

Flavor Physics and LHC  
Signals of Warped Extra  
Dimensions

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# Outline and Summary

- **Warped** extra dimensions address **Planck-weak** and **flavor** hierarchies: new (KK) particles at a **few TeV** (precision tests)
- **Common** origin for neutrino **anarchy** and charged **hierarchies** + **Higgs**-mediated flavor violation
- **Challenging** for LHC: techniques to detect highly **boosted top/W/Z** (experimentalists' input!) required

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# **WARPED** EXTRA DIMENSION

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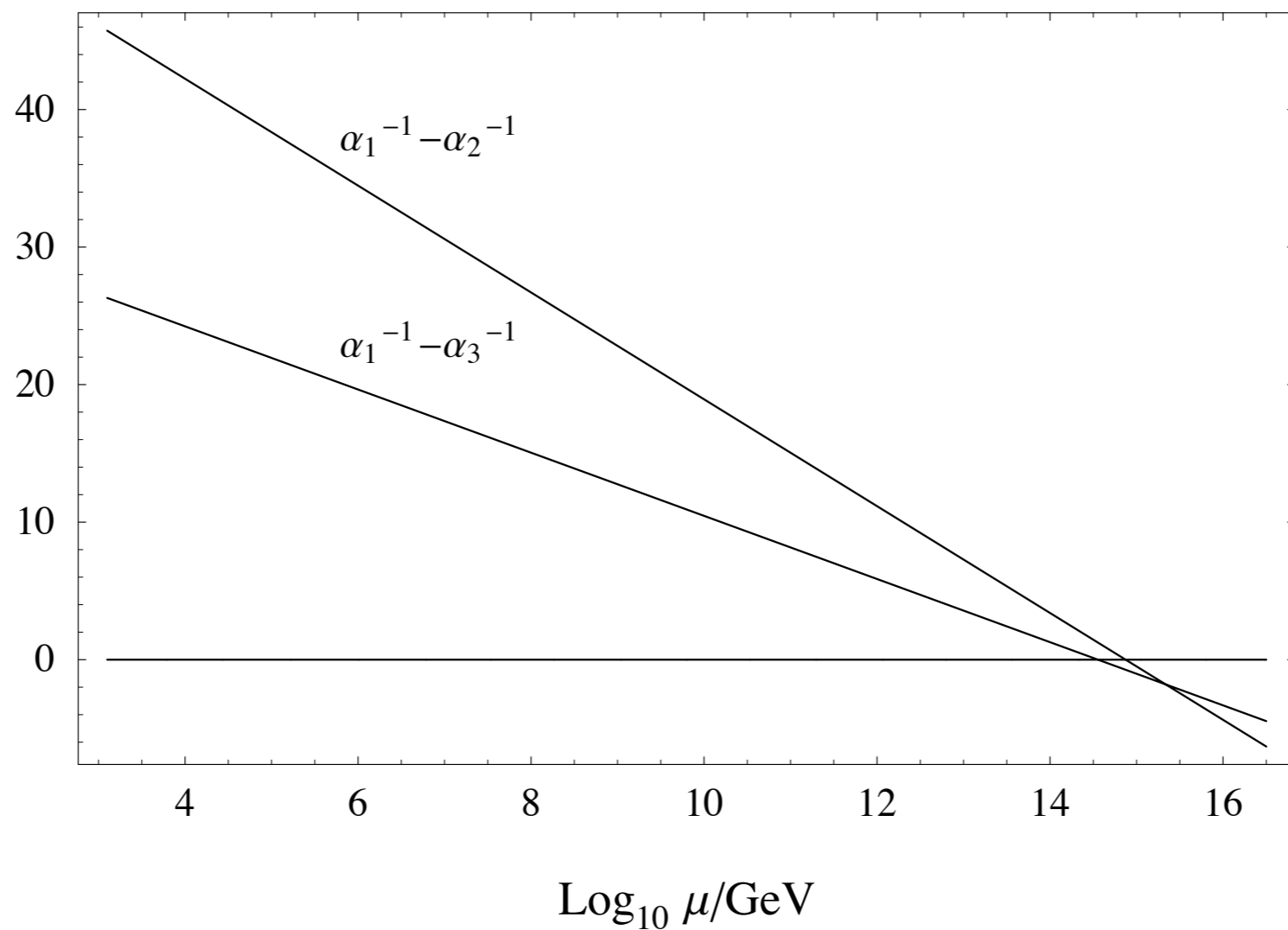
# Motivations

- Planck-weak and flavor hierarchy (without severe flavor problem)
- Weakly-coupled "tool" for 4D strong dynamics: dual to 4D composite Higgs (AdS/CFT)
- GUT's: (i) dark matter from proton stability (KA, Servant); (ii) gauge coupling unification with precision  $\sim$  SUSY (KA, Contino, Sundrum)

# Tantalizing unification: **magic** of

$\beta$ -function:  $SM - 2t_R - H$

(KA, Contino, Sundrum)

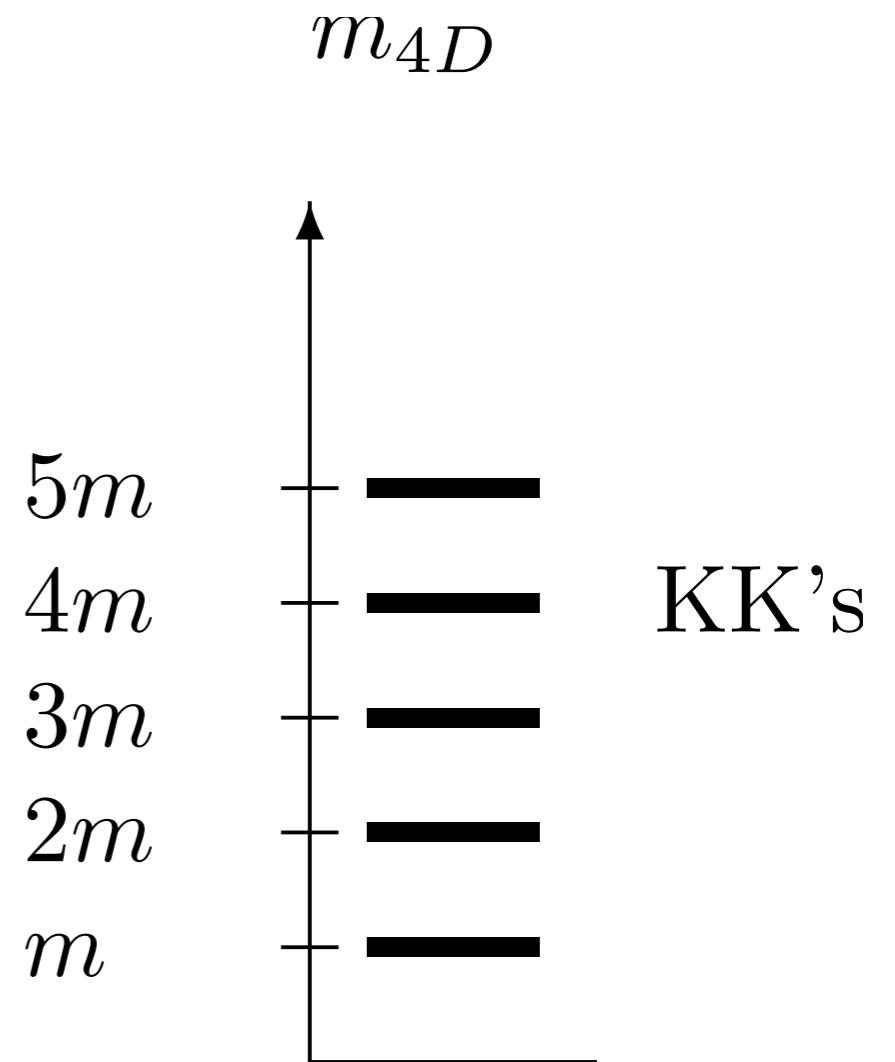
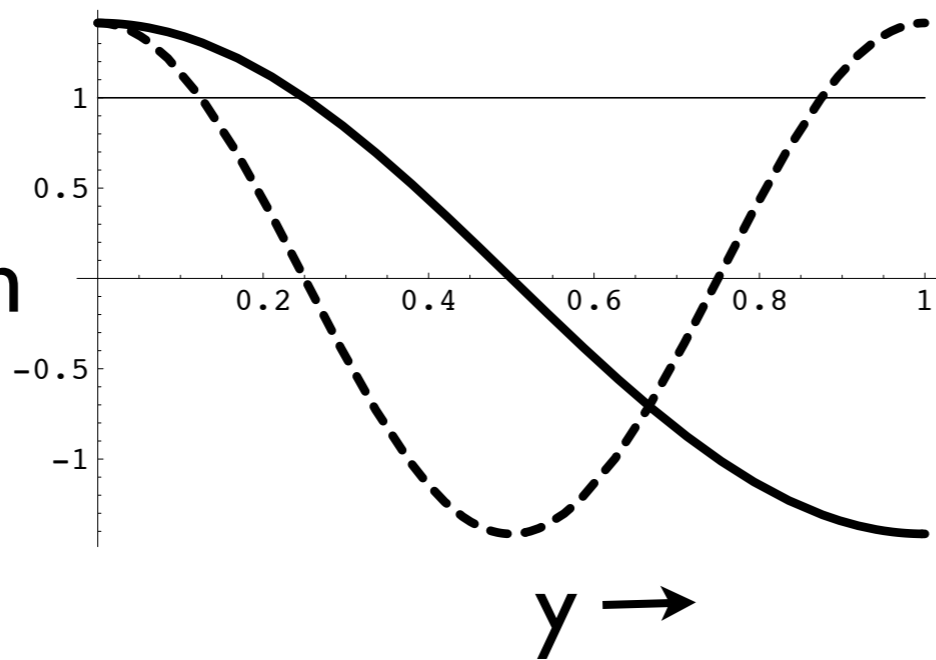


# Basics of extra dimensions

- Particle in 5D: SM  $(x_\mu, y)$   $\rightarrow$  Fourier expand  $y$  (a la 1D box)

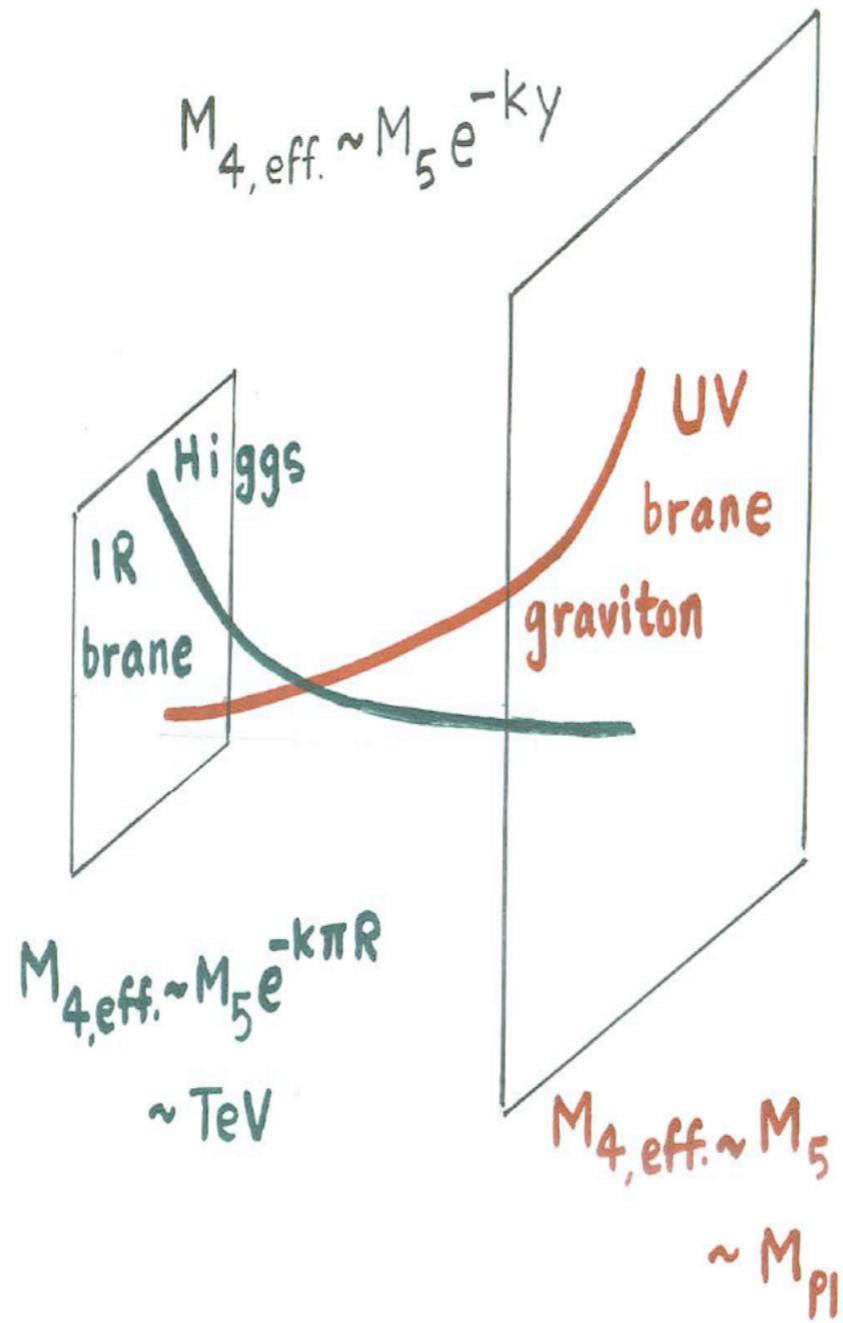
- Lightest mode (SM) + heavier (Kaluza-Klein: KK) with profiles

↑  
wavefunction



# Gravity and Higgs

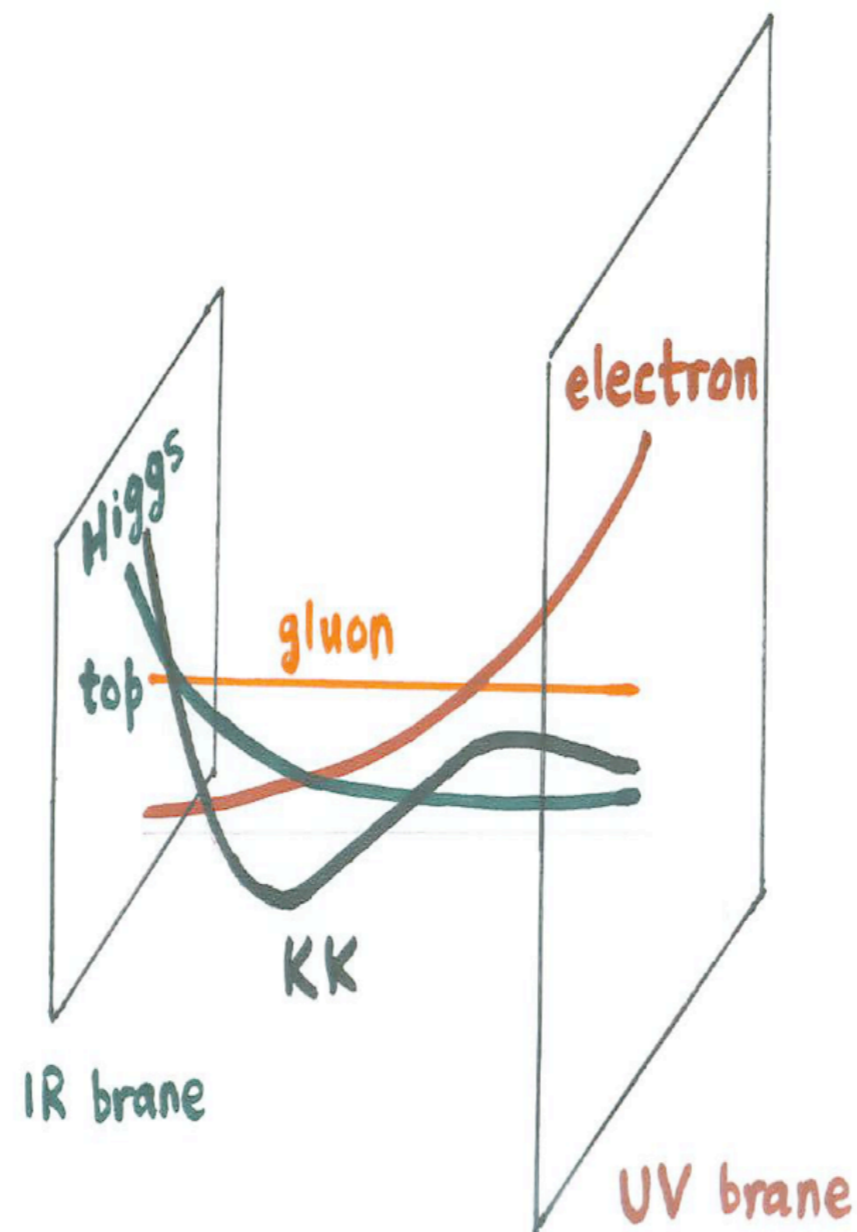
(Randall, Sundrum)



$$kR \sim \log (M_{Pl}/\text{TeV}) / \pi \sim 10$$

# SM in bulk

(Davoudiasl, Hewett, Rizzo; Pomarol; Grossman, Neubert; Chang, Hisano, Nakano, Okada, Yamaguchi; Gherghetta, Pomarol)





# Couplings from overlap of profiles

- Flavor hierarchy (fermion-Higgs) without hierarchy in 5D parameters (5D Yukawa, 5D mass  $M$ ):  
fermion profile  $\sim e^{-k\pi R M} \dots$  ...related to Planck-weak hierarchy
- Couplings to KK large (small) for top (electron)

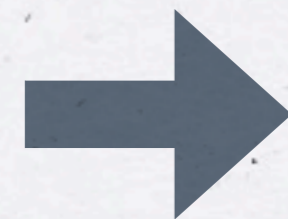
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**NO** PARITY, PRECISION TESTS  
NEW PARTICLES FEW TEV

