Search for Low Scale Gravity & Extra Dimensions at HERA, LEP , and the Tevatron

Mini-review talk

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Large Extra Spatial Dimensions (ED)

ED are a new approach to understand the Hierarchy problem, in particular in the paradigm of Arkani-Ahmed, Dimopoulos, Dvali (98)

The fundamental Planck scale could be of the order of 1 TeV, and gravity can be strong at this scale if there are extra spatial dimensions. Our SM world is confined in our usual 3+1 dimensions, while gravity propagates through Kaluza-Klein gravitons (G_{KK}) also (mainly) in the ED.

Experimental limits on Newton's law imply that the ED, if they exist, must be compactified at the submillimiter level. They can be searched for in high energy collisions.

Gravity becomes strong via $G'_N = 1 / M_S^2$ ➔ $M_S \sim 1$ TeV

$$M_{Pl} = M_D^{n+2} R^n$$

- M_{Pl} : effective (4-dim) Planck mass,
- M_D : fundamental ([4+n]dim) Planck mass,
- M_S : mass scale, $M_S \sim M_D$
- R : compactification radius

Searching for Extra Spatial Dimensions

- **Kaluza-Klein graviton G_{KK} in ED models can be probed by:**

  1) its virtual contribution to scattering processes resulting in:

  – **deviations in cross sections and asymmetries of standard model processes such as:** $f\bar{f} \rightarrow l^+ l^-$, $\gamma\ \gamma$

  $e\ q \rightarrow e\ q$

  – **new processes such as:** $g\ g \rightarrow l^+ l^-$

Accessible at HERA, LEP, Tevatron

2) direct G_{KK} emission in association with a Vector-boson

– **EW-Gauge boson and missing E_T :**

At LEP, via $ee \rightarrow \gamma G$, ZG, or at the Tevatron via $q\bar{q} \rightarrow \gamma G$

– **Mono-jet topology, which is specific to Tevatron,**

via $gg \rightarrow g\ G$, or $q\bar{q} \rightarrow gG$

Differential Cross-sections

The calculation of the effective differential cross section (e.g. of electron pair production) requires an explicit cutoff (due to the divergence of the sum over KK states), which can be set naturally at M_S. The effective cross section can be written:

$$\frac{\partial^2 \sigma}{\partial \cos\theta^* \partial M_{\ell\ell,\gamma\gamma}} = \frac{\partial^2}{\partial \cos\theta^* \partial M_{\ell\ell,\gamma\gamma}} \left(\sigma_{SM} + \sigma_4 \eta + \sigma_8 \eta^2 \right)$$

$\eta \equiv \dfrac{F}{M_S^4}$ ***and*** $\left\{ \begin{array}{ll} \sigma_{SM} \equiv & \textit{Standard model} \\ \sigma_4 \equiv & \textit{Interference} \\ \sigma_8 \equiv & \textit{Kaluza Klein} \end{array} \right.$

Formalisms

- **Hewett: Neither interference sign (~λ) nor dependence on n_{ED} is known** $\quad F = \dfrac{2}{\pi}\lambda$
- **GRW (Giudice-Rattazzi-Wells): interference sign is specified** $\quad F \approx 1$
- **HLZ (Han-Lykken-Zhang): Both interference signs and the dependence on n_{ED} are accounted for**

$$F = \begin{cases} \log\left(M_S^2/s\right) & \text{for } n=2 \\ \dfrac{2}{n-2} & \text{for } n>2 \end{cases}$$

HERA searches (virtual graviton)

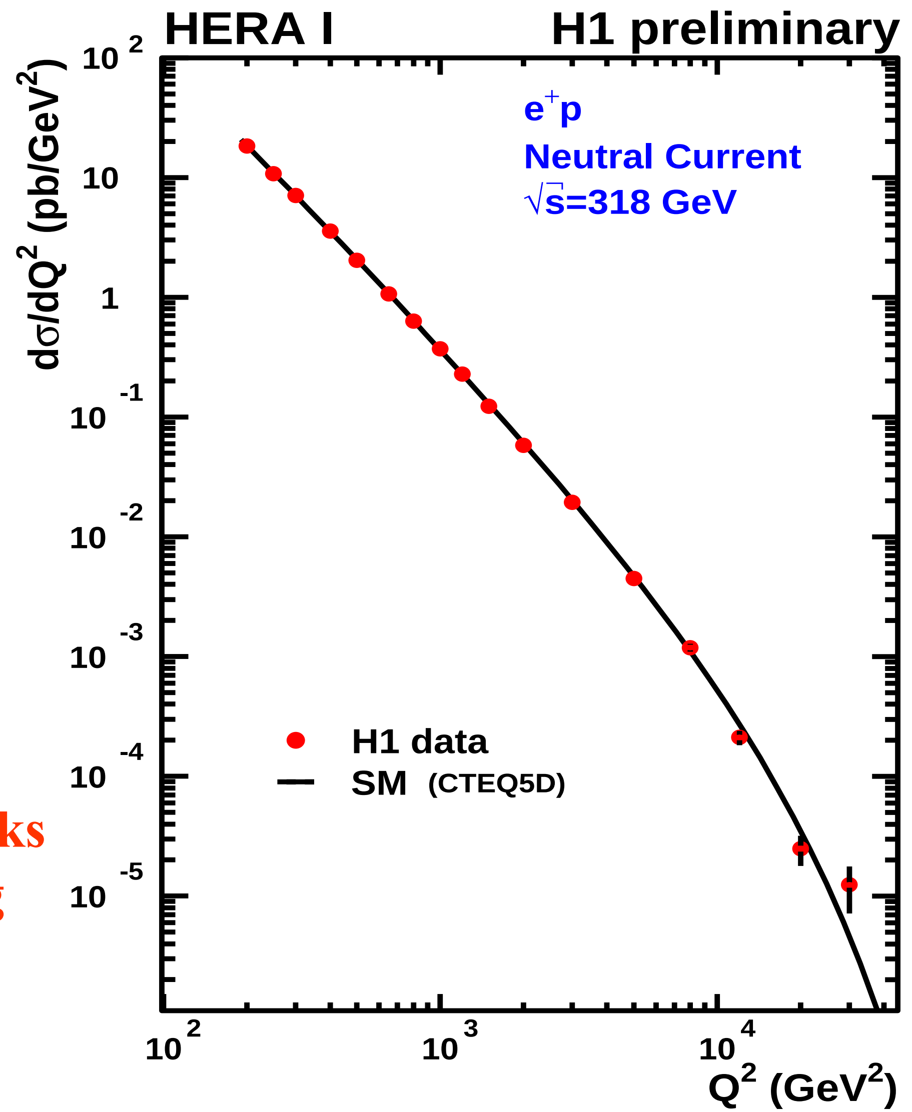
t channel exchange

Interference with the Standard Model photon or Z exchange

Fit the dsigma/dQ^2 x-section and search for deviations.

New results based on the complete HERA I data set: ~ 110 pb^{-1} in e^+p
~ 16 pb^{-1} in e^-p

NB: any observed deviation could also be interpreted in other theoretical frameworks (also true for other colliders when looking at interference effects) :
It is the combination of these effects in different processes which would allow to discriminate between models.



