5-d Higgsless Theories

HOOMAN DAVOUDIASL (IAS)

Based on:

H. D., J. Hewett, B. Lillie, and T. Rizzo:

- hep-ph/0312193
- JHEP 0405:015, 2004 (hep-ph/0403300).

Introduction

Electroweak Symmetry Breaking (EWSB) in SM:

$SU(2)_L \times U(1)_Y \to U(1)_{EM} \Rightarrow$ Massive $W^{\pm}, Z$; $m_W, m_Z \sim 100$ GeV

⊕ Simple Picture: One Higgs doublet, $\langle H \rangle = v$; $v \neq 0$.

$\Rightarrow m_W, m_Z \sim g v$; $v \sim 250$ GeV.

⊖ Hierarchy Problem: Why $m_H \sim 100$ GeV where there could be quantum corrections of $O(\Lambda_{UV}^2)$, $\Lambda_{UV} \sim \bar{M}_P, M_{GUT}, \ldots$?

Some Resolutions:

(A) Stabilize m_H: SUSY, Extra Dimensions.

(B) Eliminate the Higgs: Technicolor.

(B) ⇒ A 4-d Higgsless model with EWSB via new strong dynamics at ~ TeV, $\langle \bar{Q} Q \rangle \neq 0$, analogous to chiral symmetry breaking in QCD.

Technicolor:

(+) Dynamical, no need for fundamental scalars (which are as yet unobserved in Nature).

(−) Strong dynamics at $\Lambda \sim 4\pi v \sim 3\,\text{TeV}$.

$\Rightarrow$ Reliable calculations of precision EW observables difficult.

Q: Is there another Higgsless mechanism for mass generation?

A: Yes, the Kaluza-Klein (KK) idea.

$D = 4 + \delta$; δ dimensions of size R.

Let $\delta = 1 \Rightarrow m_{KK} = n/R$, $n = 0, 1, 2, \ldots$

m_{KK} : Momentum in extra dimensions.

$$P_5^2 = 0 = P_4^2 - (p^5)^2 \Rightarrow P_4^2 = (p^5)^2 = m_{KK}^2$$

Massless 5-d field $\xrightarrow{KK}$ Massive 4-d field

Could $m_W \neq 0$ be caused by a KK-reduction?

Two problems:

(I) Where is the zero mode? $n=0 \Rightarrow m_{KK}=0$.

(II) KK picture : geometry $\rightarrow$ $m_W = m_Z = 1/R$.

Solution: Boundary Conditions (BC's).

(I) $A(x^\mu, y) = \sum_{n=0}^{\infty} A^{(n)}(x^\mu)\, \chi^{(n)}(y)$.

Zero mode : $\chi^{(0)} = \text{Constant}$.

BC: $A(x^\mu, y)\big/_{y=0,R} = 0 \Rightarrow \chi^{(0)} = 0$ $\Rightarrow$ Zero mode removed.

(II) Non-trivial BC's, combining appropriate components of the gauge group.

$\Rightarrow$ Distinguish $W^\pm$ from Z.

$\Rightarrow m_W \neq m_Z$.

An important function of the Higgs in the SM is to unitarize $W_L^+ W_L^- \to W_L^+ W_L^-, \ldots$, by cancelling contributions that grow with energy E.

Q: What if $W^\pm, \ldots$, are massive KK modes in a Higgsless $D > 4$ theory?

Chivukula, Dicus, He Phys. Lett. B525, 175 (2002).

A: $O(E^4)$ and $O(E^2)$ terms still cancel due to the contribution from the tower of KK states.

However, perturbation theory breaks down in $D > 4$, since $g_D^2 \sim \Lambda_D^{-\delta}$.

Chivukula, Dicus, He, Nandi Phys. Lett. B 562, 109 (2003). ($D = 4+\delta$)

From naive dimensional analysis: Manohar, Georgi, Nucl. Phys. B234 (1984).

 $\propto g_D^2 \int \frac{d\Omega_D}{(2\pi)^D} \sim \frac{g_D^2}{(4\pi)^{D/2}\,\Gamma(D/2)} \sim \Lambda_D^{-\delta}$

$D=5$: $g_4^2 = g_5^2/(2\pi R)$; $m_W \sim 1/R$, $m_W/g_4 \sim v$

$\Rightarrow \Lambda_5 \sim 12\pi^2 v/g_4$; Recall $\Lambda_4 \sim 4\pi v$

$\Rightarrow \Lambda_5/\Lambda_4 \sim 3\pi/g_4 \sim 10 \to$ Larger weakly coupled regime for $D=5$.

Motivated by these considerations, Csaki et al. proposed a flat 5-d Higgsless model compactified on the interval $[0, \pi R]$; $SU(2)_L \times SU(2)_R \times U(1)$ in 5-d.

Symmetry breaking via BC's: Csaki, Grojean, Murayama, Pilo, Terning, hep-ph/0305237, Phys. Rev. D 69:055006, 2004.

$$\begin{cases} y=0: & SU(2)_L \times SU(2)_R \sim SO(4) \rightarrow SU(2)_D \\ y=\pi R: & SU(2)_R \times U(1) \rightarrow U(1)_Y \end{cases}$$

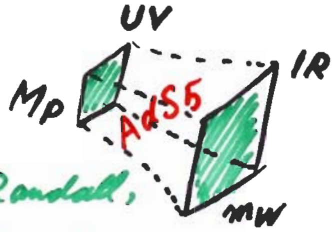
One generator $(7-3-3=1)$ survives ⇒ 4-d $U(1)_{EM}$.

This gives a pattern of masses and couplings similar to that in the SM. However, the model gives:

1) $\rho = \frac{m_W^2}{m_Z^2 \cos^2\theta_W} \approx 1.1$; 10% discrepancy with SM; too large!

2) $m_{KK} \gtrsim 240$ GeV, too small!

(Assuming unsuppressed fermionic couplings.)



Randall, Sundrum

Warped Background: AdS/CFT

Agashe, Delgado, May, Sundrum
JHEP 0308:050, 2003.

Bulk gauge symmetry ↔ CFT global symmetry

$SU(2)_L \times SU(2)_R \to SU(2)_D$ Custodial symmetry

It has been shown that the warped version of the Higgsless 5-d model ($y=0 \to$ IR-brane, $y=\pi R \to$ UV-brane) approximates the SM fairly well: $|\rho-1| \lesssim 0.01$.

Csaki, Grojean, Pilo, Terning, Phys. Rev. Lett. 92: 101802, 2004.

Loop-induced brane kinetic terms for gauge fields, of the form $-\frac{c}{4} F_{\mu\nu}F^{\mu\nu}\delta(y-\bar{y})$, can be important on UV-brane (Nomura).

Georgi, Grant, Hailu.

