The Search for Extra Spatial Dimensions at DØ

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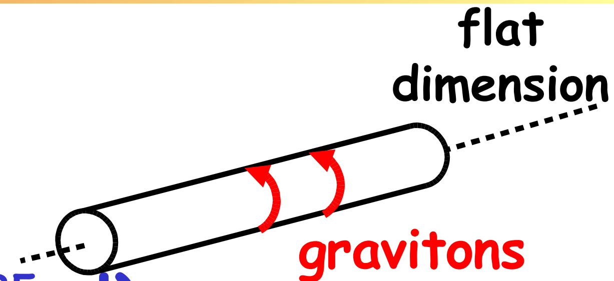
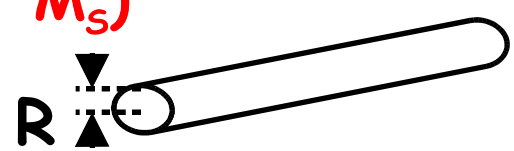
Large Extra Dimensions



- Possibly >3 spatial dimensions
  - Natural in string theory with 6 or 7 extra dimensions compactified
- "Large" extra dimensions ($>10^{-35}$m!)
  - Explain the weakness of gravity at large distances
    - Extra dimensions only accessed by gravity
    - Gravity "diluted" by volume of extra space
  - Solve the hierarchy problem (M_{planck} vs M_{EW})
  - Reduces effective M_{planck} ~ TeV/c^2
- Theories have 3 free parameters:
  - Fundamental mass scale, M_D (UV cut off M_S)
  - Compact dimension's radius, R
  - Number of compact, extra dimensions, n

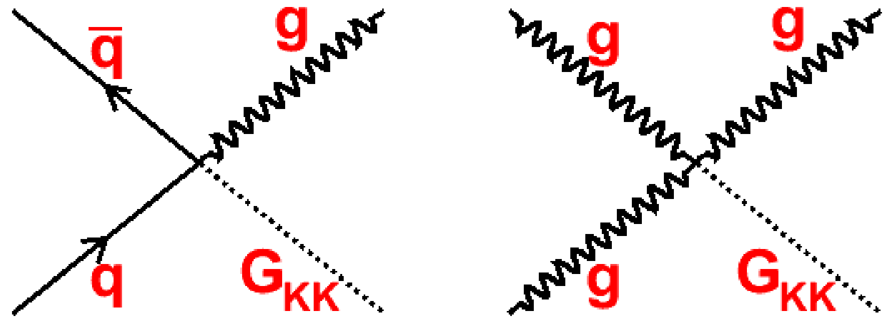


Experimental Limits

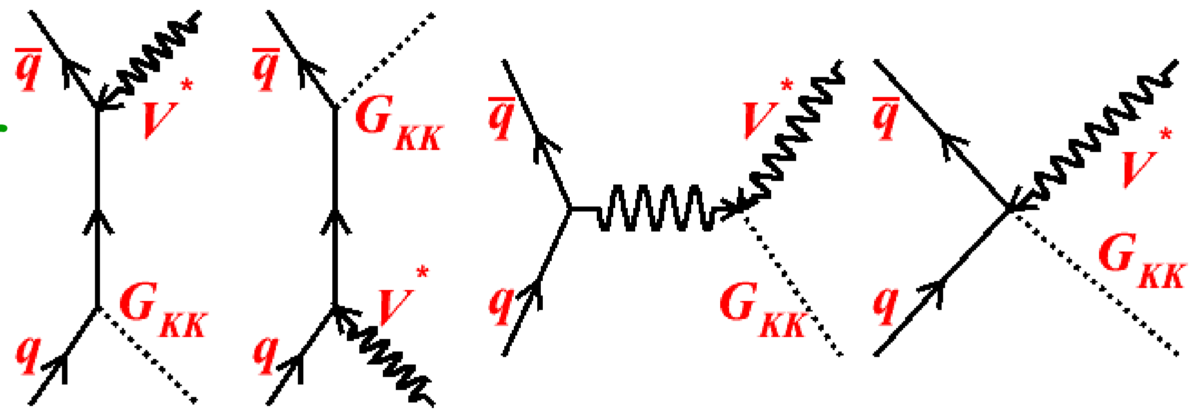
- Limits on R come from measurements of the gravitational potential, assuming M_D~1TeV/c^2
  - n=1 excluded by solar system (1/r^2 law)
  - R<0.19 mm for n=2 (Eöt-wash)
- Limits from astrophysics and cosmology
  - SN1987A neutrino flux (no graviton cooling)
  - Smoothness of the cosmic diffuse γ radiation
  - Early universe not matter dominated
- These all have limits highly dependent on 'n'
  - n=2 limits on M_D are very strong: M_D>100-2000 TeV/c^2!
  - n=3 limits are M_D>1-10 TeV/c^2
  - ...but for n>3 limits on M_D are below 1 TeV/c^2