HERA Results (Virtual Graviton)

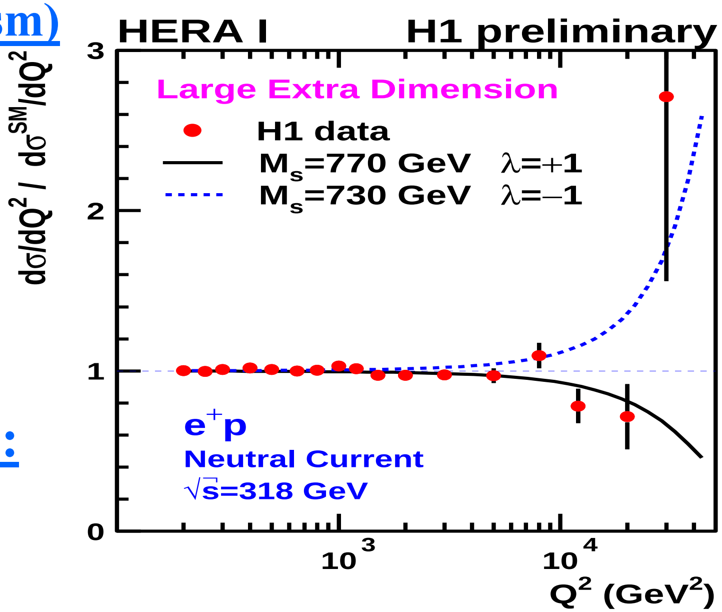
Limits (Hewett formalism)

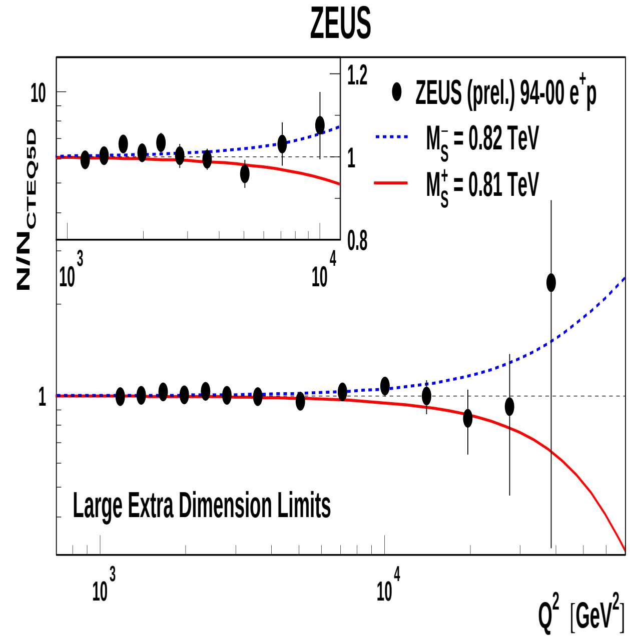
in $e^+ p$:

0.77 & 0.73 TeV (H1)

in $e^- p$:

0.58 & 0.61 TeV (H1)





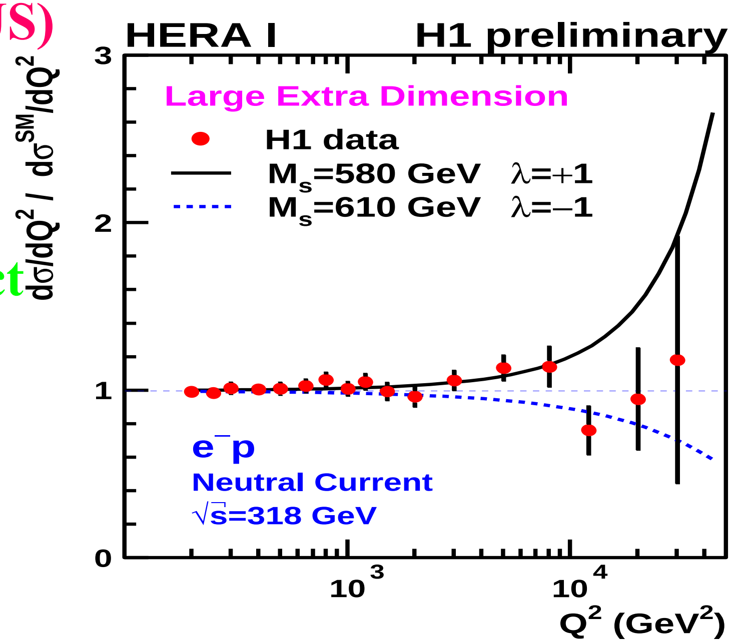
Combining e^+p & $e^- p$:

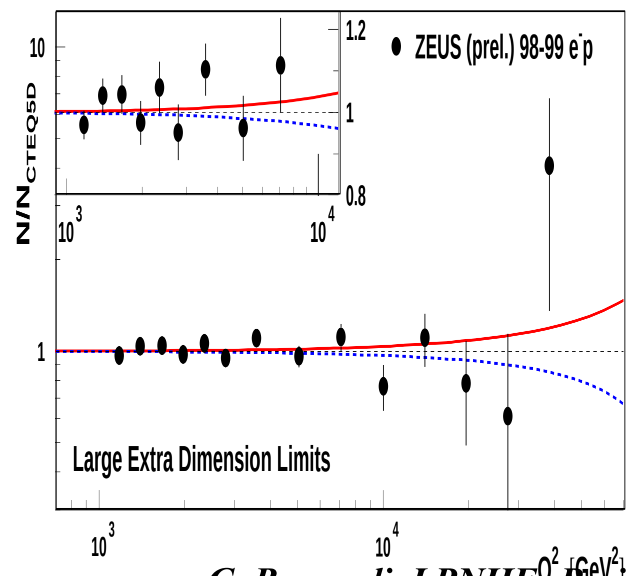
0.83 & 0.79 TeV (H1)

0.82 & 0.81 TeV (ZEUS)

