(Generalized)Tri-Boson Signals from BSM

Kaustubh Agashe (University of Maryland)

[Based on KA, Du, Hong, Sundrum (1608.00526): theory;
KA, Collins, Du, Hong, Kim, Mishra (1612.00047, 1711.09920
and 1809.07334) and KA, Ekhterachian, Kim, Sathyan (2008.06480): LHC signals]

Introduction

- (Direct) Searches for new physics (NP) at LHC in full gear/reached maturity

- lack of signals for NP so far

- To some extent, focussed on “minimal” version of extension of SM (whether SUSY or extra dimensions etc.)

Introduction (continued)

- Given above situation, searching for non-standard signals motivated

- in fact, sometimes simple modification of minimal incarnation of framework significantly changes signals (which are perhaps less constrained - than standard ones for same NP mass - thus far due to being “overlooked”, so possibly more visible in future with dedicated searches)

- in this talk, illustrate (in detail) with warped/composite Higgs in (generalized) tri-boson channel; mention others at end

Outline

- Standard warped model: (resonant) di-SM signals
- General extension:
    - Suppression of usual (di-SM) signals
    - Emergence of (generalized) “tri-boson” final states (“doubly”-resonant):

$$\mathrm{BSM}_1 \to \mathrm{BSM}_2 + \mathrm{SM};\ \mathrm{BSM}_2 \to \mathrm{SM}_1 + \mathrm{SM}_2$$

- Specific models/signals: targeted searches needed
- Other models: LR, photophobic axion

"Disclaimer"

- *General/schematic idea and summary of results only: details (plots etc.) in papers*

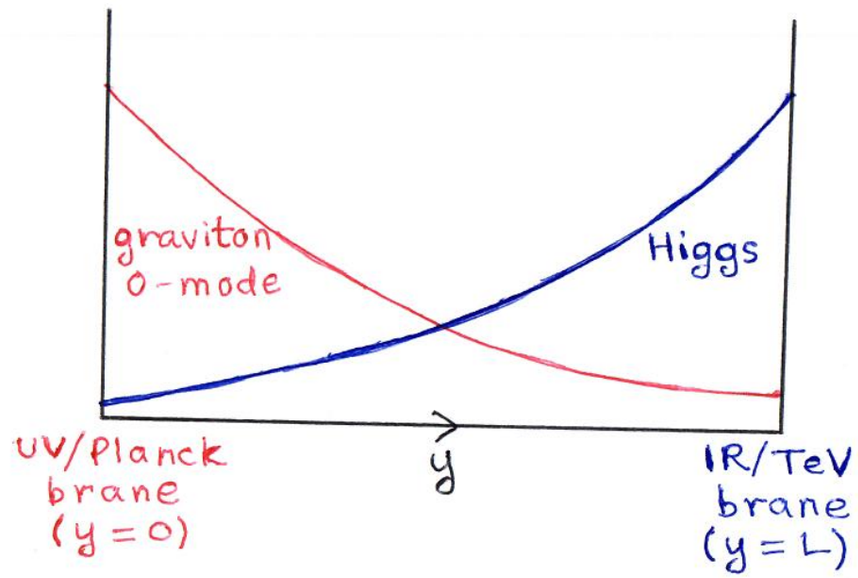
- *contact Peizhi Du (peizhidu@gmail.com) for model files*

Review of standard warped model

[dual to composite Higgs (discuss offline): here use geometrical picture (easier to visualize)]

Planck-weak hierarchy

[Randall, Sundrum (1999)]



- **master formula:** $M_{4\mathrm{D}}^{\mathrm{eff}}(y) \sim e^{-ky} M_{5\mathrm{D}}^{\mathrm{fund}}$

warp factor

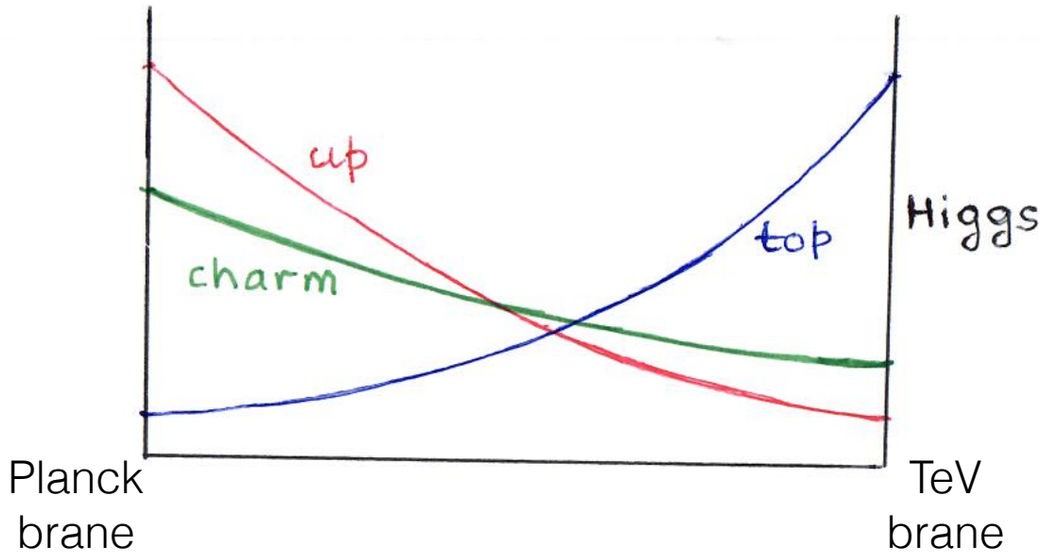
- **RS1:**

4D gravity (zero-mode graviton):
$y \sim 0 \Rightarrow M_{4\mathrm{D}}^{\mathrm{eff}} \sim M_{5\mathrm{D}}^{\mathrm{fund}}$
$\Rightarrow$ choose $M_{5\mathrm{D}}^{\mathrm{fund}} \sim M_{\mathrm{Pl}}$

Weak scale/Higgs mass:
$y \sim L \Rightarrow M_{4\mathrm{D}}^{\mathrm{eff}} \sim e^{-kL} M_{5\mathrm{D}}^{\mathrm{fund}}$
$\Rightarrow$ choose $kL \sim 30$
(*mild* hierarchy, with $k \sim M_{5\mathrm{D}}^{\mathrm{fund}}$)

4D Flavor hierarchy from 5D anarchy

[Grossman, Neubert (1999); Gherghetta, Pomarol (2000)]



SM fermions are zero-modes of 5D fields

- Coupling of modes $\propto$ overlap of profiles (in general)

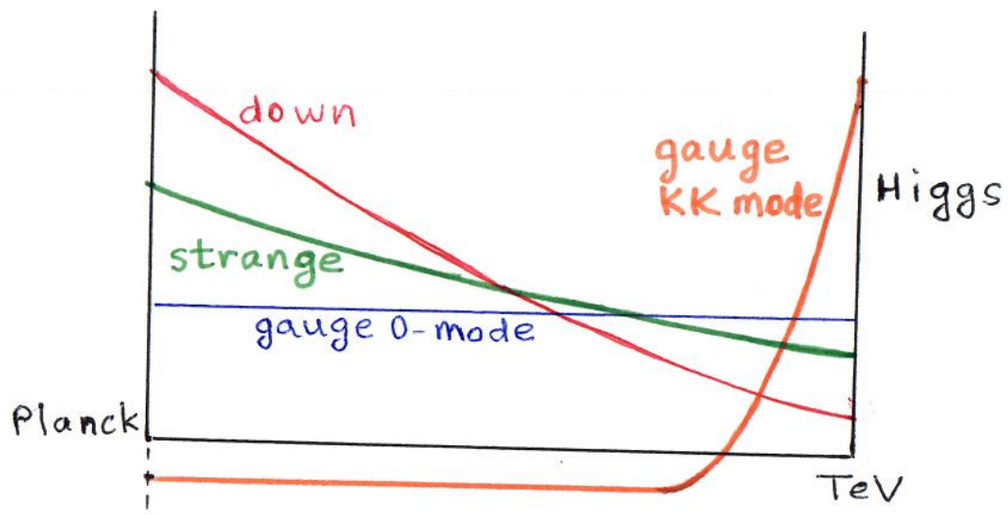
  profile of zero-mode fermion $\propto e^{-cky}$ (ck is 5D mass parameter)

- Small variation in c suffices (5D Yukawa non-hierarchical):

  $c > 1/2$ for up, charm vs. $c < 1/2$ for top

Flavor/CP violation tests

[Gherghetta, Pomarol (2000); Huber, Shafi (2000); Huber (2003); KA, Perez, Soni (2004)]



- SM gauge fields also in bulk
- New particles: Kaluza-Klein (KK) excitations of SM (near TeV brane)
- RS-GIM mechanism (flavor violation from KK $\propto$ quark masses) bound on KK scale (much) weaker than $\sim O(10^5)$ TeV for generic new physics
- still $\sim O(10)$ TeV [Csaki, Falkowski, Weiler (2008); Buras et al. (2008); Bauer et al. (2009)]
- ameliorated by flavor symmetries: a few TeV allowed

EW precision tests

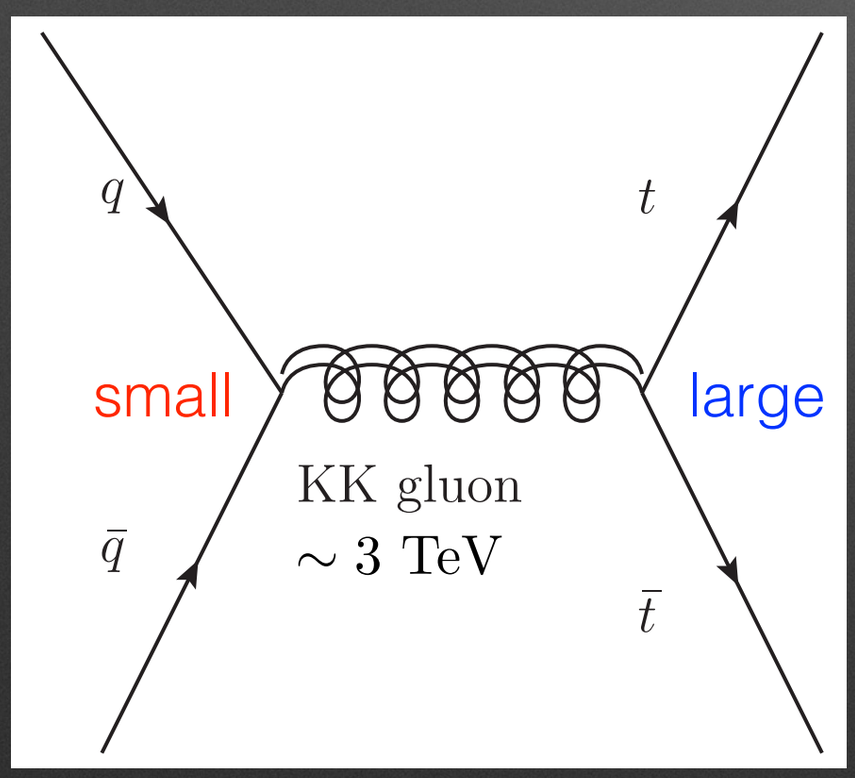
- Vanilla model: KK scale $\sim$ 5-10 TeV (from $\Delta\rho$ and $Zb\bar{b}$)

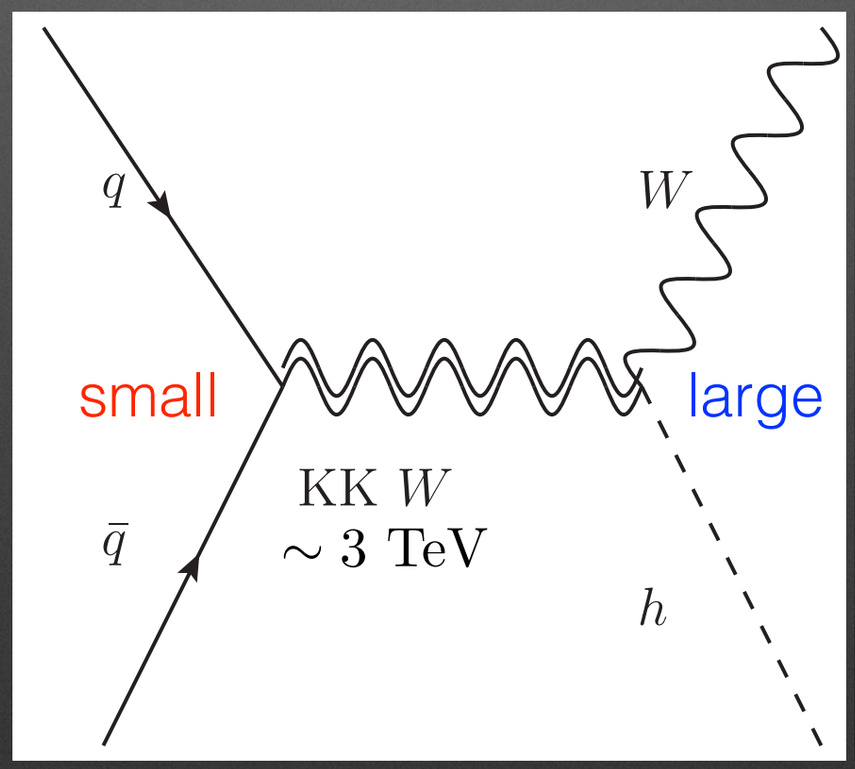
- custodial symmetries [KA, Delgado, May, Sundrum (2003); KA, Contino, Da Rold, Pomarol (2006)] relax it to ~ 3 TeV [Carena et al, (2006); Delaunay et al. (2010)]

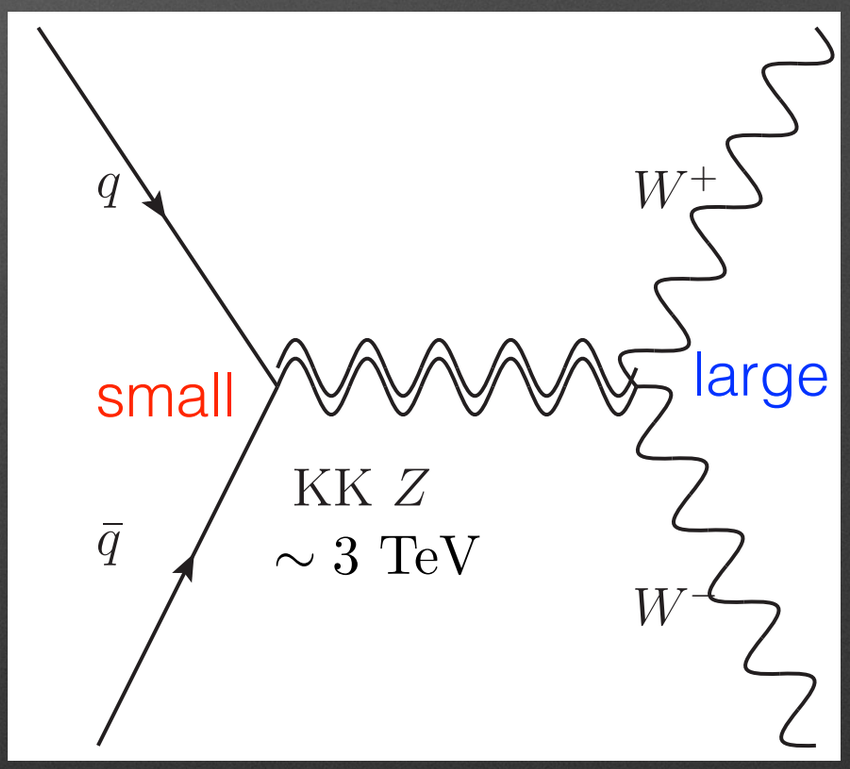
LHC signals (assume a few TeV KK scale for this slide)

- focus on gauge KK signal [for a review, see Davoudiasl, Gopalakrishna, Ponton, Santiago (2009)]

- "nearest neighbor" effect: coupling in production via $q\bar{q}$ small (one mode near TeV brane, other 2 near Planck brane); large for decay into pair of heavy SM, tt (or $W/Z_{\text{long.}}/h$) (all 3 modes near TeV brane) (cf. sequential W'/Z': decay back into $q\bar{q}$ or leptons)







- "classic" search for boosted top/$W/Z_{\text{long.}}/h$, using jet-substructure [for a review, see proceedings of "BOOST" workshops]

What if we take flavor/CP bounds at face value (no symmetries)?!

