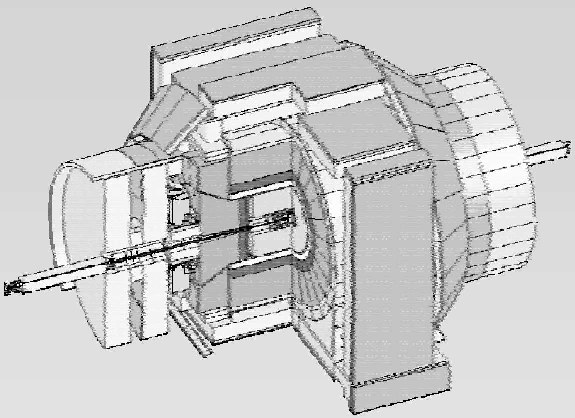
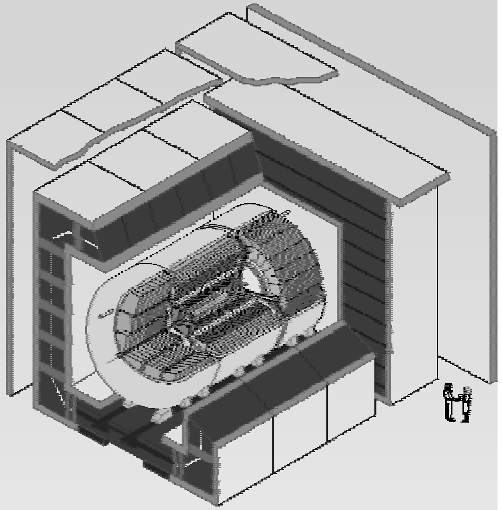
# QCD and EW Results at the Tevatron Collider



**CDF**

**DØ**



| THEN | | NOW |
|---|---|---|
| **QCD** | | |
| **&** | **@ Run I** | **Prospects for Run II** |
| **EW Physics** | | |

Personal overview: short change of many analyses!

