Review of W and Z physics at the Tevatron

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IFAE Incontri di Fisica delle Alte Energie
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Outline

- The Tevatron & the experiments
- Electroweak physics at the Tevatron
- W and Z Cross section measurements (e,μ,τ)
- W and Z asymmetries
- DiBoson production
- W Mass measurement
- Conclusions and future prospects

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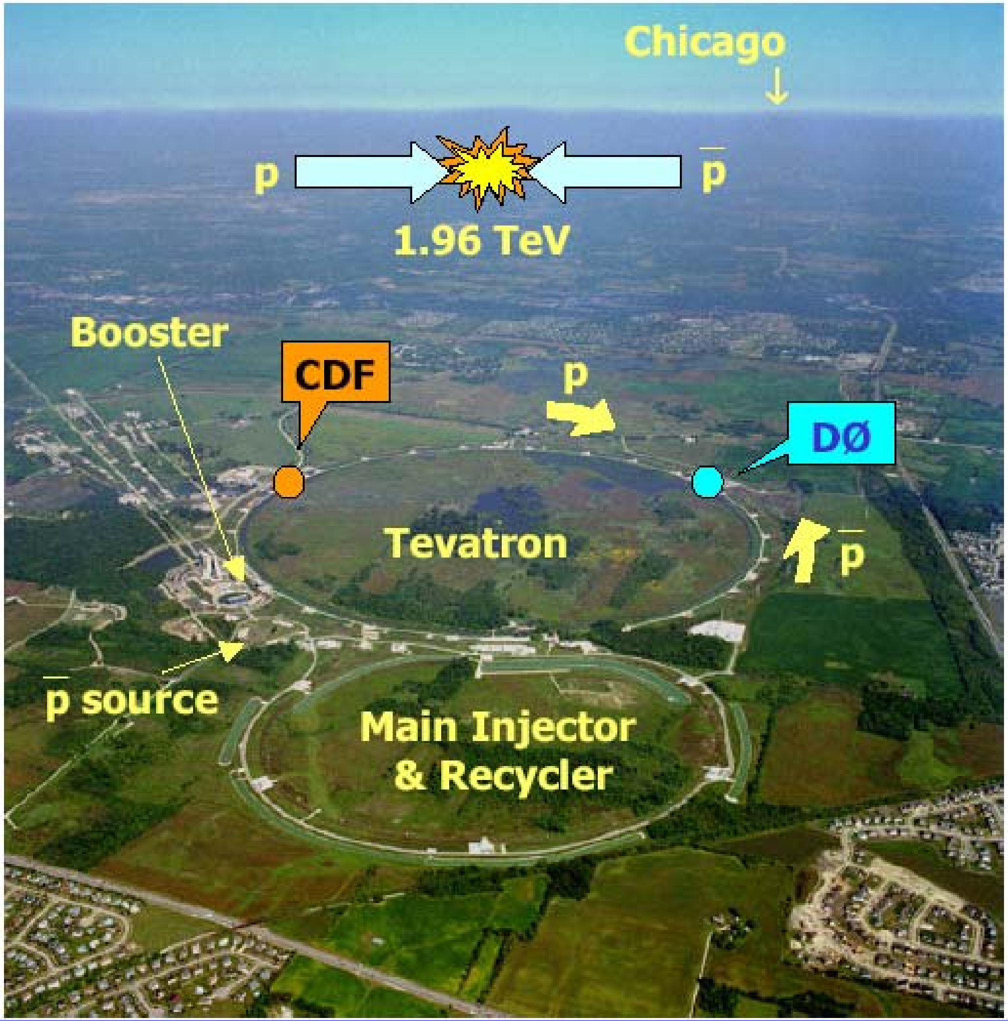
Why Electroweak Measurements at the Tevatron?

- Single boson production: couplings to the fermions
- Diboson production: self- or triple gauge couplings
- Precise Electroweak measurement are challenging:
  - Constrain the Standard Model

    OR
  - Evidence of Physics Beyond SM
- Also crucial as input for LHC physics program:
  - Input to Parton Distribution Functions
  - Some Tevatron signals will be LHC background
- After LEP era we are now into Tevatron era:
  - Tevatron is for the next few years the only accelerator that can produce Ws directly: more W's, WZ pairs, large sqrt(s) and Pt.

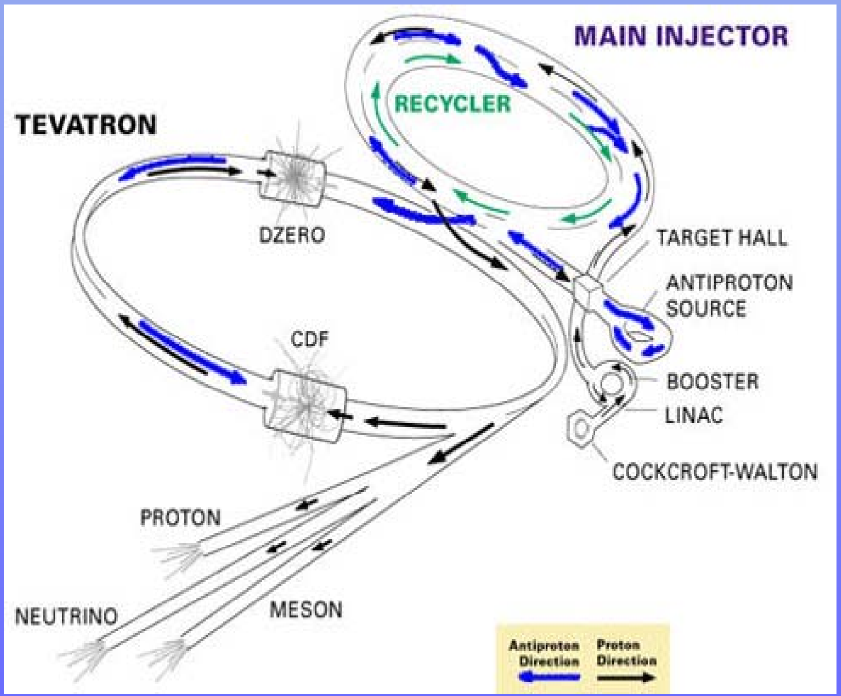
The Tevatron



Run II: $\sqrt{s}$ = 1.96 TeV

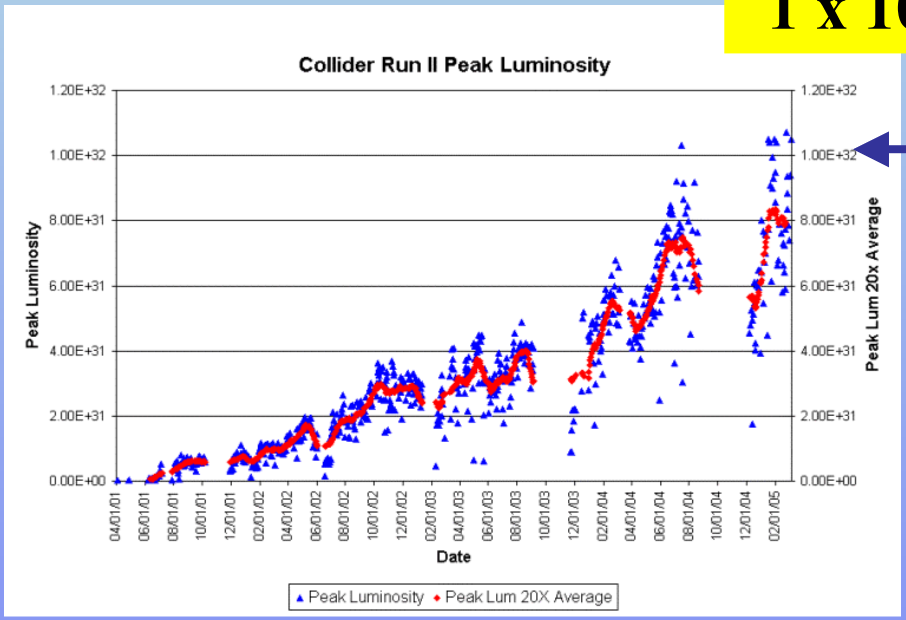
Started in spring 2001

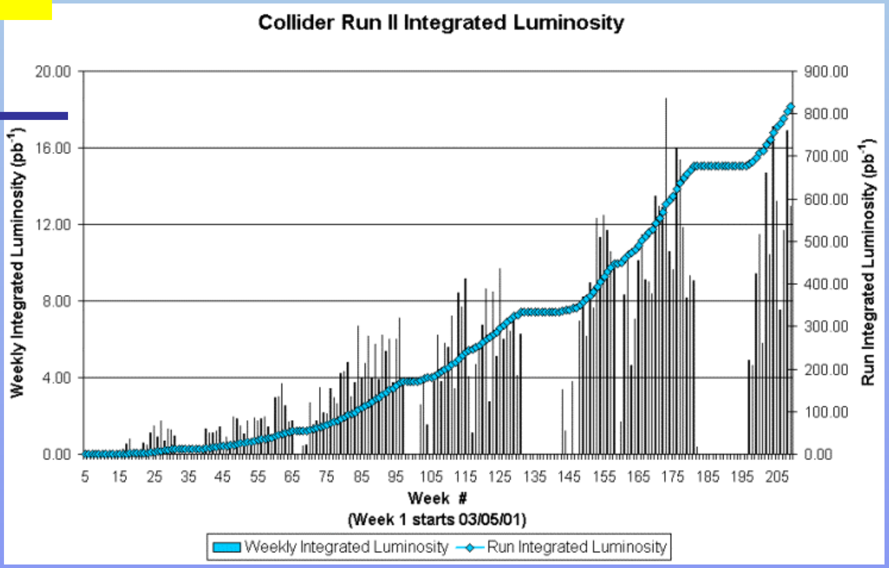
After a commissioning period, data "good for physics" since February 2002