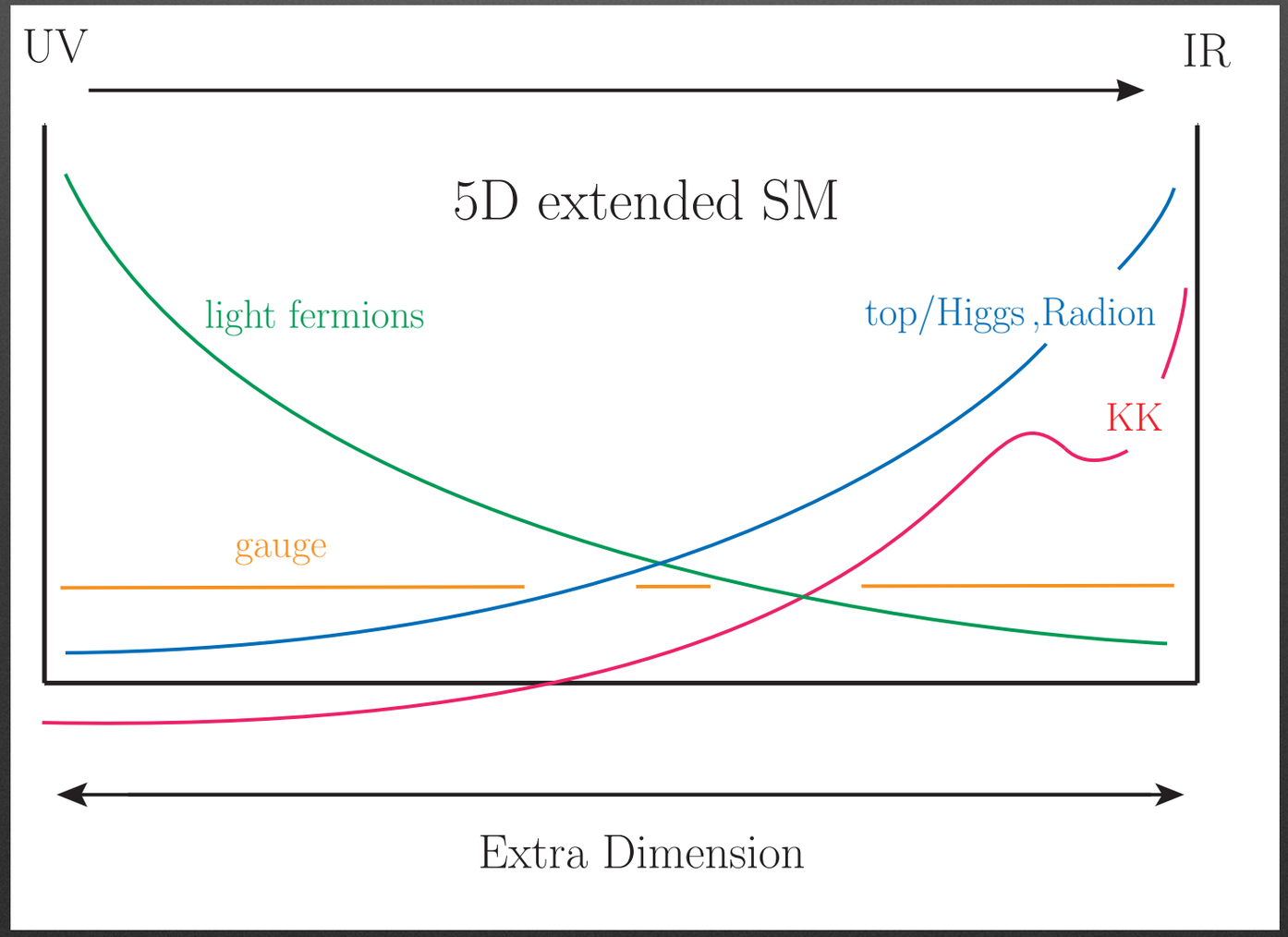
- KK scale $\sim O(10)$TeV → no on-shell production at LHC?! (indirect signals still possible)

- ….maybe not (rest of this talk)!

Standard warped model at a glance (everyone in same bulk, cf. later…)

- Two branes/endpoints

- Radion (fluctuation of size of extra dimension): also localized near TeV brane (like KK/top/Higgs), can be a bit lighter than gauge KK



(...end of review, onto new...)

Simple extension(s)

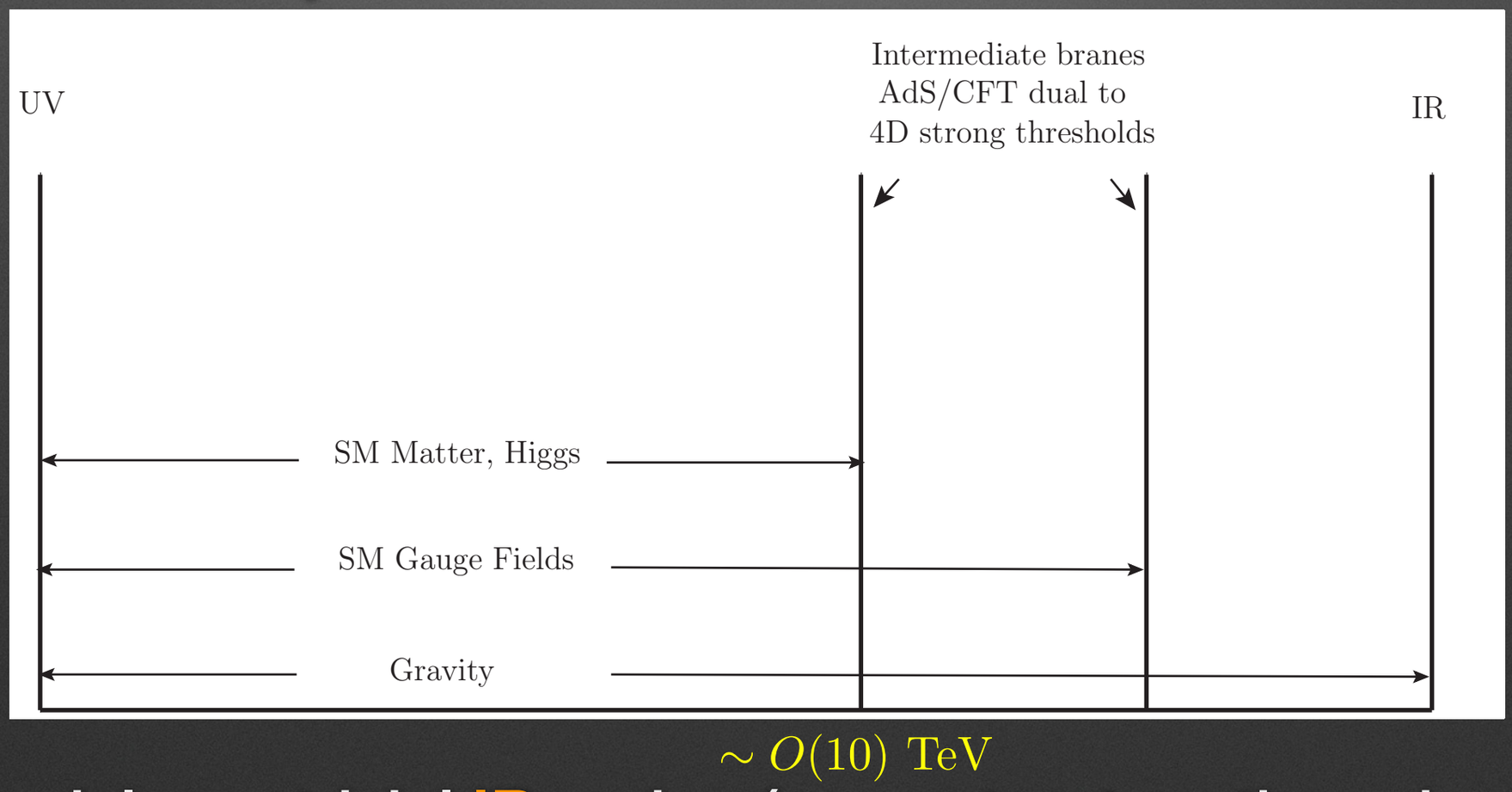
[KA, Du, Hong, Sundrum (2016)]

General framework

- various fields in different, but overlapping "bulk" regions (plausible, reasonable) → more than two branes

- matter/Higgs till $\sim O(10)$ TeV: satisfy flavor/CP

- gauge continue down to a few TeV (see later), gravity (possibly) even lower (another talk!)



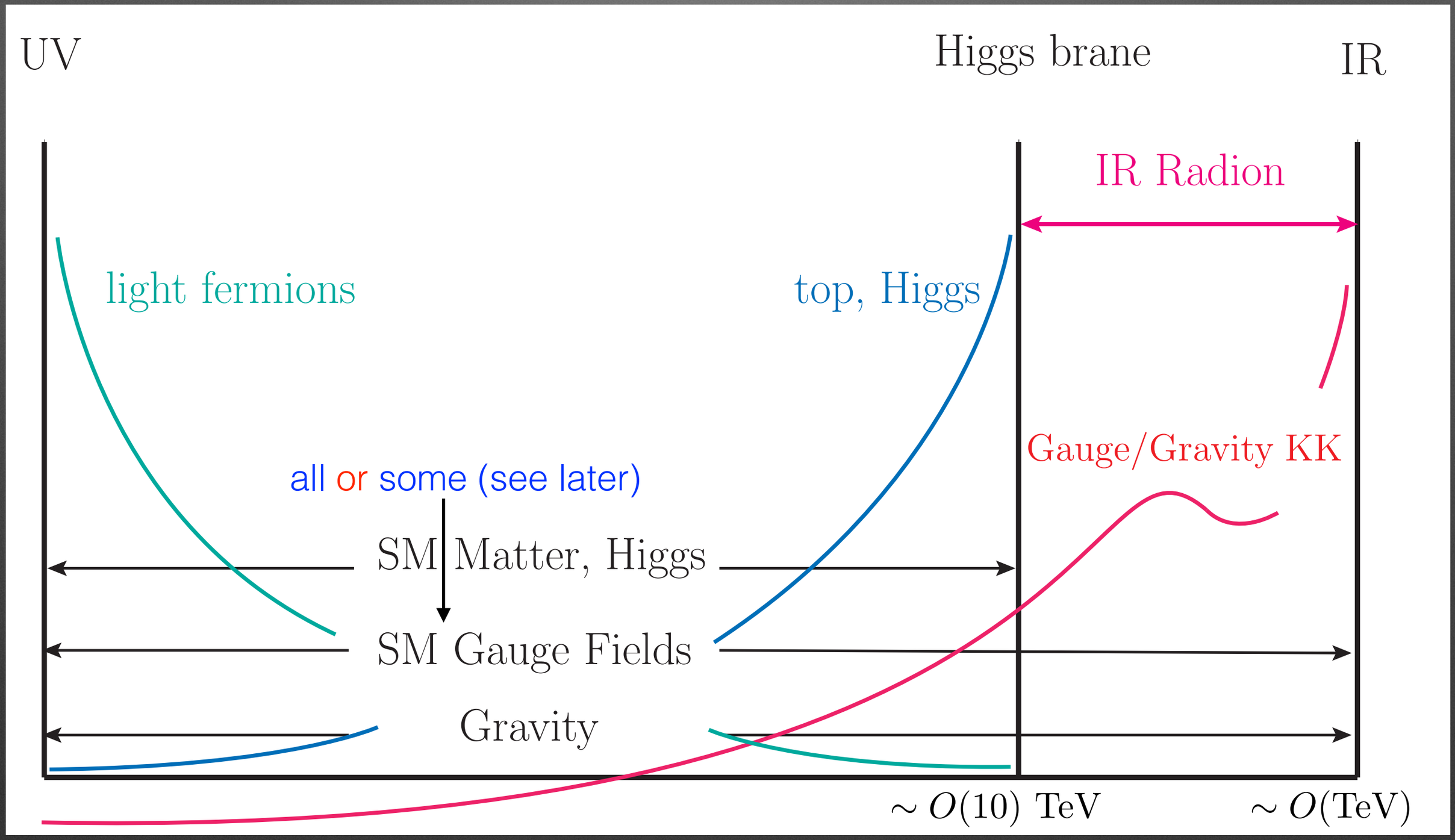
- way to model non-trivial IR region (more structure than simply one, featureless brane)

Treasure chest (opens-up model/signal-building possibilities):

focus here on

LHC signals from gauge KK (as illustration + gives multi-boson signals)

Extended warped model at a glance…



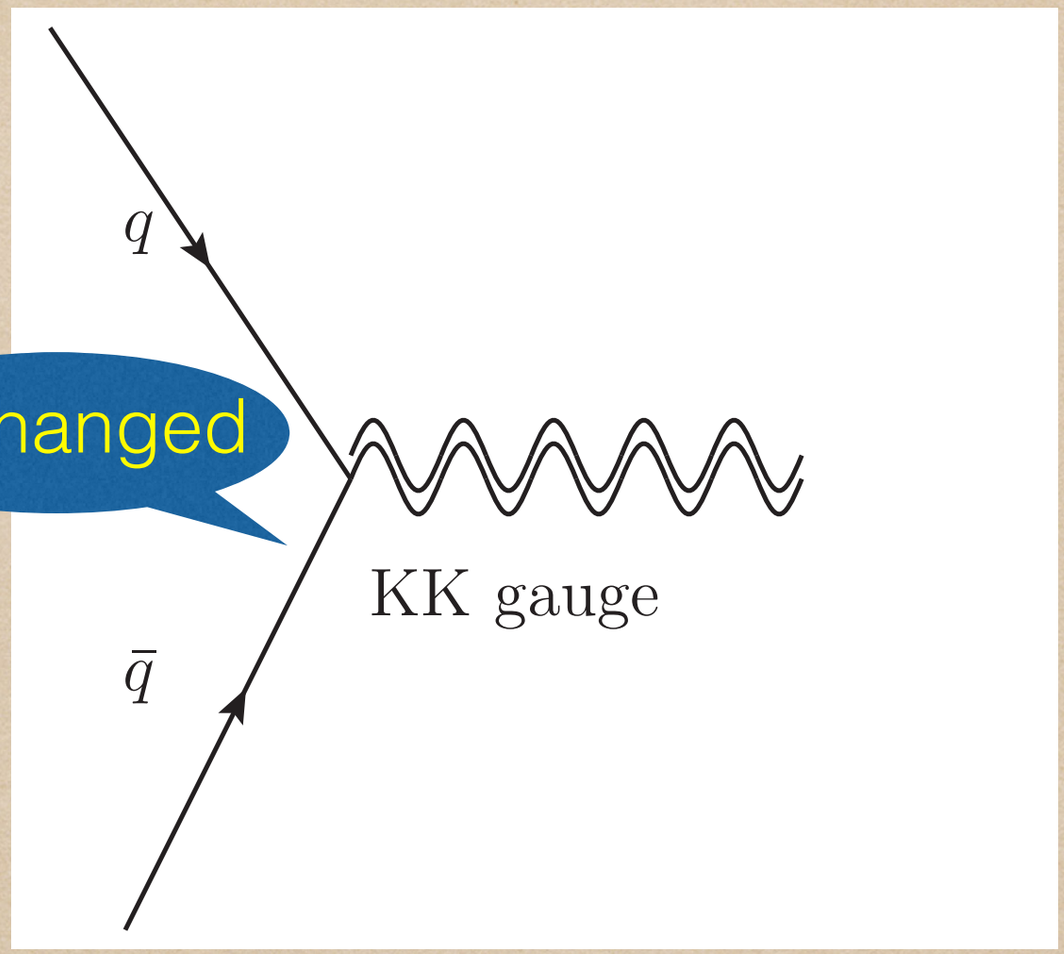
- Gauge fields in entire bulk (same as gravity) for simplicity
- (lightest) gauge KK, radion peak at (final) IR (not Higgs) brane

