Minimal Neutral Naturalness

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Ling-Xiao Xu, JHY, Shu-hua Zhu, in preparation

JHY, PRD 95 (2017) 095028
JHY, PRD 94 (2016) 111704
JHY, JHEP 1612 (2016) 134

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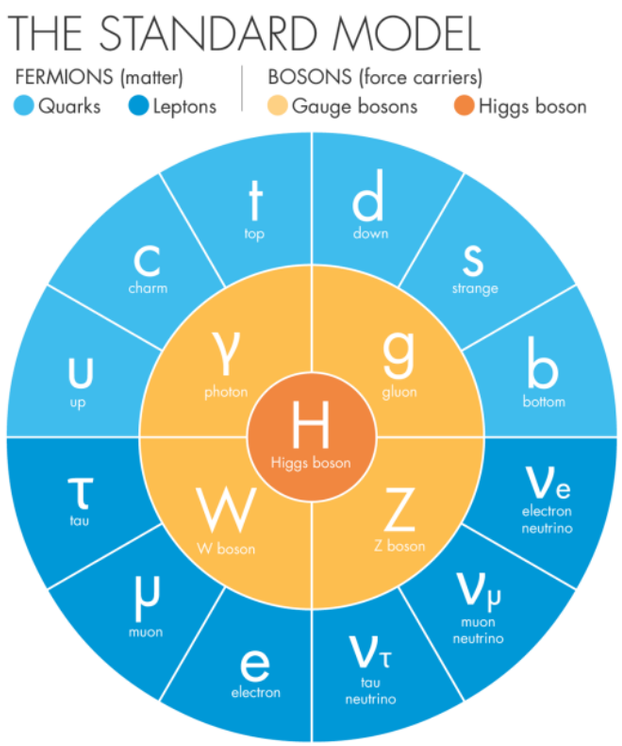
August 20, 2018

Motivation For New Physics



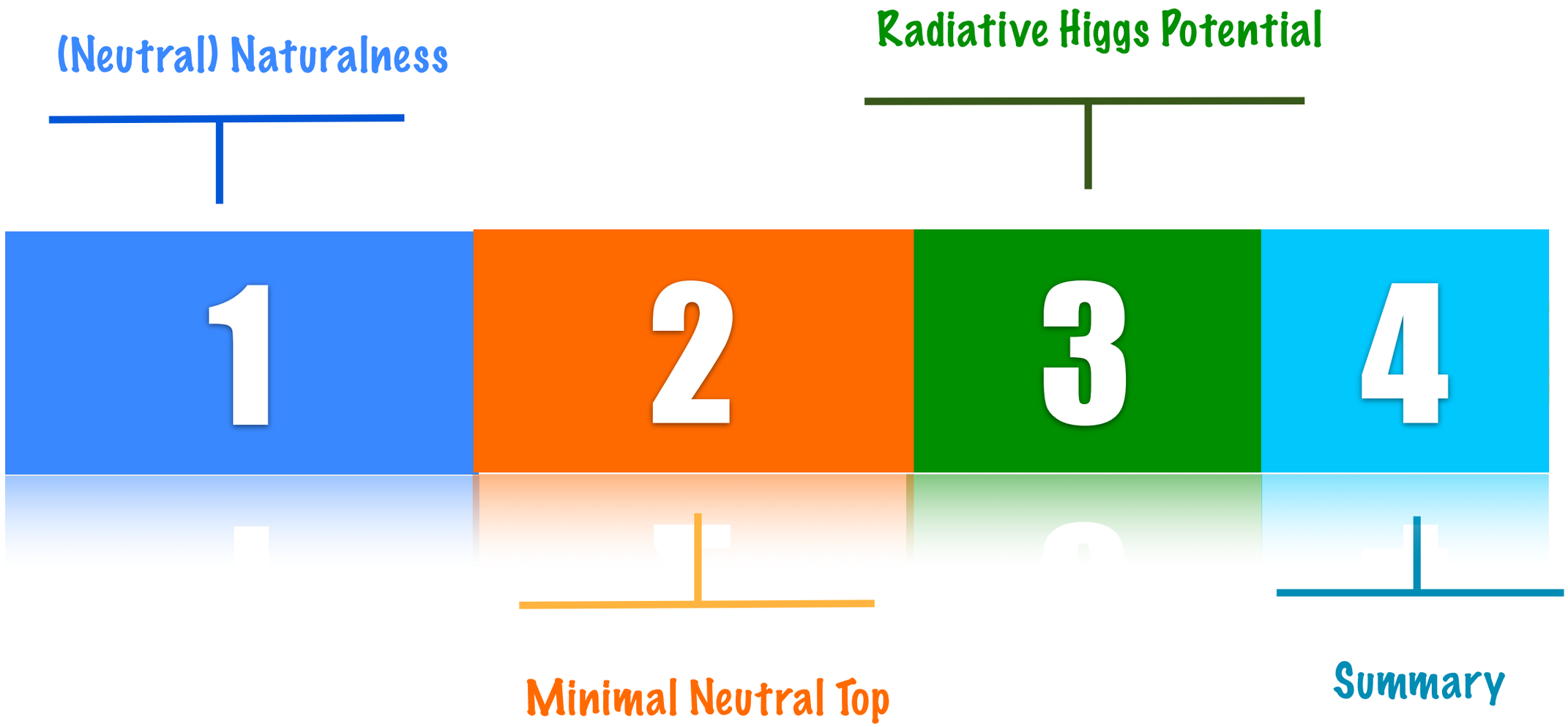
- Nature of Higgs (Higgs potential) unknow
- There are evidences of dark matter
- Matter-antimatter asymmetry

- A theory to address all of them together?

SUSY

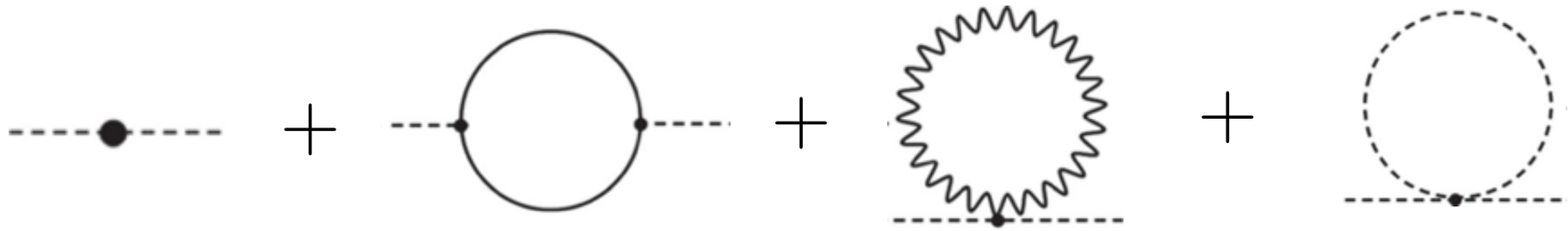
Neutral Naturalness

Outline


(Neutral) Naturalness
Radiative Higgs Potential
1
2
3
4
Minimal Neutral Top
Summary

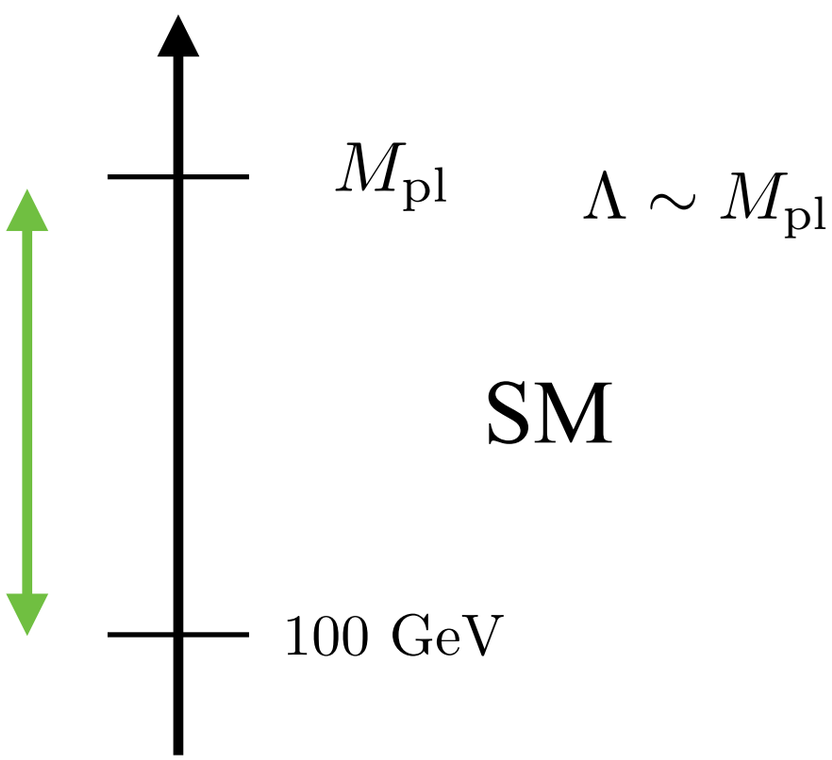
Hierarchy Problem

Higgs mass parameter

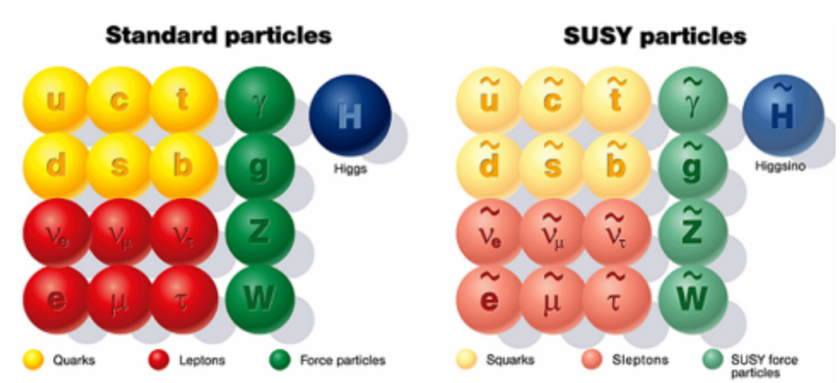
$-(100\ \mathrm{GeV})^2 =$ 

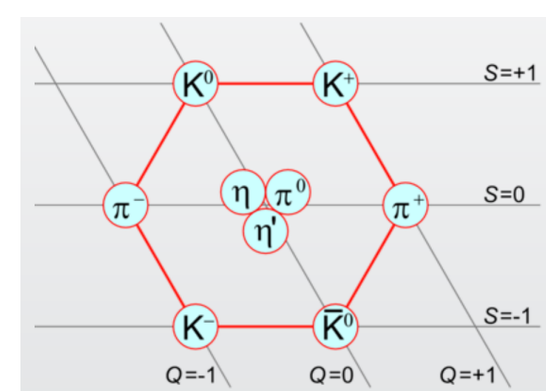
$$= \quad c\,\Lambda^2 \quad + \quad \frac{\Lambda^2}{16\pi^2}\left(-6y_t^2 + \frac{3}{4}(3g^2 + g'^2) + 6\lambda\right)$$

