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
- Effects of KK Fermions
- Conclusions

Motivation

- Randall-Sundrum models
  (Warped extra dimensions)
  - 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

Precision Electroweak Bounds

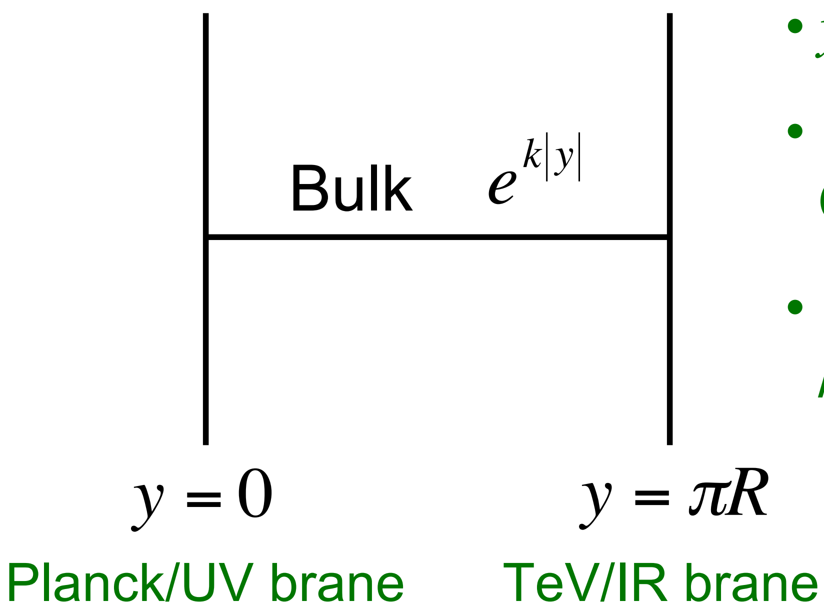
- Bound ~10 TeV for fermions in the bulk
  ~20 TeV for fermions on the brane
    - Davoudiasl, Hewett, Rizzo (hep-ph/9911262)
    - Chang, Hisano, Nakano, Okado, Yamaguchi (hep-ph/9912498)
    - Huber, Shafi (hep-ph/0005286)
    - Georgi, Grant, Hailu (hep-ph/0012379)
    - Csaki, Erlich, Terning (hep-ph/0203034)
    - 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

Motivation

- High precision top pair production measurements at the ILC may provide first evidence of lowest lying KK states

