Extra Dimensions at the LHC

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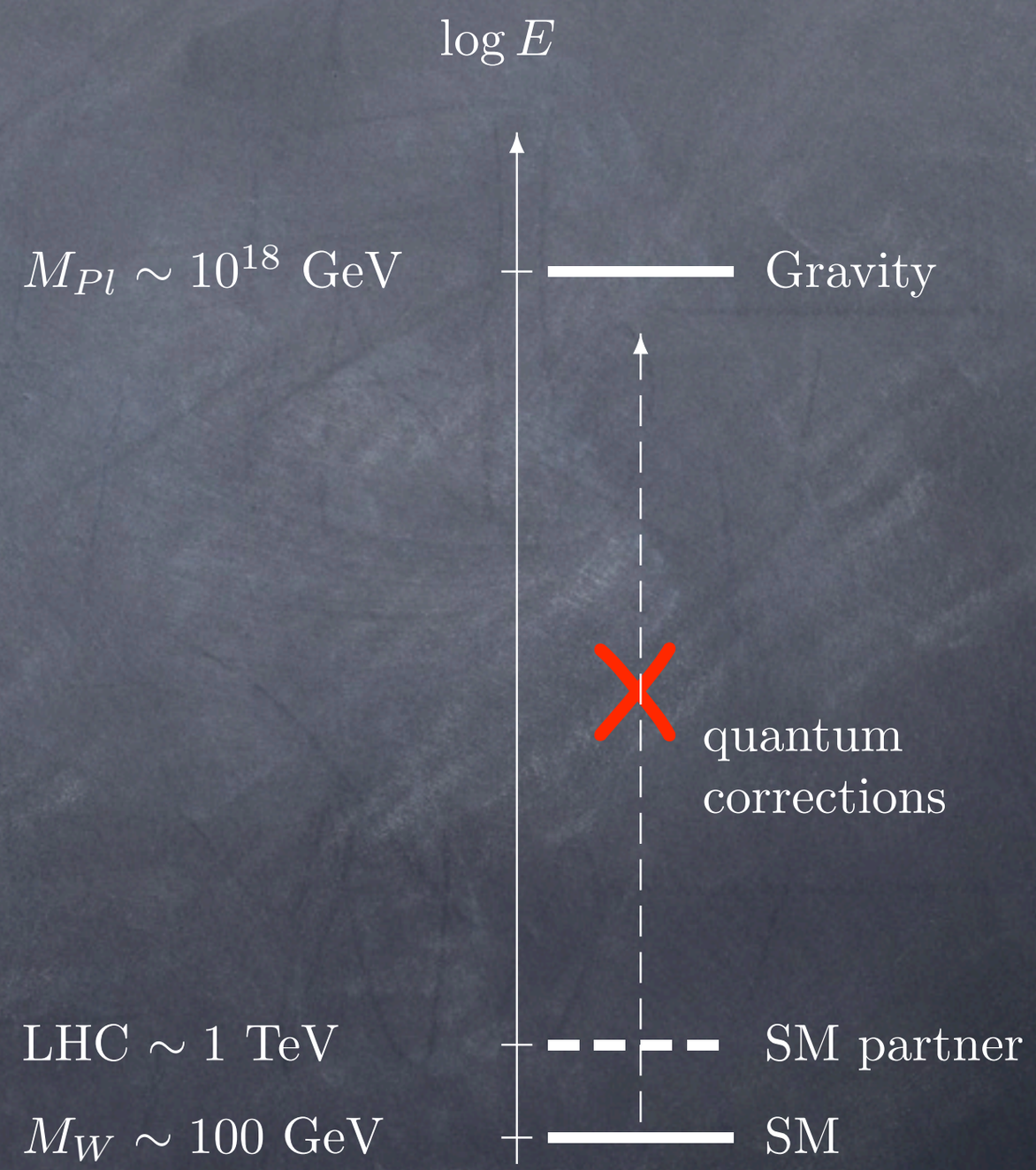
Outline and Summary

- 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

PRECISION TESTS →
NEW PARTICLES FEW TEV

2 Broad Ideas for LHC and hierarchy problem (thanks to R. Sundrum)

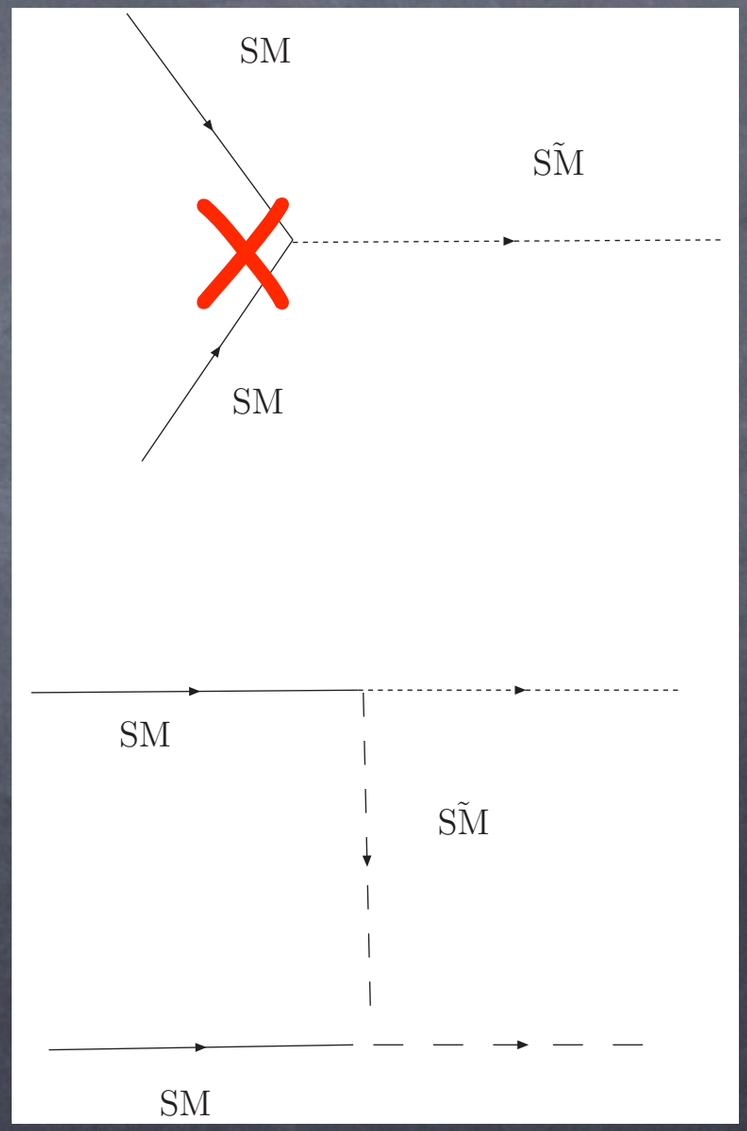
- SUSY
- non-SUSY



SUSY

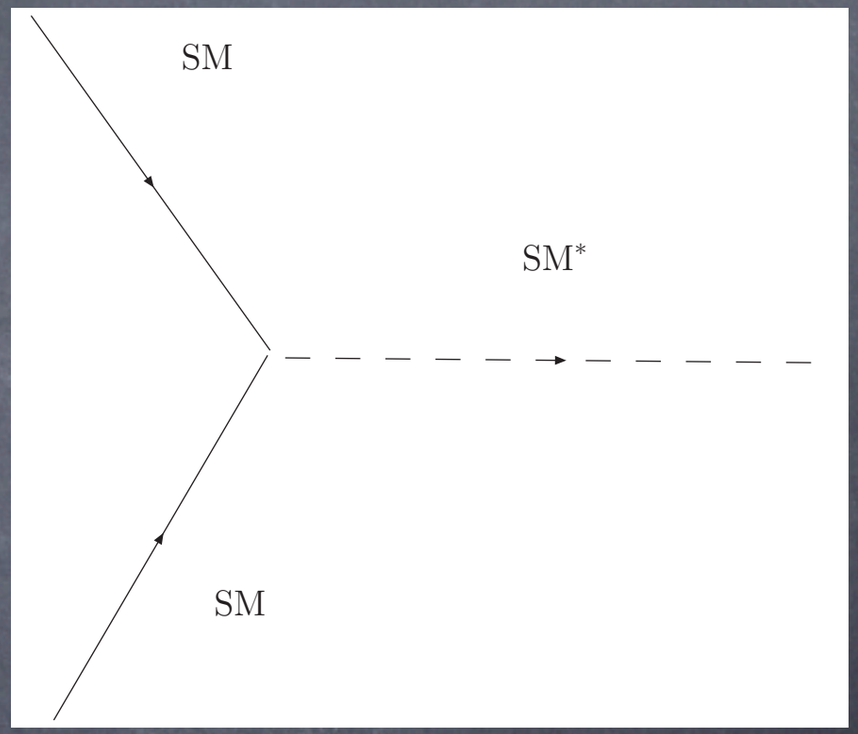
- R-parity
- Flavor-blind couplings

- no tree-level precision tests, a few 100 GeV allowed
- LSP stable: dark matter
- pair production at colliders: missing energy



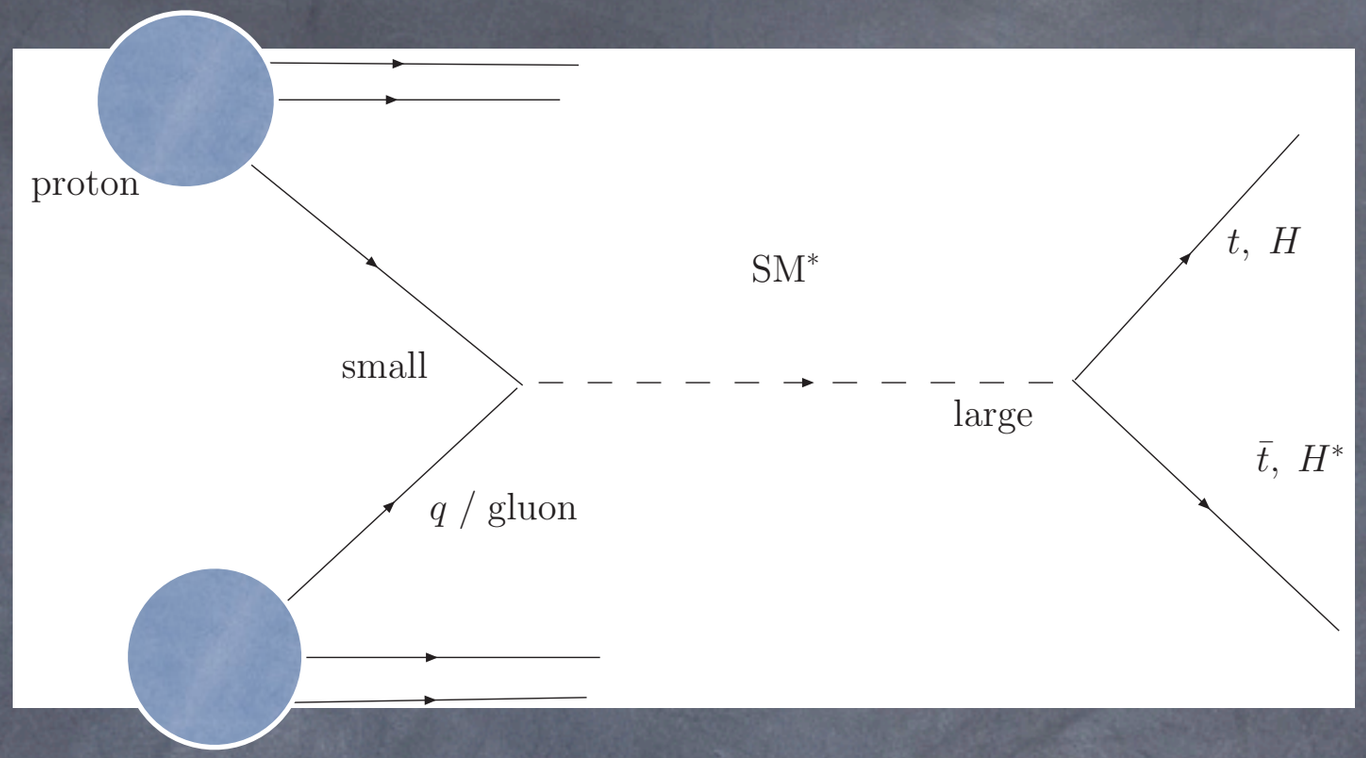
Class of non-SUSY

- no parity
- flavor-dependent couplings: large (small) for top/Higgs (light fermions)



- few TeV from precision tests (tree)
- single production, no stable particle

Non-SUSY @ 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!

