The Search for New Phenomena at the Tevatron

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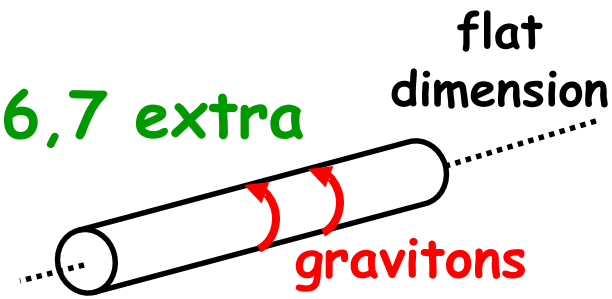
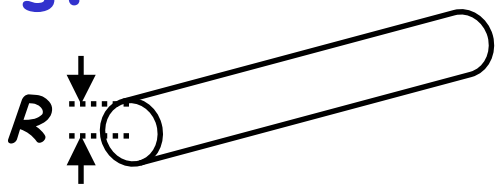
Searches Covered

- Search for Large Extra-dimensions
  - Single jet + MET (Run I,DØ)
  - Single photon + MET (Run I,CDF)
  - Di-electron/di-photon (Run I,DØ+CDF)
  - Prospects for LED in Run II
- First Generation Leptoquark preliminary search results (Run II,DØ)

Extra Dimensions

- Possibly >3 spatial dimensions
  - Natural in string theory with n=6,7 extra dimensions compactified
- "Large" extra dimensions
  - 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 (M_S)
  - Compact dimension's radius, R
  - Number of compact, extra dimensions, n



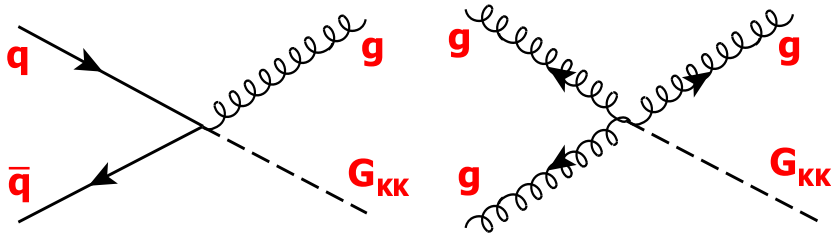


Experimental Limits

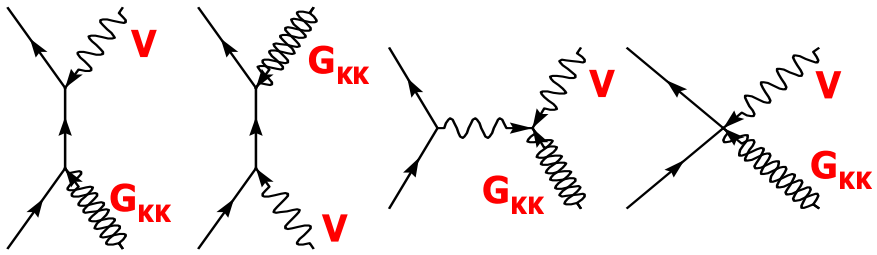
- Limits on *R* come from measurements of the gravitational potential, assuming $M_D \sim 1 TeV/c^2$
  - n=1 excluded by solar system
  - R<0.19 mm for n=2 (Eöt-wash)
- Cooling of SN1987A by graviton emission (preventing the neutrino flux) limits M_D:
  - $M_D > \sim 30$ TeV/c^2, n=2; $M_D > \sim 2$ TeV/c^2, n=3
- Smoothness of the cosmic diffuse gamma radiation (CDG) due to $G_{KK} \rightarrow \gamma\gamma$
  - $M_D > \sim 100$ TeV/c^2, n=2; $M_D > \sim 5$ TeV/c^2, n=3

Tevatron Signatures

- Gravity enhanced by phase space
  - Kaluza-Klein excitations
    - Winding of graviton about the compactified dimensions
  - Interaction as $1/M_D^2$, not $1/M_{planck}^2$
- Direct graviton production
  - Monojet+MET

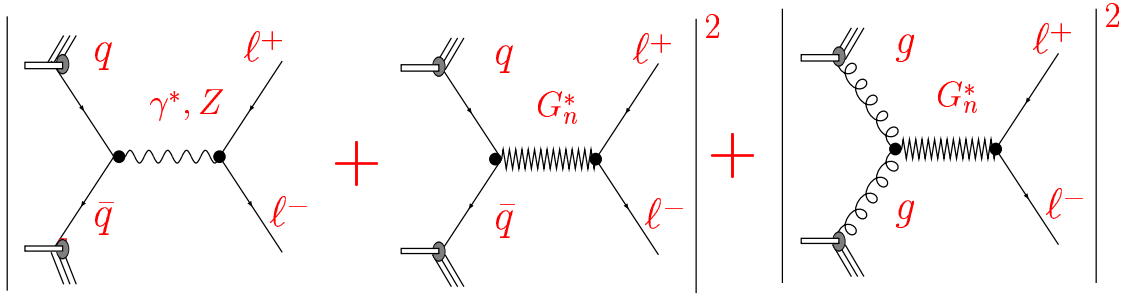


  - Vector boson + MET



Tevatron Signatures

- Virtual G_{KK} exchange
  - 2 fermions or 2 vector bosons



- Weak dependence on n
  - Cross-section, $\sigma=\sigma_{SM}+\sigma_{int}\eta_G+\sigma_G\eta_G^2$
  - Where $\eta_G=F/M_S^4$, and F is model dependent:
    - F=1 (GRW)
    - log (M_S^2/M^2) for n=2, 2/(n-2) n>2 (HLZ)
    - $2\lambda/\pi$; $\lambda=\pm1$ (Hewett) ← USED

