A Holographic Twin Higgs

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ArXiv:1411.2974 – PRL 2015

Outline

- Motivation
- Twin Higgs model

  Z. Chacko, H. S. Goh and R. Harnik, Phys. Rev. Lett. 96 (2006) 231802
- Holographic Twin Higgs model
- Phenomenology

Motivation

The main question: is the EW scale ***natural*** or ***tuned***?

naturalness $\neq$ ***colored new physics @ $\sim$1 TeV.***

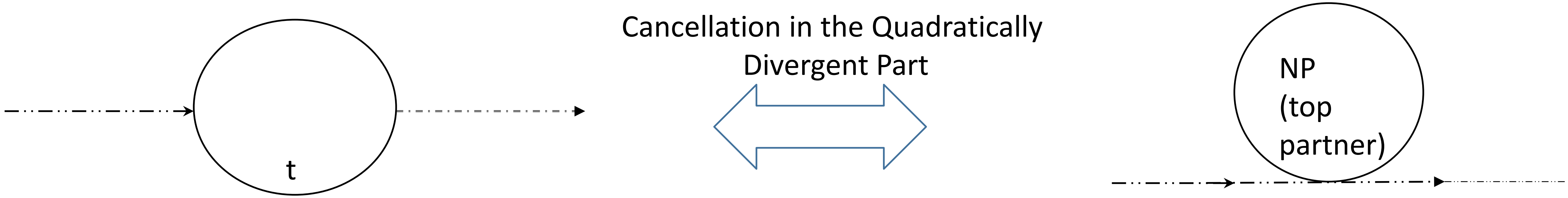
Twin Higgs

Twin Higgs needs a UV completion – ***composite/AdS***

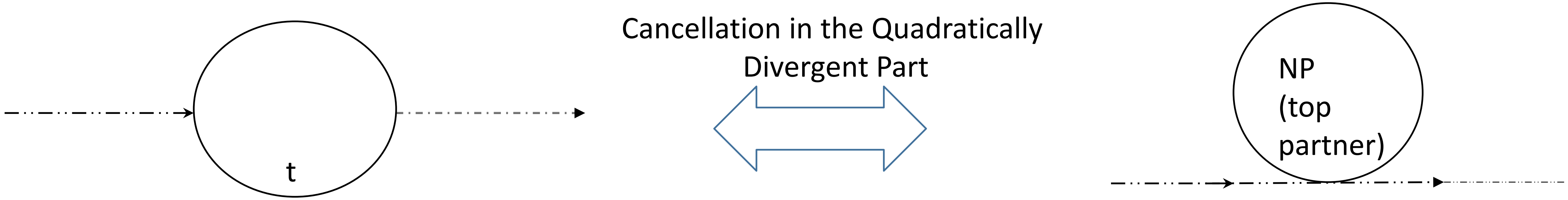
Spectrum: **SM, mirror, excitations**

Naturalness $\leftrightarrow$ Colored BSM

Naturalness ↔ Colored BSM

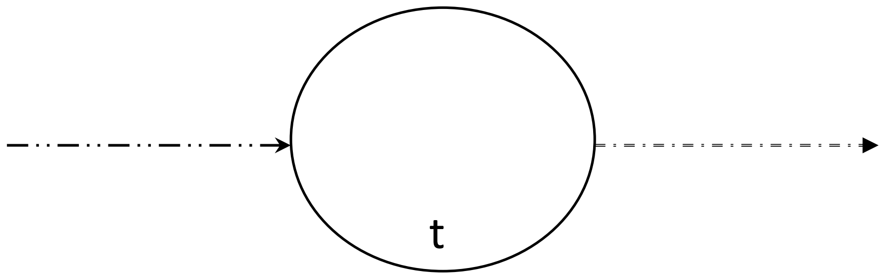


Naturalness $\leftrightarrow$ Colored BSM

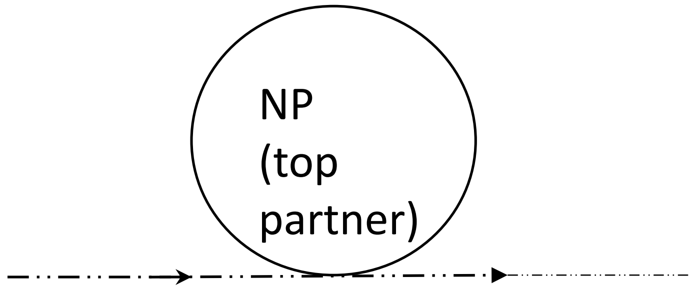


The argument:

Naturalness ↔ Colored BSM



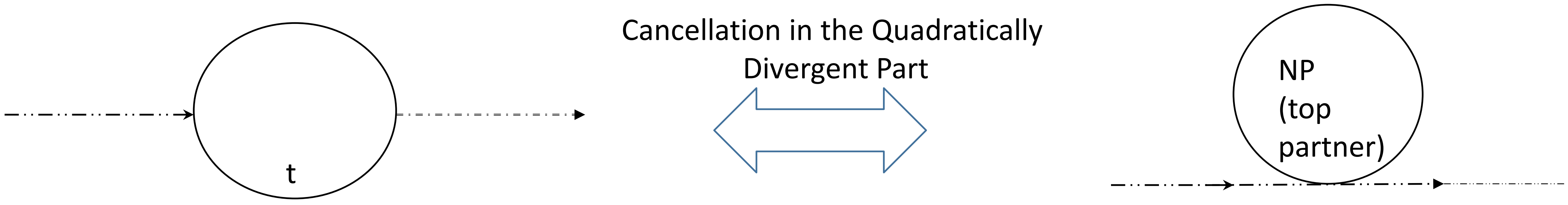
Cancellation in the Quadratically Divergent Part



The argument:

- A symmetry is required connecting top ↔ top partners

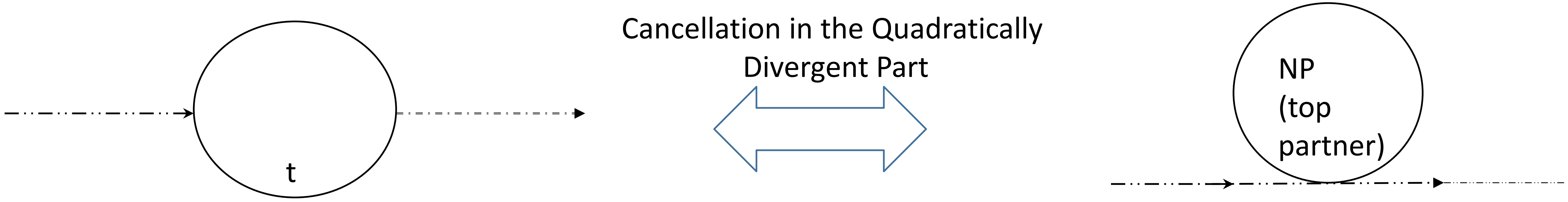
Naturalness ↔ Colored BSM



The argument:

- A symmetry is required connecting top ↔ top partners
- Naturalness requires top partners @ 1 TeV

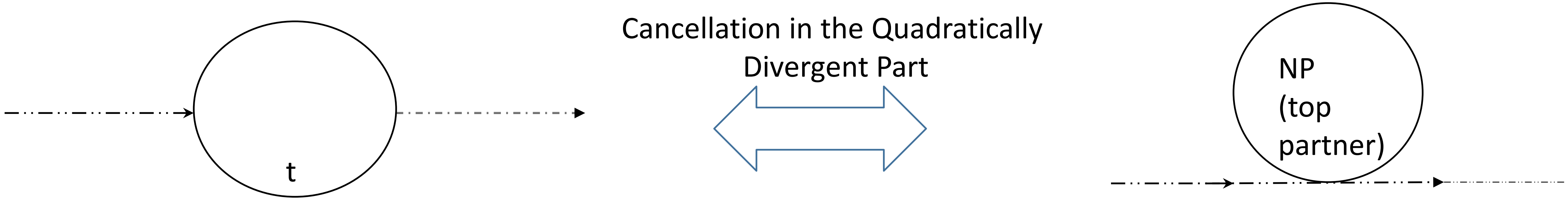
Naturalness ↔ Colored BSM



The argument:

- A symmetry is required connecting top ↔ top partners
- Naturalness requires top partners @ 1 TeV
- Colored BSM @ ~1 TeV

"Loophole"



top partners don't have to be colored! ***Just need the N_c=3 factor.***

The Twin Higgs Model

Z. Chacko, H. S. Goh and R. Harnik, Phys. Rev. Lett. 96 (2006) 231802
Bottom-up approach: N. Craig, A. Katz, M. Strassler, R. Sundrum ,arXiv:1501.05310

A global SU(4) symmetry broken by ***H*** in the fundamental: $SU(4)/SU(3)$

Gauge the group:

$$\underset{\text{SM}}{SU(2)^A} \times \underset{\text{Mirror}}{SU(2)^B}$$

$$H = \begin{pmatrix} H_A \\ H_B \end{pmatrix}$$

7 Goldstones: 6 Eaten and 1 Higgs (Pseudo-Goldstone)

Impose a Z_2 symmetry SM ↔ Mirror.

The Twin Higgs Model: Higgs Potential

Gauging the $SU(2) \times SU(2)$ breaks the $SU(4)$

$$\Delta V = \frac{9g_A^2\Lambda^2}{64\pi^2} H_A^\dagger H_A + \frac{9g_B^2\Lambda^2}{64\pi^2} H_B^\dagger H_B \xrightarrow{Z_2} \frac{9g^2\Lambda^2}{64\pi^2} H^\dagger H$$

SU(4) symmetric
does not produce a Goldstone mass.

