W Boson Cross Sections and Decay Properties at the Tevatron

Ken Bloom
University of Michigan
for the CDF and D0 Collaborations

- Run II (2002)
    - $\sqrt{s} = 1.96$ TeV, 8-17 pb^{-1}
    - Results: $\sigma^{W,Z}$
- Run I (1992-1996)
    - $\sqrt{s} = 1.8$ TeV, 80-110 pb^{-1}
    - Results: W-decay angular distributions, $\sigma^{W,Z}(p_T)$

W,Z cross sections in Run II ($\sqrt{s} = 1.96$ TeV)

- Why care about boson production cross sections?
  - Test consistency of SM couplings
  - Constrain proton PDF's
  - Understand higher-order QCD contributions
- Why *really* care about boson production cross sections?
  - Requires good understanding of experiment: detection efficiencies, backgrounds, luminosity.
  - If experimental and theoretical uncertainties are small, can be used to *measure* luminosity, normalize other measurements.
  - A pathway to the physics goals of Run II: $t \rightarrow Wb$, $(W^*, Z^*) \rightarrow (W, Z)H$, precision electroweak measurements. . . .
- An early test of the capabilities of Tevatron experiments.
- Cross sections should increase by $\sim 10\%$ from 1.8 TeV – can it be seen?

Understanding cross sections

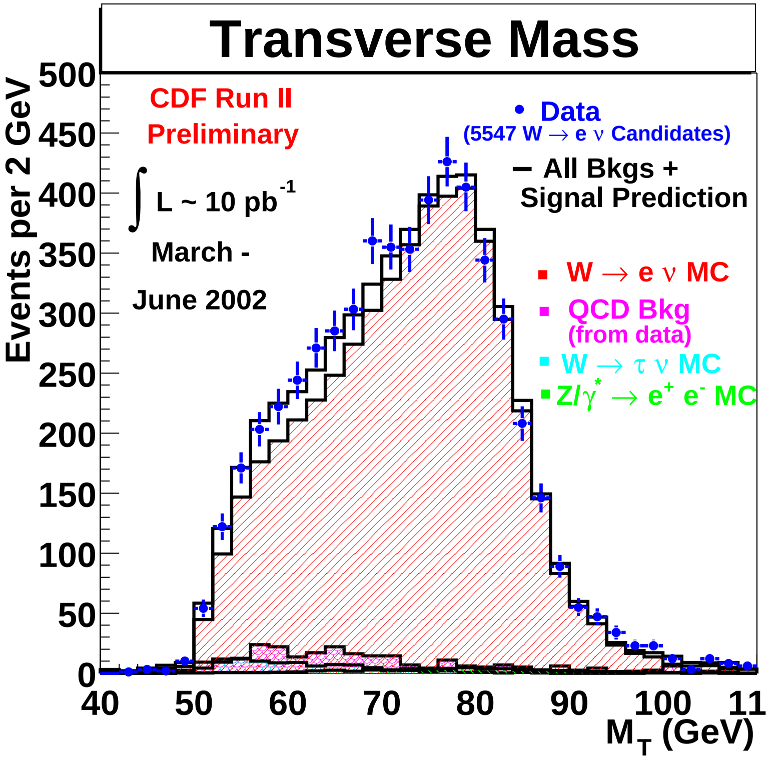
- Reminder: at the Tevatron,
  - W = one high-momentum lepton plus large missing energy (neutrino).
    - Cannot measure p_Z^ν, all measurements in transverse plane.
  - Z = two high-momentum opposite-sign leptons, $M_{\ell\ell} \sim 90$ GeV.

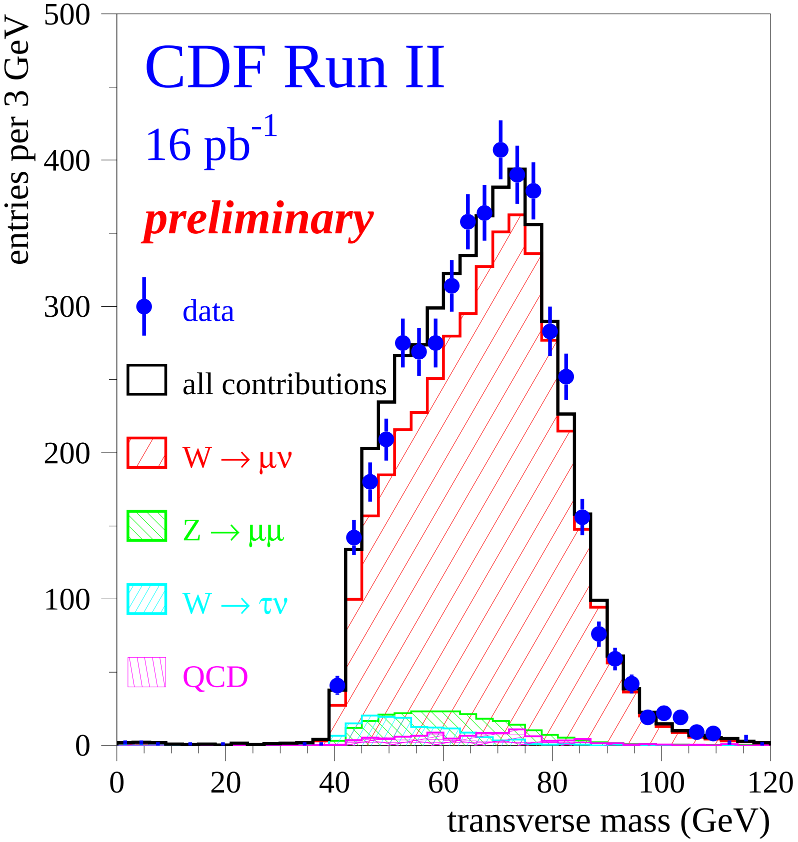
$$\sigma \cdot B = \frac{N_{obs} - N_{bg}}{A\epsilon \int \mathcal{L} dt}$$

