Extended Warped Extra-Dimensional Models and Their Physics Opportunities at Colliders

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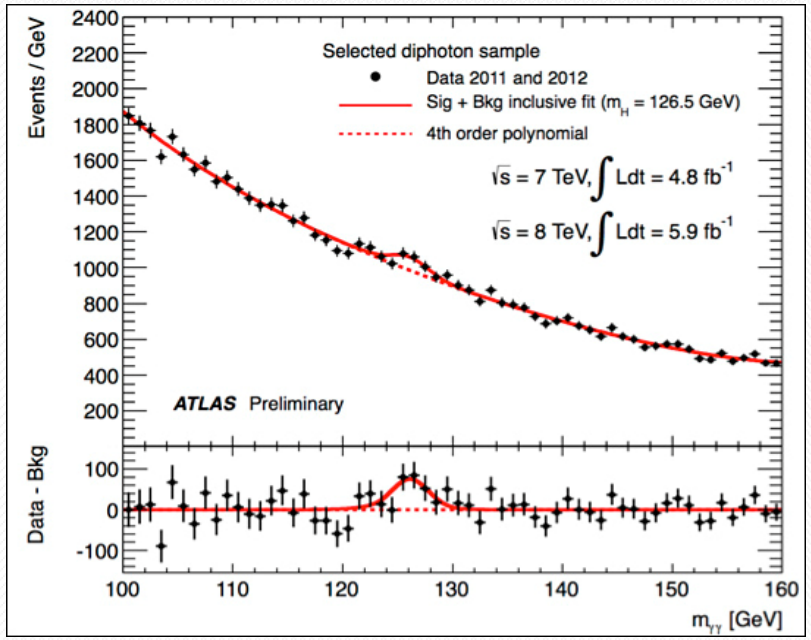
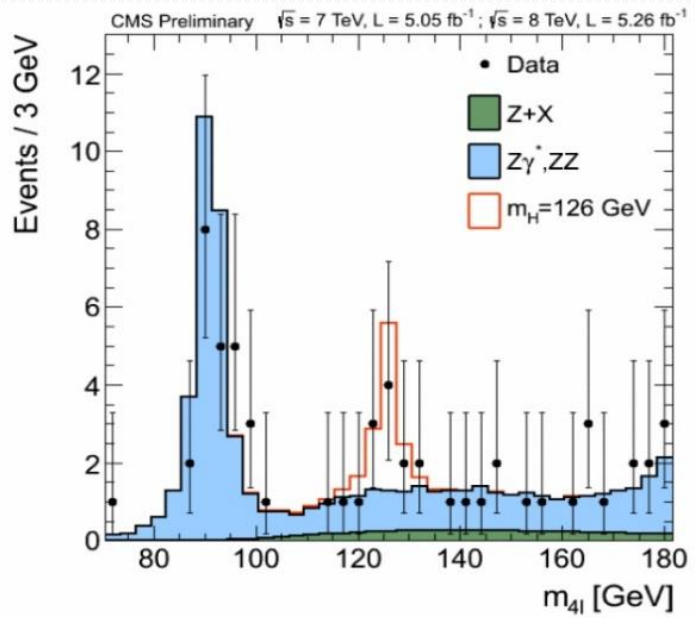
Based on K. Agashe, P. Du, S. Hong and R. Sundrum [JHEP 01 (2017) 016, arXiv: 1608.00526]
K. Agashe, J. Collins, P. Du, S. Hong, DK and R. Mishra [JHEP 05 (2017) 078, arXiv: 1612.00047]
K. Agashe, J. Collins, P. Du, S. Hong, DK and R. Mishra [PRD99 (2019) 075016, arXiv: 1711.09920]
K. Agashe, J. Collins, P. Du, S. Hong, DK and R. Mishra [JHEP 11 (2018) 027, arXiv: 1809.07334]
K. Agashe, M. Ekhterachian, DK and D. Sathyan [JHEP accepted, arXiv: 2008.06480]