New (lower) bound on gauge KK scale

- can show flavor/CP/EW precision (indirect) tests safe even for gauge KK $\ll O(10)$ TeV,
  as long as matter/Higgs (most relevant for tests) till $\sim O(10)$ TeV
  [like in standard (two branes) warped model]

- leading bound from direct search at LHC (see next)

Production of gauge KK unchanged

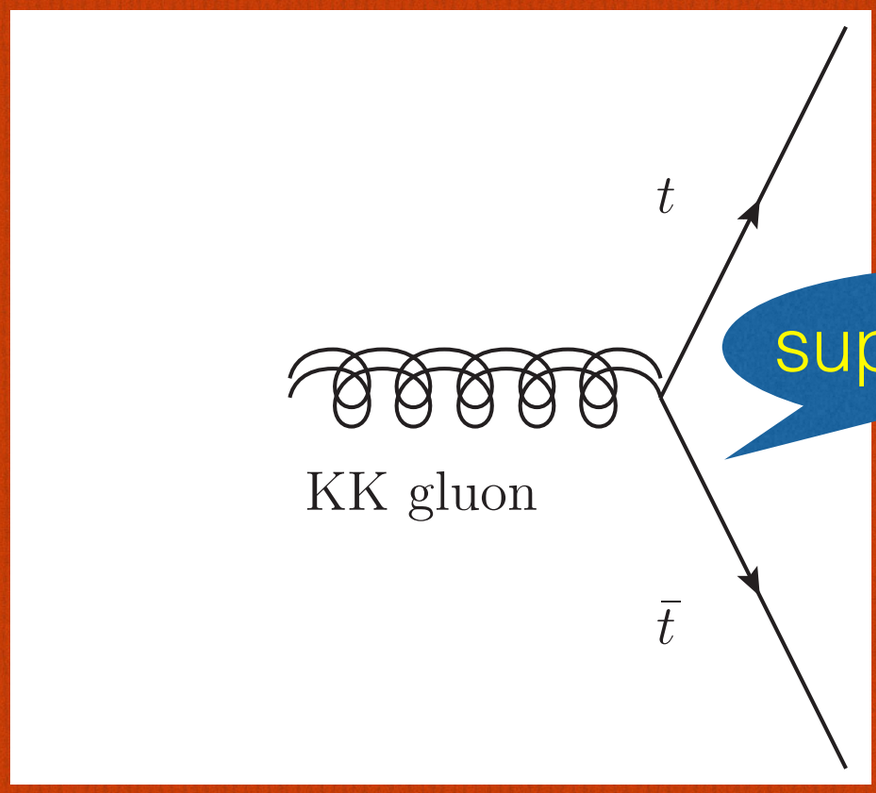


$$\text{coupling} \sim \frac{g_{\text{SM}}^2}{g_{\text{KK}}}, \text{ with } 3 \lesssim g_{\text{KK}} \lesssim 6$$

- No modification near Planck brane (where $q\bar{q}$ live)

Usual dominant decay modes of gauge KK

[$t\bar{t}$ (or $W/Z_{\rm long.}/h$)] suppressed here



all 3 near TeV brane

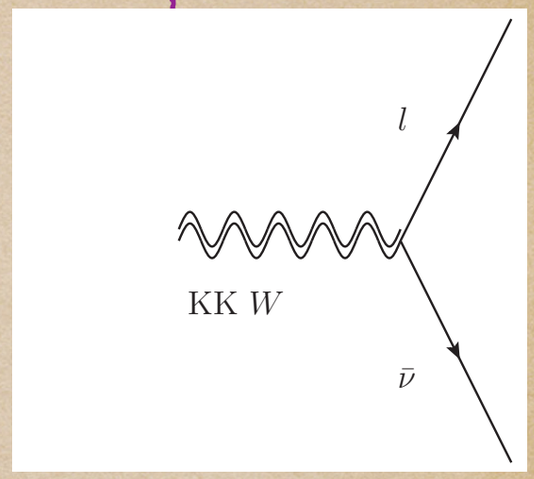
universal

$$\text{coupling} \sim g_{\rm KK}\ (\text{standard}) \to \frac{g^2_{\rm SM}}{g_{\rm KK}}\ (\text{extended}),\ \text{with}\ 3 \lesssim g_{\rm KK} \lesssim 6$$

- due to gauge KK "split" from top/Higgs

Other decay modes can then shine

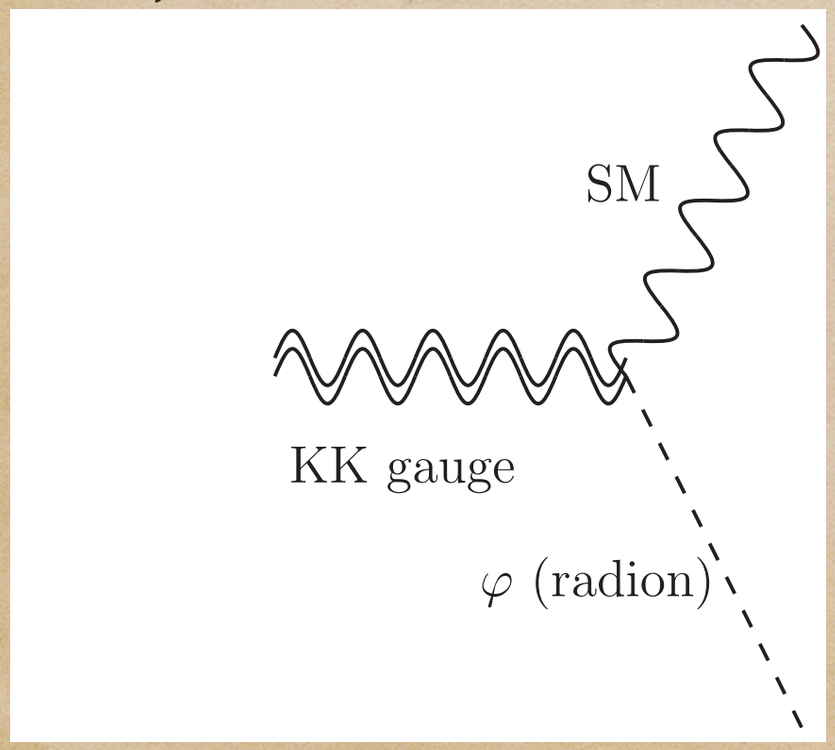
[already existed with same strength, but were swamped earlier (standard ~ 2 branes ~ model)]



- Gauge KK decay back into $q\bar{q}$ (including $t\bar{t}$)/$l\nu$ gives bounds of a few TeV (likely discovery mode)

near TeV brane near TeV brane flat

- Gauge KK decay into radion + SM gauge boson (focus of this talk): coupling "in-between" to $q\bar{q}$ and to $t\bar{t}$ in standard case (2 branes)

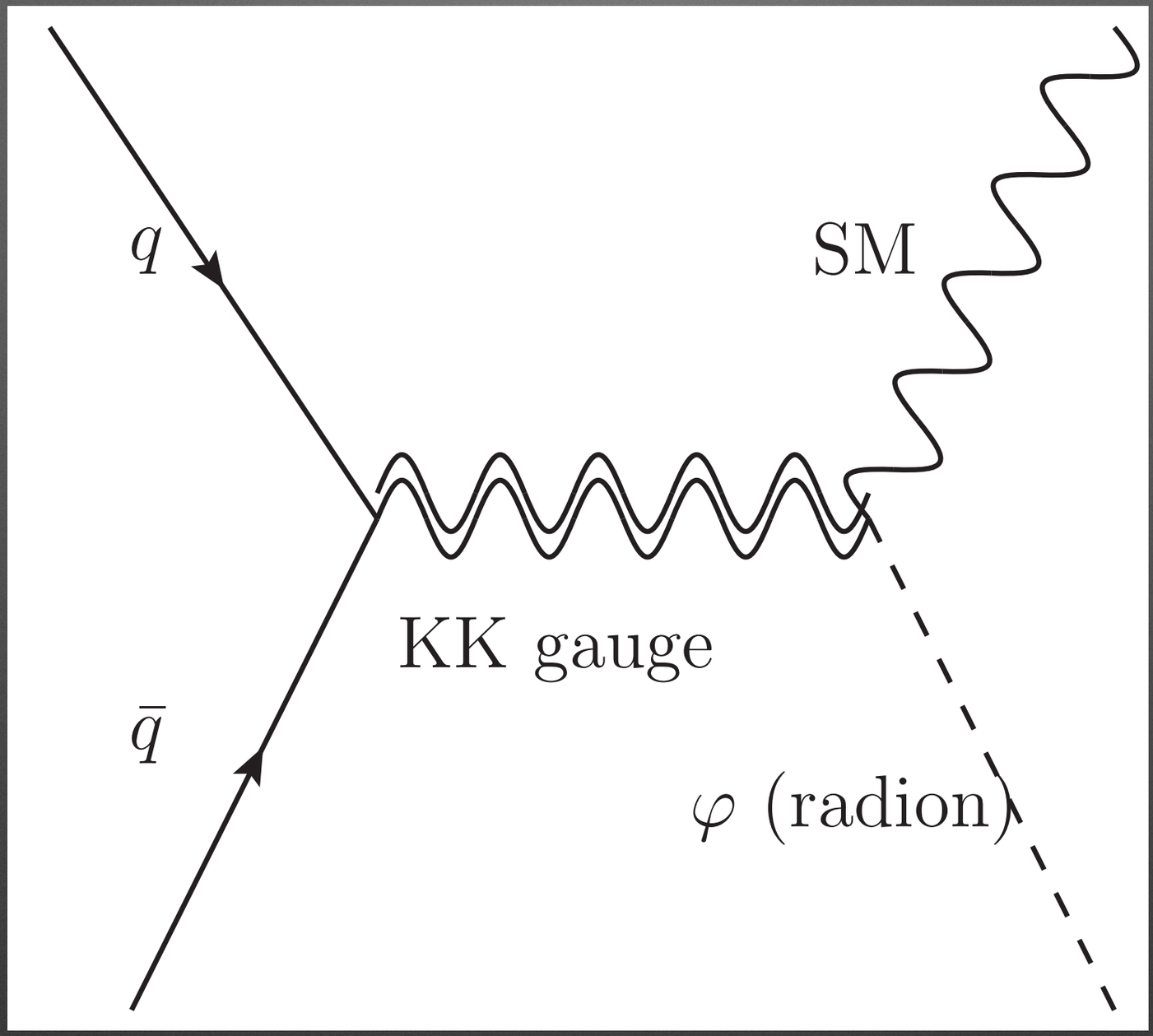


$$\sim g_{\rm SM}\,\epsilon\ \left(\text{with } \epsilon \lesssim 1\right)$$

related to stabilzation

"New" cascade decay channel for gauge KK: tri-bosons of various kinds

Basic process (I): gauge KK decay to radion



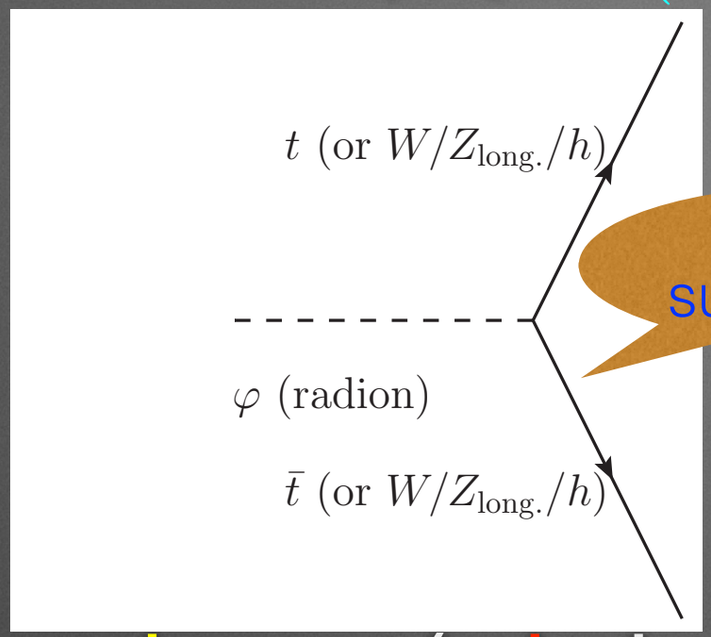
- Radion decay mode of **gauge KK** comparable to (or a bit larger than) decay into $q\bar{q}$ (or $l\nu$)

- **final** state depends on fate of **radion**

Radion decays also modified

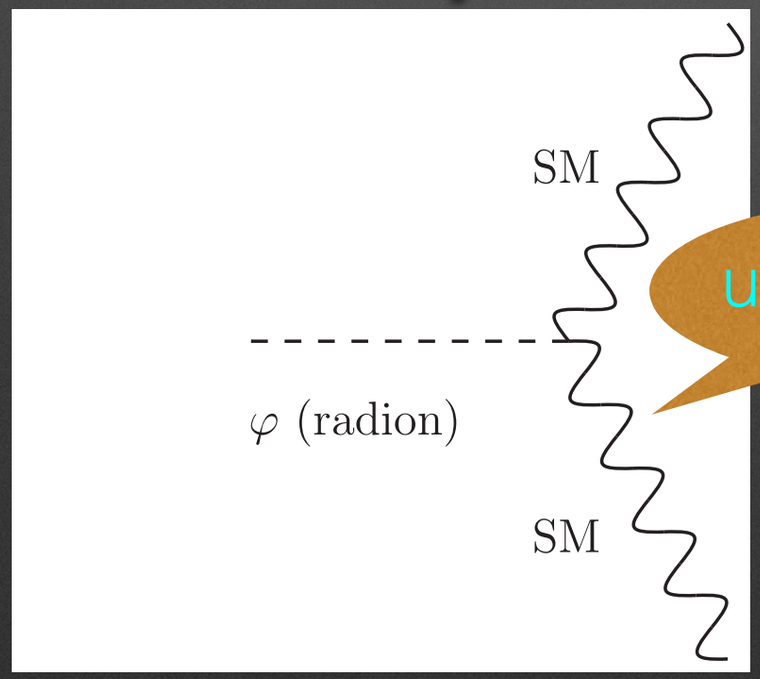
Radion (near gauge brane) "split" from top/Higgs

- Erstwhile dominant decays [$t\bar{t}$ (or $W/Z_{\text{long.}}/h$)] highly suppressed



[Radion couplings to $q\bar{q}$ (remain) negligible]

