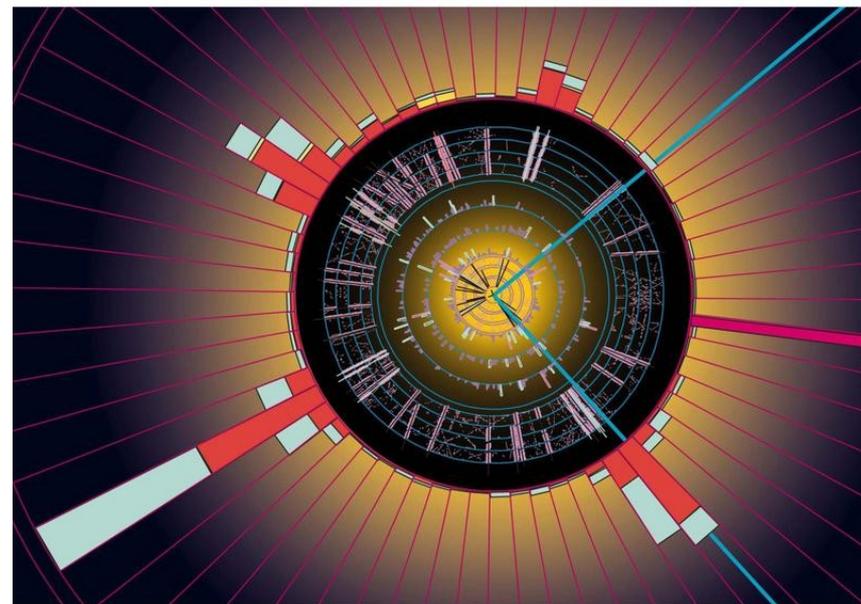
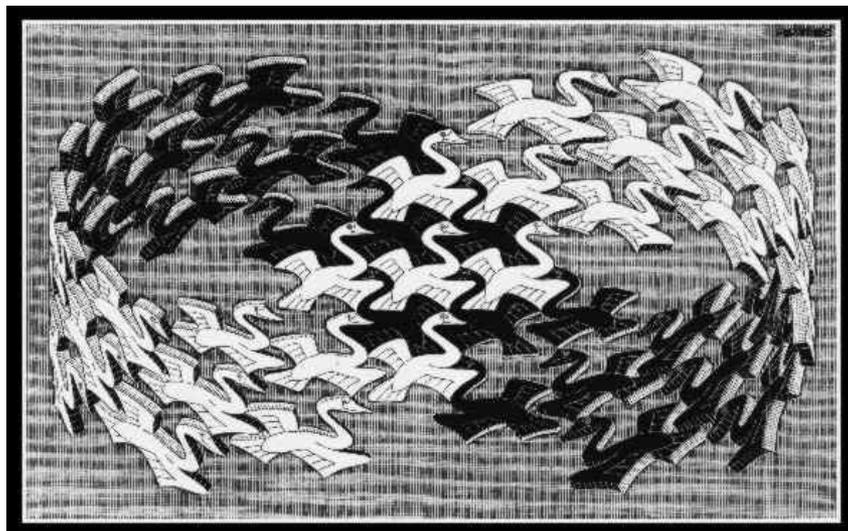


Extra dimensions and high p_T tops at the LHC

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Fermilab #97-1889D

Based on:

Lillie, Randall, Wang Lillie hep-ph/0505074
In progress

Outline:

- Introduction and motivation
- RS Model building
- Gluon KK states
- The high p_T top channel
- Other KK states
- Conclusions

The Randall-Sundrum Model

Randall and Sundrum hep-ph/9905221

Slice of AdS₅, with metric

$$ds^2 = e^{-2\sigma} \eta_{\mu\nu} dx^\mu dx^\nu - dy^2$$

\uparrow warp factor \uparrow coordinate of extra dimension
 coordinate of extra dimension

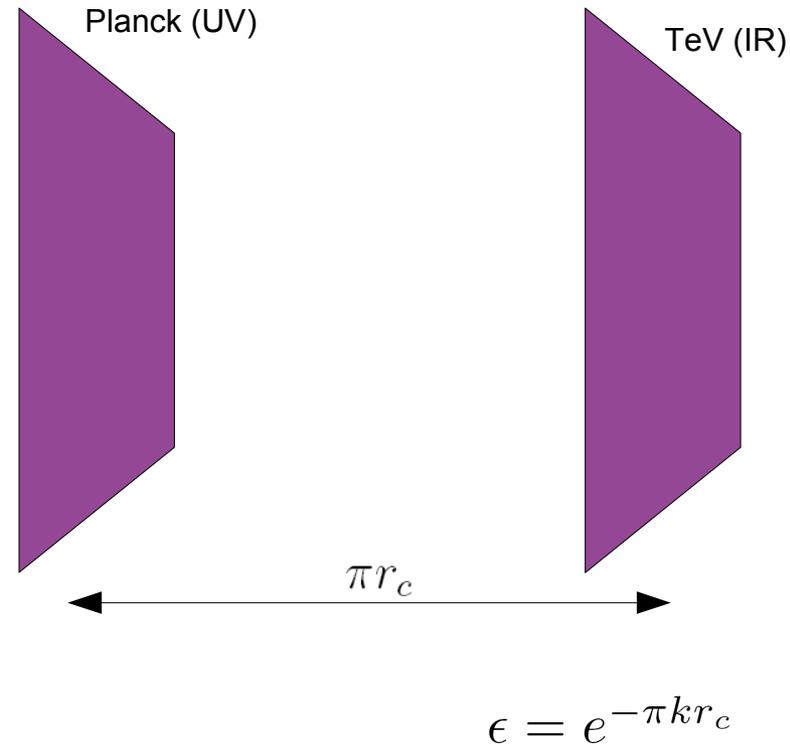
$\sigma = k|y|$ AdS curvature, $O(M_{Pl})$

Masses get scaled by $M \rightarrow M e^{-\pi k r_c}$

Solves the hierarchy problem for $kr_c \sim 11$

Can also:

- explain fermion mass hierarchy
- unify gauge couplings
- provide a dark matter candidate



Conformal coordinates

$$ds^2 = \left(\frac{R}{z}\right)^2 (dx^2 - dz^2)$$

(Parameters are natural)

Goldberger and Wise hep-ph/9907447

Where to put the SM?