Motivation

- Higgs discovery at the LHC

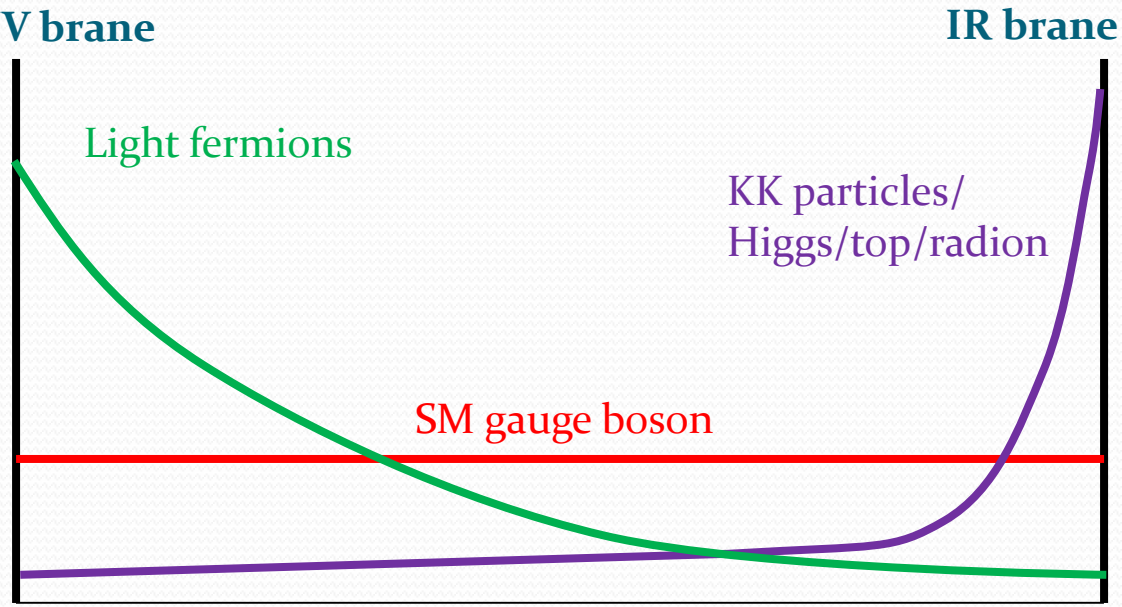




- Large hierarchy between the higgs mass (~125 GeV) and high scales → Randall-Sundrum (RS) model as a solution to the gauge hierarchy problem
- No new physics particles (including RS) → "Attacking" every single (possibly missing) corner of model space

Standard Warped Models of Bulk SM

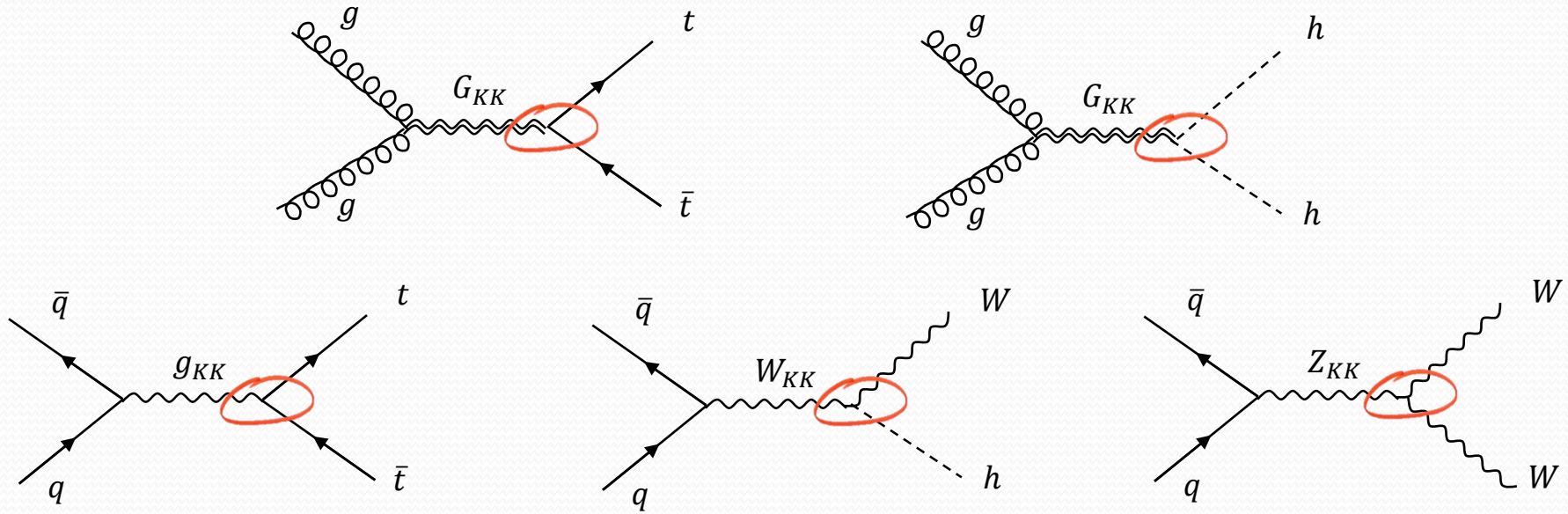
- Profiles as solutions to the wave eq. in the 5D curved spacetime
  - ✓ Zero modes: identified as SM fields
  - ✓ KK modes: new particles
  - ✓ Profiles of KK modes peaking near the IR (Higgs) brane for the fields propagating from the UV brane to the IR (Higgs) brane
- Gauge boson zero mode: flat over the bulk (where it resides)
- Radion: new particle peaking near the IR brane
- Profiles for fermion zero modes: controlled by 5D masses → A solution to the flavor puzzle



Couplings between particles ∝ overlap of the associated profiles in the extra dimension

LHC Signals

- A few example KK signals



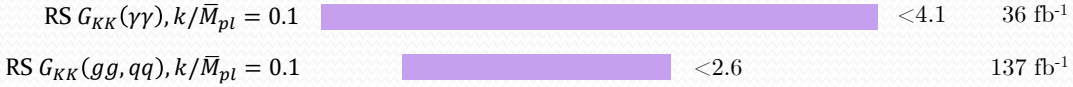
- Decay branching fractions into a pair of heavy SM particles ($t/W/Z/h$) are large as all 3 particles are peaking near the TeV brane.

