Searches for Extra Dimensions at the Tevatron

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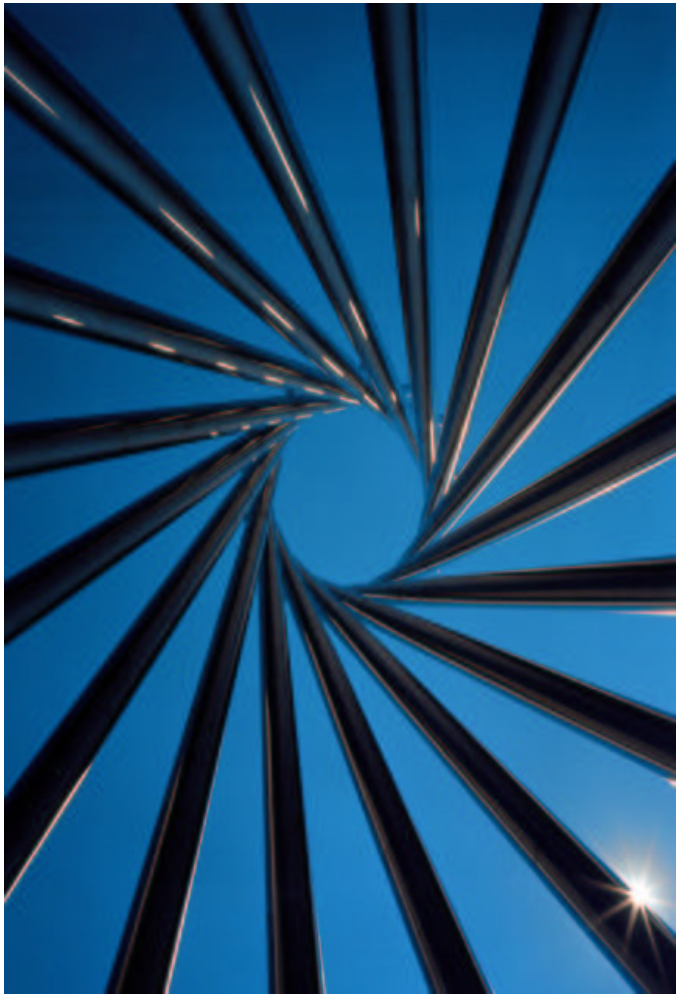

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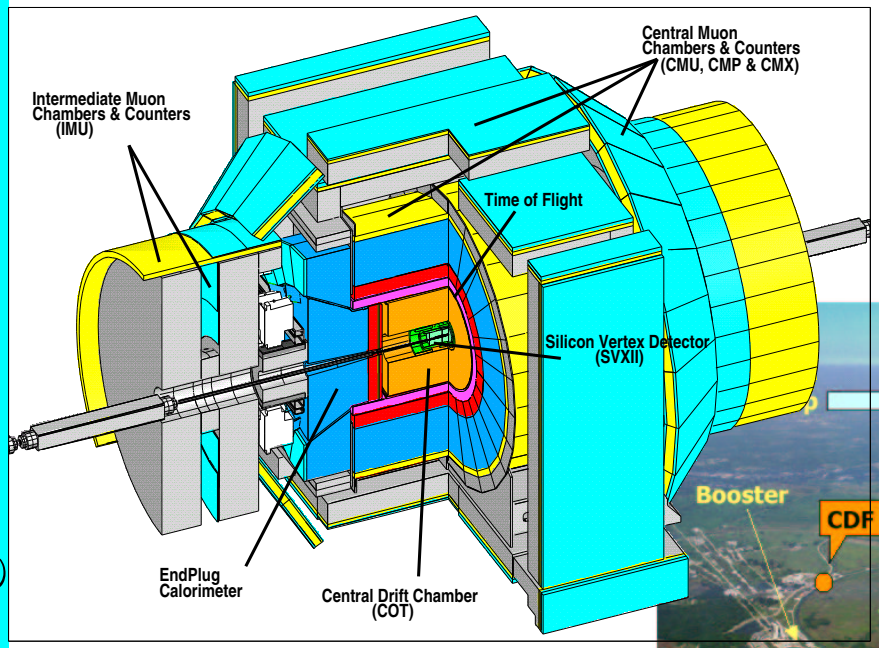
Outline:

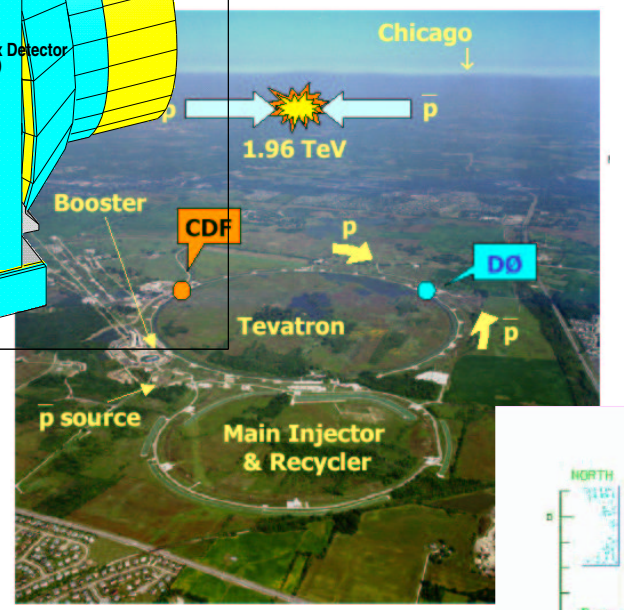
- Extra Dimension Models Explored at DØ and CDF

  (*for theory introduction: G. Burdman's talk*)
- Signatures and Event Selections
  - Virtual Kaluza-Klein (KK) Exchange
  - Direct Graviton Emission
- Preliminary Results
- Summary and Conclusions

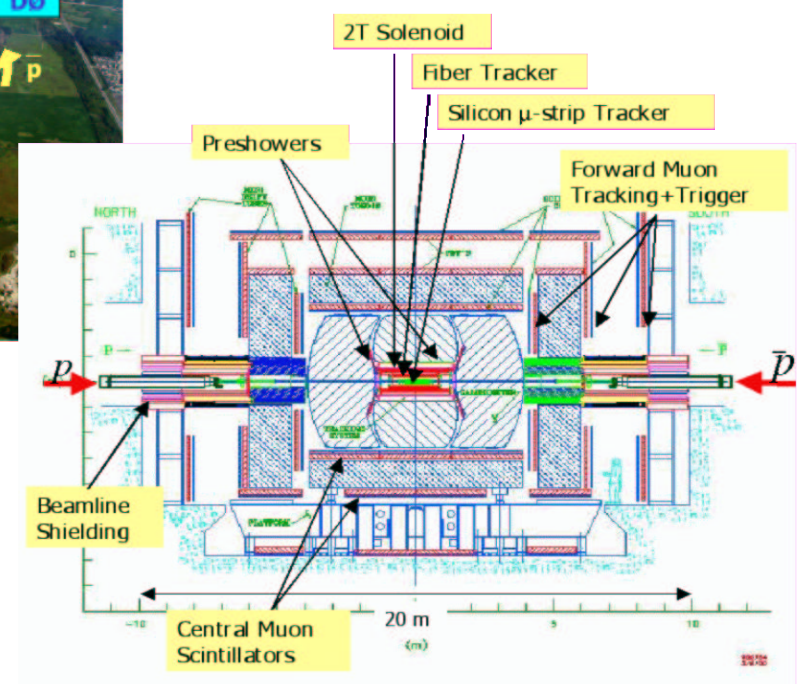
The results presented here are with $\leq 200\ pb^{-1}$ data from spring 2002- Fall 2003 of Run II Tevatron (winter '04).
All limits 95% CL and all Run II results are preliminary.

DØ and CDF at the Tevatron Run II:





- ✔ Both the Tevatron and the detectors upgraded.
- ✔ Run II has been going on successfully.



Tevatron Searches for ED:

- Models with ***n*** extra spatial dimensions
- **Focus on:**

Large ED (ADD): Arkani-Hamed, Dimopoulos, Dvali Phys Lett B429 (98)

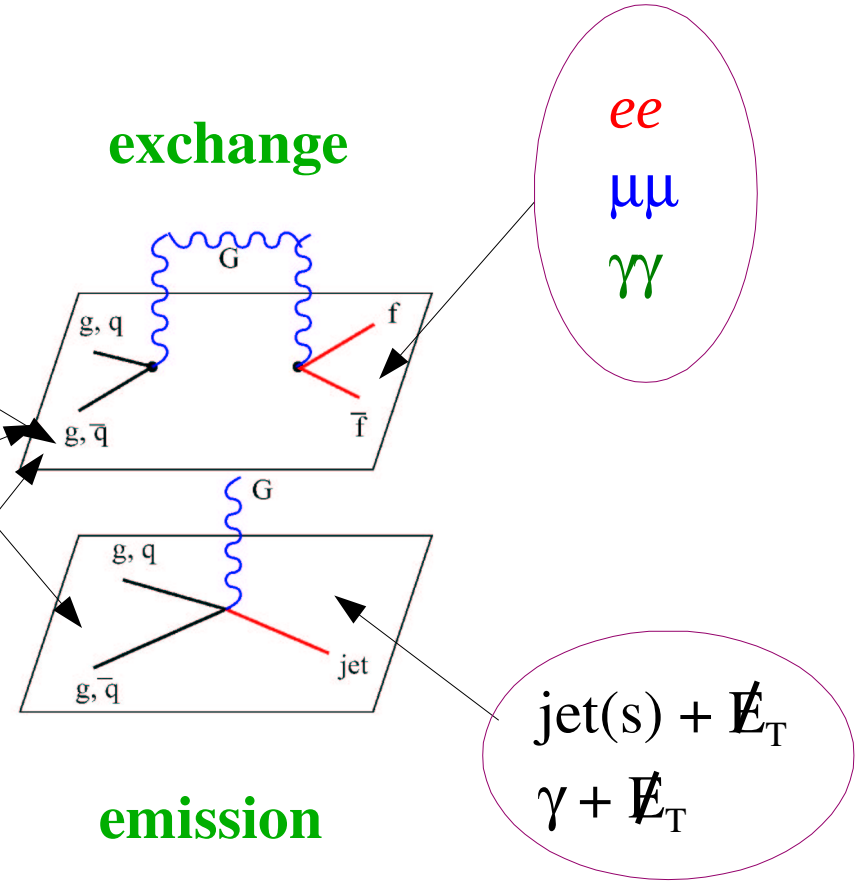
- $n > 0$ ($n > 2$), compactified
- $M^2_{Pl} \sim R^n M_S^{n+2}$, M_S: string scale

TeV^{-1} ED (DDG): Dienes, Dudas, Gherghetta Nucl Phys B537 (99)

- $n \geq 1$ ($n = 1$)
- M_C : compactification scale

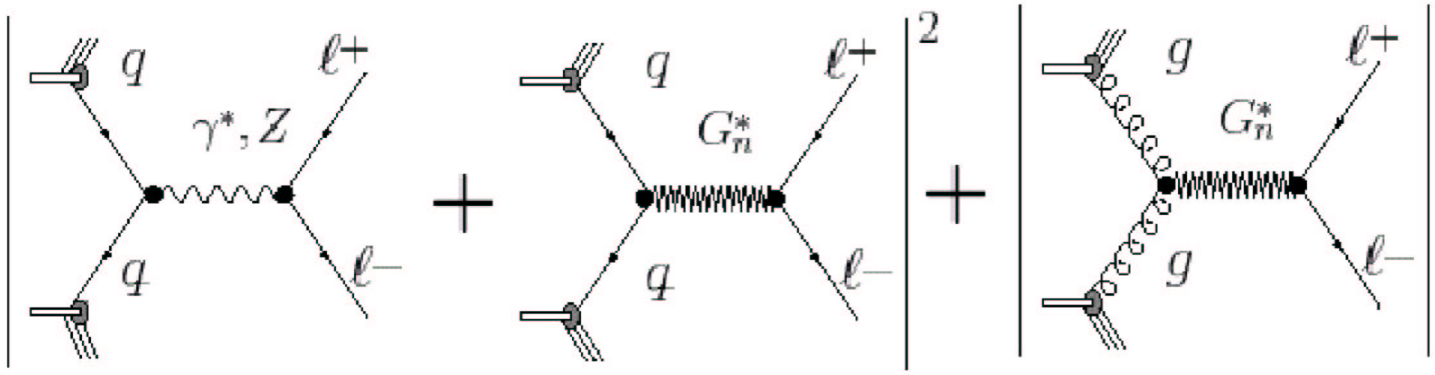
Warped ED (RS): Randall, Sundrum Phys Rev Lett 83 (99)

- $n = 1$, highly curved
- k/M_{Pl}, k : curvature scale



Virtual Exchange Searches:

- Pair production in virtual KK exchange with SM interference



- Effective cross section has three terms with one parameter:

$$\sigma = \sigma_{SM} + \eta_G \sigma_{int} + \eta_G^2 \sigma_{KK} \qquad \eta_G = \mathbf{F} / M_s^4$$

