

Tri-Boson Signals from BSM

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[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

- Searches for new physics (NP) 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)
- in this talk, illustrate (in detail) with warped/composite Higgs; 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):
$$\text{BSM}_1 \rightarrow \text{BSM}_2 + \text{SM}; \text{BSM}_2 \rightarrow \text{SM}_1 + \text{SM}_2$$
- **Specific** models/signals: **targeted** searches needed
- **Other** models: LR, phot**ophobic** axion

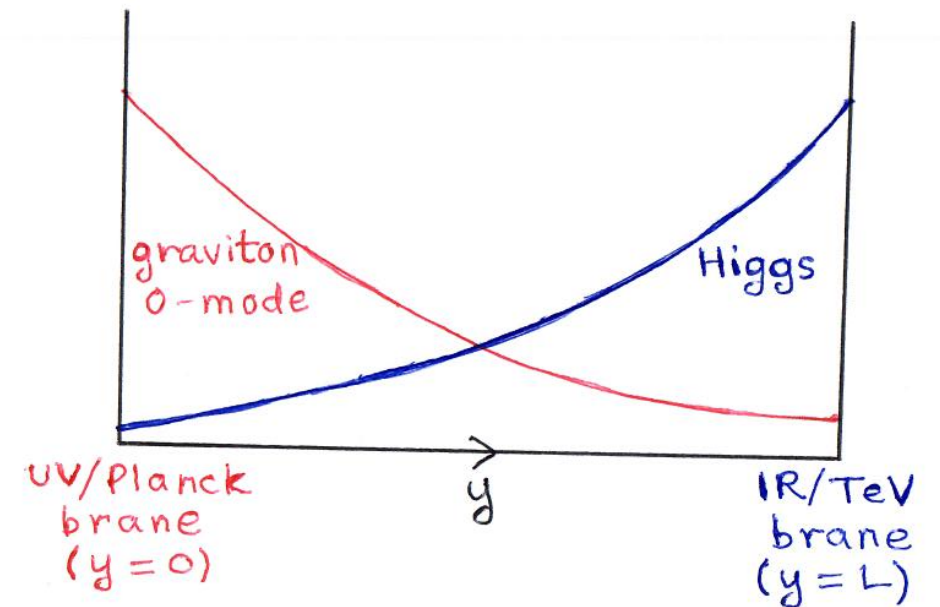
“Disclaimer”

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

warp factor

- **RS1:**

4D gravity (zero-mode graviton):

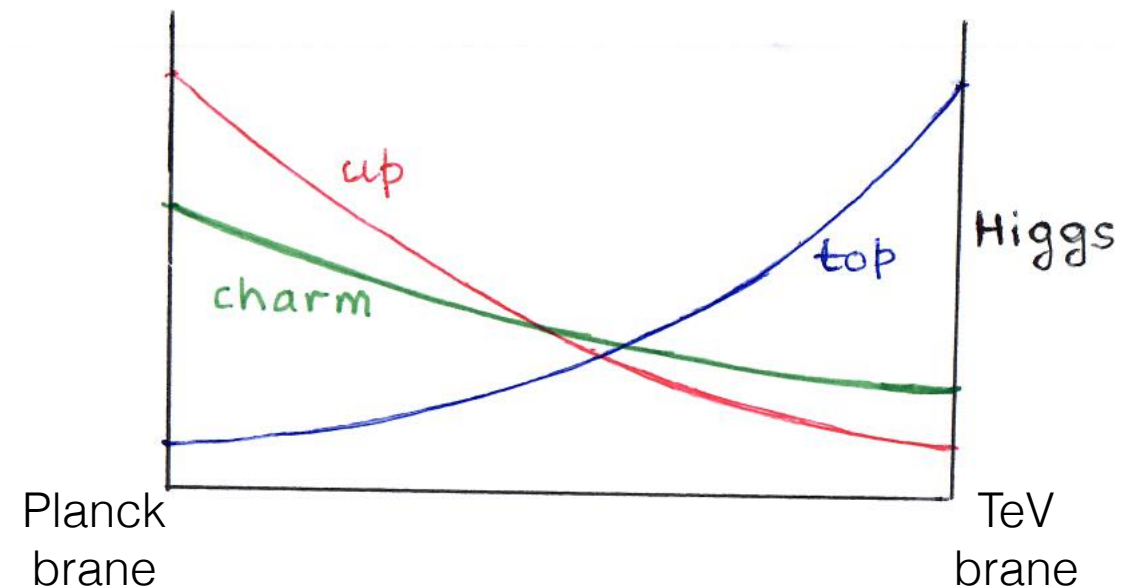
$$y \sim 0 \Rightarrow M_{4D}^{\text{eff}} \sim M_{5D}^{\text{fund}} \\ \Rightarrow \text{choose } M_{5D}^{\text{fund}} \sim M_{\text{Pl}}$$

Weak scale/Higgs mass:

$$y \sim L \Rightarrow M_{4D}^{\text{eff}} \sim e^{-kL} M_{5D}^{\text{fund}} \\ \Rightarrow \text{choose } kL \sim 30 \\ (\text{mild hierarchy, with } k \sim M_{5D}^{\text{fund}})$$

4D Flavor hierarchy from 5D anarchy

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

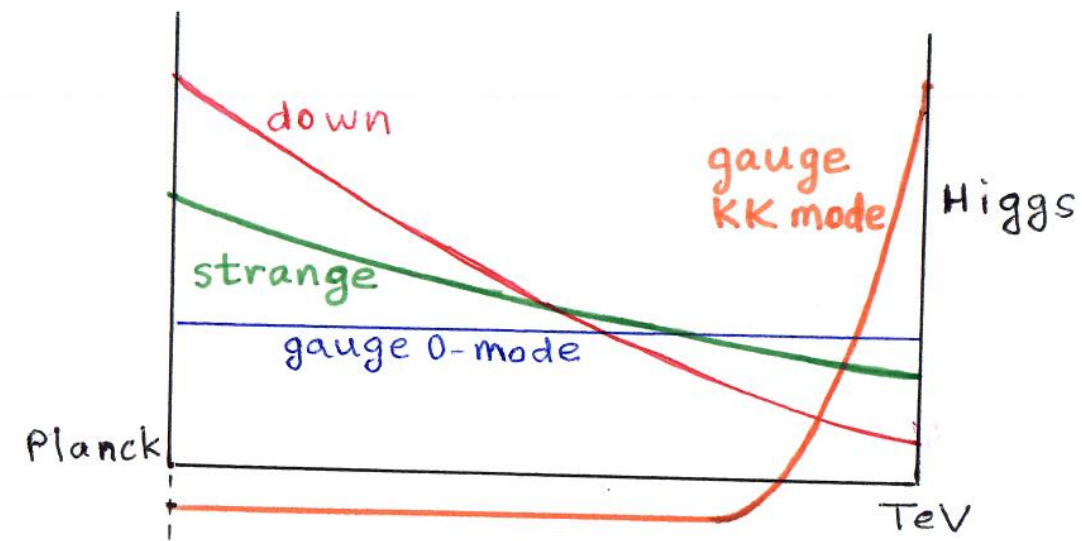


SM fermions are zero-modes of 5D fields

- **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)]



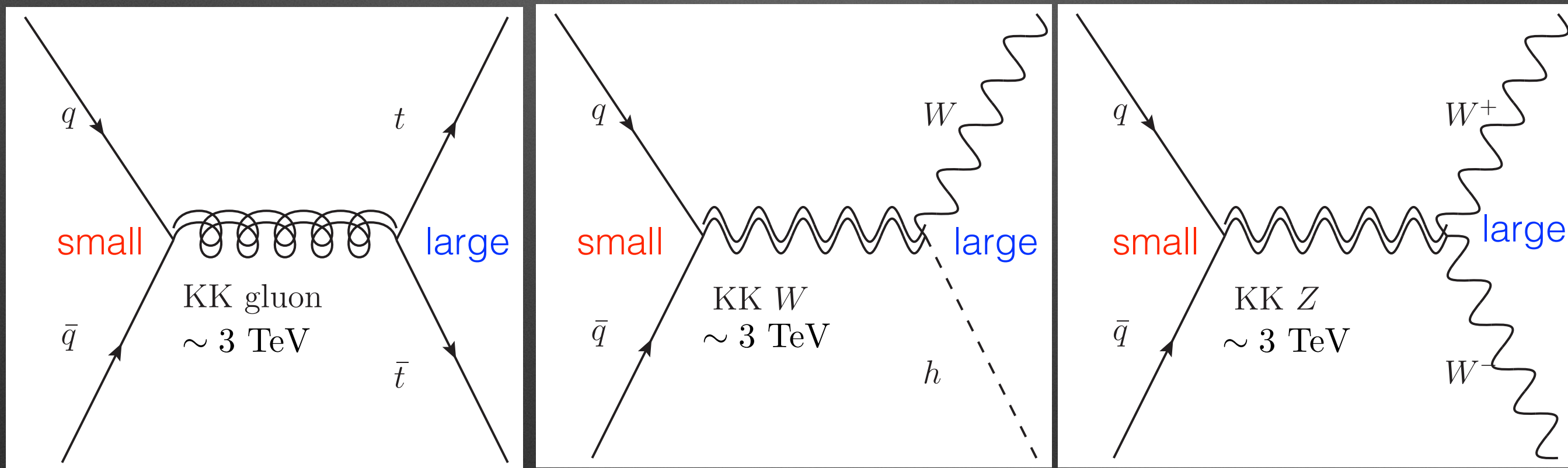
- SM gauge fields also in bulk
- New particles: Kaluza-Klein (KK) excitations of SM (near TeV brane)
- RS-GIM mechanism (flavor violation from $KK \propto$ quark masses) \rightarrow bound on KK scale (much) weaker than $\sim O(10^5)$ TeV for generic new physics
- still $\sim O(10)$ TeV [Csaki, Falkowski, 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, $t\bar{t}$ (or $W/Z_{\text{long.}}/h$) (all 3 modes near TeV brane) (cf. sequential W'/Z' : decay back into $q\bar{q}$ or leptons)



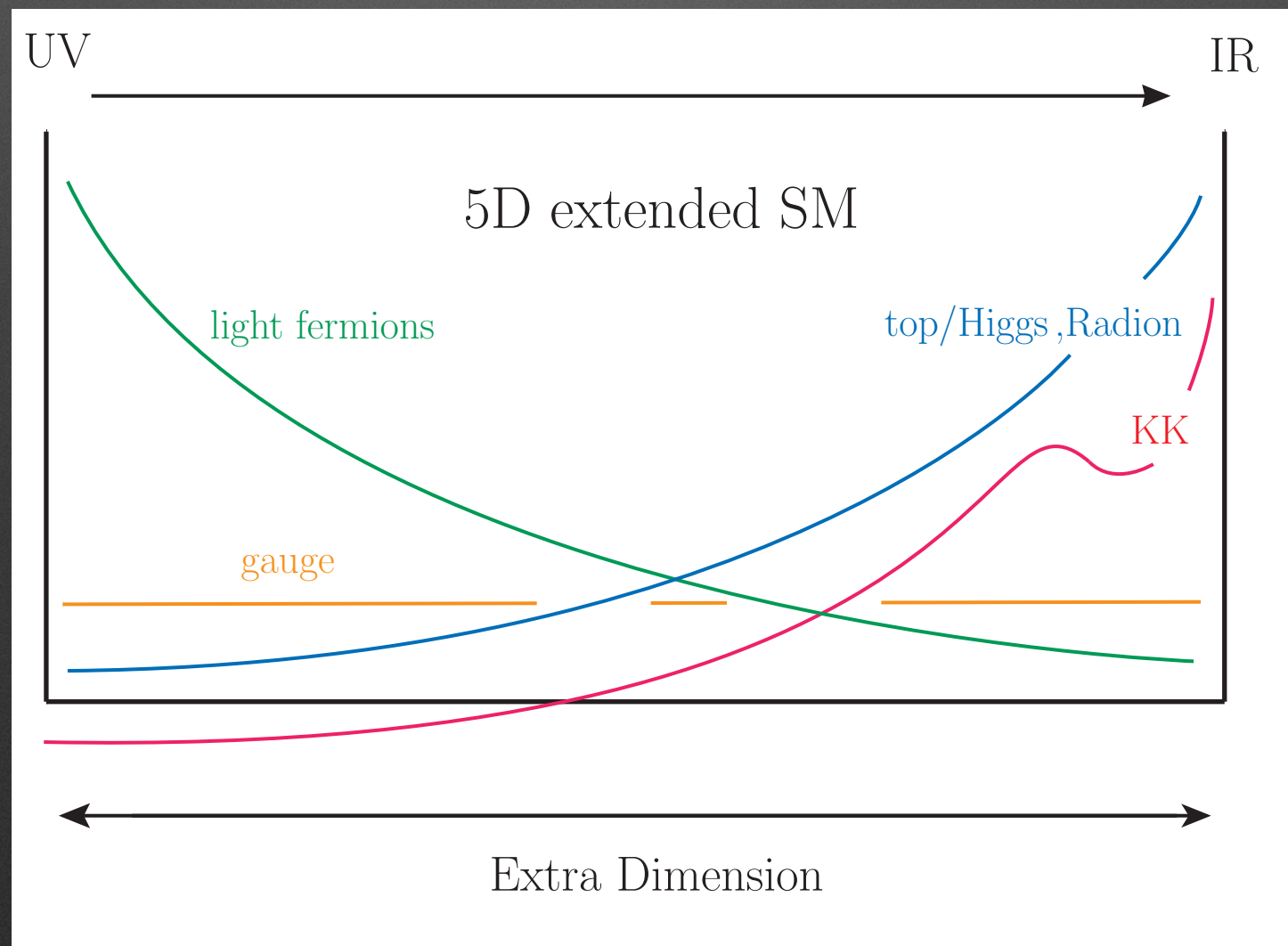
- “classic” search for boosted top/ $W/Z_{\text{long.}}/h$, using jet-substructure [for a review, see proceedings of “BOOST” workshops]

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

- KK scale $\sim O(10)\text{TeV}$  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



