

# Searches at the Tevatron

**Bill Orejudos**

**CDF Collaboration**

**Lawrence Berkeley National Laboratory**

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# *Outline*

- Tevatron, CDF, D0 *upgrades*
- Searches
  - new gauge bosons
  - technicolor, compositeness, topcolor
  - long-lived heavy charged particles
  - new physics with photons
  - Large Extra Dimensions
  - *Supersymmetry: see talk by V. Zutshi*
- Conclusion

# *The Tevatron*

$p\bar{p}$  collider

$\sqrt{s} = 1.8 \text{ TeV}$  at Run I (1992 - 96)  
about  $0.1 \text{ fb}^{-1}$  per experiment

First phase of Run II (Run IIa)  
started spring 2001

→  $\sqrt{s} = 1.96 \text{ TeV}$

→ goal :  $2 \text{ fb}^{-1}$  per experiment



# CDF Upgrade

Time-of-Flight  
(TOF) added

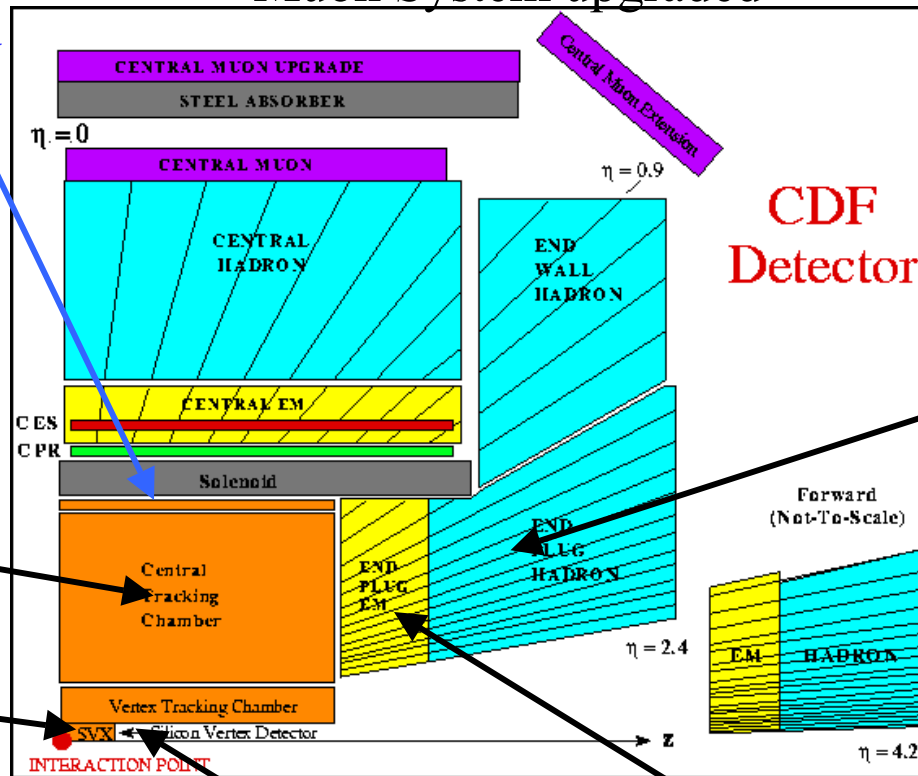
New Electronics,  
Trigger, DAQ

CTC replaced by  
COT

SVX replaced  
layer of silicon  
added to beampipe

Intermediate Silicon  
Layers (ISL) added

Muon System upgraded



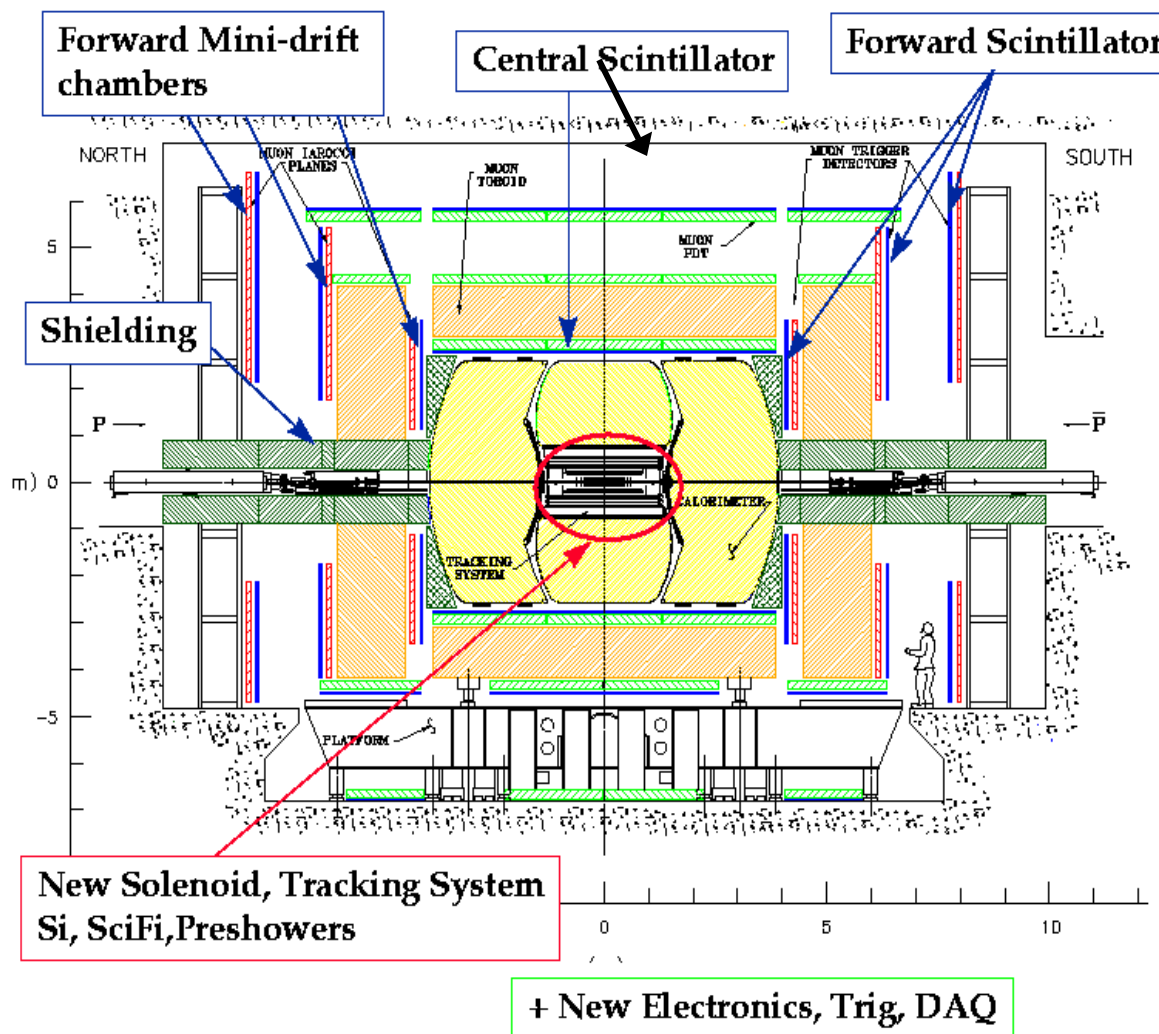
Upgrade will  
allow operation  
at high luminosity  
and extend physics  
capabilities

End Plug Calorimeters  
upgraded, extended to  
larger  $\eta$

New Forward  
Detectors

Plug Shower Max added

# *D0 Upgrade*

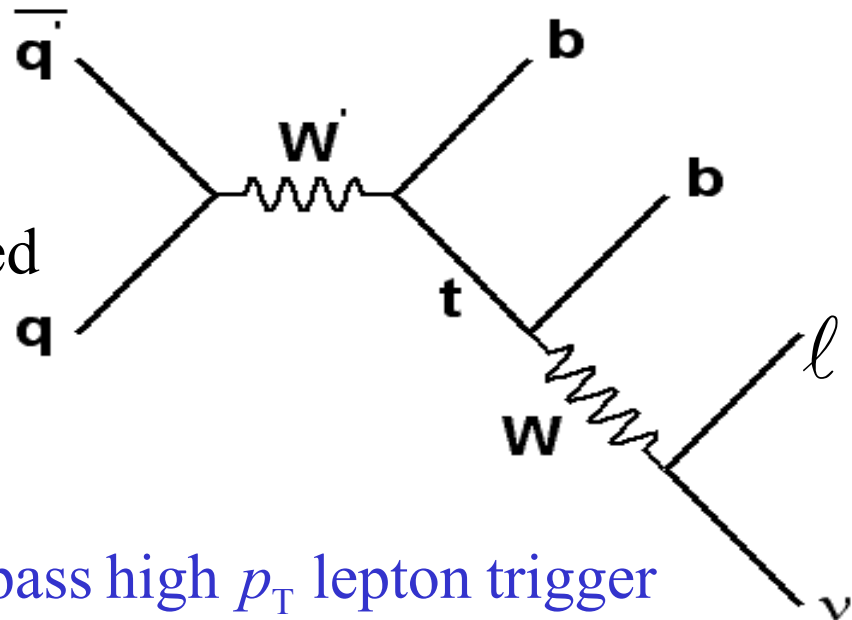


# *CDF $W'$ Search*

Older analysis looks for decay  
of  $W'$  to 2 leptons

No sensitivity in the case that  
the leptonic decay is suppressed

New CDF Run I analysis  
looks for  $W' \rightarrow tb$



Select events which pass high  $p_T$  lepton trigger

Remove dilepton events

Require lepton to be central and isolated

Require missing  $E_T > 20$  GeV (to select  $W$  candidates)

