

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

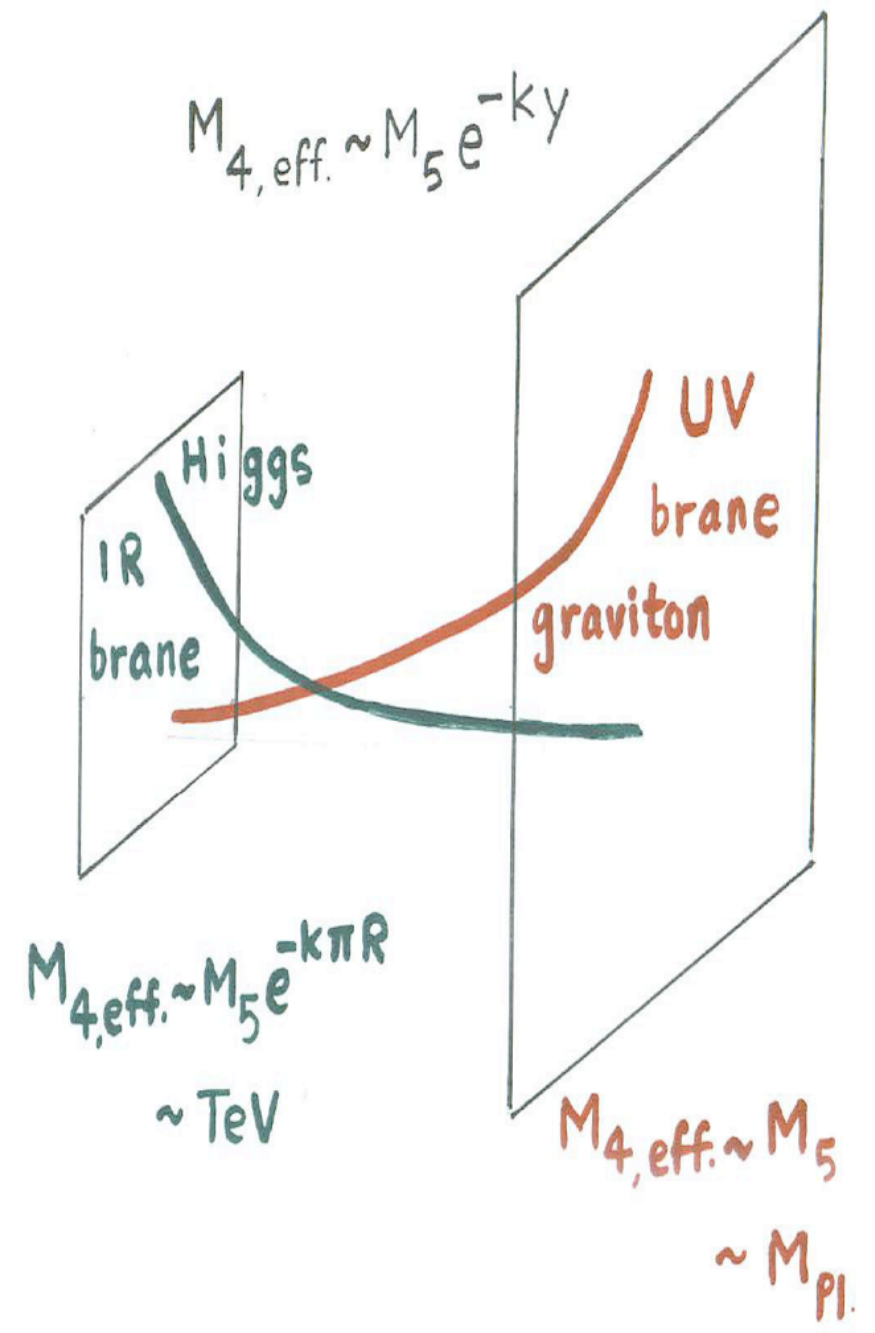
Motivations

(see talk by R. Sundrum)

- Planck-weak and flavor hierarchy
- Weakly-coupled “tool” for 4D strong dynamics: dual to 4D composite Higgs (AdS/CFT)
- GUT's: dark matter from proton stability (KA, Servant); gauge coupling unification with precision \sim SUSY (KA, Contino, Sundrum)

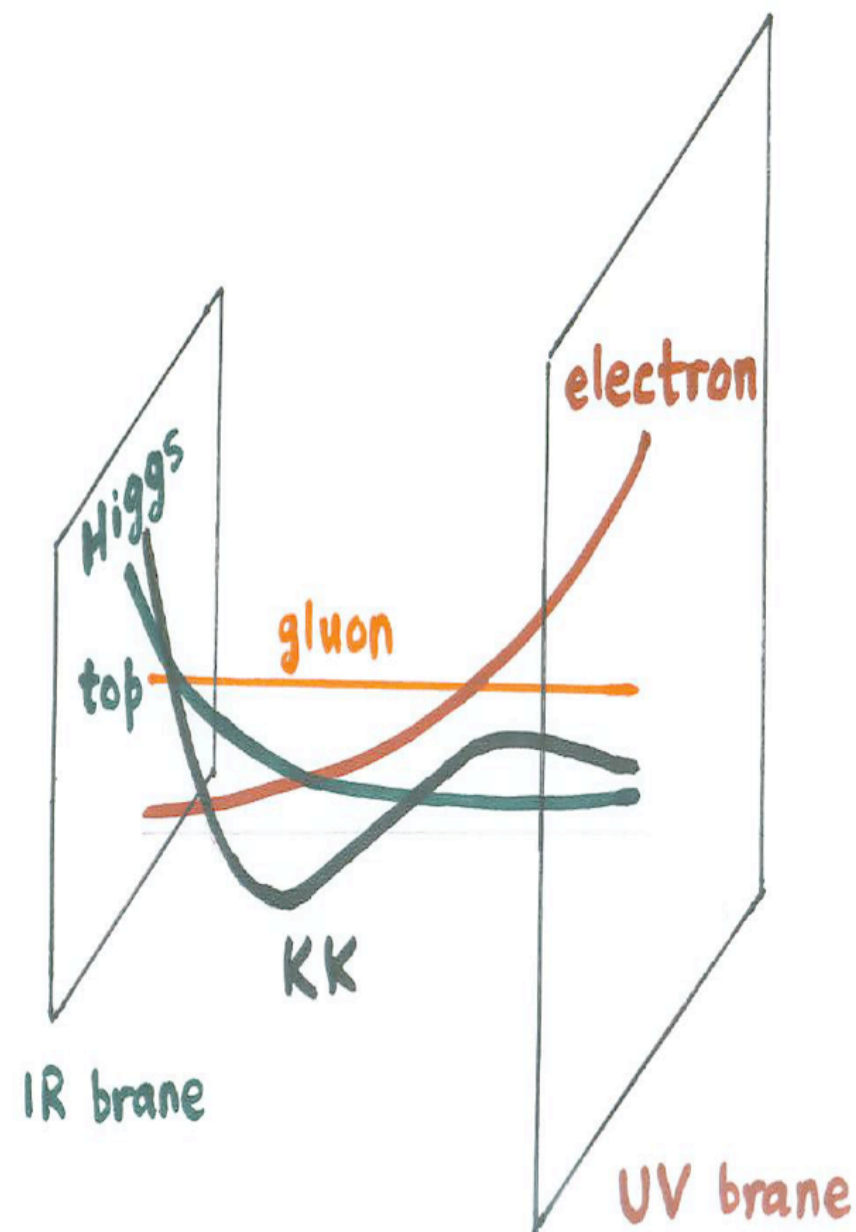
Gravity and Higgs

(Randall, Sundrum)



SM in bulk

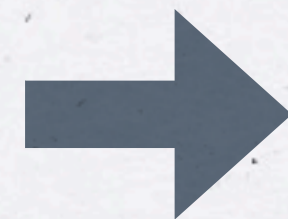
(Davoudiasl, Hewett, Rizzo; Pomarol; Grossman, Neubert; Chang, Hisano, Nakano, Okada, Yamaguchi; Gherghetta, Pomarol)



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)

