Searching for Hidden Dimensions in Space at DØ

Greg Landsberg

BROWN University

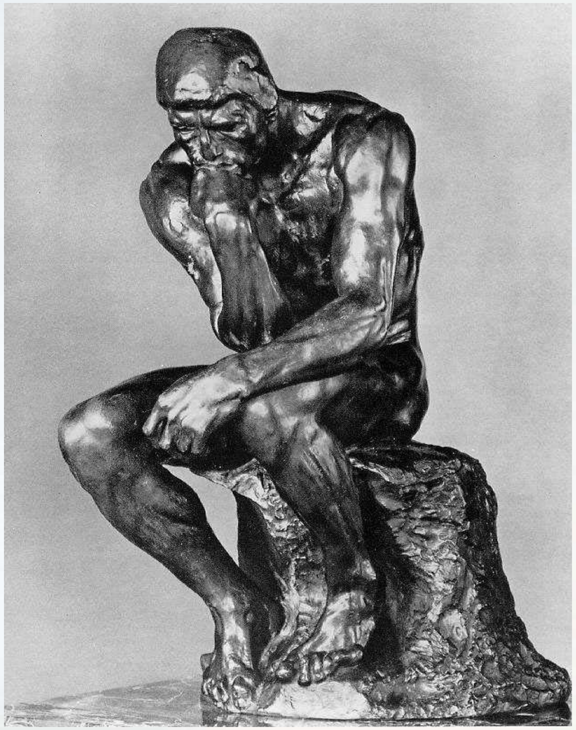
(For the DØ Collaboration)

Fermilab W&C Seminar

October 15, 2004

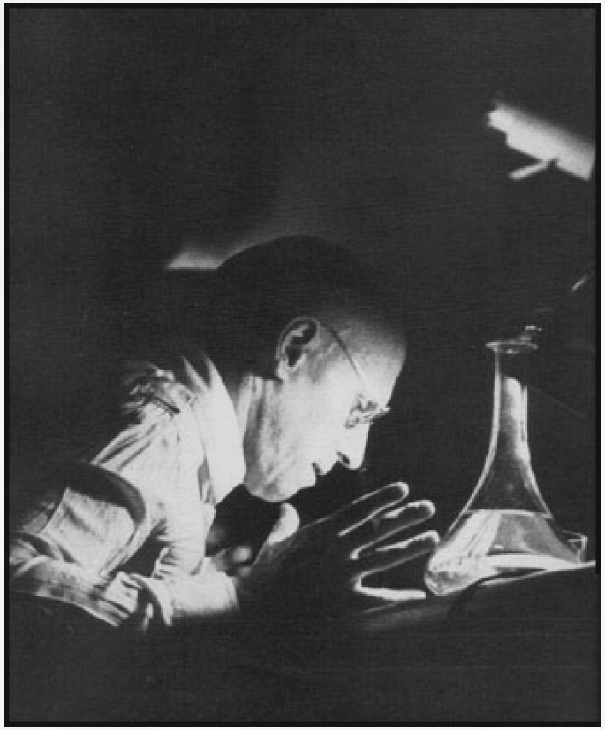
Out-Sketch

Theory/Phenomenology



Brief overview:
- ❖ Intro to Models
- ❖ Phenomenology
- ❖ Collider signatures

Tabletop Experiments



A few highlights:
- ❖ Gravity at short range
- ❖ Cosmology constraints

Accelerator Searches

Ultimate probes:
- ❖ New DØ Results on Searches for Extra Dimensions:
  - ❖ ADD Model
  - ❖ TeV^{-1} Scenario
  - ❖ RS Model
- ❖ Outlook

N.B. Large Hierarchies Tend to Collapse…

Collapse of the Soviet Union

The Nineties…

Although Keep in Mind…

- Fine tuning (required to keep a large hierarchy stable) exists in Nature:
  - Solar eclipse: angular size of the sun is the same as the angular size of the moon within 2.5% (pure coincidence!)
  - Numerology: 987654321/123456789 =

    8.000000073

    (a bottle of wine is offered for the correct answer, why?)
  - Politics: Florida recount, 2,913,321/2,913,144 =

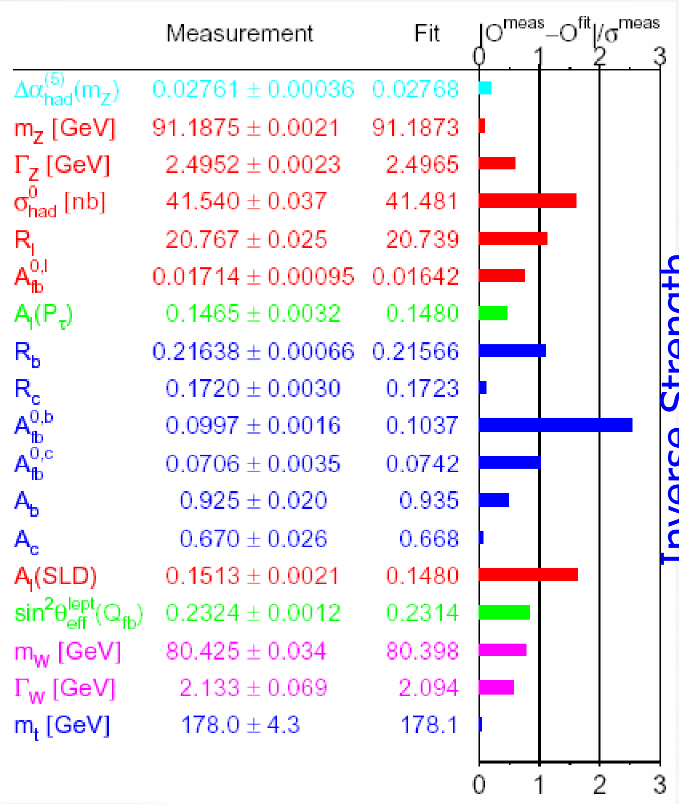
    1.000061

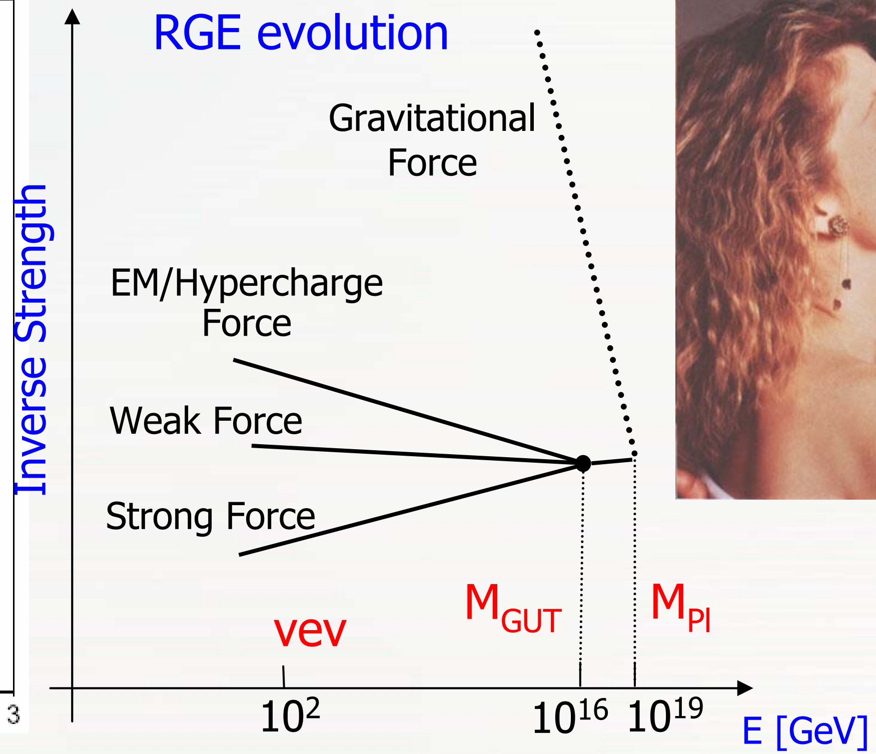
    (a slice of cheese is offered for the correct answer, why?)

[Answers should be given to me by the end of this talk]

Hierarchy of the Standard Model

Beauty … and the Beast





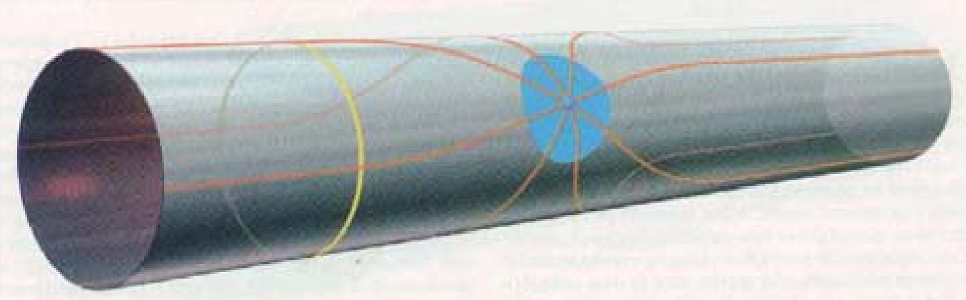
Extra dimensions might get rid of the beast while preserving the beauty!

The ADD Model

- Arkani-Hamed, Dimopoulos, and Dvali, 1998 (ADD)
- 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?

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

- Ruled out for infinite extra dimensions, but does not apply 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