Require 2 or 3 jets with  $E_T > 15$  GeV

Require at least one jet to be tagged as a  $b$ -jet

# CDF $W'$ Results

$\ell \nu jj$  invariant mass distribution :

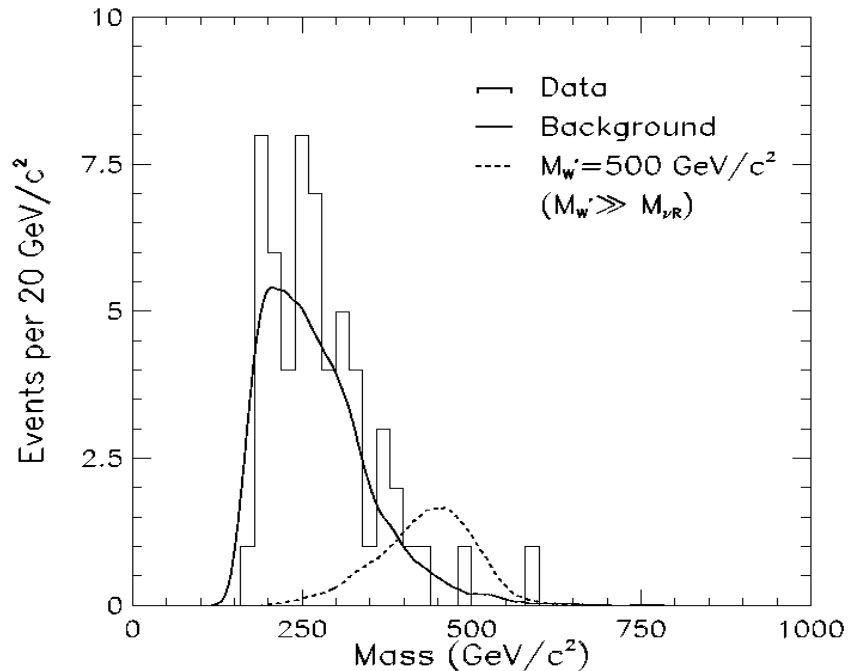
$$p_T^\nu = \text{missing } E_T$$

$p_Z^\nu$  : constrain  $M_{\ell\nu}$   
to be  $80.22 \text{ GeV}/c^2$

Background : QCD,  $t\bar{t}$ , single top

$48.0 \pm 6.0$  expected from bckgnd,

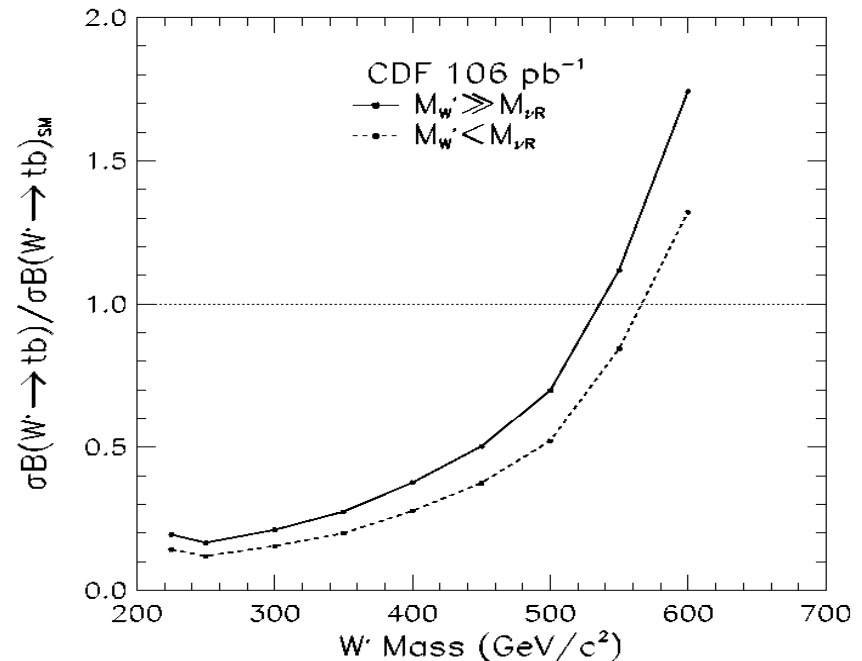
57 observed



Excluded:

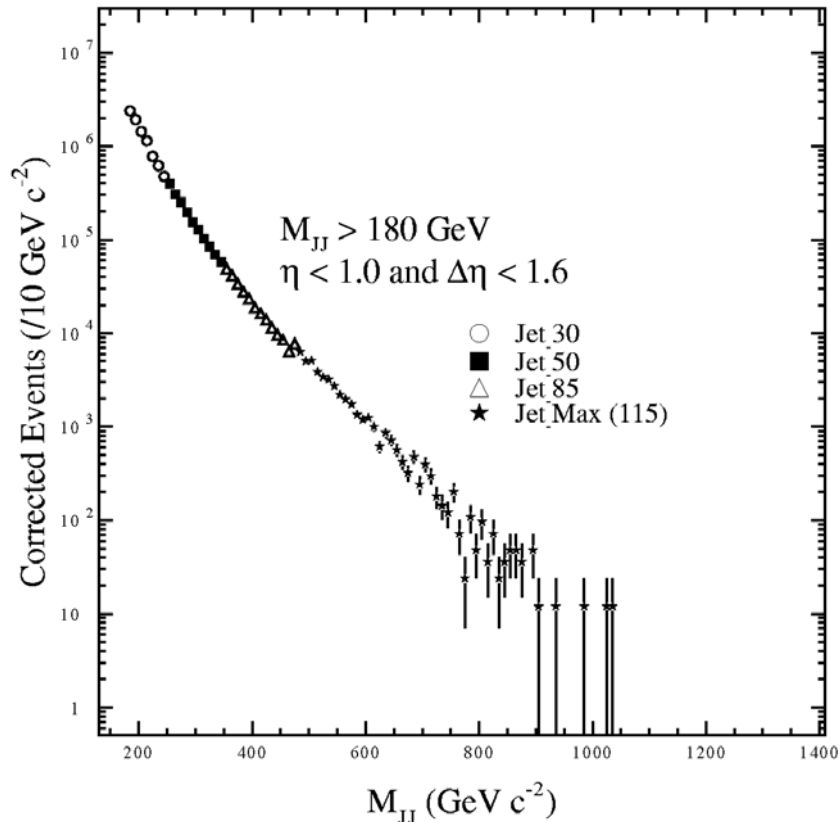
$$225 < M_{W'} < 536 \text{ (} M_{W'} \gg M_{\nu_R} \text{)}$$

$$225 < M_{W'} < 566 \text{ (} M_{W'} < M_{\nu_R} \text{)}$$



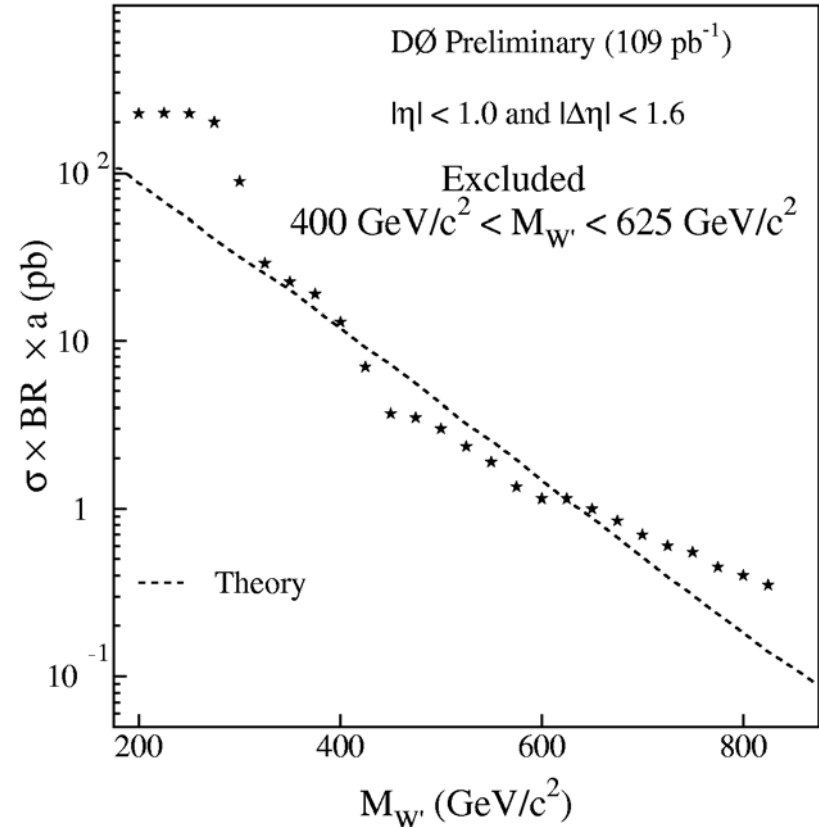
# *DØ W' Results*

DØ Preliminary (109 pb<sup>-1</sup>)



