Phenomenology of Extra Dimensions

- Large
- TeV
- ★ Warped - Davoudiasl, JLH, Rizzo
  PRL '00, PLB '00, hep-ph/0006041
  /0006097

Consequences for:

Cosmology
Astrophysics
★ Collider physics
★ Precision measurements
Flavor physics
Gravity tests

Large Extra Dimensions

Arkani-Hamed, Dimopoulos, Dvali

Motivation: Solve the hierarchy problem by removing it!

Gauss' Law:

$$M_{Pl}^2 = V_n M_*^{2+n} \quad ; \quad V_n \sim R^n$$

M_* = Fundamental Planck scale in the bulk

$\simeq$ TeV

$n=1$	$R = 10^{11}$ m	Excluded!
2	0.4 mm	$m_c = 1/R = 5 \times 10^{-4}$ eV
4	10^{-5} mm	20 keV
6	30 fm	7 MeV

<u>n=2</u>: Low M_* disfavored by Astro/Cosmology

(i) Supernova Cooling $\rightarrow M_* \gtrsim 30$ TeV — Cullen + Perelstein, Barger etal, Hanhart etal

$NN \rightarrow NN + G_n$ can cool supernova too rapidly

(ii) γ-ray flux $\rightarrow M_* \gtrsim 110$ TeV — Hall + Smith

$\nu\bar{\nu} \rightarrow G_n \rightarrow \gamma\gamma$ produces too many soft γ's

Bulk Metric: Linearized Quantum Gravity

$$G_{AB} = \eta_{AB} + \frac{h_{AB}(x^\mu, x^a)}{M_*^{n/2+1}}$$

$A = 0, \ldots, 4+n$
$\mu = 0,1,2,3$
$a = 1, \ldots, n$

with interactions

$$S_{int} = \frac{-1}{M_*^{n/2+1}} \int d^4x\, d^nx^a\, h_{AB}(x^\mu, x^a)\, T_{AB}(x^\mu, x^a)$$

Induced wall metric: $G_{\mu\nu}(x^\mu, x^a = 0)$

SM on wall: $T_{AB} = \eta^\mu_A \eta^\nu_B T_{\mu\nu}\, \delta(x^a)$

Interactions on wall: Decompose h_{AB}
impose unitary gauge
integrate S_{int} over d^nx^a via $\delta(x^a)$

Bulk fields expand into Kaluza-Klein towers upon compactification

$$\Phi(x^\mu, x^a) = \sum_{n=0}^{\infty} \phi^{(n)}(x^\mu)\, e^{inx^a/R} \cdot \frac{1}{\sqrt{V_n}}$$

$\partial^2 \Phi = 0$ gives massless mode in $4+n$ D

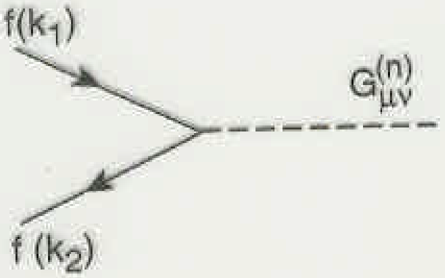
$$(\partial^2_\mu + \partial^2_a)\Phi = \sum_n \left[\partial^2_\mu \phi^{(n)}(x^\mu) - \left(\tfrac{n}{R}\right)^2 \phi^{(n)}(x^\mu) \right] e^{inx^a/R}$$

mass term with
$m = n/R$

Feynman Rules

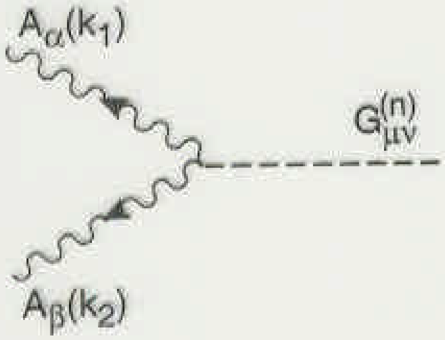
Giudice, Rattazzi, Wells

Han, Lykken, Zhang



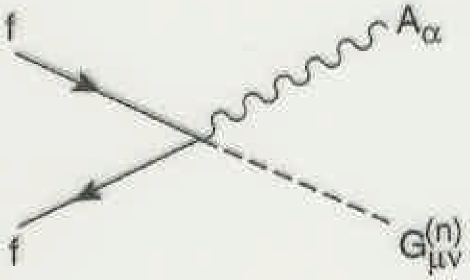
$$-\frac{i}{4\bar{M}_P}\left[W^{(f)}_{\mu\nu} + W^{(f)}_{\nu\mu}\right]$$

$$W^{(f)}_{\mu\nu} = (k_1 + k_2)_\mu \gamma_\nu \tag{53}$$



$$-\frac{i}{\bar{M}_P}\left[W^{(\gamma)}_{\mu\nu\alpha\beta} + W^{(\gamma)}_{\nu\mu\alpha\beta}\right]$$

$$\begin{aligned} W^{(\gamma)}_{\mu\nu\alpha\beta} &= \frac{1}{2}\eta_{\mu\nu}\left(k_{1\beta}k_{2\alpha} - k_1\cdot k_2\eta_{\alpha\beta}\right) + \eta_{\alpha\beta}k_{1\mu}k_{2\nu} \\ &\quad + \eta_{\mu\alpha}\left(k_1\cdot k_2\eta_{\nu\beta} - k_{1\beta}k_{2\nu}\right) - \eta_{\mu\beta}k_{1\nu}k_{2\alpha} \end{aligned} \tag{54}$$



$$-\frac{i}{2\bar{M}_P}eQ\left(X_{\mu\nu\alpha} + X_{\nu\mu\alpha}\right)$$

$$X_{\mu\nu\alpha} = \gamma_\mu\eta_{\nu\alpha}. \tag{55}$$

Massless 0-mode ⊕ all tower gravitons have same couplings to matter

Two Classes of Collider Tests

- Graviton Tower Emission

Giudice, Rattazzi, Wells
Han, Lykken, Zhang
Mirabelli, Perelstein, Peskin

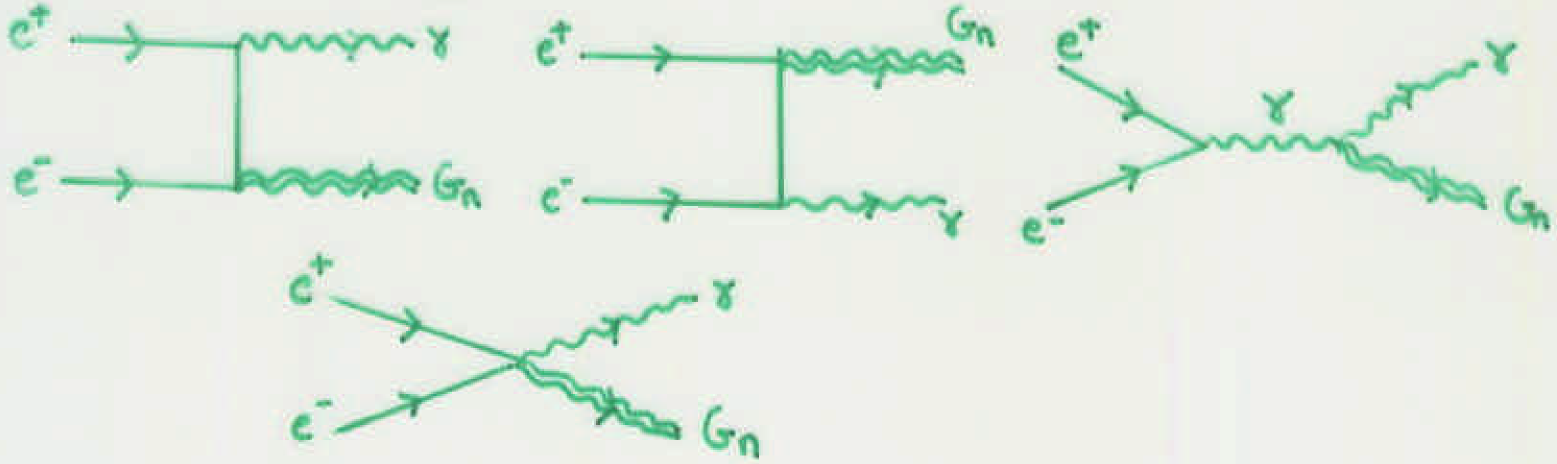
$e^+e^- \to \gamma + G_n$
$q\bar{q} \to g + G_n$
$Z \to f\bar{f} + G_n$

G_n appears as $\not{E}_T$
Model Indepent - Probes M_* directly
Sensitive to n

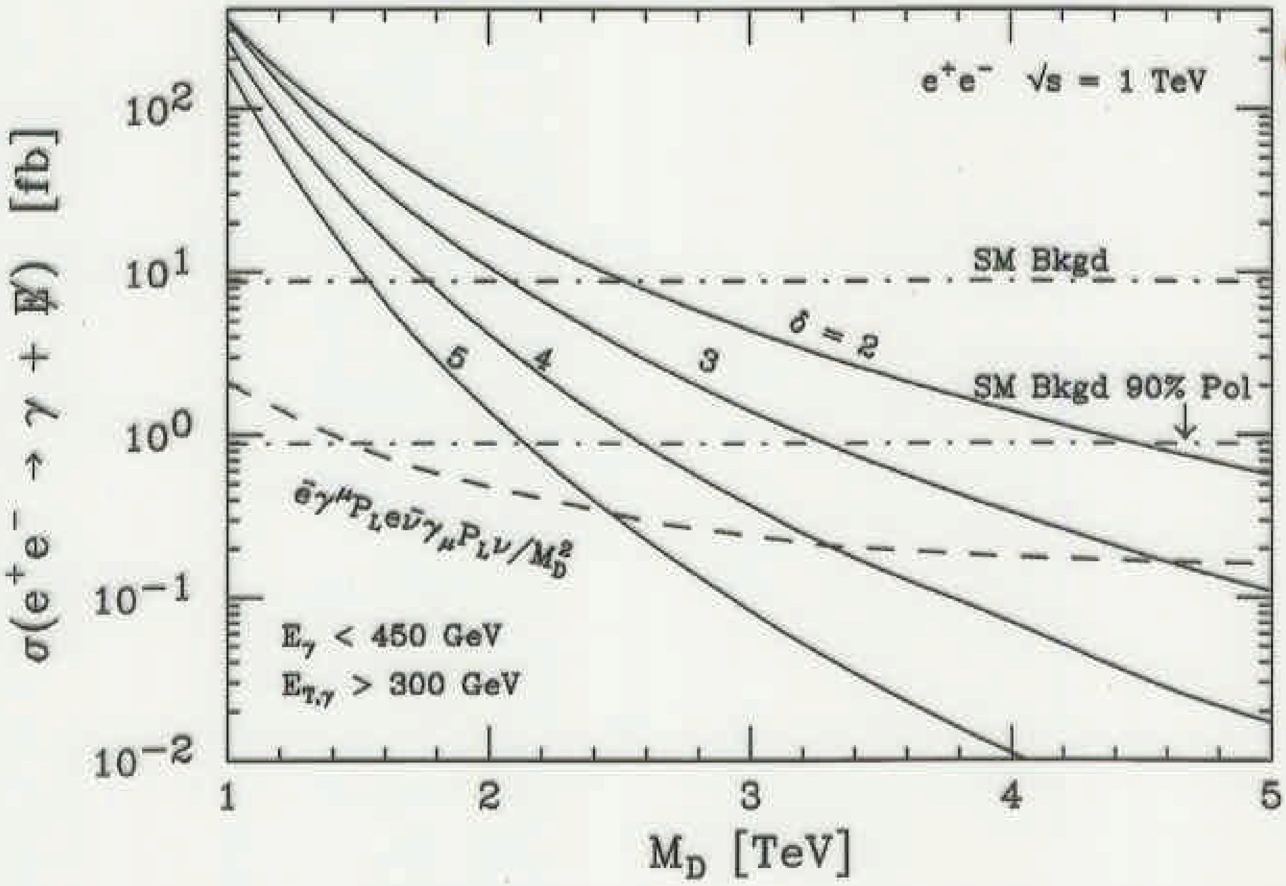
Parameterized by effective density of states

$$\frac{d^2\sigma}{dm\, d\cos\theta} = \rho(m) \frac{d\sigma}{d\cos\theta} \quad \text{with} \quad \rho(m) = R^n \Omega_{n-1} m^{n-1}$$

$e^+e^- \to \gamma + G_n$:



Graviton Emission : $e^+e^- \to \gamma + G^{(n)}$



Giudice, Ratazzi, Wells

Figure 2: Total $e^+e^- \to \gamma +$ nothing cross-section at a 1 TeV centre-of-mass energy e^+e^- collider. The signal from graviton production is presented as solid lines for various numbers of extra dimension ($\delta = 2, 3, 4, 5$). The Standard Model background for unpolarized beams is given by the upper dash-dotted line, and the background with 90% polarization is given by the lower dash-dotted line. The signal and background are computed with the requirement $E_\gamma < 450$ GeV in order to eliminate the $\gamma Z \to \gamma\bar{\nu}\nu$ contribution to the background. The dashed line is the Standard Model background subtracted signal from a representative dimension-6 operator.

Note: signal ↑ w/ $\sqrt{s}$ ↑
background ↓ w/ $\sqrt{s}$ ↑

$pp \to g + G^{(n)}$

ATLAS Simulation
Vacavant, Hinchliffe

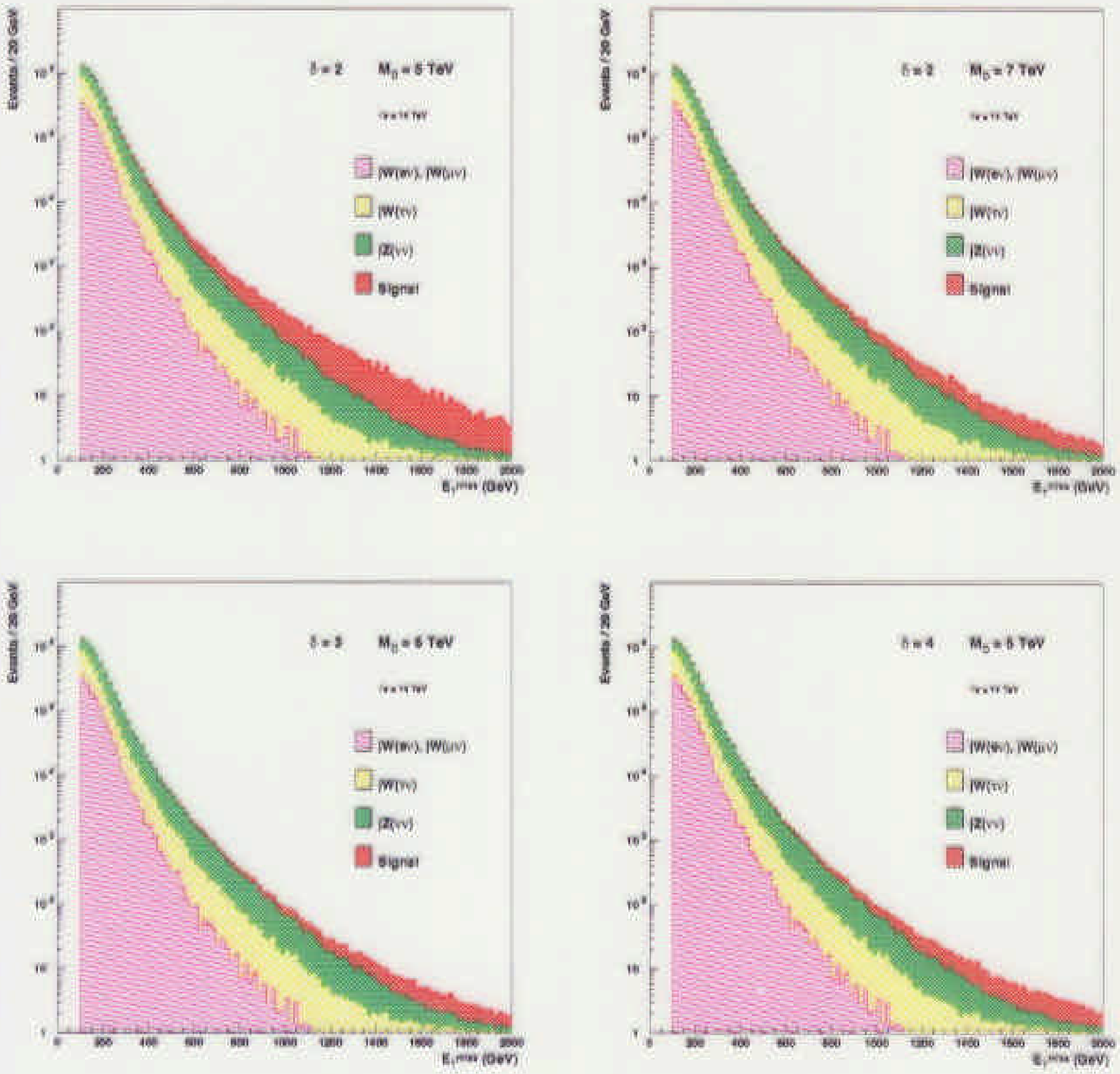


Figure 11: Distributions of the missing transverse energy in signal and in background events after the selection and for 100 fb^{-1} of integrated luminosity. Various cases (δ, M_D) for the signal are shown.