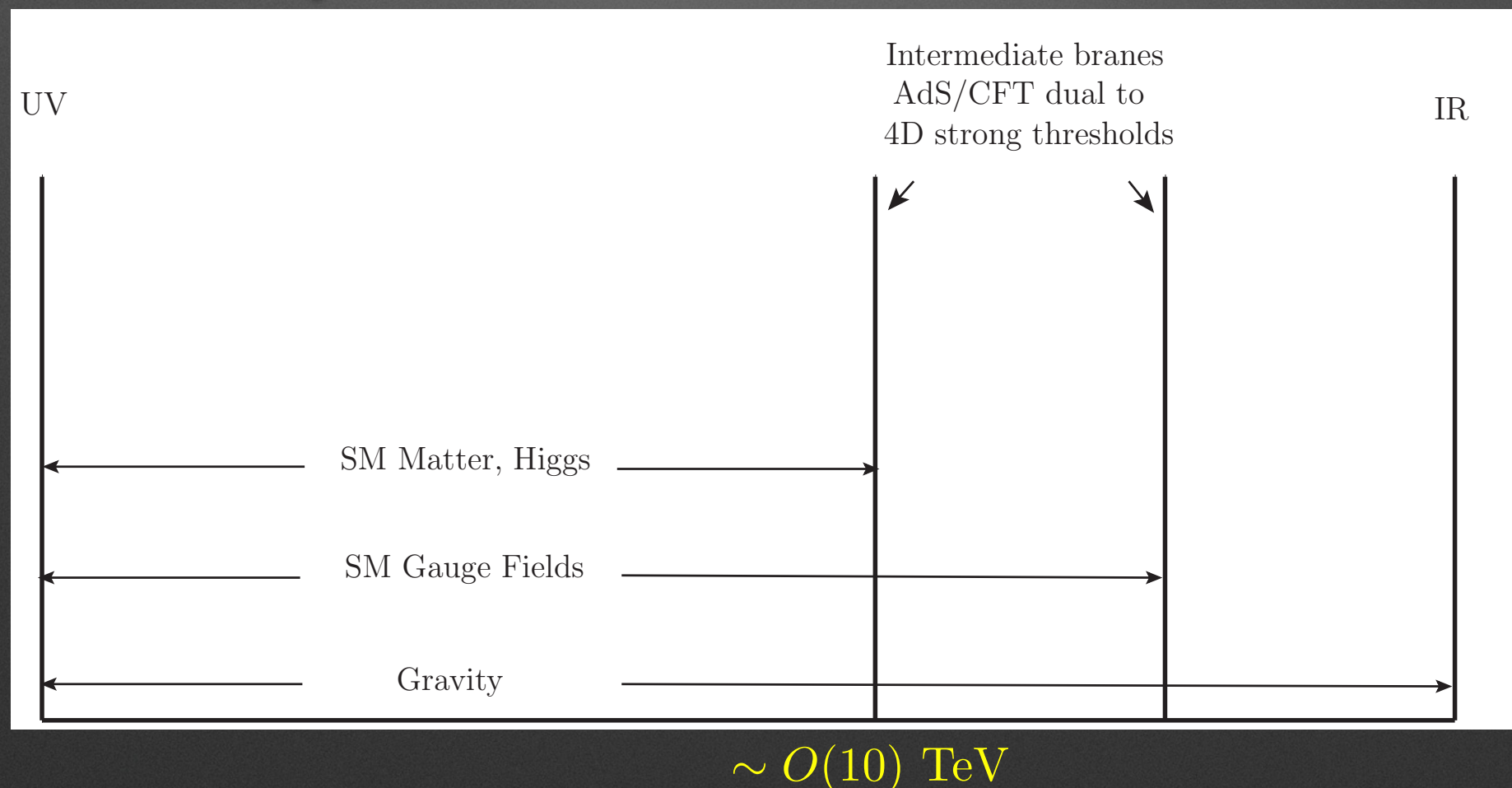
(...*end* of *review*, onto *new*...)

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!)



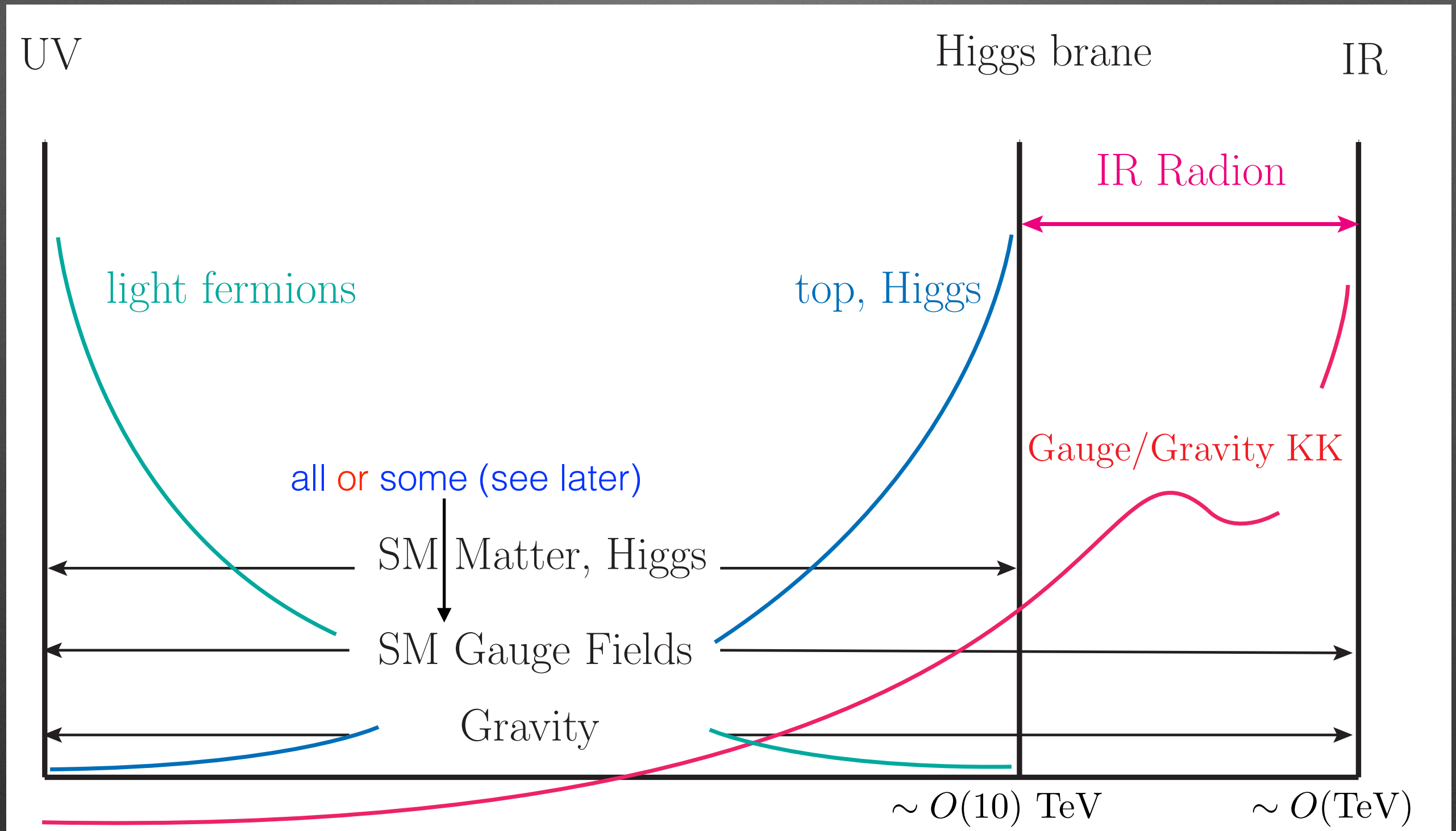
- way to model non-trivial IR region (more structure than simply one, featureless brane)

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...

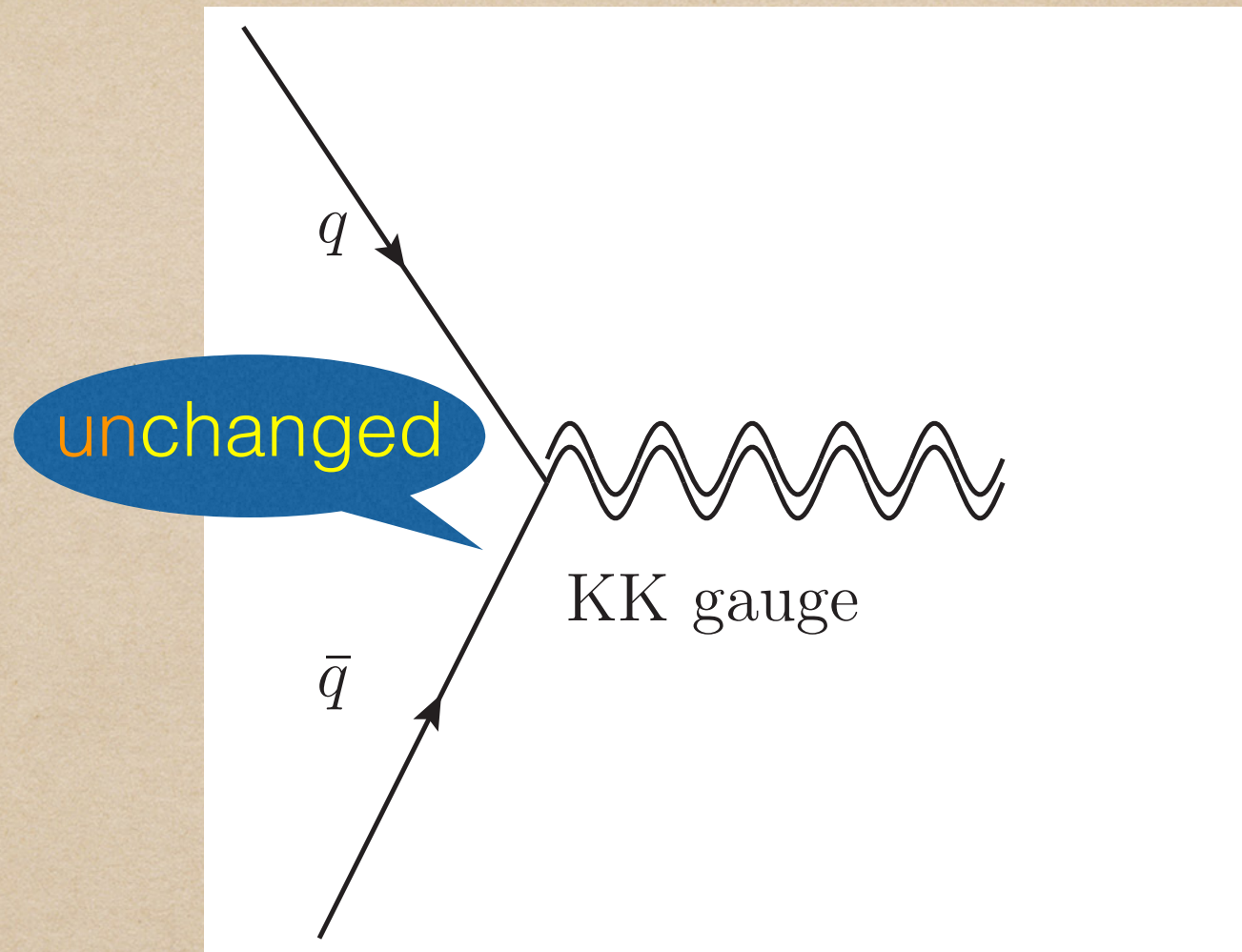


- **Gauge** fields in **entire** bulk (same as gravity) for **simplicity**
- (lightest) **gauge KK**, **radion** peak at (final) IR (**not** Higgs) brane

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**

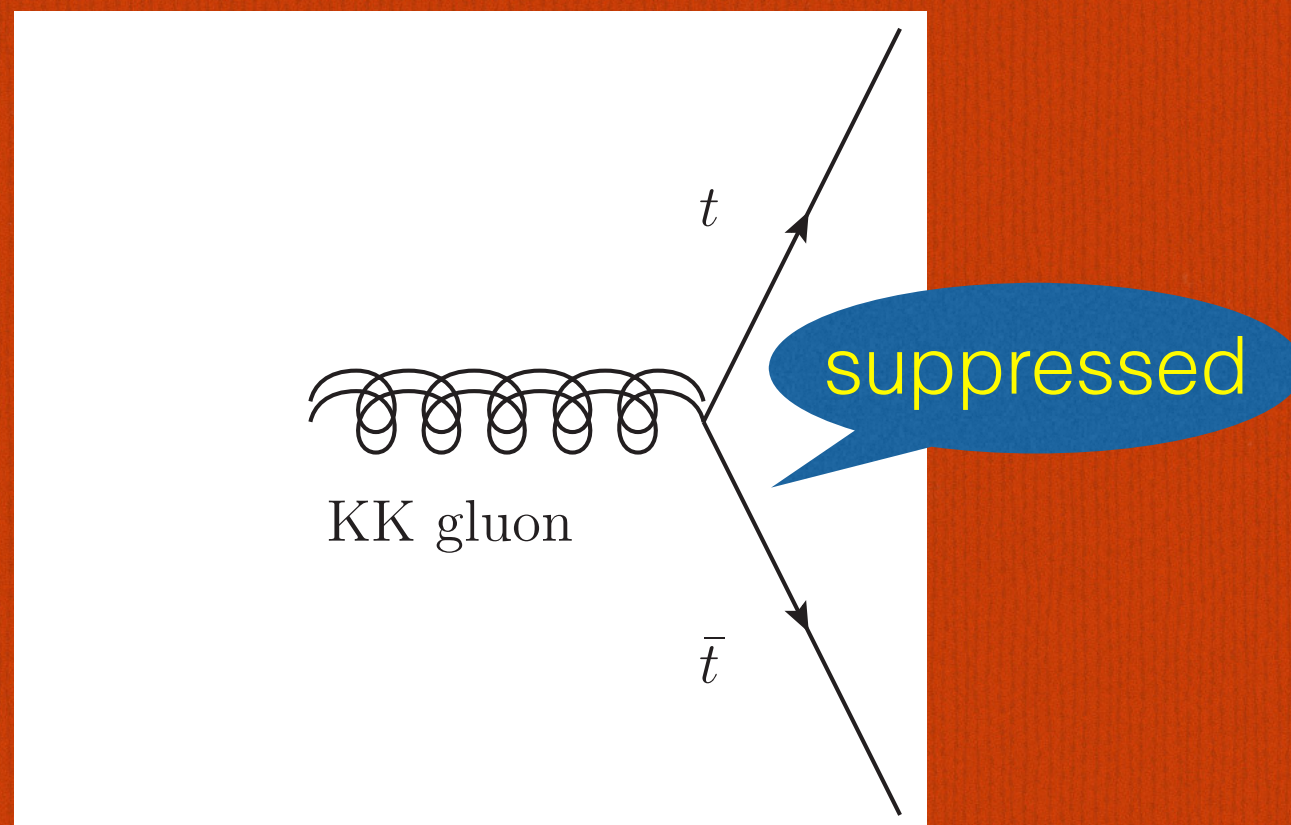


coupling $\sim \frac{g_{\text{SM}}^2}{g_{\text{KK}}}$, with $3 \lesssim g_{\text{KK}} \lesssim 6$