In EFT, cutoff just means physical thresholds of underlying physics



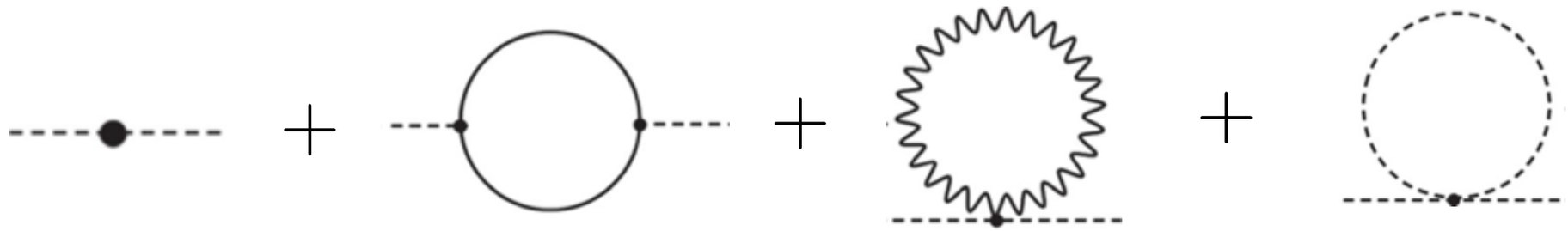
Introduce symmetry for Higgs boson





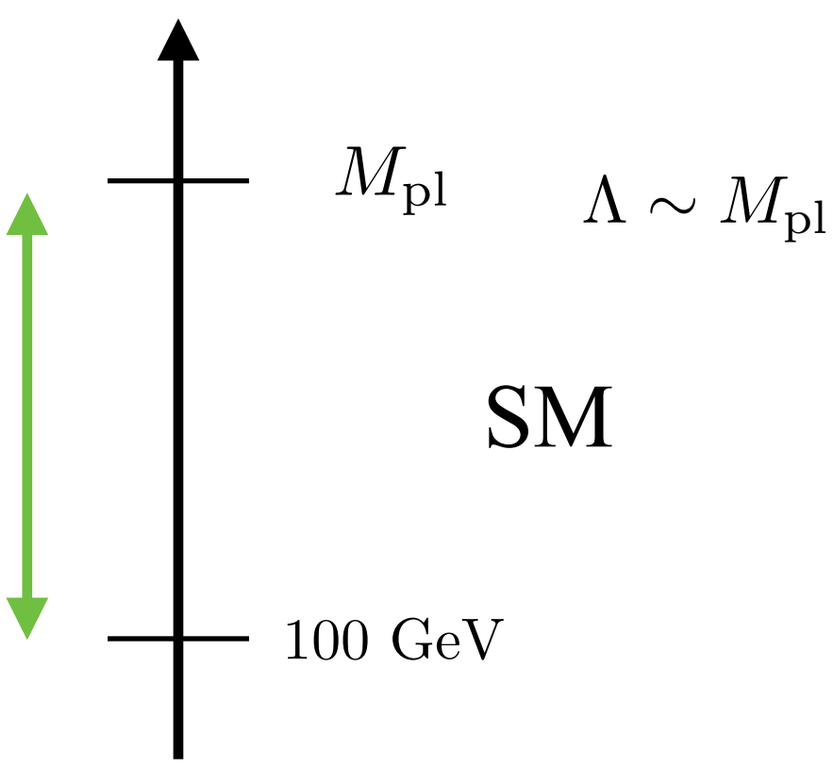
Naturalness

Higgs mass parameter

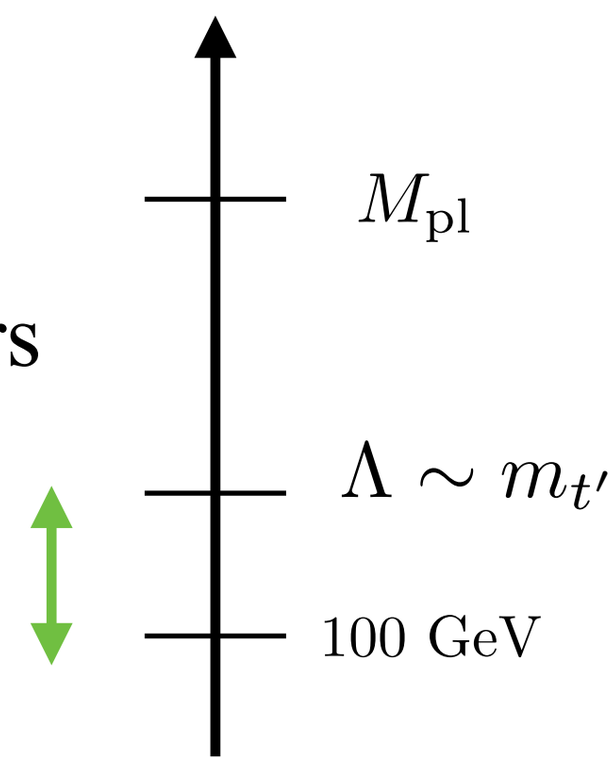
$-(100\ \mathrm{GeV})^2 =$ 

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

In EFT, cutoff just means physical thresholds of underlying physics

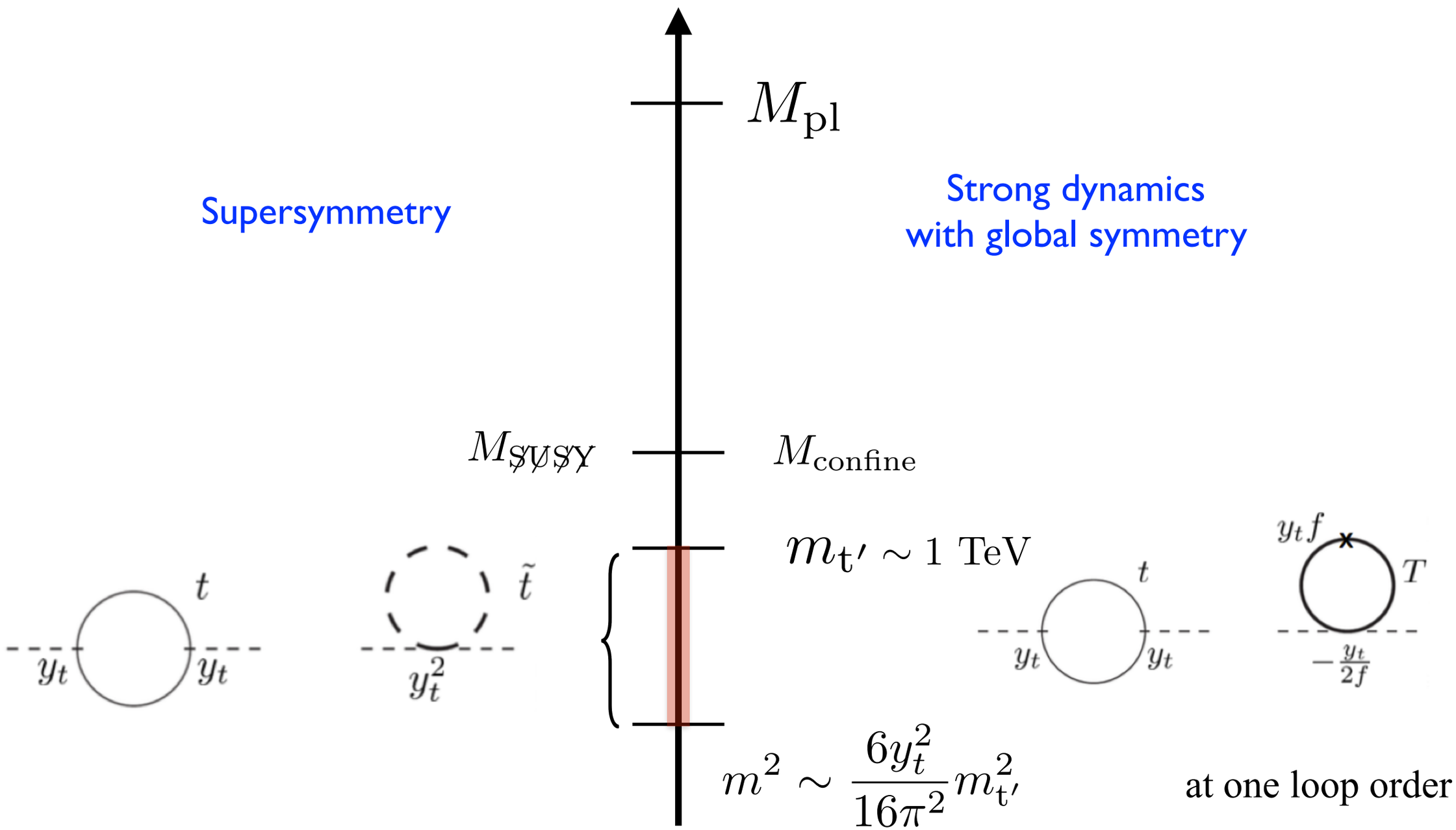


UV symmetry lowers threshold to TeV



Top Partner & Little Hierarchy

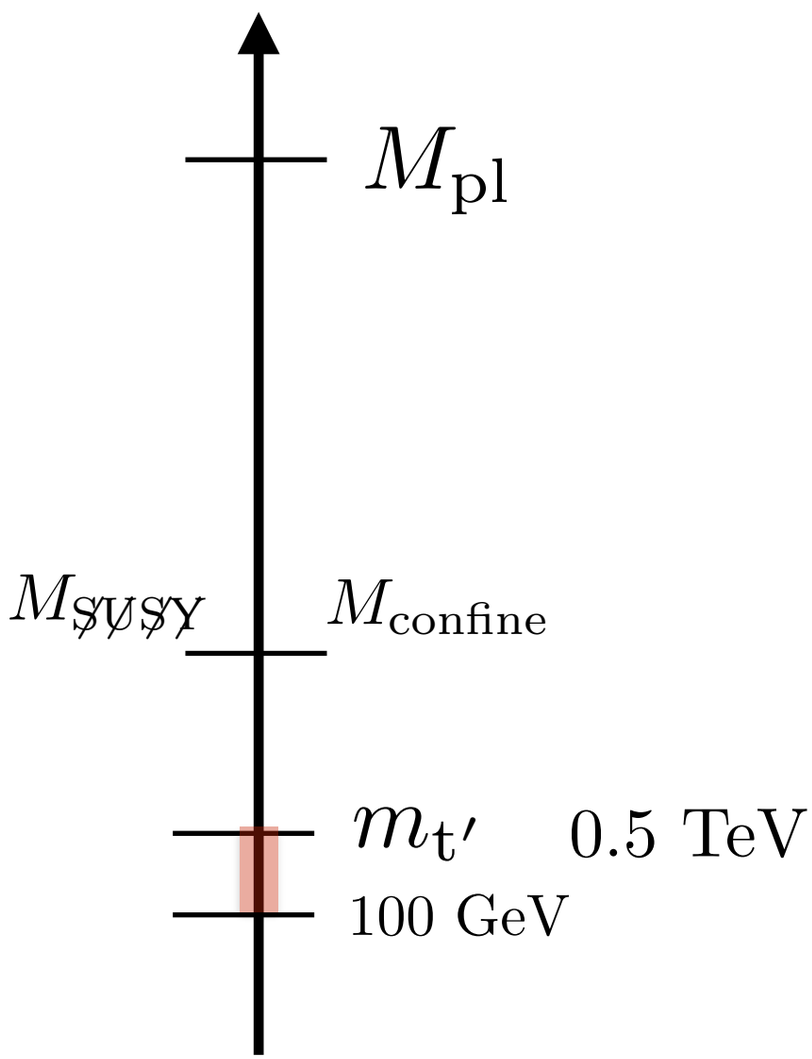
Higgs Boson only sees top partner scale, not Planck scale

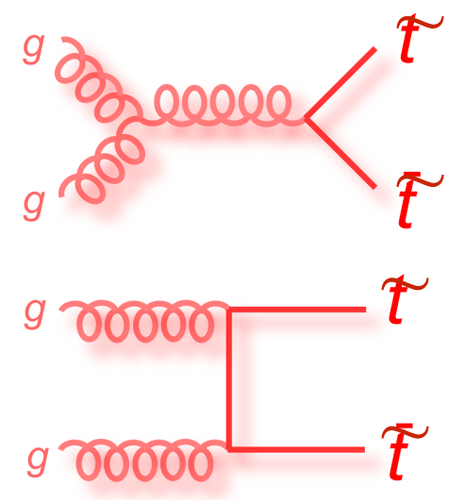


Top partner above 1 TeV, little hierarchy (percent-level tuning)!

Towards 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

Why Neutral Naturalness?

- ☑ Solve little hierarchy problem existing in SUSY and composite Higgs
- ☑ New kind of top partner (no charge under QCD)

  Xu, JHYu, Zhu, in preparation
- ☑ New dark matter candidate from hidden QCD
- ☑ Baryon asymmetry from asymmetric dark matter

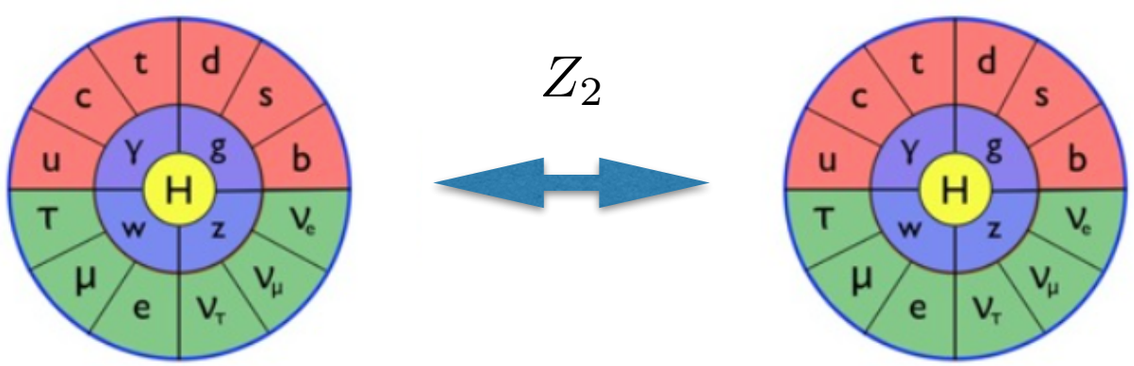
  Ramsey-Musolf, JHYu, in progress
- ☑ New scenarios for axion and dark axion

  Drapper, Kozaczuk, JHYu, 2018

Concrete Model: Twin Higgs

Mirror Standard Model

Chacko, Goh, Harnik 05



Sector A

Sector B

Accidental SU(4) symmetry in Higgs potential

$$V(H) = -m^2 H^\dagger H + \lambda (H^\dagger H)^2$$

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

Global symmetry breaking

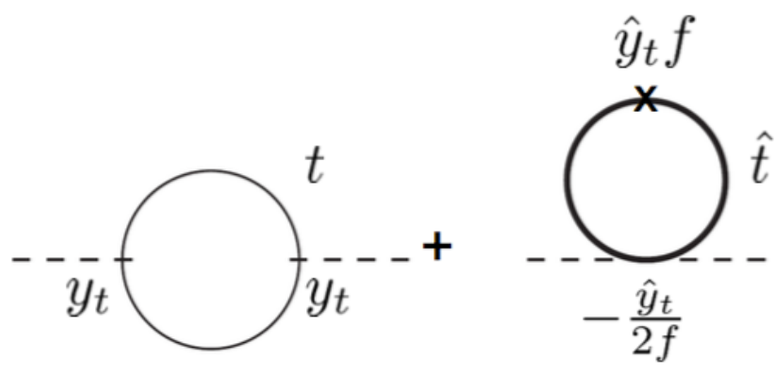
$$SU(4) : H = \begin{pmatrix} H_{\rm SM} \\ H_{\rm twin} \end{pmatrix} \to SU(3)$$

$$H \equiv \begin{pmatrix} H_A \\ H_B \end{pmatrix} \begin{matrix} \leftarrow SU(2)_A \\ \leftarrow SU(2)_B \end{matrix}$$

7 Goldstone Bosons,
Higgs as one of Goldstone Boson

Mirror Twin Higgs

Z2 symmetry is crucial for quadratic div. cancellation



$$\mathcal{L} \supset y_A \overline{q_A} H_A t_A + y_B \overline{q_B} H_B t_B$$

$$\downarrow \qquad\qquad \downarrow$$

$$h + \ldots \qquad\qquad f - \frac{h^2}{2f} + \ldots$$

Gauge/Yukawa symmetry breaks SU(4) to SU(2) x SU(2) x Z2

$$V \supset \frac{9\Lambda^2}{64\pi^2}\left(g_A^2 H_A^\dagger H_A + g_B^2 H_B^\dagger H_B\right) - \frac{6\Lambda^2}{16\pi^2}\left(y_A^2 H_A^\dagger H_A + y_b^2 H_B^\dagger H_B\right)$$

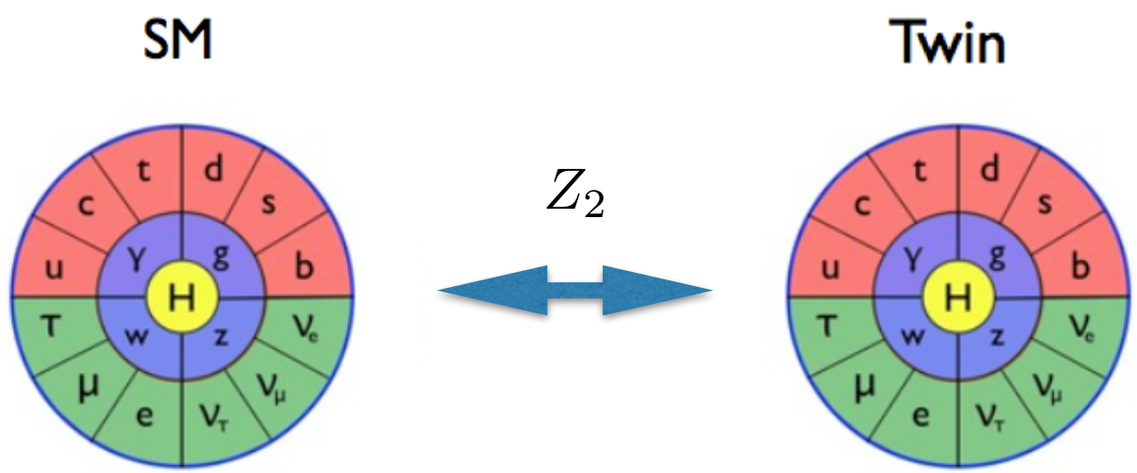
$$\xrightarrow{Z_2} \quad V \supset \left(\frac{9g^2\Lambda^2}{64\pi^2} - \frac{6\Lambda^2}{16\pi^2}\right)\left(H_A^\dagger H_A + H_B^\dagger H_B\right)$$

Accidental SU(4) symmetry preserved in leading contribution if Z2 in gauge and Yukawa terms