- Search strategy is likelihood fits as a function of η_G:

  DØ: 2D fit in M_{inv} and $\cos\theta^*$ (scattering angle in c.o.m frame)

  CDF: 1D fit in M_{inv}

- Translate into 95%CL lower limits on M_S for various formalisms:

λ conventions : $\frac{2}{\pi}\lambda_{Hewett} = F_{GRW} = F_{HLZ}$, $F_{GRW} = 1$, $F_{HLZ} = \frac{2}{n-2}(n > 2)$

Giudice, Rattazzi, Wells | Han, Lykken, Zhang

DØ diEM and dielectrons:

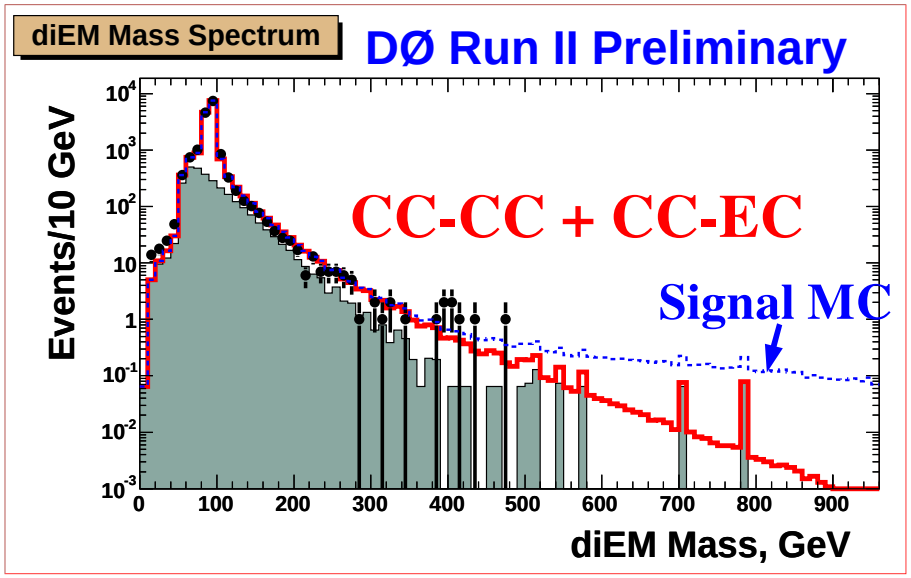
- **diEM:** Combine *ee* and γγ with no track requirement on the electron
  - Require 2 EM objects, $\mathbf{E_T > 25}$ **GeV** with track isolation

Central Cal.	Endcap Cal.
CC: $\lvert\eta\rvert < 1.1$	**EC**: $1.5 < \lvert\eta\rvert < 2.4$

⇓

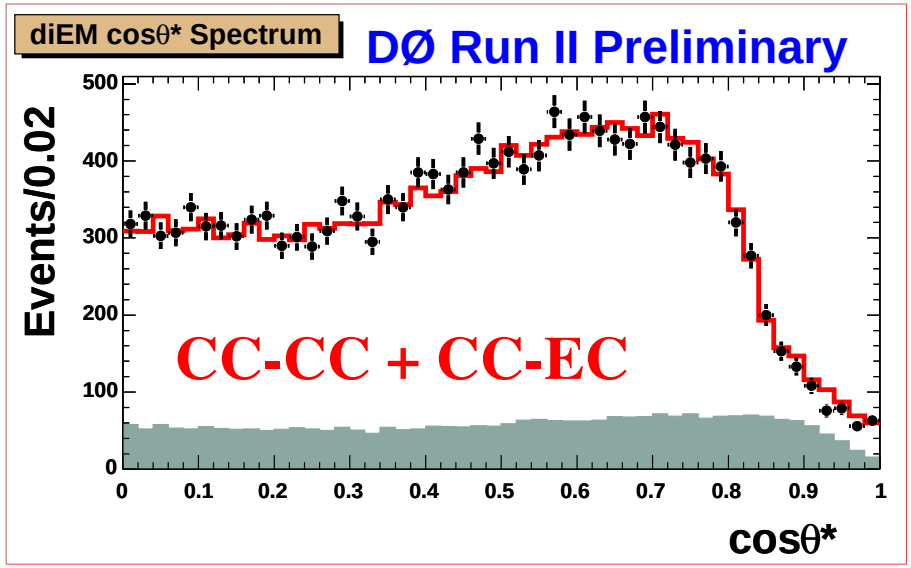
CC-CC and **CC-EC** used in results

  - Event kinematics based on vertex ID
  - Overall ID efficiency: 85 ± 1%

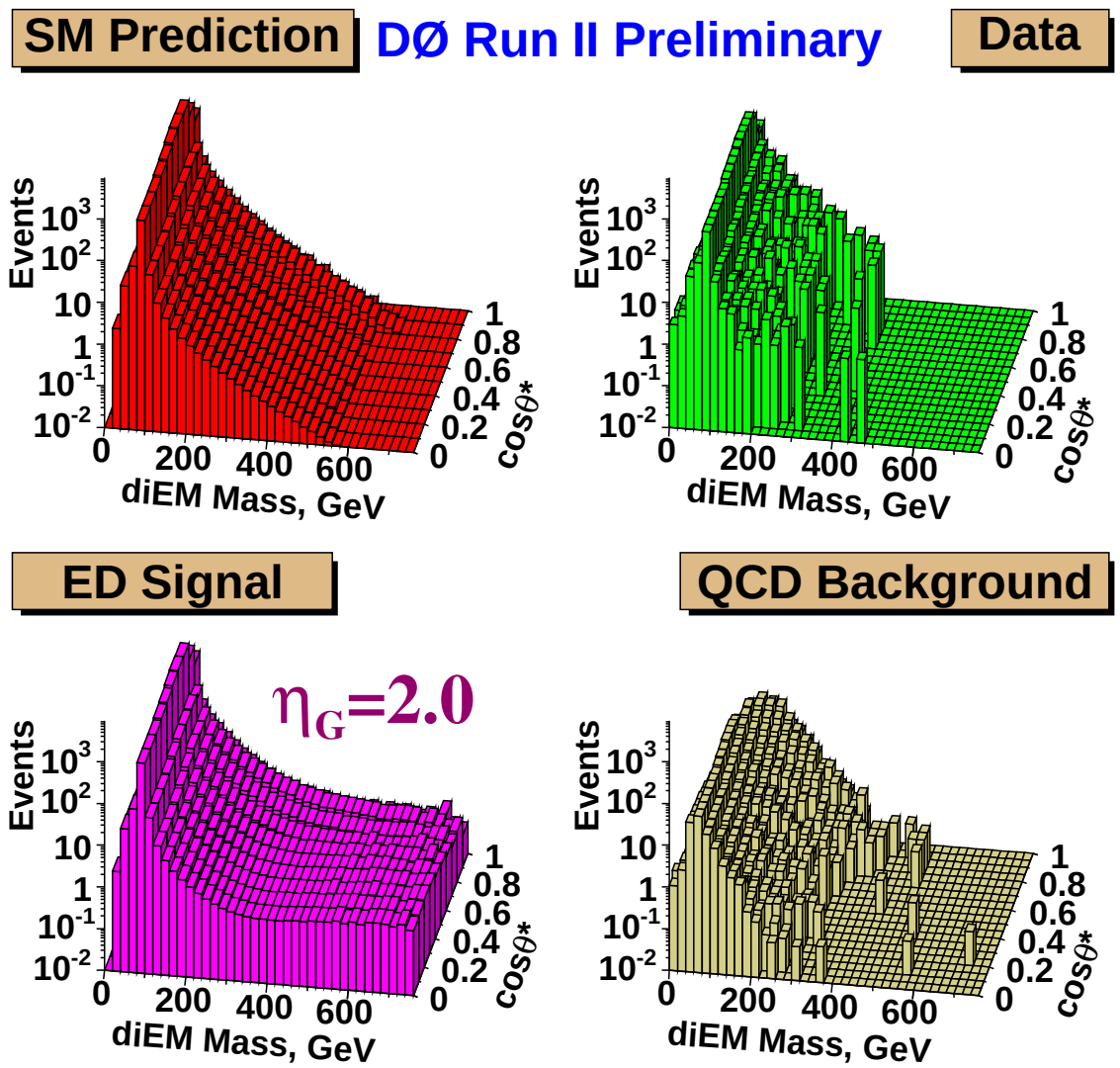


- **diele:** at least one *e* with track match, no track isolation on either

CC-CC and **CC-EC** used in results



DØ diEM:



Background contributions:

- Drell-Yan and direct $\gamma\gamma$
- Dijet and direct photon where jet(s) misindentified (fakes).
- Systematic uncertainty: 7-20%, dominated by stat+syst of instrumental background.

N_{exp}= 9.7 (1.6 QCD), N_{obs}=8 for M_{diEM}> 350GeV

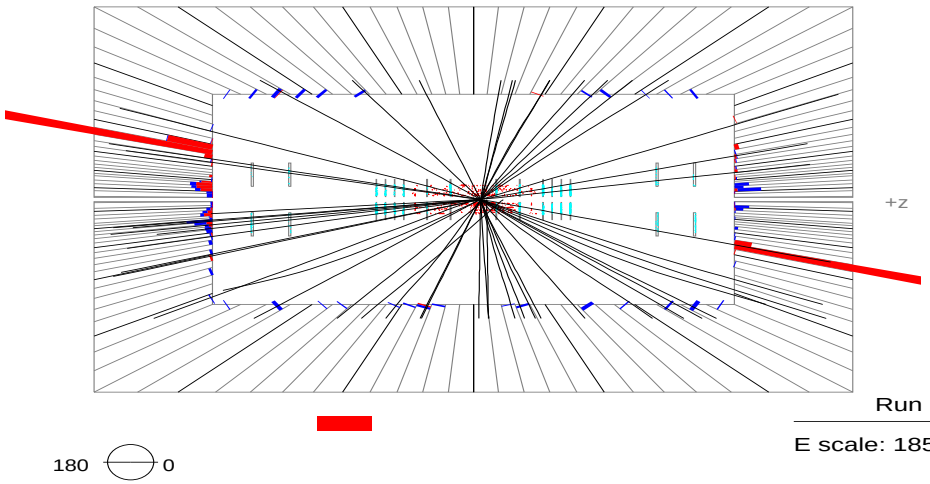
Signal systematic uncertainties:

- K-factor (K_f=1.3)
- choice of PDF
- Luminosity $\times\ \varepsilon$
- E_T dependence of efficiency
- Total=12%

Interesting DØ Events:

Run 162099 Evt 15851827 Mon Aug 19 00:30:59 2002

E scale: 76 GeV

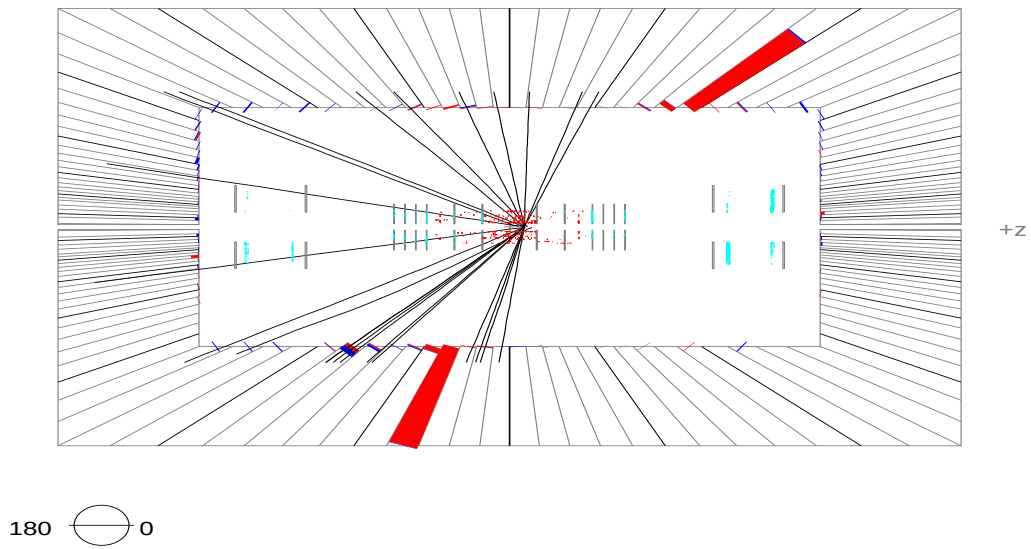


Highest e+γ (EC-EC)
M = 515 GeV

Highest diphoton
M = 436 GeV

Run 175826 Event 15382214 Wed Jan 28 19:15:22 2004

E scale: 185 GeV

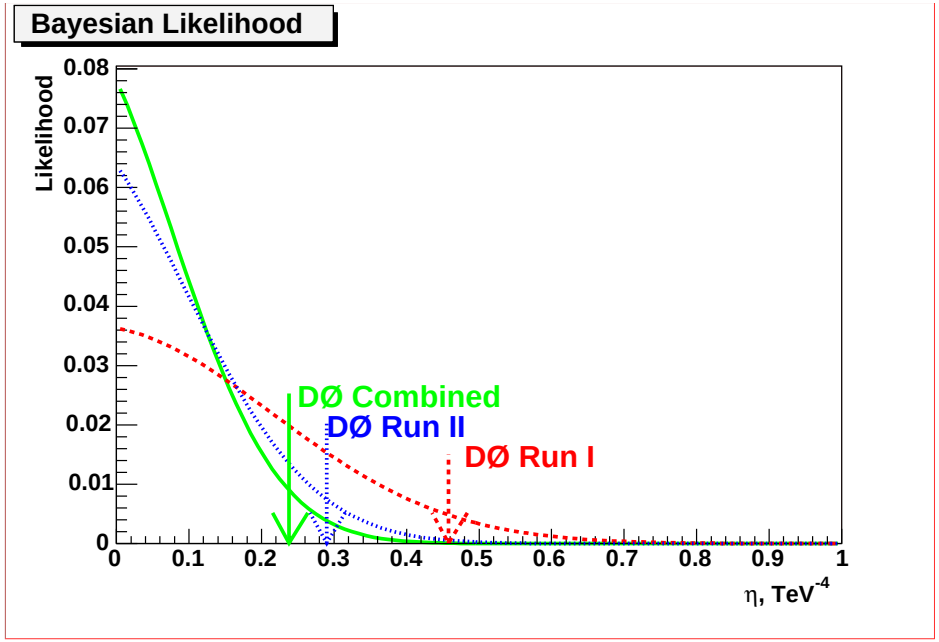


DØ diEM and dielectron LED Limit Results:

- Data agrees well with expecatations ➡ Proceed to set limits
- 2D binned information used: M_{diEM} and $\cos\theta^*$
- Limits on η_G -> 95% CL limits on M_S

Lower Limit on M_s in diEM mode (TeV):

GRW	Hewett		HLZ				
	l=-1	l=+1	n=3	n=4	n=5	n=6	n=7
1.36	1.10	1.22	1.61	1.36	1.23	1.14	1.08



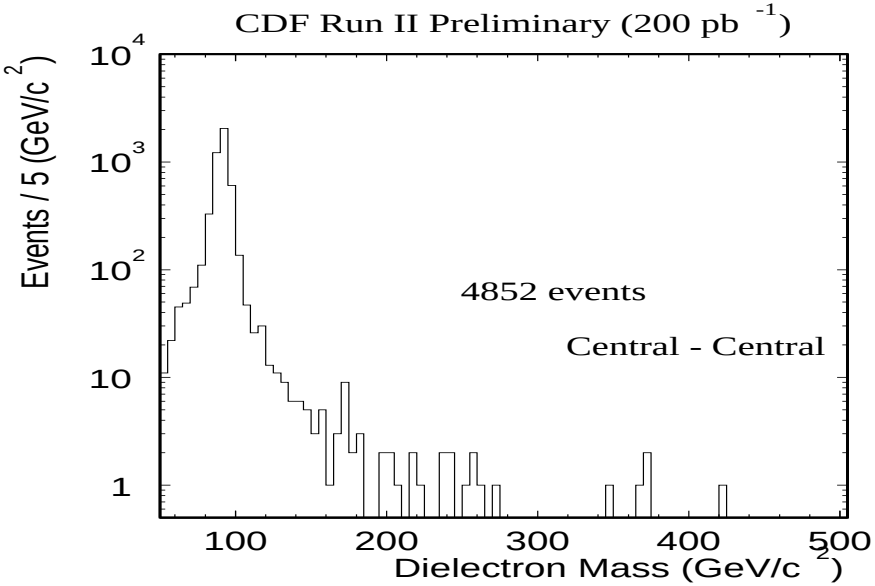
Combined with Run I:

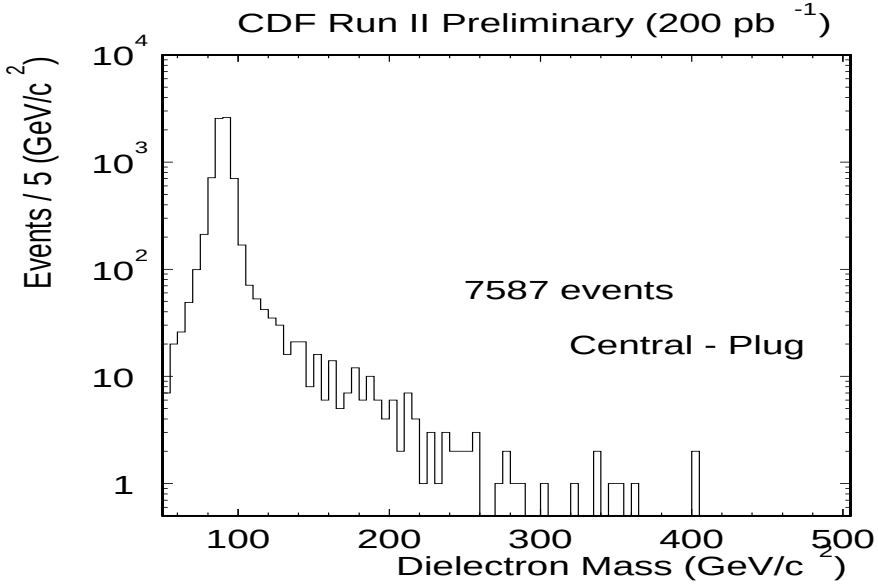
GRW	Hewett (l=+1)	HLZ (n=7)
1.43	1.28	1.14

Lower Limit on M_s in ***ee*** mode:

- M_S > **1.11** TeV

CDF dielectrons:





- Require two isolated ***e***, $\mathbf{E_T > 25}$ **GeV**

Central: $|\eta| < 1$	**P**lug: $1 < |\eta| < 3.0$

$\Downarrow$

CC and **CP** used in results

- at least one ***e*** with track required for electron pair

- Constrain ***e*** in luminous region around CDF center
- Apply energy dependent cuts for high mass efficiency
- $\not\!\!E_T$ significance cut
- Overall ID efficiency:
  CC: 92.4±0.4% **CP:** 79.2±0.5%

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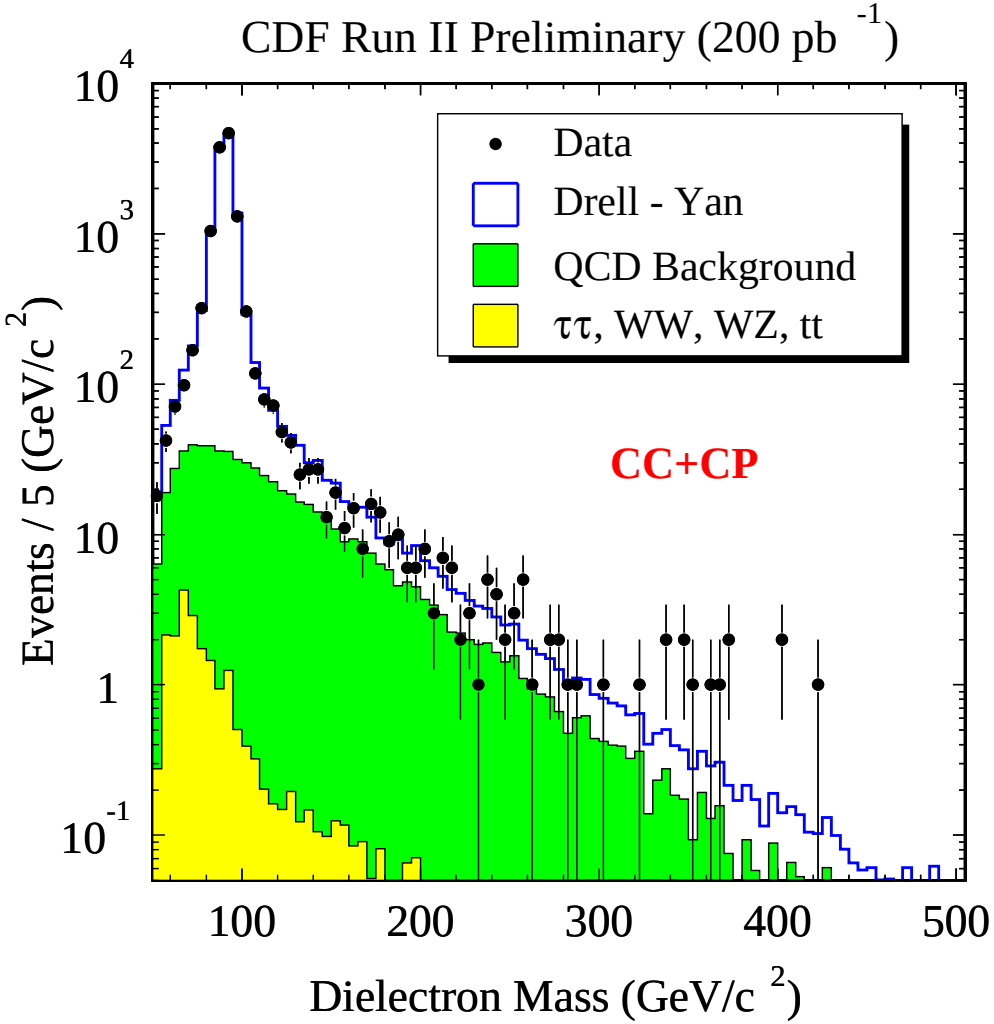
CDF dielectrons:

Background contributions:

- Drell-Yan and other SM
- QCD where jet(s) misidentified.
- CP category contributes most to QCD background

N_{exp}=4.7, N_{obs}=8
for M_{ee} > 350GeV

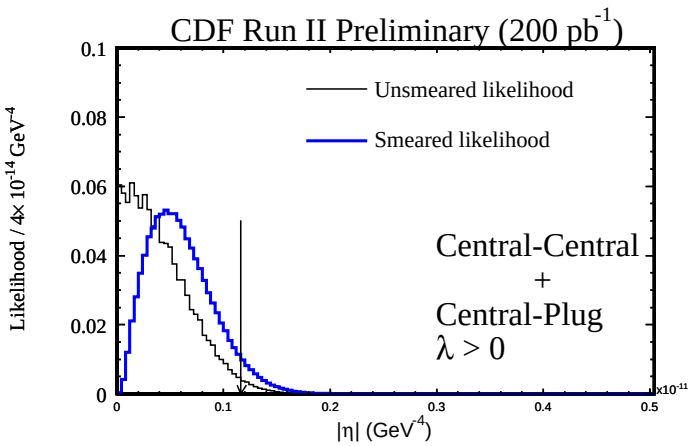


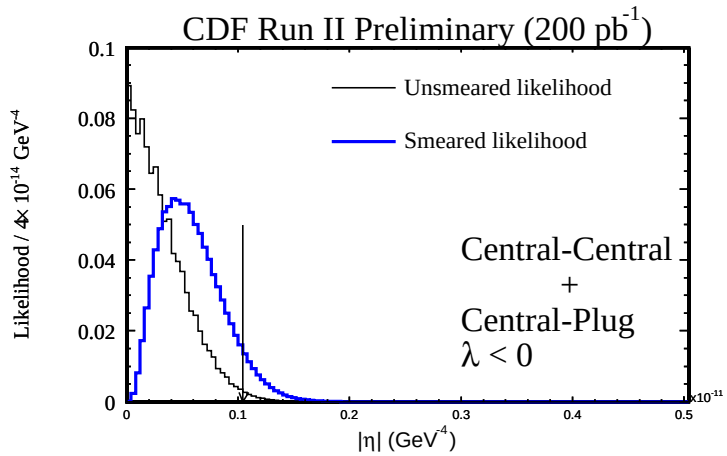
Sources of systematic uncertainties:

- Luminosity (6%)
- Energy scale/resolution
- Acceptance (PDF, MC statistics,..)
- Selection efficiencies
- Background statistics and normalization
- Signal: ~8%, QCD background: >20%

CDF Dielectron LED Limit Results:

- Data agrees with expectations ➡ Proceed to set limits
- M_{ee} distribution is used for binned likelihood
- Limits on η_G -> 95% CL limits on M_S (convention: $\eta_G=\lambda/M_S^4$)





Lower Limits on M_S (TeV):

Hewett		HLZ					GRW
λ=-1	λ=+1	n=3	n=4	n=5	n=6	n=7	
0.99	**0.96**	1.17	0.99	0.89	0.83	0.79	**1.11**

