Phenomenology of Extra Dimensions

Review: JLH, Spiropulu

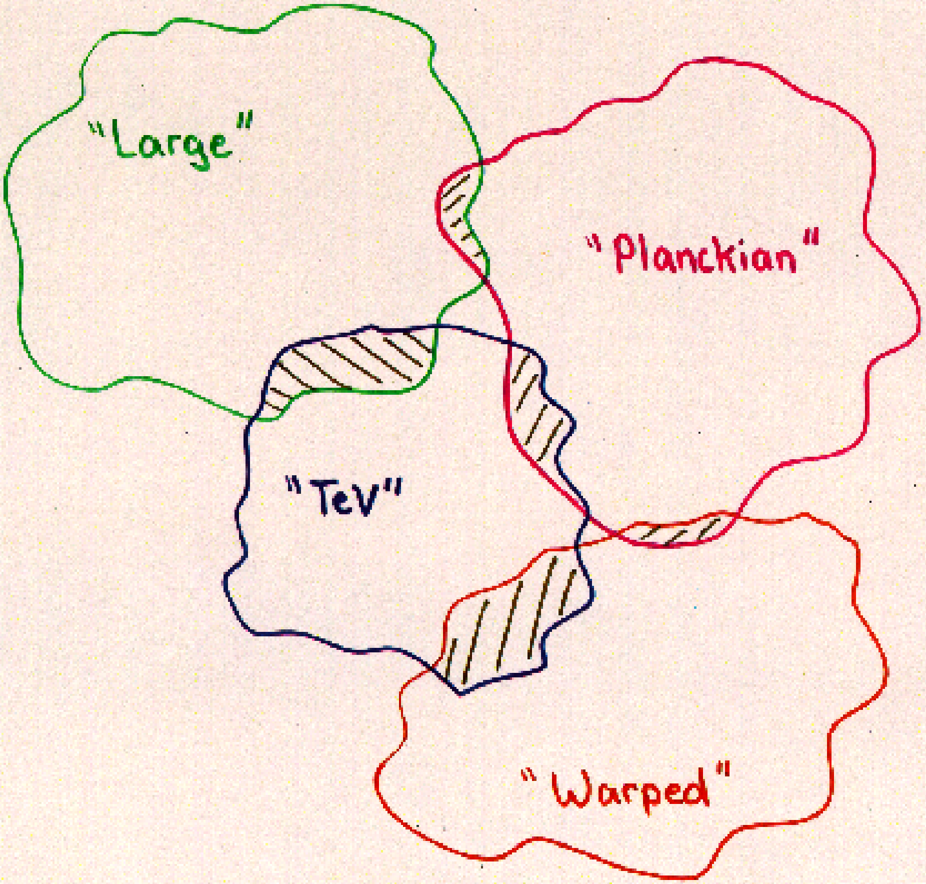
Formal Theorists: have lived in 4+n dimensio
since 1920's (Kaluza-Klein)

New Theories have testable consequences!

- Several interesting scenarios
- Each has distinctive phenomenology

- General pedagogical introduction
- Examine phenomenology of various scenarios
  - ⇒ Collider signatures

The Physics of Extra Dimensions



There are many different models with extra dimensions!

Resulting phenomenology is distinct.

Hierarchy Problem

1) Generation : $\Lambda_{Pl} \gg \Lambda_{EW}$

2) Stabilization : Λ_{EW} unstable under quantum corrections

Traditional Solution : Add new particles at Λ_{EW}

$\Rightarrow$ Supersymmetry

New Ideas : Modify Gravity

Gravity is not well-tested @ short distances

Prediction : New Physics at Λ_{EW} !

$\Lambda_{NP} \sim \Lambda_{EW} \sim \text{TeV}$

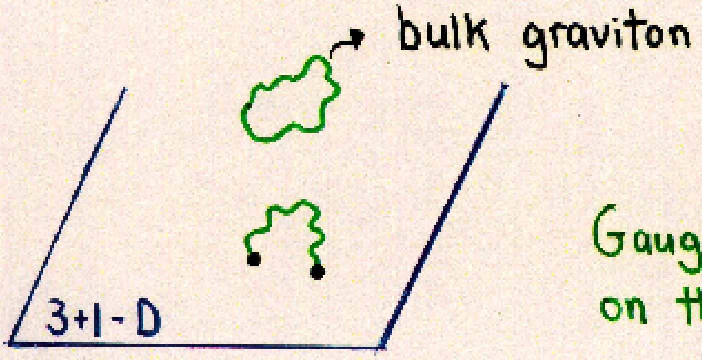
+

New Colliders @ TeV-scale

= Can decisively prove or disprove these theories !

Exciting times ahead of us!

Physics of 3-branes: string theory



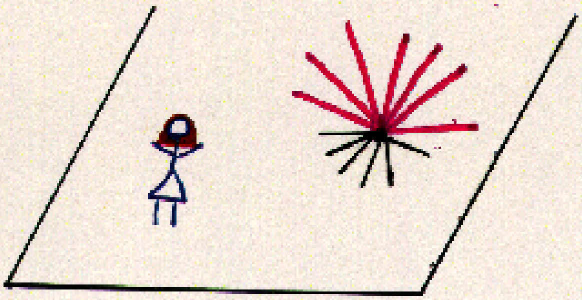
Gauge theories live on the brane

- Gauge particles live at end of strings
- Strings can pop off of brane

⇒ are neutral with no gauge charges
= bulk gravitons

N.B.: This is a very simplified picture ....

A 3-brane Universe



Standard Model
forces stuck on 3-bra

Gravitational fields
spread out over
all spacetime

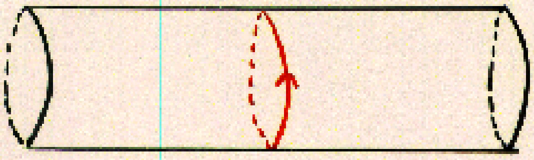
Are gravitational fields diluting too quickly?

⇒ Extra dimensions must be compactified

recover $F_{Gr} \sim 1/r^2$ on the brane

Compactification

Bulk fields expand into Kaluza-Klein towers



5-d Kinetic motion appears as mass in 4-d

⇒ Get Kaluza-Klein tower state for each 5-d revolution

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

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

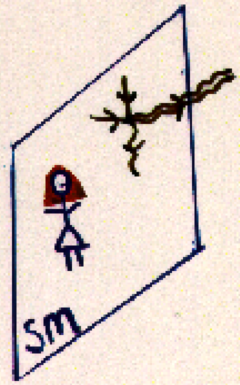
$$(\partial_\mu^2 + \partial_a^2)\Phi = \sum_n \left[\partial_\mu^2 - \left(\frac{n}{R_c}\right)^2 \right] \phi^{(n)}(x^\mu)\, e^{inx^a/R_c}$$

mass term, $m = \frac{n}{R_c}$

Large Extra Dimensions

Arkani-Hamed,
Dimopoulos, Dvali
SLAC-PUB-7801

Motivation: Solve the hierarchy problem by removing it!



SM fields are constrained to the 3-brane (the wall)

Gravity is allowed to propagate in the n extra dimensions (the bulk'

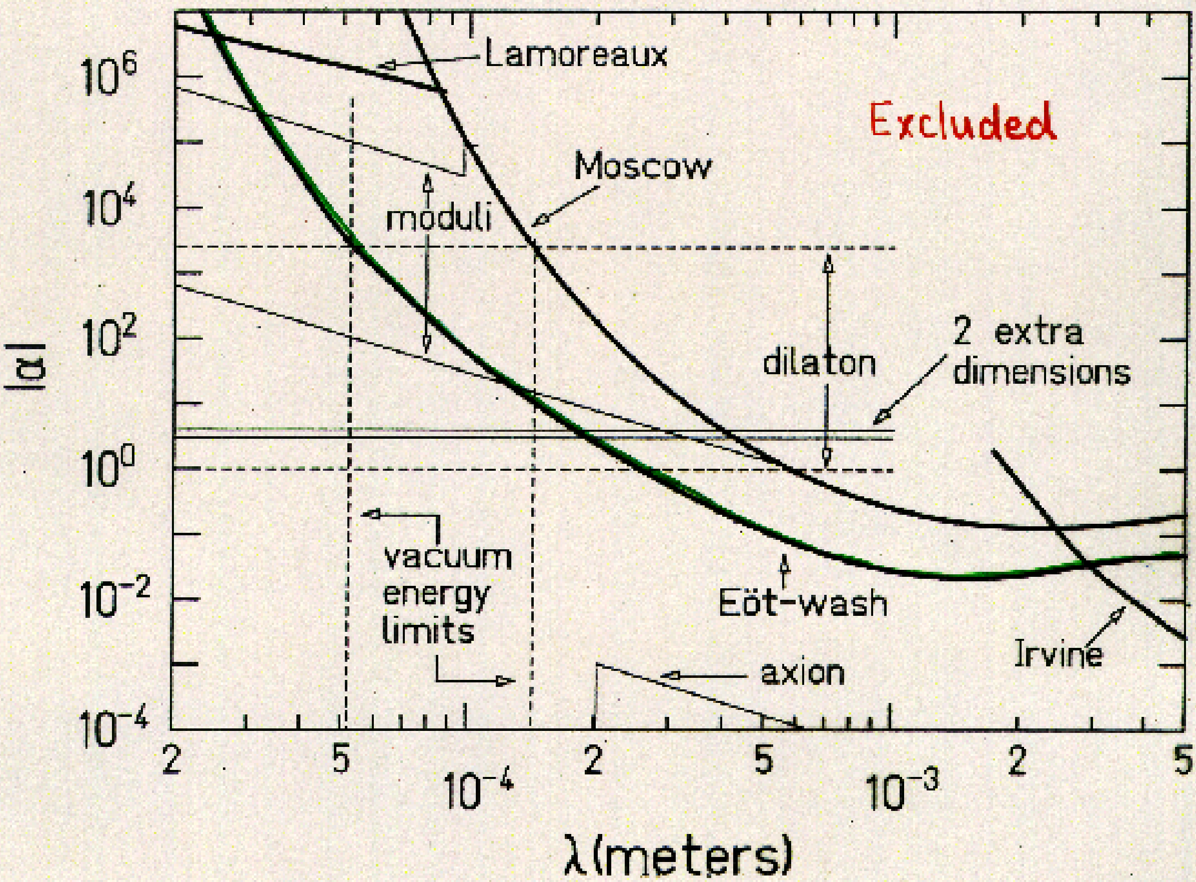
Gauss' Law: $m_{Pl}^2 = V_\delta \, m_*^{2+\delta}$; $V_\delta = A_\delta R^\delta$ *+

m_* = Fundamental Planck scale in the bulk
$\simeq$ TeV

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

*+: Assumed all δ new dim's have same size
$A_\delta = \frac{2\pi^{\delta/2}}{\Gamma(\delta/2)}$ (sphere) or $(2\pi)^\delta$ (torus) or …

