Light KK Gravitons from Extended Warped Extra Dimensions at DUNE

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Motivation

- The Randall–Sundrum framework was introduced to address the electroweak–Planck hierarchy by using a warped extra dimension, where mass scales are redshifted along the fifth dimension.

- Via AdS/CFT, the same setup can be viewed as a 4D strongly coupled sector, with KK resonances corresponding to composite states.

- Direct and indirect searches constrain RS: LHC non-observation of TeV-scale KK resonances, together with electroweak precision and flavor constraints from virtual KK effects, pushes the standard RS spectrum to multi-TeV scales.

- Extended warped geometries: different sectors terminate at different effective IR scales. Separated brane scales may open up a low-energy window for warped-sector phenomenology beyond conventional LHC searches.

Agashe, K., Du, P., Hong, S., Sundrum, R., 2017:. JHEP01(2017)016

Agashe, K., Ekhterachian, M., Kim, D., Sathyan, D., 2020. JHEP11(2020)109

Standard RS1: Warping Generates the TeV Scale

- a **5D warped extra-dimensional model** with a slice of AdS_5 bounded by branes
- Metric:

$$ds^2 = e^{-2k|y|}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2$$

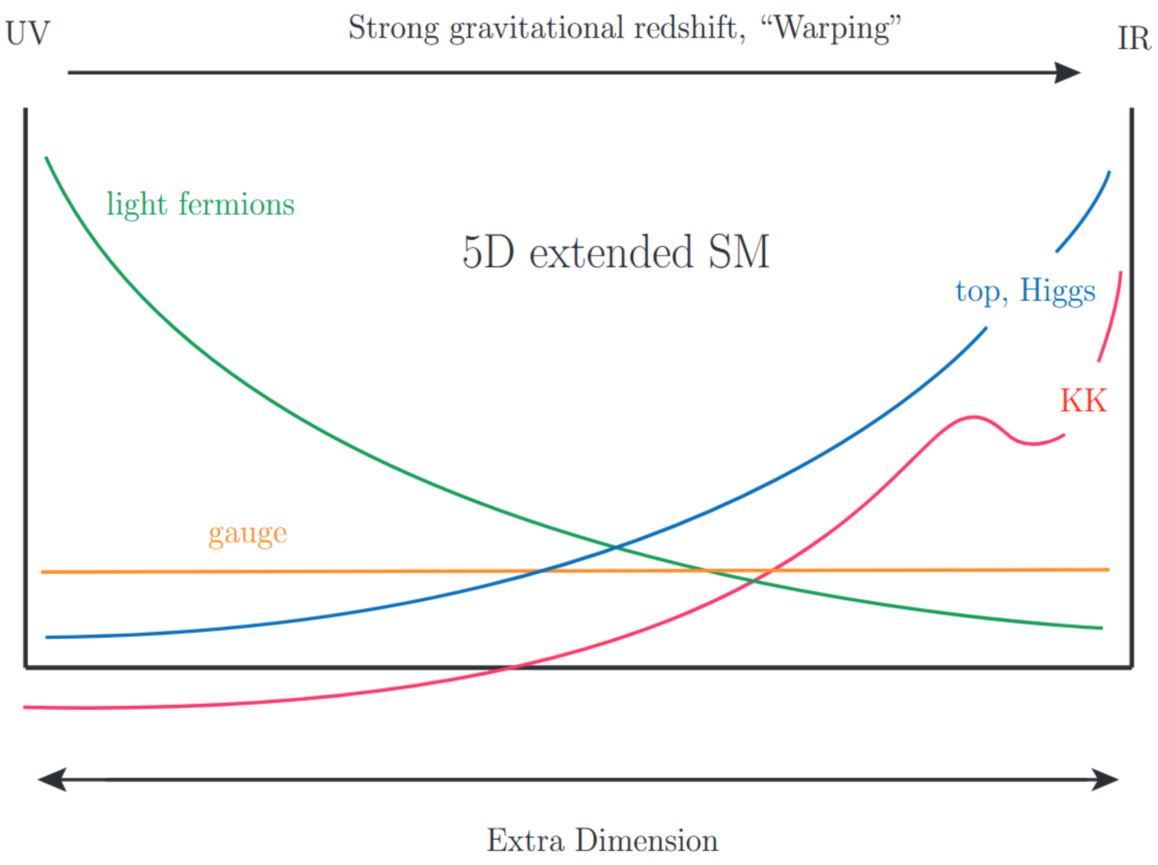
- **UV/Planck brane:** fundamental scale
- **IR brane:** warped-down scale

$$\Lambda_{\text{IR}} = ke^{-ky_{\text{IR}}}$$

- Choosing: $ky_{\text{IR}} \sim 35$

$$\Lambda_{\text{IR}} \sim \mathcal{O}(\text{TeV})$$

In minimal RS1, The IR brane sets the scale of new resonances.



Standard RS1: KK Towers

- ❑ A 5D bulk field appears in 4D as a tower of modes:

$$\Phi(x, y) = \sum_n f_n(y)\Phi^{(n)}(x)$$

- $f_n(y)$: wavefunction in the fifth dimension.
- $n = 0$: zero mode.
- $n \geq 1$: massive KK resonances.