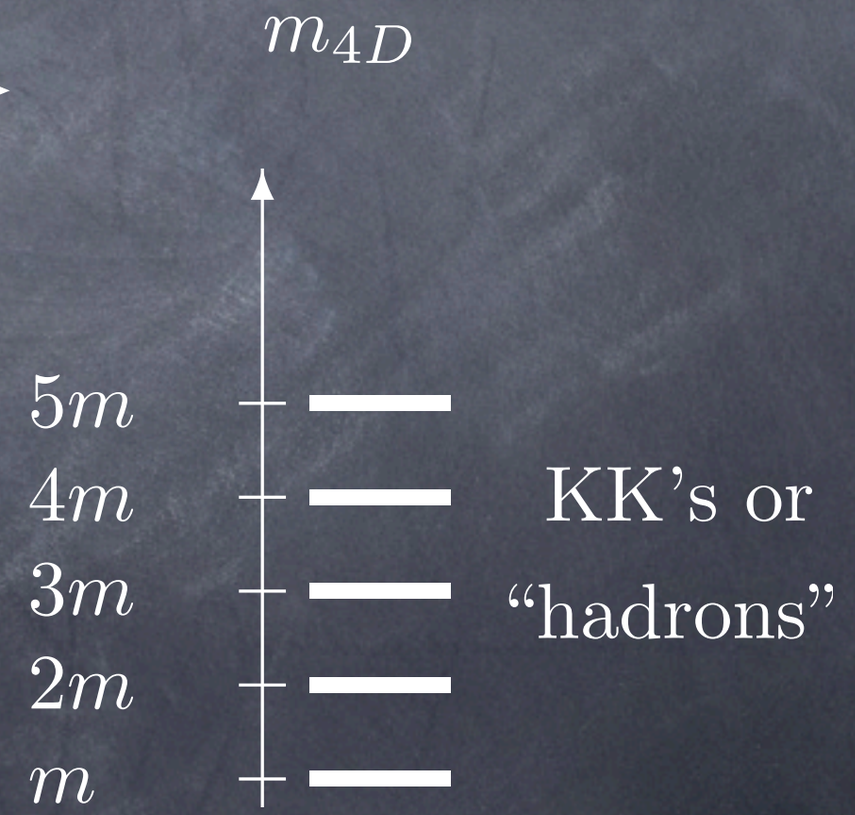
Theory for non-SUSY

- Technicolor, Composite Higgs (+ partially composite SM fermions)
- Little Higgs, Extra Dimensions (AdS/CFT duality)

Extra dimensions dual to 4D strong dynamics

(Maldacena; Gubser, Klebanov, Polyakov; Witten)

- Particle in 5D: SM (x_μ, y) ⇨
  Fourier expand y (a la 1D box)
  Lightest mode (SM) + heavier (Kaluza-Klein) with profiles



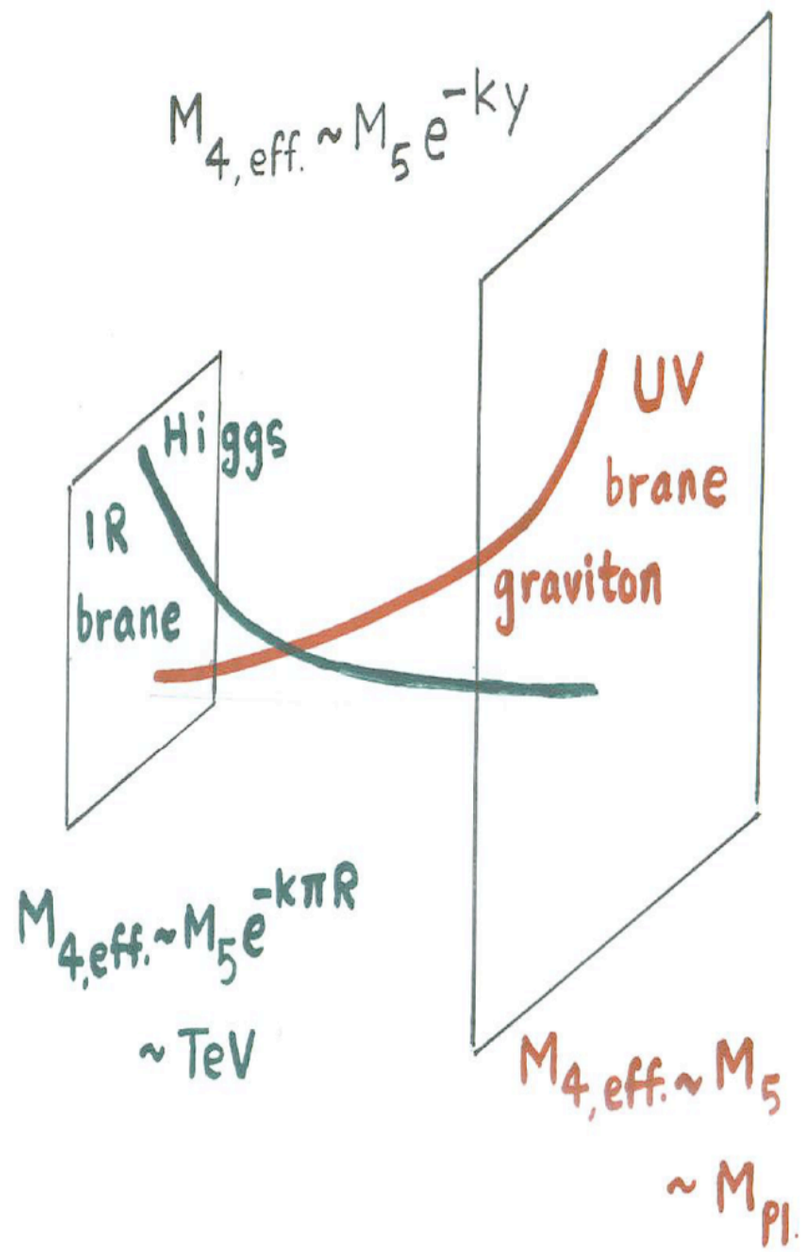
- Tower of bound states of 4D strong dynamics

Warped Extra Dimensions

- Planck-weak and flavor hierarchy
- Weakly-coupled "tool" for 4D strong dynamics

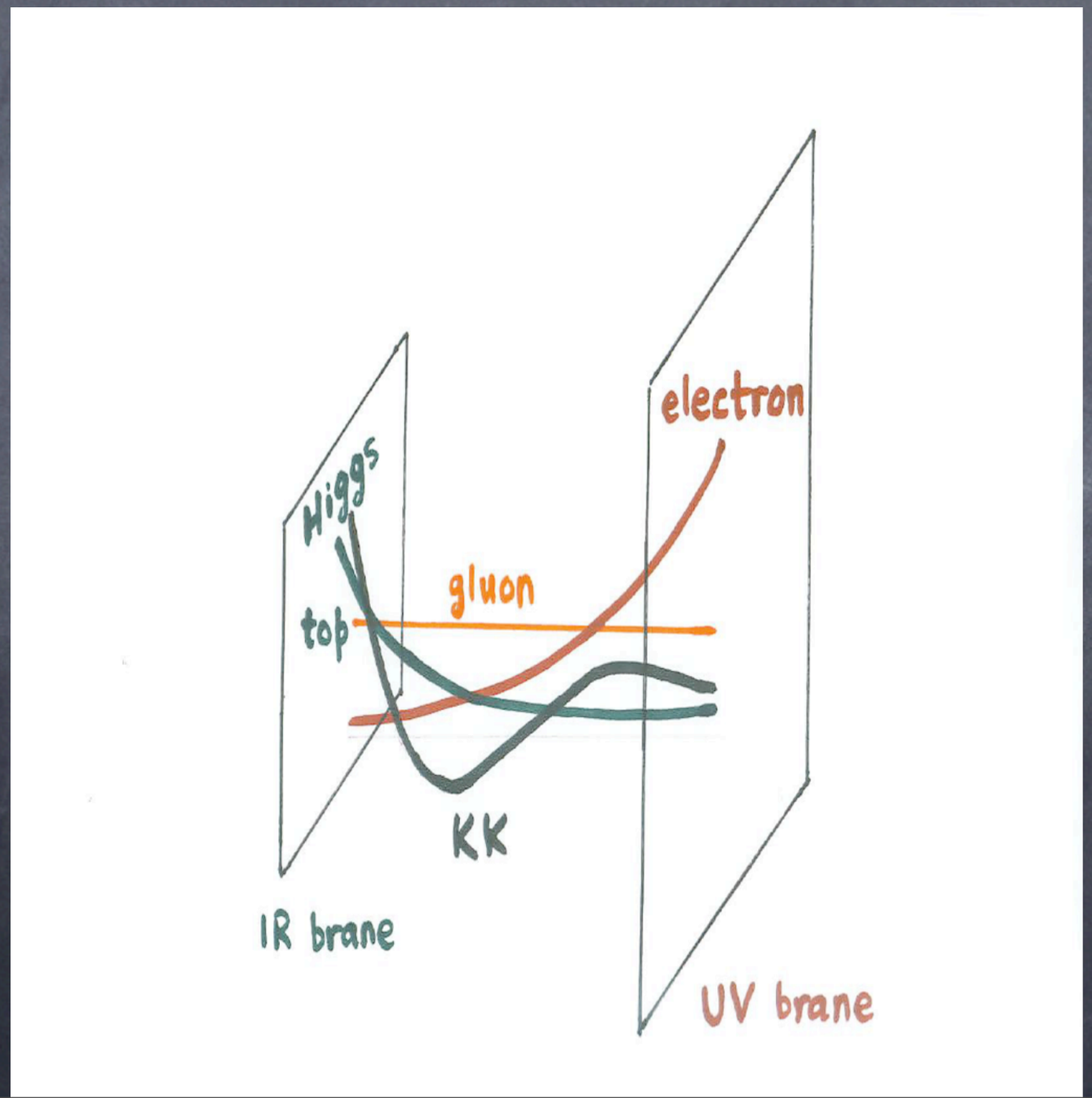
Gravity and Higgs

(Randall, Sundrum)



