

Warped Phenomenology:

Signatures of ^{Extended} Localized Gravity

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hep-ph/0211xxx, 0212xxx,
0304xxx

- The Model
- Scalar Sector
- SM on the Wall
- SM off the Wall

H. Davoudiasl, JLH, T. Rizzo:
PRLOO, PLB00, PRD01, PLB01
PLB02, hep-ph/0211xxx, 0211(12)xxx

JLH, F. Petriello, T. Rizzo:
JHEP 02

JLH, T. Rizzo: JHEP 02



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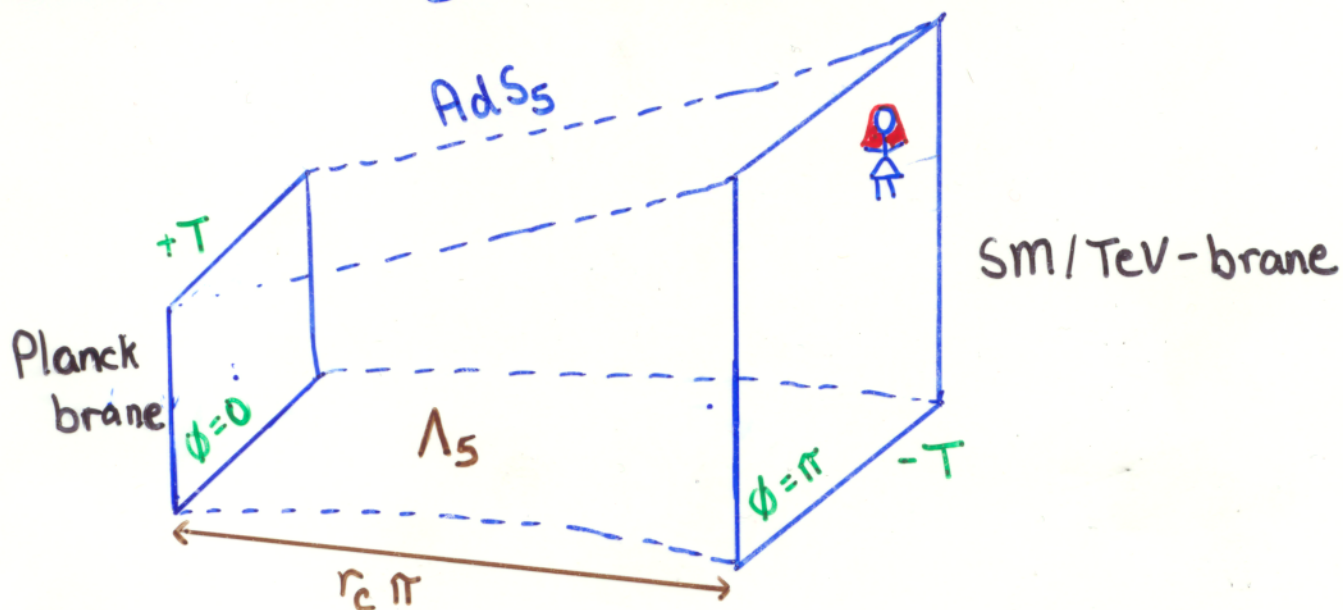
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Localized Gravity ala Randall-Sundrum



Bulk = Slice of AdS_5

Two 3-branes at $S_1/\mathbb{Z}_2$ orbifold fixed points

5-D, non-factorizable geometry

Solutions to Einstein's Eqn [w/ 4-D Poincare']

$$ds^2 = e^{-2kr_c|\phi|} \eta_{\mu\nu} dx^\mu dx^\nu + r_c^2 d\phi^2$$

Warp factor

$$0 \leq |\phi| \leq \pi$$

r_c = Compactification radius

where $\Lambda_5 = -24 m_5^3 k^2$

4-D Effective Action:

$$\bar{m}_{p1}^2 = \frac{m_5^3}{K} (1 - e^{-2Kr_c\pi}) \Rightarrow K \sim m_5 \sim \bar{m}_{p1}$$

no additional hierarchies!

Physical scales:

$$\Lambda_\phi = e^{-Kr_c|\phi|} \bar{m}_{p1}$$

For TeV-brane at $\phi = \pi$

$$\Lambda_\pi = e^{-Kr_c\pi} \bar{m}_{p1} \sim \text{TeV} \quad \text{if } Kr_c \sim 11-12$$

stabilized via
Goldberger + Wise

$\Rightarrow$ hierarchy generated by
an exponential!

Phenomenology governed by

$K/\bar{m}_{p1}$ and $\Lambda_\pi \Rightarrow$ only 2 free parameters!

5-D curvature:

$$|R_5| = 20 K^2 < m_5^2$$

(neglecting
higher-order
curvature terms)

suggests $K/\bar{m}_{p1} < 0.1$

$$\Rightarrow r_c \sim \frac{100}{\bar{m}_{p1}}$$

4-D Effective Theory:

Linear expansion of flat metric

$$G_{\alpha\beta} = e^{-2Kr_c|\varnothing|} (\eta_{\alpha\beta} + \kappa h_{\alpha\beta}) \quad \kappa = 2\bar{m}_5^{-3/2}$$

Expand into KK tower

$$h_{\alpha\beta}(x, \varnothing) = \sum_{n=0}^{\infty} h_{\alpha\beta}^{(n)}(x) \frac{\chi_h^{(n)}(\varnothing)}{\sqrt{r_c}}$$

Employ gauge $\eta^{\alpha\beta} \partial_\alpha h_{\beta\gamma}^{(n)} = 0$ & $\eta^{\alpha\beta} h_{\alpha\beta}^{(n)} = 0$

Demand $\int_{-\pi}^{\pi} d\varnothing e^{-2Kr_c|\varnothing|} \chi_h^{(m)} \chi_h^{(n)} = \delta_{mn}$

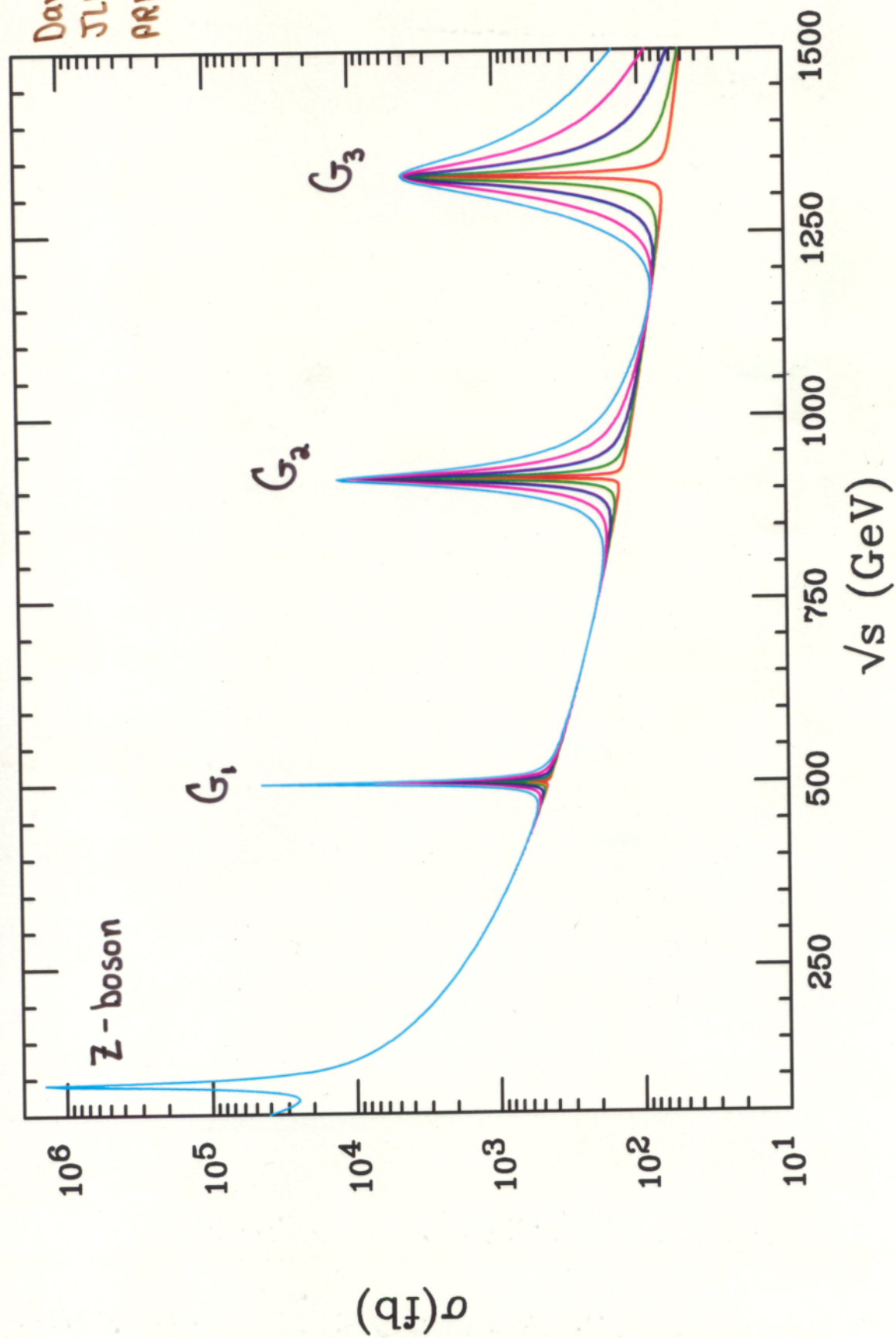
$$\chi_h^{(n)}(\varnothing) = \frac{e^{2Kr_c|\varnothing|}}{N_n} \left[J_2\left(\frac{m_n}{\kappa} e^{Kr_c|\varnothing|}\right) + \alpha_n Y_2\left(\frac{m_n}{\kappa} e^{Kr_c|\varnothing|}\right) \right]$$

For TeV-brane:

$$\begin{aligned} m_n &= x_n \kappa e^{-Kr_c\pi} \quad \text{with} \quad J_1(x_n) = 0 \\ &= x_n \frac{\kappa}{\bar{m}_{Pl}} \Lambda_{\pi} \end{aligned}$$

$\Rightarrow$ KK excitations are not evenly spaced!