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

Usual dominant decay modes of gauge KK

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



all 3 near
TeV brane

universal

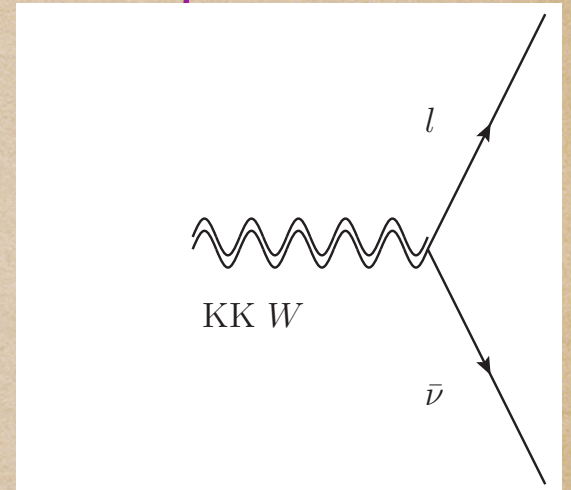
coupling $\sim g_{\text{KK}}$ (standard) $\rightarrow \frac{g_{\text{SM}}^2}{g_{\text{KK}}}$ (extended), with $3 \lesssim g_{\text{KK}} \lesssim 6$

- due to gauge KK “split” from top/Higgs

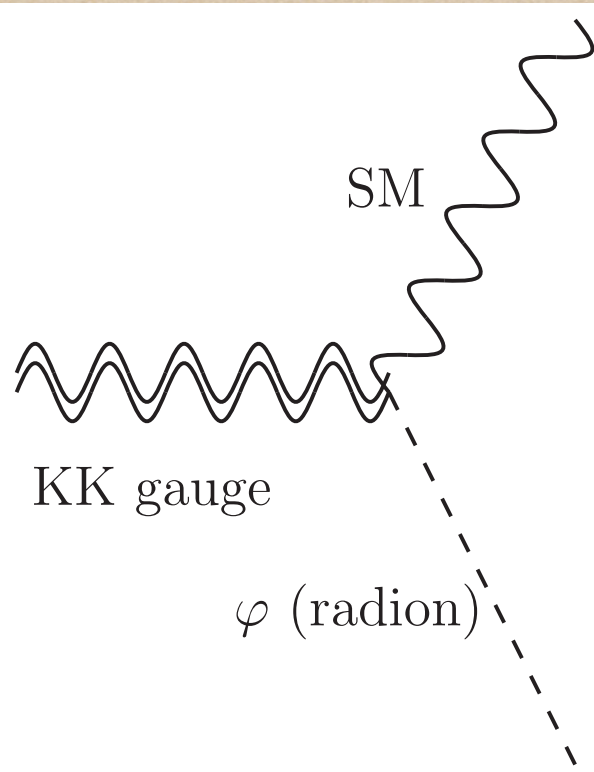
Other decay modes can then shine

[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)



- ◆ 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)

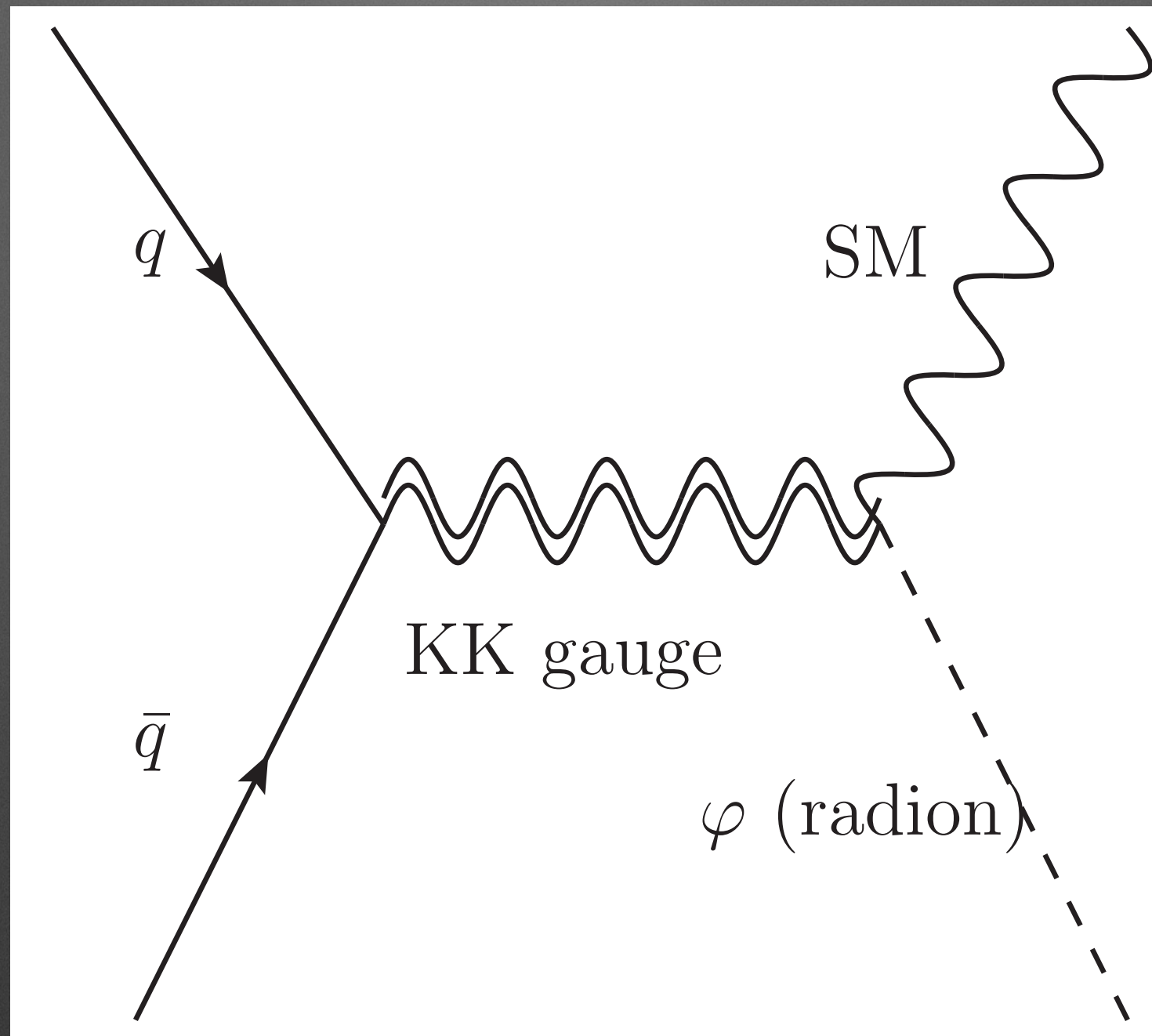


$$\sim g_{\text{SM}} \epsilon \text{ (with } \epsilon \lesssim 1)$$

related to stabilization

“New” *cascade* decay channel for
gauge KK: *tri*-bosons of various
kinds

Basic process (I): gauge KK decay to radion

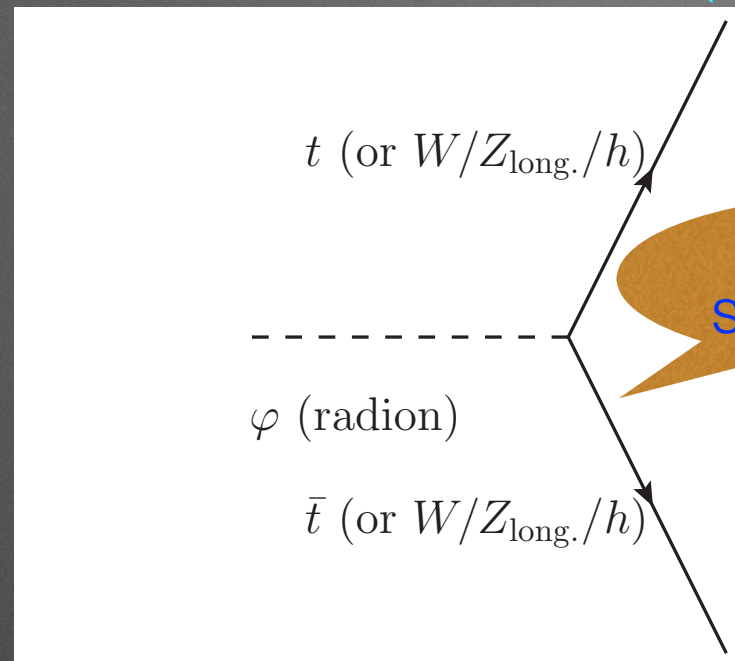


- Radion decay mode of **gauge KK** comparable to (or a bit larger than) decay into $q\bar{q}$ (or $l\nu$)
- **final** state depends on fate of **radion**

*Radion decays also
modified*

Radion (near **gauge** brane) “split” from top/Higgs

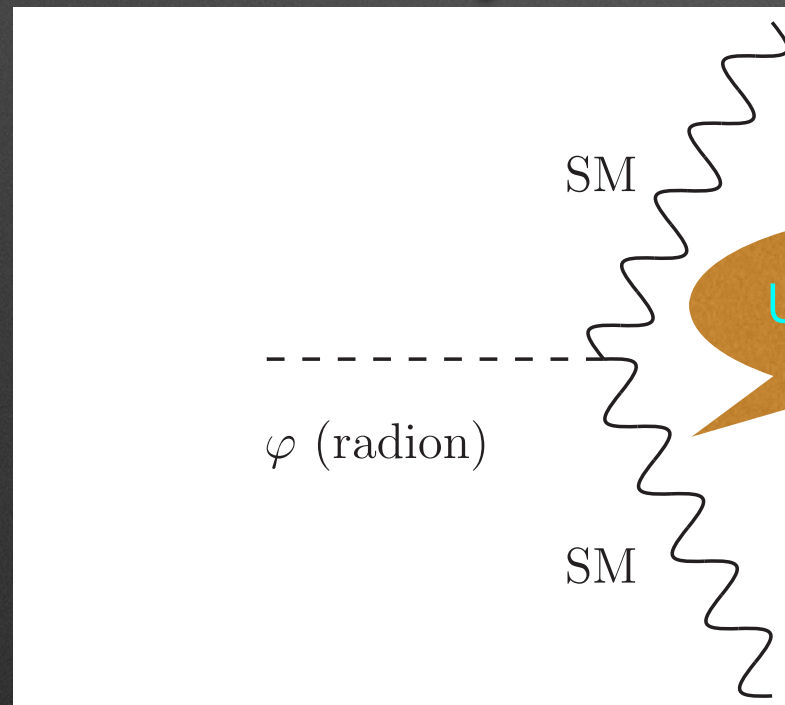
- Erstwhile dominant decays [$t\bar{t}$ (or $W/Z_{\text{long.}}/h$)] **highly suppressed**