**Bob Hirosky** **University of Virginia** **La Thuile** **March 6, 2001**

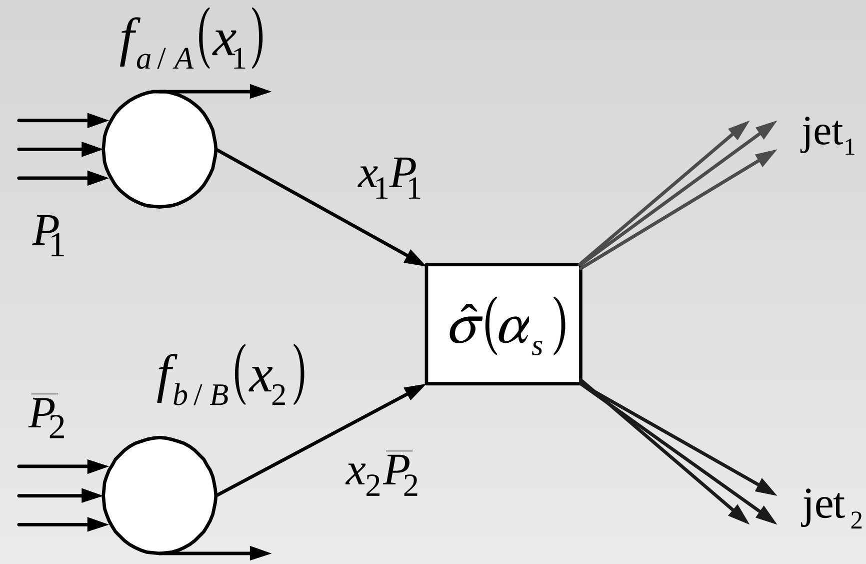
# QCD in Run I

**Jets:**

Inclusive cross sections and ratios:
pfd, pQCD, …

Dijet Angular Correlations/Mass:
compositeness, pQCD

Shapes&Fragmentation:
hard emission/shower development




**Photons:**

Inclusive cross sections

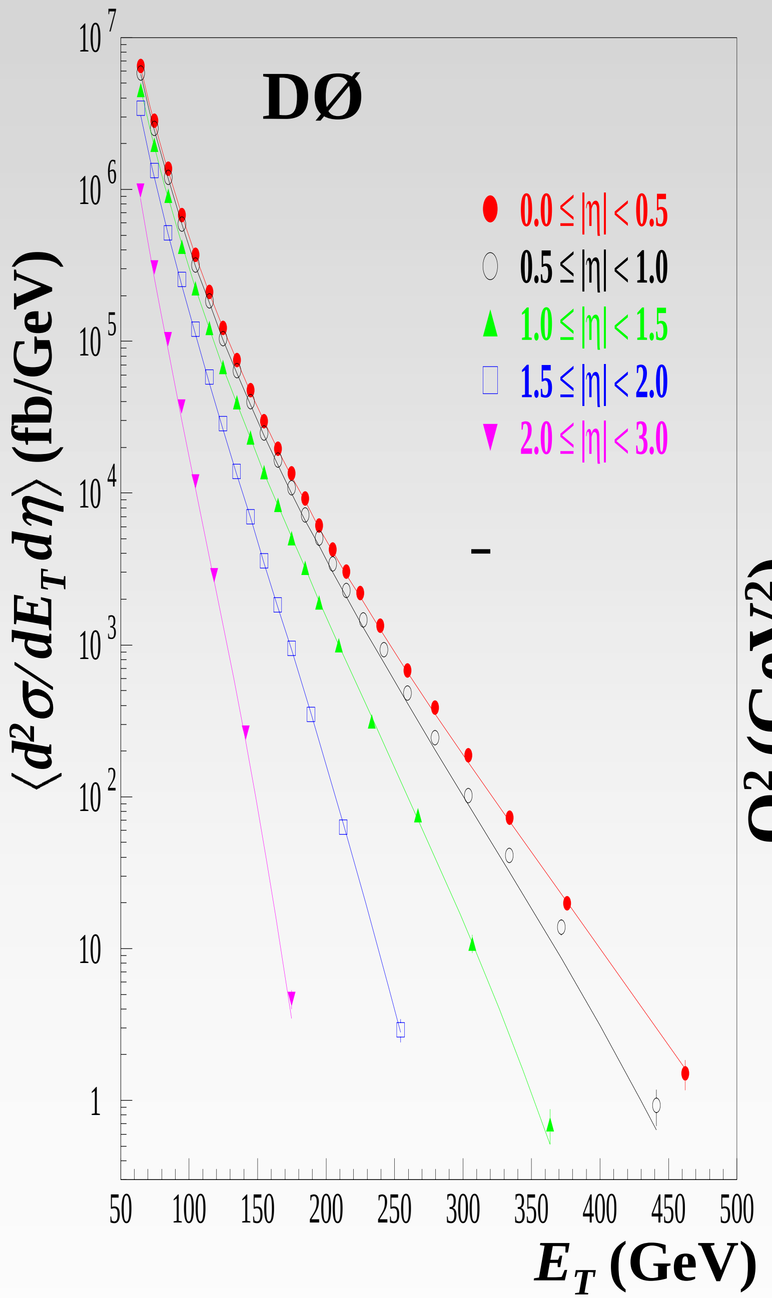
Soft Radiation/KT effects!

