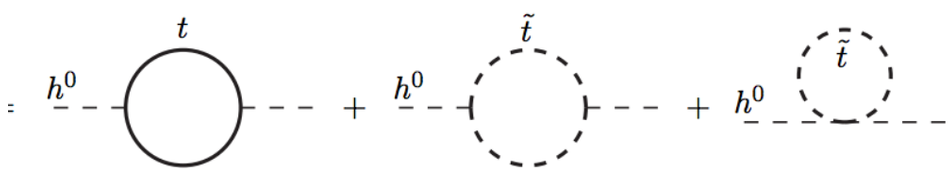
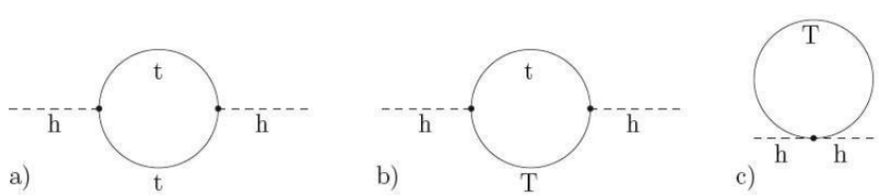


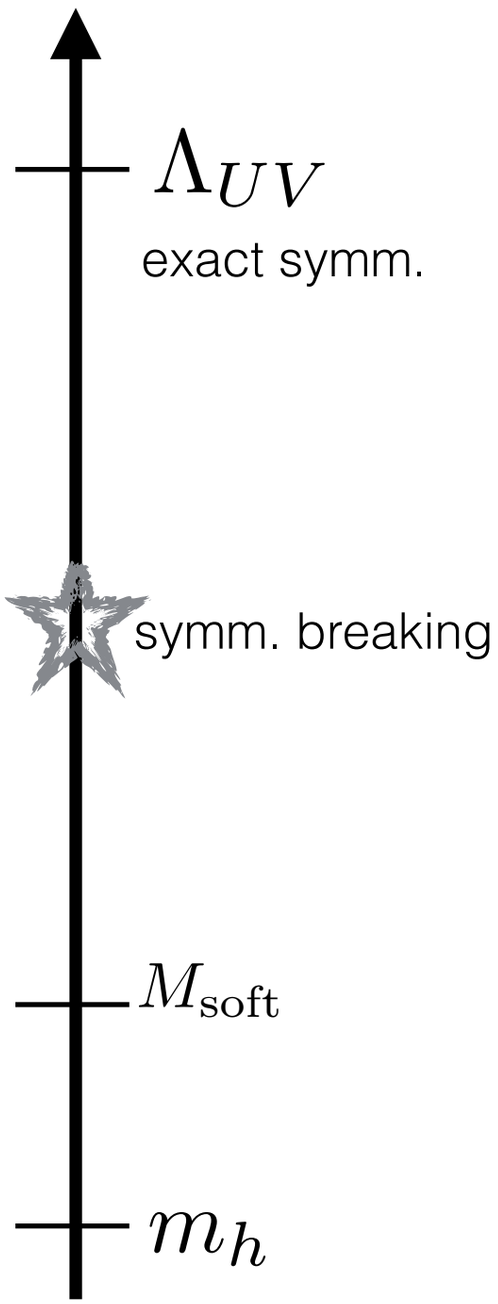
stops enter @ 1-loop

Partial Compositeness



top-partners enter @ 1-loop

Symmetries ⟷ Colored top-partners



$$m_h \ll \Lambda_{UV}$$

The Higgs UV sensitivity is cut-off by the top partners masses

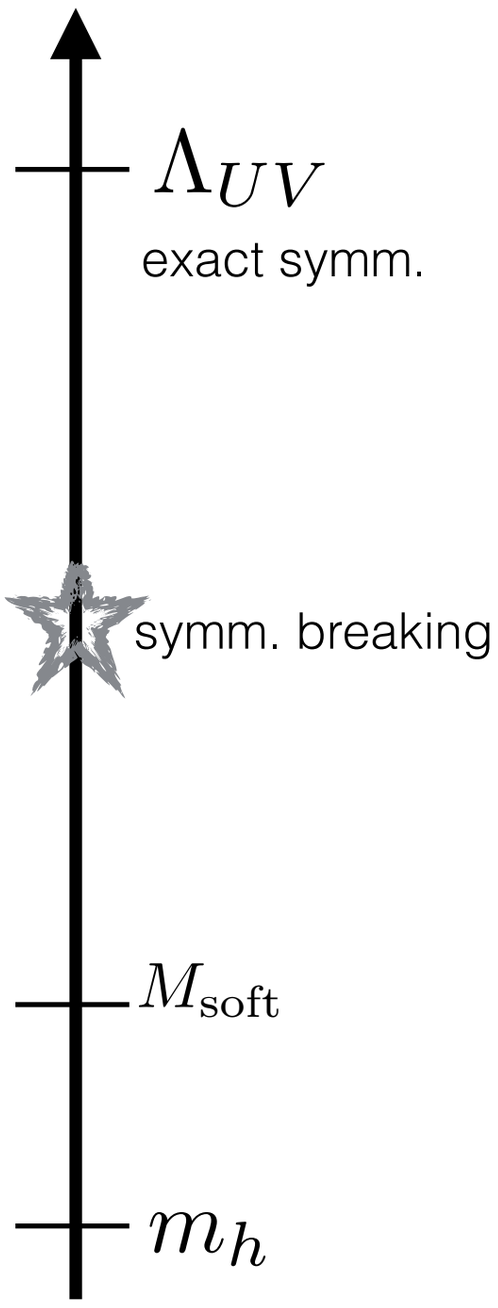
$$\delta m_h^2 = \Delta m_h^2 \approx \frac{3y_t^2}{4\pi^2} M_{\rm soft}^2 \times \log \frac{\Lambda_{UV}}{M_{\rm soft}}$$

Definition of Fine tuning

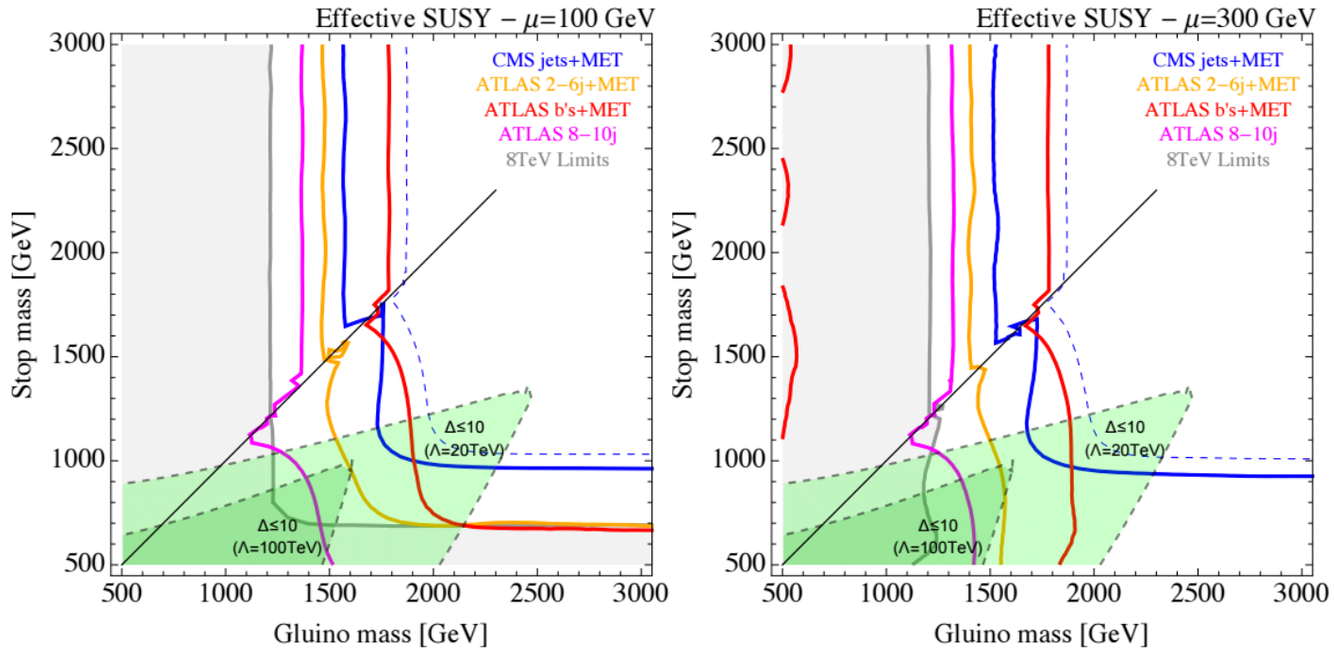
Upper bound on the top partners masses

$$M_{\rm soft}^2 \lesssim \frac{2\pi^2}{3y_t^2} \frac{\Delta\ m_h^2}{\log \frac{\Lambda_{UV}}{M_{\rm soft}}}$$

Where do we expect Color Partner to be?