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

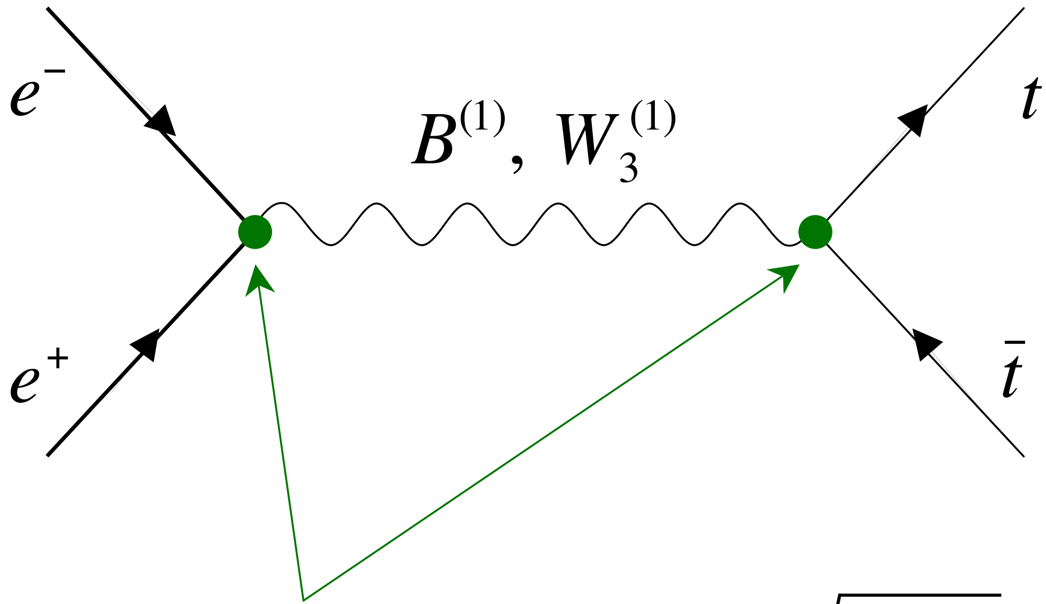
- Fermions on the brane

  All fermions have the same coupling to KK-gauge bosons

- Fermions off the brane

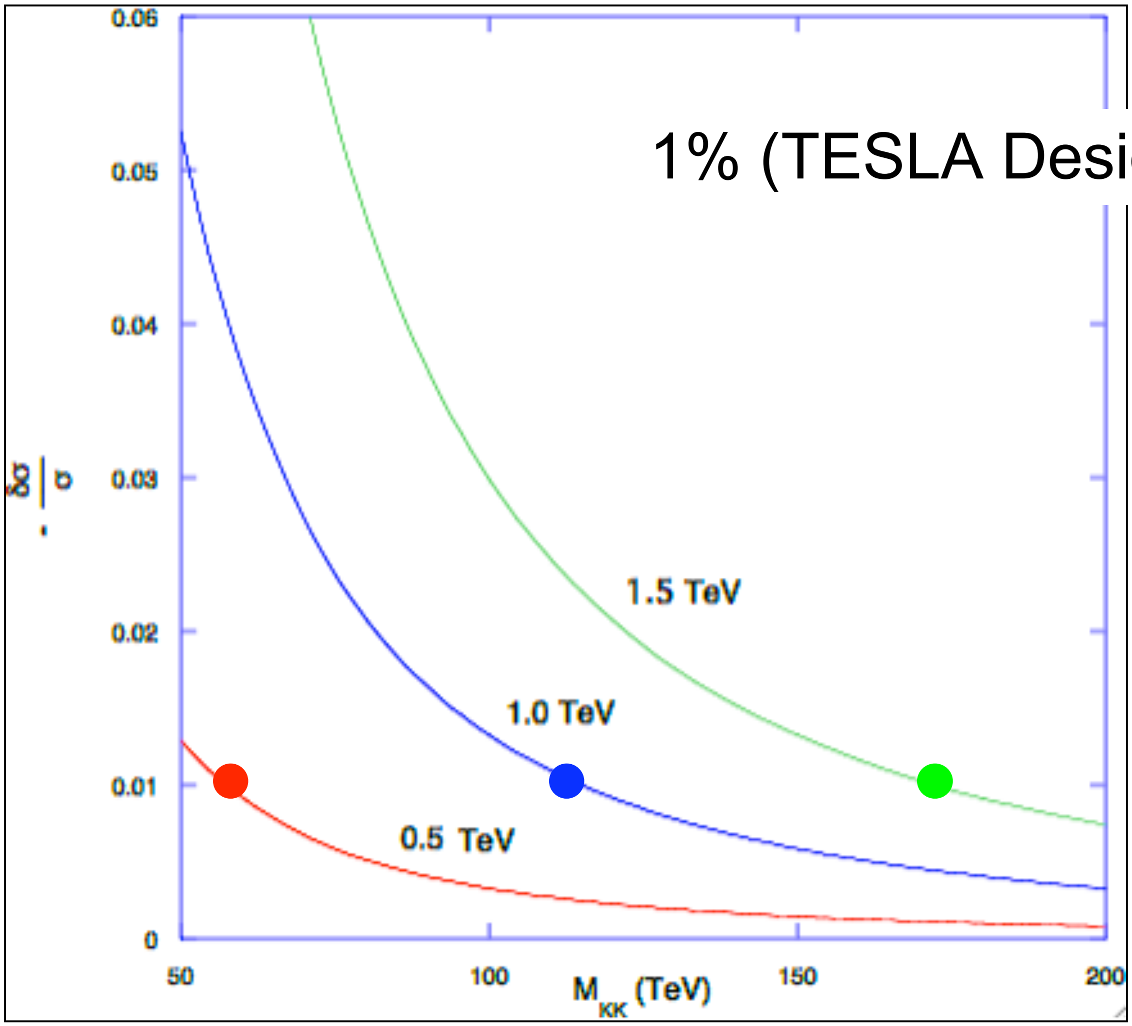
  Top quarks have larger coupling to KK-gauge bosons

Fermions on the brane



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

Results



1% (TESLA Design Report)

Results

- Include higher order modes
  - $$\sum_n \sigma_{n=1} \left(1 + \left(\frac{m_{n=1}}{m_{n=2}} \right)^2 + \left(\frac{m_{n=1}}{m_{n=3}} \right)^2 + \cdots \right)$$
  - Increases 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?

Coupling KK gauge boson to zero mode fermions

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

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

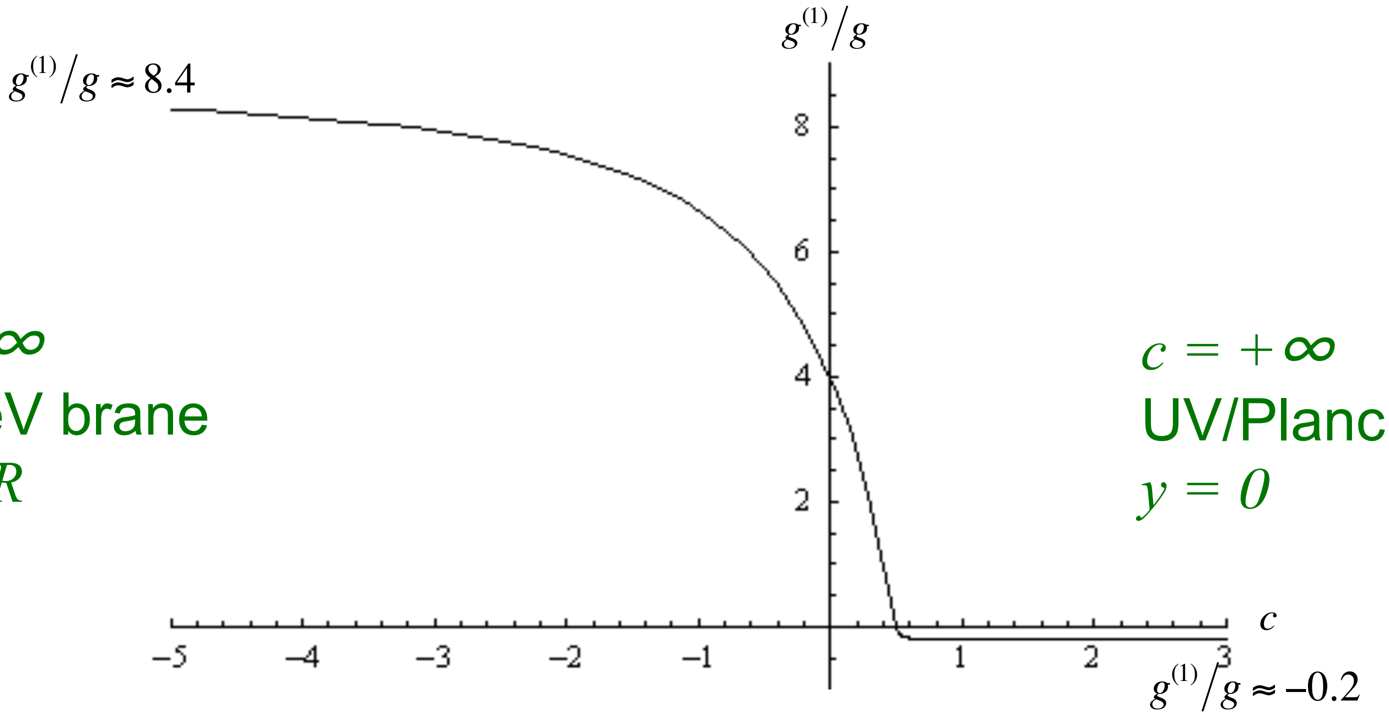
$$g^{(n)} = g\left(\frac{1-2c}{e^{(1-2c)\pi kR}-1}\right)\frac{k}{N_0}\int_0^{\pi R} dy\; e^{\sigma} e^{(1-2c)\sigma}\left[J_1\!\left(\tfrac{m_n}{k}e^{\sigma}\right)+b_1(m_n)Y_1\!\left(\tfrac{m_n}{k}e^{\sigma}\right)\right]$$

