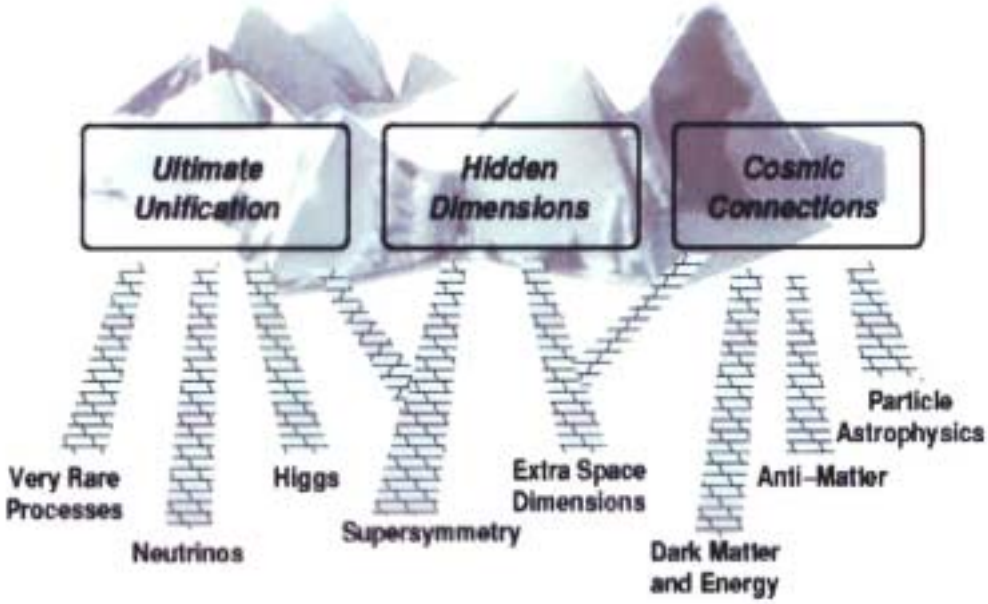
What is Particle Physics?

Our Definition

The Science of Matter, Energy, Space and Time



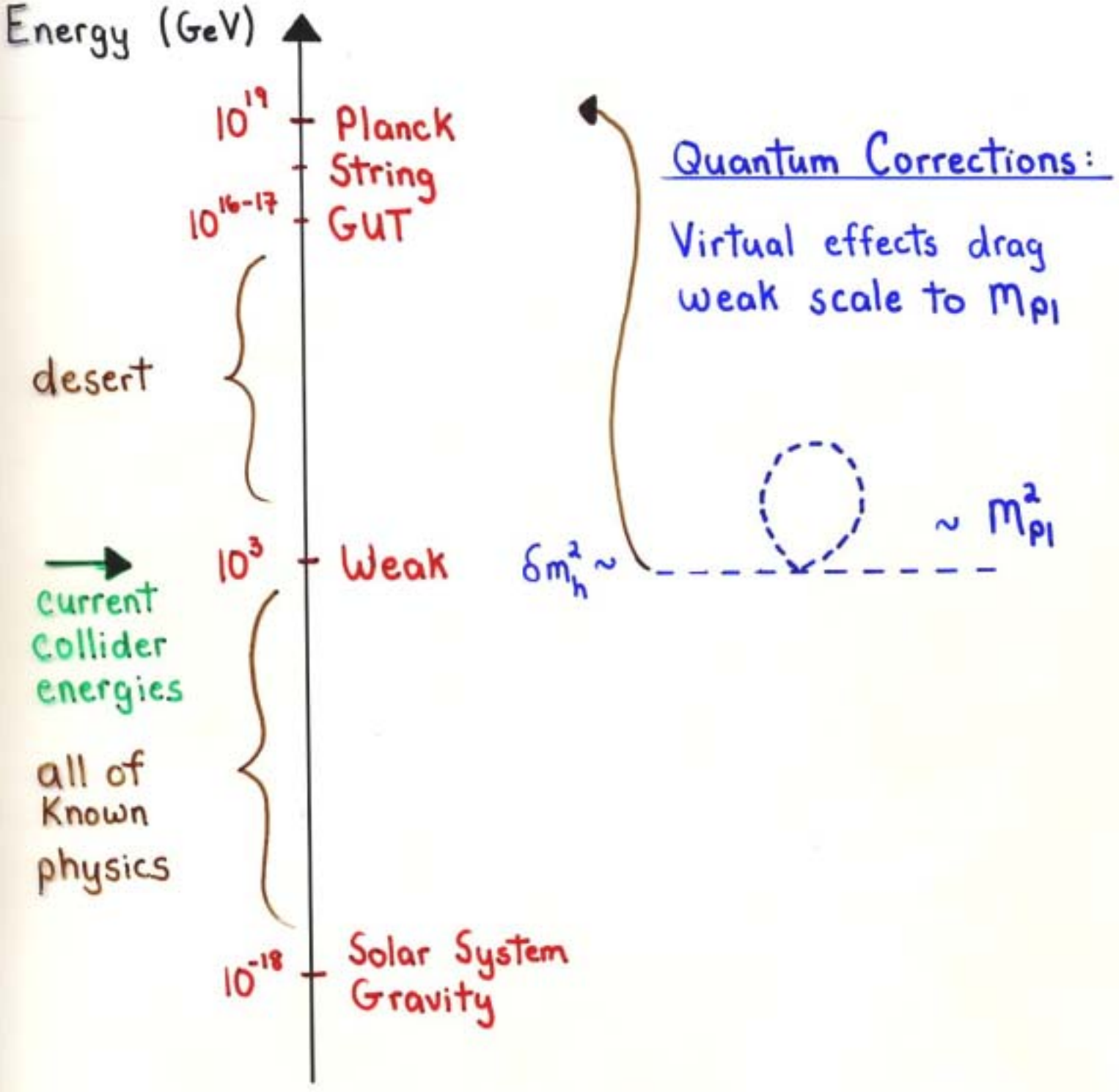
The Paths and Goals of Particle Physics

Exploring the Fabric of Spacetime

- Resolution of the Hierarchy Problem requires New Physics at the TeV scale
- One possibility is Extra Dimensions
  $\Rightarrow$ TeV scale signatures!
- Large discovery potential at future colliders
- Synergy between high energy e^+e^- and hadron colliders can probe geometric properties of the new space

