Diboson Physics at CDF

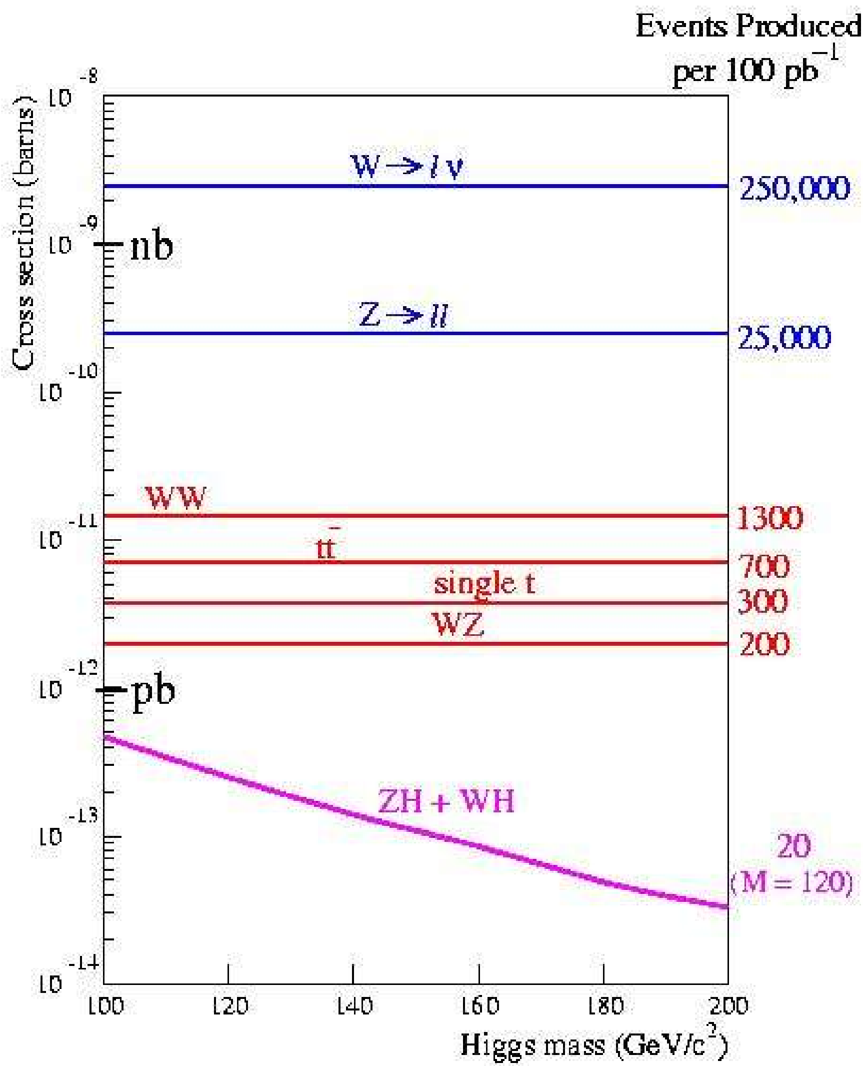
Mark Kruse
Duke University

Frontiers in Contempory Physics
Vanderbilt University, May 23-28 2005

Contents

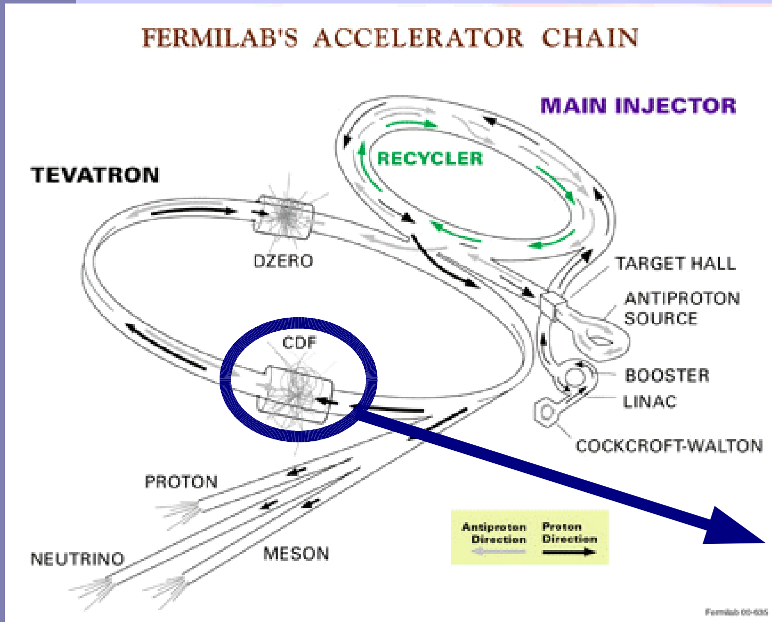
- Introduction
- Current status of CDF and the Tevatron
- W and Z studies
- $W\gamma$ and $Z\gamma$ production
- WW, WZ and ZZ production
- Prospects and Conclusions

Introduction

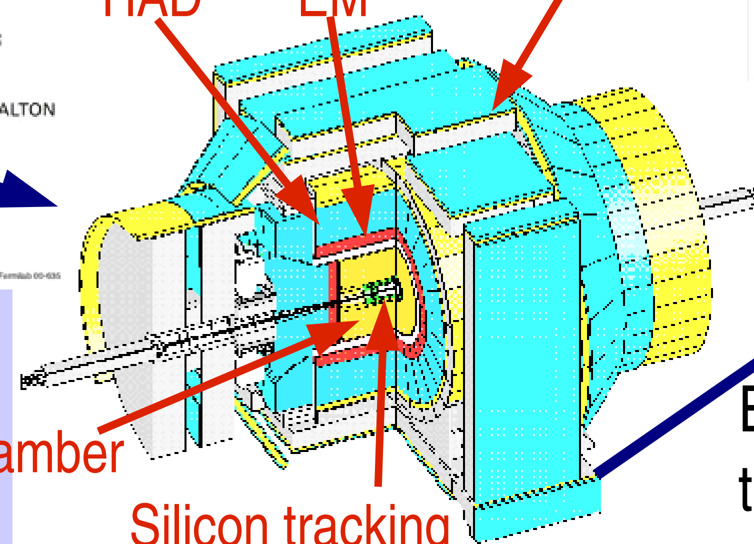


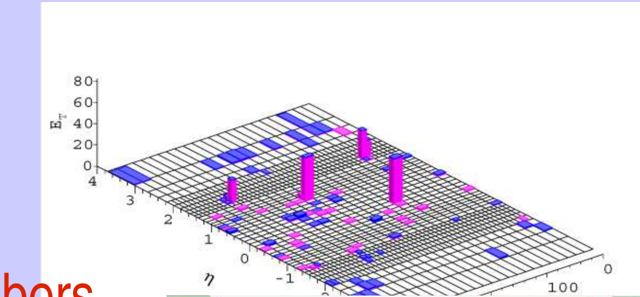
- **W's and Z's**
  - Large cross-sections/statistics
  - Precision measurements
  - Important calibrations
- **Diboson production**
  - Few pb cross-sections
  - Beginning program of precision measurements
  - Important SM tests
  - Crucial for understanding and optimizing Higgs analyses

