Extra Dimensions at the LHC

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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)

- Challenging for LHC: techniques to detect highly boosted top/W/Z (experimentalists'input!)required

- Relax constraints by KK parity: no coupling of single (lightest) new particle to SM

WARPED EXTRA DIMENSION

Motivations

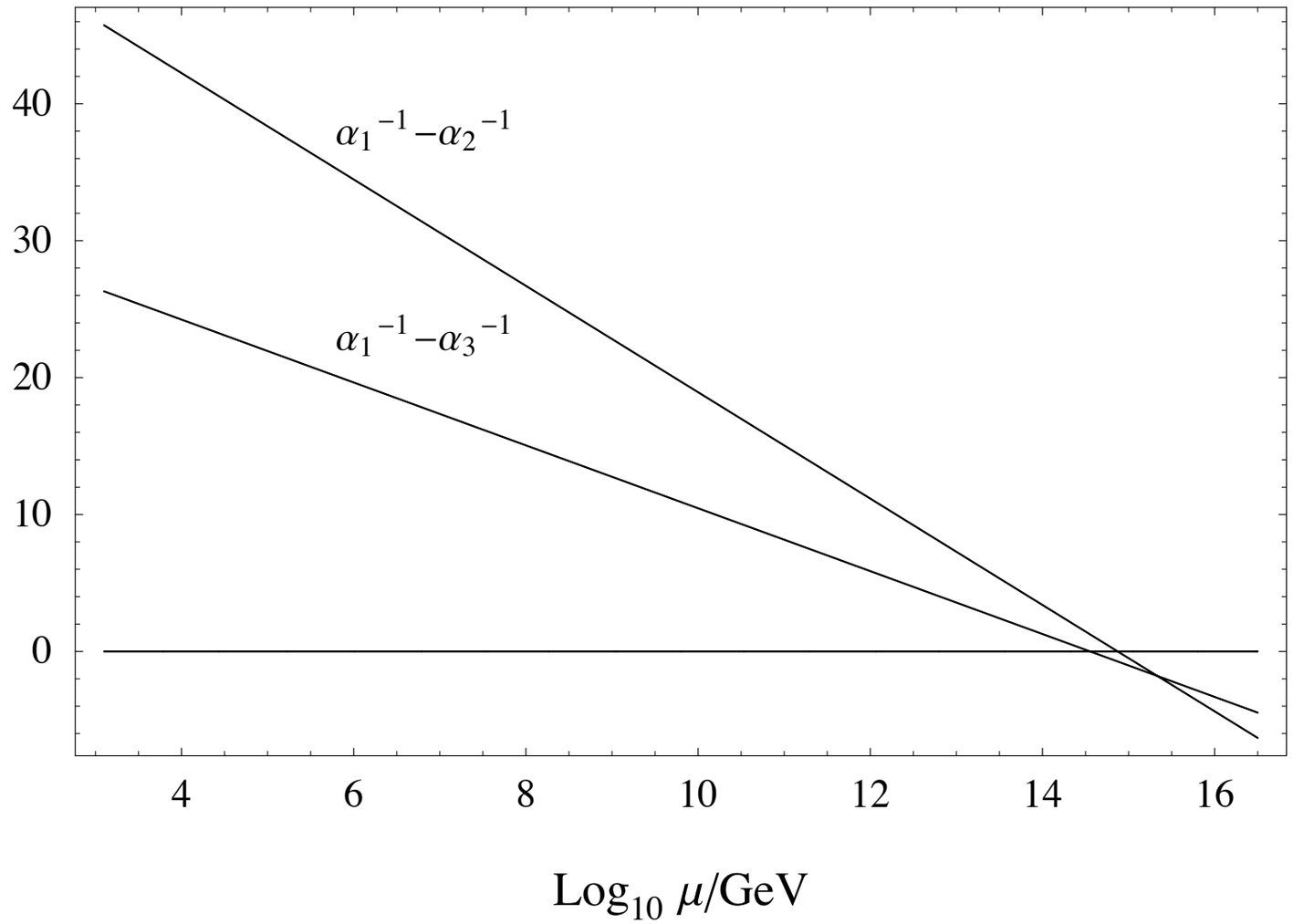
- Planck-weak and flavor hierarchy (without severe flavor problem)

- Weakly-coupled "tool" for 4D strong dynamics: dual to 4D composite Higgs (AdS/CFT)

- GUT's: (i) dark matter from proton stablity (KA, Servant); (ii) gauge coupling unification with precision $\sim$ SUSY (KA, Contino, Sundrum)

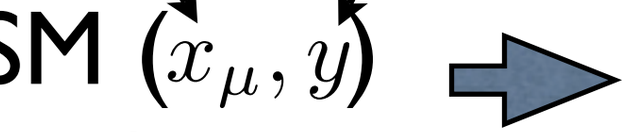
Tantalizing unification: magic of β-function: SM $-2t_R - H$

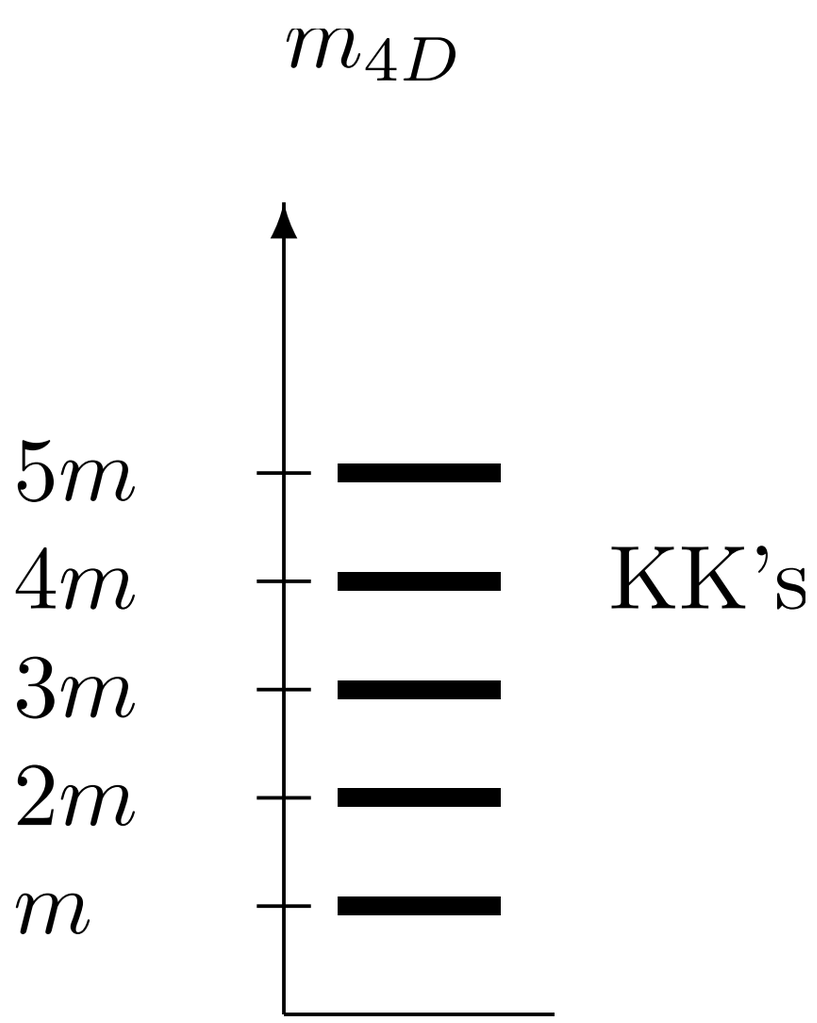
(KA, Contino, Sundrum)



Basics of extra dimensions

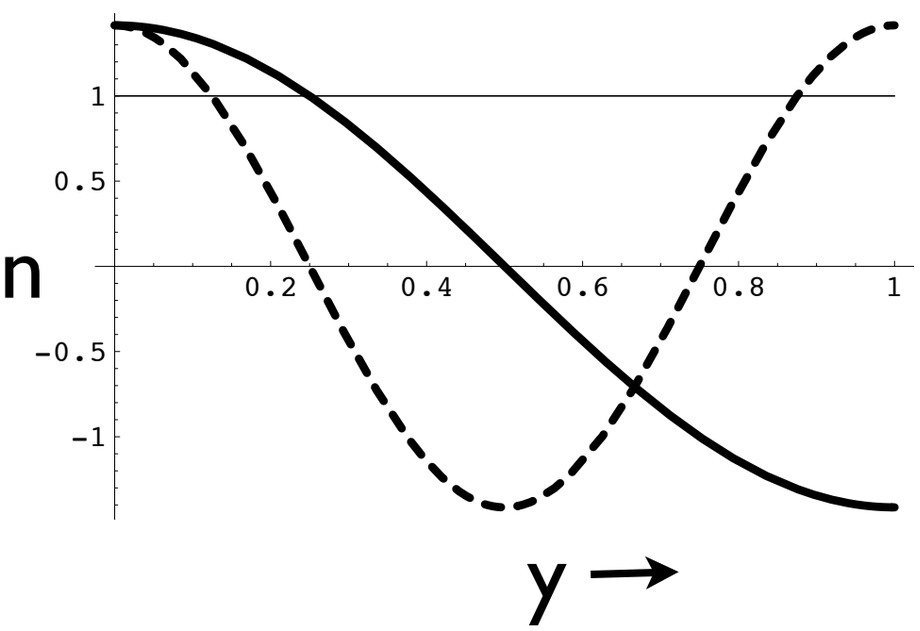
- Particle in 5D: SM (x_μ, y) — 4D, extra... Fourier expand y (a la 1D box)





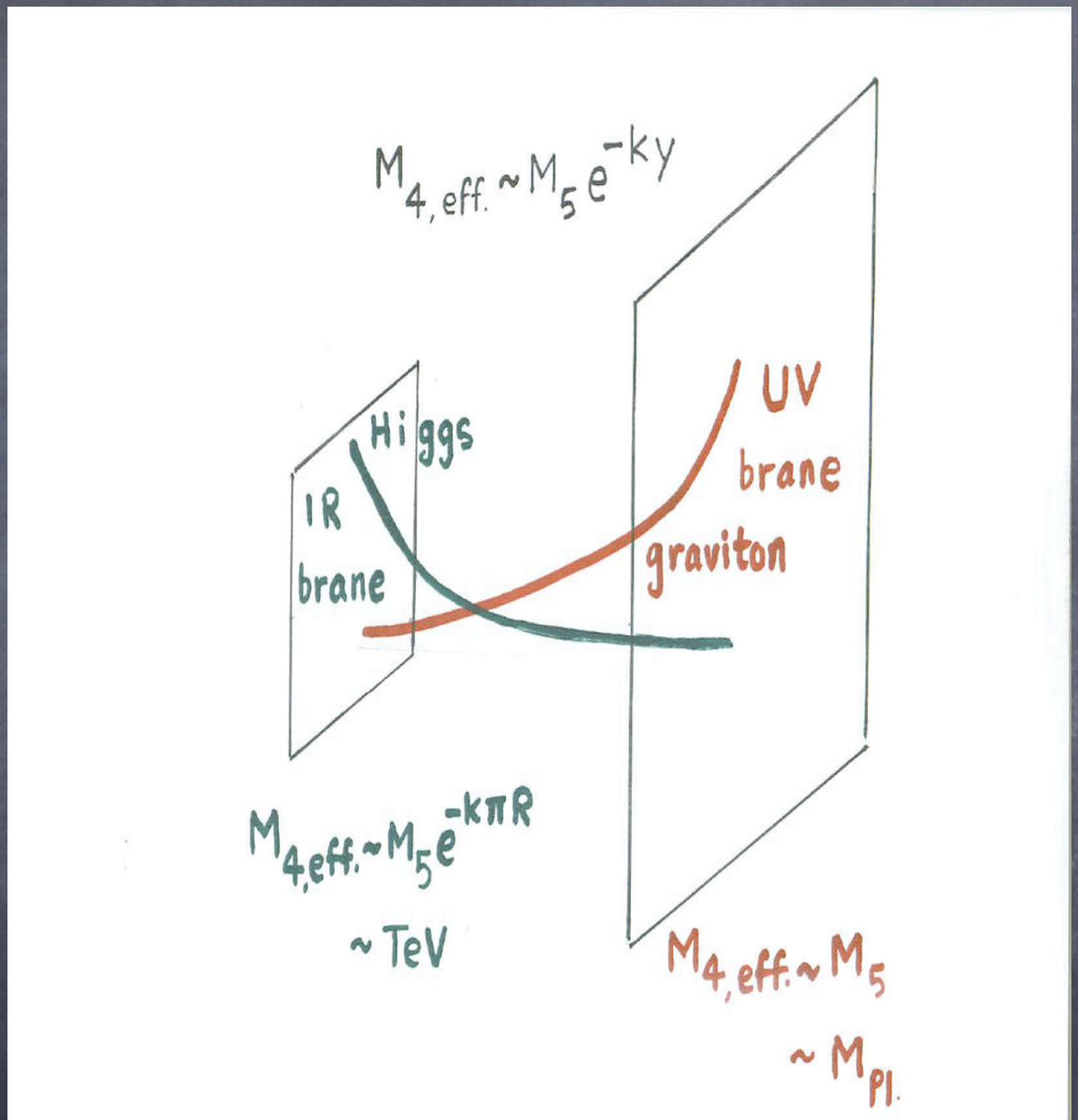
- Lightest mode (SM) + heavier (Kaluza-Klein: KK) with profiles

wavefunction ↑



Gravity and Higgs

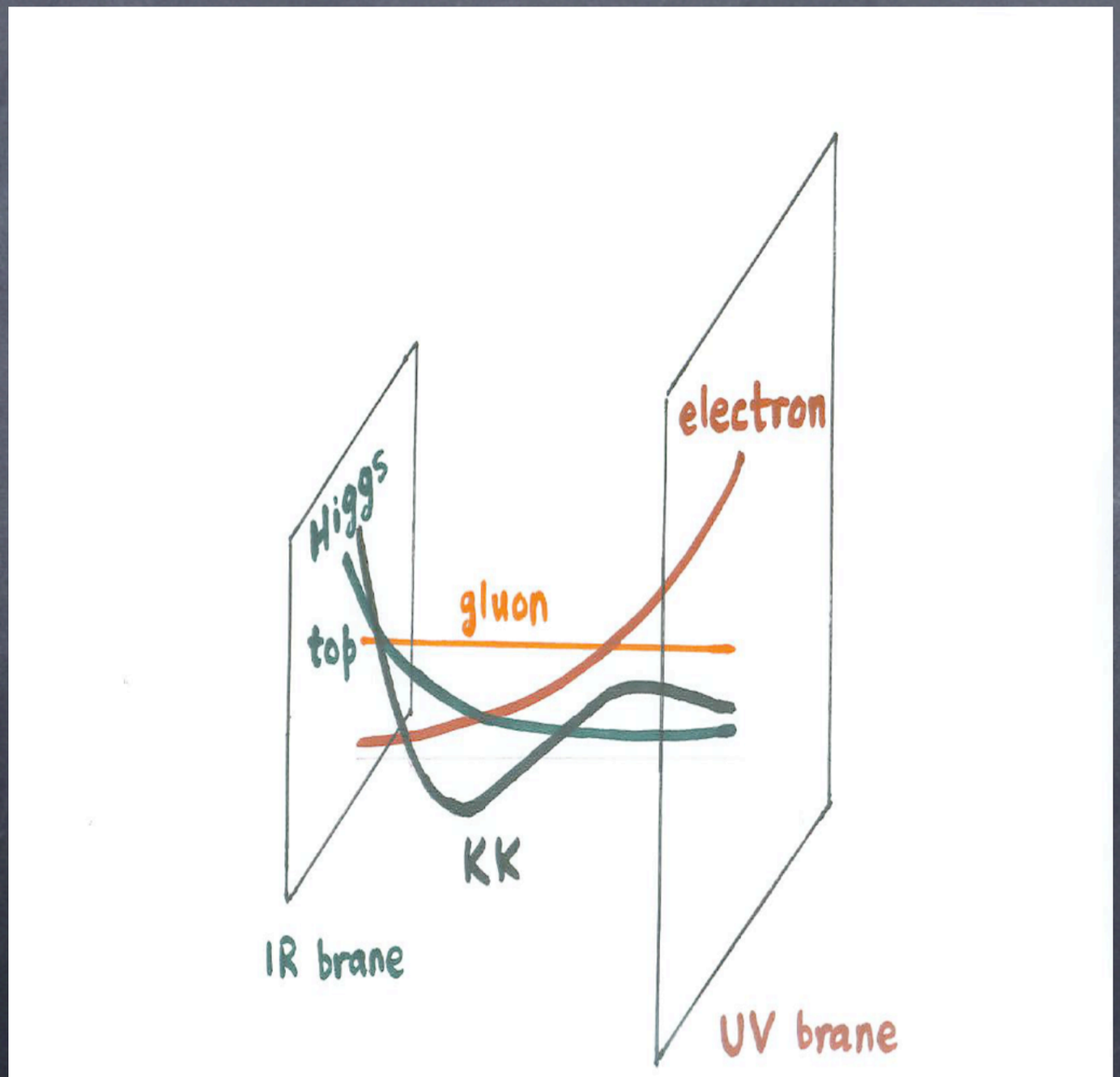
(Randall, Sundrum)



$$kR \sim \log\left(M_{Pl}/\mathrm{TeV}\right)/\pi \sim 10$$

SM in bulk

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

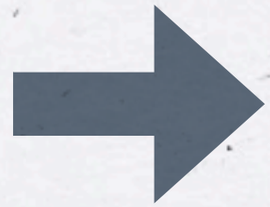


Couplings from overlap of profiles

- Flavor hierarchy (fermion-Higgs) without hierarchy in 5D parameters (5D Yukawa, 5D mass M):
  fermion profile $\sim e^{-k\pi RM\ldots}$ ...related to Planck-weak hierarchy