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

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



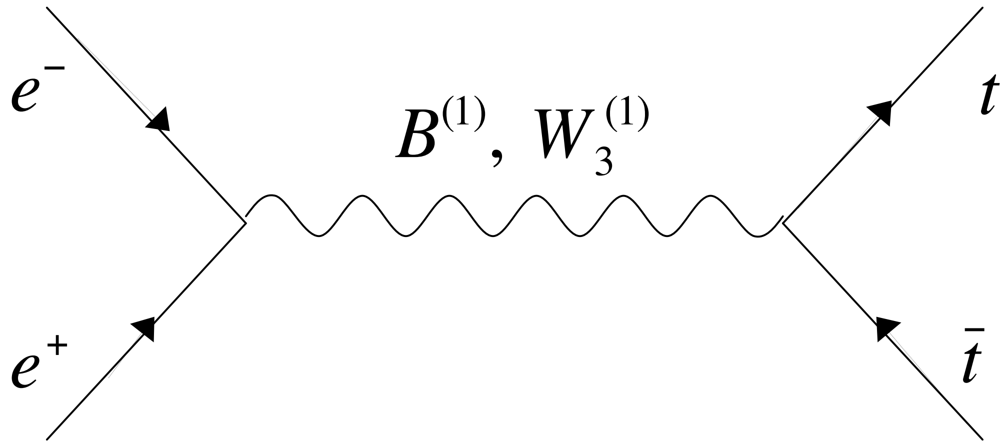
$c = -\infty$
IR/TeV brane
$y = \pi R$

$c = +\infty$
UV/Planck brane
$y = 0$

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 for several sources
  - Tree level
  - One loop
  - Mixing

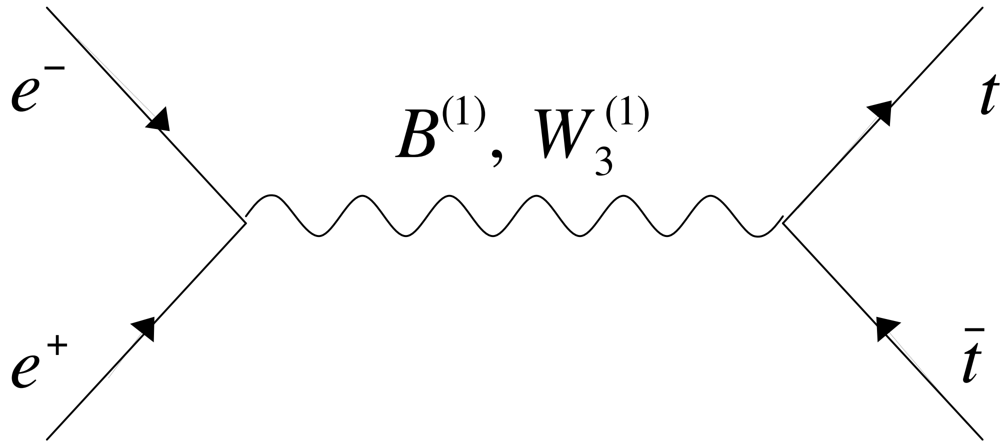
Tree level contributions



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

Similar for σ_R

Tree level contributions



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

Similar for σ_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 = SM Z^0 couplings

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

Godfrey, hep-ph/9612384

Tree level contributions

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

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

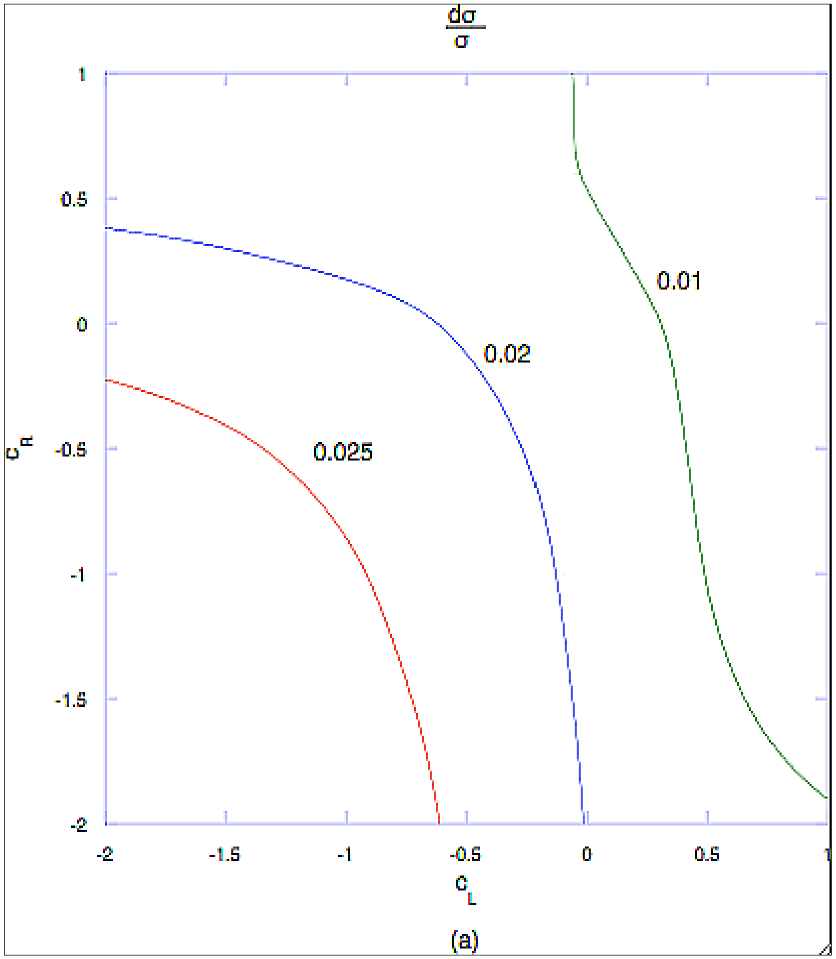
$$\alpha_{L,R} = \frac{g^{(1)}(c_{L,R})}{g}$$

