

Top Pair Production in Randall–Sundrum Models

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Outline

- Motivation
- Review of Randall–Sundrum Models
- Effects of KK Gauge Bosons
 - ◆ Fermions on the brane
 - ◆ Fermions off the brane
- Conclusions

Motivation

- Kaluza–Klein (KK) states
 - ◆ If in 10–100 TeV range, direct observation at LHC and ILC will not be possible
 - ◆ EW precision measurements may not be sufficiently sensitive
 - ◆ Use top pair production to see effects of KK gauge bosons at the ILC.

Precision Electroweak Bounds

- Bound ~ 10 TeV for fermions in the bulk
 ~ 20 TeV for fermions on the brane
 - Davoudiasl, Hewett, Rizzo (hep-ph/9911262)
 - Chang, Hisano, Nakano, Okado, Yamaguchi (hep-ph/9912498)
 - Huber, Shafi (hep-ph/0005286)
 - Georgi, Grant, Hailu (hep-ph/0012379)
 - Csaki, Erlich, Terning (hep-ph/0203034)
 - Hewett, Petriello, Rizzo (hep-ph/0203091)
- Can be weakened
 - ◆ Custodial Isospin
 - Agashe, Delgado, May, Sundrum (hep-ph/0308036)
 - ◆ Brane Kinetic Terms
 - Carena, Tait, Wagner (hep-ph/0207056)
 - Davoudiasl, Hewett, Rizzo (hep-ph/0212279)
 - ◆ A little fine-tuning

Why Randall–Sundrum Model?

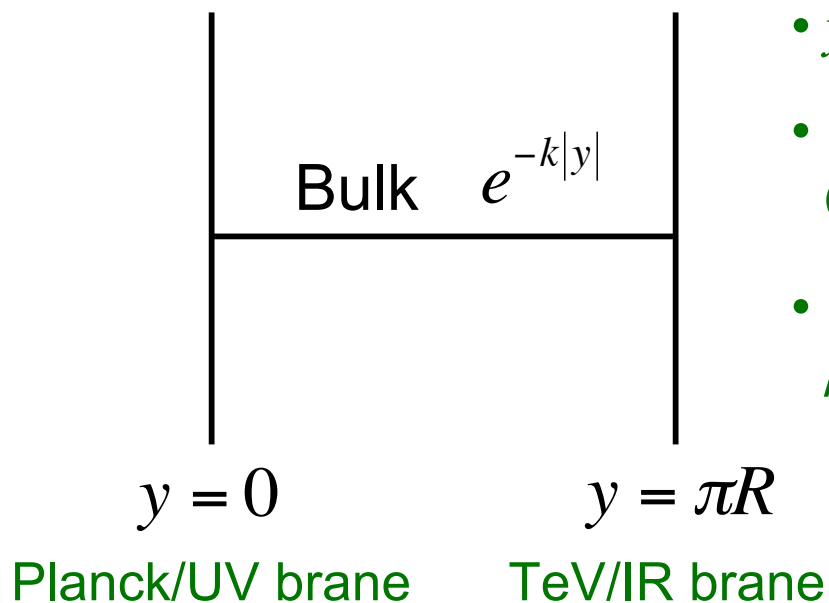
- Randall–Sundrum (RS)
 - ◆ Warped extra dimensions

$$m = e^{-\pi k R} m_0$$

- ◆ If $m_0 \sim M_{PL}$ and $kR \sim 12$,
then $m \sim \text{TeV}$
- Explains the weak scale and Planck scale hierarchy problem.

Randall–Sundrum Model

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



- y is compactified on an S^1/Z_2 orbifold
- Higgs is on TeV/IR brane
Gauge bosons in the bulk
- Hierarchy problem only solved if $kR \sim 12$

