Phenomenology of Higgsless EWK Symmetry Breaking*

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TGR

- Overview of Higgsless EWK
- The Model
- Pheno
  - EWK precision measurements
  - Collider signatures
  - WW scattering + unitarity
- Recent Developments w/ • TeV brane terms
  (prelim. results)
- Summary + Conclusions

* Special Thanks to Ben Lillie + JoAnne Hewett
in helping me prepare this talk

TGR
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* What good is a Higgs anyway?

- generates W, Z masses (with $\rho = 1$)
- generates fermion masses (not today)
- unitarizes scattering amplitudes ($W_L W_L \to W_L W_L$ etc)

$\Longrightarrow$ Can we get along <u>without</u> a Higgs?

- without introducing <u>any</u> new particles (from <u>one point</u> of view!)

* • and get 'everything' we know about the SM 'right'? (<u>TALL</u> ORDER)

$\therefore$ SM + 1 extra dimension, 'warped' as in RS, is our laboratory.....

Basic Ref's (NOT Complete!)

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

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

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

Barbieri etal ("0310285) - EWK fit, ΔS

Csaki etal ("0310355) - incorporating fermions

Davoudiasl etal (0312193) { exact calc's $\kappa \neq 1$, EWK brane terms, WW, colliders

Burdman + Nomura (0312247) - EWK consts.

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

Davoudiasl etal (0403xxx) - { TeV brane terms exactly EWK, colliders + WW

NO

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

Consider a massless 5-d field

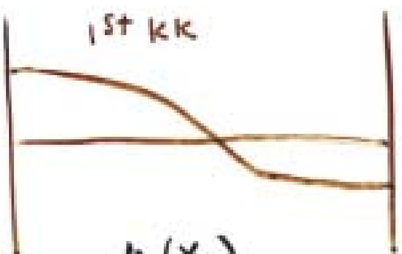
$$\partial^2 \phi = 0 \quad = (\partial_\mu \partial^\mu - \partial_5^2)\, \phi = 0$$

looks like $\quad (\partial_\mu \partial^\mu - m^2)\, \phi = 0 \leftrightarrow \Big\{$ KK tower

- The curvature of 5-d wavefunction of ϕ is related to its mass ...

e.g., flat space w/ U(1) gauge field in bulk
$\oplus$ S^1/Z orbifold BC.

$$A_\mu \sim \cos\left(\frac{n}{R} y\right) \qquad A_5 \sim \sin\left(\frac{n}{R} y\right)$$



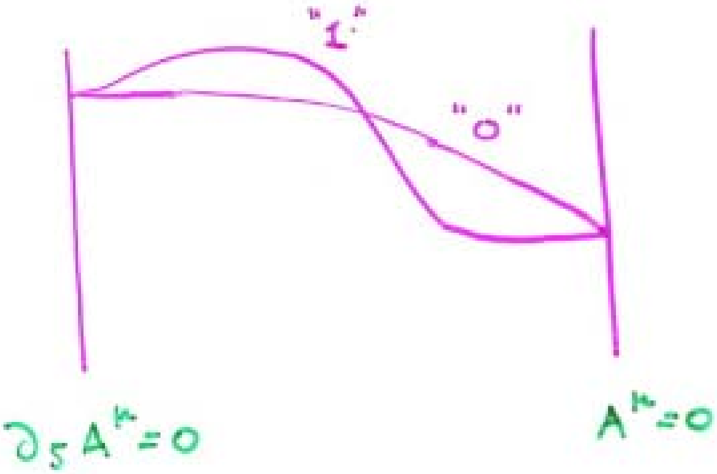
$$\partial_5 A^\mu \big| = 0$$
$$A_5 \big| = 0$$
(orbifold BC's)

The 'zero' mode is flat + x_5-independent $\therefore$ $\underline{m = 0}$

the lightest mode is massless

* If orbifold BC's are applied at both bndrs
  ^ The same
we must get a massless mode + U(1) is unbroken

Now Consider, e.g, a toy setup...



With these BC's A^μ Cannot be flat

$\therefore$ A^μ("0") is **MASSIVE**

... analytically $\Longrightarrow$

$\Longrightarrow$ Lots of questions ...

* Can we just choose ANY BC's we want consist. w/, eg, 4-d Lorentz Invariance ?

No : We are restricted to those that follow from the variation of the action at the boundaries of the interval.... [Csaki et al]

- Still leaves lots of choices !

- Can we do this to generate the SM w/ $g = 1$? w/ $SU(2)_L \times U(1)_Y \to U(1)_{QED}$?

$\rightarrow$ Yes, but the simplest idea (-> flat, $SU(2) \times U(1)$ in bulk) doesn't work...

$$A \sim \sum (a_n \cos m_n y + b_n \sin m_n y)$$

$$\partial_5 A \sim m_n \sum (-a_n \sin m_n y + b_n \cos m_n y)$$

$$A(y=0) = 0 \rightarrow a_n = 0$$

$$\partial_5 A(y=\pi R) = 0 \rightarrow \cos(m_n \pi R) = 0$$

$$\rightarrow \boxed{m_n = \frac{n+1/2}{R}}$$

$\therefore$ the lightest mode is massive!

<u>U(1) is broken</u>

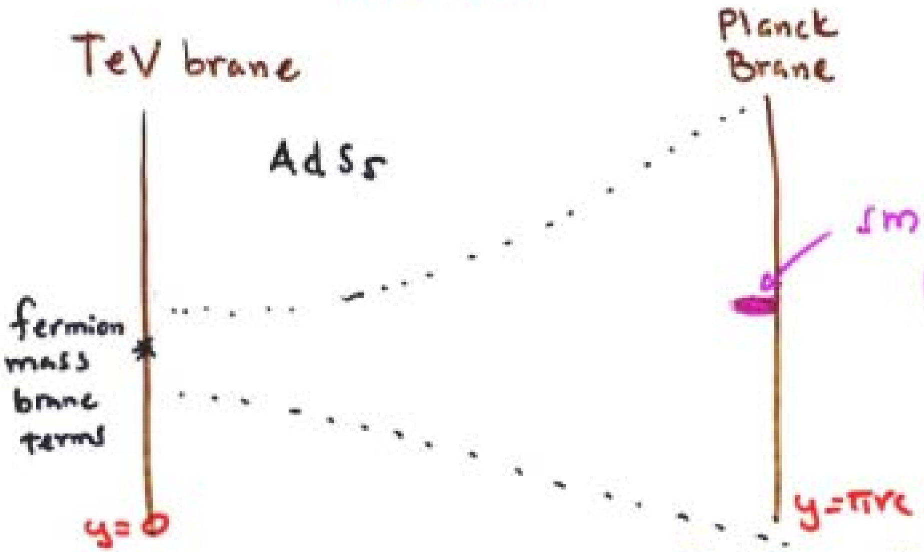
Because

- $M_{W_n} \sim \frac{2n-1}{4R}$, i.e., M_W, $3M_W$, $5M_W$ etc (too light!)

- no custodial SU(2) ($\rho \neq 1$)

$\rightarrow$ go to RS + put $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ * in bulk (Agashe et al, Csaki et al)

$$\boxed{ds^2 = e^{-2ky} dx^2 - dy^2}$$



$\boxed{kr_c \sim 11 \text{ to explain hierarchy}}$

$SU(2)_L \times SU(2)_R$
$\rightarrow SU(2)_D$

⊕

$SU(2)_R \times U(1)_{B-L}$
$\rightarrow U(1)_Y$

$\rightarrow$ LRM $\rightarrow U(1)_{QED}$

Here $SU(2)_L \times U(1)_Y$ is unbroken $\therefore$ potential brane terms

Note:
$SU(2)_D \times U(1)_{B-L}$ unbroken here
$\therefore$ brane terms possible

* global SU(2) remains after SSB
– protecting $\rho = 1$

$SU(2)_R \otimes U(1)_{B-L} \rightarrow U(1)_Y$

on Planck brane

3 generators 'broken'

$W_R^{\pm} + (A_R^3, B)$ get Planck scale masses

$SU(2)_L \otimes SU(2)_R \rightarrow SU(2)_D$

on TeV brane

$W^{\pm}, Z$ get TeV-scale masses

3 generators 'broken'

$\Rightarrow \gamma$ left massless !

Wavefunctions

$$\psi_n \sim z\left\{a_n J_1(m_n z) + b_n Y_1(m_n z)\right\}$$

KK masses

Bessel functions as in usual RS

$$\left(z \sim \frac{1}{k} e^{ky}\right)$$

$$S_{gauge} = S_{bulk} + S_{brane}$$

$$S_{bulk} = \int d^4x \int dy \sqrt{-g} \sum_i \left(-\frac{1}{4 g_{5i}^2} F_{AB}^{i} F^{AB}_{i} \right)$$

$$G = SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

- $SU(2)_R \times U(1)_{B-L} \xrightarrow[\text{Planck Brane}]{} U(1)_Y$

- $SU(2)_L \times SU(2)_R \xrightarrow[\text{TeV Brane}]{} SU(2)_D$

$\therefore$

$$S_{brane} = \int d^4x\, dy \sqrt{-g}\, \delta(y) \left\{ -\frac{1}{4\tilde{g}_L^2} F_L^{\mu\nu} F_{\mu\nu}^L - \frac{1}{4\tilde{g}_Y^2} F_Y^{\mu\nu} F_{\mu\nu}^Y \right\}$$

respect remaining brane gauge symmetries

$$+ \int d^4x\, dy \sqrt{-g}\, \delta(y - \pi R) \left\{ -\frac{1}{4\tilde{g}_{B-L}^2} F_{B-L}^{\mu\nu} F_{\mu\nu}^{B-L} - \frac{1}{4\tilde{g}_D} F_D^{\mu\nu} F_{\mu\nu}^D \right\}$$

BC

$\begin{pmatrix} SU(2)_{L,R} : & A^a_{L,R} \\ U(1)_{B-L} : & B \end{pmatrix} \quad (SU(3)_c : A^a_c)$

Planck Brane:

$$A_R^{1,2} = g_{5B}\, B - g_{5R}\, A_R^3 = 0$$

$W_R^{\pm}$ + $(B, A_R^3) \neq Y$ get Planck scale masses

$$\partial_z A^a_{L,c} = -\delta_{L,s}\,(m_1^2/k)\, A^a_{L,c}$$

$$\partial_z (g_{5B} A_R^3 + g_{5R} B) = -\delta_Y (m^2/k)(\quad)$$

(+ 5^{th} components)

TeV Brane

$(SU(2)_{L\times R} \to SU(2)_D)$

$$g_{5L} A_L^a - g_{5R} A_R^a = 0$$

(+ 5^{th} components)

$$\partial_z A_c = 0$$

$$\partial_z B = \delta_B (m_1^2/k\epsilon)\, B$$

$$\partial_z (g_{5R} A_L^a + g_{5L} A_R^a) = \delta_E (m_1^2/k\epsilon)(\quad)$$

* large $\delta_{Y,L,s}$ terms are calculable via RGE (Nomura)

$\delta_{B,E}$? expected to be small ... but ...

** e.g.,

$$\delta_L \equiv \frac{k}{2}\left(g_{5L}^2/\tilde{g}_L^2\right) \text{ etc}$$

are dimensionless parameters $O(1\text{-}10)$

- You may also ask : If there are no Higgs, where do the Goldstone bosons come from ?