LED Signatures

- Gravity enhanced by phase space
  - Winding of graviton about the compactified dimensions (Kaluza-Klein excitations)
    - Interaction as $1/M_D^2$, not $1/M_{planck}^2$, couples to E-p tensor
- Direct graviton production
  - Monojet + Missing E_T

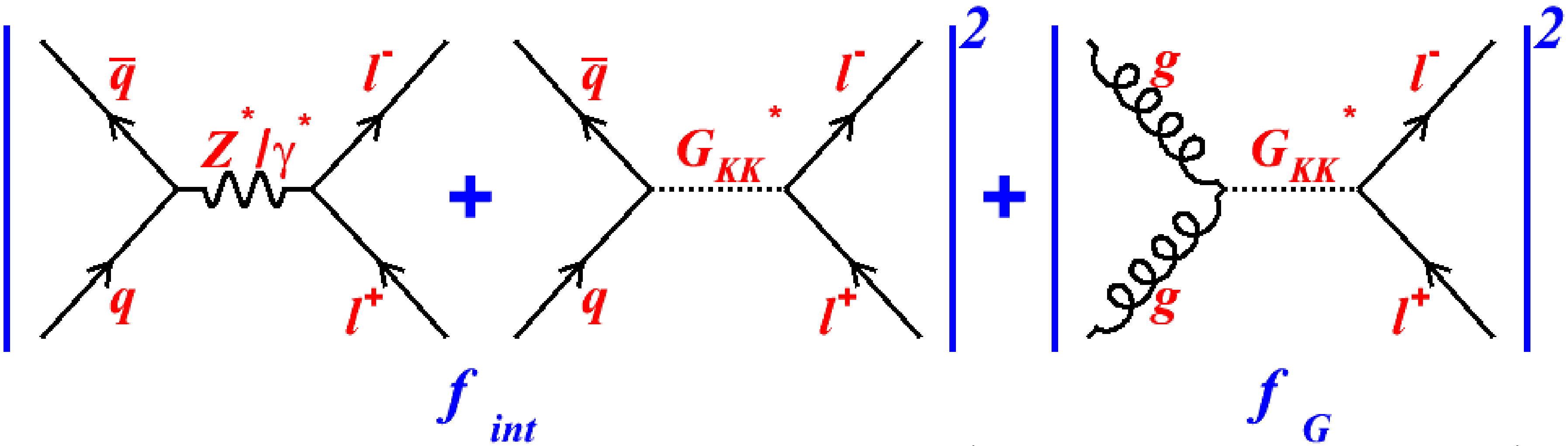


  - Vector boson + Missing E_T
    - Used at LEP

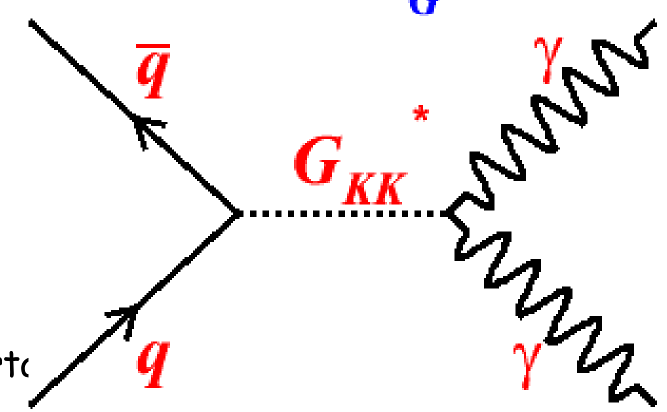


Tevatron Signatures

- Virtual graviton, G_{KK}, exchange
  - Final state two fermions/bosons (e,γ and μ at DØ)
  - Interfers with SM processes



  - Easy signal to detect at DØ
    - High mass enhancement of di-EM and di-muon spectrum
    - Low backgrounds from SM processes



Tevatron Signatures

- Differential cross section model dependent...

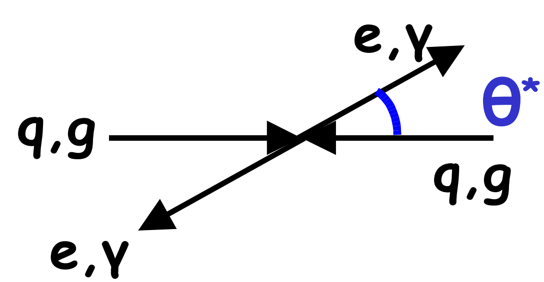
$$\frac{d^2\sigma}{dM\, d\cos\theta^*} = f_{SM} + f_{int}\,\eta_G + f_{KK}\,\eta_G^2 \qquad \eta_G = \frac{\mathcal{F}}{M_S^4}$$