Effects of KK Gauge Bosons

Two Cases

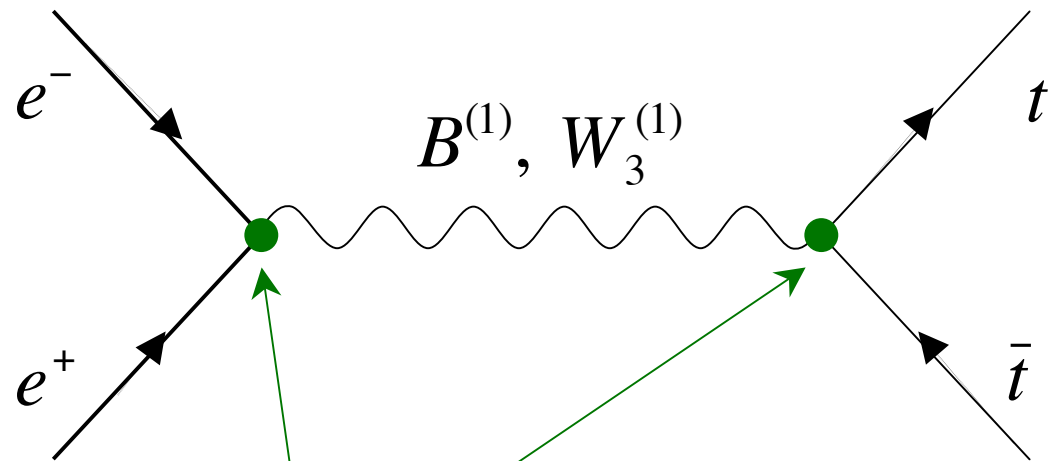
- ◆ Fermions on the brane

All fermions have the same coupling to KK-gauge bosons

- ◆ Fermions off the brane

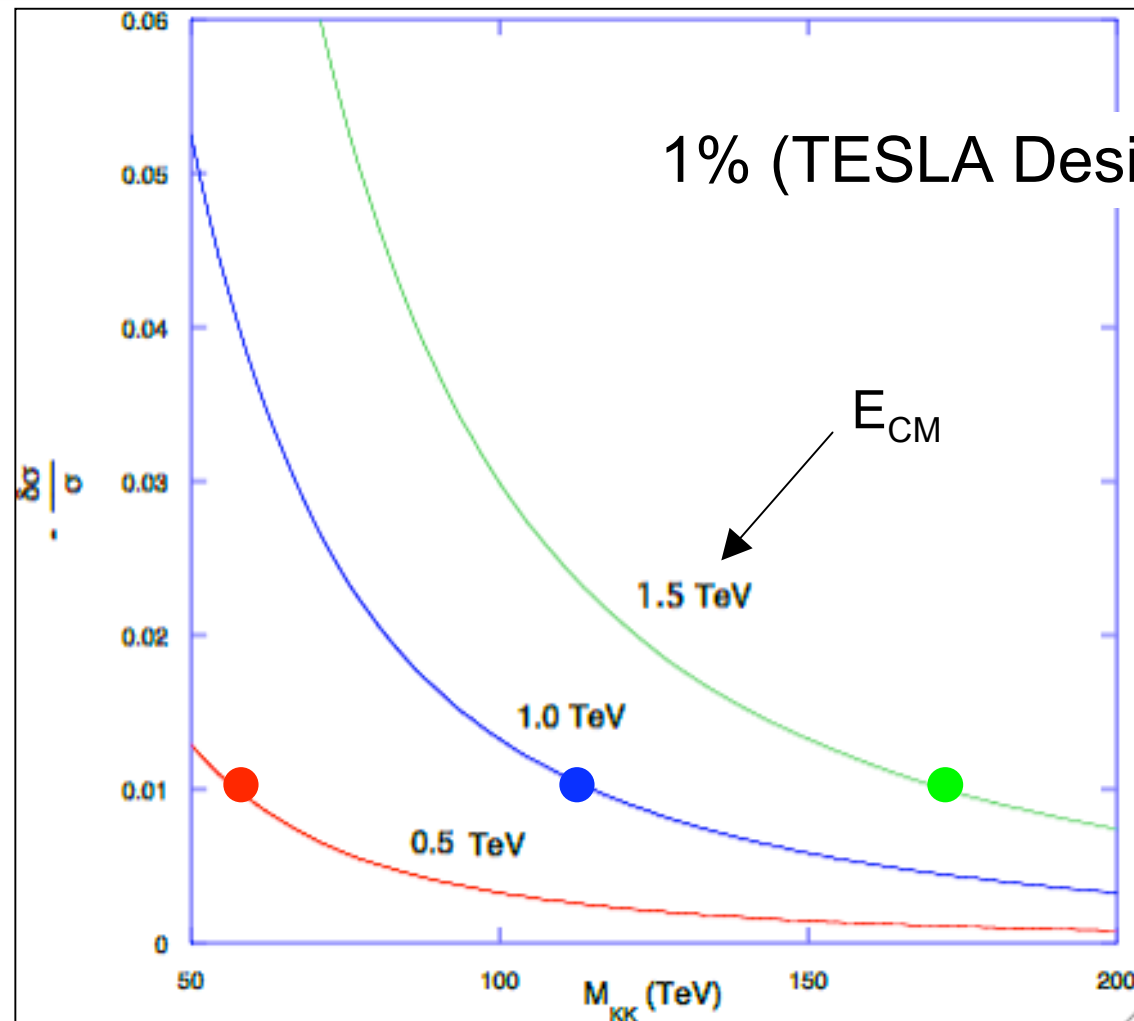
Top quarks have larger coupling to KK-gauge bosons

Fermions on the brane



couplings enhanced by $\sqrt{2\pi kR} \sim 8.4$

Results



Results

- Include higher order modes

- ◆
$$\sum_n \sigma_{n=1} \left(1 + \left(\frac{m_{n=1}}{m_{n=2}} \right)^2 + \left(\frac{m_{n=1}}{m_{n=3}} \right)^2 + \dots \right)$$