Events from jet triggers selected  
Jet  $E_T > (115, 85, 50, 30) \text{ GeV}$

Dijet mass distribution shows no  
evidence of an excess



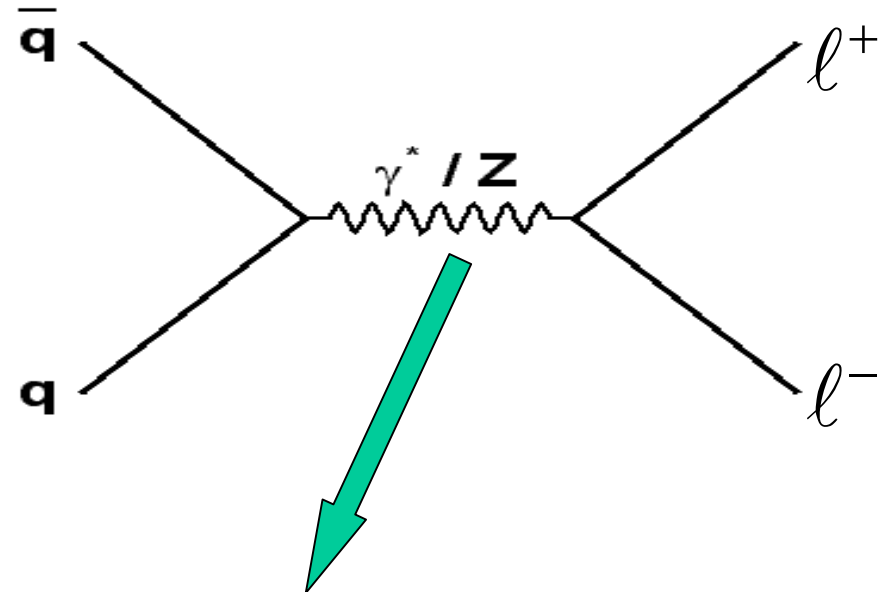
Excluded:  
 $400 < M_{W'} < 625$



# *Drell-Yan Production*

Dilepton final state can be used in searches for:

- new gauge bosons ( $Z'$ )
- large extra dimensions
- quark-lepton compositeness
- technicolor



This would be **modified** by the presence of some sort of new physics – could exchange a new gauge boson, Kaluza-Klein (KK) tower, etc

Could also have **new diagrams** leading to dilepton final states, e.g. 2 gluons coupling to KK tower.

# *Selection of Dilepton Events*

## CDF Run I Dilepton mass distribution

Events selected with  $\mu$  and  $e$  triggers

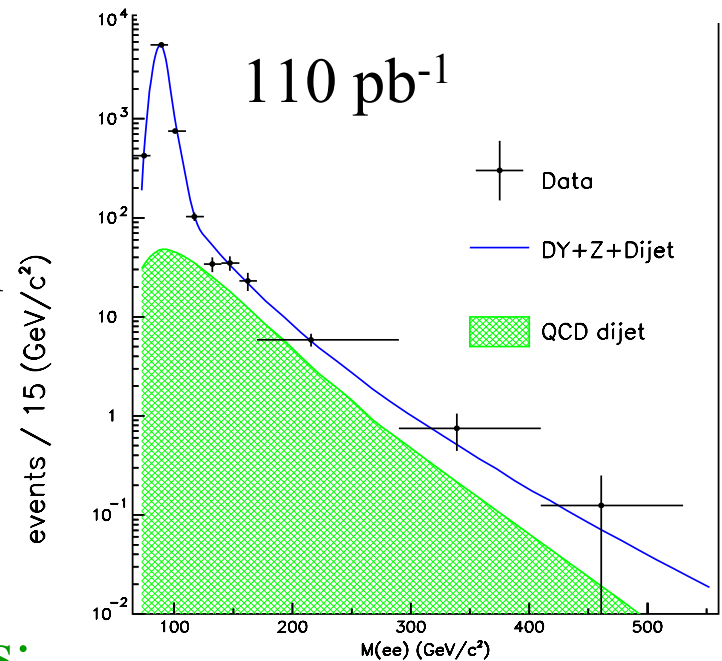
Leptons required to:

- Be oppositely charged
- Have a high transverse momentum  
electron :  $E_T > 25 \text{ GeV}$   
muon :  $p_T > 20 \text{ GeV}/c$
- Be isolated
- Originate from single vertex

Background low at high lepton inv. mass:

$$M_{l^+l^-} > 300 \text{ GeV}/c^2 : 5.6 \pm 0.6 \text{ events}$$

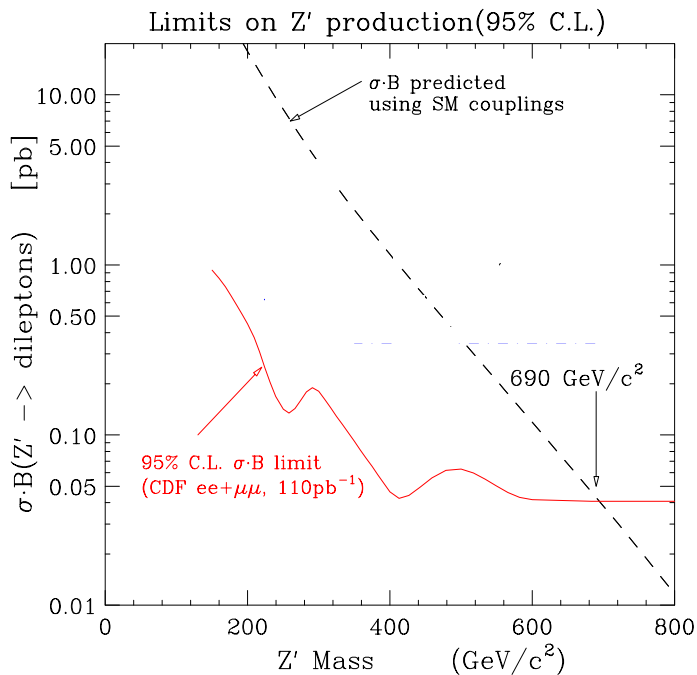
$$M_{l^+l^-} > 400 \text{ GeV}/c^2 : 1.3 \pm 0.1 \text{ events}$$



No deviation  
from SM

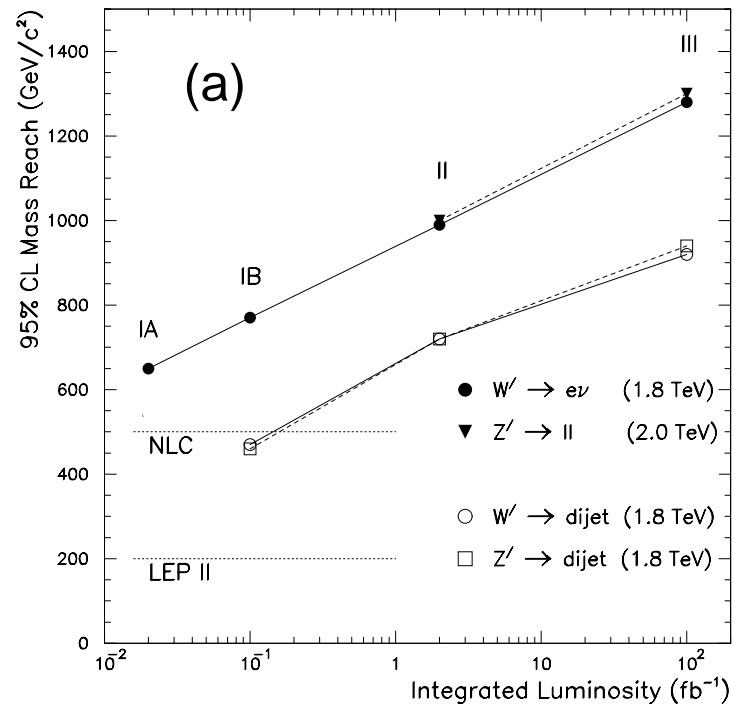
# Results and Run II Reach ( $Z'$ )

## CDF $Z'$ search



$M_{Z'} > 690 \text{ GeV}/c^2$   
(SM couplings)

