Physics Symposium AAAS 03:
The physics of extra dimensions
http://hep.uchicago.edu/cdf/smaria/ms/aaas03.html

THANKS
Charles W. Clark & the Physics Section of AAAS
Mike Strauss of AAAS

All the speakers          Joe Lykken
                          Sean Carroll
                          Eric Adelberger
                          Lisa Randall

from FNAL,  Director Mike Witherell
from DOE/Office of Science,  Peter Rosen
and Leon Lederman
What do you mean?

• Spacetime has to do with gravity and gravity with spacetime
• At very large distance scales: General Relativity
• At very short distance scales/Very High Energy scales: gravity weirdness or quantum gravity
What do you mean?

**High energy particles** have extremely small wavelengths and can probe subatomic distances: **high energy particle accelerators** serve as super-microscopes: To see **What**? The structure of matter (atoms/nuclei/nucleons/quarks)
What do you mean?

- **High energy particles** have extremely small wavelengths and can probe subatomic distances: **high energy particle accelerators** serve as super-microscopes: To see **What?**

  The structure of matter (atoms/nuclei/nucleons/quarks)

- **Spacetime** has to do with gravity and gravity with spacetime.

  At very large distance scales:
  - General Relativity

  At very short distance scales/
  - Very High Energy scales:
    - gravity weirdness or quantum gravity

- High energy particles have extremely small wavelengths and can probe subatomic distances: **high energy particle accelerators** serve as super-microscopes: To see **What?**

  The structure of matter (atoms/nuclei/nucleons/quarks)

TWO jets tagged by SVX

- fit top mass is 170 ± 10 GeV
  - $e^+$, Missing $E_T$, jet #4 from top
  - jets 1, 2, 3 from top (2 & 3 from W)
What do you mean?

High energy particles have extremely small wavelengths and can probe subatomic distances: high energy particle accelerators serve as super-microscopes: To see What?
The structure of matter (atoms/nuclei/nucleons/quarks)

• Very High Energy particle accelerators

To see What?
What do you mean?

**BINGO!**

- gravity
- weirdness or quantum gravity
- Very High Energy particle accelerators

To see What?
What do you mean?

• Spacetime has to do with gravity and gravity with spacetime

**BINGO!**

gridness or quantum gravity

• Very High Energy particle accelerators

To see What?
What do you mean?

- Spacetime has to do with gravity and gravity with spacetime

**BINGO!**

- **Spacetime** emergence phenomena
- **Very High Energy** particle accelerators

To see What?
To see What?

- Gravitons
- ..........(intermediate) string-y phenomena
- Black holes

produced in high energy collisions!!
WHAT?

• A massless spin 2 particle whose long-wavelength interactions are described by general relativity (graviton)

• A singular classical object (black hole)

produced in high energy collisions???

And what exactly is the number high???
A picture of a graviton
(CDF simulation)
A picture of a black hole (LC detector simulation)
It is a matter of scale and geometry

• From contact interaction to a gauge boson: the $G_F E^2$ behavior was tamed at short length scales

• From gauge theory to string theory the $G_N E^2$ behavior seems to be tamed at even shorter length scales (or very high energies)
  – With this comes a change in how we perceive spacetime geometry and dynamics: eg. Extra dimensions
  – The Standard Model, Supersymmetry and the Kaluza-Klein theory under one umbrella
Before-After

- At high energies we have 0-dimensional pointlike particles interacting by means of 3 out of 4 forces of nature and moving in a 3+1 space+time
- Gravity is the 4 in this picture

- At very high energies we have 1+ dimensional “things” interacting by means of 4+ out of 4 forces of nature and moving in a 3+ extra +1 multispaces+time
  - At super very high energies?
  - Imagination

⚠️ What exactly is the number super very high???
And what exactly is the number super very high???

Going down, a step at a time

- Bring down the Planck
- to the GUT
- to the TeV scale
- in string theory with extra dimensions,
- the 5th slightly bigger,
- and then even bigger
- and then more of them huge
- (eg Kaluza-Klein, Witten-Horava, Lykken, ADD, RS)
Only high Tc superconductivity you cannot solve with extra dimensions everything else YES

- EWKB
- hierarchy problem
- SUSY Breaking
- flavor Breaking
- neutrino masses
- proton decay suppression
- Grand Unification
- the cosmological constant
- ...

