Phenomenology of Higgsless EWK Models

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What good is a Higgs?

- W/Z masses w/ $\rho = 1$
- Unitarises WW scattering
- generates fermion masses (not today)

Model Goals: do it 'all' w/ no Higgs, using the 5^{th} component of gauge fields $A^{c} \equiv (A^{\mu}, A^{5})$ as a Goldstone + BC's + brane terms to break gauge symm + get correct couplings + masses TALL ORDER!

Concepts: • "Curvature" of 5-d wavefunction is related to mass..: $\partial^2 \phi \to (\partial_\mu^2 - \partial_5^2)\phi \to (\partial_\mu^2 - m^2)\phi$

→ "flat" or (x_5, y)-independent wave functions → massless fields

• Generalized BC's are important...

→ Orbifold BC's can't reduce group rank + break symmetries a la the SM.. (except...)

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Basic Ref's (NOT Complete!)

Csaki etal (hep-ph/0305237) - LR in flat space

Csaki etal (hep-ph/0308038) - simple LR in W. Space ($1/k\pi r_c$)

Nomura (" /0309189) - important Planck brane terms $g_R/g_L \neq 1$

Barbieri etal ("0310285) - EWK fit, ΔS

Csaki et al ("0310355) - incorporating fermions

Davoudiasl etal (0312193) { exact Calc's $k \neq 1$, EWK brane terms, WW, Colliders

Burdman + Nomura (0312247) - EWK consts.

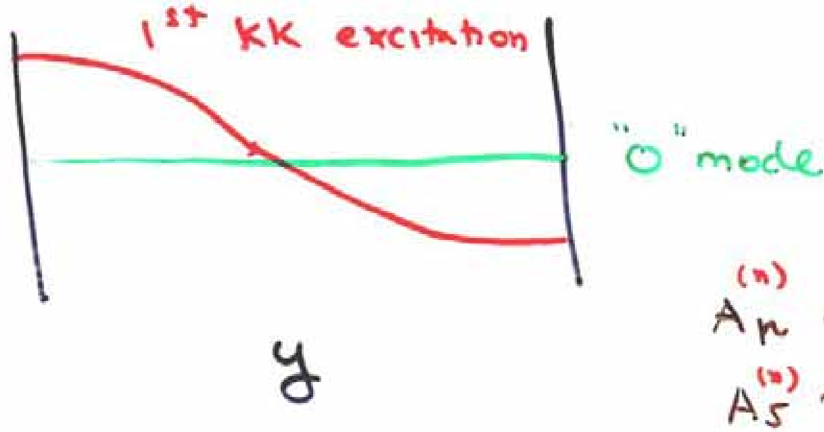
Csaki etal (040160) - TeV brane terms, ΔS can save IT?

Davoudiasl etal (0403300) - { TeV brane terms exactly EWK, Colliders + WW

<u>NO</u>

Agashe etal (0308036) { LR Symmetry protecting $\rho = 1$

Standard Case: U(1) w/ S^1/Z_2 orbifold



$$\partial A_\mu \big| = 0$$
$$A_5 \big| = 0$$

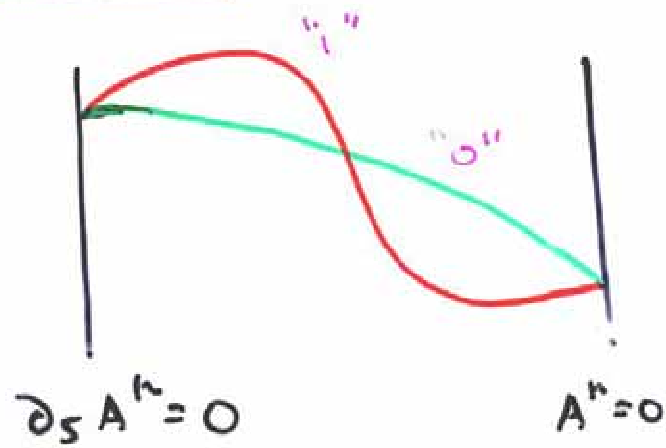
$A_\mu^{(n)} \sim \cos(ny/R)$ $\{ n = 0 \ldots$

$A_5^{(n)} \sim \sin(ny/R)$ $\{ n = 1 \ldots$

- "flat" zero mode is massless + symmetry remains unbroken
- Orbifolding removes $A_5^{(0)}$ from spectrum ∴ cannot be "eaten" as a Goldstone

$\Rightarrow$ Recall $A_\mu^{(n)}$ eat $A_5^{(n)}$ to get mass...

Toy Case: Generalized BC's...



"0" mode cannot be flat here due to BC's...

$$\begin{cases} A_\mu \sim a_n \cos m_n y + b_n \sin m_n y \\ A_\mu(y=0) = 0 \rightarrow a_n = 0 \\ \partial_5 A_\mu(\pi R) = 0 \rightarrow \cos(m_n \pi R) = 0 \\ m_n = \frac{n + 1/2}{R} \rightarrow \boxed{m_0 = \frac{1}{2R} \neq 0} \end{cases}$$

The "zero" mode is massive!

U(1) gauge symmetry is broken by BC's !!!!!

Of Course...

We can't use just any BC's... they are restricted by the variation of the action at the boundaries..

Attempt at a realistic model:

- Choose RS-type set up with $G_{bulk} = SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ ⊕ boundary kinetic terms
  - additional global symmetry helps $\rho = 1$
  - AdS_5 helps w/ mass spectrum

⇒ $SU(2)_R \otimes U(1)_{B-L} \to U(1)_Y$ on Planck brane { $W_R^{\pm}$, Z_R at Planck scale

$SU(2)_L \otimes SU(2)_R \to SU(2)_D$ on TeV brane { $W^{\pm}$, Z have TeV masses

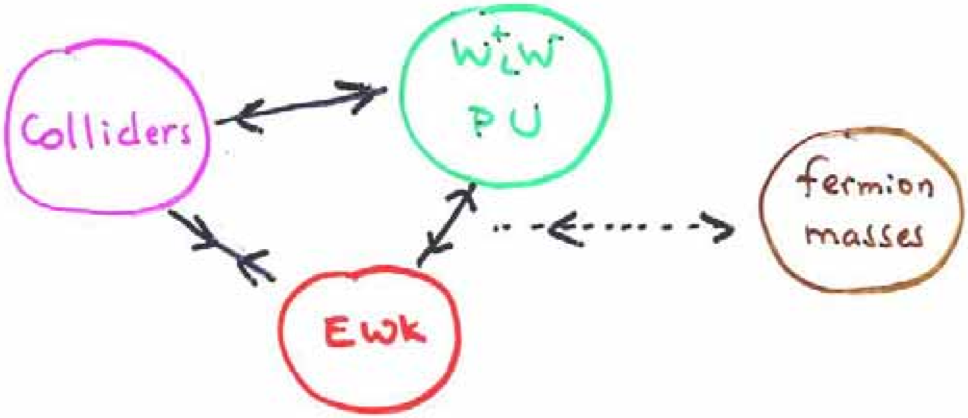
↳ QED only

Unfortunately LOTS of parameters* ...

- $g_{5L} \leftrightarrow G_F$, $\kappa = g_{5R}/g_{5L}$ (restricted), $\lambda = g_{5B}/g_{5L} \leftrightarrow M_Z$
- $\delta_{B,D,L,Y}$ describe $U(1)_{B-L}$, $SU(2)_D$, $SU(2)_L$ + $U(1)_Y$ brane kinetic terms ~ $O(1\text{-}10)$ ~ "free" parameters

* For simplicity SM fermions are all on the Planck brane here

TENSION HEADACHE:



Why? w/o a Higgs the SM violates unitarity in $W_L^+W_L^-$ scattering at $\sqrt{s} \simeq 1.8$ TeV

∴ We need some KK's lighter than this to contribute to $W_L^+W_L^-$ scattering to get P.U.

But: they can't have (yet) showed up at the Tevatron (or via LEP II contact int. searches, etc)

And: light KK's usually imply a 'disruption' of good SM EWK results

Examples: The 3 $\sin^2\theta$'s ... at tree level in the SM ..

