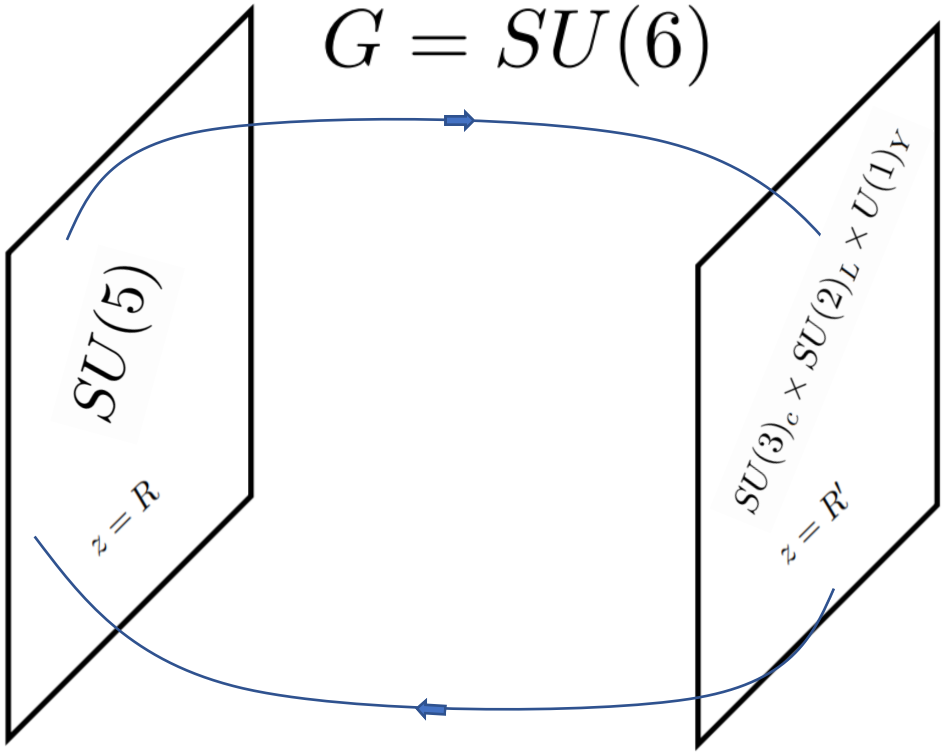
MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

SU(6) Gauge-Higgs Grand Unification



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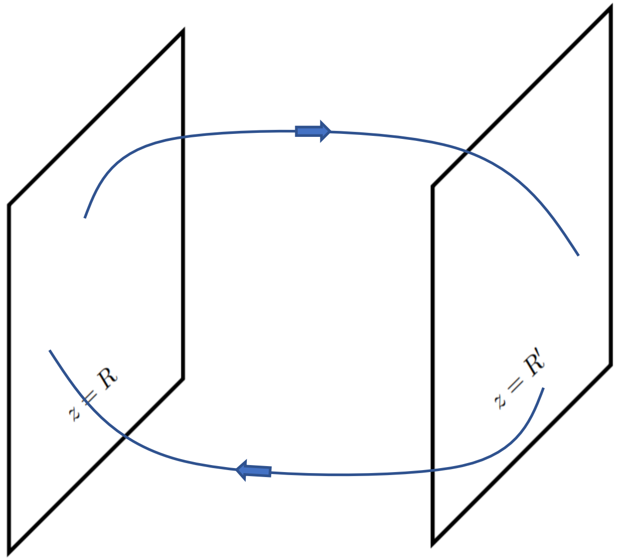
Based on Phys. Rev. D 105, 035026 (2104.07366) and upcoming work in collaboration with **Andrei Angelescu** (MPIK), **Simone Blasi**(VUB) & **Florian Goertz**(MPIK)

Gauge-Higgs Unification:
Gauge field in 5 Dimensions

Manton 1979, Hosotani, Fairlie, Hatanaka, Inami, Lim…

$$A_M = (A_\mu, A_5)$$

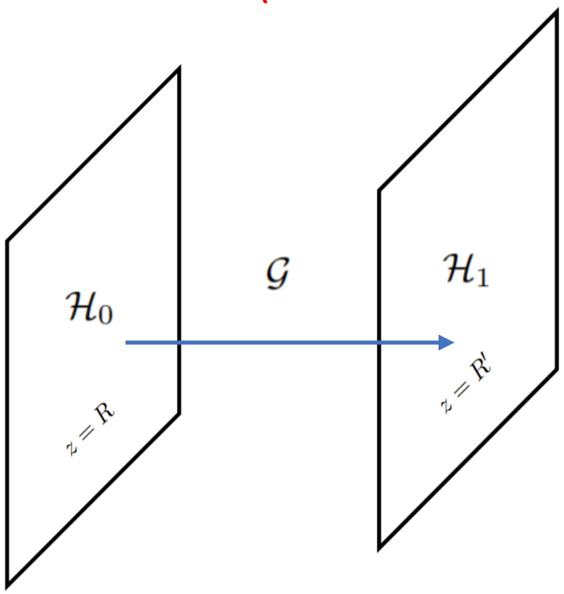
Why Gauge-Higgs Uni.?



1. No tree-level mass term by 5D gauge invariance: solution to the HP (in warped space)

$$\frac{1}{2}m_{A_5}^2 A_5^2 \notin F_{MN}F^{MN}$$

2. The scalar sector unified within the gauge sector: break the gauge symmetry by boundary conditions

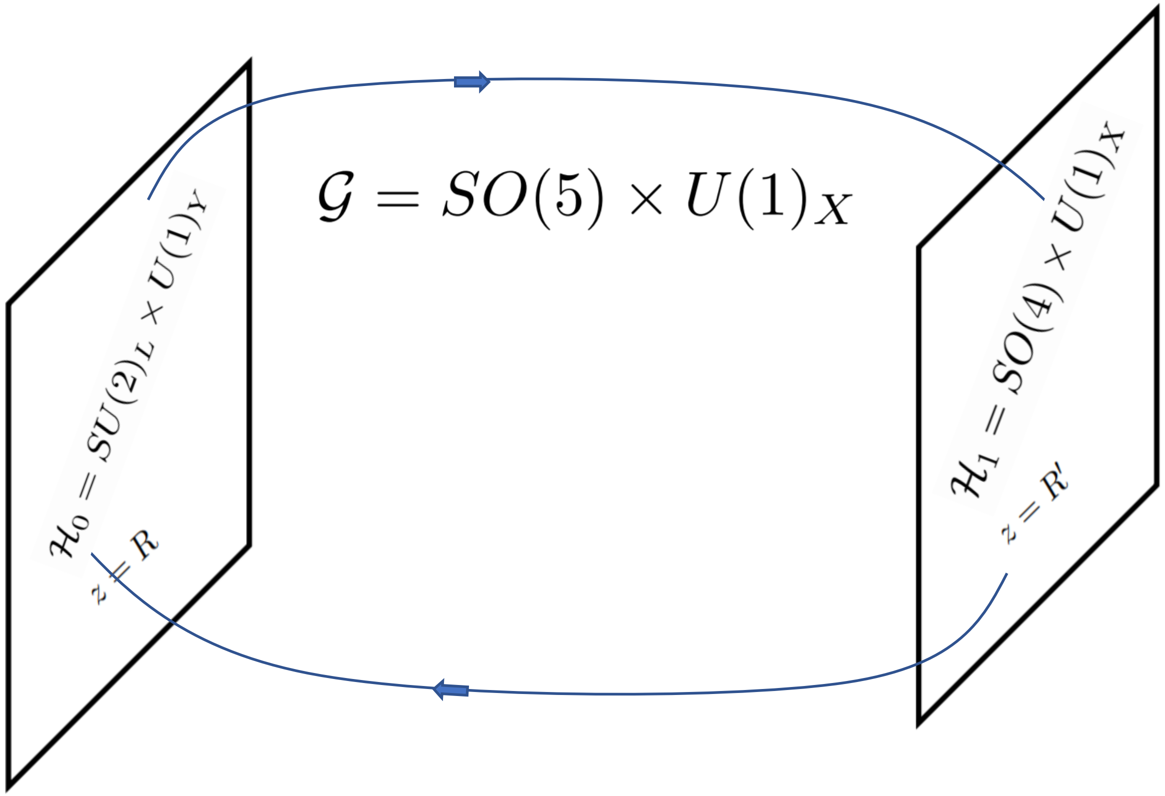


3. Dynamical origin of EWSB: Hosotani Mechanism

$$m_h \propto 1/R' \quad \left(= ke^{-kL} = m_{\rm KK}\right)$$

Agashe, Contino, Nomura, Pomarol,..

Electroweak Gauge-Higgs Unification



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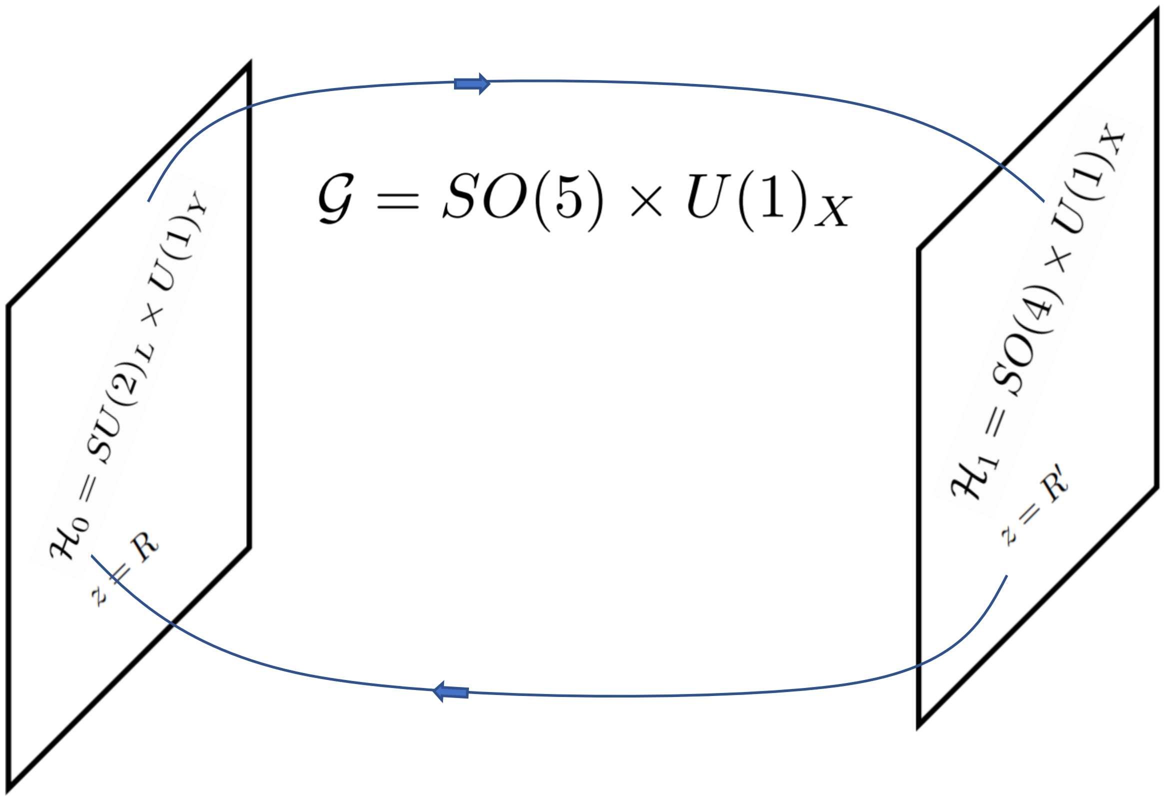
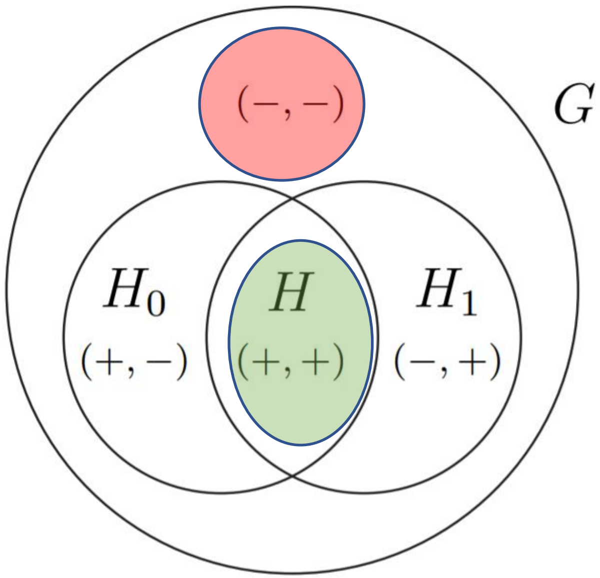
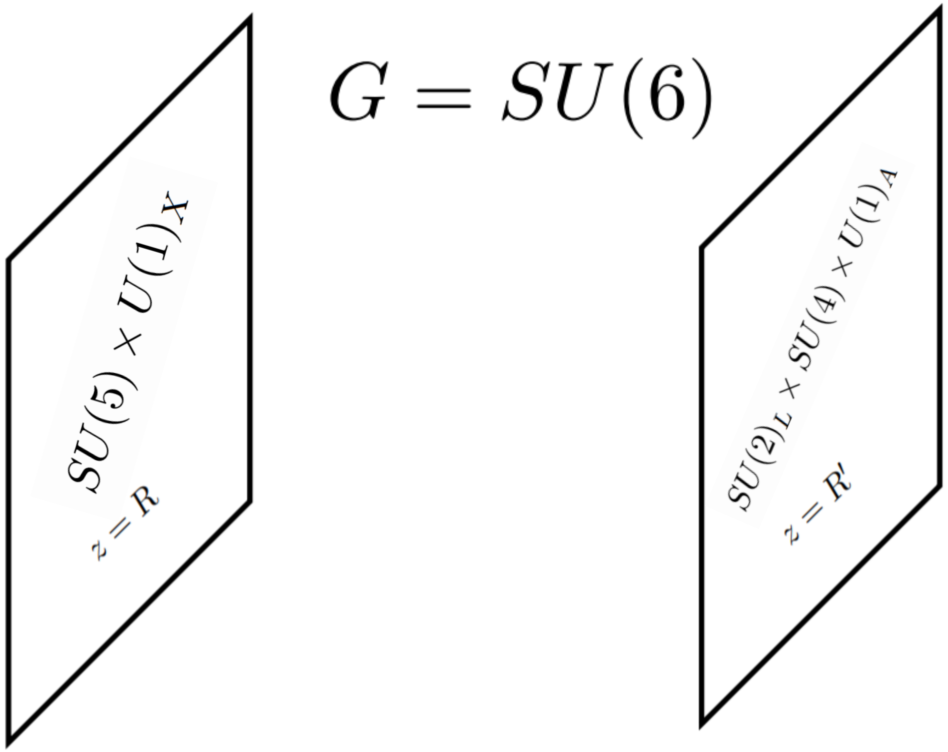