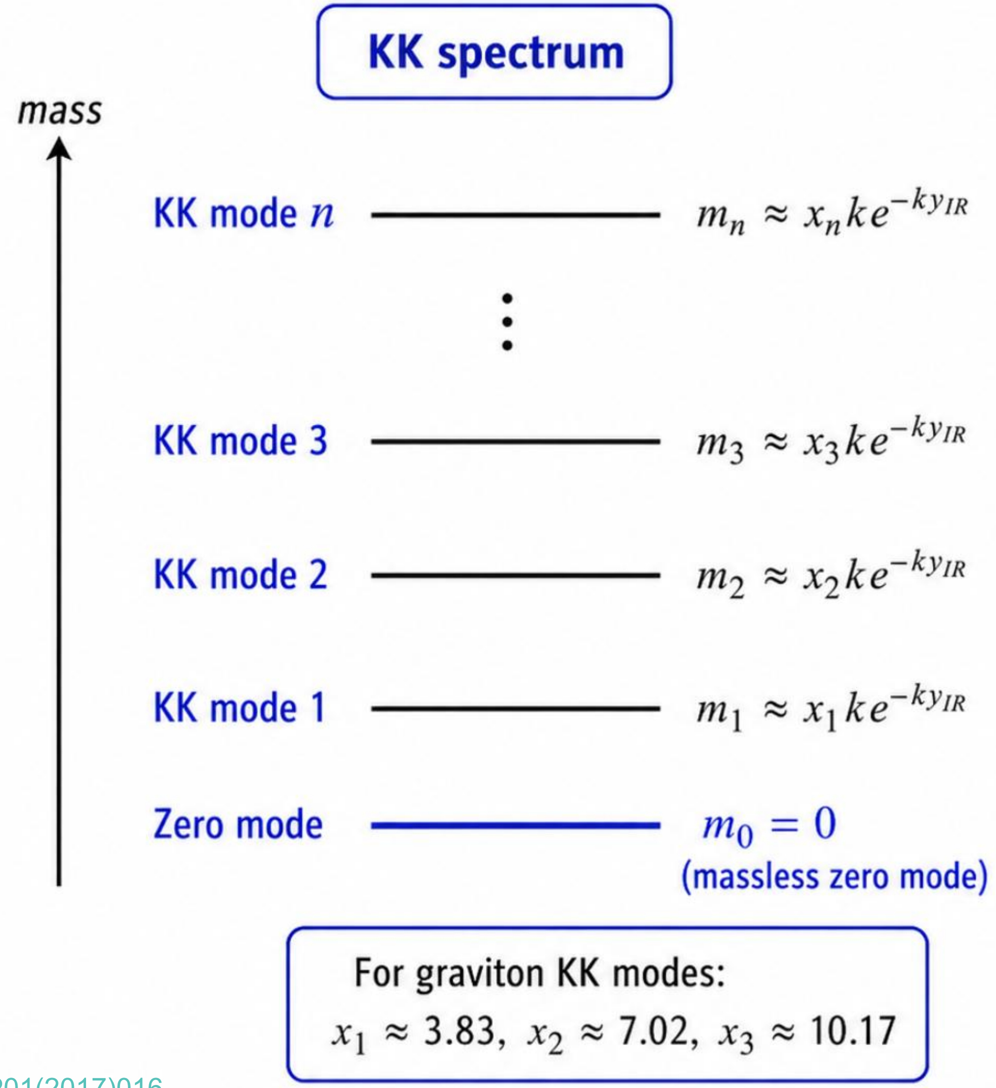
- ❑ 4D couplings are determined by overlaps of 5D profiles.

Standard two-brane RS1 ties all KK masses to the same IR scale.

- ❑ No evidence of TeV KK states from direct resonance searches and indirect precision constraints

$\Rightarrow \Lambda_{\text{IR}}$ must be pushed upward.

Can different sectors have different IR scales?