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

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

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

Tree level: Results

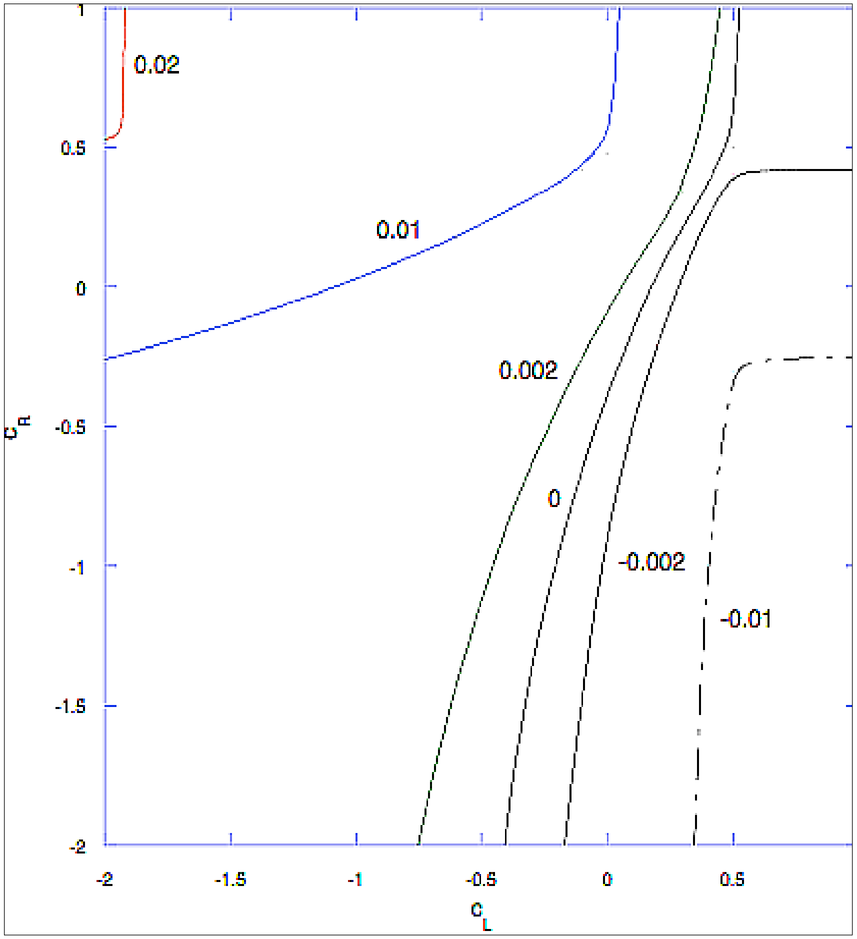


- Change in cross-section
- M_{KK} = 10 TeV

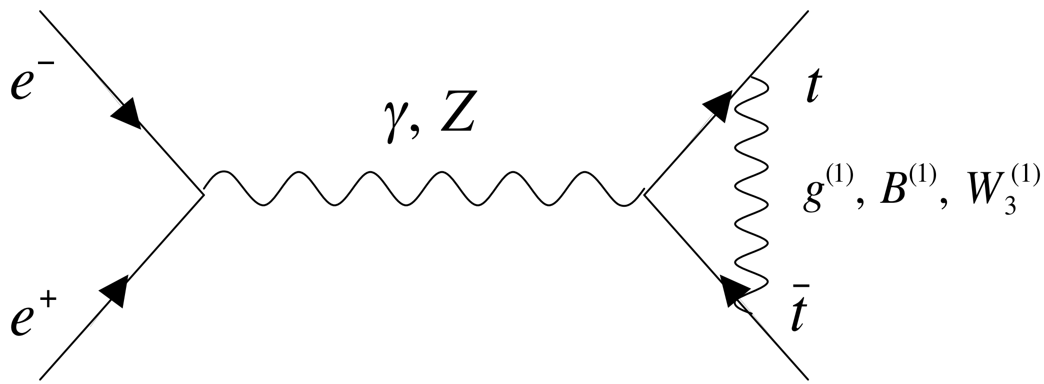
Tree level: Results

- Change in left-right asymmetry

- M_{KK} = 10 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}^γ	:	.02
F_{1A}^γ	:	.005
F_{2V}^γ	:	.015
F_{1V}^Z	:	.005
F_{1A}^Z	:	.004
F_{2V}^Z	:	.004