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

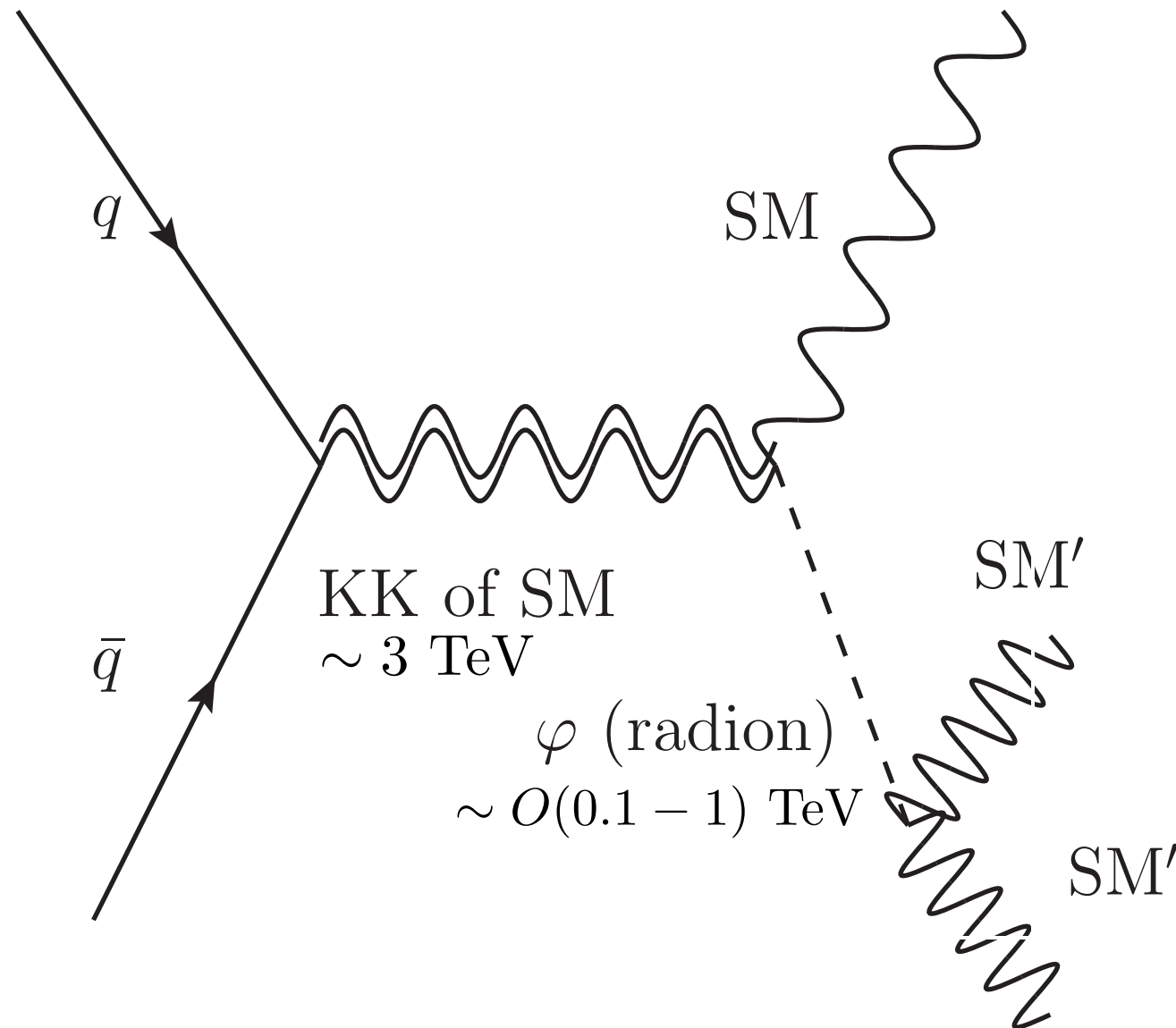



unchanged

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

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

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

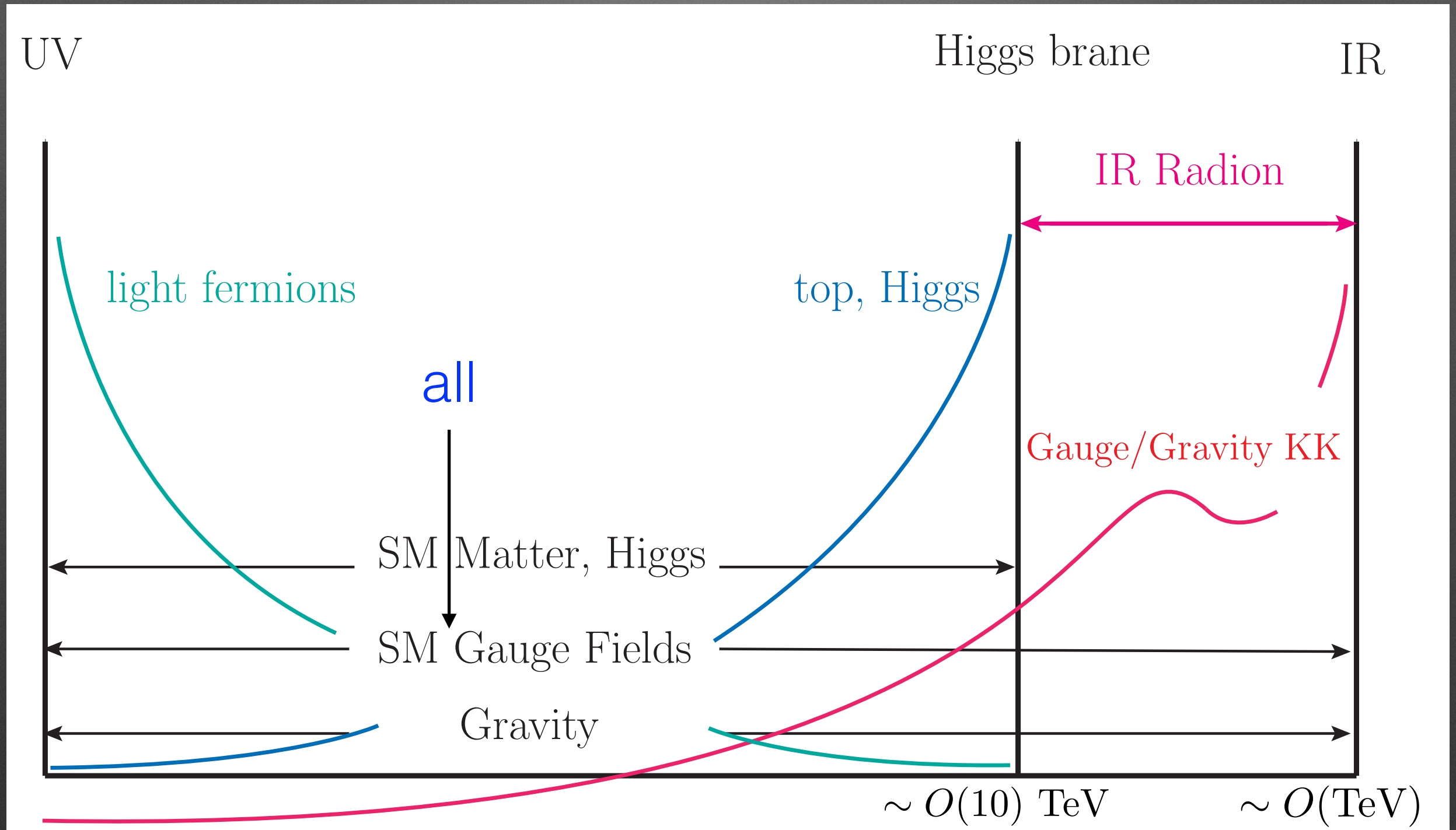


- radion heavy (not boosted) or light (boosted)  2 SM gauge bosons from its decay well-separated or merged
- more specific signals to come...

3 specific models:
(I). *All SM gauge fields in extended bulk*

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

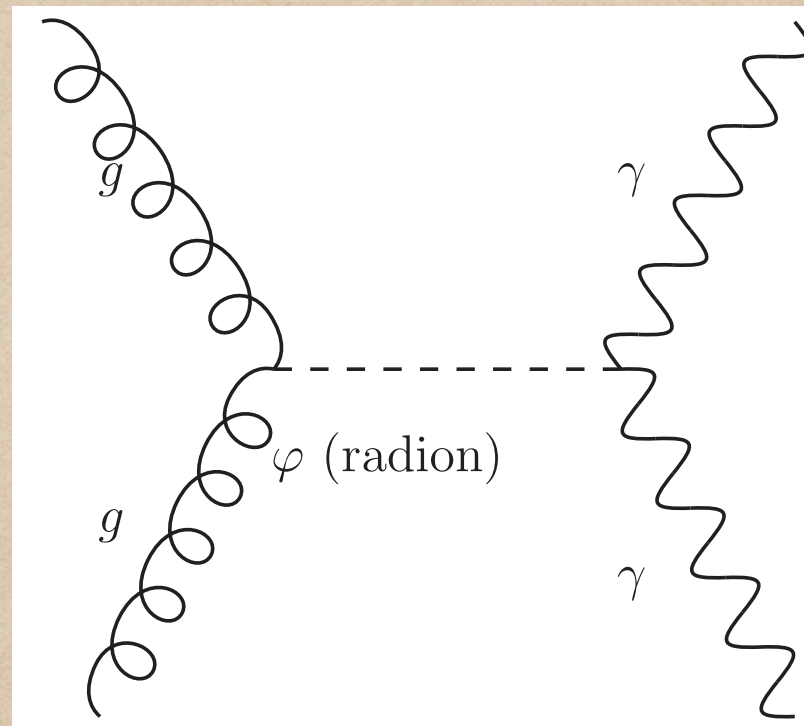
All extended model (I) at a glance...



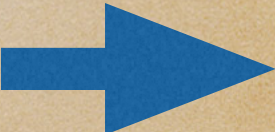
- Similar profile/mass for **QCD** vs. **EW** gauge (SM or KK)
- Role of SM or KK gauge bosons $\propto g_{\text{SM}}^2$

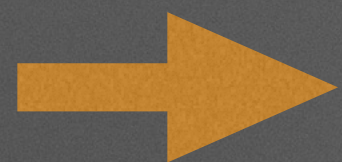
Light ($\lesssim 1$ TeV) radion **not** allowed

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



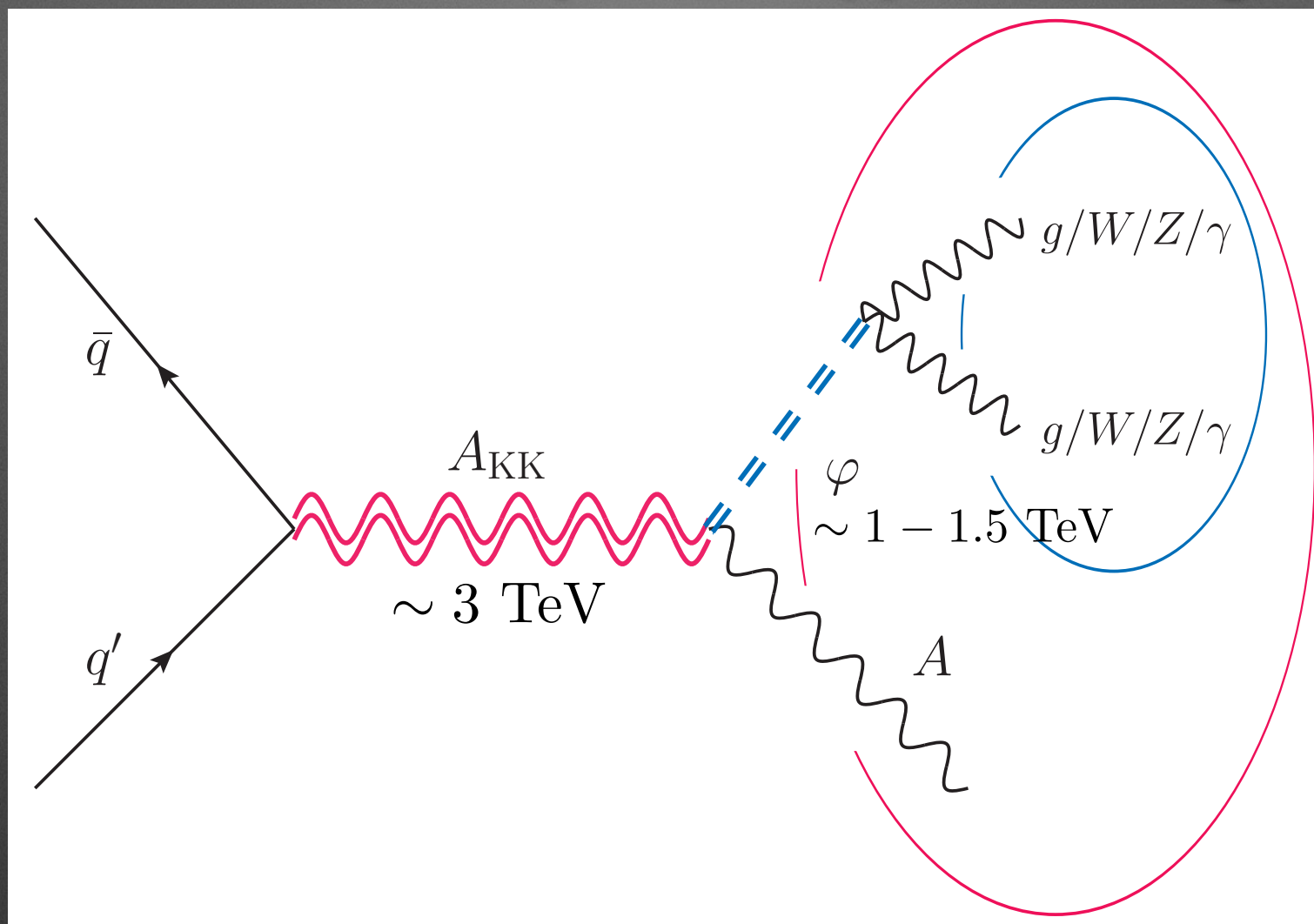
fixed at 3 TeV

- ◆ $\gtrsim 1.5$ 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)



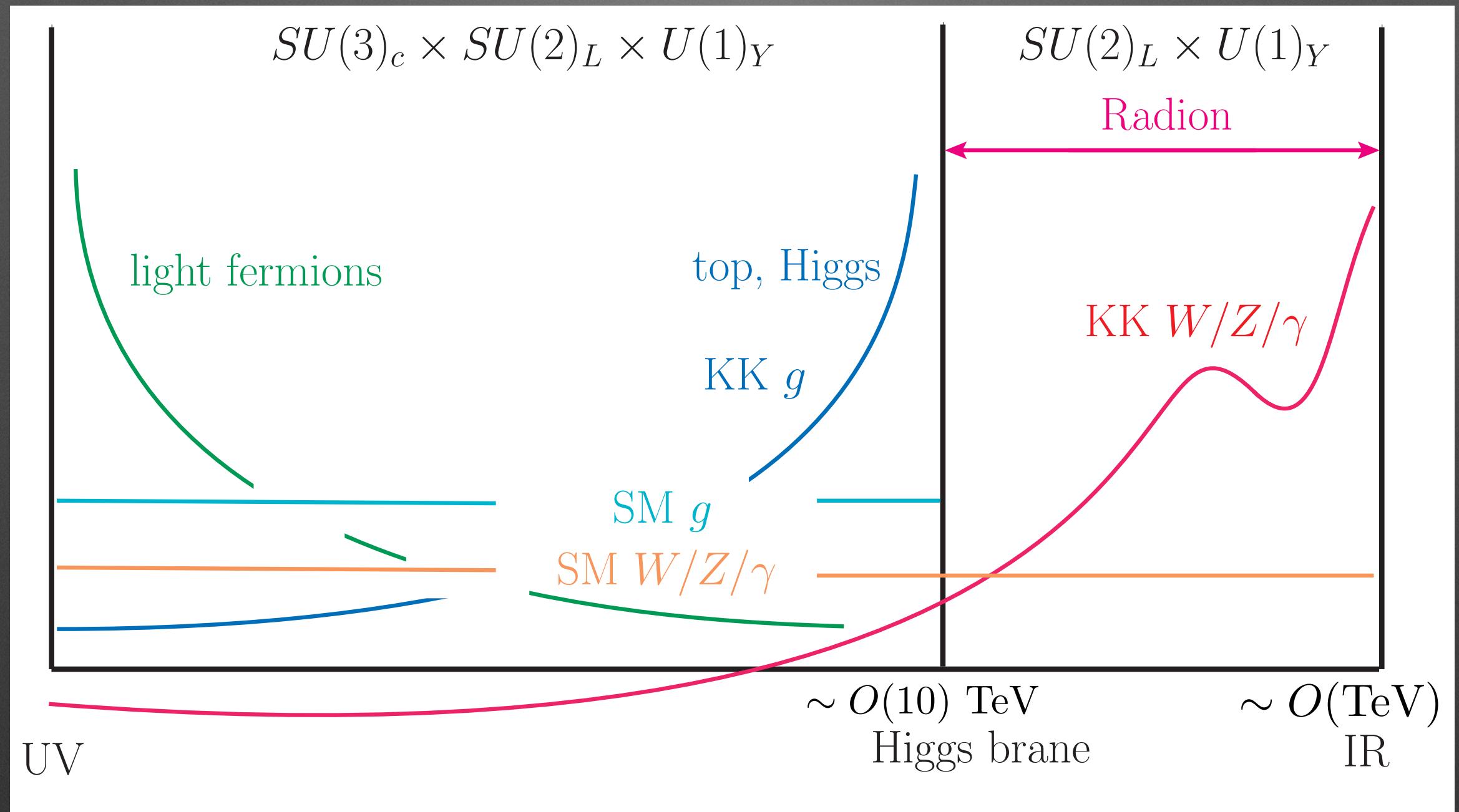
- **Largest** rate for tri-**gluon**/jet (based on KK production **and** radion decay)
- **Results** (including **background**, using **Delphes** etc.): observation of signal (**discovery** of **heavier** radion) with $\sim 300/\text{fb}$ for $\sim 3 \text{ TeV}$ KK **gluon** (and $\sim 1-1.5 \text{ TeV}$ radion); $\sim 3000/\text{fb}$ for **other** KK


(II). Only *EW* gauge fields in *extended* bulk

[...as “likely” as *all* in extended bulk as in model (I)...]