SM in bulk

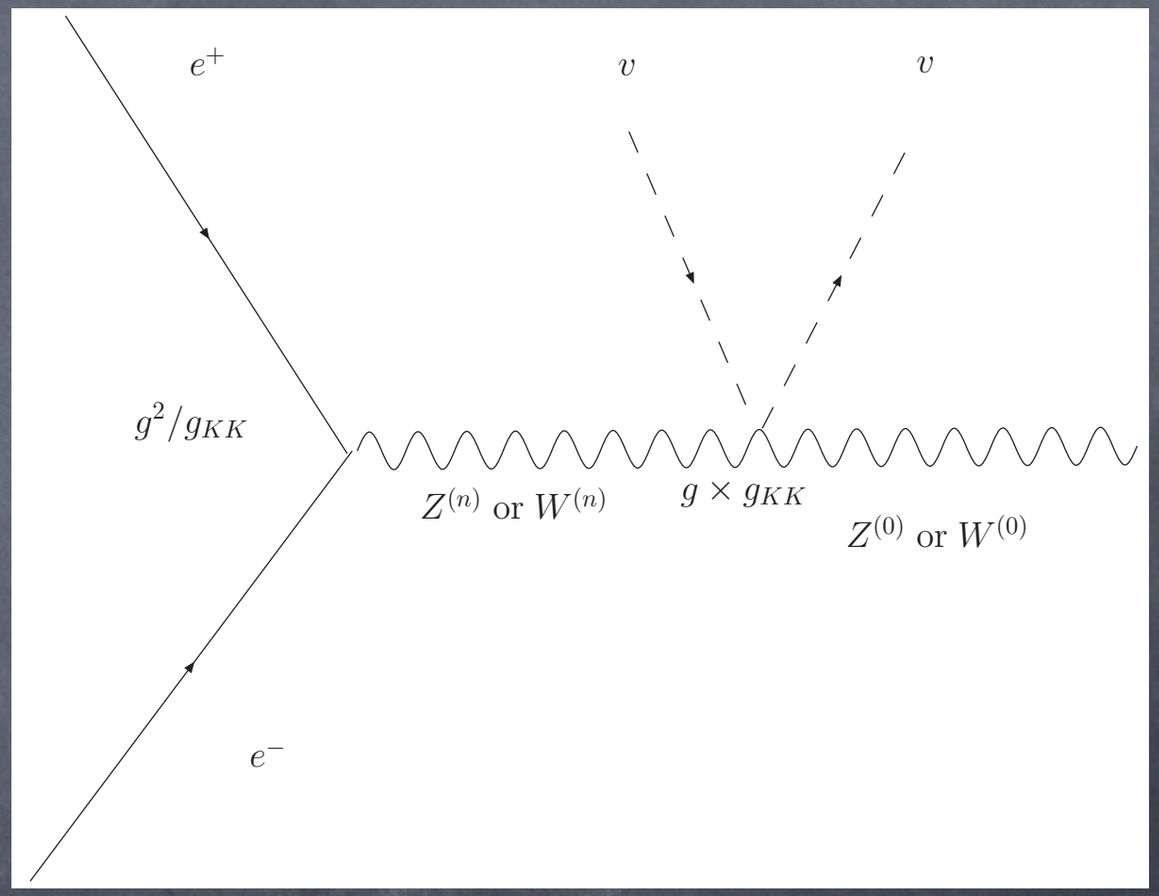
(Davoudiasl, Hewett, Rizzo; Pomarol; Grossman, Neubert; Chang, Hisano, Nakano, Okada,Yamaguchi; Gherghetta, Pomarol)



Couplings from overlap of profiles

- Flavor hierarchy (fermion-Higgs)
- Couplings to KK large (small) for top (electron)

Precision tests: S parameter



- Equivalent to shift in coupling:

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

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

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

- Non-universality in coupling to gauge KK $\propto$ 4D Yukawa (analog of GIM)
- O(8) TeV from ϵ_K for Higgs on TeV brane... (See talk by G. Perez)

...but

- "O(1) room" from size of 5D gauge and Yukawa coupling, profile for Higgs... ⇨ a few TeV scale allowed
- New ideas to parametrically relax constraints: relate profiles to 5D Yukawas... (See talks by G. Perez and C. Csaki)

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

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

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

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

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

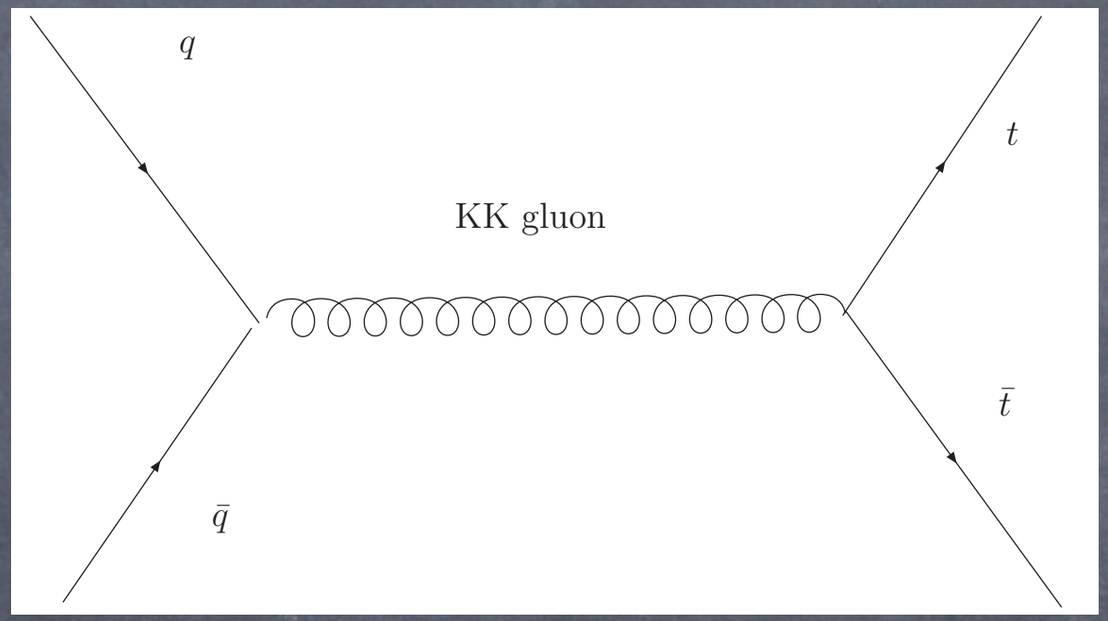
Model-independent approach:
Contino, Kramer, Son, Sundrum; Giudice, Grojean, Pomarol, Rattazzi (See talks by C. Grojean and A. Pomarol)

KK gluon

(KA, Belyaev, Krupovnickas, Perez, Virzi)

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

Production and Decay

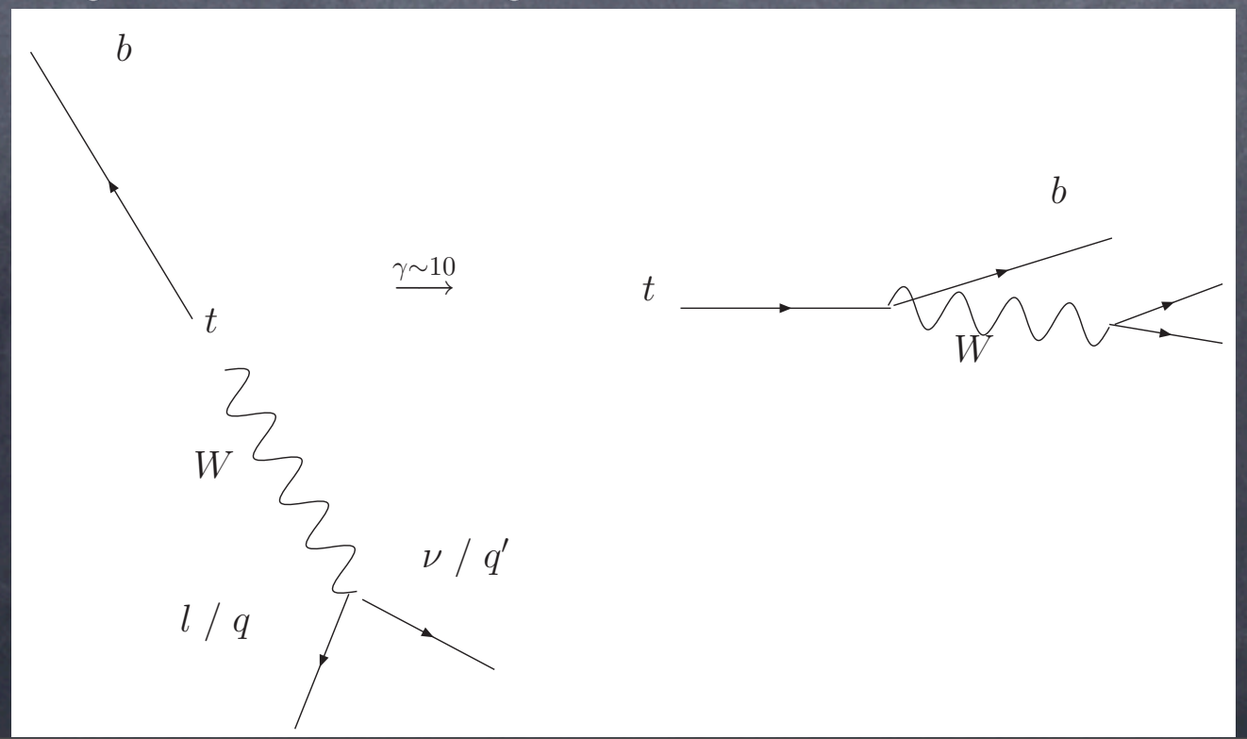


Problem: collimation of tops

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

vs.

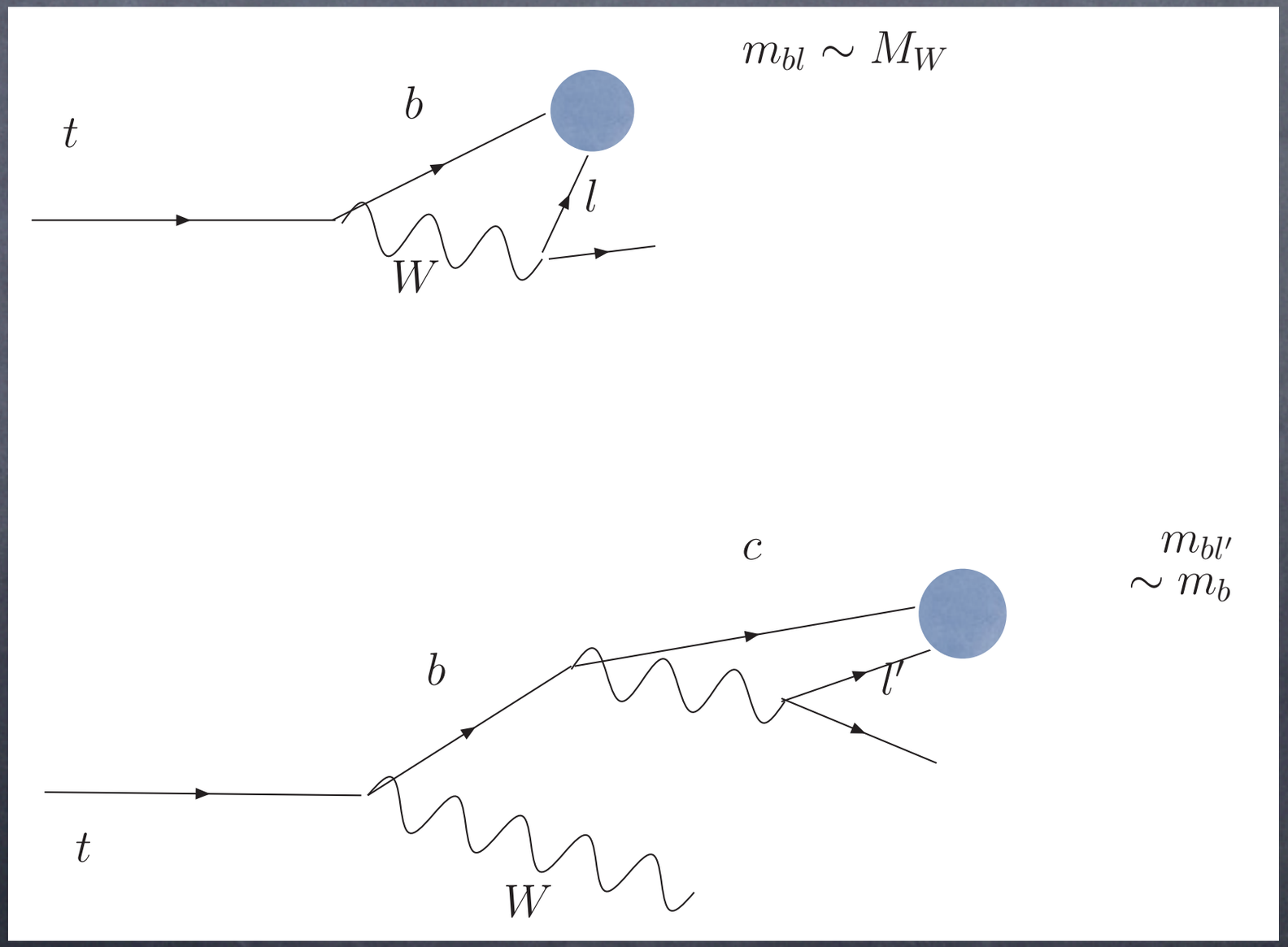
usual $\Delta R \gtrsim 0.4$ between lepton and b-jet and 2 jets from W