Pure Standard Model Term — Interference Term — Pure Graviton Term

$M = l^+ l^- / \gamma\gamma$ invariant mass

$\cos\theta^* =$ cosine scattering angle

- Effects of LED parameterized by a single variable...
  - $\mathcal{F}$ depends on formalism
  - M_S is UV cut-off of KK excitations (taken $\approx M_D$)



LED Formalisms

- Various models give different values for $\mathcal{F}$:

$$\mathcal{F}=1 \quad \text{(GRW)}$$ [Nucl. Phys. B544, 3 (1999)]

$$\mathcal{F}=\begin{cases} \log\left(\frac{M_S^2}{M^2}\right), & n=2 \\ \frac{2}{n-2}, & n>2 \end{cases} \quad \text{(HLZ)}$$ [Phys. Rev. D59 105006 (1999)]

$$\mathcal{F}=\frac{2\lambda}{\pi}=\pm\frac{2}{\pi} \quad \text{(Hewett)}$$ [Phys. Rev. Lett. 82, 4765 (1999)]

- Limits on M_s for virtual G_{KK} exchange searches will be model dependent (take $\lambda=\pm1$ for Hewett)
  - ...but only weakly dependent on n (if at all)

DØ Run II Analyses

- Several Run II LED analyses completed at DØ
  - Di-electron+di-photon analysis [200 pb^{-1}]
    - DØCONF 4336
  - Di-electron analysis (TeV^{-1} ED) [200 pb^{-1}]
    - DØCONF 4349
  - Jets + Missing E_T analysis [85 pb^{-1}]
    - DØCONF 4400
  - Di-muon analysis [246 pb^{-1}]
    - hep-ex/0506063, submitted to PRL
  - Di-lepton+di-photon (Randall-Sundrum ED) [275 pb^{-1} (EM), 246 pb^{-1} (μ)]
    - hep-ex/0505018, accepted by PRL
- This talk will concentrate on the last 3

Jets + Missing E_T

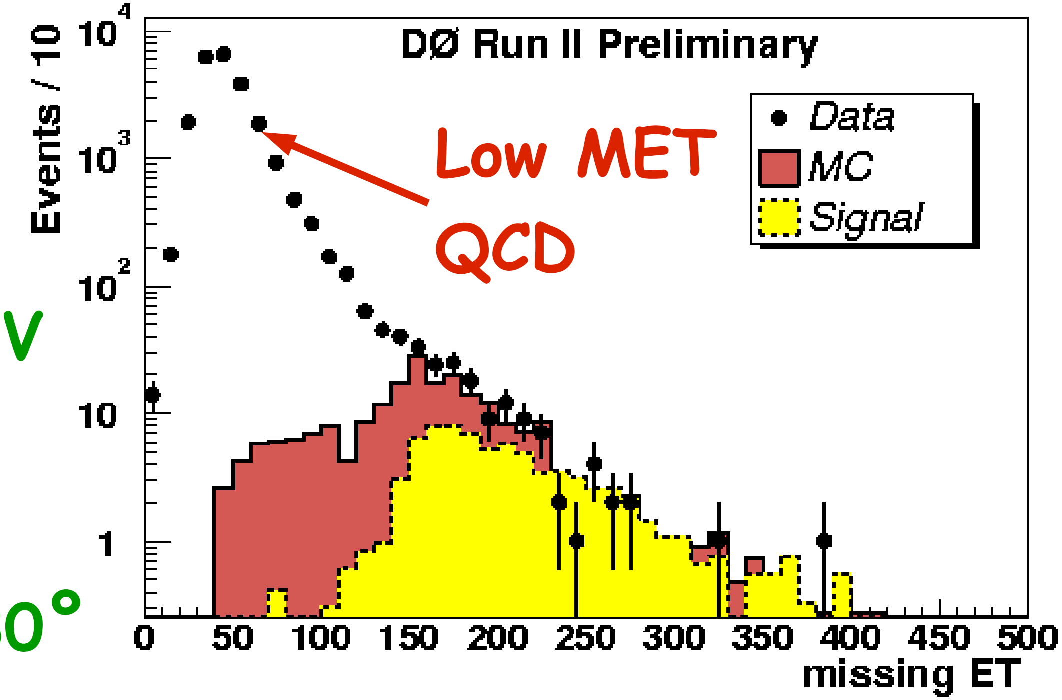
- Processes searched for

$$q\bar{q} \to G_{KK}\, g\,; \quad q\,g \to G_{KK}\, q\,; \quad g\,g \to G_{KK}\, g$$

- Major sources of SM backgrounds
  - Z + jets with $Z \to \nu\bar{\nu}$ (but also $Z \to \tau^+\tau^- / \mu^+\mu^-$)
  - W + jets with $W \to \mu\nu_\mu / \tau\nu_\tau$
- Triggering and pre-selection cuts...
  - Main trigger inefficiency from L1 trigger
    - 3 towers (0.2x0.2 in η,φ) with E_T>5 GeV (no clustering)
  - Reject noisy calorimeter events and require all jets with p_T>15 GeV/c to pass quality cuts
  - Remove QCD with mis-measured jet ET
    - Primary vertex |z|<60cm; jet charged particle E fract>0.05