Fortunately $\quad A^M \equiv (A^\alpha, A^5)$

4 vector $\quad$ scalar

... consider flat space ...

$$A_\mu = A_\mu^{(0)} + \sum_{n=1}^{\infty} \left(A_\mu^{(n)} \cos {}^{ny}/_R + A_\mu^{(n)'} \sin {}^{ny}/_R \right)$$

$$A_5 = A_5^{(0)} + \sum_{n=1}^{\infty} \left(A_5^{(n)} \cos {}^{ny}/_R + A_5^{(n)'} \sin {}^{ny}/_R \right)$$

Orbifold BC's $\rightarrow \begin{cases} \partial_5 A_\mu \,|_{0,\pi R} = 0 \\ A_5 \,|_{0,\pi R} = 0 \end{cases}$

$\rightarrow A_\mu^{(n)'} = A_5^{(n)} = \underline{A_5}^{(0)} = 0$

- $A_\mu^{(n)}$ eat $A_5^{(n)}$ $[n \geq 1]$ + get mass . but $A_\mu^{(0)}$ has no one to eat + remains massless !

Here : BC's relate co-efficients in KK decomp.

BUT $A_5^{(0)}$ remains in the spectrum to be eaten

$\rightarrow$ the source of the Goldstones

Parameters :

- g_L, g_R, g_B } overall strength ⊕ $\underline{\kappa = g_R/g_L}$, $\lambda = g_B/g_L$

fixed by M_Z

- κ_{crit} fixed by M_W $\left[\begin{array}{l} 0.66 \lesssim \kappa \lesssim 4 \\ \lambda^2 > 0 + \text{PT} \end{array}\right]$

- δ_L, δ_Y fixed by β-functions (Nomura)

⊕ G_F

- δ_E, δ_B taken $= 0$ (for now)

Three $\sin^2\theta$ story : at **TREE** level in the SM

1 - $\sin^2\theta_{os} = M_W^2/M_Z^2$ (enforced here)

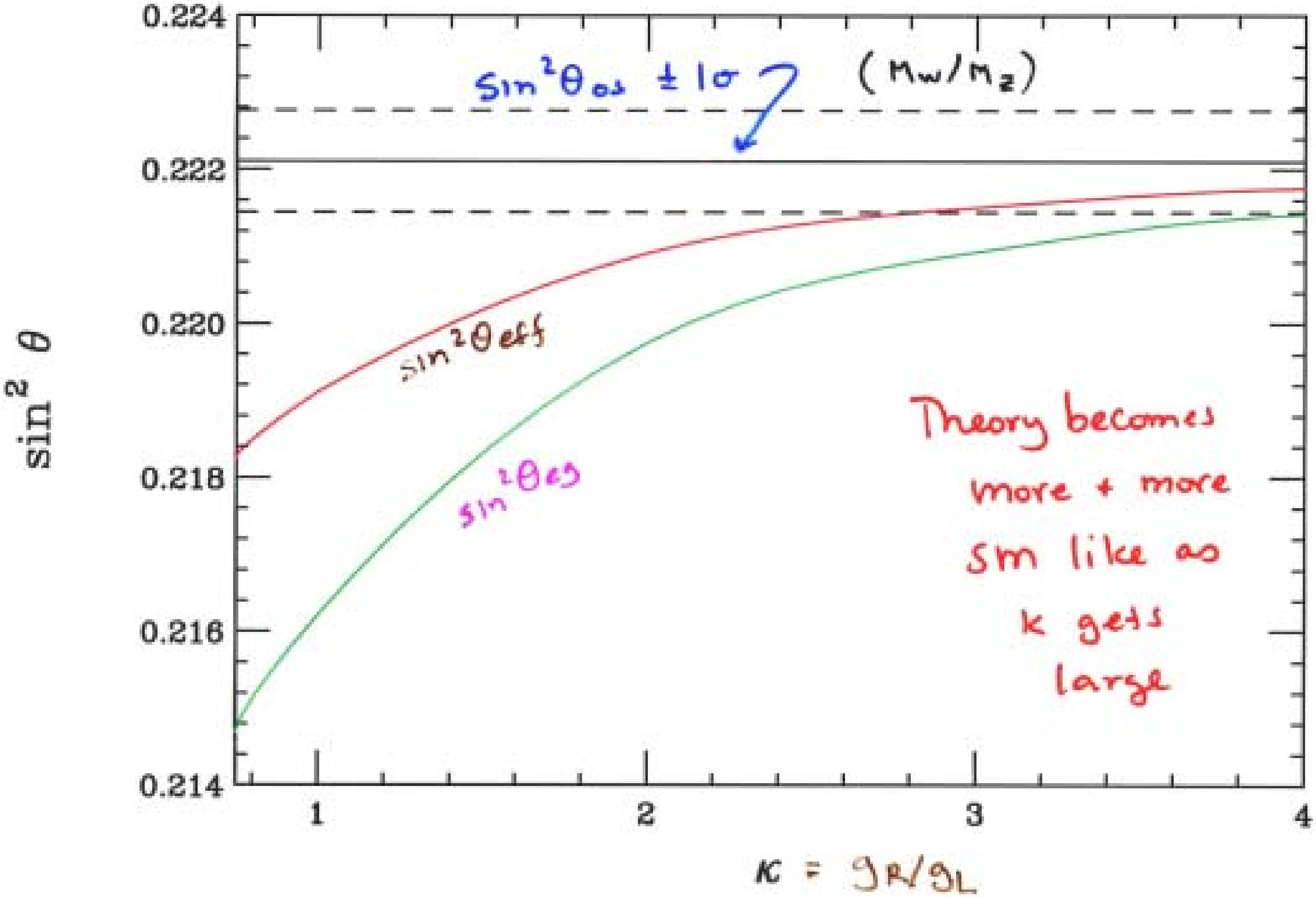
$\sin^2\theta_{eg} = e^2/g_{ffW_1}^2$ and

$$\mathcal{L} = \sqrt{\rho_2^{eff}}\,\frac{g_{ffW_1}}{c_W^{os}}\left(T_{3L} - \underline{\sin^2\theta_{eff}}\cdot Q\right) Z_{(1)}$$

are all equal - trivially. Not So Here....

→ Certainly, they must be in SM limit !!

→ must be at least 'close'.... here



→ larger κ prefered..

"pseudo" oblique analysis..*

Still at tree level... !

$$\begin{cases} \sin^2\theta_{eff} \overset{\text{note}}{=} \sin^2\theta_{os} + \dfrac{\alpha\Delta S}{4(c_w^2-s_w^2)} - \dfrac{c_w^2 s_w^2\,\alpha\Delta T}{c_w^2-s_w^2} \\ M_W^2 \overset{\text{note}}{=} M_W^2\big|_{sm}\left\{1 - \dfrac{\alpha\Delta S}{2(c_w^2-s_w^2)} + \dfrac{\alpha\Delta U}{4s_w^2} + \dfrac{c_w^2\,\alpha\Delta T}{c_w^2-s_w^2}\right\} \\ \Gamma_\nu \overset{\text{note}}{=} \Gamma_\nu\big|_{sm}(1+\alpha\Delta T) \end{cases}$$

$\Longleftrightarrow$ These relations DEFINE ΔSTU

note: $\alpha\Delta T = (\rho^2_{eff} - 1)$ from above

· loop oblique contributions EXPECTED to be small

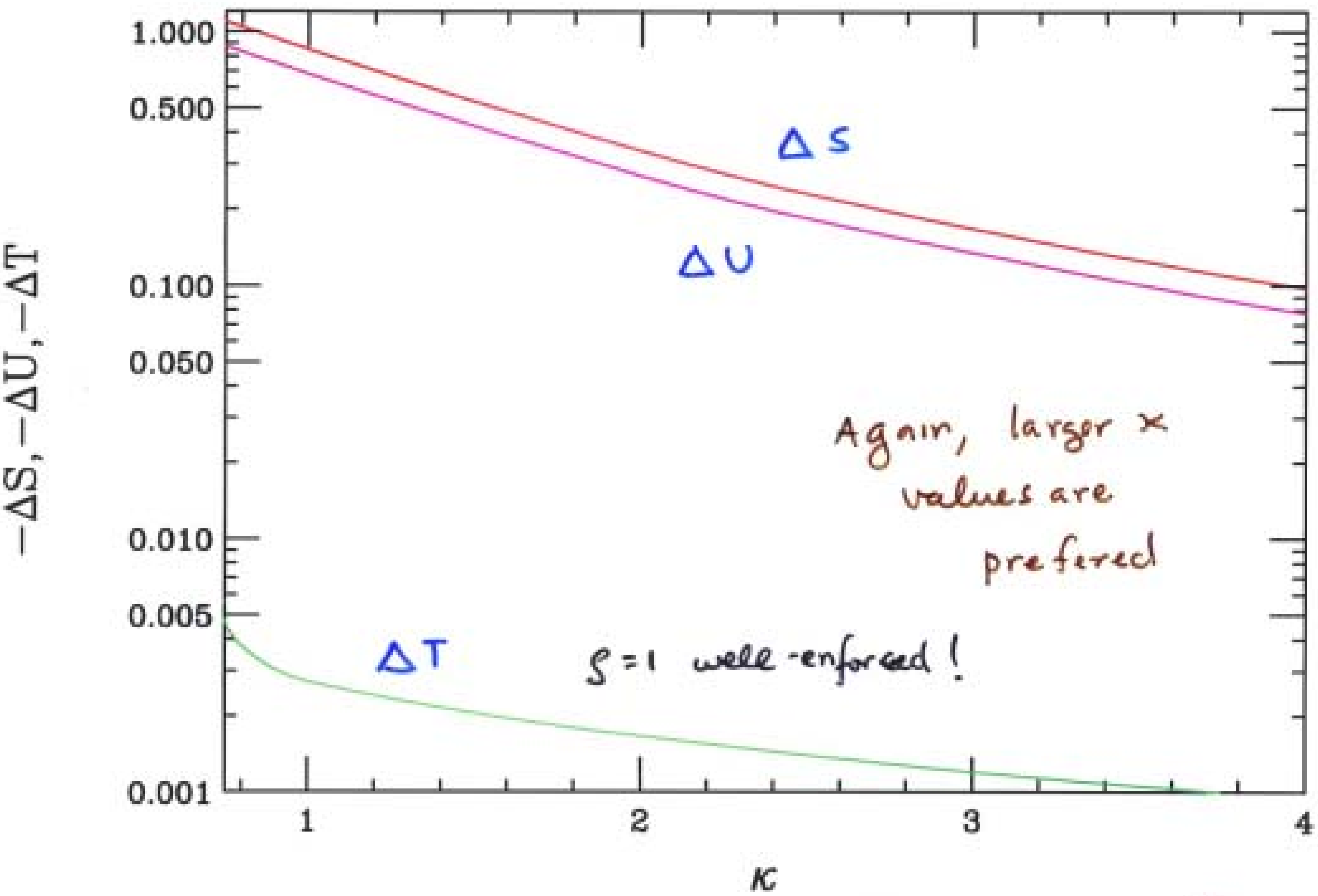
e.g., $\alpha S_{1\text{-loop}} \sim \dfrac{\alpha}{kr_c\pi}$

· issue: How to subtract out sm Higgs piece $\rightarrow$ need full 1-loop analysis $\rightarrow$ incomplete.!!

