Production of Gauge Bosons at the Tevatron

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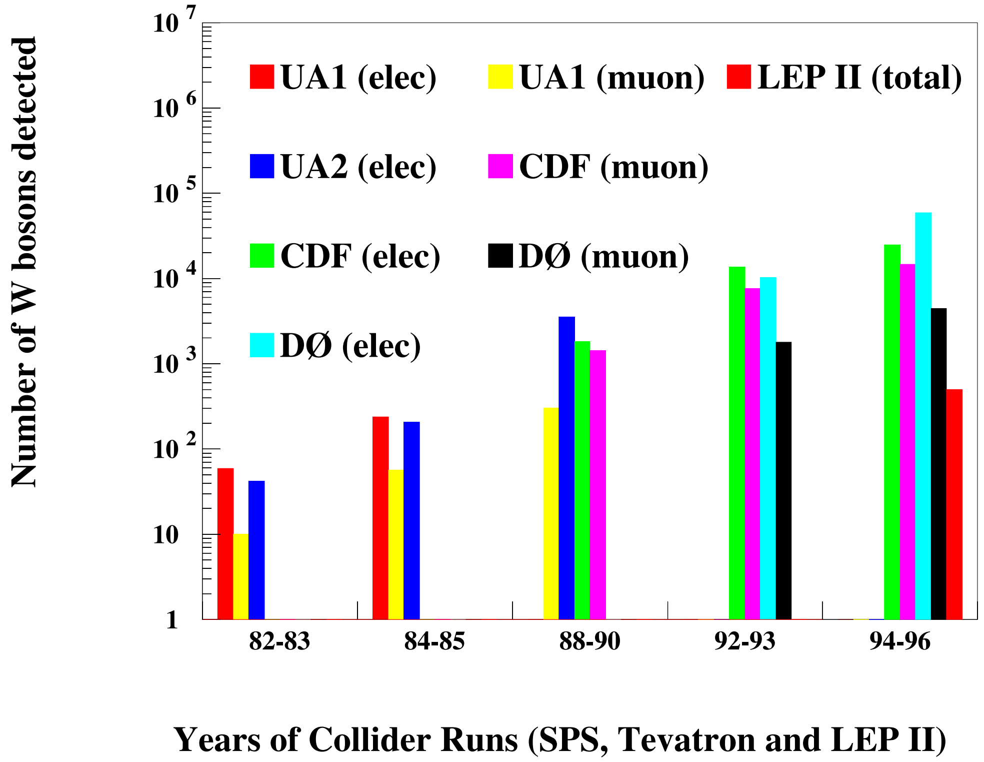
For the CDF and DØ Collaborations

The Irresistible Rise of the Standard Model,
San Miniato, April 1997

Outline

- W and Z Production x–sec (e, μ, τ)
- The Differential p_T^Z Cross–Section
- Drell–Yan Continuum Production
- W and Z + Jets Production
  - Measurement of $\overline{p}p \to W+ \geq nJets$ Cross Sections.
  - Comparison of Jet E_T, M_{jj} and ΔR_{jj} to LO QCD.
  - Measurement of the $(W+1Jet/W+0Jet)$ Cross Section Ratio.
- Conclusions and Outlook

W Bosons Detected

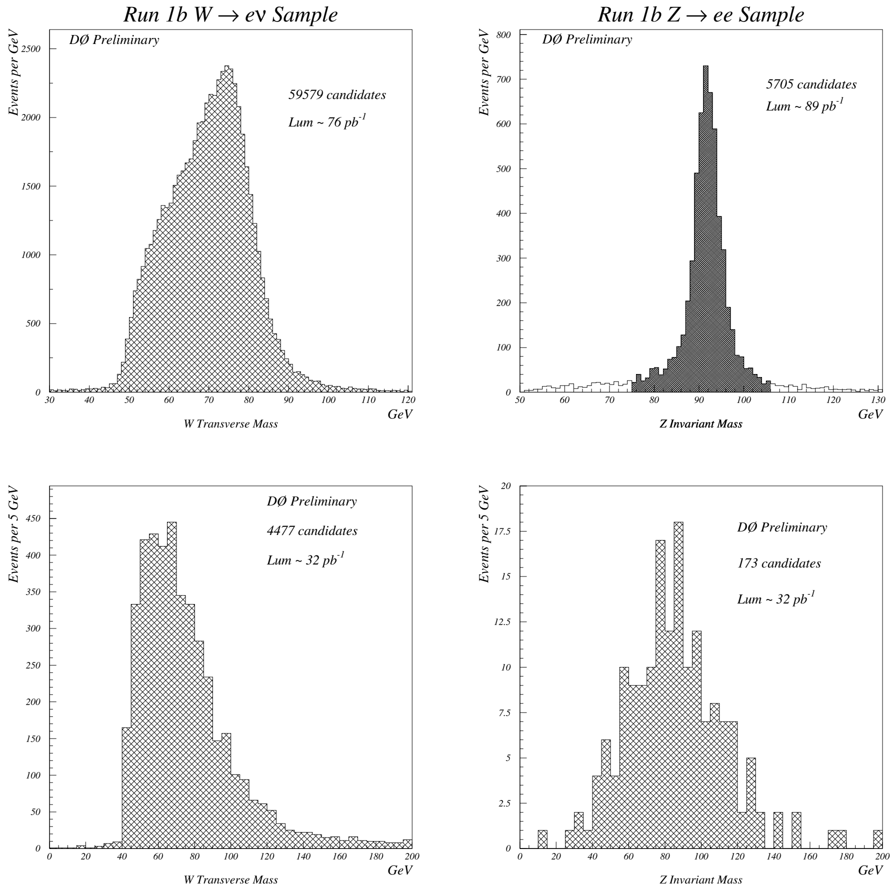


Tevatron Runs

- “Run 0 ” = 1988/90, $\int Ldt \sim 4\mathrm{pb}^{-1}$ (CDF)
- “Run 1A” = 1992/93, $\int Ldt \sim 20\mathrm{pb}^{-1}$
  - final results published for most analyses
- “Run 1B” = 1994/95, $\int Ldt \sim 90\mathrm{pb}^{-1}$
  - many preliminary results and some final results

W and Z inclusive samples

(DØ Run 1B, preliminary)



Event selection:

- high quality isolated leptons
- $p_T(\ell) > 20(\mu), 25(e)$ GeV
- Missing $E_T > 20(\mu), 25(e)$ GeV (W only)

$$\varepsilon^W(e) \approx 70\%, \qquad A^W(e) \approx 45\%$$

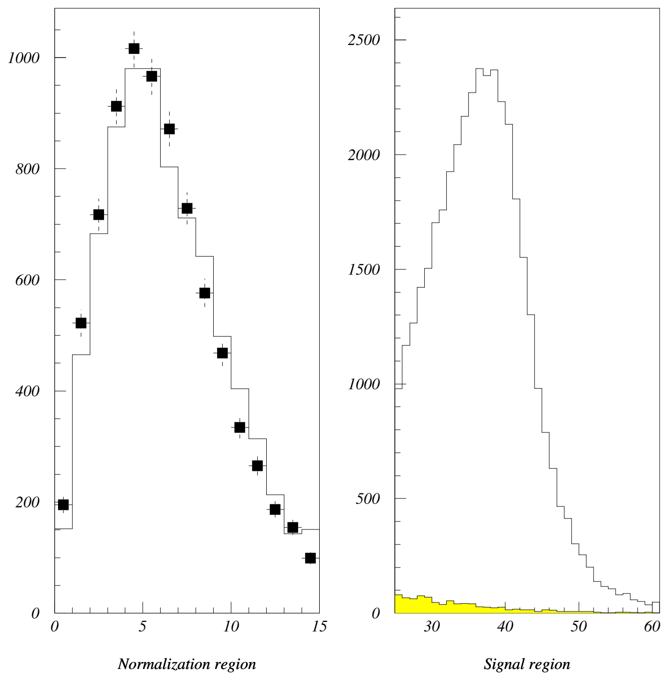
$$\varepsilon^Z(e) \approx 76\%, \qquad A^Z(e) \approx 35\%$$

$$\frac{\varepsilon_Z}{\varepsilon_W} = 1.084 \pm 0.025$$

$W \rightarrow e\nu$ Backgrounds

- Major background source is QCD dijets. One jet fluctuates electromagnetically and gets selected as an electron. The mismeasured energy fakes the $\not{E}_T$.

- Estimate normalizing the low $\not{E}_T$ spectrum of fake and good electrons and extrapolating to the signal region $\not{E}_T > 25$ GeV.



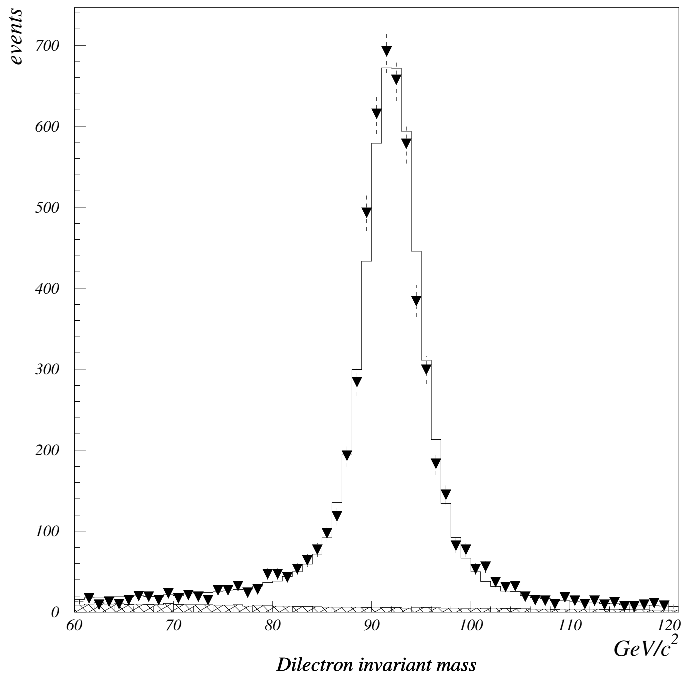
$f_{QCD}(CC) = 1.8 \pm 0.5\%$ $f_{QCD}(EC) = 14.1 \pm 2.5\%$

- Remaining backgrounds: $W \rightarrow \tau\nu$, $Z \rightarrow \tau\tau$ and $Z \rightarrow e\not{e}$, are estimated using Monte Carlo samples.

$f_{\tau} = 1.8 \pm 0.1\%$ $f_{Z \rightarrow e\not{e}} = 0.6 \pm 0.1\%$

$Z \to ee$ Backgrounds

- Major background source is QCD (dijet and direct photon), with jets faking electrons.
- Estimate by fitting the data to Signal $Z \to ee$ from Monte Carlo plus Background from data.

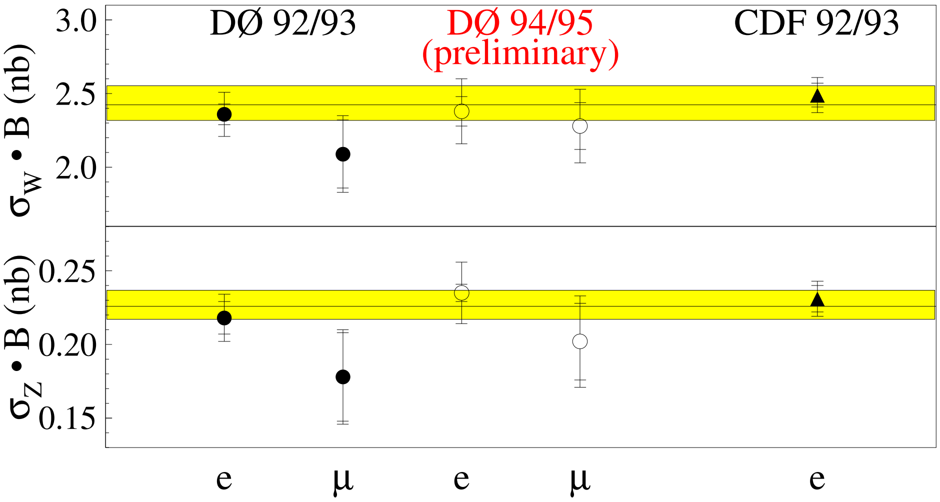


$$f_{QCD}(CC - CC) = 2.1 \pm 0.6\%$$
$$f_{QCD}(CC - EC) = 5.3 \pm 0.8\%$$
$$f_{QCD}(EC - EC) = 4.8 \pm 1.5\%$$

- Remaining backgrounds: Drell–Yan and $Z \to \tau\tau$ are estimated using Monte Carlo samples.

$f_{DY} = 1.2 \pm 0.1\%$ $\qquad$ $f_{Z \to \tau\tau}$ = negligible

W and Z cross sections



- Theory: $O(\alpha_s^2)$, Hamberg, van Neerven & Matsuura, NP B359, 313; van Neerven & Zijlstra, NP B382, 11.

- Dominant uncertainties:
  - Data: luminosity ($\approx 8\%$)
  - Theory: parton distribution functions ($\approx 3\%$)

DØ Run 1B (prelim), uncertainties: stat., syst., lum.