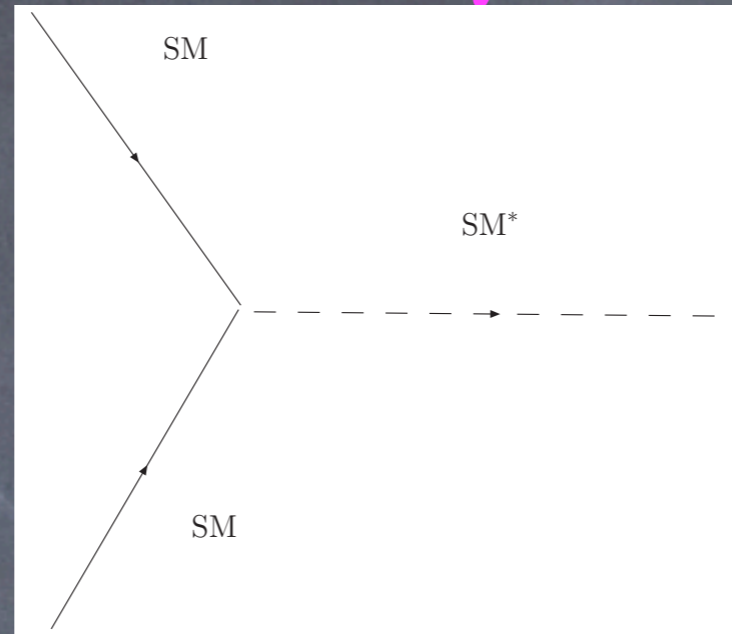
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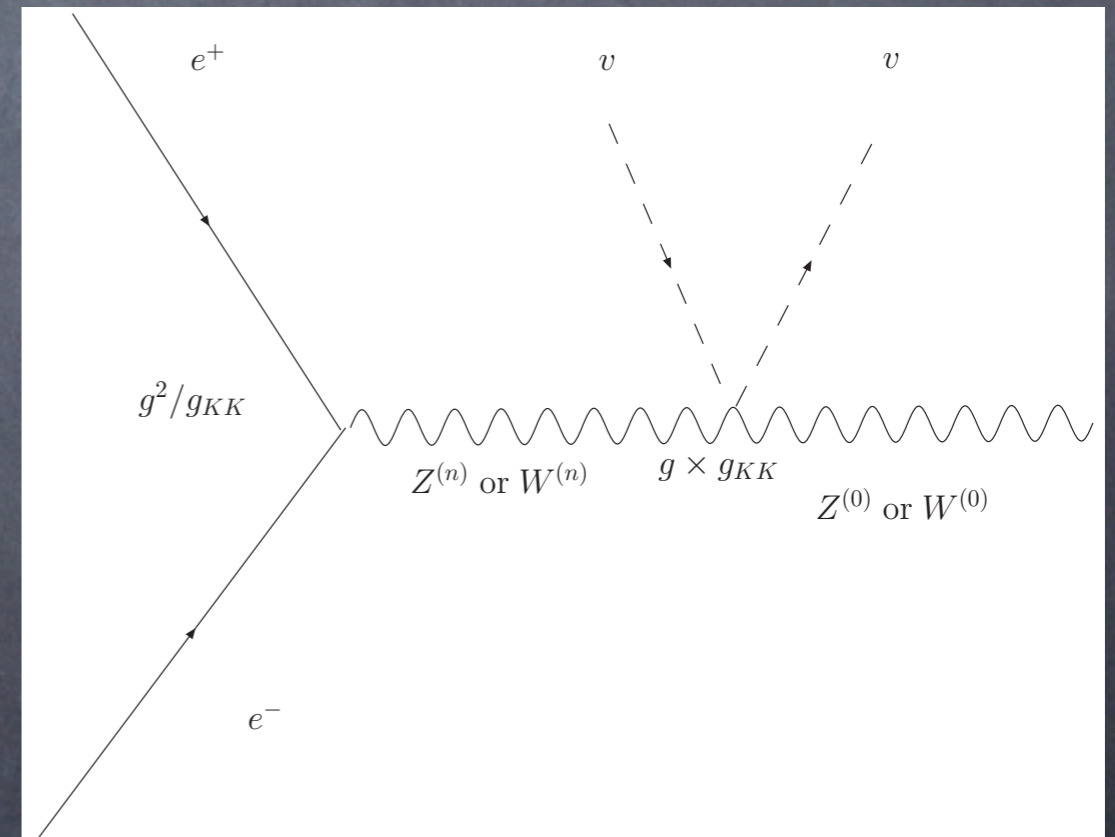
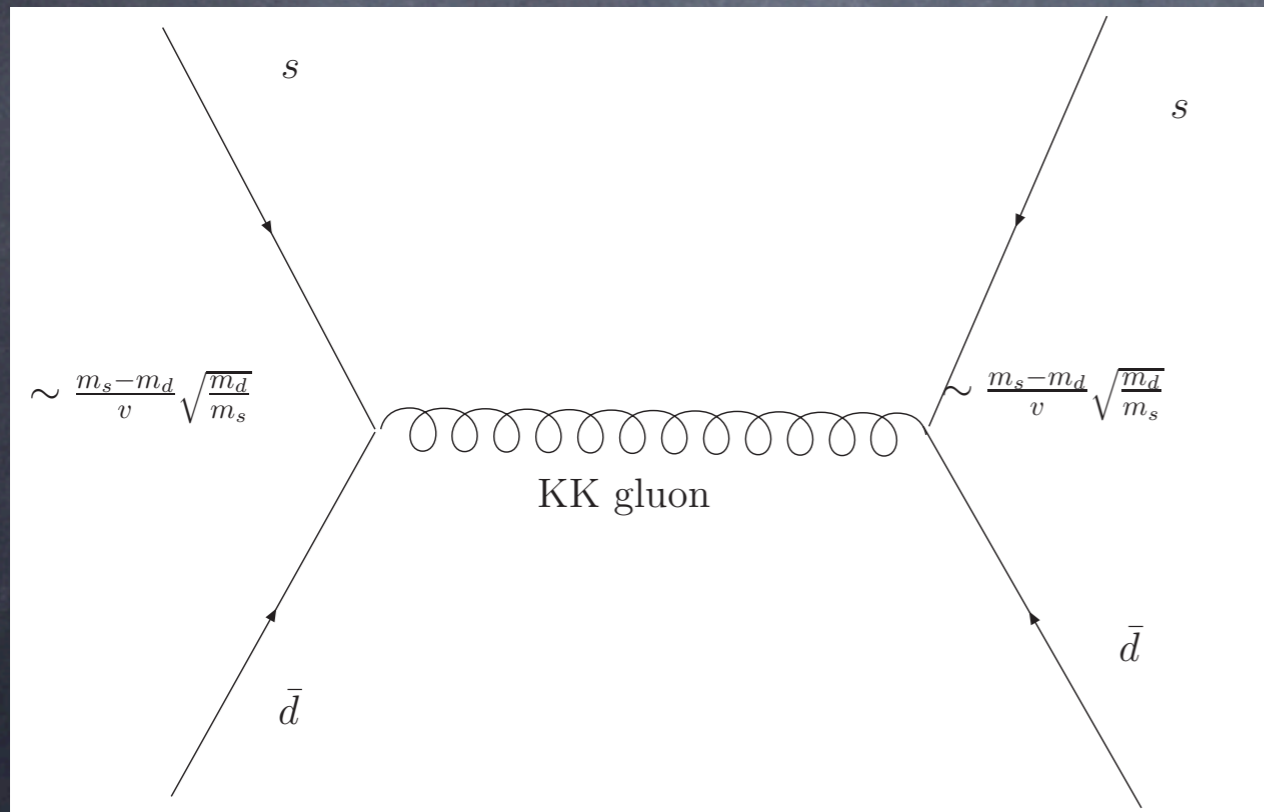


# Summary (rough)

no parity



tree-level contributions to flavor and EW precision tests



lower limit on KK mass scale:  $\sim O(3)$  TeV (built-in mechanism + model-building)

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# **EW** PRECISION TESTS

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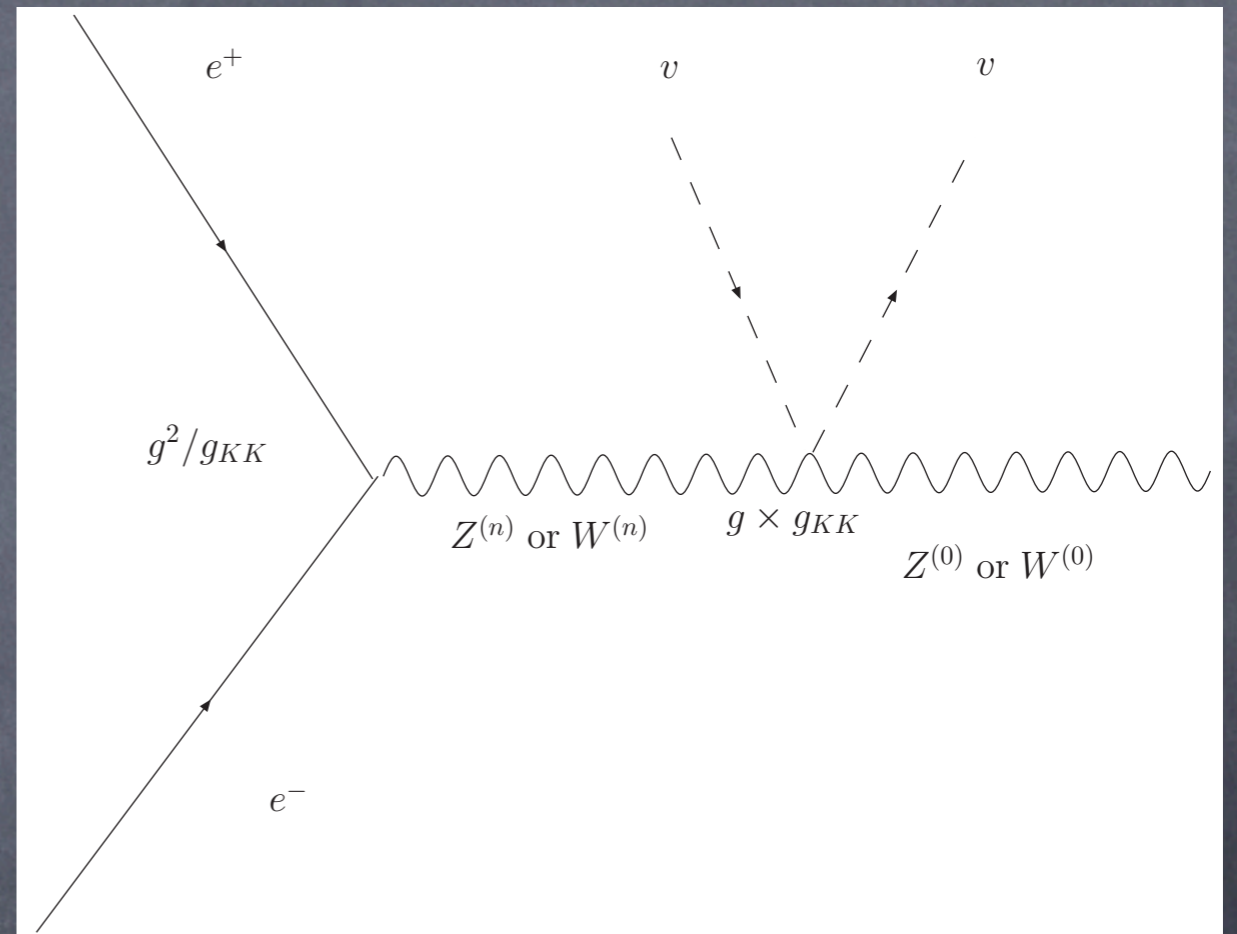
# S parameter

- Equivalent to shift in coupling:

$$\frac{\delta g_Z}{g_Z} \sim \frac{M_Z^2}{M_{KK}^2}$$


$$\lesssim 0.1\%$$

$$\Rightarrow M_{KK} \gtrsim 3\text{TeV}$$

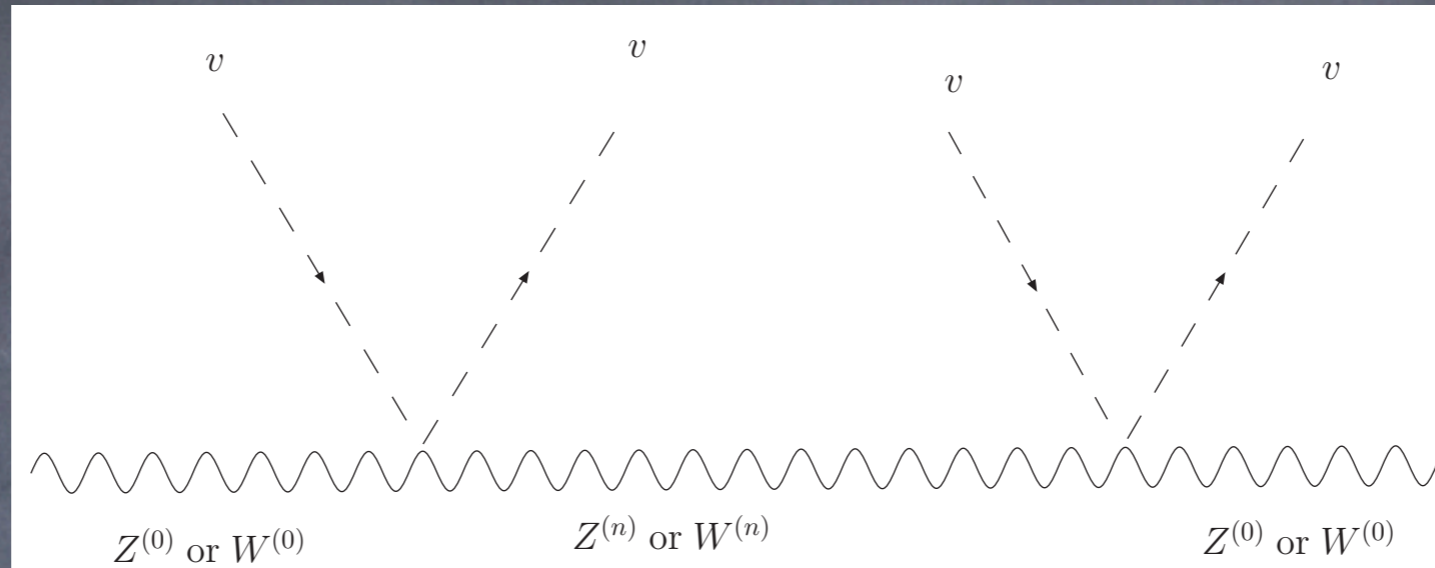


# 5D warped Higgsless models (breaking by boundary condition)

(Csaki, Grojean, Pilo, Terning)

- Flat profiles for fermions  suppression in S  
(Cacciapaglia, Csaki, Grojean, Terning)
- $< 1$  TeV KK's unitarize WW scattering

# Custodial symmetries



- **T parameter** (KA, Delgado, May, Sundrum) and **Zbb** (KA, Contino, Da Rold, Pomarol)
- EW fit with  $\sim 3$  TeV KK masses (Carena, Ponton, Santiago, Wagner)

# About “ $\sim$ ” in $\sim 3$ TeV

...due to model-**variations** (all explain hierarchies)

- **brane-localized** terms (Davoudiasl, Hewett, Rizzo; Carena, Delgado, Ponton, Tait, Wagner)
- **Higgs profile** (Davoudiasl, Lillie, Rizzo; Cacciapaglia, Csaki, Marandella, Terning)
- **“soft” wall** (metric **not** AdS near IR “brane”: McGuirk, Shiu, Zurek; Falkowski, Perez-Victoria; Batell, Gherghetta, Sword; Delgado, Diego; Aybat, Santiago)



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# **FLAVOR** PRECISION TESTS

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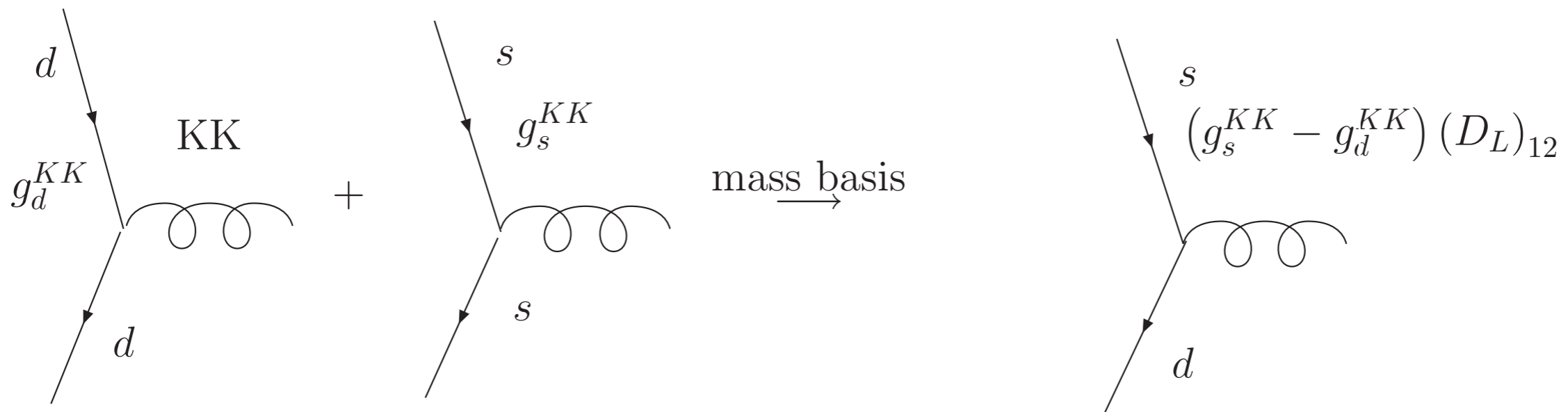
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# Flavor **hierarchy** from profiles $\rightarrow$

## flavor **violation** from KK's

- Non-universal, but diagonal coupling to gauge KK's in gauge/weak basis...

$$(\bar{d}_{L \text{ weak}} \quad \bar{s}_{L \text{ weak}}) \begin{pmatrix} g_d^{KK} & 0 \\ 0 & g_s^{KK} \end{pmatrix} \gamma^\mu A_\mu^{(n)} \begin{pmatrix} d_{L \text{ weak}} \\ s_{L \text{ weak}} \end{pmatrix}$$

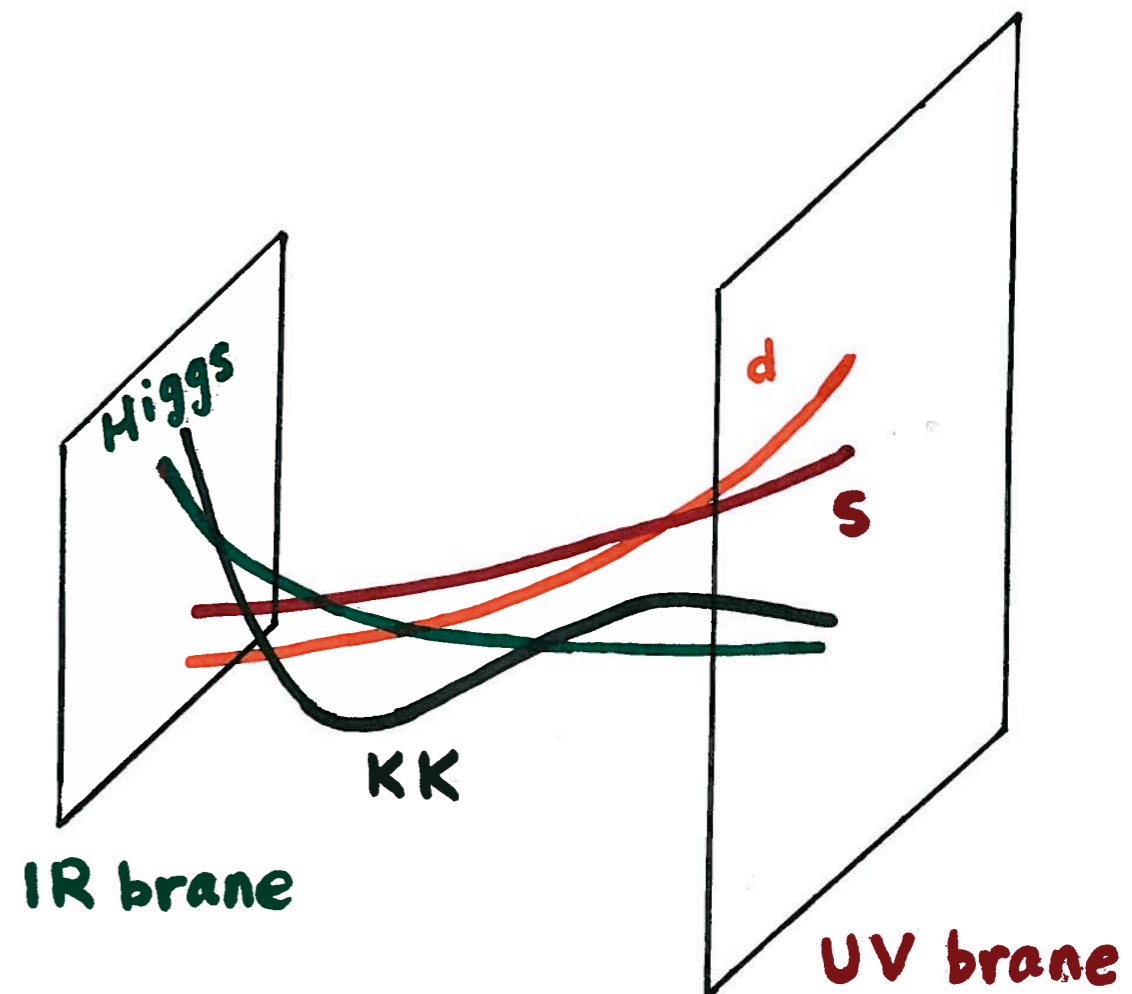


- off-diagonal in mass basis (in general):

$$\dots D_L^\dagger \text{diag} (g_d^{KK}, g_s^{KK}) D_L \dots \rightarrow (g_s^{KK} - g_d^{KK}) (D_L)_{12} \times \bar{d}_{L \text{ mass}} \gamma^\mu A_\mu^{(n)} s_{L \text{ mass}}$$

# Warped **GIM**: built-in suppression mechanism...

- **Non**-universality in gauge KK coupling  $\propto$  (difference of) 4D Yukawa:  
**Higgs profile  $\sim$  KK**  
(Gherghetta, Pomarol; Huber, Shafi; KA, Perez, Soni)



- Mixing angles  $\sim \sqrt{\frac{m_d}{m_s}}$   
➔ **O(TeV)**-scale new physics still alive (**not** in flat)!