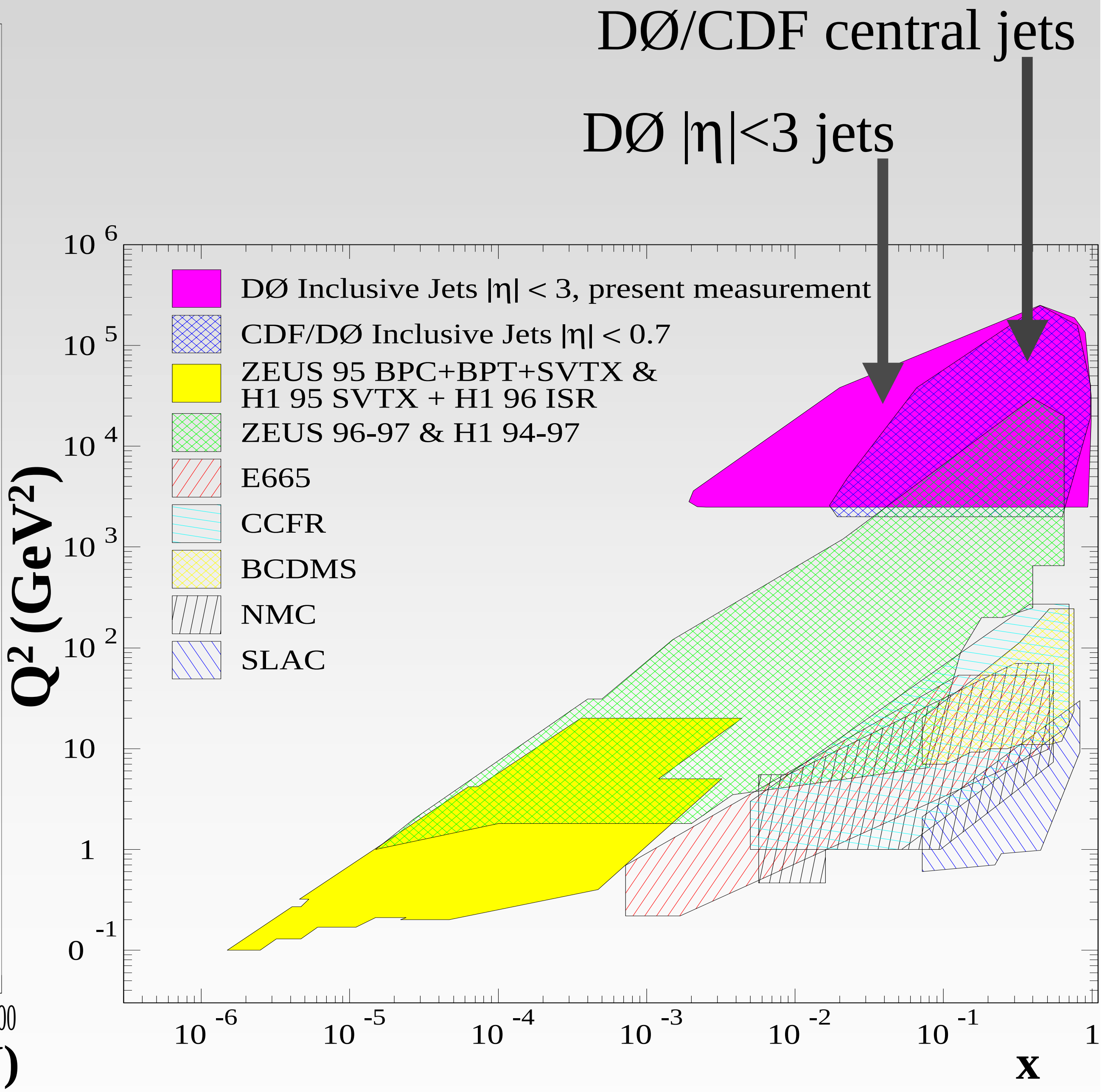
Exclusive: γ+γ, γ +charm, etc

**Hard Diffraction/DPE/Color Singlet Exchange:**

Models vs event characteristics
and fits to diffractive pdfs

# Jet Cross Sections vs Pseudorapidity



# DØ Jet CS vs. η : Quantitative comparisons to predictions

$$\chi^2 = \sum_{i,j} (D_i - T_i) \times \left[Cov_{i,j}^{Full}\right]^{-1} \times (D_j - T_j) \qquad Cov_{i,j}^{Full} = \sum_{\beta}^{errors} \rho_{i,j}^{\beta} \times \sigma_i^{\beta} \times \sigma_j^{\beta}$$

| PDF | $\chi 2$ | $\chi 2$/dof | Prob |
|---|---|---|---|
| CTEQ3M | 121.56 | 1.35 | 0.01 |
| CTEQ4M | 92.46 | 1.03 | 0.41 |
| CTEQ4HJ | 59.38 | 0.66 | 0.99 |
| MRST | 113.78 | 1.26 | 0.05 |
| MRSTgD | 155.52 | 1.73 | <0.01 |
| MRSTgU | 85.09 | 0.95 | 0.63 |

**Variations of correlation (ET & η) coefficients within the range of their uncertainties give a similar ordering of the $\chi^2$, hence a similar relative preference of PDFs.**