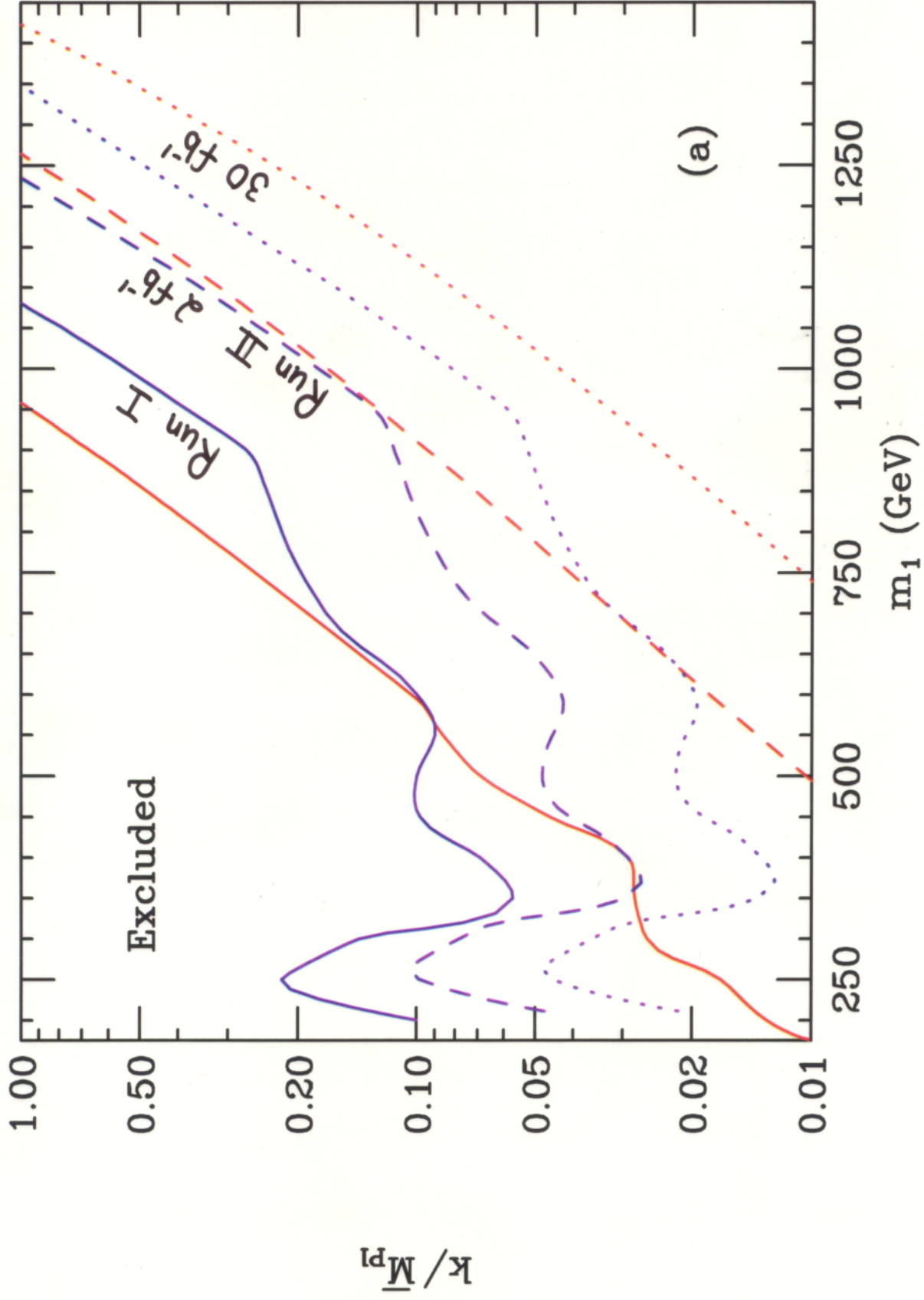
$e^+e^- \rightarrow \mu^+\mu^-$ Line Shape



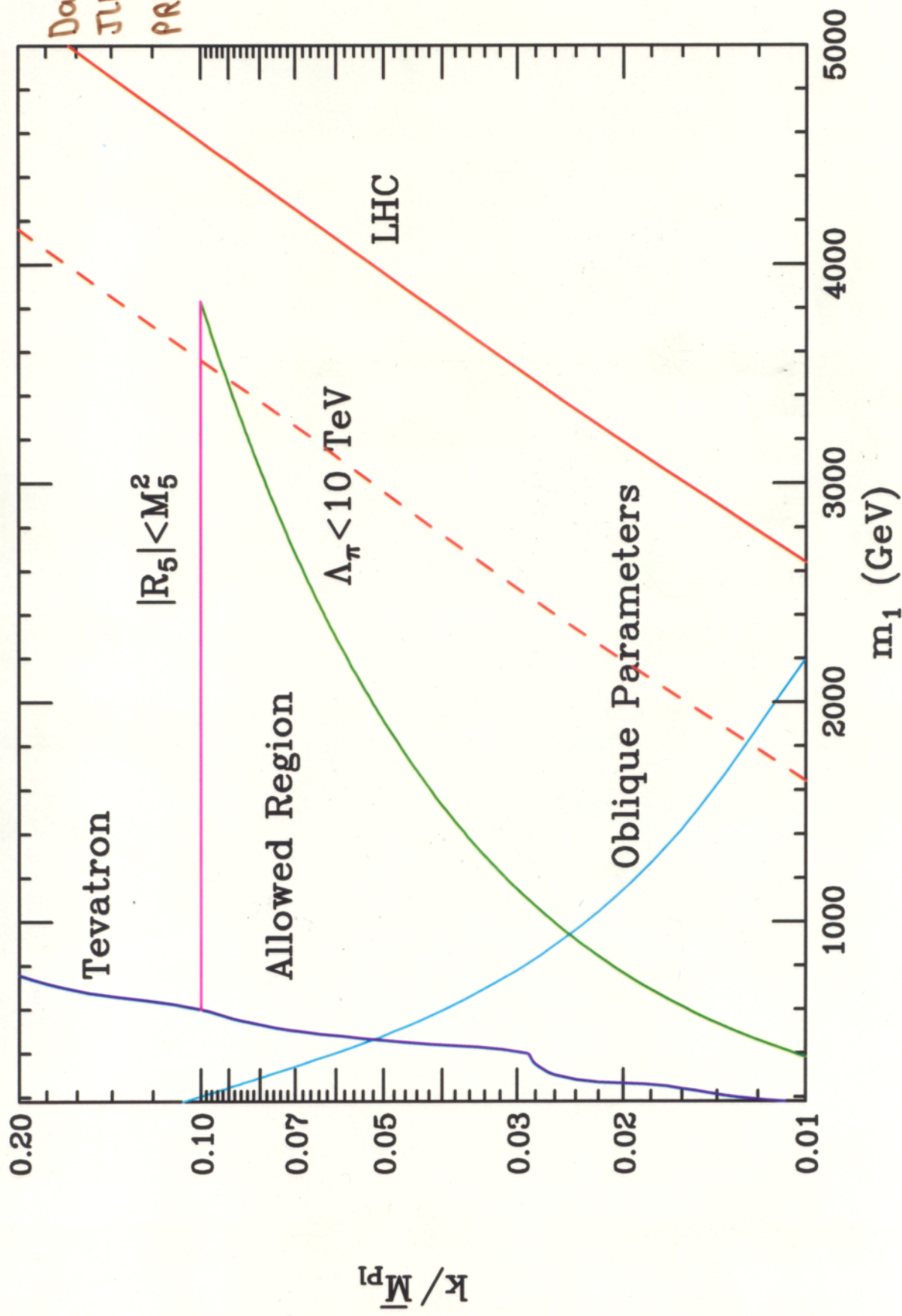
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PRL 00

LC becomes a Graviton Factory!

