W/Z Production & Asymmetries at the Tevatron

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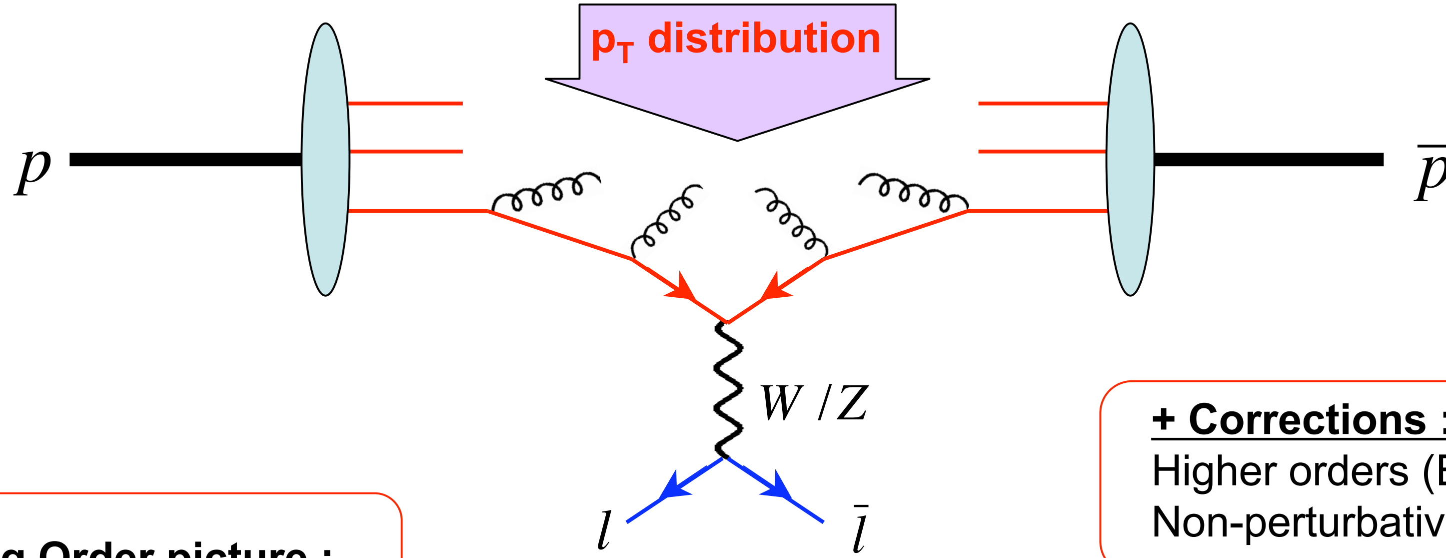
on behalf of the CDF & DØ Collaborations

- What are we Measuring & Why ?
- The Tevatron & CDF
- Cross Sections
- Asymmetries
- W Mass & Width
- Conclusions & Perspectives

W & Z Production

p_T distribution



+ Corrections :
Higher orders (EW,QCD)
Non-perturbative

Leading Order picture :

$$d\sigma_{p\bar{p}\to W/Z\to l\bar{l}} = \int \sum_{i,j=u,d,s,(c,b)} [f_i^q(x_p) f_j^{\bar{q}}(x_{\bar{p}}) + f_i^{\bar{q}}(x_p) f_j^q(x_{\bar{p}})] \times d\sigma_{q\bar{q}\to W/Z\to l\bar{l}} \; dx_p dx_{\bar{p}}$$

rapidity distribution

angular & mass distributions :

$$d\sigma_{q\bar{q}\to W/Z\to l\bar{l}}(\hat{s},\theta_l,\phi_l) \propto \text{couplings} \times \left[\frac{1}{(\hat{s} - M_{W/Z}^2)^2 + (\Gamma_{W/Z}\hat{s}/M_{W/Z})^2}\right]$$

What Measurements & Why ?

W & Z Inclusive Cross Sections

- Tests of (N)NLO perturbative QCD.
- Demonstrate systematic understanding of lepton ID, trigger efficiencies & backgrounds at 1-2 % level.
- Provide extremely well understood event ensembles for energy & momentum scale determination.
- Starting point for more exclusive measurements (e.g. W+jets).

Standard Candles

- Tevatron : $\sigma = N / L$
- LHC : $L = N / \sigma$

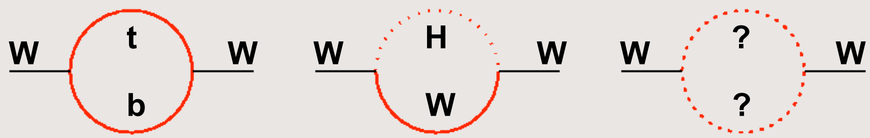
Differential Cross Sections & Asymmetries

- PDF constraints.
- EWK coupling constraints.
- Tests of perturbative QCD & non-perturbative phenomenology.

What Measurements & Why ?

W Mass

- Self-energy corrections depend on mass of top quark and Higgs boson :

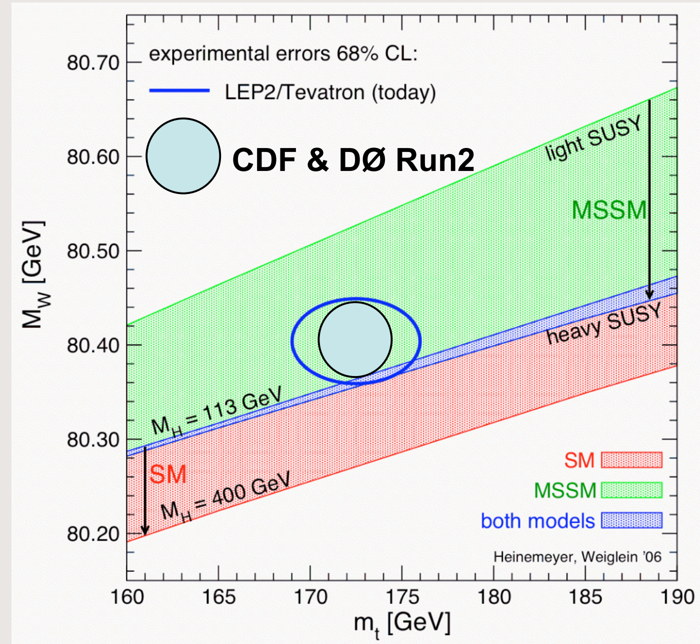


$\Delta M_W \propto M_{top}^2$ $\quad$ $\Delta M_W \propto \ln M_H$ $\quad$ New Physics

- Equivalent Higgs constraining power :

$\Delta(M_{TOP}) \approx 1.5$ GeV : $\Delta(M_W) \approx 10$ MeV

O(1%) on M_{TOP} : (< 0.1%) on M_W



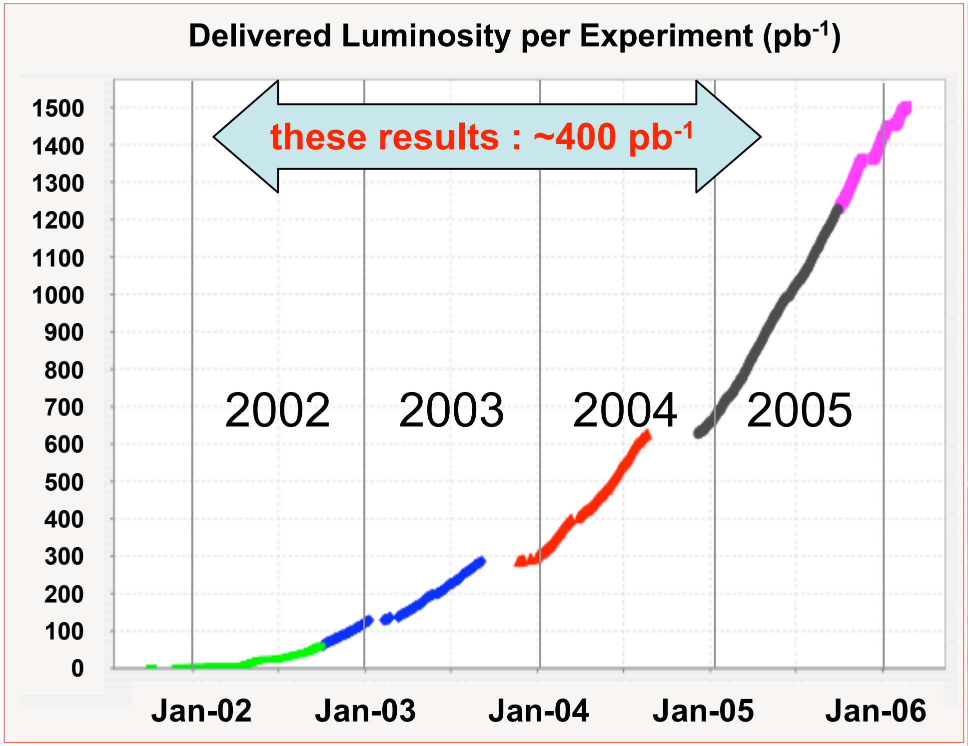
W Width

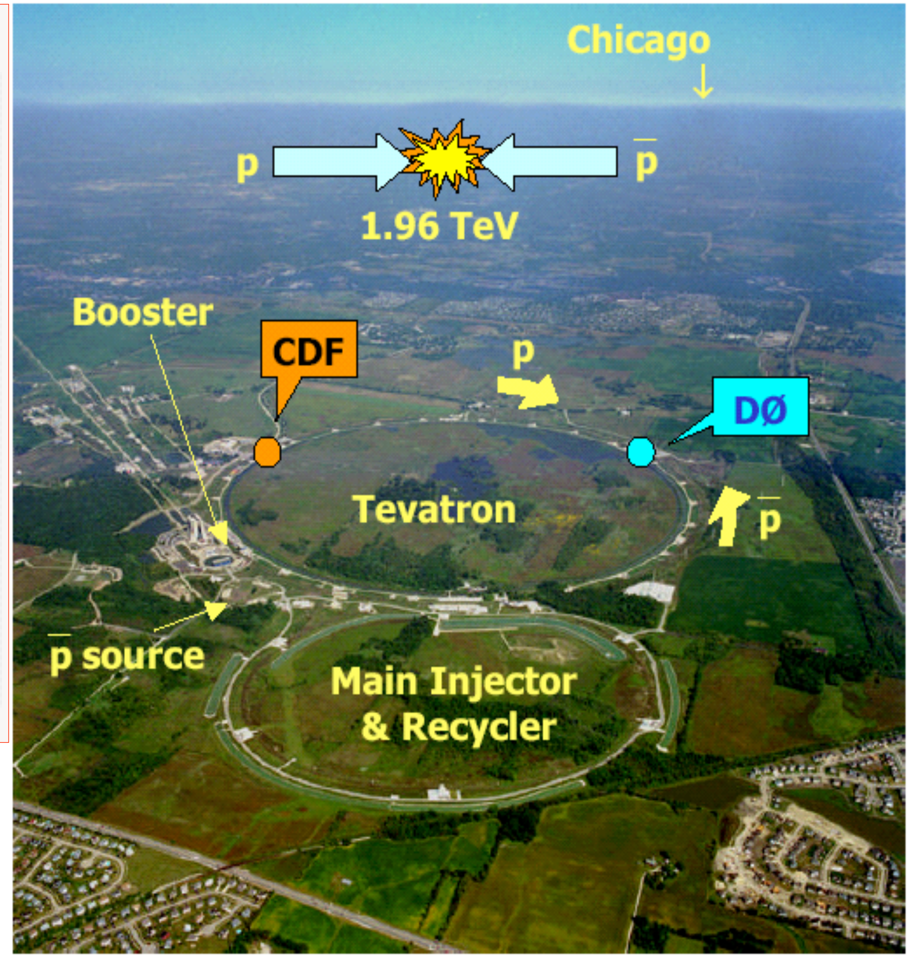
- Indirect determination can be made with very high precision. CKM constraints:

$$\Gamma_W = 3\Gamma_W^0 + 3K_{QCD} \sum_{\text{no top}} |V_{qq'}|^2 \Gamma_W^0$$

- Direct measurement is sensitive to any deviations from the SM for **M(W*) > M_W**
- The W width is a less important constraint in EWK fits than the W mass, but is nevertheless a useful SM test. Employs the same techniques as precision cross section or mass measurements.