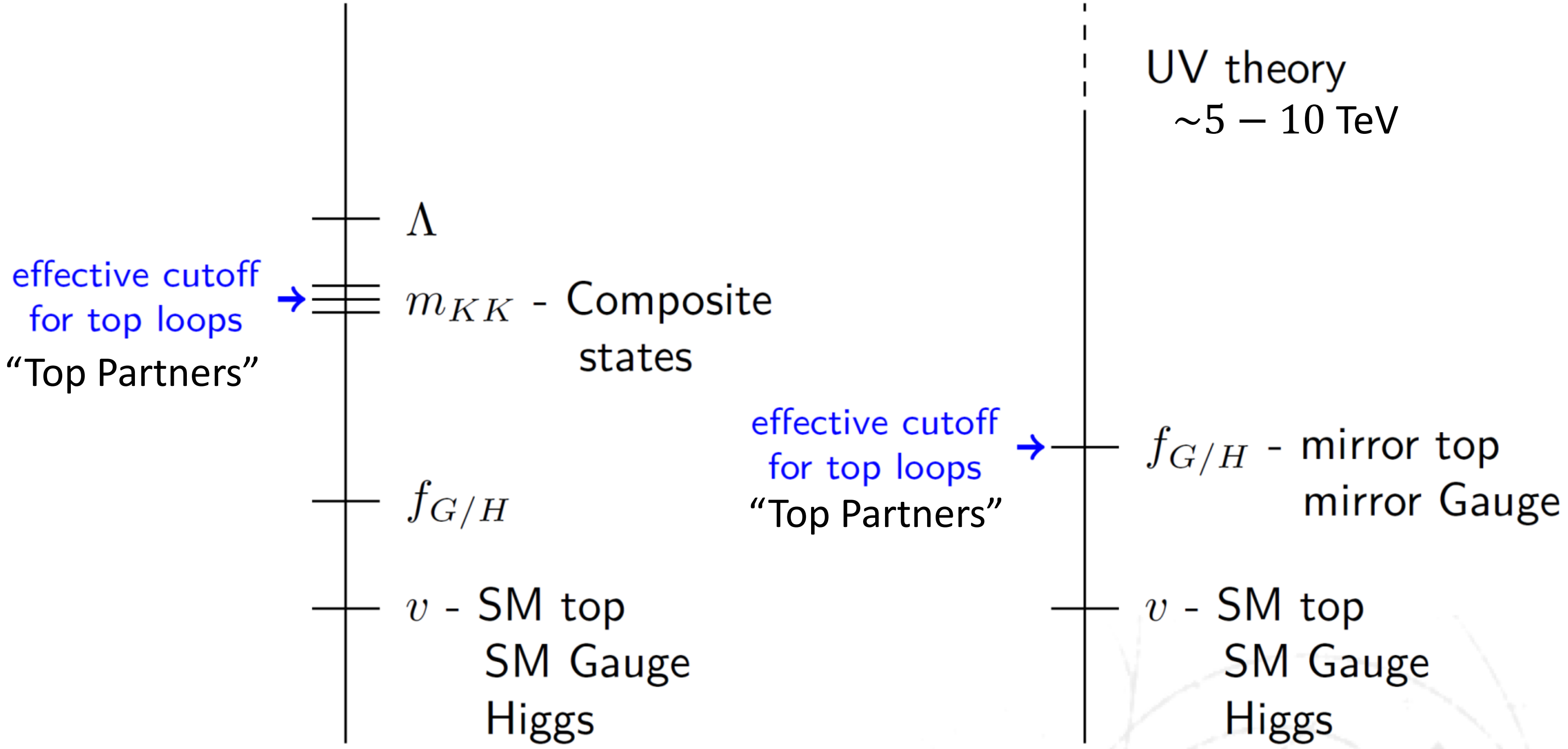
Quadratically divergent terms cancel!

To have the same effect for the top loop: ***double the SM symmetry***

$$\underbrace{\left(SU(3) \times SU(2) \times U(1)\right)^A}_{\text{SM}} \times \underbrace{\left(SU(3) \times SU(2) \times U(1)\right)^B}_{\text{“Mirror” SM}}$$

Top partners are SM singlets – “Mirror Partners”!

Twin Higgs and Composite Higgs



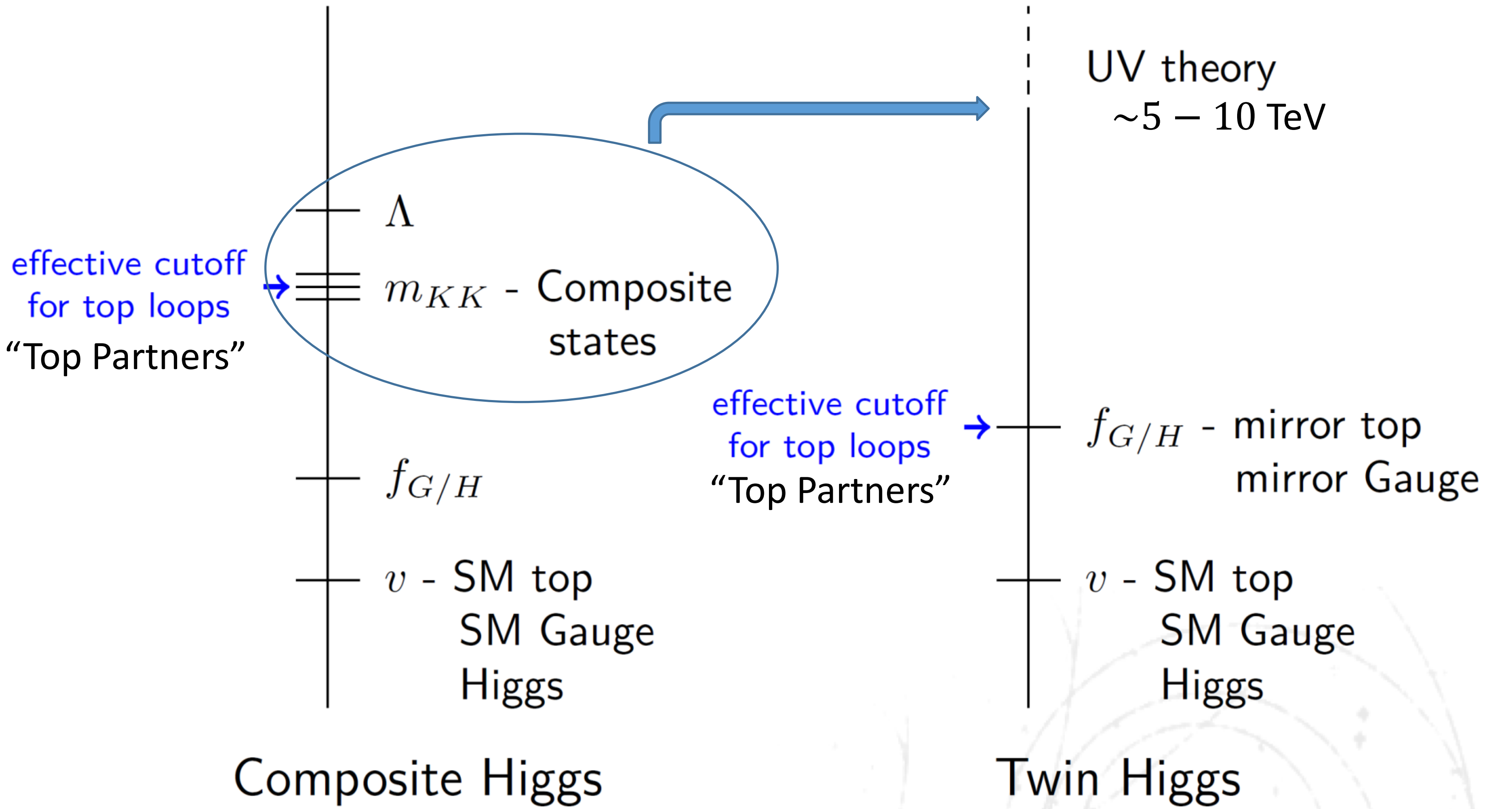
Composite Higgs

Naturalness of a PNGB Higgs
Requires light Composite states –
charged/colored naturalness

Twin Higgs

Solution to the little hierarchy problem. "Neutral Naturalness"

Composite Twin Higgs – A cartoon



Naturalness of a PNGB Higgs
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Solution to the little hierarchy problem. "Neutral Naturalness"

Composite Twin Higgs – A cartoon

SUSY:

N. Craig and K. Howe JHEP 1403 (2014) 140

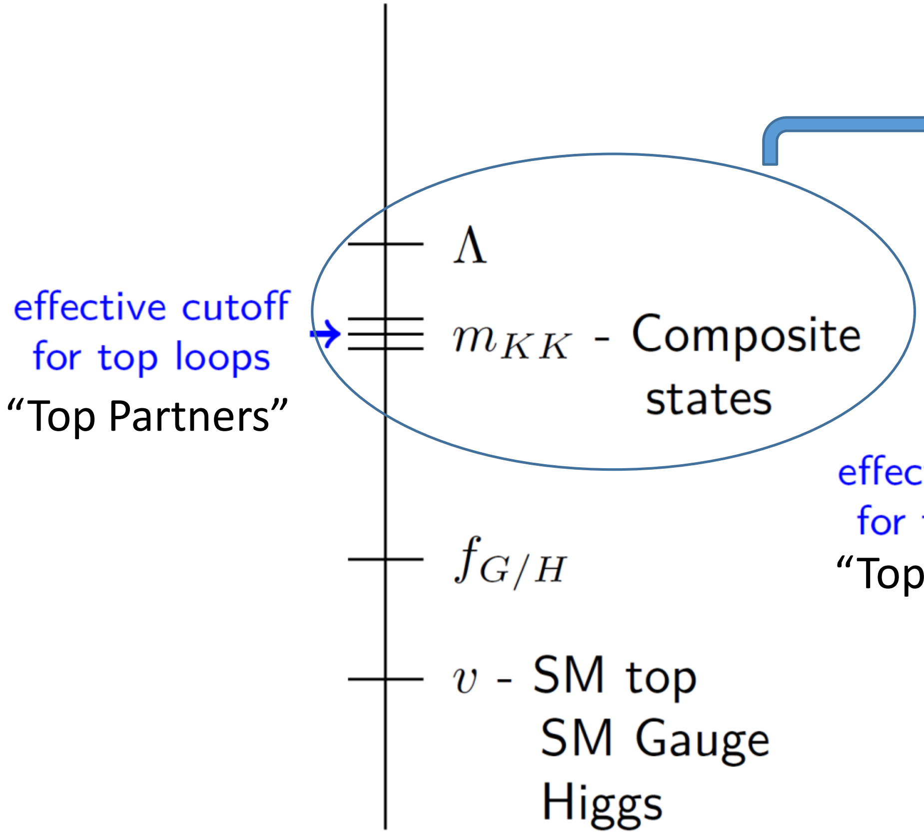
A. Falkowski, S. Pokorski, M. Schmaltz, Phys.Rev. D74(2006) 035003;

