W and Z Production at the Tevatron

Recent Results

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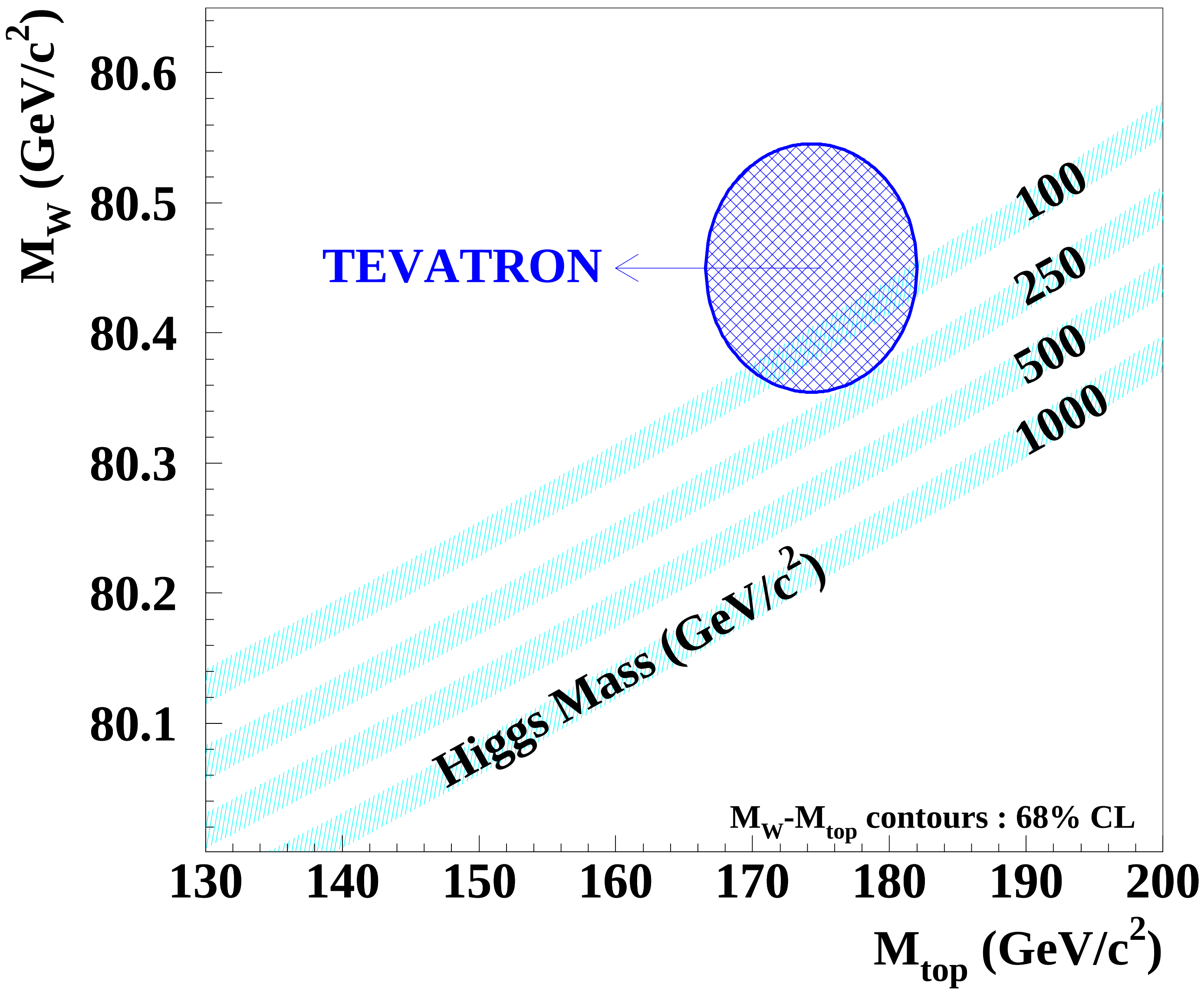
Outline

- Why?
- Methods
- Results
  - W&Z Production Cross Section and W width
  - The Differential pT Cross Sections
  - W angular distribution
- Conclusions



M_W (GeV/c^2)
80.6
80.5
80.4
80.3
80.2
80.1
TEVATRON
100
250
500
1000
Higgs Mass (GeV/c^2)
M_W-M_{top} contours : 68% CL
130
140
150
160
170
180
190
200
M_{top} (GeV/c^2)

Connections between W,Z Production, QCD and New Physics

W boson mass + top quark mass: Constrain Higgs mass

Current DØ δM_W ~ 5 -40 MeV from P_T^W model

δM_W = 10 MeV $\Rightarrow$ $\delta M_H / M_H$ = 14%

Need precise model of W production and decay for Monte Carlos

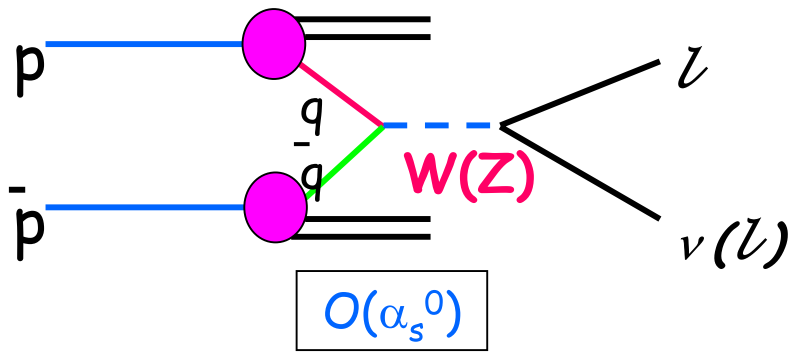
W mass measurements require low P_T^W

NLO QCD

Resummation techniques

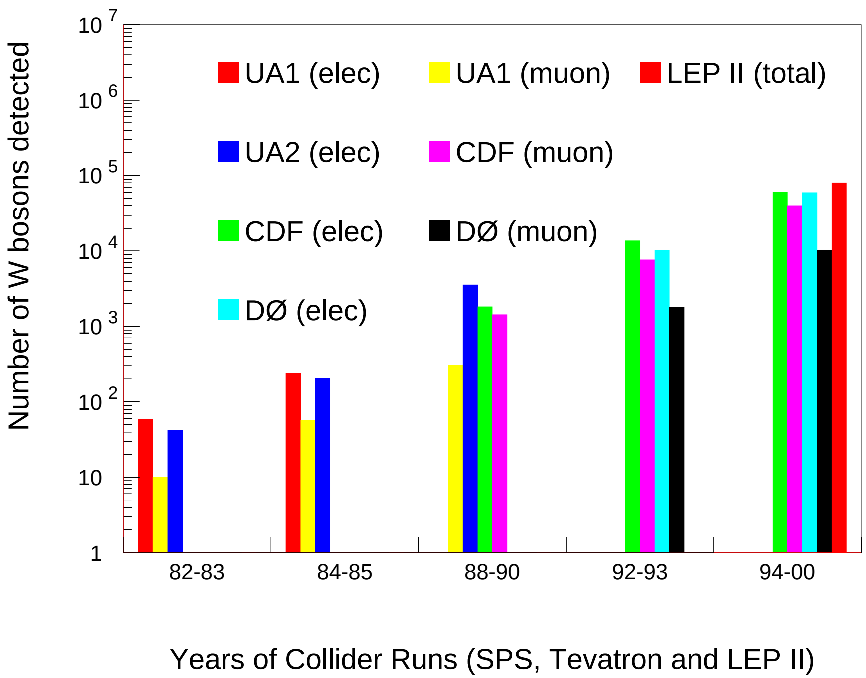
Non-perturbative QCD

Introduction to W & Z Production at the Tevatron



- Production dominated by $q\bar{q}$ annihilation
- Due to very large pp → jj production, need to use leptonic decays
  - W → lν (BR ~ 11% per mode)
  - Z → ll (BR ~ 3% per mode)

W Bosons Detected



- Distinctive event signatures
  - High P_T isolated leptons (e or μ)
  - One high P_T lepton + Missing E_T (W)
  - Two high P_T leptons (Z)
- Low backgrounds
- Large samples
- Well understood EW vertex

➔ Test QCD

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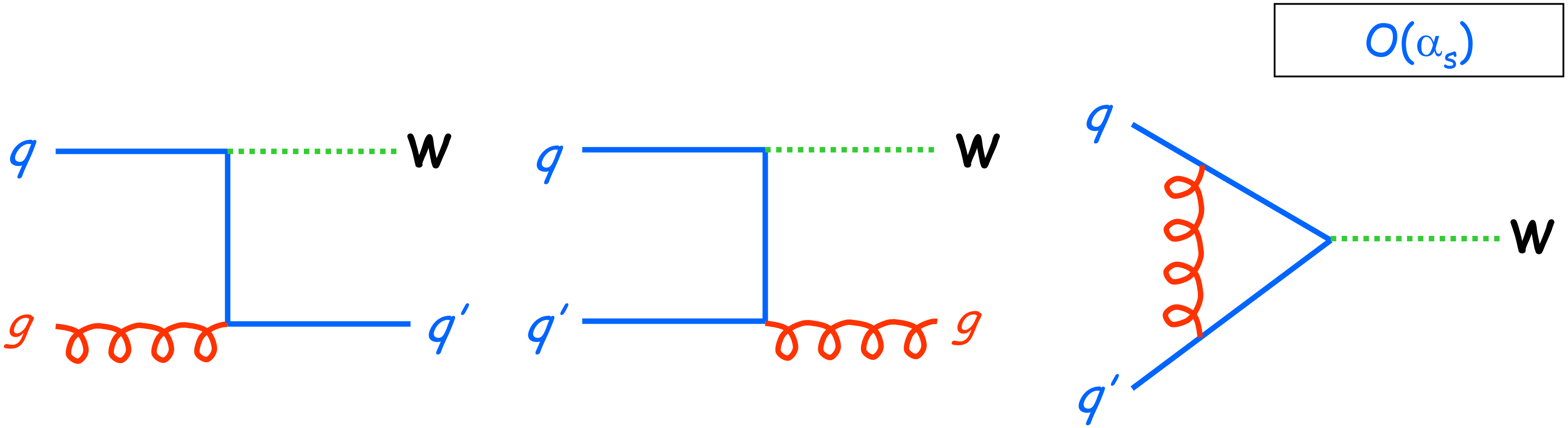
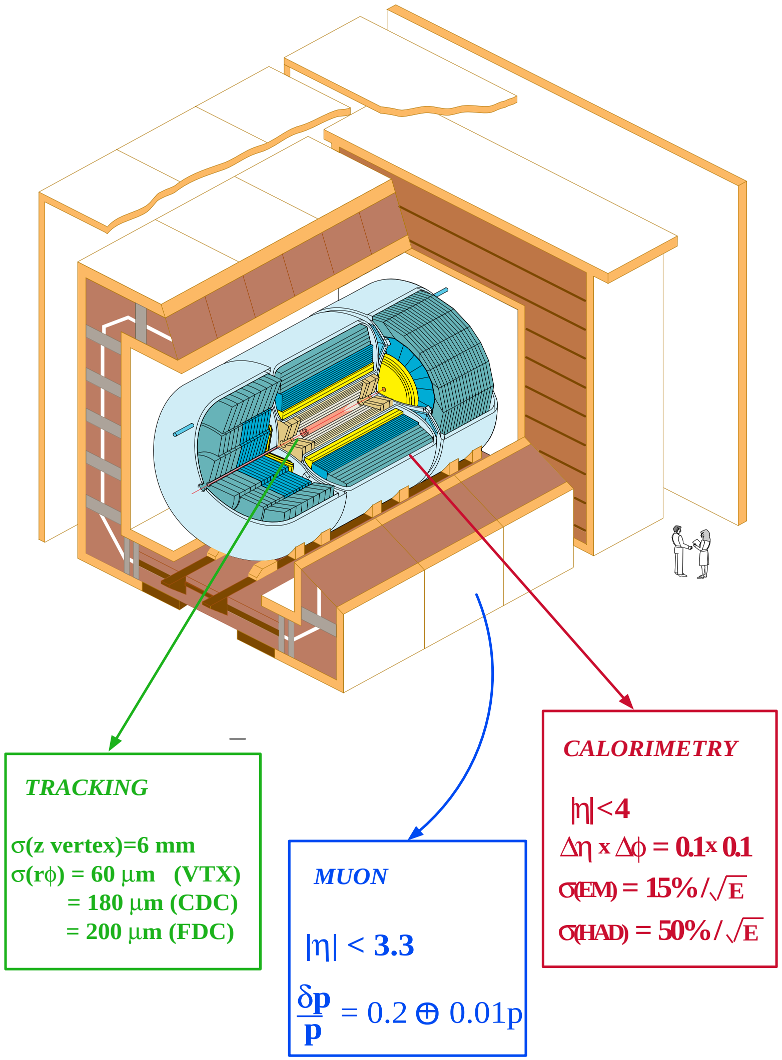
QCD Corrections: $O(\alpha_s)$



Modifications due to QCD corrections:

- Boson produced with transverse momentum ($\langle P_T \rangle \sim 10$ GeV)
- Boson + jet events possible (W + 1 jet ~ 7%, $E_T^{jet} > 25$ GeV)
- Inclusive cross sections larger (K factor ~ 18%)
- Boson decay angular distribution modified

