Extra Dimensions at the Tevatron: the Discovery Strategy

Greg Landsberg

BROWN UNIVERSITY

Durham Workshop

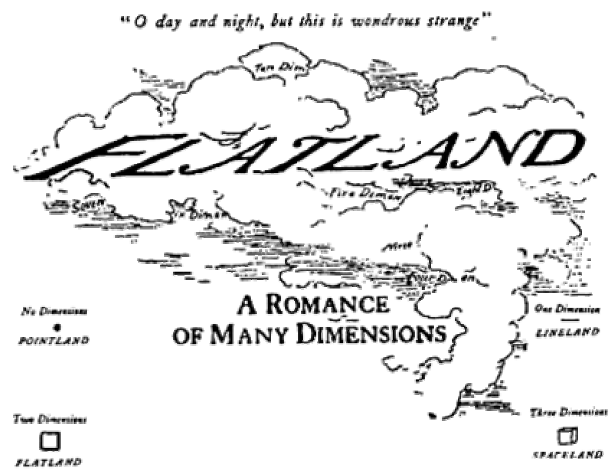
March 26, 2003

Outline

- Brief History of Space
- More Fun in Extra Dimensions
  - ADD Model
  - TeV^{-1} Scenario
  - RS Model
  - Universal Extra Dimensions
  - "Contracted" Extra Dimensions
- Current Constraints on Models with Extra Dimensions
  - Gravity at Short Distances
  - Cosmology and Astrophysics
  - Collider Probes
- Probing Extra Dimensions at the Tevatron
- Conclusions

Brief History of Space: XIX Century

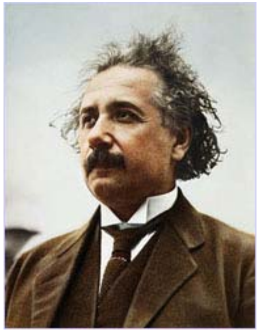
- In the XIXth century people were convinced that the universe is three-dimensional
- Bernhard Riemann was the first person to question this seemingly natural conclusion
  - In 1854, as a completion of his *Habilitation* degree at Göttingen, he gives a lecture: *"Über die Hypothesen welche der Geometrie zu Grunde liegen"* (*"On the hypotheses that lie at the foundations of geometry"*), where he gave a definition of what is known today as Riemannian space and the curvature tensor
- It was not until Einstein's general theory of relativity that Riemann's ideas were fully appreciated and understood

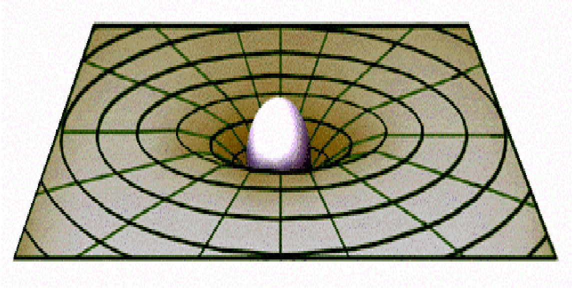


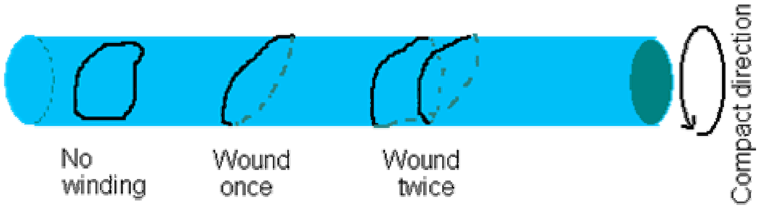
- Edwin Abbot's "Flatland" (1884)
  - The story is told by Mr. A. Square (four-sided polygon), a middle-class inhabitant of a two-dimensional world, the flatland
  - He is taken on a journey to a three-dimensional world, and upon return tries to explain higher dimensions to his cohabitants, just to be imprisoned as an imbecile…

Brief History of Space: XXth Century

- 1915: Albert Einstein formulates general theory of relativity, based on Riemannian space
  - The space is curved due to gravity; in fact curvature of the space IS gravity
  - One of the most striking prediction of this theory was existence of black holes
- 1919-1926: Theodore Kaluza and Oscar Klein showed that adding an extra compact dimension to general relativity allows to unify it with electromagnetism
- Since 1970-ies: string theory implements the idea of compact dimensions to generalize Einstein's relativity theory into quantum theory of gravity
  - These extra dimensions are curled-up extremely tight, with radii ~10^{-32} m
  - The preferred number of extra spatial dimensions is 6 or 7







Shakespeare on Compact Dimensions

"…Why bastard? wherefore base?

When my dimensions are as well compact,

My mind as generous, and my shape as true,

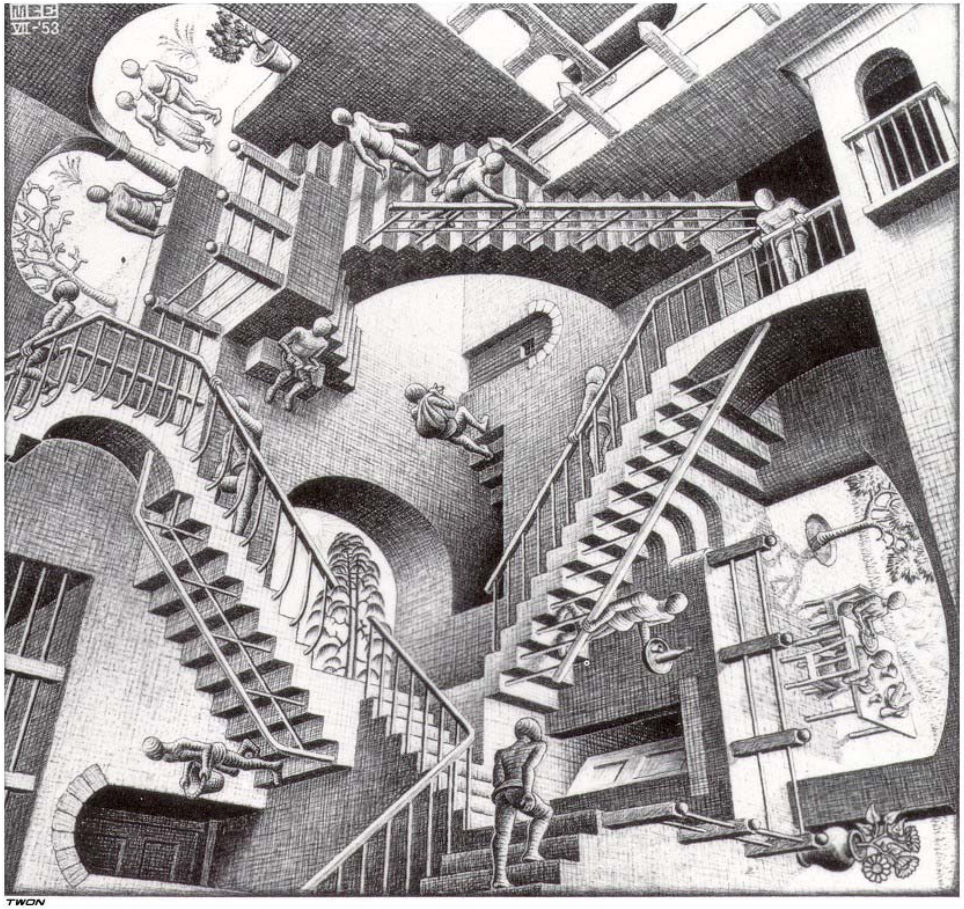
As honest madam's issue?"

(Edmund, bastard son to Gloucester)

Shakespeare, King Lear, Act 1, Scene 2

Examples of Compactified Spatial Dimensions

M.C.Escher, Mobius Strip II (1963)



M.C.Escher, Relativity (1953)

Math Meets Physics

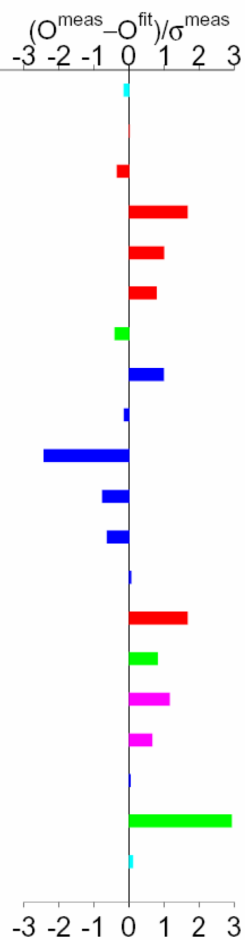
- Math physics: some dimensionalities are quite special
- Example: Laplace equation in two dimensions has logarithmic solution; for any higher number of dimensions it obeys power law instead
- Some of these peculiarities exhibit themselves in condensed matter physics, e.g. diffusion equation solutions allow for long-range correlations in 2D-systems (cf. flocking)
- Modern view in topology: one dimension is trivial; two and three spatial dimensions are special (properties are defined by the topology); any higher number is not
- Do we *live* in a special space, or only *believe* that we are special?

Life Within the Standard Model

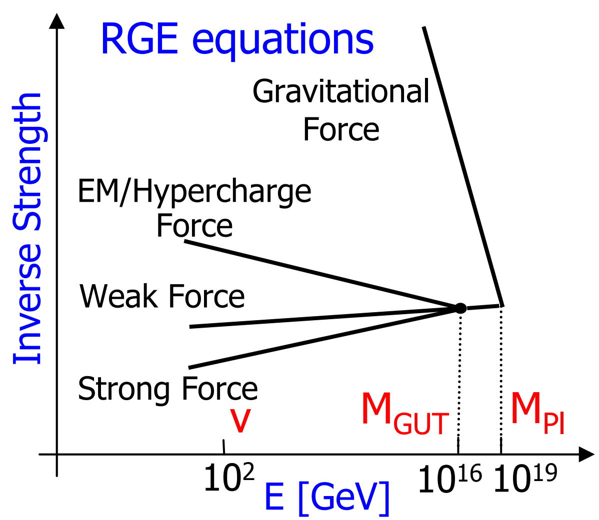
- ...is boringly precise:

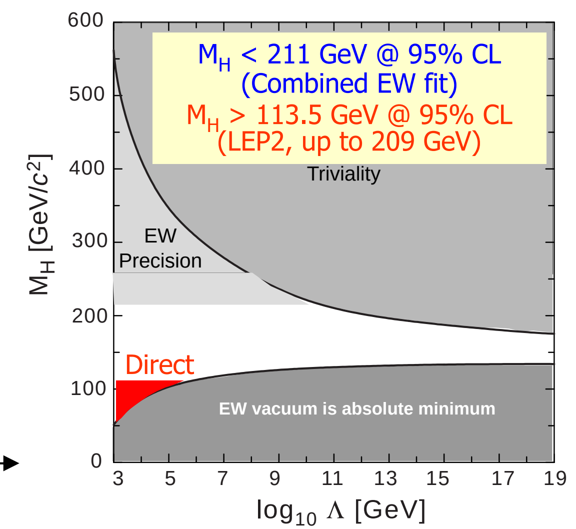
Winter 2003

	Measurement	Pull
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02761 ± 0.00036	-0.16
m_Z [GeV]	91.1875 ± 0.0021	0.02
Γ_Z [GeV]	2.4952 ± 0.0023	-0.36
σ^0_{had} [nb]	41.540 ± 0.037	1.67
R_l	20.767 ± 0.025	1.01
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.79
$A_l(P_\tau)$	0.1465 ± 0.0032	-0.42
R_b	0.21644 ± 0.00065	0.99
R_c	0.1718 ± 0.0031	-0.15
$A^{0,b}_{fb}$	0.0995 ± 0.0017	-2.43
$A^{0,c}_{fb}$	0.0713 ± 0.0036	-0.78
A_b	0.922 ± 0.020	-0.64
A_c	0.670 ± 0.026	0.07
A_l(SLD)	0.1513 ± 0.0021	1.67
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.82
m_W [GeV]	80.426 ± 0.034	1.17
Γ_W [GeV]	2.139 ± 0.069	0.67
m_t [GeV]	174.3 ± 5.1	0.05
$\sin^2\theta_W(\nu N)$	0.2277 ± 0.0016	2.94
Q_W(Cs)	-72.83 ± 0.49	0.12



- ...but not at all boring:
  - Standard Model accommodates, but does not explain:
    - EWSB
    - CP-violation
    - Fermion masses
  - Higgs self-coupling is positive, which leads to a triviality problem that bounds m_H from above
  - The natural m_H value is Λ, where Λ is the scale of new physics; if SM is the ultimate theory up to GUT scale, an extremely precise ($\sim(v/m_{GUT})^2$) fine-tuning is required

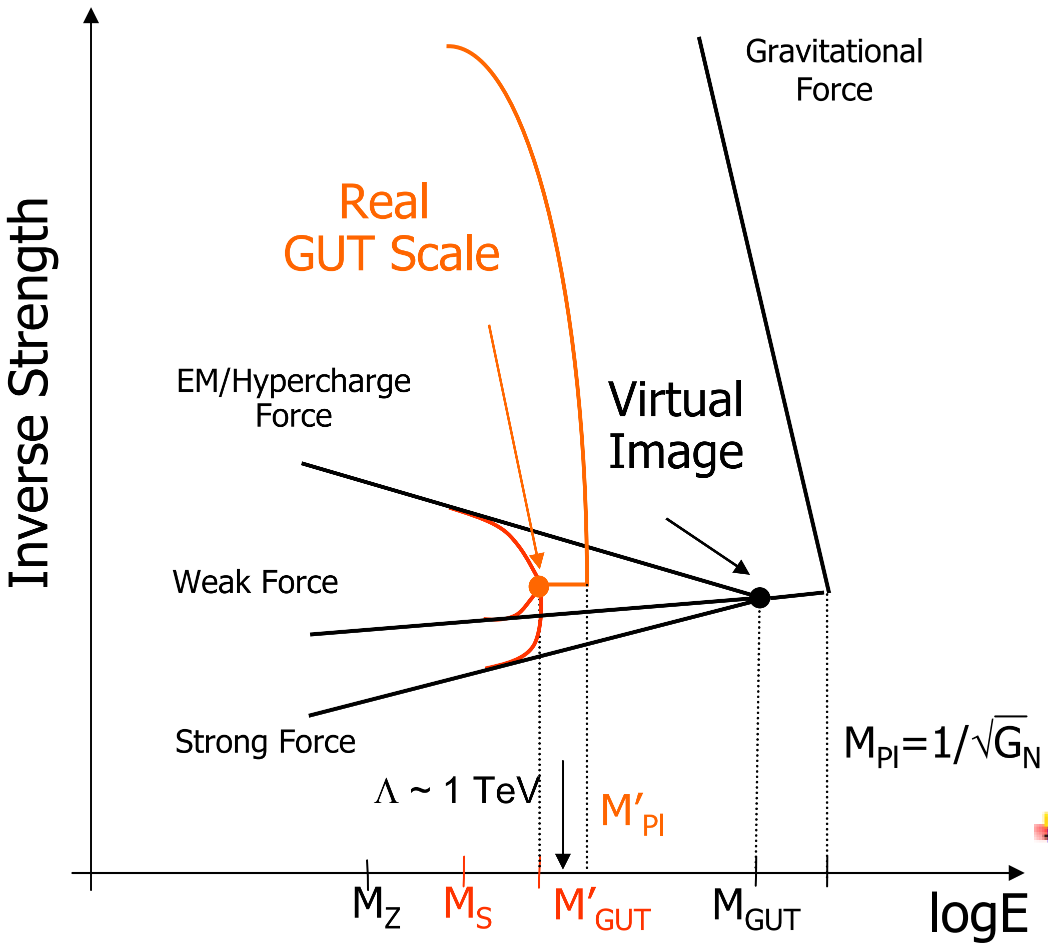




Life Beyond the Standard Model

- We must conclude that the SM is an effective theory, i.e. a low-energy approximation of a more complete model that explains things only postulated in the SM
- This new theory takes over at a scale Λ comparable to the mass of the Higgs boson, i.e. $\Lambda \sim 1$ TeV
- Two main candidates for such a theory are:
  - SUSY (SUGRA, GMSB, AMSB, $\tilde{G}$MSB)
  - Strong Dynamics (TC, ETC, topcolor, top see-saw, …)
- But: the large hierarchy of scales picture is based *solely* on the log extrapolation of gauge couplings by some 14 decades in energy
  - How valid is that?
- 1998: abstract mathematics meets phenomenology. Extra spatial dimensions have been first used to:
  - "Hide" the hierarchy problem by making gravity as strong as other gauge forces in (4+n)-dimensions (Arkani-Hamed, Dimopoulos, Dvali)
  - Explore modification of the RGE in (4+n)-dimensions to achieve low-energy unification of the gauge forces (Dienes, Dudas, Gherghetta)

Extra Dimensions at Work



- Burst of the ideas to follow:
  - 1999: possible *rigorous* solution of the hierarchy problem by utilizing metric of curved anti-deSitter space (Randall, Sundrum)
  - 2000: "democratic" (universal) extra dimensions, equally accessible by all the SM fields (Appelquist, Chen, Dobrescu)
  - 2001: "contracted" extra dimensions – use them and then lose them (Arkani-Hamed, Cohen, Georgi)
- All these models result in rich low-energy phenomenology

Using the Extra Dimension Paradigm

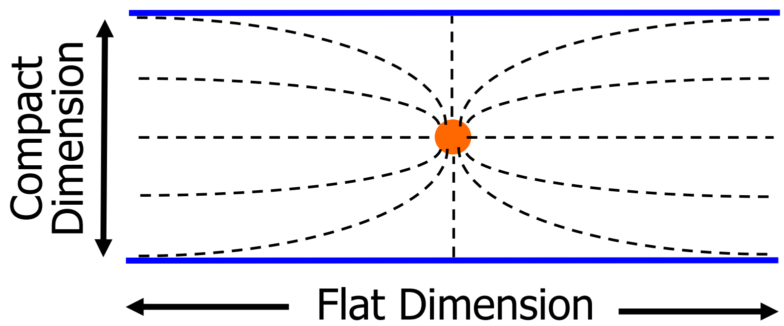
- EWSB from extra dimensions:
  - Hall, Kolda [PL **B459**, 213 (1999)] (lifted Higgs mass constraints)
  - Antoniadis, Benakli, Quiros [NP **B583**, 35 (2000)] (EWSB from strings in ED)
  - Cheng, Dobrescu, Hill [NP **B589**, 249 (2000)] (strong dynamics from ED)
  - Mirabelli, Schmaltz [PR **D61**, 113011 (2000)] (Yukawa couplings from split left- and right-handed fermions in ED)
  - Barbieri, Hall, Namura [hep-ph/0011311] (radiative EWSB via t-quark in the bulk)
- Flavor/CP physics from ED:
  - Arkani-Hamed, Hall, Smith, Weiner [PRD **61**, 116003 (2000)] (flavor/CP breaking fields on distant branes in ED)
  - Huang, Li, Wei, Yan [hep-ph/0101002] (CP-violating phases from moduli fields in ED)
- Neutrino masses and oscillations from ED:
  - Arkani-Hamed, Dimopoulos, Dvali, March-Russell [hep-ph/9811448] (light Dirac neutrinos from right-handed neutrinos in the bulk or light Majorana neutrinos from lepton number breaking on distant branes)
  - Dienes, Dudas, Gherghetta [NP **B557**, 25 (1999)] (light neutrinos from right-handed neutrinos in ED or ED see-saw mechanism)
  - Dienes, Sarcevic [PL **B500**, 133 (2001)] (neutrino oscillations w/o mixing via couplings to bulk fields)
- Many other topics from Higgs to dark matter

The ADD Model

- SM fields are localized on the (3+1)-brane; gravity is the only gauge force that "feels" the bulk space
- What about Newton's law?

$$V(r) = \frac{1}{M_{Pl}^2}\frac{m_1 m_2}{r} \to \frac{1}{\left(M_{Pl}^{[3+n]}\right)^{n+2}}\frac{m_1 m_2}{r^{n+1}}$$

- Ruled out for flat extra dimensions, but has not been ruled out for sufficiently small compactified extra dimensions:



$$V(r) \propto \frac{1}{\left(M_{Pl}^{[3+n]}\right)^{n+2}}\frac{m_1 m_2}{R^n r} \text{ for } r >> R$$