Tevatron Bump Search: Drell-Yan + Dijets



Summary of Theory + Experimental Constraints



Phenomenology on Slice of $AdS_5 \times \mathcal{M}^n$

- Embed RS in theory of quantum gravity

Case 1: Flat space

Examine $\mathcal{M}^n = S^1 [1/z_2]$

fermion localization

$\Rightarrow$ suppress proton decay
generate flavor hierarchy

$$ds^2 = e^{-2kr_c|\phi|} \eta_{\mu\nu} dx^\mu dx^\nu + r_c^2 d\phi^2 + R^2 d\theta^2$$

$\phi \in [-\pi, \pi]$
 $\theta \in [0, 2\pi]$

$\nwarrow$ radius of S^1

$$\bar{m}_{p1} = m_F^* \sqrt{\frac{2\pi R}{k} [1 - e^{-2kr_c\pi}]}$$

Naturalness: no hierarchies $R \sim 1/k$

take $1/2 \leq kR \leq 2$ in numerical studies

Graviton KK Spectrum

$$h_{\mu\nu}(x, \phi, \theta) = \sum_{n,l} h_{\mu\nu}^{(n,l)}(x) \frac{\chi^{(n)}(\phi) \varphi^{(l)}(\theta)}{\sqrt{r_c} \sqrt{R}}$$

$$\chi^{(n)}(\phi) \varphi^{(l)}(\theta) = N_n [J_\nu(z_n) + \alpha_{n\nu} Y_\nu(z_n)] \begin{cases} S_1 / Z_2 \\ \frac{1}{\sqrt{2}\pi}, & l=0 \\ \frac{\cos \theta l}{\sqrt{\pi}}, & l \neq 0 \\ e^{i\theta l} / \sqrt{2\pi}, & S_1 \end{cases}$$

$$r = \sqrt{4 + \left[\frac{l}{KR}\right]^2}$$

$$m_{nl}^2 \simeq \left[x_{n0}^2 + \frac{x_{n0} l}{KR} + \frac{l^2}{(KR)^2} \right] K^2 e^{-2Kr_c \pi}$$

$$\text{with } 2J_\nu(x_{n\nu}) + x_{n\nu} J'_\nu(x_{n\nu}) = 0$$

Value of KR determines # $l \neq 0$ states in between $n(l=0)$ states

Interactions:

$$\mathcal{L} = \frac{1}{\overline{m}_{Pl}} h_{\mu\nu}^{(0,0)}(x) T^{\mu\nu}(x) - \frac{1}{\Lambda_\pi} T^{\mu\nu}(x) \sum_{n=1}^{\infty} \sum_{l=0}^{\infty} \frac{C_l h_{\mu\nu}^{(n,l)}}{\sqrt{1 - \left(\frac{l}{KR x_{n\nu}}\right)^2}}$$

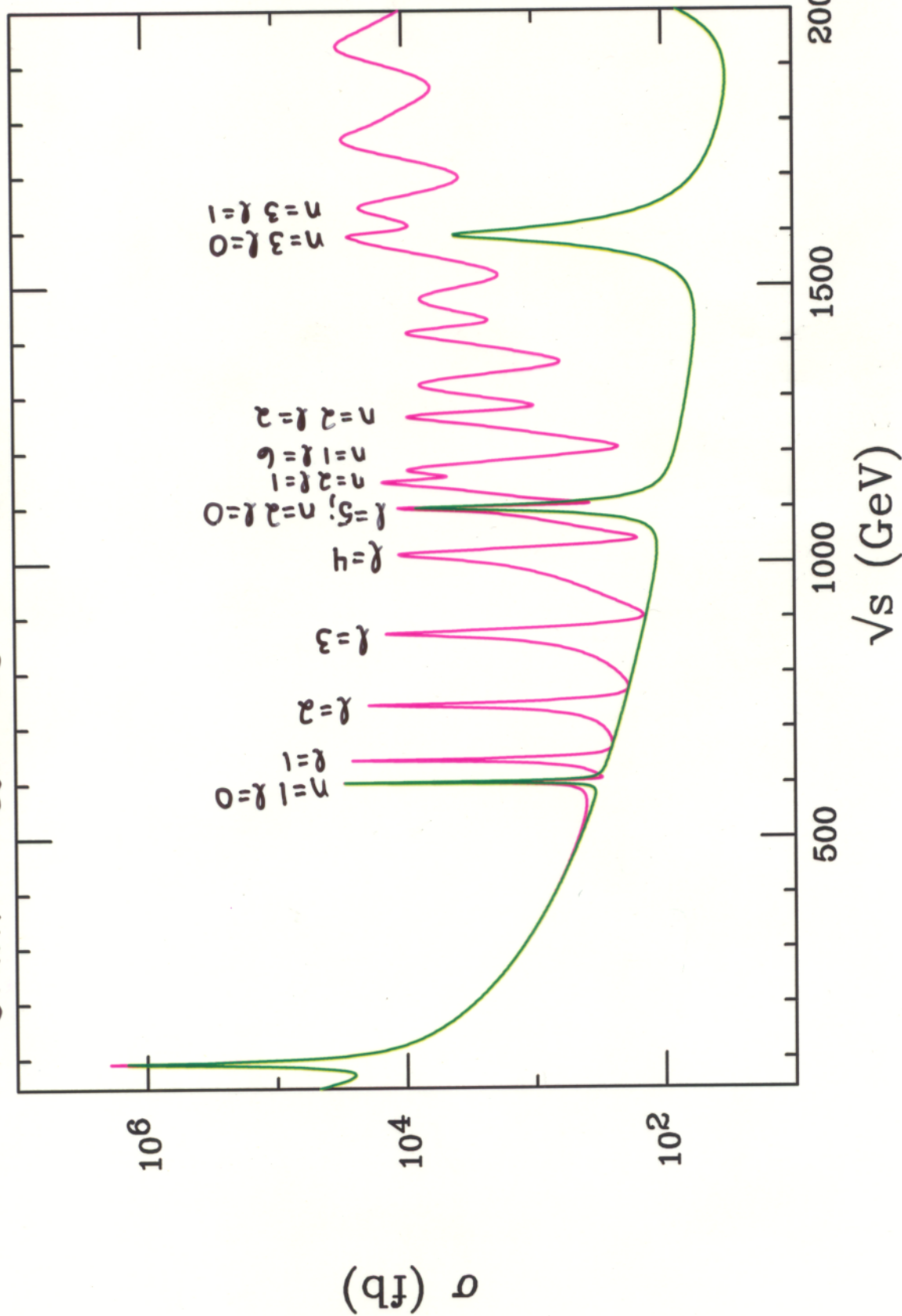
$$C_l = \begin{cases} 1 & S_1 \\ \frac{1}{\sqrt{2}} & S_1 / Z_2 \quad (l > 0) \end{cases}$$