Solution: cut on lepton-b invariant mass

- Improved lepton and b-jet isolation cut:

$$m_{bl} > 40 \text{ GeV}$$

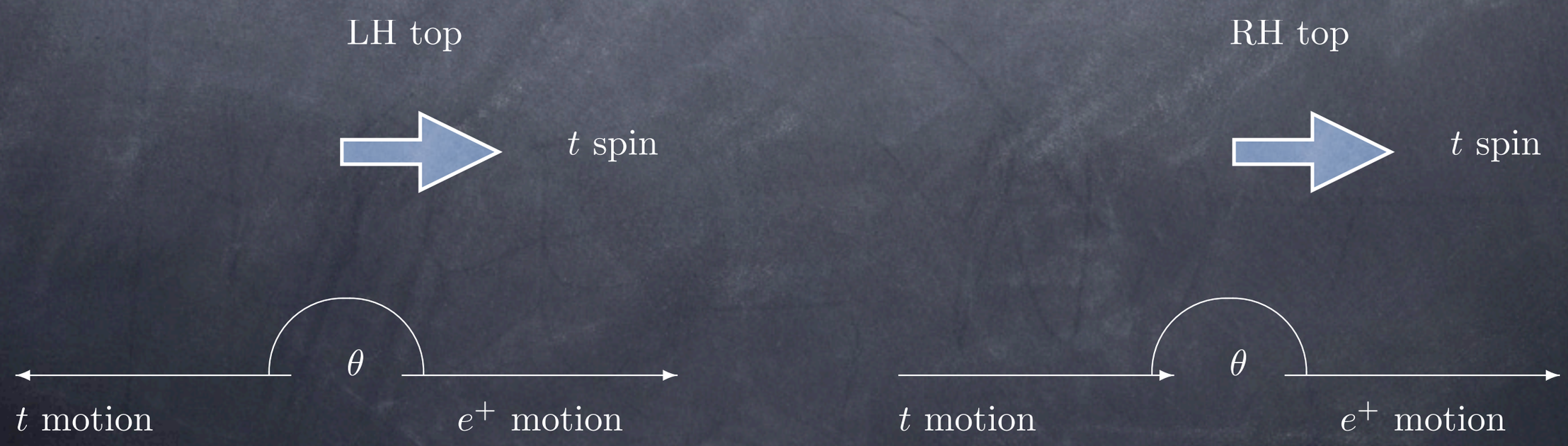


Polarization asymmetry: definition

- 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)

Discovery for 4 TeV with 100 / fb

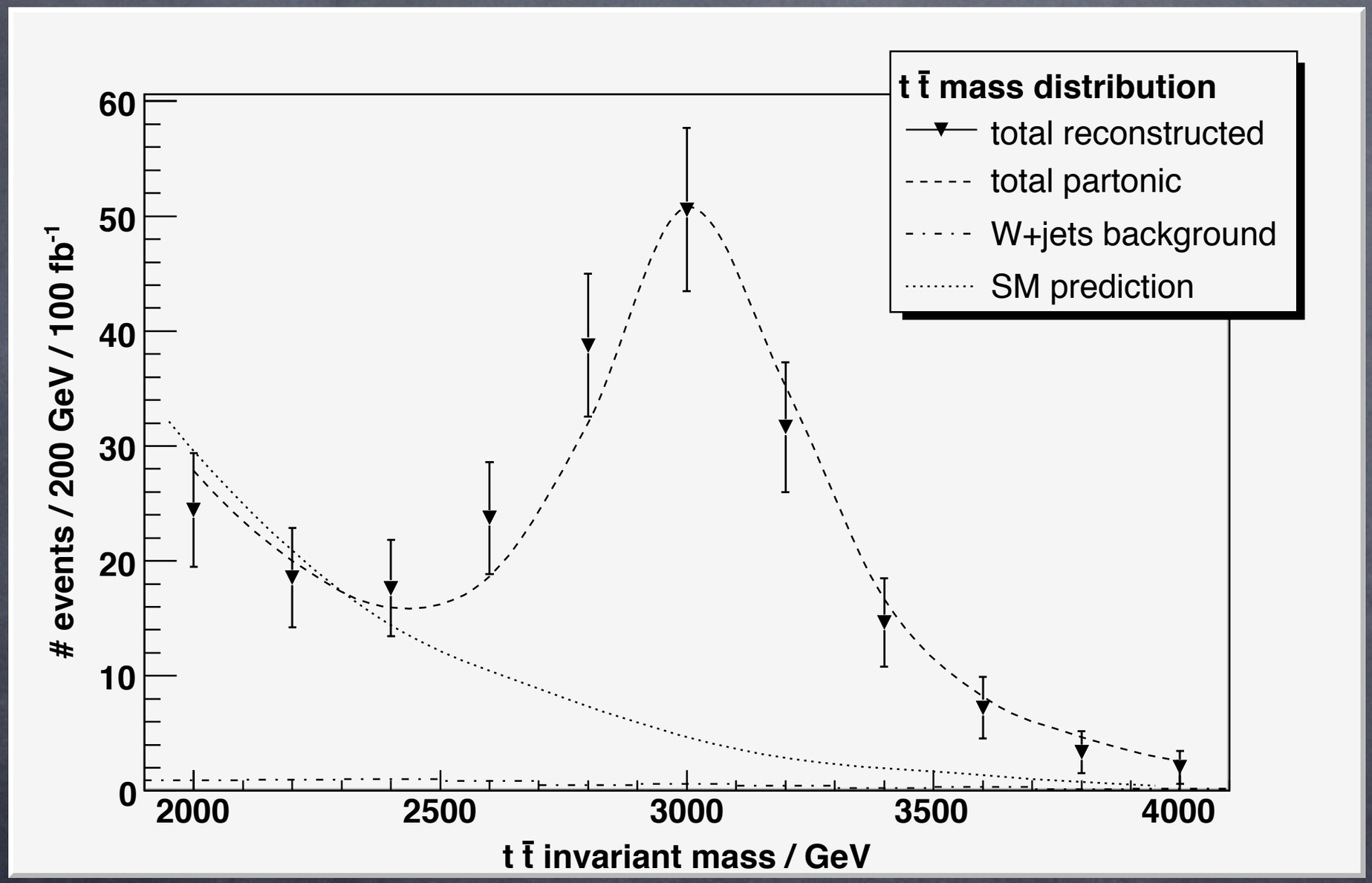
- "Bump" in differential cross-section (100 fb with 1% efficiency for 3 TeV)

correlated with

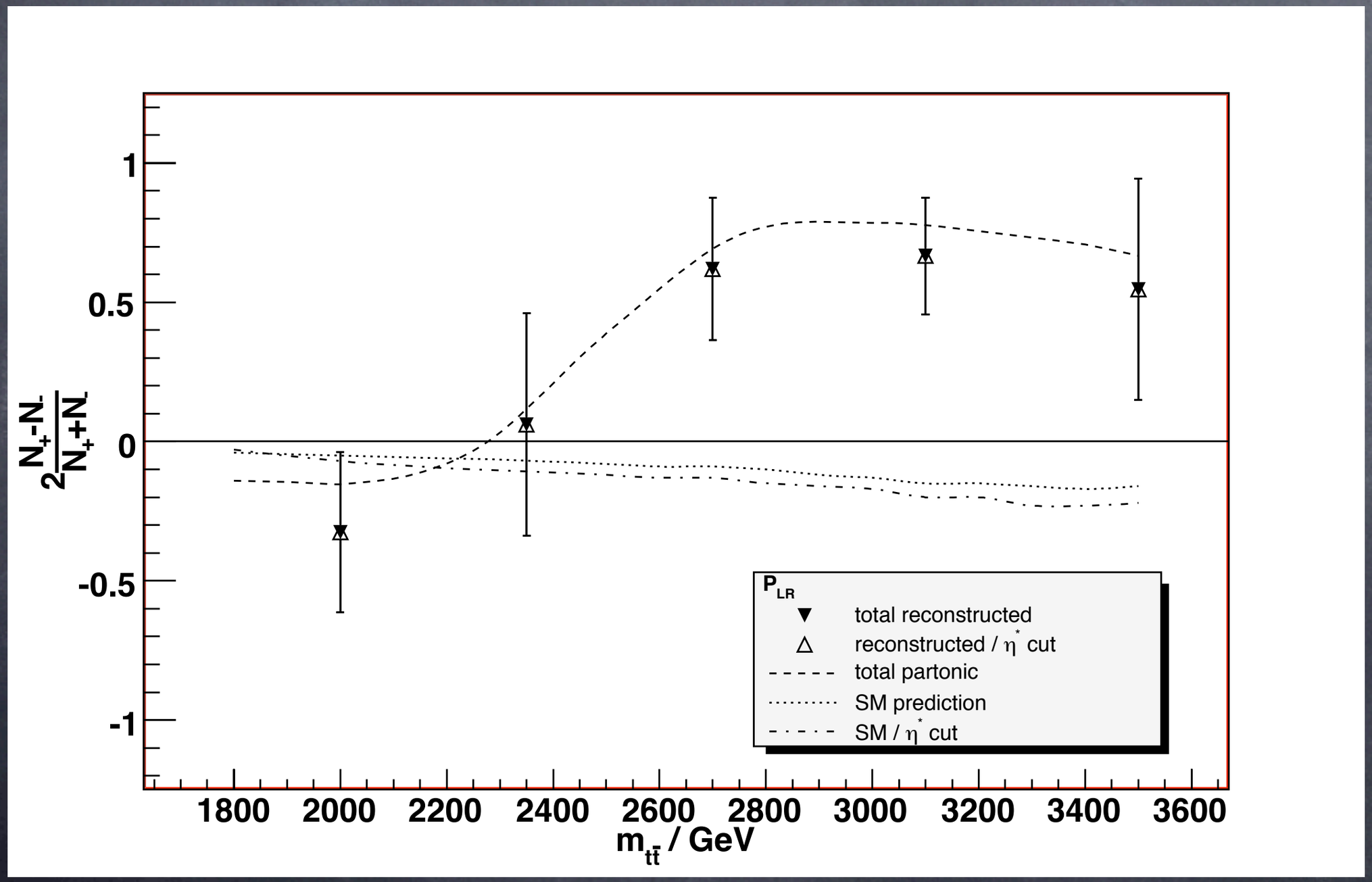
- Deviation in P_{LR} from SM

Full simulation in progress: Lee, Perez, Virzi (See also Conway, Dolen, Searle, Squires, Vazquez for hadronic top)