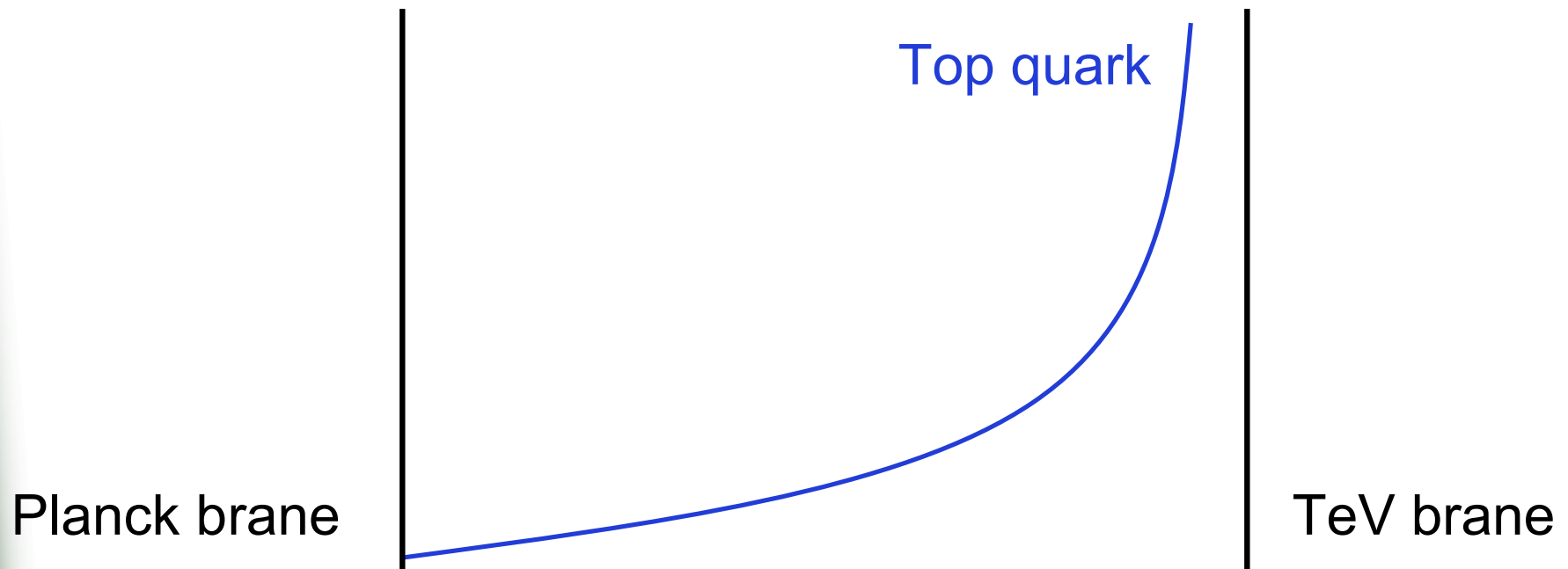
- ◆ Increases upper mass bound by 30%

Fermions off the brane

- Simple explanation for the fermion mass hierarchy
 - ◆ See (for example):
 - Gherghetta and Pomarol (hep-ph/000319)
 - Grossman and Neubert (hep-ph/9912408)
 - Huber (hep-ph/0303183)
- Why top quarks?

