Brane Terms*, KK properties + the LC

- Background on brane terms..
  - → what are they + what do they do?
- First example: gauge KK's in TeV^{-1} 5D
  - → shifts in spectrum, wave functions + couplings
- gauges in RS
- gravity in RS

} ↔ new states can be lighter than previously expected

→ LC / LHC implications: { lighter states

- Summary + Outlook

* We will limit ourselves <u>here</u> to brane kinetic terms.....

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Some Literature:

M. Carena et al
- hep-ph/0207056 — TeV^{-1}
- " /0212307 — RS

F. del Aguila et al: hep-th/0302023 — TeV^{-1}

Davoudiasl, Hewett + TGR
- hep-ph/0212279 — RS
- " /0305086 — RS gravity *

* Almost all papers deal with gauge KK states w/ matter fields at the S^1/Z_2 fixed points $y = 0, \pi R \ (\pi r_c)$

- Brane kinetic terms are naturally generated in all orbifolded theories + in models where matter exists on boundaries

[Georgi, Grant + Hailu (PLB 506, 207 '01)]

+ so should be present from the beginning in models + certainly must be examined phenomenologically!

Consider a bulk scalar in 5D: <u>eg, S^1/Z_2</u>

$$S_{bulk} = \int d^4x\, dy \ \frac{1}{2}\left[\partial_A \phi\, \partial^A \phi - V_0(\phi)\right]$$

- at the fixed points I can add terms which are 4D Lorentz invariant w/o 5D symmetry

$$S_{branes} = \int d^4x\, dy \ \sum_i \delta(y-y_i)\Big\{ a_i \left[\partial_\mu \phi\, \partial^\mu \phi\right]^{*}$$

$$+\, b_i (\partial_y \phi)^{2\,*} + c_i \left[\phi\, \partial_y^2 \phi\right]^{*} + d_i \cdot V_i(\phi) \Big\}$$

(restricting to dim-4 or less)

* brane kinetic terms ... gauges ??

$$S = \int d^4x\, dy \Big\{ -\frac{1}{4} F_{AB} F^{AB} + \sum_i \delta(y-y_i)\Big[a_i \cdot -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

$$+ \underbrace{b_i (\partial_\mu A_y)(\partial^\mu A_y)}_{\text{absent in } A_y = 0 \text{ gauge}} + c_i \underbrace{(\partial_y A_\mu)(\partial_y A^\mu)}_{A_\mu \text{ is } Z_2 \text{ even} \Rightarrow \text{ term vanishes in thin-brane limit}} \Big] \Big\}^{**}$$

** If I add a non-kinetic term $(-m^2 A_\mu A^\mu)$ I break gauge inv. on the brane ... [Higgs on brane]

The Simplest Case : $\boxed{\text{gauge KK on } S^1/Z_2}$

$$S = \int d^4x\, dy \left\{ -\frac{1}{4} F_{AB} F^{AB} - \frac{1}{4} \underline{F_{\mu\nu}} F^{\mu\nu} \left[r_0\, \delta(y) + r_\pi\, \delta(y - \pi R) \right] \right\}$$

$$\left(\delta_{0,\pi} \equiv r_{0,\pi}/R \sim O(1)(?) \right)$$ [only $\neq 0$ gauge + Lorentz Inv. form]

$$f_n = N_n \left\{ \underline{\cos(x_n y/R)} - (x_n \delta_0/2) \sin(x_n |y|/R) \right\}$$

note cusp in wave function

roots $x_n \to$ masses

- $(\delta_0 \delta_\pi x_n^2 - 4) \underline{\tan(\pi x_n)} - 2(\delta_0 + \delta_\pi) x_n = \underline{0}$

$$\frac{g_n}{g_0} = \left[\underline{\underline{2}} \cdot \frac{1 + (\delta_0 + \delta_\pi)/2\pi}{1 + \underbrace{\left(\frac{\delta_\pi}{2} x_n\right)^2} + \left(\frac{\delta_\pi + 2\delta_0}{2\pi}\right)} \right]^{1/2} \longleftrightarrow \text{KK couplings}$$

$\Rightarrow$ Shifts in mass spectrum + wave functions lead to alterations in couplings!

* See: for fixed $x_n \sim O(1)$ $g_n/g_0 \to 1/\delta_\pi x_n$ as $|\delta_\pi|$ grows

$\Rightarrow$ Brane terms generally lead to coupling reduction!!