Tevatron Peak Luminosity

1 x 10^{32}

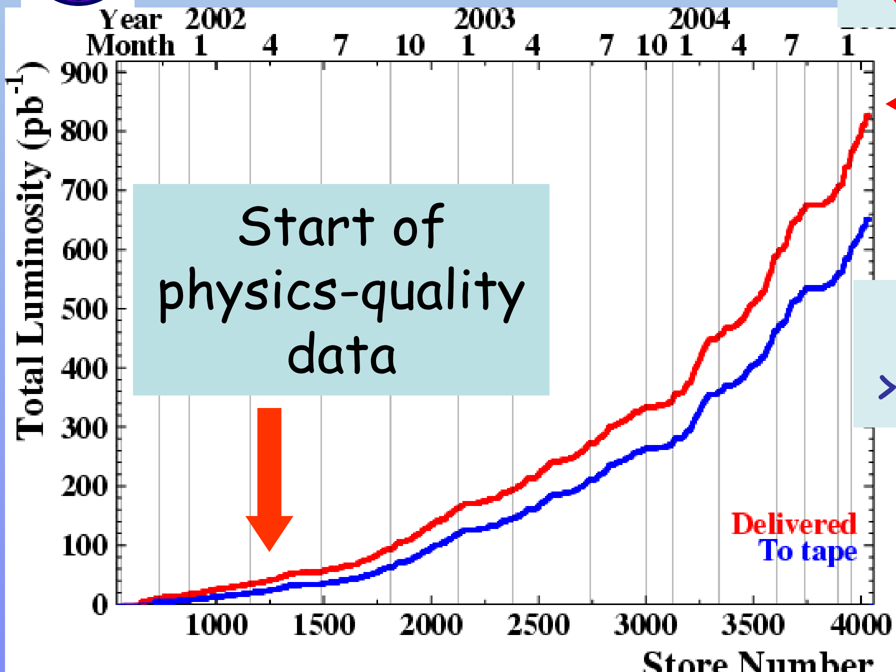




Peak Luminosities above 1 x 10^{32} cm^{-2} s^{-1} now common

Record: initial lum 1.24 x 10^{32} cm^{-2} s^{-1} on March 21rst

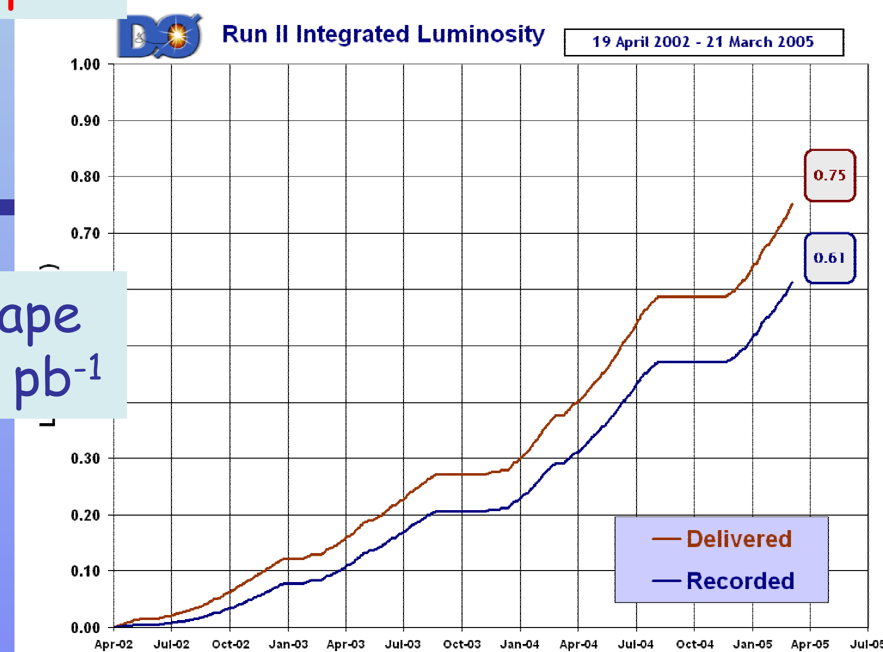
Integrated Luminosity



Start of physics-quality data

delivered >800 pb^{-1}

on tape >600 pb^{-1}



Taking data commonly with > 85% efficiency

Running stably since Feb. '02
More than 350 pb^{-1} delivered in 2004

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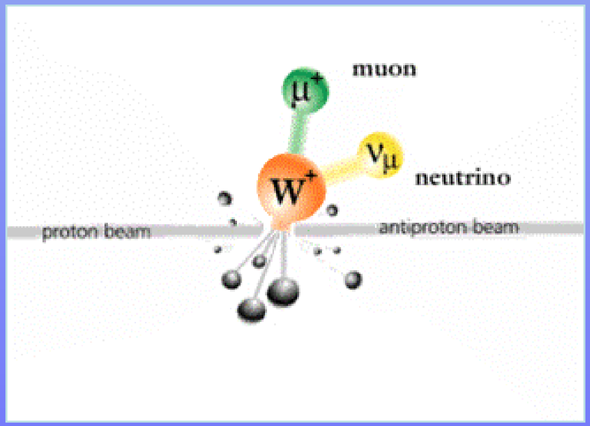
Production Processes

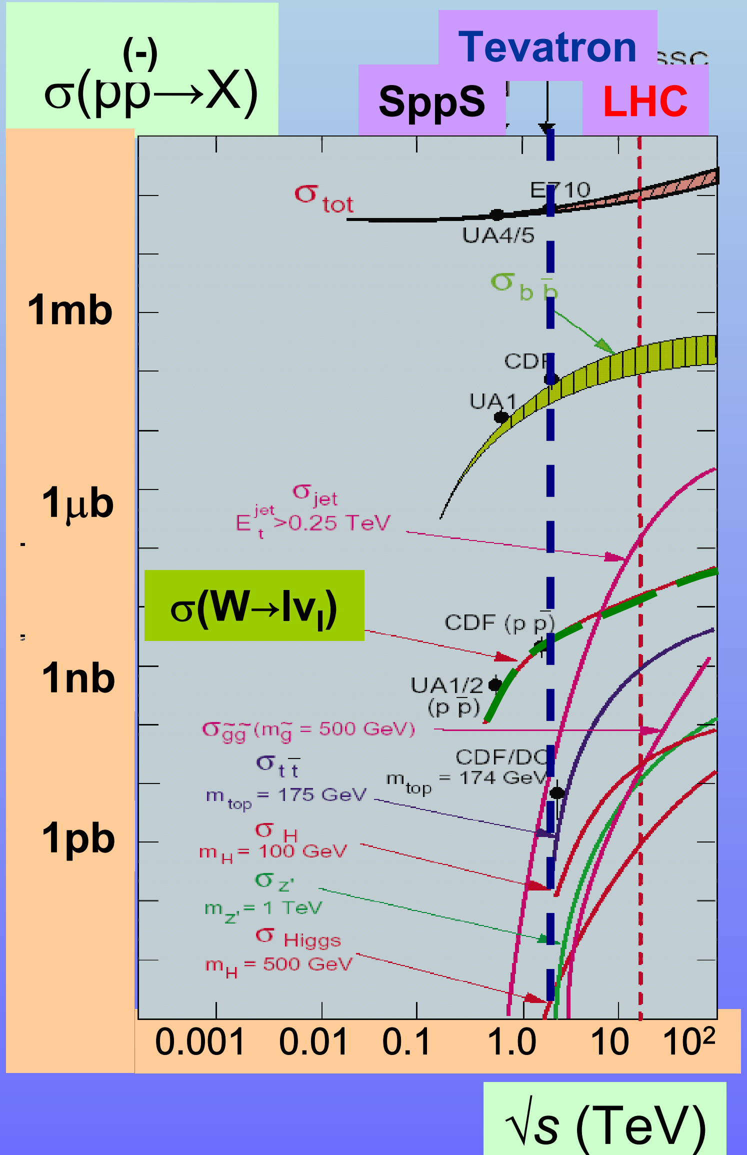
- Tevatron as a vector boson factory: *)

~30,000 W-> eν events/week

~2500 Z-> ee events/week

~120 WW, 40 WZ events/week





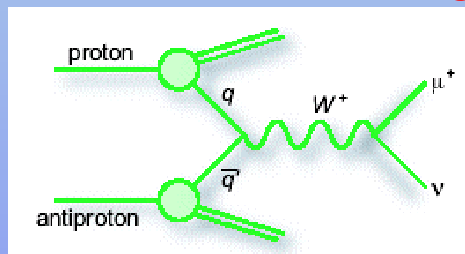
*) for L ~ 10 pb^{-1}/week

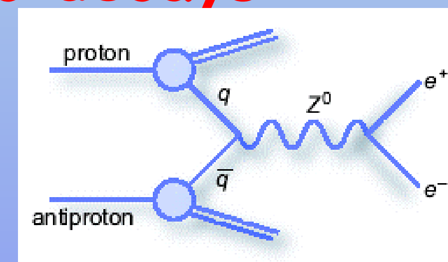
W/Z Gauge Bosons Identification

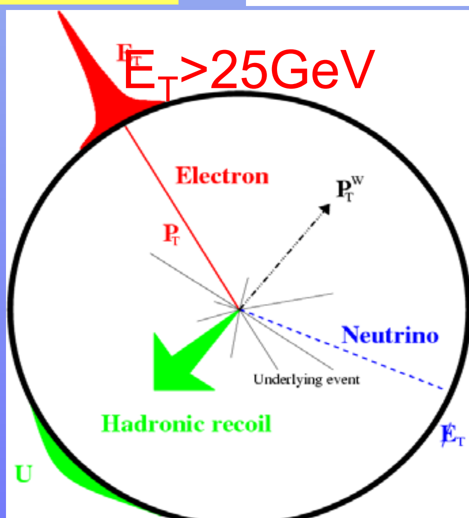
- At hadronic collider W and Z bosons hadronic decays are overwhelmed by QCD background.

  $\Rightarrow$ Identification through leptonic decays

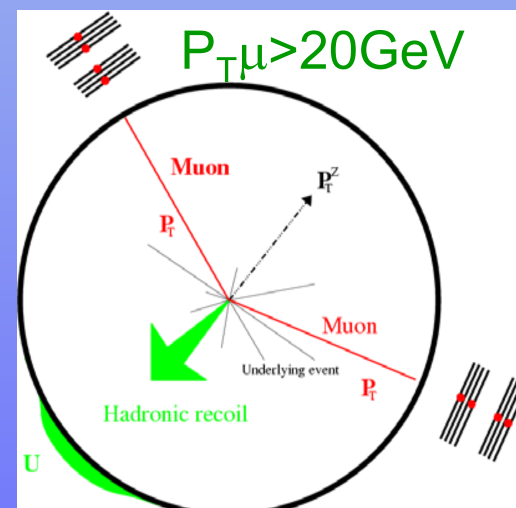
W→eν







$\not{E}_T$>25GeV



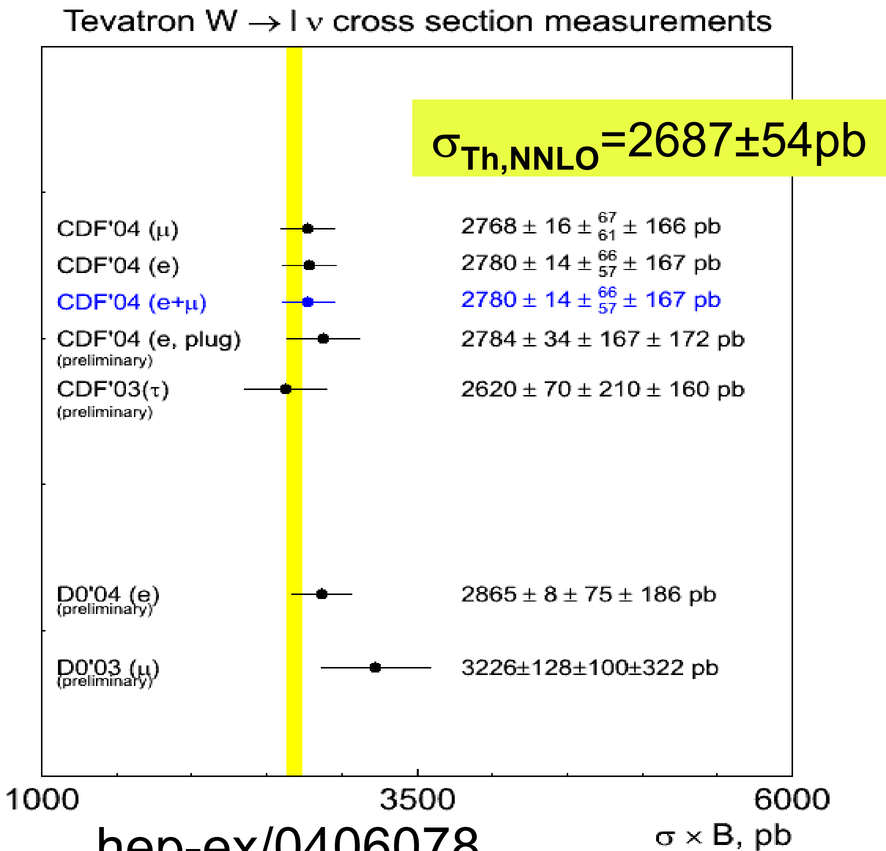
Z→μμ

$P_T\mu$>20GeV

W± signature: Isolated Energetic Lepton + $\not{E}_T$

Z Signature: Two Isolated Energetic Leptons (opposite charge)

Inclusive W/Z Cross Sections



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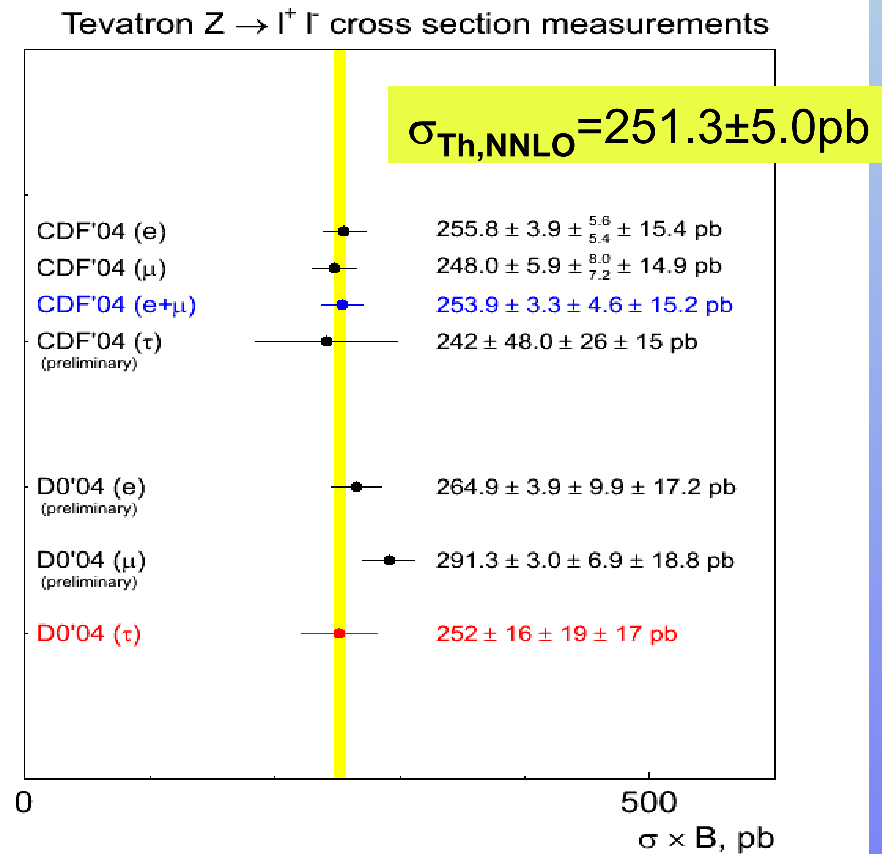