$\sin^2\theta_{os} \equiv 1 - M_W^2/M_Z^2$

$\sin^2\theta_{eg} \equiv e^2/g_{ffW}^2$

$\sin^2\theta_{eff}$ at the Z-pole

ARE all the same ... differ at loop order

⇒ Here they differ at tree level if M_W/M_Z are inputs

$\sin^2\theta$

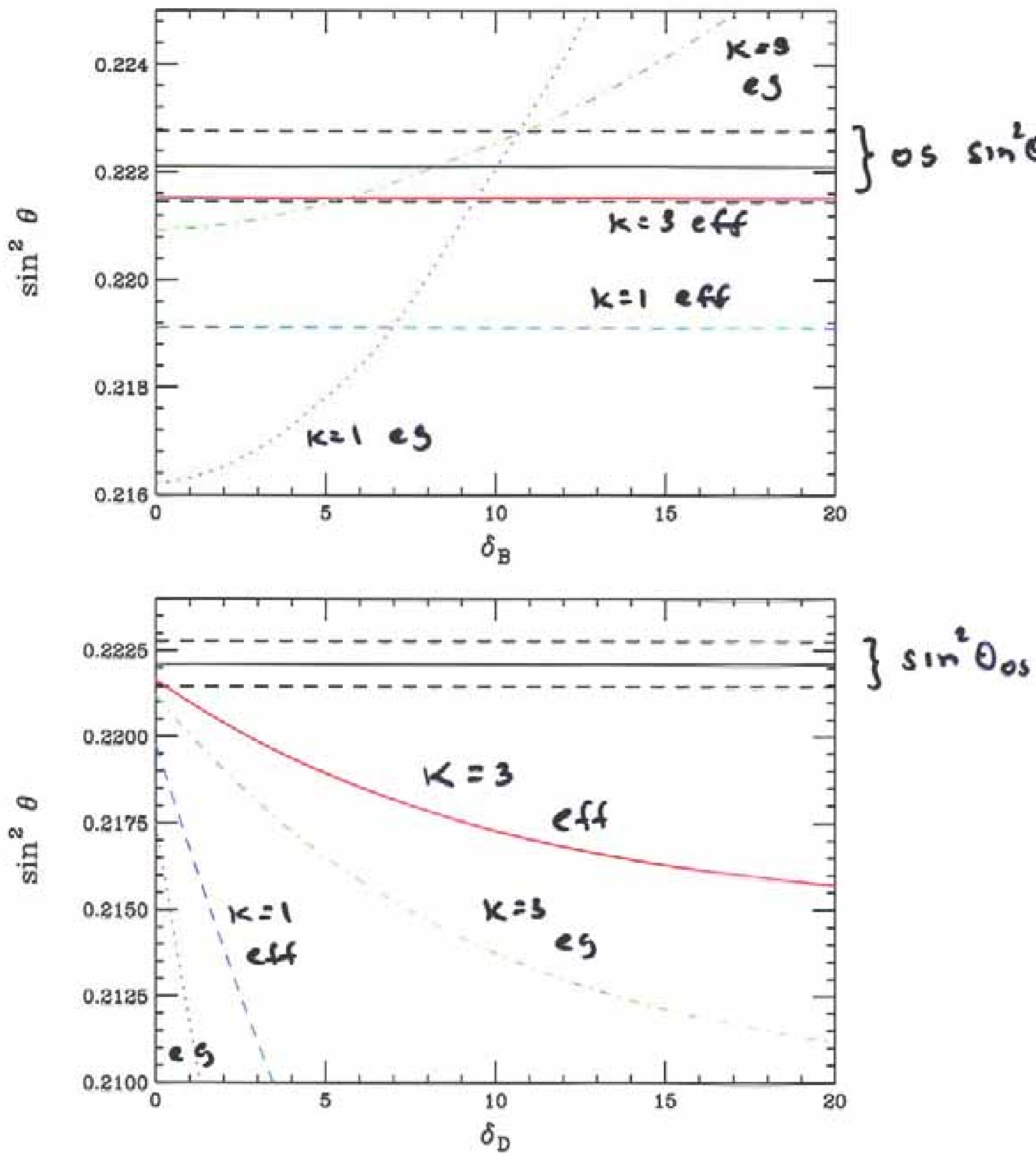


Figure 1: $\sin^2\theta$ in each of the three definitions as a function of $\delta_{B,D}$. The black horizontal solid and dashed curves correspond to the on-shell value $\pm 1\sigma$, the solid red (dashed blue) curve represents $\sin^2\theta_{eff}$ for $\kappa = 3(1)$ while the dash-dotted green (dotted magenta) curve is for $\sin^2\theta_{eg}$. 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.

<u>Clearly</u> : if we expect this model to work we'd want all 3 $\sin^2\theta$'s to be numerically "close"

- We'd want, e.g., $\boxed{\rho \simeq 1}$ to be reasonably well satisfied.. $\delta\rho \leq$ few $\cdot 10^{-3}$? [Fig]

- etc { We'd like to understand the model at loop level - lots of work.

KK spectrum : $(\delta_i = 0)$

Varying the δ_i moves the spectrum around* while [Fig] increasing K just makes everybody heavier

Colliders have not 'seen' W_2 / Z_2 yet → constraints [Fig]

... and also the issue of p.u.v. is now critical...

* and changes their various couplings ...