Constraints from Cavendish-type experiments



$\lambda \leq 220\,\mu$ Hoyle et al

$m_* \geq 1.6$ TeV for $n=2$

$$V_{\text{gravity}} \sim \frac{m_1 m_2}{M_*^{2+n}} \frac{1}{r^{n+1}} \qquad (r \ll R)$$

$$\sim \frac{m_1 m_2}{M_{Pl}^2} \frac{1}{r} \qquad (r \gg R)$$

Constraints from Astro/Cosmology

(i) SN Cooling — Cullen + Perelstein
Barger et al
Savage et al

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

(ii) γ-Ray Flux — Hall + Smith

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

(iii) Matter dominated early universe (KK states) — Fairbairn

(iv) Re-heating of universe — Hannstad

Constraints on M_* (TeV)

	$\delta = 2$	3	4	5
(i)	31	2.75	–	–
(ii)	110	5	–	–
(iii)	86	7.4	1.5	–
(iv)	167	22	4.75	1.55

$\Rightarrow$ Low M_* disfavored for $\delta = 2$

Given theoretical uncertainties, $\delta \geq 3$ **OK**

Bulk Metric: Linearized Quantum Gravity

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

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

Interactions:

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

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

Graviton KK Reduction

Massless h_{AB} in δ-dim

$$\left\{ \begin{array}{ll} h_{\mu\nu} & \text{1 massless 2-component tens} \\ h_{\mu i} & \delta \text{ massless 2-component vect} \\ h_{ij} & \tfrac{1}{2}\delta(\delta+1) \text{ real massless scala} \end{array} \right.$$

States in KK tower acquire mass by 'eating' lower spin fields

Physical Fields:

$$\left. \begin{array}{l} \text{1 massive 5-component tensor } h_{\mu\nu} \\ \delta\text{-1 massive gauge fields } A_\mu \\ \tfrac{1}{2}\delta(\delta-1) \text{ scalars} \end{array} \right\} \text{with massless zero-modes}$$

Decomposition of Graviton Field-Strength Tensor

$$h_{AB} \sim \begin{pmatrix} h_{\mu\nu} + \eta_{\mu\nu}\phi & A_{\mu a} \\ A_{\mu a} & \phi_{ab} \end{pmatrix}$$

Graviton-fermion Interactions

$$T_{AB} = \eta^{\mu}{}_{A}\,\eta^{\nu}{}_{B}\left[\bar{\psi}\gamma_\mu \partial_\nu \psi - \partial_\mu \bar{\psi}\gamma_\nu \psi\right]$$

Spin 1 KK states: $T_{\mu a} = 0$

Spin 0 KK states: $T_{ab} = 0$

$$T_\mu{}^\mu = \bar{\psi}\gamma_\mu \partial^\mu \psi - \partial_\mu \bar{\psi}\gamma^\mu \psi$$
$$= -2m\,\bar{\psi}\psi$$

Spin 2 KK states: Given by linearized G.R.

Interactions:

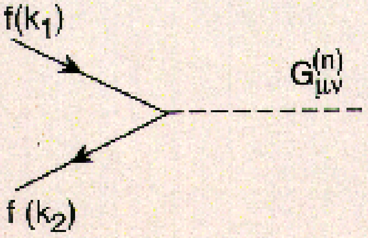
$$S = \frac{-1}{M_*^{n/2+1}} \int d^4x\, d^nx^a\, h_{AB}(x^\mu, x^a)\, T_{AB}(x^\mu, x^a)$$

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

Feynman Rules

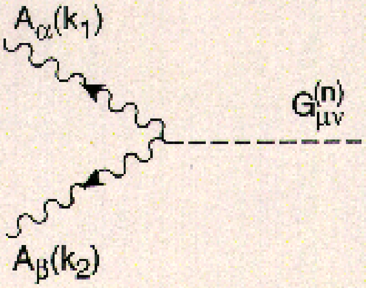
Giudice, Rattazzi, Wells

Han, Lykken, Zhang



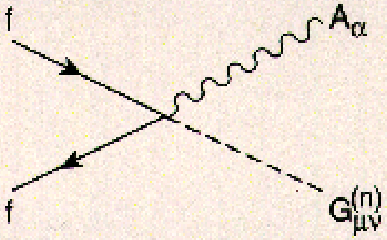
$$-\frac{i}{4\underline{\underline{\overline{M}_P}}}\left[W^{(f)}_{\mu\nu}+W^{(f)}_{\nu\mu}\right]$$

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



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

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



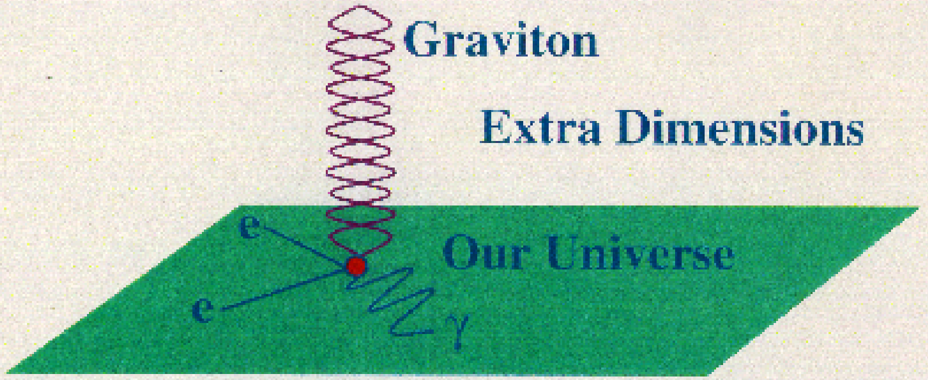
$$-\frac{i}{2\overline{M}_P}eQ\left(X_{\mu\nu\alpha}+X_{\nu\mu\alpha}\right)$$

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

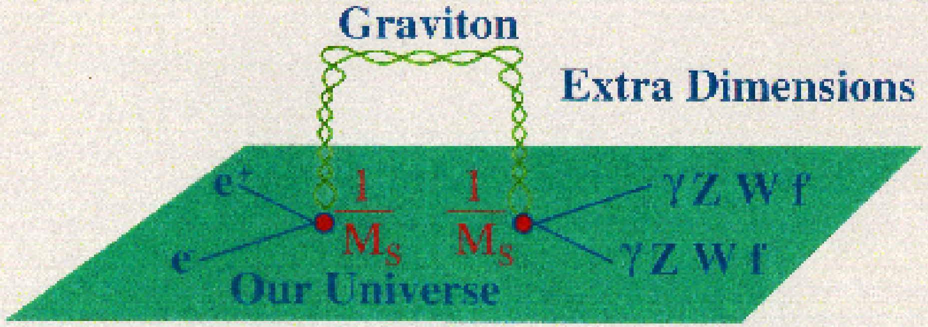
Massless 0-mode ⊕ all tower gravitons have same couplings to matter

Search Strategy

Direct Search: 1 photon or 1 Z boson + missing energy.



Indirect Search: Look for deviations from $(d\sigma/d\Omega)_{SM}$.



2 Classes of Collider Tests

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

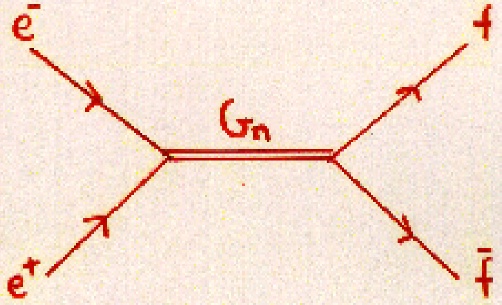
Search for 1) Deviations in Standard processes
2) New processes !

Graviton couples 1) universally to everything
2) via stress-energy tensor

Angular distributions reveal spin-2 exchange

Consider $e^+e^- \to f\bar{f}$

$$\mathcal{M} = \frac{1}{16\,\underline{\underline{m_{Pl}^2}}} \sum_n \frac{T^e_{\mu\nu}\, P^{\mu\nu\lambda\sigma}\, T^f_{\lambda\sigma}}{s - m_n^2 + i\epsilon}$$



G_n are densely packed!

$$\Rightarrow \sum_n \to \int dm^2\, \rho(m^2)$$

$$\frac{1}{m_{Pl}^2} \sum_n \frac{1}{s - m_n^2} \to \frac{1}{M_*^4}$$

JLH
Phys Rev Let
Giudice, Rattaz
We

Poor theoretical control!