Tevatron





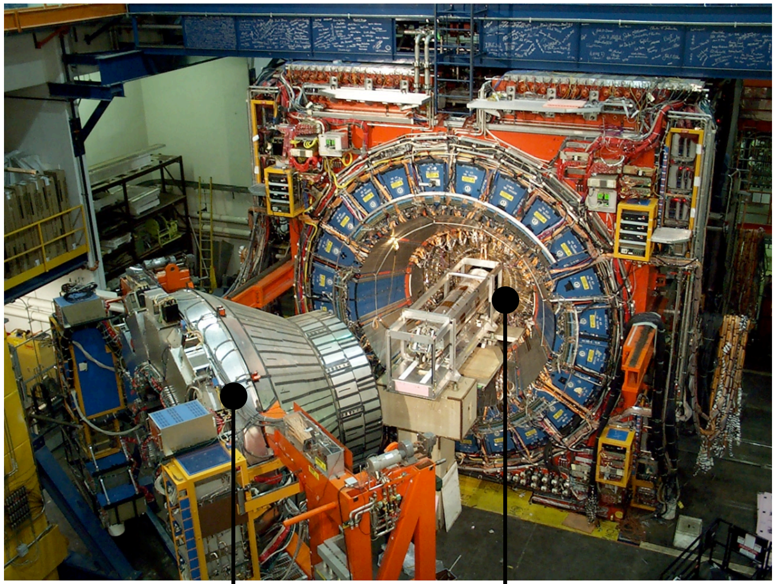
W & Z Factory

Mode	Events/Week/Exp. (before trigger & cuts)
$W \to e\nu$	~50,000
$Z \to ee$	~5000

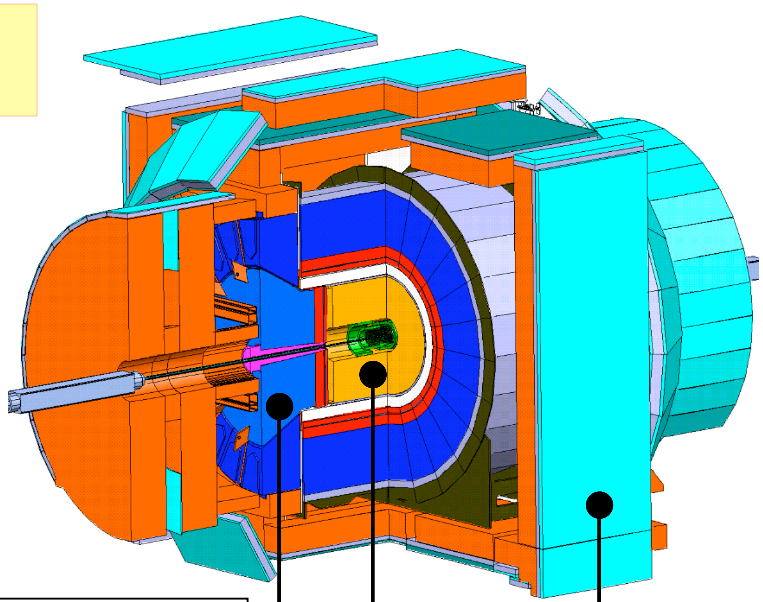
Now operating in precision regime:

$$N(Z \to ee)_{\text{Tevatron}} > N(W)_{\text{LEP}}$$

The CDF Detector



DØ detector : next talk



Drift chamber outer tracker :

$\delta p_T / p_T \approx 0.0005 \times p_T$ [GeV/c; beam constrained]; $|\eta| < 1$

Silicon vertex detector :

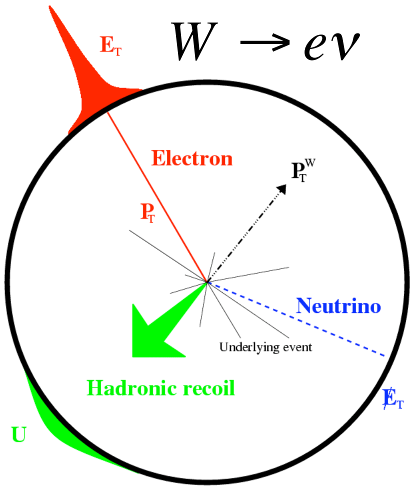
tracking coverage out to $|\eta| < 2.8$

Central calorimeter : $\delta E_T / E_T \approx 13.5\% / \sqrt{E_T} \oplus 1.5\%$ $|\eta| < 1.1$

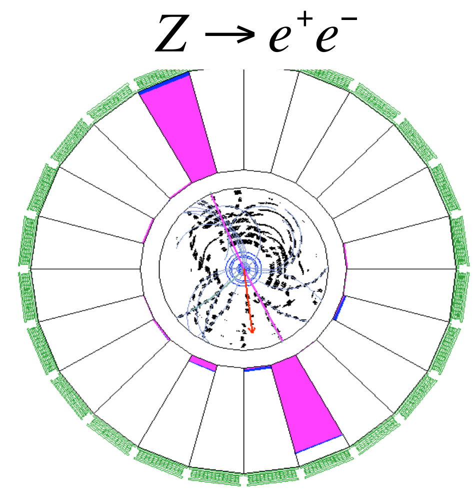
Plug calorimeter : coverage out to $|\eta| < 3.0$

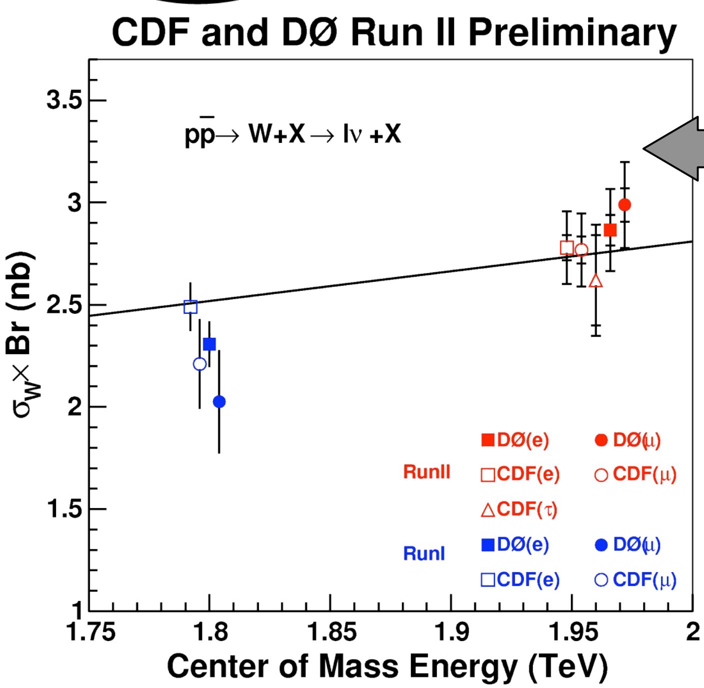
Muon chambers : coverage out to $|\eta| < 1.0$

Inclusive Cross Sections



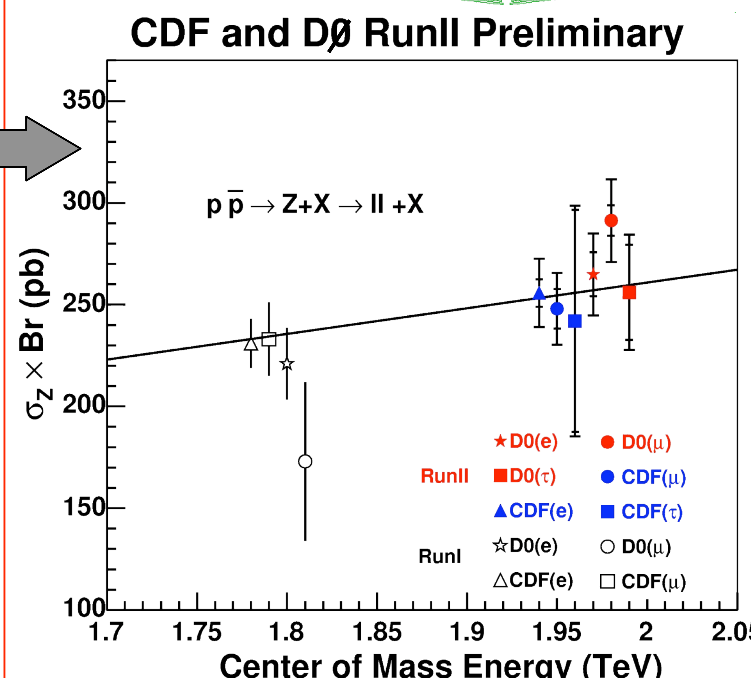
- Standard boson selections ($l+\not{E}_T$; l^+l^-)
- Mostly employ central lepton triggers.
- 1-2% systematic uncertainties (w/o luminosity):
  - PDF's
  - lepton & trigger efficiencies
  - backgrounds
- Results are in good agreement with NNLO QCD predictions.





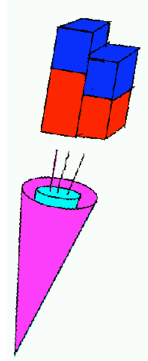
- ~70-350 pb^{-1} results.
- NNLO predictions **(Hamberg, van Neerven & Matsuura 1991; Anastasiou et al. 2004)**

CDF : PRL 94, 091803 (2005)



Tau Channel

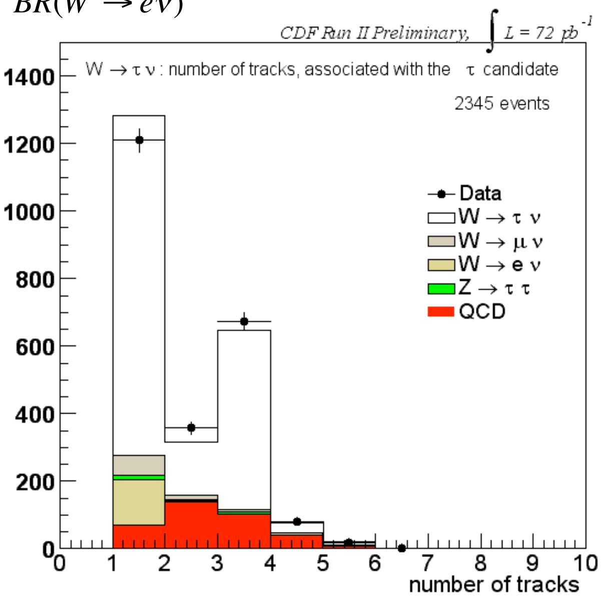
- Interesting channel :
  - to test 3rd generation lepton universality,
  - as a benchmark for searches (especially MSSM Higgs).
- Experimentally challenging.



- Isolated "pencil-jet" consistent with hadronic τ decay
  - π^0 reconstruction in EM cal / shower-max
  - neural net (DØ)
- Triggering strategies :
  - single lepton
  - lepton + track
  - $\tau + \not{E}_T$

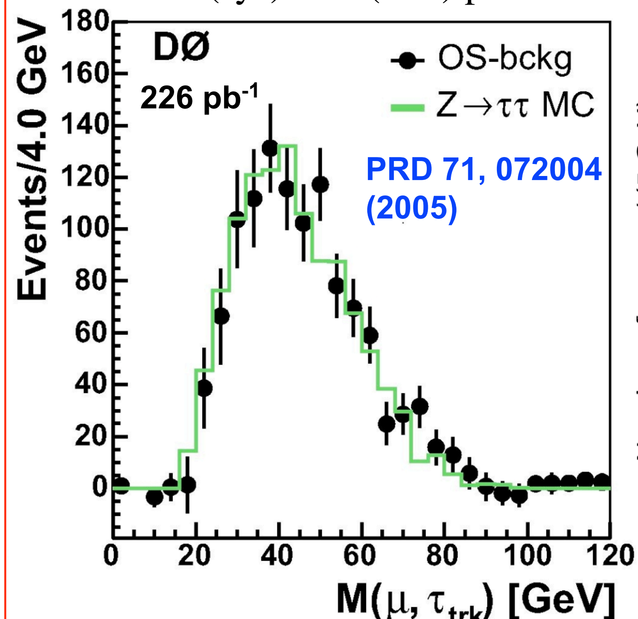
$$\sigma_W \cdot BR(W \to \tau\nu) = 2.62 \pm 0.07 \text{ (stat)} \pm 0.21 \text{ (sys)} \pm 0.16 \text{ (lum) nb}$$

$$\frac{BR(W \to \tau\nu)}{BR(W \to e\nu)} = 0.99 \pm 0.04 \text{ (stat)} \pm 0.07 \text{ (sys)}$$



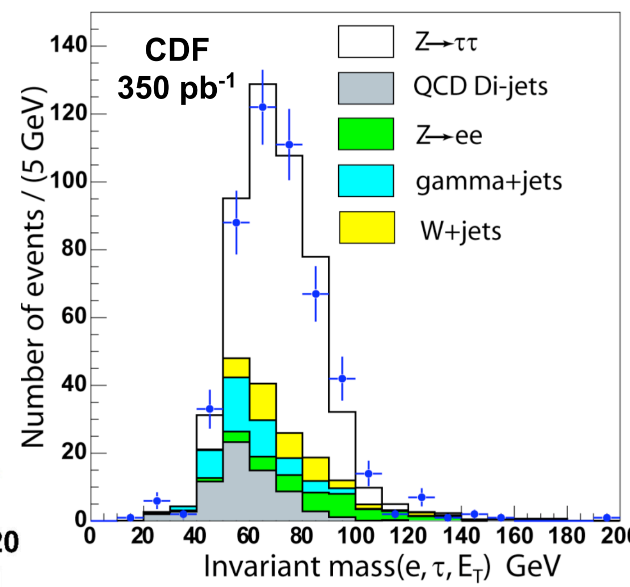
$Z \to \tau(\mu)\tau(h/e)$

$$\sigma_Z \cdot BR(Z \to \tau\tau) = 237 \pm 15 \text{ (stat)} \pm 18 \text{ (sys)} \pm 15 \text{ (lum) pb}$$