The Run 1 D0 Detector



Electron Identification

- within good fiducial region of detector
- highly EM Object
- Longitudinal & Transversal Shower Profile
- Isolated from Jet activity

} Loose electron

- Central Detector track   Tight electron

W → eν event selection

- One tight electron, E_T>25 GeV
- Missing E_T>25 GeV
- No second Loose electron with E_T>25 GeV

Z → ee event selection

- One Tight and one Loose electron, both with E_T>25 GeV
- 76 GeV < Mee < 106 GeV

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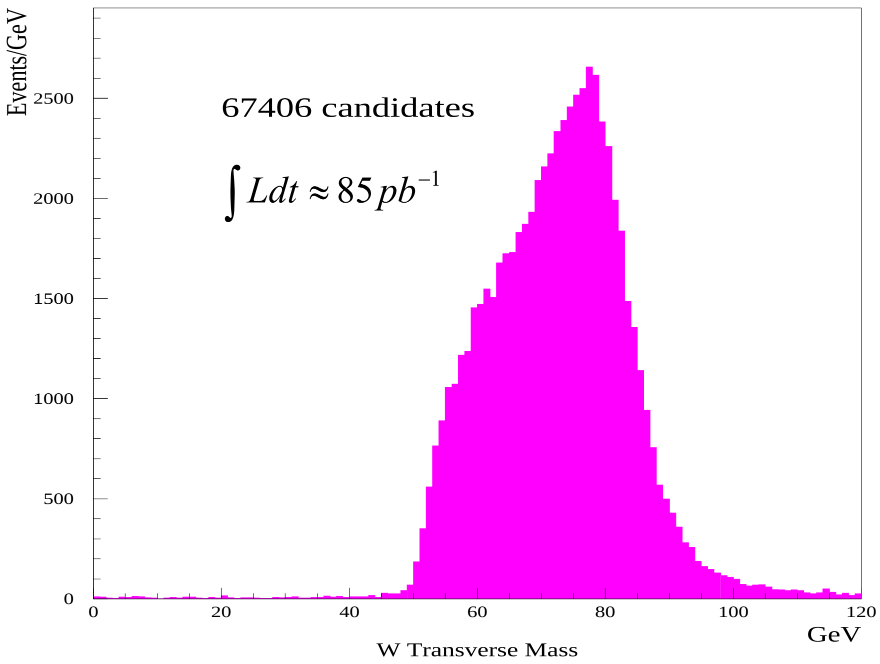
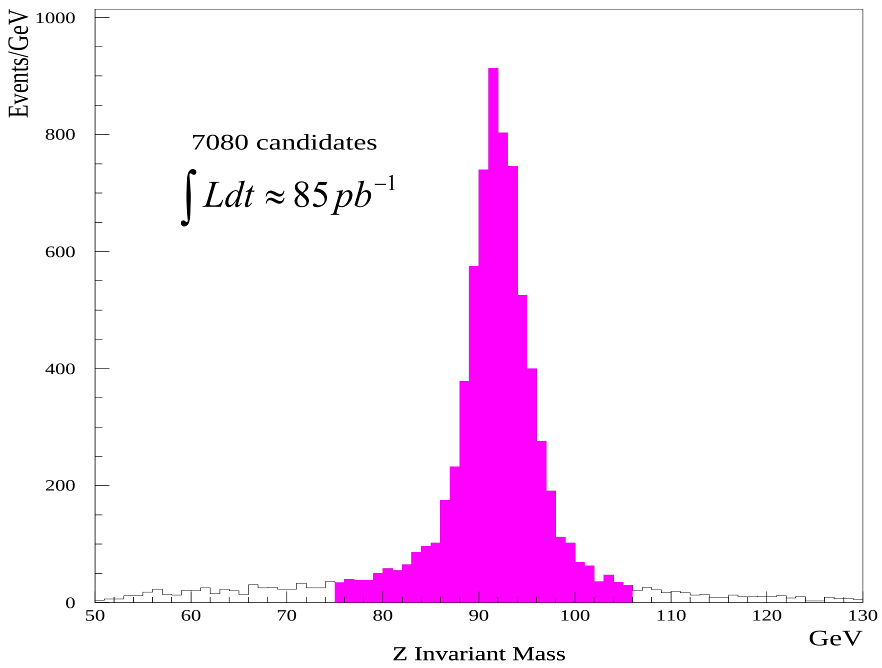
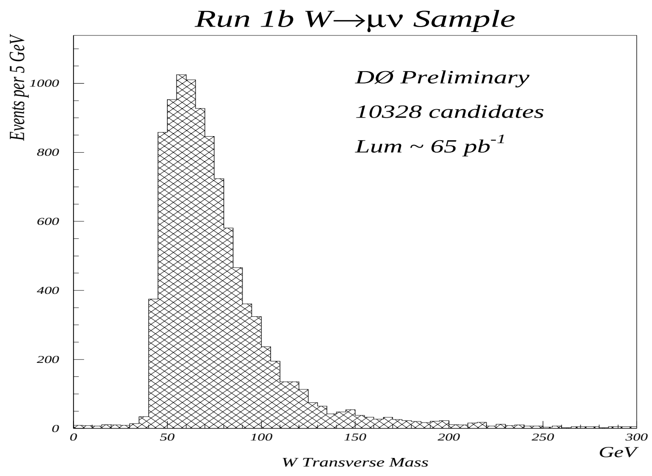
D0 W and Z candidate samples

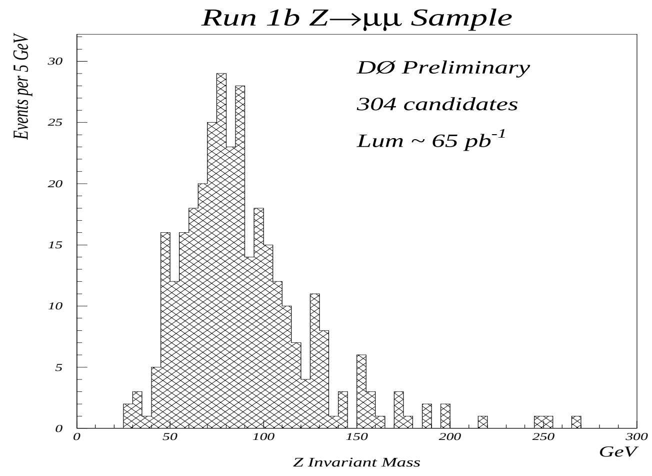
D0 W → eν



D0 Z → ee







Inclusive Cross Sections

$$\sigma(\bar{p}p \rightarrow B+X) B_R(B \rightarrow l_1 l_2) = \frac{N_{obs} - N_{bkgd}}{A \times \varepsilon \times L}$$

Backgrounds

- Major source is QCD dijets (estimated from collider data)

Acceptance
obtained from fast MC

Efficiencies
determined from
$Z \rightarrow ee$ data

Integrated
Luminosity

Efficiency Determination

Determine the single electron efficiency from collider data, using a $Z \to ee$ " Parent" sample.

- Two EM objects in the good fiducial region
- $E_T > 25$ GeV
- 86 GeV < Mee < 96 GeV
- One electron is tight
- Sample corrected for background contamination
- Second electron is unbiased & used to determine efficiency

$\varepsilon^W(e)\sim 70\%$ $\varepsilon^Z(e)\sim 76\%$

$\varepsilon^W(\mu)\sim 26\%$ $\varepsilon^Z(\mu)\sim 52\%$

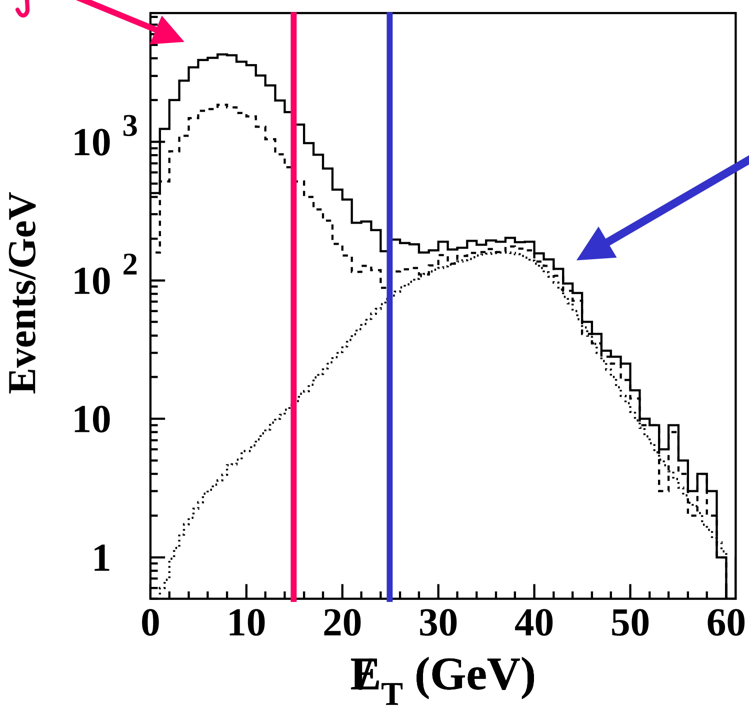
W $\rightarrow e\nu$ Backgrounds

Major background source is QCD dijet events: one jet passes the electron identification and the mismeasured energy fakes the $\not{E}_T$

- Estimated using two samples with known efficiency and rejection.

➊ Assumes that all data with $\not{E}_T$ < 15 GeV is background & that jet efficiency determined at low $\not{E}_T$ holds in signal region.

ε_j



$$\left.\begin{aligned} N_L &= N_S + N_B \\ N_T &= \varepsilon_S N_S + \varepsilon_j N_B \end{aligned}\right\} \quad f_{QCD} = \frac{\varepsilon_j N_B}{N_T}$$

$f_{QCD}(CC) \sim 5\%$ $\quad f_{QCD}(EC) \sim 14\%$

- Remaining backgrounds

$W \rightarrow \tau\nu$, $\quad Z \rightarrow \tau\tau$, $\quad Z \rightarrow e\not{e}$

estimated using Monte Carlo samples

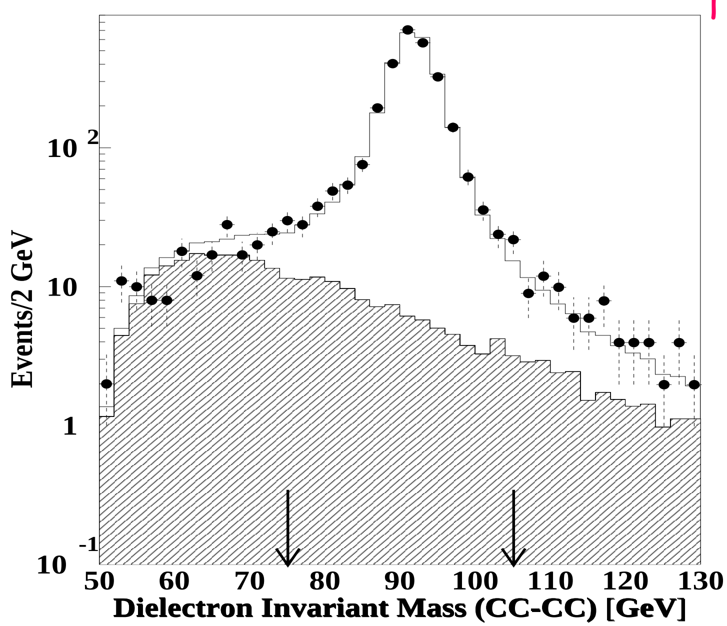
$f_\tau \sim 2\%$ $\quad f_{Zee} \sim 0.5\%$

$Z \rightarrow ee$ Backgrounds

Major background source is QCD dijet and direct photon events with jets faking electrons

• Estimated by fitting the data to Signal $Z \rightarrow ee$ from Monte Carlo plus Background from data.

$f_{QCD}(CC,CC)$~2%, $f_{QCD}(CC,EC)$~7%, $f_{QCD}(EC,EC)$~5%



• Remaining backgrounds Drell-Yan, $Z \rightarrow \tau\tau$ estimated from Monte Carlo samples

f_{DY}~1% f_{τ}~negligible

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Acceptance Calculation

Kinematic and geometric Acceptance obtained from a parametric representation of the D0 detector ("fast Monte Carlo")

- $\frac{d\sigma}{dm^W}$ From momentum dependent Breit-Wigner times Parton Luminosity Function
- $\frac{d\sigma}{dp_T dy}$ From Ladinsky-Yuan PRD50, 4239 (small p_T) and NLO pQCD Nucl.PhysB319, 37 (high p_T)
- W decay from Mirkes Nucl.Phys.B387, 3 andBerends&Kleiss ($e\nu\gamma$) Z.PhysC27, 365.
- Detector resolutions determined from data and parametrized as a function of energy and angle.