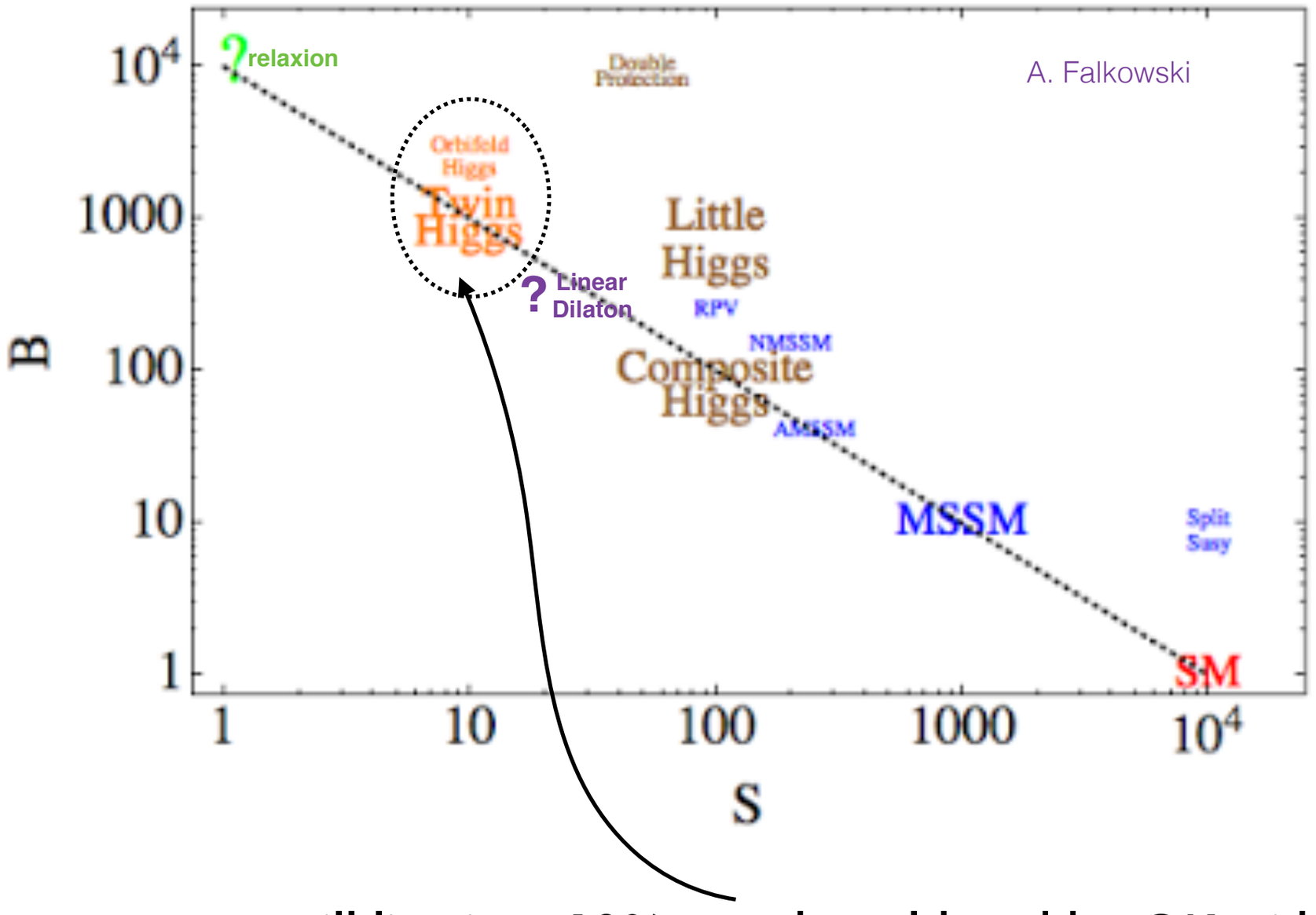
$$M^2_{\rm soft} \lesssim \frac{2\pi^2}{3y_t^2}\frac{\Delta\ m_h^2}{\log\frac{\Lambda_{UV}}{M_{\rm soft}}} \approx (500\ {\rm GeV})^2 \times \frac{\Delta}{10} \times \frac{4}{\log}$$



D. Shih et al. 1610.08059

TUNING 10% (almost) EXCLUDED BY LHC?

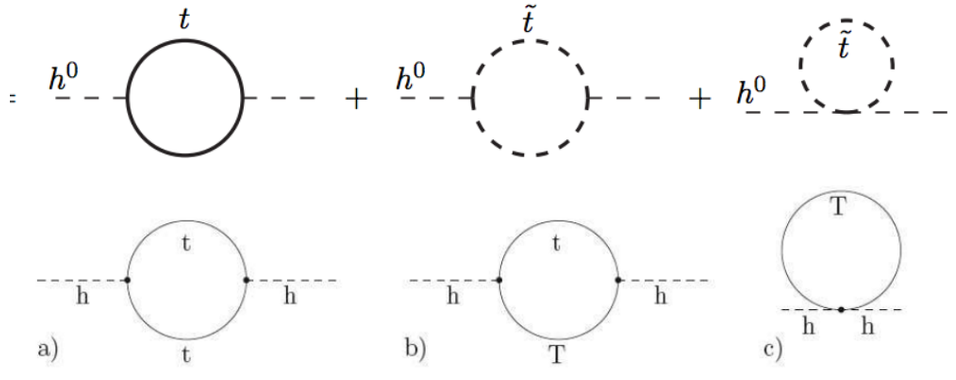
Have we written down all the Natural theories?



can we still live in a 10% tuned world and be OK with the LHC?

The rough idea...

@ 1-loop:



$\sim N_c$

Can we solve the little hierarchy problem

with N_c uncolored top-partners?

The SM Higgs is the PGB of an accidental global symmetry enforced by a discrete symmetry

which

does NOT COMMUTE with COLOR

THE TWIN HIGGS:

Z. Chacko, H.S. Goh and R. Harnik 0506256

$Z_2 : SU(3) \to SU(3)'$

FOLDED SUSY:

G. Burdman, Z. Chacko, H.S. Goh and R. Harnik 0609152

$Z_2^R : SU(3) \to SU(3)'$

. . .

more complicated discrete groups

N. Craig, S. Knapen, P. Longhi 1410.6808, 1411.7393

Accidents ⟷ Neutral Naturalness

Lets take the Twin Higgs as a benchmark scenario...

Advantages:
fully calculable 4d setup

Minimal Recipe

Double SM gauge fields, Higgs and tops

$$G_{\rm SM} \longrightarrow G^A_{\rm SM} \times G^B_{\rm SM}$$

$$H, Q_3, U_3 \longrightarrow \underbrace{H_A, Q_{3A}, U_{3A}}_{\text{visible sector}} + \underbrace{H_B, Q_{3B}, U_{3B}}_{\text{“dark” sector: neutral under SM!}}$$

Z_2 exchange symmetry: $H_A \longleftrightarrow H_B \ \ldots$

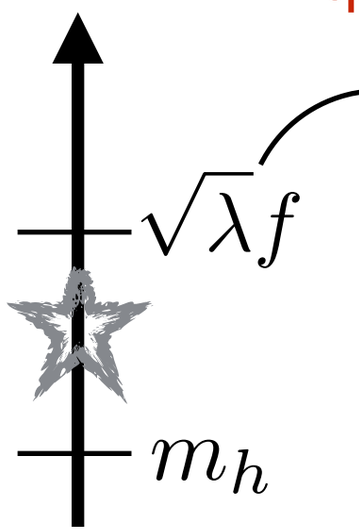
Actually a double copy of the full SM gauge group is not needed

D. Poland, J.Thaler 0808.1290

Setup I

Z_2 symm.

spontaneous breaking of the global symm.



$$\underbrace{\lambda(|H_A|^2 + |H_B|^2 - f^2)^2}_{V^{U_4}}$$

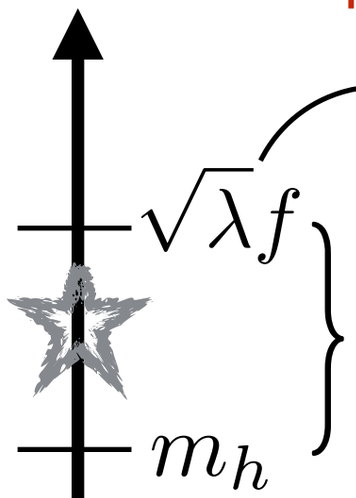
7 GB - 6 eaten = SM Higgs is a GB

+ 1 radial mode (Twin Higgs) $\sim \sqrt{\lambda} f$

Setup II

Z_2 symm.

spontaneous breaking of the global symm.



accidental global symmetry of the Higgs sector only

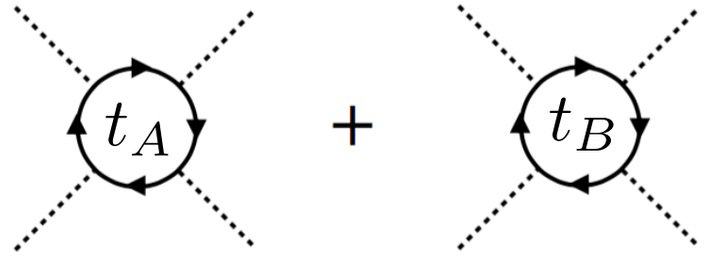
$$\underbrace{\kappa(|H_A|^4+|H_B|^4)}_{V^{\psi_4,Z_2}}$$

SM Higgs is a PGB

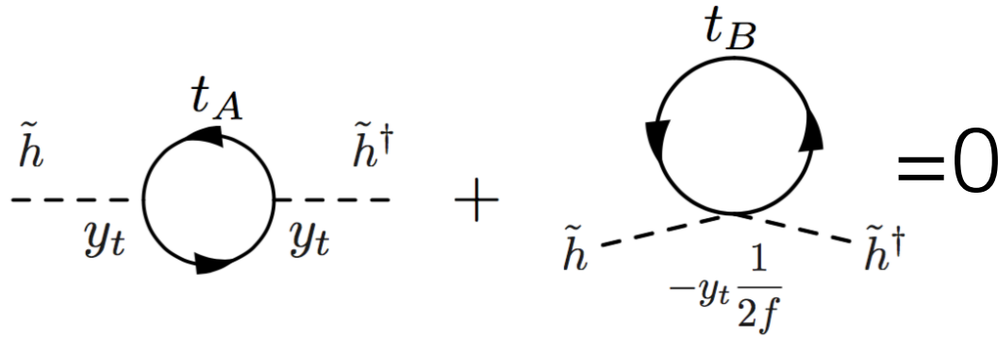
$$\kappa \sim \frac{3y_t^4}{16\pi^2} \ll \lambda$$

explicitly broken by the Yukawa sector!