- Couplings to KK large (small) for top (electron)

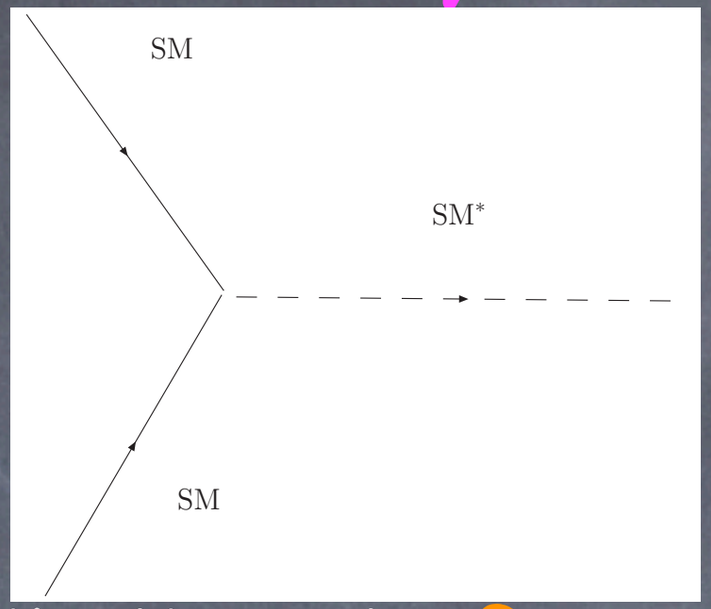
NO PARITY, PRECISION TESTS



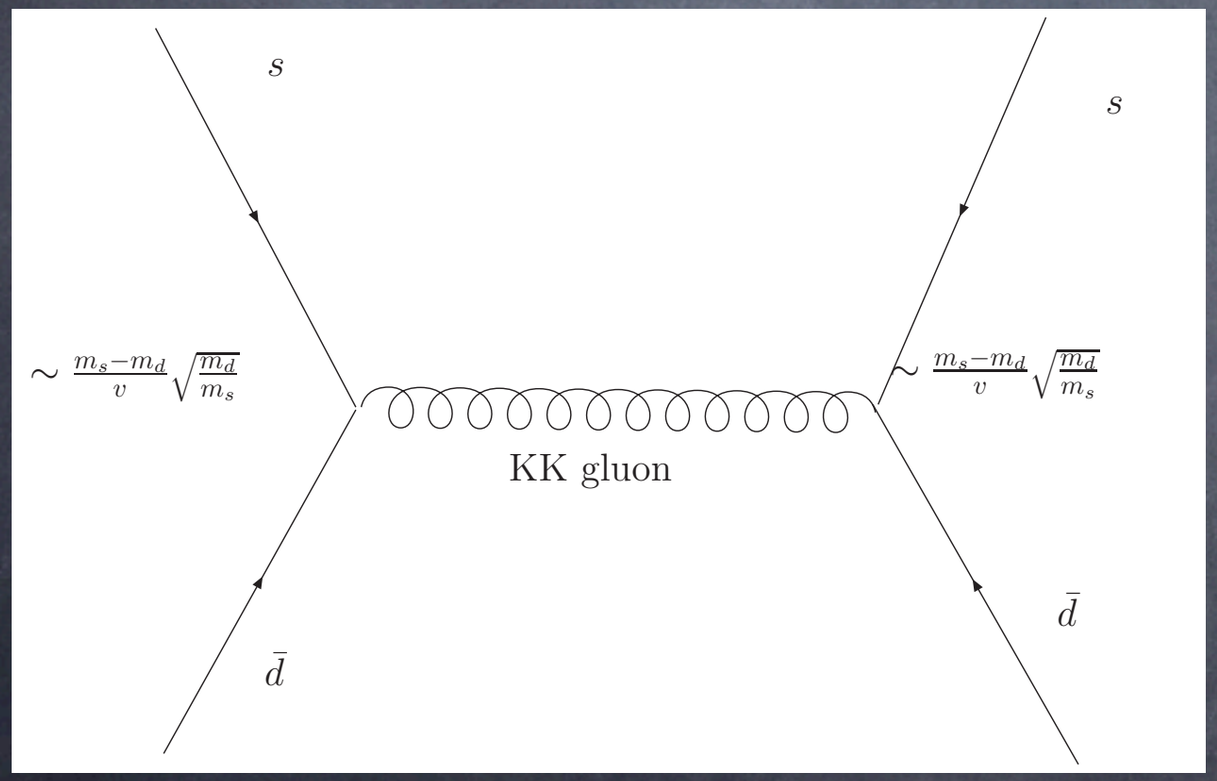
NEW PARTICLES FEW TEV

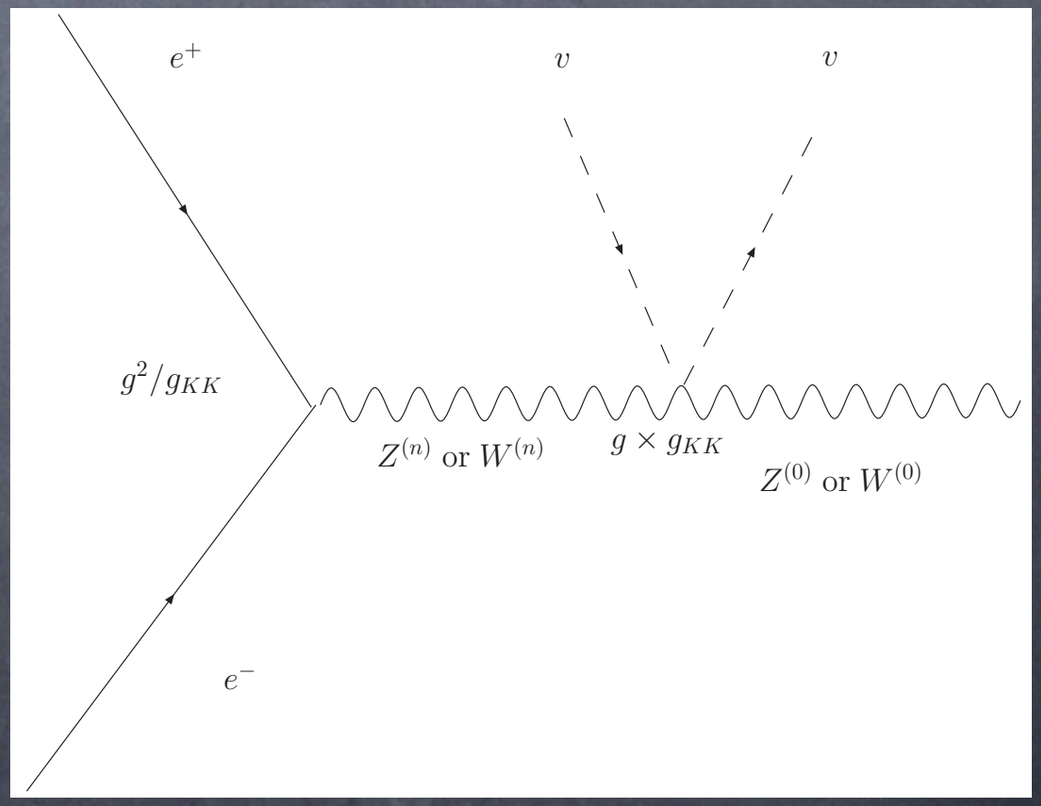
Summary (rough)

- no parity



- tree-level contributions to flavor and EW precision tests





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

EW PRECISION TESTS

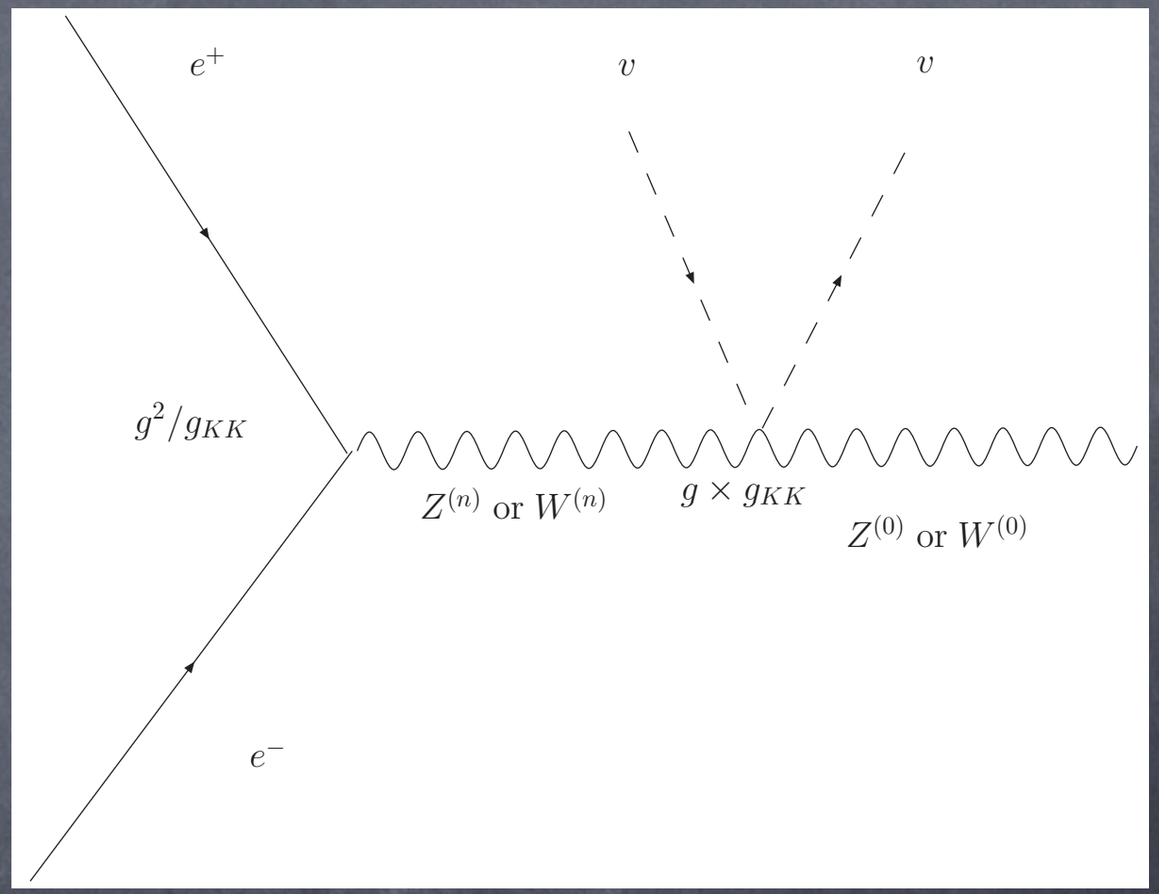
S parameter

- 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)

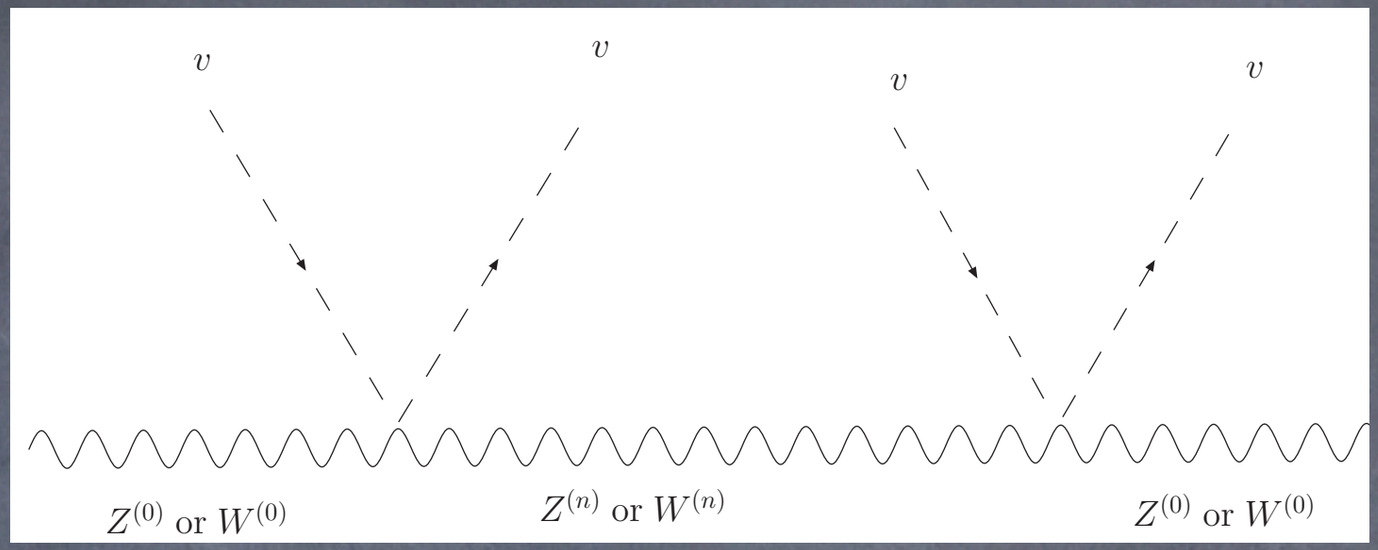
- Flat profiles for fermions ⇨ suppression in S

  (Cacciapaglia, Csaki, Grojean, Terning)

- < 1 TeV KK's unitarize WW scattering

(See talks by N. Christensen and K. Hsieh)

Custodial symmetries



- T parameter (KA, Delgado, May, Sundrum) and Zbb (KA, Contino, Da Rold, Pomarol)

- EW fit with ~3 TeV KK masses (Carena, Ponton, Santiago, Wagner)

About "~" in ~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)

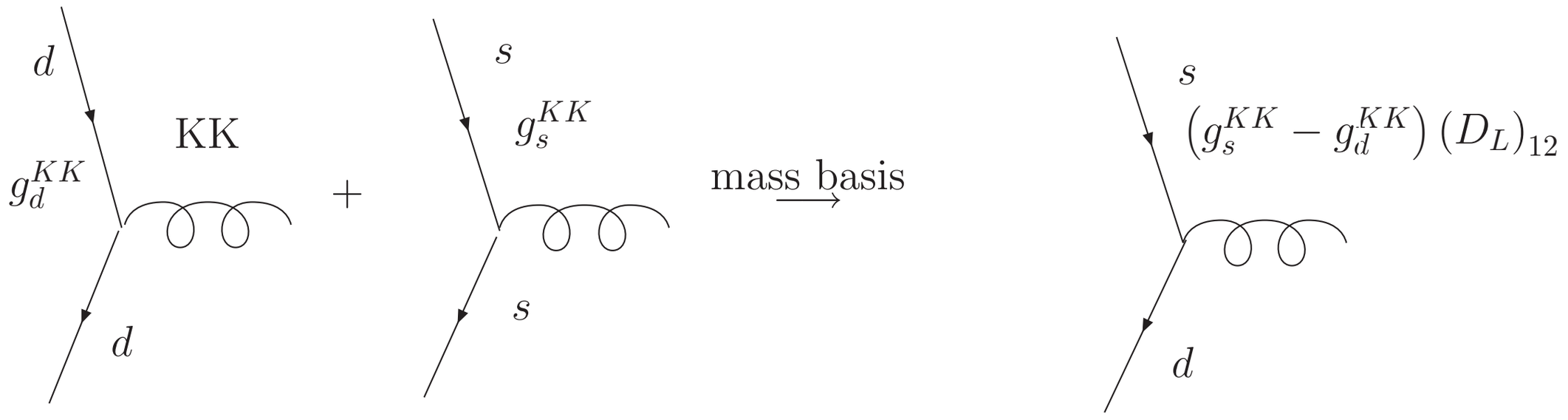
see talks

FLAVOR PRECISION TESTS

Flavor hierarchy from profiles ⇒ flavor violation from KK's

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

$$(\bar{d}_L\text{weak}\ \bar{s}_L\text{weak}) \begin{pmatrix} g_d^{KK} & 0 \\ 0 & g_s^{KK} \end{pmatrix} \gamma^\mu A_\mu^{(n)} \begin{pmatrix} d_L\,\text{weak} \\ s_L\,\text{weak} \end{pmatrix}$$

