CDF Searches for New Physics in High Mass Data & Extrapolations to ATLAS

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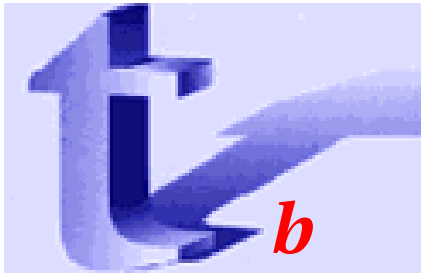
Outline

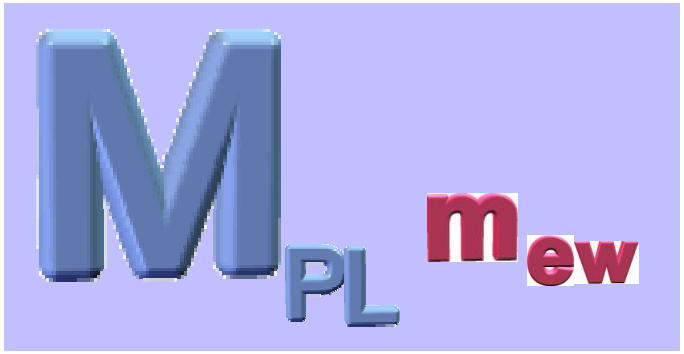
- Motivation and Introduction
- Tevatron and CDF detector
- Dilepton (ee + $\mu\,\mu$) Event Selection in 200 pb^{-1} data
- Comparison of Background Expectation to Data
- Cross section and Mass Limit Results ***(95%CL, preliminary)***
- ATLAS/LHC Prospects
- Summary and Conclusions

Results are from 2002-03. For details of this analysis and for other high mass results performed by CDF ($\gamma\gamma$, $\tau\tau$, ***W' in e***ν,...):
URL: http://www-cdf.fnal.gov/physics/exotic/exotic.html

Motivation: New Physics Searches!

♦ **There are questions SM can not alone answer:**



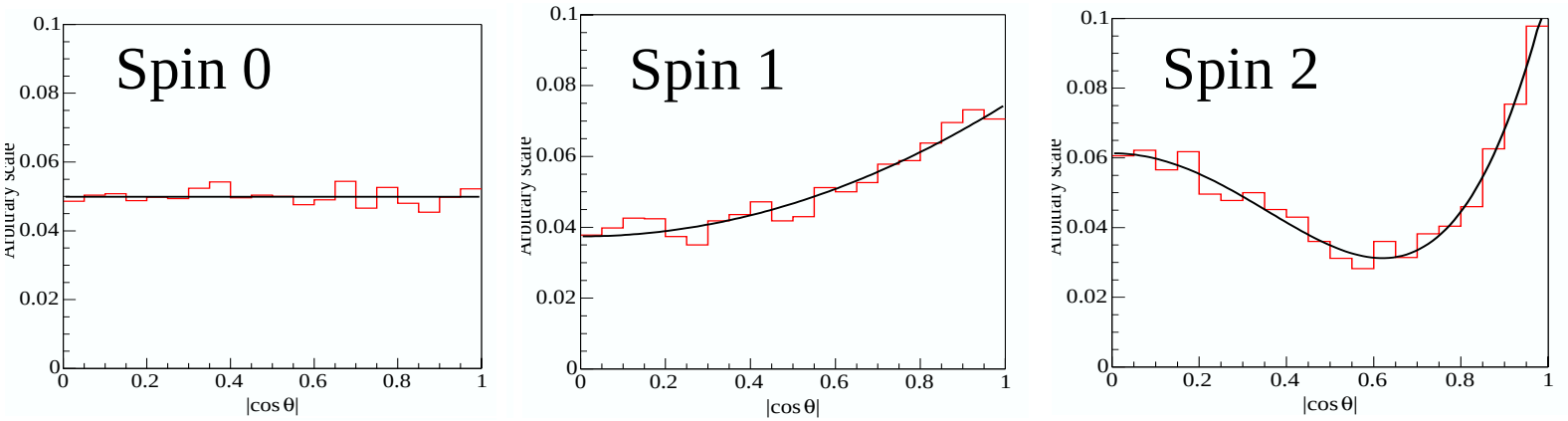


♦ **What can be beyond SM?: Many possibilities!!**

- Extended Gauge Symmetries
- Supersymmetry
- Dynamical EWK breaking
- Extra Dimensions
- ...

Strategy: Analyze High Mass Dilepton data!

- Dileptons: clean data samples with manageable backgrounds. (remember J/ψ and Z^0 !)
- Many predicted particles decay into dileptons
- A detector's sensitivity ∝ **acceptance**. For a quasi-model independent search, categorize particles w.r.t. spin properties.



- Dilepton signatures studied for searches:

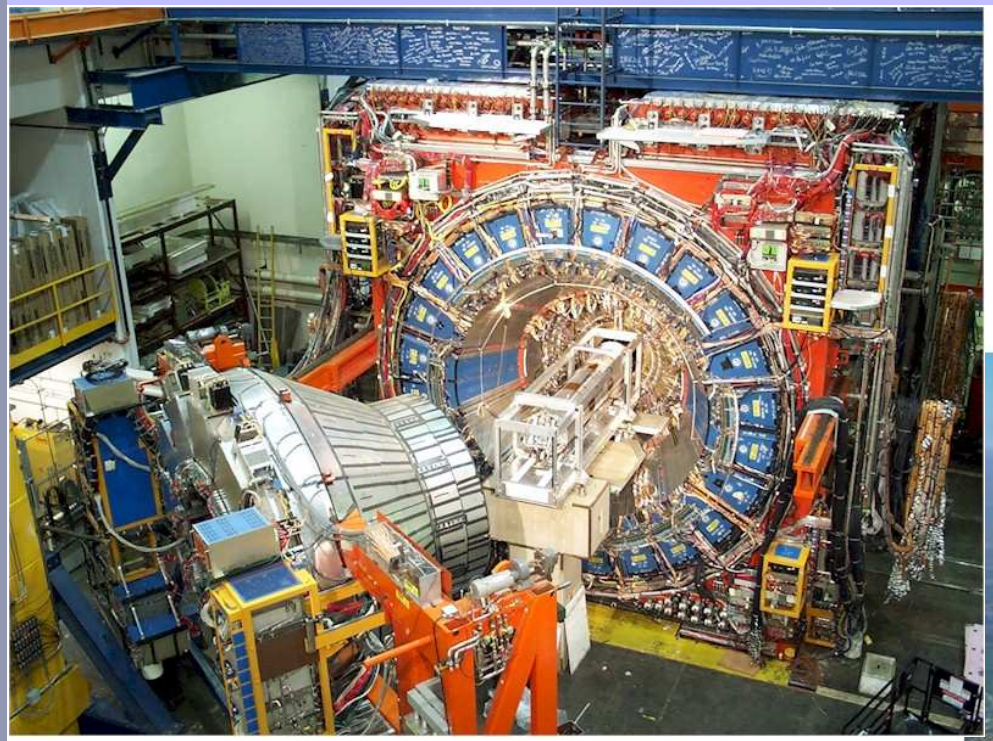
Resonance Production

- **Spin-0**: SUSY (R_P-violating $\tilde{\nu}$)
- **Spin-1**: Z' (E_6, little Higgs), Technicolor (ρ_T, ω_T)
- **Spin-2**: RS Graviton

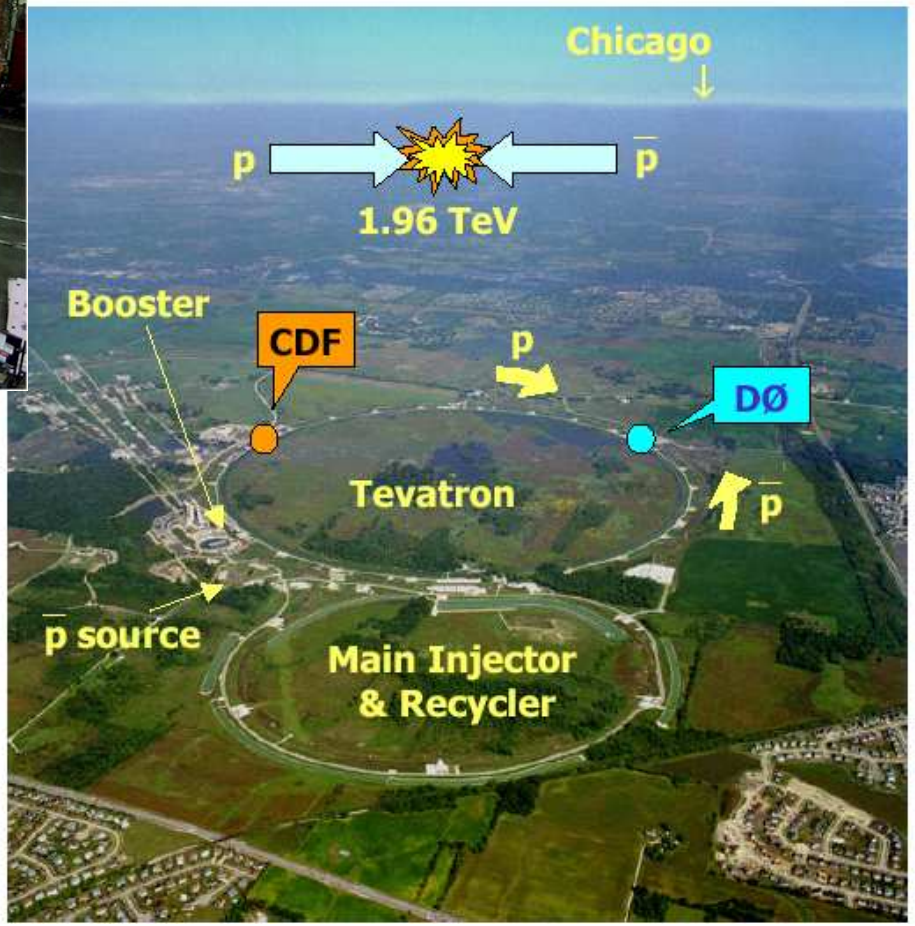
Continuous mass spectrum

- Large Extra Dimensions (ADD)

CDF Experiment at Tevatron Run II: doing well!