$$y_t(H_A Q_A U_A + H_B Q_B U_B)$$

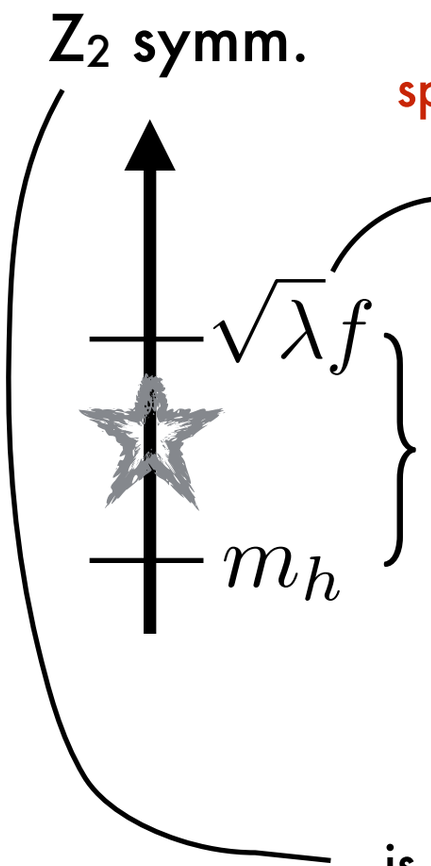


since is Z_2-preserved:



BUT NO COLORED PARTNERS!

Setup II



$$h = h_A \cos\theta + h_B \sin\theta$$

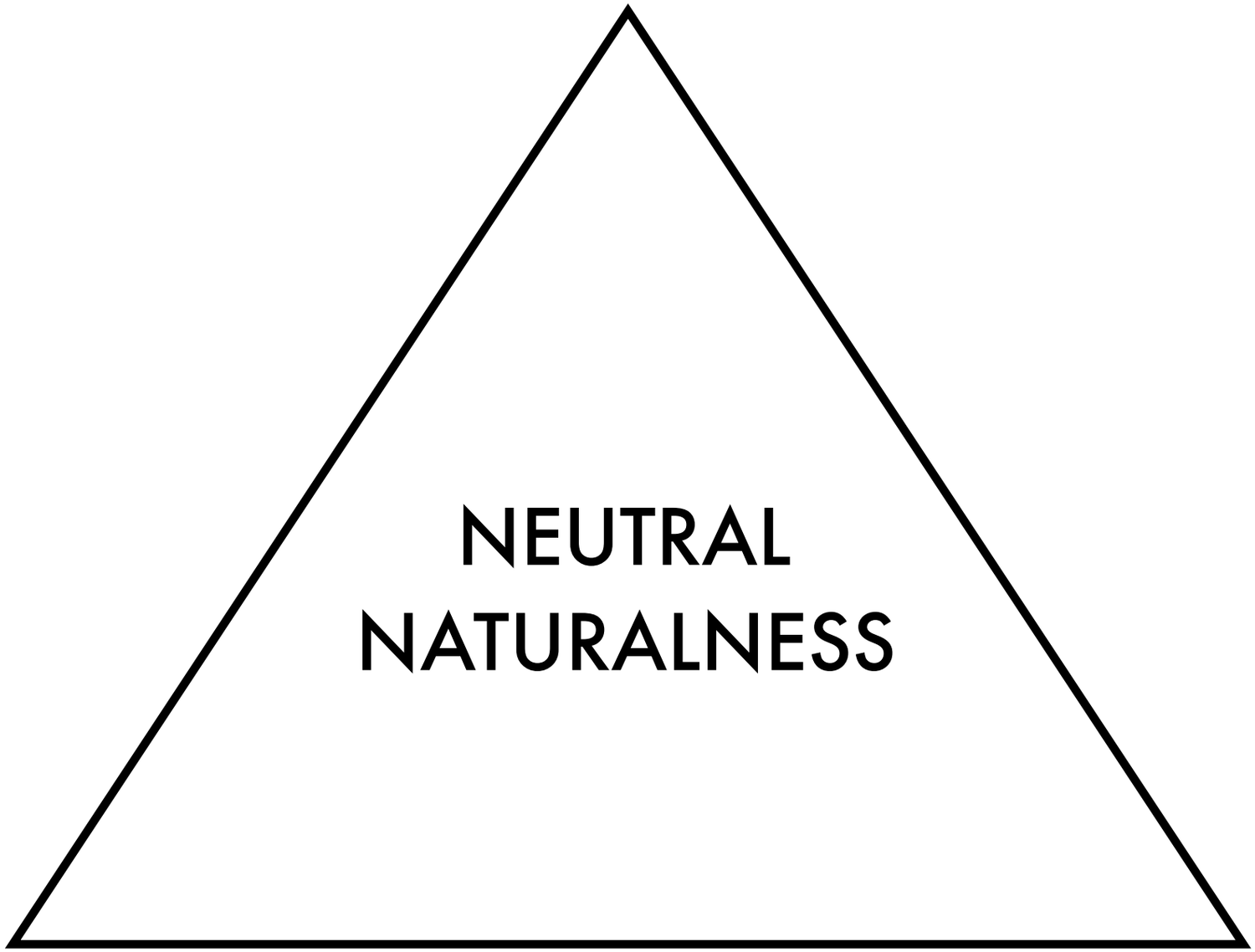
the SM Higgs cannot be 50% Dark!

$$\underbrace{\tilde{\mu}^2 |H_A|^2 + \rho |H_A|^4}_{V^{\psi_4, \not{Z}_2}} \longrightarrow$$

Z_2 breaking to get:

$$\sin\theta \approx v/f < 0.4$$

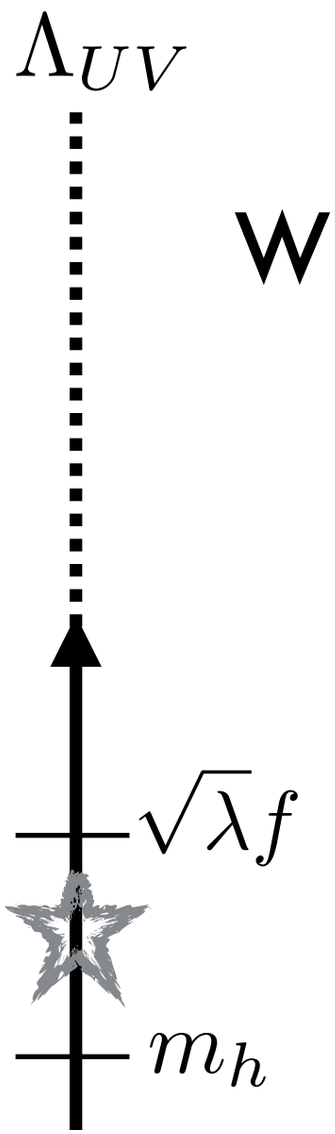
UV-completions



LHC

COSMOLOGY

We still need to solve the big hierarchy problem...



Why $\lambda f \ll \Lambda_{UV}$?

Composite Twin Higgs

P. Batra, Z.Chacko 0811.0394

M.Geller,O.Telem 1411.2974

R. Barbieri, et. al. 1501.07803

M.Low, A.Tesi, L.Wang1501.07890

R. Contino, D. Greco, R. Mahbubani, R. Rattazzi, R. Torre 1702.00797

Twin SUSY

S.Chang,L.Hall,andN.Weiner 0604076

Falkowski, S. Pokorski, M. Schmaltz 0604066

N. Craig, K. Howe 1312.1341

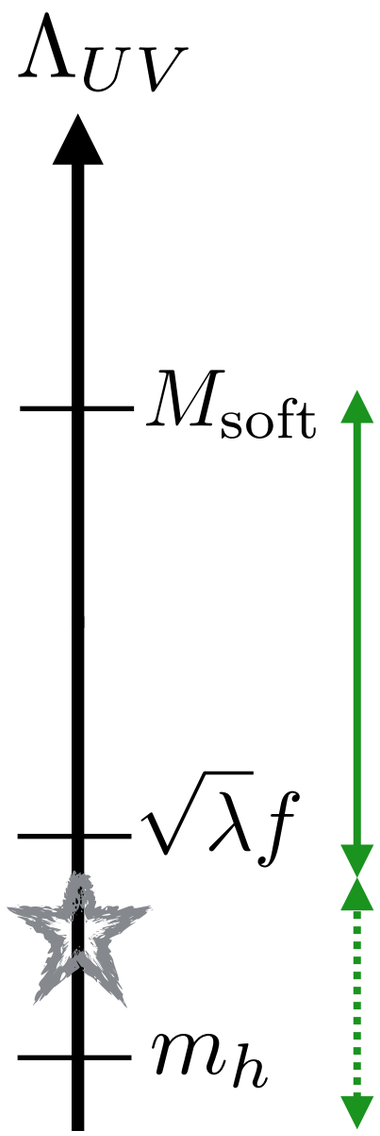
A. Katz, A. Mariotti, S. Pokorski, D.R., R. Ziegler 1611.08615

M. Badziak, K. Harigaya 1703.02122

$m_h \ll \sqrt{\lambda} f$ ✓

$$\frac{\delta f^2}{f^2} = \frac{3 y_t^2}{4\pi^2 \lambda} \frac{M_{\rm soft}^2}{f^2} \times \log \frac{\Lambda_{UV}}{M_{\rm soft}}$$ ✓✓

Within a UV completed scheme we can predict the scale of colored states needed to stabilize the accidental symmetry



$$\Delta \approx M^2_{\rm soft}/f^2 \times f^2/v^2$$

The final answer depends on how Z_2 is broken

SOFT-breaking: $\times \dfrac{f^2}{2v^2}$ $\longrightarrow$ $M^2_{\rm soft} \lesssim \dfrac{4\pi^2}{3y_t^2} \times \dfrac{\Delta m_h^2}{\log} \times \dfrac{\lambda}{\lambda_{SM}}$

$$M^2_{\rm soft} \lesssim (3\ {\rm TeV})^2 \times \frac{\Delta}{10} \times \frac{\lambda}{1} \times \frac{2}{\log}$$

$$M^2_{\rm soft} \lesssim (3\ {\rm TeV})^2 \times \frac{\Delta}{10} \times \frac{\lambda}{1} \times \frac{2}{\log}$$

it controls how "good" is the accidental symmetry

The colored states can be out of reach at the LHC with a good enough accidental symmetry

Questions for theorist

- big λ points towards a strongly coupled UV completions

  how big can we take λ ?