$Z \to \tau(e)\tau(h)$

$$\sigma_Z \cdot BR(Z \to \tau\tau) = 265 \pm 20 \text{ (stat)} \pm 21 \text{ (sys)} \pm 15 \text{ (lum) pb}$$



R(W/Z) & Indirect W Width

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

SM : 3.370 ± 0.024

SM : 226.4 ± 0.3 MeV

LEP : $BR(Z \to l^+l^-) = 0.033658 \pm 0.000023$

- Careful propagation of correlated systematics:

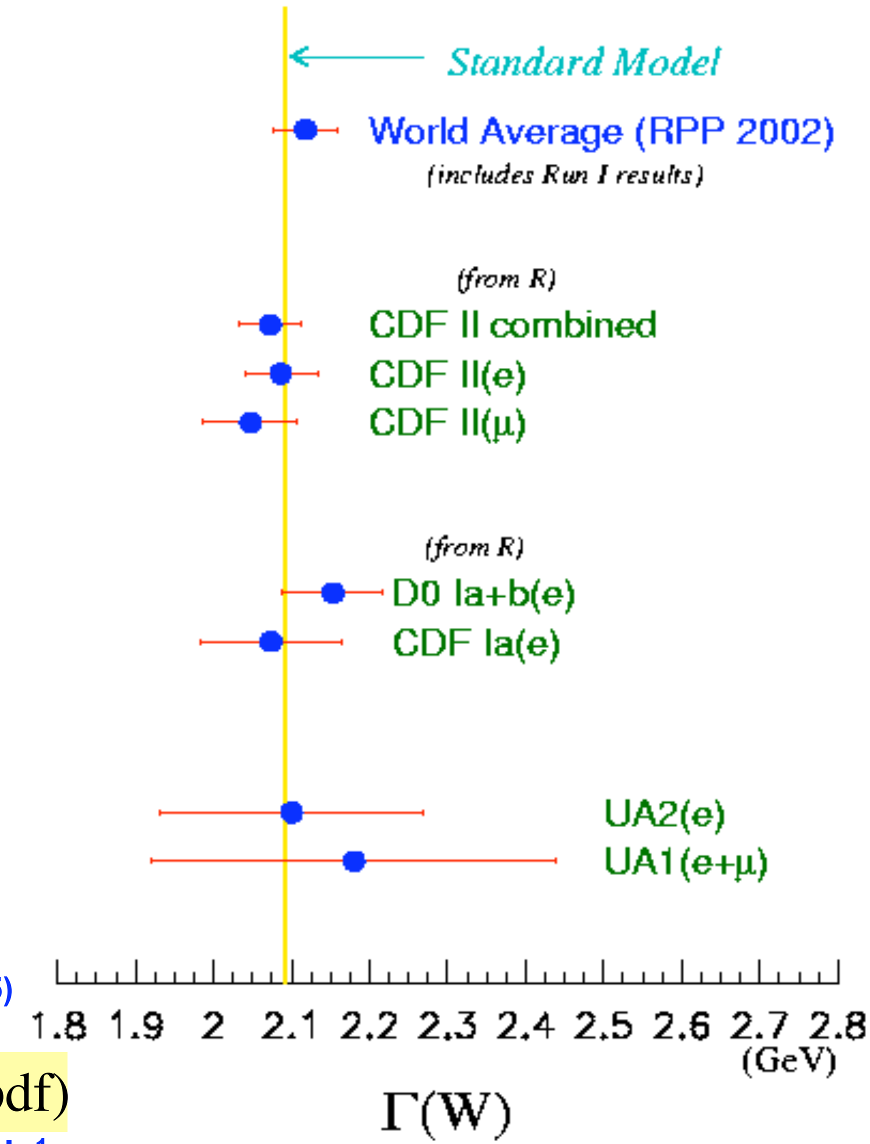
$$R = 10.92 \pm 0.15\ (\text{stat}) \pm 0.14\ (\text{syst})$$

$$\Gamma_W = 2.079 \pm 0.041\ \text{GeV}$$

CDF e+μ, 72 pb^{-1}
PRL 94, 091803 (2005)

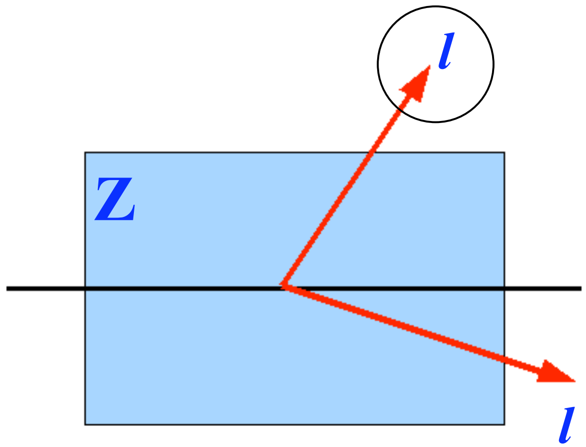
$$R = 10.82 \pm 0.16\ (\text{stat}) \pm 0.25\ (\text{syst}) \pm 0.13\ (\text{pdf})$$

D0 e, 177 pb^{-1}

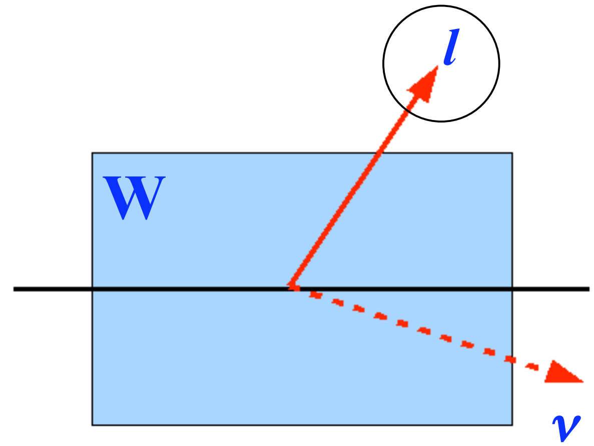


R(W/Z) : New Method

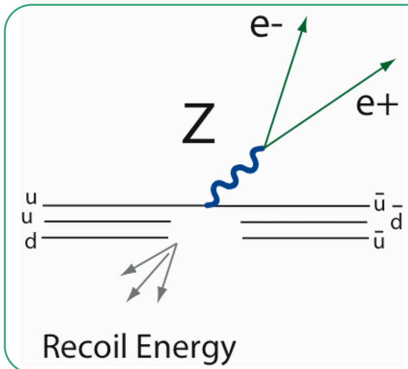
1. Design an analysis optimized for the ratio of cross-sections.
2. Start with a selection entirely symmetric between W's & Z's :



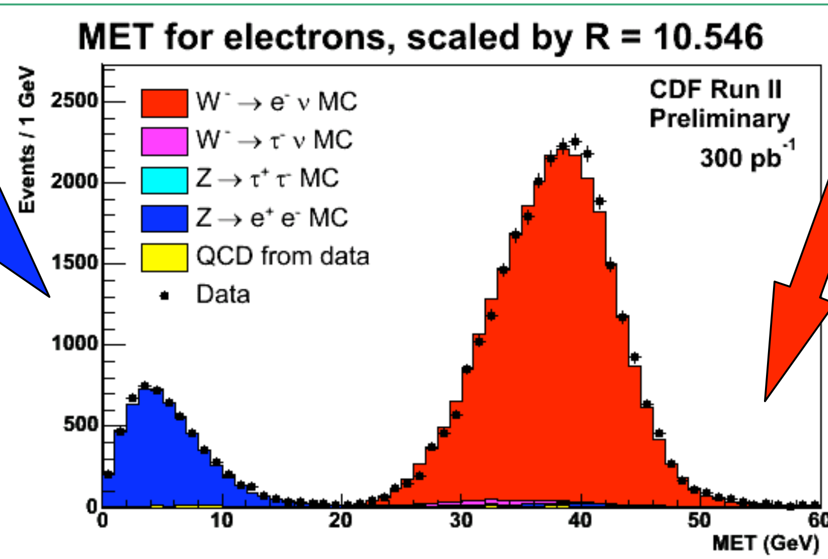
i. **Single lepton** trigger & ID cuts (E_T > 30 GeV)
ii. A hard cut on the recoil (U < 10 GeV) to suppress QCD background.



3. Fit for W & Z fractions in a discriminating variable, $\not\!\!E_T$:



i. Exclude 2nd EM object from recoil.
ii. Include all towers in $\not\!\!E_T$ calculation.



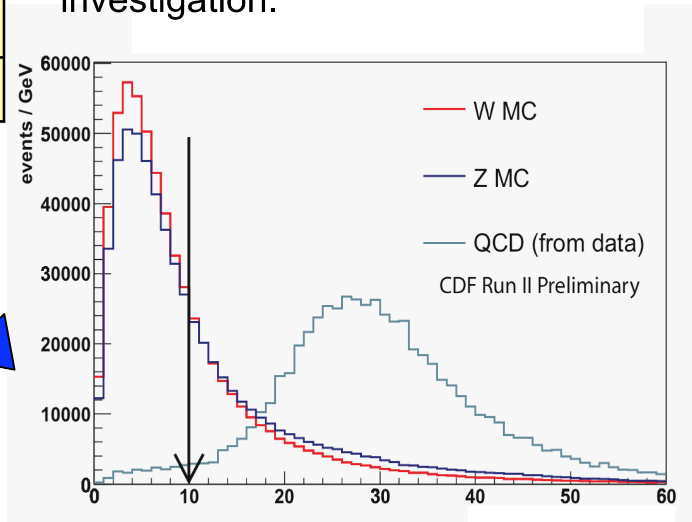
R(W/Z) : New Method

CDF PRELIMINARY	ΔR/R		
	electron (72 pb^{-1})	muon (72 pb^{-1})	electron (300 pb^{-1}) PRELIMINARY
statistical	0.0170	0.0240	0.0094
PDF	0.0065	0.0081	0.0031
material	0.0028	-	-
recoil	0.0028	0.0036	0.0040
efficiency	0.0110	0.0099	-
background	0.0037	0.0081	0.0250
missing-E_T (DY tail)	-	-	0.0050
total systematic	0.0150	0.0160	0.0260
stat. + syst.	0.0220	0.0290	0.0276

- **Significantly reduced.** With single lepton selection, W/Z rapidity distributions overlap more.
- **Eliminated.**
- **Increased.** QCD background at low recoil & $\not{E}_T$ is uncertain. Under investigation.

Preliminary systematic study & comparison with earlier analysis.

Recoil distribution for signal & QCD background



$$R = 10.55 \pm 0.09\ (\text{stat}) \pm 0.27\ (\text{syst})$$

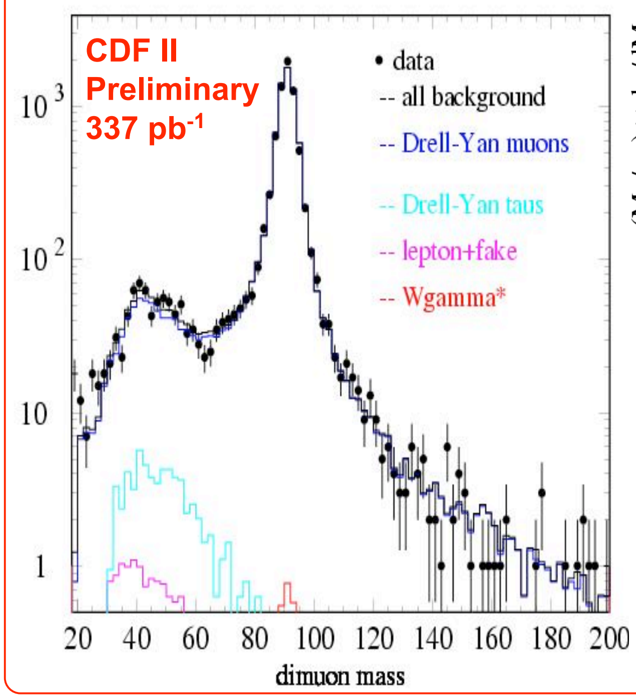
CDF e PRELIMINARY, 300 pb^{-1}

Drell-Yan dσ/dM

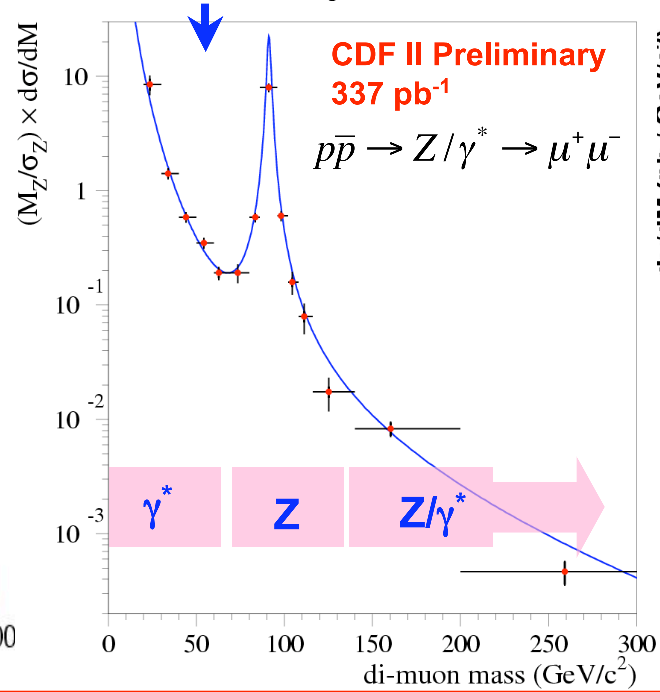
$$p\bar{p} \rightarrow Z/\gamma^* \rightarrow l^+l^- \quad (+X)$$

- A standard measurement at hadron colliders :
  - control sample for searches (Z’, SUSY dilepton channels)
  - PDF constraints.