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

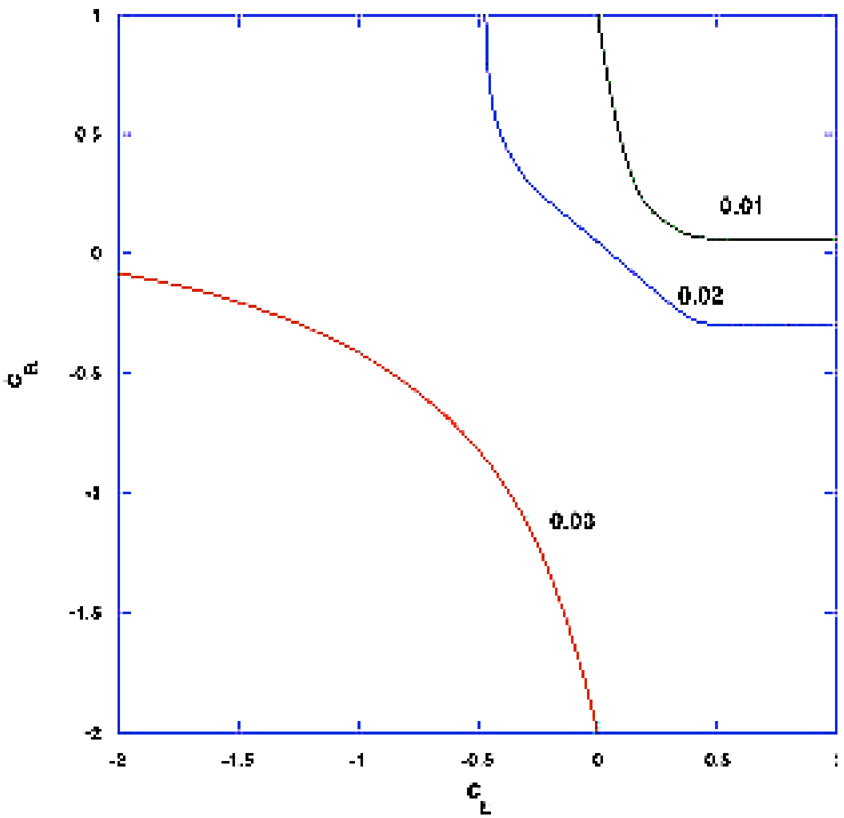
One Loop

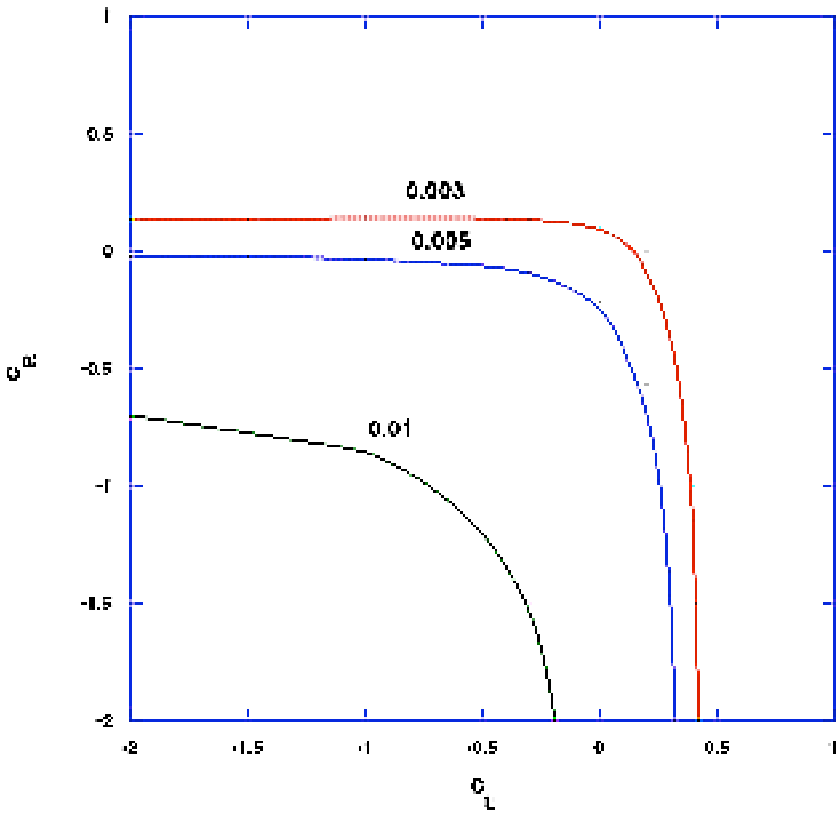
- Why look at one loop level?
  - Two top vertices, rather than one at tree level
  - Strong interaction vs. weak interaction