Collider Limits

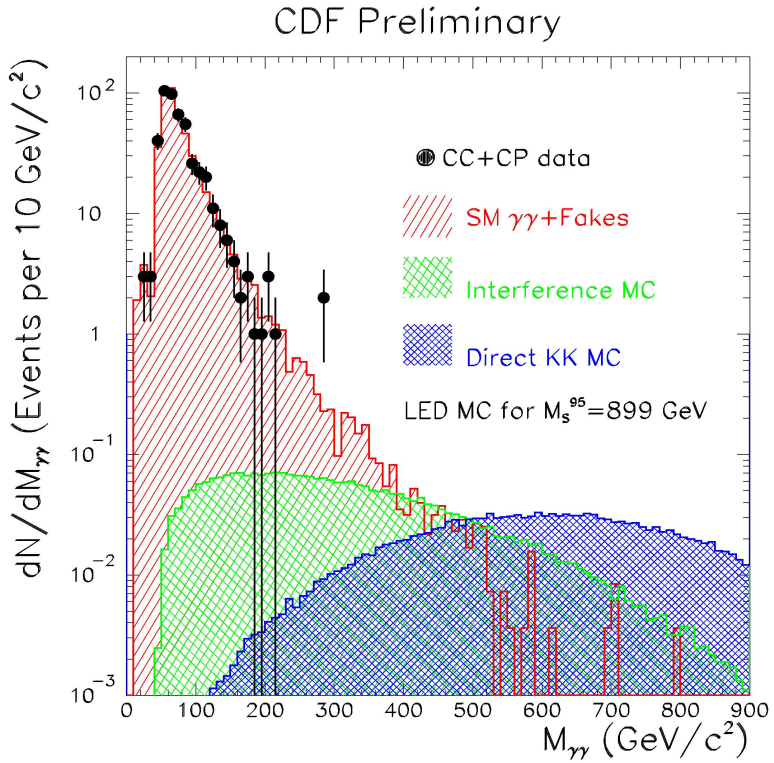
- LEP
  - $e^+e^- \rightarrow \gamma + G_{KK}$, $Z + G_{KK}$
    - $M_D > \sim 0.5$ TeV/c^2, n=6, $M_D > \sim 1.3$ TeV/c^2, n=2
  - $e^+e^- \rightarrow G_{KK} \rightarrow$ fermion/vector boson pairs
    - $M_D > \sim 0.5 - 1.2$ TeV/c^2
- HERA
  - $e^{\pm}p \rightarrow e^{\pm}p$
    - Current limits: $M_D > \sim 0.5\text{-}0.8$ TeV/c^2
    - Improve with continued HERA running

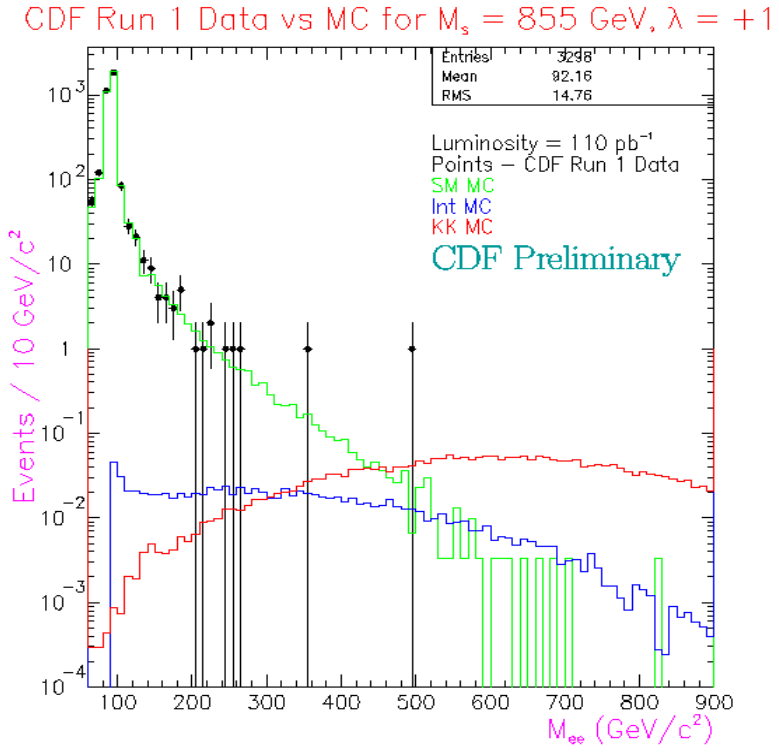
CDF Run I Virtual G_{KK} Search

- Data in agreement with Standard Model
- Unbinned likelihood function fit to invariant mass distributions
  - Extract 95% confidence limit on η_G
- Di-photon channel gives:
  - $M_S > 0.797$ TeV/c^2 ($\lambda=-1$), 0.899 TeV/c^2 ($\lambda=+1$)
- Di-electron channel gives:
  - $M_S > 0.808$ TeV/c^2 ($\lambda=-1$), 0.826 TeV/c^2 ($\lambda=+1$)
- Recently Combined:
  - $M_S > 0.853$ TeV/c^2 ($\lambda=-1$), 0.939 TeV/c^2 ($\lambda=+1$)

CDF Run I Virtual G_{KK} Search

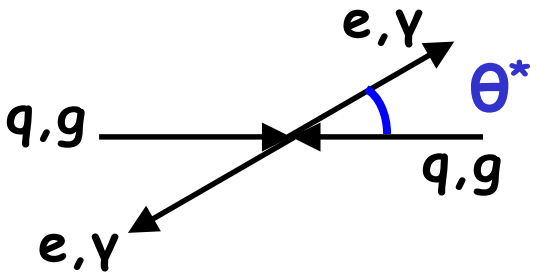
- $pp \rightarrow G_{KK} \rightarrow \gamma\gamma$ or e^+e^-
  - Photons: $|\eta|<1$, $E_T > 22$, 100 pb^{-1} 287(+192) Events
  - Electrons: $|\eta|<1$, $E_T > 25$, 110 pb^{-1} 3298 Events