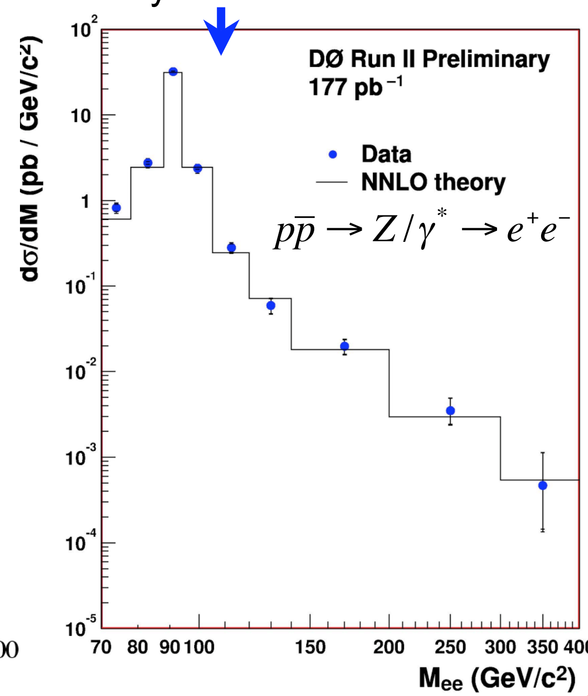
- Single lepton triggers (di-lepton triggers can be used in future)
- Low mass sculpting due to triggers/cuts (20/10 GeV **CDF**; 25 GeV **D0**). Geometric & kinematic acceptance increases at high masses.
- Backgrounds small.
- Bin size > resolution.



matrix unfolding

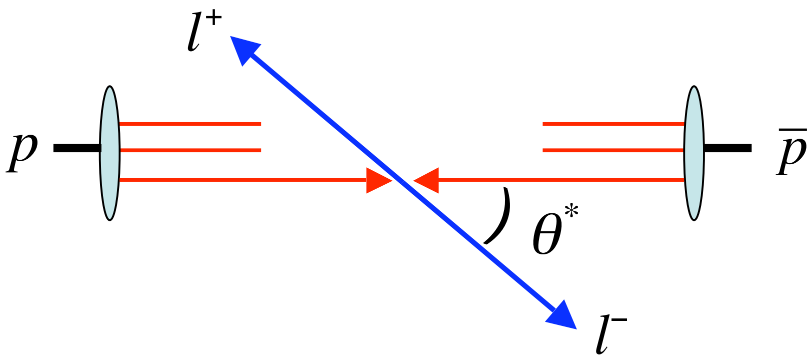


bin-by-bin correction



A_{FB}

Forward-Backward Asymmetry :

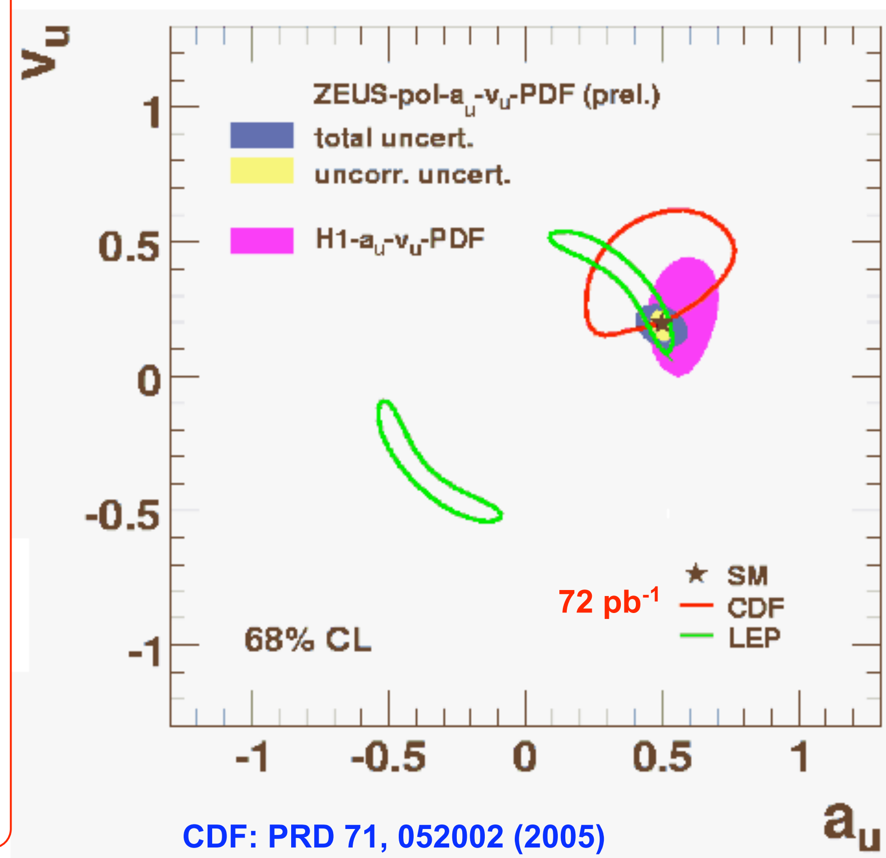


$$\sigma_{F(B)} = \int_{0(-1)}^{1(0)} \frac{d\sigma}{d\cos\theta^*}\, d\cos\theta^*$$

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

$$= f(\text{u,d,e axial \& vector couplings})$$

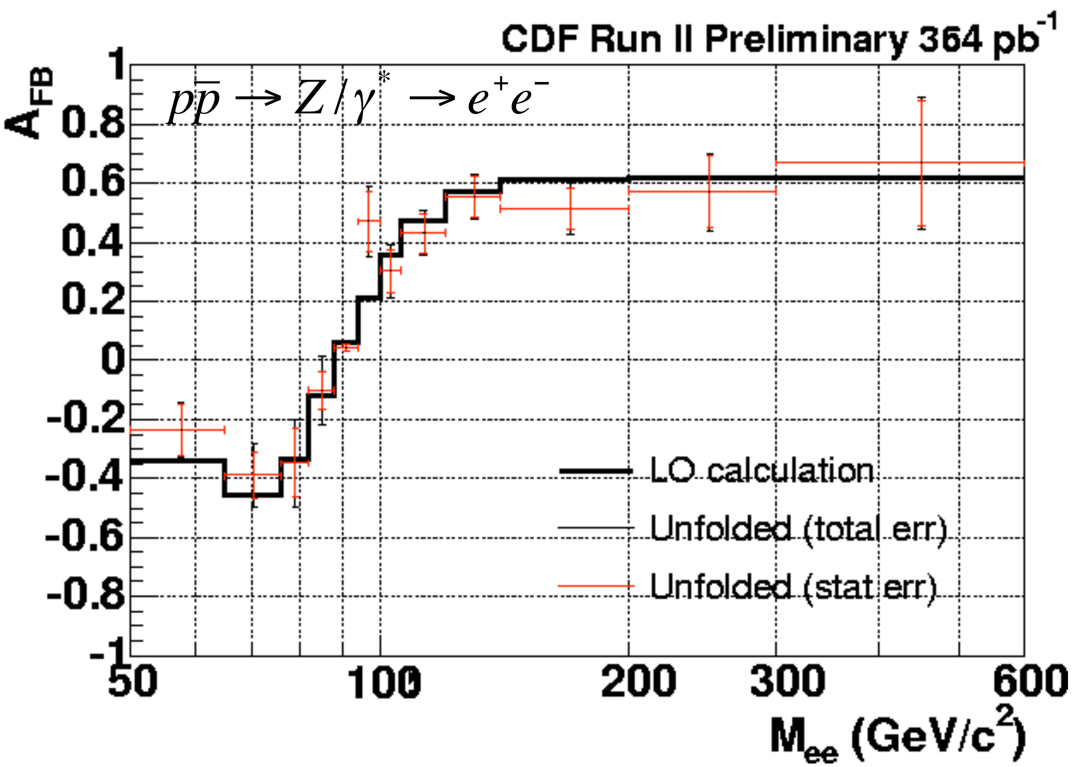
- With charged leptons in the final state, there is no sign ambiguity - useful neutral current coupling constraints :

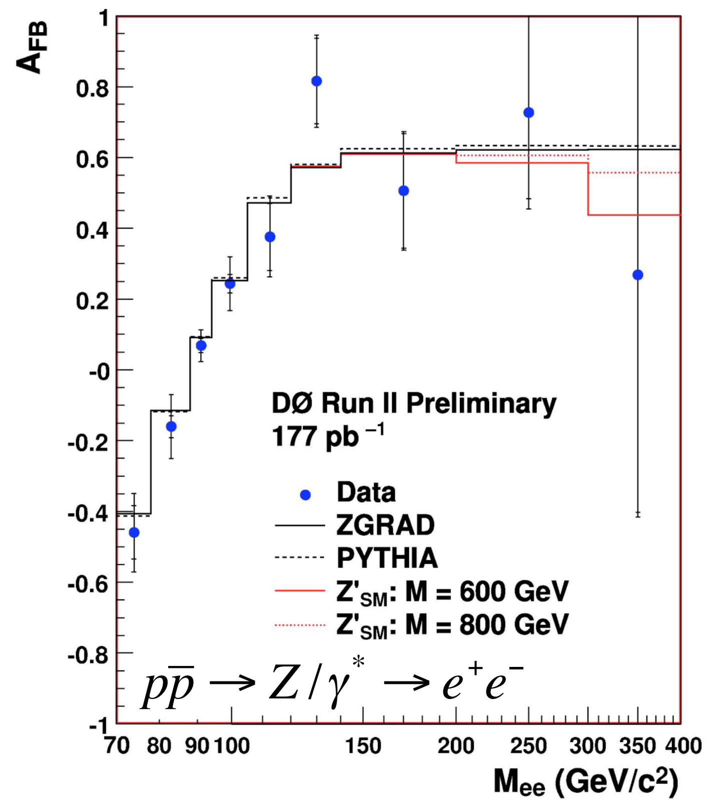


CDF: PRD 71, 052002 (2005)
Wichmann, HCP 2006

A_{FB}

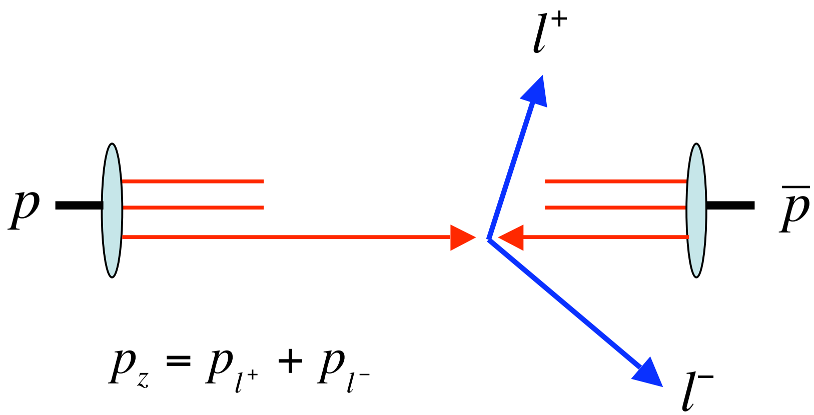
- With larger integrated luminosities, the focus is on more precise measurements at high invariant mass : new physics can interfere with SM to generate deviations.
- Statistically limited : systematics (energy scale, resolution, backgrounds) ~ 10%.
- New methods being developed to fit fully differential cos(θ^*) distribution.