$A^W(e)$~45% $A^Z(e)$~35%

$A^W(\mu)$~21% $A^Z(\mu)$~5%

Inclusive Cross Sections

PRL 75, 1456 (95), PRD 60, 52003 (99) , PRD 61, 72001 (00)

		$\sigma(W)\times BR(W\to l\upsilon)\ (nb)$	$\sigma(Z)\times BR(Z\to ll)\ (nb)$
D∅, e, 1b	Published	$2.31 \pm 0.01 \pm 0.05 \pm 0.10$	$0.221 \pm 0.003 \pm 0.004 \pm 0.010$
D∅, e, 1a	Published	$2.28 \pm 0.02 \pm 0.08 \pm 0.10$	$0.211 \pm 0.008 \pm 0.008 \pm 0.009$
D∅, μ, 1b	Preliminary	$2.31 \pm 0.08 \pm 0.10$	$0.170 \pm 0.023 \pm 0.023 \pm 0.007$
D∅, μ, 1a	Published	$2.02 \pm 0.06 \pm 0.22 \pm 0.09$	$0.172 \pm 0.022 \pm 0.021 \pm 0.008$
CDF, e, 1b	Published		$0.246 \pm 0.005 \pm 0.003 \pm 0.010$
CDF, e, 1a	Published	$2.49 \pm 0.02 \pm 0.08 \pm 0.09$	$0.231 \pm 0.008 \pm 0.009$
CDF, μ, 1b	Updated		$0.237 \pm 0.011 \pm 0.009$
CDF, μ, 1a	Published		$0.217 \pm 0.017 \pm 0.008$
CDF, μ, Run 1	Published		0.233 ± 0.013

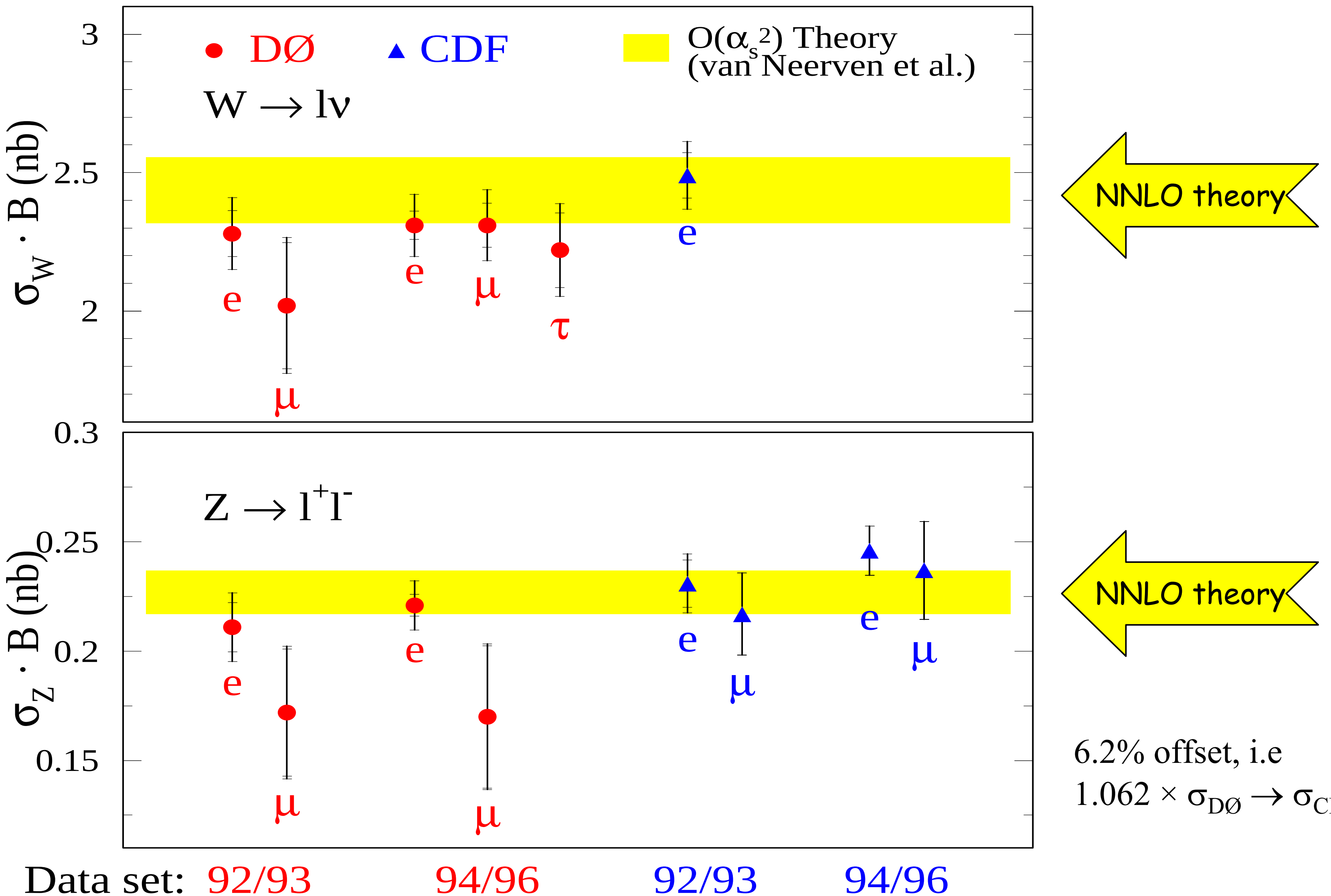
- **Measurement errors:** Stat ⊕ Sys ~ 2%, Luminosity error ~ 4%
- **Theory error:** ~ 3%, NNLO, $O(\alpha_s^2)$ (Hamberg, van Neerven, Matsuura)

  Dominated by PDF's at NLO…(need NNLO)
- **NB: Luminosity determination:** L(D0) = 1.062 x L(CDF)

  D0 uses world avg. $\sigma(p\bar{p})_{inel}$, CDF uses CDF measurement

Inclusive Cross Sections

$\sqrt{s} = 1800$ GeV



6.2% offset, i.e
$1.062 \times \sigma_{D\O} \rightarrow \sigma_{CDF}$

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Measurement of the W width

Measured:

$$\sigma(p\bar{p} \to W + X) \times BR(W \to l\upsilon)$$

$$\sigma(p\bar{p} \to Z + X) \times BR(Z \to ll)$$

Form ratio:

$$R \equiv \frac{\sigma\left(p\bar{p} \to W + X\right) \times BR(W \to l\upsilon)}{\sigma\left(p\bar{p} \to Z + X\right) \times BR(Z \to ll)}$$

$$= \frac{\sigma(W)}{\sigma(Z)} \times \frac{\Gamma(Z)}{\Gamma(Z \to ll)} \times \frac{\Gamma(W \to l\upsilon)}{\Gamma(W)}$$

SM EW

Perturbative QCD

LEP measurement

W Width

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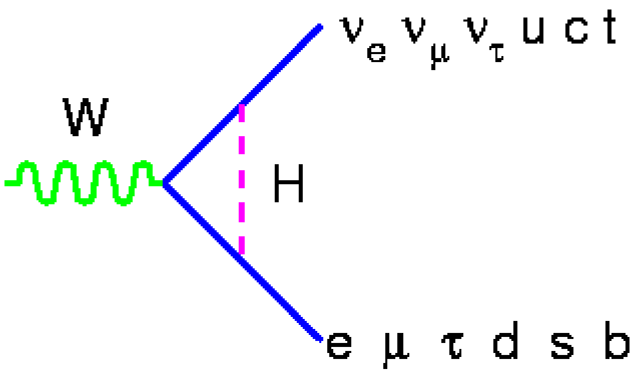
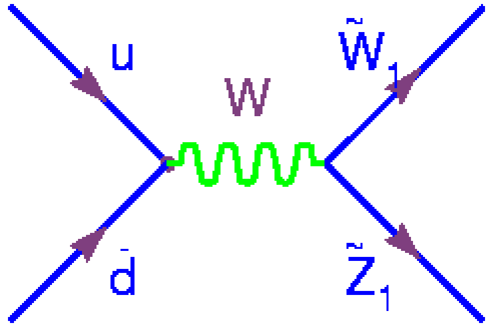
Indirect vs Direct W Width Measurements

Vertex Corrections: same for quarks and leptons, so cancel in BR($W \rightarrow l\nu$)



Rosner, Worah, Takeuchi, hep-ph/9309307

W decays:



Kalinowski and Zerwas hep-ph/9702386

Indirect has no sensitivity to corrections to the coupling of the W to fermions, but is sensitive to possible non-standard model decay modes of the W.

$$R \equiv \frac{\sigma\left(p\bar{p} \to W + X\right) \times BR(W \to e\upsilon)}{\sigma\left(p\bar{p} \to Z + X\right) \times BR(Z \to ee)}$$

PRD 61, 72001 (2000)

R = 10.43 $\pm$ 0.15 (stat) $\pm$ 0.20 (sys) $\pm$ 0.10 (theory)

B(W $\to$ eν) = 0.1066 $\pm$ 0.0015 $\pm$ 0.0021 $\pm$ 0.0016

Source of uncertainty	Size
backgrounds to the W sample from di-jets	0.158
statistics of the Z sample	0.149
ratio of W and Z acceptance	0.095
ratio of the lepton identification efficiencies for W's and Z's	0.063
backgrounds to the Z sample from di-jets	0.054
backgrounds to the W sample from Z's	0.029
background to W->eν from W->$\tau\nu$	0.022
NLO corrections to Z->eeγ	0.104
sum of systematic uncertainties	0.205
sum	0.274

2.6% total error

Luminosity error cancels in the ratio

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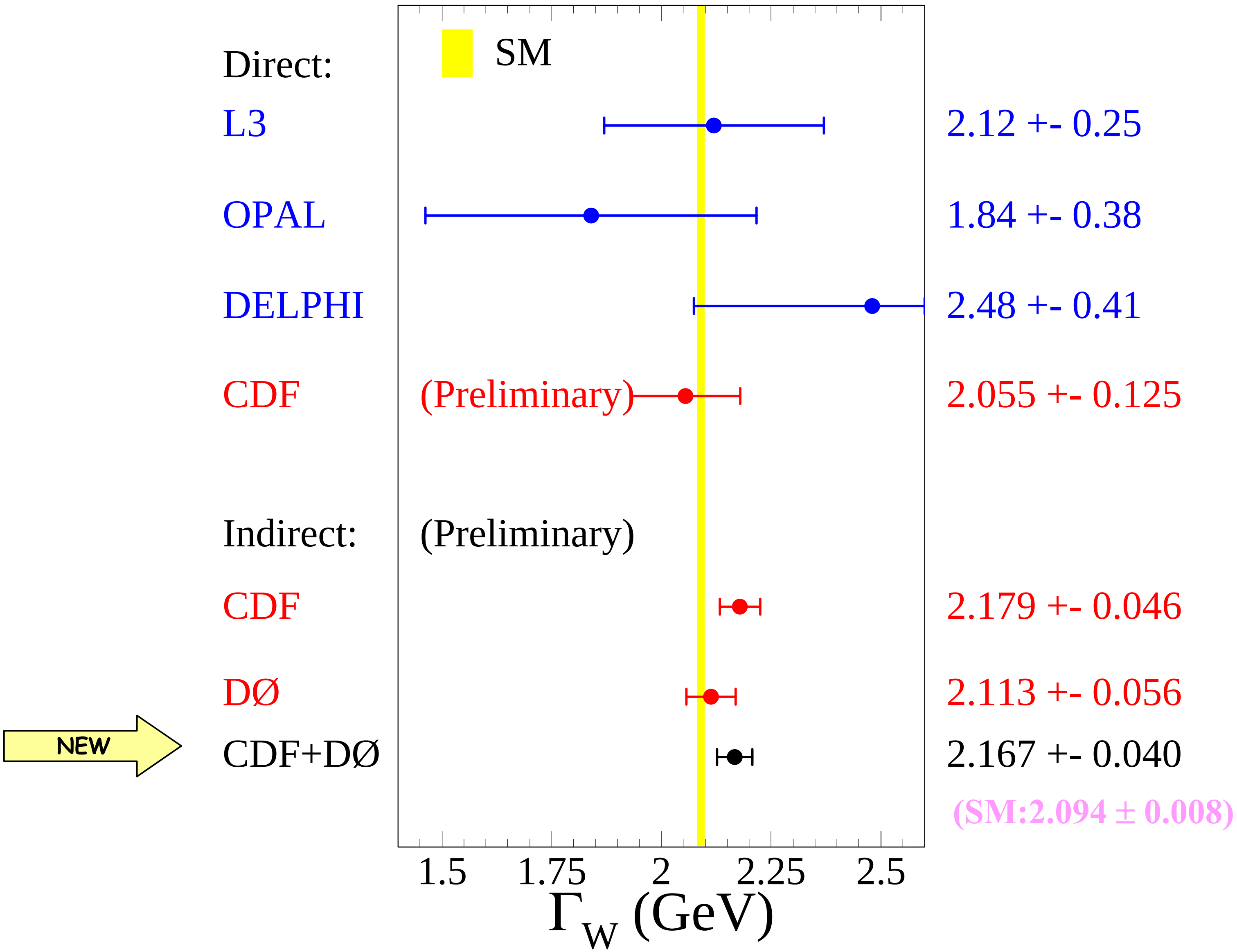
W Width