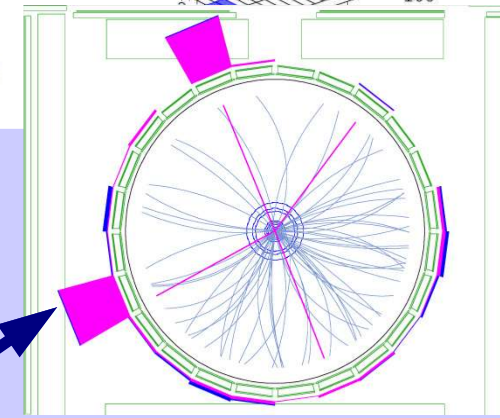
CDF in Run 2



Collision rate ~3MHz



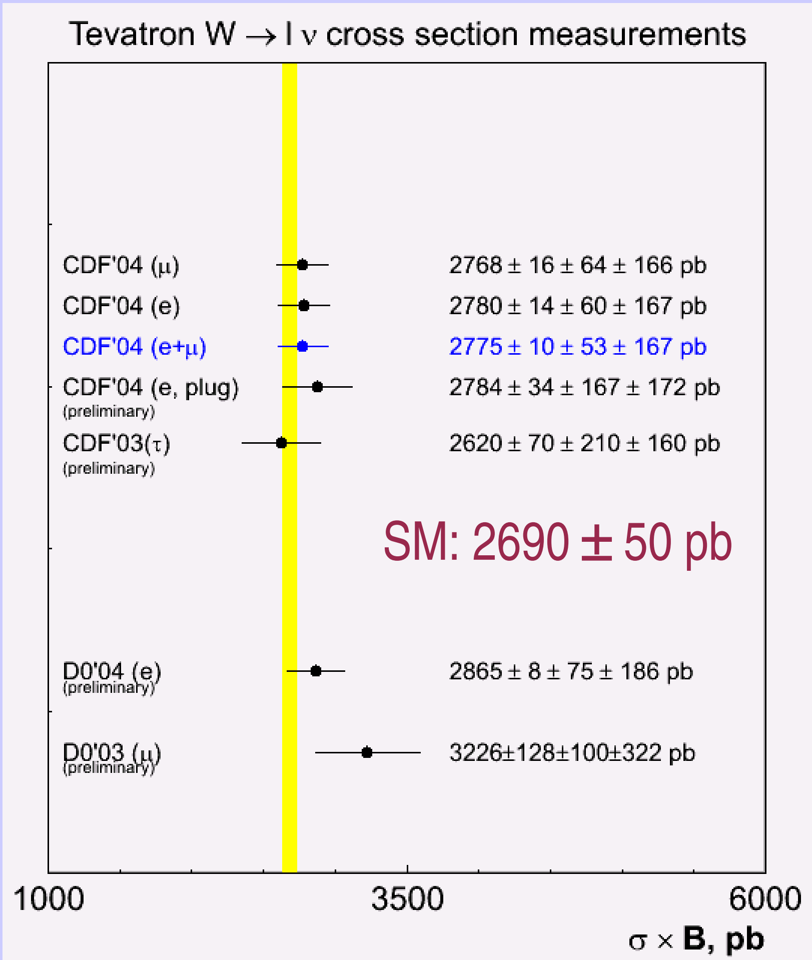


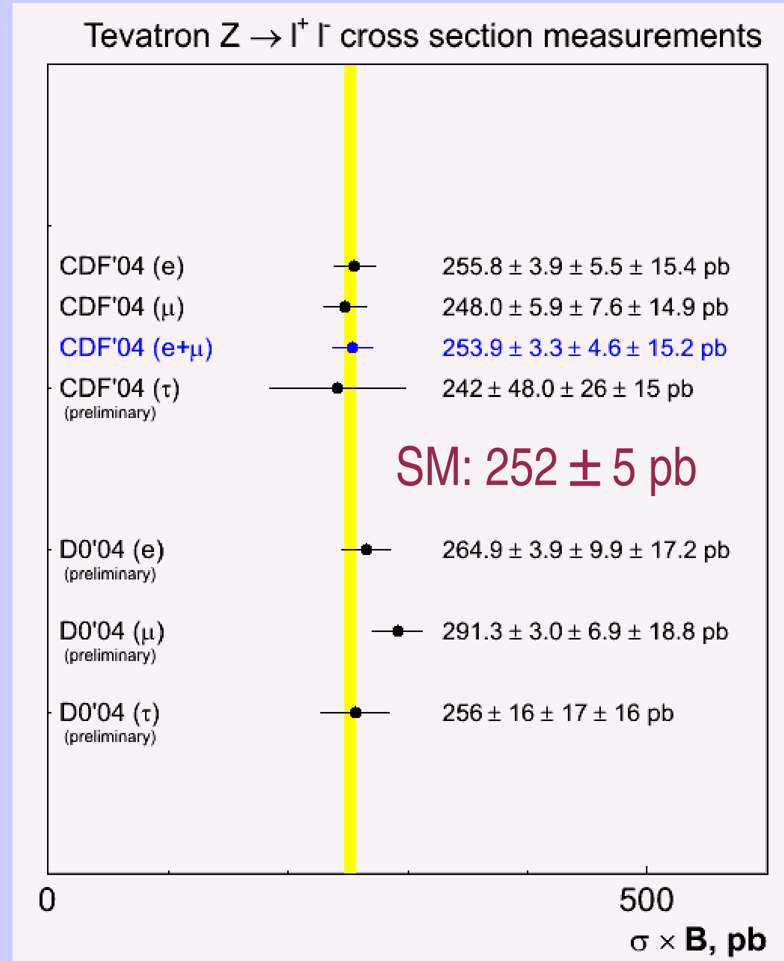


Events written to tape at ~50Hz

- Tevatron now performing well
- CDF detector running smoothly: data for analyses
  - 200 pb^{-1} (Mar-02 to Aug-03) – most results presented based on this data
  - 160 pb^{-1} (Sep-03 to Oct-04) – updates ongoing with new data
  - More data streaming in – expect 1 fb^{-1} by next year (as of a few days ago Tevatron has *delivered* 1 fb^{-1})

W and Z production





- Precision measurements using W and Z *leptonic* decays
  - 2% systematics in e/μ channel (dominated by PDF's, lepton ID efficiency)
- Yardstick for validation of all high-E_T lepton analyses

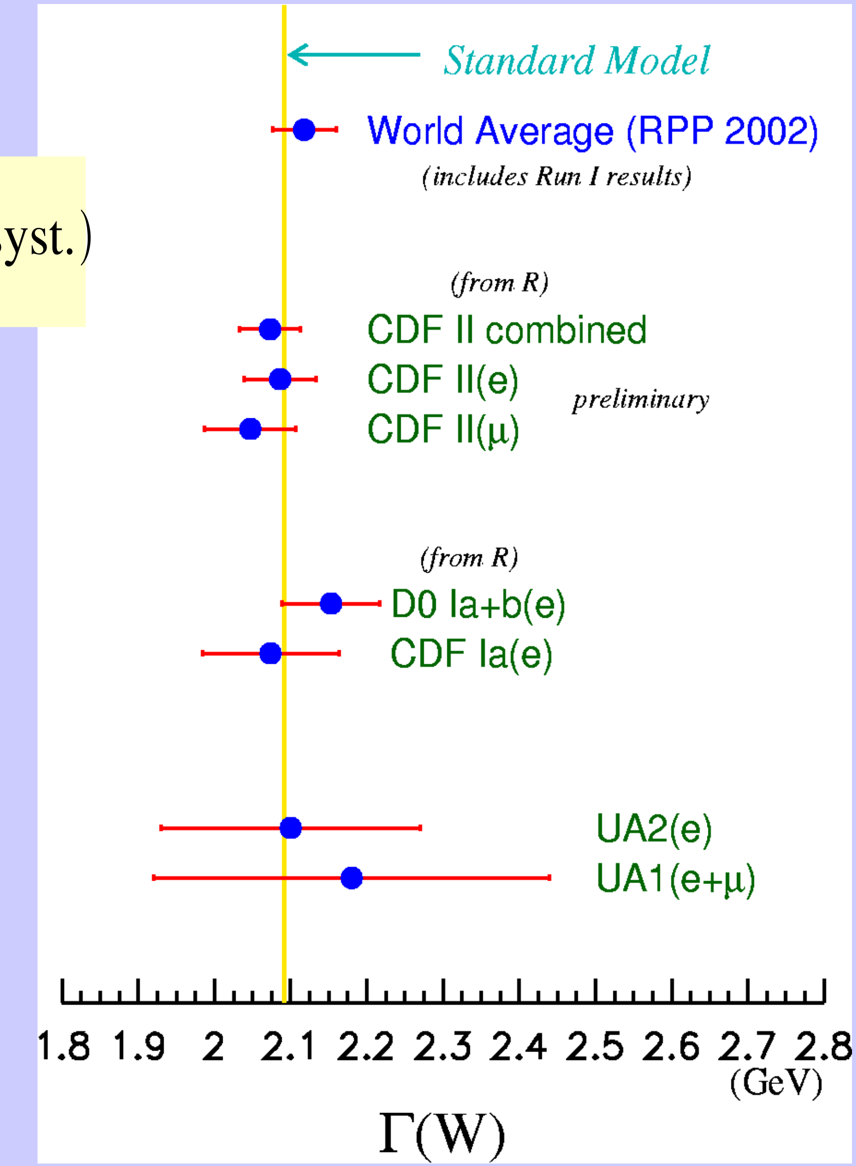
More W and Z results from Run 2

- R(W/Z): eμ combined

$$R = \frac{\sigma_W \times BR(W \to l\nu)}{\sigma_Z \times BR(Z \to l^+ l^-)} = 10.92 \pm 0.15(\text{stat.}) \pm 0.14(\text{syst.})$$

$$R = \frac{\sigma_W \times BR(W \to l\nu)}{\sigma_Z \times BR(Z \to l^+ l^-)} = \frac{\sigma_W}{\sigma_Z} \frac{\Gamma_Z}{\Gamma(Z \to l^+ l^-)} \frac{\Gamma(W \to l\nu)}{\Gamma_W}$$