Massless Gauge Bosons: $T^a \in \mathcal{H} = \mathcal{H}_0 \cap \mathcal{H}_1 = SU(2)_L \times U(1)_Y \quad \left(= A^a_\mu(+,+) \right)$

Massless Scalars: $T^a \in \mathcal{G}/\mathcal{H}_0 \cap \mathcal{G}/\mathcal{H}_1 = (1,2)_{1/2} \quad \left(= A^{\dot{a}}_\mu(-,-) \right)$

SU(6) GHGUT: Gauge sector



$$A_\mu = \left(\begin{array}{cc|ccc|c}
(++) & (++) & (+-) & (+-) & (+-) & (--) \\
(++) & (++) & (+-) & (+-) & (+-) & (--) \\
\hline
(+-) & (+-) & (++) & (++) & (++) & (-+) \\
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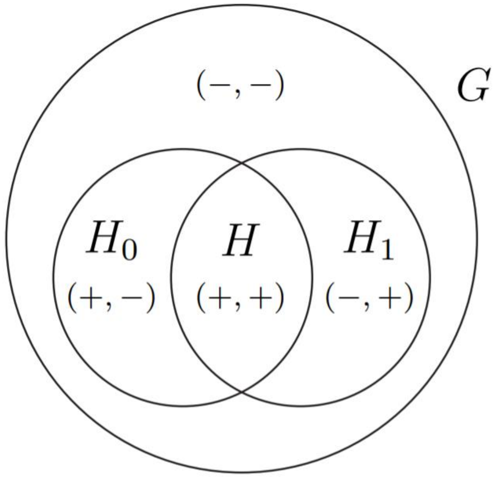
\hline
(--) & (--) & (-+) & (-+) & (-+) & (++)
\end{array}\right)$$

Can be obtained from orbifold breaking

$$P = \mathrm{diag}(1,1,1,1,1,-1)$$

$$P' = \mathrm{diag}(1,1,-1,-1,-1,-1)$$

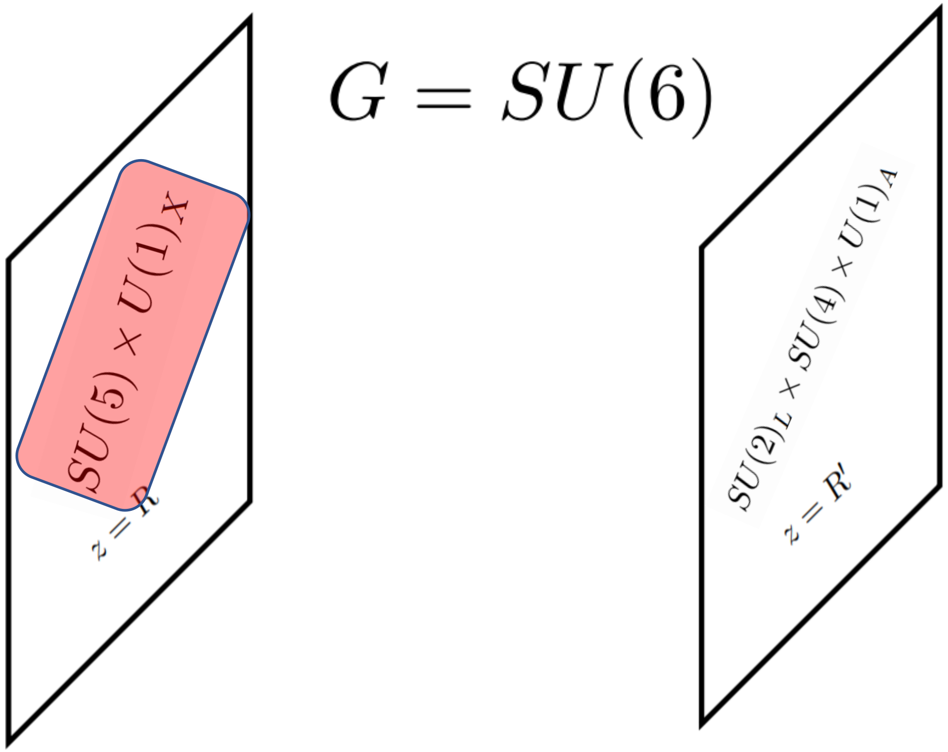
Exactly what we need!



Unbroken gauge group:

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

SU(6) GHGUT: Gauge sector



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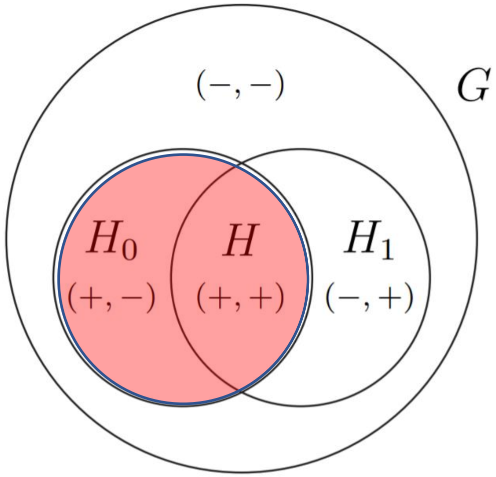

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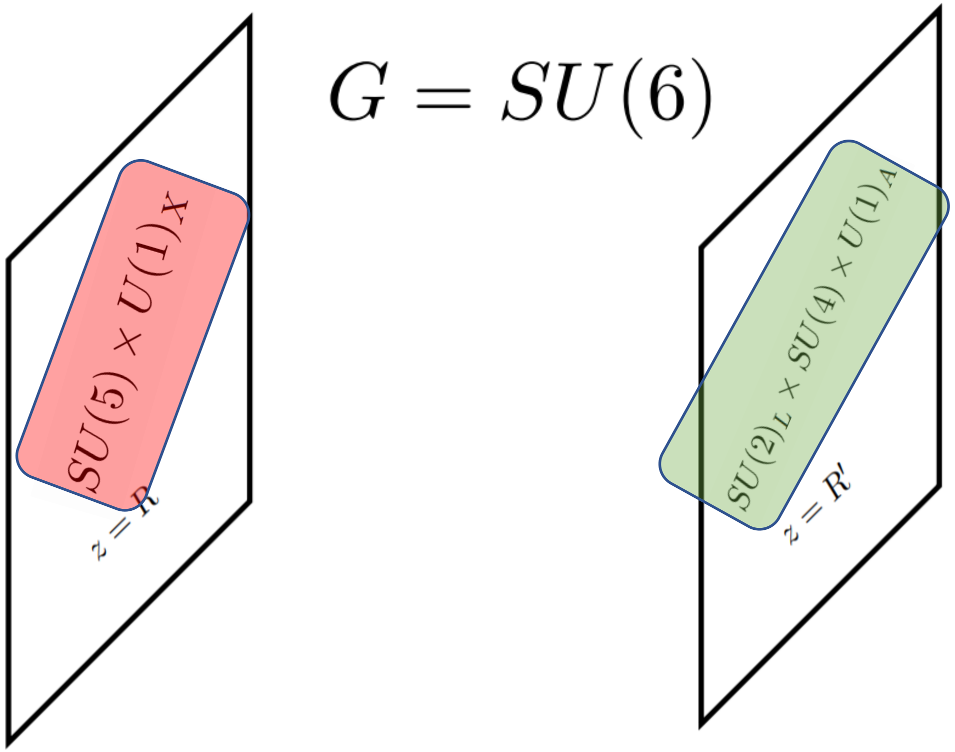

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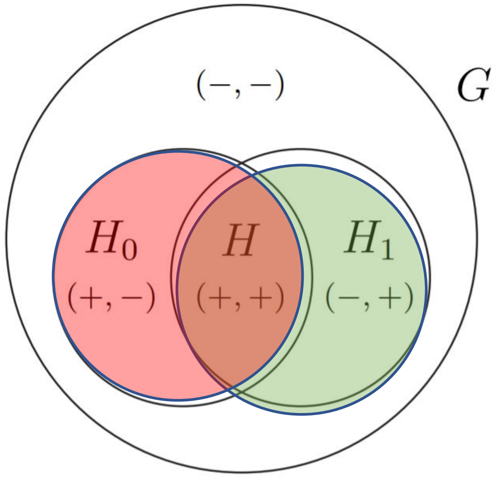