Solid : $\delta_\pi = 0$

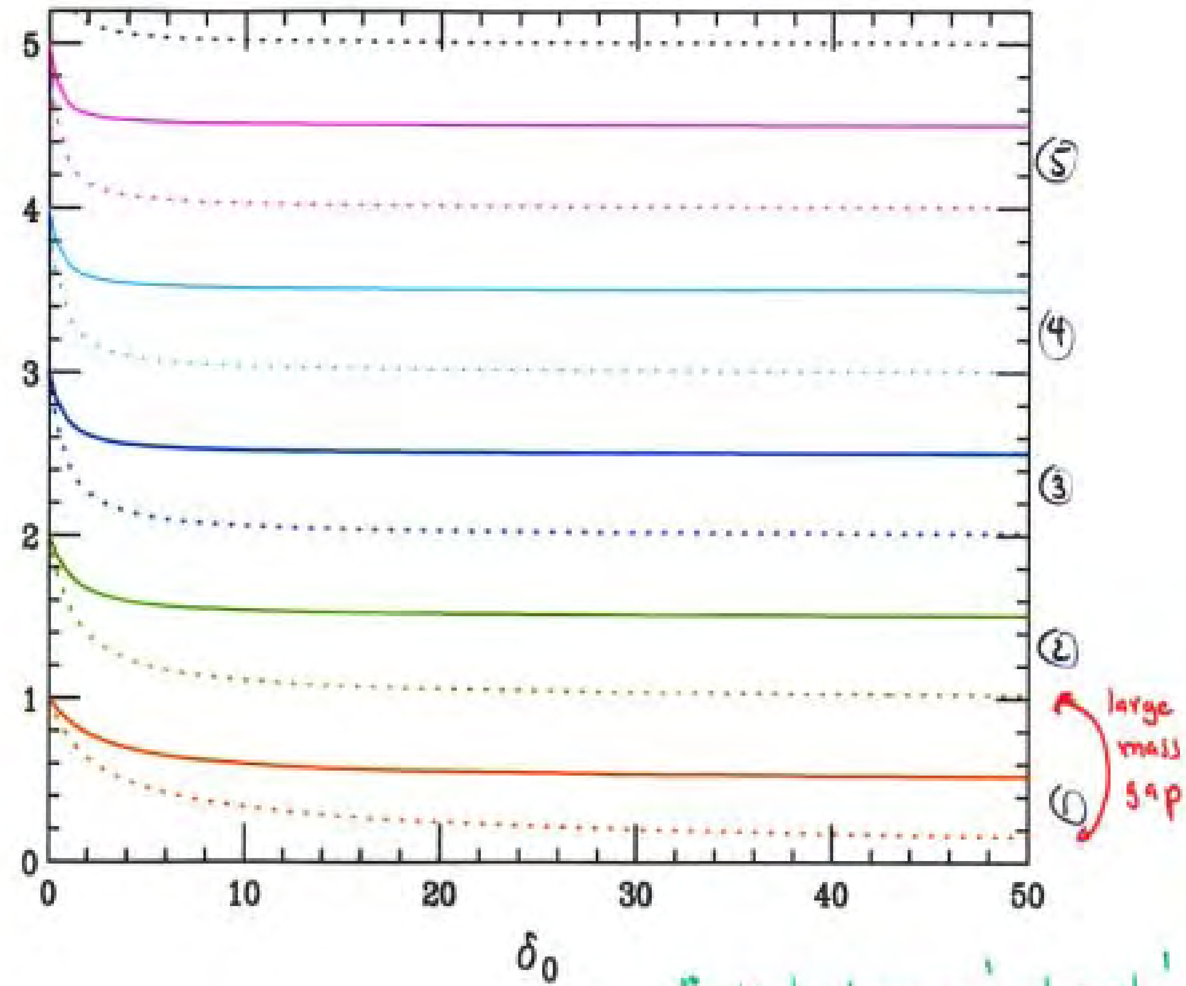
Dot : $\delta_\pi = \delta_0$

KK mass spectrum

(TeV^{-1}) $\underline{n}$

$(M_n R_c)$

x_n

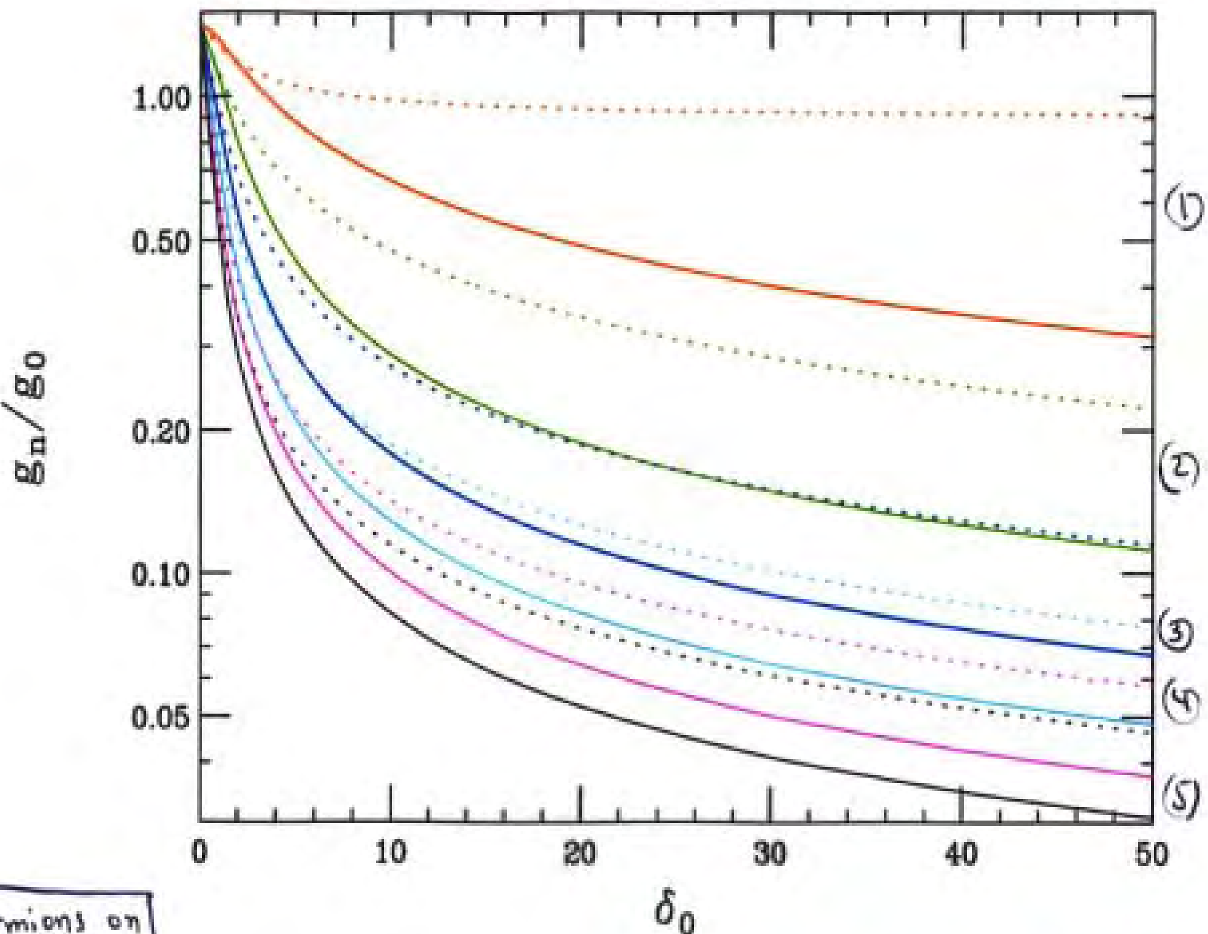


Matter on $y=0$ brane

1^{st} KK's become 'relatively' lighter by ~2-5

$(\text{TeV})^{-1}$ KK gauge couplings

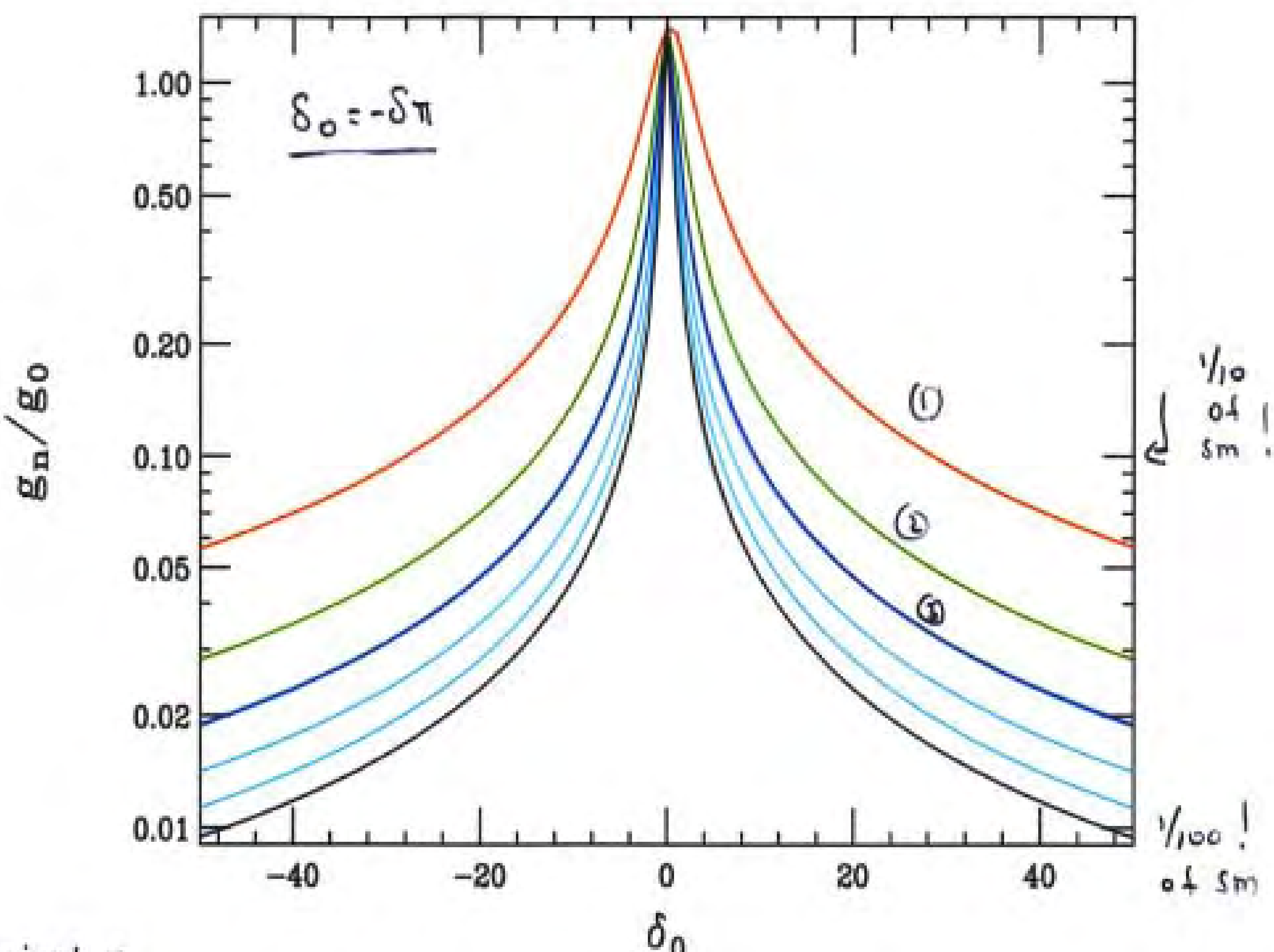
Solid : $\delta_\pi = 0$
Dot : $\delta_\pi = \delta_0$



fermions on $y=0$ brane

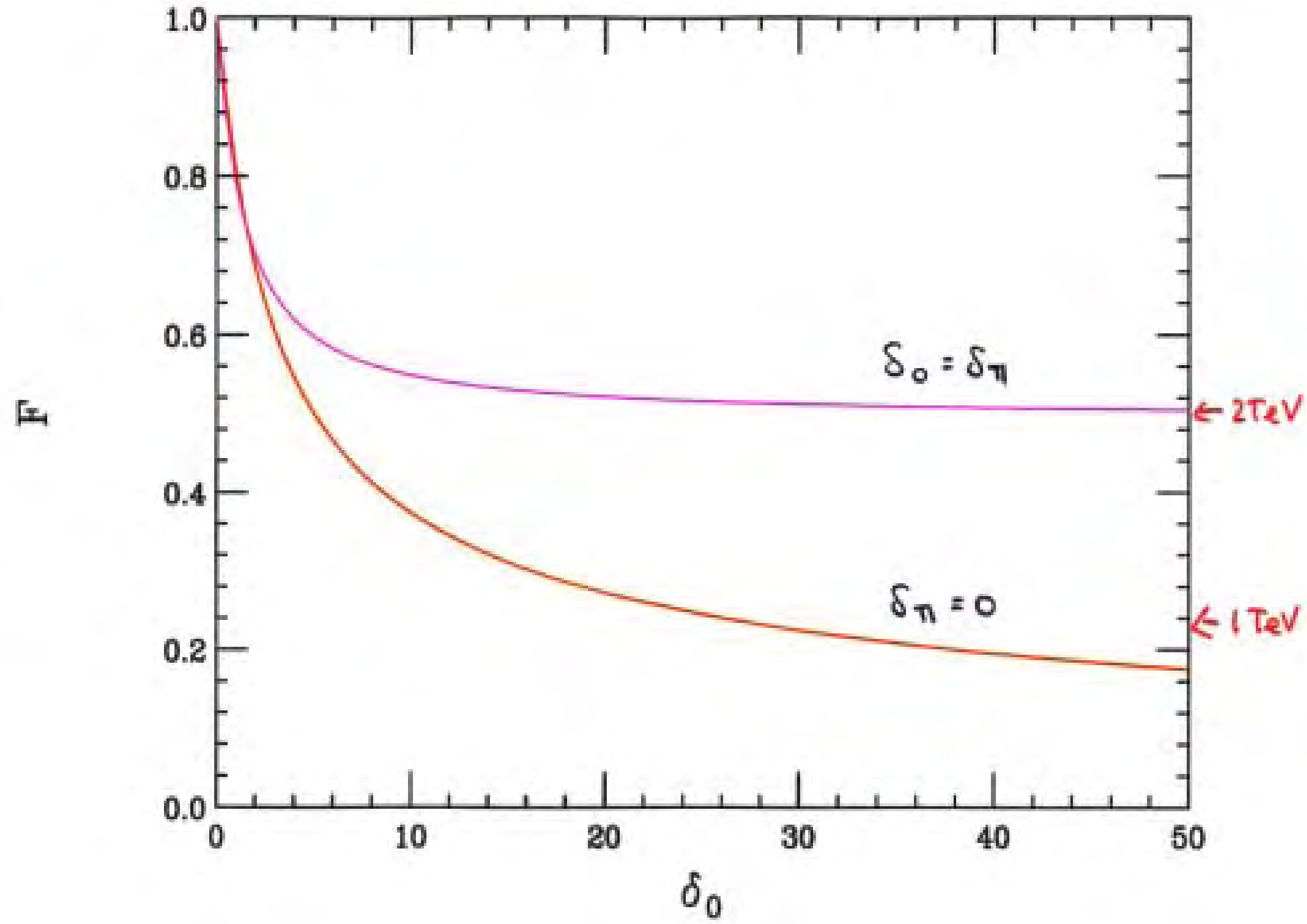
→ weak couplings reduce LHC reach and bounds from precision data