- Overall good agreement with the NNLO calculations
- Accuracy limited by the systematic effects
- Uncertainties dominated by the luminosity measuremnts (~6%)
- Other systematics: dominated by PDF uncertainties (~2%)

Lepton Universality in W Decays

From the measurements of the $W \to e\nu$ and $W \to \mu\,\nu$ cross sections obtain cross section ratio U:

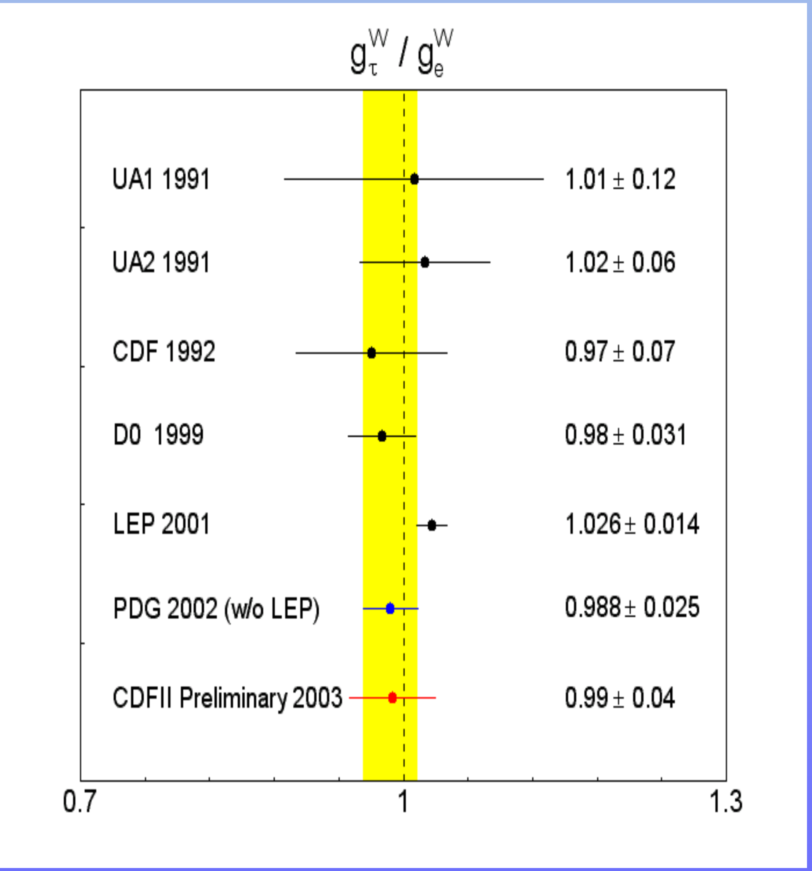
$$U = \frac{\sigma.Br(W\to\mu\nu)}{\sigma.Br(W\to e\nu)} = \frac{\Gamma(W\to\mu\nu)}{\Gamma(W\to e\nu)} = \frac{g_\mu^2}{g_e^2}$$

Many systematic uncertainties cancel out

$$\frac{g_\mu}{g_e} = 0.998 \pm 0.012$$

In the same way from $W \to e\nu$ and $W \to \tau\,\nu$ cross sections:

$$\frac{g_\tau}{g_e} = 0.99 \pm 0.02_{stat} \pm 0.04_{syst}$$



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Indirect W Width Measurements

- Checking internal consistency in the EWK sector of SM comparing with direct Γ(W) measurement

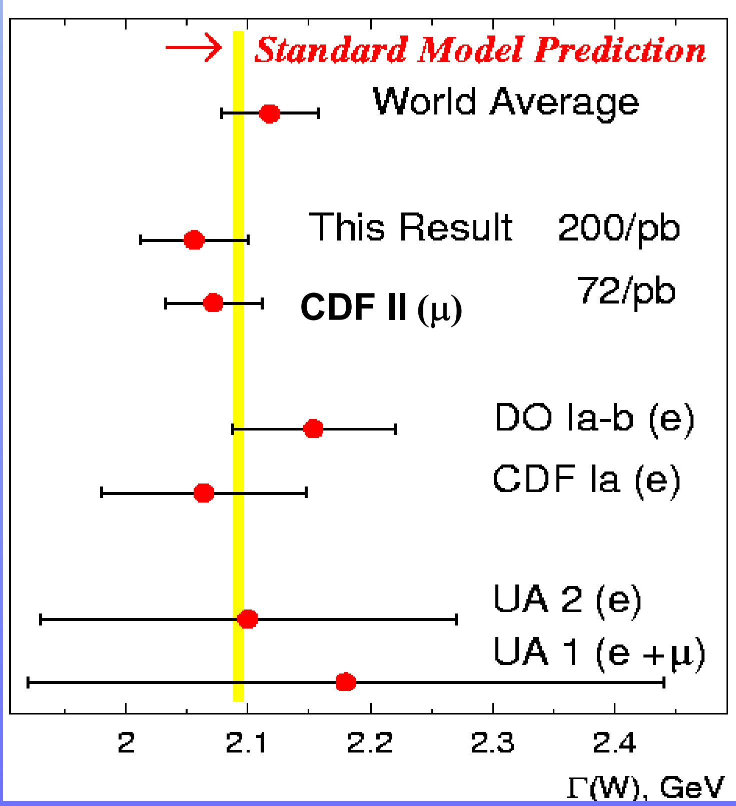
✓ convert measured value of $R = \frac{\sigma.BF(W\text{->}l\nu_l)}{\sigma.BF(Z\text{->}l^+l^-)}$

into a measurement of the W width:

$$R = \frac{\sigma(pp\text{->}W)}{\sigma(pp\text{->}Z)} \frac{\Gamma(Z)}{\Gamma(Z\text{->}ll)} \frac{\Gamma(W\text{->}l\nu_l)}{\Gamma(W)}$$

Many systematic uncertainties cancel out (e.g. luminosity)

Channel	Γ(W)(MeV)	$\int Ldt(pb^{-1})$
e+μ	2079±41	72
μ	2056±44	194
PDG	2118±41	
SM Pred.	2092.1±2.5	



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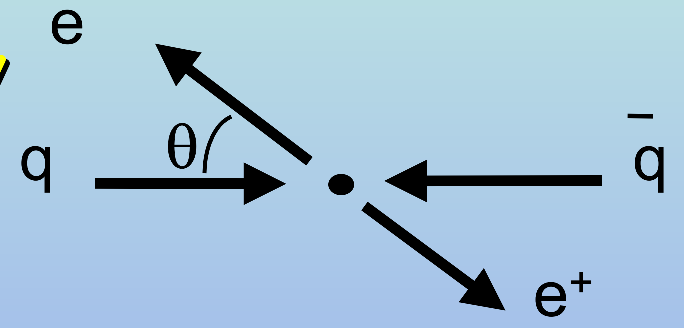
Z Asymmetry



A_{FB} arises from Axial and Vector couplings

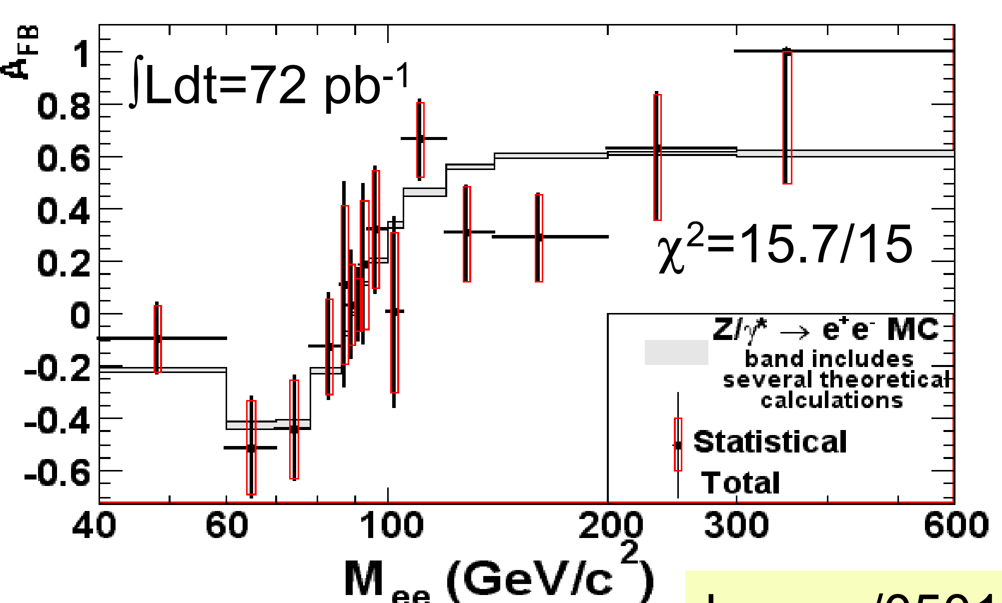
Z and γ interference term

$$\frac{d\sigma}{d\cos\theta} = A(1+\cos^2\theta) + B\cos\theta$$

$$A_{FB} = \frac{d\sigma(\cos\theta>0) - d\sigma(\cos\theta<0)}{d\sigma(\cos\theta>0) + d\sigma(\cos\theta<0)}$$

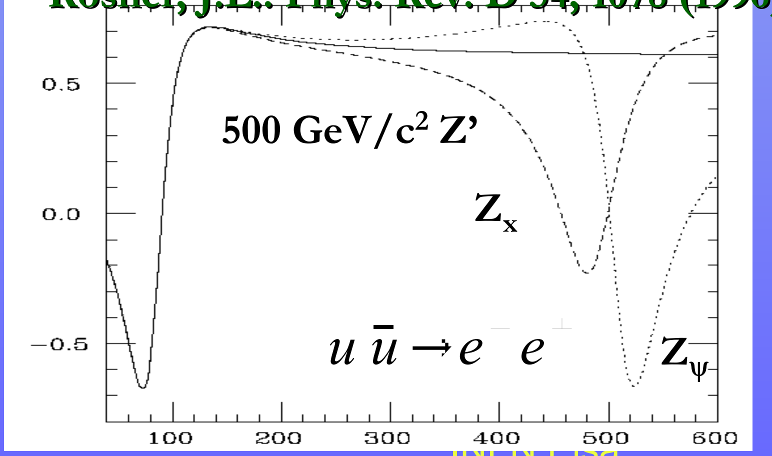
$$A_{FB} = \frac{3B}{8A}$$

- Measurement limited by statistics
- Complementary to LEP, far from the Z pole
- Sensitivity to heavy neutral bosons (Z')
- Extract quark, electron couplings and $\sin^2\theta_W^{Eff}$**=0.2238±0.004±0.003**

