W/Z properties at the Tevatron

Emily Nurse

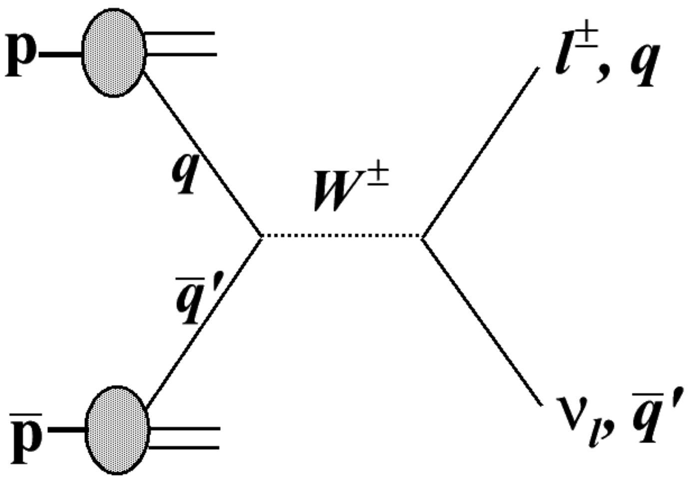
University College London

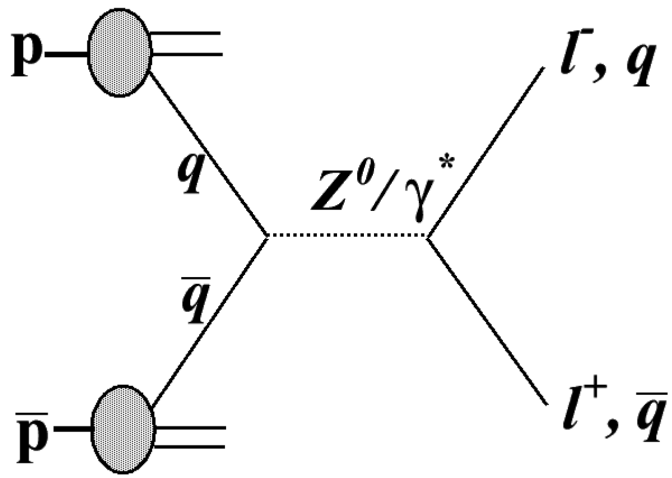
(for the DØ and CDF collaborations)

HCP, Galena, May 27th 2008

W/Z production at the Tevatron

Proton-antiproton collider : $\sqrt{s}$ = 1.96 TeV





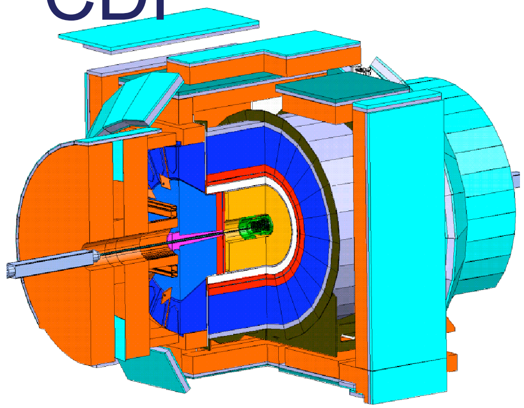
$\sigma(p\bar{p} \rightarrow W^{\pm} \rightarrow l\nu) \sim 2700$ pb

$\sigma(p\bar{p} \rightarrow Z^0 \rightarrow l^+l^-) \sim 250$ pb

- Use electron and muon decay channels to measure W/Z properties, due to their clean experimental signature.
- The large W/Z masses give their decay products large p_T.

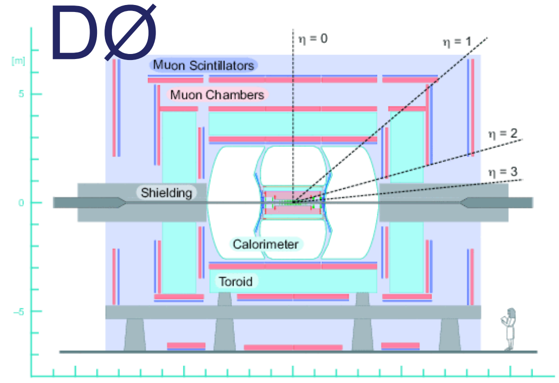
W/Z detection at DØ/CDF

CDF



$|\eta_{e(trk)}|<2.8$, $|\eta_{\mu}|<1$

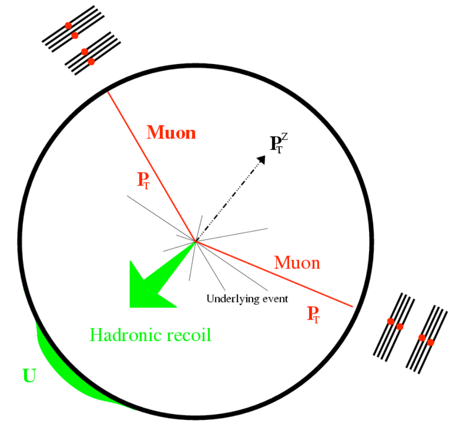
DØ



$|\eta_{e(trk)}|<3.2$, $|\eta_{\mu}|<2$

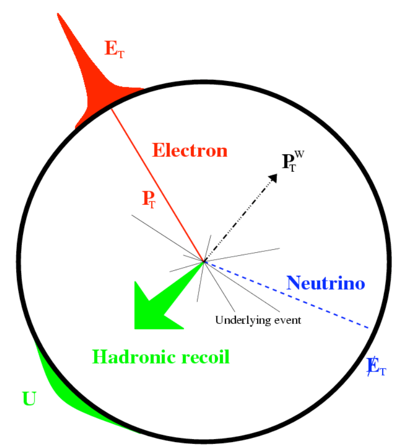
Z events:

- 2 high p_T charged leptons ($\mu^+\mu^-$ or e^+e^-).
- Both charged leptons are detected and their momenta measured.
- Muons: central tracker, muon detectors
- Electrons: central tracker, calorimeter



W events:

- 1 high p_T charged lepton, 1 high p_T neutrino ($\mu\nu$ or $e\nu$).
- Charged lepton is detected and momentum measured.
- Neutrino cannot be detected! p_T^{ν} is inferred by the "missing E_T (E_T^{miss})" in the detector.



W/Z analyses

W/Z events can be used to:

a) Constrain the QCD part of the production mechanism:
- PDF constraints
  - Forward cross-sections
  - W charge asymmetry
  - Z rapidity
- Higher order QCD constraints
  - Z p_T and W p_T
  - Z+jets and W+jets (see talk by Chris Neu)

b) Make precision measurements of EWK parameters:
- Z FB asymmetry ($\sin^2\theta_W^{eff}$)
- W width
- W mass (see talk by Ilija Bizjak)

Note: All results are fully corrected for detector acceptance and smearing effects.

(1) PDF constraints with W/Z events

Parton Distribution Functions (PDFs) describe the momentum distribution of partons in the (anti-)proton. They are obtained from parameterized fits to data (fits performed by CTEQ and MRST groups).
Well constrained PDFs are essential for many measurements and searches at hadron colliders.

Leading Order :

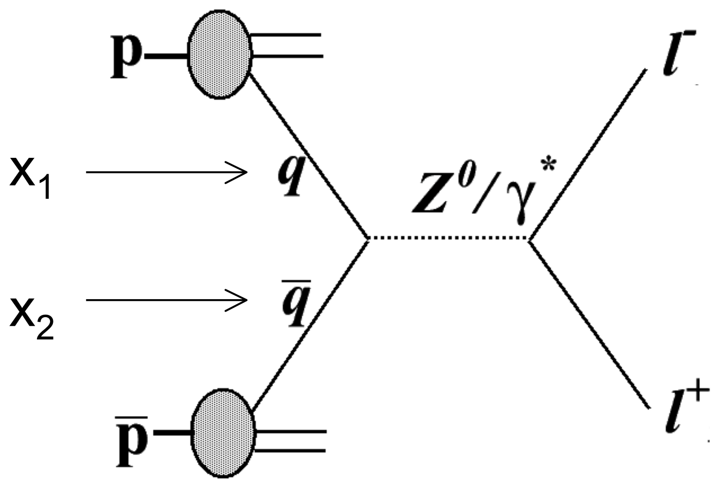
$$d\sigma_{p\bar{p}\to W/Z\to l\bar{l}} = \int \sum_{i,j=u,d,s,(c,b)} [f_i^q(x_p) f_j^{\bar{q}}(x_{\bar{p}}) + f_i^{\bar{q}}(x_p) f_j^q(x_{\bar{p}})] \times d\sigma_{q\bar{q}\to W/Z\to l\bar{l}} \; dx_p dx_{\bar{p}}$$