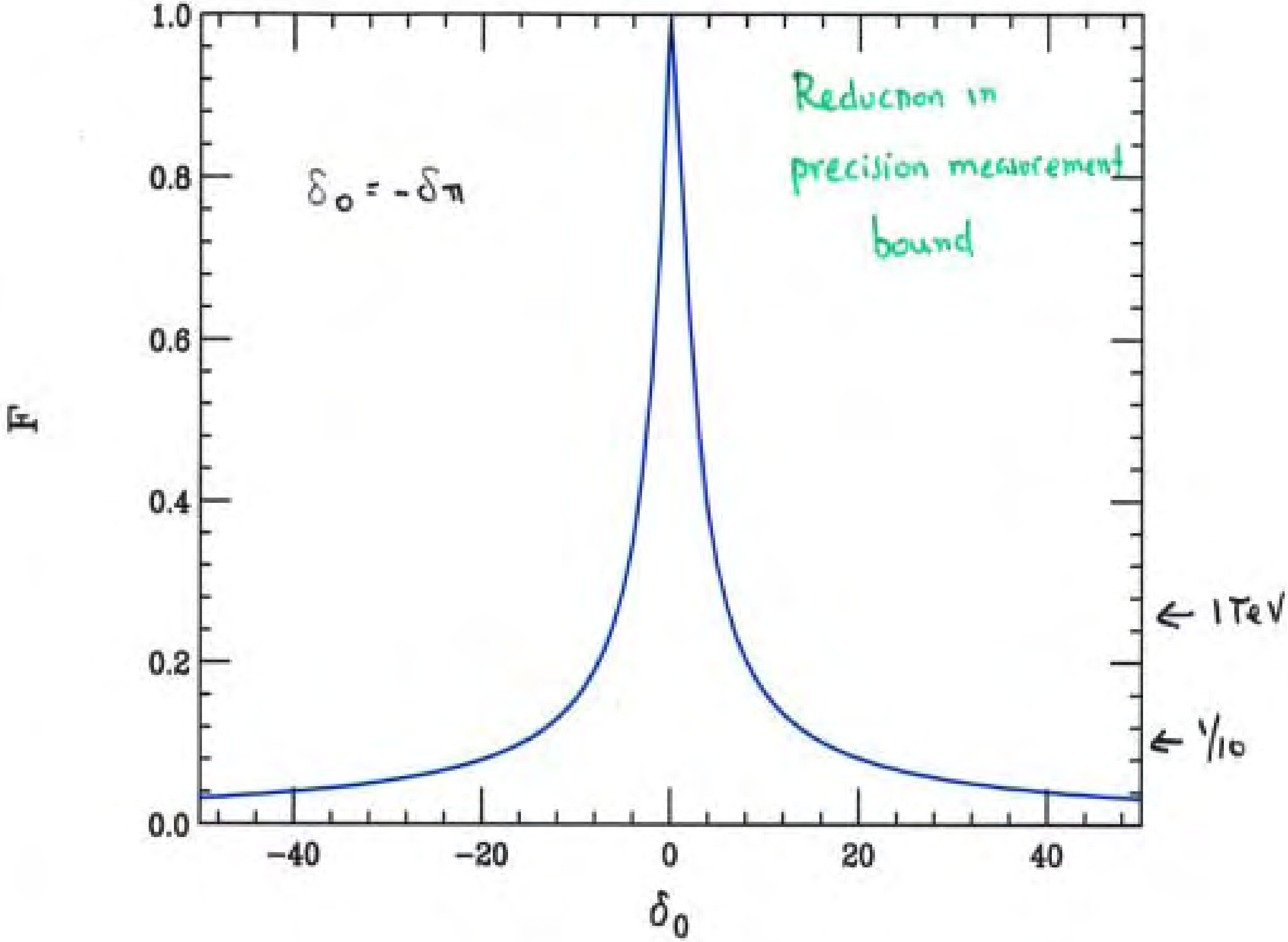
KK coupling strength : TeV^{-1}



fermions on $y=0$ brane

TeV^{-1} Reduction in precision measurement bound

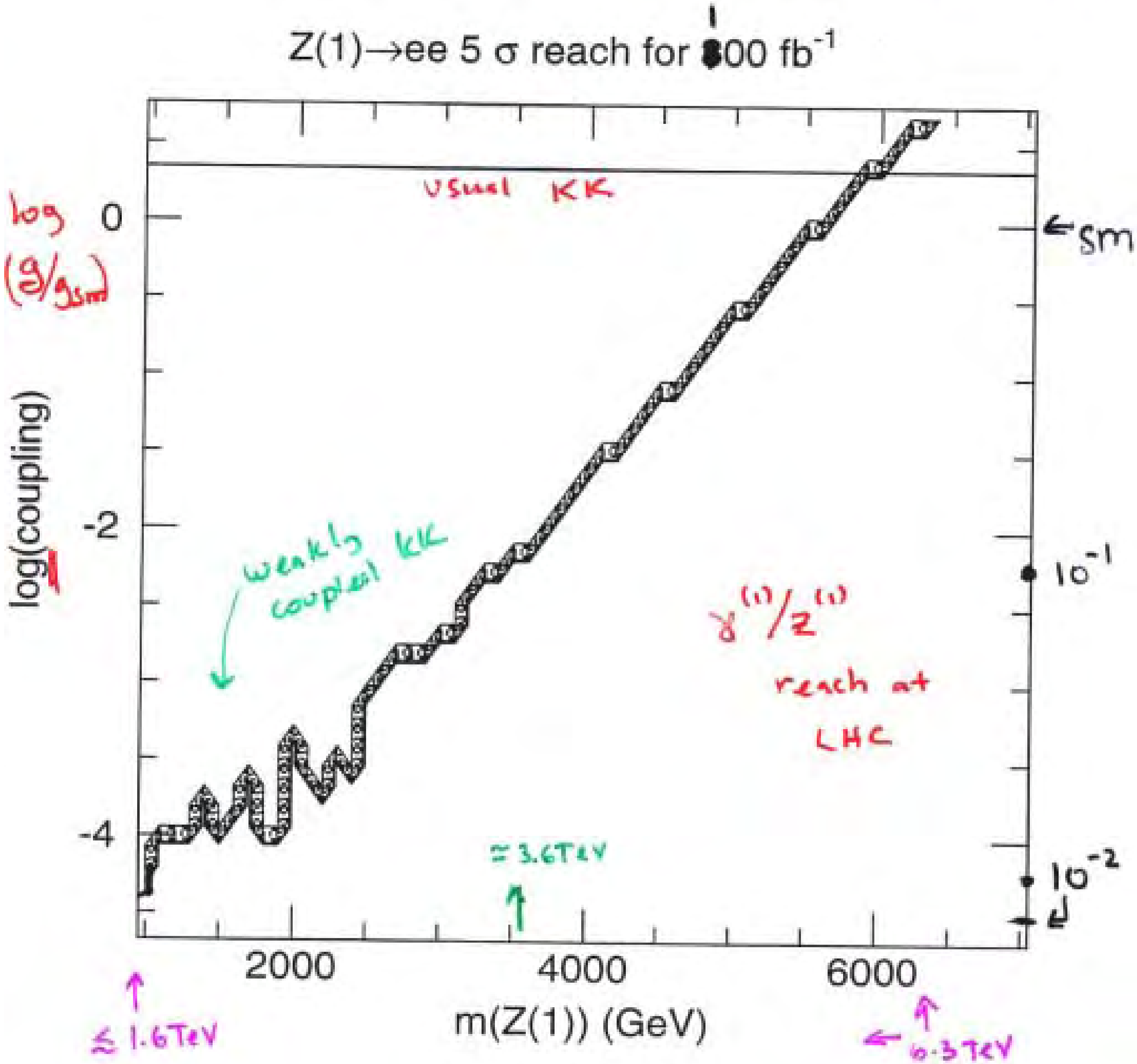




Reduction in precision measurement bound
$\delta_0 = -\delta_\pi$
F
δ_0
← 1TeV
← 1/10
1.0
0.8
0.6
0.4
0.2
0.0
-40
-20
0
20
40

LHC $\gamma/Z^{(1)}$ KK search reach

Polesello
Les Houches '03



RS gauge KK's

$$S = -\frac{1}{4}\int d^4x\, d\phi\, \sqrt{-g}\left\{ F_{AB}F^{AB} + F_{\mu\nu}F^{\mu\nu}\left[c_0\delta(\phi) + c_\pi\,\delta(\phi-\pi)\right]\right\}$$

$$\left(c_{0,\pi}\cdot kr_c/2 \equiv \delta_{0,\pi} \right)$$

$$\chi^{(n)} \equiv \frac{e^{\sigma}}{N_n}\,\zeta_1(z_n) \quad \left\{ \begin{array}{l} z_n \equiv m_n/k\, e^{\sigma} \\ \zeta_{\substack{1\\0}} \equiv \underline{J}_{\substack{1\\0}} + \alpha_n \cdot \underline{Y}_{\substack{1\\0}} \end{array} \right. \longleftrightarrow \left\{ \begin{array}{l} \text{Bessel} \\ \text{function} \end{array} \right.$$

masses

- $\zeta_0(x_n) - \underline{\underline{\delta_\pi}}\, x_n\, \zeta_1(x_n) = 0 \rightarrow m_n = kx_n e^{-kr_c\pi}$

wavefnc's

- $\alpha_n = -\dfrac{J_0(\epsilon_n) + \delta_0\,\epsilon_n J_1(\epsilon_n)}{Y_0(\epsilon_n) + \delta_0\,\epsilon_n Y_1(\epsilon_n)} \rightarrow \epsilon_n = m_n/k$

$\Rightarrow$ Again, masses and wave functions are modified

$\rightarrow$ couplings are changed too (a mess)

- modifications are more drastic than in the TeV^{-1} case ...

$\rightarrow$ Helps with an 'old' problem with RS gauges in bulk ....

The Problem : $g^{(n)}/g^{(0)} \simeq \sqrt{2\pi k r_c} \simeq 8.4$!

KK to SM coupling ratio

* Exchange of heavy KK's will disrupt precision measurements ... unless

$m_1^{gauge} \gtrsim 25\text{ TeV} \implies \Lambda_\pi \gtrsim 100\text{ TeV}$!

- a new hierarchy ?? too far from M_W ?

How can we lower $g^{(n)}$ + hence m_1^{gauge} ?

- put SM fermions in bulk too (another talk)
- allow brane kinetic terms for gauge fields to reduce couplings ...

... but can they do it ??

Couplings

$$g^{(n)}/g^{(0)} = \sqrt{2\pi k r_c}\,\sqrt{\frac{Z_0}{W\,Z_n}}$$

$$W = (1-2\delta_\pi + \delta_\pi^2 x_n^2)\left[1 - \frac{\epsilon_n^2 \zeta_1^2(\epsilon_n)\,[1+2\delta_0+\epsilon_n^2\delta_0^2]}{x_n^2\,\zeta_1^2(x_n)\,[1-2\delta_\pi + x_n^2\delta_\pi^2]}\right]$$

$$Z_0 = 1 + \frac{\delta_0+\delta_\pi}{\pi k r_c}$$

$$Z_n \simeq 1 + W^{-1}\left[2\delta_\pi + \frac{8\delta_0\delta_\pi^2 \alpha_n^2}{\pi^2 \zeta_0^2(x_n)}\right]$$

But $W, Z_n > 0$ while $Z_0 > 0$ implies

$\boxed{\delta_0 + \delta_\pi > -\pi k r_c}$ or <u>ghost</u>

$\rightarrow$ $\delta_\pi > -\pi k r_c$ $(-\pi k r_c/2)$ if $\delta_0 = 0$ or δ_π

$\therefore$ origin of disallowed regions

$\rightarrow$ <u>constraint</u>

Are $g^{(n)}$ still big? What are the bounds?

Behaviour of First 5 Roots

RS

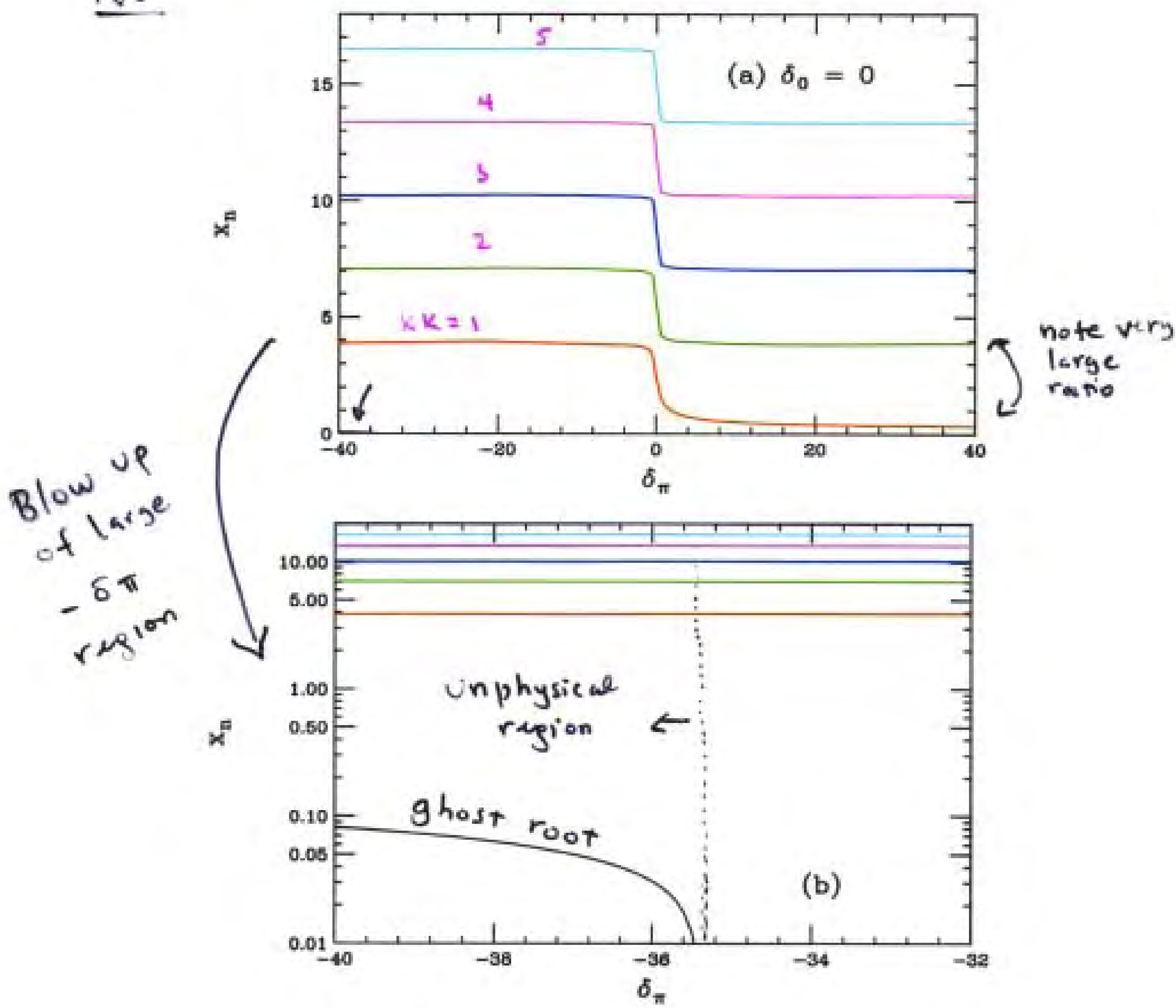


Figure 1: (a) The behavior of the first five roots as δ_π is varied, assuming $\delta_0 = 0$. Note the sharp increase in x_n near $\delta_\pi = 0$ for all KK levels. (b) The large negative δ_π region is expanded to show the new root originating at the value $\boxed{\delta_\pi = -kr_c\pi} \simeq -35.4$.

$$\boxed{0 = \mathcal{J}_0(x_n) - \delta_\pi x_n \mathcal{J}_1(x_n)}$$

Behavior of KK mass spectrum ...

