Tevatron Searches For Extra Dimensions and Leptoquarks

Sean Mattingly

Brown University

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Extra Dimensions

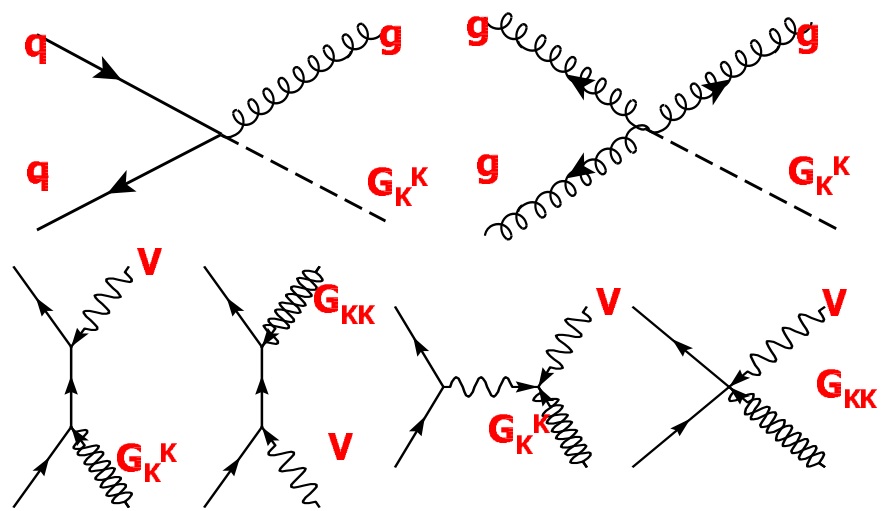
- Possibly more than 3 spatial dimensions
  - Natural in string theory with n=6,7 extra dimensions
    - Compactified at ~10^{-32}m
  - "Large" Extra Dimensions
    - Can be used to solve hierarchy problem
      - Arkani-Hamed,Dimopoulos, Dvali
      - Only gravitons propagate in these extra dimensions
    - Bring effective Planck scale (M_S) down to ~TeV
- LED sizes for M_S = 1 TeV
  - $R \approx 1/M_S(M_P/M_S)^{2/n} \approx 10^{(32/n)-19}$ m
  - ~10^{13}m, n=1; ~1 mm, n=2; ~1 nm n=3; ~10^{-12}m, n=4

Constraints on Extra Dimensions

- Solar system: n=1 ruled out
- Energy loss from supernova 1987A, red giants, sun
  - M_S > ~25 TeV, n=2; M_S > ~4 TeV, n=3
- Smoothness of cosmic diffuse radiation
  - M_S > ~100 TeV, n=2; M_S > ~5 TeV, n=3
- Eöt-Wash
  - R < 0.15mm (M_S > ~2 TeV, n=2)
- n=2 significantly constrained
- Use high energy colliders
  - Probe shorter distances for n>2

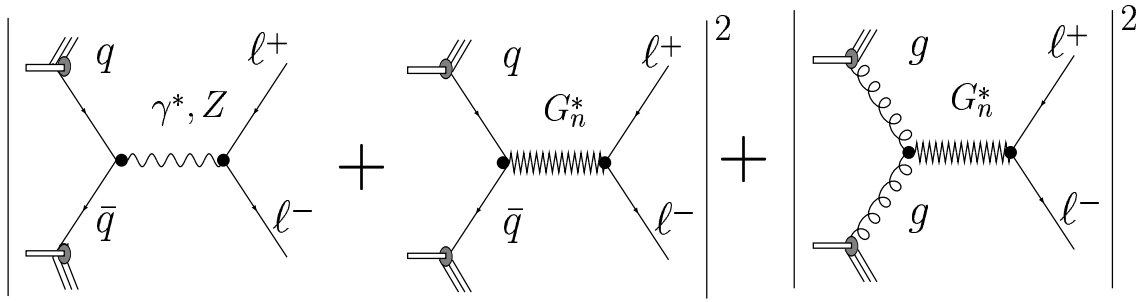
Extra Dimensions: Tevatron Signatures

- Effects of gravity enhanced by acessibility of many excited graviton states
  - Kaluza-Klein excitations
    - Gravitons winding around compactified dimensions
- Real Graviton Production
  - Monojet or single vector boson+Missing E_T
    - $1/(M_S)^{n+2}$ dependence



Extra Dimensions: Tevatron Signatures (cont)

- Virtual Graviton Exchange
  - Fermion-antifermion pairs, diboson pairs



  - Weak dependence on n
    - $\sigma = \sigma_{SM} + \sigma_{int}\eta_G + \sigma_G\eta_G^2$
    - $\eta = F/M_S^4$
    - $F = 1$ (GRW)

      $\log(M_S^2/M^2)$ for n=2, $2/(n-2)$ n>2 (HLZ)