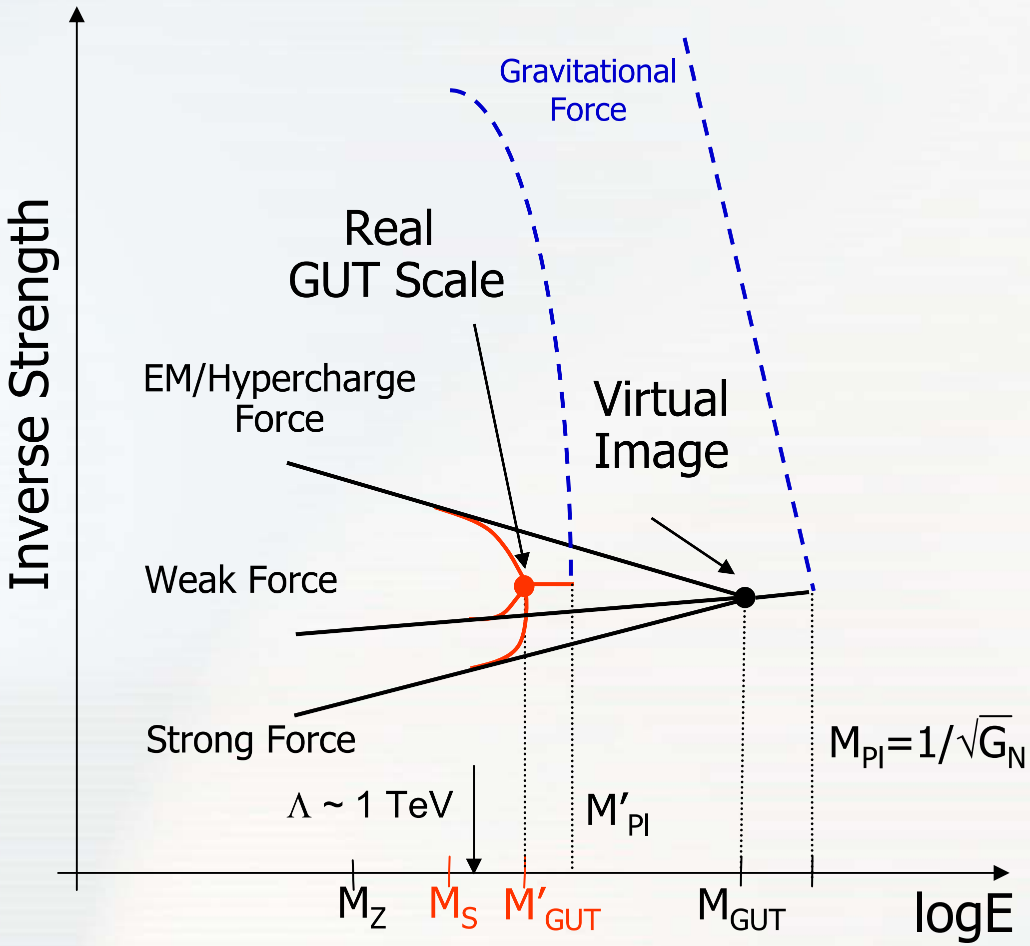
$$M_D^{n+2} \propto M_{Pl}^2 / R^n$$

- 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

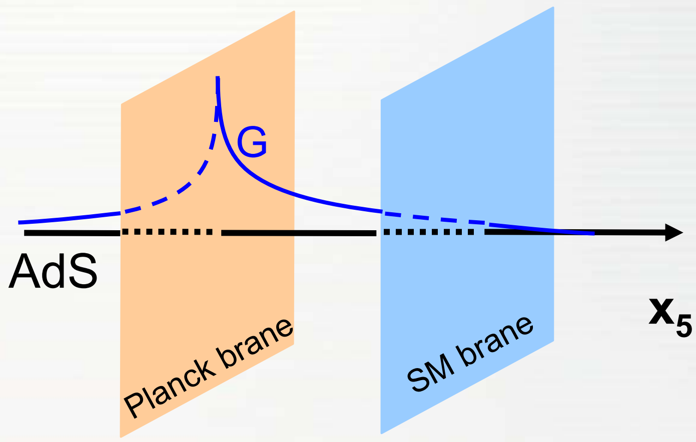
Longitudinal ED

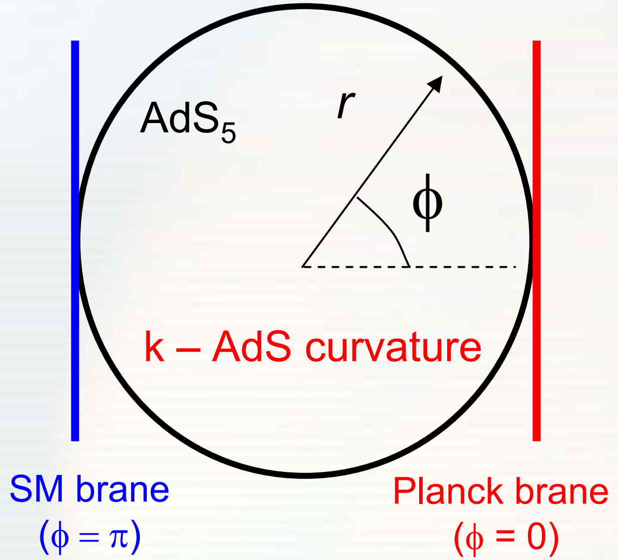


- Simultaneously, another idea has appeared:
  - Explore modification of the RGE in (4+n)-dimensions to achieve low-energy unification of three gauge forces [Dienes, Dudas, and Gherghetta, PL B436, 55 (1998)]
  - To achieve that, allow gauge bosons (g, γ, W, and Z) to propagate in an extra dimension, which is "longitudinal" to the SM brane and compactified on a "natural" EW scale: $R \sim 1\ \text{TeV}^{-1}$

Randall-Sundrum Scenario

- Randall-Sundrum (RS) scenario
[PRL **83**, 3370 (1999); PRL **83**, 4690 (1999)]
  - \+ brane – no low energy effects
  - +– branes – TeV Kaluza-Klein modes of graviton
  - Low energy effects on SM brane are given by Λ_π;
  - for $kr_c \sim 10$, $\Lambda_\pi \sim 1$ TeV and the hierarchy problem is solved naturally





$$ds^2 = e^{-2kr|\phi|}\eta_{\mu\nu}dx^\mu dx^\nu - r^2 d\phi^2$$

$$\Lambda_\pi = \overline{M}_{Pl} e^{-kr\pi}$$

Reduced Planck mass:

$$\overline{M}_{Pl} \equiv M_{Pl} / \sqrt{8\pi}$$

Differences Between the Models

ADD Model:

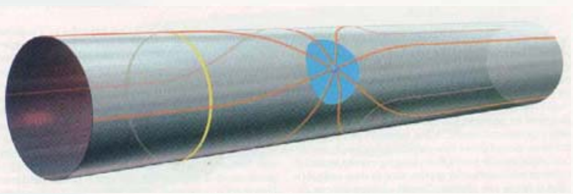
•Pro: "Eliminates" the hierarchy problem by stating that physics ends at a TeV scale

•Only gravity lives in the "bulk" space

•Size of ED's (n=2-7) between ~100 μm and ~1 fm

•Black holes at the LHC

•Con: Doesn't explain how to make ED large



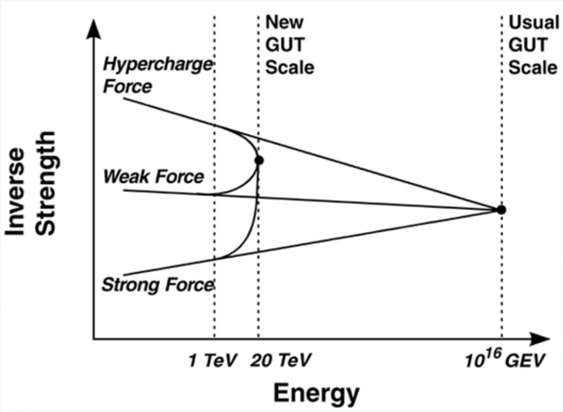
TeV^{-1} Scenario:

•Pro: Lowers GUT scale by changing running of the couplings

•Only gauge bosons (g/γ/W/Z) "live" in ED's

•Size of ED's ~1 TeV^{-1} or ~10^{-19} m

•Con: Gravity is not in the picture

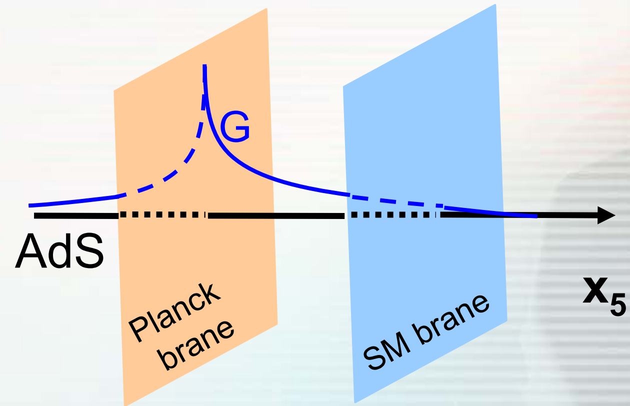


RS Model:

•Pro: A rigorous solution to the hierarchy problem via localization of gravity

•Gravitons (and possibly other particles) propagate in a single ED, w/ special metric

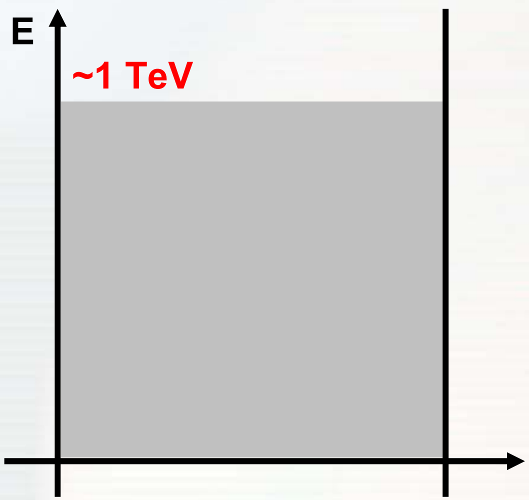
•Con: Size of ED as small as ~$1/M_{Pl}$ or ~10^{-35} m



Kaluza-Klein Spectrum

ADD Model:

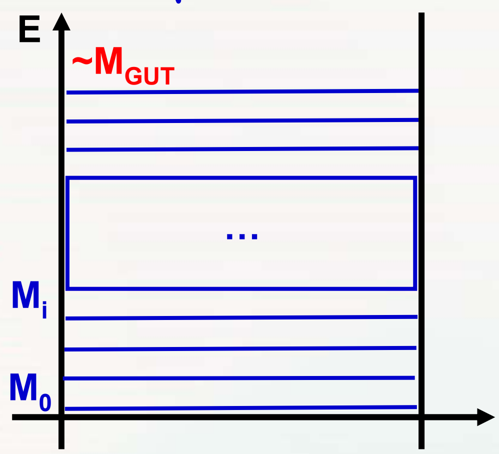
- Winding modes with energy spacing ~1/r, i.e. 1 meV – 100 MeV
- Can't resolve these modes – they appear as continuous spectrum
- Coupling: G_N per mode; compensated by large number of modes



TeV^{-1} Scenario:

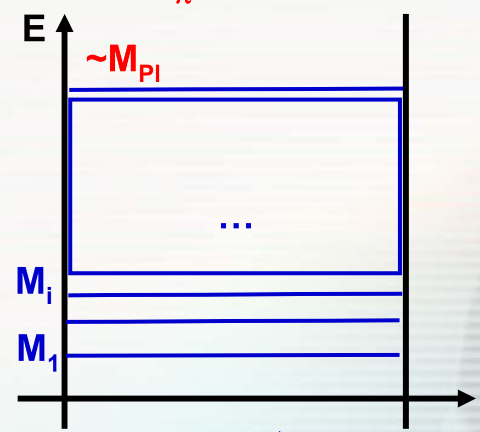
- Winding modes with nearly equal energy spacing ~1/r, i.e. ~TeV
- Can excite individual modes at colliders or look for indirect effects
- Coupling: ~g_W per mode

$$M_i = \sqrt{M_0^2 + i^2/r^2}$$



RS Model:

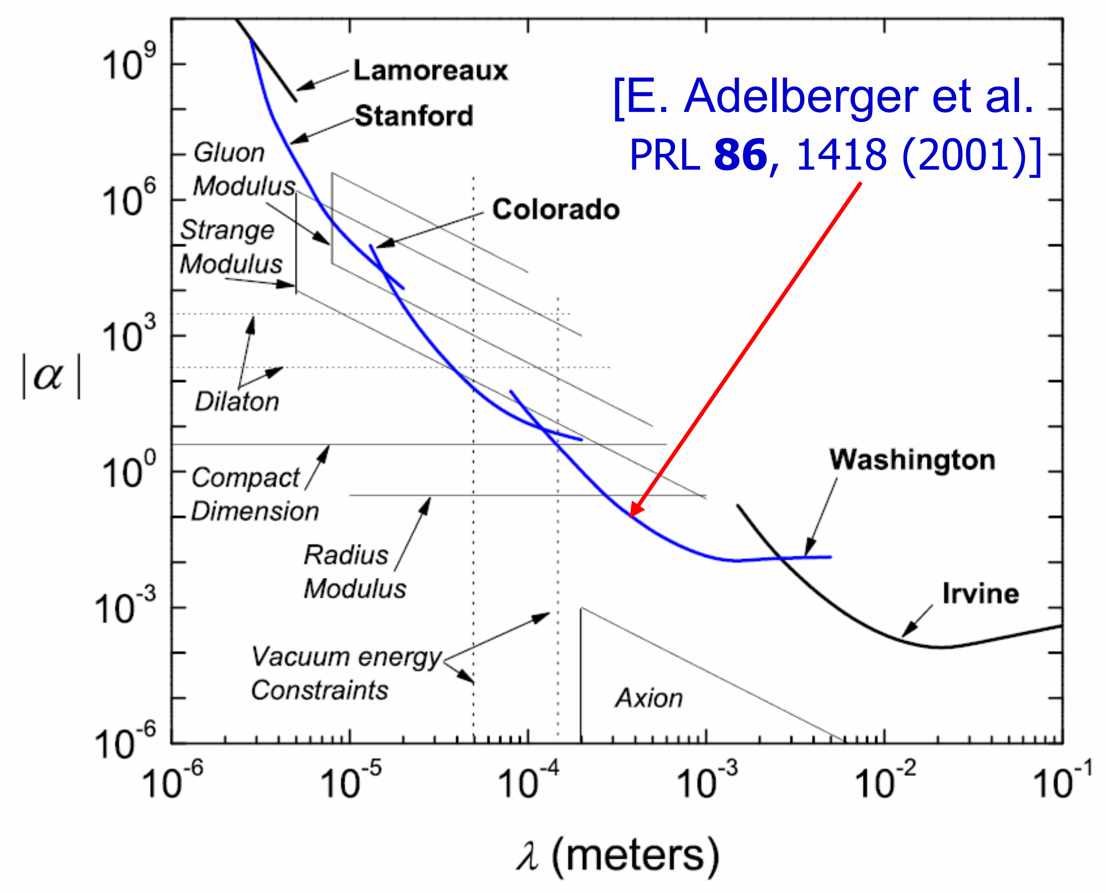
- "Particle in a box" with special AdS metric
- Energy eigenvalues are given by zeroes of Bessel function J_1
- Light modes might be accessible at colliders
- Coupling: G_N for zero mode; $1/\Lambda_\pi^2$ for the others



$$M_0 = 0; M_i = M_1 x_i / x_1 \approx M_1, 1.83M_1, 2.66M_1, 3.48M_1, 4.30M_1, \ldots$$

