Split Branes and Flavor Universal Resonances

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arXiv:1608.00526
Kaustubh Agashe, Peizhi Du, SH, Raman Sundrum

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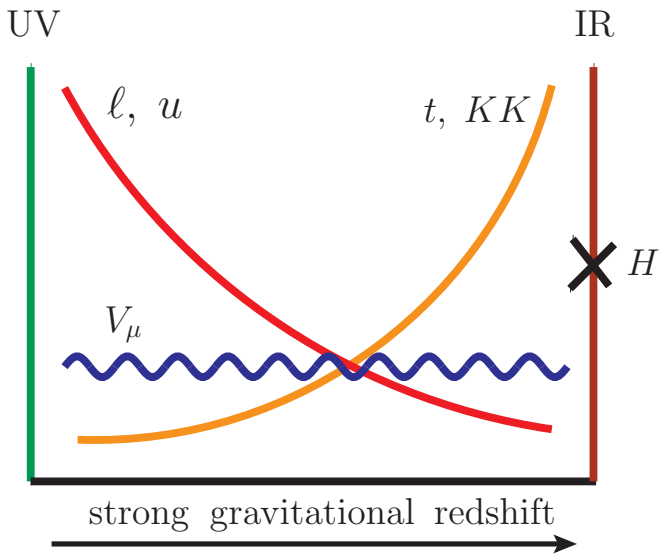
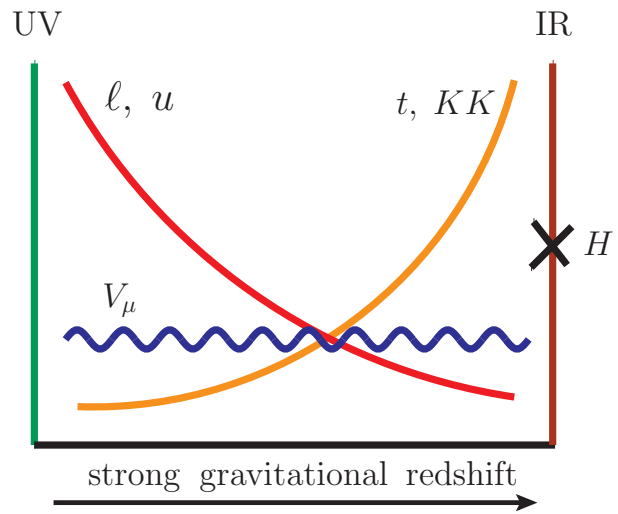
Randall-Sundrum (RS)

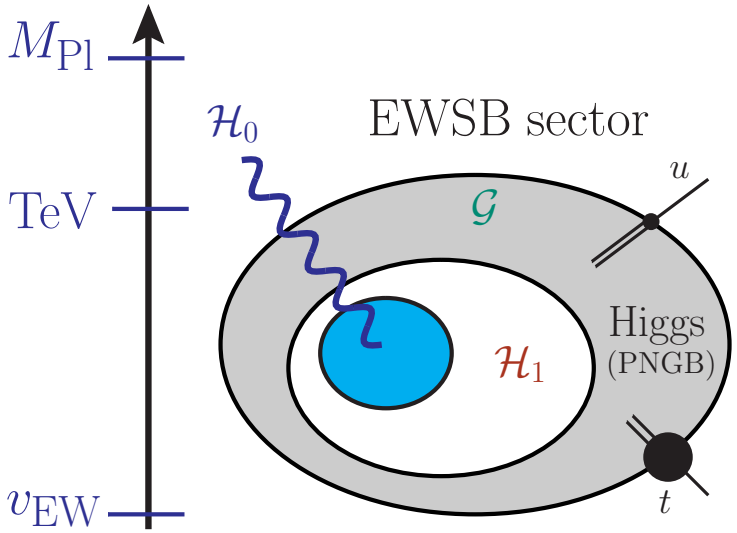


- **Hierarchy Problem**
  - ▷ Gravitational Redshift: *Warping*
    - * $\mathrm{TeV} = e^{-k\pi r_c} M_{\mathrm{pl}}$
  - ▷ Radius Stabilization
- **Flavor Structure**
  - ▷ Higgs localized at/near IR-brane
  - ▷ Localization of Fermion Zero Mode

L. Randall and R. Sundrum, Phys. Rev. Lett. 83, 3370 (1999)
L. Randall and R. Sundrum, Phys. Rev. Lett. 83, 4690 (1999)

AdS/CFT Correspondence





N. Arkani-Hamed, M. Porrati and L. Randall, JHEP 0108, 017 (2001)
R. Rattazzi and A. Zaffaroni, JHEP 0104,021 (2001)
R. Contino and A. Pomarol, JHEP 0411, 058 (2004)
R. Contino, Y. Nomura and A. Pomarol, Nucl. Phys. B 671, 148 (2003)

Where We Are Now

- LHC
  - ▷ KK particles: Mostly Decays into $H/t/W_{\mathrm{L}}/Z_{\mathrm{L}}$
  - ▷ No New Physics Signals at LHC (at least until now)
  - ▷ "Little Hierarchy Problem" may exist

- Electroweak Precision Test
  - ▷ Without Custodial Symmetry: $M_{\mathrm{KK}} > \mathcal{O}(10)\mathrm{TeV}$
  - ▷ $SU(2)_L \times SU(2)_R \times U(1)_X$: $M_{\mathrm{KK}} \gtrsim 3\mathrm{TeV}$