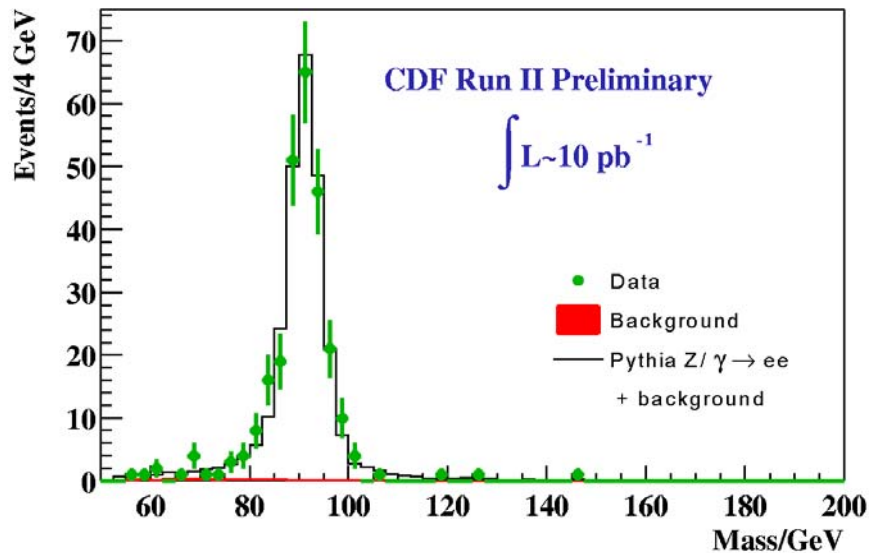
Searches for New Gauge Bosons at Fermilab



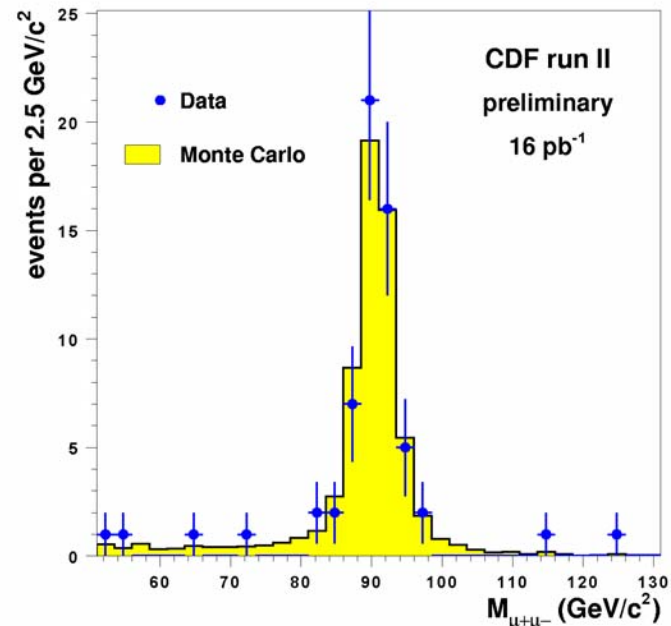
$Z'$  Run IIa reach :  $1000 \text{ GeV}/c^2$

# *Z peaks, Run II data*

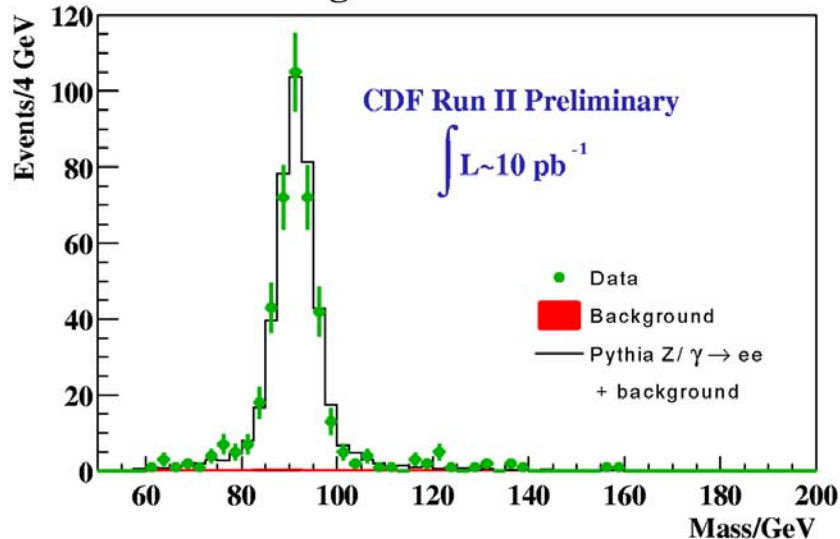
Central Dielectron Mass



Dimuon Mass



Central Plug Dielectron Mass



Analyses to look for an excess in the high mass region in progress by both CDF and D0

Drell-Yan searches can also be used to look for evidence of **technicolor** and quark-lepton **compositeness**. D0 Run I limits:

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$$\rho_{T1}, \omega_{T1} \rightarrow e^+ e^- \Rightarrow M_{\rho_{T1}, \omega_{T1}} > 225 \text{ GeV}/c^2 \quad (\text{other decays suppressed})$$

Run IIa reach : 410 GeV/c<sup>2</sup>

$$\text{compositeness scale from } e^+ e^- \Rightarrow \Lambda^+(\Lambda^-) > 3.3(4.2) \text{ TeV}$$

Run IIa  $\Lambda^+(\Lambda^-)$  reach : 6.5 (10) GeV/c<sup>2</sup>

Quark compositeness searched for in dijets. D0 Run I limits:

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$$\text{compositeness scale} \Rightarrow \Lambda^+(\Lambda^-) > 2.7(2.4) \text{ TeV}$$

$$\text{excited quarks : } q^* \rightarrow qg \Rightarrow M_{q^*} > 775 \text{ GeV}/c^2$$

Run IIa reach : 940 GeV/c<sup>2</sup>

# Technicolor searched for in other channels. CDF limits:

$$\rho_{T1} \rightarrow W \pi_{T1} \rightarrow \ell \nu b \bar{b}$$

$$170 < M_\rho < 200 \text{ GeV}/c^2$$

excluded ( $M_\pi \approx M_{\rho/2}$ )

$e$  ( $\mu$ ) with  $E_T$  ( $p_T$ )  $> 20$  GeV

Missing  $E_T > 20$  GeV

2 jets,  $E_T > 15$  GeV, one b-tagged

160-240 GeV/ $c^2$  at Run IIa

$$\omega_{T1} \rightarrow \gamma \pi_{T1} \rightarrow \gamma b \bar{b}$$

$$240 < M_\omega < 310 \text{ GeV}/c^2$$

excluded ( $M_\pi = 120 \text{ GeV}/c^2$ )

$E_T^\gamma > 25$  GeV

2 jets,  $E_T > 20$  GeV, one b-tagged

$$140 < M_\rho < 290 \text{ GeV}/c^2$$

excluded ( $M_\pi = 60 \text{ GeV}/c^2$ )

$$\rho_{T8} \rightarrow \pi_{LQ} \pi_{LQ} \rightarrow b \nu b \nu$$

$$M_\rho < 600 \text{ GeV}/c^2$$

2,3 jets with  $E_T > 15$  GeV, one b-tagged

No other jets with  $E_T > 7$  GeV, no leptons

Missing  $E_T > 40$  GeV

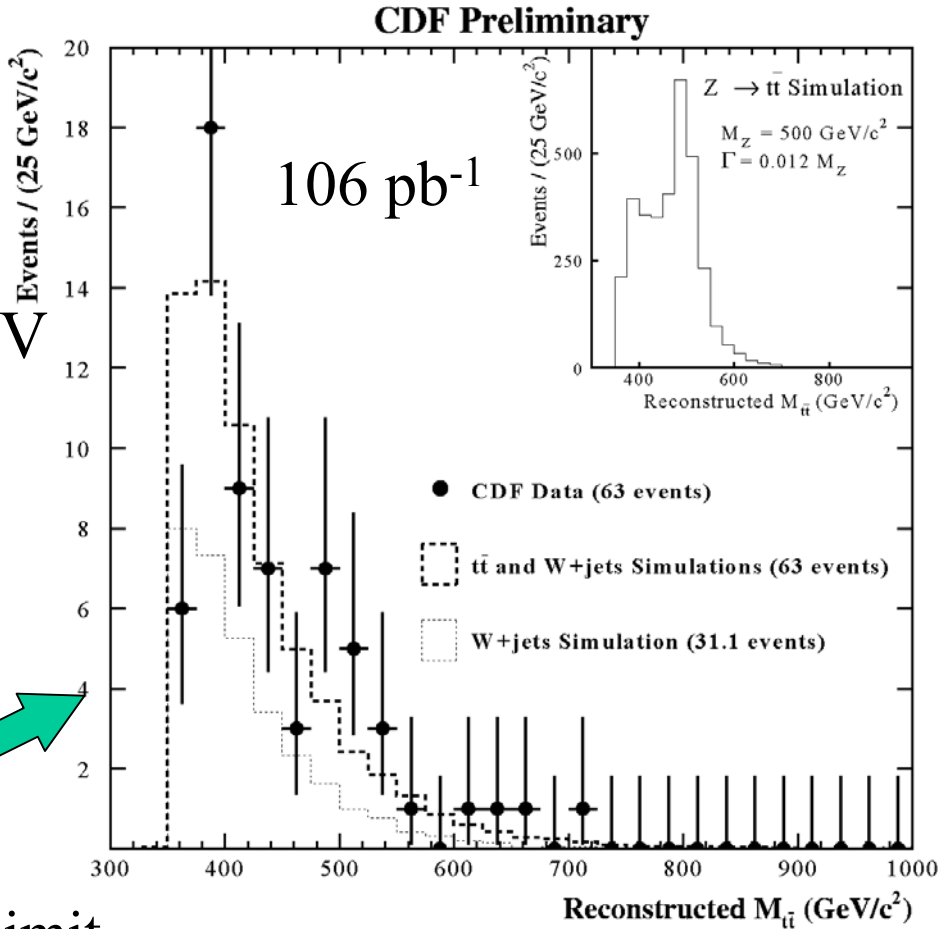
850 GeV/ $c^2$  at Run IIa

# Topcolor

Look for particle decaying to  $t\bar{t}$  (leptophobic  $Z'$ )