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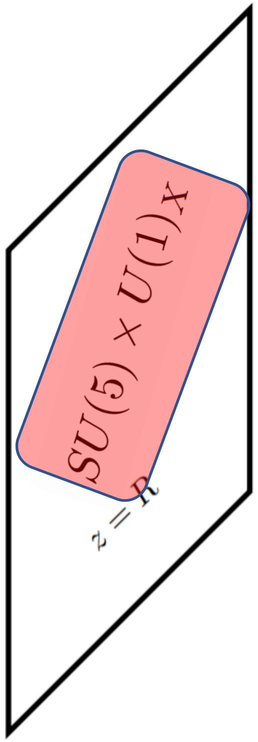
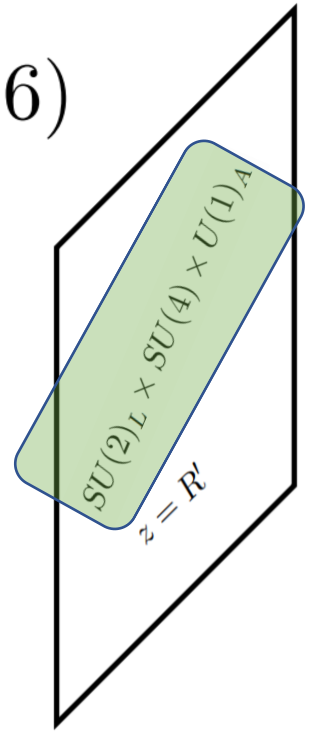
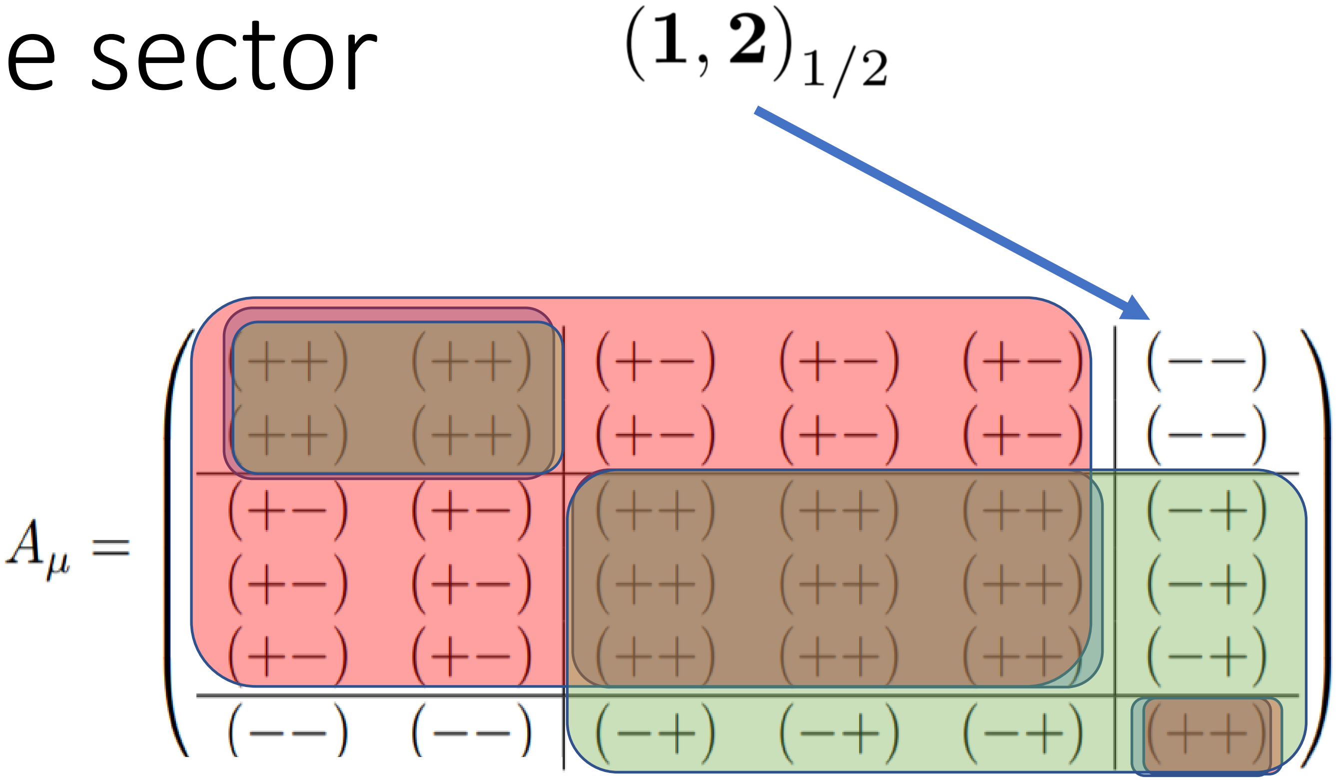
SU(6) GHGUT: Gauge sector



$$G = SU(6)$$



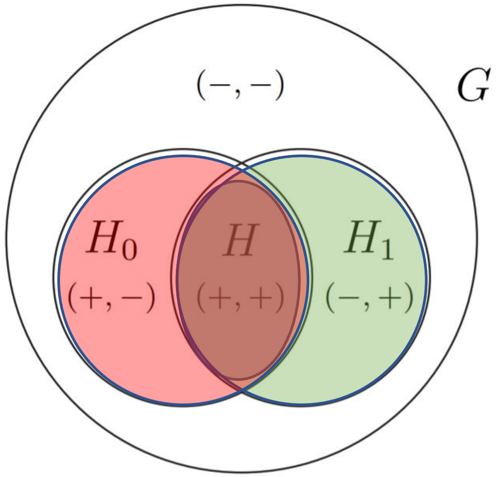


Can be obtained from orbifold breaking

$$P = \text{diag}(1, 1, 1, 1, 1, -1)$$

$$P' = \text{diag}(1, 1, -1, -1, -1, -1)$$

Exactly what we need!



Unbroken gauge group:

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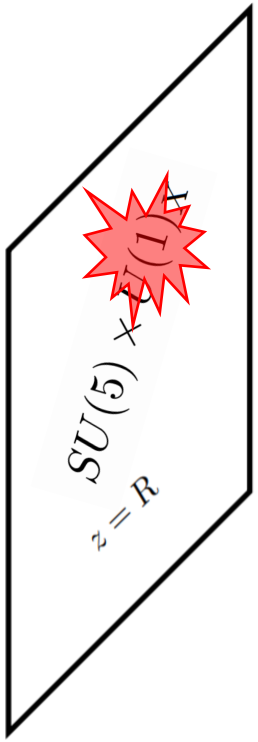
SU(6) GHGUT: Extra UV and IR breaking



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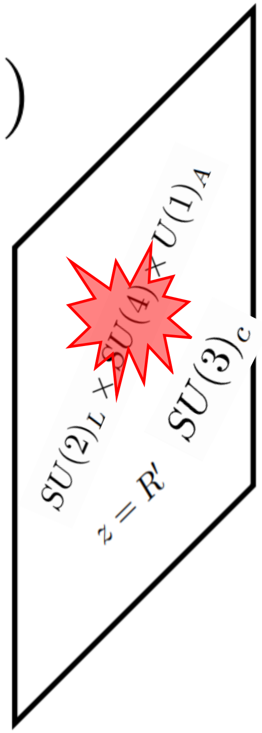

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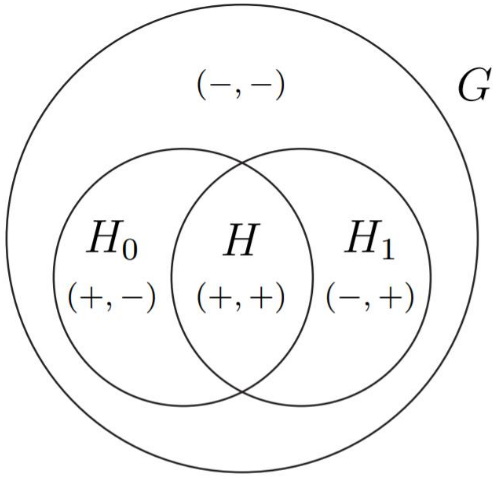

Unbroken gauge group:

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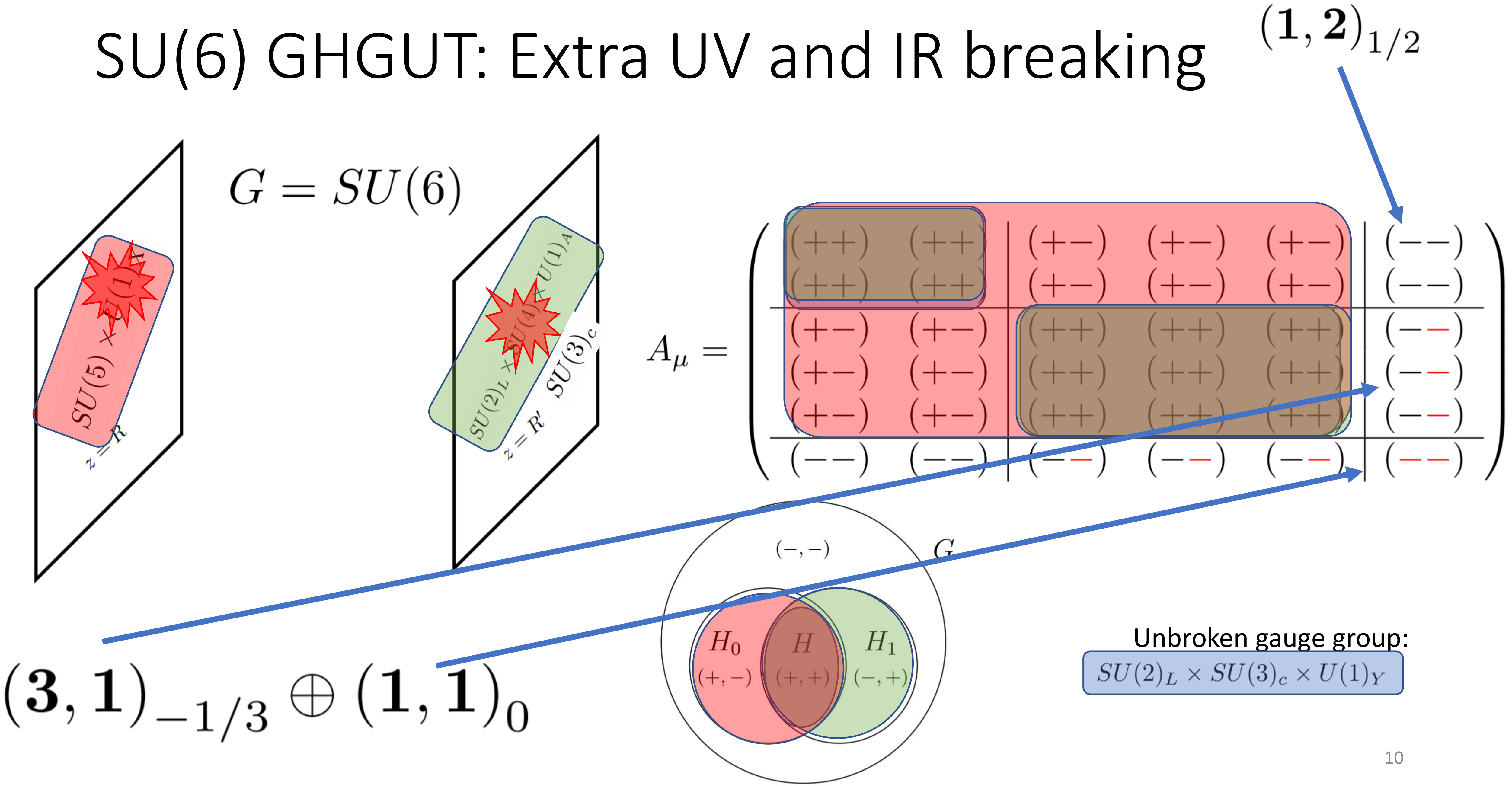
SU(6) GHGUT: Extra UV and IR breaking



Unbroken gauge group:

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

SU(6) GHGUT with Extra UV/IR Breaking: Fermionic content

$$\mathbf{20_L} = \begin{cases} \mathbf{10_L} \to & (\mathbf{3},\mathbf{2})^{-,+}_{1/6} \oplus (\mathbf{3}^*,\mathbf{1})^{-,+}_{-2/3} \oplus (\mathbf{1},\mathbf{1})^{-,+}_{1} \\ \mathbf{10^*_L} \to & (\mathbf{3}^*,\mathbf{2})^{-,+}_{-1/6} \oplus u_R(\mathbf{3},\mathbf{1})^{-,-}_{2/3} \oplus (\mathbf{1},\mathbf{1})^{-,+}_{-1} \end{cases}$$

$$\mathbf{15_L} = \begin{cases} \mathbf{10_L} \to & q_L(\mathbf{3},\mathbf{2})^{+,+}_{1/6} \oplus (\mathbf{3}^*,\mathbf{1})^{+,-}_{-2/3} \oplus e^c_R(\mathbf{1},\mathbf{1})^{+,+}_{1} \\ \mathbf{5_L} \to & (\mathbf{3},\mathbf{1})^{-,+}_{-1/3} \oplus (\mathbf{1},\mathbf{2})^{-,+}_{1/2} \end{cases}$$

$$\mathbf{6_L} = \begin{cases} \mathbf{5_L} \to & d_R(\mathbf{3},\mathbf{1})^{-,-}_{-1/3} \oplus l^c_L(\mathbf{1},\mathbf{2})^{-,-}_{1/2} \\ \mathbf{1_L} \to & \nu^c_R(\mathbf{1},\mathbf{1})^{+,+}_{0} \end{cases}$$

$$\mathbf{1_L} = (\mathbf{1},\mathbf{1})^{-,+}_{0}$$

More breaking: allows for brane masses!