Only high Tc superconductivity you cannot solve with extra dimensions everything else YES
Models of extra dimensions

• Large compact extra dimensions (ADD type)
• Warped extra dimensions (RS type)
• (most) all hybrids and combinations of above

• Fat branes, skiny branes, solid branes, soft branes, no branes, quivering branes, positive branes, negative branes, curved bulk, flat bulk, supersymmetric bulk, gravity in the bulk, gauge fields in the bulk, no gauge fields in the bulk, fermions in the bulk, no fermions in the bulk, right handed neutrinos in the bulk, &tc
(brief) Model Description & Parameters

- **ADD-type**
  - # of extra dimensions, $\delta$
  - effective Planck scale, $M_D$

\[ M_{\text{Planck}}^2 \sim R^\delta M_{Pl}^{2+\delta} \]

- **RS-type**
  - curvature of AdS$_5$, $k$
  - extent of 5th dimension, $R$

\[ \Lambda_\pi \equiv M_{Pl} (8\pi)^{-1/2} e^{-kR\pi} \]
(brief) Model Description & Parameters

• ADD
  \[ m_n = \left( \frac{n^2}{R^2} \right)^{\frac{1}{2}} n = (n_1, n_2, \ldots, n_\delta) \]
  
  - evenly spaced KK states
  - set \( M_D = 1 \text{ TeV} \)
    
    - \( \delta = 1 \ R \sim 10^{11} \text{ m} \)
    - \( \delta = 2 \ R \sim 0.4 \text{ mm} \ 1/R \sim 5 \times 10^{-4} \text{ eV} \)
    - \( \delta = 4 \ R \sim 10^{-5} \text{ mm} \ 1/R \sim 20 \text{ keV} \)
    - \( \delta = 6 \ R \sim 30 \text{ fm} \ 1/R \sim 7 \text{ MeV} \)

• RS
  \[ m_n = k x_n \Lambda_\pi (8\pi)^{\frac{1}{2}} (M_{pl})^{-1} \]
  \( x_n \) denotes the roots of the first-order Bessel function

  - not evenly spaced KK states
  - set \( \Lambda_\pi = 1 \text{ TeV} \)
    
    - \( k R \sim 11-12 \)
    - \( m_1 \sim \text{TeV order} \)
Basic Ingredients for search

• **High energy** accelerators/colliding beams
• Detectors
• Data Acquisition Electronics/Trigger systems
• People
• Imagination and Dollars (or Euros or yen)

**WE DO HAVE A LOT OF ALL**

AND ALWAYS TRY FOR BETTER AND MORE ACCELERATOR/COLLIDER/DETECTOR R&D

And what exactly is the number **high***???
Fermilab's Accelerator Chain

- Booster
- LINAC
- Cockroft - Walton

Main Injector

Tevatron

Main Injector
The Main Injector Tunnel
Preparation of RF cavities for TESLA linear collider
Collider Signatures

YAHOO! WE KNOW HOW TO DO THIS; WE HAVE STUDIED ALL THESE FINAL STATES AT COLLIDERS ALREADY TO MEASURE STANDARD MODEL PHYSICS.

- Results/Studies LEP, TeVI, TeVII, LHC, NLC/TESLA
Eg. Graviton Emission

$E_{CM}=2$ TeV Tevatron
$n=2$, $M_D=1.2$ TeV
Signal in the detector
two events are real CDF data and one is graviton simulation; which is which?
Run 152507 event 1222318

Dijet Mass = 1364 GeV (corr)

$\cos \theta^* = 0.30$

z vertex = -25 cm

$J_1 E_T = 666$ GeV (corr)
$583$ GeV (raw)

$J_1 \eta = 0.31$ (detector)
$0.43$ (correct $z$)

$J_2 E_T = 633$ GeV (corr)
$546$ GeV (raw)

$J_2 \eta = -0.30$ (detector)
$-0.19$ (correct $z$)

Corrected $E_T$ and mass are preliminary

(thanks to Rob Harris)
Analyze This (That)

- A lot of cleaning to get a good purity data sample
Backgrounds

- $Z \rightarrow \nu \nu + \text{jets}$
- $W \rightarrow \tau \nu + \text{jets}$
- $W \rightarrow e \nu + \text{jets}$
- QCD
- Dibosons
- $tt$, single top

- STRATEGY: Normalize wherever possible using data
Zee: standard(izable) candle
Summary of Backgrounds

- Uncertainties are stat. plus syst.
- QCD $\sim 14\%$ uncertainty due to jet resolution
- 4% uncertainty from the luminosity

