Phenomenology of Higgsless models

Ben Lillie

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Outline

- Introduction and motivation
- Formalism
- Precision Electroweak constraints
- Other collider signatures
- Conclusion

Motivation

Randall-Sundrum Model

One extra dimension with a warped background:

$ds^2 = \left(\frac{R}{z}\right)^2 (dx^2 - dz^2)$, $R = 1/k$,

k is the AdS curvature.

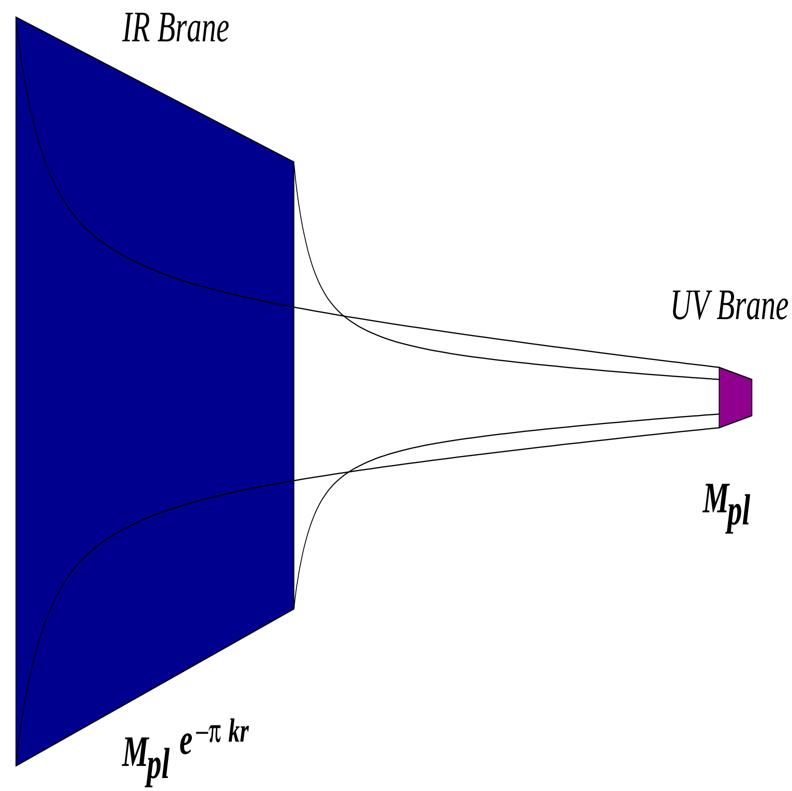
Two branes, one at R, the other at $R' = \frac{M_{Pl}}{TeV} R$.

Masses get scaled by $M \to \frac{R}{R'} M$.

Solves the Hierarchy Problem!

$\Rightarrow \log(R'/R) \approx 35$.

(Will often use $\epsilon = \frac{R}{R'} \sim 10^{-16}$.)



Randall, Sundrum hep-ph/9905221

Where do the SM fields go?

On TeV brane $\Rightarrow$ large 4-fermi opperators: $\frac{\lambda}{\Lambda^2_{\mathrm{TeV}}}\psi\bar{\psi}\psi\bar{\psi}$.

Solution to Hierarchy problem $\Rightarrow$ need to leave Higgs on TeV brane.

Also phenomenological problems with Higgs in bulk

Davoudiasl, Hewett, Rizzo hep-ph/0006041

Can move fermions to Planck brane $\Rightarrow$ 4-fermi operators supressed by M_{Pl}.

But EWSB on TeV brane $\Rightarrow$ fermions in bulk $\Rightarrow$ gauges in bulk.

Gauge bosons in the bulk can lead to gauge coupling unification

Agashe, Delgado, Sundrum hep-ph/0212028 Agashe, Servant hep-ph/0411254

RS also solves the flavor problem

5D fermions are achiral, so we can write $c_\Psi k \bar{\Psi}\Psi$.

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

Coupling to EWSB: $\lambda_{\rm eff} \sim \psi_L(R')\psi_R(R')\lambda_{\rm L}$.

So the SM fermion spectrum can be obtained

with $\mathcal{O}(1)$ Lagrangian parameters.

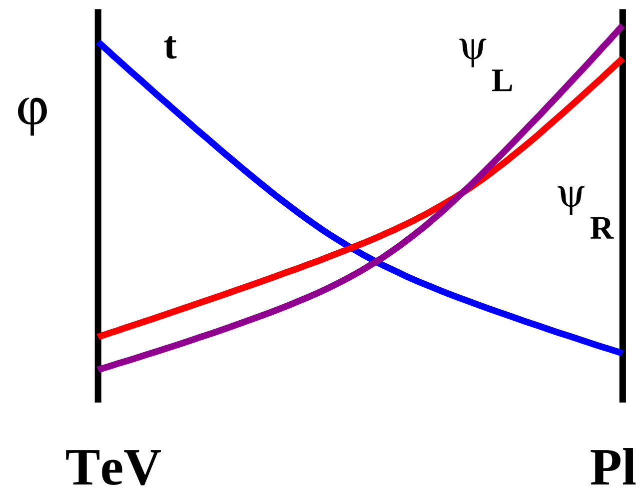
Although we'll want $\mathcal{O}(1/10)$ parameters.

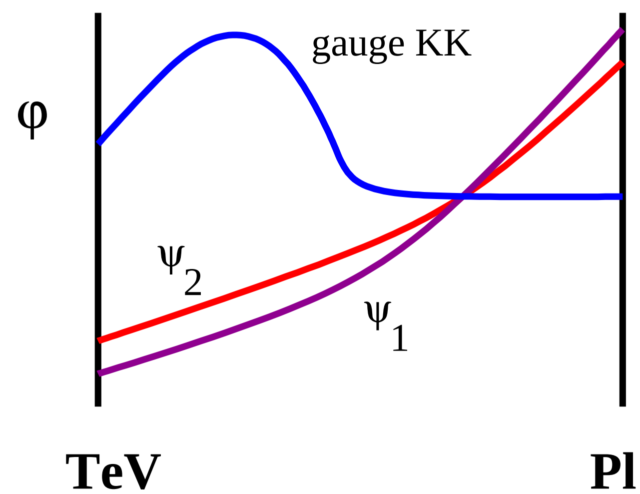
This also suppresses flavor-changing operators.

Supression active for 1st and 2nd generation,

predict new effects in 3rd gen.

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





Need a way to enforce $SU(2)_{\rm custodial}$

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

Expand gauge group: $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$.

Break $SU(2)_R \times U(1)_{B-L} \to U(1)_Y$ on Planck brane,

$SU(2)_L \times SU(2)_R \to SU(2)_D$ on TeV brane

$\Rightarrow$ only $U(1)_Q$ completely unbroken.

Note $SU(2)_{\rm Custodial} = SU(2)_D$

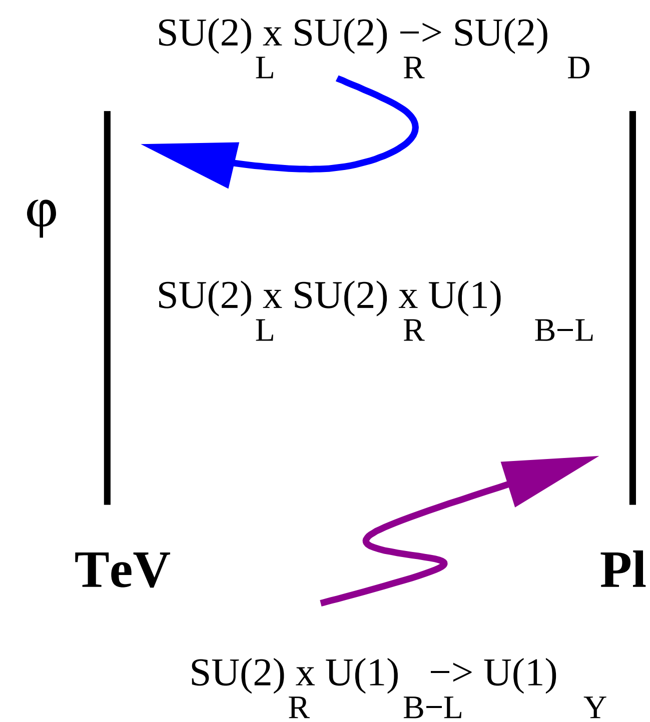
$\longrightarrow$ only broken on Planck brane.

Put right-handed fermions into $SU(2)_R$ multiplets.