# RunII:High PT reach

**Run II: (2fb-1)**

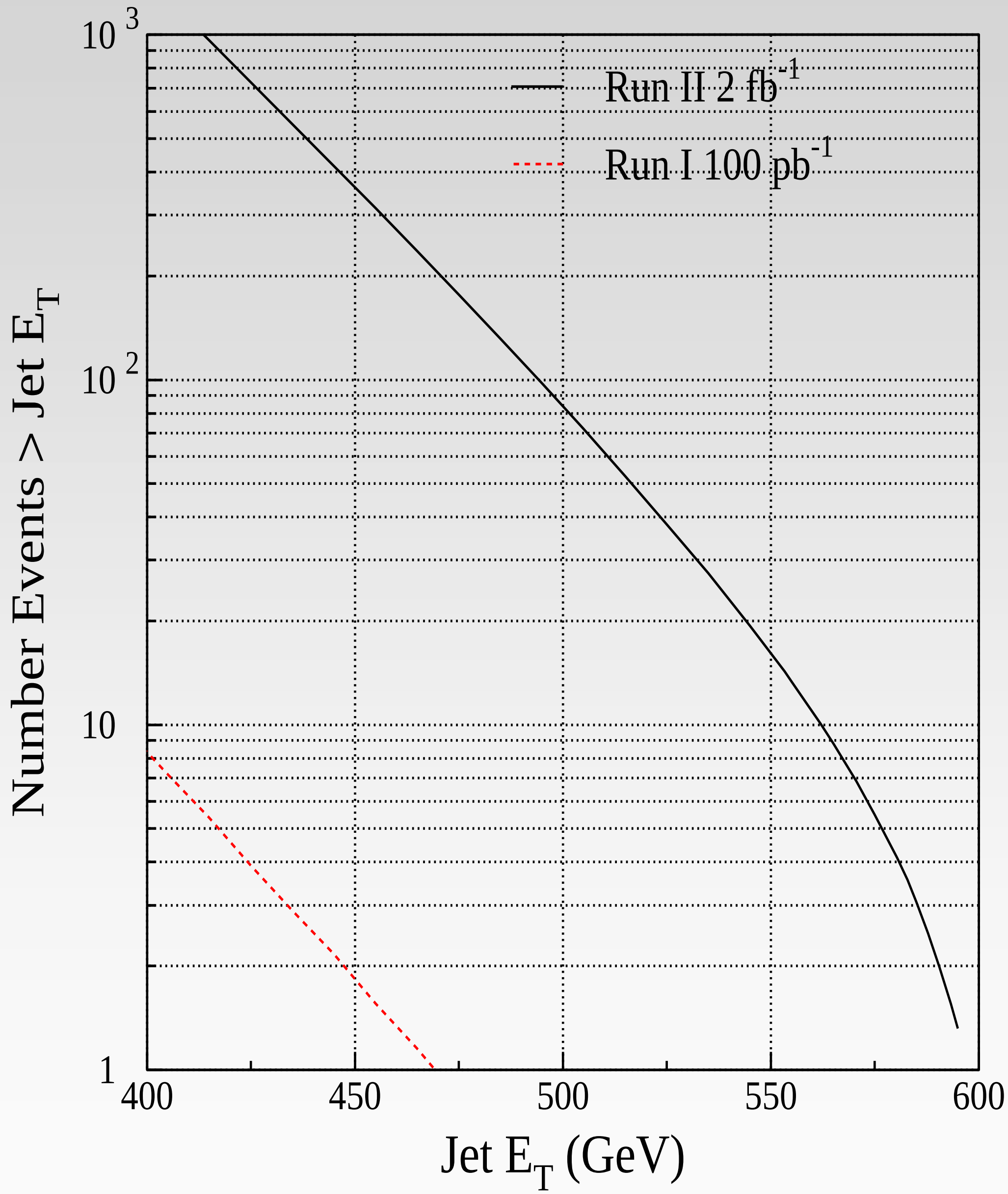
**~100 events ET > 490 GeV**

**~1K events  ET > 400 GeV**

**Run I:**

**16 Events $E_T$> 410 GeV**

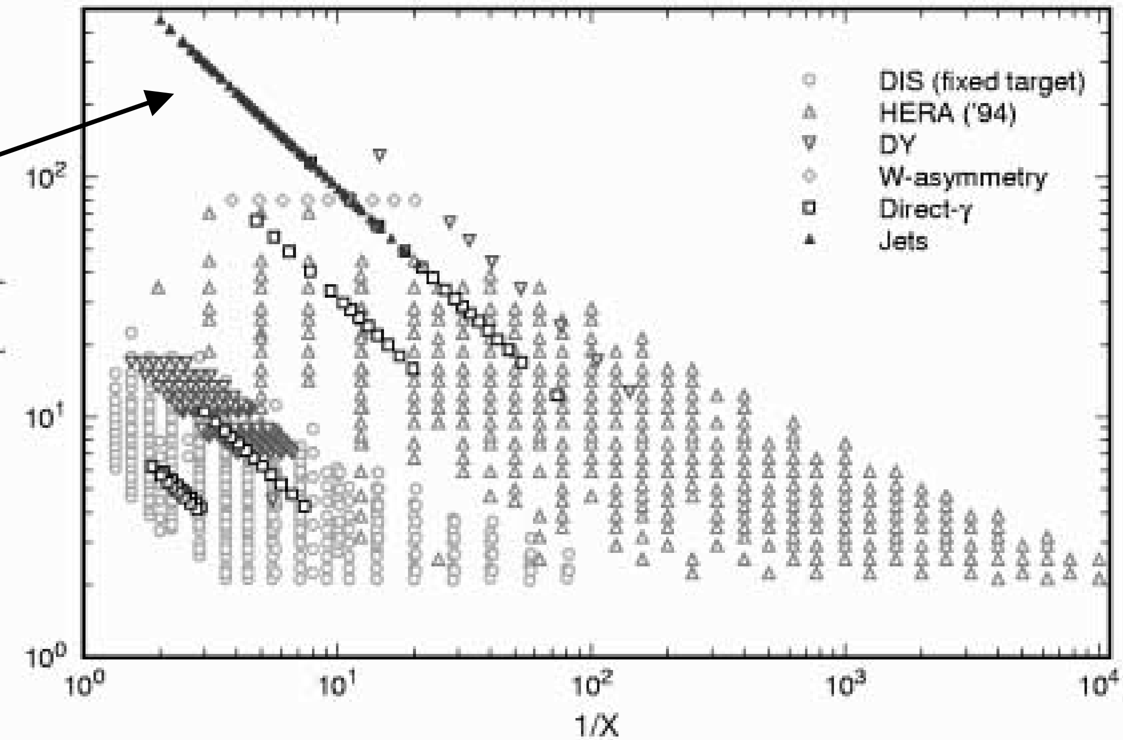