Constraints from Gravity Experiments

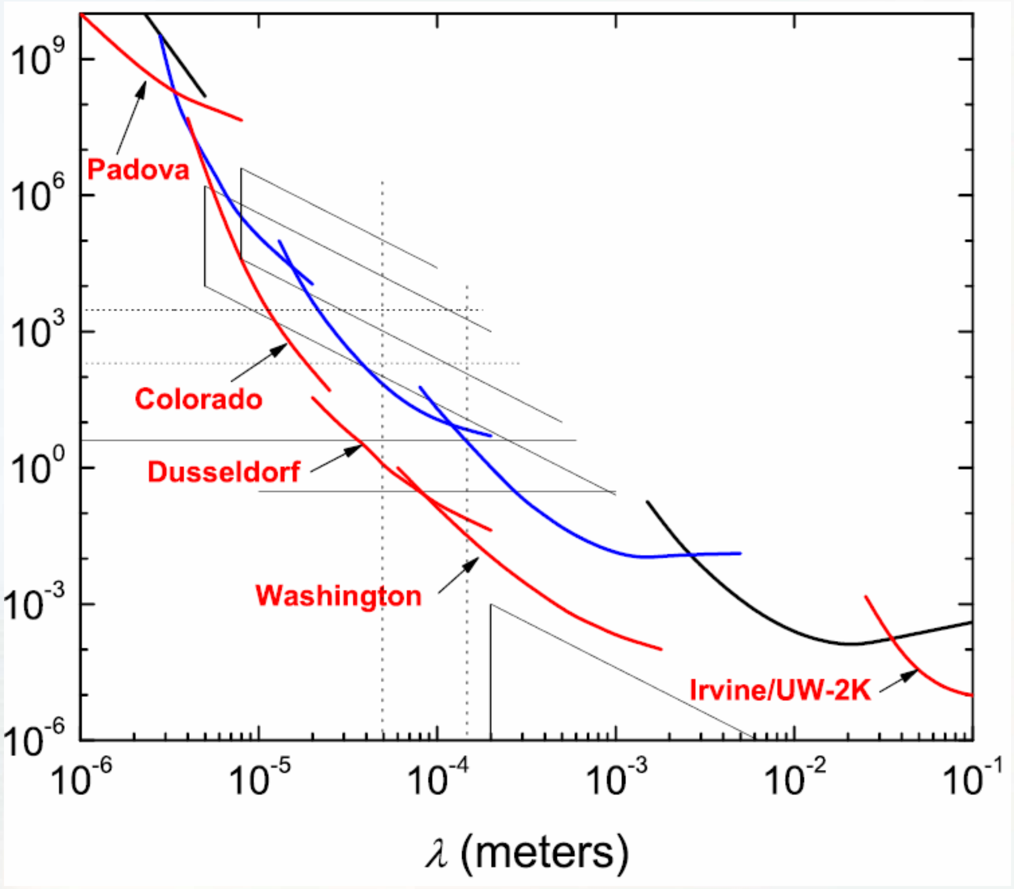
[J. Long and J. Price, hep-ph/0303057]



- Sub-millimeter gravity measurements could probe *only* n=2 case *only* within the ADD model
- 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 ≲ 0.16 mm (M_D ≳ 1.7 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
- No sensitivity to the TeV^{-1} and RS models

Constraints from Gravity Experiments

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



- Sub-millimeter gravity measurements could probe *only* n=2 case *only* within the ADD model
- 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
  - ❖ $R \lesssim 0.16$ mm ($M_D \gtrsim 1.7$ 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
- No sensitivity to the TeV^{-1} and RS models

Astrophysical and Cosmological Constraints

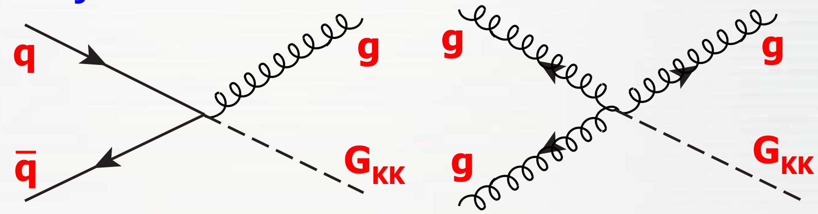
- Used to constrain the ADD scenario
- Supernova cooling due to graviton emission – an alternative cooling mechanism that would decrease the dominant cooling via neutrino emission
  - Tightest limits on any additional cooling sources come from the measurement of the SN1987A neutrino flux by the Kamiokande and IMB
  - Application to the ADD scenario [Cullen and Perelstein, PRL **83**, 268 (1999); Hanhart, Phillips, Reddy, and Savage, NP **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 $G_{KK} \to \gamma\gamma$ 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, PL **B508**, 335 (2001); Fairbairn and 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
- Virtually no constraints on TeV^{-1} and RS models

Collider Signatures for Large ED

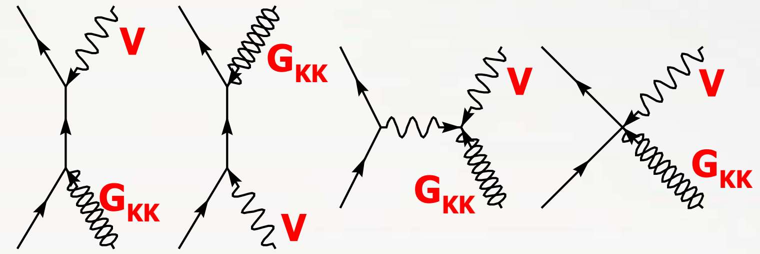
- Kaluza-Klein gravitons couple to the energy-momentum tensor, and therefore contribute to most of the SM processes
- For Feynman rules for G_{KK} see:
  - [Han, Lykken, Zhang, PRD **59**, 105006 (1999)]
  - [Giudice, Rattazzi, Wells, NP **B544**, 3 (1999)]
- Since graviton can propagate in the bulk, energy and momentum are not conserved in the G_{KK} emission from the point of view of our 3+1 space-time
- 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
- Graviton emission: direct sensitivity to the fundamental Planck scale M_D
- Virtual effects: sensitive to the ultraviolet cutoff M_S, expected to be $\sim M_D$ (and likely $< M_D$)
- The two processes are complementary

Real Graviton Emission

Monojets at hadron colliders

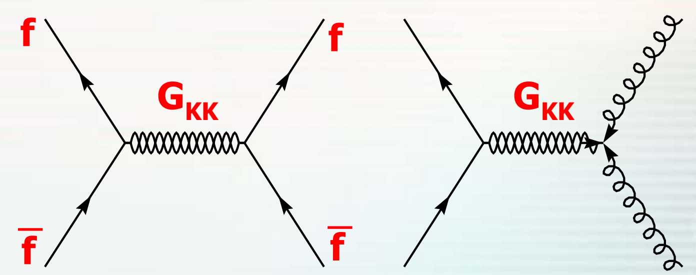


Single VB at hadron or e^+e^- colliders



Virtual Graviton Effects

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



L'EPilogue

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

Virtual Graviton Exchange [M_S(Hewett)]

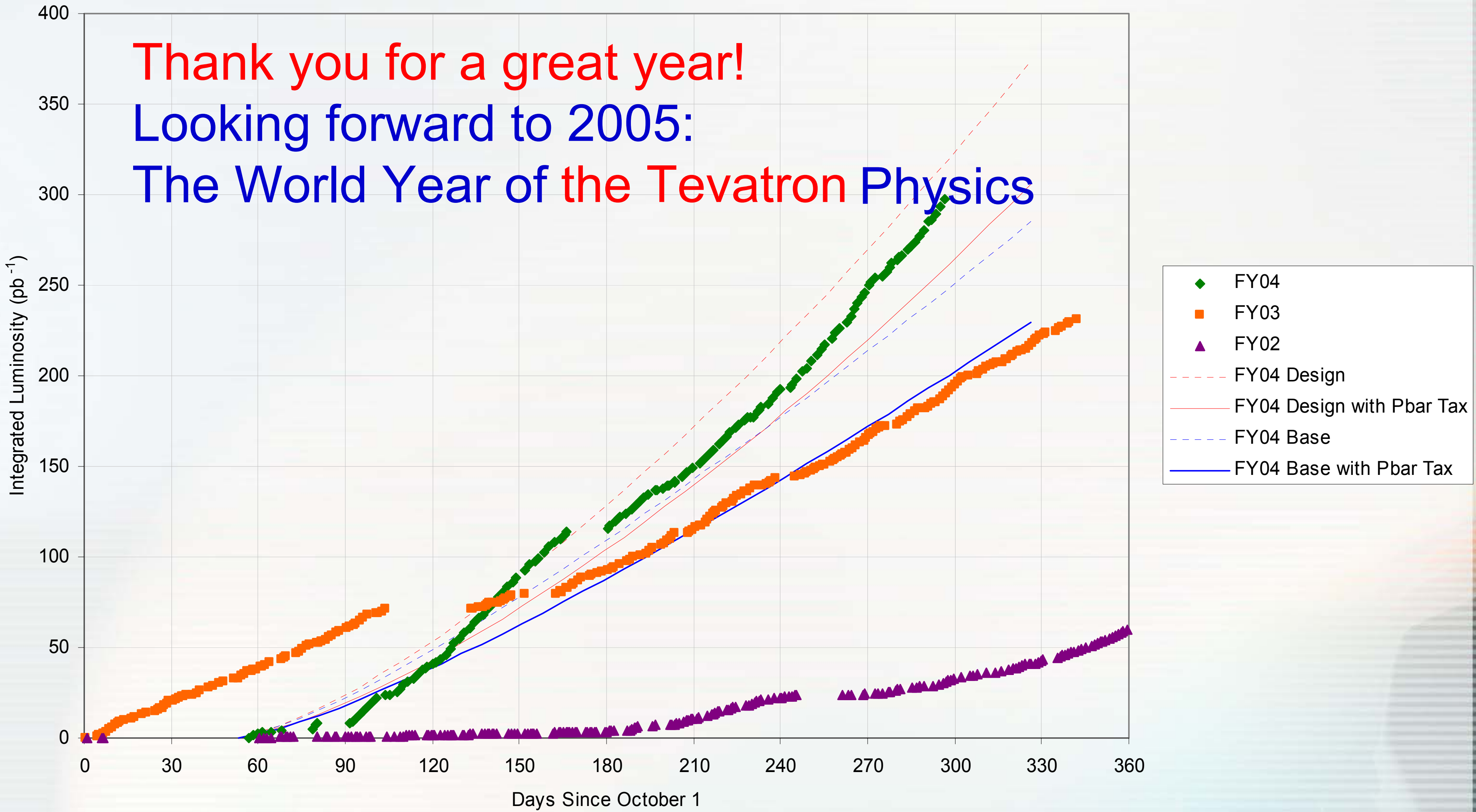
Experiment	e^+e^-	$\mu^+\mu^-$	$\tau^+\tau^-$	qq	ff	$\gamma\gamma$	WW	ZZ	**Combined**
ALEPH	1.04 0.81	0.65 0.67	0.60 0.62	0.53/0.57 0.46/0.46 (bb)	1.05 0.84	0.81 0.82			0.75/1.00 (<189)
DELPHI		0.59 0.73	0.56 0.65		0.60 0.76	0.83 0.91			0.60/0.76 (ff) (<202)
L3	0.98 1.06	0.56 0.69	0.58 0.54	0.49 0.49	0.84 1.00	0.99 0.84	0.68 0.79		1.1/1.0 (<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: 1.2/1.1

The Tevatron Performance

The FY2004 Design goal (306 pb^{-1} delivered) has been achieved

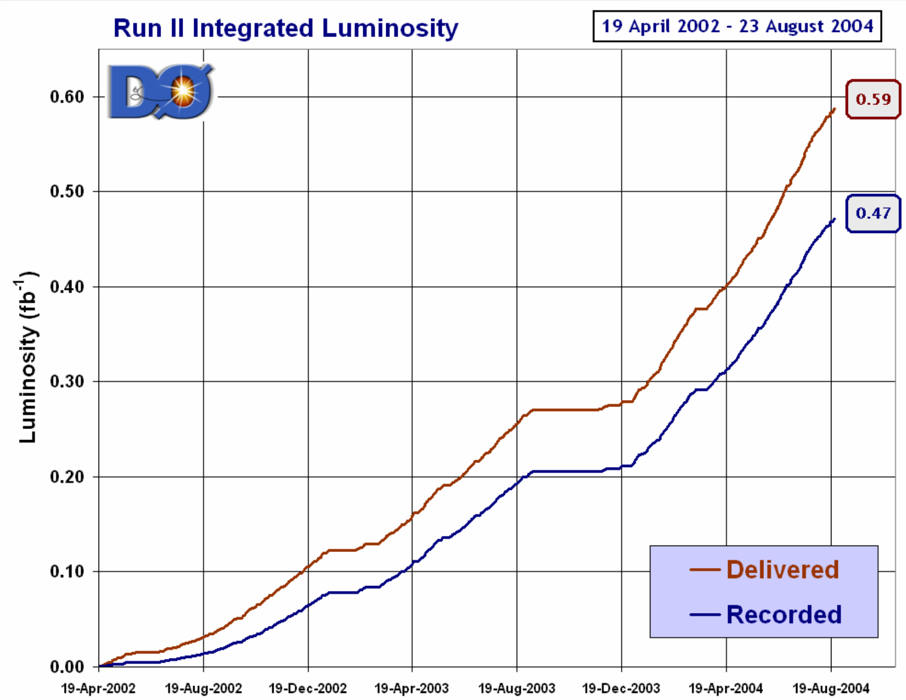
$L = 10^{32}\ cm^{-2}s^{-1}$ Record!