Mirror Twin Higgs Pheno

Mirror SM with Z2 symmetry

Due to anomaly cancellation, need whole family fermions



The Z2 symmetry needs to be broken at low energy

Analogy: SUSY needs to be broken at low energy

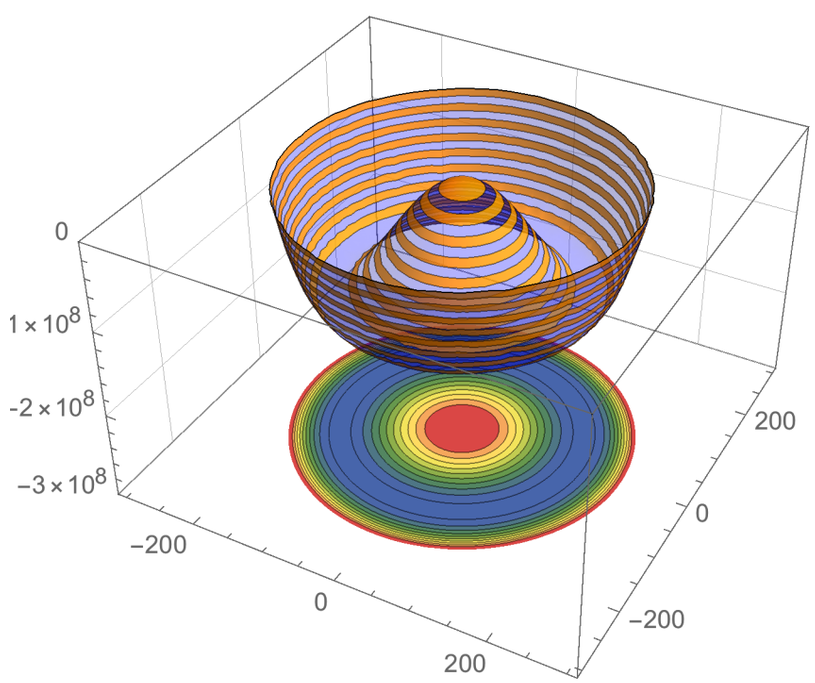
Otherwise, not agree with Higgs data

Unfold the Higgs Potential

Scalar potential with Mirror Higgs

$$V \supset \underbrace{\lambda(H_A^2 + H_B^2 - f^2)^2}_{U(4),\, Z_2}$$

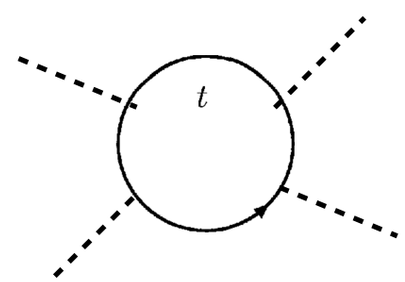
$U(4) \to U(3) = 7$ Goldstones

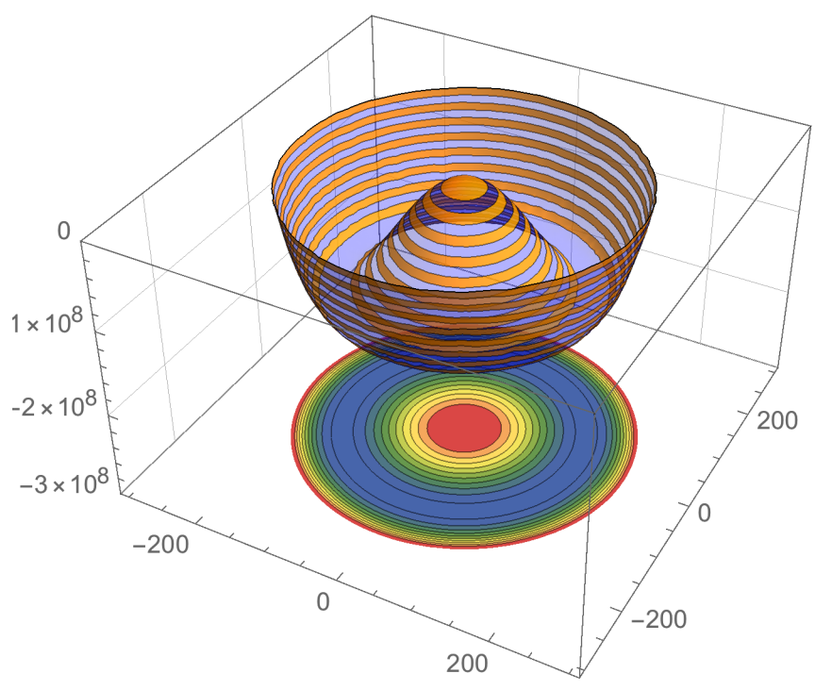


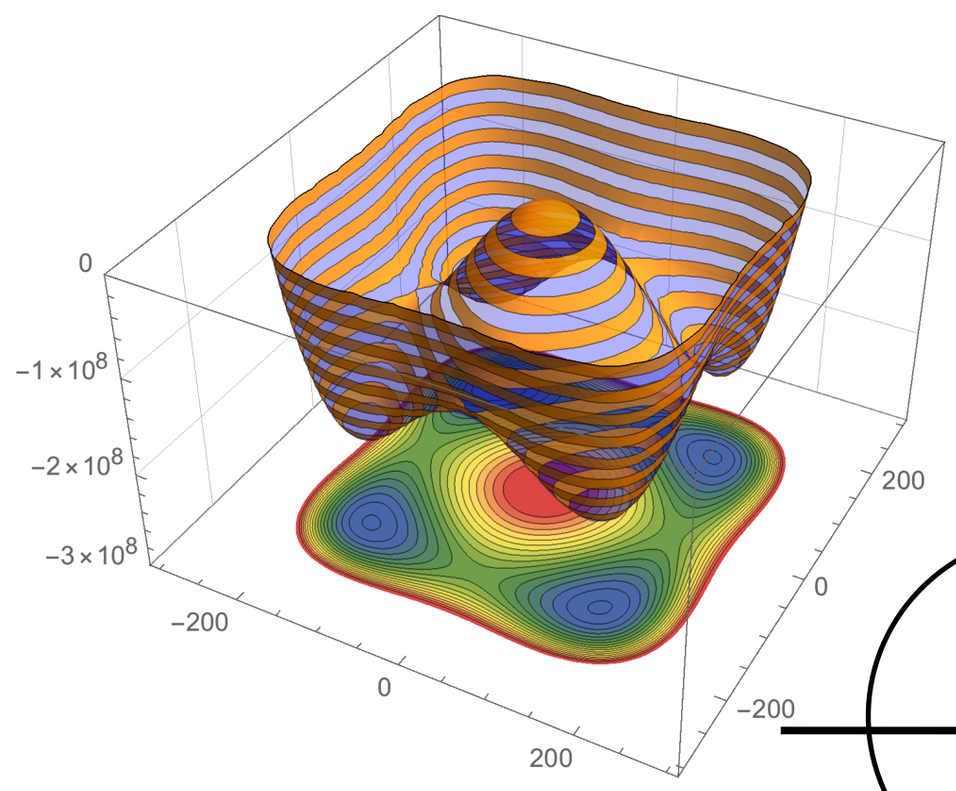
Unfold the Higgs Potential

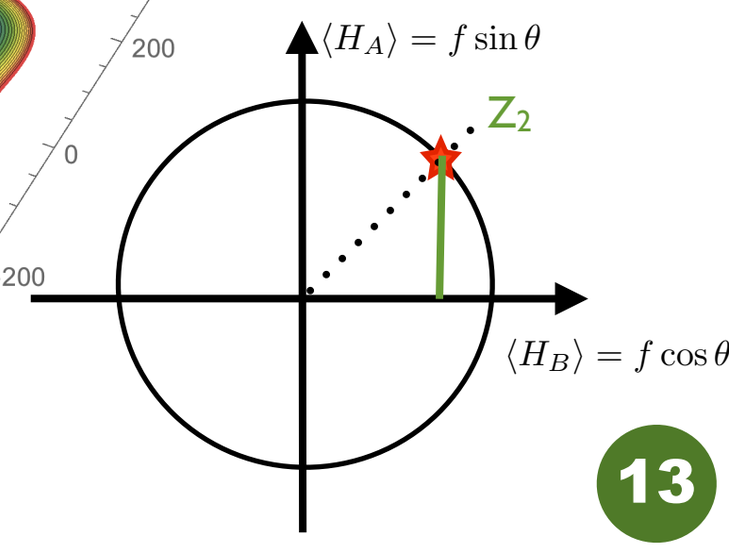
$$V \supset \underbrace{\lambda(H_A^2 + H_B^2 - f^2)^2}_{U(4),\, Z_2} - \underbrace{\frac{3y_t^4\Lambda^2}{8\pi^2}(H_A^2 + H_B^2)}_{U(4),\, Z_2} + \underbrace{\frac{3y_t^4}{16\pi^2}H_A^2 H_B^2}_{\not{U}(4),\, Z_2}$$

$U(4) \to U(3) = 7$ Goldstones

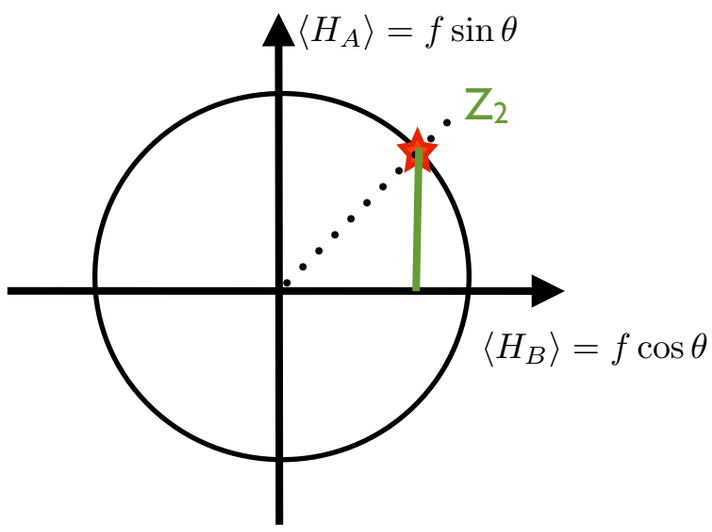


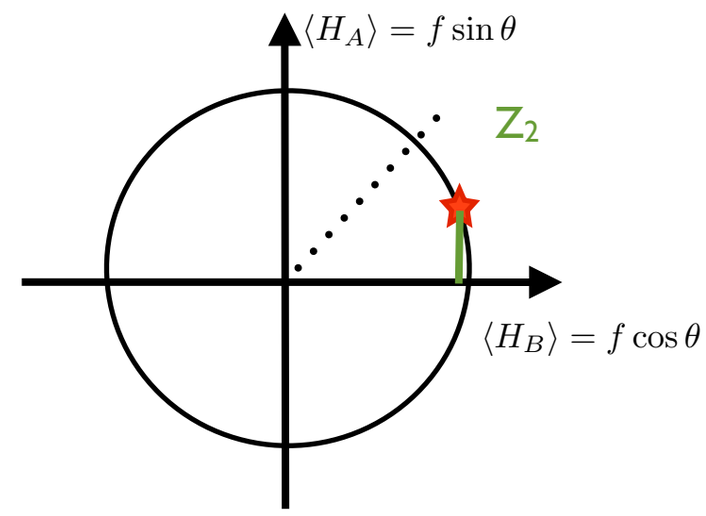






Vacuum Misalignment

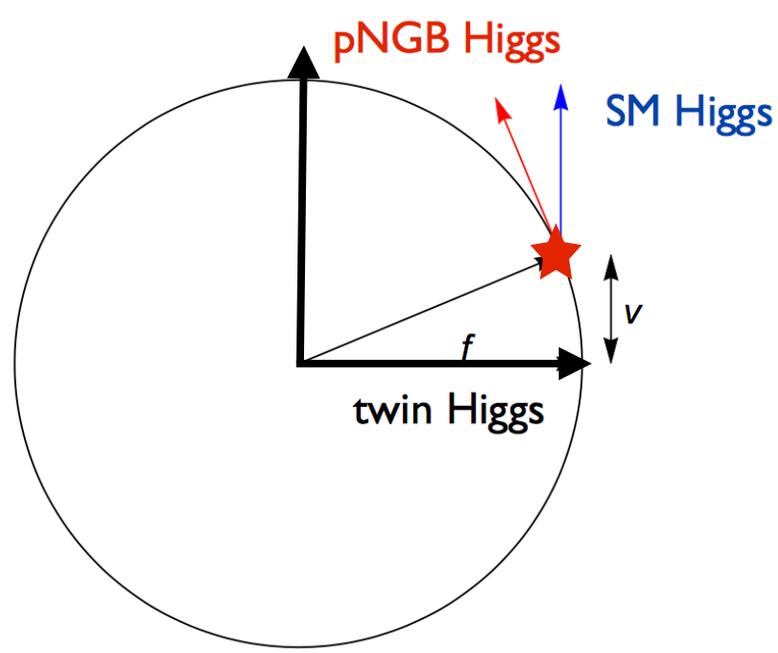




$$g_{\text{pNGB HiggsWW}} = \frac{g_{\text{SM HiggsWW}}}{\sqrt{2}}$$

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

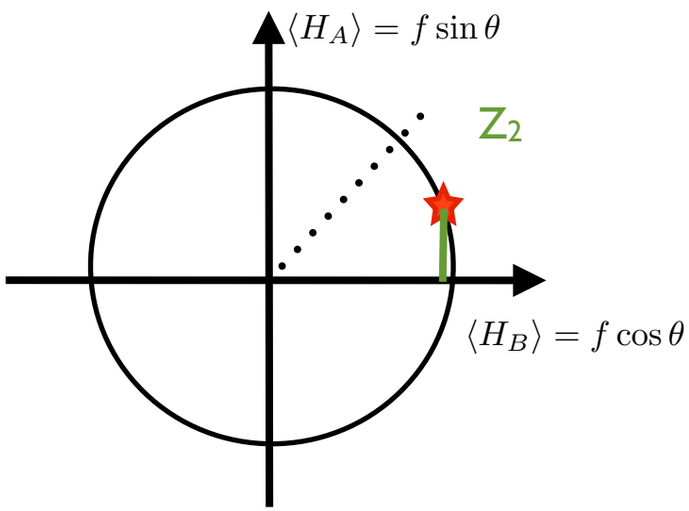
$\langle H_A \rangle = v = 246\,\text{GeV}$

Unfold the Higgs Potential

$$V \supset \underbrace{\lambda(H_A^2 + H_B^2 - f^2)^2}_{U(4),\, Z_2} - \underbrace{\frac{3y_t^4\Lambda^2}{8\pi^2}(H_A^2 + H_B^2)}_{U(4),\, Z_2} + \underbrace{\frac{3y_t^4}{16\pi^2}H_A^2 H_B^2}_{\not{U}(4),\, Z_2} + \underbrace{m'^2 H_A^2}_{\not{U}(4),\, \not{Z}_2}$$

