

# Searches for “exotica” with the Detector

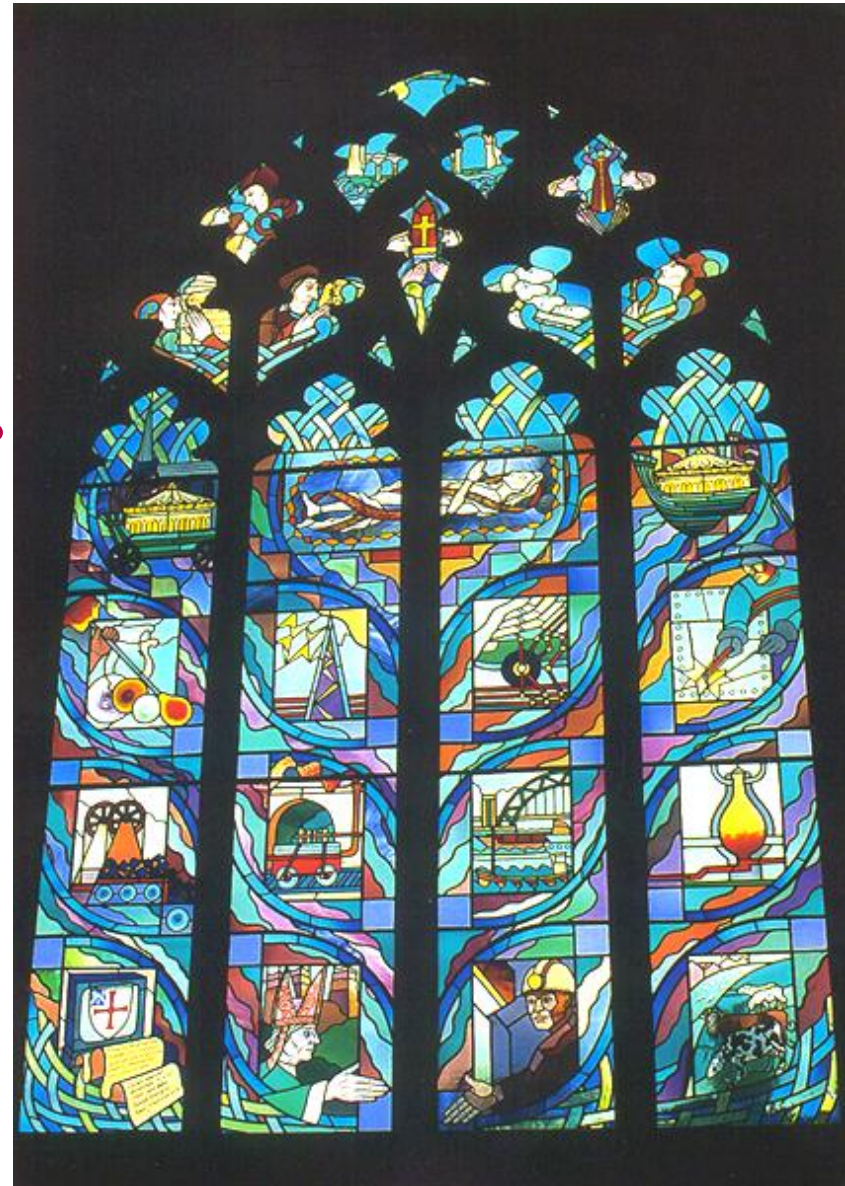
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**Oxford University**

*for the CDF Collaboration*

SUSY05 Conference, IPPP, Durham

July 18-23, 2005



The Millennium Window, Durham Cathedral

# Motivation and Strategy:



- ◆ Many questions unexplained by SM: **need BSM!**
- ◆ What can be (non-SUSY) BSM? Many possibilities!
  - ➔ Extended gauge symmetries, Dynamical EWSB, Extra dimensions, Compositeness, ...
- ◆ Many give rise to signals that can be searched in various signatures.
- ◆ A search for anomalous behavior in data will reveal hints.
- ◆ Need to estimate model signal acceptances.
- ◆ Need to understand the detector and optimize the signal.



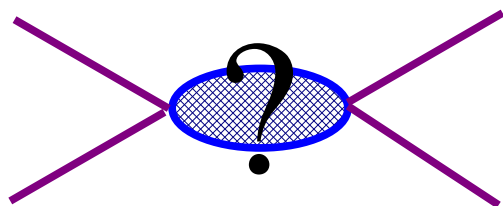
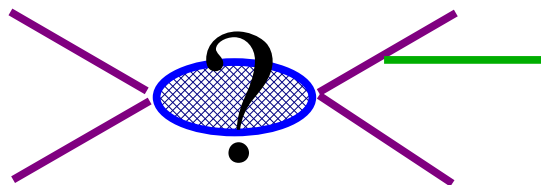
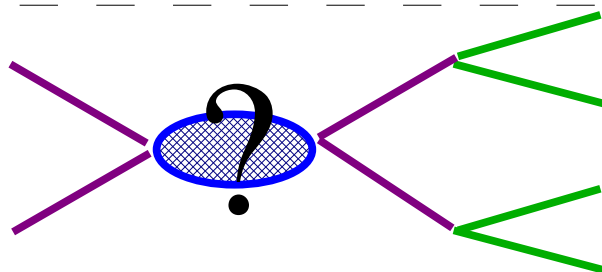
# Current Searches for non-(SUSY/Higgs) Physics:



## Process

## Particles

## Final State


 $Z'$ 
 $ee, \mu\mu, \tau\tau$ 
 $W'$ 
 $e\nu$ 
 $b'$ 
 $\mu\mu$ 
 $RS\ G$ 
 $ee, \mu\mu, \gamma\gamma$ 
 $LED\ G$ 
 $ee, j+ ME_T^*$ 

 $e^*$ 
 $ee+\gamma$ 

 $LQ$ 
 $ll+jj$ 

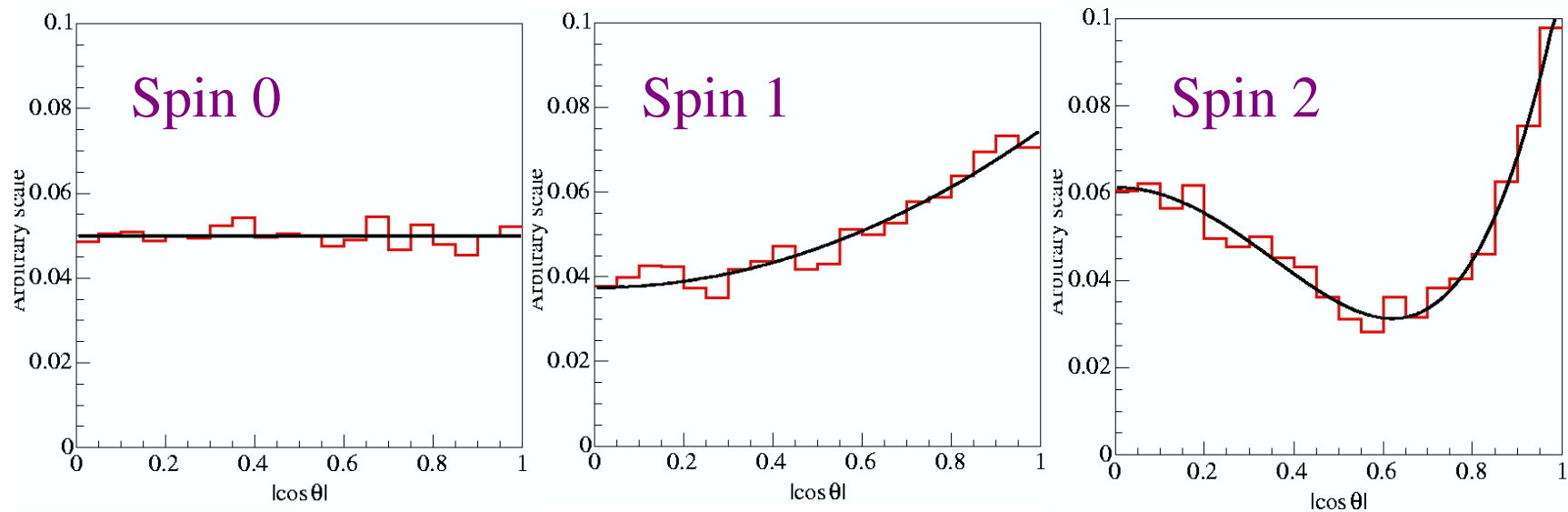
\*coming real soon!

 Only a selection of exotica presented here. For complete results by CDF: <http://www-cdf.fnal.gov/physics/exotic/exotic.html>

# One Strategy: Search for resonances in CDF data!

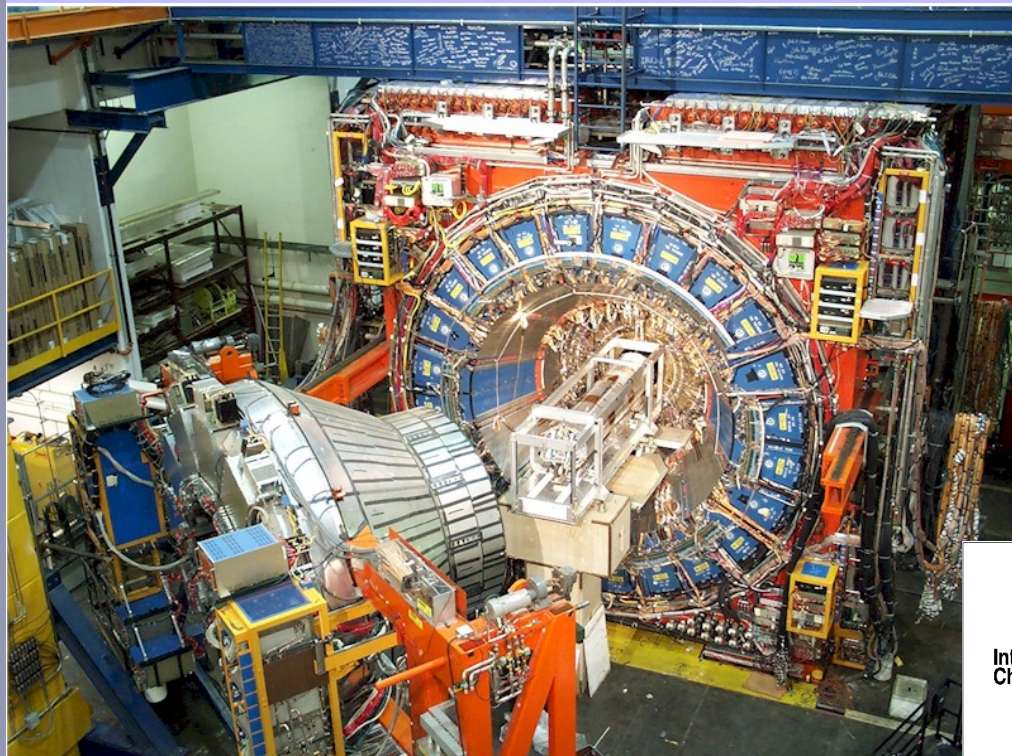


- Dileptons: clean data samples with manageable backgrounds.
- Many predicted particles best observed in dilepton decays
- A detector's sensitivity  $\propto$  **acceptance**. For a quasi-model
- independent search, categorize particles w.r.t. spin properties.



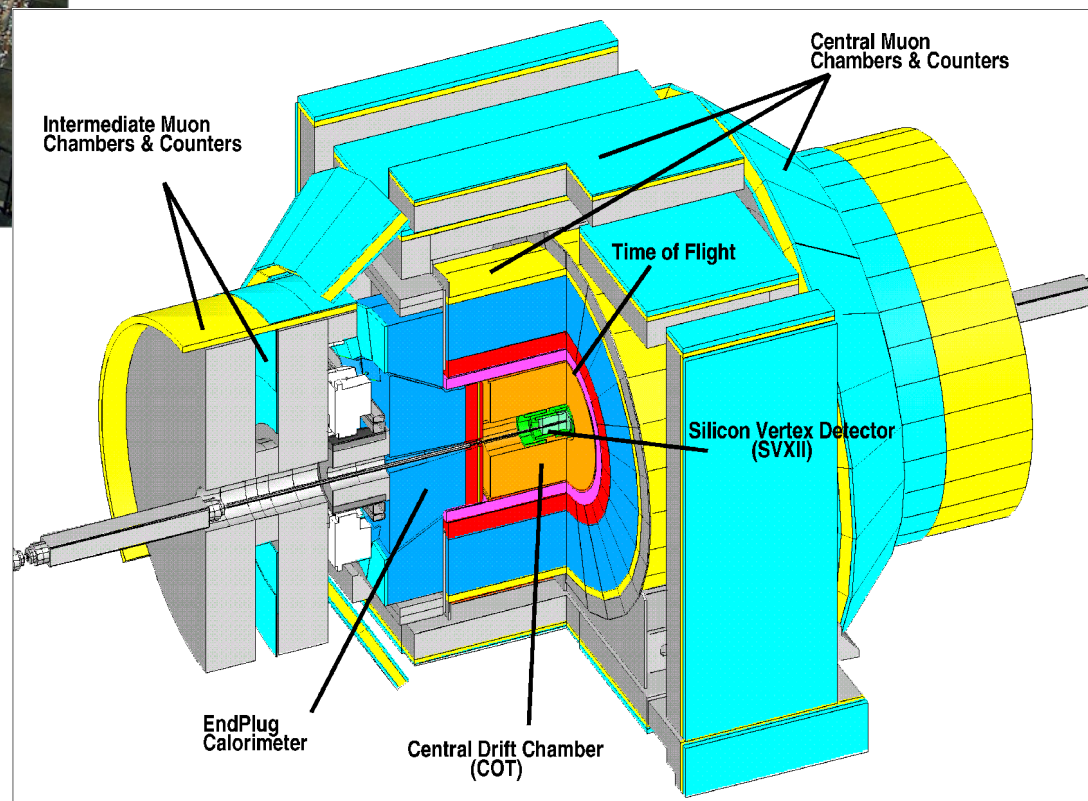
- Dileptons used for resonance searches in:
  - **Spin-0:** SUSY ( $R_p$ -violating s-v) – *see T.Kamon's talk*
  - **Spin-1:**  $Z'$  (SM-like,  $E_6$ , little Higgs), Technicolor ( $\rho_T$ ,  $\omega_T$ )
  - **Spin-2:** RS Graviton

