DEPARTMENT OF
PHYSICS

Signals of KK graviton from extended warped extra dimensions at the LHC (I)

Majid Ekhterachian

University of Maryland, College Park

ekhtera@umd.edu

In collaboration with Kaustubh Agashe, Doojin Kim, and Deepak Sathyan

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Outline

- Introduction
- Extended warped model
  - KK graviton, KK gluon, radion
  - Couplings
- KK graviton signal channels:
  - Antler topology
  - Sequential- cascade
- Details of analysis in Deepak Sathyan's talk
- Summary

Composite Higgs

- Framework of composite Higgs strongly motivated as it can generate large hierarchies observed.
- In these models Higgs is a confined composite state of strong dynamics at or above the TeV scale.
- But difficult to analyze/model, because of strong coupling.
- Holographic duality provides a weakly coupled geometric dual description.

Composite Higgs ⟷ Warped extra dimension

Holography

- Solves the (Planck weak) hierarchy problem

Randall & Sundrum 1999

$$\frac{v}{M_{Pl}} \sim e^{-kX_5}$$

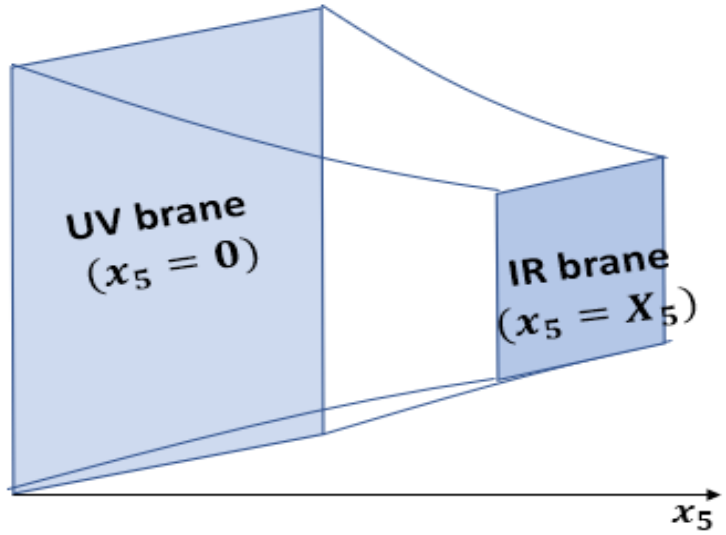
Planck-weak hierarchy obtained with $kX_5 \sim 30$

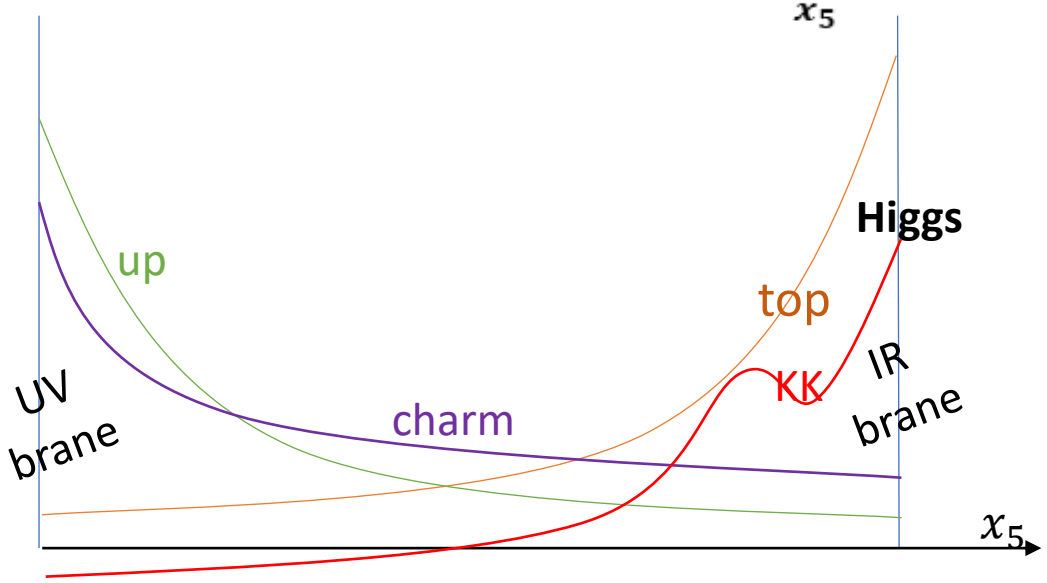
- Flavor hierarchy: 4D hierarchy from 5D anarchy

Grossman & Neubert 1999
Gherghetta & Pomarol 2000

Profile of zero-mode fermion $\sim e^{ck\,x_5}$

- 4D couplings ∝ overlap of profiles





Warped extra dimension- Current status

- No new physics signals at LHC so far
- Bounds from electroweak precision tests (with custodial symmetry): $M_{KK} \gtrsim 3\ \mathrm{TeV}$

Carena et al 2006
Delaunay et al 2010

- Flavor/CP violation bounds on generic new physics scale

$$\gtrsim 10^5 \mathrm{TeV}$$

- But much weaker with RS-GIM mechanism,

$$M_{KK} \gtrsim O(10's)\ \mathrm{of\ TeV}$$

Gherghetta & Pomarol 2000;
Huber & Shafi 2000; Huber 2003
Agashe, Perez, Soni 2004

- Possible that the hierarchy problem is solved (imperfectly) at $\gtrsim 10\ \mathrm{TeV}$ by composite Higgs, leaving a little hierarchy problem.
- With such a scale for new strong dynamics, flavor bounds can be avoided
- *No on-shell production at the LHC?*
- Can there be (flavor-safe) remnants of the strong dynamic surviving to $\sim$ TeV scale?