- Flavor/CP
  - ▷ $M_{\mathrm{KK}} > \mathcal{O}(10)\mathrm{TeV}$

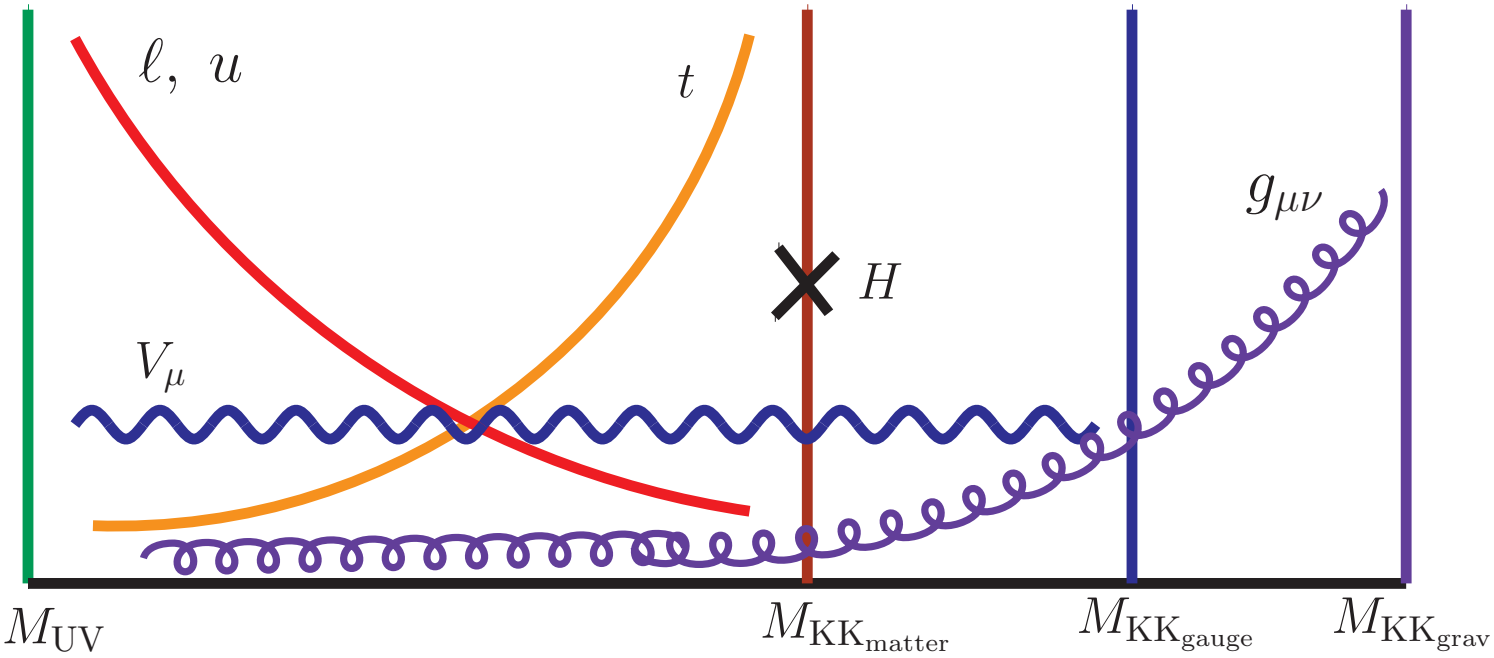
Next ?

Little Hierarchy and Light Vestiges

- Naturalness realized but not perfectly at $\sim \mathcal{O}(10)\mathrm{TeV}$
- EWPT/Flavor/CP robustly solved.
- *Light Vestiges of Naturalness* ?

Natural Extension of the minimal RS - 5D

Kaustubh Agashe, Peizhi Du, SH, Raman Sundrum, arXiv:1608.00526



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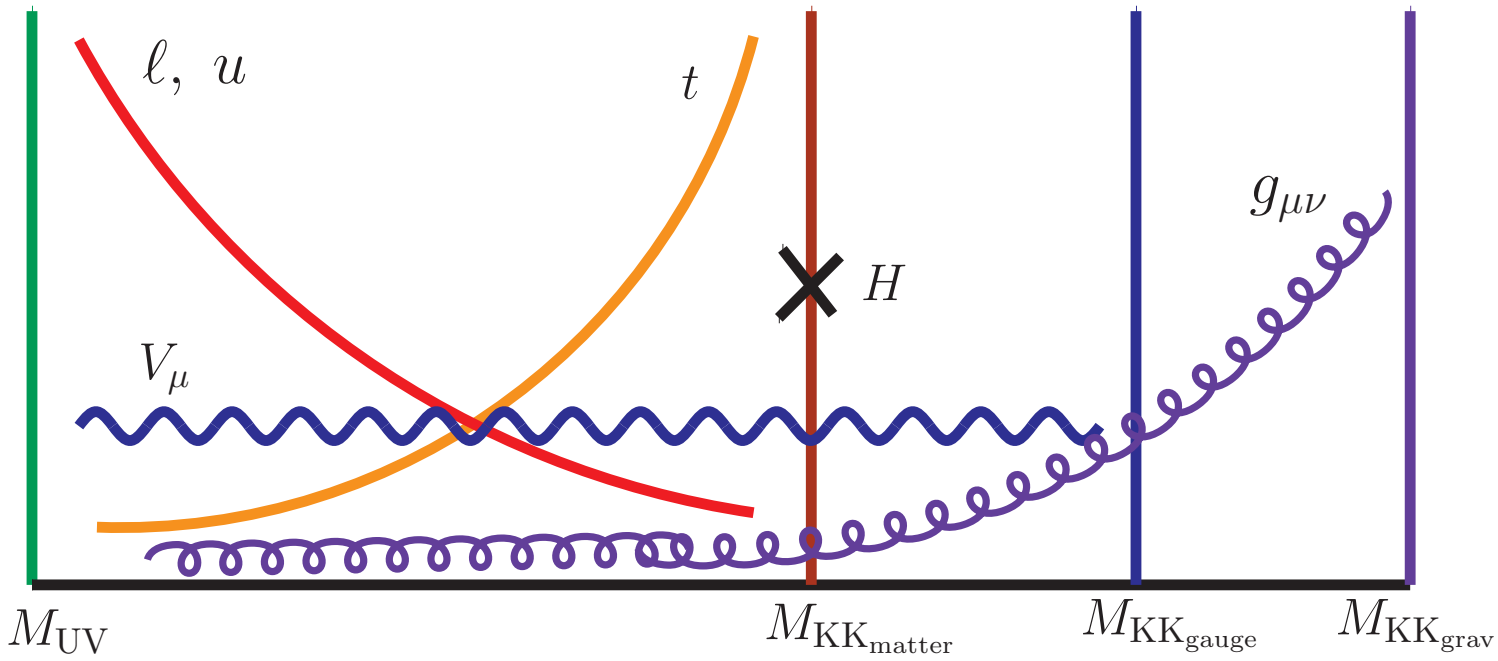
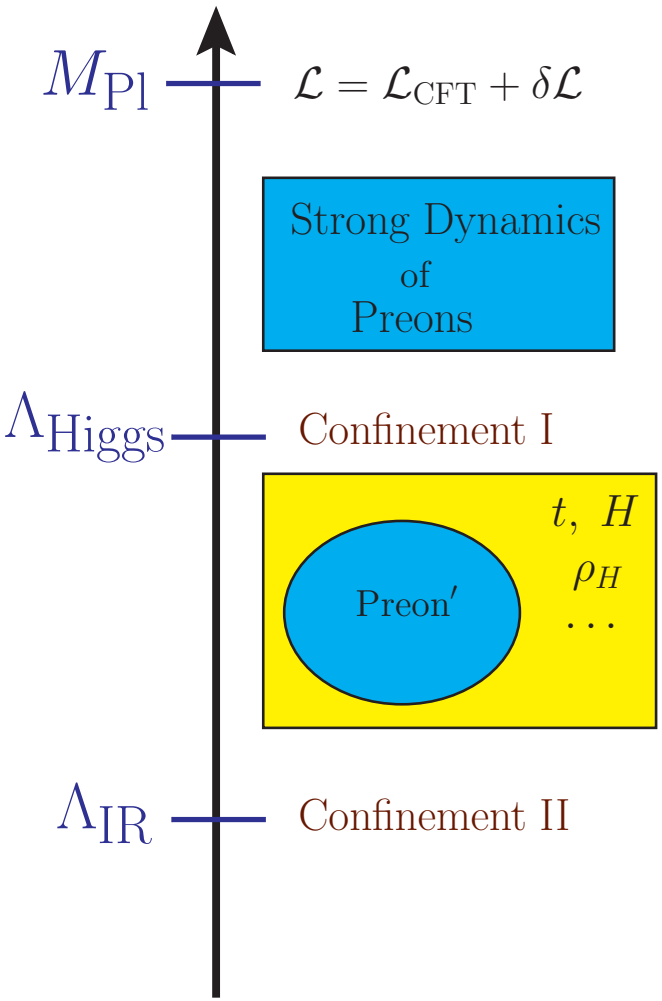
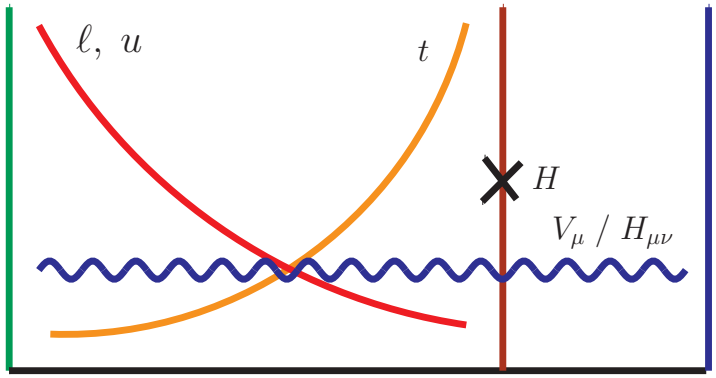