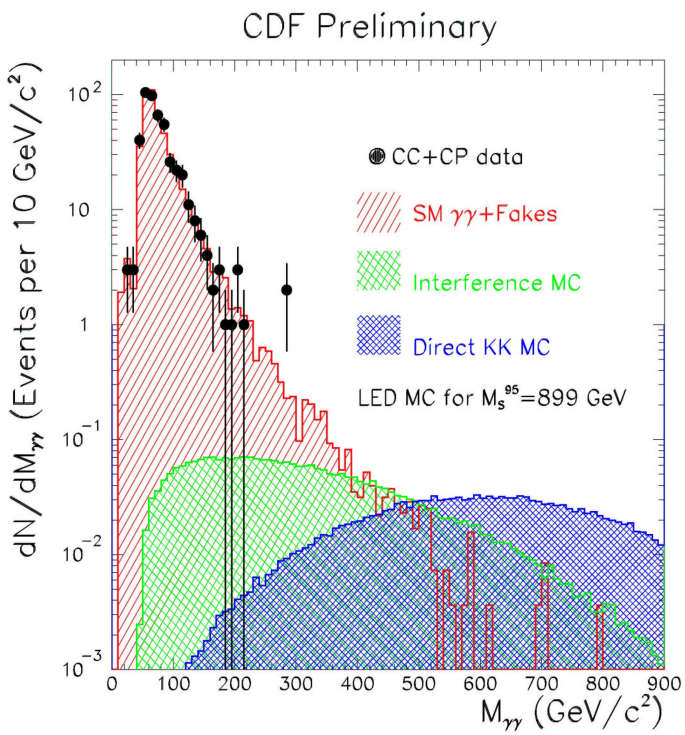
      $2\lambda/\pi$; $\lambda=\pm1$ (Hewett) ← Used in this talk

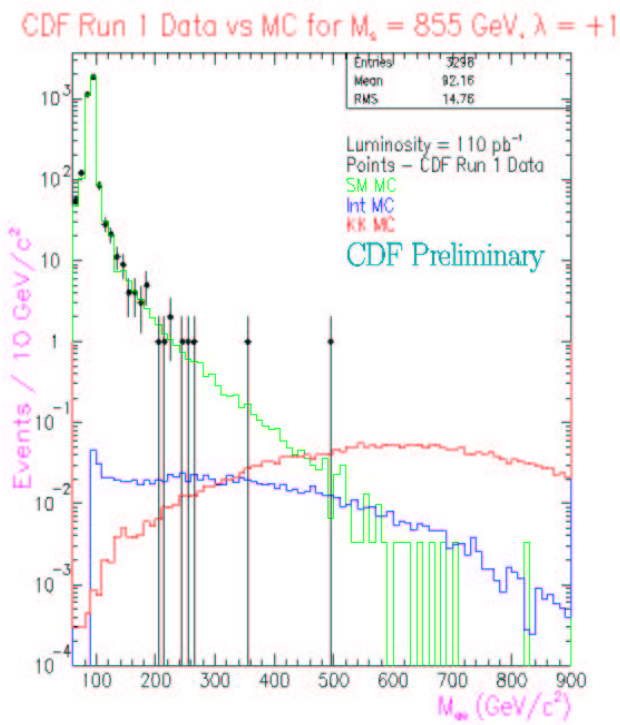
Collider Limits On Extra Dimensions

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

CDF: Run 1
Virtual Graviton 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





CDF: Run 1 Result Diphoton/Dielectron

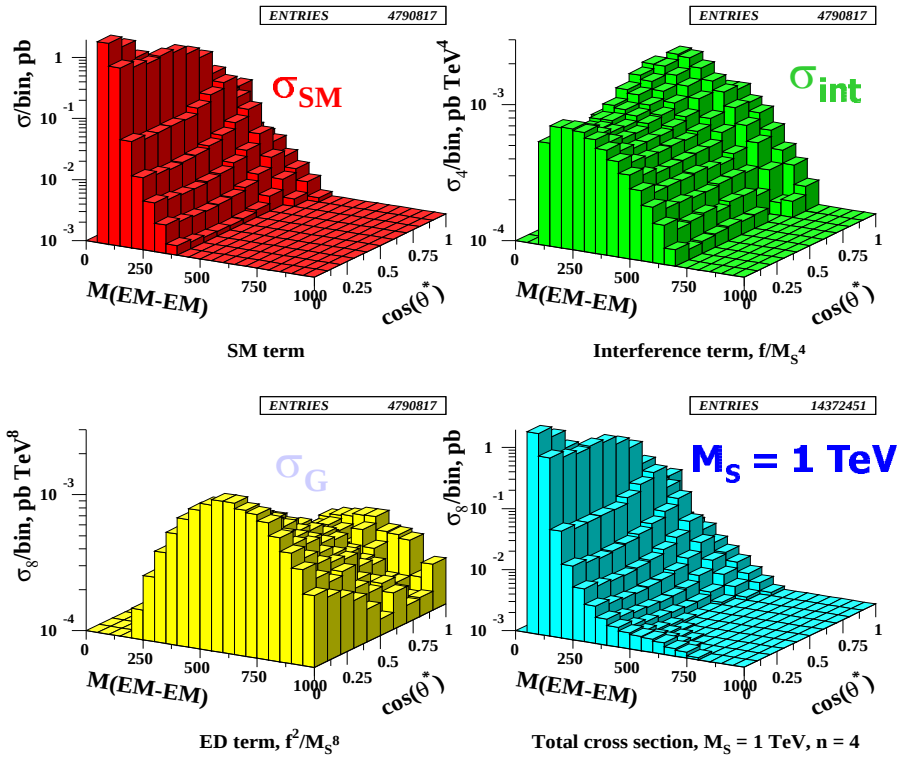
- Data in agreement with SM
- Extract M_S limit
  - Unbinned liklihood function fit to invariant mass distributions
    - Extract 95% confidence limit on η
  - Diphoton: $M_S > 0.797$ TeV (λ=-1), 0.899 TeV (λ=+1)
  - Dielectron: $M_S > 0.808$ TeV (λ=-1), 0.826 TeV (λ=+1)
  - Recently Combined:

$$M_S > 0.853 \text{ TeV } (\lambda=-1),\ 0.939 \text{ TeV } (\lambda=+1)$$

DZero: Run 1
Virtual Graviton Search

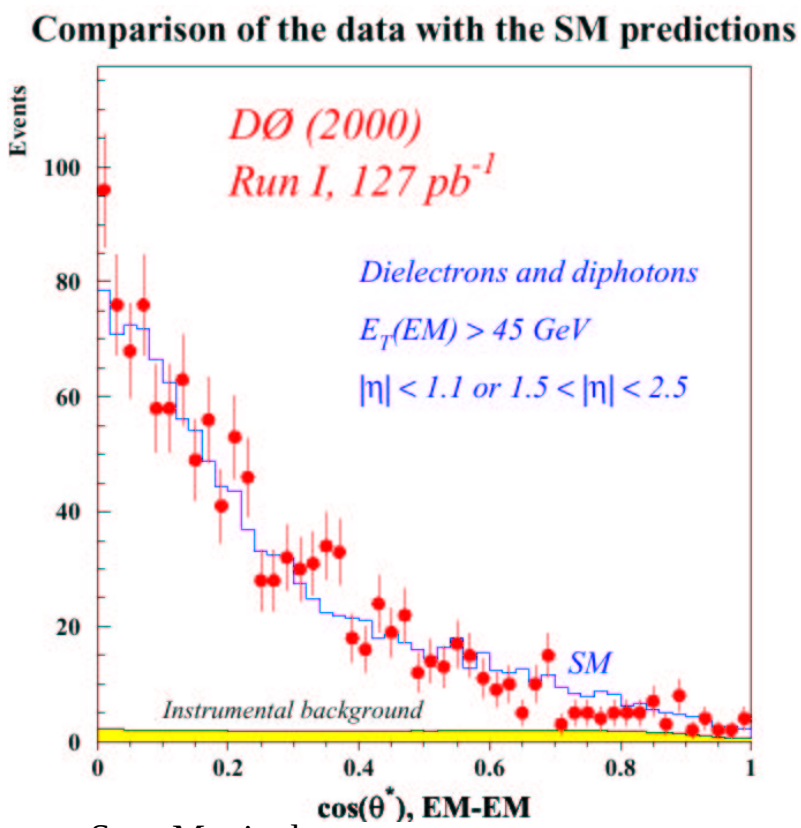
- DZero also searches in diphoton and dielectron channels (combined)
  - Fit to 2D distribution of invariant mass vs. $|\cos\theta^*|$
    - Largest contribution at high mass and low $|\cos\theta^*|$
    - 40 x 10 bins ($M \in [0,2\ \text{TeV}]$, $|\cos\theta^*| \in [0,1]$)