$\int$ KK propagators is divergent

⇒ 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

Cut-off Approach

Contact interaction limit for G_n exchange

Examine leading dimension-8 operators
& constrain $M_* |\lambda|^{-1/4}$

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

Hewett, GRW, and HLZ Formalisms

- Hewett: neither sign of the interference nor the dependence on the number of extra dimensions is known; therefore the interference term is $\sim\lambda/M_S^4$(Hewett), where λ is of order 1; numerically uses $\lambda = \pm 1$
- GRW: sign of the interference is fixed, but the dependence on the number of extra dimensions is unknown; therefore the interference term is $\sim 1/\Lambda_T^4$ (where Λ_T is their notation for M_S)
- HLZ: not only the sign of interference is fixed, but the n-dependence can be calculated in the effective theory; thus the interference term is $\sim \mathcal{F}/M_S^4$(HLZ), where $\mathcal{F}$ reflects the dependence on the number of extra dimensions:

$$\boxed{\mathcal{F} = \begin{cases} \log\left(\frac{M_S^2}{s}\right), n = 2 \\ \dfrac{2}{n-2}, n > 2 \end{cases}}$$

- Correspondence between the three formalisms:

$$\boxed{M_S(\mathbf{Hewett})\big|_{\lambda=+1} \equiv \sqrt{\frac{2}{\pi}}\Lambda_T(\mathbf{GRW})}$$

$$\boxed{\frac{\lambda}{M_S^4(\mathbf{Hewett})} = \frac{\pi}{2}\frac{\mathcal{F}}{M_S^4(\mathbf{HLZ})}}$$

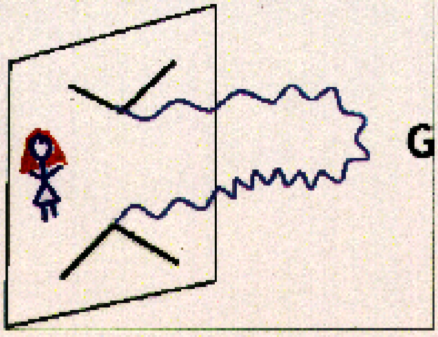
$$\boxed{\frac{1}{\Lambda_T^4(\mathbf{GRW})} = \frac{\mathcal{F}}{M_S^4(\mathbf{HLZ})}}$$

- Rule of thumb:

$$M_S(\mathbf{Hewett})\big|_{\lambda=+1} \approx M_S(\mathbf{HLZ})\big|_{n=5}$$

$$\Lambda_T(\mathbf{GRW}) = M_S(\mathbf{HLZ})\big|_{n=4}$$

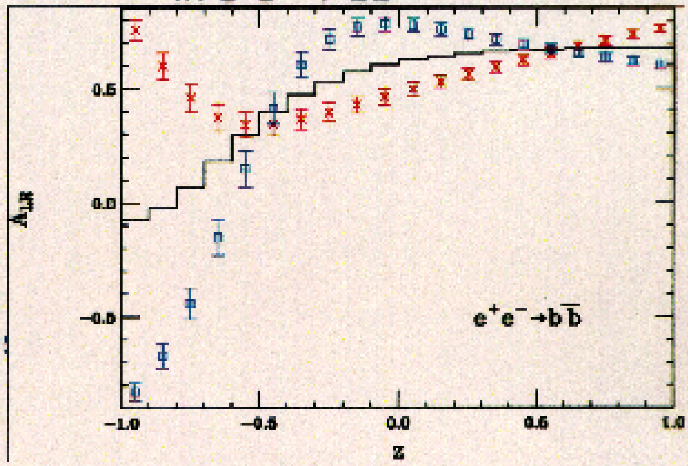
Graviton Exchange



Deviations in SM processes

Search for new processes

Polarized ∠ Dist'btn
In $e^+e^- \rightarrow b\bar{b}$



JLH

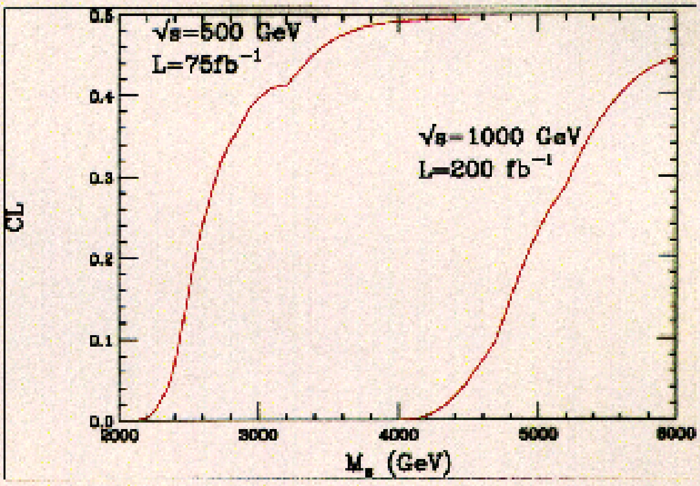
LC :	$e^+e^- \rightarrow f\bar{f}$	$\sqrt{s}$ = 500 GeV	4.1
		$\sqrt{s}$ = 1000 GeV	7.2
	$\gamma\gamma \rightarrow WW$	$\sqrt{s}$ = 1000 GeV	13.0
LHC:	$pp \rightarrow \ell^+\ell^-$		6.0

Search Reach
at 95% CL
(in TeV)

Angular Dist'btns reveal
spin-2 exchange!

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

Spin-2 determined almost
Up to kinematic limit !

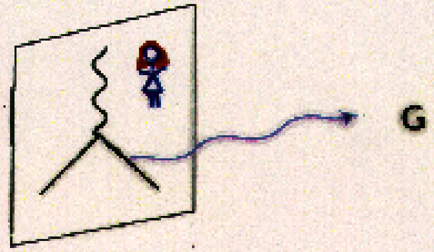


JLH

Large Extra Dimensions

$M^2_{Pl} = V_\delta M_*^{2+\delta}$;   Solves hierarchy if $M_* \sim$ TeV

Graviton Emission:



SM stuck to brane
Gravity propagates in bulk
Graviton appears as $\not{E}_T$

Giudice, Rattazzi, Wel
Han, Lykken, Zhang
Mirabelli, Perelstein, Pes

Discovery Reach in TeV for M_*

	$e^+e^- \to \gamma + G_n$	$\sqrt{s}$ = 800 GeV	2	4	6
TESLA TDR	LC	$P_{-,+} = 0$	5.9	3.5	2.5
	LC	$P_- = 0.8$	8.3	4.4	2.9
	LC	$P_- = 0.8$, $P_+ = 0.6$	10.4	5.1	3.3
ATLAS study	$pp \to g + G_n$		2	3	4
	LHC		4 – 8.9	4.5 – 6.8	5.0 – 5.8

Hinchliffe + Vacavant

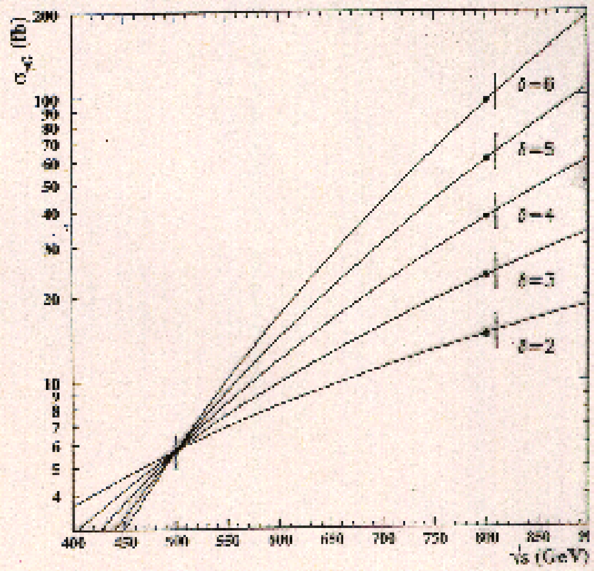
Discovery range wh
effective
theory is
valid

–Discovery likely at LHC/LC

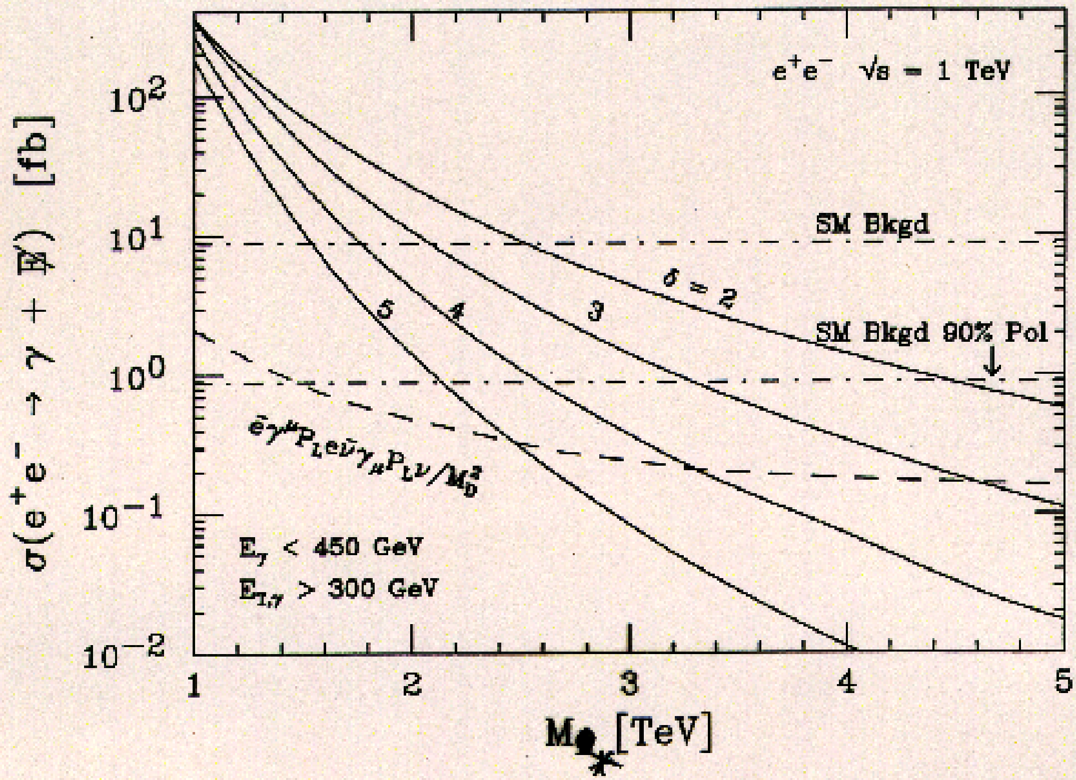
–LC probes theory

Spectrum varies with δ
as $\sqrt{s}$ increases
$\Rightarrow$ Determine M_* and δ !