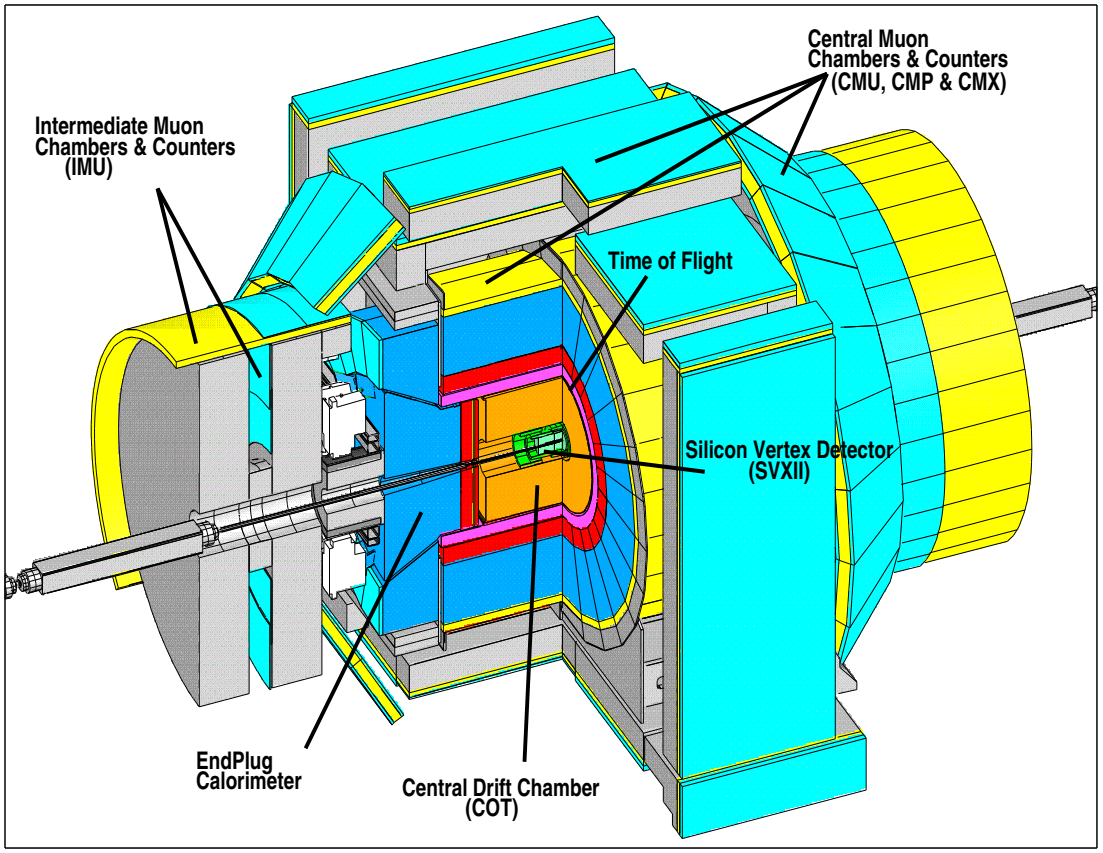
- ✔ Both the Tevatron and the detector upgraded.
- ✔ Run II has been going on successfully.



- ✔ Typical L ~ $\mathbf{1x10^{32}}$ $cm^{-2}sec^{-1}$!
- ✔ Baseline goal $\mathbf{4.4\ fb^{-1}}$ end of '09.

(numbers before 04 annual shutdown)

CDF II Detector : Lots of upgrade and maintenance effort..

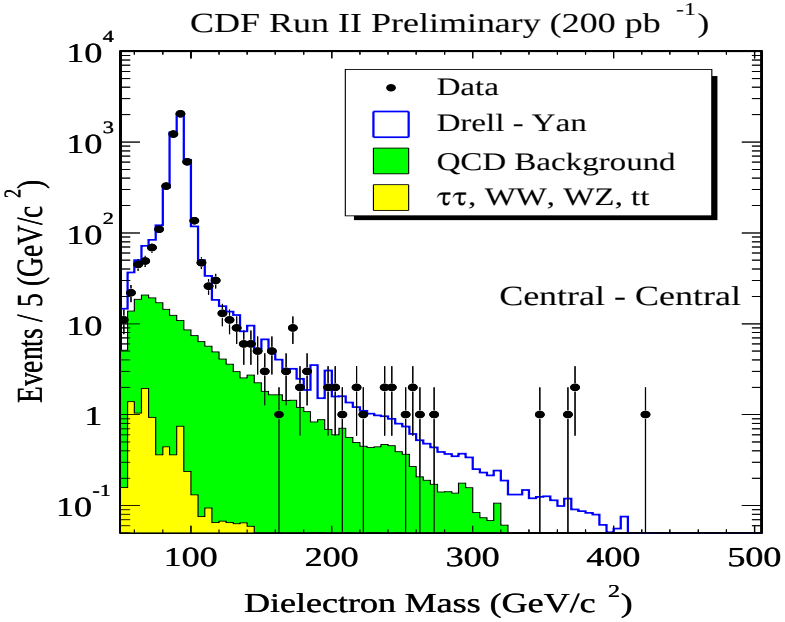


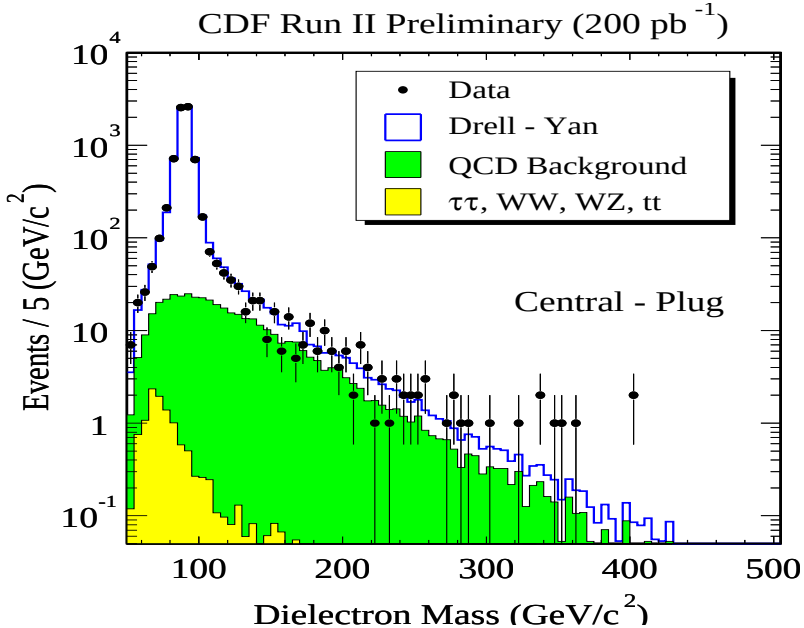
- Tracking at 1.4T B-field:
  - COT $|\eta| < 1$
  - Silicon $|\eta| < 2$
- Calorimeter:
  - Central $|\eta| < 1$
  - Plug $1 < |\eta| < 3$
- Muon Detectors:
  - Central $|\eta| < 1.1$
  - Intermediate $1 < |\eta| < 2$
- Cerenkov Luminosity Counters

$$\eta = -\ln(\tan\theta/2)$$

Dielectron Selection: ~12.5k candidates in 200 pb^{-1} data

by Koji Ikado, Osaka U.





- 2 isolated ***e***, **E_T > 25 GeV**

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

⇓

CC and **CP** categories

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

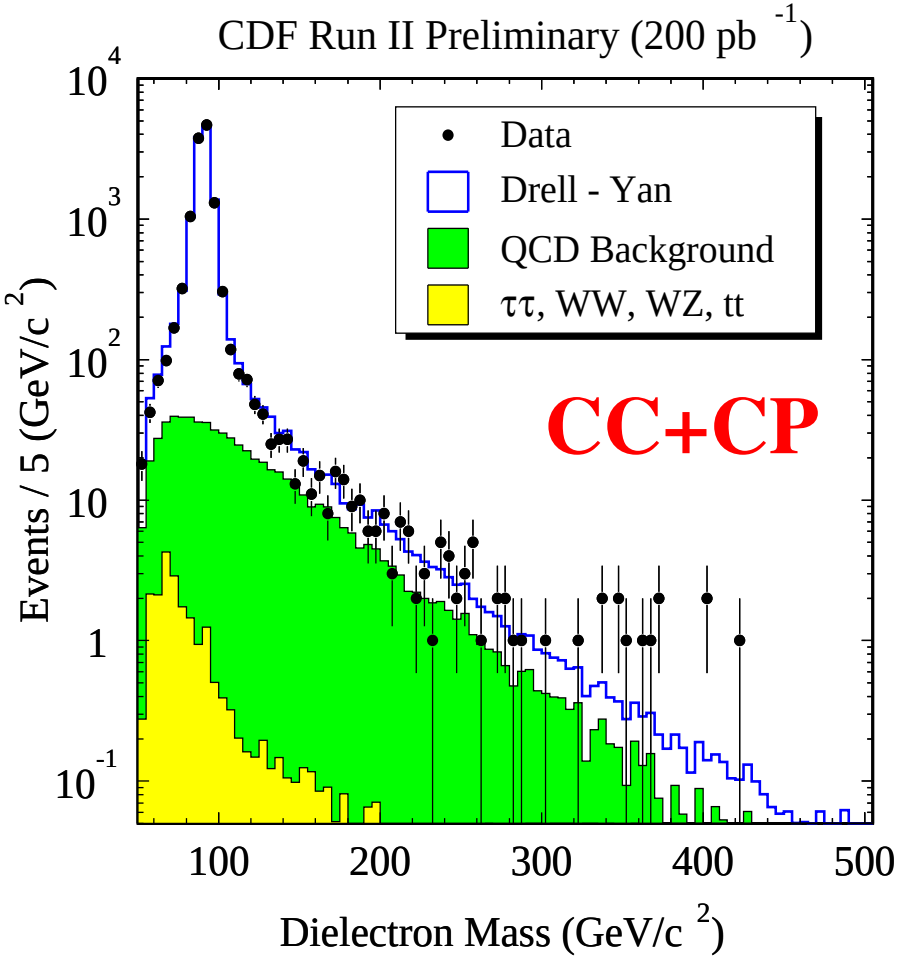
- Constrain ***e*** in CDF luminous region
- Energy dependent cuts for efficiency
- $\not\!\!E_T$ significance for QCD veto
- Overall ID efficiency:

  CC: 92.4±0.4% **CP:** 79.2±0.5%

Backgrounds:

- Drell-Yan and other SM prompt *ee*
- QCD where jet(s) misidentified as electrons

Comparison to Expectation for *ee*



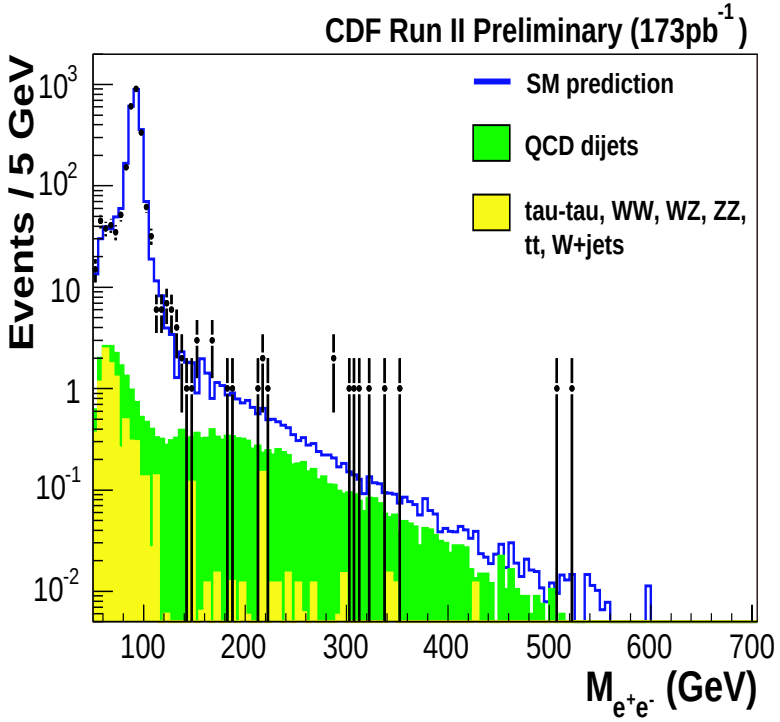
Mass >(GeV/c^2)	N_{exp}	N_{obs}
200	68.1 ± 33.3	70
250	26.2 ± 11.8	29
300	10.7 ± 4.3	14
350	4.6 ± 1.6	8
400	2.0 ± 0.7	3

systematic uncertainties:

- Luminosity (6%)
- Energy scale/resolution, efficiencies
- PDF choice , MC statistics
- QCD bgrnd shape and normalization
- Signal: ~8%, QCD background: ~50%

Comparison to Expectation for Forward *ee*: New in Run II!