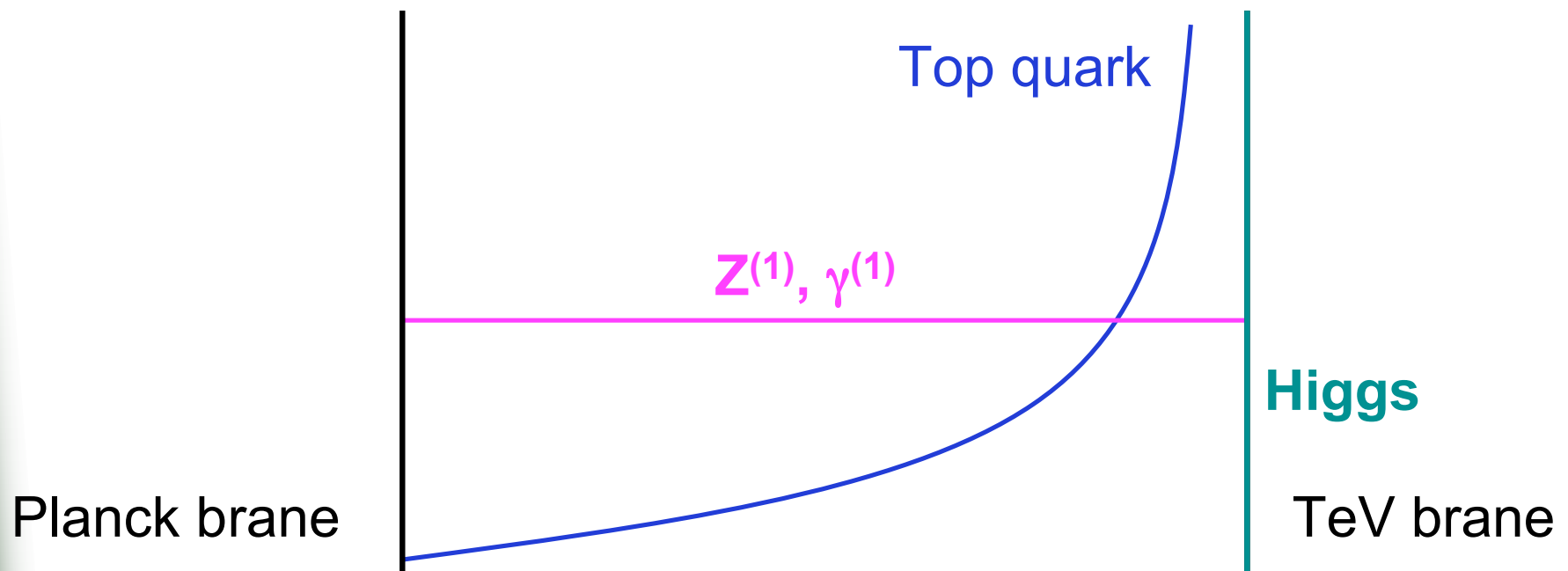
Fermions off the brane

5 dimensional wavefunctions



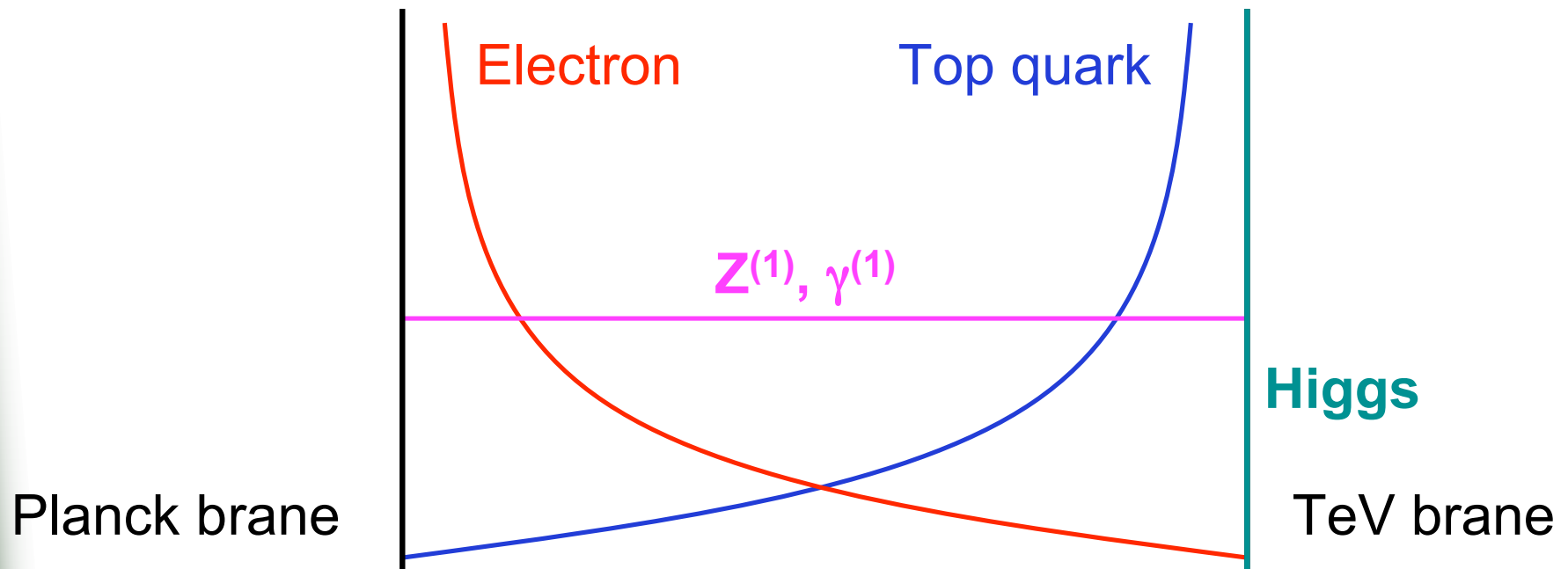
Fermions off the brane

5 dimensional wavefunctions



Fermions off the brane

5 dimensional wavefunctions



Coupling KK gauge boson to zero mode fermions

$$\int d^4x \int dy \sqrt{-g} g_5 \bar{\Psi}(x, y) i\gamma^\mu A_\mu(x, y) \Psi(x, y)$$

$$g = g_5 / \sqrt{2\pi R}$$

$$g^{(n)} = g \left(\frac{1-2c}{e^{(1-2c)\pi k R} - 1} \right) \frac{k}{N_0} \int_0^{\pi R} dy e^\sigma e^{(1-2c)\sigma} \left[J_1\left(\frac{m_n}{k} e^\sigma\right) + b_1(m_n) Y_1\left(\frac{m_n}{k} e^\sigma\right) \right]$$