S. Chang , L. J. Hall, N.Weiner Phys.Rev. D75 (2007) 035009

Orbifold:

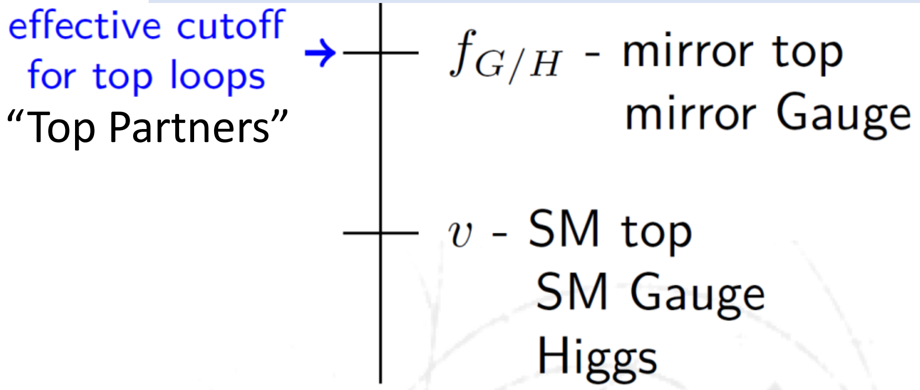
N. Craig, S. Knapen, P. Longhi, JHEP 1503 (2015) 106

N. Craig, S. Knapen, P. Longhi , Phys.Rev.Lett. 114 (2015) 6, 061803



Composite Higgs

Naturalness of a PNGB Higgs Requires light Composite states – charged/colored naturalness



Twin Higgs

Solution to the little hierarchy problem. “Neutral Naturalness”

Composite Twin Higgs – the building blocks

- Top/Gauge Partners:
  - Elementary mirror partners – naturalness up to the excitation scale.
  - Composite partners – naturalness up to Λ_{UV}

- Doubling of the elementary sector + Z_2 symmetry.

- Higgs in the coset of SO(8)/SO(7)

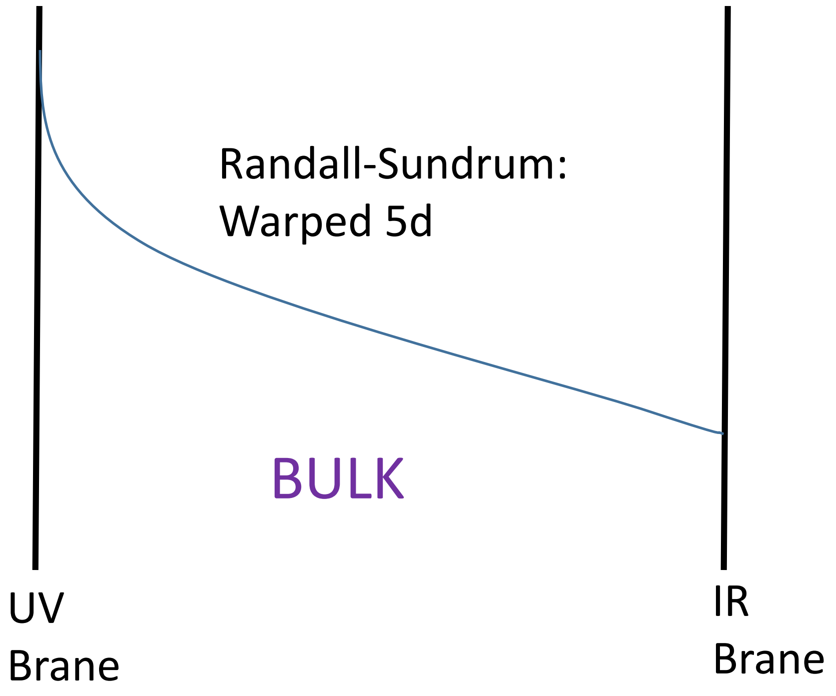
See also

M. Low, A. Tesi and L.T. Wang, arXiv:1501.07890

R. Barbieri, D. Greco, R. Rattazzi, A. Wulzer, arXiv:1501.07803

Holography – A Dictionary

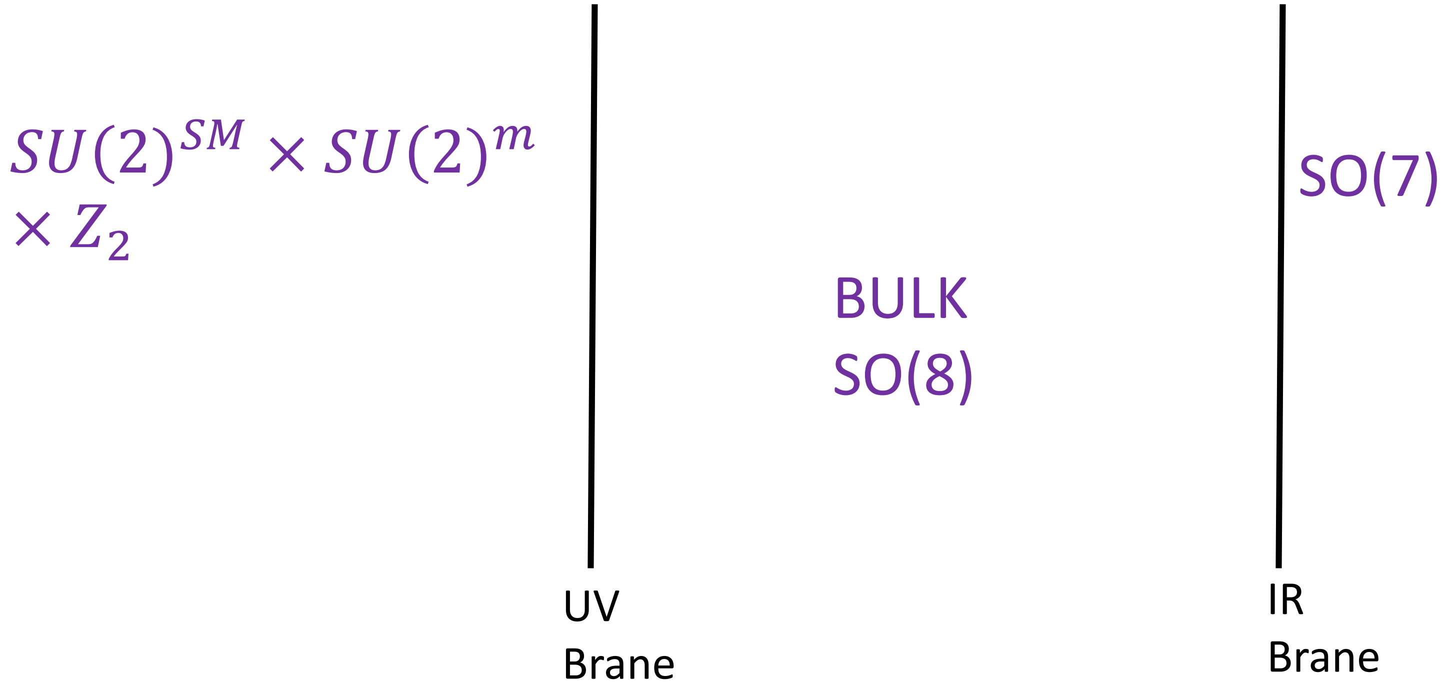
- Holography: 4d effective theory of a 5d (RS) setting.
  - 4d fields : UV brane sources in the 5d theory.
  - 4d Lagrangian: Integrating out the bulk and the IR brane.
- Under AdS/CFT:
  - UV brane: elementary sector.
  - Bulk+IR brane: strong sector.
- Symmetries
  - Bulk/IR Symmetry – Global symmetry G/H.
  - UV brane symmetry – weakly gauged symmetry.



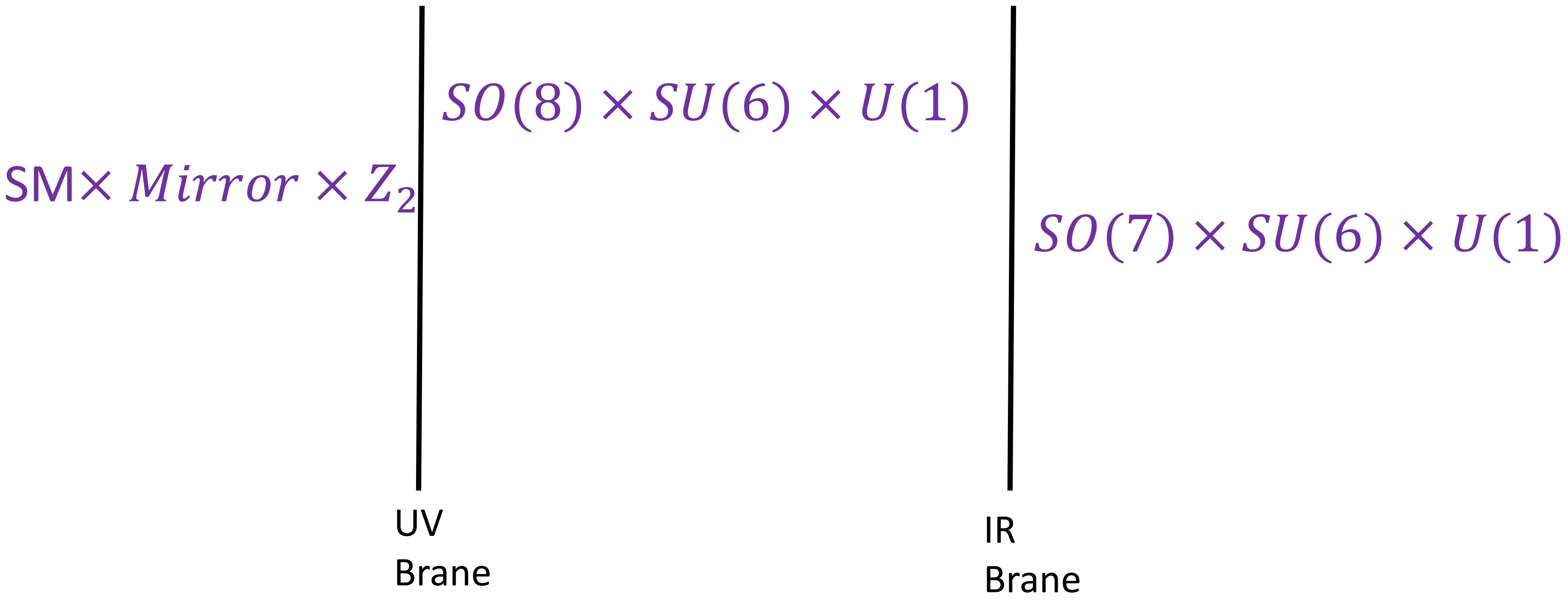
L. Randall and R. Sundrum, Phys.Rev.Lett. 83 (1999) 3370-3373