$\Rightarrow$ · In the treelevel sm $\Delta S, \Delta T, \Delta U$ (defined here) $= 0$

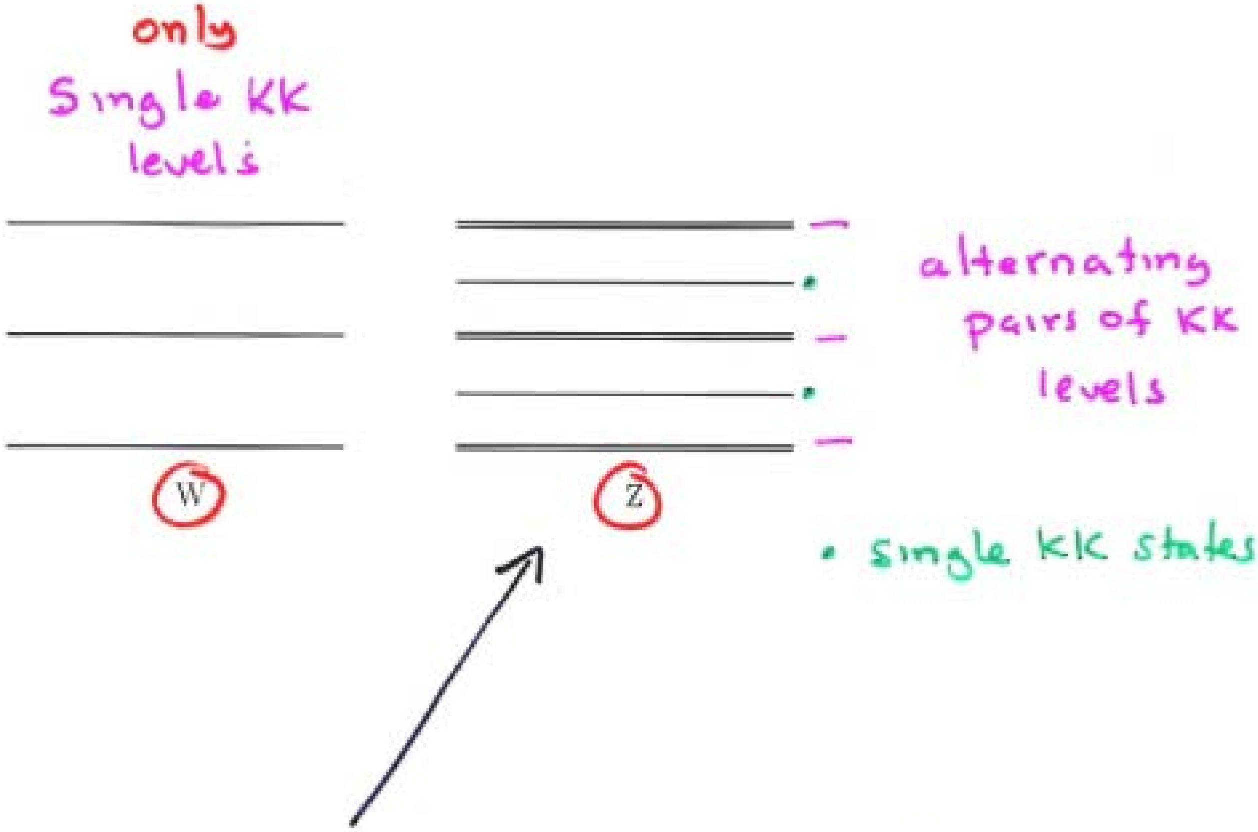
* Not to be compared w/ data w/o loop corrections

Pseudo Oblique Parameters



$\Rightarrow$ { Take $\kappa = 3$ for further study

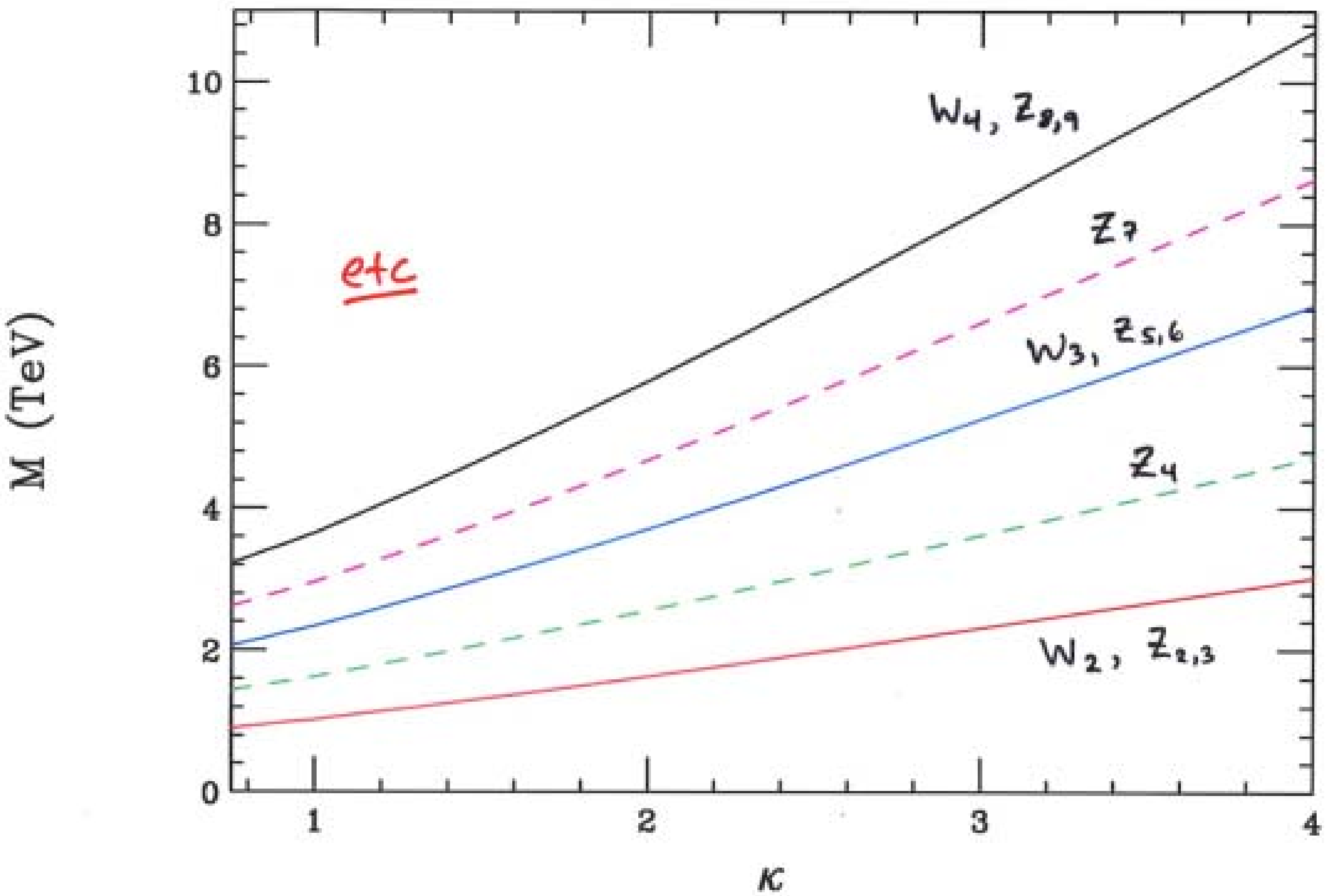
What about the KK excitations ?



- These are not just copies of $\underline{\gamma + Z}$ like in TeV or usual RS case!
- They are highly mixed by BC's ...