$$\sigma \cdot B(W \to e\nu) = 2.38 \pm 0.01 \pm 0.09 \pm 0.20\text{nb}$$

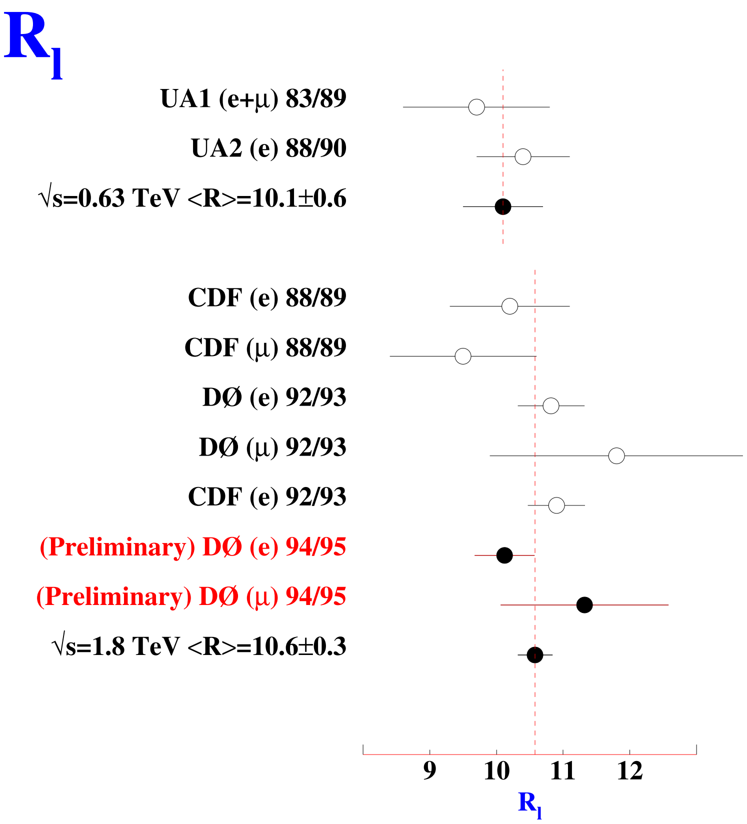
$$\sigma \cdot B(W \to \mu\nu) = 2.32 \pm 0.04 \pm 0.16 \pm 0.19\text{nb}$$

$$\sigma \cdot B(Z \to ee) = 0.235 \pm 0.003 \pm 0.005 \pm 0.020\text{nb}$$

$$\sigma \cdot B(Z \to \mu\mu) = 0.202 \pm 0.016 \pm 0.020 \pm 0.017\text{nb}$$

Expect systematic uncertainty to be reduced to $\approx 2\%$ in the Cross–Sections and to $\approx 1\%$ in the Ratio.

Cross Section Ratio (Γ_W)



$$R_\ell = \frac{\sigma(W)}{\sigma(Z)} \cdot \frac{B(W \to \ell\nu)}{B(Z \to \ell\ell)}$$
$$= \frac{\sigma(W)}{\sigma(Z)} \cdot \frac{\Gamma(W \to \ell\nu)}{B(Z \to \ell\ell)} \cdot \frac{1}{\Gamma(W)}$$

DØRun 1B (preliminary): $R_\ell = 10.32 \pm 0.43$

- $\sigma(W)/\sigma(Z)$ from theory, $B(Z)$ from LEP/SLC:
  - $B(W \to \ell\nu) = (10.43 \pm 0.44)\%$
- assume $\Gamma(W \to \ell\nu)$ as well:

$\boxed{\Gamma(W) = 2.159 \pm 0.092 \text{ GeV}}$

(SM: $\Gamma(W) = 2.077 \pm 0.014$ GeV)

$W \to \tau\nu$

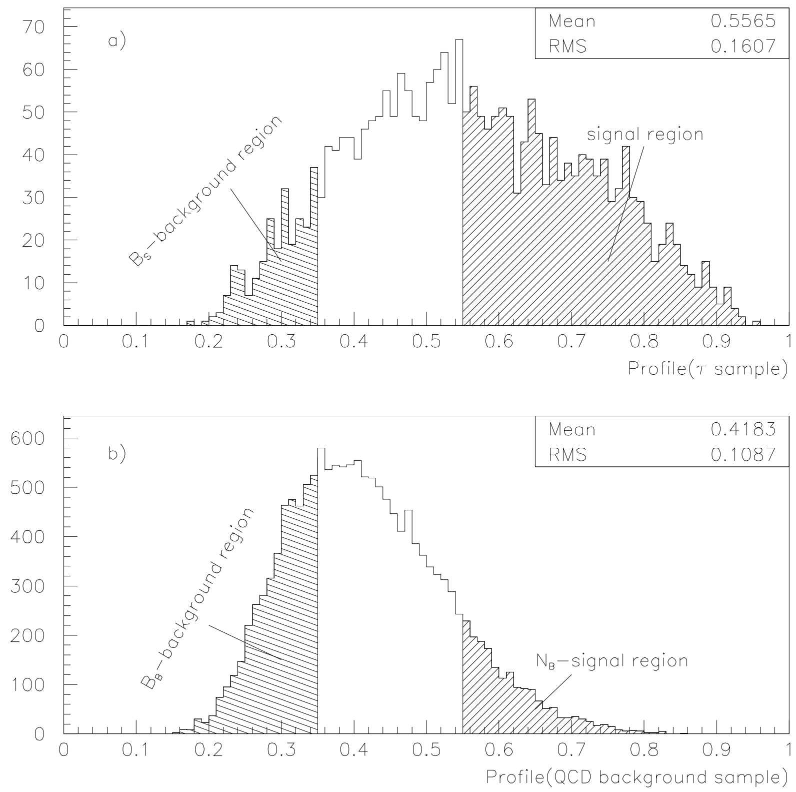
τ Candidate Selection

- Use hadronic decay of the tau: isolated, narrow jet
- E_T(jet)$>$ 25 GeV ($|\eta| < 0.9$), $\not{E}_T > 25$ GeV

Background Estimations

- QCD from Profile distribution (data), $f_{QCD} \approx 9\%$

  Profile =(sum of highest 2 tower E_T)/(cluster E_T)



- Noise from $\Delta\phi$ distribution between τ and closest CD track (data), $f_{Noise} \approx 7\%$
- Physics ($Z \to \tau\tau$,$W \to e\nu$) from Monte Carlo (3%)