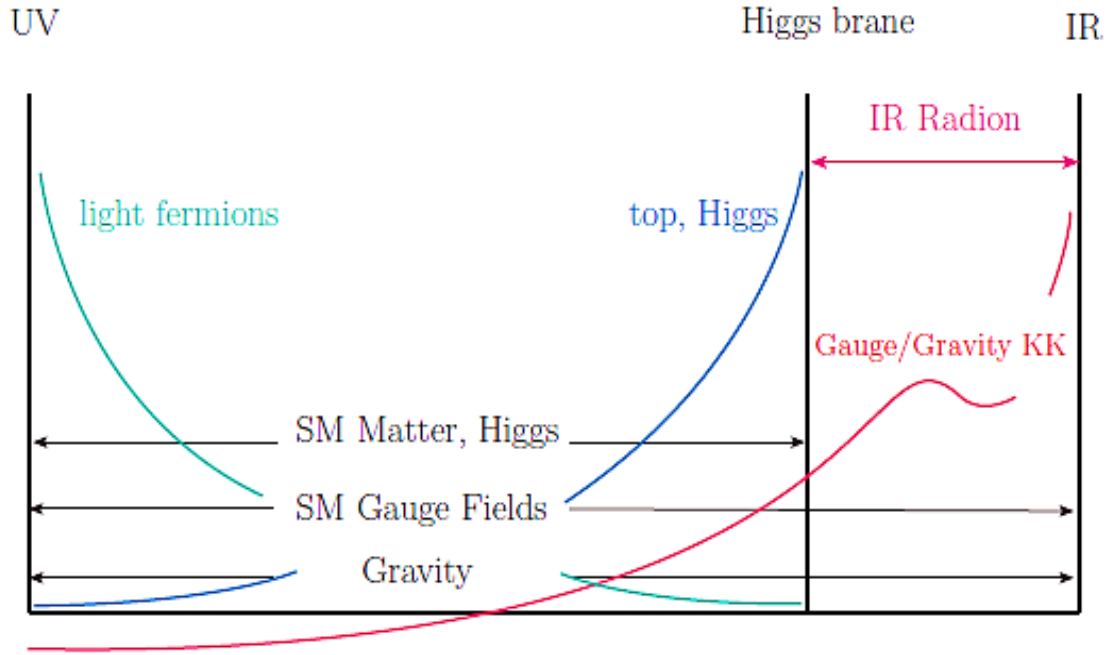
  Vestiges of naturalness, a preview of solution to the hierarchy problem
- Extended warped model

Agashe, Du, Hong, Sundrum 2016

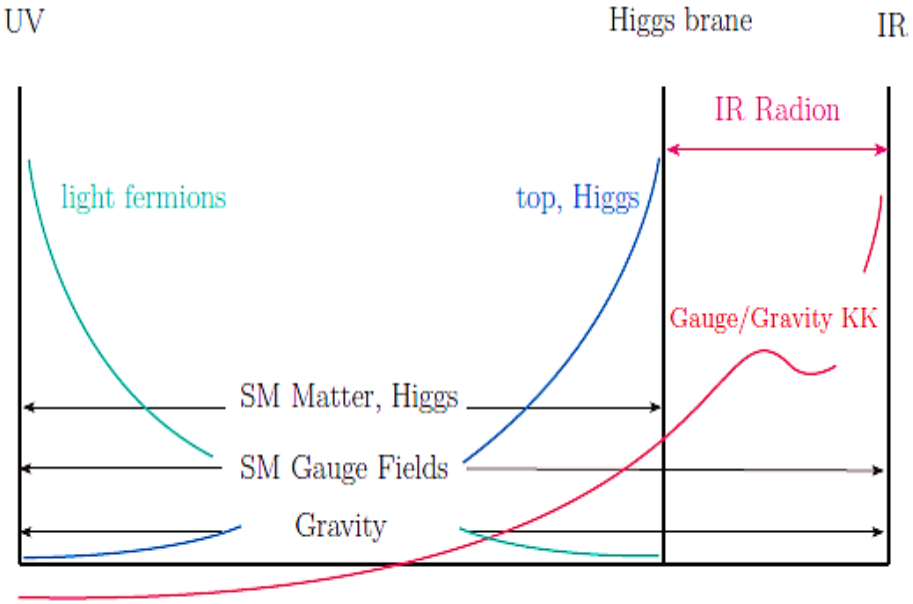
Extended Warped Model

Agashe, Du, Hong, Sundrum 2016

- An intermediate $\gtrsim 10$ TeV brane (Higgs brane)
- Fermions propagate only between the UV and the intermediate brane
  - ✓Electroweak precision and flavor/ CP violation bounds avoided
- Gauge bosons and gravity propagate in all of the bulk
  - ✓KK graviton and KK gauge bosons can still be produced at LHC energies



Lightest BSM particles



- **Radion** Two radions here, corresponding to the two brane separations.

  IR radion expected to be the lightest BSM particle.

  Decays dominantly to gluon pairs (usual decay modes to final states with H, t suppressed, due to sequestering of profiles)

KK gauge bosons LHC signals from resonant production of KK gauge bosons have been studied. Agashe, Collins, Du, Hong & Kim 2016, 2017 & 2018

Decay dominantly to a SM gauge boson and radion (usual decay modes suppressed).

KK graviton Signals from KK graviton production and decay:

- Different spin, different final states and new topologies

(In the standard scenario KK Gr, KK gauge decay to similar final states)

- The hallmark of warped extra dimension

Couplings and parameters

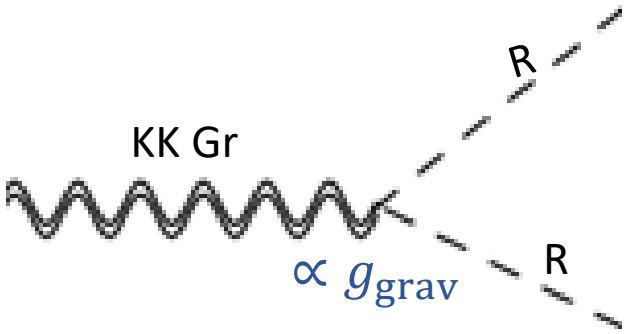
- Three parameters (in addition to masses and SM couplings):

$$g_{\text{grav}},\ g_{\text{g}_{\text{KK}}},\ \epsilon$$

g_{grav}

Coupling of 3 composites, one of them spin-2:

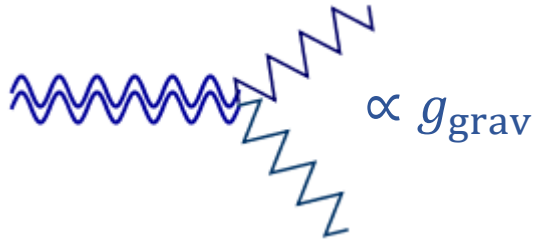
$$g_{\text{grav}} \sim \frac{4\pi}{N} \longleftrightarrow g_{\text{grav}} \sim \sqrt{\frac{k^3}{M_5^3}}$$



Coupling of KK graviton to two radions:

$$\sim \frac{g_{\text{grav}}}{M_{\text{KK}}} H^{\mu\nu} T_{\mu\nu}^{(Rad)}$$

Similarly, coupling of KK graviton to two composite vector mesons:



Couplings and parameters

- Coupling of composite vector meson to two composite fermions:

$g_{g_{KK}}$

$$g_{g_{KK}} \leftrightarrow g_5\sqrt{k}$$

Sets the mixing between composite vector meson and elementary gauge boson: $\sin_{\theta_{mixing}} \approx \frac{g_{SM}}{g_{g_{KK}}}$

$\propto \frac{g_{SM}}{g_{g_{KK}}}$

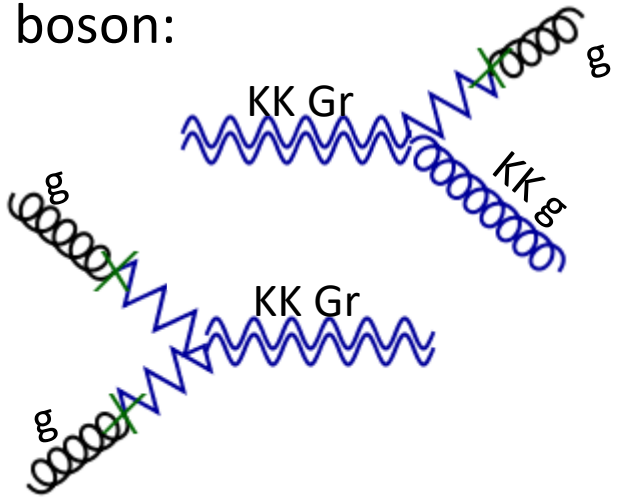
SM gauge boson admixture of elementary (mostly) and composite

- Coupling of KK graviton to a KK gauge boson and a SM gauge boson:

$$\propto \frac{g_{\text{grav}}}{M_{KK}} \frac{g_{\text{SM}}}{g_{g_{KK}}}$$

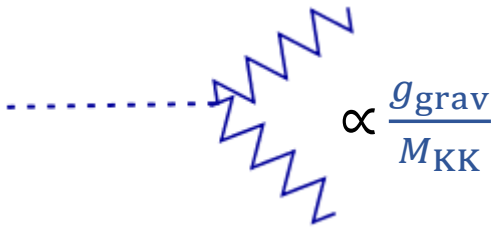
- KK graviton to two SM gauge bosons: $\propto \frac{g_{\text{grav}}}{M_{KK}} \left(\frac{g_{SM}}{g_{g_{KK}}}\right)^2$

KK graviton production



Couplings and parameters

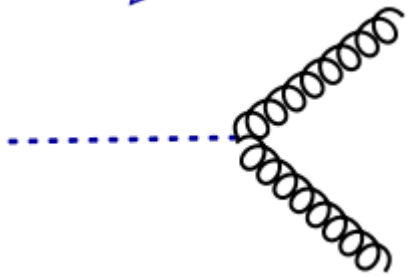
- Coupling of radion to two composite vector mesons



$$\propto \frac{g_{\text{grav}}}{M_{\text{KK}}}$$

- Coupling of radion to two SM gauge bosons:

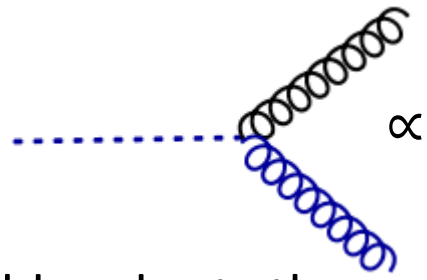
$$\sim -\frac{1}{4} g_{grav} \left(\frac{g_{SM}}{g_{g_{KK}}}\right)^2 F^a_{\mu\nu} F^{a\,\mu\nu} \frac{R}{m_{KK}}$$



$$\propto \frac{g_{\text{grav}}}{M_{\text{KK}}} \left(\frac{g_{SM}}{g_{g_{KK}}}\right)^2$$

- Coupling of radion to a KK gauge boson and a SM gauge boson:

$$\sim \epsilon\, g_{grav} \frac{g_{SM}}{g_{g_{KK}}} F^a_{\mu\nu} F^{a\,\mu\nu}_{\text{KK}} \frac{R}{m_{KK}}$$



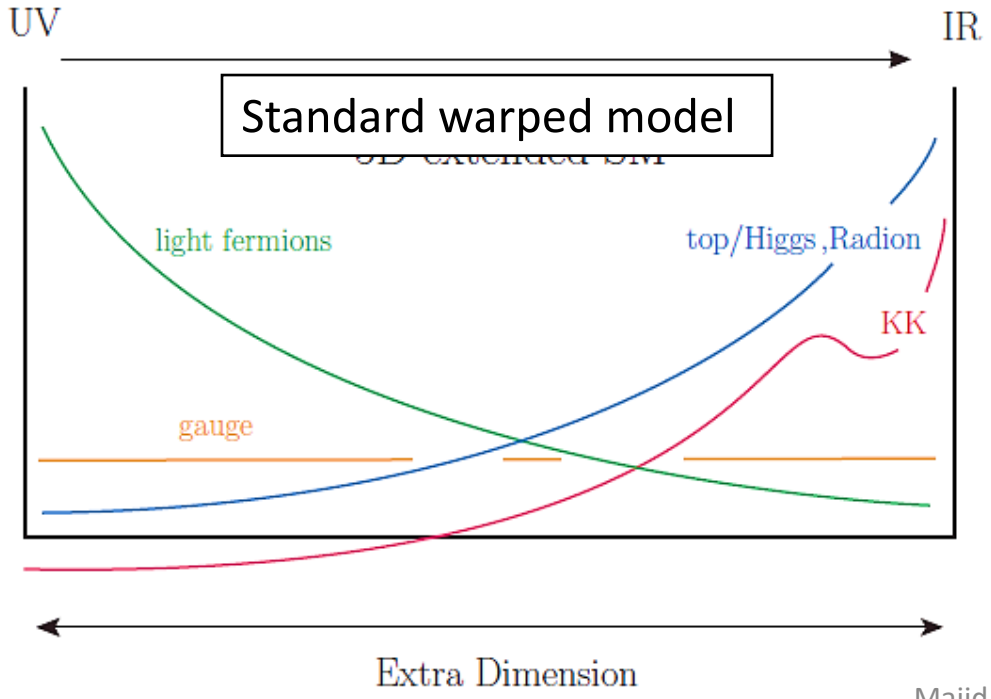
$$\propto \epsilon \frac{g_{\text{grav}}}{M_{\text{KK}}} \frac{g_{SM}}{g_{g_{KK}}}$$