Original RS model: SM on TeV brane

Problems with 4-fermion operators:

$$\frac{\lambda}{\Lambda_{\text{TeV}}^2} \psi \bar{\psi} \psi \bar{\psi}$$

Fermions on UV brane:

$$\frac{\lambda}{\Lambda_{\text{Pl}}^2} \psi \bar{\psi} \psi \bar{\psi}$$

But EWSB on TeV brane, so fermions must be **bulk** fields

(Gauge fields must also then live in bulk)

Can achieve gauge coupling unification

Agashe, Delgado, and Sundrum hep-ph/0212028

Agashe, and Servant hep-ph/0411254

Carena, Delgado, Ponton, Tait, Wagner hep-ph/0305188

Flavor problem

This is a **good** thing

5D fermions are **achiral**,
so we can write 5D mass

$$\Psi = \begin{pmatrix} \chi \\ \xi \end{pmatrix}$$

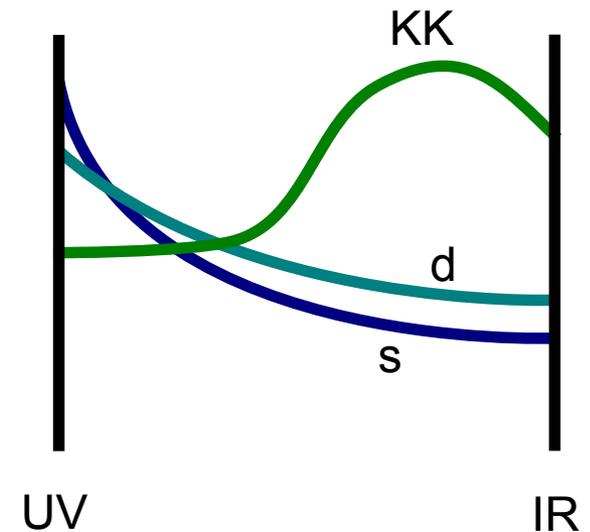
$$c_\Psi k \bar{\Psi} \Psi$$

Equations of motion have a zero mode

$$\psi_\Psi^{(0)}(z) \sim z^{-(c_\Psi - 1/2)}$$

Suppress FCNC for first two generations

Grossman and Neubert hep-ph/9912408
Gherghetta, Pomarol hep-ph/0003129



Flavor problem - cont

There's more

Coupling to EWSB (Higgs) is

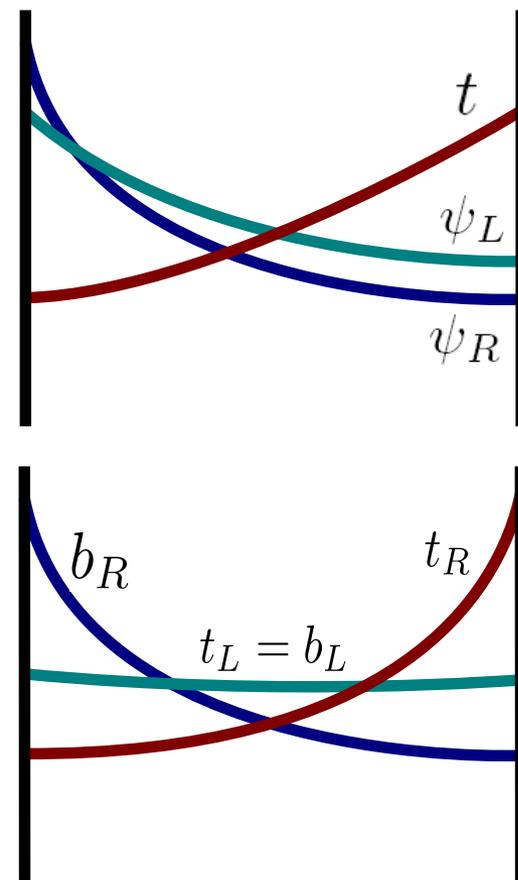
$$\lambda_{\text{eff}} \sim \psi_L(R')\psi_R(R')\lambda_L$$

Give an explanation for fermion mass hierarchy in terms of order-1 parameters!

To get the top mass right \rightarrow IR localized

$Z \rightarrow b\bar{b}$ constrains the doublet to be as far from IR as possible

Special role for the right-handed top

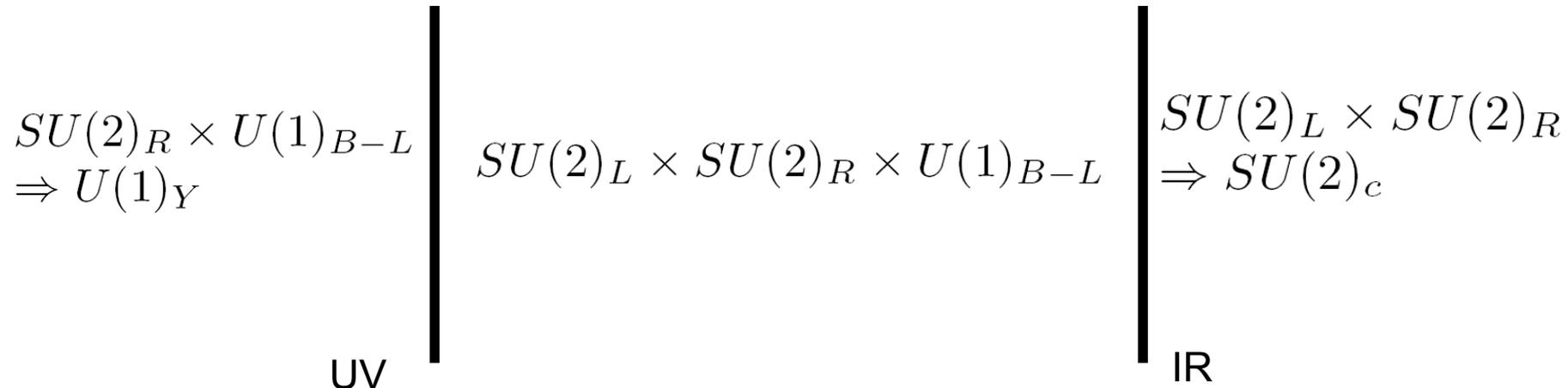


SU(2) Custodial

With just SM gauge group, large corrections to $\rho = \frac{M_W^2}{M_Z^2 \cos^2 \theta}$