SM : 3.361 ± 0.024 **LEP** **SM :** 226.4 ± 0.3 MeV



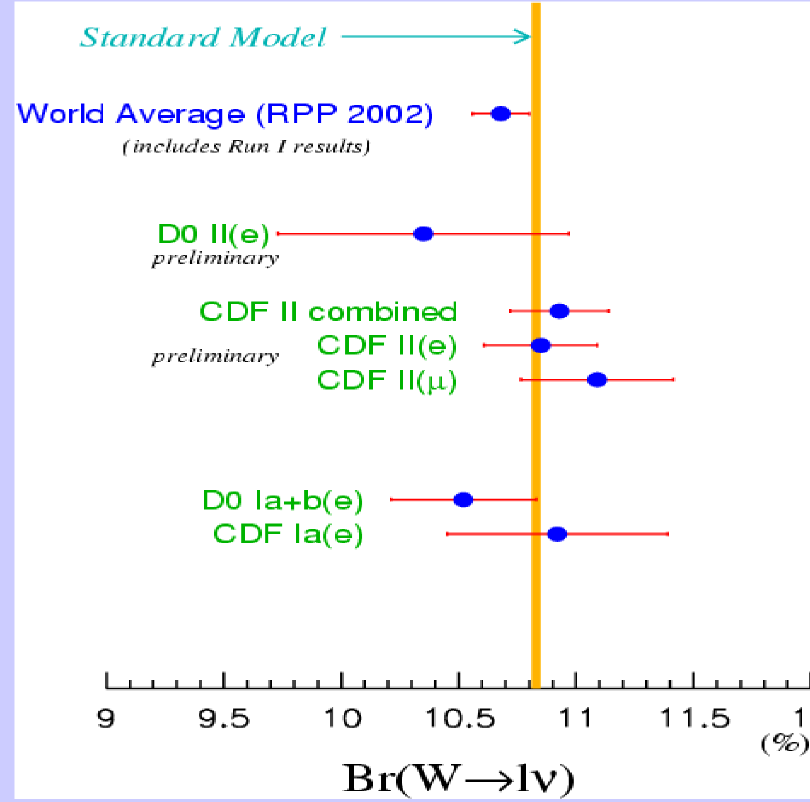
$$\Gamma_W(\text{indirect}) = 2.079 \pm 0.041 \text{ GeV}$$

$$\Gamma_W(\text{WA}) = 2.118 \pm 0.042 \text{ GeV}$$

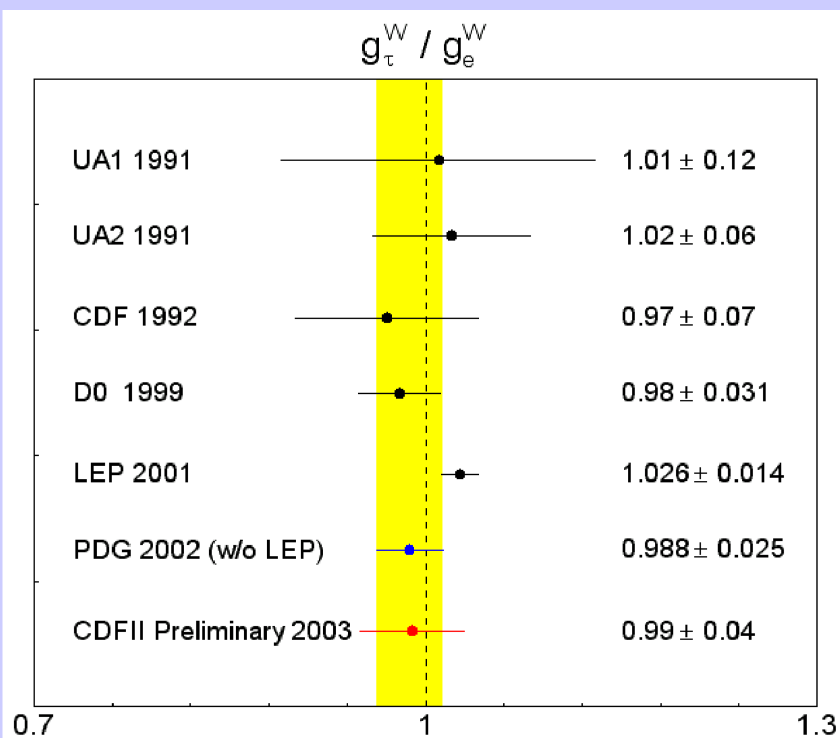
- Branching ratios:

$$\mathrm{BR}(W \to l\nu)_{\mathrm{CDF}} = 10.89 \pm 0.22\ \%$$

$$\mathrm{BR}(W \to l\nu)_{\mathrm{WA}} = 10.68 \pm 0.12\ \%$$



- Universality tests:



$$\sqrt{\frac{\mathrm{BR}(W \to \mu\nu)}{\mathrm{BR}(W \to e\nu)}} = \frac{g_\mu^W}{g_e^W}(\mathrm{CDF}) = 0.998 \pm 0.012$$

$$\sqrt{\frac{\mathrm{BR}(W \to \tau\nu)}{\mathrm{BR}(W \to e\nu)}} = \frac{g_\tau^W}{g_e^W}(\mathrm{CDF}) = 0.99 \pm 0.04$$

Phys. Rev. Lett. 94 (2005) 091803
(with more details and updates
soon to be submitted to PRD)

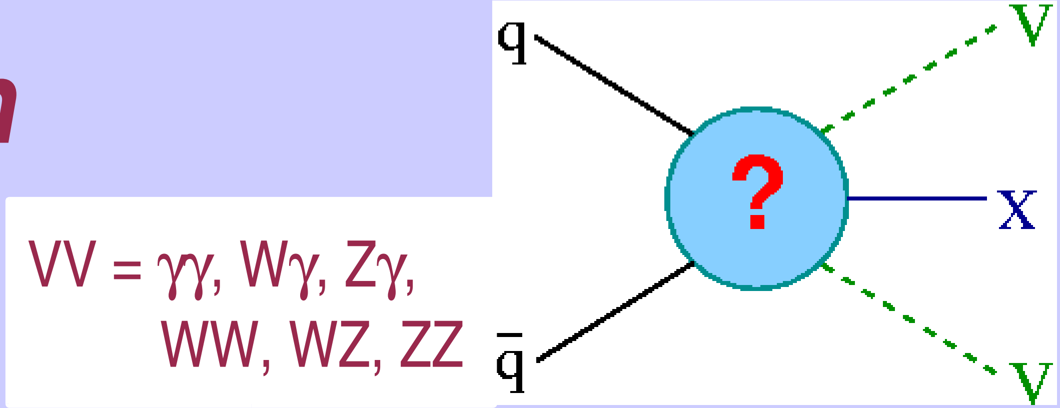
Many other W and Z measurements

- W charge asymmetry – important for PDF fits
- Cross-sections using tau decays
- Differential cross-section measurements
- Forward-backward asymmetry of $Z/\gamma^* \rightarrow ee$
- W mass

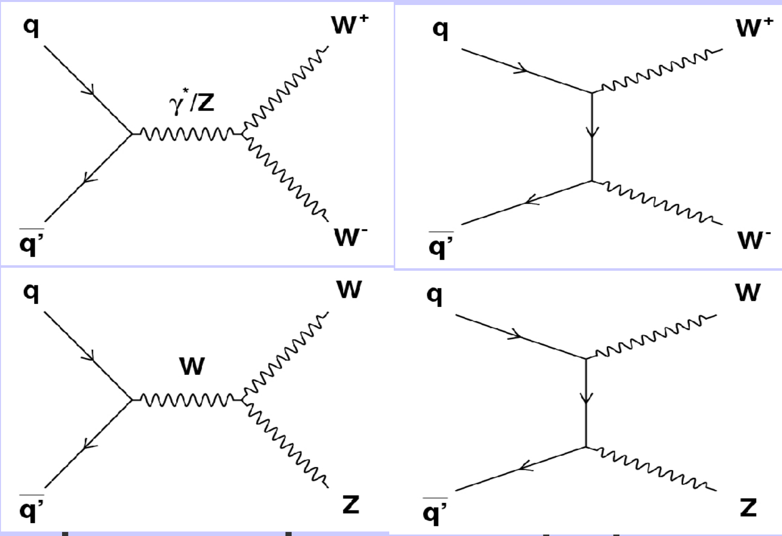
- Many new results and methods out and in progress
- All provide important precision tests of the SM

- Rest of this talk on <u>diboson</u> measurements.....