**Greater reach at large x and $Q^2$, to look for new physics and Improved systematics**



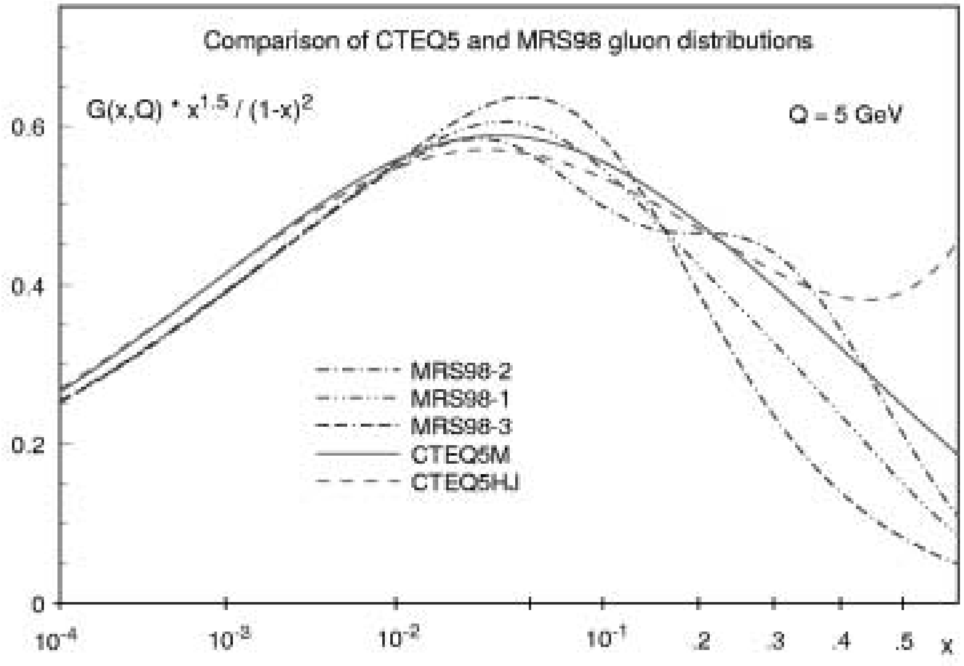
# CTEQ5 pdfs

x-Q region spanned by experimental data in CTEQ5

Tevatron jets in blue




G(x,Q)