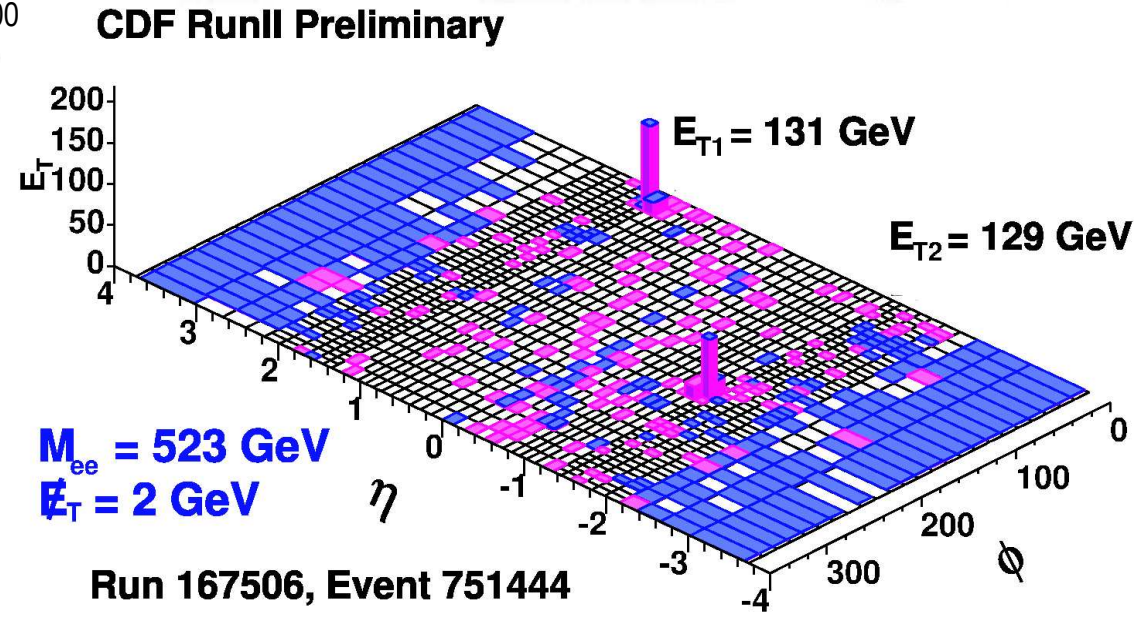
by Tim Nelson, SLAC



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

- Increased acceptance!!

Highest M_{ee} in 200 pb^{-1}

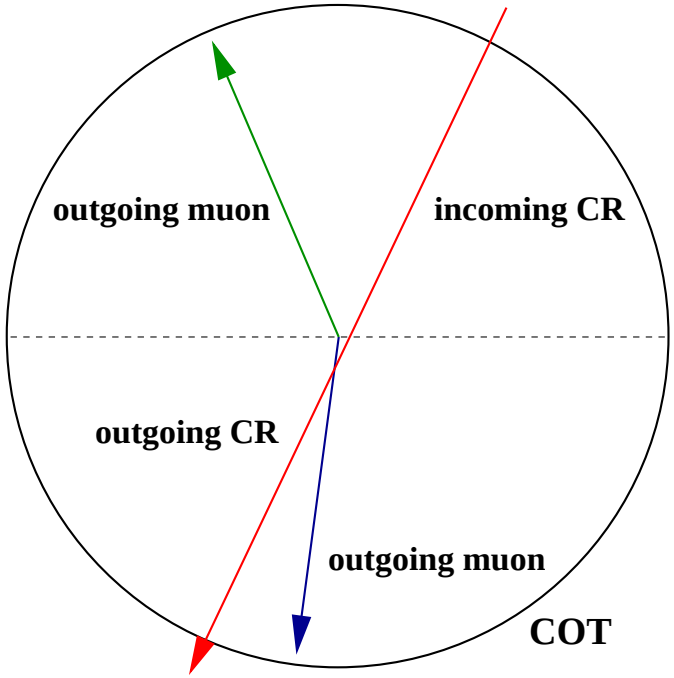


Dimuon Selection: ~ 7.5k candidates in 200 pb^{-1} data

- 2 isolated μ , p_T **> 20 GeV** (beam-constrained)

  μ_1: Central (trigger) | μ_2: $|\eta| < 1.5$

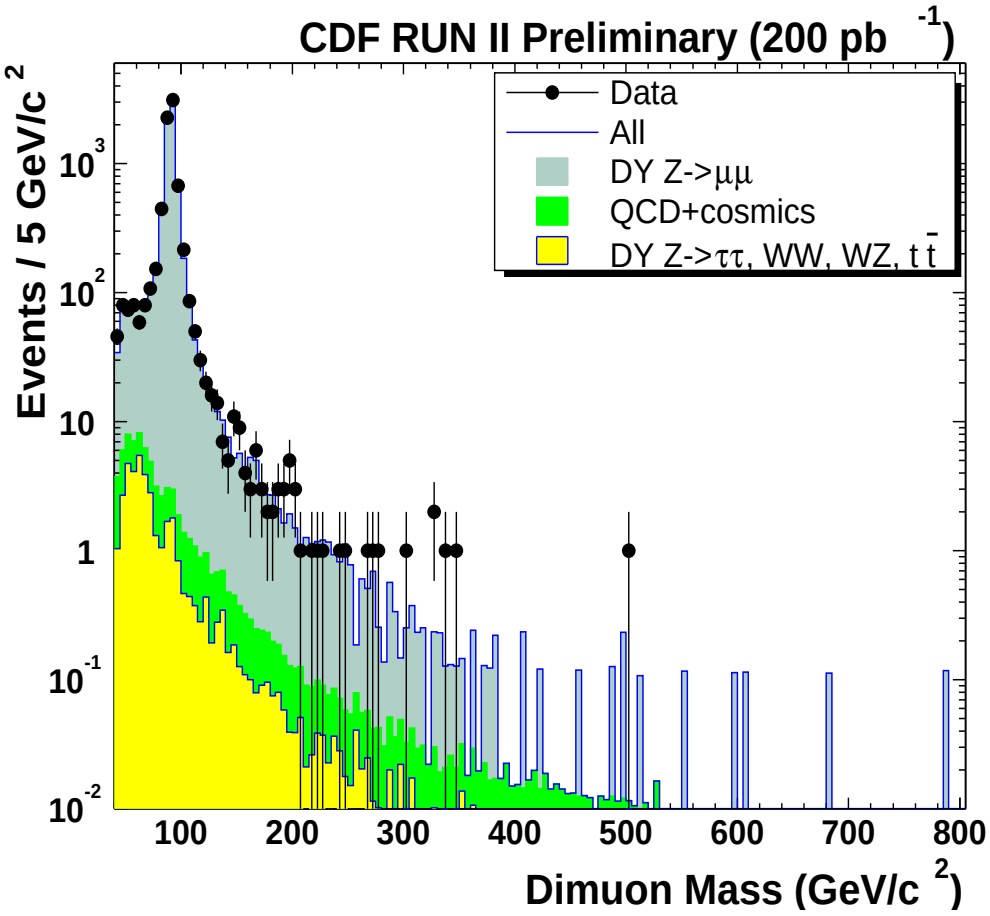
- μ_2 may include tracks w/o μ -chamber info.
- Constrain μ to CDF central region
- Momentum dependent cuts for high mass efficiency
- Veto cosmic rays using track-timing requirements
- Overall selection efficiency: $70 \pm 2\%$ (using Z/W events)
- Run II has **twice** the acceptance w.r.t Run I Z' analysis: usage of larger η coverage, optimized selection!



Backgrounds:

- Drell-Yan and other SM dimuons
- QCD where jet(s) or muonic decays of jets misidentified as high p_T muons
- Cosmic rays passing through the detector

Comparison to Expectation for μμ



Mass > (GeV/c^2)	N_{exp}	N_{obs}
200	20.88±0.97	18
250	9.44±0.49	9
300	5.22±0.32	6
350	3.23±0.24	1
400	2.28±0.19	1
450	1.79±0.16	1
500	1.24±0.13	1
550	1.03±0.11	0

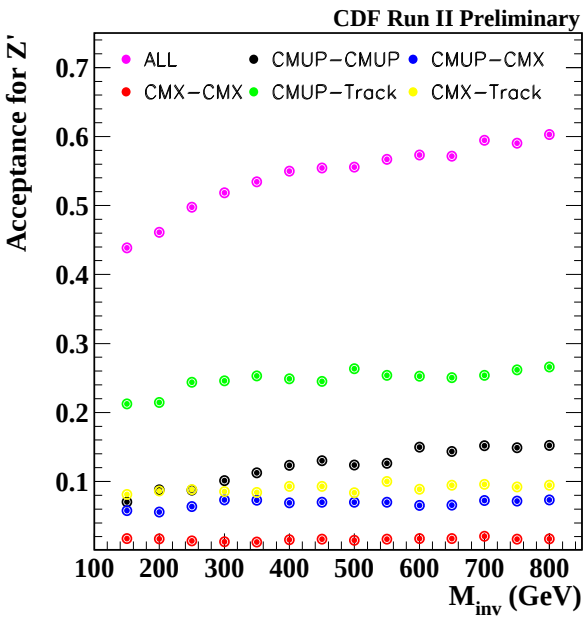
- High mass dilepton spectra consistent with prediction ➡ Proceed to set limits

systematic uncertainties:

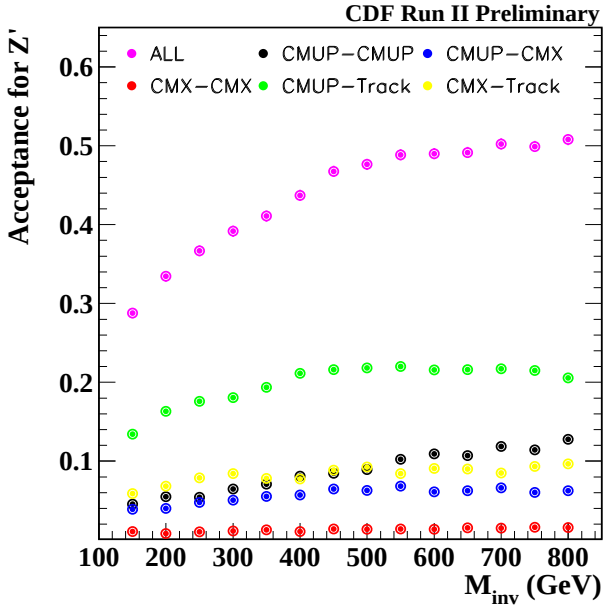
- Luminosity (6%), efficiencies
- PDF set choice
- Momentum scale/resolution
- Fake bgrnd normalization, ~20-30%
- Signal: ~8%, SM direct bgrnd: ~5%,