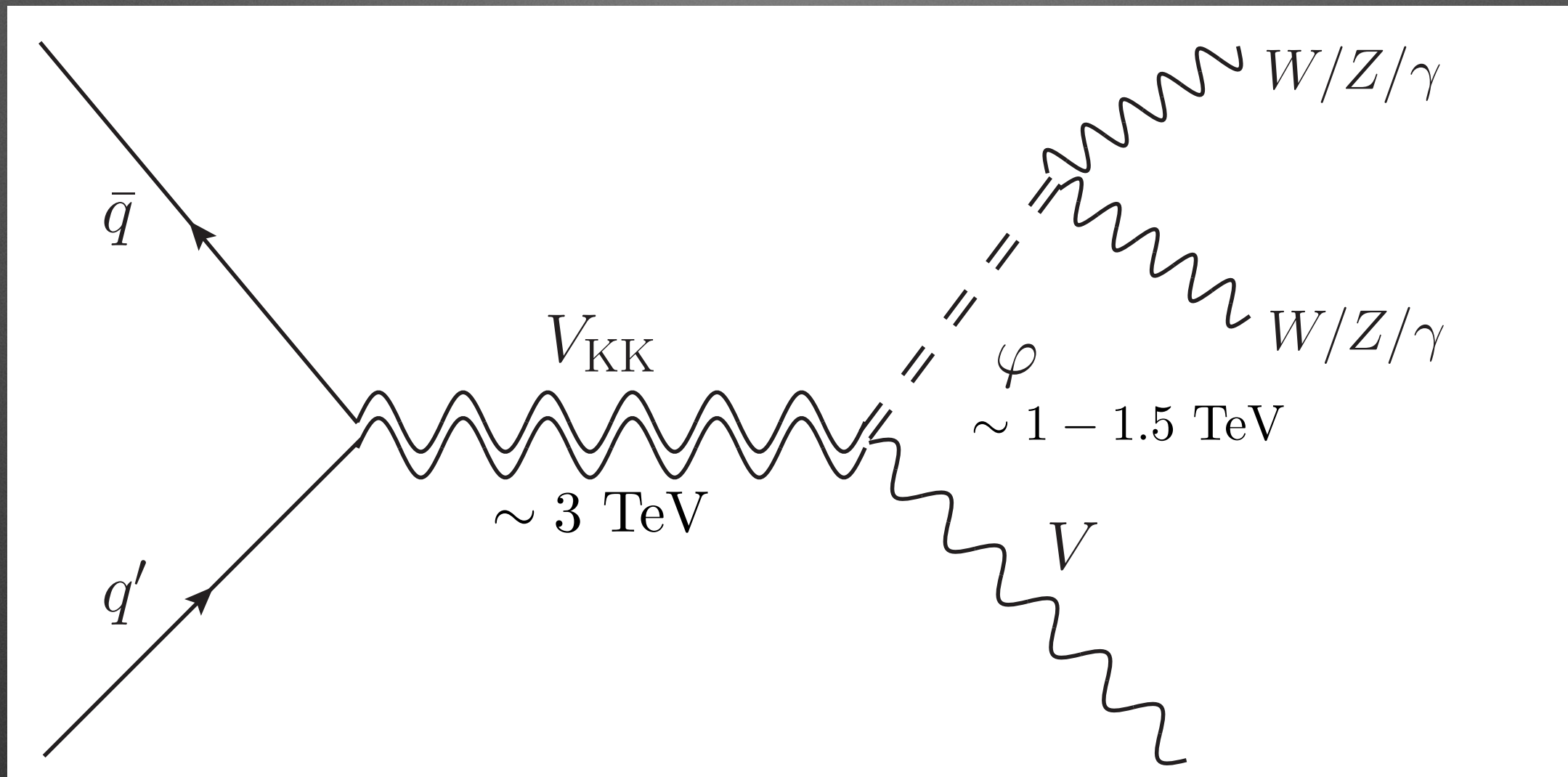
[KA, Collins, Du, Hong, Kim, Mishra (2017 and 2018)]

EW-extended model (II) at a glance...



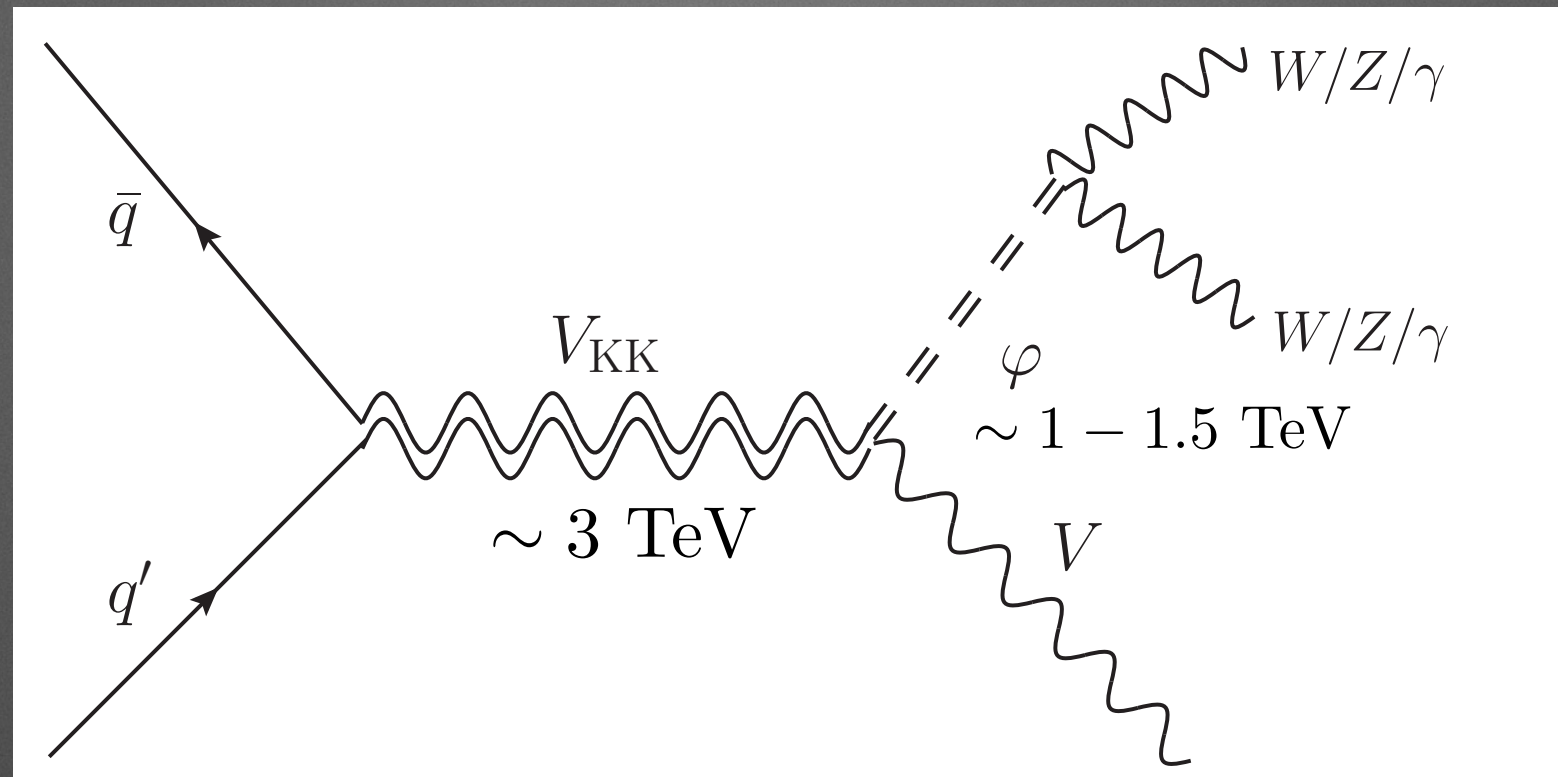
- **Gluons** (SM or KK) till $\sim O(10)$ TeV 
out of the game: KK gluon beyond LHC reach,
radion “split” from gluons


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



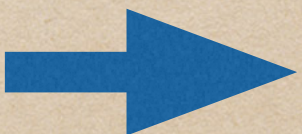
- 3 isolated $W/Z/\gamma$ (all W/Z boosted)
- largest rate for WWW (based on production of gauge KK and radion decay)

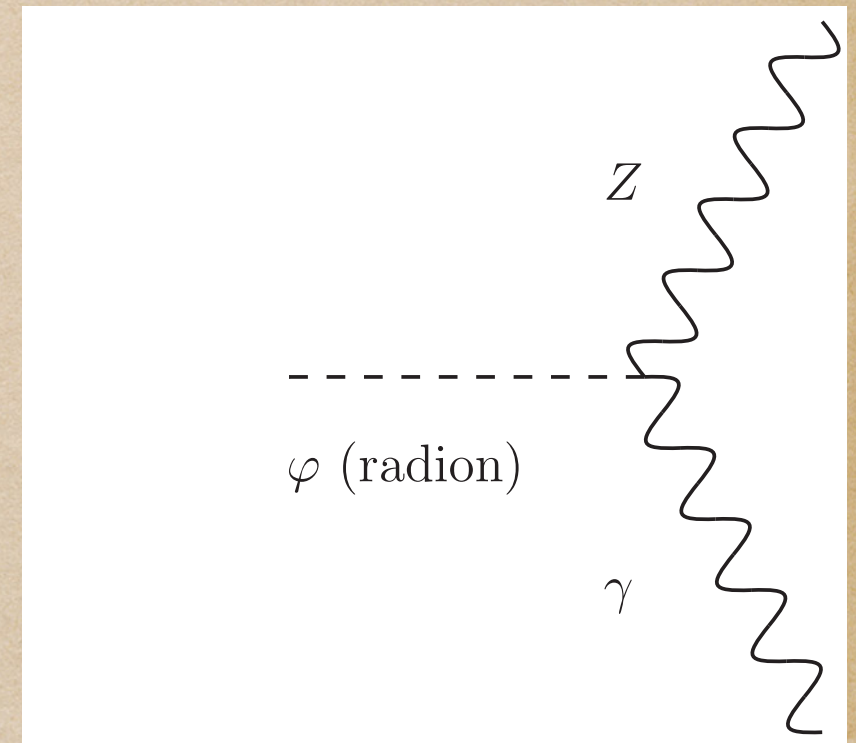
Tri-**EW**-gauge boson signals for **heavy** radion (II)



- Existing di-boson ($WW/WW/ZZ$) 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 $\sim 1-1.5 \text{ TeV}$ **radion** from decay of $\sim 3 \text{ TeV}$ KK W with $O(100)/\text{fb}$

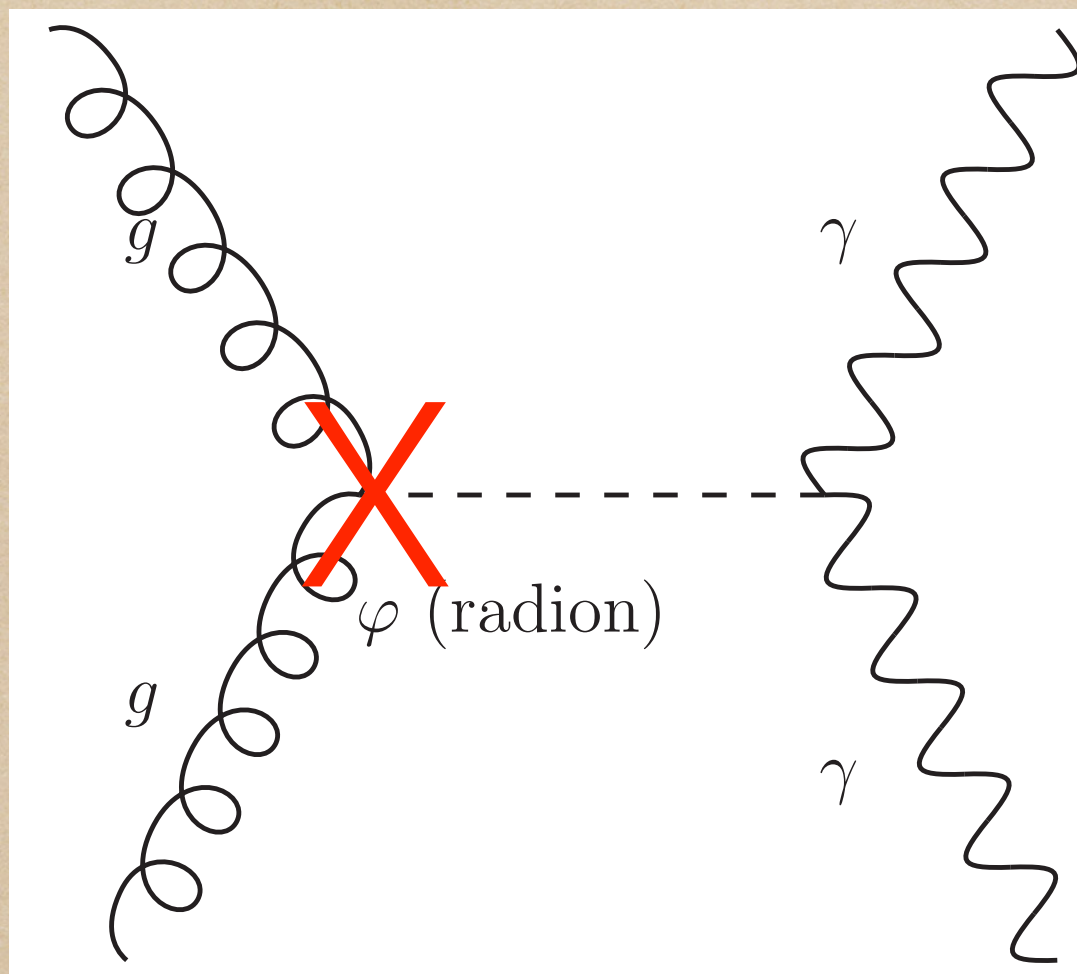
"New" radion decay: (Z + photon)


- ◆ **vanishes** in **minimal** model (focus thus far), but present in general
- ◆ also for **standard** (2 branes) model
- ◆ **hierarchy** of radion BR's:
 $WW > ZZ > (Z + \text{photon}) > \text{di-photon}$
- ◆ **boosted** Z (fat jet) for **heavy** radion 
background for (Z + photon) vs. di-photon might be less compared to SM Higgs ($Z \rightarrow$ **resolved** jets, with larger QCD background)
- ◆ **extended** model (radion from **KK** W): (**W + Z + photon**) signal