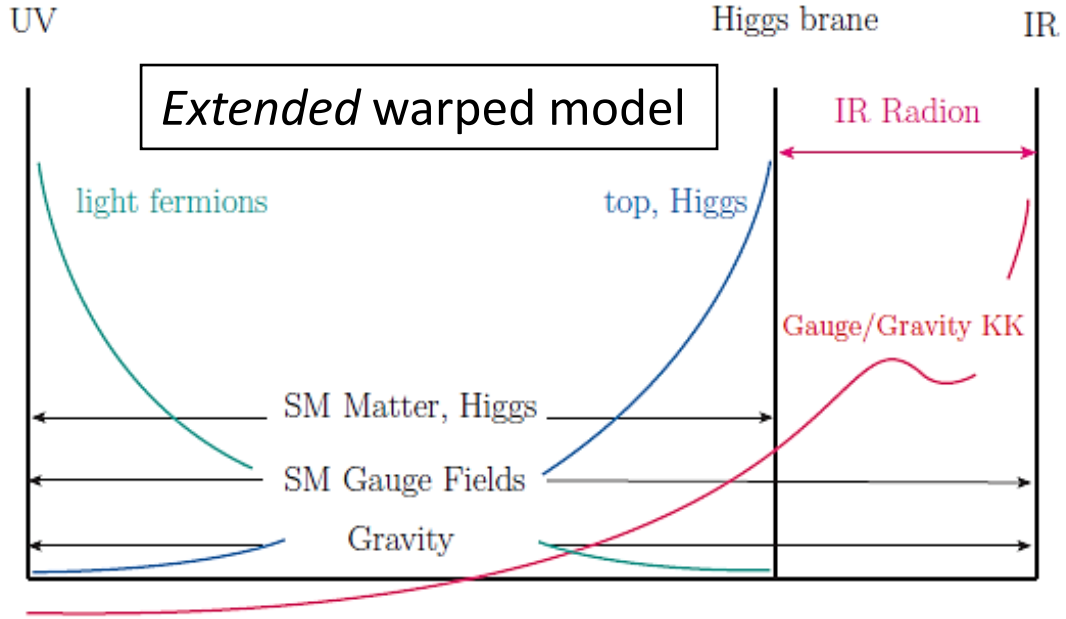
ϵ

- ϵ related to the parameters of stabilizing (Goldberger-Wise) field and sets the separation between the Higgs and the IR brane: $\ln \frac{\Lambda_{\text{Higgs}}}{\Lambda_{\text{IR}}} \sim \frac{1}{\epsilon}$

KK graviton decay channels

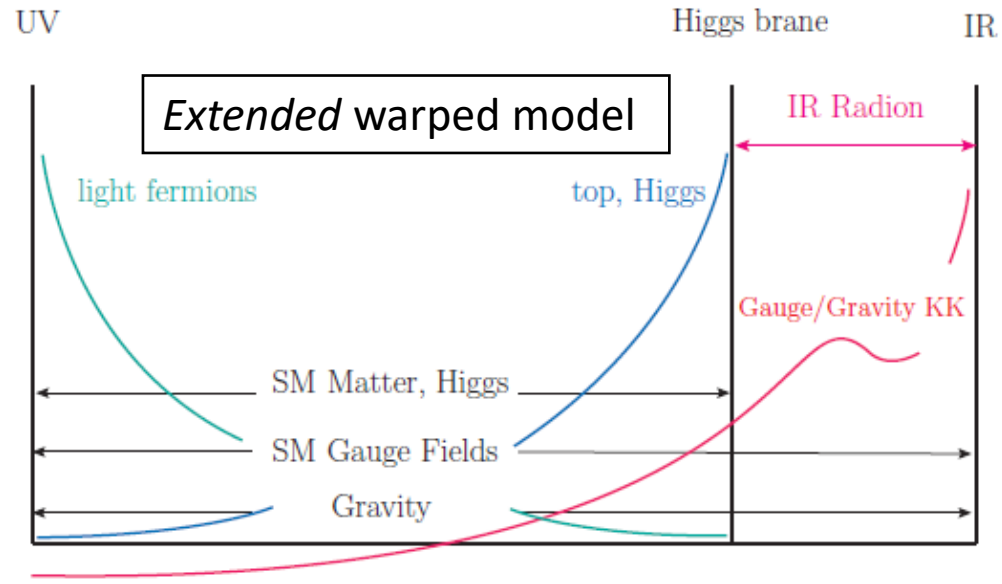
- In the standard scenario, decays dominantly to top Higgs and longitudinal W and Z.
- These channels are suppressed in the extended model, letting new channels (that have not been searched for) shine.

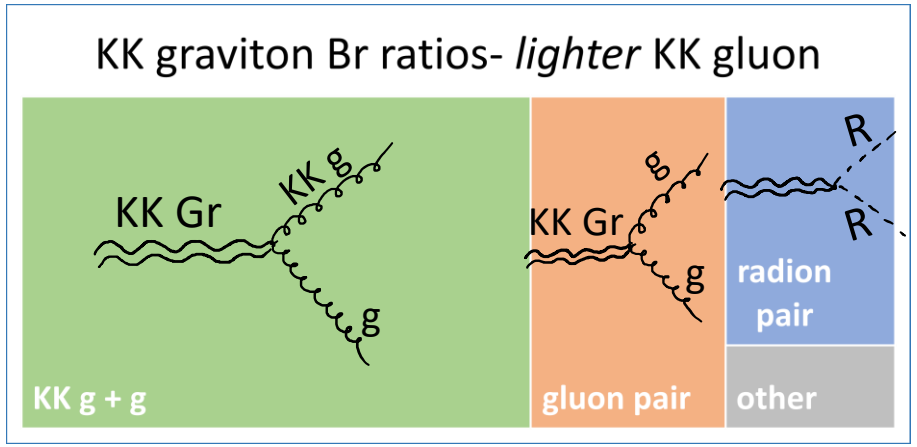


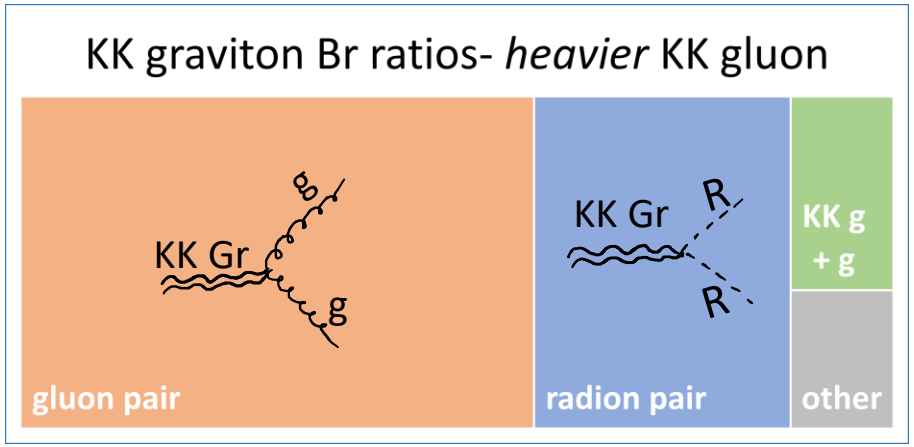


KK graviton decay channels

- In the standard scenario, decays dominantly to top, Higgs and longitudinal W and Z.
- These channels are suppressed in the extended model, letting new channels to shine.
- Main decay channels:



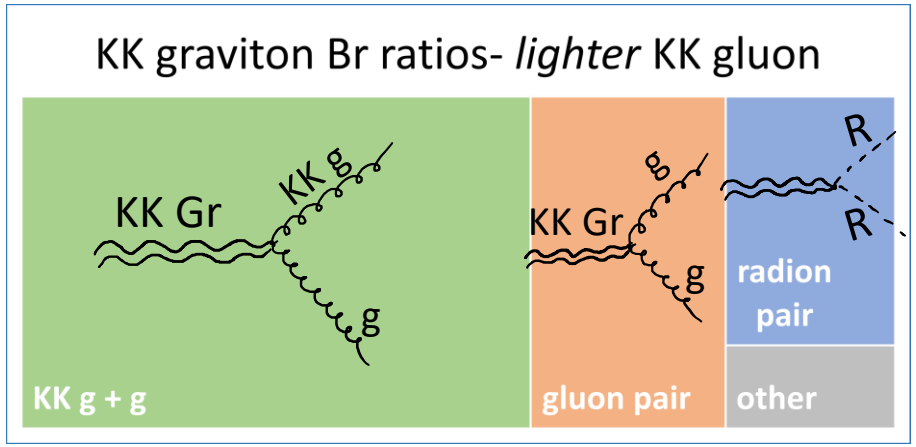


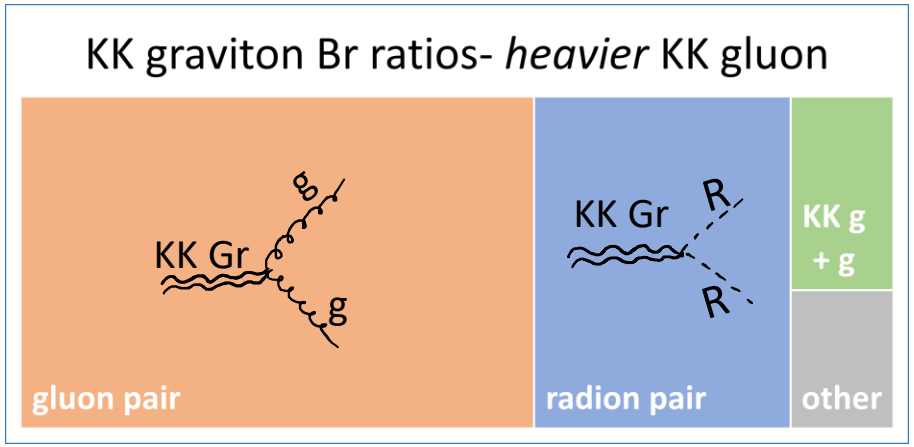


KK graviton signals

- Decay to gluon pair: dijet resonance, are looked for in the standard searches
- The two other main decay channels result in 4 jet signal with topologies that have not been searched for

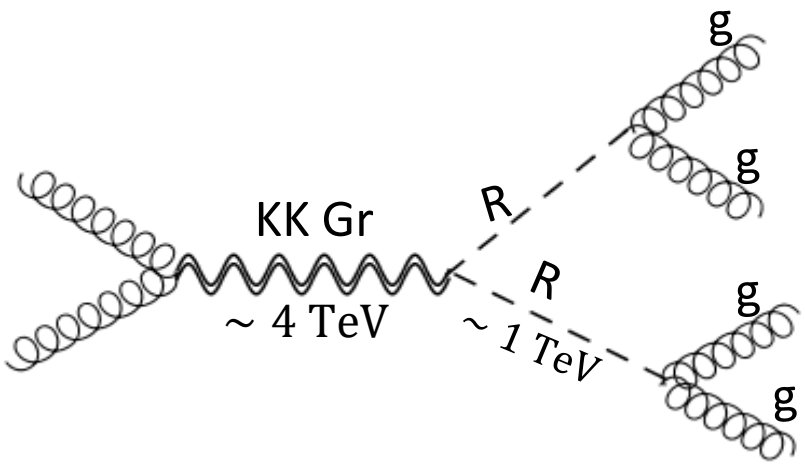
  Can have better sensitivity than standard dijet searches





Antler topology

- KK gluon decays to a pair of radions
- Each radion decays to two gluon jets
- A 4-jet resonance containing a symmetric pair of distinct dijet resonances
- Additionally, angular distribution of reconstructed dijet resonances can be used to increase sensitivity and distinguish spin 2 of KK graviton