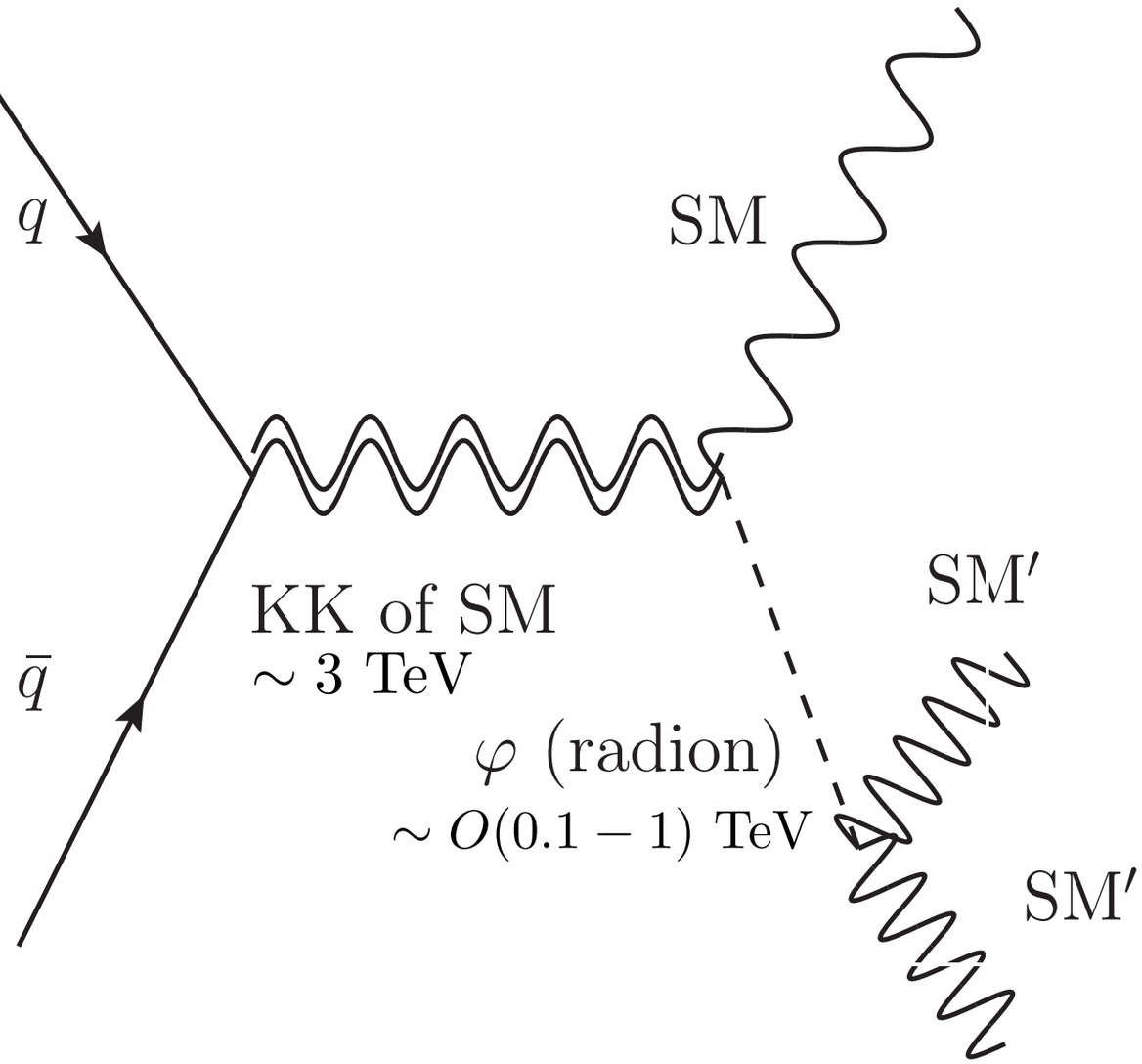
- Pair of SM gauge bosons (sub-dominant in standard warped model) take over in extended warped model



$\propto g^2_{\text{SM}}$ (and d.o.f.)

- Two radions for 2 separations: focus on lighter one (~fluctuation of gauge brane vs. heavier one that of top/Higgs brane)

Basic process (II): emergence of "tri"-boson signal (putting it all together)



- radion heavy (not boosted) or light (boosted)
  2 SM gauge bosons from its decay well-separated or merged

- more specific signals to come…

3 specific models:

(I). All SM gauge fields in extended bulk

[KA, Collins, Du, Hong, Kim, Mishra (2016)]

(II). Only EW gauge fields in extended bulk

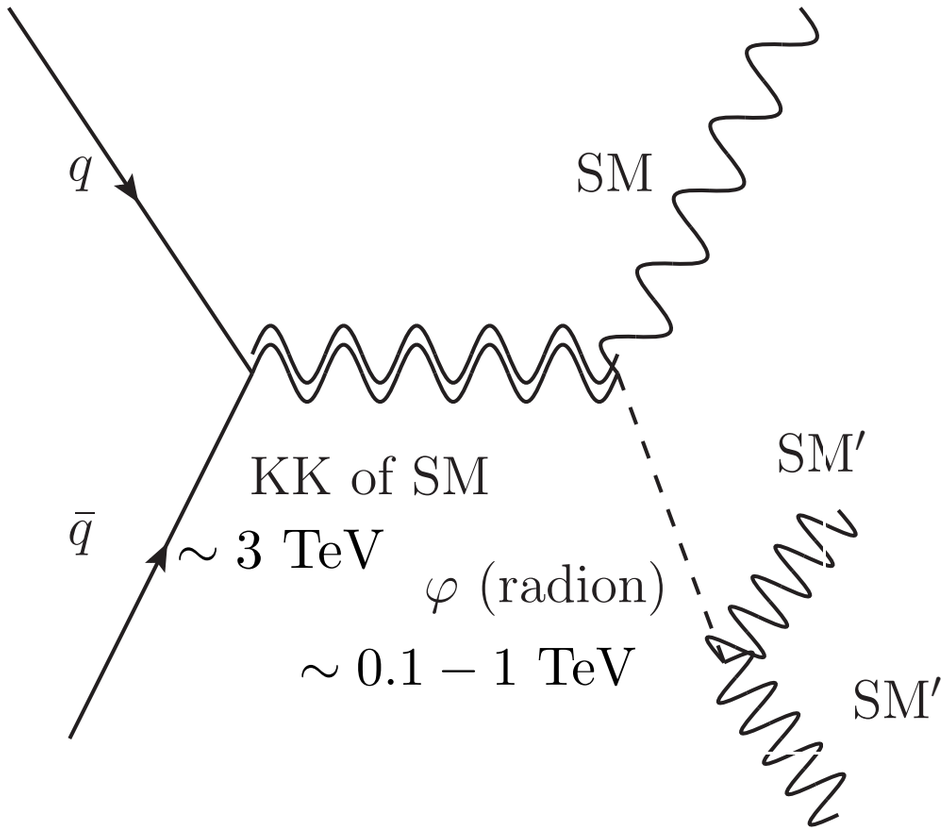
[…as "likely" as all in extended bulk as in model (I)…]

[KA, Collins, Du, Hong, Kim, Mishra (2017 and 2018)]

(III). Only QCD in extended bulk

[KA, Collins, Du, Hong, Kim, Mishra (unpublished note);
KA, Ekhterachian, Kim, Sathyan (2020)]

Summary table/diagram



Signal features → (gauge KK $\sim$ 3 TeV) Radion mass ↓	General topology	Which gauge bosons *can* "play"?	(I). All SM gauge in extended bulk (1612.00047)	(II). Only EW in extended bulk (1711.09920 & 1809.07334)	(III). Only QCD in extended bulk (2008.06480)
Heavy ($\gtrsim$ 1 TeV)	Tri-boson, with 2 resonances: 2-particle (radion) & 3-particle (gauge KK)	gluons *and/or* EW	*Mixture* of gluons and EW gauge bosons (3 gluon/jet is largest)	*Mixture* of $W/Z/\gamma$ (WWW is largest): for WWW etc., *combinatorics* makes *existing* di-boson search *in*efficient	*Only* 3 gluon/jet: *combinatorics* makes *existing* di-jet search *in*efficient
Light $O(100)$ GeV	isolated boson + *boosted*/merged *di*-boson resonance (radion) (combined resonance: gauge KK)	*Either* gluons *or* EW, i.e., *not* both	*not* possible (ruled out by di-photon searches)	$W/Z/\gamma$+ boosted/merged $WW/ZZ/Z\gamma/\gamma\gamma$: search for 4-prong jet or lepton(s) inside 2-prong jet (for WW/ZZ); photon inside Z-jet/leptons; allow $\Delta R_{\gamma\gamma} \lesssim 0.4$	gluon + boosted/merged di-gluon: *different* (in N-subjettiness etc.) from $q\bar{q}$

- goldmine of signals to choose from!

(Similar topology of signals possible with other new physics)

CMS and ATLAS took the bait!

- 3 isolated W and (boosted di-W + isolated W) analyses:

All hadronic: CMS-B2G-21-002 (2112.13090)

Semi-leptonic: CMS-B2G-20-001(2201.08476)

- Boosted di-gluon + isolated gluon:

CMS-EXO-20-007 (2201.02140)

- leptonic W + di-gluon :

ATLAS: CERN-EP-2022-179 (2211.08945)

…can ATLAS (and other channels) be so far behind?!

KK graviton

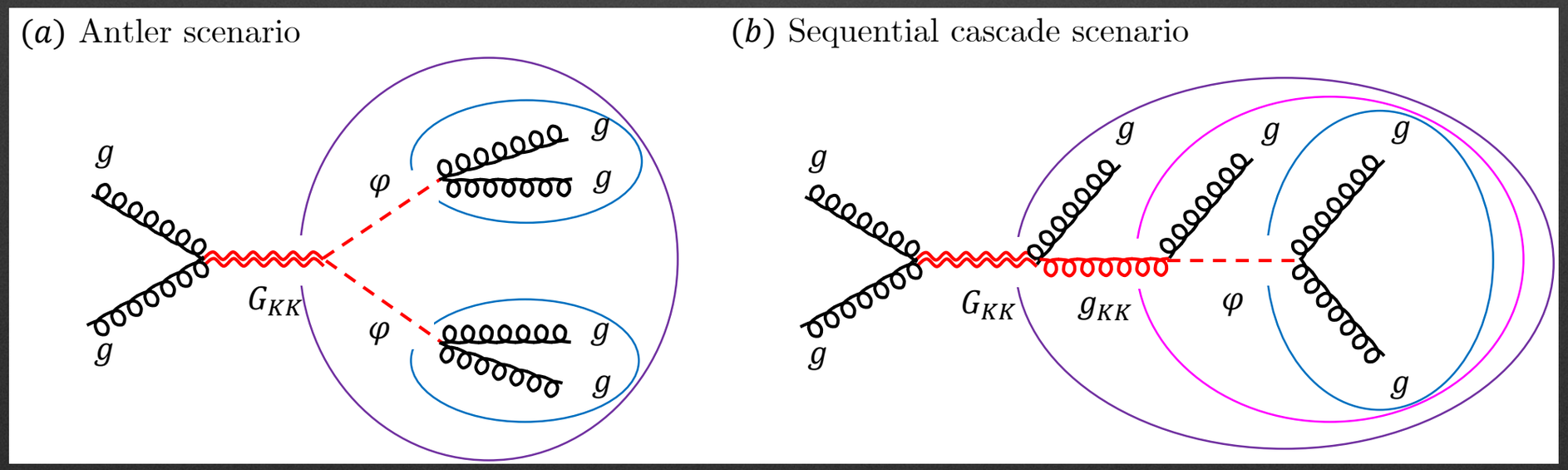
similar story: usual decay channels suppressed, other/pre-existing more important

Quadri-boson signals from KKgraviton

[KA, Ekhterachian, Kim, Sathyan (2020), with only QCD in extended bulk]

- production via gluon fusion as usual
- decay to top/Higgs and WW/ZZ suppressed (vs. standard)
- decay to di-gluon, gluon + KK gluon and di-radion dominant

- 4-jet signal (with 2 or 3 resonances):



Other examples/models

(giving tri-boson signals)

Left-Right symmetric (LR) model

- extend EW gauge symmetry to $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$
- spontaneous breaking (at $\sim$TeV): $SU(2)_R \times U(1)_{B-L} \to U(1)_Y$ using extended scalar sector
- (one of) standard signals: $W_R^{\pm}$ and Z' [extra $U(1)$]:

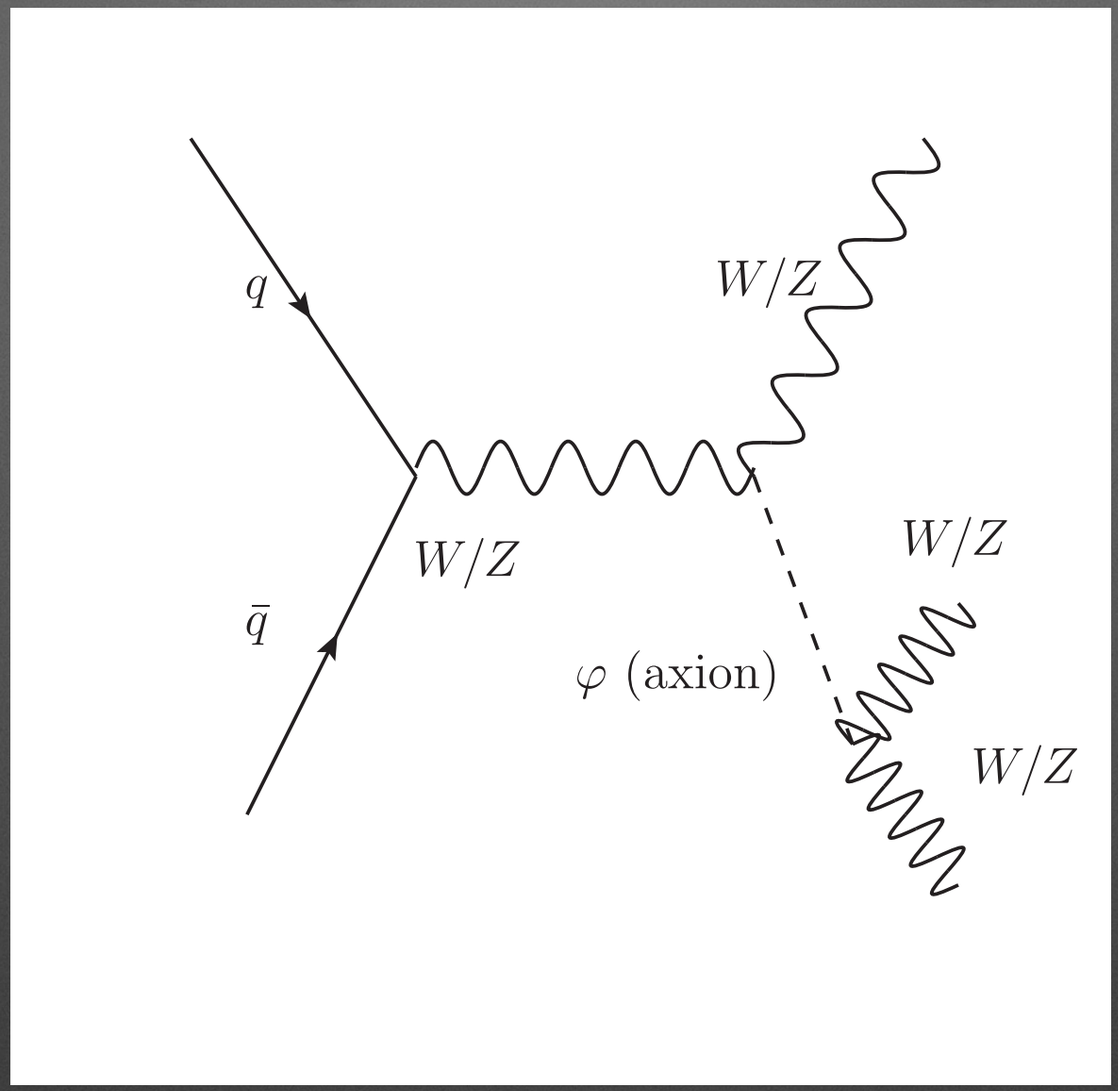
$$W_R^{\pm},\ Z'\ (\text{a few TeV}) \to \text{di-bosons}\ (W, Z, h)$$

- modified signals (similar to warped model: 2 resonances…):

$$W_R^{\pm},\ Z' \to W/Z/h + \varphi\ (extra\ \text{scalar}),\ \text{followed by}\ \varphi \to WW/ZZ...$$

Photophobic axion-like particle (ALP)

[Craig, Hook, Kasko (2018)]



- suppressed coupling to di-photon (unlike usual)
- coupling to WW/ZZ…dominates, giving tri-W/Z signal
- only 1 resonance, different than 2 in warped and LR models

Conclusions

- Simple modification of standard warped model can dramatically change LHC signals: instead of di-top/W/Z/Higgs final states, variety of
  - tri-boson or
  - novel fat-jet (boosted/merged di-"boson") + boson

W/Z/gluon/photon

- requires new/dedicated searches

- similar lesson for other frameworks (broaden searches):

$$\mathrm{BSM}_1 \to \mathrm{BSM}_2 + \mathrm{SM};\ \mathrm{BSM}_2 \to \mathrm{SM}_1 + \mathrm{SM}_2$$