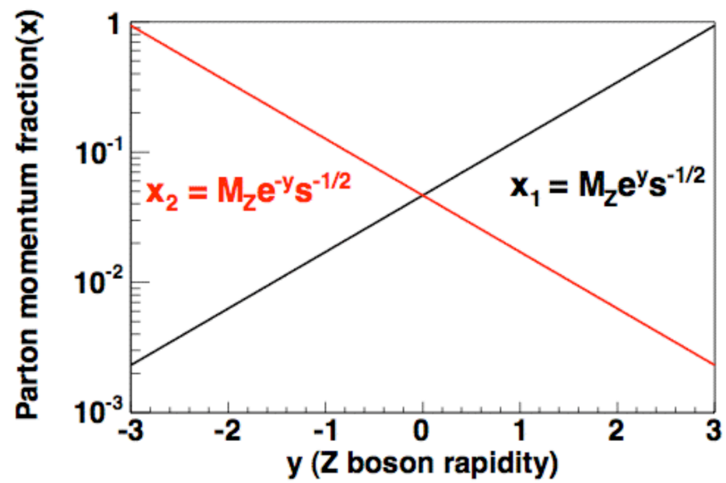
probability of quark i to carry proton momentum fraction x

PDF constraints from W/Z data:

1) Z rapidity
2) W charge asymmetry

Z rapidity



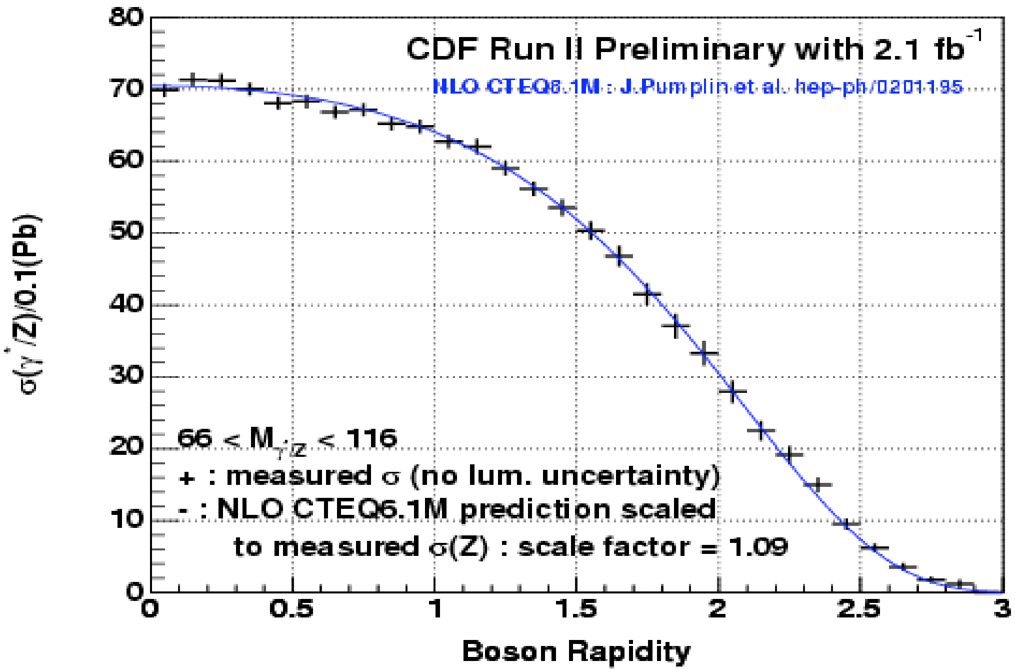


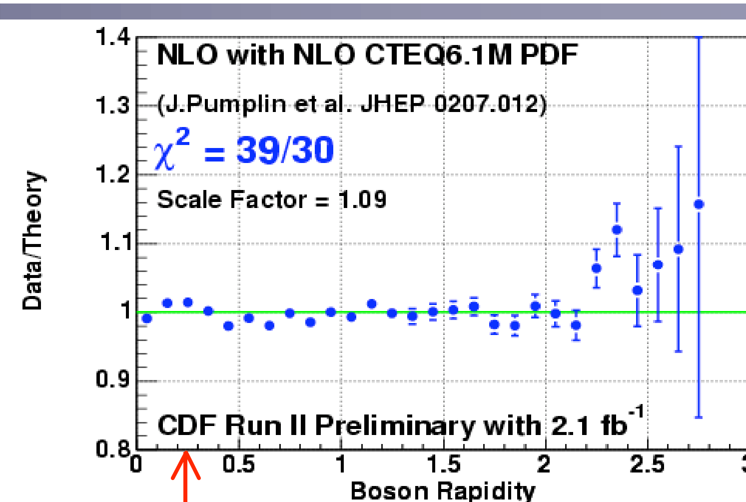
$$rapidity = y = \frac{1}{2} ln \frac{E + p_L}{E - p_L}$$

- Z rapidity (y_Z) is dependant on $x_{1,2}$
- A measurement of $d\sigma/dy$ constrains PDFs

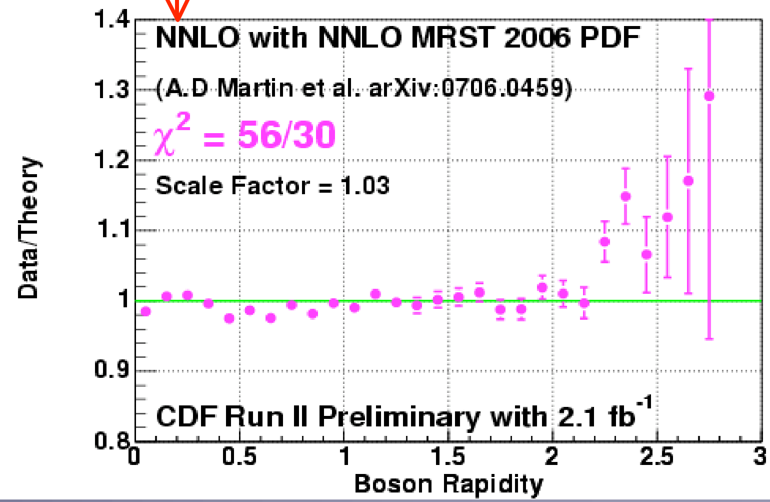
New 2.1 fb^{-1} CDF measurement (~170,000 $Z \rightarrow ee$ events with $|\eta_e|<2.8$)

Z rapidity

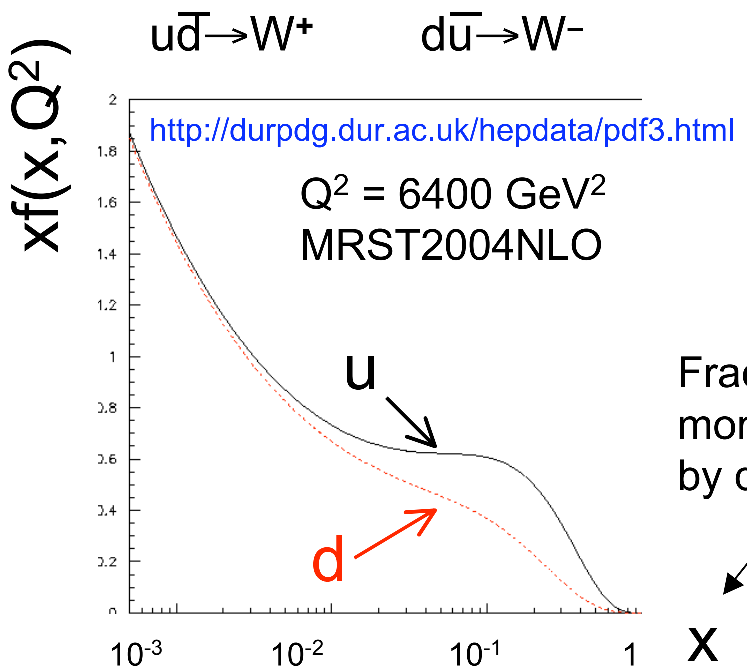




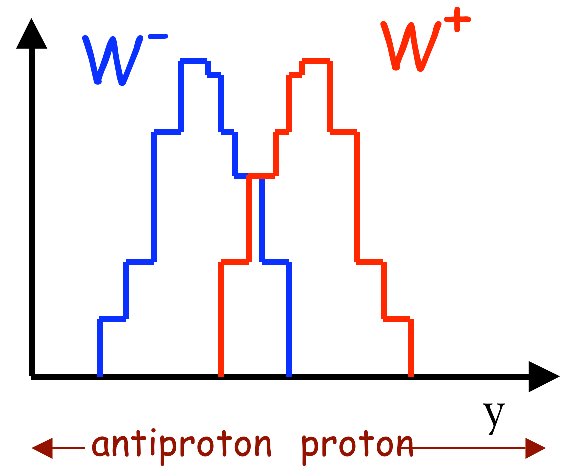
statistical errors only

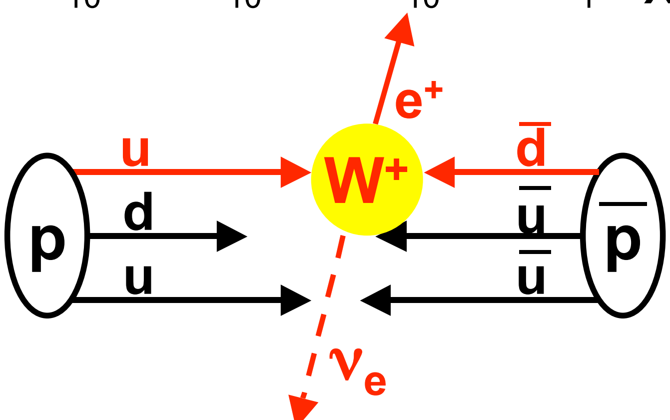


W charge asymmetry: introduction



Fraction of proton momentum carried by quark





$$A(y_W) = \frac{d\sigma_+/dy_W - d\sigma_-/dy_W}{d\sigma_+/dy_W + d\sigma_-/dy_W}$$