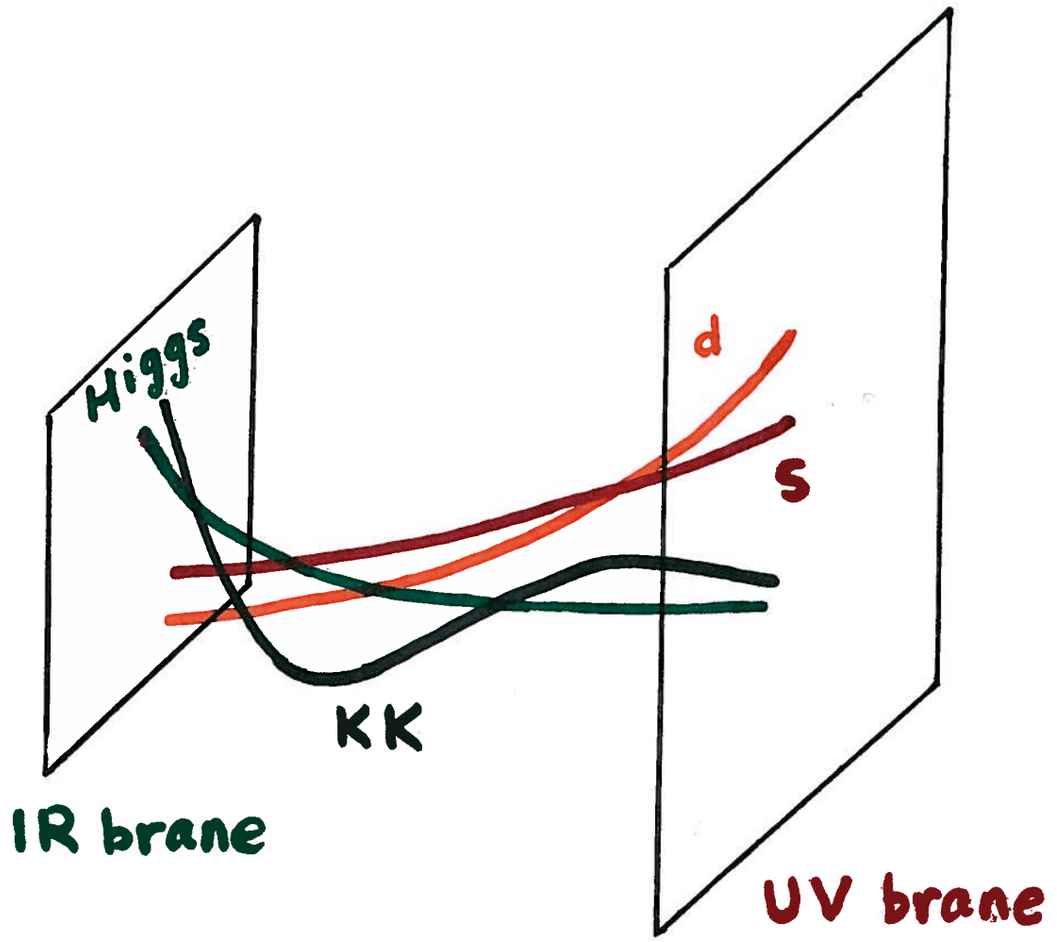


- off-diagonal in mass basis (in general):

$$...\mathrm{D}_L^\dagger \mathrm{diag}\left(g_d^{KK}, g_s^{KK}\right) D_L ... \rightarrow \left(g_s^{KK} - g_d^{KK}\right)(D_L)_{12} \times$$
$$\bar{d}_L\mathrm{mass}\gamma^\mu A_\mu^{(n)} s_L\,\mathrm{mass}$$

Warped GIM: built-in suppression mechanism...

- Non-universality in gauge KK coupling $\propto$ (difference of) 4D Yukawa:
  Higgs profile ~ 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)!

Summary (rough)of quark and lepton sectors: warped GIM, but 1 or 10 TeV?

- ~O(10) TeV from ϵ_K (Csaki, Falkowski, Weiler) and from LFV including neutrino mixings (Perez, Randall; KA)

...but...

- room from multiple "O(1)" factors: e.g. Higgs profile/size of 5D Yukawa for quarks (KA, Azatov, Zhu: see talk by A. Azatov); "decoupling" neutrino mixing from charged leptons using Dirac (KA, Okui, Sundrum) or new $SU(2)_R$ representations (KA) ⟹ ~O(5) TeV allowed

- flavor symmetries (Fitzpatrick, Perez, Randall; Santiago; Csaki, Falkowski, Weiler; Csaki, Grossman, Perez, Surujon, Weiler); smaller than Planck-weak UV-IR hierarchy (Davoudiasl, Perez, Soni) for parametric suppression

About "~O" in ~O(5 or 10) TeV

...due to...

- "~..." : soft wall etc. like for EW precision tests

- "O...": scan over 5D Yukawa entries (intrinsic to solution to flavor puzzle) → mild tuning allows lower KK scale (Blanke, Buras, Duling, Gori, Weiler)

anarchic

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

hierarchical

Other sources of flavor violation

- Higgs exchange: see talk by L. Zhu

- Radion ("fluctuations of size of extra dimension") exchange: see talk by M. Toharia

Don't give up on ~3 TeV KK scale!!!

LHC SIGNALS FOR KK PARTICLES

Couplings of gauge KK's

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

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

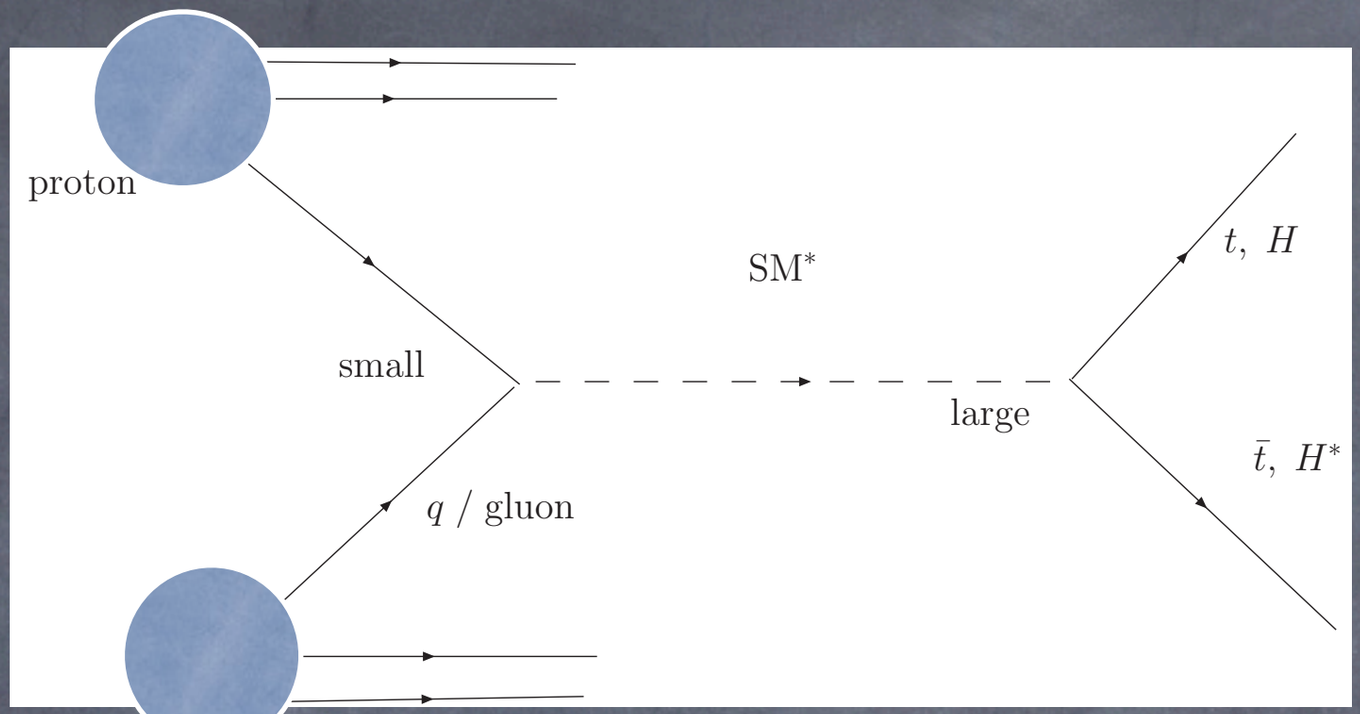
$$\frac{g_{\mathrm{RS}}^{Q^3\bar{Q}^3\,A^{(1)}}}{g_{\mathrm{SM}}}, \frac{g_{\mathrm{RS}}^{t_R\bar{t}_R\,A^{(1)}}}{g_{\mathrm{SM}}} \simeq 1 \text{ to } \xi \approx 1 \text{ to } 5,$$

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

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

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 ⇒ broad resonances

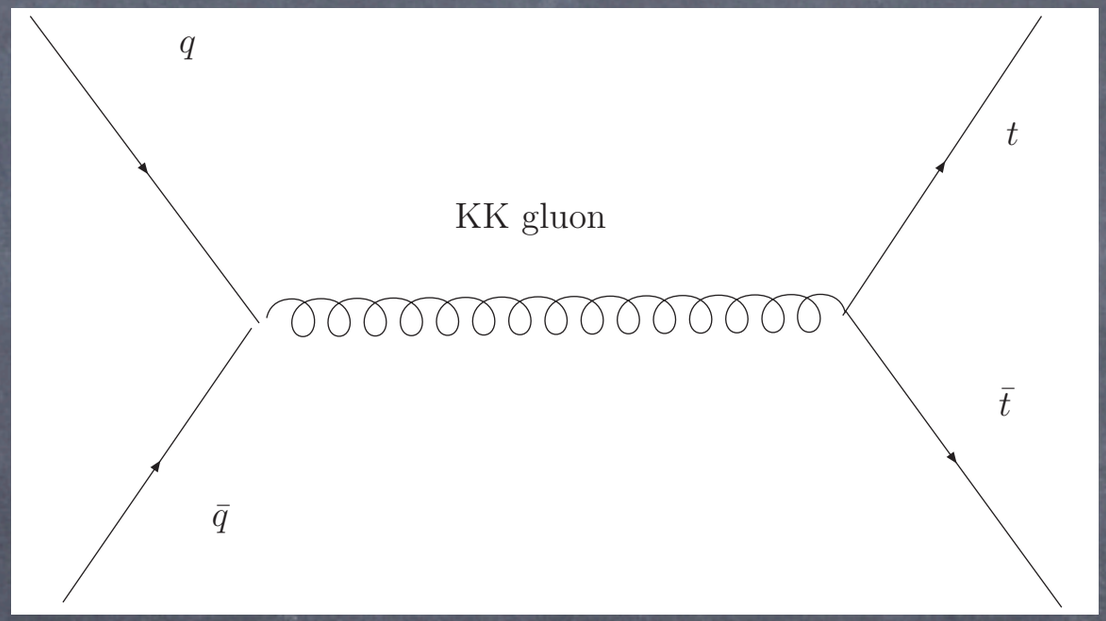
....but not out!

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` ...+ talk by K. Kumar)

Production and Decay

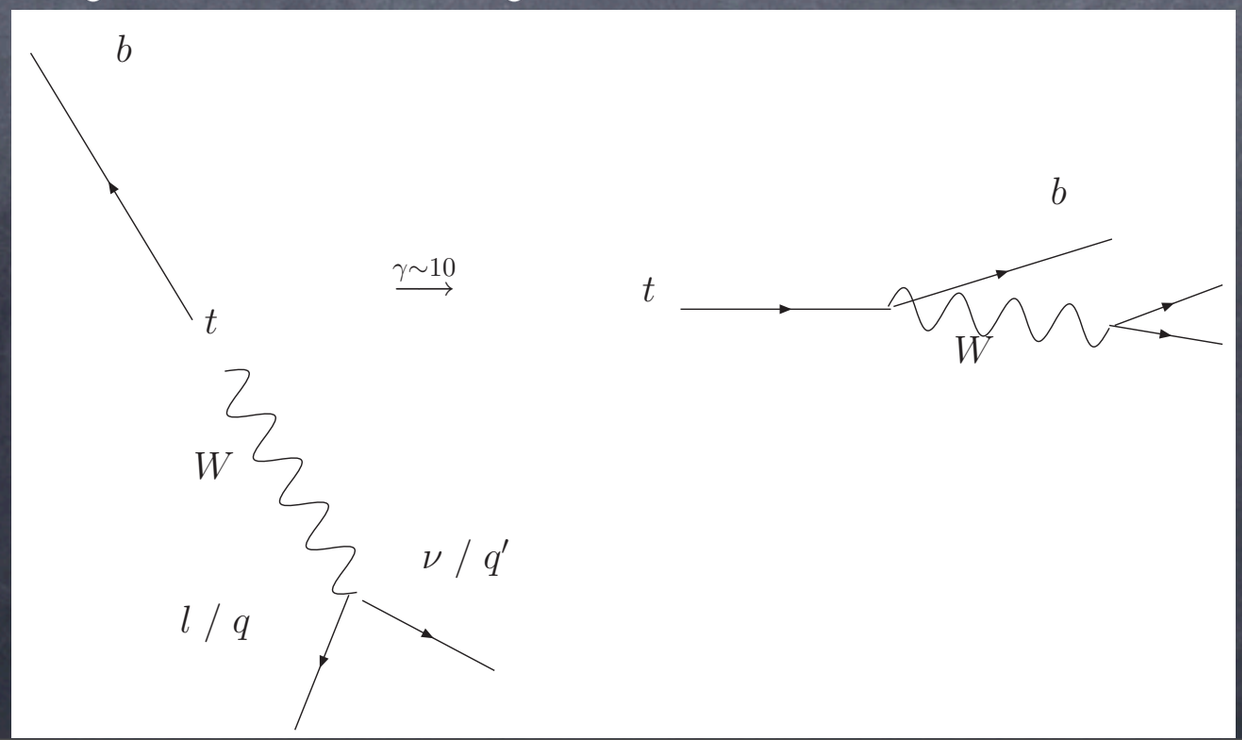


Problem: collimation of tops

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

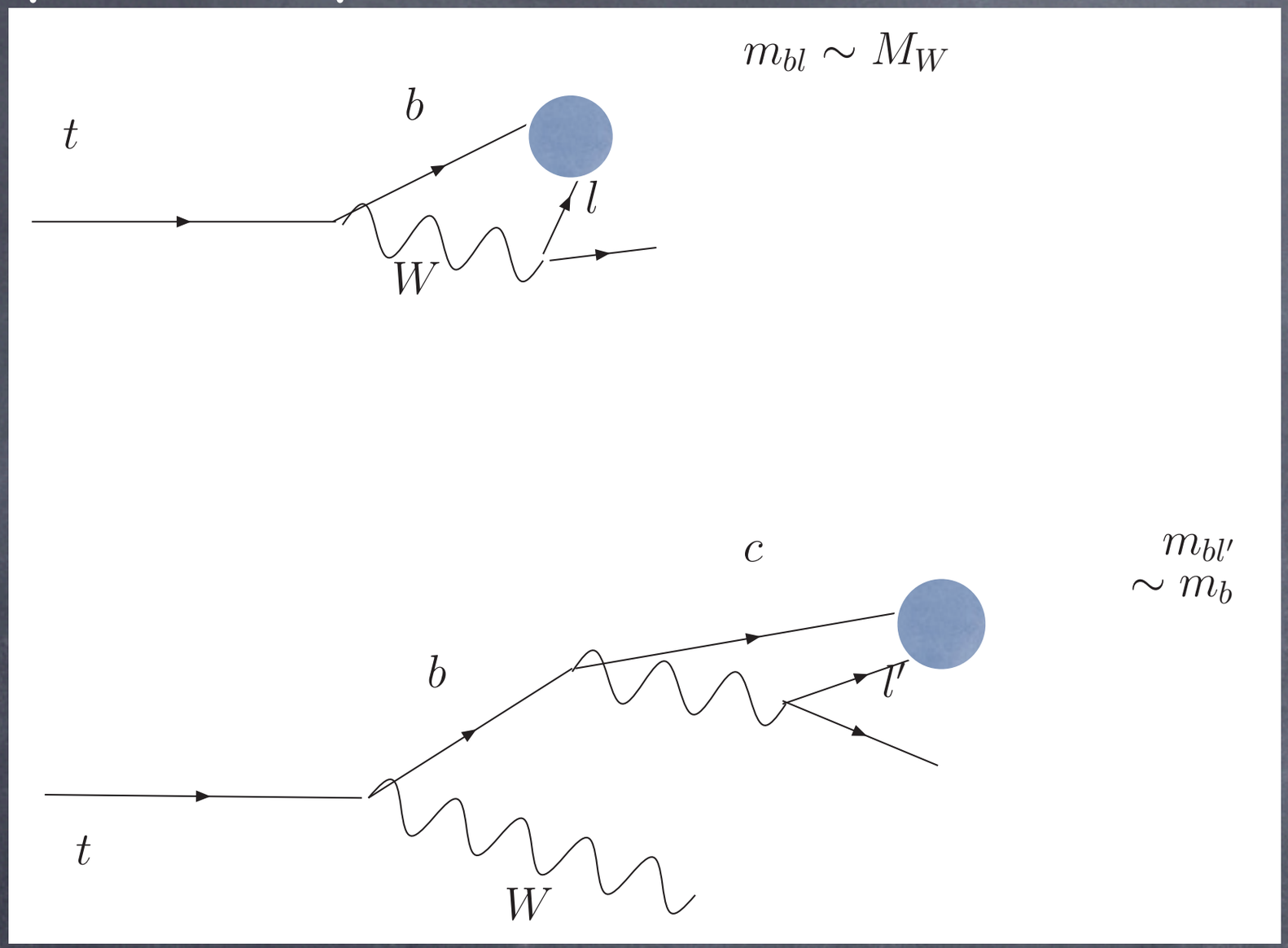
vs.