- Minimal RS is a special case: $M_{\rm KK_{matter}} = M_{\rm KK_{gauge}} = M_{\rm KK_{grav}}$
- Position of branes stabilized via *Goldberger-Wise Mechanism*
  - ▷ "little" hierarchy: $M_{\rm KK_{matter}} \gtrsim M_{\rm KK_{gauge}} \gtrsim M_{\rm KK_{grav}}$

W. D. Goldberger and M. B. Wise, Phys. Rev. Lett. 83, 4922 (1999)

Mimimal Extension - For the rest of the talk

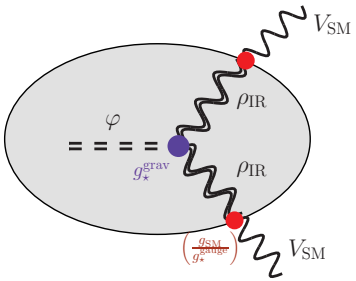




- Safe from flavor/CP and EWPM !
- Below $\Lambda_{\rm Higgs}$ = vectorlike confinement

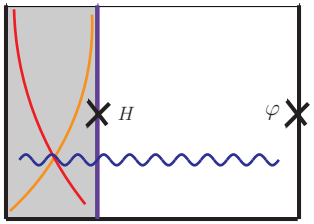
Phenomenology - Radion

- Spin-0: Production / Decay
  - ▷ flavor-blind coupling



$$\Rightarrow\ g_\star^{\rm grav}\left(\frac{g_{\rm SM}}{g_{\star\ {\rm IR}}^{\rm gauge}}\right)^2 F_{\mu\nu}F^{\mu\nu}\frac{\varphi}{\Lambda_{\rm IR}}$$

  - ▷ flavor non-universal coupling



$$\Rightarrow\ \kappa\left(\frac{\Lambda_{\rm IR}}{\Lambda_{\rm Higgs}}\right)^{4-\epsilon} g_{\star\ {\rm IR}}^{\rm grav}\frac{\varphi}{\Lambda_{\rm IR}}\left[m_t\bar{t}t+(\partial_\mu H)^\dagger\,\partial^\mu H\right]$$

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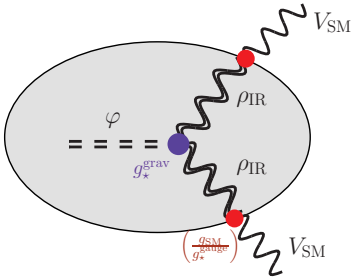

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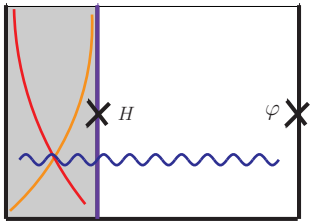

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Phenomenology - Gauge KK

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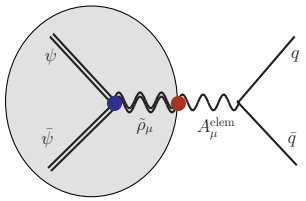
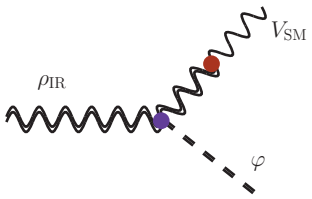


$$\Rightarrow \quad \frac{g_{\rm SM} g_{\rm elem}}{g_\star^{\rm gauge}} \bar{q} \rho^\mu \gamma_\mu q \quad \Rightarrow \quad \text{Production !}$$



$$\Rightarrow \quad \lambda \epsilon g^{\rm grav}_{\star\,{\rm IR}} \left(\frac{\Lambda_{\rm IR}}{\Lambda_{\rm Higgs}} \right)^{-\epsilon} \frac{g_{\rm elem}}{g^{\rm gauge}_{\star\,{\rm IR}}} \rho^{\mu\nu} F^{\mu\nu} \frac{\varphi}{\Lambda_{\rm IR}}$$

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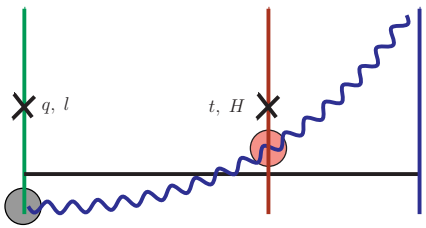

$$\Rightarrow \quad \frac{\left(g^{\rm gauge}_{\star\,{\rm UV}}\right)^2}{g^{\rm gauge}_{\star\,{\rm IR}}} \left(\frac{\Lambda_{\rm IR}}{\Lambda_{\rm Higgs}} \right)^2 \rho^\mu_{\rm IR} \left(\bar{t} \gamma_\mu t + H^\dagger D_\mu H \right)$$

Phenomenology - Gauge KK

- Spin-1: Probing top/Higgs Compositeness

$$\delta\mathcal{L} \sim \left[-\frac{g^2_{\mathrm{SM}}}{g^{\mathrm{gauge}}_{\star\,\mathrm{IR}}} + h\frac{g^{\mathrm{gauge}\ 2}_{\star\,\mathrm{UV}}}{g^{\mathrm{gauge}}_{\star\,\mathrm{IR}}} \left(\frac{\Lambda_{\mathrm{IR}}}{\Lambda_{\mathrm{Higgs}}} \right)^2 \right] \bar{q}\gamma^\mu \rho_\mu q, \qquad h > 0 \ \text{ in 5D}$$