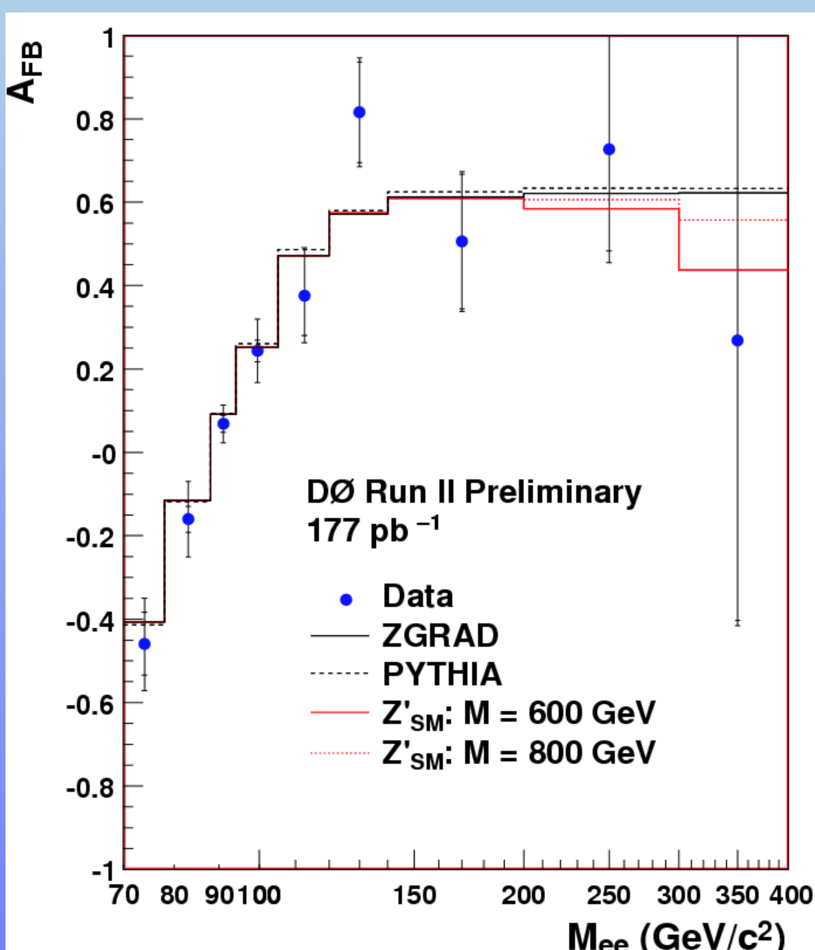


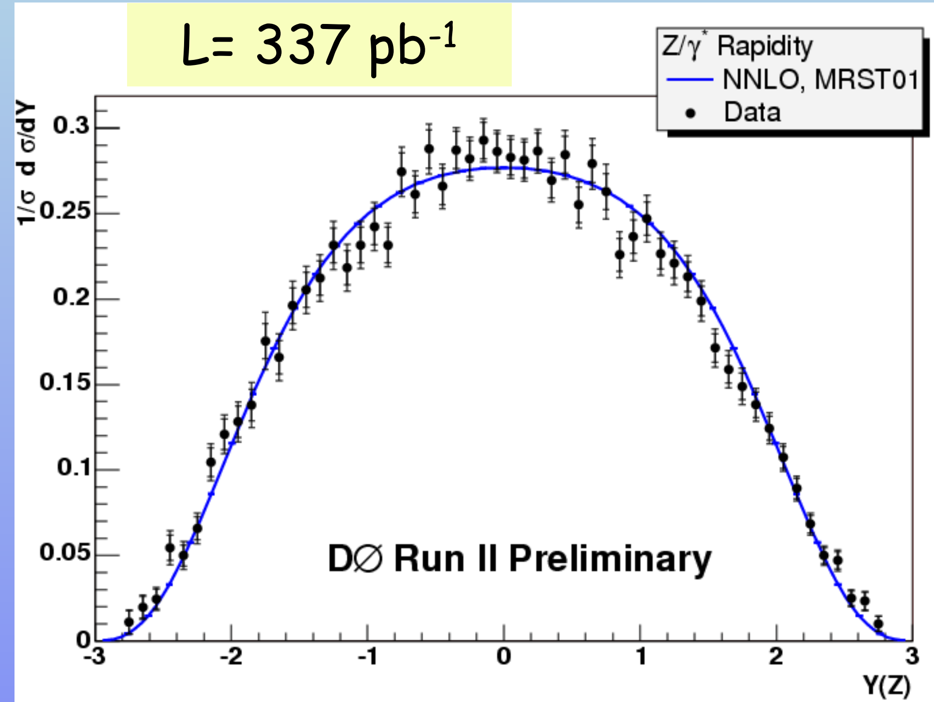
hep-ex/0501023

Rosner, J.L.: Phys. Rev. D 54, 1078 (1996)



Z Asymmetry & dσ/dy(Z)

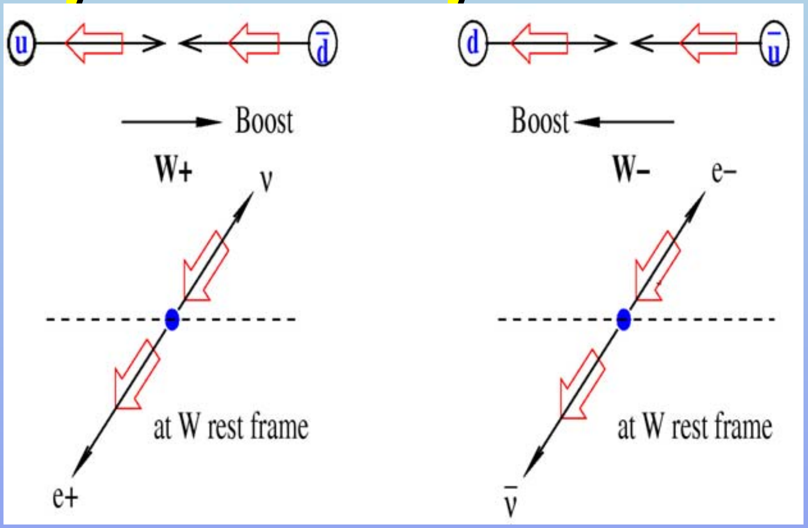


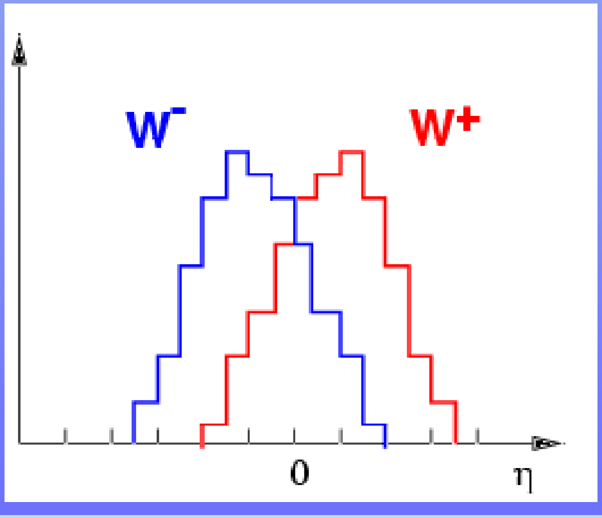


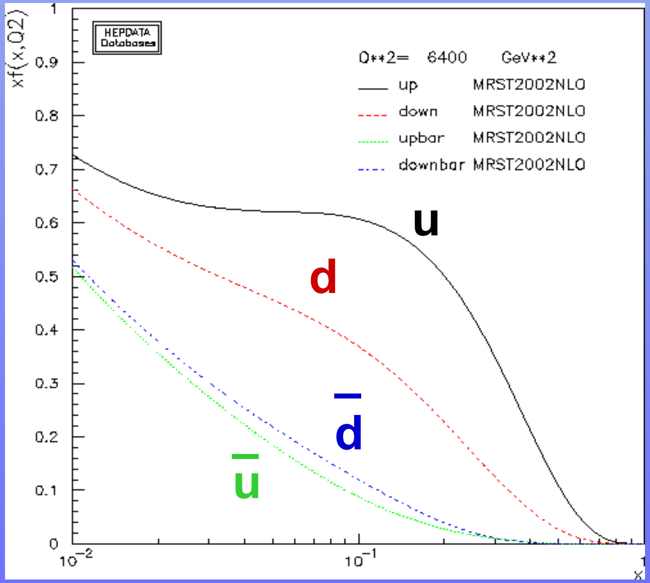
The use of the D0 forward calorimeter provides data over almost the entire rapidity range accessible at Tevatron.
Generally good agreement with NNLO prediction

W Charge Asymmetry

- u quark inside proton carries higher fraction of p momentum than d-bar quark
- Use W's to probe the proton structure
  - ➢obtain info on momentum distributions of the quarks and gluons (PDF's)







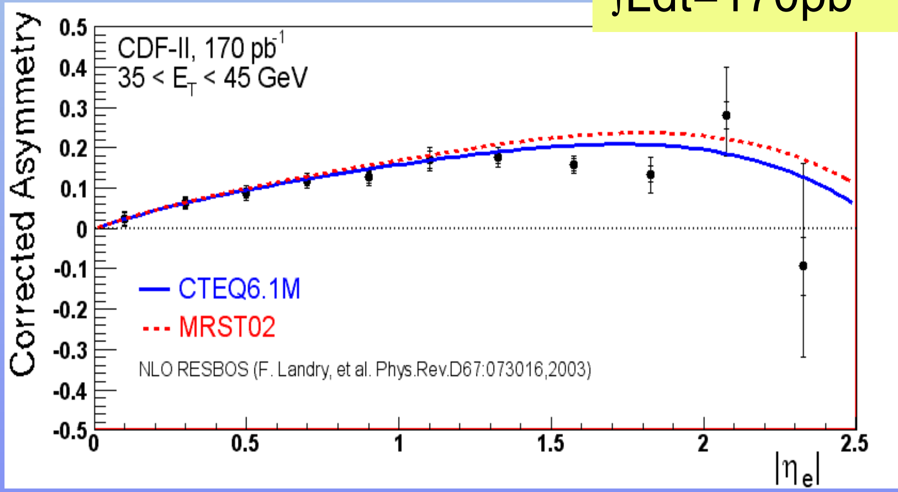
←anti-proton direction proton direction→

W Charge Asymmetry

- Production asymmetry in ppbar->WX is sensitive to U/D

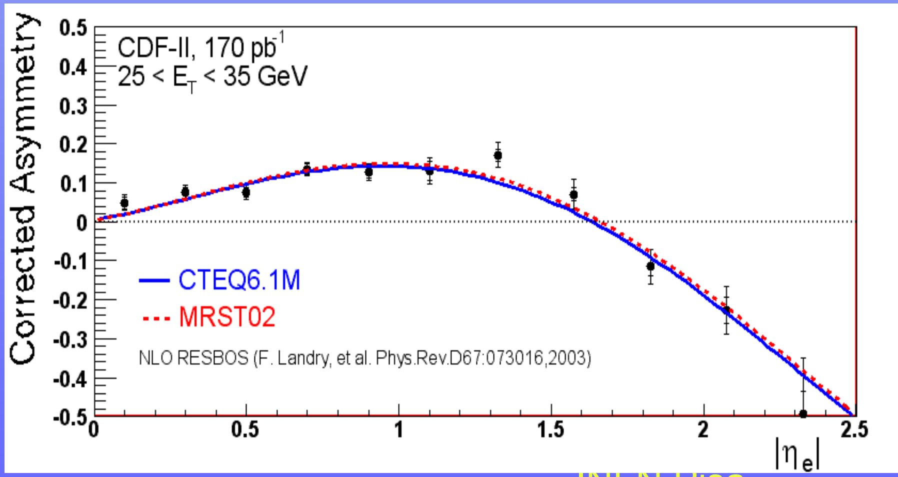
$$A(y_W) = \frac{d\sigma(W^+)/dy - d\sigma(W^-)/dy}{d\sigma(W^+)/dy + d\sigma(W^-)/dy}$$

$\int Ldt = 170 pb^{-1}$



- Measured: e asymmetry: convolution of W production asymmetry + V-A decay

$$A(\eta_l) = \frac{d\sigma(e^+)/d\eta - d\sigma(e^-)/d\eta}{d\sigma(e^+)/d\eta + d\sigma(e^-)/d\eta}$$



- charge ID at high |η| is crucial

  misID probability ~4% at |η| ~ 2

- Bin data in P_T (2 bins) to increase sensitivity

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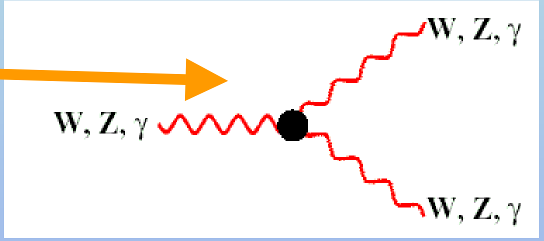
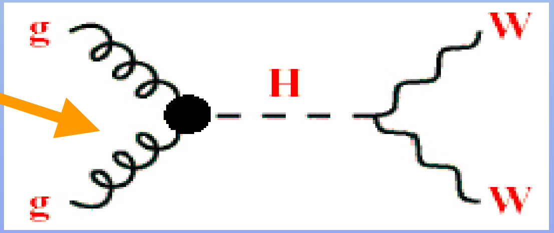
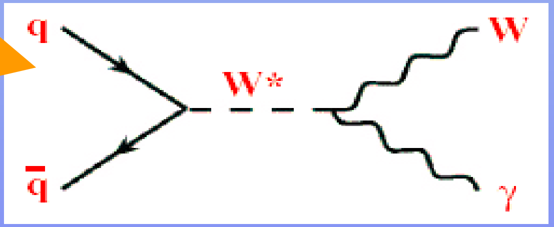
Diboson production

- Test Gauge Boson Self Interactions
- SM Higgs searches
- Resonance searches: Look for excess with respect to SM in kinematical distributions







Complementarity with LEP experiments:
Probing at higher $\sqrt{s}$
Exploring different coupling combination

- **WW** to probe **WWγ** and **WWZ** coup.
- **Wγ** to probe **WWγ** coupling
- **WZ** to probe **WWZ** coupling

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Wγ (Zγ) selection

For Wγ/Zγ Photon Id is crucial:
Main backgrounds:

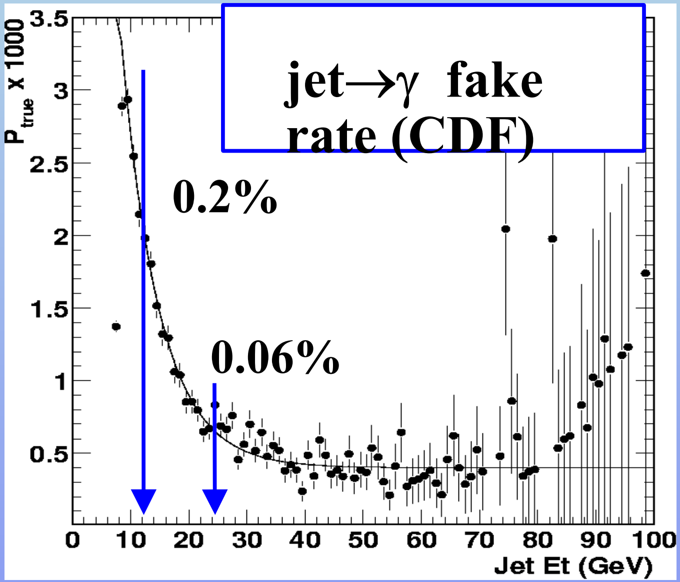
- **W + jets where**
  - $\pi^0 \rightarrow \gamma\gamma$,
  - jets faking photon