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: $m_{bl} > 40$ 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 ⇨ $P_{LR} = 0$

- Warped extra dimension: KK gluon coupling to LH and RH top quark different ⇨ $P_{LR} \sim \pm O(1)$

- 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

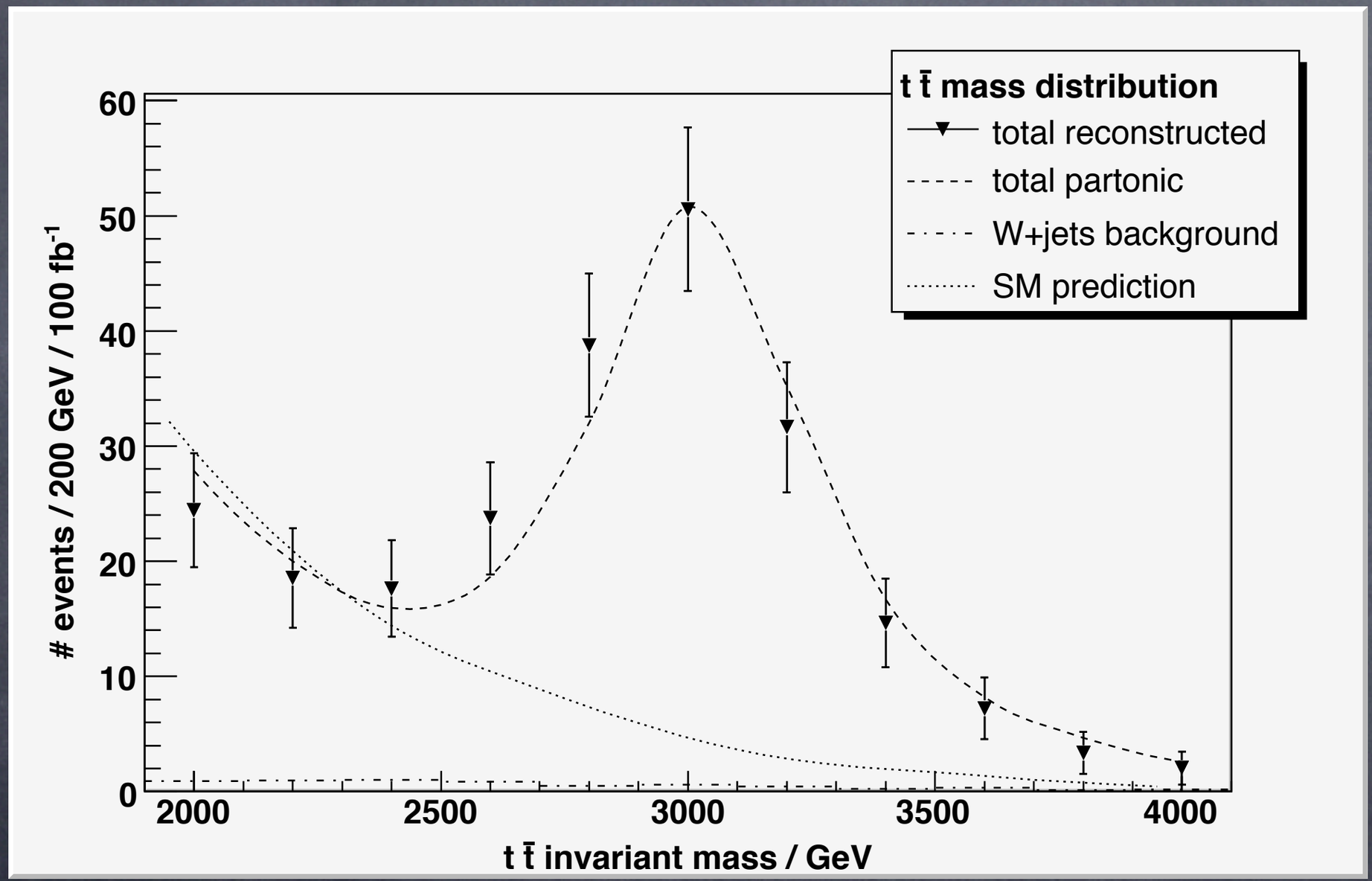
Discovery for 4 TeV with 100 / fb

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

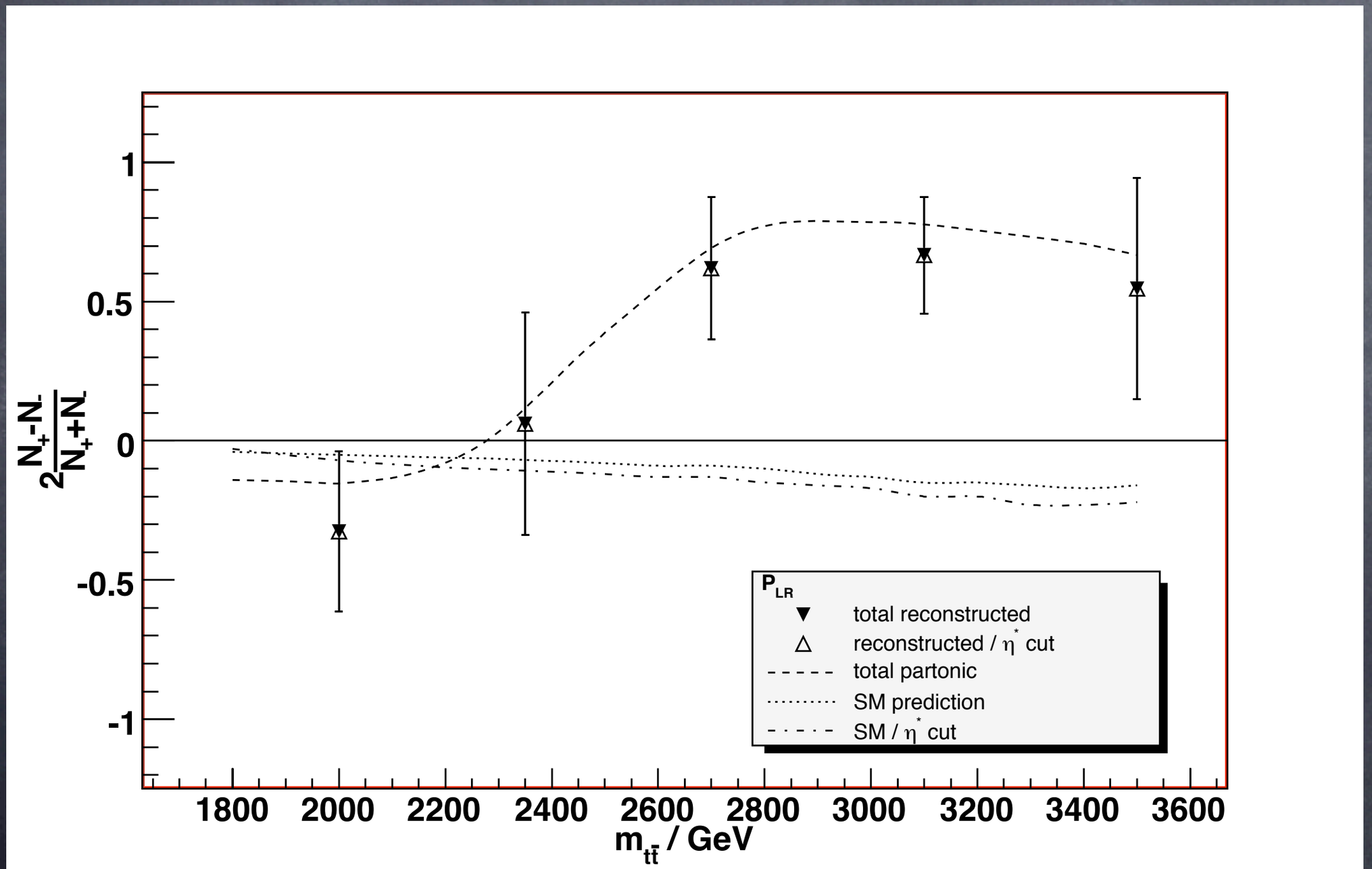
correlated with

- Deviation in P_{LR} from SM

Differential cross-section



Polarization asymmetry



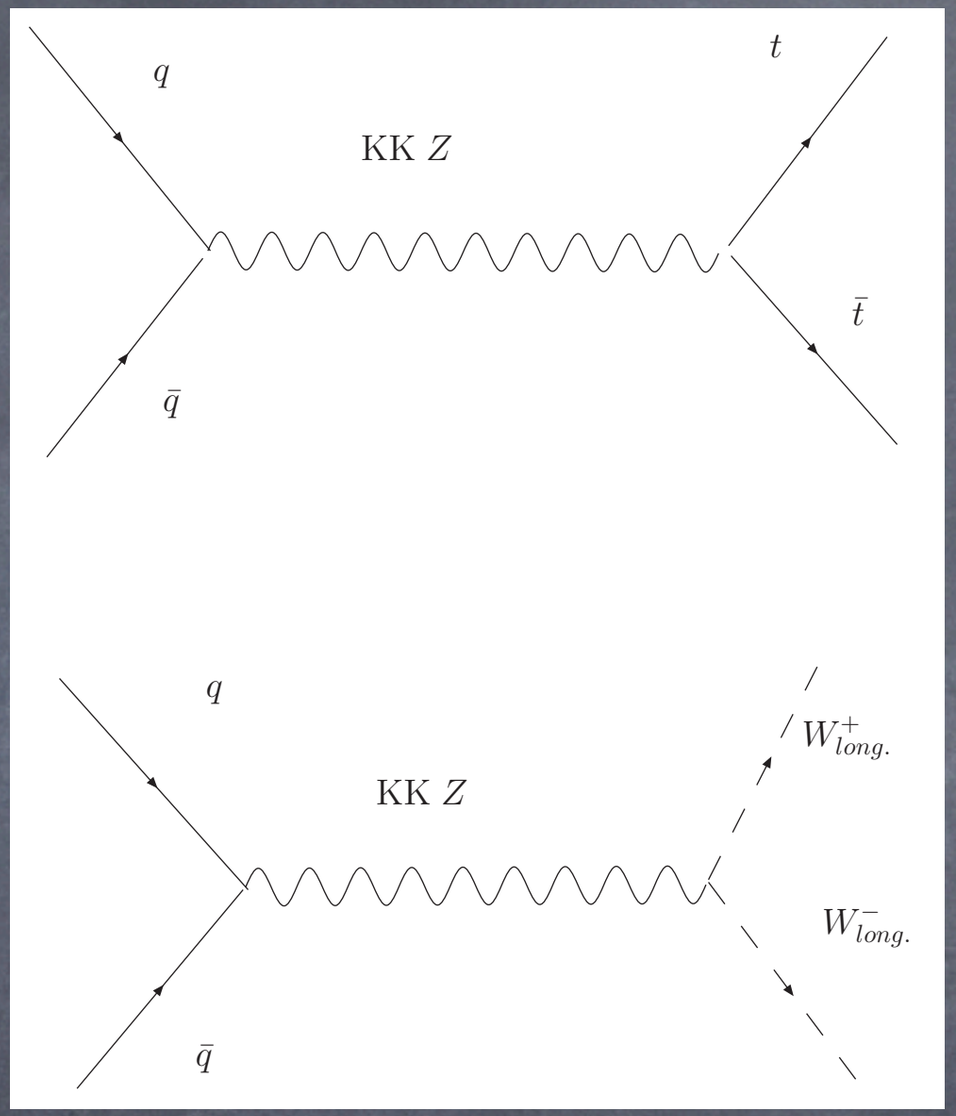
…DON'T FORGET BOOSTED W/Z!

KK Z

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

(See also Djouadi, Moreau, Singh)