Diboson Production



- Standard Model cross-sections at 1.96 TeV
  - $\sigma(p\bar{p} \rightarrow WW) = 12.5 \pm 0.8\ pb$
  - $\sigma(p\bar{p} \rightarrow WZ) = 3.7 \pm 0.4\ pb$
  - $\sigma(p\bar{p} \rightarrow ZZ) = 1.4 \pm 0.1\ pb$



- Wγ and Zγ cross-sections depend on γ characteristics
- Direct test of triple gauge boson couplings
  - Enhanced W/Z and lepton P_T spectra → anomalous couplings
  - Use all VV final states; probe at higher CM energy than LEP
- Resonance searches: e.g. gg → H → WW

$W\gamma$ and $Z\gamma$ selection

- Select $W \rightarrow l\nu$ and $Z \rightarrow l^+l^-$ events
  - High-E_T electrons and muons (> 20 GeV)
  - For W events: large missing-E_T and $30 < M_T(l\nu) < 120$ GeV
  - For Z events: $76 < M(l^+l^-) < 106$ GeV

- Look for additional photons
  - Isolated EM cluster with $E_T > 7$ GeV
  - $|\eta^\gamma| < 1.1$ and $\Delta R(l,\gamma) < 0.7$
  - High efficiency (>95%) after all ID
  - Jet $\rightarrow \gamma$ fake rate: about 0.2% at 7 GeV, 0.06% at 25 GeV

$W\gamma$ results

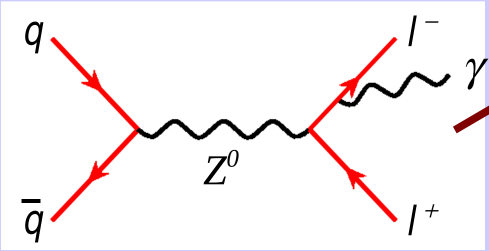
	Electron	Muon
W+ γ MC	126.8 ± 5.8	95.2 ± 4.9
W+jet BG	59.5 ± 18.1	27.6 ± 7.5
W+ γ (tau)	1.5 ± 0.2	2.3 ± 0.2
Z+ γ	6.3 ± 0.3	17.4 ± 1.0
Total SM	194.1 ± 19.1	142.4 ± 9.5
data	195	128
σ*BR	19.4 ± 2.1 ± 2.9	16.3 ± 2.3 ± 1.8

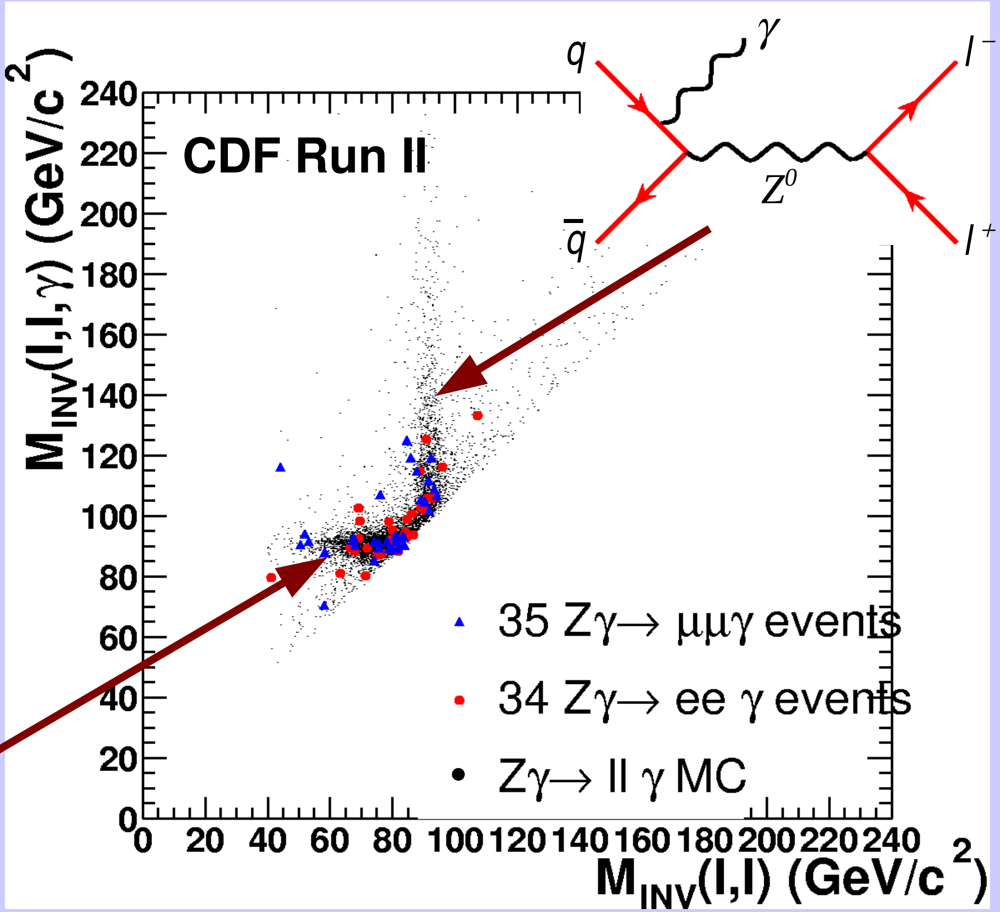
$$\sigma(W\gamma)\times BR(W\to l\nu) = 18.1 \pm 1.6_{(stat)} \pm 2.4_{(syst)} \pm 1.2_{(lum)}\, pb$$

$$\sigma(W\gamma)\times BR(W\to l\nu)_{SM} = 19.3 \pm 1.4\, pb$$ (Baur, Han, Ohnemus, 93/98)

Zγ results

	Electron (±sys)	Muon (± sys)
Z+γ MC	30.9 ± 1.6	33.2 ± 1.5
Z+jet BG	2.8 ± 0.9	2.1 ± 0.7
Total SM	33.7 ± 1.8	35.3 ± 1.6
data	35	35
σ*BR	4.7 ± 0.8 ± 0.3	4.5 ± 0.8 ± 0.2