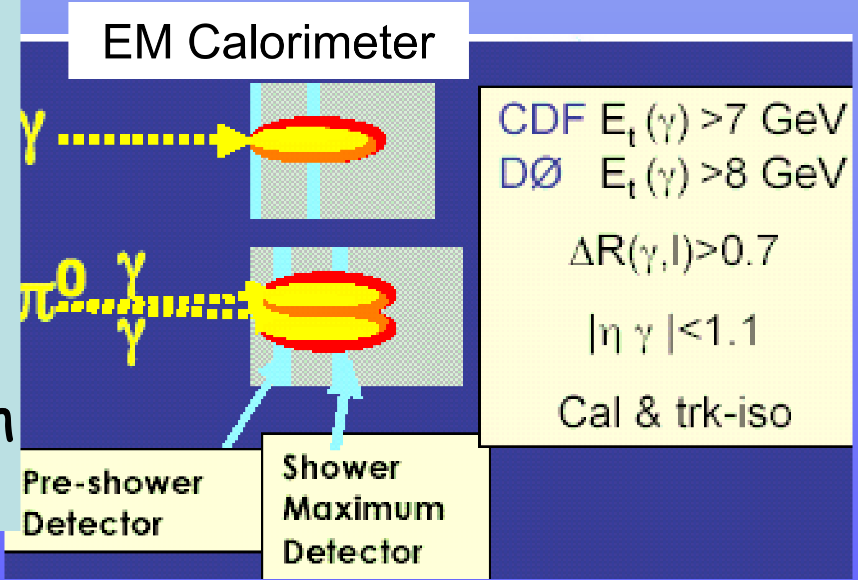
CDF Fake Rates:

0.2% @JetE_T=10 GeV
0.06% JetE_T>25GeV

D0 Fake Rates:

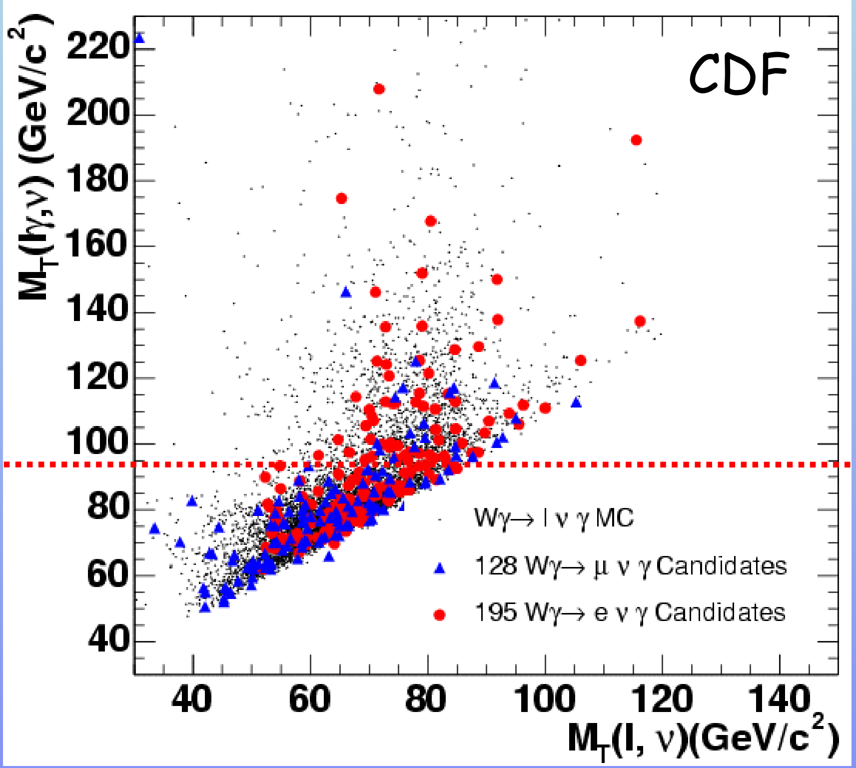
~ 0.4% to 0.2% decreasing with E_T





Wγ Production

Effects of anomalous couplings more pronounced at high $M_T(W\gamma)$



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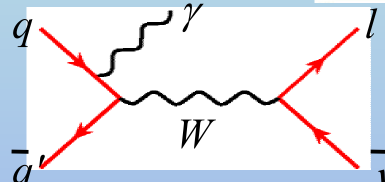
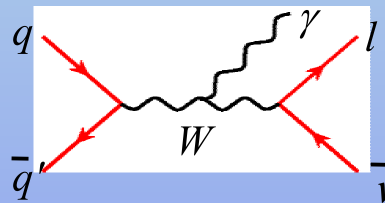
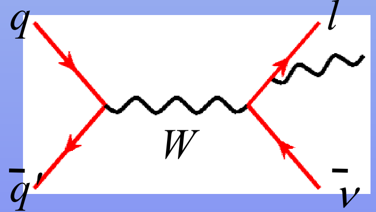


ISR



WWγ

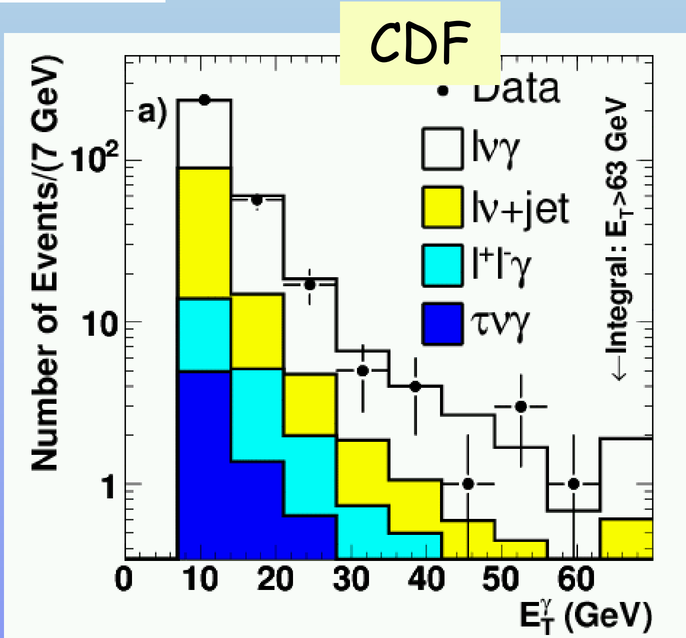


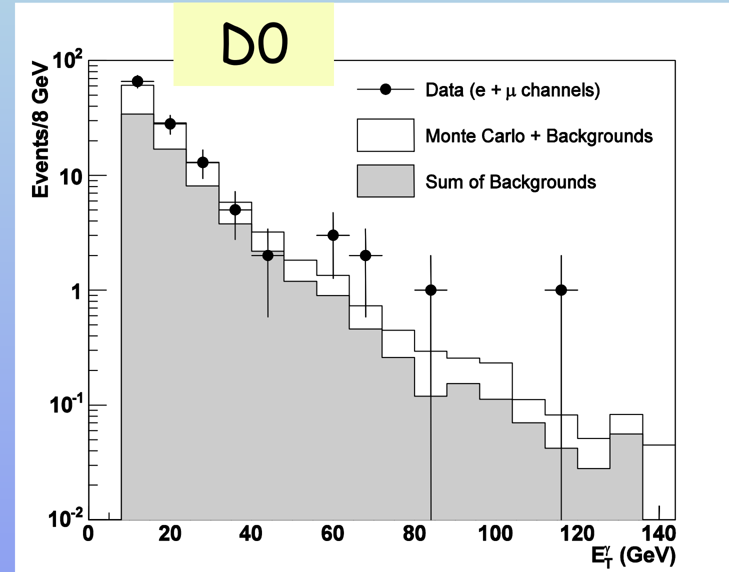
FSR

cluster transverse mass : $M_T^2(l\gamma, \not{E}_T) = [(M_{l\gamma}^2 + |\vec{p_T}(l) + \vec{p_T}(\gamma)|^2)^{1/2} + \not{E}_T]^2 - |\vec{p_T}(l) + \vec{p_T}(\gamma) + \vec{\not{E}}_T|^2$

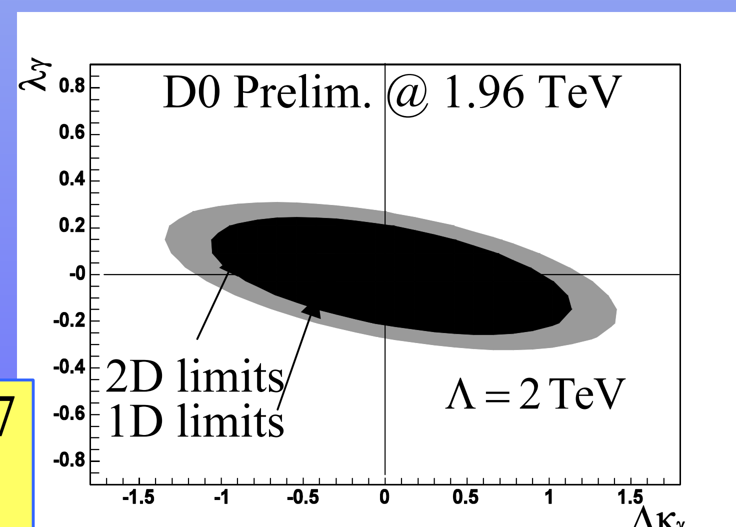
	Events(e+μ)	Back(%)	σ•B(Wγ→lνγ) (pb)	σ x B_{Th}(pb)
CDF	195+128	35(e),33(μ)	$18.1 \pm 1.6_{stat} \pm 2.4_{sys} \pm 1.2_{lum}$	19.3 ± 1.4
D0	112+161	54(e),44(μ)	$14.8 \pm 1.6_{stat} \pm 1.0_{sys} \pm 1.0_{lum}$	16.0 ± 0.4

WWγ: triple gauge couplings (2005)





No significant excess with respect to MC



CP-conserving effective lagrangian with 2 coupling parameters:

(Baur,Berger 1990)

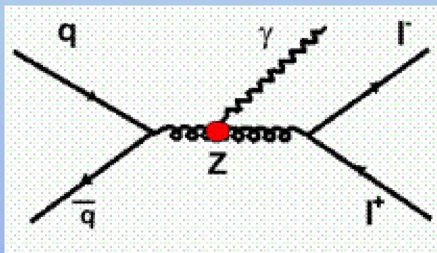
1D limits @ 95% C.L.

$$-0.93 < \Delta\kappa_{\gamma} < 0.97$$

$$-0.22 < \lambda_{\gamma} < 0.22$$

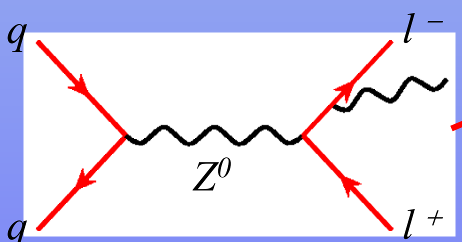
Tevatron Run 1limit for λ_{γ} improved!

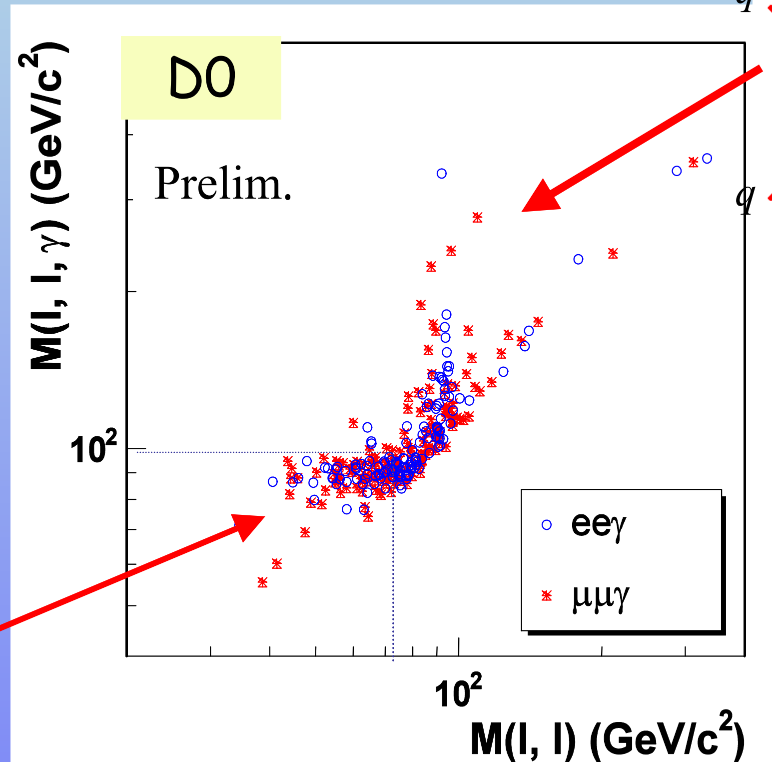
Zγ production

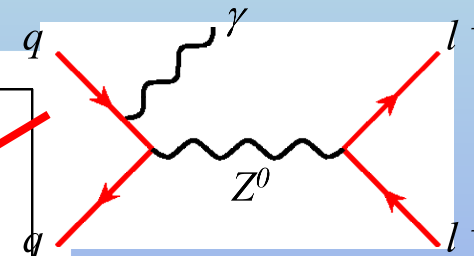


= 0?