- "Classic" search for boosted $t/W/Z/h$ using jet sub-structure techniques is possible.

LHC Bounds on KK Particles

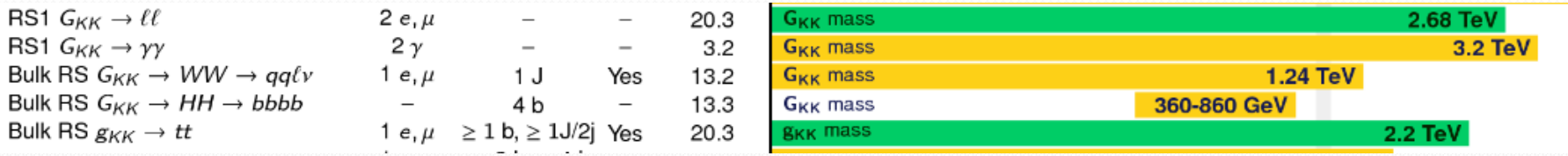
CMS 2016

CMS 2014



CMS 2020

ATLAS 2016



ATLAS 2020

- LHC has already ruled out 1-4 TeV scale KK particles
  - → Probing KK particles living at missing corners via new search strategies and/or in channels "swamped" by already-studied modes

Bounds from Precision Measurements

What if we take flavor/CP bounds at face value

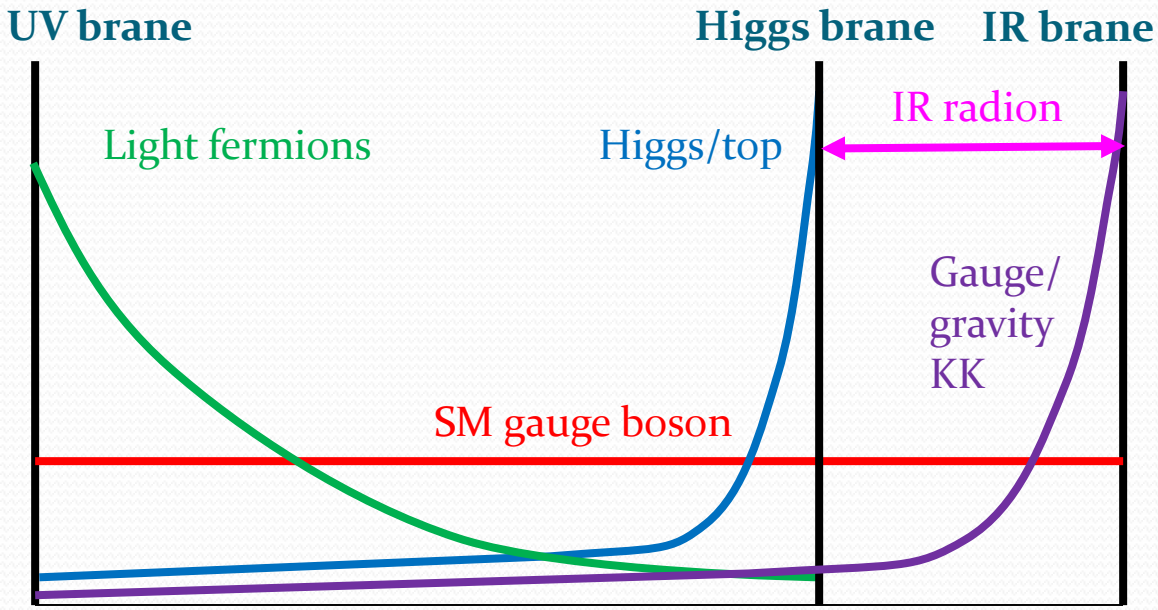
(i.e., no symmetries to evade them)?!

- KK scale becomes $\mathcal{O}(10)$ TeV $\Rightarrow$ No on-shell production of KK particles at the LHC, indirect signals still possible. [e.g., Csaki, Falkowski, Weiler, JHEP 0809 008]

- Maybe not, underlying models would be realized in a different way.

"Extended" Warped Models of Bulk SM

- Gauge fields propagating in the entire bulk down to the IR brane vs. SM matter fields (and Higgs) propagating down to the Higgs brane.
- (Lightest) gauge/gravity KK, radion peaking at the (final) IR brane, not the Higgs brane.
- Possible to show that models are safe from flavor/CP/EW precision tests even for gauge KK $\ll \mathcal{O}(10)$ TeV (no symmetries), as long as matter/Higgs (most relevant for the tests) reside down to $\mathcal{O}(10)$ TeV
- Leading bounds coming from direct searches at the LHC!