A Holographic Twin Higgs model – EW part

Custodial Symmetry: Bulk SO(8), IR SO(7) Instead of $SU(4)$ and $SU(3)$



A Holographic Twin Higgs model – full model



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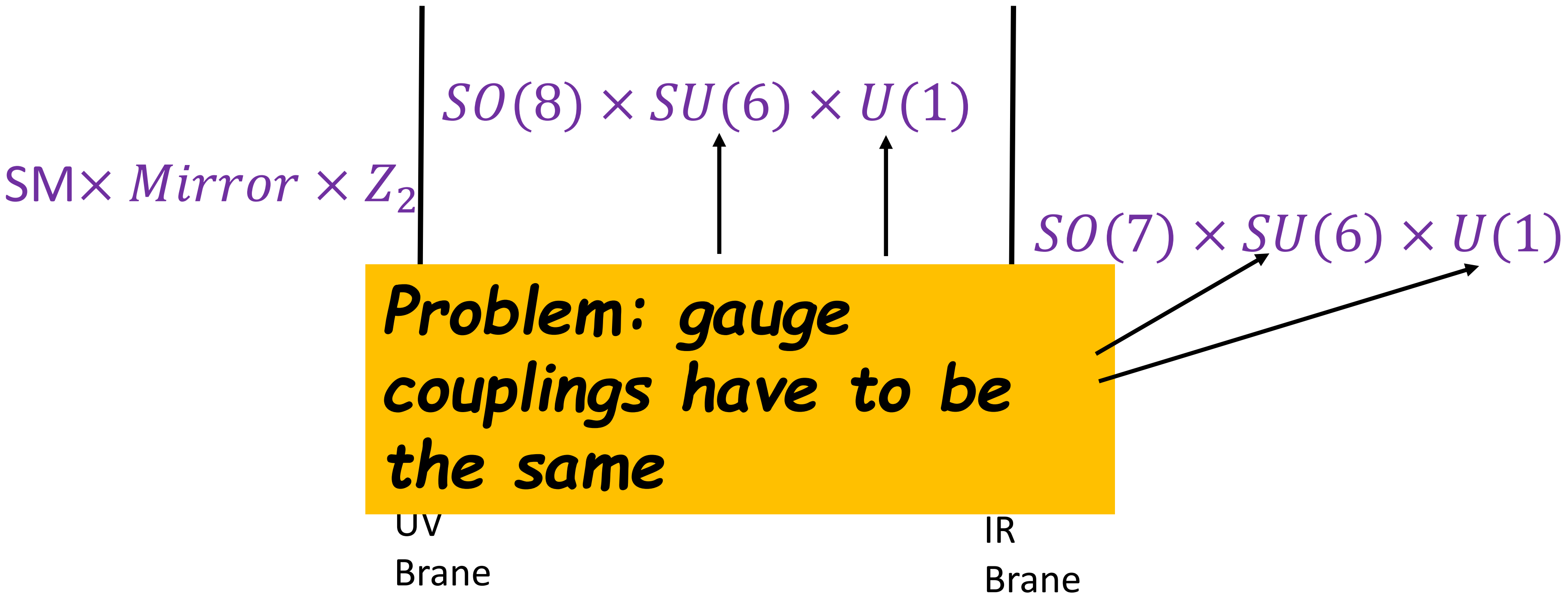

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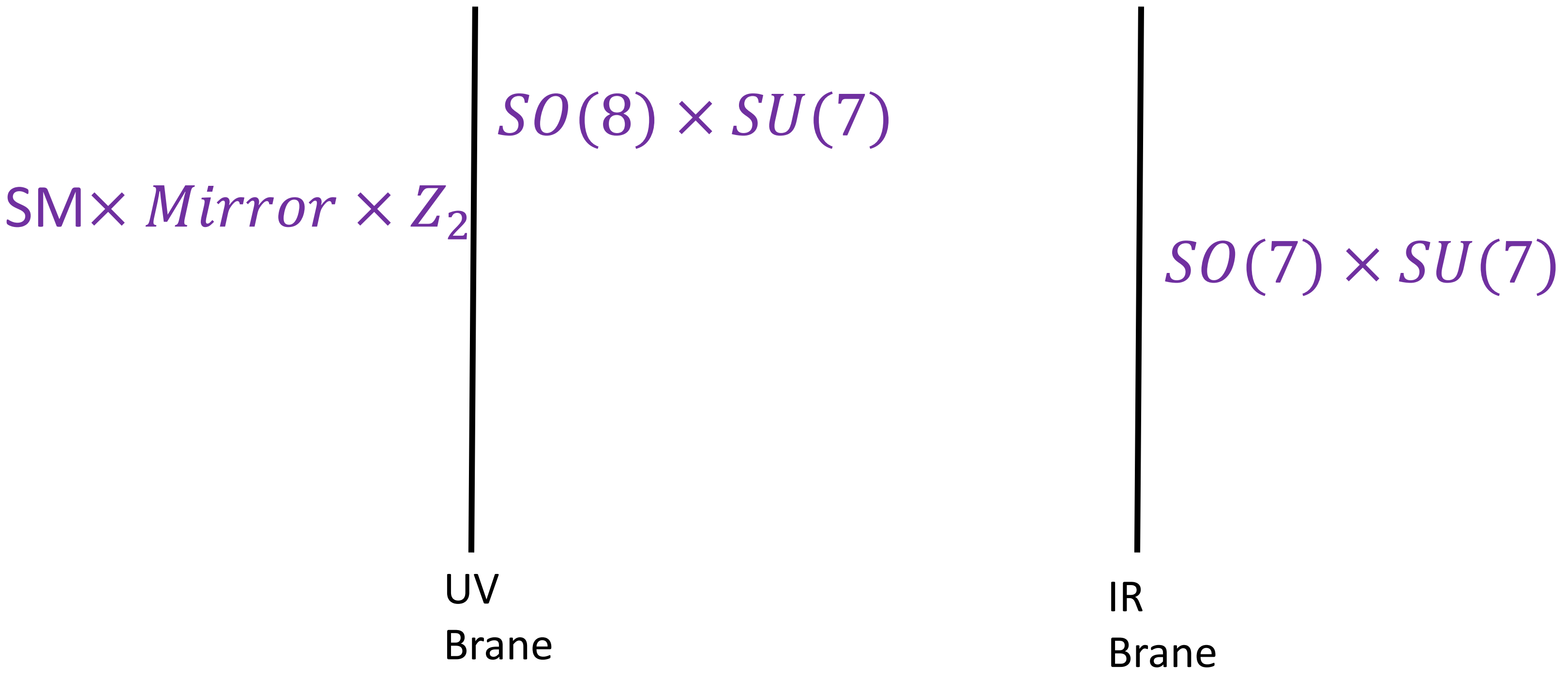

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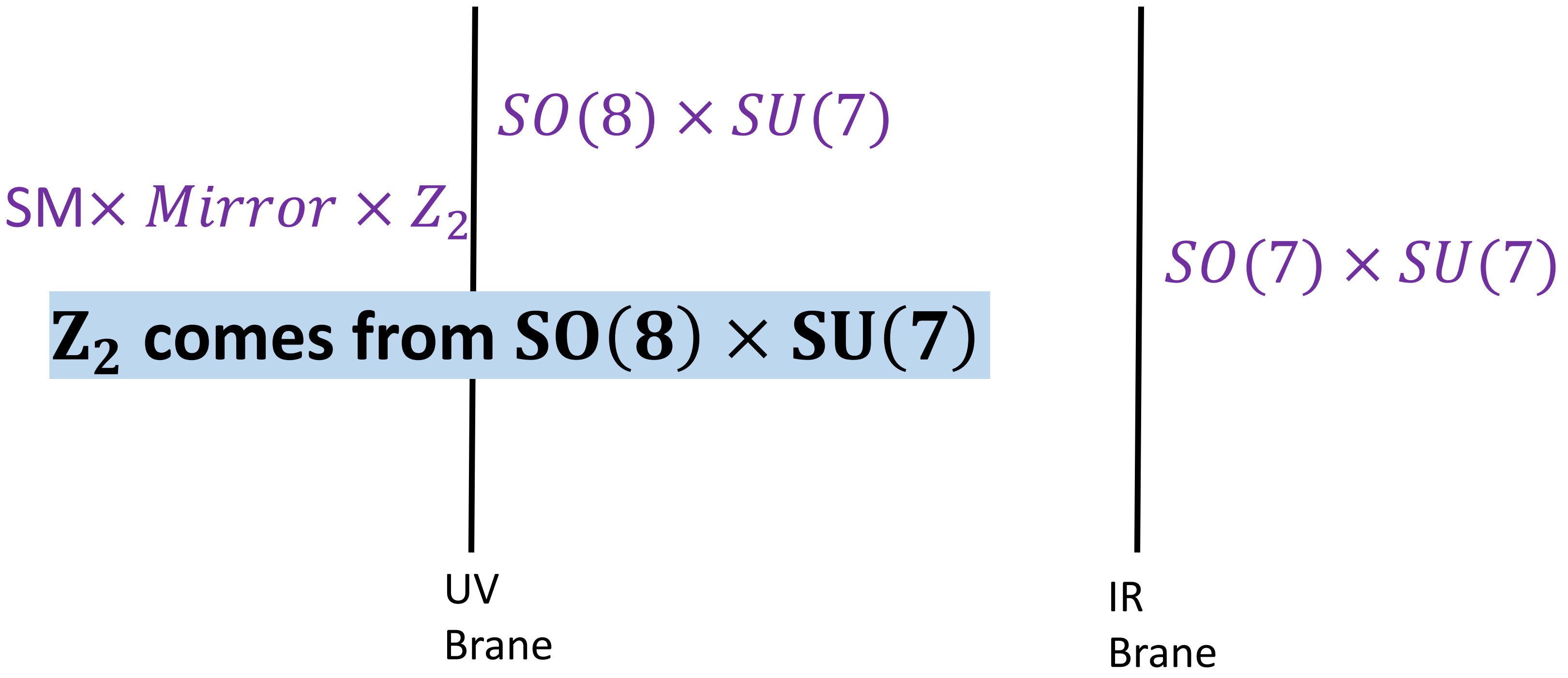