  lighter member of pair is $\approx Z_{B-L}$

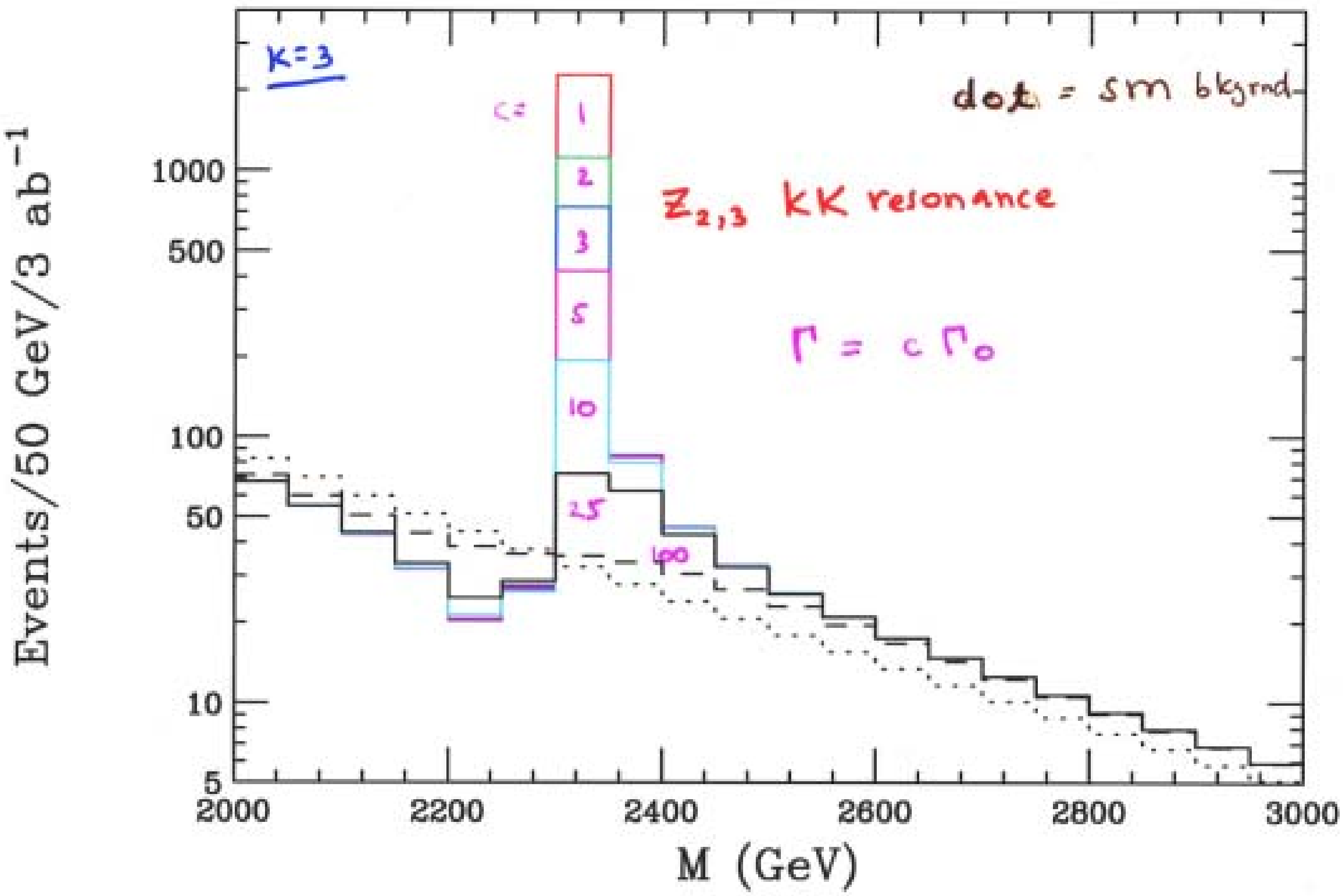
KK excitation spectrum



Note that KK masses ↑ as κ ↑

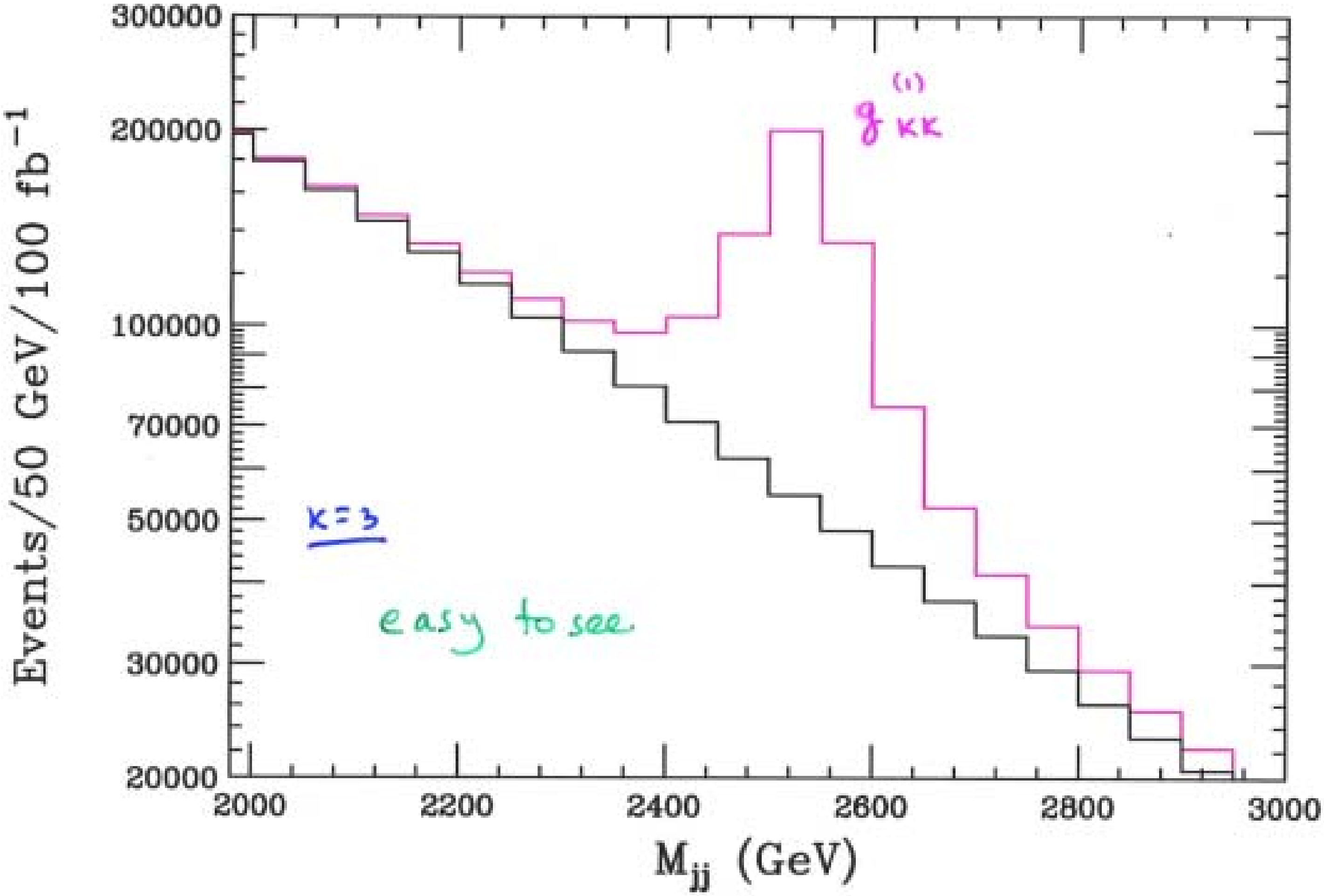
– again more SM-like... decoupling

LHC · Drell-Yan production

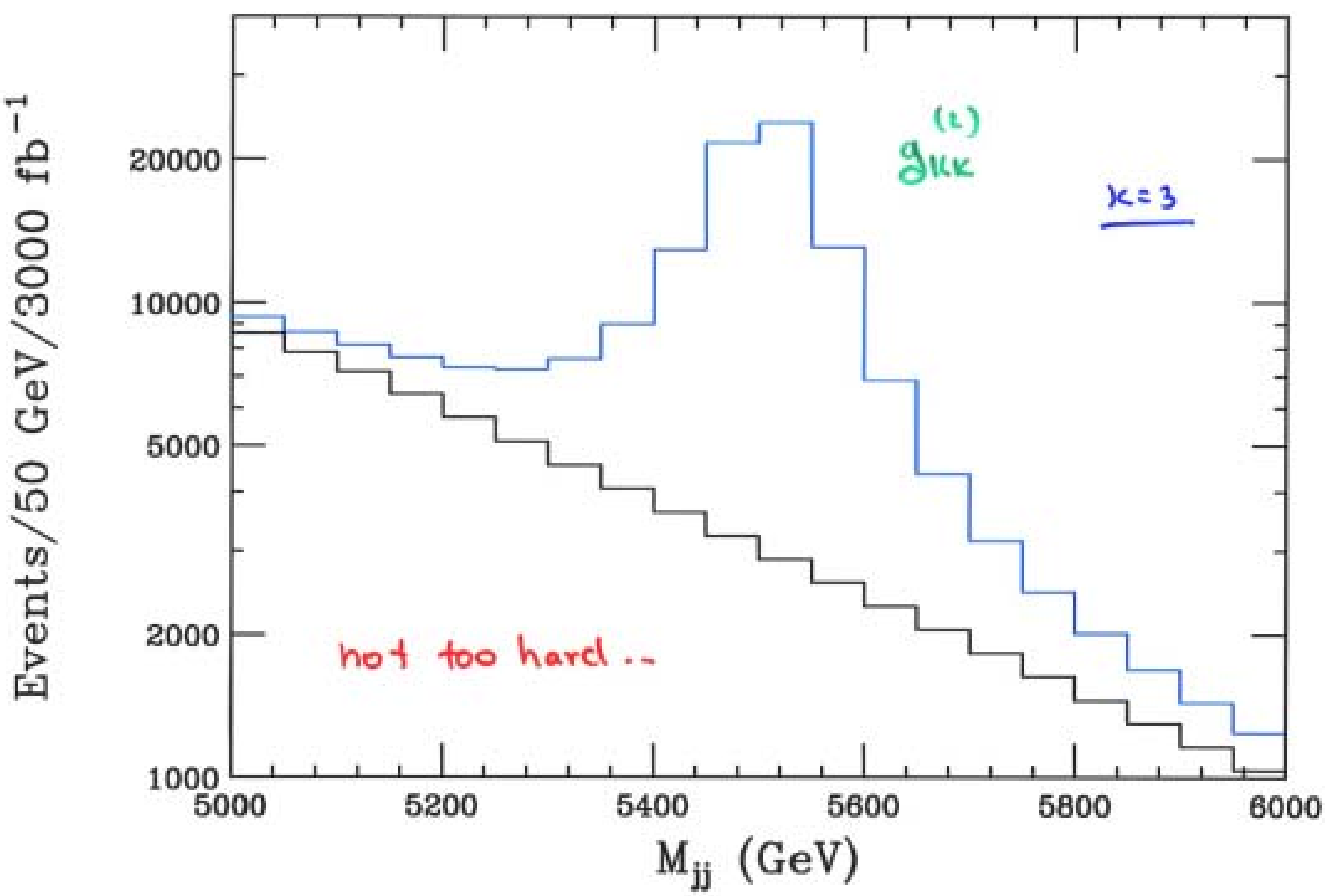


Some examples

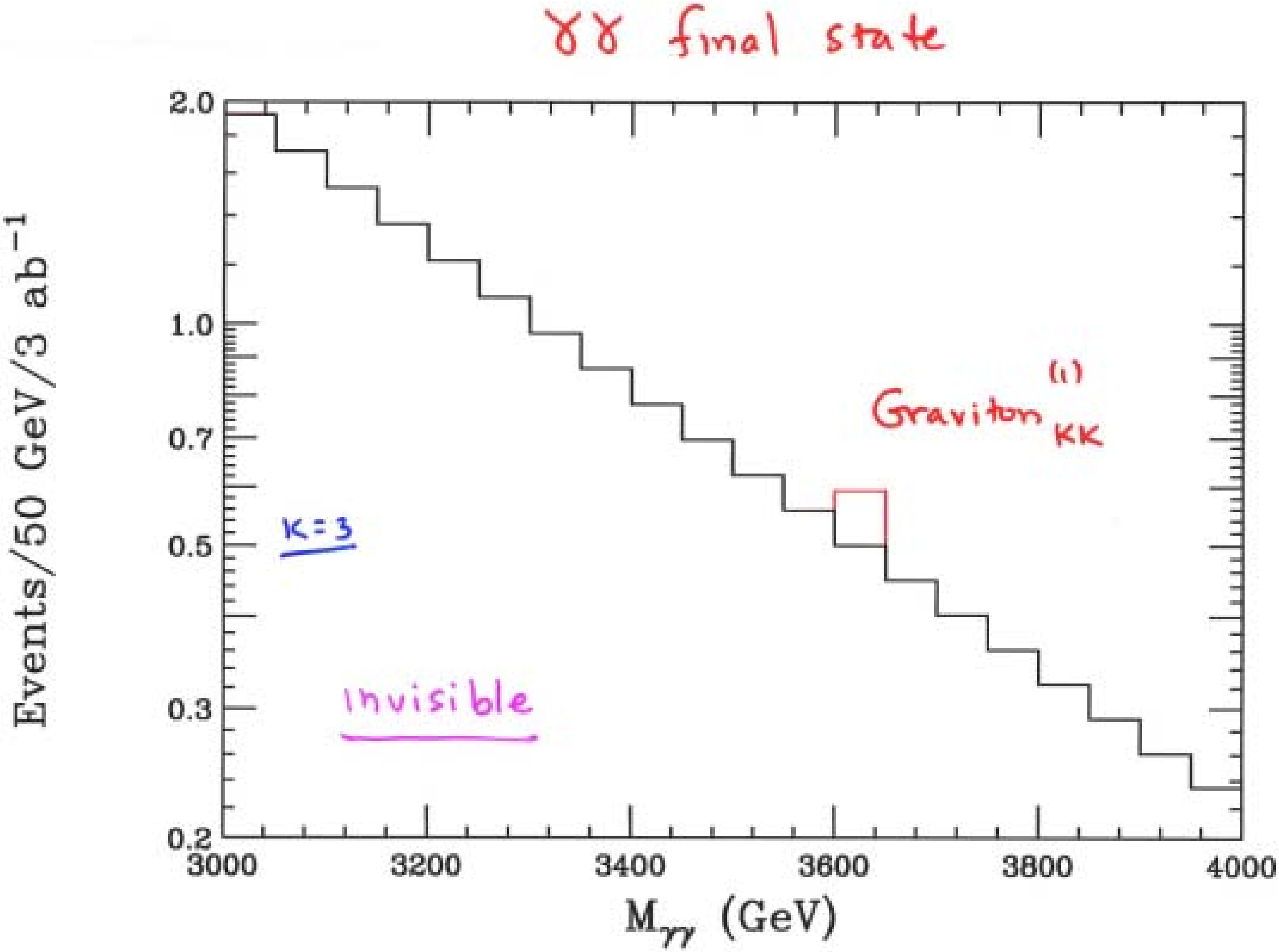
LHC dijet resonance



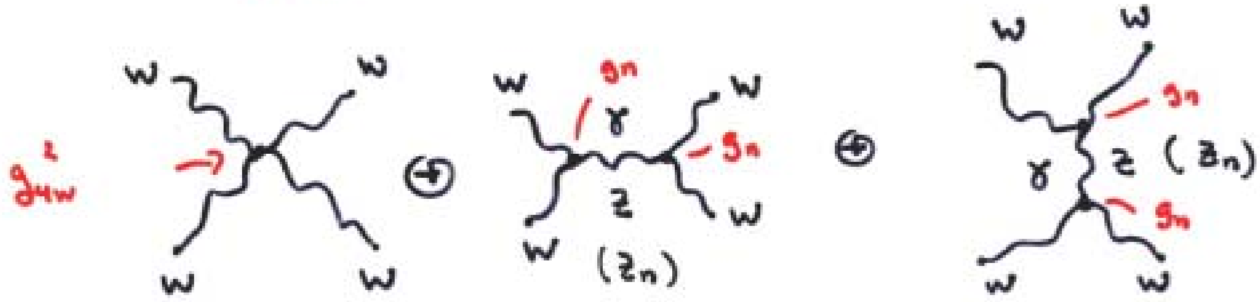
LHC dijets



Events/50 GeV/3000 fb^{-1}
20000
10000
5000
2000
1000
5000
5200
5400
5600
5800
6000
M_{jj} (GeV)
$g_{KK}^{(1)}$
$\kappa=3$
not too hard ..