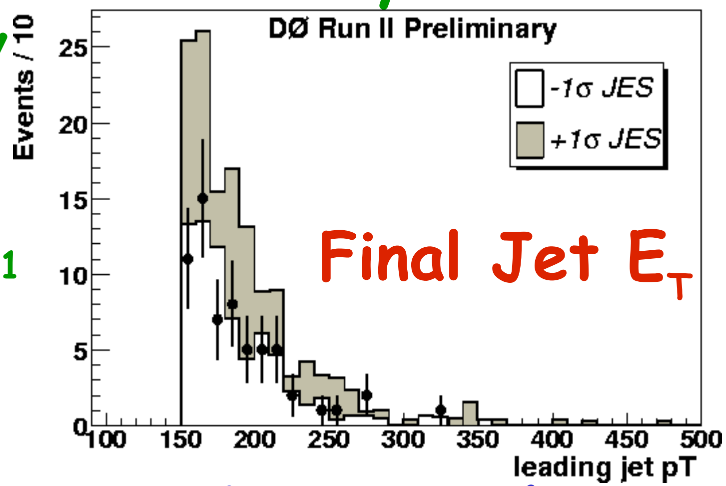
Jets + Missing E_T

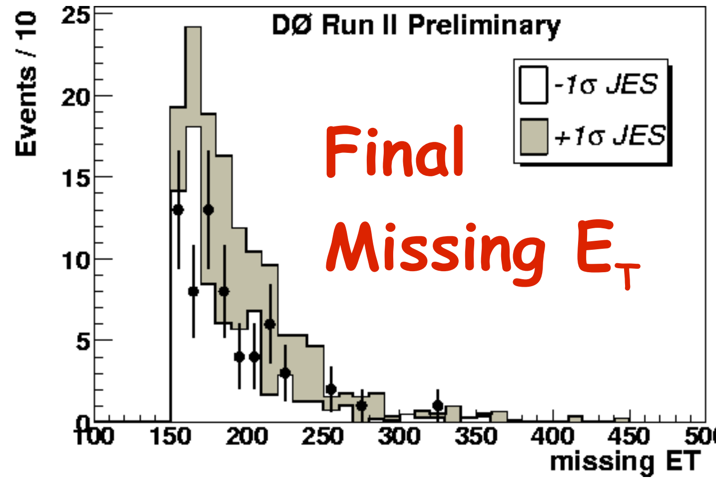
- Final event selection cuts
  - leading jet p_T>150 GeV/c; $|\eta_{det}|$<1; EM energy fraction<0.95; charged particle energy fract.>0.05
  - No EM object or isolated muon with p_T>10 GeV/c
    - Missing E_T after these cuts shown....
  - Missing E_T > 150 GeV
  - Second leading jet p_T < 50 GeV/c
  - Min. $\Delta\Phi$(MET,jet)>30°



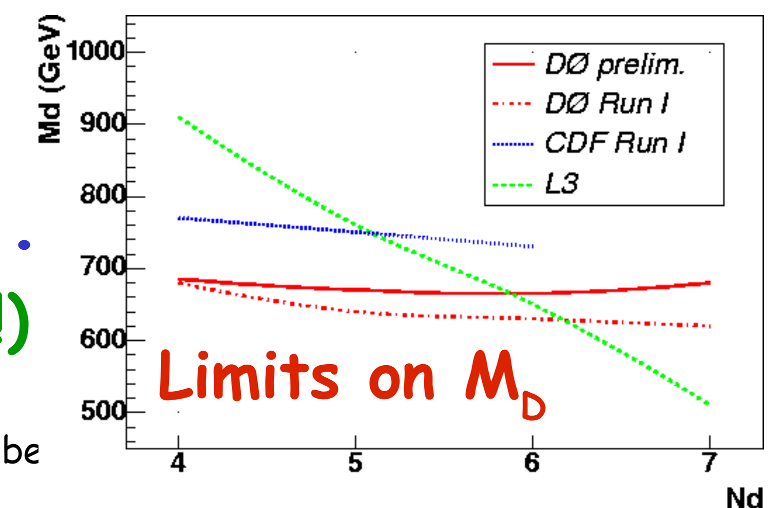
Jets + Missing E_T

- MC Simulation: n=4-7 for M_D=0.6-0.8 TeV/c²
- Data consistent with background
  - Largest uncertainty is Jet Energy Scale (JES)
  - 85 pb^{-1} data





- Limits on M_D better than DØ Run I, should improve...
  - Lots of new data to use (x10!)
  - JES now greatly improved