With full HERA II upgrade (1 fb^{-1}), expect sensitivity up to about

1 TeV / exp.



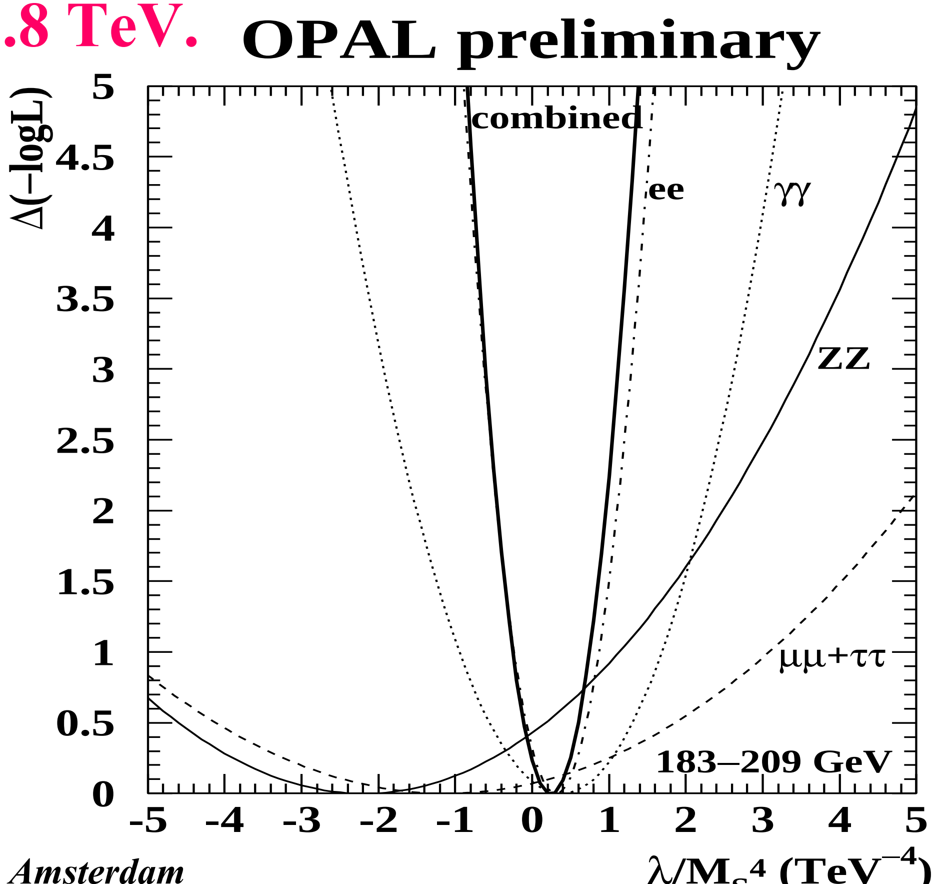


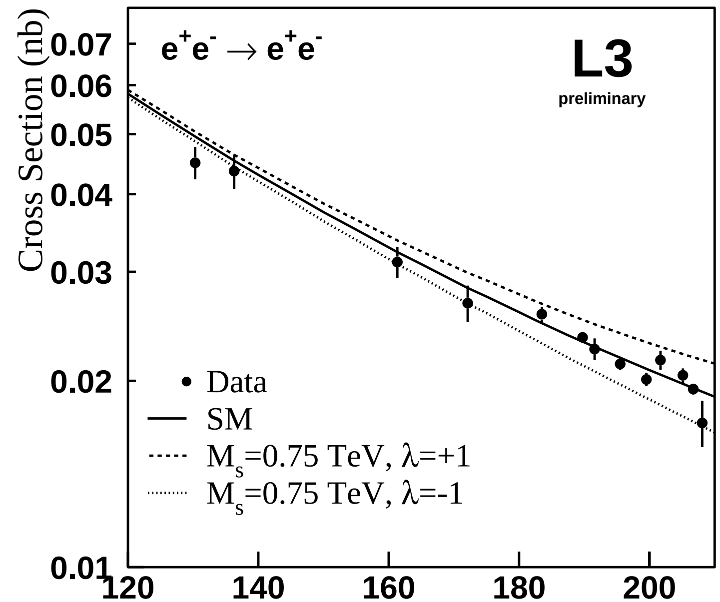
LEP 2 Searches for Virtual Graviton effects

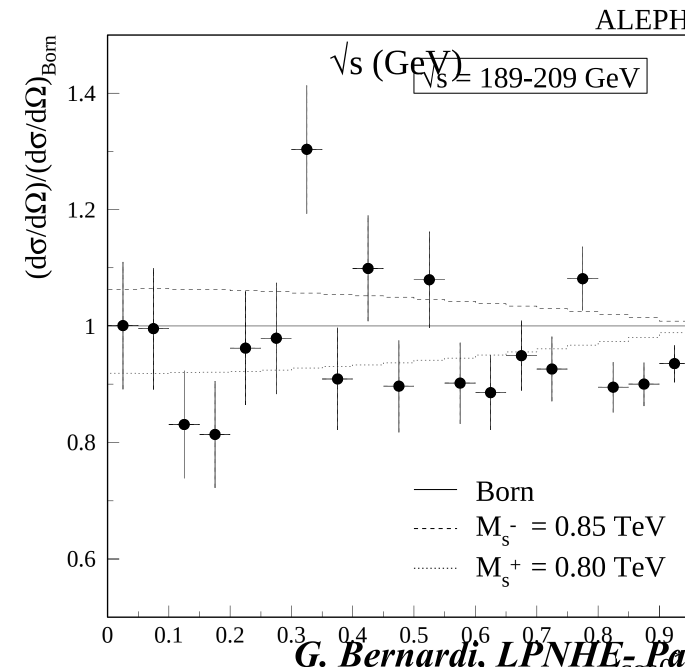
The most sensitive channels are :

Dielectron s- and t-channel production,
Diphoton production.

Limits on M_S (Hewett) obtained from ZZ, WW, $\mu\mu$, $\tau\tau$, qq are between 0.5 and 0.8 TeV.







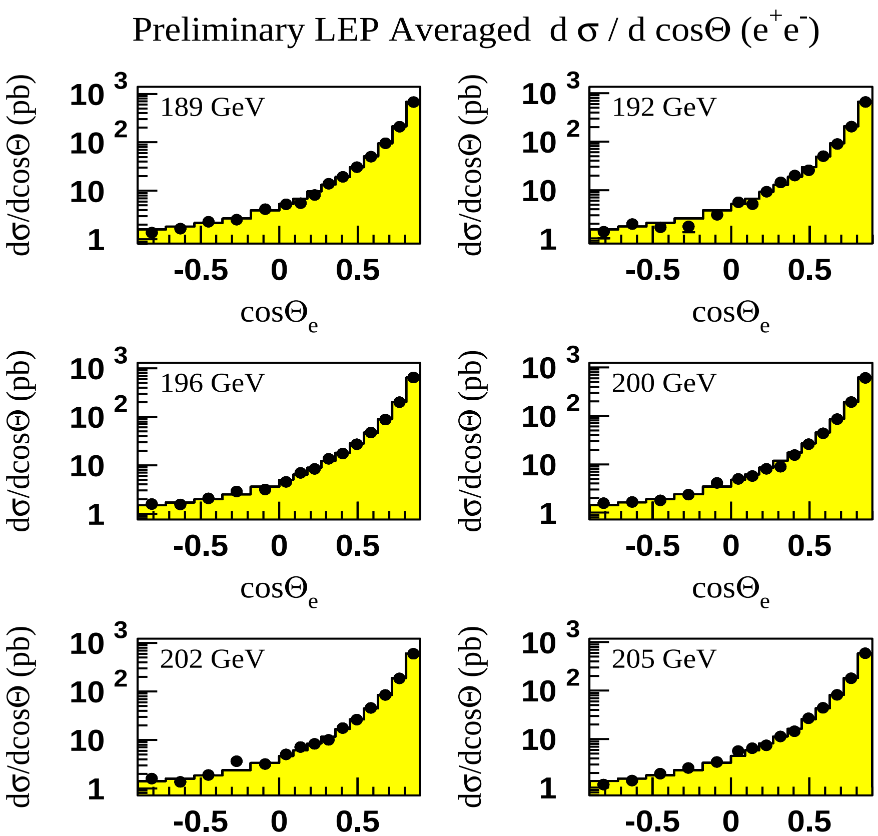
LEP 2 Results on Virtual Graviton effects