$\delta\rho^{z}_{eff}$

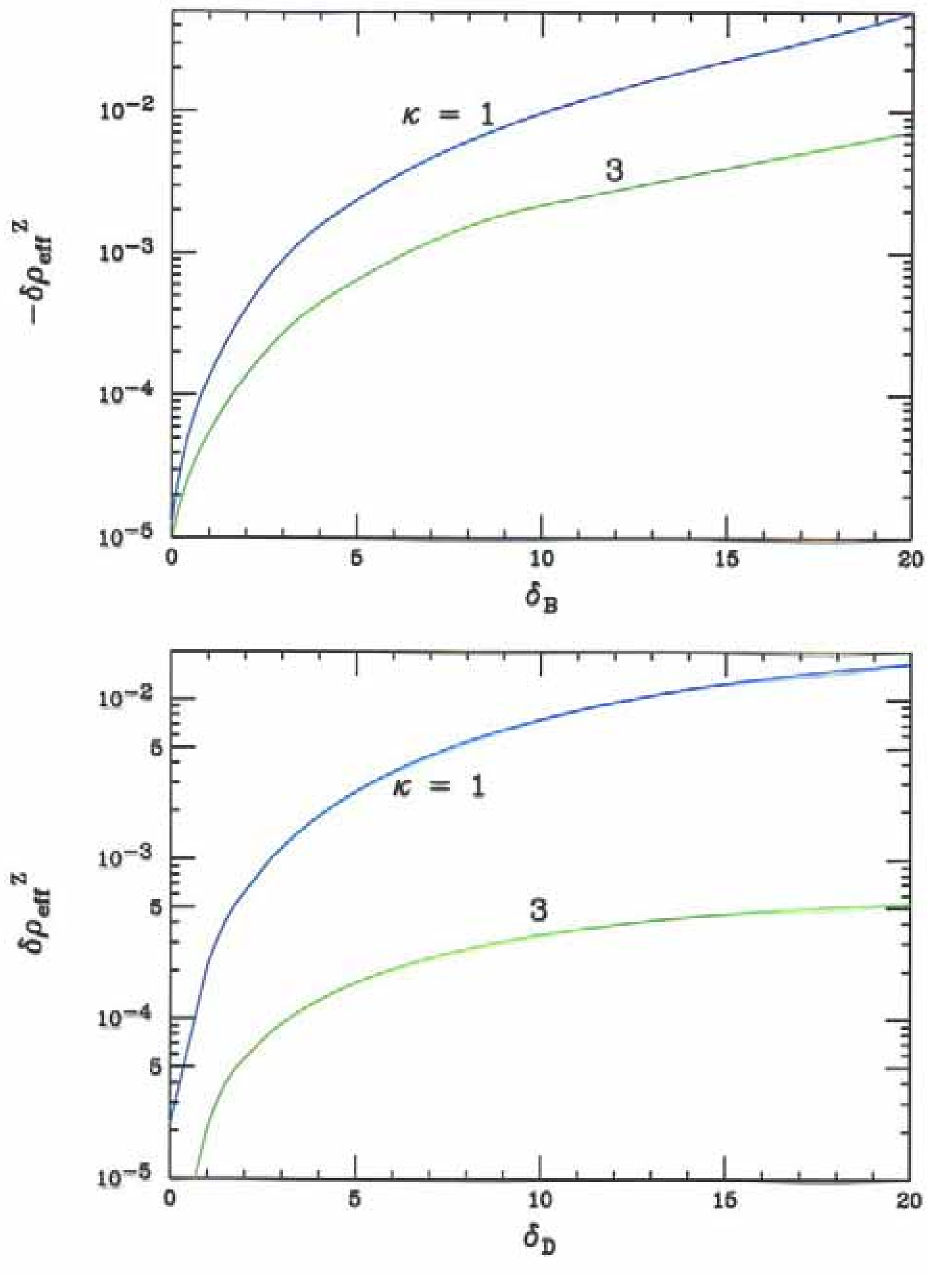


Figure 3: $\delta\rho^{Z}_{eff}$ as a function of $\delta_{B,D}$ for $\kappa = 1$ and 3. We take only one IR kinetic term to be non-vanishing at a time.

neutral KK spectrum

κ = 1

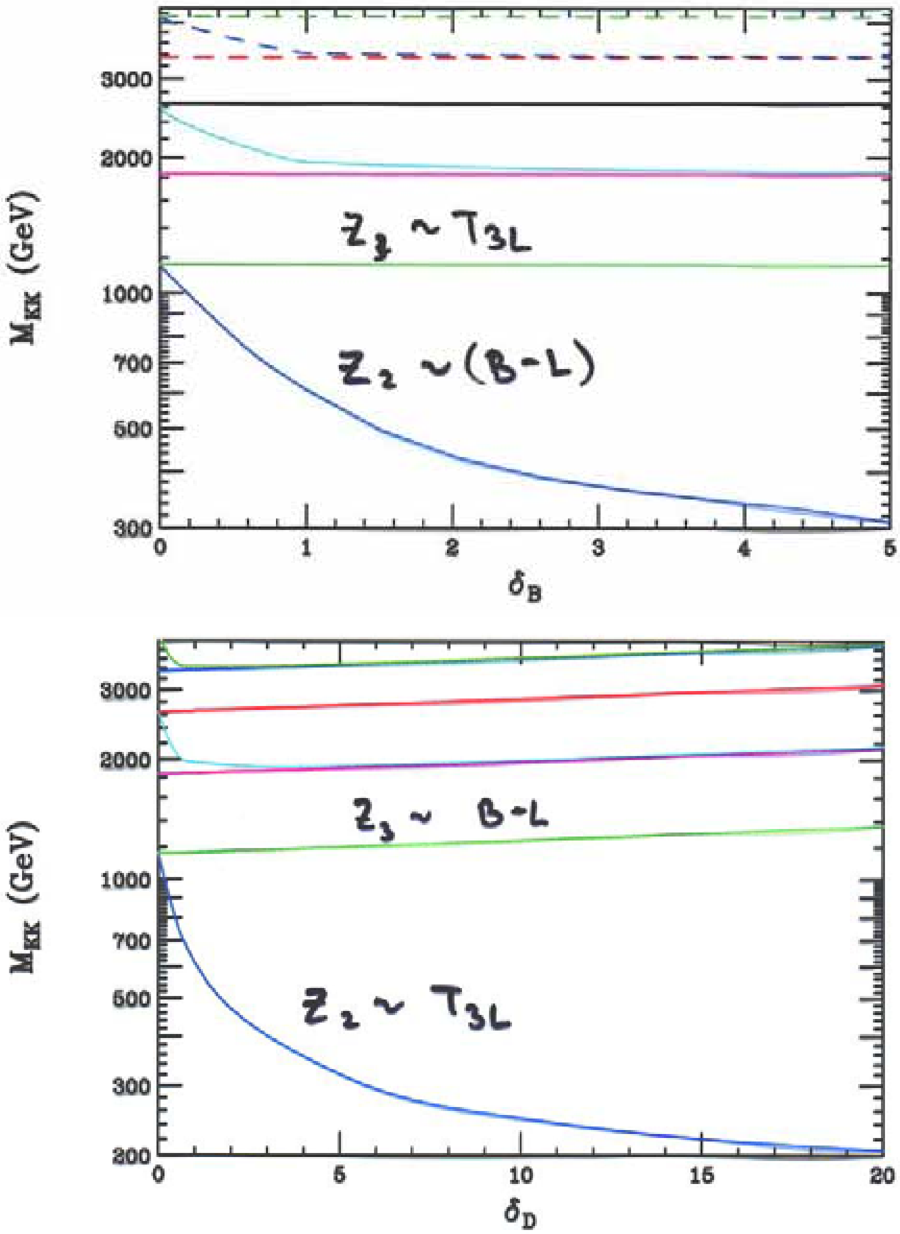
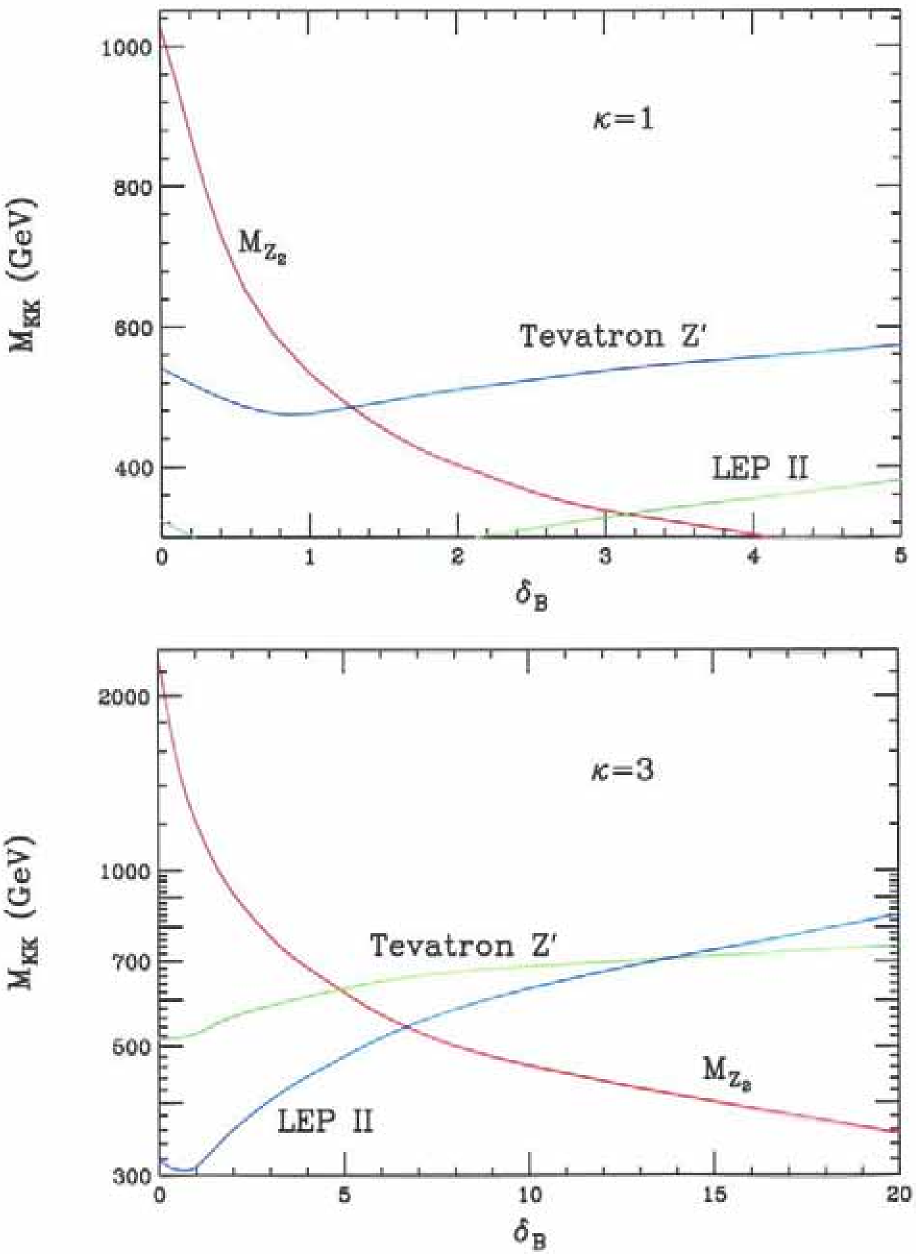


Figure 5: Behavior of the neutral KK mass spectrum as a function of $\delta_{B,D}$. From bottom to top on the left the curves correspond to the states $Z_{2,3,..}$. $\kappa = 1$ has been assumed. We take only one IR kinetic term to be non-vanishing at a time.