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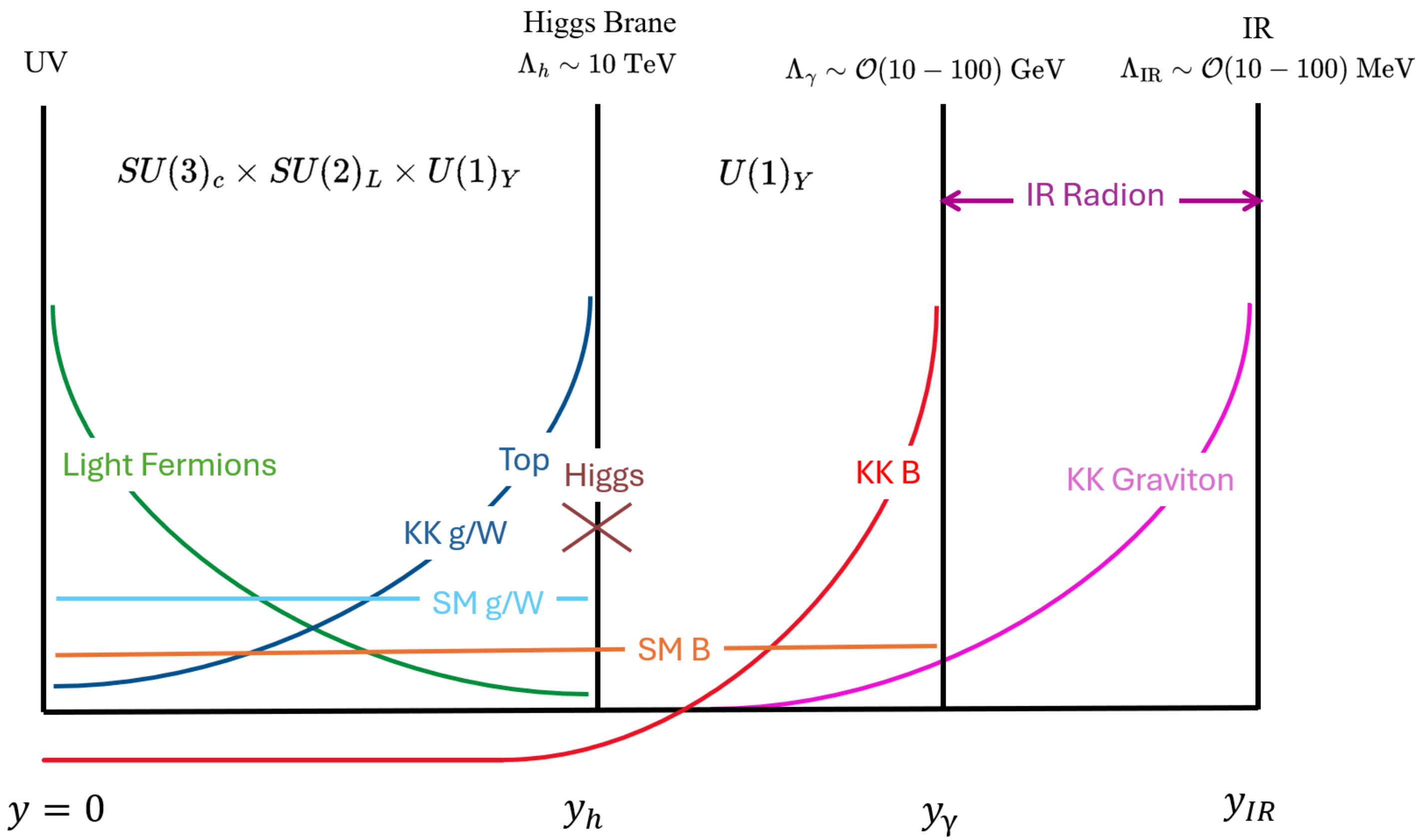
Extended RS Setup: Separated IR Scales

- We extend minimal RS1 by allowing different sectors to terminate at different positions in the warped dimension
- The gravitational sector propagates on the full interval: $0 \leq y \leq y_{\text{IR}}$
- The hypercharge gauge boson can propagate in the extended bulk till intermediate $\sim\mathcal{O}(10-100)$ GeV brane
- If gravity propagates deeper into the bulk than the SM, while the photon/hypercharge sector extends to an intermediate scale, light KK gravitons can remain accessible to low-energy/high-intensity experiments.



Sector	Interval	Scale controlling KK modes
Higgs, fermions, $SU(3)_C \times SU(2)_L$	$0 \leq y \leq y_h$	$\Lambda_h \sim \mathcal{O}(10)\ TeV$
$U(1)_Y$ or portal vector	$0 \leq y \leq y_\gamma$	$\Lambda_\gamma \sim \mathcal{O}(10-100)\ GeV$
Gravity	$0 \leq y \leq y_{\text{IR}}$	$\Lambda_{\text{IR}} \sim \mathcal{O}(10-100)\ MeV$

Extended RS Setup: EW Precision problem

- Extending hypercharge to a deeper brane creates light hypercharge KK modes. Therefore KK vector modes can affect precision observables.
- For the hypercharge KK profiles $f_B^{(n)}(y) = \frac{e^{ky}}{N_n}\left[J_1\left(z_n^B(y)\right) + \beta_n Y_1\left(z_n^B(y)\right)\right]$ $\quad z_n^B(y) = (m_n^B/k)e^{ky}$

  For low-lying hypercharge KK modes, near the higher-energy branes $\quad z_n^B(y) = (m_n^B/k)e^{ky} \ll 1$

$$f_B^{(n)}(y) \simeq \frac{e^{ky}}{N_n}\left[\frac{z_n^B(y)}{2} - \frac{2\beta_n}{\pi z_n^B(y)} + \cdots\right] = \frac{1}{N_n}\left[-\frac{2\beta_n k}{\pi m_n^B} + \mathcal{O}\left(e^{2ky}\right)\right]$$

$$\left|\frac{g_1}{g_0}\right| \equiv \frac{g_{B^{(1)}\mathrm{h}}}{g_{B^{(0)}\mathrm{h}}} = \frac{f_B^{(1)}(y_\mathrm{h})}{f_B^{(0)}(y_\mathrm{h})} \simeq f_B^{(1)}(y_\mathrm{h}) \simeq -0.178$$

  If unsuppressed, they generate large corrections to electroweak precision observables and four-fermion operators.