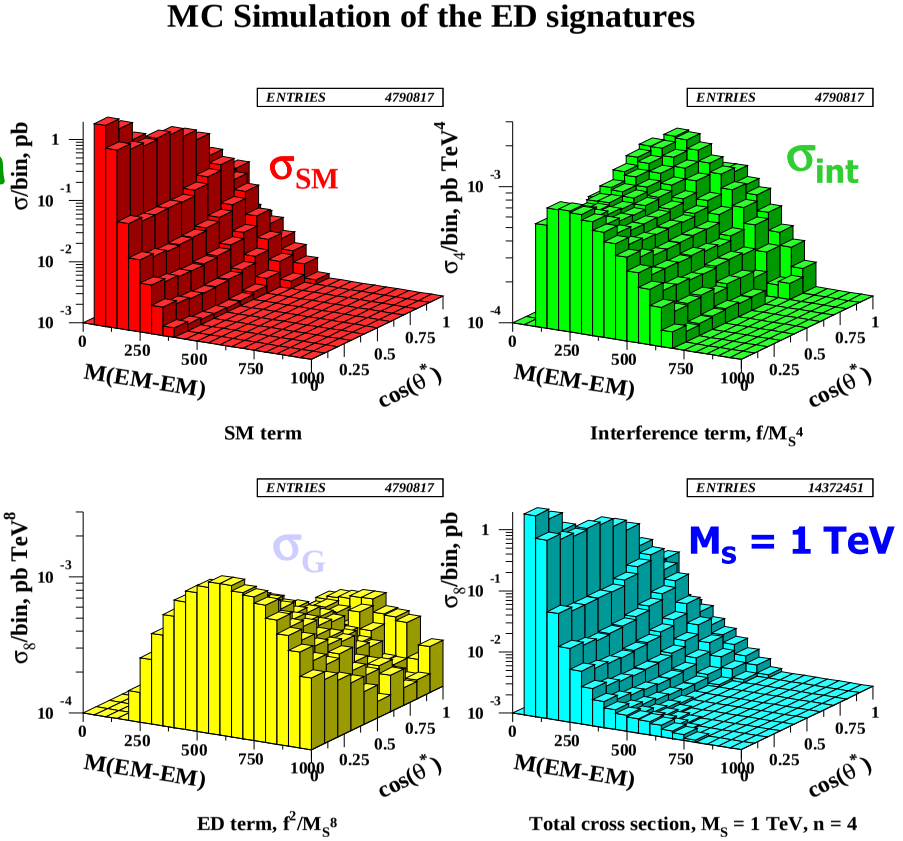




DØ Run I Virtual G_{KK} Search

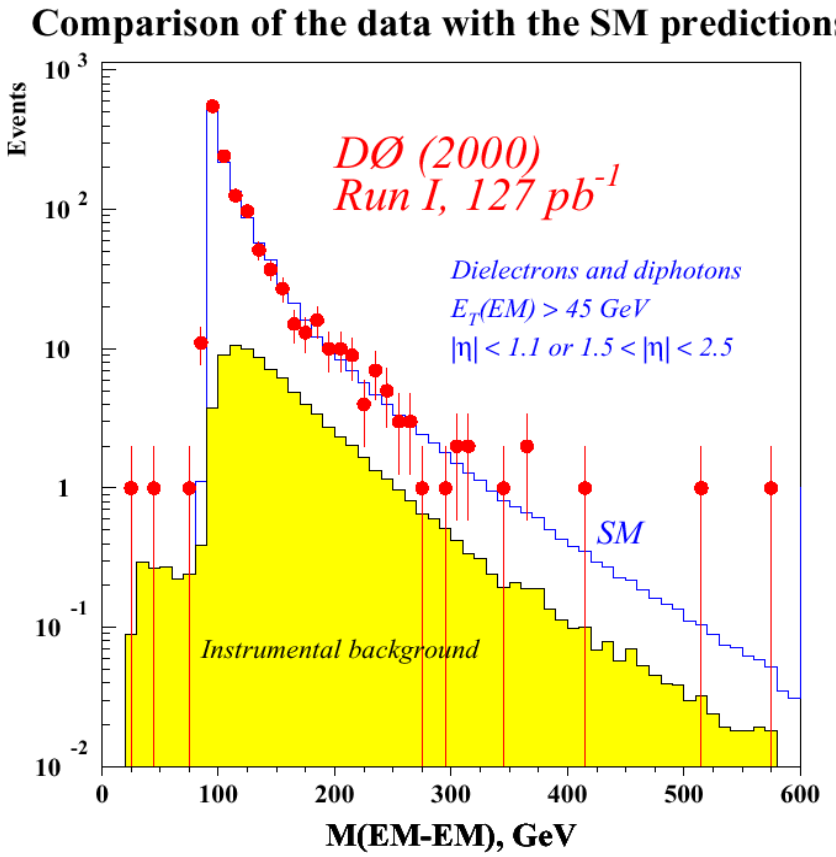
- DØ also searches in di-photon and di-electron channels (combined)
  - Fit to 2D distribution of invariant mass vs. $|\cos\theta^*|$
  - Largest contribution at high mass and low $|\cos\theta^*|$
  - 40 x 10 bins
    - $0<M<1$ TeV/c^2
    - $0<|\cos\theta^*|<1$