[Agashe, Du, Hong, Sundrum, JHEP 1701 016]

Couplings between particles ∝ overlap of the associated profiles in the extra dimension

Summary and Comparison: Mass, Production, and Decay

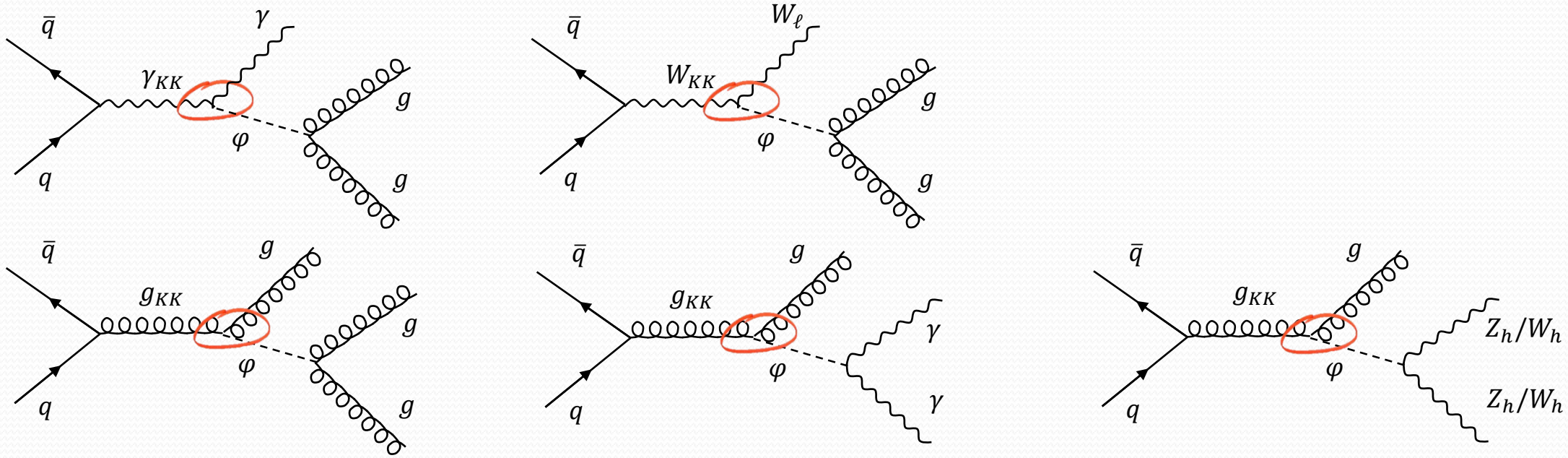
		Standard	Extended
KK fermion	Mass	$\gtrsim \mathcal{O}(10)$ TeV	$\gtrsim \mathcal{O}(10)$ TeV
KK gauge	Mass	$\gtrsim \mathcal{O}(10)$ TeV	A few TeV
	Production	$q\bar{q}$	$q\bar{q}$
	Decay	$t\bar{t}, hh$ ($\gg$ radion $+ \gamma/W/Z/g$)	$f\bar{f}$ (universally), radion $+ \gamma/W/Z/g$
Radion	Mass	$\gtrsim \mathcal{O}(10)$ TeV/(a few)	$\mathcal{O}(1)$ TeV
	Production	gg	gg
	Decay	$t\bar{t}, hh$	$gg \gg WW/ZZ \gg \gamma\gamma$

Gauge KK particles are still reachable/accessible at the LHC through channels that received less attention under the standard framework!

$\Rightarrow$ By "sequestering" of KK particles/radion from top/Higgs (see the picture in the previous slide), the usual dominant decay modes for them are suppressed.

Model I. All SM Gauges in the Extended Bulk: Cascade Decays

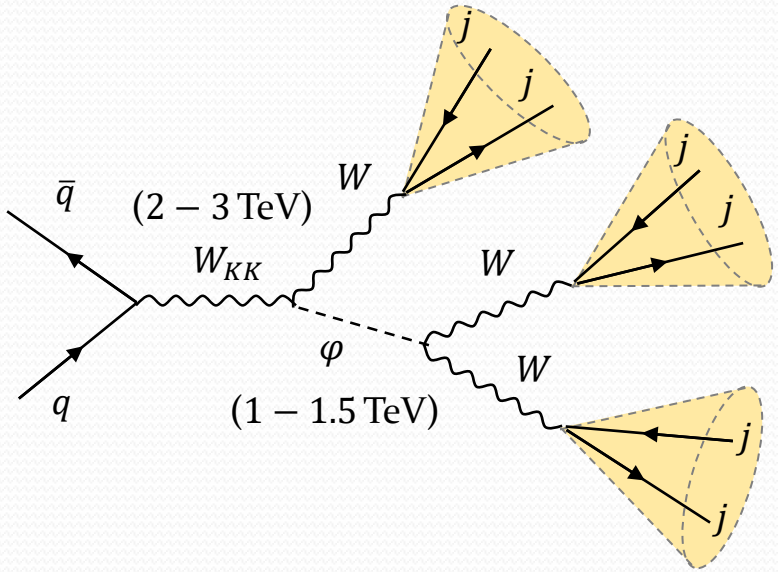
- (Pre-existing) channels "standing out"
  - ✓ Radion (φ) usually lighter than gauge KK particles: a sizable rate of KK gauge → gauge + φ
  - ✓ Radion decaying dominantly to gg, then $WW/ZZ \gg \gamma\gamma$