Search Reach:

$n = 2$	$M_* = 4 - 7.5$ TeV
3	4.5 - 5.9
4	5.0 - 5.3

• Graviton Tower Exchange $XX \to G_n \to YY$

Search for 1) Deviations in SM processes
2) New processes!

Graviton couples 1) universally to everything
2) via $T_{\mu\nu}$

Angular distributions reveal massive spin-2 exchange

Poor theoretical control!

Σ KK propagators is divergent

$\Rightarrow$ Sensitivity to unknown ultraviolet physics

Approaches:

- 'Naive' cut-off — JLH; Giudice etal; Han etal
- Brane fluctuations — Bando etal
- Weakly Coupled String Theory — Dudas, Mourad; Accomando etal; Cullen etal

Effective Theory - Cut-off Approach

- Gravity becomes strong at M_* $\Rightarrow$ need full theory!
- Work in weak-field limit $s \ll M_*^2$

Examine leading dimension-8 operators

$\Rightarrow$ contact interaction limit for G_n exchange

$\Rightarrow$ Constrain $M_* |\lambda|^{-1/4}$

$$\mathcal{M} = \frac{\lambda}{M_*^4} \left\{ \begin{array}{l} \bar{f}\gamma_\mu f \, \bar{\ell}\gamma^\mu \ell \, (p_{\bar{f}} - p_f)\cdot(p_{\bar{\ell}} - p_\ell) \\ + \bar{f}\gamma_\mu f \, \bar{\ell}\gamma_\nu \ell \, (p_{\bar{f}} - p_f)^\nu (p_{\bar{\ell}} - p_\ell)^\mu \end{array} \right\}$$

$$\frac{d\sigma}{dz} \sim A(1+z^2) + Bz \qquad\qquad z = \cos\theta$$

$$- \frac{\lambda s^2}{M_*^4}\left[C z^3 - D(1-3z^2) \right]$$

$$+ \frac{\lambda^2 s^4}{M_*^8}\left[E(1-3z^2+4z^4) \right]$$

$\Rightarrow$ Unique signal for spin-2 exchange!

Angular Distributions for $e^+e^- \to f\bar{f}$

$\sqrt{s} = 500$ GeV $M_s = 1.5$ TeV

$\frac{\text{Events}}{\text{bin}}$

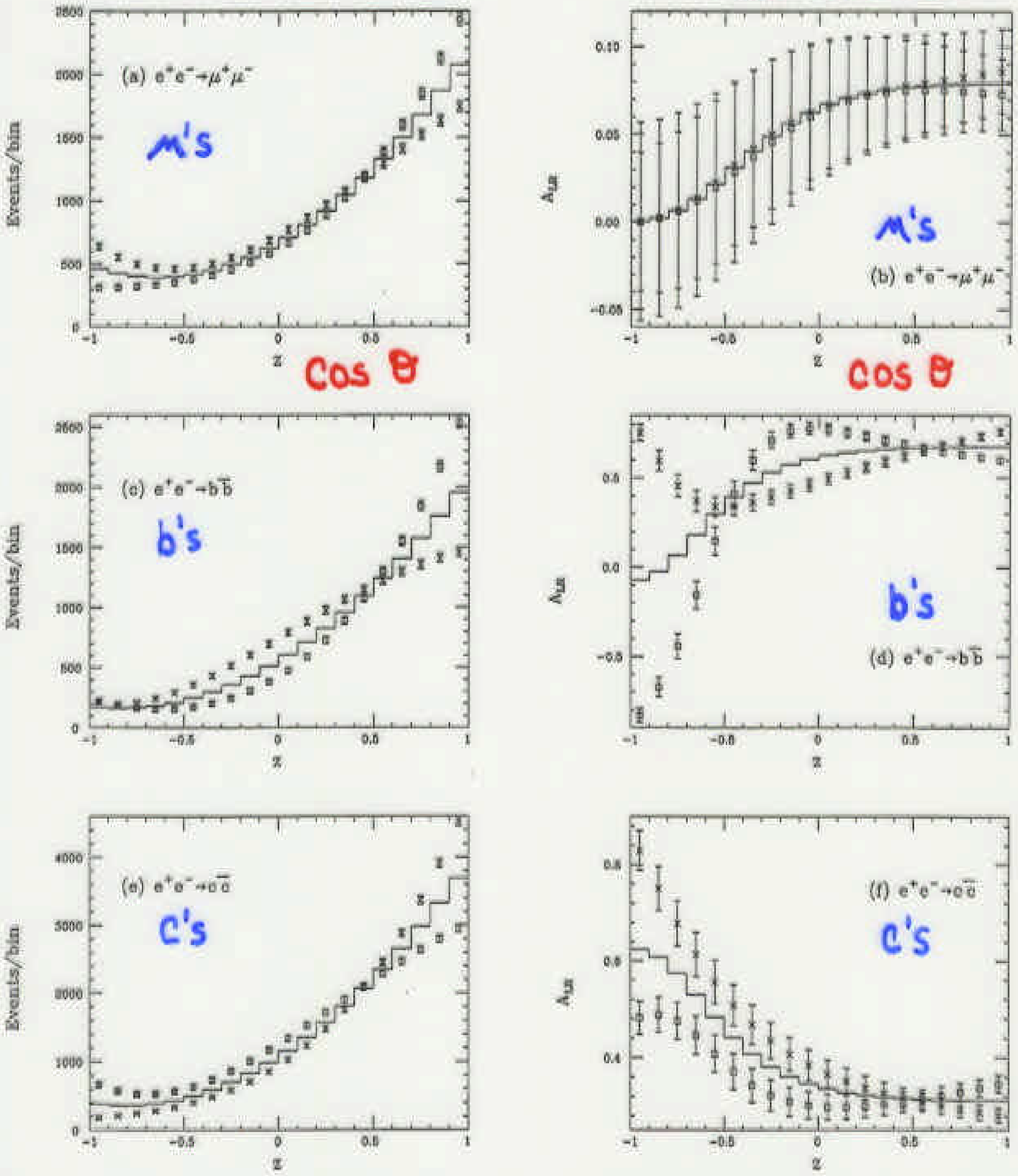
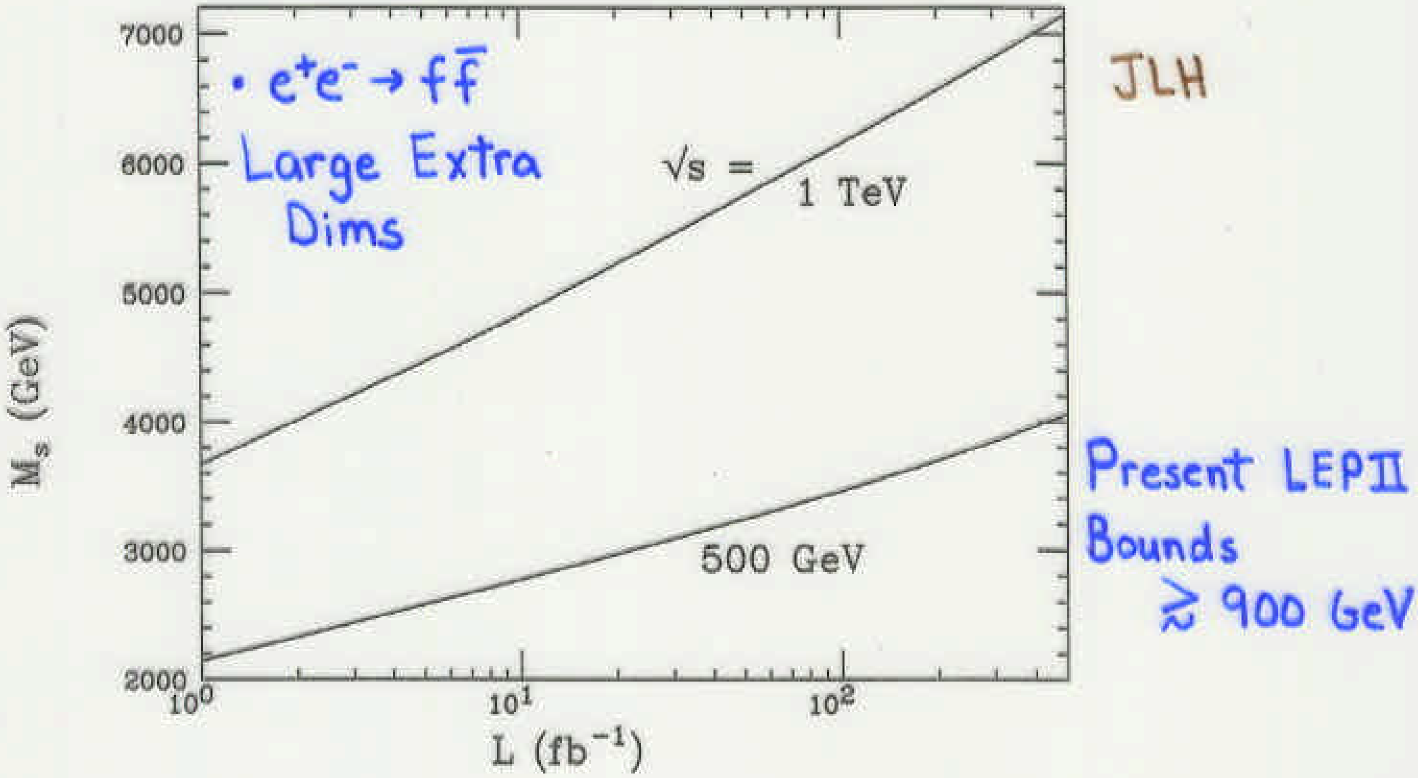
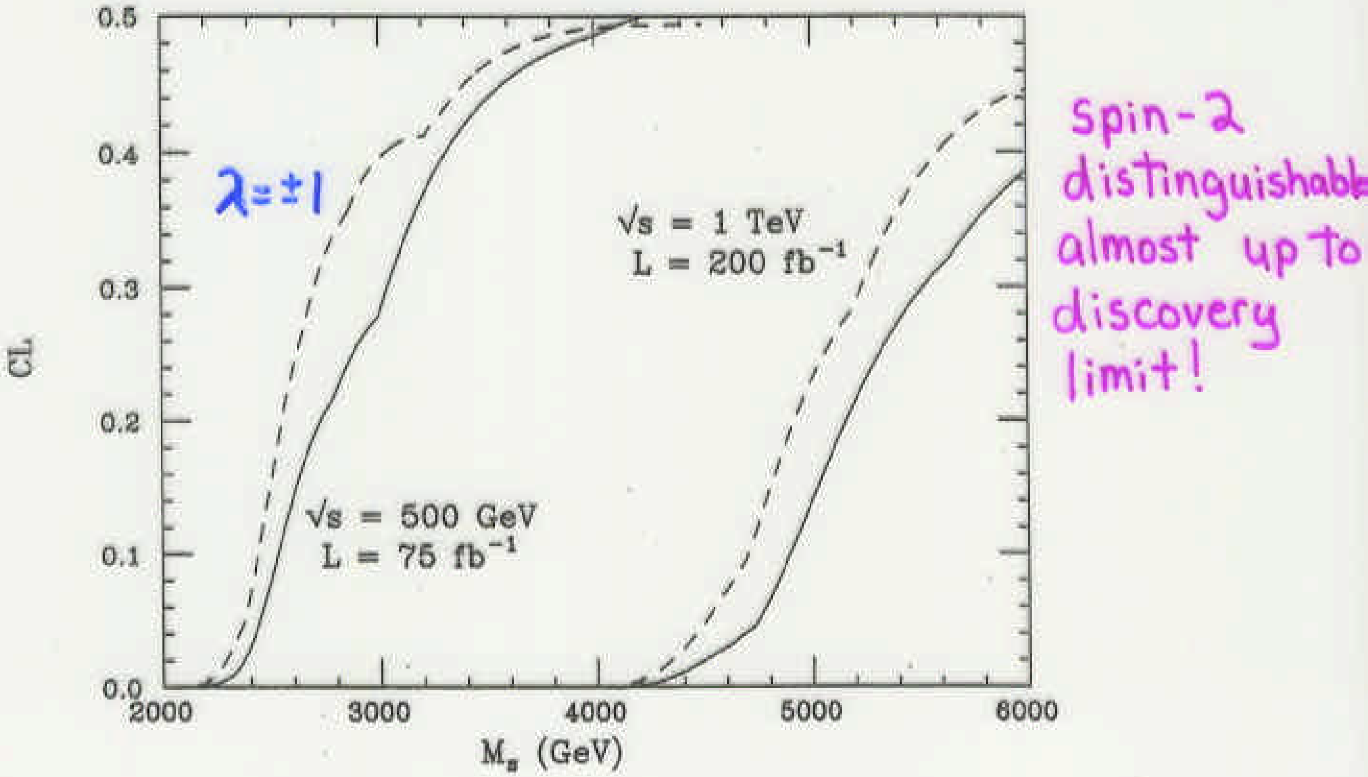


Figure 1: Bin integrated angular distribution and z-dependent Left-Right asymmetry for $e^+e^- \to \mu^+\mu^-$, $b\bar{b}$, $c\bar{c}$. In each case, the solid histogram represents the SM, while the 'data' points are for $M_s = 1.5$ TeV with $\lambda = \pm 1$. The error bars correspond to the statistics in each bin.