# CDF@TeVatron: Where we search for exotica!



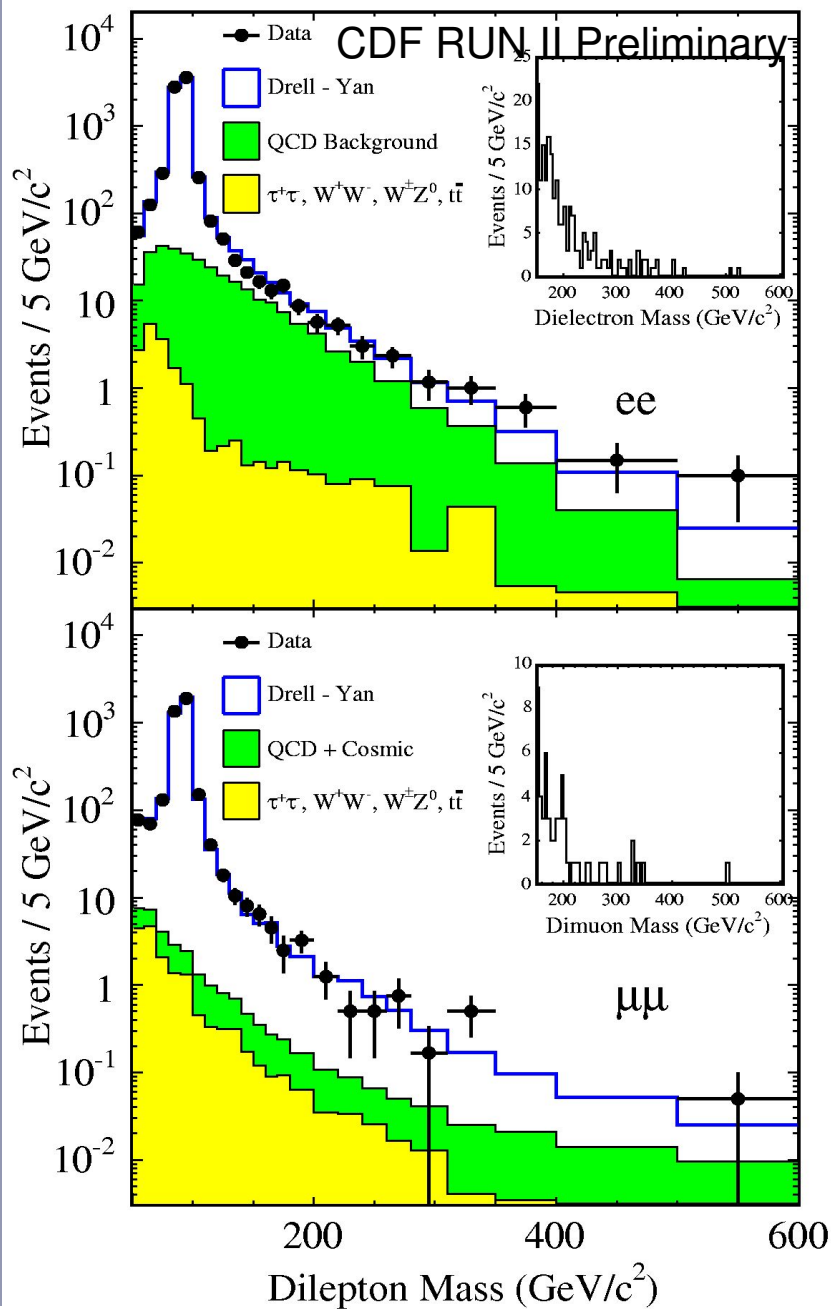
- ✓ More than  $1.0 \text{ fb}^{-1}$  delivered.
- ✓ Expected **4-8  $\text{fb}^{-1}$**  by end of '09.
- ✓ Analysis shown use initial  $0.2 - 0.45 \text{ fb}^{-1}$

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





# Dilepton Selection in 200 pb<sup>-1</sup> Data:



- 2 isolated  $e$  ( $\mu$ ),  $E_T(p_T) > 25$  (20) GeV/c
- Uses both Central and Forward electrons  
Forward dielectrons: **NEW!**
- at least one  $e$  with track required for  $e$ -pair  
(Central pairs require both)

## Backgrounds:

- Drell-Yan and other SM backgrounds
- QCD where jet(s) misidentified as leptons
- Cosmic rays passing through CDF

## Systematic uncertainties:

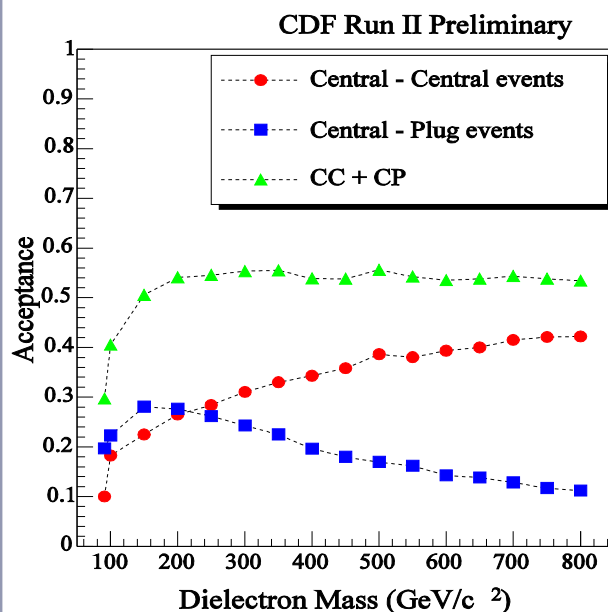
- Luminosity (6%)
- E/p scale/resolution, efficiencies, PDF
- Total signal unc: ~10%
- Background shape and normalization
- $e$  (QCD): 40-80%,  $\mu$  (QCD,cosmic): 20-30%



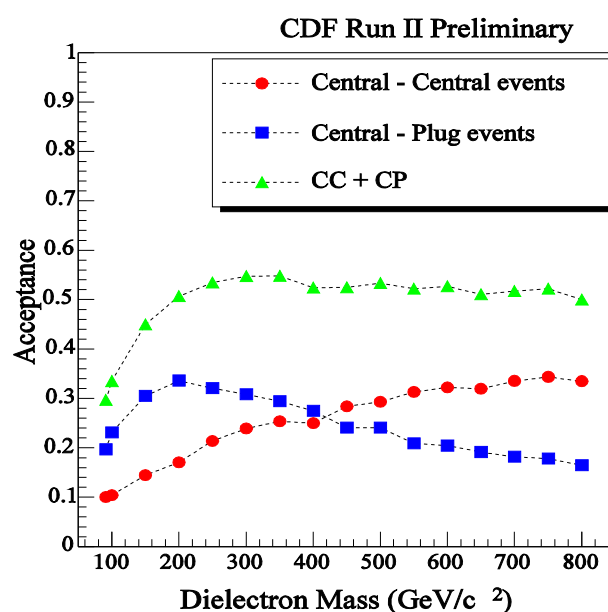
# Dilepton Searches in $200 \text{ pb}^{-1}$ Data:

- ◆ High mass dilepton spectra consistent with prediction
  - ➔ limits for spin 0,1,2 particles
- ◆ Signal acceptances  $\sim 50\%$  at high mass, for both channels
- ◆ Combination: double the data size!
- ◆ Test lepton universality comparing individual channels!

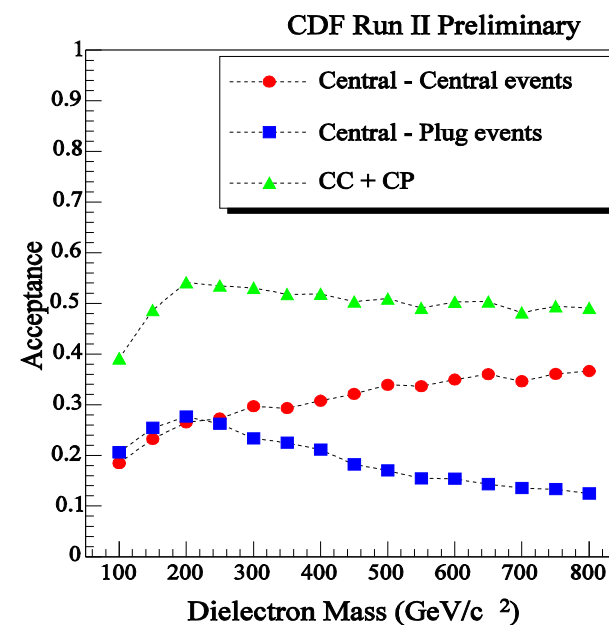
## Spin-0



## Spin-1



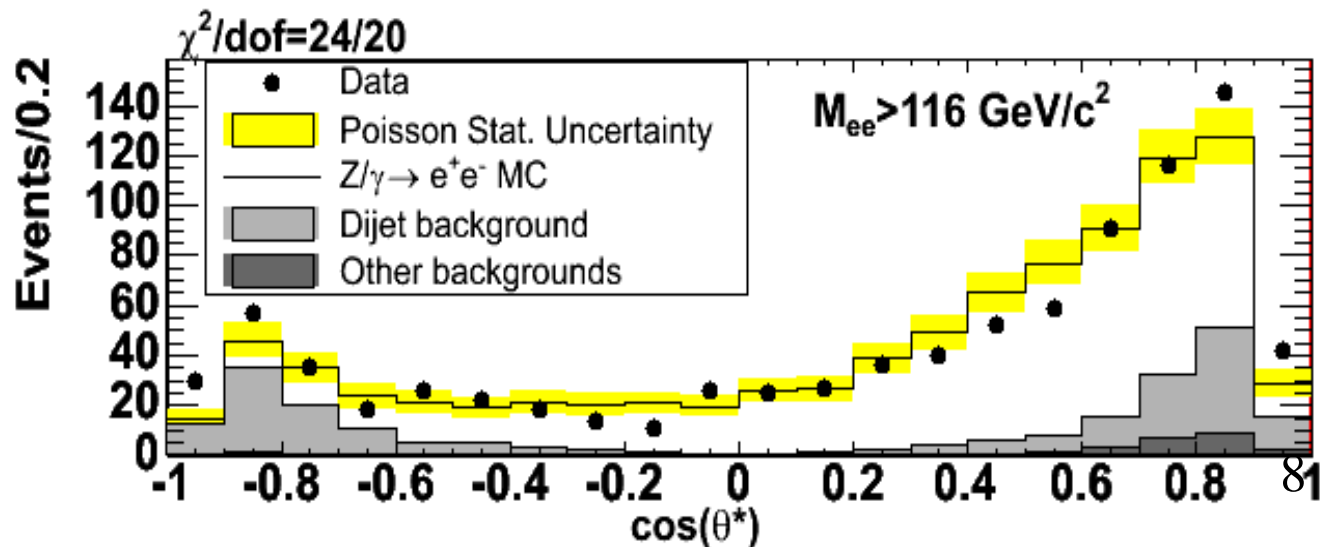
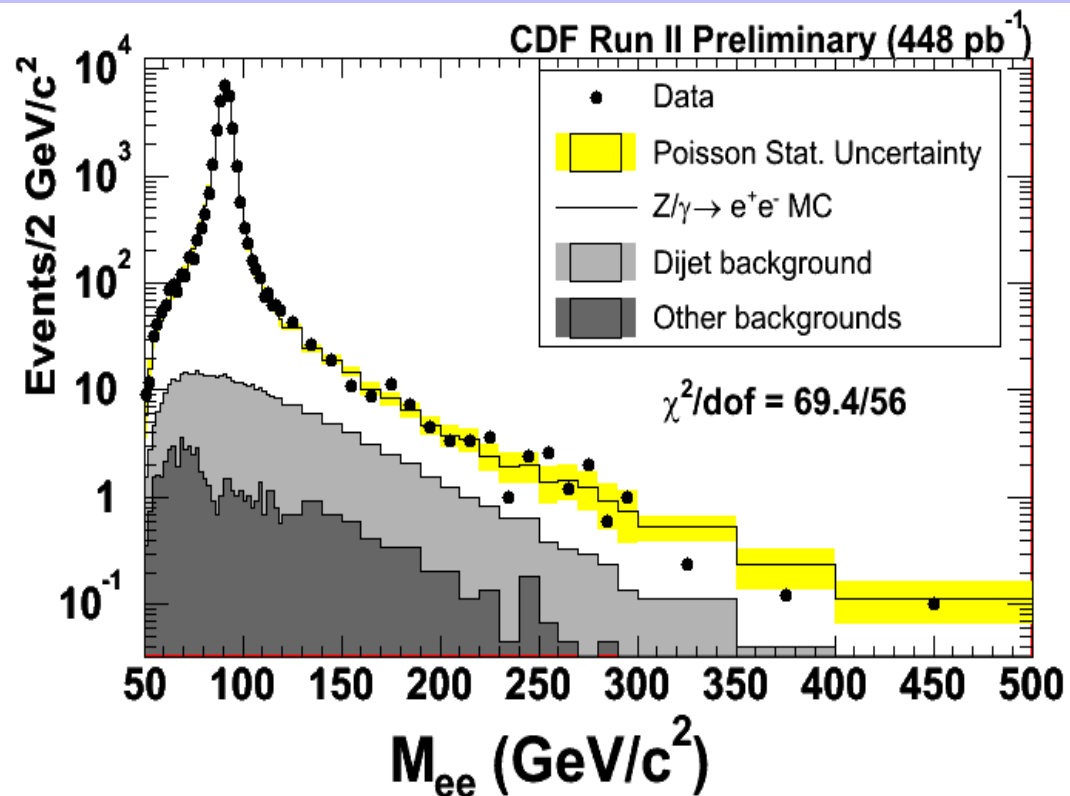
## Spin-2