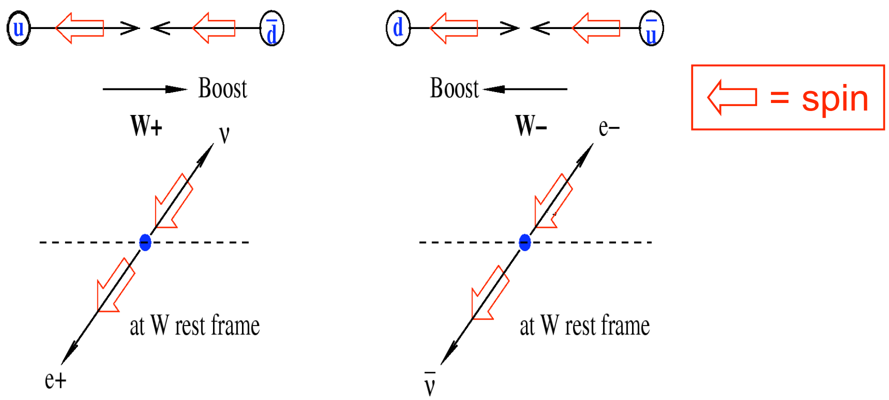
helps constrain $f_u(x)/f_d(x)$

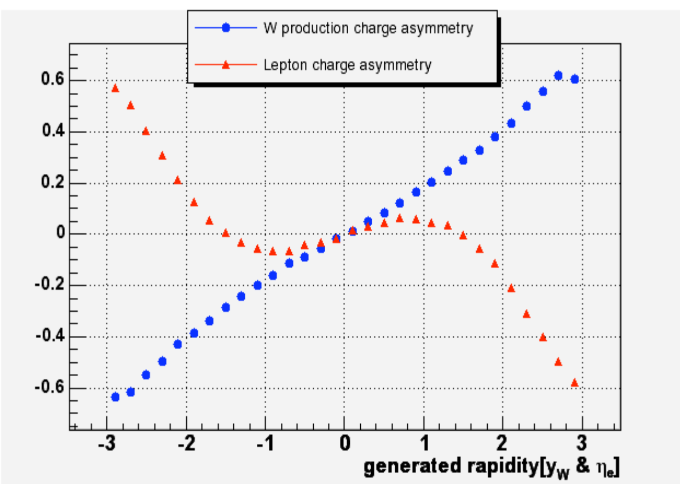
W charge asymmetry: from lepton charge asymmetry

- Since p_L^{ν} is not known the $W^{\pm}$ rapidity cannot be reconstructed ∴ traditionally the *lepton charge asymmetry* is measured: →

$$A(\eta_l) = \frac{d\sigma_+/d\eta_l - d\sigma_-/d\eta_l}{d\sigma_+/d\eta_l + d\sigma_-/d\eta_l}$$

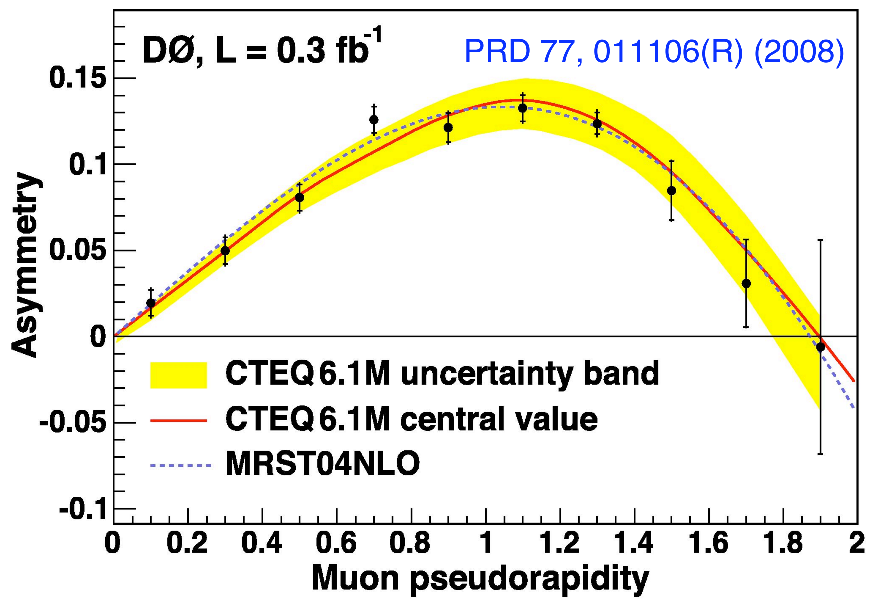
- *But* the V-A structure of the $W^{+(-)}$ decay favors a backward (forward) $l^{+(-)}$.





0.3 fb^{-1} DØ measurement

(~190,000 $W \rightarrow \mu\nu$ events with $|\eta_\mu|<2$):

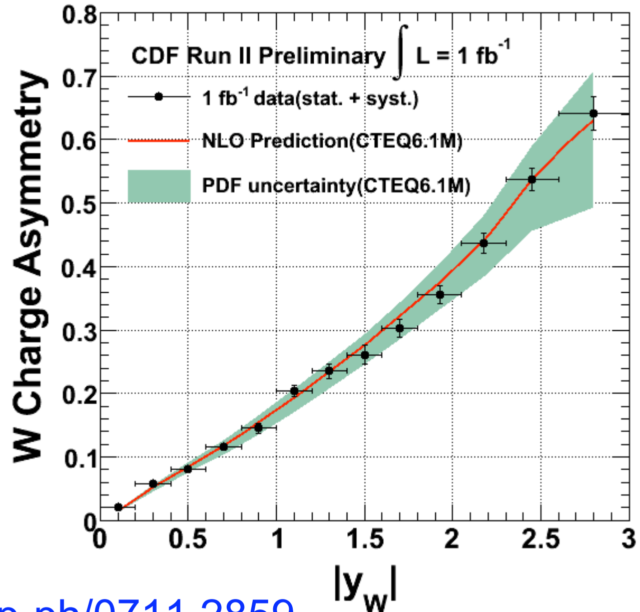


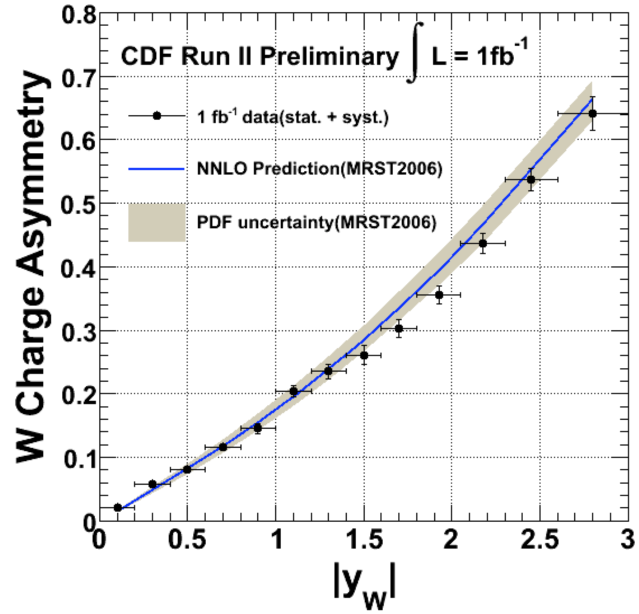
W charge asymmetry: direct measurement

It is also possible to extract $A(y_W)$ directly:

- p_L^{ν} determined by constraining M_W = 80.4 GeV$\rightarrow$ two possible y_W solutions.
- Each solution receives a weight probability according to:
  - V-A decay structure
  - W cross-section: $\sigma(y_W)$
- Process iterated since $\sigma(y_W)$ depends on asymmetry