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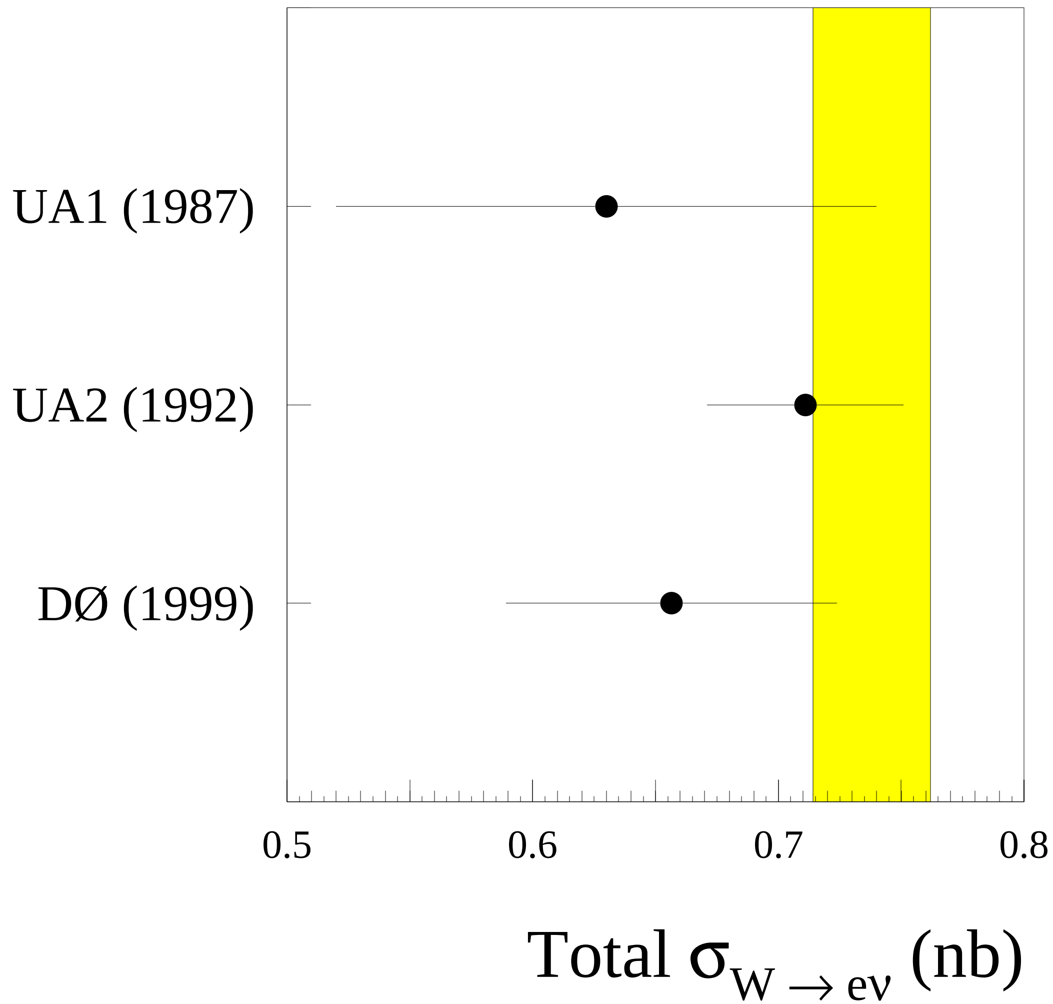
Inclusive Cross Sections

$\sqrt{s} = 630$ GeV



PRD 61, 72001 (2000)

$$\sigma(p\bar{p} \to WX) = 658 \pm 67\ pb$$

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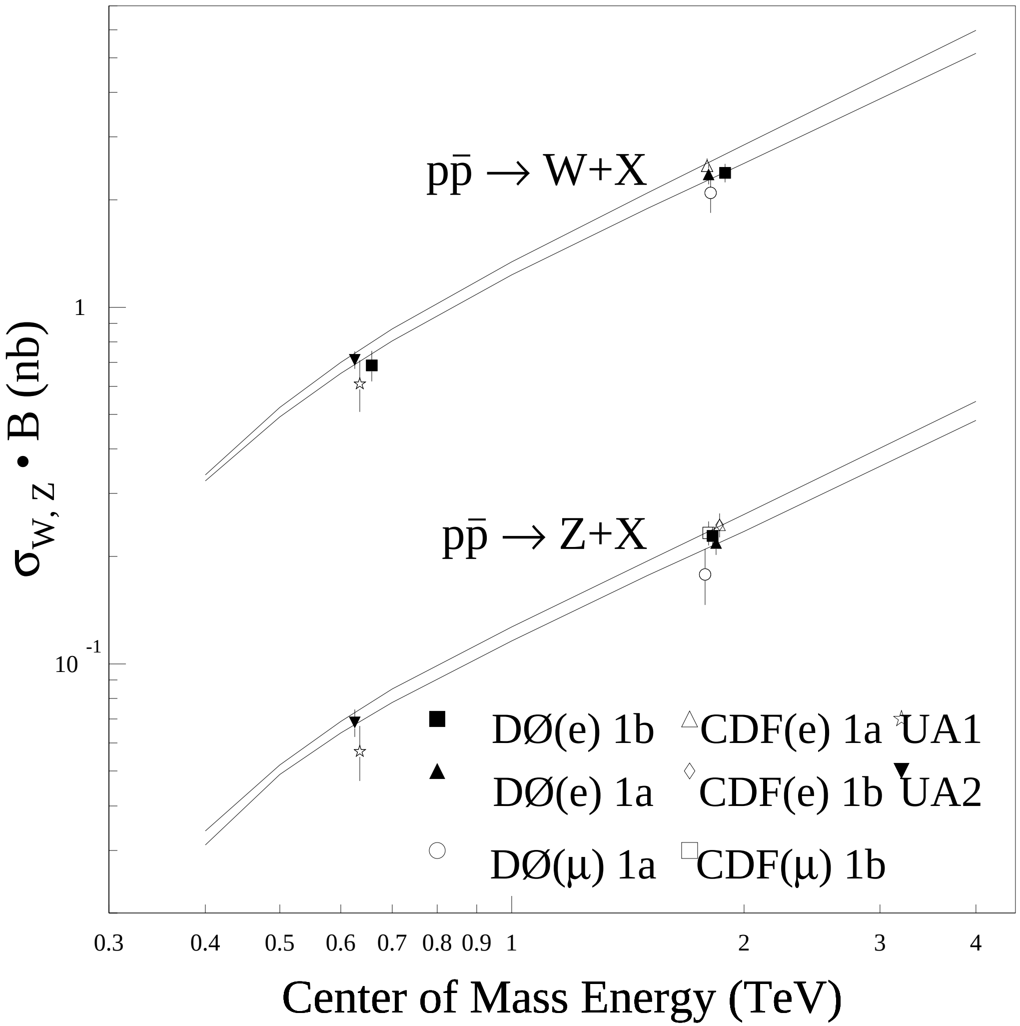
Inclusive Cross Sections



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Introduction to W, Z P_T Theory

$$\frac{d\sigma}{dp_T^2} \sim \frac{\alpha_s}{p_T^2} \ln\left(\frac{Q^2}{p_T^2}\right)\left[v_1 + v_2\alpha_s \ln^2\left(\frac{Q^2}{p_T^2}\right)\right]$$

- **Large P_T region** ($P_T \geq 30$ GeV): Use pQCD, $O(\alpha_s^2)$ calculations exist

  Ellis, Martinelli, Petronzio (83); Arnold & Reno (89); Arnold, Ellis, Reno (89); Gonsalves, Pawlowski, Wai (89)

- **Small P_T region** ($\Lambda_{QCD} < P_T < 10$ GeV): Resum large logs

  Altarelli, Ellis, Greco, Martinelli (84); Collins, Soper, Sterman (85)

- **Very low P_T region** ($P_T \sim \Lambda_{QCD}$): Non-perturbative parameters extracted from data

  b-space:

  Parisi-Petronzio (79); Davies-Stirling (84); Collins-Soper-Sterman (85); Davies, Webber, Stirling (85); Arnold- Reno-Ellis (89); **AK**: Arnold-Kaufann (91); **LY**: Ladinsky-Yuan (94)

  pt-space:

  Dokshitser-Diaknov-Troian (80); Ellis-Stirling (81); Altarelli-Ellis-Greco-Martinelli (84); Gonsalves-Pawlowksl-Wai (89); **ERV**: Ellis-Ross-Veseli (97); Ellis-Veseli (98)

Differential $P_T(W)$ & $P_T(Z)$ Cross Sections

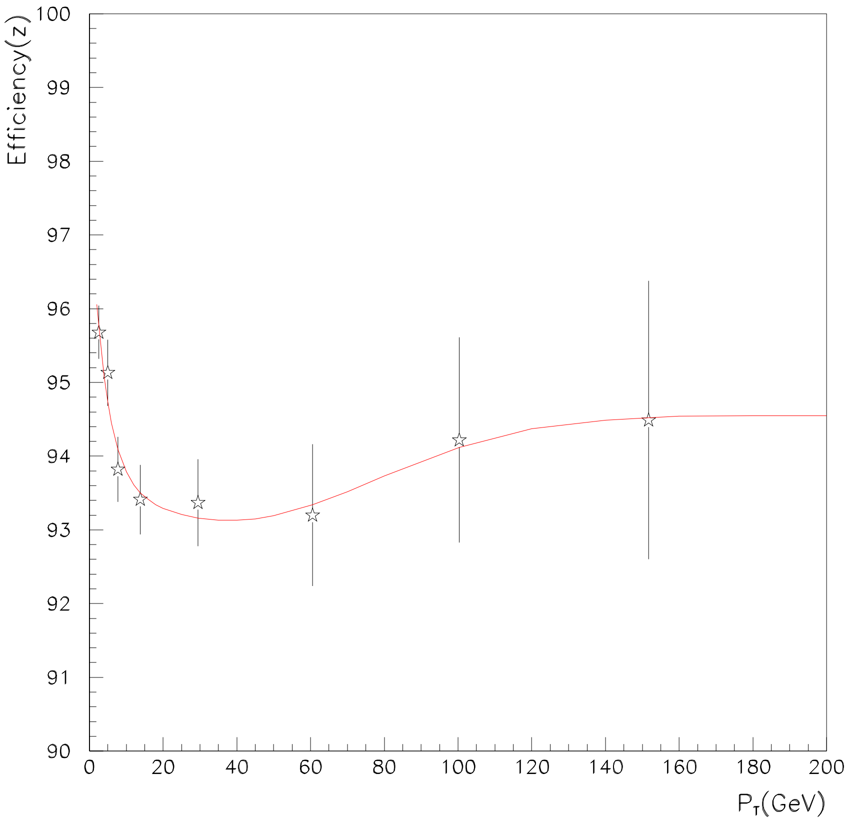
Need to determine all quantities as a function of P_T

$$\frac{d\sigma}{dp_T^i} = \frac{d_i - b_i}{a_i \times \varepsilon_i \times L \times \Delta p_T^i}$$

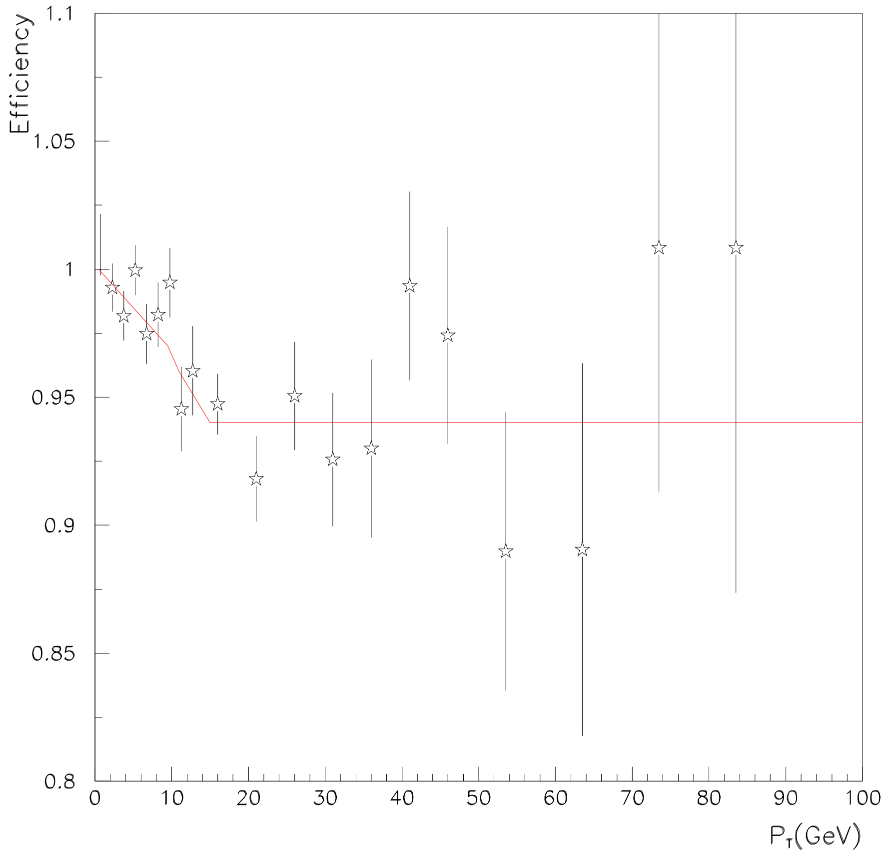
- Acceptance vs P_T obtained from Fast Monte Carlo
- Efficiency vs P_T obtained from Herwig W&Z events with full detector simulation and overlayed with zero bias events.
- Backgrounds vs P_T obtained from data (QCD) and Monte Carlo (physics)
- Measurement corrected for acceptance and detector effects using an iterative unfolding method.
- Previous measurements by UA1, UA2, CDF (Run 0) and D0 (Run 1A).