  R. Contino, D. Greco, R. Mahbubani, R. Rattazzi, R. Torre 1702.00797

- Is this the best we can do?

  A. Katz, A. Mariotti, S. Pokorski, D.R.

  R. Ziegler 1611.08615

how big can we take λ ?

R. Contino, D. Greco, R. Mahbubani, R. Rattazzi, R. Torre 1702.00797

$$SO(N)/SO(N-1): \quad \mu\frac{d\lambda}{d\mu} = \frac{N+8}{32\pi^2}\lambda^2$$

$N \gtrsim 8$ to get the Twin Higgs

Twin has an accidental Custodial: $SO(4)_A \times SO(4)_B$

enhanced to $SO(8)$ for $\kappa \to 0$

$$\lambda \lesssim \sqrt{2}\pi^2 \approx 14$$

One can get a similar bound looking at 2-2 scattering of composite states in an explicit CH constructions

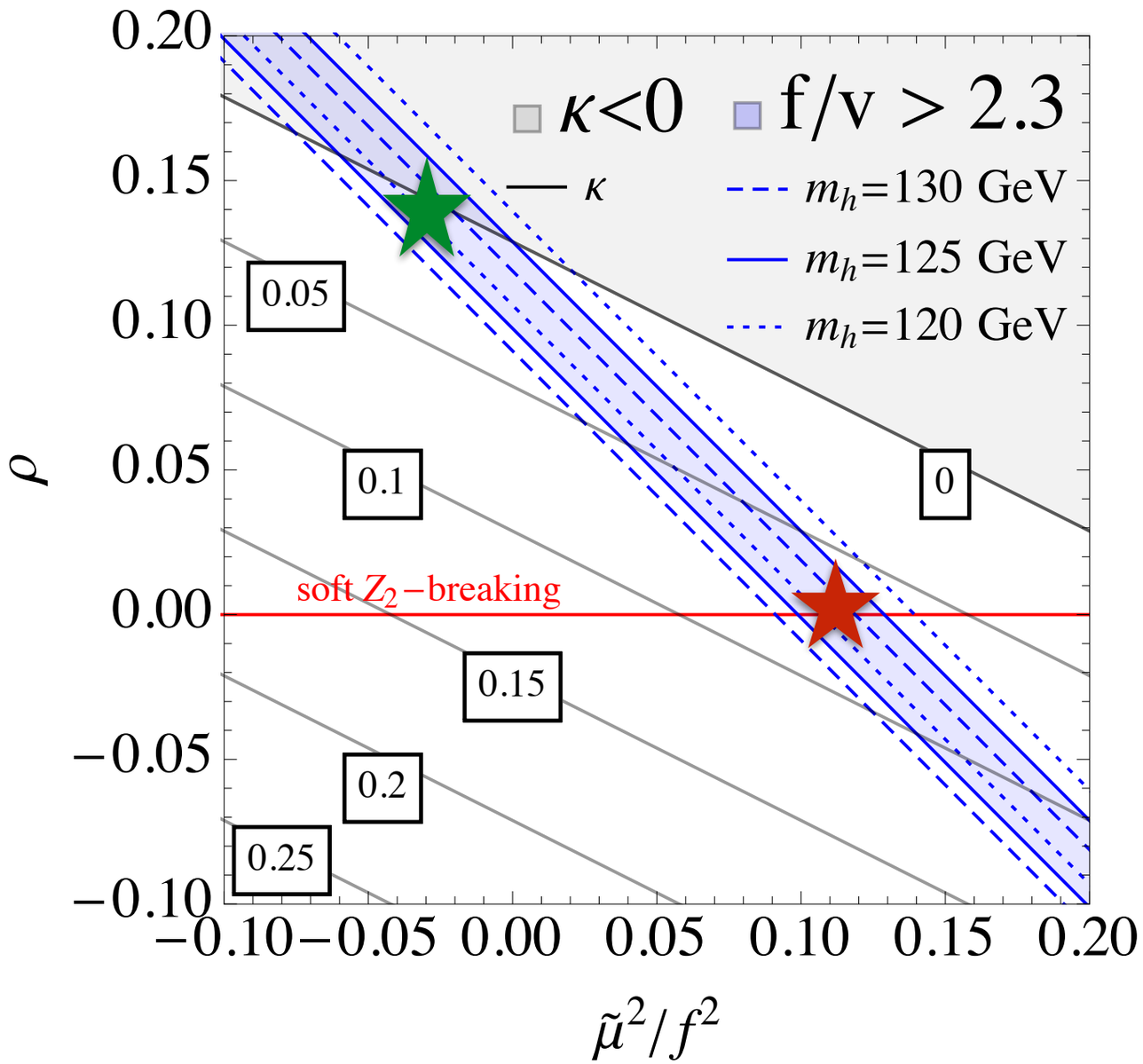
⟶ COLORED STATES up to ~ 10 TeV

Is this the best we can do?

$$\Delta \approx \boxed{M_{\rm soft}^2/f^2} \times \boxed{f^2/v^2}$$

The final answer depends on how Z_2 is broken!

$$\frac{2v^2}{f^2} = \frac{2\kappa - \tilde{\mu}^2/f^2}{2\kappa + \rho}$$



★ SOFT-breaking:

$\tilde{\mu}^2 \approx 2\kappa f^2$ to get $f/v > 2.3$

★ HARD-breaking:

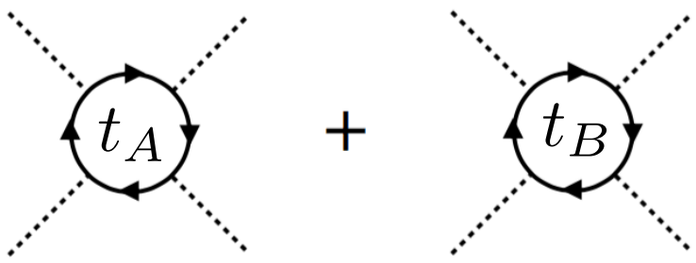
we want $\kappa \ll \rho$

★ "boost" of hard-breaking LIMITED BY

1 Higgs mass constraint $m_h^2 = 4v^2\,(2\kappa + \rho)$

$$M^2_{\rm soft} \lesssim \frac{4\pi^2}{3y_t^2}\,\frac{\Delta m_h^2}{\log}\,\frac{\lambda}{\lambda_{SM}} \times \frac{m_h^2}{8\kappa v^2}$$