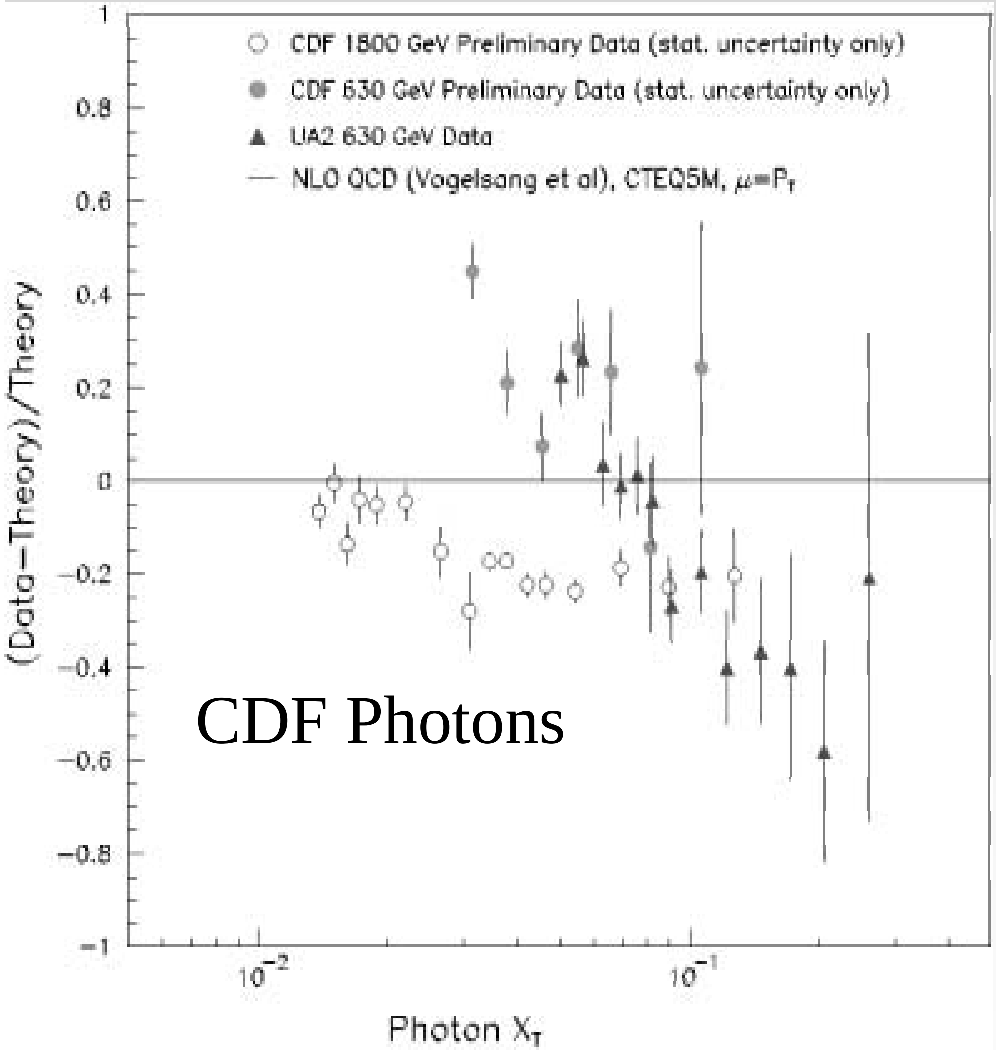


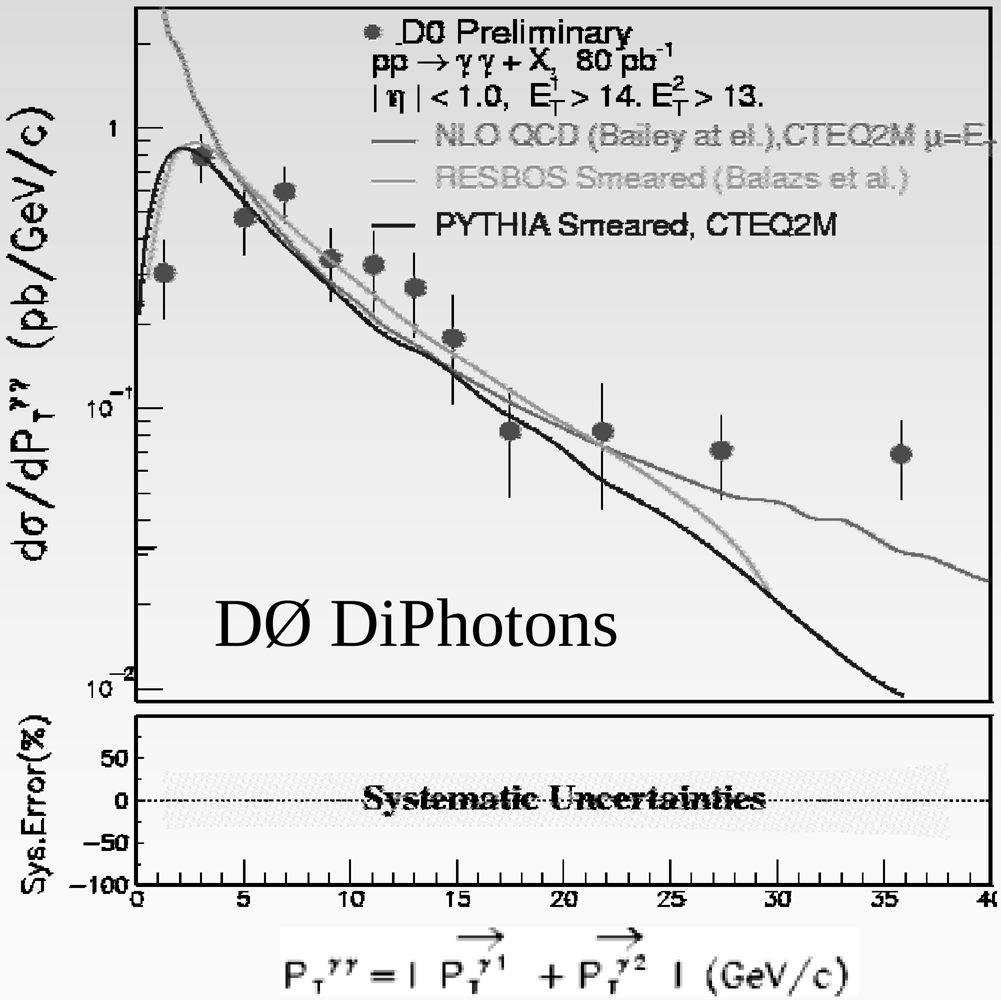

Tevatron jet data serves as strong constraint in medium x region

**In RunII scale errors reduce w/ Gamma+jet stats. for moderate to high PT jets offering significant constraints on *g*'s**

# Photon Scaling Diphotons

Resummed calc. in good agreement with data

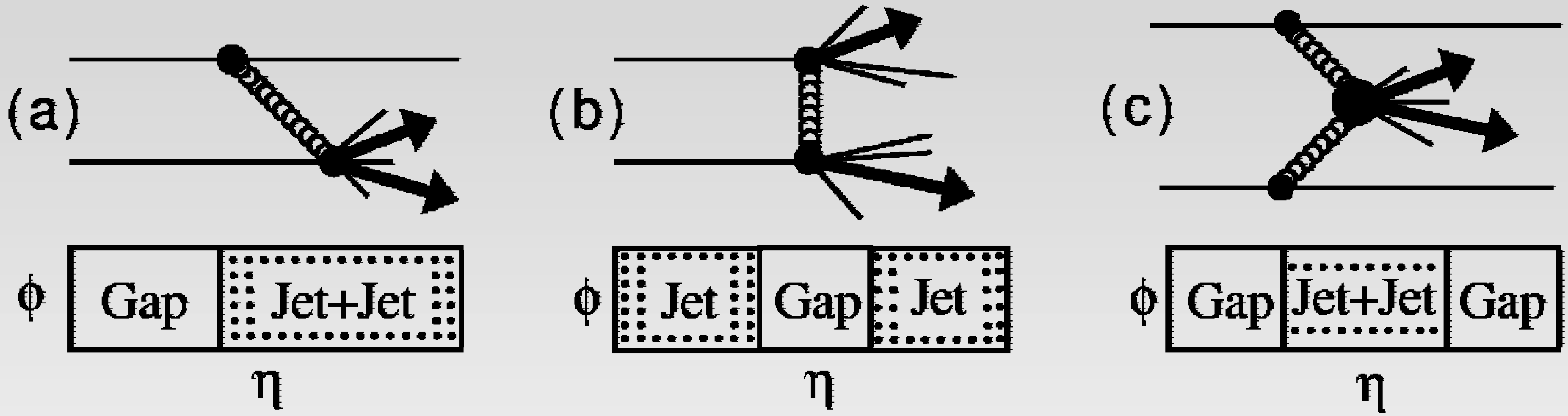



**Measure of soft emission effects**

# Hard Diffraction at Run I

Hard Diffraction = Hard Scattering + Rapidity Gap / Leading p (p-bar)




**Single Diffraction**

**Double Diffraction**

*a.k.a. Hard CSE*

**Double Pomeron Exchange**

New observation in RunI

Hardest/Largest PT observations of these classes of events

# CDF: Diffractive W, dijet and b-bbar at sqrt(s)=1800 GeV

Published CDF Results

- Diffractive $W$ production PRL 78 (1997) 2698

$$R_W[\frac{SD}{ND}] = [1.15 \pm 0.51(stat) \pm 0.20(syst)]\%$$

$(p_T^e > 20 \text{ GeV/c}, |\eta^e| < 1.1, \not{E}_T > 20 \text{ GeV}, \xi < 0.1)$