Signal Acceptances: ~50% at high mass

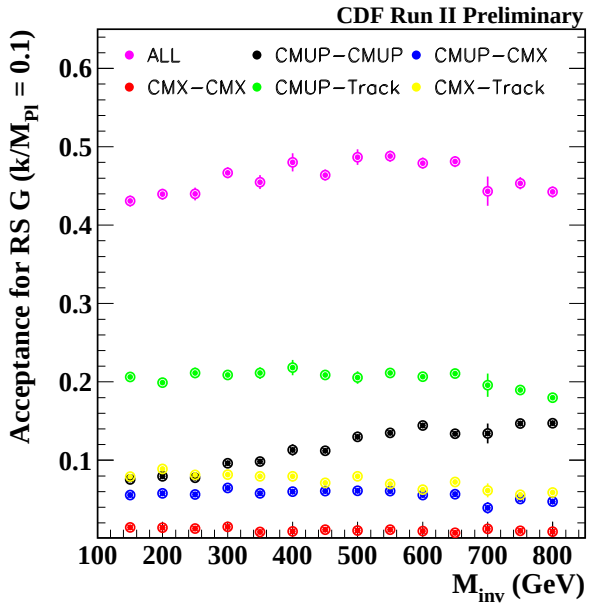
Spin-0 (Higgs)



Spin-1 (Z')



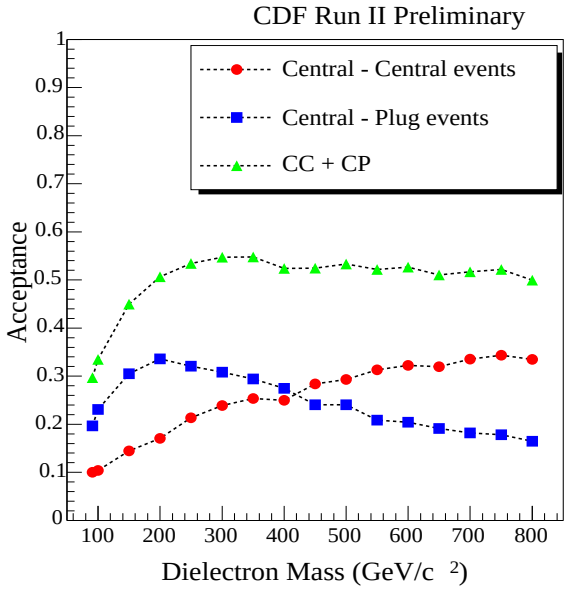
Spin-2 (RS G)



Angular dependence

➜ Variations in Acceptance

Spin-1 *ee*



Limits on New Physics: combine the channels!

- 95%CL upper limits on $\sigma \cdot BR(X \to \ell\ell)$ for spin-**0, 1, 2:**

$$L(\alpha/\eta) = \prod_i \frac{\mu_i^{n_i} e^{-\mu_i}}{n_i!}$$

- n_i: observed events
- $\mu_i = \alpha N_i^{sig} + N_i^{bgrd}$ *(resonant particles)*
- $\mu_i = N_i^{sig}(\eta) + N_i^{bgrd}$ *(LED spectrum)*

- Systematic uncertainties: via pseudo-experiments comparing nominal S+B templates to 1σ -varied templates
- Uncertainties separated into **correlated and uncorrelated** terms and a correlation matrix formed
- A **joint** likelihood formed from individual channels as posterior densities in signal cross section, $\mathcal{L}(\sigma)$.
- Final limits calculated by:

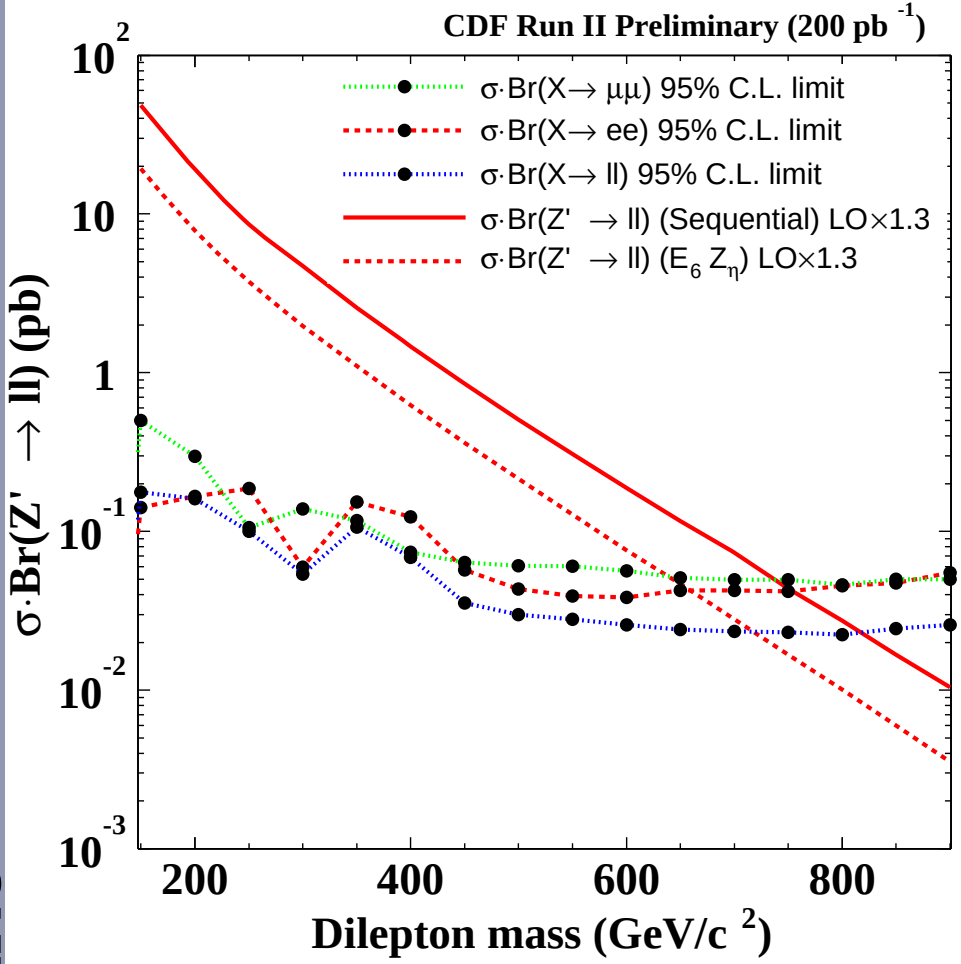
$$\mathcal{L}(\alpha) = \int_0^\infty \frac{d\alpha'}{\sqrt{2\pi(\Delta\alpha')^2}} \mathcal{L}(\alpha')\, e^{\frac{-(\alpha-\alpha')^2}{2(\Delta\alpha')^2}}$$

- 95%CL cross section limits, via **integration**:

$$\mathcal{L}(\sigma_{95}) = (\text{norm.}) \int_0^{0.95} \mathcal{L}(\sigma)\mathrm{d}\sigma$$

Results - Spin-1 particles: the Z' saga continues!

- $\sigma \cdot BR(X \to \ell\ell) \sim< \mathbf{25\ fb}$ (95%CL), for M > 600 GeV/c^2
- Lower mass bounds on SM-like Z', E_6 model Z' (del Aguila *et al.*, **NPB287/87**)



$M_{Z'}$ Lower Mass limit (GeV/c^2)

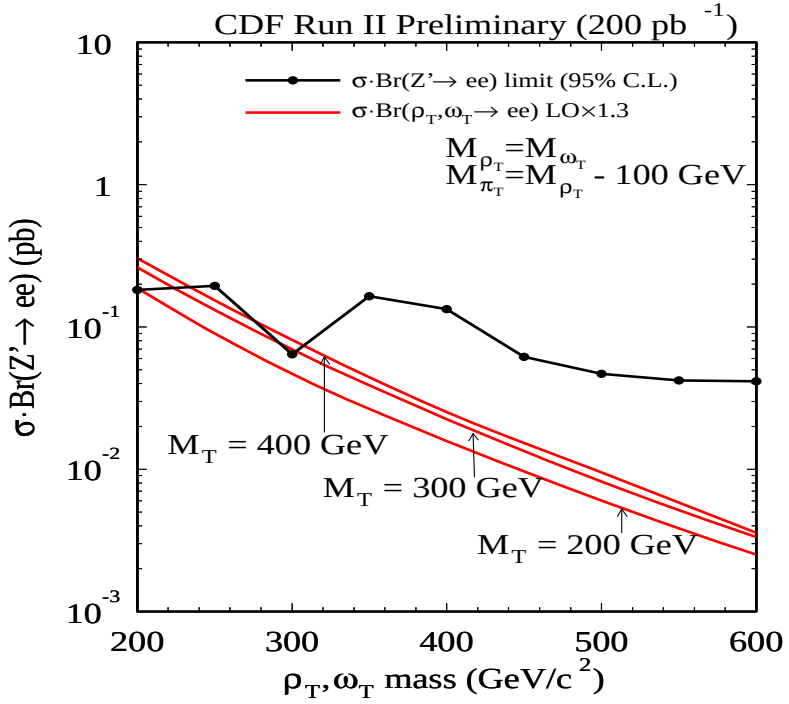
Model	*ee*	μμ	*ll*	*ll* Run I
Z'_{SM}	750	735	**815**	**690**
Z'_{ψ}	635	600	690	
Z'_{χ}	620	585	670	
Z'_{η}	655	640	715	620
Z'_{I}	575	540	610	

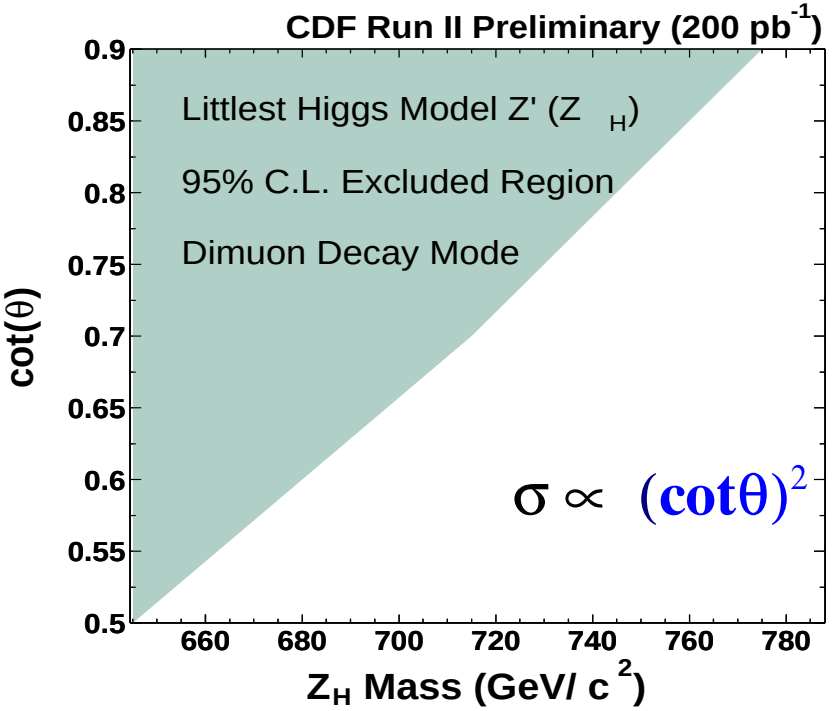
θ_{E6}	0	π/2	$\sin^{-1}\sqrt{3/8}$	$\sin^{-1}\sqrt{5/8}$
Z'	Z_{χ}	Z_{ψ}	Z_{η}	Z_{I}

- D0 Run II **ee** preliminary limit: M > **780** GeV/c^2

(First) Results for T-mesons ρ_T , ω_T & Little Higgs SU(2) Z_H

Lane&Mrenna, **PRD67/99** Han *et al.*, **PRD67/03**





TechniColor Mass limit (GeV/c²)

