Institute of Theoretical Physics
Chinese Academy of Sciences

Naturalness in Post-Naturalness Era

Jiang-Hao Yu (于江浩)
中国科学院理论物理研究所

第十五届粒子物理、核物理和宇宙学交叉学科前沿问题研讨会

In collaboration with Ling-Xiao Xu, Ramsey-Musolf, Rui Zhang and Shou-hua Zhu

August 23, 2018

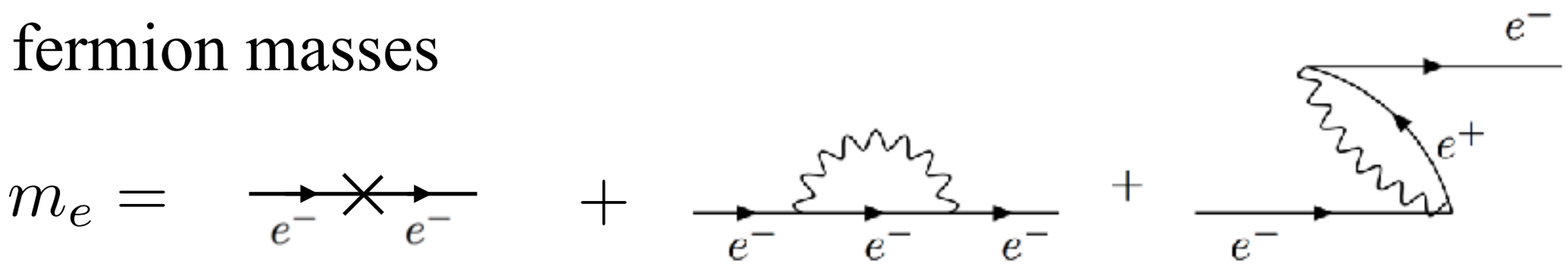
Outline

1. What is Naturalness?
2. Naturalness Scenarios
3. Post-Naturalness Scenarios
4. Summary

Hierarchical Scales

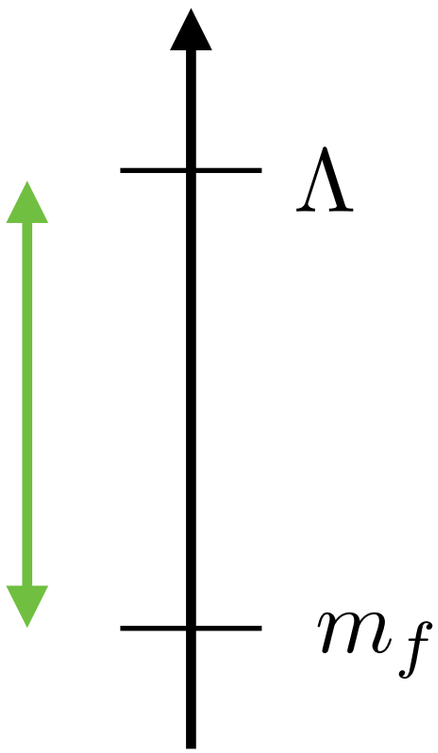
In particle physics, hierarchical scales are common, such as hierarchy between electron mass and Planck scale

SM fermion masses



$$= \quad m_e^0 \quad + \quad \frac{3e^2}{16\pi^2} m_e^0 \ln \frac{m_e^0}{\Lambda}$$

Weisskopf, 1939



Take $\Lambda = M_{\rm pl}$

$$511 \text{ KeV} = 564.98 \text{ KeV} - 53.98 \text{ KeV}$$

Spin-1/2

$m\Psi\bar{\Psi}$

$\Psi \to e^{i\alpha\gamma_5}\Psi$

(chiral symmetry)

$\delta m \propto m$

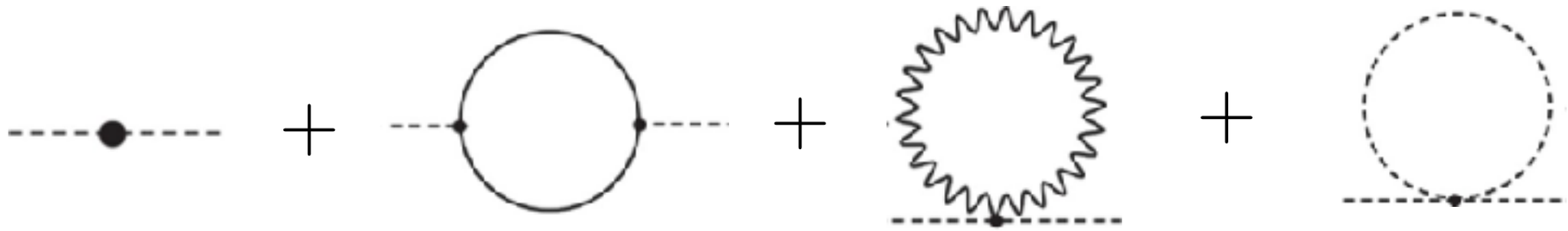
Natural!

Hierarchy Problem

Now consider W and Z masses, or EW vev, or Higgs mass

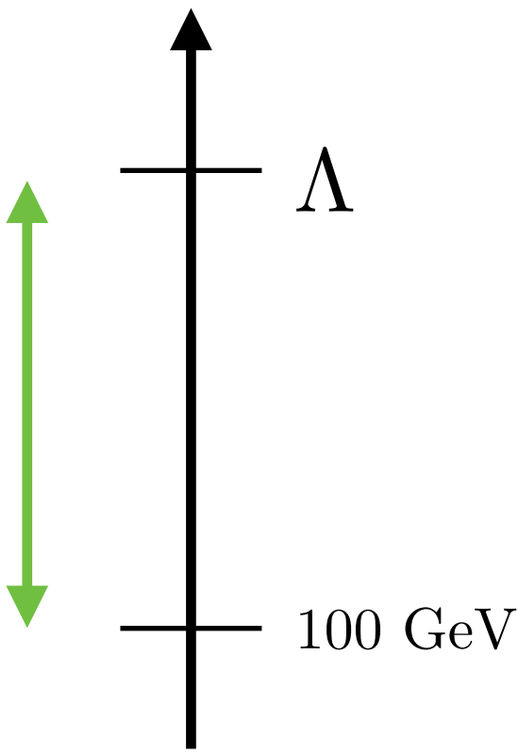
$$m_W^2 \sim v^2 \sim m^2 \sim (100\ \mathrm{GeV})^2 \ll M_{\mathrm{pl}}^2$$

Higgs mass parameter

$-(100\ \mathrm{GeV})^2 =$ 

$$= \quad (m^0)^2 \quad + \quad \frac{\Lambda^2}{16\pi^2}\left(-6y_t^2 + \frac{3}{4}(3g^2 + g'^2) + 6\lambda\right)$$

Susskind 1979
t'Hooft 1980
Veltman, 1981
Witten, 1981



Take $\Lambda = M_{\mathrm{pl}}$

$$-(100\ \mathrm{GeV})^2 = +\,361278909847893073945209328789289\mathbf{07398}\ \mathrm{GeV}^2$$
$$-\,361278909847893073945209328789289\mathbf{17398}\ \mathrm{GeV}^2$$

Need fine tuning, Hierarchy problem!

Why Cutoff at Planck Scale?

Take cutoff to be infinity, recover typical renormalization in QFT

It seems hierarchy problem disappears!

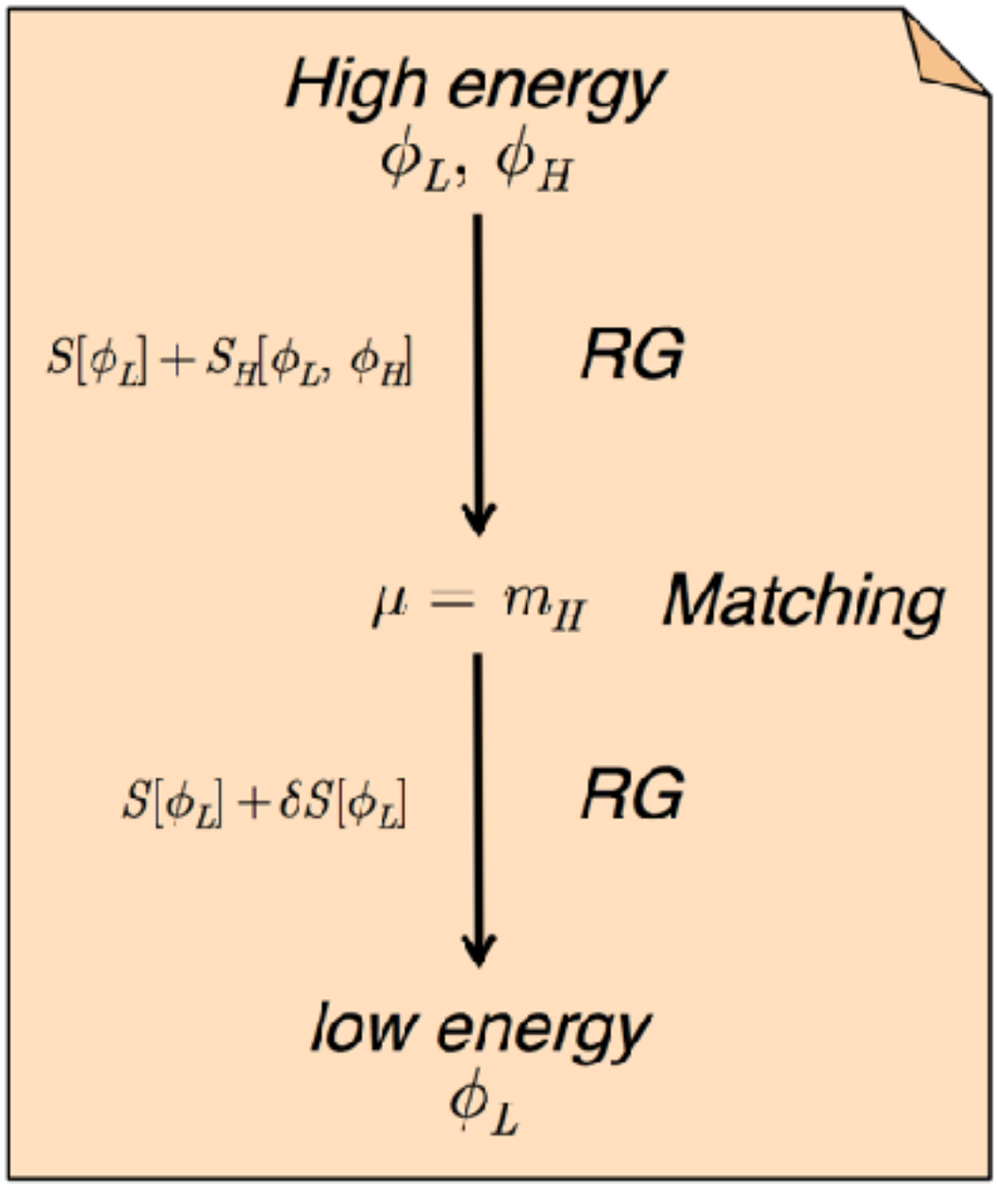
Some argue dim-reg solves hierarchy problem

Understand the cutoff ….

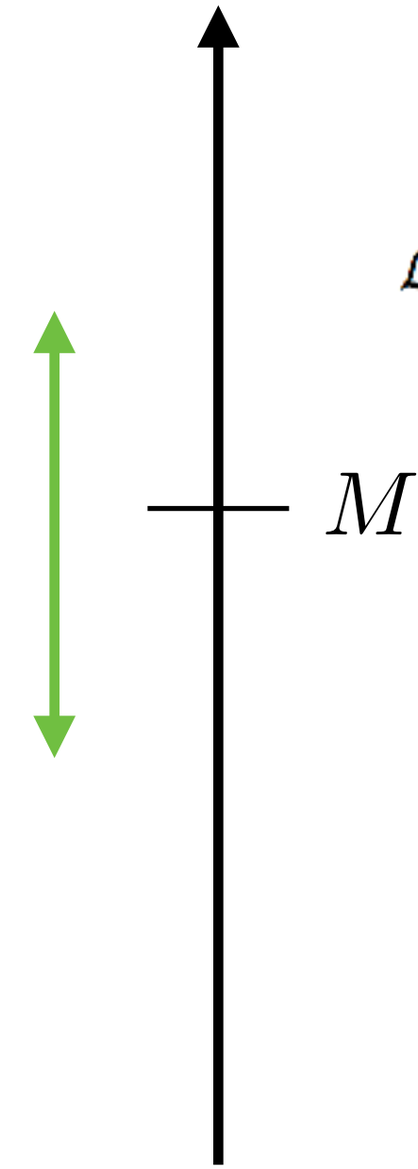
Cutoff in EFT

In EFT, cutoff means the physical threshold of underling physics

Wilson, 1971



Cutoff in Higgs Potential

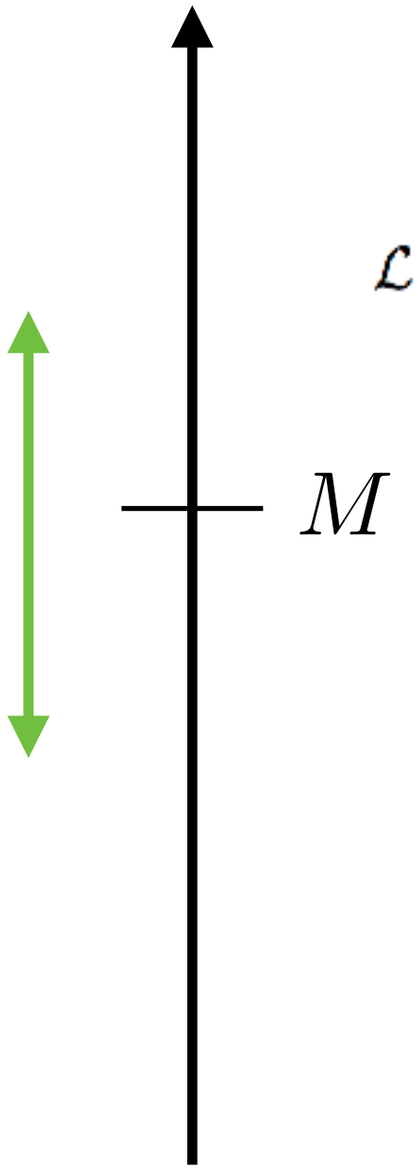


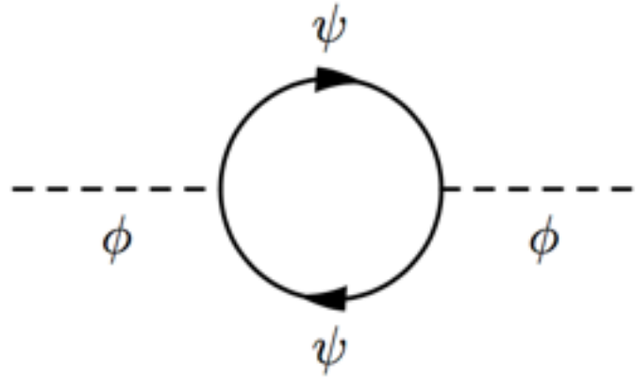
$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m^2\phi^2 - \frac{\lambda}{4!}\phi^4 + \bar{\Psi} i \not{\partial}\Psi - M\bar{\Psi}\Psi + y\phi\bar{\Psi}\Psi$$