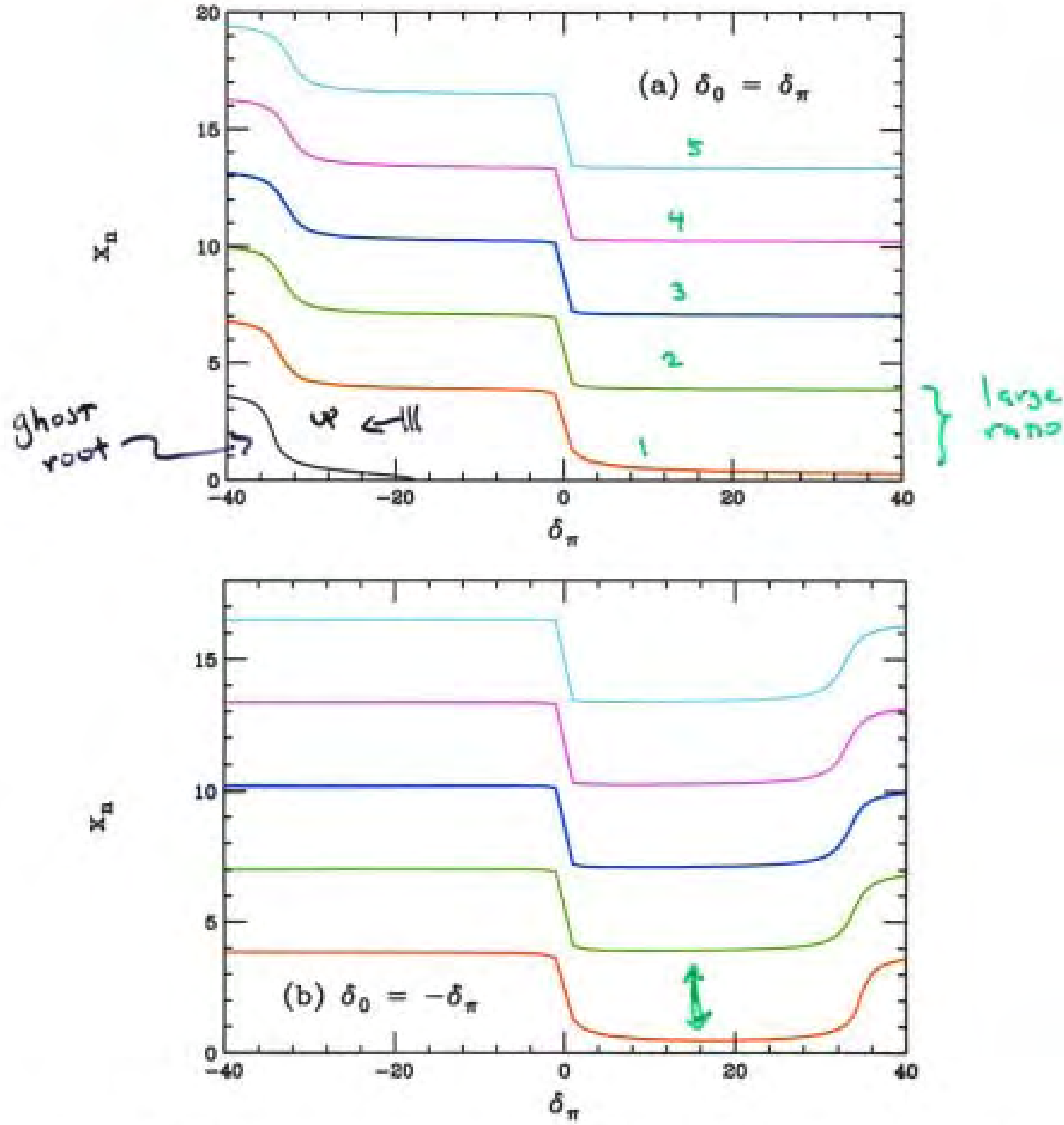
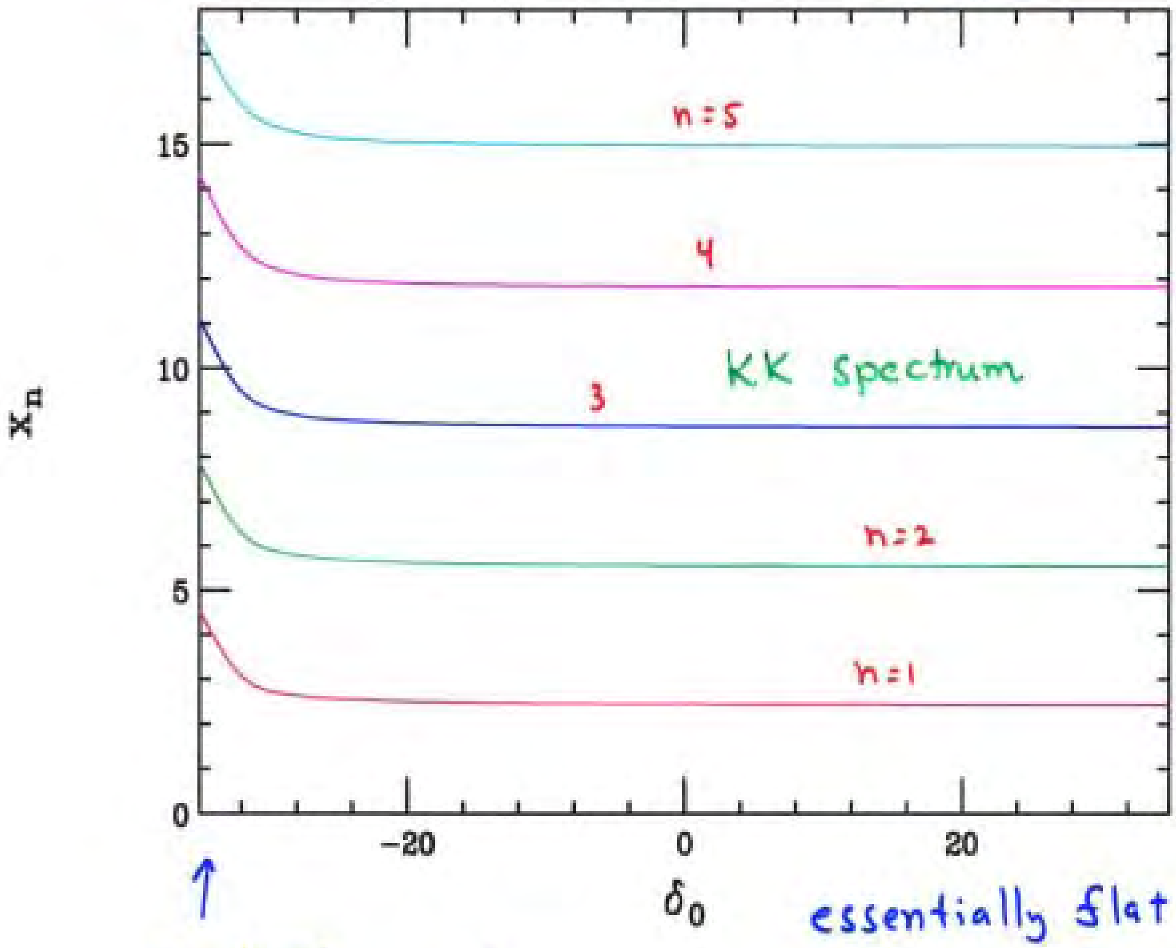


Figure 2: (a) The behavior of the first five roots as a function of δ_π for the case $\delta_0 = \delta_\pi$. Here, the new root appears at the value $\delta_\pi = -kr_c\pi/2 \simeq -17.7$. (b) Same as above for the case $\delta_0 = -\delta_\pi$.

$\zeta_0(x_n) - \delta_\pi x_n \zeta_1(x_n) = 0$

$\delta_\pi = 0$



essentially flat →

↑ α_n grows large

<-

KK tower couplings - first five states

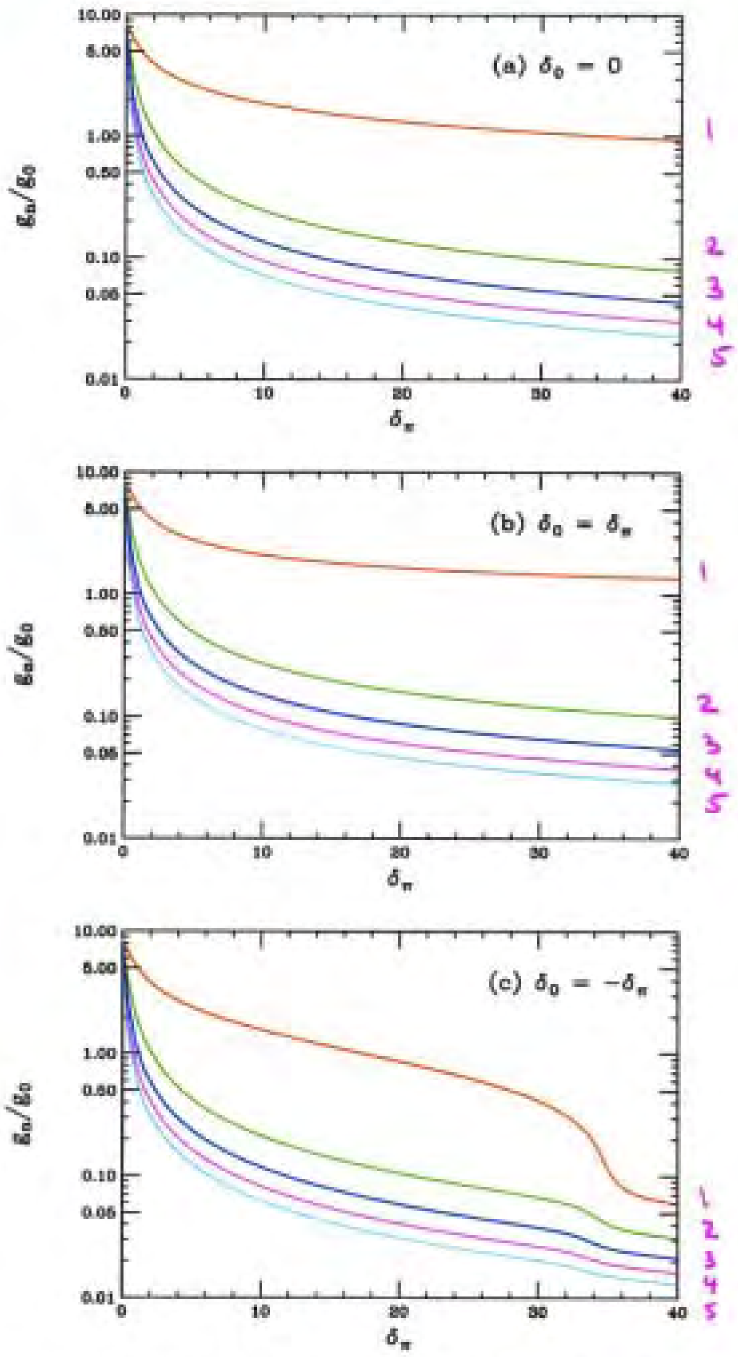


Figure 4: The ratios of the first five KK couplings to that of the zero-mode as a function of δ_π for the cases (a) $\delta_0 = 0$, (b) $\delta_0 = \delta_\pi$, and (c) $\delta_0 = -\delta_\pi$. The lightest (heaviest) KK mode corresponds to the top (bottom) curve in each case.