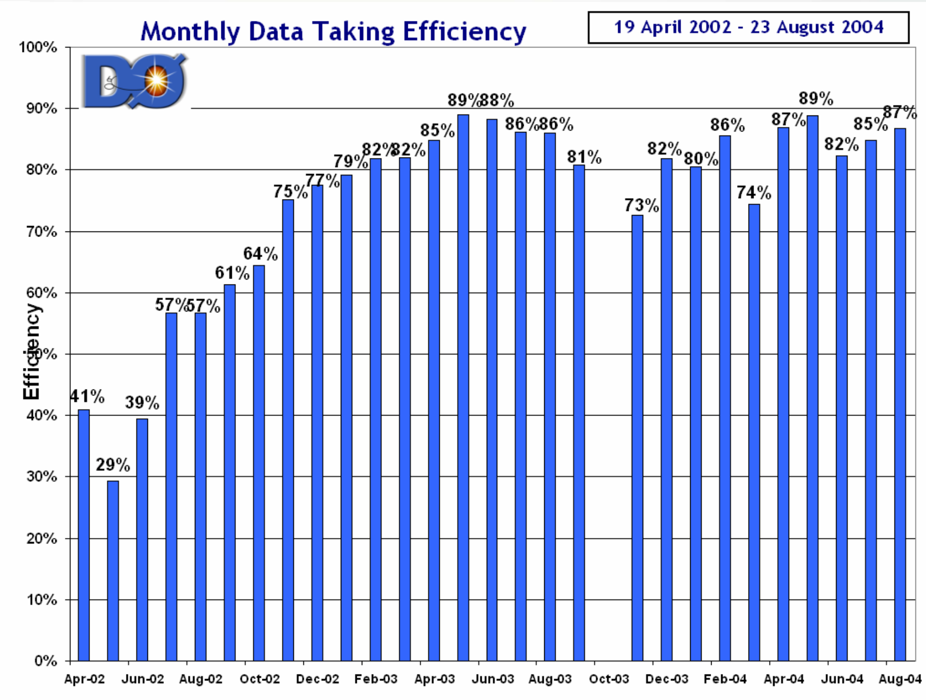


DØ Performance

Nearly 0.5 fb^{-1} has been logged to tape

1 billion events recorded as of August 2!





- The experiment is ≈85% efficient over the last year; 80% average efficiency in Run II
- Most of the analyses shown in this talk are based on ~200 pb^{-1}, which corresponds to the 2002-2003 data

Monojets: Tainted History

EXPERIMENTAL OBSERVATION OF EVENTS WITH LARGE MISSING TRANSVERSE ENERGY ACCOMPANIED BY A JET OR A PHOTON(S) IN $p\bar{p}$ COLLISIONS AT $\sqrt{s}$ = 540 GeV

[PL, **139B**, 115 (1984)]

UA1 Collaboration, CERN, Geneva, Switzerland

VOLUME 54, NUMBER 6 PHYSICAL REVIEW LETTERS 11 FEBRUARY 1985

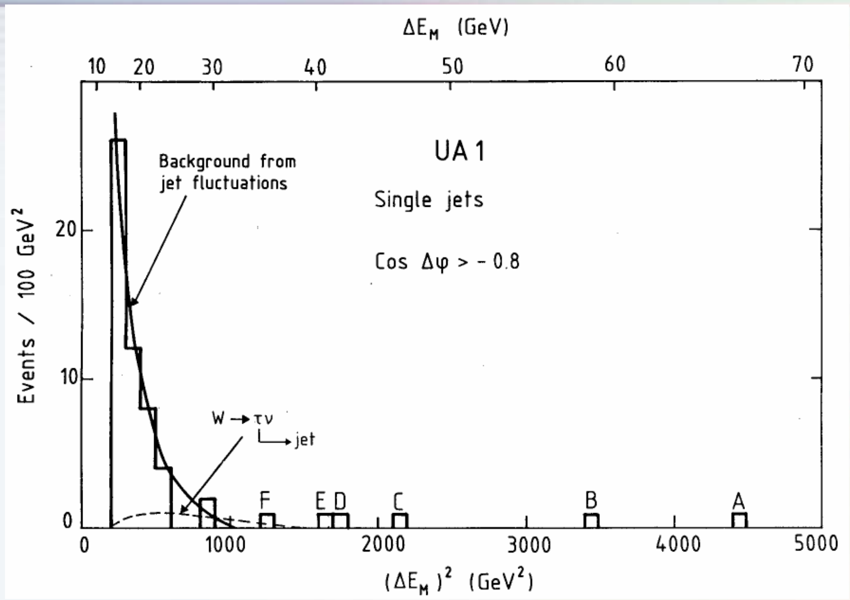
Monojets from *Z* Decay without Extra Neutrinos or Higgs Particles

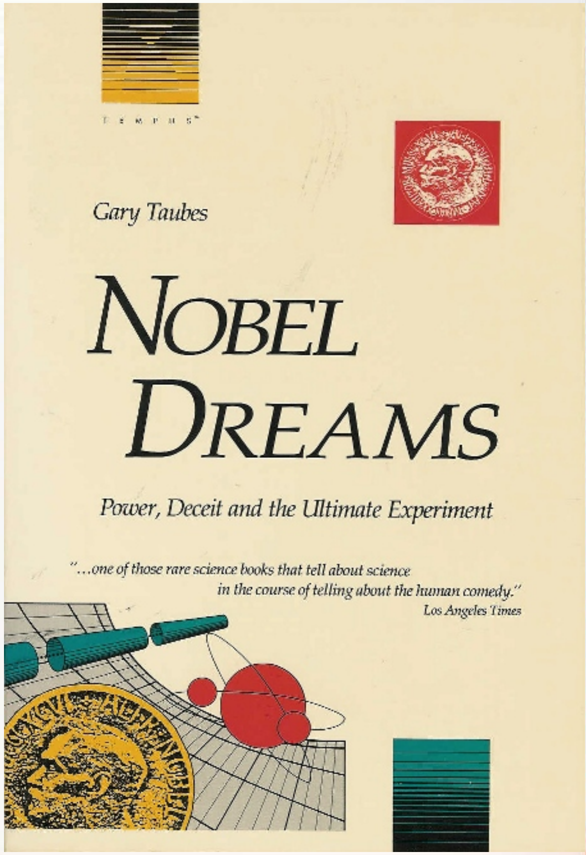
Stephen F. King
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 26 November 1984)

closely spaced photons). We cannot find an explanation for such events in terms of backgrounds or within the expectations of the Standard Model.

The recent discovery of monojets by Arnison *et al.*[1] at the CERN $p\bar{p}$ collider has caused ripples of excitement throughout the particle physics world, since they cannot be explained by the minimal standard model.[2]

Monojets: Tainted History

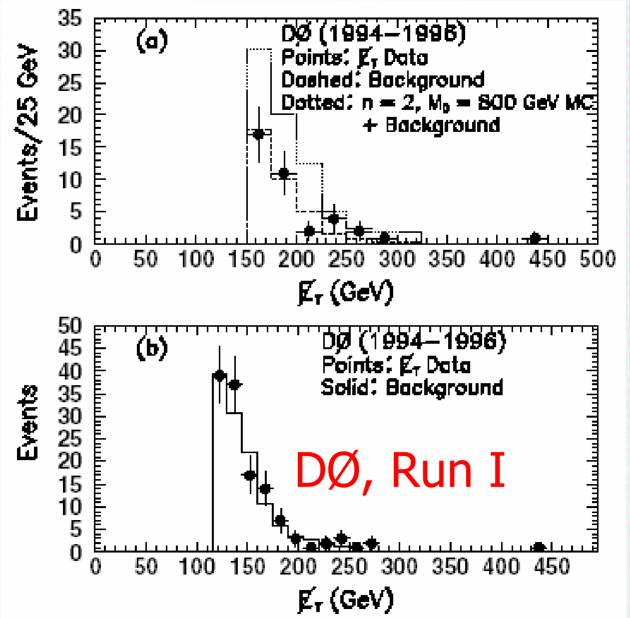


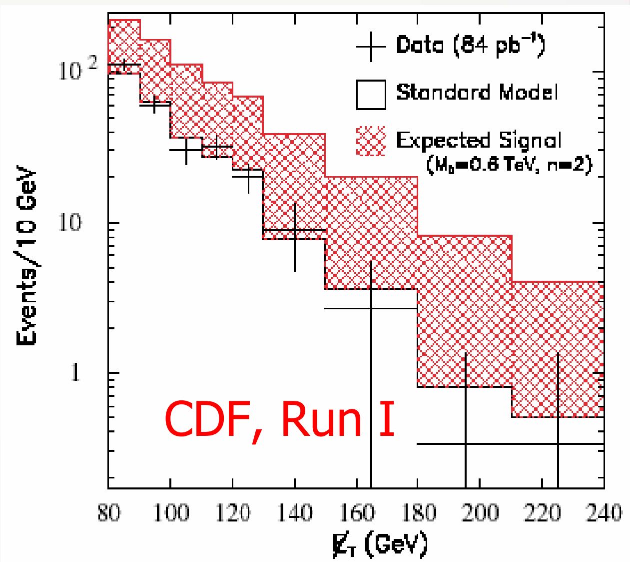


- These monojets turned out to be due to unaccounted background
- The signature was deemed doomed and nearly forgotten
- It took many years for the successful monojet analyses at a hadron collider to be completed (at CDF and DØ)

Search for Monojets at the Tevatron

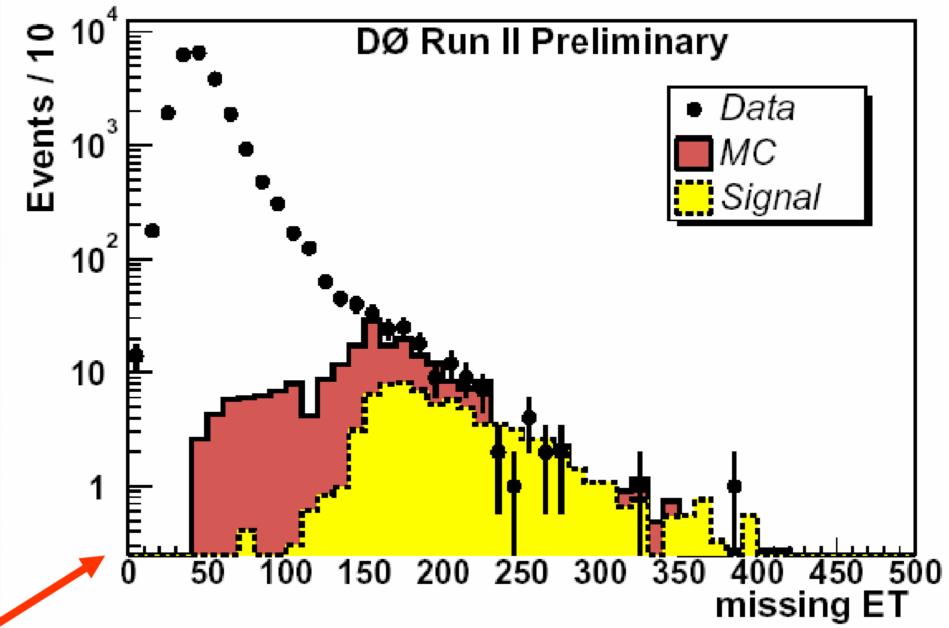
- Challenge: large instrumental background from mismeasured ME_T, cosmics, and $W(\tau\nu)$
- Irreducible physics background from $Z(\nu\nu)$ + jet(s): forces to use high jet p_T, ME_T cuts
- Pioneered in Run I by DØ [PRL **90**, 251802 (2003)]: $M_D > 0.63 - 0.89$ TeV (n=6-2)
- Recently superseded by CDF [PRL **92**, 121802 (2004)]: $M_D > 0.71 - 1.00$ TeV (n=6-2)
- CDF has pioneered similar search in $\gamma + ME_T$, albeit less sensitive [PRL **89**, 281801 (2002)]





Monojet Event Selection

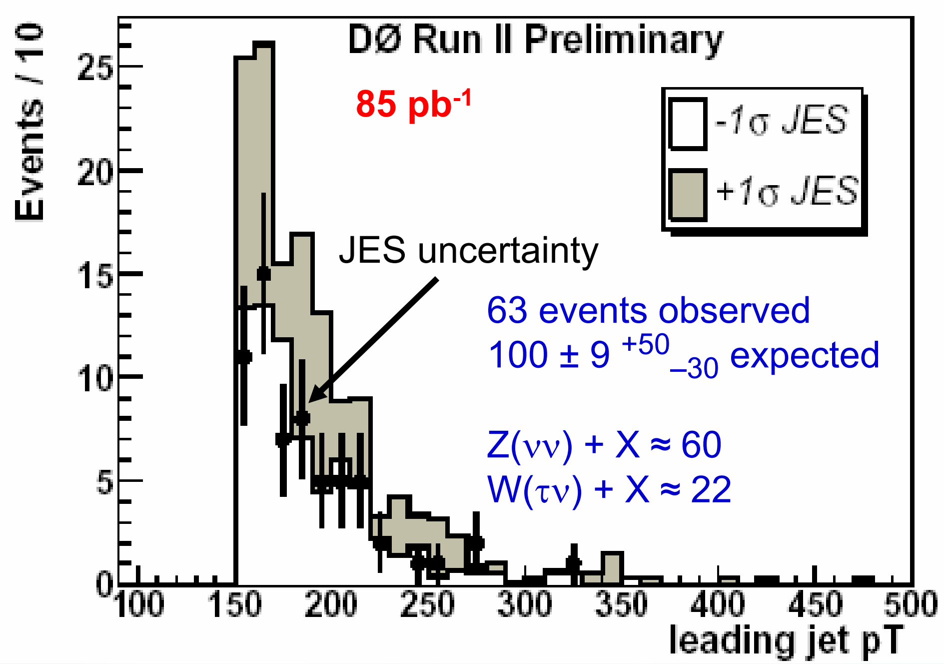
- New Run II DØ analysis based on ~85 pb^{-1} of data, collected with special trigger, requiring $MH_T = -\Sigma\vec{p}_T(\text{jets}) > 20$ GeV
- Offline, jets require to have associated tracks and confirm primary vertex
- Jet quality cuts reduce instrumental background from calorimeter noise
- Leading jet $p_T > 150$ GeV;
- $ME_T > 150$ GeV
- No extra jets with $p_T > 50$ GeV are allowed; no isolated leptons
- ME_T vector is required to be separated by at least 30° in azimuth from any jet in the event