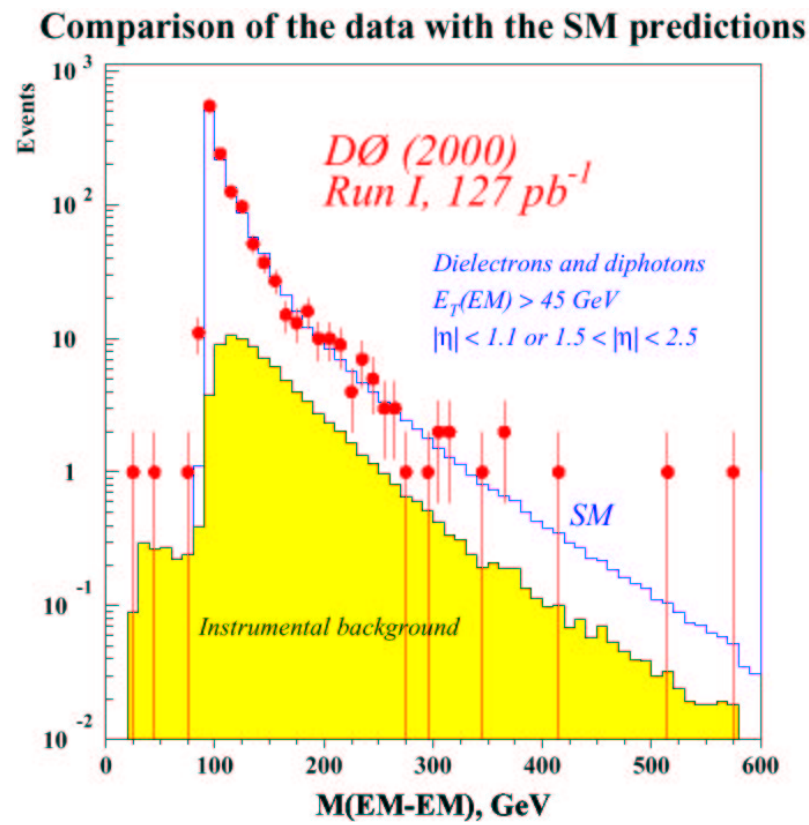
MC Simulation of the ED signatures



DZero: Run 1 Data
Di-EM

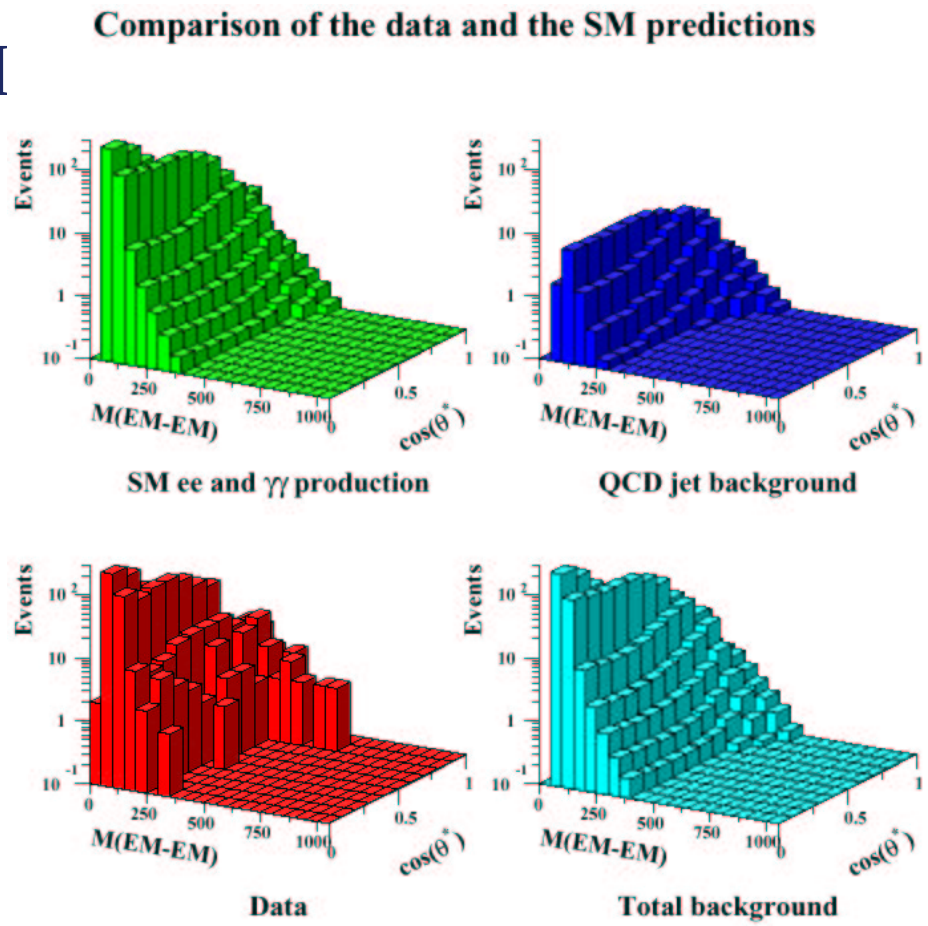
- 2 EM objects required (1250 events ,127 pb^{-1})
  - E_T > 45 GeV, |η|<1.1 or 1.5<|η|<2.5





DZero: Run 1 Result
Di-EM

- 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 (λ=+1)
  - $M_S > 1.0$ TeV (λ=-1)



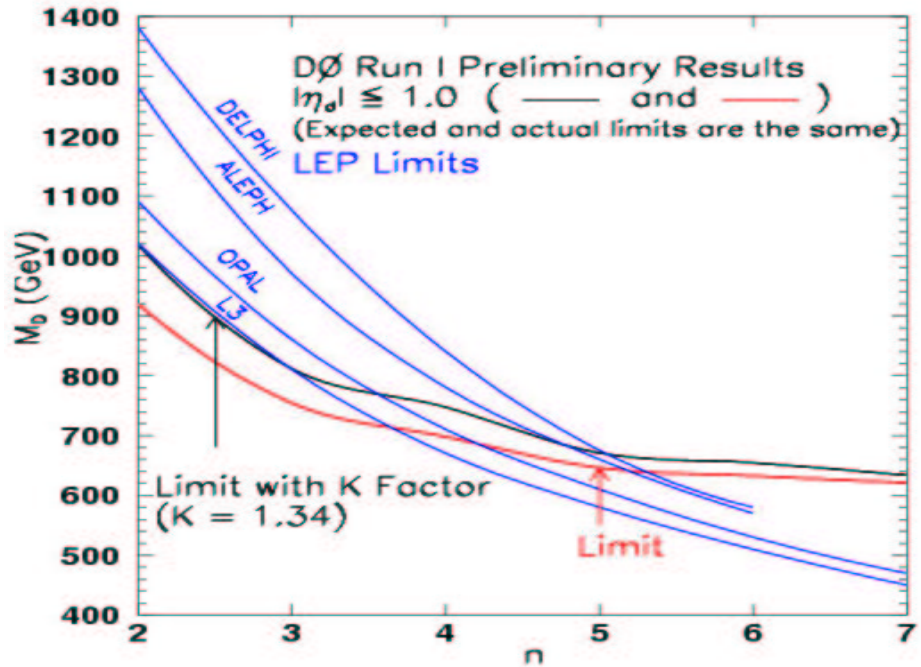
DZero: Run 1 Graviton Production Search

- $qq \rightarrow g + G_{KK}$
  - Graviton escapes detector
  - Observe jet + missing E_T
    - First such search at a hadron collider
  - Missing $E_T > 150$ GeV
  - Leading Jet (cone 0.5): $E_T > 150$ GeV, $|\eta| < 1.0$
  - Second Jet: $E_T < 50$ GeV, not pointing at missing E_T
    - Suppress QCD background and mismeasured jets
  - Search in ~79 pb^{-1} of Run 1 data