95% CL Search Reach for Graviton Exchange



Confidence Level of fit of spin-2 data to spin-1 hypothesis



Drell-Yan Production: $q\bar{q} \to \gamma, Z, G^{(n)} \to \ell^+\ell^-$

$gg \to G^{(n)} \to \ell^+\ell^-$

JLH

Tevatron

$m_s = 800$ GeV

LHC

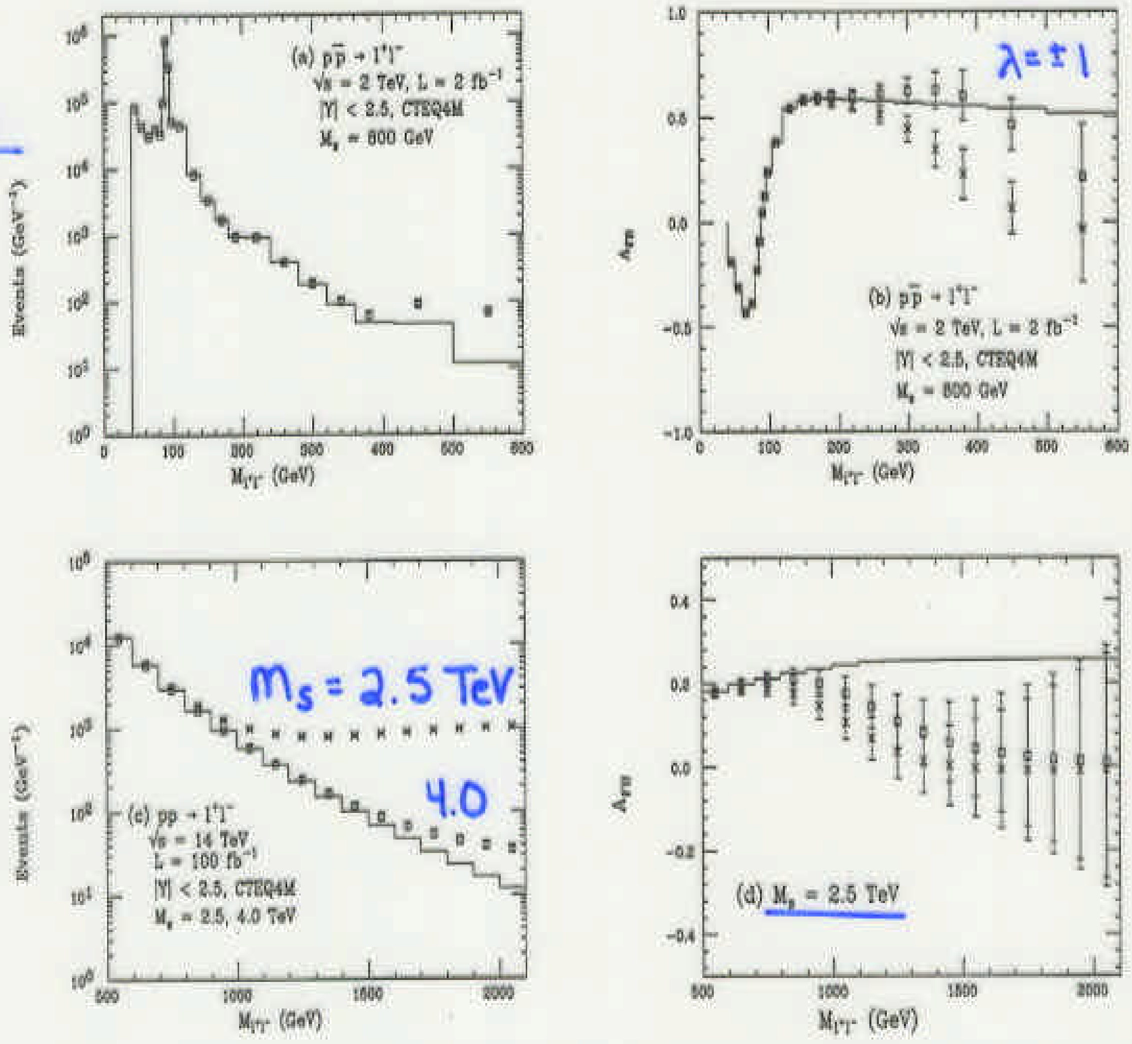


Figure 3: Bin integrated lepton pair invariant mass distribution and forward-backward asymmetry for Drell-Yan production at the Main Injector and the LHC. The SM is represented by the solid histogram. The data points represent graviton exchanges with (a) $M_s = 800$ GeV and $\lambda = +1$ or -1, (b) $M_s = 800$ GeV and $\lambda = +1$ and -1, (c) $M_s = 2.5$ and 4.0 TeV and $\lambda = +1$ or -1, (d) $M_s = 2.5$ TeV and $\lambda = +1$ and -1.

Search Reach

Tevatron: $m_s \sim 1$-1.5 TeV

LHC: $m_s \sim 4$-5.2 TeV

5-D Standard Model

(Antoniadis etal)

Do all n dimensions have to be the same size?

Let $R^n = R_1^p R_2^{n-p}$ with $R_1 \sim$ large
$R_2 \sim$ small $\sim 1/\text{TeV} \sim 1/m_*$

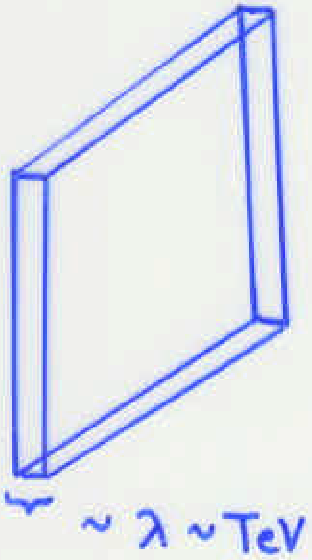
$$\Rightarrow m_{Pl}^2 = R_1^p m_*^{p-n} m_*^{n+2}$$
$$= R_1^p m_*^{p+2} \qquad \text{with } 2 \leq p \leq 6$$

SM fields can propagate in small R_2^{n-p} dimensions!

5-DSM: 1 extra small dimension

Degenerate $\gamma/W/Z/g$ KK towers
with $g^{(n)} = \sqrt{2}\, g^{(0)}$

Precision EW data: $m_c \gtrsim 3\text{-}4$ TeV
(Rizzo, Wells)



Fat-branes

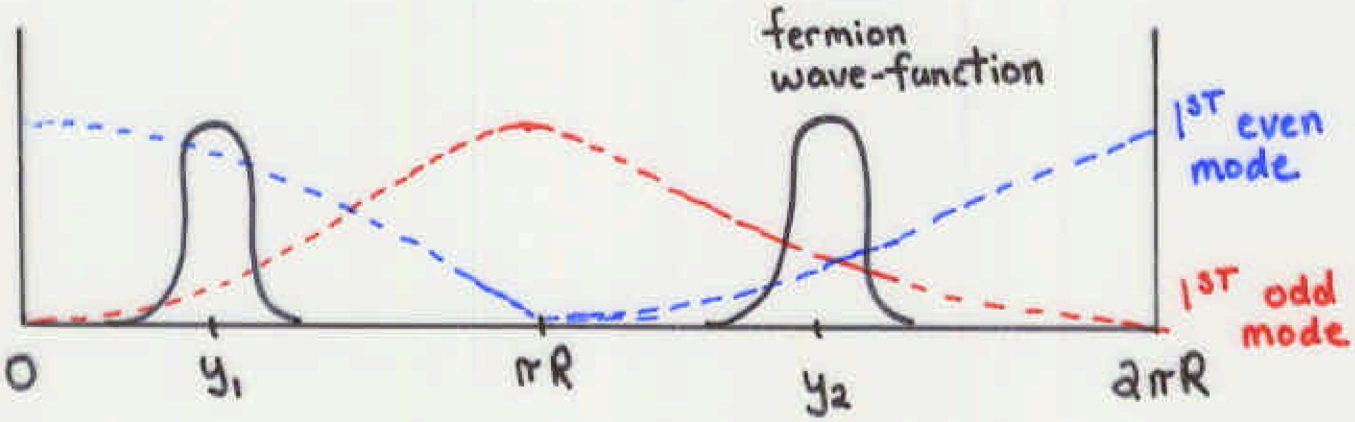
Modifies $\not{E}_T$ signatures
by form factor $\Rightarrow$ reduced signal
(De Rújula etal)

Search Reach:

Experiment		m_c Reach (TeV)
LEP II		3.1
Tevatron	2 fb^{-1}	1.1
	20 fb^{-1}	1.3
LHC	100 fb^{-1}	6.3
NLC	$\sqrt{s}$ = 0.5 TeV	13
	1.0 TeV	23
	1.5 TeV	31

Separated Fermions

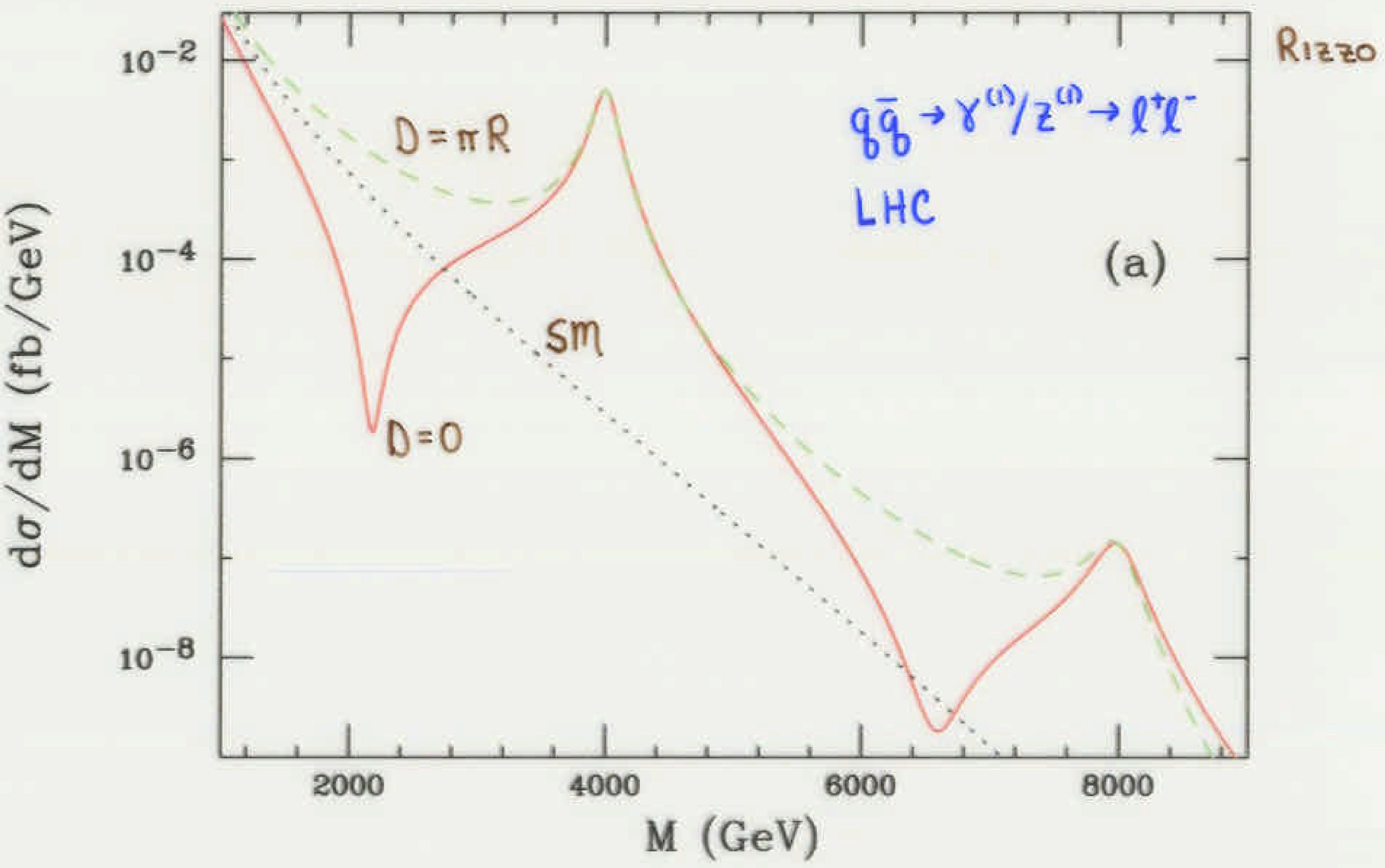
(Arkani-Hamed, Schmaltz)



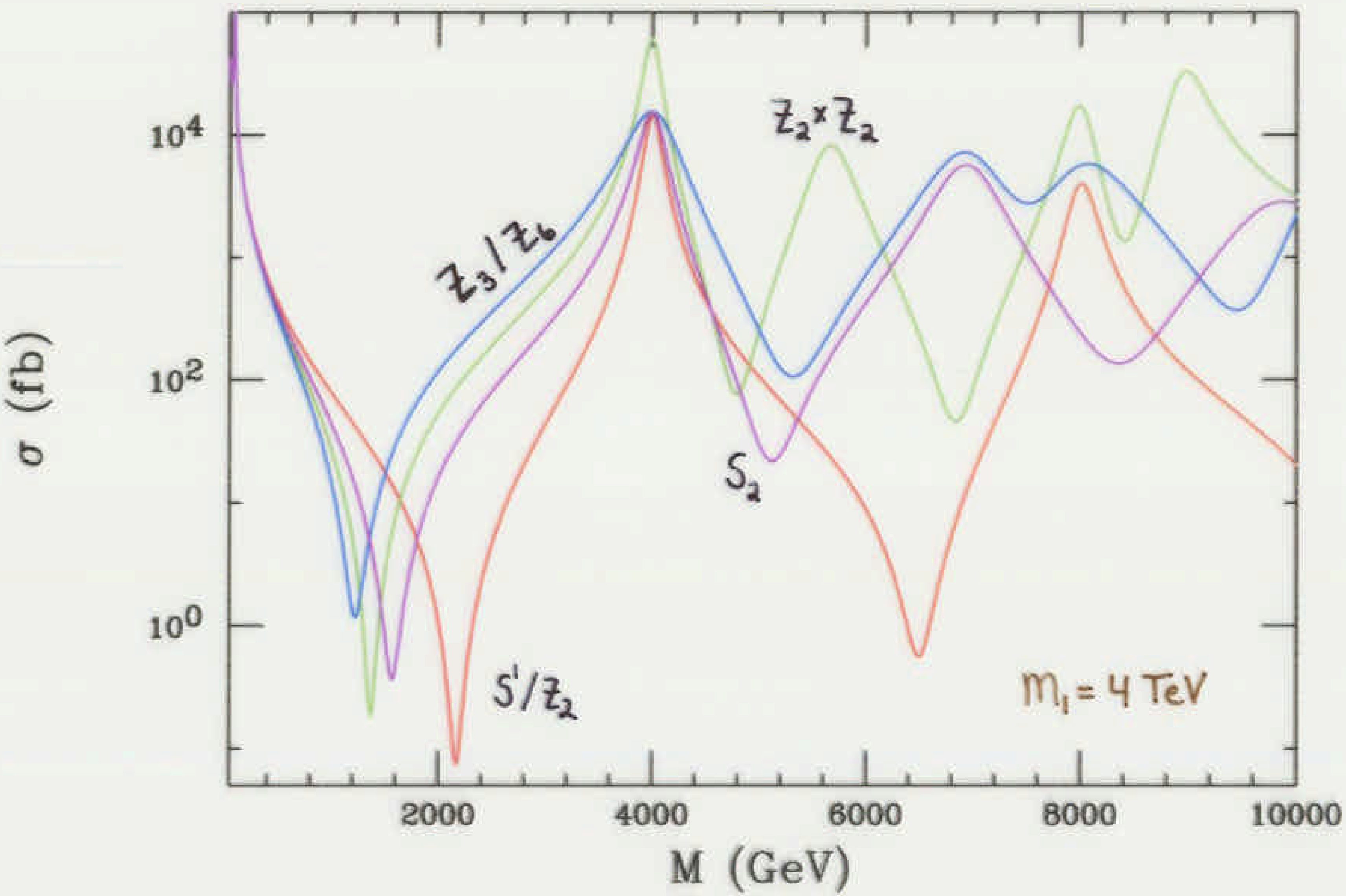
KK gauge coupling to fermions:

$$= \sqrt{2}\, g^{(0)} \int dy \;\bar{\psi}_1(y)\, \psi_2(y)\, G(y)$$

D = separation of fermions in 5th dimension

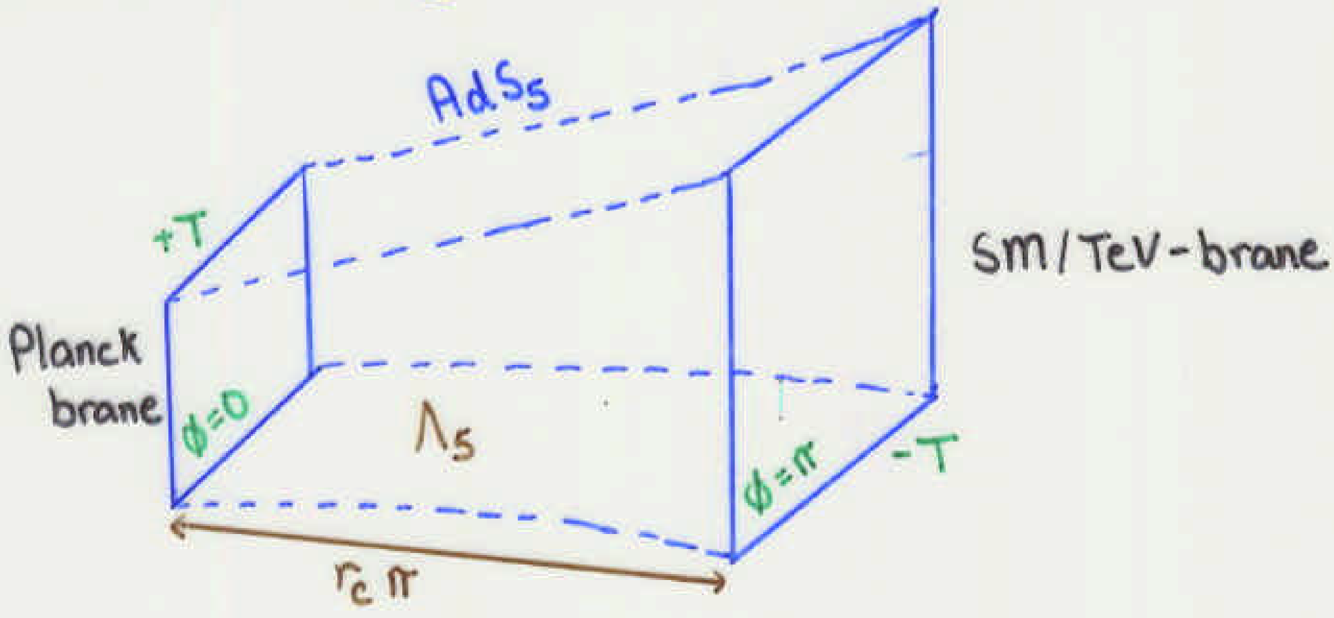


KK Excitation Pattern $\mu^+\mu^- \to e^+e^-$



Can determine model of compactification and # of dimensions!