- Brane-localized kinetic terms(BLKTs) can be used to control precision-electroweak constraints while preserving an enhanced coupling between KK gravitons and the photon

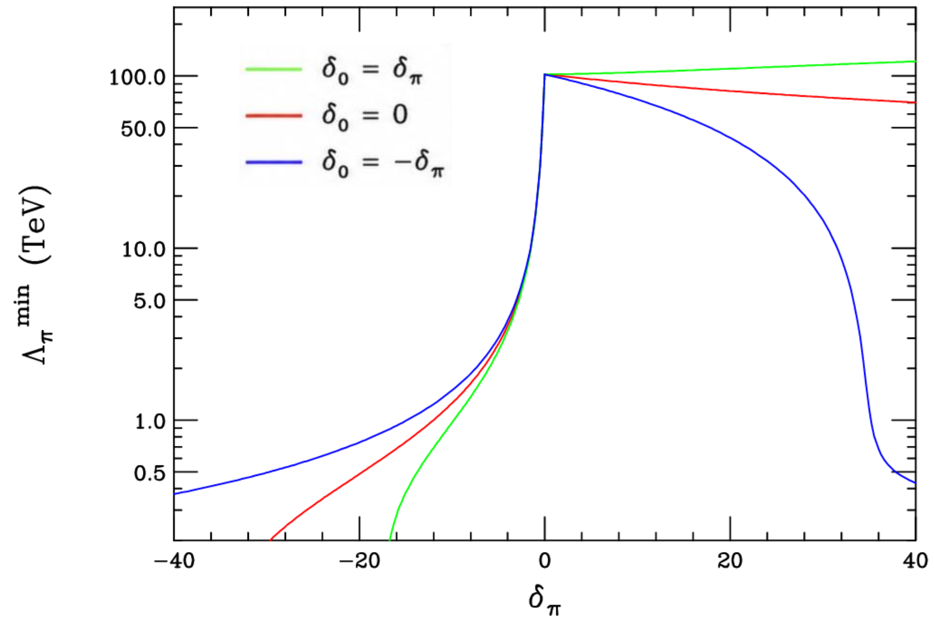
Addressing Precision Constraints: BLKTs

$$S_B \supset -\frac{1}{4}\int_0^{y_y} dy B_{MN}B^{MN} - \frac{1}{4}\sum_i \frac{\delta_i}{k} B_{\mu\nu}B^{\mu\nu}\delta\left(y-y_i\right)$$

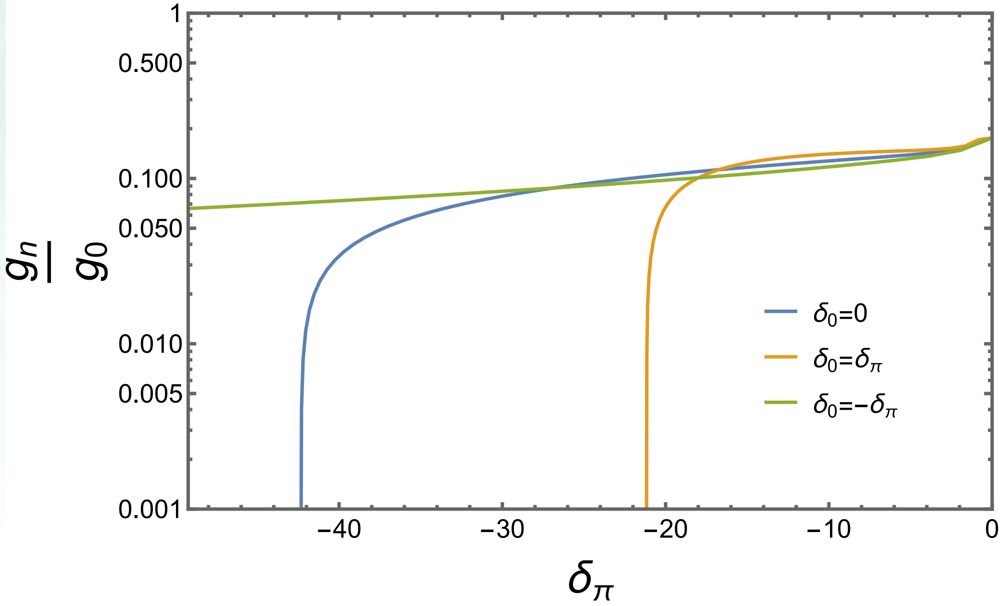
$$Z_0 \equiv 1 + \frac{\delta_{\rm UV}+\delta_\gamma}{k y_\gamma} \qquad g' = \frac{g_{5Y}}{\sqrt{y_\gamma Z_0}}$$

$$g_n^h \sim g' f_B^{(n)}\left(y_h\right)\sqrt{y_\gamma Z_0}$$

For Minimal RS: (Davoudiasl et al. 2003)



For Extended RS setup:



Without BLKTs: light B_n modes couple too strongly to SM fields.
With BLKTs: wavefunctions and normalizations are modified.

BLKTs allow light vector modes while reducing their dan gerous SM couplings.