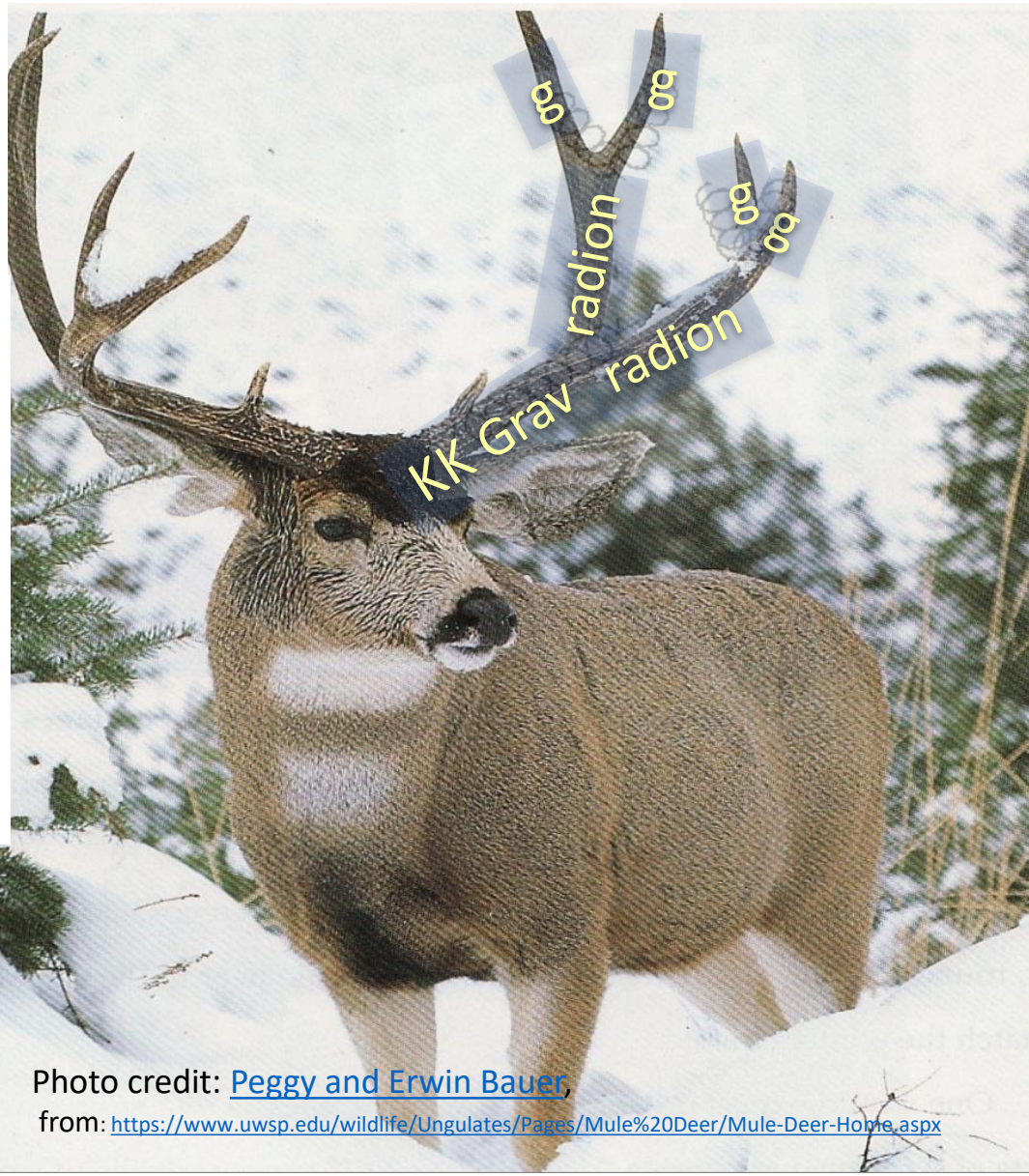


Photo credit: Peggy and Erwin Bauer,
from: https://www.uwsp.edu/wildlife/Ungulates/Pages/Mule%20Deer/Mule-Deer-Home.aspx

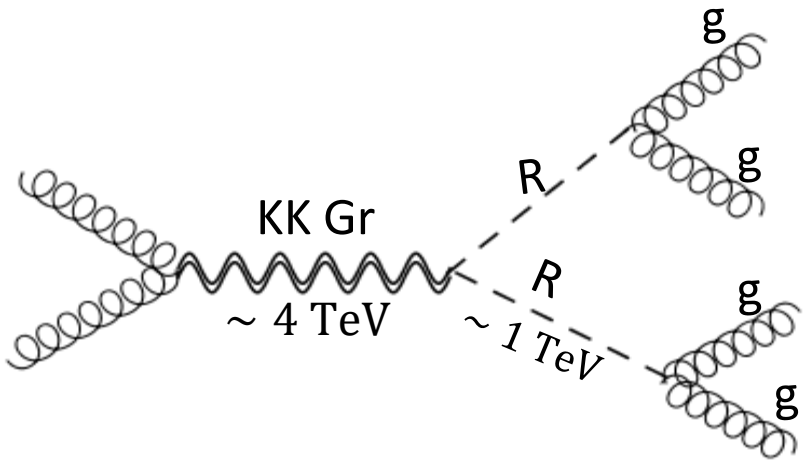
The name antler for this topology have been used in Han, Kim & Song 2009

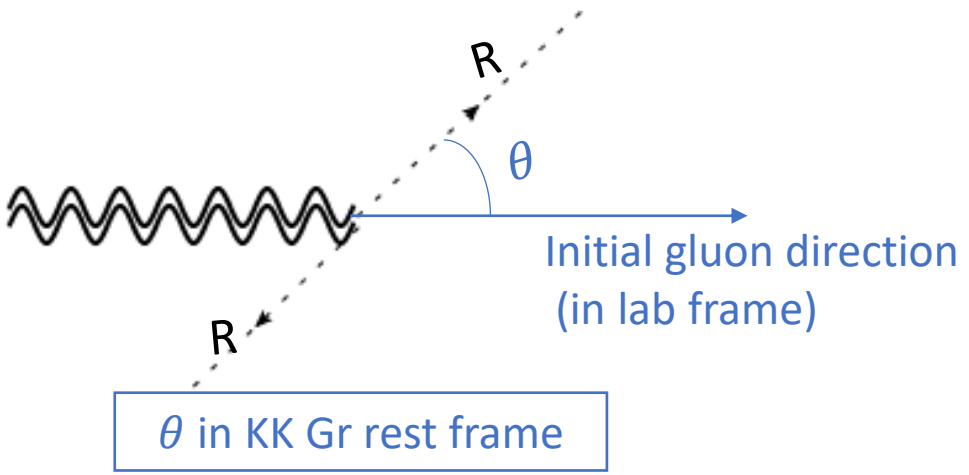
Antler topology

- KK gluon decays to a pair of radions, each radion decays to two gluon jets
- A 4-jet resonance containing a symmetric pair of distinct dijet resonances
- Additionally, angular distribution of reconstructed dijet resonances can be used to increase sensitivity and distinguish spin 2 of KK graviton

$$\frac{d\sigma}{d\cos\theta} \propto \sin^2\theta$$

- For one of benchmarks can increase the significance from $\geq 3\sigma$ to $\geq 5\sigma$