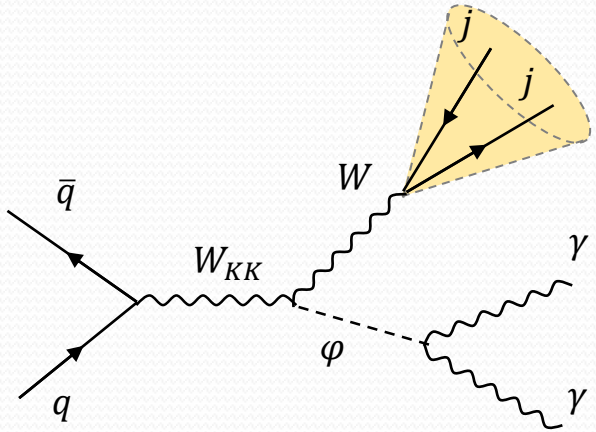


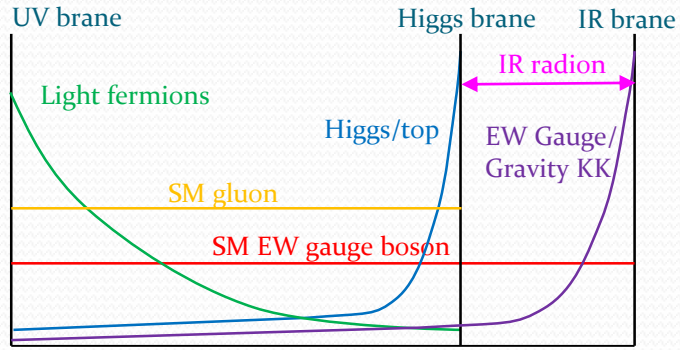
- $\sim 3-10\sigma$ excess would be expected at the upcoming (HL-)LHC runs. [Agashe, Collins, Du, Hong, **DK**, Mishra, JHEP 1705 078]

Model II. EW Gauges in the Extended Bulk: Tri-Boson Signals

- Only SM EW gauge bosons propagate in the full bulk → radion dominantly decays into EW gauge bosons (Remember these decay modes exist in the previous model, although negligible). [Agashe, Collins, Du, Hong, **DK** and Mishra, PRD99 075016]





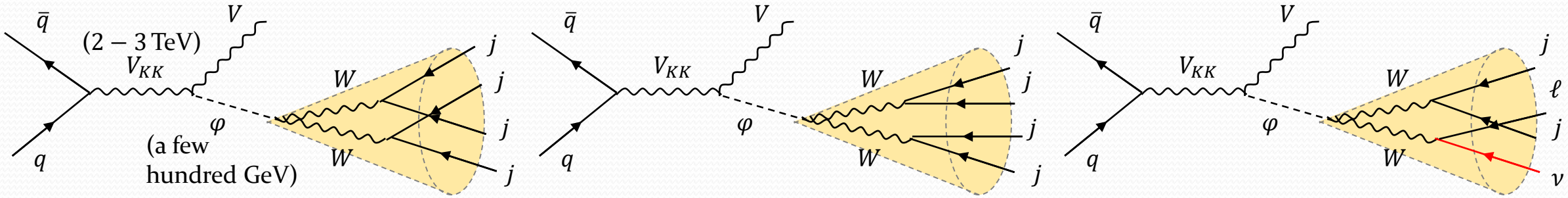


- A simple variation: Only $U(1)_Y$ field propagating in the full bulk → Tri-photon signal.

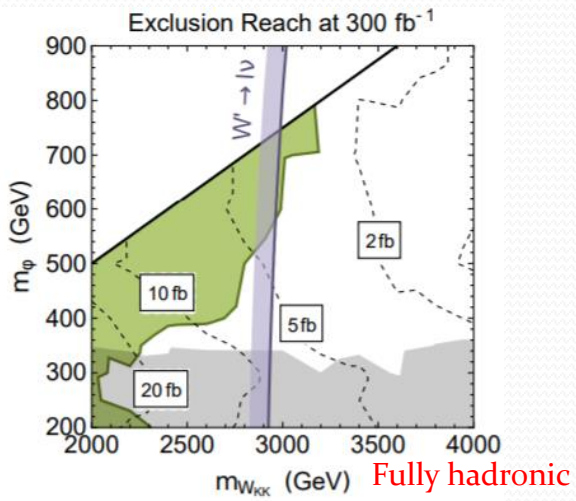
- 3 boosted (massive) gauge bosons [Agashe, Collins, Du, Hong, **DK** and Mishra, PRD99 075016] vs. not covered by standard searches (typically) selecting two hardest boosted (SM $Z/W/t/h$) jets [Aguilar-Saavedra (2017)]
- $\sim 4-5\sigma$ excess would be expected with 300 fb^{-1}