Drell-Yan dσ/dy

Rapidity differential cross section :



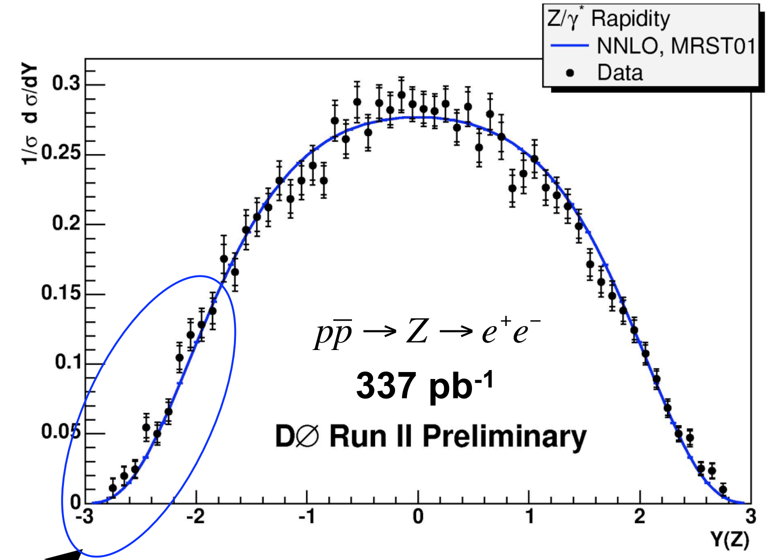
$$p_z = p_{l^+} + p_{l^-}$$

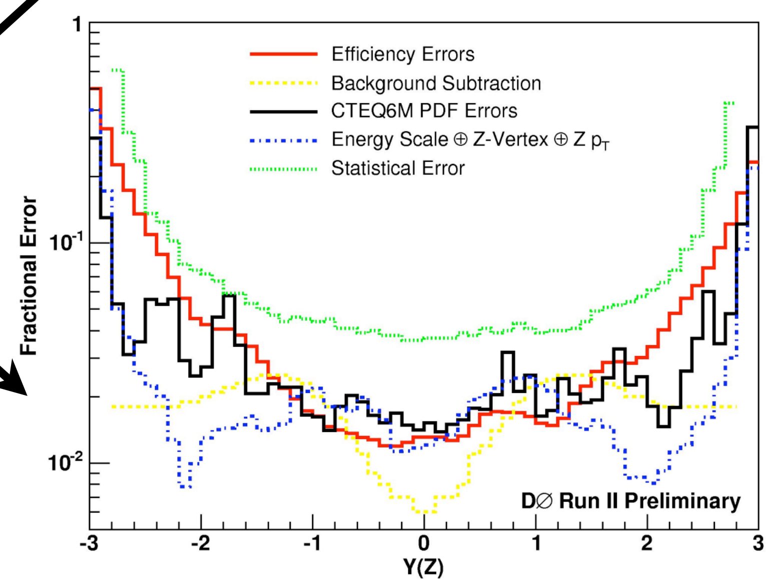
$$y = \frac{1}{2}\ln\left(\frac{E^Z + p_z^Z}{E^Z - p_z^Z}\right)$$

- At leading order :

$$x_p, x_{\bar{p}} = \left(\frac{M}{\sqrt{s}}\right)e^{\pm y}$$

- High-y → high-x
- Currently statistically limited.





σ_W (forward region)

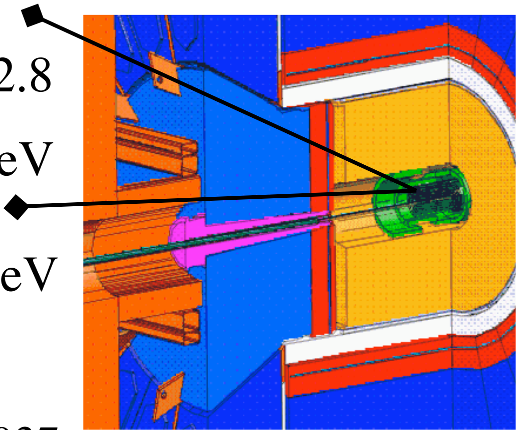
- A new & technically challenging analysis :
  - Silicon tracking for electron ID
  - Different triggering strategy ($E_T^e + \not{E}_T$)
  - Backgrounds

$$\sigma_W \cdot BR(W \to e\nu) =$$
$$2.796 \pm 0.013 \text{ (stat) } ^{+0.095}_{-0.090} \text{ (sys)} \pm 0.168 \text{ (lum) nb}$$

$1.2 \le \eta_e \le 2.8$

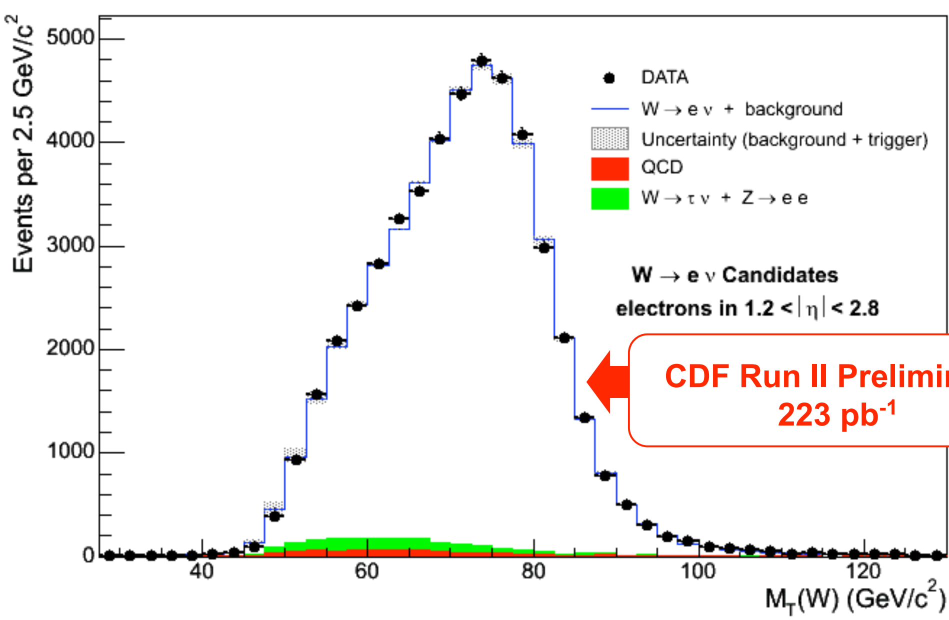
$E_T^e > 20$ GeV

$\not{E}_T > 25$ GeV

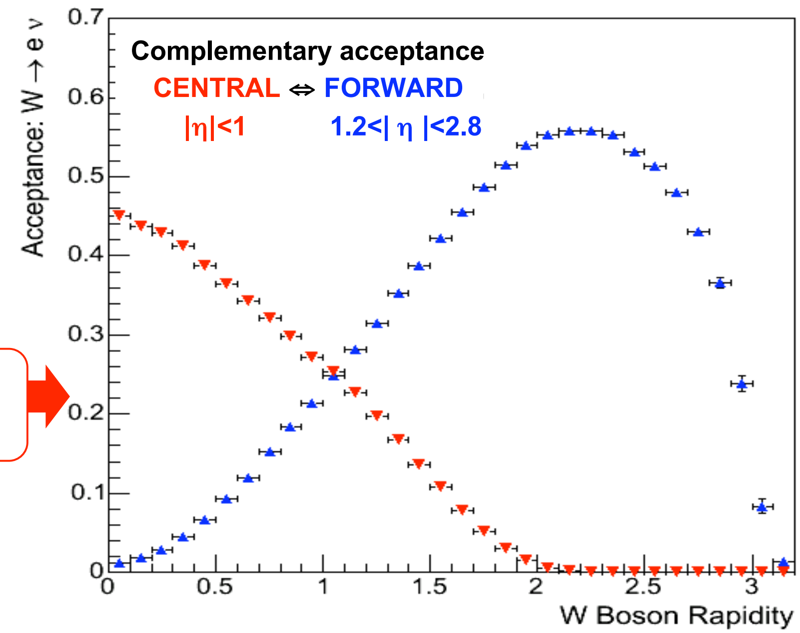


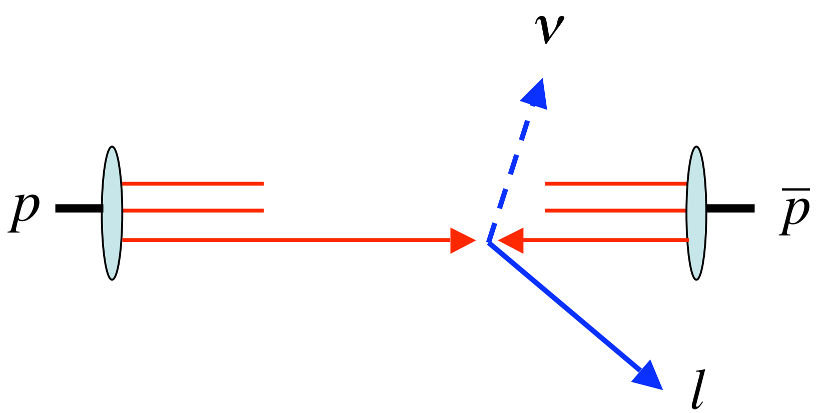
- Compare with central analysis :

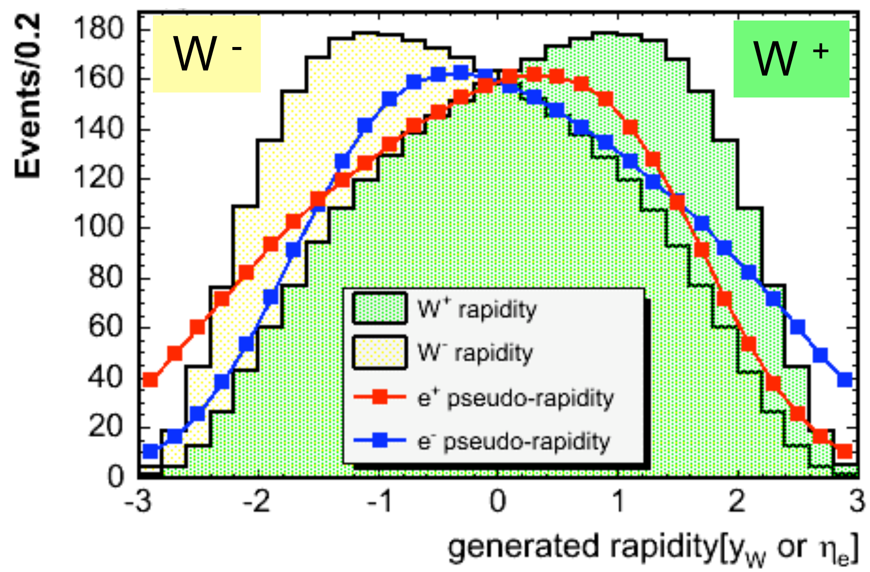
$R_{exp}^{central/forward} = 0.925 \pm 0.033$ ⟺ $R_{CTEQ\,6.1}^{central/forward} = 0.924 \pm 0.037$, $R_{MRST\,01E}^{central/forward} = 0.941 \pm 0.012$ ⟺ PDF constraint



CDF Run II Preliminary
223 pb⁻¹







- Production asymmetry :

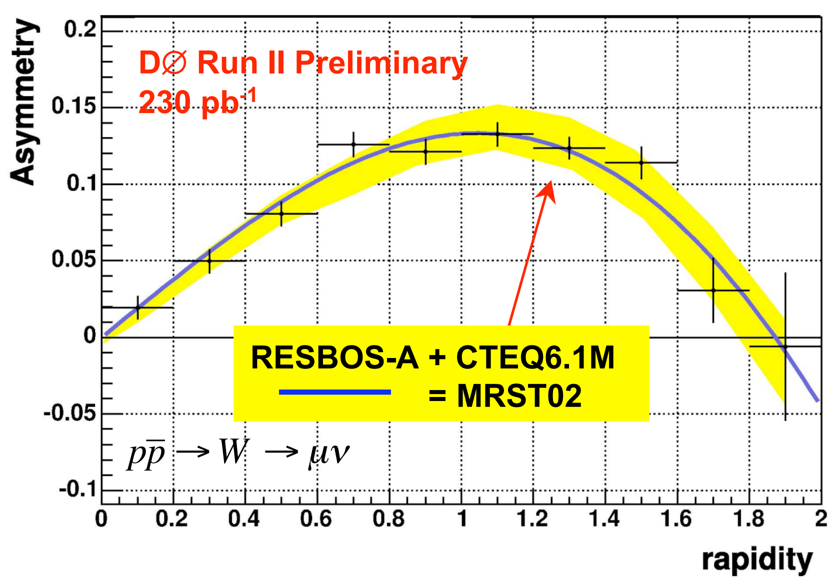
$$A(y_W) = \frac{\frac{d\sigma_+}{dy} - \frac{d\sigma_-}{dy}}{\frac{d\sigma_+}{dy} + \frac{d\sigma_-}{dy}} \approx \frac{u(x_p)d(x_{\bar{p}}) - d(x_p)u(x_{\bar{p}})}{u(x_p)d(x_{\bar{p}}) + d(x_p)u(x_{\bar{p}})} \approx F\left[(d/u)_{x_p}, (d/u)_{x_{\bar{p}}}\right]$$