M_T	*ll*
500	**320**
400	315
300	310
200	225

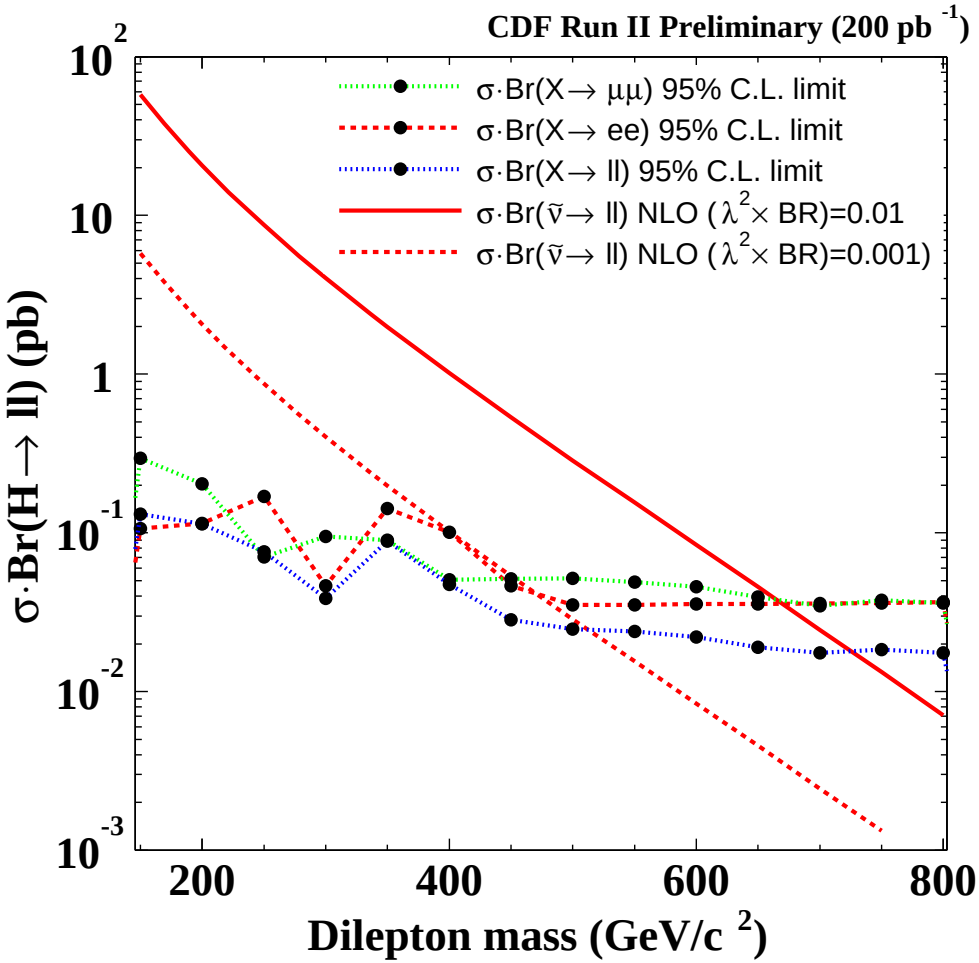
- M > **200-300** GeV/c² (*ee*, D0, **PRL87/01**)

Z_H Mass limit (GeV/c²)

cotθ	*ee*	μμ	*ll*
1	810	805	**875**
0.9	785	780	850
0.7	735	715	800
0.6	700	685	765
0.5	665	640	720

Results - Spin-0 particles: First direct limits on stau-ν

- $\sigma \cdot BR(X \to \ell\ell) \sim< \mathbf{20\ fb}$ (95%CL), for M > 600 GeV/c^2
- Lower mass bounds on a RPV τ -sneutrino using NLO theory curve
- $\sigma \propto \lambda'^2_{Yukawa} \times$ **BR** (Choudhury *et al.*, **NPB660/03**)



$M(\tilde{\nu})$ Lower Mass limit (GeV/c^2)

$\lambda'^2 \times$ BR	*ee*	μμ	*ll*
0.1	670	665	**725**
0.05	615	590	665
0.01	470	455	510

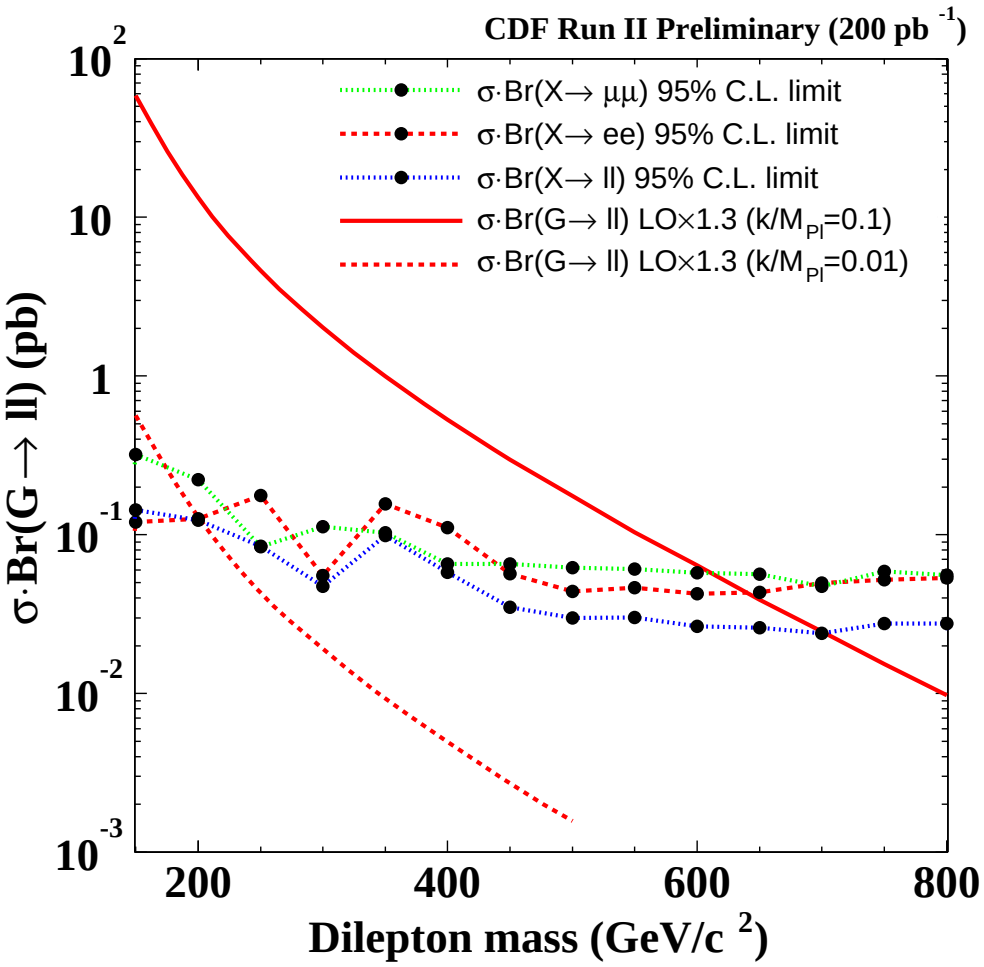
- Prev. limits: M < **100** GeV/c^2 (**PDG03**)

(mostly model dependent)

Results - Spin-2 particles: First direct limits on RS G*

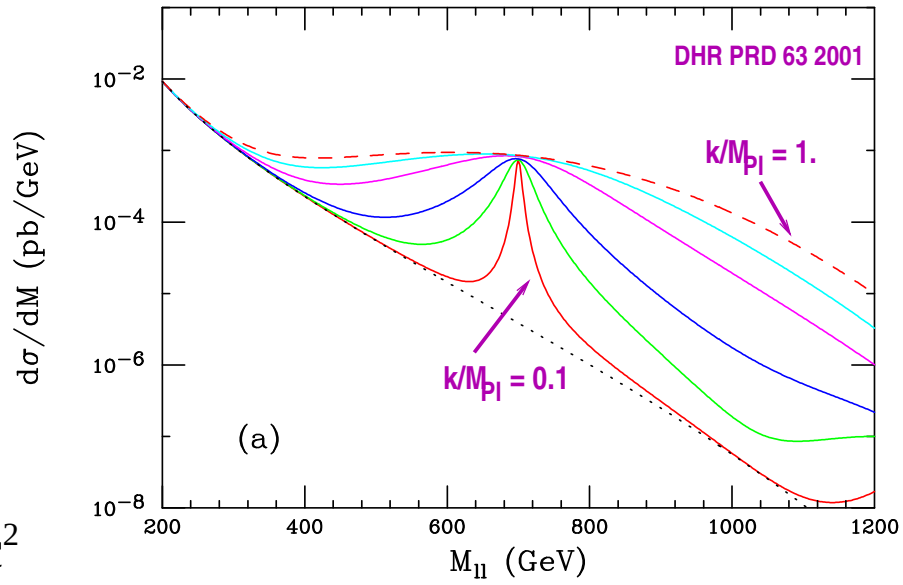
Randall&Sundrum, **PRL83/99**

- $\sigma \cdot BR(X \to \ell\ell) <$ **25 fb** (95%CL), for M > 600 GeV/c^2
- Lower mass bounds on the 1st excited state of a RS graviton, w/ coupling **k/M_{Pl}**



M_G Lower Mass limit (GeV/c^2)

k/M_{Pl}	*ee*	μμ	*ll*
0.1	640	610	**700**
0.07	555	530	610
0.05	485	455	525
0.01	200	170	200



- D0 Run II diEM preliminary: M > **785** GeV/c^2

Results - Spin-2 particles: LED

ADD, **PLB429/98**

- Virtual G exchange, sum of KK modes
- M_{ee} distribution for binned likelihood in η_G
- Limits on η_G ➡ on M_S , various formalisms:

$$\sigma = \sigma_{SM} + \eta\,\sigma_{int} + \eta^2\sigma_{KK}$$
$$\eta = \lambda / M_s^4,\ \lambda_{Hewett} = \pm 1$$

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

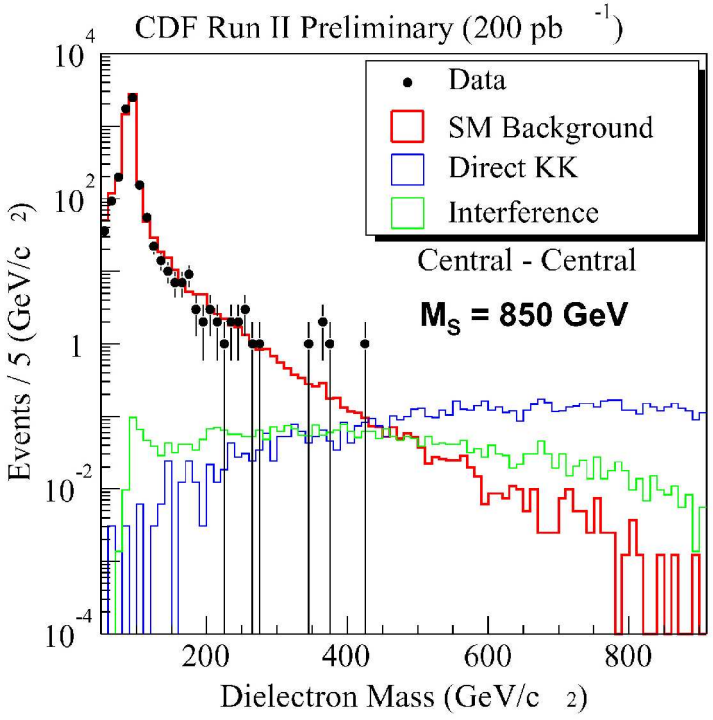
Giudice, Rattazzi, Wells Han, Lykken, Zhang