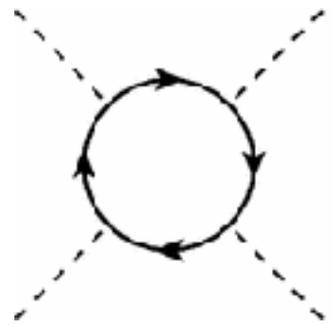
$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m^2\phi^2 - \frac{\lambda}{4!}\phi^4$$

Cutoff in Higgs Potential

$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m^2\phi^2 - \frac{\lambda}{4!}\phi^4 + \bar{\Psi} i \not{\partial}\Psi - M\bar{\Psi}\Psi + y\phi\bar{\Psi}\Psi$$



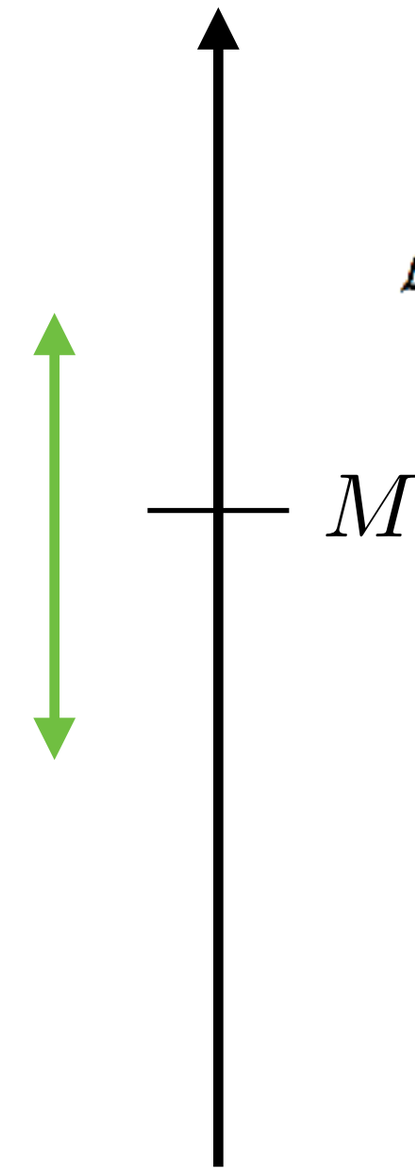




$$\Sigma_2(p^2) = \frac{4y^2}{16\pi^2}\left[\left(\frac{3}{\bar{\epsilon}} + 1 + 3\log(\mu^2/M^2)\right)\left(M^2 - \frac{p^2}{6}\right) + \frac{p^2}{2} - \frac{p^2}{20M^2} + \dots\right]$$

In Dim-Reg

Cutoff in Higgs Potential



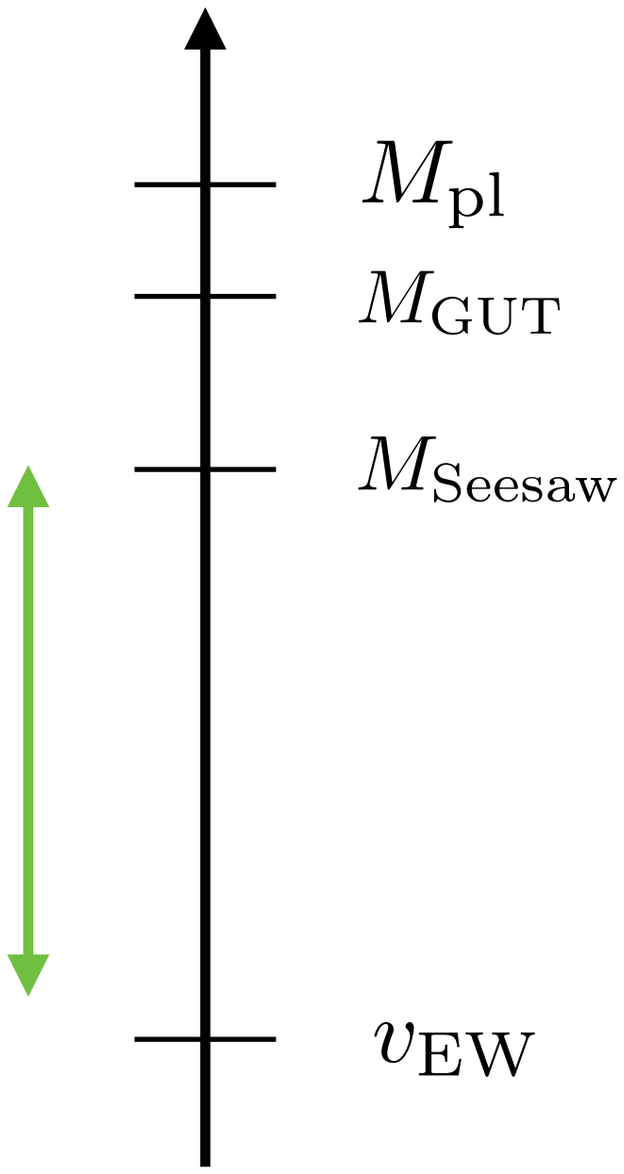
$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m^2\phi^2 - \frac{\lambda}{4!}\phi^4 + \bar{\Psi} i \not{\partial}\Psi - M\bar{\Psi}\Psi + y\phi\bar{\Psi}\Psi$$

$$\mathcal{L} = \left(1 - \frac{4}{3}\frac{y^2}{16\pi^2}\right)\cdot\frac{1}{2}(\partial\phi)^2 - \left(m^2 - \frac{4y^2}{16\pi^2}M^2\right)\cdot\frac{1}{2}\phi^2 + \dots$$

In one loop matching, threshold correction to Higgs mass parameter appears, even in Dim-Reg!

Cutoff Scale

Smolin, 1980



$$\mathcal{S} = \int d^4x\sqrt{-g}\left[-M_{\rm pl}^2 R + g^{\mu\nu}\partial_\mu\phi^\dagger\partial_\nu\phi - m^2\phi^2 - \lambda\phi^4 + \cdots\right]$$

Quantum gravity correction

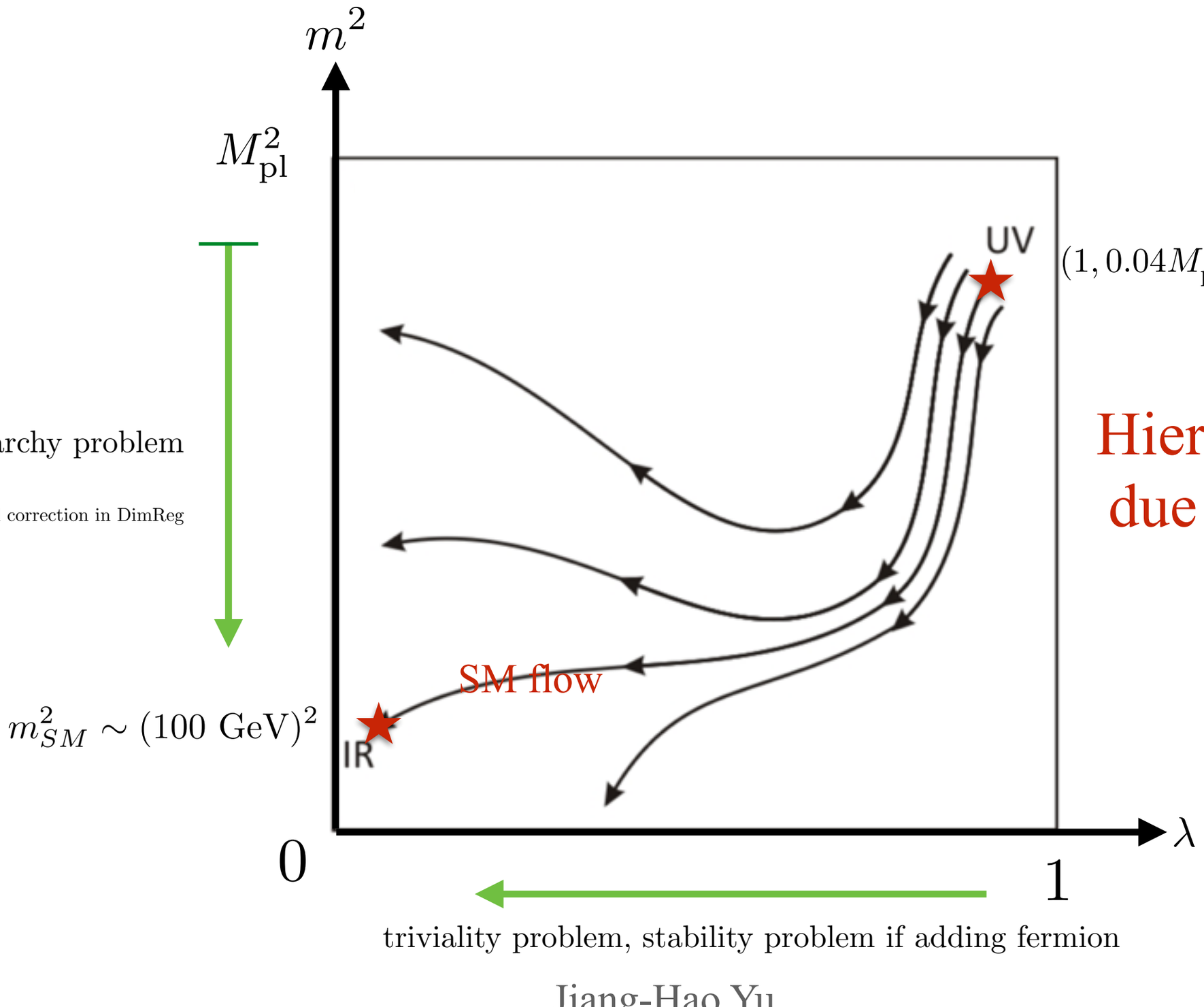
$$\delta m^2 \sim \frac{1}{16\pi^2} M_{\rm pl}^2 \phi^2$$

If no new scale above SM, or special quantum gravity, then no threshold, no hierarchy problem!

Wilsonian Hierarchy Problem

Susskind, 1979
Wilson, 1971

Running from Planck scale

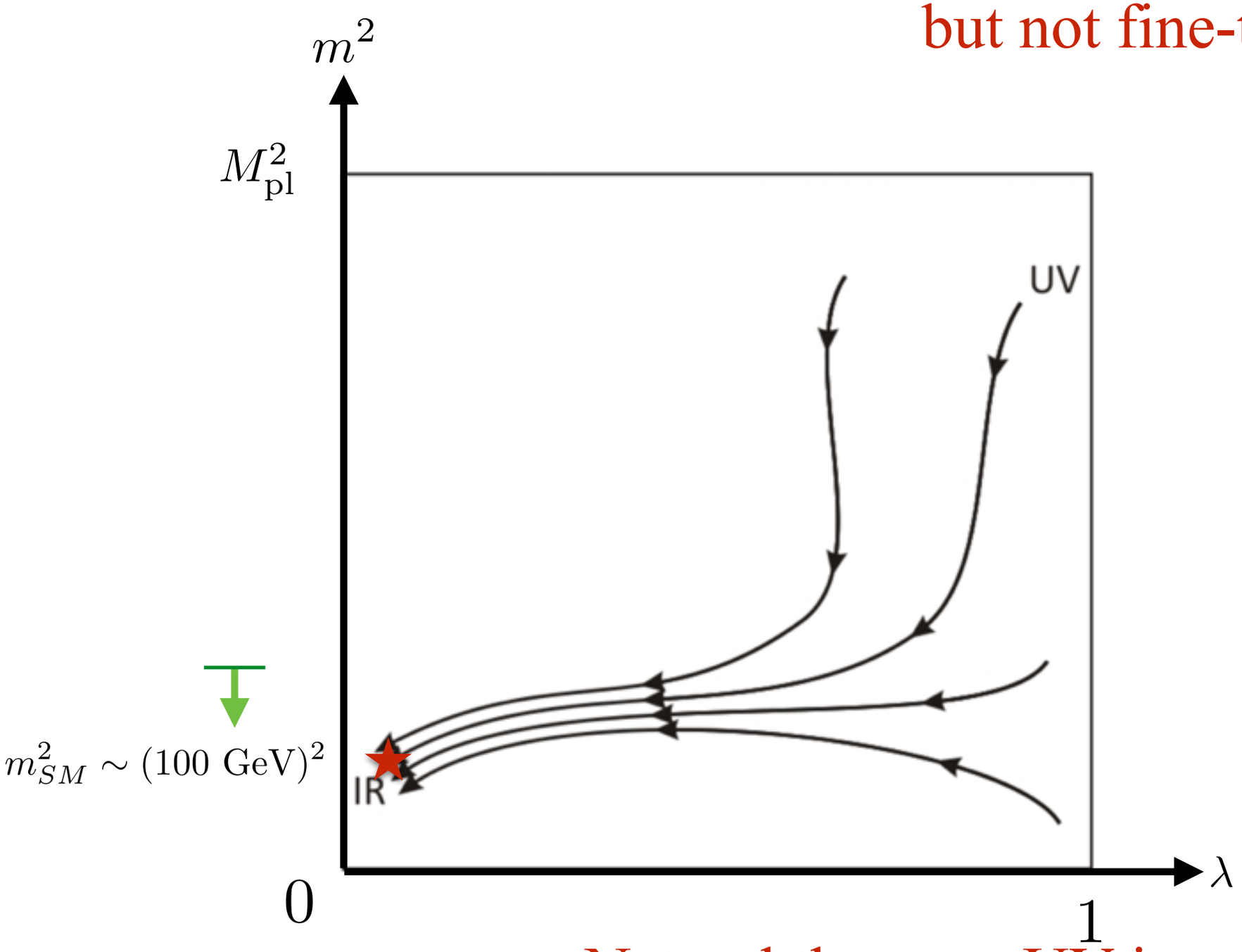


Hierarchy problem due to fine-tuned!

Wilsonian Naturalness

IR is not sensitive to UV physics

Hierarchy
but not fine-tuned!