Localized Gravity ala Randall-Sundrum



Bulk = Slice of AdS_5

Two 3-branes at S_1/Z_2 orbifold fixed points

5-D, non-factorizable geometry

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

$$ds^2 = \underbrace{e^{-2kr_c|\phi|}}_{\text{Warp factor}} \eta_{\mu\nu}\, dx^\mu dx^\nu + r_c^2\, d\phi^2$$

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

r_c = compactification radius

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

4-D Effective Action:

$$\overline{m}_{Pl}^2 = \frac{m_5^3}{k}\left(1 - e^{-2kr_c\pi}\right) \quad \Rightarrow k \sim m_5 \sim \overline{m}_{Pl}$$

no additional hierarchies!

Physical scales:

$$\Lambda_\phi = e^{-kr_c|\phi|}\,\overline{m}_{Pl}$$

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

$$\Lambda_\pi = e^{-kr_c\pi}\,\overline{m}_{Pl} \sim \text{TeV} \quad \text{if} \quad kr_c \sim 11\text{-}12$$

stabilized via Goldberger + Wise

⇒ hierarchy generated by an exponential !

Phenomenology governed by

$k/\overline{m}_{Pl}$ and Λ_π ⇒ only 2 free parameters

5-D curvature:

$$|R_5| = 20\,k^2 < m_5^2$$

(neglecting higher-order curvature terms)

suggests $k/\overline{m}_{Pl} < 0.1$

4-D Effective Theory:

Linear expansion of flat metric

$$G_{\alpha\beta} = e^{-2kr_c|\phi|}\left(\eta_{\alpha\beta} + \kappa h_{\alpha\beta}\right) \qquad \kappa = 2 m_5^{-3/2}$$

Expand into KK tower

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

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

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

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

For TeV-brane:

$$m_n = x_n k e^{-kr_c\pi} \qquad \text{with} \qquad J_1(x_n) = 0$$

$$= x_n \frac{k}{\overline{M}_{Pl}}\Lambda_\pi$$

⇒ KK excitations are not evenly spaced!

Interactions

$$\mathcal{L} \sim \frac{-1}{M_5^{3/2}} T^{\alpha\beta}(x)\, h_{\alpha\beta}(x, \phi=\pi)$$

$$= \frac{-1}{\overline{M}_{Pl}} T^{\alpha\beta}(x)\, h^{(0)}_{\alpha\beta}(x) - \frac{1}{\Lambda_\pi} T^{\alpha\beta}(x) \sum_{n=1}^{\infty} h^{(n)}_{\alpha\beta}(x)$$

zero-mode decouples

TeV - suppressed
⇒ can be directly produced!

Phenomenology

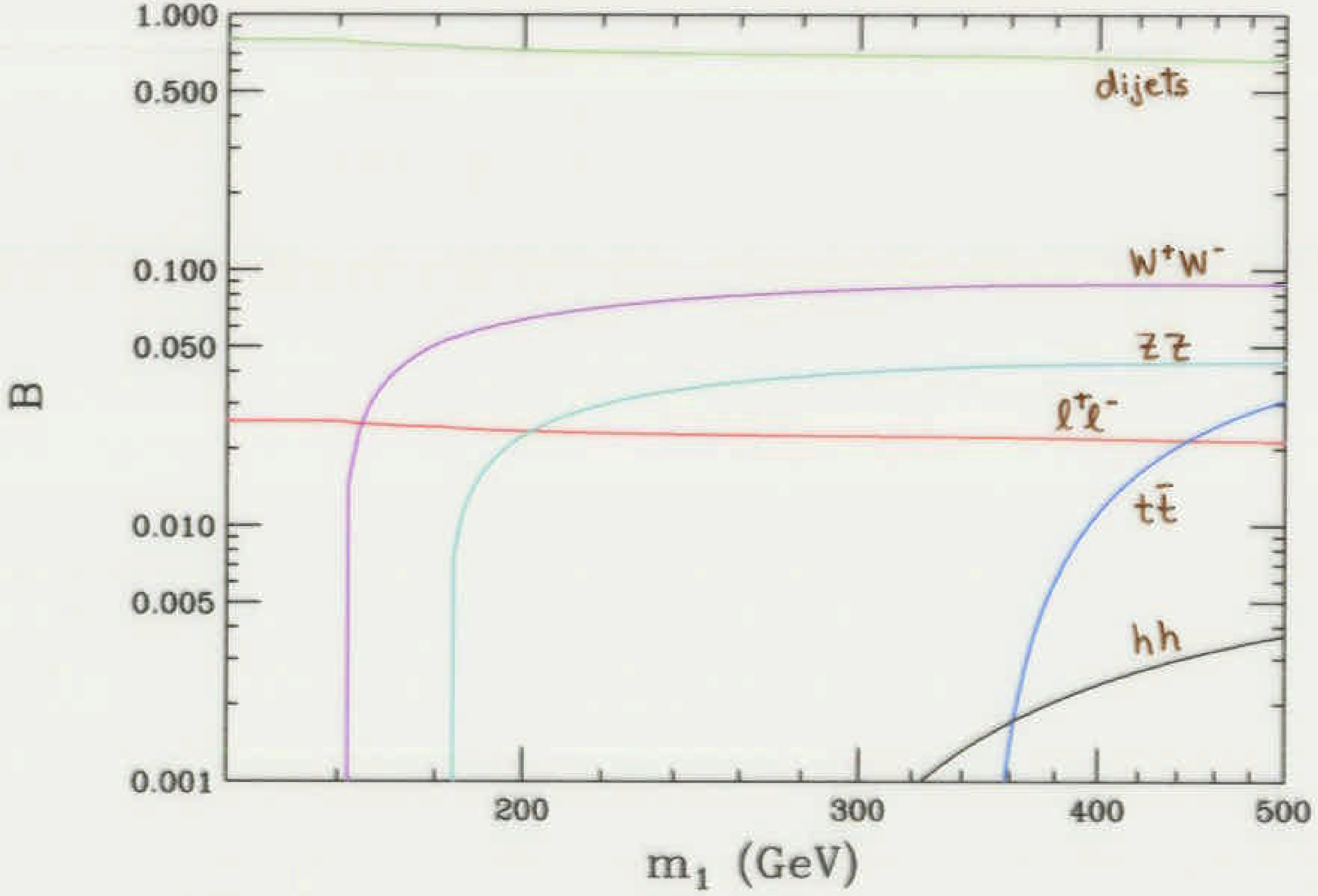
- Graviton resonance production
- Graviton contributions to EW oblique parameters
- 'Light, skinny' Gravitons $\left[k/\overline{M}_{Pl} \lesssim 0.01 \right]$

  Graviton emission

- Below resonance exchange

  "Contact interaction" limits

Graviton Branching Fractions



$B_{\gamma\gamma} = 2\,B_{\ell^+\ell^-}$

KK Graviton Drell-Yan Spectrum

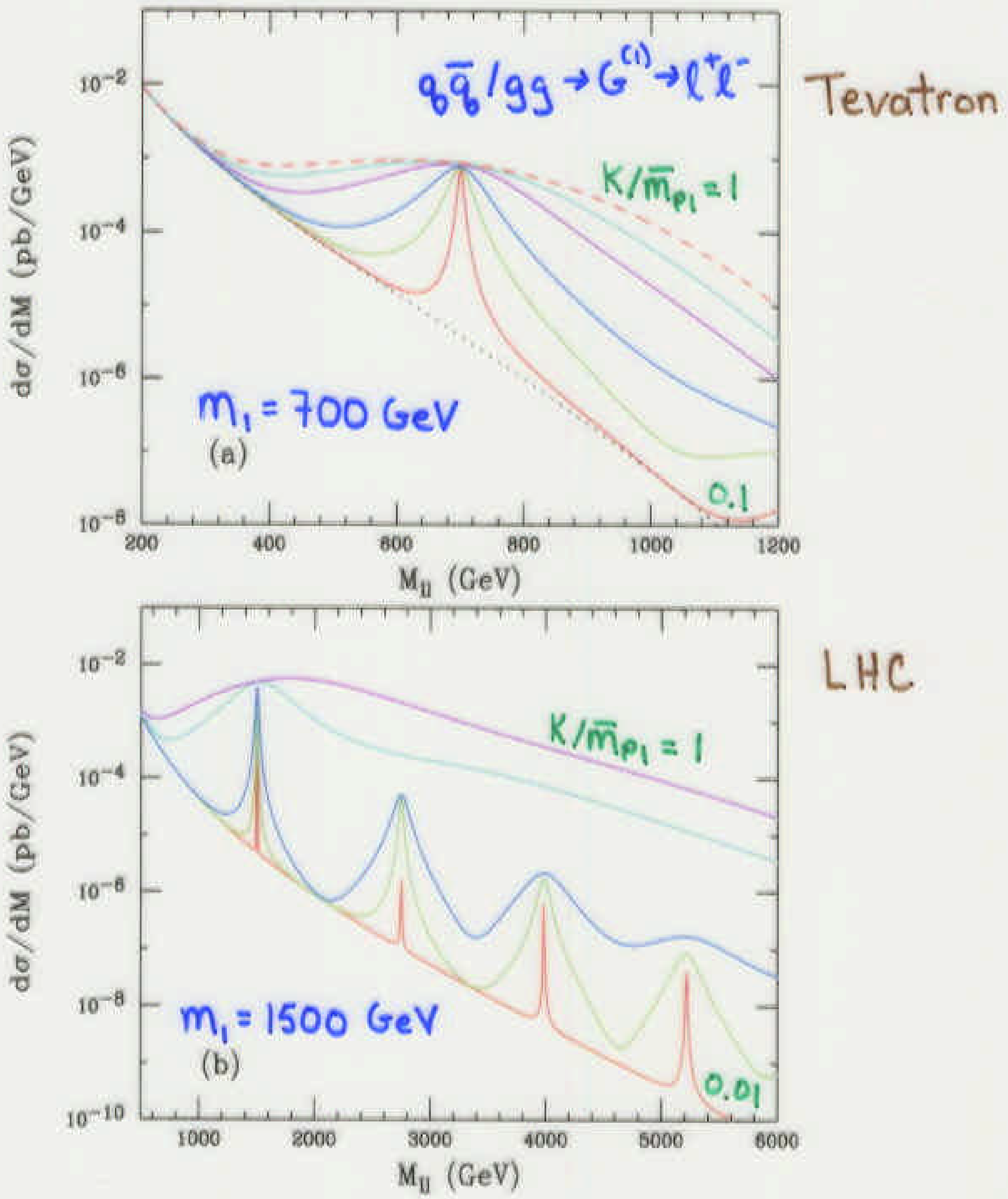
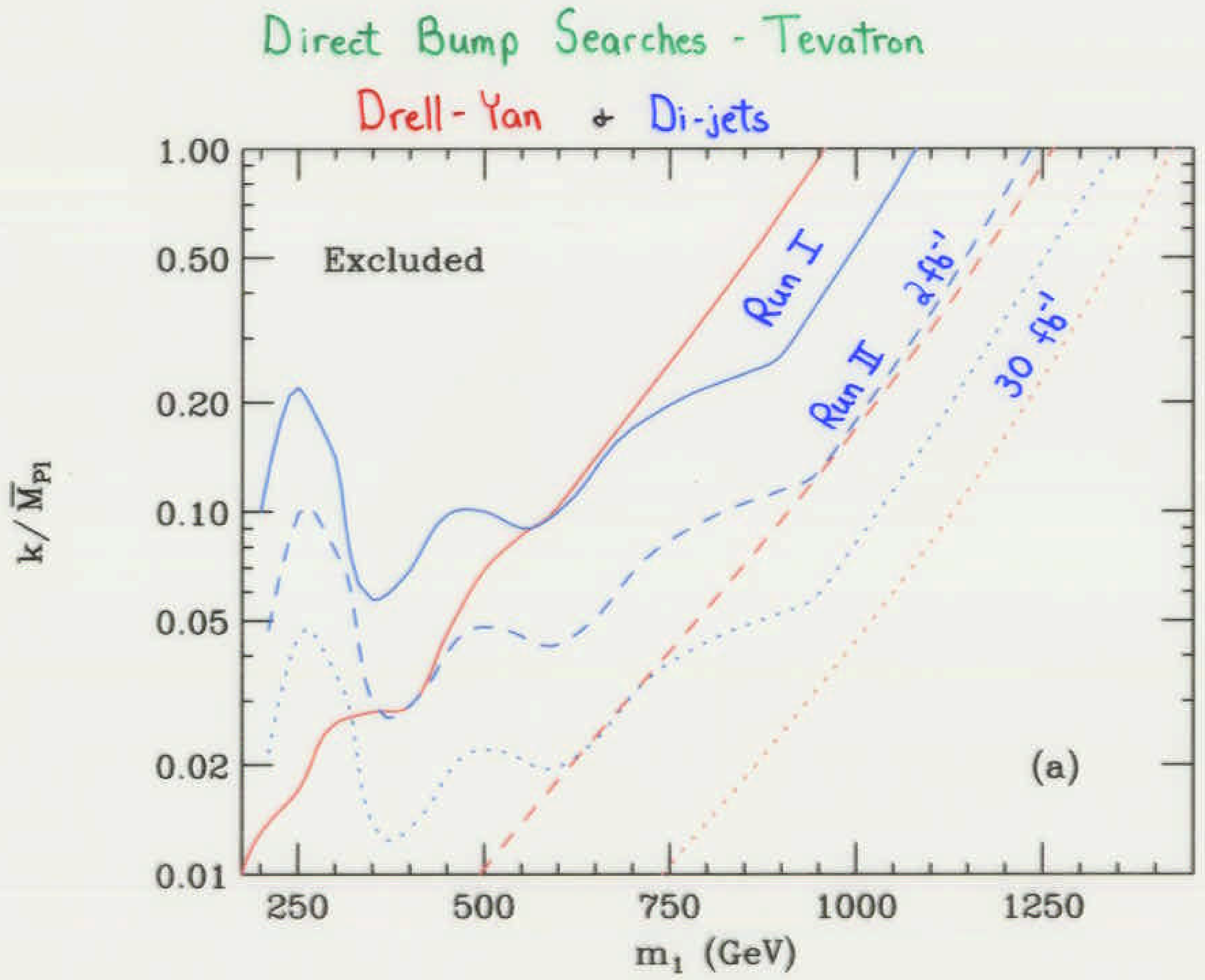
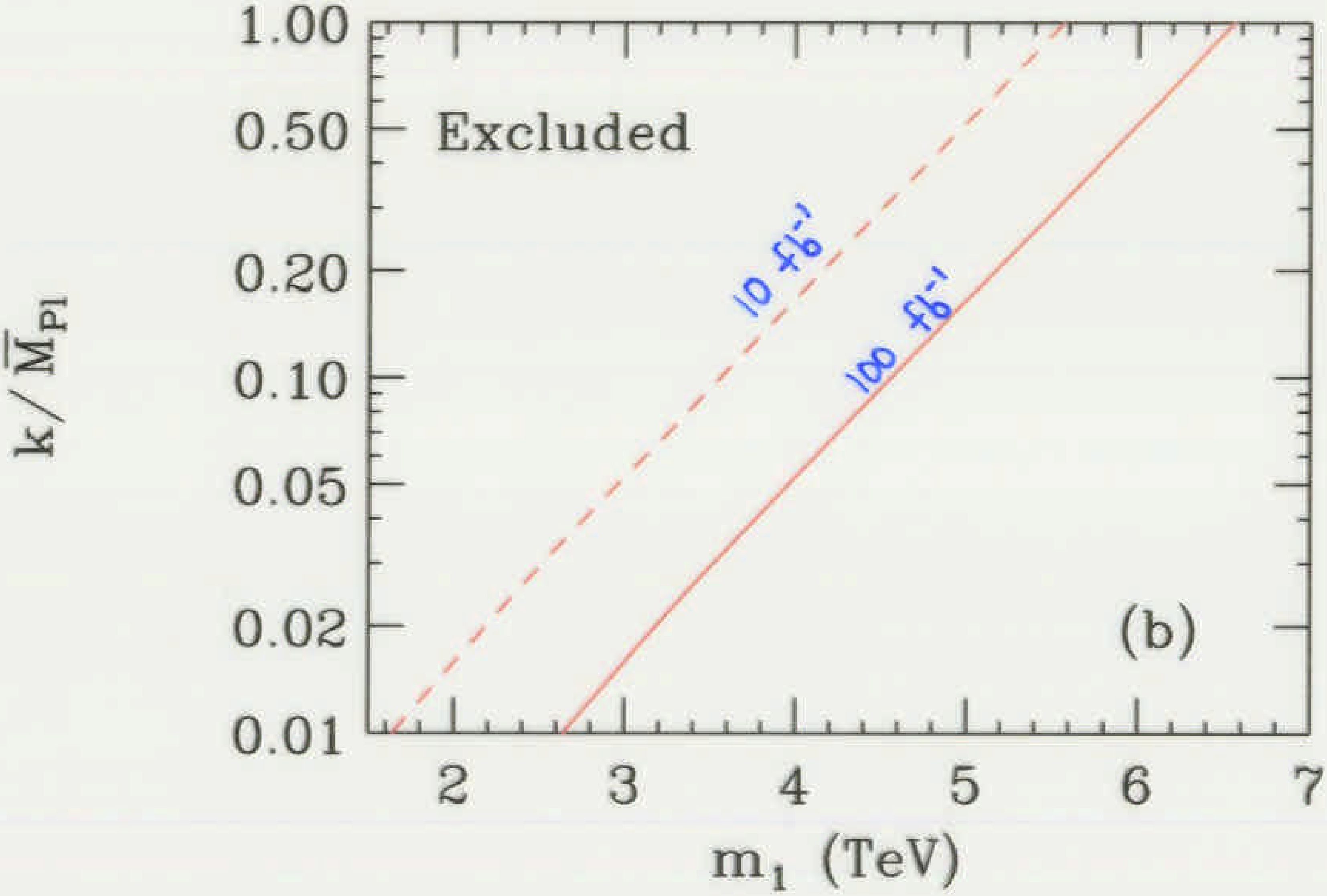