$SU(2)_c$ only present on IR brane

Solution: Expand gauge group

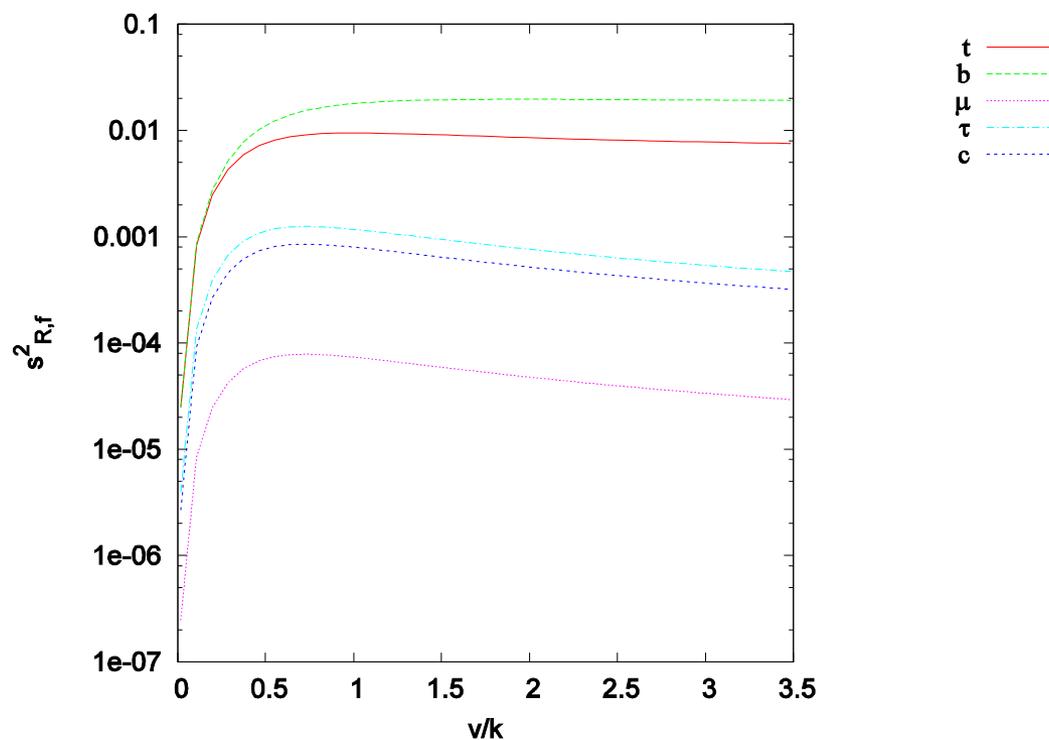


Agashe, Delgado, May, Sundrum hep-ph/0308036
 also Carena, Delgado, Ponton, Tait, Wagner hep-ph/0410344

SU(2) Custodial - cont.

Boundary conditions on UV brane force W_R to vanish there

Again, special role for the right-handed top
(possibly visible to ILC at top threshold)



Bye, bye Higgs

Effect of v is to suppress the wavefunction at the IR brane

Two limits $v/k \ll 1$

“Higgsed” case

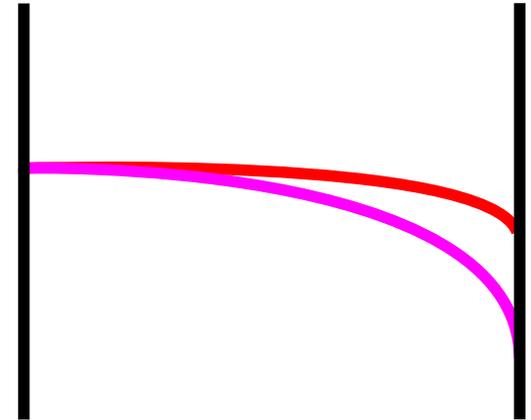
hep-ph/0207056

$v/k \gg 1$

“Higgsless” case

$M_W \xrightarrow{v \rightarrow \infty} \text{finite}$

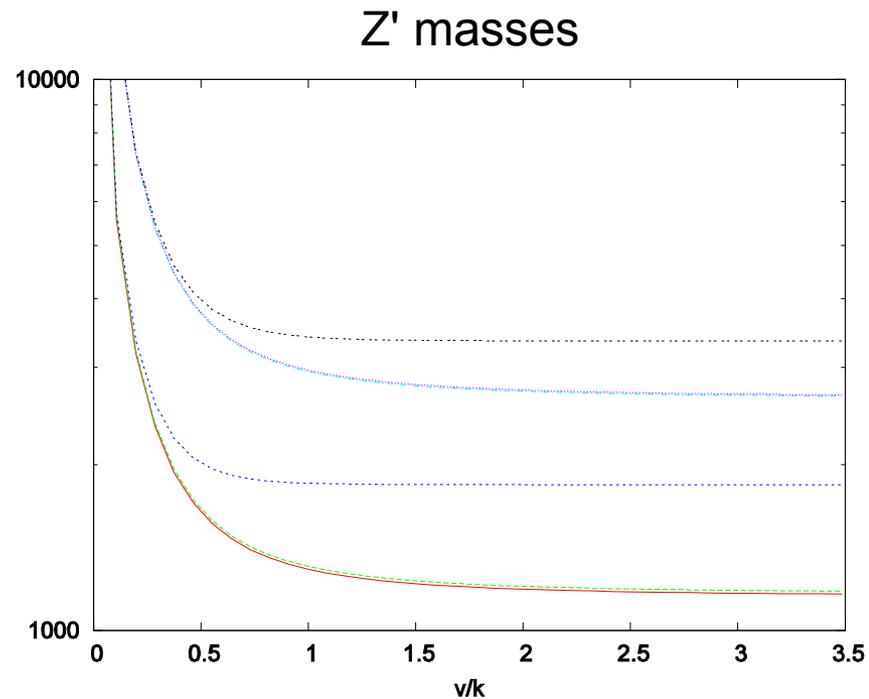
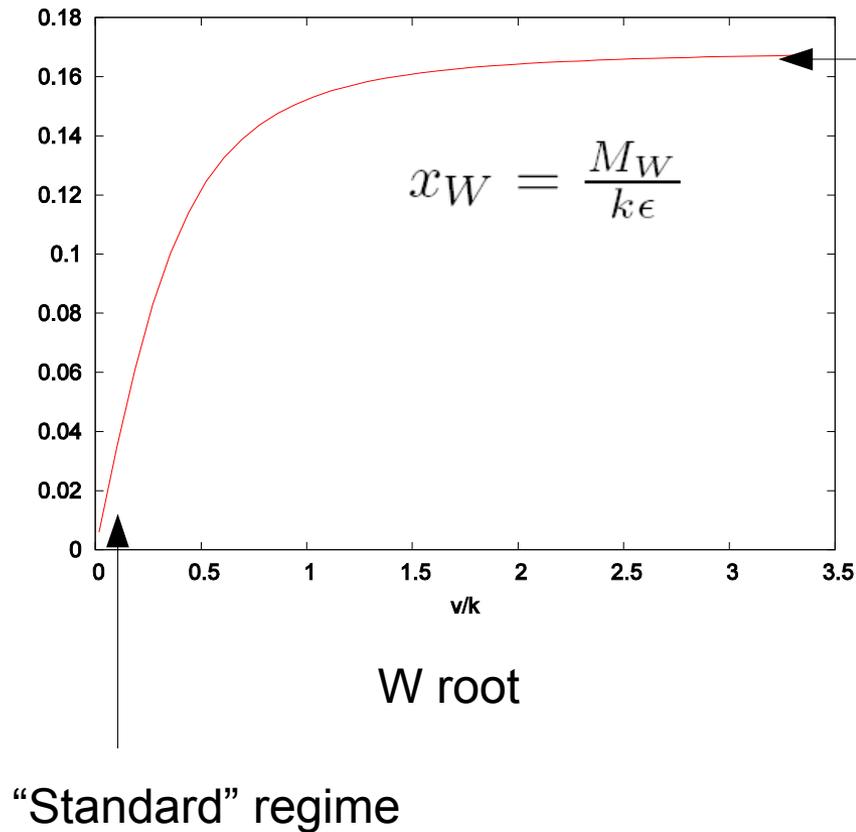
Higgs decouples in this limit