Couplings of KK states

huge
coupling
suppression
⋮

Clearly, KK's
⇒ can be
much lighter

→ bound ?

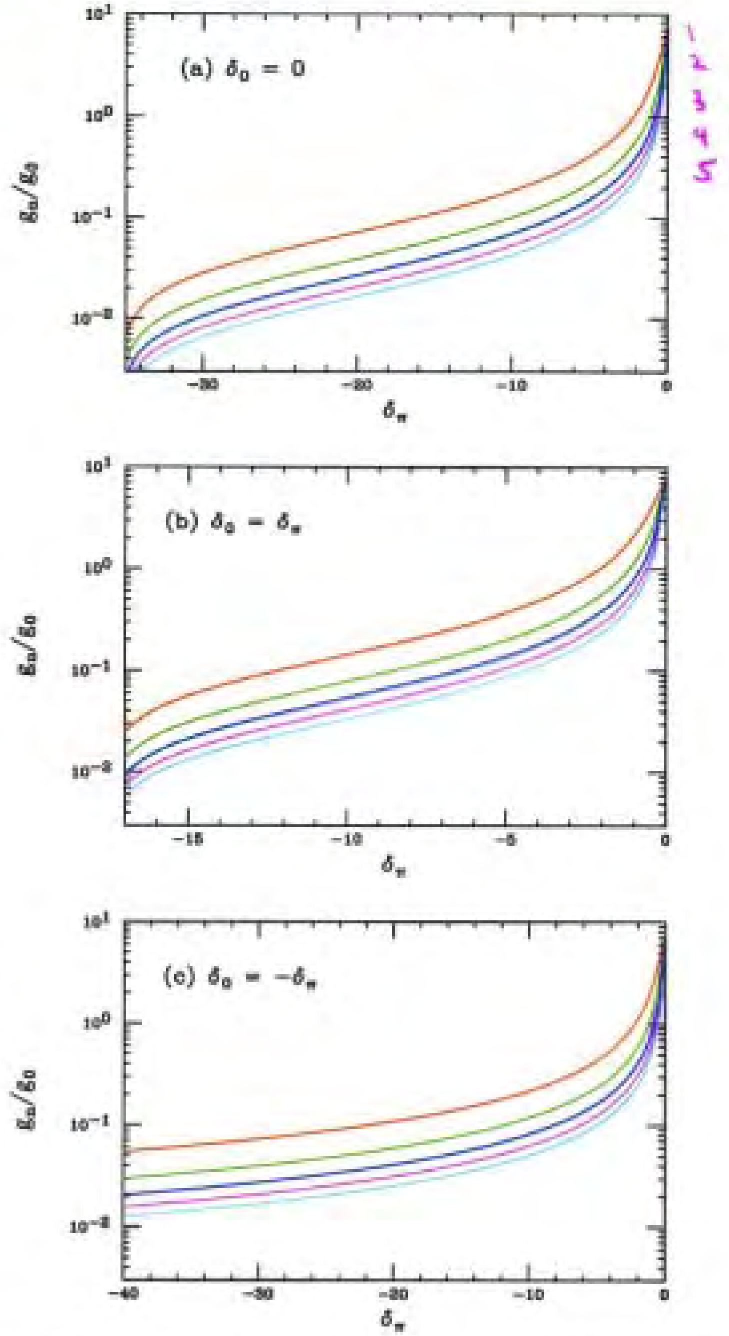
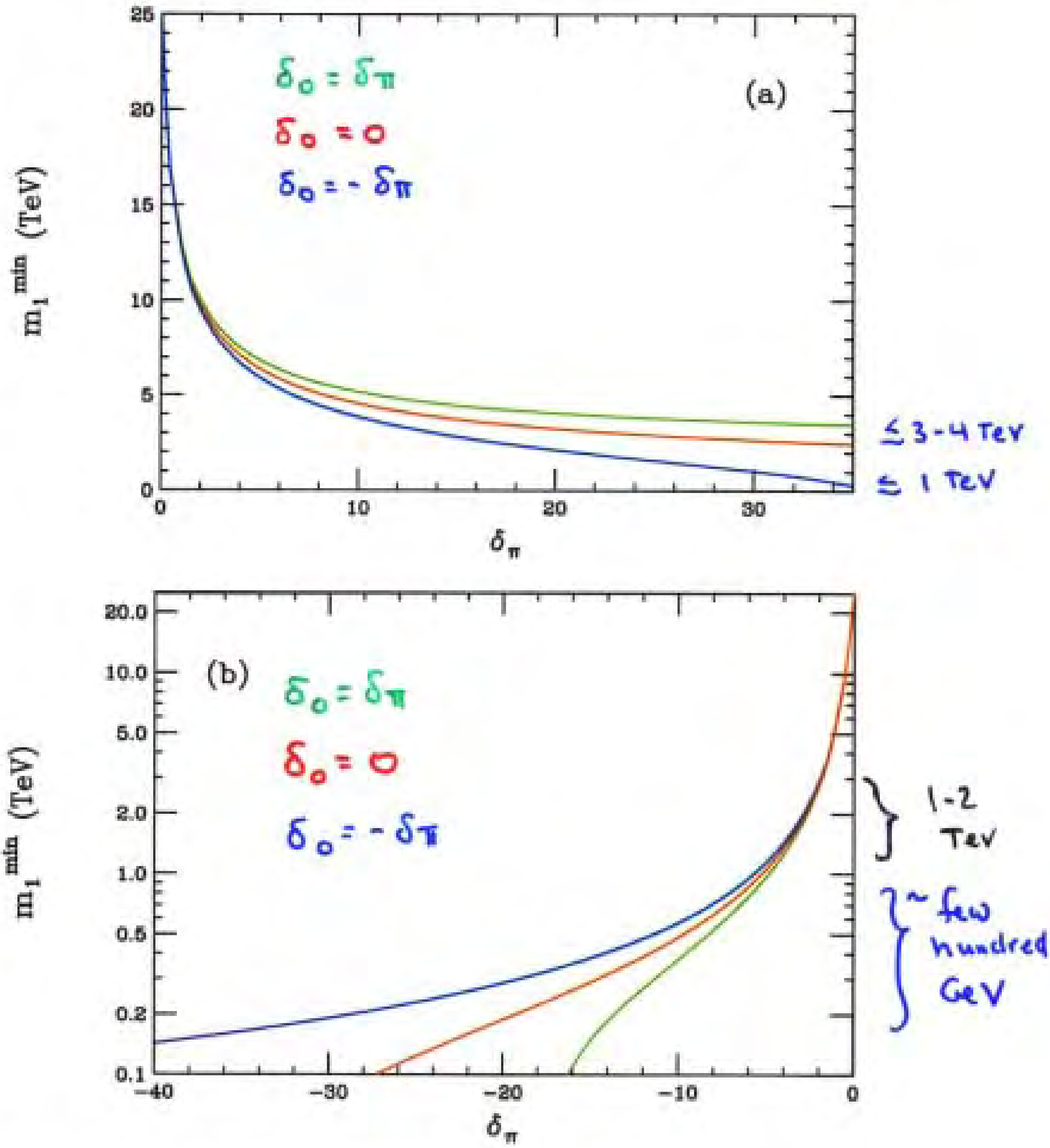


Figure 5: The ratios of the first five KK couplings to that of the zero-mode as a function of negative δ_π for the cases (a) $\delta_0 = 0$, (b) $\delta_0 = \delta_\pi$, and (c) $\delta_0 = -\delta_\pi$. The lightest (heaviest) KK mode corresponds to the top (bottom) curve in each case.

Electroweak lower bound ...

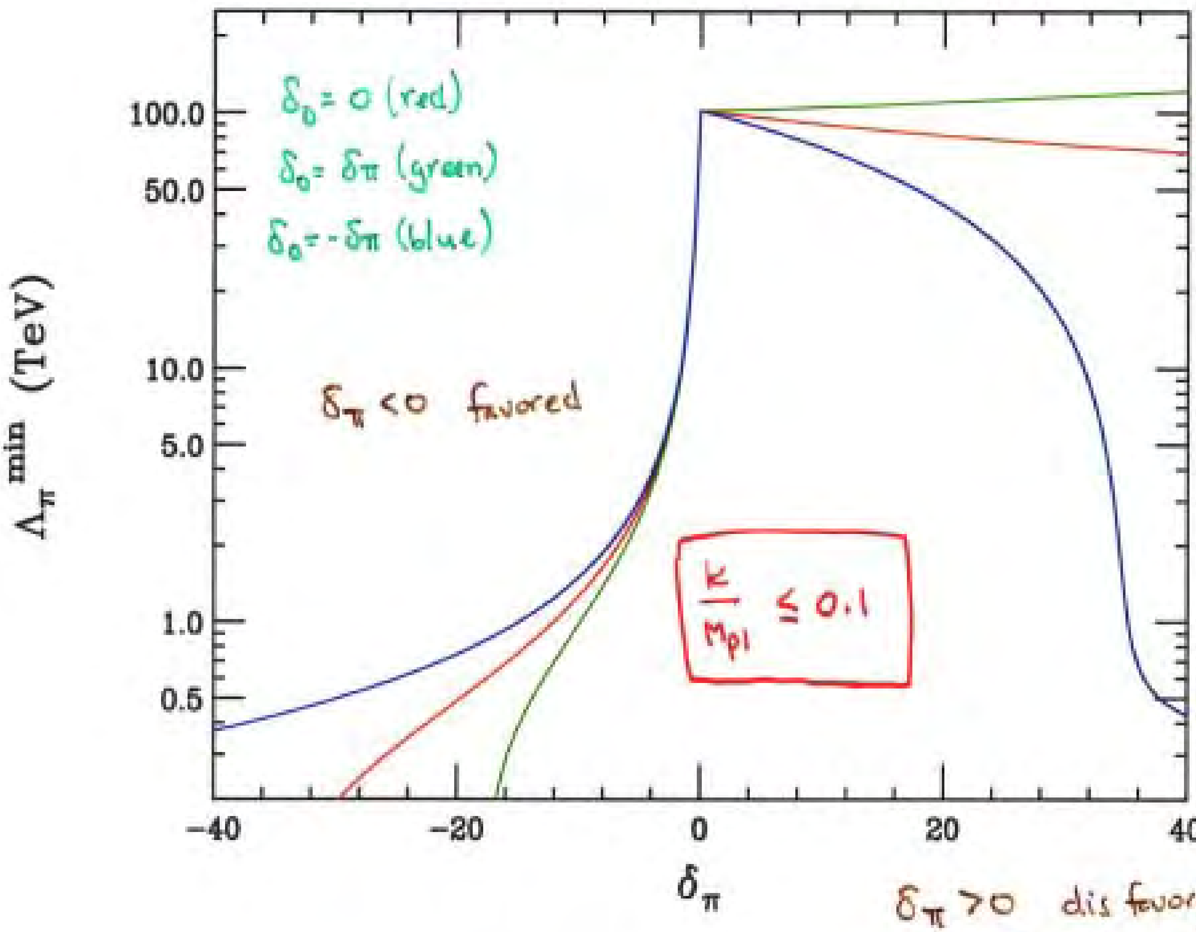
$(m_h = 115\,\mathrm{GeV})$



note scale

Figure 6: (a) Lower bound on the mass of the lightest gauge boson KK excitation as a function of $\delta_\pi \geq 0$ from a fit to the precision electroweak data for the cases $\delta_0 = \delta_\pi$ (top/green), $\delta_0 = 0$ (middle/red), and $\delta_0 = -\delta_\pi$ (bottom/blue). (b) Same as above but now for the region $\delta_\pi \leq 0$ with $\delta_0 = \delta_\pi$ (bottom/green), $\delta_0 = 0$ (middle/red), and $\delta_0 = -\delta_\pi$ (top/blue).