2 IR contributions to κ from top-loops



R. Contino, D. Greco, R. Mahbubani, R. Rattazzi, R. Torre 1702.00797

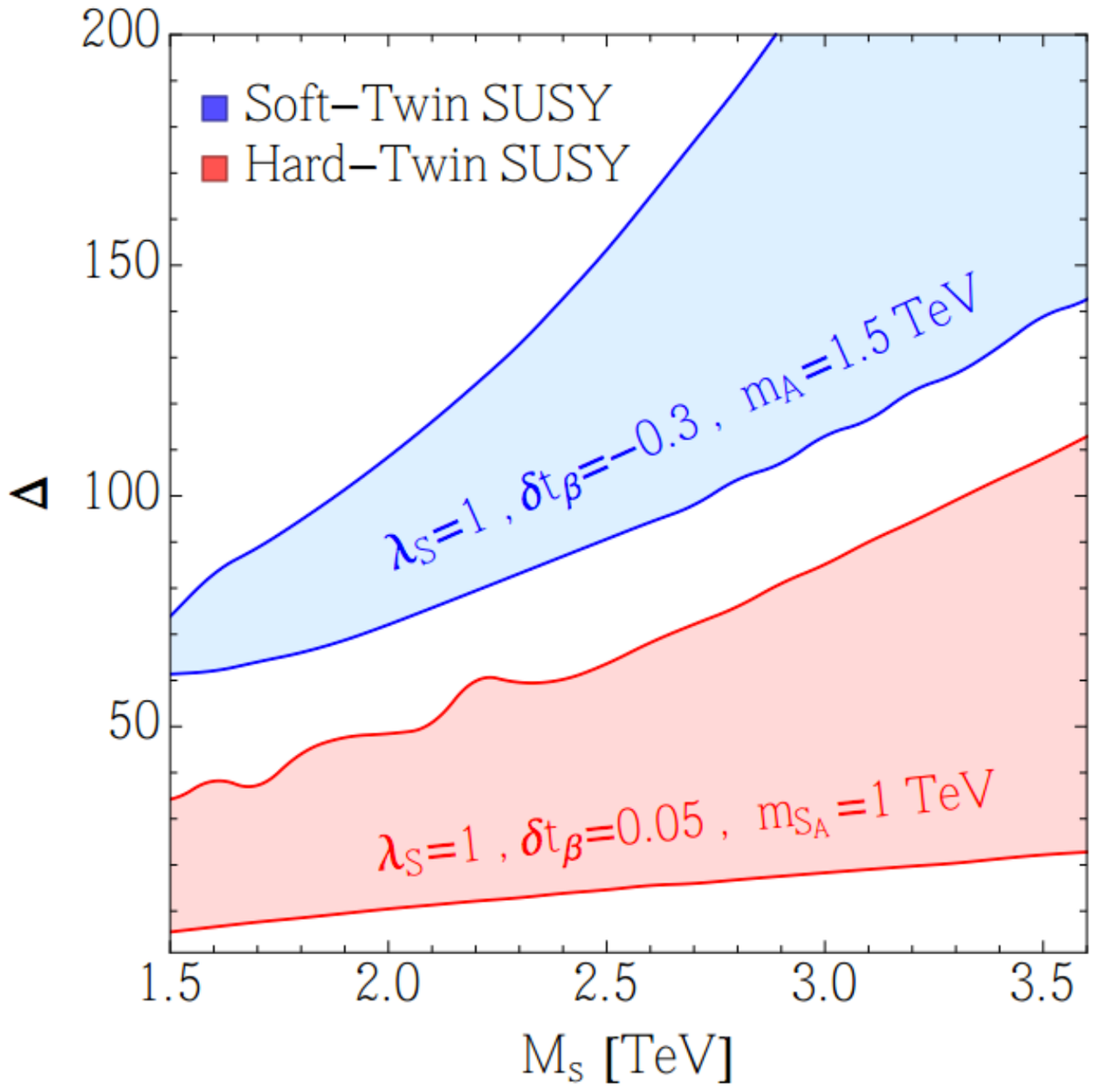
D. Greco, K. Mimouni 1609.05922

$$\frac{m_h^2}{8\kappa v^2} \sim 3$$

HOWEVER in concrete perturbative models
the Higgs mass can be smaller than in C.H. (tree level mixing etc..)

HARD Z_2 -breaking in Twin SUSY

A. Katz, A. Mariotti, S. Pokorski, D.R. R. Ziegler 1611.08615



$\Delta \sim 10\%$ in a perturbative model up to 100 TeV

THEORY take home message

The Twin Higgs is an existence proof
of a class of theories with

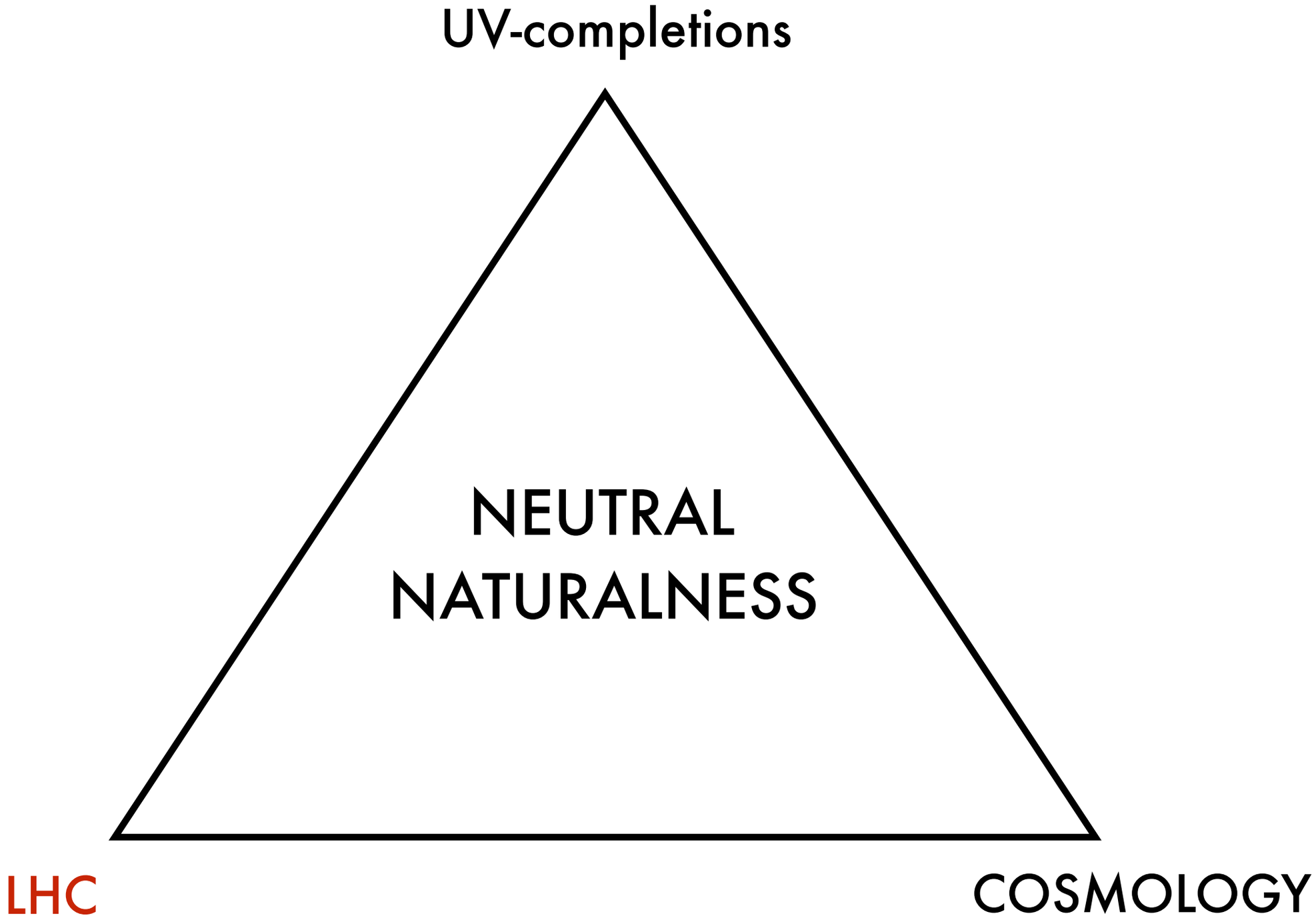
$$\Delta \sim 10\%$$

& no colored states within the LHC-reach

Composite Twin Higgs	Softly-broken Z_2 works better	$M^2_{\rm soft} \lesssim \frac{4\pi^2}{3y_t^2} \times \frac{\Delta m_h^2}{\log} \times \frac{\lambda}{\lambda_{SM}}$
Twin SUSY	Hardly-broken Z_2 works better	$M^2_{\rm soft} \lesssim \frac{4\pi^2}{3y_t^2} \frac{\Delta m_h^2}{\log} \frac{\lambda}{\lambda_{SM}} \times \frac{m_h^2}{8\kappa v^2}$

QUESTION: How seriously we should take this Mirror Symmetry?

R. Barbieri, L. Hall, K. Harigaya 1609.05589


UV-completions
NEUTRAL
NATURALNESS
LHC
COSMOLOGY

Is there something left to see for Neutral Naturalness @ LHC?

BASIC BUILDING BLOCKS have sharp pheno predictions

$$\underbrace{\lambda(|H_A|^2+|H_B|^2-f^2)^2}_{V^{U_4}}$$ radial mode (Twin Higgs) $$m_H \sim \sqrt{\lambda} f$$

$$\underbrace{\tilde{\mu}^2|H_A|^2+\rho|H_A|^4}_{V^{\not\Psi_4,\not\mathbb{Z}_2}}$$ mixing $$h = h_A\cos\theta + h_B \sin\theta$$ $$\sin\theta \sim v/f$$

Which one is the more promising depends on the UV completion solving the BIG hierarchy problem...

Indirect searches through Higgs couplings

the SM Higgs mixes with a singlet: $\mu_h \sim \mu_h^{\rm SM} \cos\theta$ $\qquad \dfrac{g_{hhh}}{g_{hhh}^{\rm SM}} \sim \cos\theta$

the BR are left unchanged because they are rescaled by the same amount!

1σ reach in	$\sin\theta^2$	$\left\lvert 1 - \frac{g_{hhh}}{g_{hhh}^{\rm SM}} \right\rvert$
LHC8	0.2	–
LHC14	0.08-0.12	–
HL-LHC	4-8×10^{-2}	0.5
HE-LHC	–	0.2
FCC-hh	–	0.08
ILC	2×10^{-2}	0.21-0.83
ILC-up	4×10^{-3}	0.13-0.46
CLIC	2-3×10^{-3}	0.1-0.21
CEPC	2×10^{-3}	–
FCC-ee	1×10^{-3}	–