# Dielectron Selection in 450 pb<sup>-1</sup> Data:

- 2 isolated  $e$ ,  $E_T > 25$  GeV/c
- both  $e$  require track-match
- Uses only Central electrons
- Utilize both  $M_{ee}$  and  $\cos\theta^*$ 
  - ~25% improvement in limits over  $M_{ee}$ -only
- $N_{\text{pred}} = 125 \pm 11(\text{stat})$ ,  
 $N_{\text{obs}} = 120$ , for  $M_{ee} > 200$  GeV/c<sup>2</sup>
- Excellent agreement!

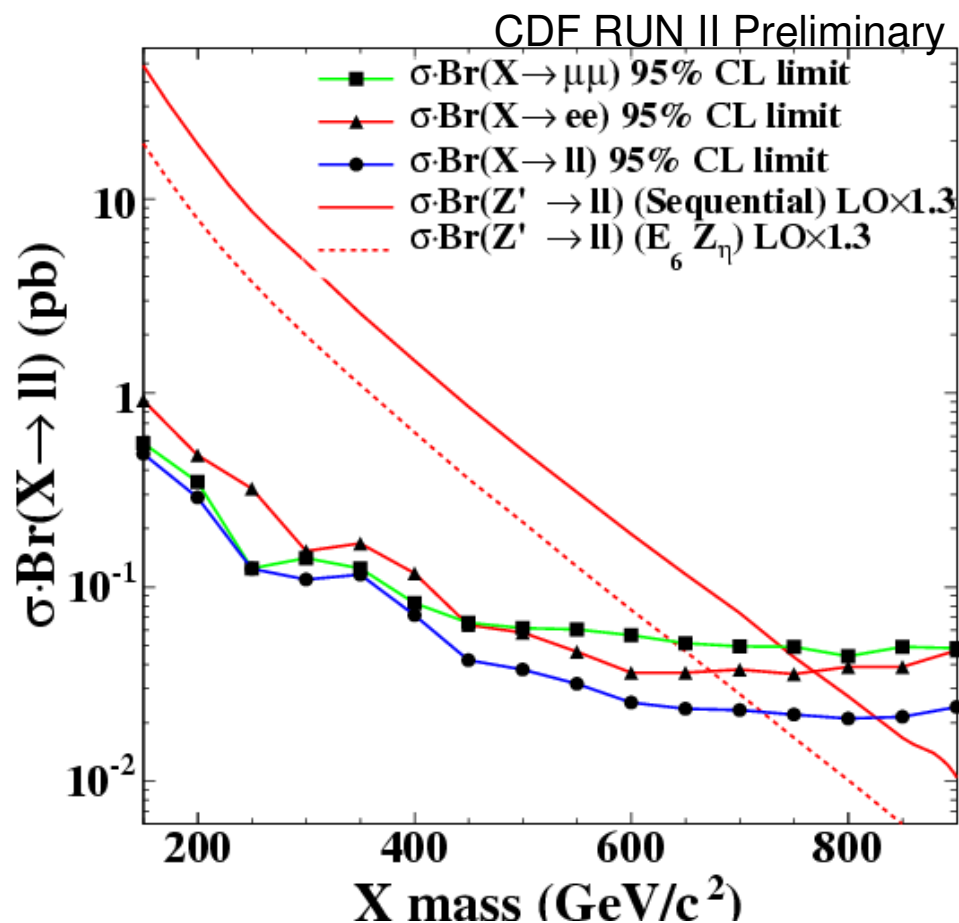






# Heavy Neutral Gauge Bosons: Spin-1 ( $200 \text{ pb}^{-1}$ )

- Spin-1 results:  $\sigma \cdot \text{BR}(X \rightarrow \ell\ell) < \sim 25 \text{ fb}$  (95%CL), for  $M > 600 \text{ GeV}/c^2$
- Lower mass bounds on SM-like  $Z'$ ,  $E_6 Z'$  (del Aguila *et al.*, NPB287-419/87)



- D0 Run II prelim. limits in  $200\text{-}250 \text{ pb}^{-1}$ :  
 $M > 780$  ( $680$ )  $\text{GeV}/c^2$ , for  $ee$  ( $\mu\mu$ )

## $M_{Z'}$ Lower Mass limits ( $\text{GeV}/c^2$ )

Model	$ee$	$\mu\mu$	$\ell\ell$ (Run I)
$Z'_{\text{SM}}$	770	740	<b>825</b> (690)
$Z'_{\psi}$	645	585	675
$Z'_{\chi}$	630	605	690
$Z'_{\eta}$	675	640	720
$Z'_I$	570	540	615

## Techni-meson Mass limit

$M_T$	$\ell\ell$	Lane&Mrenna, PRD67-115011/03
500	280	
400	270	

## Little Higgs $Z_H$ Mass limit

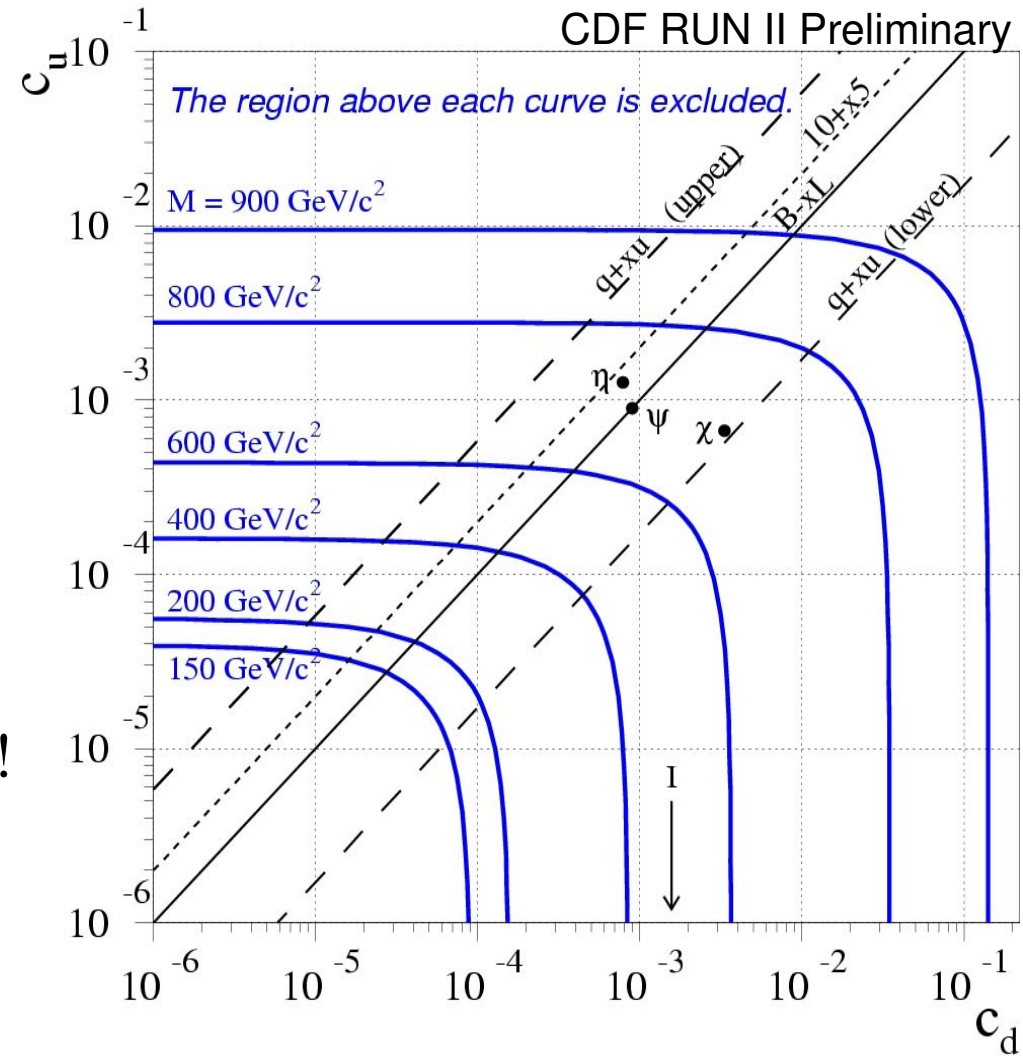
$\cot\theta$	$\ell\ell$	Han <i>et al.</i> , PRD67-095004/03
1.0	885	
0.5	725	

# Limits on $Z'$ : Generic Couplings ( $200 \text{ pb}^{-1}$ ):

CDDT, PRD70-093009/04

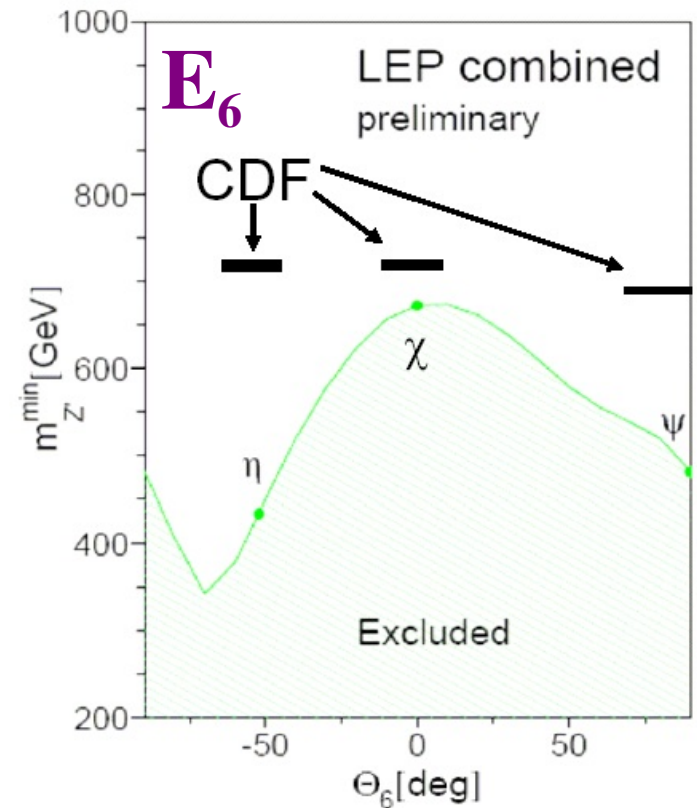
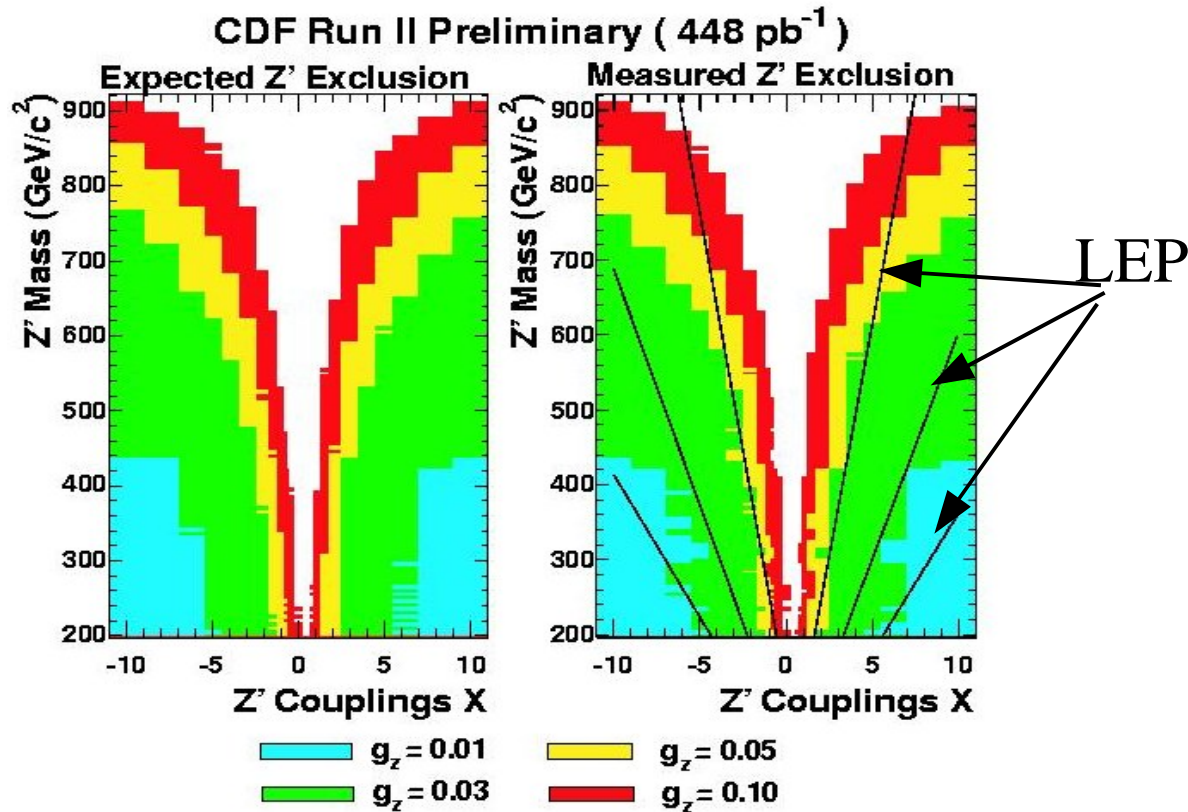


- Generalize U(1)  $Z'$  couplings:
- 4 classes defined by 3 parameters
  - Mass of  $Z'$
  - Strength,  $g_{Z'}$
  - Parameter  $x$
- Exclude portions of 2D  $c_u$ - $c_d$  plane for a given  $Z'$  mass.  
( $c_{u,d}$ : model dependence of  $Z'$ )
- **Pin** your favorite model on the plot!