Collider Constraints



Note, however,

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.

Tevatron bounds are particularly sensitive to fermion localization assumptions...

Collider Constraints

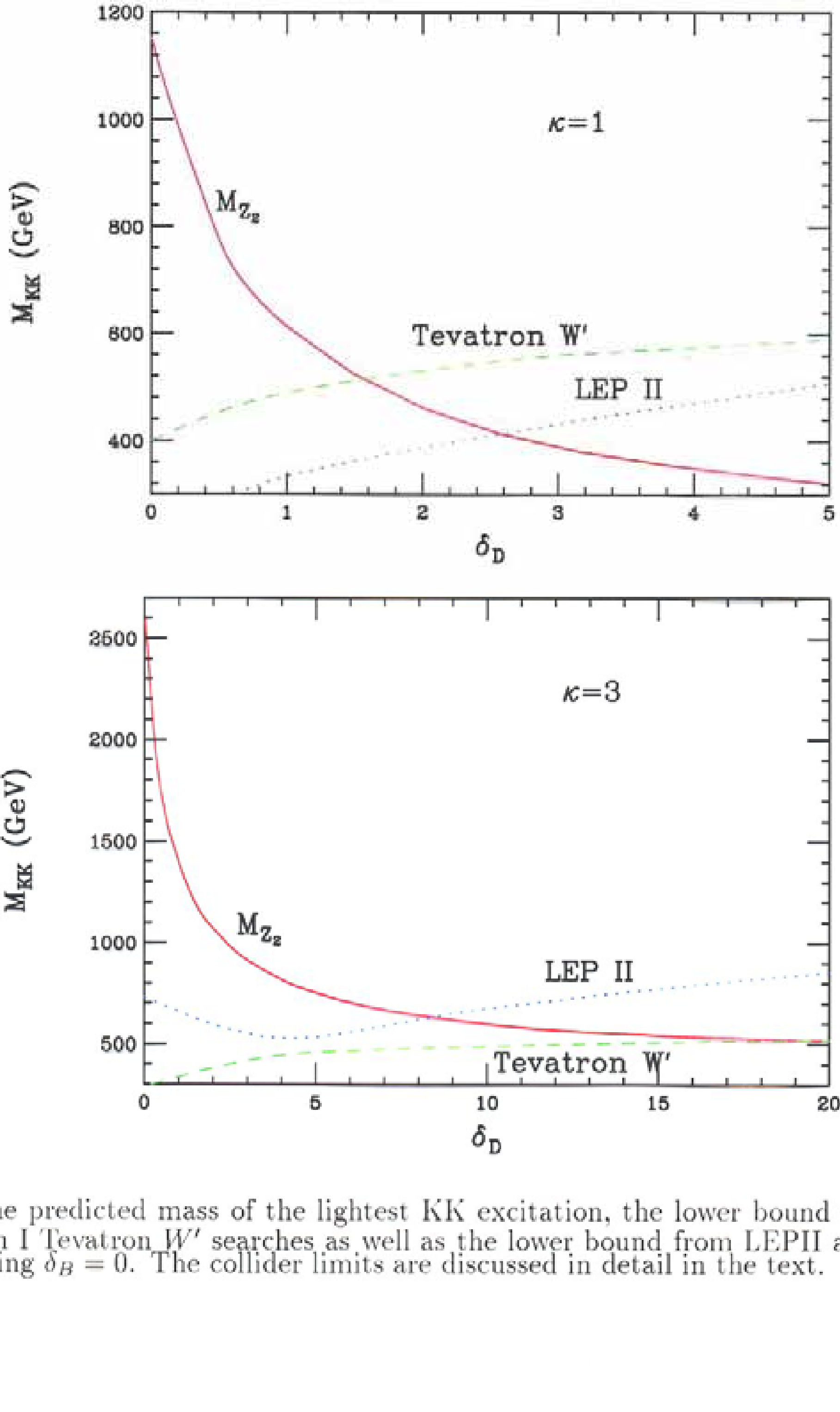
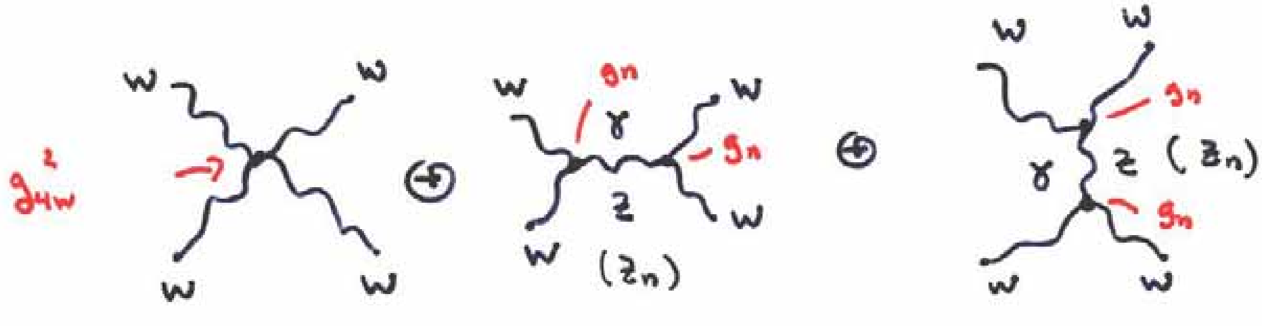


Figure 7: The predicted mass of the lightest KK excitation, the lower bound on the mass from the Run I Tevatron W' searches as well as the lower bound from LEPII as a function of δ_D, assuming $\delta_B = 0$. The collider limits are discussed in detail in the text.

$W_L W_L$ - unitarity



• each amplitude $\sim s^2$ but gauge invariance reduces it to $\sim s$ in sum

removes $\sim s$-like growth

Here we have no Higgs ∴ the KK's ⊕ diffs in couplings must → Unitarity

Sum Rules

$$g_{4W}^2 = \sum_{n=\gamma,\ldots} g_n^2$$

(Csaki et al)