Have we <u>really</u> solved the problem ??



!!!

$\delta_\pi > 0$ disfavored

unless $\delta_0 = -\delta_\pi$, δ_π large

✱ What about gravity ... the <u>basic component</u> of RS ??

$$S = \frac{1}{4} M_5^3 \int d^4x \int r_c d\phi \sqrt{-g} \left\{ R^{(5)} + \left[g_0 \delta(\phi) + g_\pi \delta(\phi - \pi) \right] \underline{\underline{R^{(4)}}} \right\}$$

usual Einstein gravity

induced brane curvature

$$\left[g_{0,\pi} k r_c / 2 \equiv \gamma_{0,\pi} \right]$$

Bessel fns again

$$\chi^{(n)} = \frac{e^{2\sigma}}{N_n} J_2(z_n) \quad ; \quad J_1(x_n) - \gamma_\pi x_n J_2(x_n) = 0$$

<u>wavefunctions</u> <u>masses</u>

$$\boxed{\overline{M}_{Pl}^2 = \frac{M_5^3}{k}(1 + 2\gamma_0)} \qquad (\gamma_0 > -1/2)$$

$$\mathcal{L}_{KK} = \frac{1}{\Lambda_\pi} T_{\mu\nu} \sum_n \left(\frac{1 + 2\gamma_0}{1 + \underline{\underline{\gamma_\pi^2 x_n^2}} - 2\gamma_\pi} \right)^{1/2} \underline{h^{\mu\nu}_{(n)}}$$

- <u>Level dependent</u> + <u>decrease</u> w/ increasing $|\gamma_\pi|$!

($\gamma_0 = 0$ in what follows ... simple rescaling)

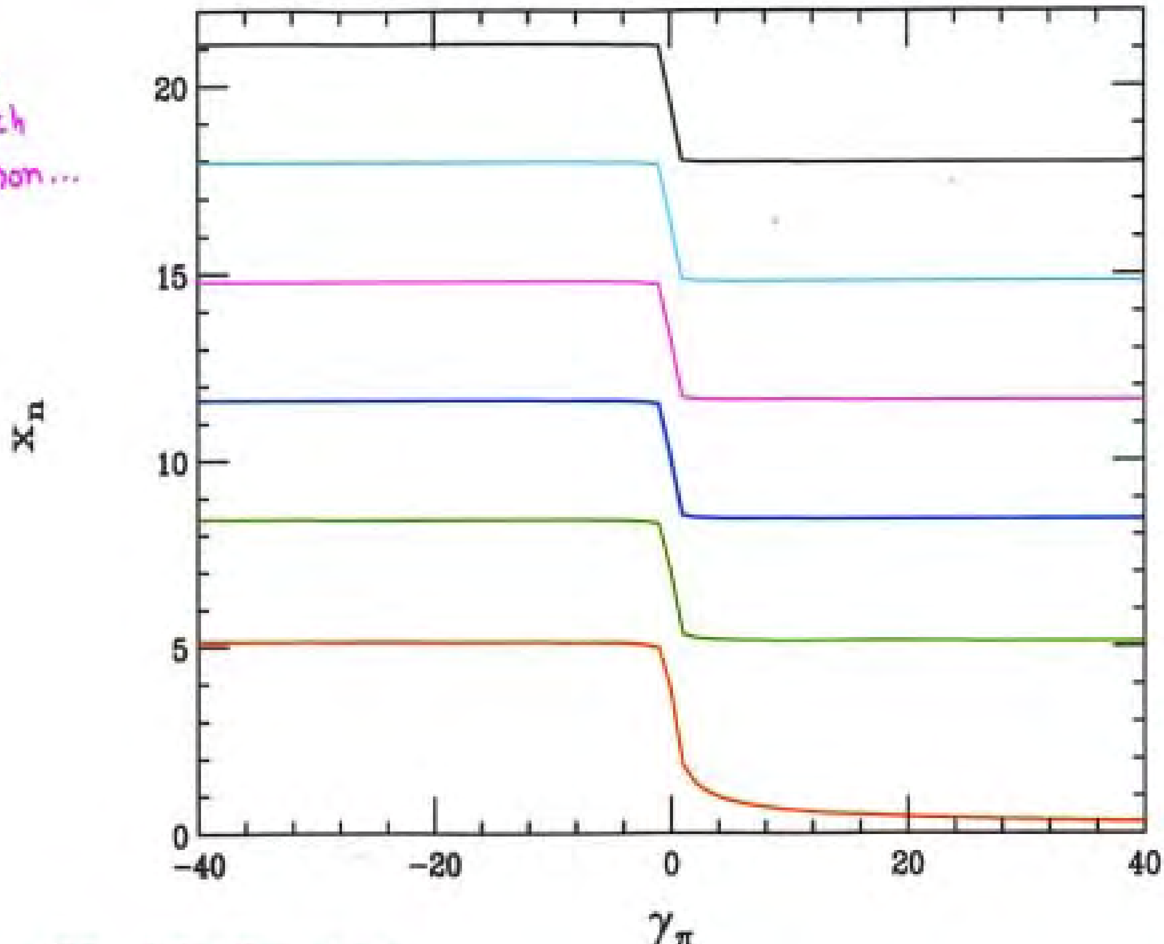
- wavefunctions + masses are γ_0 independent !

<u>Overall</u>, behavior more simple that gauge KK's as γ_0 plays little role

RS graviton KK level spectrum

(γ_0 independant)

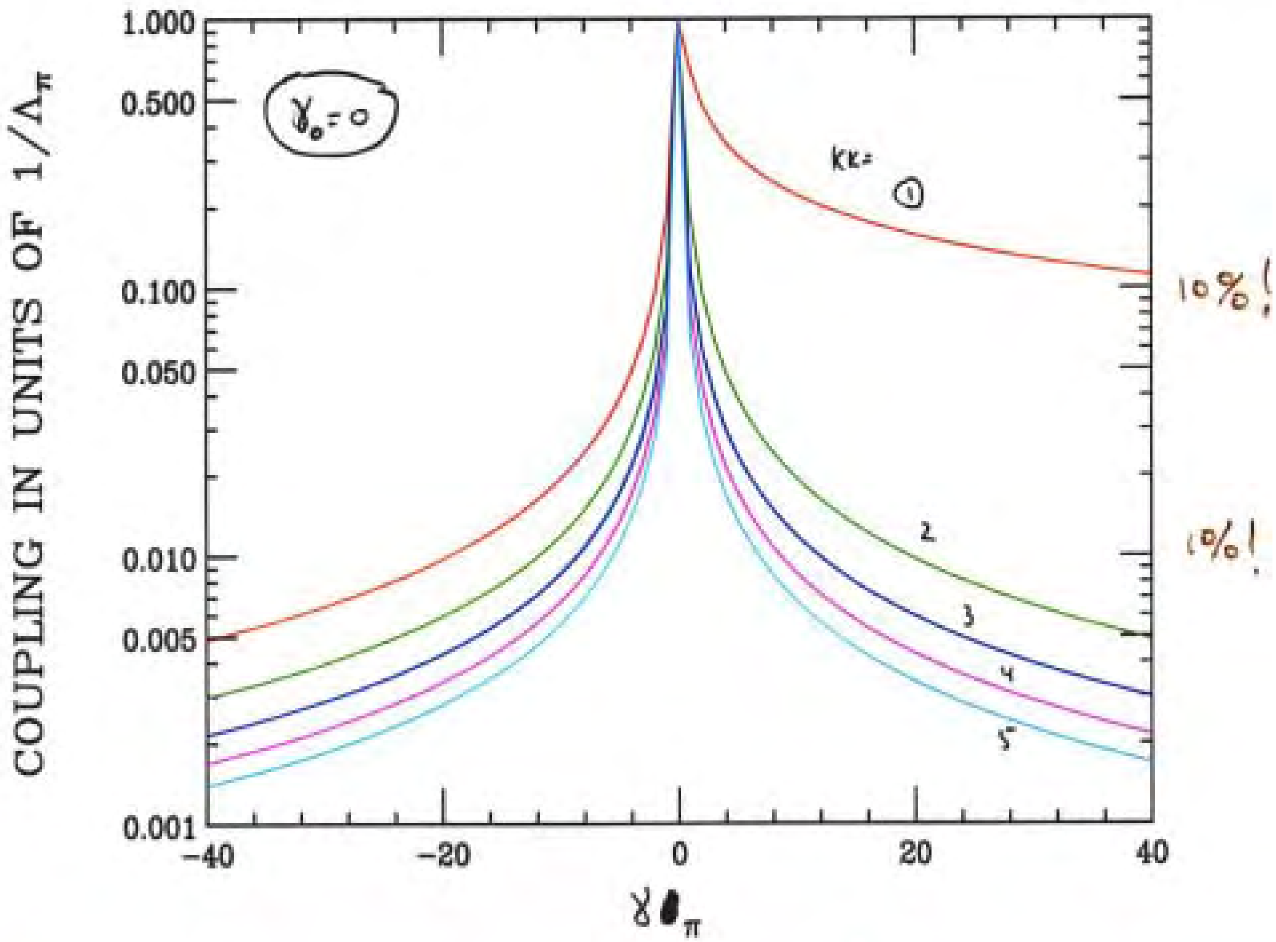
not much action...