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  - $\dfrac{\Lambda_{\rm Higgs}}{\Lambda_{\rm IR}} \sim \dfrac{g_{\star\,\rm UV}^{\rm gauge}}{g_{\rm SM}}$

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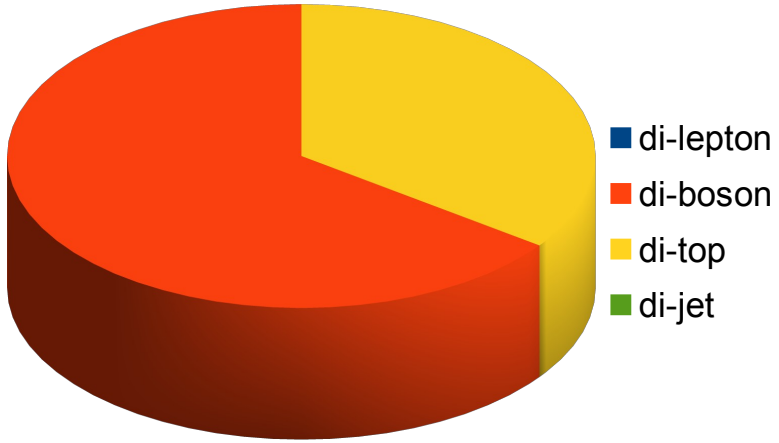
- BR of Z with $M_{\rm H} = 3$ TeV



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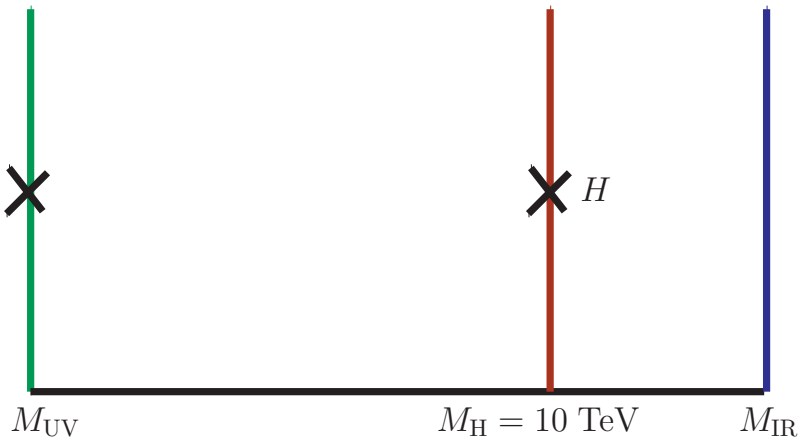

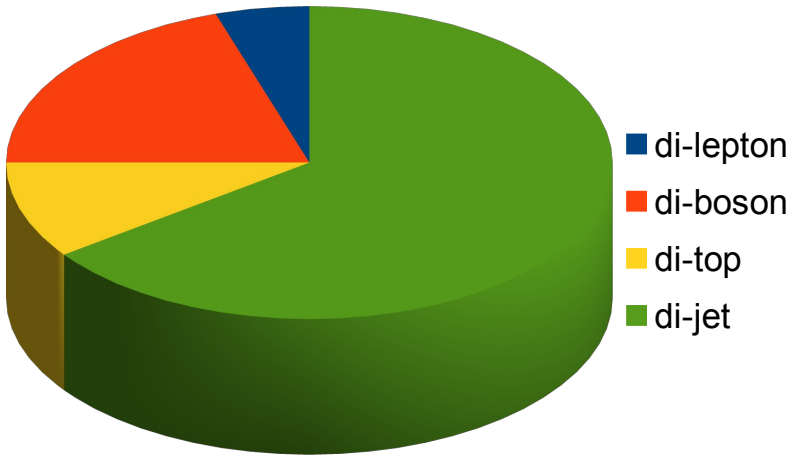

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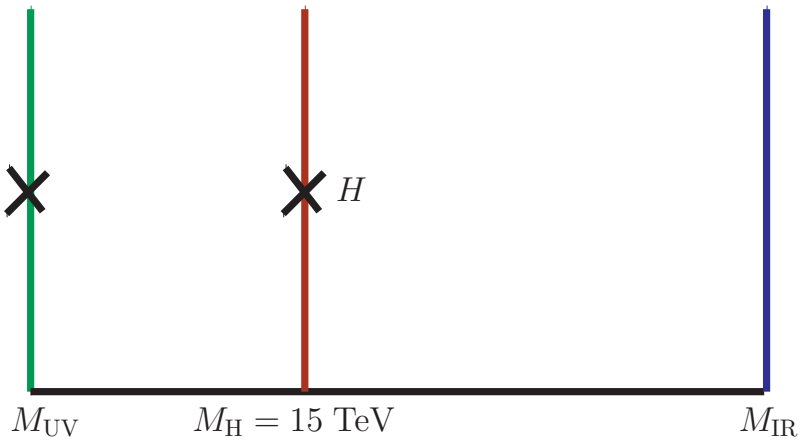

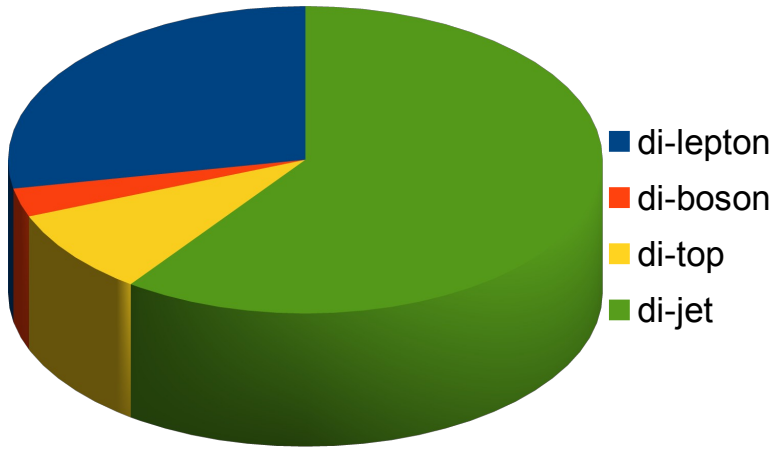

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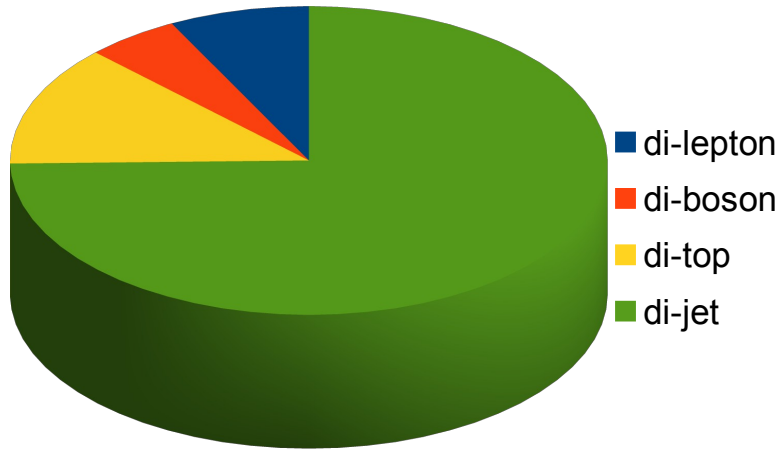