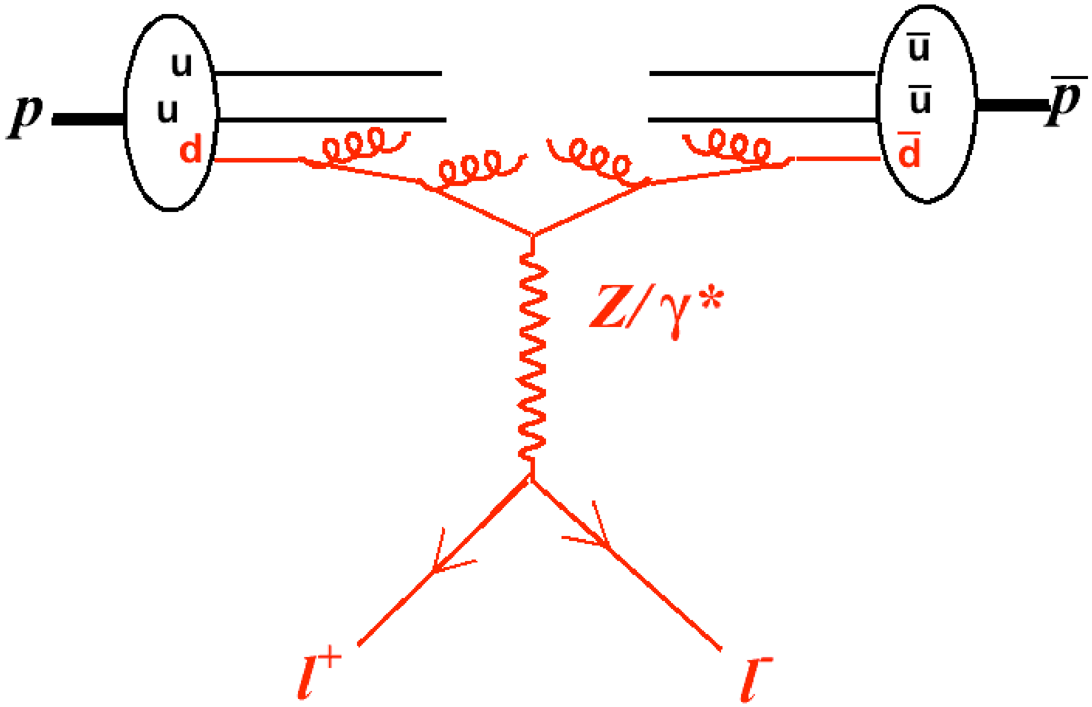
1 fb^{-1} CDF measurement (~715,000 $W\rightarrow e\nu$ events with $|\eta_e|<2.8$):





Analysis method: arXiv:hep-ph/0711.2859

(2) QCD constraints with Z events

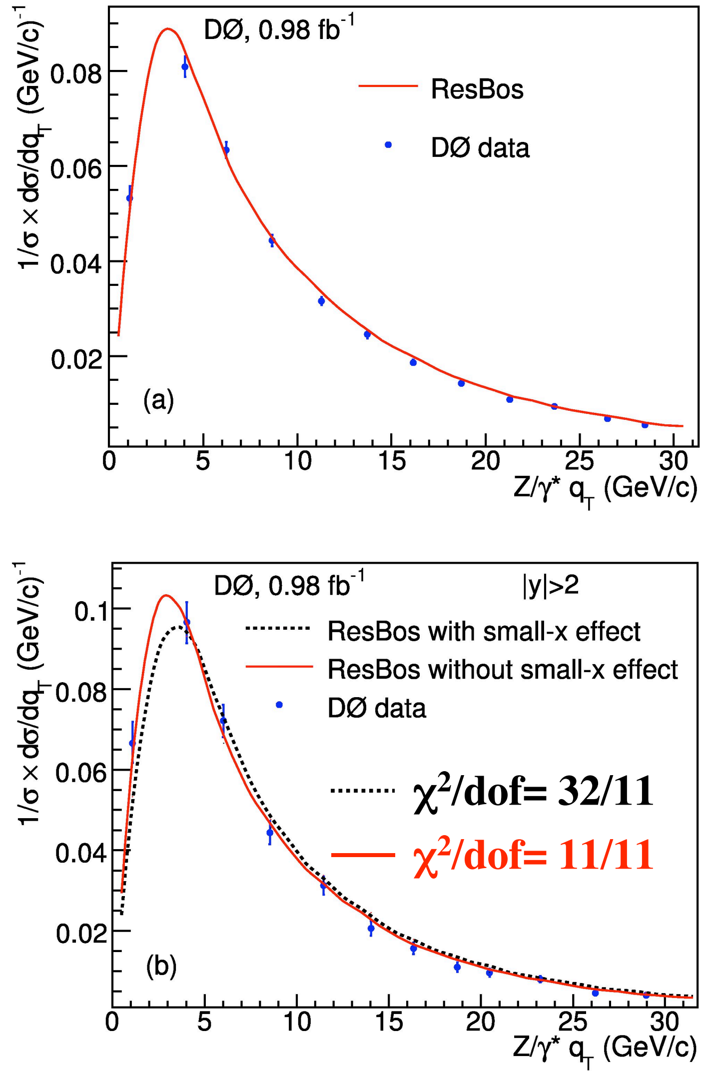


- Measuring the Z p_T distribution tests QCD predictions for initial state gluon radiation → tune and validate calculations and Monte Carlo generators.
- High Z p_T dominated by single (or double) hard gluon emission (pQCD reliable).
- Low Z p_T dominated by multiple soft emissions (resummation techniques/parton shower Monte Carlos with non-perturbative models required).

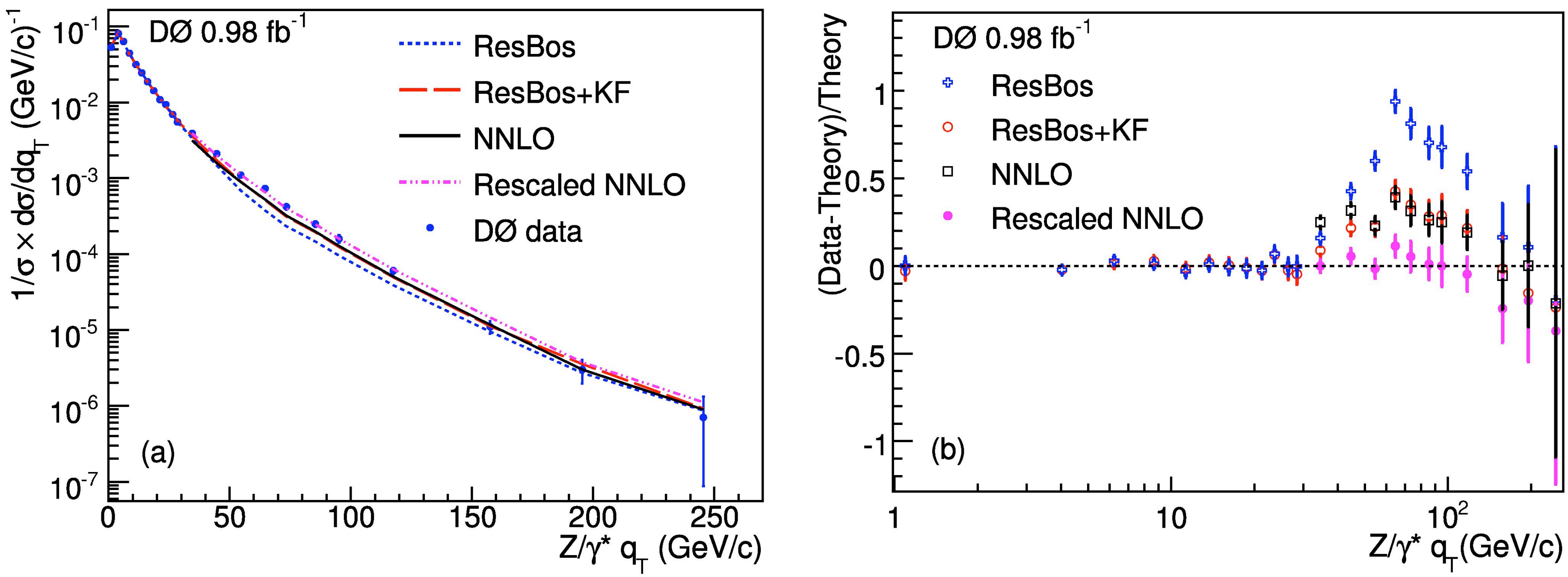
Z p_T

New 0.98 fb^{-1} DØ measurement
(~64,000 $Z \rightarrow ee$ events with $|\eta_e|<3.2$)

- Z p_T < 30 GeV region agrees well with ResBos (NLO QCD + CSS resummation with BNLY non-perturbative form factor).
- The Z p_T distribution is predicted to broaden at small-x (large $|y_Z|$) - important for the LHC!
- Broadening modeled with an additional “small-x” form factor.
- Data with $|y_Z|$ > 2 prefers ResBos *with-out* “small-x” form factor (NOTE: non-perturbative parameters have not been retuned with additional form factor!).