No ZZγ Triple Gauge Coupling in Standard Model at tree level



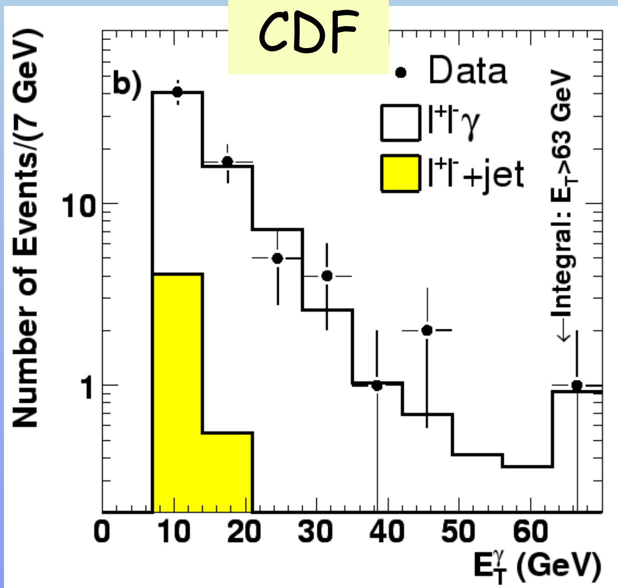


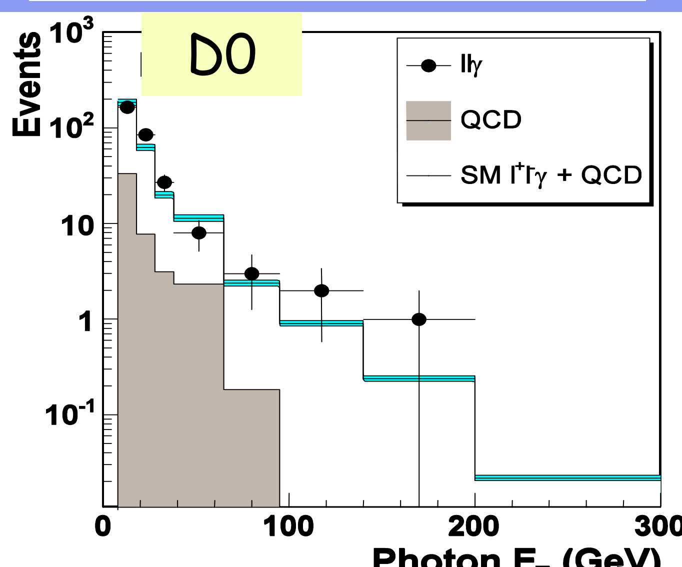


Main background: Z + jet where jet mimics a photon

	Events(e+μ)	Back(%)	$\sigma \bullet B(Z\gamma \to ll\gamma)$ (pb)	$\sigma \times B_{Th}$(pb)	
CDF	36+35	7.8(e),5.8(μ)	$4.6 \pm 0.5_{stat+syst} \pm 0.3_{lum}$	4.5 ± 0.3	hep-ex/0410008
D0	138+152	17(e),15(μ)	$4.2 \pm 0.4_{stat+syst} \pm 0.3_{lum}$	3.9 ± 0.2	hep-ex/0502036

Zγ: neutral diboson couplings





$E_T(\gamma)$ Distribution

1D limits at 95% CL

LEP	Tevatron (D0)
$-0.049 < h^\gamma_{30} < 0.008$	$-0.23 < h^\gamma_{30} < 0.23$
$-0.002 < h^\gamma_{40} < 0.034$	$-0.019 < h^\gamma_{40} < 0.019$
$-0.20 < h^Z_{30} < 0.07$	$-0.23 < h^Z_{30} < 0.23$
$-0.05 < h^Z_{40} < 0.12$	$-0.020 < h^Z_{40} < 0.020$

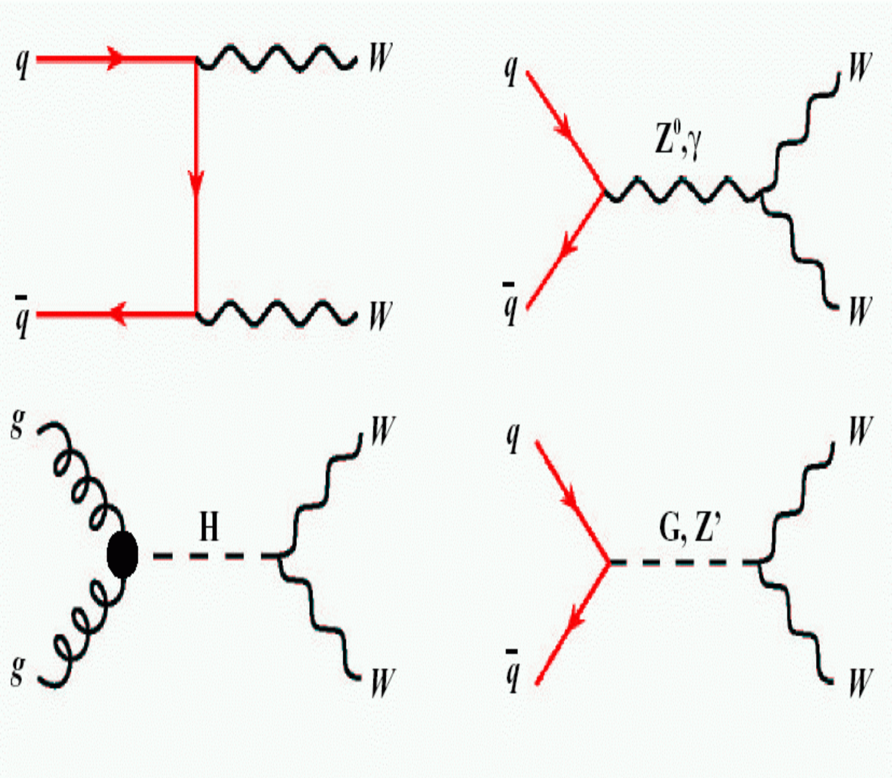
hep-ex/0502036

Most general ZVγ coupling is parametrized by 2 CP-violating (h_1, h_2) and 2 CP-conserving (h_3, h_4) complex coupling parameters(Baur,Berger 1993). Tevatron has better limits on h_4 than LEP

WW production

- Very important for the Higgs searches: gg->H->WW
- Test of SM: self-interaction of the heavy bosons (WWγ/Z)
- Search for new heavy boson states
- Large statistics of WW events at LEP2 (~10K/expt)
- Run I: only one measurement with limited sensitivity (CDF, 5 evts 1.3 ±0.3 bkgrd):

$\sigma(WW) = (10.2\ ^{+6.1}_{-5.2} \pm 1.6)$ pb



Prediction for the cross section:
$\sigma(WW\text{-}> ll\nu\nu)_{NLO} = (12.4 \pm 0.8)$ pb

@ 1.96 TeV

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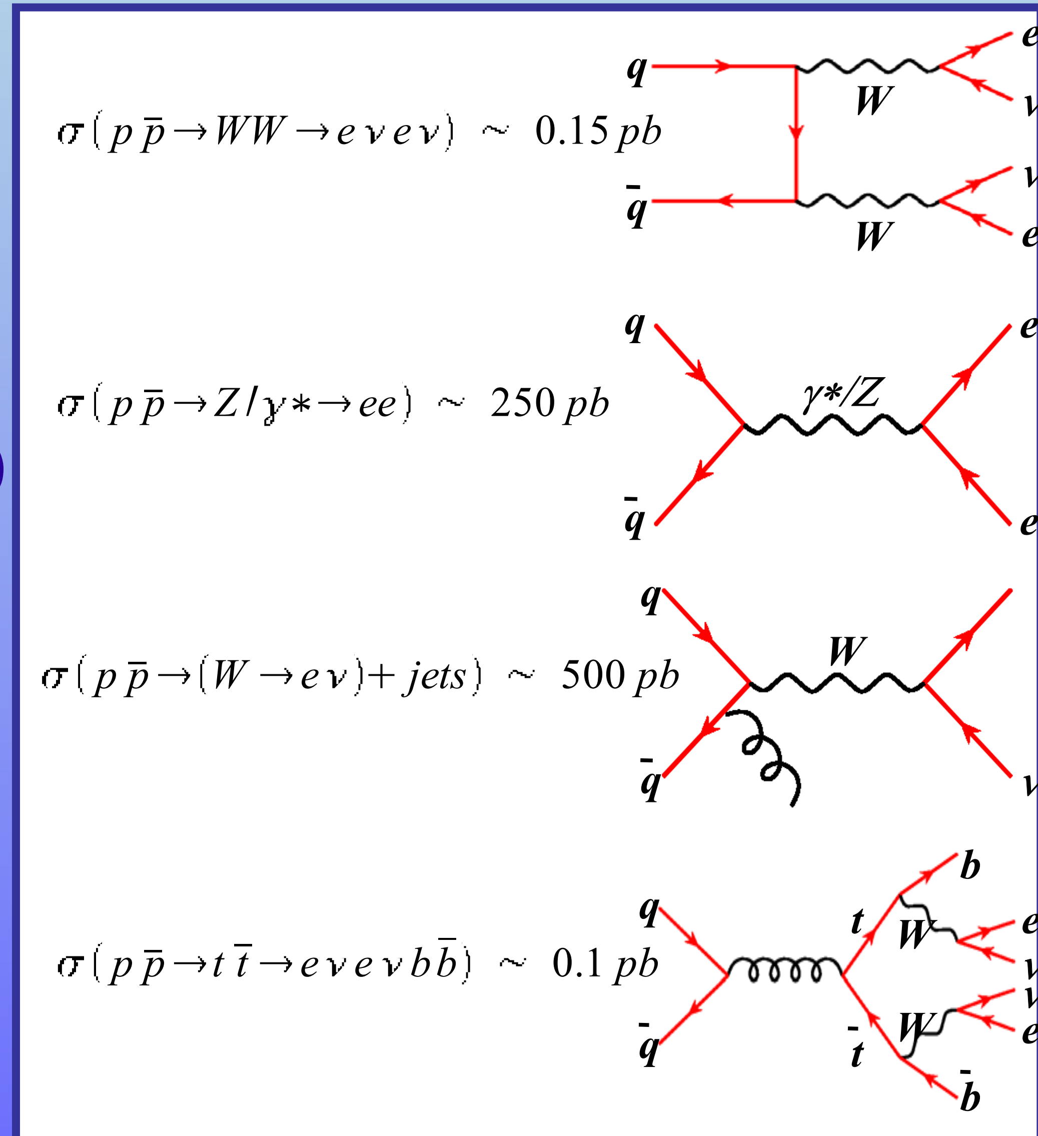
WW event selection

- First goal for Run II:
  - establish the signal
- CDF and D0 used dilepton channel
  - BR~5%, best sensitivity (S/B)
- Selection:
  - 2 isolated leptons, large $\not{E}_T$
- Background sources:
  - Drell-Yan with fake $\not{E}_T$
  - W+jets/γ (fake leptons)
  - tt , WZ, ZZ



