Probing Quantum Gravity in the Lab

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String Phenomenology Workshop

August 4, 2003
Outline

- Brief History of Strings
- More Fun in Extra Dimensions
  - ADD Model
  - TeV$^{-1}$ Scenario
  - RS Model
  - Universal Extra Dimensions
- Current Constraints on Models with Extra Dimensions
  - Gravity at Short Distances
  - Cosmology and Astrophysics
  - Collider Probes
- Conclusions
Just A Century Ago...

Classical Physics

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The Thirties

Quantum Mechanics
GR
KK Tower
E & M
Strings ?

© Posidonius ~150 B.C.

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The Seventies
The Nineties

Late nineties: “Velvet” Revolution in String Theory
- Large and TeV-size Extra Dimensions
- Randall-Sundrum
- NCQFT
- ...

Not noticed by string theorists for some time
- Revolution in psychology: string theory meets the experiment

Birth of String Phenomenology
- Glasgow BSM Meeting (Y2K)

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String Theory Meets the Experiment
String Theory Meets the Experiment

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The 20??-ies?

QG
Cosmology
Λ
CDM
SUSY
EWSB
CP
Flavor

String Phenomenology

String Theory
The 20??-ies?

Cosmology
SUSY
QG
Particle Physics

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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?

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A $1B Question

Can we use extra dimensions of string theory to solve the hierarchy problem?
Life Beyond the Standard Model

The natural $m_H$ value is $\Lambda$, where $\Lambda$ is the scale of new physics; if SM is the ultimate theory up to GUT scale, an extremely precise ($\sim (v/m_{\text{GUT}})^2$) fine-tuning is required.

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 $\Lambda$ comparable to the mass of the Higgs boson, i.e. $\Lambda \sim 1$ TeV.

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) – ADD
- Explore modification of the RGE in (4+n)-dimensions to achieve low-energy unification of the gauge forces (Dienes, Dudas, Gherghetta)
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

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E. Adelberger et al.
PRL 86, 1418 (2001)

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:

- $R \leq 0.15$ mm ($M_D \geq 4$ 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.
Constraints from Gravity Experiments: Future

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
  - $M_D > 25-30$ TeV (n=2)
  - $M_D > 2-4$ TeV (n=3)
- Distortion of the cosmic diffuse gamma radiation (CDG) spectrum due to the $G_{KK} \to \gamma\gamma$ 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 $\gamma$-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

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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)
- 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

Virtual Graviton Emission
Fermion or VB pairs at hadron or $e^+e^-$ colliders

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## LEP2 Constraints

### Virtual Graviton Exchange \([M_S(Hewett)]\)

<table>
<thead>
<tr>
<th>Experiment</th>
<th>(e^+e^-)</th>
<th>(\mu^+\mu^-)</th>
<th>(\tau^+\tau^-)</th>
<th>(qq)</th>
<th>(ff)</th>
<th>(\gamma\gamma)</th>
<th>(WW)</th>
<th>(ZZ)</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALEPH</td>
<td>1.04</td>
<td>0.65</td>
<td>0.60</td>
<td>0.53/0.57</td>
<td>1.05</td>
<td>0.81</td>
<td></td>
<td></td>
<td>0.75/1.00 (&lt;189)</td>
</tr>
<tr>
<td></td>
<td>0.81</td>
<td>0.67</td>
<td>0.62</td>
<td>0.46/0.46 (bb)</td>
<td>0.84</td>
<td>0.82</td>
<td></td>
<td></td>
<td>0.60/0.76 (ff) (&lt;202)</td>
</tr>
<tr>
<td>DELPHI</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.1/1.0 (&lt;202)</td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.17/1.03 (&lt;209)</td>
</tr>
<tr>
<td>L3</td>
<td>0.98</td>
<td>0.56</td>
<td>0.58</td>
<td>0.49</td>
<td>0.84</td>
<td>0.99</td>
<td>0.68</td>
<td>0.79</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.06</td>
<td>0.69</td>
<td>0.54</td>
<td>0.49</td>
<td>1.00</td>
<td>0.84</td>
<td>0.68</td>
<td>0.79</td>
<td></td>
</tr>
<tr>
<td>OPAL</td>
<td>1.15</td>
<td>0.62</td>
<td>0.54</td>
<td>0.49</td>
<td>0.62</td>
<td>0.89</td>
<td>0.63</td>
<td>0.74</td>
<td>1.17/1.03 (&lt;209)</td>
</tr>
<tr>
<td></td>
<td>1.00</td>
<td>0.66</td>
<td>0.54</td>
<td>0.49</td>
<td>0.66</td>
<td>0.83</td>
<td>0.63</td>
<td>0.74</td>
<td>1.17/1.03 (&lt;209)</td>
</tr>
</tbody>
</table>