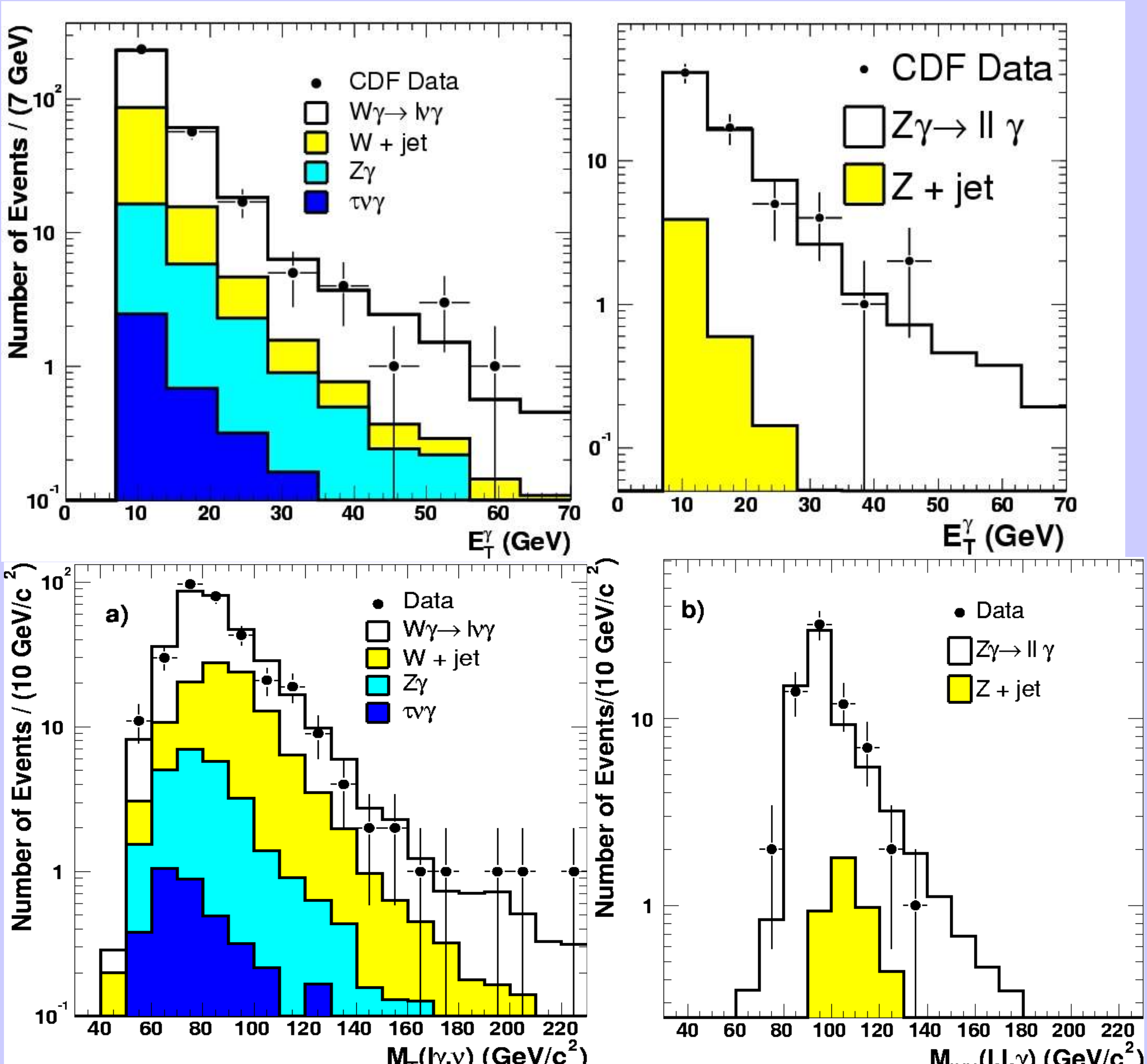


$$\sigma(Z\gamma)\times BR(Z\to l^+ l^-) = 4.6 \pm 0.5_{(stat)} \pm 0.2_{(syst)} \pm 0.3_{(lum)}\, pb$$

$$\sigma(Z\gamma)\times BR(Z\to l^+ l^-)_{SM} = 4.5 \pm 0.3\, pb$$ (Baur, Han, Ohnemus, 93/98)

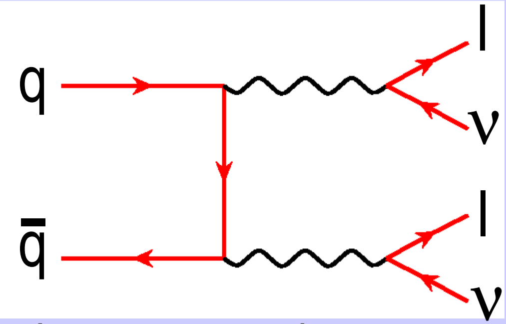
Phys. Rev. Lett. 94 (2005) 041803

Wγ and Zγ kinematics



- Data well described over large range of photon E_T
- No hint of new physics at high mass

WW



- Cross-section measured in <u>dilepton</u> channel
  - ***WW→lνlν (l=e,μ)***
  - BR small (about 5%) but good signal/background (about 2:1)
  - Also important background for other analyses ($t\bar{t}$, H → WW, ...)
- Selection:
  - One isolated E_T > 20 GeV electron or muon
  - Missing E_T > 25 GeV
  - Then: **(1) <u>Dilepton</u>**: 2nd isolated lepton, topological cuts, 0 jets
    (2) <u>Lepton + Track</u>: 2nd isolated track, topological cuts, 0 or 1 jets
  - "Lepton + Track" analysis has larger acceptance and lower purity
- Main backgrounds: Drell-Yan, W + jets, $t\bar{t}$

WW results

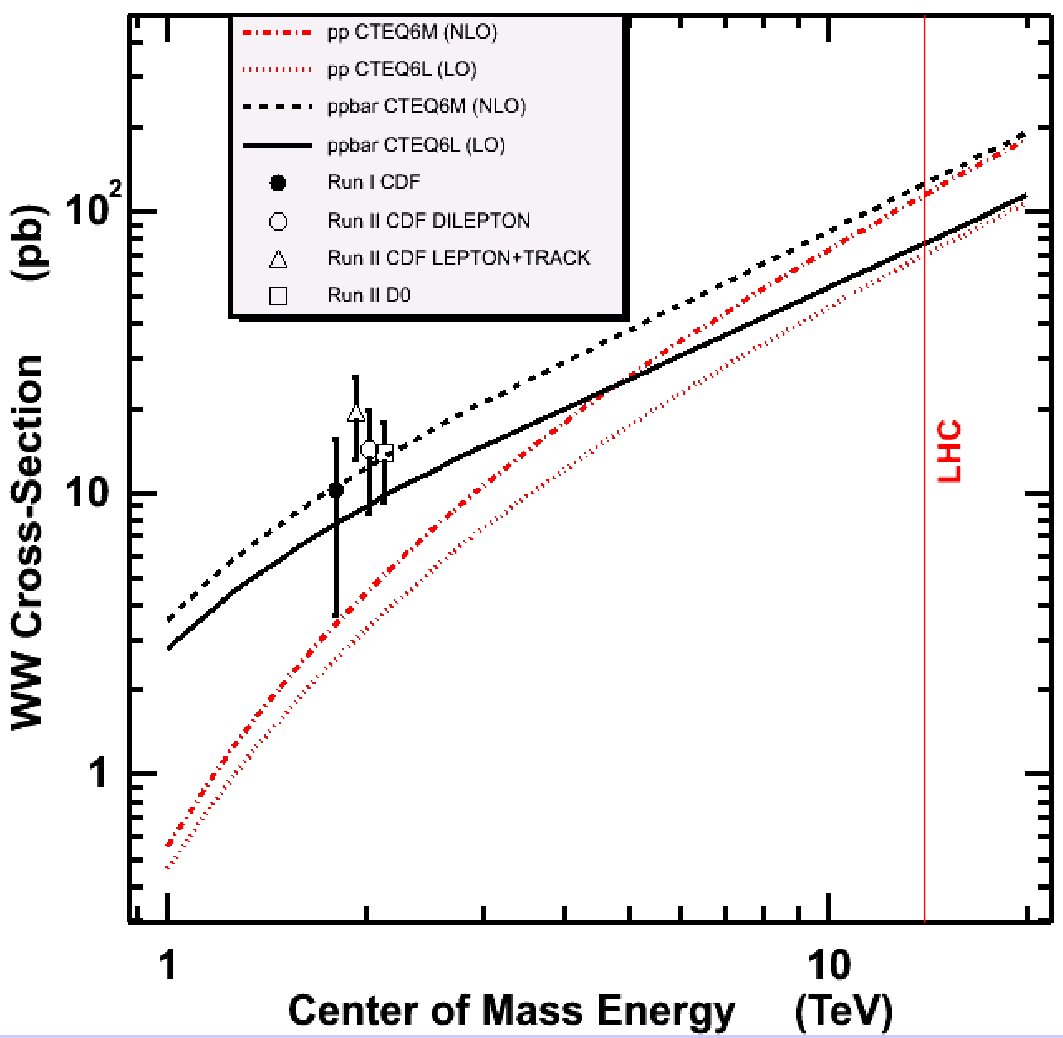
	DILEPTON	LEPTON+TRACK (STAT ERR.)
WW Signal	11.3 ± 1.3	16.3 ± 0.4
Drell–Yan Background	1.8 ± 0.4	1.8 ± 0.3
Fake Background	1.1 ± 0.5	9.1 ± 0.8
Other Background	1.9 ± 0.2	4.2 ± 0.1
Total Background	4.8 ± 0.7	15.1 ± 0.9
Total Expected	16.1 ± 1.6	31.5 ± 1.0
Data Observed	17	39
σ(WW) [pb]	$14.3^{+5.6}_{-4.9}(stat) \pm 1.6(syst) \pm 0.9(lum)$	$19.4 \pm 5.1(stat) \pm 3.5(syst) \pm 1.2(lum)$