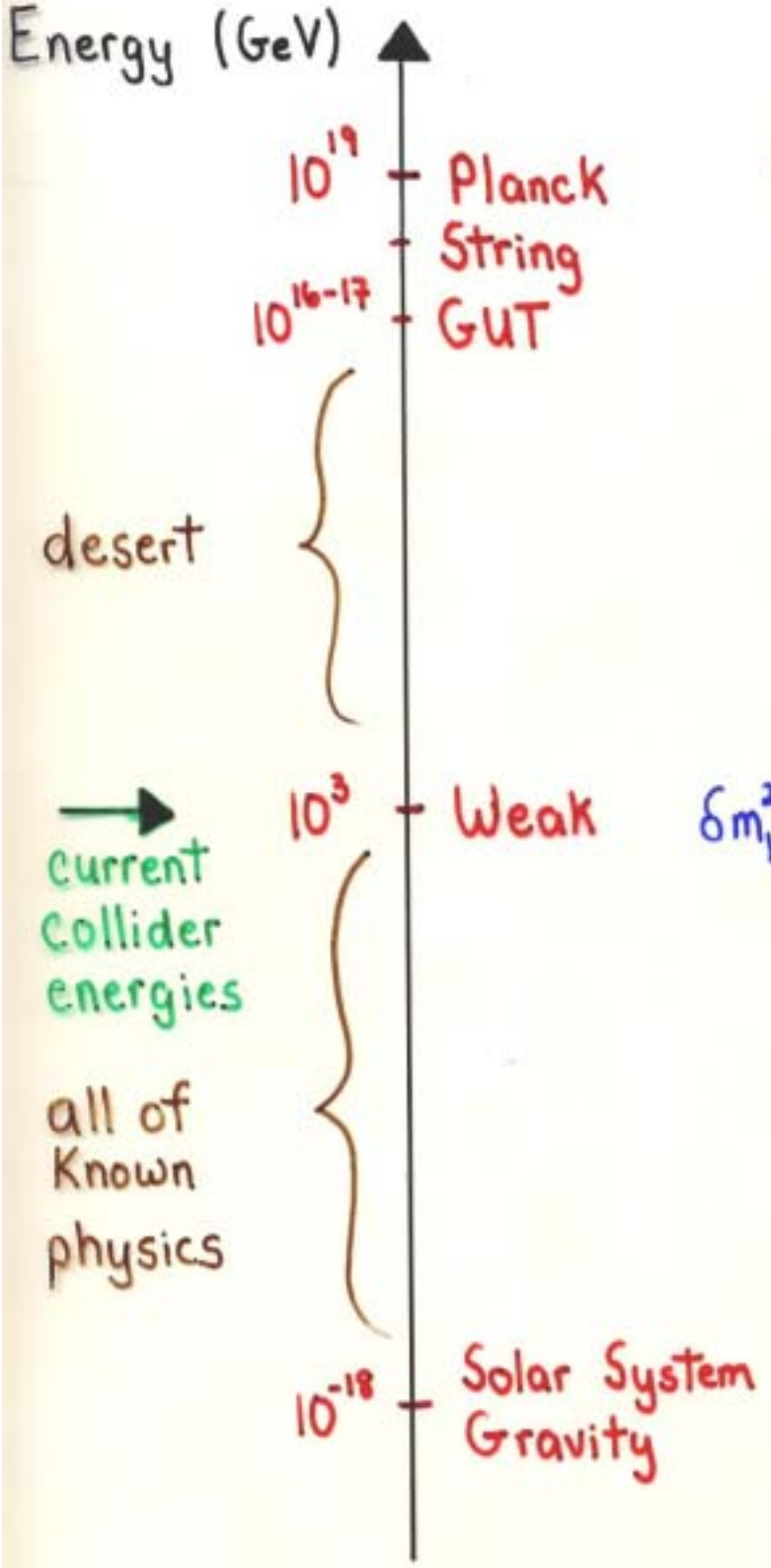
$\Rightarrow$ **Discovery of Extra Dimensions would have profound impact on our view of the universe!**

The Hierarchy Problem



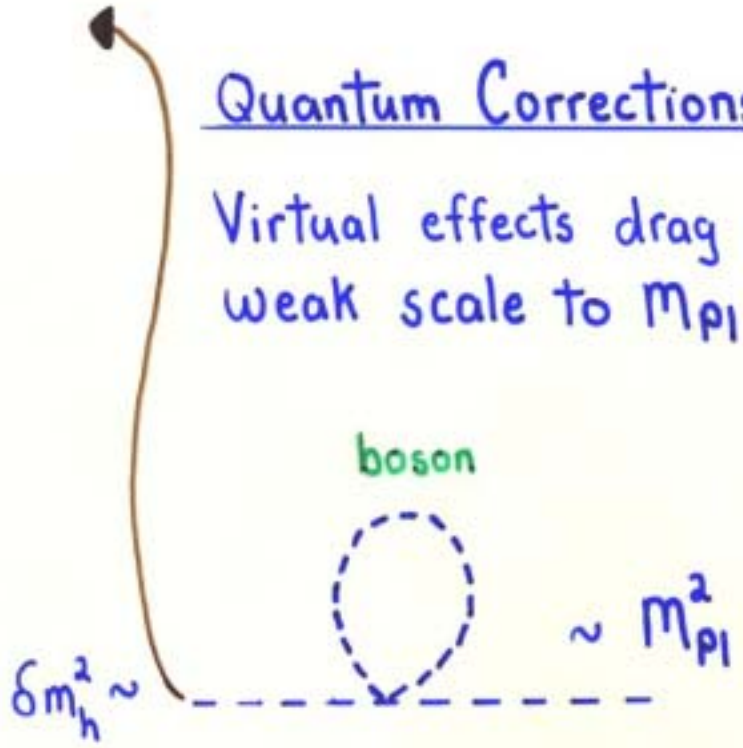
The Hierarchy ~~Problem~~ Solution

Supersymmetry!



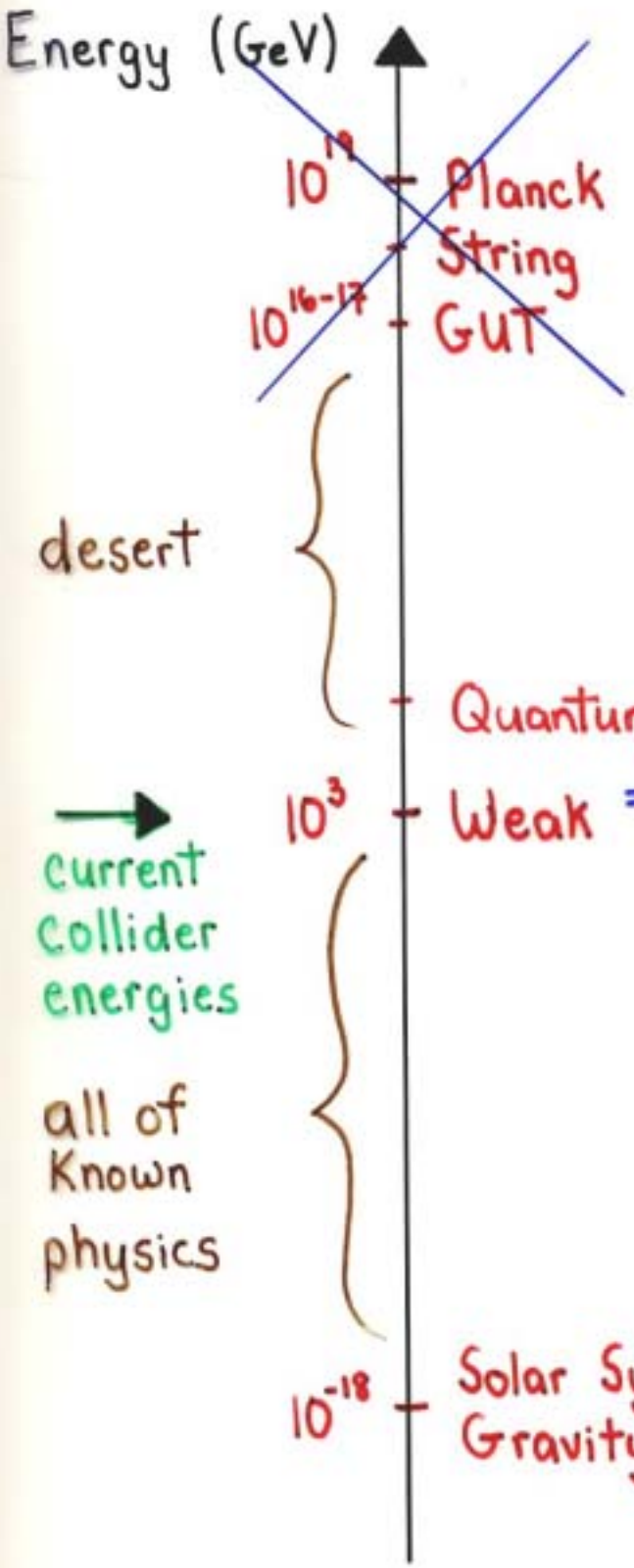
Quantum Corrections:

Virtual effects drag weak scale to m_{Pl}



Large virtual effects cancel order by order in perturbation theory

The Hierarchy ~~Problem~~ Solution



Extra Dimensions!