Di-muon LED

- Search for high invariant mass $\mu\mu$ state
  - Use both DØ's inner tracker (2T solenoid field) and outer muon counters (1.8T toroidal field, $|\eta_{det}|<2$)
  - Require matched track $p_T>15$ GeV/c
- Remove cosmic rays with two cuts
  - Hits in muon counters within 10ns of expected time
  - $\eta_{\mu 1}+\eta_{\mu 2}$ > 5σ from 0 compared to known cosmics
  - Signal efficiency for these cuts is (99±1)%
- Remove muons from b/c quark decays with isolation cuts… $\Delta R=\sqrt{(\Delta\eta)^2+(\Delta\phi)^2}$

$$\sum_{\Delta R\leq 0.5}(p_T)<2.5\,\mathrm{GeV/c} \qquad \sum_{\Delta R\leq 0.4}(E_T)-\sum_{\Delta R\leq 0.1}(E_T)<2.5\,\mathrm{GeV}$$

Di-muon LED

- 1μ efficiency (80±4)% measured with $Z\to\mu\mu$
- Remaining background mis-measured Drell-Yan
  - Problem of gross mismeasurement of high p_T muons
    - Tracking resolution gaussian in $1/p_T$
- Use weighted average of muon p_T
  - Assumes equal muon p_T which is good for high mass

$$\frac{1}{p'_{T_1}} = \frac{1}{p'_{T_2}} = \frac{[w_1/p_{T_1} + \epsilon\, w_2/p_{T_2}]}{w_1 + w_2}$$

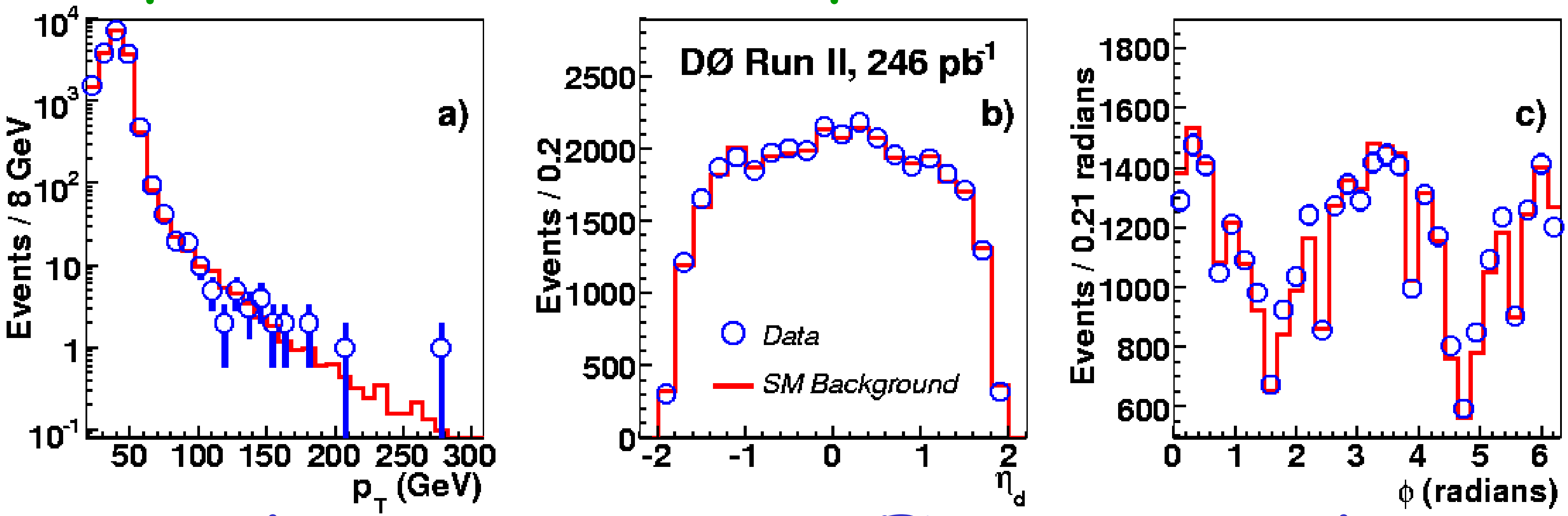
$$w_{1,2} = \frac{1}{\sigma^2(1/p_{T_{1,2}})}$$

$$\mu^{\pm}\mu^{\pm} \to \epsilon = -1$$
$$\mu^{\pm}\mu^{\mp} \to \epsilon = +1$$

  - where $\sigma(1/p_T)$ is uncertainty on $1/p_T$ (from $Z\to\mu\mu$)
  - ~30% drop in mass RMS and ~1% drop in resolution