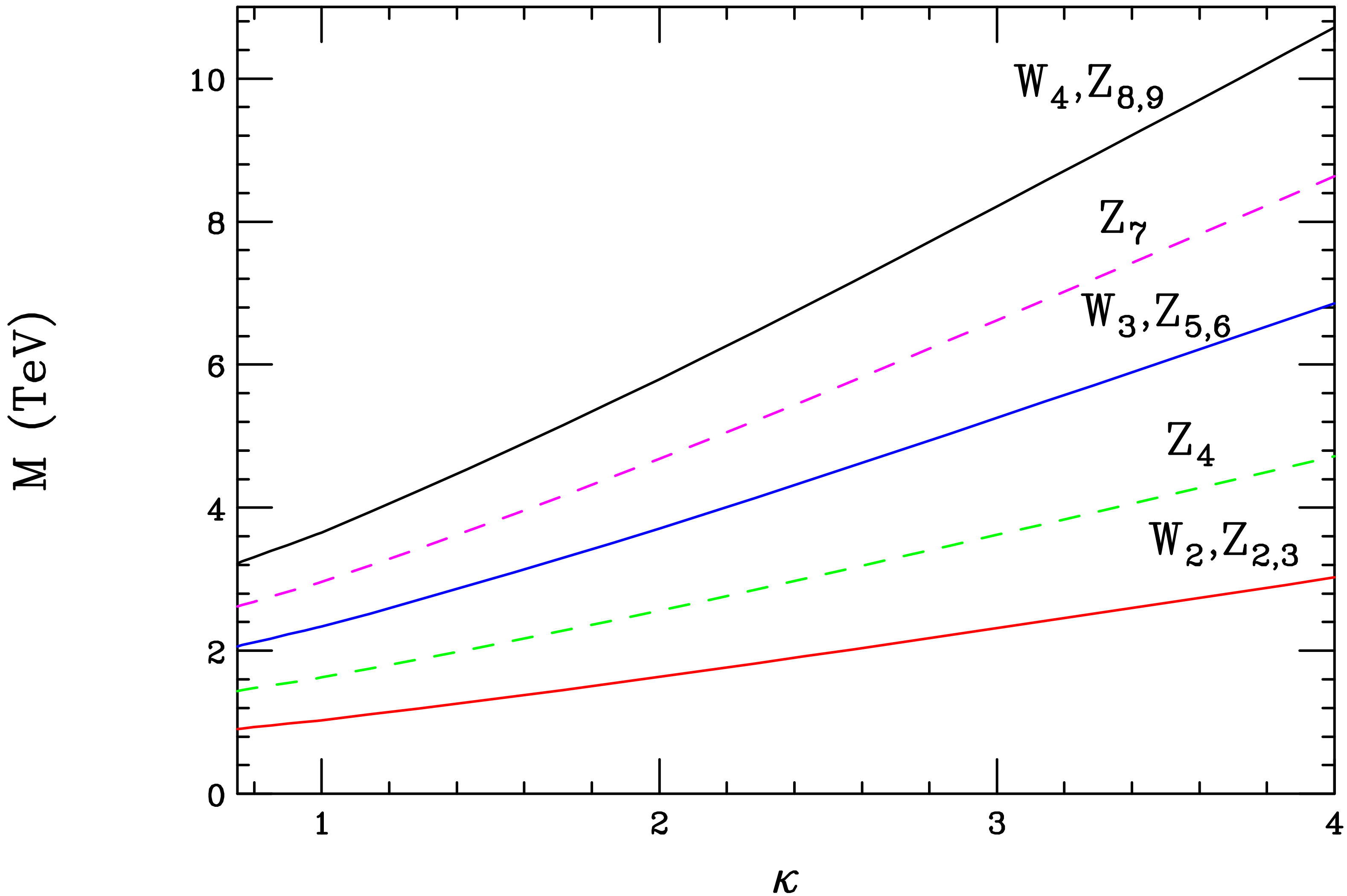
$$Q_R = \begin{pmatrix} u_R \\ d_R \end{pmatrix}.$$

Define $\kappa = \frac{g_{5R}}{g_{5L}}$, $\lambda = \frac{g_{5B}}{g_{5L}}$.

Agashe, Delgado, May, Sundrum hep-ph/0308036



$Z' Masses$



Brane Localized Kinetic Terms

We can also add to the action

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

for each unbroken gauge group i.

Carena, Tait, Wagner `hep-ph/0207056`

Davoudiasl, Hewett, Rizzo `hep-ph/0212279`

Also for fermions

$$S_{\rm brane} = \int d^5x\sqrt{G}2i\alpha_f\bar{\Psi}\gamma^a e_a^\mu\partial_\mu\Psi\delta(z - z_{\rm brane}).$$

for each fermion f.

These can improve agreement with precision EW observables.

Carena, Delgado, Ponton, Tait, Wagner `hep-ph/0410344`

Electroweak Constraints

- Require *rough* agreement with tree-level SM relations. In our scheme:

$1 - \sin^2\theta_{\rm os} \equiv \frac{m_W^2}{m_Z^2}$. $\lambda(= g_{5B}/g_{5L})$ fixed by M_Z

We can also define:

$\sin^2\theta_{eg} \equiv \frac{e^2}{g^2_{\mu\bar{\nu}W_1}}$ Could be any light fermion

From the coupling of the neutral KKs to fermions, as measured on the Z-pole:

$$\sqrt{\rho^Z_{\rm eff,f}}\,\frac{g_{f\bar{f}W_1}}{c_W^{\rm os}}\left(T_{\rm 3L} + \sin^2\theta_{R,f}T^3_R - \sin^2\theta_{\rm eff,f}Q\right)$$

- In the SM at *tree-level*, all these must be equal.
- Note

$$\rho^Z_{\rm eff,f} = g^2_{Z_1 f\bar{f}}/g^2_{W_1 f\bar{f}}.$$

We can match this onto the 5D covariant derivative:

$$\int_R^{R'} \frac{dz}{z}\, g_{5L} \left(T^{aL} A^{aL} + \kappa T^{aR} A^{aR} + \lambda \frac{B-L}{2} B \right)$$

For neutral bosons $\longrightarrow$

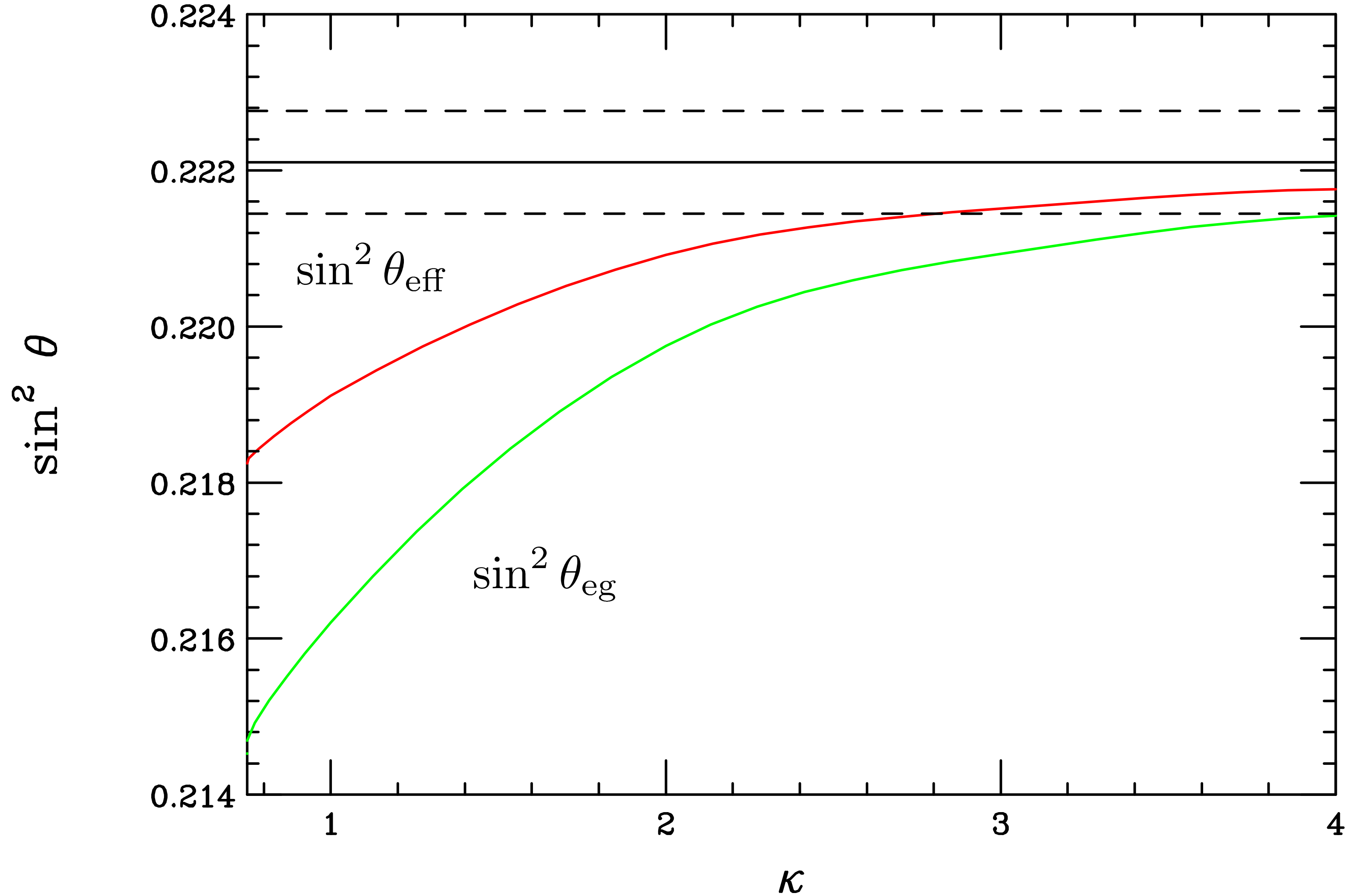
$$\underbrace{g_{5L}(I^{3L} - \lambda I^B)}_{g_{f\bar{f}Z^{(n)}}} \left(T^{3L} + \underbrace{\kappa \frac{(\kappa I^{3R} - \lambda I^B)}{(I^{3L} - \lambda I^B)}}_{\sin^2\theta_{R,f}} T^{3R} + \underbrace{\frac{\lambda I^B}{(I^{3L} - \lambda I^B)}}_{-\sin^2\theta_{\mathrm{eff,f}}} Q \right) Z$$