Simplest model:
Large Extra Dimensions

Weak = Fundamental scale in $4+\delta$ dimensions

$$m_{Pl}^2 = (\text{Volume})_\delta \, m_D^{2+\delta}$$

Gravity propagates in $D = 3+1+\delta$ dimensions

The Hierarchy ~~Problem~~ Solution

Energy (GeV)

10^{19} – Planck

String

$10^{16\text{-}17}$ – GUT

desert

10^{3} – Weak

current collider energies

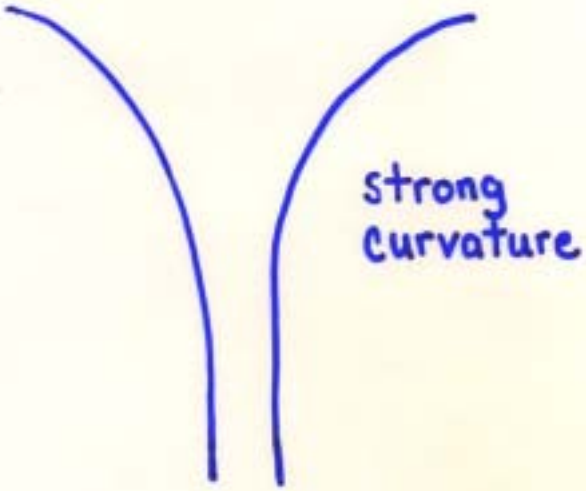
all of Known physics

10^{-18} – Solar System Gravity

Extra Dimensions!

Model II:

Warped Extra Dims



$\Lambda_{WK} = M_{Pl}\, e^{-Krπ}$

Once a signal is discovered:

What do we learn?

- Prove signal is gravity
- Determine Fundamental scale
- Measure number of extra dims
- Measure size of extra dimensions
- Determine geometry of extra dimensions: flat versus curved
- Measure brane tension and thickness
- Determine location of SM particles
- ....

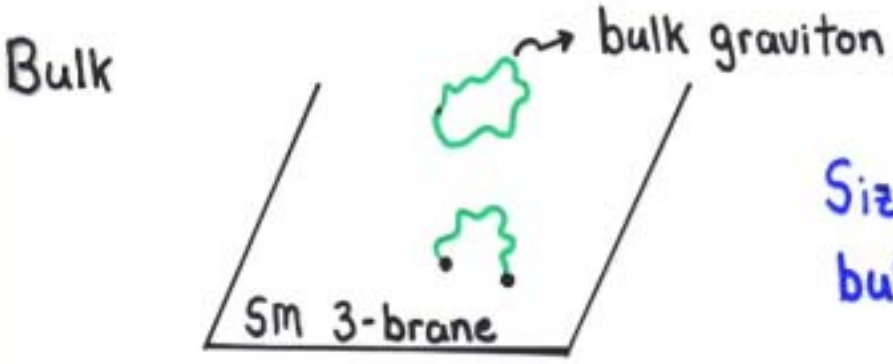
⇒ **Explore the Additional Spacetime with Collider Data!**

A Few Concepts from Kindergarten String Theory…

Physics of Branes: Spatial Dimensional Subspace

Our 3+1-dim subspace = 3-brane

Embedded in $D = 3+\delta+1$ space = bulk

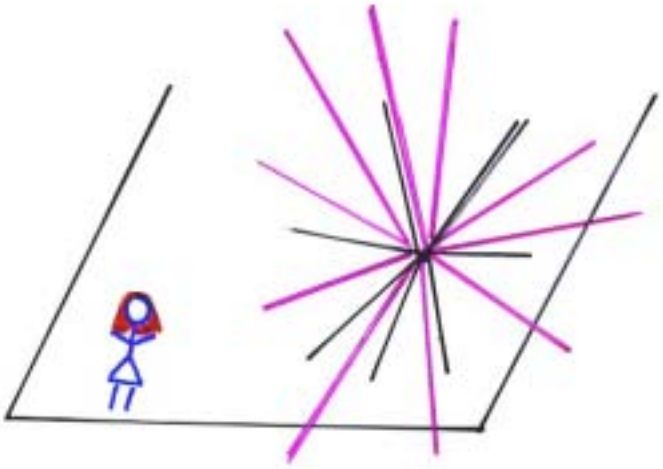


Size + geometry of bulk can vary

String Theory provides mechanism to 'localize' fields on brane

- Gauge theories live on brane
- Gauge particles live at end of strings
- Closed strings are neutral
  ⇒ can pop off brane = bulk gravitons

Compactification



Standard Model forces stuck on 3-brane

Gravitational fields spread out over all spacetime

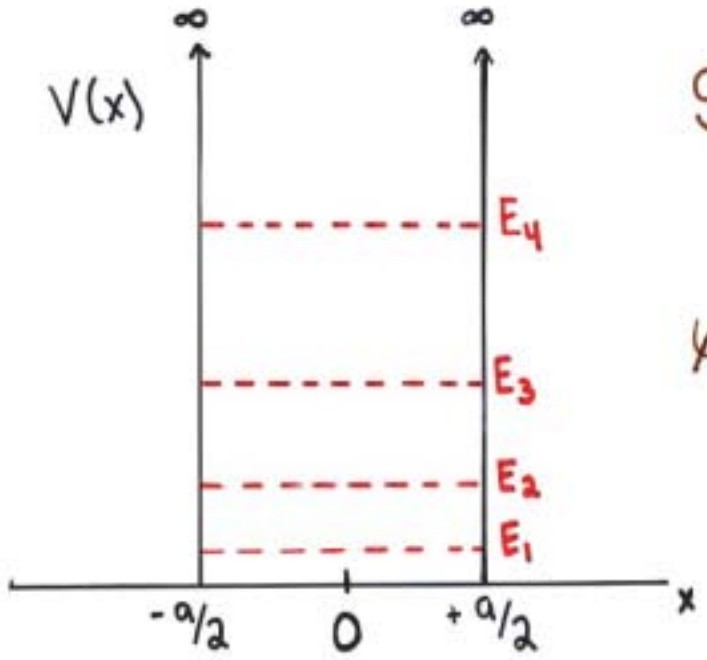
Are gravitational fields diluting too quickly?

⇒ Extra dimensions must be compactified!

$F_{Gr} \sim \frac{1}{r^2}$ recovered on 3-brane

Particle in a Box

Infinite Square-Well potential



Sol'n to Schroedinger Eqn:

$$\psi_n(x) = \begin{cases} A_n \cos K_n x, & n = 1, 3, 5, \ldots \\ B_n \sin K_n x, & n = 2, 4, 6, \ldots \end{cases}$$

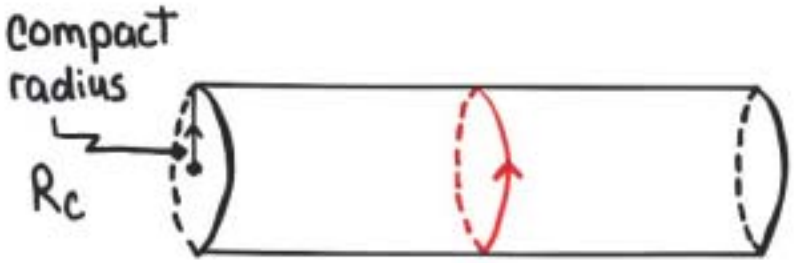
where $K_n = n\pi/a$

Momentum of the particle is Quantized!

$E_n \sim n^2/a^2$ (non-relativistic)

Fields in Compact Dimensions:

Expand into Kaluza-Klein towers



δ-d kinetic motion is quantized!

$$p_\delta^2 = \frac{\vec{n}\cdot\vec{n}}{R_c^2}$$

Appears as tower of massive particles in 4-d

$$m_{\vec{n}}^2 = \frac{\vec{n}\cdot\vec{n}}{R_c^2}$$

with identical spin & quantum numbers

mode numbers $\vec{n} = (n_1, n_2, \ldots n_\delta)$ label KK excitation

- **Experimental observation of KK states:**

  Signals existence of extra dimensions

- **Properties of KK states:**

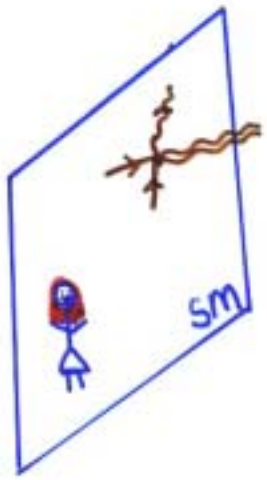
  Determined by geometry of extra dimensions

  $\Rightarrow$ measured by experiment!

Large Extra Dimensions

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

Motivation: Solve the hierarchy problem by removing it!