Y. Nomura, JHEP 0311:050, 2003.

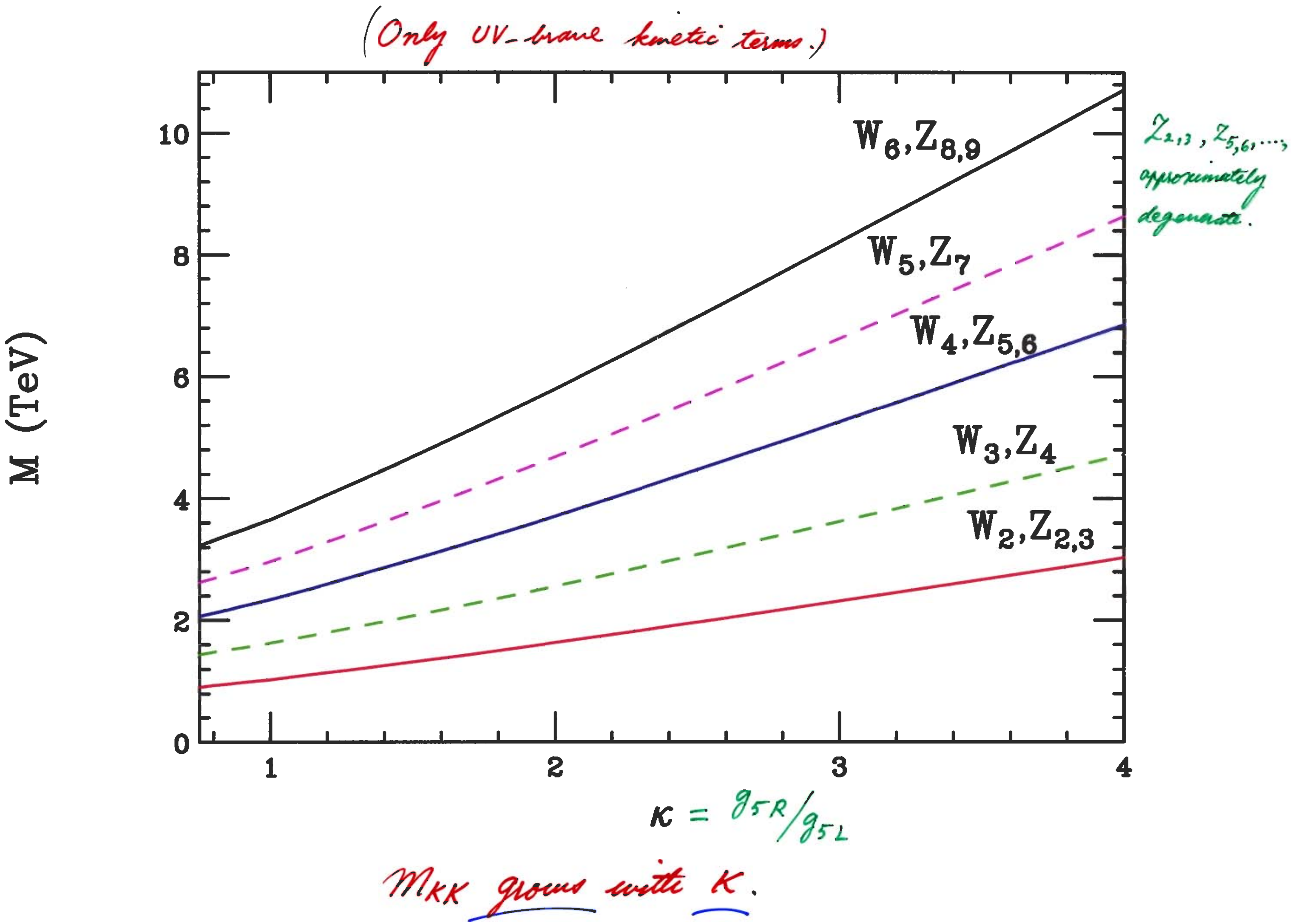
Phenomenology

Warped Higgsless Model (WHM).

H.D., Hewett, Lillie, Rizzo, hep-ph/0312193.

Loop-induced UV-brane terms for $SU(2)_L$ and $U(1)_Y$ (fixed by data). $\kappa \equiv g_{5R}/g_{5L}$, allow for $\kappa \neq 1$.

Bulk: $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$; Fermions on UV-brane.



(Only UV-brane kinetic terms.)
M (TeV)
0
2
4
6
8
10
1
2
3
4
$W_6, Z_{8,9}$
W_5, Z_7
$W_4, Z_{5,6}$
W_3, Z_4
$W_2, Z_{2,3}$
$Z_{2,3}, Z_{5,6}, \ldots,$ approximately degenerate.
$\kappa = g_{5R}/g_{5L}$
M_{KK} grows with κ.

8

Comparison with the SM

The on-shell definition of θ_W:

$$\cos^2\theta_W\Big|_{OS} \equiv \frac{m_W^2(SM)}{m_Z^2(SM)} \Rightarrow \sin^2\theta_W\Big|_{OS} \approx 0.2221$$

The $Z^{(n)}$ coupling to SM fermions can be written as:

$$\frac{g_{Z_n}}{\cos\theta_W|_{OS}}\left(T_{3L}^f - s_n^2 Q^f\right),$$

↳ given by wavefunctions.

where T_{3L}^f : 3rd component of isospin,

$s_1^2 \equiv \sin^2\theta_W\Big|_{eff}$, Q^f : electric charge.

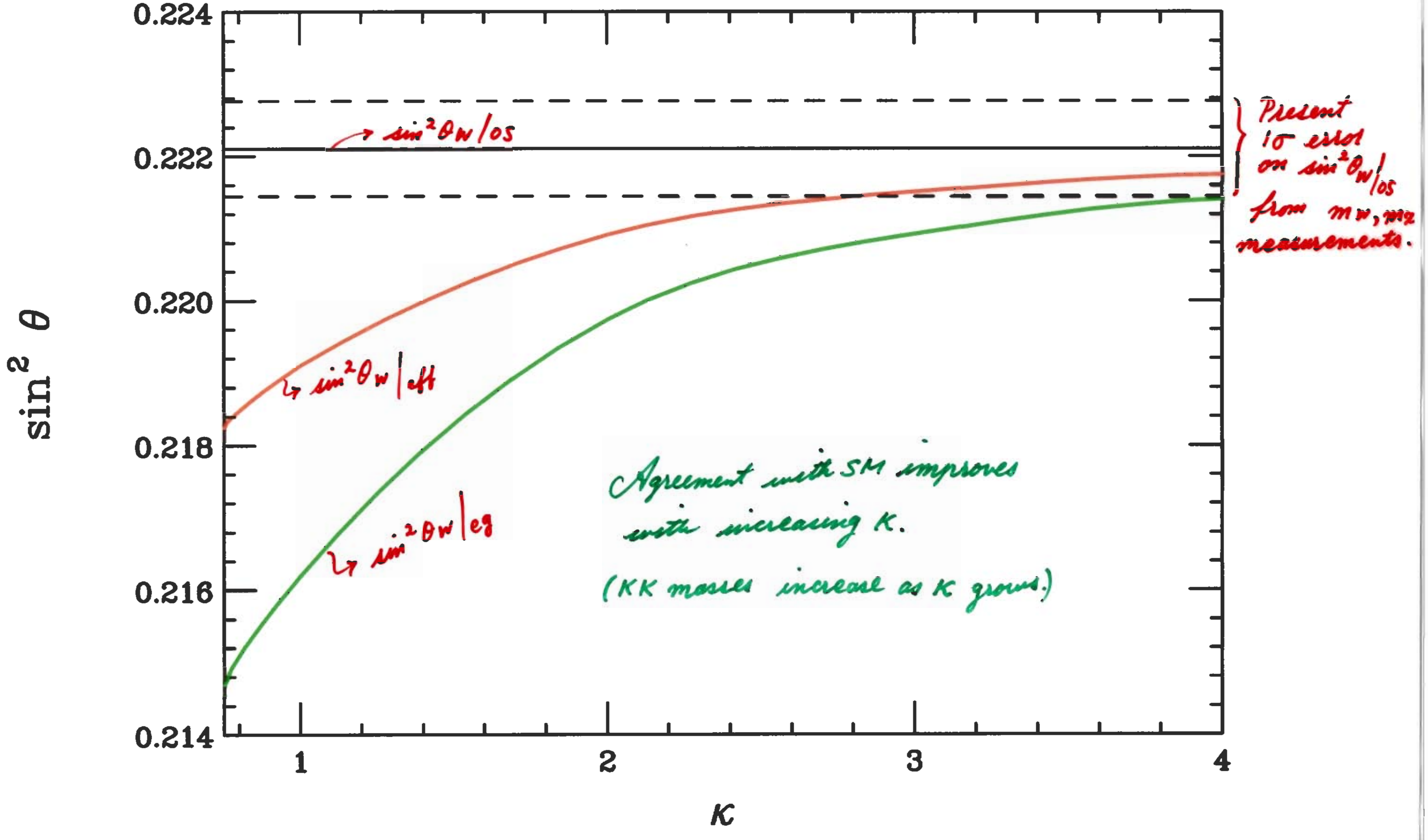
In addition, we define:

$$\sin^2\theta_W\Big|_{eg} = e^2/g_{W1}^2 ,$$

where the right-hand side can be calculated, given the input parameters. In SM, at tree level:

$$\sin^2\theta_W\Big|_{OS} = \sin^2\theta_W\Big|_{eff} = \sin^2\theta_W\Big|_{eg} .$$

We compute deviations from this relation in WHM.

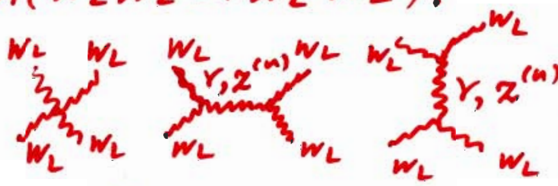

sin² θ
0.224
0.222
0.220
0.218
0.216
0.214
1
2
3
4
κ
sin²θW|os
sin²θW|eff
sin²θW|eg
Agreement with SM improves with increasing κ.
(KK masses increase as κ grows.)
Present 1σ error on sin²θW|os from mW, mZ measurements.

EW relations favor $K \gg 1$. However, the theory is no longer "weakly interacting" in this regime.

Barbieri, Pomarol, Rattazzi, hep-ph/0310285.
Burdman, Nomura, hep-ph/0312247.
Cacciapaglia, Csaki, Grojean, Terning, hep-ph/0401160.
Theory space analysis: Foadi, Gopalakrishna, Schmidt, JHEP 0403:042, 2004.
Barbieri, Pomarol, Rattazzi, Strumia, hep-ph/0405040

We consider tree-level unitarity of $A(W_L^+ W_L^- \to W_L^+ W_L^-)$.

Cancellation of $\mathcal{O}(E^4)$ and $\mathcal{O}(E^2)$ terms:



$$u_1 \equiv 1 - \sum_{n=1,\gamma}^{\infty} g_{11n}^2 / g_{1111}^2 = 0 \quad ; \quad u_2 \equiv 1 - \frac{3}{4} \sum_{n=1}^{\infty} \left(\frac{g_{11n}^2}{g_{1111}^2} \frac{m_{Z_n}^2}{m_{W_n}^2} \right) = 0 .$$

For $K = 3$, using the first 10 KK modes:

$u_1 \sim 10^{-7}$, $u_2 \sim 10^{-3}$; convergence improves with more KK modes.

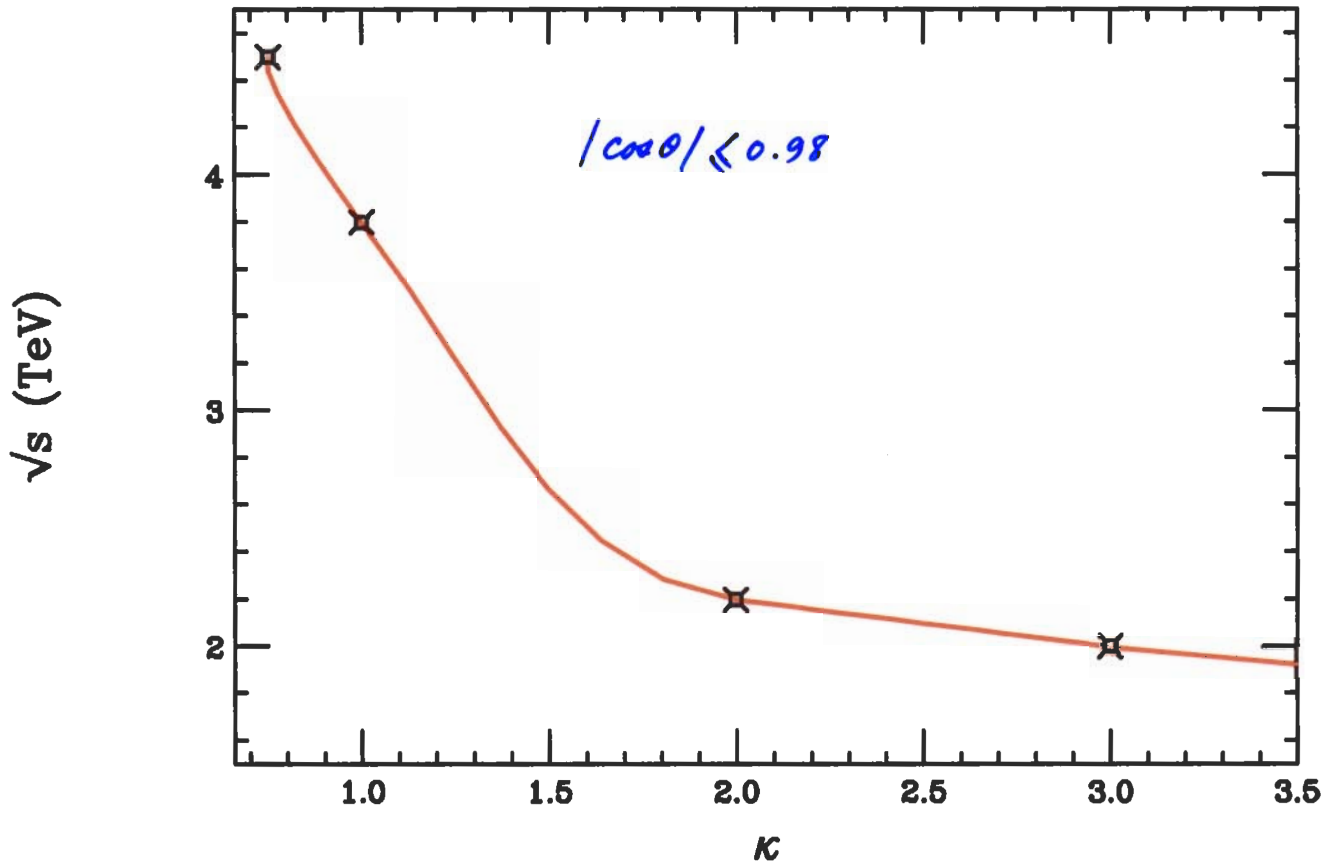
Tree-level unitarity:

$$\left| Re \left[\frac{1}{32\pi} \int_{-1}^{1} d(\cos\theta) \, (-iA) \right] \right| \leq 1/2 .$$