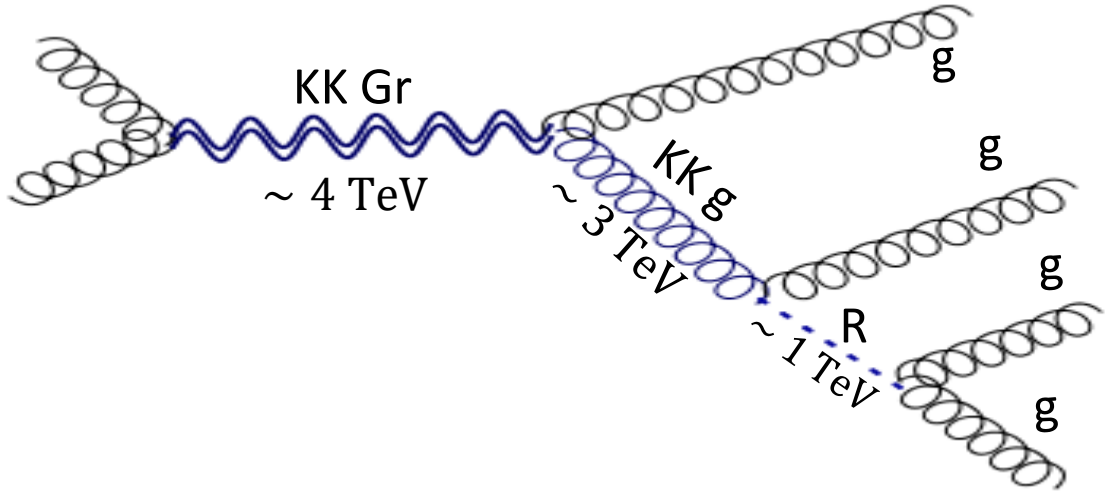


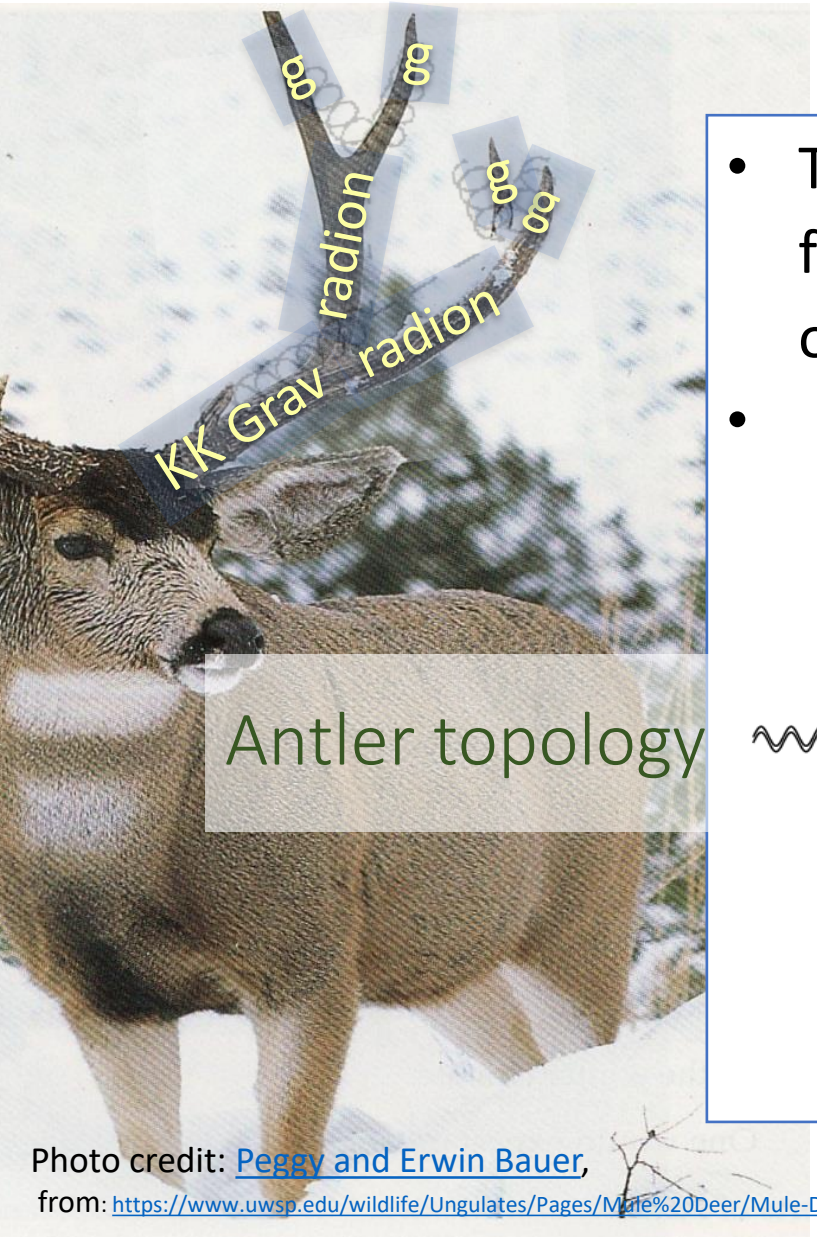


Sequential-cascade topology

- Hierarchical resonances:

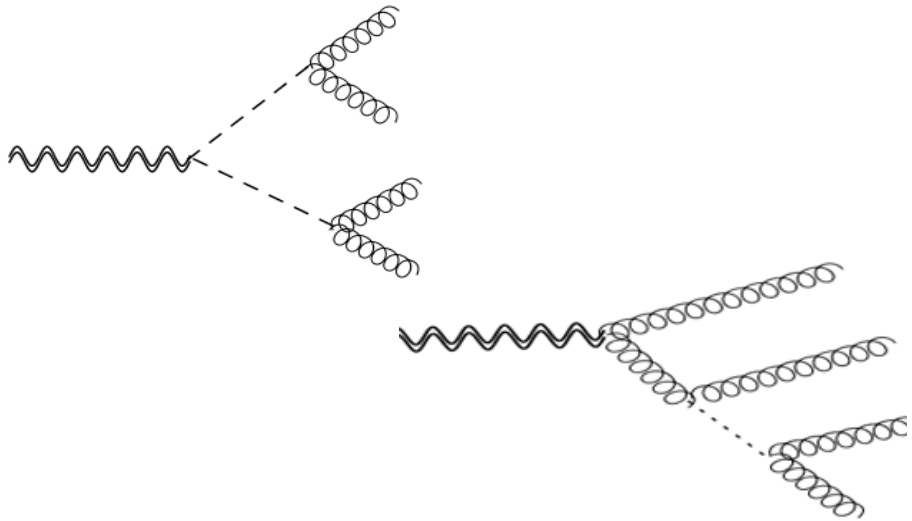
  An overall 4 jet resonance (KK graviton), containing a tri-jet resonance (KK gluon) and that containing a dijet resonance (radion)