γγ final state
Graviton$^{(1)}_{KK}$
κ=3
invisible
Events/50 GeV/3 ab^{-1}
$M_{\gamma\gamma}$ (GeV)
2.0
1.0
0.7
0.5
0.3
0.2
3000
3200
3400
3600
3800
4000

$W_L W_L$ - unitarity



- each amplitude $\sim s^2$ but gauge invariance reduces it to $\sim s$ in <u>sum</u>

removes $\sim s$-like growth

<u>Here</u> we have no Higgs $\therefore$ the KK's $\oplus$ diffs in couplings must $\rightarrow$ <u>Unitarity</u>

Sum Rules

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

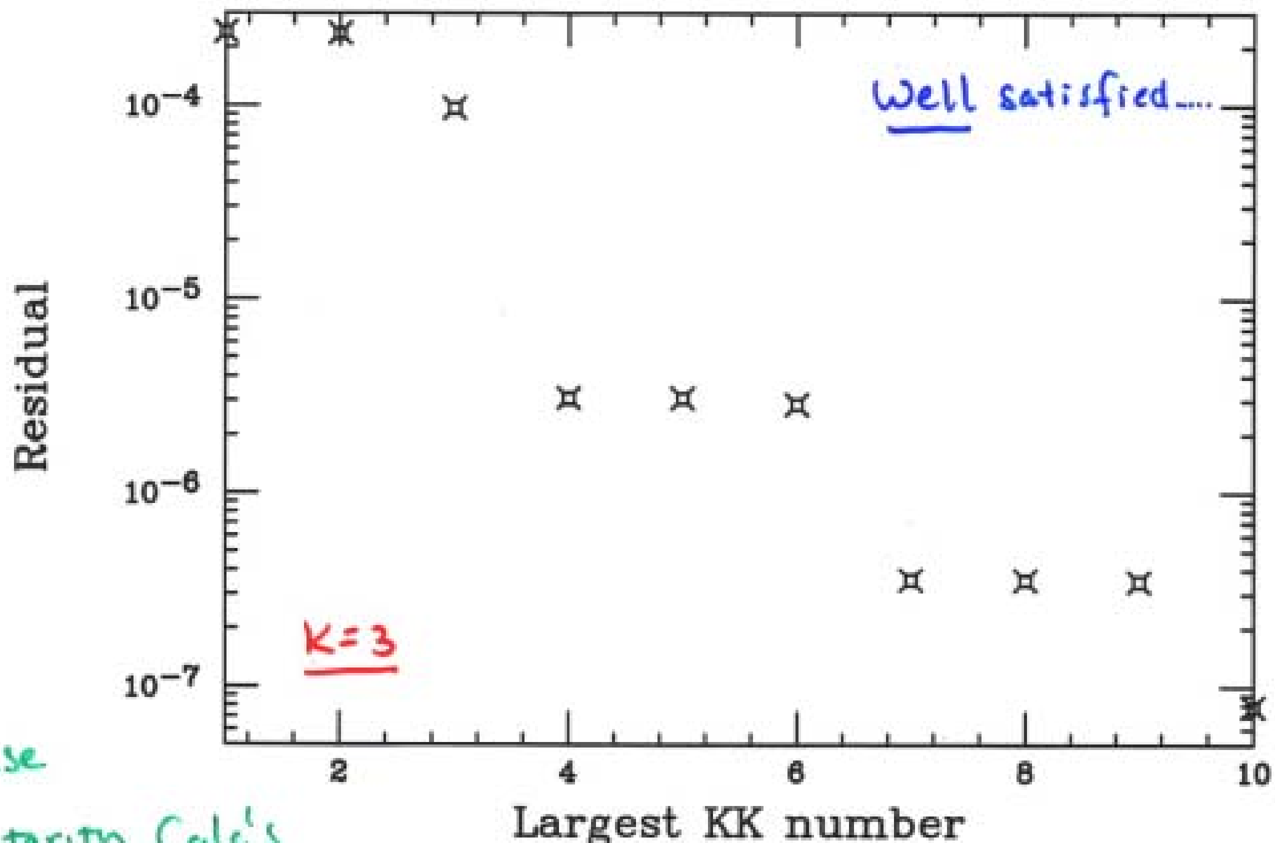
$$g_{4w}^2 = \frac{3}{4} \sum_{n=\ldots} g_n^2 M_n^2 / m_W^2$$

(Csaki etal)

<u>Necessary</u> conditions for asymptotic unitarity

$\Rightarrow$ <u>NOT</u> <u>SUFFICIENT</u> !!

Residuals in First Sum Rule as more KKs are added..

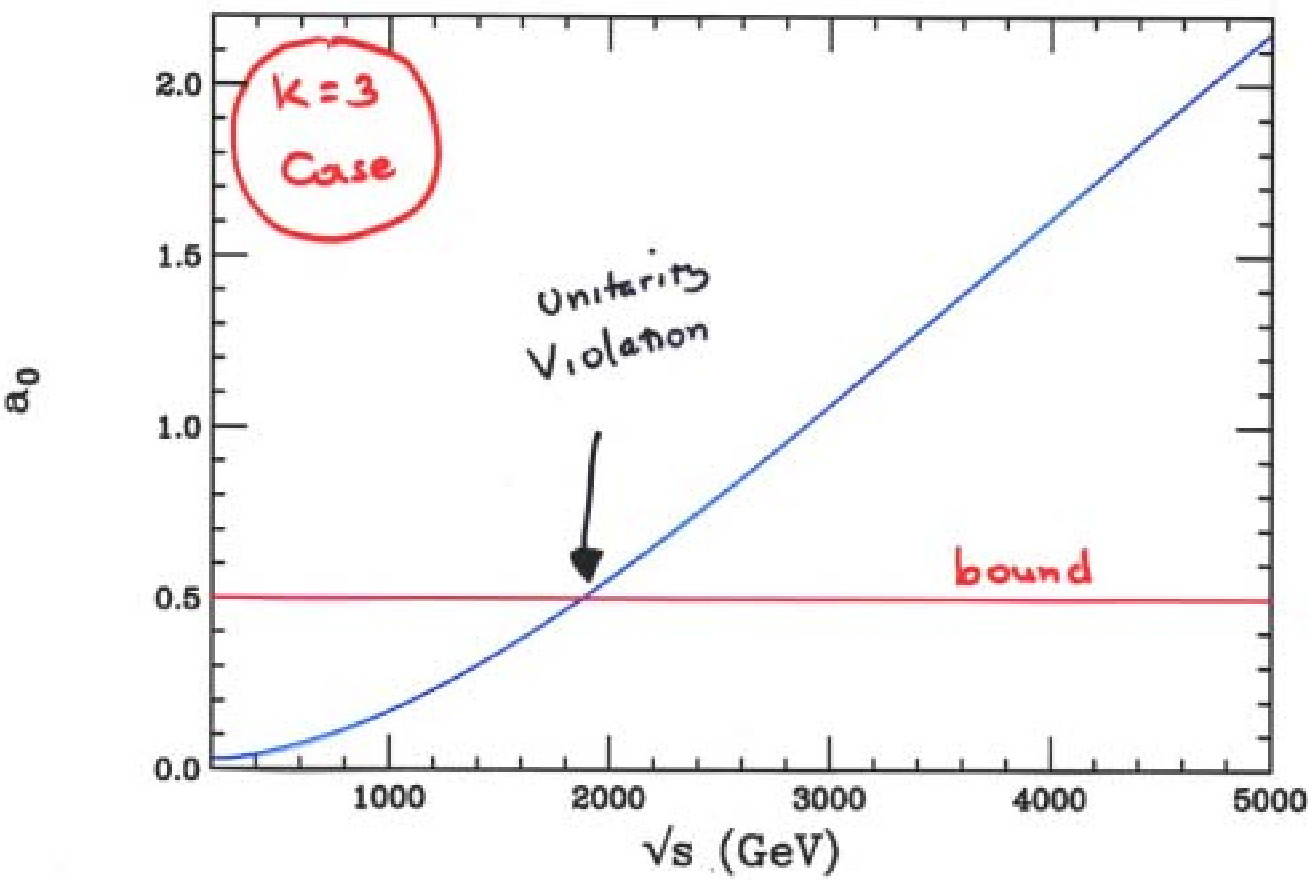


These Unitarity Calc's require very high precison + were checked on 3 platforms using { MAPLE MATHEMATICA FORTRAN codes... here + in what follows..