NO PARITY, PRECISION TESTS
NEW PARTICLES FEW TEV

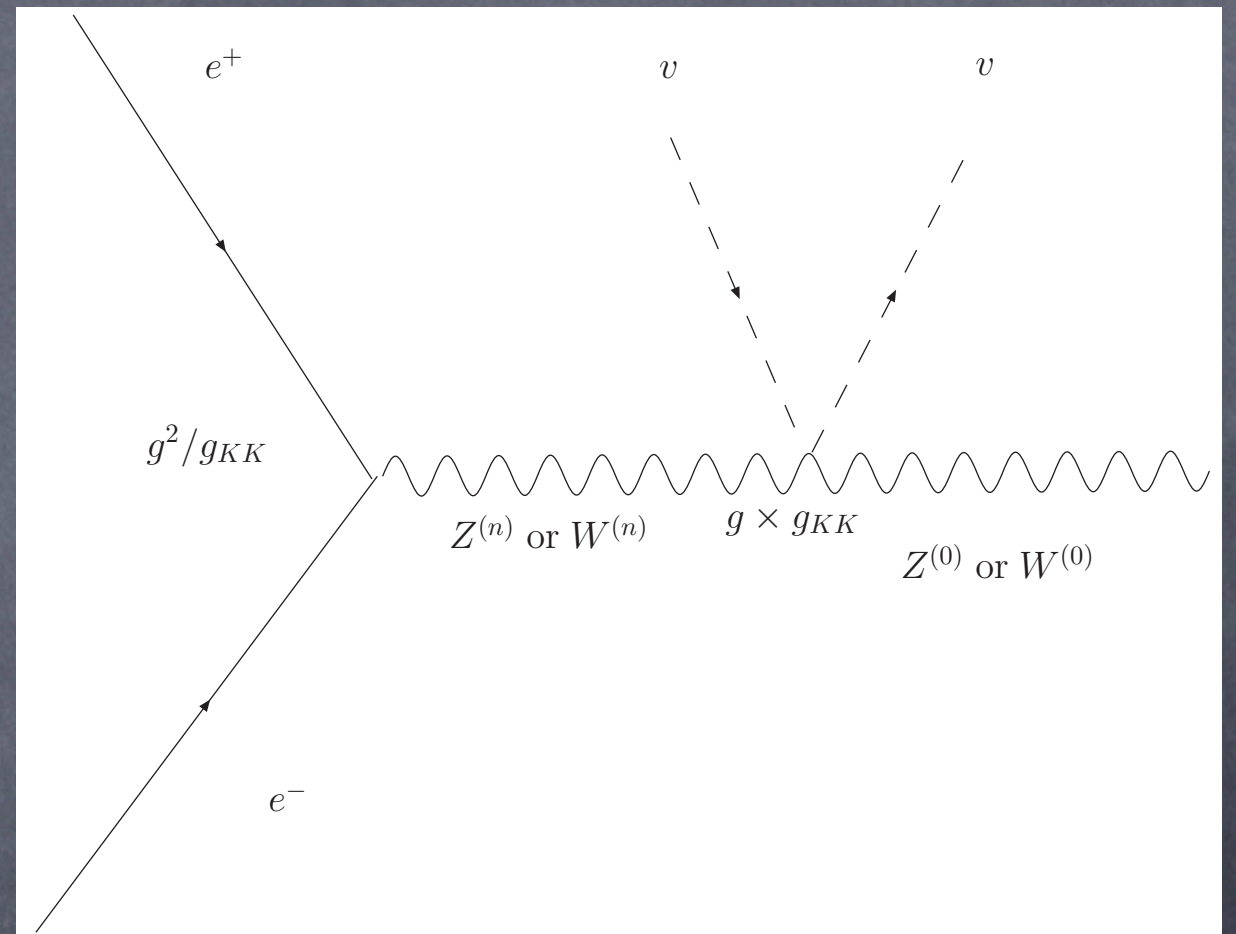


Precision tests: S parameter


Equivalent to shift in coupling:

$$\frac{\delta g_Z}{g_Z} \sim \frac{M_Z^2}{M_{KK}^2} \lesssim 0.1\%$$

$$\Rightarrow M_{KK} \gtrsim \text{a few TeV}$$



5D warped Higgsless models (breaking by boundary condition) (Csaki, Grojean, Pilo, Terning)

- Flat profiles for fermions 
suppression in S
- < 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 **2-3 TeV** KK masses
(Carena, Ponton, Santiago, Wagner)

Flavor constraints for anarchy

(see talk by L. Randall)

- **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**...(Csaki, Falkowski, Weiler; see also Bona et al.; KA et al.; Davidson, Isidori, Uhlig; Fitzpatrick, Perez, Randall; Davoudiasl, Perez, Soni)

...but...

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

- “O(1) room” in **each of profile** for Higgs (size of 5D Yukawa), 5D **gauge** coupling...



- **O(5)** TeV scale allowed **even with anarchy** by ϵ_K [**other** (loop) processes need to be checked]
- 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 **a few TeV** allowed (even if 20 TeV for natural size) \Rightarrow tuning?


...or...

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

Lepton sector: anarchy

- 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 a la quarks with anarchy)
- profiles as "input" (fit to data), flavor violation suppressed even for a few TeV KK scale using choice of charges under $SU(2)_R$; $O(1)$ room in 5D Yukawa, Higgs profile...

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)

LHC SIGNALS FOR KK PARTICLES

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

$$\begin{aligned} \frac{g_{RS}^{q\bar{q}, l\bar{l}} A^{(1)}}{g_{SM}} &\simeq \xi^{-1} \approx \frac{1}{5}, \\ \frac{g_{RS}^{Q^3 \bar{Q}^3 A^{(1)}}}{g_{SM}}, \frac{g_{RS}^{t_R \bar{t}_R A^{(1)}}}{g_{SM}} &\simeq 1 \text{ to } \xi \approx 1 \text{ to } 5, \\ \frac{g_{RS}^{HH A^{(1)}}}{g_{SM}} &\simeq \xi \approx 5, \\ \frac{g_{RS}^{A^{(0)} A^{(0)} A^{(1)}}}{g_{SM}} &\simeq 0 \end{aligned}$$

Model-independent approach:

Contino, Kramer, Son, Sundrum; Giudice, Grojean, Pomarol,
Rattazzi (see talk by C. Grojean)

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



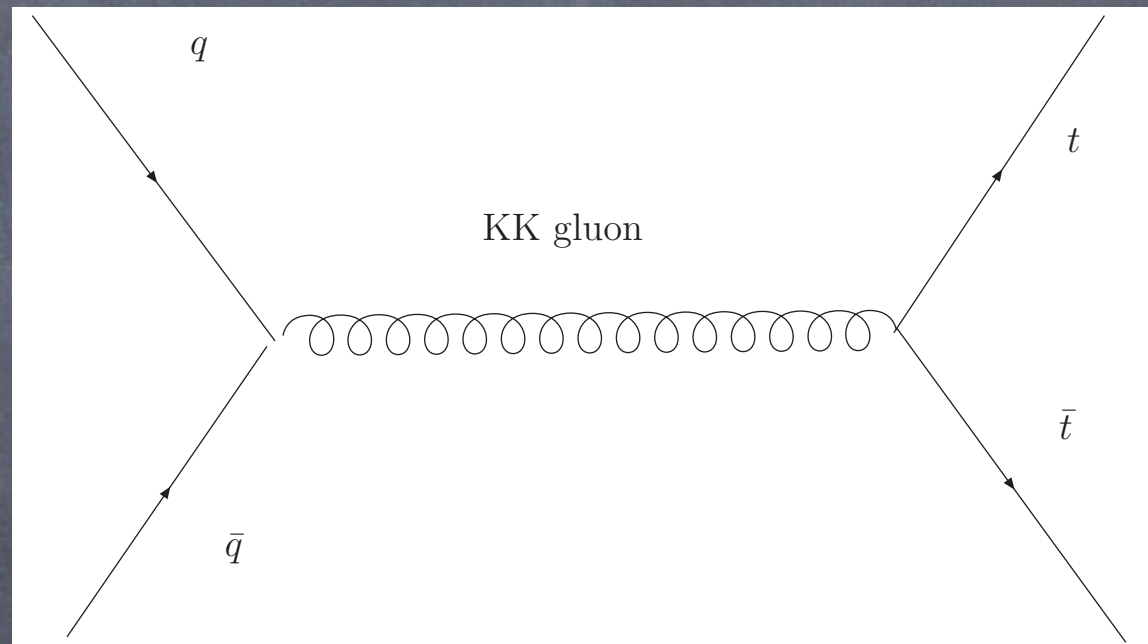
- Production suppressed: weak coupling to constituents of **proton**
- Decays to top/W/Z/Higgs: **golden** channels (leptons, photons) **suppressed**
- Strong coupling \Rightarrow **broad** resonances
...but **not** out!

KK gluon

(KA, Belyaev, Krupovnickas, Perez, Virzi)

(See also Lillie, Randall, Wang; Lillie, Tait, Shu;
Djouadi, Moreau, Singh; Baur, Orr...)