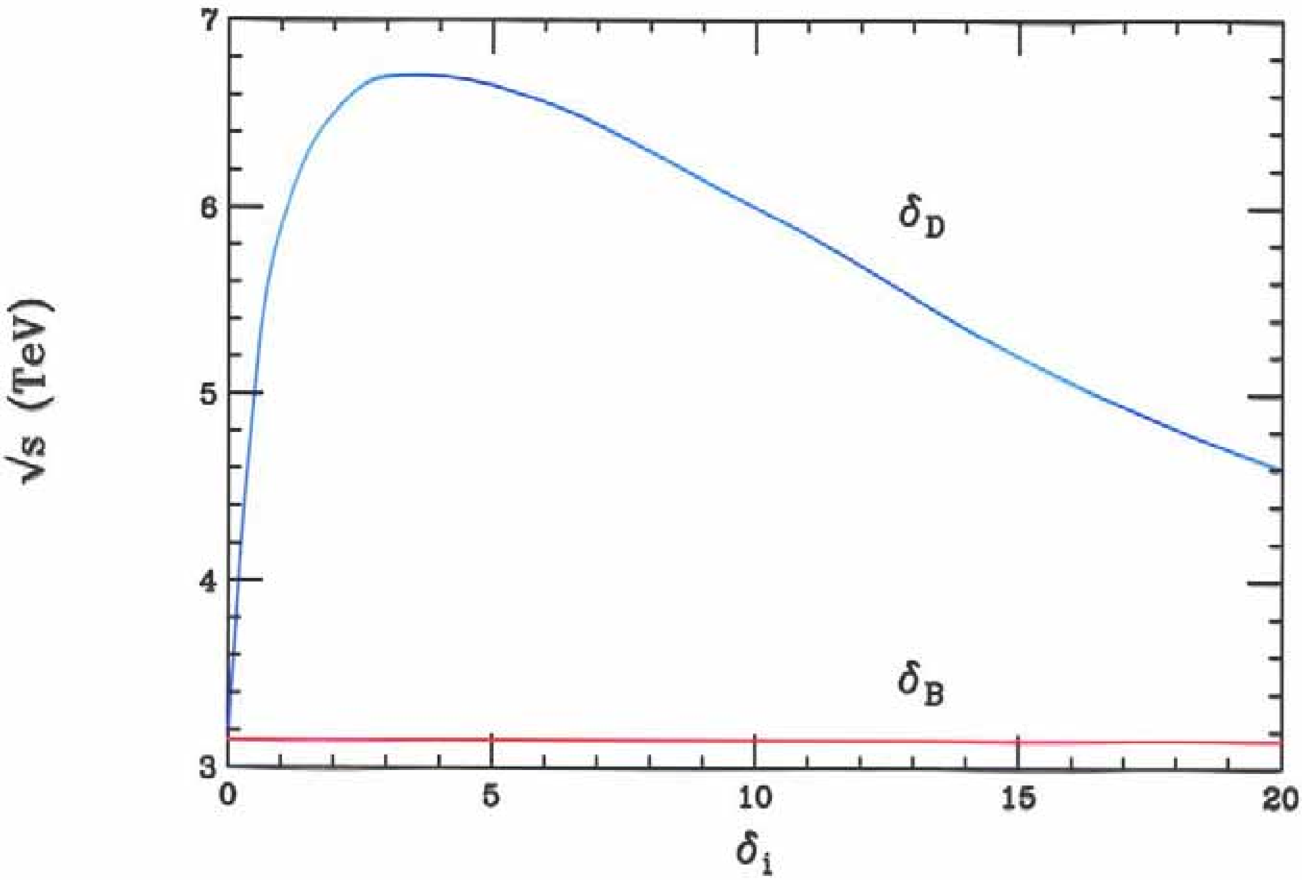
$$g_{4W}^2 = \frac{3}{4} \sum_{n=\ldots} g_n^2 M_n^2 / m_W^2$$

Necessary conditions for asymptotic unitarity

⇒ NOT SUFFICIENT !!

Scale of Unitarity Violation

(Recall, Higgsless SM is ≃1.8 TeV)



$|\mathrm{Re}\, a_0| < 1/2$

K = 1

$$a_0 = \frac{1}{32\pi}\int_{-1}^{1} d\cos\theta \; A(W_L^+ W_L^- \to W_L^+ W_L^-)$$ { 0^{th} partial wave

An explicit calculation tells us:

We can improve PUV over the SM but we're not there yet! [Fig]

We do not (yet) have a model satisfying all requirements!

• Expected Collider signatures of a 'real' model..

⇛ light Z'-like KK's coupling to $\sim T_3$ are probably a must + will (should have reduced couplings to fermion pairs ...

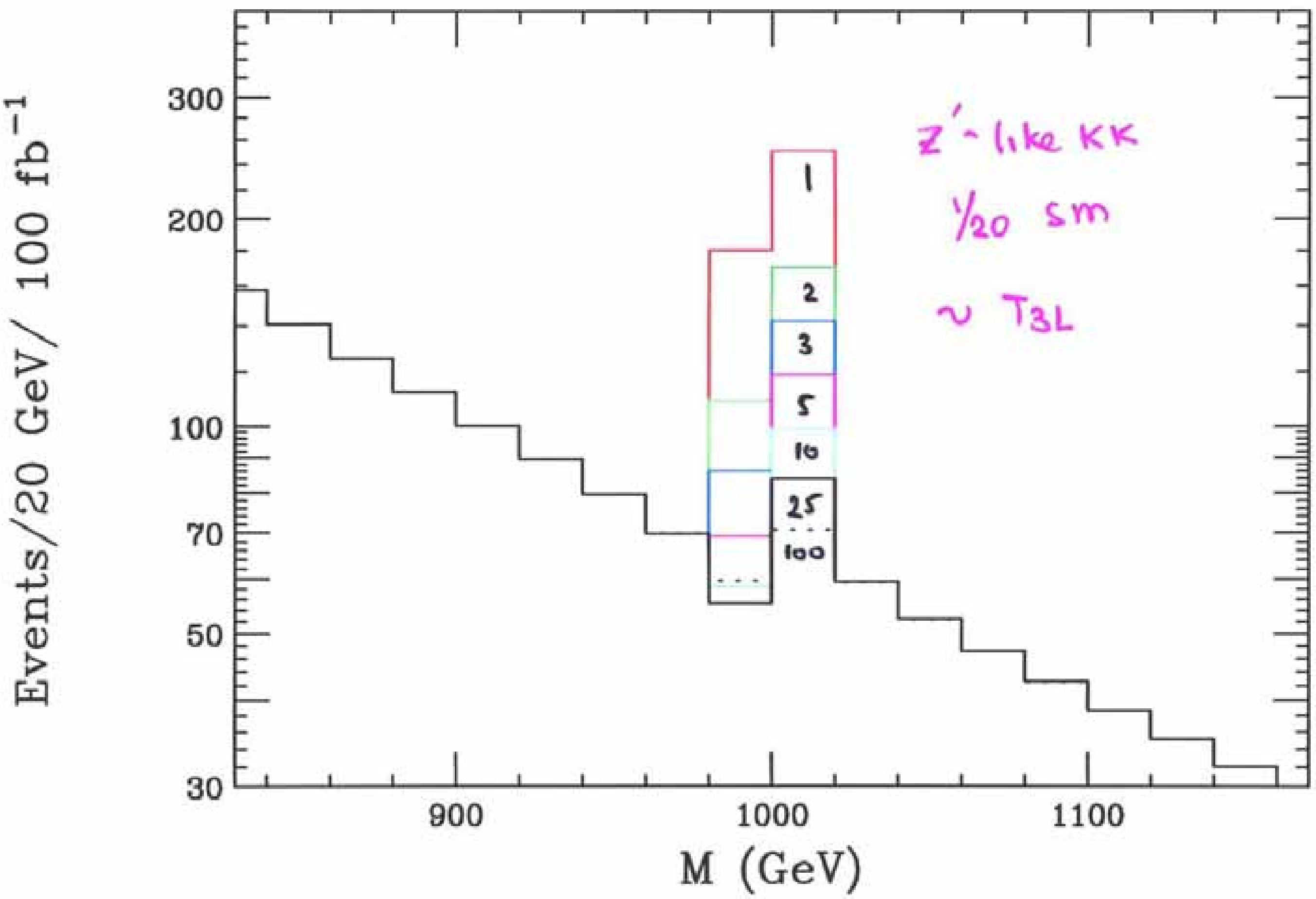
⇒ These should not be missed at the LHC!*