...Similarly for second sum rule...

$$a_0 \equiv \frac{1}{32\pi} \int_{-1}^{1} d\cos\theta \; A(W_L W_L \to W_L W_L) \Big\{ \begin{matrix} 0^{th} \\ \text{partial} \\ \text{wave} \end{matrix}$$

The 'test' $\Rightarrow$ $\boxed{|\mathrm{Re}\, a_0| < 1/2}$



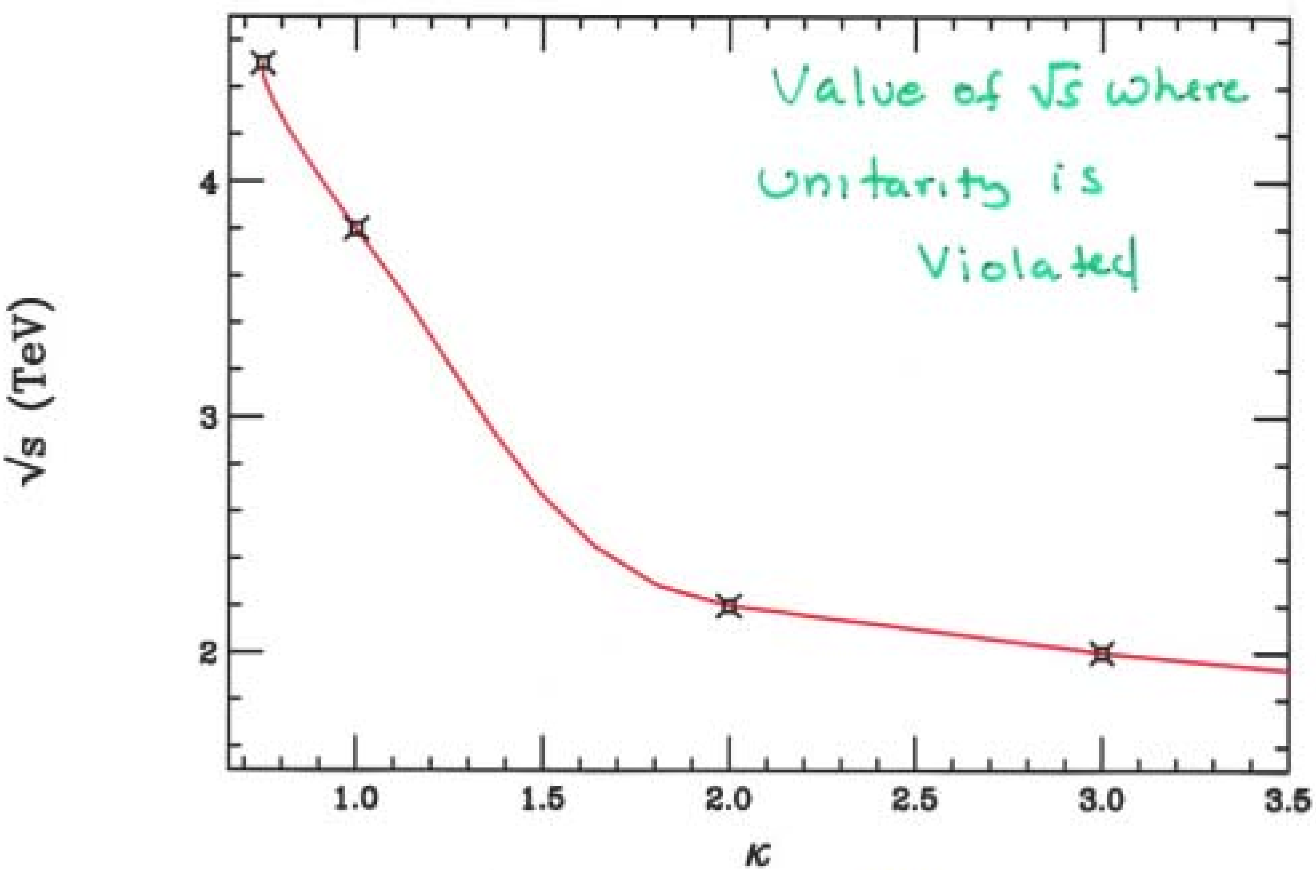
Unitarity violated near ~ 1.9 TeV

... not much better than SM with no $\underline{H}$

... in fact...

$W_L W_L$ Unitarity:

→ doesn't look good ....



Never satisfied !!

{ Flat case w/ $\kappa = 1$ is unitary...
but violates EWK very badly !! }

... so it can be done..!

Recent Developements

What can we do ?

- Csaki et al suggest $U(1)_{B-L}$ brane terms on TeV brane may/will help with WW + EKW ...

→ Turn on $\delta_B \neq 0$

⟹ What we need ...... (at least)

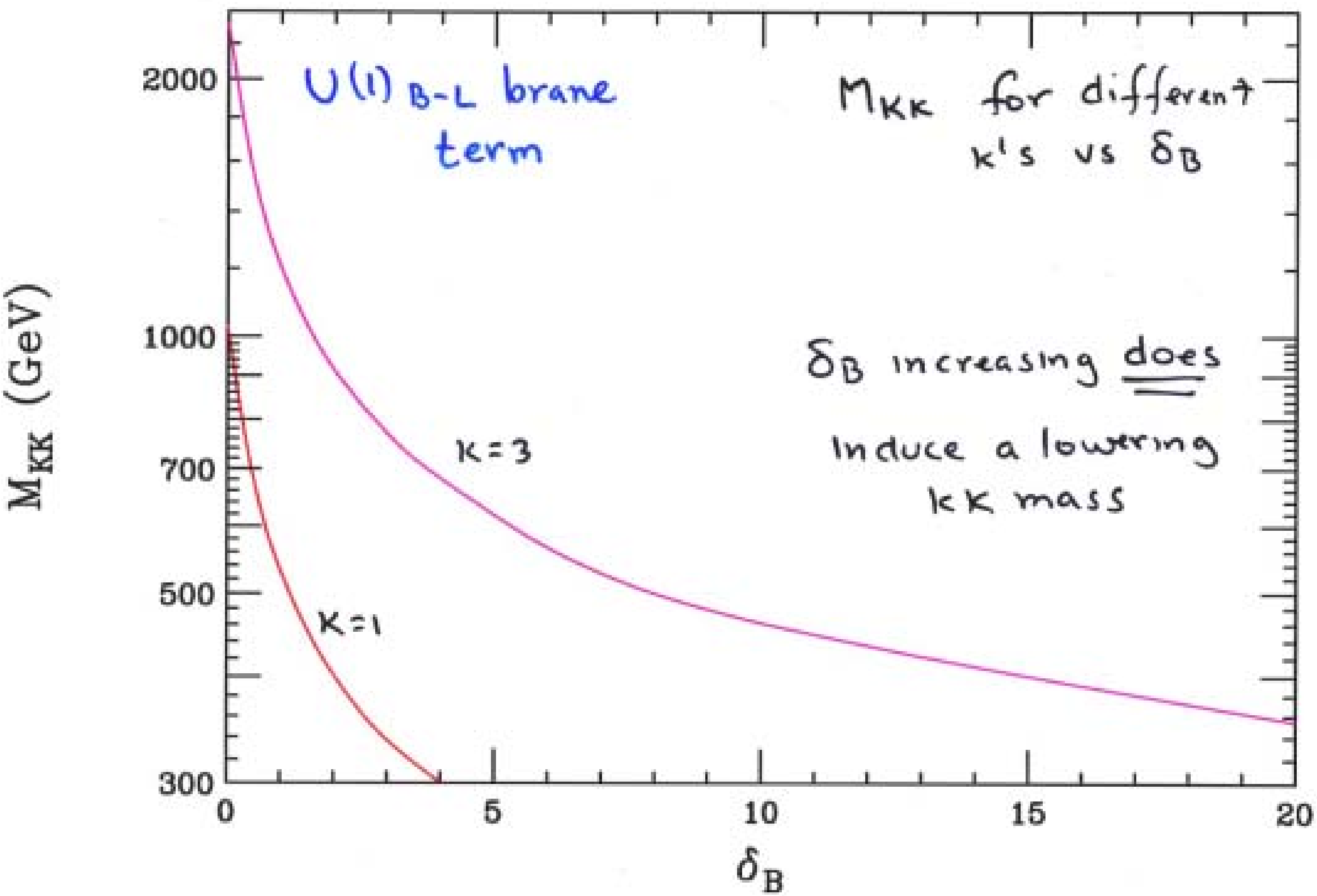
- lower KK masses w/ correct WW coupls.
- adjust EWK parameters ... small ΔS etc + $\sin^2\theta_i$ obser
- avoid any collider bounds etc

Does $\delta_B \neq 0$ do all this ? ?

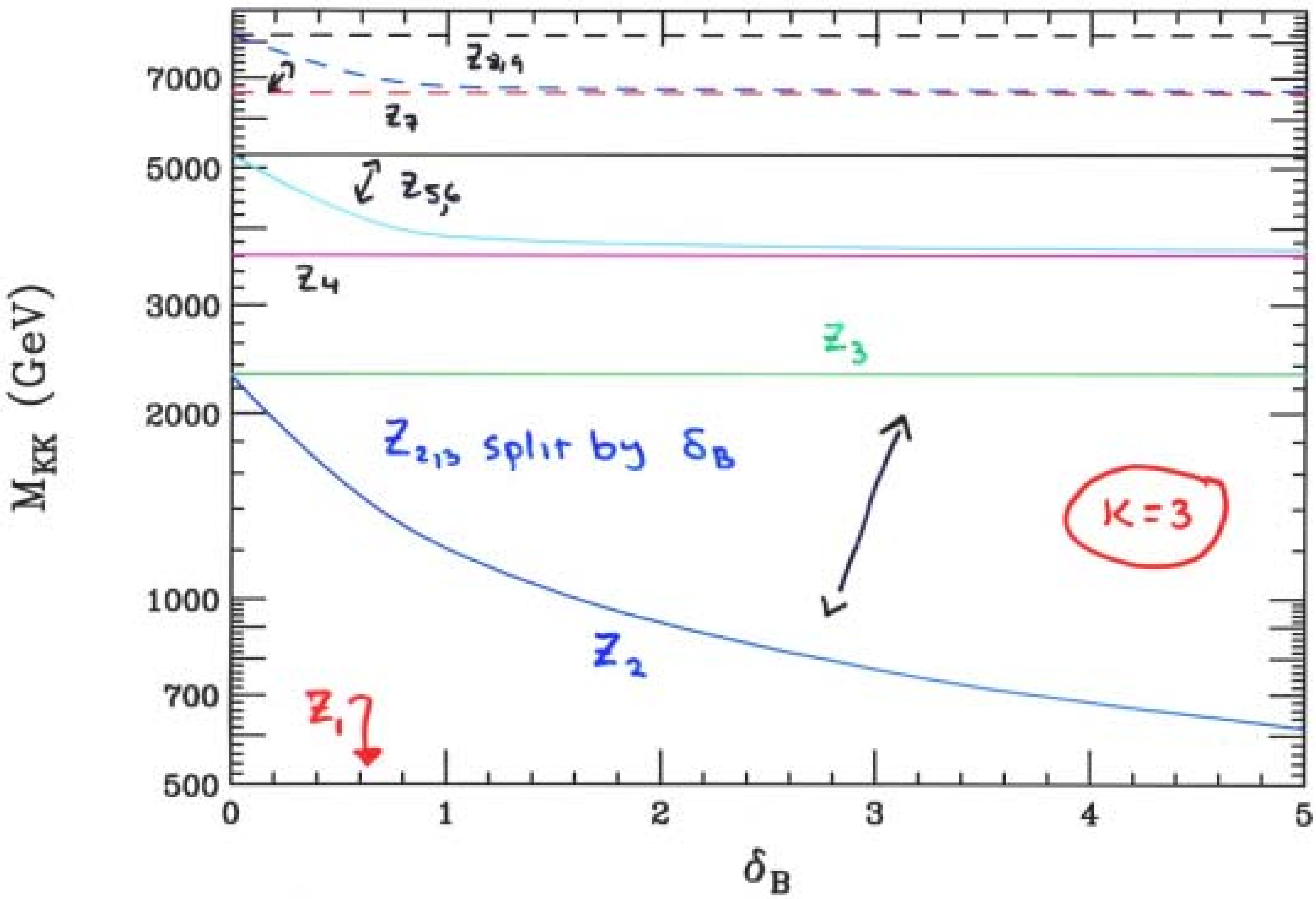
∴ It will modify the mostly "Z_{B-L}-like" tower members ...

BUT .... let's look at some preliminary results ...