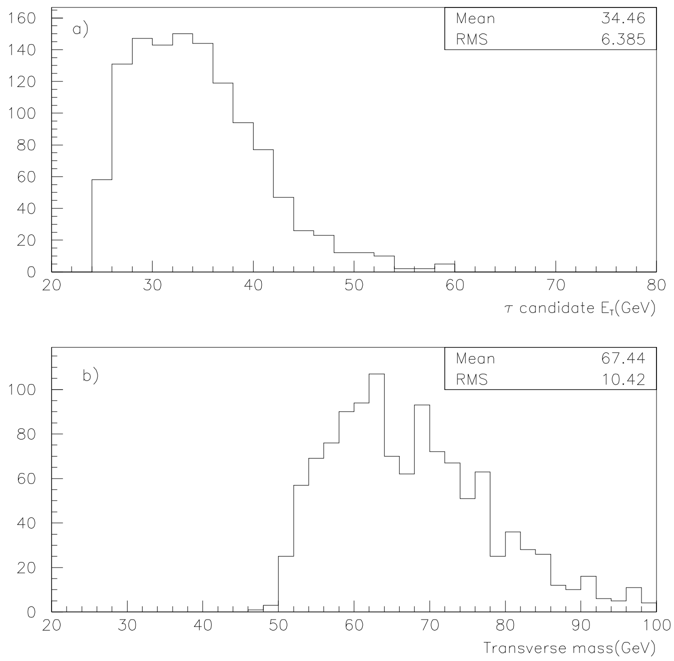
$W \to \tau\nu$ Inclusive Cross Section

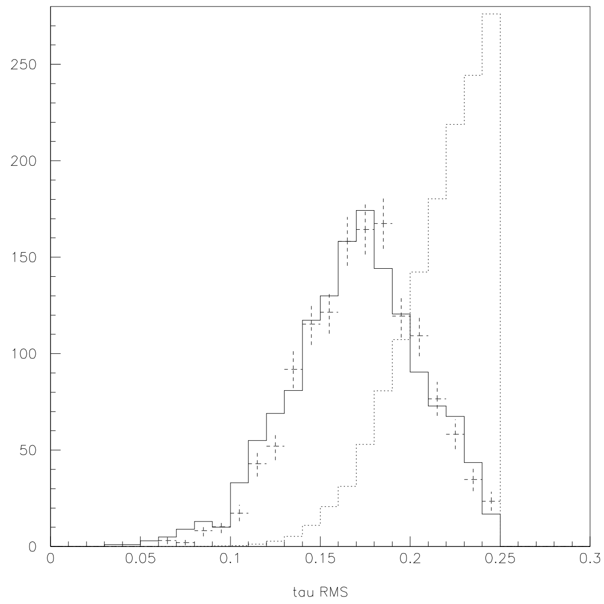
(DØ Run 1, preliminary)

	Number of Events
Final Data Sample	1202
QCD Background	$106 \pm 7 \pm 5$
Noise Events	81 ± 14
$Z \to \tau\tau$	32 ± 5
$W \to e\nu$	3 ± 1

Acceptance $\times$ efficiency: 0.38

Luminosity: $16.8 \pm 0.9\mathrm{pb}^{-1}$





$$\sigma \cdot B(W \to \tau\nu) = 2.38 \pm 0.09 \pm 0.10\mathrm{nb}$$

$$\boxed{g_\tau^W / g_e^W = 1.00 \pm 0.02 \pm 0.03}$$

Differential p_T^Z Cross Section

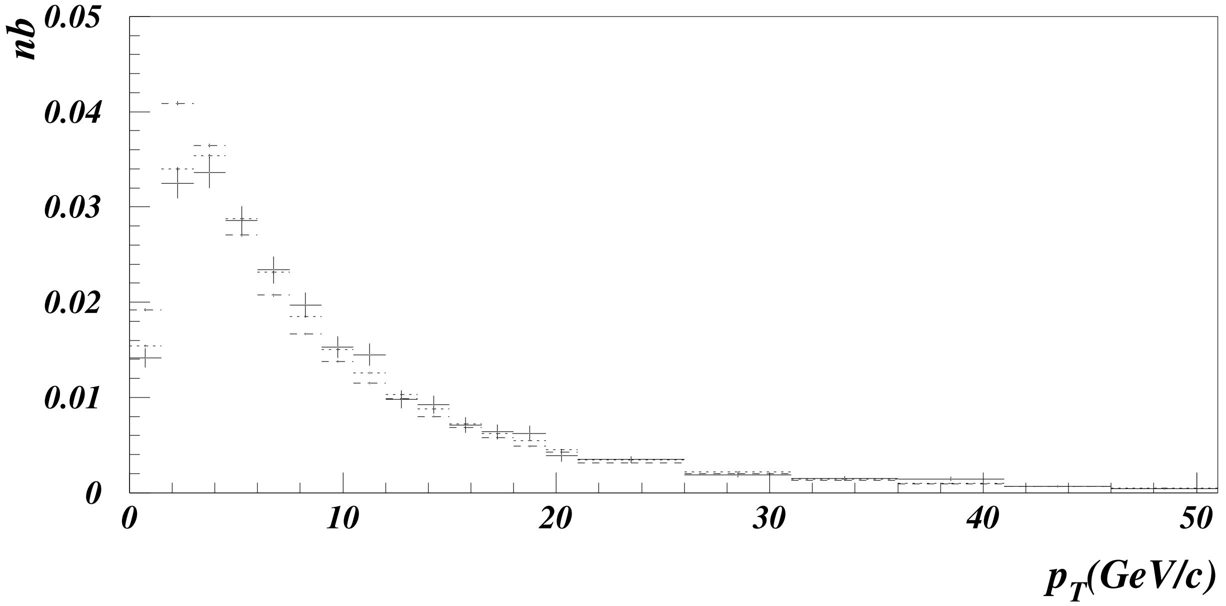
- Test Vector Boson Production phenomenology (Ladinsky–Yuan 1993, Arnold–Kauffman 1990.)
- Look for New Physics
- Reduce systematic uncertainty in W Mass and Direct Width measurements.

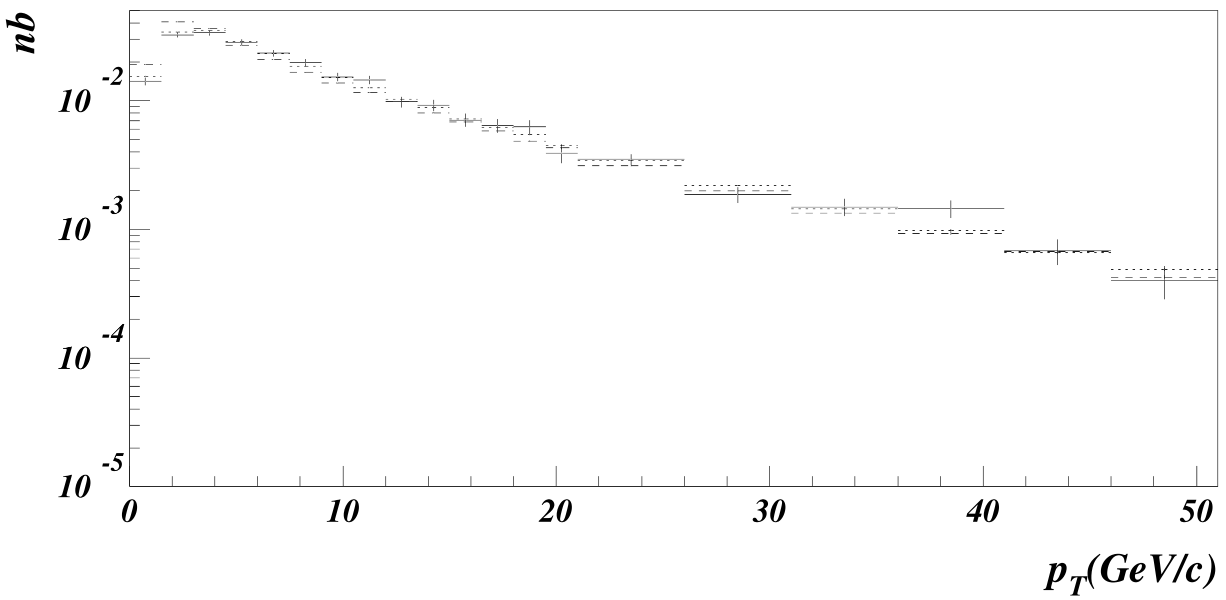
Need to determine all quantities as a function of p_T^Z

- Measure $\sigma_i = (N_i^{obs} - N_i^{bkd})/(A_i\varepsilon_i)$ normalized to DØ measured σ_e^Z.
- Acceptance vs p_T^Z obtained from fast Monte Carlo.
  - Input p_T^Z from Ladinsky–Yuan with MRSA structure functions
  - Detector simulation taken from W mass analysis.
- Efficiency vs p_T^Z obtained from HERWIG $Z \to ee$ with full detector simulation and overlayed zero bias events.
- Primary background is QCD ($\approx 3\%$)
  - Total background level from fit to M_{ee}.
  - Background shape vs p_T^Z obtained from data

Differential p_T^Z Cross Section

(DØ Run 1B, preliminary)





Data (full), Ladinsky–Yuan (dotted), Arnold-Kauffman (dashed).