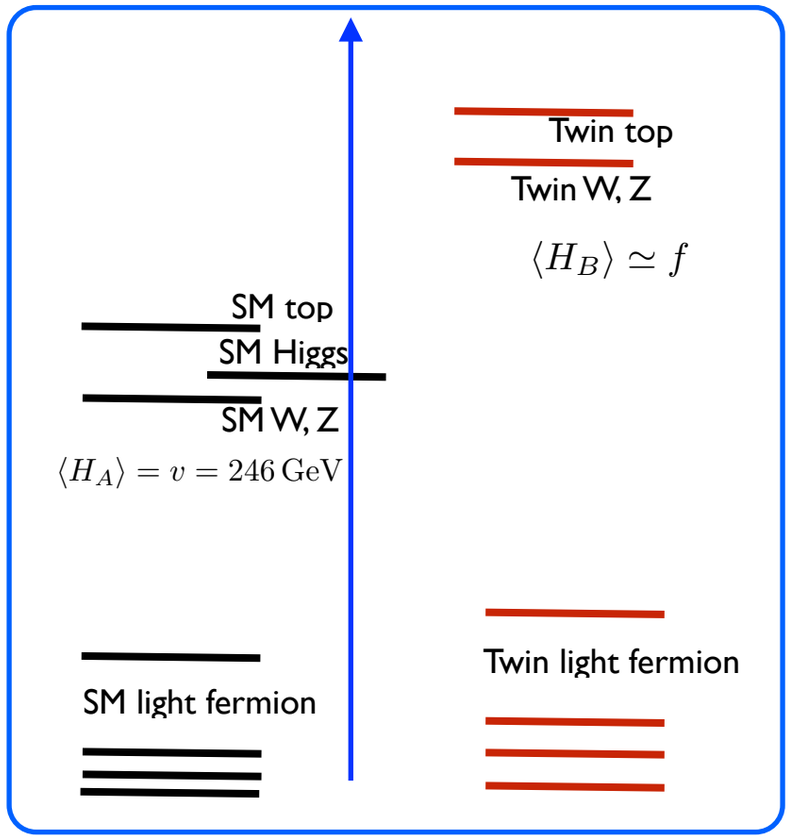
$U(4) \to U(3) = 7$ Goldstones

Z2 broken
pGB gets
125 GeV mass



$\langle H_A \rangle = v \ll \langle H_B \rangle \simeq f$

Twin Higgs Spectra



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

Disadvantage

The Z2 breaking mechanism is unknown

Dark radiation Neff constraint very tight

Hidden sector needs Mirror SM

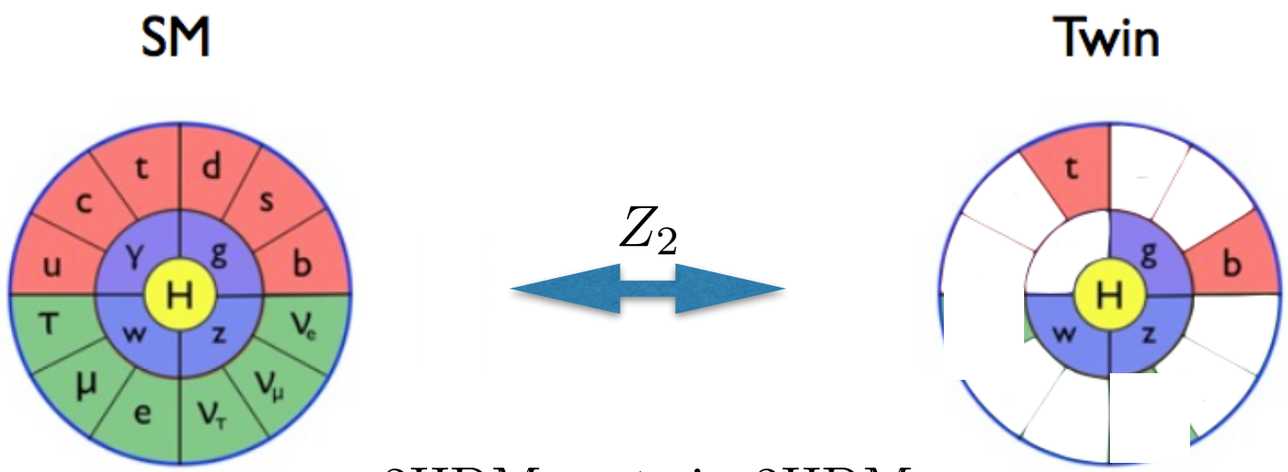
Twin Two Higgs Doublet Model

Extend the Higgs Sector with vector like top

J-H.Yu, PRD 2016

J-H.Yu, JHEP 2016

H_A, H'_A



H_B, H'_B

2HDM $\leftrightarrow$ twin 2HDM

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

Higgs potential is fully predictive
(soft breaking term radiatively generated)

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

Yukawa-gauge cancellation to obtain 125 GeV Higgs mass!

No need whole generation fermions

Minimal Neutral Naturalness

Twin Higgs Setup:

- ? Additional weak twin symmetry is unnecessary
- ? Top partner is chiral, need whole generation fermions

A Minimal Neutral Naturalness model:

- ✓ Minimal hidden sector [No hidden SU2 and U1]
- ✓ No need whole generation hidden fermions
- ✓ Dark Radiation Neff constraint could be avoided
- ✓ Custodial symmetry is still protected

Minimal Neutral Top Model

Based on SO(5)/SO(4) coset, instead of SU(4)/SU(3)

$$H = \exp\left[i\begin{pmatrix} \mathbf{0}_{4\times4} & \mathbf{h} \\ \mathbf{h} & 0 \end{pmatrix}\right]\begin{pmatrix} \mathbf{0}_4 \\ f \end{pmatrix} \simeq \begin{pmatrix} \mathbf{h} \\ f - \frac{1}{2f}\mathbf{h}^2 \end{pmatrix}$$

Introduce color neutral, vector-like top partners

$$\tilde{\mathbf{q}} \sim (1,3,2)_Y \qquad \tilde{T} \sim (1,3,1)_Y$$

Embed into SO(5) multiplet, add SU(6) global symmetry

$$\mathcal{Q}_L = \begin{pmatrix} \mathbf{q}_L & \tilde{\mathbf{q}}_L \\ 0 & \sqrt{2}\tilde{T}_L \end{pmatrix} \qquad \mathcal{T}_R = \begin{pmatrix} t_R & \tilde{T}_R \end{pmatrix}$$

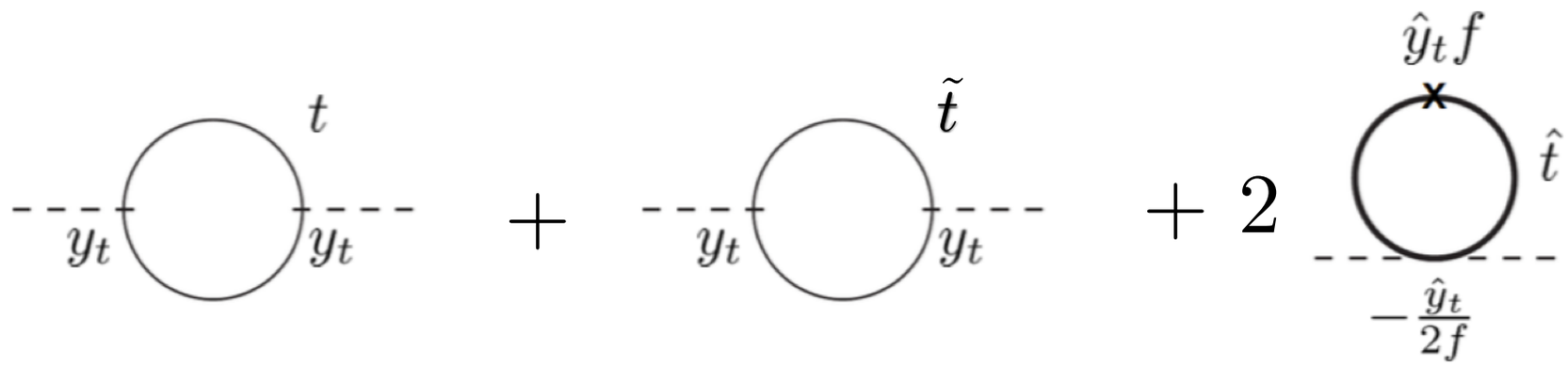
$$\mathcal{L} \supset y_t \overline{\mathcal{Q}}_L \mathcal{H} \mathcal{T}_R + m_q \overline{\mathcal{Q}}_L \mathcal{Q}_R + h.c.$$

How Quadratic Div. Cancelled?

SU(6) symmetry guarantees Quadratic Div. Cancellation

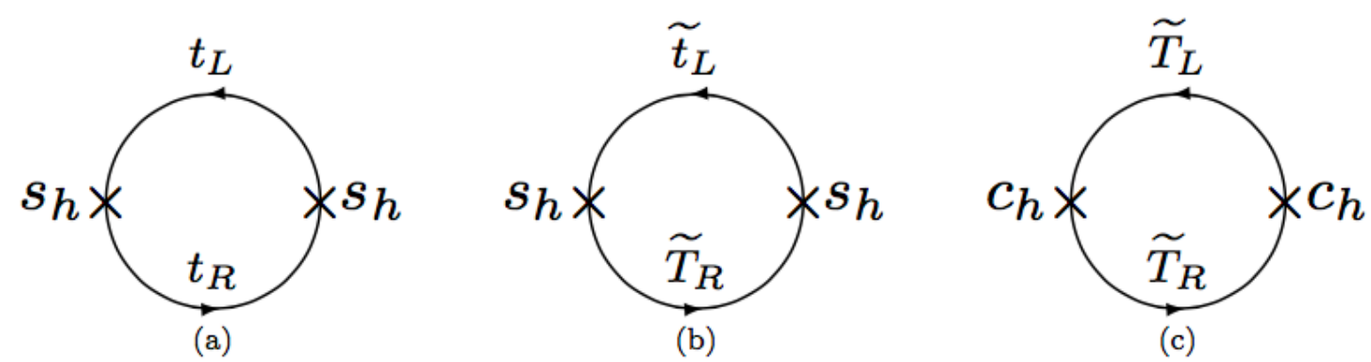
$$\mathcal{L} \supset y_t \overline{\mathbf{q}}_L H t_R + y_t \overline{\tilde{\mathbf{q}}}_L H \tilde{T}_R + \sqrt{2} y_t \overline{\tilde{T}}_L (f - \frac{H^\dagger H}{f}) \tilde{T}_R + h.c.$$

$m_h^2 =$



Hidden Doublet *Hidden Singlet*

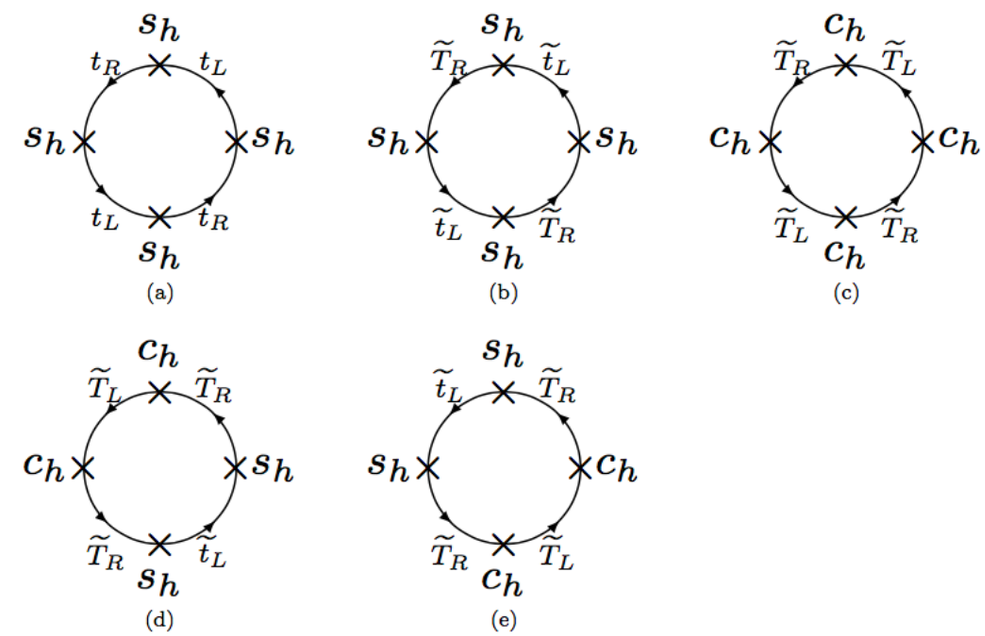
$$V(h) \sim \frac{y_L^2 f^2 N_c \Lambda^2}{16\pi^2} \left(\frac{1}{2} s_h^2 + \frac{1}{2} s_h^2 + c_h^2 \right)$$

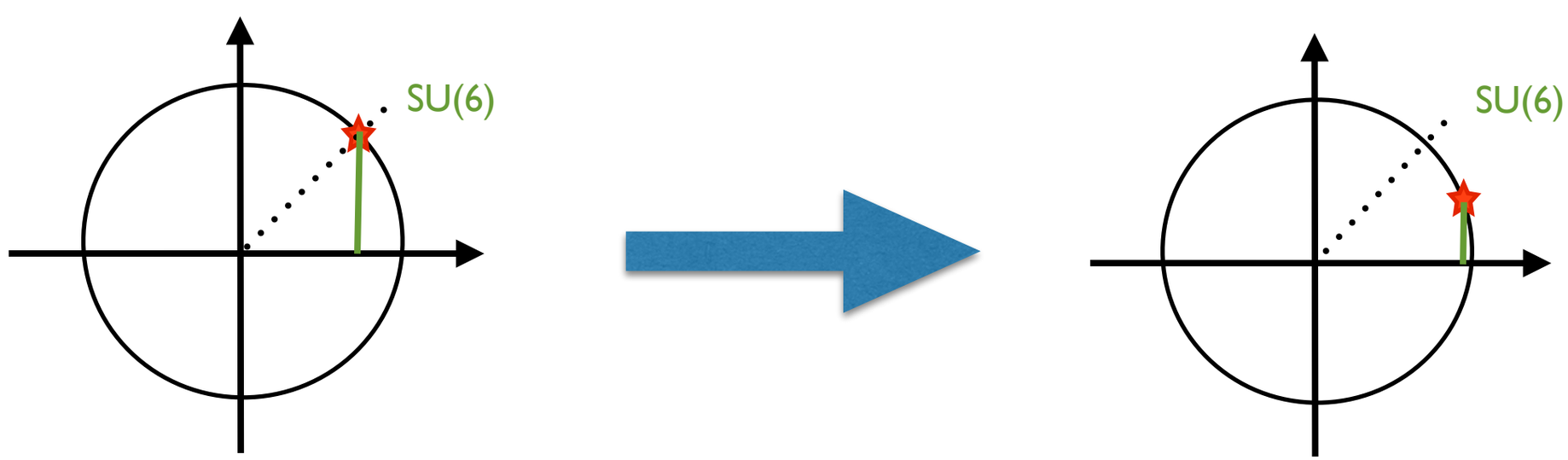


Unfold the Higgs Potential

Higgs potential is radiatively generated

$$V(h) \sim \frac{y_L^4 f^4 N_c \log\Lambda^2}{16\pi^2}\left(\frac{1}{2}s_h^4 + s_h^2 c_h^2 + c_h^4\right)$$
$$\sim \frac{y_L^4 f^4 N_c \log\Lambda^2}{16\pi^2}\left(-s_h^2 + \frac{1}{2}s_h^4\right).$$

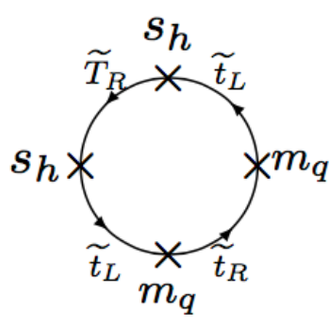




Vacuum Misalignment

Break SU(6) symmetry radiatively via mass term

$$\mathcal{L} \supset y_t \overline{\mathcal{Q}}_L \mathcal{H} \mathcal{T}_R + m_q \overline{\mathcal{Q}}_L \mathcal{Q}_R + h.c.$$



(a)

$$\sim \frac{y_L^2 f^2 N_c \ \log\Lambda^2}{16\pi^2} \ m_q^2 \ s_h^2.$$

Fully radiatively generated Higgs potential

$$V(h) \sim \frac{y_L^4 f^4 N_c \ \log\Lambda^2}{16\pi^2} \left[\left(\frac{m_q^2}{y_f^2 f^2} - 1 \right) s_h^2 + \frac{1}{2} s_h^4 \right].$$

Correct Higgs VEV is obtained!