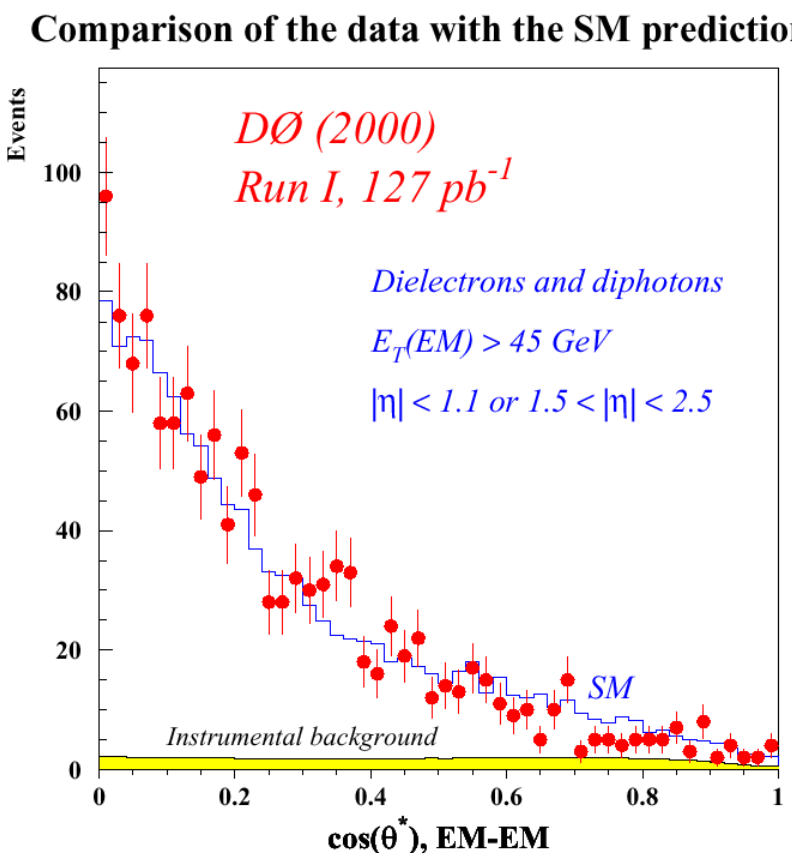




DØ Run I Di-EM Data

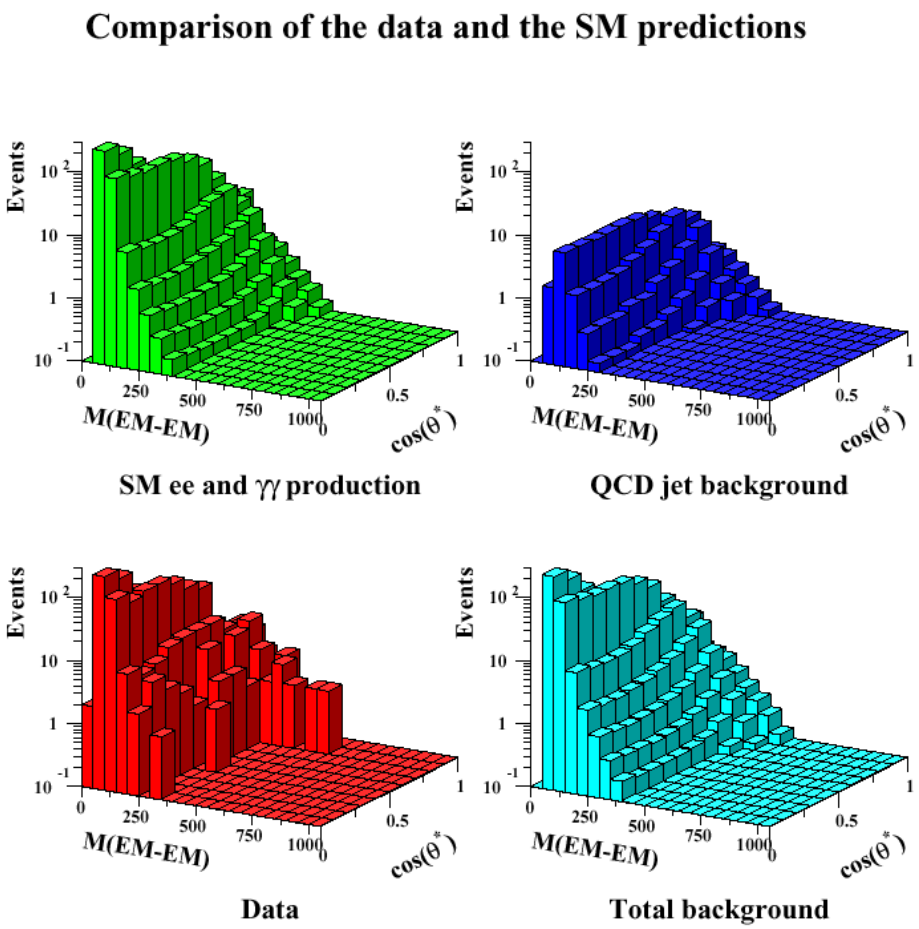
- 2EM objects required (1250 events, 127 pb^{-1})
  - E_T>45 GeV, $|\eta|$<1.1 or 1.5<$|\eta|$<2.5





DØ Run I Di-EM Results

- Data in agreement with SM
- Highest mass events
  - 575 GeV, $\cos\theta^* = 0.86$
  - 520 GeV, $\cos\theta^* = 0.84$
- 95% CL
  - $M_S > 1.1$ TeV/c^2 (λ=+1)
  - $M_S > 1.0$ TeV/c^2 (λ=-1)

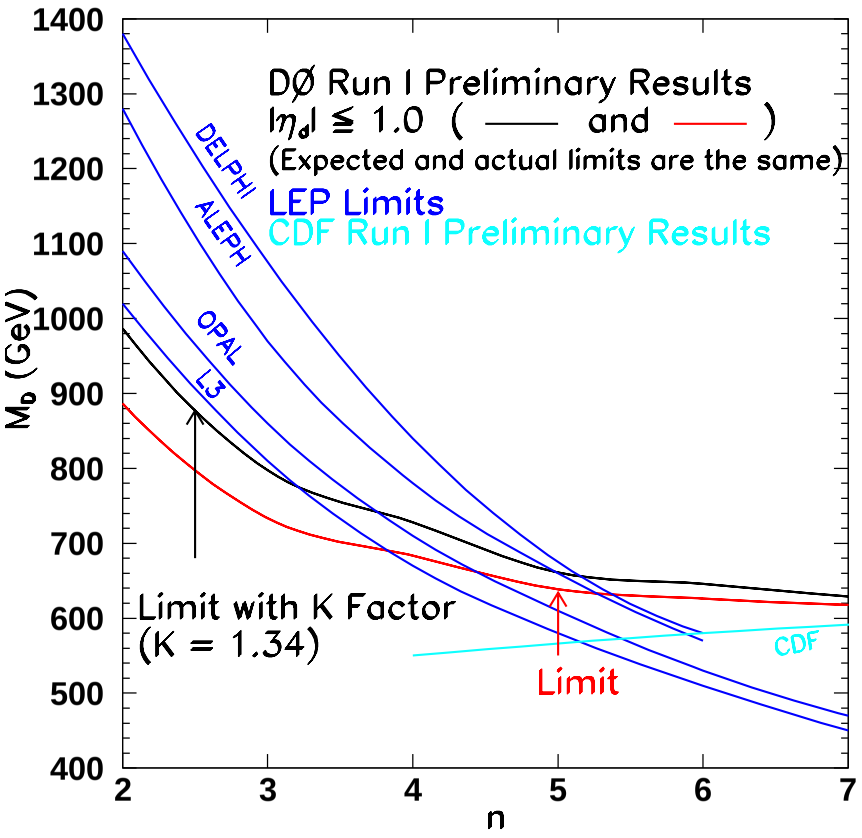


DØ Run I $qq \rightarrow G_{KK}+g$ Search

- Search for G_{KK} production in ~79 pb^{-1} data
  - Graviton escapes detector = Missing E_T
    - Final state is single jet + missing E_T
    - First such search at a hadron collider
  - Require missing E_T>150 GeV
  - Require central, leading jet (0.5 cone)
    - E_T>150 GeV and $|\eta| \leq 1.0$
  - Require second jet (if any)
    - E_T<50 GeV and $|\Delta\varphi(\text{jet2, missing } E_T)|$>15°
    - Suppress QCD background and mismeasured jets
  - Confirm primary vertex using jet pointing
    - Rejects cosmic ray and mis-vertexed events