(We use $|\cos\theta| \leq 0.98$)

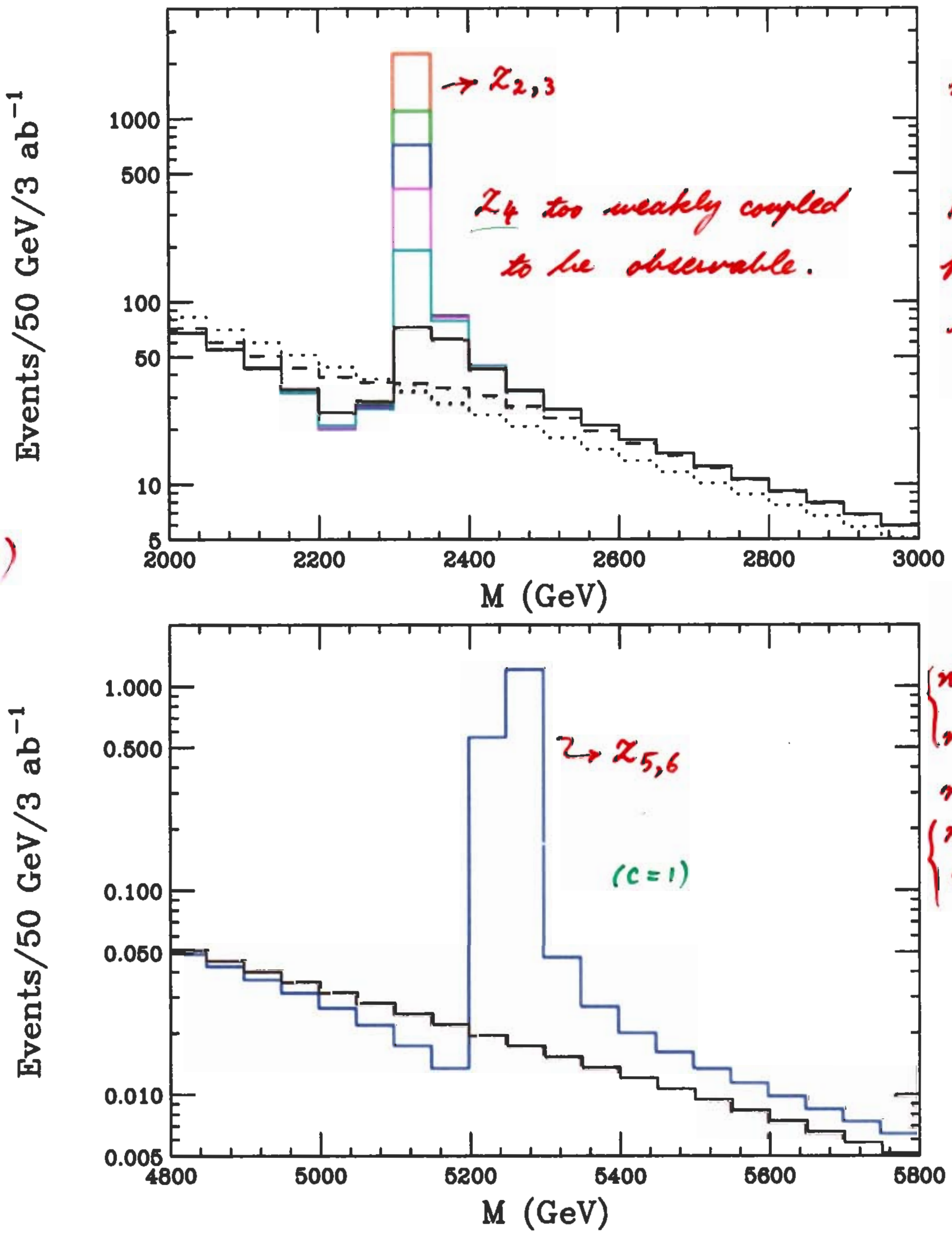
Scale of Tree-Level Unitarity Violation (TUV)

$W_L^+ W_L^- \rightarrow W_L^+ W_L^-$



Note: At each value of $\sqrt{s}$ in the above plot, addition of more KK modes worsens TUV. For $\kappa \lesssim 2$, we do not expect good agreement with EW precision data.

Drell-Yan Production (Z_n)



n^{th} KK width: $\Gamma_n = c\,\Gamma_n^0$; Γ_n^0 $\forall$ SM fermions on the UV-brane. $1 \leq c \leq 100$

($K = 3$)

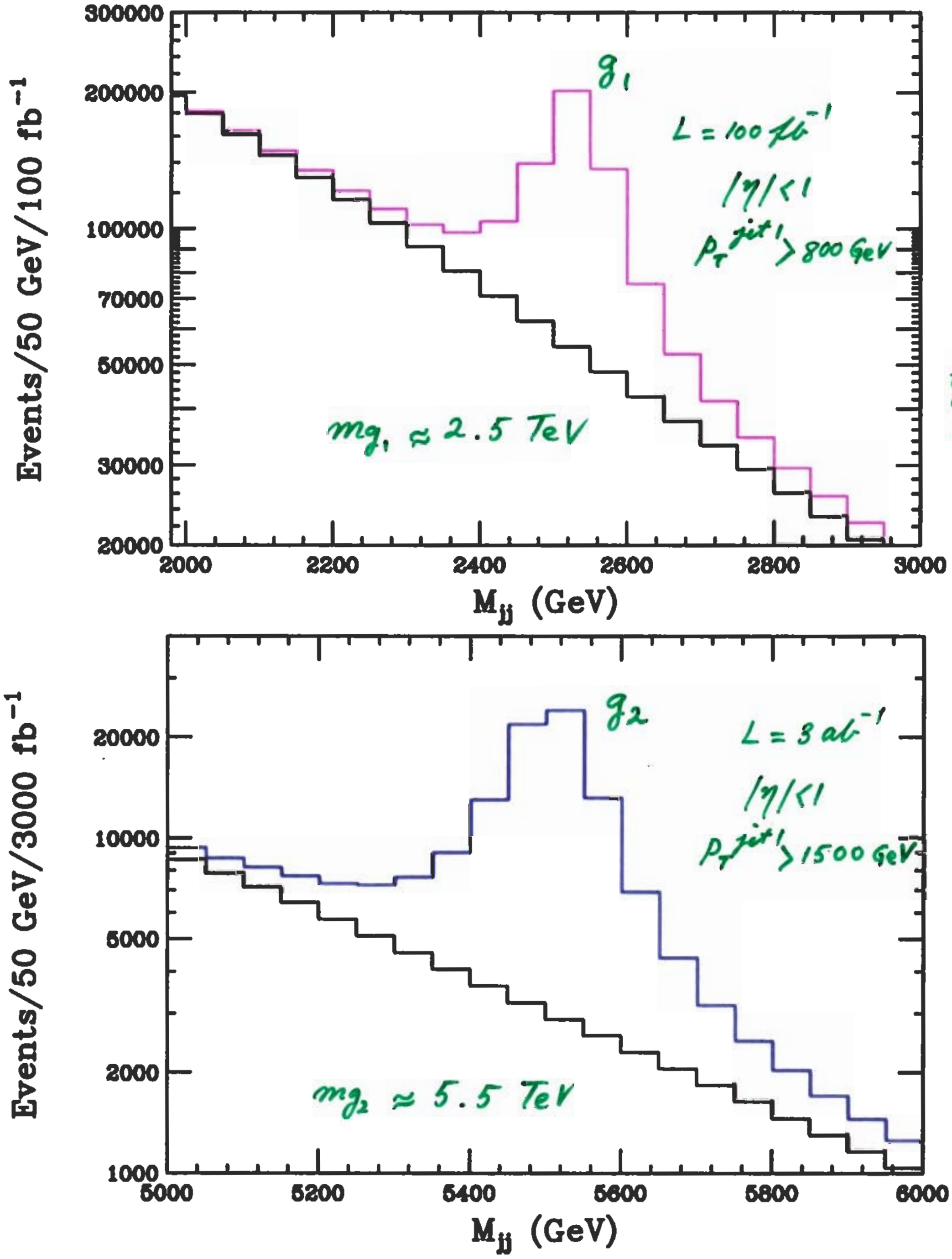
	g_{Z_n}/g_{SM}
$n=2$	0.106
$n=3$	0.163
$n=4$	0.065
$n=5$	0.072
$n=6$	0.113