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...1 or 10 TeV?

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# Quark flavor constraints for anarchy

- analog of GIM...

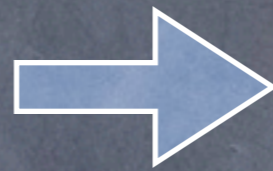
...but...

- $\sim O(20)$  TeV from  $\epsilon_K$  for Higgs on TeV brane, tree-level matching (Csaki, Falkowski, Weiler; see also Fitzpatrick, Perez, Randall; Davidson, Isidori, Uhlig)

...but...

# Model dependence (cf. EW precision tests)...

- “O(1) room” in **each of profile** for Higgs (size of 5D Yukawa), **loop**-level 5D **gauge** coupling (not so relevant for EW precision tests)...



- $\sim$  **O(5)** TeV scale allowed **even with anarchy** by  $\epsilon_K$  [**and**  $b \rightarrow s\gamma; \epsilon'/\epsilon$ ] (KA, Azatov, Zhu; Gedalia, Isidori, Perez)
- SM uncertainties:  $m_{d,s}$ ; matrix elements (**different** Lorentz structure than SM); also for lepton flavor violation: conversion in nuclei!

# Flavor symmetries

- Mixing angles smaller by **a few** vs. "natural" size (ratio of profiles)  $\Rightarrow$   $\sim 3$  **TeV** allowed (even if  $\sim 20$  TeV for natural size)  $\Rightarrow$  (mild) tuning (Blanke, Buras, Duling, Gori, Weiler)?

...or...

- flavor **symmetries** for **naturally** small mixing angles: relate (**same** as in anarchic) 5D mass to 5D Yukawas (**still anarchic**) (Fitzpatrick, Perez, Randall; Csaki, Grossman, Perez, Surujon, Weiler)

# Lepton sector: anarchy with large LH charged lepton mixing


- **See-saw** model (Huber, Shafi): Dirac masses (charged leptons, quarks) + Majorana masses for **RH** neutrinos on UV brane
- Large LH neutrino mixings  $\Rightarrow$  **non**-hierarchical profiles for LH leptons (cf. hierarchical for quarks with anarchy)???
- profiles as "input" (fit to data)
- LH **charged** lepton mixing large  $\Rightarrow$   $\sim O(10)$  TeV from lepton **flavor violation** with minimal  $SU(2)_R$  representations (Perez, Randall; KA)



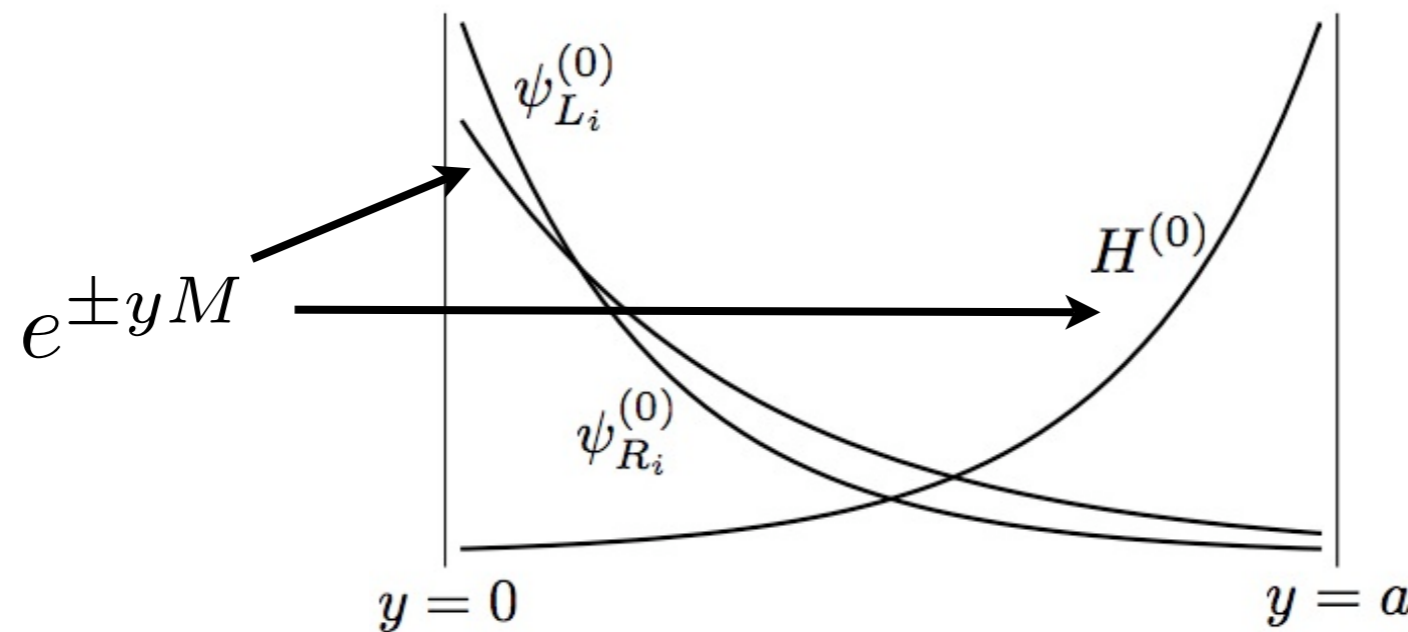
# Model-dependence...

- $\sim O(5)$  TeV KK scale using non-minimal choice of representations (custodial symmetry: KA)

# Lepton sector: flavor symmetries

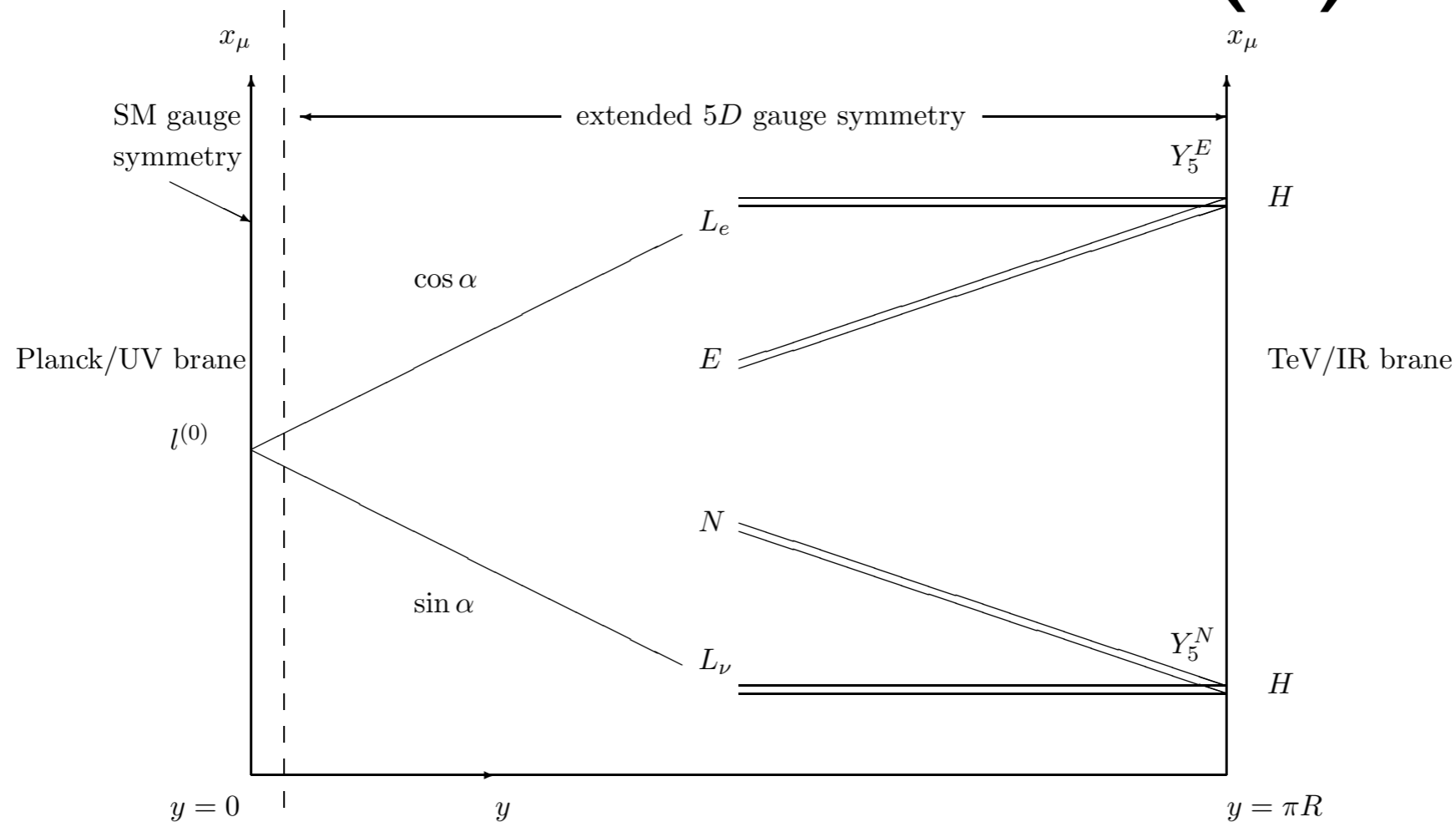
- **non**-hierarchical profiles for LH leptons (cf. quarks)   
flavor symmetry (Perez, Randall; Csaki, Delaunay,  
Grojean, Grossman)
- Flavor symmetries suppress flavor **violation** (see also  
Chen, Yu)

# Decoupling charged LH lepton mixing from neutrinos (I)



- **Dirac** masses (KA, Okui, Sundrum) from overlap near **Planck** brane ( $\nu: M_{\ell_{L_i}} + M_{\nu_{R_j}} > M_H$ ) or TeV brane (charged lepton:  $M_{\ell_{L_i}} + M_{e_{R_j}} < M_H$ )
- LH lepton profiles **small/hierarchical** near **TeV** brane, **large/non-hierarchical** near **Planck** brane  $\longrightarrow$
- neutrino **anarchy** (!) + (super)**smallness** from Higgs profile (cf. charged lepton **hierarchy**, smallness from lepton profiles) +  $\sim O(5)$  TeV scale (**minimal** representations: KA, Blechman, Petriello)

# Decoupling charged LH lepton mixing from neutrinos (II)



- ⊗ **non-minimal** representations (KA): LH lepton “made of” **2** components (one for neutrino mass; other for charged) with **different** profiles + custodial symmetry ➔

- ⊗ KK scale  $\sim O(3)$  TeV

# About “ $\sim \bigcirc$ ” in $\sim \mathcal{O}(5 \text{ or } 10) \text{ TeV}$

...due to...

- “ $\sim \dots$ ” : soft wall etc. like for EW precision tests
- “ $\bigcirc \dots$ ” : **scan** over 5D Yukawa entries (**intrinsic** to solution to flavor puzzle)  $\Rightarrow$  **mild** tuning allows lower KK scale (Blanke, Buras, Duling, Gori, Weiler)

**anarchic**

$$4\text{D Yukawa} \propto \text{LH profiles} \times \begin{pmatrix} 1 & 2e^{i\pi/3} & 1/3e^{-\pi/4} \\ 3i & -1 & \dots \\ \dots & 1/2 & \dots \end{pmatrix} \times \text{RH profiles}$$

**hierarchical**

# Other sources of flavor violation

- **Higgs** exchange
- **Radion** (“fluctuations of size of extra dimension”) exchange (Azatov, Toharia, Zhu)

# Higgs-mediated flavor

## violation (I)

(KA, Contino; Azatov, Toharia, Zhu; see also del Aguila, Perez-Victoria, Santiago)  
 profile at TeV brane

anarchic

$$\frac{m}{v} \sim f_L \left( Y_5 + Y_5^3 \frac{v^2}{M_{KK}^2} \right) f_R$$

$$Y_4 \sim f_L \left( Y_5 + 3Y_5^3 \frac{v^2}{M_{KK}^2} \right) f_R$$

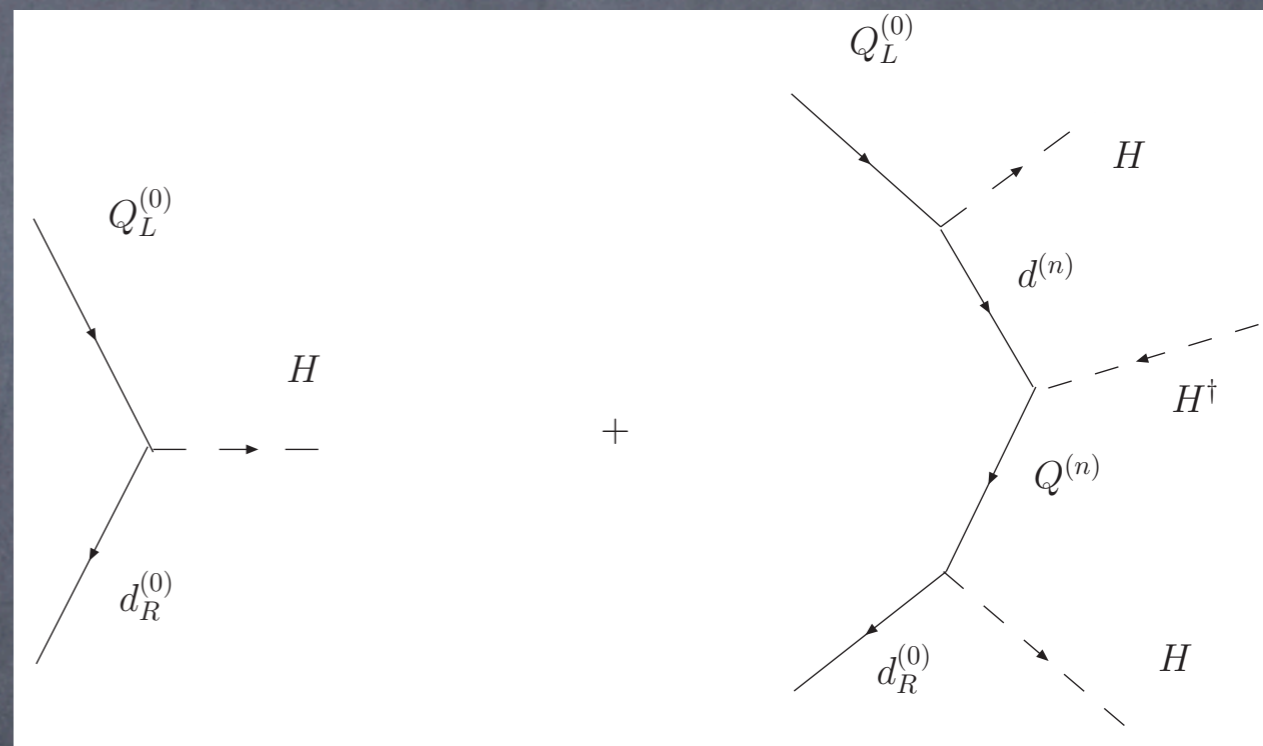
combinatorial

$$\sim \frac{m}{v} + 2f_L \left( Y_5^3 \frac{v^2}{M_{KK}^2} \right) f_R$$

$$\sim \frac{m}{v} \left[ 1 + O \left( \frac{Y_5^2 v^2}{M_{KK}^2} \right) \right]$$

$$\not\propto \frac{m}{v}$$

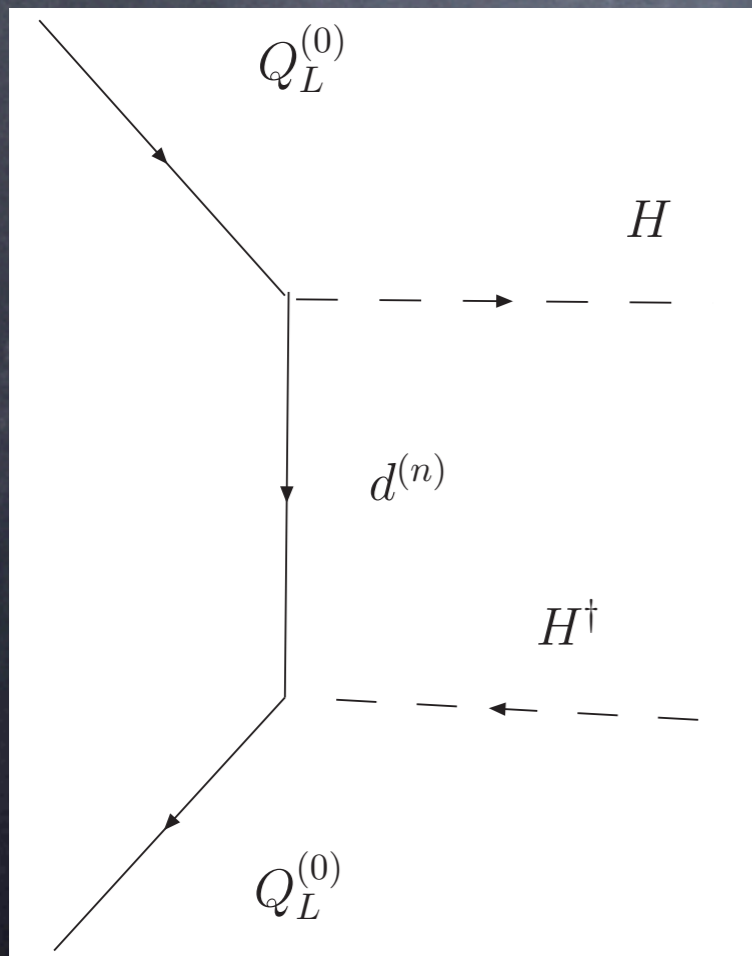
anarchic



# Higgs-mediated flavor violation (II)

$$\delta(\text{kinetic term}) \sim f_{L,R} \left( Y_5^2 \frac{v^2}{M_{KK}^2} \right) f_{L,R}$$

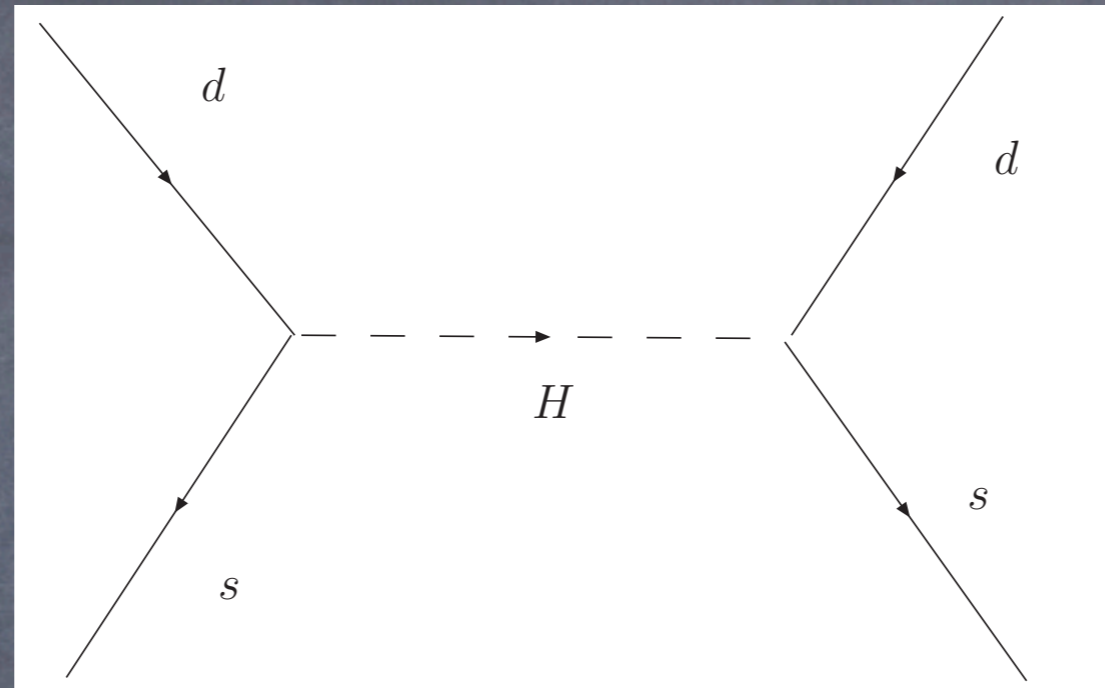
$\Rightarrow$  converts into *non-derivative* after canonical:



$$\delta Y_4 \sim O \left[ \frac{m}{v} \left( \frac{Y_5^2 v^2}{M_{KK}^2} \right) f_{L,R}^2 \right]$$



# Constraints



- $\epsilon_K$ : from **non**-derivative (derivative/kinetic suppressed by  $f$ 's...as **strong** as from KK gluon!