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**

0.78 0.77 CDF I (*ee*)

1.1 D0 I (diEM)

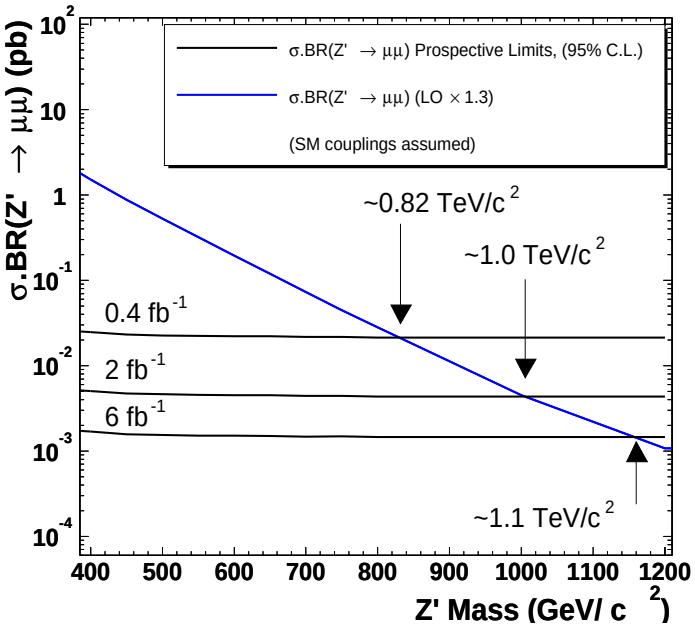


- D0 Run II **diEM** preliminary: $M_S >$ **1.36** TeV

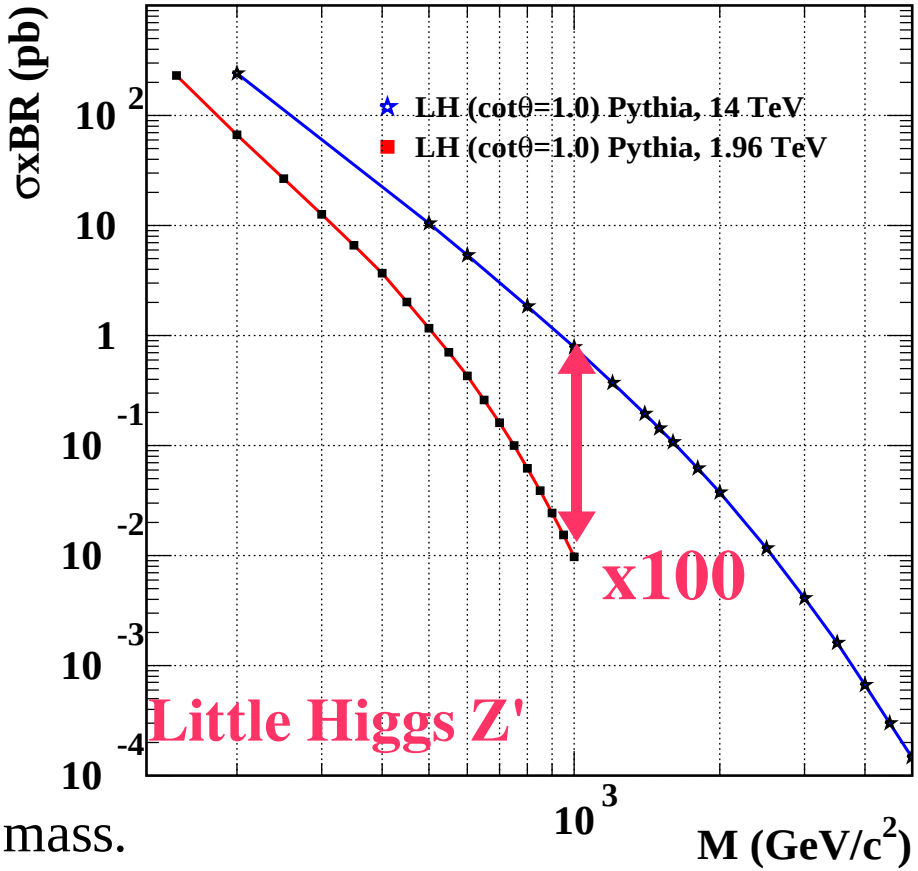
Future prospects at LHC: find 'em *or* destroy 'em!

Heavy gauge boson prospects:

- Tevatron: Z' limits w/ null obs/bgrd, cannot push too far...

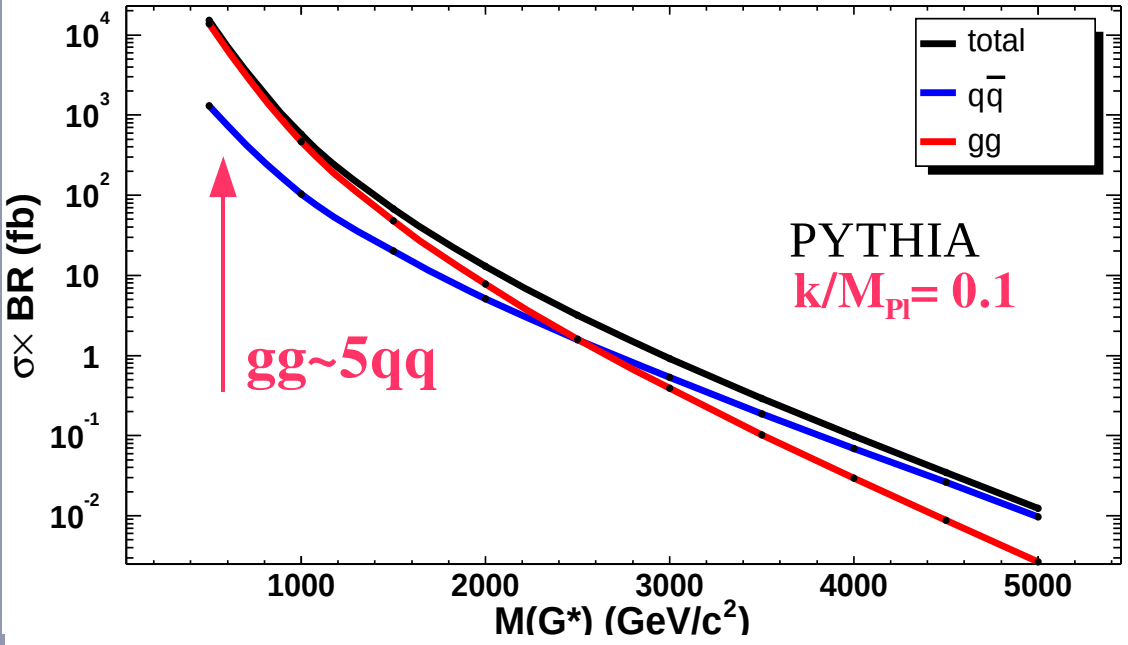


- LHC (**14 TeV**): for a **2 TeV/c²** SM-like Z', after running one year (**20 fb⁻¹**), as many as **2000** events!



- Angular distributions to distinguish, if peak observed!
- DY irreducible bgrd suppressed at high mass.

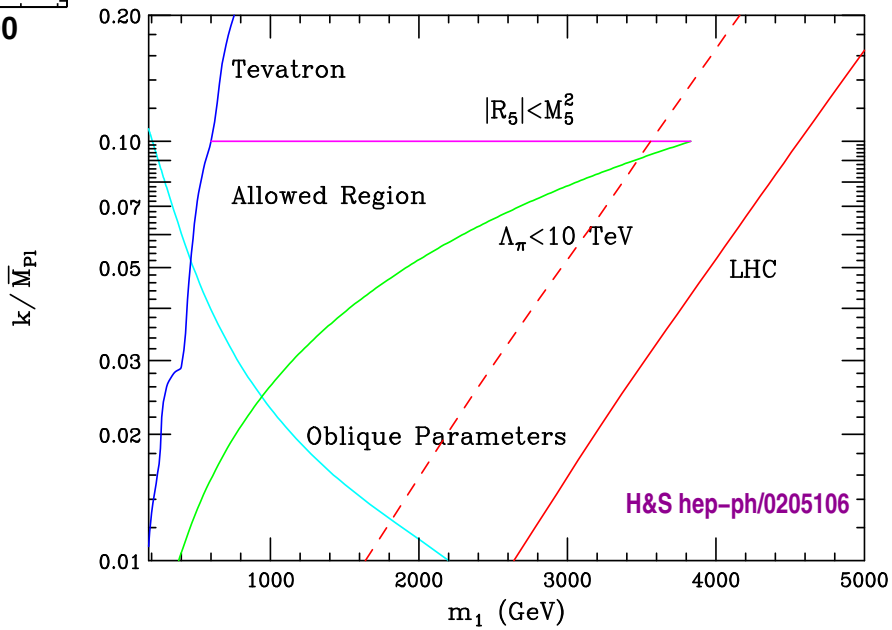
Future prospects at LHC: Extra Dimensions



- For 1st year of running, reach as high as ~**2TeV/c²** for 100 events (generator level, assume 50% acceptance)!

- NLO corrections (K_f) ~1.6 at LHC

  (Mathews, et al., **IPPP04/70**)



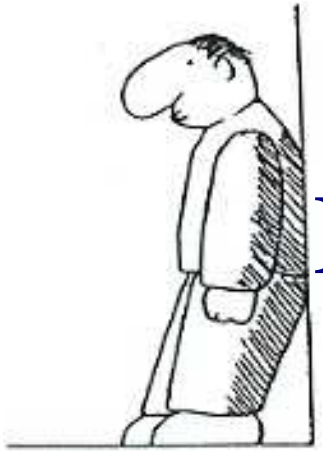
Conclusions

✌ CDF **analyzed** 200 pb^{-1} high mass *ee*+μμ data and set preliminary combined σ •BR and mass constraints on various particles @95%CL.

❦ We have **surpassed** sensitivity of Run I searches. Current CDF limits **exceed** the published limits of previous direct searches. We are updating and **finalizing** the results and their interpretation, for publication.

❦ We also **pioneered** exploration of some models and search strategies and obtained the first Tevatron results within ED, RPV-SUSY, TC and LH.