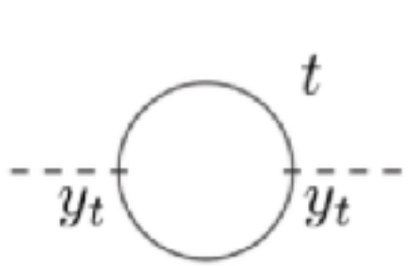
Natural theory = UV insensitive!

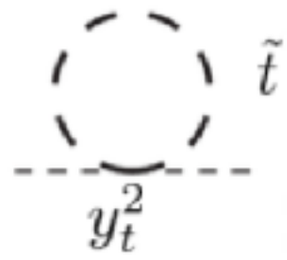
New Symmetry in UV

Introduce new symmetry to protect Higgs mass (No Quad. Div.)

Supersymmetry

$H \leftrightarrow \tilde{H}$

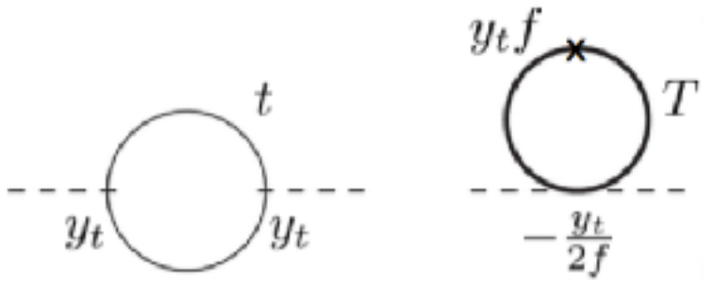




Hierarchy Problem Solutions

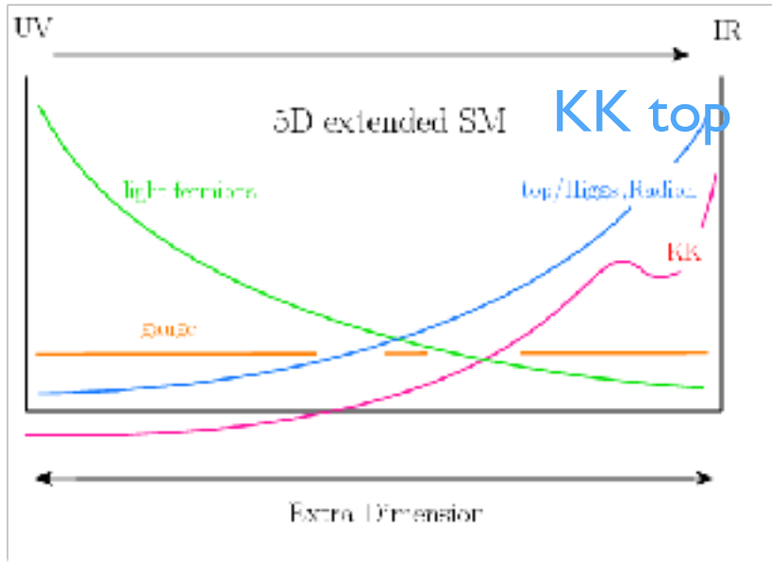
Composite Higgs

shift: $h \to h + a$

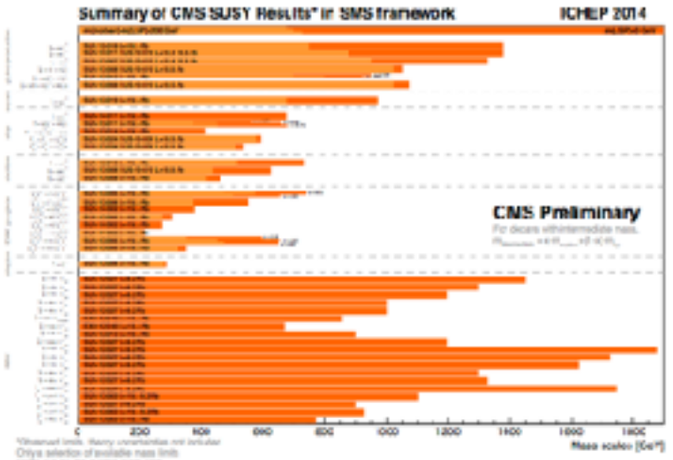


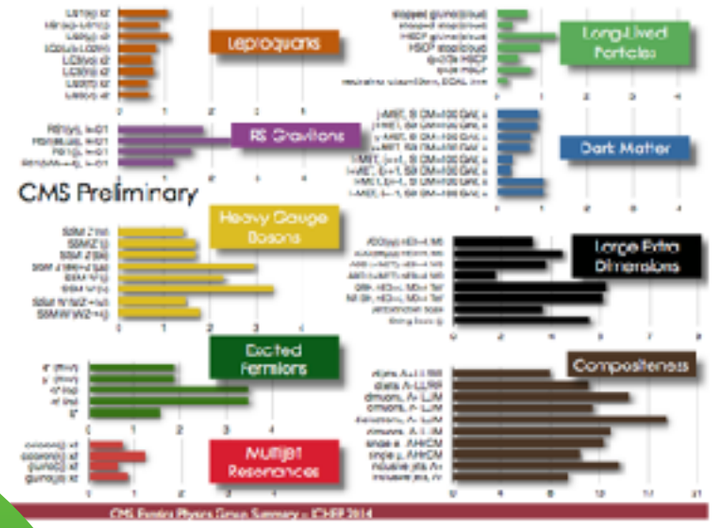
Extra Dimension

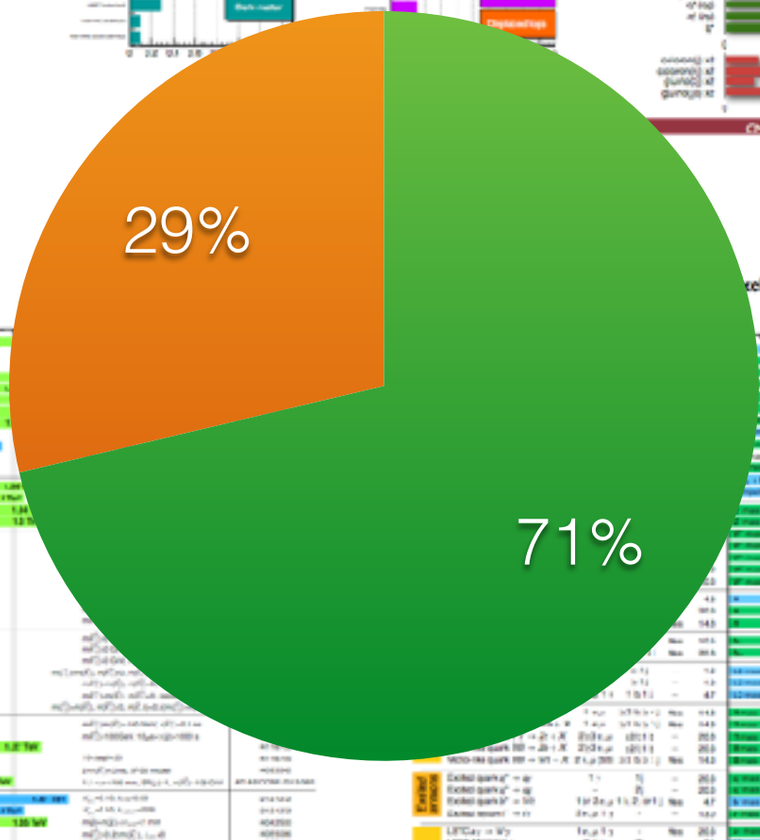
Conformal: $h \to e^{\omega} h$

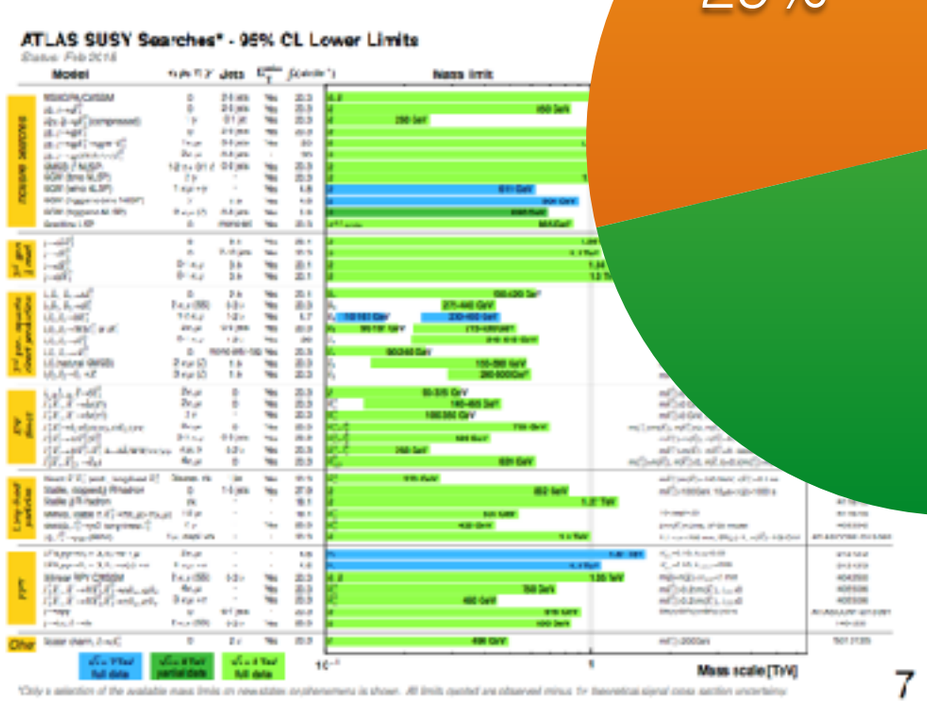


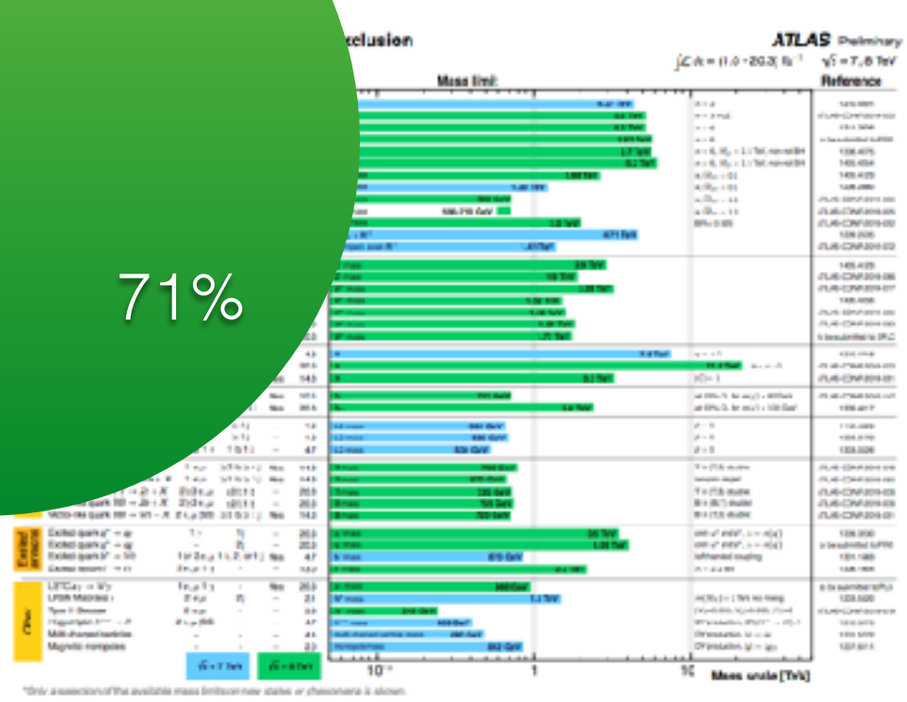
LHC Searches





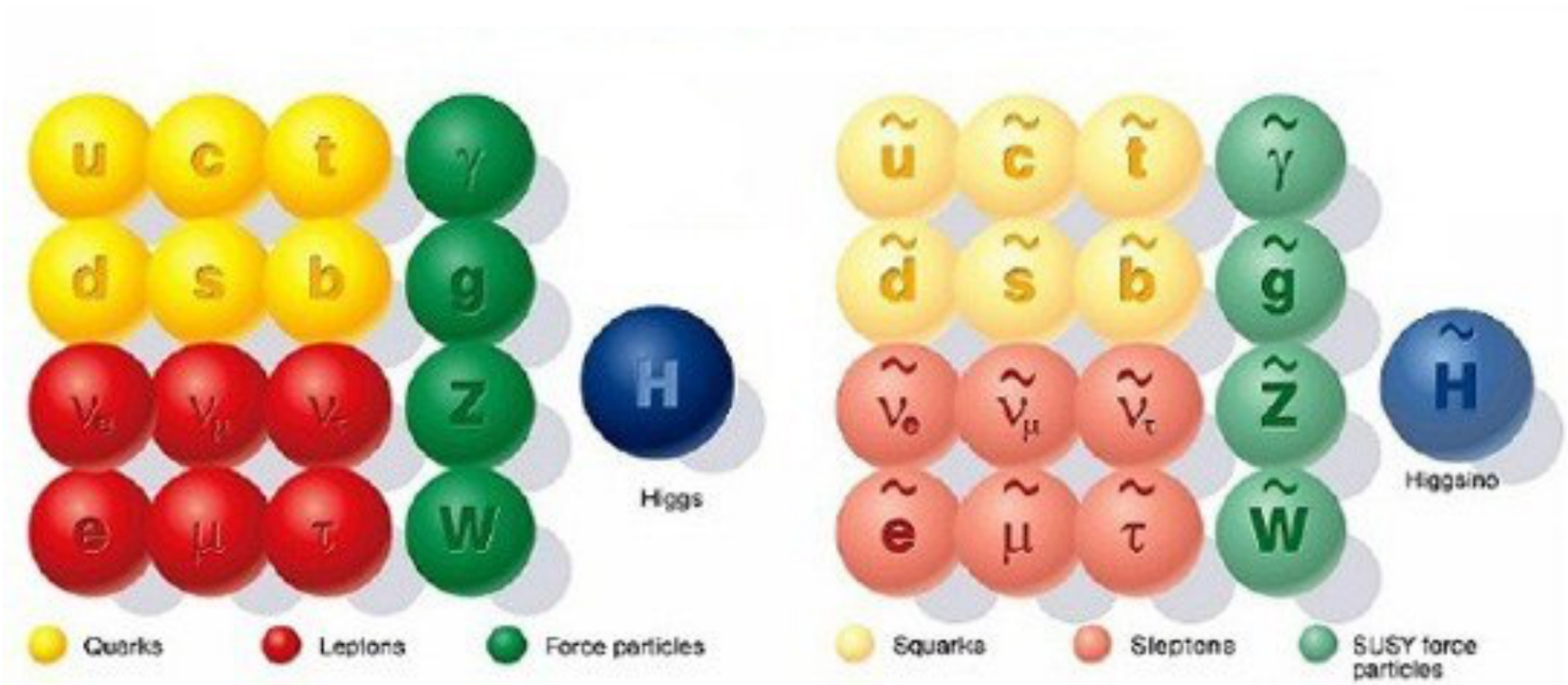