Figure 13: Top panel: Event rate for Drell-Yan production of the $Z_{2,3}$ gauge KK states, in the electron channel, as a function of the invariant mass of the lepton pair at the LHC with 3 ab^{-1} of integrated luminosity. The dotted histogram corresponds to the SM background, while the histograms from the top down (represented by red, green, blue, magenta, cyan, solid, and dashed) correspond to letting the width float with a value of $c = 1, 2, 3, 5, 10, 25, 100$. Bottom Panel: Event rate for Drell-Yan production of the $Z_{5,6}$ gauge KK states as a function of the invariant mass of the lepton pair at the LHC with 3 ab^{-1} of integrated luminosity (blue histogram). The bottom solid histogram corresponds to the SM background.

$L = 3$ ab^{-1} (Upgraded LHC) ; $L \sim 100$ fb^{-1} $\rightarrow$ $N/30$

GLUON KK PRODUCTION

$q\bar{q} \to q\bar{q}$ (Dijet)



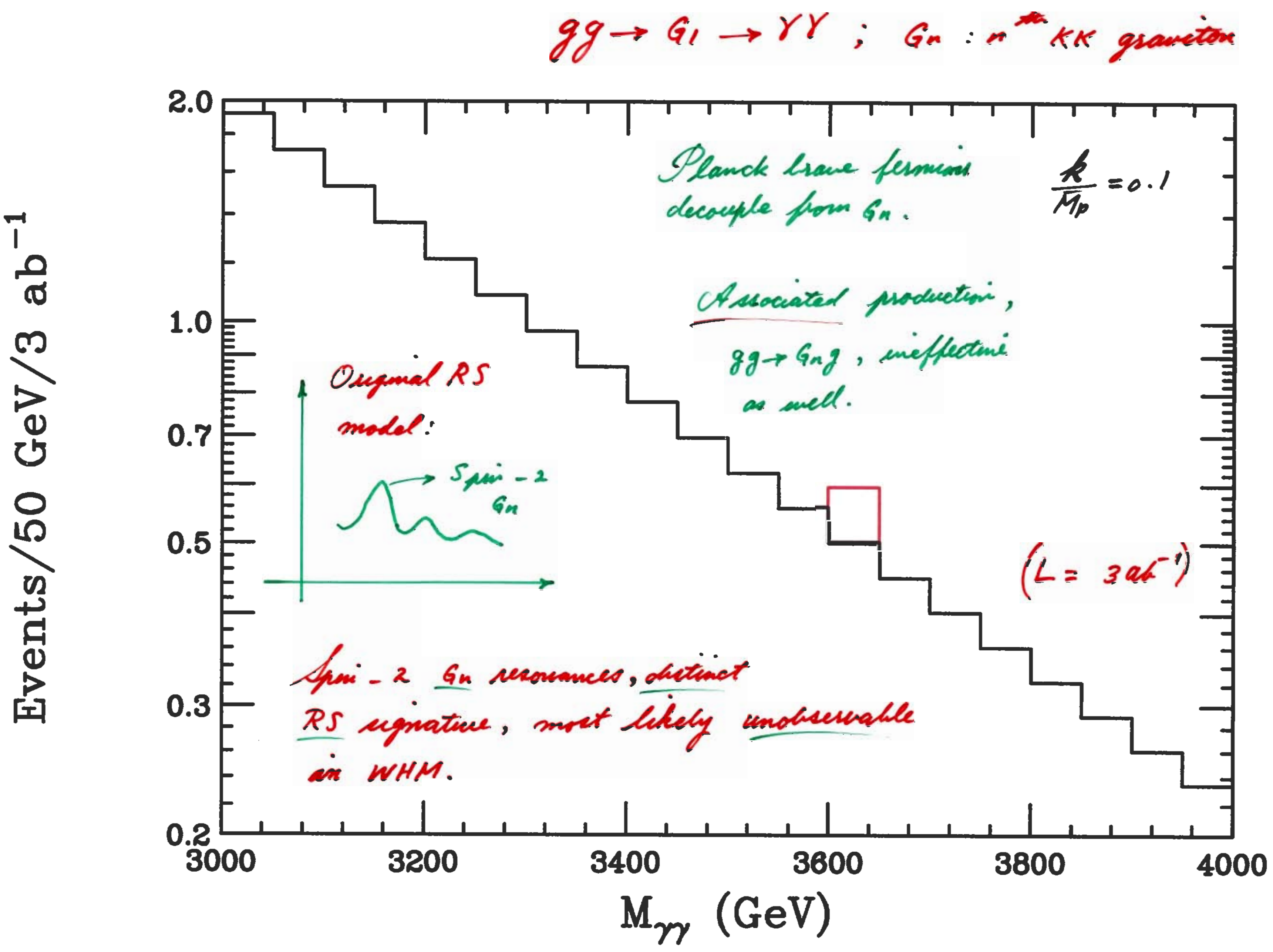
Very large rates!

Gluon brane kinetic term with $\delta_s \approx -30$, from (α_s, β_s).

Figure 14: Production of the first (top panel) and second (bottom panel) gluon KK excitation in the dijet channel as a function of the dijet invariant mass. The SM background is given by the black histogram.

$m_{g_1} - m_{\chi_{2,3}} = 200$ GeV (Presence of brane kinetic terms.)

$m_{g_2} - m_{g_1} \neq m_{g_1}$ (Suggests a warped background.)



gg → G1 → γγ ; Gn : nth KK graviton
k/Mp = 0.1
Planck brane fermions decouple from Gn.
Associated production, gg → Gn g, ineffective as well.
Original RS model:
Spin-2 Gn
(L = 3 ab⁻¹)
Spin-2 Gn resonances, distinct RS signature, most likely unobservable in WHM.
Events/50 GeV/3 ab⁻¹
2.0
1.0
0.7
0.5
0.3
0.2
3000
3200
3400
3600
3800
4000
Mγγ (GeV)

16/

In general, we may add brane-terms consistent with the symmetries of the theory at each brane.

IR-brane kinetic terms for $U(1)_{B-L}$ and $SU(2)_D$:

(1) Improve agreement with EW data.