Z p_T

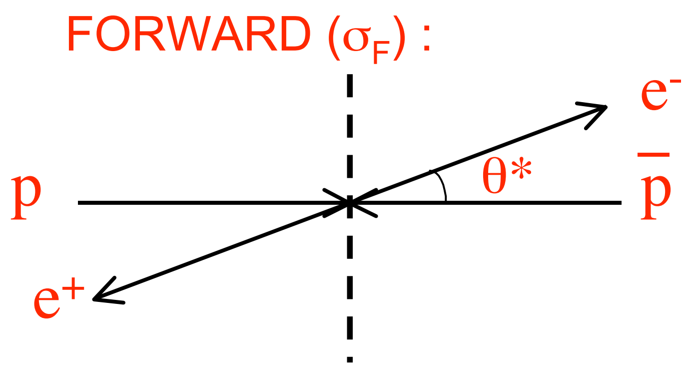


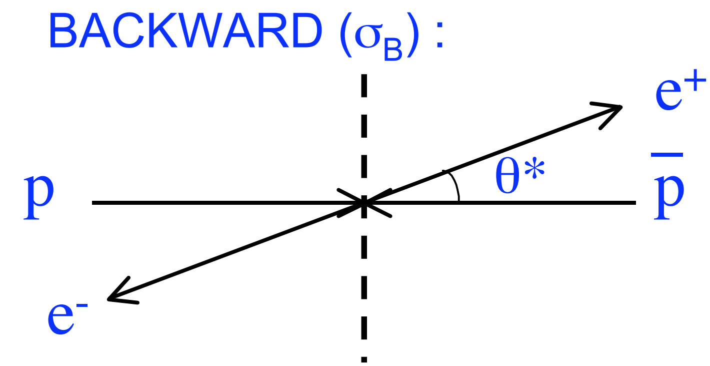
- In Z p_T > 30 GeV region a NNLO k-factor is required.
- Even then the theory is too low.
- The NNLO shape agrees if normalized at Z p_T = 30 GeV.

(3) Precision measurements

1) Extract $\sin^2\theta_w^{eff}$ from Z/γ^* forward-backward asymmetry
2) Direct measurement of W width

Z/γ^* forward-backward asymmetry





$\cos\theta^*$: in Collins-Soper frame (W rest frame)

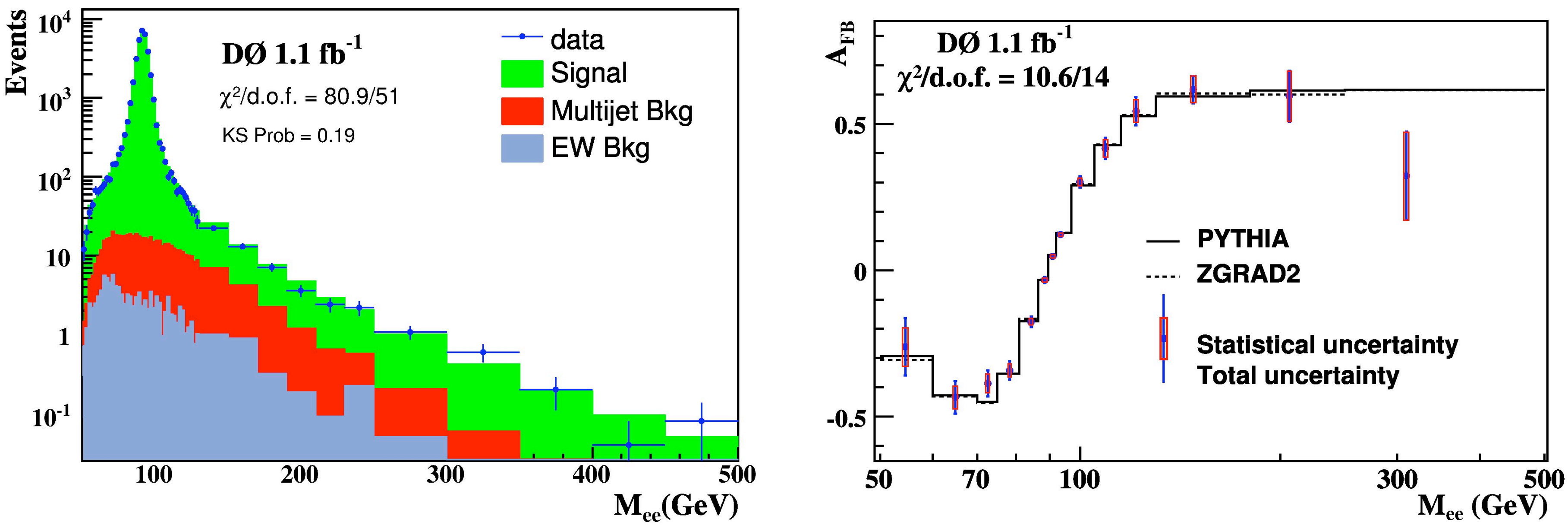
Z and Z/γ^* couplings to fermions have *vector* : $d\sigma/d\cos\theta^* \sim 1 + \cos^2\theta^*$ and *axial-vector* : $d\sigma/d\cos\theta^* \sim \cos\theta^*$ components.

$$\boxed{A_{FB} = (\sigma_F - \sigma_B)\ /\ (\sigma_F + \sigma_B)}$$

A_{FB} depends on M_{Z/γ^*}
A_{FB} sensitive to $\sin^2\theta_w^{eff}$

Z/γ* forward-backward asymmetry

New 1.1 fb^{-1} DØ measurement (~36,000 $Z \rightarrow ee$ events with $|\eta_e|<2.5$)



- Measurement consistent with the SM prediction (note: large M_{Z/γ^*} region sensitive to a new Z' boson).
- $\sin^2\theta_w^{eff}$ extracted from fit to A_{FB}:
  - 0.2327 ± 0.0019 (DØ 1.1 fb^{-1})   arXiv:hep-ph/0804.3220
  - 0.23152 ± 0.00014 (current world average)

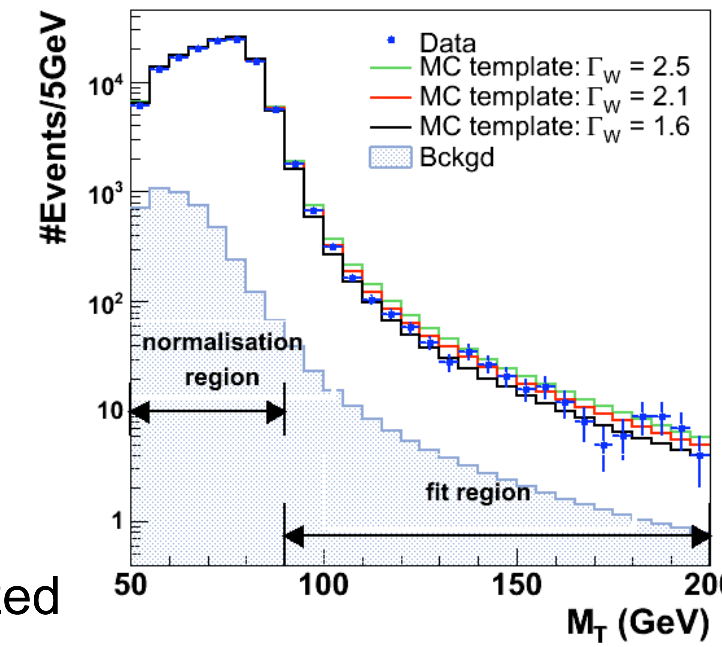
W width

- Measuring Γ_W tests the *very precise* Standard Model prediction:

  $\Gamma_W^{SM} = 2091 \pm 2$ MeV **[PDG:** J. Phys. G **33,** 1]

- Ideally Γ_W would be extracted from the decay products invariant mass.
- Since the neutrino isn't detected we construct the transverse mass:

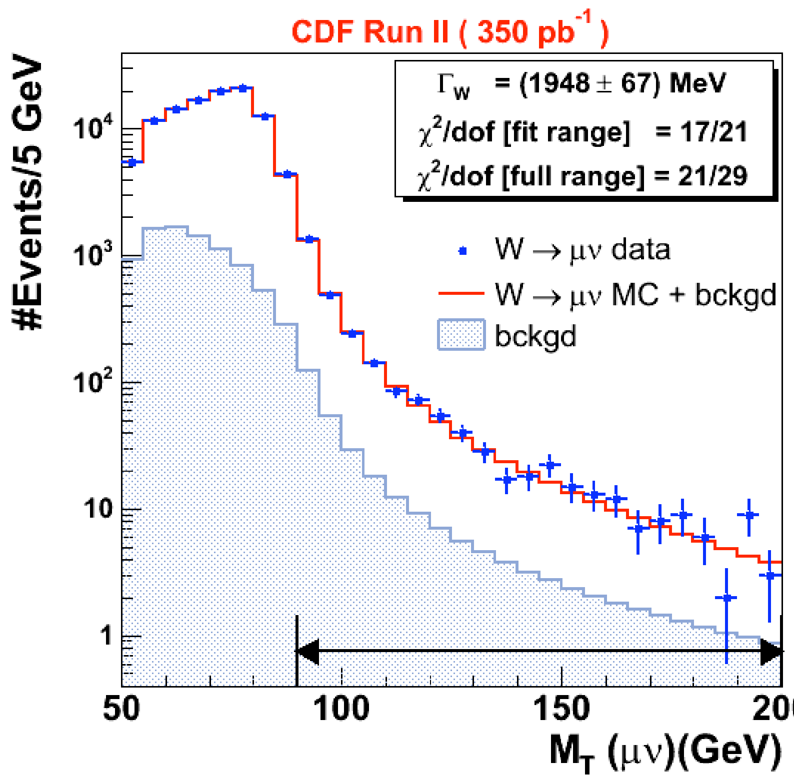
$$m_T = \sqrt{2 p_T^{\,l} p_T^{\,\nu} (1 - \cos\phi_{l\nu})}$$

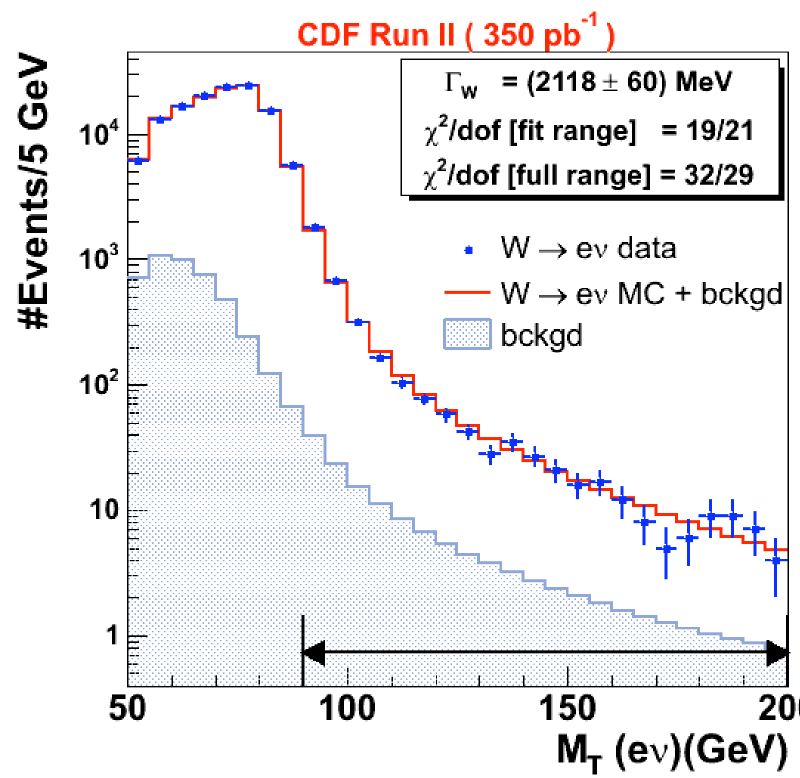


- Fit for Γ_W in the high m_T tail.
- Require a very accurate, fast parameterized detector simulation, tuned to Z and W data.

W width

350 pb^{-1} CDF measurement (~109,000 $W \to \mu\nu$ and ~127,000 $W \to e\nu$ events)





PRL 100, 071801

$\boxed{\Gamma_W = 2032 \pm 73 \text{ (stat + syst) MeV}}$

(Γ_W^{SM} = 2091 MeV)

World's most precise measurement! (reduces average uncertainty by 20%)

W Width: Indirect measurement

$$R_{exp} = \frac{\sigma \cdot BR\,(W \to l\nu)}{\sigma \cdot BR\,(Z \to ll)}$$

Precision LEP Measurements

SM Calculation

NNLO Calculation

$$R = \frac{\sigma_W}{\sigma_Z} \times \frac{\Gamma(W \to l\nu)}{\Gamma(W)} \times \frac{\Gamma(Z)}{\Gamma(Z \to ll)}$$

CDF Run II **INDIRECT width :**

2092 ± 42 MeV 72 pb^{-1}

J. Phys. G 34 2457-2544, PRL 94, 091803

CDF Run II **DIRECT width :**

2032 ± 73 MeV 350 pb^{-1}

PRL 100, 071801

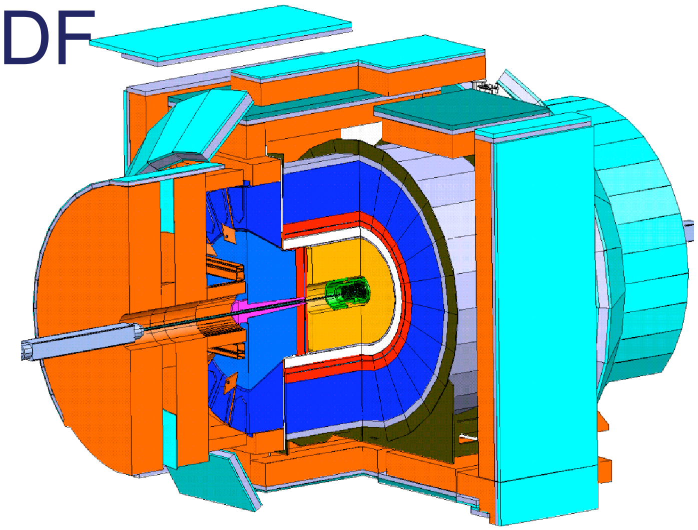
Summary

- Lots of interesting W/Z results from the Tevatron.
- New measurements providing constraints for PDF fits:
  - Z rapidity [CDF]
  - W charge asymmetry [CDF]
- New Z p_T measurement, testing inclusive and "small x" region [DØ].
- New $\sin^2\theta_w^{eff}$ measurement from A_{FB} [DØ].
- W width measurement (world's most precise measurement!) - consistent with SM and indirect measurement [CDF].

Back-up slides

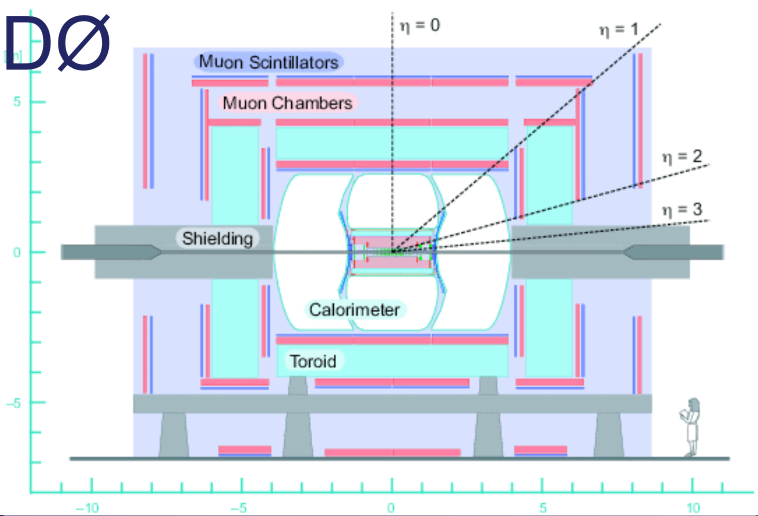
Backup : W/Z detection at DØ/CDF

CDF



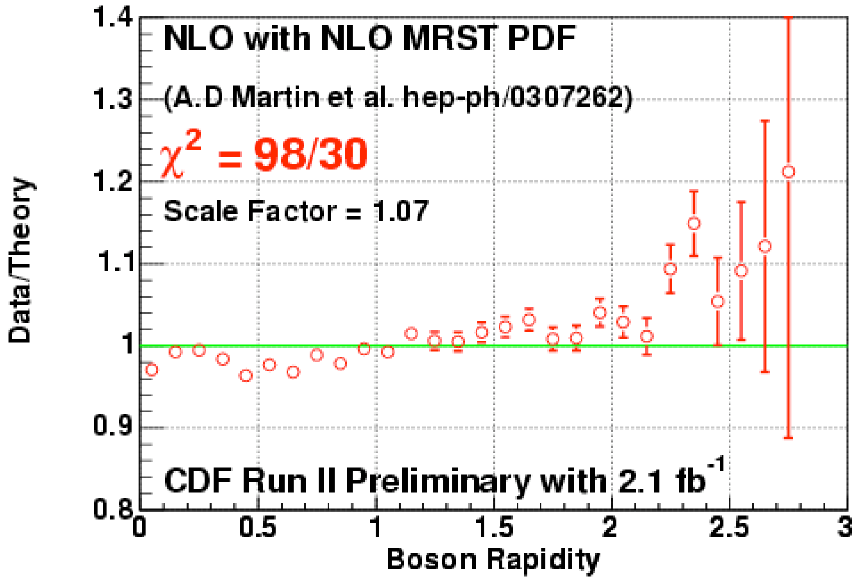
- Silicon detectors ($|\eta|<\sim2.8$)
- Central drift chambers ($|\eta|<\sim1.5$)
- Tracking resolution : $\sigma(p_T)/p_T \sim 0.05\% \times p_T$
- Segmented sampling calorimeters ($|\eta|<\sim3.6$)
  EM: $\sigma(E)/E \sim 13.5\% / \sqrt{E_T} \oplus 1.5\%$
- Muon detectors ($|\eta|<\sim1.0$)