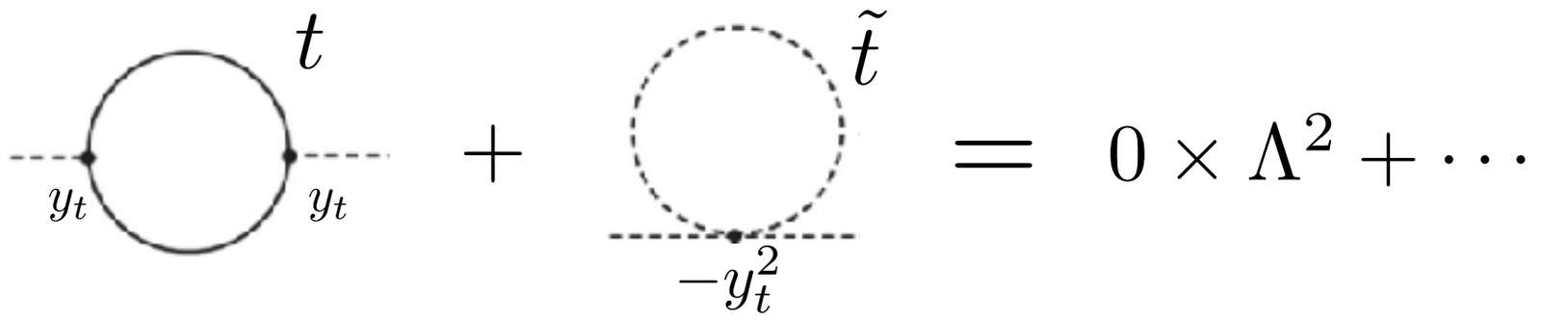


Naturalness provides a guiding map for BSM searches

Supersymmetry



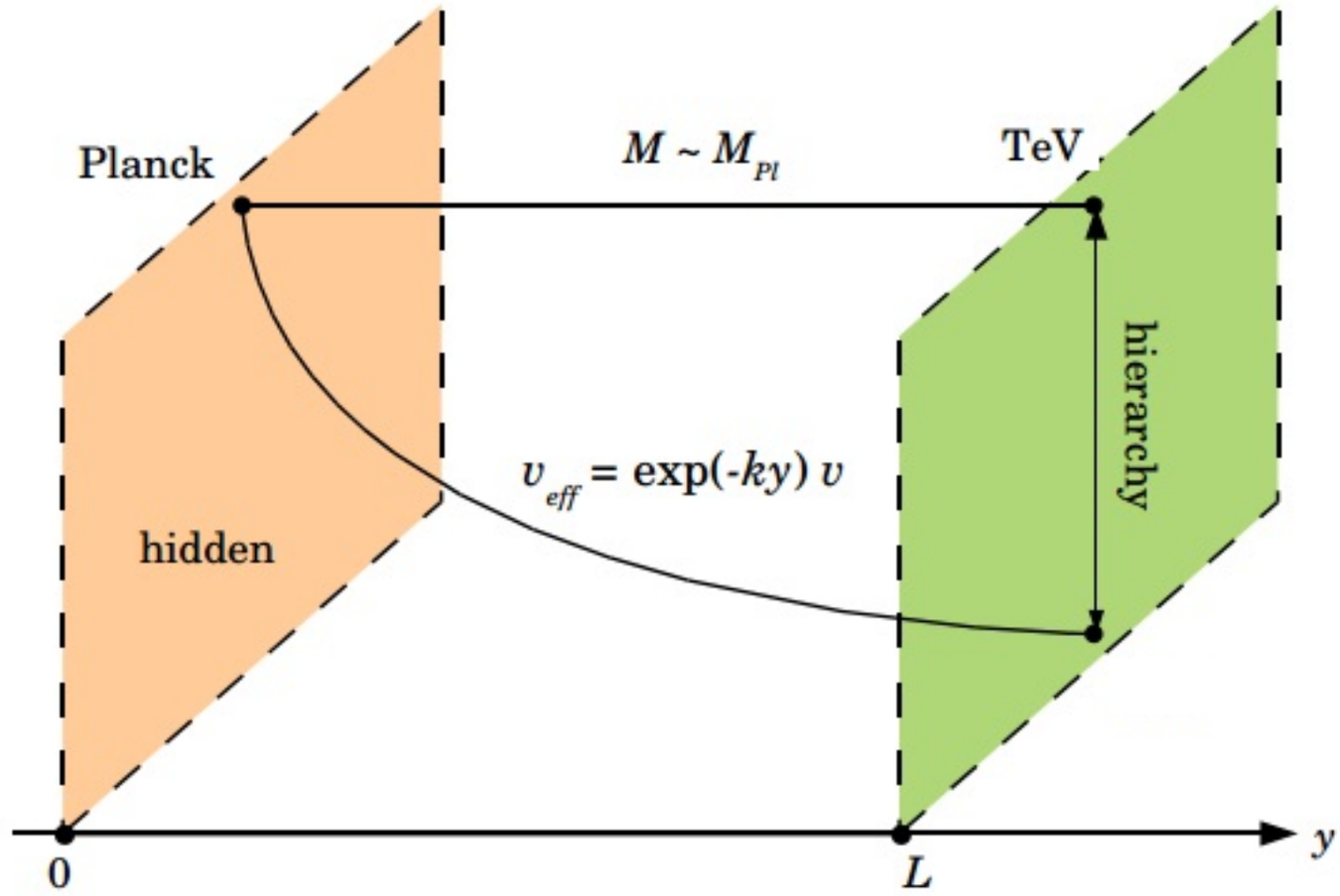
Standard particles **SUSY particles**



Extra Dimensions

Randall, Sundrum, 1999

Arkani-Hamed, Dimopoulos Dvali, 1998

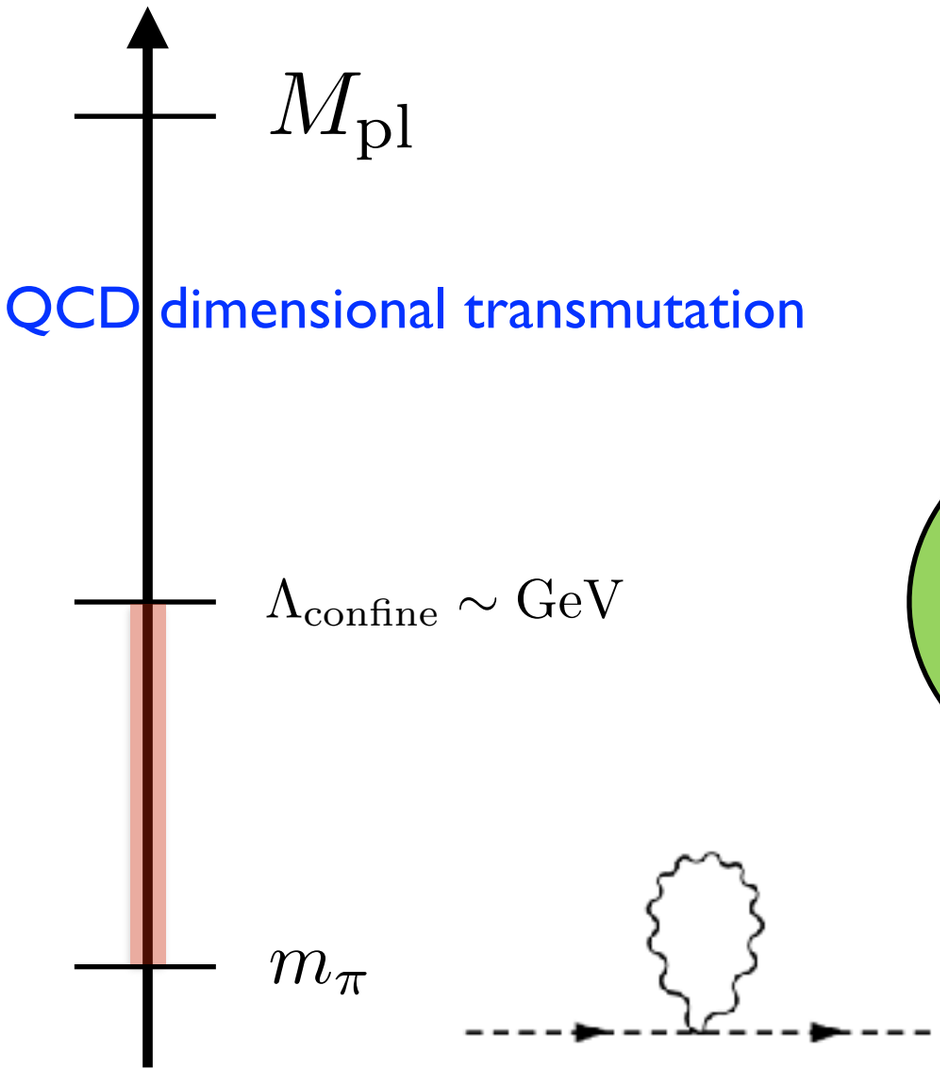


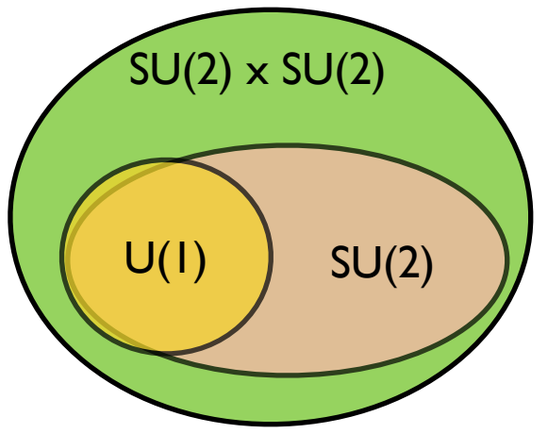
Randall-Sundrum: conformal symmetry breaking at TeV scale

Large Extra Dim: lower scale of quantum gravity

Cutoff of the theory is close to the Higgs mass

Pion as Pseudo-Goldstone





$$M^2_{\pi^+} - M^2_{\pi^0} = \frac{3e^2}{16\pi^2}\Lambda^2 \qquad \Lambda < 850\ {\rm MeV}$$

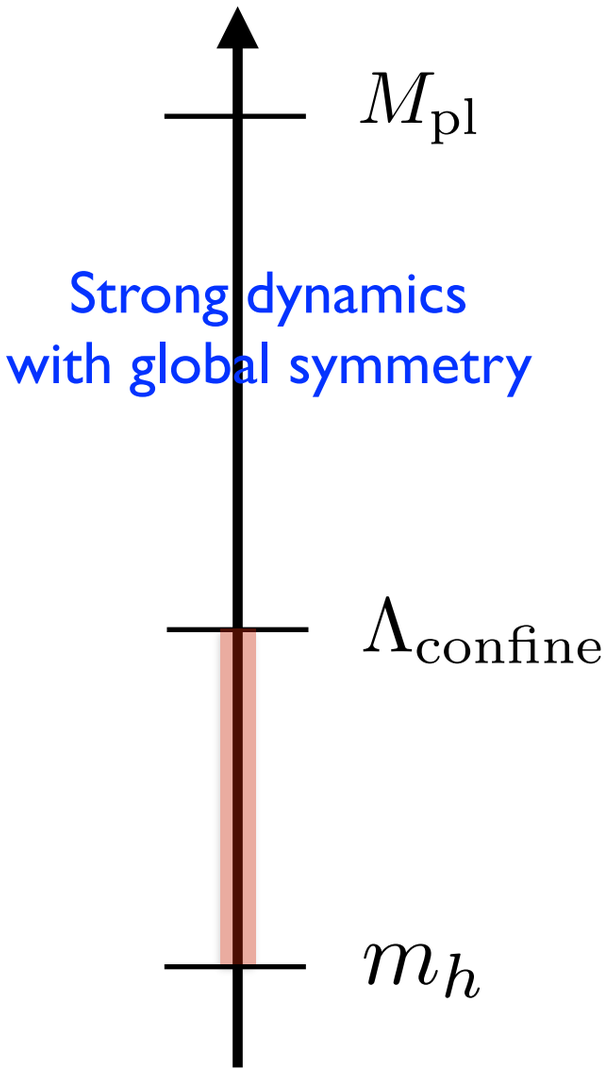
Rho meson appears at 770 MeV!