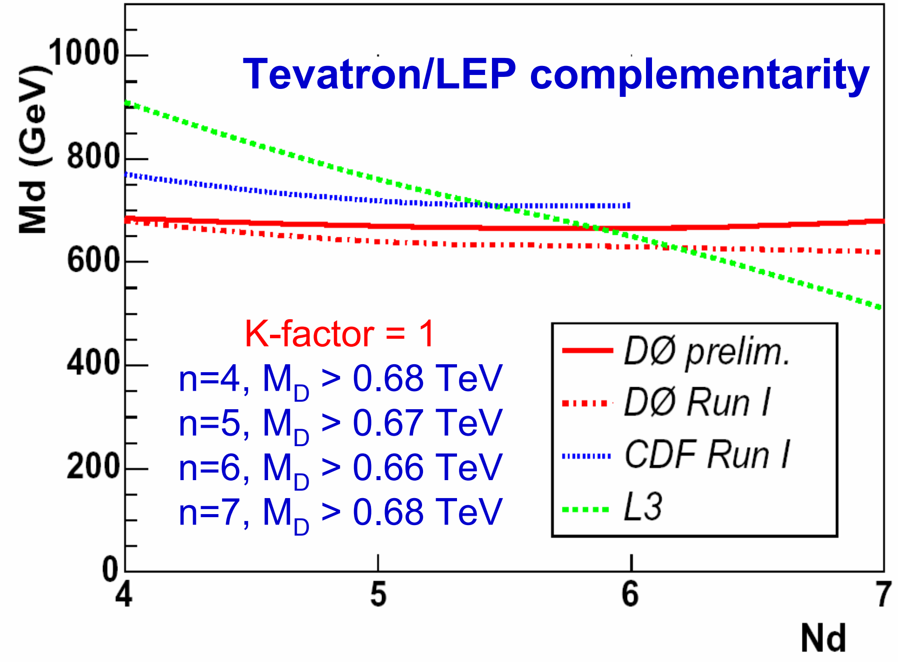


- Overall signal (M_D = 0.7 TeV, n=6) efficiency: ~5%; mainly due to high p_T cut
- 63 events (out of the initial sample of 360K) pass final selections
- Signal simulation: PYTHIA augmented with Lykken-Matchev's code

Monojet Results

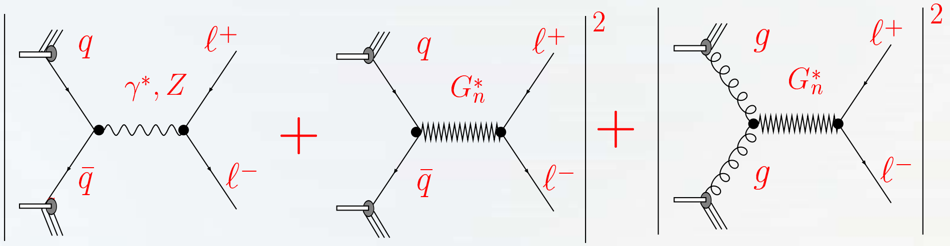
- Major systematics from jet energy scale – to be reduced soon (JES errors have been reduced by a factor of ~2 since these results became public)
- Sensitivity already exceeds that for DØ in Run I, but still below CDF's Run I result
- Impressive sensitivity already achieved with less data due to superior detector and higher energy
- An update with much higher statistics and better detector understanding soon





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):



~3% of the total

- Therefore, production cross section has three terms: SM, interference, and direct gravity effects:

$$\frac{d^2\sigma}{d\cos\theta^* dM} = \frac{d^2\sigma_{SM}}{d\cos\theta^* dM} + \eta_G f_1(\cos\theta^*, M) + \eta_G^2 f_2(\cos\theta^*, M)$$

$$\eta_G = a(n)/M_S^4,\ a(n) \sim 1$$

- The sum in KK states is divergent in the effective theory, so in order to calculate the cross sections, an explicit cut-off is required
- An expected value of the cut-off $M_S \approx M_D$, as this is the scale at which the effective theory breaks down, and the string theory needs to be used to calculate production
- There are three major conventions on how to write the effective Lagrangian:
  - Hewett [PRL **82**, 4765 (1999)]
  - Giudice, Rattazzi, Wells [NP **B544**, 3 (1999); revised version, hep-ph/9811291]
  - Han, Lykken, Zhang [PRD **59**, 105006 (1999); revised version, hep-ph/9811350]
- Fortunately all three conventions turned out to be equivalent and only the definitions of M_S are different

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 $\sim a(n)/M_S^4$(HLZ), where a(n) reflects the dependence on the number of extra dimensions:

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

- Correspondence between the three formalisms:

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

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

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

- Rule of thumb:

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

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

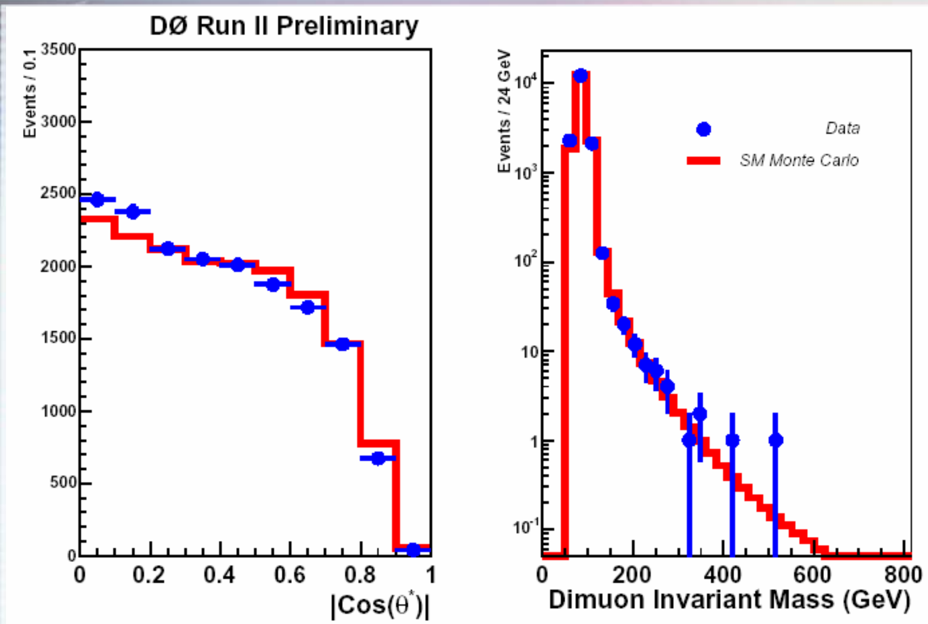
Search for Large ED in Dimuons

- Data set: 250 ± 16 pb^{-1}, ~17K dimuon candidate events:

Selection	Number of events passing cut
Starting sample	115,009
Bad run removal	108,574
Duplicate events removed	105,863
Track quality cuts	65,163
Dimuon invariant mass > 50 GeV	40,744
Cosmic veto	25,811
Isolation requirements	17,193
After p_T fixed re-apply mass cut	16,796

- QCD and cosmics backgrounds made negligible by tight muon ID cuts (isolation and timing)
- Major remaining background: SM Drell-Yan production
- Use special technique to take care of poorly measured high-p_T muons
- Use 2D-analysis based on $M_{\mu\mu}$ and $|\cos\theta^*|$ yielding maximum sensitivity to large ED [Cheung & GL, PRD **62**, 076003 (2000)]
- Extract signal by fitting data with the sum of the SM, interference, and direct graviton templates, with η_G being a parameter of the fit

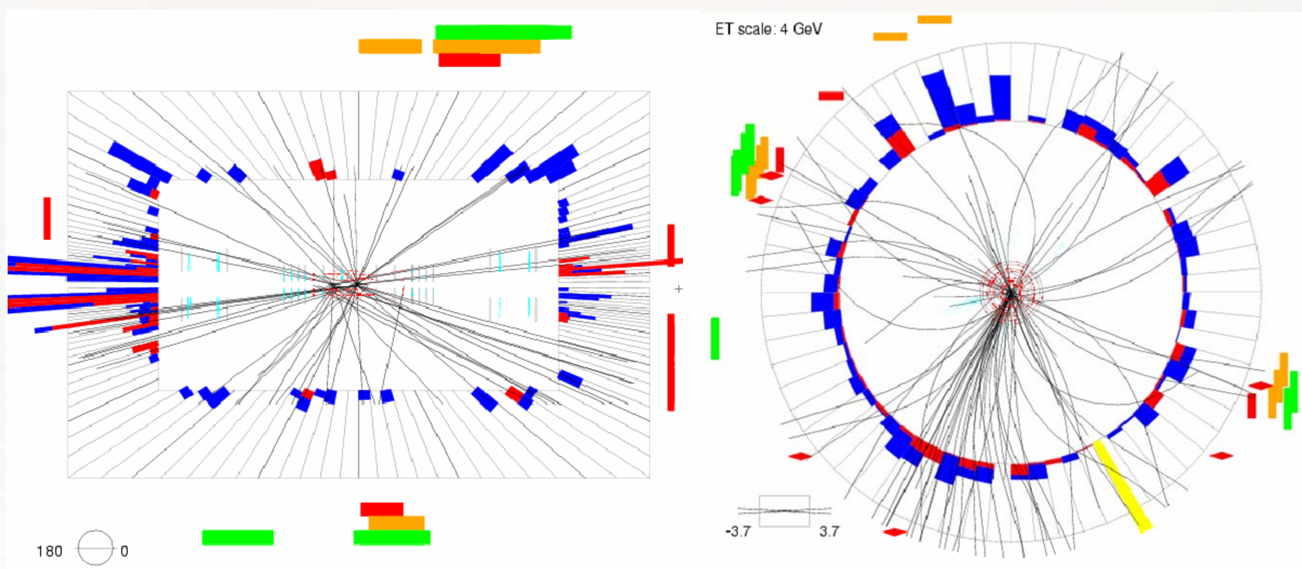
Comparison of Data and the SM



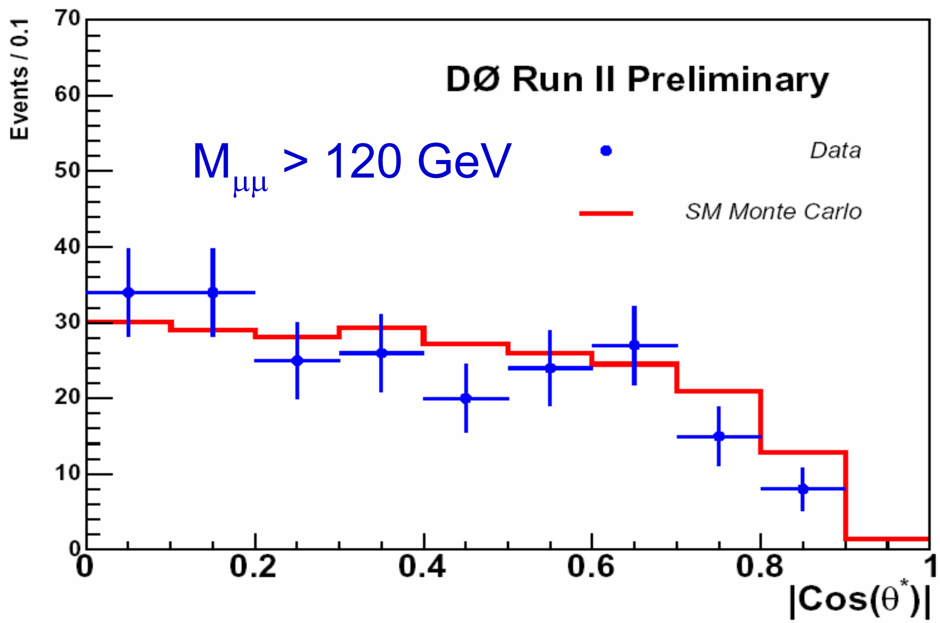
Min. $M_{\mu\mu}$	Bckgd	N in data	Poisson P
120 GeV	221	213	0.71
180 GeV	43.6	43	0.56
240 GeV	15.1	15	0.54
300 GeV	6.4	5	0.45
360 GeV	3.2	2	0.82
420 GeV	1.7	1	0.82
480 GeV	1.0	1	0.64
510 GeV	0.83	1	0.56
540 GeV	0.67	0	1.0