big gap

no graviton ghosts anywhere .. HOWEVER

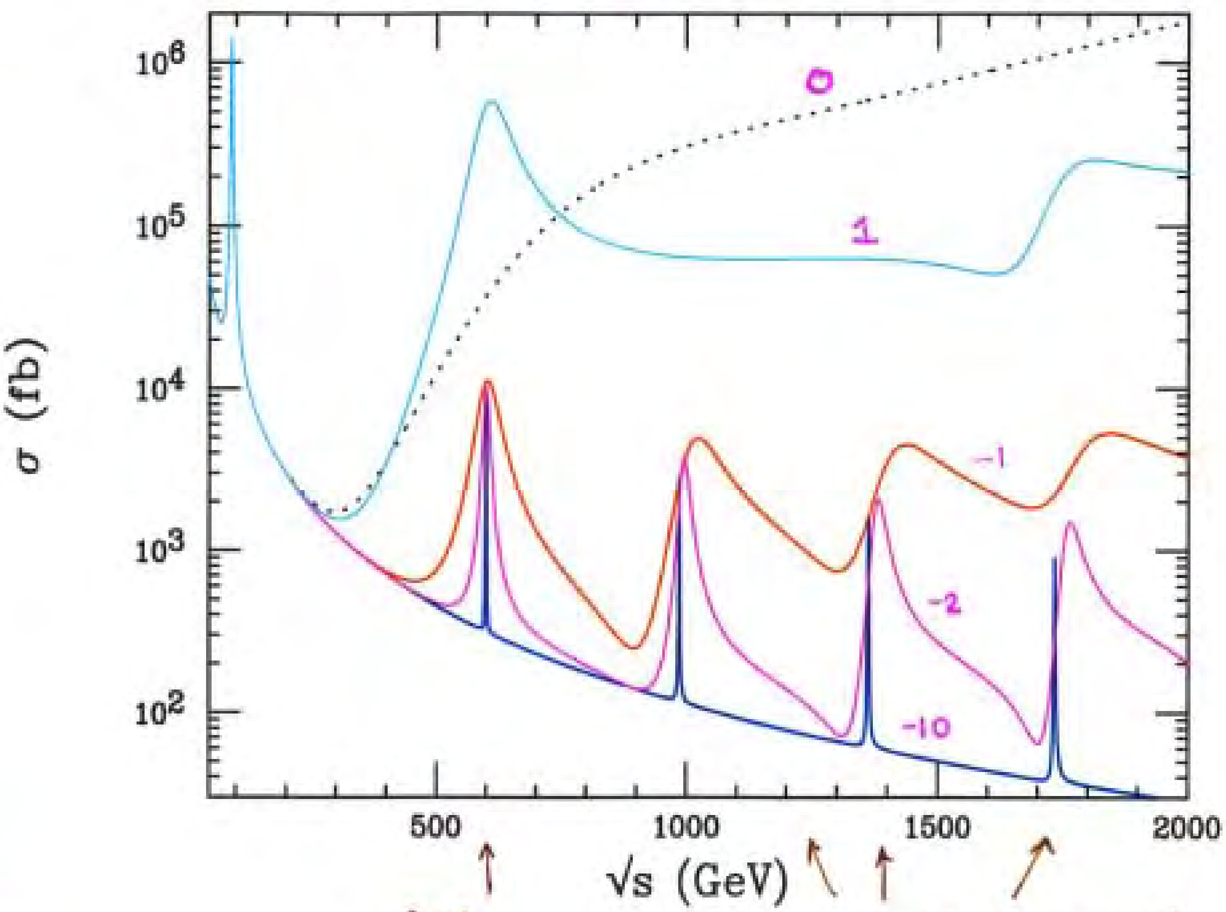
graviton KK's get reduced couplings



Mass Spectrum + coupling shift do strange things to "bumps" at LC...

brane terms turn a shoulder to a set of narrow resonances....

$\frac{k}{M_{Pl}} = 1$ (!)

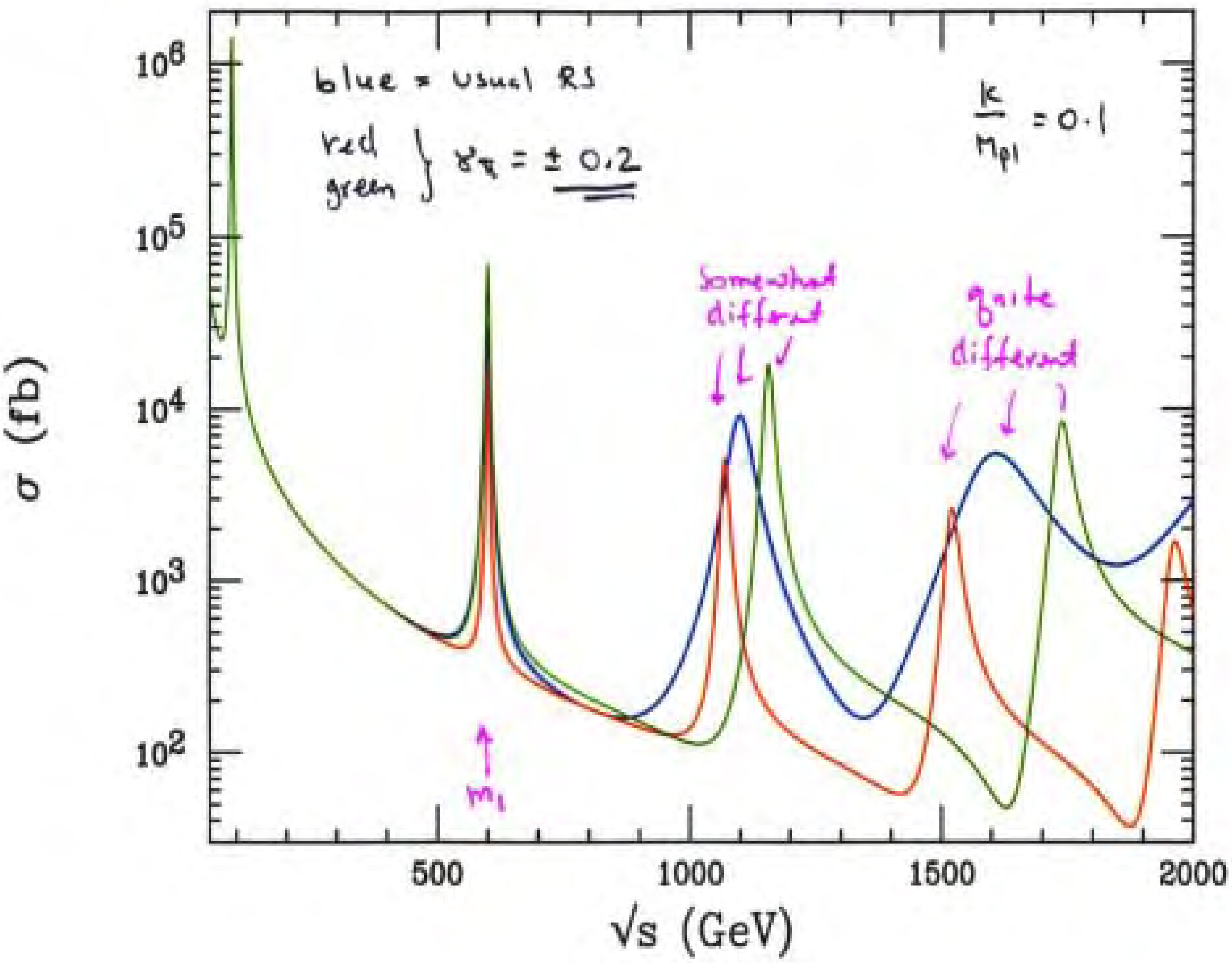


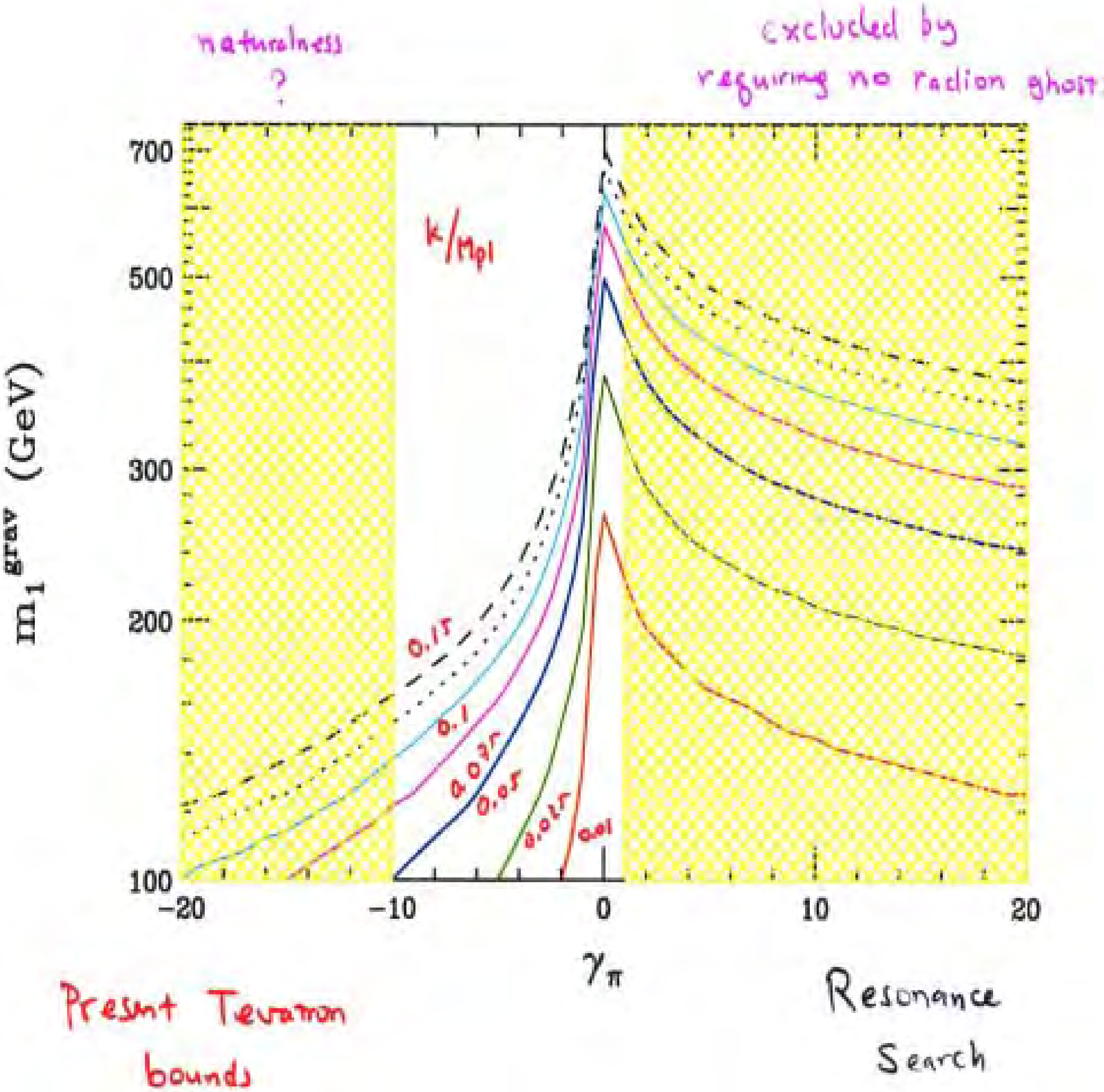
same m_1

note displacement of peaks

$\underline{\gamma_0 = 0}$

Even small δ_π can shift shape + resonance positions

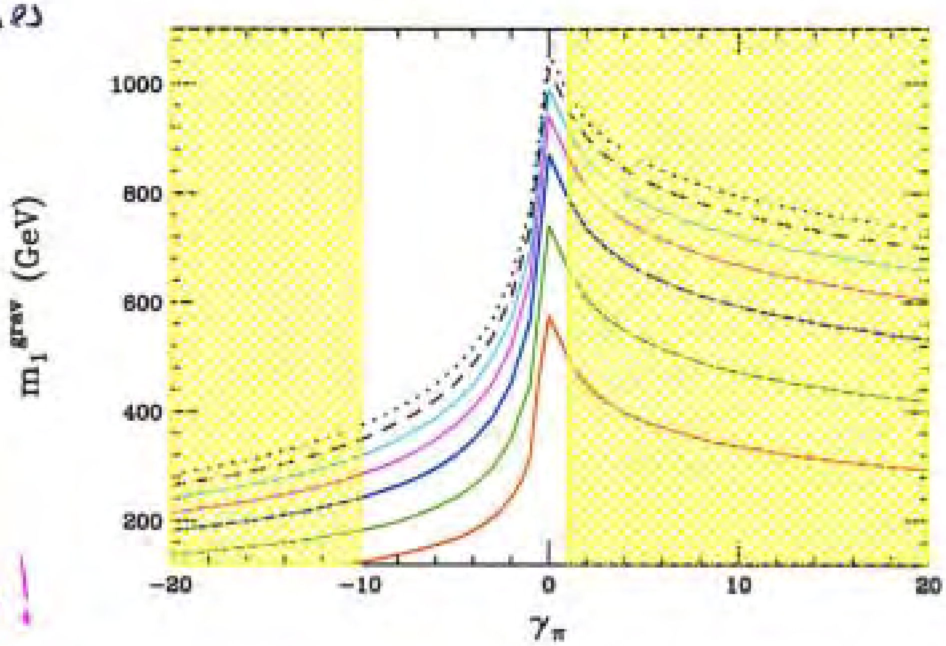




naturalness
?
excluded by
requiring no radion ghosts
k/Mpl
0.15
0.1
0.075
0.05
0.025
0.01
700
500
300
200
100
m1grav (GeV)
-20
-10
0
10
20
γπ
Present Tevatron
bounds
Resonance
Search