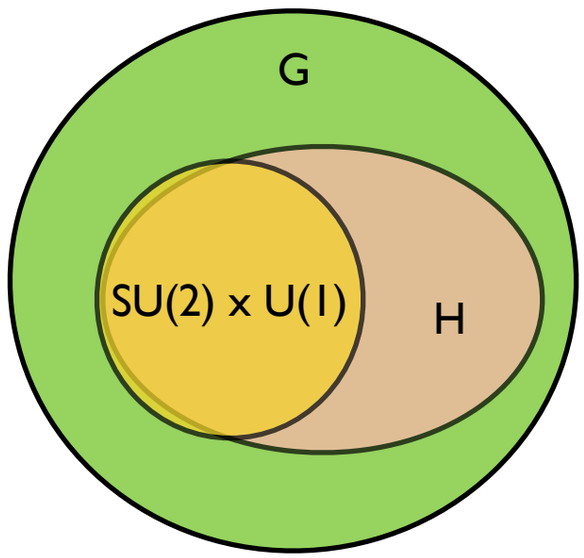
$$\frac{M_{K_L^0} - M_{K_S^0}}{M_{K_L^0}} = \frac{G_F^2 f_K^2}{6\pi^2}\ \sin^2\theta_c\ \Lambda^2$$

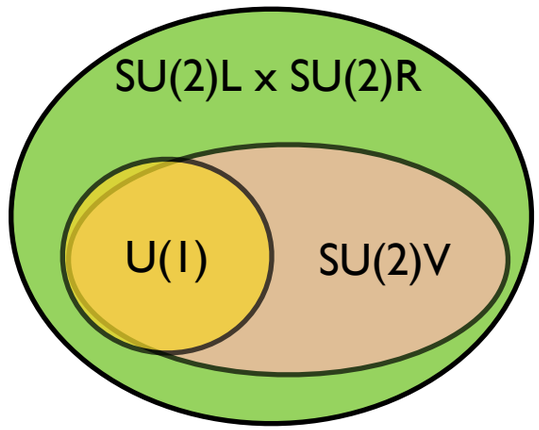
New physics effects appears near physical threshold

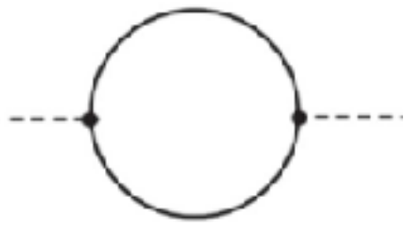
Higgs as Pseudo-Goldstone

Georgi, Kaplan, 1980









$$m^2 = -\frac{6y_t^2}{16\pi^2}\Lambda^2$$

$$\Lambda < 500 \text{ GeV}$$

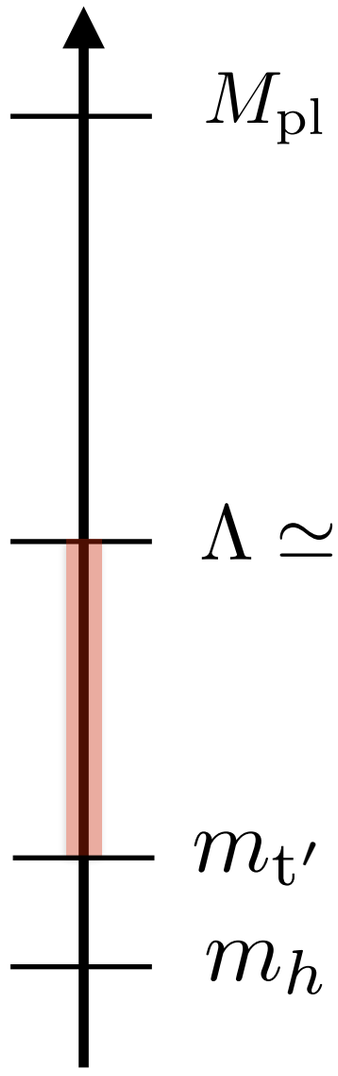
No new physics at 0.5 TeV, push to around 5 TeV (EWPT)

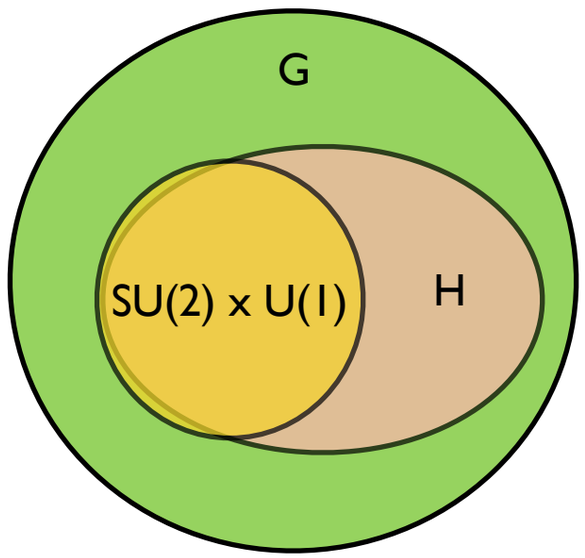
Introduce additional symmetry

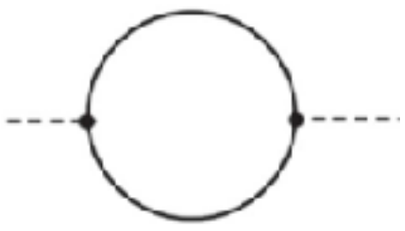
Little Higgs & Composite Higgs

Arkani-Hamed, et. al., 2001

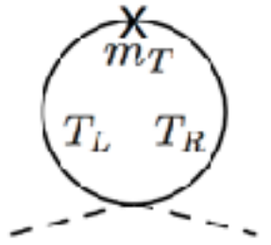
Contino, Pomarol., 2005







$$m^2 = -\frac{6y_t^2}{16\pi^2}\Lambda^2 +$$

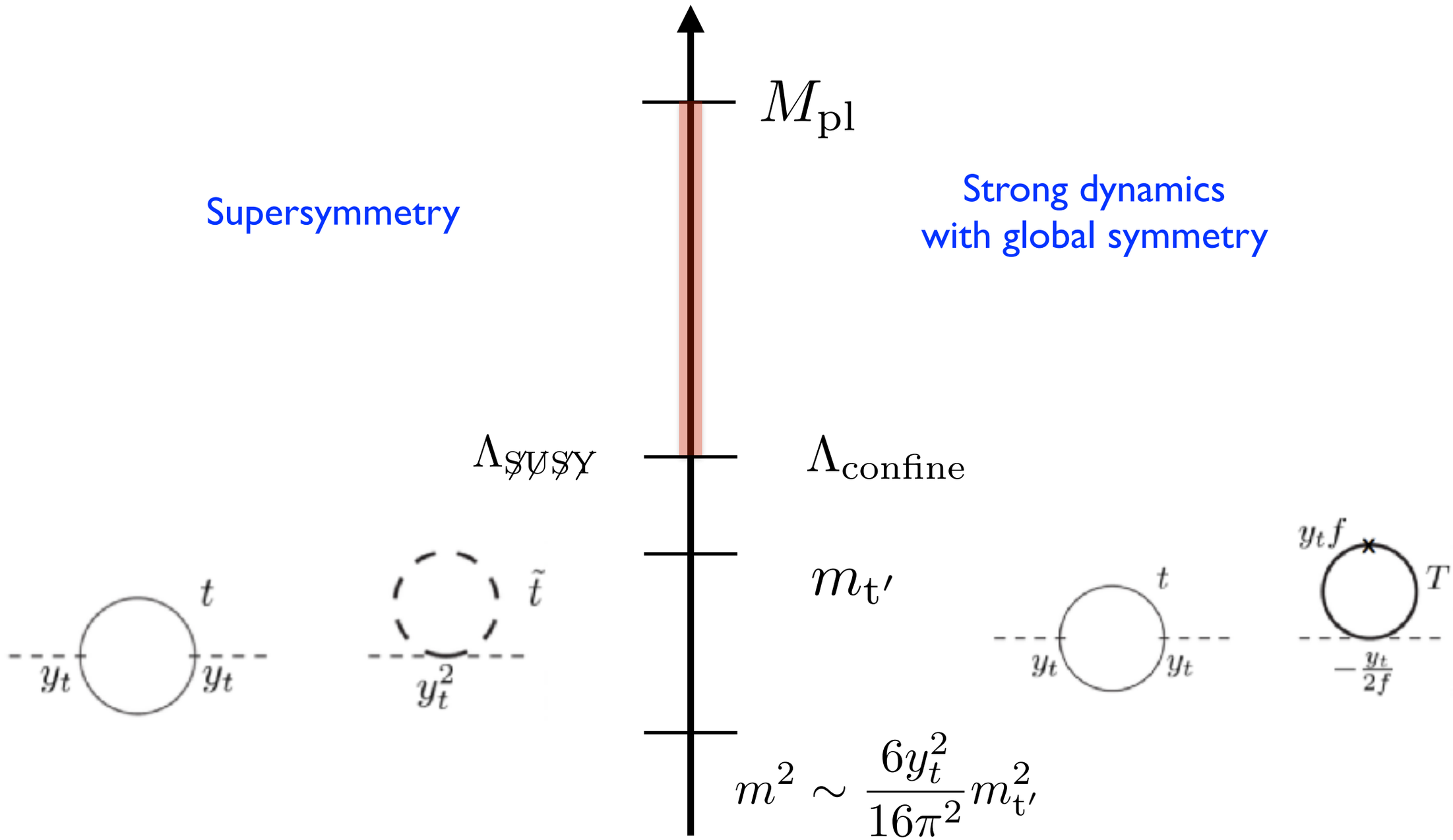


Little/composite: collective symmetry from top partner

Push new physics scale up to 10 TeV, with mT = 500 GeV

Top Partner Scale

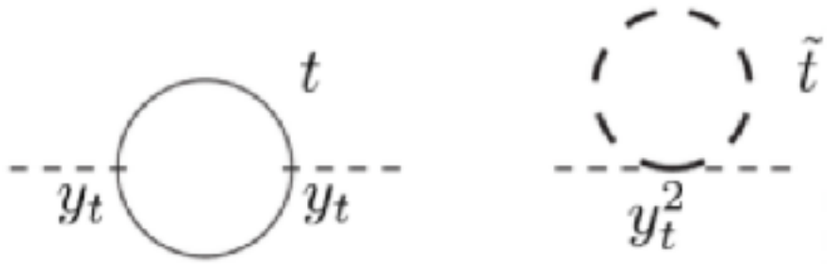
Although no Quad. Div., Higgs mass is sensitive to top partner scale



New symmetry lowers the scale from Planck to top partner scale

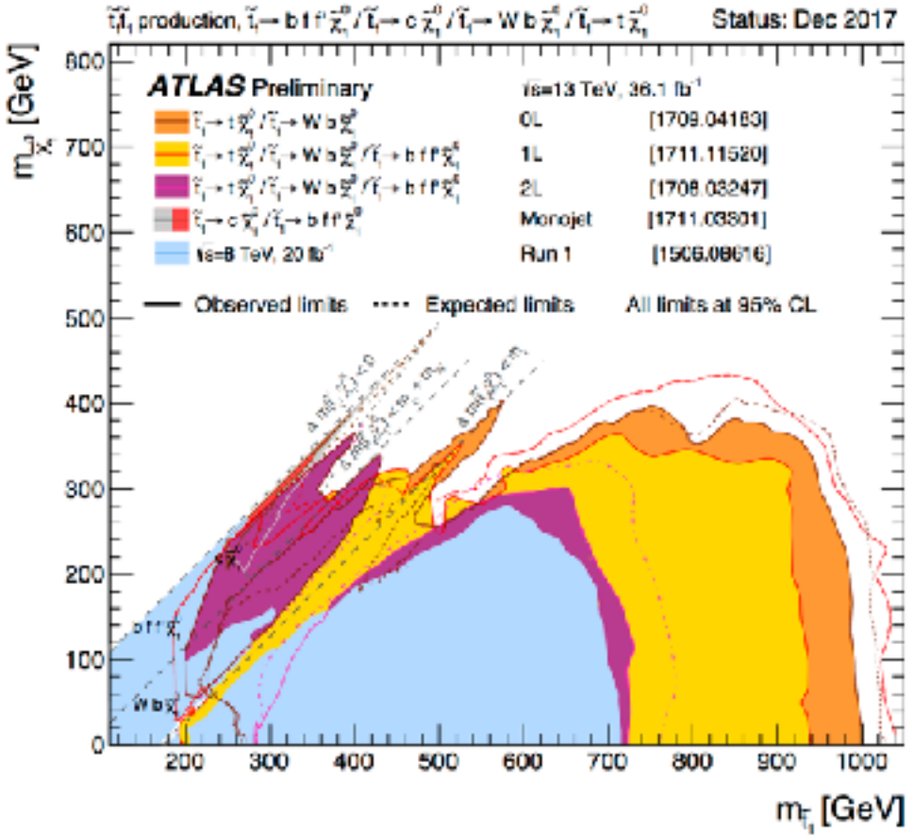
Top Partner Searches

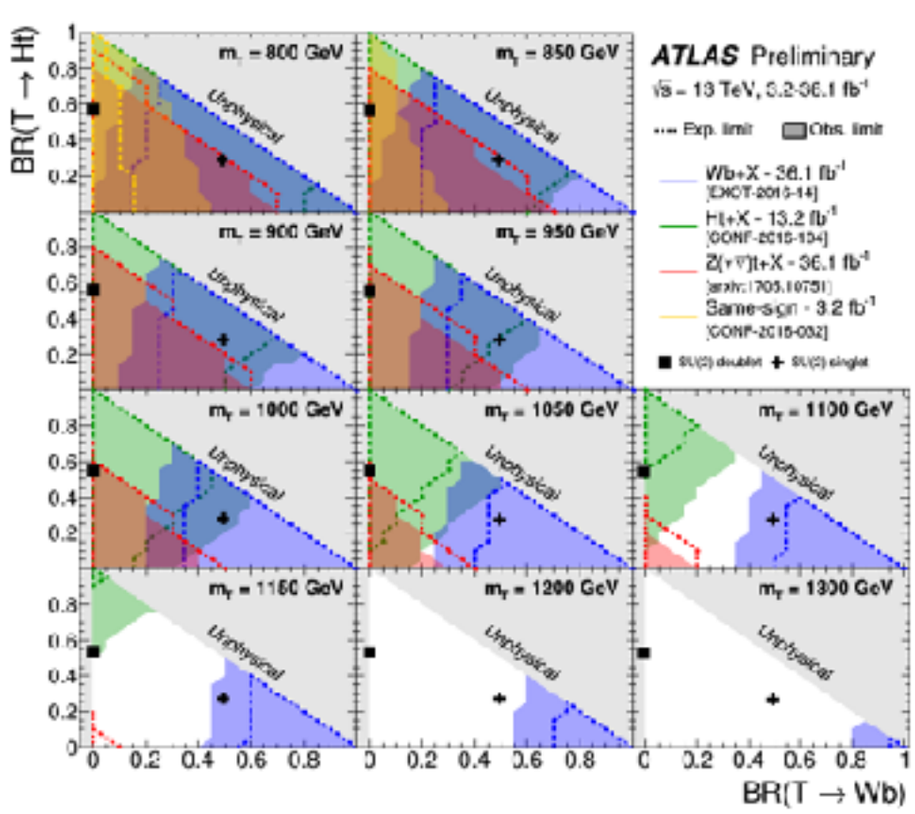
Higgs mass radiative correction:

$$m^2 \sim$$ 

$$\sim \frac{3y_t^2}{4\pi^2}\tilde{m}^2 \log \Lambda^2/\tilde{m}^2$$

Smoking gun signature: sub-TeV top partner





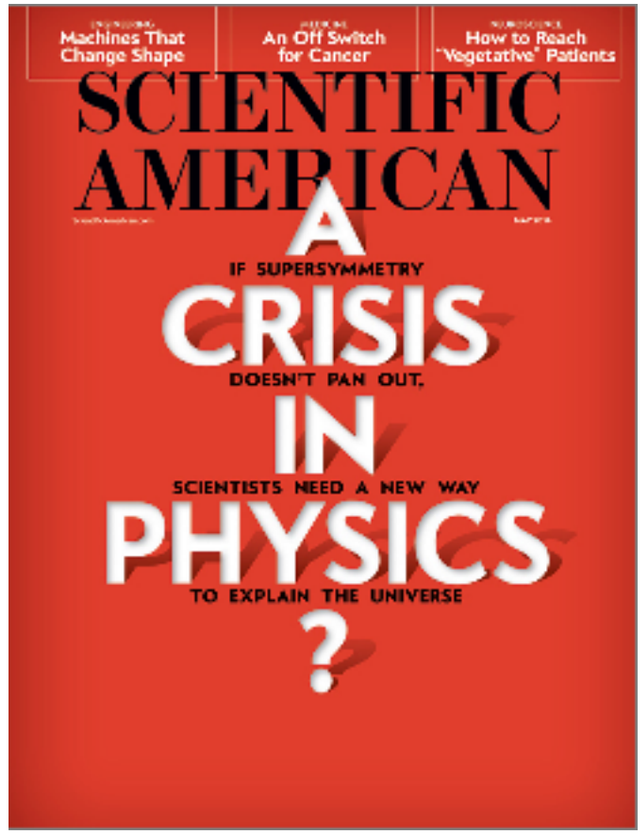
Reintroduce fine-tuning

Nightmare Scenario

SM + No new particle

Quantamagazine

What No New Particles Means for Physics



BackRe(Action)

Home | Talk To A Scientist | Comment Rules | About

Saturday, August 06, 2016

The LHC "nightmare scenario"

New Scientist

HOME NEWS TECHNOLOGY SPACE PHYSICS HEALTH EARTH HUMANS LIFE TOPICS EVENTS JOBS

Home | Features | Physics | Space

FEATURE 28 February 2018, updated 9 March 2018

Truth before beauty: Our universe is uglier than we thought

Our cosmos is failing to meet the rigorous beauty standards set by physicists. Is it time to face up to the fact we may live in an uglyverse?