### LEP Combined: 1.2/1.1
HERA Search for Virtual Graviton Effects

\( e^+p \rightarrow e^+p \)

t-channel exchange, similar to Bhabha scattering diagrams; based on the GRW formalism (both H1 and ZEUS in fact set limits on \( \Lambda_T \), but call it \( M_S \))

Usual SM, \( Z/\gamma^* \) interference, and direct \( G_{KK} \) terms

Analysis method: fit to the \( d\sigma/dQ^2 \) distribution

Current H1 limits: \( \Lambda_T > 0.82/0.78 \) TeV (\( M_S > 0.73/0.70 \) TeV)

Current ZEUS limits: \( \Lambda_T > 0.81/0.82 \) TeV (\( M_S > 0.72/0.73 \) TeV)

Expected sensitivity up to 1 TeV with the ultimate HERA data set
Hadron Colliders: Virtual Graviton Effects

- High-mass, low $|\cos\theta|$ tail is a characteristic signature of LED [Cheung, GL, PRD 62 076003 (2000)]
- 2-dimensional method resolves this tail from the high-mass, high $|\cos\theta|$ tail due to collinear divergencies in the SM diphoton production
- Best limits on the effective Planck scale come from the DØ Run I data:
  - $M_S(Hewett) > 1.1/1.1$ TeV ($\lambda = +1/−1$)
  - $\Lambda_T(GRW) > 1.3$ TeV
  - $M_S(HLZ) > 1.0-1.4$ TeV (n=2-7)
- Combined with Run I DØ result:
  - $\Lambda_T(GRW) > 1.4$ TeV – tightest to date
- Sensitivity in Run II and at the LHC (HLZ):

<table>
<thead>
<tr>
<th>Process</th>
<th>Run II, 2 fb$^{-1}$</th>
<th>Run II, 20 fb$^{-1}$</th>
<th>LHC, 100 fb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^+e^- + \mu^+\mu^-$</td>
<td>1.3-1.9 TeV</td>
<td>1.7-2.7 TeV</td>
<td>6.5-10 TeV</td>
</tr>
<tr>
<td>$\gamma\gamma$</td>
<td>1.5-2.4 TeV</td>
<td>2.0-3.4 TeV</td>
<td>7.5-12 TeV</td>
</tr>
<tr>
<td>$e^+e^- + \mu^+\mu^+ + \gamma$</td>
<td><strong>1.5-2.5 TeV</strong></td>
<td><strong>2.1-3.5 TeV</strong></td>
<td><strong>7.9-13 TeV</strong></td>
</tr>
</tbody>
</table>

Run II, 130 pb$^{-1}$

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Hadron Colliders: Real Graviton Emission

\[ q\bar{q}/gg \rightarrow q/gG_{KK} \]

- jets + ME_T final state
- \( Z(\nu\bar{\nu}) + \text{jets} \) 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
- Expected reach for Run II/LHC:

<table>
<thead>
<tr>
<th>n</th>
<th>( M_D ) reach, Run I</th>
<th>( M_D ) reach, Run II</th>
<th>( M_D ) reach, LHC 100 fb(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1100 GeV</td>
<td>1400 GeV</td>
<td>8.5 TeV</td>
</tr>
<tr>
<td>3</td>
<td>950 GeV</td>
<td>1150 GeV</td>
<td>6.8 TeV</td>
</tr>
<tr>
<td>4</td>
<td>850 GeV</td>
<td>1000 GeV</td>
<td>5.8 TeV</td>
</tr>
<tr>
<td>5</td>
<td>700 GeV</td>
<td>900 GeV</td>
<td>5.0 TeV</td>
</tr>
</tbody>
</table>

Theoretical prediction:

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

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Black Holes on Demand

Scientists are exploring the possibility of producing miniature black holes on demand by smashing particles together. Their plans hinge on the theory that the universe contains more than the three dimensions of everyday life. Here's the idea:

Particles collide in three dimensional space, shown below as a flat plane.

As the particles approach in a particle accelerator, their gravitational attraction increases steadily.

When the particles are extremely close, they may enter space with more dimensions, shown above as a cube.

The extra dimensions would allow gravity to increase more rapidly so a black hole can form.

Such a black hole would immediately evaporate, sending out a unique pattern of radiation.