1st KK mass (Z_2)

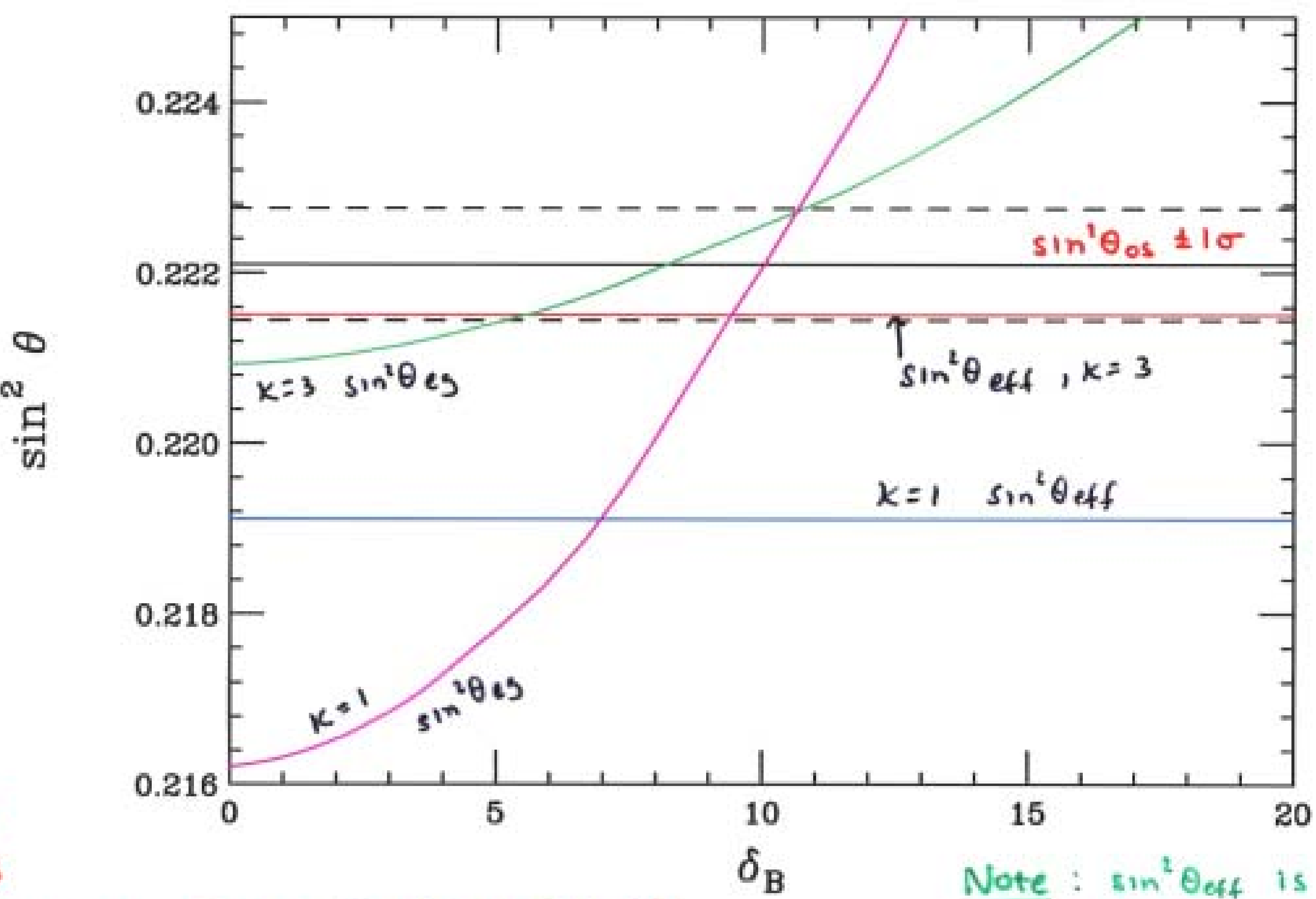


KK level shifts due to δ_B



δ_B splits almost degenerate Z_n pairs ....

$\sin^2\theta_{os,\,eff,\,eg}$ vs δ_B

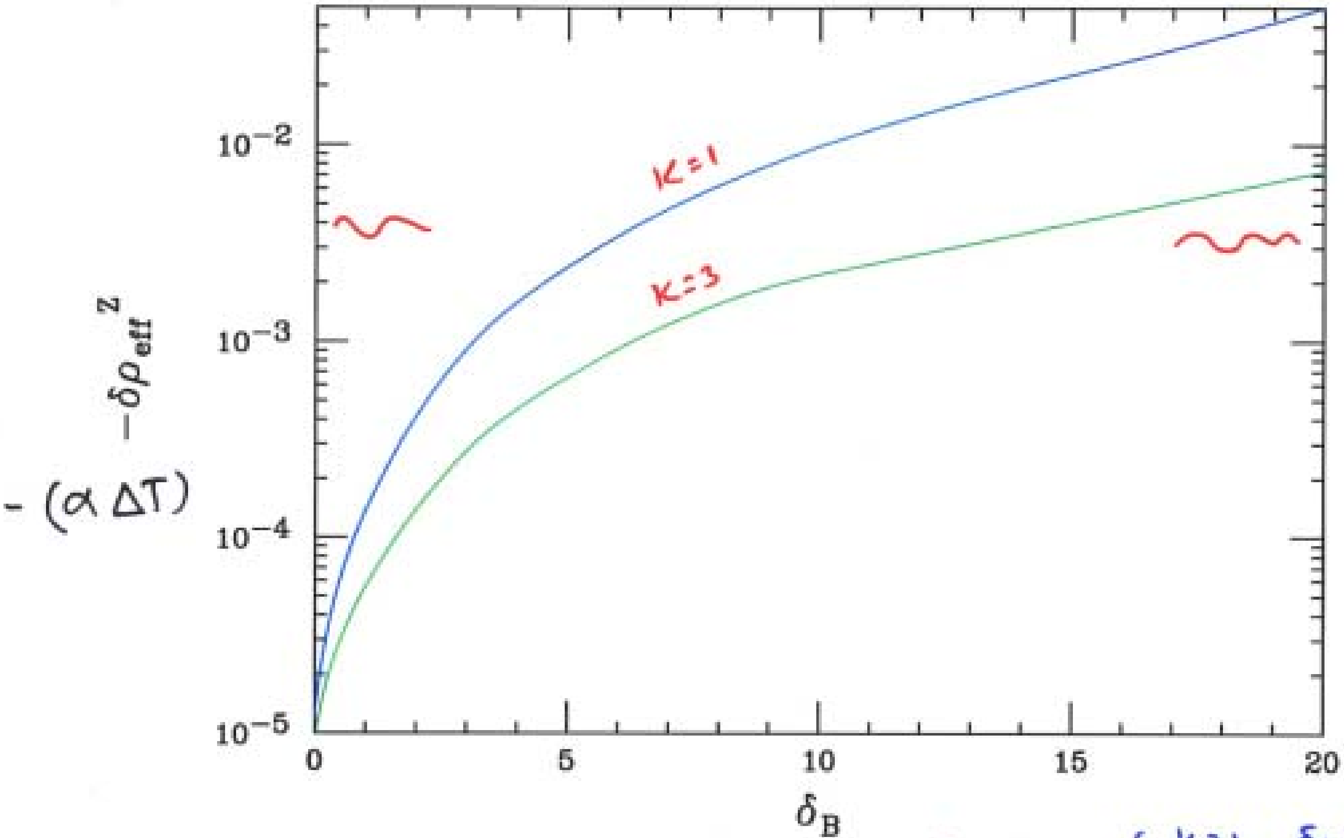


Best Cases

k=1 $\delta_B \simeq 10$ ($\sin^2\theta_{eff}$ still off)

k=3 $\delta_B = 8$ looks very good!!

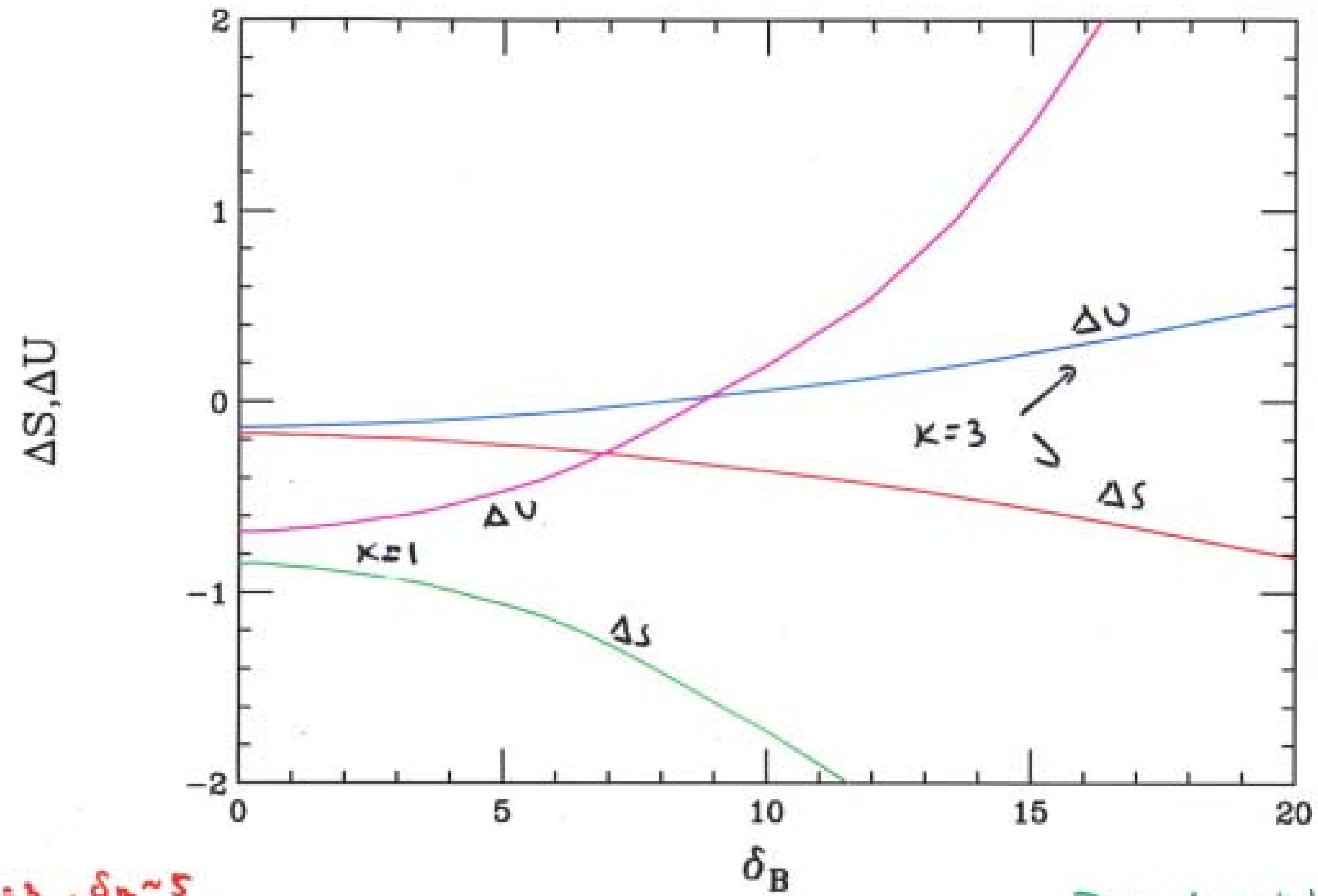
Note: $\sin^2\theta_{eff}$ is essentially δ_B independent.