Naturalness

Post-Naturalness Era

Giudice 2017: We are entering into post-naturalness era!

Neutral Naturalness in UV

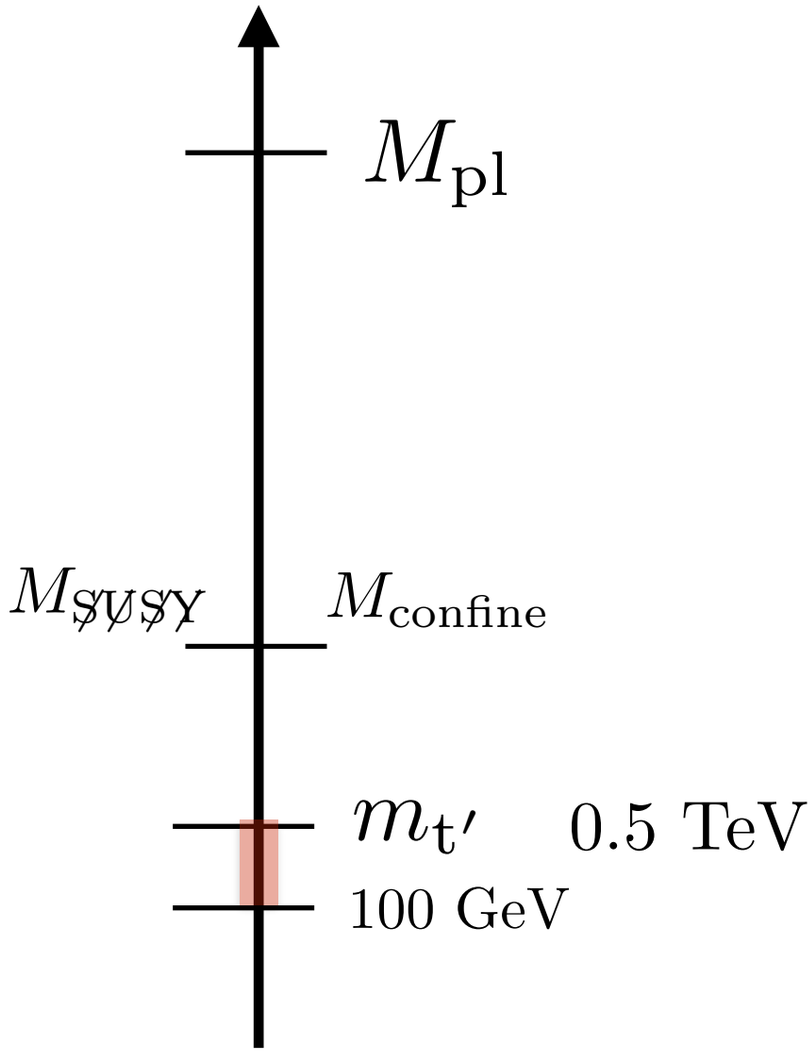
Anthropic Multiverse

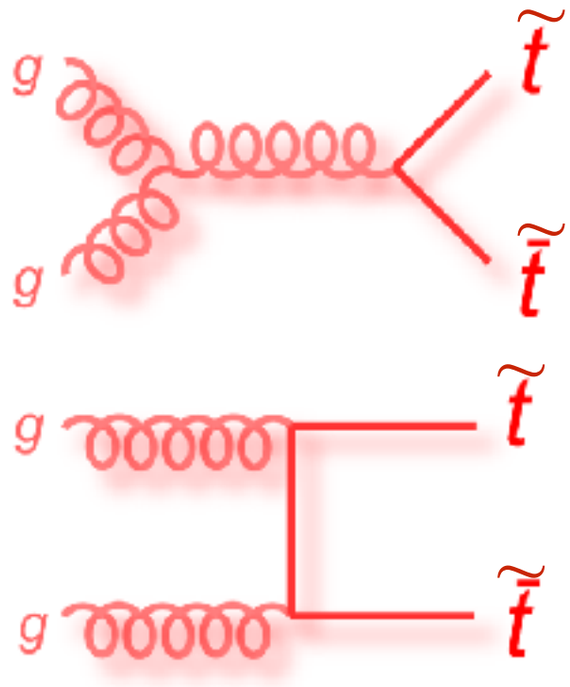
Dynamical selection in IR

Seems Naturalness paradigm runs out of mileage …

Neutral Naturalness

Can we lower top partner search limit to have natural theory?





Top partner is not charged under SU(3)color!

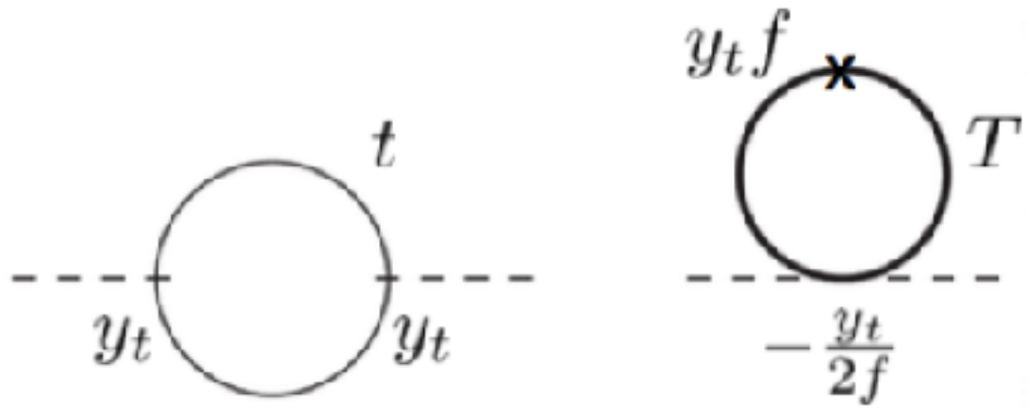
Neutral naturalness = QCD neutral top partner

Craig, Katz, Strassler, Sundrum, 2015

Color Neutral Top Partner

Still need symmetry for Higgs boson:

Craig, Katz, Strassler, Sundrum, 2015



Top quark loop has 3 d.o.f

Top partner is charged under hidden SU(3)color!

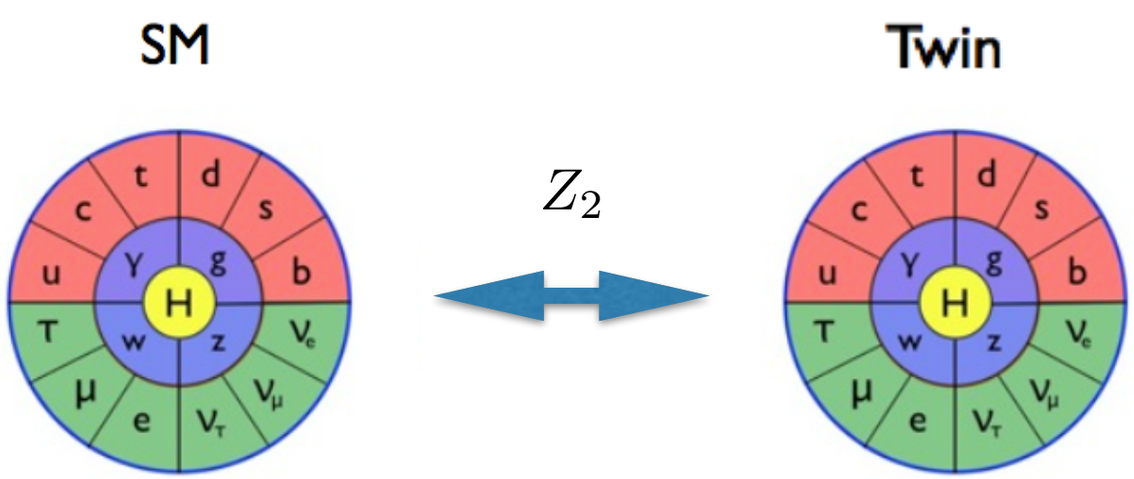
No mixing between top and top partner

Additional symmetry to ensure color neutral top partner

SU(3)QCD x SU(3)hidden

Concrete Model: Twin Higgs

Mirror Standard Model



Chacko, Goh, Harnik 2005

Top partner carries twin QCD color, twin EW symmetry

Accidental SU(4) symmetry for Higgs Boson

$$H = \begin{pmatrix} H_{\rm SM} \\ H_{\rm twin} \end{pmatrix} \equiv \begin{pmatrix} H_A \\ H_B \end{pmatrix} \begin{matrix} \leftarrow SU(2)_A \\ \leftarrow SU(2)_B \end{matrix} \Big\} \; SU(4) : H = \begin{pmatrix} H_{\rm SM} \\ H_{\rm twin} \end{pmatrix} \rightarrow SU(3)$$

7 Goldstone Bosons,
Higgs as one of Goldstone Boson

Mirror Twin Higgs

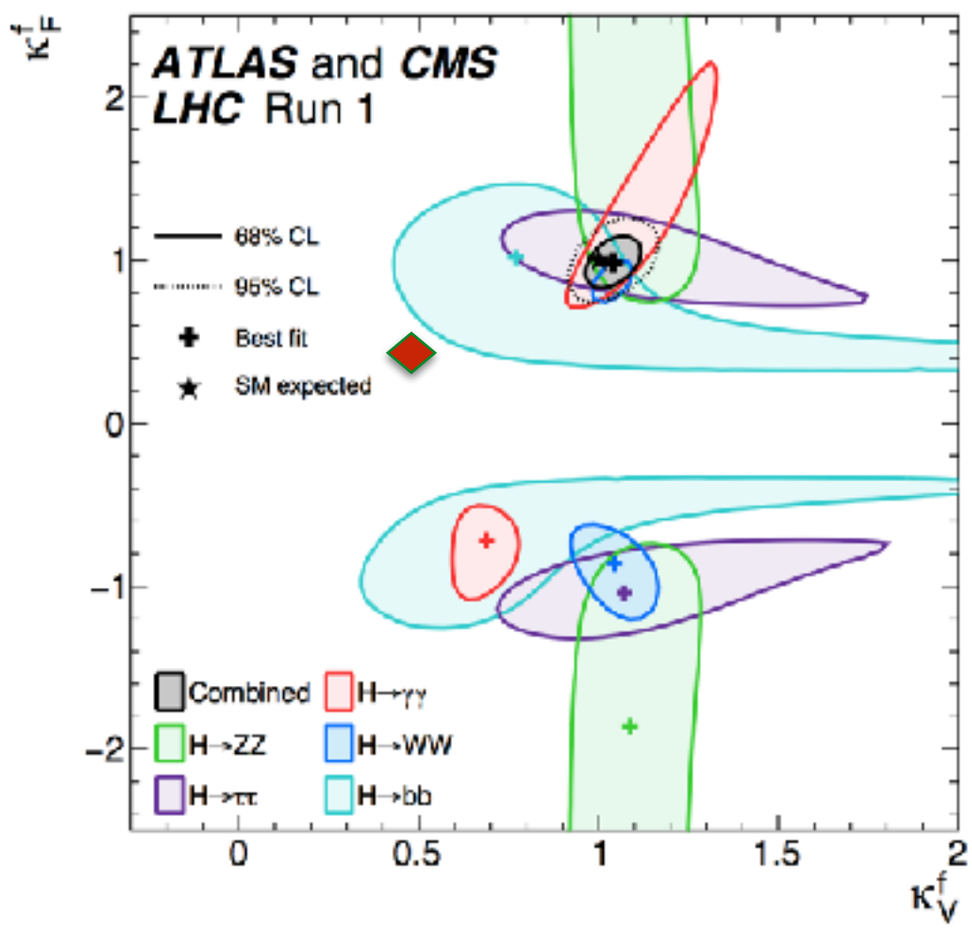
The Z2 symmetry needs to be broken at low energy

Analogy: SUSY needs to be broken at low energy

$$g_{\text{pNGB HiggsWW}} = \frac{g_{\text{SM HiggsWW}}}{\sqrt{2}}$$

SM and Twin spectra

$\langle H_B \rangle = \langle H_A \rangle = f/\sqrt{2}$



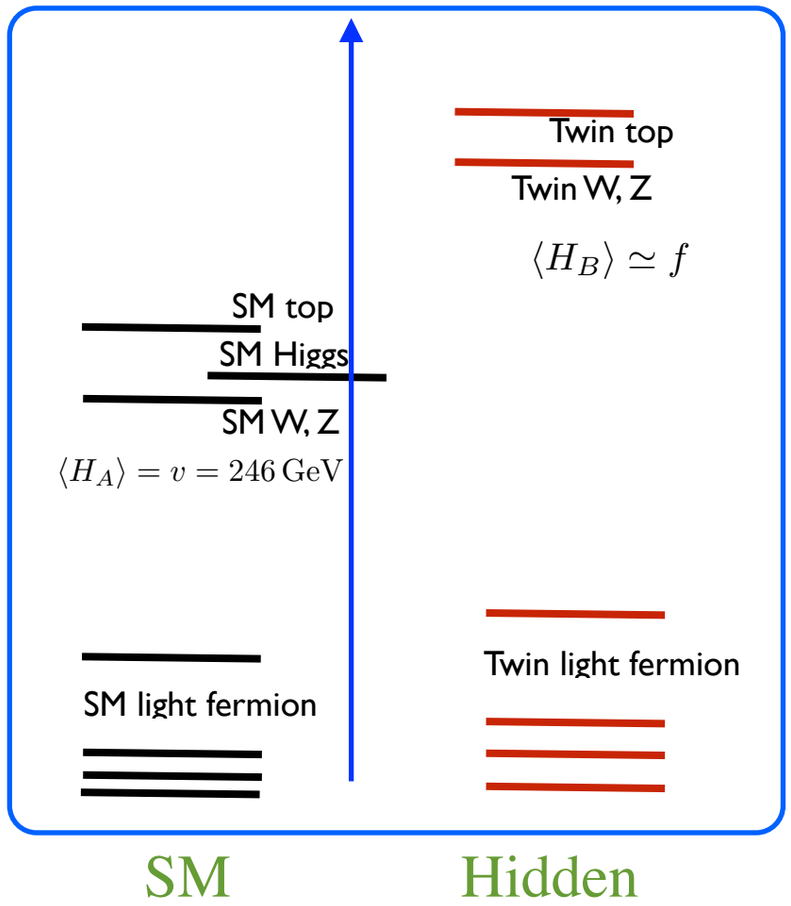
Twin spectra

$\langle H_B \rangle \simeq f$

SM spectra

$\langle H_A \rangle = v = 246\,\text{GeV}$

Twin Higgs Spectra



- ☑ Higgs pheno
- ☑ Twin top signature
- ☑ Dark matter candidate
- ☑ Cosmological signature