- But what we typically measure is the lepton charge asymmetry :

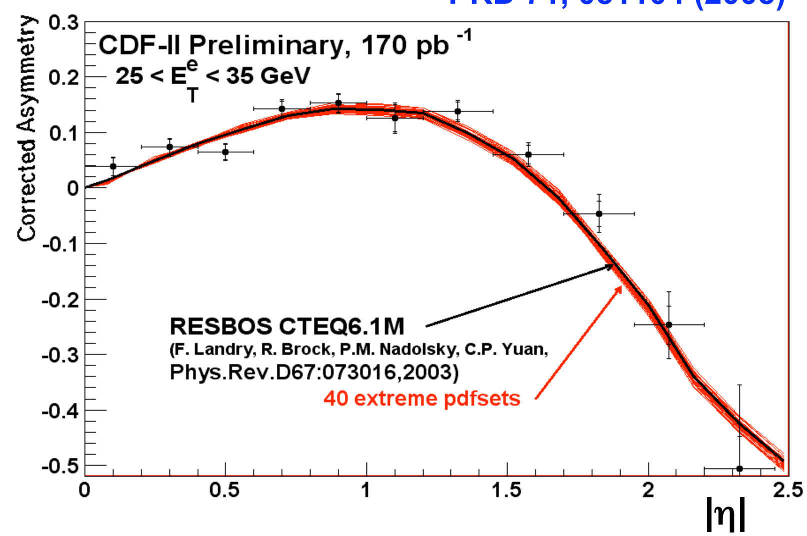
$$A(\eta_l) = \frac{d\sigma_+/d\eta - d\sigma_-/d\eta}{d\sigma_-/d\eta + d\sigma_+/d\eta} = A(y_W) \otimes (V - A)$$

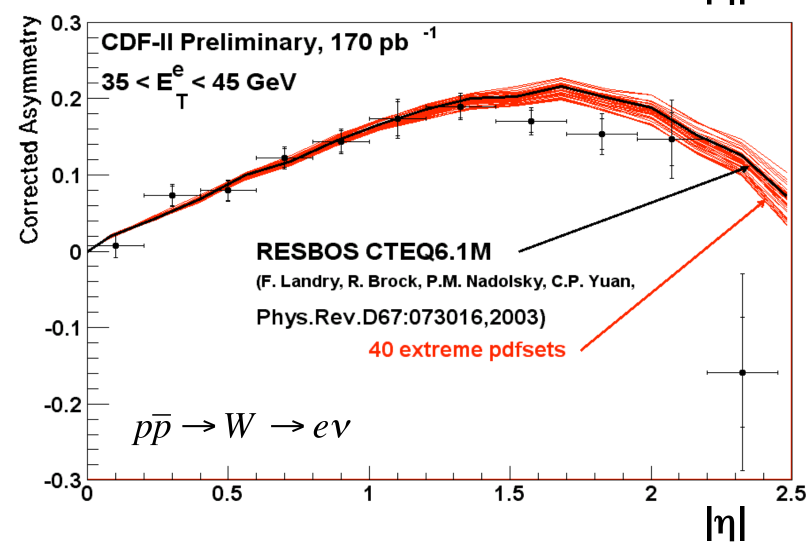
W Charge Asymmetry

- Experimental issues are :
  - Forward lepton ID & triggering
  - Lepton charge mis-identification rates : ($\mu \approx 10^{-4}$; **e** $\approx 10^{-1\text{-}2}$)
  - Backgrounds
- Experimental uncertainties comparable to existing PDF spreads.

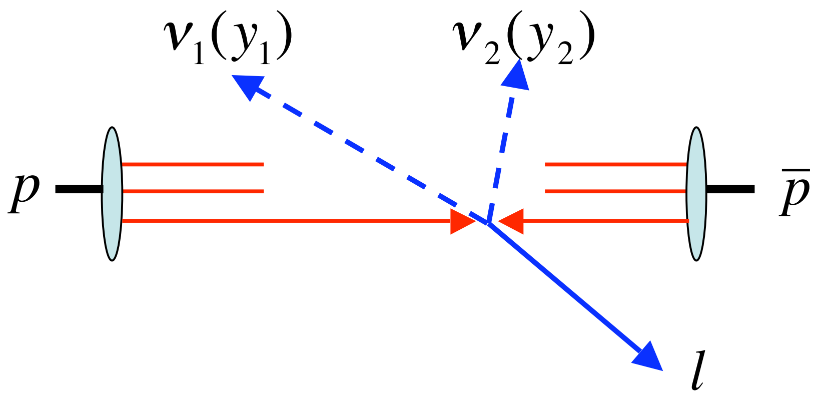


PRD 71, 051104 (2005)





W Production Asymmetry



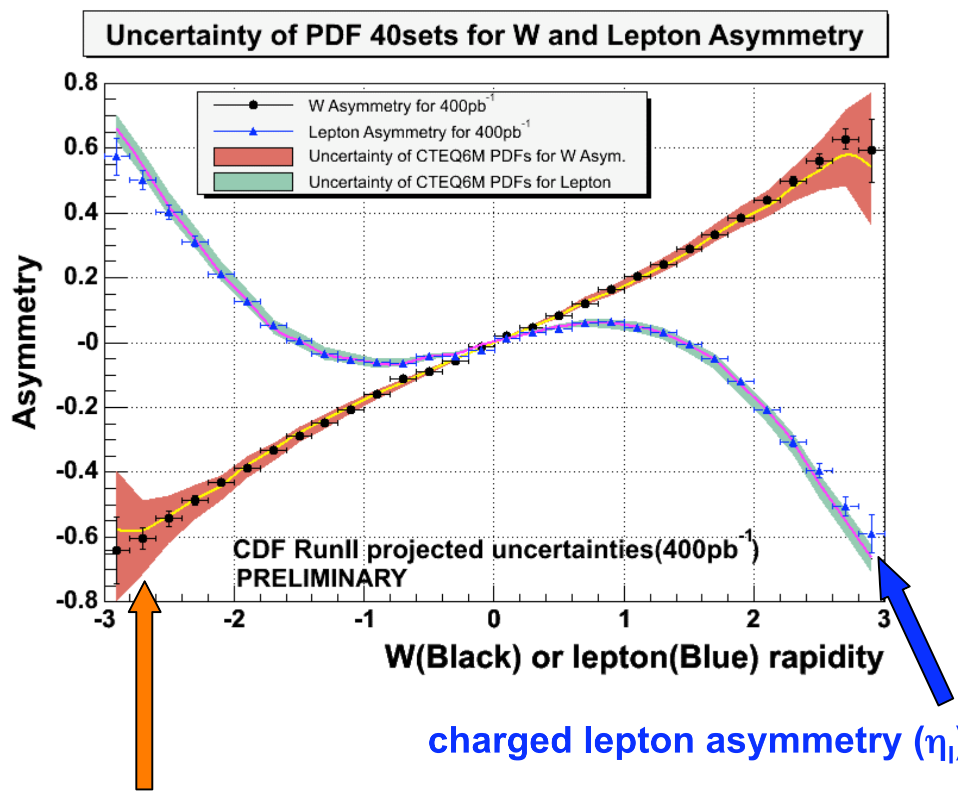
- Reconstruct the production asymmetry distribution $A(y_W)$ directly ?

1. Find 2 solutions using M_W constraint.
2. Weight each by a factor taking into account production & decay :

$$P_{1,2}(\pm\cos\theta^*, y_W, p_T^W)$$

3. Resolve dependence on y_W iteratively to yield $A(y_W)$.

- Preliminary CDF Monte Carlo analysis shows significantly increased sensitivity :

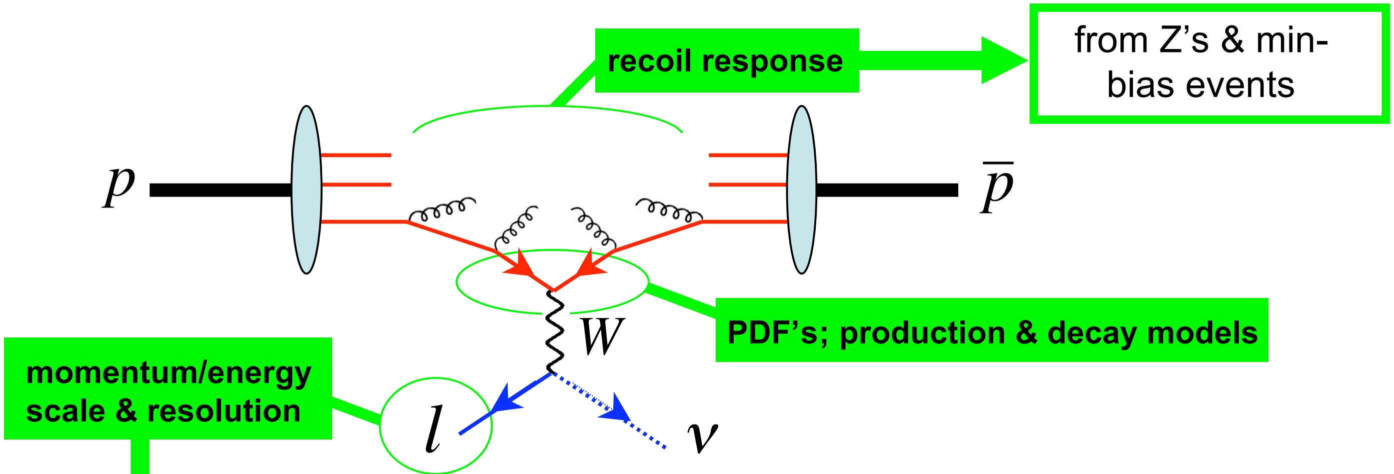


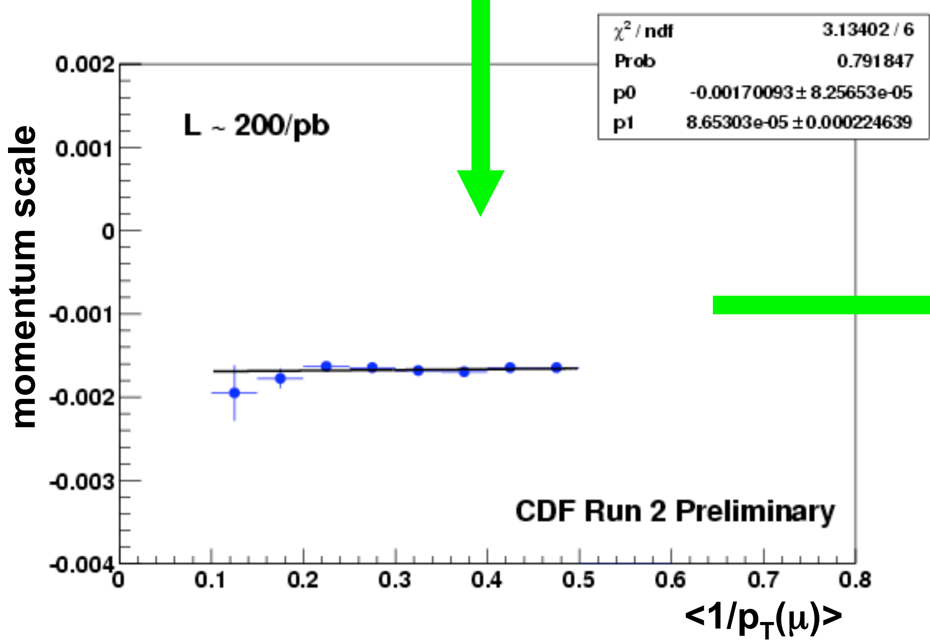
charged lepton asymmetry (η_l)

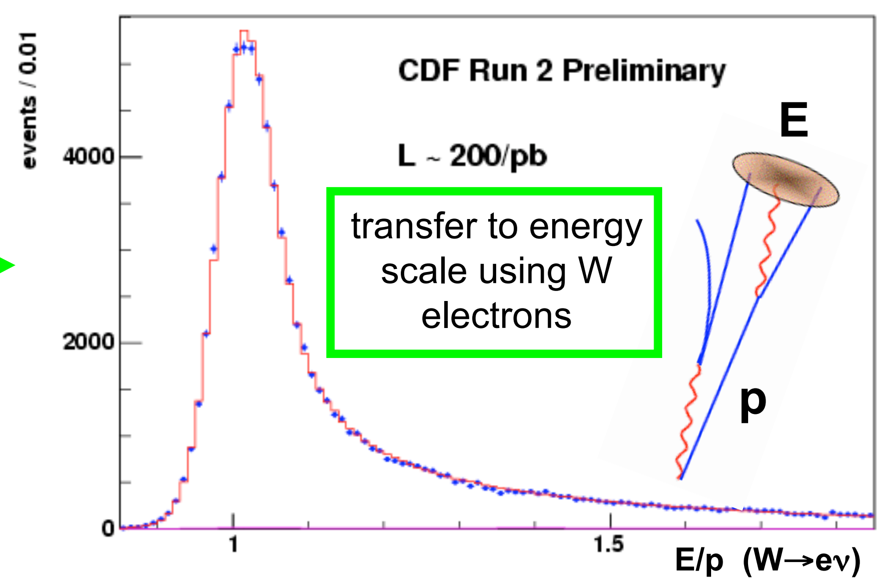
production charge asymmetry (y_W)

W Mass

- Requires exquisite (≡10 MeV) understanding of W production & detection.