L–Y describes the data better than A–K for $p_T^Z < 15$ GeV (χ^2 dof $= 1.25$ vs 9.2).

Drell–Yan Continuum Production

- Measure $d^2\sigma/dMdy$ ($|y| < 1$) for $\overline{p}p \rightarrow l^+l^- + X$.
- Compare to Standard Model Drell–Yan prediction and search for evidence of compositeness.

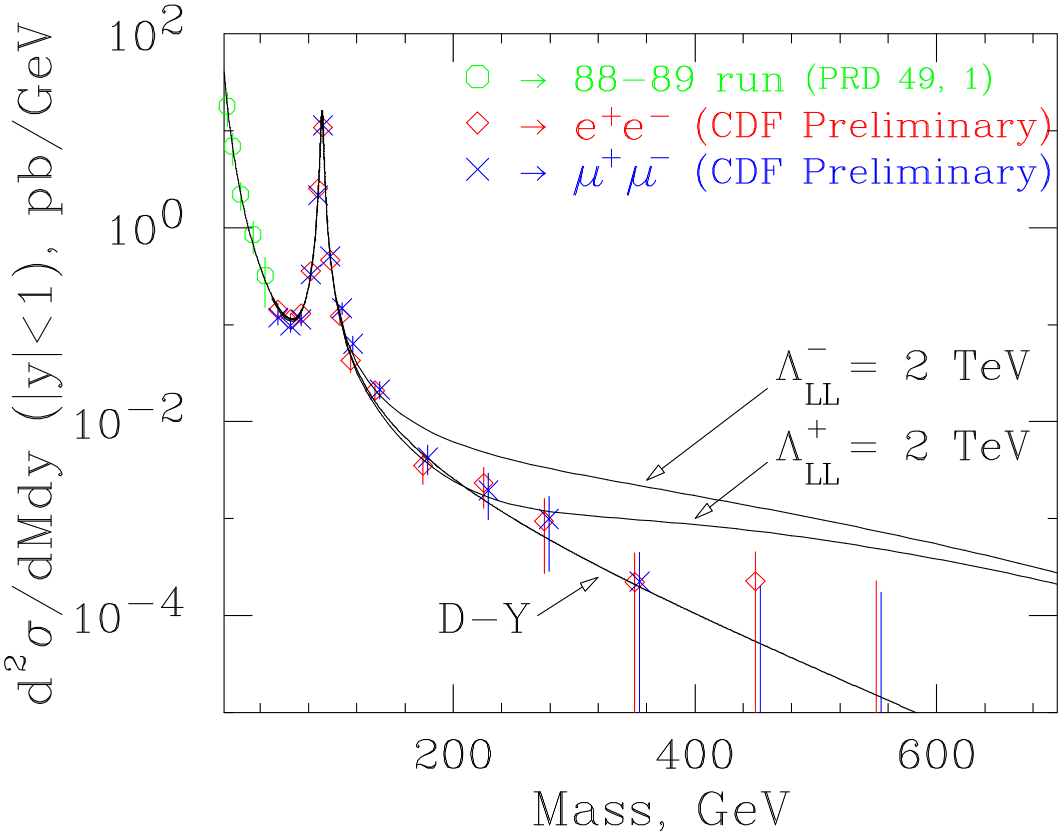
- Event selection
  - high quality isolated central leptons (e, μ).
  - $E_T^l > 20$ GeV, $M_{ll} > 50$ GeV.
  - Candidate pairs have opposite electric charge.

- Backgrounds
  - QCD dijets estimated from same–charge ll pairs.
  - Diboson and Top estimated from opposite–charge $e\mu$ pairs.

- Compositeness Models
  - Assume deviation of data from SM prediction is due to composite fermions and quarks with common substructure.
  - Calculate $d^2\sigma/dMdy$ in LL QCD aproximation including ELHQ amplitudes (PRL 50, 811 and Rev. Mod. Phys. 56, 579) to establish compositeness scale.
  - Consider different chiral models categorized by the signed interaction strengths.

Drell–Yan Continuum Production

(CDF Run 1, preliminary)



- Data and theory normalized in 50 – 150 GeV range.
- D–Y curve is Standard Model NLL QCD from A. D. Martin *et al*, Phys. Lett. B354 1995.
- LL chiral model giving largest differences shown.
- No significant deviation from the Standard Model is found.
- Improved limits on compositeness scales are obtained at single sided 95% Confidence Level for the combined e, μ data.
- $\Lambda_{ql} \sim 3 - 6$ TeV depending on the model.

Measurement of $\sigma_n^e(W + nJets)$

- Measure $p\overline{p} \rightarrow W+ \geq nJet$ Cross Sections.