- Results
  - Too small for M_{KK} = 10 TeV
  - Many features for M_{KK} = 5 TeV

One Loop: Results

F_{1V}^{γ} $\quad$ M_{KK} = 5 TeV $\quad$ F_{1V}^{Z}

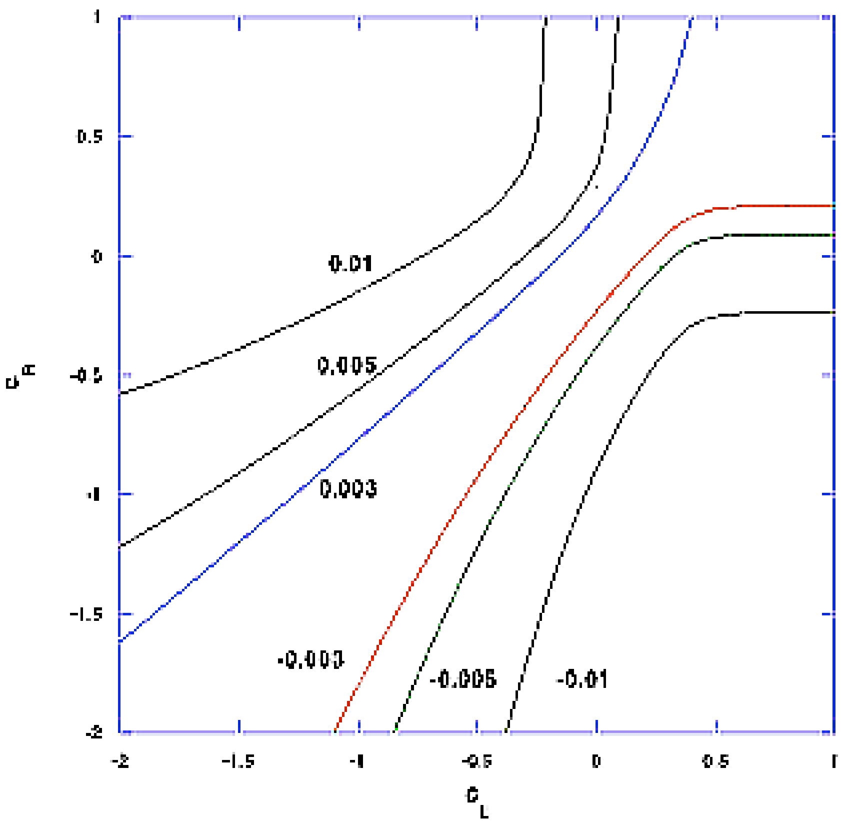


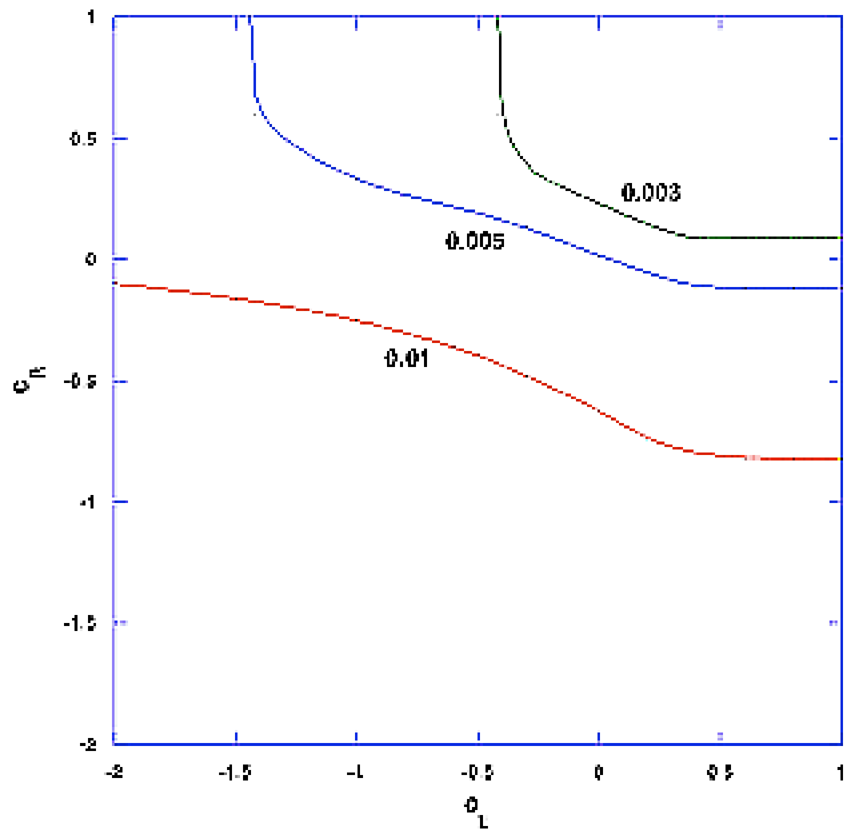


$F_{1V}^{\gamma} \;:\; .02$ $\qquad$ $F_{1V}^{Z} \;:\; .005$

One Loop: Results

F_{1A}^{γ} M$_{KK}$ = 5 TeV F_{1A}^{Z}

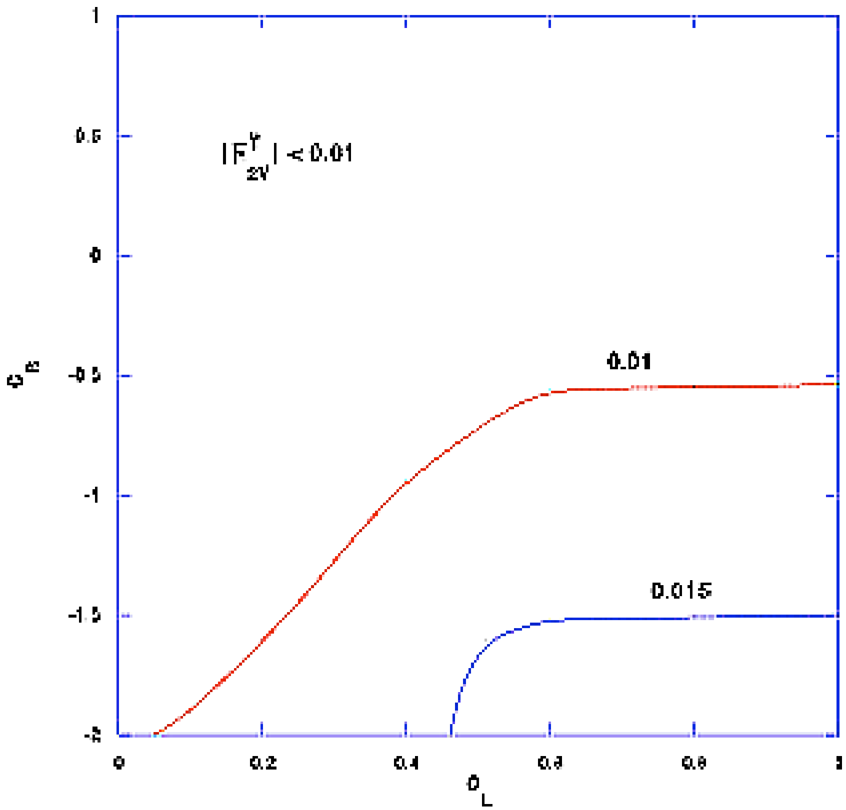


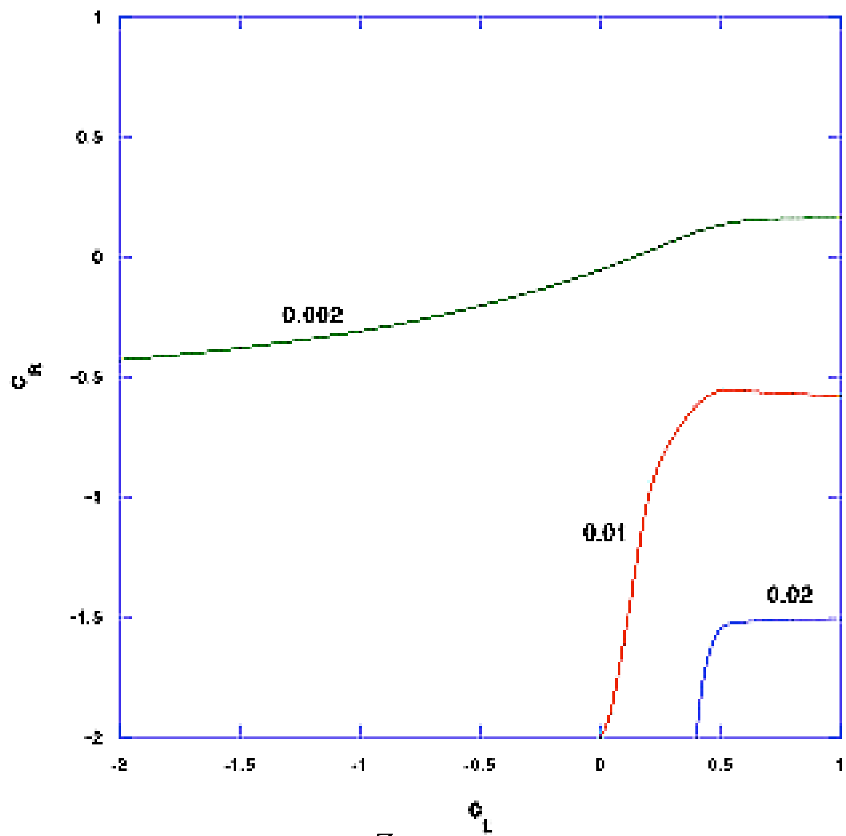


F_{1A}^{γ} : .005 F_{1A}^{Z} : .004

One Loop: Results

F_{2V}^{γ} M$_{KK}$ = 5 TeV F_{2V}^{Z}





F_{2V}^{γ} : .015 F_{2V}^{Z} : .004

Mixing: Z and $Z^{(1)}$