Production and Decay

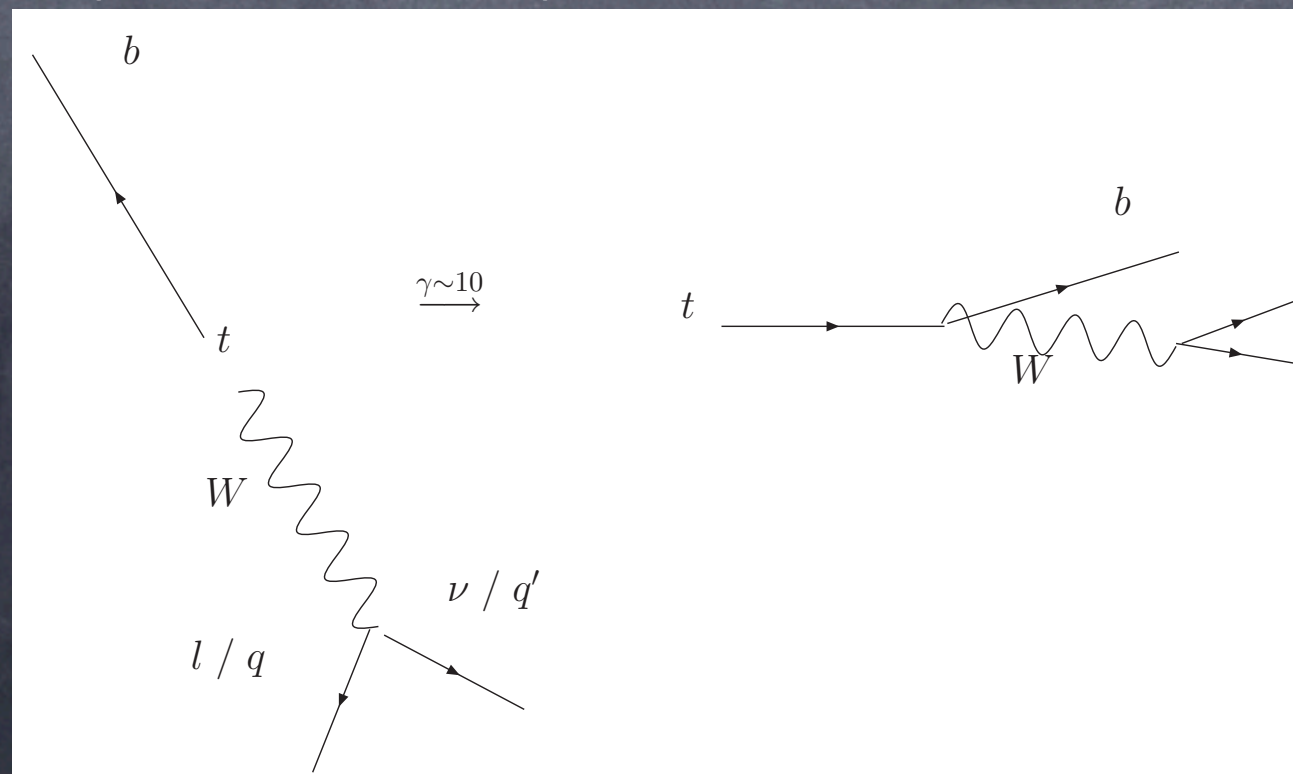


Problem: collimation of tops

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

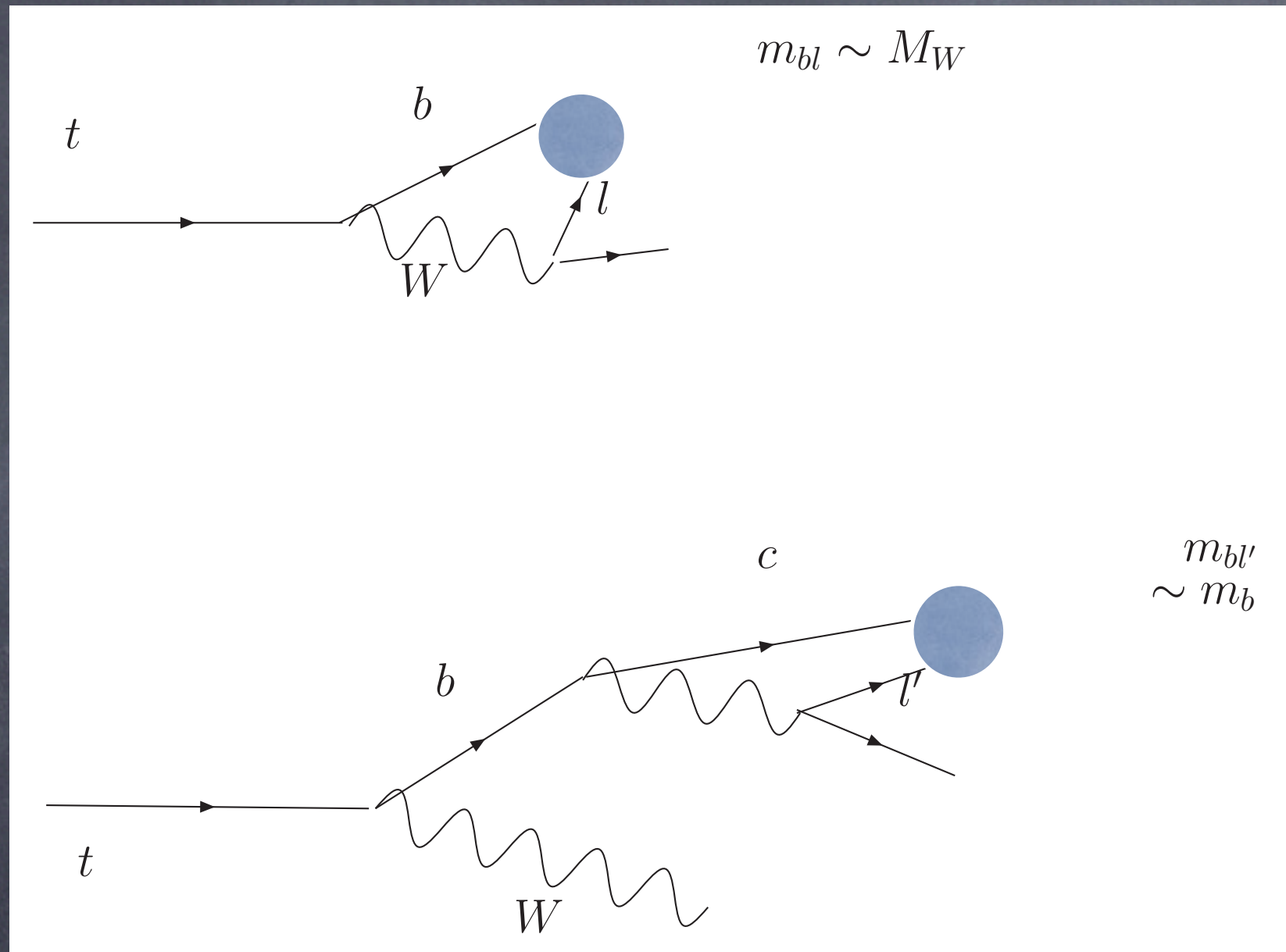
vs.

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 (Conway, Dolen, Searle, Squires, Vazquez); substructure (Thaler, Wang; Kaplan, Rehermann, Schwartz, Tweedie); IR safe event shapes (Almeida, Lee, Perez, Sterman, Sung, Virzi) (see talk by L-T. Wang)

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

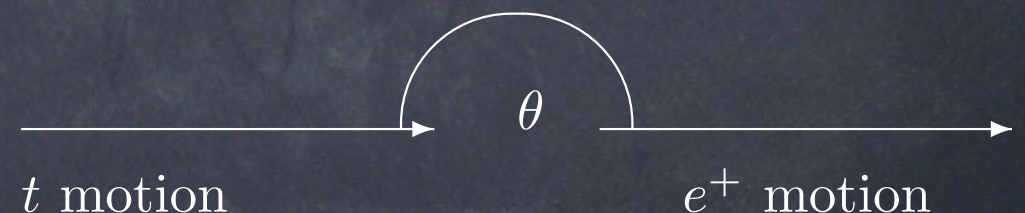
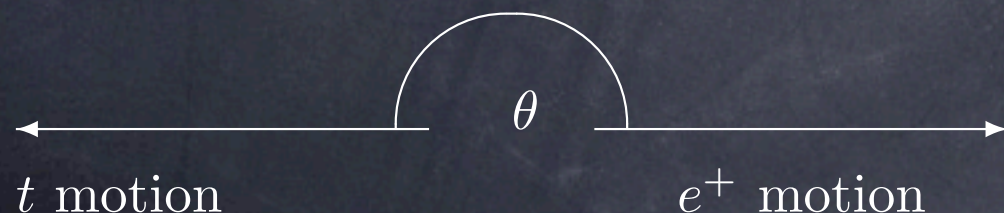


t spin

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)