Wilson


$\sigma_{\gamma G}$ (fb)
200
100
90
80
70
60
50
40
30
20
10
9
8
7
6
5
4
$\delta=6$
$\delta=5$
$\delta=4$
$\delta=3$
$\delta=2$
400
450
500
550
600
650
700
750
800
850
9
$\sqrt{s}$ (GeV)

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



Giudic
Rataz
We

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.

	2	4	6
$_{-,+} = 0$	5.9	3.5	2.5
$P_- = 80\%$	8.3	4.4	2.9
$P_- = 80\%$ $P_+ = 60\%$	10.4	5.1	3.3

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

LEP2 Lower 95% CL M_S(Hewett) Limits (TeV)

	$e^+e^- \to \gamma G$					$e^+e^- \to ZG$				
Experiment	n=2	n=3	n=4	n=5	n=6	n=2	n=3	n=4	n=5	n=6
ALEPH	1.28	0.97	0.78	0.66	0.57	0.35	0.22	0.17	0.14	0.12
DELPHI	1.38	**1.02**	0.84	**0.68**	0.58	☒	☒	☒	☒	☒
L3	1.02	0.81	0.67	0.58	0.51	0.60	0.38	0.29	**0.24**	**0.21**
OPAL	1.09	0.86	0.71	0.61	0.53	☒	☒	☒	☒	☒

Color coding
🟩 ≤184 GeV
🟨 ≤189 GeV
🟦 >200 GeV
λ=-1 λ=+1 GL

Virtual Graviton Exchange

Experiment	e^+e^-	$\mu^+\mu^-$	$\tau^+\tau^-$	qq	ff	$\gamma\gamma$	WW	ZZ	**Combined**
ALEPH	1.04 0.81	0.65 0.67	0.60 0.62	0.53/0.57 0.49/0.49 (bb)	1.05 0.84	0.81 0.82	☒	☒	0.75/1.00 (<189)
DELPHI	☒	0.59 0.73	0.56 0.65	☒	0.60 0.76	0.70 0.77	☒	☒	0.60/0.76 (ff) (<202)
L3	0.98 1.06	0.56 0.69	0.58 0.54	0.49 0.49	0.84 1.00	0.99 0.84	0.68 0.79	1.2 ? 1.2 ?	1.3/1.2 (<202) ?
OPAL	1.15 1.00	0.62 0.66		☒	0.62 0.66	0.89 0.83	☒	0.63 0.74	1.17/1.03 (<209)

Supersymmetric Bulk

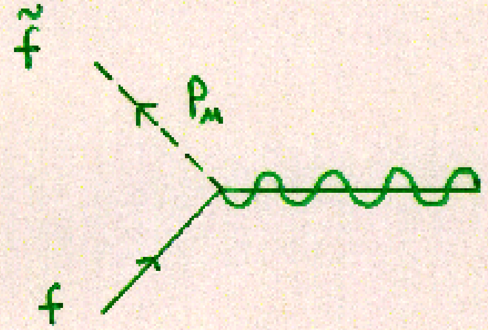
JLH, Sadri

Motivation : Embed ADD in string theory
Stabilize size of dimensions

N=2 SUSY in bulk breaks to N=1 SUSY on brane

Full supermultiplet in bulk

Compactify ⇒ KK towers of gravitons AND gravitinos



$$\bar{\Omega}_\nu \quad \frac{-i}{2\sqrt{2}\,\overline{M}_p}\, p_\mu \gamma^\mu \gamma^\nu$$

KK Gravitino Exchange : t-channel

$$\sum_{\tilde{n}} P^{\tilde{n},\mu\nu} \sim -i \int_{m_0^2}^{\Lambda_c^2} dm_{\tilde{n}}^2\, \rho(m_{\tilde{n}}^2)\, \frac{|m_{\tilde{n}}|^{\alpha-2}}{t - m_{\tilde{n}}^2}$$

$\alpha = 0,1,2,3$

Contributions to $e^+e^- \to \tilde{e}^+_{L,R}\,\tilde{e}^-_{L,R}$

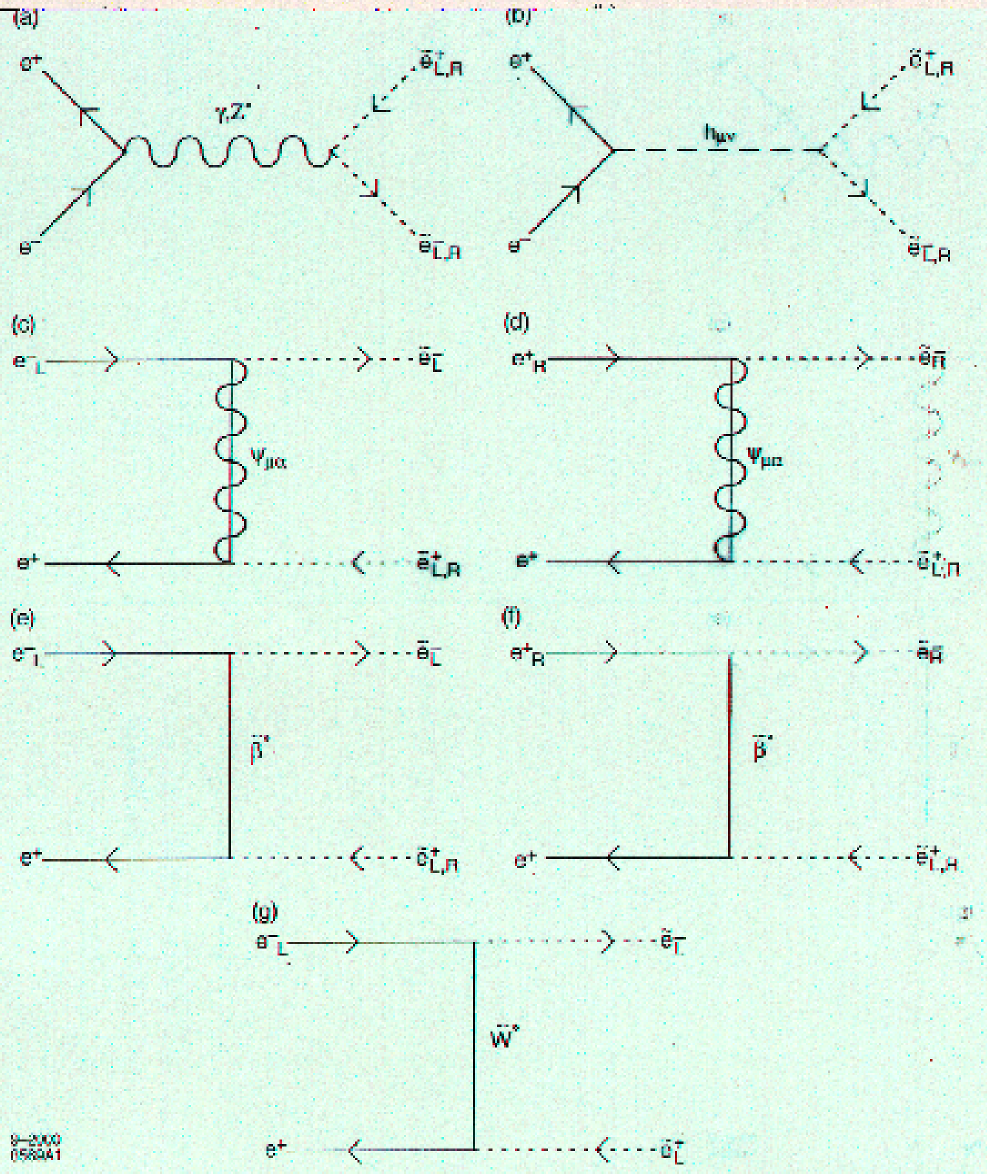
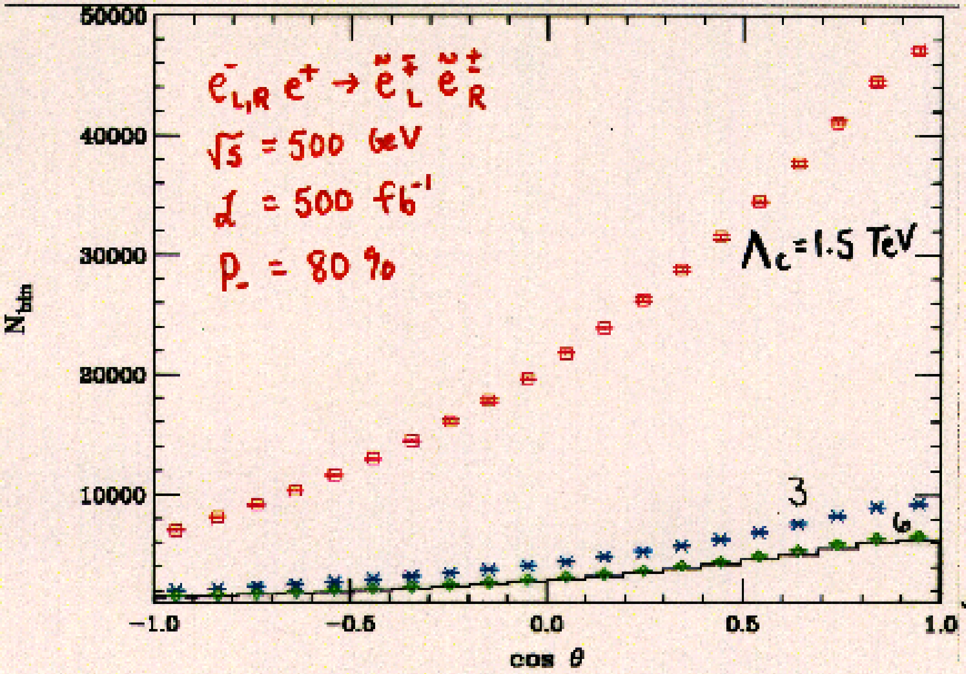


Figure 2: Various processes contributing to scalar pair production.

Supersymetric Large Extra Dimensions

- Exchange KK towers of Gravitons and Gravitinos!
- Large t-channel contribution to $e^+e^- \to \tilde{e}^+\tilde{e}^-$ from Gravitino exchange



$\delta = 6$

JLH, Sadri

Sensitivity in excess of M_* ~ 10 TeV @ $\sqrt{s}$ = 500 GeV

Unique sensitive probe to a supersymmetric bulk!