- $e$  ( $\mu$ ) with  $E_T$  ( $p_T$ )  $> 20$  GeV
- Missing  $E_T > 20$  GeV
- 4 jets,  $E_T > 15$  GeV  
4<sup>th</sup> jet:  $E_T > 8$  GeV if one other jet b-tagged

Fit performed to get  $M_{t\bar{t}}$



$M_{t\bar{t}}$  distribution consistent w/ SM

leptophobic  $Z'$  limit

Run IIa reach  $1100 \text{ GeV}/c^2$   
( $\Gamma = 0.04 M_{Z'}$ )

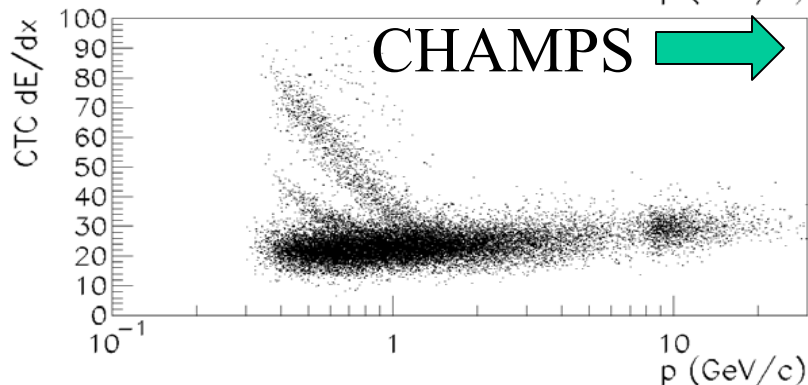
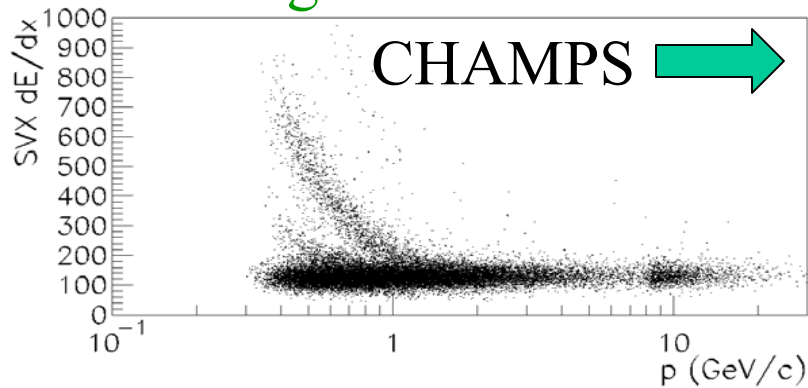
$M_{Z'} > 780 (480) \text{ GeV}/c^2$  for nat. width  $\Gamma = 0.04 M_{Z'}$  ( $0.012 M_{Z'}$ )

# CHAMPS

Charged Massive Particles,  
long-lived enough to leave  
detector

Heavy, slow moving particle

- Large time-of-flight (TOF)
- Large  $dE/dx$

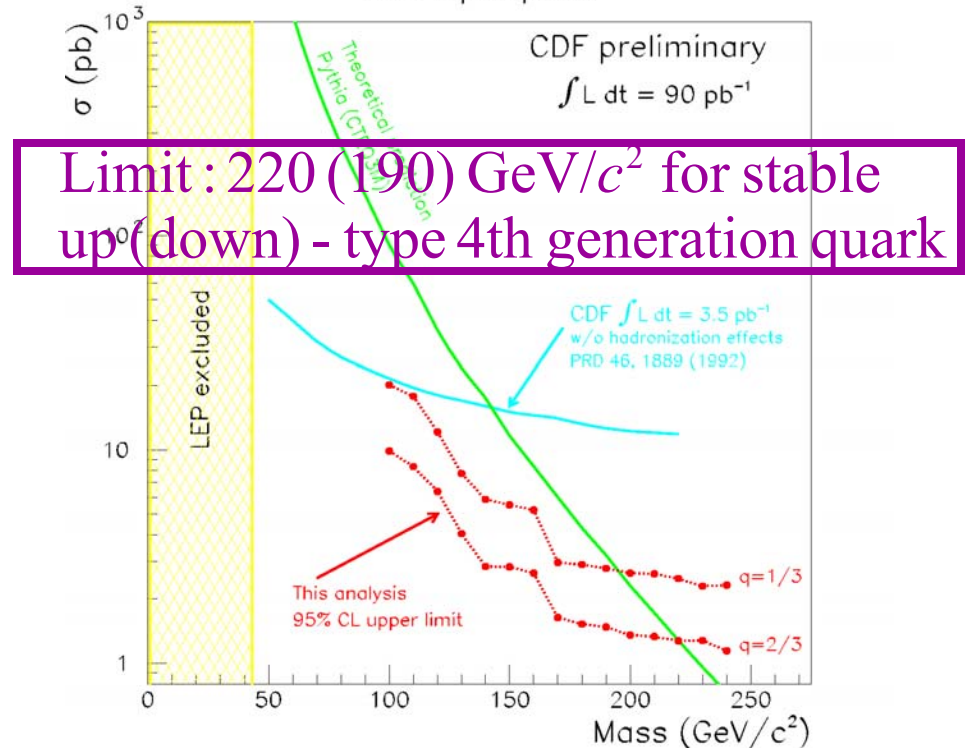


CDF Run I analysis:

- High  $p_T$  trk w/ large  $dE/dx$
- Use high  $p_T$  muon trigger

background:  $12 \pm 2.0$  events  
observed: 12 events

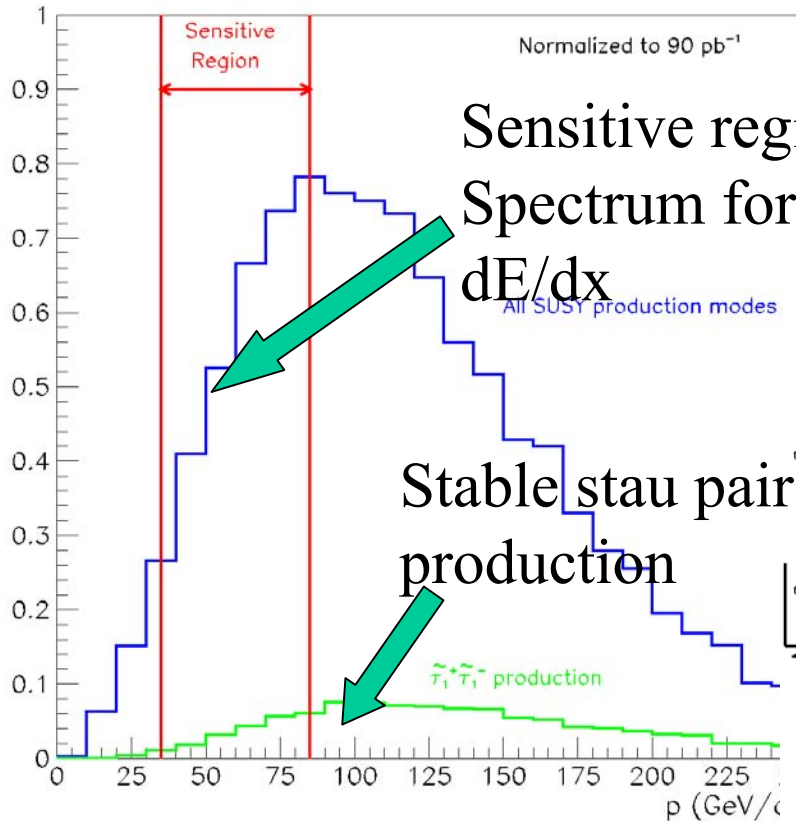
Limits on Stable Charged Massive Particles  
color triplet quarks