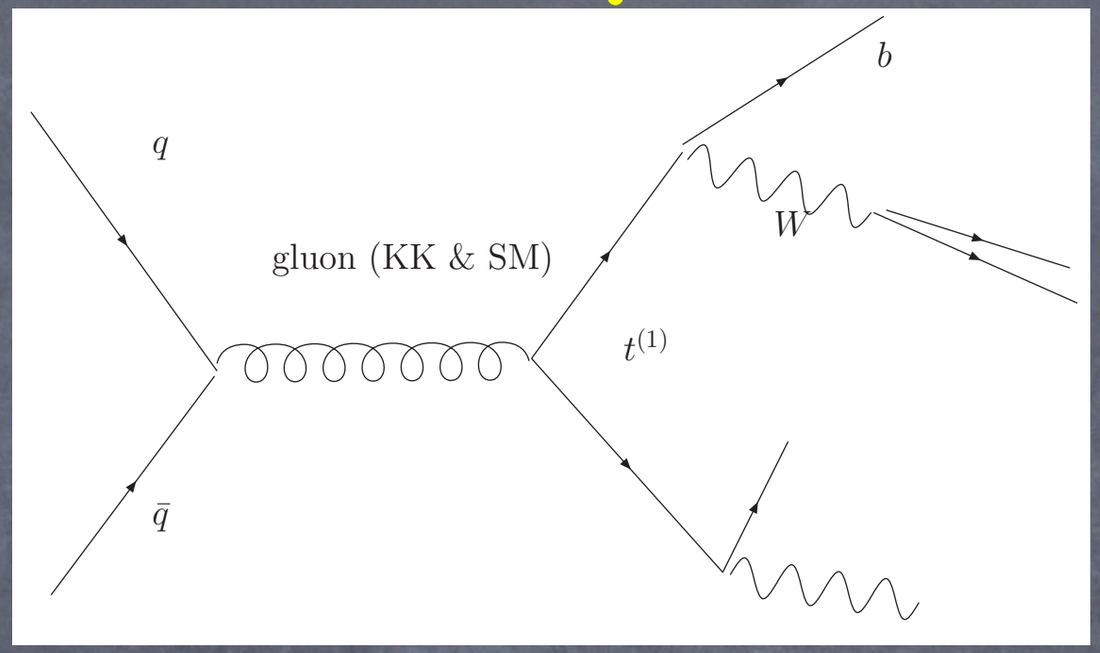
Differential cross-section



Polarization asymmetry



KK gluon decays to KK tops



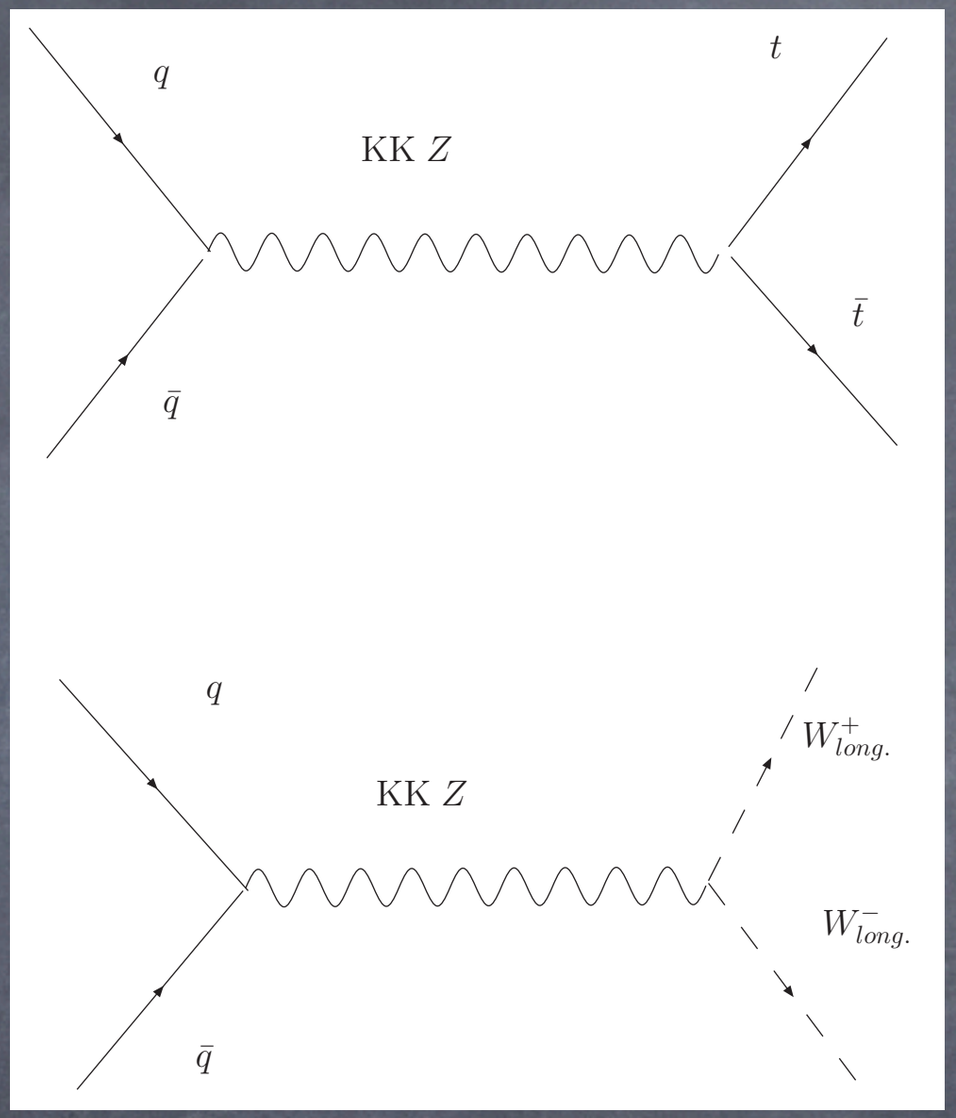
- KK tops (1 TeV) not boosted, decay into Wb (well-separated, but 2 jets from W still collimated)
  (Carena, Medina, Panes, Shah, Wagner)

KK Z

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

(See also Djouadi, Moreau, Singh)

Production and Decay



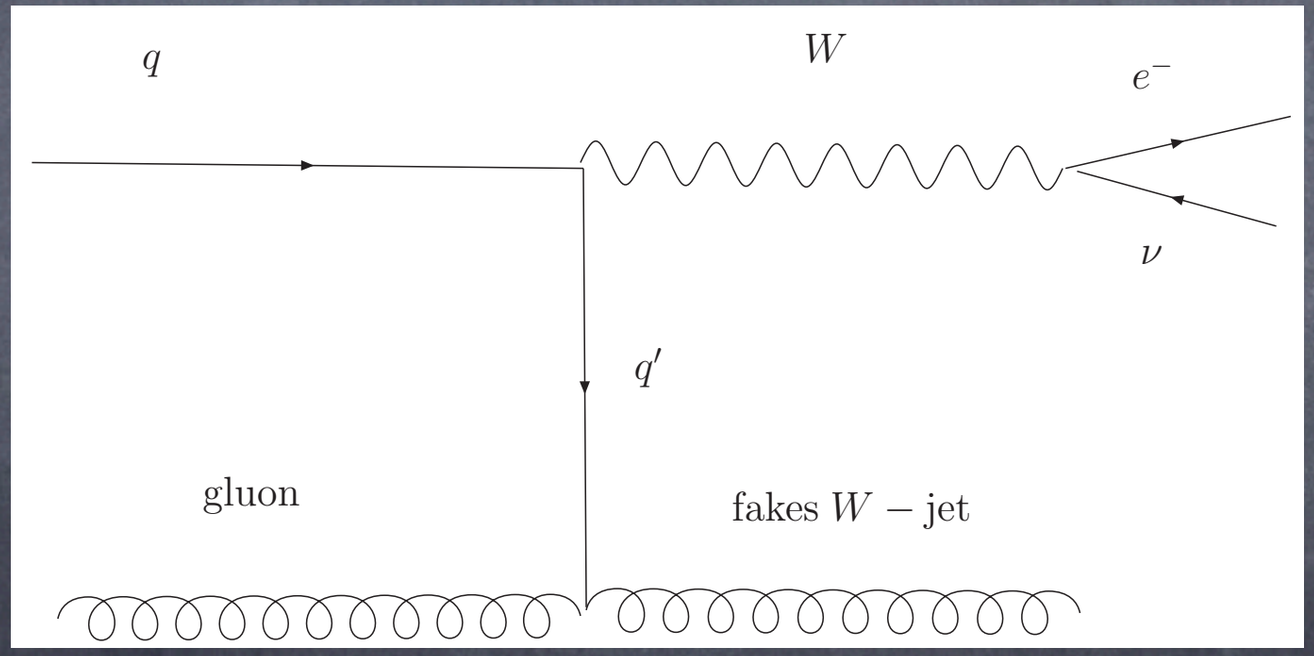
Decays to tops swamped
by KK gluon

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

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

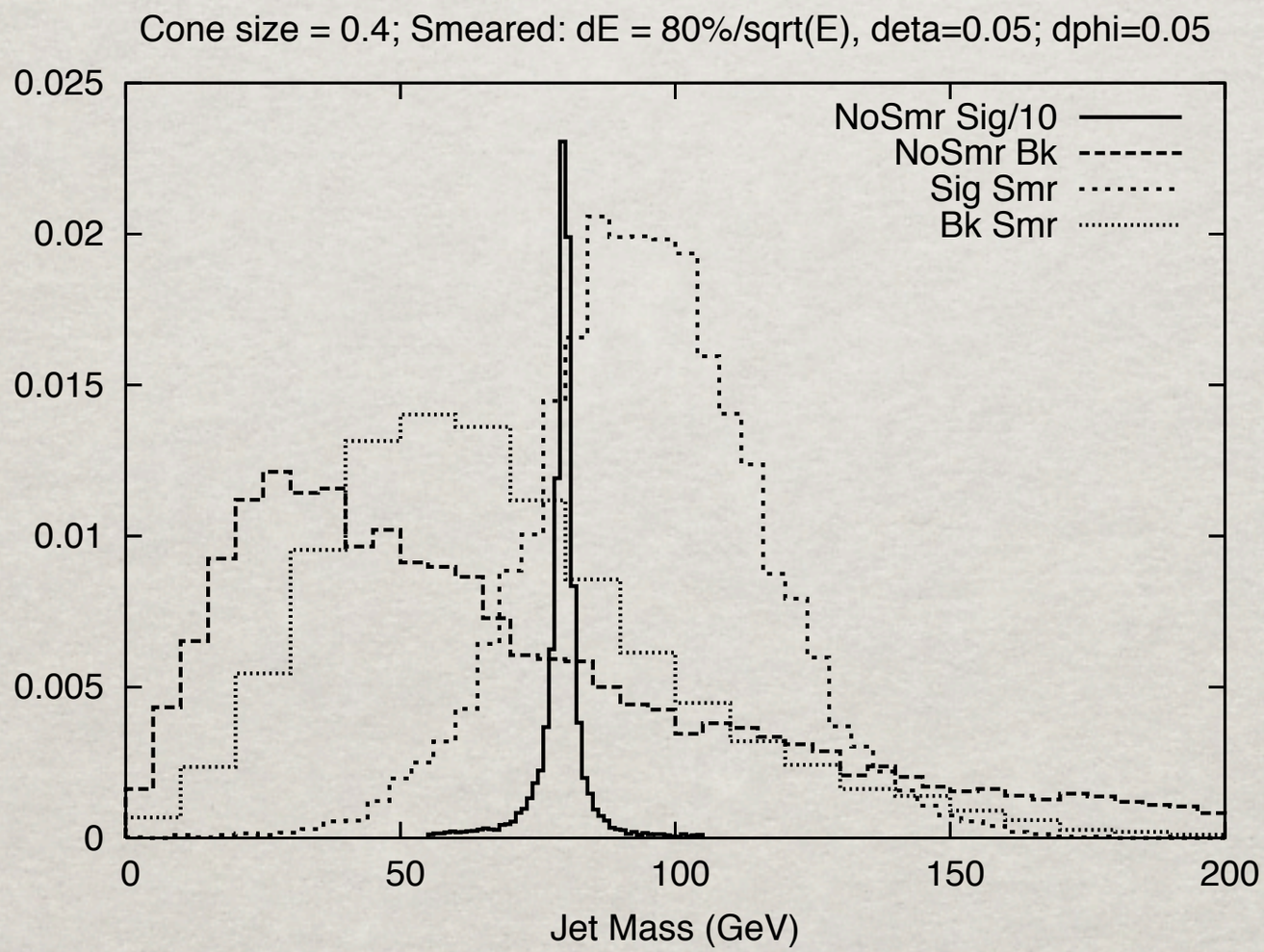
KK $Z \to W^+W^- \to l^+\nu jj$: can reconstruct, but...