Phenomenology

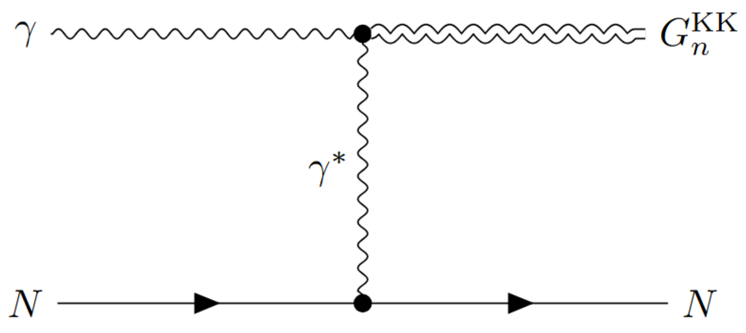
- KK Graviton Spectrum: $$h_{\mu\nu}(x,y) = \sum_{n=0}^{\infty} h_{\mu\nu}^{(n)}(x) f_G^{(n)}(y)$$

$$m_n \simeq x_n^G k e^{-ky_{\rm IR}} \sim \mathcal{O}(10-100)\ \text{MeV} \qquad \Delta m_G \sim \pi \Lambda_{\rm IR} \sim \mathcal{O}(10-100)\ \text{MeV}$$

A deep gravity brane gives a light, dense KK graviton tower.

The photon/hypercharge sector probes the intermediate region and provides the visible portal to the graviton tower.

- Primakoff production of KK gravitons can be probed in high-intensity fixed-target/beam-dump environments, including the DUNE near-detector setup.



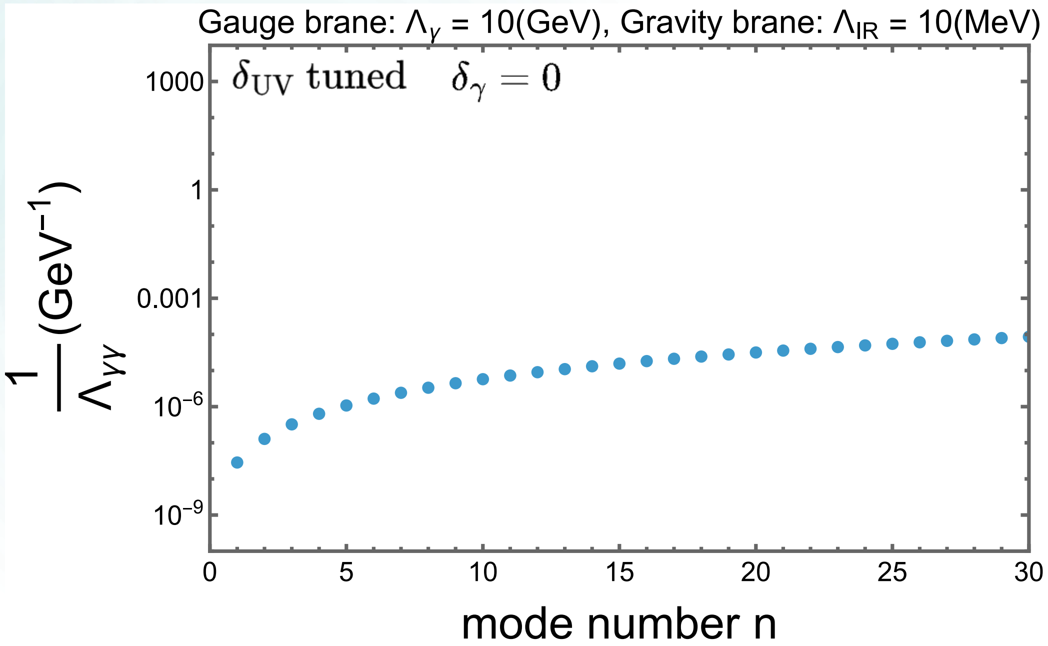
- The range of KK modes accessible at beam dump is controlled by the warped IR scale. A deeper IR brane lowers the KK mass spacing, enabling production of higher KK modes within the available energy range.