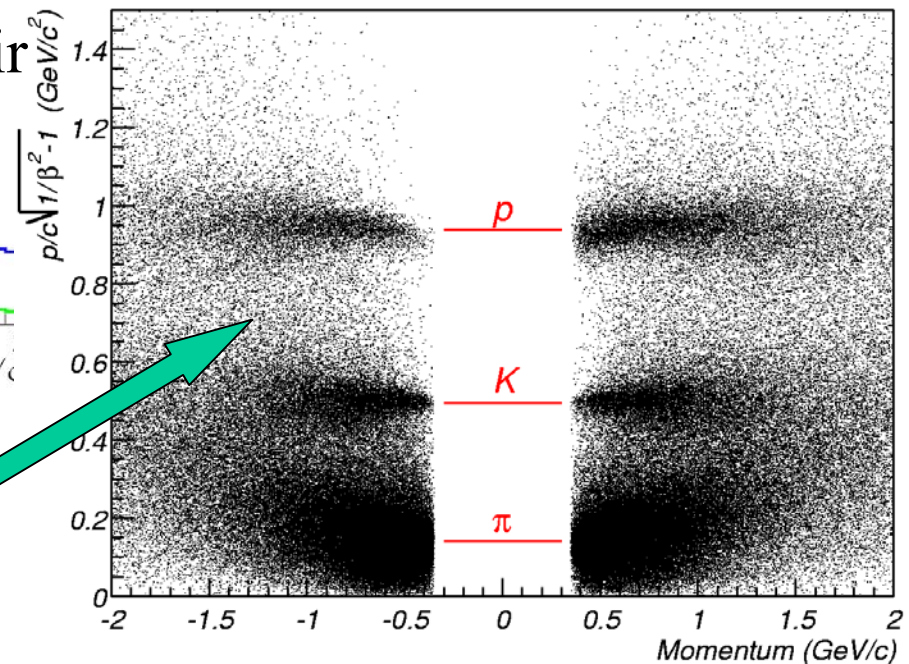
Limit: 220 (190)  $\text{GeV}/c^2$  for stable  
 $u^0(d)$  - type 4th generation quark



# CHAMPS at Run II



CDF Time-of-Flight : Tevatron store 860 - 12/23/2001



Separation at higher values  
of  $\beta\gamma$  using time-of-flight

# CDF Run II CHAMP Analysis

Select events with  
high  $p_T$  muon trigger

Track must have large  $p_T$ ,  
be isolated, have large TOF

Signal Sample:  $p_T > 40$  GeV/c

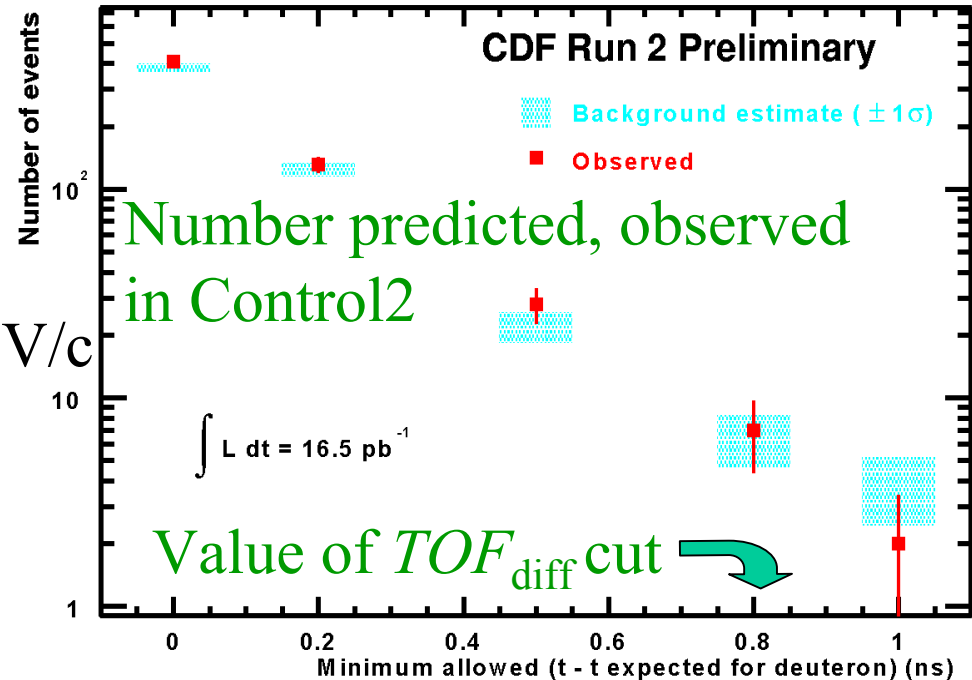
Control Sample:  $p_T > 20, < 40$  GeV/c

➤ Control1:  $p_T > 20, < 30$  GeV/c

➤ Control2:  $p_T > 30, < 40$  GeV/c

$$TOF_{Diff} = TOF_{Meas} - TOF_{Exp}^{Deut}$$

30 < Pt < 40 GeV/c (background-dominated region)

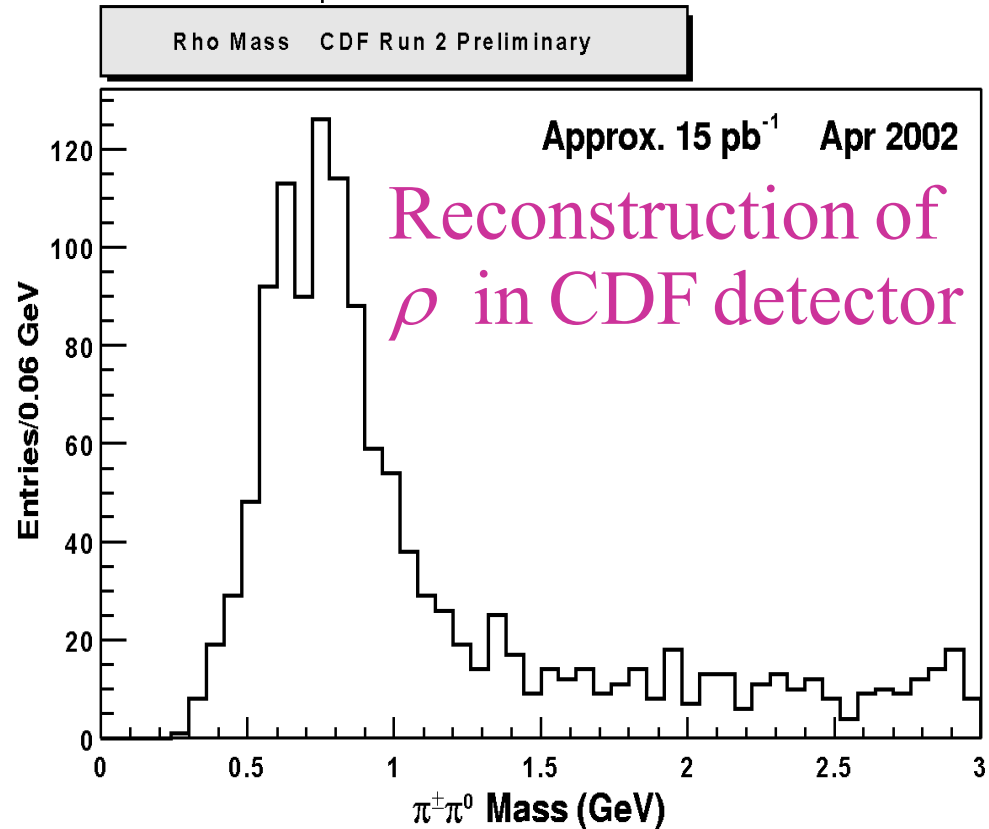
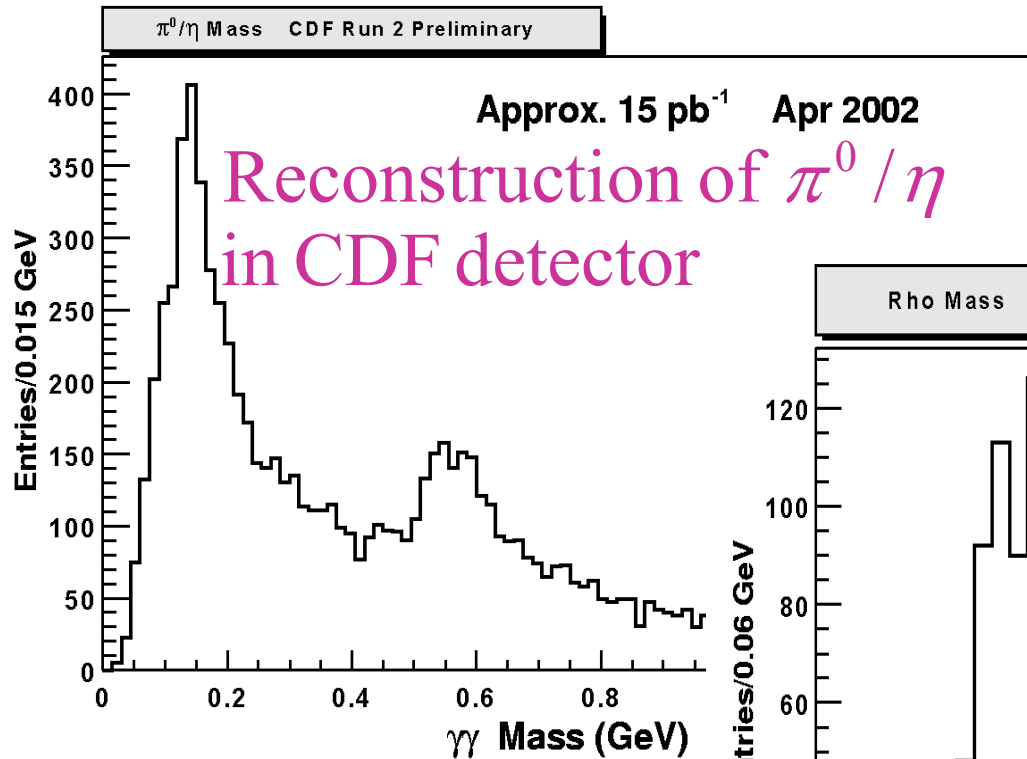


Expected Background:

$$N_{Sig}^{TOF_{Diff} > m} = \frac{N_{Sig}^{TOF_{Diff} > -0.2}}{N_{Control}^{TOF_{Diff} > -0.2}} \times N_{Control}^{TOF_{Diff} > m} \rightarrow 2.2 \pm 0.8 \text{ bck. exp. } (TOF_{diff} > 1.0 \text{ ns})$$

# Photon Physics at Run II

Searches for new physics  
are in progress...