# Signals

$$\text{BR} (t \rightarrow cH) \sim 10^{-4}$$

LHC sensitivity:  $5 \times 10^{-5}$  (Aguilar-Saavedra, Branco)

$$\text{BR} (H \rightarrow tc) \sim 5 \times 10^{-3}$$

no dedicated study yet!

(both derivative and non...:  $f_{t_R} \sim 1$ )

# PGB: flavor alignment

for **non-derivative** (KA, Contino)

flavor structure

same for all generations

$$Q_L (Y_5 H + Y_5^3 H^3 .. + \dots) d_R \xrightarrow{\text{resums to}} Y_5 (Q_L d_R \times \text{periodic in } H)$$

$\Rightarrow$  diagonal shift only in  $Y_4^{\text{non-derivative}}$   
( $\propto$  explicit breaking)

- Derivative  $\delta Y_4$  same as generic case
- Constraints ( $f$ 's small) weaker than, but signals ( $f$ 's large) same as generic case!

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**DON'T GIVE UP ON ~3 TEV  
GAUGE KK SCALE!!!**

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# LHC SIGNALS FOR $KK$ PARTICLES

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# Couplings of gauge KK's

...from profiles ( $\xi \equiv \sqrt{\log(\text{UV}/\text{IR})} \sim \sqrt{\log(M_{Pl}/\text{TeV})} \sim 5$ )  
 Gherghetta, Pomarol; Davoudiasl, Hewett, Rizzo

$$\frac{g_{RS}^{q\bar{q}, l\bar{l} A^{(1)}}}{g_{SM}} \simeq \xi^{-1} \approx \frac{1}{5},$$

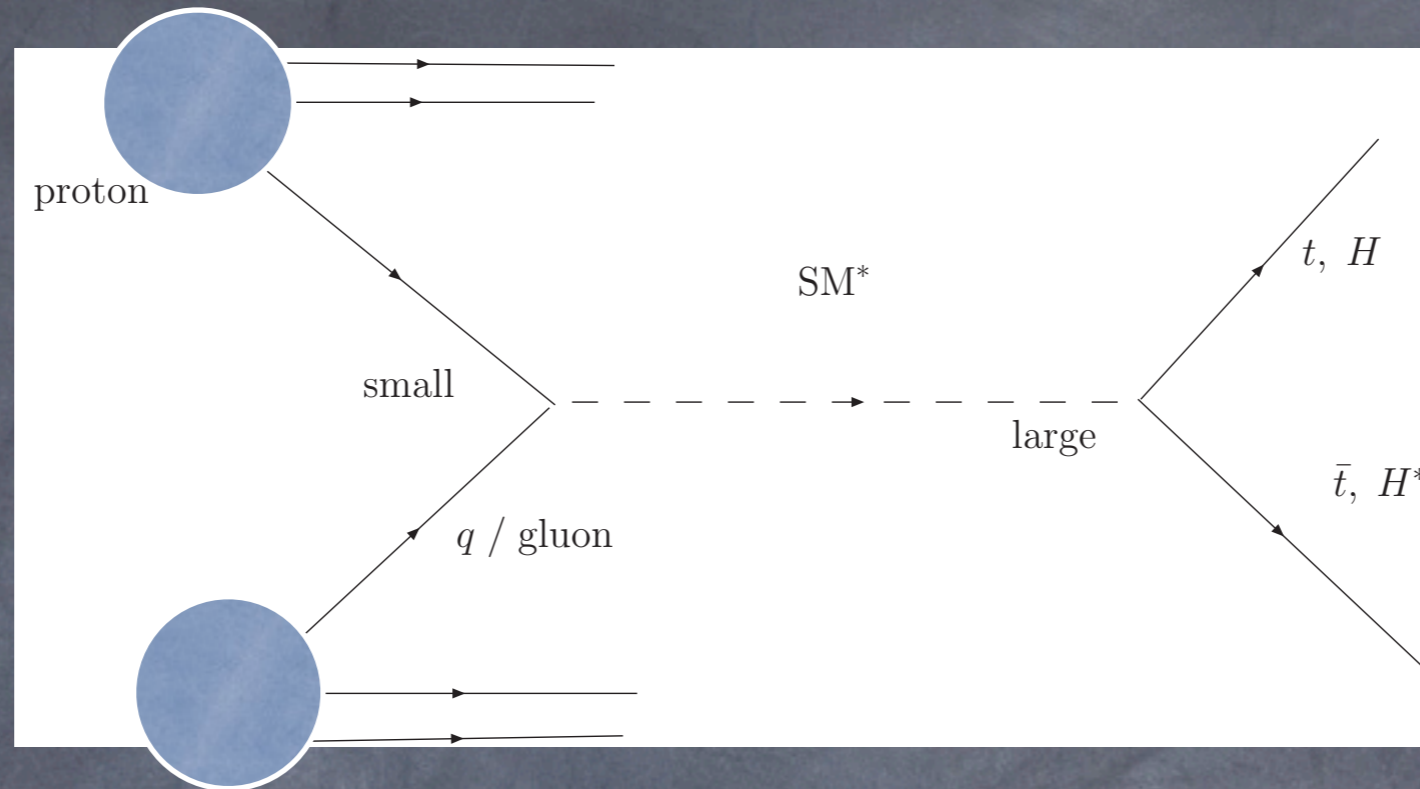
$$\frac{g_{RS}^{Q^3 \bar{Q}^3 A^{(1)}}}{g_{SM}}, \frac{g_{RS}^{t_R \bar{t}_R A^{(1)}}}{g_{SM}} \simeq 1 \text{ to } \xi \approx 1 \text{ to } 5,$$

$$\frac{g_{RS}^{HH A^{(1)}}}{g_{SM}} \simeq \xi \approx 5,$$

$$\frac{g_{RS}^{A^{(0)} A^{(0)} A^{(1)}}}{g_{SM}} \simeq 0$$

Model-independent approach: Contino, Kramer, Son, Sundrum;  
 Giudice, Grojean, Pomarol, Rattazzi

# Composite/Warped SM @ LHC: 3 strikes...



- Production suppressed: weak coupling to constituents of **proton**
- Decays to top/W/Z/Higgs: **golden** channels (leptons, photons) **suppressed**
- Strong coupling  $\Rightarrow$  **broad** resonances  
...but **not** out!

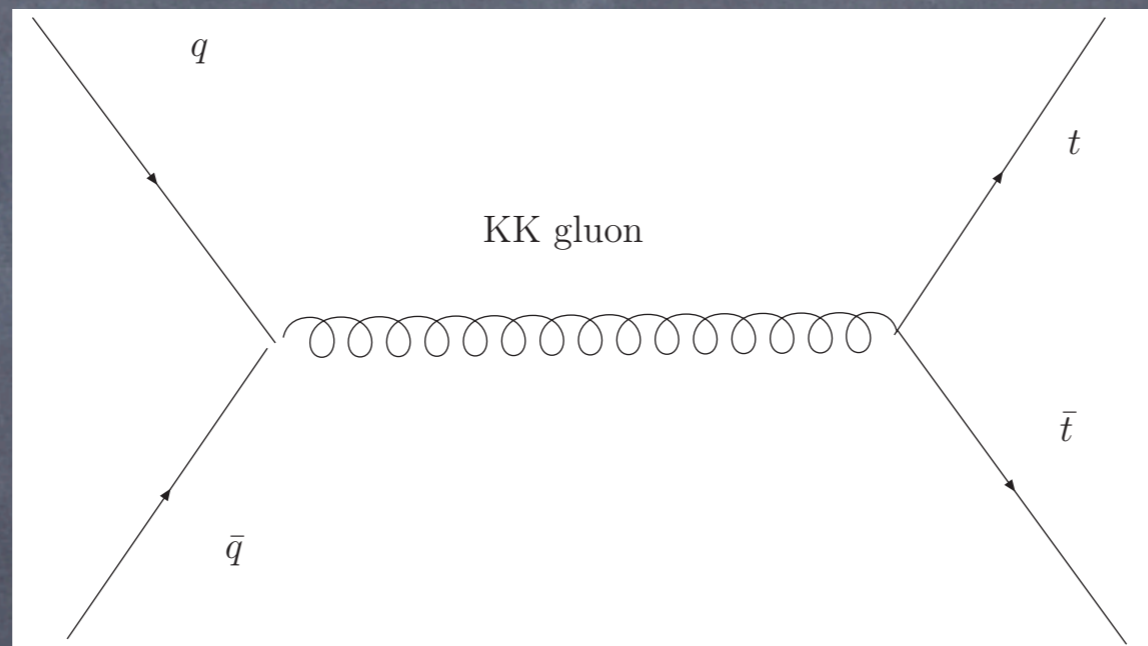
# KK gluon (and boosted tops)

(KA, Belyaev, Krupovnickas, Perez, Virzi)

(See also Lillie, Randall, Wang; Lillie, Shu, Tait;  
Guchait, Mahmoudi, Sridhar; Djouadi, Moreau, Singh; Baur, Orr; Bai,  
Han; Kumar, Tait, Vega-Morales; Evans, Luty)



# Production and Decay

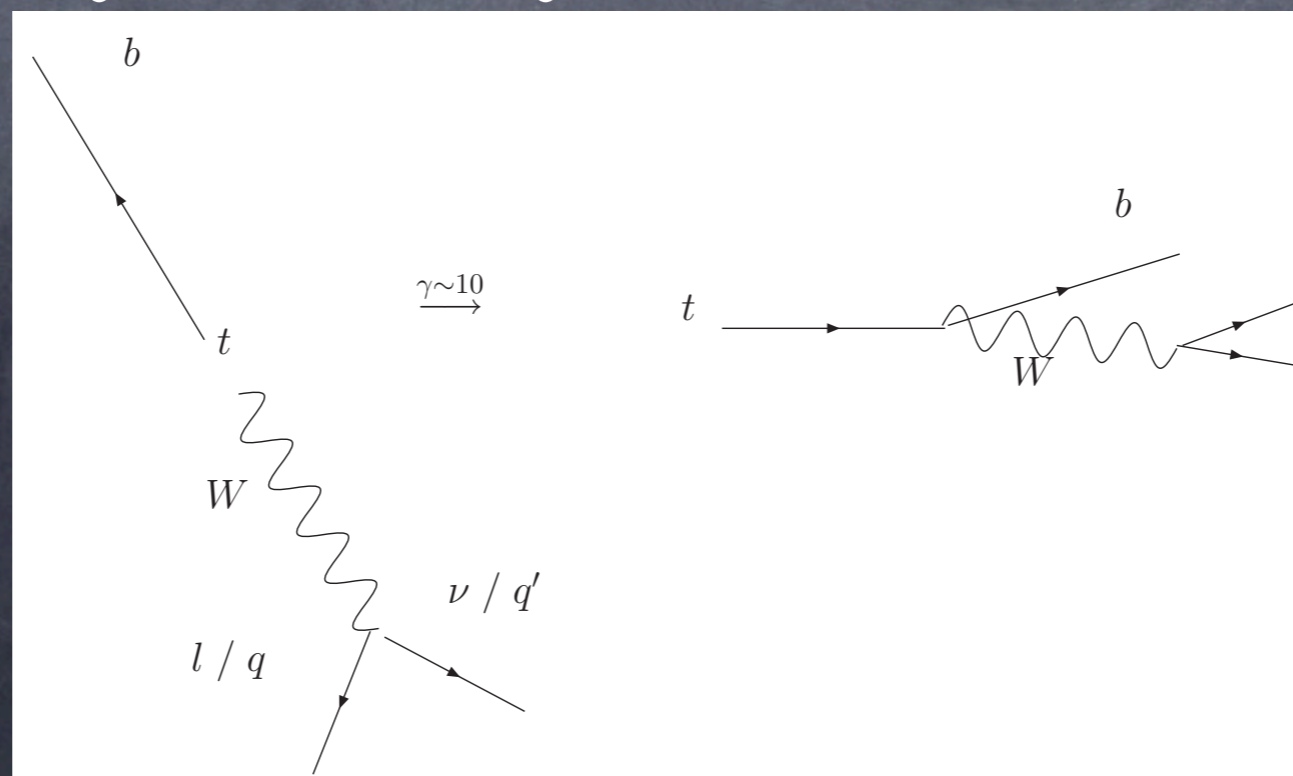


# Problem: collimation of tops

- opening angle  $\sim m_t/E \sim 0.1$

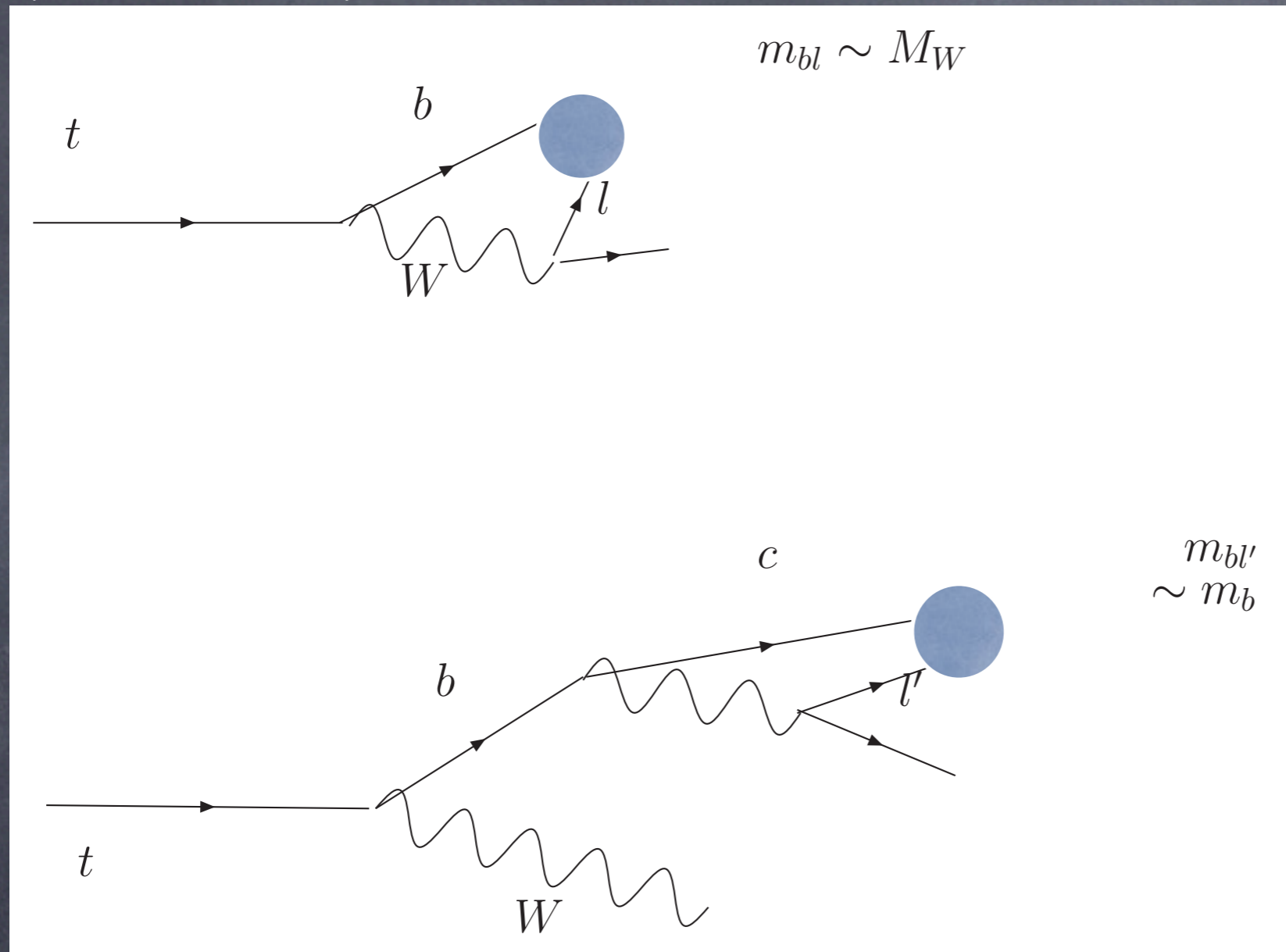
vs.

usual  $\Delta R \gtrsim 0.4$  between lepton and b-jet and 2 jets from W



# Solution: cut on lepton-b invariant mass

- Improved lepton and b-jet isolation cut:  $m_{bl} > 40 \text{ GeV}$



- Jet mass/substructure/event shapes** (Thaler, Wang; Kaplan, Rehermann, Schwartz, Tweedie; Almeida, Lee, Perez, Sterman, Sung, Virzi...+ experimental talks/notes)...