- W + jet SM background



Solution: jet mass cut

(See also Smith, Skiba; Holdom)



Results for KK Z

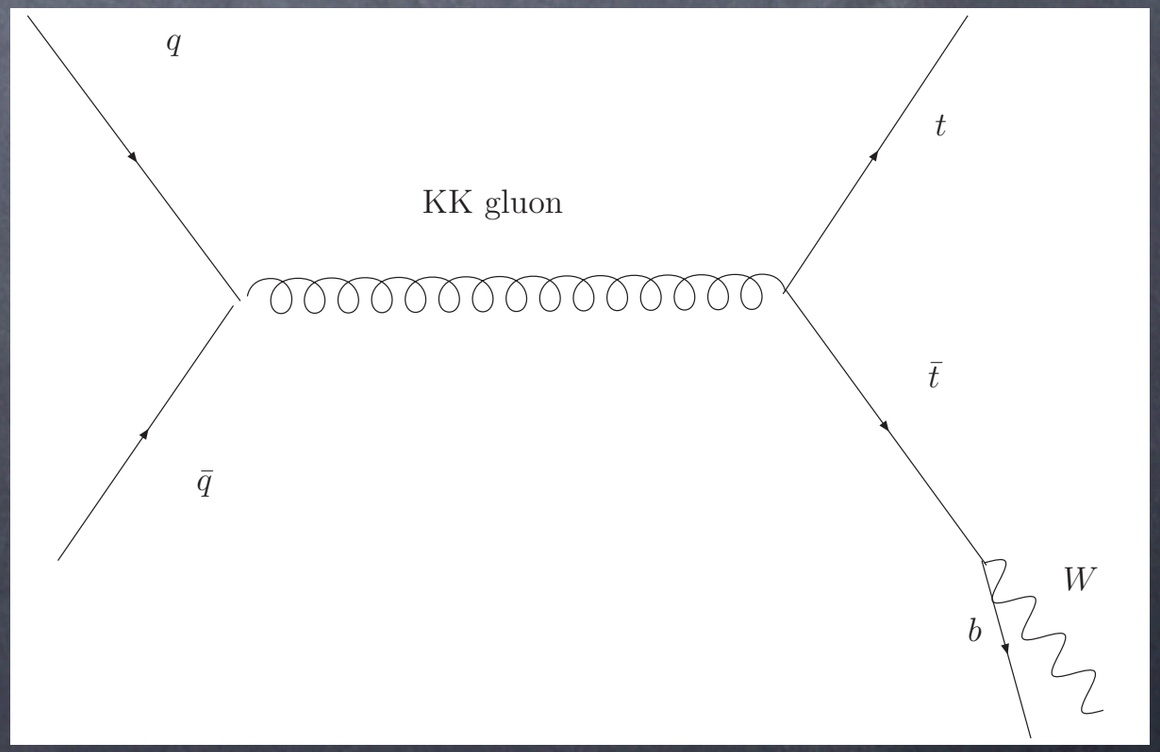
- Reach of 2 (3) TeV for 100/fb (1000/fb) from semileptonic WW

- Similar from $\mathrm{KK}\ Z \to Zh$

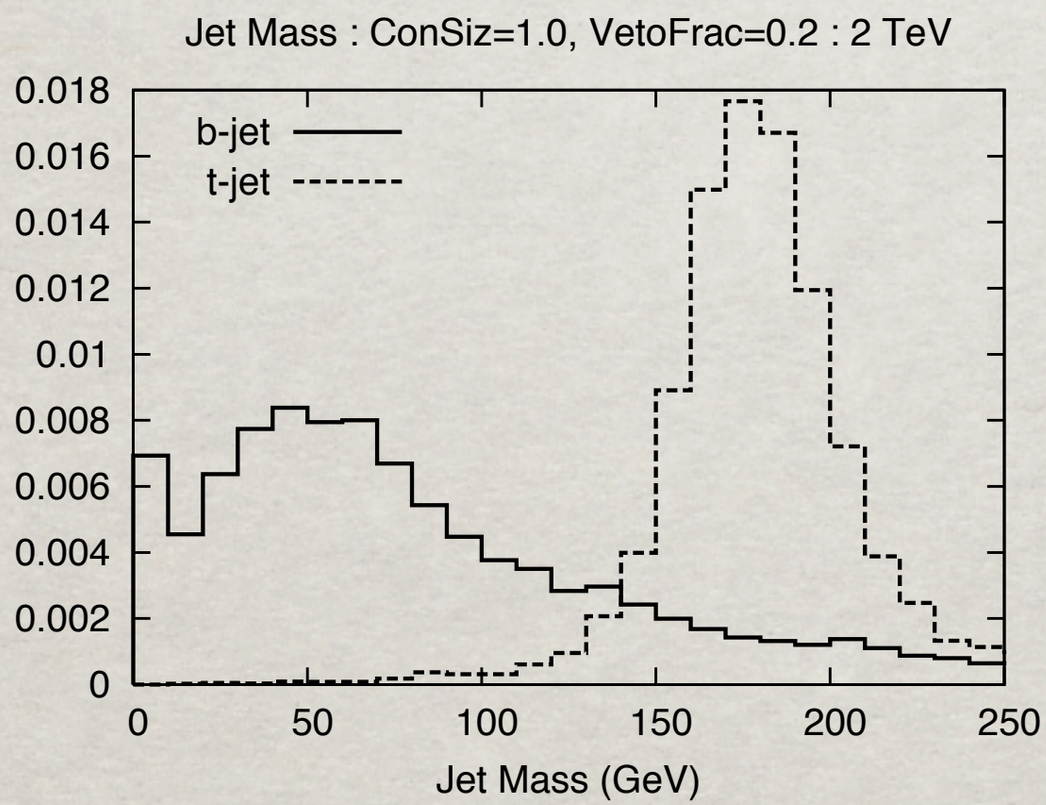
KK W

(KA, Gopalakrishna, Han, Huang, Soni)

- KK $W \to WZ \to l^+ l^- l' \bar{\nu}'$ (clean) can be reconstructed
- Decays to top + bottom: KK gluon background



... REDUCIBLE BY JET MASS CUT

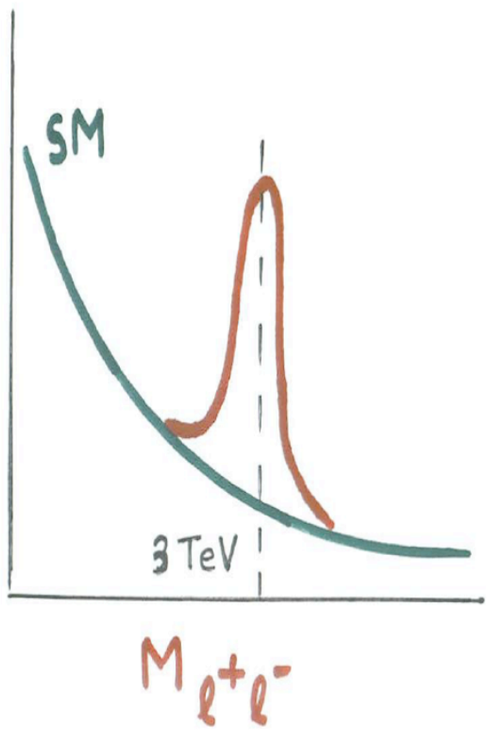


Other Signals

- 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: $t \to cZ$ with BR of 10^{-5} (see G. Perez's talk)