lower values of δ_B prefered

$$\begin{cases} k=1 & \delta_B \lesssim 6 \\ k=3 & \delta_B \lesssim 15 \end{cases}$$

Pseudo-Obliques - go nuts

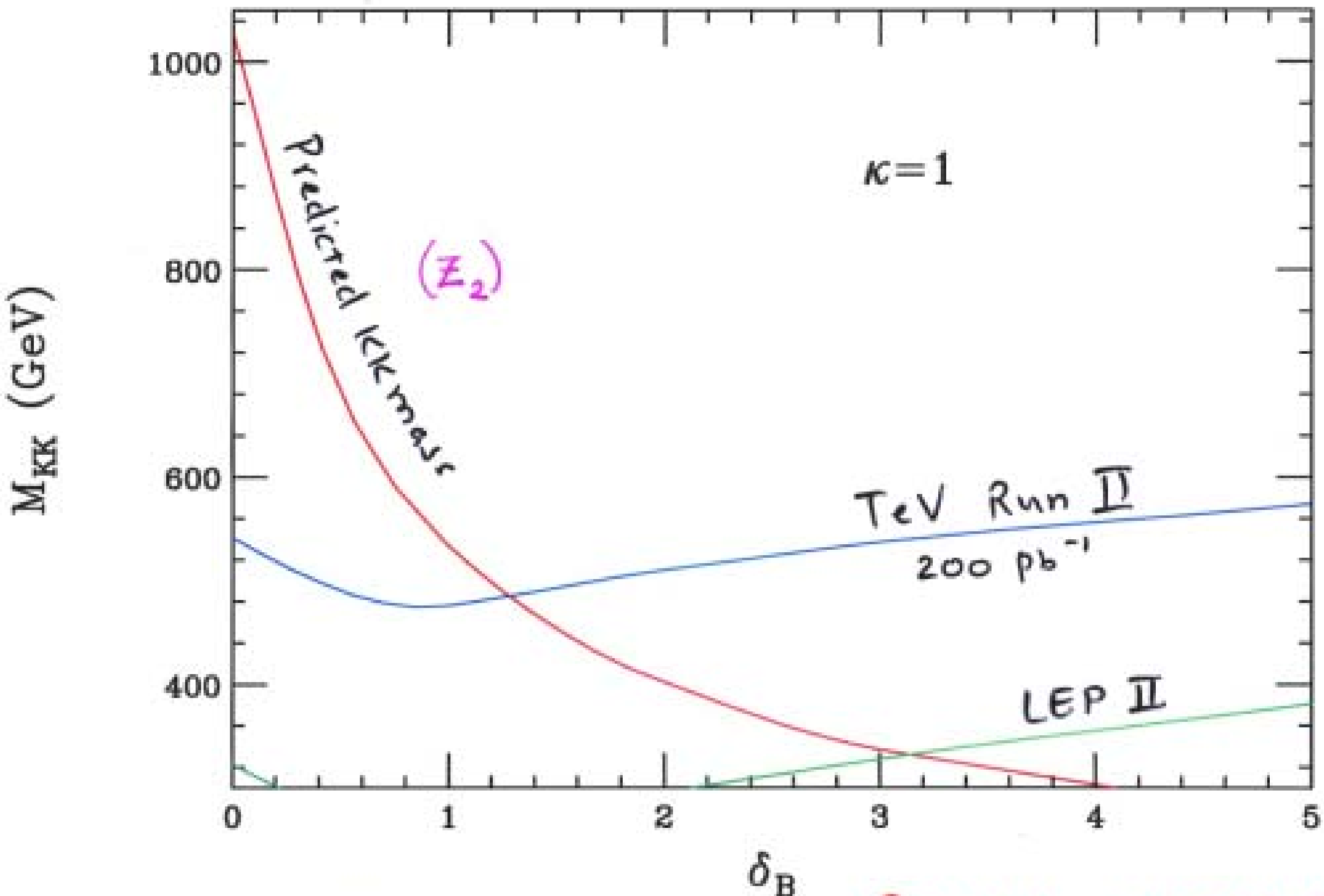


K=3 , $\delta_B \sim 5$
not too bad

This doesn't look good...

but... loops ?

Collider Bounds

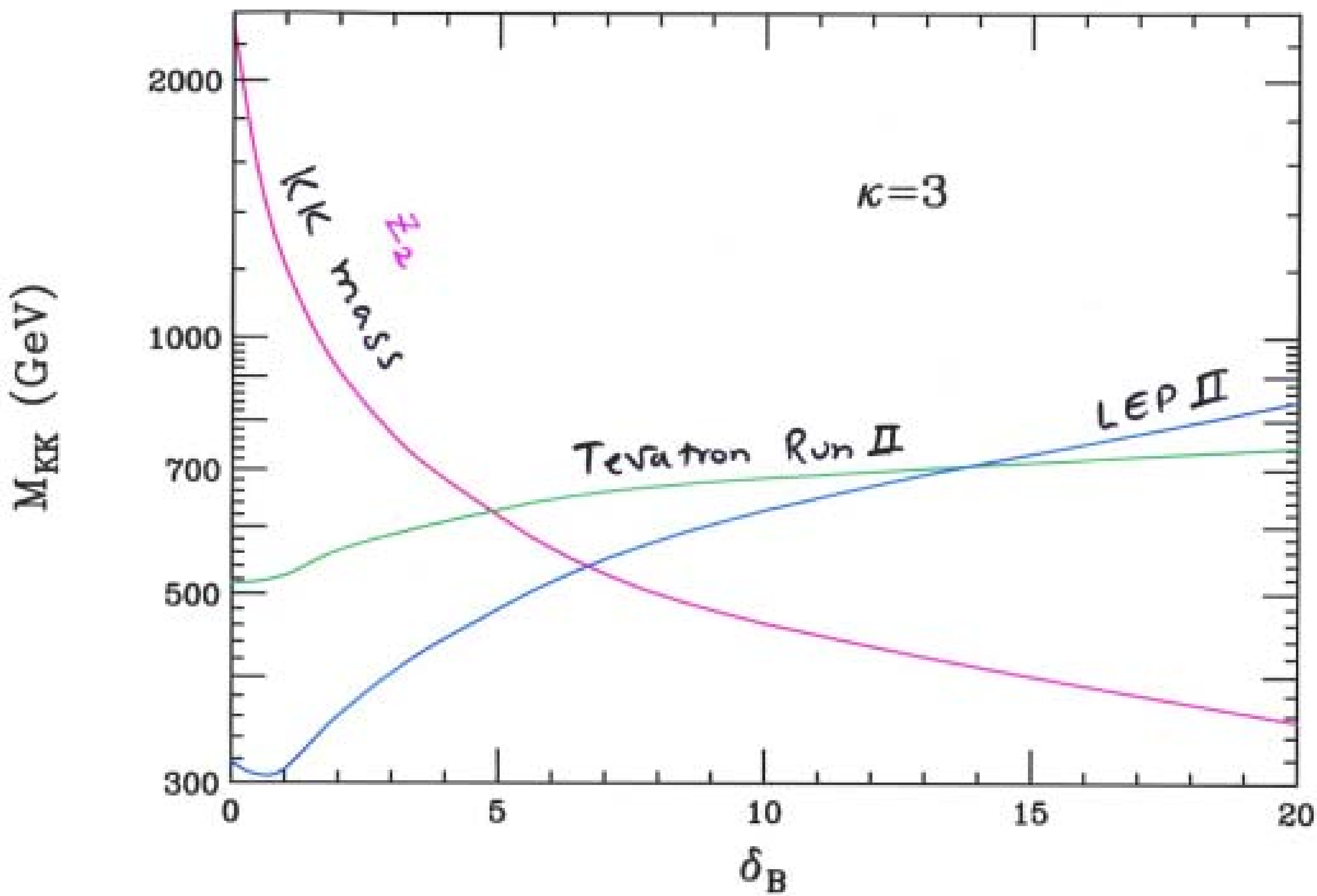


$\delta_B \lesssim 1.3$? from TeV II

(move t_R ?)

$\delta_B \leq 3.2$ no matter what!
thanks to LEP II

Collider Bounds



$\delta_B \leq 5 \sim 7$ From TeV II + LEP II

However $W_L W_L$ unitarity is not affected by $\delta_B \neq 0$ ** since it modifies the $U(1)_{B-L}$ parts of the Z_n [Plot]

And

$W_L W_L$ goes thru 'isospin' couplings -

projection of Z_n onto $\underline{T_{3L}}$

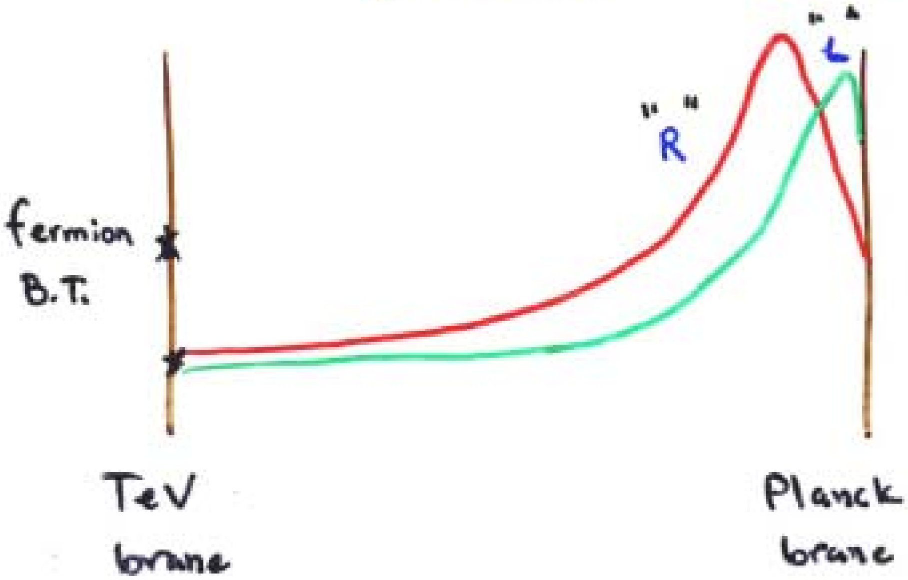
$\left.\begin{array}{l} g\,s_W \ (\gamma) \\ g\,c_W \ (Z) \end{array}\right\}$ in SM

→ $\delta_B \neq 0$ $\boxed{\text{doesn't help us}}$...

At least not by itself ....

→ Keep looking !!

** ie, $\sqrt{s}_{\text{violation}}$ is δ_B indep. to $\sim O(10^{-3})$ for $0 \leq \delta_B \leq 20$! - This is a '3 platform' analysis - critical 'zero' mode - fermion bulk wavefunctions



Peak location determined by 5d Dirac mass terms

BC's give chiral zero mode - <u>except</u> for TeV BT's → links zero modes of "L" + "R"

→ "sm" masses

Conclusions

- Higgsless E~~W~~K is an extremely interesting idea
- Models exist where precision measurements + collider bounds can be satisfied → **testable**

Needed:

- loop-order EWK analysis ⇔ Higgs 'removal'

* How to get Unitarity in $W_L W_L$ w/o upsetting everything else ??

Clearly a lot more work needs to be done ....