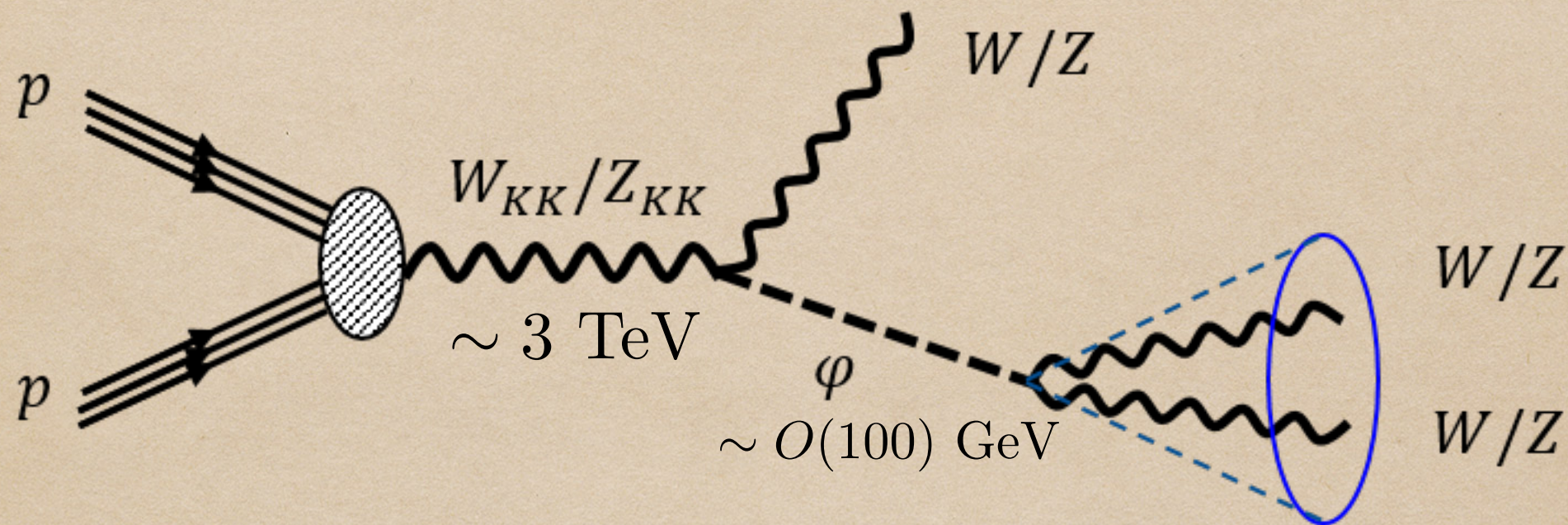
New: **light** [$\sim O(100)$ GeV] radion allowed


(even **lighter** is **unnatural**)



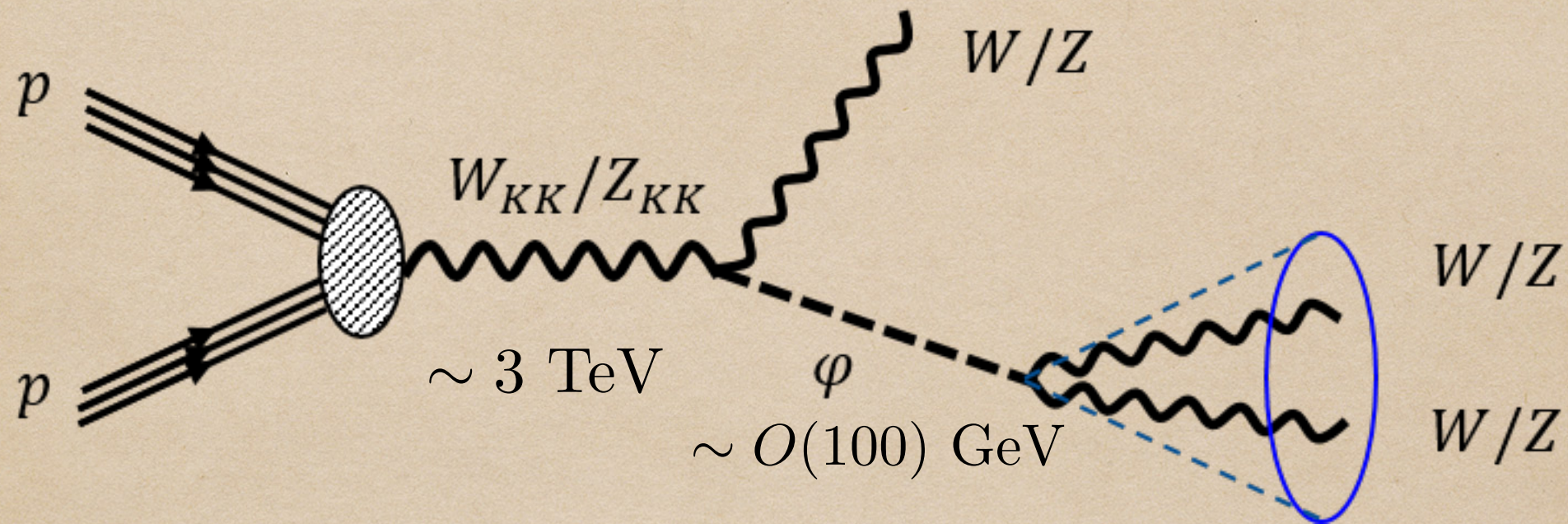
- ◆ Usual dominant **direct production** turned **off** (even if radion BR to di-photon enhanced: decay into EW only), **WW** fusion small **difficult** to **discover** via this channel 
- ◆ **Instead**, radion **dominantly** produced (**boosted**) from **decay** of a few TeV **gauge KK** (its coupling to $q\bar{q}$ **significant**/**unchanged**)

Boosted/merged **di**-boson [$+$ (boosted) boson] (1)



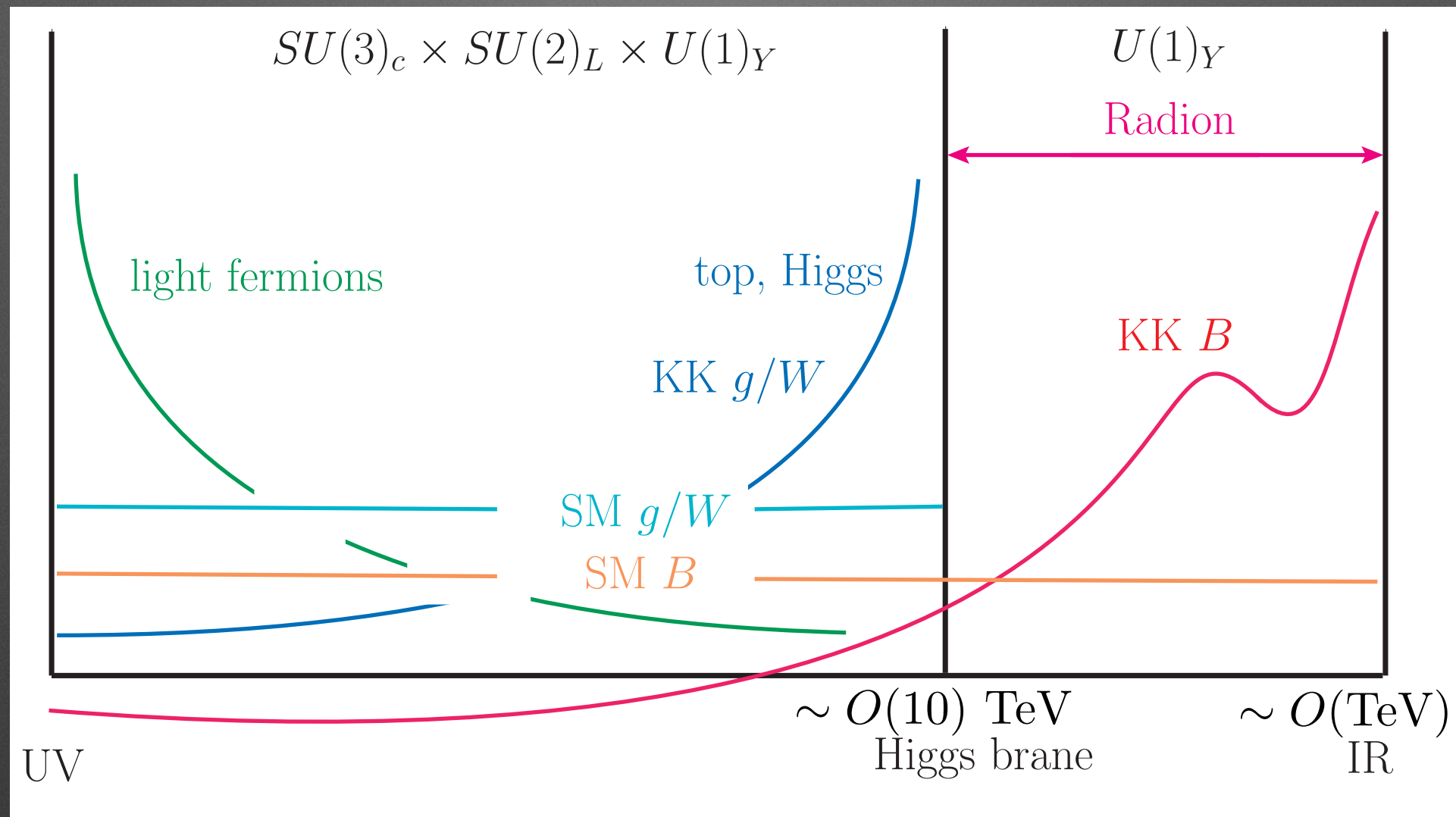
- ◆ 4-prong **fat**-jet (or lepton buried in 2-prong fat-jet), with mass **not** $W/Z/\text{Higgs}/\text{top}$  likely "**missed**" with current searches (need **dedicated** algorithm)

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



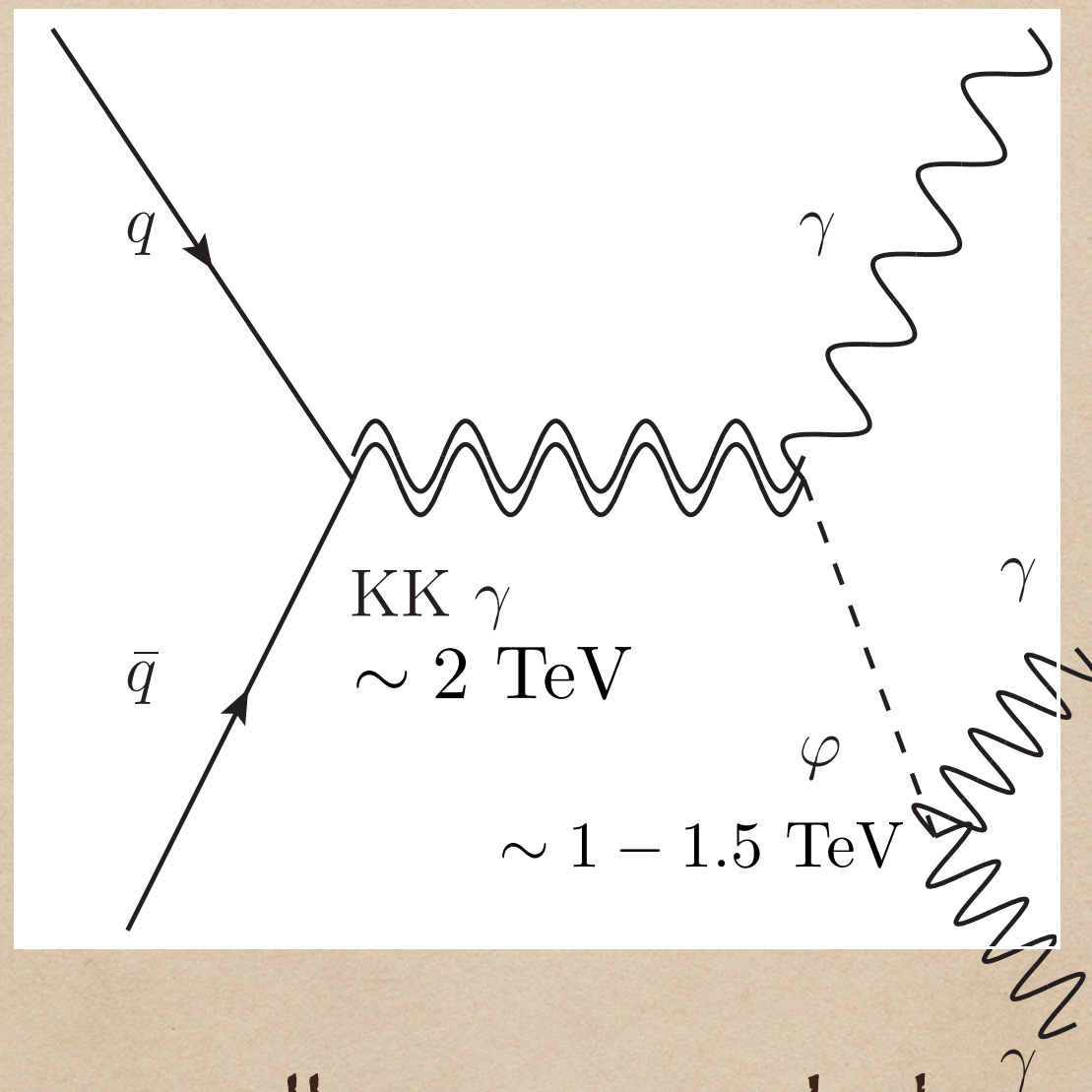
- ◆ 2 resonances: **fat**-jet **and** [fat-jet + (isolated) W]
- ◆ Results (including **background**, using **Delphes** etc.):
discovery of (light) **radion** from decay of $\sim 3 \text{ TeV}$ KK W
with $\sim 300/\text{fb}$ (**combining** fully-hadronic and semi-leptonic channels)


Only **hypercharge** in **extended** bulk



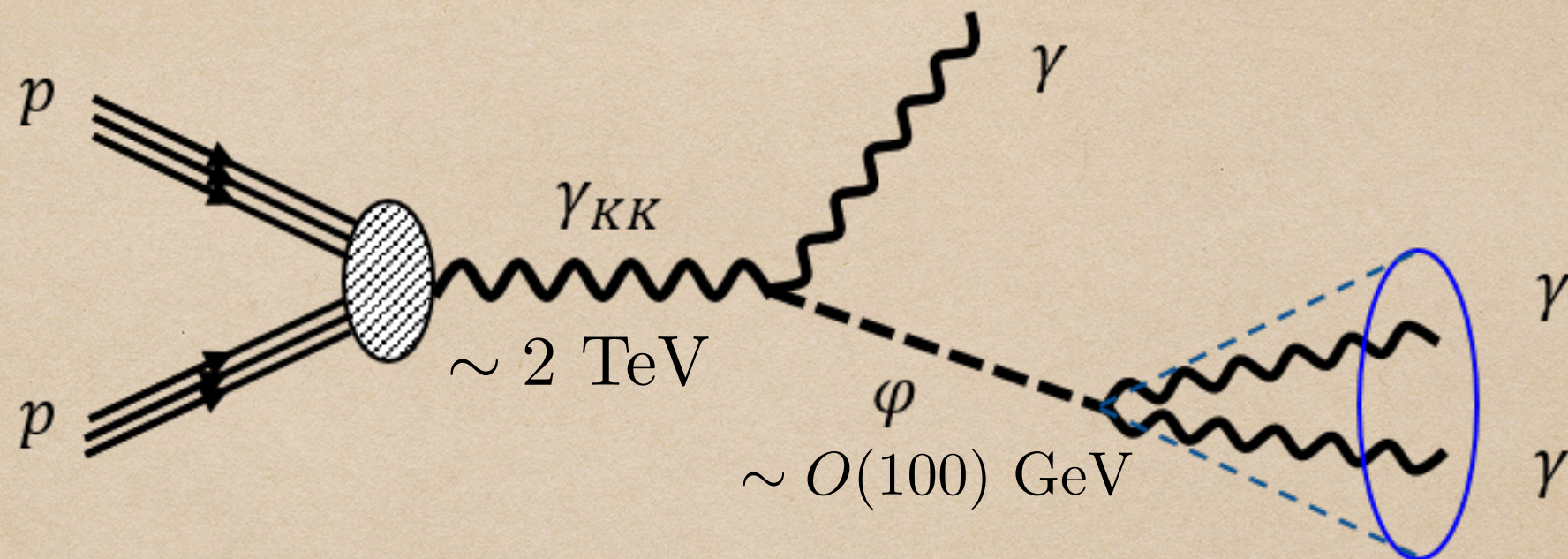
- At a glance: **gluons/ W/Z** out of picture...
- Only **KK** hypercharge (\sim photon + bit of Z)
- **Radion** decays into di-photon [+ bit into ZZ and (Z + photon)]

Tri-photon (with 2 resonances) ...