Warped Geometry + Fat Brane

$$KR = 1$$

$$K/\overline{M}_{Pl} = 0.03$$

Graviton resonances in $e^+e^- \rightarrow \mu^+\mu^-$

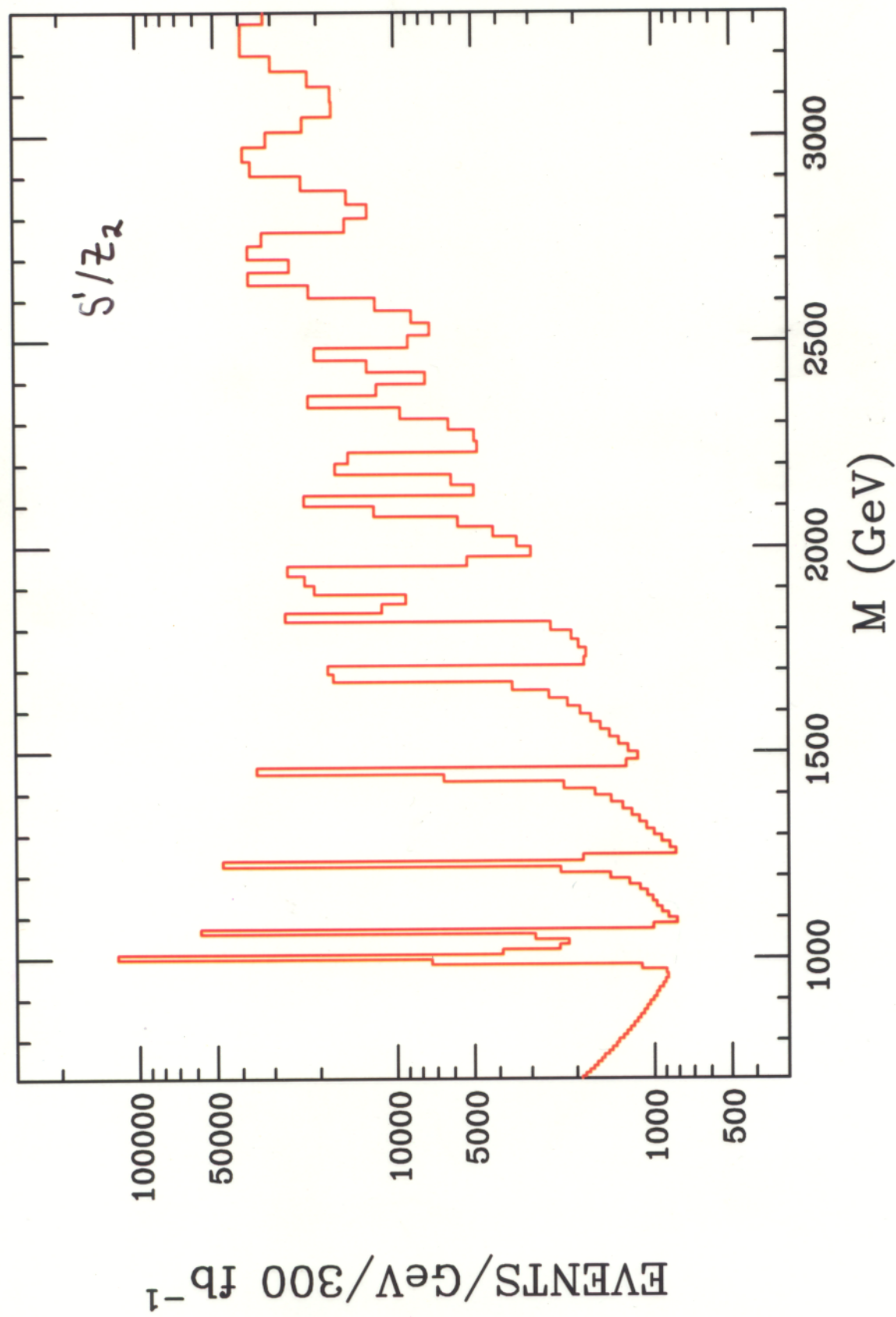


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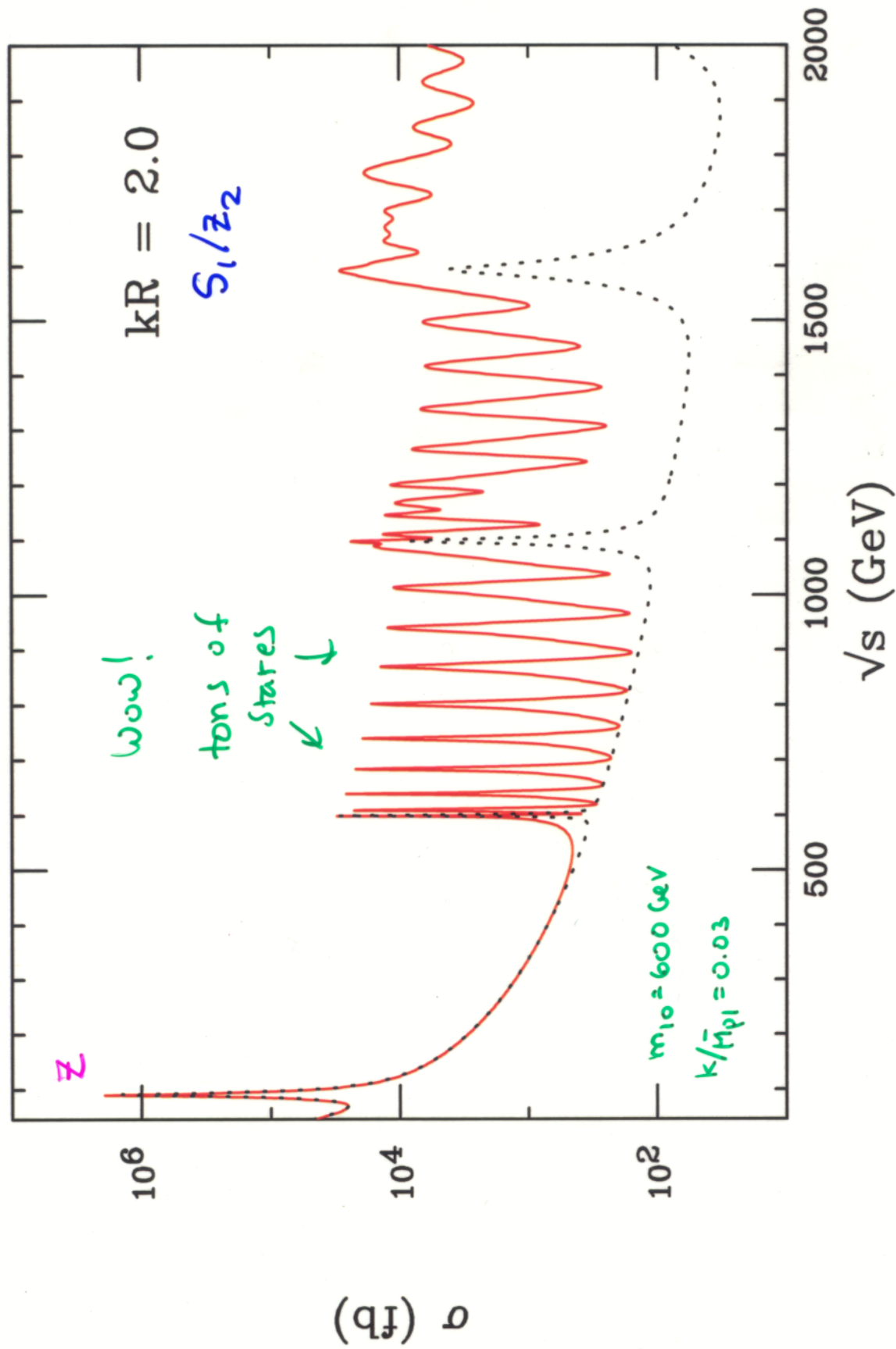
Graviton Spectroscopy

$$m_{n\ell} \approx \left[x_n^2 + \frac{\ell^2}{(KR_c)^2} \right]^{\frac{1}{2}} K e^{-K\pi r_c}$$

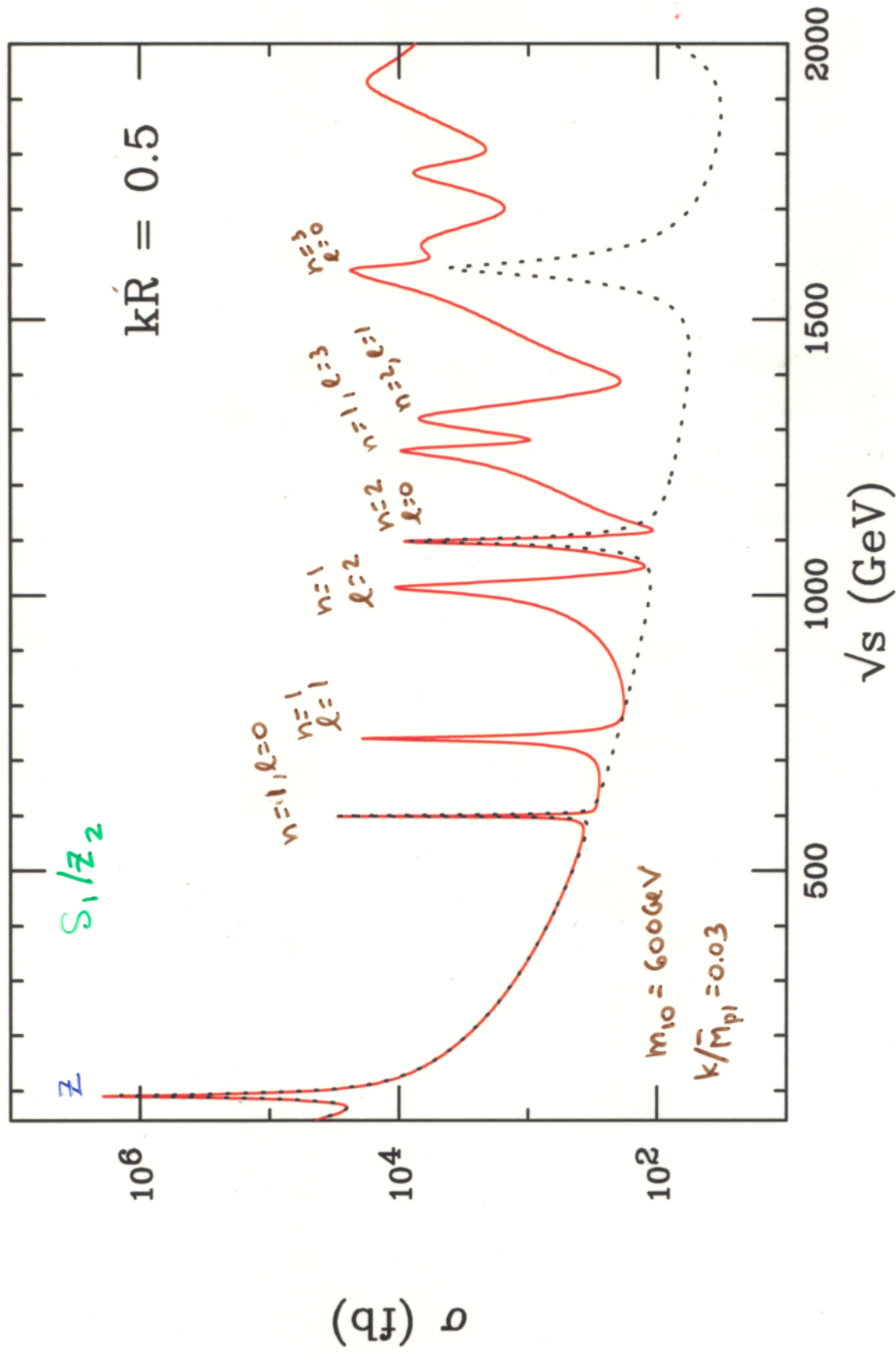
Drell-Yan at LHC w/ smearing



increasing kR we get a denser forest ...