# Z' Coupling Limits ( $450 \text{ pb}^{-1}$ ):

## $d-xu$ models



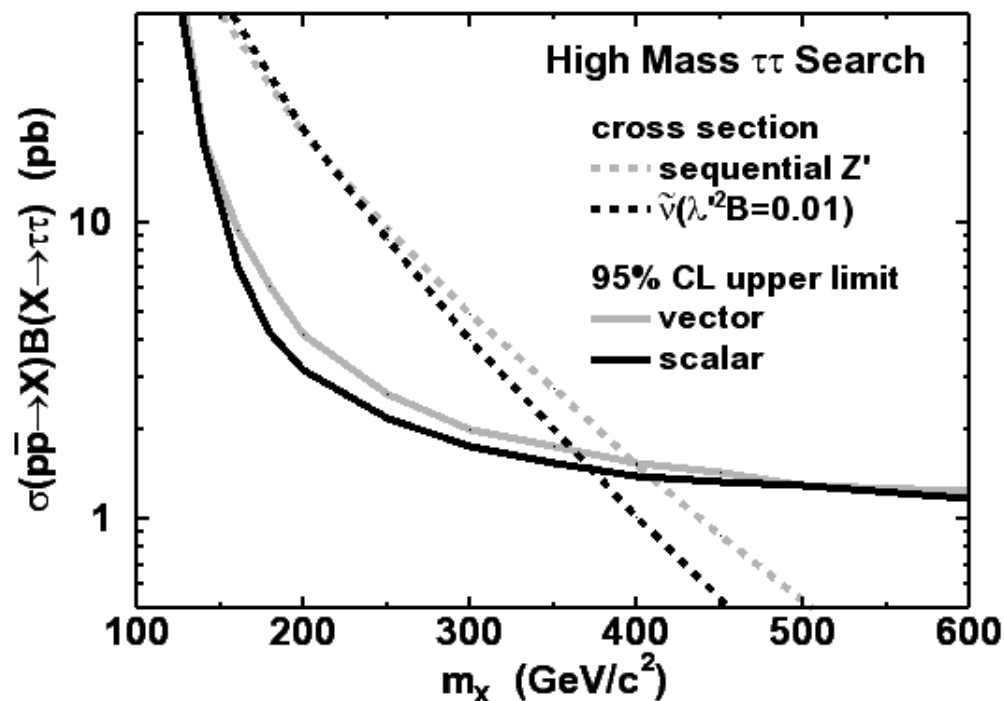
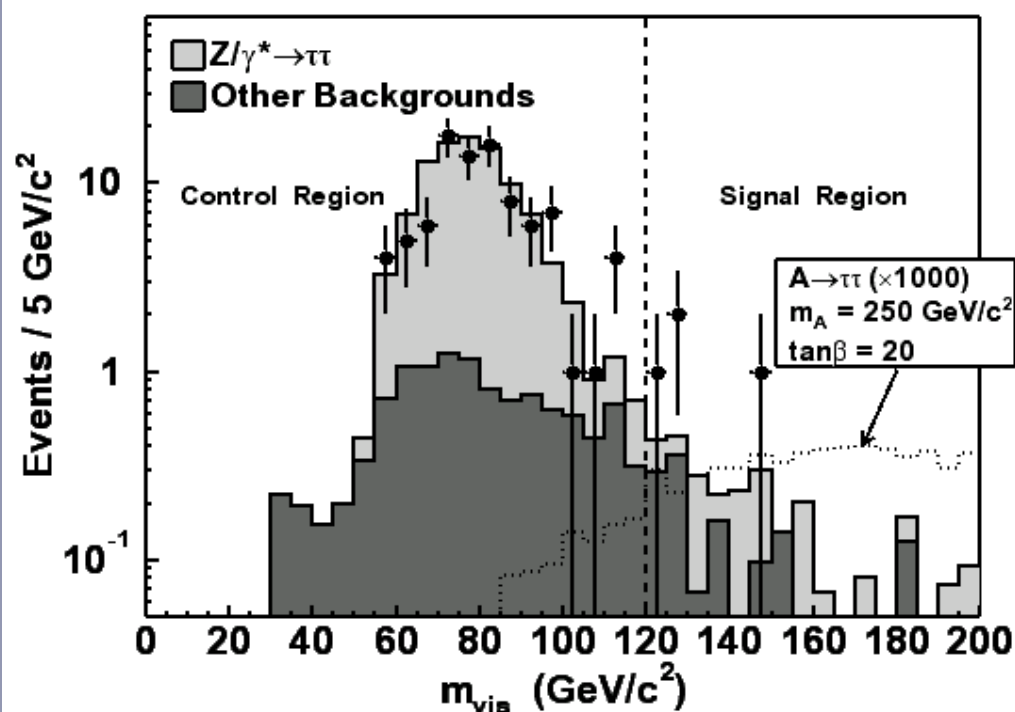
- 4 classes of Z' models explored
- Limits set using  $CL_s$  method
- Current Tevatron best limit:  $M(Z'_{SM}) > 845 \text{ GeV}/c^2$

# Z' in Ditau: First TeV results with 3<sup>rd</sup> generation!

CDF, hep-ex/0506034



- Excellent job in Tau ID at hadron colliders!
- Good agreement in signal region ( $M_{\text{visible}}(ME_T, \tau, 1) > 120 \text{ GeV}/c^2$ ) → set limits!



Upper Limits on  $\sigma \cdot \text{BR}$  (fb),  
at high mass

$ee$	$\mu\mu$	$\tau\tau$
~50	~50	~1500

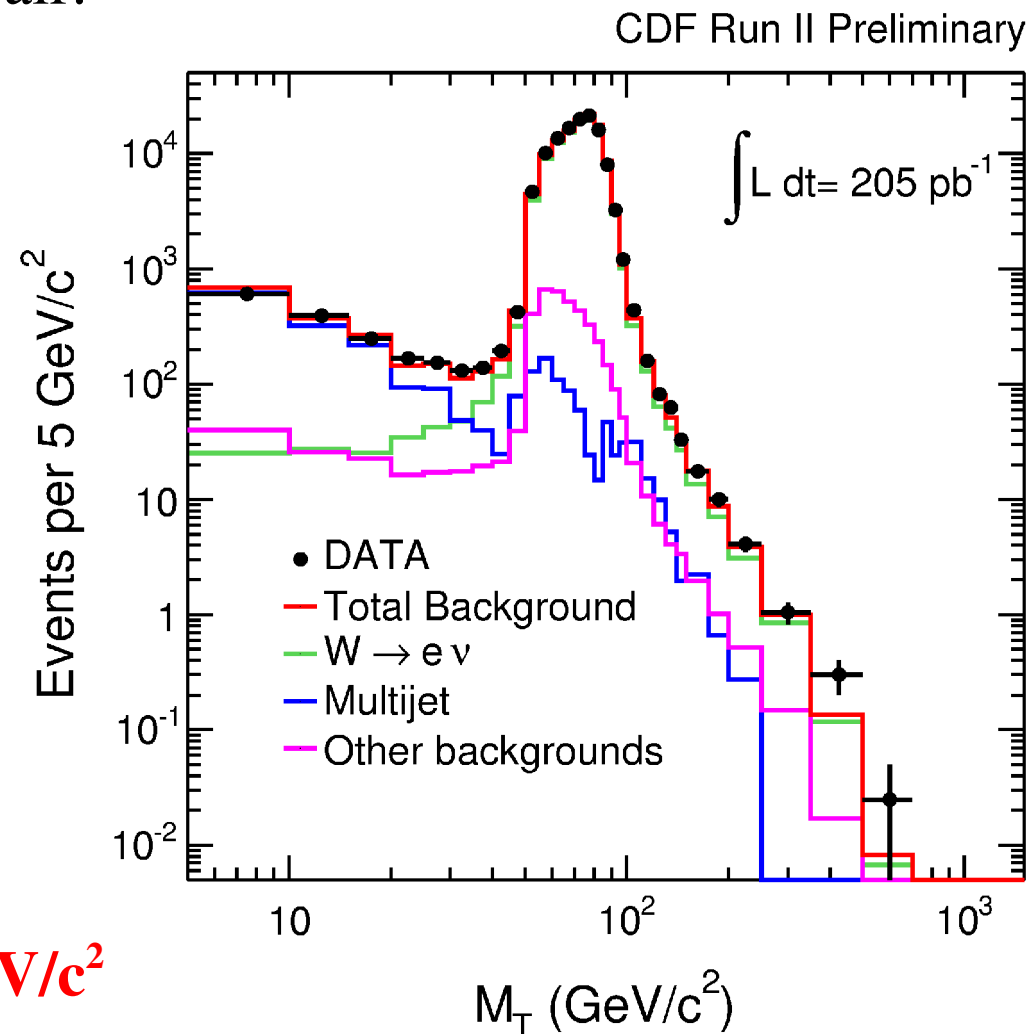
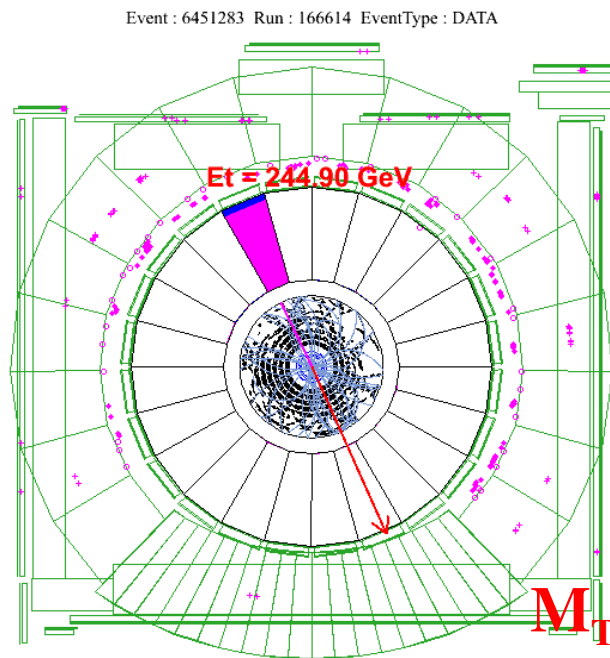
Lower Limits on  $M_{Z'}$  ( $\text{GeV}/c^2$ )