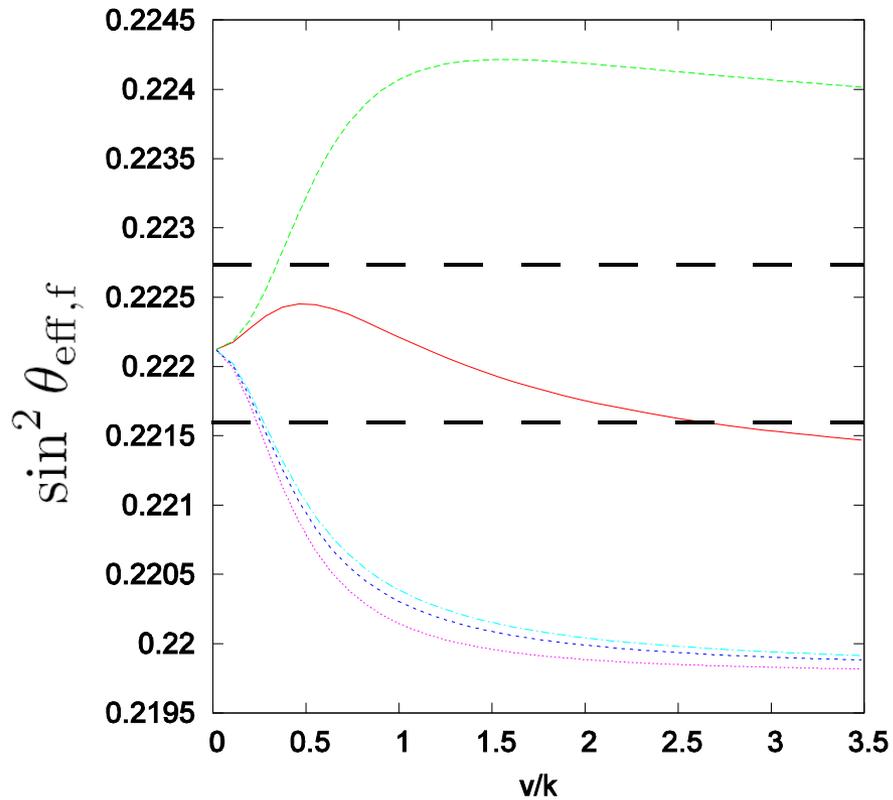
↑
Expect corrections from wavefunction distortion

Csaki, Grojean, Murayama, Pilo, and Terning hep-ph/0305237
Csaki, Grojean, Pilo, and Terning hep-ph/0308038

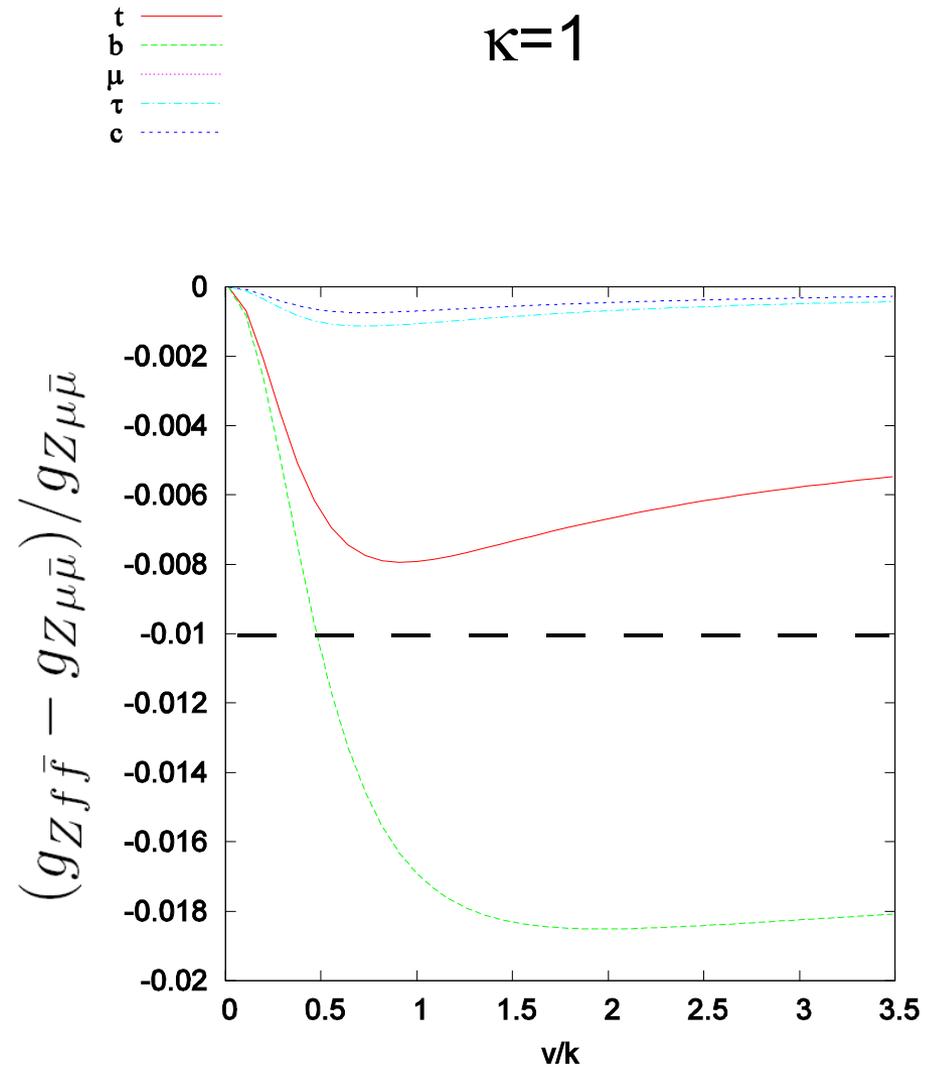
Gauge spectrum



Electroweak constraints



- Prec. EW requires $v/k \leq 1/2$
- $Z \rightarrow b\bar{b}$ requires $v/k \leq 1/4$



A note on the spectrum

In the simplest model: KK electroweak and KK gluon resonances are degenerate

But: we can add terms to the action

$$S_{\text{brane}} = \int d^5x \sqrt{G} \frac{\delta_i}{2kg_{5i}} (F^i)^2 \delta(z - z_{\text{brane}})$$