The highest-mass candidate event:

- $M_{\mu\mu}$ = 522 GeV
- $|\cos\theta^*|$ = 0.15
- N_{jet} (p_T>15 GeV) = 0
- $\not{E}_T^{cal}$ = 6 GeV
- p_T = 258 GeV
- $\eta_{1,2}$ = 0.03, 0.4
- $\phi_{1,2}$ = 5.9, 2.6



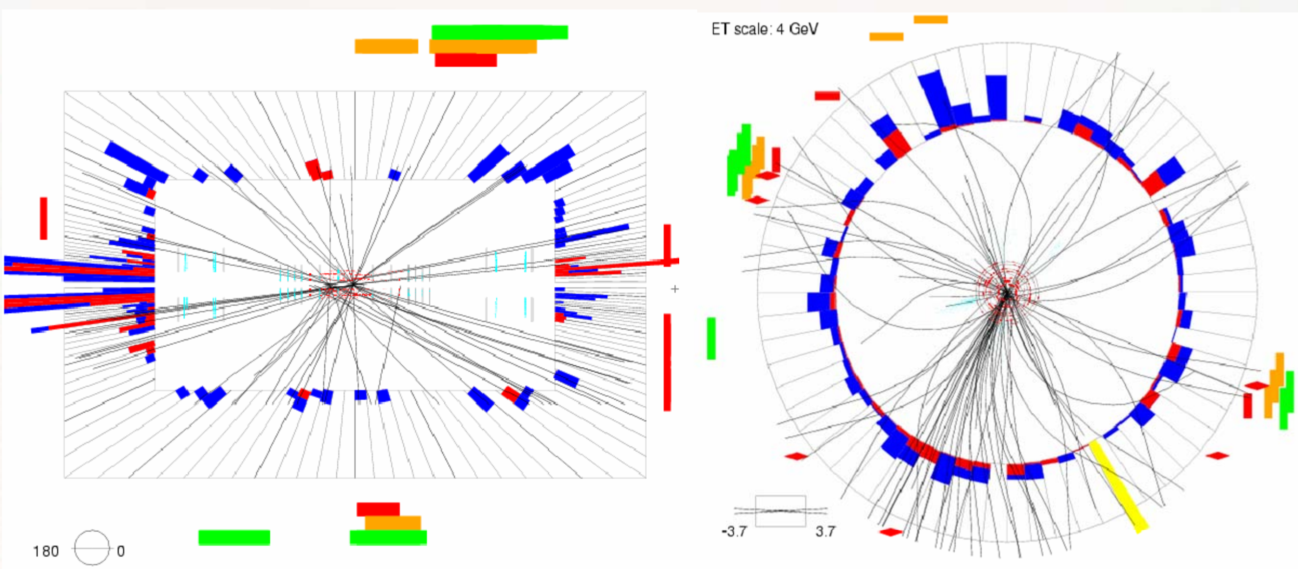
Comparison of Data and the SM



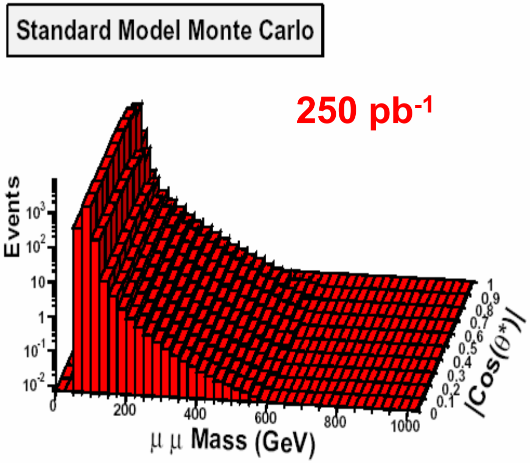
Min. $M_{\mu\mu}$	Bckgd	N in data	Poisson P
120 GeV	221	213	0.71
180 GeV	43.6	43	0.56
240 GeV	15.1	15	0.54
300 GeV	6.4	5	0.45
360 GeV	3.2	2	0.82
420 GeV	1.7	1	0.82
480 GeV	1.0	1	0.64
510 GeV	0.83	1	0.56
540 GeV	0.67	0	1.0

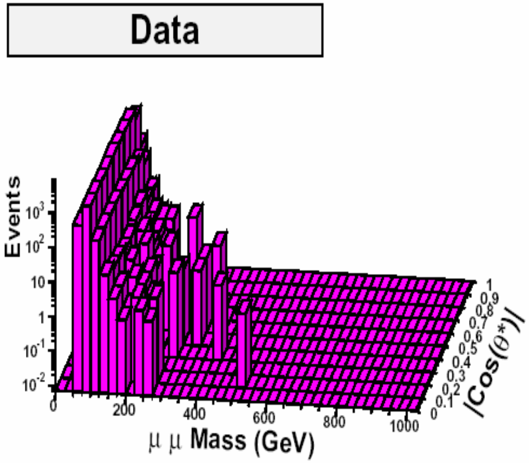
The highest-mass candidate event:

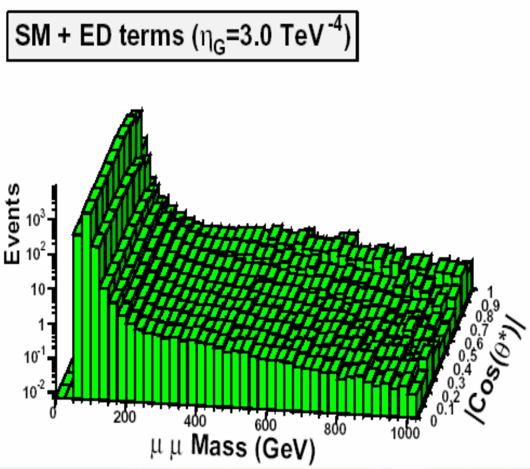
- $M_{\mu\mu}$ = 522 GeV
- $|\cos\theta^*|$ = 0.15
- N_{jet} (p_T>15 GeV) = 0
- $\not{E}_T^{cal}$ = 6 GeV
- p_T = 258 GeV
- $\eta_{1,2}$ = 0.03, 0.4
- $\phi_{1,2}$ = 5.9, 2.6



Limits on Large ED from Dimuons

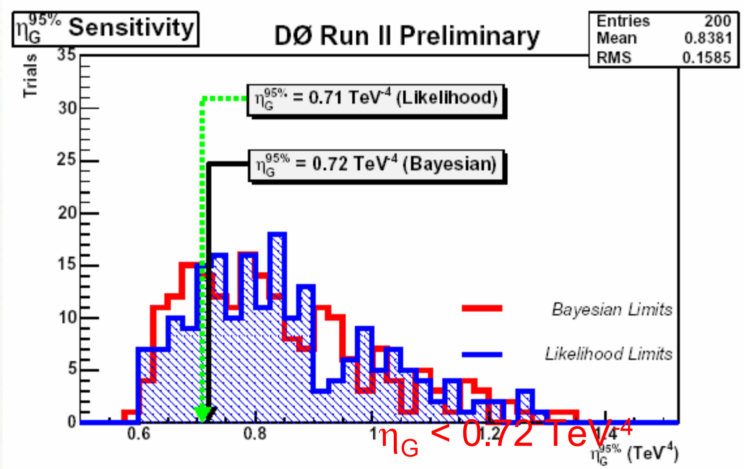






DØ Run II Preliminary

Source of systematics	Uncertainty
K-factor	10%
Choice of p.d.f.	5%
p_T dependence on efficiency	5%
Choice of MC p_T smearing	4%
MC to Data Normalization	1%
Total	13%



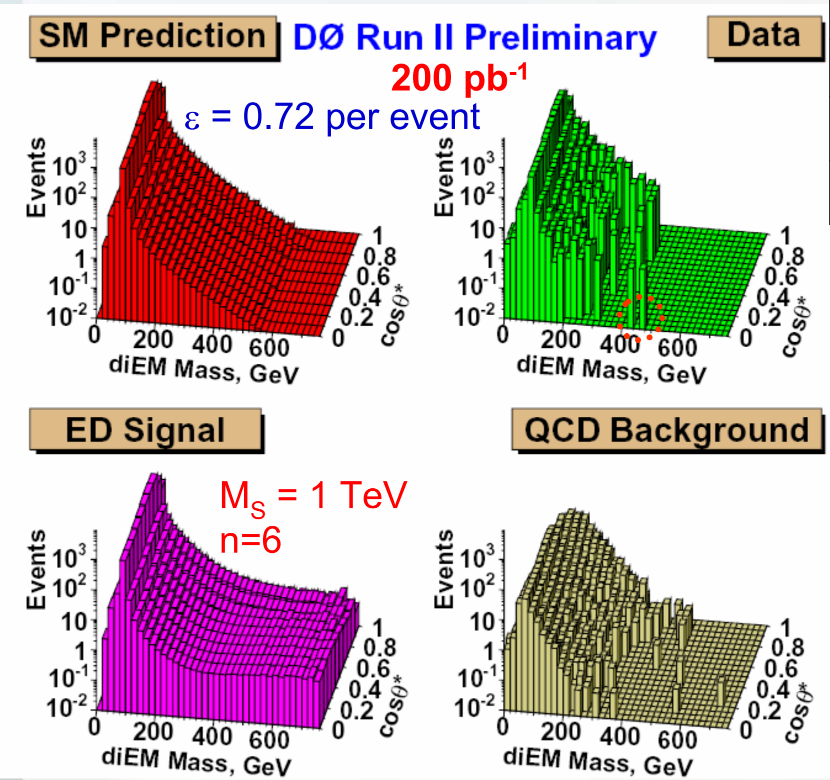
$\eta_G < 0.72$ TeV^{-4}

- Fit to 2D-templates via bilinear form in η_G
- First search in the dimuon channel at hadron colliders
- Current sensitivity approaches that for combination of all LEP channels
- Best limits on large ED in the dimuon channel have been set

Hewett		GRW	HLZ (TeV, @95% CL)					
$\lambda = +1$	$\lambda = -1$		$n = 2$	$n = 3$	$n = 4$	$n = 5$	$n = 6$	$n = 7$
0.97	**0.95**	**1.09**	**1.00**	**1.29**	**1.09**	**0.98**	**0.91**	**0.86**

Search for Large ED in the diEM Channel

- Combine diphotons and dielectrons into "di-EM objects" to maximize efficiency
- High-mass, low |cosθ*| tail is a characteristic signature of large ED [Cheung & GL, PRD **62**, 076003 (2000)]



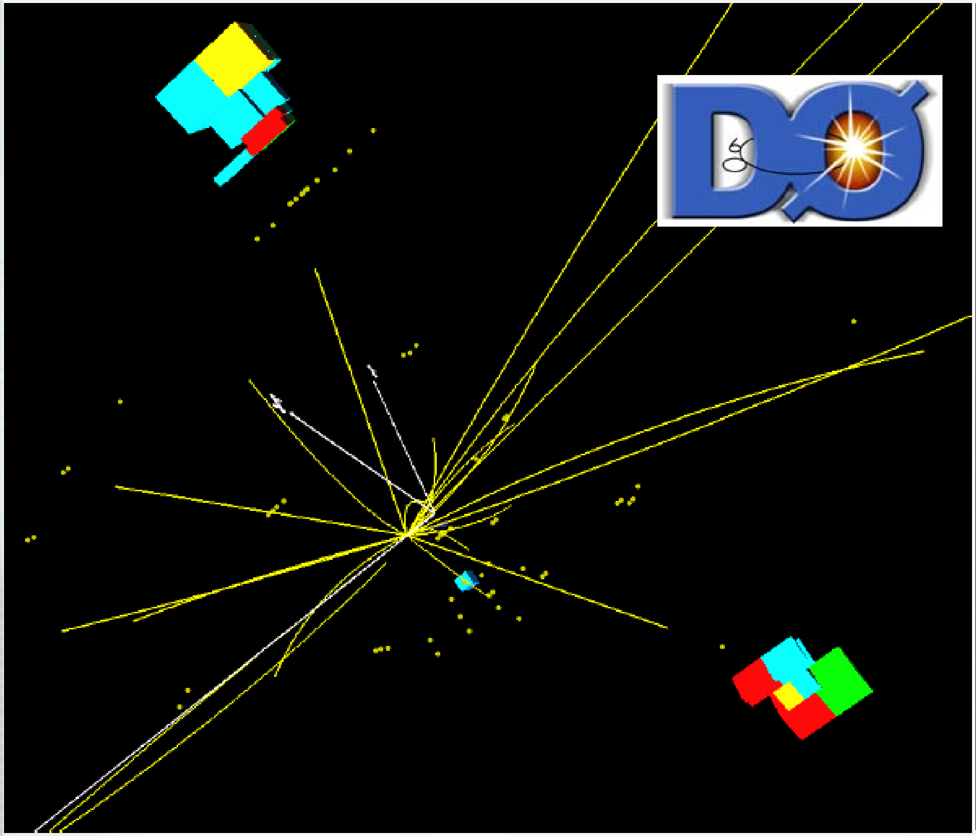
- Sensitivity is dominated by the diphoton channel (2 → 1 + 1)
- Data agree well with the SM predictions; proceed with setting limits on large ED: alone or in combination with published Run I result [PRL **86**, 1156 (2001)]:

Hewett		GRW	HLZ					(TeV, @95% CL)
$\lambda = +1$	$\lambda = -1$		$n = 2$	$n = 3$	$n = 4$	$n = 5$	$n = 6$	$n = 7$
1.22	**1.10**	**1.36**	**1.56**	**1.61**	**1.36**	**1.23**	**1.14**	**1.08**
1.28	**1.16**	**1.43**	**1.67**	**1.70**	**1.43**	**1.29**	**1.20**	**1.14**
		r_{max}	**170 μm**	**1.5 nm**	**5.7 pm**	**0.2 pm**	**21 fm**	**4.2 fm**

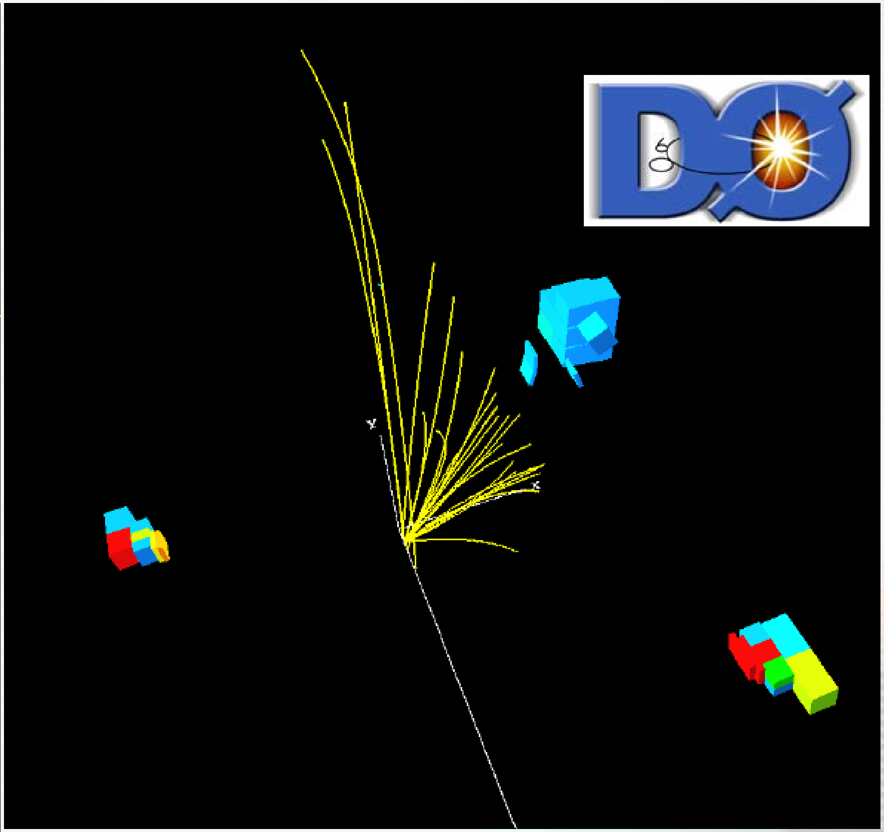
- These are the most stringent constraints on large ED for n > 2 to date, among all the experiments
- For n=2, sensitivity is approaching that of the tabletop gravity measurements (M_D = 1.7 TeV, r < 160 μm)

Interesting Candidate Events

- While the DØ data are consistent with the SM, the two highest-mass candidates have anomalously low value of cosθ^* typical of ED signal:



Event Callas: M_{ee} = 475 GeV, cosη^* = 0.01

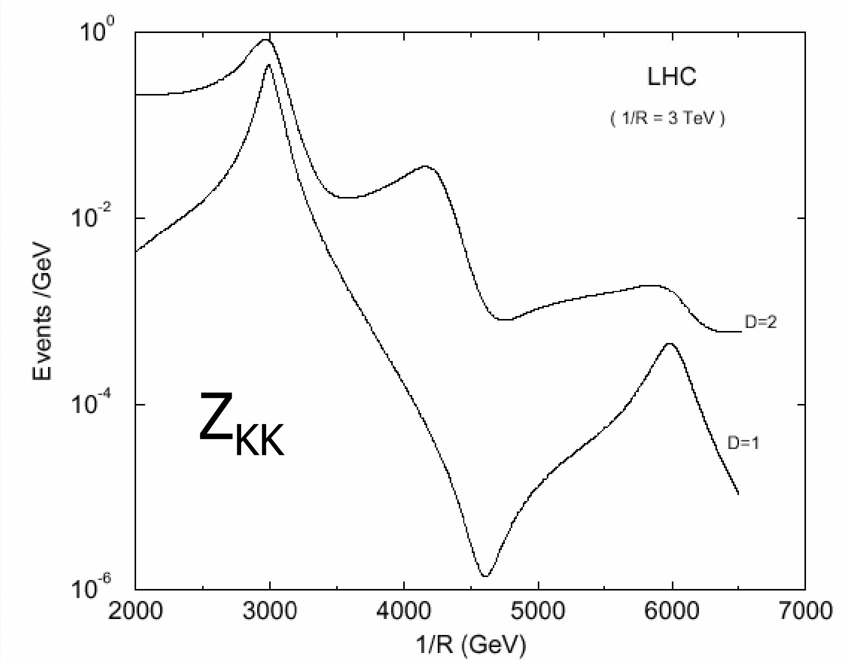


$M_{\gamma\gamma}$ = 436 GeV, cosη^* = 0.03

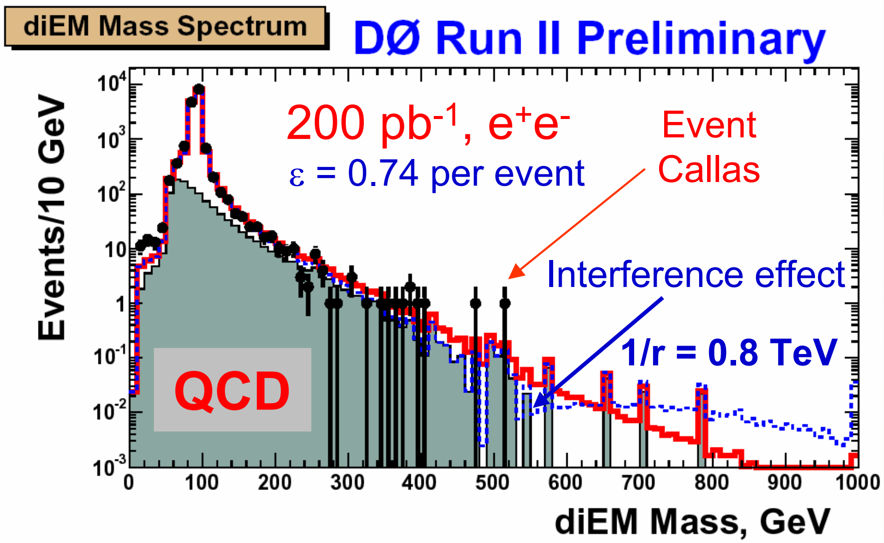
TeV^{-1} Extra Dimensions

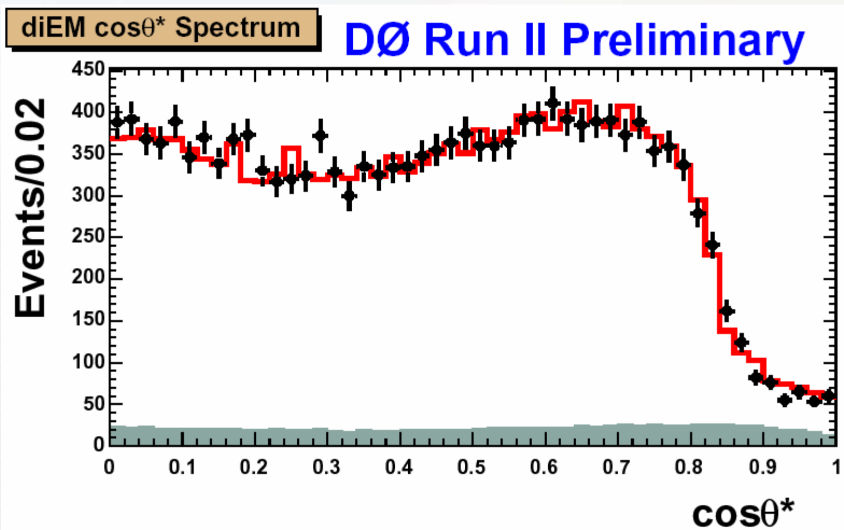
- Intermediate-size extra dimensions with ~TeV^{-1} radius
- Introduced by [Antoniadis, PL **B246**, 377 (1990)] in the string theory context
- Used by [Dienes, Dudas, and Gherghetta, PL **B436**, 55 (1998)] to allow for low-energy unification
  - Expect Z_{KK}, W_{KK}, g_{KK} resonances at the LHC energies
  - At lower energies, can study effects of virtual exchange of the Kaluza-Klein modes of vector bosons
- Current indirect constraints come from precision EW measurements: 1/r ~ 6 TeV
- No dedicated experimental searches at colliders to date

[Antoniadis, Benaklis, and Quiros, PL **B460**, 176 (1999)]



First Dedicated Search for TeV^{-1} ED

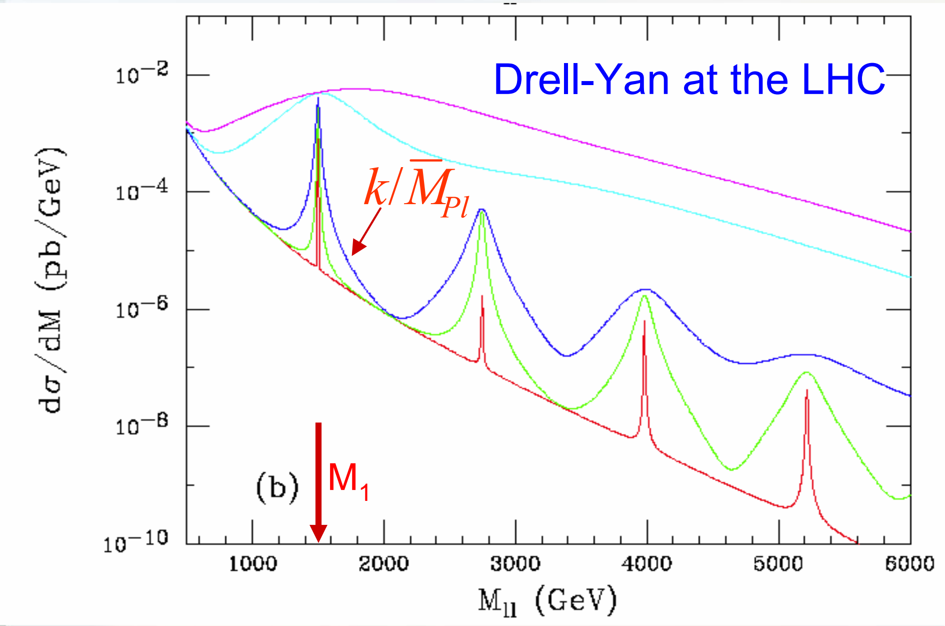


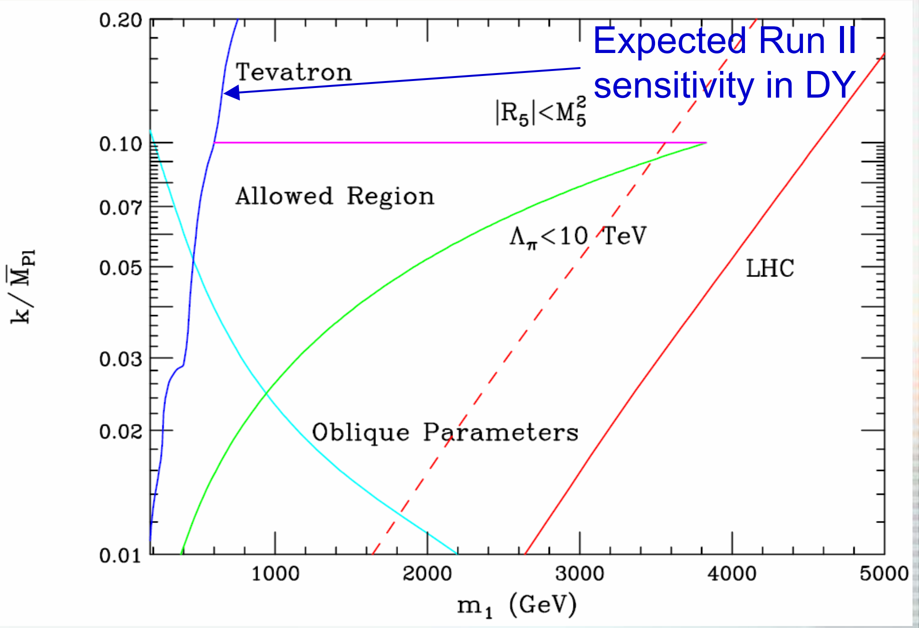


- While the Tevatron sensitivity is inferior to the indirect limits, it explores the effects of virtual KK modes at higher energies, i.e. complementary to those in the EW data
- DØ has performed the first dedicated search of this kind in the dielectron channel based on 200 pb^{-1} of Run II data ($Z_{KK}, \gamma_{KK} \rightarrow e^+e^-$)
- Based on the same diEM sample, with an additional requirement of at least one track
- 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)]
- Data agree with the SM predictions, which resulted in the following limit on their size:
  - ❖ $1/r > 1.12$ TeV @ 95% CL
  - ❖ $r < 1.75 \times 10^{-19}$ m