- Mixing between Z boson and the KK-Z boson
- Biggest effect with right-handed top coupling

Mixing: Z and $Z^{(1)}$

$$\frac{\delta\left(g_Z^{t_R}\right)}{g_Z^{t_R}} \sim \frac{m_Z^2}{\left(0.41\, M_{KK}\right)^2} \frac{1-2c_R}{3-2c_R}\left(\frac{-\pi\, kR}{2}+\frac{5-2c_R}{4\left(3-2c_R\right)}\right)$$

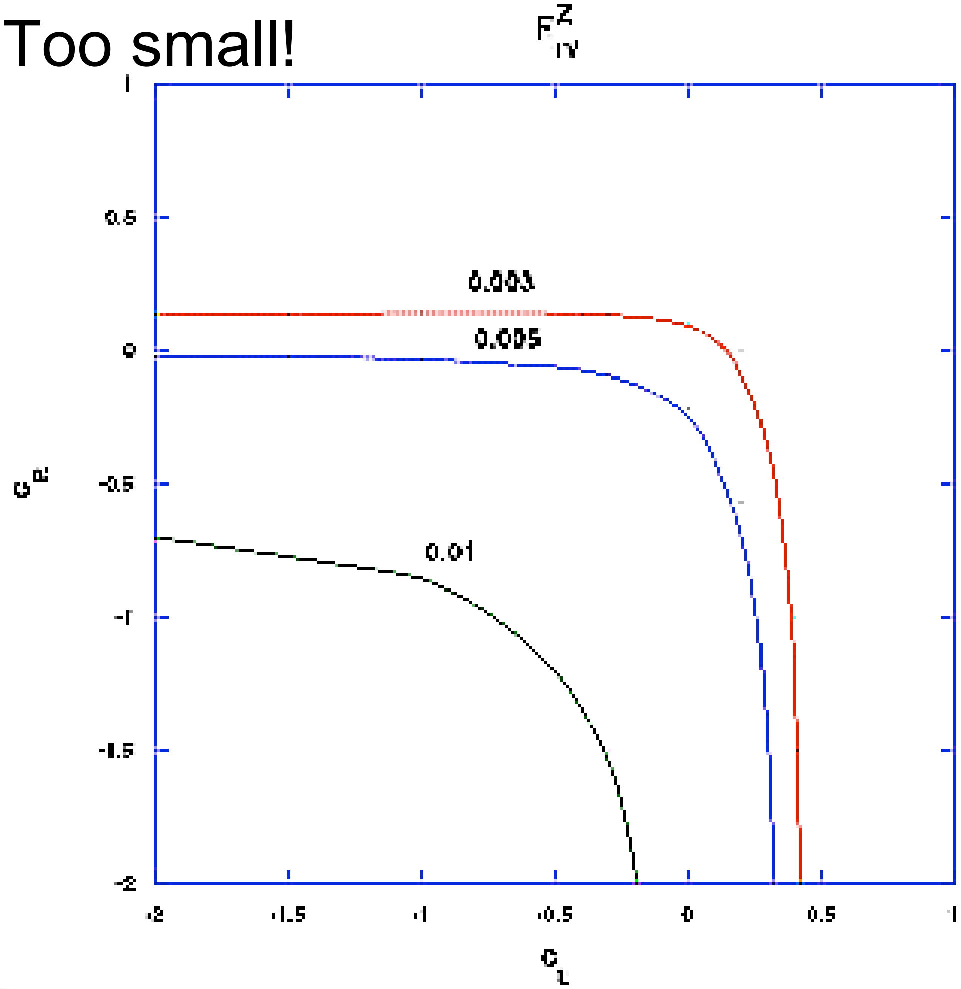
$$\delta F_{1V}^Z = \delta F_{1A}^Z = -\frac{\tan\theta_W}{3}\frac{\delta\left(g_Z^{t_R}\right)}{g_Z^{t_R}}$$

δF_{1V}^Z	c_R
0	½
0.002	0
0.004	–0.2

Agashe, hep-ph/060112
Agashe, et al., hep-ph/0308036

Mixing: Z and $Z^{(1)}$

Too small!