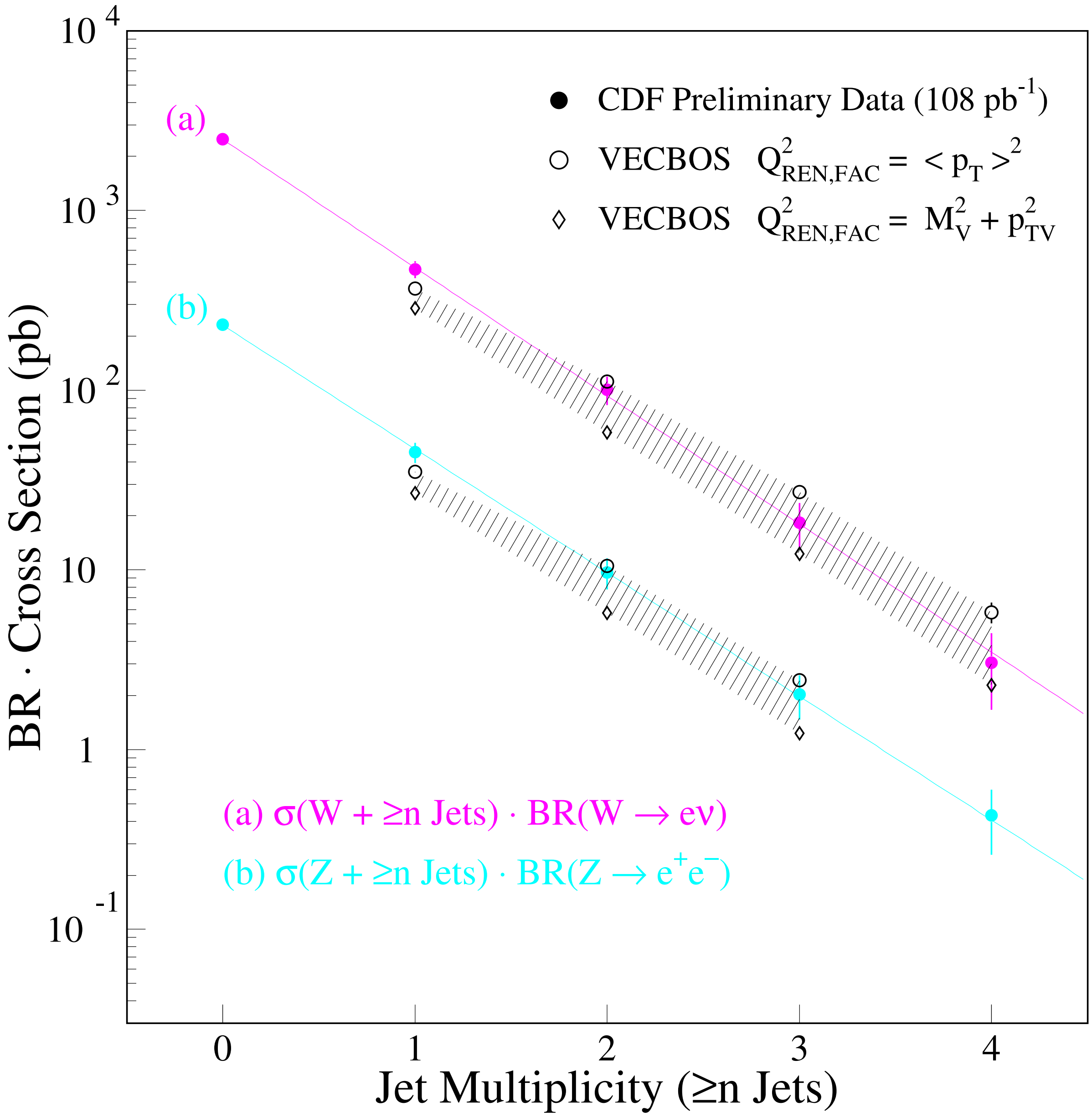
$$\sigma_n^e = \sigma_0^e \frac{(N_n - B_n)\varepsilon_0}{(N_0 - B_0)\varepsilon_n} \text{ for } n = 1, 4.$$

- Compare to LO QCD predictions with MRSA' and CTEQ3M:
  - VECBOS MC calculates the LO Matrix Elements.
  - HERWIG produces gluon radiation and fragmentation.
  - Full CDF Detector Simulation
- Restrict analysis to central electrons in η.
- Jets reconstructed using 0.4 fixed cone algorithm.

Need to determine all quantities as a function of the number of jets.

- Backgrounds
  - QCD multijet background (2.9% to 27%)
  - $W \rightarrow \tau\nu$, $Z \rightarrow \tau\tau$, $Z \rightarrow e\not{e}$ (3%)
  - Top, Diboson (0.1% to 17%)
- Overall detection efficiencies $\approx$ 20%

Measurement of $\sigma_n^e(W + nJets)$
(CDF Run 1, preliminary)

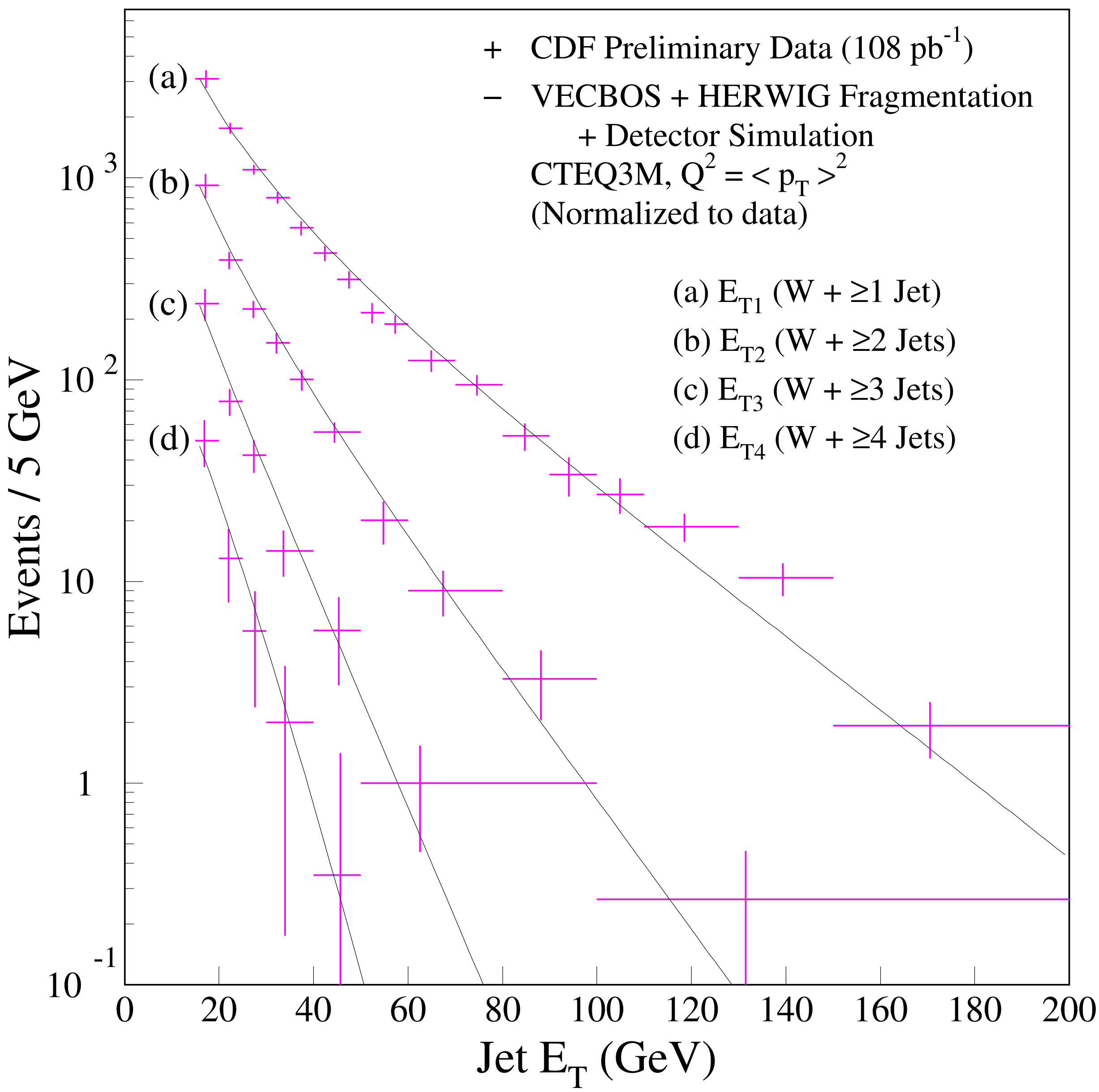


$W + njets$ cross sections are a factor of 1.7 larger than LO QCD Prediction for $Q^2 = M_W^2 + p_T^{W\ 2}$

$Z + njets$ are from F. Abe *et al*, Phys. Rev. Lett. **77,** 1996.