Production and Decay



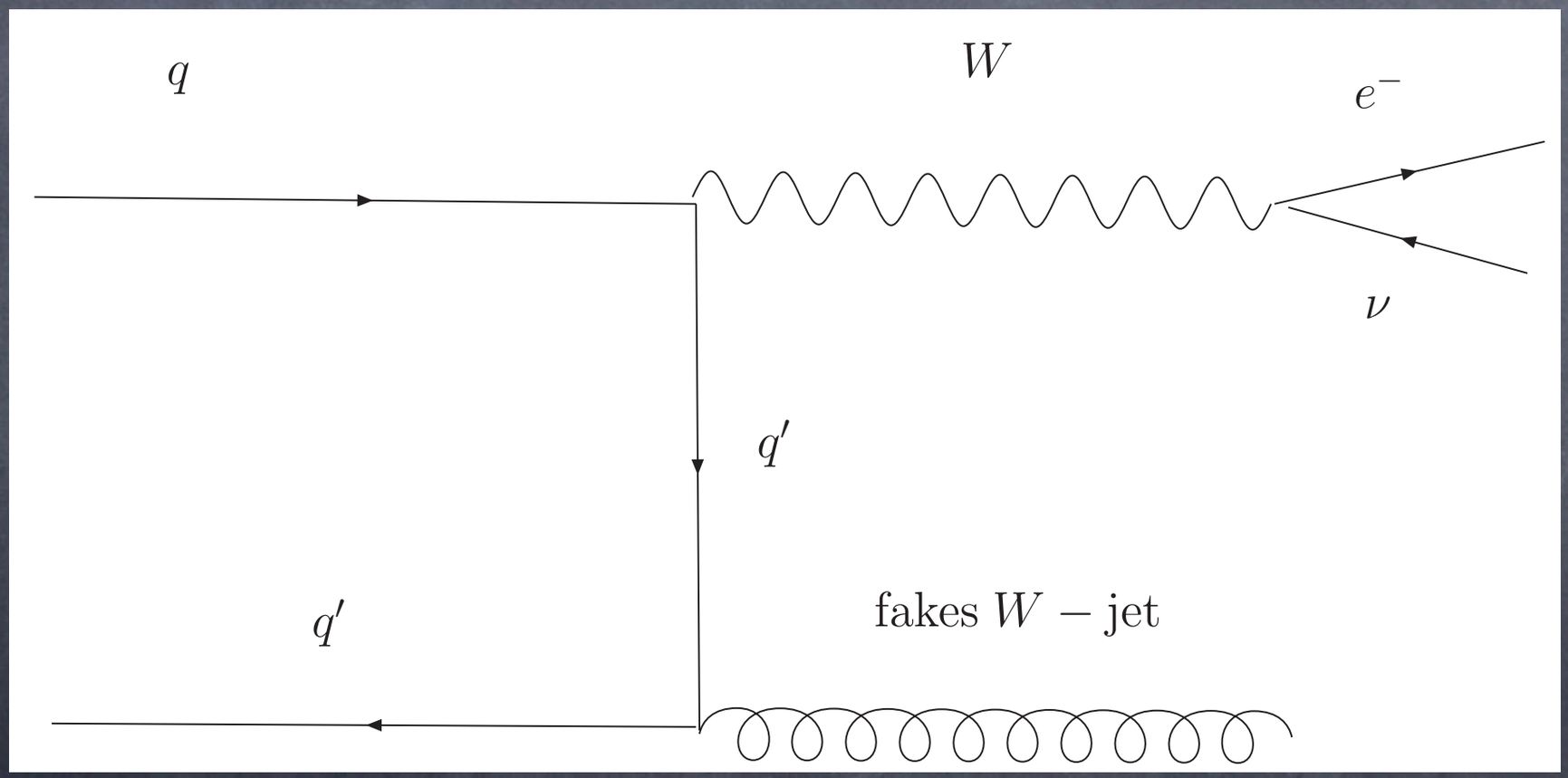
Decays to tops swamped by KK gluon

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

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

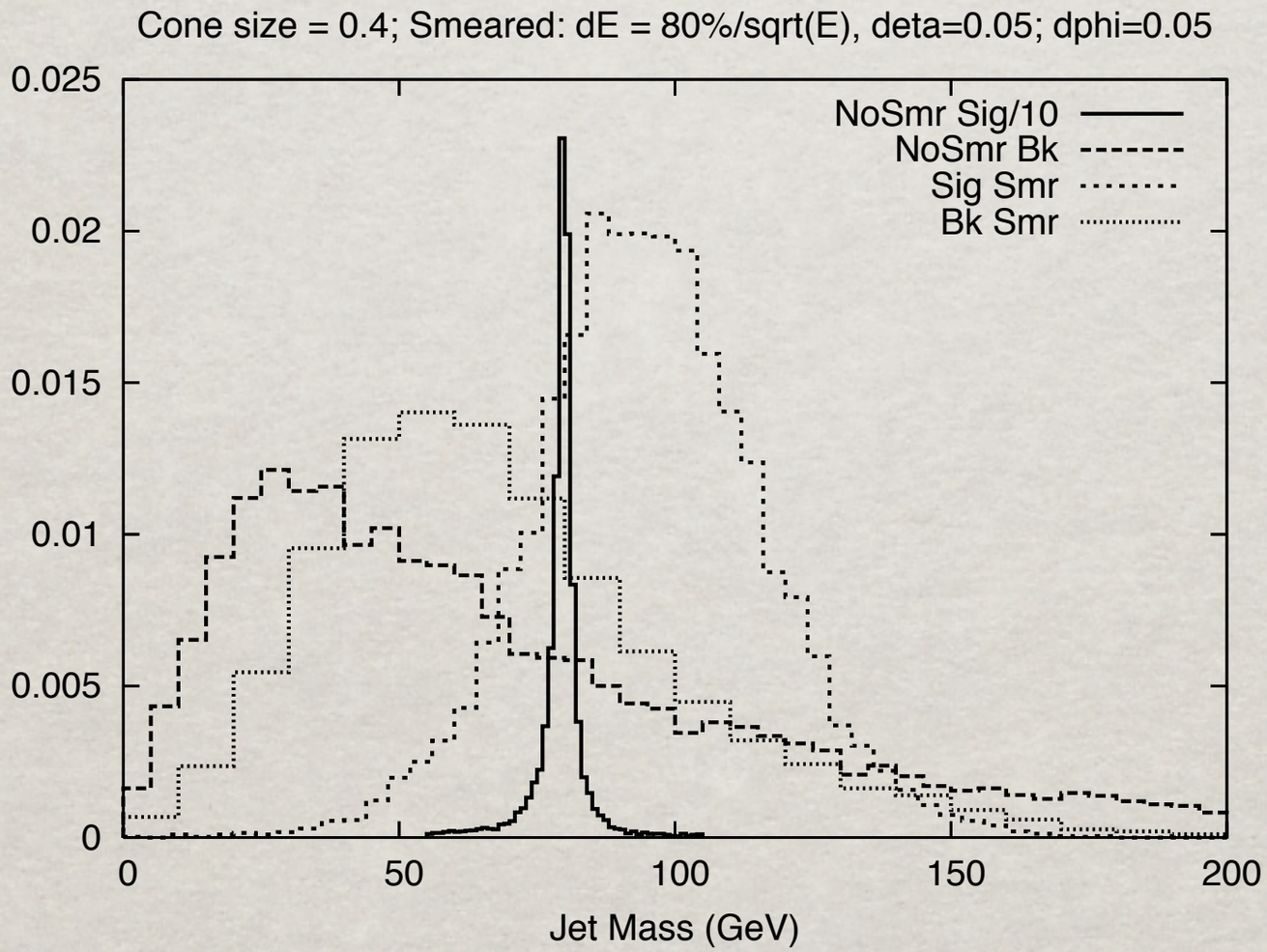
KK $Z \to W^+W^- \to l^+\nu jj$: can reconstruct, but...

- W + 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 $\mathrm{KK}\ Z \to Zh$

BOOSTED TOP (VETO) AND W/Z!

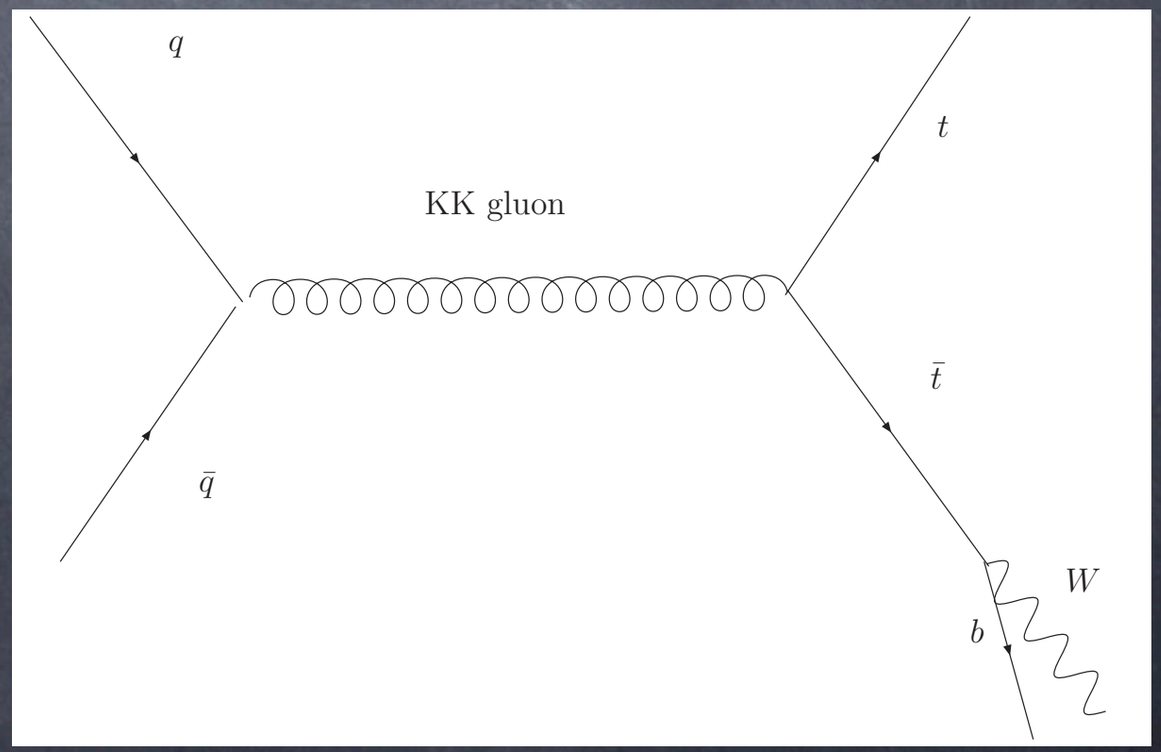
KK W

(KA, Gopalakrishna, Han, Huang, Soni)

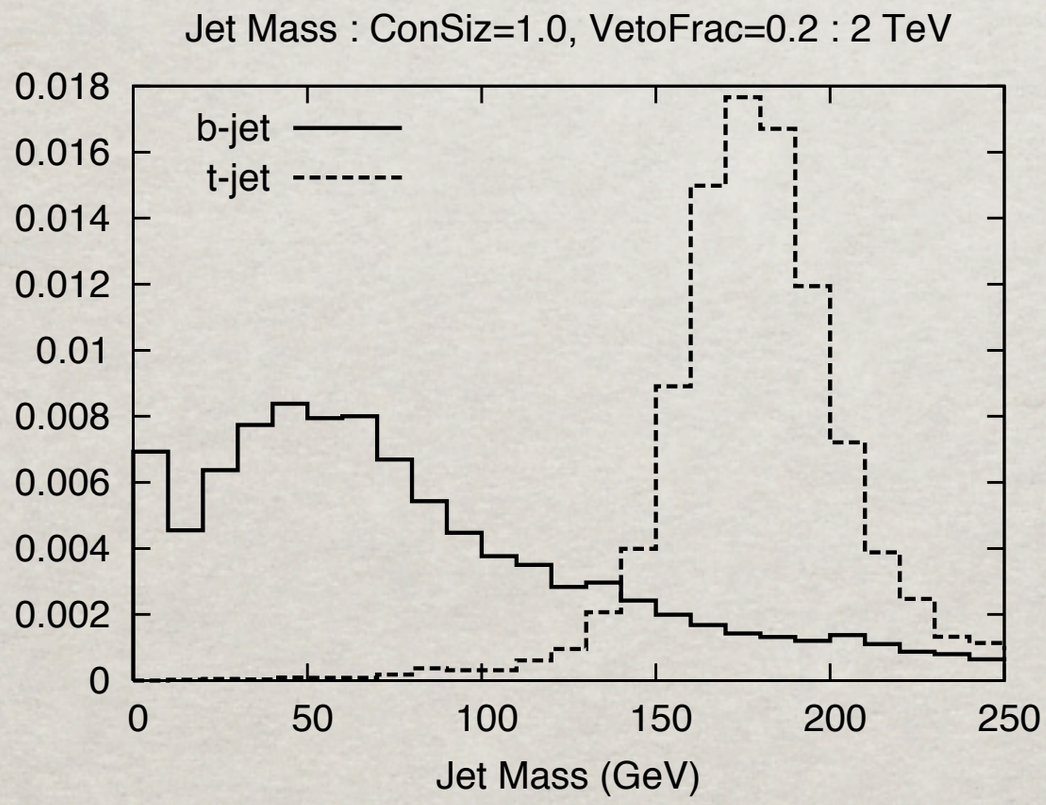
- $\mathrm{KK}\ W \to WZ \to l^+ l^- l' \bar{\nu}'$ (clean) can be reconstructed

$\mathrm{KK}\ W \to WZ \to l^+\nu\ (\mathrm{or} l^+ l^-) +$ jets (like KK Z)

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



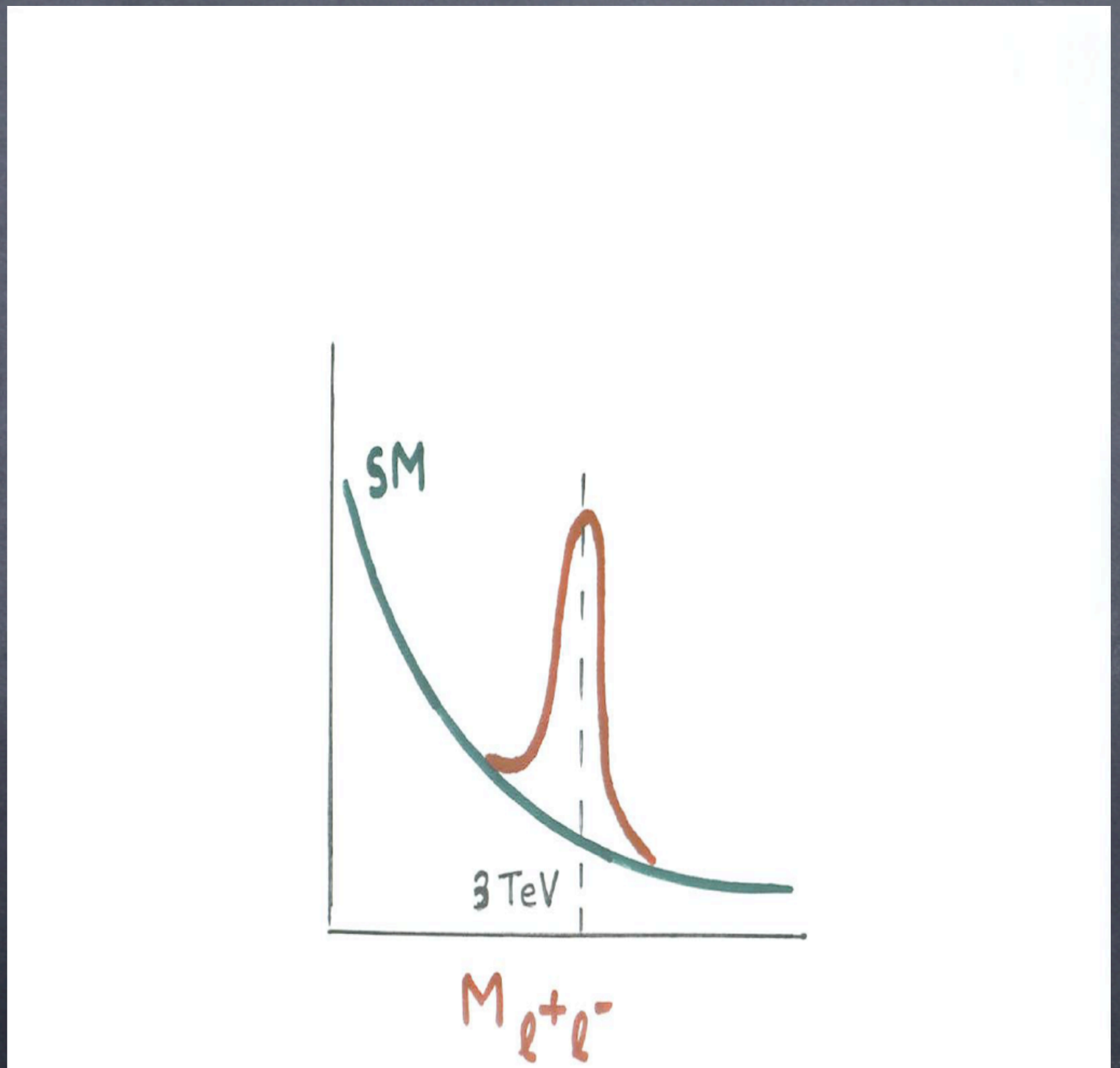
... REDUCIBLE BY JET MASS CUT (BOOSTED TOP VETO!)



"ORIGINAL" RS1: BRANEWORLD

Golden decays:

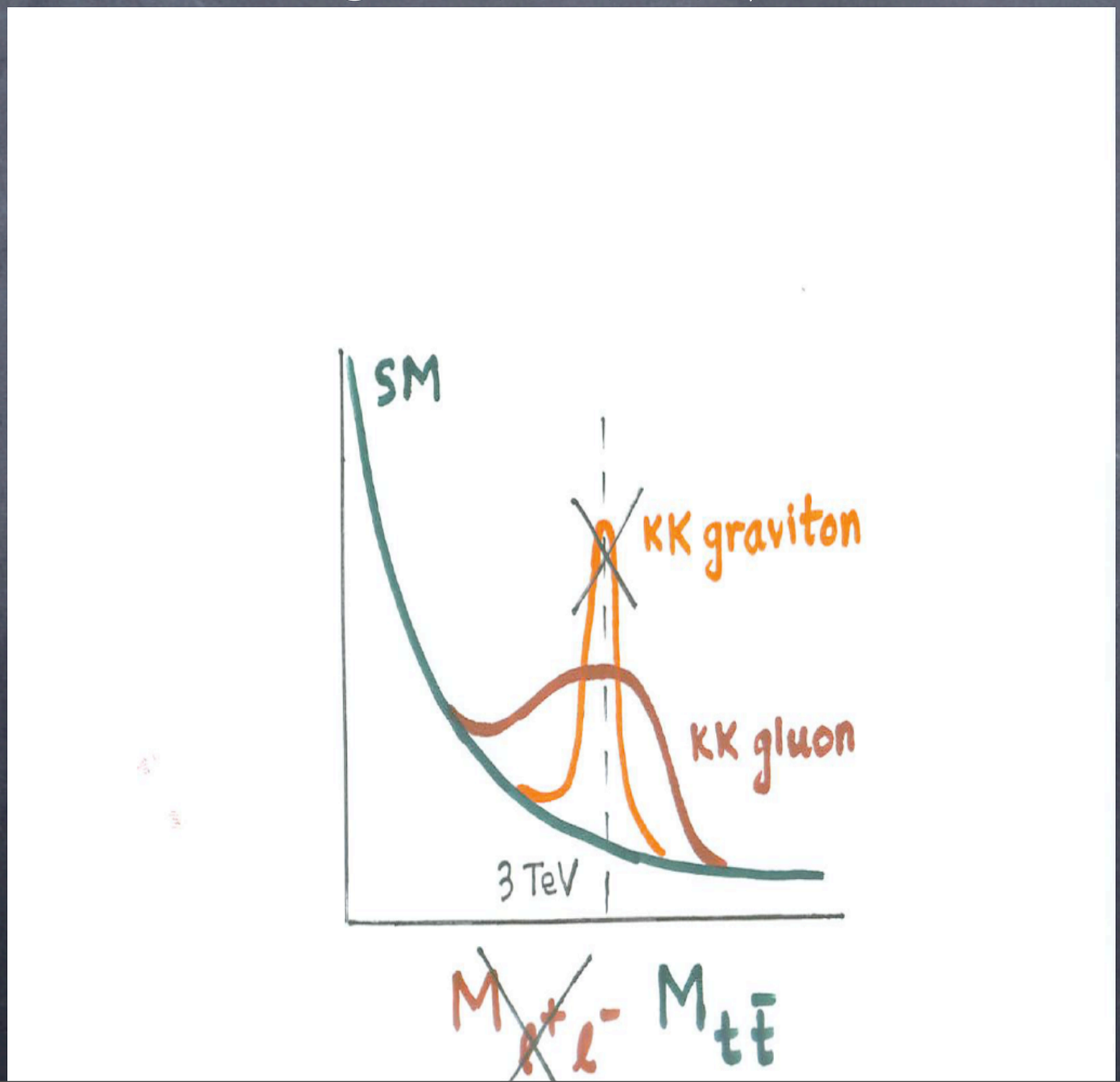
KK graviton $\rightarrow l^+l^-$, $\gamma\gamma$ (Davoudiasl, Hewett, Rizzo)