DZero: Run 1 Result
Missing E_T + jet

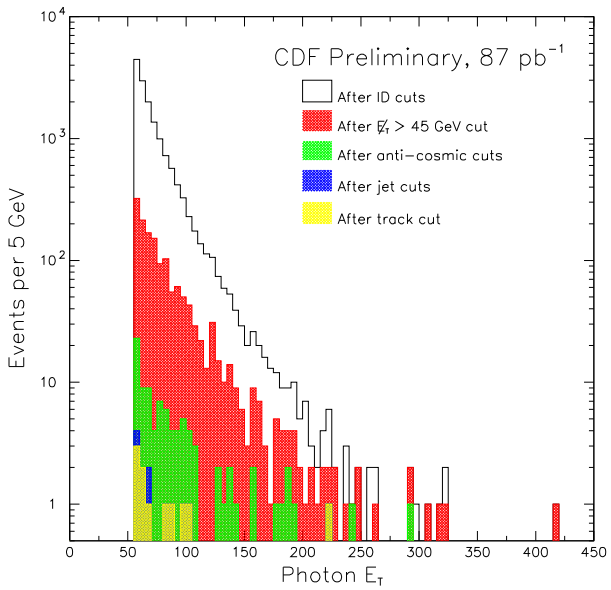
- Estimated backgrounds
  - From Ws and Zs = 30
  - From QCD = 8
- 38 events pass cuts
- Limit as function of n

M_S Limits (GeV) vs. n



CDF: Run 1 Result
Missing $E_T + \gamma$

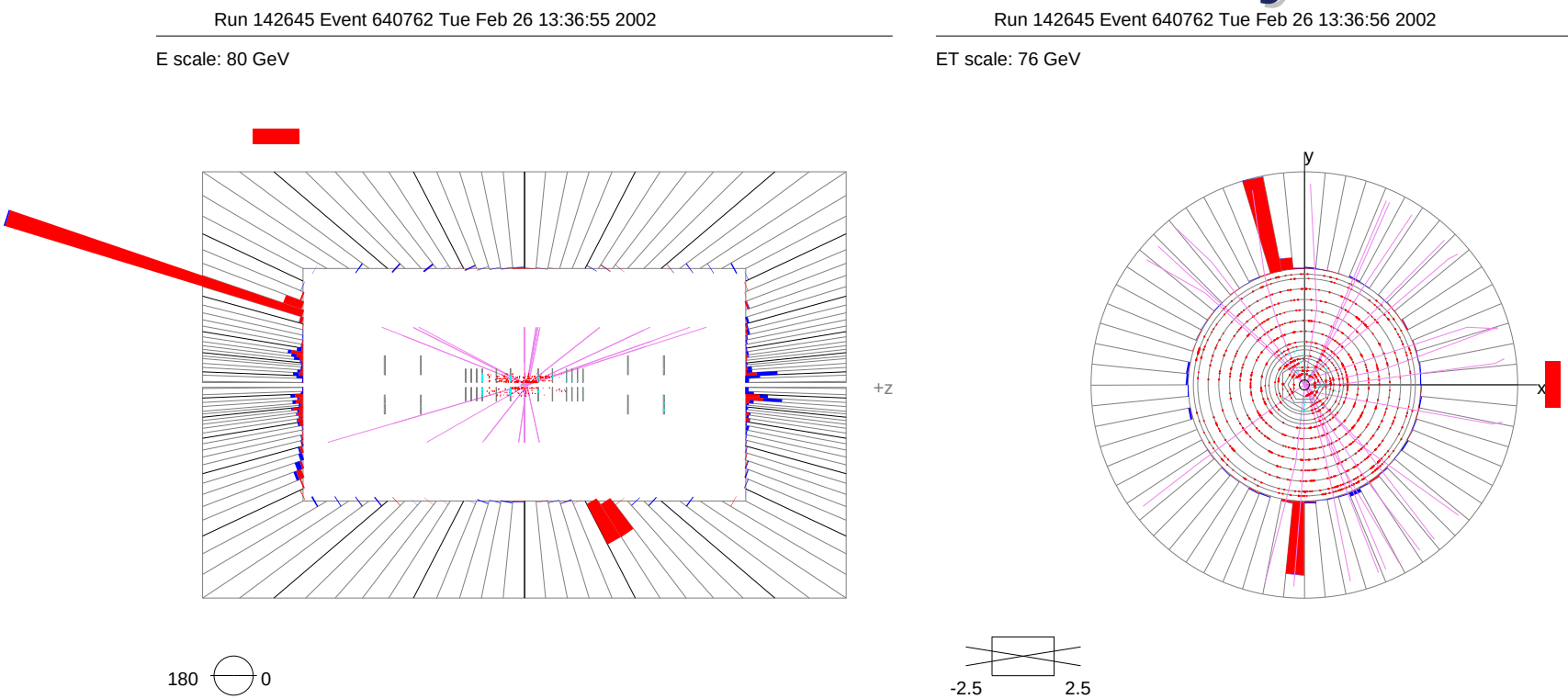
- $qq \rightarrow G_{KK}\gamma$
  - $E_T^{\gamma} > 55$ GeV, $|\eta^{\gamma}| < 1$, missing $E_T > 45$ GeV
  - No jets w/ $E_T > 15$ GeV, no tracks w/ $p_T > 5$ GeV
- 11 events (87 pb^{-1})
  - Background estimate = 11 ± 2
- M_S limits
  - $M_S > 550$ GeV, n=4
  - $M_S > 580$ GeV, n=6
  - $M_S > 600$ GeV, n=8