+ they can be studied in detail at LC, e.g., telling us how they couple

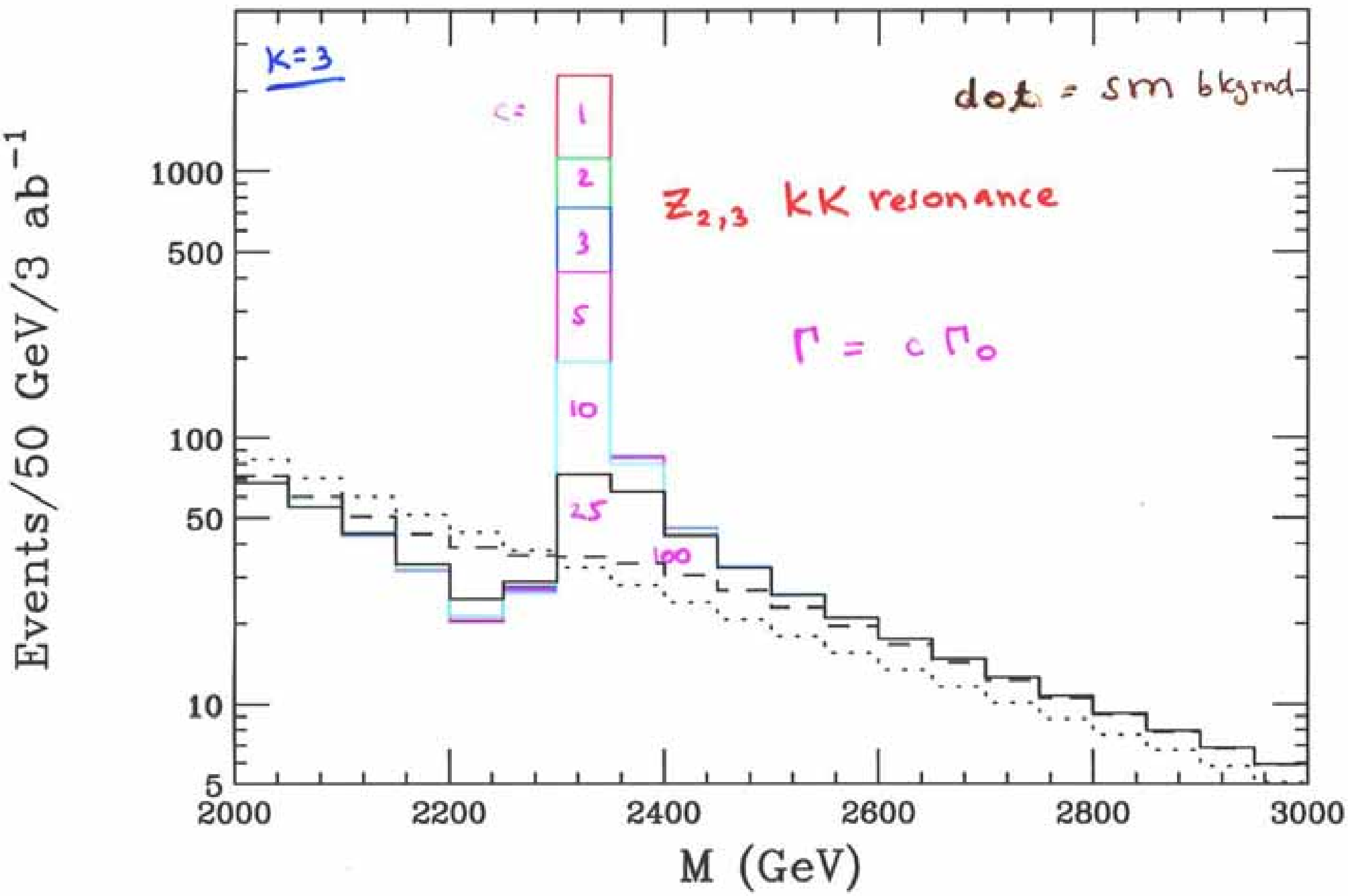
→ Verify predicted properties ....