Where $I^i = \int_R^{R'} dz/z\, \zeta_i \psi_f \psi_{\bar{f}}$. $\sin^2\theta_{R,f} = 0$ for planck brane fermions.

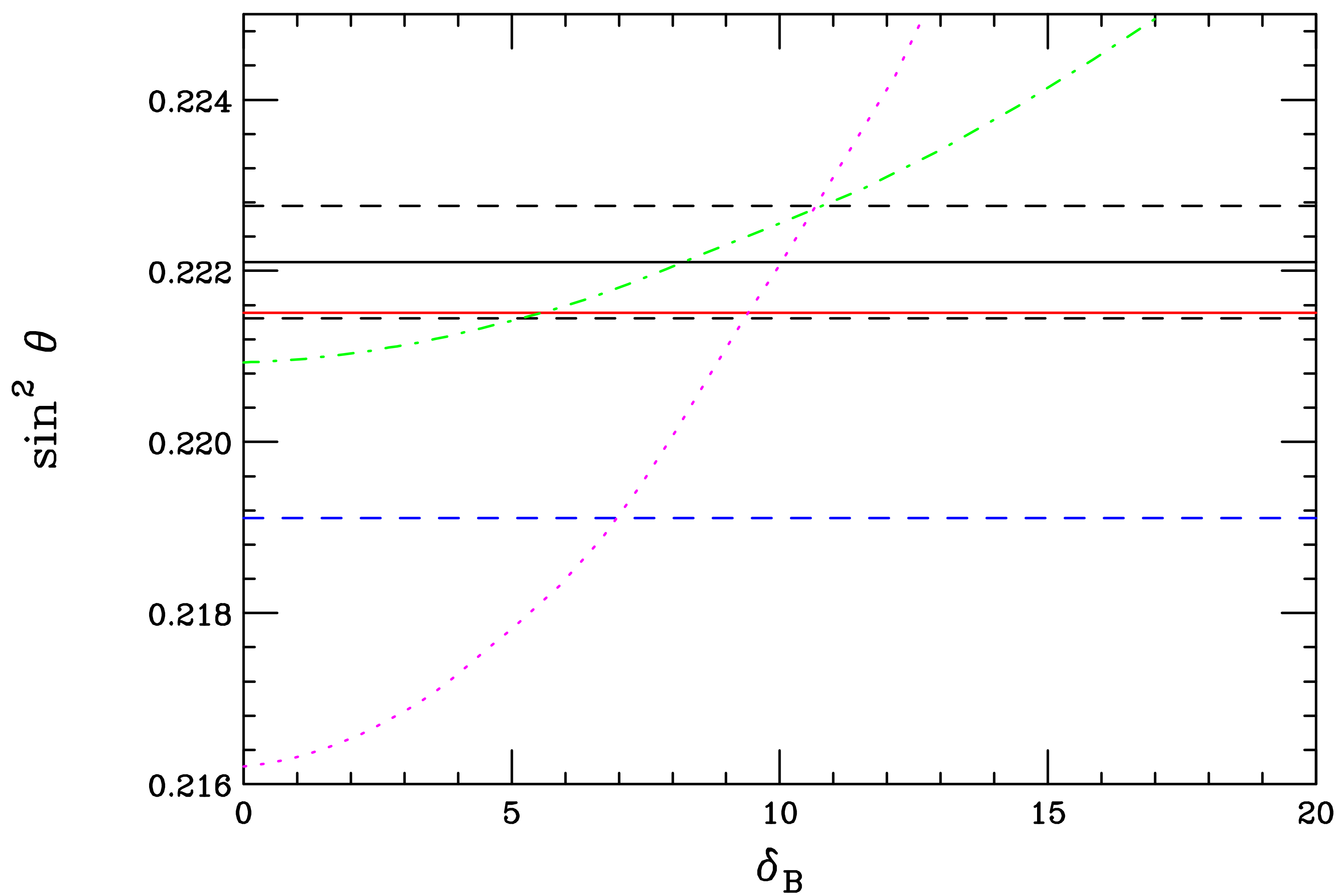
Similarly for charged bosons.