Disadvantage

Yu, PRD 2016 (rapid communication)
Yu, JHEP 2016

The Z2 breaking mechanism is unknown

Dark radiation Neff constraint very tight

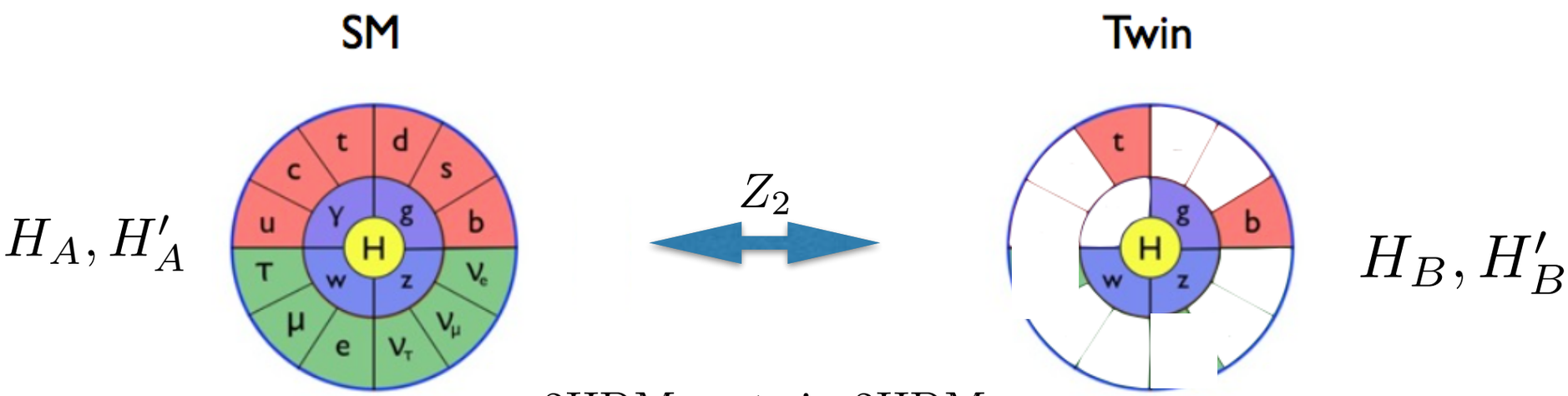
Hidden sector needs Mirror SM

Twin Two Higgs Doublet Model

Extend the Higgs Sector with vector like top

J-H.Yu, PRD 2016

J-H.Yu, JHEP 2017



2HDM $\leftrightarrow$ twin 2HDM

Type-I/II Twin 2HDM $\quad H \equiv \begin{pmatrix} H_A \\ H_B \end{pmatrix}, H' \equiv \begin{pmatrix} H'_A \\ H'_B \end{pmatrix}$

Z2 symmetry is radiatively broken via vacuum alignment

Higgs potential is fully predictive

$$V(h) \simeq -\left(\frac{3y_t^4 f^2}{16\pi^2} - \frac{g^4 f'^2}{16\pi^2}\right) h^2 + \frac{3y_t^4}{16\pi^2} h^4$$

Yukawa-gauge cancellation to obtain 125 GeV Higgs mass!

Minimal Neutral Top Model

Xu, Yu, Zhu, in progress

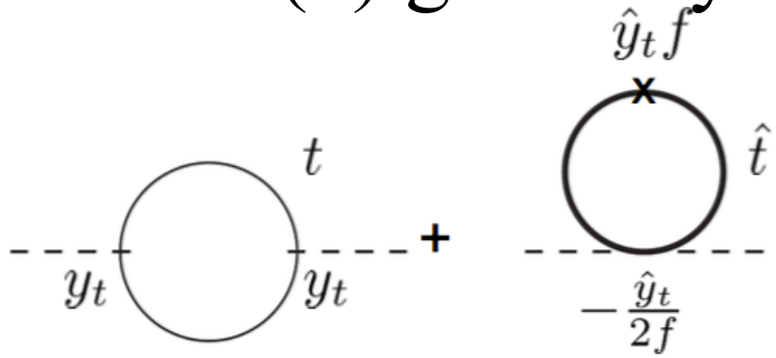
☑ Minimal hidden sector [No hidden SU2 and U1]

☑ Custodial symmetry is still protected

No additional hidden fermion needed

free hyper-charge assignment

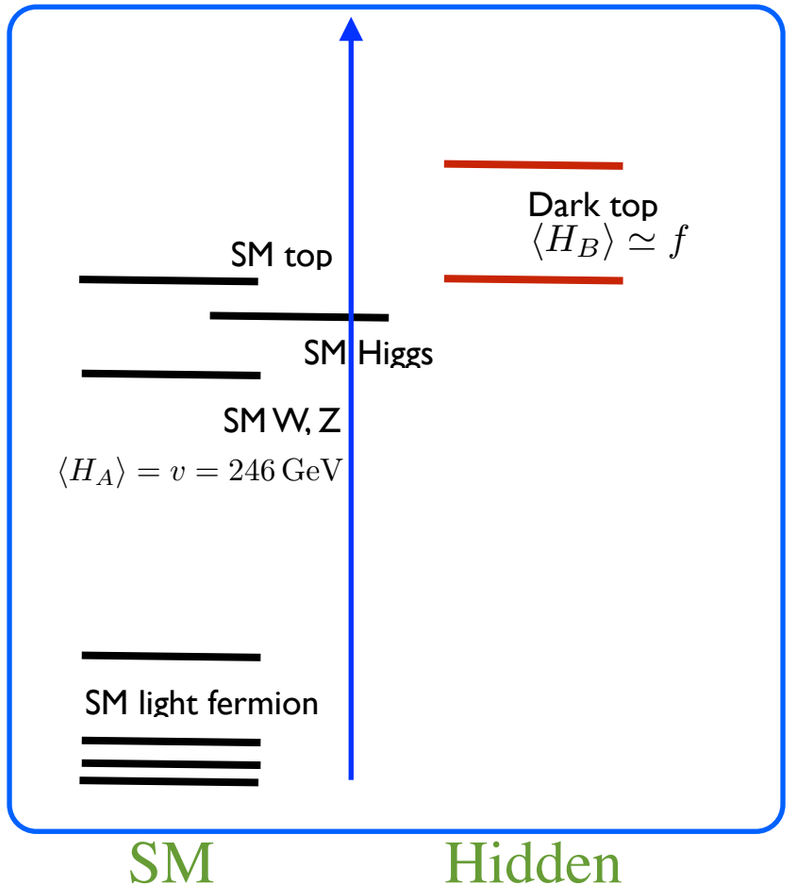
Yukawa terms with SU(6) global symmetry embedded

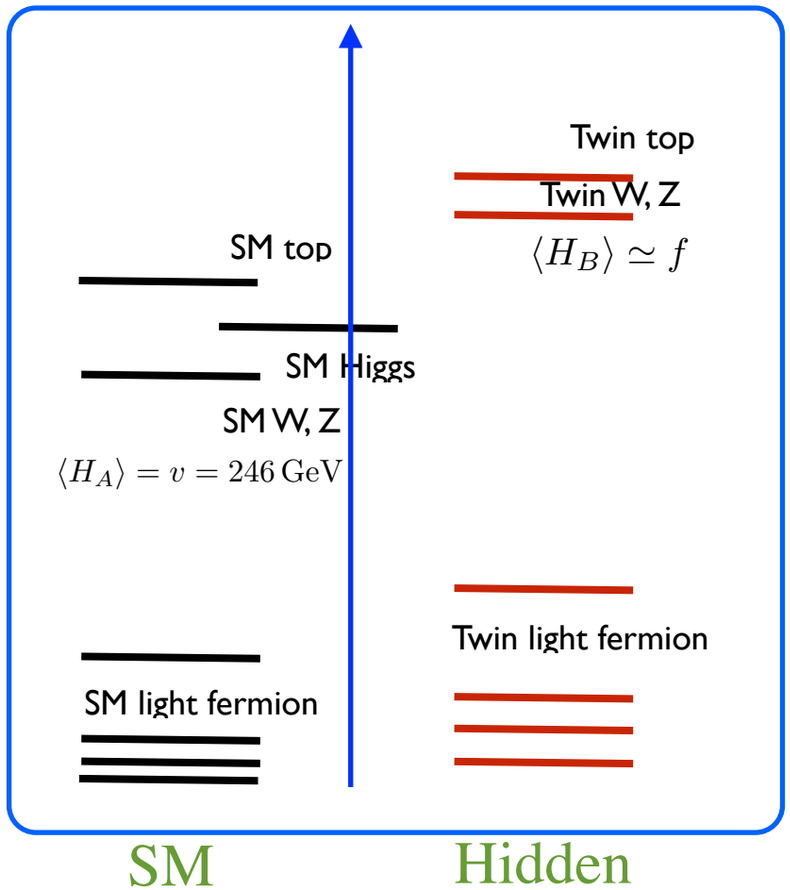


Top partner hypercharge freely assigned. No hypercharge, DM

Hidden Sector Spectra

Comparison between this model and twin Higgs model spectra



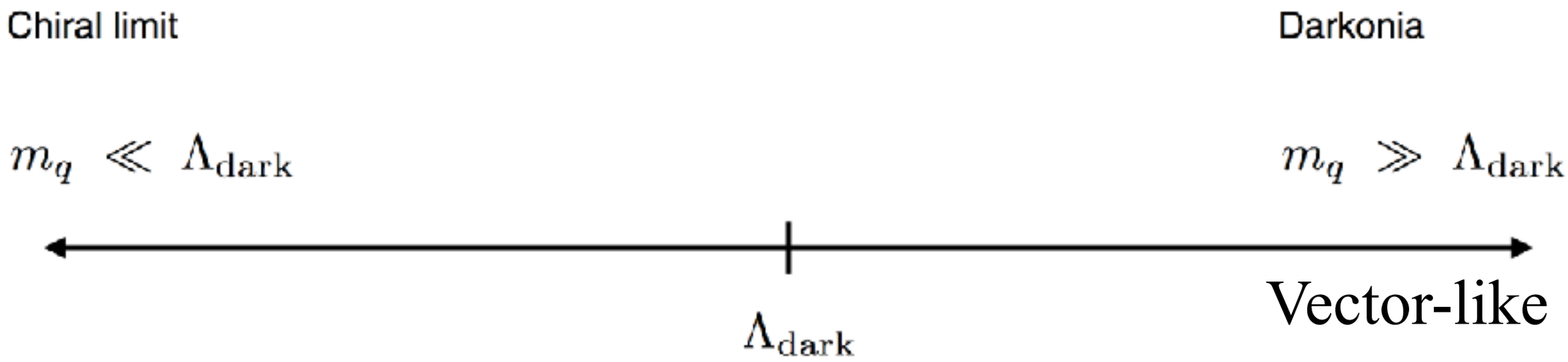


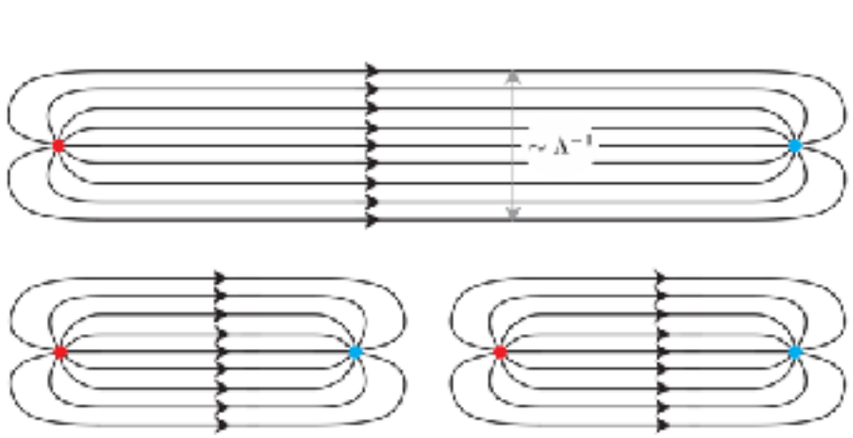
Top partner is QCD-neutral, only carries hidden SU(3) color

W, Z loop cancellation: composite setup with W' Z'

Hidden QCD Sector

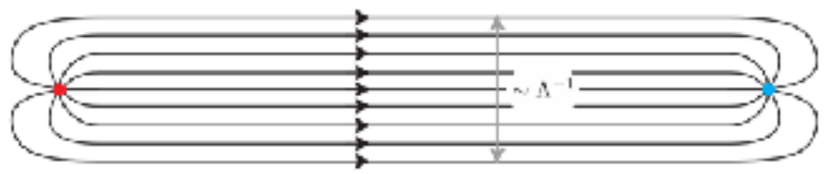
Top partner does not carry QCD color and EW charge