SM fields confined to 3-brane

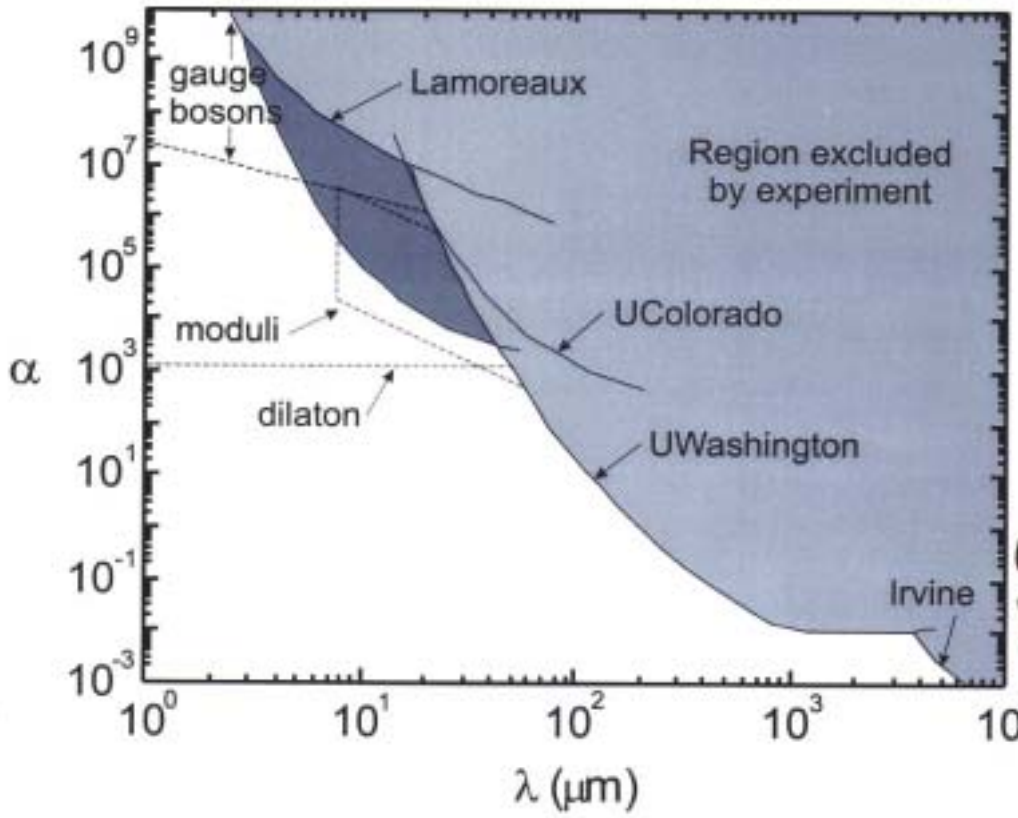
Gravity becomes strong in the bulk

Gauss' Law: $M_{Pl}^2 = V_\delta M_D^{2+\delta}$; $V_\delta \sim R_c^\delta$

M_D = Fundamental scale in the bulk
$\simeq$ TeV

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

Constraints from Cavendish-type exp'ts



Chiaverini etal
hep-ph/020935

$$V_{gravity} \sim \frac{m_1 m_2}{M_D^{2+\delta}} \frac{1}{r^{\delta+1}} \qquad (r < R_c)$$

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

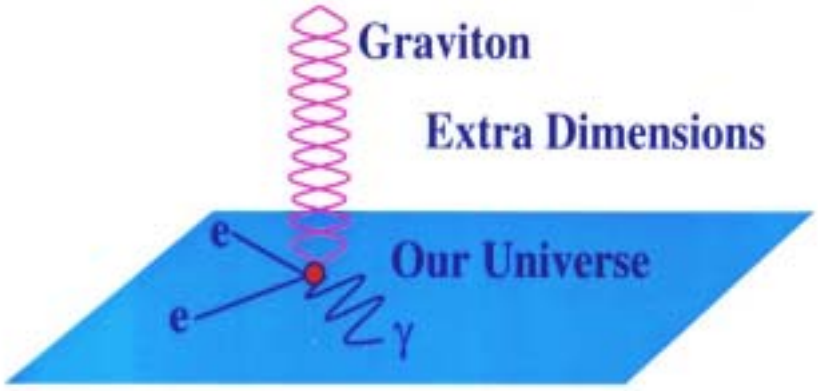
For $\delta = 2$: $\lambda \leq 190\ \mu$ $\quad [M_D \gtrsim 1.8\ \text{TeV}]$

Constraints from Astrophysics/Cosmology

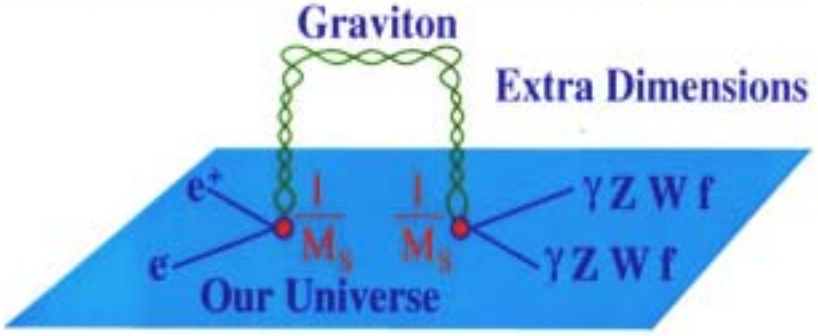
M_D (TeV)	$\delta = 2$	3	4	5
Supernova Cooling	30	2.5		
Cosmic Diffuse γ-Rays				
Sne	80	7		
$\upsilon\bar{\upsilon}$ Annihilation	110	5		
Reheating	170	20	5	1.5
Neutron Star	450	30		
Matter Dominated Universe	85	7	1.5	
Neutron Star Heating	1700	60	4	1

Low M_D disfavored for $\delta \leq 3$

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



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



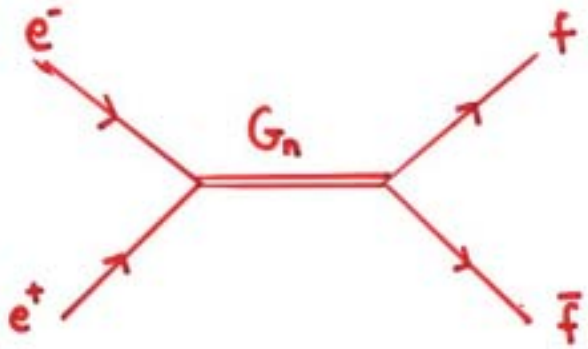
Graviton Tower Exchange $XX \to G_n \to YY$

Search for 1) Deviations in SM processes
2) New processes! $(gg \to \ell^+\ell^-)$

Angular distributions reveal spin-2 exchange

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

$$\mathcal{M} = \frac{1}{16\, M_{Pl}^2} \sum_{\vec{n}} \frac{T^e_{\mu\nu}\, P^{\mu\nu\lambda\sigma}\, T^f_{\lambda\sigma}}{S - m_n^2 + i\epsilon}$$



G_n are densely packed!