Cacciapaglia, Csaki, Grojean, Terning `hep-ph/0409126`

$$\kappa = g_{5R}/g_{5L}$$



$$\kappa = g_{5R}/g_{5L} = 1, 3$$



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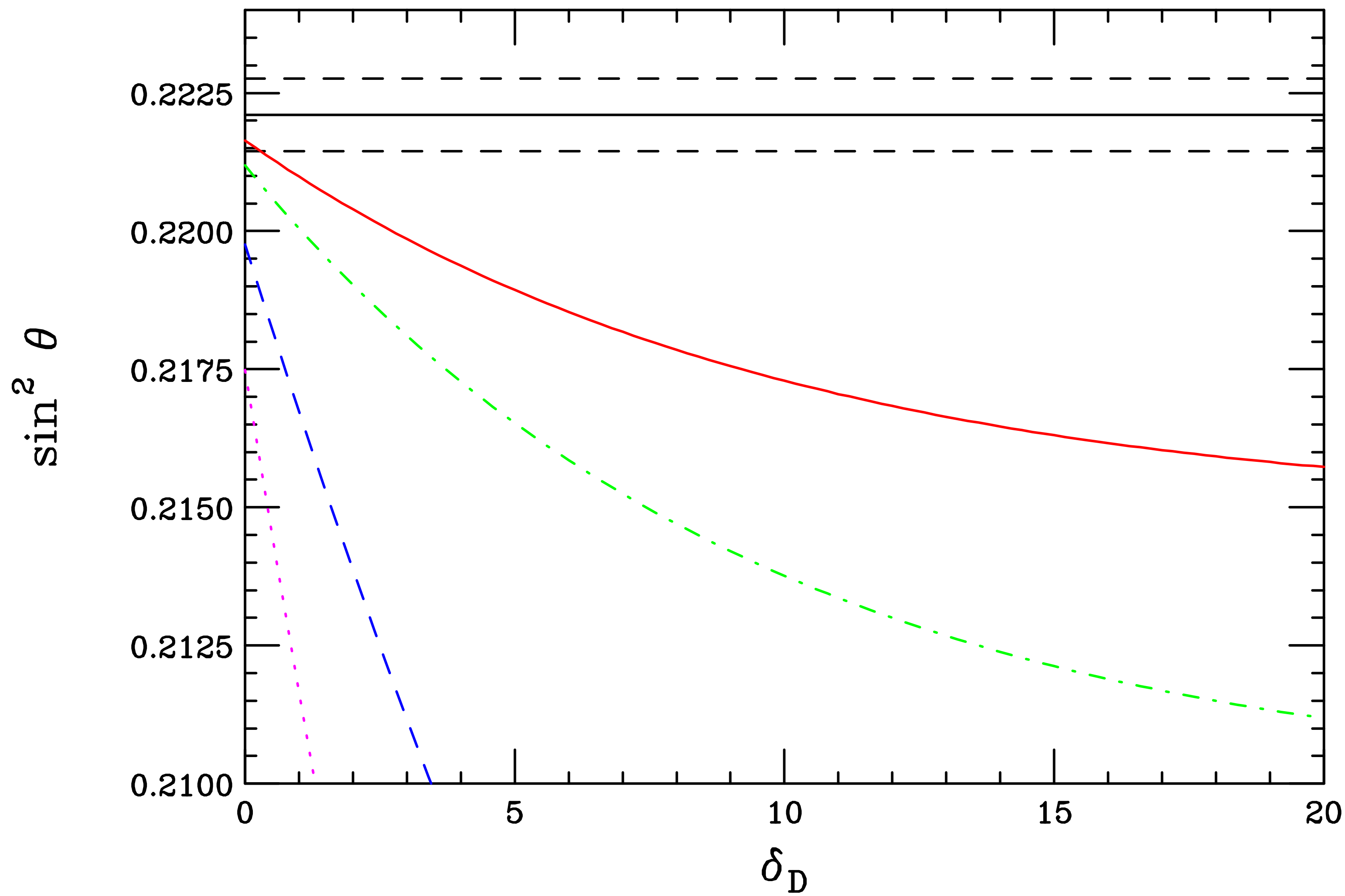
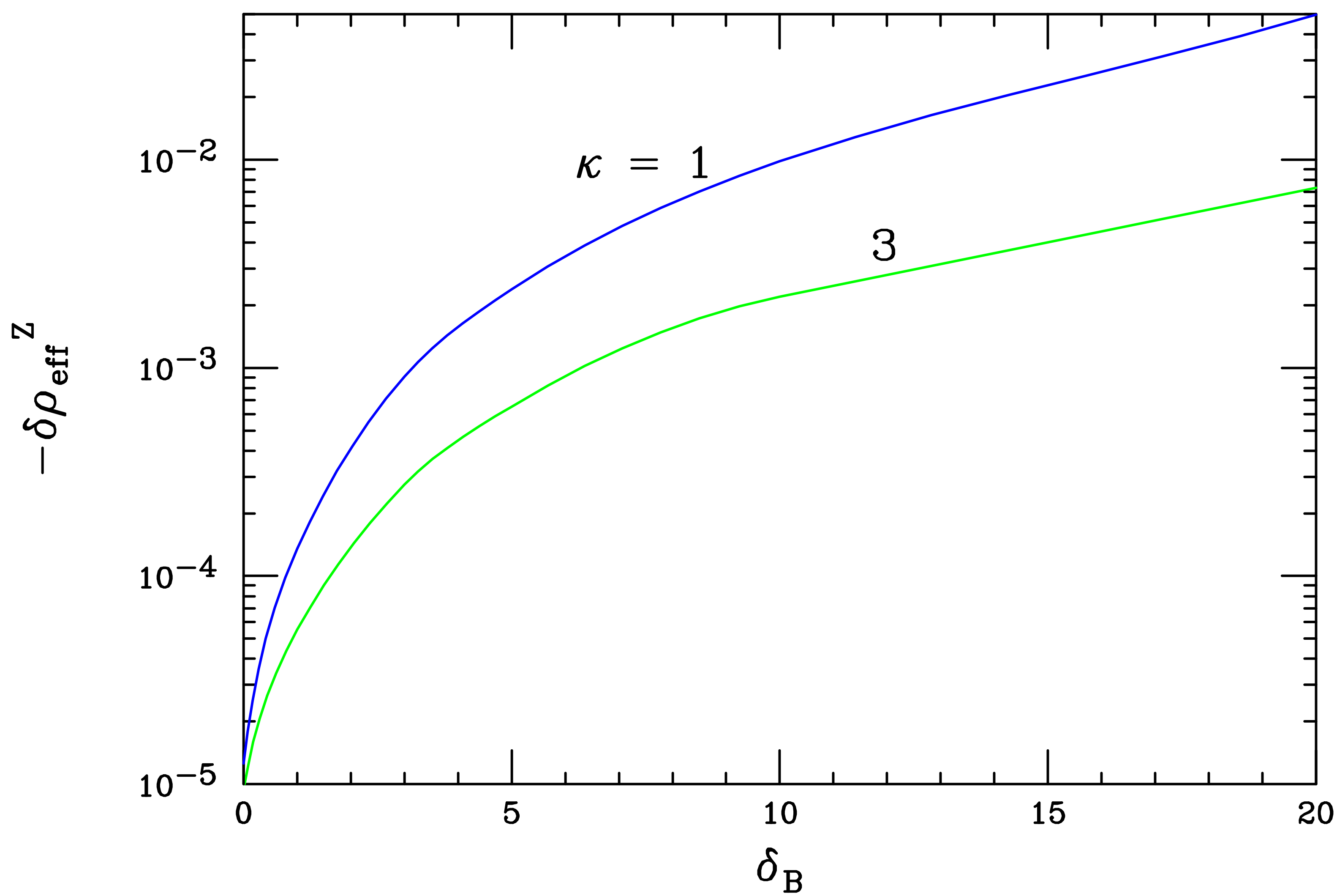


$$\kappa = g_{5R}/g_{5L}$$



Perturbative Unitarity

We look at the S-wave partial amplitude, a_0.

$$a_0 = \frac{1}{32\pi} \int_{-z_0}^{z_0} d\cos\theta\, A(W_L^+ W_L^- \to W_L^+ W_L^-)$$

Apply the partial wave unitarity test

$$|\mathrm{Re}(a_0)| \le \frac{1}{2}$$

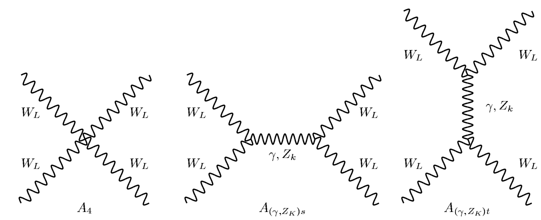
All numerical calculations done independently on at least two platforms. Required agreement to 12 digits.

Angular cut $z_0 \sim 0.99$ to remove photon pole. Checked stability to variation of z_0.

Expand at high $\sqrt{s}$

$$A \approx A_4 \frac{s^2}{m_W^4} + A_2 \frac{s}{m_W^2} + A_0 + \mathcal{O}(1/s)$$

In Higgsless limit: two sum rules guarantee cancellation



$$A_4 \sim g_{1111}^2 - \sum_{k=\gamma,1}^{\infty} g_{11k}^2 = 0$$

$$A_2 \sim 4 m_W^2 g_{1111}^2 - 3 \sum_{k=1}^{\infty} m_k^2 g_{11k}^2 = 0$$

The first is zero by completeness of wavefunctions. The second is true for pure Neumann or Dirichlet boundary conditions.

Note: these are Necessary, but not Sufficient conditions for perturbative unitarity.

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

hep-ph/0302263 Chivukula, Dicus, He, and Nandi

Results:

In SM without a Higgs, find Perturbative Unitarity Violation at 1.7 TeV.