# *New Physics with Photons*

CDF has searched for new physics in the Run I diphoton sample:

- $E_T > 22$  GeV, both photons
- Photons isolated
- Bckgnd: Jets faking photons

No excess in diphoton sample.

Search for bosophilic higgs

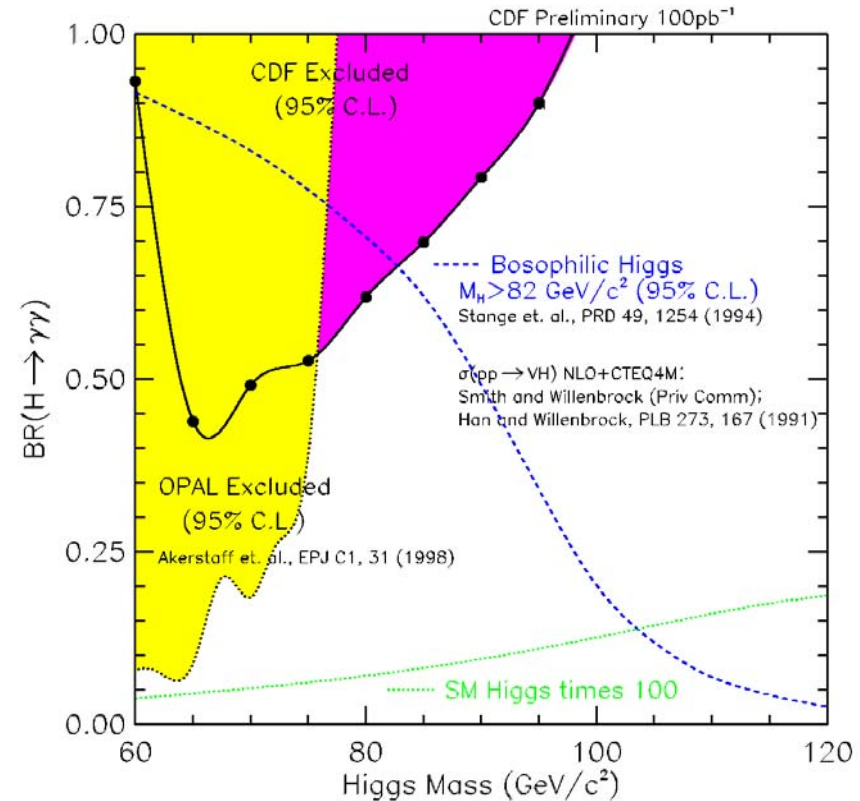
$H W/Z \rightarrow \gamma\gamma W/Z$

Selecting  $W/Z$ :

$e$  ( $\mu$ ) with  $E_T$  ( $p_T$ )  $> 20$  GeV **OR**

Missing  $E_T > 20$  GeV **OR**

2 jets,  $E_T > 15$  GeV,  $M_{jj} > 40, < 130$  GeV/ $c^2$



No excess in  
Diphoton- $W/Z$  sample

$M_H > 82 GeV/c^2$

# *Inclusive Photon+Lepton Search*

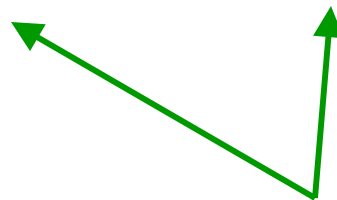
CDF has performed a model independent search at Run I for new physics that gives leptons, photons, missing  $E_T$  in final state

CDF Preliminary (86 pb<sup>-1</sup>)

Category	Predicted $\mu_{SM}$	Observed $N_0$	P(N > N <sub>0</sub>   $\mu_{SM}$ )%
All $l, \gamma, X$	–	77	–
Z - like $e, \gamma$	–	17	–
Two - Body $l, \gamma, X$	$24.9 \pm 2.4$	33	9.3
Multi - Body $l, \gamma, X$	$20.2 \pm 1.7$	27	10.0
Multi - Body $l, l, \gamma, X$	$5.8 \pm 0.6$	5	61.0
Multi - Body $l, \gamma, \gamma, X$	$0.02 \pm 0.02$	1	1.5
Multi - Body $l, \gamma, MET, X$	$7.6 \pm 0.7$	16	0.7

Main Backgrounds:

$W + \gamma, Z + \gamma, l + \text{fake } \gamma$



# Large Extra Dimensions

D0 has searched for LED in  
diphoton/dielectron sample

2 EM objects

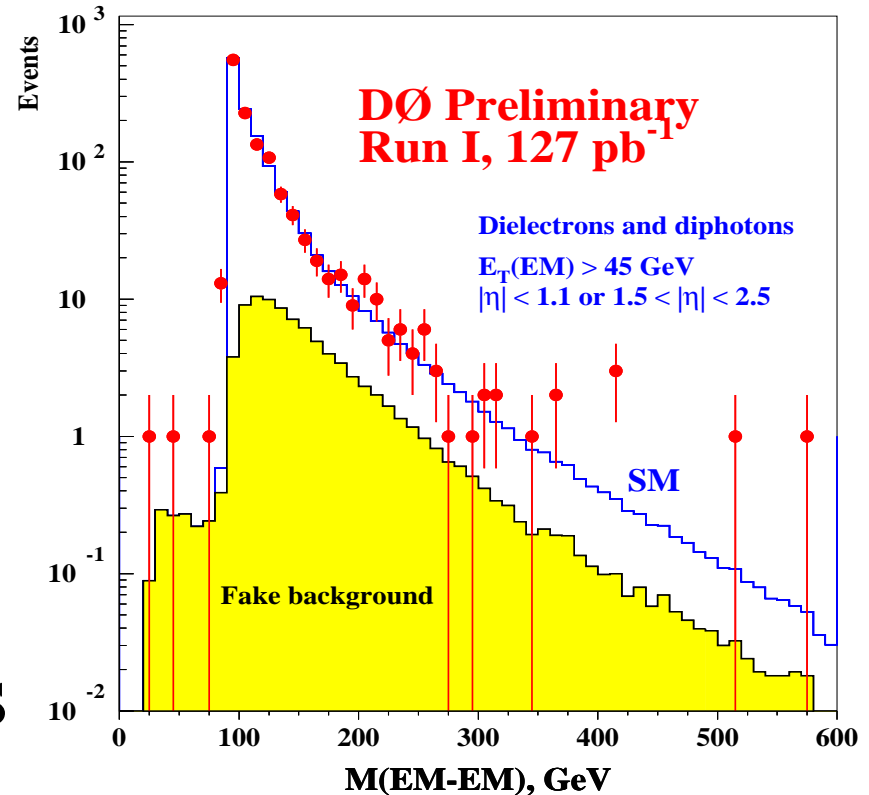
➤  $E_T > 45$  GeV for each

➤ Missing  $E_T < 25$  GeV

1282 events in sample

Bckgnd: Drell-Yan,  $\gamma\gamma$ , fakes

Comparison of the data with the SM predictions



Invariant mass, angular dist.  
of EM objects considered

No deviation from SM,  
Limit on eff. string scale  $M_S$

$M_S > 1.1$  (1.0)  $\text{TeV}/c^2$  for  
const. (dest.) interference  
between Kaluza-Klein and  
SM contributions