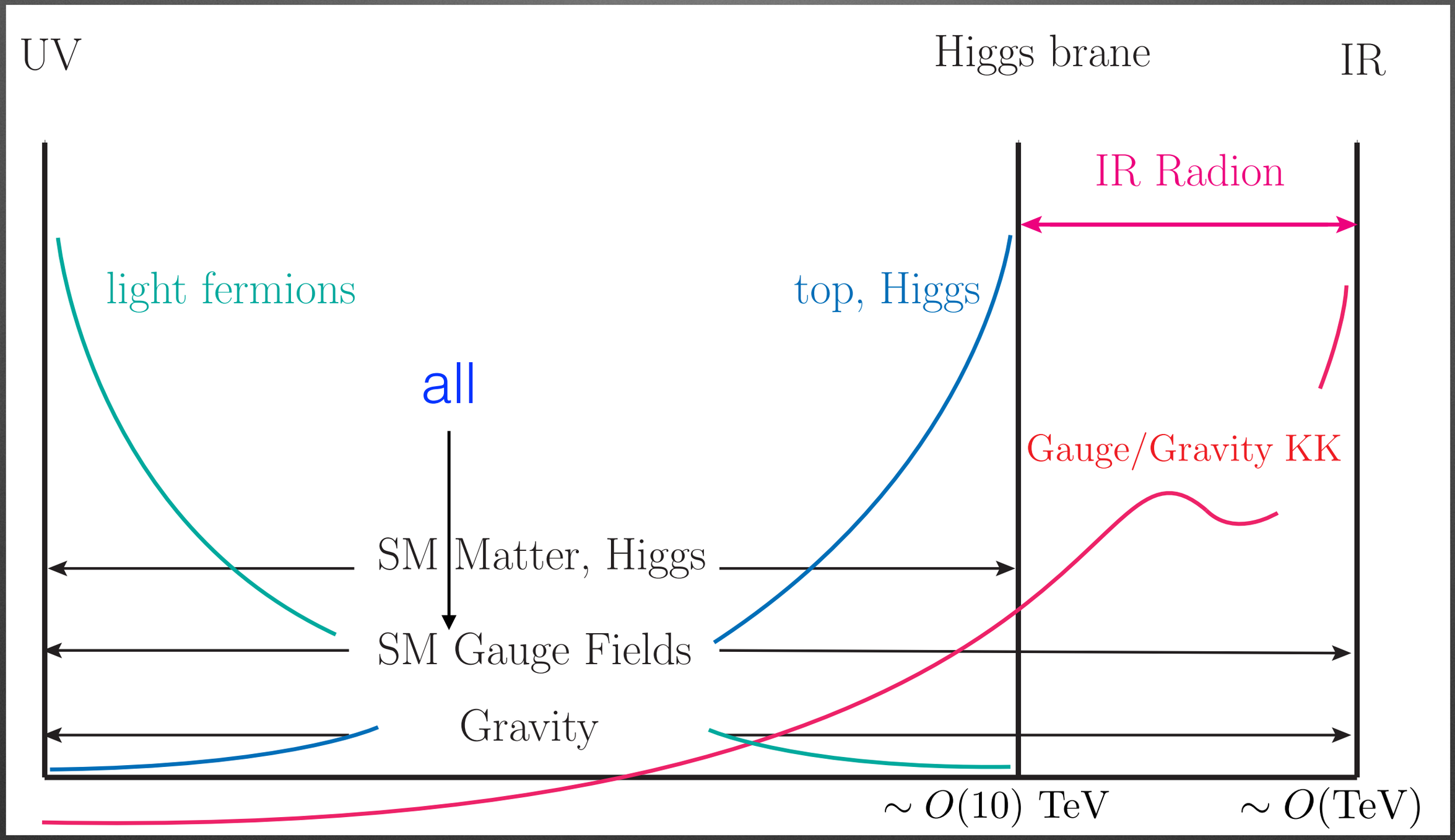
Back-ups

3 specific models:

(I). All SM gauge fields in extended bulk

[KA, Collins, Du, Hong, Kim, Mishra (2016)]

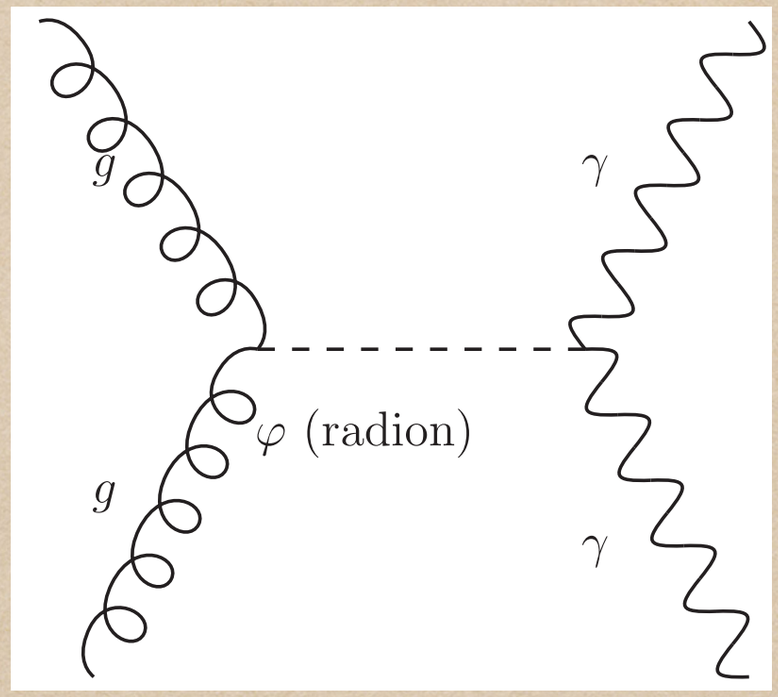
All extended model (I) at a glance…



- Similar profile/mass for **QCD** vs. **EW** gauge (SM or KK)
- Role of SM or KK gauge bosons $\propto g^2_{\mathrm{SM}}$

Light ($\lesssim$1 TeV) radion not allowed

- Di-photon bound from direct production of radion (also likely discovery channel for radion for ~1 TeV/on edge of current bound):



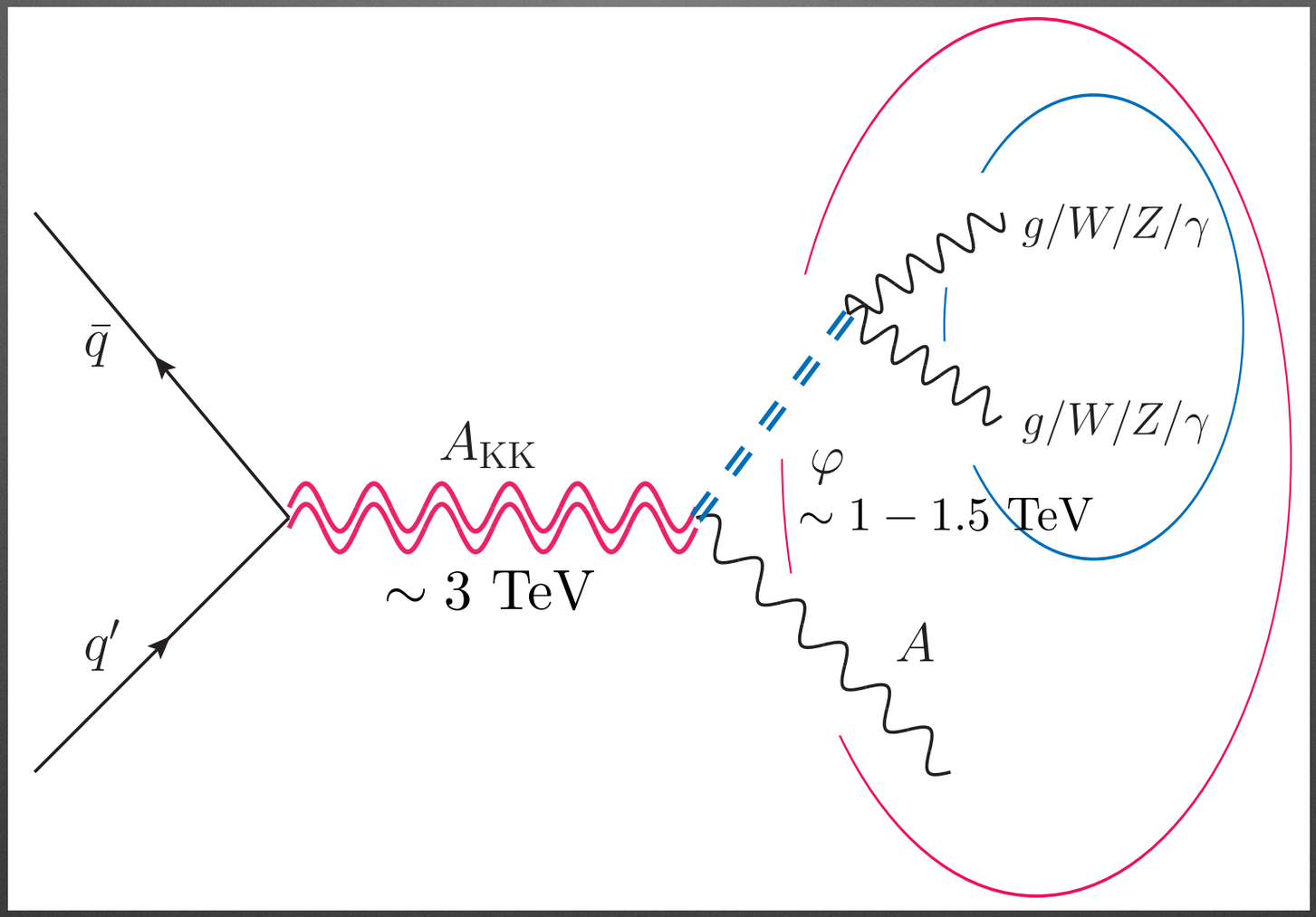
fixed at 3 TeV

- $\gtrsim$1.5 TeV radion (well above current bound), production via gauge KK dominates over direct (likely discovery channel)

- Radion ($\gtrsim$1 TeV) produced from few TeV gauge KK not boosted → 2 SM gauge bosons from it well-separated (and from "prompt" SM gauge boson)

(Genuine) Tri-Boson signals: basic structure/warm-up

- 2 resonances: di- and tri-boson (use to suppress background: signal small)



- Largest rate for tri-gluon/jet (based on KK production and radion decay)

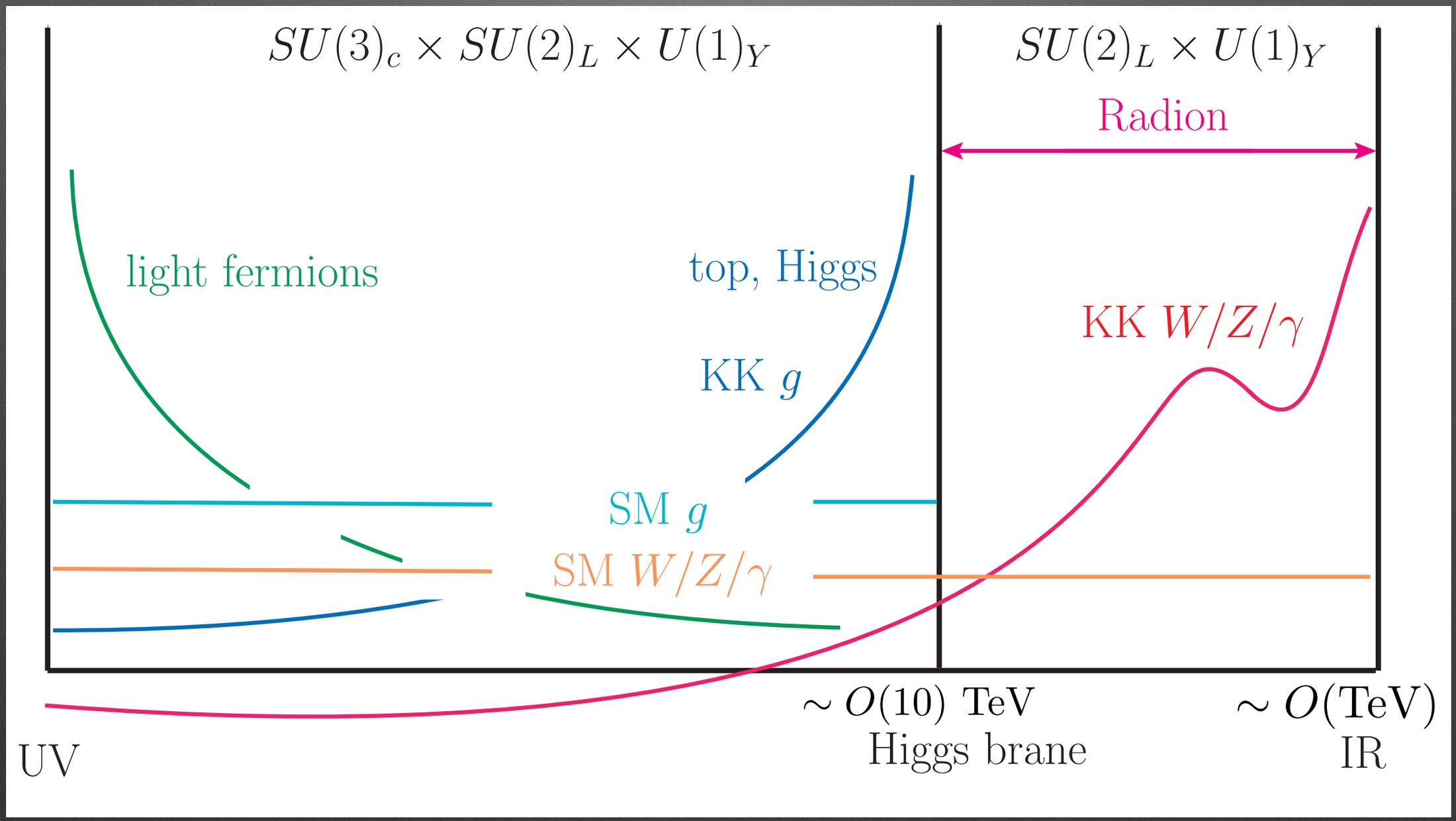
- Results (including background, using Delphes etc.): observation of signal (discovery of heavier radion) with $\sim$300/fb for $\sim$3 TeV KK gluon (and $\sim$1-1.5 TeV radion); $\sim$3000/fb for other KK

(II). Only EW gauge fields in extended bulk

[…as "likely" as all in extended bulk as in model (I)…]