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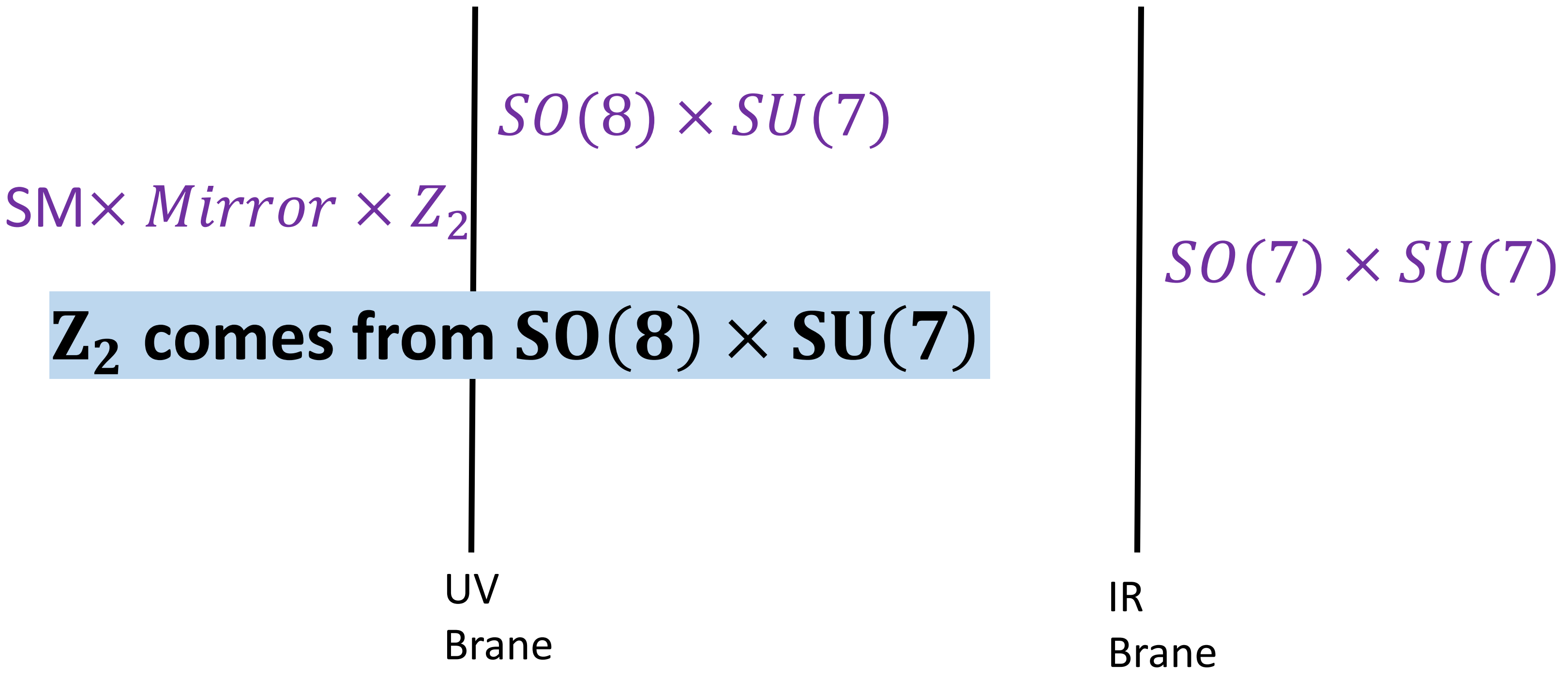
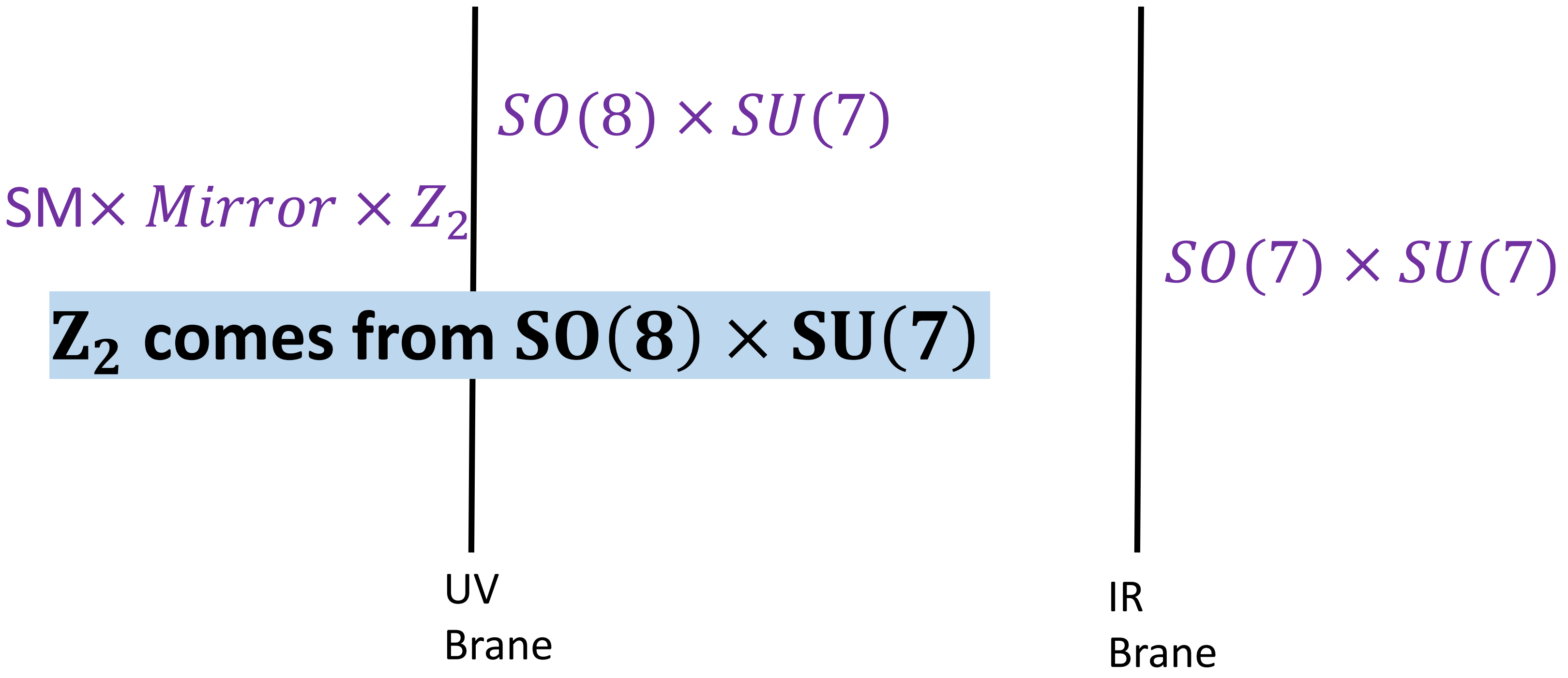


$\mathbf{Z_2}$ comes from $\mathbf{SO(8) \times SU(7)}$

Z_2: UV boundary conditions $(+) \rightarrow (+)_m$
gauge couplings $g = g^m$

A Holographic Twin Higgs model – full model



Z_2: UV boundary conditions $(+) \to (+)_m$

gauge couplings $g = g^m$

Zero mode → Mirror Zero mode

Symmetries

$$SU(7) \rightarrow SU(3) \times U(1) \times SU(3) \times U(1)$$

Color T_7 Mirror Color T_7^m

$$SO(8) \rightarrow SU(2)_L \times U(1)_R \times SU(2)_L^m \times U(1)_R^m$$

Weak T_R^3 Mirror Weak T_{mR}^3

Fermions: Group Theory

Fermions: Group Theory

Hypercharge

Fermions: Group Theory

Hypercharge

$$Y = \frac{4}{3}T_7 + T_R^3 \ , \ \ Y^m = \frac{4}{3}T_7^m + T_{mR}^3$$

Fermions: Group Theory

Hypercharge

$$Y = \frac{4}{3}T_7 + T_R^3 \ , \ \ Y^m = \frac{4}{3}T_7^m + T_{mR}^3$$

All quarks are in the **7** of SU(7)

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All quarks are in the **7** of SU(7)

$SU(7)$ $\qquad$ $SU(3) \times SU(3) \times U(1) \times U(1)$

$$\mathbf{7} = (\mathbf{1},\mathbf{1})_{-\frac{3}{2},-\frac{3}{2}} + (\mathbf{3},\mathbf{1})_{\frac{1}{2},0} + (\mathbf{1},\mathbf{3})_{0,\frac{1}{2}}$$

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(+,+) boundary conditions: Quarks, Mirror Quarks

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Q_L: **8** of SO(8), t_R: **1** of SO(8).