HL-LHC can go up to $f/v \sim 4-5$

future ee-colliders $f/v \gtrsim 10$

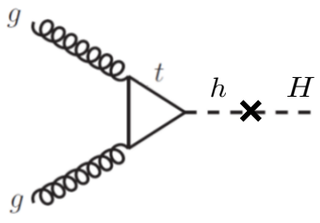
Buttazzo, Sala, Tesi 1505.05488

Direct searches of the Twin Higgs

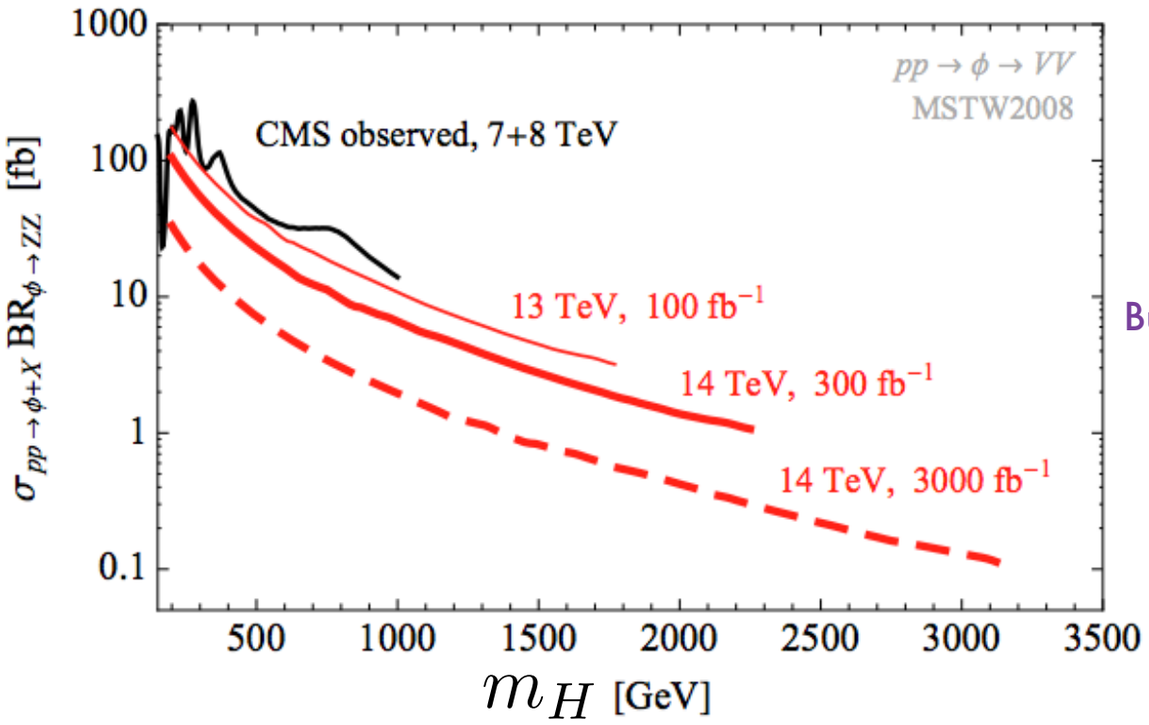
These are promising in Twin SUSY *only* $m_H \sim \sqrt{\lambda} f$

$\lambda \lesssim 1$ ⟶ radial mode within LHC reach

The radial mode is produced in gluon fusion through mixing



The radial mode goes 1/7th (or 1/4th) into ZZ *(Golstone th.)*



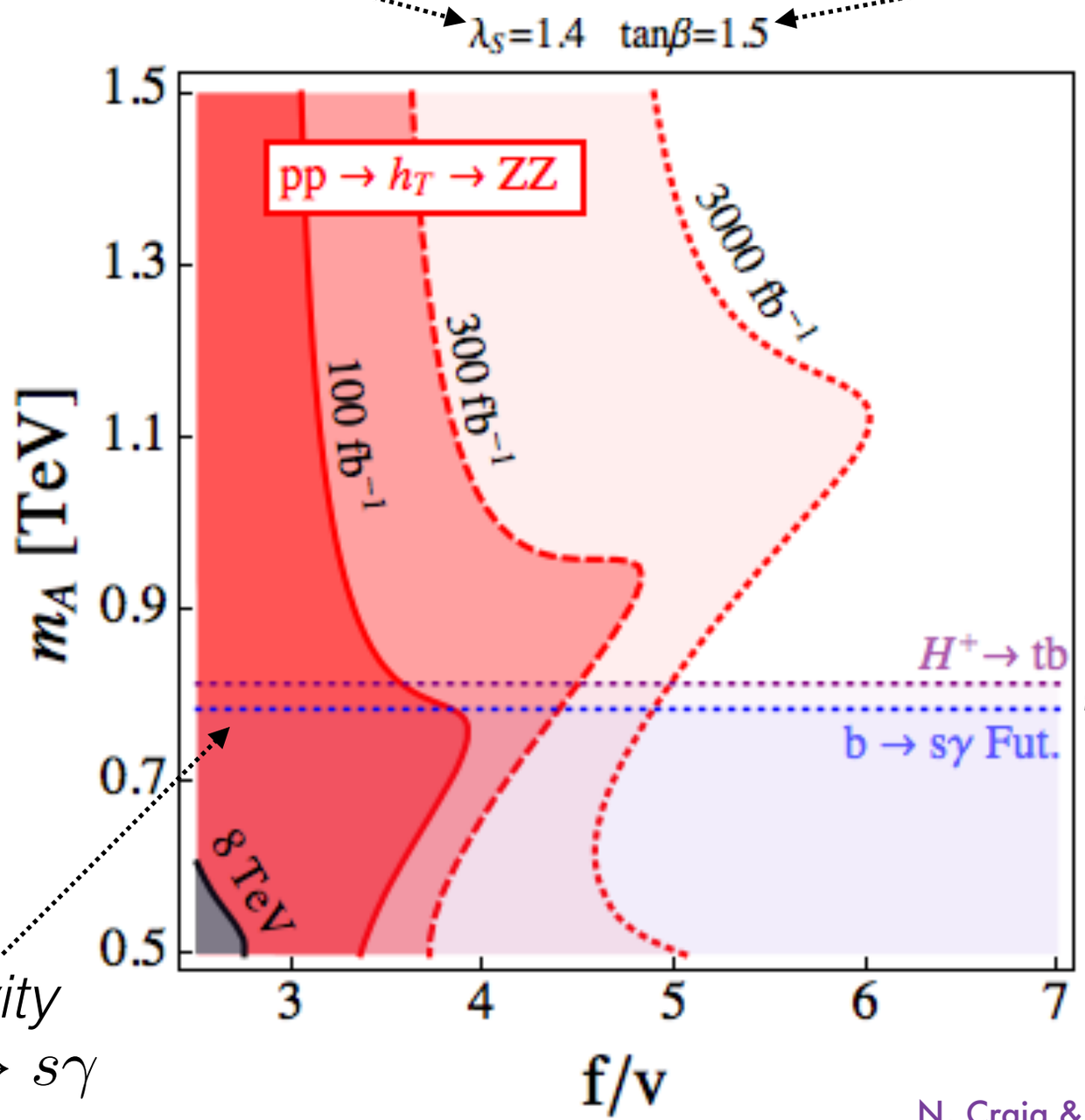
Buttazzo, Sala, Tesi 1505.05488

Recast in the Twin SUSY parameter space

A. Katz, A. Mariotti, S. Pokorski, D.R. R. Ziegler 1611.08615

large for best FT

Small to keep colored states out of reach



future sensitivity of $b \to s\gamma$

probing MSSM-like Higgses @ small t_β

N. Craig & many others 1504.04630, 1605.08744

Is the Dark Sector completely unaccessible?

To answer this question we should specify the full Dark Sector spectrum

What is the LTP?
(lightest Twin particle)

Twin neutrino/Twin lepton ⟶ Invisible decay of the SM Higgs

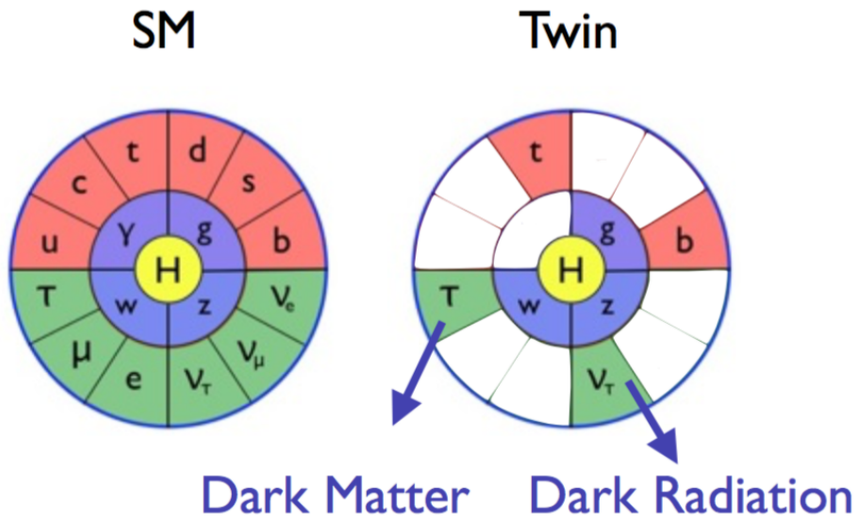
Twin hadron ⟶ Exotic decays of the SM Higgs

The Dark Sector hadronizes & comes back to US

N. Craig, A. Katz, M. Strassler, R. Sundrum 1501.05310

Example: Fraternal Twin Higgs:

Twin confinement $\hat{\Lambda}_3 \approx 1 - 10 \text{ GeV}$

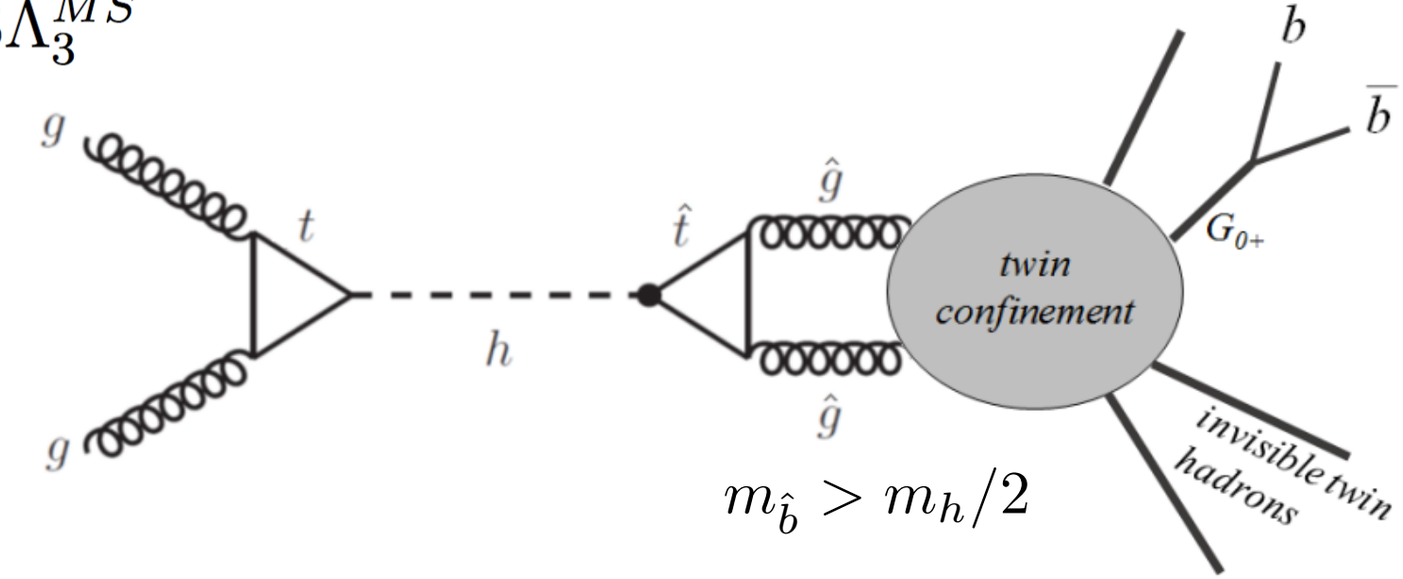


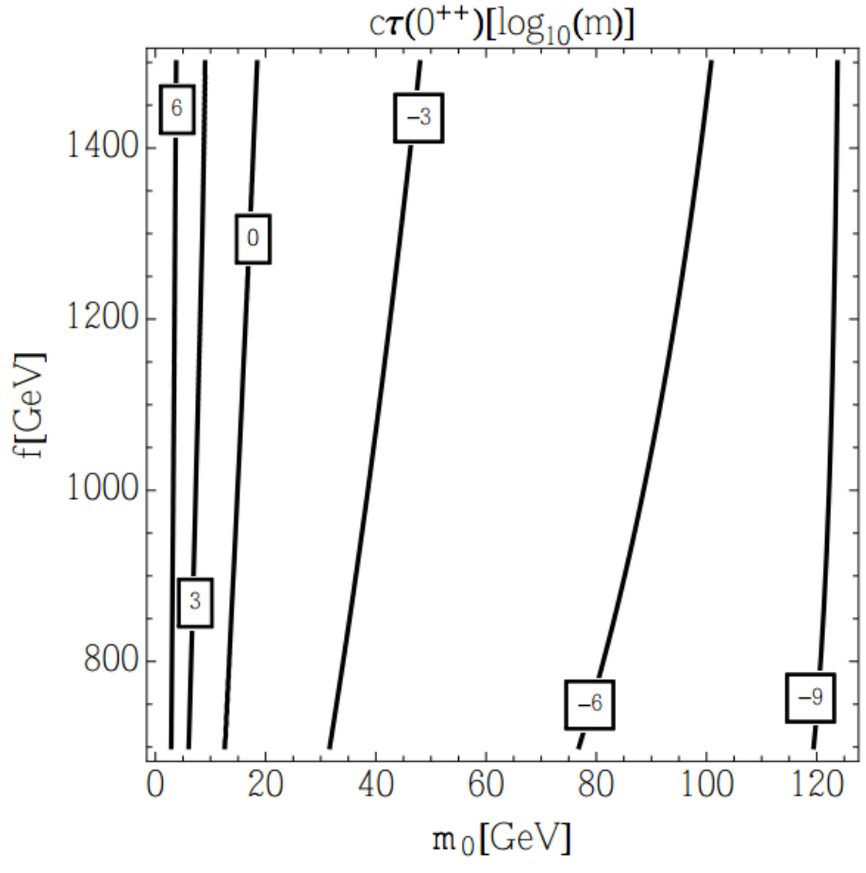
If glueball 0^{++} is the LTP:

$$\mathcal{L} \supset -\frac{\hat{\alpha}_3}{6\pi}\frac{v}{f}\frac{h}{f}\hat{G}^a_{\mu\nu}\hat{G}^{\mu\nu}_a$$

pure glue QCD lattice hep-lat/9901004, hep-lat/0510074

$$m_0 = 6.8\hat{\Lambda}_3^{\overline{MS}}$$





Glueball decay typically displaced…

$$\cdot\ \mathrm{Br}(h \to \text{twin hadrons}) > 10^{-4}$$

100-1000 displaced events from $\sim 10^7$ SM Higgses GREAT OPPORTUNITY!

Curtin, Verhaaren 1506.06141

What about the extra Twin SUSY Higges?
Are invisible BR's an opportunity of discovery also for them?

N. Craig, S. Gori, D. R. work in progress

LHC take home message

The Twin Higgs generically predicts &
extended Higgs sector

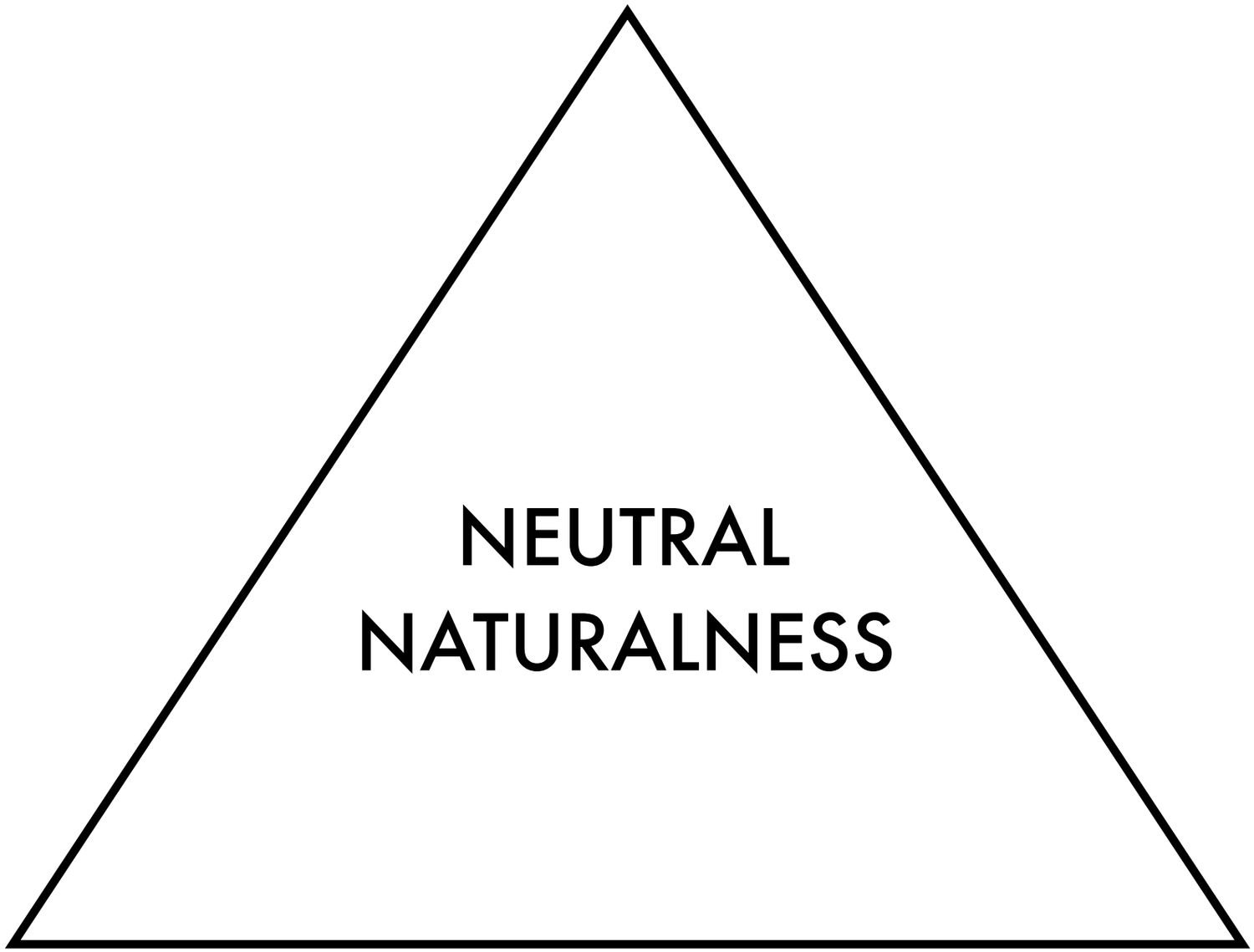
+

dark mirror states

Good motivation for:
- Higgs coupling precisions
- Searches for extra Higgses
- Displaced signatures

...