(2) Lower KK masses, expected to enhance unitarity.

Cacciapaglia, Csaki, Grojean, Terning

We found that the $U(1)_{B-L}$ term can achieve (1).

The $U(1)_{B-L}$ and $SU(2)_D$ terms both lower KK masses, but only $SU(2)_D$ term affects unitarity (W-scattering is a non-Abelian process, independent of $U(1)_{B-L}$).

(2) suggests that there could be collider constraints on the IR-brane terms.

H.D., J. Hewett, B. Lillie, T. Rizzo
JHEP 0405:015, 2004.

Brane terms; $S = \int d^4x\, dy \sqrt{-G}\, [-\frac{1}{4} \lambda c_i F_{\mu\nu}^{(i)} F^{\mu\nu(i)} \delta(y - \pi\lambda) + \ldots]$

$\delta_i = \frac{k\lambda c_i}{2}$, $k\lambda \approx 11.27$, where $e^{k\lambda\pi}$ is the RS warp factor.

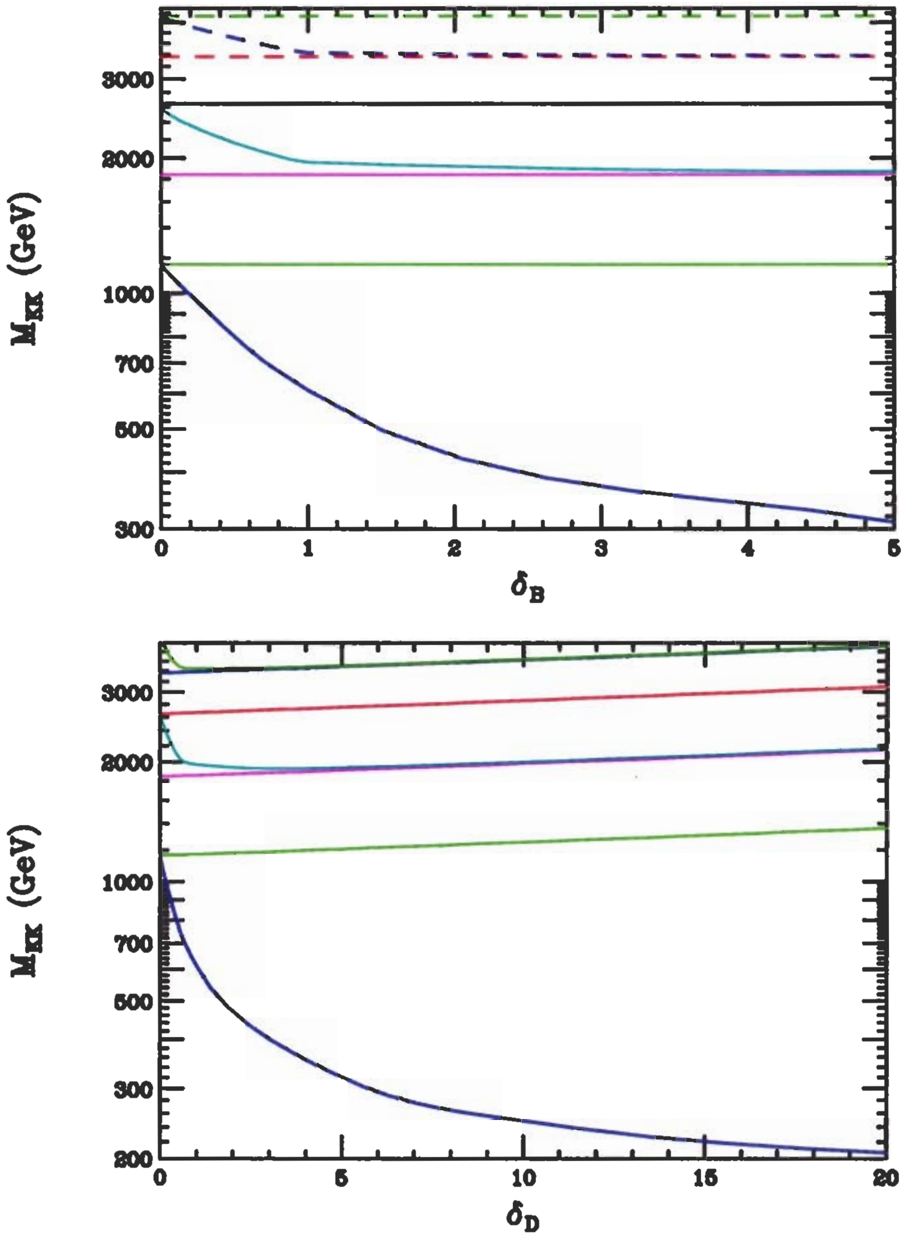


Figure 5: Behavior of the neutral KK mass spectrum as a function of $\delta_{B,D}$. From bottom to top on the left the curves correspond to the states $Z_{2,3,..}$. $\kappa = 1$ has been assumed. We take only one IR kinetic term to be non-vanishing at a time.