IV. Conclusion

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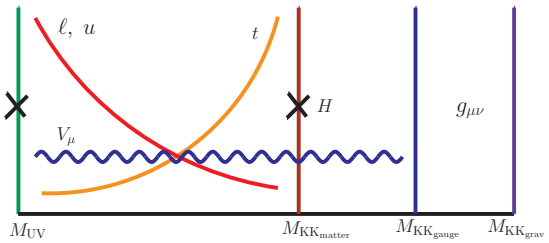

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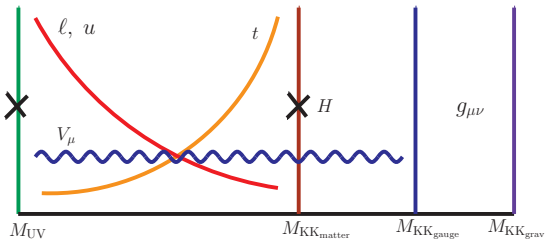

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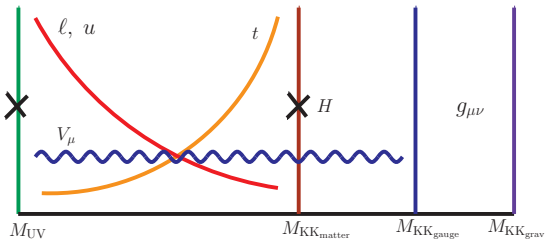

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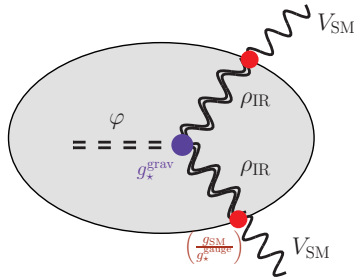
  - ▷ Flavor Universal Resonances: Radion

Radius Stabilization,



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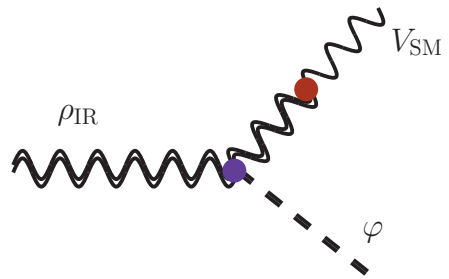

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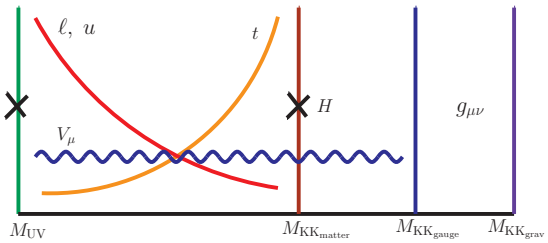

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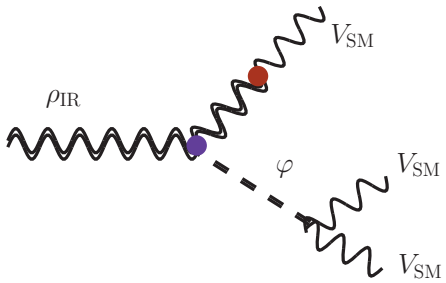

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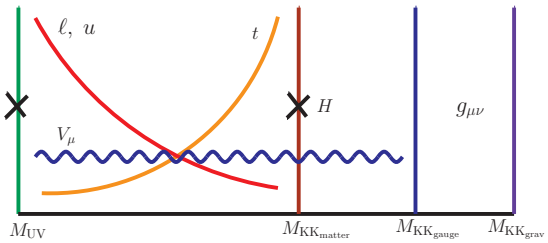

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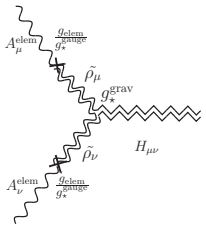

$M_{\rm KK_{grav}} < M_{\rm KK_{gauge}}$ Healthy !

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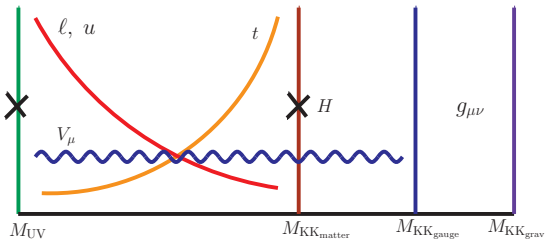

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$THANK\ \ YOU\ \ !$

Backup: Low Eergy Experiments

- Contributions from physics at $\Lambda_{\rm H}$ is suppressed by $\dfrac{1}{\Lambda_{\rm H}^n}$.
  - ▷ Contributions from KK fermions are the same as in Minimal RS (but with $\Lambda_{\rm IR} = 1$ TeV $\rightarrow$ $\Lambda_{\rm H} = \mathcal{O}(10)$ TeV)
  - ▷ Safe from EWPT/flavor/CP constraints !

- Contribution from *Flavor Universal Resonances* ?
  - ▷ $Radion$?

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- Contribution from *Flavor Universal Resonances* ?
  - ▷ $Radion$? $KK\ \ Graviton$?

$$\left(\frac{\Lambda_{\rm IR}}{\Lambda_{\rm Higgs}}\right)^4 \frac{\left(g_{\star\,\rm UV}^{\rm grav}\right)^2}{g_{\star\,\rm IR}^{\rm grav}} \frac{H^{\mu\nu}}{\Lambda_{\rm IR}} T_{\mu\nu}^{(t/H)}$$

Backup: Low Eergy Experiments

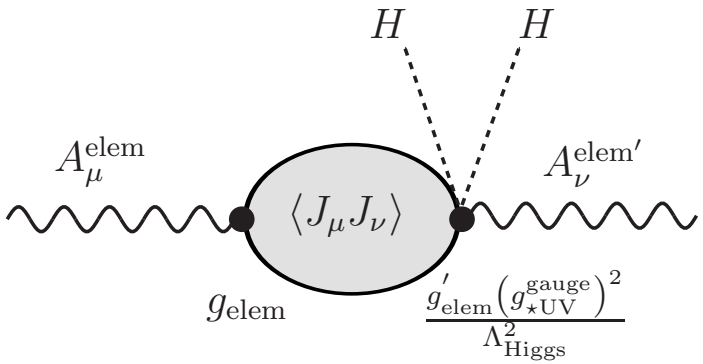
- Contributions from physics at $\Lambda_{\rm H}$ is suppressed by $\dfrac{1}{\Lambda_{\rm H}^n}$.
  - ▷ Contributions from KK fermions are the same as in Minimal RS (but with $\Lambda_{\rm IR} = 1$ TeV $\rightarrow$ $\Lambda_{\rm H} = \mathcal{O}(10)$ TeV)
  - ▷ Safe from EWPT/flavor/CP constraints !