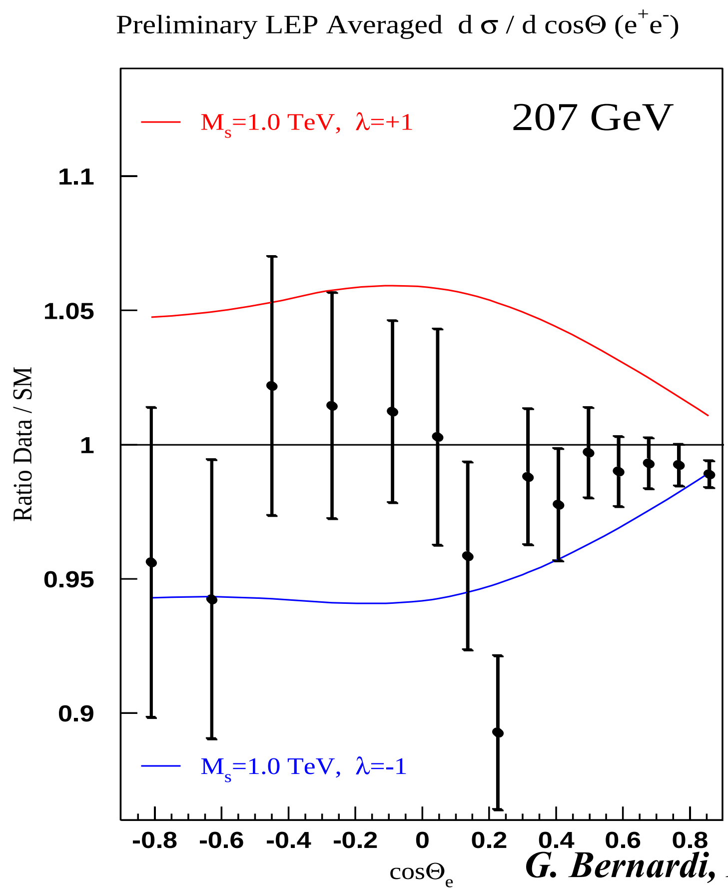
Experiment / Process	*$e^+ e^-$ (λ=+1 / λ=-1)*	*$\gamma\gamma$ (λ=+1 / λ=-1)*
ALEPH	*0.81 / 1.04*	*0.80 / 0.85*
DELPHI	*-*	*0.77 / 0.70*
L3	*1.04 / 1.05*	*0.84 / 0.99*
OPAL	*1.00 / 1.15*	*0.81 / 0.96*

Combining all $e^+ e^-$ results, taking into account error correlation, the expected limits are:

M_S > 1.20 TeV (λ = +1)

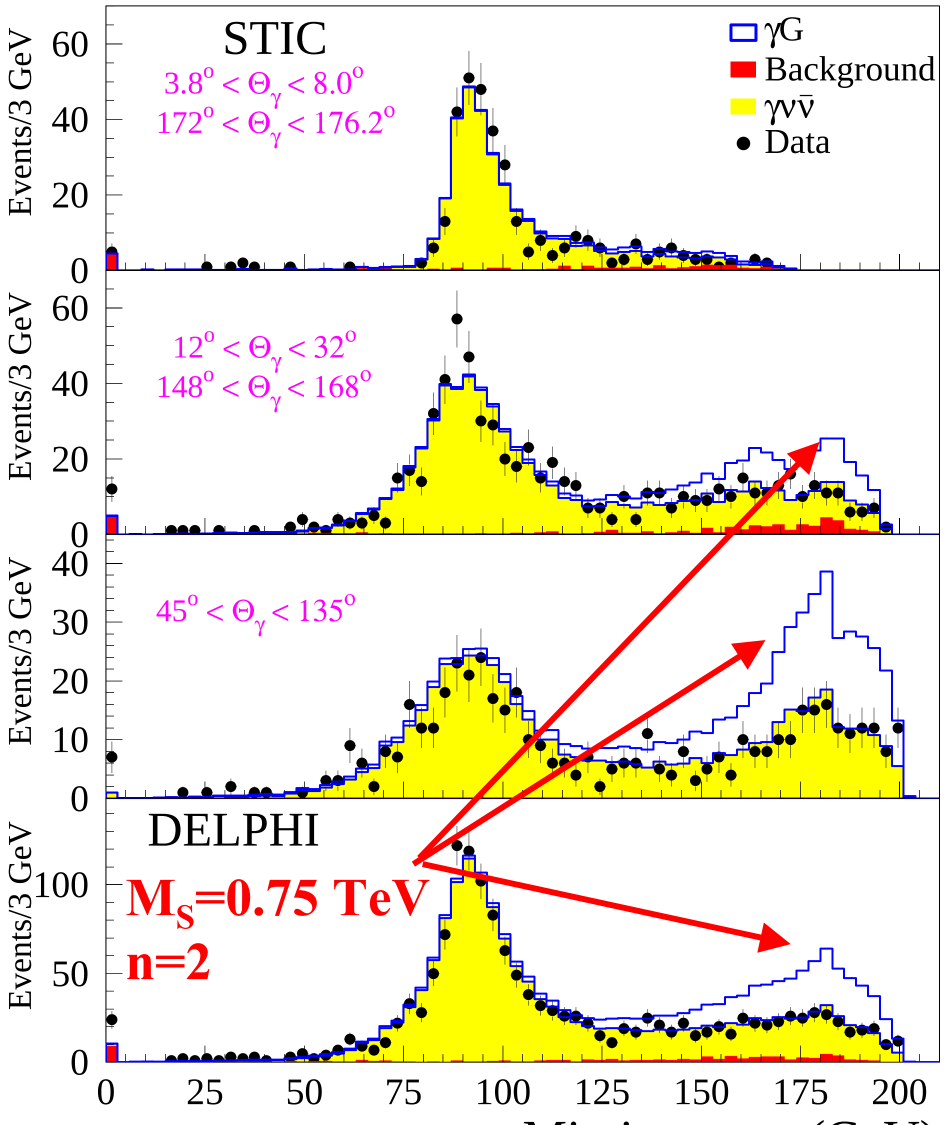
M_S > 1.09 TeV (λ = -1)





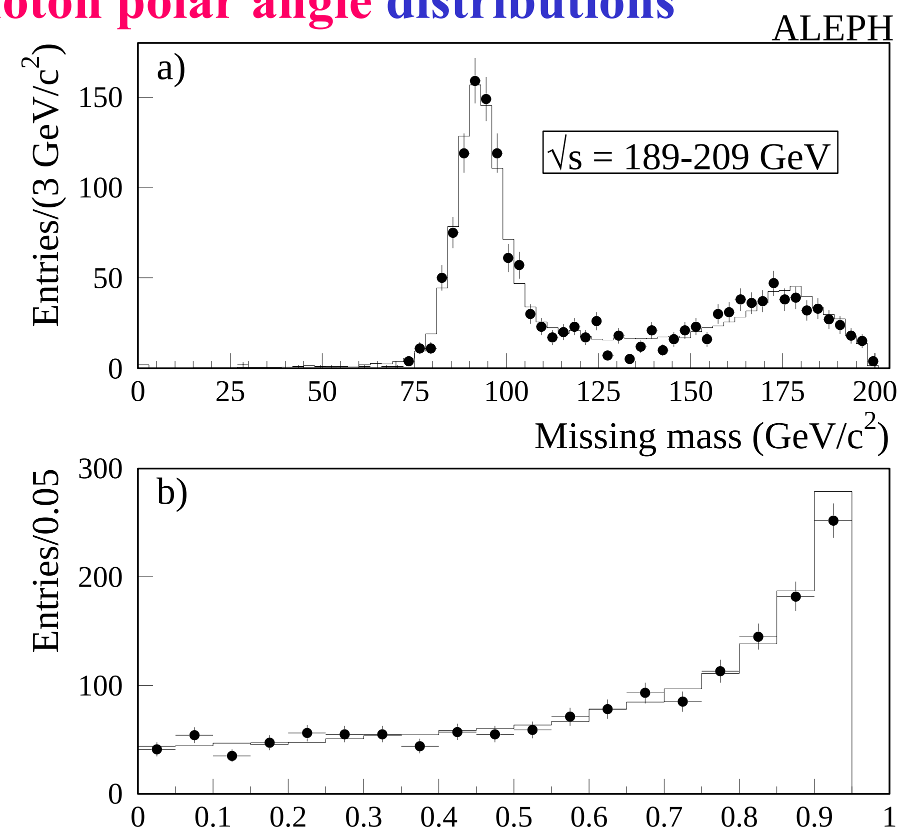
LEP2 Searches for Direct G_{kk} prod.