Selection efficiencies vs P_T

$W \rightarrow e\nu$



$Z \rightarrow ee$



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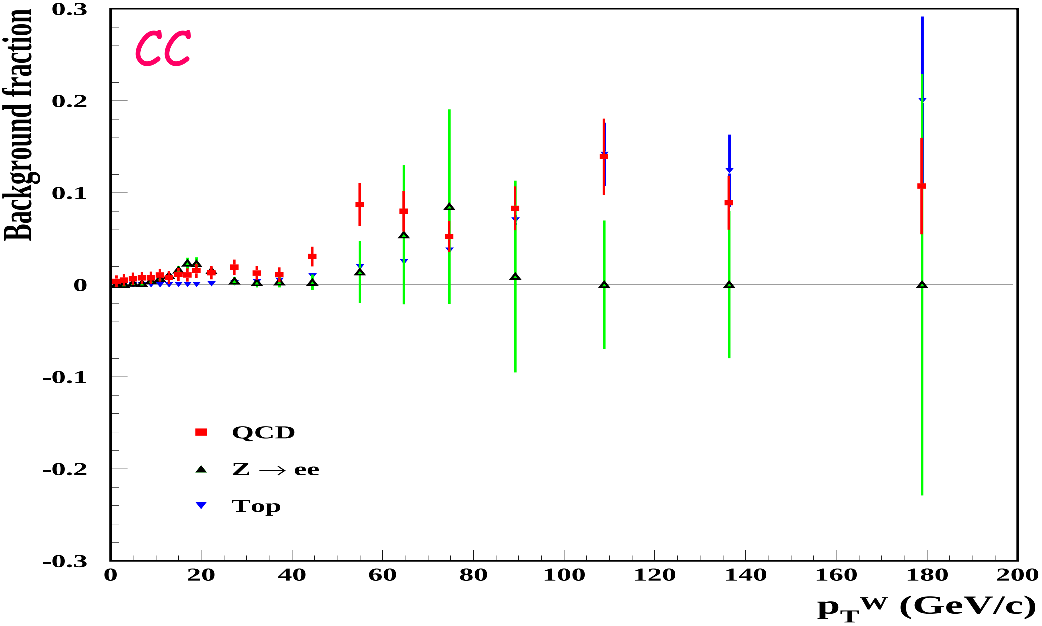
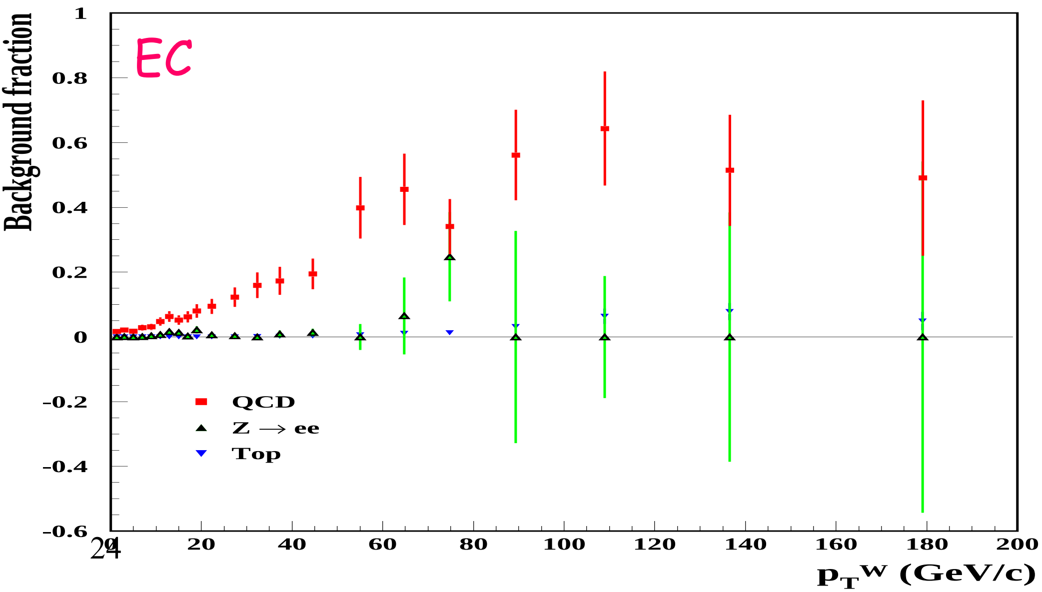
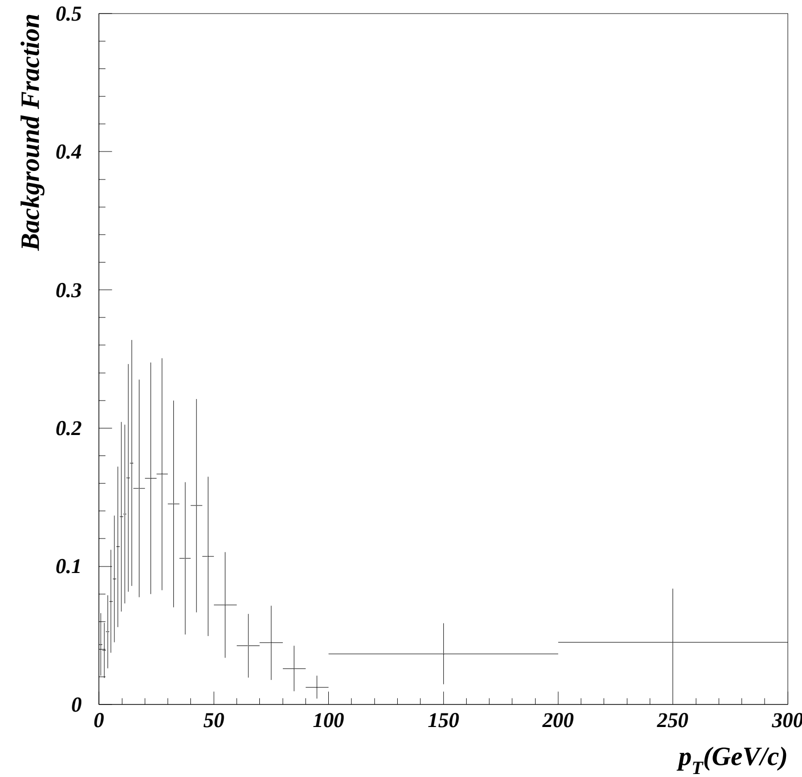
$W \rightarrow e\nu$

Backgrounds vs P_T



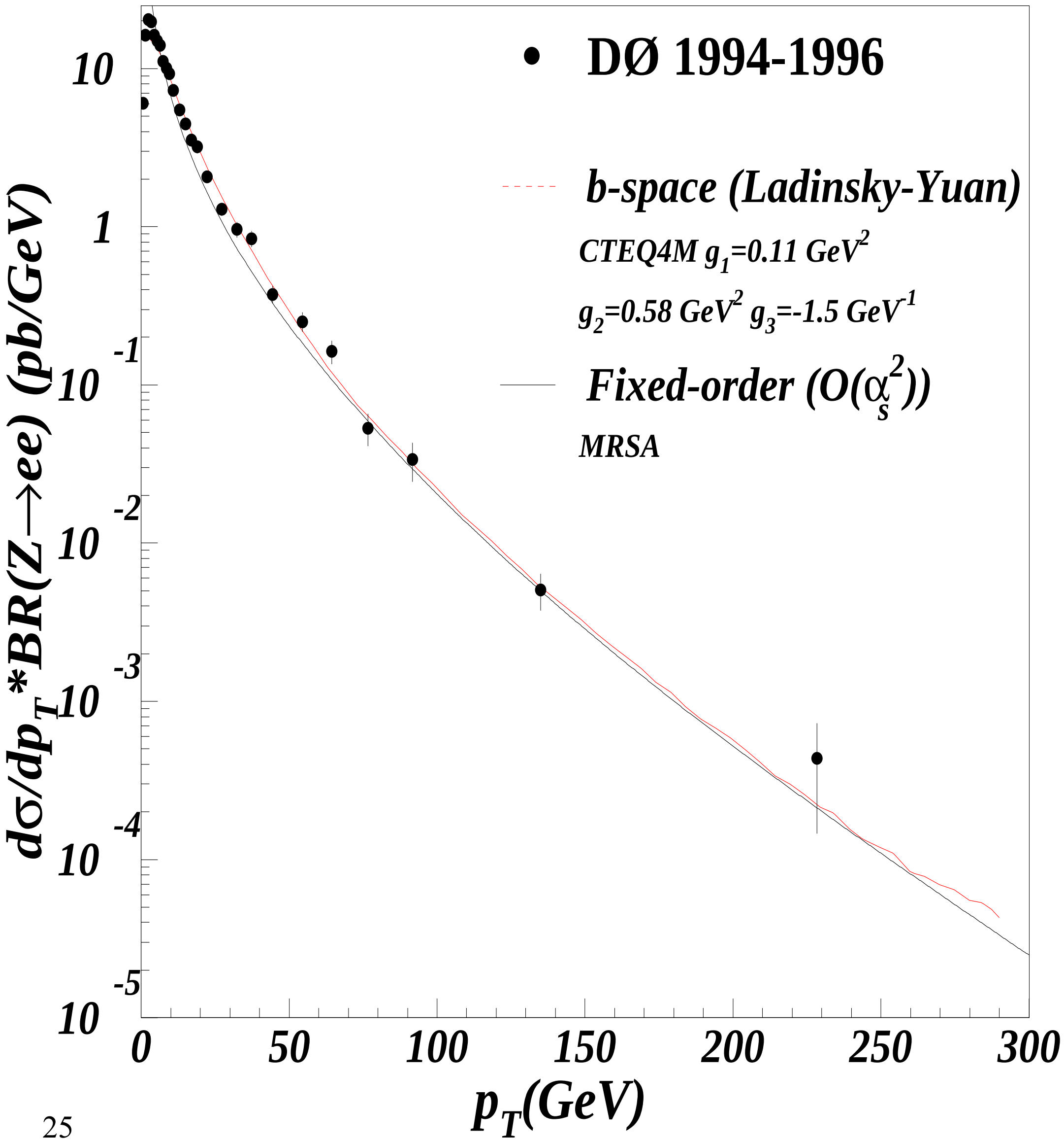


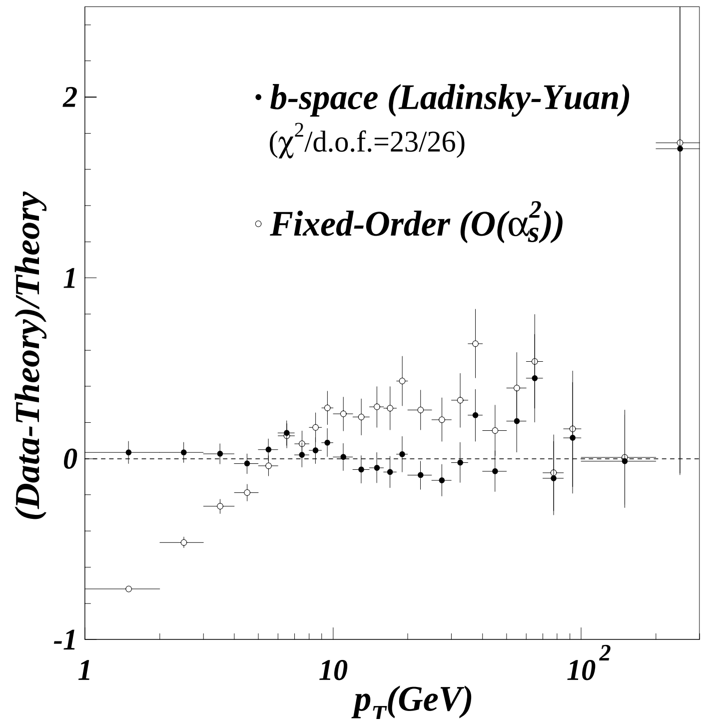
$Z \rightarrow ee$



D0 Z P_T measurement

PRD 61, 32004 (2000) & PRL 84, 2792 (2000)