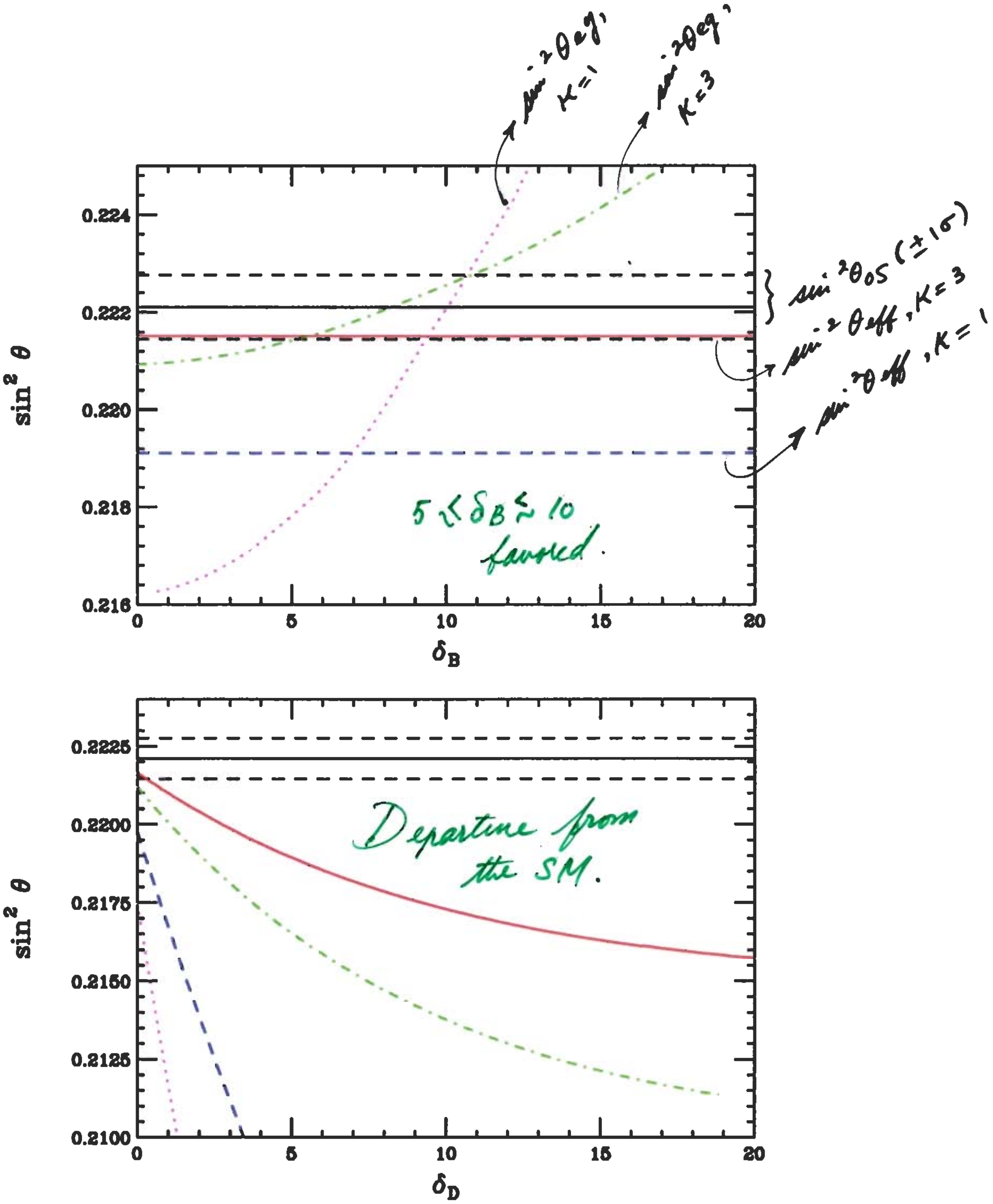


Figure 1: $\sin^2\theta$ in each of the three definitions as a function of $\delta_{B,D}$. The black horizontal solid and dashed curves correspond to the on-shell value $\pm 1\sigma$, the solid red (dashed blue) curve represents $\sin^2\theta_{eff}$ for $\kappa = 3(1)$ while the dash-dotted green (dotted magenta) curve is for $\sin^2\theta_{eq}$. The top (bottom) panel illustrates the effects of including the $U(1)_{B-L}$ $(SU(2)_D)$ kinetic term. We take only one IR kinetic term to be non-vanishing at a time.

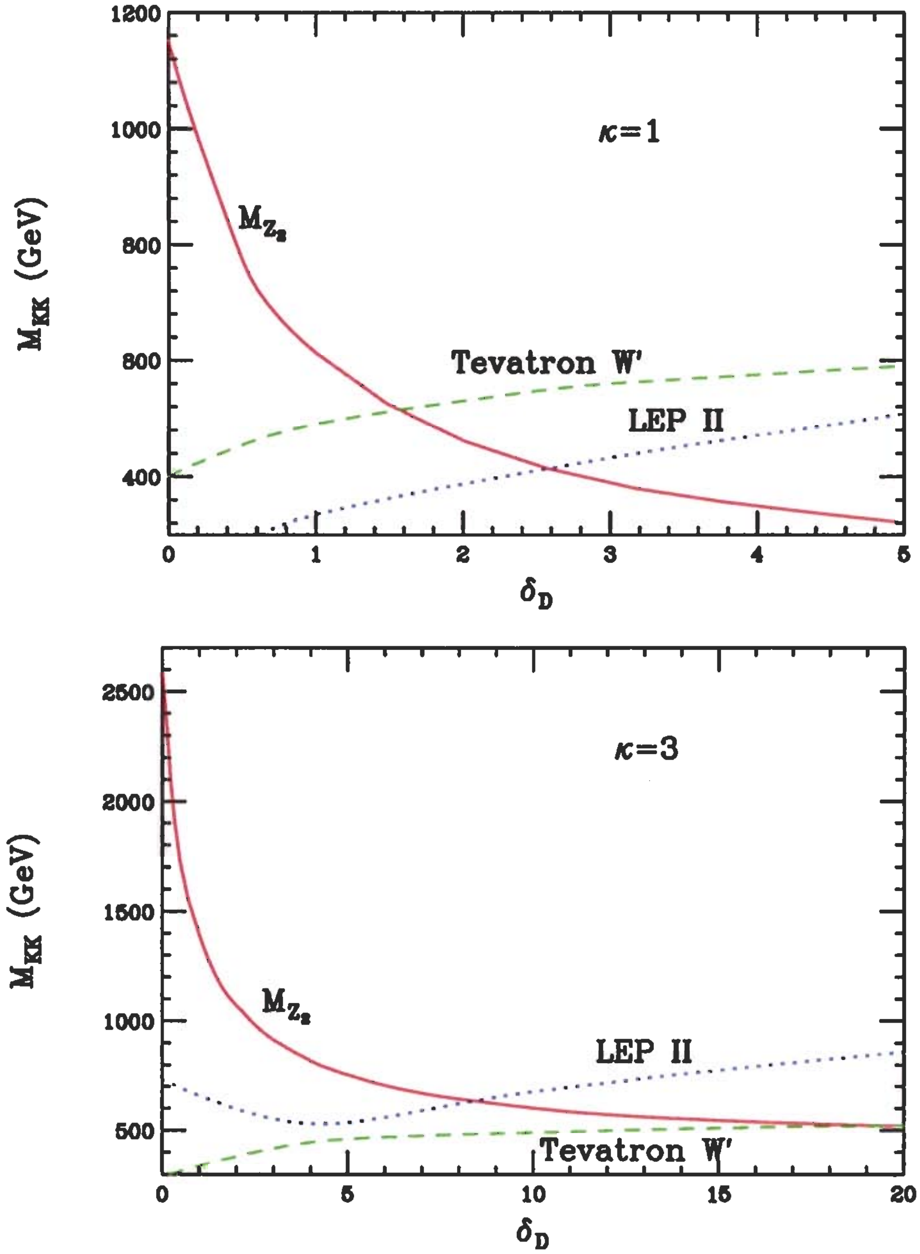


Figure 7: The predicted mass of the lightest KK excitation, the lower bound on the mass from the Run I Tevatron W' searches as well as the lower bound from LEPII as a function of δ_D, assuming $\delta_B = 0$. The collider limits are discussed in detail in the text.

20.

LEP bounds: Insensitive to bulk fermion configuration (light fermions localized near the UV-brane).