Shift the lightest modes \rightarrow order 1 shifts between EW and gluon KKs

Precision EW bounds are a guide for the scale,
but don't directly apply to gluon modes

Carena, Tait, Wagner hep-ph/0207056

Formalism – gluon resonances

Start by looking at a single resonance, mass m :

Parameterize the couplings by:

$$g_{q\bar{q}g^{(1)}} = \lambda g_s$$

$$g_{b_{L,R}\bar{b}_{L,R}g^{(1)}} = \lambda_{b_{L,R}} \lambda g_s$$

$$g_{t_{L,R}\bar{t}_{L,R}g^{(1)}} = \lambda_{t_{L,R}} \lambda g_s$$

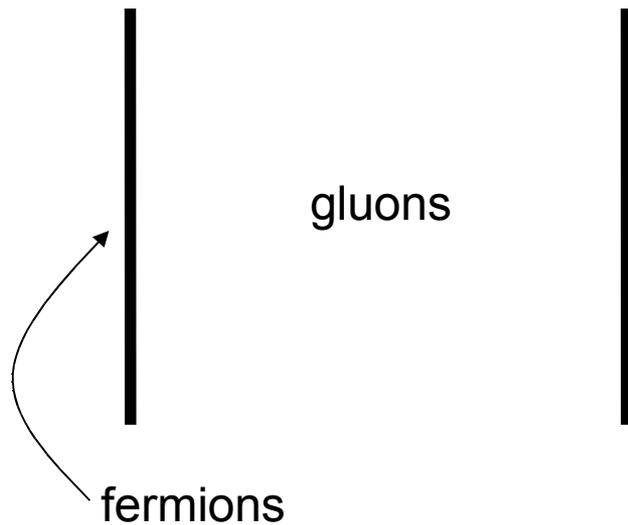
Note that the $g^{(0)}g^{(0)}g^{(1)}$ vertex is zero by orthogonality

$$\int dy \sqrt{g} \chi_{g^{(0)}} \chi_{g^{(0)}} \chi_{g^{(1)}} = \chi_{g^{(0)}} \int dy \sqrt{g} \chi_{g^{(0)}} \chi_{g^{(1)}} = 0$$