- Elements of cross-section measurement:
  - N_{obs} = number of events observed
  - N_{bg} = estimated number of background events
  - A = kinematic and geometric acceptance
  - ϵ = total efficiency
  - $\int \mathcal{L} dt$ = integrated luminosity

Understanding samples – CDF $W \to e\nu$, $W \to \mu\nu$

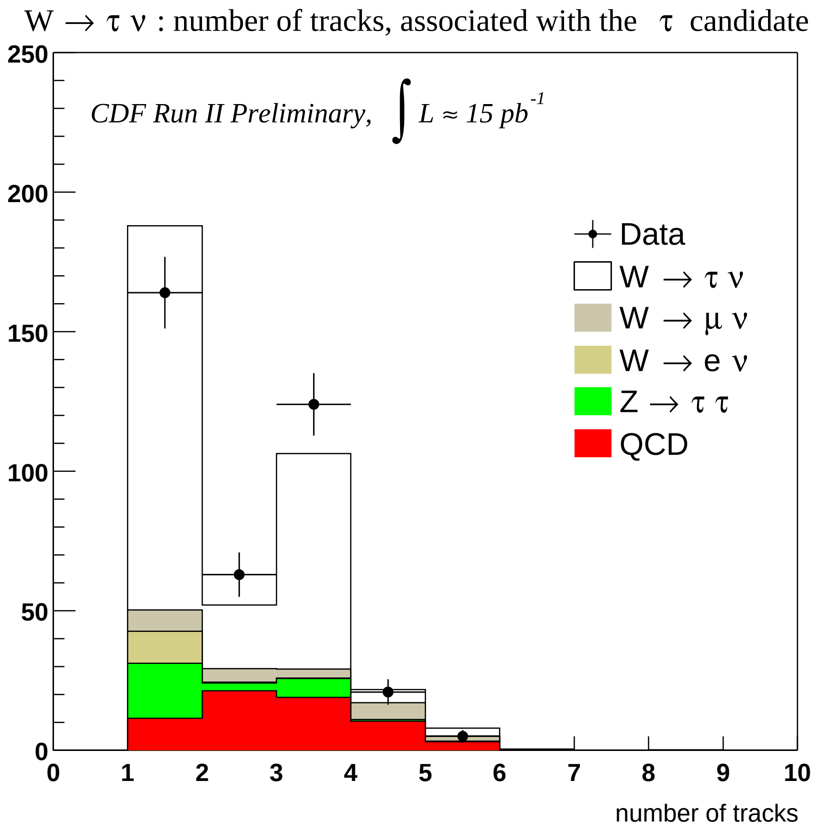
- Lepton plus $\not{E}_T$ sample accounted for by $W \to \ell\nu$, $Z \to \ell\ell$, $W \to \tau\nu$, QCD jets (fake leptons) and cosmic rays.





Understanding samples – CDF $W \to \tau\nu$

- Look at isolated, high-p_T monojet events with large missing energy.
- See charged-track multiplicity in jet consistent with τ decay, after accounting for backgrounds.