Jet E_T Distributions

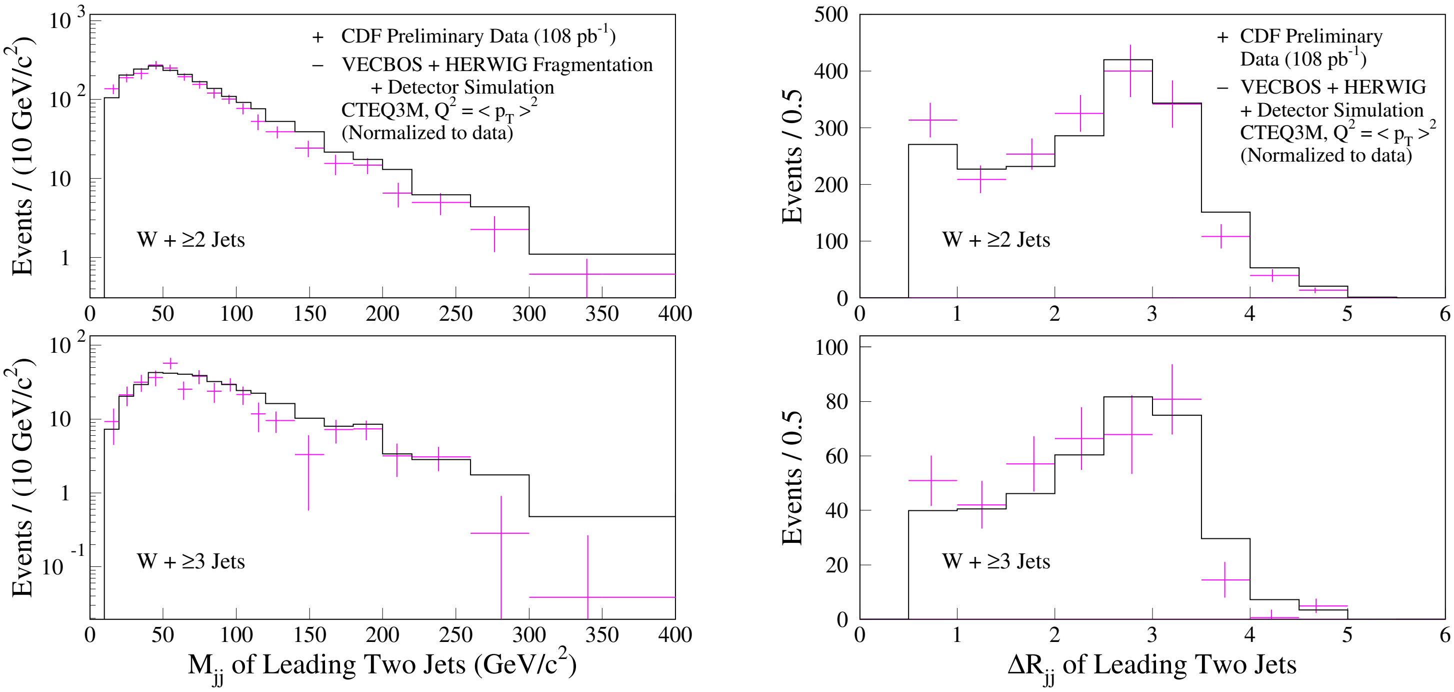
(CDF Run 1, preliminary)



Error bars include statistical uncertainties and background subtraction systematics.

M_{jj} and ΔR_{jj} Distributions

(CDF Run 1, preliminary)



Error bars include statistical uncertainties and background subtraction systematics.

LO QCD reproduces well the Jet Production Distributions for E_T, M_{jj} and ΔR_{jj}.

Measurement of $R_{10} \equiv \frac{\sigma_e(W+1Jet)}{\sigma_e(W+0Jets)}$

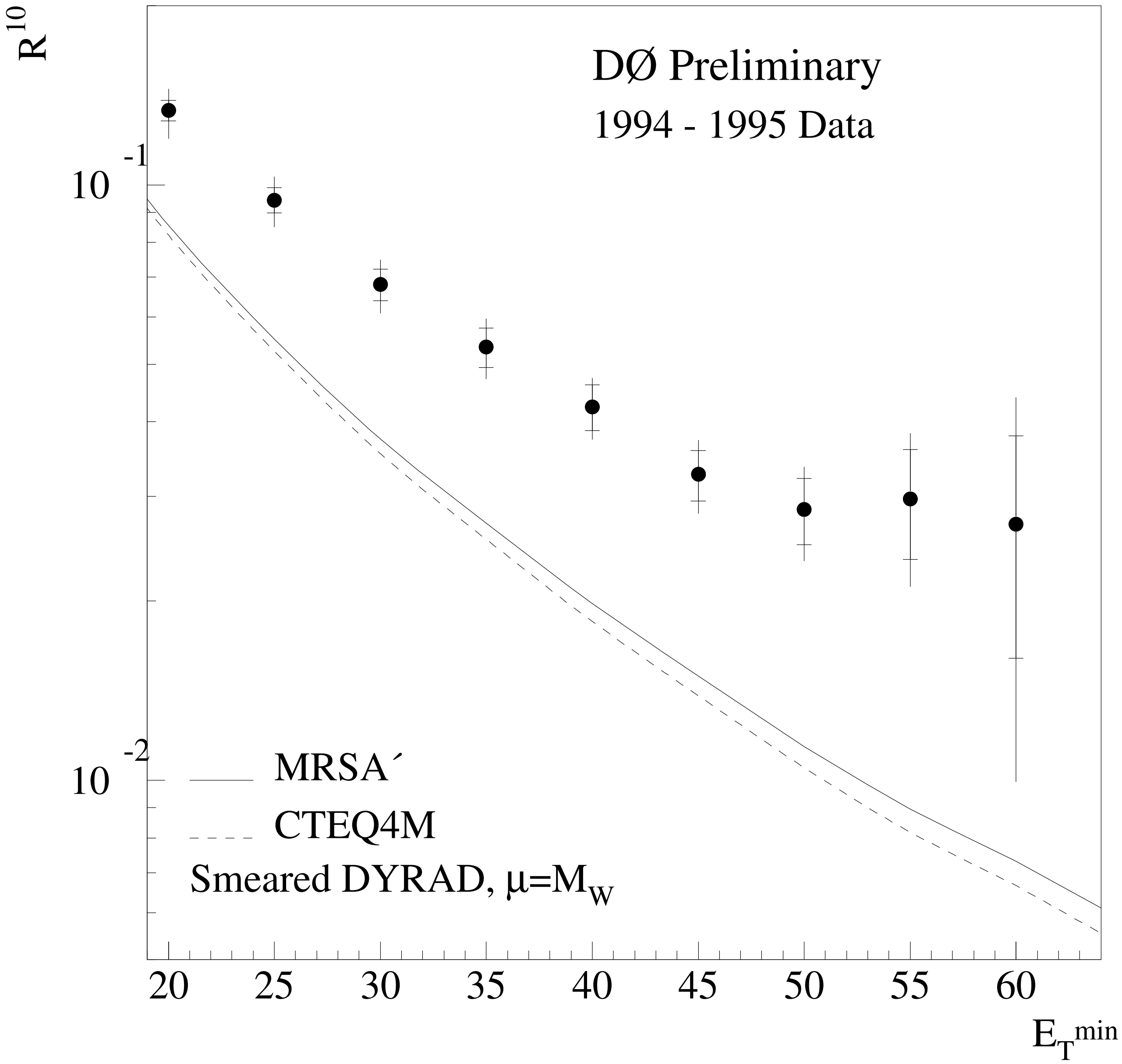
- Study R_{10} vs Jet E_T^{min} in 20–60 GeV range.
- Compare to NLO calculations DYRAD Monte Carlo (Giele, Glover, Kosower 1993, NPB403) tailored to the experimental e and jet definition.
  - Restrict analysis to central electrons in η.
  - Jets reconstructed using 0.7 fixed cone algorithm.