$e^+e^- \rightarrow \gamma\, G_{KK}$ ➔ Photon + Missing E_T signature ➔ Missing mass



Largest sensitivity for photons in the central region.

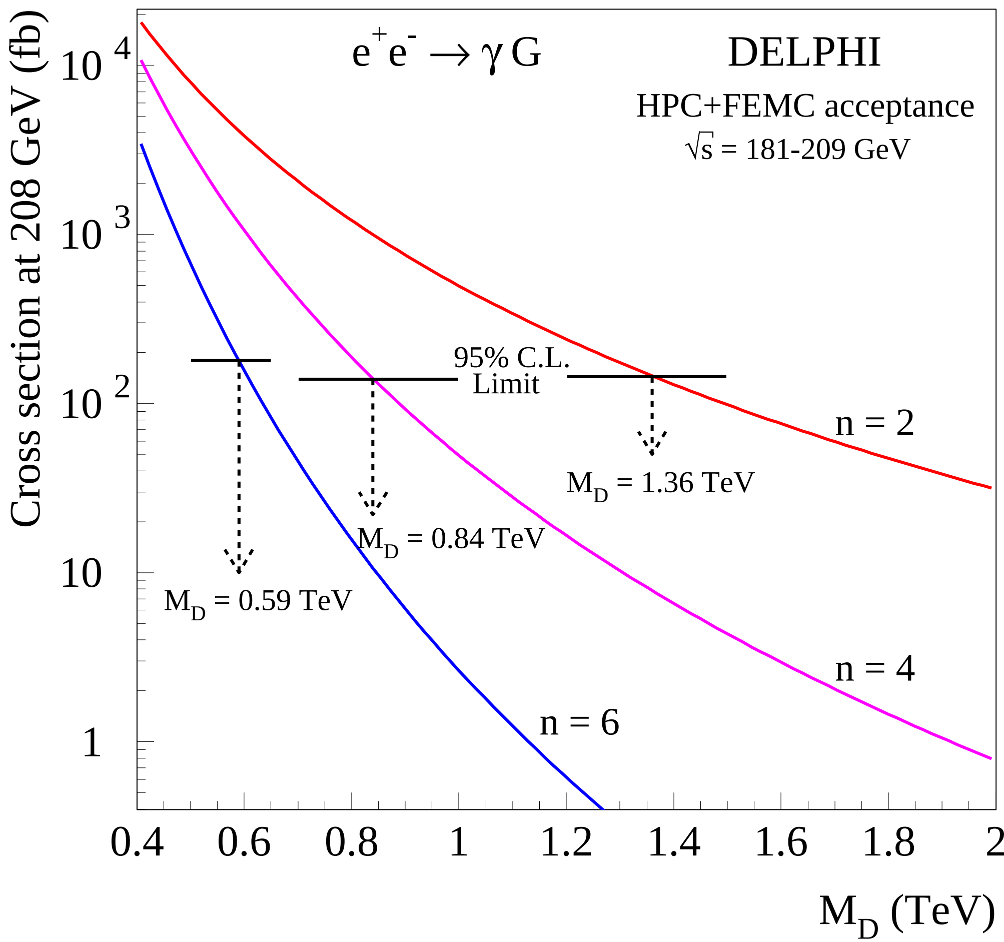
Limits derived from a 2-d binned max. likelihood fit to the missing mass vs photon polar angle distributions



LEP2 results from Direct Searches

$e^+e^- \rightarrow \gamma G$:   ($e^+e^- \rightarrow ZG$ gives limits at 0.6-0.2 TeV (n=2-6)

Experiment	*n=2*	*n=4*	*n=6*
ALEPH	*1.26*	*0.77*	*0.57*
DELPHI	*1.36*	*0.84*	*0.59*
L3	*1.02*	*0.67*	*0.51*
OPAL	*1.09*	*0.71*	*0.53*

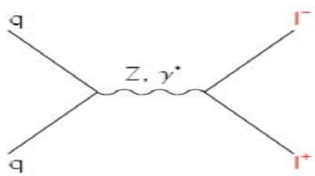


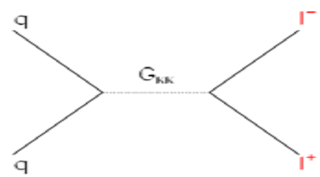
This translates in a limit on the size (radius) of the extra-dimensions of :

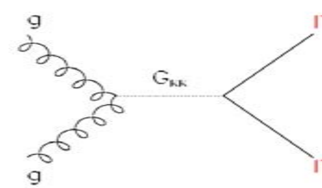
R < 0.26 mm for n=2
R < 13 pm for n=4
R < 6 10^{-12} m for n=6

Virtual Graviton Exchange @ Hadron Colliders

- **di-lepton production:**
  - **Standard model annihilation process interferes with the G_{KK} exchange additional process**
  - **Production process through gluon fusion specific to KK Graviton exchange in the s-channel at hadron colliders**

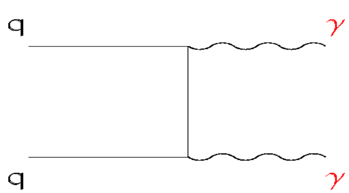


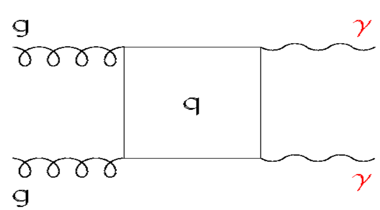




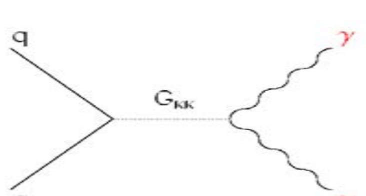
Standard model | **Extra Dimension terms**

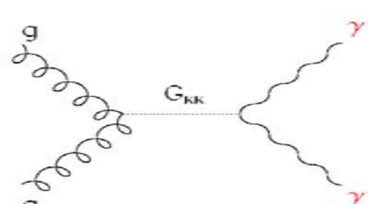
- **di-photon production:**
  - **Only interference between SM and G_{KK} exchange**