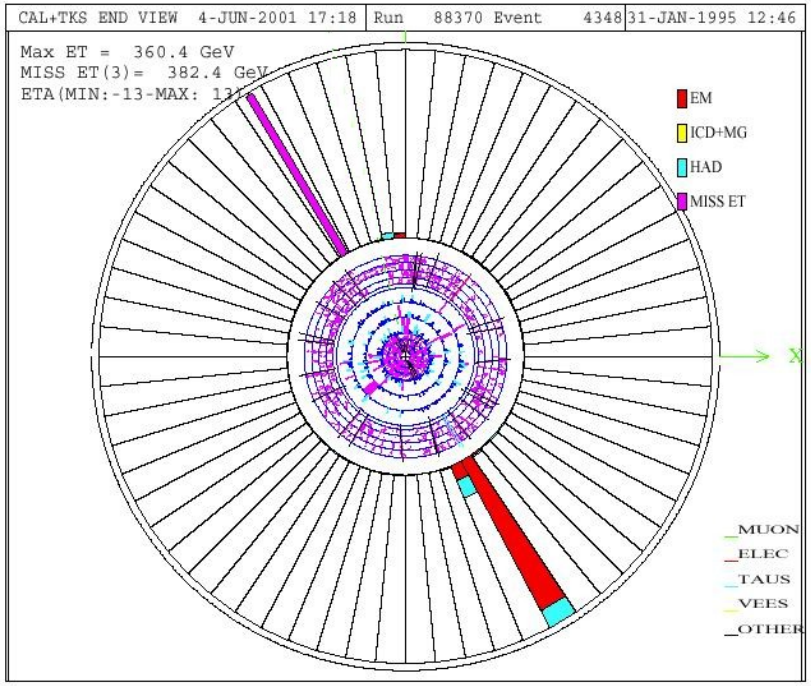
DØ Run I $qq \rightarrow G_{KK}+g$ Results

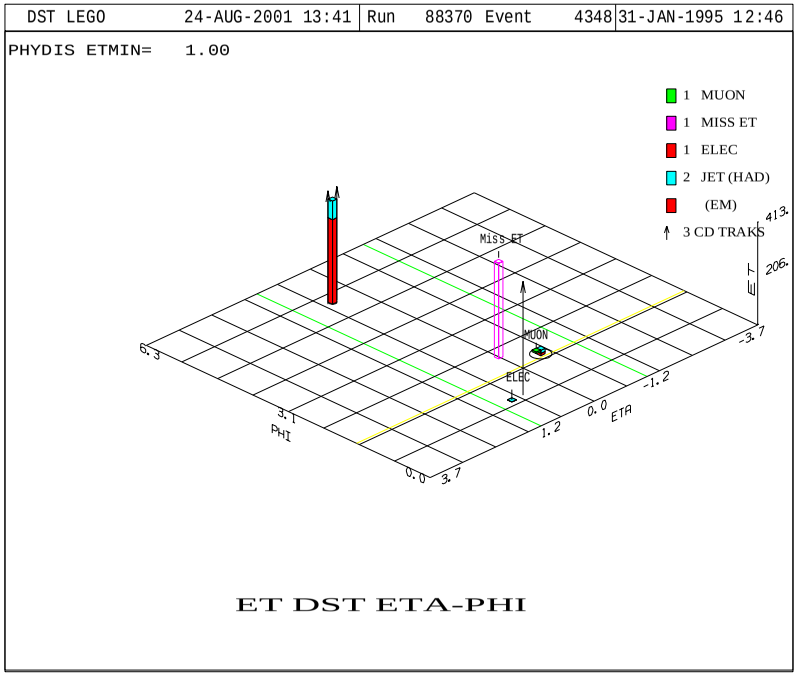
- Background Total=38.0±9.6 events
  - W/Z=30.2±6.4
  - QCD/Cosmics=7.8±7.1
- Data contains 38 events!
- Limit M_D as function of n
  - K factor estimates NLO effects missing from MC