$(M_D R_c)^\delta$ states are exchanged! $(\sim 10^{32}$ for $\delta = 2)$

$$\Rightarrow \sum_{\vec{n}} \to \int dm^2\, \rho(m^2)$$

$$\frac{1}{M_{Pl}^2} \sum_{\vec{n}} \frac{1}{S - m_n^2} \to \frac{1}{M_D^4}$$

JLH, PRL 99
Giudice, Rattazzi, Wells

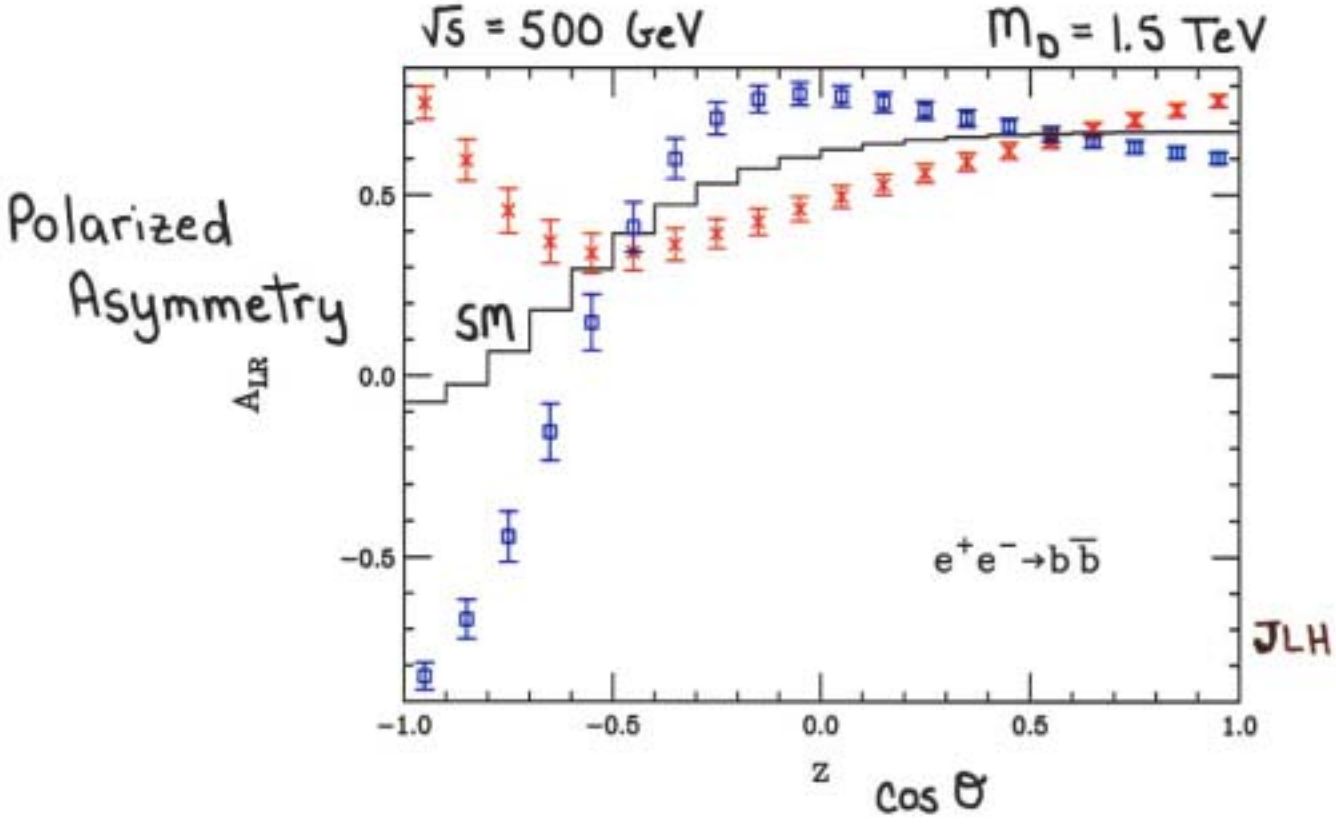
Search Reach at Future Colliders

		$\sqrt{s}$	M_D (TeV)
LC:	$e^+e^- \to f\bar{f}$	500 GeV	5.0
		1 TeV	8.4
	$\gamma\gamma \to \gamma\gamma$	1 TeV	3.5
	$\gamma\gamma \to WW$		13.0
	$e\gamma \to e\gamma$		8.0
LHC:	$pp \to l^+l^-$	14 TeV	7.5
	$pp \to \gamma\gamma$		7.1

(@ design luminosity)

LHC/LC Explore the parameter space which is relevant to the hierarchy!

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



- Governed by spin of exchanged particle

Expand $\frac{d\sigma}{d\cos\theta}$ in moments of $P_n(\cos\theta)$

Spin-2 exchange: $\langle P_{3,4}(\cos\theta)\rangle \neq 0$

$\langle P_{n>4}(\cos\theta)\rangle = 0$

Fit to simulated $e^+e^- \to f\bar{f}$ data: Rizzo

5σ ID of spin-2 for $M_D \lesssim (5\text{-}6)\sqrt{s}$

Graviton Tower Emission

Giudice, Rattazzi, Wells
Mirabelli, Perelstein, Peskin

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

G_n appears as missing energy
Model independent - Probes M_D directly
Sensitive to δ

Parameterized by density of states

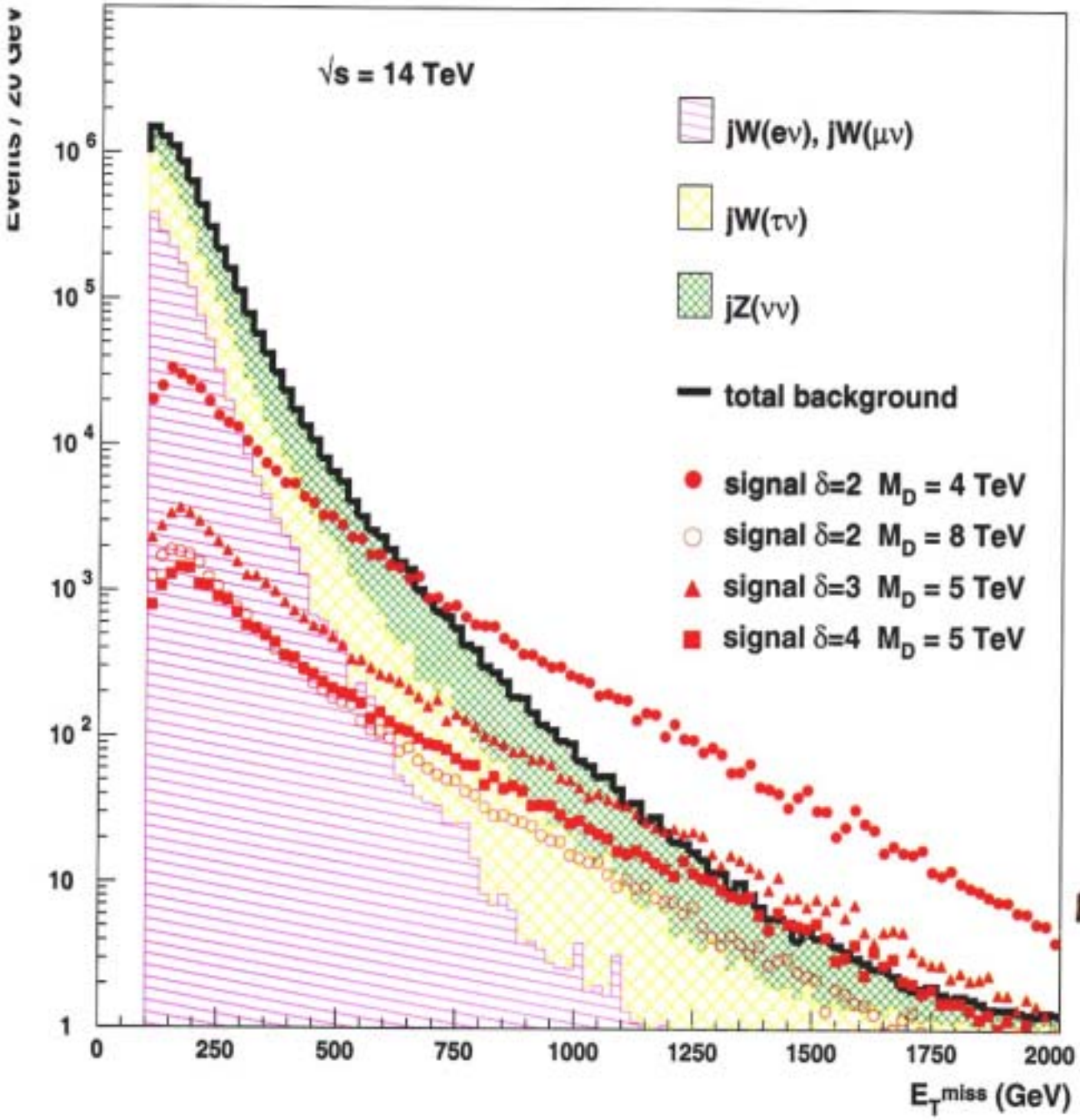
$$\sigma \sim \frac{1}{m_{Pl}^2} (E R_c)^\delta \to \frac{1}{m_D^2} \left(\frac{E}{m_D}\right)^\delta$$

Discovery Reach for M_D (TeV)