Standard model



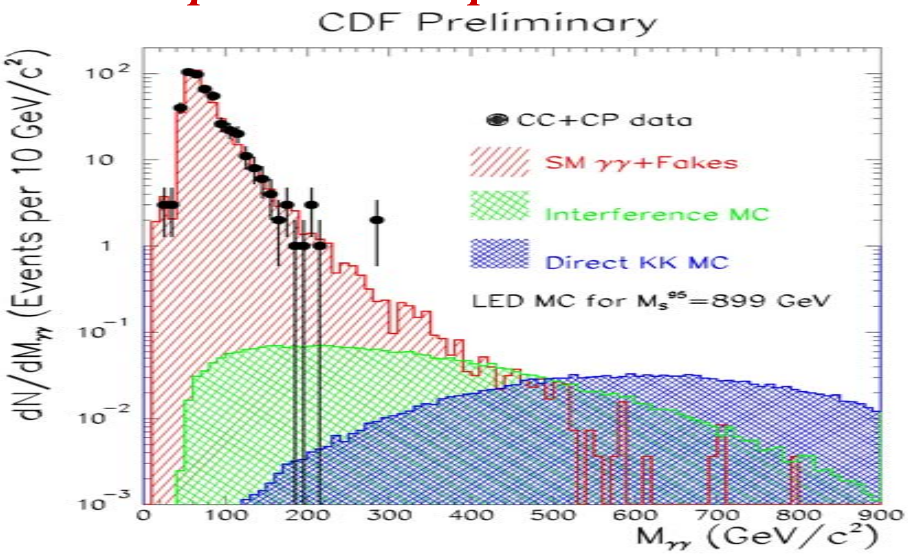


Extra Dimension terms

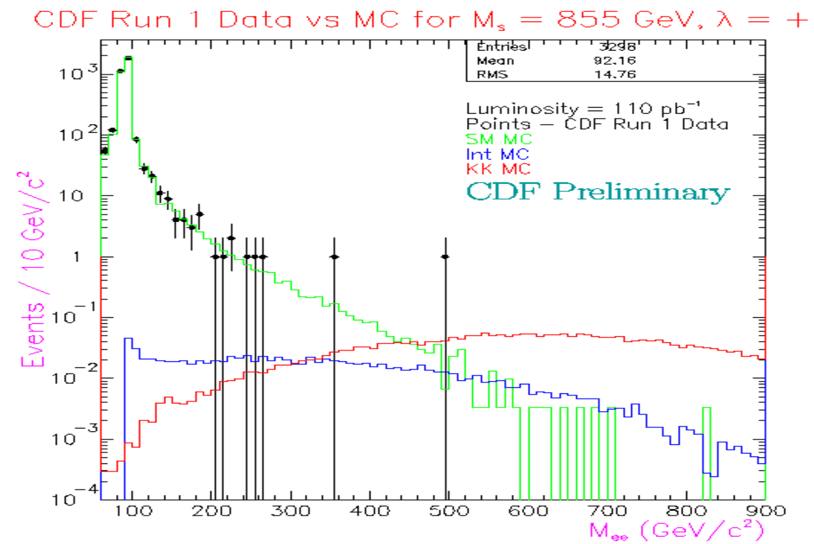
Exclusive Dielectron/Diphoton Production at CDF

- **Improve the purity of the Dielectron channel using the magnetic field information**

Diphoton mass spectrum



Dielectron mass spectrum



- **Limits on M_S (Hewett formalism):**

  Unbinned likelihood fit to invariant mass distributions

  – **Diphoton : M_S > 0.80 TeV (λ= -1), 0.90 TeV (λ=+1)**

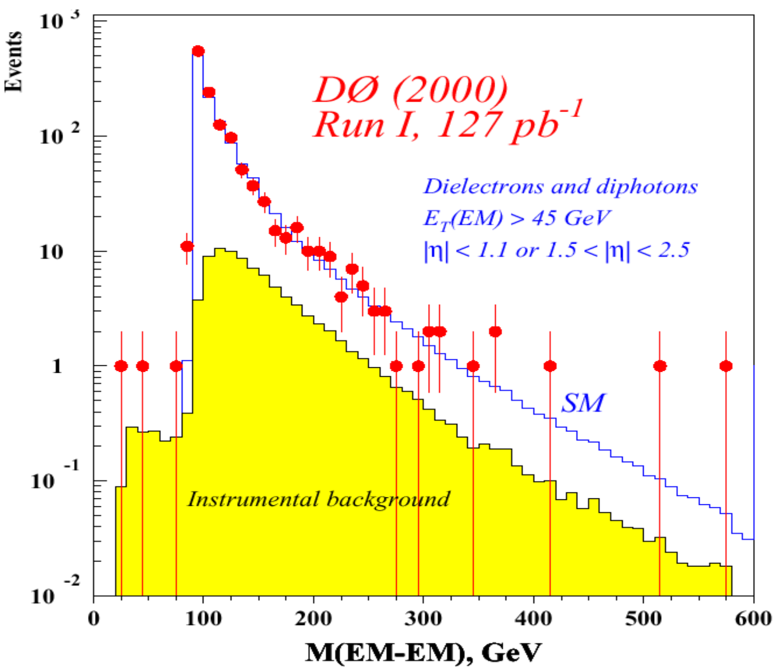
  – **Dielectron: M_S > 0.81 TeV (λ= -1), 0.83 TeV (λ=+1)**

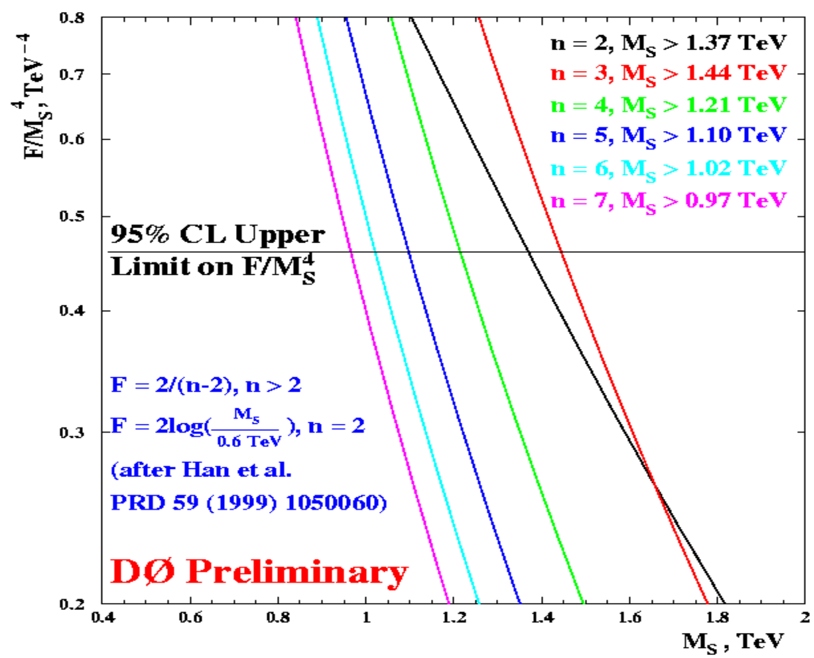
  – **Combination:**

  M_S > 0.85 TeV (λ=-1) and 0.94 TeV (λ=+1)

Inclusive Dielectron/Diphoton Production at DØ

di-EM signature: Adding dielectrons and diphoton signatures maximizes the discovery potential. Combine the information from the $\cos\theta^*$ and invariant mass distributions in a two-dimensional binned likelihood to derive the limits in HLZ and Hewett formalism





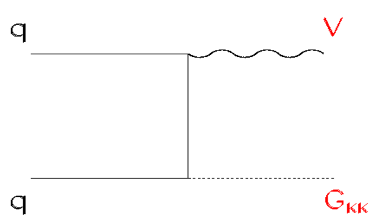
In the Hewett formalism: $M_S > 1.1$ GeV for $\lambda = +1$

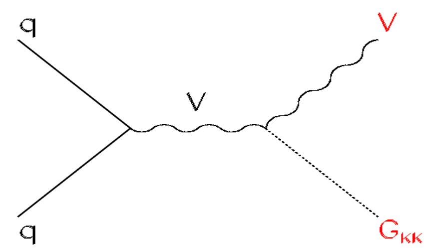
$M_S > 1.0$ GeV for $\lambda = -1$

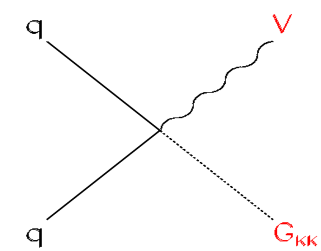
Real Kaluza-Klein Graviton Emission

Real G_{KK} emission in association with a vector-boson:

- EW-Gauge boson (γ) and missing E_T . Similar to the LEP topology without the total missing energy constraint. Larger $\sqrt{s}$ but also larger backgrounds.