See also: Ghavri, McMullen, Nandi hep-ph/0602014

Typical values

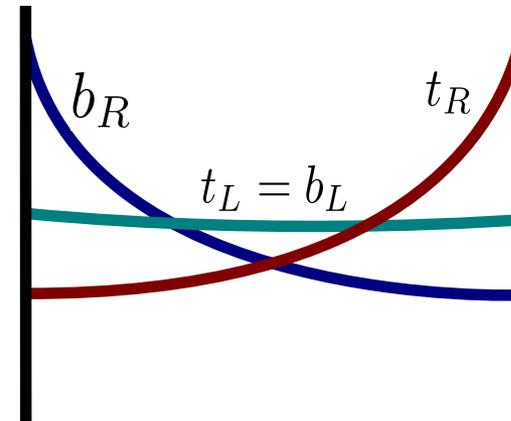
Flat extra dimension



$$\lambda = \sqrt{2}$$

$$\lambda_{b_{L,R}} = \lambda_{t_{L,R}} = 1$$

Randall-Sundrum



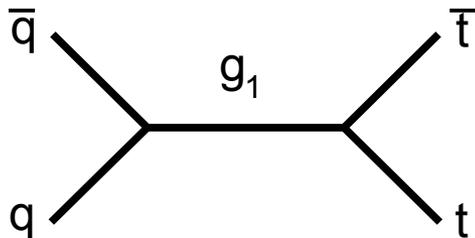
$$\lambda = 0.2$$

$$\lambda_{b_L} = \lambda_{t_L} = 5$$

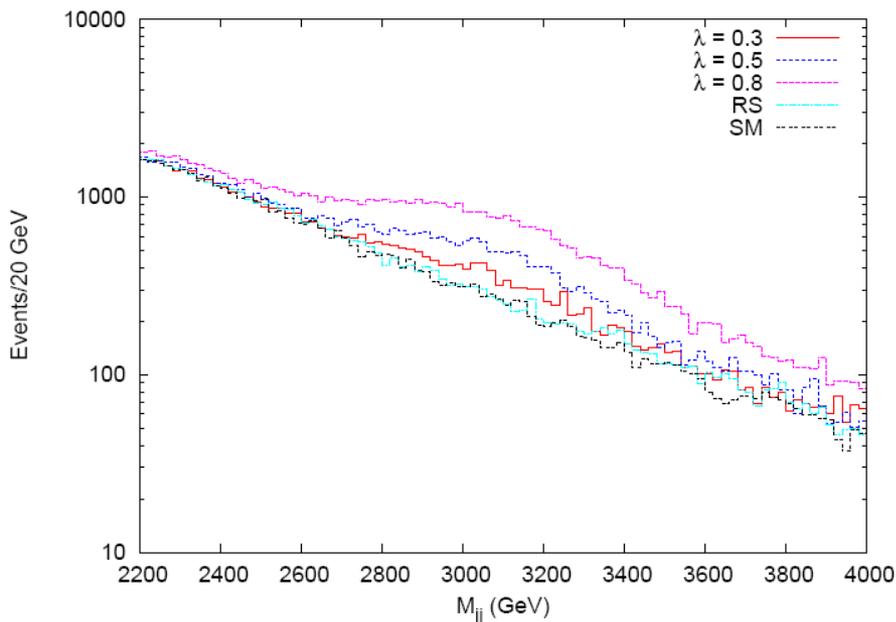
$$\lambda_{b_R} = 1$$

$$\lambda_{t_R} = 20$$

Resonant production

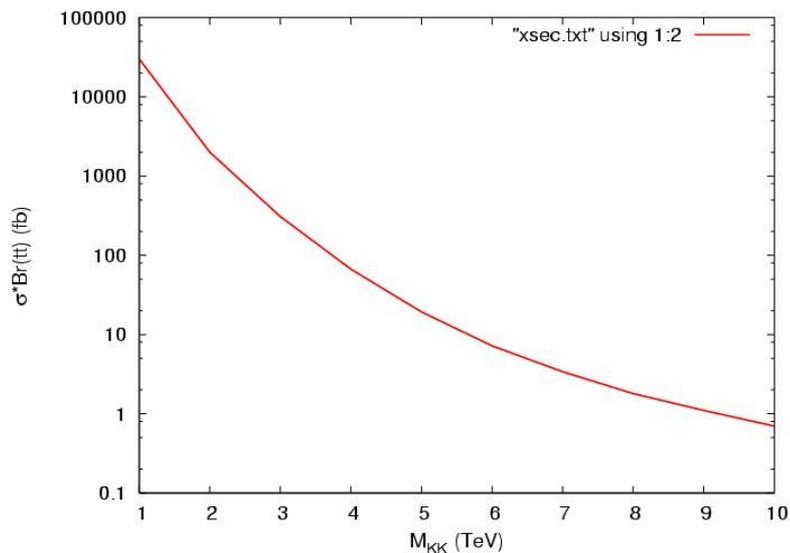


Dominant decay mode is to $t\bar{t}$



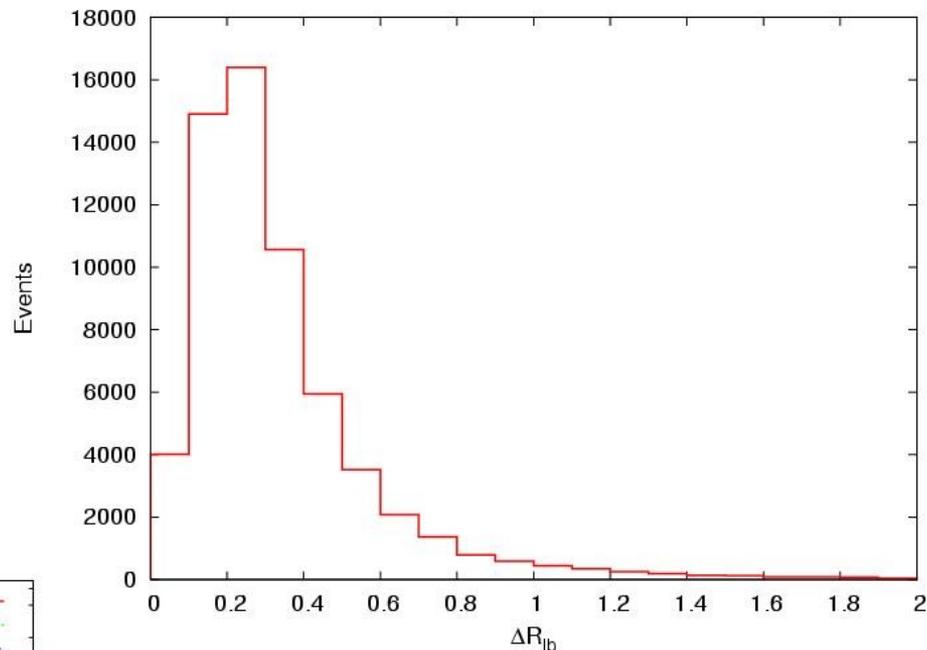
Decays into dijets no good

(all events and cross-sections generated by Madgraph and Madevent)



Problem: merging

High boost means the top decay products will have a small opening angle



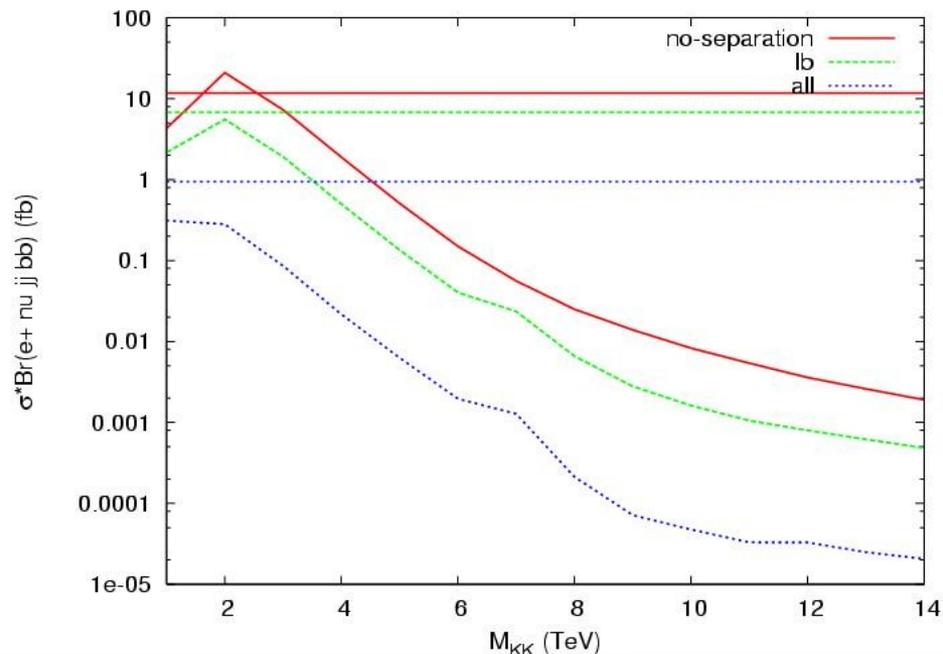
Cross-section with cuts:

$$|\eta| < 2.5$$

$$p_{T,jet} > 20 \text{ GeV}$$

$$p_{T,lead} > 500 \text{ GeV}$$

Can try to use the tails



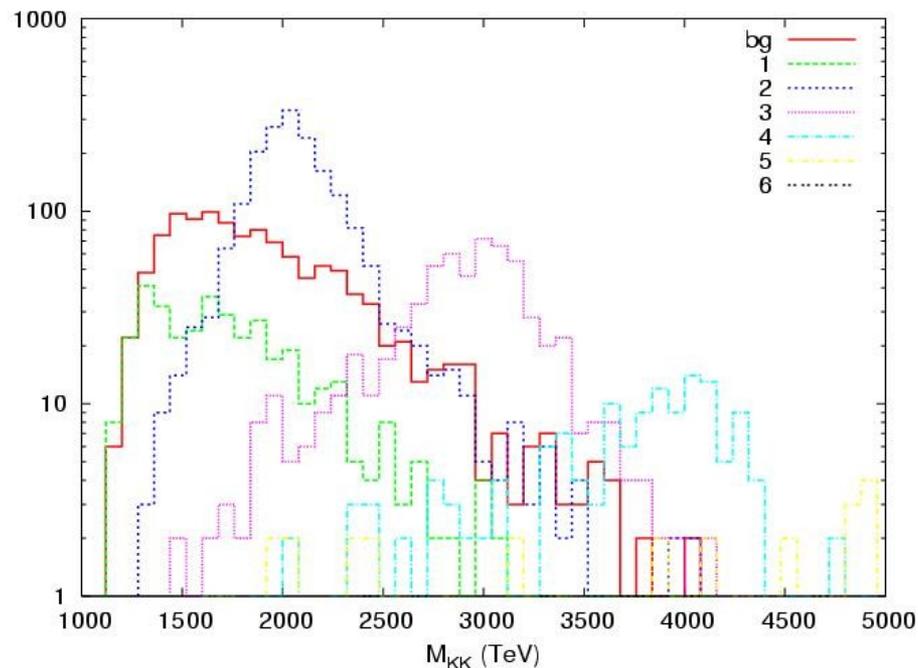
How do we identify top?