As we lower kR the forest 'spreads-out'



Colliders tell us the size of the additional dimension

Case 2: Curved Manifolds

Examine S^2

$$ds^2 = e^{-2kr_c|\phi|} \eta_{\mu\nu} dx^\mu dx^\nu + r_c^2 d\phi^2 + R^2 (d\theta^2 + \sin^2\theta d\omega^2)$$

$$\theta \in [0, \pi], \quad \omega \in [0, 2\pi]$$

Einstein's Eqn's:

$$\Lambda_F = -24 m_F^5 K^2 + \frac{4 m_F^5}{R^2}$$

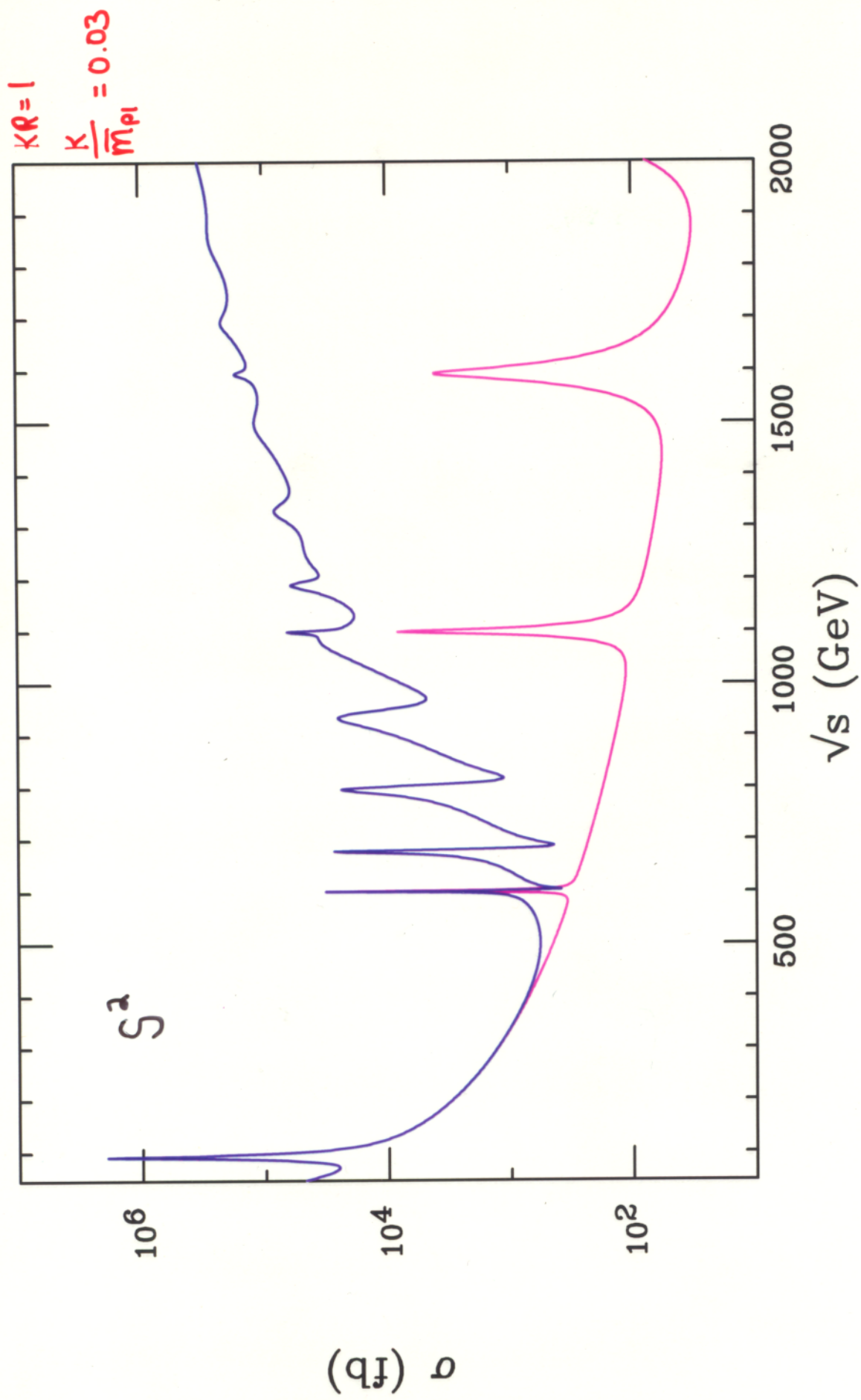
positive curvature
of sphere creates
warping!

$$\bar{m}_{p1}^2 = \frac{4\pi R^2}{K} m_F^5 (1 - e^{-2kr_c\pi})$$

$$h_{\mu\nu}(x, \phi, \theta, \omega) = \sum_{n,m,l} h_{\mu\nu}^{(n,m,l)}(x) \frac{\chi^{(n)}(\phi) Y_l^m(\theta, \omega)}{\sqrt{r_c} R}$$

$$\chi^{(n)}(\phi) \text{ as before w/ } \nu = \sqrt{4 + \frac{l(l+1)}{(KR)^2}}$$

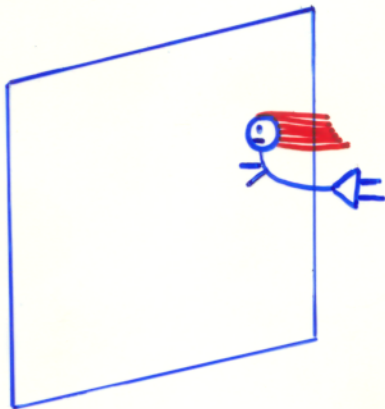
$$\mathcal{L} = -\frac{1}{\bar{m}_{p1}} h_{\mu\nu}^{(0,0,0)}(x) T^{\mu\nu}(x) - \frac{1}{\Lambda_F} T^{\mu\nu}(x) \sum_{l=0}^{\infty} \sum_{n=1}^{\infty} \frac{h^{(n,0,l)}(x)}{\sqrt{2l+1} \sqrt{1 - \frac{l(l+1)}{(KRx_{\mu\nu})^2}}}$$



$$\frac{K}{\bar{m}_{p1}} = 0.03$$

$$KR = 1$$

Peeling the SM off the Wall



Model building scenarios require SM bulk fields

- Gauge coupling unification
- Supersymmetry breaking
- γ Mass spectrum
- Fermion Mass hierarchy
-

Gauge Fields in bulk alone:

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⇒ Gauge boson KK towers
with $g_{KK} = 8.4 g_{SM}$

EW Data: $m_1^A > 25 \text{ TeV} \Rightarrow \Lambda_{\pi} \gtrsim 100 \text{ TeV} !$

The presence of the S'/Z_2 orbifold and/or matter fields on the two branes induce new kinetic terms at loop-order (Georgi, Grant Hailu)

$$S = S_{\text{gauge}} + S_{\text{matter}}$$

$$S_{\text{gauge}} = \int d^4x \int d\phi \sqrt{-g} \left\{ -\frac{1}{4} F_{AB} F^{AB} + c_0 \delta(\phi) \cdot -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + c_\pi \delta(\phi - \pi) \cdot -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \right\}$$

Induced brane kinetic terms

W/o a detailed model, c_0, π are dimensionless + $O(1)$ parameters

Gauge invariance $\oplus$ thin brane limit implies these are the only dim-4 terms that can be written down (we can always take $A_5 = 0$)

e.g., $\delta \cdot \partial_5 A^\mu \partial_5 A_\mu \rightarrow 0$ even in $U(1)$ case

Modifies KK reduction

$$A_n(x, \phi) = \sum_n A_n^{(n)}(x) \frac{\chi^{(n)}(\phi)}{\sqrt{r_c}} \quad \text{as before}$$

$$\partial_\phi (e^{-2\sigma} \chi^{(n)}) + [1 + c_0 \delta(\phi) + c_\pi \delta(\phi - \pi)] r_c^2 m_n^2 \chi^{(n)} = 0$$

$$\left\{ \begin{array}{l} \int d\phi \{1 + c_0 \delta(\phi) + c_\pi \delta(\phi - \pi)\} \chi^{(n)} \chi^{(m)} = z_n \delta_{nm} \\ \int d\phi e^{-2\sigma} [\chi^{(n)}]' [\chi^{(m)}]' = z_n m_n^2 r_c^2 \delta_{nm} \end{array} \right.$$

$$\rightarrow \chi^{(n)} = \frac{e^\sigma}{N_n} \zeta_1(z_n) \quad \left\{ \begin{array}{l} z_n \equiv m_n / k e^\sigma \\ \zeta_1 \equiv J_1 + \alpha_n Y_1 \end{array} \right.$$