CDF Run I: 0.78 0.77

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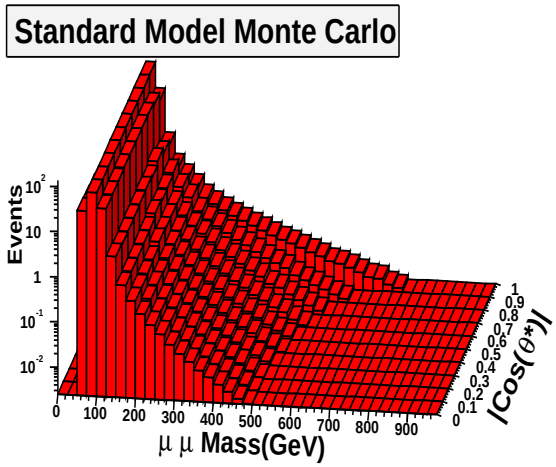
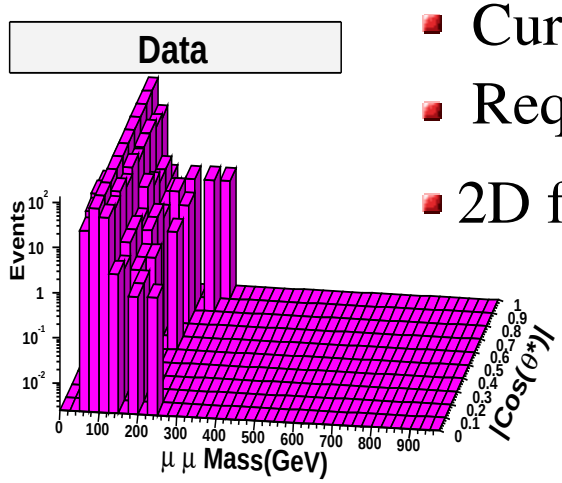
DØ dimuon LED Limit Results:

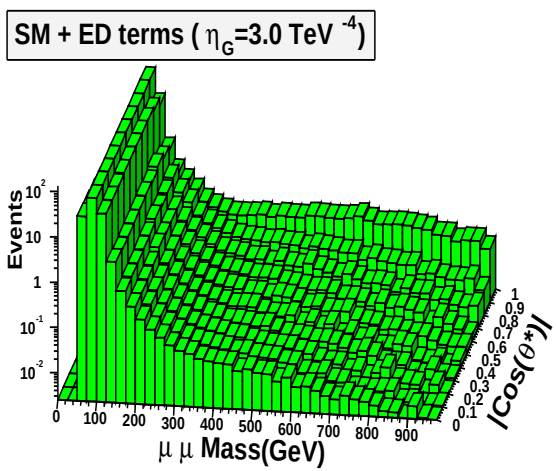




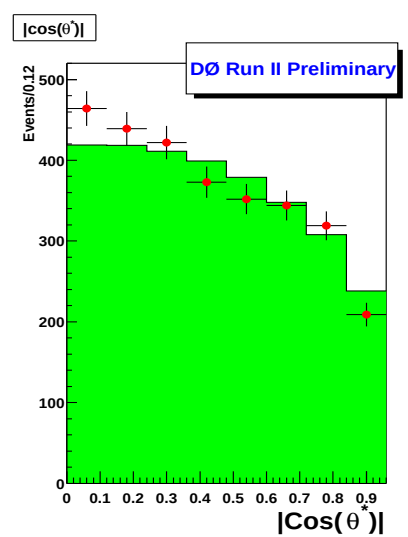
- Current results using 100 pb^{-1} data
- Require 2 μ, p_T **> 15 GeV**
- 2D fit in $M_{\mu\mu}$ and $\cos\theta^*$

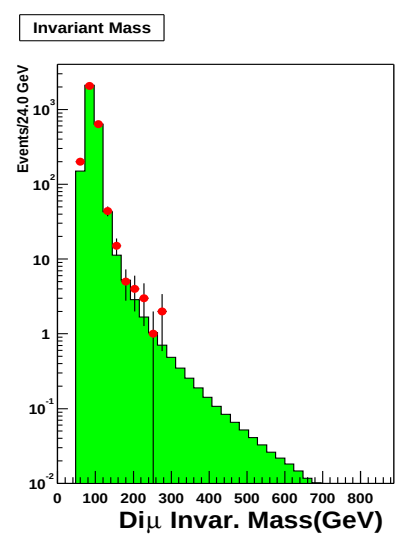
Lower limit on M_s(GRW):

0.88 TeV



DØ Run II Preliminary





Summary for LED Results in Virtual Exchange Signature:

Preliminary Run II Lower limits for M_S (TeV):

		diEM	dielectron		dimuon
Convention		**D0**	**CDF**	**D0**	**D0**
GRW		1.36	1.11	1.11	0.88
Hewett	l=-1	1.1	0.99		
	l=+1	1.22	0.96		
HLZ	n=3	1.61	1.12		
	n=4	1.36	0.99		
	n=5	1.23	0.89		
	n=6	1.14	0.83		
	n=7	1.08	0.79		

DØ Run I: (diEM) PRL 86 (01)

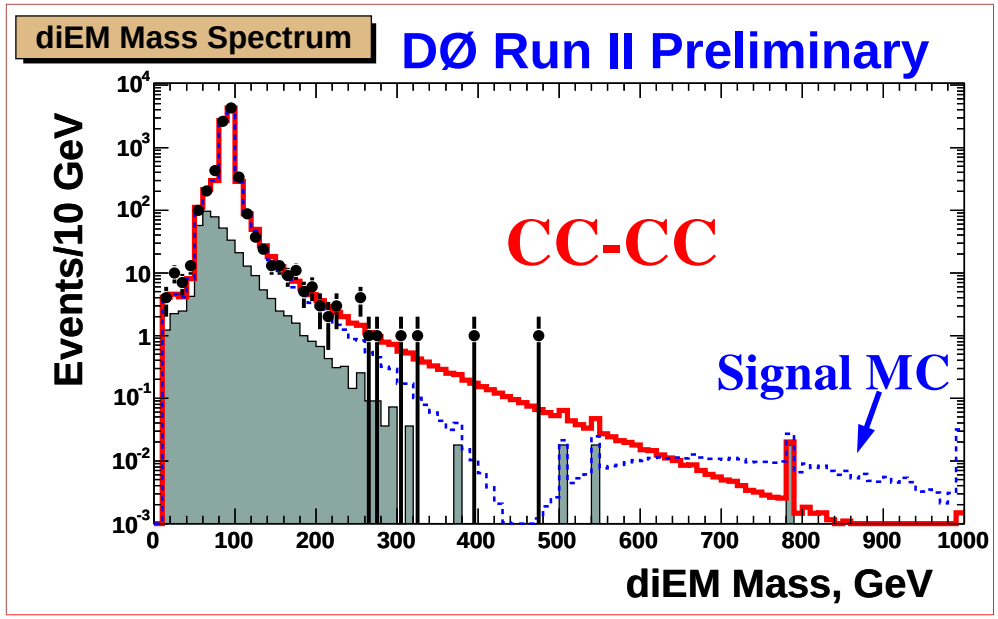
$M_S > \mathbf{1.1}$ (1.0) TeV for λ=+1(−1)

LEP: (L3) PDG (03)

$M_S > \mathbf{0.84}$ (0.99) TeV for λ=+1(−1)

DØ Results for TeV^{-1} ED: Dielectron Channel

- SM bosons can propagate in ED: mixing and interference among SM bosons and their higher order KK modes
- Study Z/γ virtual KK state effects, parameterized by: $\eta_C = \pi^2/3M_C$
- N_{exp}=12.1 (4.3 QCD), N_{obs}=9 for M_{diEM}>350GeV & EC-EC incl.
- Background uncertainty: 10%
- Signal uncertainty: 12%
- Limits set same way as LED



Lower Limit on M_C in ***ee*** mode:

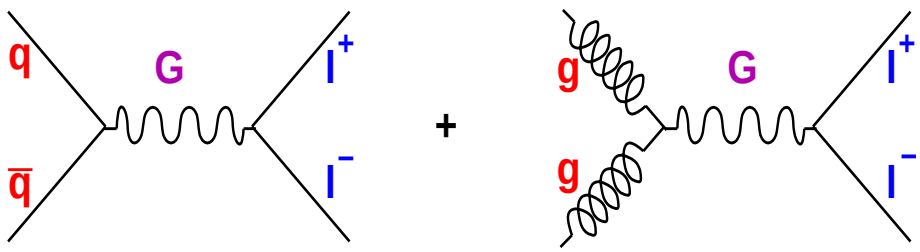
- η_C< 2.63 TeV^{-2} -> **M_C > 1.12 TeV** @95%CL

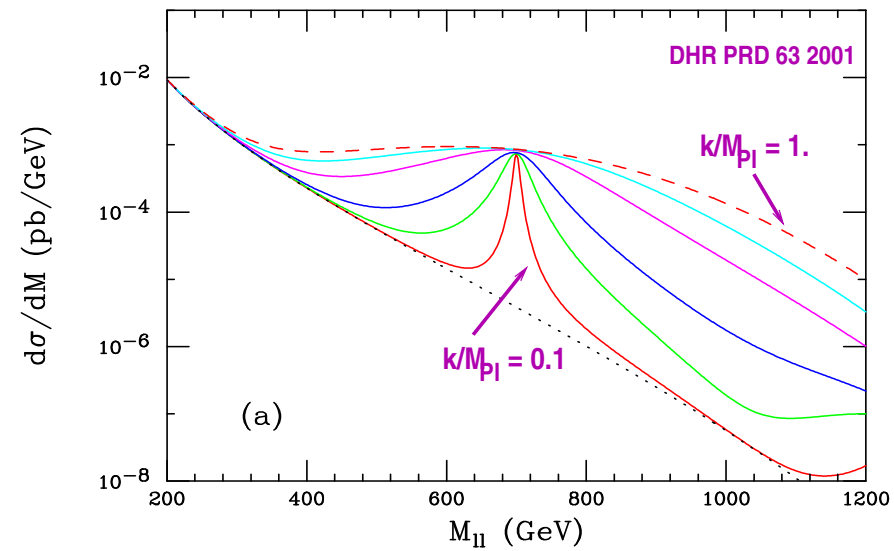
Indirect and Combined Searches:

- LEP combined: M_C > 6.6 TeV, All: M_C > 6.8 TeV

Resonant Graviton Searches: Randall-Sundrum Model

- 5-D warped space-time via an $e^{-2kr_c\pi}$ factor predicts low mass graviton resonances
- coupling parameter (k/M_{Pl})



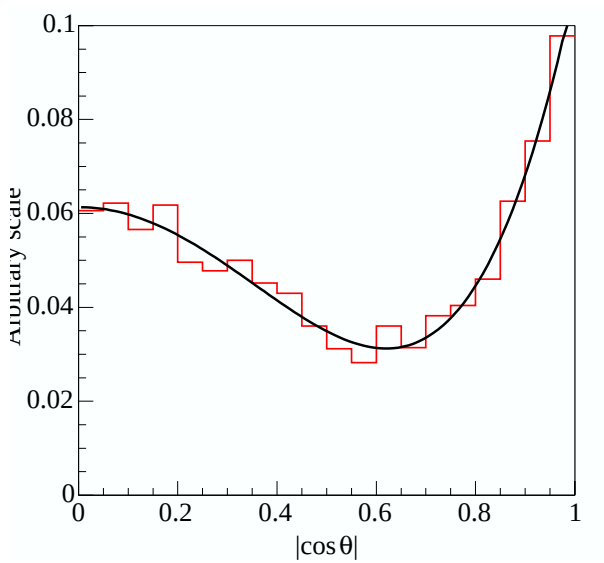


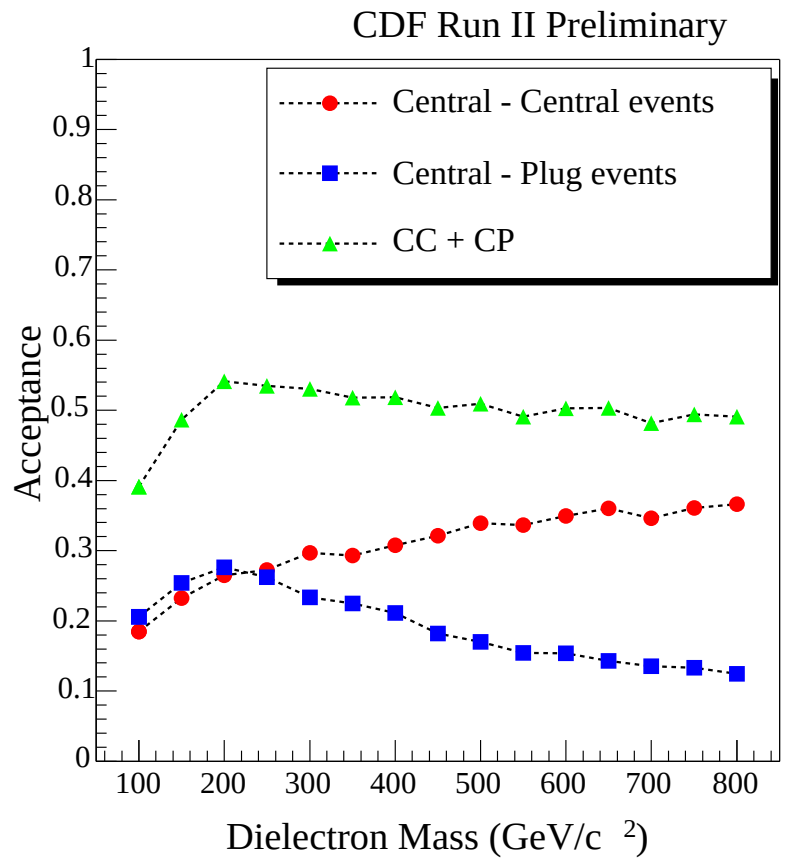
- CDF searches in **diLEP**(**ee**+μμ) + γγ channels (BR(G→*ll*)= ½ BR(G→γγ))
- **diLEP**: Binned likelihood method
- γγ: Counting limits using 3σ mass-window around resonance