CF. SM (– HIGGS) IN THE BULK

$$\begin{aligned} \text{KK graviton} &\to l^+l^-, \cancel{\gamma\gamma} \\ &\to t\bar{t},\ WW \text{ (boosted)} \end{aligned}$$

+ KK gluon, W, Z, γ



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

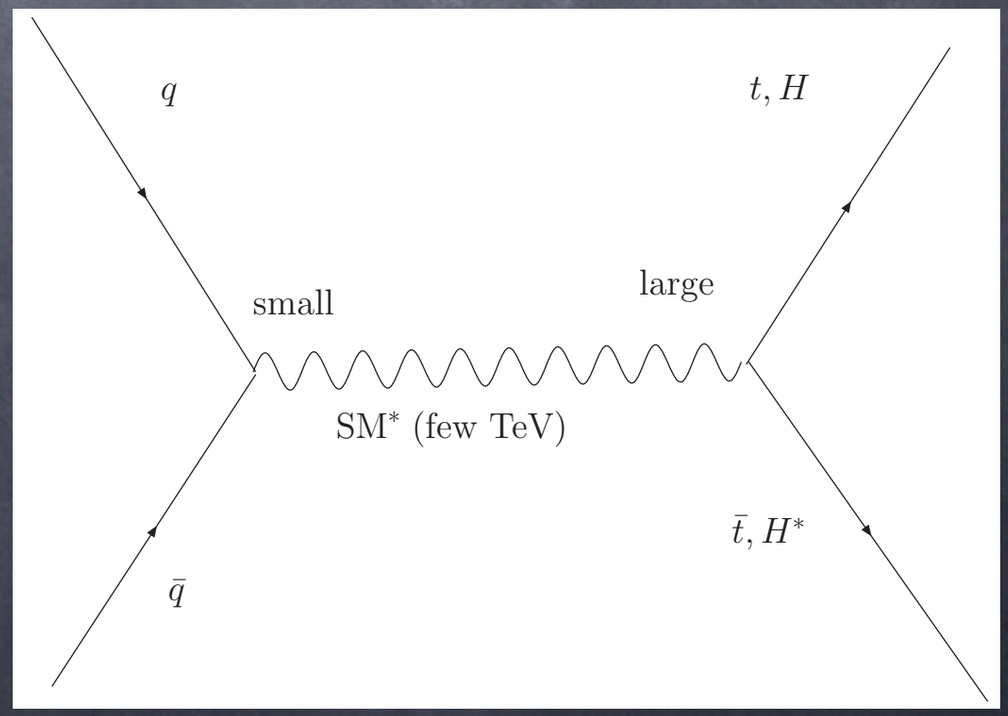
Top quark and Higgs (*longitudinal* W/Z) "special": mechanism of electroweak symmetry breaking

couple strongly to *new* particles

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

Resonance production: decays to top and $H/W/Z$

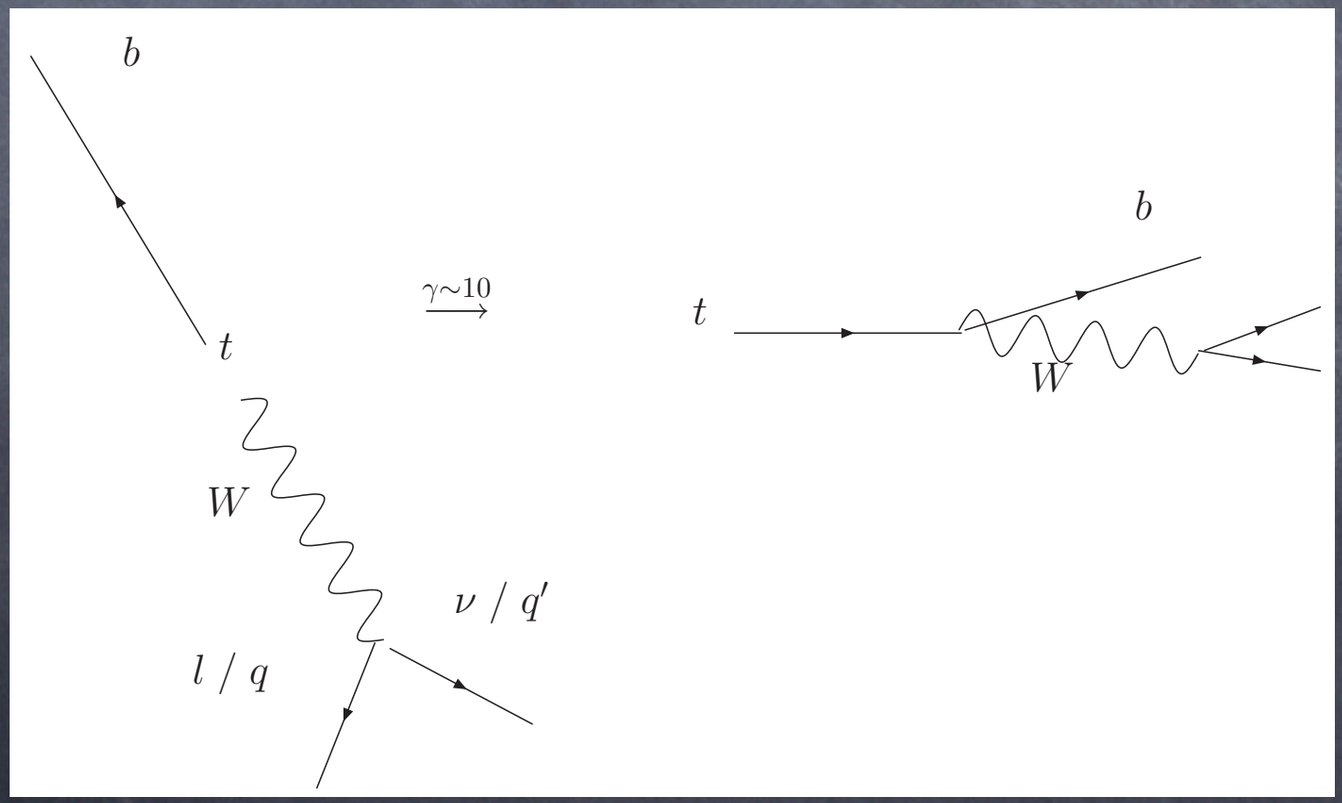
(highly boosted!)



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

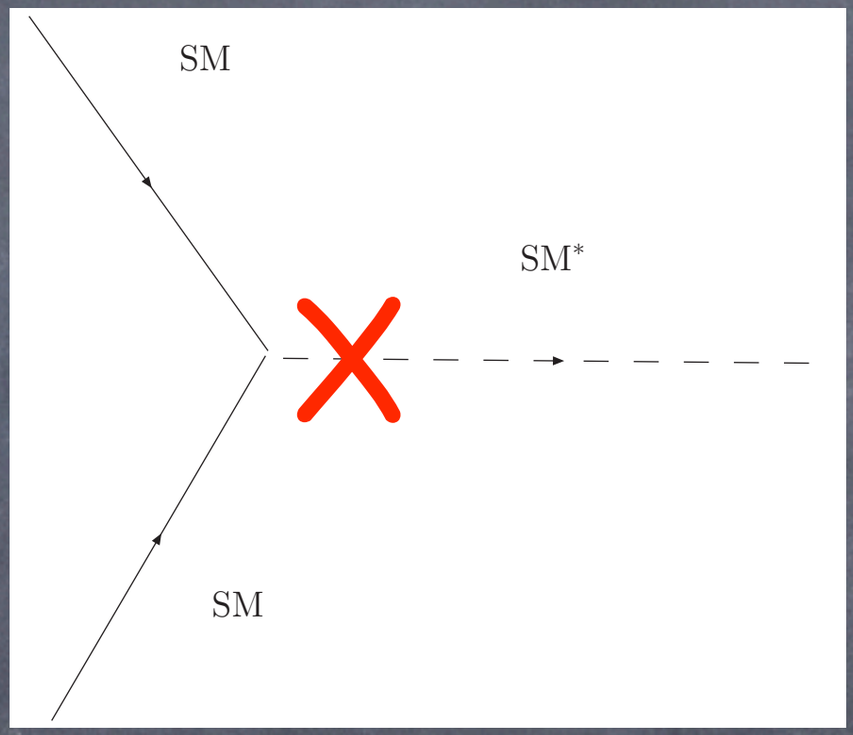
(More) Studies needed...

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



KK PARITY IN WARPED EXTRA DIMENSION

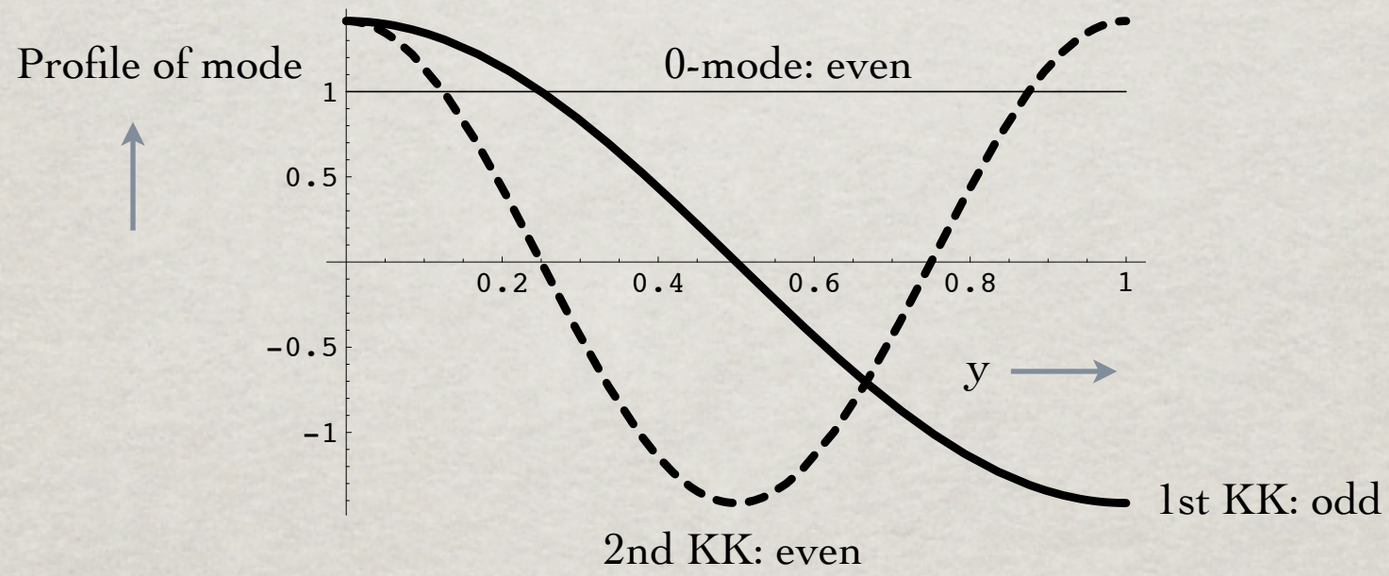
KK parity in flat universal extra dimensions (UED), T-parity in Little Higgs



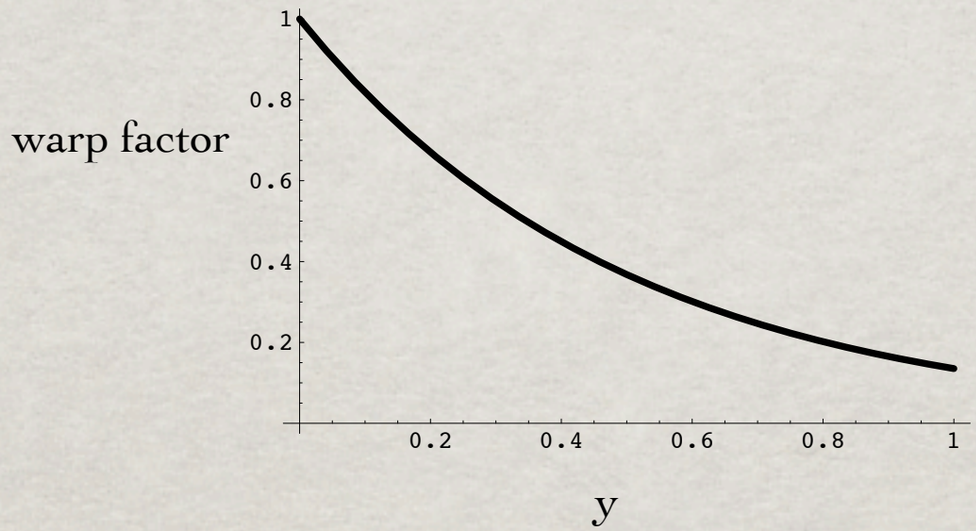
- valid only up to 10's TeV

KK PARITY IN UED

- Reflection about midpoint



No KK parity in single AdS slice

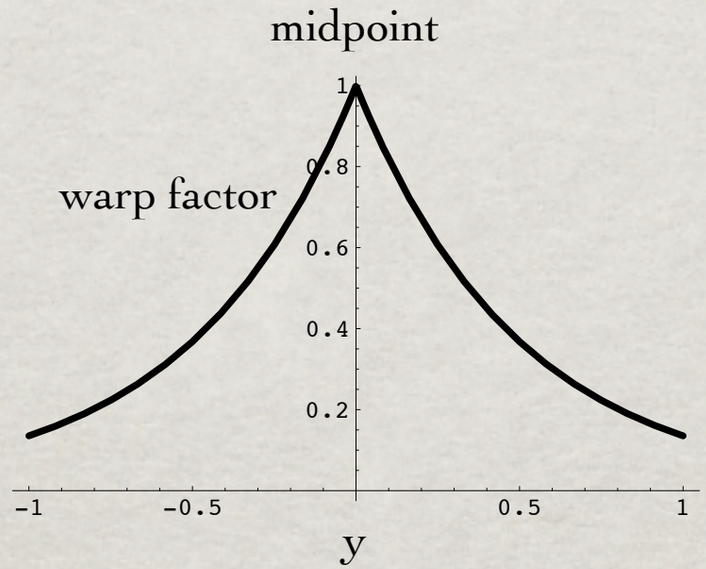


- Warp factor not symmetric about midpoint (cf. flat metric)

Join 2 AdS slices

(KA, Falkowski, Low, Servant)

(See also Thaler, Yavin; Panico, Ponton, Santiago, Serone; Csaki, heinonen, perelstein, spethmann: double fields in **single** slice)

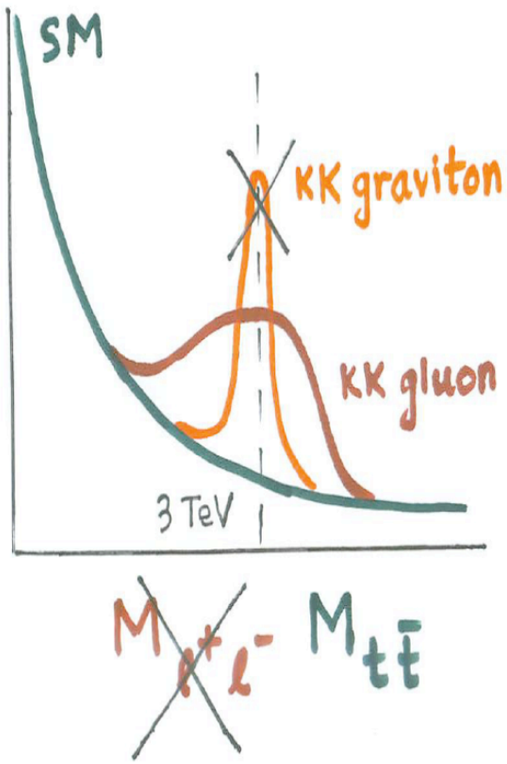


- KK parity interchanges 2 slices

Conclusions

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

well-motivated models with a few TeV broad resonances decaying into highly boosted (collimated) top/W/Z/Higgs!



Back-up slides

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 ⇨ $m_H^2 < 0$ (KA, Contino, Pomarol...)

Quark flavor constraints for anarchy

- Non-universality in coupling to gauge KK $\propto$ 4D Yukawa: analog of GIM (Gherghetta, Pomarol; Huber, Shafi; KA, Perez, Soni)

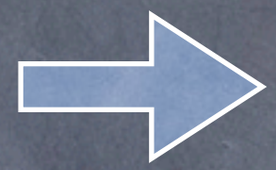
...but...

- ~ O(20) TeV from ϵ_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)...



- ~ O(5) TeV scale allowed even with anarchy by ϵ_K [and $b \to s\gamma$] (KA, Azatov, Zhu)

- 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) ⇒ ~3 TeV allowed (even if ~20 TeV for natural size) ⇒ (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 ⇒ non-hierarchical profiles for LH leptons (cf. hierarchical for quarks with anarchy)???