CDF $W \to e\nu$ and $W \to \mu\nu$ cross sections

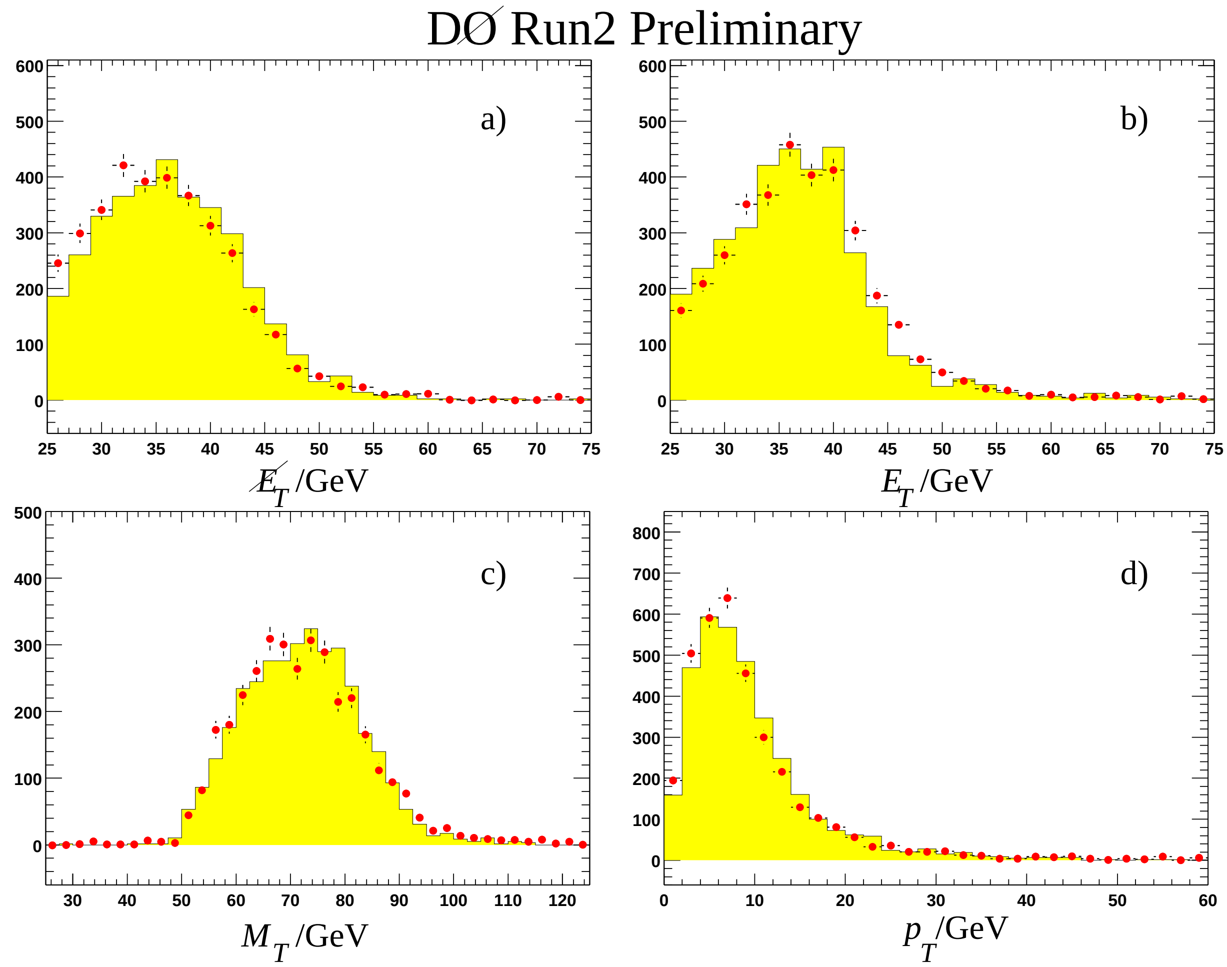
CDF Run II Preliminary

	$W \to e\nu$	$W \to \mu\nu$
N_{obs}	5547	4561
N_{bg}	409 ± 85	569 ± 63
A (%)	23.4 ± 0.9	14.2 ± 0.4
ϵ (%)	81.1 ± 1.8	63.2 ± 3.8
$\int \mathcal{L} dt$ (pb^{-1})	10.4 ± 1.0	16.5 ± 1.6
$\sigma \cdot B$ (nb)	$2.60 \pm 0.03_{stat}$ $\pm 0.13_{sys} \pm 0.26_{lum}$	$2.70 \pm 0.04_{stat}$ $\pm 0.19_{sys} \pm 0.27_{lum}$

- 10% luminosity uncertainty is an upper limit!
- Best CDF Run I result: $\sigma \cdot B(W \to e\nu) = 2.49 \pm 0.12$ nb.
- Theory predictions at NNLO (W. Stirling):
  - $\sigma \cdot B = 2.50$ nb @ $\sqrt{s} = 1.8$ TeV $\to$ 2.73 nb @ $\sqrt{s} = 1.96$ TeV
- Measurements consistent with expected rise in cross section.

Understanding samples – D0 W $\rightarrow e\nu$

- D0 electron plus $\not\!\!E_T$ sample accounted for by same processes.



D0 W $\rightarrow e\nu$ and cross section

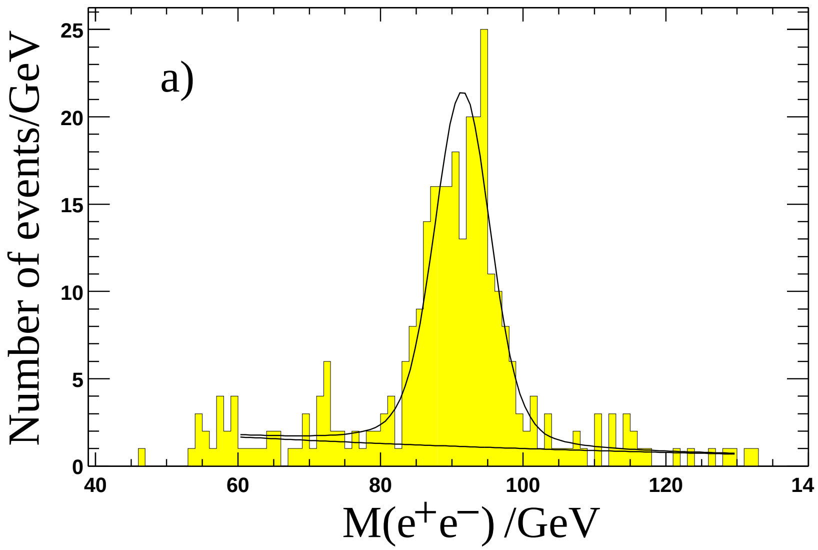
D0 Run II Preliminary

	W $\rightarrow e\nu$
N_{obs}	9205
N_{bg}	5782 $\pm$ 357
A (%)	19.6 $\pm$ 0.9
ϵ (%)	86.5 $\pm$ 3.6
$\int \mathcal{L} dt$ (pb^{-1})	7.5 $\pm$ 0.8
$\sigma \cdot B$ (nb)	$2.67 \pm 0.06_{stat}$ $\pm 0.33_{sys} \pm 0.27_{lum}$