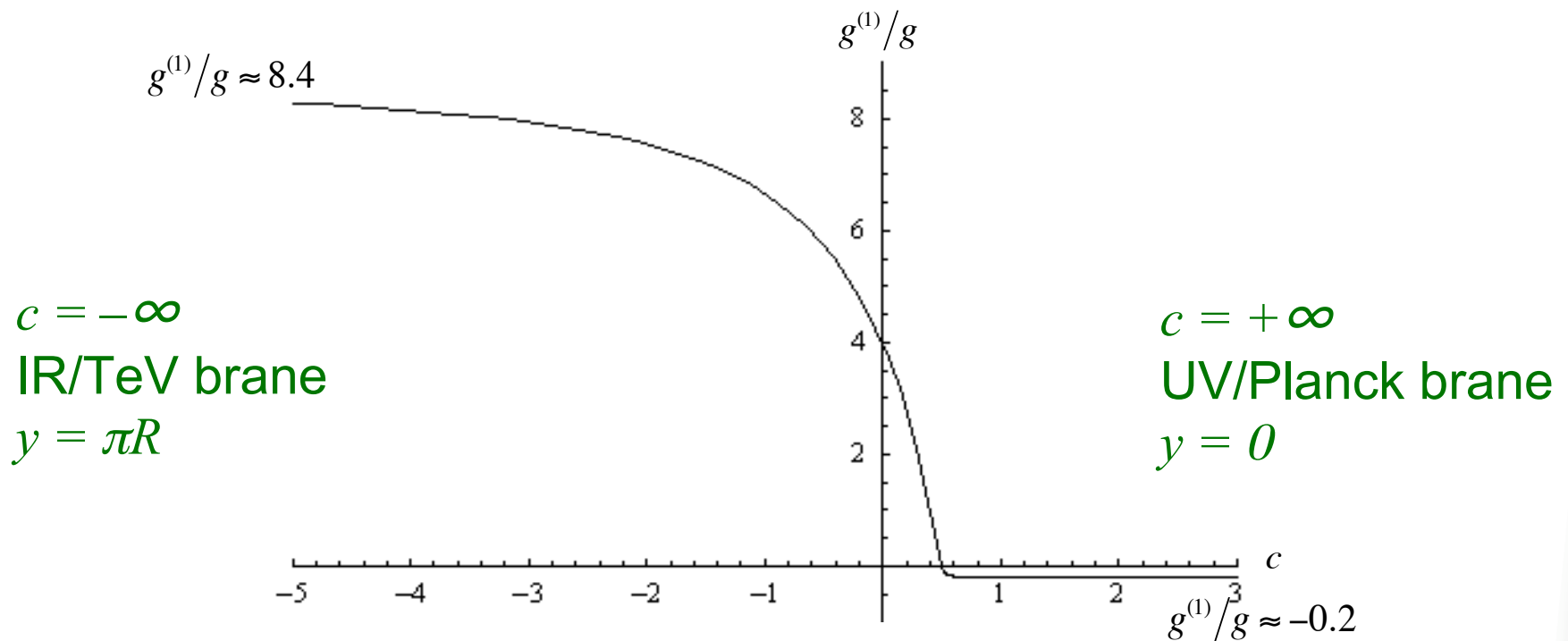
Gherghetta and Pomarol, hep-ph/0003129

c = mass parameter

(can differ for left- and right-handed fermions, i.e. c_L and c_R)

Coupling KK gauge boson to zero mode fermions

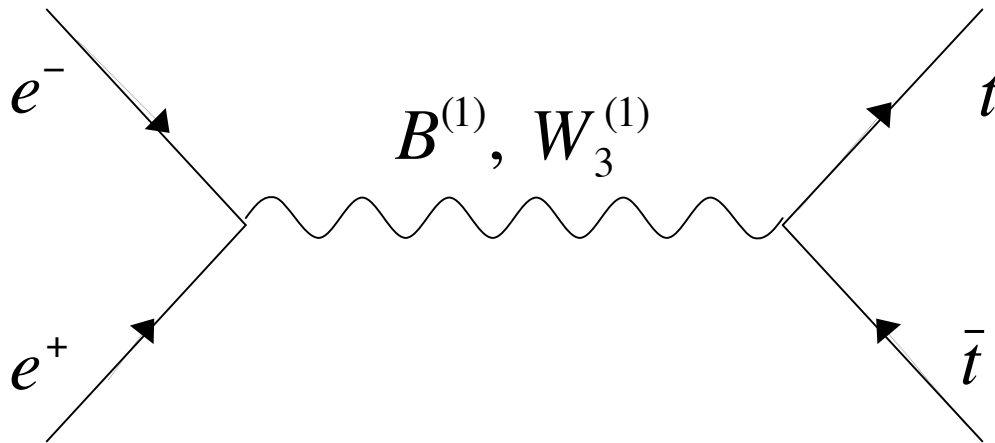
$$g^{(n)} = g \left(\frac{1-2c}{e^{(1-2c)\pi k R} - 1} \right) \frac{k}{N_0} \int_0^{\pi R} dy e^\sigma e^{(1-2c)\sigma} \left[J_1 \left(\frac{m_n}{k} e^\sigma \right) + b_1(m_n) Y_1 \left(\frac{m_n}{k} e^\sigma \right) \right]$$