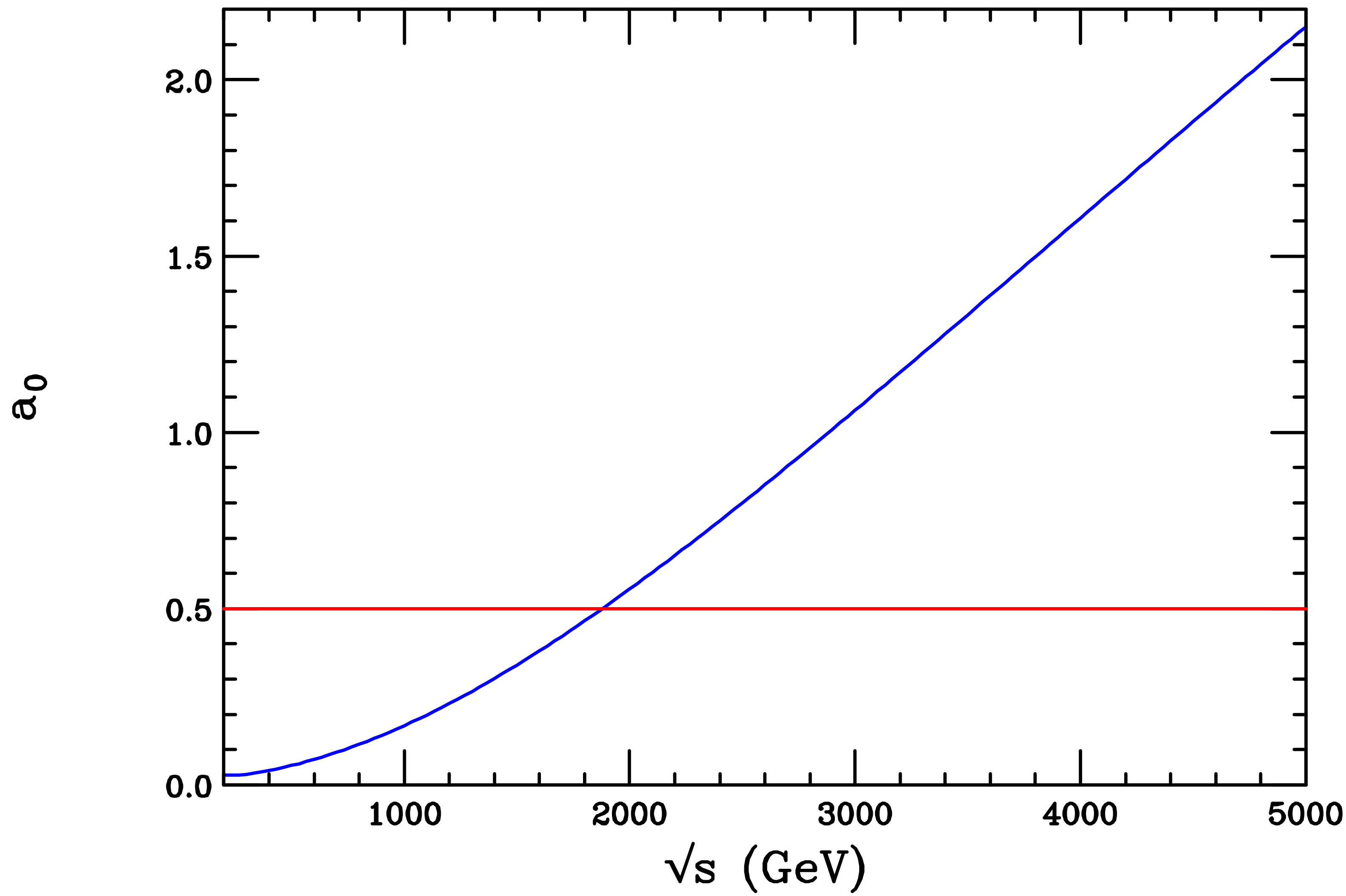
Direct application in Higgsless models generically produces a low PUV scale

Lower than NDA scale: $\epsilon \frac{24\pi^3}{g_5^2}$

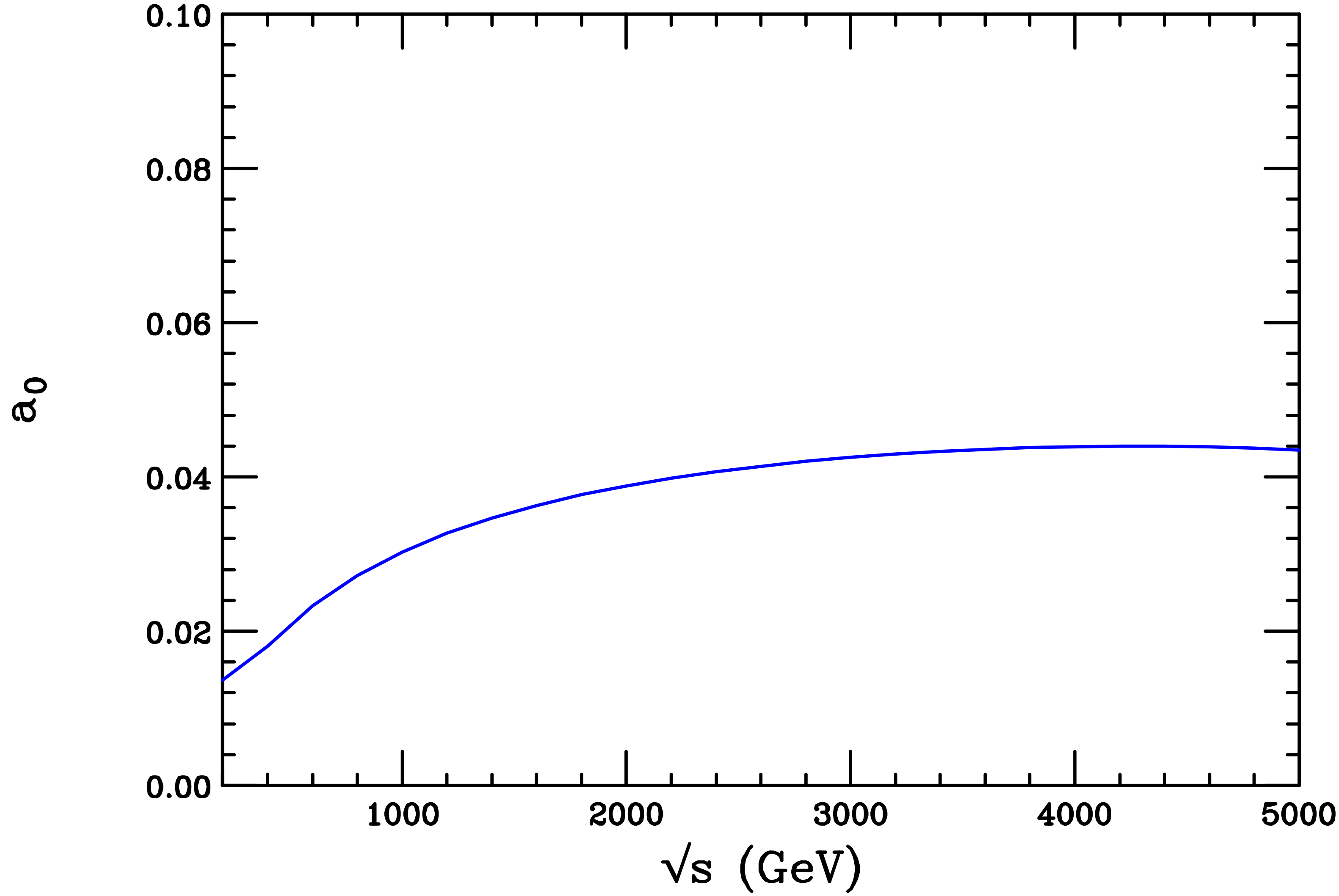
Questions about interpretation of results