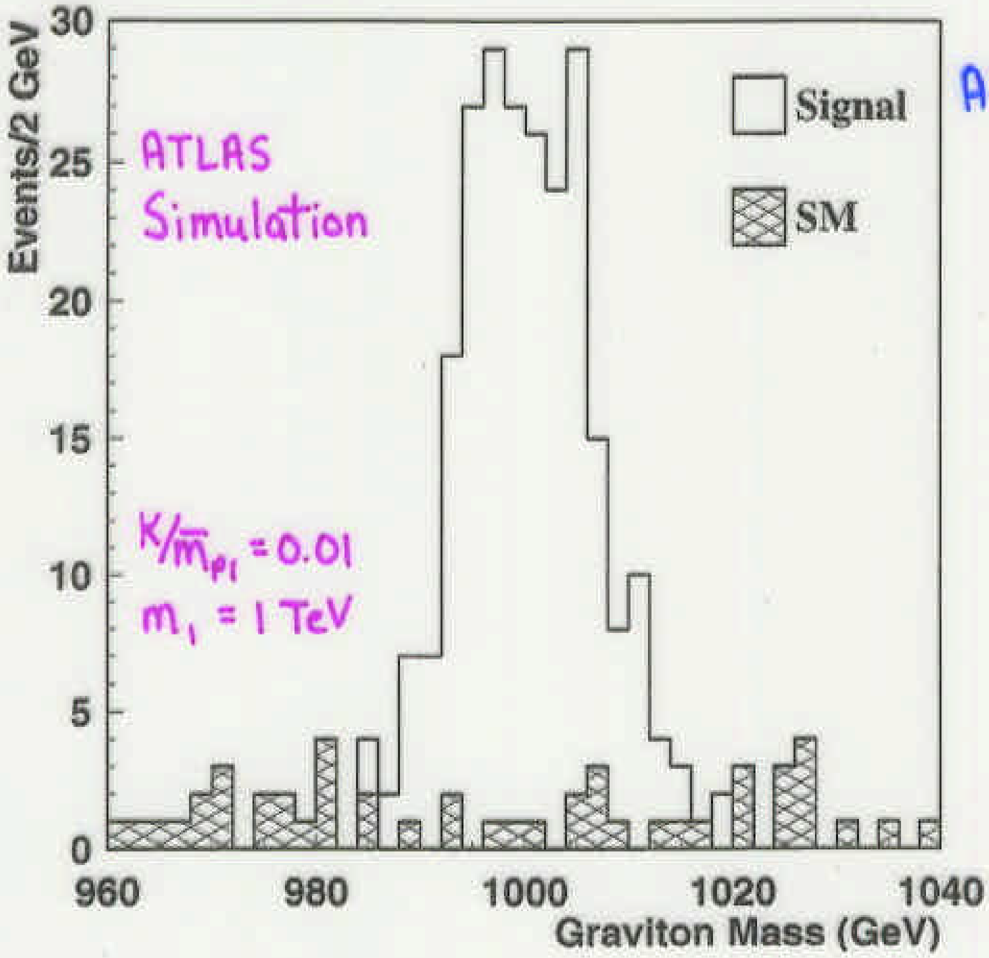
Figure 17: Drell-Yan production of a (a) 700 GeV KK graviton at the Tevatron with $k/\overline{M}_{Pl} =$ 1, 0.7, 0.5, 0.3, 0.2, and 0.1, respectively, from top to bottom; (b) 1500 GeV KK graviton and its subsequent tower states at the LHC. From top to bottom, the curves are for $k/\overline{M}_{Pl} =$ 1, 0.5, 0.1, 0.05, and 0.01, respectively.


Direct Bump Searches - Tevatron
Drell - Yan & Di-jets
1.00
0.50
0.20
0.10
0.05
0.02
0.01
Excluded
Run I
Run II
2 fb⁻¹
30 fb⁻¹
(a)
250
500
750
1000
1250
m₁ (GeV)
k / M̄_Pl

Drell-Yan @ LHC



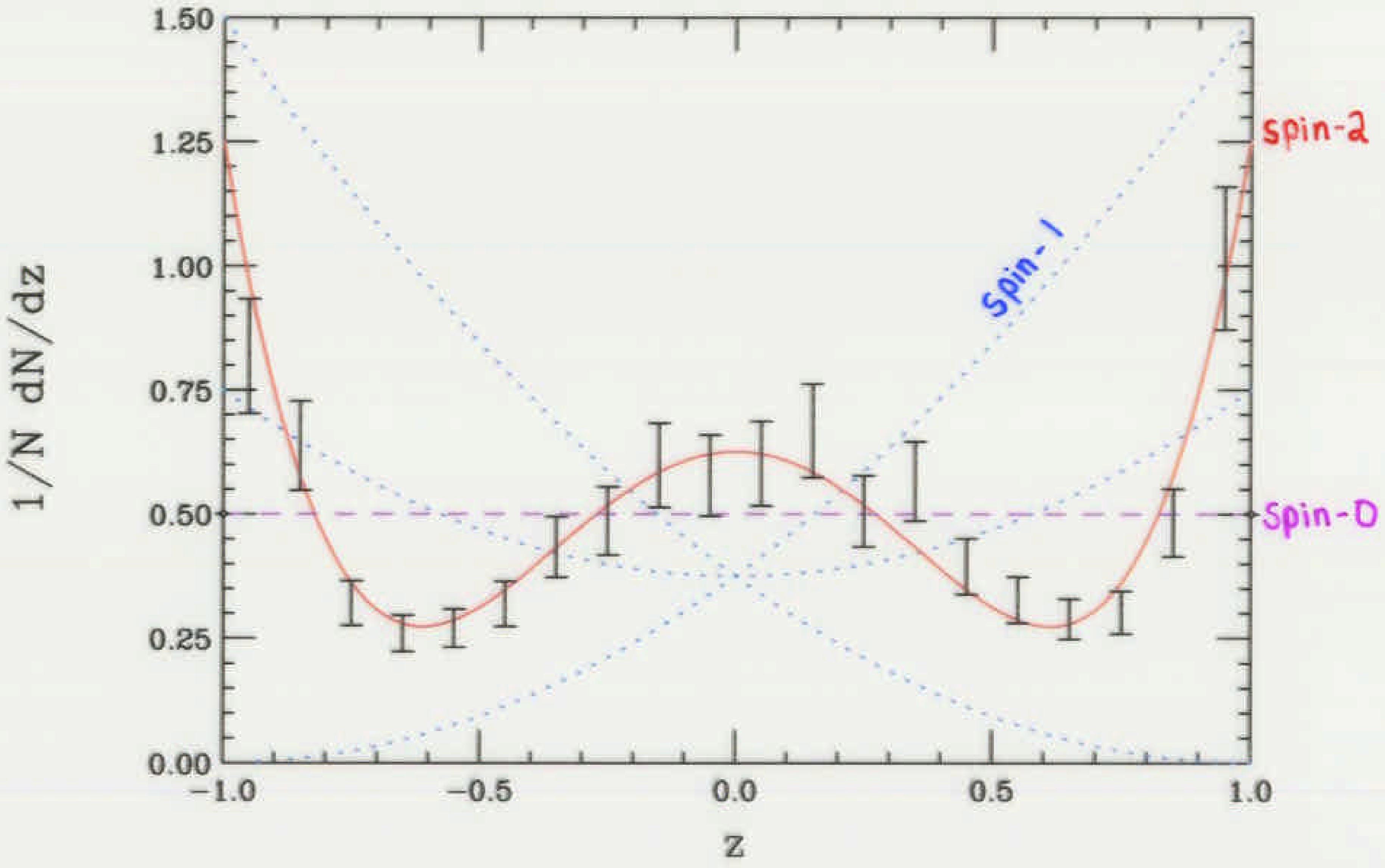
Narrow-width Graviton Resonance



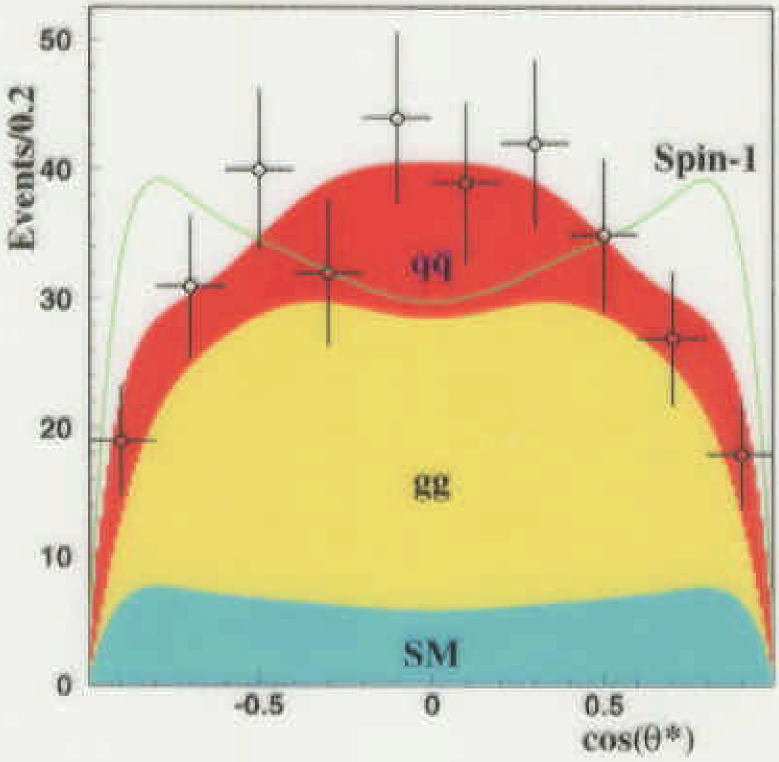
Allanach et al

ATLAS search reach: $m_1 \sim 1830$ GeV for $\kappa/\overline{m}_{Pl} = 0.01$

On-Resonance Spin Determination



Spin-2 Determination from Drell-Yan



Allanach et al
ATLAS Simulation

m_1 = 1 TeV
100 fb^{-1}

Figure 4: The angular distribution of data (points with errors) in the test model for $m_G = 1000$ GeV and 100 fb^{-1} of integrated luminosity. The stacked histograms show the contributions from the Standard Model (SM), gg production (gg) and $q\bar{q}$ production ($q\bar{q}$). The curve shows the distribution expected from a spin-1 resonance.

distributions, defined as

$$\begin{aligned} L = {} & x_q \cdot f_q(\theta^*) \cdot A_q(M,\theta^*)/I_q(M) + x_g \cdot f_g(\theta^*) \cdot A_g(M,\theta^*)/I_g(M) \\ & + x_{DY} \cdot f_{DY}(\theta^*) \cdot A_{DY}(M,\theta^*)/I_{DY}(M) \end{aligned} \tag{4.1}$$

where x_i is the fraction of the events from each contributing process, $f_i(\theta^*)$ is the angular distribution of the process, $A_i(M,\theta^*)$ is the acceptance of the detector as a function of the mass of the electron pair and θ^*, and

$$I_i(M) = \int_{-1}^{1} f_i(\theta^*) \cdot A_i(M,\theta^*)\, d\cos\theta^* \tag{4.2}$$

$i = q, g, DY$ for the processes $q\bar{q} \to G$, $gg \to G$, and $q\bar{q} \to Z/\gamma^*$ respectively. Only the shape of the distribution is used in the statistical tests, and the coefficients x are constrained such that

$$x_q + x_g + x_{DY} = 1 \tag{4.3}$$

In order to evaluate the discovery reach of the experiment, in terms of its ability to reveal the spin-2 nature of the resonance, the following procedure was followed, intended to mimic an ensemble of possible experimental runs:

Graviton Drell-Yan cross section

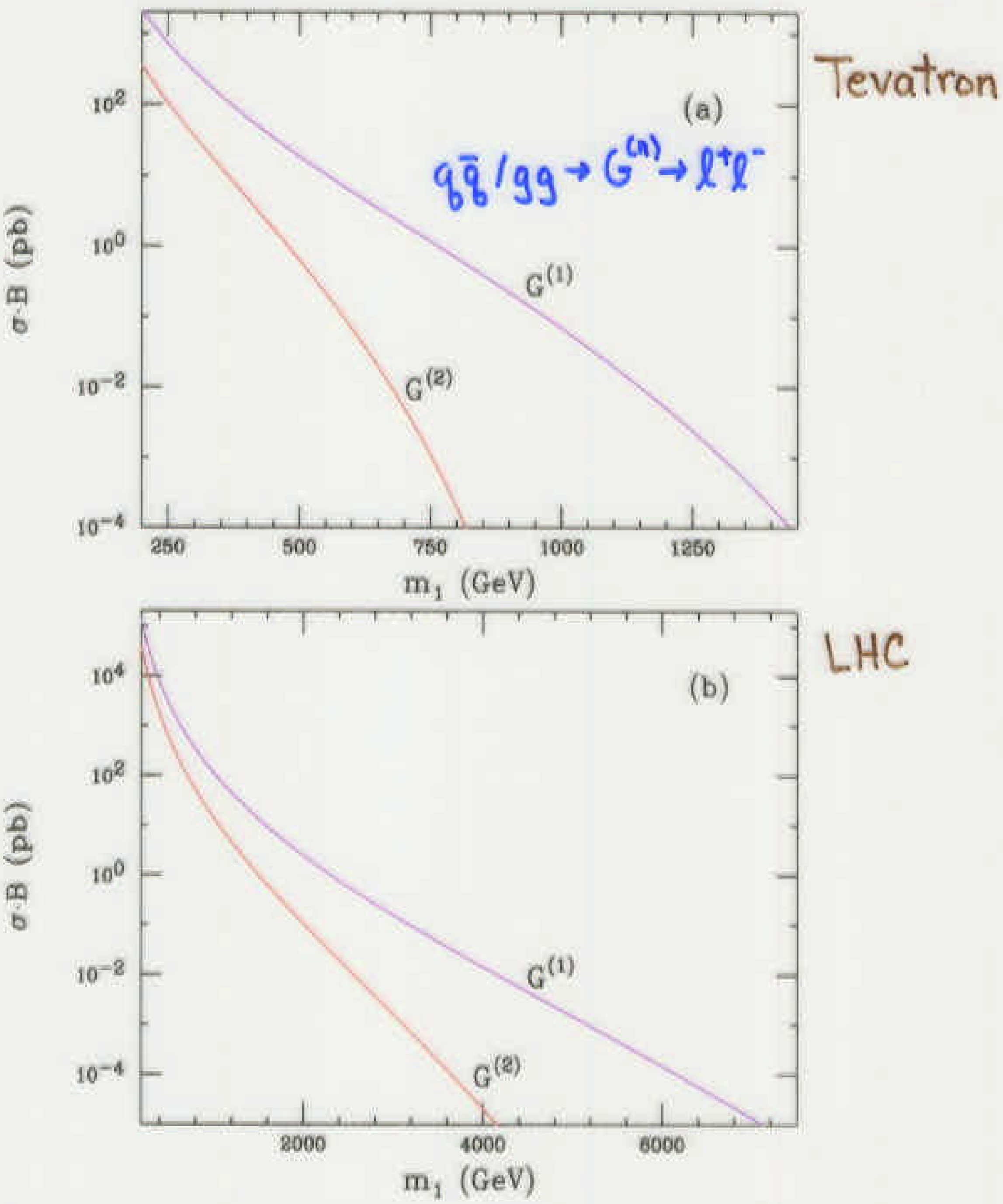
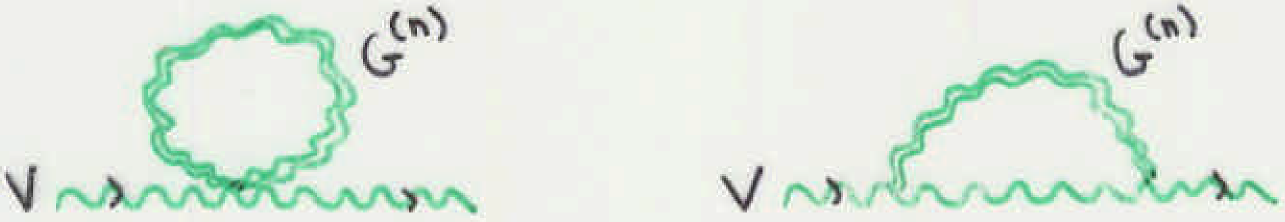


Figure 18: Cross sections for Drell-Yan production at the (a) Tevatron and (b) LHC of the first two graviton KK states coupling to the SM on the wall as a function of m_1. The upper (lower) curve in each case is for the first (second) KK state. Here, we have set $k/\overline{M}_{Pl} = 0.1$.

Constraints from Precision Measurements

Corrections to Gauge Boson self-energies:



For large extra dimensions: $M_* > 1.2-1.5\,\text{TeV}$

[Han, Marfatia, Zhang]

For RS, KK sum must be performed explicitly.

Gravity becomes strong for $p > \Lambda_\pi$

$\Rightarrow$ introduce cut-off $\Lambda_{cut} = \Lambda_\pi \lambda$

$$\Pi(p^2) = \frac{1}{48\pi^2} \sum_n \left[\frac{\Lambda_c}{m_n}\right]^4 \left[\frac{1}{3} + \frac{4m_n^2}{\Lambda_c^2} + \frac{10m_n^4}{\Lambda_c^4} + \frac{10m_n^6}{\Lambda_c^6} \ln \frac{m_n^2/\Lambda_c^2}{1+\frac{m_n^2}{\Lambda_c^2}}\right]$$

Data constrains oblique parameters: global fit

$S = -0.04 \pm 0.10$

$T = -0.06 \pm 0.11$

KK Graviton contributions to oblique parameters

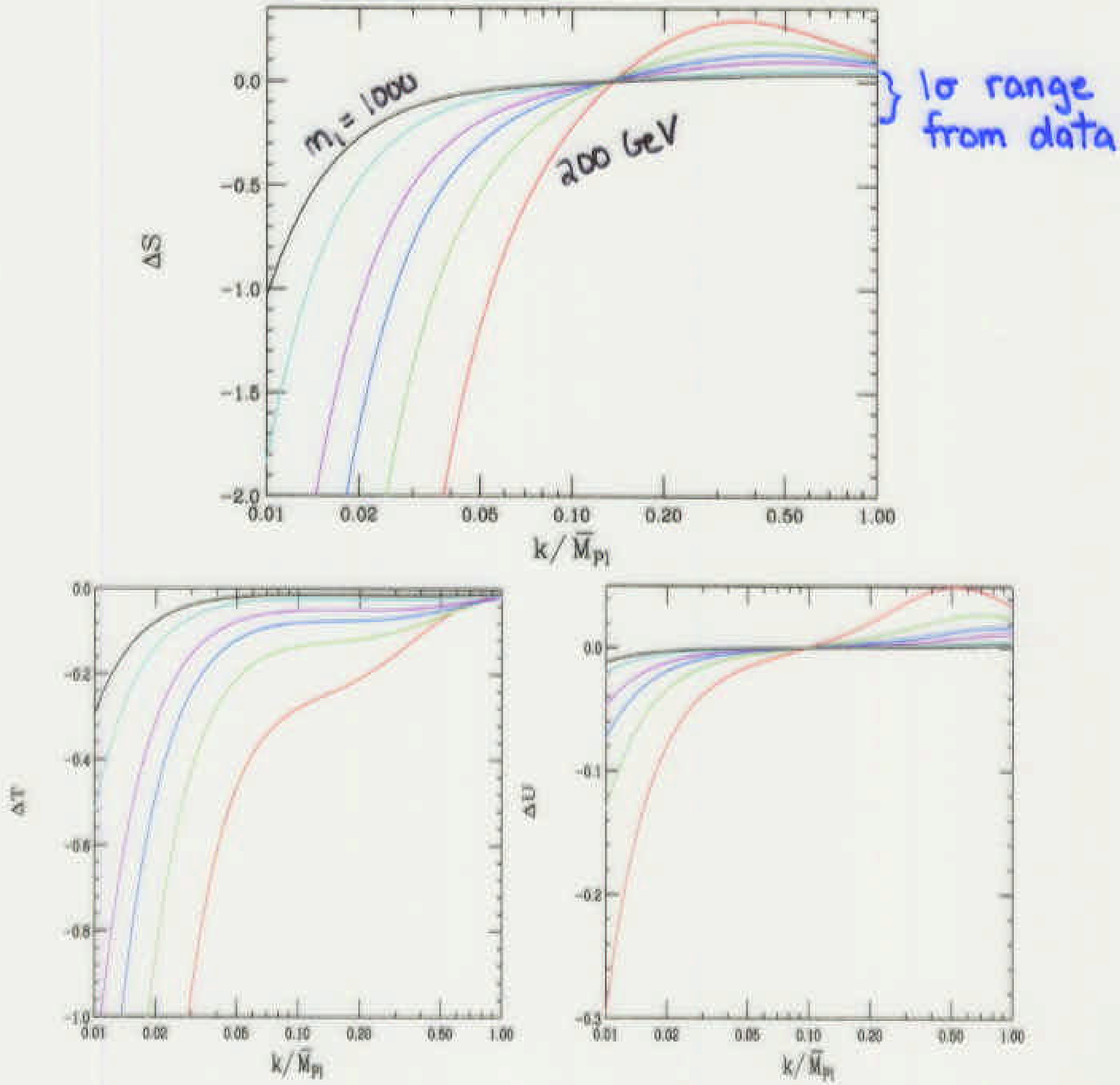
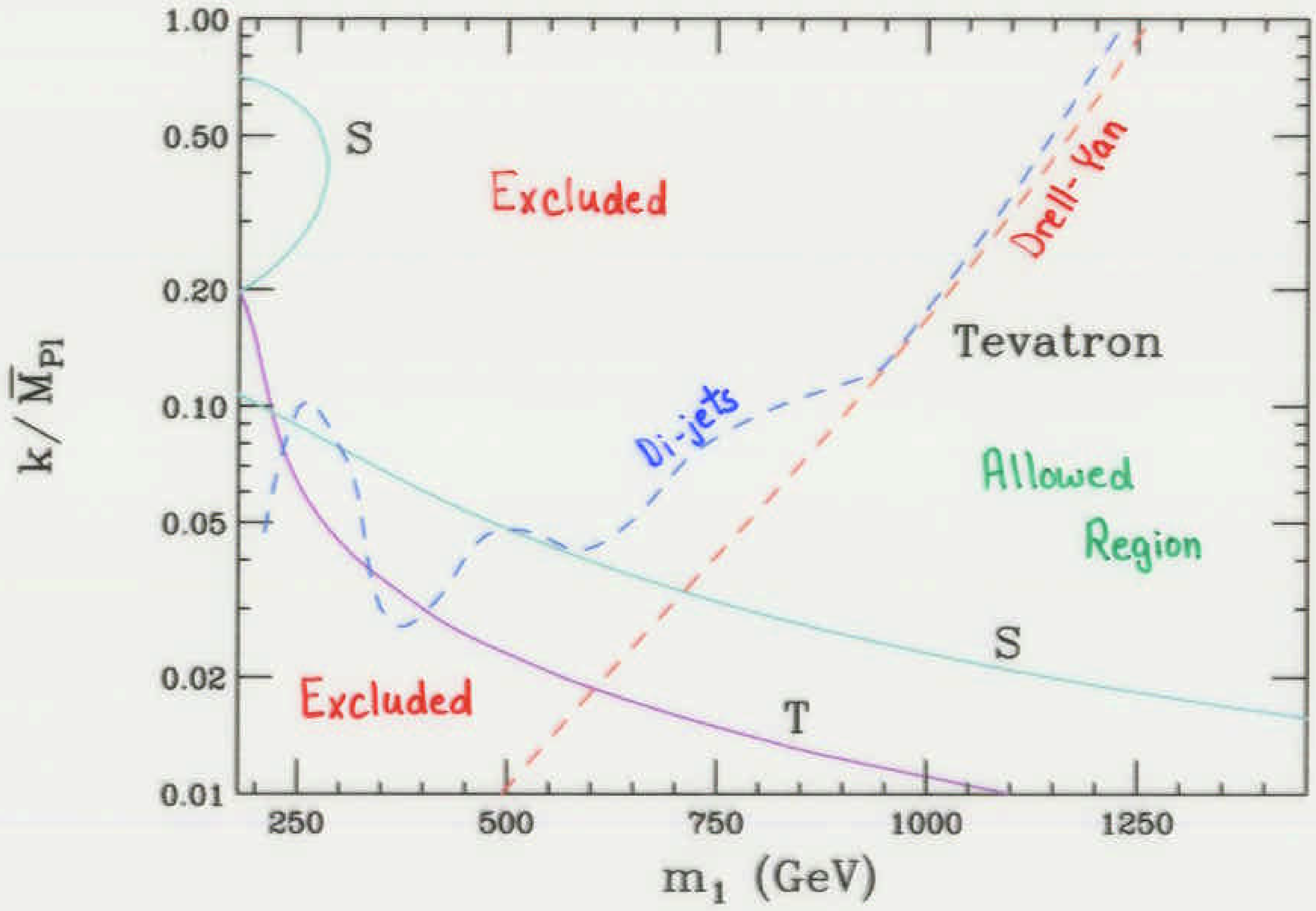
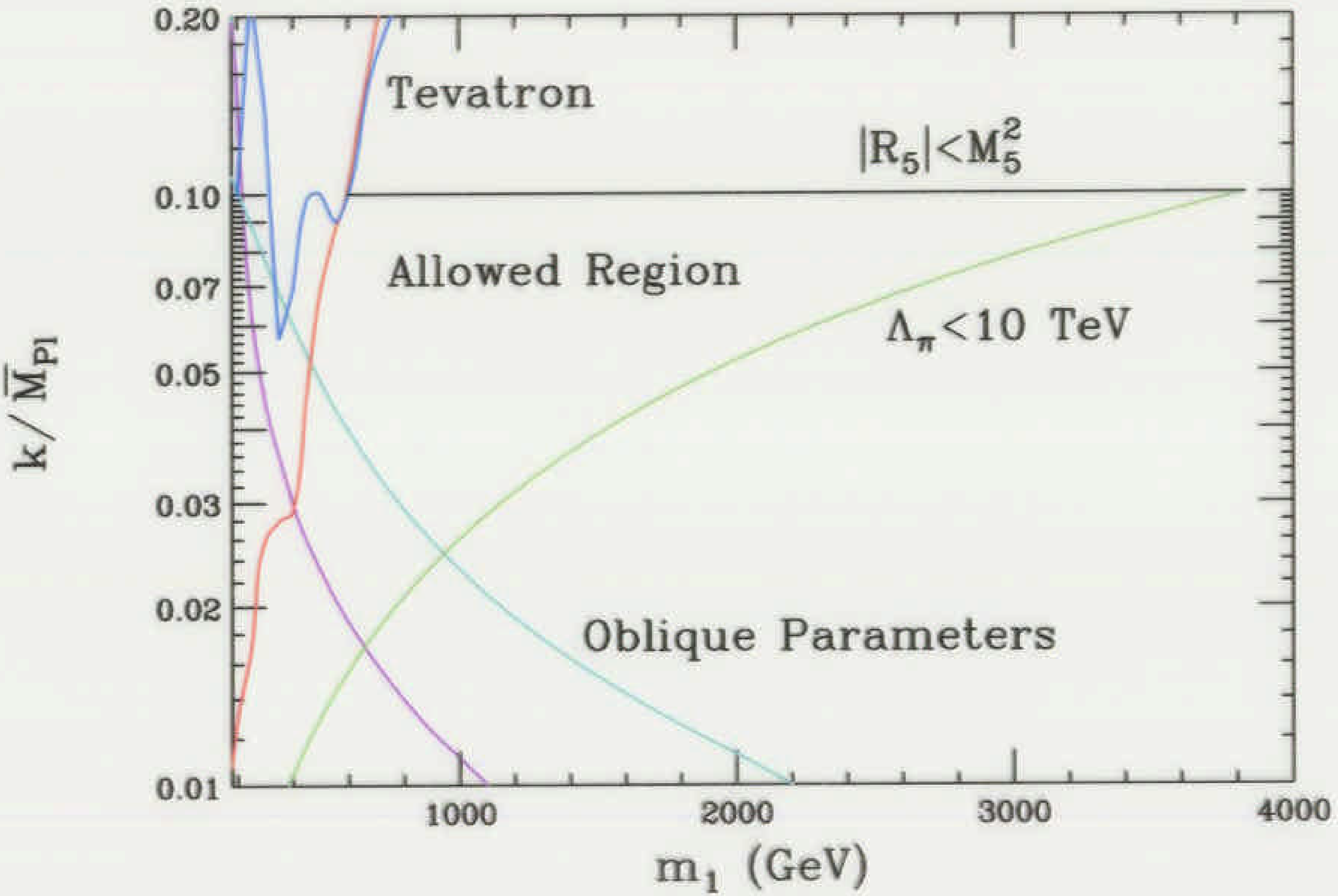


Figure 12: Shifts in the oblique parameters S, T, and U as functions of $k/\overline{M}_{Pl}$ when the SM resides on the TeV-brane. From bottom to top the curves correspond to m_1^{grav} = 200, 300, 400, 500, 750, and 1000 GeV.