- Gravity is fundamentally strong force, bit we do not feel that as it is diluted by the volume of the bulk
- $G'_N = 1/\left(M_{Pl}^{[3+n]}\right)^2 \equiv 1/M_D^2$; $M_D \sim 1$ TeV

$$M_D^{n+2} \propto M_{Pl}^2 / R^n$$

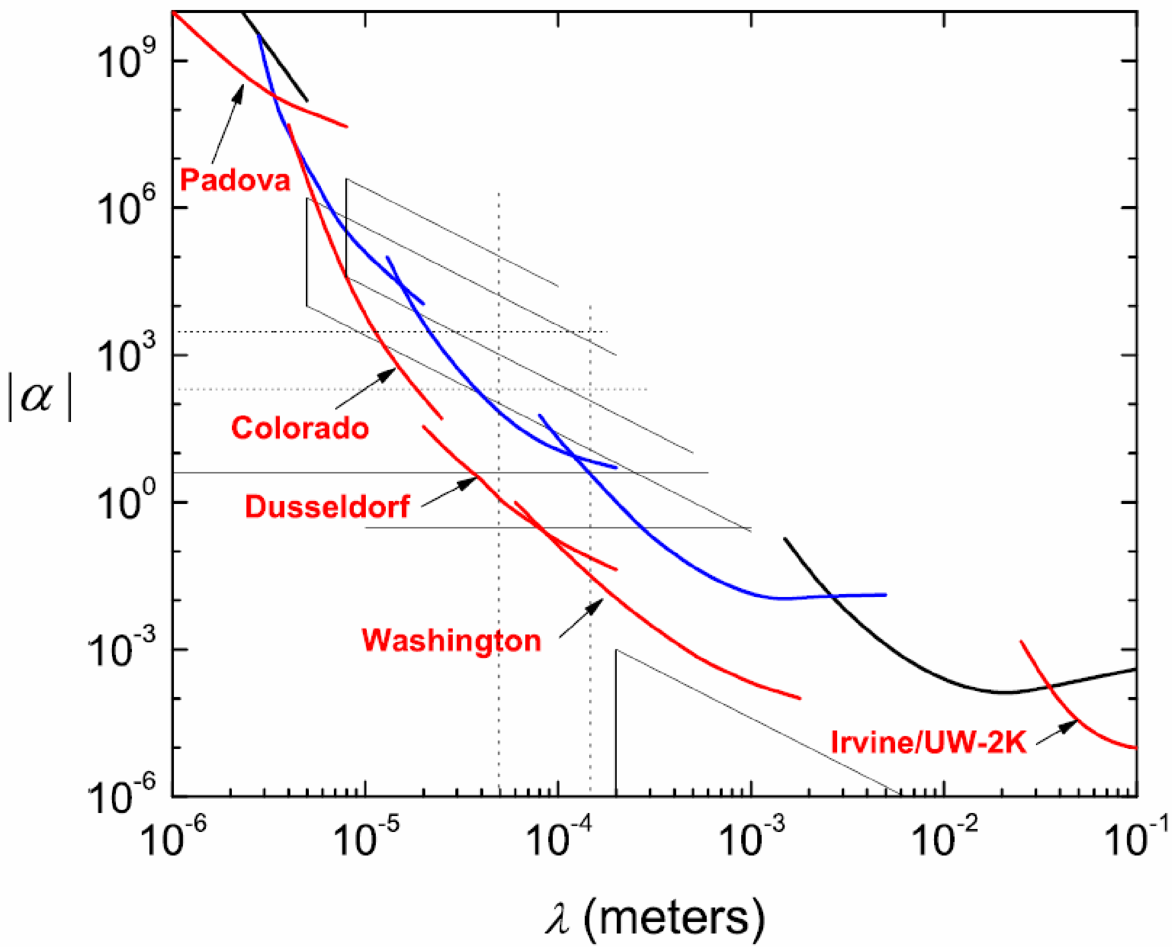
- More precisely, from Gauss's law:

$$R = \frac{1}{2\sqrt{\pi} M_D}\left(\frac{M_{Pl}}{M_D}\right)^{2/n} \propto \begin{cases} 8\times 10^{12} m, & n=1 \\ 0.7\, mm, & n=2 \\ 3\, nm, & n=3 \\ 6\times 10^{-12} m, & n=4 \end{cases}$$

- Amazing as it is, but no one has tested Newton's law to distances less than ~ 1mm (as of 1998)
- Thus, the fundamental Planck scale could be as low as 1 TeV for n > 1

Constraints from Gravity Experiments

[J. Long, J. Price, hep-ph/0303057]



- Sub-millimeter gravity measurements could probe n=2 case in the ADD hypothesis
- The best sensitivity so far have been achieved in the U of Washington torsion balance experiment – a high-tech "remake" of the 1798 Cavendish experiment
  - R $\lesssim$ 0.15 mm ($M_D \gtrsim$ 4 TeV)
- Sensitivity vanishes quickly with the distance – can't push limits further down significantly
- Started restricting ADD with 2 extra dimensions; can't probe any higher number
- Ultimately push the sensitivity by a factor of two in terms of the distance

Astrophysical and Cosmological Constraints

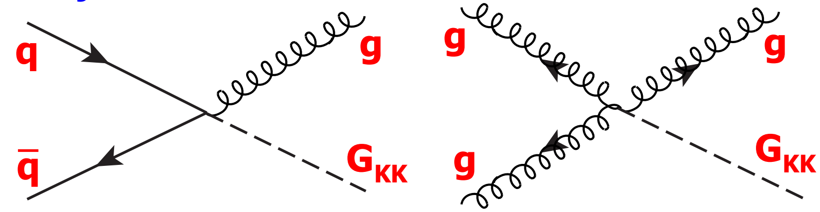
- Supernova cooling due to graviton emission – an alternative cooling mechanism that would decrease the dominant cooling via neutrino emission
  - Tightest limits on any additional cooling sources come from the measurement of the SN1987A neutrino flux by the Kamiokande and IMB
  - Application to the ADD scenario [Cullen and Perelstein, PRL **83**, 268 (1999); Hanhart, Phillips, Reddy, and Savage, Nucl. Phys. **B595**, 335 (2001)]:
  - M_D > 25-30 TeV (n=2)
  - M_D > 2-4 TeV (n=3)
- Distortion of the cosmic diffuse gamma radiation (CDG) spectrum due to the $G_{KK} \rightarrow \gamma\gamma$ decays [Hall and Smith, PRD **60**, 085008 (1999)]:
  - M_D > 100 TeV (n=2)
  - M_D > 5 TeV (n=3)
- Overclosure of the universe, matter dominance in the early universe [Fairbairn, Phys. Lett. **B508**, 335 (2001); Fairbairn, Griffiths, JHEP 0202, **024** (2002)]
  - M_D > 86 TeV (n=2)
  - M_D > 7.4 TeV (n=3)
- Neutron star γ-emission from radiative decays of the gravitons trapped during the supernova collapse [Hannestad and Raffelt, PRL **88**, 071301 (2002)]:
  - M_D > 1700 TeV (n=2)
  - M_D > 60 TeV (n=3)
- Caveat: there are many known (and unknown!) uncertainties, so the cosmological bounds are reliable only as an order of magnitude estimate
- Still, n=2 is largely disfavored

Collider Signatures for Large Extra Dimensions

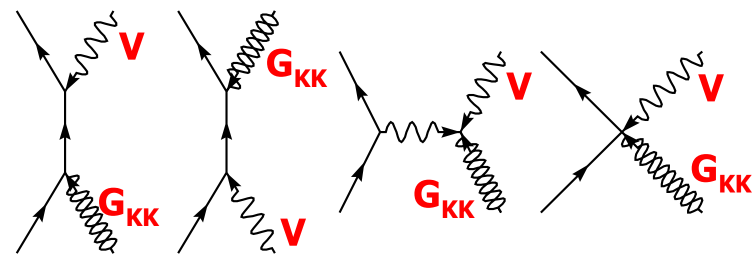
- Kaluza-Klein gravitons couple to the momentum tensor, and therefore contribute to most of the SM processes
- For Feynman rules for G_{KK} see:
  - Han, Lykken, Zhang, PR **D59**, 105006 (1999)
  - Giudice, Rattazzi, Wells, Nucl. Phys. **B544**, 3 (1999)
- Since graviton can propagate in the bulk, energy and momentum are not conserved in the G_{KK} emission from the point of view of our 3+1 space-time
- Since the spin 2 graviton in generally has a bulk momentum component, its spin from the point of view of our brane can appear as 0, 1, or 2
- Depending on whether the G_{KK} leaves our world or remains virtual, the collider signatures include single photons/Z/jets with missing E_T or fermion/vector boson pair production

Real Graviton Emission

Monojets at hadron colliders

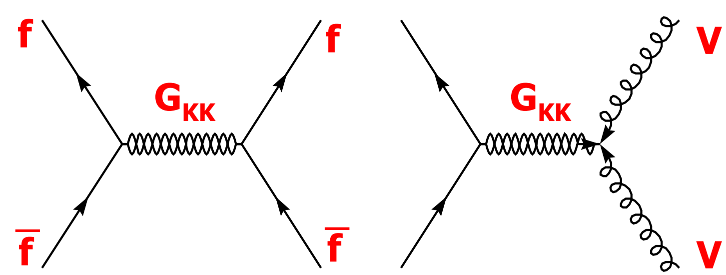


Single VB at hadron or e^+e^- colliders



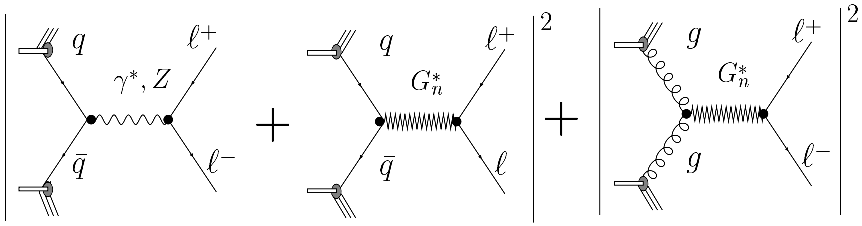
Virtual Graviton Emission

Fermion or VB pairs at hadron or e^+e^- colliders



Virtual Graviton Effects

- In the case of pair production via virtual graviton, gravity effects interfere with the SM (e.g., l^+l^- at hadron colliders):



- Therefore, production cross section has three terms: SM, interference, and direct gravity effects
- The sum in KK states is divergent in the effective theory, so in order to calculate the cross sections, an explicit cut-off, M_S, is required
- An expected value of the cut-off is $\approx M_D$, as this is the scale at which the effective theory breaks down, and the string theory needs to be used to calculate production
  - Still direct emission and virtual effects are complementary methods of probing ADD model
- Unfortunately, a number of similar papers calculating the virtual graviton effects appeared simultaneously
- Hence, there are three major conventions on how to write the effective Lagrangian:
  - Hewett, Phys. Rev. Lett. **82**, 4765 (1999)
  - Giudice, Rattazzi, Wells, Nucl. Phys. **B544**, 3 (1999); revised version, hep-ph/9811291
  - Han, Lykken, Zhang, Phys. Rev. **D59**, 105006 (1999); revised version, hep-ph/9811350
- Fortunately (after a lot of discussions and revisions) all three conventions turned out to be completely equivalent and only the definitions of M_S are different:

$$\frac{d^2\sigma}{d\cos\theta^* dM} = \frac{d^2\sigma_{SM}}{d\cos\theta^* dM} + \frac{a(n)}{M_S^4} f_1\left(\cos\theta^*, M\right) + \frac{b(n)}{M_S^8} f_2\left(\cos\theta^*, M\right)$$

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:

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

- Correspondence between the three formalisms:

$$M_S(\mathbf{Hewett})\big|_{\lambda=+1} \equiv \sqrt[4]{\frac{2}{\pi}}\Lambda_T(\mathbf{GRW})$$

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

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

- Rule of thumb:

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

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

LEP2 Constraints

Experiment	$e^+e^- \to \gamma G$ n=2	n=3	n=4	n=5	n=6	$e^+e^- \to ZG$ 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 [M_S(Hewett)]