Fermions off the brane

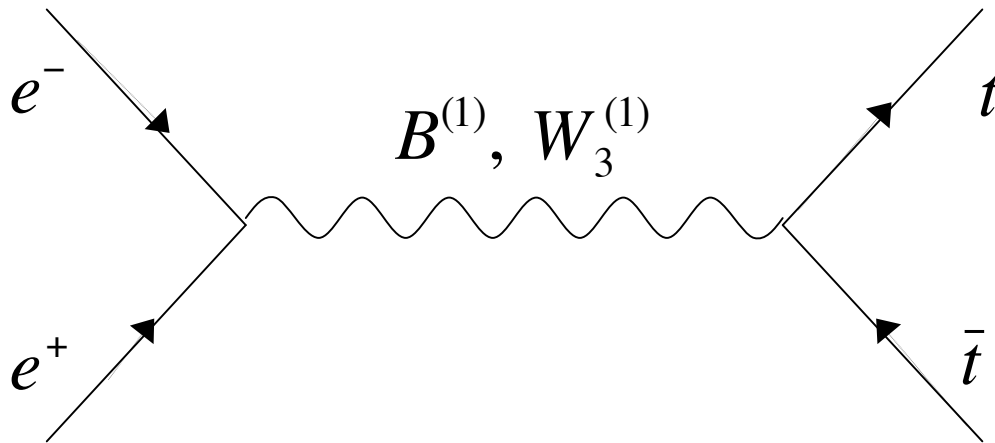
- Why tops?
 - ◆ Top quarks are closer to the IR/TeV brane and thus have a larger coupling to the KK-gauge bosons
- Contributions from several sources
 - ◆ Tree level
 - ◆ One loop

Tree level contributions



$$\frac{d\sigma_L}{d\cos\theta} = \frac{\pi\alpha^2}{4s} \left\{ |C_{LL}|^2 (1 + \cos\theta)^2 + |C_{LR}|^2 (1 - \cos\theta)^2 \right\} \text{ Similar for } \sigma_R$$

Tree level contributions



$$\frac{d\sigma_L}{d\cos\theta} = \frac{\pi\alpha^2}{4s} \left\{ |C_{LL}|^2 (1 + \cos\theta)^2 + |C_{LR}|^2 (1 - \cos\theta)^2 \right\} \quad \text{Similar for } \sigma_R$$

$$C_{ij} = -Q_f + \frac{C_i^e C_j^t}{c_w^2 s_w^2} \frac{s}{(s - M_Z^2) + i\Gamma_Z M_Z} + \sum_{Z'=B^{(1)}, W_3^{(1)}} \frac{(g_{Z'}/g_{Z^0}) C_i^{e'} C_j^{t'}}{c_w^2 s_w^2} \frac{s}{(s - M_{Z'}^2) + i\Gamma_{Z'} M_{Z'}}$$

$C_i^t = \text{SM } Z^0 \text{ couplings}$

$C_i^{t'} = Z' \text{ couplings}$

Godfrey, hep-ph/9612384

Tree level contributions

$$\sigma = \frac{\pi\alpha^2}{3s} \left[|C_{LL}|^2 + |C_{RL}|^2 + |C_{LR}|^2 + |C_{RR}|^2 \right]$$

$$A_{LR}^f = \frac{\sigma(e_L^-) - \sigma(e_R^-)}{\sigma(e_L^-) + \sigma(e_R^-)}$$