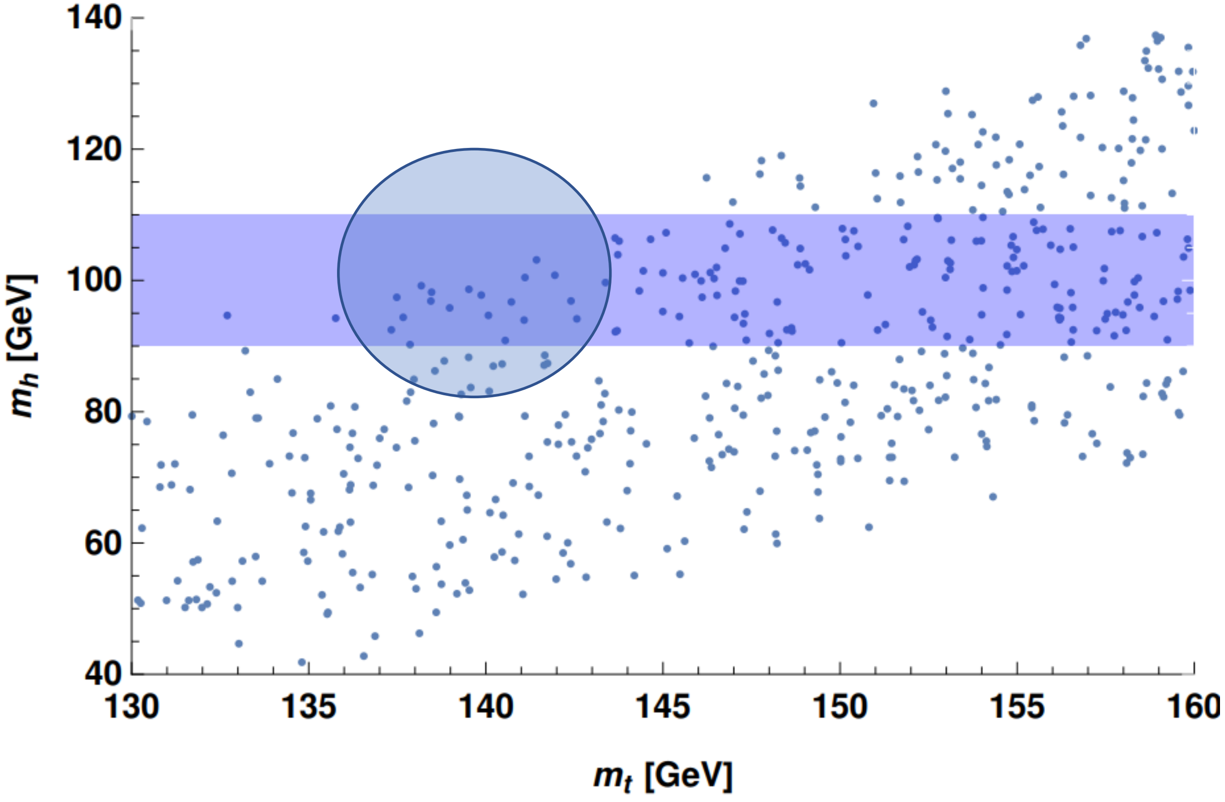
$$S_{UV} = \int \mathrm{d}^4x \left(M_u \psi_{\mathbf{20},10} \chi_{\mathbf{15},10} + \mathrm{h.c.}\right)$$

$$S_{IR} = \int \mathrm{d}^4x \left(\frac{R}{R'}\right)^4 \left(M_{\tilde{u}} \psi_{\mathbf{15},(3^*,1)} \chi_{\mathbf{20},(3^*,1)} + M_d \chi_{\mathbf{15},(3,1)} \psi_{\mathbf{6},(3,1)} + M_l \chi_{\mathbf{15},(1,2)} \psi_{\mathbf{6},(1,2)} + M_\nu \chi_{\mathbf{6},1} \psi_{\mathbf{1}} + \mathrm{h.c.}\right)$$

Reproduce all SM masses of the three generations + no light exotics!

Higgs potential

$$V_r(v,c,s) = \frac{N_r}{(4\pi)^2}\int_0^\infty dp\, p^3 \log(\rho_r(-p^2,v,c,s))$$



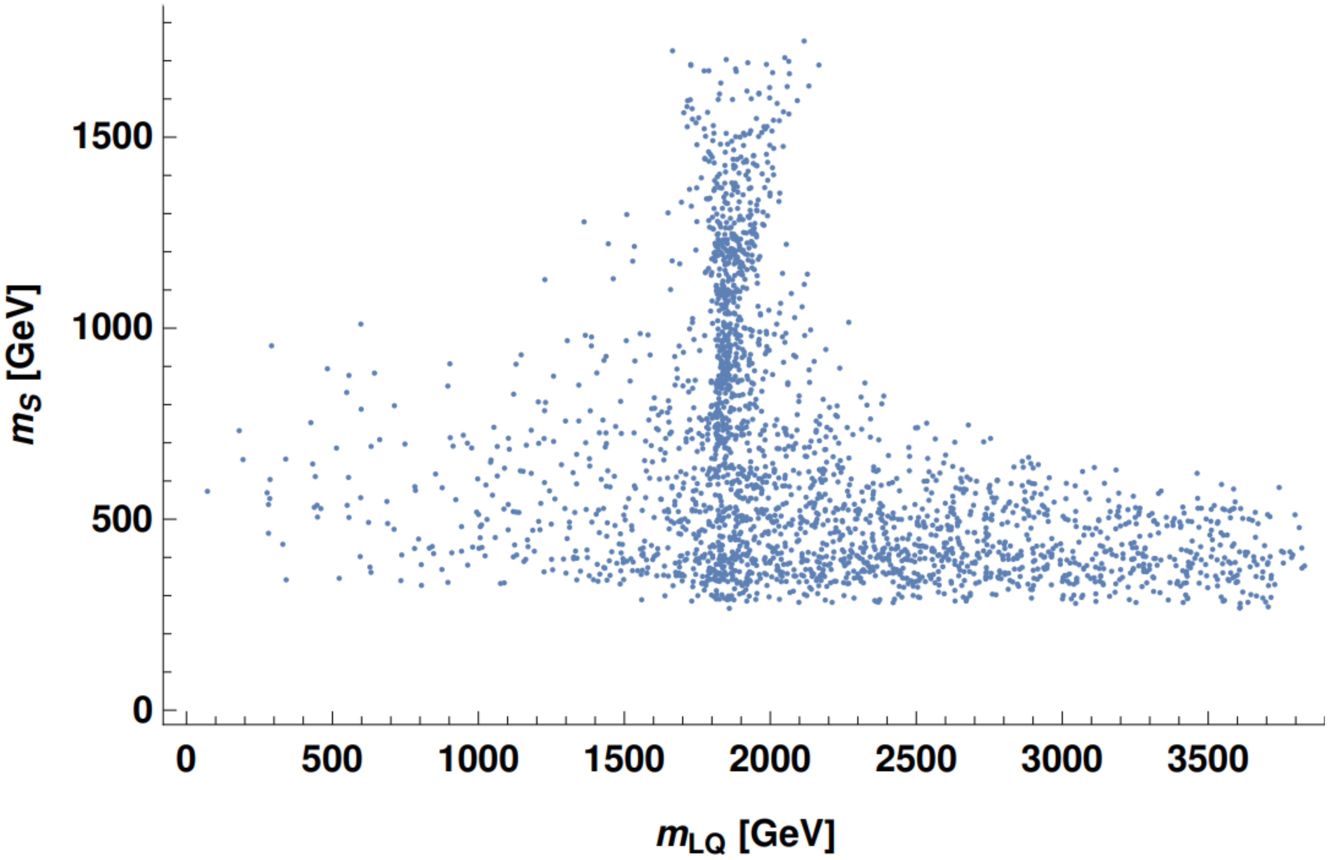
$$1/R' \sim 10\text{TeV}$$

Tuning at the 0.1% level..

However, correct quartic!

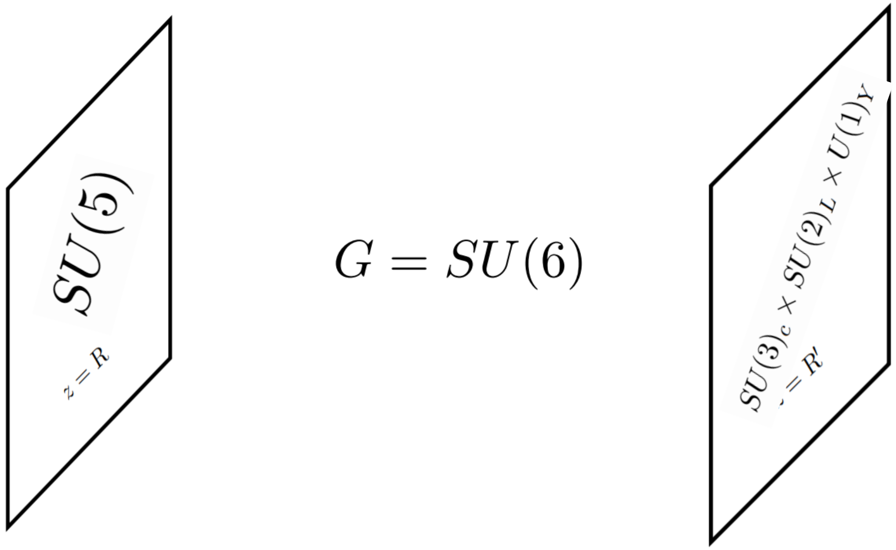
Exotic scalar spectrum: $(\mathbf{3},\mathbf{1})_{-1/3} \oplus (\mathbf{1},\mathbf{1})_0$

$$1/R' \sim 10\text{TeV}$$



- No vev for colored scalar !

What about the X,Y gauge bosons? $(\mathbf{3},\mathbf{2})_{5/6}$



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$$m_{(+,-)} = \frac{2}{R'\sqrt{2\log(\frac{R'}{R}) - 1}} \sim 0.25/R'$$

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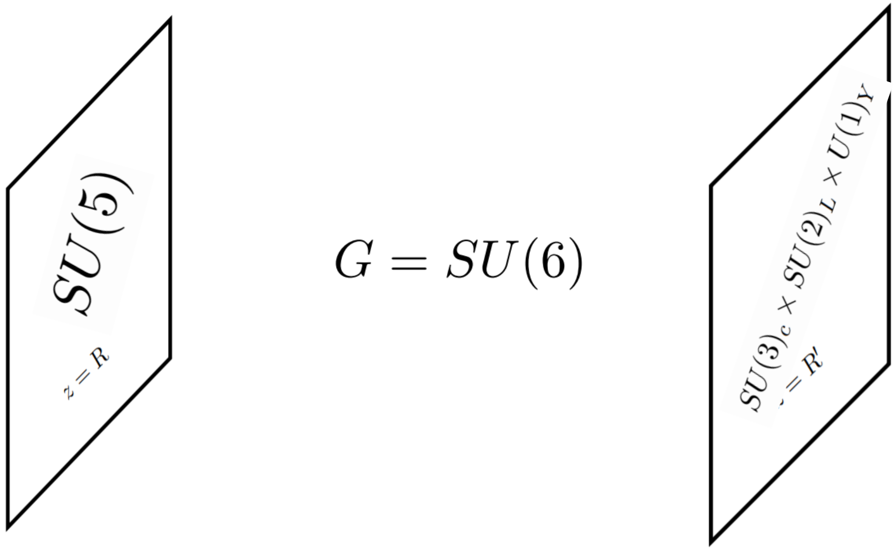