- Systematic uncertainty dominated by background estimates
- Best D0 Run 1 result: $\sigma \cdot B(W \rightarrow e\nu) = 2.36 \pm 0.15$ nb
- Measurement consistent with expected rise in cross section.

σ^Z and cross-section ratio – D0 electrons

D0 Run II preliminary



- Z cross section: $\sigma \cdot B(Z \to ee) = 266 \pm 20_{\text{stat}} \pm 20_{\text{sys}} \pm 27_{\text{lum}}$ pb
- Also measure $R = \sigma^W/\sigma^Z$: $R_e = 10.0 \pm 0.8_{\text{stat}} \pm 1.3_{\text{sys}}$
- Theory gives R = 10.91; D0 Run I result R = 10.90 ± 0.52.
- With

$$R_e = \frac{\sigma(p\bar{p} \to W)}{\sigma(p\bar{p} \to Z)} \frac{\Gamma(W \to e\nu)}{\Gamma(Z \to ee)} \frac{\Gamma(Z)}{\Gamma(W)}.$$

extract

$$\Gamma(W) = 2.26 \pm 0.18_{\text{stat}} \pm 0.29_{\text{sys}} \pm 0.04_{\text{ext}}\ \text{GeV},$$

current world average 2.114 ± 0.043 GeV.

Cross-section ratio – CDF muons

- Measure ratio in muon channel:

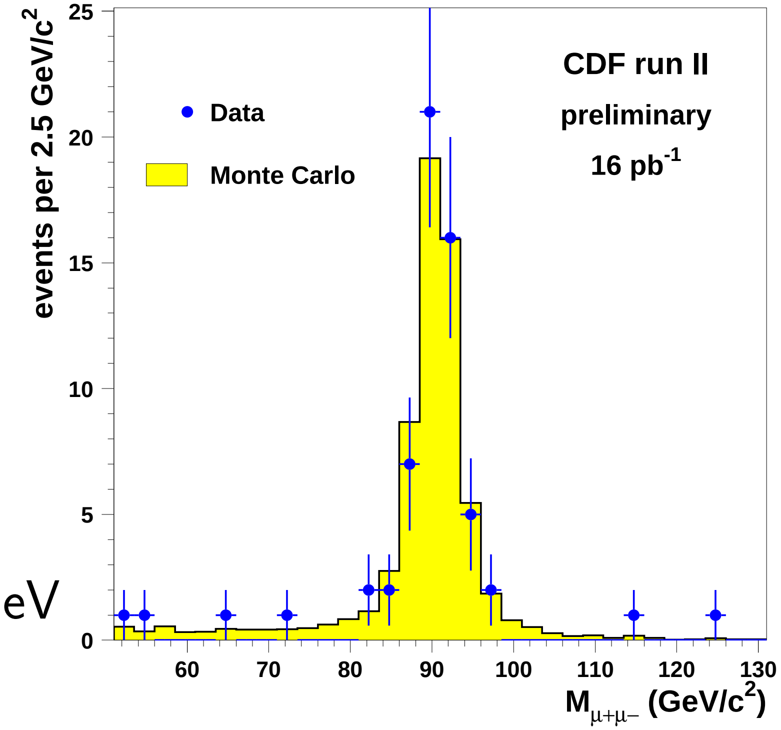
$$R_\mu = 13.66 \pm 1.94^{+1.08}_{-1.16}$$

(CDF Run II preliminary)

- CDF Run I result:
  $R_e = 10.90 \pm 0.32 \pm 0.29$.