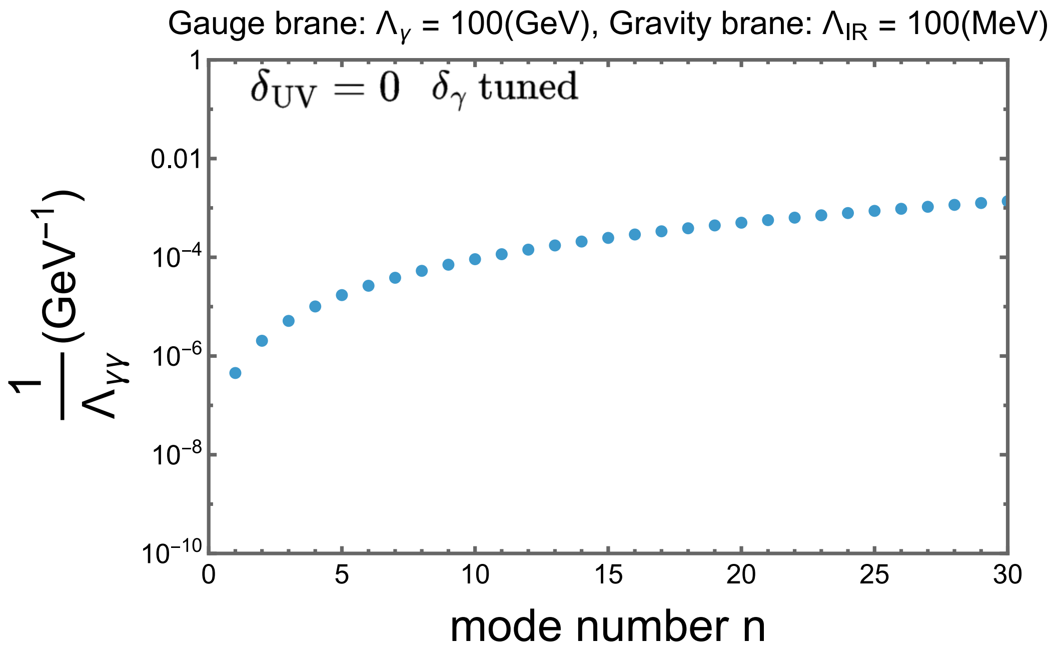
Effective KKG couplings to photon

$G_n\gamma\gamma$ is controlled by overlap of graviton and photon profiles

$$\mathcal{L}_{\text{int}} \supset -\sum_n \frac{1}{\Lambda^{(n)}_{\gamma\gamma,\text{ eff}}} h^{(n)}_{\mu\nu} T^{(0)\mu\nu}_{\gamma}$$

$$\frac{1}{\Lambda^{(n)}_{\gamma\gamma,\text{ eff}}} = \frac{c_W^2}{M_5^{3/2}\left(y_\gamma + \frac{1}{k}(\delta_{\text{UV}}+\delta_\gamma)\right)}\left[\int_0^{y_\gamma} dy f_G^{(n)}(y) + \frac{\delta_{\text{UV}}}{k} f_G^{(n)}(0) + \frac{\delta_\gamma}{k} f_G^{(n)}(y_\gamma)\right]$$