# Summary of polarization asymmetry

- SM QCD: equal LH and RH top quarks  $\Rightarrow P_{LR} = 0$
- Warped extra dimension: KK gluon coupling to LH and RH top quark different  $\Rightarrow P_{LR} \sim \pm O(1)$
- Measure polarization of top quark by correlating direction of **lepton** in top quark **rest** frame with direction of boost of top quark in parton **center-of-mass** frame

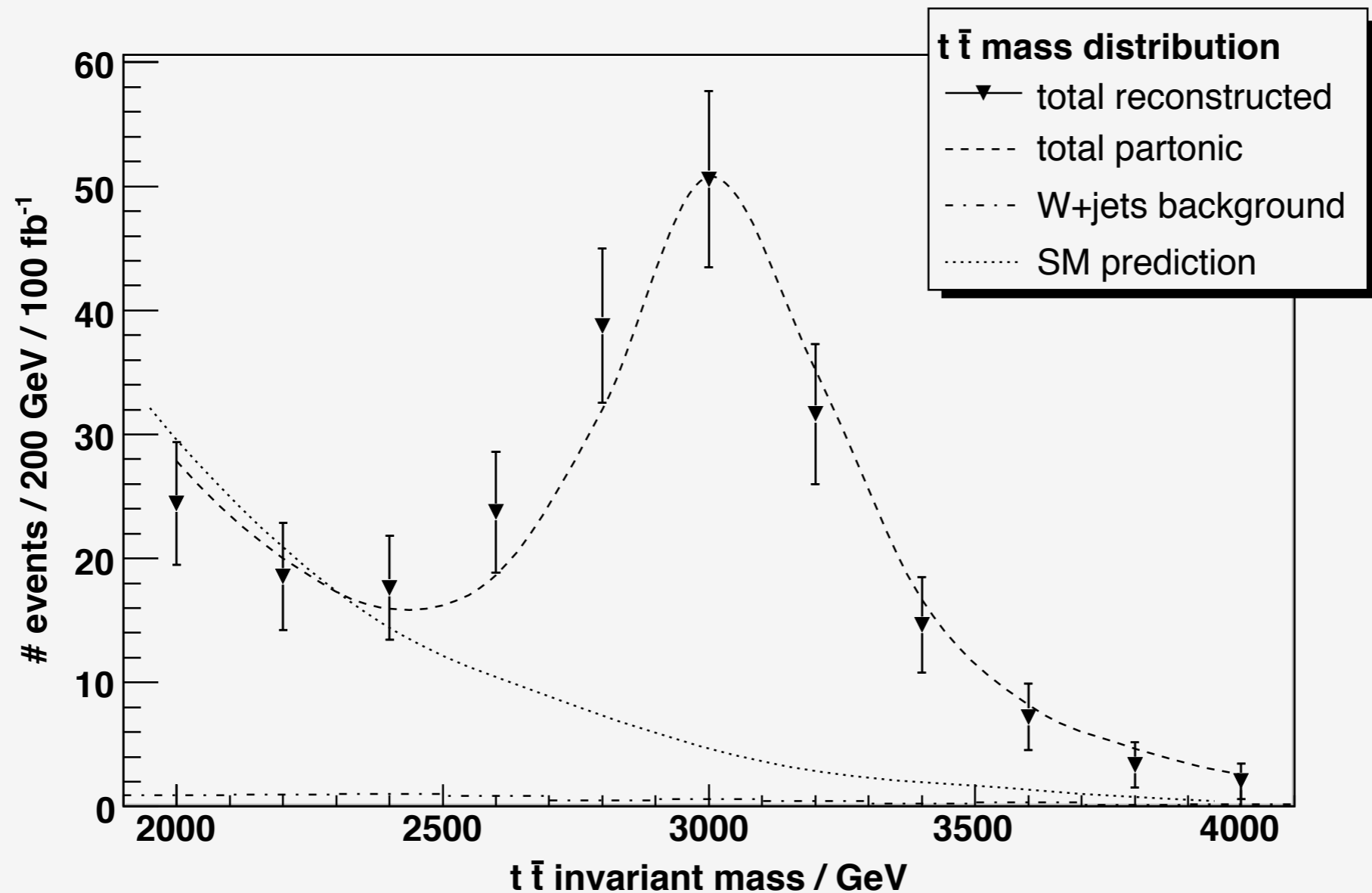
# Discovery for 4 TeV with 100 / fb

- “Bump” in differential cross-section  
(100 fb before 1% efficiency for 3 TeV)

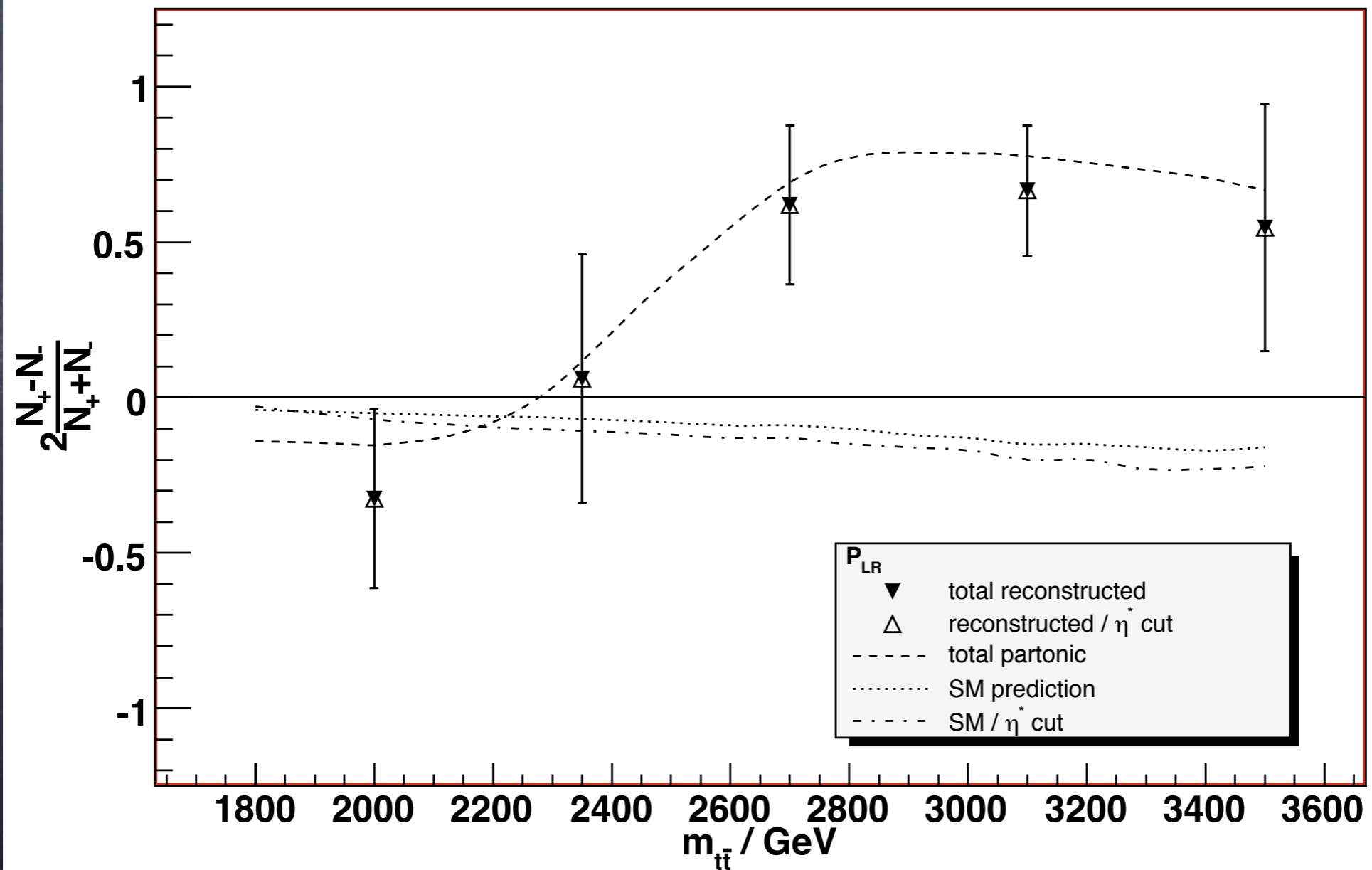
correlated with

- Deviation in  $P_{LR}$  from SM

# Differential cross-section



# Polarization asymmetry



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...DON'T FORGET BOOSTED  
W/Z!

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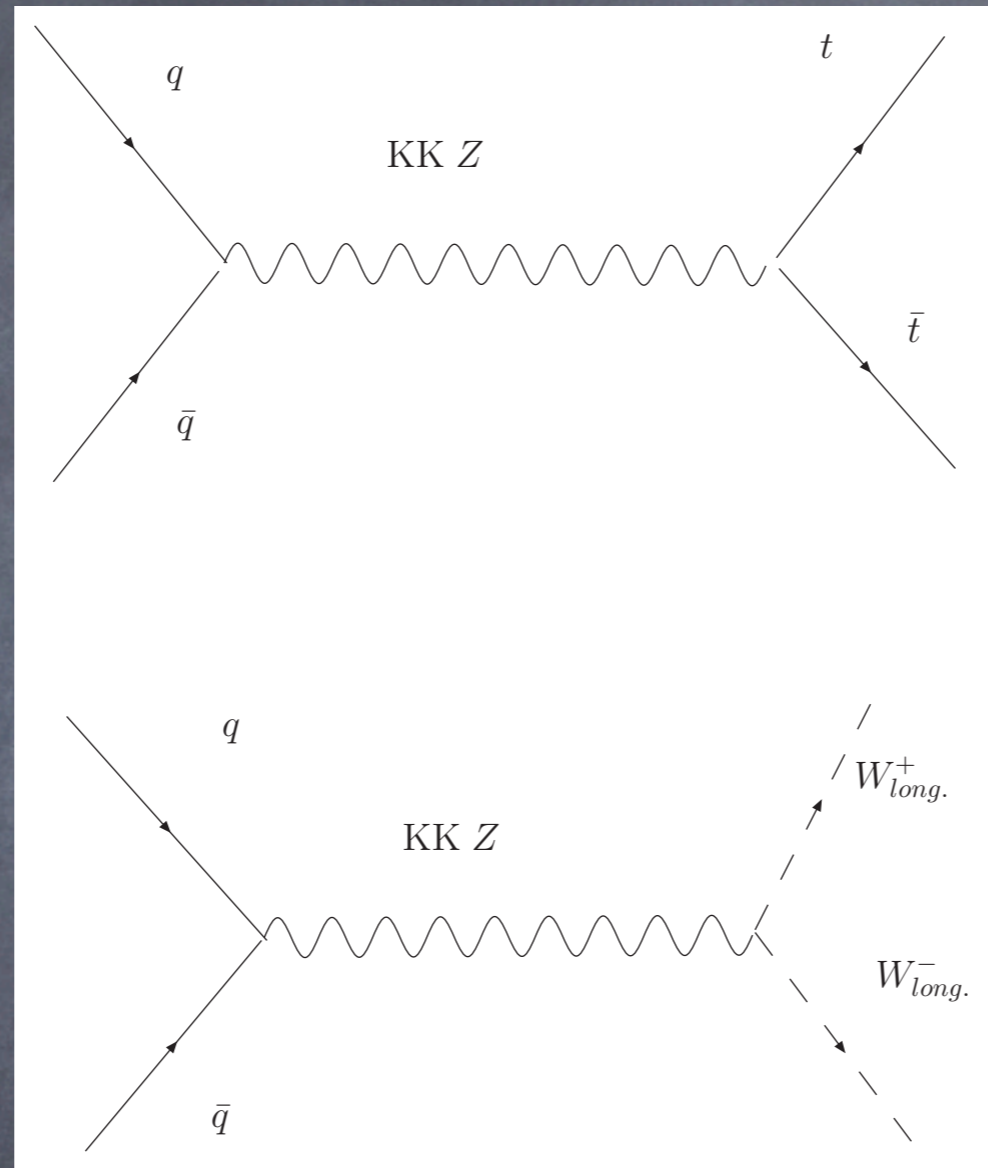


KK Z

(KA, Davoudiasl, Gopalakrishna, Han, Huang, Perez,  
Si, Soni)

(See also Djouadi, Moreau, Singh)

# Production and Decay



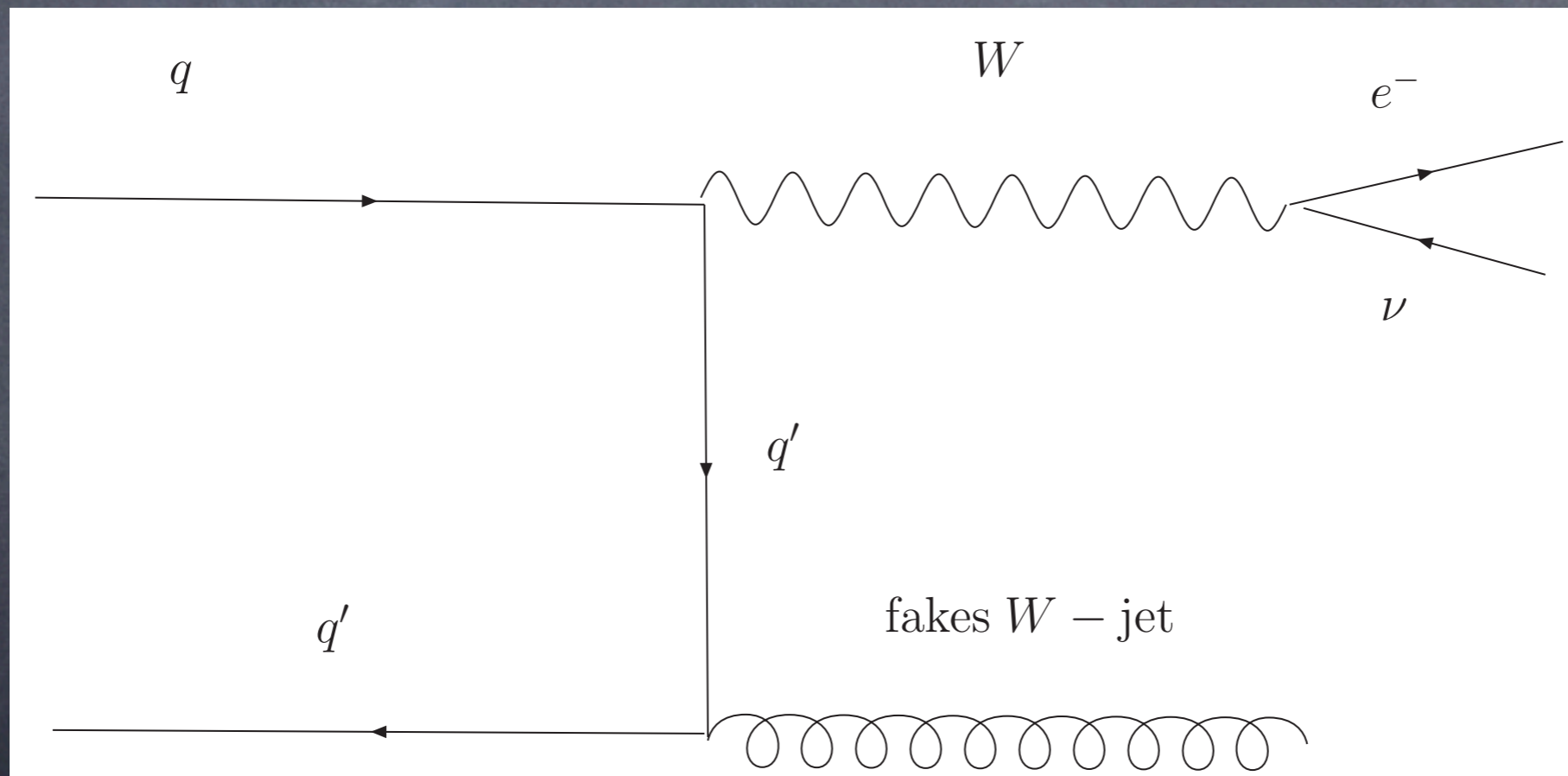
Decays to tops swamped  
by KK gluon

KK  $Z \rightarrow W^+W^- \rightarrow l^+l'^-\nu\bar{\nu}'$ : clean, but...

- cannot reconstruct WW invariant mass
- neutrinos back-to-back

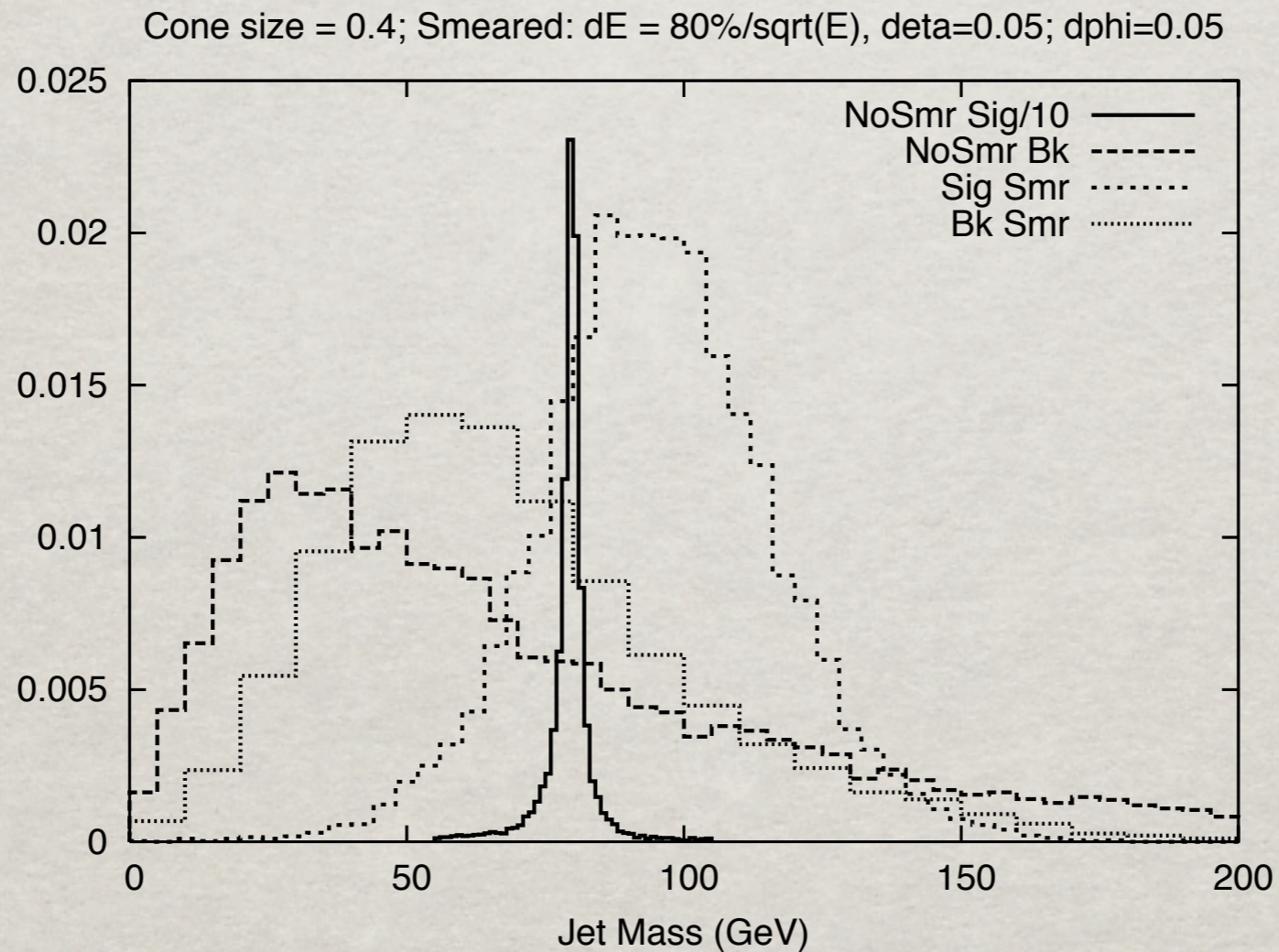
KK  $Z \rightarrow W^+W^- \rightarrow l^+\nu jj$ : can reconstruct, but...