Randall-Sundrum Model Parameters

- Need only two parameters to define the model: k and r_c
- Equivalent set of parameters:
  - The mass of the first KK mode, M_1
  - Dimensionless coupling $k/\overline{M}_{Pl}$
- To avoid fine-tuning and non-perturbative regime, coupling can't be too large or too small
- $0.01 \leq k/\overline{M}_{Pl} \leq 0.10$ is the expected range
- Gravitons are narrow

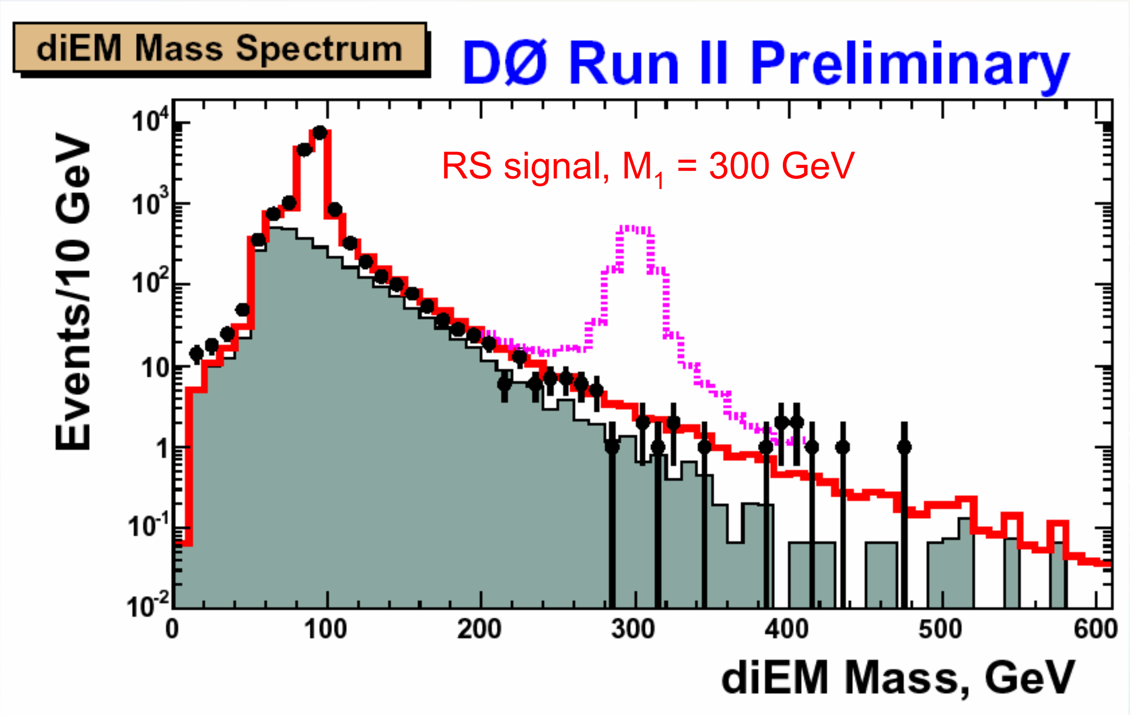




[Davoudiasl, Hewett, and Rizzo, PRD **63**, 075004 (2001)]

Search for RS Gravitons

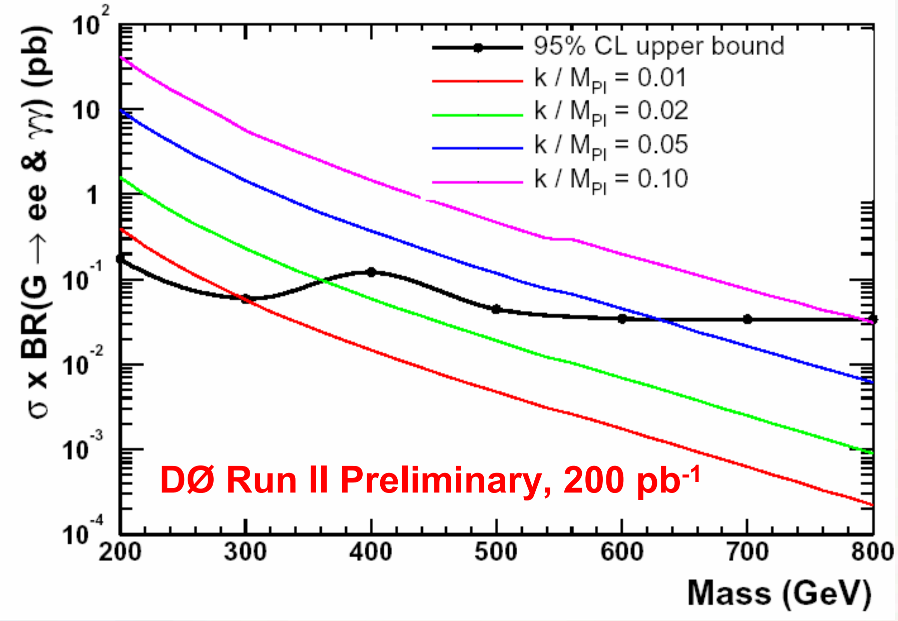
- DØ has just completed preliminary analysis and produced first results in August
- Analysis based on 200 pb^{-1} of e^+e^- and $\gamma\gamma$ data – the same data set as used for searches for large ED
- "Naturally" combine two channels by NOT distinguishing between electrons and photons; ε = 0.85 per EM object or 0.72 per event!
- Search window size has been optimized to yield maximum signal significance



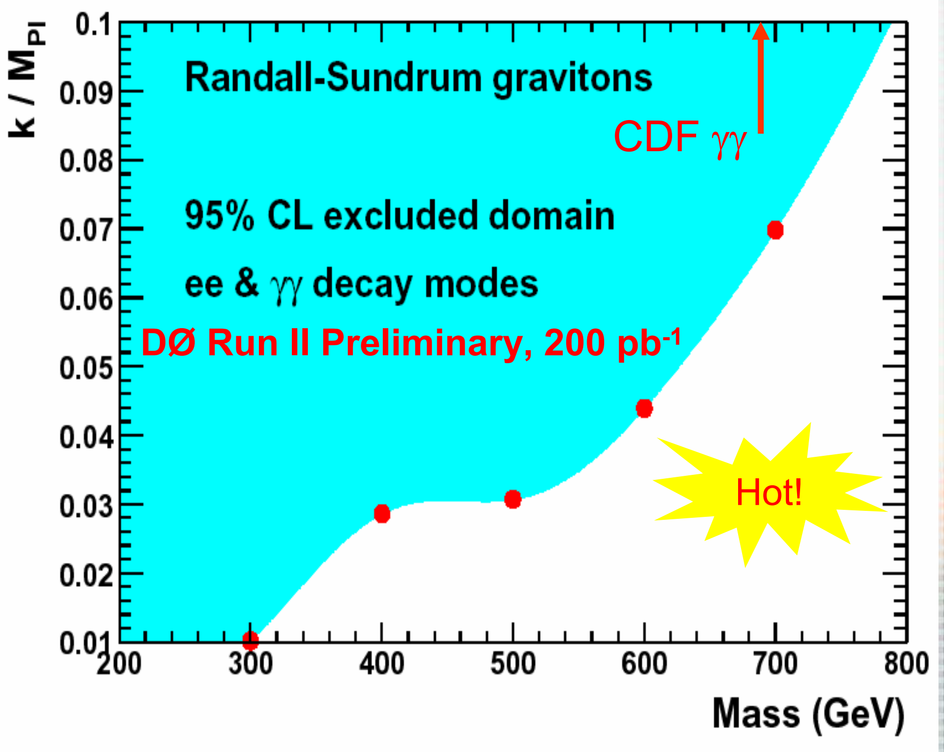
DØ Limits in the ee+γγ Channel

The tightest limits on RS gravitons to date

Assume fixed *K*-factor of 1.3 for the signal



Masses up to 780 GeV are excluded for k/M_{Pl} = 0.1

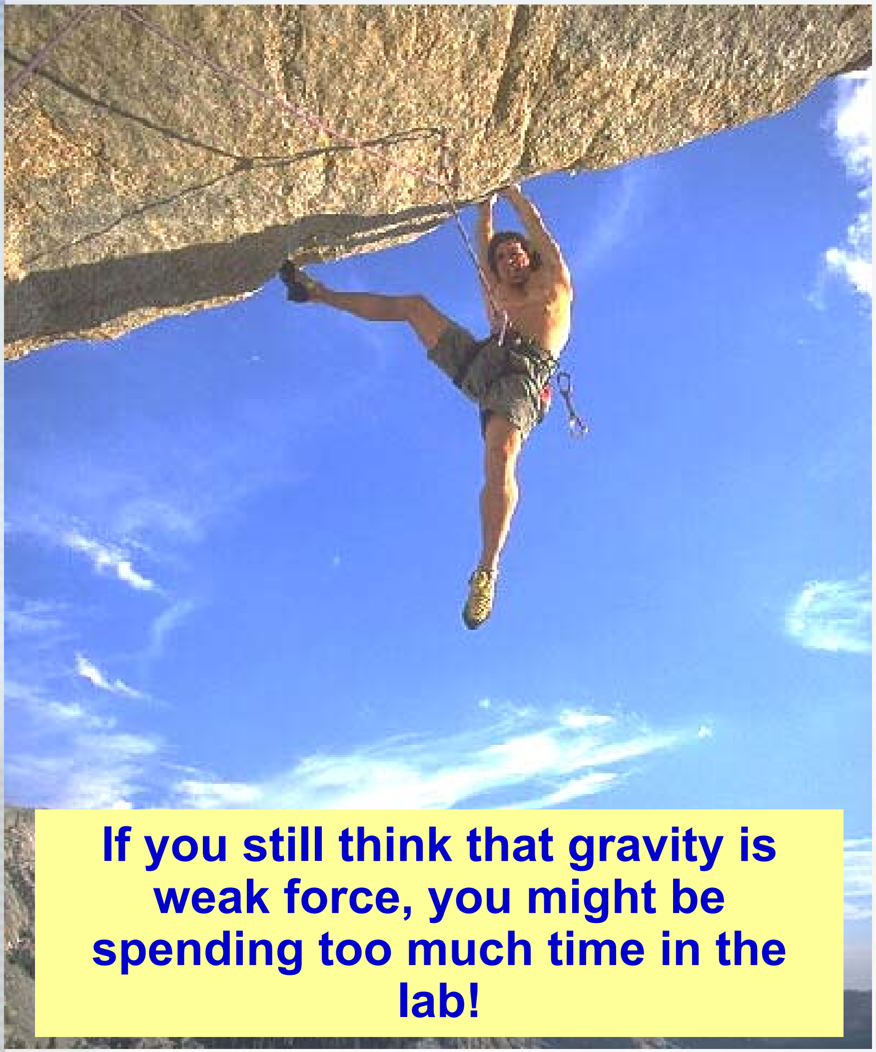


Already better limits than the sensitivity for Run II, as predicted by theorists!

Outlook

- While the data agree well with the SM, a few interesting candidate events have been observed
  - N.B.: The three highest-mass events: ee, $\mu\mu$, and $\gamma\gamma$ – all have low value of $|\cos\theta^*|$!
- We expect an increase in sensitivity to ED models by a factor of ~2 within the next few years of the Tevatron operations, which would bring us into interesting area of the allowed parameter space
- Twice the analyzed statistics is already on tape, and more will come soon
- Then it'd be up to the LHC to either disprove or confirm the existence of extra dimensions in space with low-energy phenomenology

Conclusions



- Colliders offer ultimate probe of models with extra spatial dimensions
- Tevatron is the highest-energy machine today and has an excellent opportunity to find first signs of extra dimensions in space
- Accelerator performance is excellent and both CDF and DØ have a large number of new results in this area
- Sensitivities beyond the existing limits have been achieved already:
  - Tightest limits on large ED to date
  - Best limits on RS gravitons
  - Quick progress towards monojet searches with superior sensitivity
- Stay tuned for more exciting results to come with larger data sets – any day now could bring a dramatic discovery!

P.S. Fine Tuning Explained…

- Fine tuning explained:
  - Numerology: 987654321/123456789 = 8.000000073 ?
    - Numerology it is not!

$$\lim_{N\to\infty} \frac{NML\ldots 987654321}{123456789\ldots LMN} = N-2$$

  - Seeing is believing:
    - In hexadecimal system, FEDCBA987654321/123456789ABCDEF = 14.000000000000000183