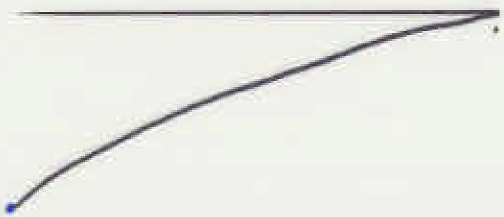
Present Constraints on RS Model



Exp't + Theory Constraints



⇒ No-lose scenario for LHC!



Peeling the SM Off the Wall

1) Gauge bosons in the bulk

(DHR
Pomarol)

$$S_A = -1/4 \int d^5x \sqrt{-G}\, G^{MK} G^{NL} F_{KL} F_{MN}$$

KK expand: $A_\mu(x,\phi) = \sum_n A_\mu^{(n)}(x) \dfrac{\chi_A^{(n)}(\phi)}{\sqrt{r_c}}$

$$\chi_A^{(n)}(\phi) = \frac{e^\sigma}{N_A}\left[J_1\left(\frac{m_n}{k}e^\sigma\right) + \alpha_n Y_1\left(\frac{m_n}{k}e^\sigma\right)\right]$$

$$\mathcal{L}_{f\bar{f}A} \sim g\bar{\psi}\gamma^\mu\psi\left[A_\mu^{(0)}(x) + \sqrt{2\pi k r_c}\sum_{n=1}^{\infty} A_\mu^{(n)}(x)\right]$$

For $\Lambda_\pi = e^{-kr_c\pi}\,\overline{M}_{Pl} \sim \text{TeV}$

$$g^{(n)} = \sqrt{2\pi k r_c}\, g^{(0)} \sim (8-9)\, g^{(0)} \;!$$

⇒ Tough constraints from Precision EW Data!

Data constrains $m_1^A > 23\text{ TeV}$

For $\Lambda_\pi \sim 1\text{ TeV}$ violates curvature constraint
$|R_5| = 20k^2 < M_5^2$

<OR>

For $|R_5| < M_5^2$ $\Lambda_\pi > 100\text{ TeV}$

DHR
[Chang et al
Grossman, Neubert
Gherghetta, Pomarol]

2) Fermions in the bulk

$$S_f = \int d^5x \sqrt{-G}\left[e^{\sigma} \delta_n^m \left(\frac{i}{2} \bar{\Psi} \gamma^n \partial_m \Psi + \text{h.c.} \right) - \text{sgn}(\phi) m \bar{\Psi}\Psi \right]$$

Note: $\Psi(-y) = \pm \gamma_5 \Psi(y) \Rightarrow \bar{\Psi}\Psi$ is odd under Z_2

KK expand: $\Psi_{L,R}(x,\phi) = \sum_n \Psi_{L,R}^{(n)}(x) \frac{e^{2\sigma}}{\sqrt{r_c}} f_{L,R}^{(n)}(\phi)$

integrate over ϕ + impose orthonormality

$$\Rightarrow f_{L,R}^{(n)}(\phi) = \frac{e^{\sigma/2}}{N_n^{L,R}} \left[J_{1/2 \mp \nu}(z_n^{L,R}) + \beta_n^{L,R} Y_{1/2 \mp \nu}(z_n^{L,R}) \right]$$

Choose $f_R^{(n)}$ Z_2-odd

$f_L^{(n)}$ Z_2-even $\Rightarrow f_L^{(0)} = \frac{e^{\nu\sigma}}{N_0^L} \equiv$ SM fermions

Find $\nu \gtrsim -0.9/-0.8$ to reproduce SM Yukawa's

★ Introduces an additional parameter

$$m_{bulk} = \nu k \quad ; \quad \nu \sim \mathcal{O}(1)$$

Find zero-modes couple more weakly than wall fields

⇒ Serious reduction in collider sensitivity to RS phenomena!

Coupling Coefficients

$f^{(0)}\bar{f}^{(0)}A^{(n)}$:

$$C_{00n}^{f\bar{f}A}=\frac{g^{(n)}}{g^{SM}}=\sqrt{2\pi kr_c}\left[\frac{1+2\nu}{1-\epsilon^{2\nu+1}}\right]\int_\epsilon^1 dz\ z^{2\nu+1}\frac{J_1(x_n^A z)+\alpha_n^A Y_1(x_n^A z)}{|J_1(x_n^A)+\alpha_n^A Y_1(x_n^A)|}, \qquad (51)$$

$f^{(0)}\bar{f}^{(0)}G^{(n)}$:

$$C_{00n}^{f\bar{f}G}=\frac{1}{\epsilon}\left[\frac{1+2\nu}{1-\epsilon^{2\nu+1}}\right]\int_\epsilon^1 dz\ z^{2\nu+2}\frac{J_2(x_n^G z)}{|J_2(x_n^G)|}, \qquad (52)$$

$A^{(0)}A^{(0)}G^{(n)}$:

$$C_{00n}^{AAG}=\frac{1}{\epsilon}\ \frac{2(1-J_0(x_n^G))}{\pi kr_c(x_n^G)^2|J_2(x_n^G)|}, \qquad (53)$$

$f^{(\ell)}\bar{f}^{(0)}A^{(n)}$:

$$C_{\ell 0n}^{f\bar{f}A}=\sqrt{2\pi kr_c}\left|\frac{2(1+2\nu)}{1-\epsilon^{2\nu+1}}\right|^{1/2}\int_\epsilon^1 dz\ z^{\nu+3/2}\ \frac{J_f(x_\ell^L z)}{|J_f(x_\ell^L)|}\ \frac{J_1(x_n^A z)+\alpha_n Y_1(x_n^A z)}{|J_1(x_n^A)+\alpha_n Y_1(x_n^A)|}, \qquad (54)$$

$f^{(\ell)}\bar{f}^{(0)}G^{(n)}$:

$$C_{\ell 0n}^{f\bar{f}G}=\frac{1}{\epsilon}\left|\frac{2(1+2\nu)}{1-\epsilon^{2\nu+1}}\right|^{1/2}\int_\epsilon^1 dz\ z^{\nu+5/2}\ \frac{J_f(x_\ell^L z)}{J_f(x_\ell^L)}\ \frac{J_2(x_n^G z)}{|J_2(x_n^G)|}, \qquad (55)$$

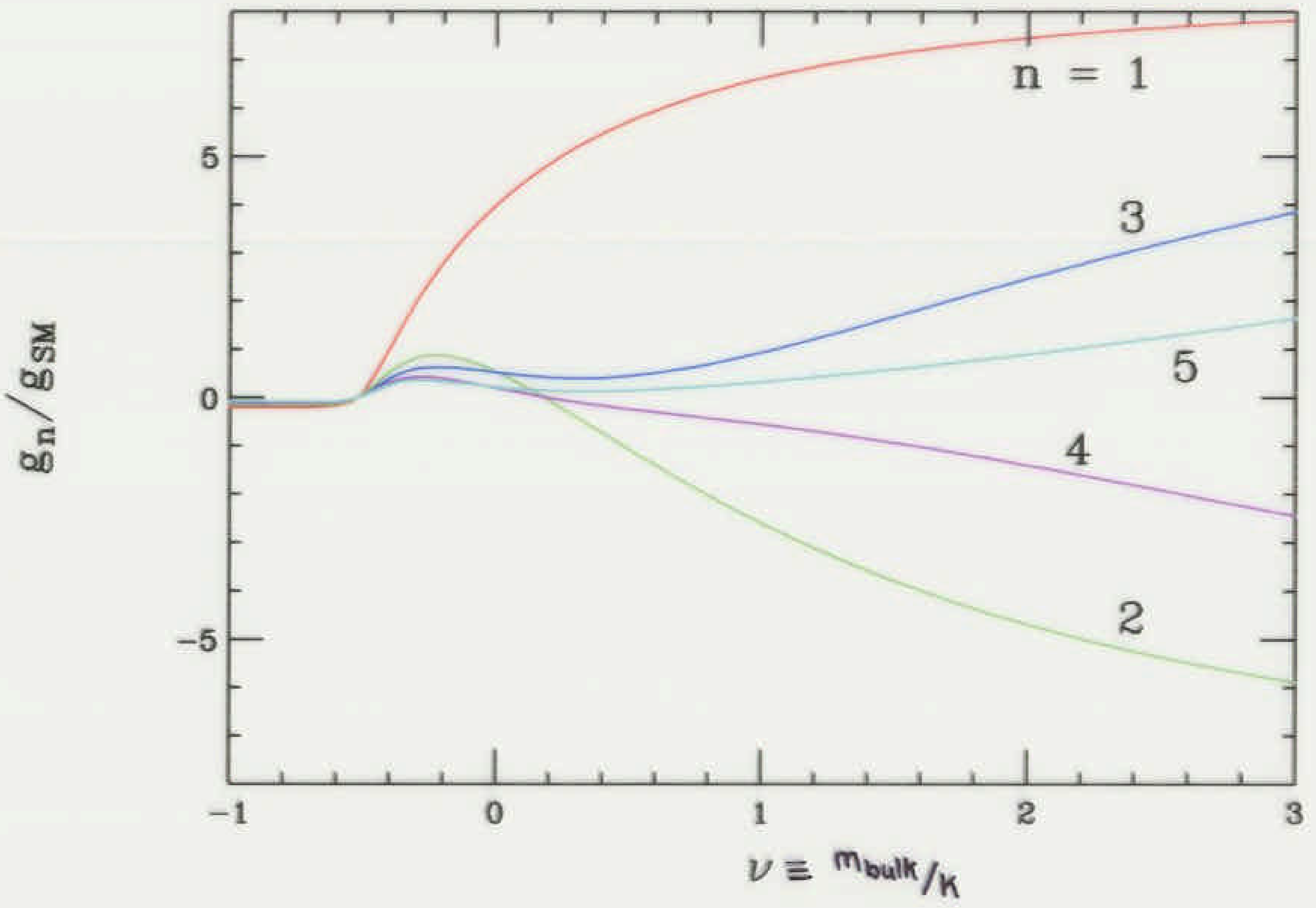
$A^{(\ell)}A^{(0)}G^{(n)}$:

$$C_{\ell 0n}^{AAG}=\frac{2}{\epsilon\sqrt{2\pi kr_c}}\int_\epsilon^1 dz\ z^2\ \frac{J_1(x_\ell^A z)+\alpha_\ell^A Y_1(x_\ell^A z)}{|J_1(x_\ell^A)+\alpha_\ell^A Y_1(x_\ell^A)|}\ \frac{J_2(x_n^G z)}{|J_2(x_n^G)|}, \qquad (56)$$

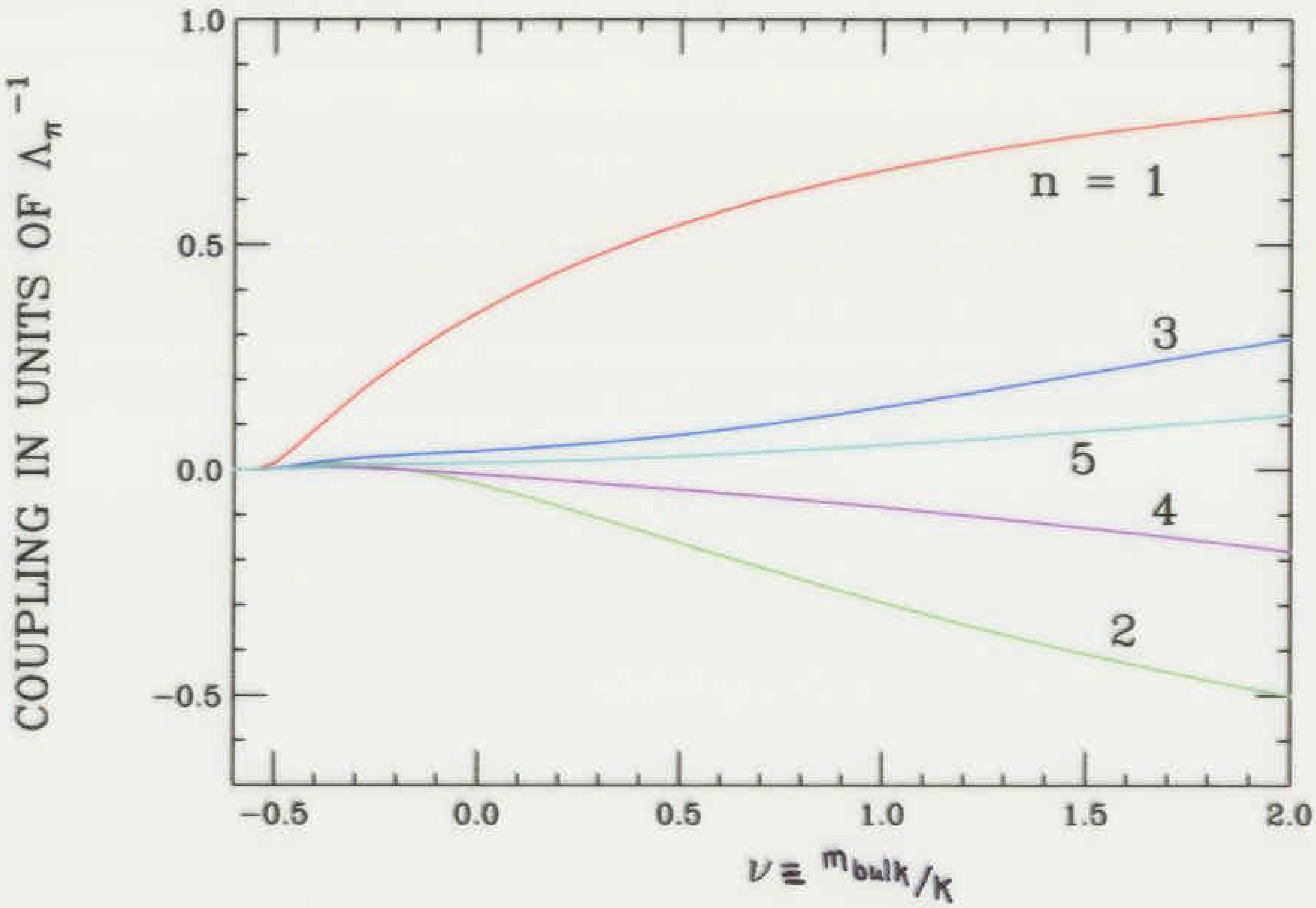
$f^{(\ell)}\bar{f}^{(0)}A^{(0)}G^{(n)}$:

$$C_{\ell 00n}^{f\bar{f}AG}=\frac{1}{\epsilon}\left|\frac{2(1+2\nu)}{1-\epsilon^{2\nu+1}}\right|^{1/2}\int_\epsilon^1 dz\ z^{\nu+5/2}\ \frac{J_f(x_\ell^L z)}{|J_f(x_\ell^L)|}\ \frac{J_2(x_n^G z)}{|J_2(x_n^G)|}, \qquad (57)$$