Fully Radiative Higgs Potential

Higgs potential is fully predictive

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

Twin Higgs: Yukawa-gauge cancellation

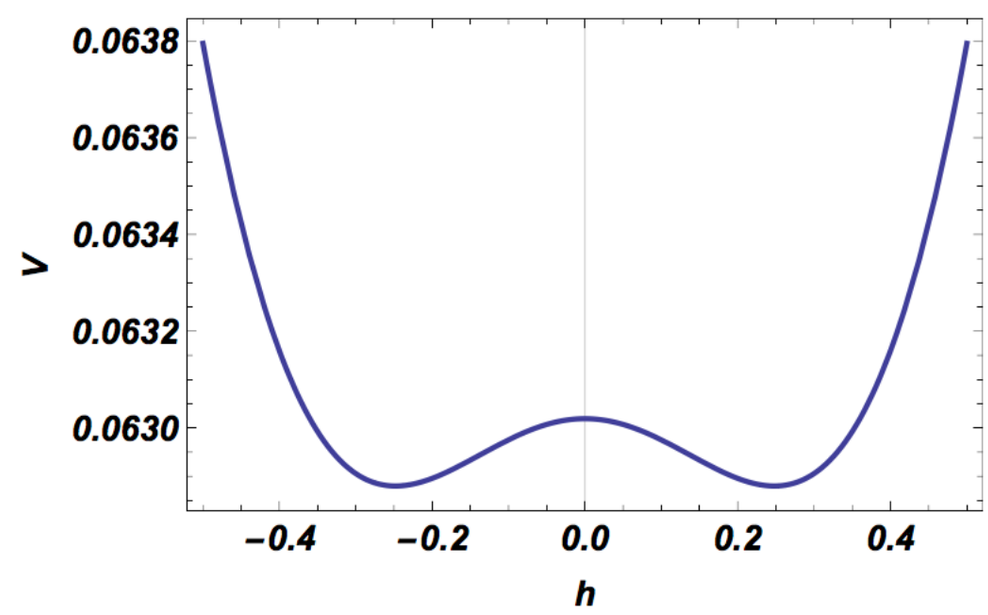
$$V(h) \simeq -\left(\frac{3y_t^4 f^2}{16\pi^2} - \frac{g'^4 f^2}{16\pi^2}\right) h^2 + \frac{3y_t^4}{16\pi^2} h^4$$

Composite Higgs: Yukawa-gauge cancellation

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

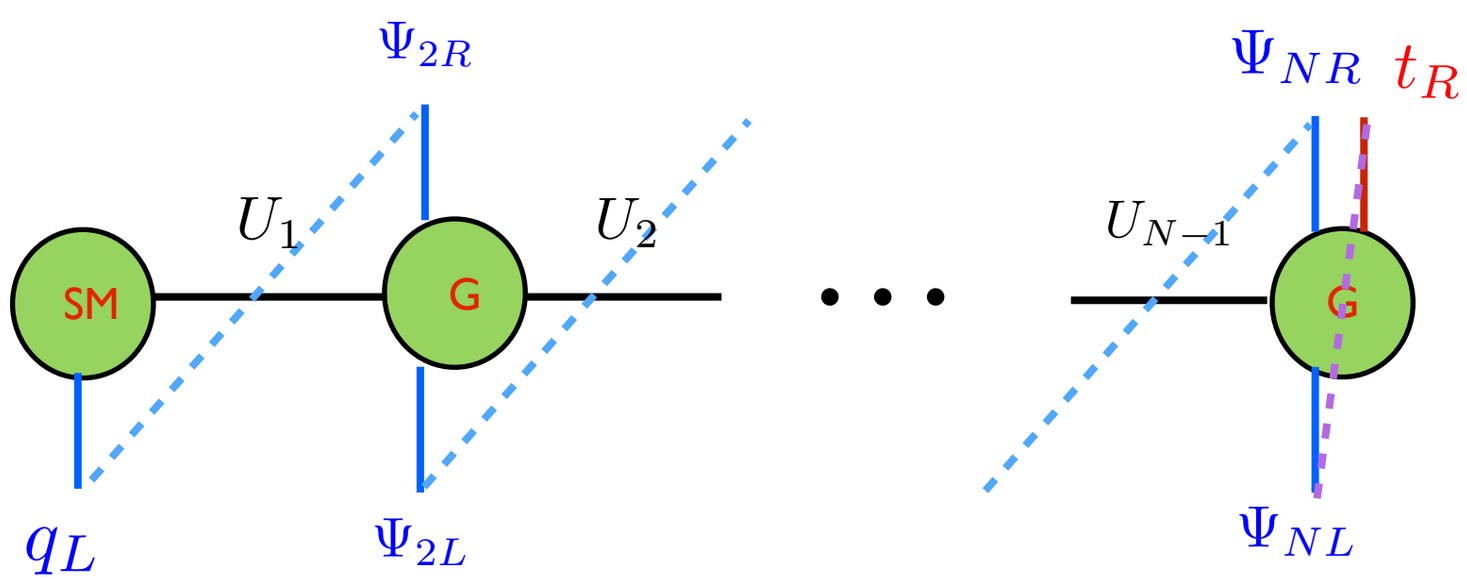
Minimal Neutral Top: Yukawa-Yukawa cancellation

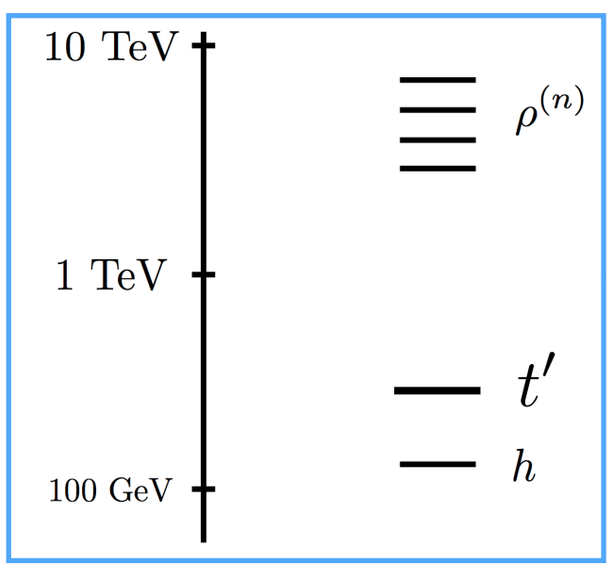
A new way to obtain vacuum misalignment



Composite Neutral Top Model

By including N-site composite states with partial compositeness





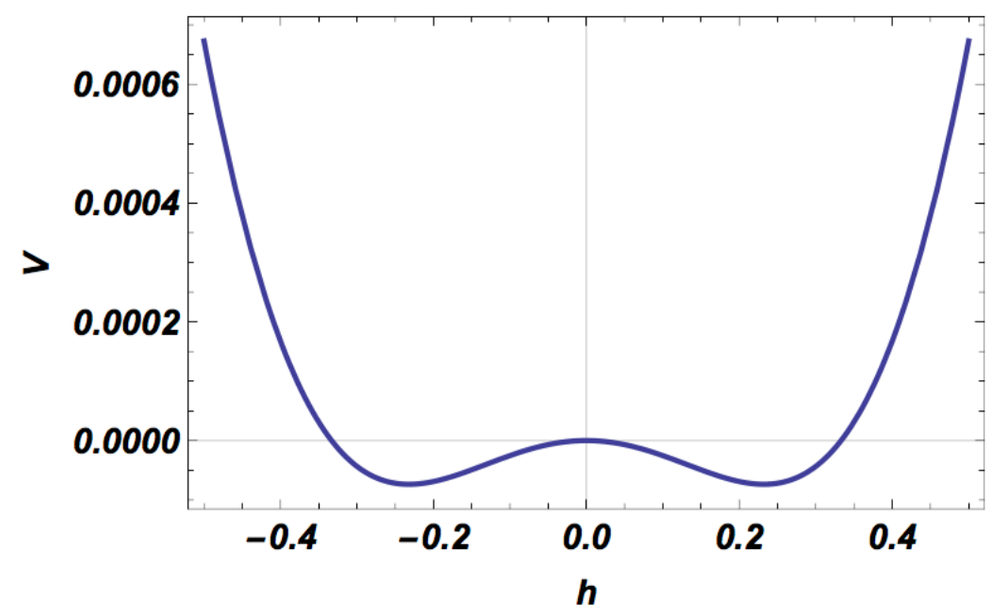
W,Z loop cancellation
via composite rho states

Composite Neutral Top Model

In two site construction, using CCWZ

Higgs potential becomes finite (no UV dependence)

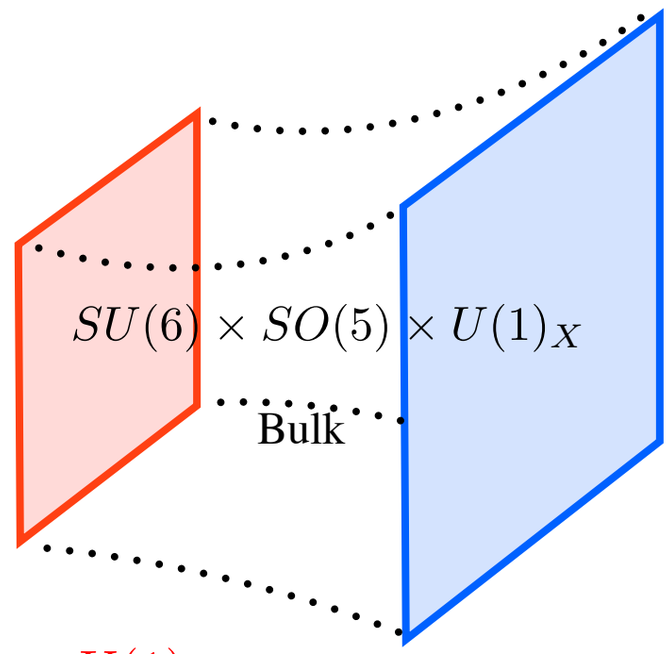
$$
\begin{aligned}
V(h) &\simeq -\gamma_f s_h^2 + \beta_f s_h^4 \\
&\simeq -\frac{3\left(a\, y^2 f^2 m^2 - \widetilde{a}\, \widetilde{y}^2 f^2 \widetilde{m}^2\right)}{16\pi^2} s_h^2 \\
&\quad + \frac{3\left(b\, y^4 f^4 + \widetilde{b}\, \widetilde{y}^4 f^4\right)}{16\pi^2} s_h^4
\end{aligned}
$$



Full UV dynamics: conformal symmetry at high scale

UV Dynamics: Wilson Line Higgs

Extra Dimensional Setup via AdS/CFT



$SU(3) \times SU(3)' \times SU(2)_L \times U(1)_Y$
UV Brane

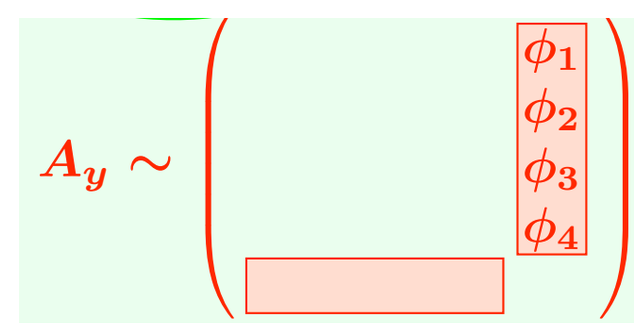
$SU(3) \times SU(3)' \times SO(4) \times U(1)_X$
IR Brane