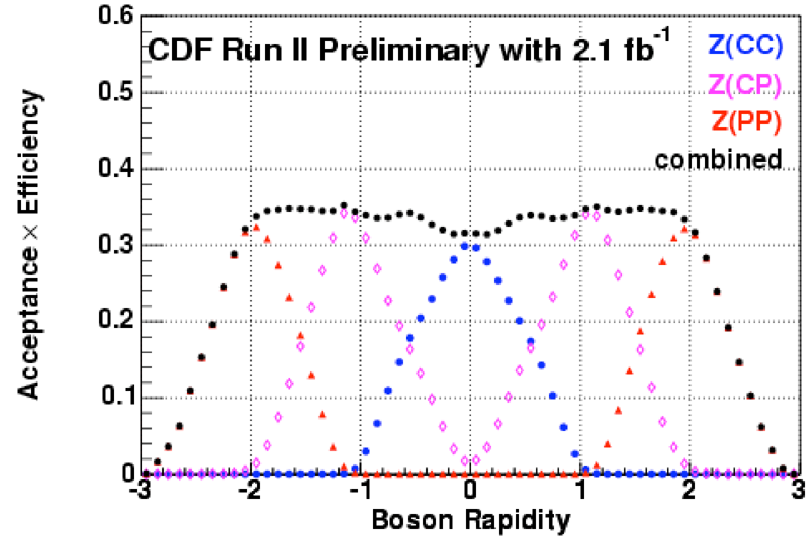
DØ

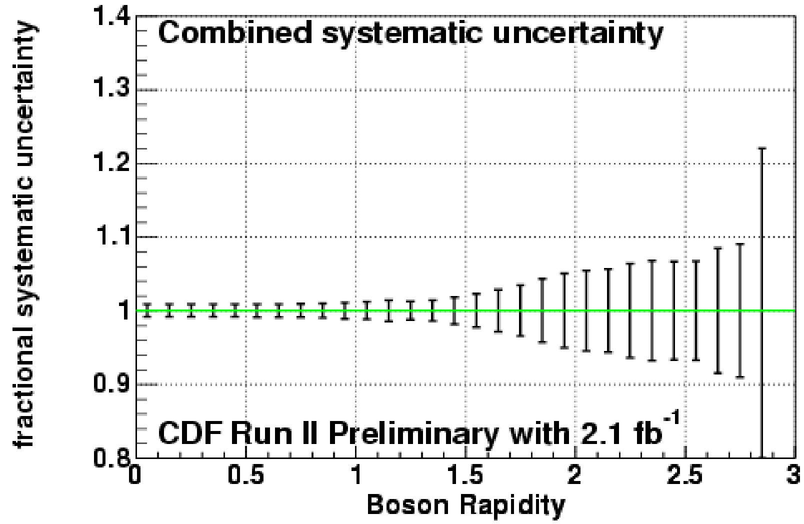


- Silicon detectors ($|\eta|<\sim3.2$)
- Central fiber tracker ($|\eta|<\sim2$)
- Tracking resolution : $\sigma(p_T)/p_T \sim 0.2\% \times p_T$
- Segmented sampling calorimeters ($|\eta|<\sim4.2$)
  EM: $\sigma(E)/E \sim 15\% / \sqrt{E} \oplus 4\%$
- Muon detectors ($|\eta|<\sim2.0$)