- $W + \text{jet SM background}$



# SOLUTION: JET MASS CUT

(SEE ALSO SMITH, SKIBA; HOLDOM; BUTTERWORTH,  
COX, FORSHAW; BUTTERWORTH, ELLIS, RAKLEV;  
BUTTERWORTH, DAVISON, RUBIN, SALAM...+  
EXPERIMENTAL TALKS/NOTES)



# Results for KK Z

- Reach of 2 (3) TeV for 100/fb (1000/fb) from semileptonic WW
- Similar from  $KK Z \rightarrow Zh$

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**BOOSTED TOP (VETO) AND  
W/Z!**

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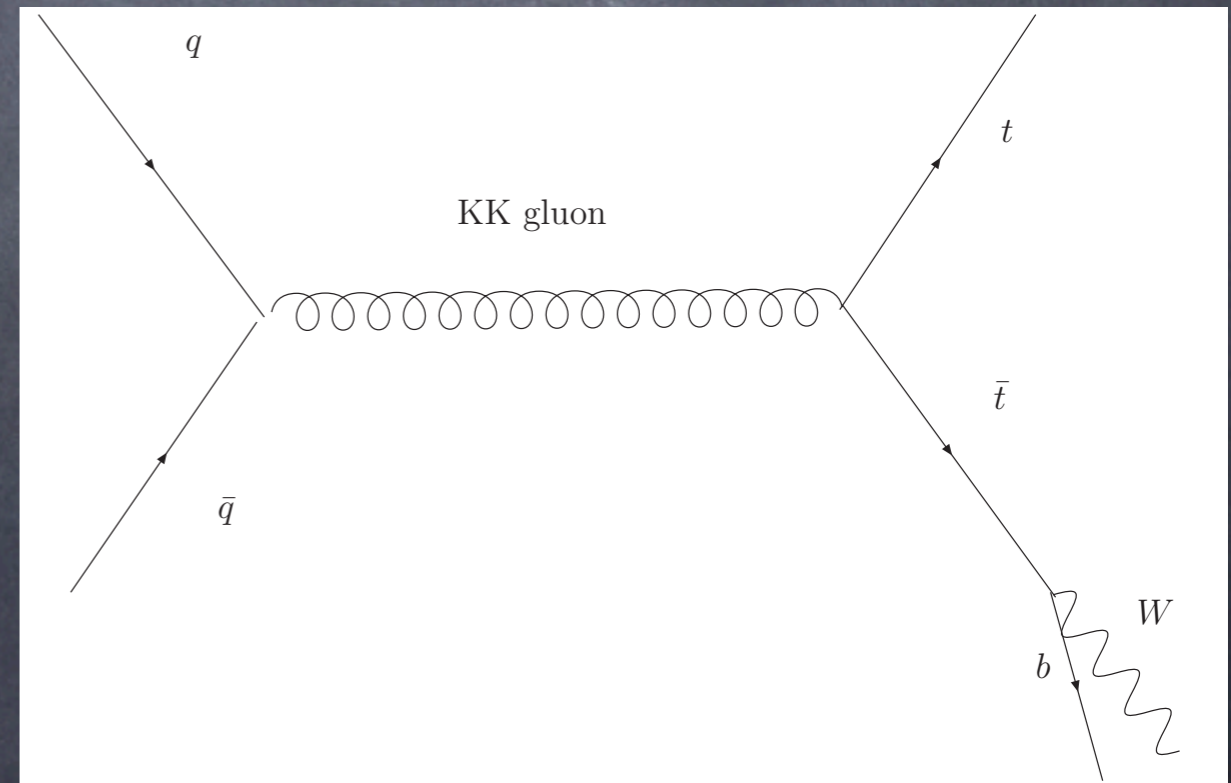
# KK W

(KA, Gopalakrishna, Han, Huang, Soni)

- $KK W \rightarrow WZ \rightarrow l^+ l^- l' \bar{\nu}'$   
(clean) can be reconstructed

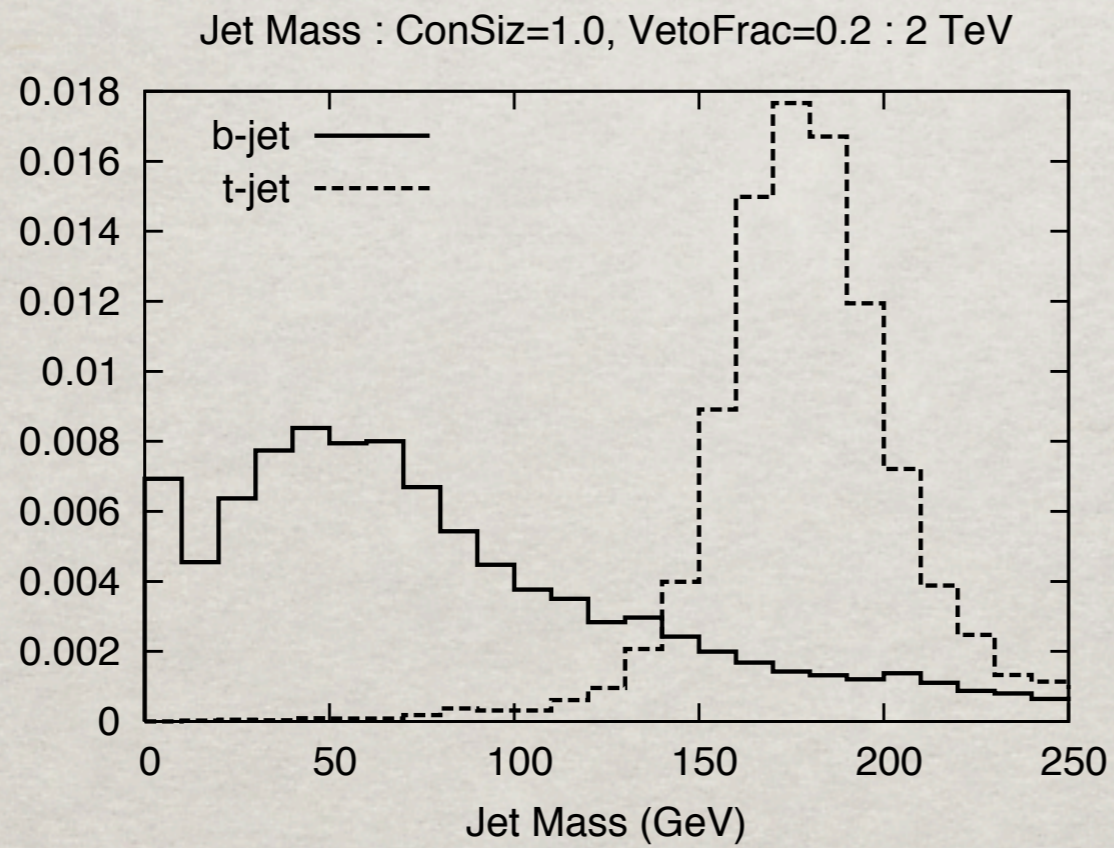
$KK W \rightarrow WZ \rightarrow l^+ \nu$  (or  $l^+ l^-$ ) + jets  
(like  $KK Z$ )

- Decays to top + bottom:  
**KK gluon background**  
(boosted top!)





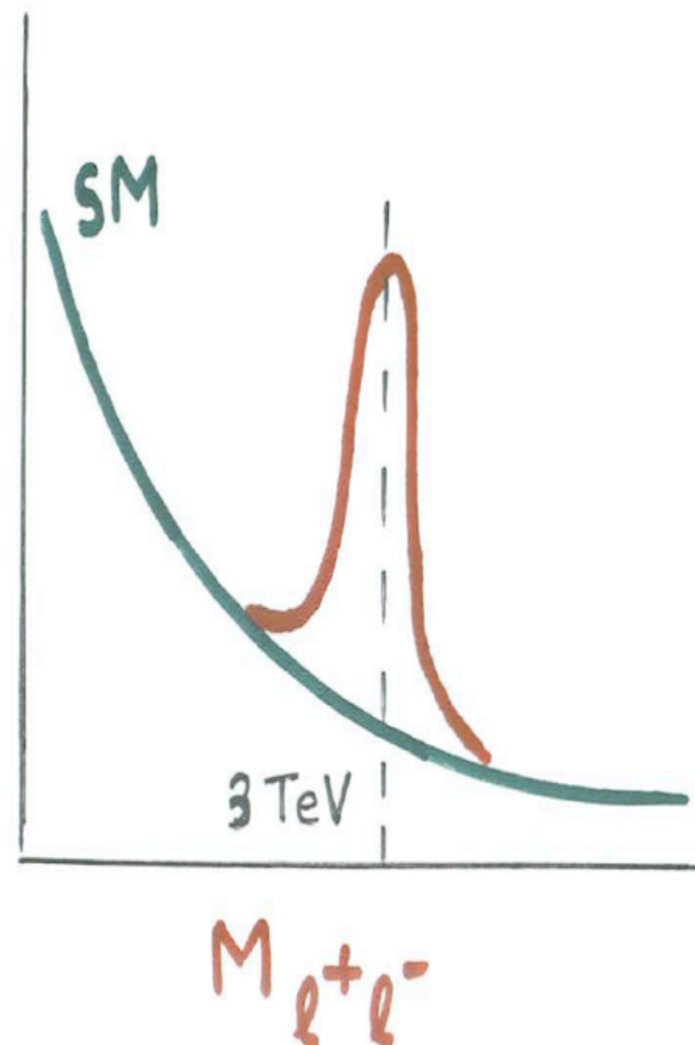
●●● REDUCIBLE BY JET MASS CUT  
(BOOSTED TOP VETO!)



# “ORIGINAL” RS1: BRANEWORLD

Golden decays:

KK graviton  $\rightarrow l^+l^-$ ,  $\gamma\gamma$  (Davoudiasl, Hewett, Rizzo)

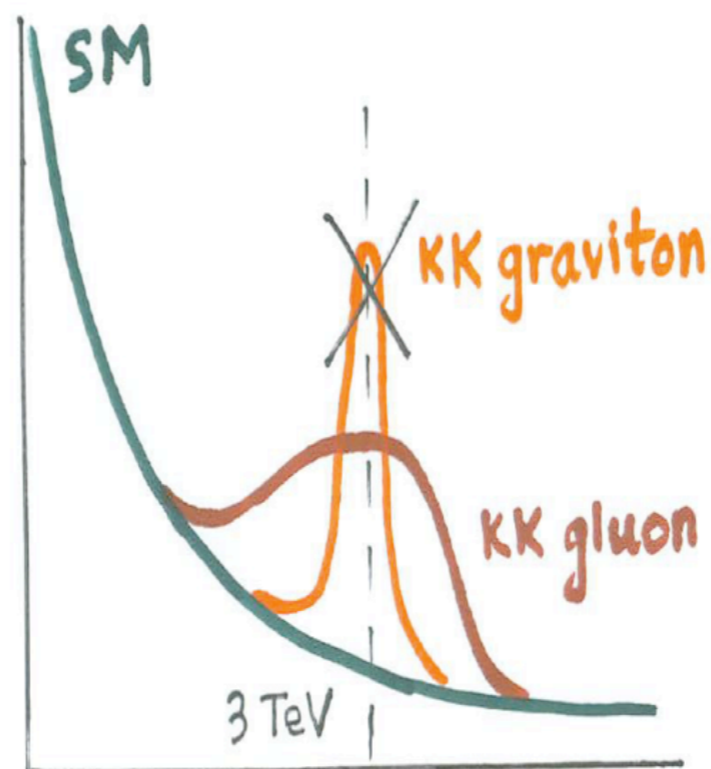


# CF. SM (– HIGGS) IN THE BULK

KK graviton  $\rightarrow l^+l^-$   ~~$\gamma\gamma$~~

$\rightarrow t\bar{t}, WW$  (boosted)

+ KK gluon,  $W, Z, \gamma$



~~$M_{l^+l^-}$~~   $M_{t\bar{t}}$

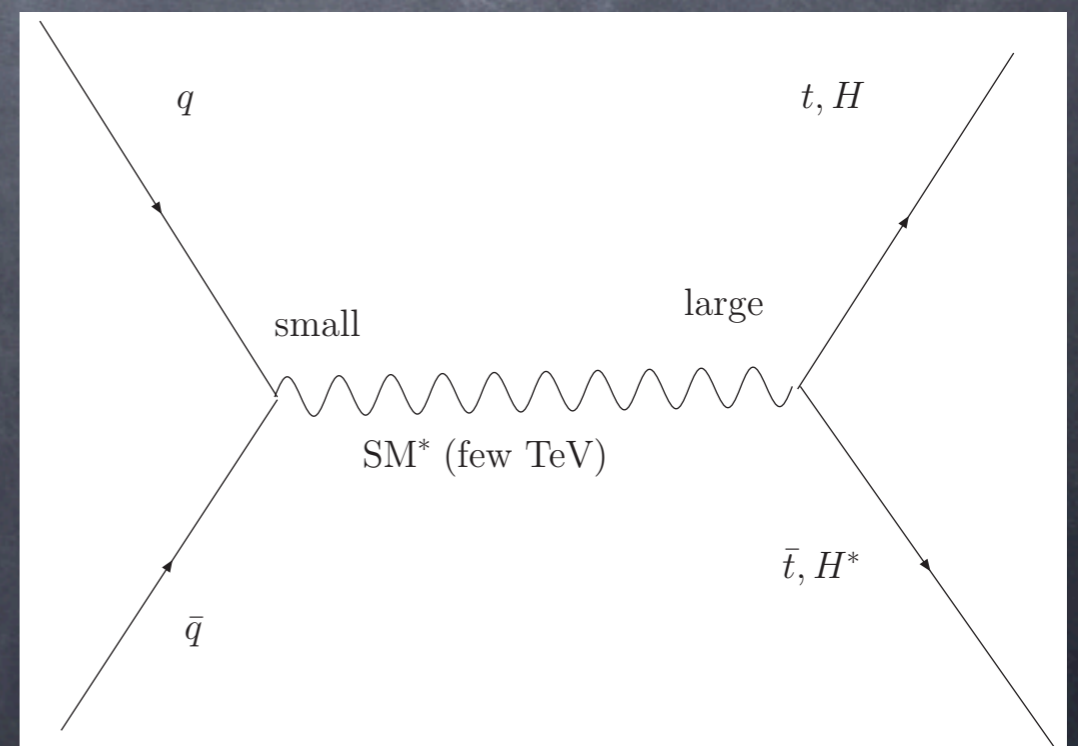
# SIGNALS FOR A *CLASS* OF MODELS, *NOT* JUST WARPED EXTRA DIMENSION

Top quark and Higgs (*longitudinal W/Z*) “special”:  
mechanism of electroweak symmetry breaking

couple strongly to *new* particles

- New particles couple *singly* to SM:  
precision tests  $\Rightarrow \sim$  a few TeV

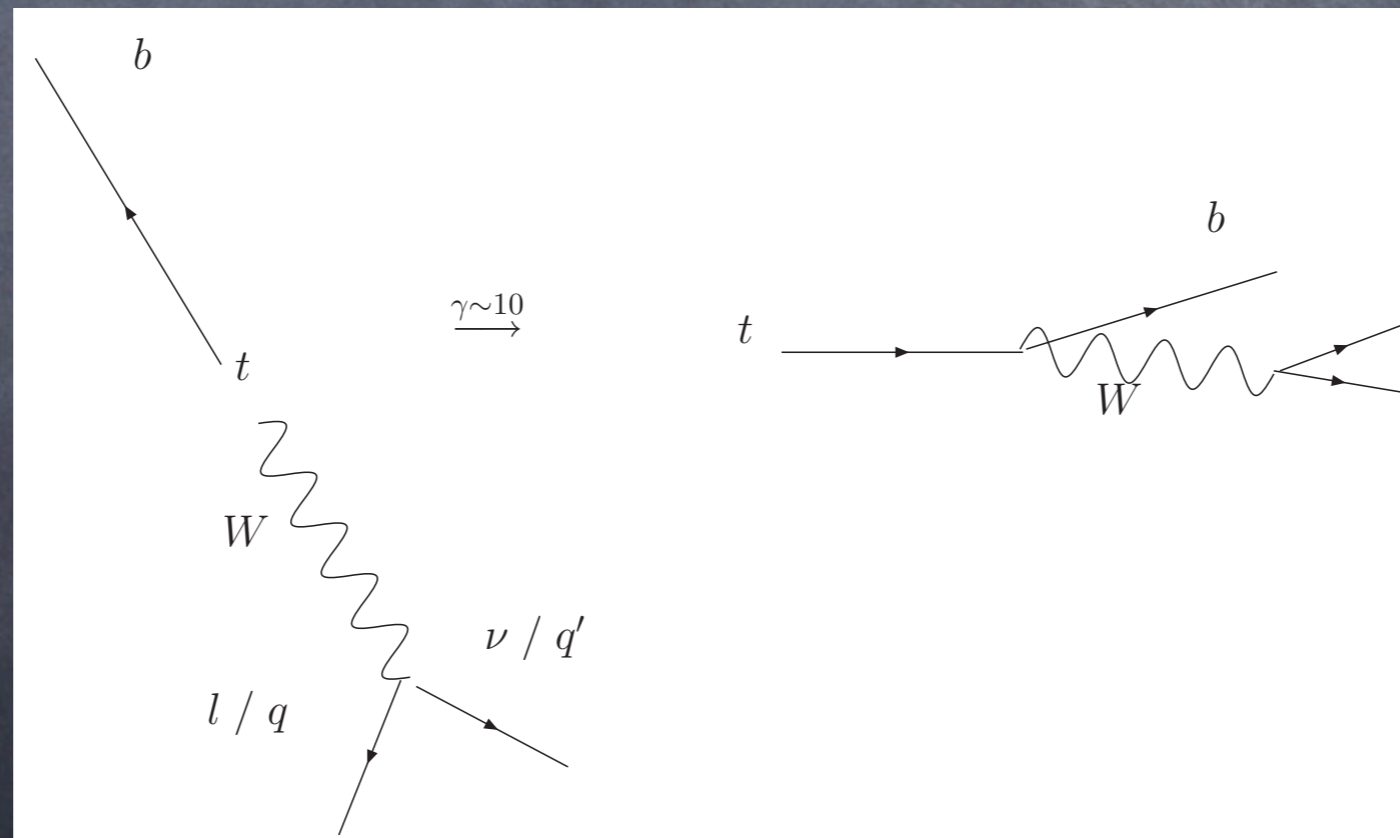
Resonance production:  
decays to top and *H/W/Z*  
(highly boosted!)



# DETECTION OF BOOSTED ( $\gamma \gtrsim 10$ ) TOP, $W$ , $Z$ , $H$ ...

(More) Studies needed...