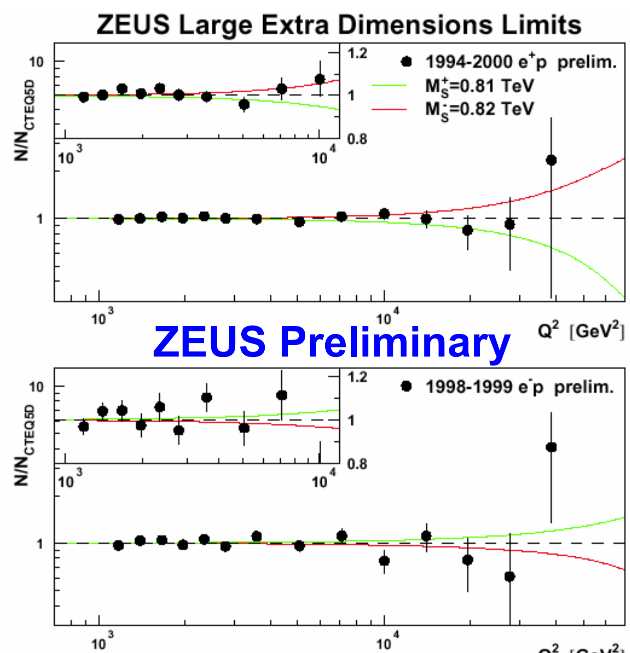
Experiment	e^+e^-	$\mu^+\mu^-$	$\tau^+\tau^-$	qq	ff	$\gamma\gamma$	WW	ZZ	Combined
ALEPH	1.04 0.81	0.65 0.67	0.60 0.62	0.53/0.57 0.46/0.46 (bb)	1.05 0.84	0.81 0.82			0.75/1.00 (<189)
DELPHI		0.59 0.73	0.56 0.65		0.60 0.76	0.83 0.91			0.60/0.76 (ff) (<202)
L3	0.98 1.06	0.56 0.69	0.58 0.54	0.49 0.49	0.84 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)

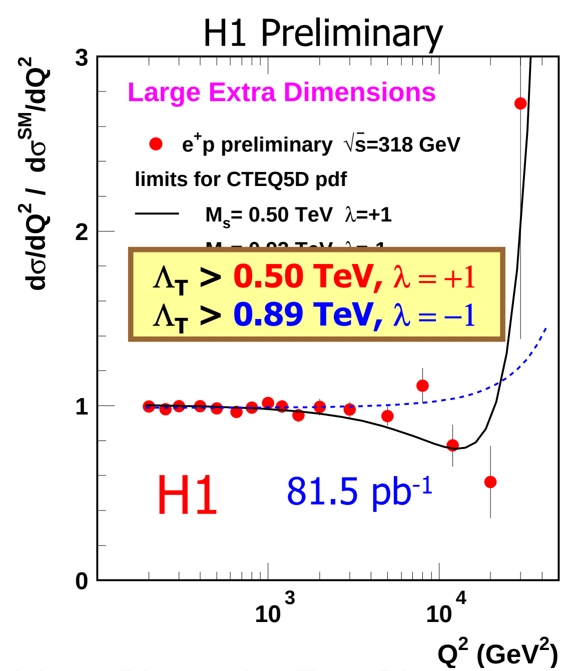
LEP Combined: 1.1/1.2

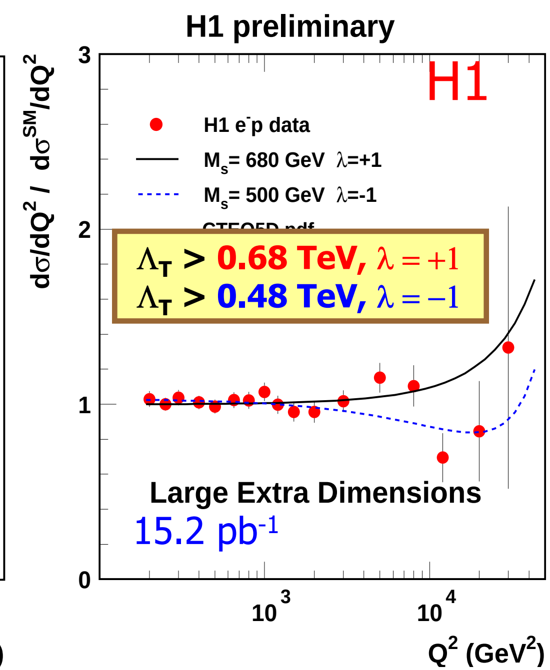
HERA Search for Virtual Graviton Effects

- $e^{\pm}p \rightarrow e^{\pm}p$
  - t-channel exchange, similar to Bhabha scattering diagrams; based on the GRW formalism (both H1 and ZEUS in fact set limits on Λ_T, but call it M_S)
  - Usual SM, Z/γ^* interference, and direct G_{KK} terms
  - Analysis method: fit to the $d\sigma/dQ^2$ distribution
  - Current H1 limits: Λ_T > 0.63/0.93 TeV (M_S > 0.56/0.83 TeV)
  - Current ZEUS limits: Λ_T > 0.81/0.82 TeV (M_S > 0.66/0.66 TeV)
  - Expected sensitivity up to 1 TeV with the ultimate HERA data set

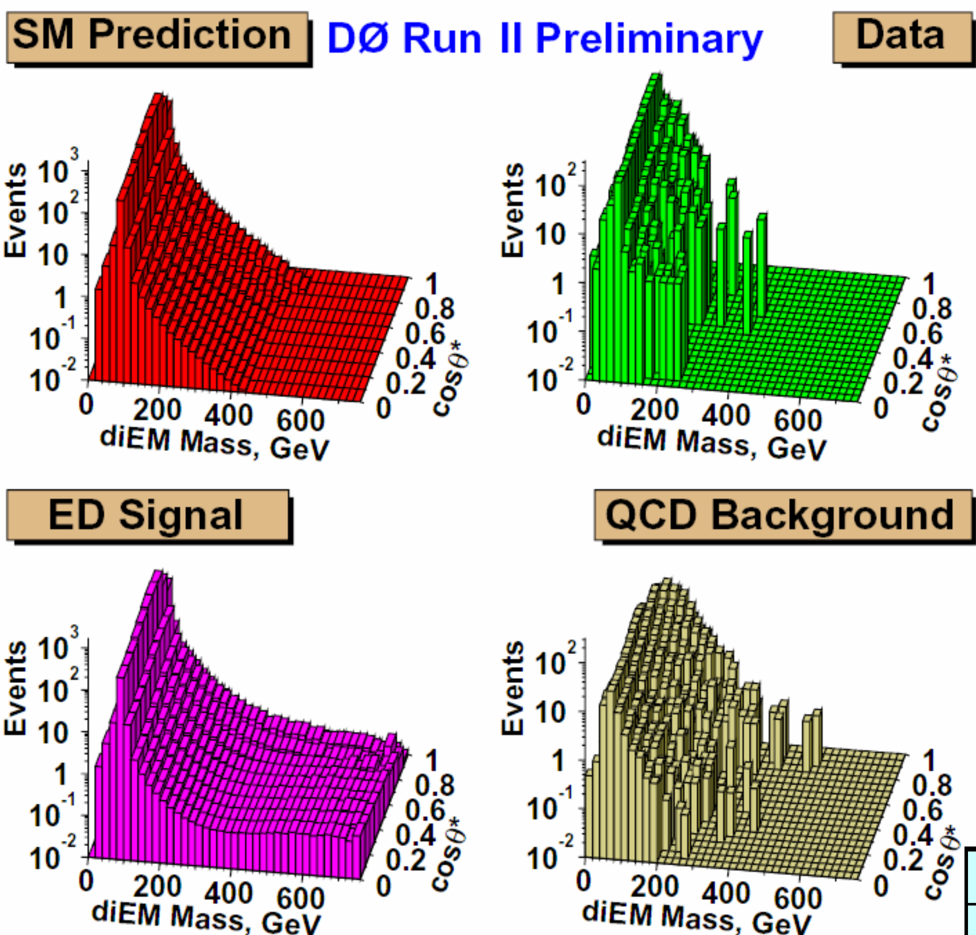
Phys. Lett. **B479**, 358 (2000) – e^+p, 35.6 pb^{-1}