Highest MET Event in Sample

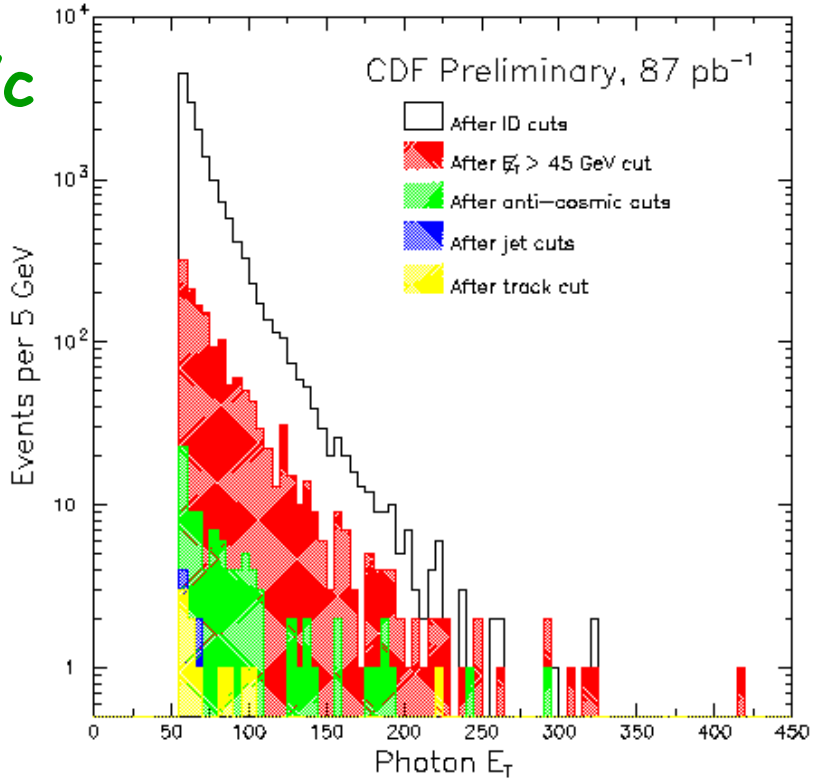
Jet E_T = 466 GeV
Missing ET = 443 GeV





CDF Run I γ+Missing ET

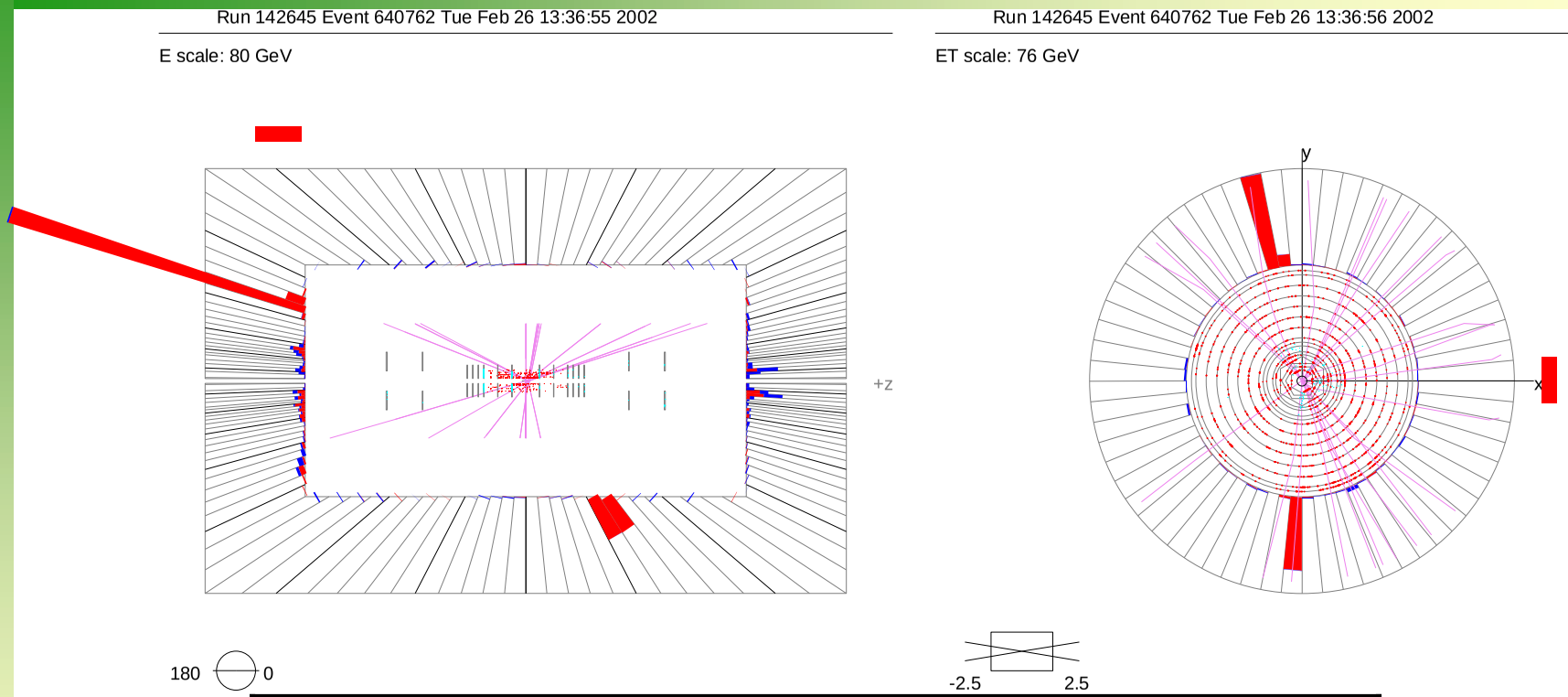
- Search for $qq \rightarrow \gamma + G_{KK}$
  - $E_T^{\gamma} > 55$ GeV, $|\eta^{\gamma}| < 1$
  - missing $E_T > 45$ GeV
  - No jets with $E_T > 15$ GeV
  - No tracks with $p_T > 5$ GeV/c
- 11 events observed in 87 pb^{-1} of data
  - Background estimate
    - 11±2 events
- M_S limits
  - $M_S > 550$ GeV/c^2, n=4
  - $M_S > 580$ GeV/c^2, n=6
  - $M_S > 600$ GeV/c^2, n=8



Run II Prospects for LED

- Current sensitivities limited by statistics
- Significant increase in luminosity for RunII and small increase in CM energy from 1.8 TeV to 1.96 TeV
  - Run I, 0.13 fb^{-1}
  - Run IIa, 2 fb^{-1} → M_S sensitivity x2 Run I
  - Run IIb, 20 fb^{-1} → M_S sensitivity x3 Run I
- Run II so far…
  - >10 pb^{-1} analysed to date

DØ RunII Di-EM Candidate



EM1	EM2
E_T = 91.1 GeV η = -1.83 φ = 1.79 Loose low p_T SMT track match	E_T = 67.1 GeV η = +0.60 φ = 4.65 Loose low p_T CFT track match
M(diEM) = 286 GeV; cosθ* = 0.90; ME_T = 25.9 GeV;	

Leptoquarks

- Leptoquarks suggested by apparent symmetry between lepton and quark sectors
  - Couple directly to leptons and quarks
  - Inter-generational mixing strongly constrained by FCNC limits
  - Scalar (spin 0) or vector (spin 1)
    - Vector coupling model is dependent
      - Yang-Mills coupling or Minimal coupling
- Pair produced at Tevatron

$$p\bar{p} \rightarrow g \rightarrow LQ\overline{LQ} \rightarrow l^{+}l^{-}q\bar{q}, l^{\pm}\nu q\bar{q}, \nu\bar{\nu}q\bar{q}$$

1st Generation Limits

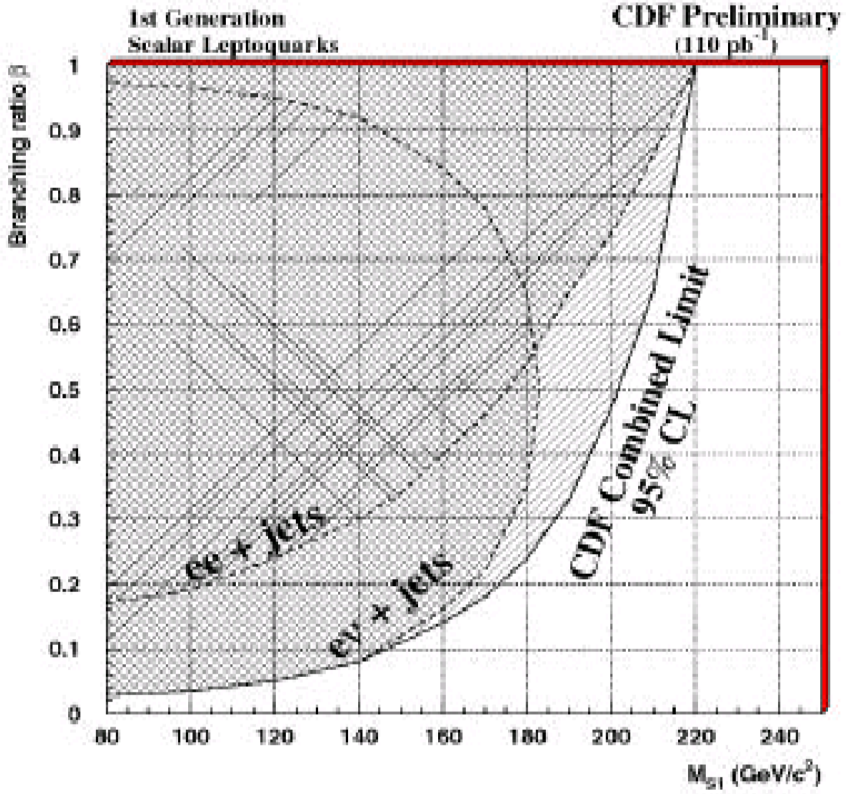
- DØ and CDF Run I results
  - Search for eeqq, evqq (CDF) and ννqq (DØ)
- Limits depend on β=BR(LQ→lq)
- Combined DØ and CDF result
  - β=1, scalar LQ: 242 GeV/c^2