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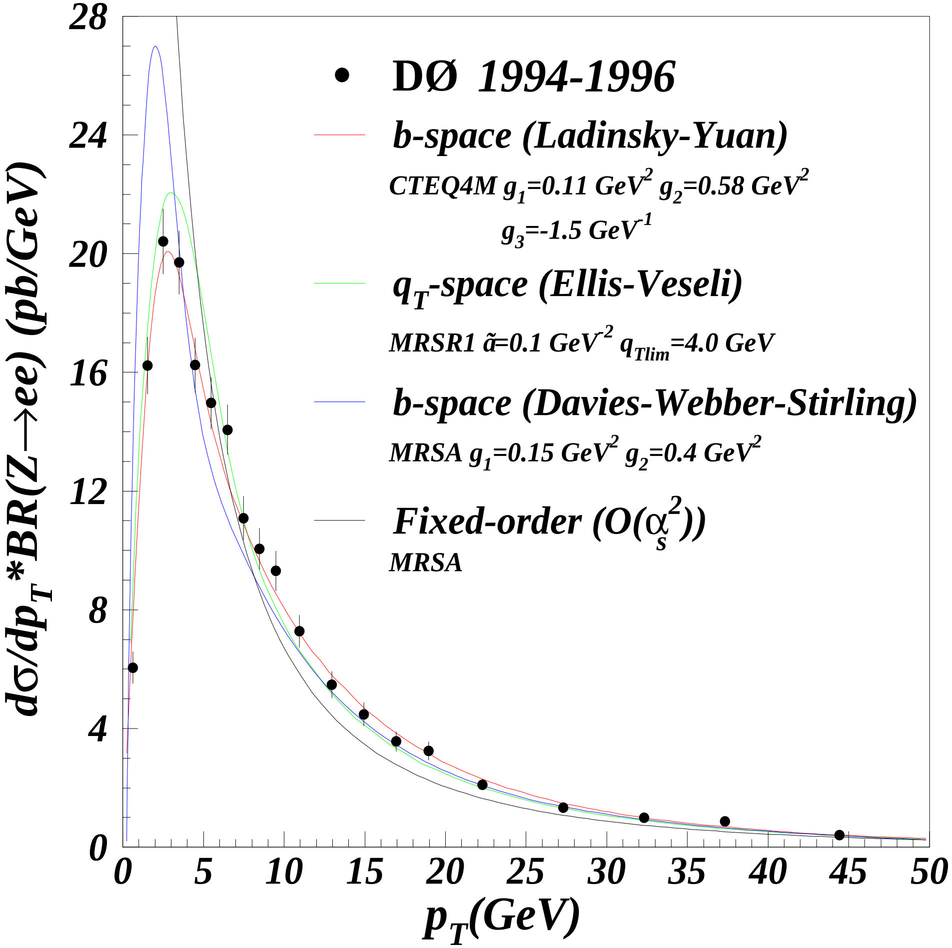
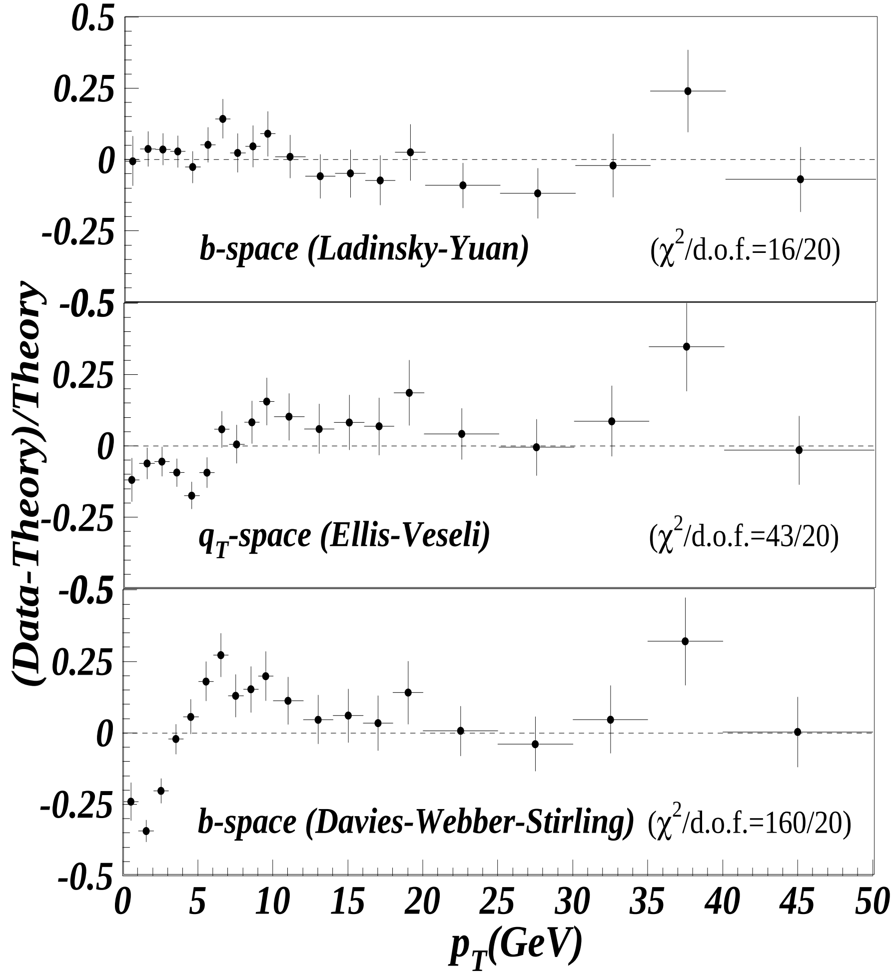
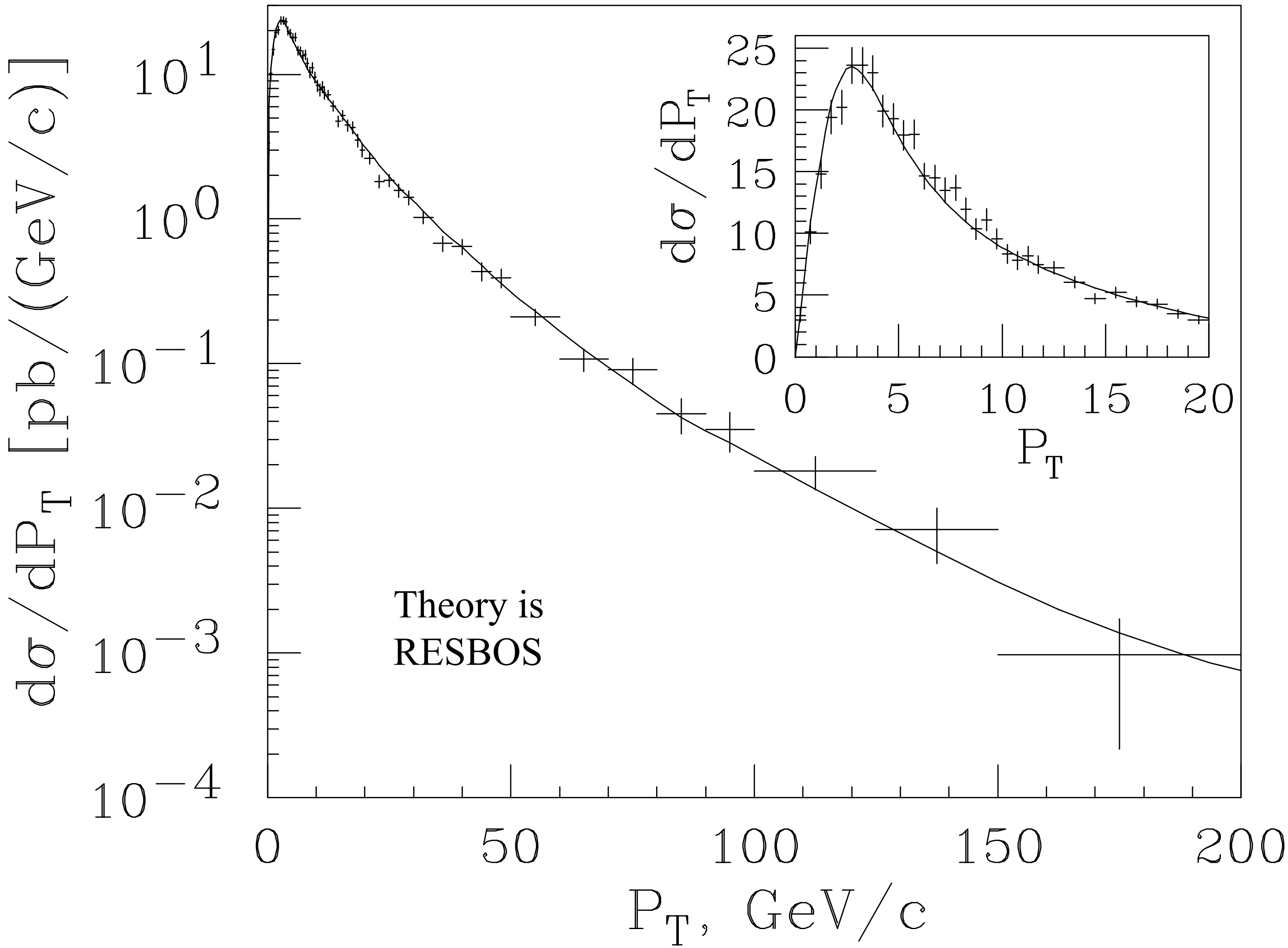




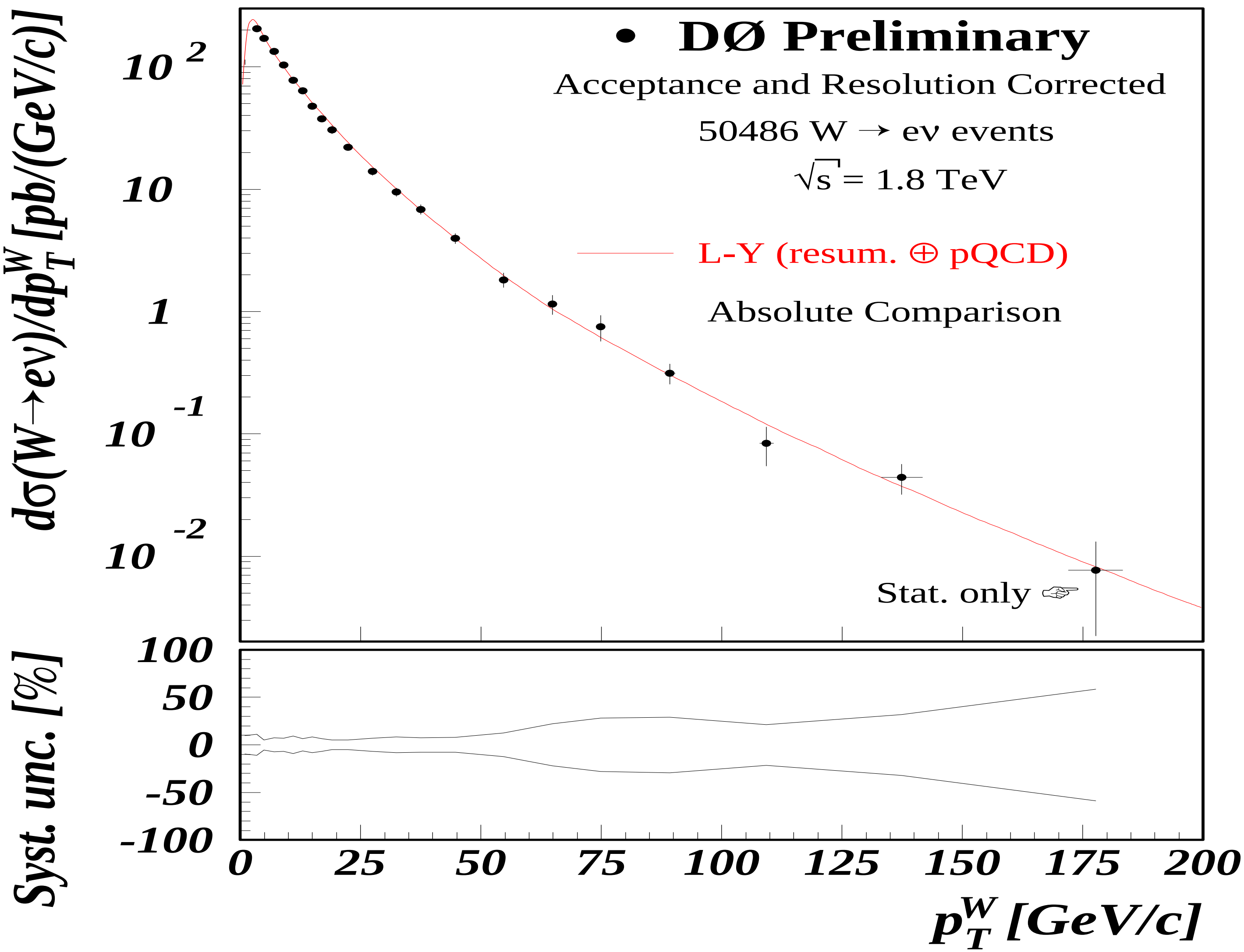
CDF Z P_T measurement

PRL 84, 845(2000)