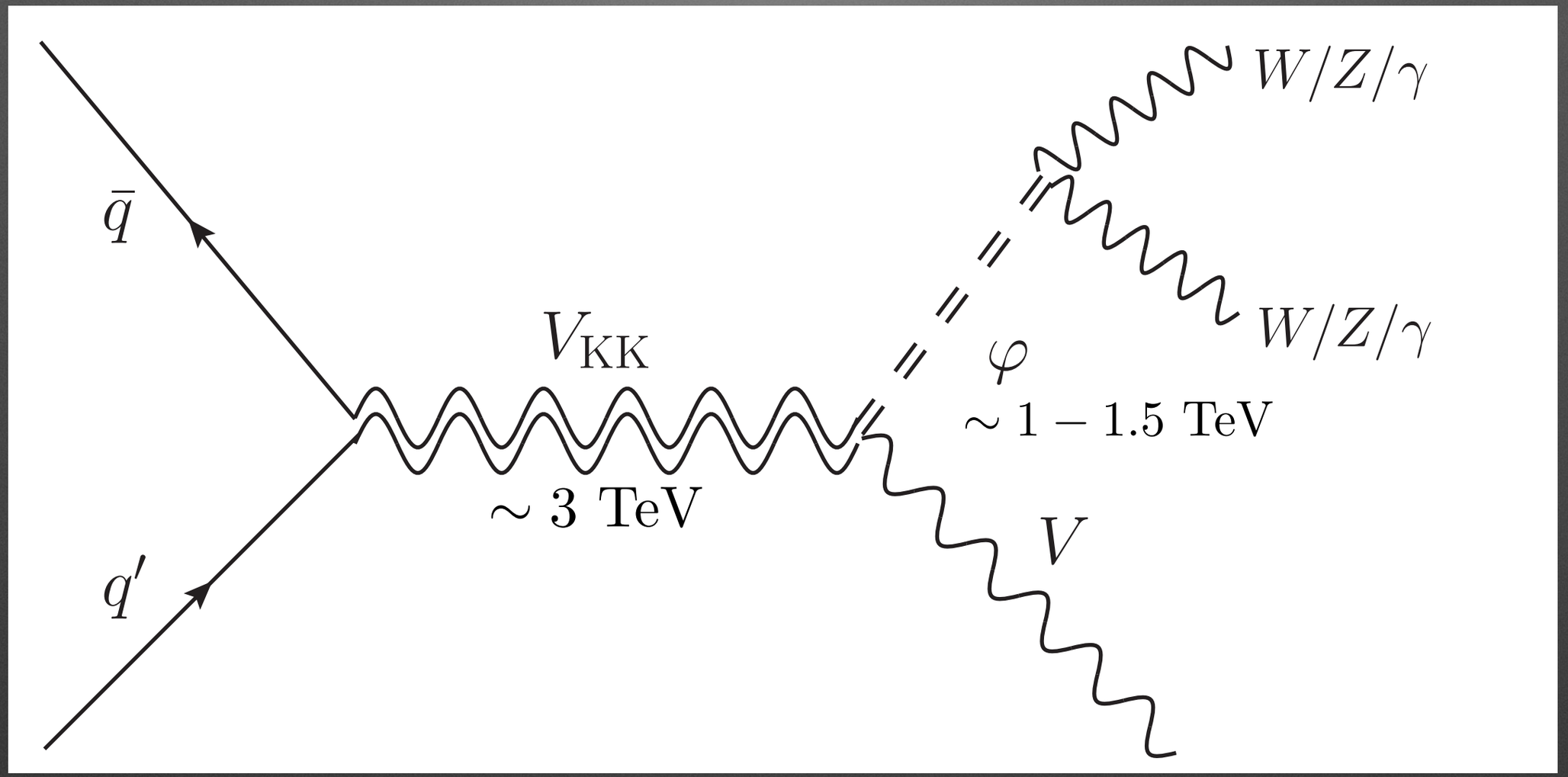
[KA, Collins, Du, Hong, Kim, Mishra (2017 and 2018)]

EW-extended model (II) at a glance…



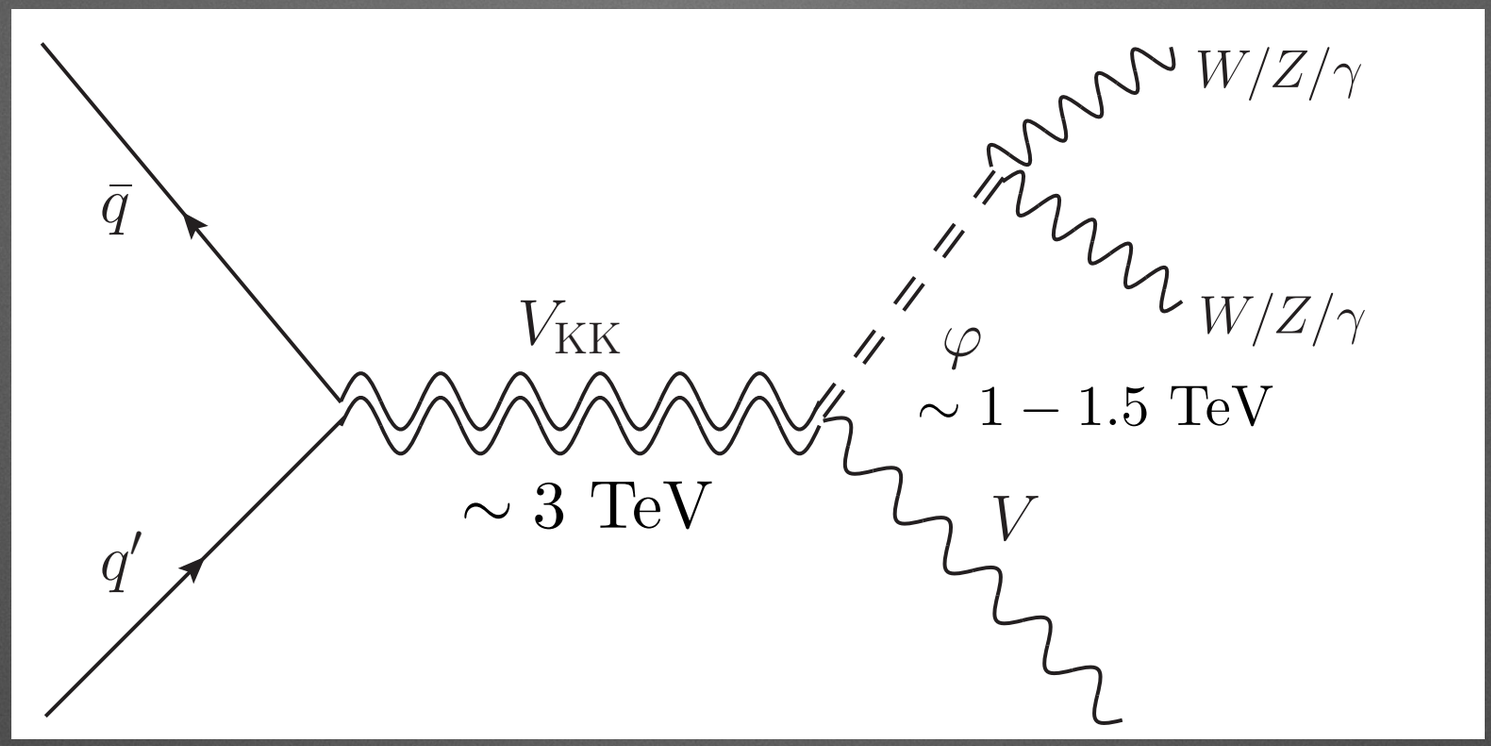
- **Gluons** (SM or KK) till $\sim O(10)$ TeV **out** of the game: KK gluon beyond LHC reach, radion “split” from gluons

Tri-EW-gauge boson signals for heavy radion (I)



- 3 isolated $W/Z/\gamma$ (all W/Z boosted)
- largest rate for WWW (based on production of gauge KK and radion decay)

Tri-EW-gauge boson signals for heavy radion (II)



- Existing di-boson ($WW/WZ/ZZ$) search selects two hardest W/Z, not from radion typically
  not efficient here (excess, but no bump)

- dedicated search needed: invariant mass of various combinations of di-bosons (for digging out radion) + invariant mass of tri-boson (for getting to gauge KK)

coupling to gluons/direct production suppressed (more later)

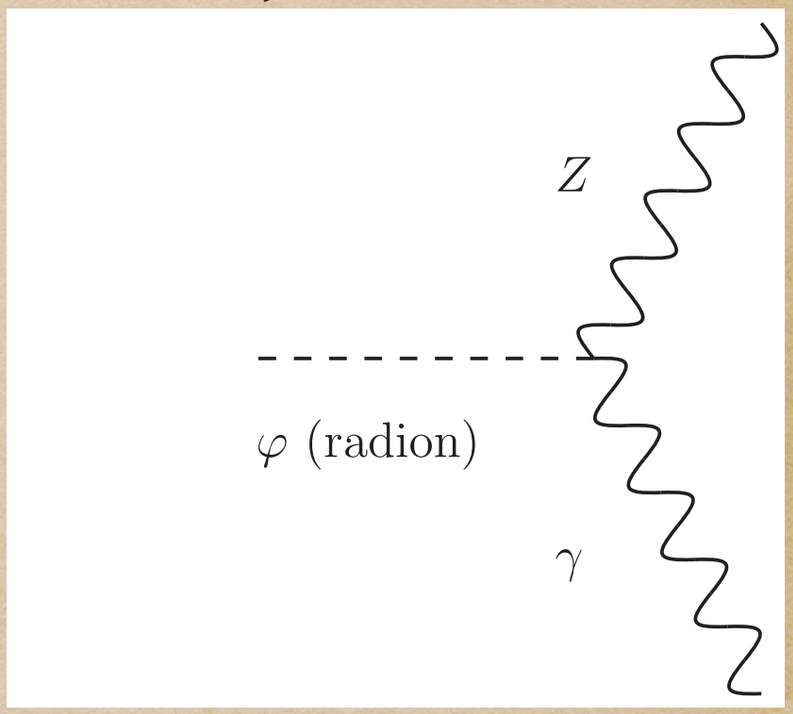
- Results (including background, using Delphes etc.): discovery of $\sim$1-1.5 TeV radion from decay of $\sim$3 TeV KK W with $O(100)$/fb

"New" radion decay: (Z + photon)

- vanishes in minimal model (focus thus far), but present in general

- also for standard (2 branes) model

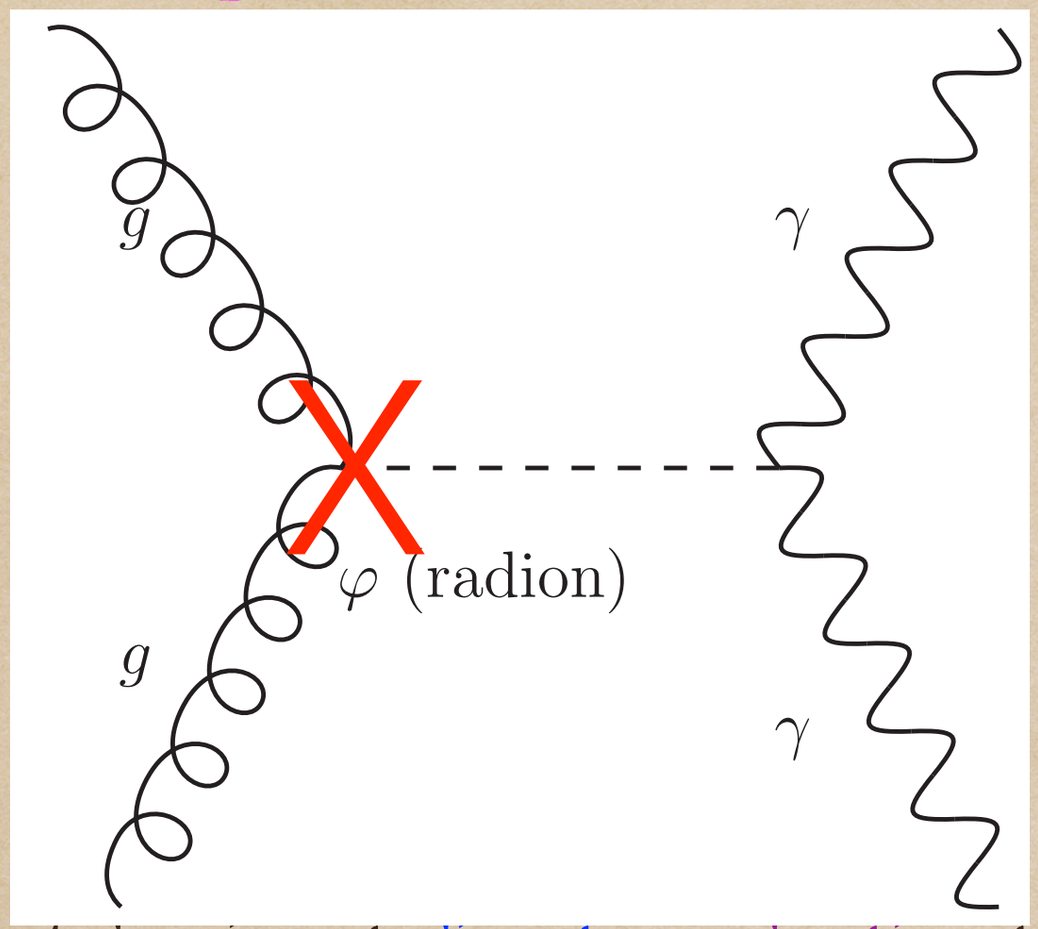
- hierarchy of radion BR's:
  WW > ZZ > (Z + photon) > di-photon



- boosted Z(fat jet) for heavy radion → background for (Z + photon) vs. di-photon might be less compared to SM Higgs (Z → resolved jets, with larger QCD background)

- extended model (radion from KK W): (W + Z + photon) signal

New: light [$\sim O(100)$ GeV] radion allowed



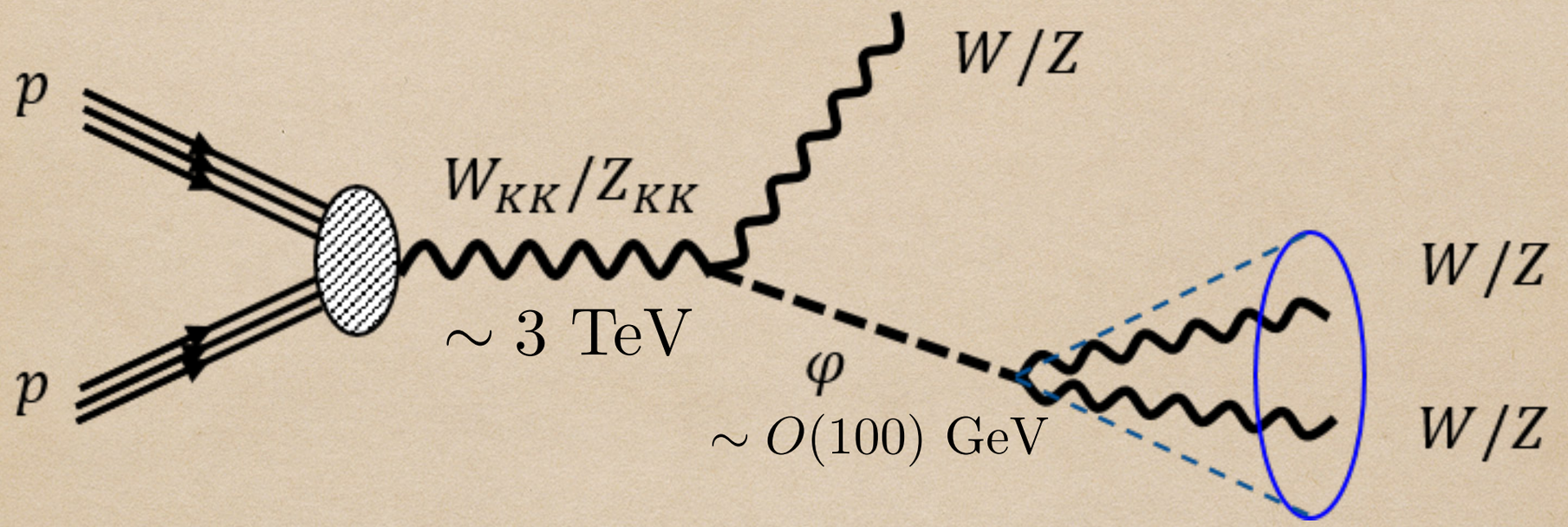
(even lighter is unnatural)

- Usual dominant direct production turned off (even if radion BR to di-photon enhanced: decay into EW only), WW fusion small → difficult to discover via this channel

- Instead, radion dominantly produced (boosted) from decay of a few TeV gauge KK (its coupling to $q\bar{q}$ significant/unchanged)