"ORIGINAL" RS1: BRANEWORLD

Golden decays:
KK graviton $\rightarrow l^+l^-,\ \gamma\gamma$

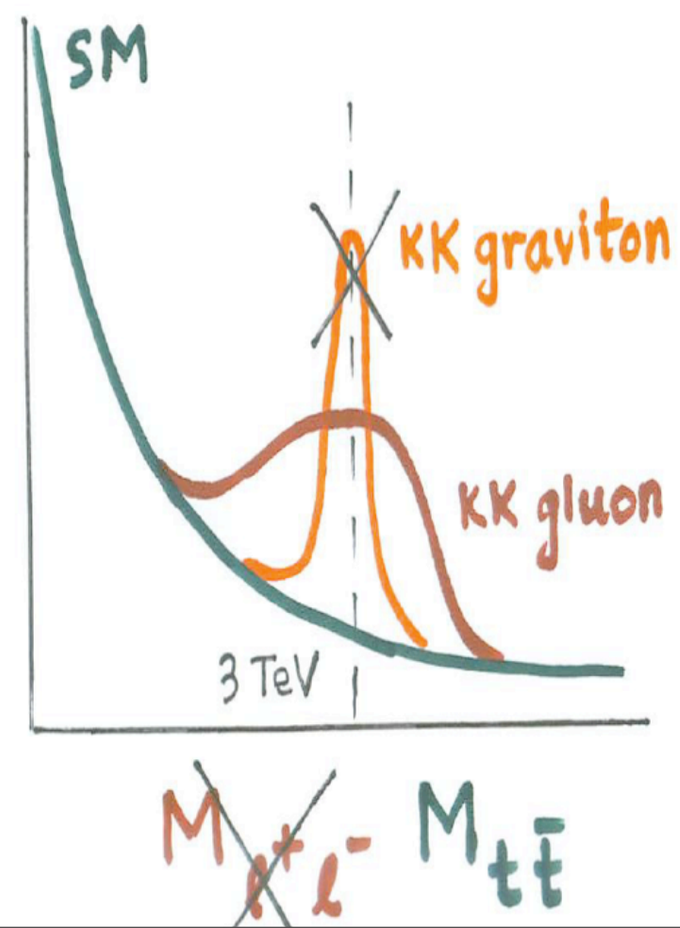


CF. SM (– HIGGS) IN THE BULK

KK graviton $\rightarrow$ l^+l^-, $\cancel{\gamma\gamma}$

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

+ KK gluon, W, Z, γ



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

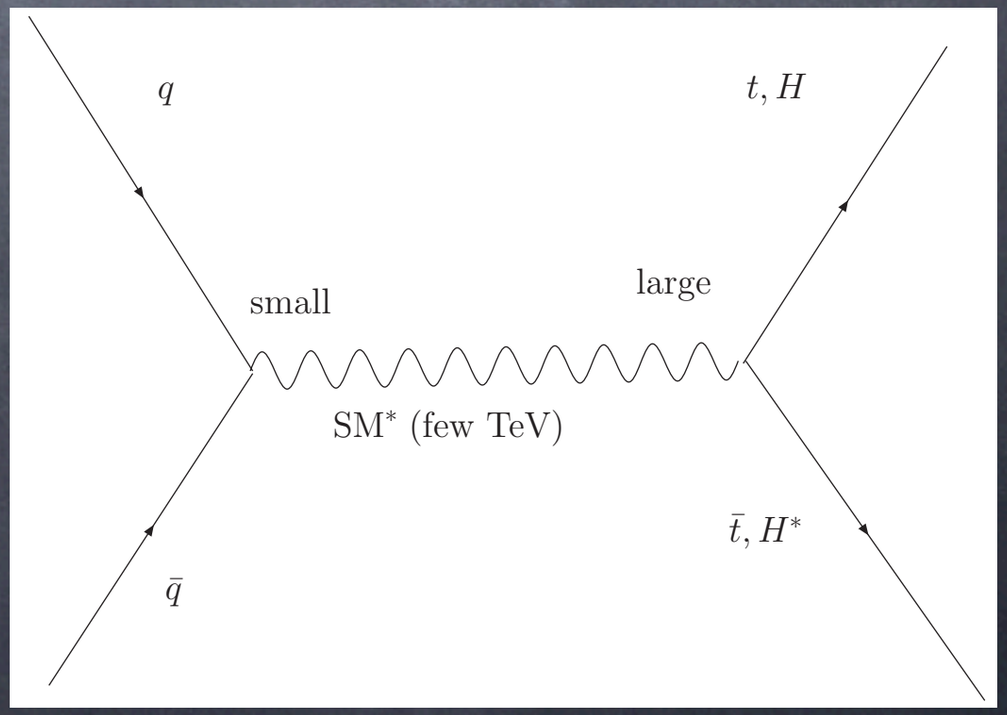
Top quark and Higgs (*longitudinal* W/Z) "special":
mechanism of electroweak symmetry breaking

couple strongly to *new* particles

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

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

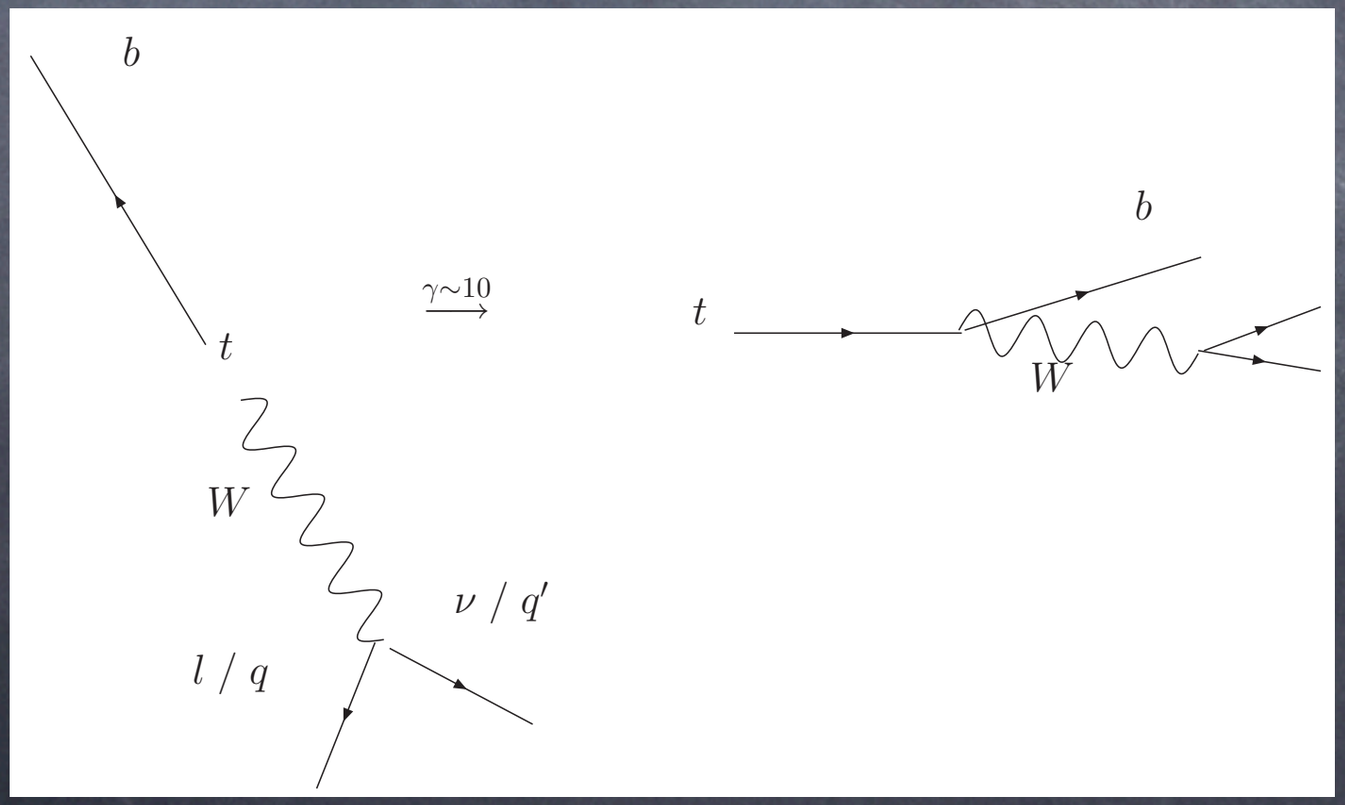
(highly boosted!)



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

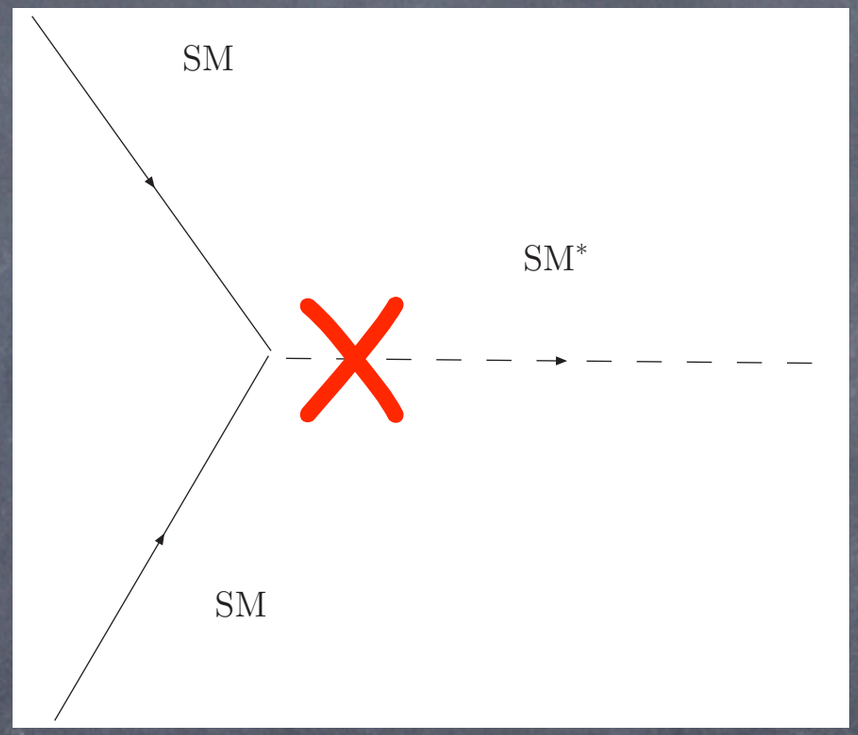
(More) Studies needed...

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



KK PARITY IN WARPED EXTRA DIMENSION

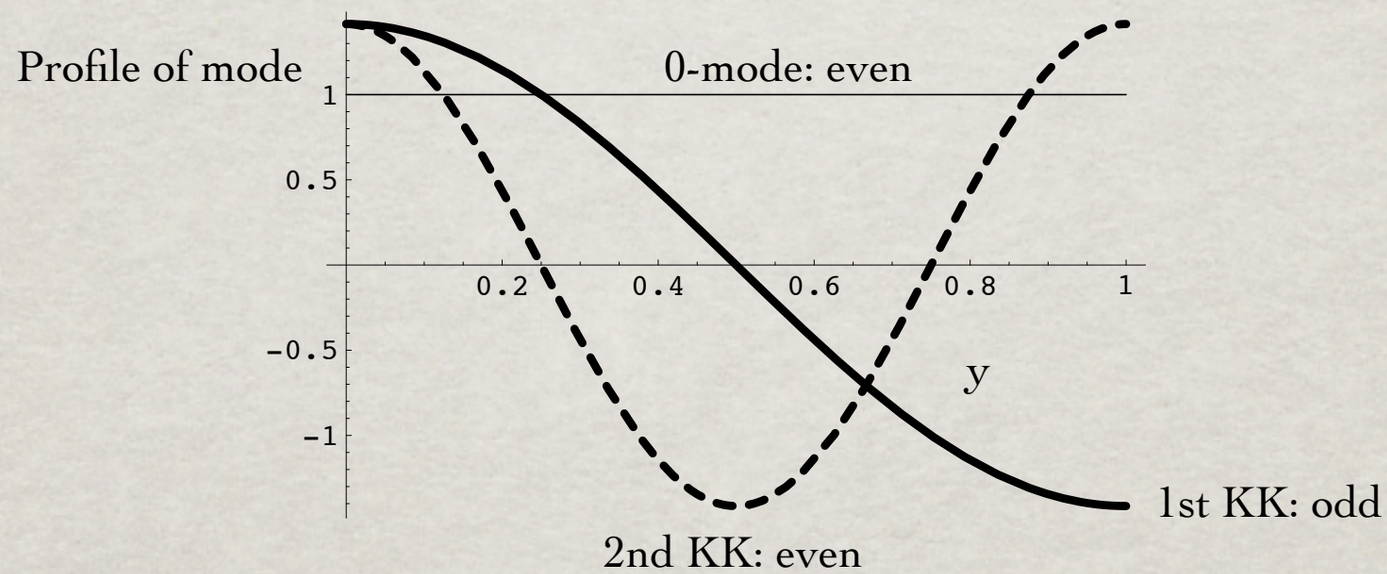
KK parity in flat universal extra dimensions (UED), T-parity in Little Higgs