Hadron Colliders: Virtual Graviton Effects

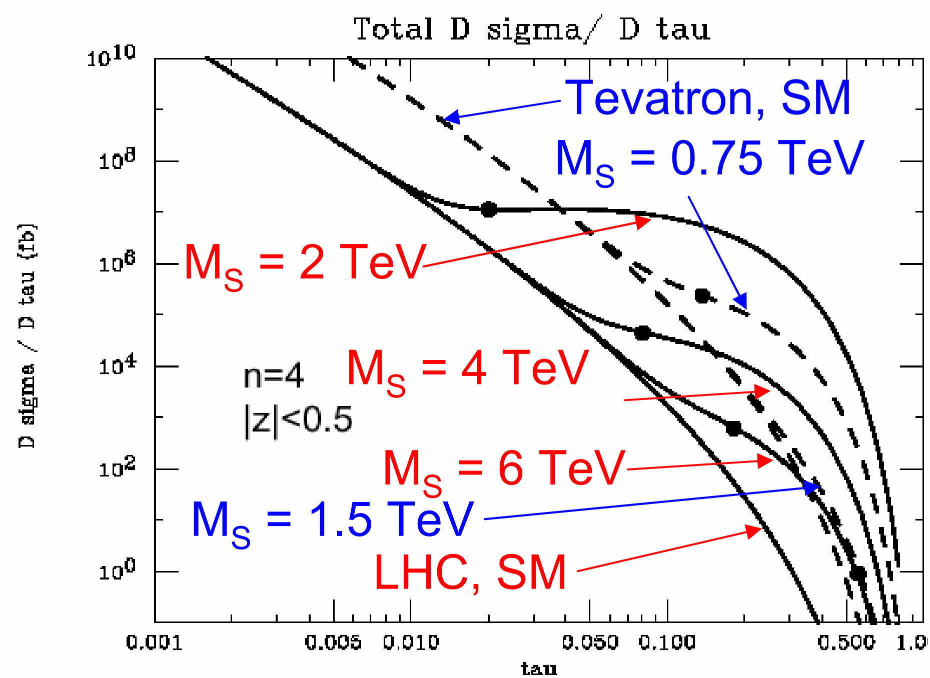


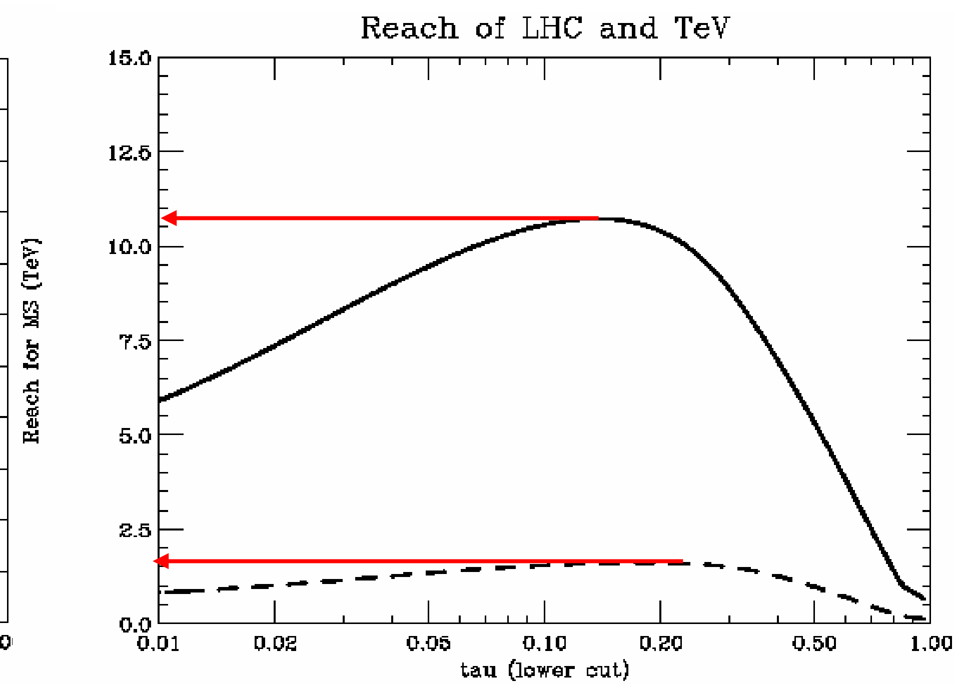
- High-mass, low |cosθ| tail is a characteristic signature of LED [Cheung, GL, PRD **62** 076003 (2000)]
- 2-dimensional method resolves this tail from the high-mass, high |cosθ| tail due to collinear divergencies in the SM diphoton production
- Best limits on the effective Planck scale come from the DØ Run I data:
  - M_S(Hewett) > 1.1/1.0 TeV ($\lambda = +1/-1$)
  - Λ_T(GRW) > 1.2 TeV
  - M_S(HLZ) > 1.0-1.4 TeV (n=2-7)
- Similar limits already set with Run II data (see Liang Han's talk)
- Sensitivity in Run II and at the LHC (HLZ):

	Run II, 2 fb^{-1}	Run II, 20 fb^{-1}	LHC, 100 fb^{-1}
$e^+e^- + \mu^+\mu^-$	1.3-1.9 TeV	1.7-2.7 TeV	6.5-10 TeV
$\gamma\gamma$	1.5-2.4 TeV	2.0-3.4 TeV	7.5-12 TeV
$e^+e^- + \mu^+\mu^- + \gamma\gamma$	**1.5-2.5 TeV**	**2.1-3.5 TeV**	**7.9-13 TeV**

ADD and Dijet Production at Hadron Colliders

- [Atwood, Bar-Shalom, Sony, PRD **62**, 056008 (2000)], used HLZ formalism
- Look at the dijet production cross section as a function of $\tau = s/\hat{s}$
- Reach at the Tevatron ~1.5 TeV (2 fb^{-1}), at the LHC ~10 TeV (30 fb^{-1}) – comparable to that in the dilepton/diphoton channels
- Also, $t\bar{t}$ invariant mass and p_T at the Tevatron or LHC (Run IIa reach: ~1.2 TeV; LHC: ~6 TeV) [Rizzo, hep-ph/9910255 (1999)]





Hadron Colliders: Real Graviton Emission

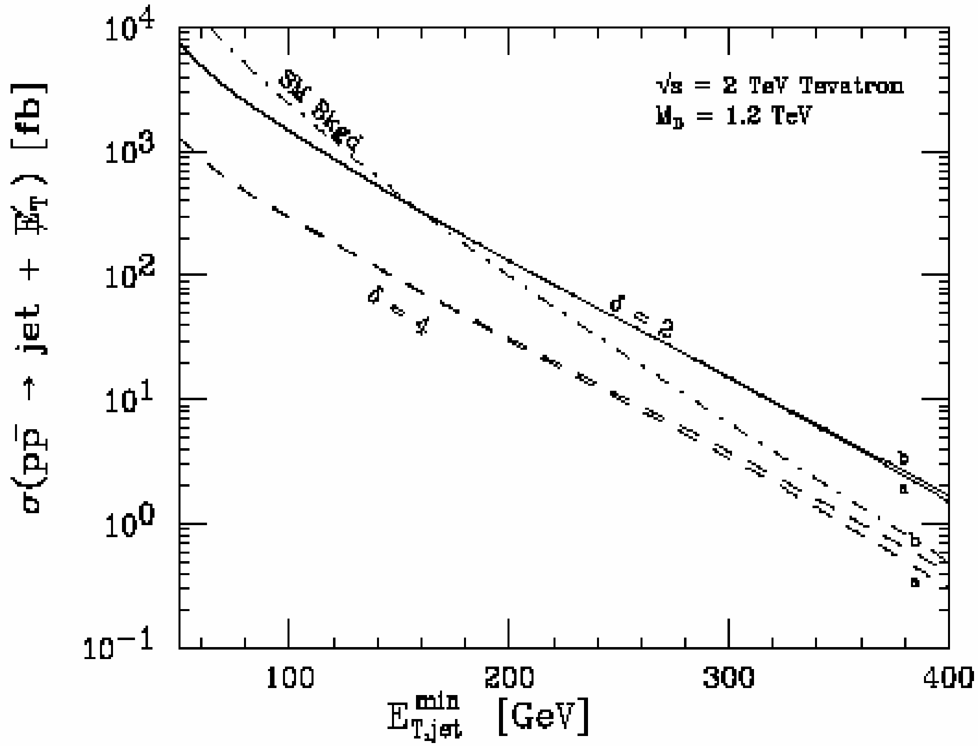
- $q\bar{q}/gg \to q/gG_{KK}$
  - jets + ME_T final state
  - $Z(\nu\nu)$+jets is irreducible background
  - Challenging signature due to large instrumental backgrounds from jet mismeasurement, cosmics, etc.
  - DØ pioneered this search and set limits [hep-ex/0302014] $M_D > 0.7$-1.1 TeV
  - CDF just announced similar preliminary limits
  - Cf. Tracey Pratt's and Liang's talks
  - Expected reach for Run II/LHC:

n	M_D reach, Run I	M_D reach, Run II	M_D reach, LHC 100 fb^{-1}
2	1100 GeV	1400 GeV	8.5 TeV
3	950 GeV	1150 GeV	6.8 TeV
4	850 GeV	1000 GeV	5.8 TeV
5	700 GeV	900 GeV	5.0 TeV

Theory:

[Giudice, Rattazzi, Wells, Nucl. Phys. **B544**, 3 (1999) and corrected version, hep-ph/9811291]

[Mirabelli, Perelstein, Peskin, PRL **82**, 2236 (1999)]

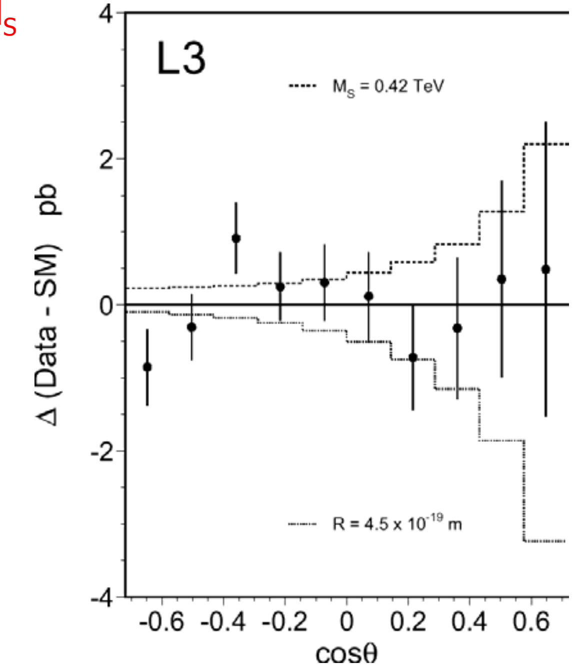


Novel Signature for Direct Graviton Emission

- Single vector boson production at hadron colliders has been looked at briefly [Balazs, He, Repko, Yuan, Dicus, PRL **83**, 2112 (1999)], but:
  - Only leptonic decays have been considered
  - Sensitivity to M_D in Run IIa is 0.9-1.1 TeV, i.e. slightly worse than in the monojet channel
  - Cross section is large: ~1 pb for both channels in Run II
- We propose a novel channel: $W/Z(jj) + G_{KK}$, with a clear advantage of an enhanced branching fraction (σxB ~ 0.6 pb)
- This channel ($\geq$2j + ME_T) is sensitive to both $q/g+G_{KK}$ and $W/Z(jj) + G_{KK}$ channels (!)
- Furthermore, the dominant $Z(\nu\nu)$+jets background can be reduced significantly for the latter signal by requiring M_{jj} ~ 85 GeV
- Some phenomenological work remains to be done to calculate the cross section accurately; it's certainly worth doing as the sensitivity should be superior to that in any other channel!

Stringy Models

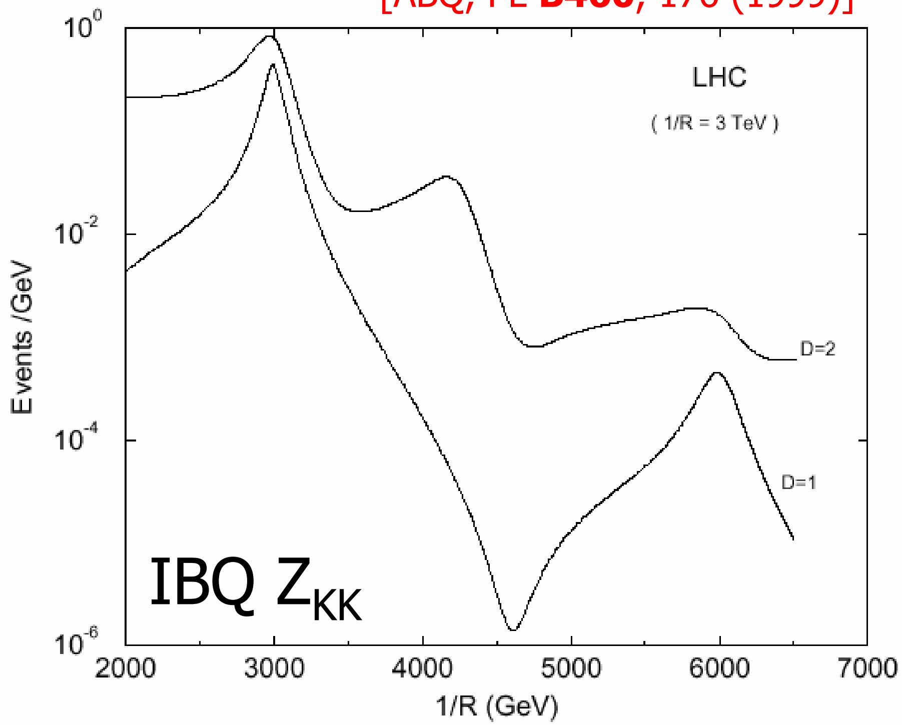
- Recent attempts to embed the idea of large extra dimensions in string models:
  - Shiu/Shrock/Tye [Phys. Lett. B **458**, 274 (1999)]
    - Type I string theory on a Z_n orbifold
    - Consider resulting twisted moduli fields which sit on the fixed points of the orbifolds and their effects on gg → gg scattering
    - These fields acquire mass ~1 TeV due to SUSY breaking, and their coupling with the bulk fields is suppressed by the volume factor
    - Since they couple to gravitons, these fields can produce bulk KK modes of the latter
    - Current sensitivity to the string scale, M_S, from CDF/DØ dijet data is ~1 TeV
- Cullen/Perelstein/Peskin, [Phys. Rev. D **62**, 055012 (2000)]
  - Embed QED into Type IIB string theory with n=6
  - Calculate corrections to $e^+e^- \rightarrow \gamma\gamma$ and Bhabha scattering due to string Regge excitations
  - L3 has set limit $M_S > 0.57$ TeV @ 95% CL
  - Also calculate $e^+e^-, gg \rightarrow \gamma G$ cross section
  - Another observable effect is a resonance in $q\bar{q} \rightarrow g^*$ at M_S