- profiles as "input" (fit to data)

- LH charged lepton mixing large ⇒ ~10 TeV from lepton flavor violation with minimal $SU(2)_R$ representations (Perez, Randall; KA)

- ~ 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)

Lepton sector: decoupling charged LH lepton mixing from neutrinos

- Dirac masses (KA, Okui, Sundrum) from overlap near Planck brane: smallness from Higgs profile
  LH lepton profiles small/hierarchical near TeV brane, large/non-hierarchical near Planck brane

  → ~O(5) TeV KK scale (with minimal representations: KA, Blechman, Petriello)

- non-minimal representations (KA): LH lepton "made of" 2 components (one for neutrino mass; other for charged) with different profiles + custodial symmetry →

- KK scale ~ O(3) TeV

Cannot suppress S with non-AdS

- Hirn, Sanz: general Higgs profile and warp factor
- Pathology: $\mathrm{vev}^2 < 0$ 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 ⟹ loops span extra dimension, sensitive to Planck and TeV cut-off scales (AdS/CFT more intuitive)

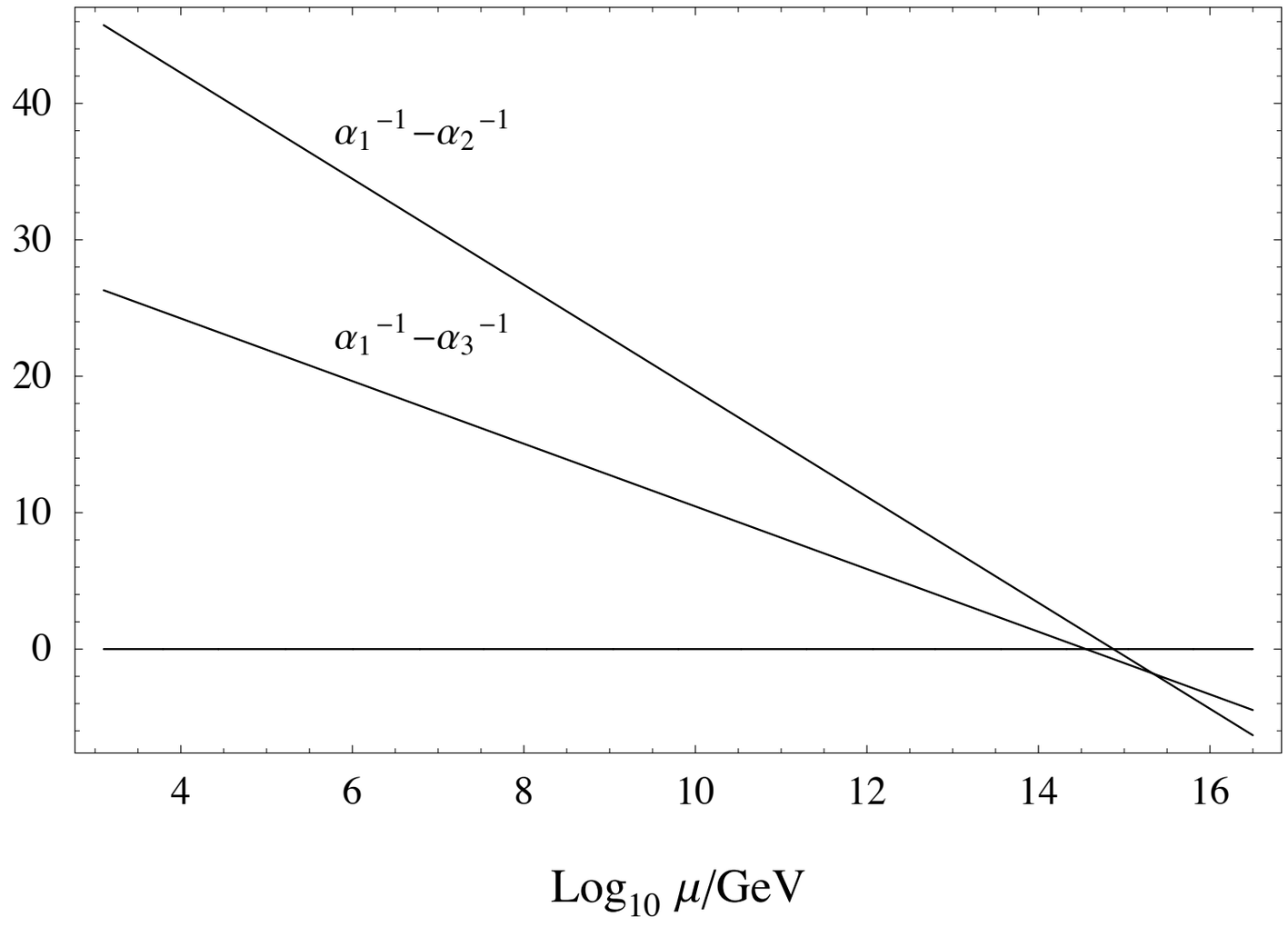
- Gauge boson loops: non-universal; effectively cut-off at high scale (a la SM)

- 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

β-function: SM $-2t_R - H$

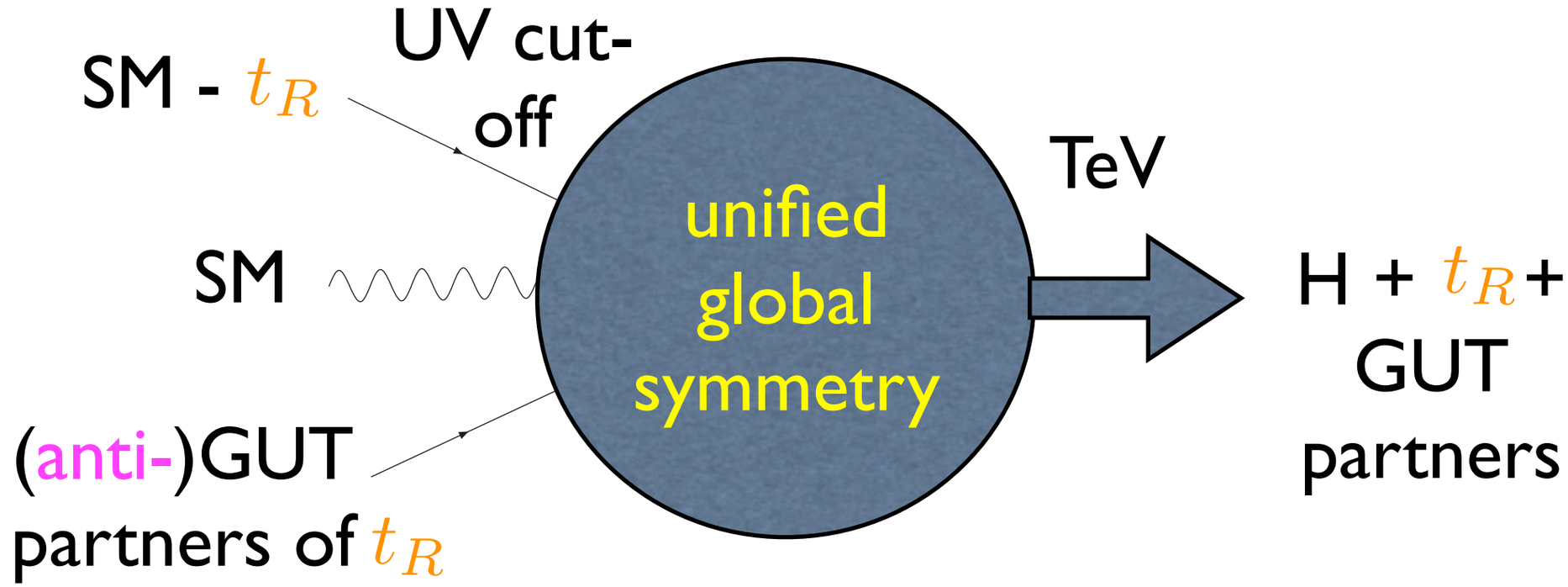
(KA, Contino, Sundrum)



($2^{\mathrm{nd}} - t_R$: running due to light GUT partners)

Unification in CFT picture

- Global unified symmetry for CFT ⇨ LO running of SM gauge couplings from CFT loops universal
- Composite t_R and H ⇨ 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 ⟺ CFT has global unified symmetry

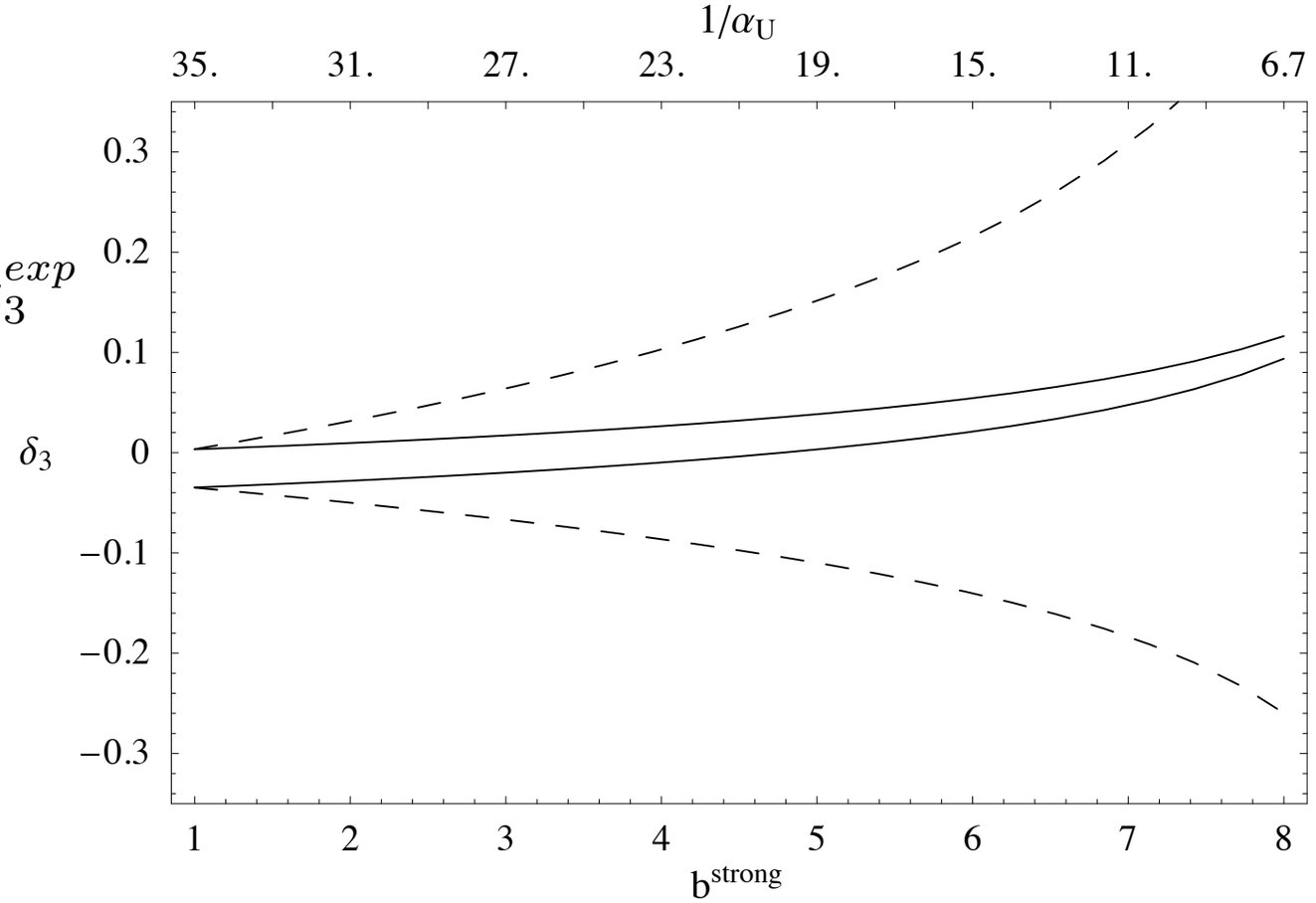
- Localization parameter (bulk mass) of t_R: unification improved relative to SM in entire range (preferred by precision data); precision unification for sizable range

NLO precision ~SUSY

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

$$\sim \quad 0.1 \text{ in SUSY}$$

$$(\alpha_3 \text{ at } M_Z)$$



(size of 4D strong sector)

→ Landau pole below GUT scale

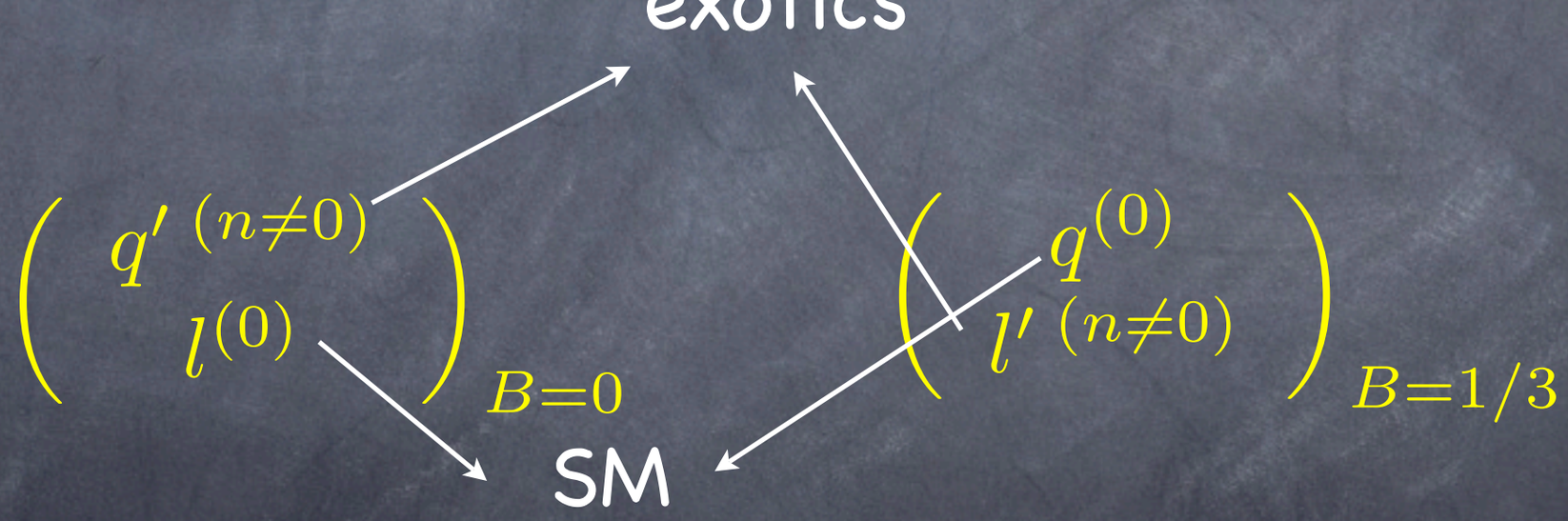
Signals

- Complete GUT multiplets at few TeV scale (KK gauge bosons and fermions)

- light GUT partners of t_R for precision unification

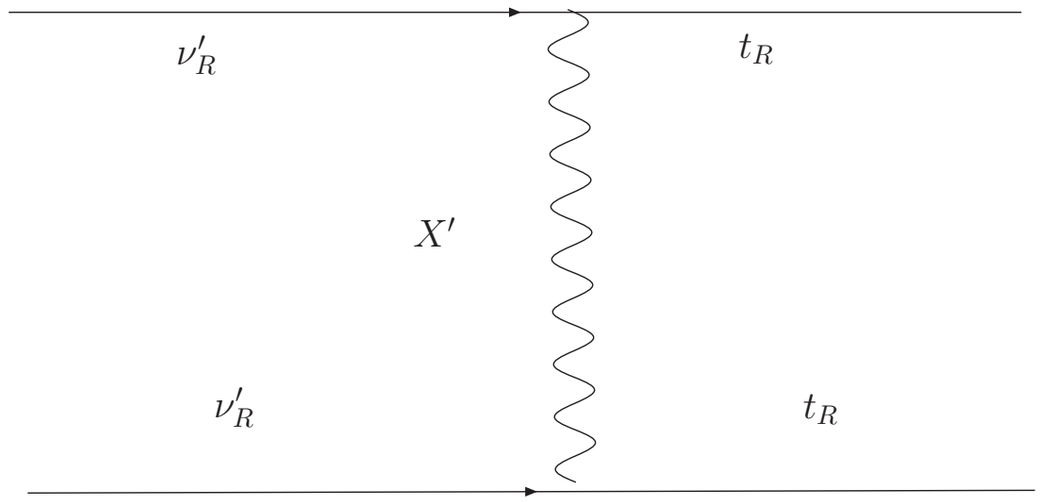
Stable particle from Proton stability
(KA, Servant)

- 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)