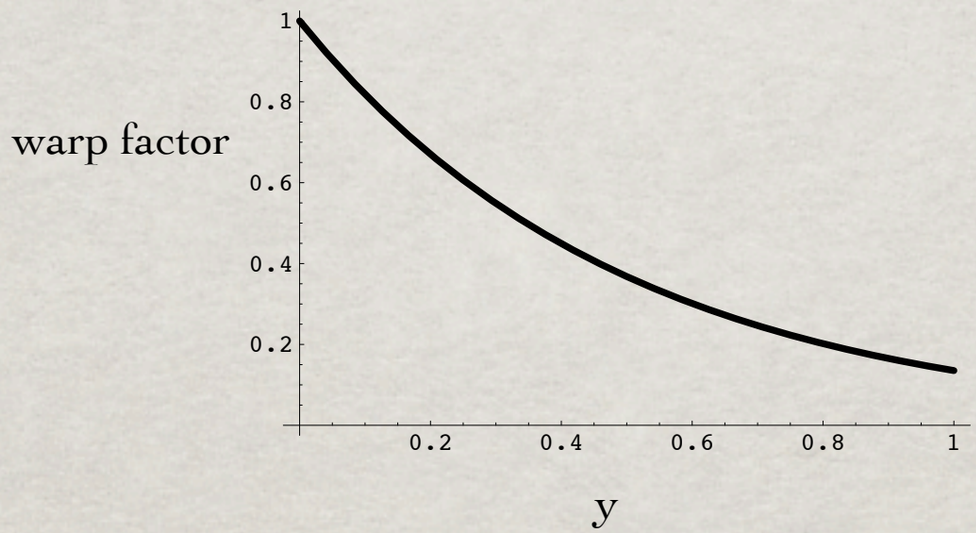
- valid only up to 10's TeV

KK parity in UED
(See talk by K. Kong)

- Reflection about midpoint



No KK parity in single AdS slice

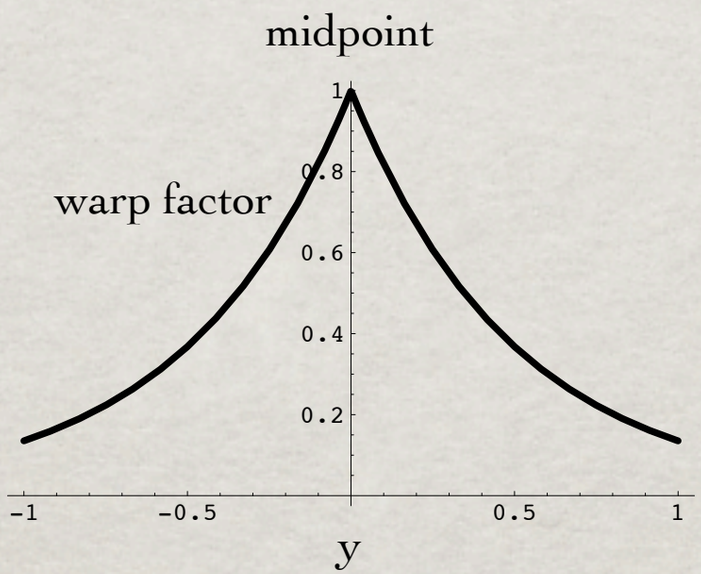


- Warp factor not symmetric about midpoint (cf. flat metric)

Join 2 AdS slices

(KA, Falkowski, Low, Servant)

(See also, Panico, Ponton, Santiago, Serone)



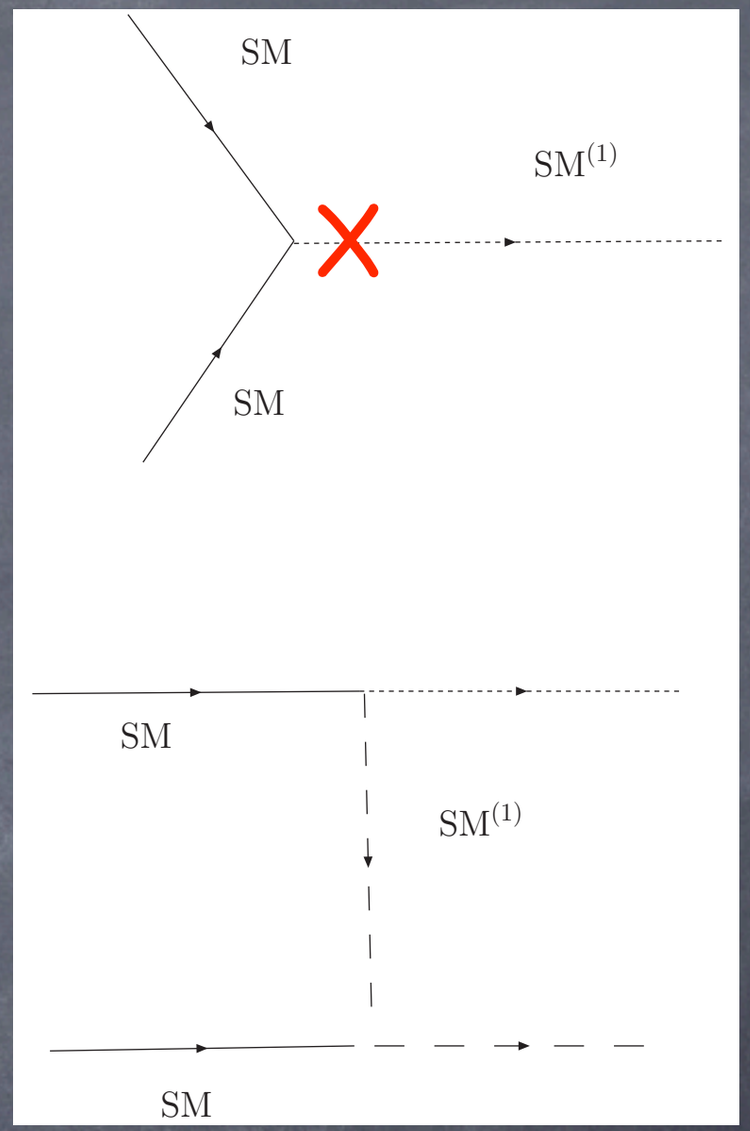
- KK parity interchanges 2 slices

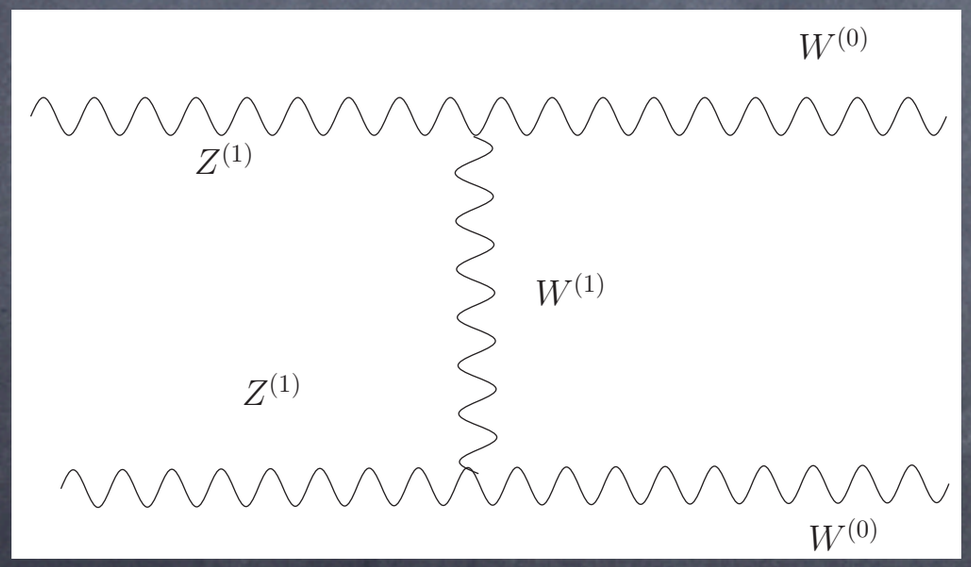
Motivation and Spectrum

- 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

Phenomenology

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

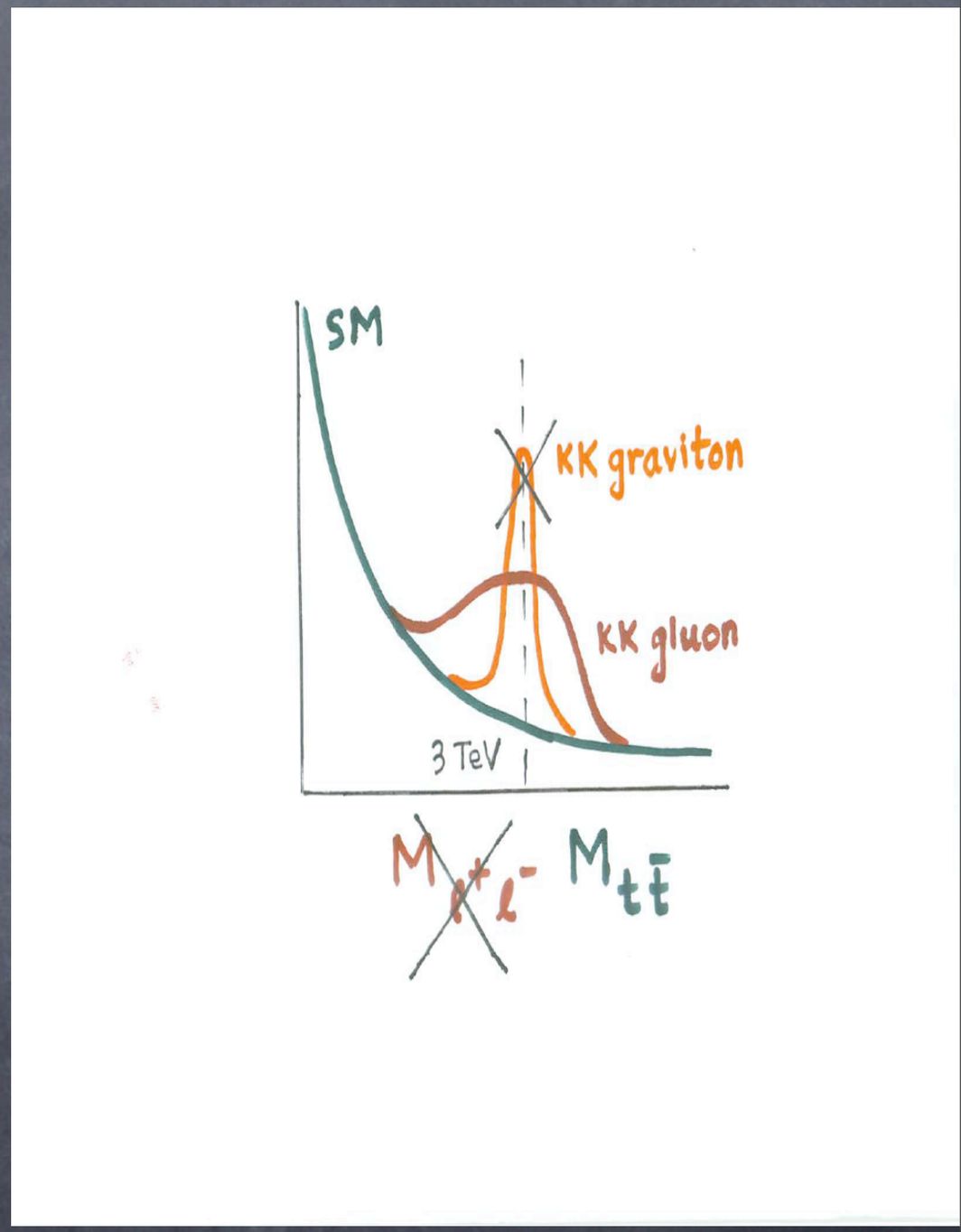




Conclusions

- 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: vev^2 < 0 to suppress S (KA, Csaki, Grojean, Reece: see C. Grojean's talk) (See also McGuirk, Shiu, Zurek)

Gauge-Higgs unification

(see talks by C. Grojean and A. 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 $\Rightarrow$ $m_H^2 < 0$

5D Higgs**less** models (breaking by boundary condition)

(See talks by C. Csaki and C. Grojean)

- Flat profiles for fermions ⇨ cancellation in S
- < 1 TeV KK's unitarize WW scattering