Model II. EW Gauges in the Extended Bulk: Boosted Di-Bosonic Radion

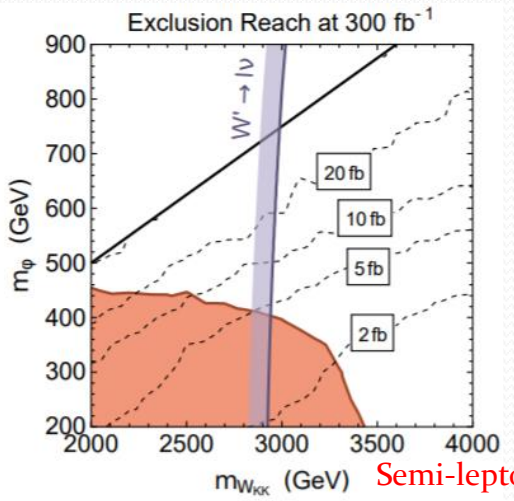
- Boosted φ jet with richer structures → Dedicated substructure techniques! [Agashe, Collins, Du, Hong, **DK** and Mishra, JHEP1811 027]



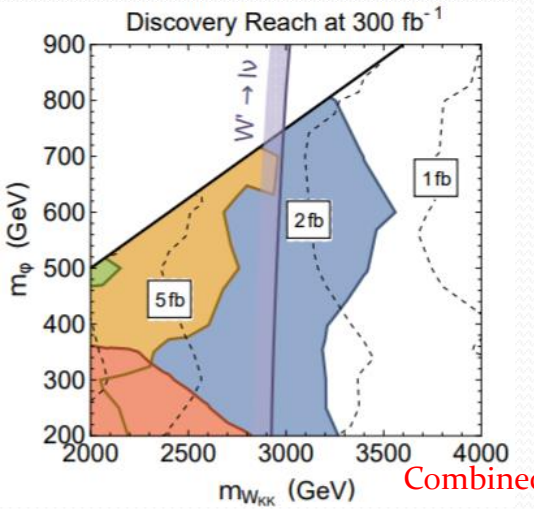
[Fully merged] [Intermediately merged] [Semi-leptonic radion jet]



Fully hadronic



Semi-leptonic

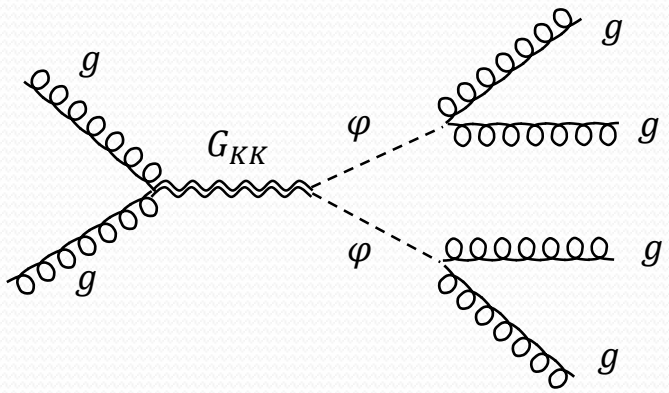


Combined discovery reach

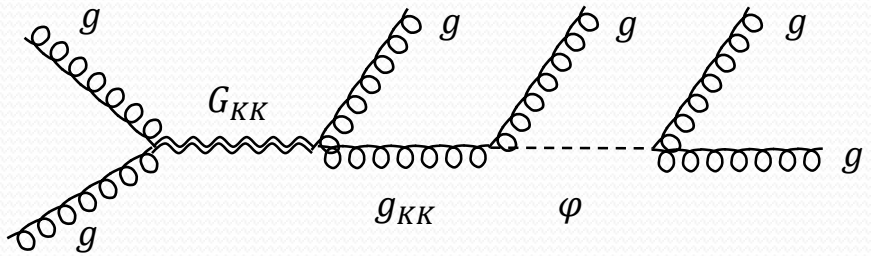
(cf. W_{KK} would be discovered in the $W' \to \ell\nu$ search as well.)