1st Gen	β	Scalar (GeV/c)	Vector Minimal Coupling (GeV/c^2)	Vector Yang-Mills Coupling (GeV/c^2)
DØ	1	225(242)	292	345
	0.5	204	282	337
	0	79	160	208
CDF	1	220(242)	280	330
	0.5	202	265	310

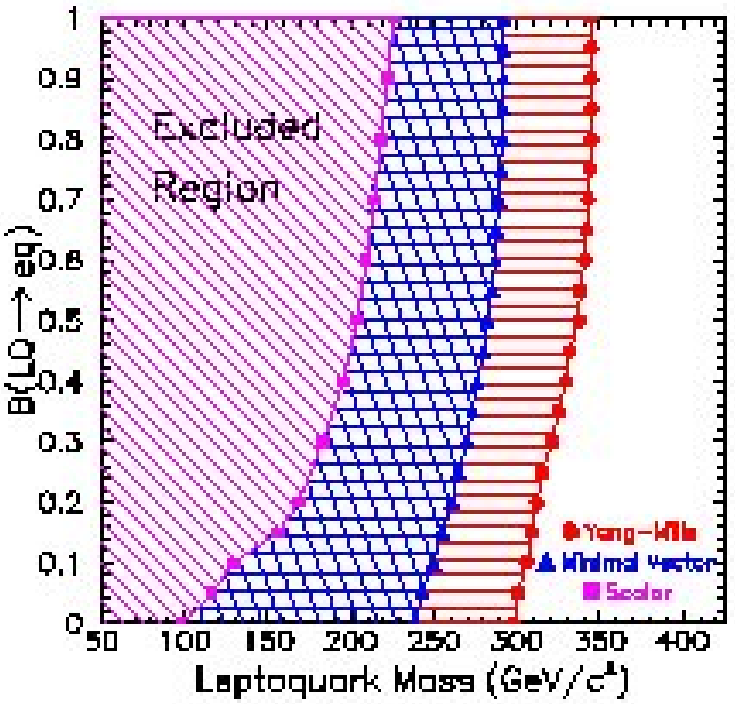
LEP2 results
- β=1, scalar LQ
  - Limit ~85 GeV/c^2
- β=1, vector LQ
  - Limit ~90 GeV/c^2
  - Coupling dependent