- Use the tail of the distribution to find 4-jet events
- Look for jets with leptons carrying a large fraction of the jet energy
- B-tagging (efficiency at high p_T - bad)
- Look at jet topology (best idea – beyond this paper)
- Use jet mass – peaks at 8-10 GeV for light jets. Should be able to tell that apart from 172.

Invariant mass dist.

Cutting on invariant mass
will increase signal to
background

Width is from intrinsic with
and from detector smearing
of jets
(crude theorists version:
perturb with a gaussian)



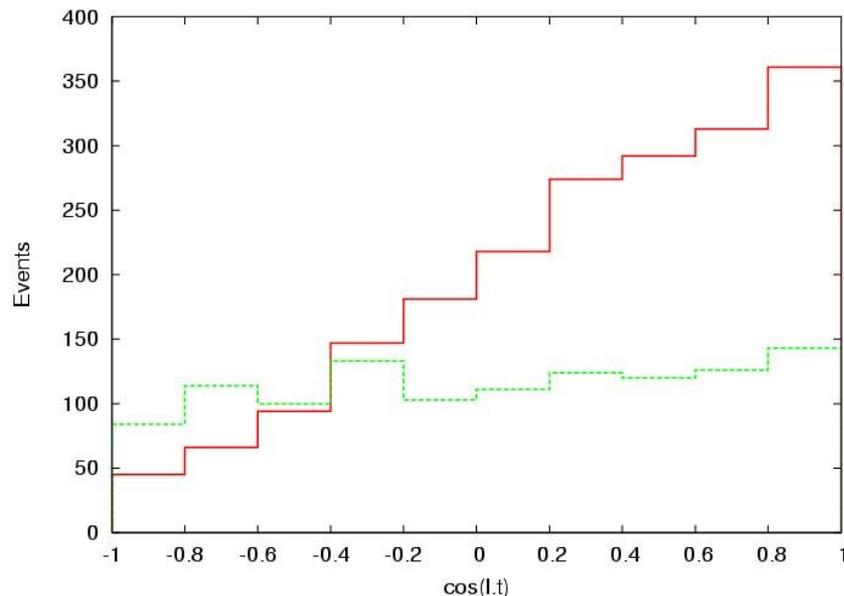
Polarization

- Tops come out almost 100% right-handed
- Can we measure this?

$$\frac{d\Gamma}{\Gamma d\cos\phi} = (1 + \alpha_i \cos\phi)$$

Angle between top polarization and decay product in the top rest frame

Depends on decay product



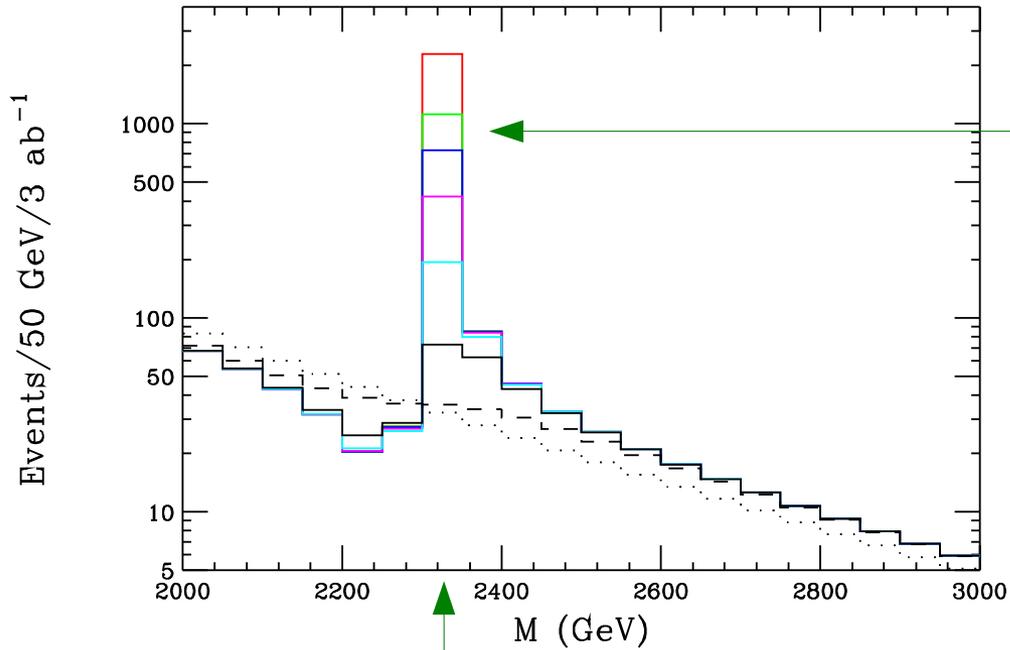
Need to reconstruct the top rest frame

- Use the tail?
- Get boost from E and top mass?
- Use a proxy (lepton p_T)?

Spin information

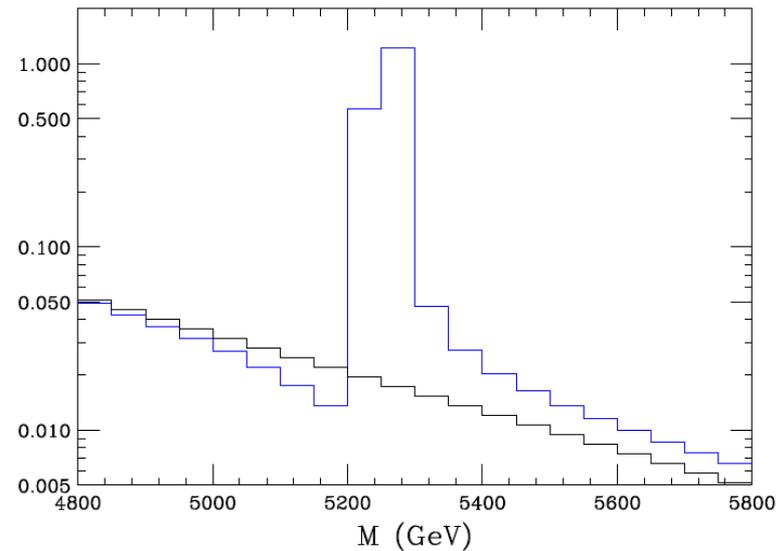
- Resonance is spin 1
- Couples to right-handed tops
- Should be straightforward