$ee$	$\mu\mu$	$\tau\tau$
770	740	395

# Heavy Charged Bosons: $W'$ Selection ( $200 \text{ pb}^{-1}$ )



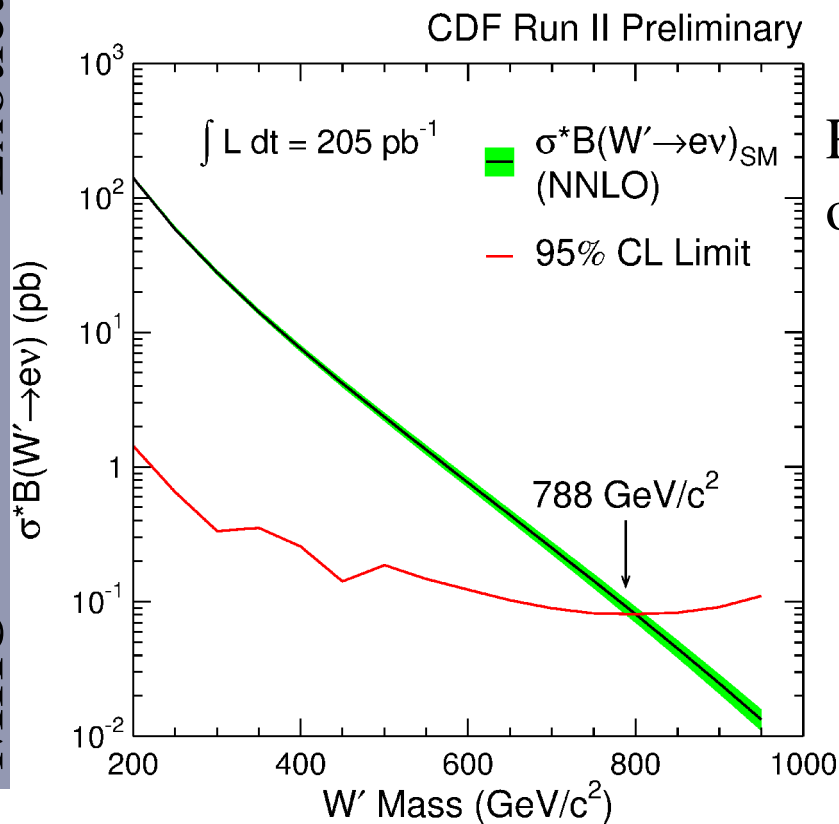
- A dilepton signature where one lepton is a high  $ME_T$   
1 isolated  $e$ ,  $E_T > 25 \text{ GeV}/c$ ,  $ME_T > 25 \text{ GeV}/c$
- Signal in  $M_T$  distribution of the l-pair.
- Veto di- $e$  events
- Requires good understanding of backgrounds and  $ME_T$
- $W'$  Acc $\times$ Eff  $\sim 45\%$



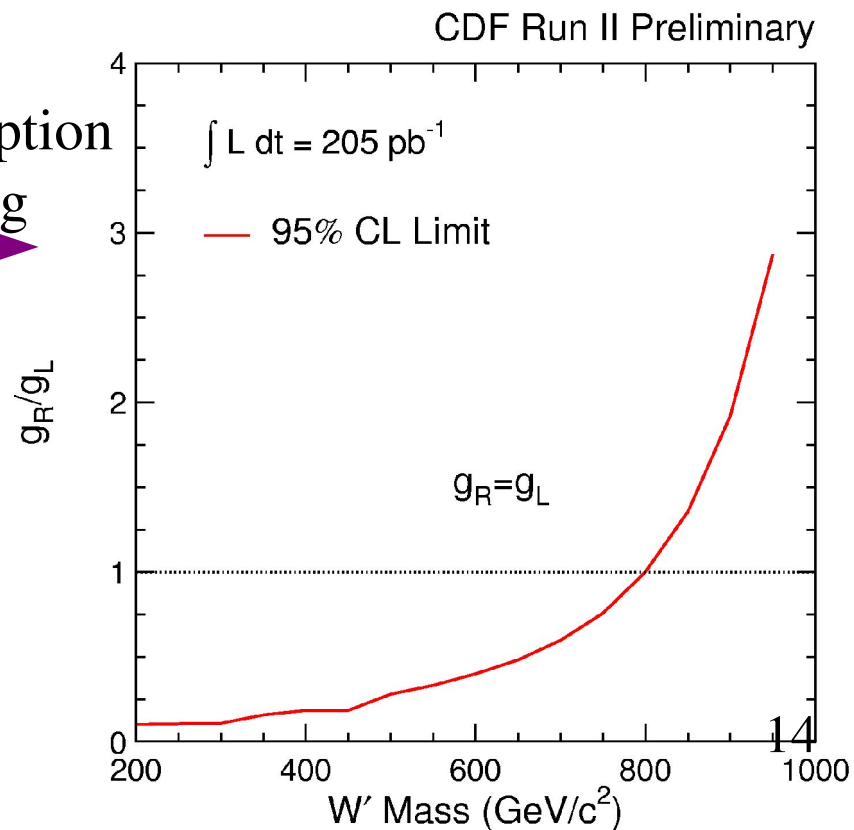
# Heavy Charged Bosons: $W'$ Searches ( $200 \text{ pb}^{-1}$ )



- Very good agreement with prediction
  - Limits on a  $SU(2)_R$  from EGS Left-Right symmetric models
- $\nu$  from  $W'$  decay is assumed light and stable
- Binned likelihood fitting used for limits on  $\sigma \cdot \text{BR}(W' \rightarrow e\nu)$
- Dominant systematic uncertainties: PDF and  $M_T$  shape due to  $e$  energy scale
- $M_{W'} > 788 \text{ GeV}/c^2$** , CDF Run I:  $754 \text{ GeV}/c^2$



Release assumption  
on SM coupling



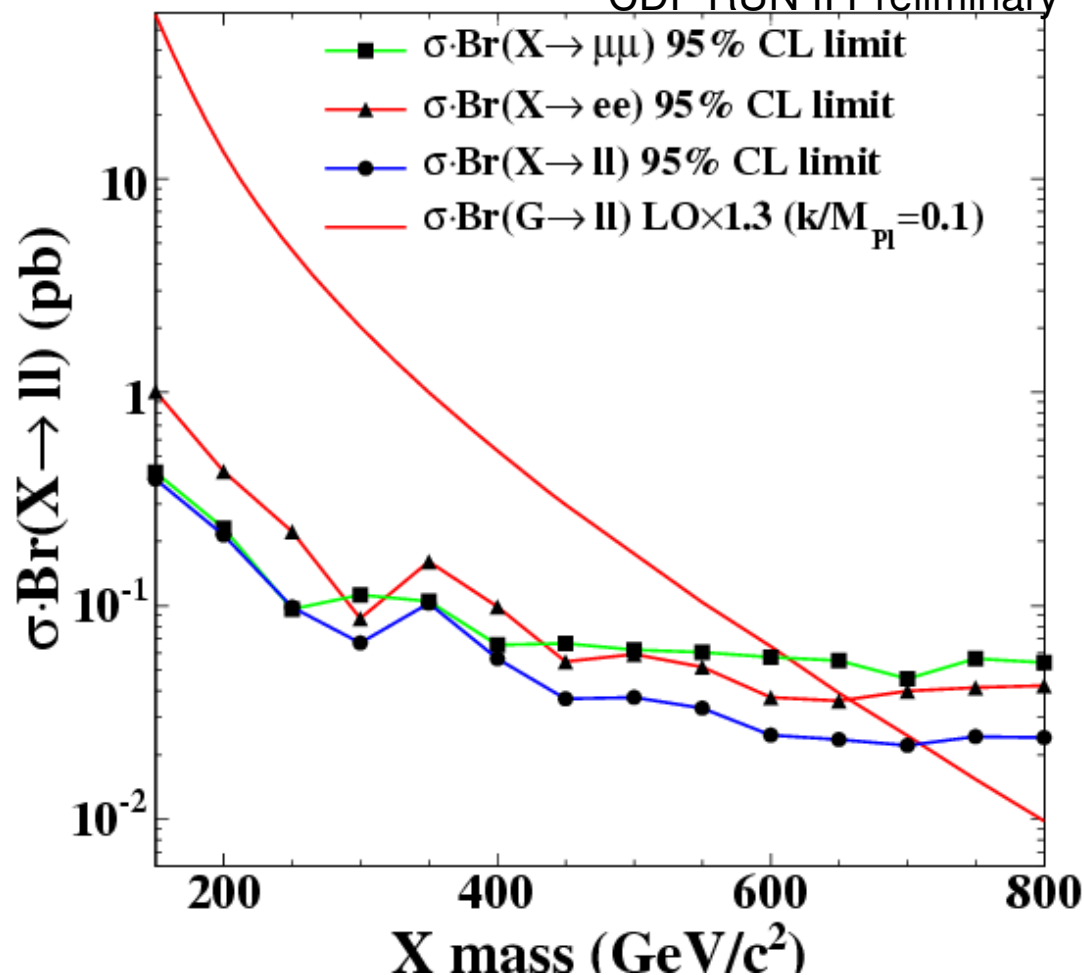
# Warped ED Searches: Spin-2 Results ( $200 \text{ pb}^{-1}$ )

Randall&Sundrum, PRL83-3370/99



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

CDF RUN II Preliminary



$M_G$  Lower Mass limit ( $\text{GeV}/c^2$ )

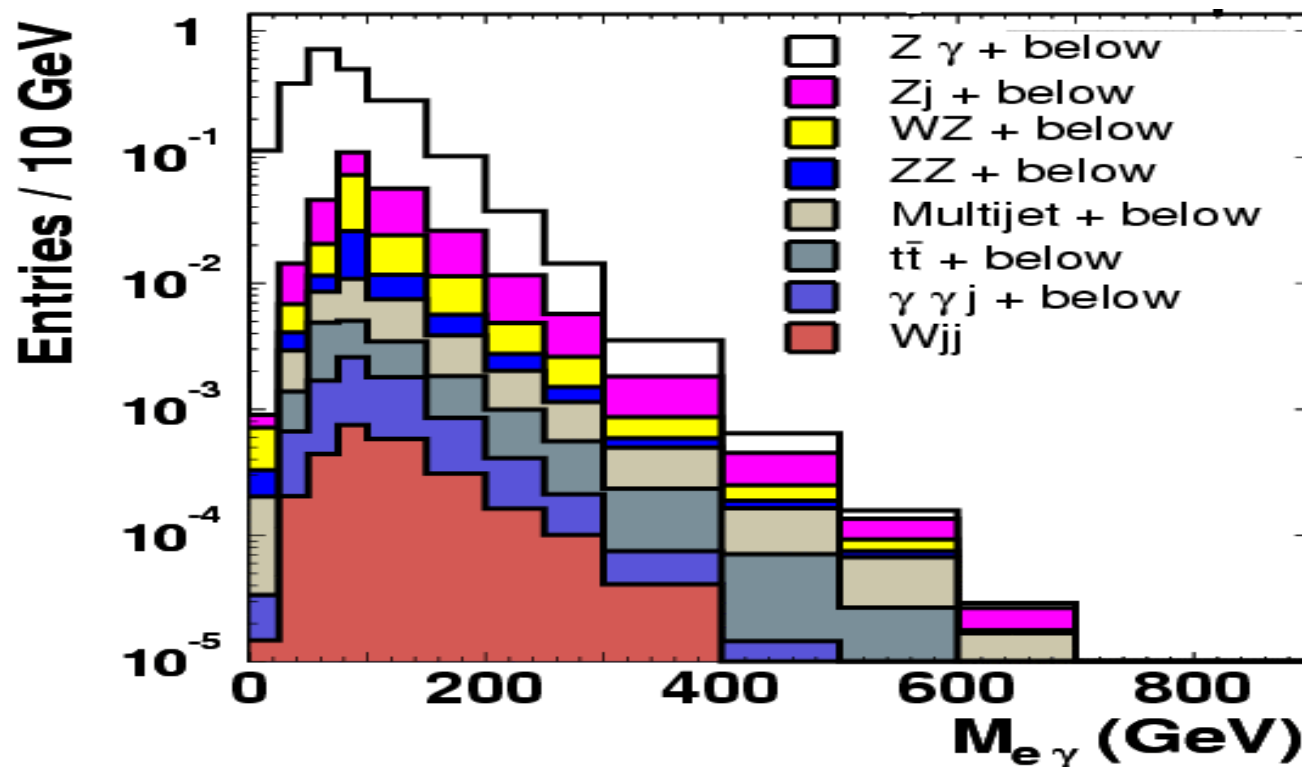
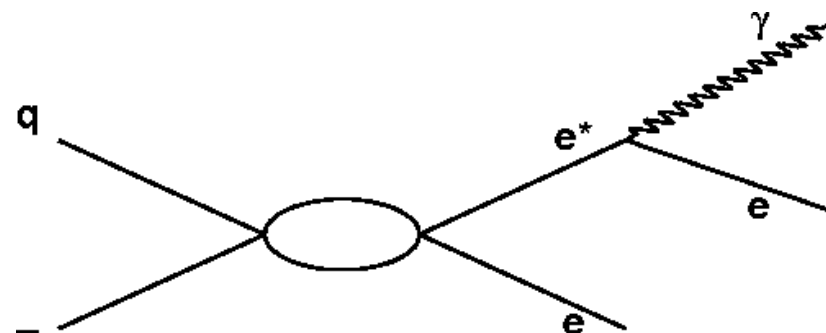
$k/M_{\text{Pl}}$	$ee$	$\mu\mu$	$ll$
0.1	660	610	710
0.07	540	530	620
0.05	470	455	510
0.01	--	165	170

- D0 Run II diEM preliminary:  $M > 785 \text{ GeV}/c^2$



# Excited/Exotic Electrons ( $200 \text{ pb}^{-1}$ )

- Search for excited electrons as a sign of their compositeness
- Resonance in  $e+\gamma$  mass spectrum in the radiative decay of high  $E_T e$
- Main background contribution from  $Z+\gamma/j$
- $N_{\text{obs}} = 3$ ,  $N_{\text{pred}} = 3.03 \pm 0.08 \pm 0.4$