LHC: Small signal in squark pair production
gluino production needs to be studied

TeV^{-1} - size Extra Dimensions

Antoniadis

The SM goes into the bulk!

Many model building choices

- Are $SU(3)_c$, $SU(2)_L$, + $U(1)_Y$ all in the bulk? Same # of dims?
- Higgs in bulk or on brane?
- Fermions
  - fixed points
  - in bulk
  - localized at various points on a thick brane

For simplicity, examine 1 extra dimension compactified on S^1/Z_2 (circle of radius R, folded in half)

TeV^{-1} Extra Dimensions (Fat Branes)

- Arise naturally from string theory — Antoniadis
- Mechanism to suppress proton decay — Arkani-Hamed, Schmal

Gauge bosons free to propagate in $R_c \sim$ TeV

$\Rightarrow$ Degenerate KK towers for γ / Z / W / g

Discovery Reach for KK γ / Z (TeV): Ala Z' search

Direct	Run II		2 fb^{-1}	1.1
	LHC		100 fb^{-1}	6.3
ndirect	LC	$\sqrt{s}$ = 0.5 TeV	500 fb^{-1}	13.0
	LC	$\sqrt{s}$ = 1.0 TeV	500 fb^{-1}	23.0
	LC	$\sqrt{s}$ = 1.5 TeV	500 fb^{-1}	31.0

Snowmass / LesHouches '01 :

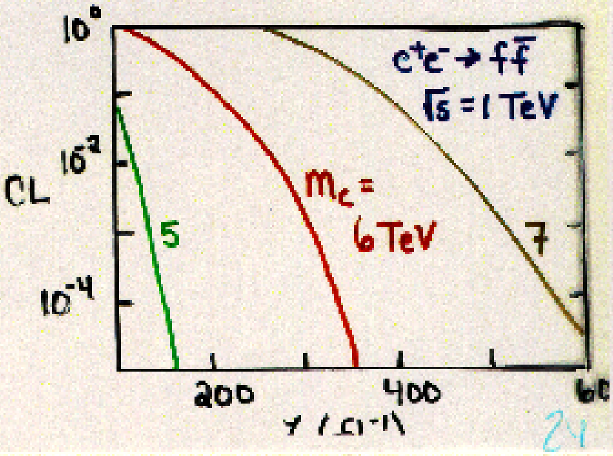
LHC Indirect Reach

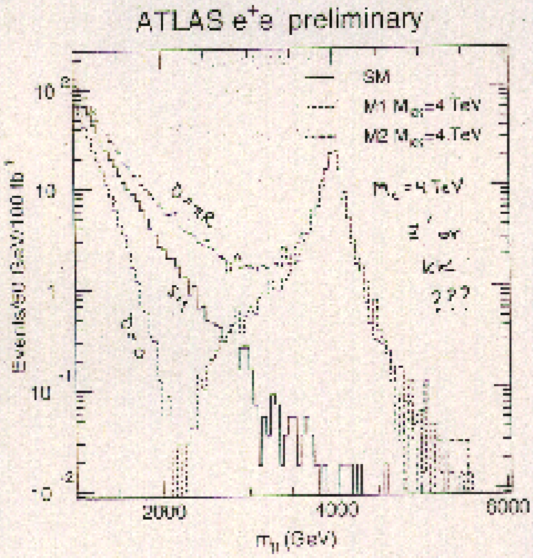
ATLAS Study : $m_c \sim 8$ TeV — Polesel

2 Pheno studies — JLH, Rizzo; Cheung Land

Can KK γ/Z be distinguished from GUT Z' ? — Rizzo

LHC:	$m_c = 4$ TeV	5 TeV
D = 0	CL < 10^{-10}	CL ~ 0.3%
D = πR	CL ~ 70%	CL ~ 100%

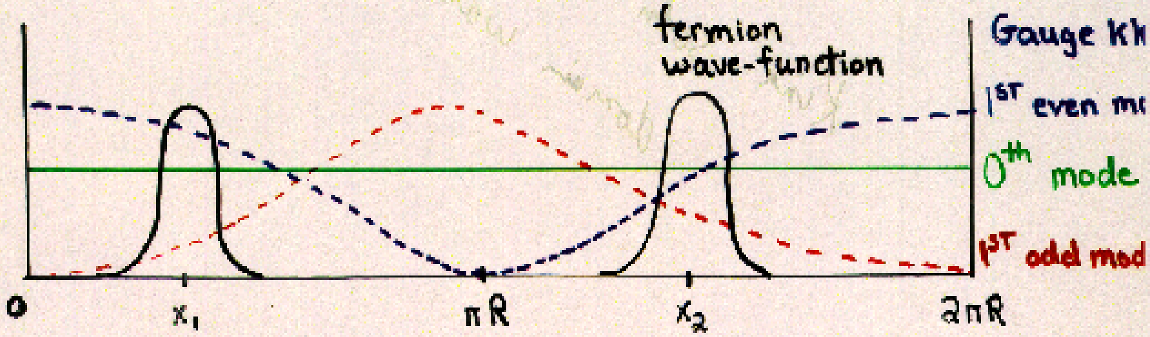



ATLAS e+e preliminary
SM
M1 M_KK=4 TeV
M2 M_KK=4.TeV
M_c = 4 TeV
Events/50 GeV/100 fb^-1
10^2
10
1
10^-1
10^-2
2000
4000
6000
m_ll (GeV)
???

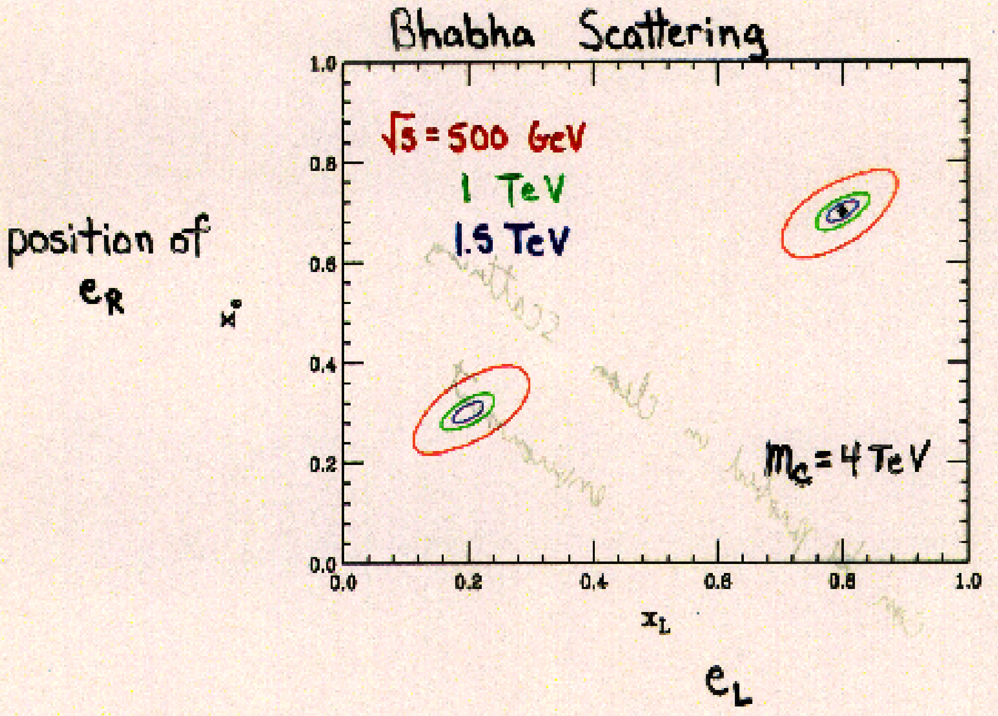
Separated Fermions

Arkani-Hamed, Schmaltz

Fermions can be localized at different points in a thick brane



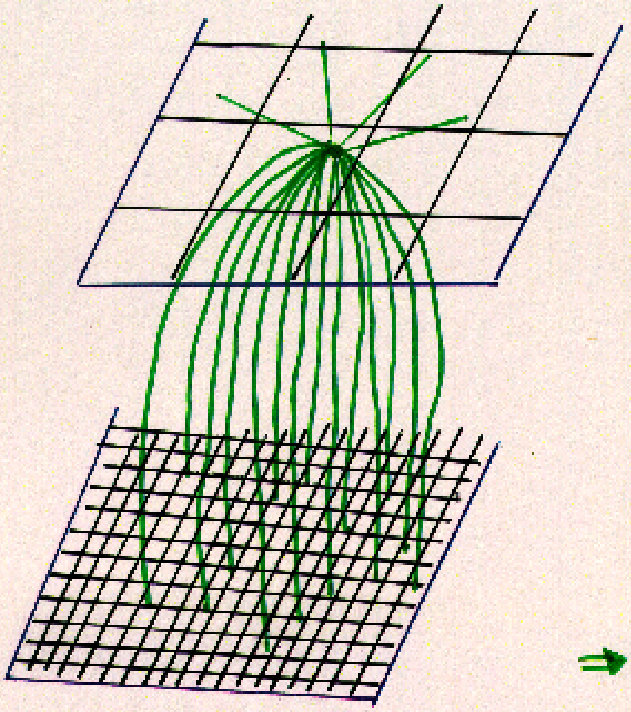
Gauge KK couplings probe relative fermion locations!