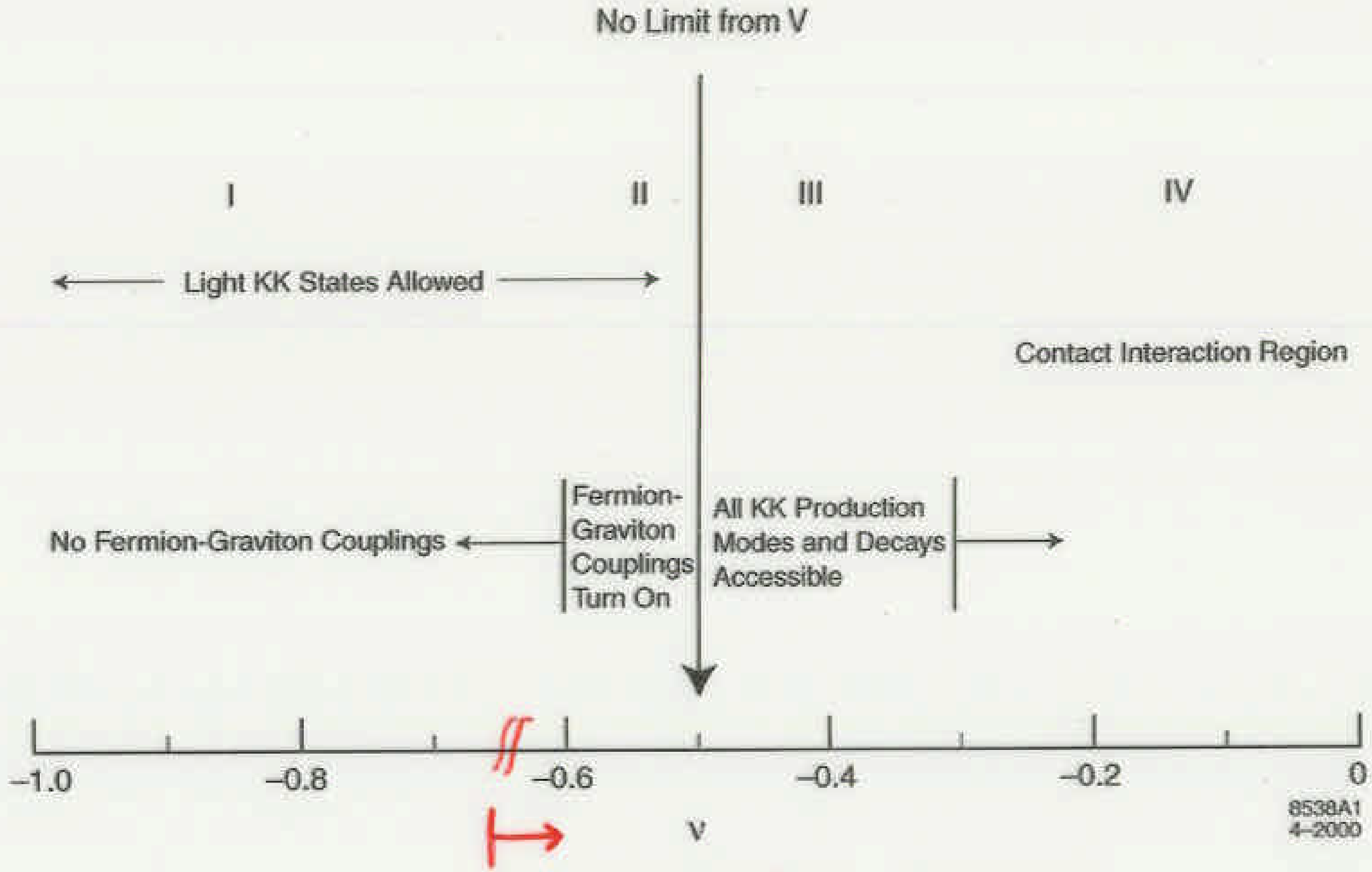
KK Gauge Tower couplings to zero-mode fermions



KK Graviton tower couplings to zero-mode fermions

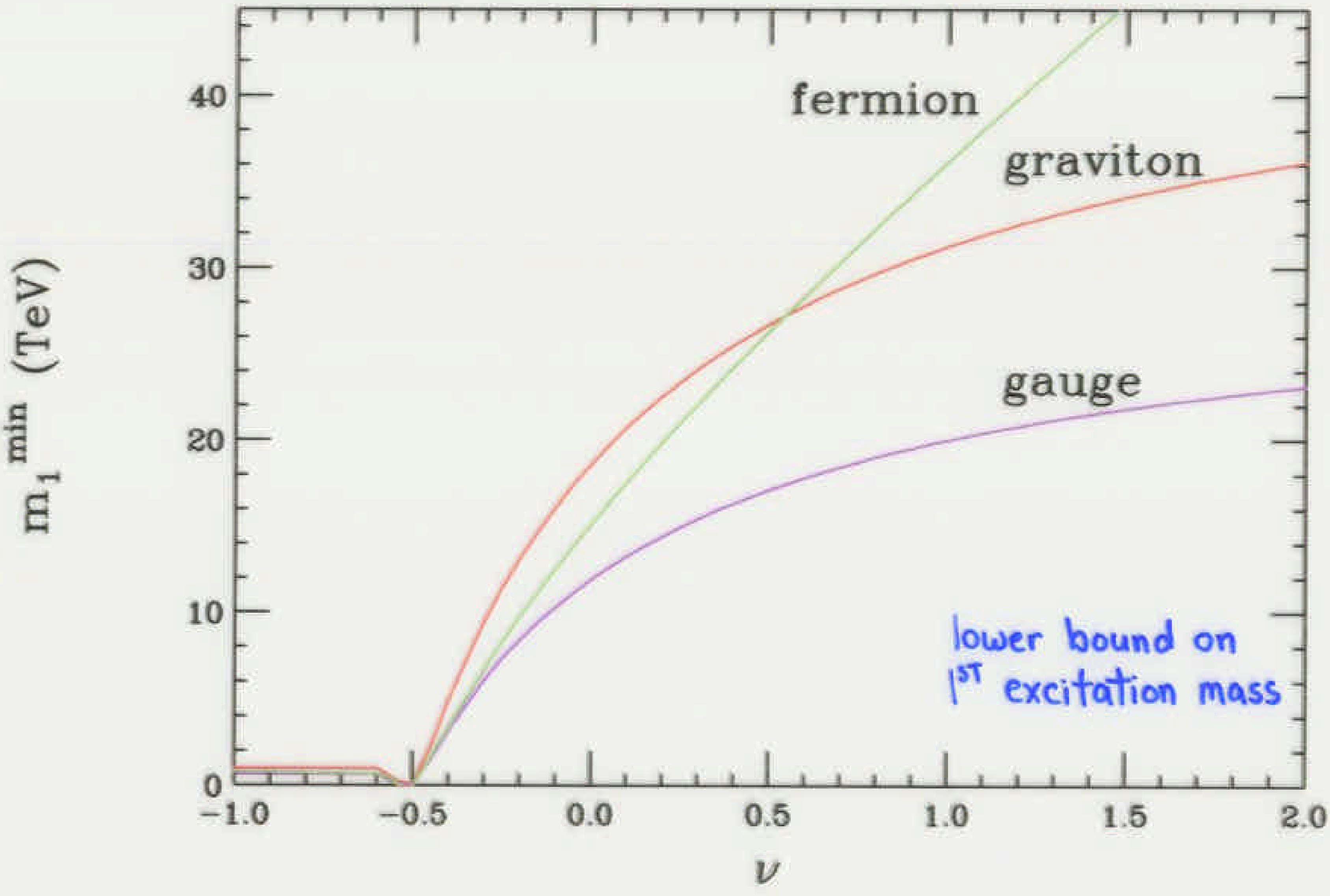


Suggests Distinct Phenomenological Regions

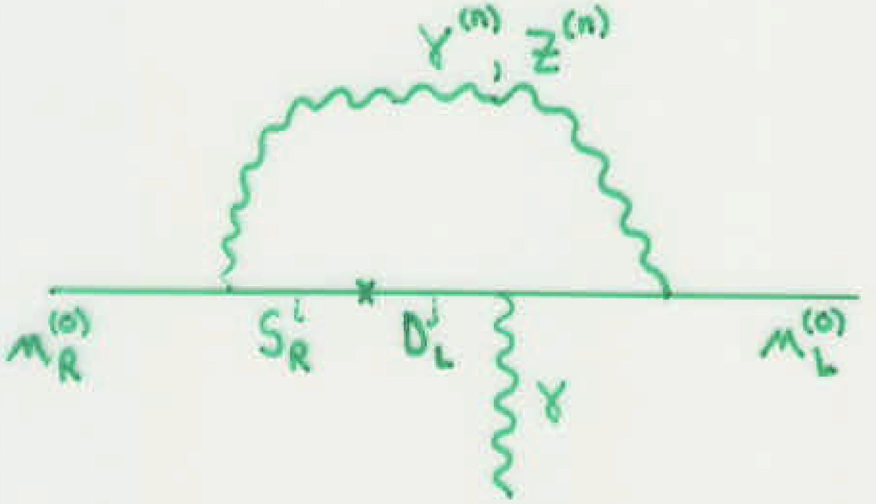


Constraint from Yukawa's + $g-2|_\mu$

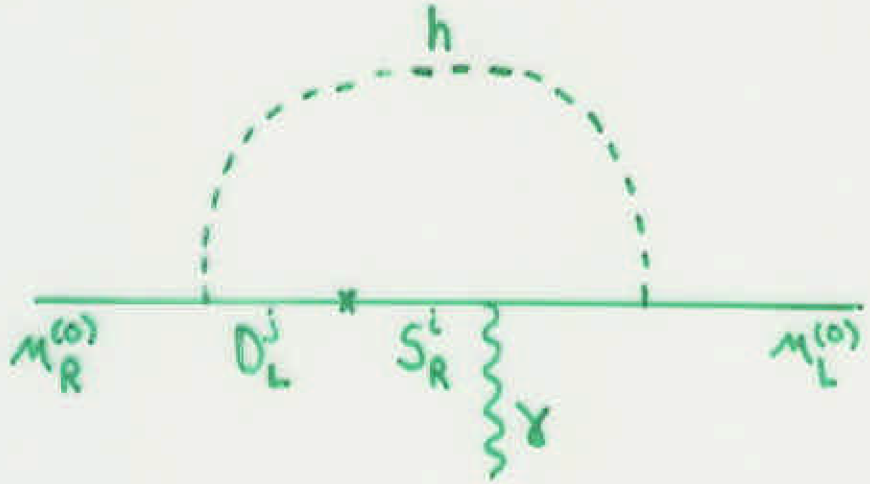
Constraints from Precision EW Data



$g-2|_\mu$: Dominant Contributions



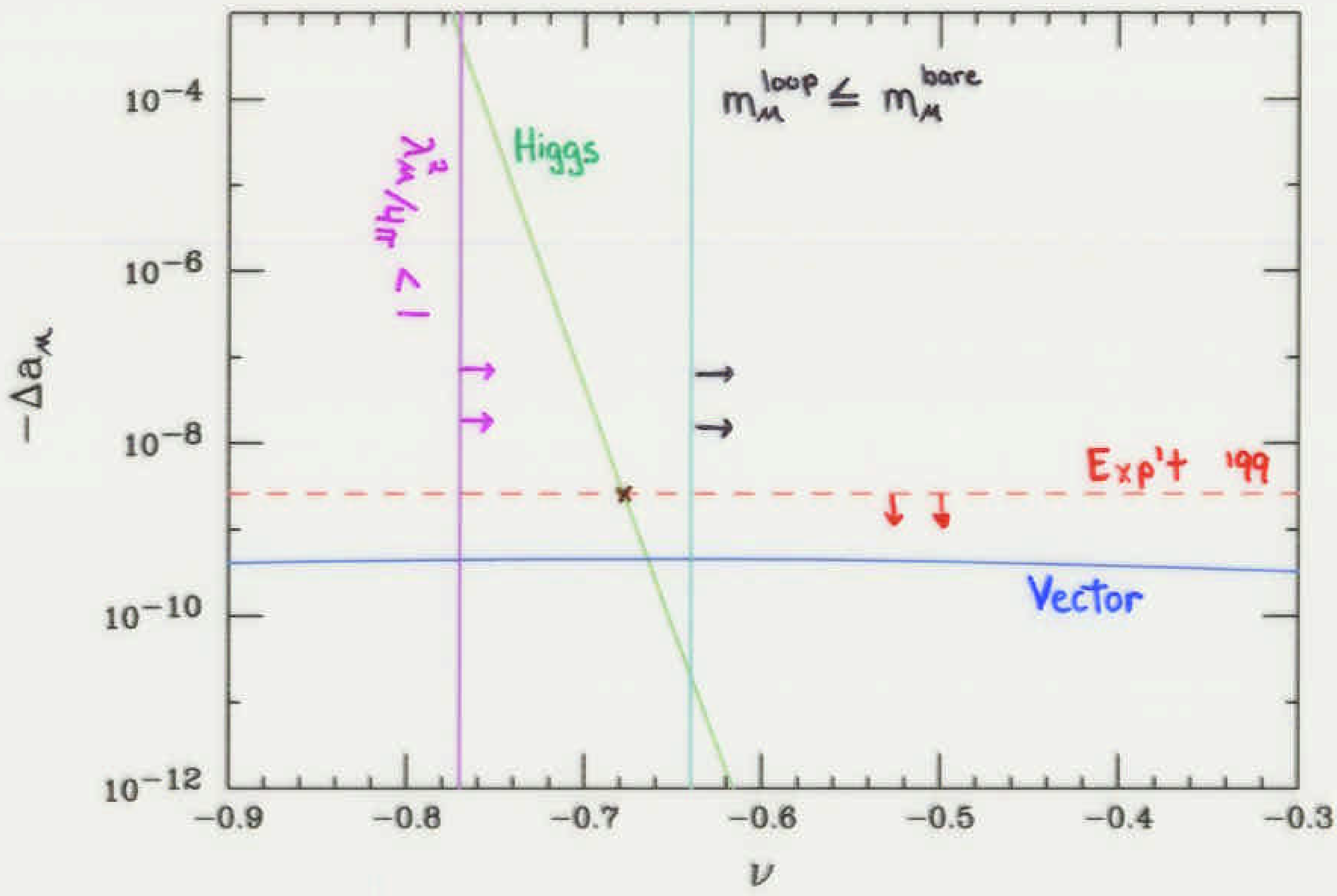
$$\sim \frac{m_\mu^2}{m_{KK}^2}$$



$$\sim \frac{m_\mu^4}{m_{KK}^2 v_4^2} \left| \frac{1+2\nu}{1-\left(e^{-kr_c\pi}\right)^{2\nu+1}} \right|^{-2}$$

blows up for $\nu < -0.5$

All other contributions further suppressed by m_μ^n / m_{KK}^n


$-\Delta a_\mu$
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
−0.9
−0.8
−0.7
−0.6
−0.5
−0.4
−0.3
ν
$\lambda_\mu^2/4\pi < 1$
Higgs
$m_\mu^{loop} \leq m_\mu^{bare}$
Exp't '99
Vector

Conclusions

- Extra Dimensions provide novel approach to hierarchy problem!
- Two classes of theories - each with distinctive phenomenological tests at the weak scale

Large Extra Dimensions: predict

change in F_{Grav} at $d \lesssim 1$ mm

change in $f\bar{f}$ production + $\not{E}_T$ dist's at colliders

Warped Extra Dimensions: predict

Graviton resonances at colliders

No-lose theorem @ LHC!