$$\text{w/} \quad \int d\phi \chi^{(n)} \chi^{(n)} = 1$$

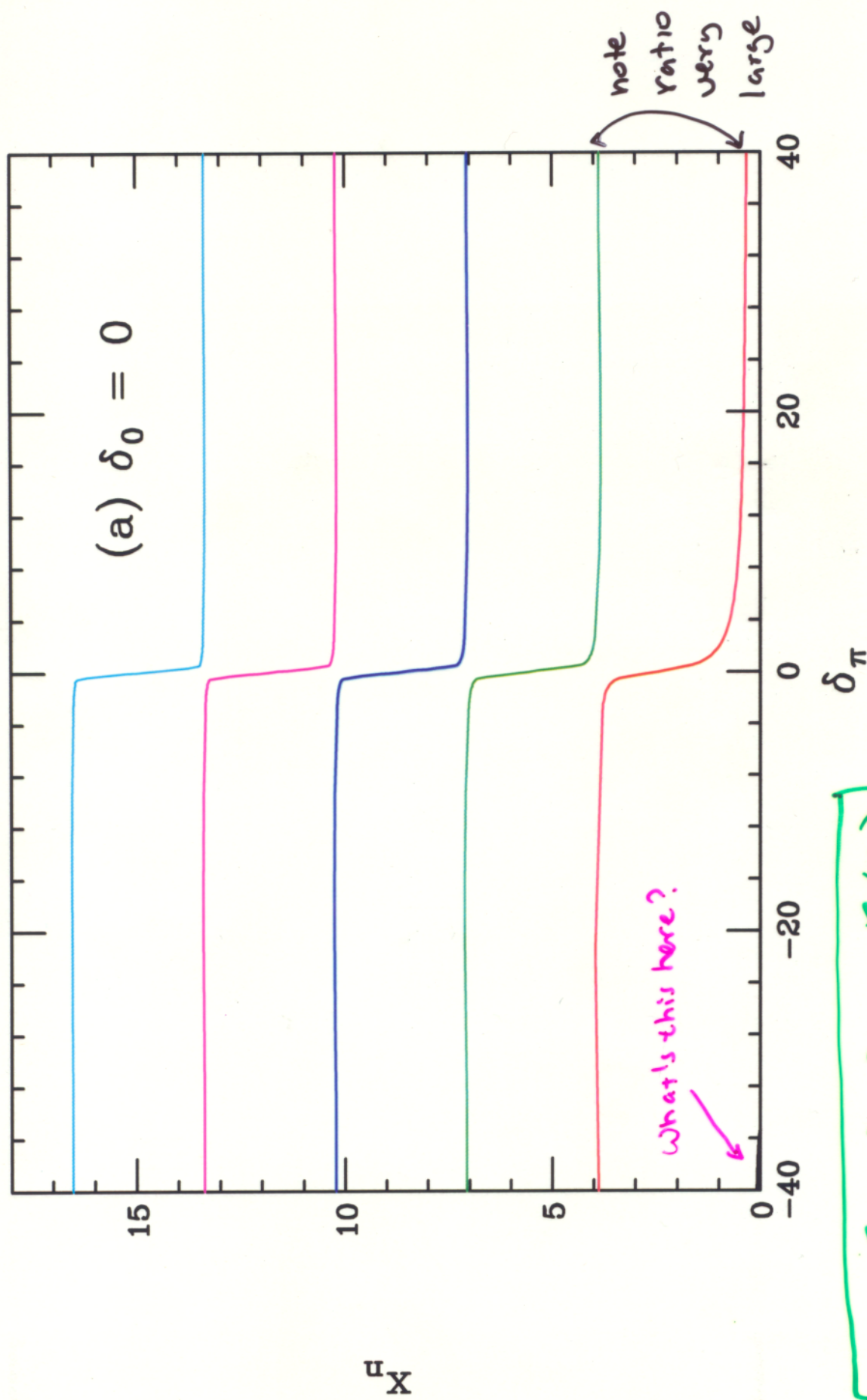
$$\text{boundary conditions} \Rightarrow \left[\delta_{0,\pi} \equiv \frac{k r_c}{2} c_{0,\pi} \sim \mathcal{O}(10) ? \right]$$

$$\left\{ \begin{array}{l} J_0(x_n) - \delta_\pi x_n \zeta_1(x_n) = 0 \\ \alpha_n = - \frac{J_0(\epsilon_n) + \delta_0 \epsilon_n J_1(x_n)}{Y_0(\epsilon_n) + \delta_0 \epsilon_n Y_1(x_n)} \end{array} \right. \quad \left. \begin{array}{l} m_n = x_n k e^{-k r_c \pi} \\ \epsilon_n \equiv m_n / k \end{array} \right.$$

• masses + wave functions are modified ..

So ??

Behaviour of First 5 KK roots



$$0 = S_0(x_n) - \delta_\pi x_n S_1(x_n)$$

Couplings

$$g^{(n)}/g^{(0)} = \sqrt{2\pi k r_c} \sqrt{\frac{z_0}{W z_n}}$$

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

$$z_0 = 1 + \frac{\delta_0 + \delta_\pi}{\pi k r_c}$$

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

But $W, z_n > 0$ while $z_0 > 0$ implies

$$\boxed{\delta_0 + \delta_\pi > -\pi k r_c} \quad \text{or} \quad \underline{\text{ghost}}$$

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

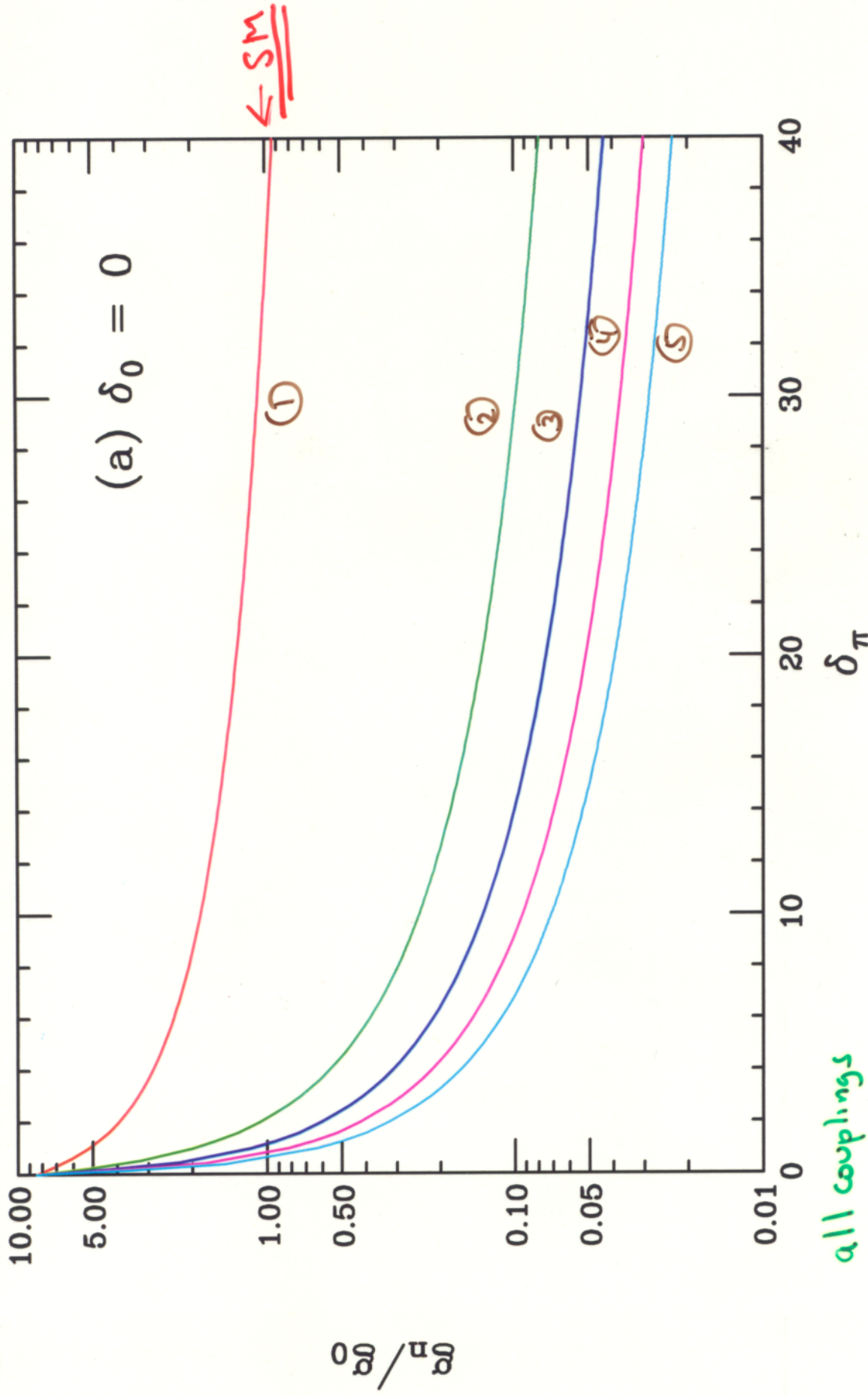
∴ origin of disallowed regions

→ constraint

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

much weaker couplings!