S_1/Z_2

Rizzo

Non-Factorizable Curved Geometry - 'Warped' Space



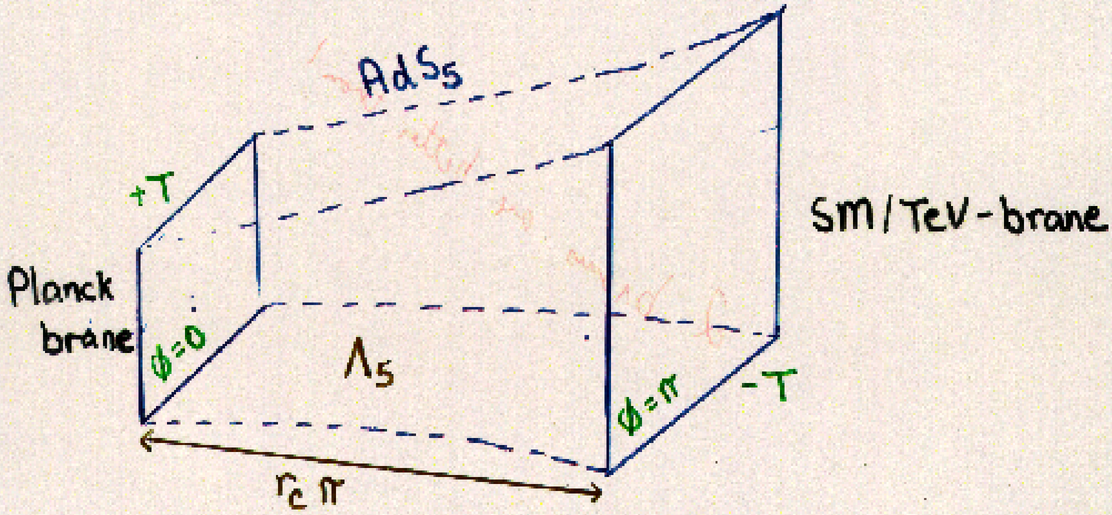
Area of each grid
is equal

Field lines spread out
faster with more volume

⇒ Drop to bottom brane

Gravity appears weak on top brane!

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']

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

Warp factor

$0 \le |\phi| \le \pi$

r_c = compactification radius

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

4-D Effective Action:

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

no additional hierarchie

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

$$\Rightarrow r_c \sim \frac{100}{\overline{m}_{Pl}}$$

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

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

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

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:

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

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

⇒ 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

Davoudiasl, JLH, Rizzo
PRL '00
PLB '00
PRD '01
PLB '00
hep-ph/0010066

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

  Graviton emission
- Below resonance exchange

  "Contact interaction" limits

KK Graviton Drell-Yan Spectrum

Davoudiasl, J
Rizzo PRL '

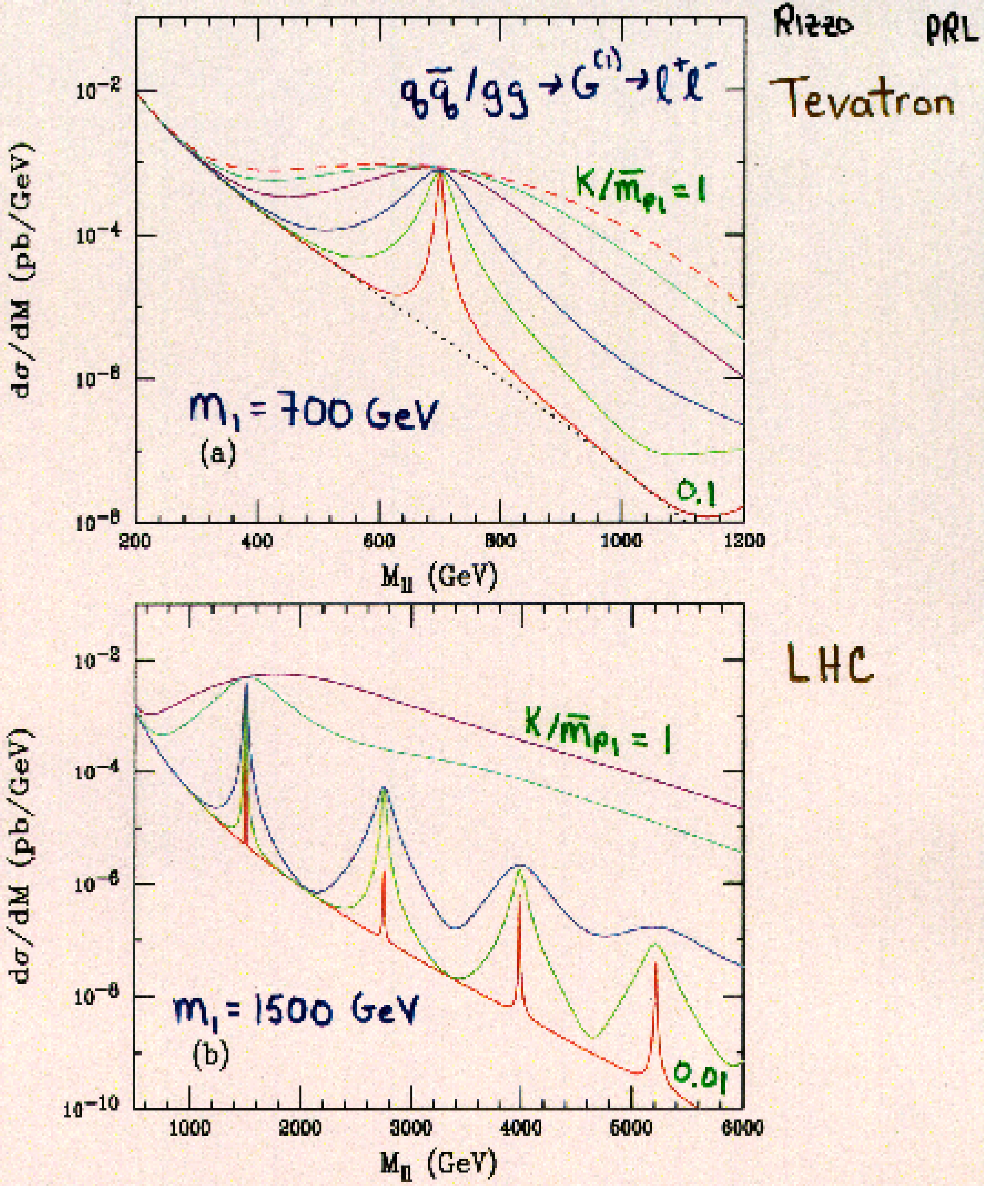


Figure 17: Drell-Yan production of a (a) 700 GeV KK graviton at the Tevatron with $k/\overline{M}_{Pl}$ = 1, 0.7, 0.5, 0.3, 0.2, and 0.1, respectively, from top to bottom; (b) 1500 GeV KK graviton and its subsequent tower states at the LHC. From top to bottom, the curves are for $k/\overline{M}_{Pl}$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