Cacciapaglia, Csaki, Grojean, Terning hep-ph/0409126

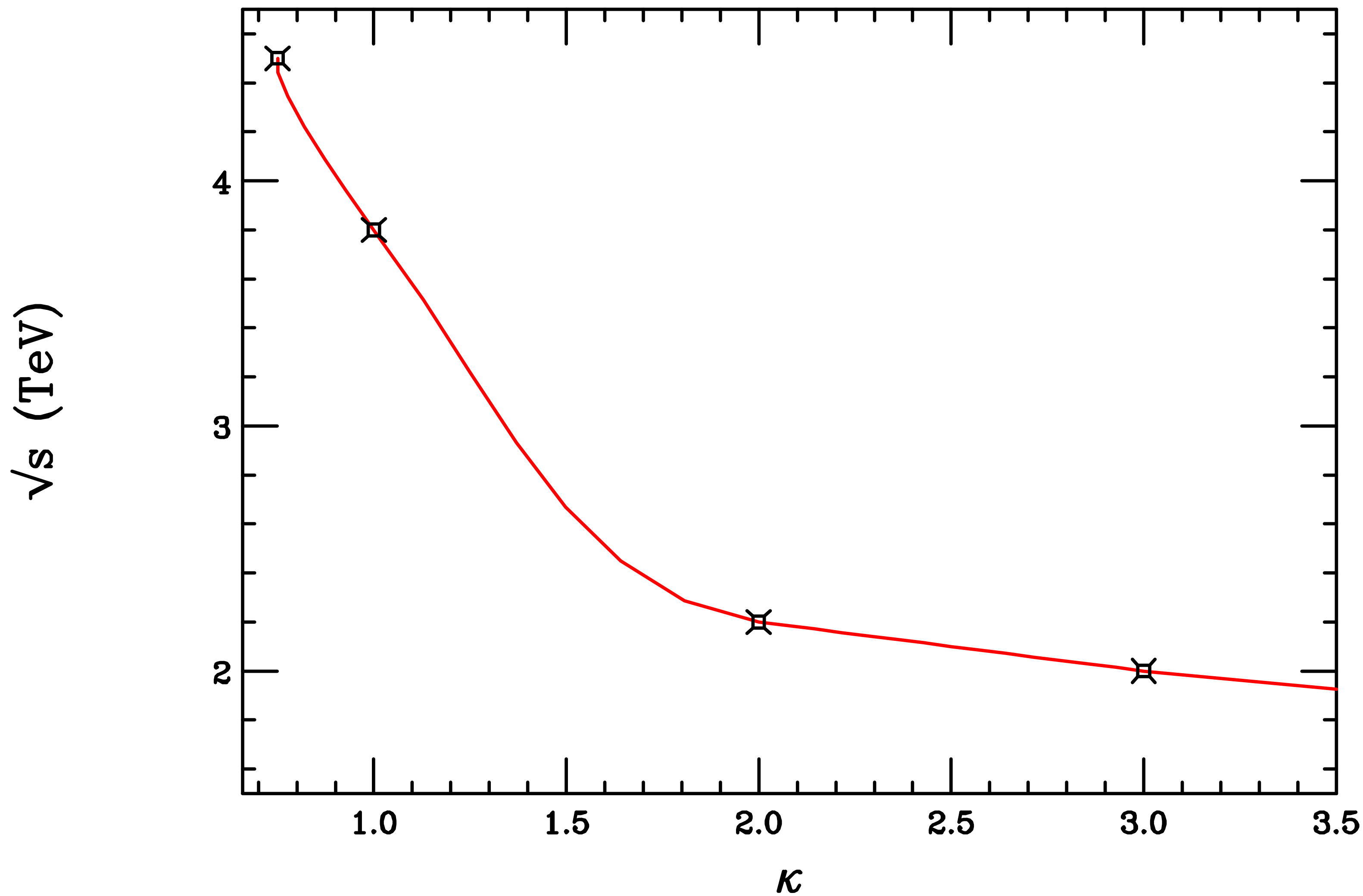
$$a_0,\, \kappa = g_{5R}/g_{5L} = 1$$



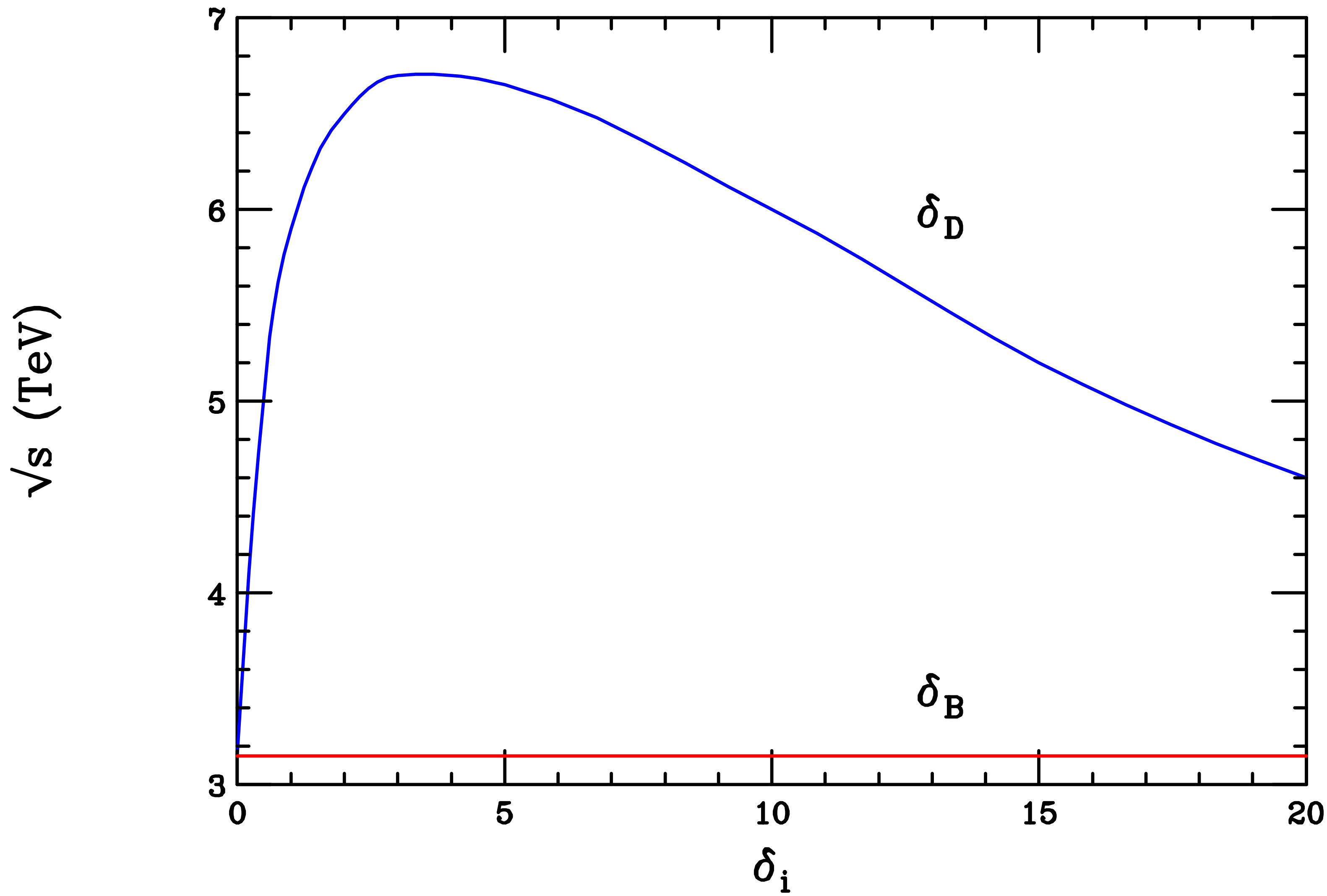
a_0, Flat Higgsless case



PUV scale



PUV scale, Brane-terms



Monte Carlo Exploration of Higgsless Models

For this survey, all fermions localized to Planck brane.

Allow gauge BLKTs, no fermion BLKTs.

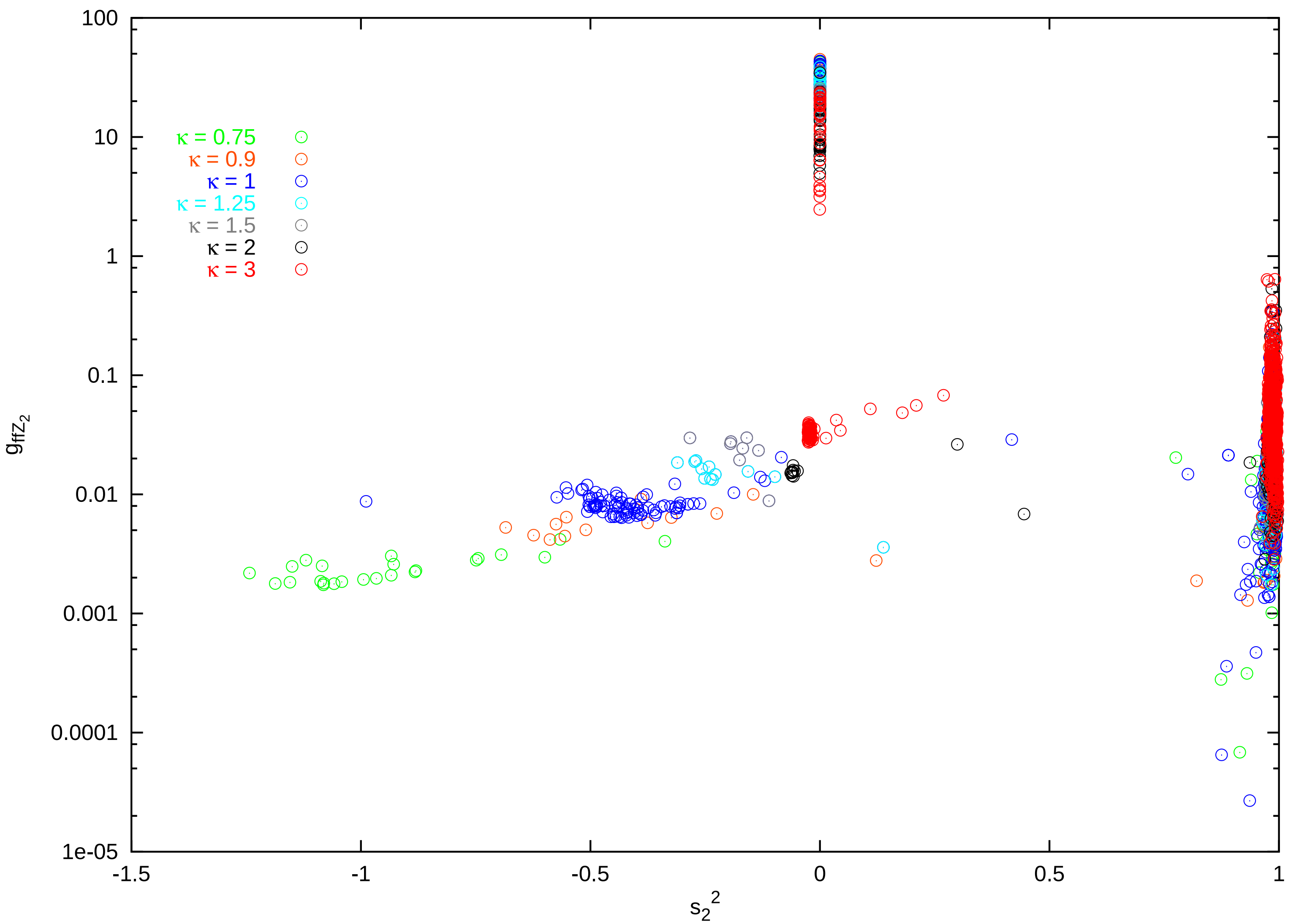
Pick parameter set $\{\kappa, \delta_i\}$, then demand

- No ghosts or tachyons.
- Consistency with precision electroweak tree-level relations
  $$|\delta\rho| < 0.005, \quad \frac{|\sin^2\theta_i - \sin^2\theta_{\rm OS}|}{\sin^2\theta_{\rm OS}} < 0.005.$$
- KK states not excluded by Tevatron or LEP II.
- KK states light enough and coupled correctly to help with perturbative unitarity

We tried $\sim$ 4.5 million points. About $12,000$ passed all electroweak and collider constraints. Zero passed perturbative unitarity constraints.