Backup: Z rapidity





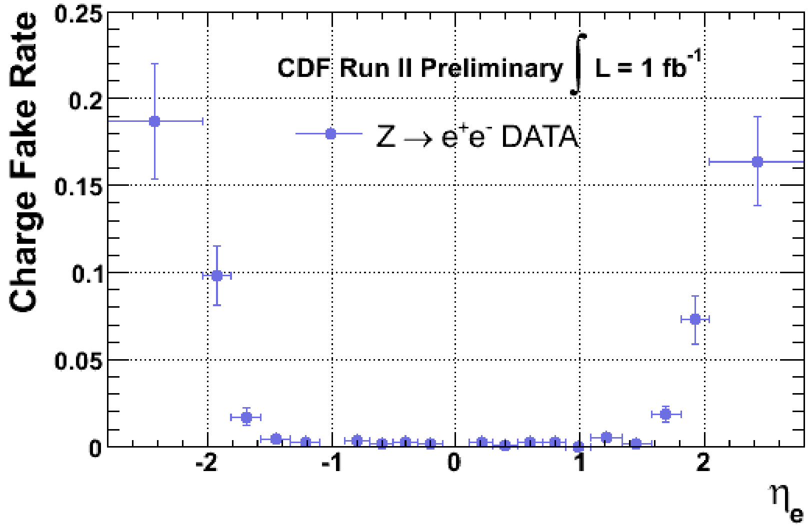


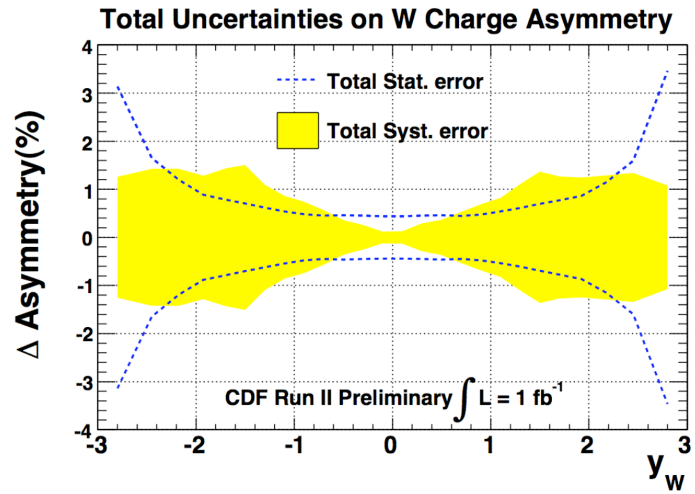
PDF constraint: ~0.75 < y < ~2

Backup: Z rapidity

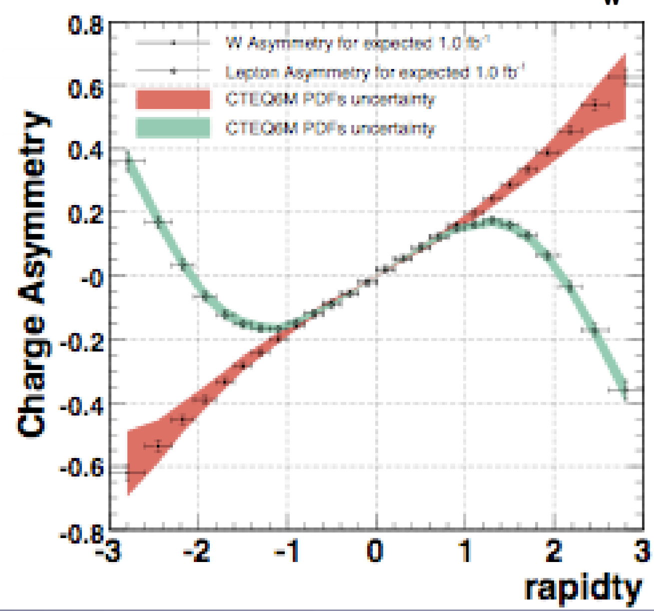
y	σ	*stat.* δ	*sys.* δ	material	BKG	tracking	ID	zvtx	calib
0.05	69.84	0.74	0.59	0.13	0.06	0.00	0.57	0.00	0.09
0.15	71.31	0.74	0.58	0.12	0.06	0.00	0.57	0.00	0.04
0.25	71.18	0.74	0.59	0.11	0.06	0.00	0.57	0.00	0.03
0.35	69.99	0.72	0.59	0.10	0.07	0.00	0.58	0.00	0.00
0.45	68.06	0.70	0.58	0.08	0.06	0.00	0.57	0.00	0.01
0.55	68.29	0.70	0.61	0.07	0.07	0.00	0.59	0.00	0.06
0.65	66.79	0.69	0.60	0.06	0.07	0.00	0.59	0.00	0.01
0.75	67.13	0.70	0.61	0.06	0.07	0.00	0.60	0.00	0.00
0.85	65.15	0.69	0.65	0.05	0.08	0.00	0.63	0.00	0.10
0.95	64.79	0.68	0.71	0.05	0.08	0.00	0.71	0.00	0.01
1.05	62.72	0.67	0.75	0.12	0.08	0.00	0.73	0.00	0.01
1.15	61.99	0.66	0.88	0.11	0.09	0.00	0.74	0.01	0.45
1.25	58.97	0.65	0.74	0.09	0.10	0.01	0.72	0.03	0.06
1.35	56.12	0.64	0.80	0.08	0.12	0.02	0.79	0.06	0.03
1.45	53.55	0.63	0.98	0.07	0.12	0.05	0.94	0.10	0.20
1.55	50.32	0.62	1.14	0.05	0.14	0.03	1.12	0.13	0.11
1.65	46.79	0.60	1.32	0.04	0.14	0.02	1.30	0.15	0.14
1.75	41.50	0.58	1.46	0.03	0.14	0.14	1.42	0.16	0.22
1.85	37.03	0.56	1.62	0.03	0.13	0.14	1.59	0.16	0.11
1.95	33.26	0.54	1.65	0.02	0.11	0.20	1.63	0.16	0.04
2.05	27.89	0.52	1.53	0.05	0.10	0.24	1.49	0.14	0.02
2.15	22.48	0.50	1.29	0.04	0.08	0.22	1.26	0.12	0.07
2.25	19.09	0.51	1.14	0.03	0.07	0.21	1.12	0.10	0.01
2.35	14.91	0.51	0.90	0.02	0.04	0.18	0.88	0.07	0.02
2.45	9.47	0.48	0.61	0.01	0.03	0.13	0.60	0.04	0.00
2.55	6.16	0.48	0.39	0.01	0.01	0.02	0.39	0.03	0.00
2.65	3.47	0.47	0.27	0.00	0.01	0.03	0.27	0.02	0.00
2.75	1.69	0.45	0.13	0.00	0.00	0.01	0.13	0.01	0.00
2.85	1.11	0.64	0.11	0.00	0.00	0.04	0.11	0.01	0.00
2.95	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	258.21	0.67	4.77	0.33	0.44	0.33	4.64	0.30	0.37

Backup: W charge asymmetry





	PDF	Et	Recoil	CFR	BKG	Trig	ID	Syst.	Stat.
$0<\lvert y_W\rvert<0.2$	0.00027	0.00014	0.0011	0.00017	0.00043	0.00029	0.00016	0.0013	0.0031
$0.2<\lvert y_W\rvert<0.4$	0.00077	0.00038	0.0022	0.00011	0.00091	0.0008	0.00067	0.0027	0.0032
$0.4<\lvert y_W\rvert<0.6$	0.0015	0.00055	0.0022	0.00018	0.0011	0.0013	0.0017	0.0037	0.0033
$0.6<\lvert y_W\rvert<0.8$	0.0022	0.00071	0.0034	0.00025	0.0015	0.0014	0.003	0.0055	0.0032
$0.8<\lvert y_W\rvert<1$	0.0024	0.00071	0.0042	0.00031	0.002	0.0011	0.0047	0.0072	0.0034
$1<\lvert y_W\rvert<1.2$	0.0027	0.00079	0.0033	0.0004	0.0018	0.00089	0.0069	0.0084	0.0038
$1.2<\lvert y_W\rvert<1.4$	0.0028	0.0015	0.0067	0.00047	0.0018	0.00059	0.0078	0.011	0.0043
$1.4<\lvert y_W\rvert<1.6$	0.0028	0.0014	0.011	0.00035	0.0014	0.0004	0.0085	0.014	0.005
$1.6<\lvert y_W\rvert<1.8$	0.0029	0.0026	0.0092	0.00077	0.0012	0.00028	0.0089	0.013	0.0055
$1.8<\lvert y_W\rvert<2$	0.0034	0.0031	0.0082	0.0022	0.0013	0.00056	0.008	0.013	0.0062
$2<\lvert y_W\rvert<2.3$	0.0042	0.0053	0.0059	0.0044	0.0021	0.0017	0.0085	0.013	0.0083
$2.3<\lvert y_W\rvert<2.6$	0.005	0.0062	0.004	0.0045	0.0019	0.0027	0.0086	0.014	0.011
$2.6<\lvert y_W\rvert<3$	0.0053	0.006	0.0043	0.0014	0.001	0.0028	0.0065	0.012	0.023



Backup: Z p_T

Collins-Soper-Sterman resummation formalism: Sums LL terms ($\ln^n(p_T/Q)$) + sub-logs

Non-perturbative form factor: Brock-Landry-Nadolsky-Yuan (BLNY):

$$\exp\,[-g_1 - g_2\ln(Q/2Q_0) - g_1 g_3 \ln(100x_1x_2)]b^2$$

$g_1 = 0.21 \pm 0.01$; $g_2 = 0.68^{+0.01}_{-0.02}$; $g_3 = -0.6^{+0.05}_{-0.04}$;

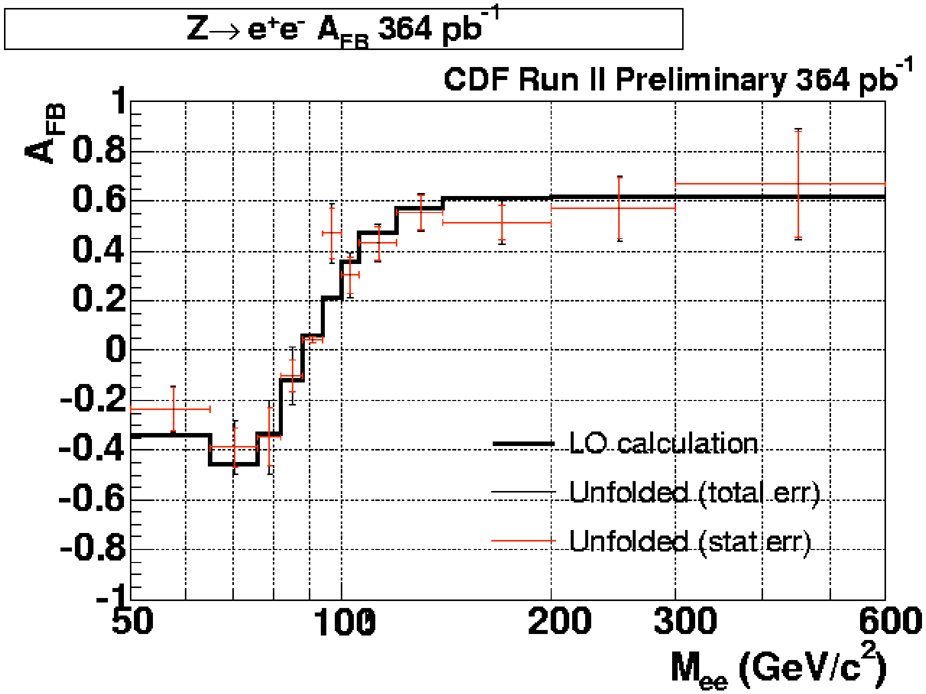
From fits to R209, E288, E605 fixed target Drell-Yan data (5< shat <18 GeV) + CDF Run I

D0 result: $g_2 = 0.77 \pm 0.06$

Small-x: Expect enhancements ln(1/x) in matrix elements above order α_s.

Modified form-factor agrees with p_T in DIS : $e + p \rightarrow \gamma^* \rightarrow e + \text{hadron(s)}$

Backup: Z/γ* forward-backward asymmetry



CDF (resonance search):
$m_{Z'} > 966$ GeV (SM couplings)
$m_{graviton} > 850$ GeV($k/M_{Pl} = 0.1$)

D0 : $\sin^2\theta_w^{eff} = 0.2327 \pm 0.0018$ (stat.) ± 0.0006 (syst.)

Primarily PDFs, and EM energy scale/resolution

NuTeV: $\sin^2\theta_w = 0.2277 \pm 0.0013$ (stat.) $\pm$ 0.0009 (syst.)

Backup: W width

	$\Delta\Gamma_W$ [MeV]		
	Electrons	Muons	Common
Lepton Scale	21	17	12
Lepton Resolution	31	26	-
Simulation	13	-	-
Recoil	54	49	-
Lepton ID	10	7	-
Backgrounds	32	33	-
$p_T(W)$	7	7	7
PDF	20	20	20
QED	10	6	6
W mass	9	9	9
Total systematic	79	71	27
Statistical	60	67	-
Total	99	98	27