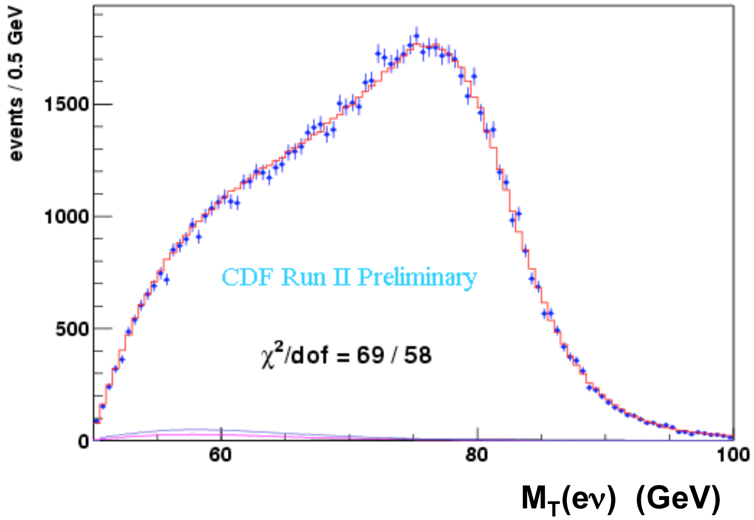


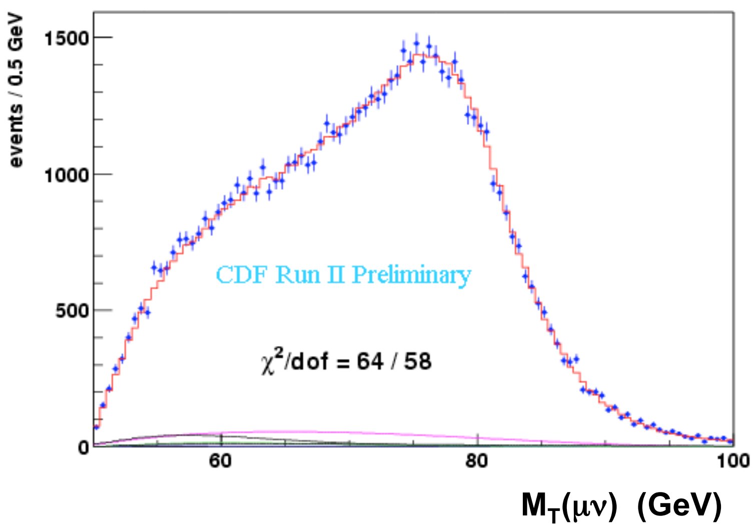




W Mass

CDF Blinded Mass Fits :





CDF Preliminary Systematic Uncertainty 200 pb^{-1}

Systematic [MeV]	Electrons (Run 1b)	Muons (Run 1b)	Common (Run 1b)
Lepton Energy Scale & Resolution	70 (80)	30 (87)	25
Recoil Scale & Resolution	50 (37)	50 (35)	50
Backgrounds	20 (5)	20 (25)	
Production & Decay Model	30 (30)	30 (30)	25 (16)
Statistics	45 (65)	50 (100)	
Total	105 (110)	85 (140)	60 (16)

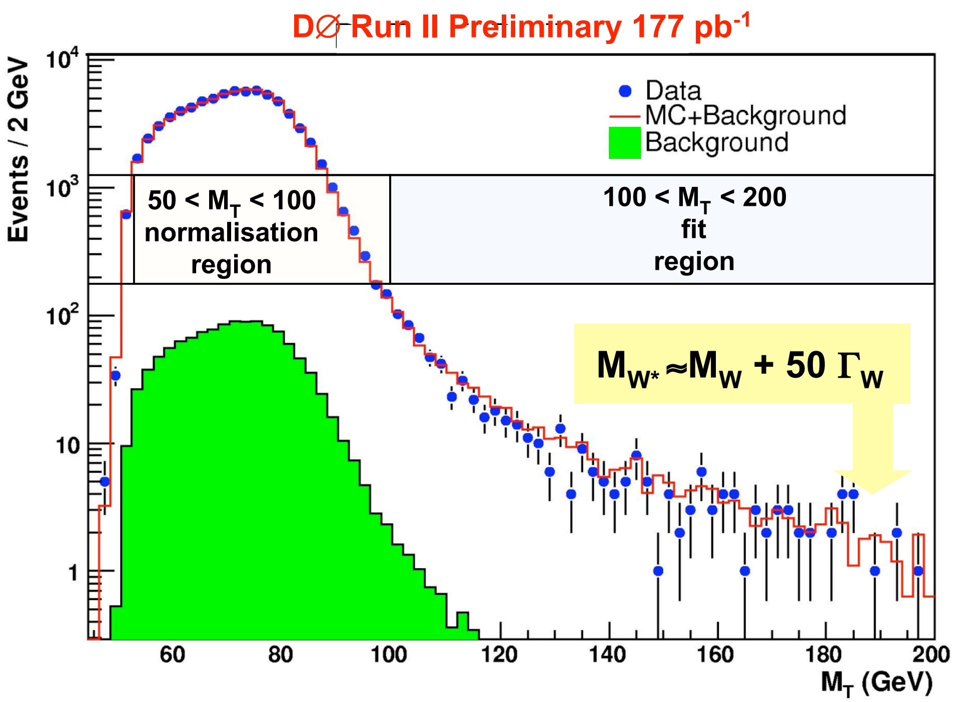
- Combined uncertainty **76 MeV** (cf Run 1 combined of 79 MeV)
- Currently finalising analysis details & <u>exhaustive</u> cross-checks.

Direct W Width

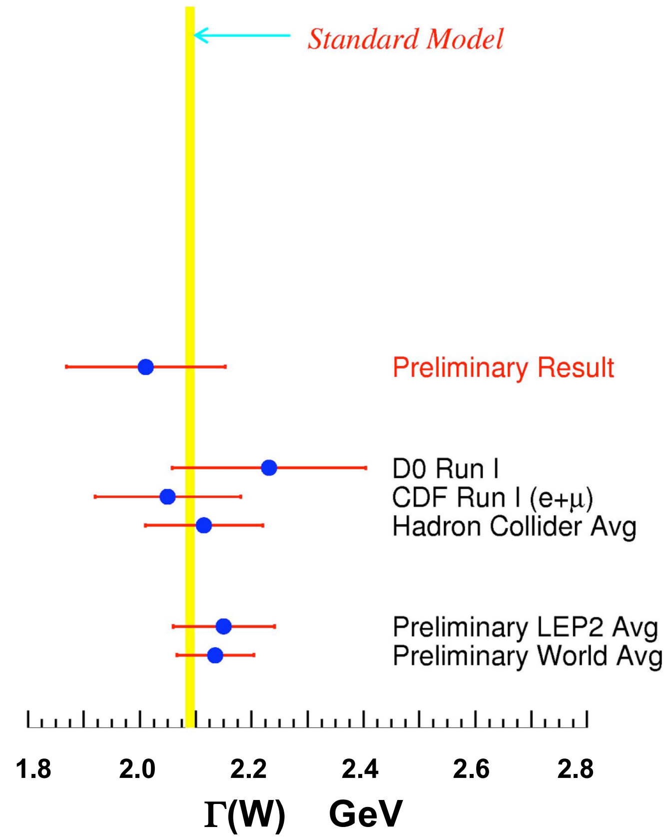
- Rather than measure the peak region, measure the tail of high mass W's.

Lineshape ≈ Breit-Wigner (M_W,Γ_W) ⊗ PDF's ⊗ Resolution

- BW has non-Gaussian tails → worry about non-Gaussian resolutions & backgrounds. Normalise to peak & fit to tail → partly a counting experiment.



$$\Gamma_W = 2.011 \pm 0.093\ (\mathrm{stat}) \pm 0.107\ (\mathrm{syst})\ \ \mathrm{GeV}$$

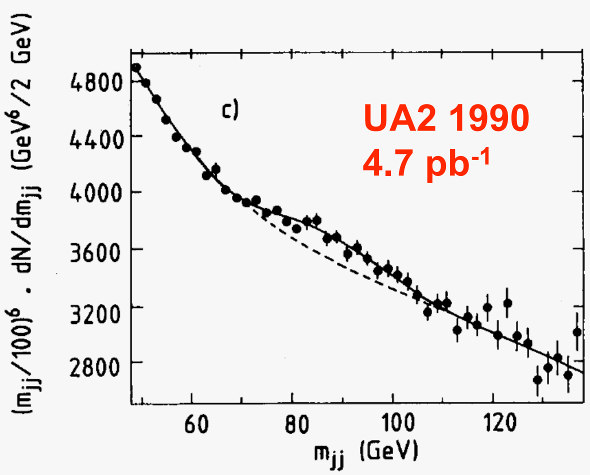


Conclusions & Perspectives

- The Tevatron experiments have completed a first round of W & Z measurements :
  - Inclusive cross-sections
  - Differential cross-sections
  - Asymmetries

- Results here based on 400 pb^{-1} of data
- Expect final Run II results to have 10-20 times this !

- A next generation of measurements are being designed for enhanced sensitivity to the underlying physics parameters (couplings, PDF's etc.)
- Avoiding hard systematics requires the development of new analysis techniques.
- These results are helping to :
  - Understand the environment for a precision W mass measurement.
  - Define Standard Candles that will be used at the LHC



- What will be possible at the LHC ?
- How will the LHC environment compare to the Tevatron ?

- **UA2 W/Z→jj**
- CDF/D0 cannot even trigger on these events

Backup

Challenges

Measurement	Observable	Experimental Challenges
• (Differential) Cross Sections	• (Differential) Event Yields	• Acceptances & Backgrounds
• W Mass	• Jacobean peak : $d\sigma/dM_T$ • Lepton p_T distribution	• Energy & Momentum Scales • Detector Response Modelling • Production Model
• W Width	• Width of $d\sigma/dM_T$ (direct) • Ratio of W/Z cross-sections (indirect)	• = W Mass (direct) • = Cross-Sections (indirect)
• Neutral Current Couplings & Electroweak Mixing Angle	• Forward-backward asymmetry	• Resolution & Smearing • Backgrounds
• Parton Distribution Function Constraints	• Rapidity distribution : $d\sigma/dy$ • Lepton angular charge asymmetry	• Forward lepton ID • Charge identification

V_{cs} From R

$$\Gamma_W = 3\Gamma_W^0 + 3\left(1 + \frac{\alpha_S}{\pi} + 1.409\left(\frac{\alpha_S}{\pi}\right)^2 - 12.77\left(\frac{\alpha_S}{\pi}\right)^3\right)\sum_{\text{no top}} \left|V_{qq'}\right|^2 \Gamma_W^0$$

$$V_{ud}, V_{us}, V_{ub}, V_{cd}, V_{cs}, V_{cb}$$

$$\left|V_{cs}\right| = 0.967 \pm 0.030$$

given:

$$\alpha_S = 0.120; \quad \Gamma_W^0 = 226.4\,MeV$$

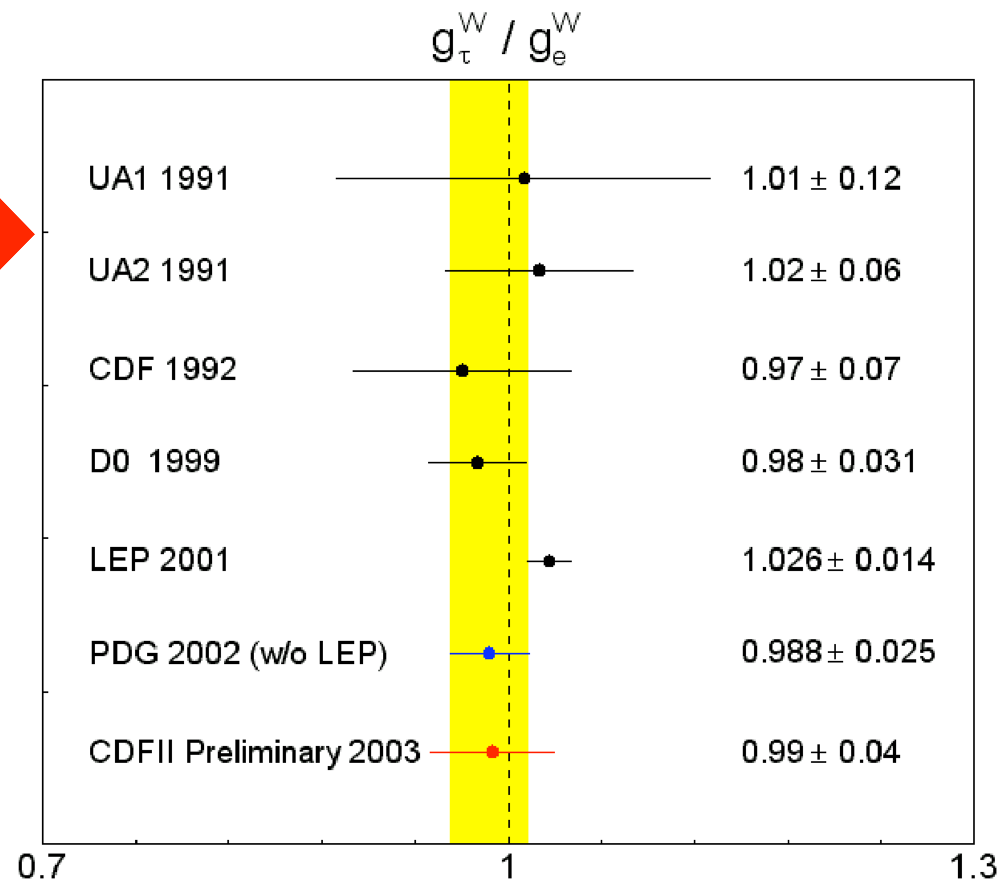
& world measurements of other CKM matrix elements.