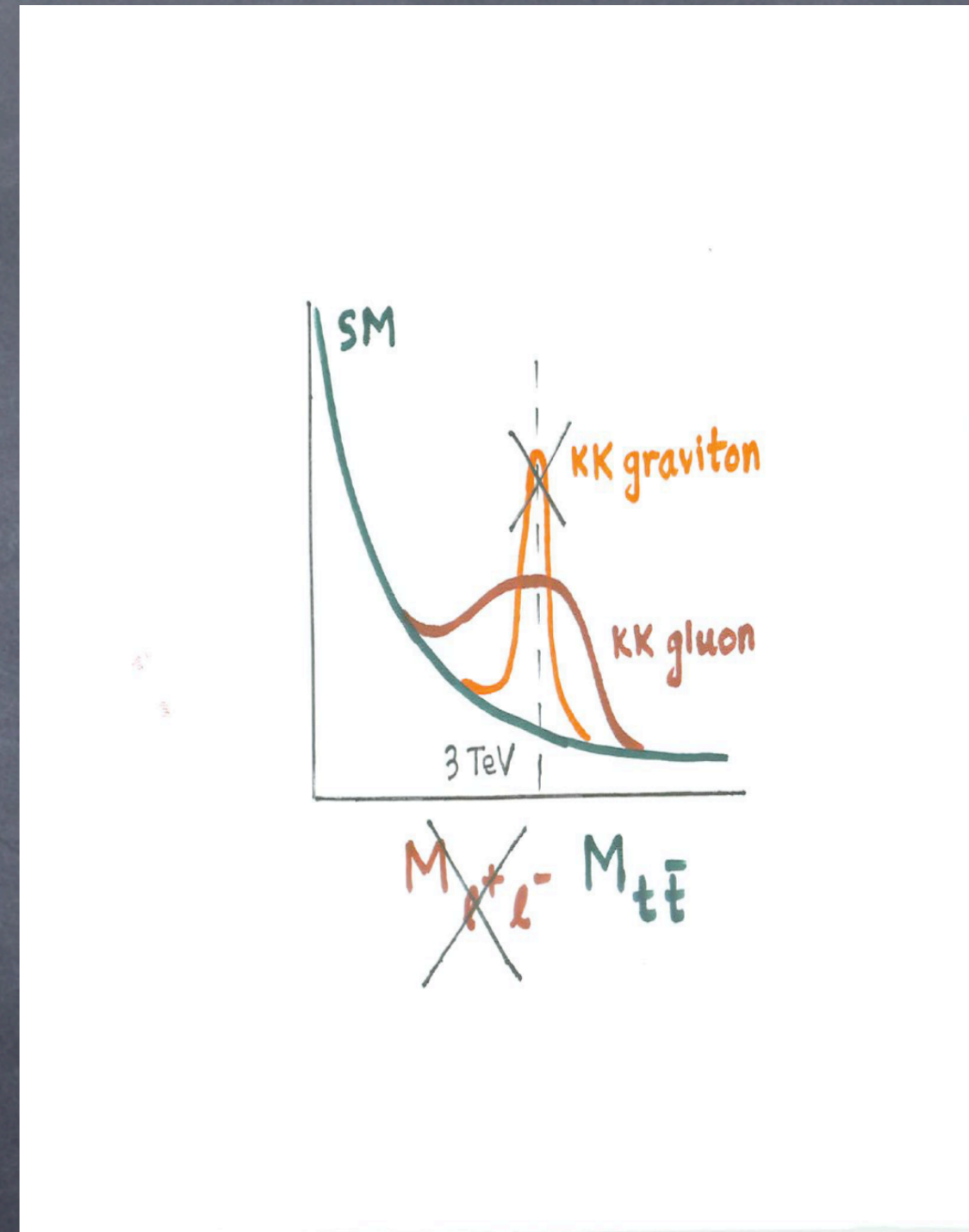
Detector-level simulation of  $m_{bl}$ , substructure, jet mass...



# Conclusions

- can't wait for LHC to start!
- keep open mind...

warped extra dimension: well-motivated framework (Planck-weak and flavor hierarchies) with a few TeV broad resonances decaying into highly boosted (collimated) top/W/Z/Higgs!



Back-up slides

# Calculability in 5D

- Non-renormalizable (couplings of mass dimension  $< 0$ ) divergences at some loop order less control than 4D models...
- ...unless counterterm forbidden by symmetry, e.g. T parameter with custodial isospin; Gauge-Higgs potential
- tree-level contribution for operator, e.g., 4-fermion, loops/cut-off smaller perturbative expansion (with modestly small parameter)
- loop-level contribution for operator not protected by symmetry (e.g., dipole): might not perturbative expansion



# Warped Gauge-Higgs unification

(Contino, Nomura, Pomarol)

4D scalar

- Higgs from 5D gauge fields:  $A_M = A_\mu + A_5$
- Higgs **localized** near TeV brane,  
potential from loops (calculable):  
heavy top  $\Rightarrow m_H^2 < 0$  (KA, Contino, Pomarol...)

# Cannot suppress $S$ with non-AdS

- Hirn, Sanz: general Higgs profile and warp factor
- **Pathology**:  $v_{\text{ev}}^2 < 0$  to suppress  $S$  (KA, Csaki, Grojean, Reece; see also McGuirk, Shiu, Zurek)

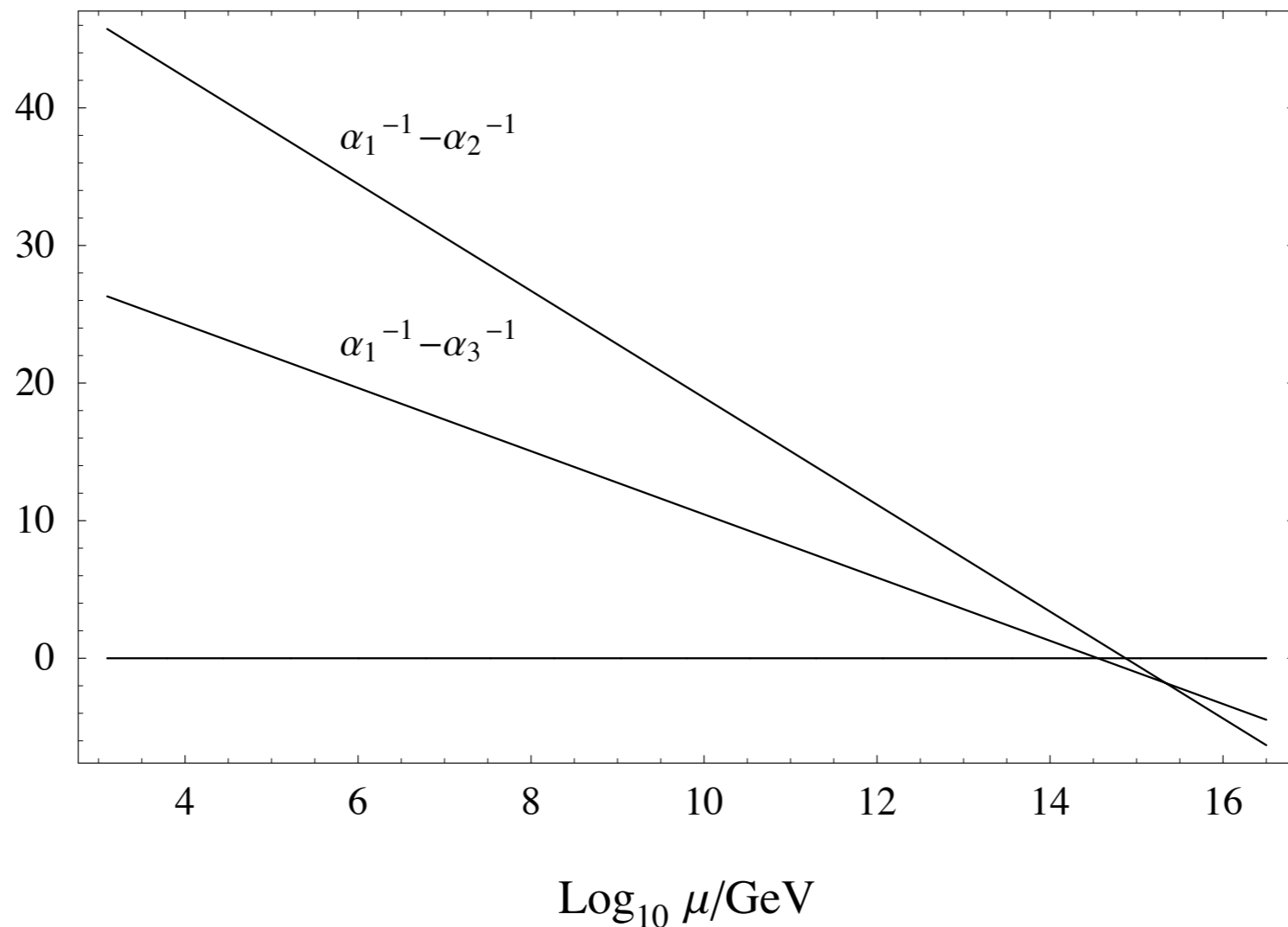
# "Running" of Gauge Coupling

(Pomarol; Randall, Schwartz; Goldberger, Rothstein; KA, Delgado, Sundrum; Choi, Kim; Contino, Creminelli, Trincherini)

- **Subtle**: gauge bosons flat  $\Rightarrow$  loops span extra dimension, sensitive to Planck and TeV cut-off scales (AdS/CFT more intuitive)
- **Gauge boson** loops: non-universal; effectively cut-off at high scale (a la SM)
- **Fermion** loops non-universal (unlike SM):  $t_R$  & H (near TeV brane) loop cut-off at **TeV**; other fermion (near UV brane) loops cut-off at high scale

# LO unification: **magic** of $\beta$ -function: SM $-2t_R - H$

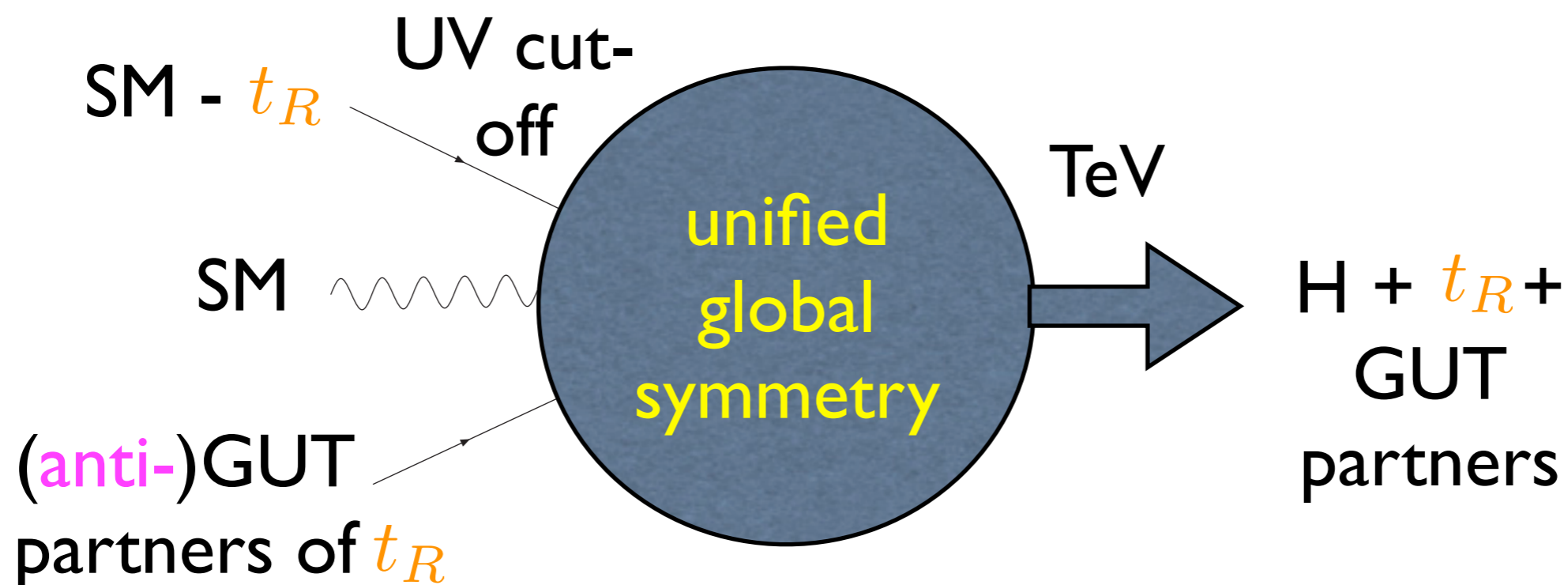
(KA, Contino, Sundrum)



( 2<sup>nd</sup>  $- t_R$ : running due to **light** GUT partners)

# Unification in CFT picture

- Global **unified** symmetry for CFT  $\Rightarrow$  LO running of SM gauge couplings from CFT loops universal
- **Composite**  $t_R$  and H  $\Rightarrow$  above TeV, replace running due to  $t_R$  and H by CFT
- Add **external** fermions to make composite GUT partners of  $t_R$  heavy



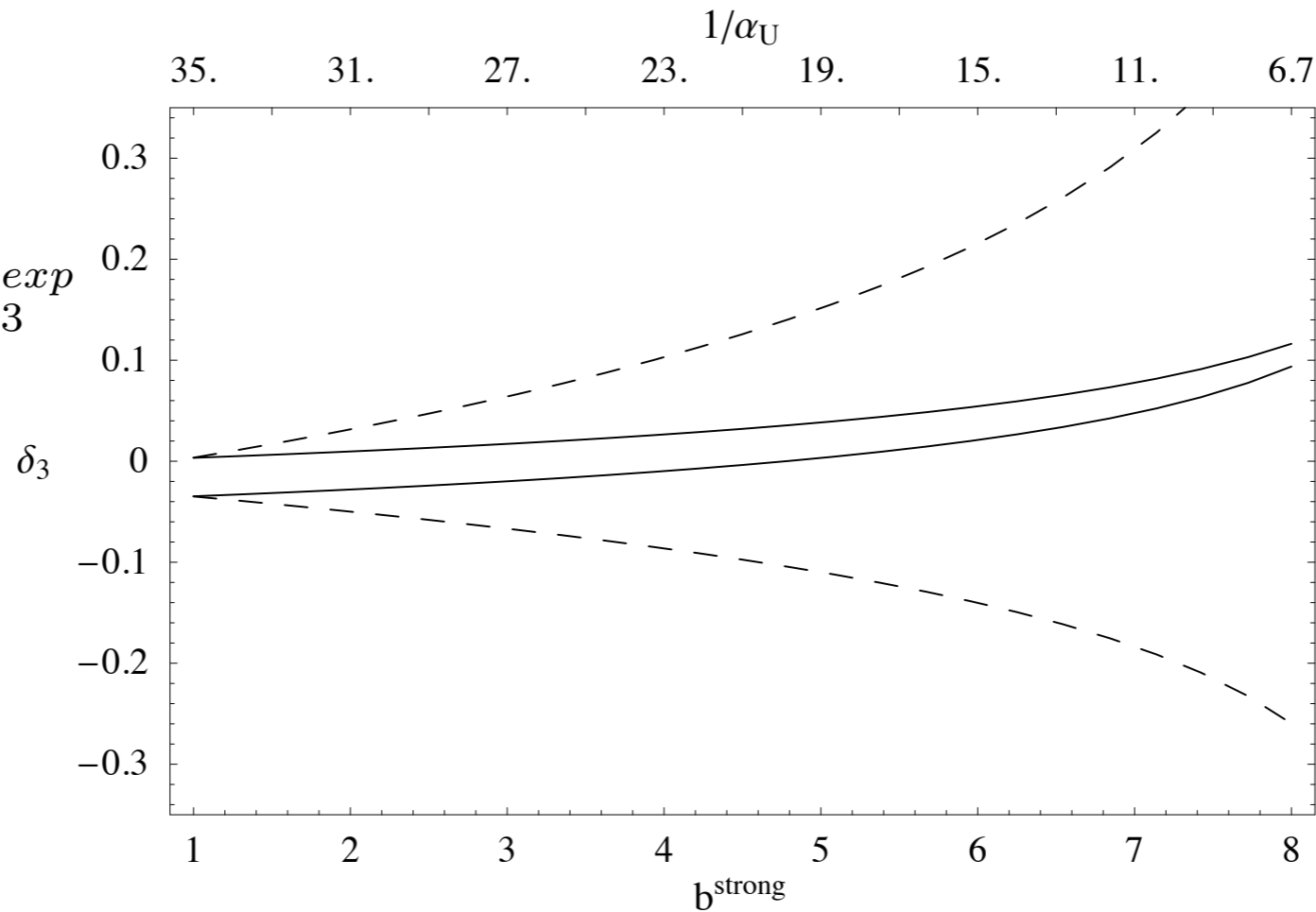
# Assumptions

- Bulk **unified gauge** symmetry  $\longleftrightarrow$  CFT has **global** unified symmetry
- Localization parameter (bulk mass) of  $t_R$ :  
unification improved relative to SM in **entire**  
range (preferred by precision data); **precision**  
unification for sizable range

# NLO precision $\sim$ SUSY

$$\delta_3 = \left( \alpha_3^{theory} - \alpha_3^{exp} \right) / \alpha_3^{exp}$$

$\sim 0.1$  in SUSY  
( $\alpha_3$  at  $M_Z$ )



(size of 4D strong sector)

→ Landau pole  
below GUT  
scale

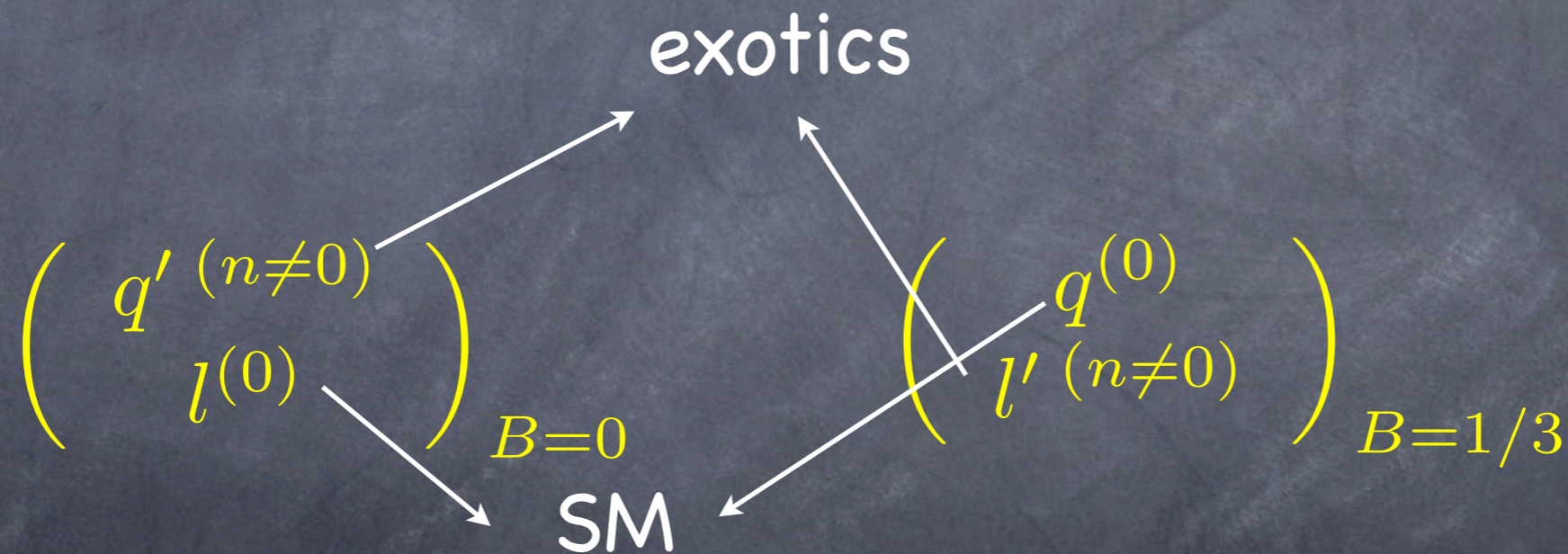
# Signals

- **Complete** GUT multiplets at few TeV scale (KK gauge bosons and fermions)
- **light** GUT partners of  $t_R$  for precision unification