- Extract

$$\Gamma(W) = 1.67 \pm 0.24^{+0.14}_{-0.13} \pm 0.01 \text{ GeV}$$

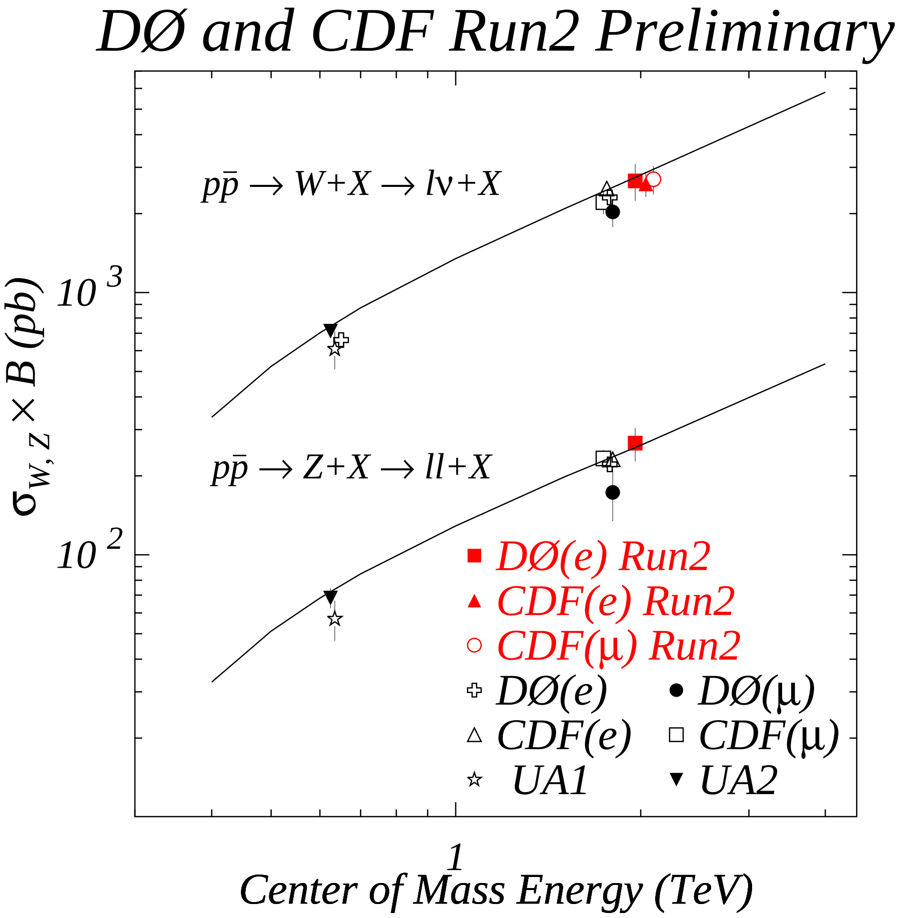


Cross-section summary – CDF/D0 Run II preliminary

	$\sigma(\mathrm{W} \longrightarrow \ell\nu)$ (nb)
CDF(e)	$2.60 \pm 0.03 \pm 0.13 \pm 0.26$
CDF(μ)	$2.70 \pm 0.04 \pm 0.19 \pm 0.27$
D0(e)	$2.67 \pm 0.06 \pm 0.33 \pm 0.27$

	$\sigma(\mathrm{Z} \longrightarrow \ell\ell)$ (pb)
D0(e)	$266 \pm 20 \pm 20 \pm 27$

	R
D0(e)	$10.0 \pm 0.8 \pm 1.3$
CDF(μ)	$13.7 \pm 1.9^{+1.1}_{-1.2}$



W-decay angular distributions

- Understanding QCD effects in W production helps reduce uncertainties in $\mathrm{M_W}$ and other electroweak measurements.
- Without QCD, $\mathrm{p_T^W} = 0$, differential cross section for charged lepton in W decay $\propto (1 \pm \cos\theta)^2$.
- In NLO QCD, differential cross section in Collins-Soper rest frame is

$$\frac{d^4\sigma}{dp_T^W dy d(\cos\theta) d\phi} \propto 1 + \cos^2\theta + A_0(1-3\cos^2\theta)/2 + A_1\sin2\theta\cos\phi + A_2(\sin^2\theta\cos2\phi)/2 + A_3\sin\theta\cos\phi + A_4\cos\theta + A_5\sin^2\theta\cos2\phi + A_6\sin2\theta\sin\phi + A_7\sin\theta\sin\phi$$

where $\mathrm{A_i}$ depend on $\mathrm{p_T^W}$, y.

- Angular distributions at $\mathrm{p_T^W} \neq 0$ probe $\mathrm{A_i}$, predicted by NLO QCD.
- Previous D0 measurement of $\mathrm{A_0}$, new CDF results for $\mathrm{A_0}$, $\mathrm{A_2}$ and $\mathrm{A_3}$.