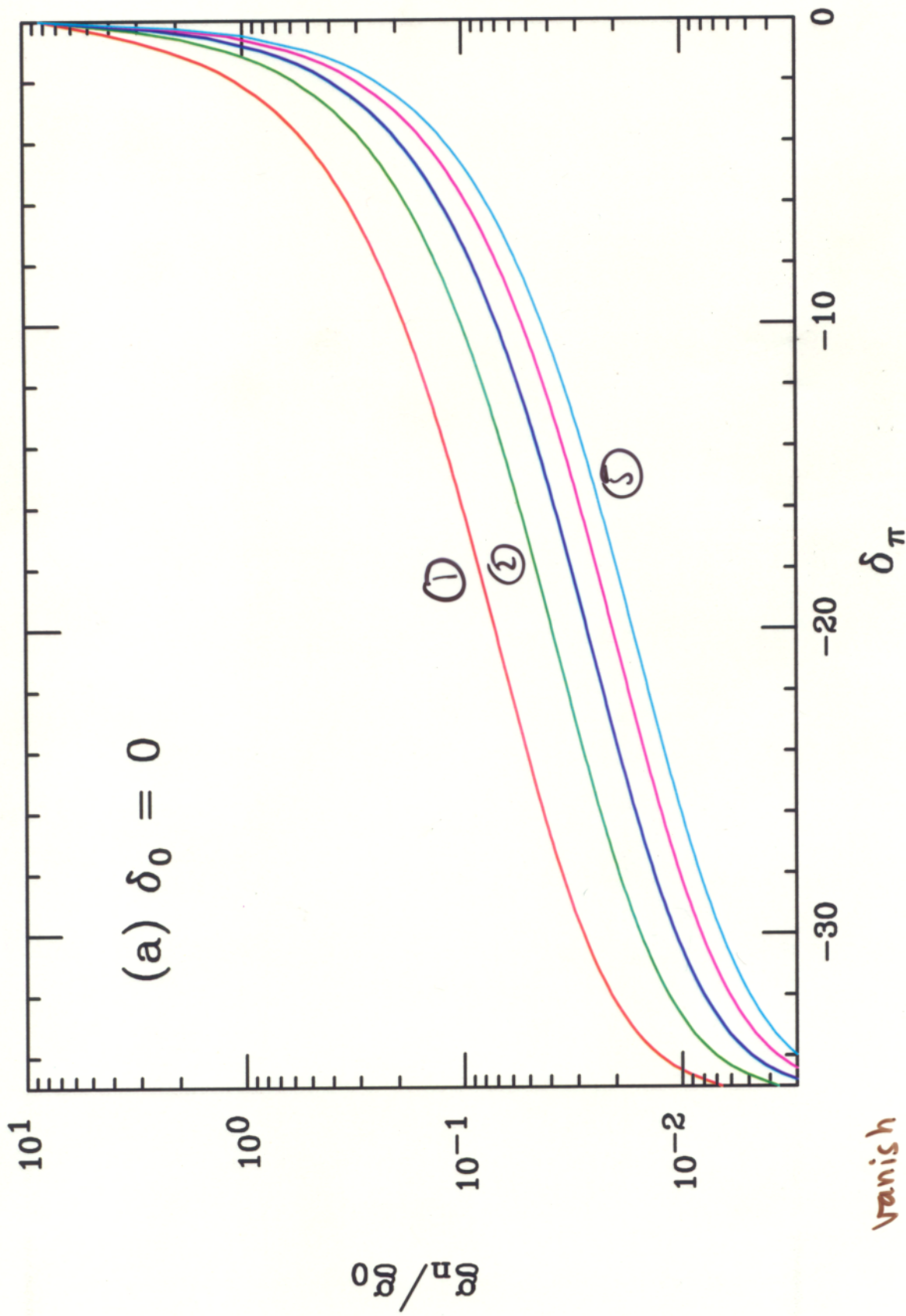
KK couplings decrease with $\delta\pi$



all couplings are n-independent

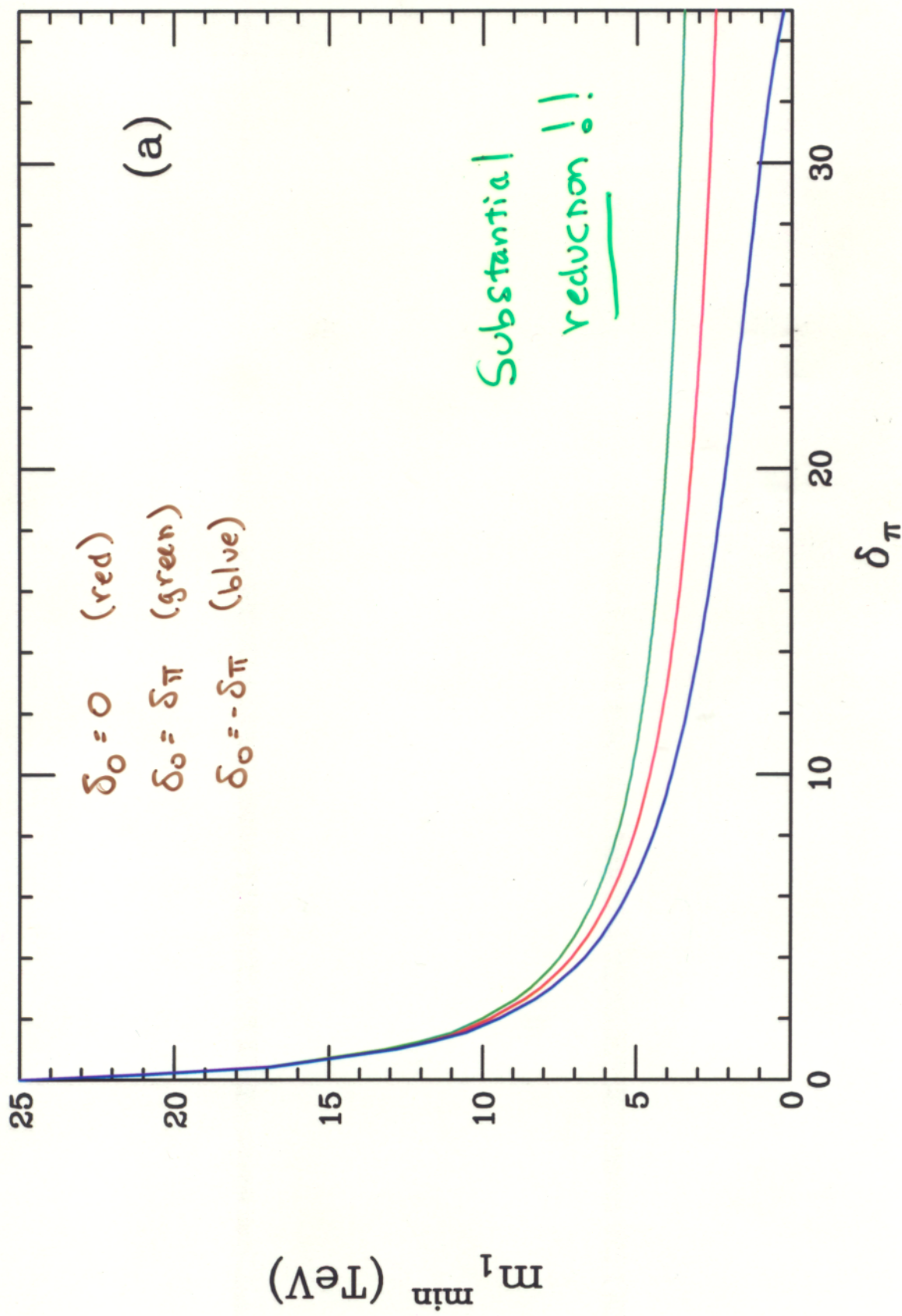
Higher KK's rapidly decouple

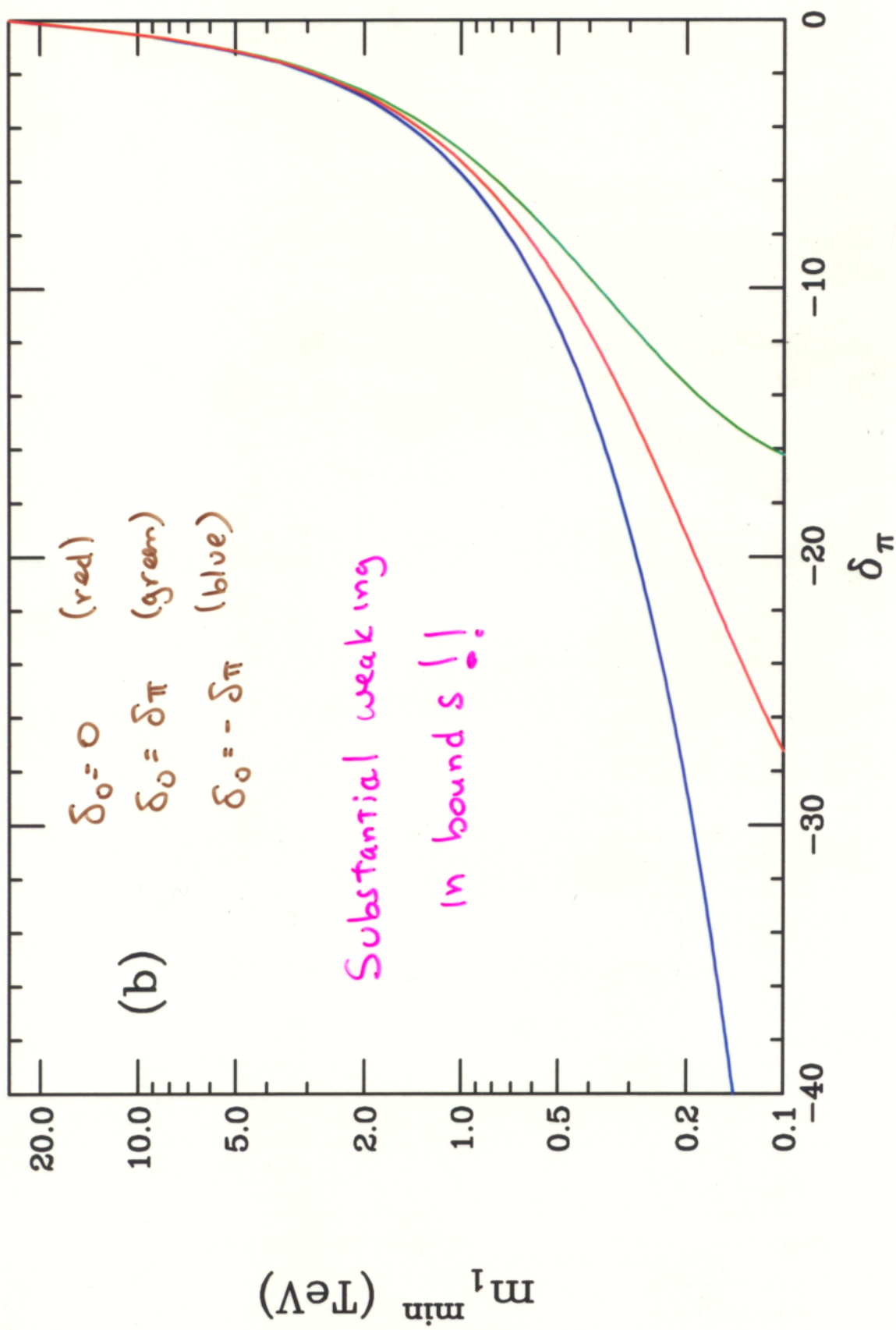
very rapid fall off in $\delta\pi < 0$ region