Boundary Conditions

$SU(3) \times SU(3)' \times SU(2)_L \times U(1)_Y$

Wilson Line Breaking

$SU(3) \times SU(3)' \times U(1)_{\rm em}$

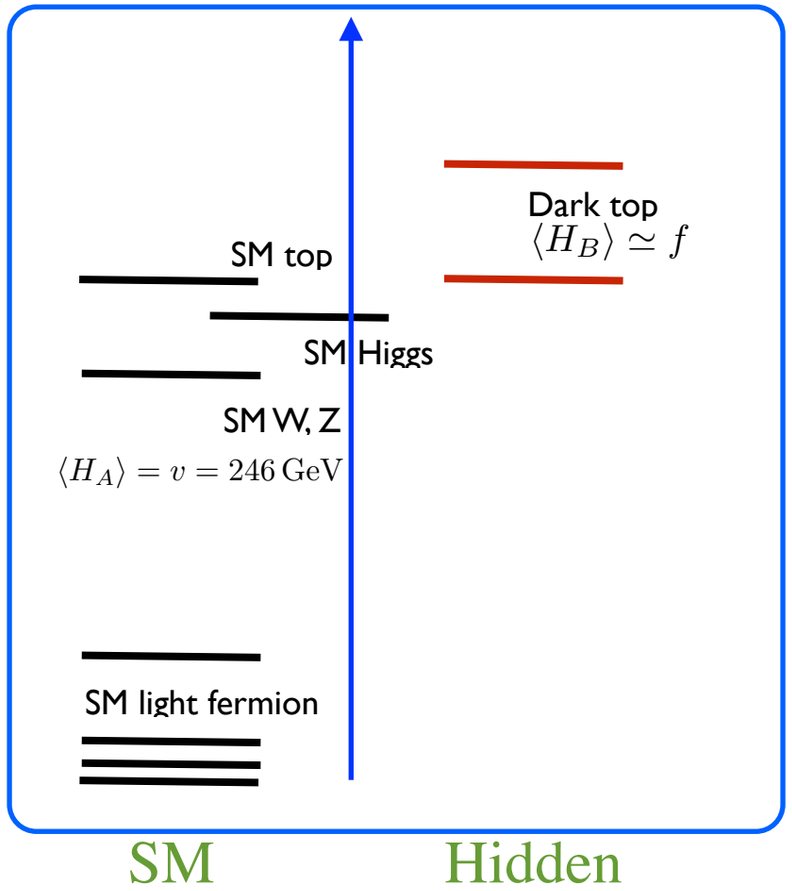


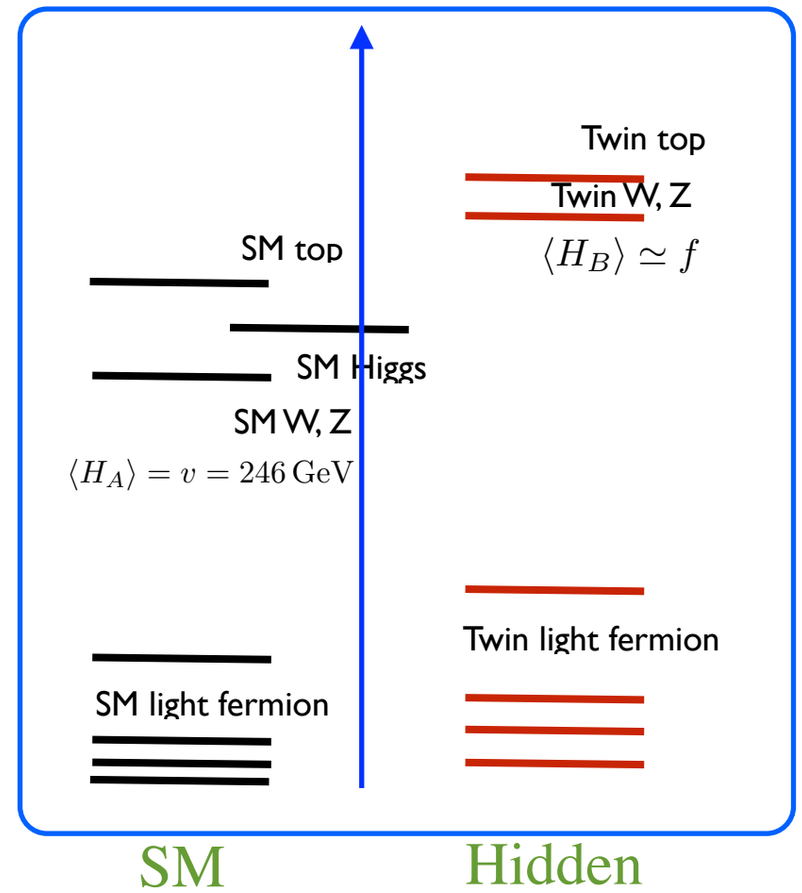
$A_y \to A_y + \partial_y \epsilon$

AdS/CFT

Hidden Sector Spectra

Comparison between this model and twin Higgs model spectra

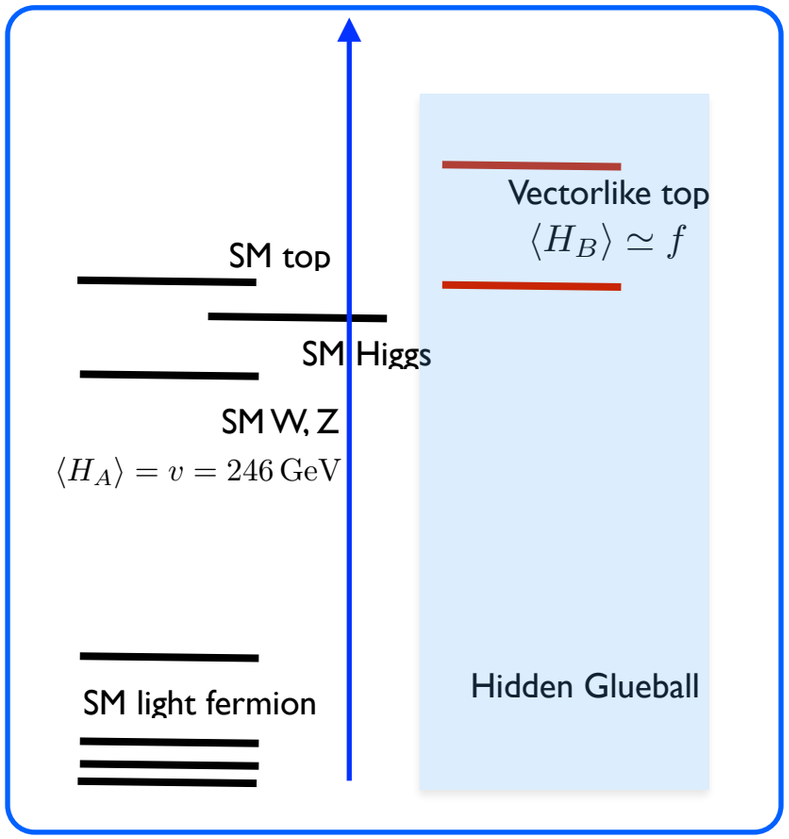




Top partner is QCD-neutral, only carries hidden SU(3) color

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

Mass Spectra and Pheno



- ☑ Higgs pheno
- ☑ Hidden fermion signature
- ☑ Dark matter candidate
- ☑ Cosmological signature

Higgs pheno: (Higgs portal to Hidden sector)

$$g_{hVV}, g_{htt}, g_{hhtt}, \Gamma_{\rm inv}$$

Dark Matter candidate: hidden baryon/pion

Hidden QCD Sector

Confined hidden SU(3) color with fundamental fermions

Bosonic TC / induced EWSB	Carone, Simmons; hep-ph/9207273 Brod, Drobnak, Kagan, Stamou, Zupan; 1407.8188 Chang, Luty, Salvioni, Tsai; 1411.6023
Quirks	Kang, Luty; 0805.4642
Vector-like confinement	Kilic, Okui, Sundrum; 0906.0577 Kilic, Okui; 1001.4526
Quirky DM	GK, Roy, Terning, Zurek; 0909.2034
Stealth DM	Appelquist et al (LSD Collaboration); 1402.6656; 1503.04203; 1503.04205
Dark Meson DM Bai-Hill Buckley-Neil	 Bai, Hill; 1005.0008 Buckley, Neil; 1209.6054
SIMP (WZW 3->2)	Hochberg, Kuflik, Murayama, Volansky, Wacker; 1411.3727 Hochberg, Kuflik, Murayama; 1512.07917
Light/heavy chiral DM	Harigaya, Nomura; 1603.03430 Co, Harigaya, Nomura; 1610.03848

How Dark fermion transforms under SM group?

Twin Higgs: chiral under dark SU(2)

Neutral Top: vector like under SM SU(2)

Hidden QCD Sector

Dark fermion masses relative to confinement scale

Chiral limit

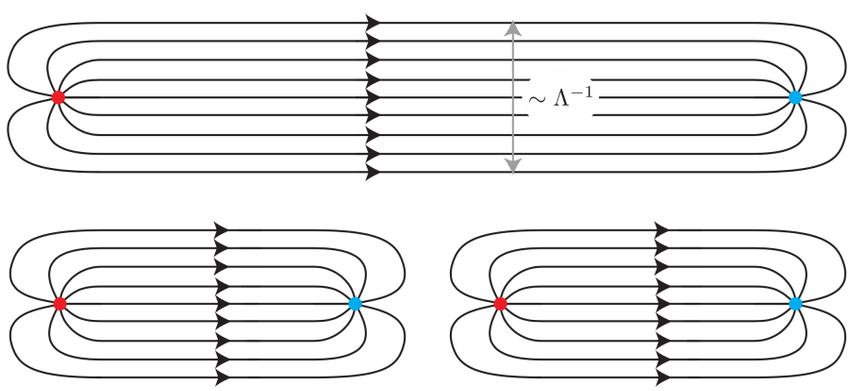
Darkonia

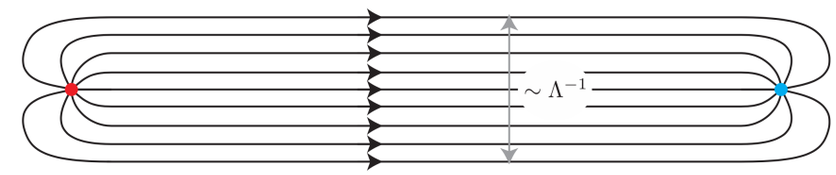
$m_q \ll \Lambda_{\rm dark}$

$m_q \gg \Lambda_{\rm dark}$

$\Lambda_{\rm dark}$

Vector-like





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

QCD string with hadronization

Stable macroscopic string

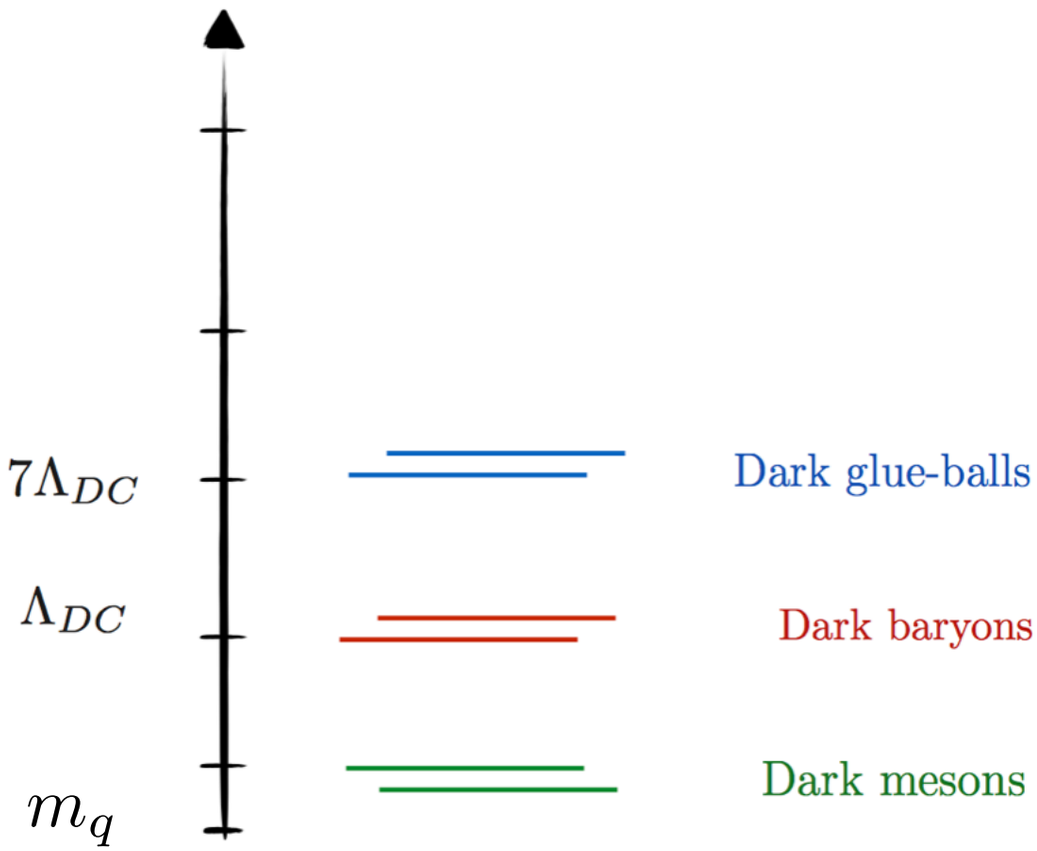
Quark

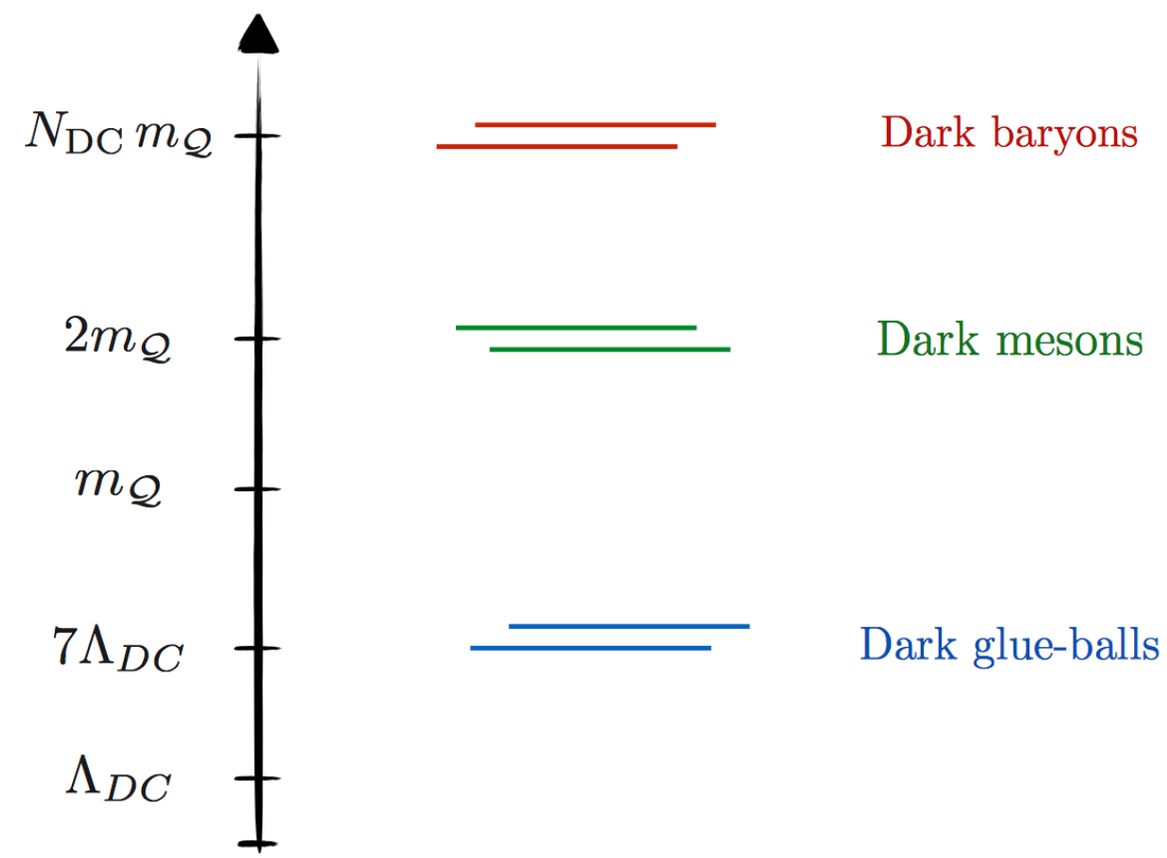
Quirk

Jiang-Hao Yu

Kang, Luty, 09

Hidden Hadronic Spectra



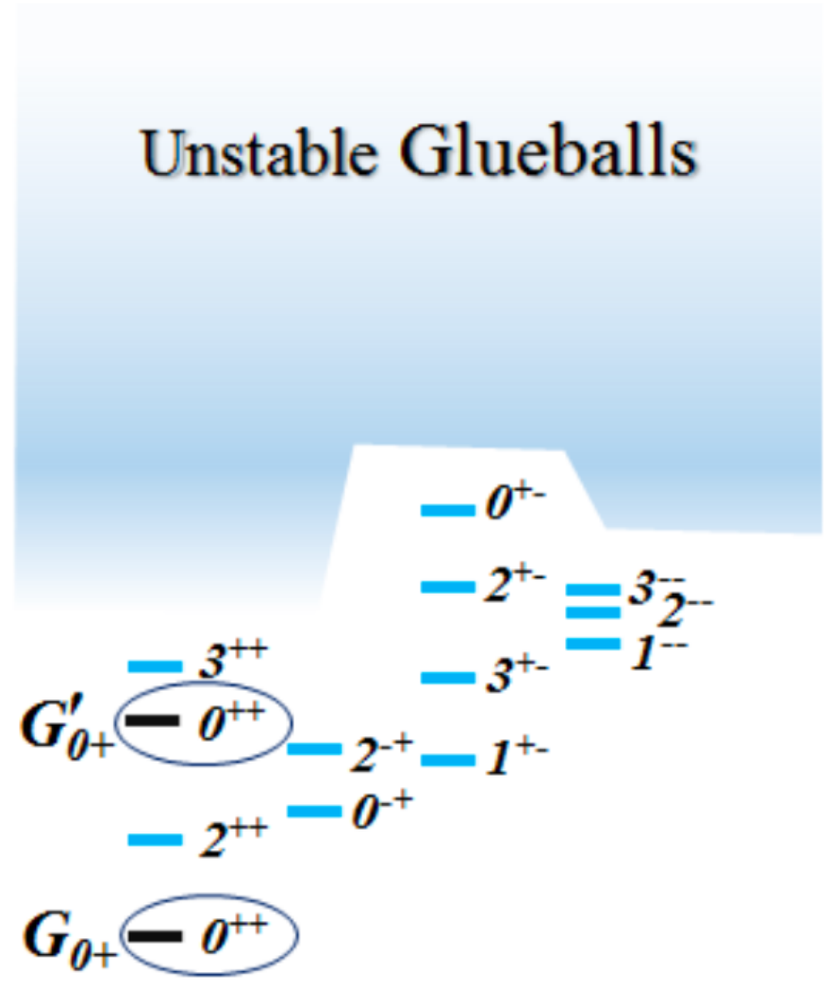


Dark baryon or meson stable depending on parity/baryon number

Dark glueball dark matter?