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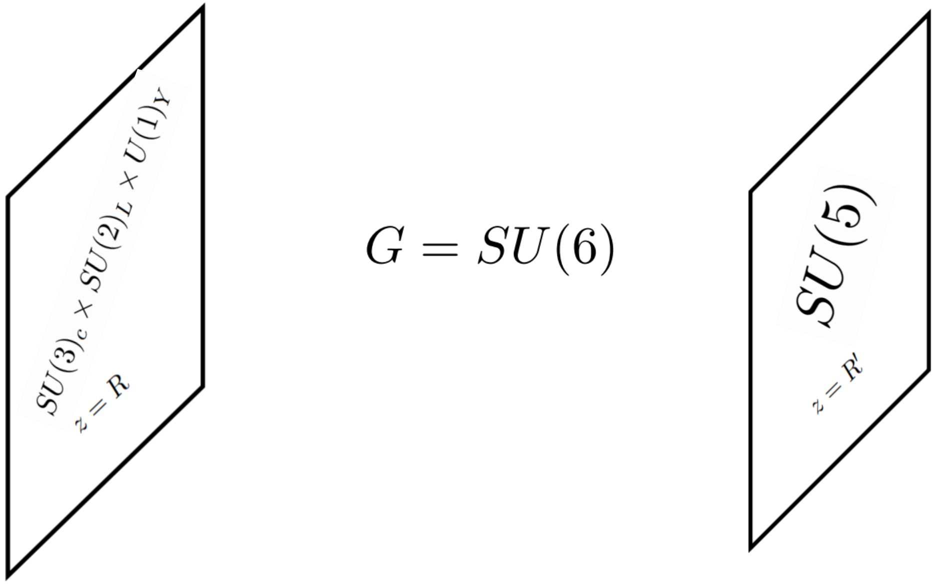


$$A_\mu = \left(\begin{array}{cc|ccc|c} (++) & (++) & (-+) & (-+) & (-+) & (--) \\ (++) & (++) & (-+) & (-+) & (-+) & (--) \\ \hline (-+) & (-+) & (++) & (++) & (++) & (--) \\ (-+) & (-+) & (++) & (++) & (++) & (--) \\ (-+) & (-+) & (++) & (++) & (++) & (--) \\ \hline (--) & (--) & (--) & (--) & (--) & (--) \end{array}\right)$$

$$m_{(-,+)} \sim 2.45/R'$$

Little Hierarchy Problem : $1/R' \gtrsim 10\text{TeV}$

Unique to GHGUT

- Constraints on leptoquarks coupling to first generation fermions (Crivellin, Schnell arXiv: 210406417)

$$m_{X,Y} \gtrsim 2.5 \text{ TeV}$$

- Constraints from the colored scalar: QCD double production

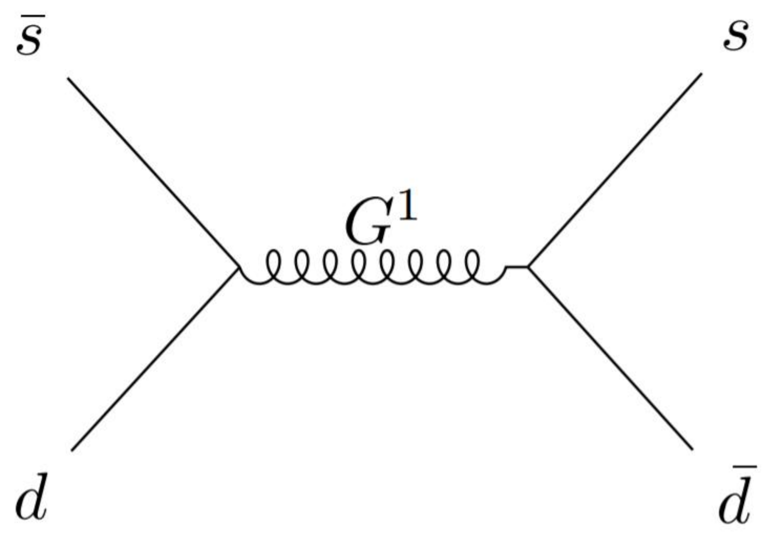
$$m_{S_1} \gtrsim 2 \text{ TeV}$$

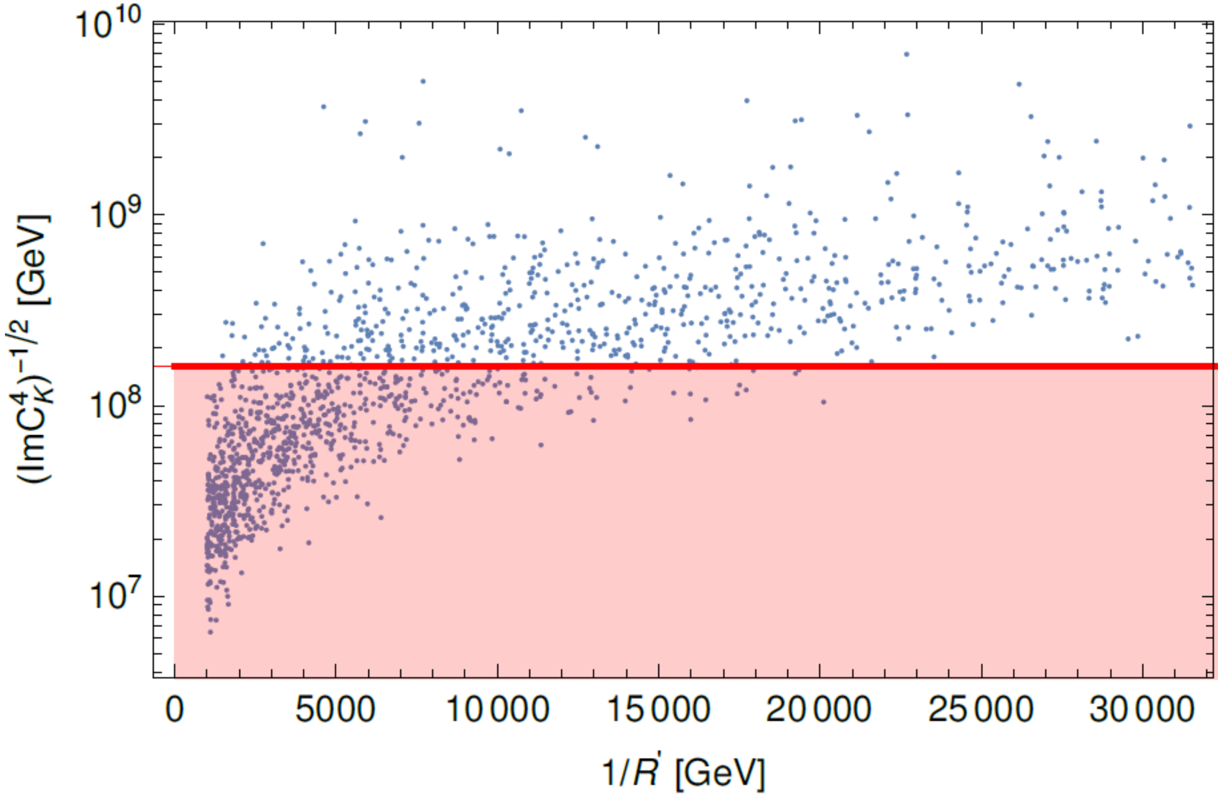
All extra dim models

- Constraints from FCNCs (Csaki, Falkowski, Weiler arXiv:08041954)

$$m_{KK,\text{Gluon}} \gtrsim 25 \text{ TeV}$$

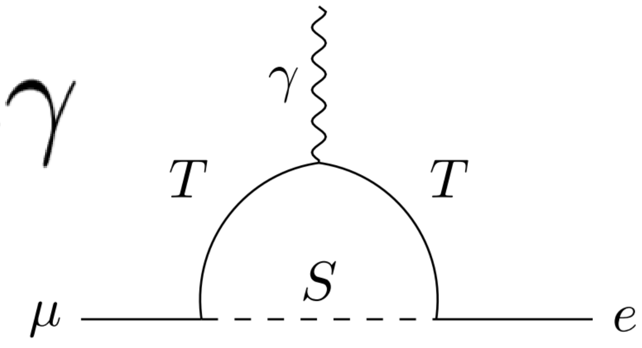
Tree-level flavor violation: Meson Mixing





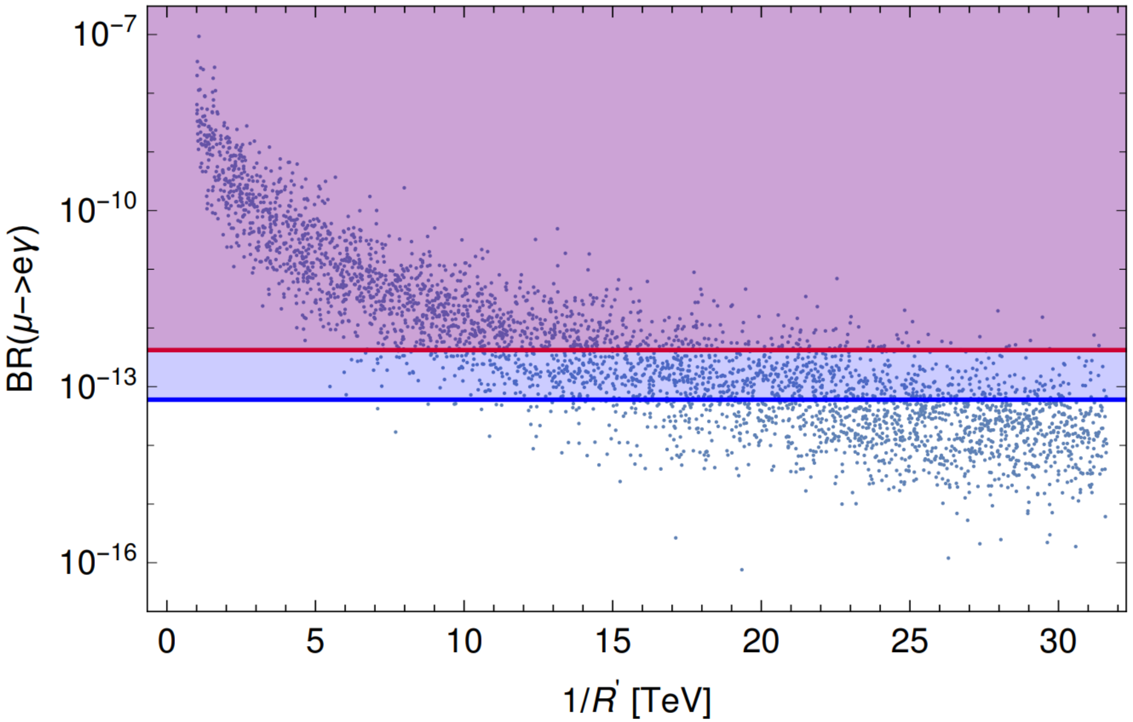
$$\mathcal{H} \supset C_4^K Q_4^{ds} \sim \left(\frac{g^{ds}}{m_{G^1}}\right)^2 (\bar{d}_L^{\alpha} s_{R,\alpha})(\bar{d}_R^{\beta} s_{L,\beta})$$

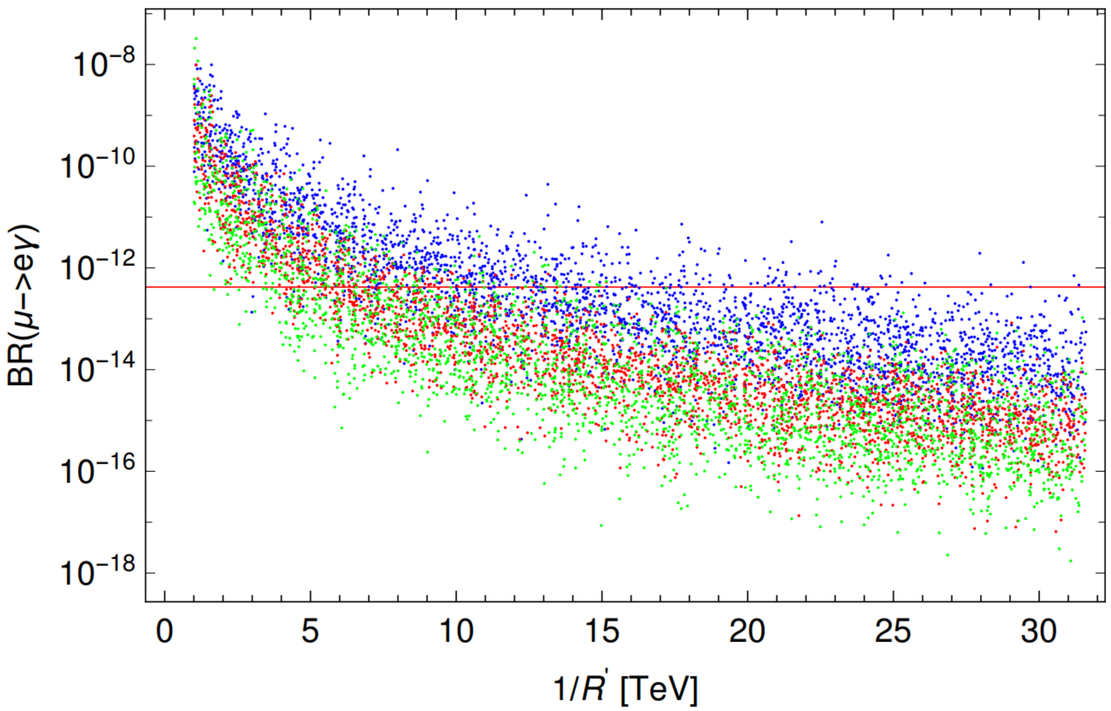
Loop-level flavor violation: $\mu \to e\gamma$



MEG (2016) $\mathrm{Br}(\mu \to e\gamma) < 4.2 \times 10^{-13}$

MEG II (20??) $\mathrm{Br}(\mu \to e\gamma) < 6 \times 10^{-14}$





- S leptoquark
- Higgs
- Z boson

Proton Decay: no perturbative decay

There is no proton decay if one can consistently extend baryon number to each new field such that it is conserved at each vertex.