TeV^{-1} Extra Dimensions

- Intermediate-size extra dimensions with ~TeV^{-1} radius
- Introduced by Antoniadis [PL **B246**, 377 (1990)] in the string theory context; used by Dienes/Dudas/Ghergnetta [PL **B436**, 55 (1998)] to allow for low-energy unification
  - SM gauge bosons can propagate in these extra dimensions
  - Expect Z_{KK}, W_{KK}, g_{KK} resonances
  - Effects of the virtual exchange of the Kaluza-Klein modes of vector bosons at lower energies
- Gravity is not included in this model

[ABQ, PL **B460**, 176 (1999)]



- Antoniadis/Benaklis/Quiros [PL **B460**, 176 (1999)] – direct excitations; require LHC energies

Current Limits on TeV^{-1} ED

From Cheung/GL [PRD **65**, 076003 (2002)]

	η (TeV^{-2})	η_{95} (TeV^{-2})	M_C^{95} (TeV)
LEP 2:			
hadronic cross section, ang. dist., $R_{b,c}$	$-0.33\ ^{+0.13}_{-0.13}$	0.12	5.3
μ, τ cross section & ang. dist.	$0.09\ ^{+0.18}_{-0.18}$	0.42	2.8
ee cross section & ang. dist.	$-0.62\ ^{+0.20}_{-0.20}$	0.16	4.5
LEP combined	$-0.28\ ^{+0.092}_{-0.092}$	0.076	6.6
HERA:			
NC	$-2.74\ ^{+1.49}_{-1.51}$	1.59	1.4
CC	$-0.057\ ^{+1.28}_{-1.31}$	2.45	1.2
HERA combined	$-1.23\ ^{+0.98}_{-0.99}$	1.25	1.6
TEVATRON:			
Drell-yan	$-0.87\ ^{+1.12}_{-1.03}$	1.96	1.3
Tevatron dijet	$0.46\ ^{+0.37}_{-0.58}$	1.0	1.8
Tevatron top production	$-0.53\ ^{+0.51}_{-0.49}$	9.2	0.60
Tevatron combined	$-0.38\ ^{+0.52}_{-0.48}$	0.65	2.3
All combined	$-0.29\ ^{+0.090}_{-0.090}$	0.071	6.8

Tevatron Tests in Run II

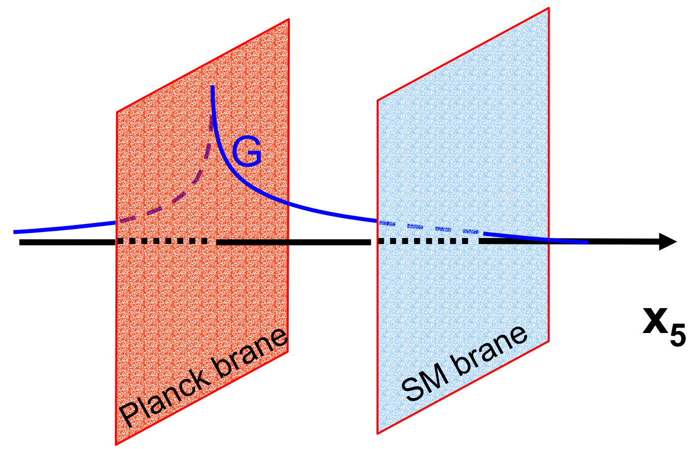
- We expect the dijet and DY production to be the most sensitive probes of TeV^{-1} extra dimensions
- The 2D-technique similar to the search for ADD effects in the virtual exchange yields the best sensitivity in the DY production [Cheung/GL, PRD **65**, 076003 (2002)]
- Similar (or slightly better) sensitivity is expected in the dijet channel; detailed cuts and NLO effects need to be studied
- Run IIb could yield sensitivity similar to the current limits from indirect searches at LEP
- These tests are complementary in nature to those via loop diagrams at LEP

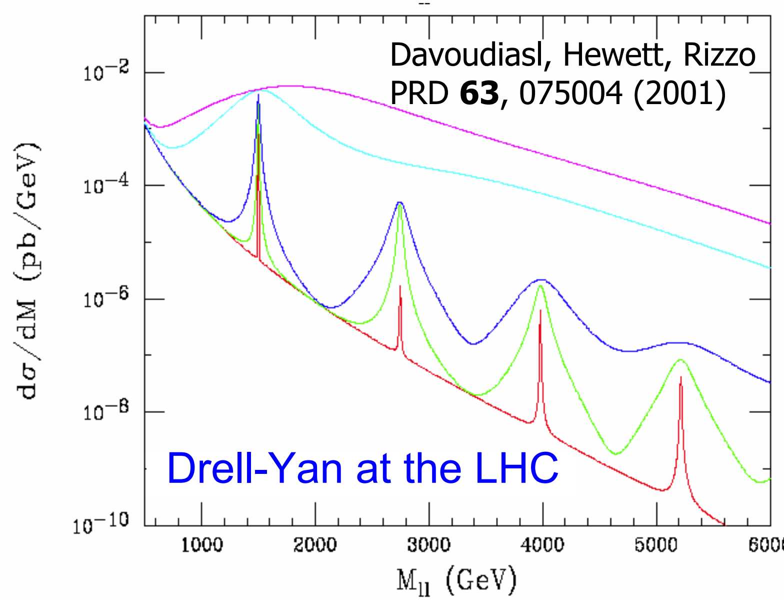
	η_{95} (TeV^{-2})	95% C.L. lower limit on M_C (TeV)
Run 1 (120 pb^{-1})	1.62	1.4
Run 2a (2 fb^{-1})	0.40	2.9
Run 2b (15 fb^{-1})	0.19	4.2
LHC (14 TeV, 100 fb^{-1}, 3% systematics)	1.81×10^{-2}	13.5
LHC (14 TeV, 100 fb^{-1}, 1% systematics)	1.37×10^{-2}	15.5

From Cheung/GL [PRD **65**, 076003 (2002)]

Randall-Sundrum Scenario

- Randall-Sundrum (RS) scenario
  [PRL **83**, 3370 (1999); PRL **83**, 4690 (1999)]
  - Gravity can be localized near a brane due to the non-factorizable geometry of a 5-dimensional space
  - + brane (RS) – no low energy effects
  - +– branes (RS) – TeV Kaluza-Klein modes of graviton
  - ++ branes (Lykken-Randall) – low energy collider phenomenology, similar to ADD with n=6
  - –+– branes (Gregory-Rubakov-Sibiryakov) – infinite volume extra dimensions, possible cosmological effects
  - +–+ branes (Kogan et al.) – very light KK state, some low energy collider phenomenology

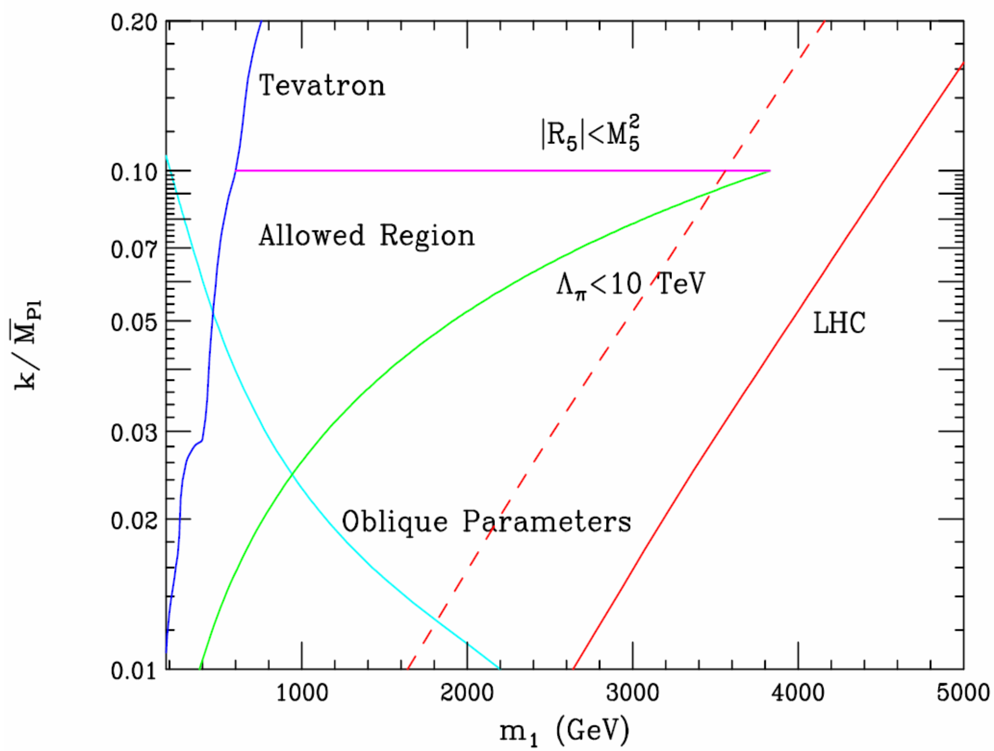




Current Constraints

- Neither gravity experiments, nor cosmology provide interesting limits on most of the RS models
- Existing limits come from collider experiments, dominated by precision electroweak measurements at LEP
- As the main effect involves direct excitation of the G_{KK} levels, energy is the key
- Given the existing constraints and the theoretically preferred parameters, there is not much the Tevatron can do to test RS models
- Extra degree of freedom due to the compact dimension results in a light scalar field – the radion (see Helenka's talk for details)
- Again, Tevatron sensitivity is very limited; LHC is the place to probe RS models (see Andy's and Caroline's talks)

$$\overline{M}_{Pl}^2 = \frac{M_5^3}{k}\left(1 - e^{-2kr_c\pi}\right); \quad \Lambda_\pi = \overline{M}_{Pl} e^{-kr_c\pi}$$