δF^Z_{1V}	c_R
0	½
0.002	0
0.004	–0.2

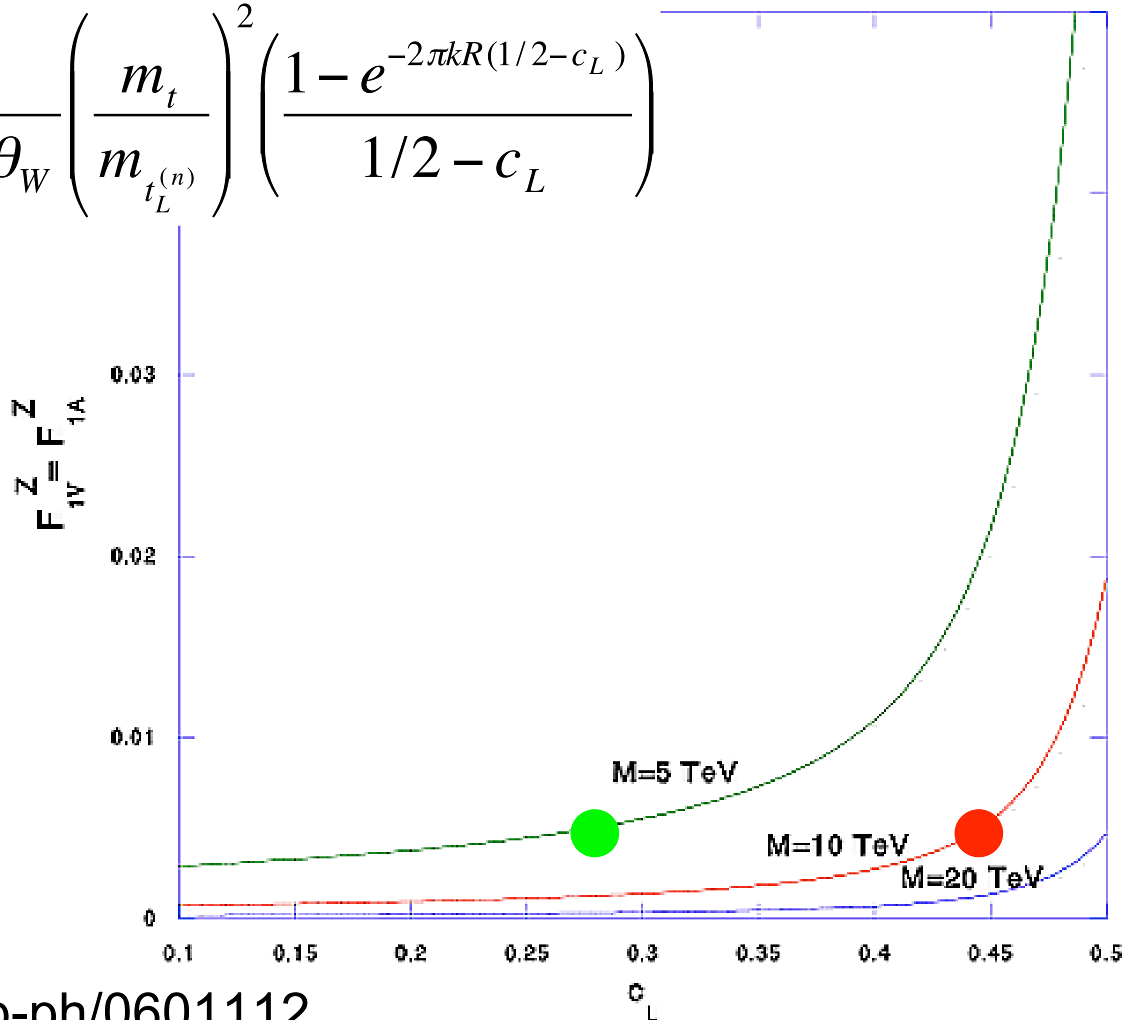
M_{KK} = 5 TeV

F^Z_{1V} : .005

Effects of KK Fermions

$$\delta F_{1V}^{Z} = \delta F_{1A}^{Z} \sim \sum_{n} \frac{-1}{2\sin 2\theta_W}\left(\frac{m_t}{m_{t_L^{(n)}}}\right)^2 \left(\frac{1-e^{-2\pi kR(1/2-c_L)}}{1/2-c_L}\right)$$

$$F_{1V}^{Z} \;:\; .005$$
$$F_{1A}^{Z} \;:\; .004$$



Mixing of top and KK-top quarks

Agashe, hep-ph/0601112

Effects of Brane Kinetic Terms

$$S = -\int d^4x \int_0^{\pi R} dy \sqrt{-G} \left(i\overline{\Psi}\,\Gamma^A e_A^M D_M \Psi + im(y)\overline{\Psi}\,\Psi + 2\alpha_f \delta(y-\pi R)\overline{\Psi}_L \gamma^a e_a^\mu \partial_\mu \Psi_L \right)$$

brane kinetic term

- For $\alpha > 0$:
  - IR ($y = \pi R$) BKTs repel KK-wavefunctions from brane
  - Decreases coupling of zero-mode fermions to KK-gauge bosons

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

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