Constraints from Drell-Yan + di-jet production

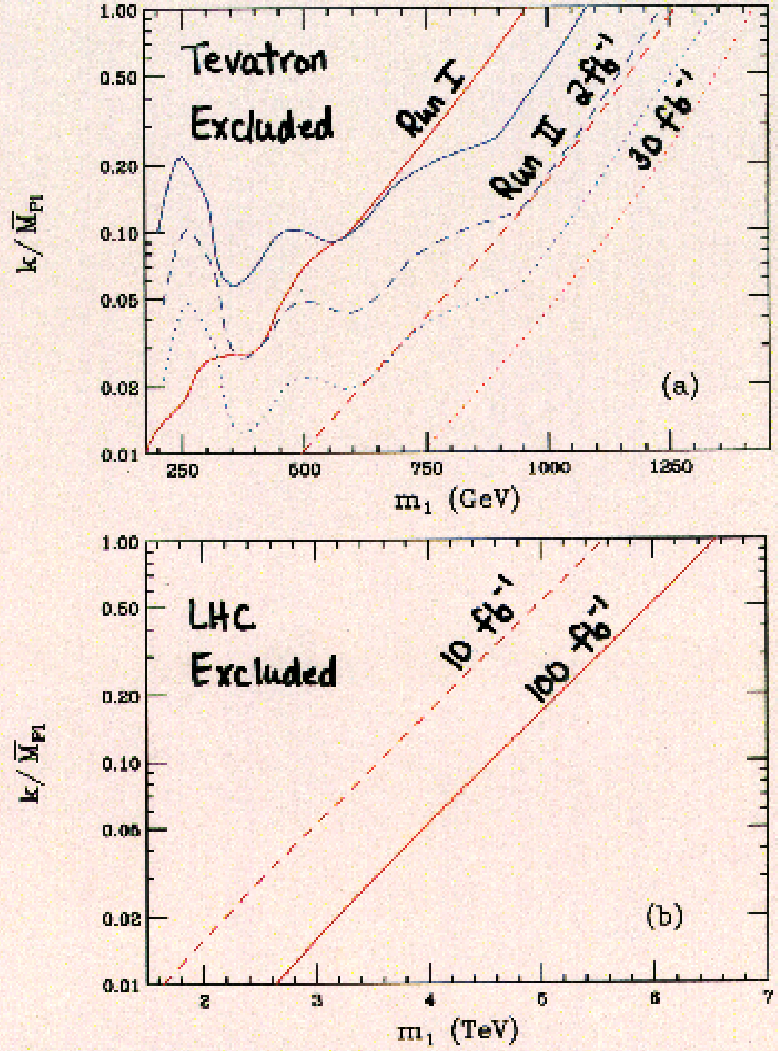
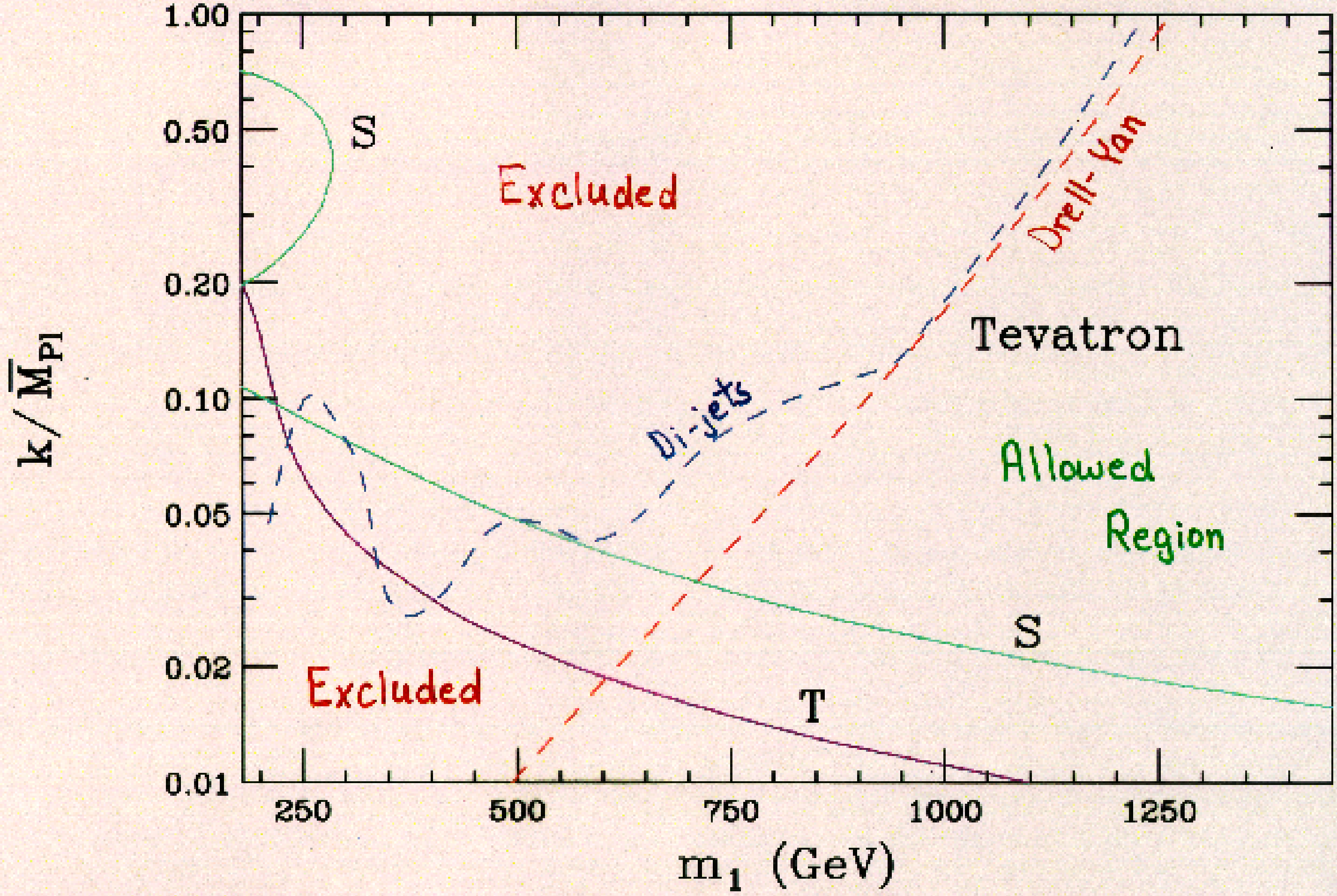
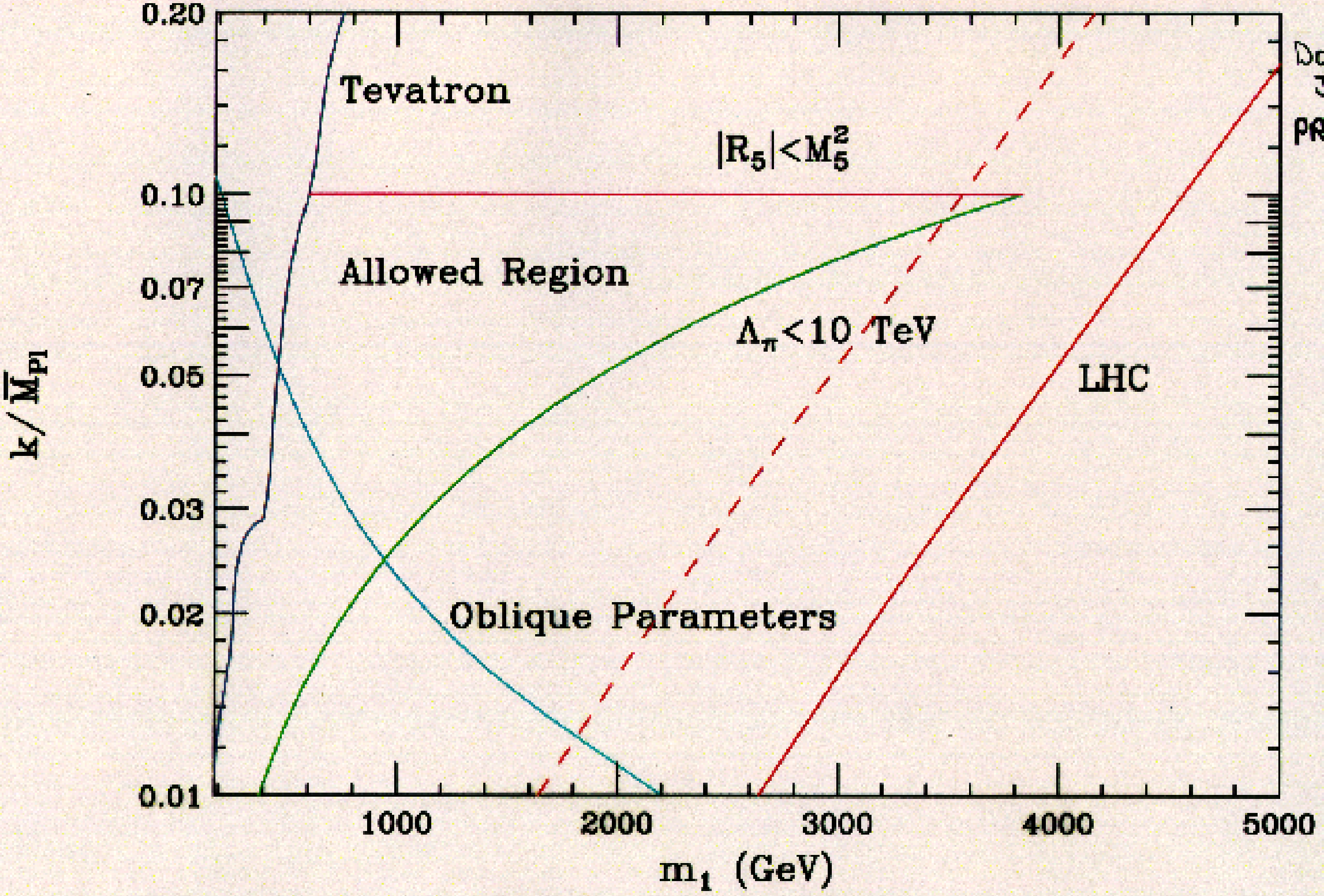


Figure 1: Exclusion regions for resonance production of the first KK graviton excitation in (a) the Drell-Yan (corresponding to the diagonal lines) and dijet (represented by the bumpy curves) channels at the Tevatron and (b) Drell-Yan production at the LHC. (a) The solid curves represent the results for Run I, while the dashed, dotted curves correspond to Run II with 2, 30 fb^{-1} of integrated luminosity, respectively. (b) The dashed, solid curves correspond to 10, 100 fb^{-1} . The excluded region lies above and to the left of the curves.

Present Constraints on RS Model

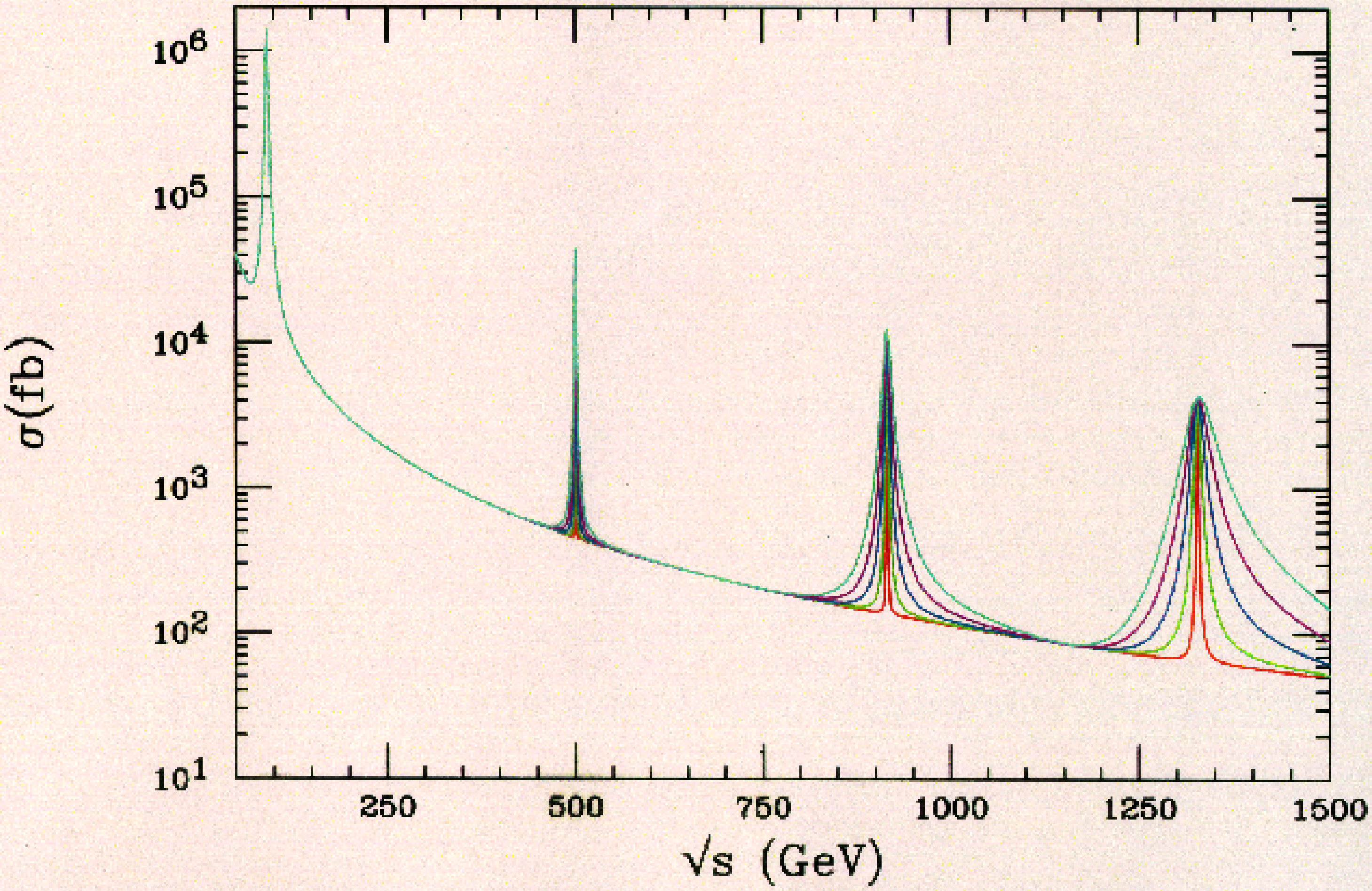


Summary of Theory + Exp't Constraints

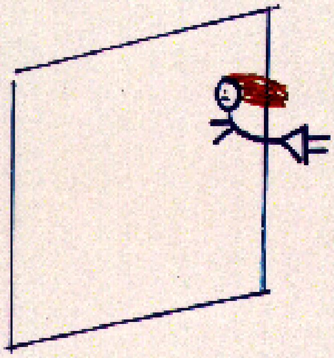


Davoudiasl
JLH, Rizzo
PRD '01

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



Peeling the SM off the Wall



Davoudiasl, JLH, Rizzo
PLB '00
PRD '01

- Gauge Fields in Bulk Alone

  EW Data $m_1^A > 25$ TeV! [violates curvature constraint]