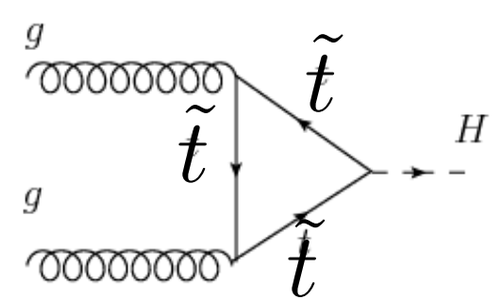
Hidden Glueball Spectra

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



WIMP or SIMP Dark Matter

Composite dark matter from dark QCD

If all quirks, baryonic dark matter very heavy (10 TeV)

Introduce lepton doublet to be DM

Very similar to wino dark matter

If b quark below confinement, stable pion dark matter

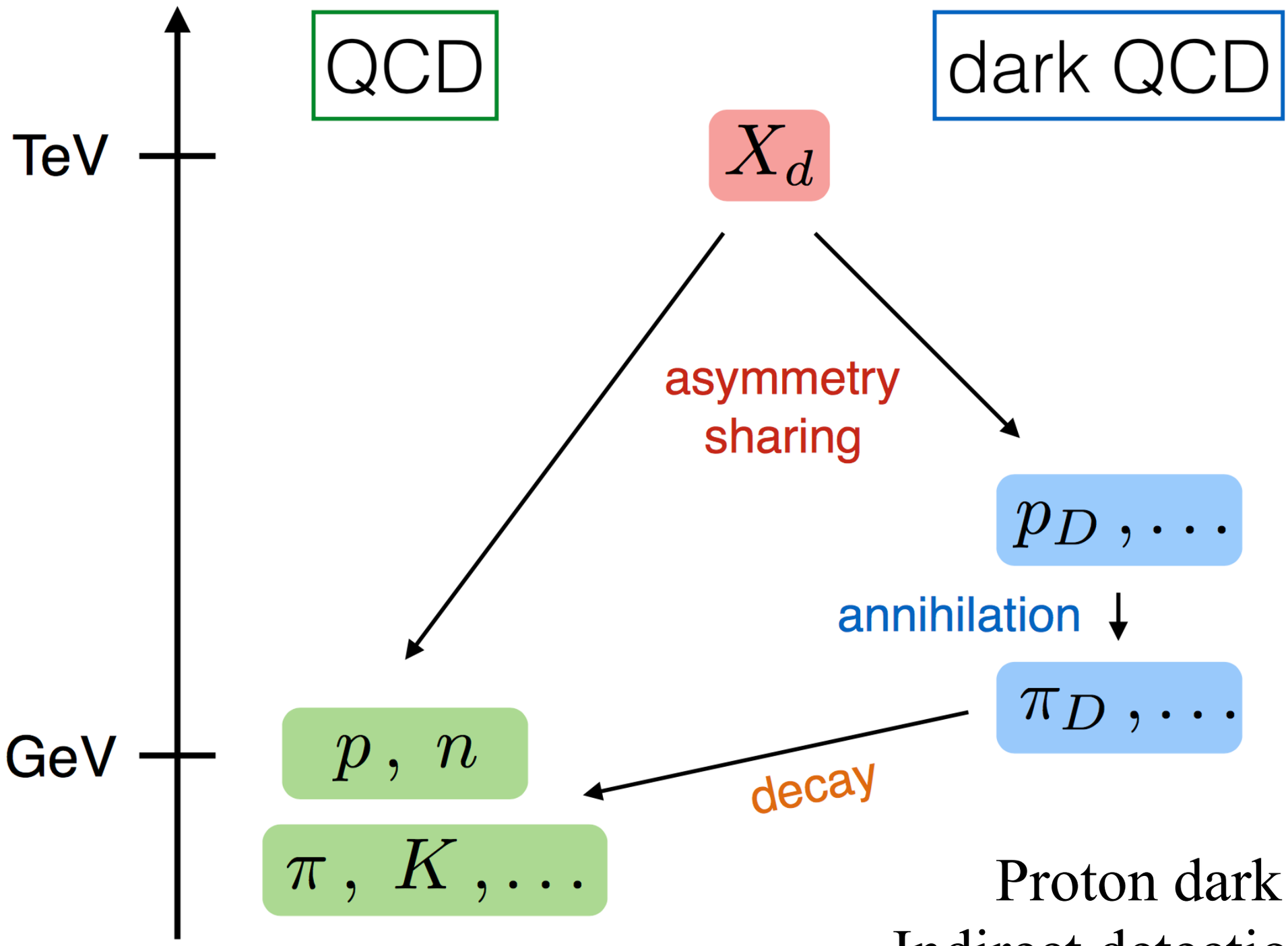
Need parity between two bottom states

SIMP scenario

$$\mathcal{L}_{3\to 2} = \frac{2}{5\pi^2 f_\pi^5}\epsilon^{\mu\nu\rho\sigma}\mathrm{Tr}\,\left(\pi\partial_\mu\pi\partial_\nu\pi\partial_\rho\pi\partial_\sigma\pi\right).$$

Hochberg, Kuflik, Murayama, 18

Asymmetric Dark Matter



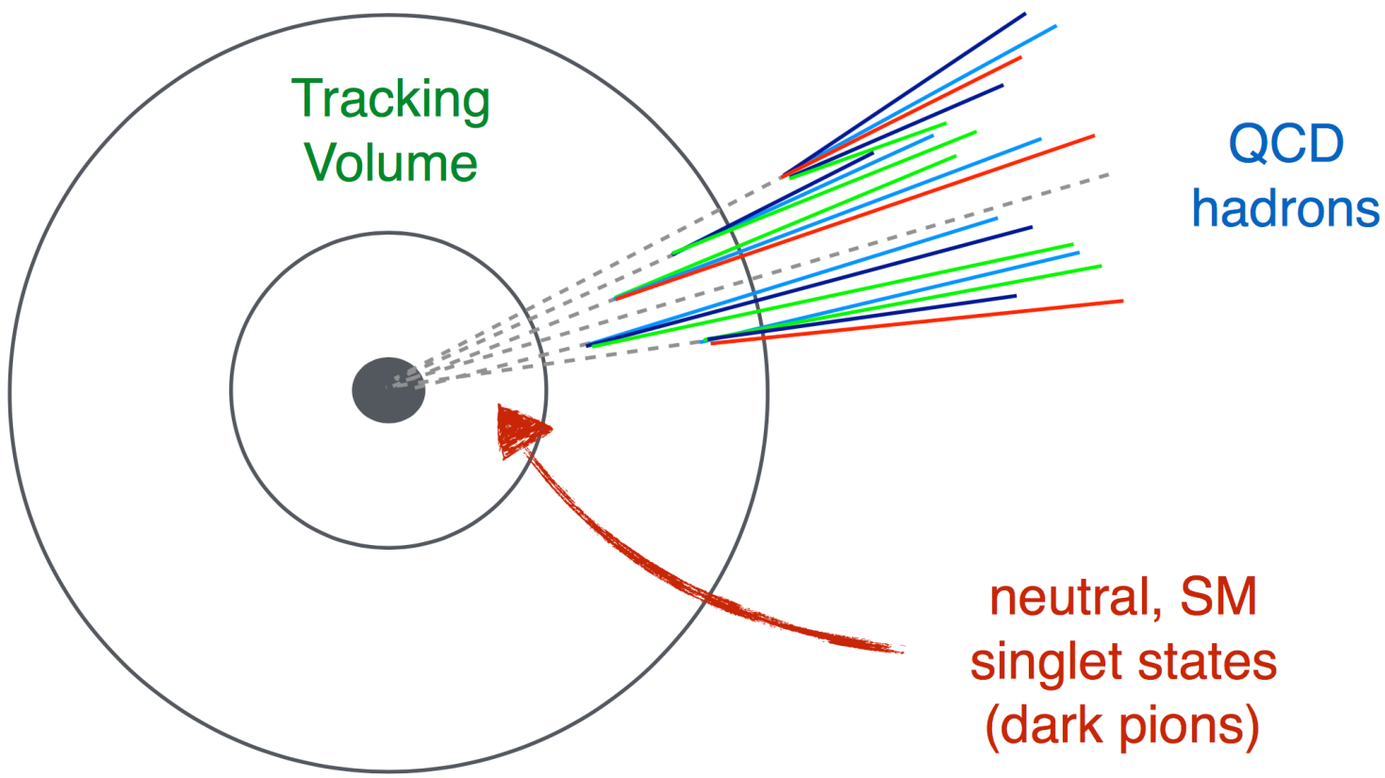
Proton dark matter
Indirect detection signature

Exotic Pion Signature

Quark signature for $m_{\tilde{q}} \ll \tilde{\Lambda}$

If baryon dark matter, pion unstable

$$c\tau(\pi_D \to \mathrm{SM}) \sim \frac{M_X^4}{m_{\pi_D}^5} \sim \mathrm{cm} \times \left(\frac{\mathrm{M_X}}{\mathrm{TeV}}\right)^4 \left(\frac{\mathrm{GeV}}{\mathrm{m_{\pi_D}}}\right)^5$$

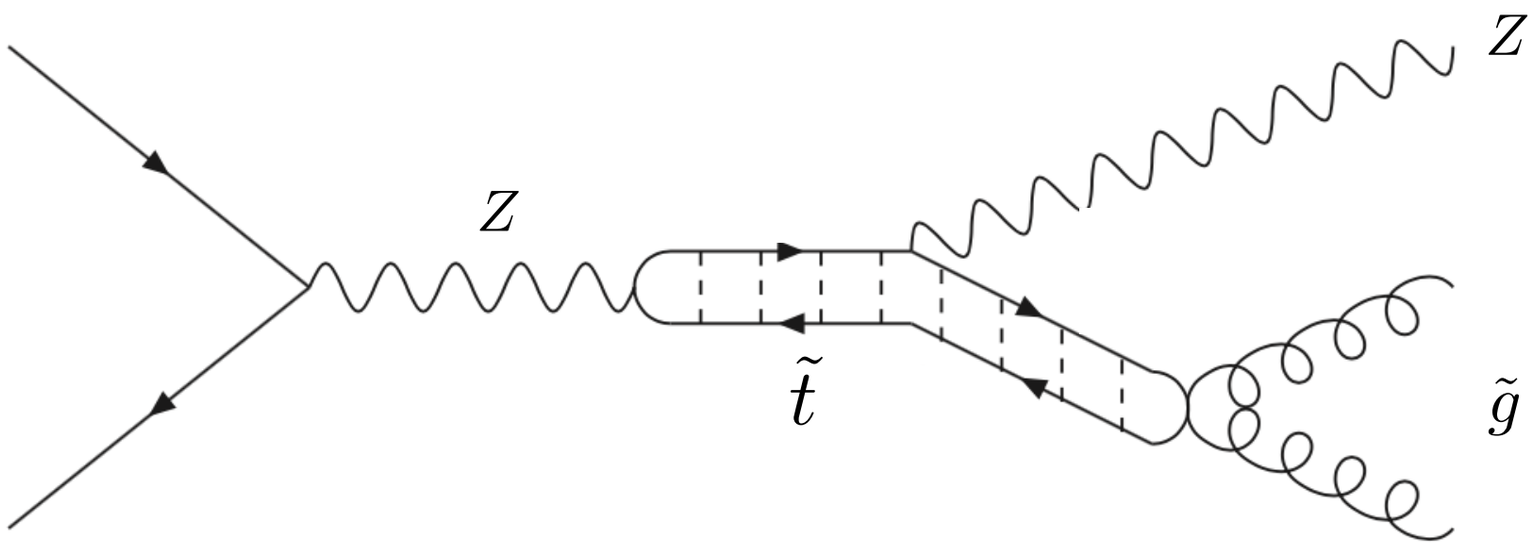


Top partner signature very similar to wino searches

Exotic Top Partner Signature

If top partner carries hyper charge

Quirk signature for $m_{\tilde{q}} \gg \tilde{\Lambda}$

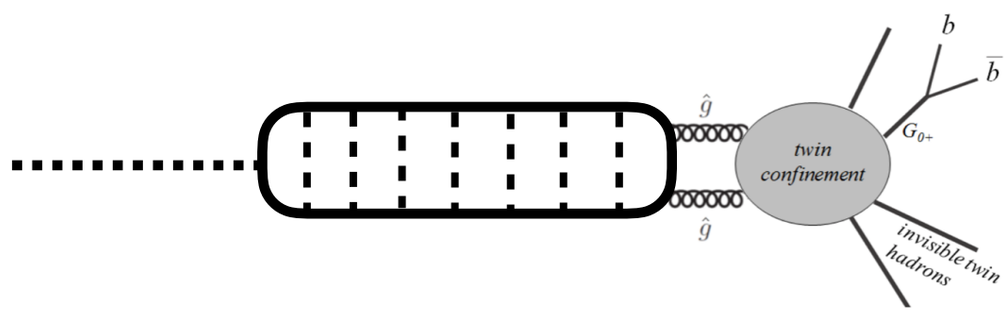


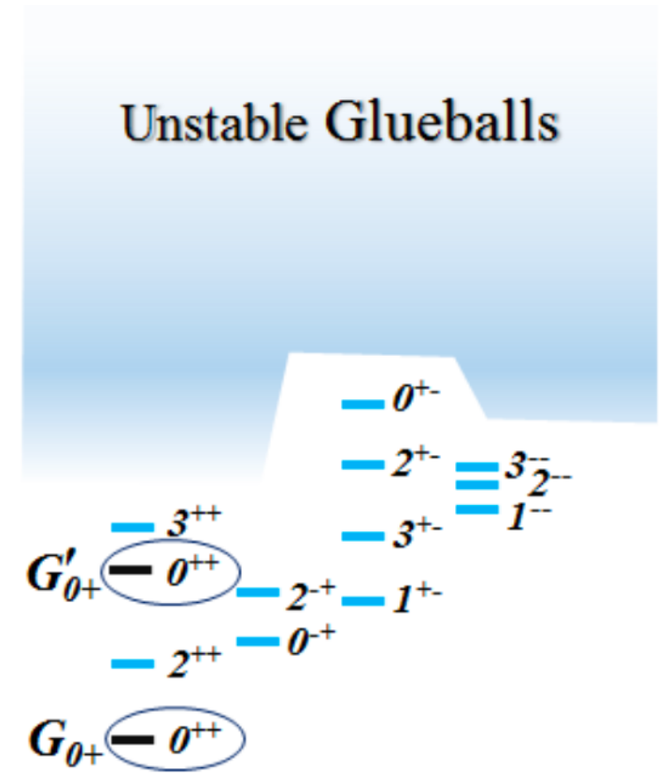
tt forms bound states

Either mono-Z or Z + displaced vertices

Higgs Exotic Decay Signal

Higgs exotic decay signature (universal)