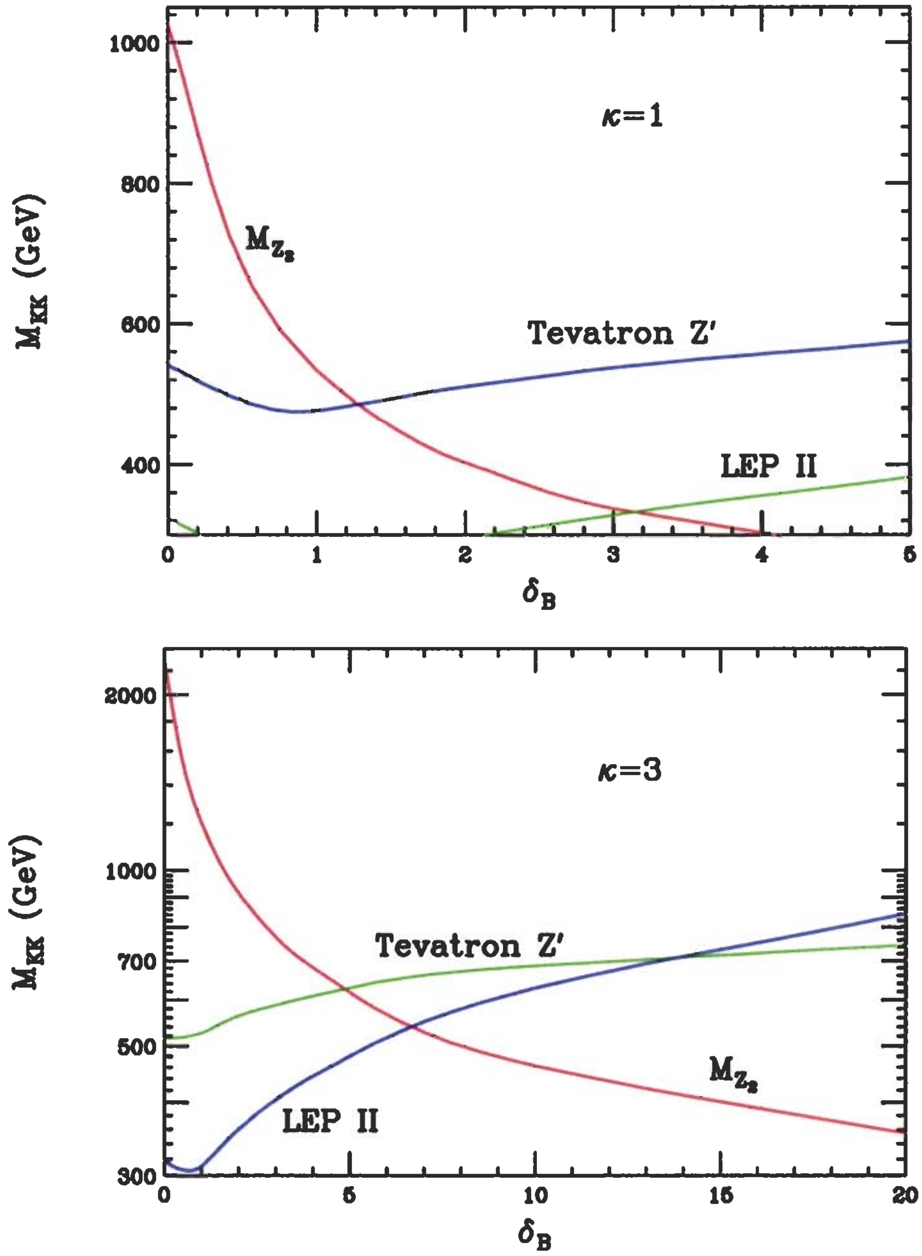
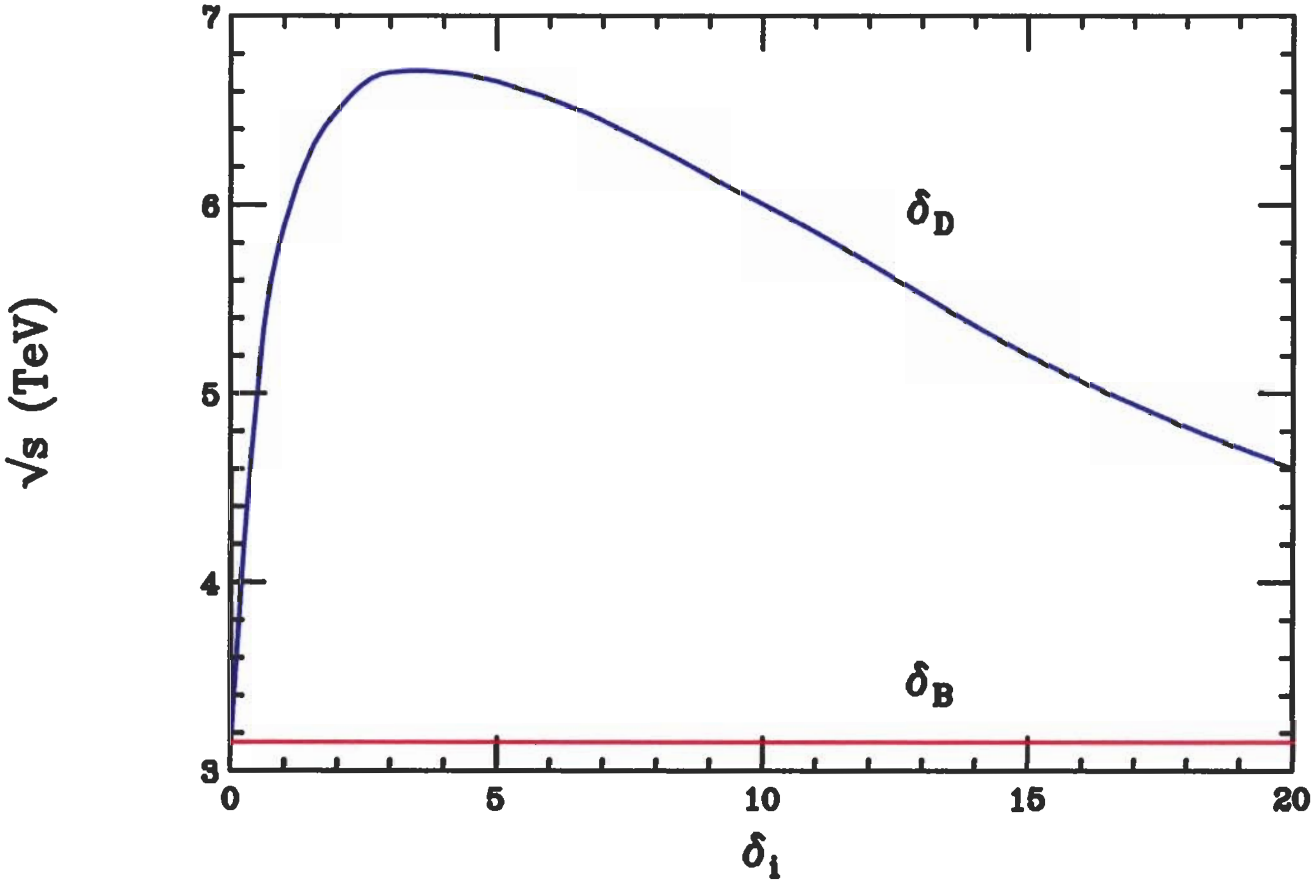


Figure 6: The predicted mass of the lightest KK excitation, the lower bound on the mass from the Run II* Tevatron Z' searches as well as the lower bound from LEPII as a function of δ_B, assuming $\delta_D = 0$. The collider limits are discussed in detail in the text.

* Using 200 pb^{-1} of integrated luminosity.
LEP: Below threshold, contact interactions.
Tevatron: Direct production.

Scale of Perturbative Unitarity Violation

(K = 1)



Conclusions

- 5-d Higgsless models represent a novel approach to EWSB. The warped versions of this approach have realistic features, such as custodial symmetry.
- Various analyses seem to indicate that agreement with precision EW data may not be achieved over the "weakly interacting" regime of the WHM. However, a more reliable comparison with EW data may require a knowledge of loop corrections in the model.
- The WHM will have accessible signals at the LHC.
- IR-brane kinetic terms are important for the WHM phenomenology. They modify the KK couplings and can reduce KK masses, perhaps to within the reach of the Tevatron. $SU(2)_D$ IR terms can extend perturbativity to 6-7 TeV.