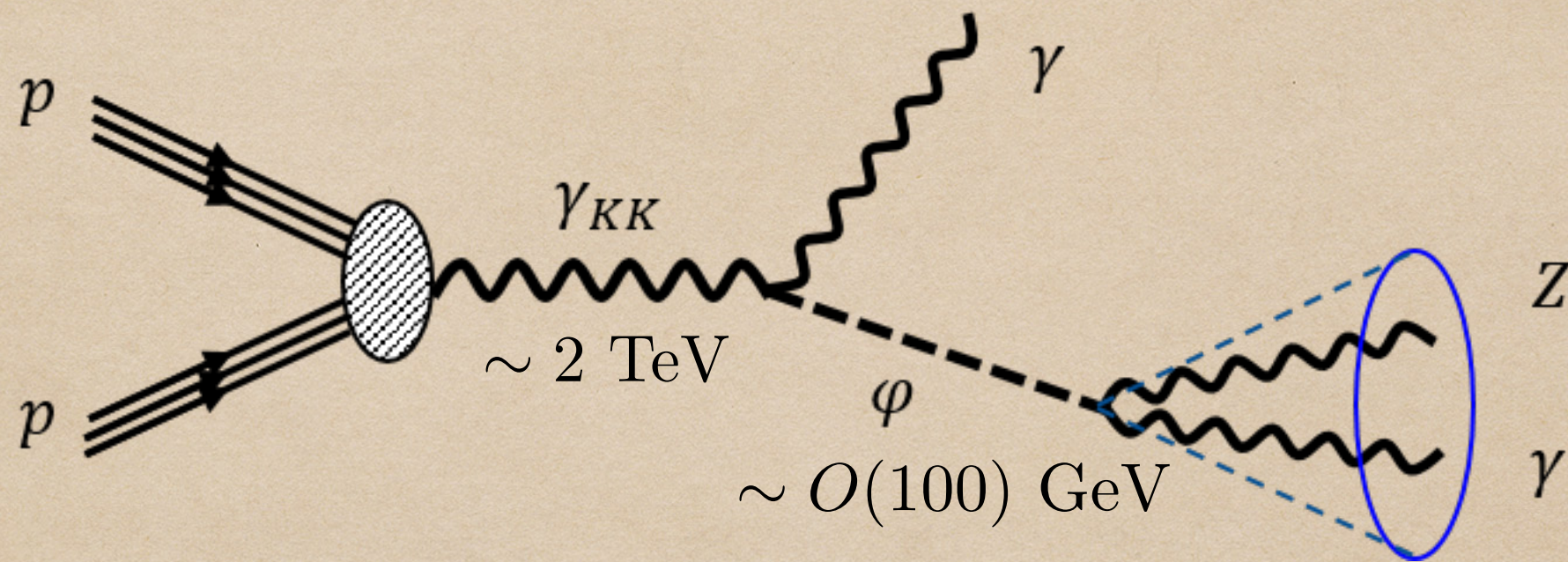
- ◆ Heavy radion: 3 well-separated photons 
negligible background, but combinatorial ambiguity
motivates dedicated search

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



- ◆ Light [$\sim O(100) \text{ GeV}$], 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 ($Z + \text{photon}$)

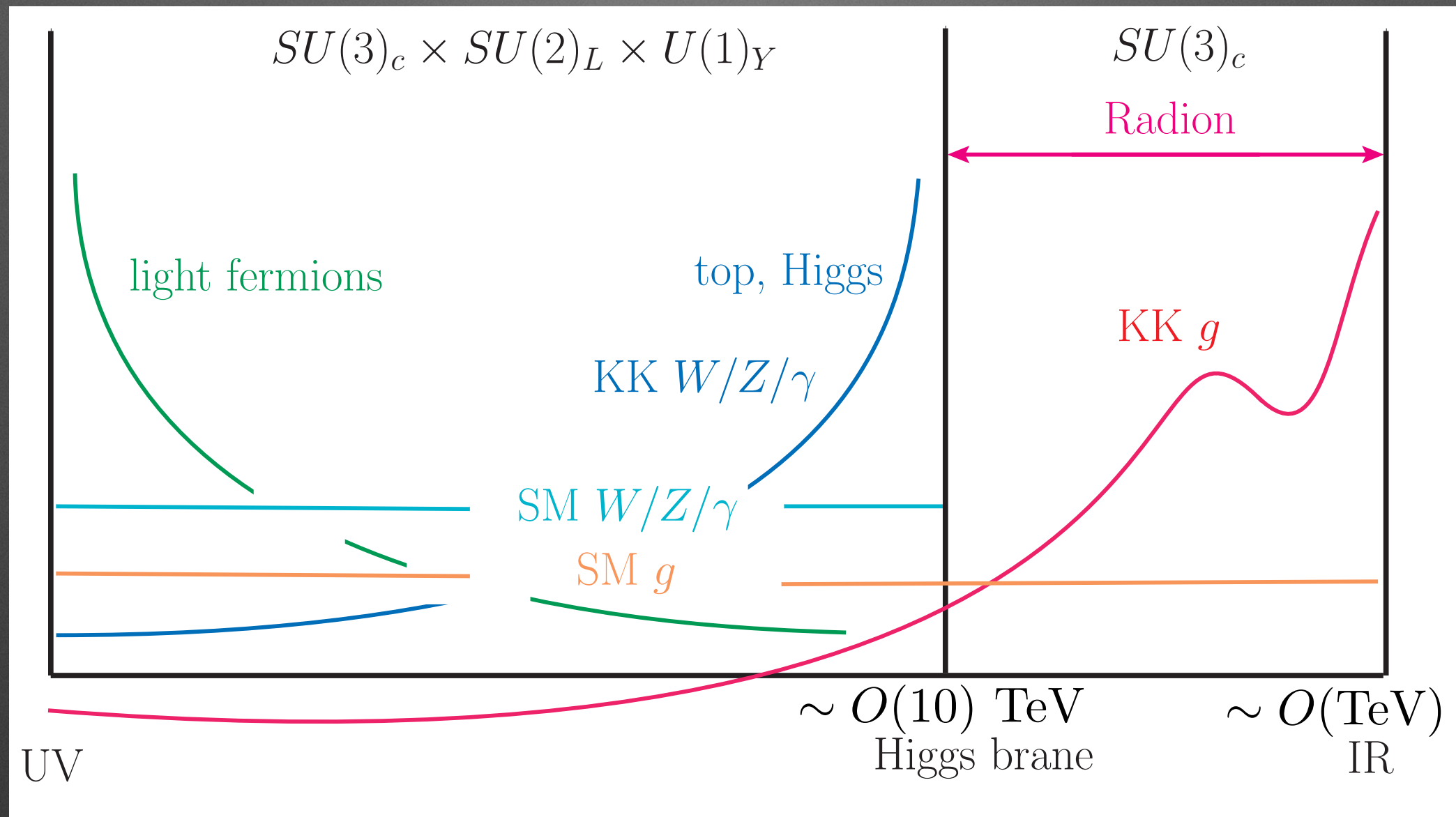


- ◆ from **light** radion decay
- ◆ photon inside Z -jet (hadronic) or (photon + leptons) "jet"

*(III). Only QCD in extended
bulk*

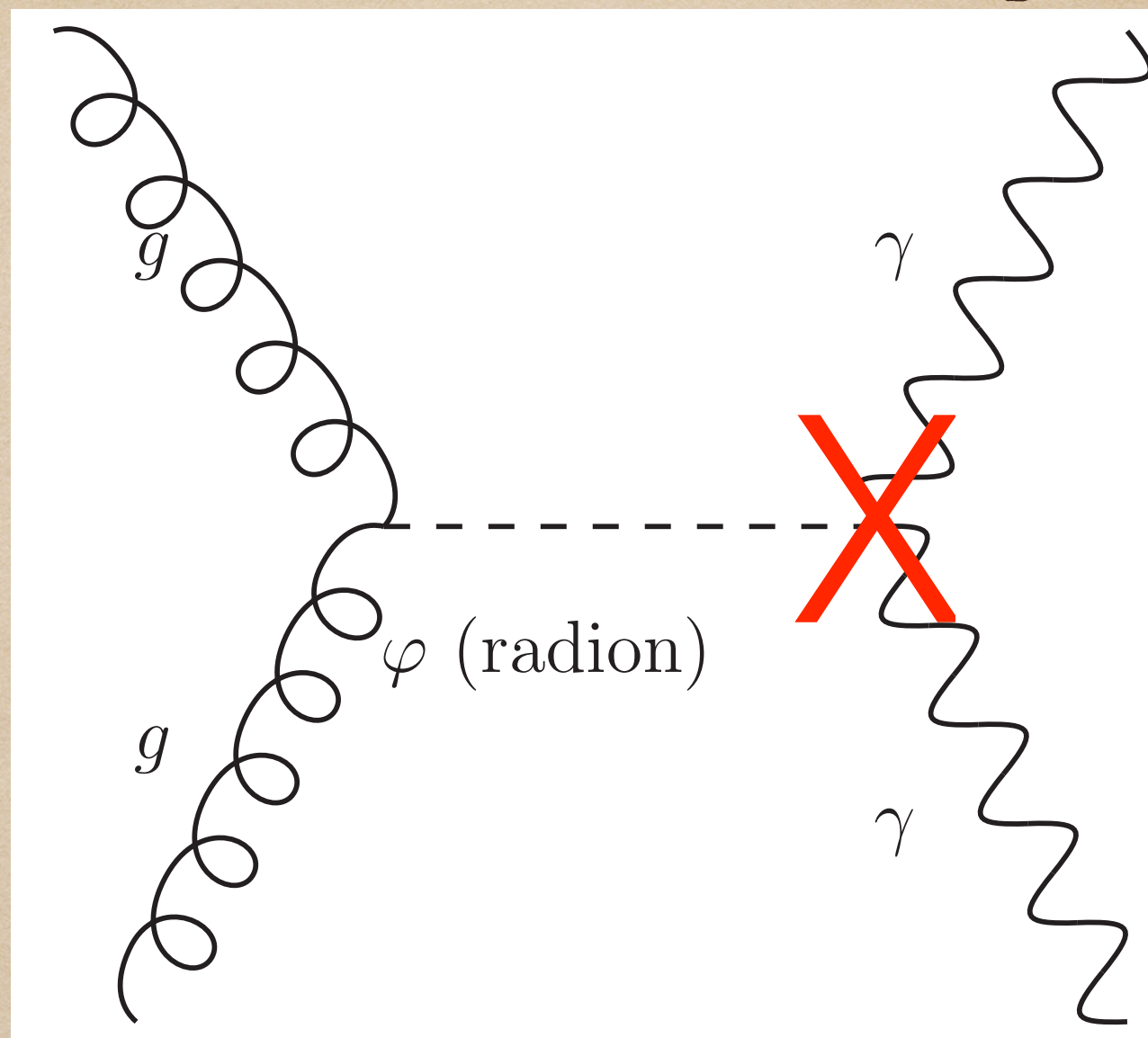
[KA, Collins, Du, Hong, Kim, Mishra (unpublished note)]

QCD-extended model (III) at a glance...



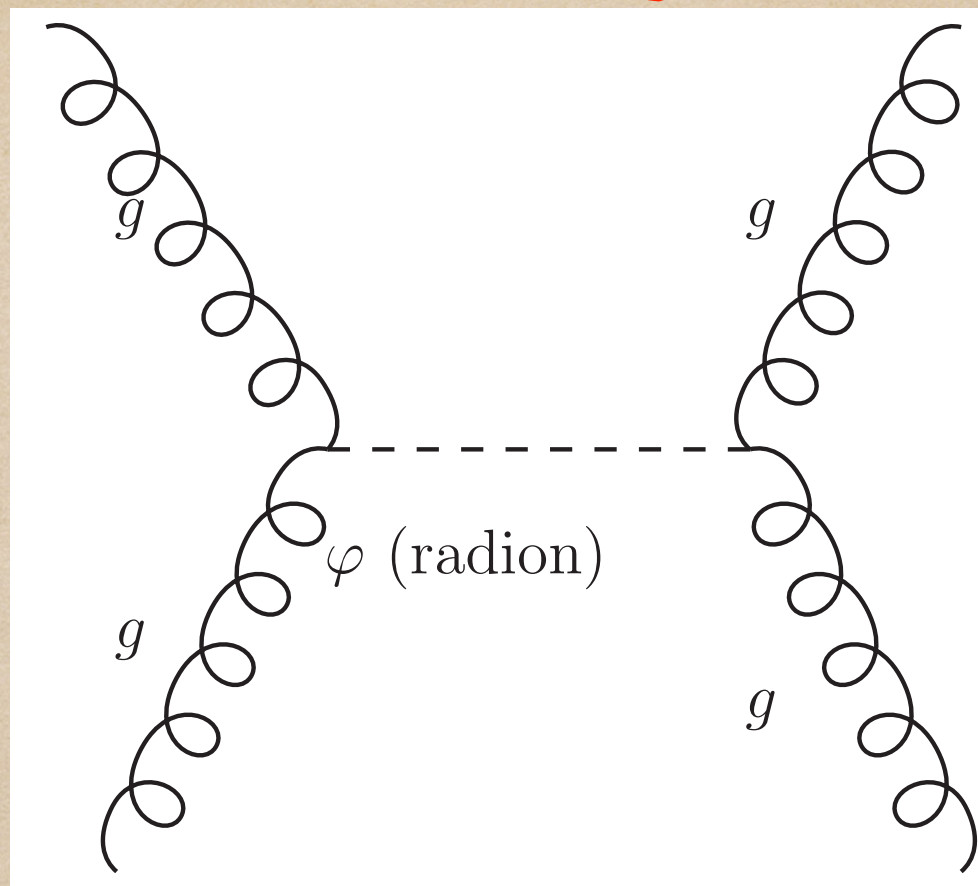
- **EW** gauge bosons (SM or KK) till $\sim O(10)$ TeV \longrightarrow out of action
- **Heavy** radion as in case (I): (well-separated) tri-gluon/jet

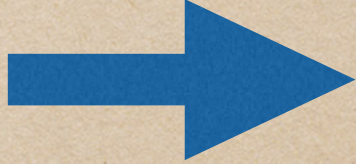
Light radion [$\sim O(100)$ GeV] (again) allowed