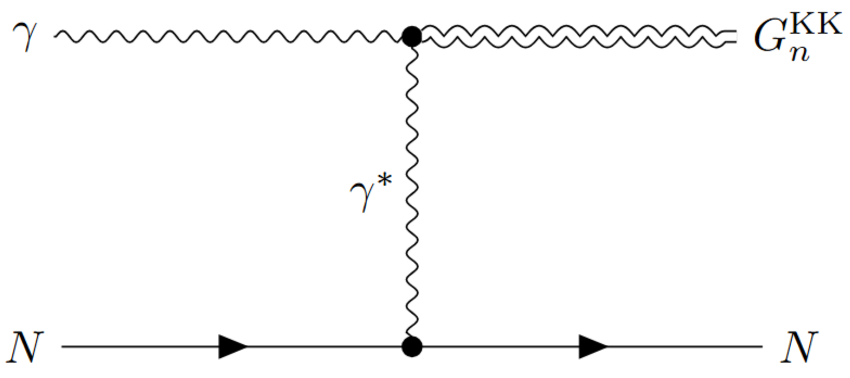


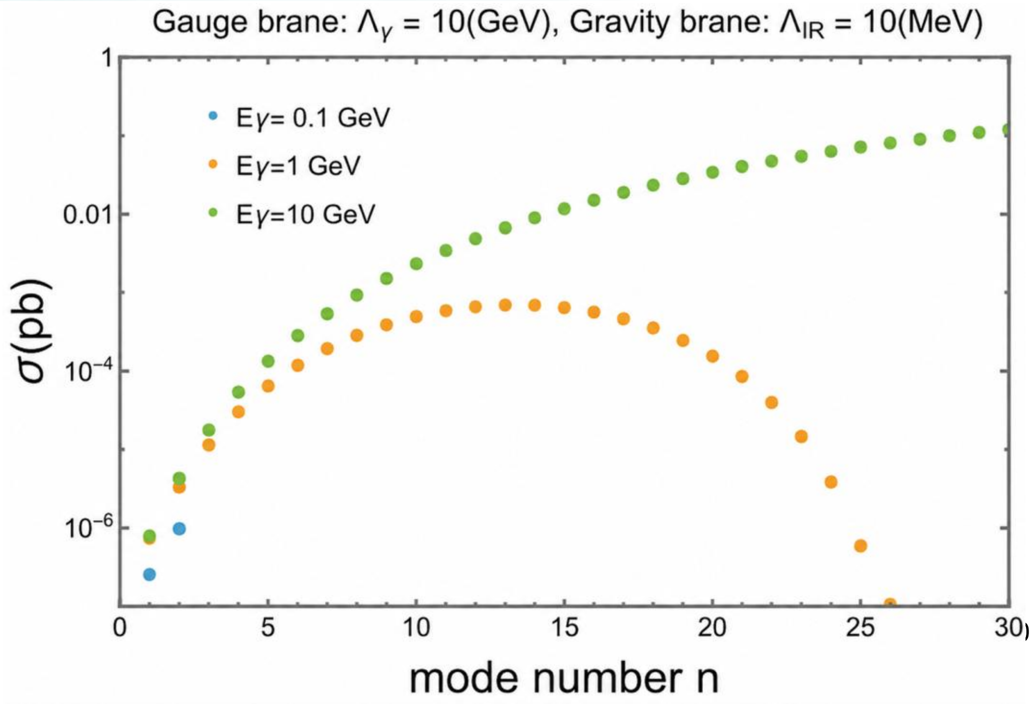


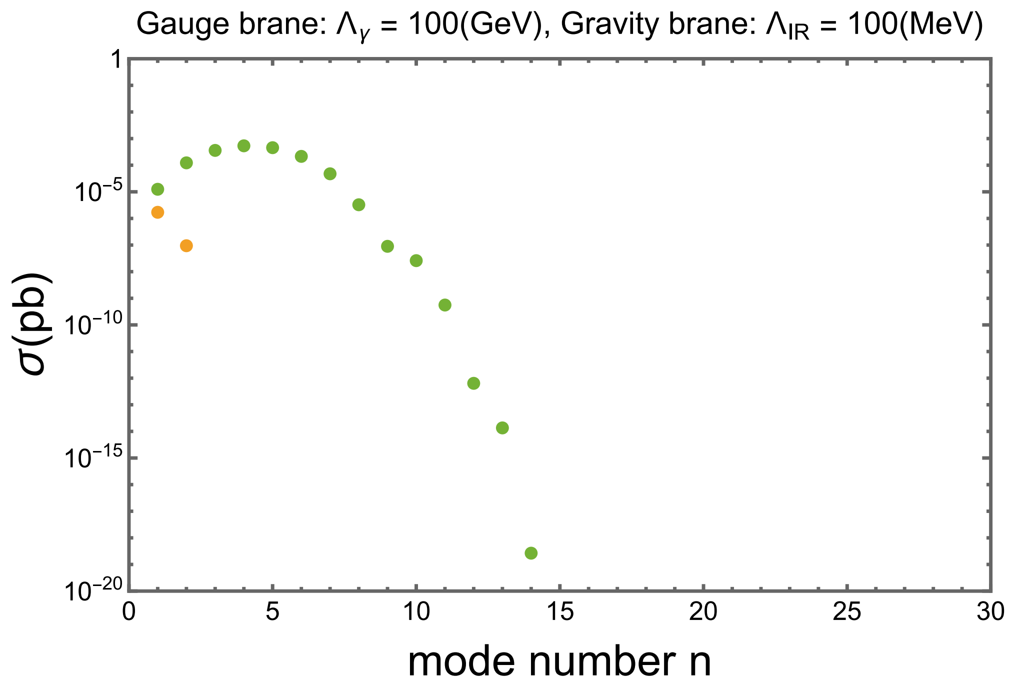
DUNE Phenomenology

KKG Production:

- DUNE can produce modes with $m_n^G \sim \text{GeV}$.
- Depending on IR brane position, the produced modes could be high up in a dense tower.







DUNE Phenomenology

Detection: produced $G_n \to$ hidden cascade $\to$ terminal $G_1 \to \gamma\gamma$

Cascade decays:

- Intratower graviton decays: $G_n \to G_m G_\ell$
- Decay to radion final states: $G_n \to rr \qquad G_n \to G_m r \qquad \text{whenever } m_n^G > m_m^G + m_r$

Direct visible decay to photons (suppressed): $G_n \to \gamma\gamma$

Terminal Diphoton decay: If $m_1^G < 2m_r$, then the decay $G_1 \to rr$ is forbidden

$$\Gamma(G_1 \to \gamma\gamma) \simeq \frac{(m_1^G)^3}{80\pi \left(\Lambda^{(1)}_{\gamma\gamma,\text{eff}}\right)^2}$$

$$\ell_{\text{lab}} = \frac{E_{G_1}}{m_1} c\tau = \frac{80\pi\hbar c E_{G_1}}{g_{\gamma\gamma}^2 m_1^4} \simeq 500\text{ m} \left(\frac{E_{G_1}}{1\text{ GeV}}\right)\left(\frac{0.1\text{GeV}}{m_1^G}\right)^4 \left(\frac{1.0\times 10^{-6}\text{GeV}^{-1}}{g_n^{(1)}}\right)^2$$

Conclusions

- In minimal RS1, one IR brane controls all KK scales, so LHC and electroweak precision limits push the spectrum heavy.
- In this work we separate the relevant IR scales. The Higgs and electroweak sector remain tied to a high scale, while gravity can propagate deeper and generate a light dense KK graviton tower.
- An intermediate photon/hypercharge brane provides a portal to produce these modes.
- The main model-building challenge is precision constraints from light gauge KK modes, which we control parametrically with BLKTs.
- The resulting phenomenology is well matched to fixed-target experiments like DUNE: Primakoff production of excited KK gravitons, hidden-sector cascade decays, and possibly displaced diphoton decays of the terminal mode.

Backup

EWSB

$$S_H \supset \int d^4x \left[(D_\mu H)^\dagger (D^\mu H) - \lambda \left(|H|^2 - \frac{v^2}{2} \right)^2 \right]_{y=y_\mathrm{h}}$$

$$D_\mu = \partial_\mu - \frac{ig_{5W}}{2} W_\mu^a(x, y_\mathrm{h}) \sigma^a - \frac{ig_{5Y}}{2} B_\mu(x, y_\mathrm{h}), \quad \langle H \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$$

$$\mathcal{L}_\mathrm{neutral} = \frac{v^2}{8} \left[g_{5W} W_\mu^3(x, y_\mathrm{h}) - g_{5Y} B_\mu(x, y_\mathrm{h}) \right]^2$$

$$W_\mu^3(x,y) = \frac{1}{\sqrt{y_h}} \sum_{n \geq 0} f_W^{(n)}(y) W_\mu^{3(n)}(x), \quad B_\mu(x,y) = \frac{1}{\sqrt{y_\gamma}} \sum_{n \geq 0} f_B^{(n)}(y) B_\mu^{(n)}(x)$$