Resonance Searches

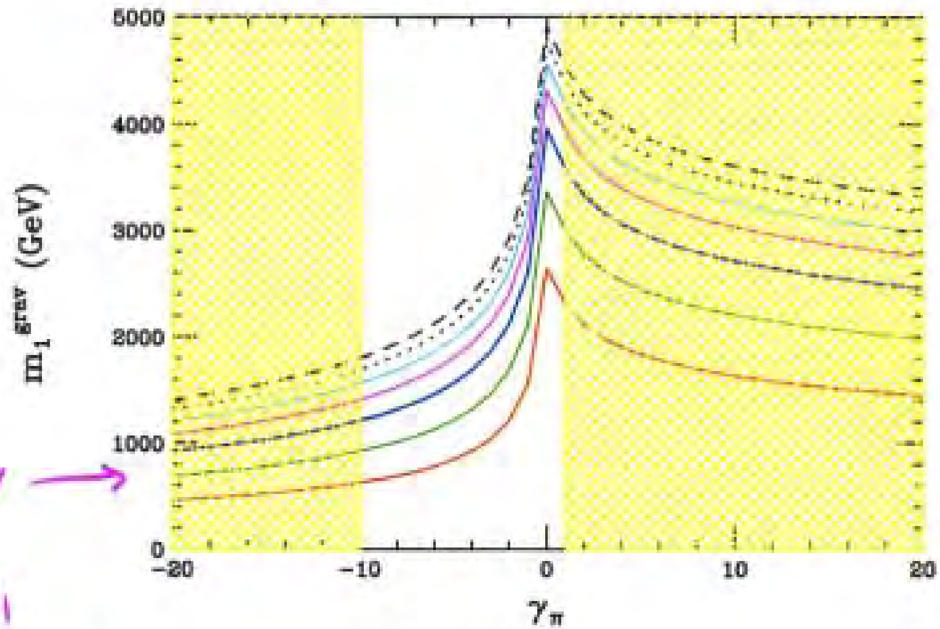
Collider Reaches (Future)



Run II

Huge reach reductions!

Figure 7: Same as the previous figure but now for Run II, $\sqrt{s} = 1.96$ TeV, Tevatron assuming an integrated luminosity of 5 fb^{-1}.



LHC

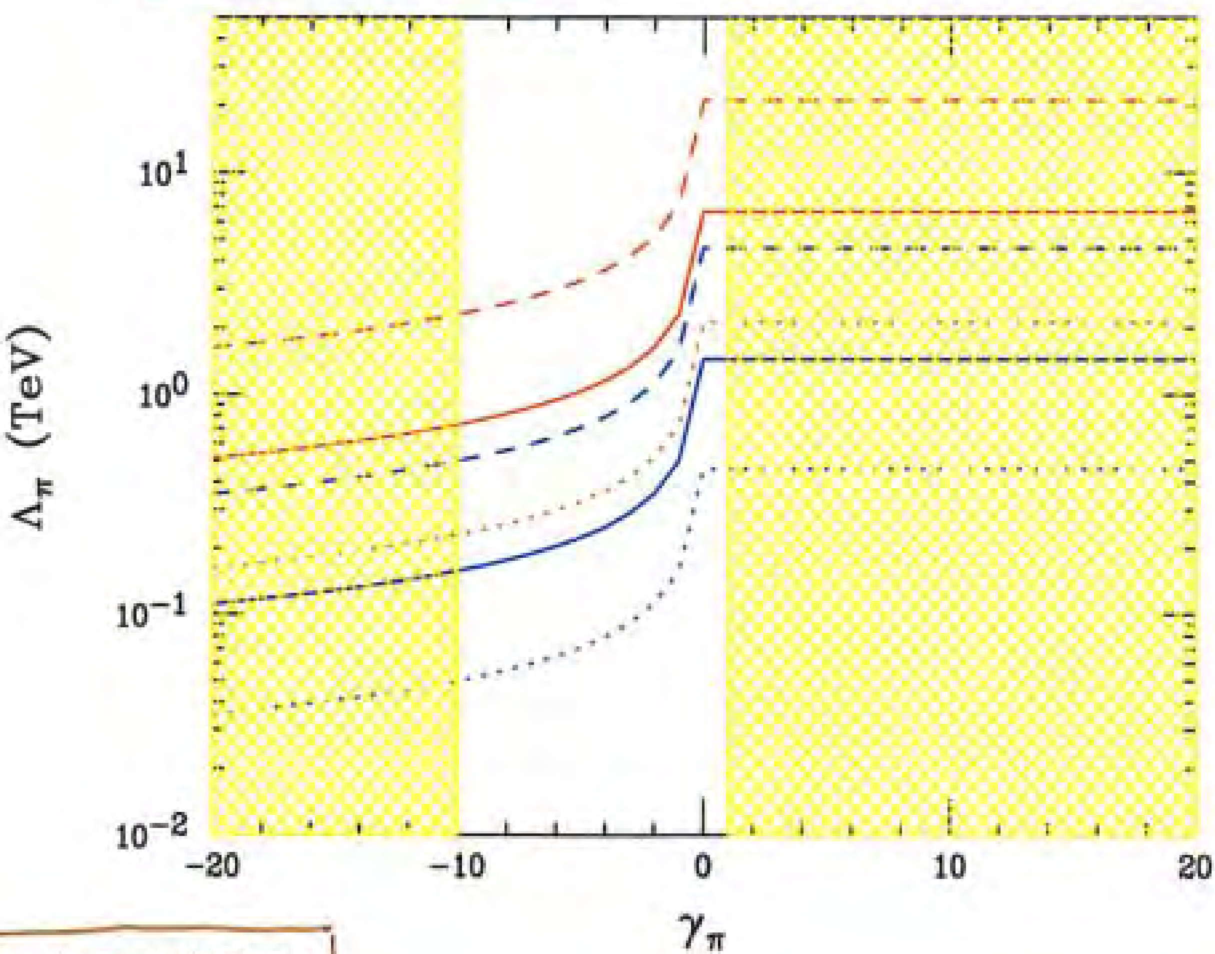
600 GeV

reduced by ~4!

Figure 8: Same as the previous figure but now for the LHC with an integrated luminosity of 100 fb^{-1}.

Tevatron $2\,fb^{-1}$ = blue
LHC $100\,fb^{-1}$ = red

k/M_{Pl} = 0.01 dash
0.1 solid
1 dots

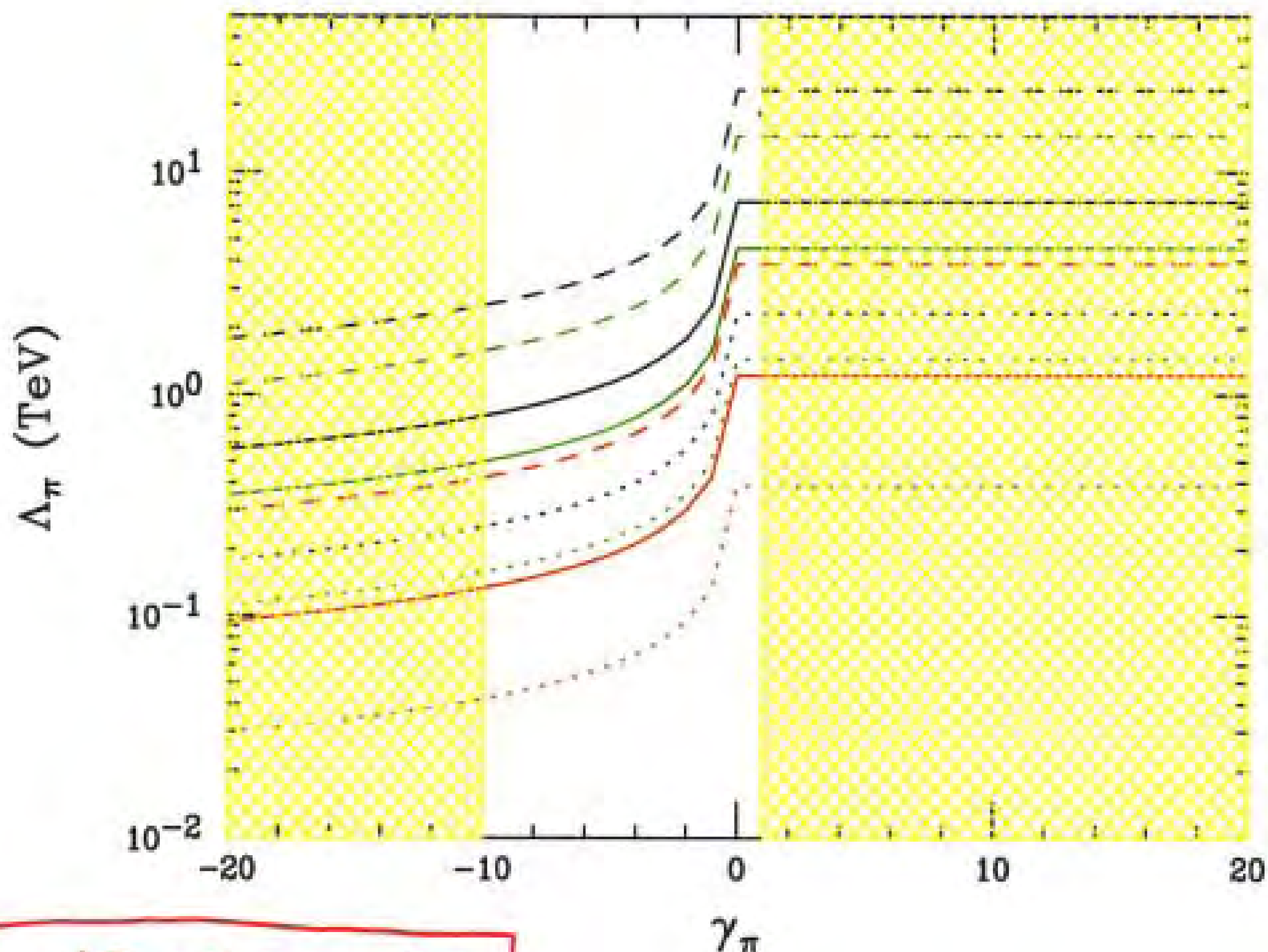


Contact interaction bounds

reduced by $\gamma_\pi \neq 0$!

LEP II = red
500 GeV = green } 500 fb^{-1}
1 TeV = black }

k/M_{Pl} = 0.01 dash
0.1 solid
1 dot



e^+e^- collider contact interaction reaches

Summary + Outlook

- Brane terms are present in essentially all ED models
- They modify the mass spectrum, wave functions + couplings of KK modes...
- Generally they allow for lighter, more weakly coupled KK's + alters expectations at LHC/LC
- Can have further implications that need to be explored...
- More work needed to explore this...