DO W P_T measurement

submitted to PRL, hep-ex/0010026



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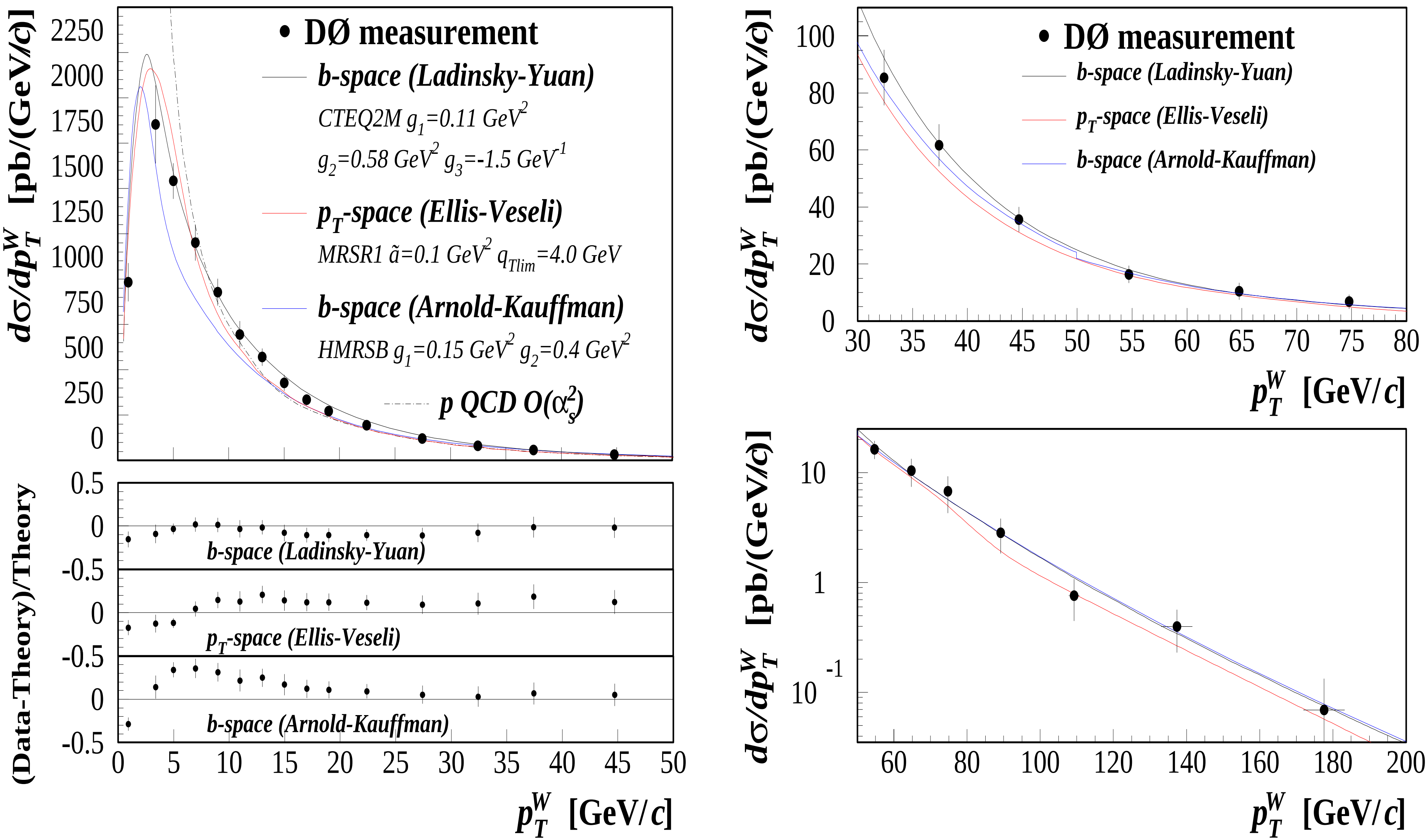
D0 W P_T measurement

submitted to PRL, hep-ex/0010026



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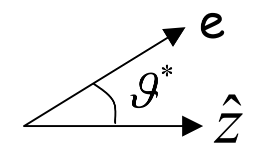
W Decay Distribution

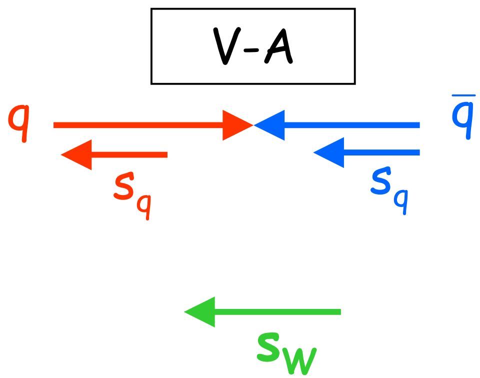
Angular distribution of electron in W rest frame:

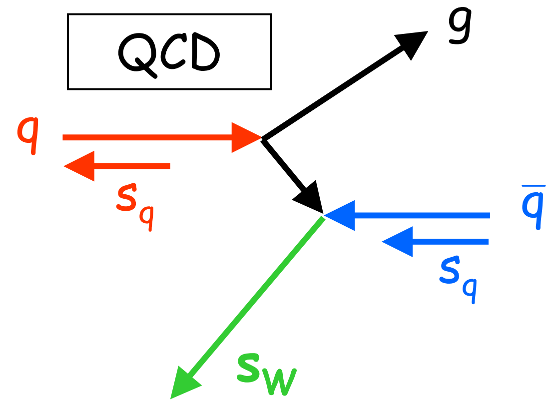
Pure V-A: $$\frac{d\sigma}{d\cos\vartheta^*} \propto (1 + P(W)\cos\vartheta^*)^2$$



Collins-Soper frame

NLO QCD corrections to production modify this distribution:





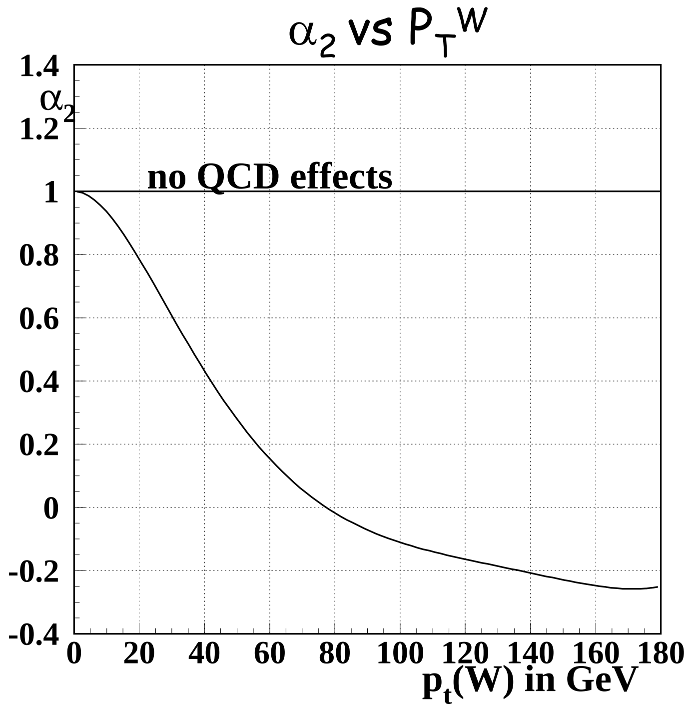
V-A + QCD: $$\frac{d\sigma}{d\cos\vartheta^*} \propto 1 + P(W)\alpha_1\cos\vartheta^* + \alpha_2\cos^2\vartheta^*$$

Mirkes, NP B387, 3 (1992) - $O(\alpha_s^2)$.

W Decay Distribution - α_2

$$\frac{d\sigma}{d\cos\vartheta^*} \propto 1 + P(W)\alpha_1 \cos\vartheta^* + \alpha_2 \cos^2\vartheta^*$$

V-A: $\alpha_2 = 1$



Including this effect in W mass Monte Carlo: ΔM_W ~ 40 MeV (D0)

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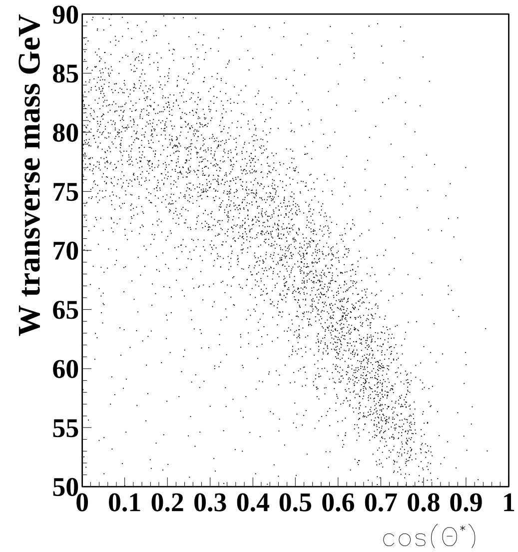
Method to measure α_2



- $P_Z(\nu)$ unknown: W rest frame cannot be reconstructed
- Use correlation between $\cos\theta^*$ and M_T^W to infer $\cos\theta^*$ on a statistical basis

- Define probability function

$$f(m_T, \cos\theta^*) = \frac{1}{N} g(m_T/\cos\theta^*) h(\cos\theta^*)$$

- For each $P_T(W)$ bin, plot background subtracted $m_T(W)$ and get

$$n_i = \sum_{m_{T_j}} N_{m_{T_j}} f(m_{T_j}, \cos\theta_i^*)$$

- Compare to n_i templates from MC

- Use log-likelihood to determine best value of $\alpha_2(P_T(W))$

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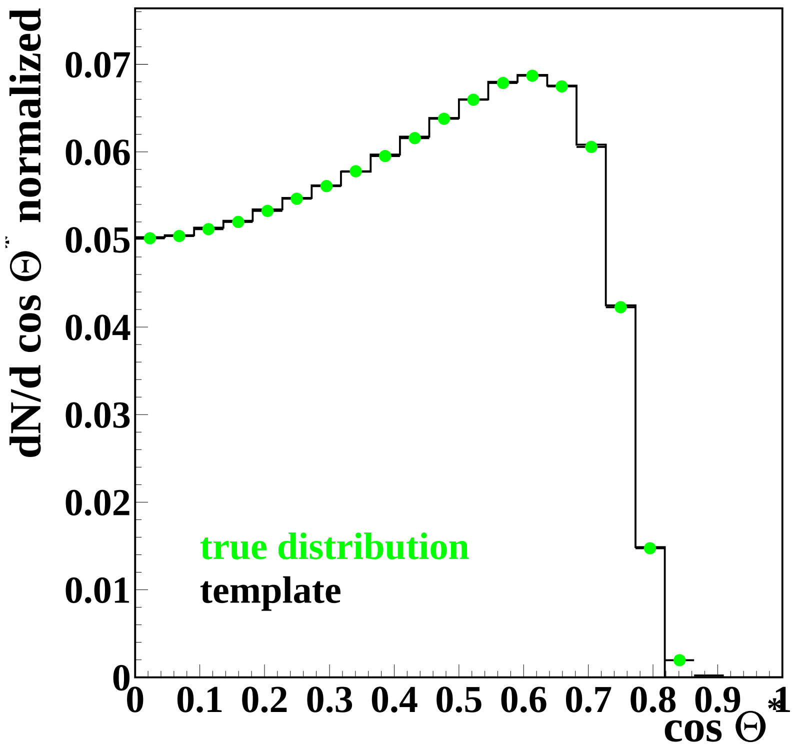
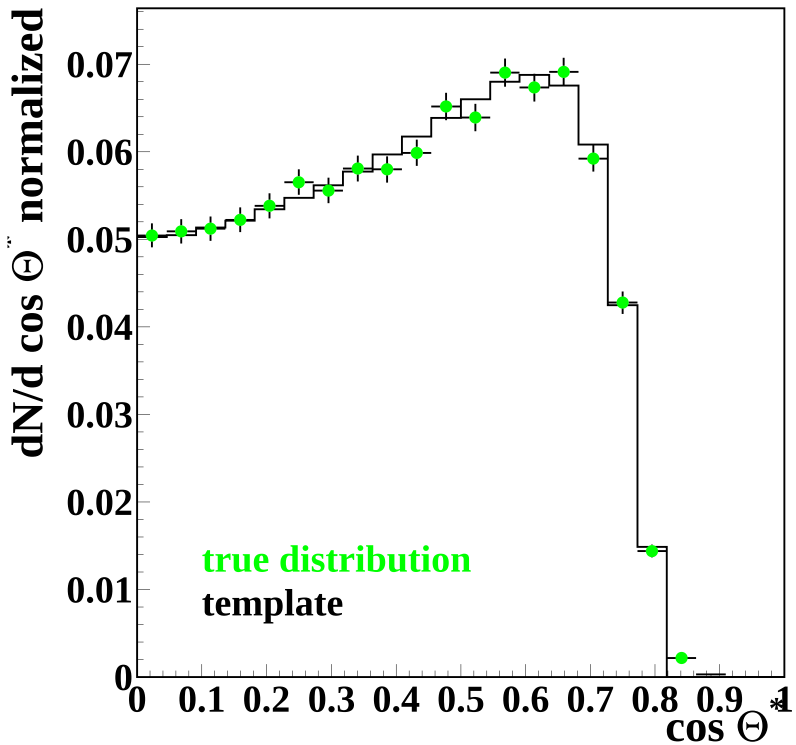
Monte Carlo Closure Test