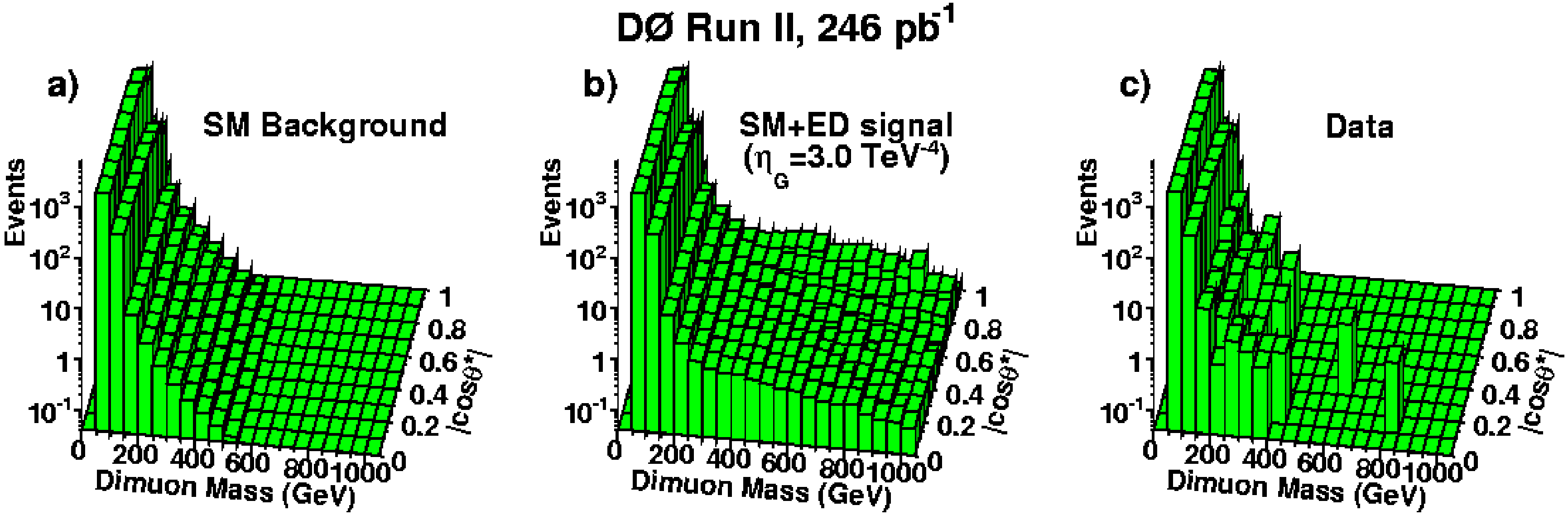
Di-muon LED

- Data consistent with SM backgrounds
  - Dominated by Drell-Yan
  - φ plot shows detector acceptance effects



- To set limits compare to LED Monte-Carlo
  - MC normalized to data using Z peak (50-120 GeV/c^2)
  - Use Bayesian fit to get limits on η_G...

Di-muon LED



- 95% CL limits on η_G give M_S limits [TeV/c^2]...

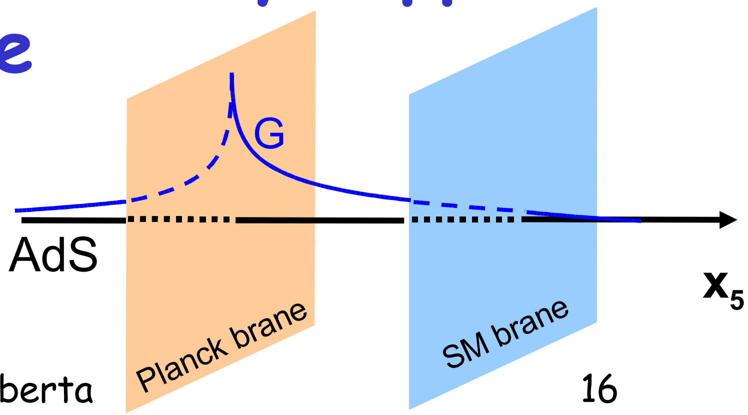
GRW	HLZ						Hewett	
	n=2	n=3	n=4	n=5	n=6	n=7	λ=+1	λ=-1
1.07	1.09	1.27	1.07	0.97	0.90	0.85	0.96	0.93

- Di-EM Run I+II combined limit [DØCONF 4336]

GRW	HLZ						Hewett
	n=2	n=3	n=4	n=5	n=6	n=7	λ=+1
1.43	1.67	1.70	1.43	1.29	1.20	1.14	1.28

Randall-Sundrum ED

- An alternative model for extra spatial dimensions is the Randall-Sundrum theory
  - Avoids need for compactification
- Model has two, 3+1D space-times (branes) embedded in a 5D anti-deSitter space
  - SM-brane contains all the SM particles
  - Planck-brane contains gravity
- Graviton wavefunction exponentially suppressed away from the Planck-brane
  - Two model parameters
    - Single ED radius, R
    - AdS_5 curvature, k (warp factor)