# Results for Excited Electrons ( $200 \text{ pb}^{-1}$ )

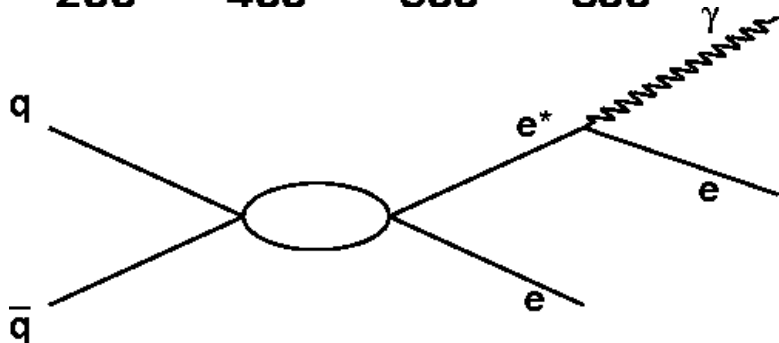
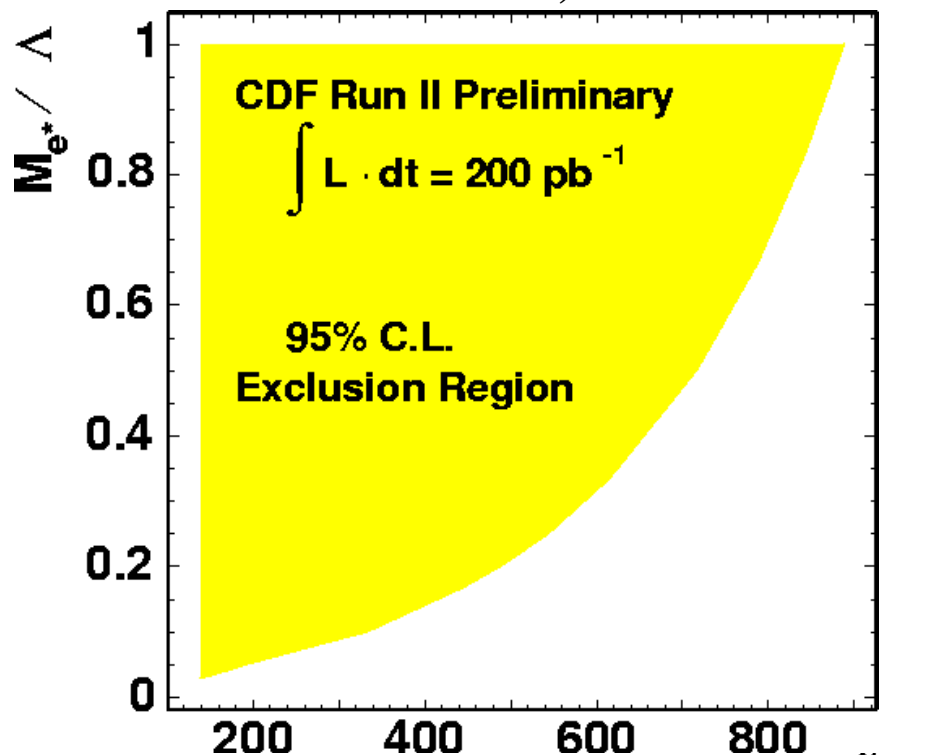
CDF,PRL94-101802/05



## Contact Interaction Model

- First limits ever

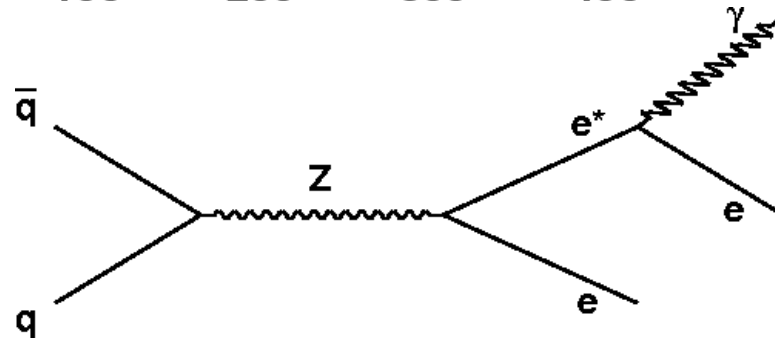
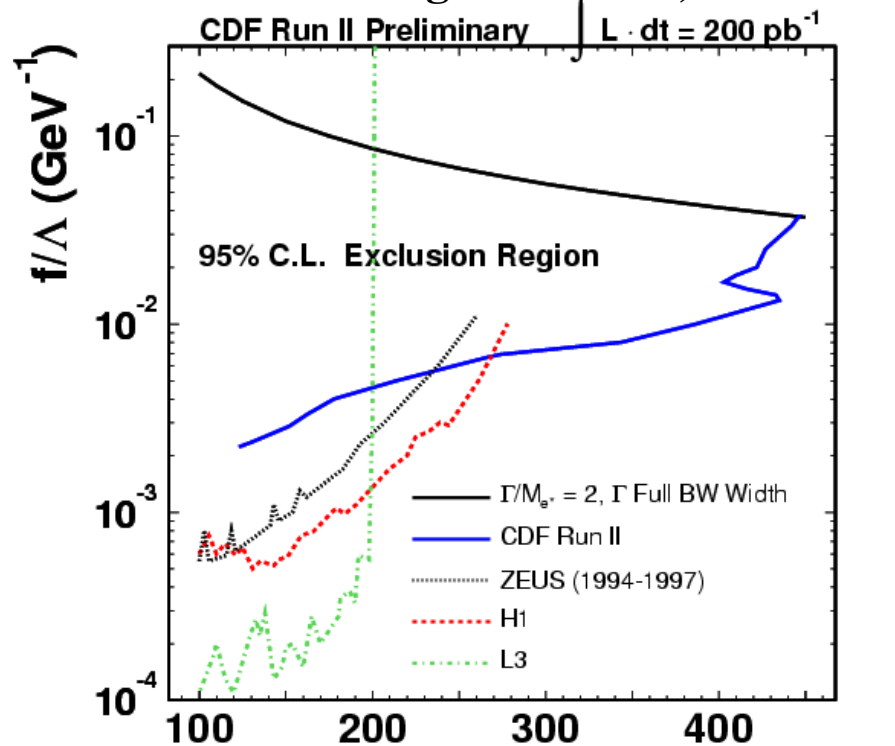
Baur et al.,PRD42-815/03



## Gauge Mediated Model

- exceed previous limits

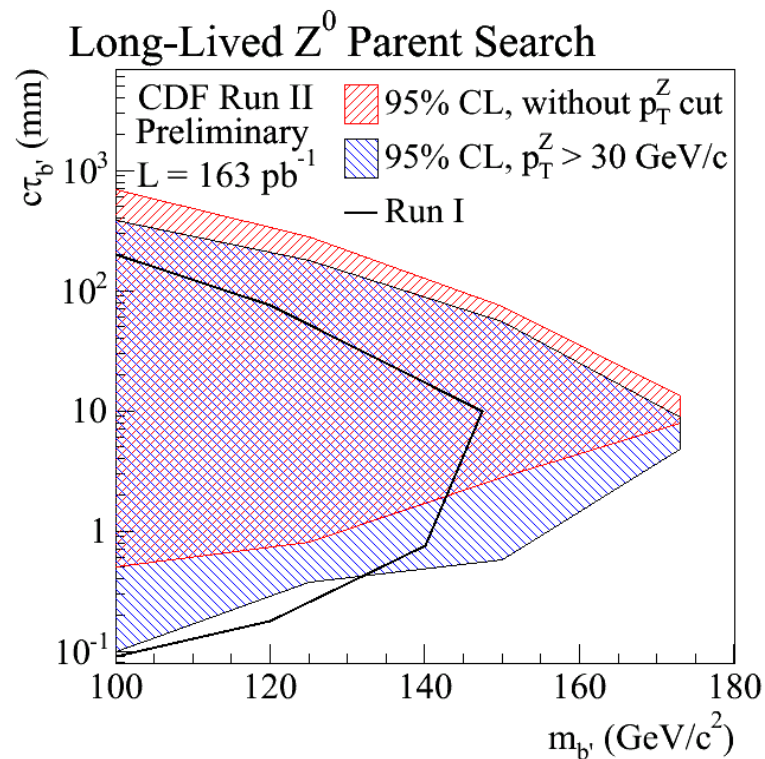
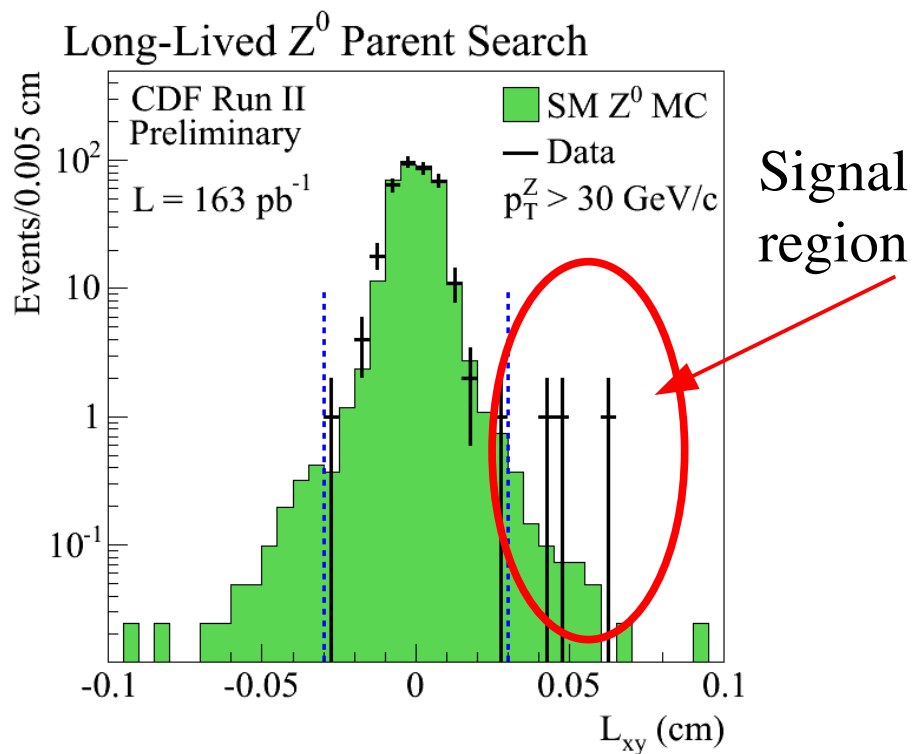
Hagiwara et al.,ZPC29-115/85





# Long-lived Parents of Z: $b' \rightarrow Zb$ ( $163 \text{ pb}^{-1}$ )

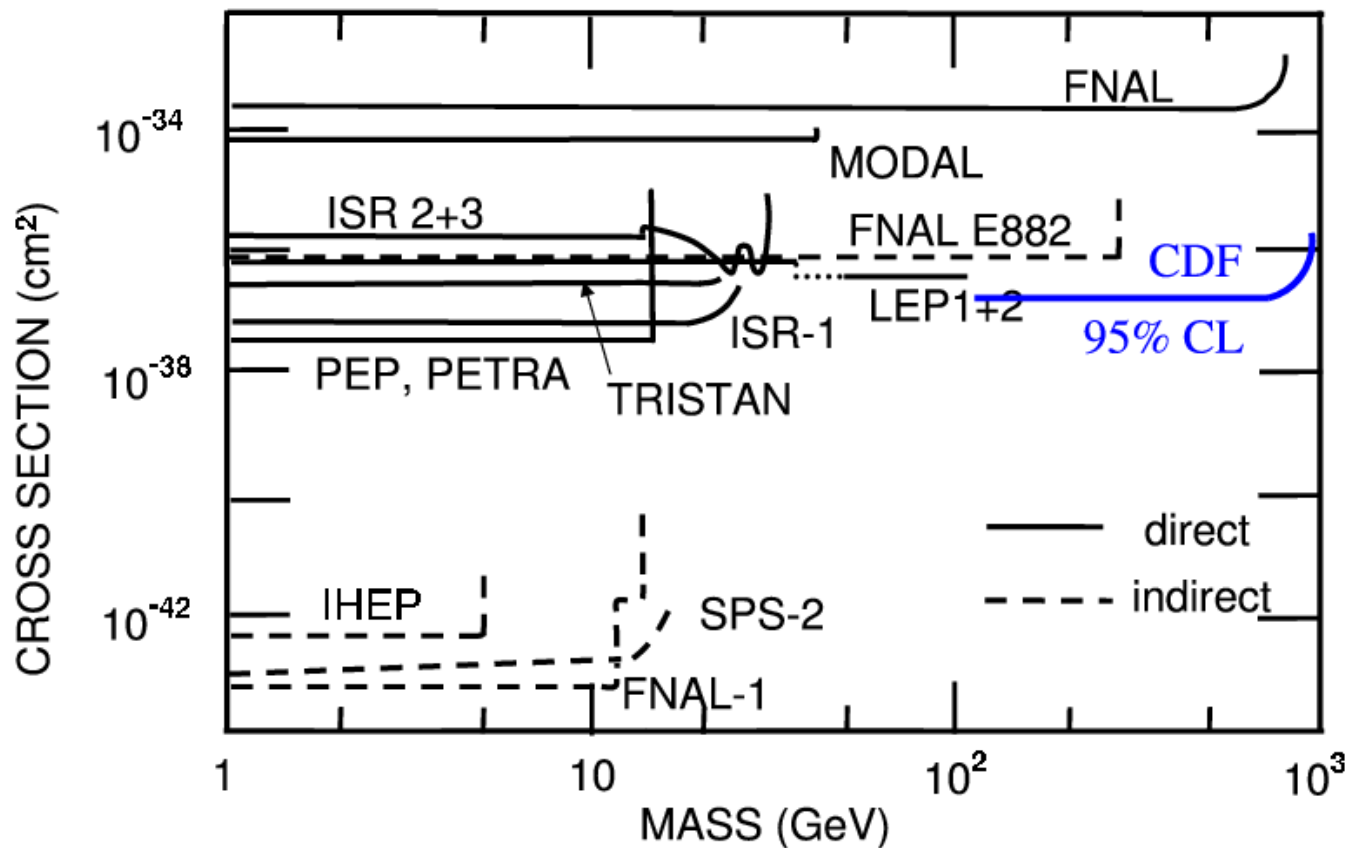
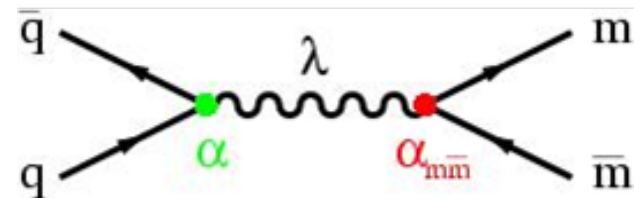
- Long lived particles predicted in various models
- CDF search using vertex information of dimuons of Z decays
- Limits on a 4<sup>th</sup> generation b-quark: as a function of mass and lifetime
- Improvement over Run I results!