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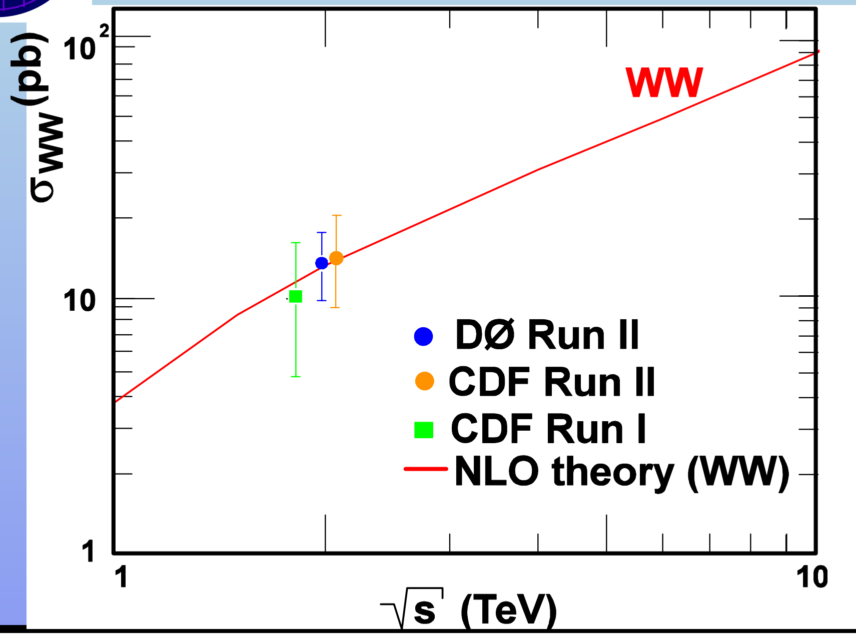
WW Production



<u>Run II WW signal established</u>

P(background fluc.) = 2.3×10^{-7}
=> ~ 5.2 standard deviations (D0)

Studies of the mode most sensitive to self-interactions of the W's are in progress: $p\bar{p} \to W(l\nu)W(qq)$

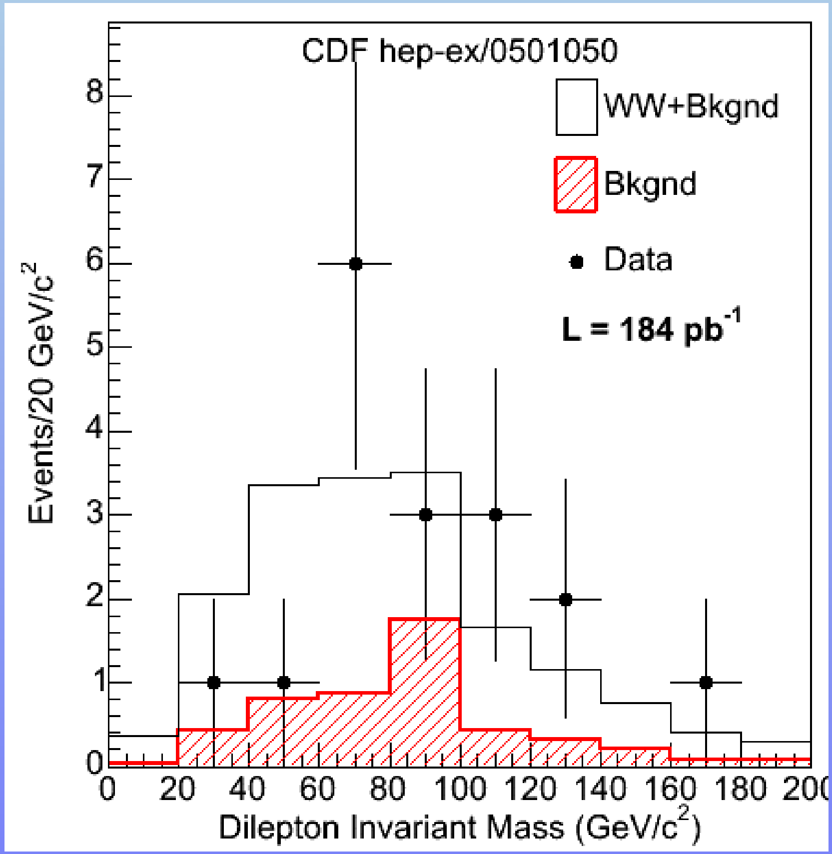
	D0 (224-252 pb^{-1})			CDF (184 pb^{-1})		
Process	ee	μμ	eμ	ee	μμ	eμ
WW signal	3.42±0.05	2.10±0.05	11.10±0.10	2.6±0.3	2.5±0.3	5.1±0.6
Total BKGD	2.30±0.21	1.95±0.41	3.81±0.17	$1.9^{+1.3}_{-0.3}$	$1.3^{+1.6}_{-0.4}$	1.9±0.4
Observed	6	4	15	6	6	5

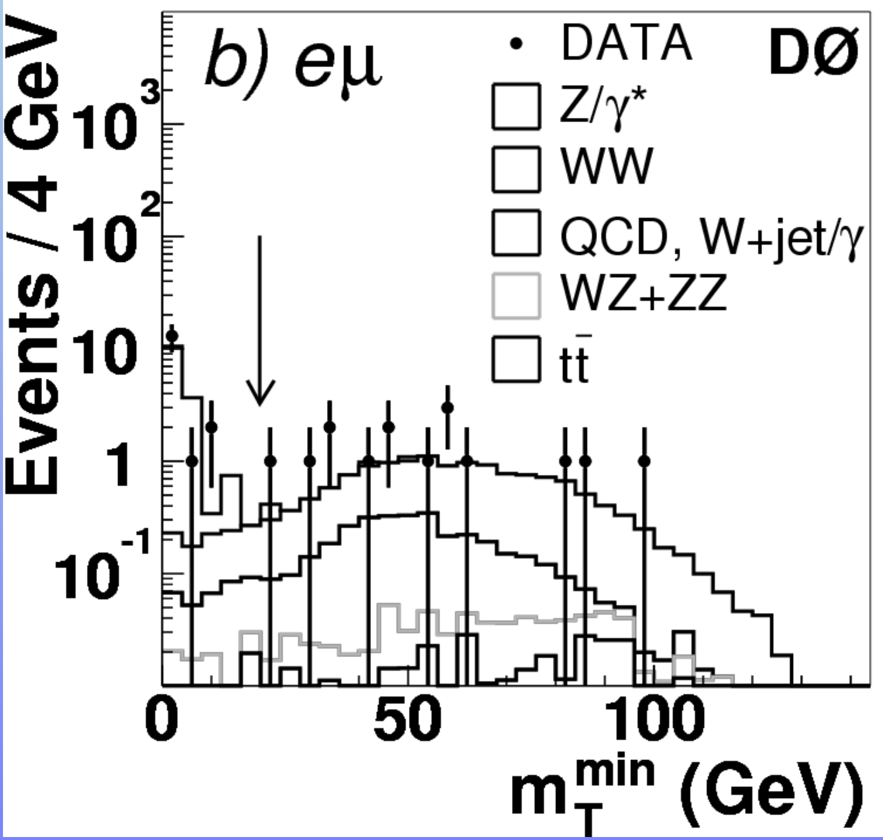
$$\sigma(WW) = 13.8^{+4.3}_{-3.8}(stat.)^{+1.2}_{-0.9}(sys.) \pm 0.9(lum.) \text{ pb}$$

$$\sigma(WW) = 14.6^{+5.8}_{-5.1}(stat.)^{+1.8}_{-3.0}(sys.) \pm 0.9(lum.) \text{ pb}$$

hep-ex/0410066 hep-ex/0501050

WW Kinematics

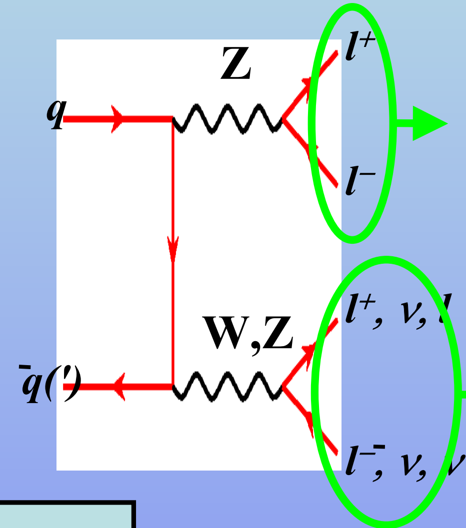




Kinematics of observed events is consistent with the WW production

WZ and ZZ Searches

- Expect very few events
- final state unique for hadron machines



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

l^+l^- : $76 < M(l^+l^-) < 106$ GeV
$l\nu$: lepton + $\not{E}_T > 20$ GeV
$\nu\nu$: large $\not{E}_T$-significance

$\sigma(pp \to ZZ/ZW+X)^{TH}_{NLO} = 5.0 \pm 0.4$ pb

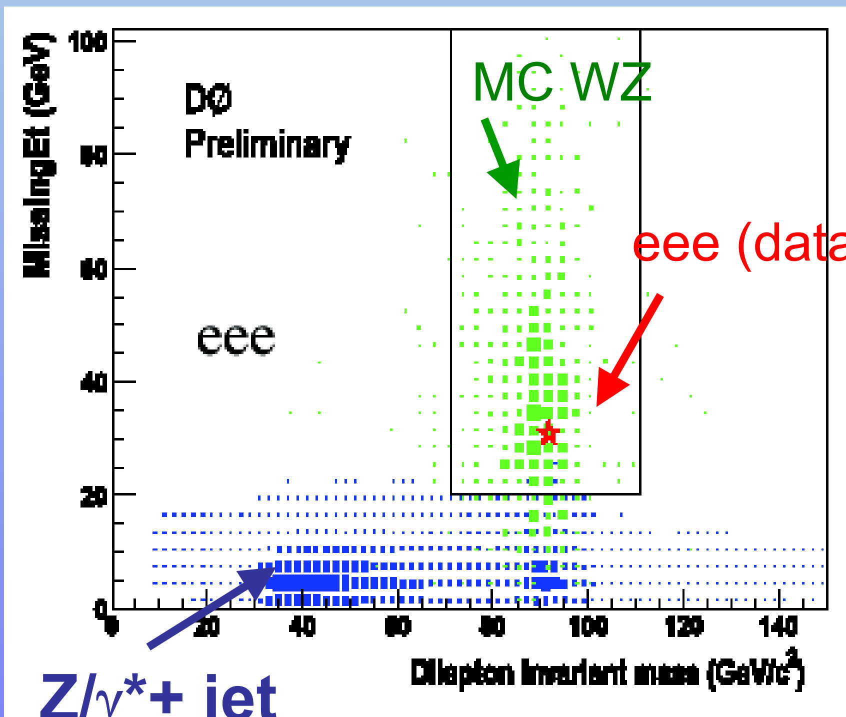
	4 Lep	3 Lep	2 Lep	Comb.
WZ/ZZ	0.06±0.01	0.91±0.07	1.34±0.21	2.31±0.29
Bkg	0.01±0.02	0.07±0.06	0.94±0.22	1.02±0.24
Bkg+Sig	0.07±0.02	0.98±0.09	2.28±0.35	3.33±0.42
Data	0	0	3	3

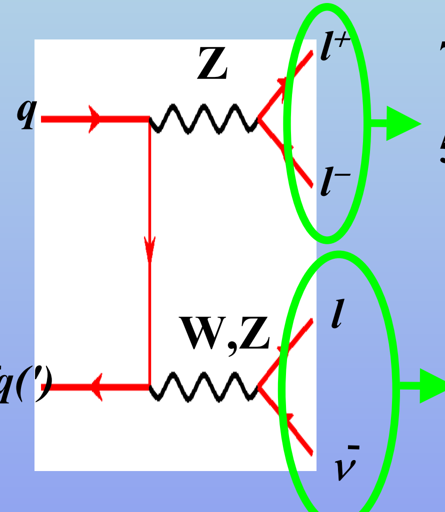
hep-ex/0501021

$\sigma(pp \to ZZ/ZW+X)_{CDF} < 15.2$ pb @95% C.L.