$X^\dagger, Y^\dagger \sim (3^*, 2)_{5/6}$

B=1/3 B=-1/3 B=0

In 4D GUTs: $$\mathbf{10} \to q_L(\mathbf{3}, \mathbf{2})_{1/6} \oplus u_R^c(\mathbf{3}^*, \mathbf{1})_{-2/3} \oplus e_R^c(\mathbf{1}, \mathbf{1})_1$$

$X, Y \sim (3, 2)_{-5/6}$

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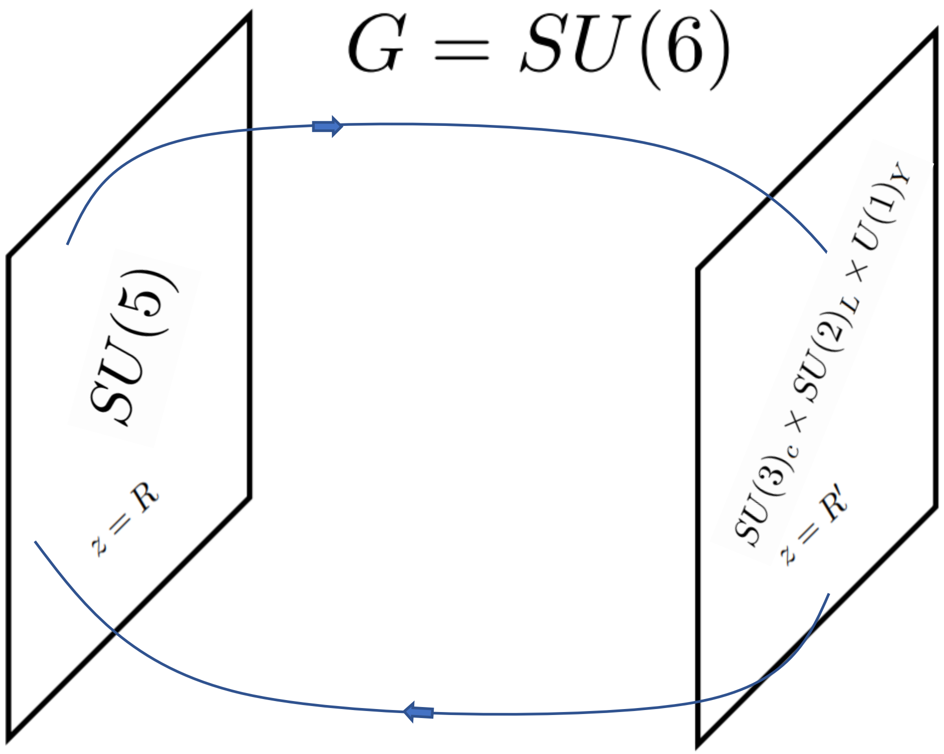
$X, Y \sim (3, 2)_{-5/6}$

In Gauge-Higgs GUTS: $$\mathbf{20} = \begin{cases} \mathbf{10} \to & q'_L(\mathbf{3},\mathbf{2})^{-,+}_{1/6} \oplus (\mathbf{3}^*,\mathbf{1})^{-,+}_{-2/3} \oplus e^{c\prime}_R(\mathbf{1},\mathbf{1})^{-,+}_{1} \\ \mathbf{10}^* \to & (\mathbf{3}^*,\mathbf{2})^{-,+}_{-1/6} \oplus u_R(\mathbf{3},\mathbf{1})^{-,-}_{2/3} \oplus (\mathbf{1},\mathbf{1})^{-,+}_{-1} \end{cases}$$

What about effective operators mediating proton decay ? Turns out this baryon number can be gauged in the model!

Conclusions

- Viable SU(6) GHGUT by introducing more breaking on the boundaries
- Minimal fermionic content leads to SM spectrum without light exotics
- Proton decay forbidden, exotics scalars, light X,Y bosons!
- Lots of directions to explore: flavor hierarchies, gauge coupling running, baryogenesis…



Thank you!

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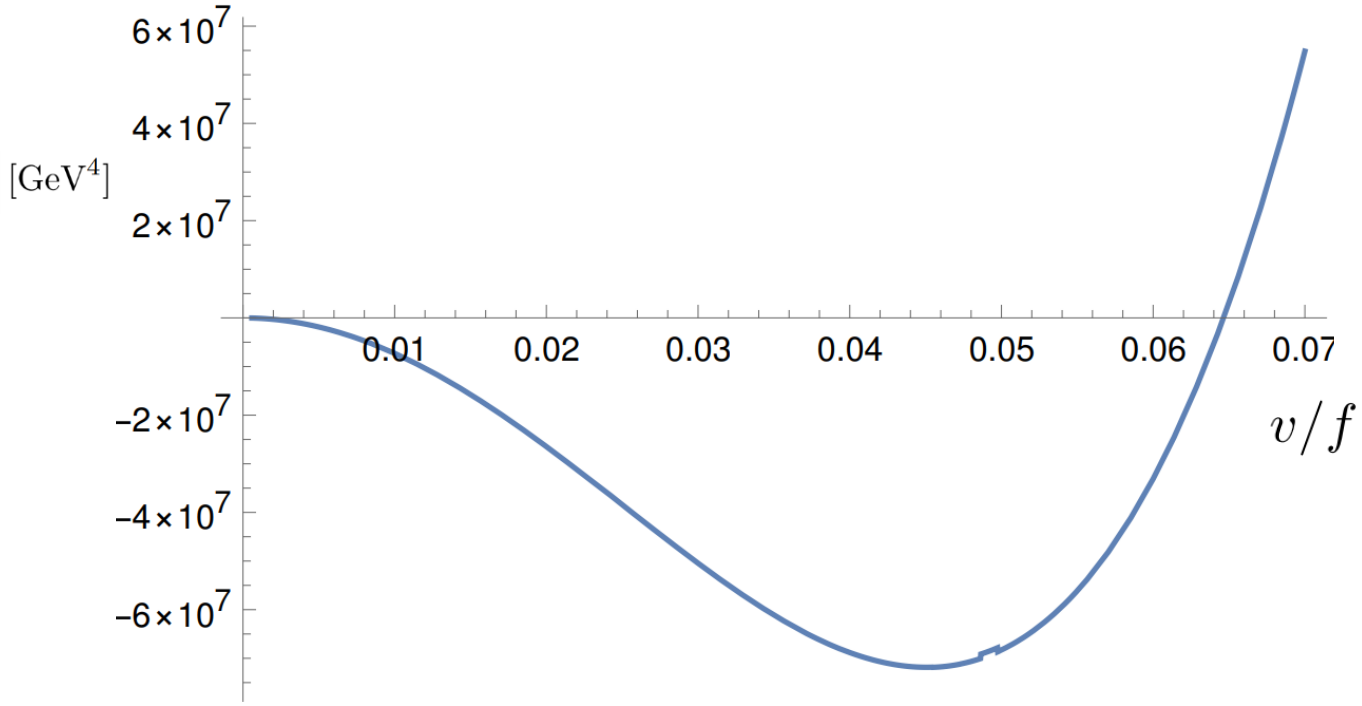
Higgs potential

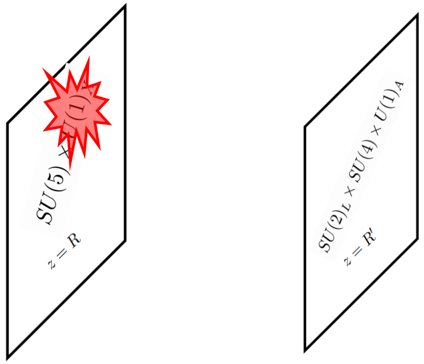


$$1/R' \sim 10\mathrm{TeV}$$

$$f = \frac{2}{g\sqrt{\log R'/R R'}} \sim 5.3\mathrm{TeV}$$

$$v_{SM}/f \sim 0.05$$

SU(6) GHGUT: Extra UV Breaking $SU(5)\times U(1)_X \to SU(5)$



- Via UV brane scalar

$$S_{UV}=\int \mathrm{d}^4x\left((D_\mu\Phi_X)^\dagger(D^\mu\Phi_X)-V(\Phi^\dagger\Phi)+M_u\Phi^\dagger\psi_{\mathbf{20},10}\chi_{\mathbf{15},10}+\mathrm{h.c.}\right)$$

$$\partial_5 A_\mu^X(z=R)=v_X A_\mu^X(z=R)$$

$$\mathbf{20_L}=\begin{cases}\mathbf{10_L}\to & (\mathbf{3},\mathbf{2})^{-,+}_{1/6}\oplus(\mathbf{3}^*,\mathbf{1})^{-,+}_{-2/3}\oplus(\mathbf{1},\mathbf{1})^{-,-}\\ \mathbf{10^*_L}\to & (\mathbf{3}^*,\mathbf{2})^{-,+}_{-1/6}\oplus u_R(\mathbf{3},\mathbf{1})^{-,-}_{2/3}\oplus(\mathbf{1},\mathbf{1})^{-,+}_{-1}\end{cases}$$

$$\mathbf{15_L}=\begin{cases}\mathbf{10_L}\to & q_L(\mathbf{3},\mathbf{2})^{+,+}_{1/6}\oplus(\mathbf{3}^*,\mathbf{1})^{+,-}_{-2/3}\oplus e^c_R(\mathbf{1},\mathbf{1})^{+,+}_{1}\\ \mathbf{5_L}\to & d_R(\mathbf{3},\mathbf{1})^{-,-}_{-1/3}\oplus(\mathbf{1},\mathbf{2})^{-,+}_{1/2},\end{cases}$$

- Via gauge boundary conditions

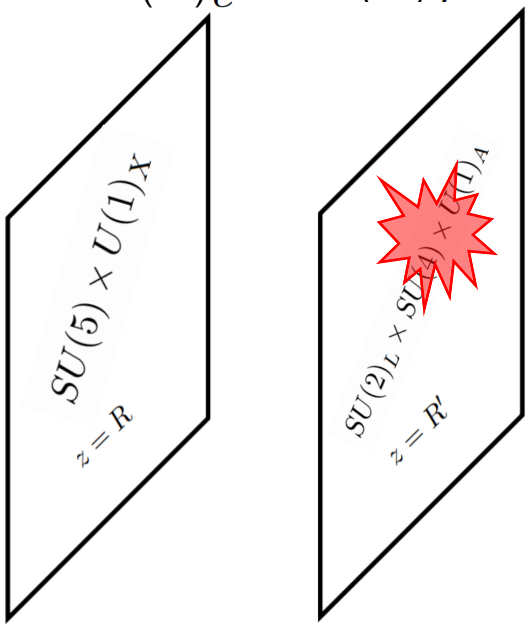
$$A_\mu=\left(\begin{array}{cc|ccc|c}(++)&(++)&(+-)&(+-)&(+-)&(--)\\(++)&(++)&(+-)&(+-)&(+-)&(--)\\ \hline (+-)&(+-)&(++)&(++)&(++)&(-+)\\(+-)&(+-)&(++)&(++)&(++)&(-+)\\(+-)&(+-)&(++)&(++)&(++)&(-+)\\ \hline (--)&(--)&(-+)&(-+)&(-+)&(-+)\end{array}\right)$$

Solves problems:

- Massless U(1)_X is eliminated!
- Up quark is massive!
- Still too constrained..