Craig, Katz, Strassler, Sundrum, 15

Hidden glueball decay via Higgs

Displaced vertices

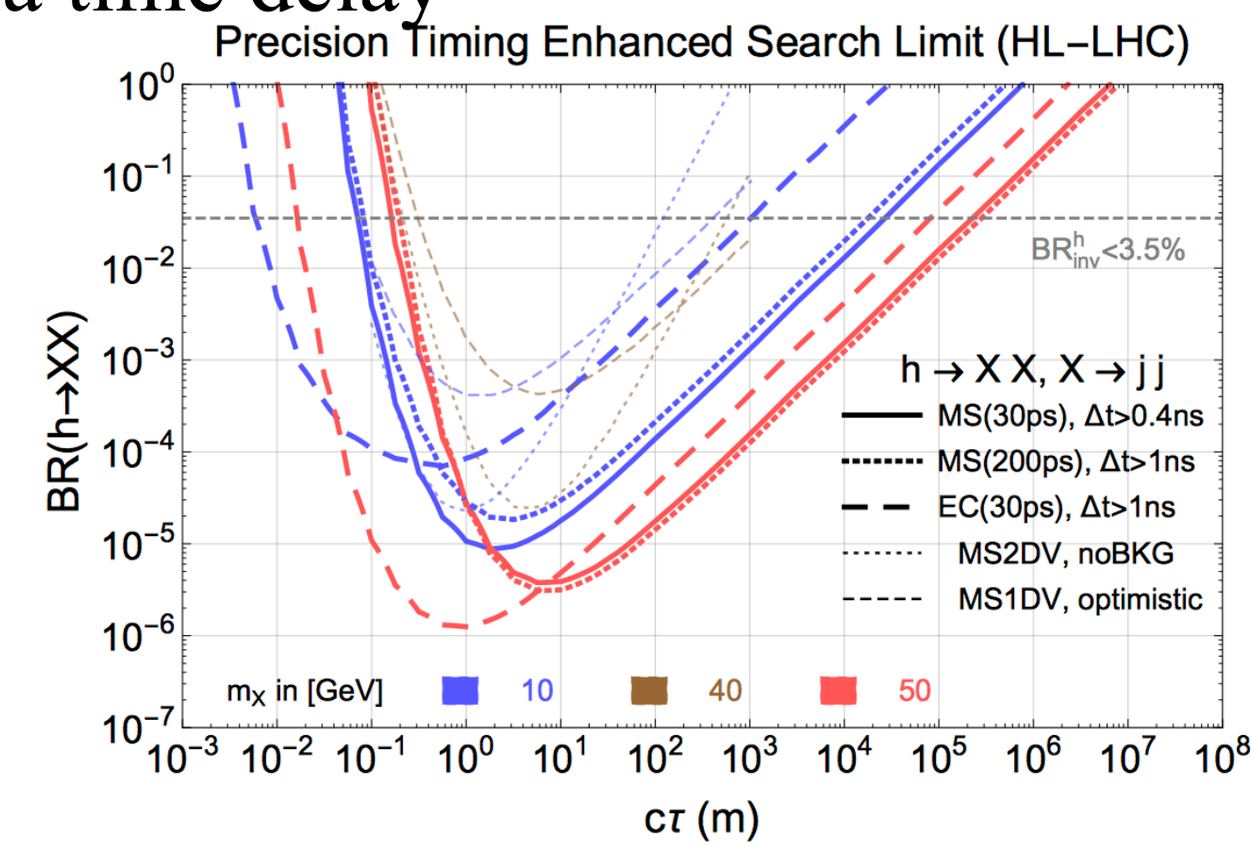
Displaced Vertices Searches

Generic feature in minimal neutral naturalness

Current ATLAS and CMS searches

HL-LHC upgrade: precision timing (resolution 25 ps)

Distinguish signal via time delay



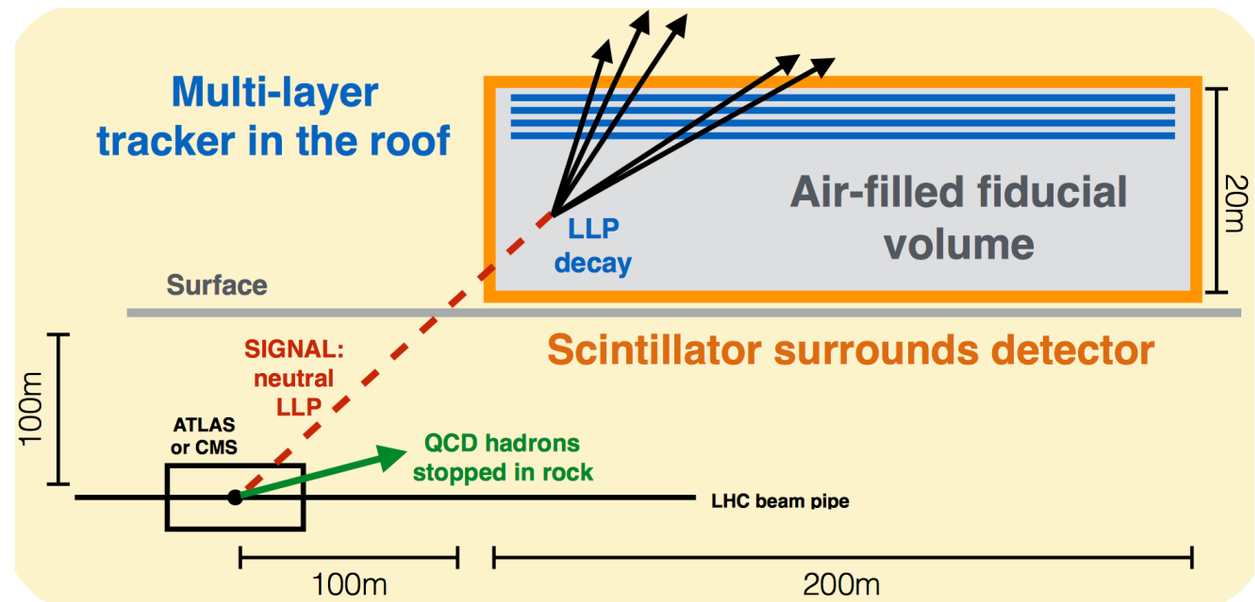
Liu, Liu, Wang, 2018

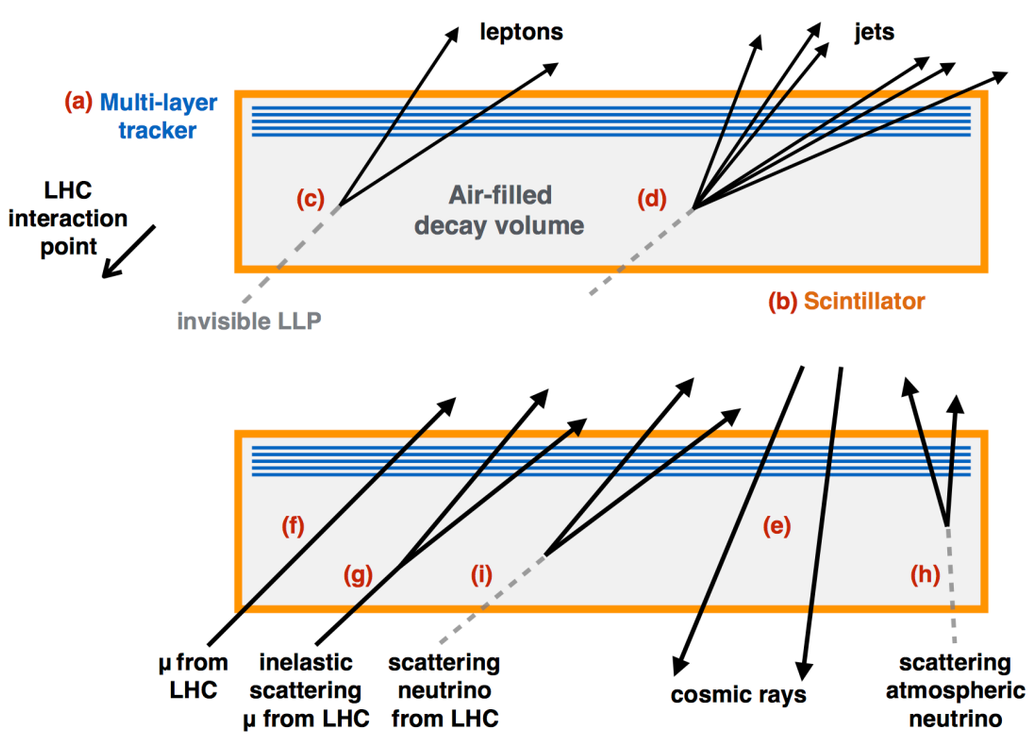
Displaced Vertices Searches

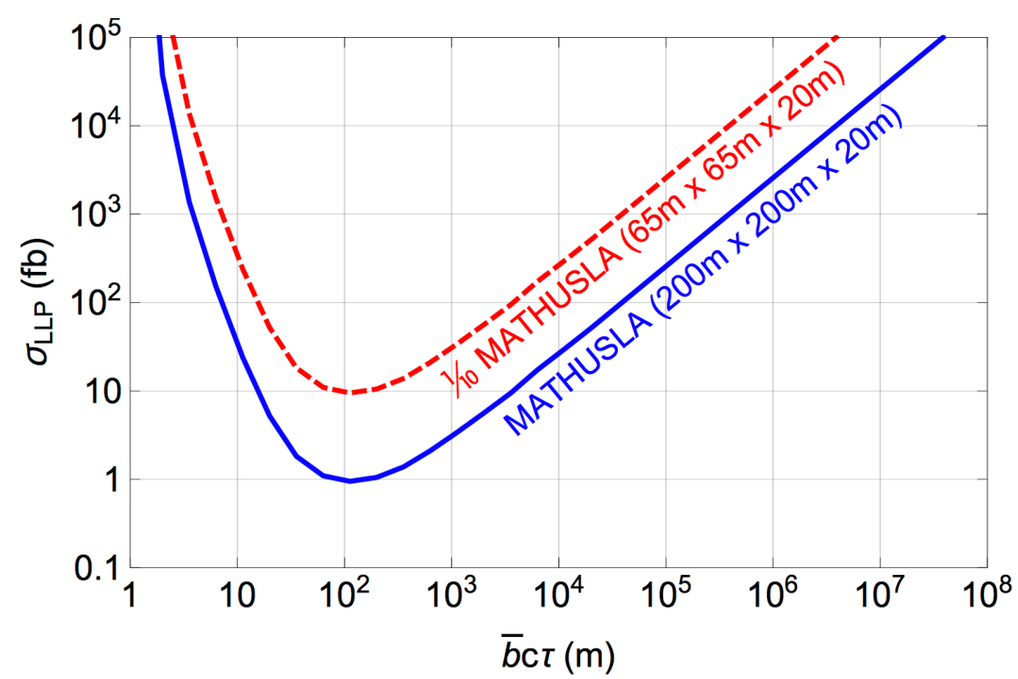
Mathusla and other proposals

MAssive Timing Hodoscope for Ultra Stable neutraL pArticles

MATHUSLA







Curtin, et. al, 2018

Summary and Future Directions

- ☑ Neutral naturalness could address hierarchy/dark matter
- ☑ Higgs potential is radiatively generated in minimal neutral top
- ☑ Hidden QCD has very rich dark matter and collider pheno

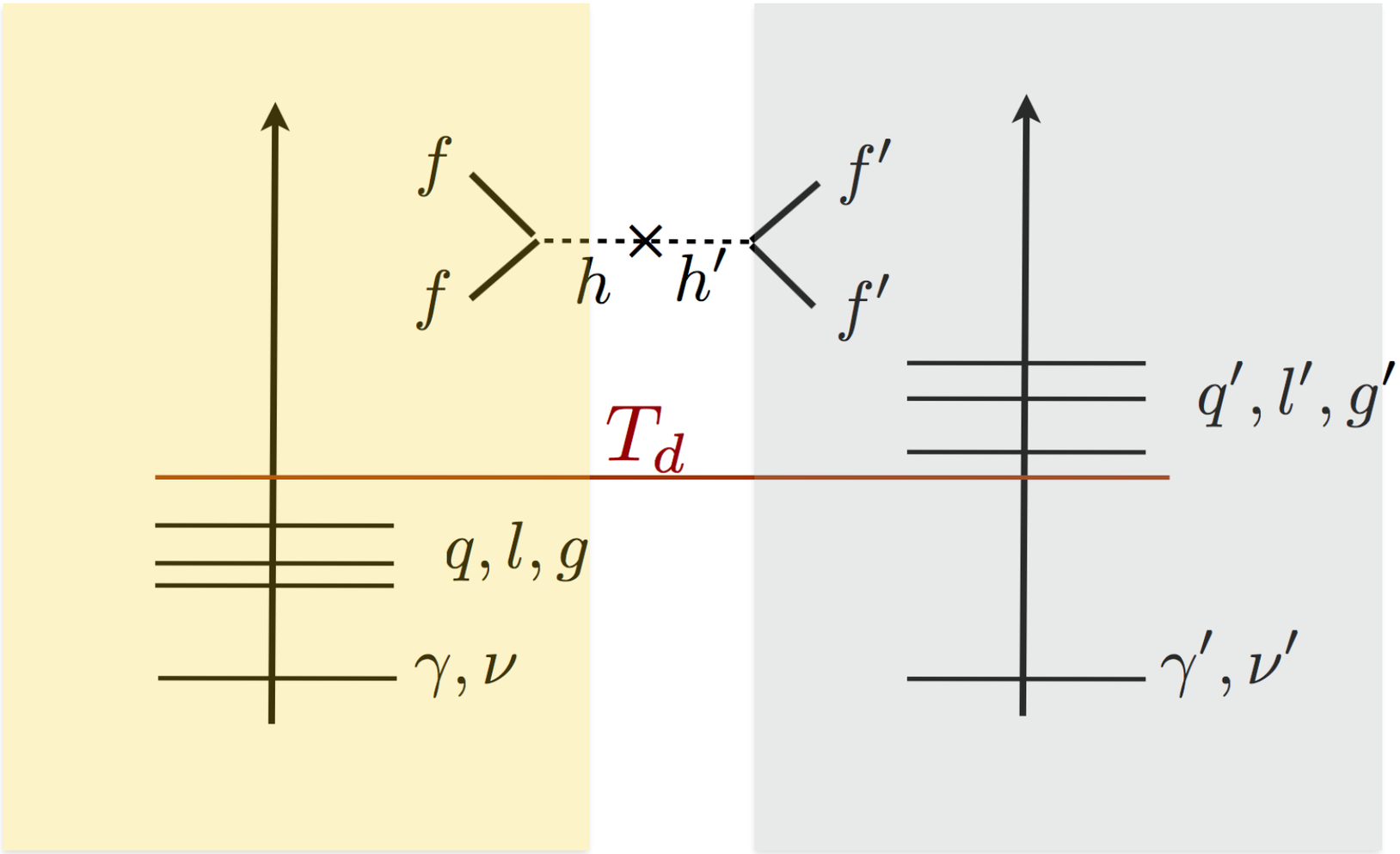
In neutral naturalness, lots of studies need to be done!

new color sector, exotic collider/Higgs pheno,
UV extension, dark QCD cosmology, etc

Thank you!

Backup Slides

Hidden Sector



Dark Radiation Constraint