- Fix : Add Fermions in the bulk

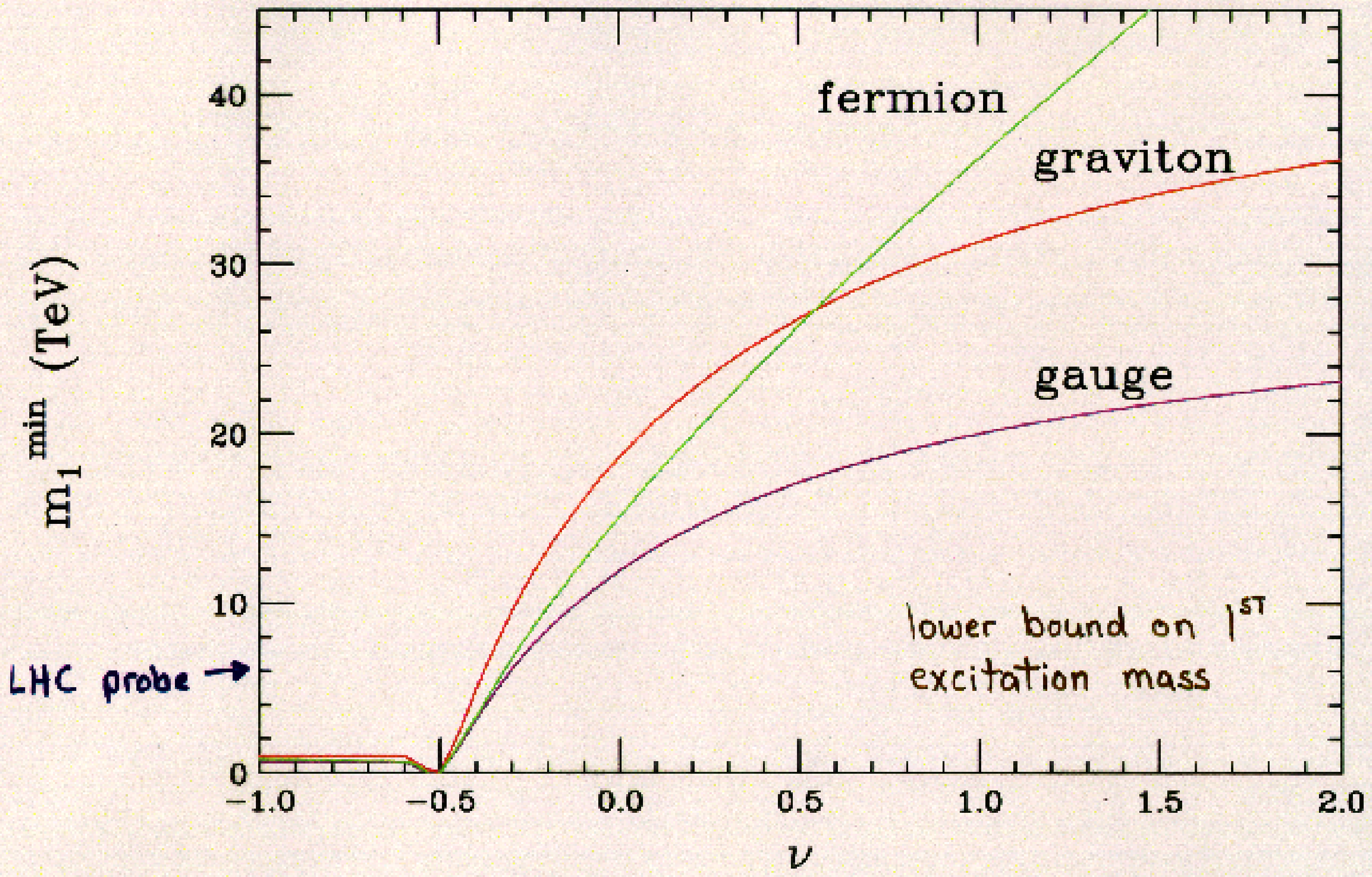
  ⇒ Introduces 3RD parameter

  $m_f^{bulk} = \nu K$, $\nu \sim \mathcal{O}(1)$

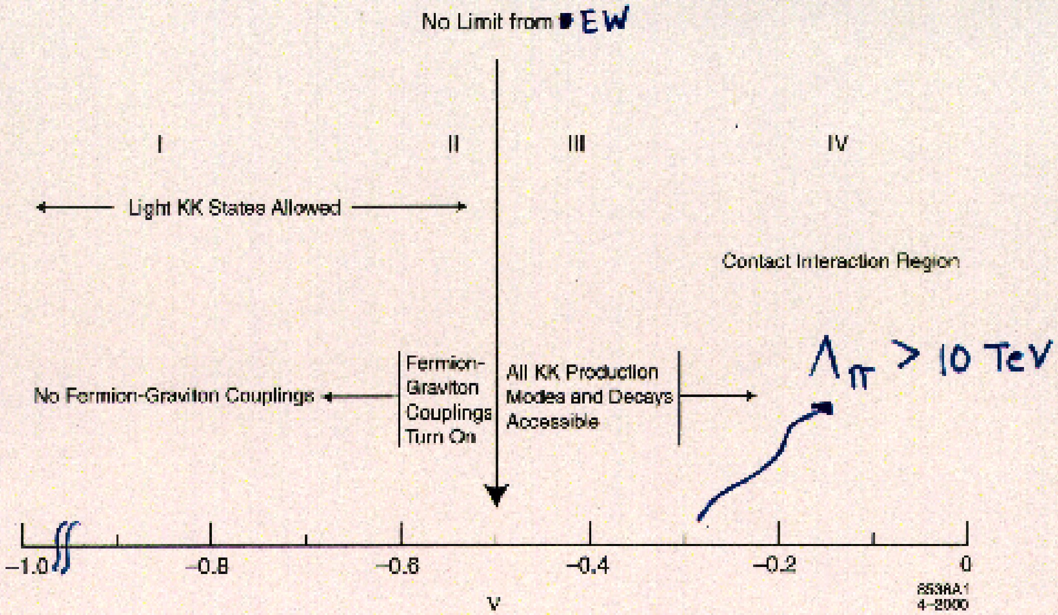
  Zero-mode KK fermions couple more weakly than Wall fields

⇒ Serious reduction in collider sensitivity!

Precision EW Data Constraints



Suggests Distinct Phenomenological Regions



No Limit from EW

← Light KK States Allowed →

Contact Interaction Region

$\Lambda_\pi > 10$ TeV

No Fermion-Graviton Couplings ←

Fermion-Graviton Couplings Turn On

All KK Production Modes and Decays Accessible →

Constraint from
No fine-tuning of
Yukawa's

Summary:

Large Extra Dimensions:

Gravity only in bulk.
Finely spaced KK tower. [Σ states yields observability
Consequences for Cavendish-type exp't.
Large Astro/Cosmo constraints for $n=2$.
Collider Probes: Graviton Emission } Present: $M_* \gtrsim$ Te
Exchange } Future: $M_* \gtrsim 6$-7

TeV^{-1} Extra Dimensions:

Large Model Building Choices!
SM in bulk
Fermions: Fixed points - $M_c \gtrsim 4$ TeV
Localized - Natural supression of p dk
Bulk - Evades Limits! $M_c \gtrsim 400$ GeV

Localized Gravity:

No new hierarchies
Direct Graviton Resonance production
LHC probes parameter space: SM on wall
Drastic change in phenomenology: SM off wall

The Physics of Extra Dimensions

Spring '98: Extra Dimensional Revolution!

Plethora of Models now exist

- Began classification of models and resulting phenomenology
  Snowmass 2001 Davoudiasl, JLH, Rizz

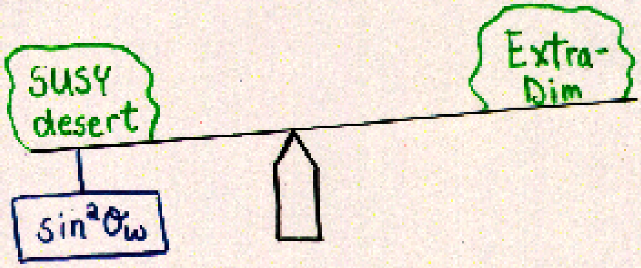
Use Extra Dimensional Geometry to:

- Solve hierarchy problem
- Generate EWSB
- Generate SUSY Breaking
- Generate flavor breaking
- Generate ν masses (see-saw from the bulk)
- Suppress proton decay

✓ • Grand Unification possible with power law running Dienes Randal
- Progress on cosmological constant problem

Rash of New Ideas!

Implications for Tabletop/Flavor/Collider/Astro-Cosmological/Precision EW Physics!



Exp't will decide!