SU(6) GHGUT: Extra IR Breaking

$$SU(2)_L \times SU(4) \times U(1)_A \to SU(2)_L \times SU(3)_c \times U(1)_Y$$



- Via IR brane scalar

$$S_{IR} = \int \mathrm{d}^4x \left((D_\mu \Phi_A)^\dagger (D^\mu \Phi_A) - V(\Phi_A^\dagger \Phi_A) \right)$$

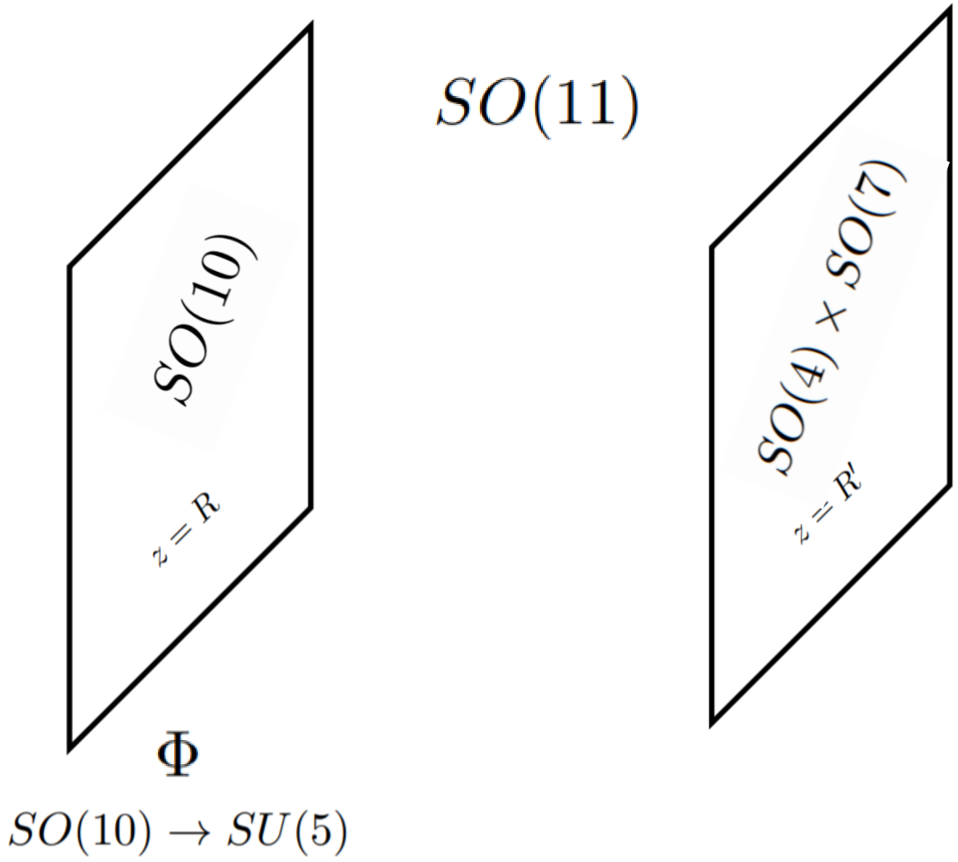
7 (pseudo) Nambu Goldstone bosons

$$SU(4) \times U(1)_A / SU(3)_c \times U(1)_Y = (3,1)_{-1/3} \oplus (3^*,1)_{1/3} \oplus (1,1)_0$$

- Via gauge boundary conditions

$$A_\mu = \left(\begin{array}{cc|ccc|c} (++) & (++) & (+-) & (+-) & (+-) & (--) \\ (++) & (++) & (+-) & (+-) & (+-) & (--) \\ \hline (+-) & (+-) & (++) & (++) & (++) & (--) \\ (+-) & (+-) & (++) & (++) & (++) & (--) \\ (+-) & (+-) & (++) & (++) & (++) & (--) \\ \hline (--) & (--) & (--) & (--) & (--) & (--) \end{array} \right)$$

SO(11)
A custodial GHGUT



- Higgs too light

Top quark	Bulk parameters			Brane parameters			Higgs
m_t[GeV]	c_0	c_1	c_2	μ_2	μ_3	μ_6	m_H[GeV]
165.0	0.3696	0.4286	0.2970	9.05×10^{10}	21.8	0.00249	50.96
170.0	0.3559	0.4293	0.3120	5.20×10^{10}	36.8	0.00420	51.77
175.0	0.3496	0.4286	0.3270	2.95×10^{10}	62.8	0.00719	53.52

- Light exotics

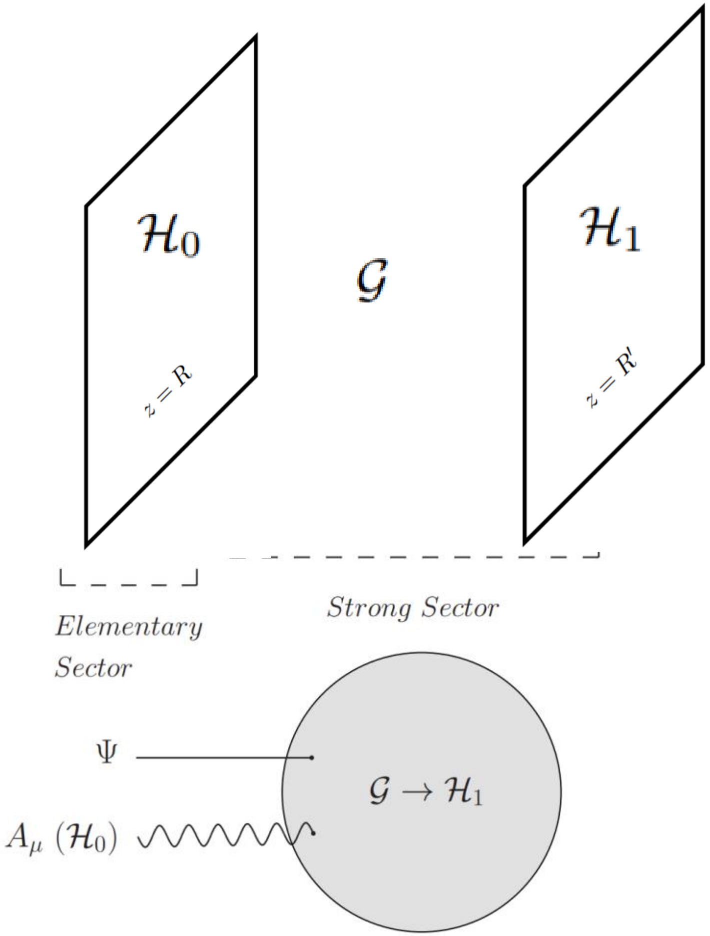
$$\frac{m_{\hat{u}}}{m_u} = \cot\tfrac{1}{2}\theta_H$$

→ Can be solved in 6D: generalized RS metric

Hosotani, Yamatsu arXiv: 1710.04811
Hosotani, Yamatsu arXiv: 1706.03503

Holographic dictionary

Extra dimensional models/Composite Higgs models



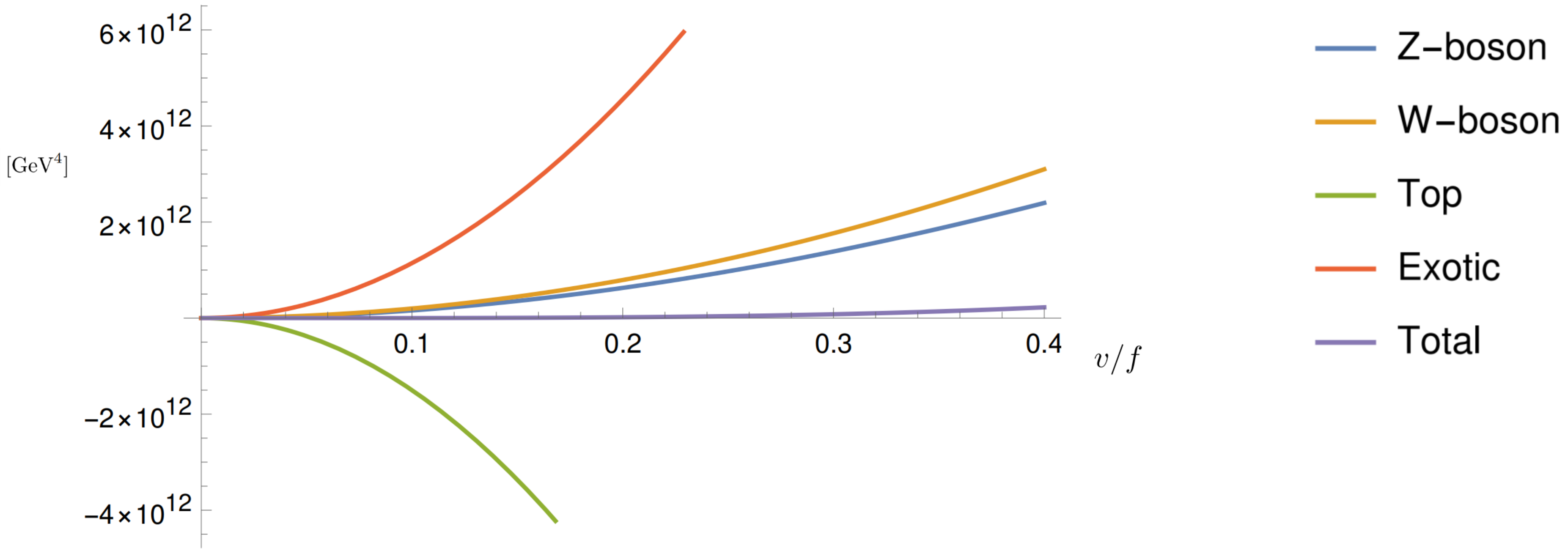
The 5D model gives a calculable model
for the strong sector.
Otherwise, we are left with form factors that we have to approximate using the large SU(N) formalism

$$\frac{1}{N} \Longleftrightarrow \frac{g_5^2}{16\pi^2} \ll 1$$

Higgs potential

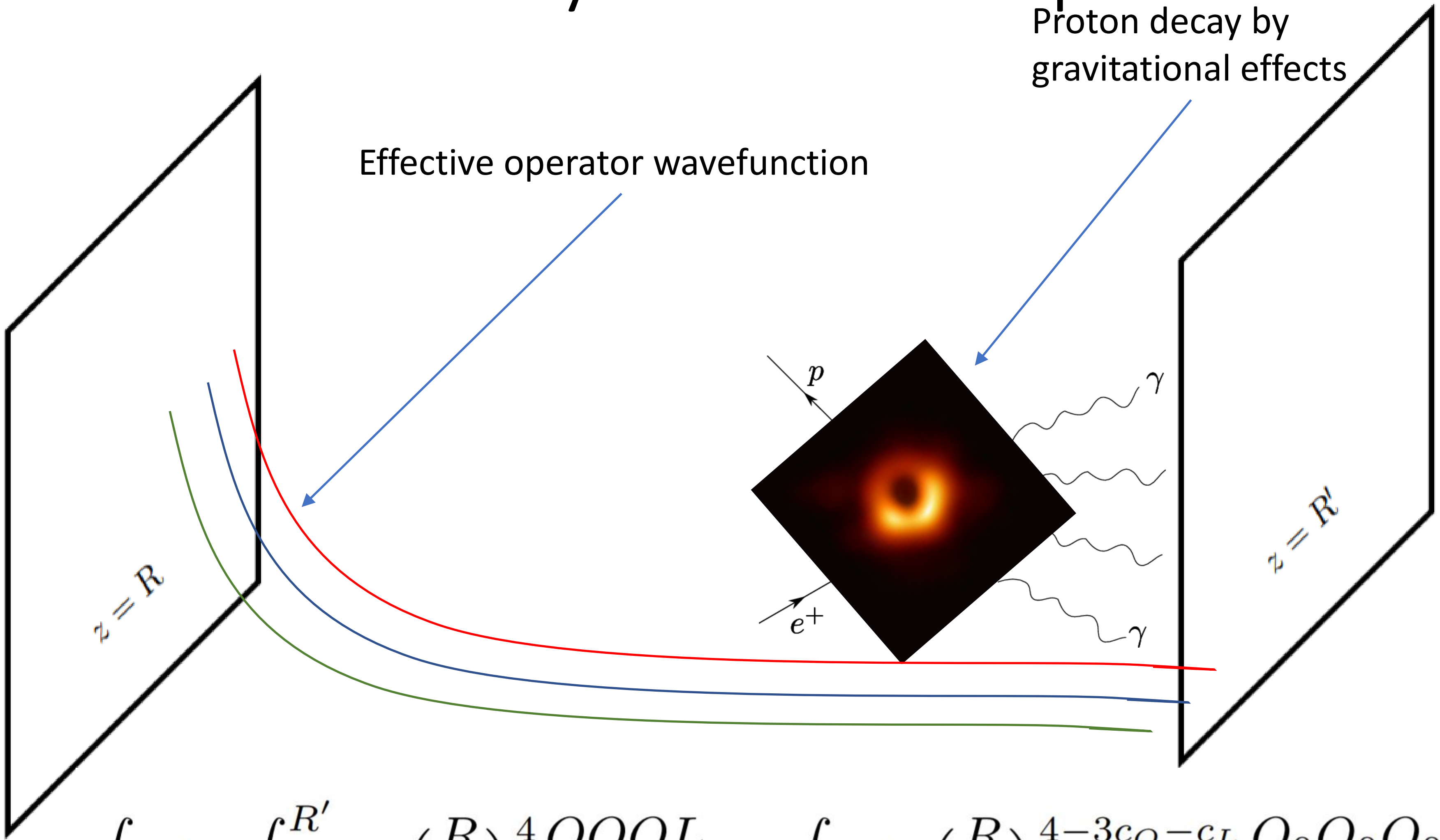
Little Hierarchy

$$1/R' \sim 10\text{TeV}$$



$$f = \frac{2}{g\sqrt{\log R'/R R'}} \sim 5.3\text{TeV}$$

Proton decay: effective operators in the bulk



$$\int \mathrm{d}^4x \int_R^{R'} \mathrm{d}z \left(\frac{R}{z}\right)^4 \frac{QQQL}{M_{\mathrm{pl}}^3} \sim \int \mathrm{d}^4x \left(\frac{R}{z}\right)^{4-3c_Q-c_L} \frac{Q_0Q_0Q_0L_0}{M_{\mathrm{pl}}^2}$$