NYT, 9/11/01
Schwarzschild radius is given by Argyres et al., hep-th/9808138 [after Myers/Perry, Ann. Phys. 172 (1986) 304]; it leads to:

\[
\sigma(\hat{s} = M_{BH}^2) = \pi R_s^2 = \frac{1}{M_P^2} \left[ \frac{8 \Gamma \left( \frac{n+3}{2} \right)}{M_P n + 2} \right]^{2/(n+1)}
\]

Hadron colliders: use parton luminosity w/ MRSD-' PDF (valid up to the VLHC energies)

\[
\frac{d\sigma(pp \to BH + X)}{dM_{BH}} = \frac{dL}{dM_{BH}} \delta(ab \to BH) \big|_{\hat{s} = M_{BH}^2}
\]

\[
\frac{dL}{dM_{BH}} = \frac{2M_{BH}}{s} \sum_{a,b} \int_{\frac{M_{BH}^2}{s}}^{1} dx_a f_a(x_a) f_b\left(\frac{M_{BH}^2}{sx_a}\right)
\]

[Dimopoulos, GL, PRL 87, 161602 (2001)]

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Black Hole Decay

**Hawking temperature:** $R_S T_H = (n+1)/4\pi$ (in natural units $\hbar = c = k = 1$)

**BH radiates mainly on the brane**
[Emparan/Horowitz/Myers, hep-th/0003118]
- $\lambda \sim 2\pi/T_H > R_S$; hence, the BH is a point radiator, producing s-waves, which depends only on the radial component
- The decay into a particle on the brane and in the bulk is thus the same
- Since there are much more particles on the brane, than in the bulk, decay into gravitons is largely suppressed

**Democratic couplings to $\sim 120$ SM d.o.f. yield probability of Hawking evaporation into $\gamma, l^\pm,$ and $\nu \sim 2\%, 10\%,$ and $5\%$ respectively**

Averaging over the BB spectrum gives average multiplicity of decay products:

$$\langle N \rangle \approx \frac{M_{BH}}{2T_H}$$

**Stefan’s law:** $\tau \sim 10^{-26}$ s

[Dimopoulos, GL, PRL 87, 161602 (2001)]

Note that the formula for $\langle N \rangle$ is strictly valid only for $\langle N \rangle \gg 1$ due to the kinematic cutoff $E < M_{BH}/2$; If taken into account, it increases multiplicity at low $\langle N \rangle$
LHC: Black Hole Factory

Spectrum of BH produced at the LHC with subsequent decay into final states tagged with an electron or a photon

[Dimopoulos, GL, PRL 87, 161602 (2001)]

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Space-Probes at the LHC

Relationship between $\log T_H$ and $\log M_{BH}$ allows to find the number of ED, this result is independent of their shape!

This approach drastically differs from analyzing other collider signatures and would constitute a “smoking cannon” signature for a TeV Planck scale.

\[ \log T_H = -\frac{1}{n+1} \log M_{BH} + \text{const} \]

---

**Table:**

<table>
<thead>
<tr>
<th>$M_P$</th>
<th>1 TeV</th>
<th>2 TeV</th>
<th>3 TeV</th>
<th>4 TeV</th>
<th>5 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n=2$</td>
<td>1%/0.01</td>
<td>1%/0.02</td>
<td>3.3%/0.10</td>
<td>16%/0.35</td>
<td>40%/0.46</td>
</tr>
<tr>
<td>$n=3$</td>
<td>1%/0.01</td>
<td>1.4%/0.06</td>
<td>7.5%/0.22</td>
<td>30%/1.0</td>
<td>48%/1.2</td>
</tr>
<tr>
<td>$n=4$</td>
<td>1%/0.01</td>
<td>2.3%/0.13</td>
<td>9.5%/0.34</td>
<td>35%/1.5</td>
<td>54%/2.0</td>
</tr>
<tr>
<td>$n=5$</td>
<td>1%/0.02</td>
<td>3.2%/0.23</td>
<td>17%/1.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$n=6$</td>
<td>1%/0.03</td>
<td>4.2%/0.34</td>
<td>23%/2.5</td>
<td></td>
<td>Fit fails</td>
</tr>
<tr>
<td>$n=7$</td>
<td>1%/0.07</td>
<td>4.5%/0.40</td>
<td>24%/3.8</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**References:**

[Dimopoulos, GL, PRL 87, 161602 (2001)]
A Black Hole Event Display

5 TeV $e^+e^-$ machine (CLIC)

TRUENOIR MC generator

[Courtesy Albert De Roeck and Marco Battaglia]
First Detailed LHC Studies

First studies already initiated by ATLAS and CMS

- ATLAS – Cambridge HERWIG-based generator with more elaborated decay model [Harris/Richardson/Webber]
- CMS – TRUENOIR [GL]

Simulated black hole event in the ATLAS detector [from ATLAS-Japan Group]
Higgs Discovery in BH Decays

- Example: 130 GeV Higgs particle, which is tough to find either at the Tevatron or at the LHC
- Higgs with the mass of 130 GeV decays predominantly into a bb-pair
- Tag BH events with leptons or photons, and look at the dijet invariant mass; does not even require b-tagging!
- Use a typical LHC detector response to obtain realistic results
- Time required for 5 sigma discovery:
  - $M_p = 1$ TeV – 1 hour
  - $M_p = 2$ TeV – 1 day
  - $M_p = 3$ TeV – 1 week
  - $M_p = 4$ TeV – 1 month
  - $M_p = 5$ TeV – 1 year
- Standard method – 1 year w/ two well-understood detectors!