If we reduce the cut $0.005 \to 0.001$ volume shrinks by ~ 10.

Points passing precision electroweak cuts

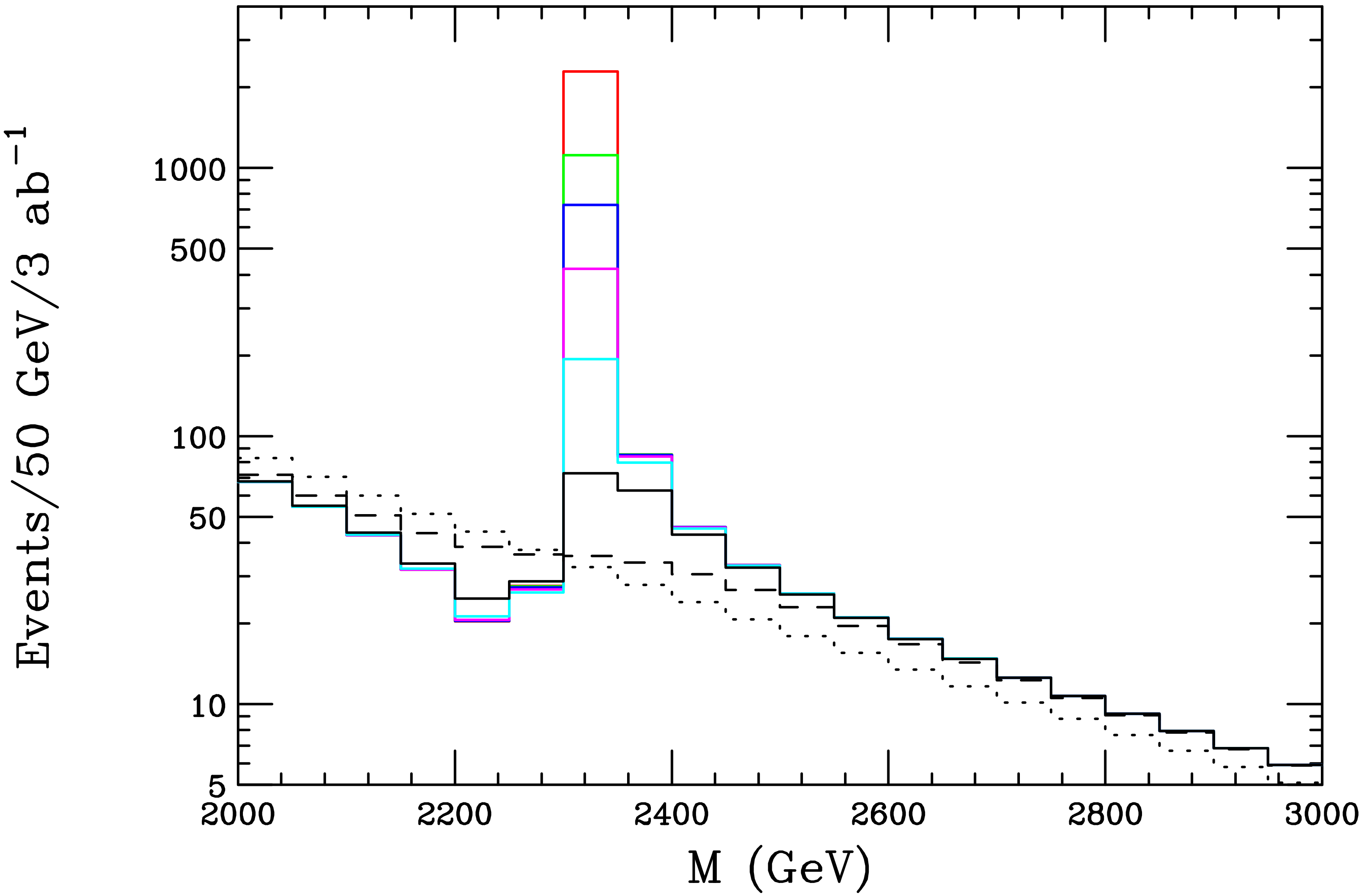


Generic Collider Signatures

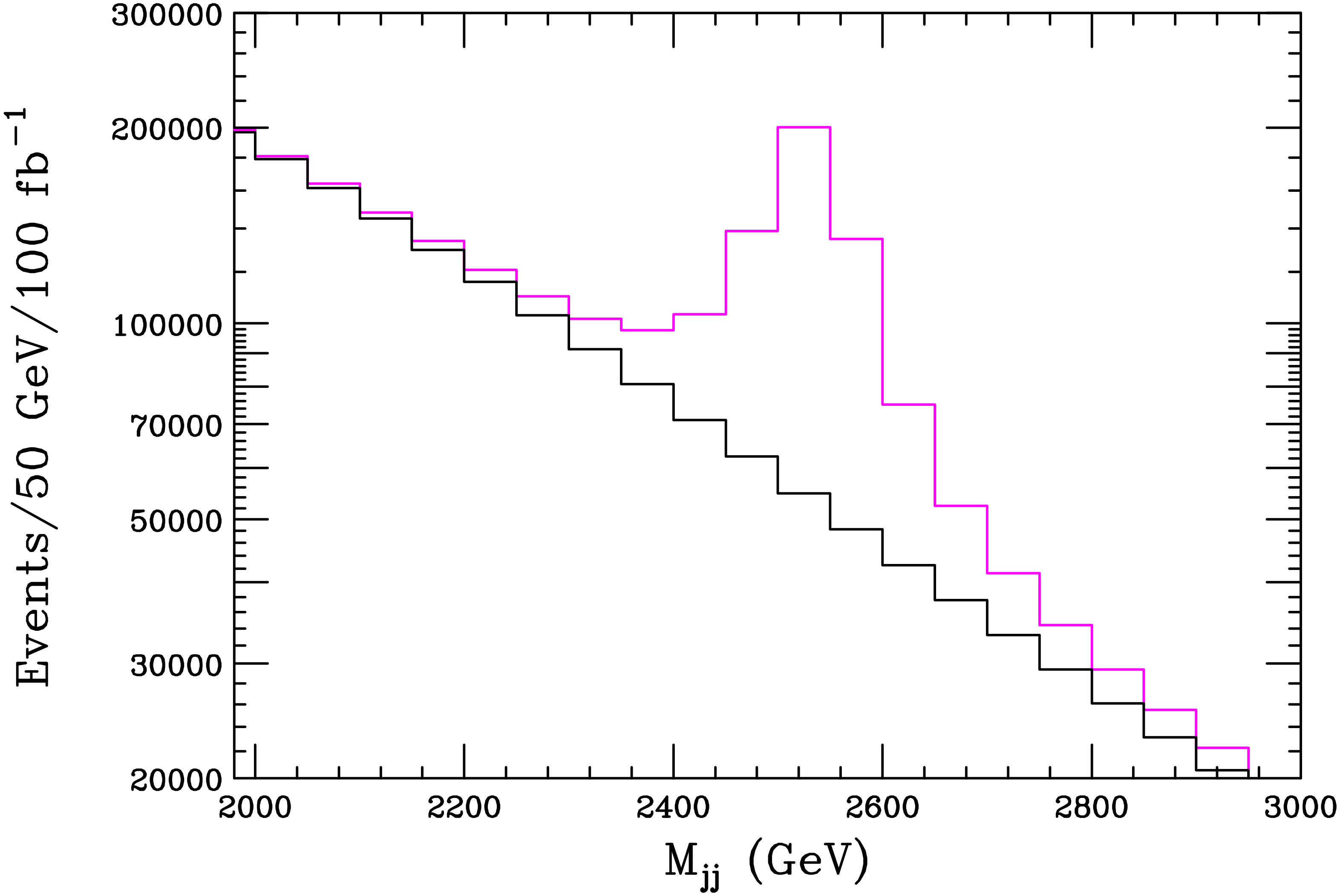
What does this model look like at colliders?