CDF dielectron:

- Same event selection as LED search
- Using spin-2 acceptance for limits on
  $\sigma \cdot BR(G \rightarrow ee)$ and **M_G** as a function of k/M_{Pl}

Generator level spin-2 (full η range)



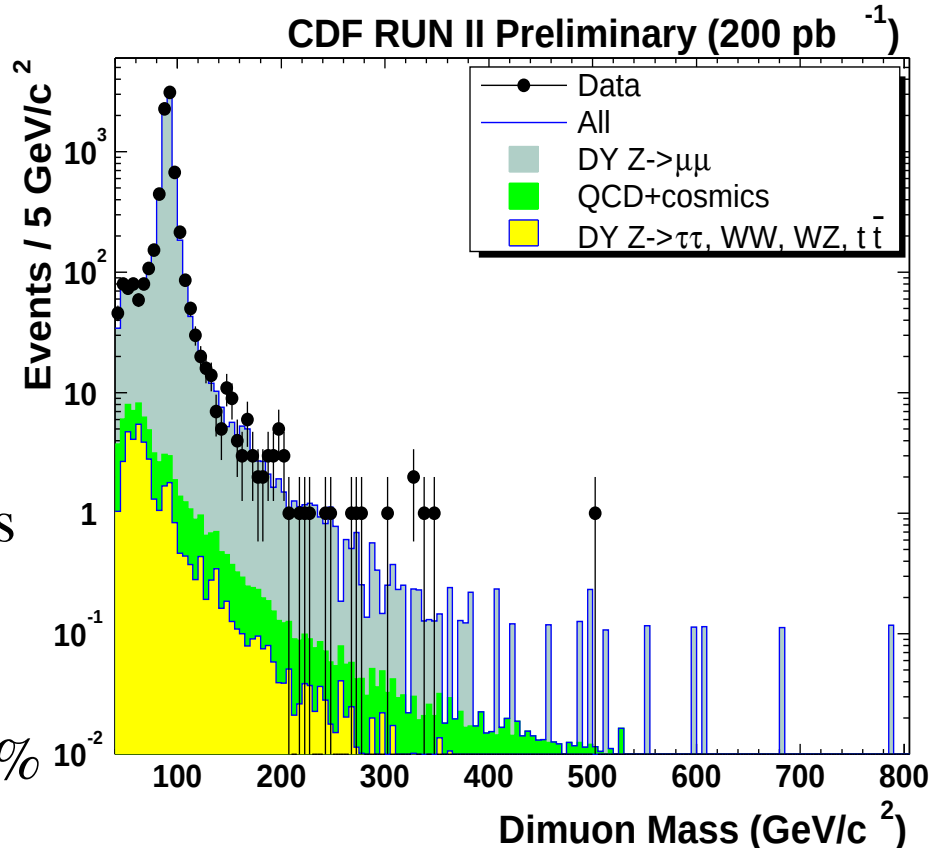


CDF dimuon:

- Require two isolated μ, p_T **> 20 GeV**

μ_1: Central | μ_2: $|\eta| < 1.5$

- μ_2 may include tracks w/o μ-chamber information
- Constrain z_μ to CDF central region
- Momentum dependent cuts for high mass efficiency
- Backgrounds: SM and QCD+cosmics
- Veto cosmics by track-timing cuts
- $N_{exp}=3.2\pm0.2$, $N_{obs}=1$, $M_{\mu\mu}>350$GeV
- Overall selection efficiency: ~70 ± 2%
- Signal systematic uncertainty: ~8%
- Background unc: 5% (SM), 20-30% (fakes)



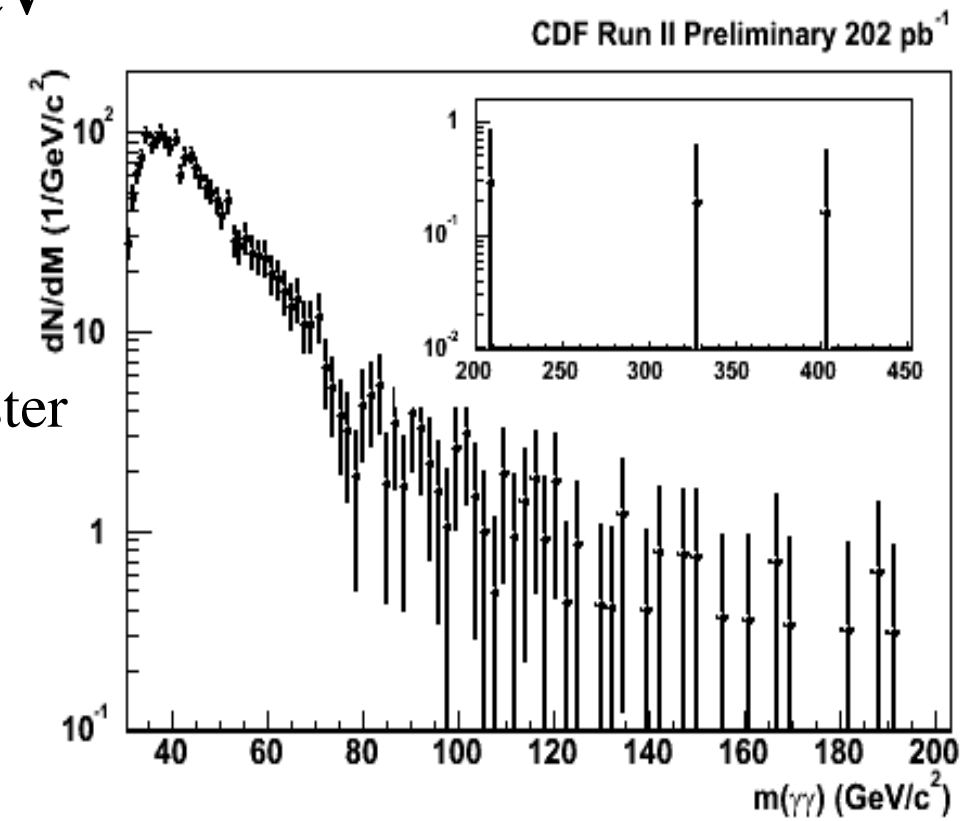
◆ Data and background expectations agree ➡ Set limits, similar to ***ee***

CDF diphoton:

- Require two isolated γ, E_T **> 15 GeV**

$\gamma\gamma$: Central, $|\eta| < 1.1$

- An event vertex exists
- No 3D tracks pointing to EM cluster
- $M_{diphoton} > 30$ GeV
- Overall selection efficiency:
  ~ 50- 55 ± 2 %



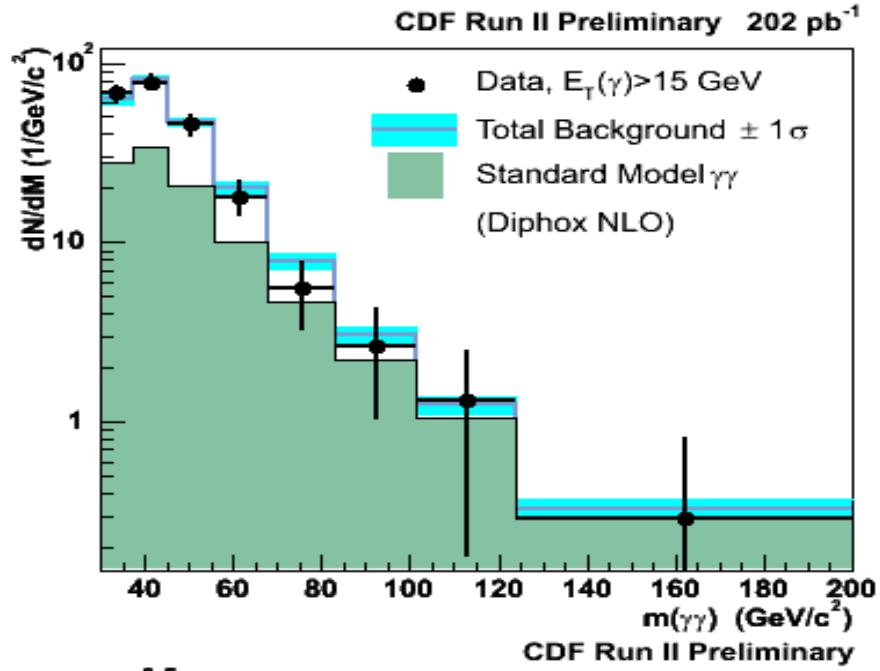
➥ CDF diphoton results first presented in this conference!

CDF diphoton:

Background contributions:

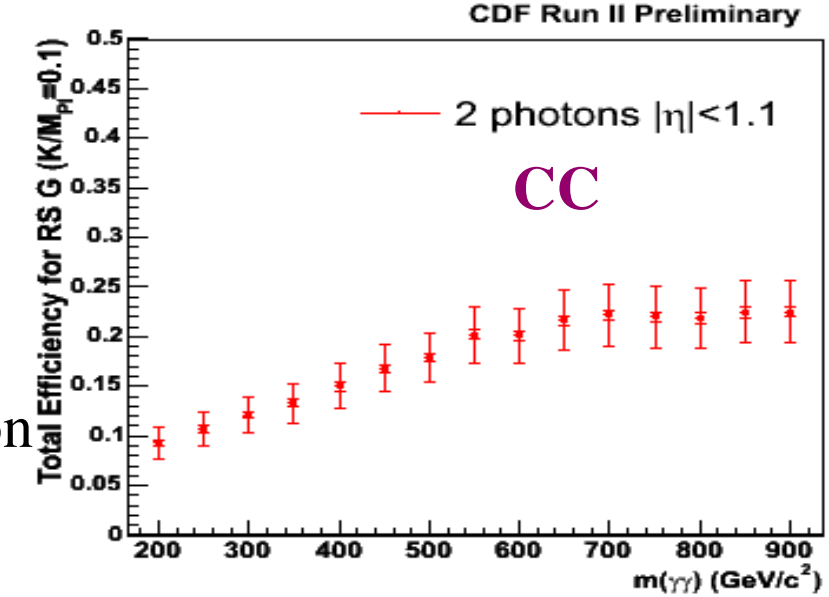
- SM direct diphoton production
- QCD where jet(s) misidentified in γ+jet, jet+jet events.

$N_{exp} = 0.6 \pm 0.2$, $N_{obs} = 1$, for $M_{\gamma\gamma} > 350$GeV



Sources of systematic uncertainties:

- Choice of PDF, FSR/ISR
- Energy scale
- Selection efficiencies
- Background statistics and normalization
- Total signal uncertainty: ~15%
- Background uncertainty: 20-25%



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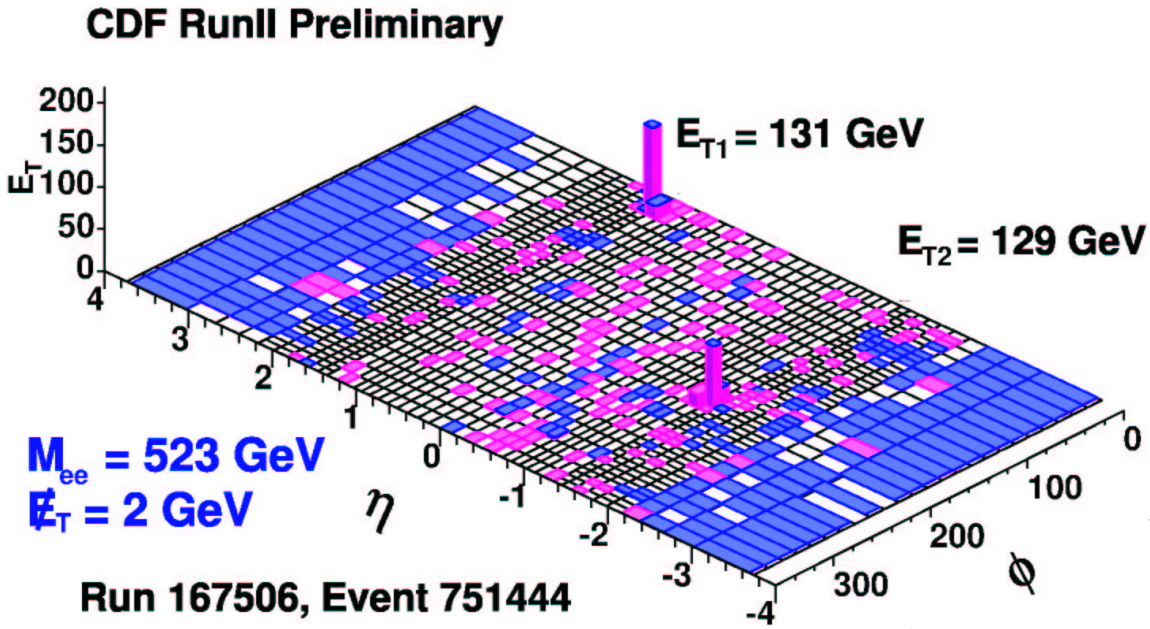
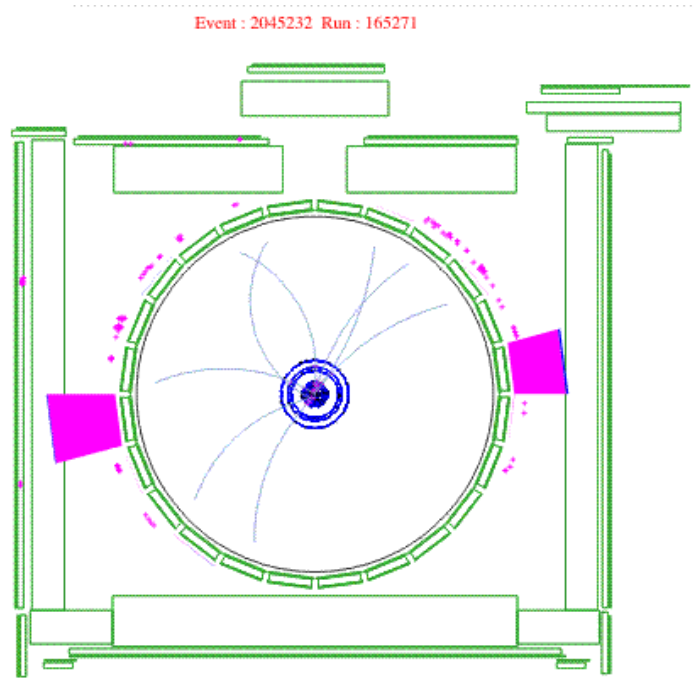
Interesting CDF Events:



Highest *ee* (Plug-Plug)

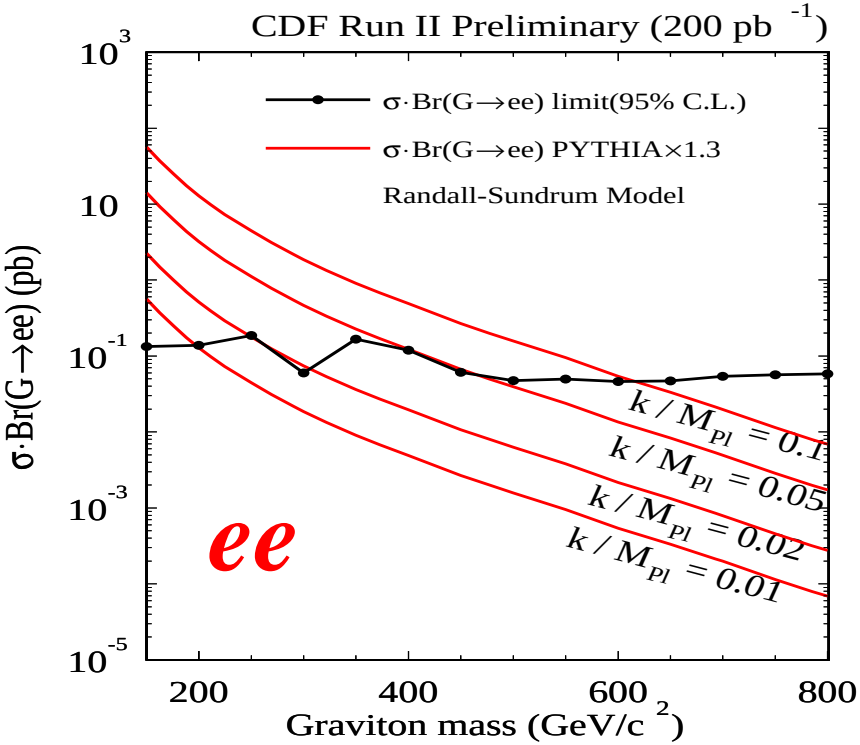
Highest diphoton

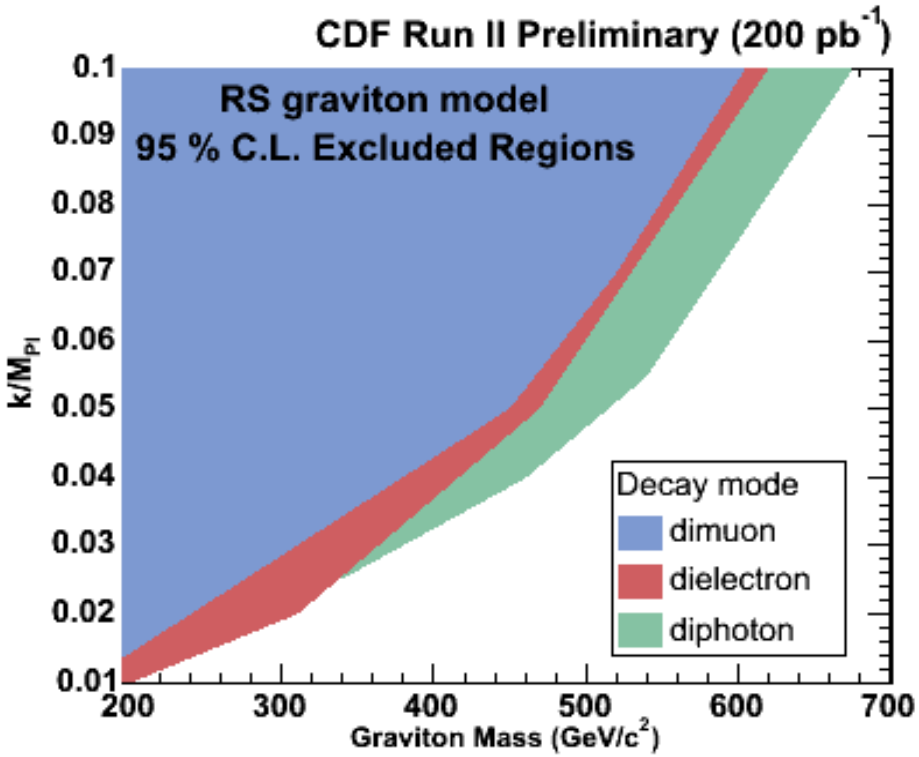


Diphoton Mass = 405 GeV

Photon Et = 172, 175 GeV

CDF Results for RS Graviton:





Upper Limits on σ•BR (fb), at high mass

ee	μμ	γγ
~50	~50	~100

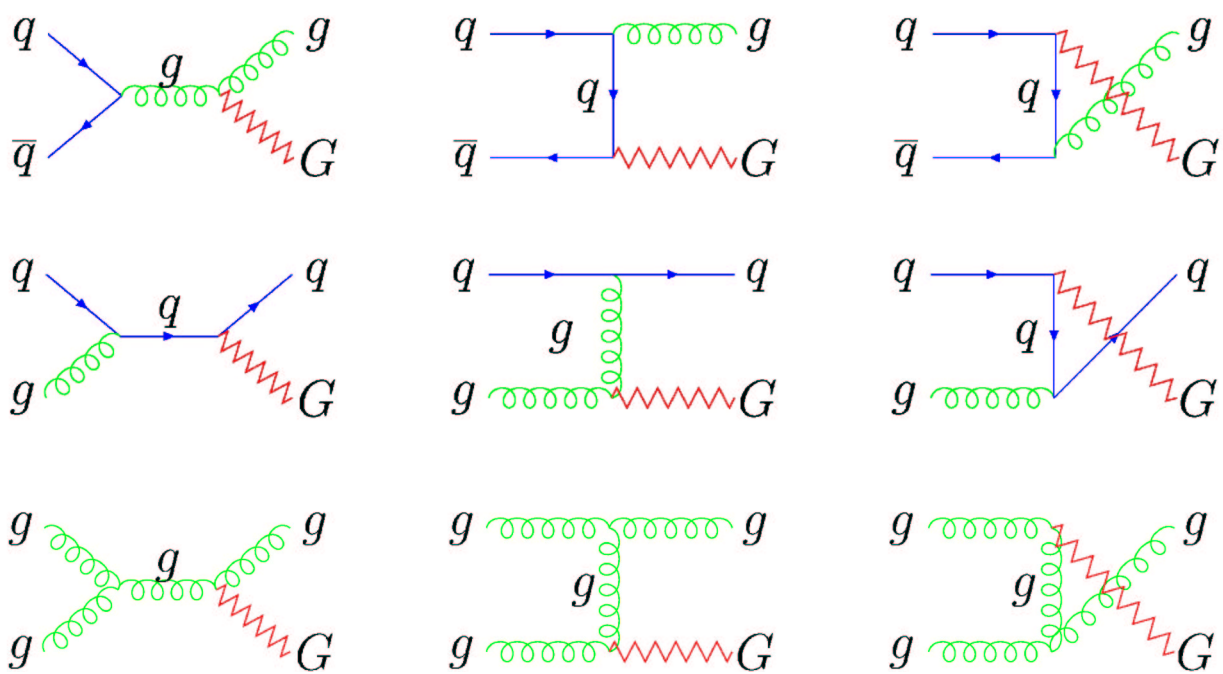
Lower Limits on M_G (GeV), k/M_{Pl}=0.1

ee	μμ	γγ
620	605	675

Graviton Emission Signature: LED Model

- Graviton produced along with a jet (or photon): escapes out of the 3D brane, not detected
- Monojet like topology with high missing E_T

- $q\bar{q} \rightarrow gG$
- $qg \rightarrow gG$
- $gg \rightarrow gG$

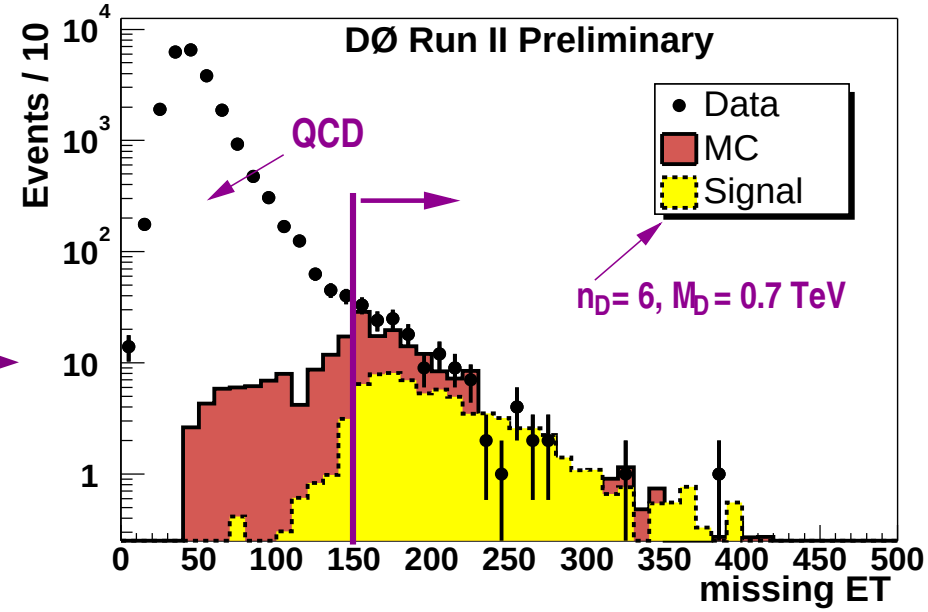


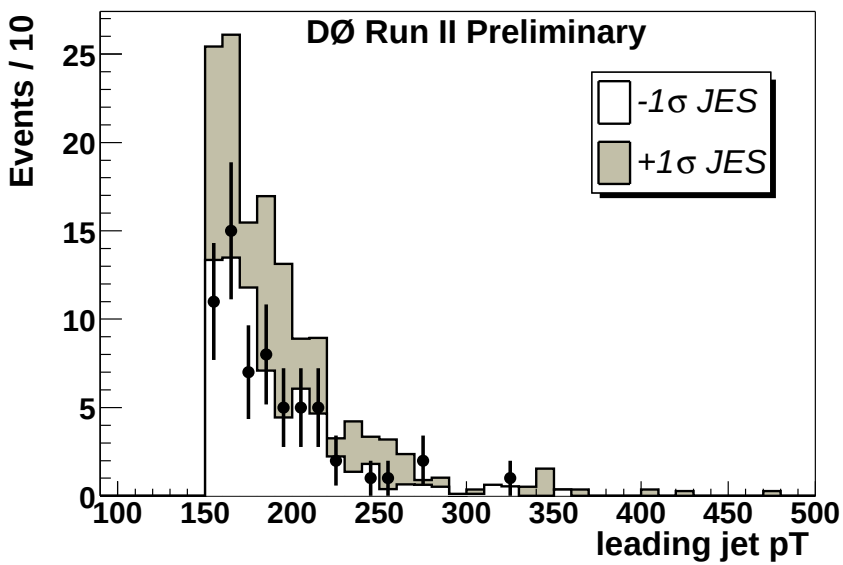
DØ jet+$\not\!\!E_T$ Signature (85 pb^{-1}):

Final sample selection:

- $\not\!\!E_T$ > 150 GeV
- P_T (jet1) > 150 GeV, |η|< 1.0
- P_T (jet2) < 50 GeV
- Δφ($\not\!\!E_T$, jet1) > 30º

} not incl.