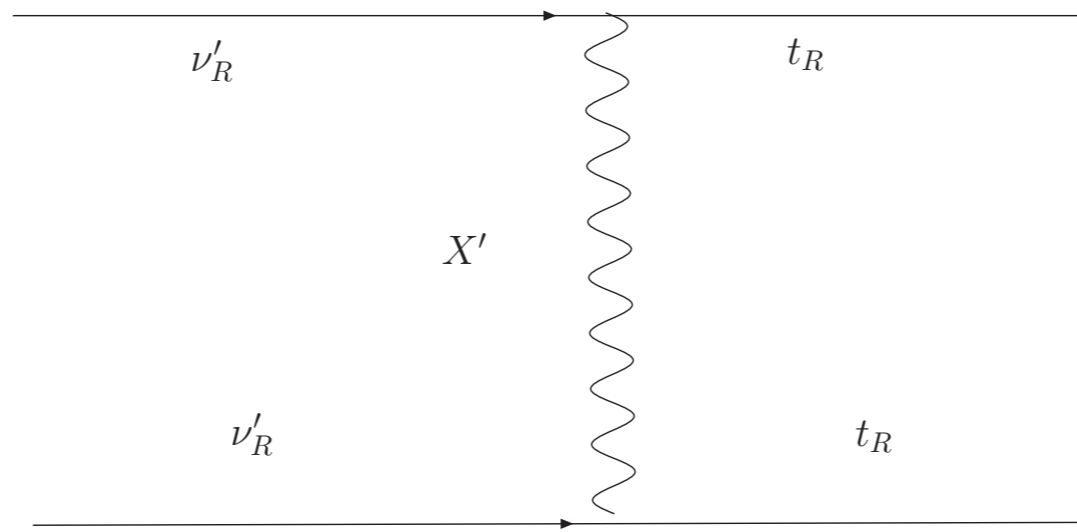
# Stable particle from Proton stability (KA, Servant)

- **Orbifold GUT's** (GUT breaking on boundary: Hall, Nomura): quark and lepton zero-modes from **different** multiplets; assign multiplets baryon-number of zero-mode (**split** multiplets for proton stability)

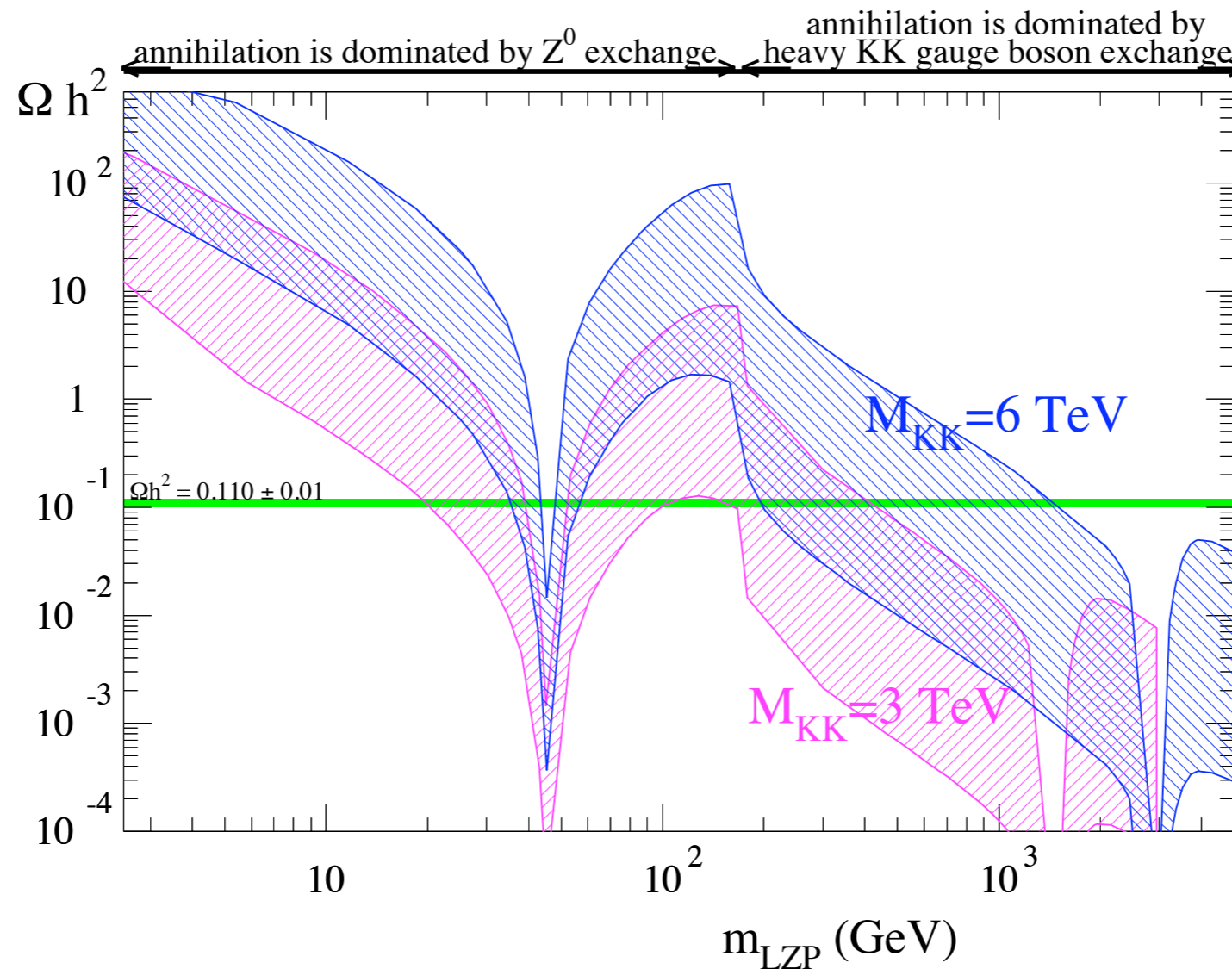


- Extra particles (**no** zero-modes) are "exotic" ("**wrong**" combination of B and color: SM have right...)  $\Rightarrow$  lightest stable

# Exotic $\nu'_R$ partner of $t_R$ as WIMP dark matter: I

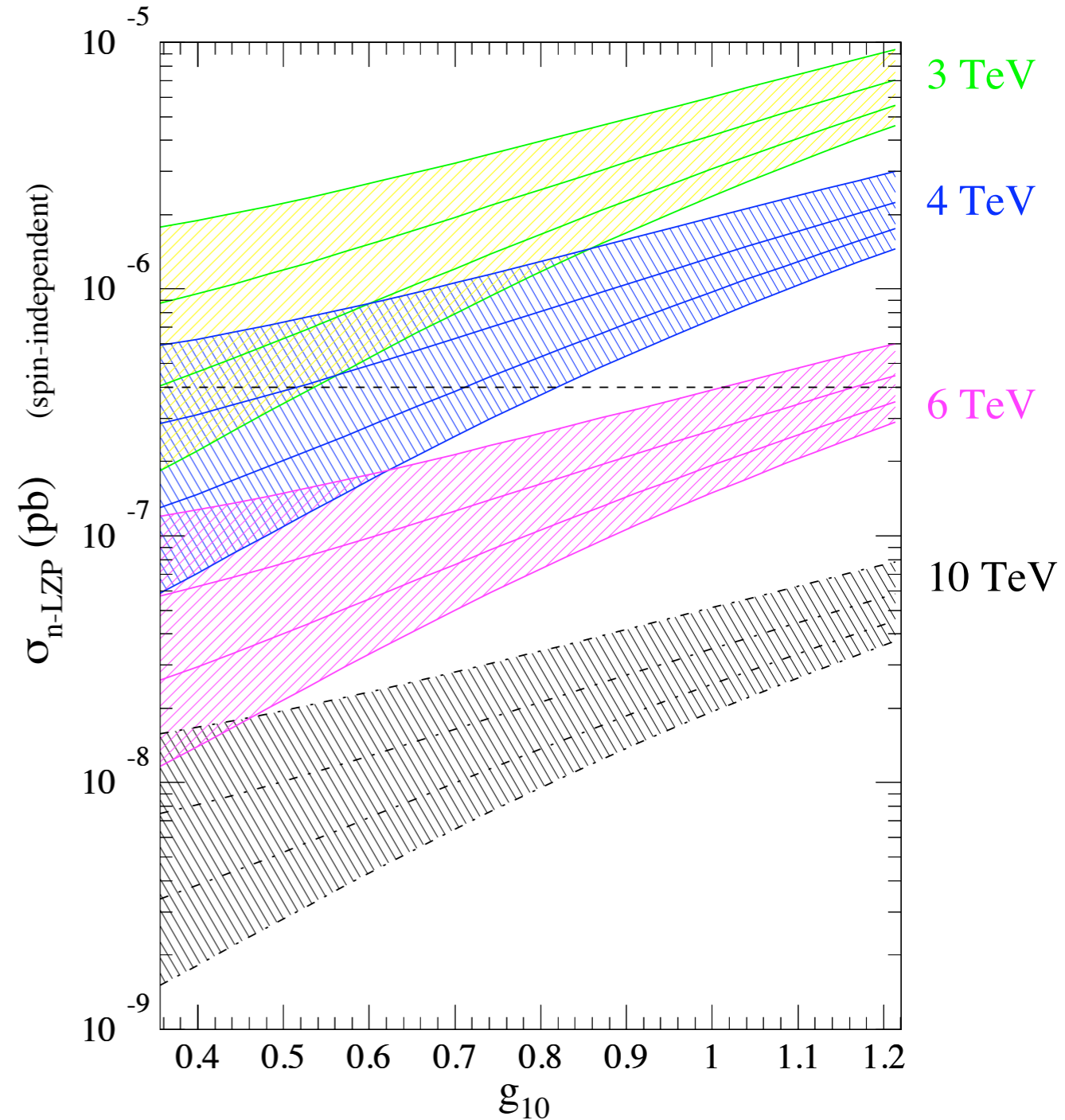
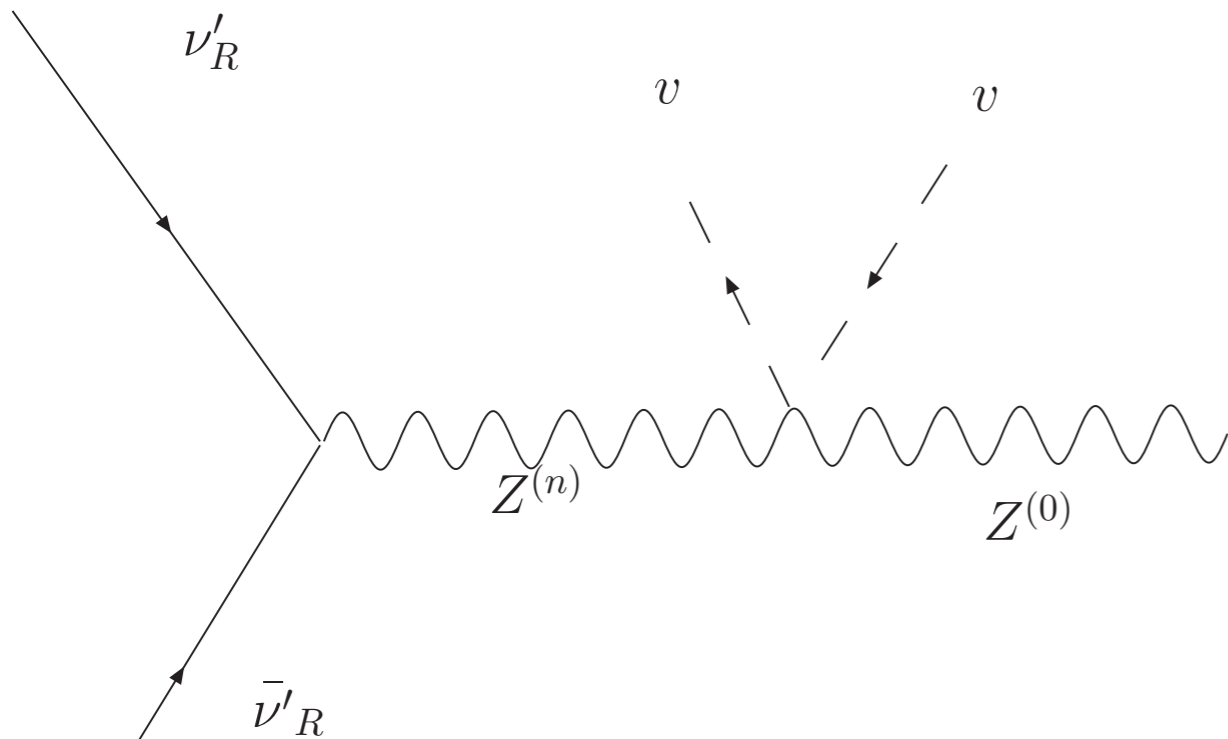


- Annihilation:

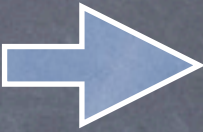


# Exotic $\nu'_R$ partner of $t_R$ as **WIMP** dark matter: II

- Direct detection (**small** coupling to  $Z$ ):



# Polarization asymmetry: definition

- Positron in direction of top spin   
"forward-backward" asymmetry

$$P_{LR} \equiv 2 \times \frac{N_+ - N_-}{N_+ + N_-}$$

RH (LH) top:  $P_{LR} = \pm 1$

LH top

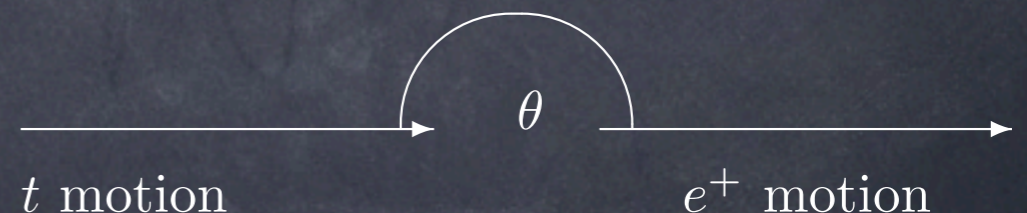
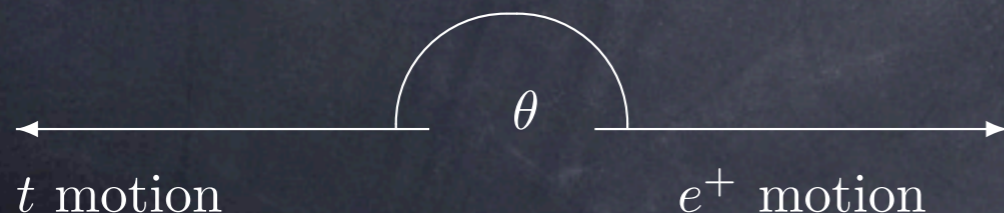


$t$  spin

RH top



$t$  spin



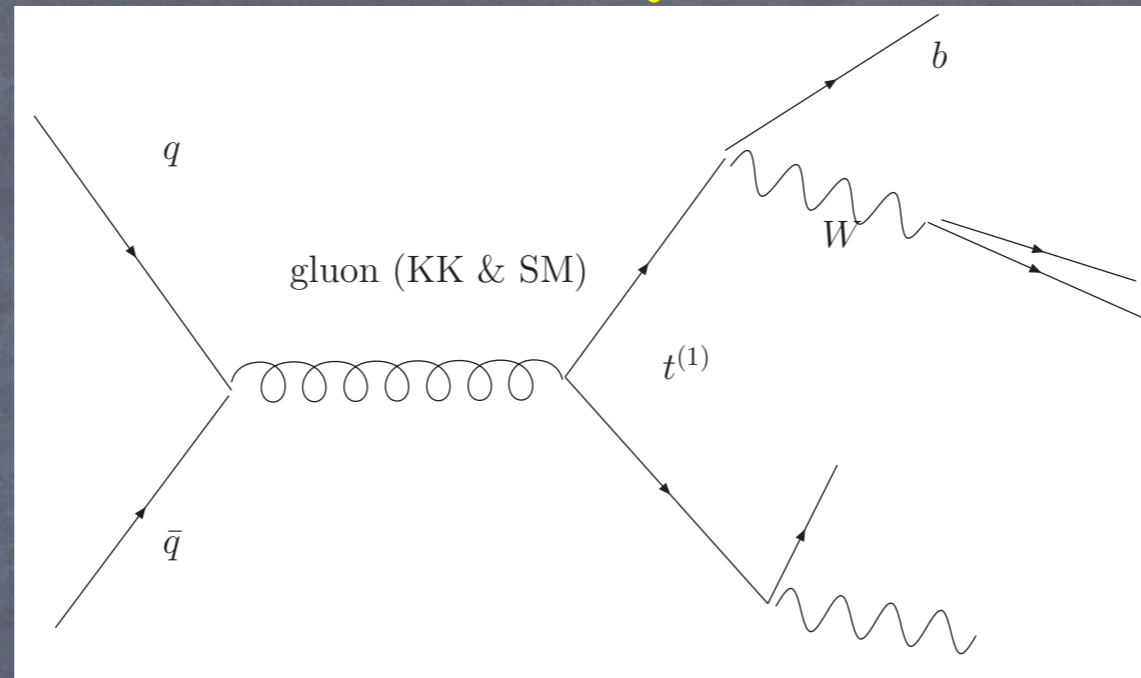
# Polarization asymmetry: SM vs. Warped

• SM:  $P_{LR} \sim g_Z^4 / g_{QCD}^4$  and  $< 0$   
(pure QCD gives 0)

vs.

$O(1)$  for warped extra dimension (KK  
gluon decays to RH or LH top)

# KK gluon decays to KK tops



- KK tops (1 TeV) not boosted, decay into  $Wb$  (well-separated, but 2 jets from  $W$  still collimated)  
(Carena, Medina, Panes, Shah, Wagner)

# Other Signals

- KK graviton decays to tops, WW, ZZ: 2 to 3 TeV with 100–1000 /fb (Fitzpatrick, Kaplan, Randall, Wang; KA, Davoudiasl, Perez, Soni; Antipin, Atwood, Soni; Antipin, Soni)
- Heavy KK fermions: via KK gluon (Davoudiasl, Rizzo, Soni); via longitudinal W/Z-bottom fusion (a la in little Higgs)?
- Light KK fermions (Dennis, Karagoz Unel, Servant, Tseng; Contino, Servant; Atre, Carena, Han, Santiago: see talk by A. Atre)
- **Virtual** effects:  $t \rightarrow cZ$  with BR of  $10^{-5}$  (KA, Perez, Soni)

(+ low-energy flavor violation + DM direct detection..)

# Motivation and Spectrum for warped KK parity

- **Odd** KK's at **1** TeV, cut off Higgs mass
- **Even** KK's at **few** TeV pass precision tests
- **Lightest** KK particle (LKP) stable:  
Dark Matter

("Complete" models: flavor, custodial isospin...to be done)



# Phenomenology

- Odd KK's **pair**-produced
- Large Brane Kinetic terms  
KK **Z** Dark Matter  
(cf. KK **photon** in UED)