Drell-Yan



Different widths to account for fermion location

Generically will be lighter than studied here



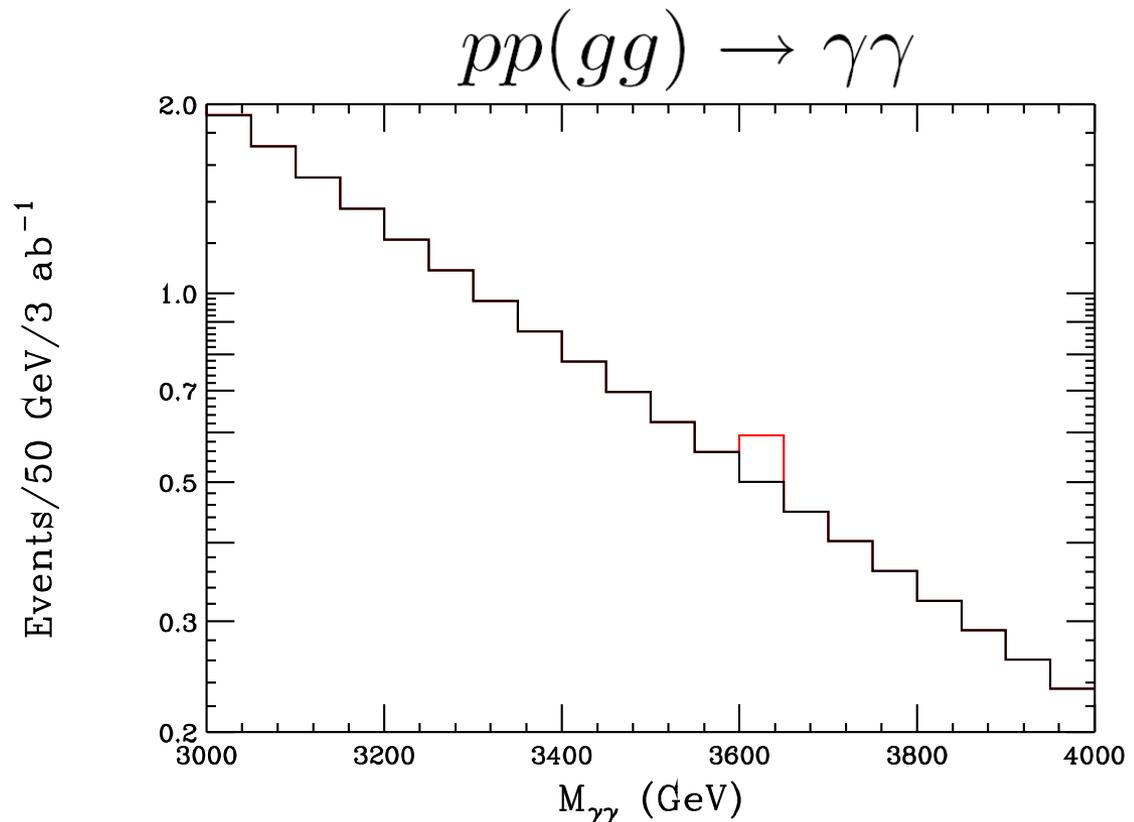
Graviton KK excitations

NOT visible (in standard channels)

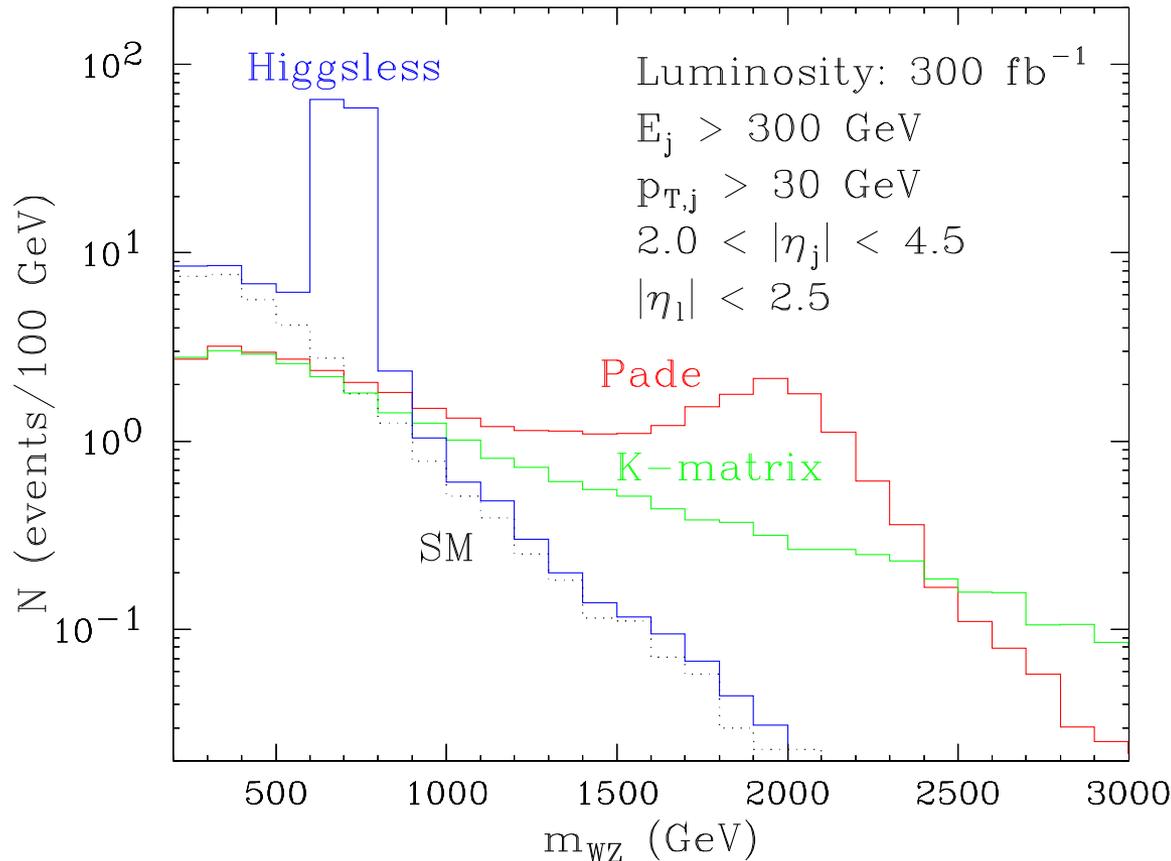
Light fermions near Planck brane, so graviton couplings highly suppressed

Gauge bosons have volume suppression

Need to use couplings to top and Higgs



$$W_L^\pm Z_L \rightarrow W_L^\pm Z_L$$



Directly connected to the Higgsless mechanism

Birkedal, Matchev, and Perelstein hep-ph/0412278

Conclusions

- The Randall-Sundrum model can solve the Hierarchy and flavor problems
- Right-handed tops play an important role
- Resonances in $t\text{-}\bar{t}$ will likely be the strongest signal of the model
- Graviton KK states potentially unobservable
- May obtain detailed information (spin, polarization) from gluon resonances

Questions

- How well can we identify high p_T tops?
- How well can we reconstruct the top rest frame?