<table>
<thead>
<tr>
<th>Background</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z \rightarrow \nu \bar{\nu}$</td>
<td>$160.3 \pm 11.5$</td>
</tr>
<tr>
<td>$W \rightarrow \tau \nu_\tau$</td>
<td>$46.6 \pm 5.5$</td>
</tr>
<tr>
<td>$W \rightarrow \mu \nu_\mu$</td>
<td>$23.8 \pm 5.0$</td>
</tr>
<tr>
<td>$W \rightarrow e \nu_e$</td>
<td>$18.1 \pm 4.3$</td>
</tr>
<tr>
<td>top, dibosons</td>
<td>$3.9 \pm 0.2$</td>
</tr>
<tr>
<td>Total EWK</td>
<td>$252.5 \pm 14.4$</td>
</tr>
<tr>
<td>QCD</td>
<td>$21.7 \pm 6.7$</td>
</tr>
<tr>
<td>Total predicted</td>
<td>$274.1 \pm 15.9$</td>
</tr>
<tr>
<td>Data Observed</td>
<td>$284$</td>
</tr>
</tbody>
</table>
DATA vs PREDICTIONS

CDF Preliminary

- Predicted Total
- Predicted Invisible Z
- Observed (84 pb⁻¹)

Events/10 GeV

$E_T$ (GeV)

80 100 120 140 160 180 200 220 240
Signal Expectations

<table>
<thead>
<tr>
<th>$M_D$ (GeV)</th>
<th>$n=2$</th>
<th>$n=4$</th>
<th>$n=6$</th>
</tr>
</thead>
<tbody>
<tr>
<td>600</td>
<td>471</td>
<td>274</td>
<td>232</td>
</tr>
<tr>
<td>700</td>
<td>254</td>
<td>109</td>
<td>68</td>
</tr>
<tr>
<td>800</td>
<td>149</td>
<td>49</td>
<td>23</td>
</tr>
<tr>
<td>900</td>
<td>93</td>
<td>24</td>
<td>9</td>
</tr>
<tr>
<td>1000</td>
<td>61</td>
<td>13</td>
<td>4</td>
</tr>
<tr>
<td>1100</td>
<td>42</td>
<td>7</td>
<td>2</td>
</tr>
<tr>
<td>1200</td>
<td>29</td>
<td>4</td>
<td>1</td>
</tr>
</tbody>
</table>
The limit

<table>
<thead>
<tr>
<th></th>
<th>n=2</th>
<th>n=4</th>
<th>n=6</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF (K=1.0)</td>
<td>995</td>
<td>768</td>
<td>707</td>
</tr>
<tr>
<td>D0 (K=1.0)</td>
<td>886</td>
<td>663</td>
<td>626</td>
</tr>
<tr>
<td>D0 (K=1.34)</td>
<td>987</td>
<td>728</td>
<td>646</td>
</tr>
<tr>
<td>ALEPH</td>
<td>1280</td>
<td>780</td>
<td>570</td>
</tr>
<tr>
<td>DELPHI</td>
<td>1380</td>
<td>840</td>
<td>580</td>
</tr>
<tr>
<td>L3</td>
<td>1020</td>
<td>670</td>
<td>510</td>
</tr>
<tr>
<td>OPAL</td>
<td>1090</td>
<td>710</td>
<td>530</td>
</tr>
</tbody>
</table>
Monojet + missing energy: LHC reach

\begin{center}
\begin{tabular}{|l|l|l|l|l|}
\hline
\textit{n} & \textit{14\ TeV} & \textit{14\ TeV} & \textit{28\ TeV} & \textit{28\ TeV} \\
\textbf{100\ fb^{-1}} & \textbf{1000\ fb^{-1}} & \textbf{100\ fb^{-1}} & \textbf{1000\ fb^{-1}} \\
\hline
2 & 9 & 12 & 15 & 19 \\
3 & 6.8 & 8.3 & 11.5 & 14 \\
4 & 5.8 & 6.9 & 10 & 12 \\
\hline
\end{tabular}
\end{center}
Future G Emission sensitivity

<table>
<thead>
<tr>
<th>$e^+e^- \rightarrow \gamma + G_n$</th>
<th>2</th>
<th>4</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>LC $P_{-,+} = 0$</td>
<td>5.9</td>
<td>3.5</td>
<td>2.5</td>
</tr>
<tr>
<td>LC $P_\pm = 0.8$</td>
<td>8.3</td>
<td>4.4</td>
<td>2.9</td>
</tr>
<tr>
<td>LC $P_\pm = 0.8, P_\pm = 0.6$</td>
<td>10.4</td>
<td>5.1</td>
<td>3.3</td>
</tr>
<tr>
<td>$pp \rightarrow g + G_n$</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>LHC</td>
<td>4 – 8.9</td>
<td>4.5 – 6.8</td>
<td>5.0 – 5.8</td>
</tr>
</tbody>
</table>