Tevatron: Run 2 and Extra Dimensions

- Current sensitivities limited by statistics
- Run 2: significant increase in luminosity and small increase in CM energy from 1.8 TeV to 2 TeV
  - Run 1, 0.13 fb^{-1}
  - Run 2a, 2 fb^{-1} → M_S sensitivity ~doubles vs. Run 1
  - Run 2b, 20 fb^{-1} → M_S sensitivity ~triples vs. Run 1
- Run 2 so far…
  - ~10 pb^{-1} analyzed

DZero: Run 2 Preliminary Di-EM



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; $\cos\theta^*$ = 0.90; ME_T = 25.9 GeV;	

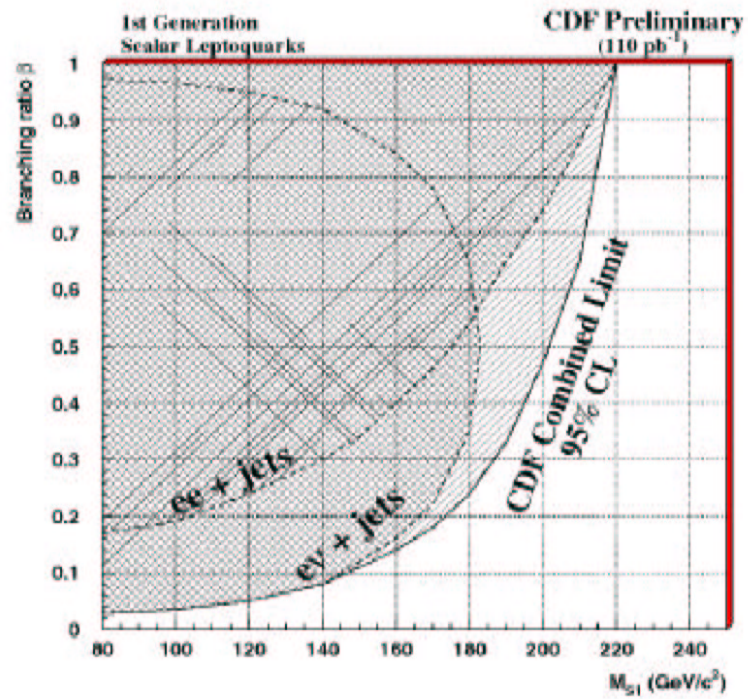
Leptoquarks

- Leptoquarks suggested by apparent symmetry between lepton and quark sectors
  - Couple directly to both leptons and quarks
  - Carry color and fractional electric charge
  - Vector or scalar bosons
  - GUTs, technicolor, R-parity violating supersymmetry, compositeness models
  - Strict FCNC limits imply LQ couple only within a single generation
    - LQ → $l^{\pm}q$, νq

Tevatron Leptoquark Limits

- Existing Tevatron LQ Searches
  - Limits depend on type of LQ (scalar/vector, generation), LQ-q-l couplings and β=BR(LQ → $l^{\pm}q$)
- 1st generation LQ

1st Gen.	β	Scalar (GeV/c)	Vector Minimal Coupling (GeV/c)	Vector Yang-Mills Coupling (GeV/c)
DZero	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



Tevatron Leptoquark Limits

- 2nd Generation

2nd Gen	β	Scalar (GeV/c)	Vector Minimal Coupling (GeV/c)	Vector Yang-Mills Coupling (GeV/c)
DZero	1	200	275	325
	0.5	180	260	310
	0	79	160	208
CDF	1	202		
	0	123	171	222

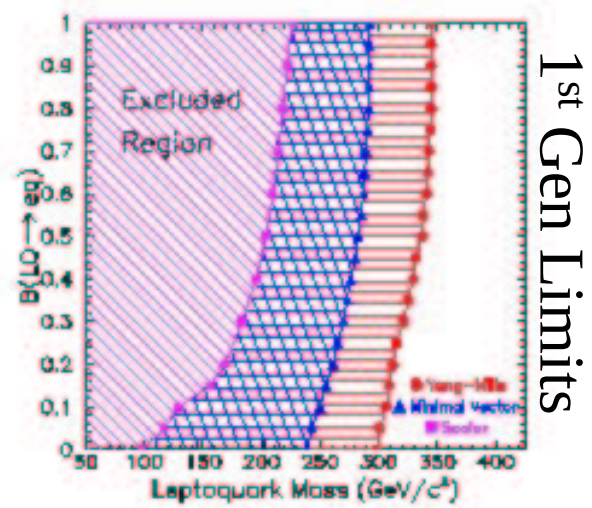
- 3rd Generation

3rd Gen	β	Scalar (GeV/c)	Vector Minimal Coupling (GeV/c)	Vector Yang-Mills Coupling (GeV/c)
DZero	0.5			209
	0	94	148	216
CDF	1	99	170	225
	0	148	199	250