WZ search

final states with 3 leptons have
no irreducible SM backgrounds





71 GeV< M(e^+e^-) < 111 GeV

50 GeV< M($\mu^+\mu^-$) < 130 GeV

lepton Pt > 15 GeV

missing Et > 20 GeV

D0(285-320pb^{-1})	3 leptons ch
WZ signal	2.04 ± 0.13
Bckgd	0.71 ± 0.08
Expec. Total	2.75 ± 0.15
Observed	3

$\sigma(pp \rightarrow ZW+X) < 13.3$ pb @95% C.L

3 events -> cross section estimate ->

$\sigma(pp \rightarrow ZW+X) = 4.5^{+3.5}_{-2.6}$ pb

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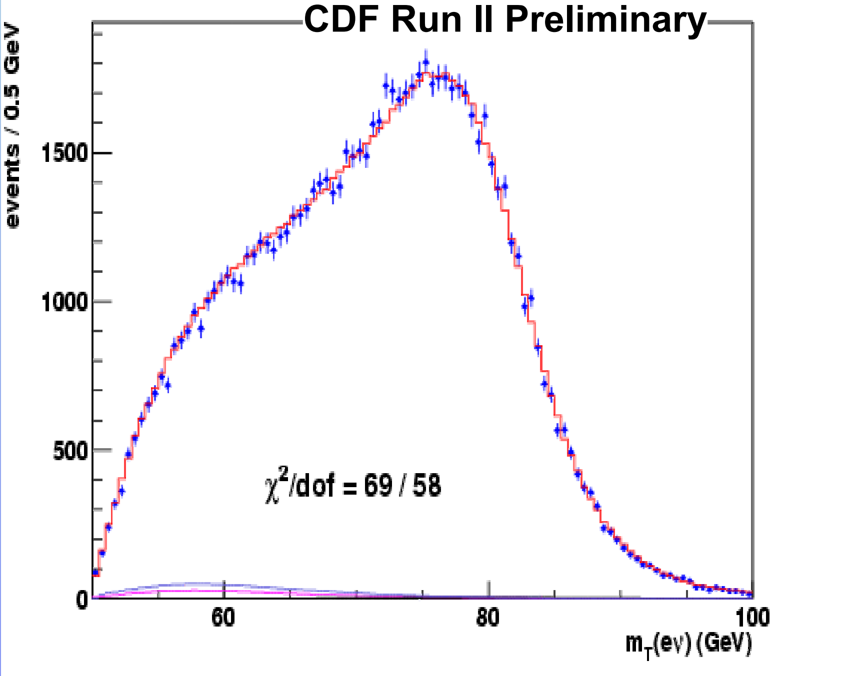
W Boson Mass



- W mass from fit of transverse mass distribution
- With $L=200pb^{-1}$ (ICHEP2004)
  $\Delta M_W = 76$ MeV/c^2 (e+μ) combined
  → Already better than RunI CDF
- With $2fb^{-1}$ expect
  $\Delta(Mw) \sim 30 MeV/c^2$
  ✓theoretical uncertainties [if not improved] will become important
- Will use next PDFs fits with CDF W charge asymmetry measurement included

- Theoretical / phenomenological inputs:
  ✓QED radiation
  ✓QCD : W Pt spectrum, PDF's

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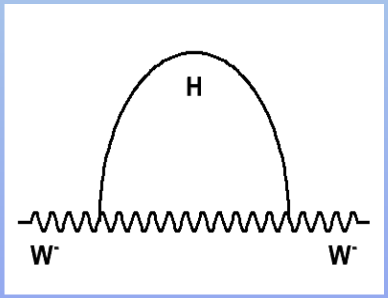
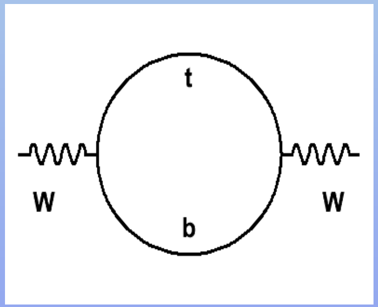
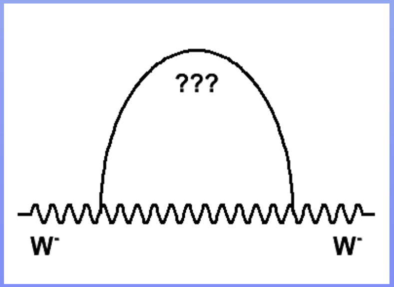
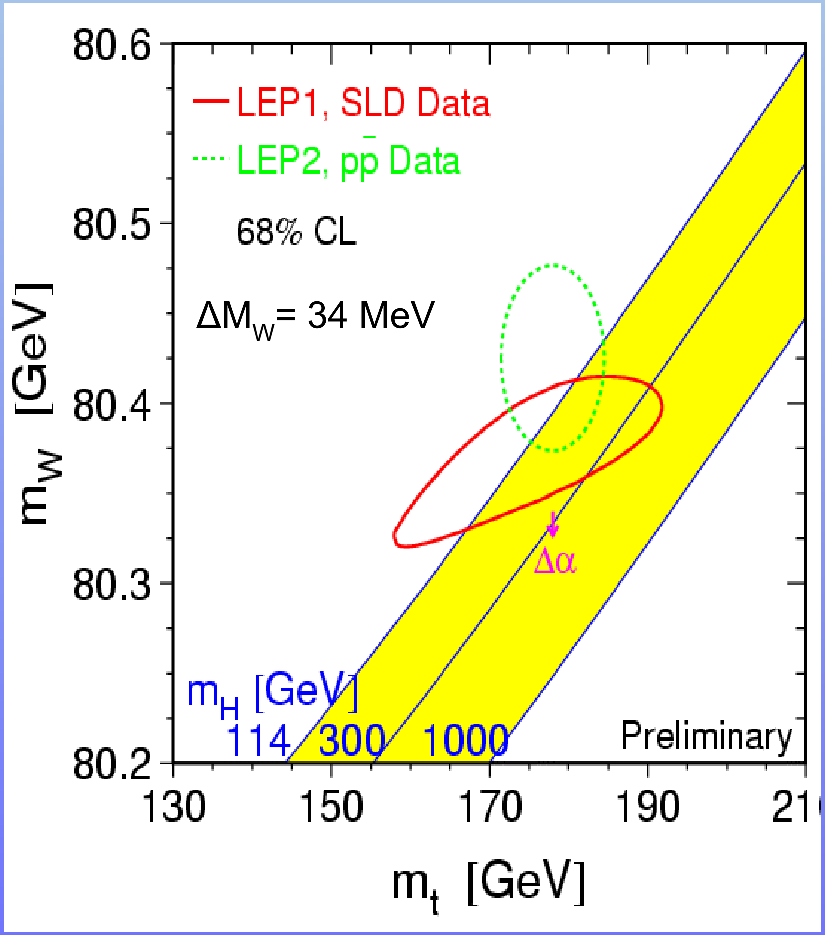
Contributions to W Mass

W propagator includes H, tb, hypothetical new particle loops









Precise knowledge of M_W constrains SM M_H, as well as hypothetical new particles

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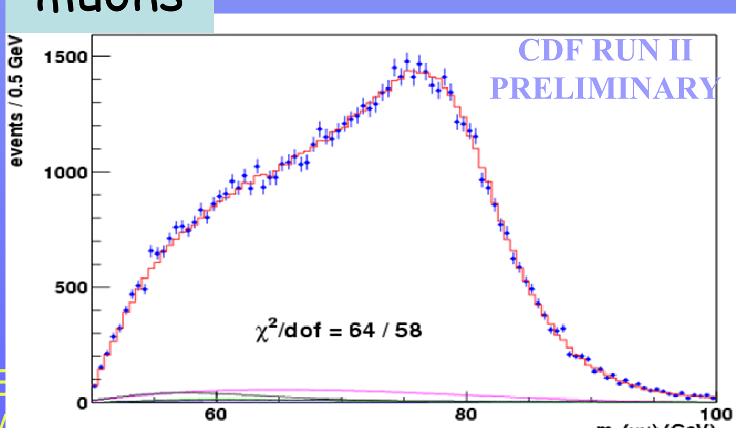
CDF RunII W Mass

CDF RUN II PRELIMINARY

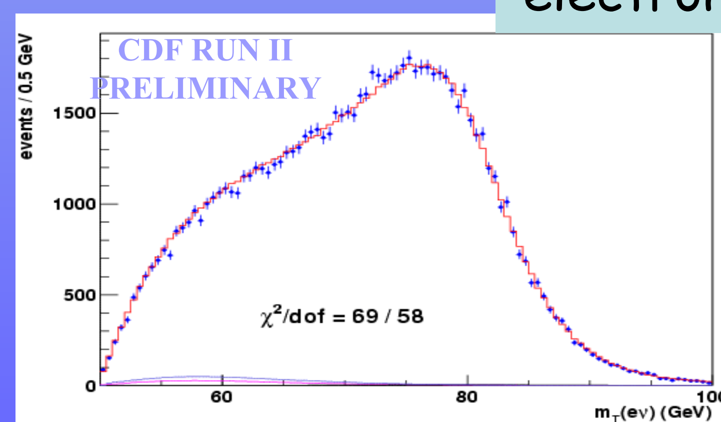
Systematic	Electrons (Run 1b)	Muons (Run 1b)
Lepton Energy Scale and Resolution	70 (80)	30 (87)
Recoil Scale and Resolution	50 (37)	50 (35)
Backgrounds	20 (5)	20 (25)
Statistics	45 (65)	50 (100)
Production and Decay Model	30 (30)	30 (30)
Total	105 (110)	85 (140)

Total uncertainty (76 MeV) already lower than CDF Run 1 (79 MeV)

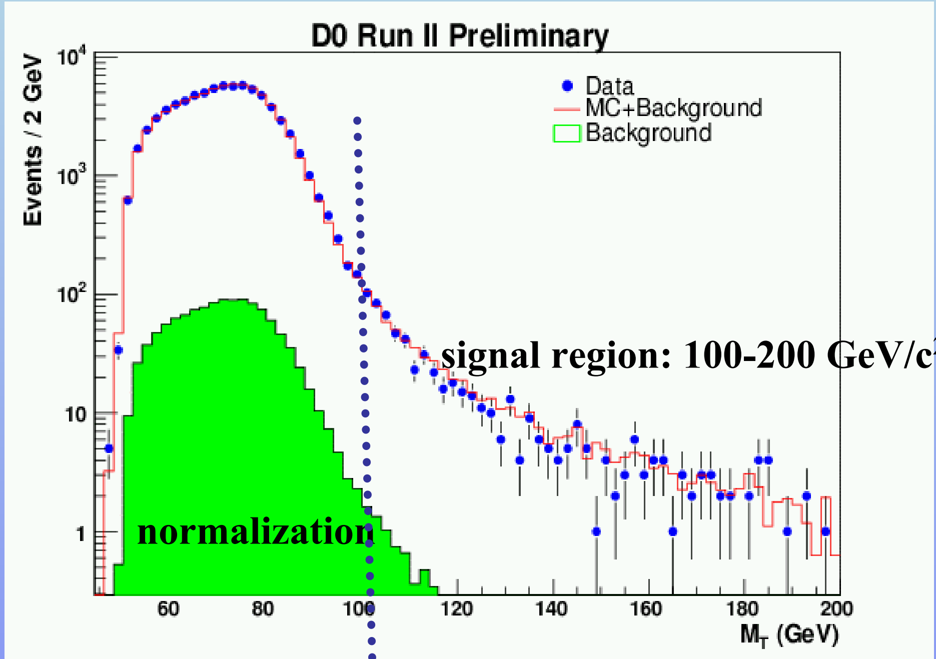
muons

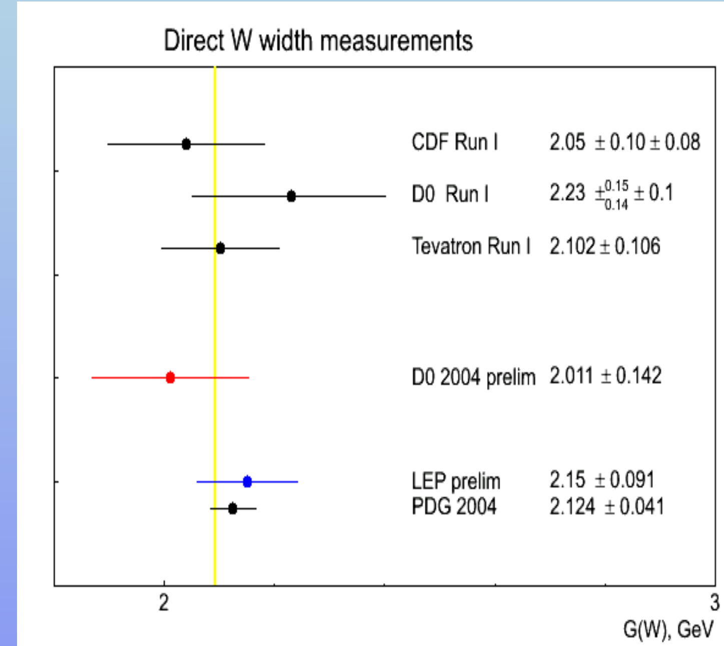


electrons



W width: direct measurement





- Determine W width using the tail of $M_T(l\nu)$ distribution
- Event counting experiment: 75K W->eν candidates total
  - ✓Normalization: $50 < M_T < 100$ GeV/c^2
  - ✓625 events $100 < M_T < 200$ GeV/c2 signal region
- consistent with SM and indirect measurements
- Syst. error dominated by EM&Had resolution and underlying event

Conclusions

- Most of Run I measurements re-established and/or already improved + new Run II results:
  - ⇒W/Z Inclusive cross section, widths, BF in all leptonic channels
  - ⇒Significant number of diboson candidate events:
    - ✓Many new results on diboson production – important steps towards the Higgs searches
  - ⇒First Run II measurement of the W width
- New W charge asymmetry data included in PDF2005 fits

The Road Ahead

- Looking forward to high precision EWK measurements:
  - ⇒ W boson Mass
  - ⇒differential W/Z cross sections
    - ✓$d\sigma/dy$ measurements in Z's will further constrain PDF uncertainties.
    - ✓$d\sigma/dp_T$ in both W's and Z's will further test QCD predictions.
- **Tevatron experiments just starting to explore potential of Run II data**