Table 1: 95% CL sensitivity to the fundamental scale $M_D$ in TeV for different values of $\delta$, from the emission process for various polarization configurations and different colliders as discussed in the text. $\sqrt{s} = 800$ GeV and 1 ab$^{-1}$ has been assumed for the LC and 100 fb$^{-1}$ for the LHC. Note that the LHC only probes $M_D$ within the stated range.
Randall-Sundrum Gravitons

Figure 4: The cross section for $e^+e^- \rightarrow \mu^+\mu^-$ including the exchange of a KK tower of gravitons in the Randall-Sundrum model with $m_1 = 500$ GeV. The curves correspond to $k/\bar{M}_{Pl}$ in the range 0.01 – 0.05.

<table>
<thead>
<tr>
<th></th>
<th>$k/\bar{M}_{Pl}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.01</td>
</tr>
<tr>
<td>LEP II</td>
<td>4.0</td>
</tr>
<tr>
<td>LC $\sqrt{s} = 0.5$ TeV</td>
<td>20.0</td>
</tr>
<tr>
<td>LC $\sqrt{s} = 1.0$ TeV</td>
<td>40.0</td>
</tr>
<tr>
<td>Tevatron Run II</td>
<td>5.0</td>
</tr>
<tr>
<td>LHC</td>
<td>20.0</td>
</tr>
</tbody>
</table>

Table 3: 95% CL search reach for $\Lambda_\pi$ in TeV in the contact interaction regime taking 500, 2.5, 2, and 100 fb$^{-1}$ of integrated luminosity at the LC, LEP II, Tevatron, and LHC, respectively. From (34).

- 500 GeV KK graviton/ its tower of states at a lepton collider

  Davoudiasl, Hewett, Rizzo
Randall-Sundrum Gravitons

Figure 4: The cross section for $e^+e^- \rightarrow \mu^+\mu^-$ including the exchange of a KK tower of gravitons in the Randall-Sundrum model with $m_1 = 500$ GeV. The curves correspond to $k/\sqrt{\Lambda}$ in the range $0.01 - 0.05$.

<table>
<thead>
<tr>
<th></th>
<th>$k/\sqrt{\Lambda}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEP II</td>
<td>4.0 1.5 0.4</td>
</tr>
<tr>
<td>LC $\sqrt{s} = 0.5$ TeV</td>
<td>20.0 5.0 1.5</td>
</tr>
<tr>
<td>LC $\sqrt{s} = 1.0$ TeV</td>
<td>40.0 10.0 3.0</td>
</tr>
<tr>
<td>Tevatron Run II</td>
<td>5.0 1.5 0.5</td>
</tr>
<tr>
<td>LHC</td>
<td>20.0 7.0 3.0</td>
</tr>
</tbody>
</table>

Table 3: 95% CL search reach for $\Lambda_\pi$ in TeV in the contact interaction taking 500, 2.5, 2, and 100 fb$^{-1}$ of integrated luminosity at the LC, 1 Tevatron, and LHC, respectively. From (34).
RS Gravitons at CDF RUNII

Current limit with $\mathcal{L} = 16\,pb^{-1}$

Expected limit later in Run II

CDF Run II Preliminary

$\sigma_{BR}(G \rightarrow \mu^+\mu^-)$ prediction

$\sigma_{BR}(G \rightarrow \mu^+\mu^-)$ limit (95% C.L.)

Graviton Mass (GeV/c^2)

L = 16 pb^{-1}

CDF Run II Preliminary

$\sigma_{BR}(G \rightarrow \mu^+\mu^-)$ prediction

$\sigma_{BR}(G \rightarrow \mu^+\mu^-)$ limit (95% C.L.)

Graviton Mass (GeV/c^2)

L = 100 pb^{-1}

L = 200 pb^{-1}

L = 2 fb^{-1}

k/M_{Pl} = 0.1

k/M_{Pl} = 0.085

k/M_{Pl} = 0.07

k/M_{Pl} = 0.01
A spin 2 graviton: Can we tell?

Figure 5: The angular distribution of “data” at the LHC from Drell-Yan production of the first graviton KK excitation with $m_1 = 1.5$ TeV and 100 fb$^{-1}$ of integrated luminosity. The stacked histograms represent the Standard Model contributions, and $gg$ and $qar{q}$ initiated graviton production as labeled. The curve shows the expected distribution from a spin-1 resonance. From (36).