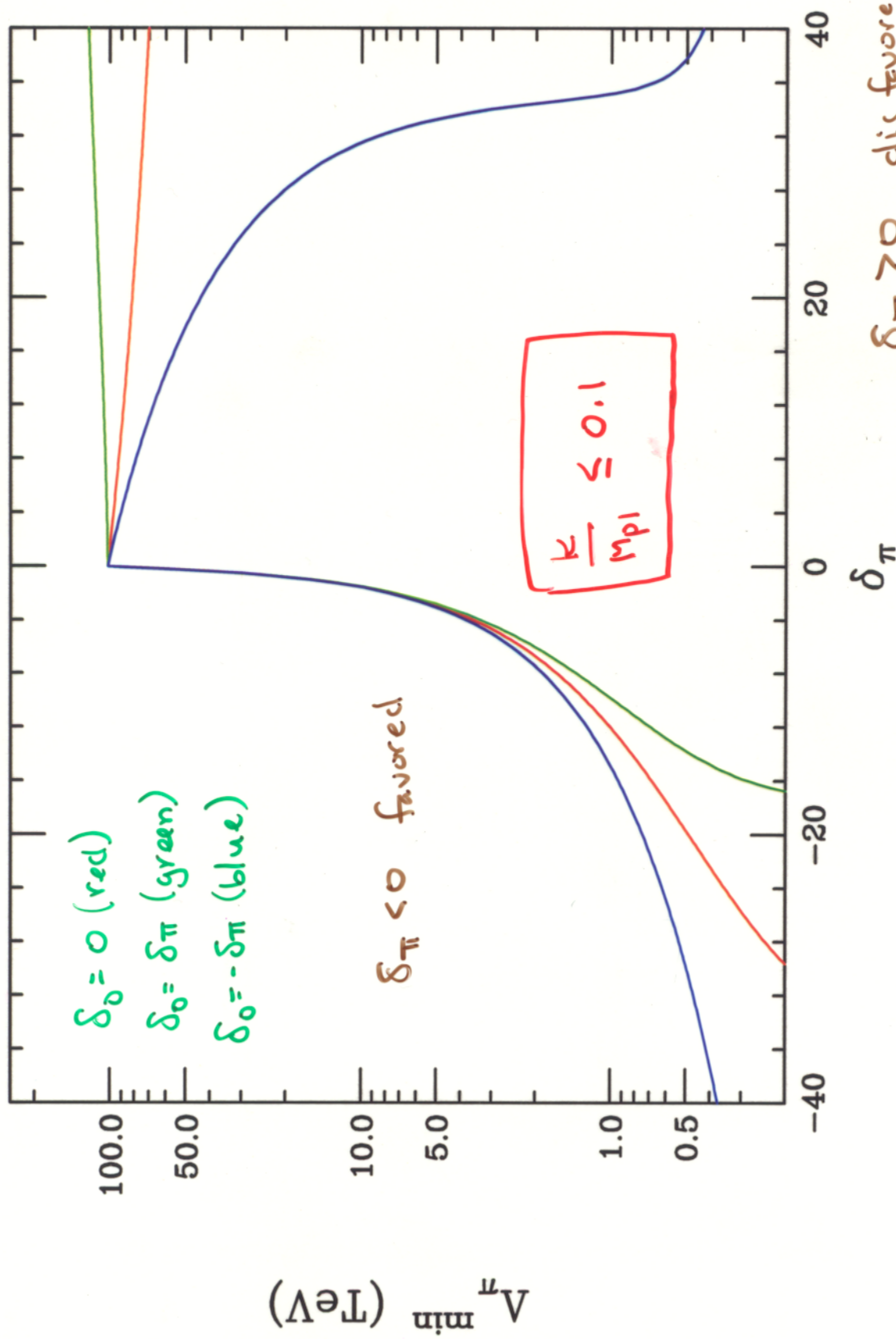
vanish
at $\delta\pi = -\pi k r_c \sim -38$

Precision measurement bounds $\delta_{\pi} \geq 0$





Have we really solved the problem ? ?

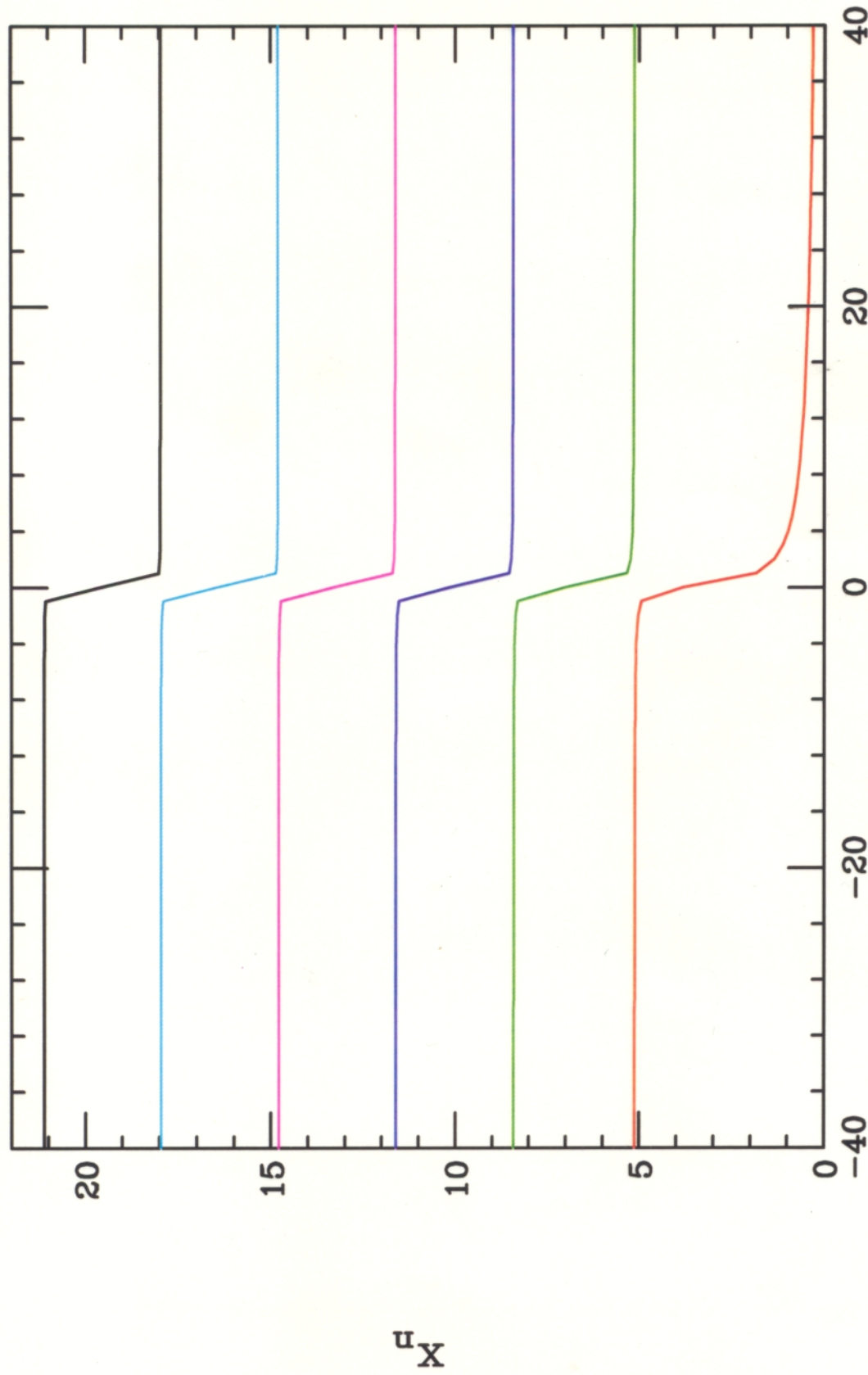


unless $\delta_0 = -\delta_{\pi}$, δ_{π} large

!!!

brane kinetic terms for gravity?

DHR, in progress



no δ_0 sensitivity

graviton KK's get reduced couplings