- Contribution from *Flavor Universal Resonances* ?
  - ▷ *Radion* ? *KK Graviton* ? *KK Gauge* !

$$\frac{\left(g_{\star\,\rm UV}^{\rm gauge}\right)^2}{g_{\star\,\rm IR}^{\rm gauge}} \left(\frac{\Lambda_{\rm IR}}{\Lambda_{\rm Higgs}}\right)^2 \rho_{\rm IR}^{\mu} \left(\bar{t}\gamma_\mu t + H^\dagger D_\mu H\right)$$

Backup: Low Eergy Experiments

- Contributions from $KK\ \ Gauge$ (S-parameter).



$$g_{\rm elem}\left(g^{\rm gauge}_{\star\ \rm UV}\right)^2 A^{\rm elem}_\mu \langle J^\mu_{\rm strong\ IR} J^\nu_{\rm strong\ IR}\rangle \frac{J^{\rm t/H}_\nu}{\Lambda^2_{\rm Higgs}}$$

Backup: Low Eergy Experiments

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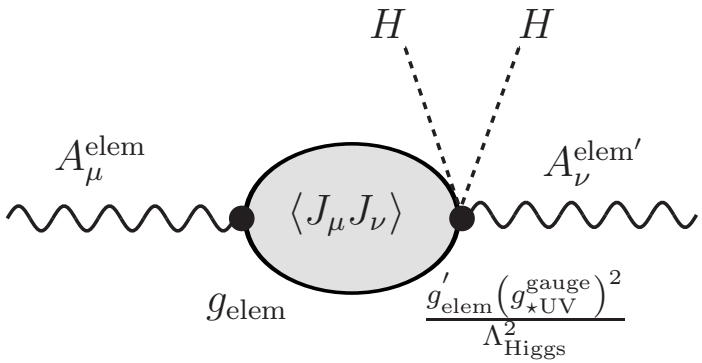
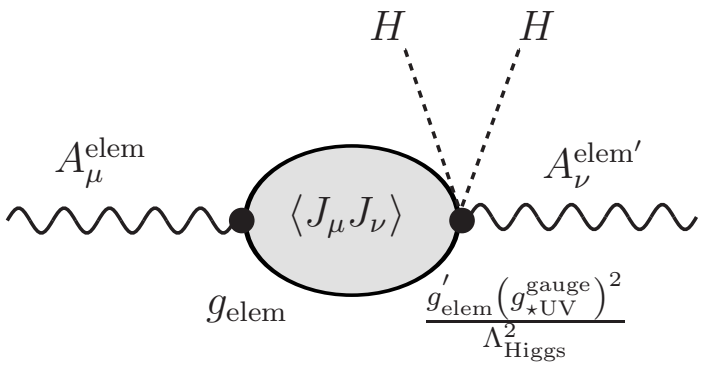


$$g_{\rm elem}\left(g^{\rm gauge}_{\star\ \rm UV}\right)^2 A^{\rm elem}_\mu \langle J^\mu_{\rm strong\ IR} J^\nu_{\rm strong\ IR}\rangle \frac{J^{\rm t/H}_\nu}{\Lambda^2_{\rm Higgs}}$$

$$\begin{aligned} \delta\mathcal{L} &\sim C\, W^3_{\mu\nu} B_{\mu\nu} H^\dagger H, \text{ with} \\ C &\equiv \frac{g g' S}{16\pi v^2} \end{aligned}$$

Backup: Low Eergy Experiments

- Contributions from $KK\ \ Gauge$ (S-parameter).



$$\langle J^\mu_{\text{strong IR}} J^\nu_{\text{strong IR}} \rangle \sim \left(\eta_{\mu\nu} - \frac{p_\mu p_\nu}{p^2} \right) p^2 \log p^2$$

$$\delta\mathcal{L} \sim C\, W^3_{\mu\nu} B_{\mu\nu} H^\dagger H, \text{ with}$$

$$C \equiv \frac{g g' S}{16\pi v^2}$$

$$C_{\text{strong IR}} \sim g g' \log\left(\Lambda_{\text{Higgs}}/\Lambda_{\text{IR}}\right)/\Lambda^2_{\text{Higgs}}$$

Backup: Low Eergy Experiments

- Contributions from $KK\ \ Gauge$ (flavor violation).

$$\frac{J^{\mathrm{t}}_{\mu}}{\Lambda^2_{\mathrm{Higgs}}}\langle J^{\mu}_{\text{strong IR}} J^{\nu}_{\text{strong IR}}\rangle \frac{J^{\mathrm{t}}_{\nu}}{\Lambda^2_{\mathrm{Higgs}}}$$

Backup: Low Eergy Experiments

- Contributions from $KK\ \ Gauge$ (flavor violation).

$$\frac{J^{\mathrm{t}}_{\mu}}{\Lambda^2_{\mathrm{Higgs}}}\langle J^{\mu}_{\text{strong IR}} J^{\nu}_{\text{strong IR}}\rangle \frac{J^{\mathrm{t}}_{\nu}}{\Lambda^2_{\mathrm{Higgs}}}$$

$$* \quad J^{\mathrm{t}}_{\mu} \sim \bar{t}\gamma_{\mu}t$$

$$* \quad \langle J^{\mu}_{\text{strong IR}} J^{\nu}_{\text{strong IR}}\rangle \sim \Lambda^2_{\mathrm{Higgs}}$$

$$\frac{J^{\mathrm{t}}_{\mu}}{\Lambda^2_{\mathrm{Higgs}}}\langle J^{\mu}_{\text{strong IR}} J^{\nu}_{\text{strong IR}}\rangle \frac{J^{\mathrm{t}}_{\nu}}{\Lambda^2_{\mathrm{Higgs}}} \sim \frac{(\bar{t}t)^2}{\Lambda^2_{\mathrm{Higgs}}}$$