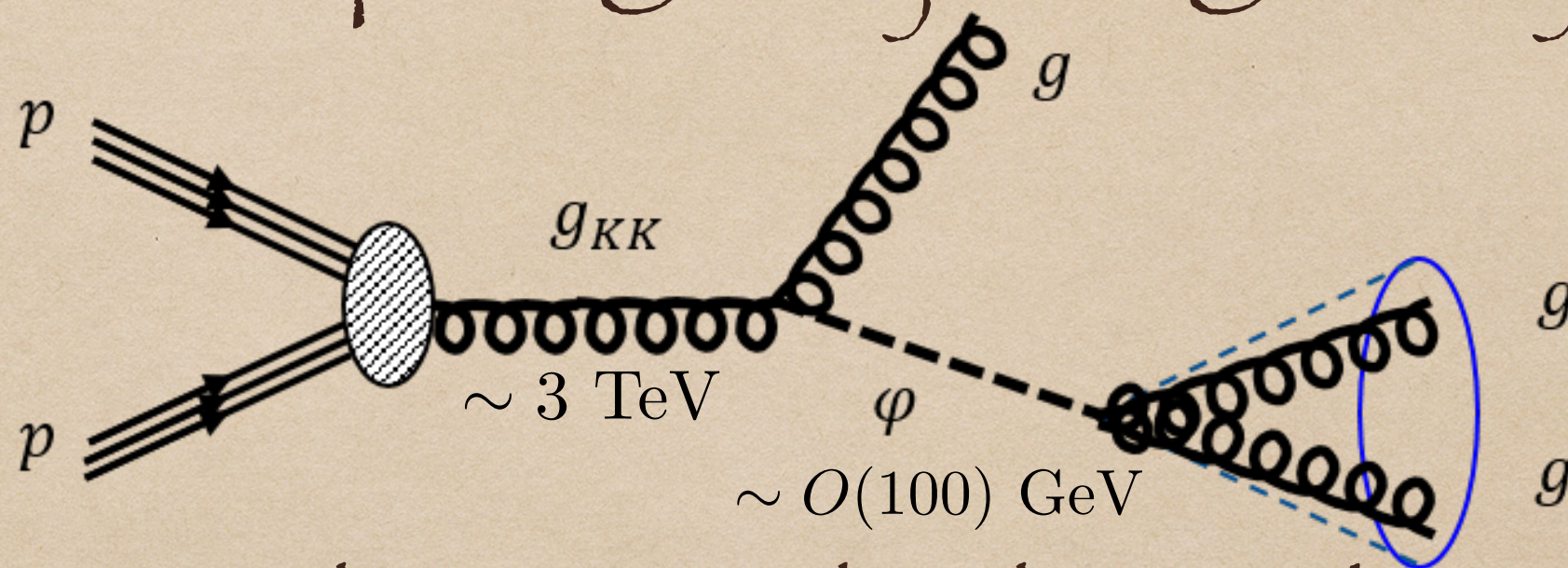
- ◆ Now production **unchanged**, but **decay** to di-**photon** turned **off** (radion “split” from EW gauge bosons)

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 $h \rightarrow b\bar{b}$) or...

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

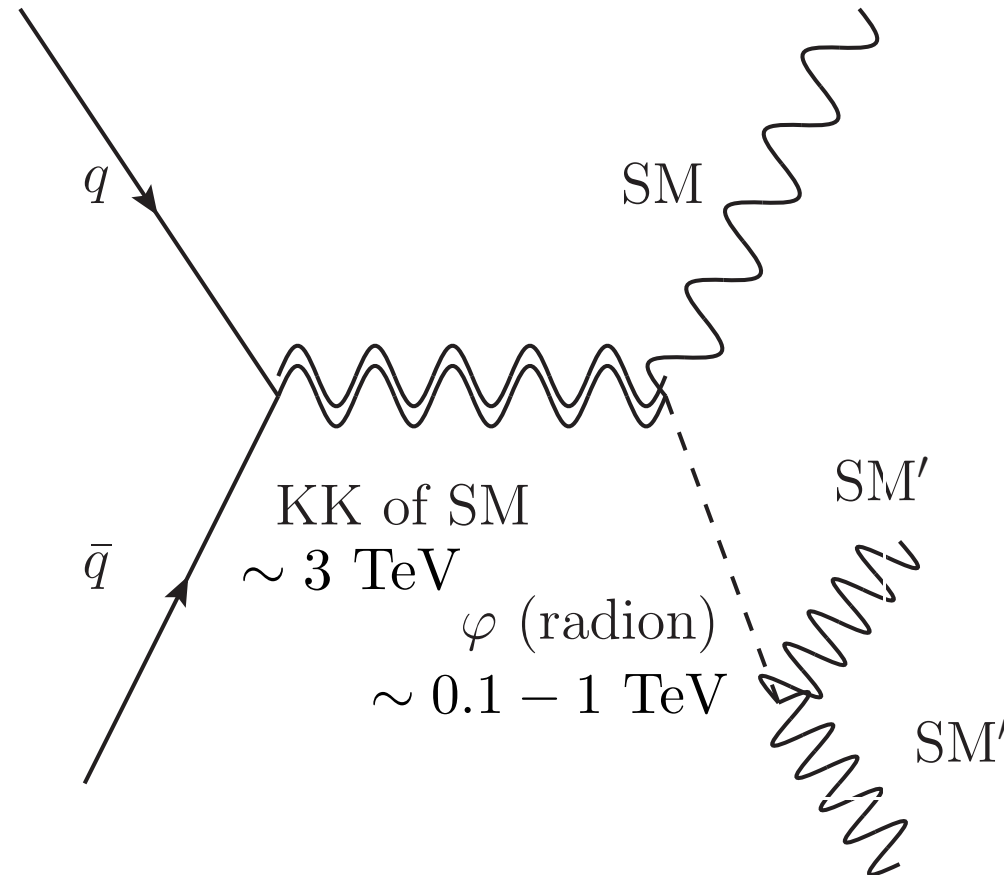


- ◆ **different** (N-subjettiness) than boosted/merged $q\bar{q}$ (latter studied, e.g., light Z' : CMS -PAS-EXO-17-001) \rightarrow **dedicated** search required
- ◆ 2 resonances: fat-jet **and** [fat-jet + (isolated) jet], use to **suppress** background

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 (~ 1 TeV), but via **KK gluon** (fixing that mass at ~ 3 TeV) instead if **heavier**

Summary table/diagram



Signal features \rightarrow (gauge KK $\sim 3 \text{ TeV}$) Radion mass \downarrow	General topology	Which gauge bosons <i>can</i> “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 ($\gtrsim 1 \text{ TeV}$)	Tri-boson, with 2 resonances: 2-particle (radion) & 3-particle (gauge KK)	gluons <i>and/or</i> EW	<i>Mixture</i> of gluons and EW gauge bosons (3 gluon/jet is largest)	<i>Mixture</i> of $W/Z/\gamma$ (WWW is largest): for WWW etc., <i>combinatorics</i> makes <i>existing</i> di-boson search <i>inefficient</i>	<i>Only 3</i> gluon/jet: <i>combinatorics</i> makes <i>existing</i> di-jet search <i>inefficient</i>
Light $O(100) \text{ GeV}$	isolated boson + <i>boosted/merged di</i> -boson resonance (radion) (combined resonance: gauge KK)	<i>Either</i> gluons <i>or</i> EW, i.e., <i>not</i> both	<i>not</i> possible (ruled out by di-photon searches)	$W/Z/\gamma$ + <i>boosted/merged</i> $WW/ZZ/Z\gamma/\gamma\gamma$: 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 + <i>boosted/merged di</i> -gluon: <i>different</i> (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?!

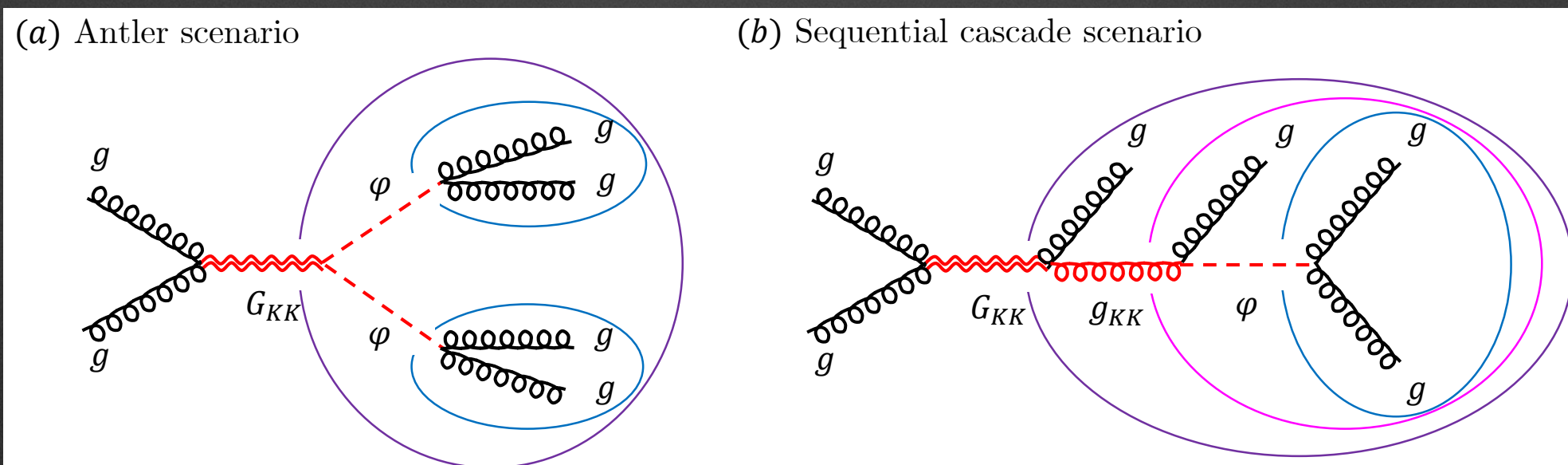
KK graviton

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

Quadri-boson signals from **KK**graviton

[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 $\sim \text{TeV}$): $SU(2)_R \times U(1)_{B-L} \rightarrow U(1)_Y$ using extended scalar sector
- (one of) **standard** signals: W_R^\pm and Z' [**extra** $U(1)$]:

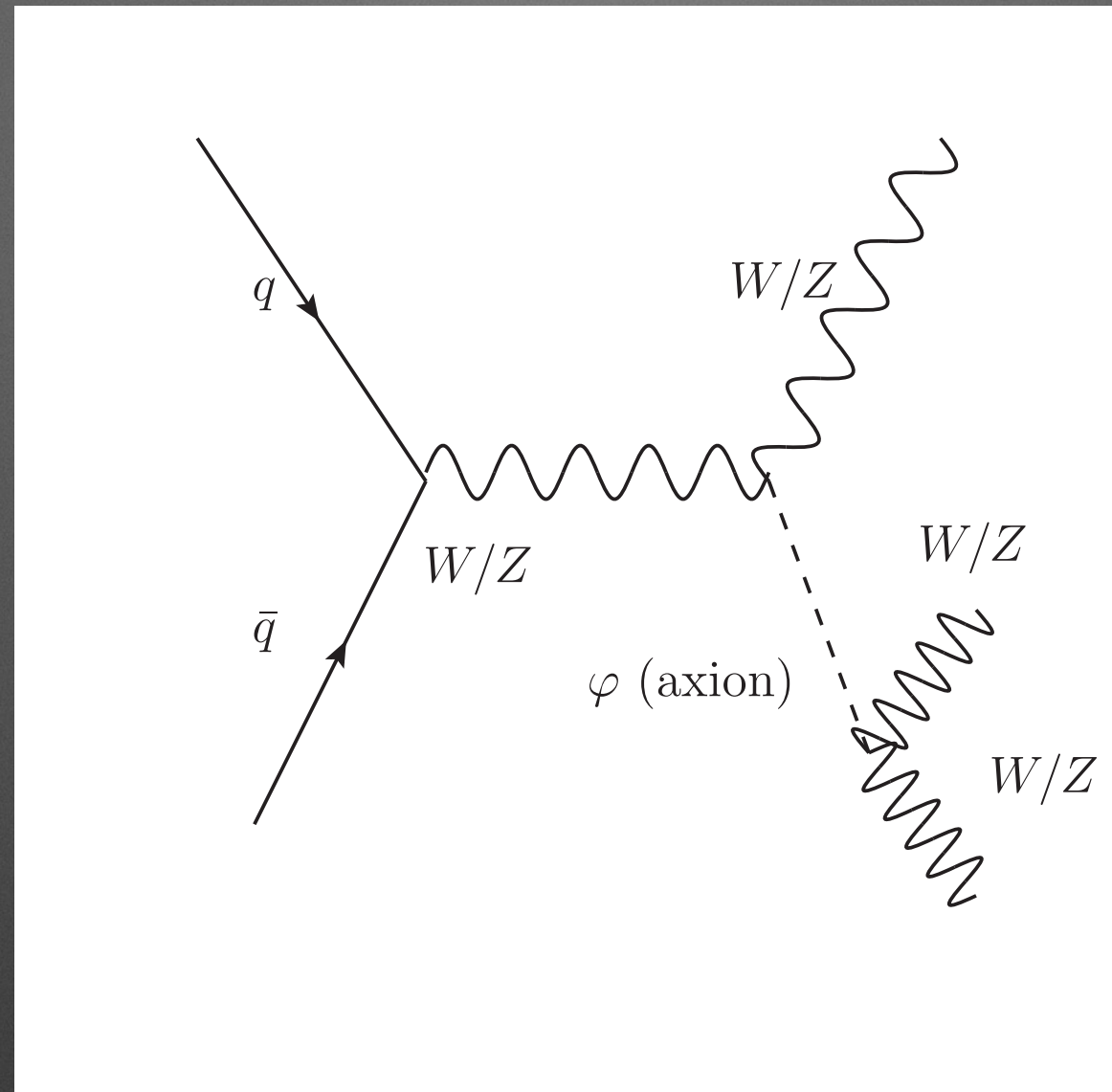
$$W_R^\pm, Z' \text{ (a few TeV)} \rightarrow \text{di-bosons } (W, Z, h)$$

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

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

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
- ❖ requires new / **dedicated** searches
- ❖ similar lesson for **other** frameworks (**broaden** searches):
$$\text{BSM}_1 \rightarrow \text{BSM}_2 + \text{SM}; \text{BSM}_2 \rightarrow \text{SM}_1 + \text{SM}_2$$

Back-ups


*Probe **Higgs** compositeness
[at $\sim O(10)$ 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

$$\sim g_{\text{SM}}^2 / g_{\text{KK}} + g_{\text{KK}} \Lambda_{\text{gauge}}^2 / \Lambda_{t/H}^2$$


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