Need to determine all quantities as a function of Jet E_T^{min}

- Primary background is QCD dijet and direct photon production.
  - Fraction of background from **1.5%** to **20%**
  - Shape vs Jet E_T^{min} obtained directly from data.
- Physics background $Z \rightarrow e\not{e}$ and $Z \rightarrow \tau\tau$. ($W \rightarrow \tau\nu$ included in sample).
  - Fraction of background from **0.5%** to **2%**.
  - Shape vs Jet E_T^{min} obtained from signal Monte Carlo.
- Efficiency vs Jet E_T^{min} obtained from $Z \rightarrow ee$ data.
- Acceptance vs Jet E_T^{min} included in Monte Carlo.
- Dominating uncertainties at $E_T^{min} = 25$ **GeV**
  - Electron selection efficiency ($\pm 5\%$).
  - Jet Energy Scale ($\pm 5\%$).

Measurement of $R_{10} vs E_T^{min}$

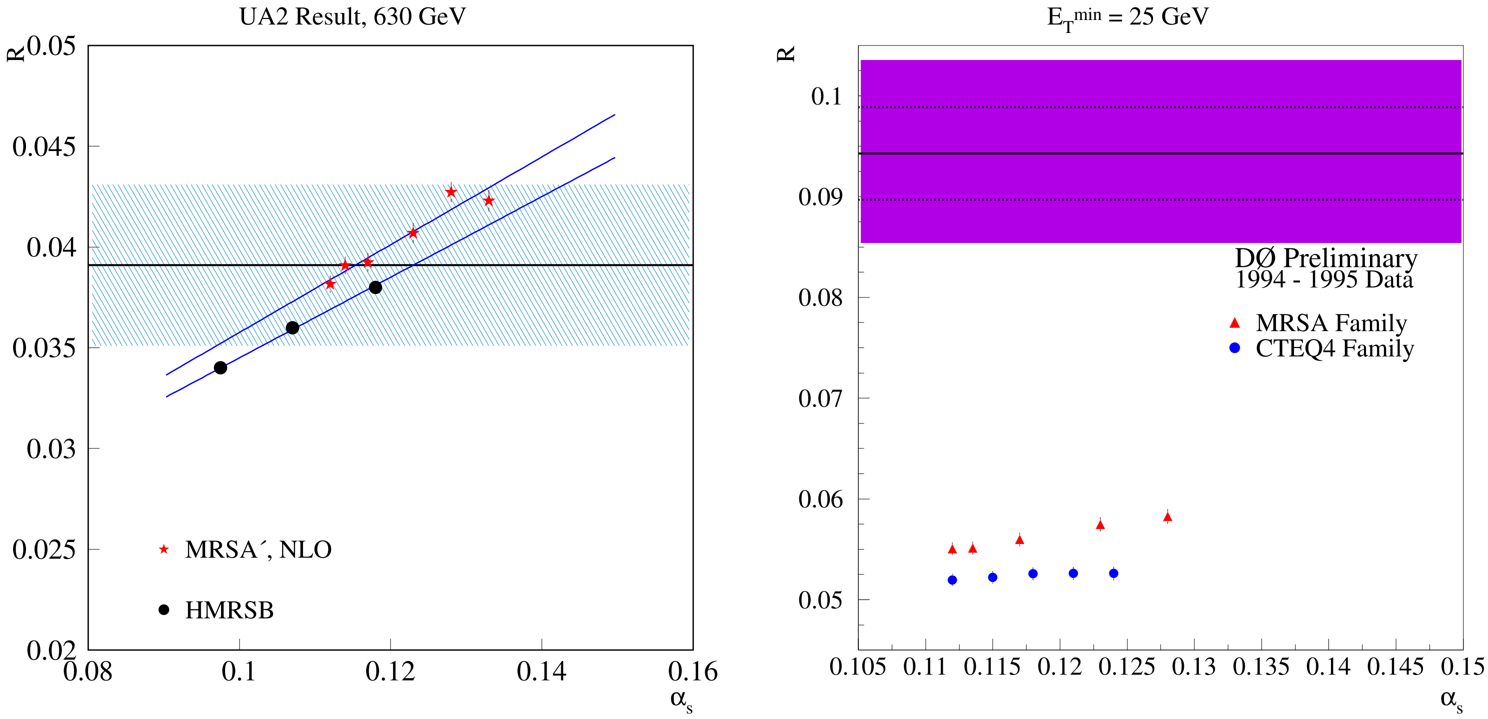
(DØ Run 1B, preliminary)



- DYRAD describes the trend of the data vs E_T^{min} but not the absolute value.

Measurement of $R_{10} vs \alpha_s$

(DØ Run 1B, preliminary)



- DYRAD agrees with the UA2 result ($\sqrt{s} = \mathbf{630\ GeV}$) and reproduces the total DØ W Cross Section.
- NLO QCD with currently available PDF's underestimate the ratio at $\sqrt{s} = \mathbf{1.8\ TeV}$
- UA2 and DØ are sensitive to different x regions of the PDF's and different mixtures of partons in the proton.

Conclusions and Outlook

- Shown Preliminary Tevatron (CDF and DØ) results from Run 1B data.

  e, μ, τ x-sections, $W/Z + Jets$.

  (W Mass Measurement and Diboson Production shown in electroweak session.)

- SM prediction for Γ_W and Drell–Yan production agrees with data.

- Set q and l compositeness scales to $\Lambda_{ql} \sim 3 - 6$ TeV

- NLO QCD underestimates $W + 1Jet$ production measurement from both experiments.

- The jet production distributions (E_T, M_{jj}, ΔR_{jj}) are well modelled by LO QCD.

- **Work is in progress on** p_T^W , R_{10}^Z, Γ_W **(direct measurement),** $W \to \tau\nu$ **charge asymmetry,** x_s, ...

- **DØ and CDF are currently upgrading their detectors and expect to collect** $\approx 2fb^{-1}$ **of data during Run 2(1999–2002).**