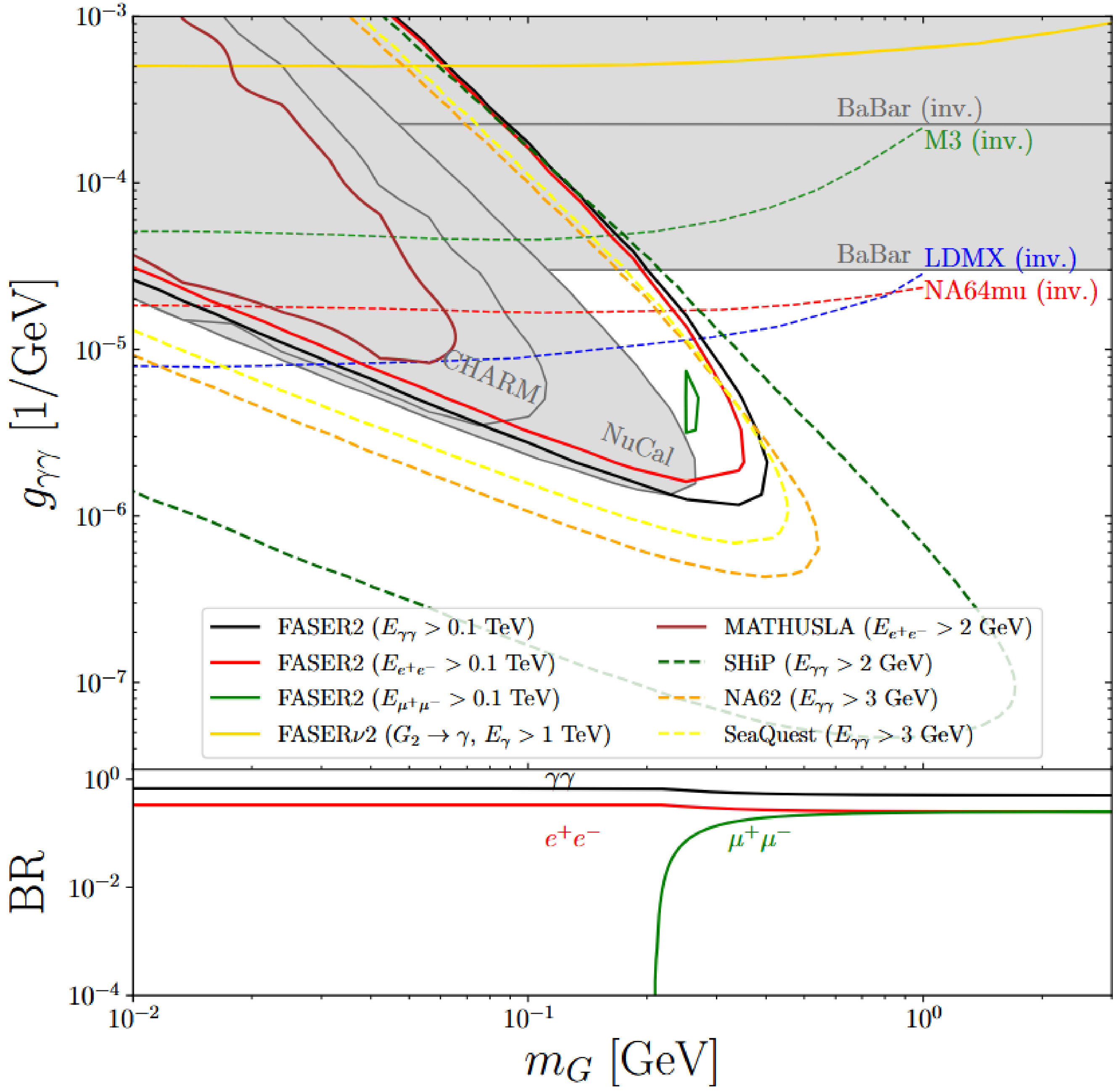
$$\left(M^2\right)_{W_m W_n} = \left(m_n^W\right)^2 \delta_{mn} + \frac{v^2}{4} g^2 f_W^{(m)}(y_h) f_W^{(n)}(y_h)$$

$$\left(M^2\right)_{B_m B_n} = \left(m_n^B\right)^2 \delta_{mn} + \frac{v^2}{4} g'^2 f_B^{(m)}(y_h) f_B^{(n)}(y_h)$$

$$\left(M^2\right)_{W_m B_n} = -\frac{v^2}{4} g g' f_W^{(m)}(y_h) f_B^{(n)}(y_h).$$

$$A_\mu^{(0)} = s_W W_\mu^{3(0)} + c_W B_\mu^{(0)}$$

$$Z_\mu^{(0)} = c_W W_\mu^{3(0)} - s_W B_\mu^{(0)}$$



Jodłowski, Krzysztof. "Probing Some Photon Portals to New Physics at Intensity Frontier Experiments." Physical Review D 108, no. 11 (2023): 115017. 2658416, p. 115017. INSPIRE. https://doi.org/10.1103/PhysRevD.108.115017