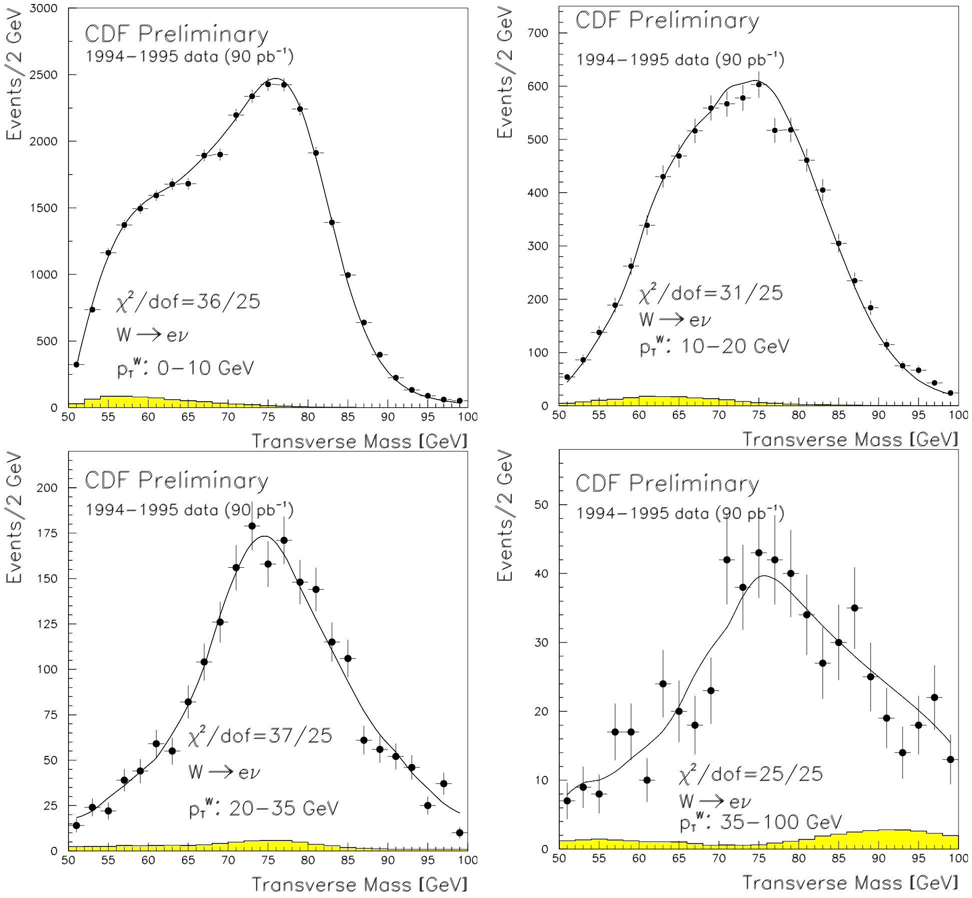
CDF A_0 *via* M_T distribution

- Integrating over ϕ,

$$\frac{d\sigma}{d(\cos\theta)} \propto 1 \pm \alpha_1 \cos\theta + \alpha_2 \cos^2\theta,$$

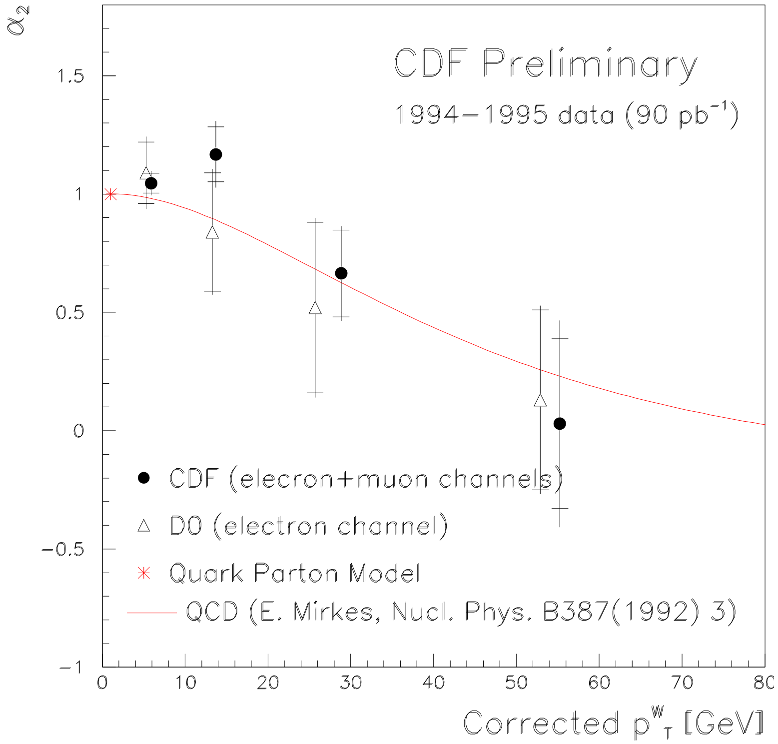
with $\alpha_1 = A_4/(2+A_0)$, $\alpha_2 = (2-3A_0)/(2+A_0)$.

- M_T distribution is sensitive to α_2. $\Rightarrow$ study shape as a function of p_T^W.