QCD string with hadronization

Quark

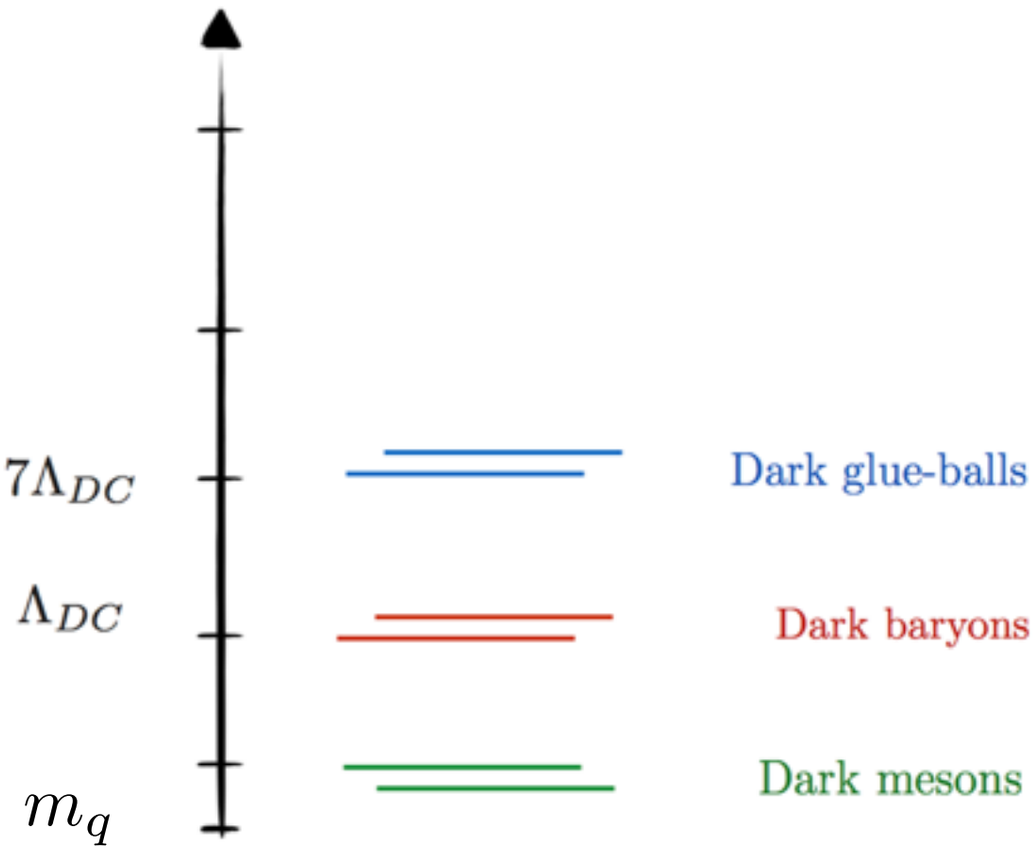


$$\Gamma_{\rm break} \sim e^{-m_Q^2/\Lambda^2}$$

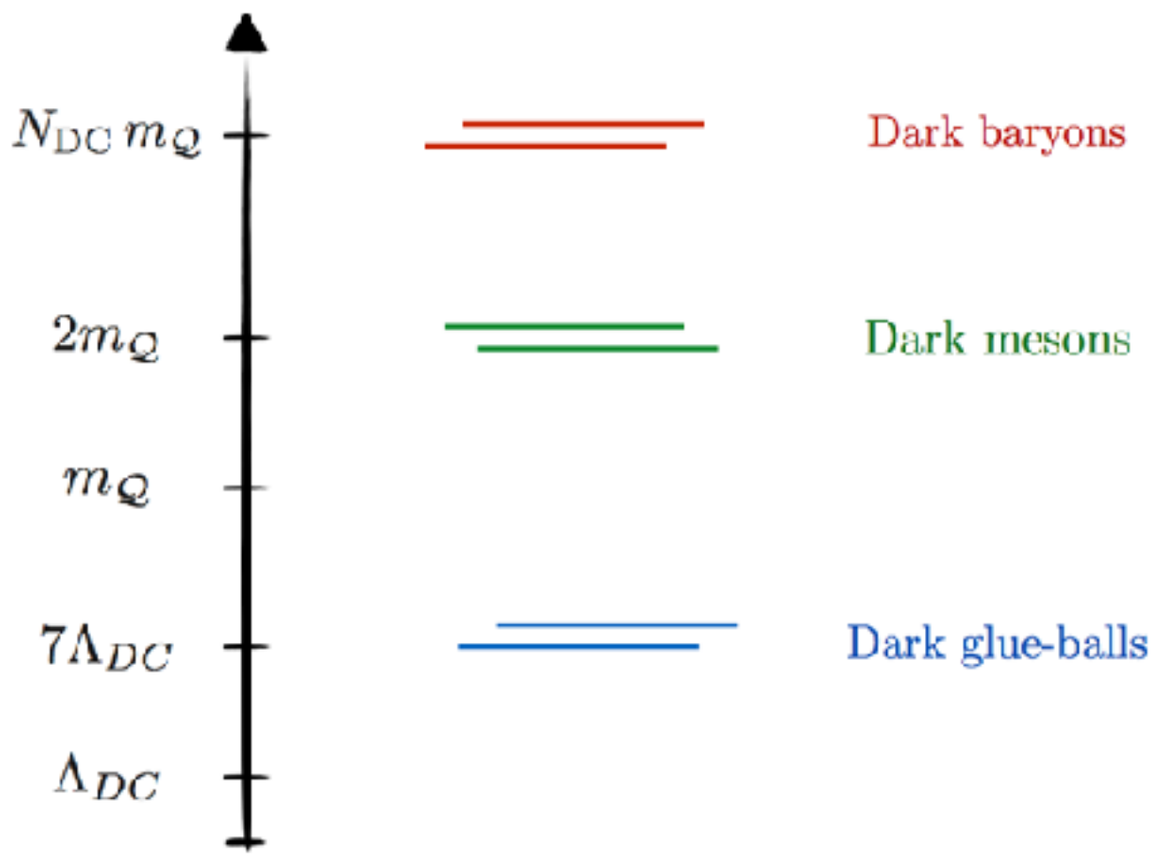
Stable macroscopic string

Quirk

Hidden Hadronic Spectra



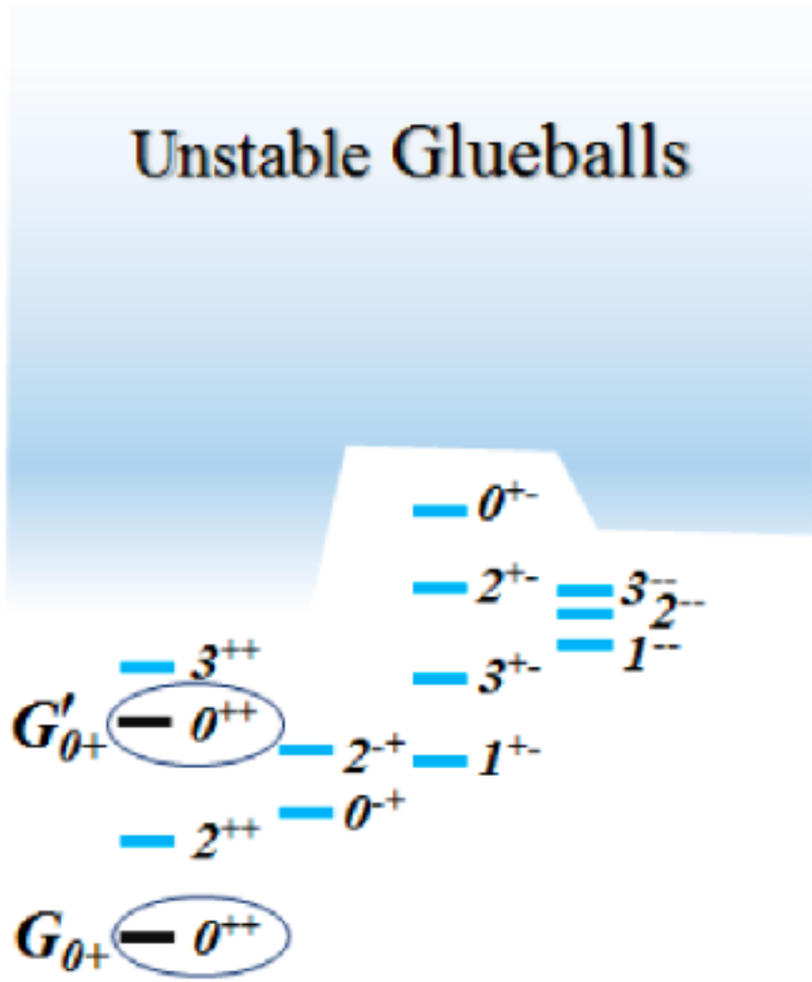
Dark baryon or meson stable depending on parity/baryon number



Dark glueball dark matter?

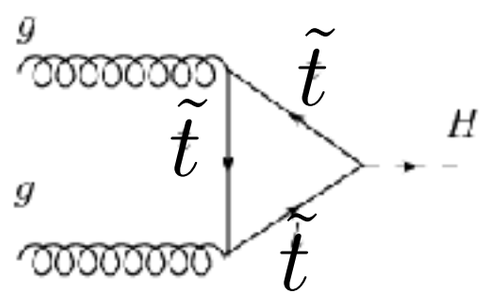
Hidden Glueball Spectra

i	J^{PC}	$m_i/m_{0^{++}}$
1	0^{++}	1.00
2	2^{++}	1.39
3	3^{++}	2.13
4	0^{-+}	1.50
5	2^{-+}	1.79
6	1^{+-}	1.70
7	3^{+-}	2.05
8	2^{+-}	2.40
9	0^{+-}	2.74
10	1^{--}	2.23
11	2^{--}	2.27
12	3^{--}	2.39



Forestell, Morrissey, Sigurdson, 16

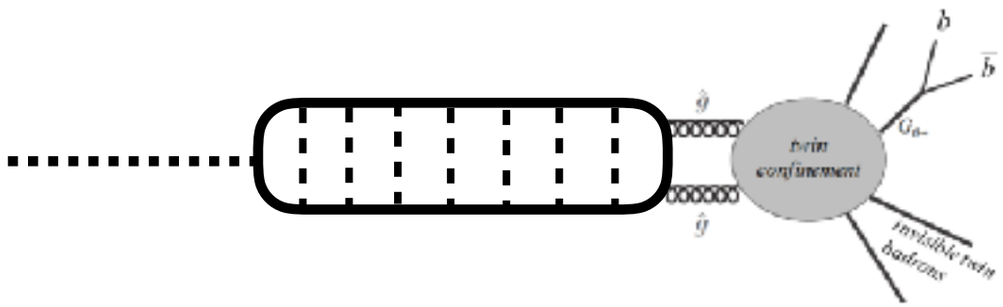
Glueball decays via off-shell Higgs to SM final states



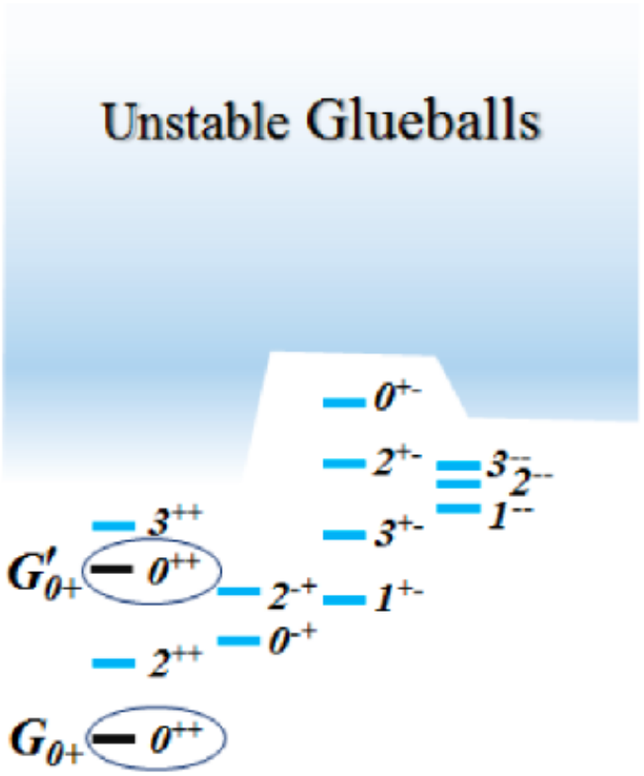
Hidden QCD Signature

Top partner cannot be produced via QCD and EW processes

Only appears in Higgs exotic decay



Displaced vertices



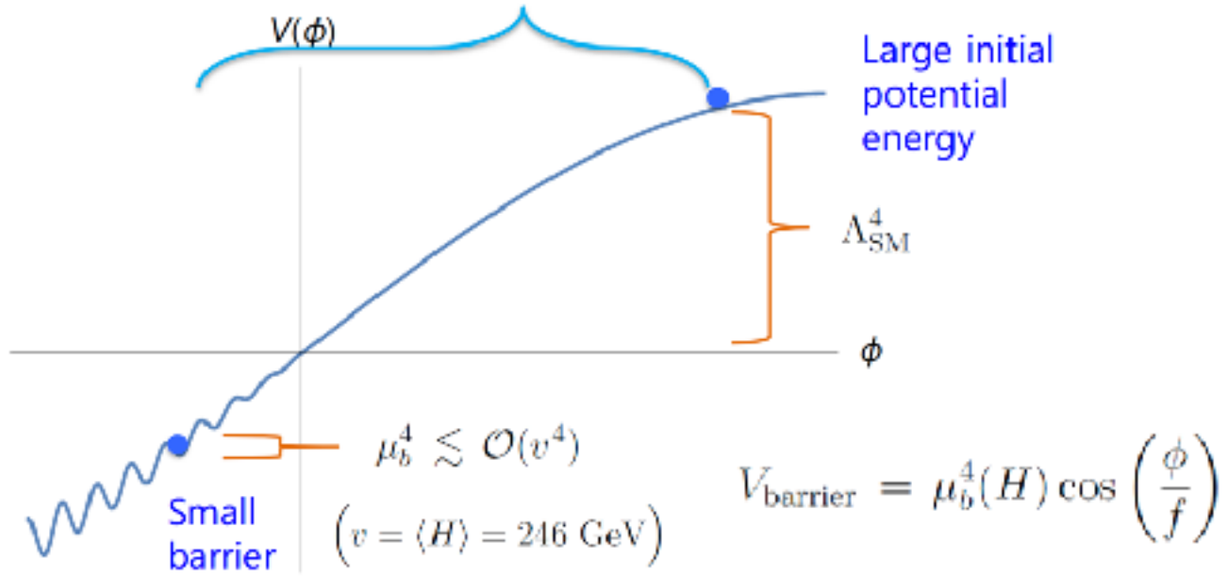
Craig, Katz, Strassler, Sundrum, 15

Hidden glueball decay via Higgs

Dynamical Selection in IR

Relaxion

Kaplan, Graham, et. al. 2015



NNaturalness

Arkani-Hamed, et. al. 2017

+ cosmological dynamics which prefer to reheat the lightest sector to form the Universe

Critical Higgs, etc

Summary

Summary and Future Directions

☑ There are many kinds of naturalness solution proposals.

UV symmetry and IR dynamical selection

☑ Neutral naturalness might provide last refuge for naturalness!

Twin Higgs,
minimal neutral top


In neutral naturalness, lots of studies need to be done!

new color sector, exotic collider/Higgs pheno, cosmo, etc

Thank you!