# *CDF search with $\gamma$ + Missing $E_T$*

Graviton emission:

$$q\bar{q} \rightarrow G_{kk}\gamma$$

$$E_T^\gamma > 55 \text{ GeV}$$

$$\text{Missing } E_T > 45 \text{ GeV}$$

$$\text{No jets with } E_T > 15 \text{ GeV}$$

$$\text{No tracks with } p_T > 5 \text{ GeV}/c$$

Main bckgnd : Cosmic Rays,

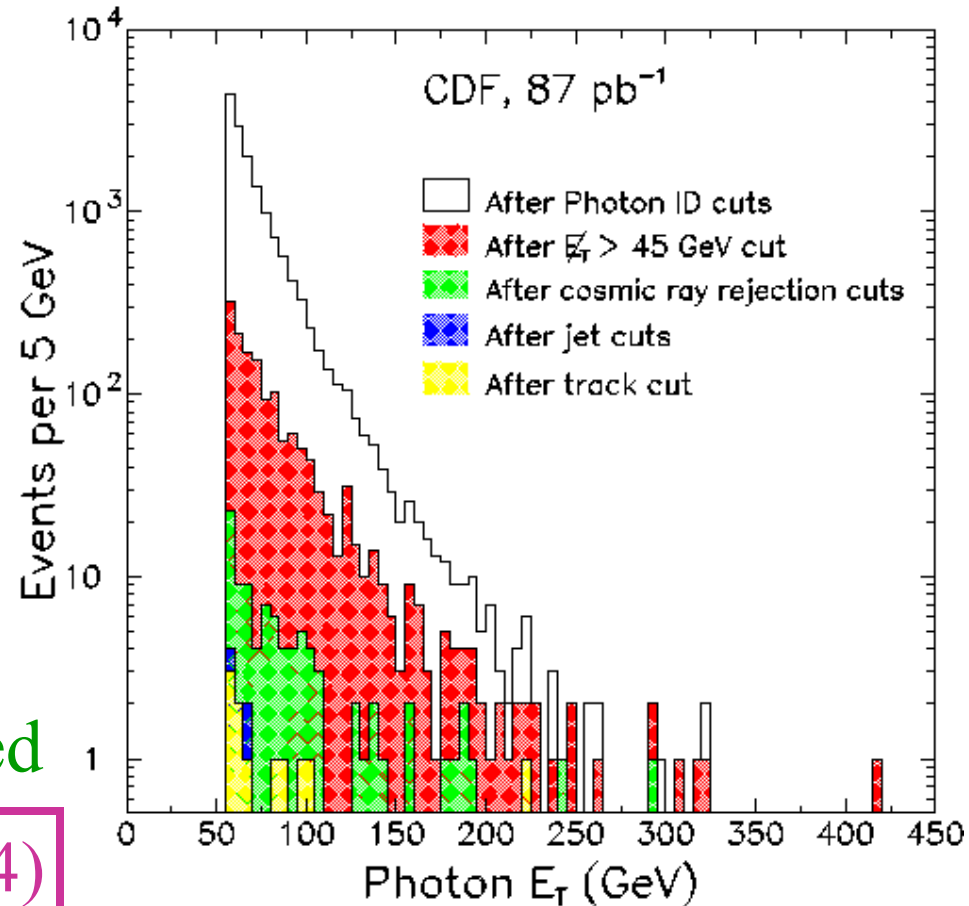
$$Z \rightarrow \nu\bar{\nu}\gamma$$

$11.0 \pm 2.2$  expected, 11 observed

$$M_s > 549 \text{ GeV}/c^2 \quad (n = 4)$$

$$M_s > 581 \text{ GeV}/c^2 \quad (n = 6)$$

$$M_s > 602 \text{ GeV}/c^2 \quad (n = 8)$$



# *D0 search with jets and missing $E_T$*

LED search,  $G_{KKg}$  final state

$E_T(\text{jet1}) > 150 \text{ GeV}$

$E_T(\text{jet2}) < 50 \text{ GeV}$

Missing  $E_T > 150 \text{ GeV}$

Missing  $E_T$ , jet2  $> 15^\circ$  apart

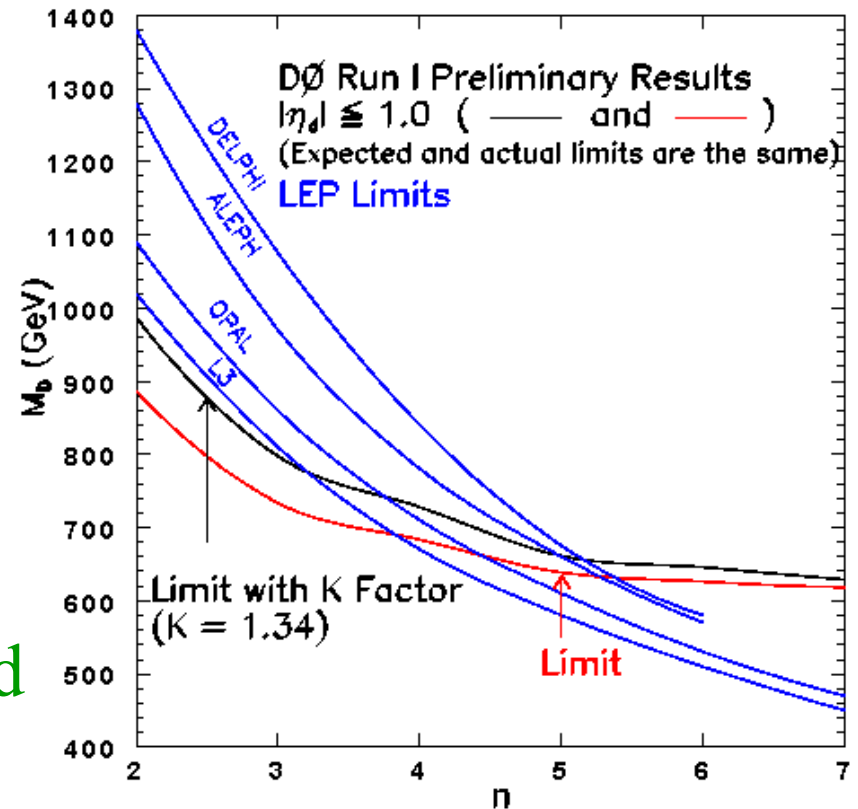
No isolated muons

Main bckgnd :  $Z \rightarrow \nu\bar{\nu}$  jets  
QCD/Cosmics  
 $W \rightarrow \tau\nu$  jets

$38.0 \pm 9.6$  expected, 38 observed

$$M_s > 886 \text{ GeV}/c^2 (n = 2)$$

$$M_s > 617 \text{ GeV}/c^2 (n = 7)$$





# Limits from Run II

D0 has repeated LED search in diphoton/dielectron final state

2 EM objects

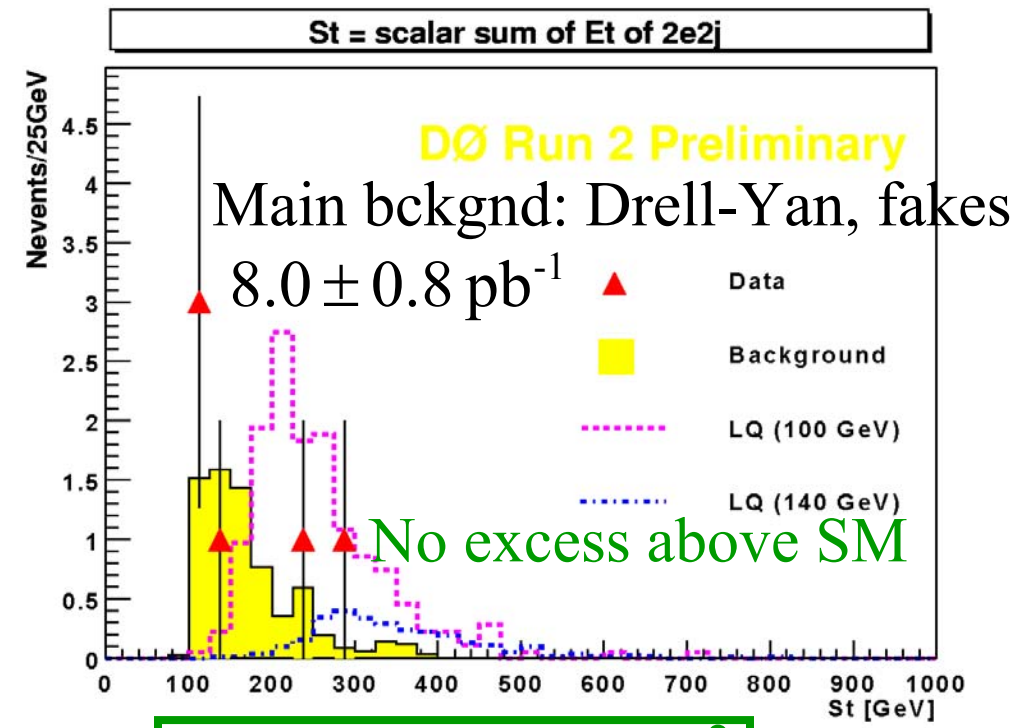
- $E_T > 25$  GeV for each
  - Missing  $E_T < 30$  GeV
- $9.85 \pm 0.38 \text{ pb}^{-1}$  used

No deviation from SM

$M_S > 0.82 \text{ TeV}/c^2$  for const. interference between Kaluza-Klein and SM contributions

D0 leptoquark search

- 2 EM clusters w/  $E_T > 25$  GeV
- $> 1$  jet w/  $E_T > 20$  GeV
- Z veto



$M_{LQ} > 113 \text{ GeV}/c^2$

Still need more data to improve on Run I results

# *Conclusion*

- D0 and CDF have searched for new physics with many different signatures
  - Dileptons
  - Dijets
  - Diphotons
  - Jets with a heavy flavor tag
  - Jets and missing  $E_T$
  - Photon and missing  $E_T$
  - Inclusive photons+leptons
  - Large  $dE/dx$  and large time-of-flight
- Many different models have been explored
- No evidence yet for new physics
- Run II has started, searches are in progress!