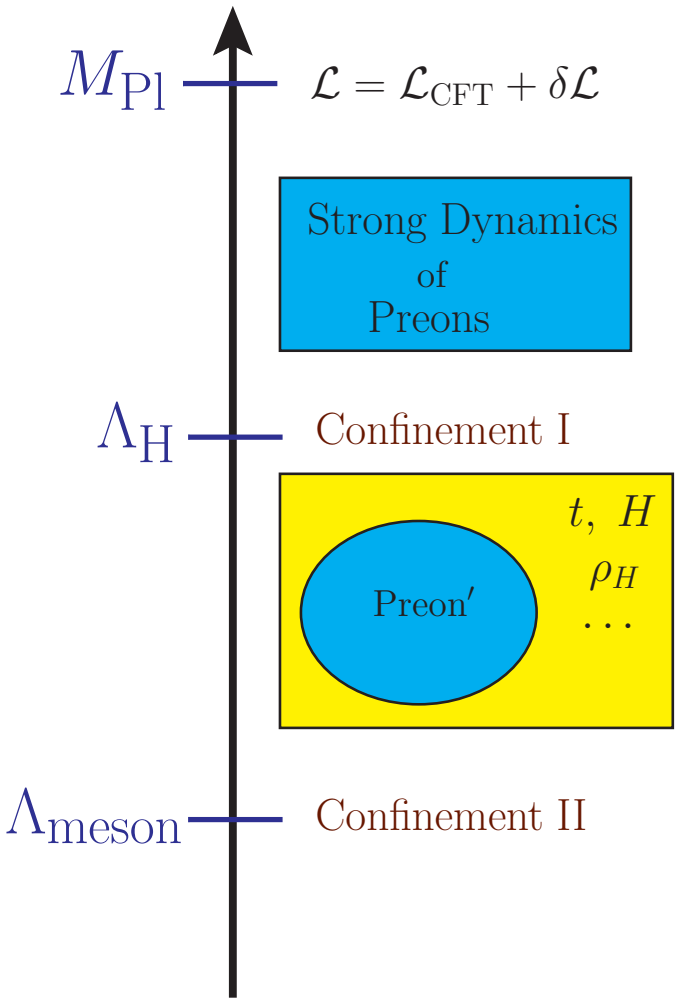
Backup: Radion Coupling to SM gauge boson

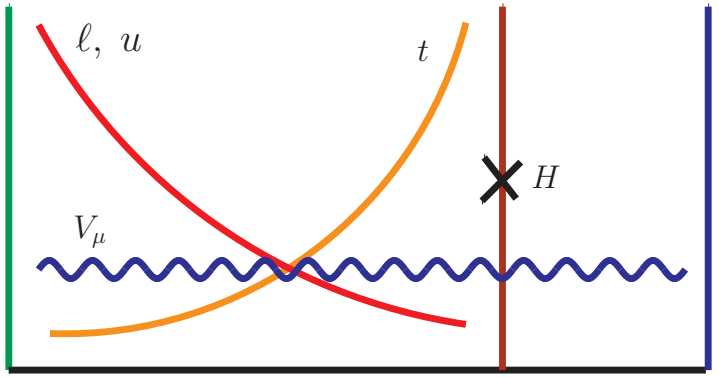
- Radion: Coupling to SM gauge boson

$$\frac{1}{g_{\rm SM}^2} \approx \frac{1}{g_{\rm UV}^2} + b_{\text{strong UV}} \log\left(\frac{\Lambda_{\rm UV}}{\Lambda_{\rm Higgs}}\right) + b_{\text{strong IR}} \log\left(\frac{\Lambda_{\rm Higgs}}{\Lambda_{\rm IR}}\right) + (b_{\rm SM} - b_{\text{top, Higgs}}) \log\left(\frac{\Lambda_{\rm UV}}{\Lambda_{\rm Higgs}}\right) + b_{\rm SM} \log\left(\frac{\Lambda_{\rm Higgs}}{M_Z}\right)$$

  - $b_{\rm strong} = \dfrac{O\left(N_{\rm strong}\right)}{16\pi^2} \sim \dfrac{1}{\left(g_\star^{\rm gauge}\right)^2} \sim \dfrac{1}{g_5^2 k}$
  - 5D: $\dfrac{\pi r_c}{g_5^2} = \dfrac{k\pi r_c}{g_5^2 k} = \dfrac{1}{g_5^2 k} \ln e^{k\pi r_c} = \dfrac{1}{g_5^2 k} \ln\left(\dfrac{\Lambda_{\rm UV}}{\Lambda_{\rm IR}}\right)$

Backup: Available Parameter Space

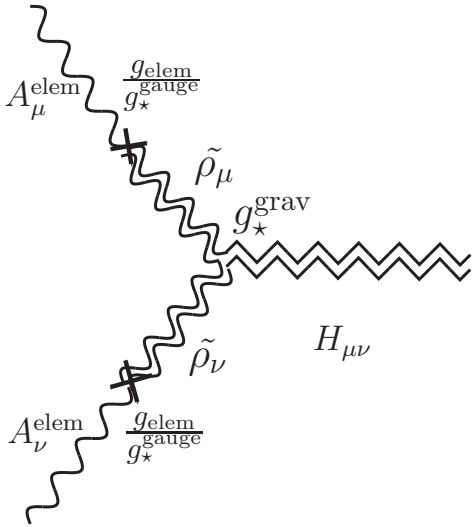




- $g_\star^{\rm grav} \equiv \sqrt{\dfrac{k^3}{M_5^3}}$
  - ▷ $g_{\star\,\rm UV}^{\rm grav} < g_{\star\,\rm IR}^{\rm grav} \lesssim 3$
- $g_\star^{\rm gauge} \equiv g_5\sqrt{k}$
  - ▷ $g_{\star\,\rm UV}^{\rm gauge} \sim g_{\star\,\rm IR}^{\rm gauge} \sim 3$

Backup: Spectrum and Couplings - Gravity KK

- Spin-2: Couplings to the SM gauge boson (Flavor-blind)



$$\triangleright \quad \delta\mathcal{L}\left(\Lambda_{\rm IR}\right) \sim \frac{g_{\star\,\rm IR}^{\rm grav}}{\Lambda_{\rm IR}} H^{\mu\nu} T_{\mu\nu}^{(\tilde{\rho})}$$

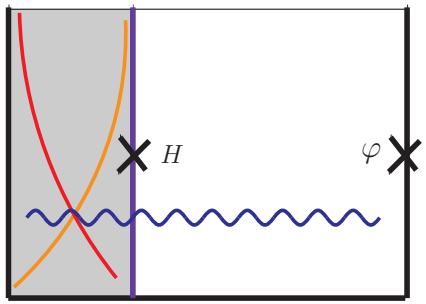
$$\rightarrow \left(\frac{g_{\rm SM}}{g_{\star\,\rm IR}^{\rm gauge}}\right)^2 \frac{g_{\star\,\rm IR}^{\rm grav}}{\Lambda_{\rm IR}} H^{\mu\nu} T_{\mu\nu}^{(\rm gauge)}$$

- Spin-2: Coupling to Radion (Flavor-blind)

$$\triangleright \quad \delta\mathcal{L}\left(\Lambda_{\rm IR}\right) \sim \frac{g_{\star\,\rm IR}^{\rm grav}}{\Lambda_{\rm IR}} H^{\mu\nu} T_{\mu\nu}^{(\varphi)}$$