Randall-Sundrum ED

- M_{PL}-scale operators on Planck-brane give low energy effects on SM-brane

$$\Lambda_\pi \sim \overline{M}_{pl} e^{-k\pi R} \qquad \overline{M}_{pl} = M_{pl} / \sqrt{8\pi}$$

  - Heirarchy problem solved if Λ_π~1 TeV/c^2

- Only gravitons propagate in ED and so appear as a Kaluza-Klein tower of excitations
  - Zeroth KK mode, $G^{(0)}$, is massless and couples to SM fields with gravitional strength, $1/M_{PL}$
  - Excited modes couple with strength $1/\Lambda_\pi$
    - Decay to di-boson or di-fermion (ang.mom. suppressed) pairs

- Rewrite parameters in terms of observables:

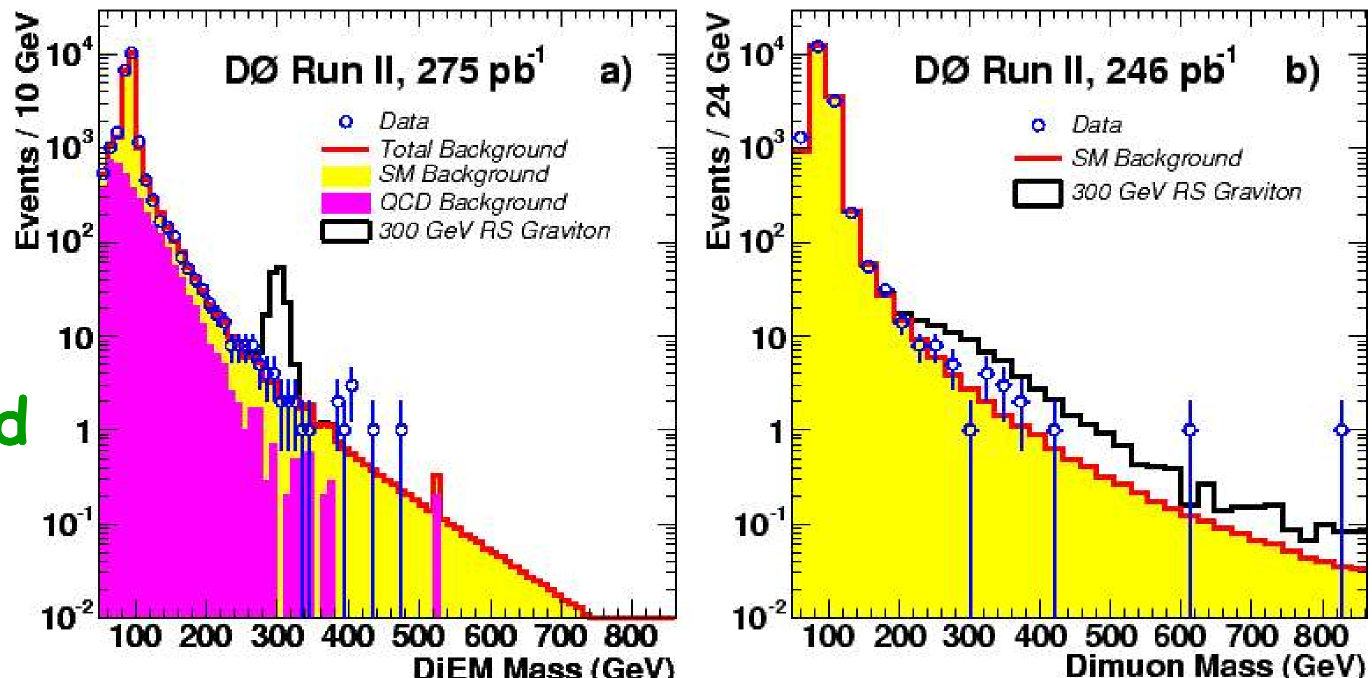
$$\text{SM coupling} = k / \overline{M}_{pl} \qquad \text{Mass of } G^{(1)} = M_1$$

Randall-Sundrum ED

- Existing limits on RS parameters from precision electro-weak data rather weak
  - First dedicated search for RS gravitions
- Look for two final state signatures
  - di-EM: no tracking so covers both $e^{\pm}$ and photons
  - di-muons: details same as LED di-muon search
- EM object requirements
  - ET>25 GeV and isolated in calorimeter
  - Shower shape consistent with e/γ
  - Central ($|\eta|<1.1$) and forward ($1.5<|\eta|<2.4$) regions accepted but at least one EM object must be central