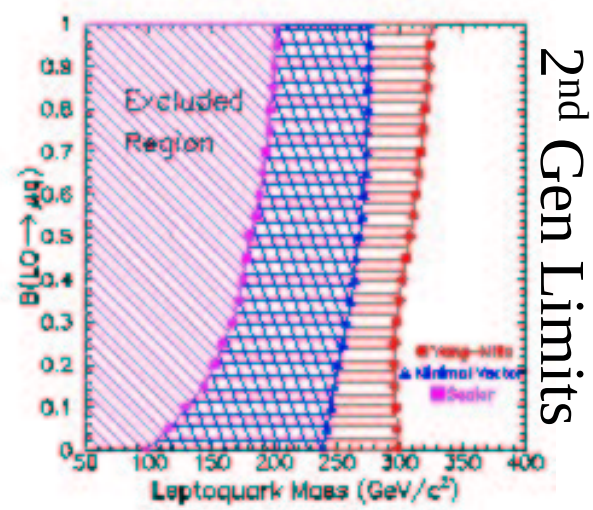
Recent DZero LQ Result

- Similar to previous DZero analysis but with 10x data (~85 pb^{-1})
  - pp → g → LQ LQ → ννqq
    - Two jets + missing E_T
  - 2 jets (cone 0.5) $E_T > 50$ GeV,
    Missing $E_T > 40$ GeV,
    $\Delta R(\text{jets}) = \text{sqrt}(\Delta\eta^2 + \Delta\phi^2) > 1.5$
  - 231 events pass cuts
    - Background estimation = 242 ± 18.9

1st, 2nd, 3rd Gen LQ Limits	β	Scalar (GeV/c)	Vector Minimal Coupling (GeV/c)	Vector Yang-Mills Couplin (GeV/c)
DZero	0	98	238	298



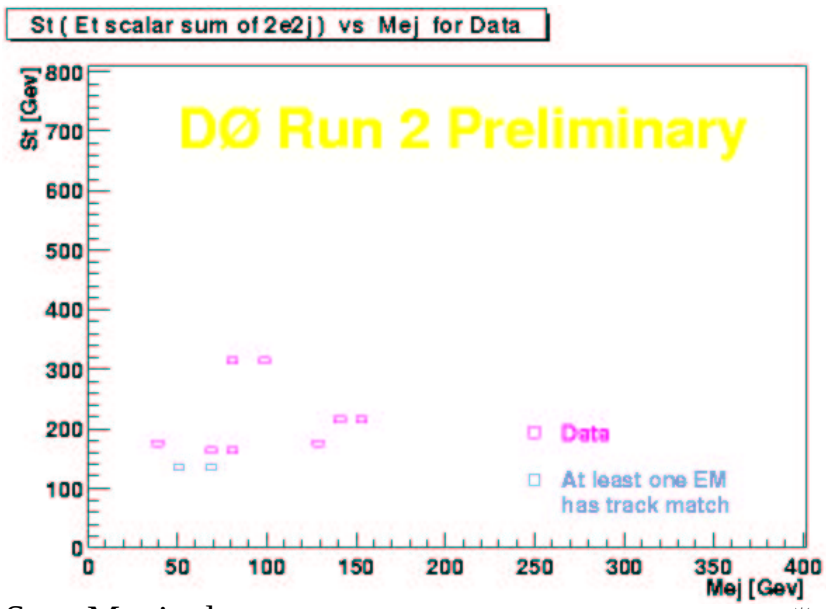
1st Gen Limits

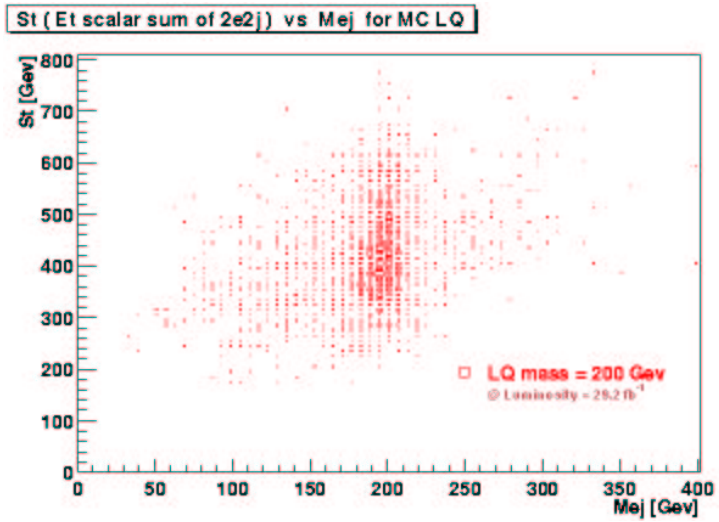


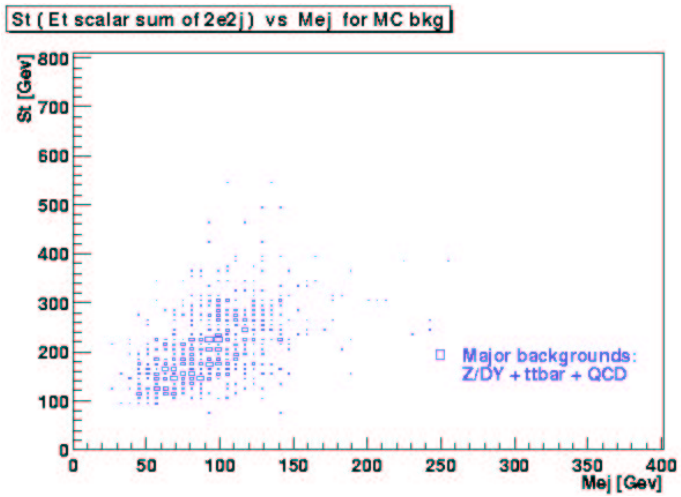
2nd Gen Limits

Leptoquarks and Run 2

- Increase in luminosity and energy should increase sensitivity by ~100 GeV
- Initial DZero search (~10 pb^{-1})
  - LQ LQ → eeqq
  - 2 EMs E_T > 25 GeV + 2 jets E_T > 20GeV
  - 5 events, 1 with track matches