Backup: Spectrum and Couplings - Gravity KK

- Spin-2: Couplings to t/H (flavor non-universal)



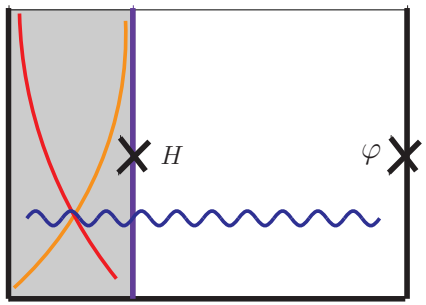
▷ $\delta\mathcal{L}\left(\Lambda_{\text{Higgs}}\right) \sim \dfrac{\left(g^{\text{grav}}_{\star\ \text{UV}}\right)^2}{\Lambda^4_{\text{Higgs}}} T^{\mu\nu\ (t/H)} T^{(\text{strong IR})}_{\mu\nu}$

▷ $\delta\mathcal{L}\left(\Lambda_{\text{IR}}\right) \sim \left(\dfrac{\Lambda_{\text{IR}}}{\Lambda_{\text{Higgs}}}\right)^4 \dfrac{\left(g^{\text{grav}}_{\star\ \text{UV}}\right)^2}{g^{\text{grav}}_{\star\ \text{IR}}} \dfrac{H^{\mu\nu}}{\Lambda_{\text{IR}}} T^{(t/H)}_{\mu\nu}$

* $T^{\text{strong IR}}_{\mu\nu} \sim \dfrac{\Lambda^3_{\text{IR}}}{g^{\text{grav}}_{\star\ \text{IR}}} H_{\mu\nu}$

Backup: Spectrum and Couplings - Gravity KK

- Spin-2: Couplings to t/H (flavor non-universal)



▷ $\delta\mathcal{L}\left(\Lambda_{\text{Higgs}}\right) \sim \dfrac{\left(g^{\text{grav}}_{\star\ \text{UV}}\right)^2}{\Lambda^4_{\text{Higgs}}} T^{\mu\nu\ (t/H)} T^{(\text{strong IR})}_{\mu\nu}$

▷ $\delta\mathcal{L}\left(\Lambda_{\text{IR}}\right) \sim \left(\dfrac{\Lambda_{\text{IR}}}{\Lambda_{\text{Higgs}}}\right)^4 \dfrac{\left(g^{\text{grav}}_{\star\ \text{UV}}\right)^2}{g^{\text{grav}}_{\star\ \text{IR}}} \dfrac{H^{\mu\nu}}{\Lambda_{\text{IR}}} T^{(t/H)}_{\mu\nu}$

* $T^{\text{strong IR}}_{\mu\nu} \sim \dfrac{\Lambda^3_{\text{IR}}}{g^{\text{grav}}_{\star\ \text{IR}}} H_{\mu\nu}$

- ▷ Flavor Non-Universal Coupling to top/Higgs
- ▷ Too small to be Sensitivity to top/Higgs Compositeness
- ▷ Highly suppressed → No Flavor-violating processes !

Backup: Derivation of KK V - V - φ coupling

- KK V - V - φ coupling (Flavor-blind)
- $\mathcal{L}\left(\Lambda_{\rm Higgs}\right) \ni \mathcal{L}_{\rm CFT} + \lambda\, \Lambda_{\rm Higgs}^{\epsilon}\, \mathcal{O}_{\rm GW}$
- In IR,
  - $\lambda \left(\dfrac{\Lambda_{\rm IR}}{\Lambda_{\rm Higgs}}\right)^{-\epsilon}$ and $\mathcal{O}_{\rm GW} \ni \Lambda_{\rm IR}^{-\epsilon}\, \tilde{\rho}^{\mu\nu}\, \tilde{\rho}_{\mu\nu}$

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  - $\delta\mathcal{L}\left(\Lambda_{\rm IR}\right) \sim \lambda \left(\dfrac{\Lambda_{\rm IR}}{\Lambda_{\rm Higgs}}\right)^{-\epsilon} \tilde{\rho}^{\mu\nu}\, \tilde{\rho}_{\mu\nu} \ni \lambda\epsilon g_{\star\,\rm IR}^{\rm grav} \left(\dfrac{\Lambda_{\rm IR}}{\Lambda_{\rm Higgs}}\right)^{-\epsilon} \dfrac{\varphi}{\Lambda_{\rm IR}} \tilde{\rho}^{\mu\nu}\, \tilde{\rho}_{\mu\nu}$

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- $\mathcal{L}\left(\Lambda_{\rm Higgs}\right) \ni \mathcal{L}_{\rm CFT} + \lambda\, \Lambda_{\rm Higgs}^{\epsilon}\, \mathcal{O}_{\rm GW}$
- In IR,
  - $\lambda \left(\dfrac{\Lambda_{\rm IR}}{\Lambda_{\rm Higgs}}\right)^{-\epsilon}$ and $\mathcal{O}_{\rm GW} \ni \Lambda_{\rm IR}^{-\epsilon} \tilde{\rho}^{\mu\nu}\, \tilde{\rho}_{\mu\nu}$
  - $\delta\mathcal{L}\left(\Lambda_{\rm IR}\right) \sim \lambda \left(\dfrac{\Lambda_{\rm IR}}{\Lambda_{\rm Higgs}}\right)^{-\epsilon} \tilde{\rho}^{\mu\nu}\, \tilde{\rho}_{\mu\nu} \sim \lambda\epsilon g_{\star\,\rm IR}^{\rm grav} \left(\dfrac{\Lambda_{\rm IR}}{\Lambda_{\rm Higgs}}\right)^{-\epsilon} \dfrac{\varphi}{\Lambda_{\rm IR}} \tilde{\rho}^{\mu\nu}\, \tilde{\rho}_{\mu\nu}$
  - $\delta\mathcal{L}\left(\Lambda_{\rm IR}\right) \sim \lambda\epsilon g_{\star\,\rm IR}^{\rm grav} \left(\dfrac{\Lambda_{\rm IR}}{\Lambda_{\rm Higgs}}\right)^{-\epsilon} \dfrac{g_{\rm elem}}{g_{\star\,\rm IR}^{\rm gauge}} \rho^{\mu\nu}\, F^{\mu\nu}\, \dfrac{\varphi}{\Lambda_{\rm IR}}$
    - Using $\gamma - \rho$ mixing

Backup: Derivation of KK V - V - φ coupling

- KK V - V - φ coupling (Flavor-blind)

$$\delta\mathcal{L}\left(\Lambda_{\rm IR}\right) \sim \lambda\epsilon g_{\star\,\rm IR}^{\rm grav}\left(\frac{\Lambda_{\rm IR}}{\Lambda_{\rm Higgs}}\right)^{-\epsilon}\frac{g_{\rm elem}}{g_{\star\,\rm IR}^{\rm gauge}}\rho^{\mu\nu}F^{\mu\nu}\frac{\varphi}{\Lambda_{\rm IR}}$$