U(6): Gauged Baryon number

$$SU(6) \to U(6) = SU(6) \times U(1)_C \to G_{SM} \times U(1)_B$$

$U(1)_C$:

$$\Psi_6 \to e^{i\alpha}\Psi_6$$

$$\Psi_{15} \to e^{2i\alpha}\Psi_{15}$$

$$\Psi_{20} \to e^{3i\alpha}\Psi_{20}$$

C is (spontaneously) broken by the brane masses and B is the remaining symmetry

$$T_C = \mathrm{diag}(1,1,1,1,1,1)$$

$$T_B \to \frac{1}{3}\mathrm{diag}(0,0,1,1,1,0)$$

$$B\Psi_6 = \begin{cases} \mathbf{5} \to & e^{i\alpha/3} d_R(\mathbf{3},\mathbf{1})^{-,-}_{-1/3} \oplus l^c_L(\mathbf{1},\mathbf{2})^{-,-}_{1/2} \\ \mathbf{1} \to & \upsilon^c_R(\mathbf{1},\mathbf{1})^{+,+}_0 \end{cases}$$

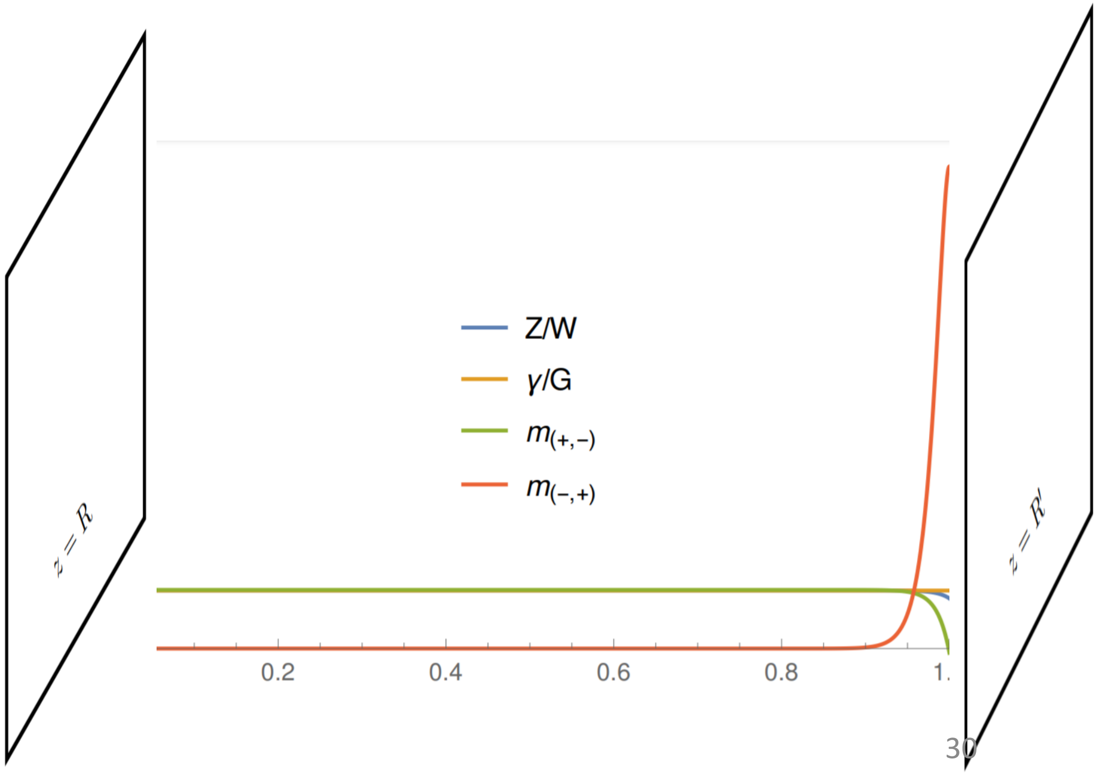
$$B\Psi_{20} = \begin{cases} \mathbf{10} \to & e^{i\alpha/3} q'_L(\mathbf{3},\mathbf{2})^{-,+}_{1/6} \oplus e^{2i\alpha/3}(\mathbf{3}^*,\mathbf{1})^{-,+}_{-2/3} \oplus e^{c\prime}_R(\mathbf{1},\mathbf{1})^{-,+}_{1} \\ \mathbf{10}^* \to & e^{2i\alpha/3}(\mathbf{3}^*,\mathbf{2})^{-,+}_{-1/6} \oplus e^{i\alpha/3} u_R(\mathbf{3},\mathbf{1})^{-,-}_{2/3} \oplus e^{i\alpha}(\mathbf{1},\mathbf{1})^{-,+}_{-1} \end{cases}$$

What about the X,Y gauge bosons? $(\mathbf{3},\mathbf{2})_{5/6}$

$$m_{(+,-)} = \frac{2}{R'\sqrt{2\log(\frac{R'}{R}) - 1}} \sim 0.25/R'$$

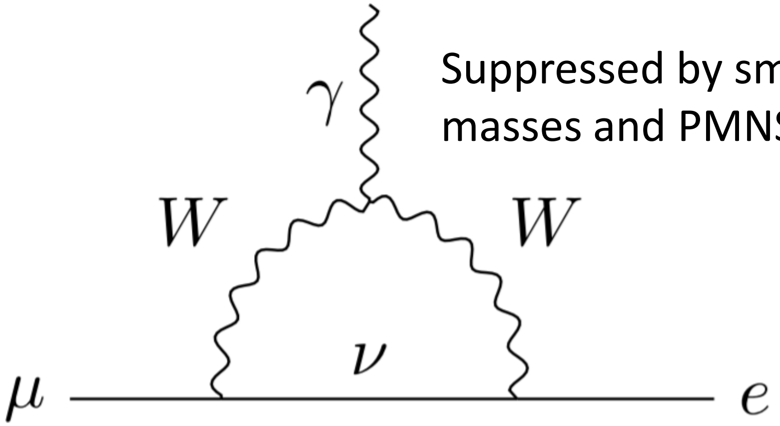
$$m_{(-,+)} \sim 2.45/R'$$

$$A_\mu = \left(\begin{array}{cc|ccc|c}
(++) & (++) & (+-) & (+-) & (+-) & (--) \\
(++) & (++) & (+-) & (+-) & (+-) & (--) \\
\hline
(+-) & (+-) & (++) & (++) & (++) & (--) \\
(+-) & (+-) & (++) & (++) & (++) & (--) \\
(+-) & (+-) & (++) & (++) & (++) & (--) \\
\hline
(--) & (--) & (--) & (--) & (--) & (--)
\end{array}\right)$$

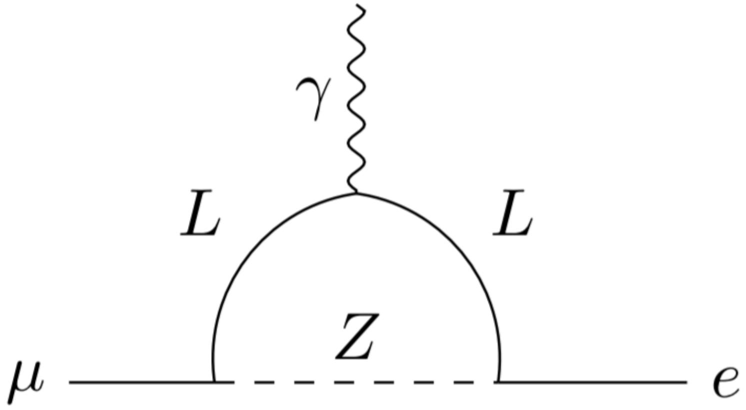


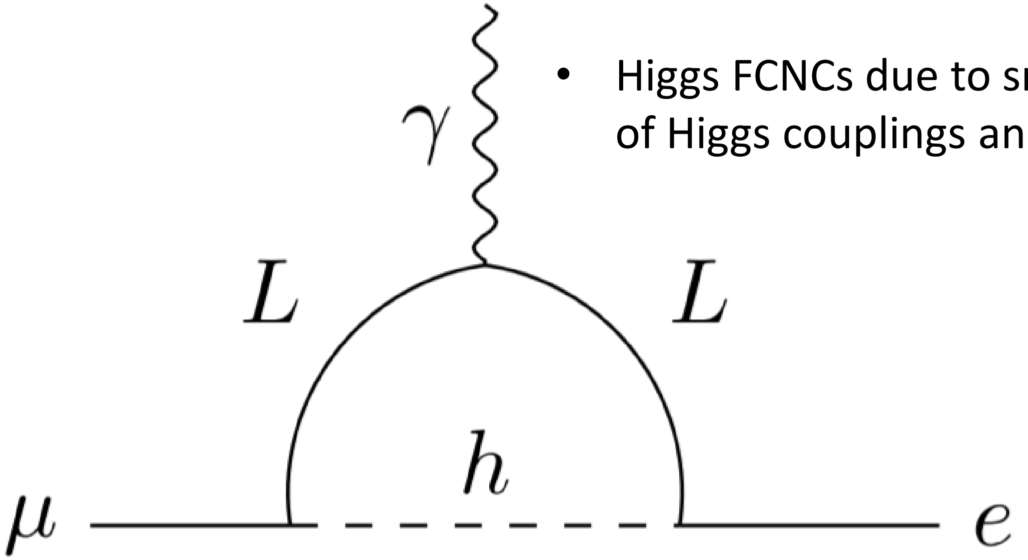
Flipping the gauge symmetries on the UV and IR brane switches the X,Y gauge bosons from (+,-) modes to (-,+) modes

Loop-level flavor violation: $\mu \to e\gamma$

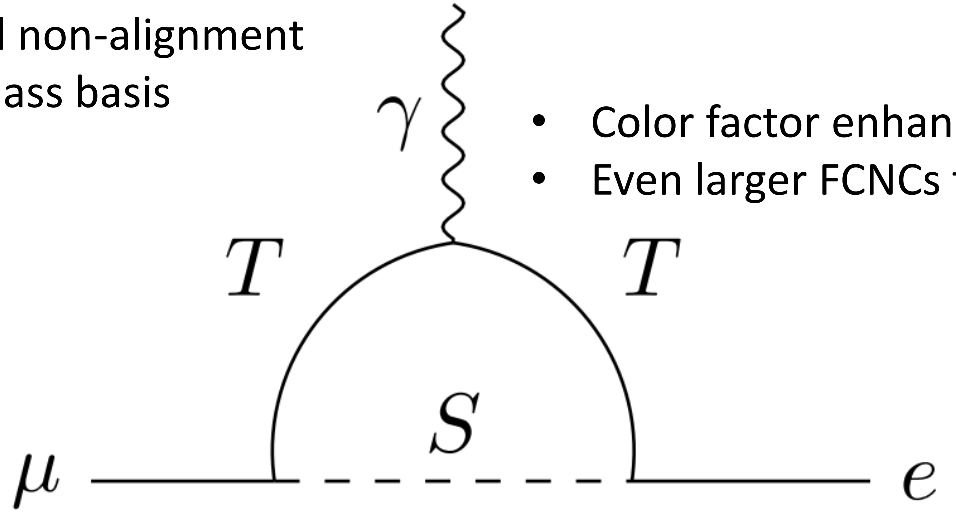


Suppressed by small neutrino masses and PMNS unitarity





- Higgs FCNCs due to small non-alignment of Higgs couplings and mass basis



- Color factor enhancement
- Even larger FCNCs than Higgs