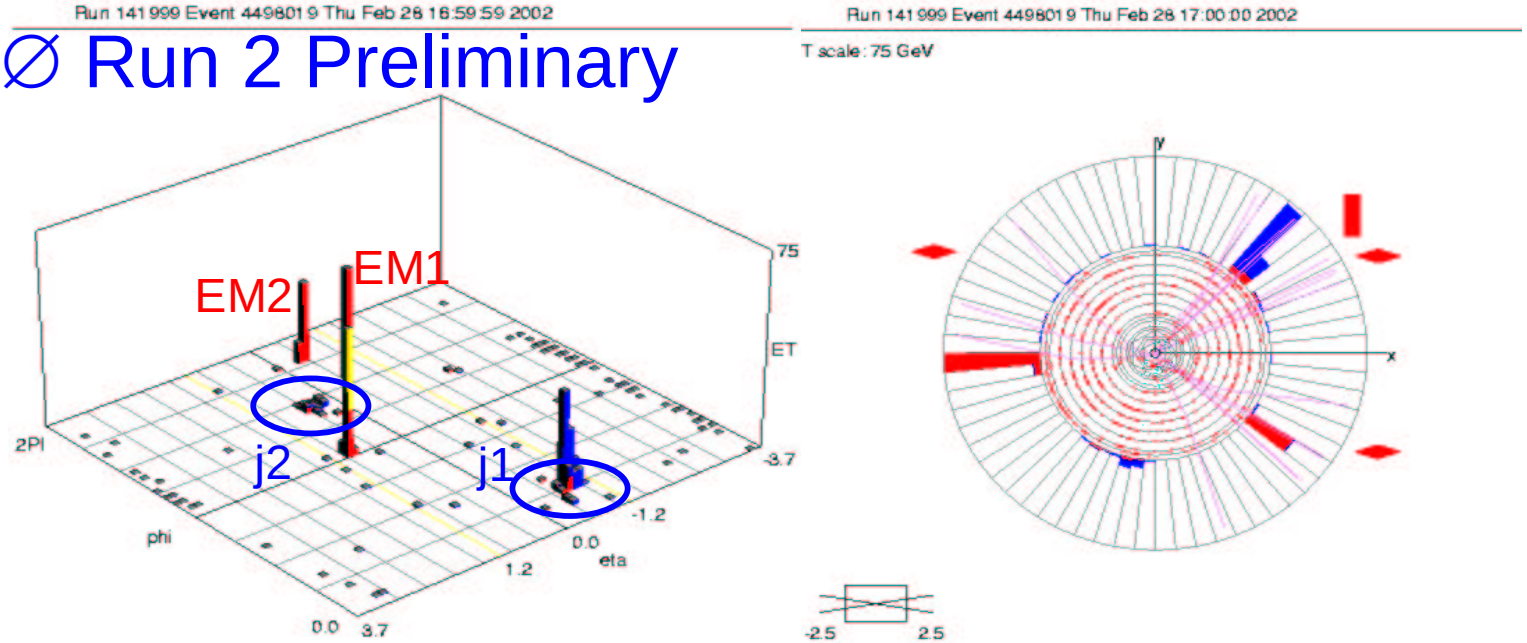






Most Energetic eeqq Candidate Event

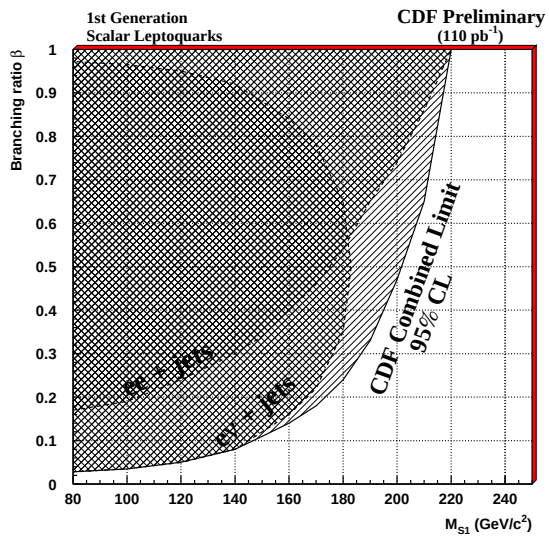
DØ Run 2 Preliminary



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

- Extra Dimensions
  - Tevatron Run 1 limits on large extra dimensions
    - M_S > ~1 TeV
  - Run 2a(2b) doubles(triples) sensitivity
- Leptoquarks
  - Tevatron Run 1 limits on LQ mass
    - $M_{LQScalar}$ > ~100-240 GeV (depending on LQ generation, β)
    - $M_{LQVector}$ > ~200-350 GeV (depending on gen., coupling, β)
  - Run 2 increases sensitivity by ~100 GeV
- First tastes of Run 2 data


1st Generation
Scalar Leptoquarks
CDF Preliminary
(110 pb^{-1})
Branching ratio β
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
80
100
120
140
160
180
200
220
240
M_{S1} (GeV/c^2)
CDF Combined Limit
95% CL
ee + jets
eν + jets