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

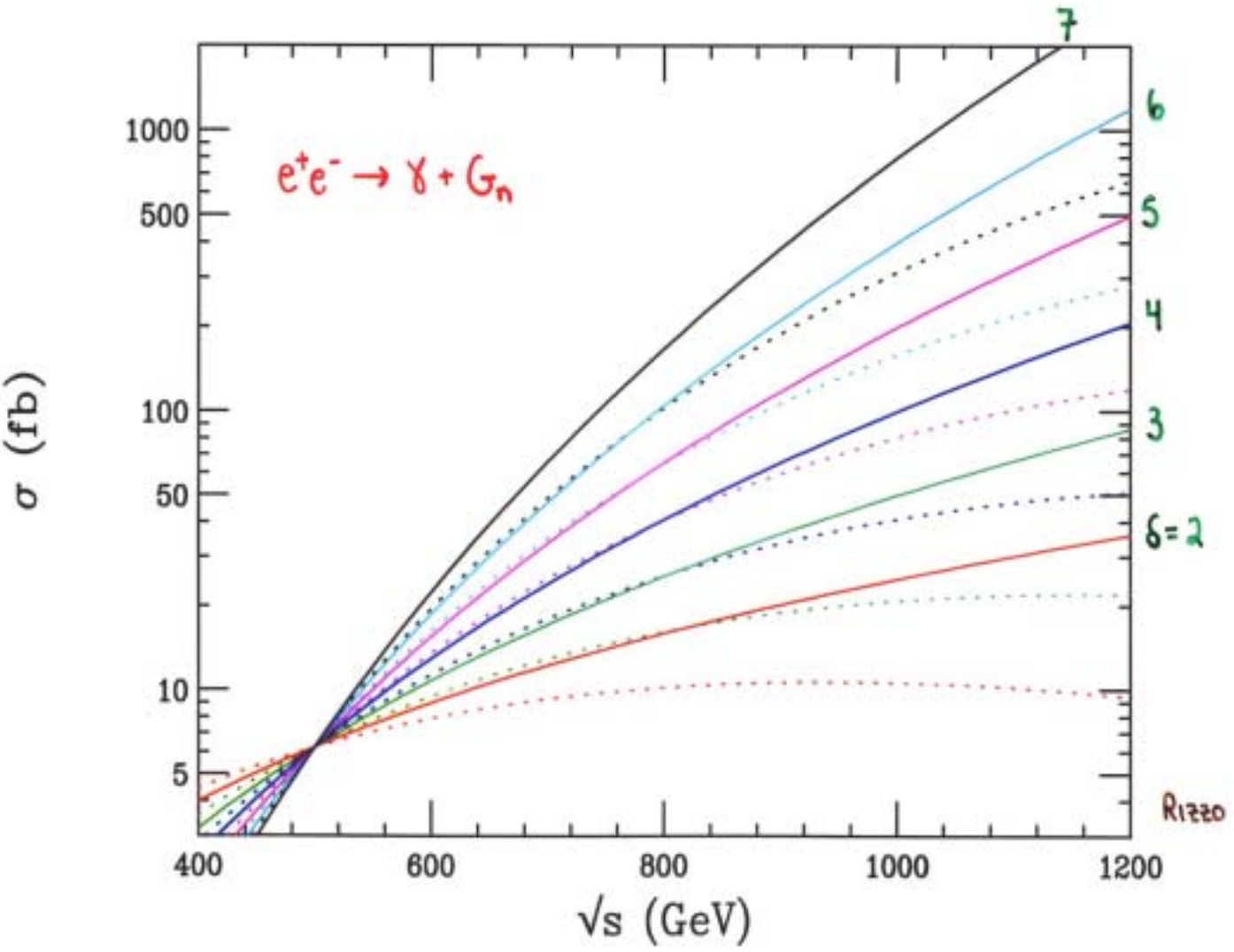
Simulated Graviton Emission at LHC

Events / 20 GeV



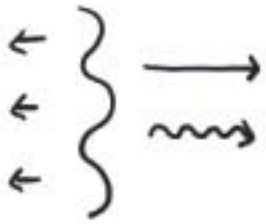
Hinchliffe, Vacavant

Determination of Number of Extra Dimensions



Normalized to $M_D = 5$ TeV, $\delta = 2$ at $\sqrt{s} = 500$ GeV

Branes gone soft : Graviton Emission $e^+e^- \to \gamma G_n$



soft brane
can recoil

Suppresses KK tower couplings

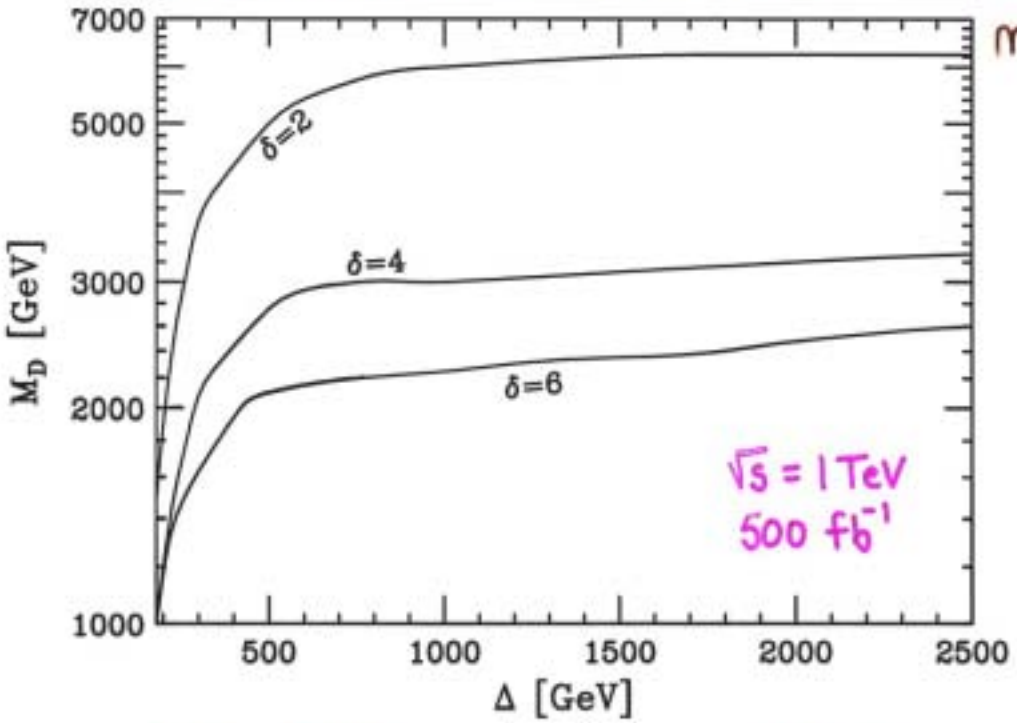
$$g_n^2 \to g_n^2 \, e^{-m_n^2/\Delta^2}$$

$\Delta \sim \sqrt{T}$ wall tension $\lesssim m_D$

Search Reach is reduced

$$\left.\frac{d^2\sigma}{dx_\gamma \, d\cos\theta}\right|_{soft} \to \left.\frac{d^2\sigma}{dx_\gamma \, d\cos\theta}\right|_{stiff} e^{-s(1-x_\gamma)/\Delta^2}$$

Reach in $e^+e^- \to \gamma G_n \to \gamma \not{E}_T$



Murayama Wells

⇐ soft brane stiff brane ⇒

TeV^{-1} - size Extra Dimensions

Can arise naturally in string theory Antoniadis

The SM goes into the bulk!