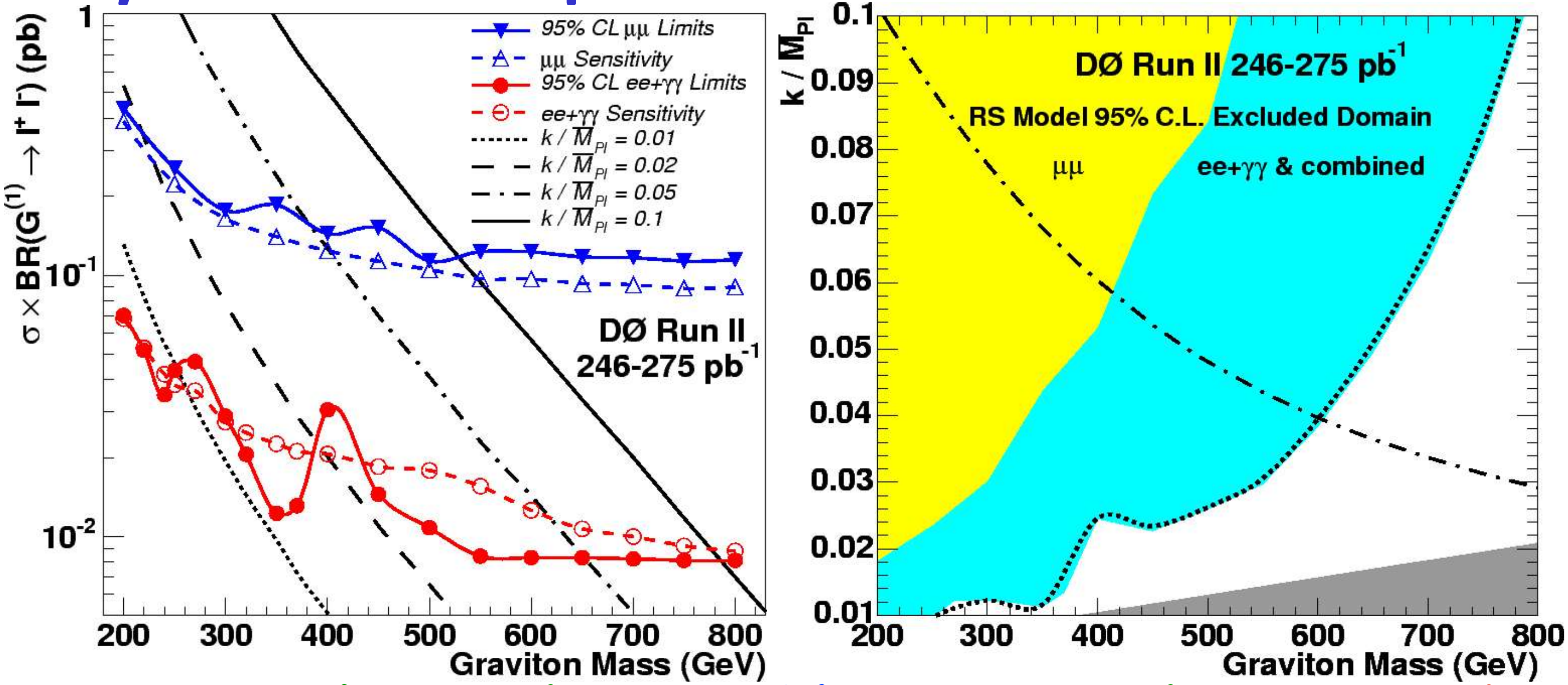
Randall-Sundrum ED

- Major background Drell-Yan + direct diphotons
- Additional instrumental background for di-EM
  - QCD multi-jet and direct photon events where one jet is reconstructed as an electron, est. from data
- Data consistent with SM...
  - Plots show effect of different detector resolutions for EM and muons (E vs. p)



Randall-Sundrum ED

- Bayesian techniques used to set limits



  - μμ mass limits shown in **blue**, ee+γγ shown in **red**
- Excluded region in M_1 and $k/\overline{M}_{pl}$ space shown
  - The dot-dash line is precision Electro-weak limit

Conclusions

- First ~250pb^{-1} of Run II data analysed and no evidence of ED found
  - Limits well above Run I limits
  - World leading limits for n>3
- First direct search for R-S gravitons complete
  - Greatly expands precision E-W excluded region
- Now have over 800pb^{-1} of Run II data on tape
  - 802pb^{-1} as of 7th July 2005
  - Expect over 1fb^{-1} by end of 2005
- This will significantly increase the reach of the ED analyses
  - Hope for more exciting results in the future!

TeV^{-1} ED

- Differs from "normal" LED in that SM gauge fields also propagate in the EDs
  - Only chiral fermions confined to our 3+1D world
- Consequences:
  - GUT scale much reduced since power-law running of couplings much faster above compactification scale
  - Kaluza-Klein excitations for SM gauge bosons
- Results in additional contributions to the di-lepton mass spectrum
  - Only di-lepton spectrum affected because couplings different from the graviton