- Largest SM background from Z->υυ+jet(s)
- N_{exp}=100.2 ±6.2 (stat) ±7.5(thy) +50% -30% (Jet Energy Scale)
- Signal uncertainty: 20%
- Data: N_{obs} = 63 (~5% efficiency)

Expected & observed agree within errors

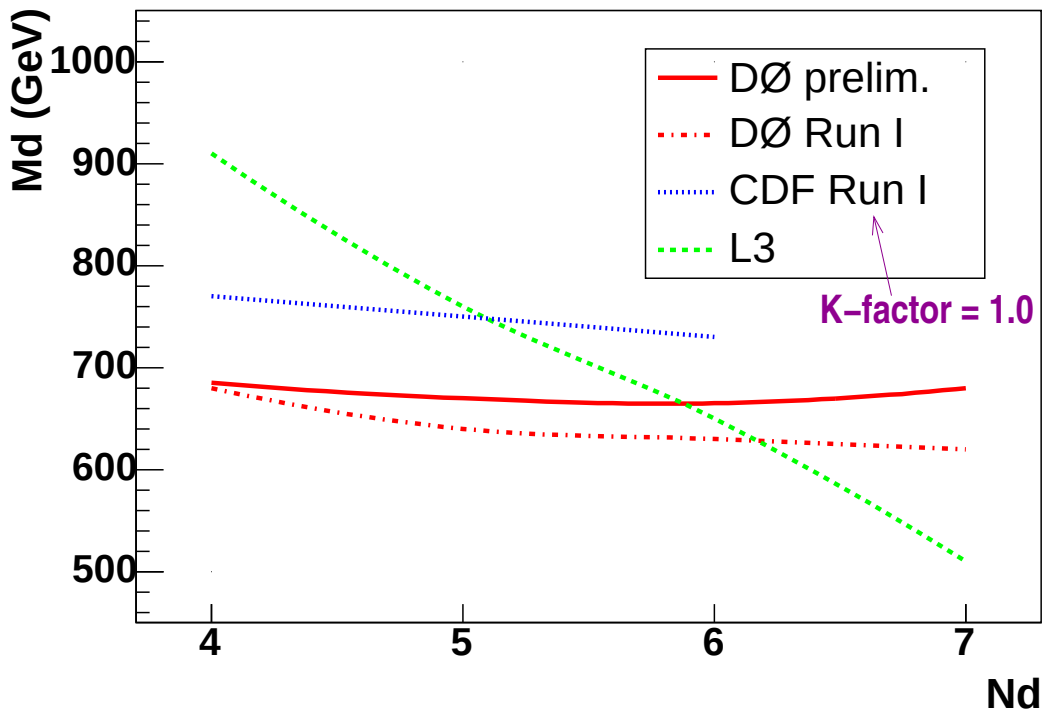
HCP2004

DØ Limits for LED in jet+$\not\!\!E_T$ Signature:

- Set limits in the absence of events in data
- Use LEP CLs approach.
- Upper limit in N_{signal}: 84
- Expected limits of 111.4 (median) ± 28.1 (RMS) agree with actual limits.

Lower Limit on M_D (K_f=1.3)

n_D	M_D> (TeV)
4	0.68
5	0.67
6	0.66
7	0.68



➡ Once uncertainties settled, analysis will be more competitive

Conclusions:

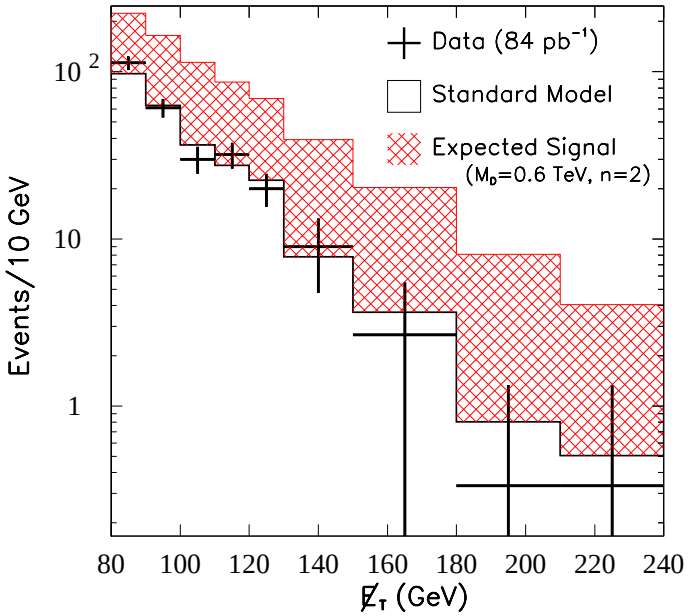
- Tevatron and its experiments are performing very well: most analyses include the 200 pb^{-1} data recorded until end of 2003.
- DØ and CDF are actively engaged in Extra Dimension searches in high mass ee+$\mu\mu$+$\gamma\gamma$ and jet+$\not{E}_T$.
- More ED signatures (especially $\not{E}_T$ based) are being explored!
- Current LED limits of the Tevatron experiments exceed published limits of previous direct searches. For some models/search strategies, the DØ/CDF analyses are the first!

☞ Hadron Colliders (Tevatron now, LHC soon) are great places to search for extra dimensions!

(*) Many thanks to all DØ and CDF colleagues!

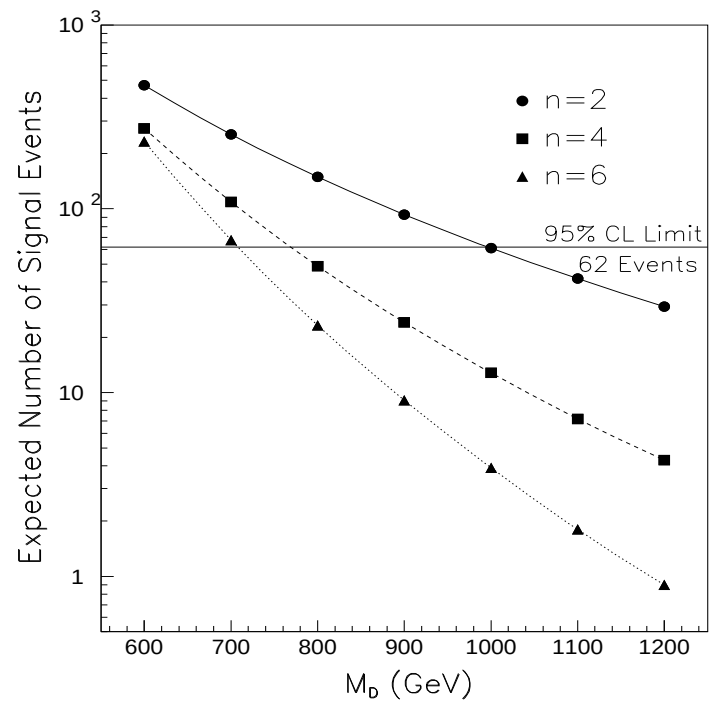
Backup Slides

CDF Run I result for LED in jet+ME_T signature:



Final sample selection:

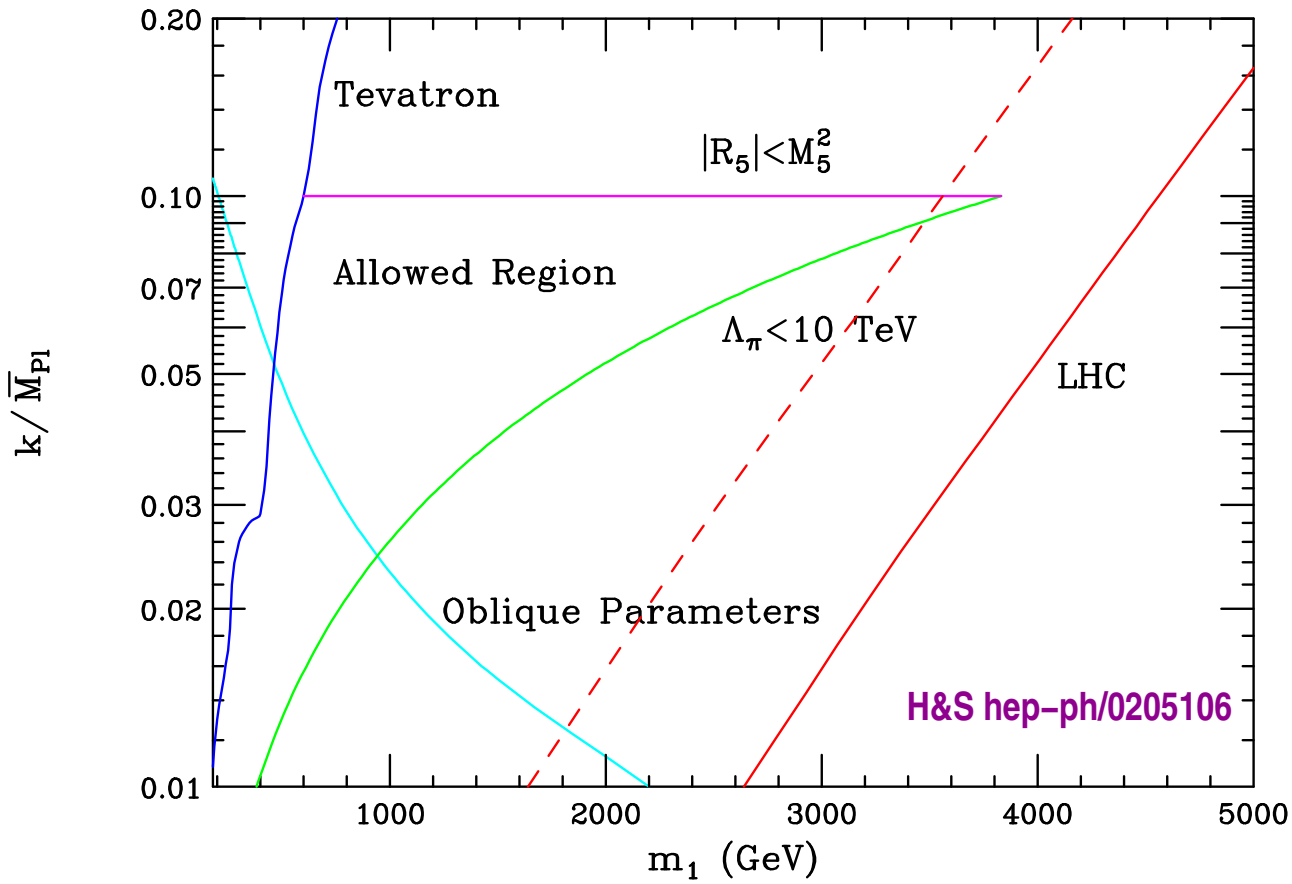
- $\not{E}_T \geq 80$ GeV
- E_T (jet1) ≥ 80 GeV, $|\eta| < 1.1$
- E_T (jet2) ≥ 30 GeV
- $N_{obs} = 284$, $N_{exp} = 274.1 \pm 15.9$



Lower Limit on M_D (K_f=1) (TeV) and Upper limit on R

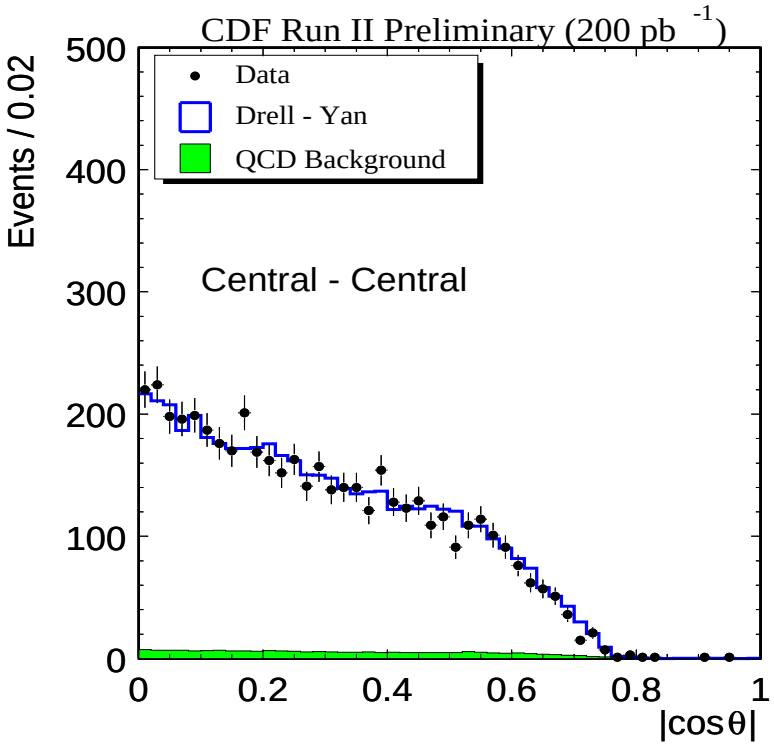
$n_D = 2$	$n_D = 4$	$n_D = 6$
1.0	0.77	0.71
0.48 mm	0.014 nm	42 fm