Large Statistics



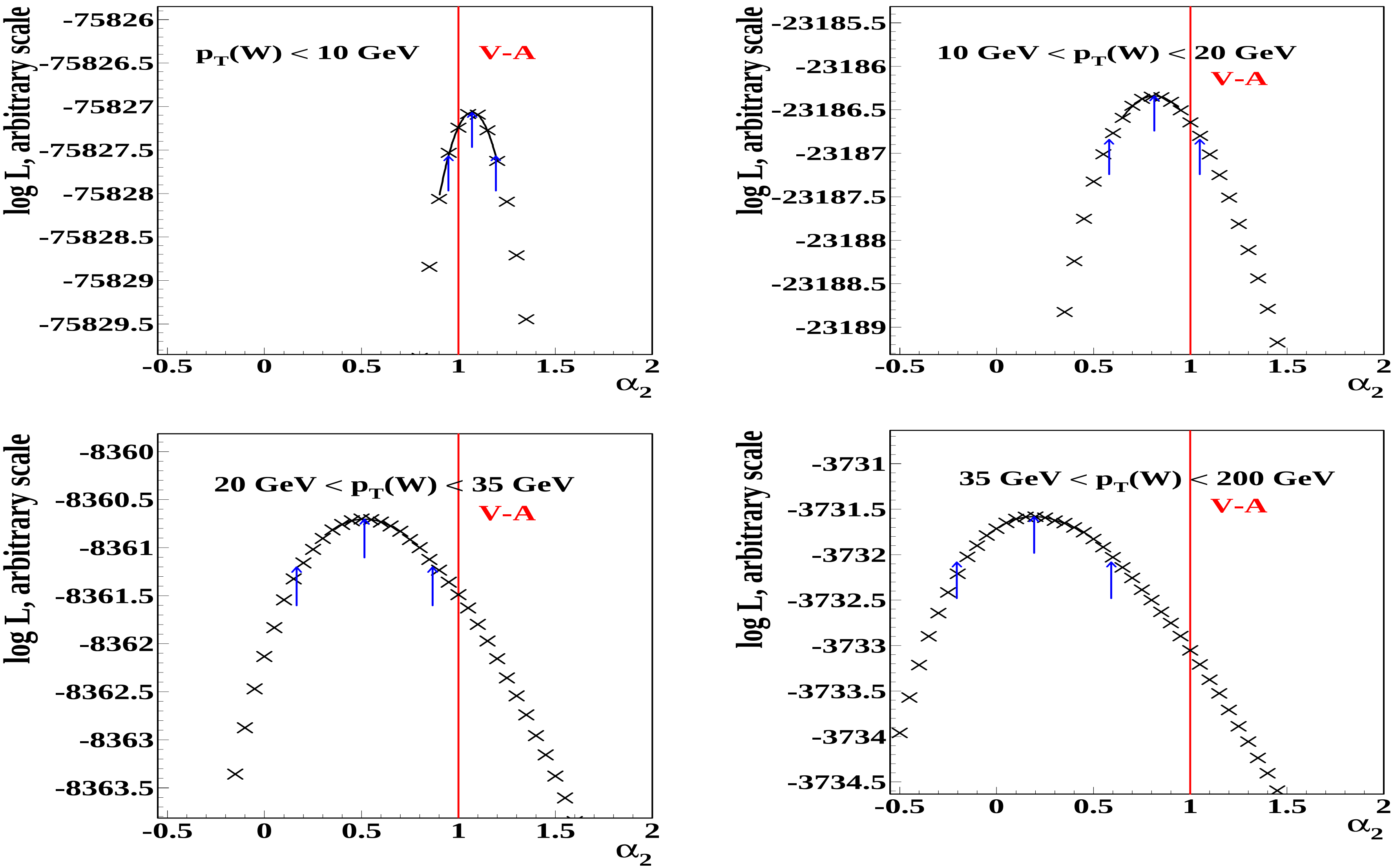
Statistics Scaled to Data



Method works!

Log-likelihood distributions

α_2 gets smaller for larger P_T



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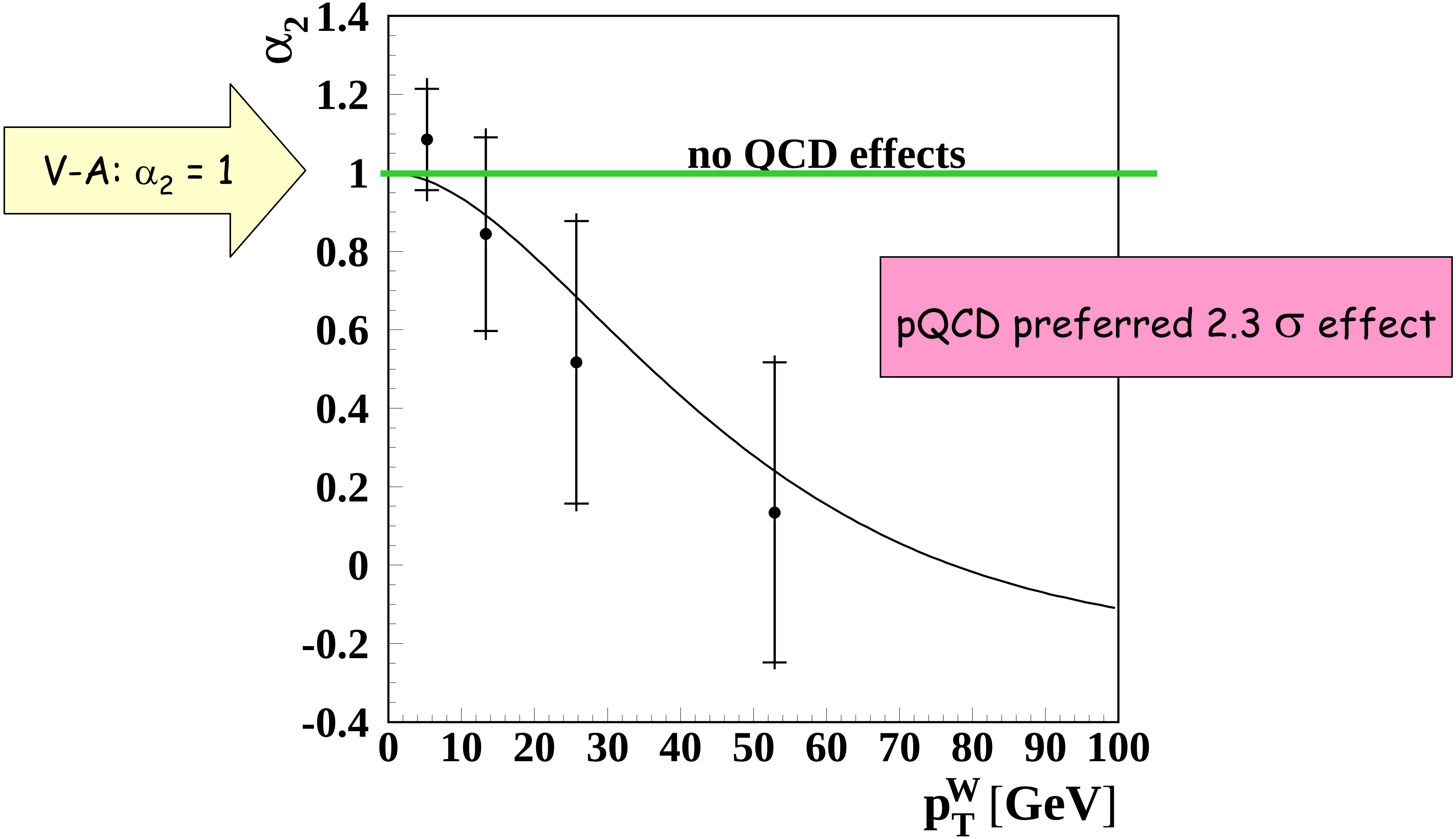
W Decay Distribution - α_2

Submitted to PRD, hep-ex/0009034



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W Decay Distribution - α_2

Submitted to PRD, hep-ex/0009034

p_T (GeV)	0-10	10-20	20-35	35-200
α_2,measured	1.09	0.84	0.52	0.13
Stat. Errors	±0.13	±0.25	±0.36	±0.38
α_2,predicted	0.98	0.89	0.68	0.24
Mean p_T^W	5.3	13.3	25.7	52.9
Combined Syst.	±0.08	±0.09	±0.12	±0.12

Measurement dominated by statistics

Systematic Errors

p_T (GeV)	0-10	10-20	20-35	35-200
QCD	±0.04	±0.05	±0.09	±0.07
$Z \rightarrow ee$	±0.01	±0.01	±0.02	±0.04
ttbar	±0.00	±0.00	±0.00	±0.02
EM scale	±0.06	±0.05	±0.03	±0.04
Had Scale	±0.03	±0.01	±0.04	±0.04
Had Resol	±0.02	±0.02	±0.05	±0.06
fixed α_1	±0.01	±0.05	±0.03	±0.03
Total syst.	±0.08	±0.09	±0.12	±0.12

Estimated by generating cos θ^* templates with varied parameters.

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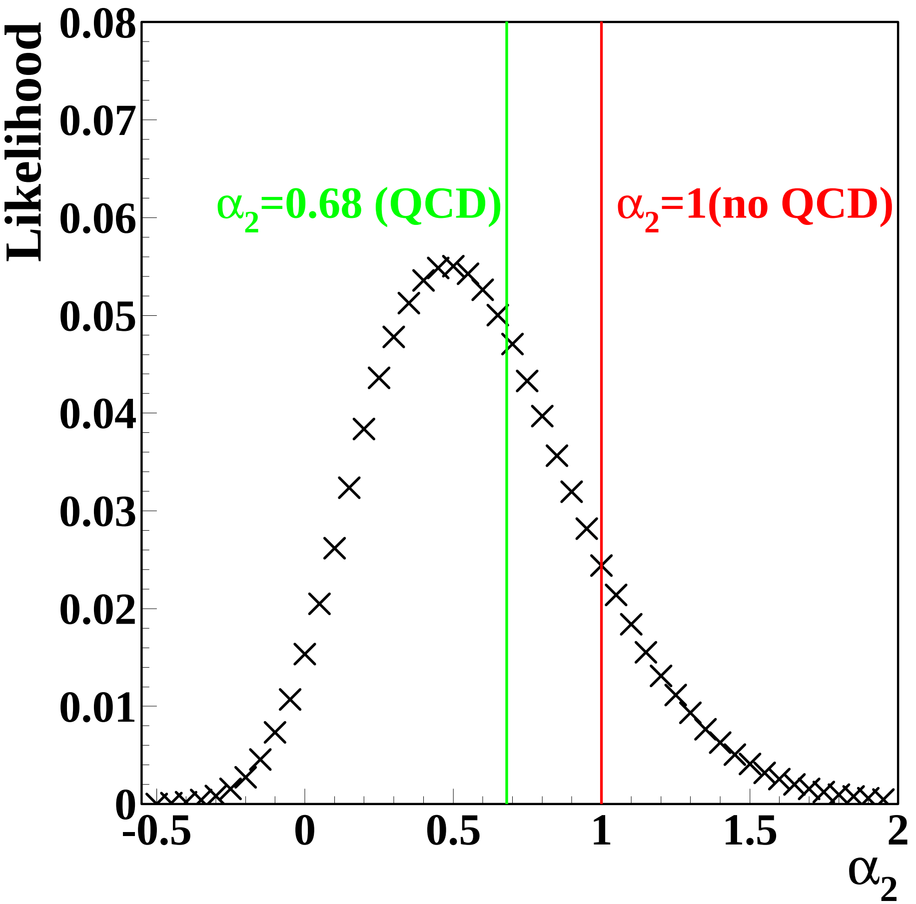
Significance Calculation

Odds-Ratio Method

$$R = \frac{\prod_i p_i(\alpha_2(QCD))}{\prod_i p_i(\alpha_2(no\ QCD))}$$



Log R = 0.5 → 1 σ

We get 2.3σ

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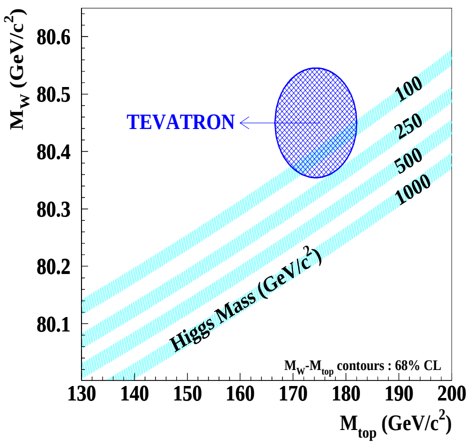
Connections between W,Z Production, QCD and New Physics

W boson mass + top quark mass: Constrain Higgs mass



Current CDF/DØ δM_W ~ 5-40 MeV from $P_T{}^W$ model

δM_W = 10 MeV $\Rightarrow$ $\delta M_H/M_H$ = 14%

W production Monte Carlos tuned to Z data

NLO QCD

Non-perturbative QCD

Resummation techniques

W measured distributions "confirm" formalism(s)

Z P_T distributions constrain non-pert. parameters

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Conclusions

- **W, Z inclusive cross sections** in good agreement with SM.
  Stat ⊕ Sys ~ 2%, Luminosity error ~ 4%, Theory error: ~ 3%
  Maybe use to *determine* luminosity in Run II.

- **W width** measurement (direct and indirect) in good agreement with SM.
  Indirect measurement error ~ 3%

- **W, Z P_T distributions** measured.
  D0 measurements over wide range of P_T with errors ~ 10 - 20%
  Testing NLO QCD + resummation + non-perturbative models,
  implications for Higgs P_T predictions.

- QCD correction to **W decay distribution** confirmed.
  D0 measurement of α_2 vs P_T^W

Preparing for Run 2: expect to collect 2fb^{-1} during 2001-2003

W/Z + jets will have statistics comparable to Run 1 jet physics

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