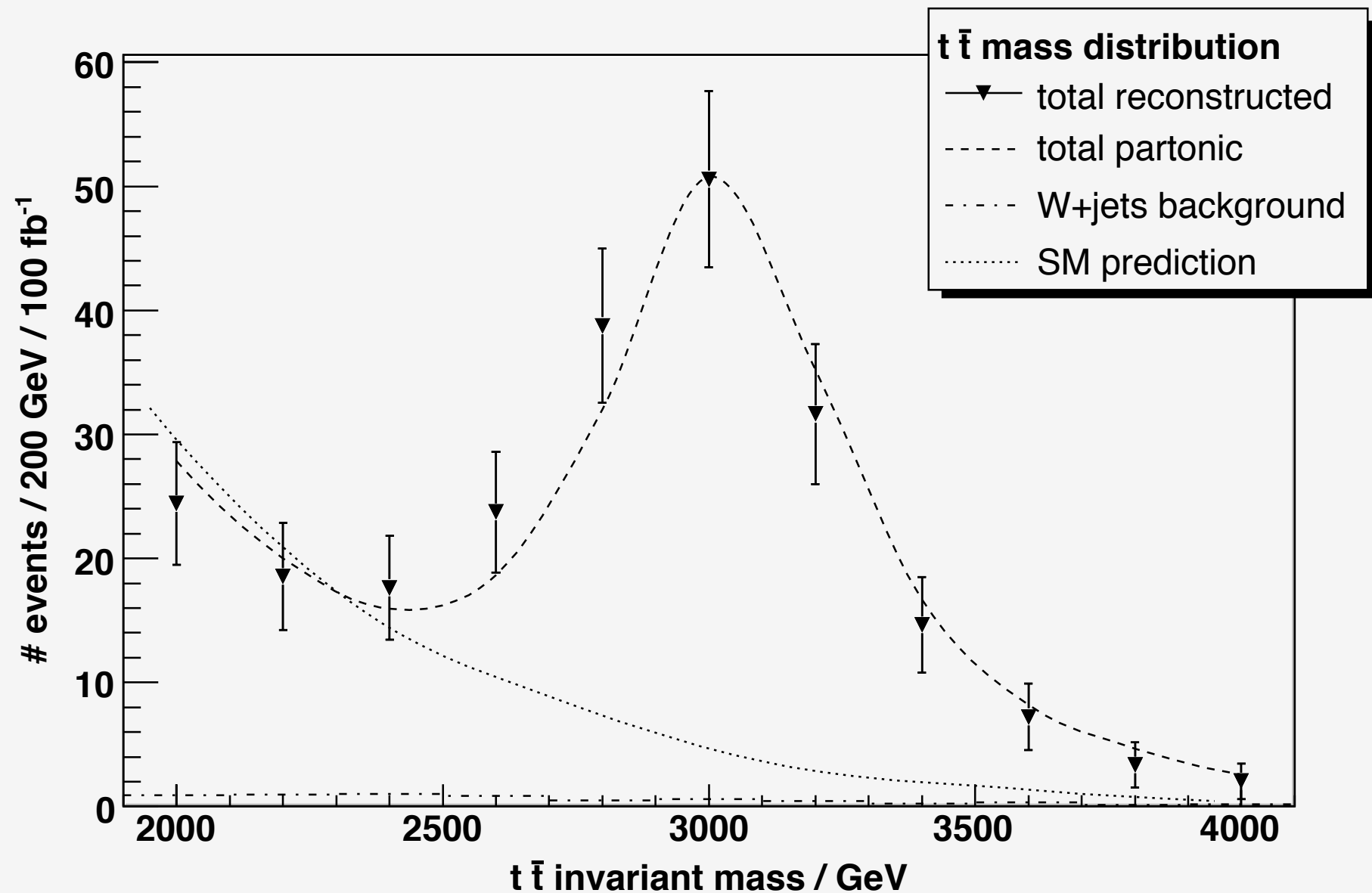
Discovery for 4 TeV with 100 / fb

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

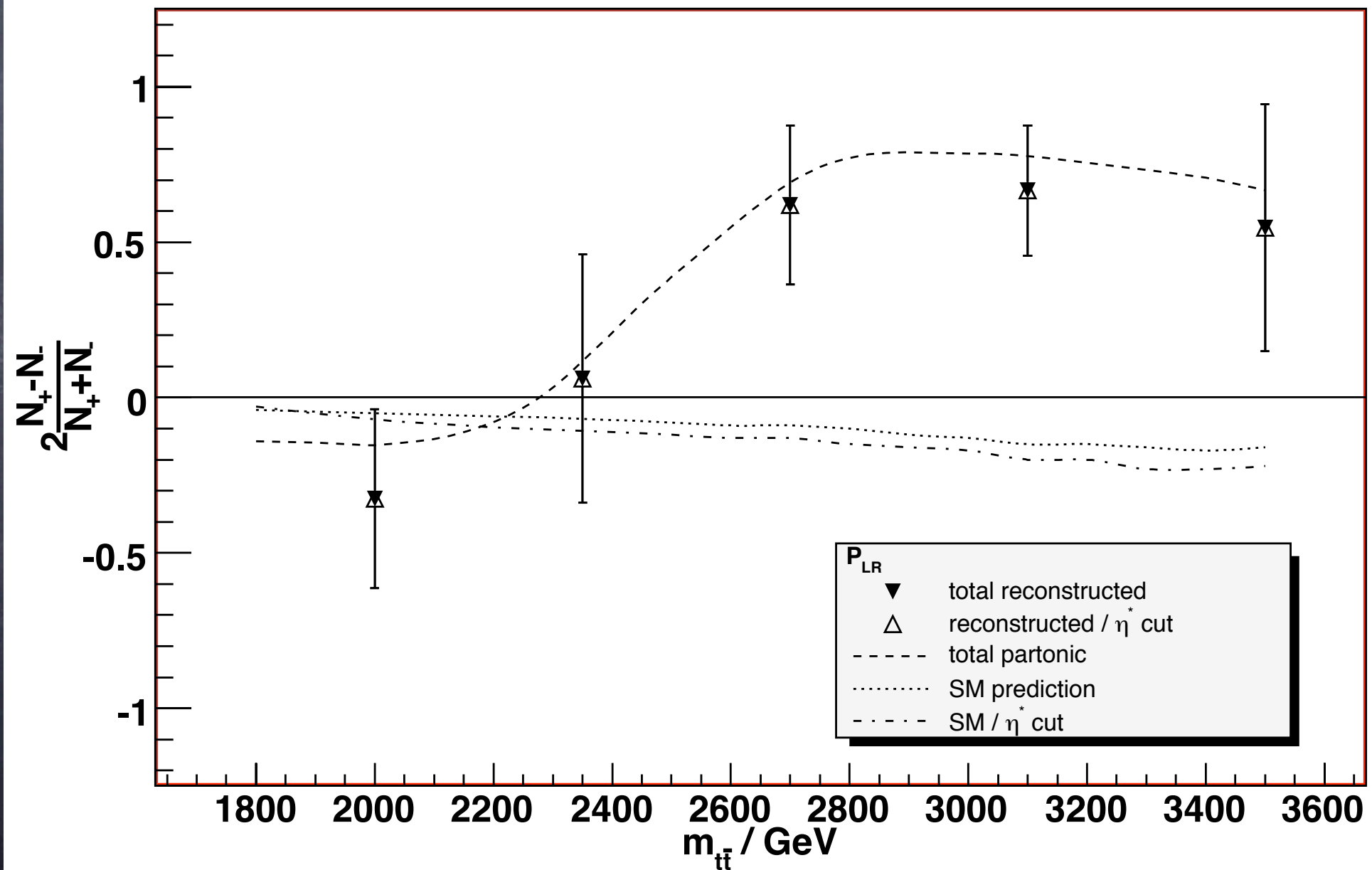
correlated with

- Deviation in P_{LR} from SM

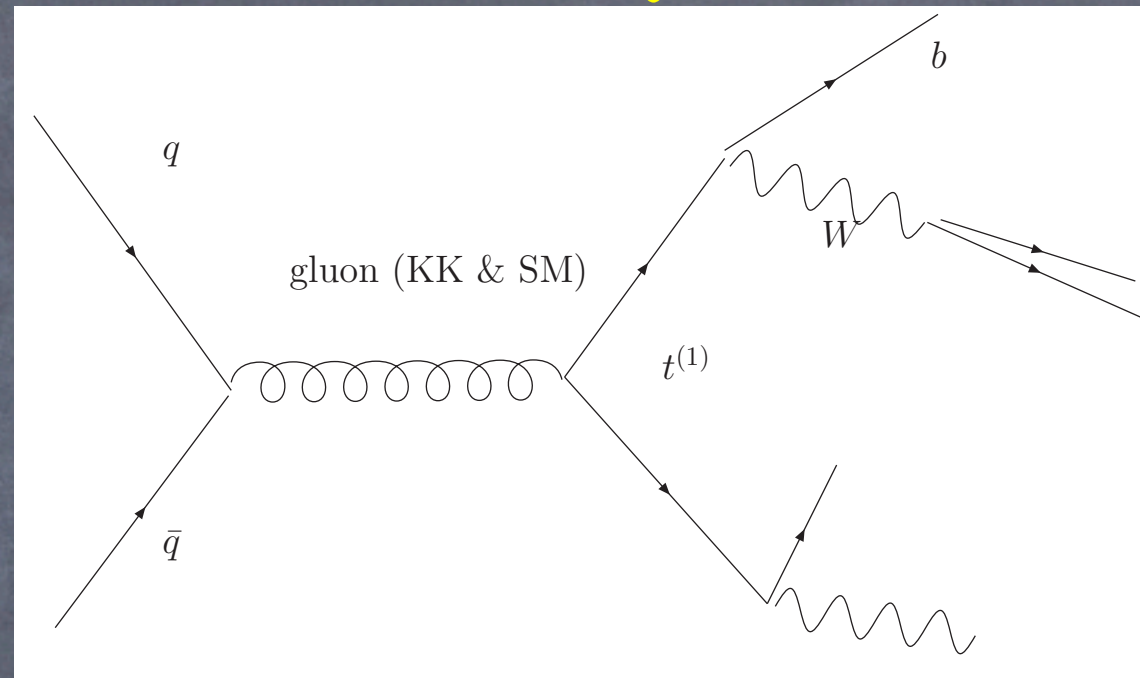
Differential cross-section



Polarization asymmetry



KK gluon decays to KK tops



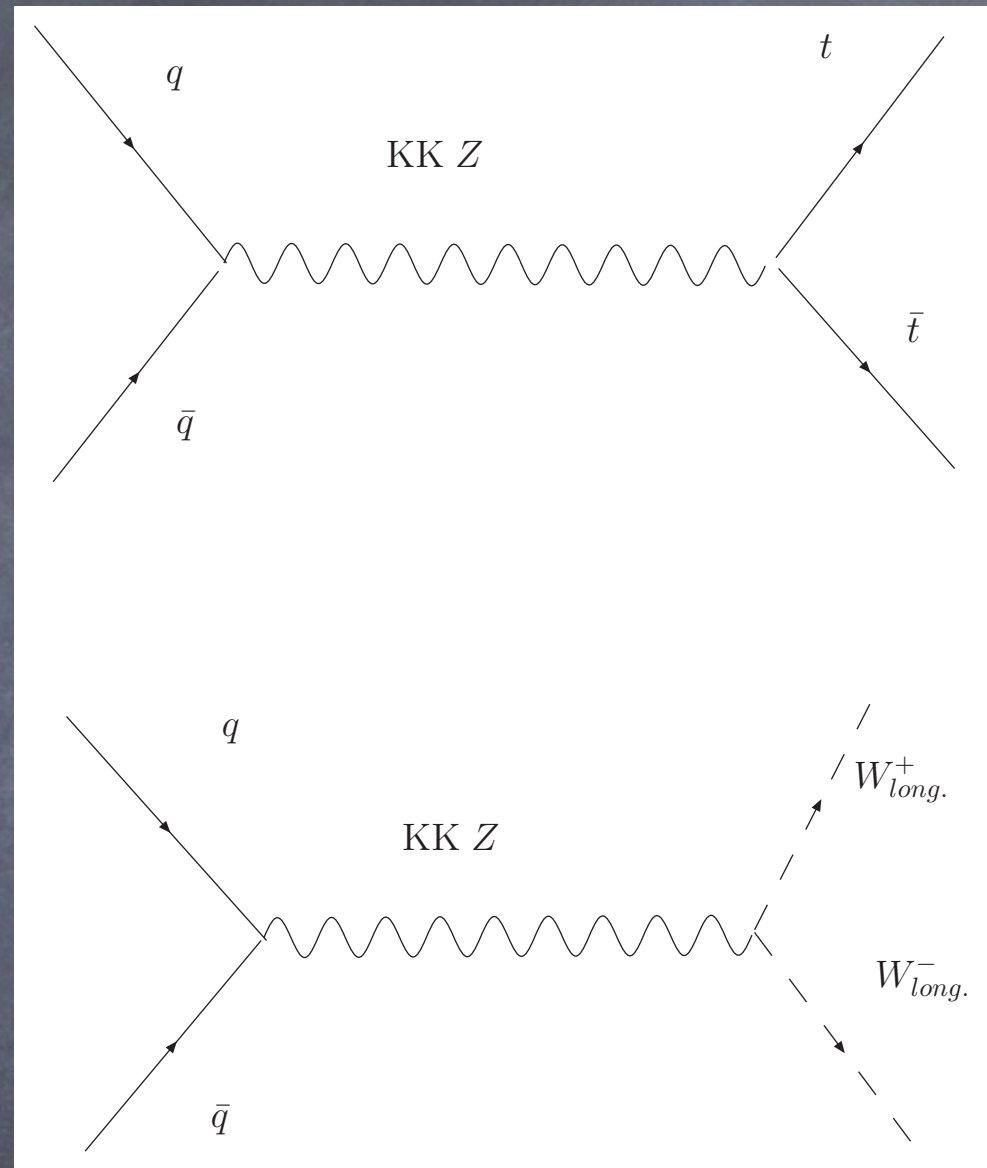
- KK tops (1 TeV) not boosted, decay into Wb (well-separated, but 2 jets from W still collimated)
(Carena, Medina, Panes, Shah, Wagner)