* Unless their couplings are small + they are smeared out by resolution effects

Drell - Yan at LHC



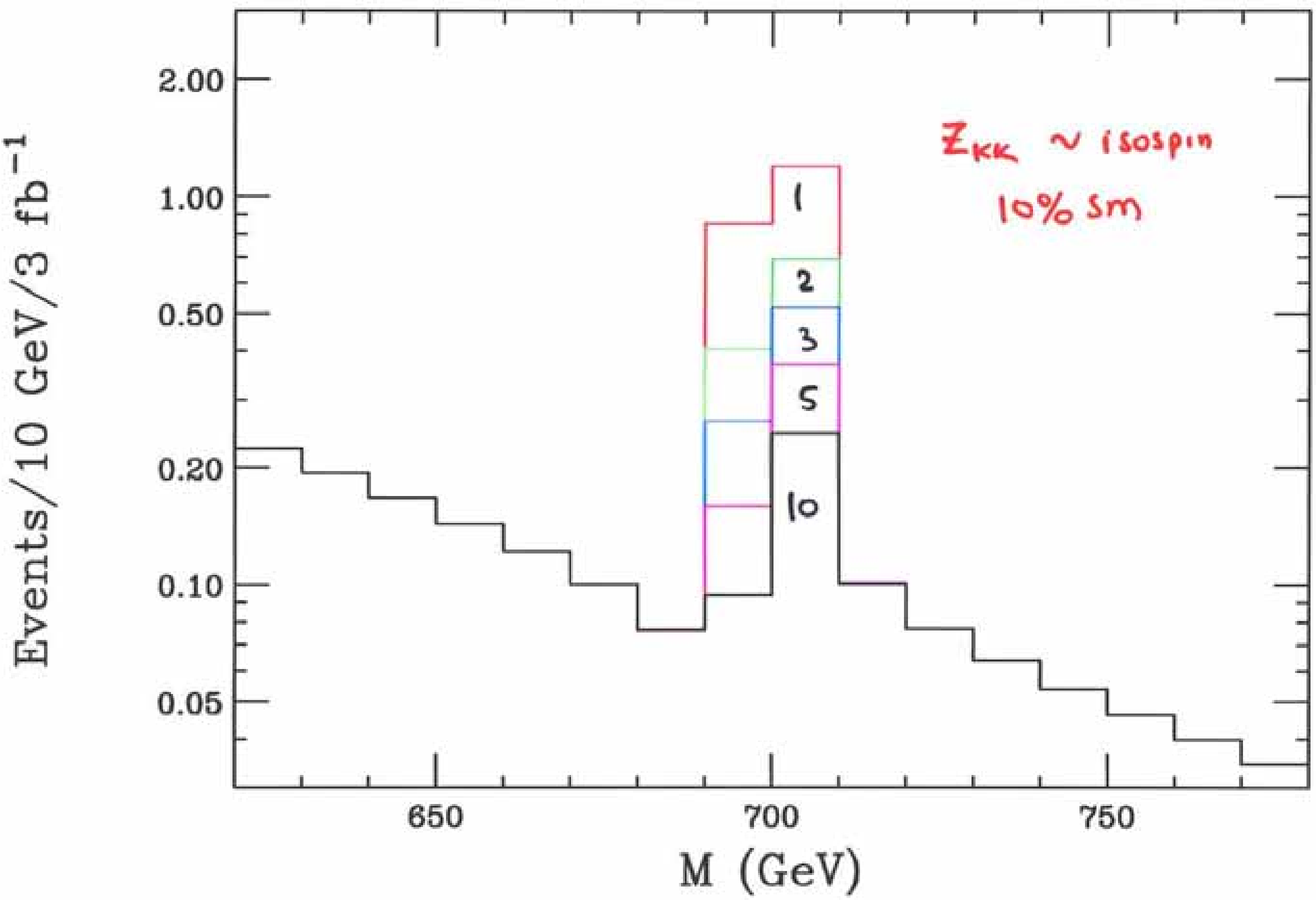
LHC Drell-Yan production



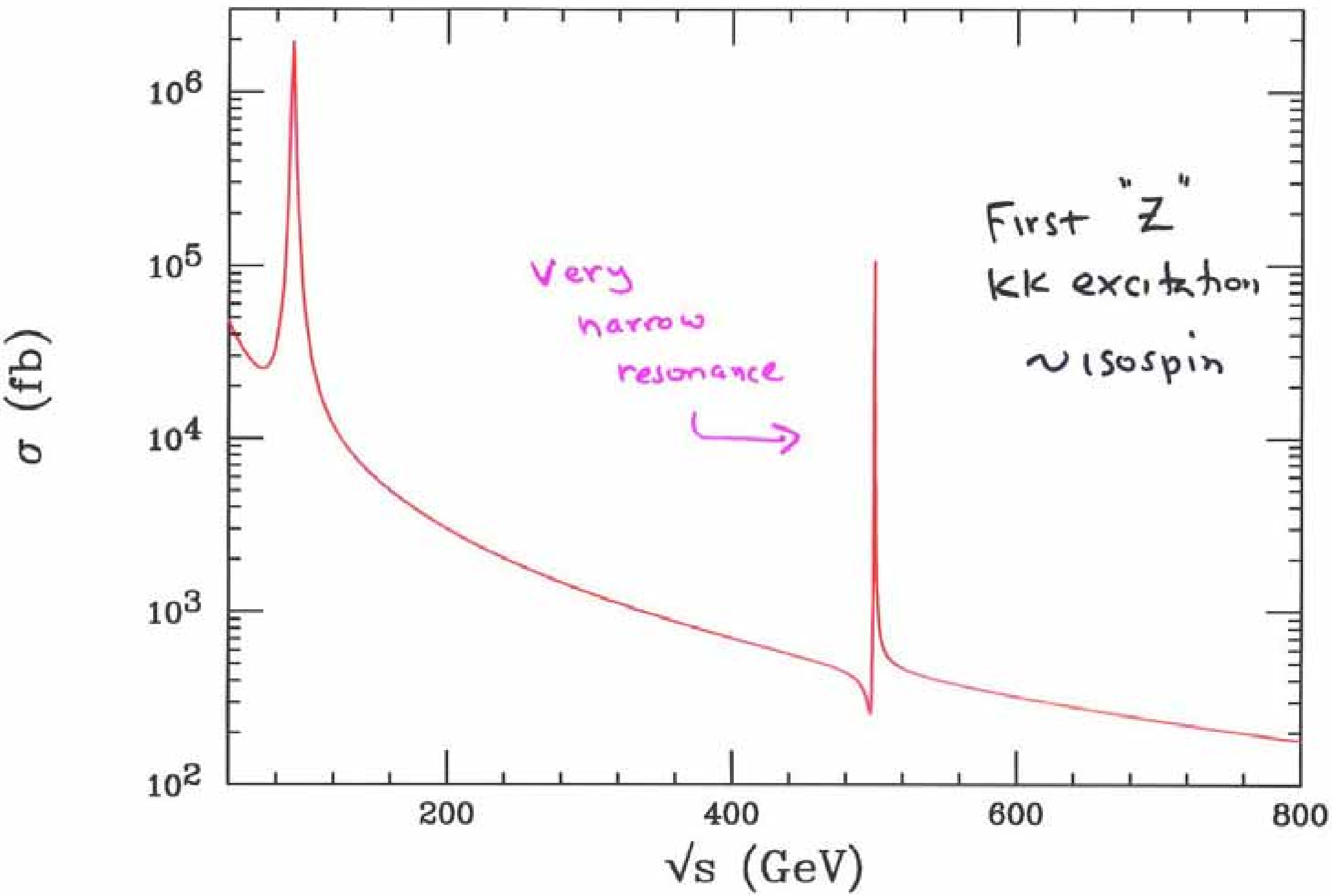
Some examples

Tevatron Run II

Drell-Yan

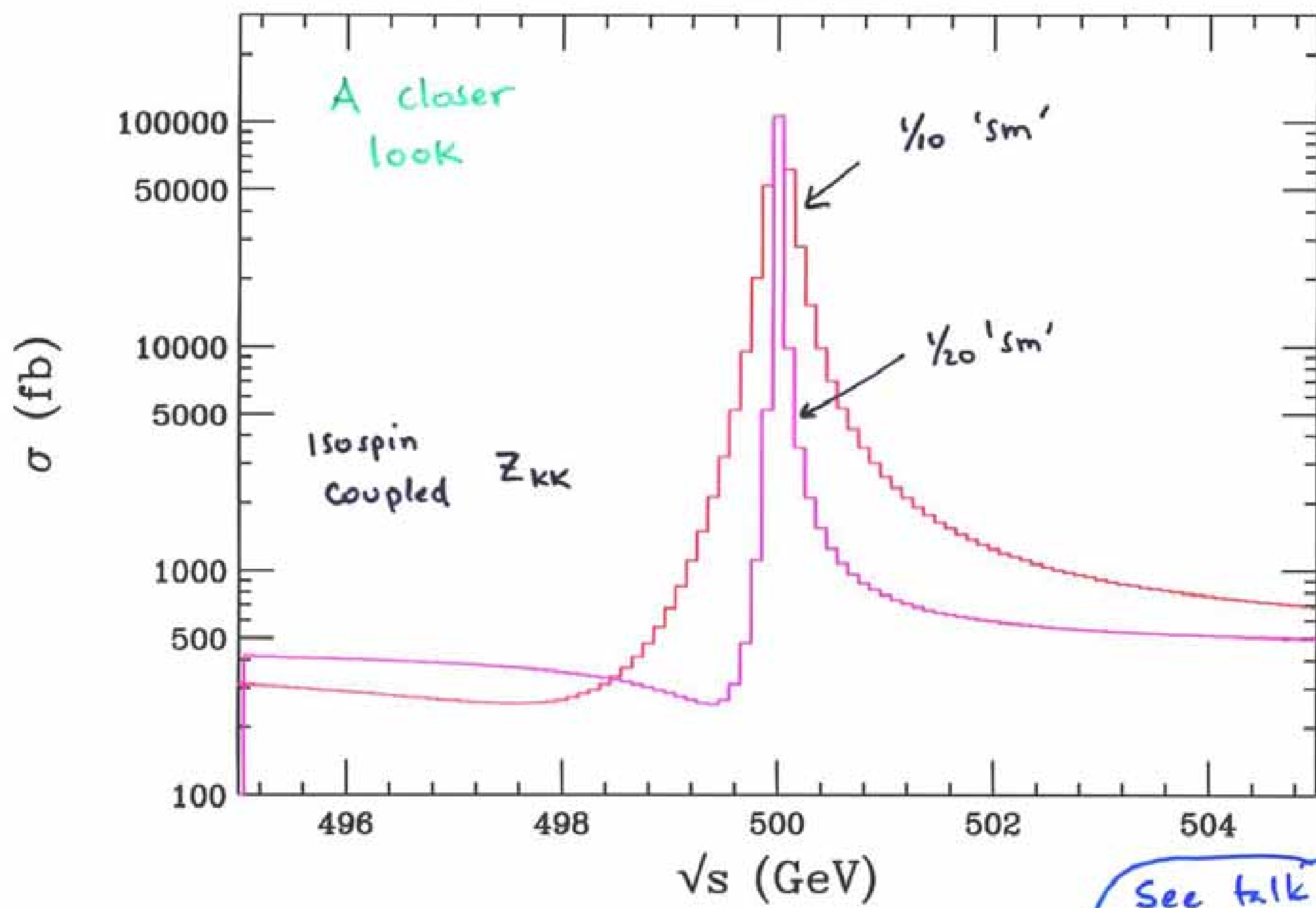


$e^+e^- \to \mu^+\mu^-$



10^6
10^5
10^4
10^3
10^2
σ (fb)
200
400
600
800
√s (GeV)
Very narrow resonance
First "Z" KK excitation ~isospin