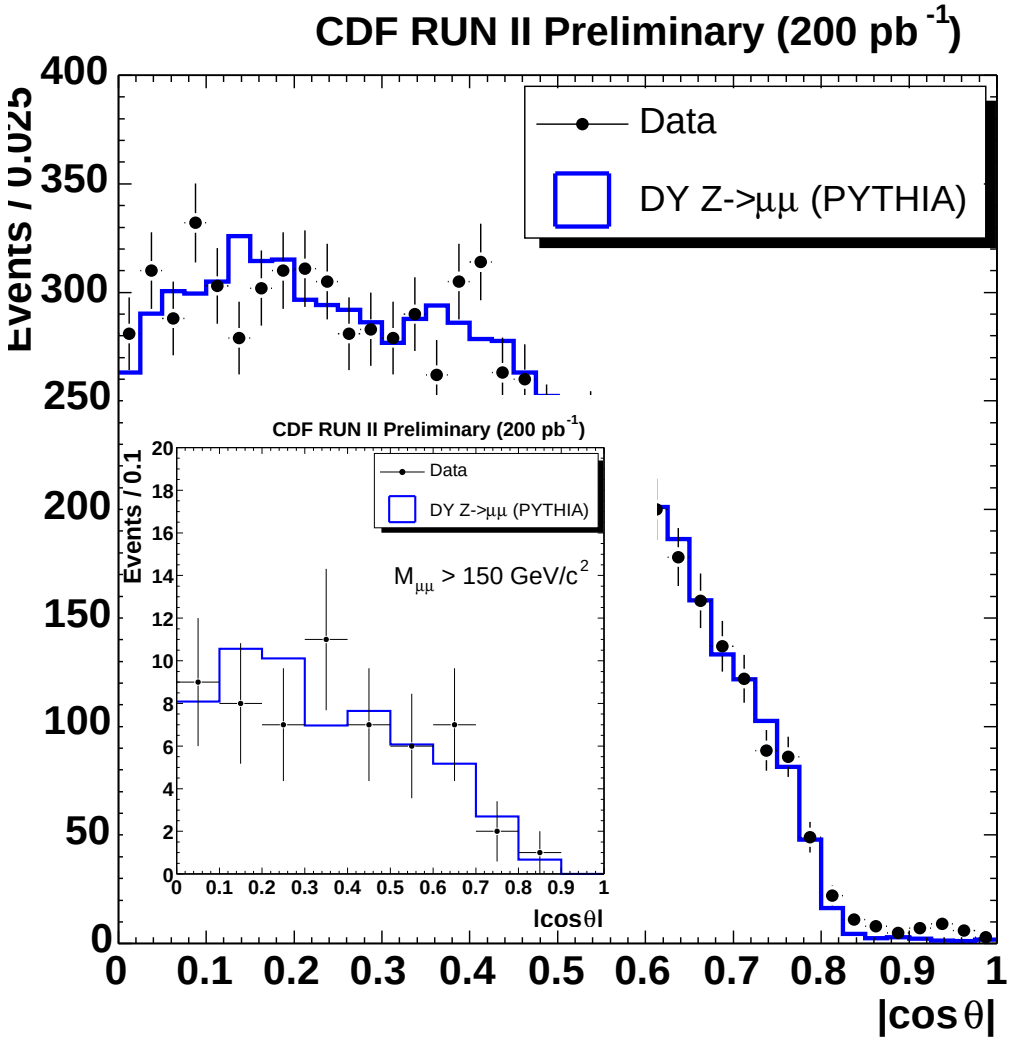
Constrained Parameter Space for RS-ED model:



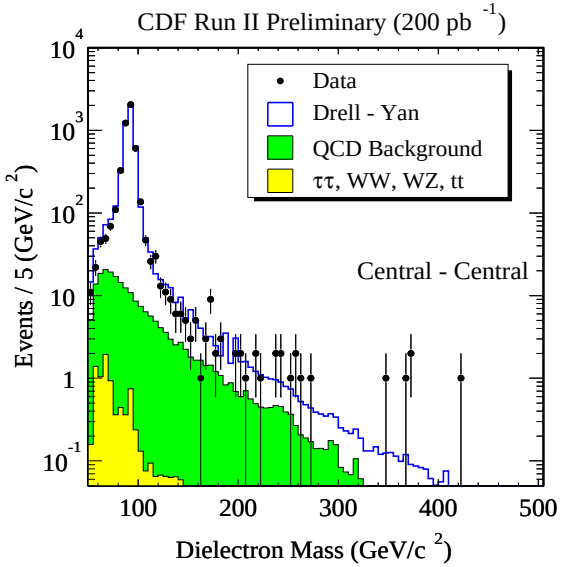
CDF cosθ*:

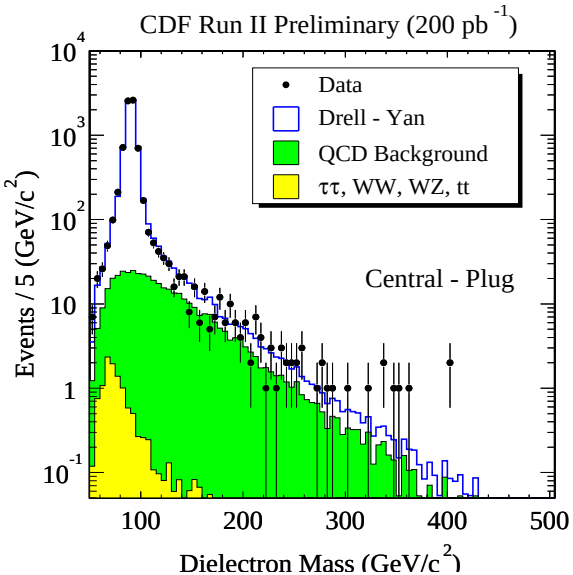
- cosθ distribution comparison with Drell-Yan background

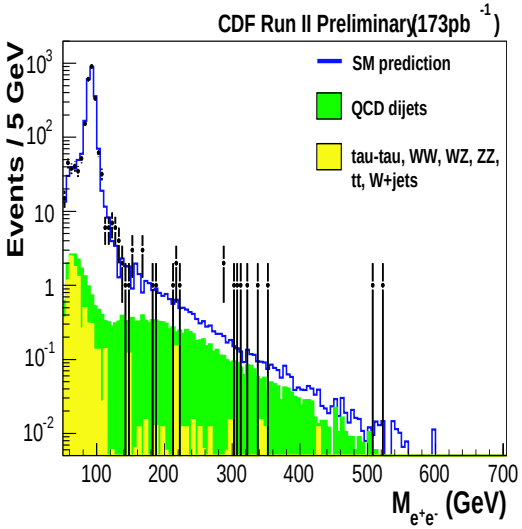


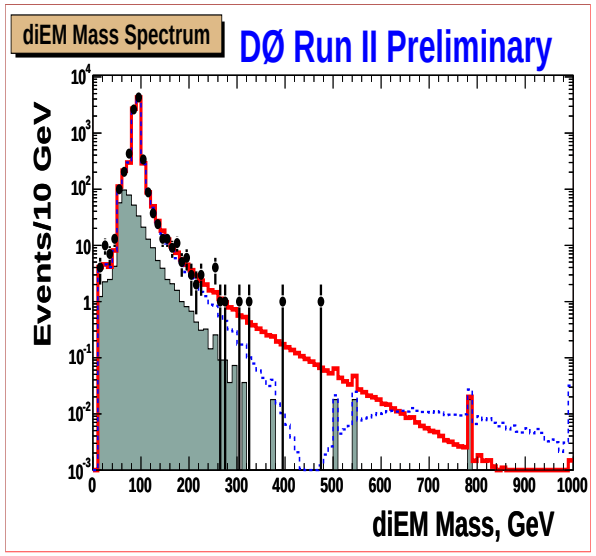


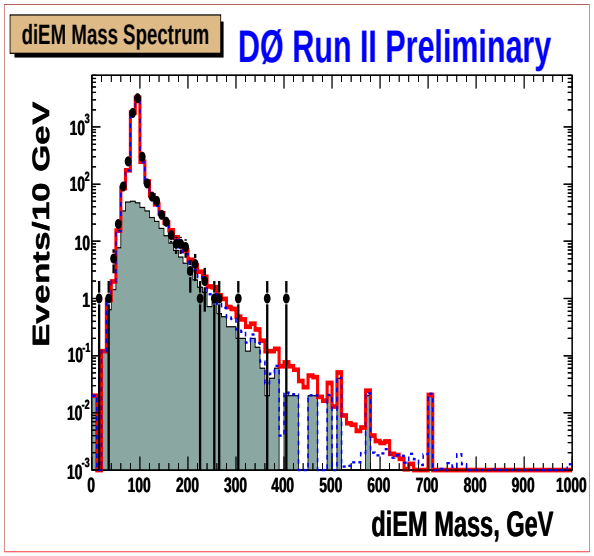
Dielectron comparison for CDF and DØ:

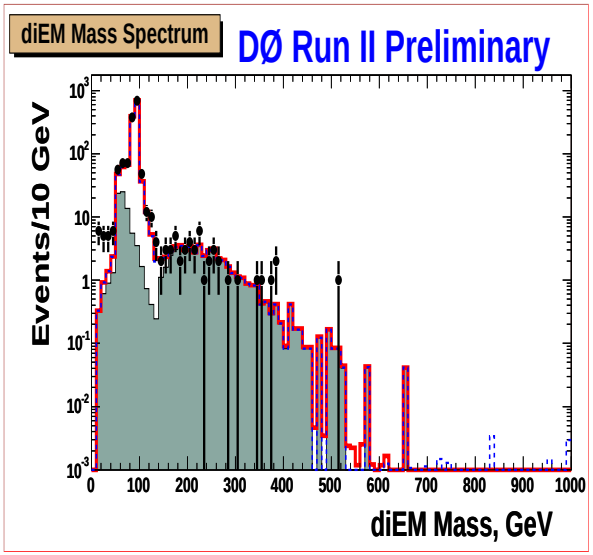




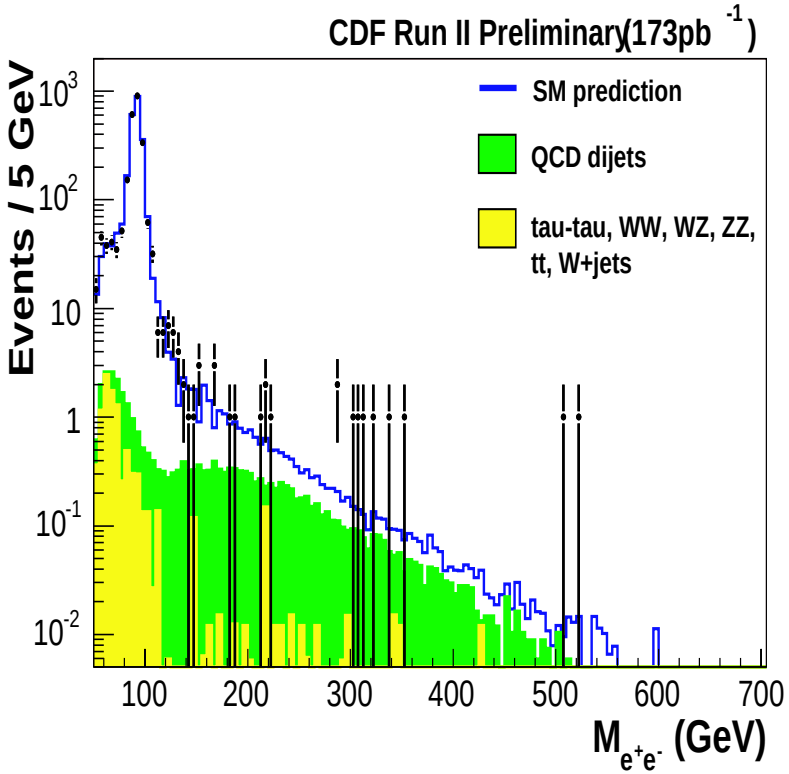








Comparison to Expectation (CDF CC+CP and PP *ee*):



Mass Cut	N_{PRED}	N_{DATA}
0	2414 ± 58	2387
50	2410 ± 58	2381
100	144 ± 6.7	149
150	20.8 ± 3.7	22
200	10.2 ± 2.2	14
250	5.0 ± 1.2	10
300	2.5 ± 0.7	8
350	1.4 ± 0.33	3
400	0.71 ± 0.17	2
450	0.39 ± 0.09	2
500	0.21 ± 0.04	2
550	0.10 ± 0.03	0

CC+CP

Mass >(GeV/c^2)	N_{exp}	N_{obs}
250	25.1	29
300	10.4	14
350	4.7	8
400	2.4	3
450	1.4	0