Model building choices:

- Gauge fields in the bulk
- Higgs in bulk or on brane?
- Fermions
  - fixed points
  - bulk
  - localized

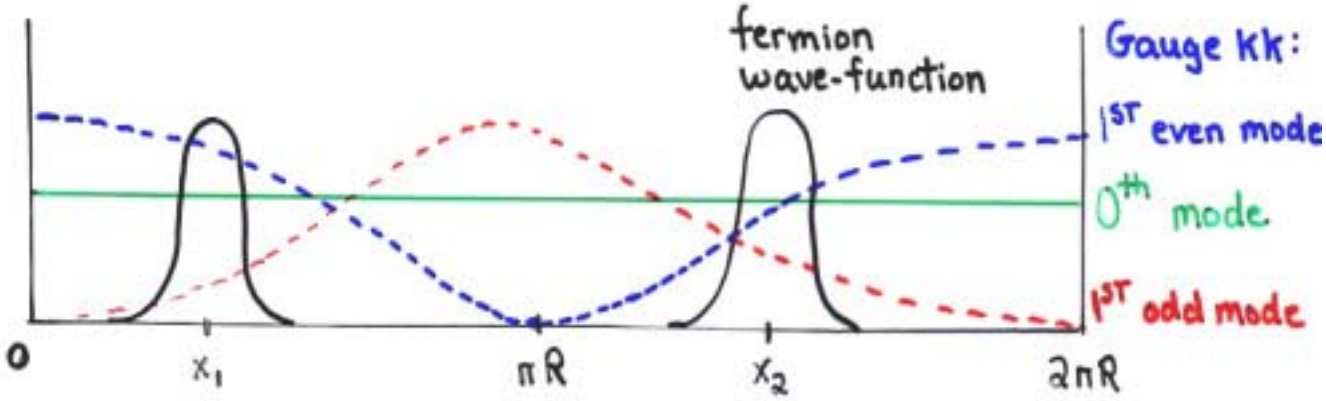
Discovery Reach for γ/Z KK state (TeV)

LHC:	100 fb^{-1}		6.3	direct production
LC:	500 fb^{-1}	$\sqrt{s}$ = 500 GeV	13.0	indirect exchange
		1.0 TeV	23.0	
		1.5 TeV	31.0	

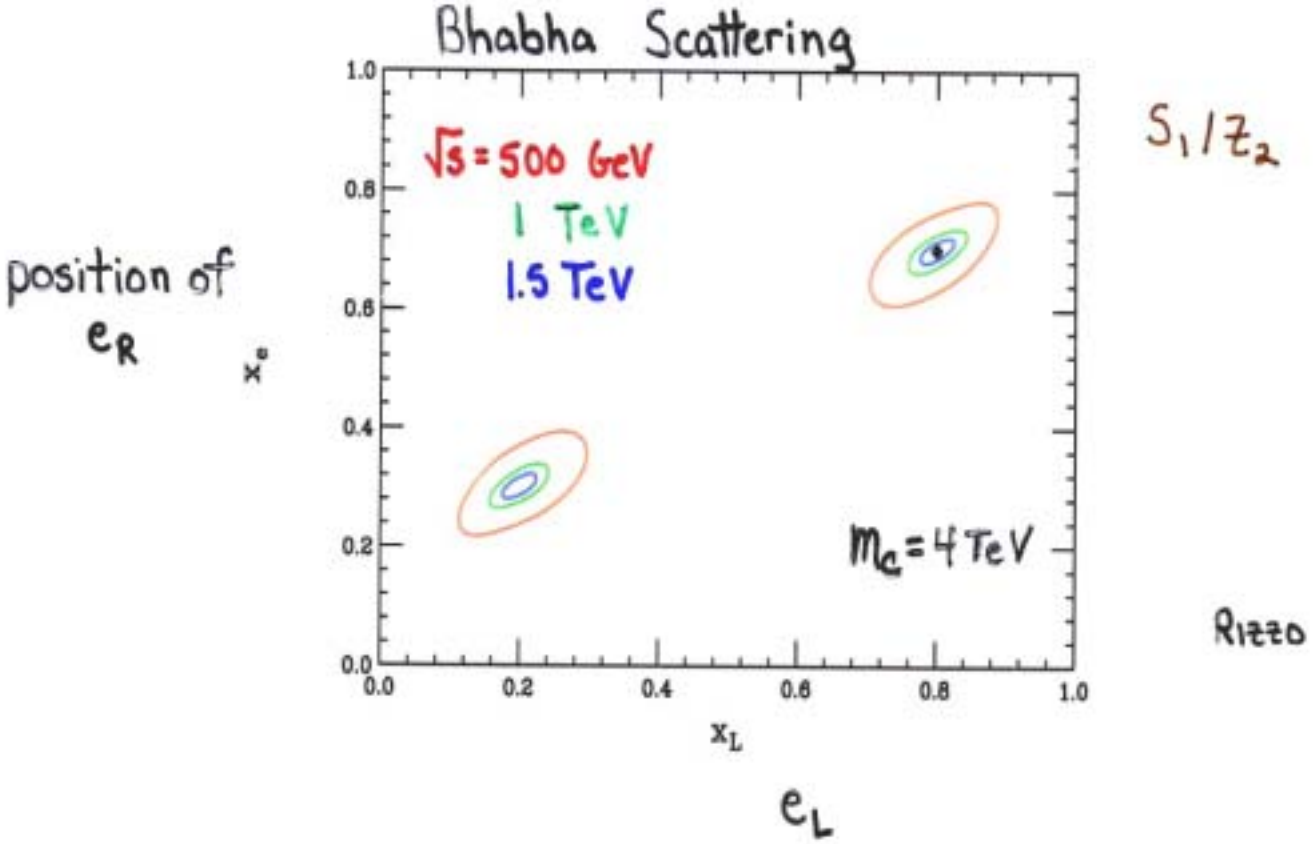
Separated Fermions

Arkani-Hamed, Schmaltz

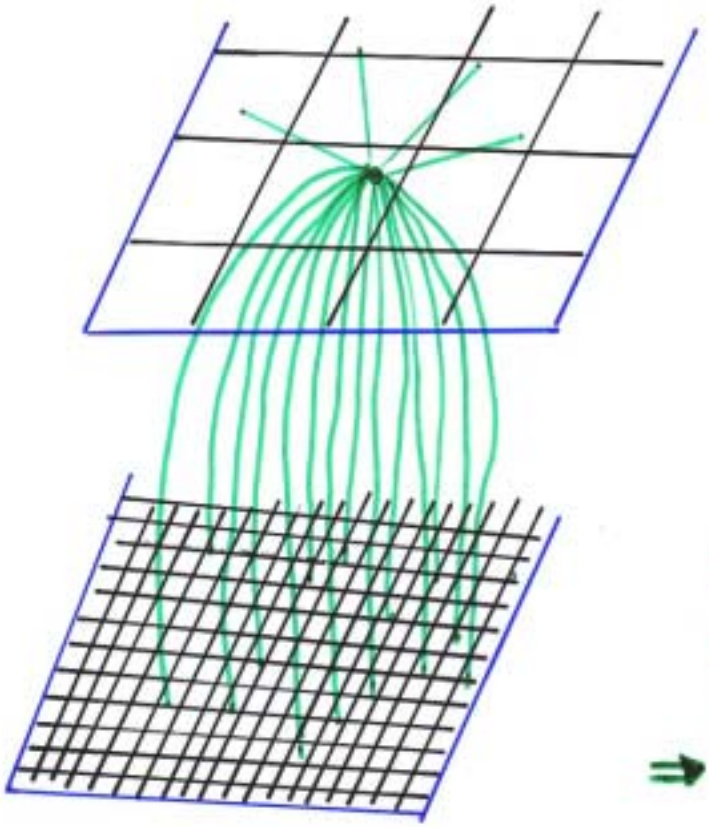
Fermions can be localized at different points in a thick brane



Gauge KK couplings probe relative fermion locations!