1st Generation Run I Limits

CDF

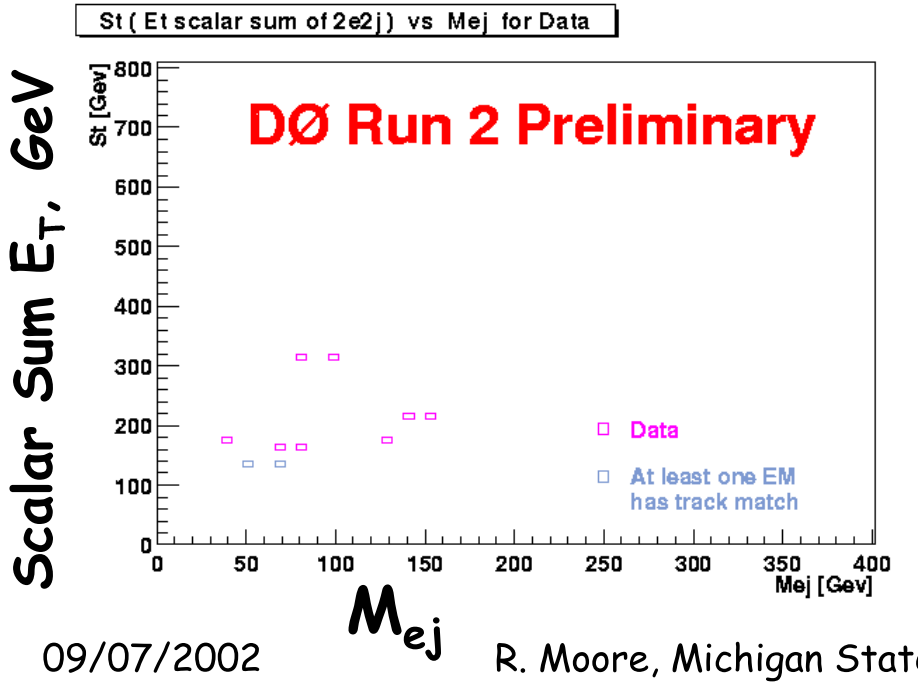


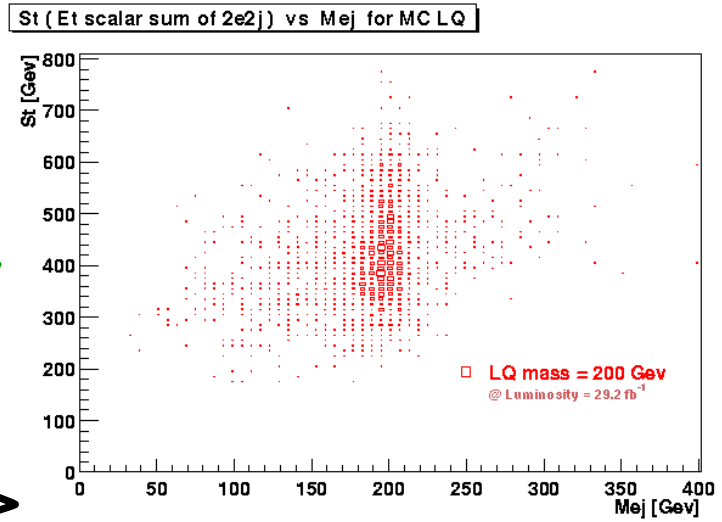
DØ

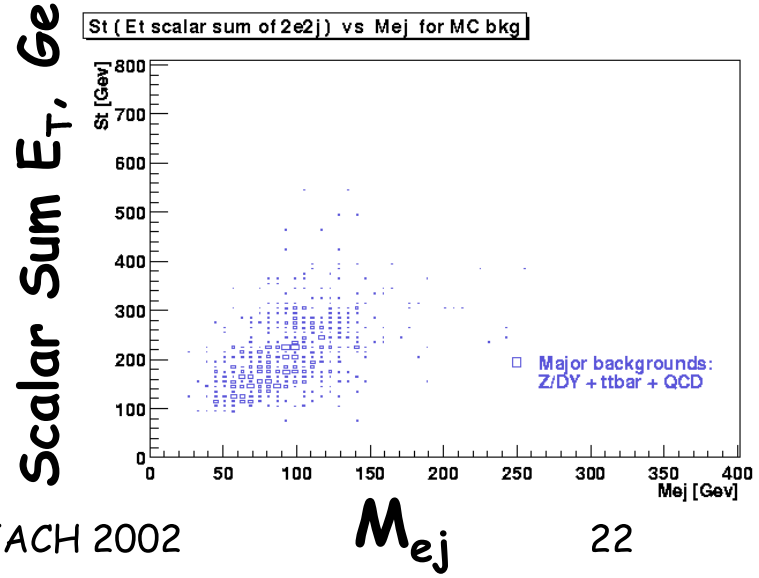


1st Generation LQ in Run II

- Luminosity and energy increases sensitivity by ~100GeV/c^2
- Initial DØ search (10pb^{-1})
  - LQLQ → eeqq
  - 2 EM E_T>25GeV + 2jets E_T>20GeV
  - 5 events, 1 with track matches

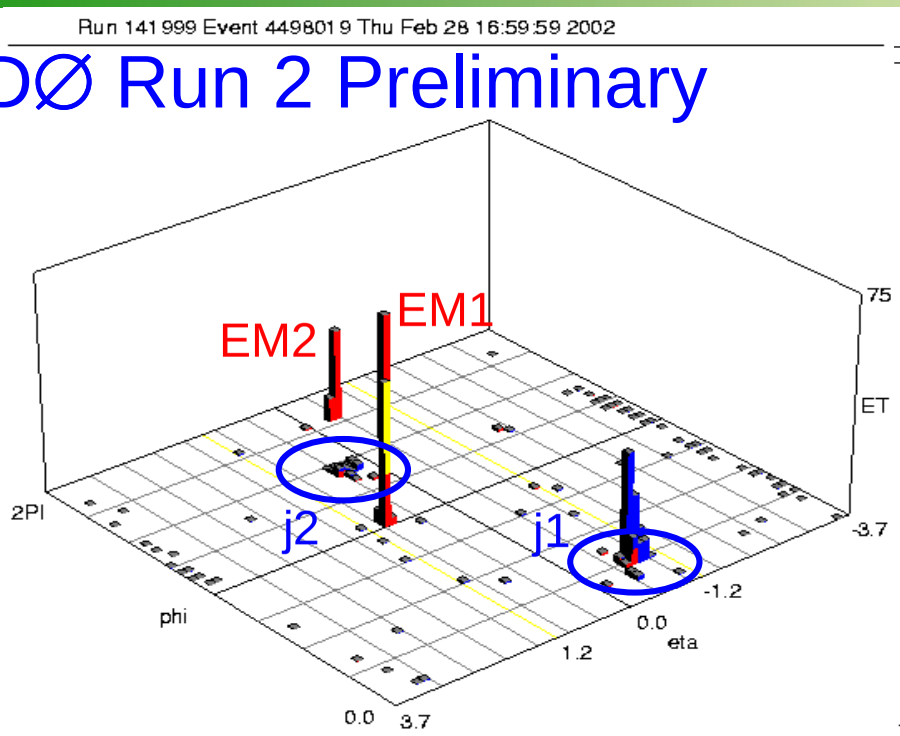


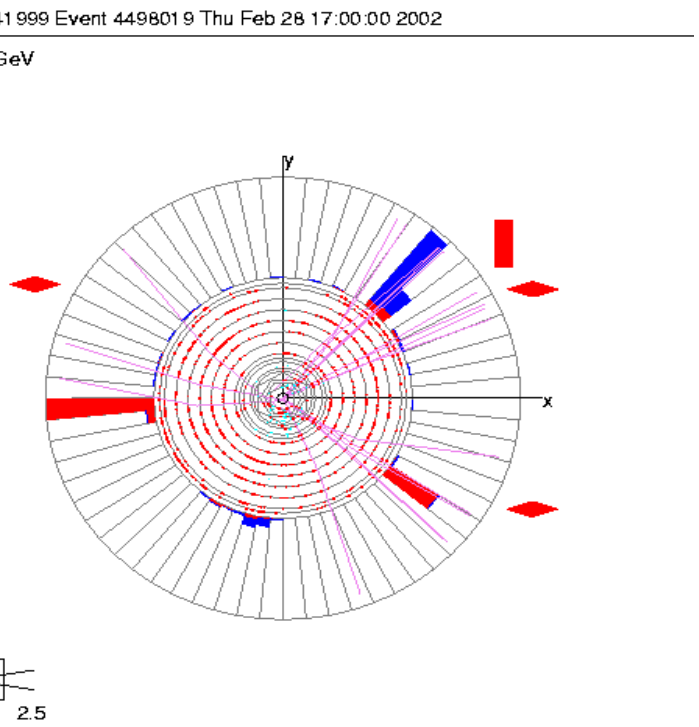




Most Energetic eejj Event

DØ Run 2 Preliminary





EM1	EM2	j1	j2
E_T = 113 GeV η = 0.60 φ = 3.23 No track match	E_T = 39.5 GeV η = -0.82 φ = 5.65 Low p_T track match	E_T = 129 GeV η = -1.03 φ = 0.78	E_T = 33.8 GeV η = 0.08 φ = 4.48
S_T = 315 GeV; M_{ee} = 162 GeV; M_{ej} = 81 GeV, 97 GeV			

Conclusions

- Large Extra Dimensions
  - Colliders can probe higher *n* values than other experimental methods
  - Tevatron Run I limits M_S>~1 TeV/c^2
  - Increase in M_S sensitivity by a factor of 2-3 in Run IIa-b (i.e. 2-3 TeV/c^2)
- Leptoquark
  - Tevatron Run I limits:
    - $M_{LQScalar}$ >~100-240 GeV/c^2 (LQ generation, β)
    - $M_{LQVector}$ >~200-350 GeV/c^2 (LQ generation, coupling, β)
  - Run 2 increases sensitivity by ~100 GeV/c^2
- Now getting our first look at Run II data…