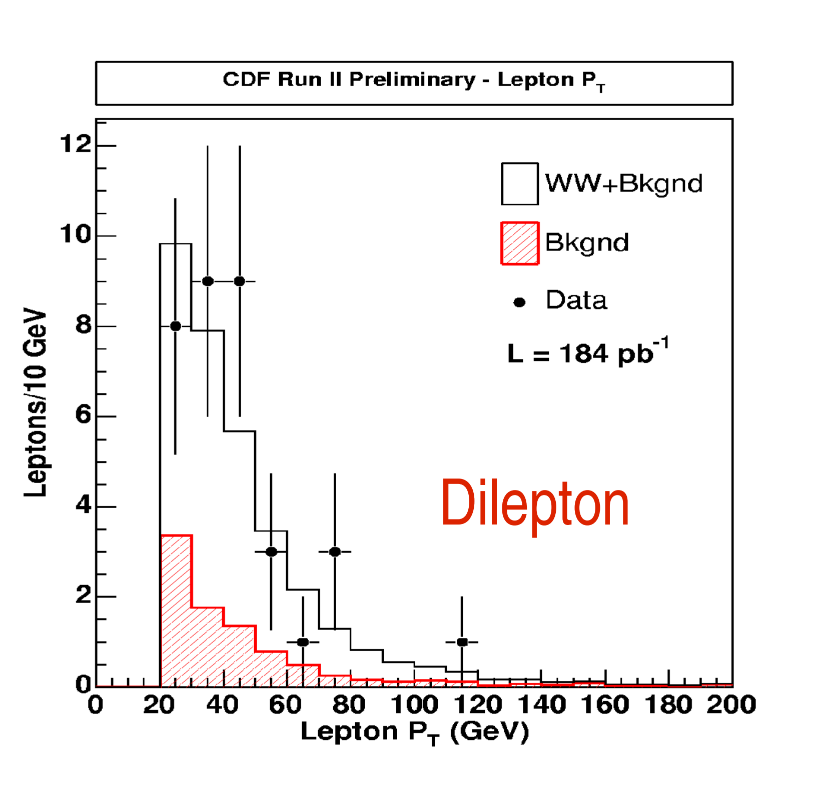
$$\sigma(WW) = \frac{N_{\mathrm{DATA}} - N_{\mathrm{BKG}}}{\epsilon \times L \times BR(WW \rightarrow l \nu l \nu)}$$

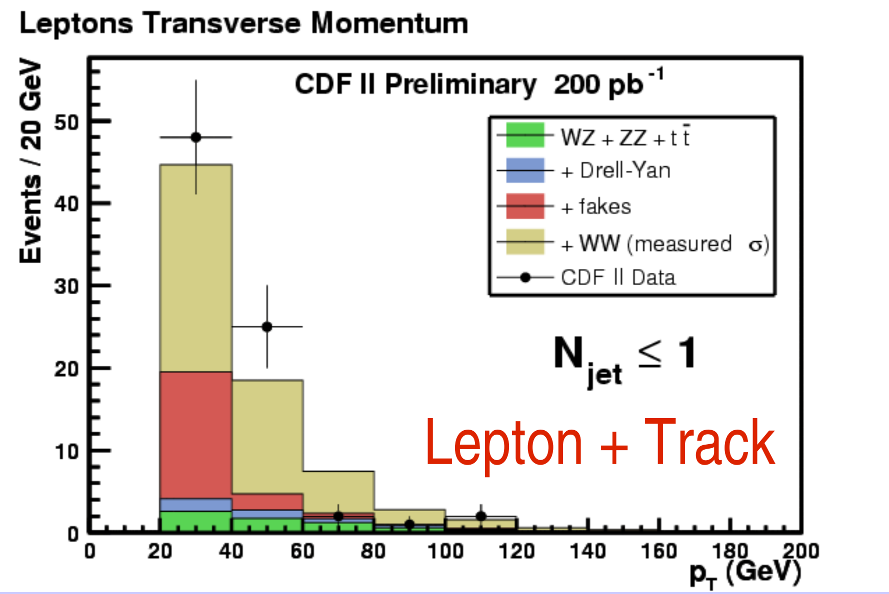
hep-ex/0501050, submitted to PRL

- 2 measurements consistent given estimated acceptance overlap
- Consistent with NLO prediction of 12.5 ± 0.8 pb (Campbell & Ellis, '99)

WW results







- Good agreement with expectations
- Distributions being fitted to extract anomalous coupling limits

Selected candidates

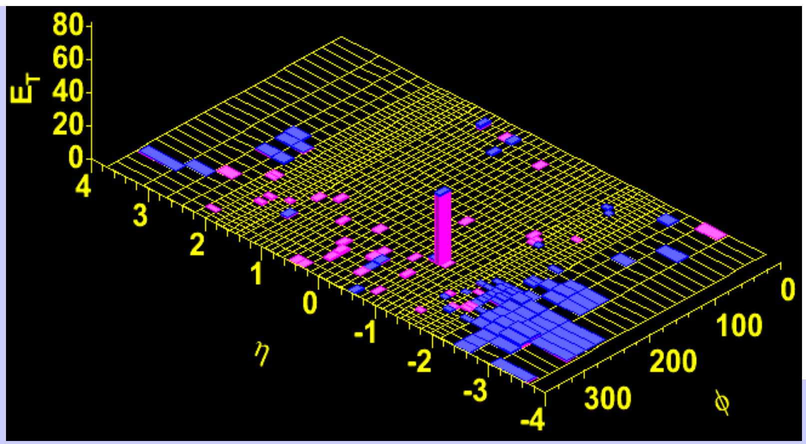
- eμ event
  - very clean channel
  - S:B ~ 4:1

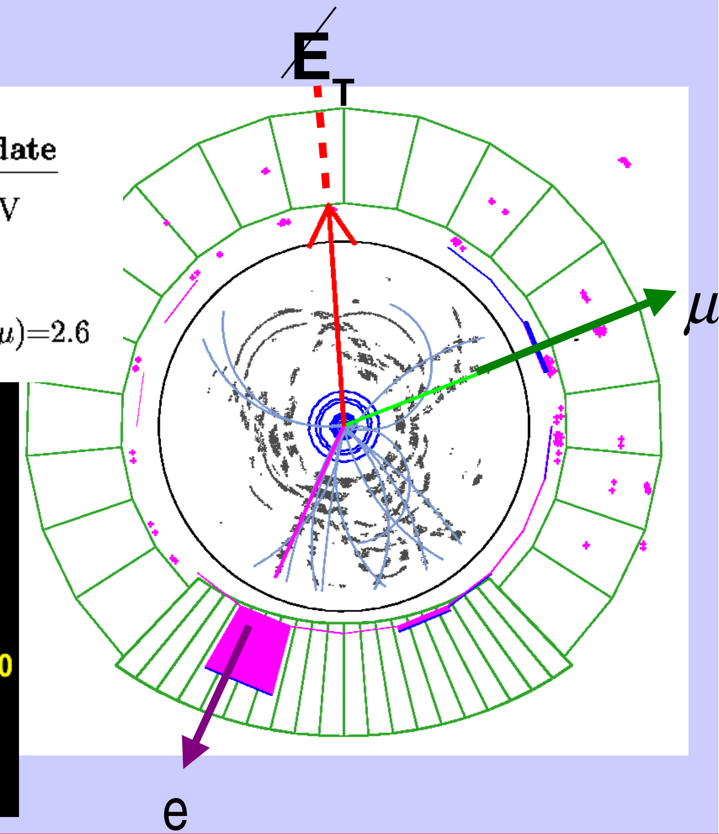
Run 155364 Event 3494901 : $WW \rightarrow e^+\nu_e\mu^-\bar{\nu}_\mu$ Candidate

$p_T(e) = 42.0$ GeV/c; $p_T(\mu) = 20.0$ GeV/c; $M_{e\mu} = 81.5$ GeV

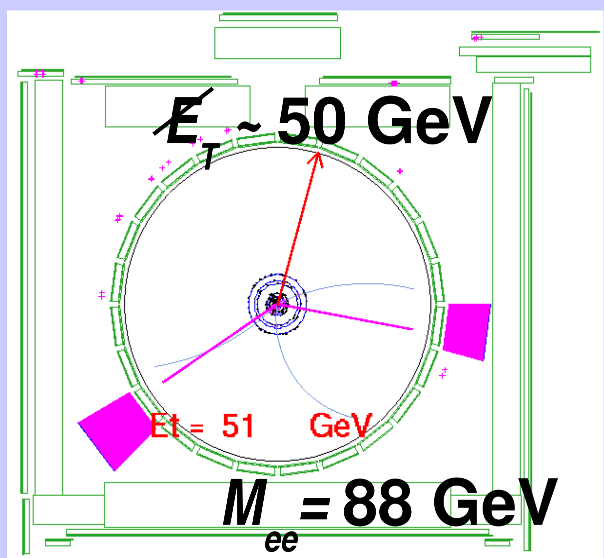
$\not{E}_T = 64.8$ GeV; $\Phi(\not{E}_T) = 1.6$