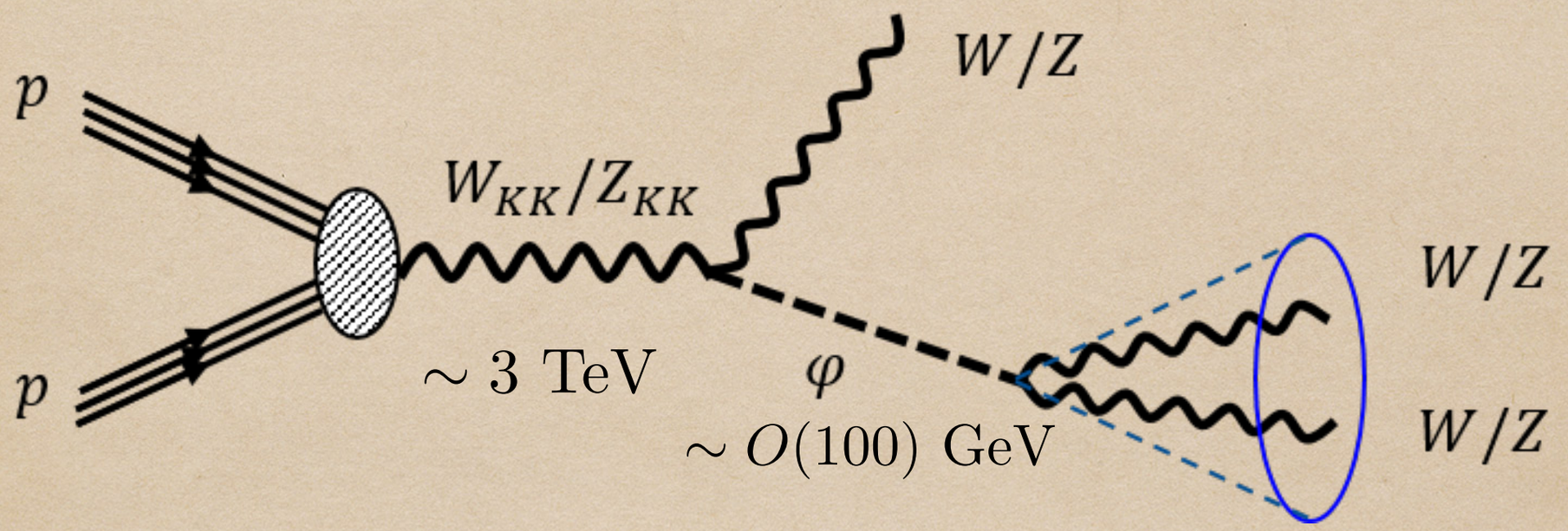
Boosted/merged di-boson [+ (boosted) boson] (I)

W/Z



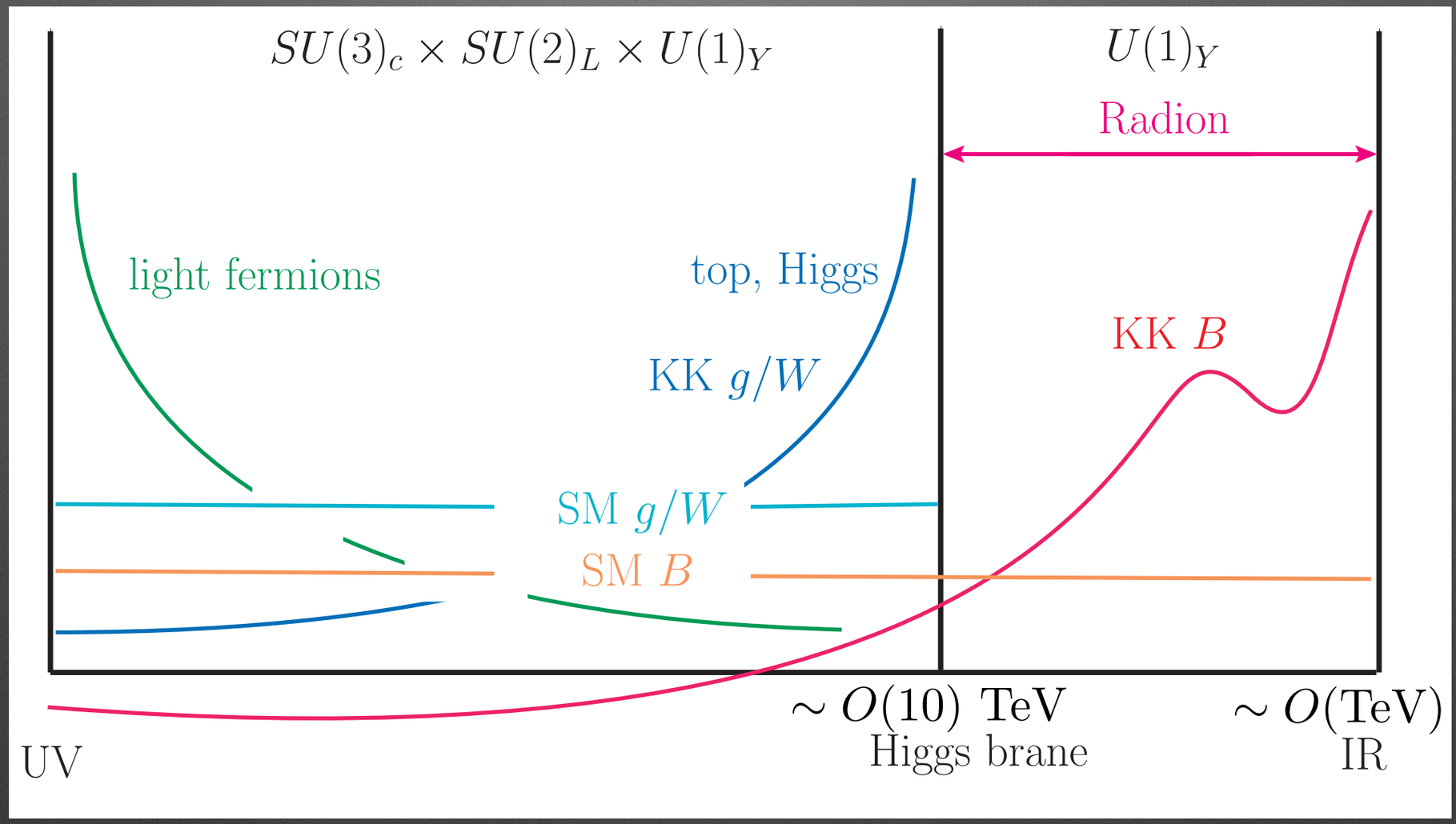
- 4-prong fat-jet (or lepton buried in 2-prong fat-jet), with mass not W/Z/Higgs/top → likely "missed" with current searches (need dedicated algorithm)

Boosted/merged di-boson [+ (boosted) boson] (II)



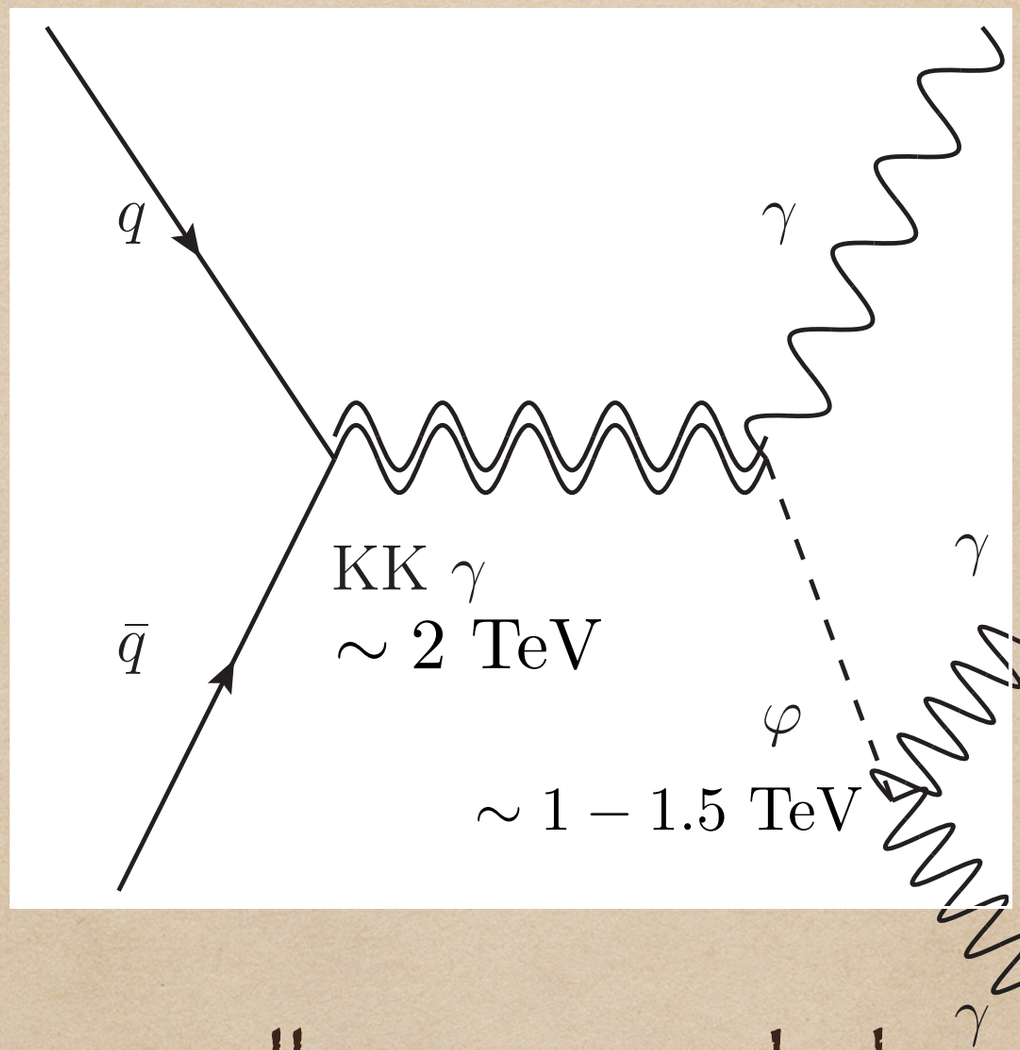
- 2 resonances: fat-jet and [fat-jet + (isolated) W]
- Results (including background, using Delphes etc.): discovery of (light) radion from decay of ~3 TeV KK W with ~300/fb (combining fully-hadronic and semi-leptonic channels)

Only hypercharge in extended bulk



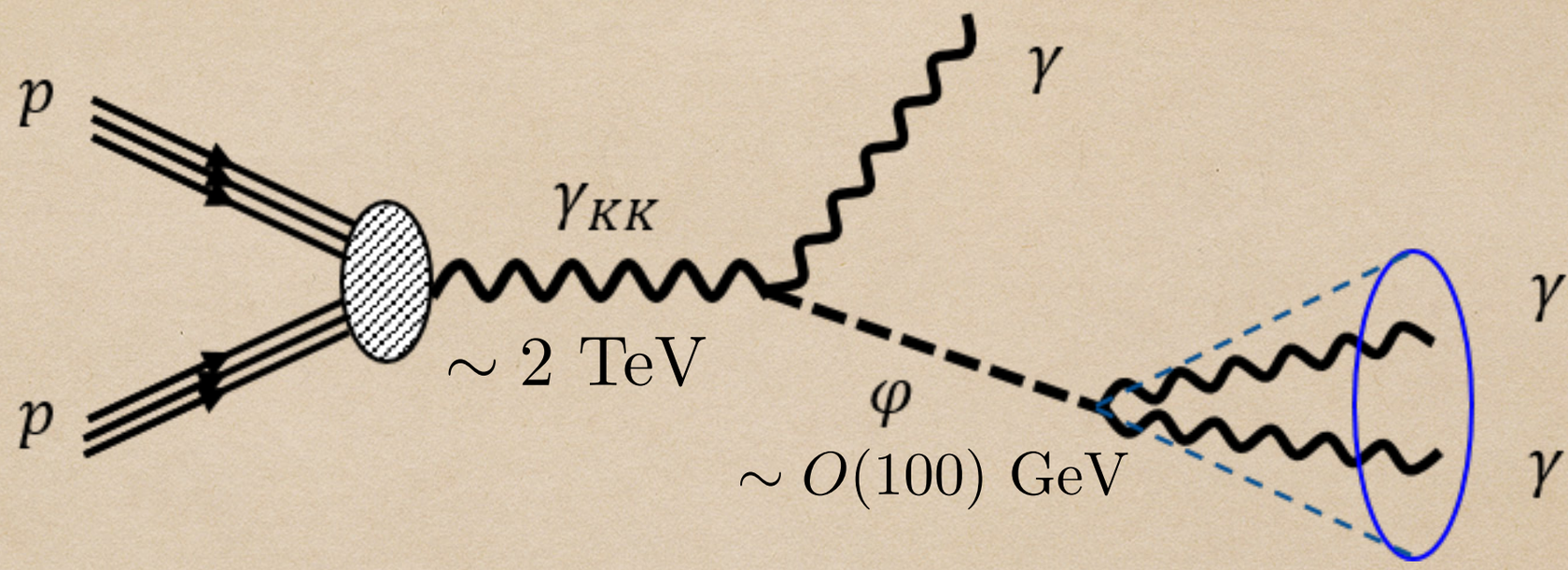
- At a glance: gluons/W/Z out of picture…
- Only KK hypercharge (~photon + bit of Z)
- Radion decays into di-photon [+ bit into ZZ and (Z + photon)]

Trí-photon (with 2 resonances)...



- Heavy radion: 3 well-separated photons negligible background, but combinatorial ambiguity motivates dedicated search

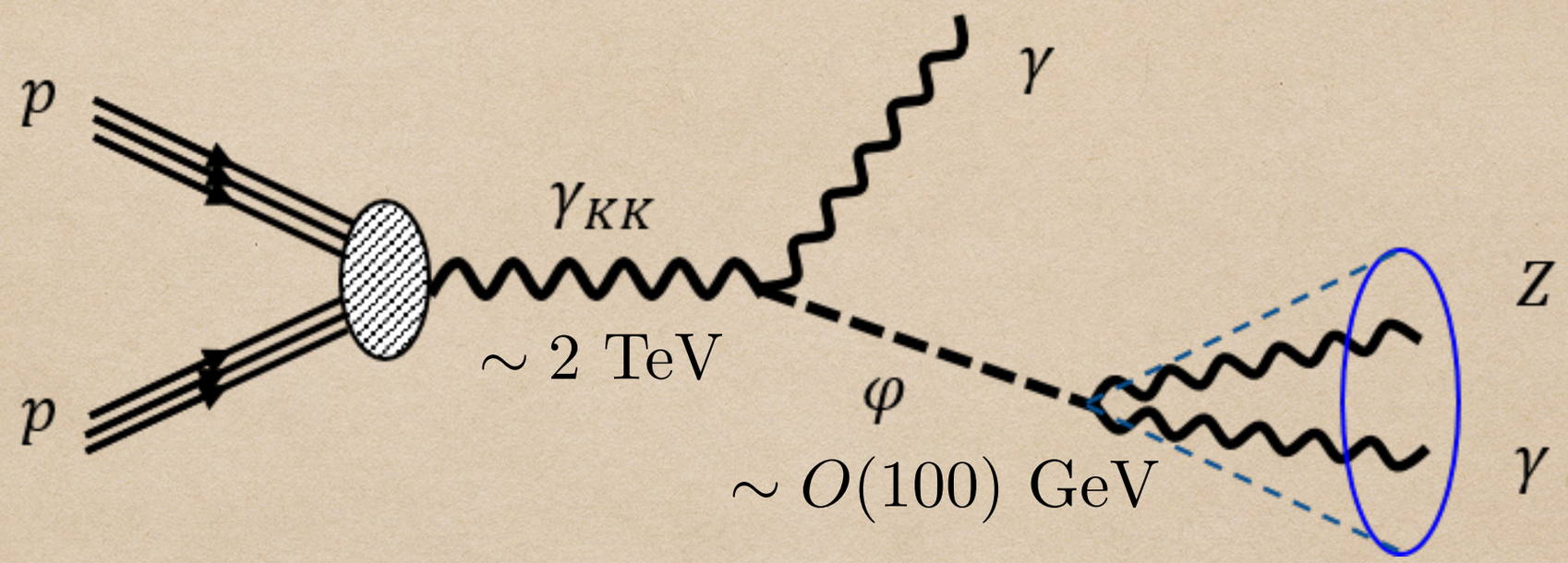
...or, boosted/merged di-photon + photon