Model III. Gluon in the Extended Bulk: Four-Jet Signals of KK Graviton

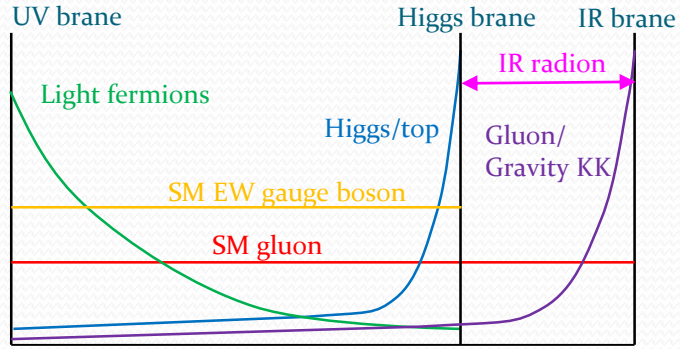
- Gravity propagates in the full bulk → lightest KK graviton (of a few TeV) accessible at the LHC like other gauge KK modes. [Agashe, Ekhterachian, **DK** and Sathyan, arXiv:2008.06480]



["Radion" channel – antler topology]



["KK gluon" channel – 3-step cascade decay]



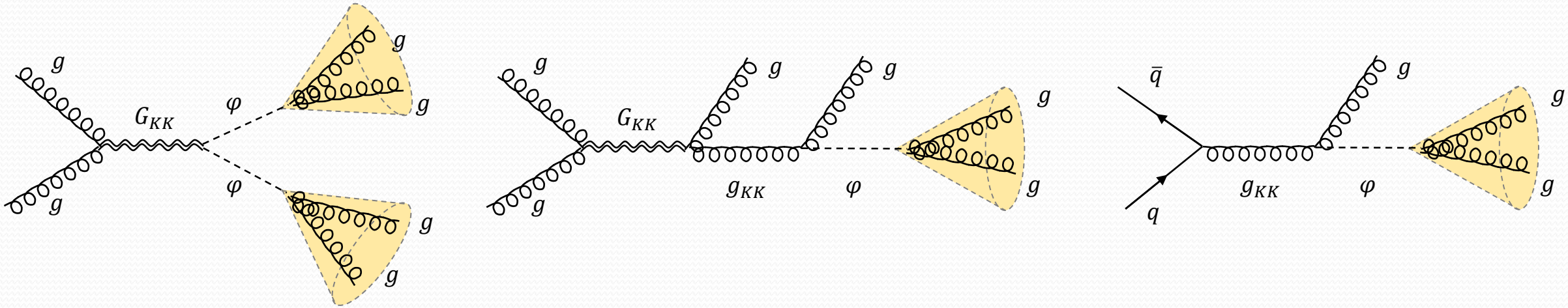
- Not restricted to this variation (i.e., working for Model I) , but this allows these modes to "stand out" more.

- Aligned with the existing effort of 4-jet searches in the context of spin-2 resonance.
- ~$2.5 - 5\sigma$ excess would be expected at 3,000 fb^{-1}

Proposed Future Plans

- Possible project I: Phenomenology of extended warped extra-dimensional models at higher energy colliders, e.g., $27/100$ TeV future colliders.
  - ✓ Exploring parameter space of heavier KK masses
  - ✓ Precision studies for the models (upon discovery)

- Possible project II: (Assuming Model III) KK graviton/gluon search in the boosted radion jet regime, i.e., $m_{KK} \gg m_{\varphi}$.



Conclusions

- Warped extra-dimensional model as a solution to gauge and flavor hierarchy puzzles
- "Extended" framework of warped extra-dimensional models not only inheriting the above virtues but making significant impact on collider phenomenology:
  - ✓ "**Gold Mine**" - Novel discovery opportunities for KK particles (which were "swamped" by others) through various channels, e.g., *cascade decays of warped vectors*, (*boosted*) *tri-boson*, *boosted radion jet*, and *four-jet signal*.
  - ✓ Inspiring the search effort for other new physics models giving similar experimental signatures.
- Dedicated triggering needed?

Back-up

Original RS to Warped RS with ≥ 2 Branes

	Original [1]	Warped [2]	Extended [3]
No. of branes	UV (Planck), IR (TeV)	UV, IR	UV, IR, Higgs
Graviton	Entire bulk	Entire bulk	Entire bulk
Higgs	IR brane	IR brane	Higgs brane
SM light fermions (top)	IR brane	(Bulk) towards UV (IR)	(UV to Higgs) towards UV (Higgs)
SM gauge fields	IR brane	Entire bulk	Entire bulk
Radions	(Bulk) towards IR	(Bulk) towards IR	UV radion: (UV to Higgs) towards Higgs IR radion: (Higgs to IR) towards IR

[1] Randall and Sundrum (1999)
[2] Davoudiasl, Hewett and Rizzo (1999); Pomarol (1999); Grossman and Neubert (1999); Chang et al. (1999); Gherghetta and Pomarol (2000)
[3] Agashe, Du, Hong and Sundrum (2016)
❖ A corresponding KK tower arises for the particles propagating in the bulk.