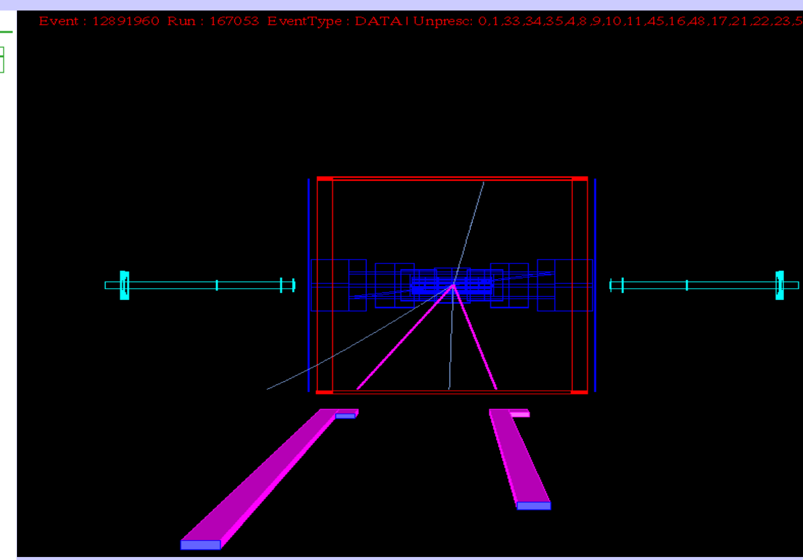
$\Delta\Phi(\not{E}_T$, lepton$) = 1.3$; $\Delta\Phi(e,\mu) = 2.4$; Opening-Angle(e,μ)=2.6



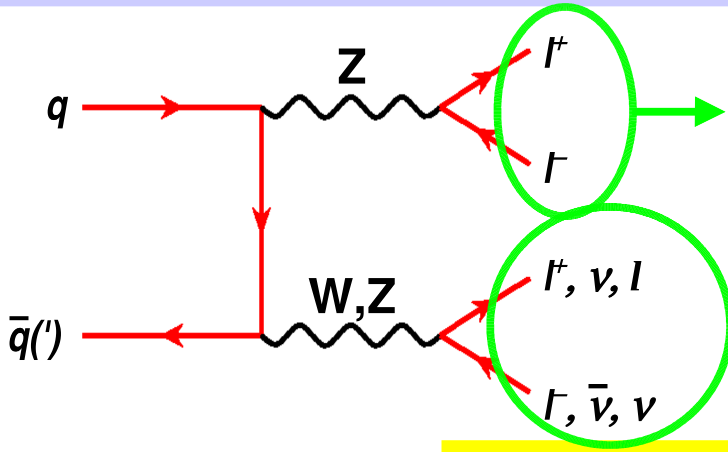


- WW → eν eν
  or
  ZZ → ee νν ?





Search for WZ / ZZ



$76 < M(l^+l^-) < 106$ GeV

l^+l^- : $76 < M(l^+l^-) < 106$ GeV

$l\,\nu$: lepton + $\not\!\!E_T > 20$ GeV

$\nu\bar{\nu}$: large $\not\!\!E_T$-significance

Select Z -> ee, μμ

In addition require:

1 — 2 more leptons consistent with Z -> ee, μμ

sensitive to:
ZZ -> $l^+l^-l^+l^-$

2 — 1 extra lepton and missing E_T > 20

sensitive to:
ZW -> $l^+l^-l\,\nu$
ZZ -> $l^+l^-l^+l^-$

3 — significant missing E_T

sensitive to:
ZZ -> $l^+l^-\nu\nu$
ZW -> $l^+l^-l\,\nu$
ZZ -> $l^+l^-l^+l^-$

WZ / ZZ results

CDF Run II			$\mathcal{L}$=194 pb^{-1}	
Process	$l_1 l_2 l_3 l_4$	$l_1 l_2 l_3 \not\!\!E_T$	$l_1 l_2 \not\!\!E_T$	Combined
ZZ	0.07 ± 0.01	0.13 ± 0.01	0.87 ± 0.14	1.07 ± 0.15
ZW	-	0.81 ± 0.07	0.86 ± 0.14	1.67 ± 0.19
ZZ+ZW	0.07 ± 0.01	0.94 ± 0.08	1.73 ± 0.27	2.72 ± 0.33
WW	-	-	1.26 ± 0.20	1.26 ± 0.20
Fake	0.01 ± 0.02	0.07 ± 0.06	0.56 ± 0.30	0.64 ± 0.34
Drell-Yan	-	-	0.31 ± 0.13	0.31 ± 0.13
$t\bar{t}$	-	-	0.08 ± 0.02	0.08 ± 0.02
Total Background	0.01 ± 0.02	0.07 ± 0.06	2.21 ± 0.38	2.29 ± 0.42
Expected S. + B.	0.08 ± 0.02	1.01 ± 0.10	3.94 ± 0.57	5.01 ± 0.64
Data	0	0	4	4

$$\sigma(pp \rightarrow WZ/ZZ) < 13.9\ pb$$

Phys. Rev. D 71, 091105 (2005)

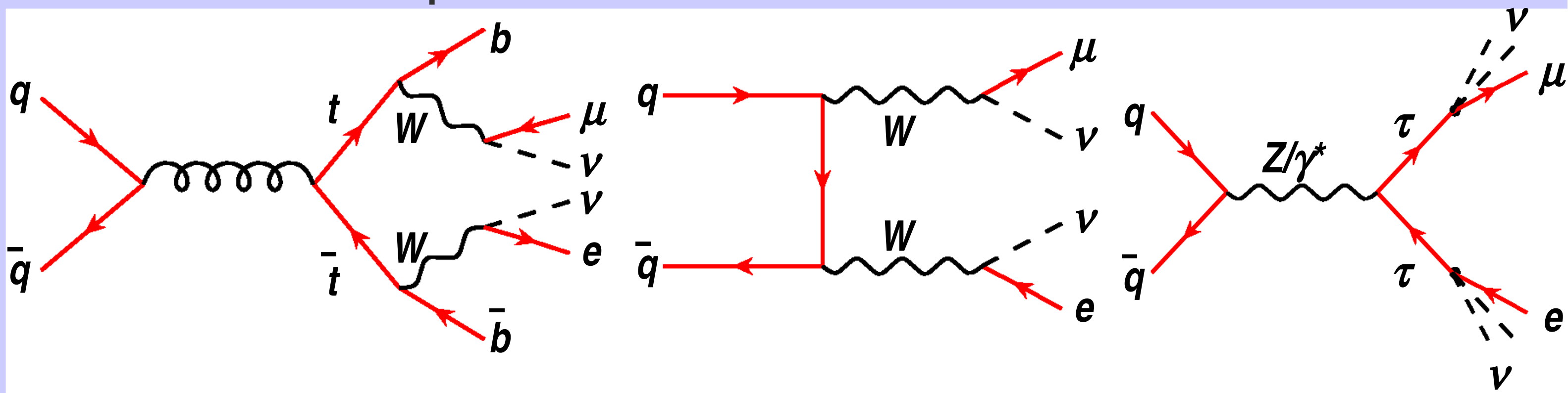
$$\sigma(pp \rightarrow WZ/ZZ)_{NLO} = 5.0 \pm 0.4\ pb$$

Future diboson studies

- Use $W\gamma$, $Z\gamma$, WW analyses to study the $WW\gamma$ and WWZ couplings, and search for anomalous couplings
- About 1 fb^{-1} required for observation of WZ and ZZ
- Additional final states for greater acceptance:
  - Hadronic decays of one V in WW, WZ, ZZ
  - Include τ decays of V
- Optimize use of data by using a more global analysis approach.....