$e^+e^- \to \mu^+\mu^-$



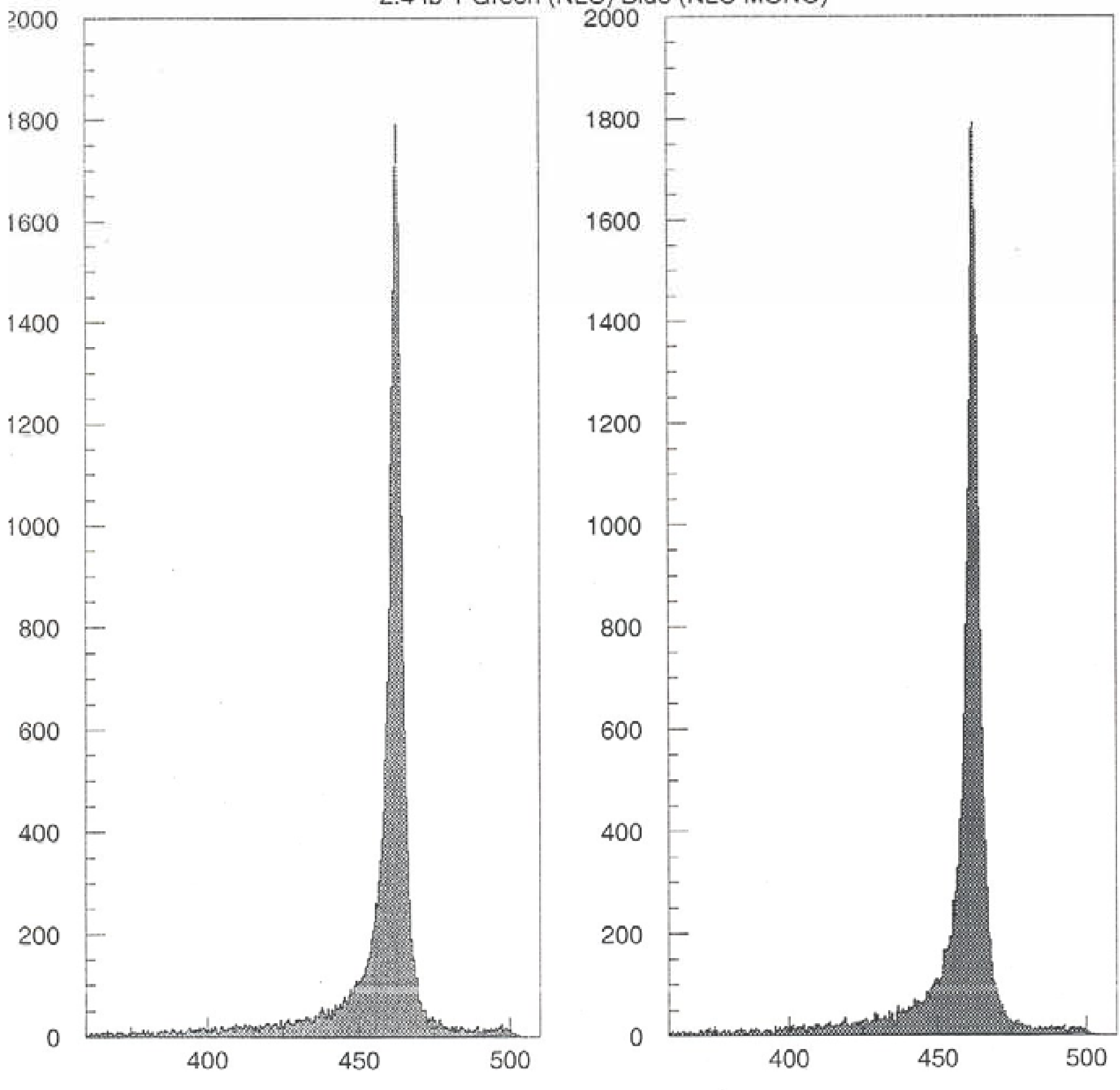
See talk by A. Freitas

Z'-like KK eLC

w/ radiative return

Tim Barklow

2.4 fb-1 Green (NLC) Blue (NLC MONO)



Summary / Conclusions

(1) Higgsless models offer a potential method of EW symmetry breaking w/ a Higgs using extra dimensions

(2) The simplest models examined so far do not have all the required features + even they are not yet fully explored

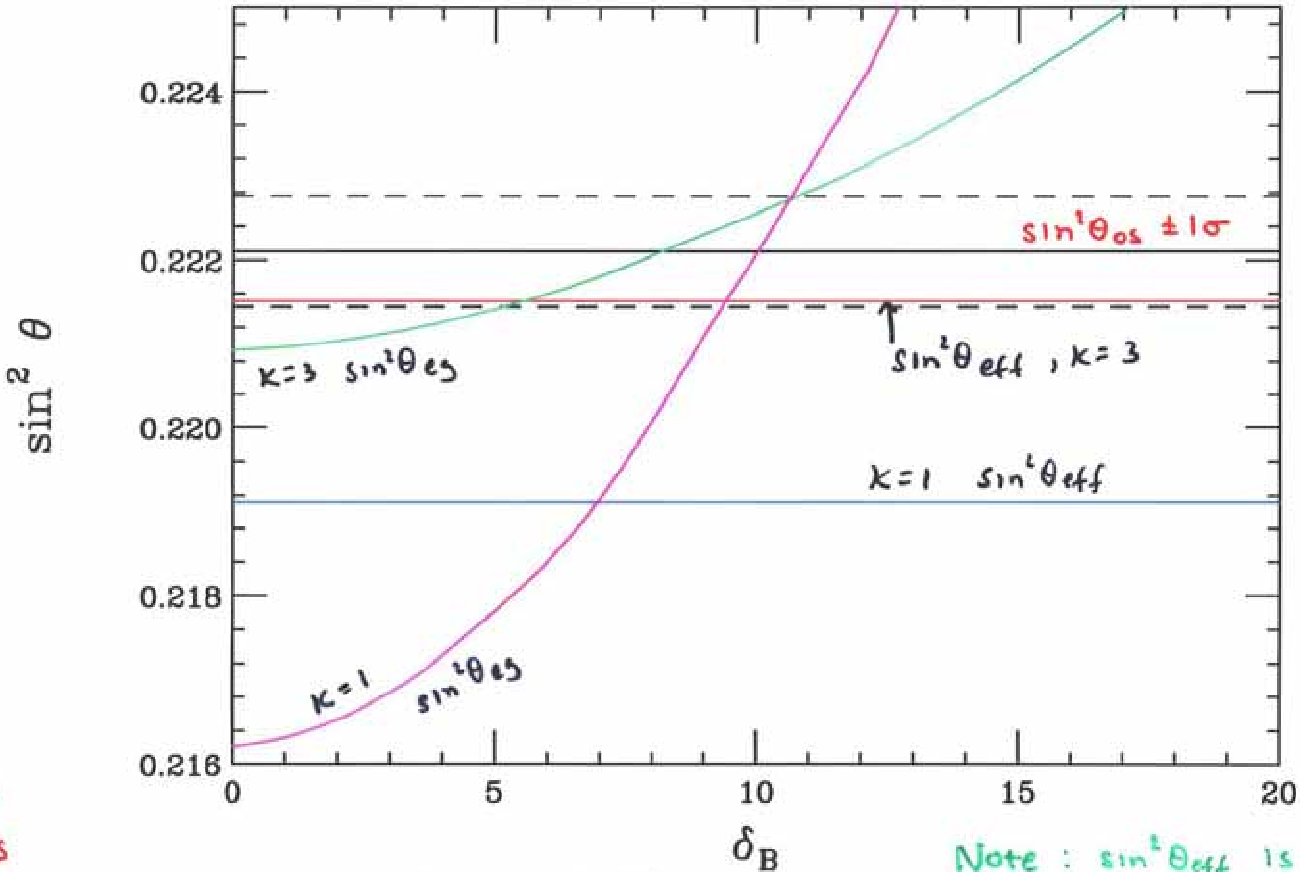
(3) Many (All ?) of the desired properties of a sucessful model have been identified → most likely signature

→ light Z/W-like KK states w/ small fermion couplings

→ → Visible at LHC, LC (or even TeV ??)

(4) A lot more work is needed to see if this idea can really work...

$\sin^2\theta_{os,\,eff,\,eg}$ vs δ_B



Best Cases

- k=1 $\delta_B \simeq 10$ ($\sin^2\theta_{eff}$ still off)
- k=3 $\delta_B = 8$ looks very good!!

Note: $\sin^2\theta_{eff}$ is essentially δ_B independent.

Now in bookstores near you...

A novel about the SSC and the Higgs boson

Soon to be a movie??