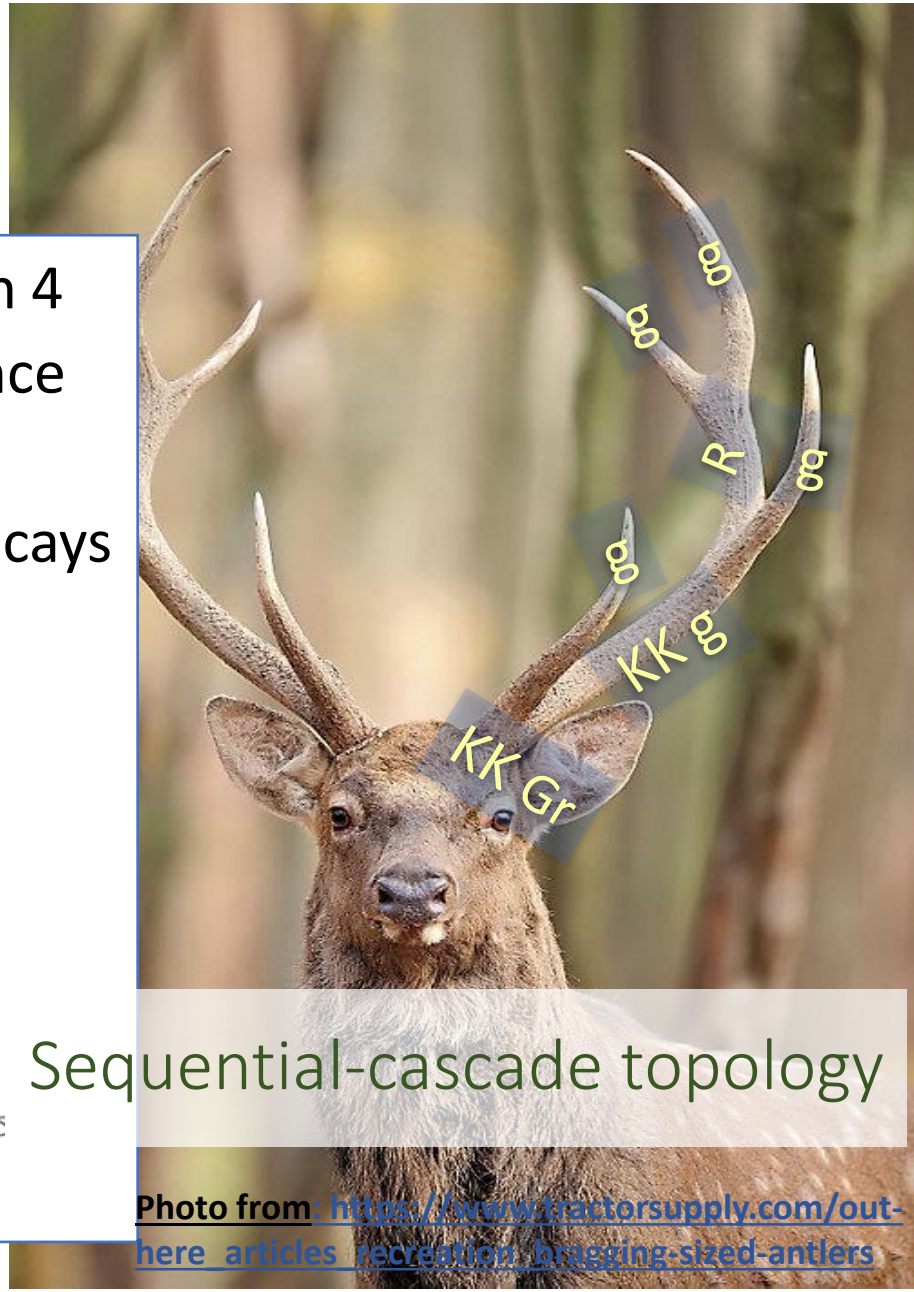




Antler topology

- The only possible topologies with 4 final states arising from a sequence of $1 \rightarrow 2$ resonant decays
- Both arising from KK graviton decays





Sequential-cascade topology

Photo credit: Peggy and Erwin Bauer, from: https://www.uwsp.edu/wildlife/Ungulates/Pages/Mule%20Deer/Mule-Deer-Home.aspx

Photo from: https://www.tractorsupply.com/out-here_articles_recreation_bragging-sized-antlers

KK graviton signals

- For heavier KK gluon, channel with antler topology dominates

  (for example: $M_{\mathrm{KK\,gr}} = 4\ \mathrm{TeV}$, $M_{\mathrm{KK\,gluon}} = 3.7\ \mathrm{TeV}$, $m_{\mathrm{radion}} = 1\ \mathrm{TeV}$)

- For lighter KK gluon, contribution of two channels are comparable

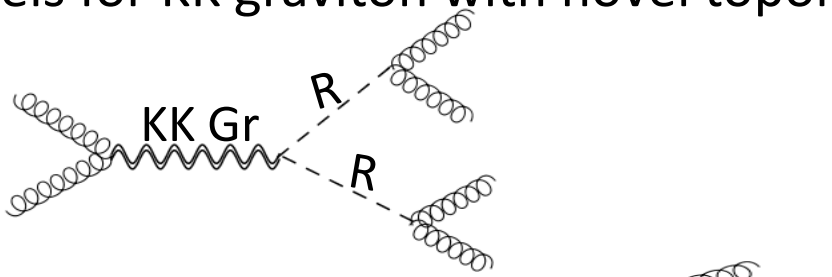
  (for example: $M_{\mathrm{KK\,gr}} = 4\ \mathrm{TeV}$, $M_{\mathrm{KK\,gluon}} = 3\ \mathrm{TeV}$, $m_{\mathrm{radion}} = 1\ \mathrm{TeV}$)

- Can get 5σ significance at HL-LHC with $3000\ \mathrm{fb}^{-1}$ luminosity and $14\ \mathrm{TeV}$ CM energy, in some region of parameter space for both cases
- Better sensitivity than the standard dijet resonance search
- See the next talk by Deepak Sathyan for details of analysis.

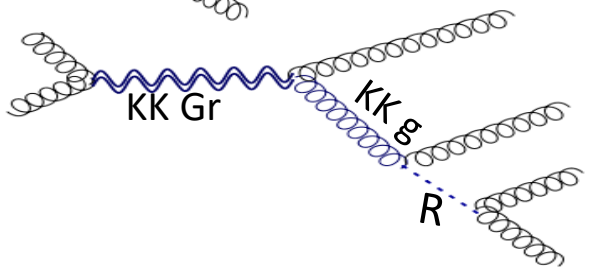
Summary

- Extended warped model safe from flavor and EW precision bounds while still accessible at the LHC.
- Two 4-jet signal channels for KK graviton with novel topologies:

Antler



Sequential cascade:



- Can be the discovery channels for KK graviton at HL-LHC, motivating new dedicated searches for these topologies.

Thank you!