UV-completions

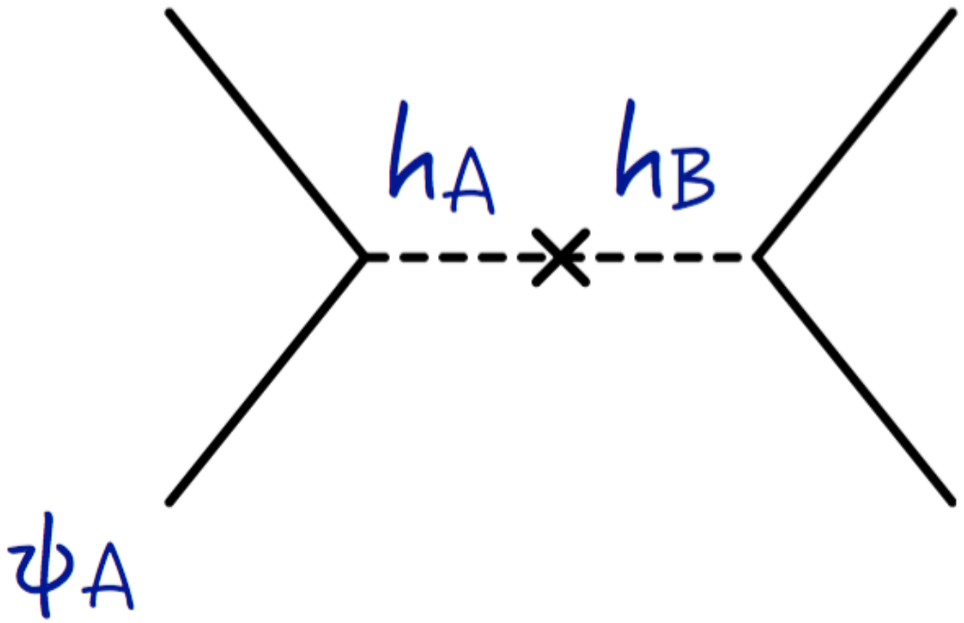


LHC

COSMOLOGY

Mirror World

Barbieri, Hall, Gregoire 0509242



Higgs portal compelling in Twin Higgs

$$n\sigma v \sim \frac{y_A^2 y_B^2}{m_h^4} \times \frac{v^2}{f^2} T^5$$

The SM and the Twin sector do not decouple before @ 3 GeV

Thermal History

~GeV

$$\rho_A : \rho_B = g_*^A : g_*^B$$

$\approx Z_2$ - symm

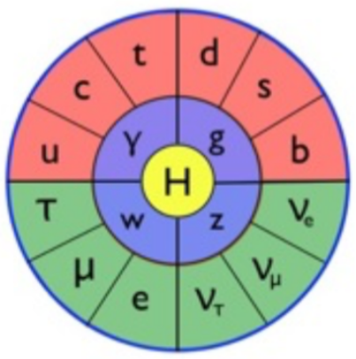
~MeV

$$\rho_A \approx \rho_B$$

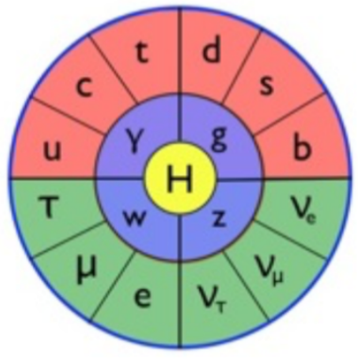
energy density in Dark Radiation affects the expansion rate

constraint on ρ/ρ_{SM} $\longleftrightarrow$ $\Delta N_{\rm eff}$

SM



Twin Higgs



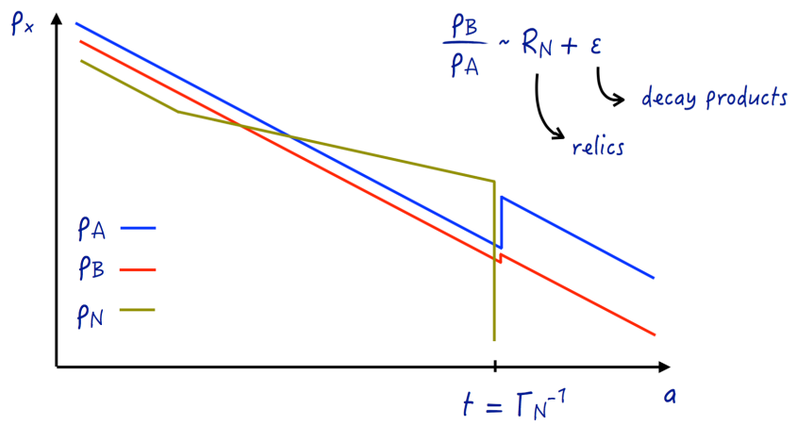
$$\Delta N_{\rm eff} \sim 7.4 \times \frac{\rho_B}{\rho_A}|_{0.1\rm Mev}$$ ruled out!

Twin Cosmology sucks!

CHANGE COSMOLOGY

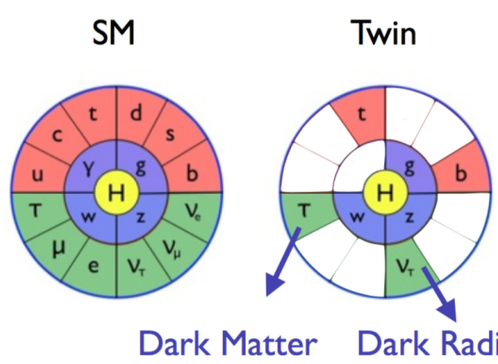
matter domination+ late decay

Z. Chacko, N. Craig, P. Fox, R. Harnik 1611.07975



CHANGE SPECTRUM

Fraternal: 3rd gen. only



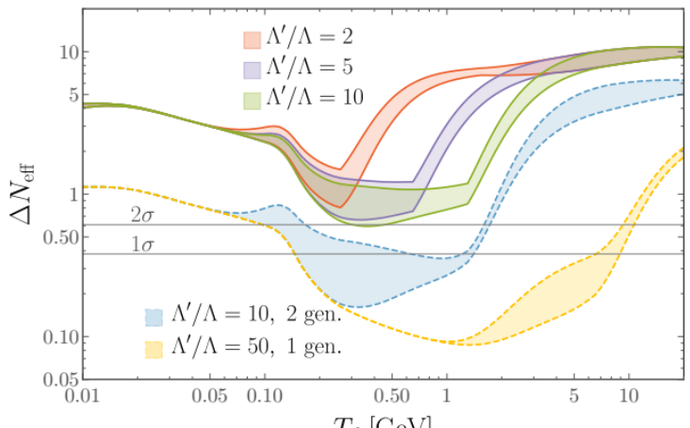
N. Craig, A. Katz, M. Strassler, R. Sundrum 1501.05310

Minimal: tuning decoupling

$$\Lambda'_{QCD} < T_{dec} < \Lambda_{QCD}$$

R. Barbieri, L. Hall, K. Harigaya

C. Csaki, E. Kuflik, S. Lombardo



COSMO take home message

There are ways of making Twin Cosmology work!

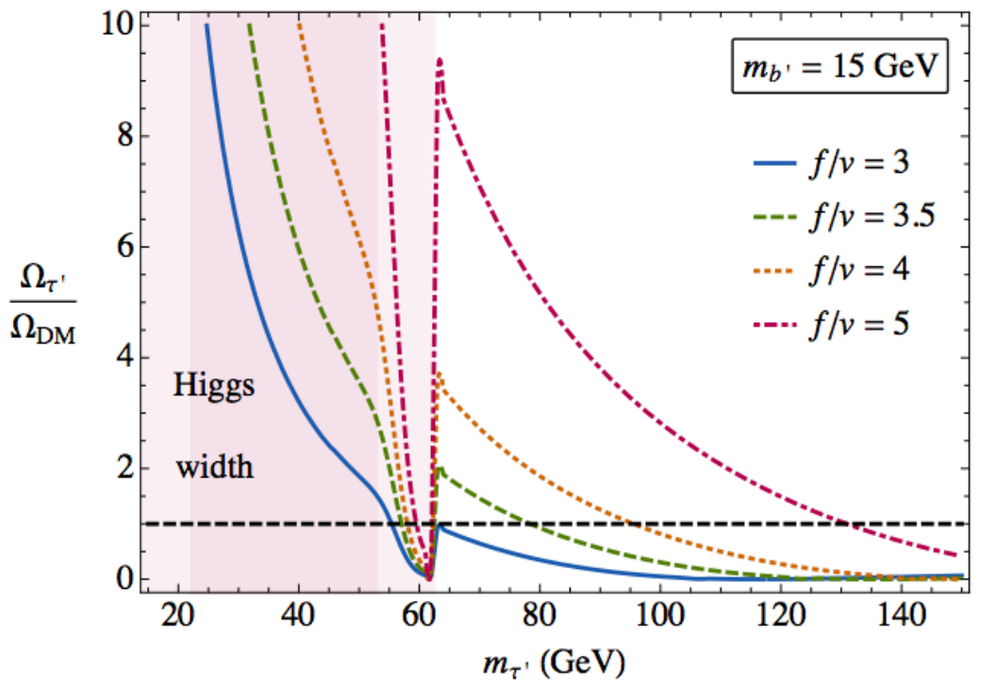
Cosmological solutions have implications on { fine-tuning, LHC phenomenology, Dark Matter }

Example : Fraternal WIMPs

Twin tau is stable if we do not gauge Twin hypercharge

N. Craig, A. Katz 1505.07113

I. Garcia Garcia, R. Lasenby, J. March-Russell 1505.07109

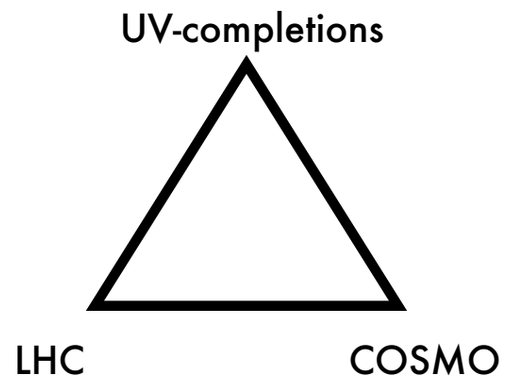


Conclusion

"Is neutral naturalness the beautiful reason we haven't seen anything, or the last desperate hope of theorists?"

–G. Giudice

either ways it gives motivation



to look at LHC data differently: *spectacular rare events*

to test new cosmological scenarios

to think more deeply about accidental symmetries in QFT

MERCI/DANK JE