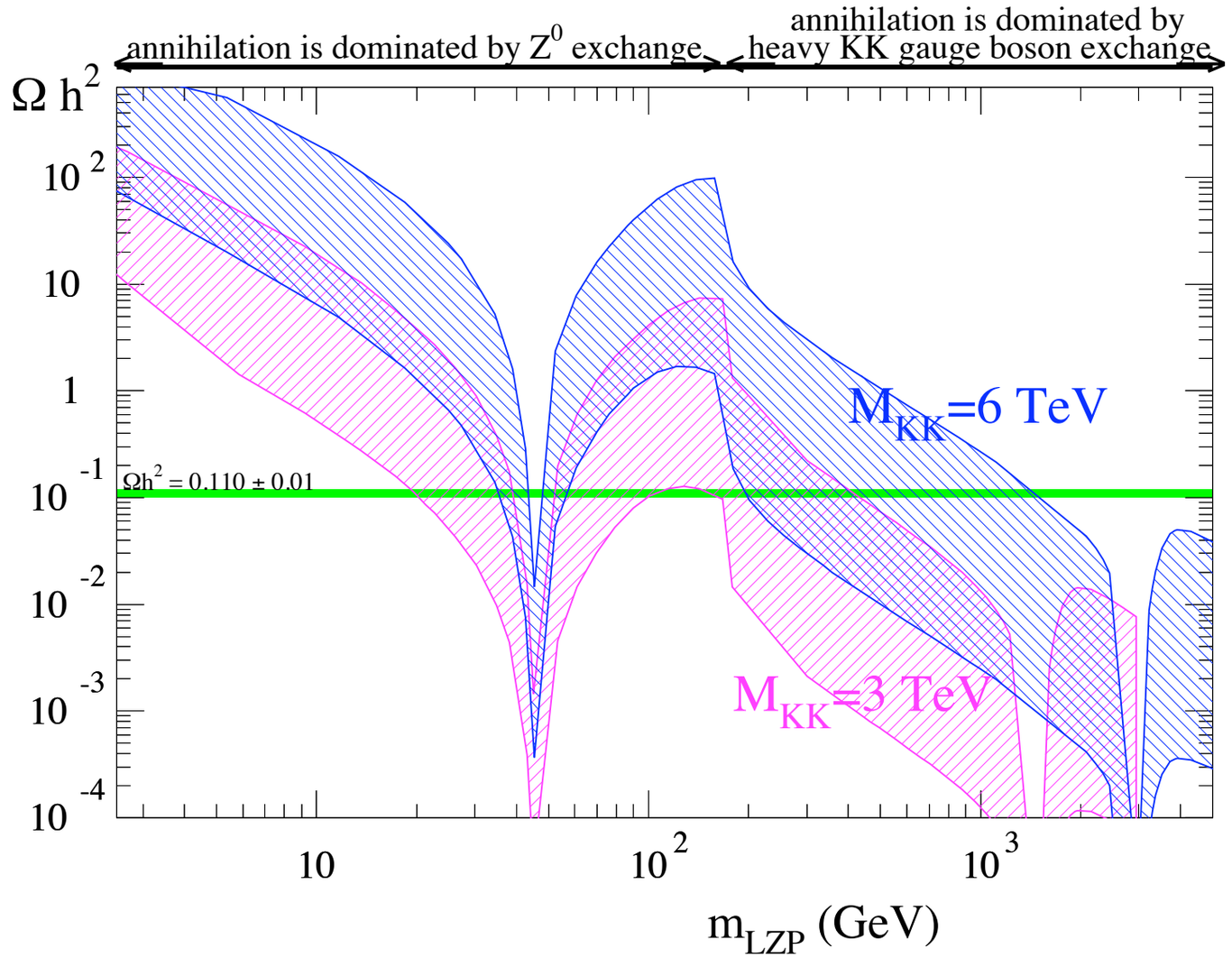


- Extra particles (no zero-modes) are "exotic" ("wrong" combination of B and color: SM have right...) ⇒ lightest stable

Exotic ν'_R partner of t_R as WIMP dark matter: I

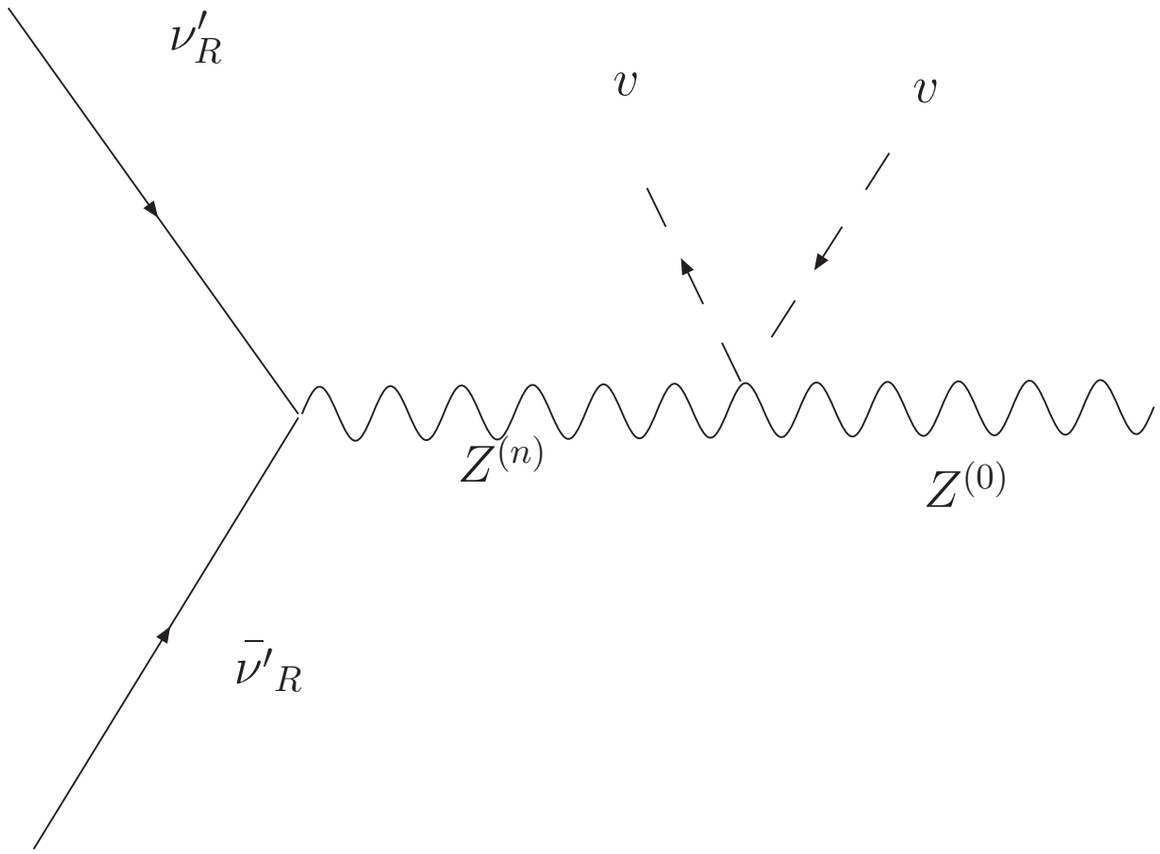


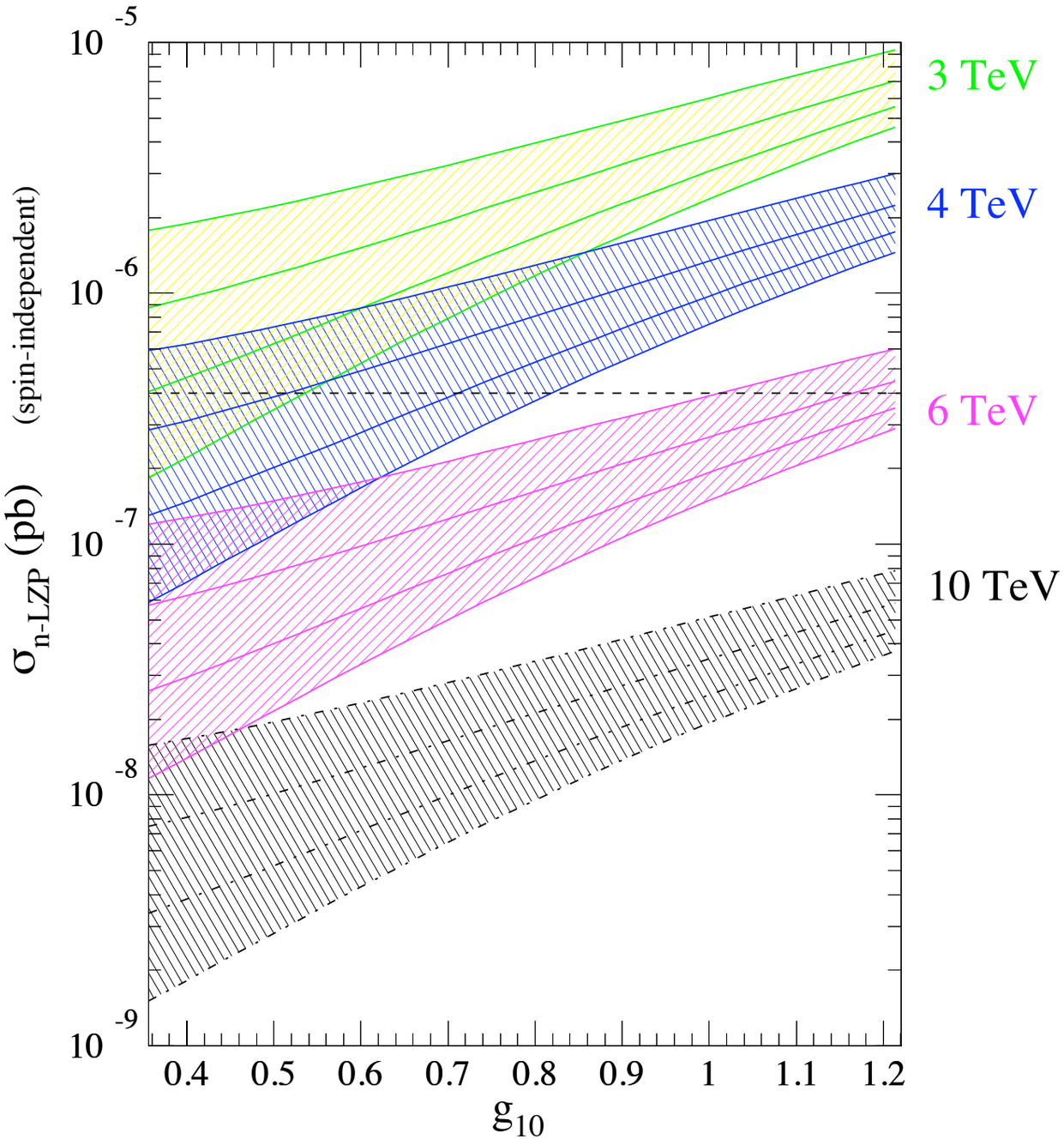
- Annihilation:



Exotic ν'_R partner of t_R as WIMP dark matter: II

- Direct detection (small coupling to Z):



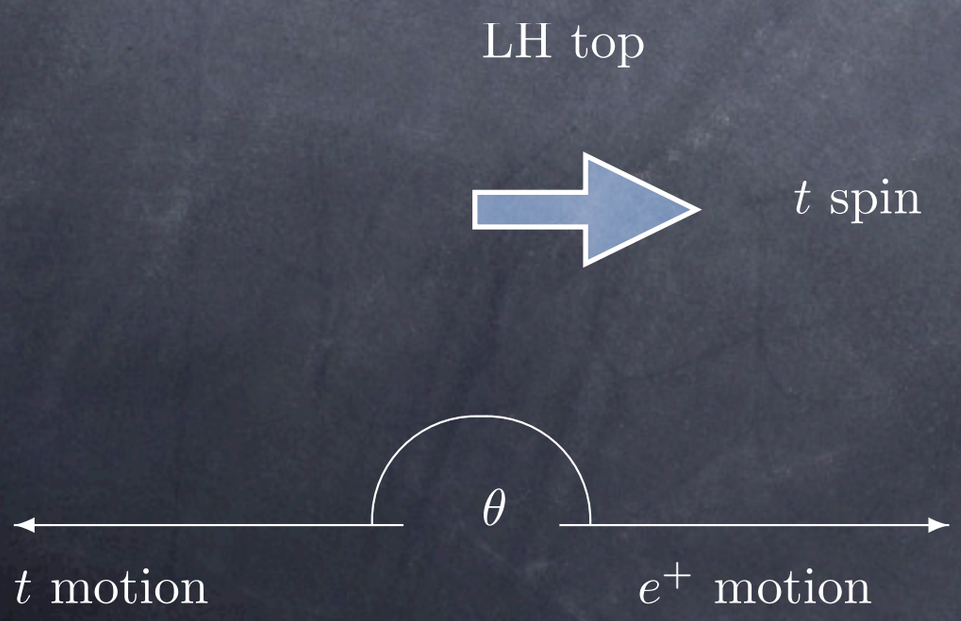


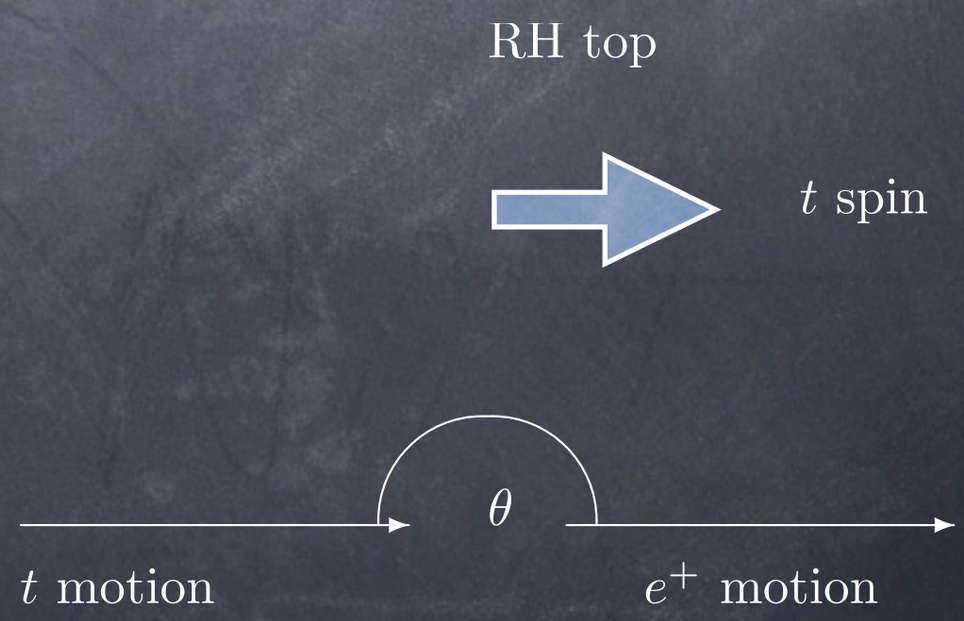
Polarization asymmetry: definition

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

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

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





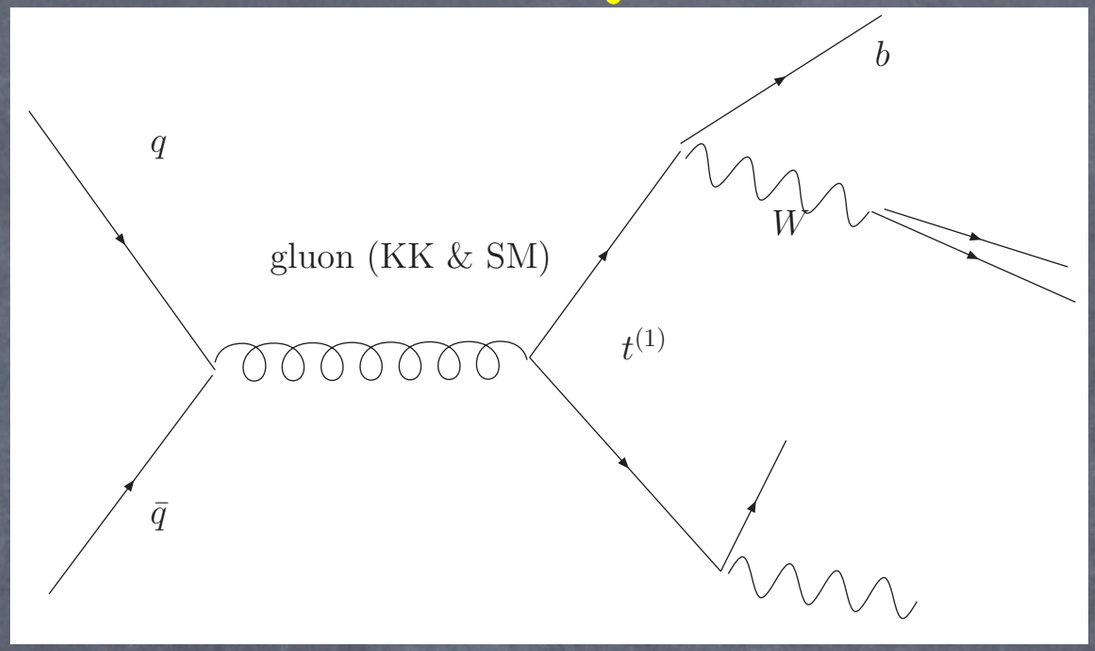
Polarization asymmetry: SM vs. Warped

- 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: $t \to cZ$ 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)