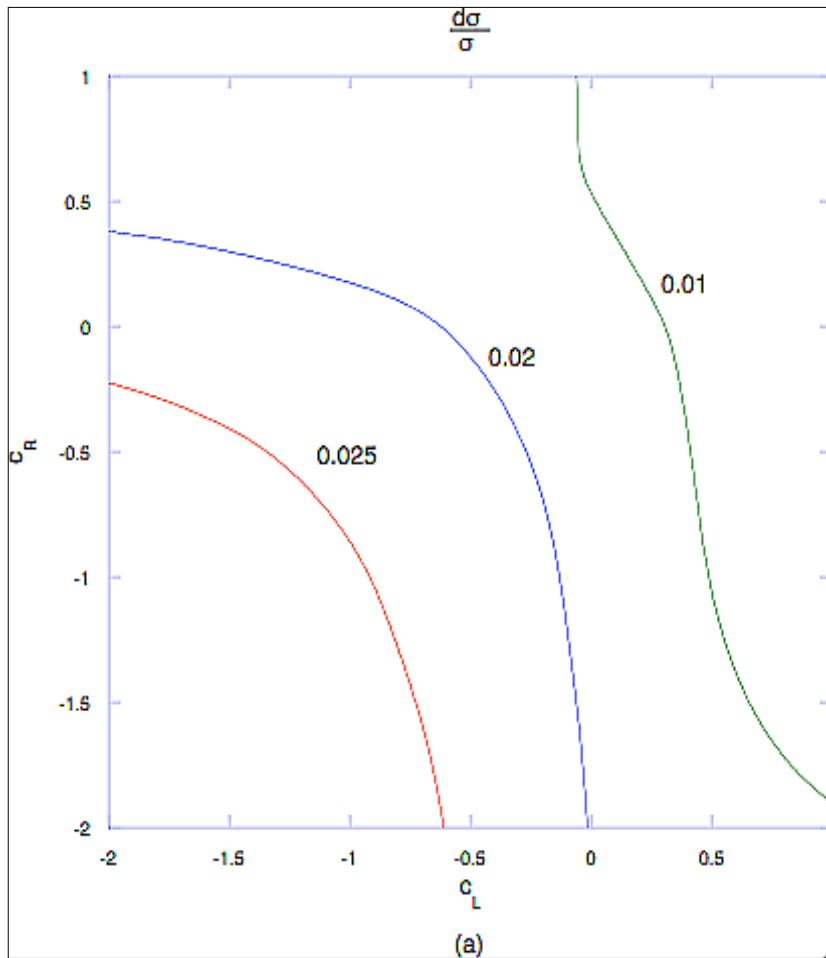
$$\alpha_{L,R} = \frac{g^{(1)}(c_{L,R})}{g}$$

$$\frac{\delta\sigma}{\sigma} = (0.24\alpha_L + 0.14\alpha_R) \frac{s}{M_{KK}^2}$$