- Light [$\sim O(100)$ GeV], boosted radion: isolated photon + merged di-photon

  existing search require isolation $\Delta R_{\gamma\gamma} \gtrsim 0.3$, vs. here $\Delta R_{\gamma\gamma} \sim 100\ \text{GeV}/1\ \text{TeV} \sim O(0.1)$ → not efficient, need to relax isolation (dedicated search)

Boosted/merged (Z + photon)

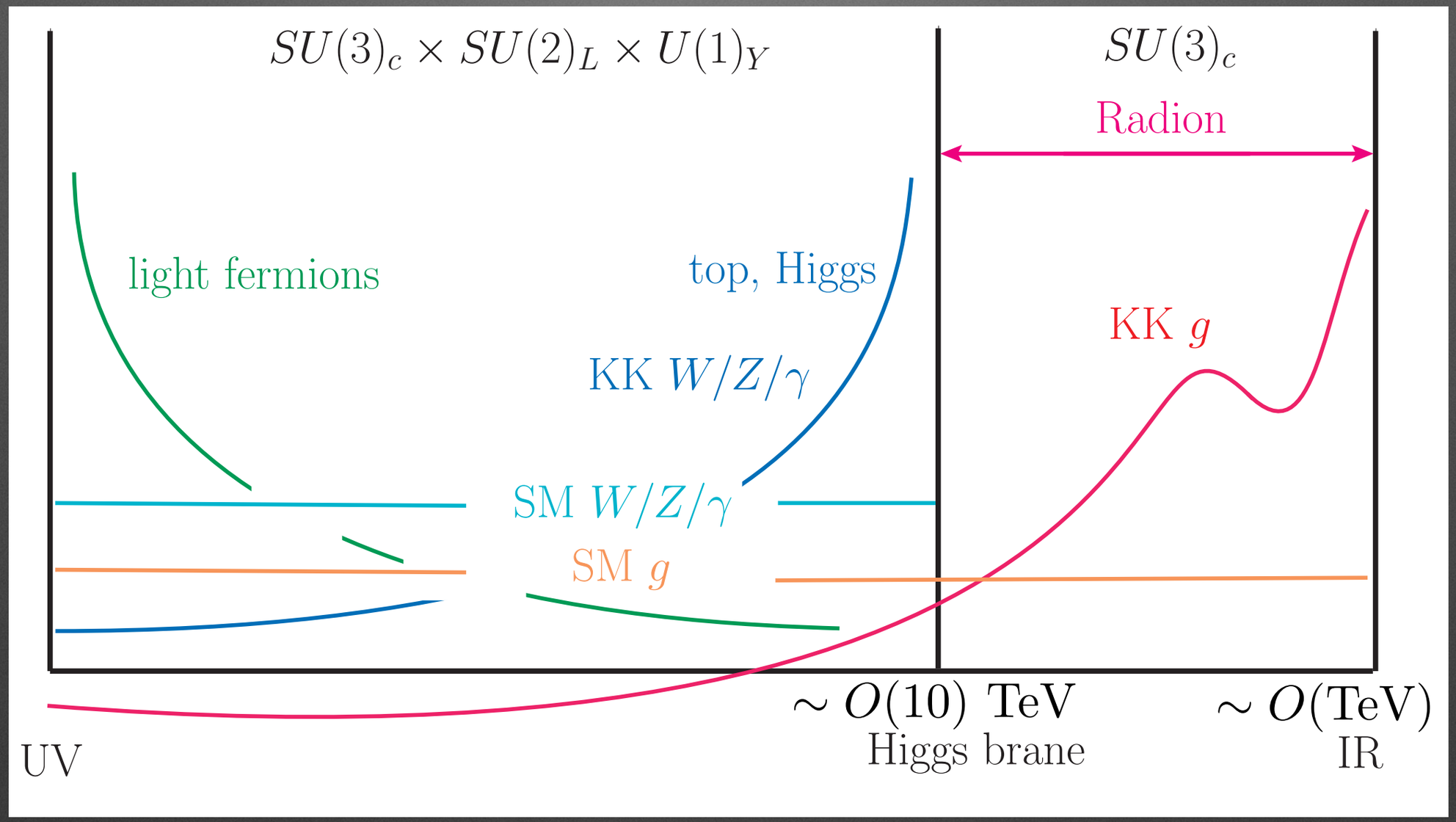


- from light radion decay
- photon inside Z-jet (hadronic) or (photon + leptons) "jet"

(III). Only QCD in extended bulk

[KA, Collins, Du, Hong, Kim, Mishra (unpublished note)]

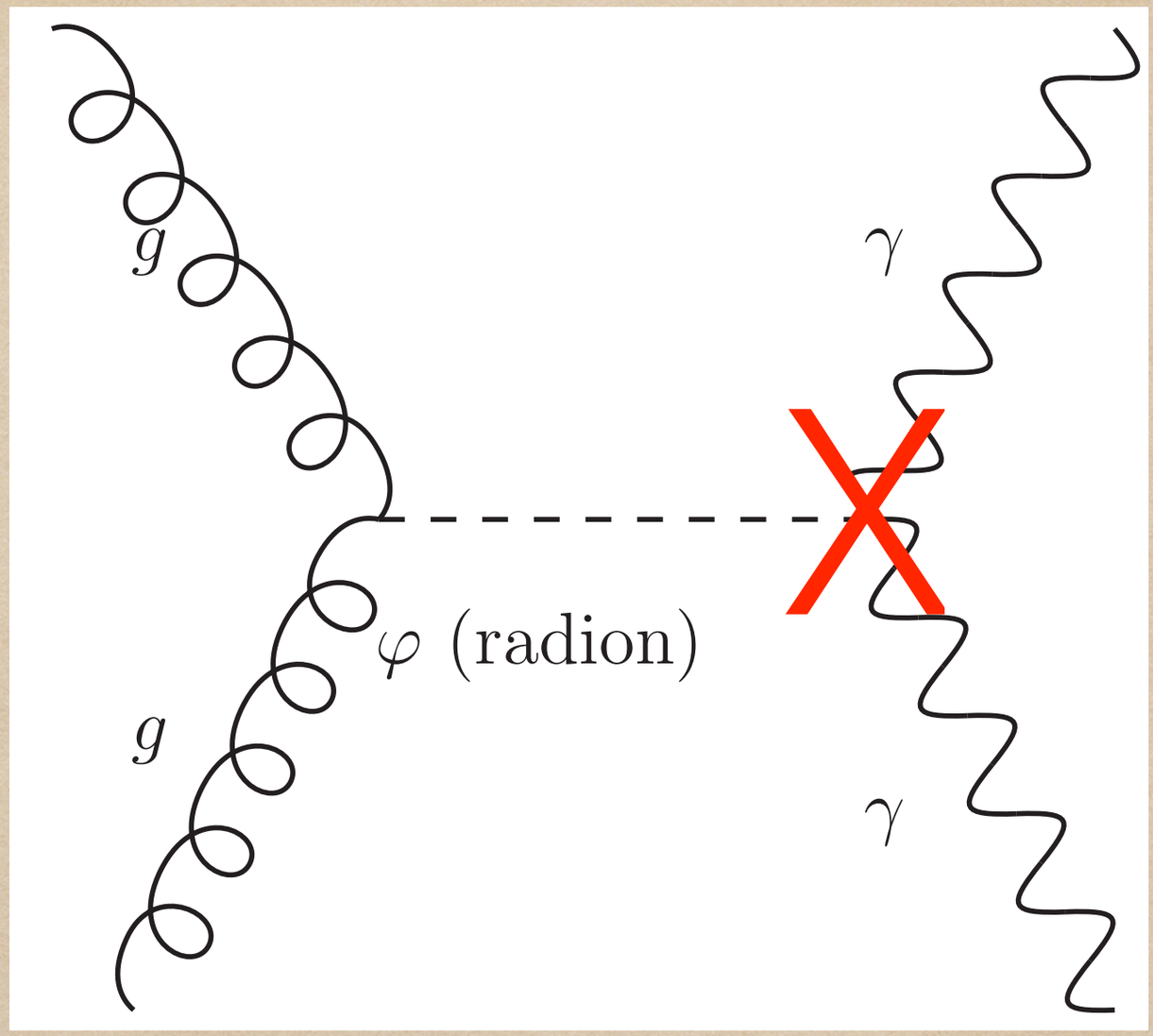
QCD-extended model (III) at a glance…



- **EW** gauge bosons (SM or KK) till $\sim O(10)$ TeV **out** of action

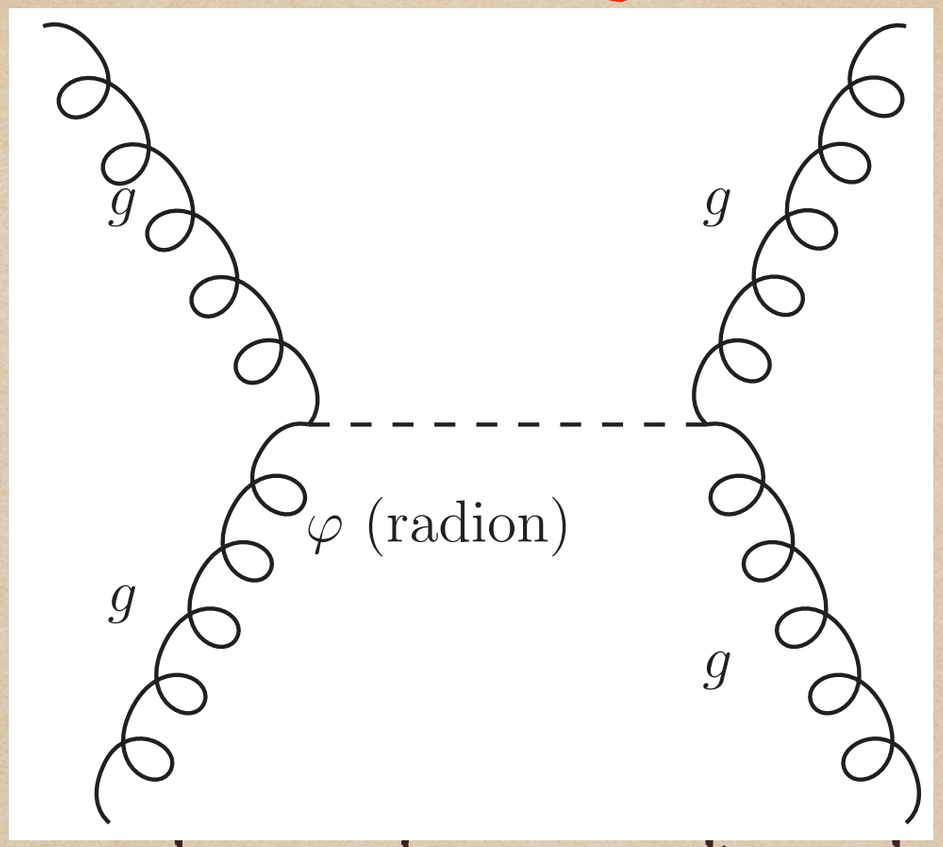
- **Heavy** radion as in case (I): (well-separated) tri-gluon/jet

Light radion [$\sim O(100)$ GeV] (again) allowed



- Now production unchanged, but decay to di-photon turned off (radion "split" from EW gauge bosons)

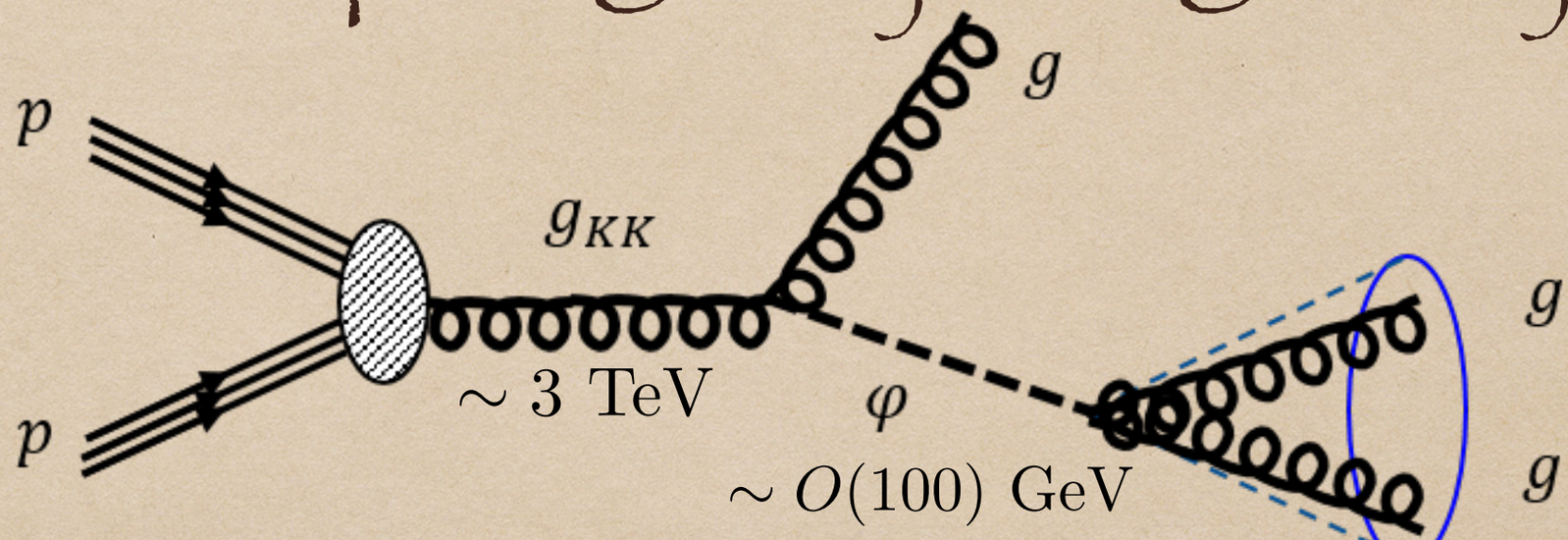
Light radion decay to di-gluon



- directly produced (not boosted) radion
  2 gluons well-separated [di-jet signal,
  with invariant mass $\sim O(100)$ GeV], buried in background

- reduce background by boosting to give merged
  di-gluon: either by ISR (as for $h \to b\bar{b}$) or...

KK gluon → boosted/merged di-gluon (2-prong fat-jet) + gluon/jet



- different (N-subjettiness) than boosted/merged $q\bar{q}$ (latter studied, e.g., light Z': CMS -PAS- EXO-17-001) → dedicated search required

- 2 resonances: fat-jet and [fat-jet + (isolated) jet], use to suppress background

New feature: Discovery of KK gluon (and radion)?

- KK gluon decay BR to radion and $q\bar{q}$ (usual di-jet) comparable

- Radion signal of KK gluon has more "structure" than simple di-jet:
  3 isolated gluons/jets (for heavy radion) or
  [(isolated gluon/jet + boosted/merged di-gluon/jet) for light radion]

→ QCD background (to dedicated search for above "tri"-jet) likely smaller than for usual di-jet

→ sensitivity to KK gluon larger in new channel

- Light radion missed in usual (non-boosted) di-jet search (direct production from gluon fusion) → use KK gluon decay instead

- Heavy radion (resolved jets: whether direct production or via KK gluon) discovery via usual di-jet if radion just above that bound ($\sim$1 TeV), but via KK gluon (fixing that mass at $\sim$3 TeV) instead if heavier

Probe Higgs compositeness
[at ~ $O(10)$ TeV] ?!

(Above is testing compositeness
of spin-1 resonances)

…via precision analysis of gauge KK decay modes [KA, Du, Hong, Sundrum (2016)]

- gauge KK coupling to top/Higgs:

spin-1 compositeness scale

top/Higgs compositeness scale

$$\sim g_{\rm SM}^2/g_{\rm KK} + g_{\rm KK}\ \Lambda^2_{\rm gauge}/\Lambda^2_{t/H}$$

- For $\Lambda_{t/H} \sim O(10)$ TeV (and $g_{\rm KK} \sim$ a few), top/Higgs compositeness component modulates coupling (gauge KK decay BR's) by $\sim O(1)$