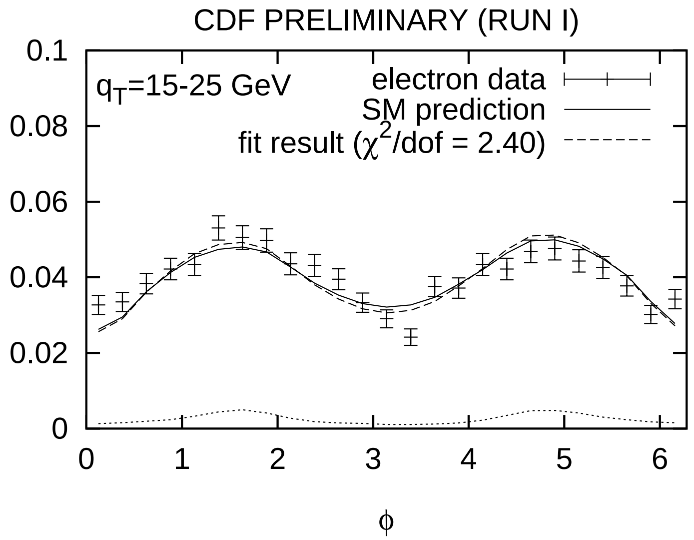
CDF A_0 results

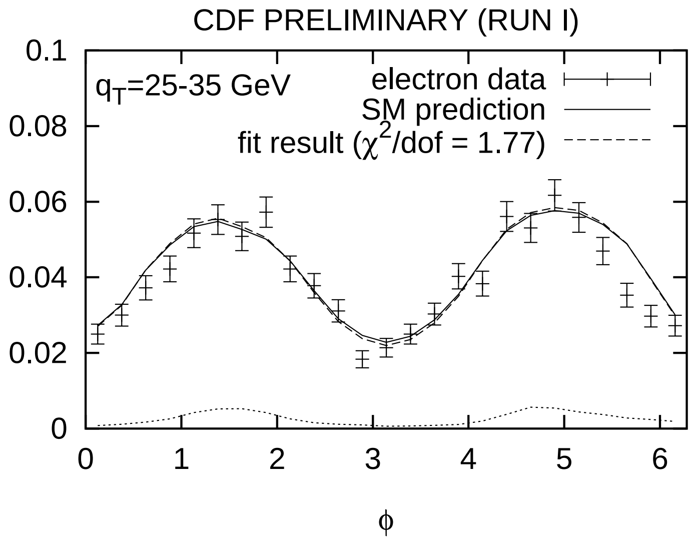
- Measured $\alpha_2(p_T^W)$ is consistent with QCD predictions, and D0 measurements.
- Decreasing α_2 = increasing longitudinal polarization!
- Results are statistics-limited, systematic uncertainties dominated by M_W, p_Z^W, and recoil model.

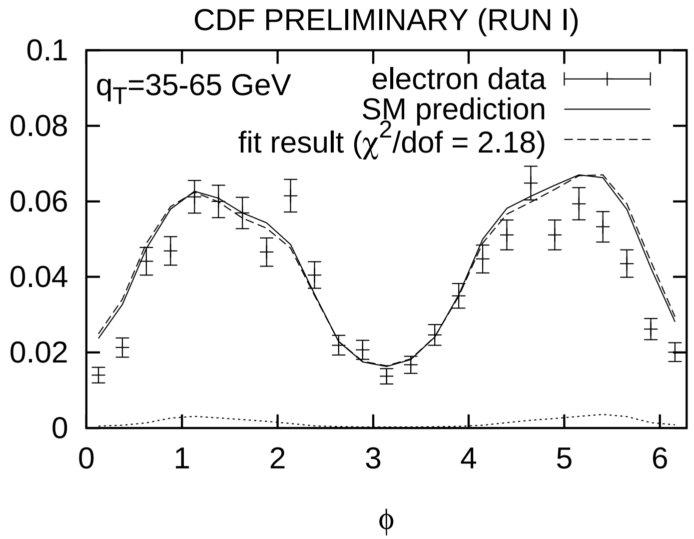


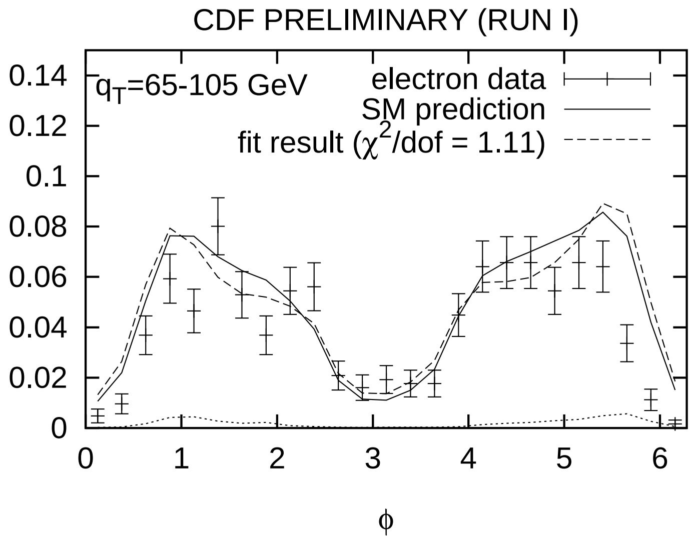
CDF A_2 and A_3 *via* ϕ distribution

- The lepton ϕ distribution is sensitive to A_2 and A_3.
- Require at least one hadronic jet in the event, so that $p_T^W > 0$.


CDF PRELIMINARY (RUN I)

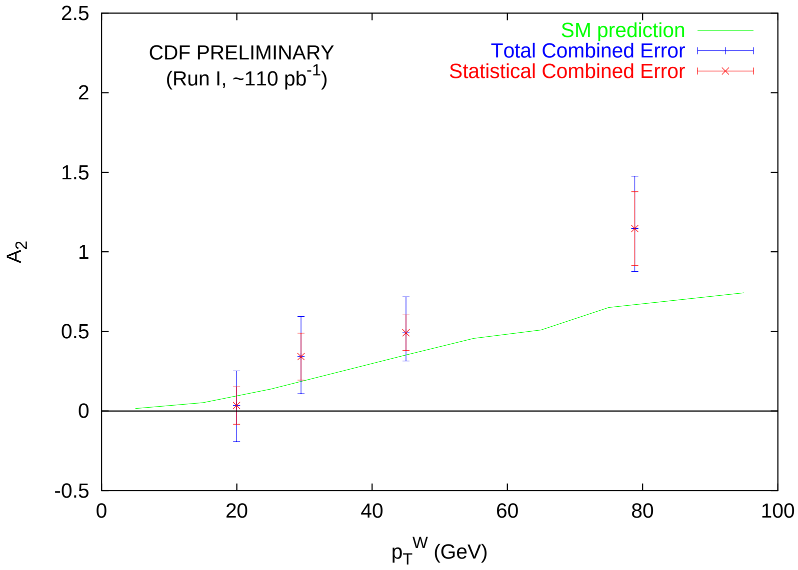

CDF PRELIMINARY (RUN I)