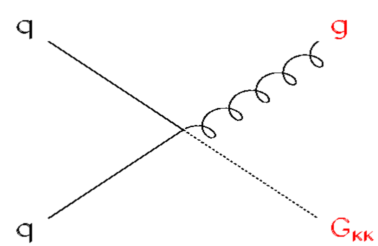


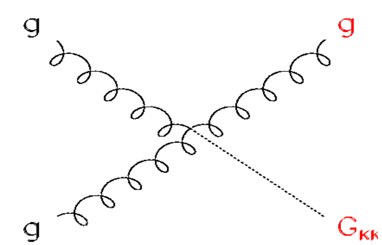




KK Graviton's signature: photon + missing (transverse) energy

- Mono-jet topology: Topology specific to Tevatron, two production processes:





KK Graviton's signature: jet + missing (transverse) energy

CDF: Single Photon – Missing Energy Search

Search Selection (on L ~ 87pb^{-1})

- One photon with Transverse energy in excess of 55 GeV and within the pseudo-rapidity range $|\eta^{\gamma}| < 1$
- Missing E_T > 45 GeV
- No jets with E_T > 15 GeV
- No tracks with p_T > 5 GeV

Background dominated (~60%) by Cosmic rays where a muon undergoes a brehmsstrahlung in the CEM

Second most important background (30%) $Z\gamma \rightarrow \nu\nu\gamma$

Results

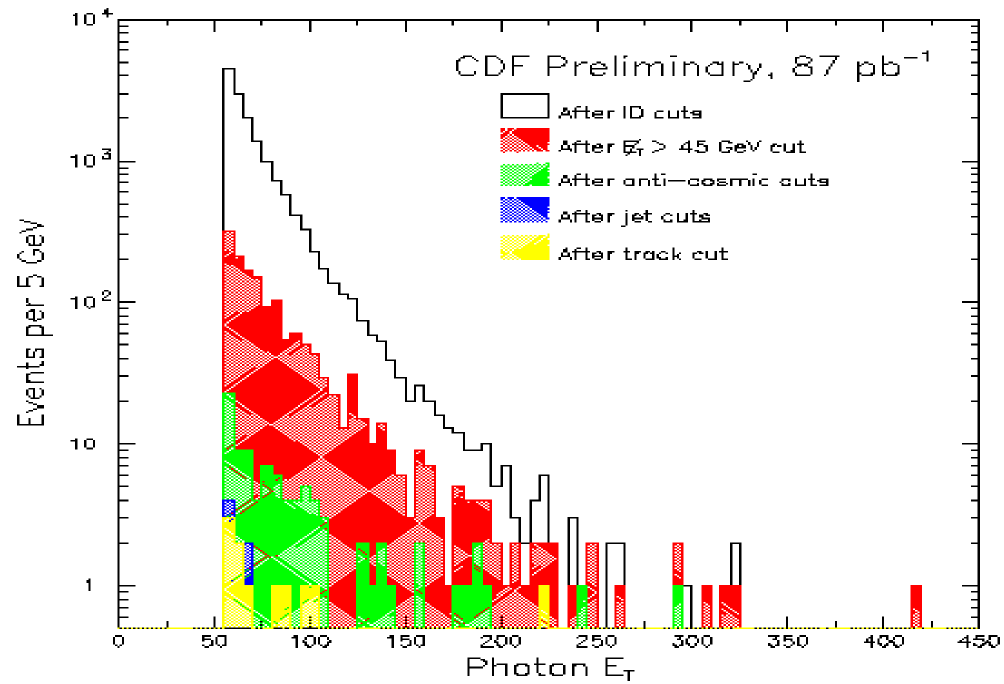
- Background estimate=11 ± 2
- Observed events =11

Limits

n=4 M_S > 0.55 TeV

n=6 M_S > 0.58 TeV

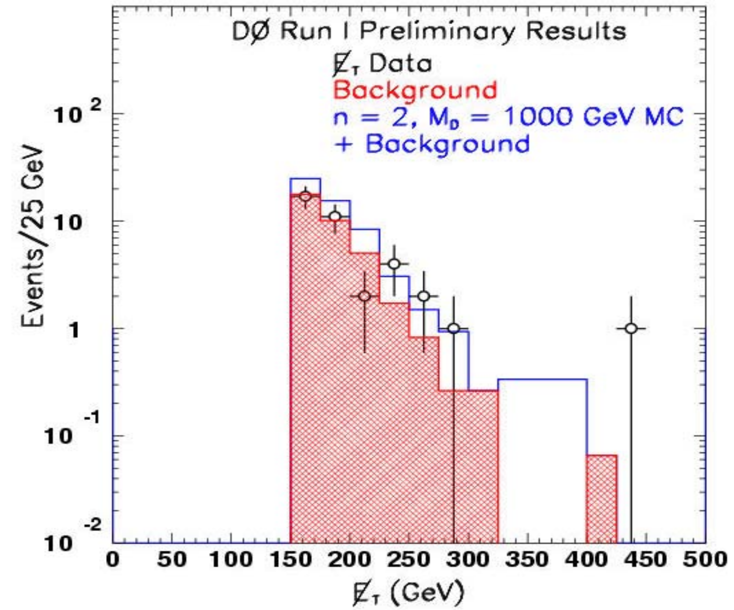
n=8 M_S > 0.60 TeV



DØ: mono-Jet Search

Search Selection (on L ~ 80pb^{-1})

- One or two 0.5 cone jets
- Missing E_T : > 150 GeV
- Leading Jet: E_T > 150 GeV, $|\eta| < 1.0$
- Second Jet: E_T < 50 GeV, not pointing at missing E_T to suppress QCD backgnd