- First one or two electroweak gauge boson KK modes visible at the LHC
- First two or three gluon KK modes highly visible at LHC
- Features in $W_L W_L$ scattering.
- Graviton KK resonances at best difficult to see

Drell-Yan production

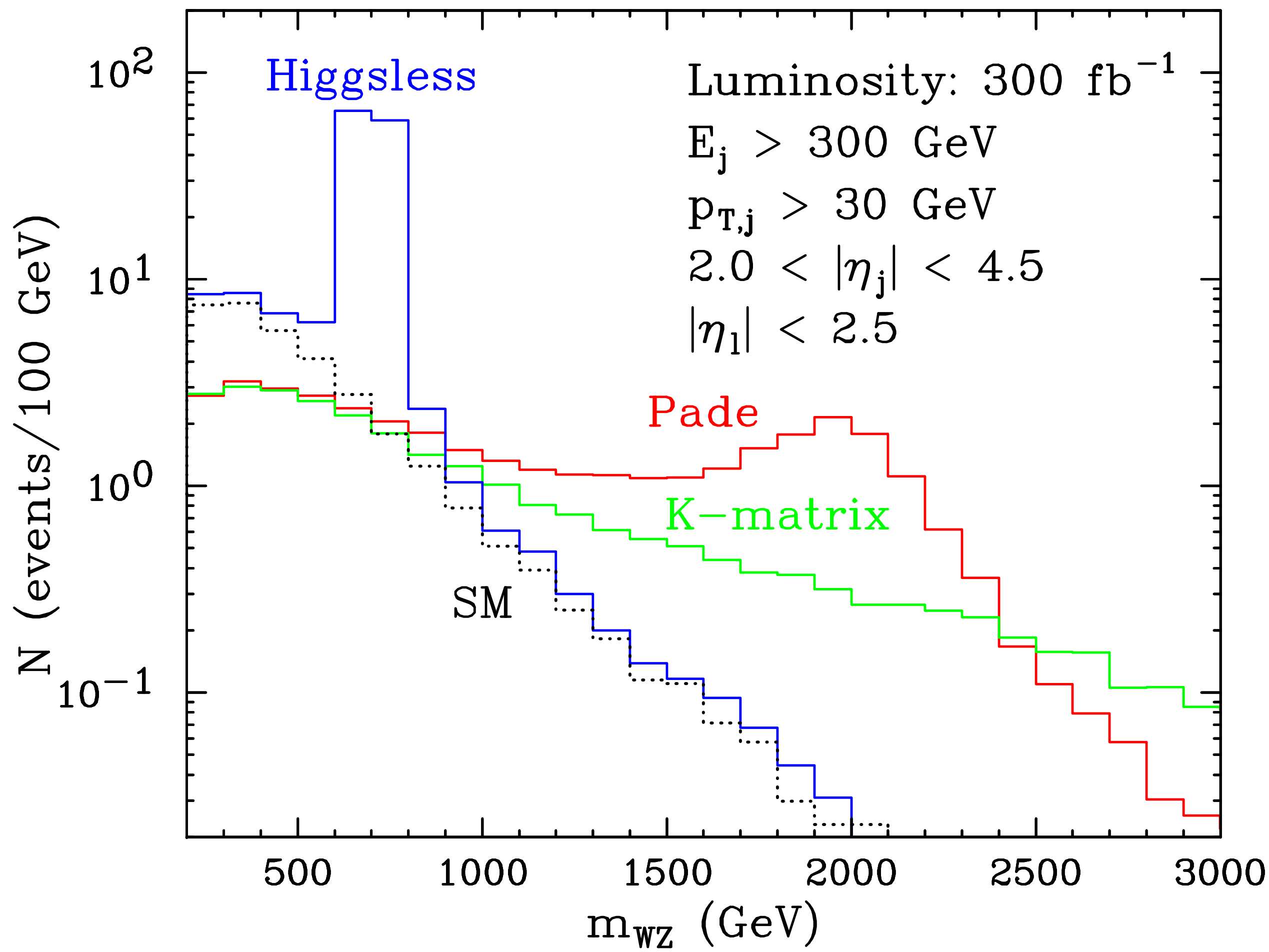


Dijets

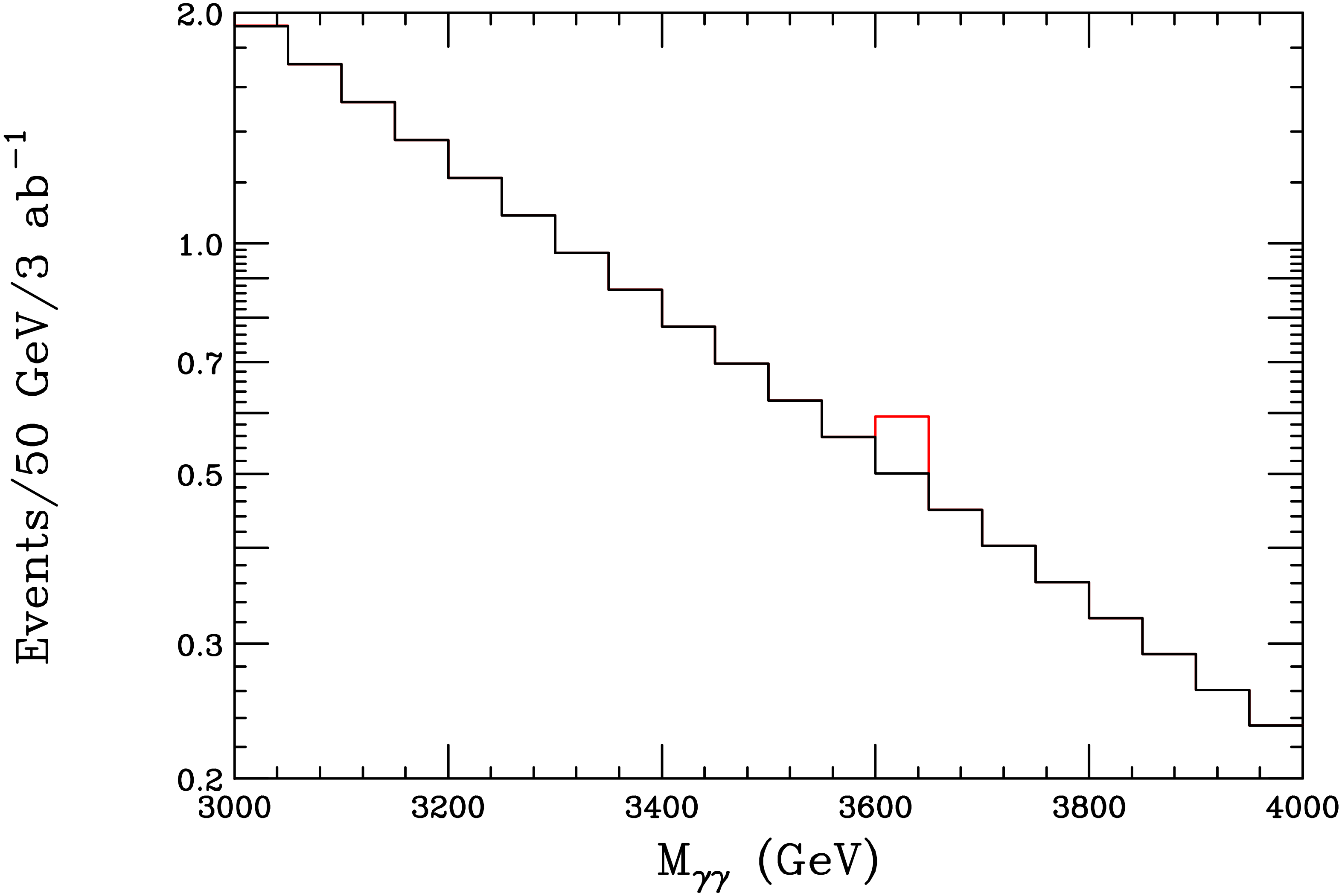

300000
200000
100000
70000
50000
30000
20000
Events/50 GeV/100 fb^{-1}
2000
2200
2400
2600
2800
3000
M_{jj} (GeV)

Resonances in WZ scattering

Birkedal, Matchev, and Perelstein hep-ph/0412278



Problem - No Graviton!



Conclusions

- Regions of parameter space are consistent with all precision electroweak and collider constraints
- Tension between precision EW and unitarity constraints
- Signals are easily visible at the LHC and possibly ILC