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$m_1$ Reach (TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tevatron Run II 2 fb$^{-1}$</td>
<td>1.1</td>
</tr>
<tr>
<td>LHC 100 fb$^{-1}$</td>
<td>6.3</td>
</tr>
<tr>
<td>LEP II</td>
<td>3.1</td>
</tr>
<tr>
<td>LC $\sqrt{s} = 0.5$ TeV 500 fb$^{-1}$</td>
<td>13.0</td>
</tr>
<tr>
<td>LC $\sqrt{s} = 1.0$ TeV 500 fb$^{-1}$</td>
<td>23.0</td>
</tr>
<tr>
<td>LC $\sqrt{s} = 1.5$ TeV 500 fb$^{-1}$</td>
<td>31.0</td>
</tr>
</tbody>
</table>

Table 4: 95% CL search reach for the mass $m_1$ of the first KK gauge boson excitation (46).
Angular distributions in graviton production & decay (ATLAS)

- a $gg \rightarrow G \rightarrow ff$
- b $qq \rightarrow G \rightarrow ff$
- c $gg \rightarrow G \rightarrow gg, \gamma\gamma$
- a $qq \rightarrow G \rightarrow gg, \gamma\gamma$
- d $gg \rightarrow G \rightarrow WW, ZZ$
- e $qq \rightarrow G \rightarrow WW, ZZ$
- f $gg \rightarrow G \rightarrow HH$
- g $qq \rightarrow G \rightarrow HH$
$G \rightarrow WW \rightarrow 1\nu+\text{jets}(\text{ATLAS})$
HYBRID CASE:
ONE FLAT COMPACT ED
AND ONE RS TYPE ED

A map of the geometry of the extra space!

Davoudiasl, Hewett, Rizzo
HYBRID CASE:
ONE FLAT COMPACT ED
AND ONE RS TYPE ED

A map of the geometry of the extra space!

Davoudiasl, Hewett, Rizzo
Something about Black Holes

- goes back to early work by D’Eath and Payne [more recent Eardley+Giddings gr-qc/0201034, Yoshino+Nambu gr-qc/0209003]
Black Hole, mass, radius, entropy

- A gravitational potential well where the energy to get out of the well is greater than the total energy = Black Hole
- $G_NM_{BH} \cdot (R_S)^{-1} = 1 \rightarrow G_NM_{BH} = R_s$
  - the radius of a black hole $\propto$ mass of the black hole
- Entropy $S_{BH} \sim$ black hole area $\sim R_s^2 \sim M_{BH}^2$
High Energy vs High Entropy

- At higher and higher energies the production of a class of objects with higher and higher entropy will suppress the production of everything else…

- or, iow above the energy scale where BH can be produced, ONLY BH will be produced

- what is that energy scale? Is it possible that LHC turns on and we can only do diffraction particle physics and the rest is all black holes? And stringy stuff?
BH domination

- Conservatively BH production should dominate for $M_{BH} \sim (5-10)M^*$
- Cross section: $\sigma_{ij} \ BH = F(s) \ \pi R^2_S$
- $F(s) < 1$ (not all energy gets trapped, geometrical considerations for spherical formation etc)
BH Production

- Total cross section for BH formation eg.
- for $n=2\ldots7$ by proton-proton scattering at LHC (14 TeV).
  Assume $M*=1$ TeV and
- threshold for Black Hole formation at $M_{BH,min}=3$ $M*=3$ TeV

Cavaglia et al./hep-ph/0210296
Remarks

• Anything NEW at **high energies** will clue us in
• The models are models not theories -- but when you find even one solution to a tough problem you take it seriously and investigate it exhaustingly with experimental tests
• We do this kind of physics scale by scale and we are lucky to be breaking into crucial energy scales experimentally today

🎉 And what exactly is the number (super very) **high??**
Remarks

- Anything NEW at **high energies** will clue us in
- The models are models not theories -- but when you find even one solution to a tough problem you take it seriously and investigate it exhaustingly with experimental tests
- We do this kind of physics scale by scale and we are lucky to be breaking into crucial energy scales experimentally today

⚠️ And what exactly is the number (super very) **high???

⚠️ WE DON’T KNOW ; ONLY THE EXPERIMENT CAN (AND WILL) TELL.
• [Sean Carroll] ...there is a lot of very smart people working hard, loosing sleep and eating fast-food trying to solve this problem
• [Joe Lykken] ...we have to measure experimentally; we can’t predict it so easily starting from theory
• [Eric Adelberger] ...interesting experimental challenge to see extraordinarily weak forces
• [Lisa Randall] I really want to get up to higher energies

• for the video go to