KK Z

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

(See also Djouadi, Moreau, Singh)

Production and Decay



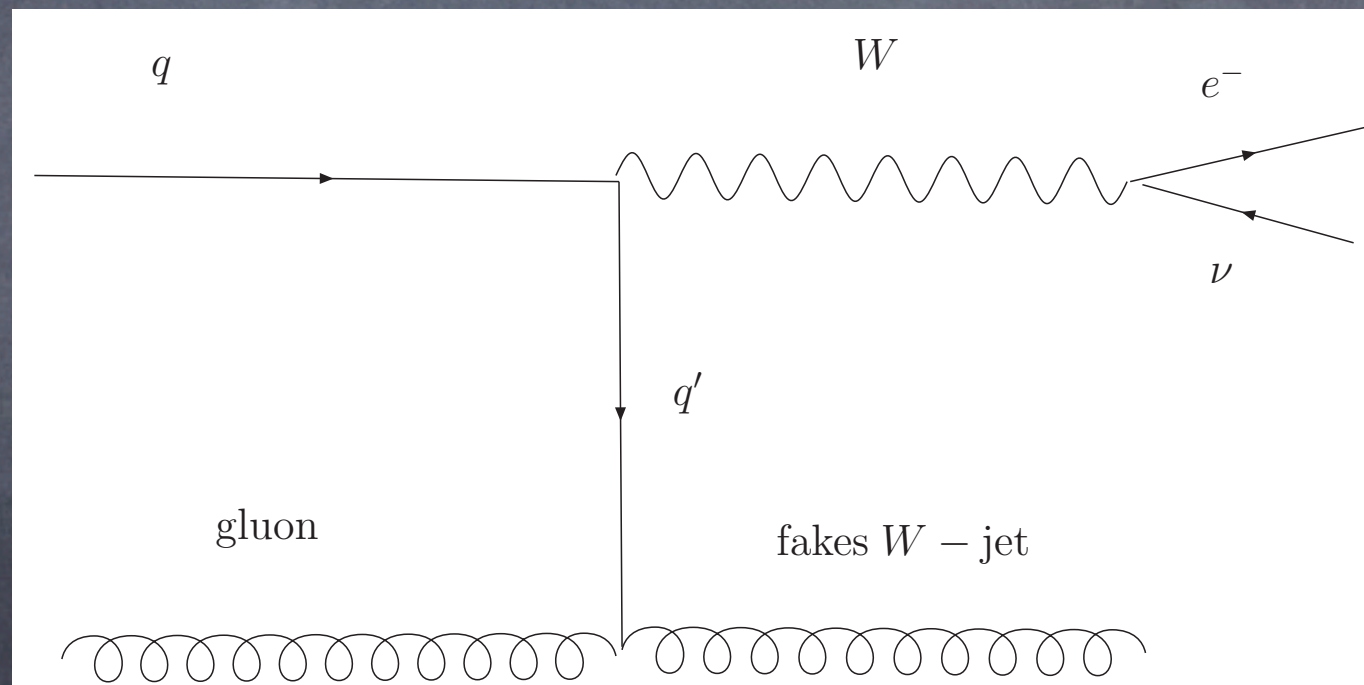
Decays to tops swamped
by KK gluon

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

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

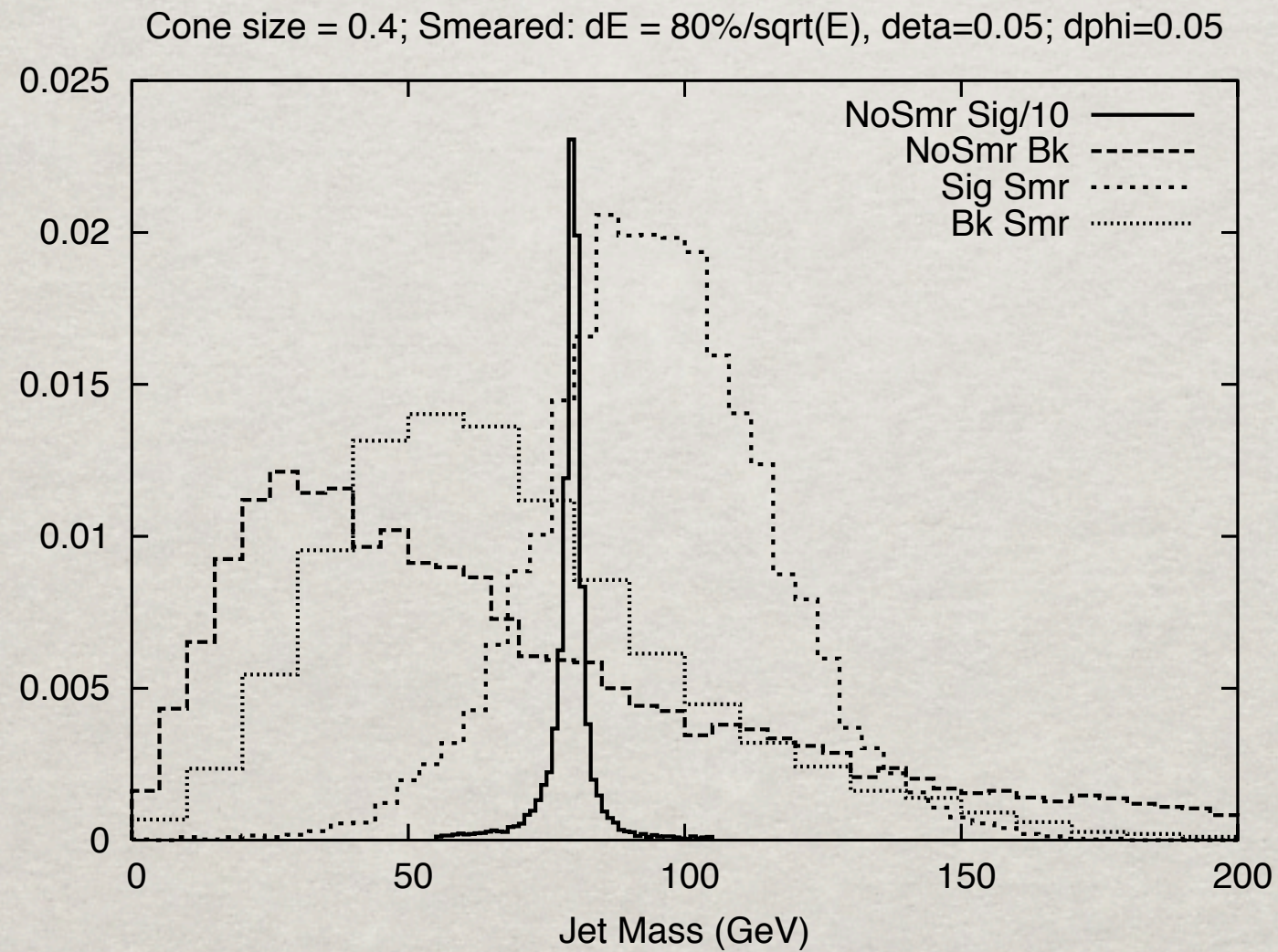
KK $Z \rightarrow W^+W^- \rightarrow l^+\nu jj$: can reconstruct, but...

- W + jet SM **background**



SOLUTION: JET MASS CUT

(SEE ALSO SMITH, SKIBA; HOLDOM)



Results for KK Z

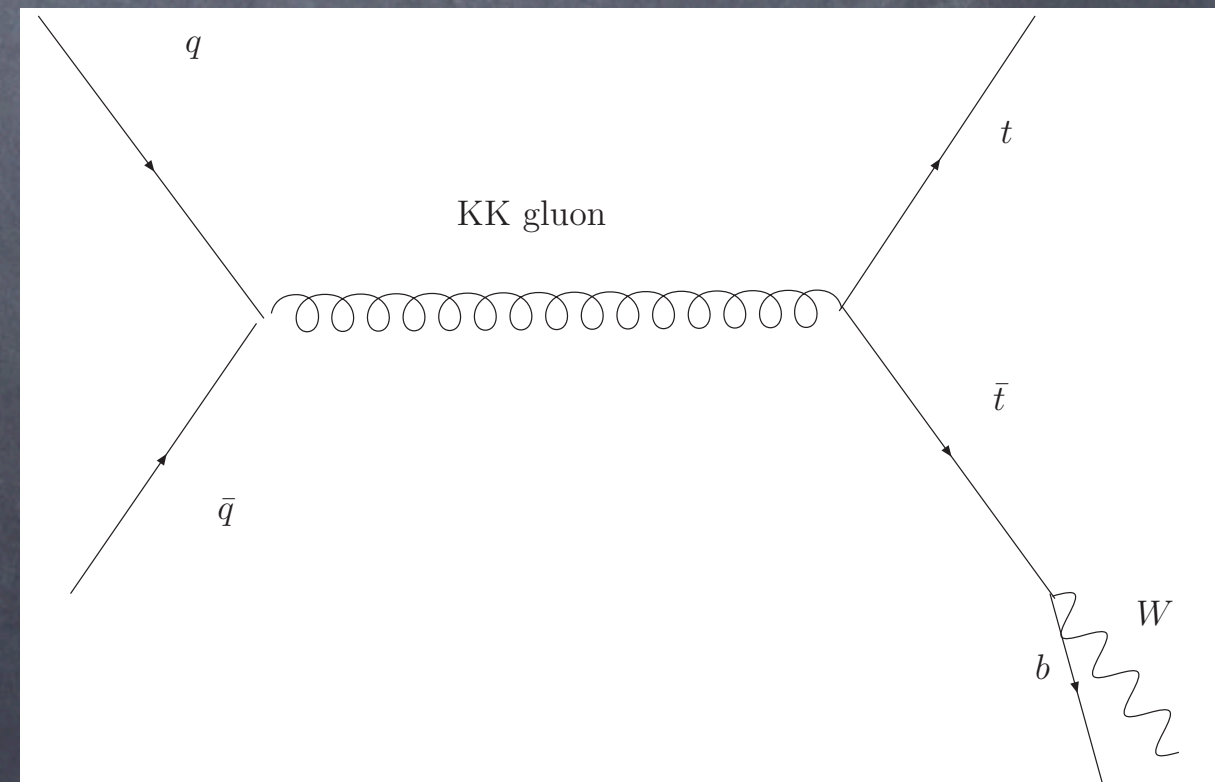
- Reach of 2 (3) TeV for 100/fb (1000/fb) from semileptonic WW
- Similar from $KK Z \rightarrow Zh$