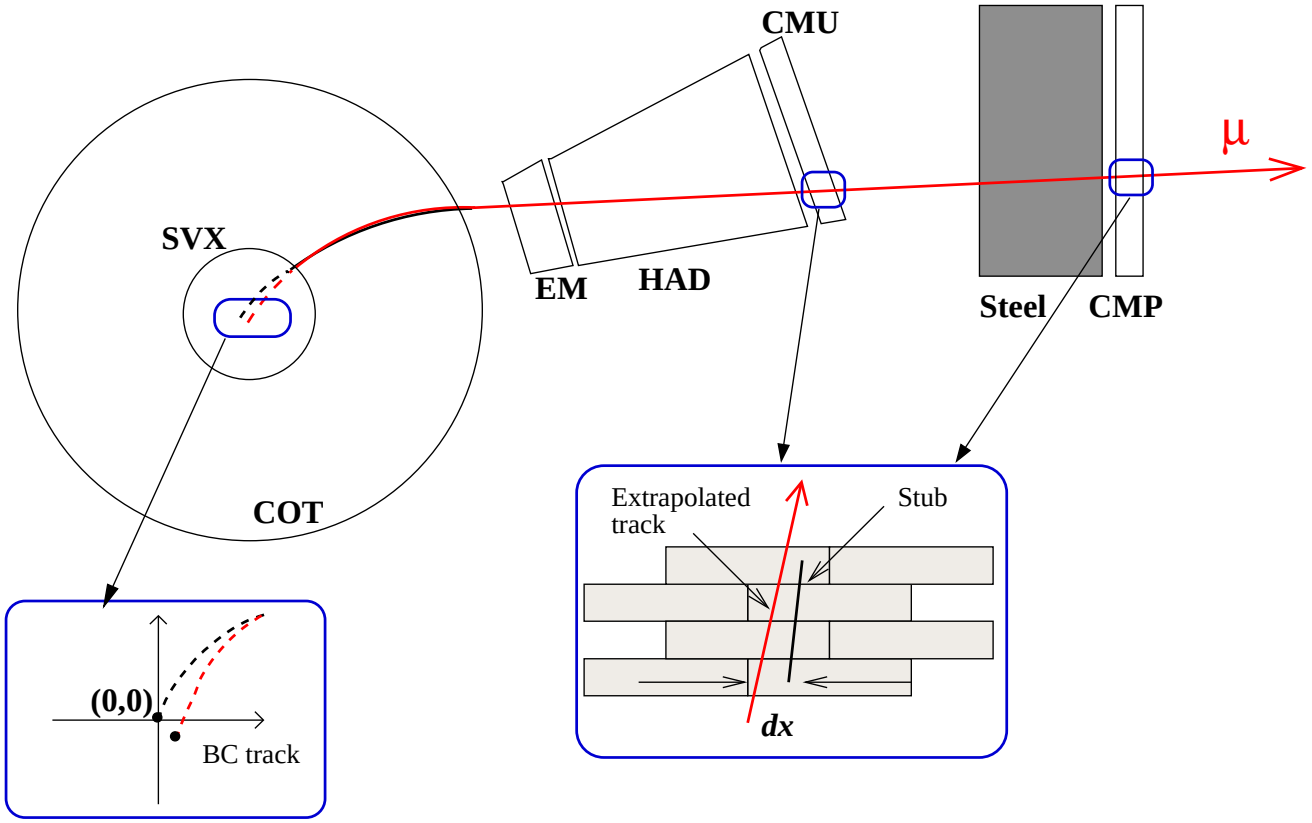
☞ LHC will **benefit** from the experiences gained at the Tevatron and will **nail down** the BSM! Stay tuned!



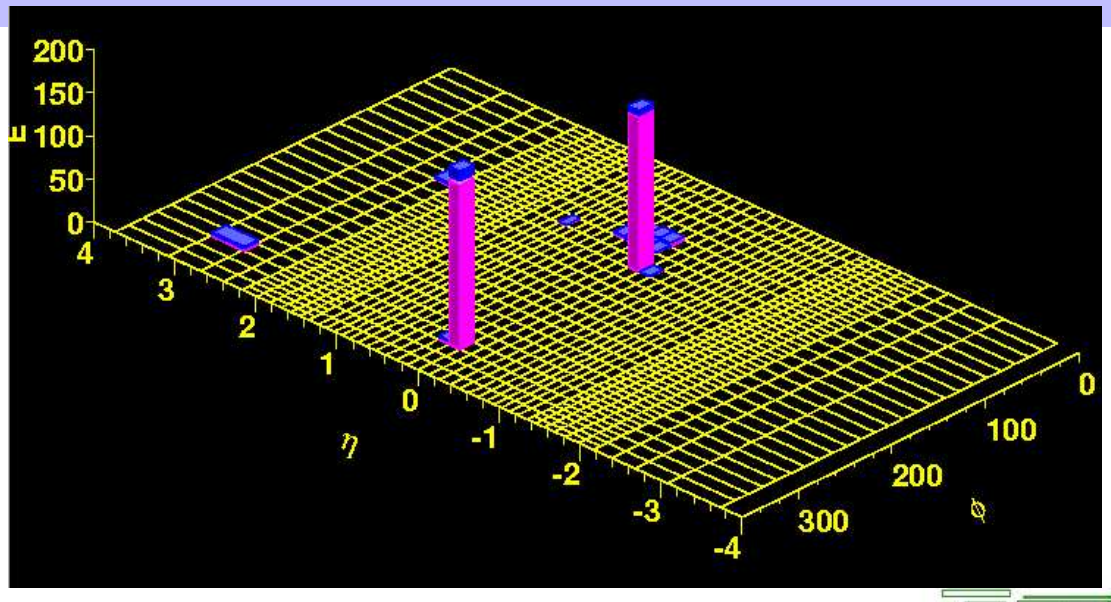
Backup Slides

Data Sample: Inclusive High E_T electron and muon triggers

- μ triggered on a central μ chamber "stub" **matched** to a track in tracker (+ scintillator tags, if available).
- μ 4-mom. obtained from tracker and tagged by μ -stubs (using $r-\phi$) during reconstruction **->** 8 dimuon types possible!
- ***e*** triggered on a central EM (or jet) cluster **matched** to a track in the central tracker (**if** low E_T threshold) **->** high efficiency aimed!

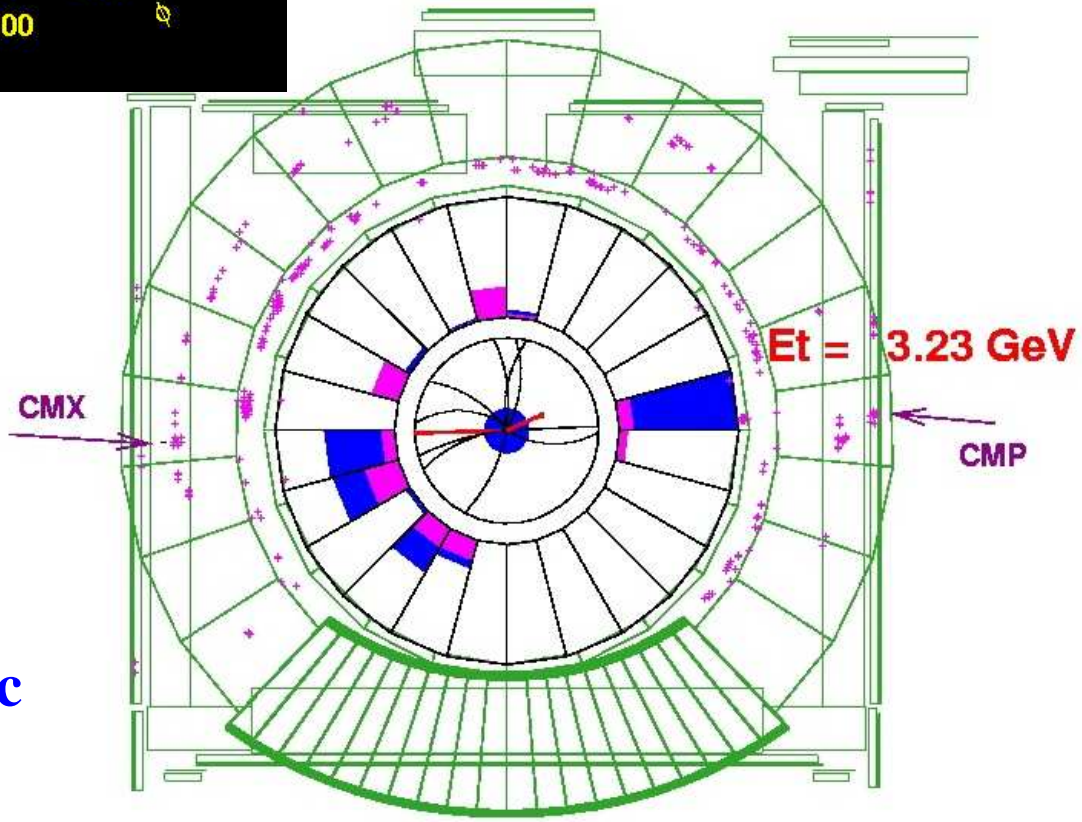


Typical High Mass Dilepton Events:



$M_{ee} = 371\ GeV/c^2$

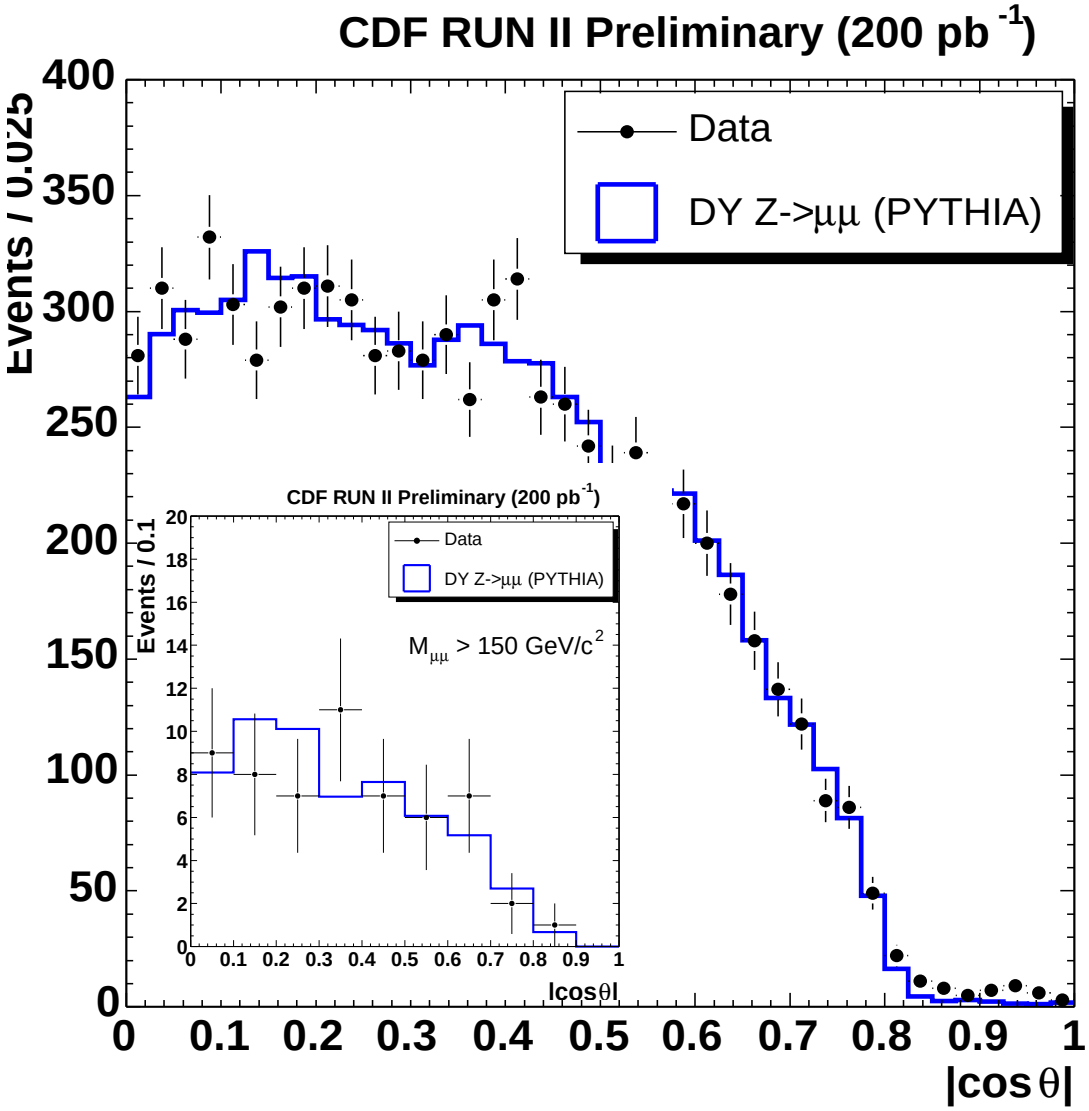
$E_{T1,2} = 203, 180\ GeV/c$



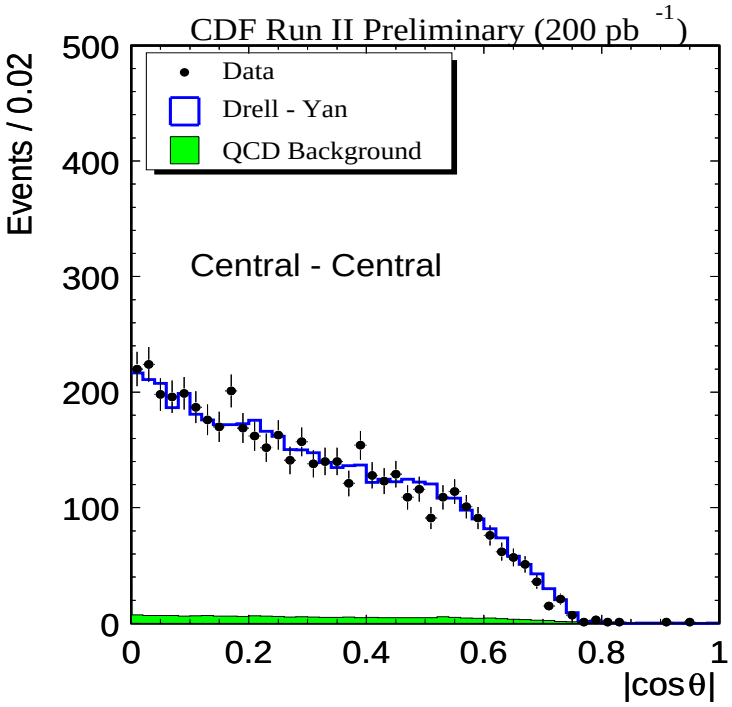
$M_{\mu\mu} = 203\ GeV/c^2$

$p_{T1,2} = 104, 89\ GeV/c$

Comparison to Expectation: cosθ* spectra in agreement with data

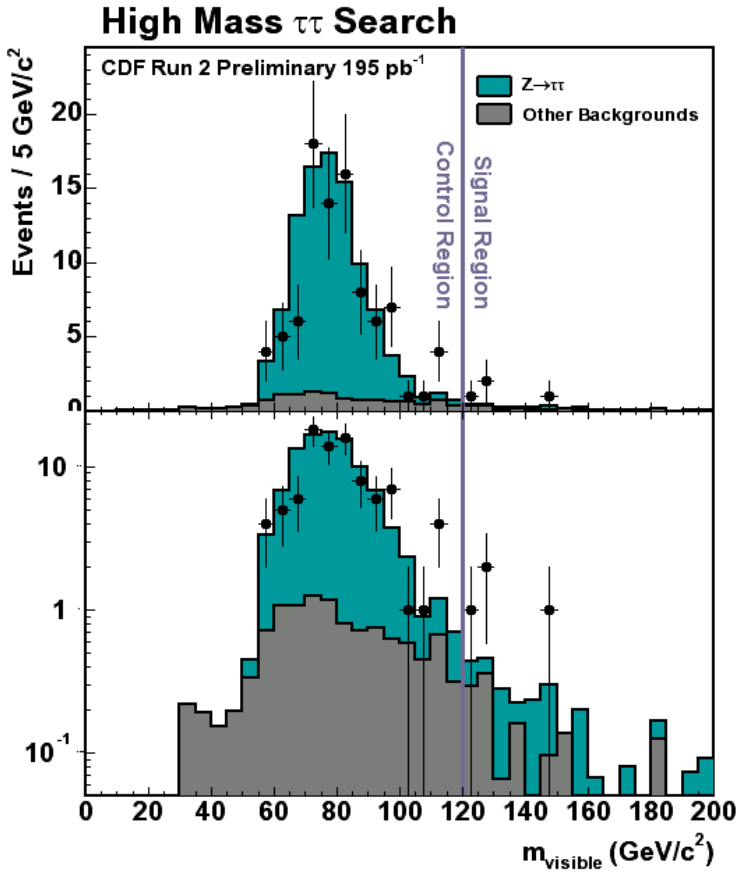


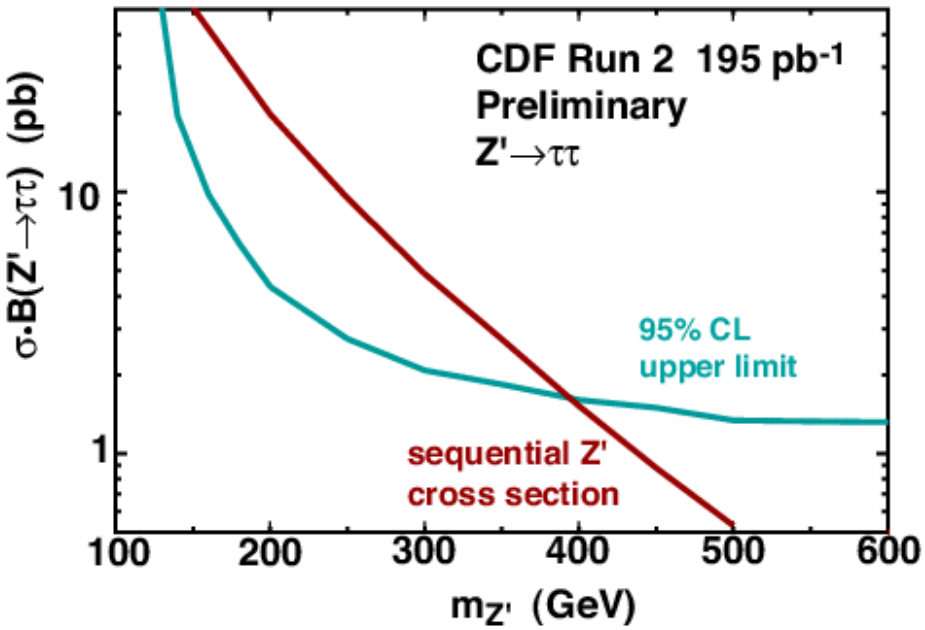
- Not used in the final results



$$\cos\theta^*_{CS} = \frac{2}{M\sqrt{M^2+P_T^2}}\left(\ell_1^+\ell_2^- - \ell_1^-\ell_2^+\right) \quad ,\ell_i^\pm = \frac{1}{\sqrt{2}}(\ell^0 \pm \ell^3) \quad ,i = 1,2$$

Ditau Z' Results: First TeV results with 3rd generation!





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

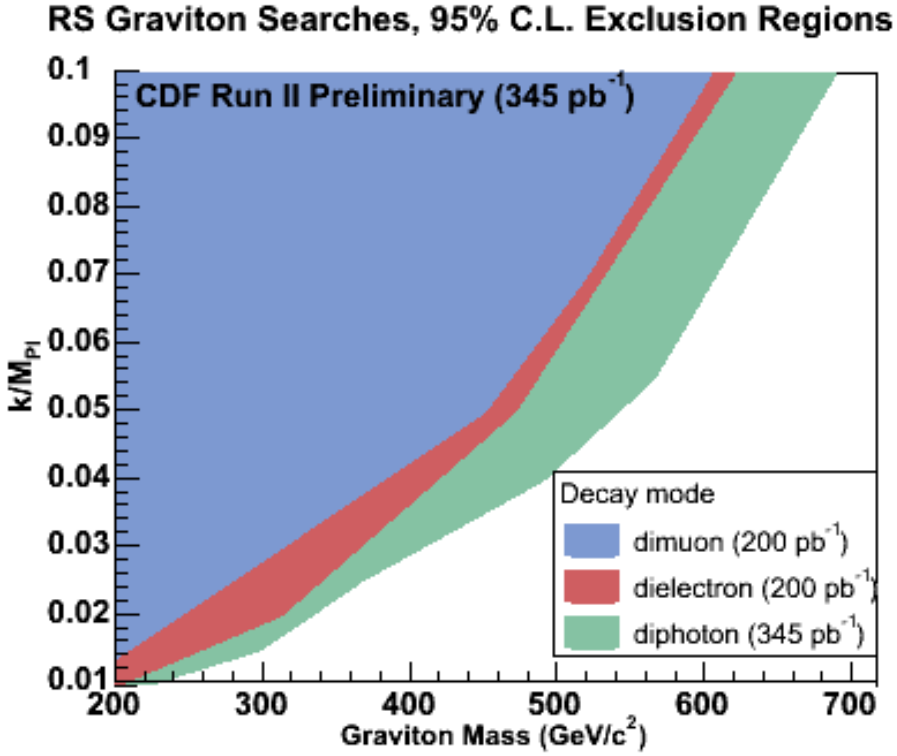
ee	μμ	ττ
~50	~50	~1500

Lower Limits on $M_{Z'}$ (GeV/c^2)

ee	μμ	ττ
620	605	395

Diphoton Results for RS Graviton

- Counting limits using 3σ mass window around reference RS G mass



BR(G→ℓℓ) = ½ B(G→γγ)

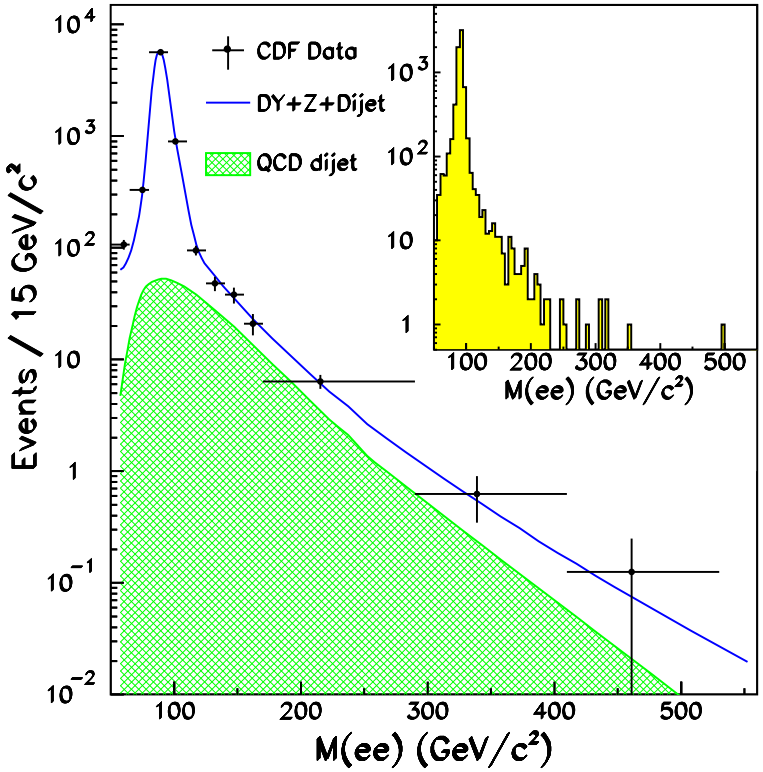
Upper Limits on σ•BR (fb), at high mass

ee	μμ	γγ(375 /pb)
~50	~50	~70

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

ee	μμ	ℓℓ	γγ
620	605	700	690

CDF Run I high mass spectra: Limits at 1.8 TeV



ee

μμ