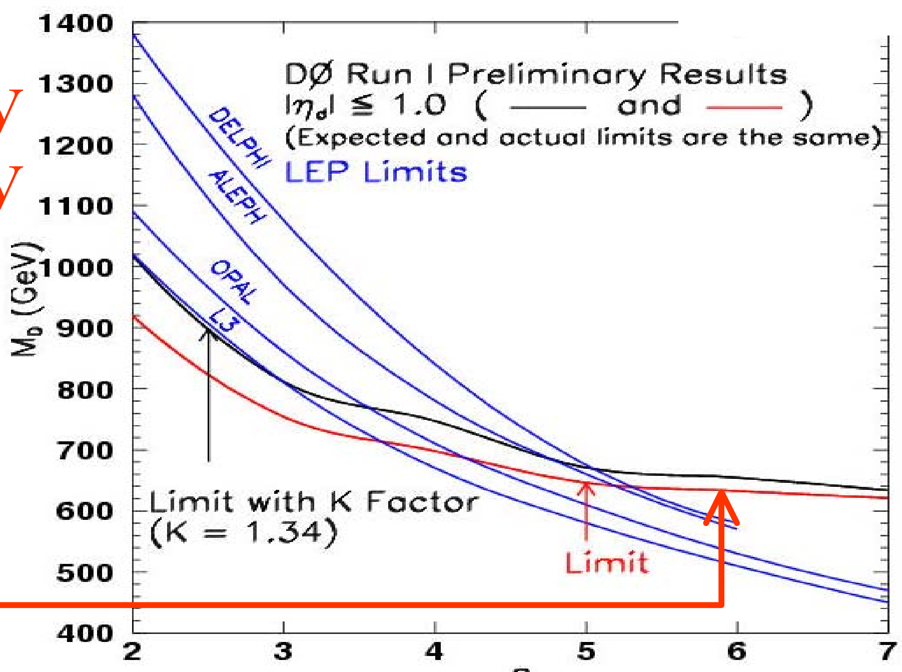


Limits

n=4: M_S> 0.70 TeV
n=6: M_S> 0.63 TeV

cf Delphi:
n=4 M_S> 0.84 TeV
n=6 M_S> 0.58 TeV

Improvement at large n

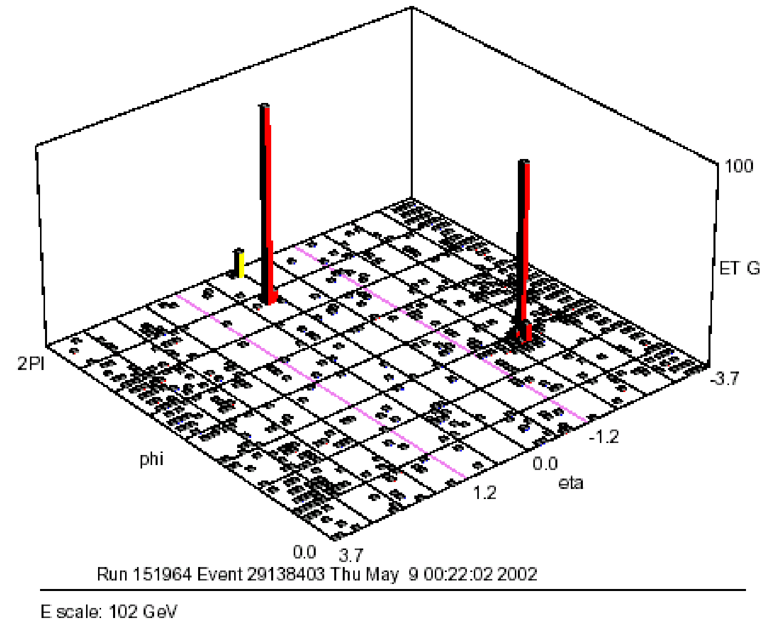


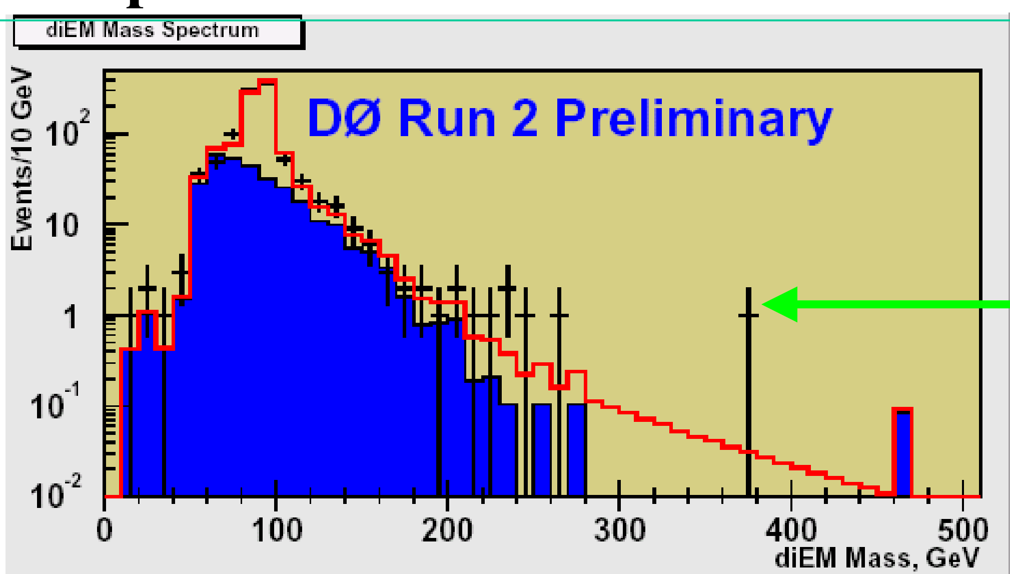
- W's, Z's = 30 ± 4
- QCD,Cosmics= 8 ± 7
- Total =38 ± 8
- Observed events = 38

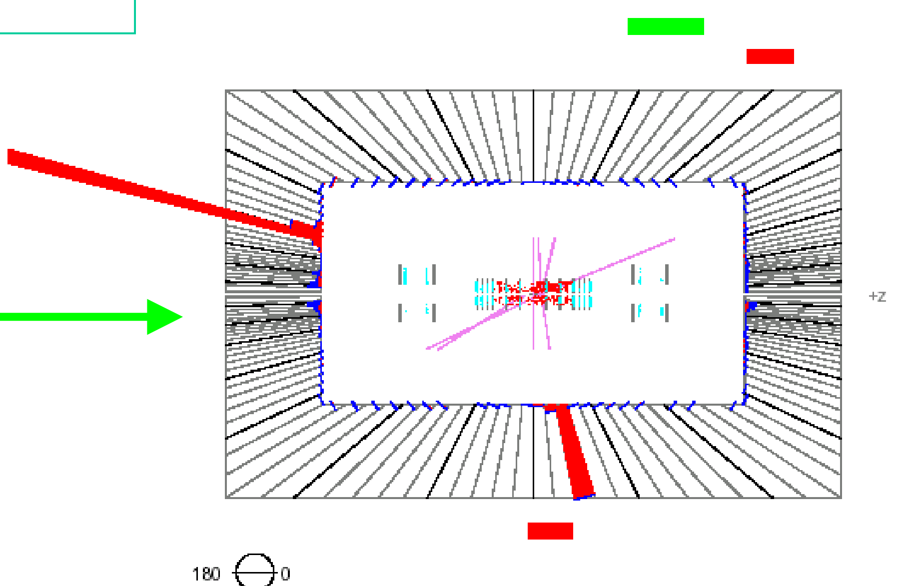
First Run II Results : di-em search at DØ

- Tevatron Run II has started 3/2001
- about 50 pb^{-1} have been delivered
- New ED analysis based on 9.9 pb^{-1} in the di-em channel, with the upgraded DØ detector (tracking, DAQ, muon)
- Data compatible with SM background:

  $\rightarrow$ $M_S > 0.82$ TeV ($\lambda = +1$)
- Expects 0.15 fb^{-1} $\rightarrow$ end 2002
- Expects 2.0 fb^{-1} $\rightarrow$ 2005







Conclusions and Outlook

- **The HERA, LEP and Tevatron experiments have searched for signs of extra spatial dimensions, both in direct and indirect way**
- **In none of the channels searched for has any sign of a deviation from the background expectation been observed**
- **Limits are presently of the same order of magnitude in all experiments, with limits on the gravity mass scale up to about 1.4 TeV for n=2, 1.2 TeV for n=4, 1.0 TeV for n=6,**

  i.e. $M_S > 1.1$ TeV (1.0 TeV) for $\lambda > +1$ (-1)
- **The Tevatron Run II program has successfully started with a promising observation potential, and should be in position to discover ED, if they exist, up to about**

  $M_S = 2$ to 3 TeV (Runs IIa , IIb)