# Magnetic Monopoles ( $\sim 35 \text{ pb}^{-1}$ ):

- Dedicated trigger built for a unique signature: large ToF pulses, ionization in tracker, curvature in  $r$ - $z$  plane.
- World's best limits on a heavy Dirac monopole with DY-like signature:  
For  $M_{\text{monopole}} = 360 \text{ GeV}/c^2$ ,  $\sigma \cdot \text{BR} < 0.3 \text{ pb}$  (95% CL)

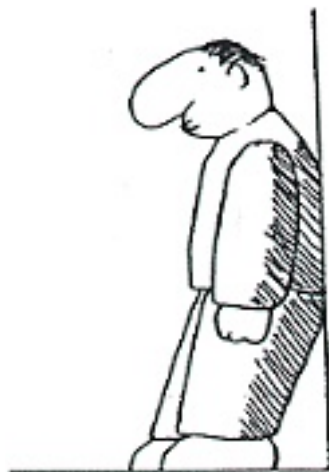


# Conclusions



-  CDF has **analyzed** up to  $450 \text{ pb}^{-1}$  energetic data and many new physics searches are underway.
-  Current CDF limits **exceed** published limits of previous direct searches! We are also updating the results and their interpretation, constantly.
-  We have also **pioneered** exploration of some models and search strategies and obtained the first Tevatron results within many models: EGS, ED, ...
-  More Tevatron data **on the way**. The world of exotica may be just around the corner. **Stay tuned!**





## Backup Slides

Scalar Leptoquarks ( $200 \text{ pb}^{-1}$ )

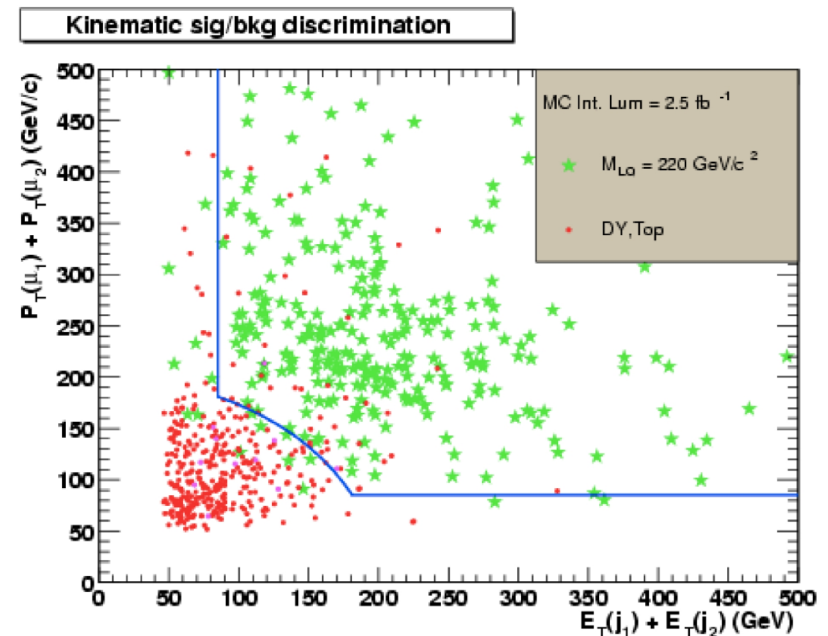
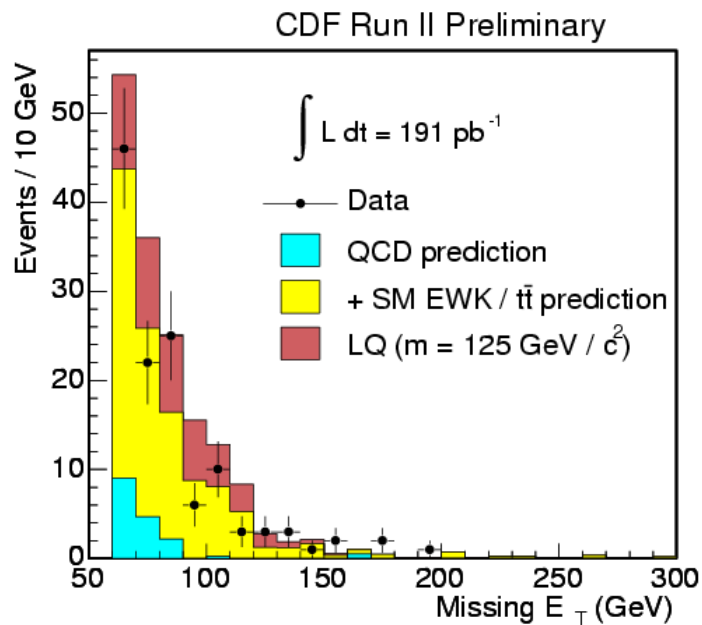
RS in diphoton ( $375 \text{ pb}^{-1}$ )

ADD in dielectron ( $200 \text{ pb}^{-1}$ )

Highest mass dielectron events

# Scalar Leptoquarks:

- ♦ Why not an additional symmetry between leptons and quarks (L, B)?  
 ➔ Leptoquarks!
- ♦ LQ searches in resonant pair production mode: signature:  $2l+2j$
- ♦ Decays parametrized by  $\beta = B(LQ \rightarrow lq)$
- ♦ Optimize selection for the distinct topology against backgrounds
- ♦  $2\nu 2j$  channel requires a good understanding of  $ME_T$

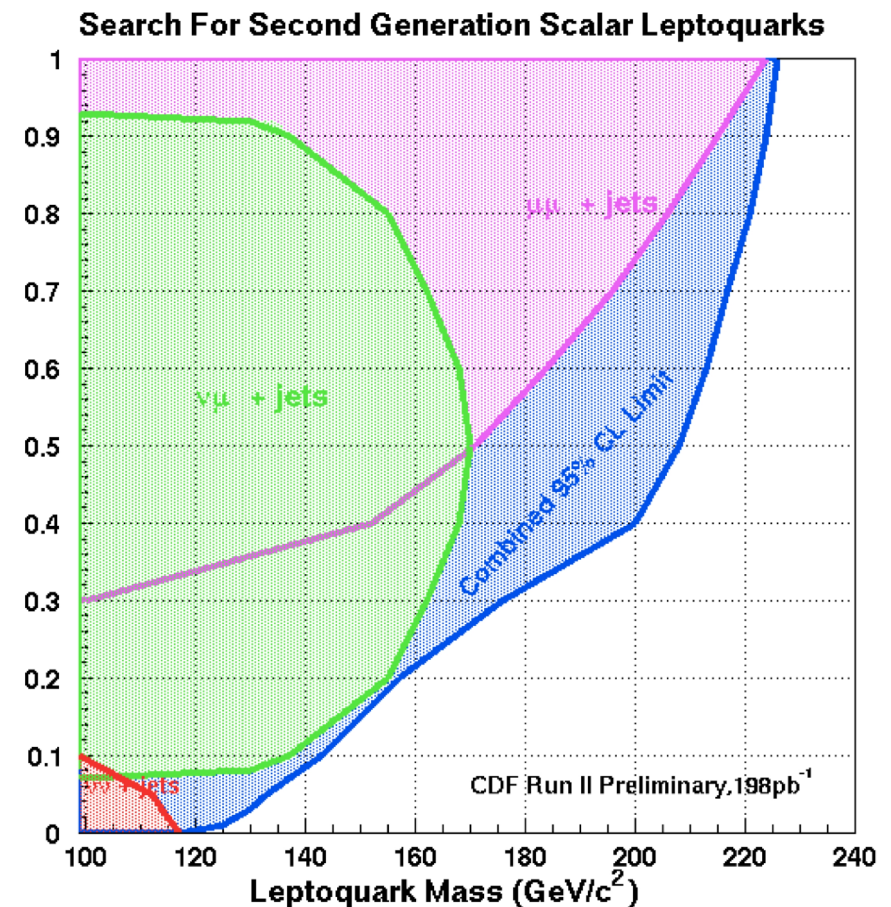
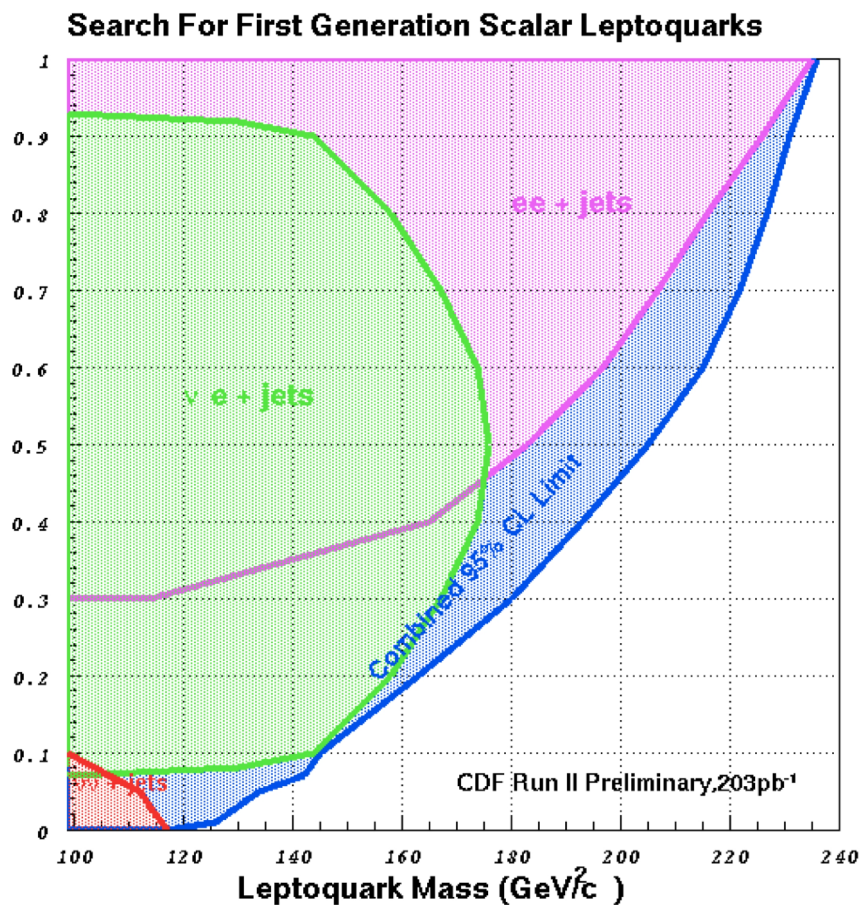


# Scalar Leptoquarks: Combined results ( $200 \text{ pb}^{-1}$ )



- ◆  $\beta = 1.0$  and  $0.5$  and  $0.0$  results.
- ◆  $M_{LQ} > 235$  ( $224$ )  $\text{GeV}/c^2$ ,  $\beta=1.0$ , 1<sup>st</sup> (2<sup>nd</sup>) gen.
- ◆ D0: RI+II (I)  $M_{LQ} > 256$  ( $251$ )  $\text{GeV}/c^2$ ,  $\beta=1.0$ , 1<sup>st</sup> (2<sup>nd</sup>) gen.