Global analysis approach

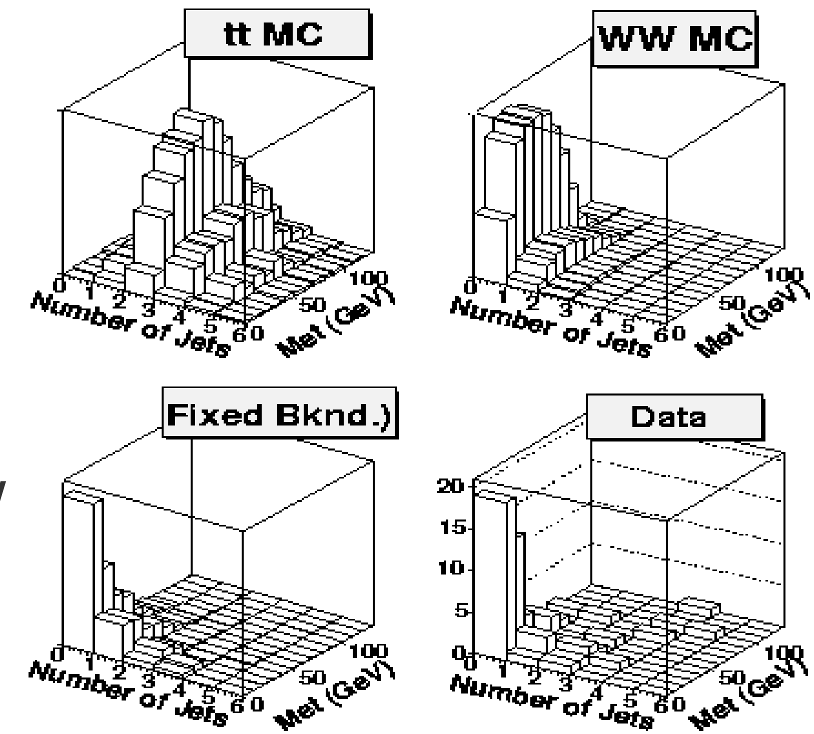
- Relatively few SM processes in the high-E_T dilepton channel
  - eμ the cleanest channel: processes have different characteristics:
  - $t\bar{t}$:
  - WW :
  - $Z \rightarrow \tau\tau$:



- Exploit differences in Missing-E_T versus jet multiplicity, after requiring 2 isolated leptons
  - Fit data to SM processes in this 2-D phase space
  - Philosophy is not to “cut” backgrounds but rather include them in the fit, thereby significantly improving statistics

Global dilepton analysis

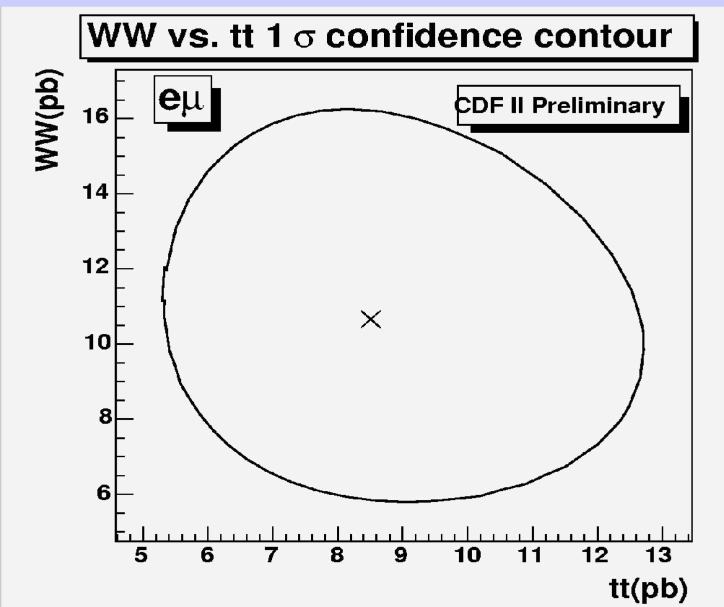
- Preliminary results of SM cross-section measurements encouraging – full statistical power of data being used
- Method may be particularly useful for new physics searches



CDF II Preliminary

eμ space

Only 2 isolated leptons required

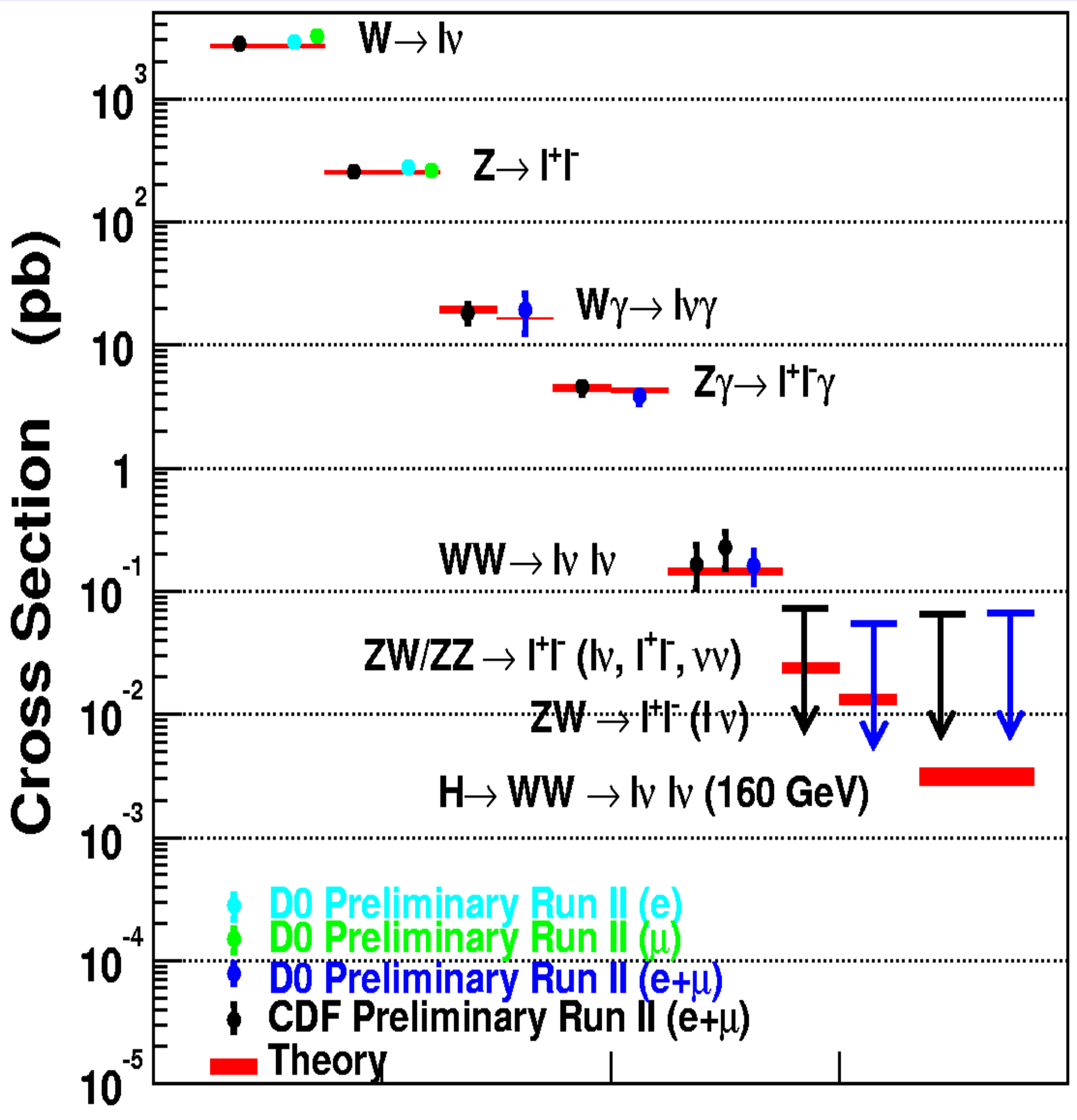


CDF Run II Preliminary 200pb^{-1}

	$e\mu$ only	$ee+\mu\mu+e\mu$	Theory
$\sigma(t\bar{t})$ (pb)	$8.6^{+3.4}_{-3.2}\pm0.9$	$8.6^{+2.5}_{-2.4}\pm1.1$	6.7 ± 0.3
$\sigma(WW)$ (pb)	$11.5^{+3.6}_{-3.6}\pm0.6$	$12.6^{+3.2}_{-3.0}\pm1.2$	12.5 ± 0.8
$\sigma(Z\to\tau\tau)$ (pb)	$233^{+45}_{-42}\pm17$	–	253.1 ± 0.5

In ee & μμ channels significant MET required

Summary of measurements



- Diboson signals established and measured at the Tevatron:
  - $W\gamma/Z\gamma$ with much greater precision than in Run 1
  - WW for first time at the Tevatron
  - WZ/ZZ not yet significant but observation expected soon

Conclusions

- A variety of diboson measurements now completed and published in Run 2 by CDF: $W\gamma/Z\gamma$ PRL, WW PRL, WZ/ZZ PRD.
- Current measurements use 200 pb^{-1} , but updates, optimizations, and new analyses, are round the corner with twice this luminosity.
- Looking forward to continued good Tevatron running, where, with substantially more data:
  - precision diboson measurements
  - discovery of WZ/ZZ production
  - discovery of, or stringent limits on, new physics (Higgs, anomalous couplings,....)
- Many new ideas and analyses now in full swing – stay tuned