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$SO(8)$ $\quad SU(2) \times SU(2) \times U(1) \times U(1)$

$$\mathbf{8} = (\mathbf{2},\mathbf{1})_{-\frac{1}{2},0} + (\mathbf{1},\mathbf{2})_{0,-\frac{1}{2}} + \cdots$$

Fermions: Group Theory

Hypercharge

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Q_L $\qquad$ Q_L^m

Fermions: Group Theory

Hypercharge

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Q_L $\quad Q_L^m$

Fermions: Group Theory

Hypercharge

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All quarks are in the **7** of SU(7)

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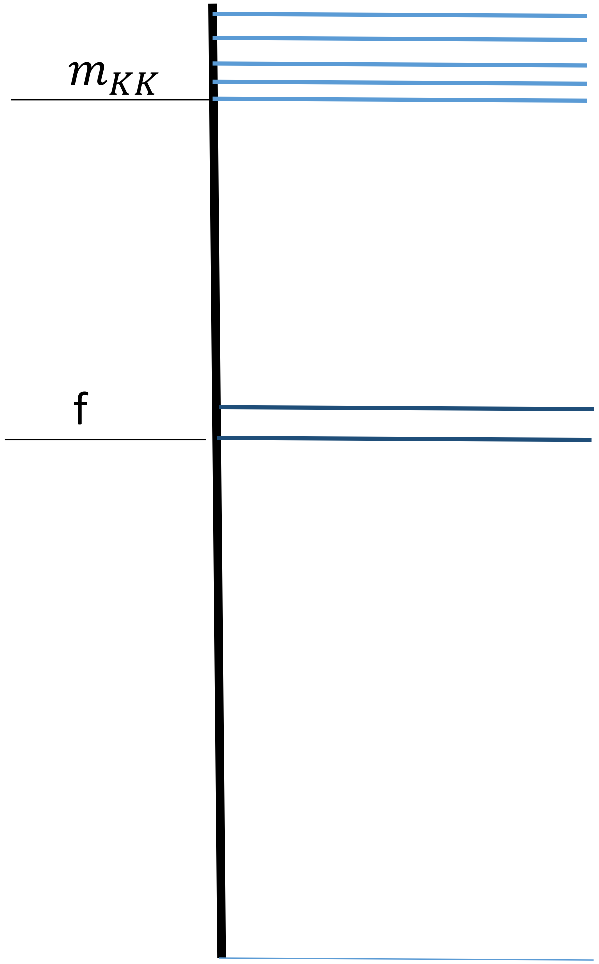
$$\mathbf{8} = (\mathbf{2},\mathbf{1})_{-\frac{1}{2},0} + (\mathbf{1},\mathbf{2})_{0,-\frac{1}{2}} + \cdots$$

Q_L $\quad Q^m_L$

The Spectrum (before EWSB)

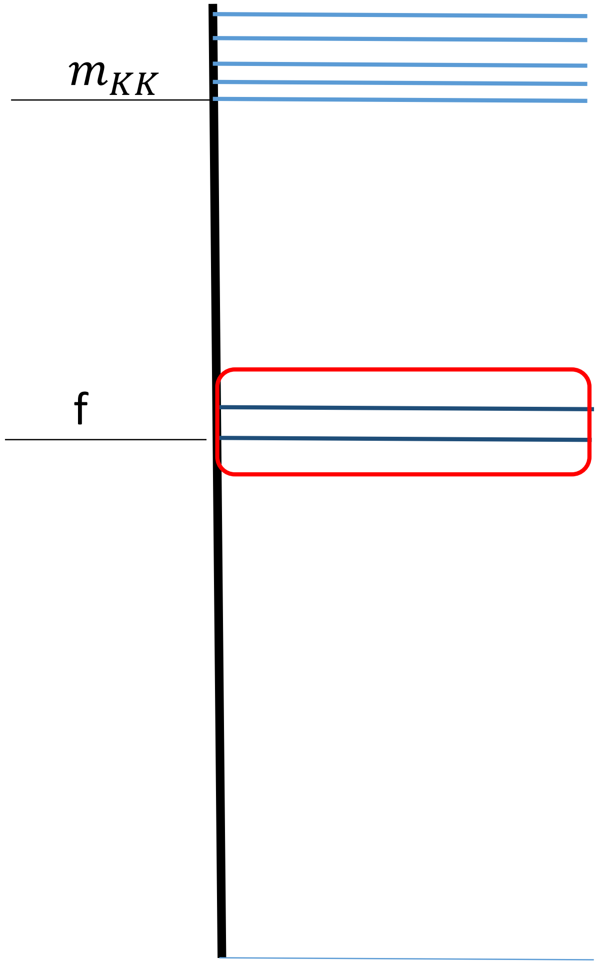


Vector Like Quarks (colored)
KK-gluons
Mirror excitations
Exotic: Mirror **and** SM charged

Mirror Top $\quad m_t^m = y_t f$
Mirror Gauge

SM fermions
Light mirror fermions $\quad m_f^m = \frac{f}{v} m_f$

The Spectrum (before EWSB)



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Mirror Top $m_t^m = y_t f$
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SM fermions
Light mirror fermions $m_f^m = \frac{f}{v} m_f$

The Higgs Potential – No Z_2-Breaking

Free parameters:

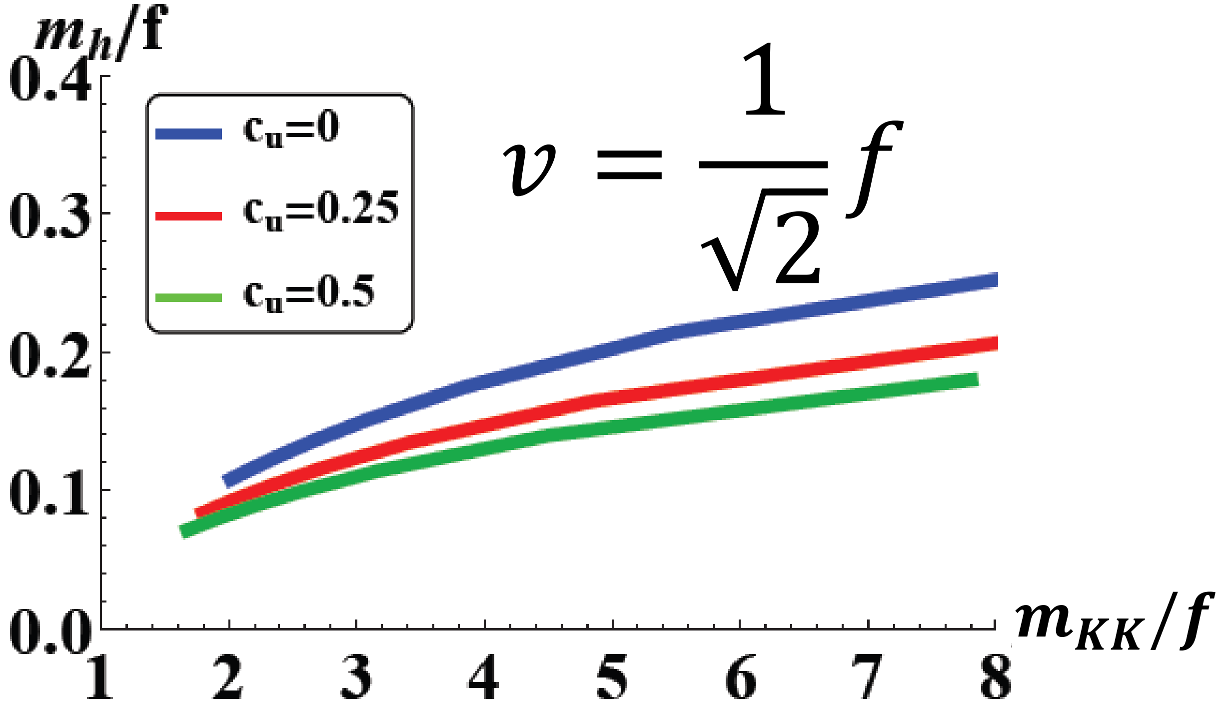
$\boldsymbol{f}$: the pion scale

$\boldsymbol{m_{KK}}$: the KK scale (scale of excitations)

$\boldsymbol{c_q}$, $\boldsymbol{c_u}$: bulk masses

$\boldsymbol{m_q^1}$: IR brane mass (5d Yukawa)

The top+gauge Contribution:



$$v = \frac{1}{\sqrt{2}} f$$

The Higgs Potential

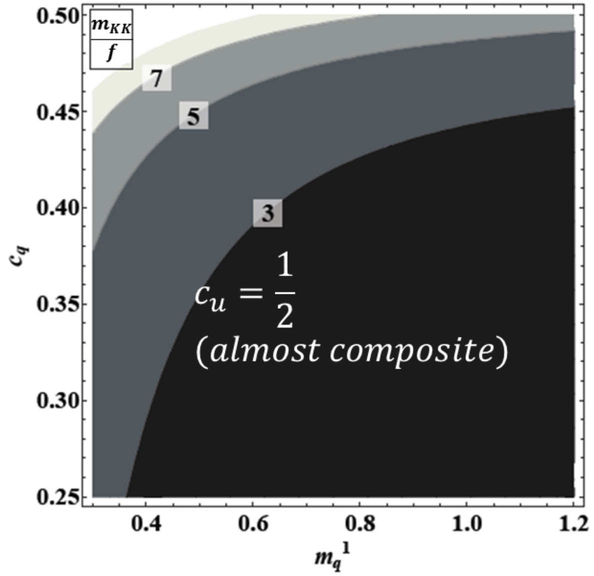
- Similarly to the original twin-Higgs, $v = \frac{f}{\sqrt{2}}$.

- To get $v \ll f$
  - Z_2 breaking contribution to the Higgs potential.
  - Tuning between the Z_2 and $\not{Z_2}$ terms.