- See Tracey's talk for detail on the Tevatron searches

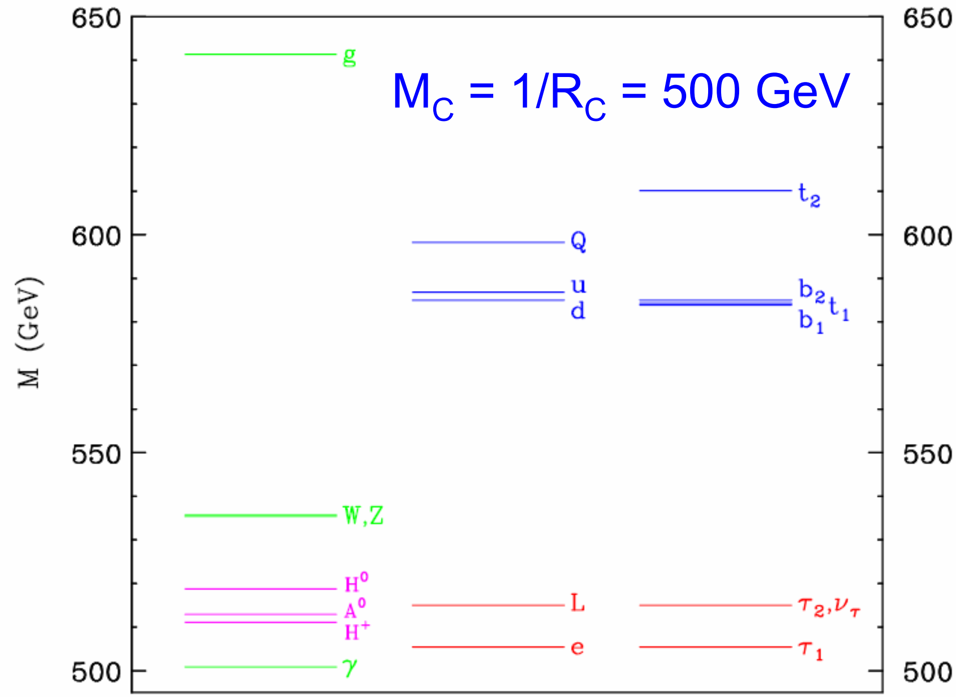
Universal Extra Dimensions

- The most "democratic" ED model: *all* the SM fields are free to propagate in extra dimension(s) with the size $R_c = 1/M_c \sim 1$ TeV^{-1} [Appelquist, Cheng, Dobrescu, PRD **64**, 035002 (2001)]
  - Instead of chiral doublets and singlets, model contains vector-like quarks and leptons
  - Gravitational force is not included in this model
- The number of universal extra dimensions is not fixed:
  - it's feasible that there is just one (MUED)
  - the case of two extra dimensions is theoretically attractive, as it breaks down to the chiral Standard Model and has additional nice features, such as guaranteed proton stability, etc.
- Every particle acquires KK modes with the masses $M_n^2 = M_0^2 + M_c^2$, n = 0, 1, 2, …
- Kaluza-Klein number (n) is conserved at the tree level, i.e. $n_1 \pm n_2 \pm n_3 \pm \ldots = 0$; consequently, the lightest KK mode cold be stable (and is an excellent dark matter candidate [Cheng, Feng, Matchev, PRL **89**, 211301 (2002)])
- Hence, KK-excitations are produced in pairs, similar to SUSY particles
- Consequently, current limits (dominated by precision electroweak measurements, particularly T-parameter) are sufficiently low ($M_c \sim 300$ GeV for one ED and of the same order, albeit more model-dependent for >1 ED)

UED Phenomenology

- Naively, one would expect large clusters of nearly degenerate states with the mass around $1/R_C$, $2/R_C$, …
- Cheng, Feng, Matchev, Schmaltz: not true, as radiative corrections tend to be large (up to 30%); thus the KK excitation mass spectrum resembles that of SUSY!
- Minimal UED model with a single extra dimension, compactified on an S_1/Z_2 orbifold
  - Odd fields do not have 0 modes, so we identify them w/ "wrong" chiralities, so that they vanish in the SM
- Q, L (q, l) are SU(2) doublets (singlets) and contain both chiralities

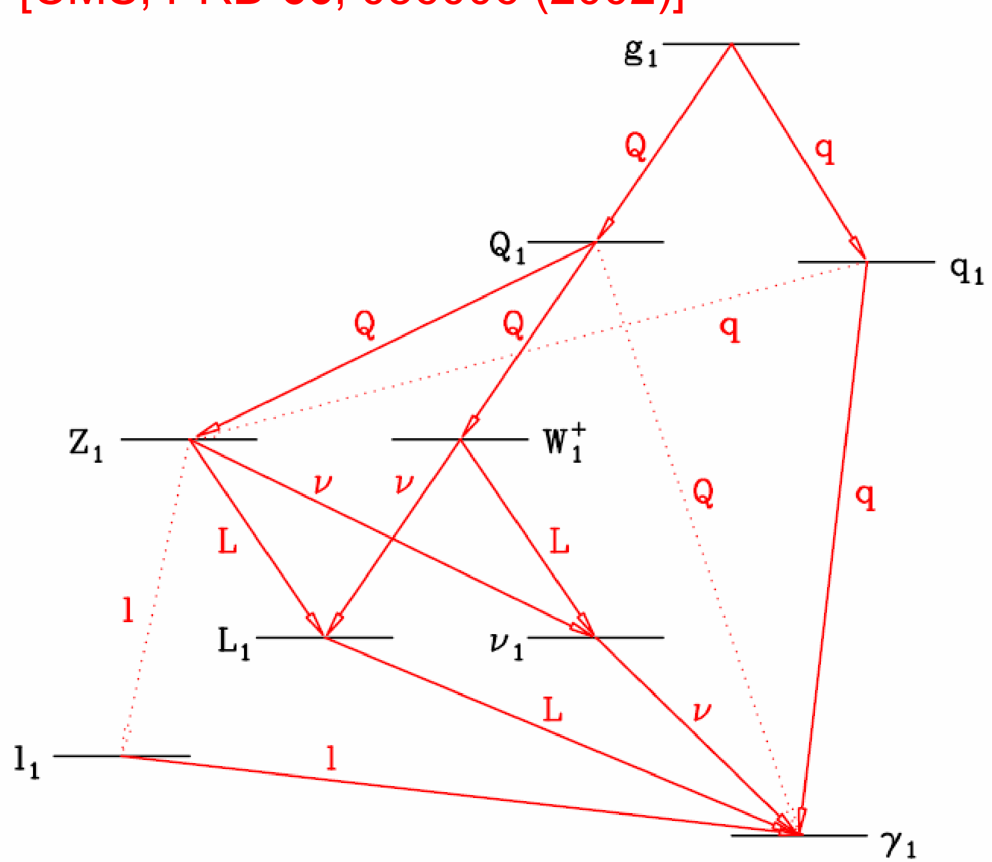
[Cheng, Matchev, Schmaltz, PRD **66**, 056006 (2002)]



UED Spectroscopy

- First level KK-states spectroscopy

[CMS, PRD **66**, 056006 (2002)]



Decay:

$B(g_1 \to Q_1 Q) \sim 50\%$

$B(g_1 \to q_1 q) \sim 50\%$

$B(q_1 \to q\gamma_1) \sim 100\%$

$B(t_1 \to W_1 b,\ H_1^+ b) \sim$

$B(Q_1 \to QZ_1 : W_1 : \gamma_1) \sim 33\% : 65\% : 2\%$

$B(W_1 \to \nu L_1 : \nu_1 L) = 1/6 : 1/6$ (per flavor)

$B(Z_1 \to \nu\nu_1 : LL_1) \sim 1/6 : 1/6$ (per flavor)

$B(L_1 \to \gamma_1 L) \sim 100\%$

$B(\nu_1 \to \gamma_1 \nu) \sim 100\%$

$B(H_1^{\pm} \to \gamma\gamma_1,\ H^{\pm *}\gamma_1) \sim 100\%$

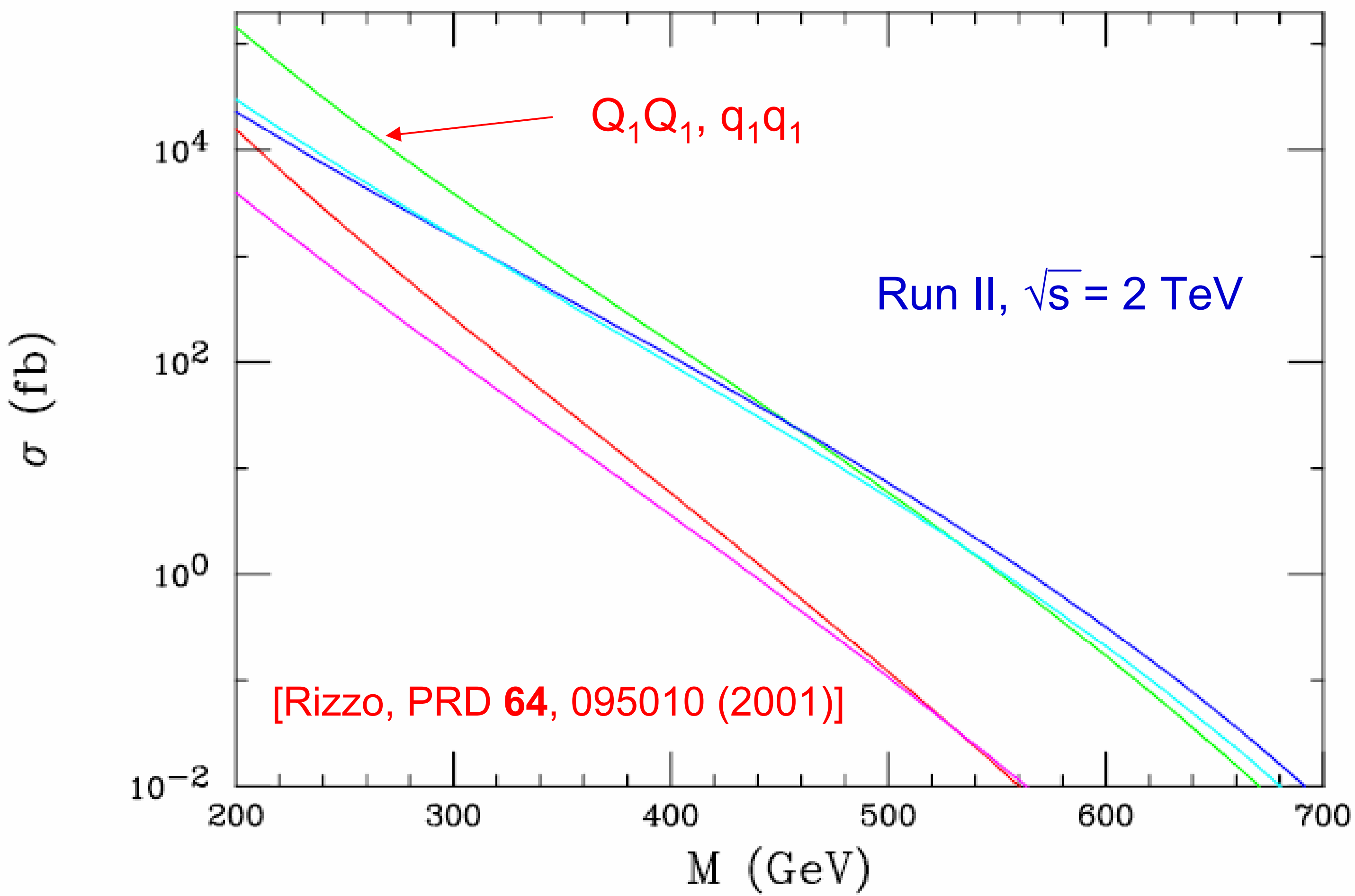
Production:

$q_1 q_1 + X \to ME_T$ + jets ($\sim\sigma_{had}/4$); but: low ME_T

$Q_1 Q_1 + X \to V_1 V'_1$ + jets $\to$ 2-4 ℓ + ME_T ($\sim\sigma_{had}/4$)

Production Cross Section

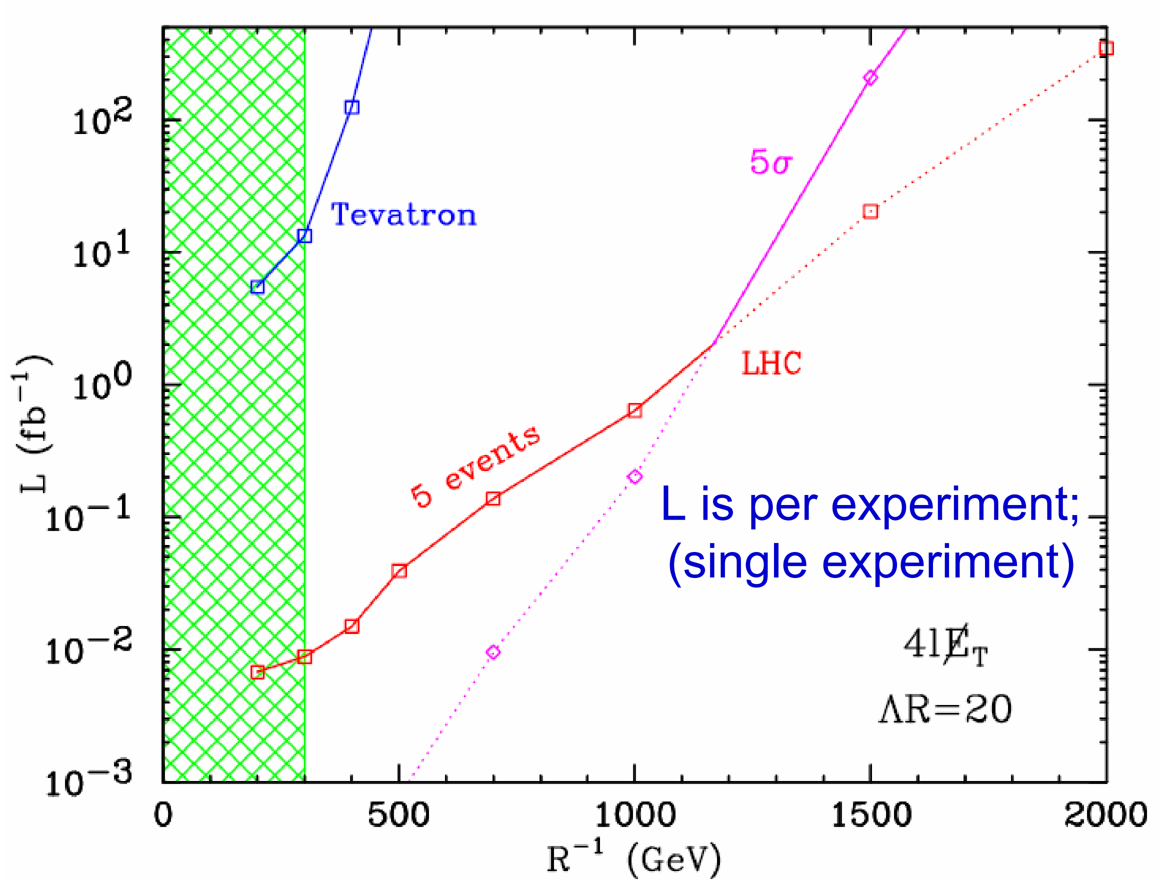
Reasonably high rate up to M ~ 500 GeV



Sensitivity in the Four-Lepton Mode

- Only the gold-plated 4-leptons + ME_T mode has been considered in the original paper
- Sensitivity in Run IIb can exceed current limits
- Much more promising channels:
  - dileptons + jets + ME_T + X (x9 cross section)
  - trileptons + jets + ME_T + X (x5 cross section)
- Detailed simulations is required: would love to see this in a MC
- One could use SUSY production with adjusted masses and branching fractions as a quick fix

[Cheng, Matchev, Schmaltz, PRD **66**, 056006 (2002)]



Almost No Extra Dimensions

- Novel idea: build a multidimensional theory that is reduced to a four-dimensional theory at low energies [Arkani-Hamed, Cohen, Georgi, Phys. Lett. **B513**, 232 (1991)]
- An alternative EWSB mechanism, the so-called Little Higgs (a pseudo-goldstone boson, responsible for the EWSB) [Arkani-Hamed, Cohen, Katz, Nelson, JHEP **0207**, 034 (2002)]
- Limited low-energy phenomenology: one or more additional vector bosons; a charge +2/3 vector-like quark (decaying into V/h+t), necessary to cancel quadratic divergencies), possible additional scalars (sometimes even stable!), all in a TeV range
- Unfortunately, the Tevatron reach is very poor; LHC would be the machine to probe this model
- However: keep an eye on it – this is currently the topic du jour in phenomenology of extra dimensions; new signatures are possible!

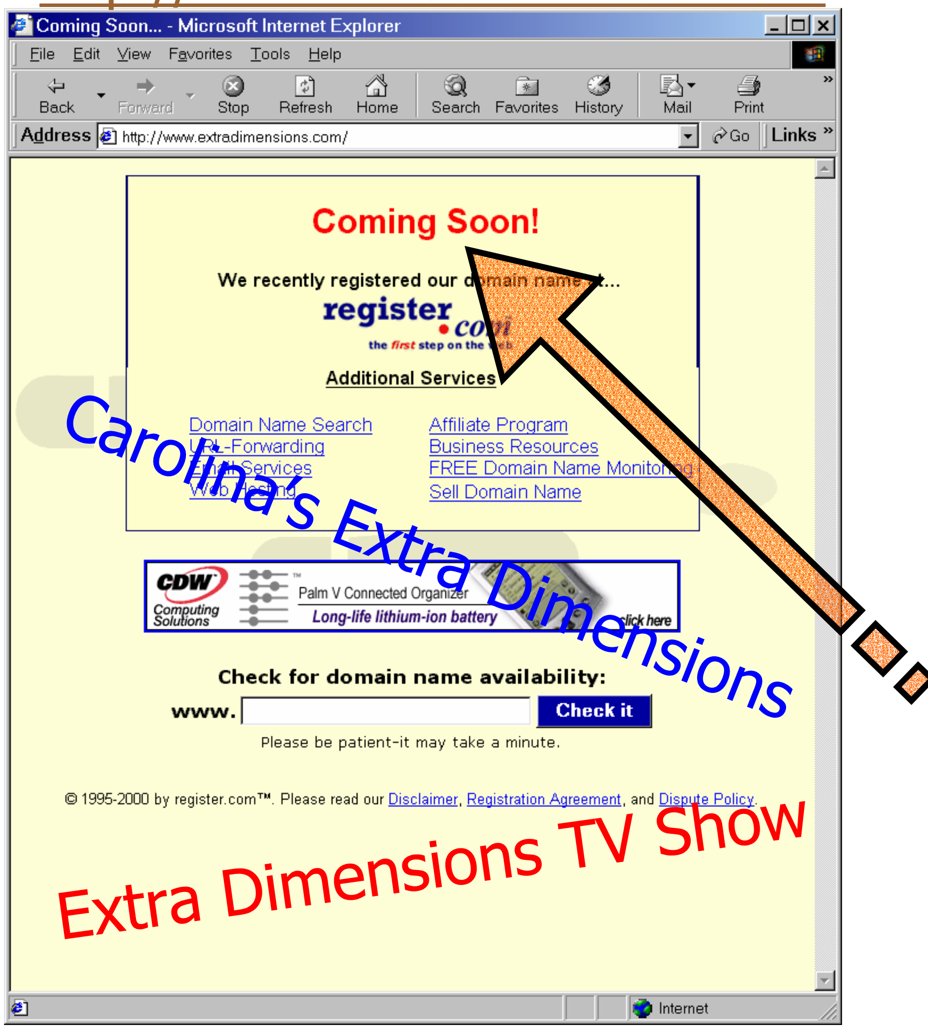
Most Promising Tevatron Signatures

- ED are one of the most exciting novel ideas, and yet barely tested experimentally:
  - ADD: virtual graviton effects, direct graviton emission, string resonances
  - TeV^{-1} dimensions: V_{KK}, virtual effects
  - RS: graviton excitations, SM particle excitation, radion, direct graviton emission
  - Universal extra dimensions: rich SUSY-like phenomenology

Channel	Extra Dimensions Probe	Other New Physics
Dilepton	ADD, TeV^{-1}, RS	Z′, compositeness
Diphotons	ADD, some RS	Compositeness, higgs, monopoles
Dijet	ADD, TeV^{-1}, Strings	Compositeness, technicolor
Monojets	ADD, some RS	Light gravitino, other SUSY
Monophotons	ADD, some RS	GMSB, light gravitino, $ZZ\gamma/Z\gamma\gamma$ couplings
Monoleptons	TeV^{-1}, some RS	W′
Dijet + ME_T	ADD, Universal	SUGRA, Leptoquarks
Leptons + ME_T	Universal	SUGRA

Conclusions

http://www.extradimensions.com



On 2/15/00 patent 6,025,810 was issued to David Strom for a "hyper-light-speed antenna." The concept is deceptively simple: "The present invention takes a transmission of energy, and instead of sending it through normal time and space, it pokes a small hole into another dimension, thus sending the energy through a place which allows transmission of energy to exceed the speed of light." According to the patent, this portal "allows energy from another dimension to accelerate plant growth." - from the AIP's "What's New", 3/17/00

- Stay tuned – this page might be owned by Fermilab in just a few years from now!