Non-Factorizable Curved Geometry - 'Warped' Space



Area of each grid is equal

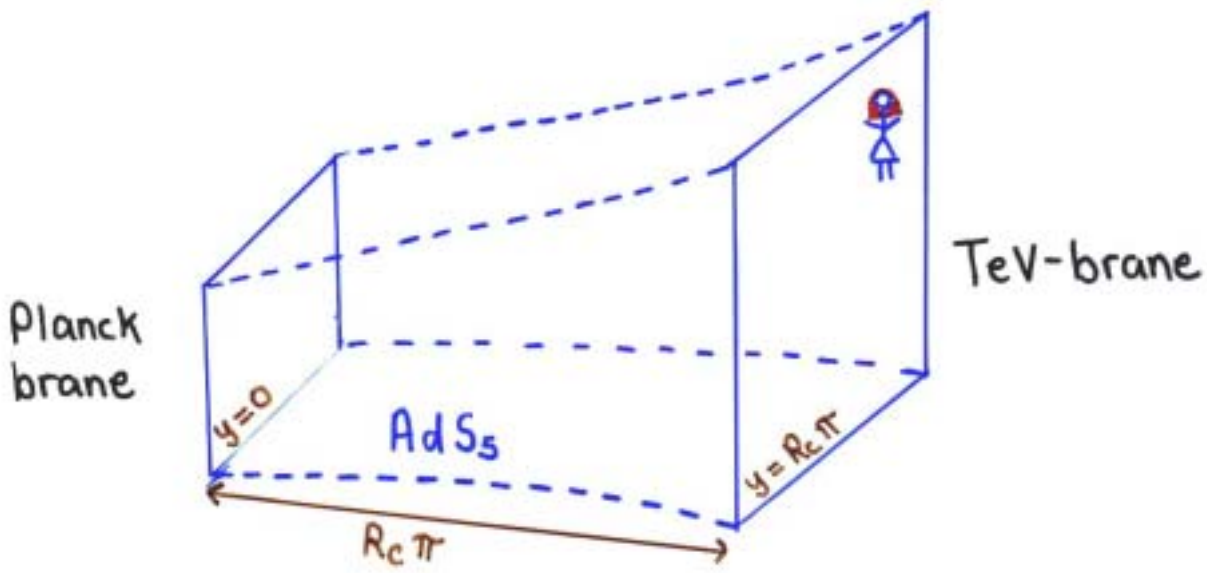
Field lines spread out faster with more volume

⇒ Drop to bottom brane

Gravity appears weak on top brane!

Localized Gravity

Randall, Sundrum



Bulk = Slice of AdS_5

$\Lambda_5 = -24\, m_5^3\, k^2$ ← curvature scale

5-D non-factorizable geometry:

$$ds^2 = e^{-2ky}\,\eta_{\mu\nu}\,dx^\mu dx^\nu - dy^2$$

e^{-2ky} ← Warp factor

$m_5 \sim m_{Pl} \sim k$ ⇒ no additional hierarchies!

Physical scales on SM 3-brane:

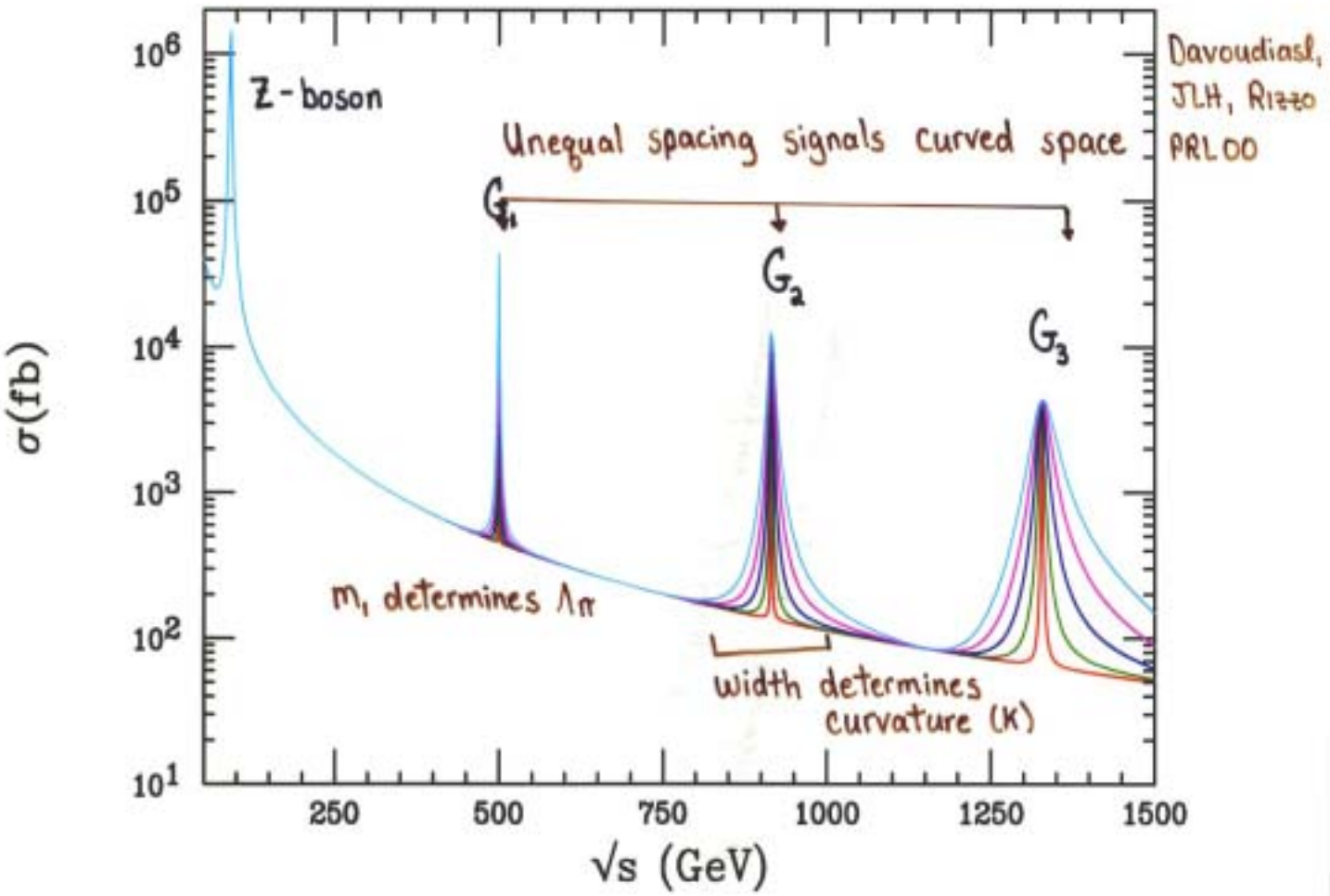
$$\Lambda_\pi = e^{-kR_c\pi}\, m_{Pl}$$

$\simeq$ TeV if $kR_c \sim 11$

Naturally stabilized via Goldberger-Wise

Hierarchy is generated by an exponential!

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



LC becomes a Graviton Factory!

Summary

- **Resolution of the Hierarchy requires New Physics at the TeV Scale**
- **One possibility is the existence of Extra Dimensions with signatures at the TeV Scale!**
- **Large discovery potential at future colliders**
- **The synergy between high energy e^+e^- and Hadron Colliders can probe the geometric properties of the new space**

$\Rightarrow$ Discovery of Extra Dimensions would have profound impact on our view of the Universe!

Limits from $G_{KK}\gamma$ Emission

H. Zheng

LEP: B. Vachon; hep-ex/0201029 v2

n	2	3	4	5	6	7
ALEPH (189-209 GeV) M_D Limit (TeV)	1.28	0.97	0.78	0.66	0.57	—
DELPHI (181-209 GeV) M_D Limit (TeV)	1.38	—	0.84	—	0.58	—
L3 (189 GeV) M_D Limit (TeV)	1.02	0.81	0.67	0.58	0.51	0.45
OPAL (189 GeV) M_D Limit (TeV)	1.09	0.86	0.71	0.61	0.53	0.47

CDF: hep-ex/0205057

n	4	6	8
M_D Limit (TeV)	0.55	0.58	0.60

Limits from Virtual G_{KK} Effects

H. Zheng

- Different notations used in different processes:
  - M_D is the fundamental mass scale – real graviton
  - M_S is the ultraviolet cutoff of the divergent sum over the KK excitations – virtual effects
- No exact relation between M_D and M_S is available
- M_D and M_S are expected to be of the same order

Hewett convention

DØ [PRL 86 (2001) 1156]: Ms (λ = +1) > 1.1 TeV; Ms (λ = -1) > 1.0 TeV

LEP Combined Results [hep-ex/0111063 v2]: Ms (λ = +1) > 1.0 TeV; Ms (λ = -1) > 1.1 TeV

CDF Preliminary [hep-ex/0111063 v2]: Ms (λ = +1) > 0.8 TeV; Ms (λ = -1) > 0.9 TeV