$\sigma = 15$ nb

$M_p = 1$ TeV, 1 LHC-hour (!)

ATLAS resolutions

An exciting prospect for discovery of other new particles w/ mass $\sim 100$ GeV!
Recent attempts to embed the idea of large extra dimensions in stringy models:

  - 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 $gg \rightarrow gg$ scattering
  - These fields acquire mass $\sim 1$ 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 $\sim 1$ 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 $M_S$
Another possibility is to produce brane excitations, i.e. brane “wobbling” in extra dimensions.

These degrees of freedom exhibit themselves as new particles, branons, from the point of view of a 4-dimensional observer.

Look for pair production (to respect Lorentz invariance) of branons in $e^+e^-/q\bar{q}' \rightarrow B+B+ME_T$.

If the brane tension $f \ll M_S$, these excitation are dominating at low energies where direct and virtual graviton emission is suppressed.
Intermediate-size extra dimensions with $\sim$TeV$^{-1}$ radius

Introduced by Antoniadis [PL B246, 377 (1990)] in the string theory context; used by Dienes/Dudas/Gherghetta [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

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

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### Current Limits on TeV$^{-1}$ ED

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

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

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Tevatron and LHC Tests

- 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.

<table>
<thead>
<tr>
<th></th>
<th>( \eta_{95} ) (TeV⁻²)</th>
<th>95% C.L. lower limit on ( M_C ) (TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run 1 (120 pb⁻¹)</td>
<td>1.62</td>
<td>1.4</td>
</tr>
<tr>
<td>Run 2a (2 fb⁻¹)</td>
<td>0.40</td>
<td>2.9</td>
</tr>
<tr>
<td>Run 2b (15 fb⁻¹)</td>
<td>0.19</td>
<td>4.2</td>
</tr>
<tr>
<td>LHC (14 TeV, 100 fb⁻¹, 3% systematics)</td>
<td>1.81 \times 10⁻²</td>
<td>13.5</td>
</tr>
<tr>
<td>LHC (14 TeV, 100 fb⁻¹, 1% systematics)</td>
<td>1.37 \times 10⁻²</td>
<td>15.5</td>
</tr>
</tbody>
</table>

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

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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.

Nevertheless both the CDF and DØ collaborations are testing these models; first results already available.

Extra degree of freedom due to the compact dimension results in a light scalar field – the radion.

LHC is the place to probe RS models.

$\bar{M}_{Pl}^2 = \frac{M_5^3}{k} \left(1 - e^{-2k\pi}\right)$; \(\Lambda_\pi = \bar{M}_{Pl} e^{-k\pi}\)
Universal Extra Dimensions

The most “democratic” ED model: all the SM fields are free to propagate in extra dimension(s) with the size $R_c = 1/M_c \sim 1 \text{ TeV}^{-1}$ [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. $n_1 \pm n_2 \pm n_3 \pm ... = 0$; 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 ($M_c \sim 300 \text{ GeV}$ for one ED and of the same order, albeit more model-dependent for >1 ED)
Sensitivity in the Four-Lepton Mode

- Only the gold-plated 4-leptons + MET mode has been considered in the original paper.

- Sensitivity in Run IIb can exceed current limits.

- Much more promising channels:
  - dileptons + jets + MET + X (x9 cross section)
  - trileptons + jets + MET + 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)]

L is per experiment; (single experiment)

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Non-Commutative Geometry

- Non-commutative QED in the $e^+e^- \rightarrow \gamma\gamma$ production at LEP
- Laws of physics depend on the position in space; use the sidereal reference frame
- $\Lambda < 142$ GeV has been excluded by OPAL

Time Integrated $\phi$

- OPAL preliminary
  - $e^+e^- \rightarrow \gamma\gamma$  $\cos\theta < 0.6$
  - $\eta = 0^\circ$  $\Lambda_{NC} > 169$ GeV

Time Dependent

- $\eta = 120^\circ$  $\eta = 55^\circ$
- $\Lambda_{NC} = 142$ GeV
  - $e^+e^- \rightarrow \gamma\gamma$  $|\cos\theta| < 0.6$
Conclusions

String theory entered a new realm: the realm of string phenomenology

While not guaranteed, there are rich possibilities for quantum gravity to exhibit itself below the Planck scale, perhaps significantly below

These possibilities would result in rich phenomenology, which could be tested in the lab as soon as in the next decade

Some of the scenarios offer no less than “ultimate unification” – the unification of particle physics, astrophysics, and astronomy

If any of the above would be confirmed, we might be witnessing the greatest revolution in our field ever, and we could be a part of it