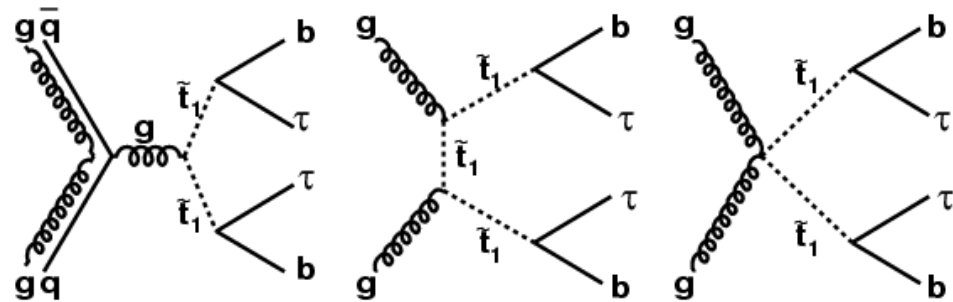
◆



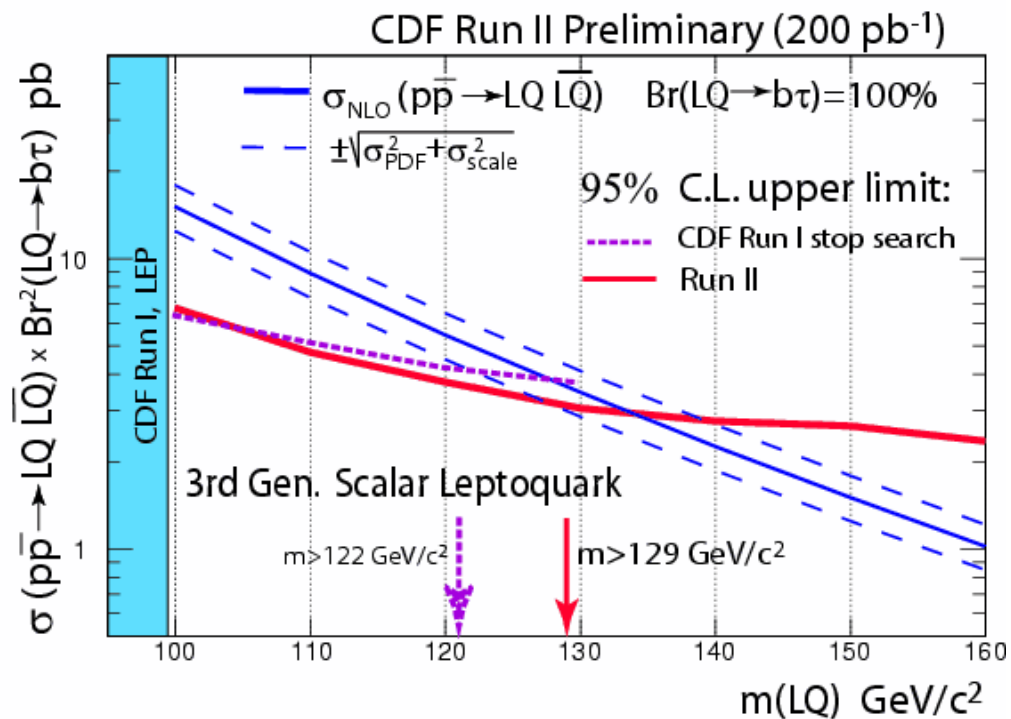
# Scalar Leptoquarks: 3<sup>rd</sup> generation (200 pb<sup>-1</sup>)



- ♦ Search in  $\tau_{\text{lep}}, \tau_{\text{had}} + jj$  channel
- ♦ Results for  $\beta = 1.0$ ,  
 $M_{\text{LQ}} > 129 \text{ GeV}/c^2$



**CDF completing  
full generations!**

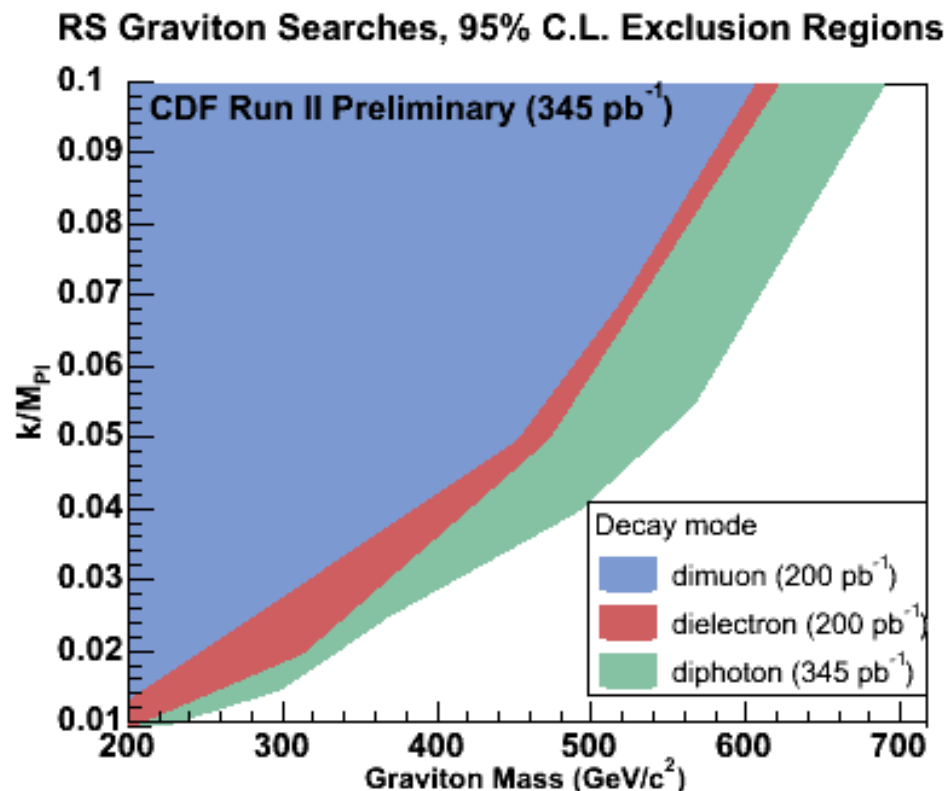






# Results for RS $G^*$ with Diphotons ( $375 \text{ pb}^{-1}$ ):

- Counting limits using  $3\sigma$  mass window around reference RS  $G$  mass



$$\text{BR}(G \rightarrow \ell\ell) = \frac{1}{2} \text{B}(G \rightarrow \gamma\gamma)$$

Upper Limits on  $\sigma \cdot \text{BR}$  (fb),  
at high mass

$ee$	$\mu\mu$	$\gamma\gamma(375 \text{ /pb})$
$\sim 50$	$\sim 50$	$\sim 70$

$M_G$  Lower Limits ( $\text{GeV}/c^2$ ),  $k/M_{Pl}=0.1$

$ee$	$\mu\mu$	$\ell\ell$	$\gamma\gamma$
660	610	710	690

# Large ED Searches: Dielectron data ( $200 \text{ pb}^{-1}$ )

ADD, PLB429/98



- ◆ Virtual G exchange, sum of KK modes
- ◆  $M_{ee}$  distribution for binned likelihood in  $\eta_G$
- ◆ Limits on  $\eta_G \rightarrow$  on  $M_S$ , various formalisms:

$$\sigma = \sigma_{SM} + \eta \sigma_{int} + \eta^2 \sigma_{KK}$$

$$\eta = \lambda / M_S^4, \lambda_{Hewett} = \pm 1$$

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

Giudice, Rattazzi, Wells

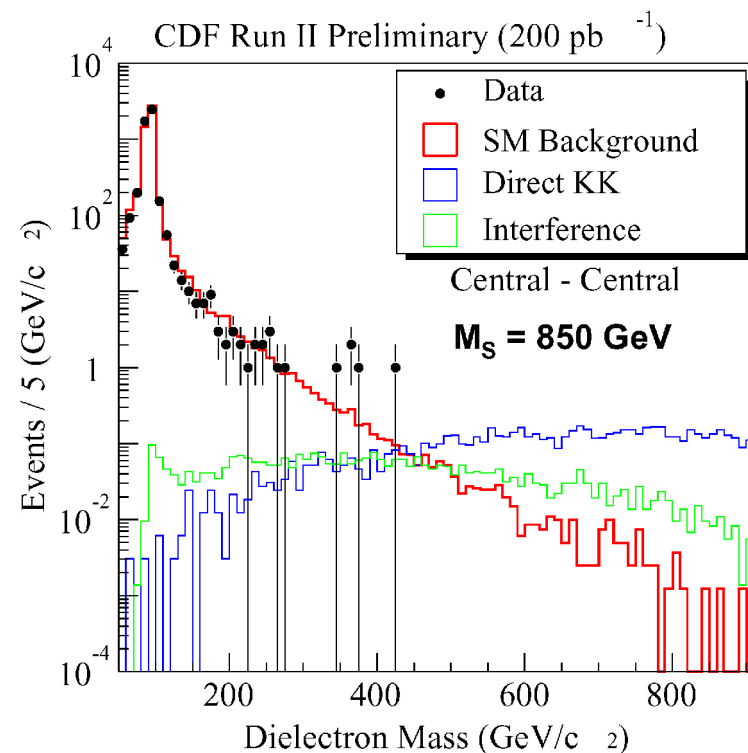
Han, Lykken, Zhang

## Lower Limits on $M_S$ (TeV):

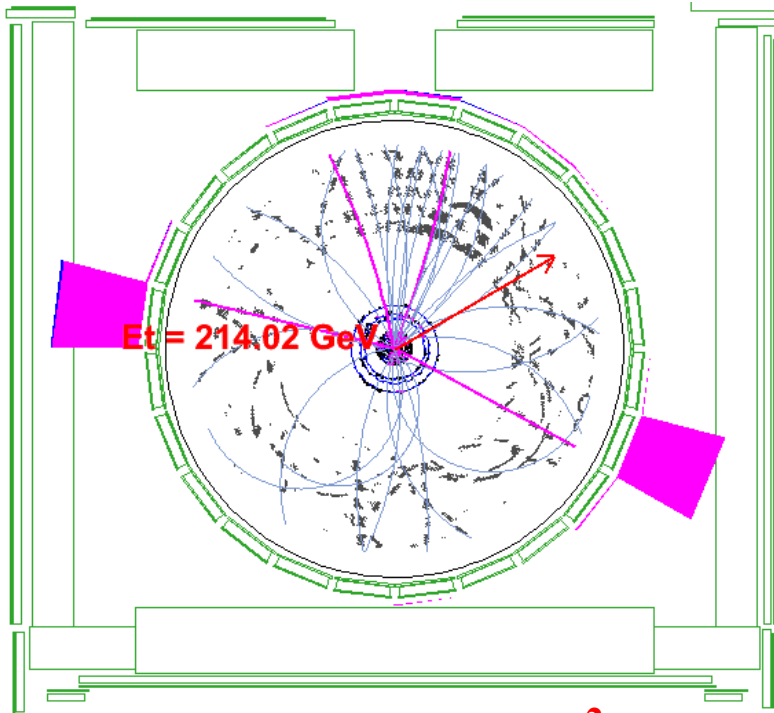
Hewett		HLZ					GRW
$\lambda=-1$	$\lambda=+1$	$n=3$	$n=4$	$n=5$	$n=6$	$n=7$	
<b>0.99</b>	<b>0.96</b>	1.17	0.99	0.89	0.83	0.79	<b>1.11</b>

**0.78 0.77 CDF I ( $ee$ )**

- D0 Run II **diEM** preliminary:  $M_S > \mathbf{1.36 \text{ TeV}}$

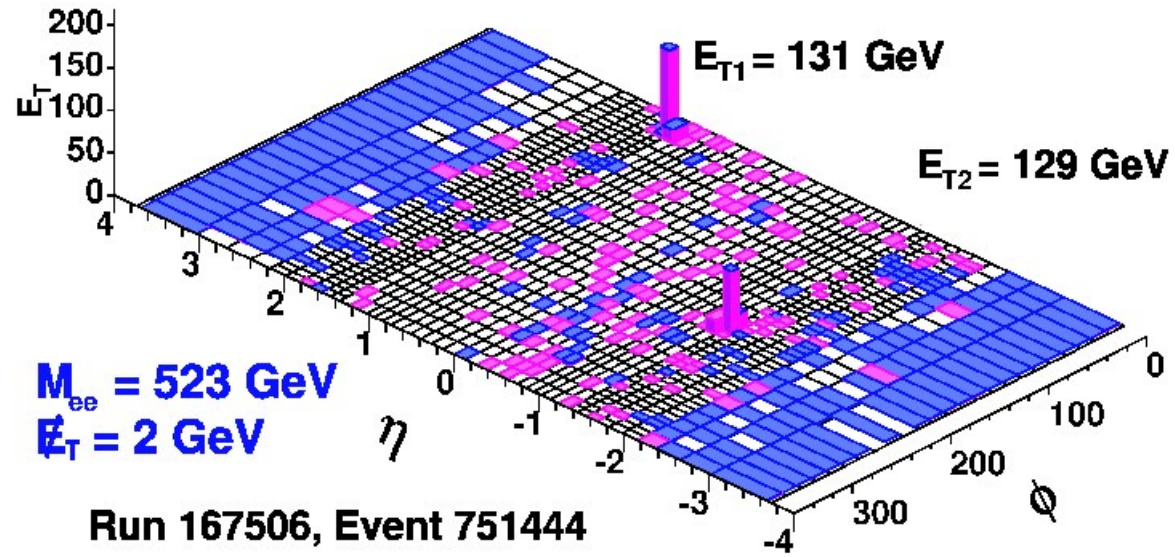


# CDF Highest Mass Dielectron Events:



$$M_{ee} = 470 \text{ GeV}/c^2$$

## CDF RunII Preliminary



Highest  $M_{ee}$  in  $200 \text{ pb}^{-1}$