KK W

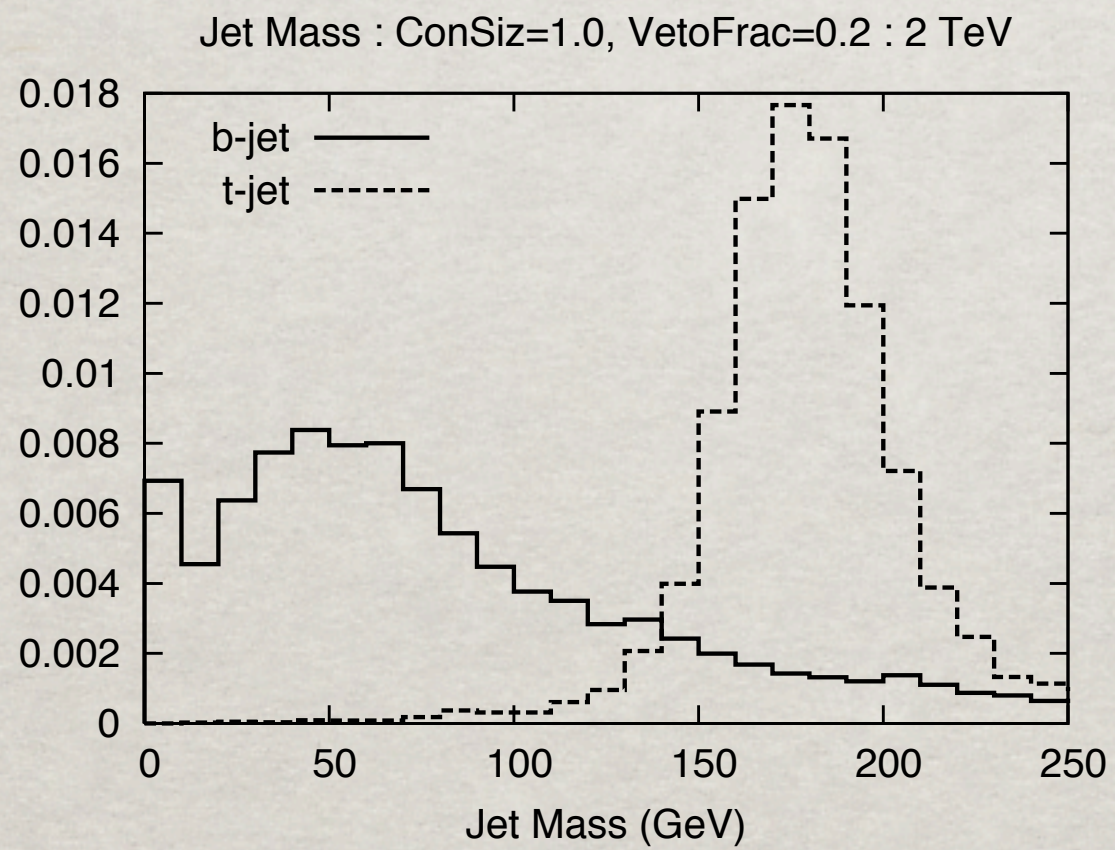
(KA, Gopalakrishna, Han, Huang, Soni)

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

- Decays to top + bottom:
KK gluon background



... REDUCIBLE BY JET MASS CUT



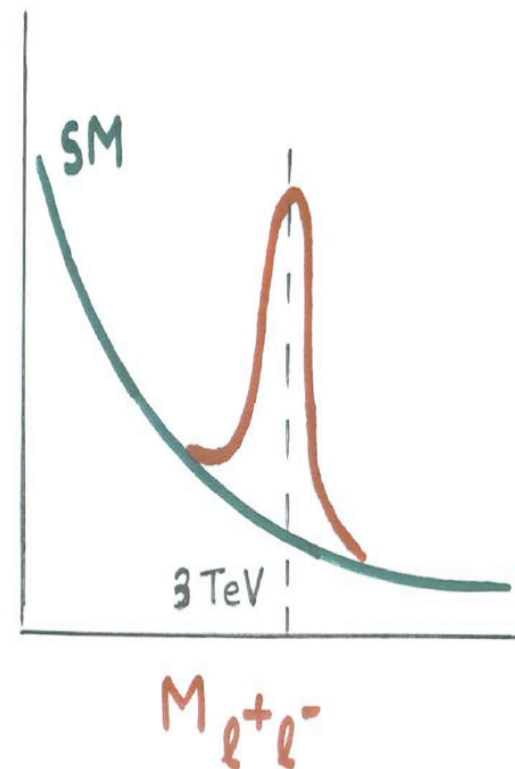
Other Signals

- 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)
- Light KK fermions (Dennis, Karagoz Unel,
Servant, Tseng; Contino, Servant)
- **Virtual** effects: $t \rightarrow cZ$ with BR of 10^{-5}
(KA, Perez, Soni)

“ORIGINAL” RS1: BRANEWORLD

Golden decays:

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

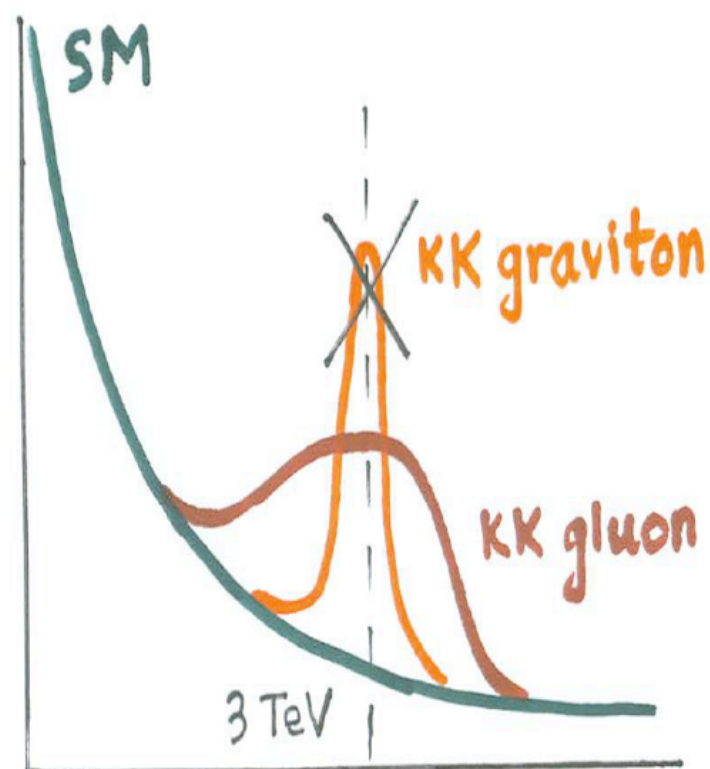


CF. SM (– HIGGS) IN THE BULK

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

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

+ KK gluon, W, Z, γ



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

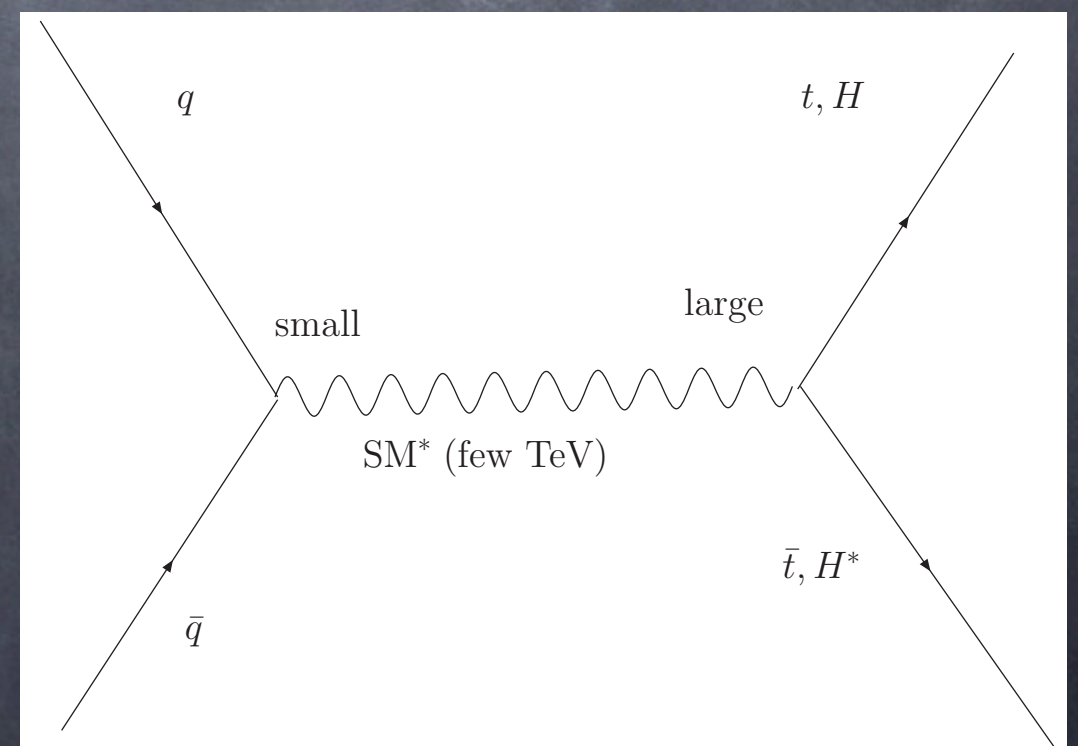
SIGNALS FOR A *CLASS* OF MODELS, *NOT* JUST WARPED EXTRA DIMENSION

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

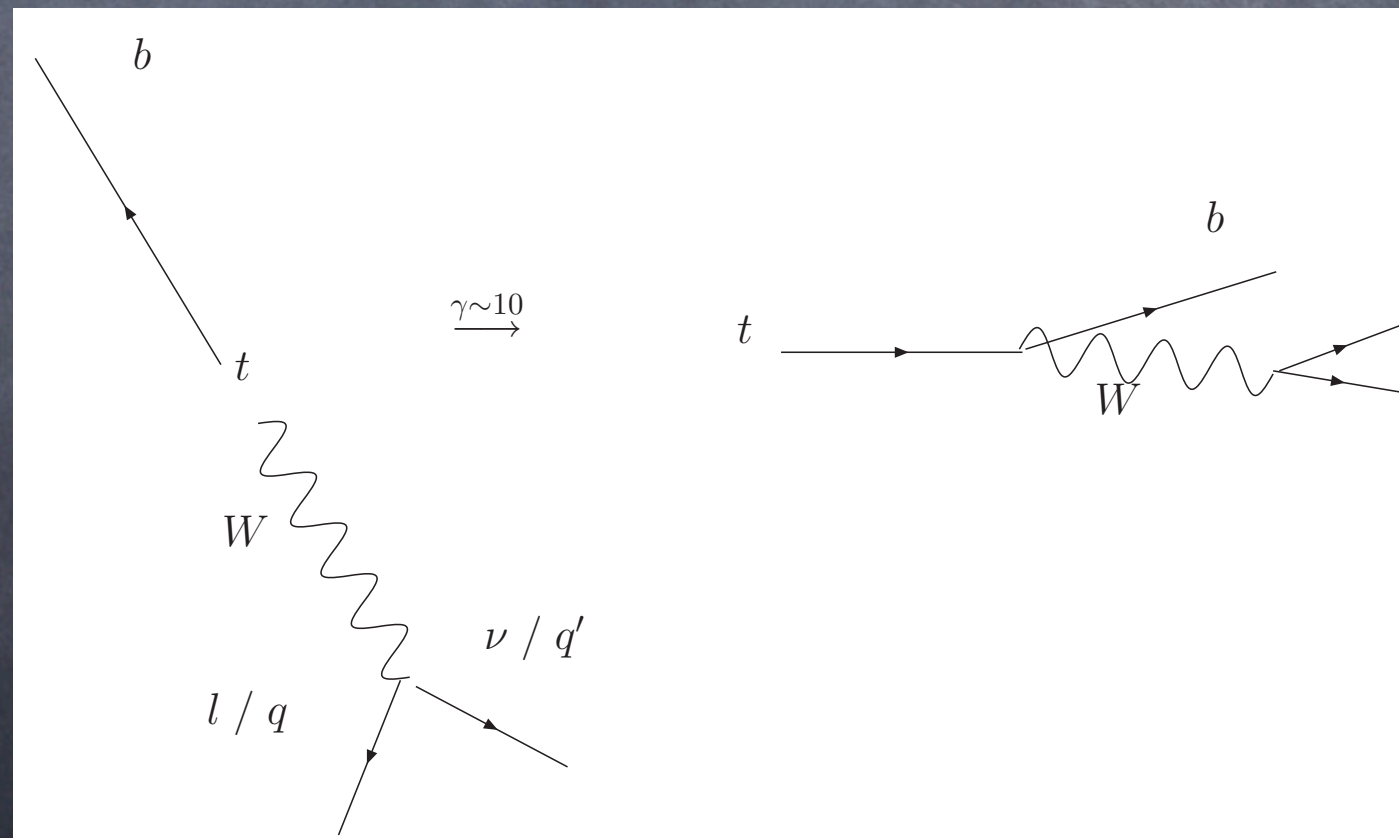
Resonance production:
decays to top and *H/W/Z*
(highly boosted!)



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

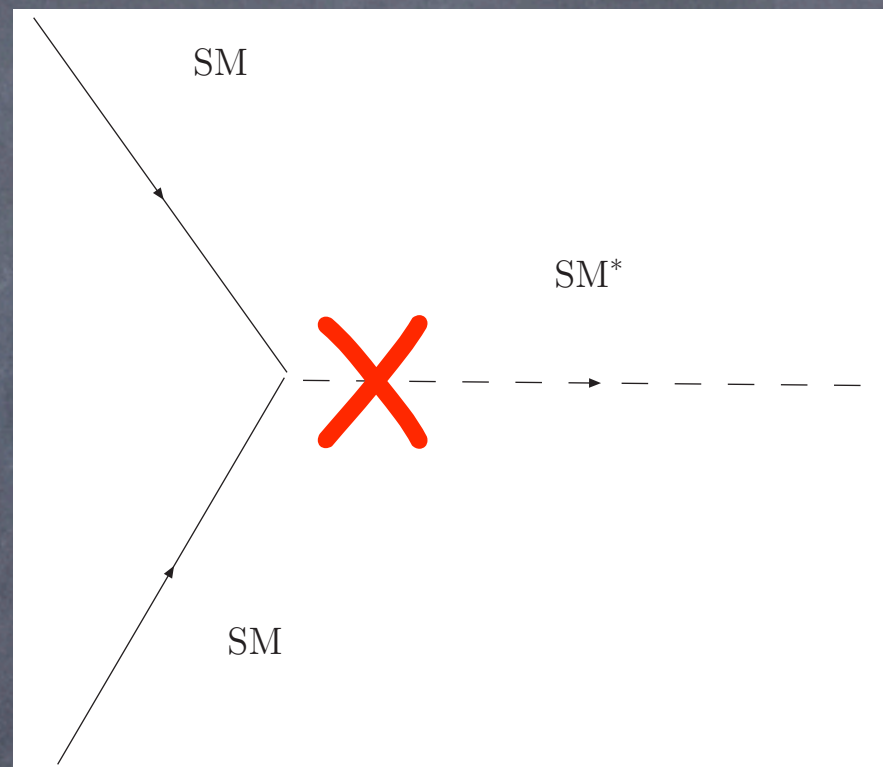
(More) Studies needed...

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



KK PARITY IN WARPED EXTRA DIMENSION

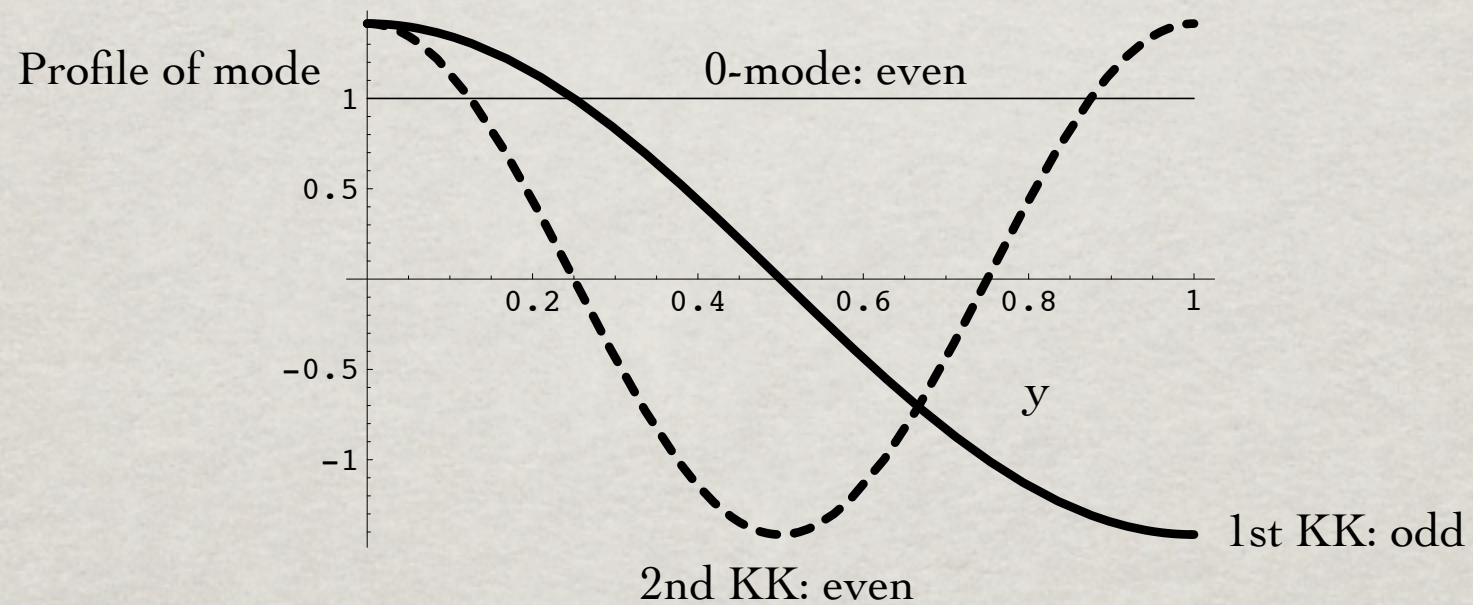
KK parity in flat universal extra dimensions (UED), T-parity in Little Higgs