- The Higgs mass $\boldsymbol{m_h^2 \sim \frac{3y_t^4}{8\pi^2} f^2}$ ⟷ In composite Higgs $\boldsymbol{m_h^2 \sim \frac{3y_t^2}{8\pi^2} m_{KK}^2}$

- The ratio $\frac{m_{KK}}{f} < 4\pi$ (On the CFT side $\frac{m_{KK}}{f} = \frac{4\pi}{\sqrt{N}}$)

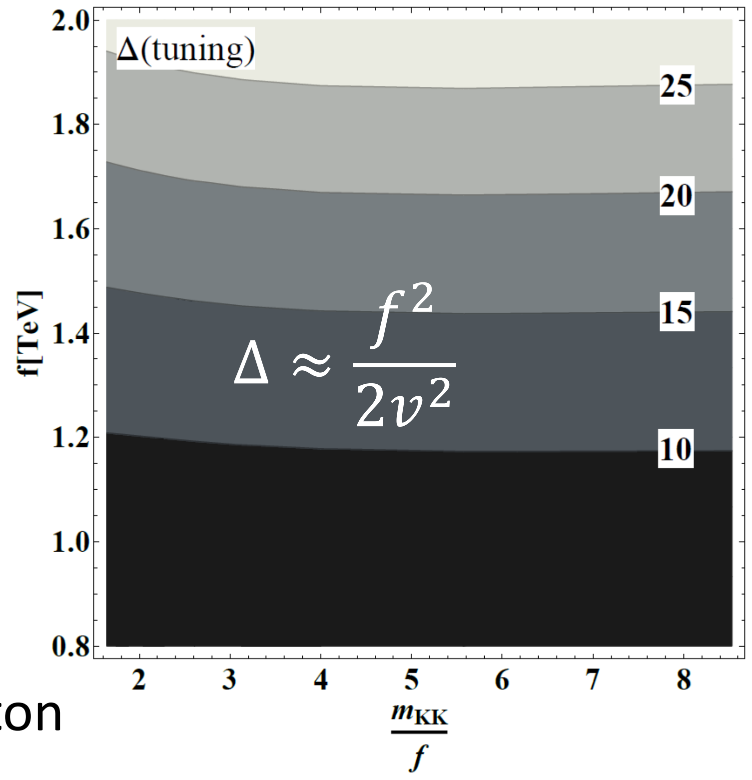
- ***The scale of excitations $\boldsymbol{m_{KK}}$ can be high (almost) without tuning!***



The Tuning

- To correct the EWSB pattern, we need an additional Z_2-breaking term (similar to the original twin Higgs)

$$V(h) = \mu^2 f^2 \sin^2 \frac{h}{f}$$



- <u>10% tuning</u>: $f = 1.2\ TeV$

- We need a Z_2 breaking mechanism
  - Avoid light d.o.f. – mirror neutrinos and mirror photon
  - Need the Z_2 for top+gauge

Z_2 breaking

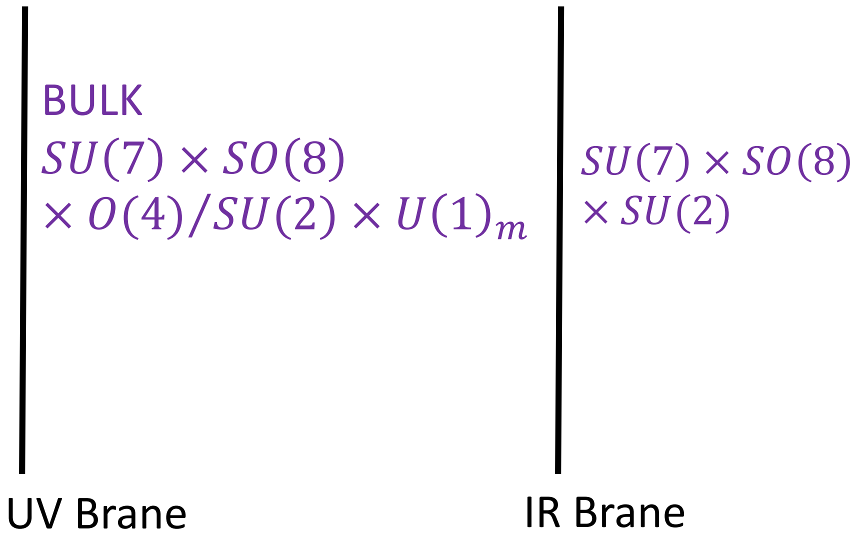
- Two possible ways to break Z_2
  - Elementary Sector
    1. Project out the unwanted states
    2. Generate a $\not{Z}_2$ term in the Higgs potential by detuning the SM and mirror contributions

M. Low, A. Tesi and L.T. Wang, arXiv:1501.07890
R. Barbieri, D. Greco, R. Rattazzi, A. Wulzer, arXiv:1501.07803

  - Strong Sector – Mirror Yukawa Couplings as free paramers ← our work
    1. Assume high enough mirror masses (but still $m \ll 100\ GeV$)
    2. Generate a Z_2 term in the Higgs potential by either SM or new contributions.

Z_2 breaking

Z_2 breaking in the strong sector: bulk and IR brane



$$O(4) = SU(2) \times SU(2)_m \times Z_2$$

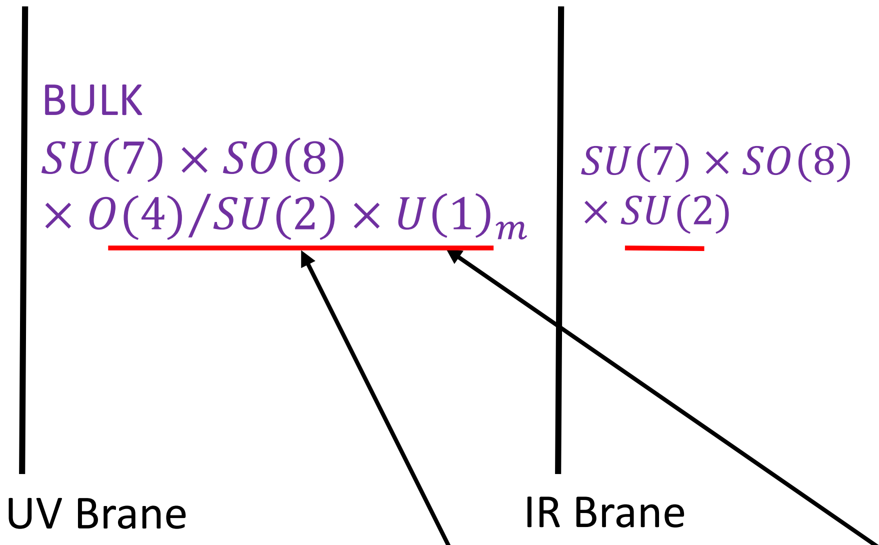
$$\boldsymbol{Z_2^{mirror}} \textbf{ in } \boldsymbol{SU(7) \times SO(8) \times O(4)}$$

Hypercharge is modified

$$Y = T_R^3 + \frac{4}{3}T^7 + T^4 \ , \ Y^m = T_{mR}^3 + \frac{4}{3}T_m^7 + T_m^4$$

Z_2 breaking

Z_2 breaking in the strong sector: bulk and IR brane



$$O(4) = SU(2) \times \cancel{SU(2)_m}^{\,U(1)_m} \times \cancel{Z_2}$$

$$\cancel{\boldsymbol{Z_2}}^{\,\boldsymbol{mirror}}\ \textbf{\textit{in}}\ \boldsymbol{SU(7) \times SO(8) \times \cancel{O(4)}}$$

Hypercharge is modified

$$Y = T^3_R + \frac{4}{3}T^7 + T^4\ ,\ \cancel{Y^m} = T^3_{mR} + \frac{4}{3}T^7_m + \cancel{T^4_m}$$

IR brane

Massive Mirror photon!

Z_2 breaking fermions

~~O~~(4) in the bulk → ***different bulk masses*** for mirrors if <u>charged under O(4)</u> .

No mirror symmetry for the Yukawa couplings of O(4) multiplets.

Free masses for mirror partners of light fermions.

Generate the new term in the Higgs potential

with a singlet of SM+mirror (28 of SO(8))

$$V(h) = \mu^2 f^2 \sin^2 \frac{h}{f}$$

Z_2 protects the Higgs potential

$$\boldsymbol{m_{mirror}} = \boldsymbol{m_{SM}} \frac{\boldsymbol{f}}{\boldsymbol{v}}$$

~~Z_2~~

$m_{mirror} = Free$
<<100 GeV

Fermion	$SU(7)$	$SO(8)$	$U(1)_4 \times U(1)_4^m \subset O(4)$
Quarks: Third Generation			
Ψ_L^Q	**7**	**8**	**1**
Ψ_R^t	**7**	**1**	**1**
Ψ_R^b	**7**	**28**	**1**
Light Quarks and Leptons			
$\Psi_L^{Q/L}$	**7/1**	**8**	$(0,0) \in \mathbf{6}$
$\Psi_R^{u/\nu}$	**7/1**	**28** or **1**	$(0,0) \in \mathbf{6}$
$\Psi_R^{d/e}$	**7/1**	**28**	$(0,0) \in \mathbf{6}$
New Singlets			
Ψ_L^{35}	**1**	**35v**	**1**
Ψ_L^{28}	**1**	**28**	$(0,0) \in \mathbf{6}$

The model - essentials

Z_2 for top and gauge - protects the Higgs potential.

Mirror top and mirror gauge < O(TeV) mass

Mirror partner masses of light quark and leptons are free parameters ⟶ ***No tensions with cosmology***

(not much larger than $\mathrm{O(GeV)}$)

With less than 10% tuning, $\boxed{f \sim 1\,TeV, m_{KK} > 5\,TeV}$

EW data

Due to the high scale of excitations – Tree level contribution are small

- T is protected by custodial symmetry.
- S requires $m_\rho \sim m_{KK} > 3\,TeV$
- $Z \rightarrow \overline{b_L} b_L$ protected by the left-right parity in our model (SO(7) on the IR brane)

Loop contributions need to be fully examined – might push f up

Phenomenology - Precision Higgs

Higgs invisible decay: $h \to \overline{b^m} b^m$

$$\mathrm{Br}_{inv} \approx \frac{v^2}{f^2} Br(h \to bb) \quad \rightarrow \quad f = 1\,TeV \quad \mathrm{Br}_{inv} \approx 3\%$$

Accessible @ future lepton colliders:

Facility	ILC			ILC(LumiUp)	TLEP (4 IP)		CLIC		
$\sqrt{s}$ (GeV)	250	500	1000	250/500/1000	240	350	350	1400	3000
$\int \mathcal{L}dt$ (fb^{-1})	250	+500	+1000	1150+1600+2500‡	10000	+2600	500	+1500	+2000
$P(e^-, e^+)$	$(-0.8, +0.3)$	$(-0.8, +0.3)$	$(-0.8, +0.2)$	(same)	$(0, 0)$	$(0, 0)$	$(0, 0)$	$(-0.8, 0)$	$(-0.8, 0)$
Γ_H	12%	5.0%	4.6%	2.5%	1.9%	1.0%	9.2%	8.5%	8.4%
κ_γ	18%	8.4%	4.0%	2.4%	1.7%	1.5%	–	5.9%	<5.9%
κ_g	6.4%	2.3%	1.6%	0.9%	1.1%	0.8%	4.1%	2.3%	2.2%
κ_W	4.9%	1.2%	1.2%	0.6%	0.85%	0.19%	2.6%	2.1%	2.1%
κ_Z	1.3%	1.0%	1.0%	0.5%	0.16%	0.15%	2.1%	2.1%	2.1%
κ_μ	91%	91%	16%	10%	6.4%	6.2%	–	11%	5.6%
κ_τ	5.8%	2.4%	1.8%	1.0%	0.94%	0.54%	4.0%	2.5%	<2.5%
κ_c	6.8%	2.8%	1.8%	1.1%	1.0%	0.71%	3.8%	2.4%	2.2%
κ_b	5.3%	1.7%	1.3%	0.8%	0.88%	0.42%	2.8%	2.2%	2.1%
κ_t	–	14%	3.2%	2.0%	–	13%	–	4.5%	<4.5%
BR_{inv}	0.9%	< 0.9%	< 0.9%	0.4%	0.19%	< 0.19%			

S. Dawson, A. Gritsan, H. Logan, J. Qian, C. Tully, R. Van Kooten, A. Ajaib and A. Anastassov et al., arXiv:1310.8361 [hep-ex].