Existing Bounds on Heavy Resonances

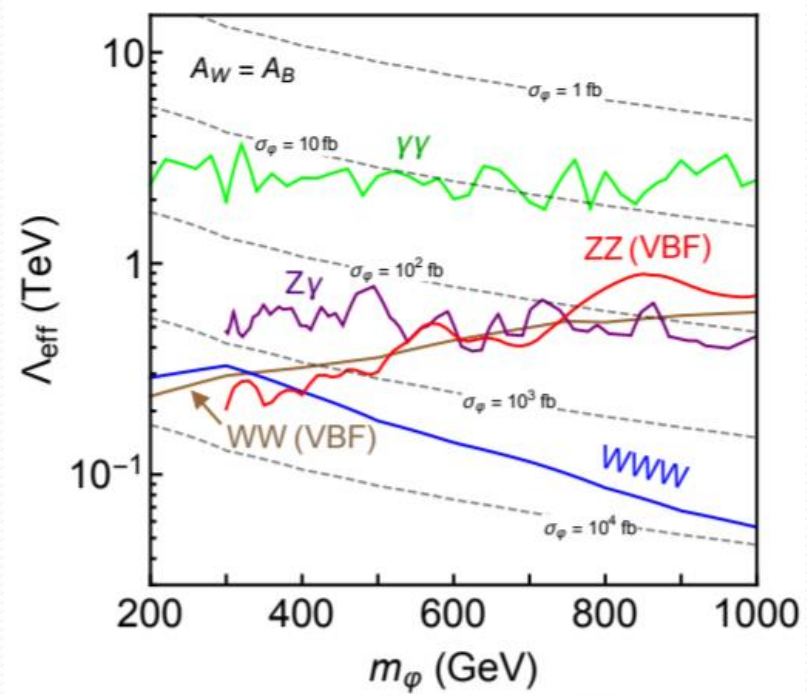


Figure 2: Bounds on tensor-type coupling of scalar to SM EW gauge bosons in the $m_\varphi - \Lambda_{\rm eff}$ plane. Five relevant searches are shown: ATLAS diphoton (green), ATLAS diboson WW (VBF, fully leptonic, in brown), ATLAS diboson ZZ (VBF, $\ell\ell qq + \nu\nu qq$ in red), CMS $Z\gamma$ (leptonic, in purple), and ATLAS triboson WWW (blue). Regions below the solid lines are excluded by the corresponding experiments. The dashed lines show the scalar production cross section $\sigma(pp \to \varphi)$ (sum of both VBF and associated production). For ZZ and $Z\gamma$, results are shown only down to 300 GeV because relevant experimental search results are reported only to that point.

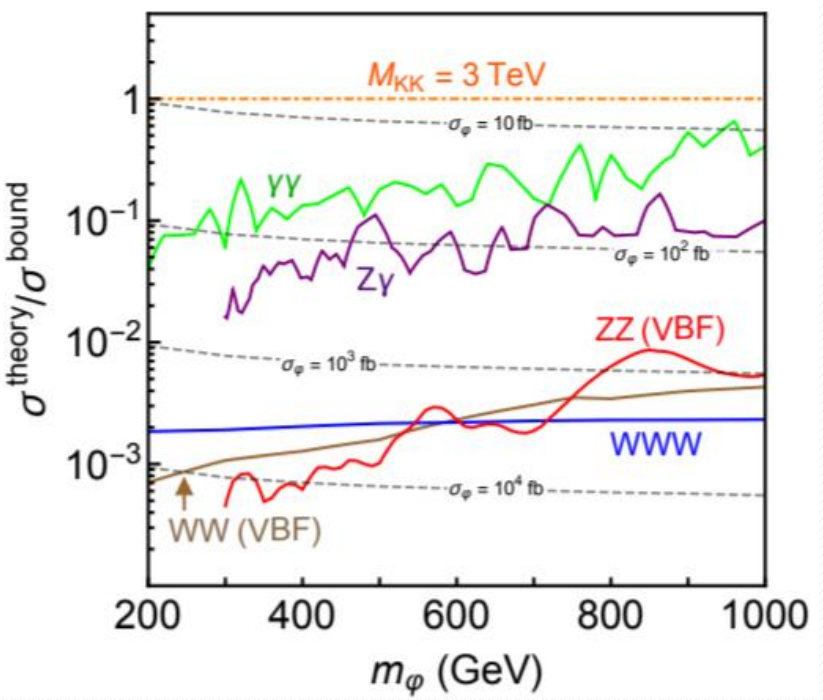


Figure 10: The ratio of cross section predicted by the warped model to the experimental bounds as a function of m_φ. Five relevant searches are shown: ATLAS diphoton (green), ATLAS diboson WW (fully leptonic, in brown), ATLAS diboson ZZ ($\ell\ell qq + \nu\nu qq$ in red), CMS $Z\gamma$ (leptonic, in purple), and ATLAS triboson WWW (blue). Regions below the solid lines are excluded by the corresponding experiments. The dashed lines show the scalar/radion production cross section $\sigma(pp \to \varphi)$, sum of both VBF and associated production. For ZZ (red) and $Z\gamma$ (purple), results are shown only down to 300 GeV because relevant experimental search results are reported only to that point. The orange dashed dot line indicates our benchmark point with $m_{\rm KK} = 3$ TeV.

Model III: Existing Bounds on Heavy Resonances