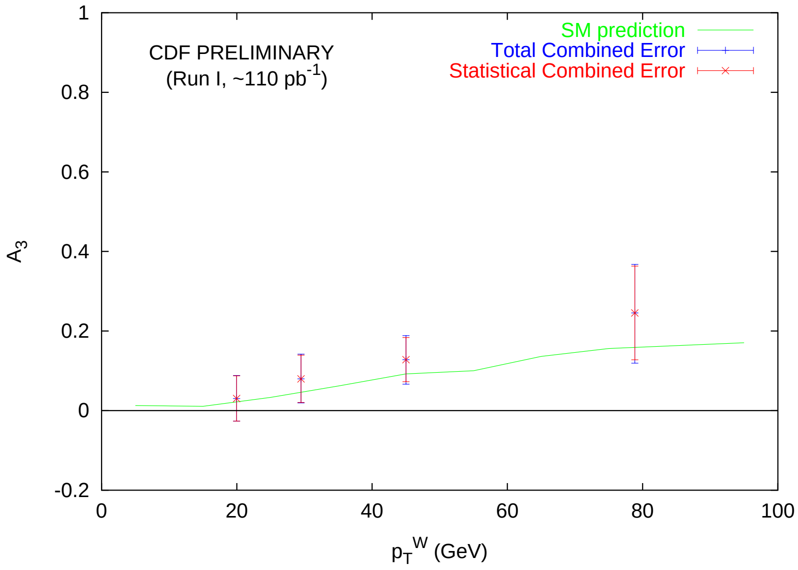

CDF PRELIMINARY (RUN I)


CDF PRELIMINARY (RUN I)

CDF A_2 and A_3 results

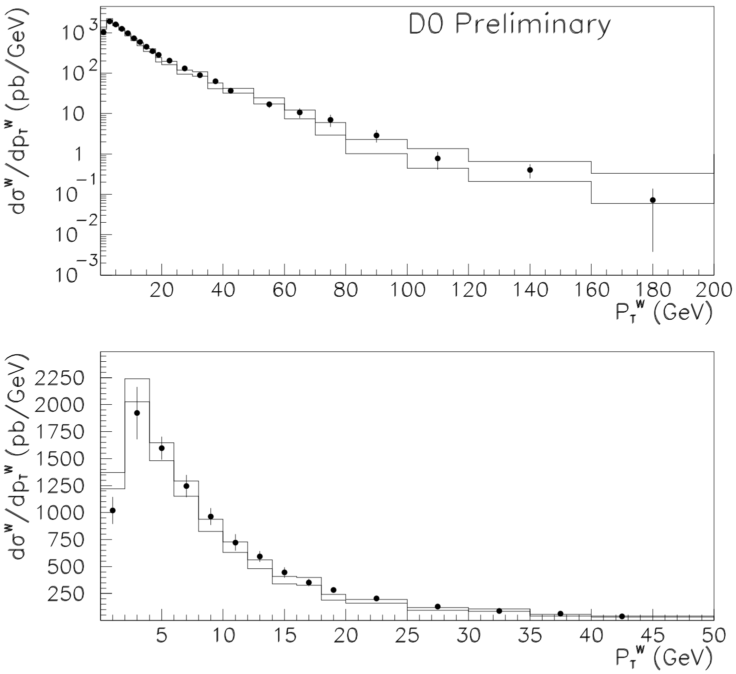
- Results consistent with QCD prediction.
- A_2 result is systematics limited, dominated by knowledge of $A_{0,4}$, renormalization and factorization scale.
- A_3 result is statistics-limited.





D0 measurement of $\mathrm{R}(\mathrm{p_T})$

- Measure $\mathrm{d}\sigma^W/\mathrm{dp}_T^W$ by measuring $\mathrm{R}(\mathrm{p_T}) = \frac{\mathrm{d}\sigma^W}{\mathrm{dp}_T^W} / \frac{\mathrm{d}\sigma^Z}{\mathrm{dp}_T^Z}$.
  - Trade systematic/theoretical uncertainties for statistical uncertainty from Z measurements.
- Good agreement (histograms) with direct measurement (points), method becomes more precise with larger datasets.
- See PL **B517**, 299 (2001).



Summary

- Sophisticated analyses of Run I data soon to be completed.
- Run II analyses of W and Z bosons are underway:
  - Established techniques to identify bosons with high efficiency.
  - Good understanding of acceptances and efficiencies, will improve.
  - W cross-section measurements are
    - consistent with theory predictions and previous measurements
    - *systematics limited*
  - Z cross section, R are statistics-limited.
- A solid foundation for future high-p_T physics studies!