Lepton Universality

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

- Directly from cross-section ratio.
- Similar precision to LEP

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



- More recent LEP results :

$$g_\mu / g_e = 0.997 \pm 0.010$$

$$g_\tau / g_e = 1.036 \pm 0.015$$

$$g_\tau / g_\mu = 1.039 \pm 0.014$$

Luminosity from W/Z Production

- Consider CDF W cross section measurement using 72 pb^{-1}.
- Current luminosity determination uses forward Cerenkov detector.
  Uncertainty is 6% :

$$\frac{\sigma(L)}{L} = 2.5\% \oplus 5.5\%$$

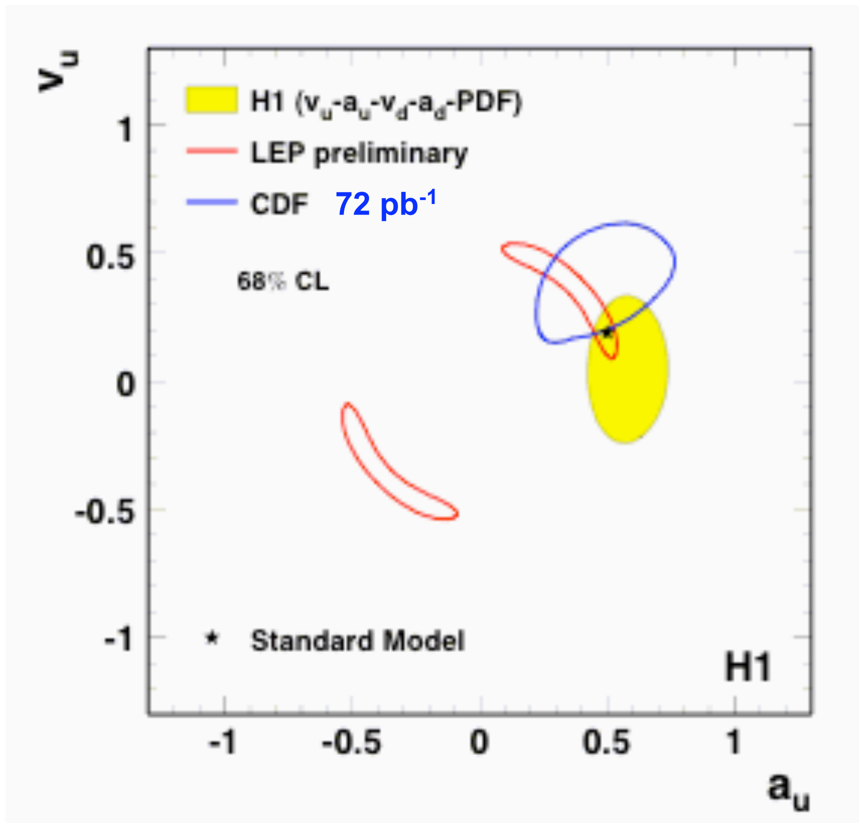
$\sigma_{TOT}(p\bar{p})$ ← 2.5%; σ_{EXP} (lumi detector acceptance) ← 5.5%

By comparison :

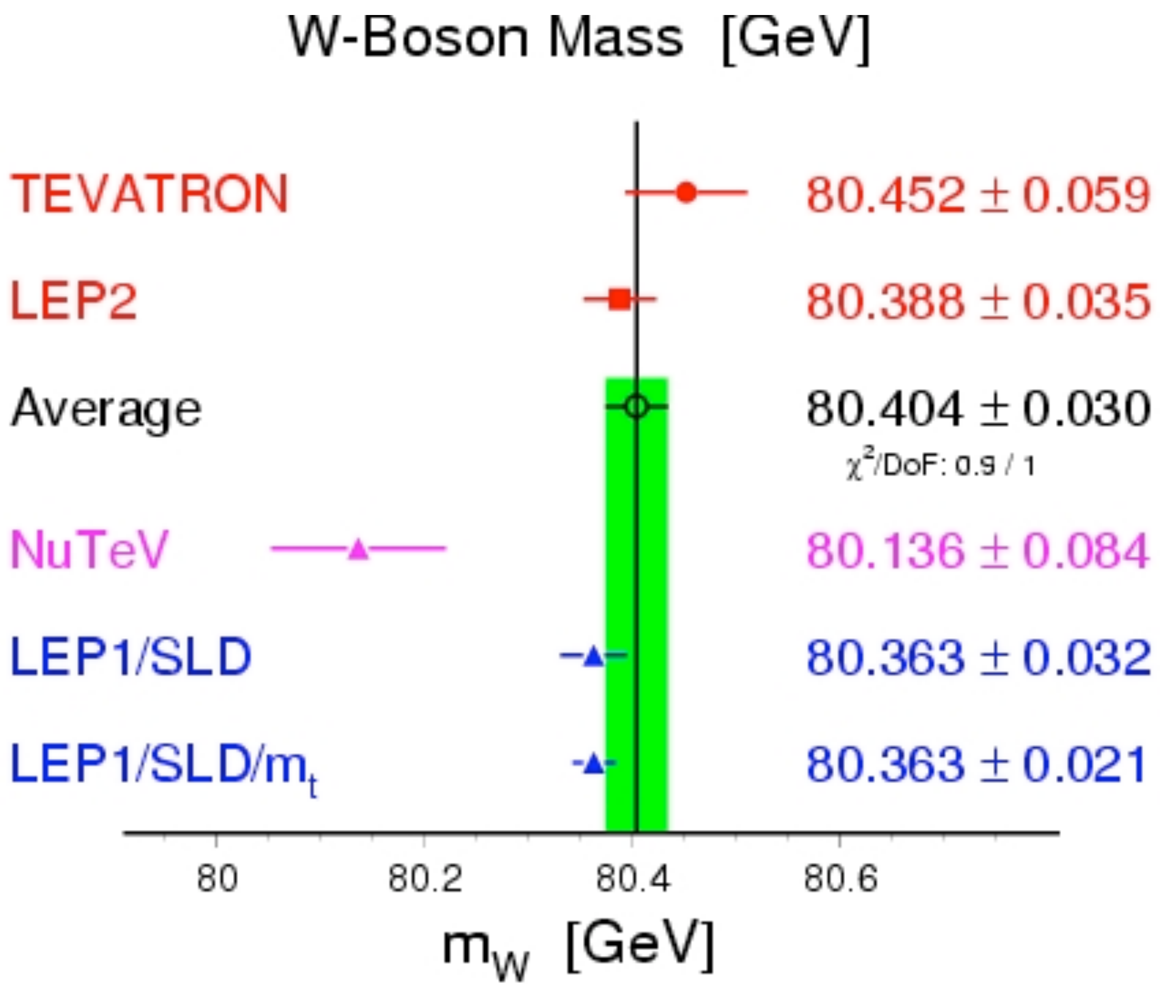
- Systematic uncertainty on W cross-section measurement : 2%
- NNLO theory uncertainty : 2-3%.

- Already a viable (integrated) luminosity method.
- Work on ongoing to identify optimal observables etc.
- Another possibility is to explicitly measure ratios : σ_X / σ_W

NC Couplings (Older)

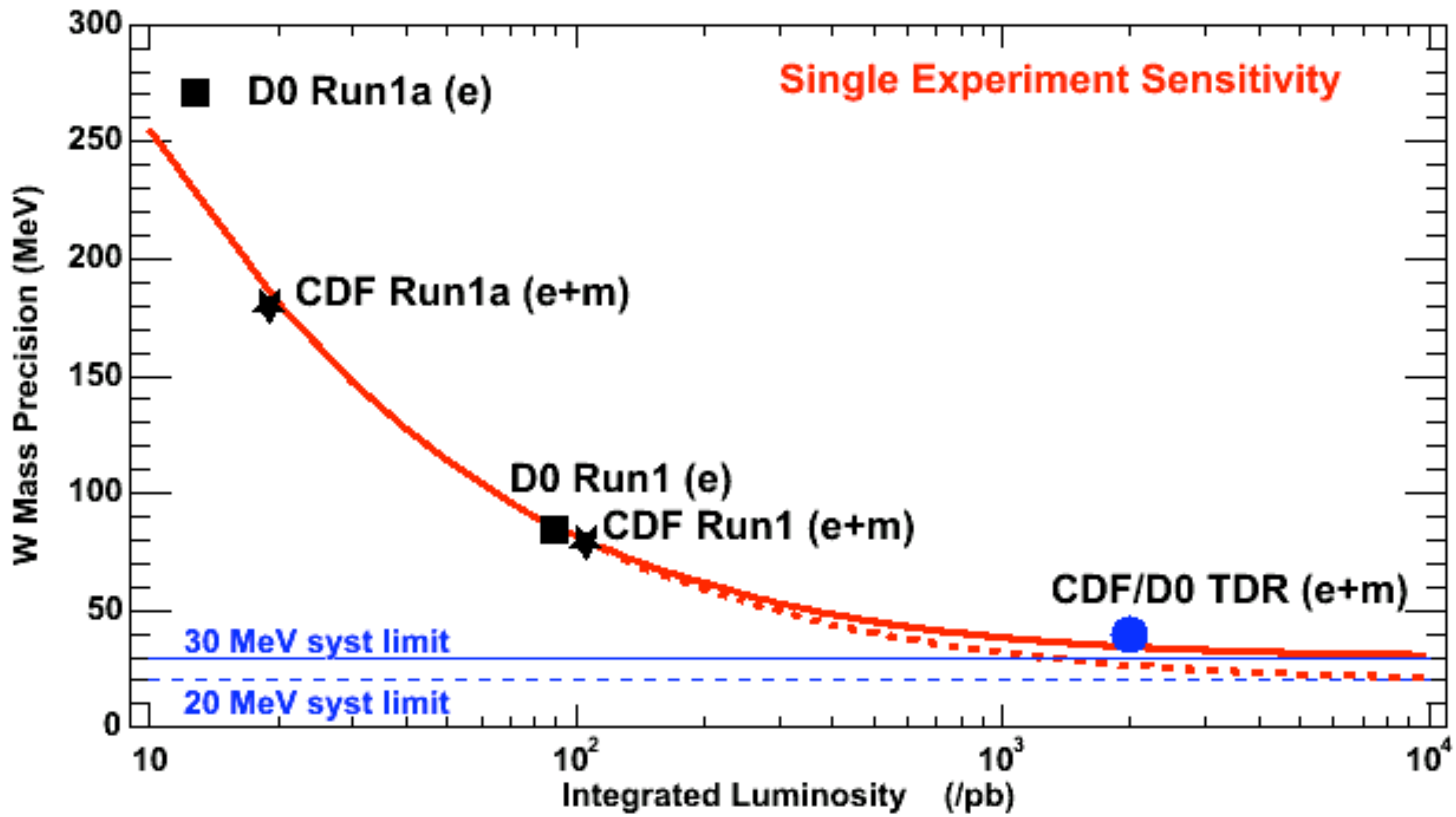


W Mass



W-Boson Mass [GeV]
TEVATRON
80.452 ± 0.059
LEP2
80.388 ± 0.035
Average
80.404 ± 0.030
χ²/DoF: 0.9 / 1
NuTeV
80.136 ± 0.084
LEP1/SLD
80.363 ± 0.032
LEP1/SLD/mt
80.363 ± 0.021
80
80.2
80.4
80.6
mW [GeV]

W Mass : Run 2 Projection



The DØ Detector

Central Fiber Tracker :

Tracking out to |η|<1.8 in 2 T B-field

Silicon Tracker :

Coverage out to |η|<3

Muon System :

Near hermetic coverage out to |η|<2

Momentum measurement in 1.8 T toroidal magnet

Calorimetry :

Covers the region out to |η|<4