Phenomenology - Precision Higgs

- Similarly to all composite models, the Higgs couplings are suppressed

$$g_{hXX} = g_{hXX}^{SM} \cos\left(\frac{v}{f}\right)$$

- The fit to c_V is translated into a limit on f:

Facility	LHC	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC	TLEP (4 IPs)
$\sqrt{s}$ (GeV)	14000	14000	250/500	250/500	250/500/1000	250/500/1000	350/1400/3000	240/350
$\int \mathcal{L}dt$ (fb^{-1})	300/expt	3000/expt	250 + 500	1150 + 1600	250 + 500 + 1000	1150 + 1600 + 2500	500 + 1500 + 2000	10000 + 2600
$\xi = v^2/f^2$	$0.16 - 0.24$	$0.08 - 0.16$	0.016	0.008	0.008	0.008	0.02/0.006/0.004	0.002
f (GeV)	$500 - 615$	$615 - 870$	1950	2750	2750	2750	1750/3175/3700	5500

B. Bellazzini, C. Csaki, J. Serra, arXiv:1401.2457 [hep-ph]

Phenomenology-composite VLQ

- The scale of VLQ excitations: $m_{KK} \approx 5\,TeV$
  - $\mathbf{2}_{\frac{7}{6}}$ @ 4-7 TeV
  - $\mathbf{2}_{\frac{1}{6}}$ @ 6-10 TeV
- No limit from the LHC,

  Accessible at a 100 TeV collider

95% exclusion projection for m_T ($Q = +5/3$) with 3000 fb^{-1} comparing analysis and parton luminosity scaling using arXiv:1312.2391 (CMS, 19.5 fb^{-1})

PDF set	8 TeV	14 TeV	33 TeV	100 TeV
MSTW2008nnlo68cl	0.8 TeV	2.2 TeV	4.2 TeV	9.6 TeV
NNPDF23_nnlo_as_0018	0.8 TeV	2.2 TeV	4.2 TeV	9.6 TeV
CT10nlo	0.8 TeV	2.2 TeV	4.3 TeV	9.6 TeV

95% exclusion projection for m_T comparing analysis and parton luminosity scaling using arXiv:1309.0026 (Bhattacharya, et al.) with 3000 fb^{-1}

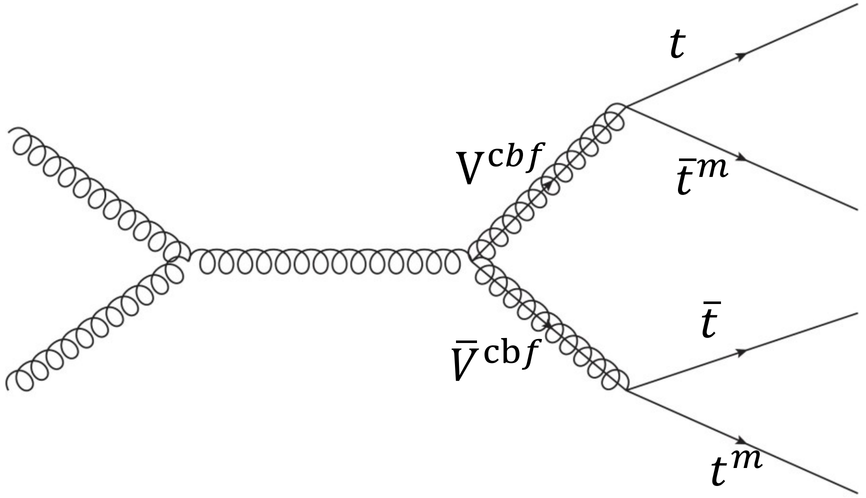
PDF set	14 TeV	33 TeV	100 TeV	33 TeV	100 TeV
MSTW2008nnlo68cl	1.8 TeV	3.4 TeV	7.4 TeV	3.4 TeV	7.4 TeV
NNPDF23_nnlo_as_0018	1.8 TeV	3.4 TeV	7.5 TeV	3.4 TeV	7.5 TeV
CT10nlo	1.8 TeV	3.4 TeV	7.3 TeV	3.4 TeV	7.4 TeV

L.T. Wang, "Fermionic Partners at 100 TeV", Workshop on Physics at a 100 TeV Collider, SLAC, 2014.

Phenomenology – Some exotics (KK)

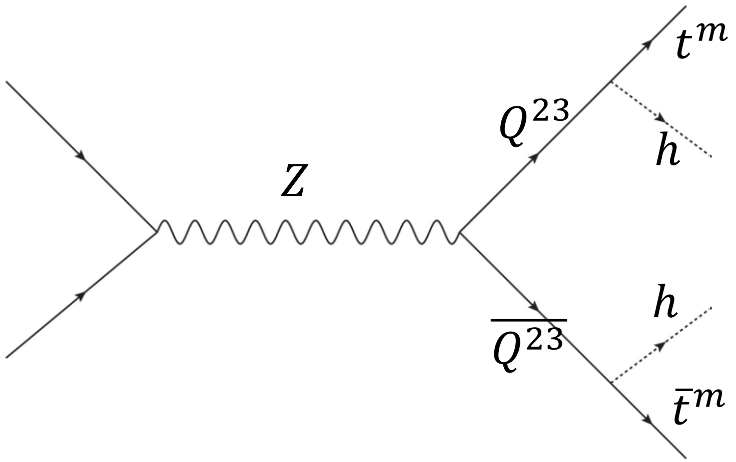
- Vectors:

$V^{cbf}(3, \bar{3})$



- Quarks:

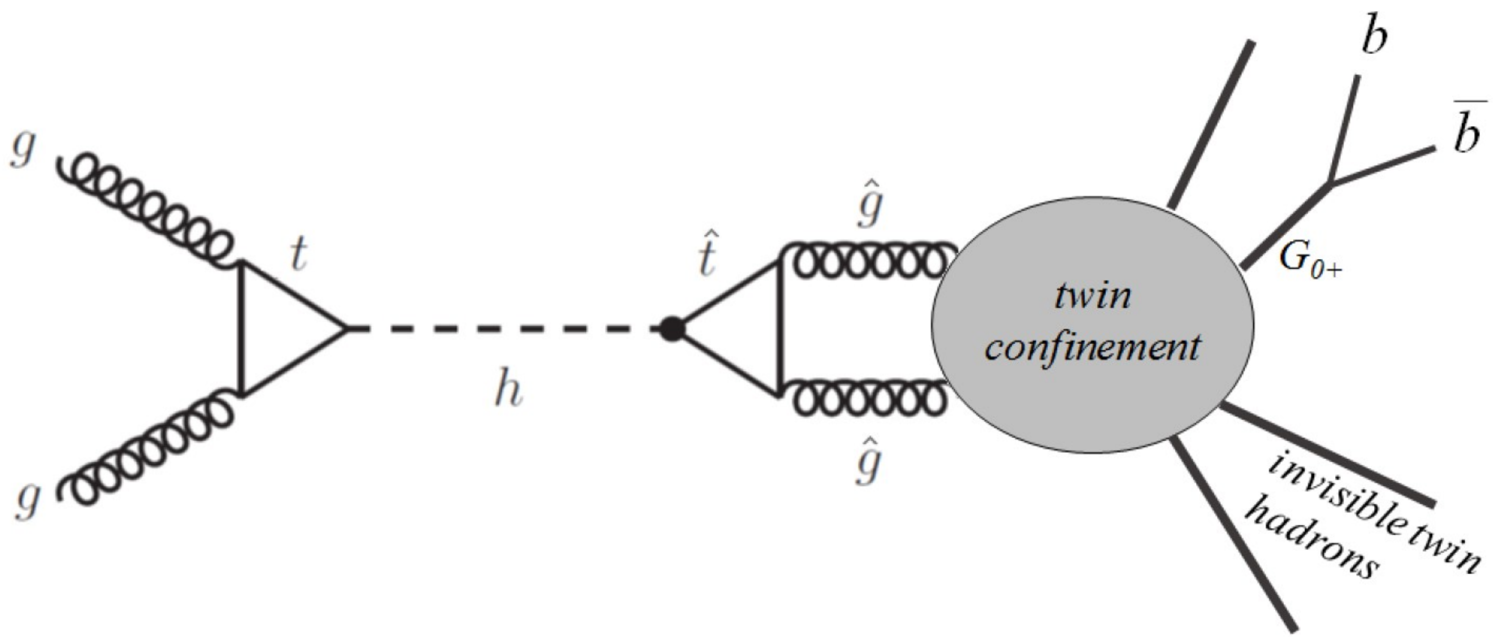
$Q^{23}(1,3,2,1)$



Phenomenology – Hidden valley

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

- Exotic Displaced Vertex pheno



Summary

- Holographic twin Higgs model:
  - The elementary sector is doubled with a Z_2 to include mirror partners for SM states. The Z_2 originates from the bulk symmetry.
  - A Z_2 breaking mechanism.
- KK excitations are heavy without tuning - $m_{KK} \sim 5 - 10\ TeV$, and for 10% tuning $f \sim 1\ TeV$
- Phenomenology:
  - Higgs precision
  - VLQ searches at a 100 TeV collider.
  - Exotics