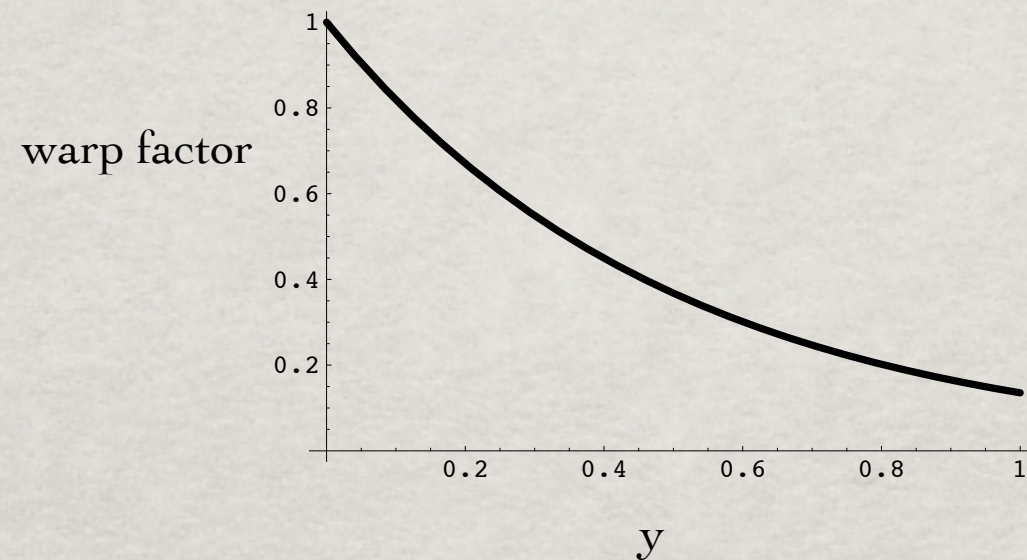
- valid only up to 10's TeV

KK PARITY IN UED

☼ Reflection about midpoint



NO KK PARITY IN SINGLE ADS SLICE

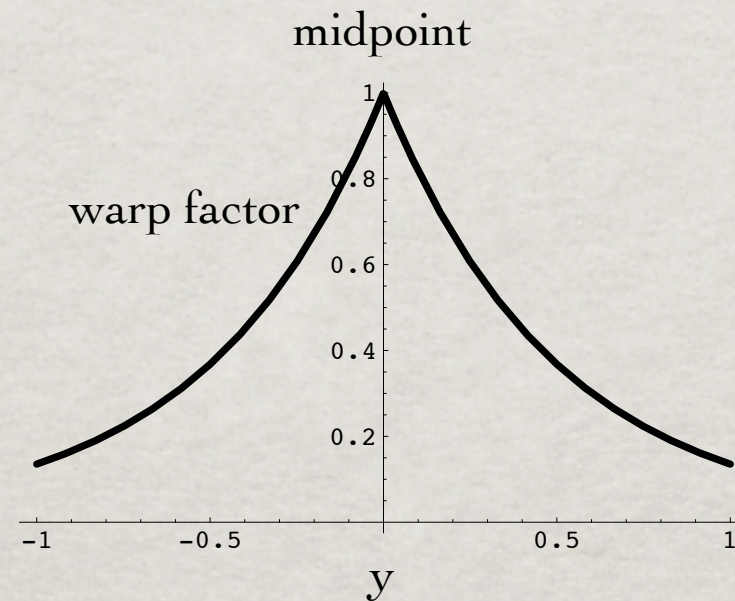


- ✱ Warp factor **not** symmetric about midpoint
(cf. **flat** metric)

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

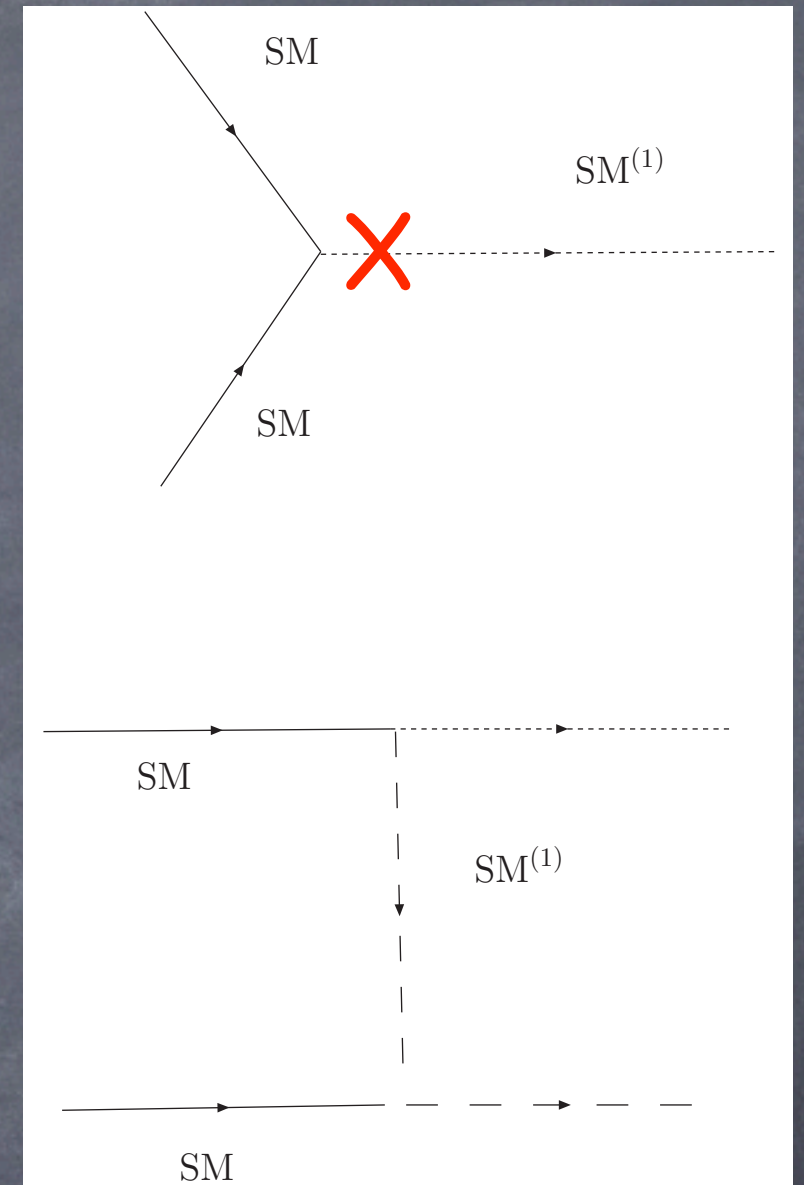
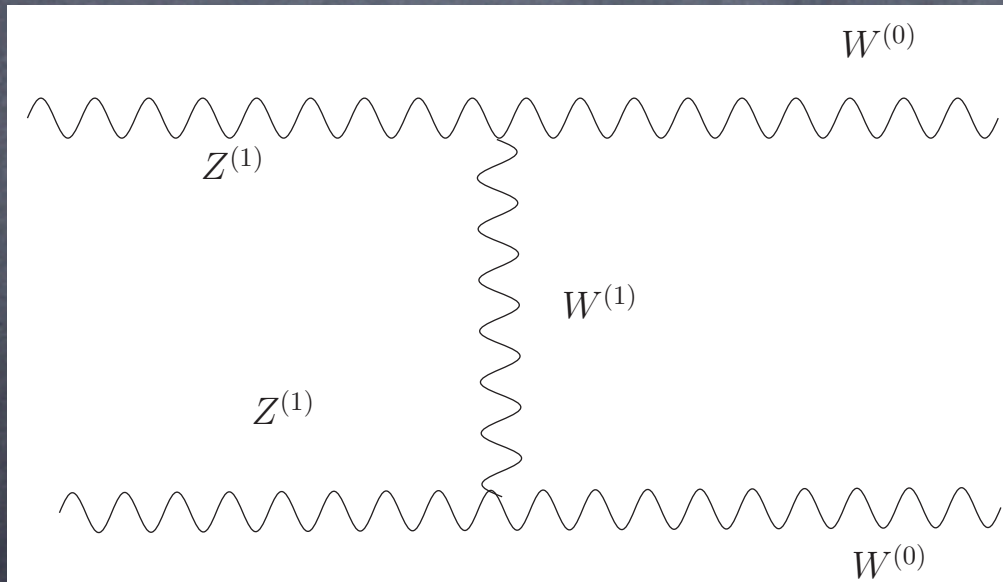
Motivation and Spectrum

- **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

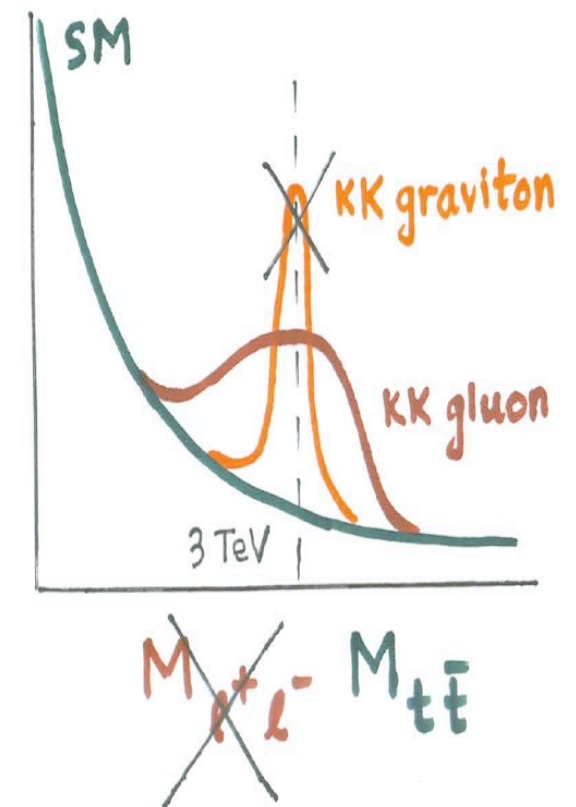
- Odd KK's **pair**-produced
- Large Brane Kinetic terms
KK **Z** Dark Matter
(cf. KK **photon** in UED)



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!



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)

Warped Gauge-Higgs unification

(Contino, Nomura, Pomarol; KA, Contino, 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 $\Rightarrow m_H^2 < 0$