$$\delta A_{FB} = (-0.04\alpha_L - 0.03\alpha_R) \frac{s}{M_{KK}^2}$$

$$\delta A_{LR} = (-0.26\alpha_L - 0.19\alpha_R) \frac{s}{M_{KK}^2}$$

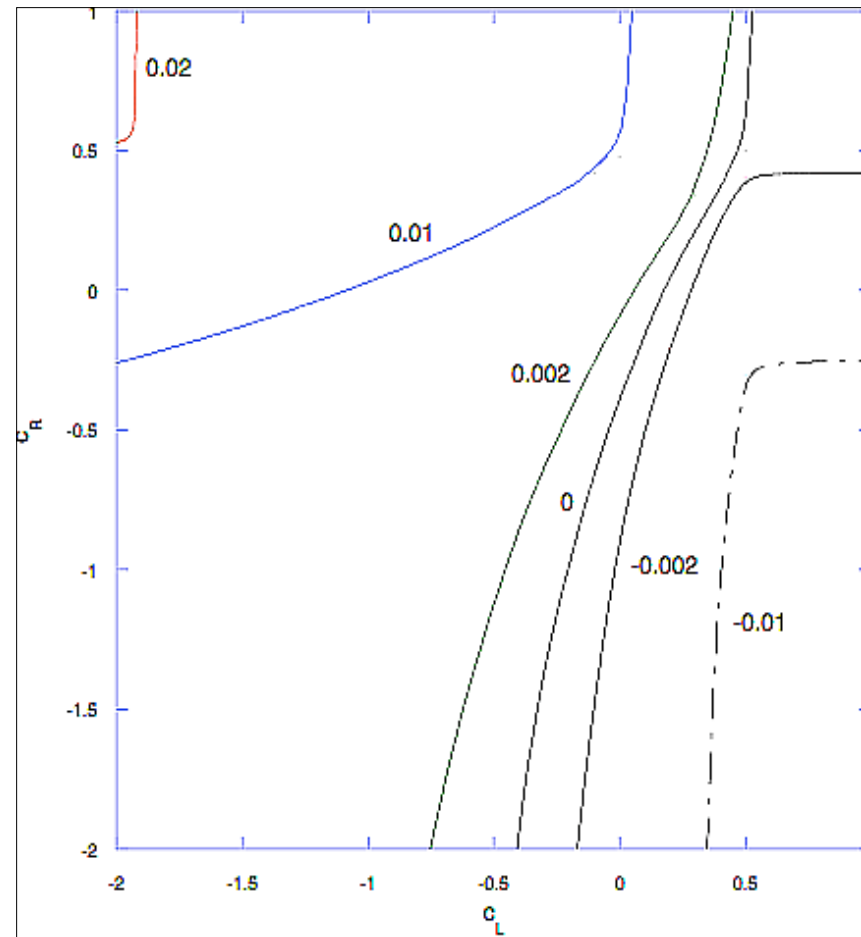
Tree level: Results



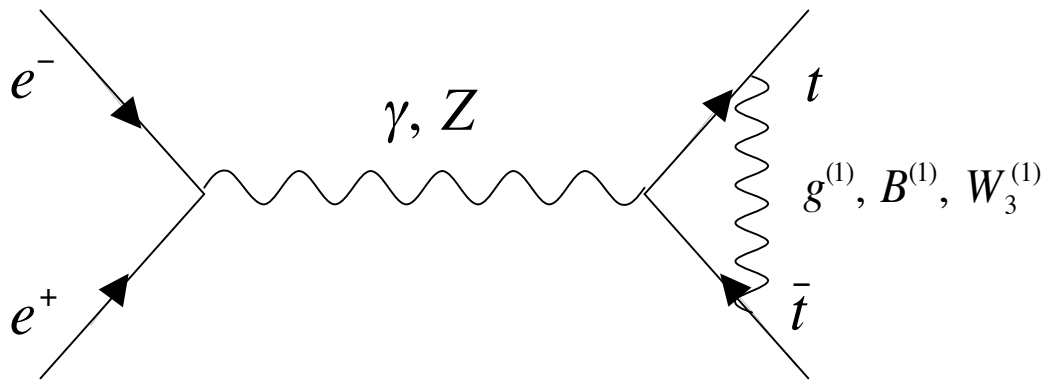
- Change in cross-section
- $M_{KK} = 10 \text{ TeV}$

Tree level: Results

- Change in left-right asymmetry
- $M_{KK} = 10 \text{ TeV}$



One loop



$$\Gamma_{\mu}^V(q^2) = -ie \left[\gamma_{\mu} \left(F_{1V}^V(q^2) + \gamma_5 F_{1A}^V(q^2) \right) + \frac{i\sigma_{\mu\nu} q^{\nu}}{2m} \left(iF_{2V}^V(q^2) \right) \right]$$

Snowmass, hep-ex/0106057

Baur, hep-ph/0508151

DESY, hep-ph0106315

$$F_{1V}^{\gamma} : .02$$

$$F_{1A}^{\gamma} : .005$$

$$F_{2V}^{\gamma} : .015$$

$$F_{1V}^Z : .005$$

$$F_{1A}^Z : .004$$

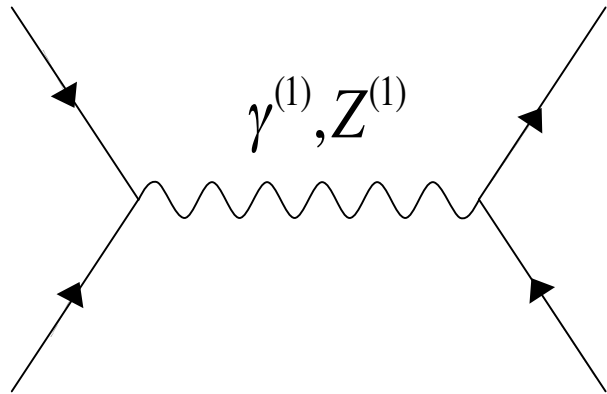
$$F_{2V}^Z : .004$$

Assume: $\int \mathcal{L} dt = \text{ab}^{-1}$
 $E_{\text{CM}} = 1 \text{ TeV}$

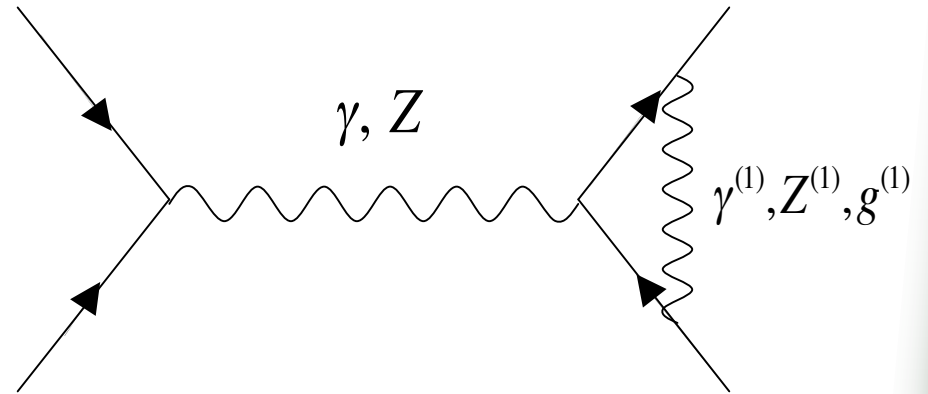
One Loop

- Why look at one loop level?
 - ◆ Two top vertices, rather than one at tree level
 - ◆ Strong interaction vs. weak interaction
- Results
 - ◆ Too small for $M_{KK} = 10$ TeV
 - ◆ Many features for $M_{KK} = 5$ TeV

Fermions off the brane



Tree level: σ, A_{LR}, A_{FB}



One loop: $F^{\gamma, Z}$

However, both processes contribute at the ILC,
a unified approach is needed.

Conclusions

- Top pair production could be the first evidence of KK states.
- Probe:
 - ◆ 120 TeV (fermions on the brane)
 - ◆ 10 TeV in many regions of c_L, c_R space

arXiv: hep-ph/0603105

Physical Review D 73

Funded by NSF grant PHY-023400

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