- Diffractive dijet production PRL 79 (1997) 2636

$$R_{JJ}[\frac{SD}{ND}] = [0.75 \pm 0.05(stat) \pm 0.09(syst)]\%$$

$(E_T^{jet} > 20 \text{ GeV}, 1.8 < |\eta^{jet}| < 3.5, \eta_1\eta_2 > 0, \xi < 0.1)$

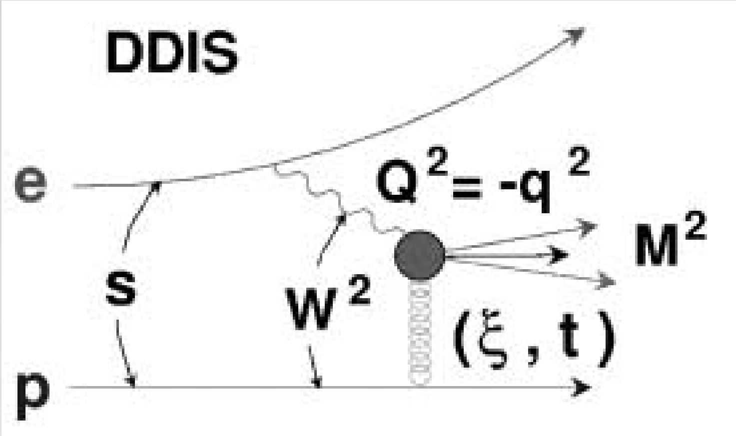
- Diffractive $b\bar{b}$ production PRL 84 (2000) 232

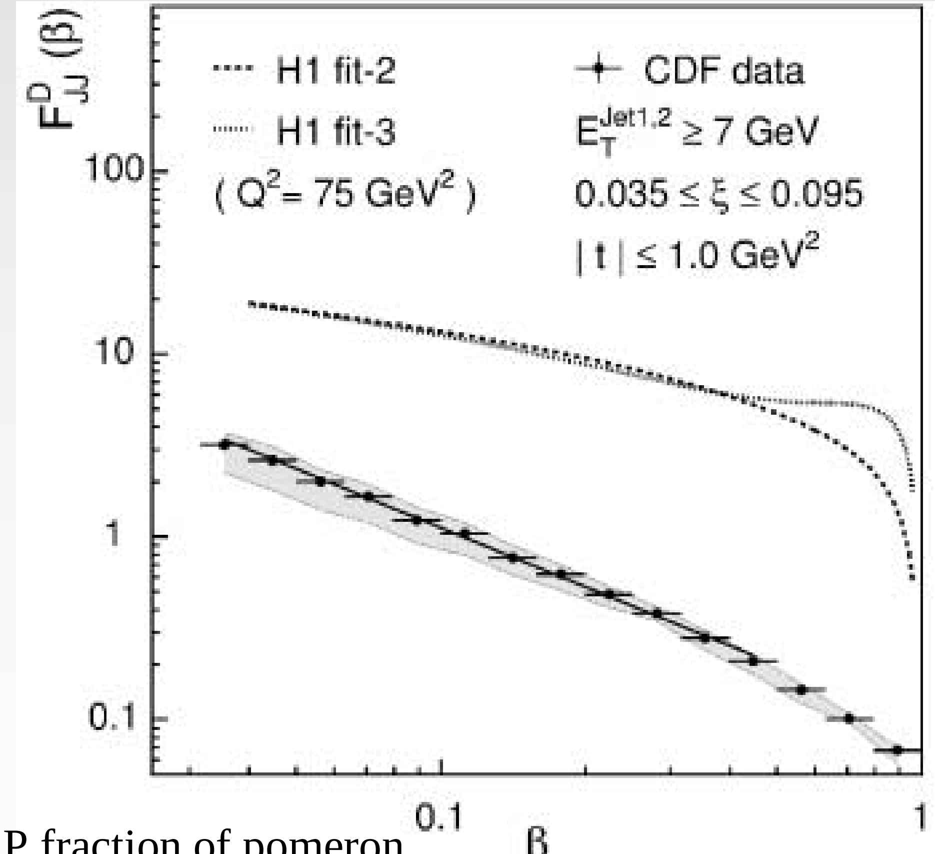
$$R_{b\bar{b}}[\frac{SD}{ND}] = [0.62 \pm 0.19(stat) \pm 0.16(syst)]\%$$

$(p_T^e > 9.5 \text{ GeV/c}, |\eta^e| < 1.1, \xi < 0.1)$

$$\Downarrow$$

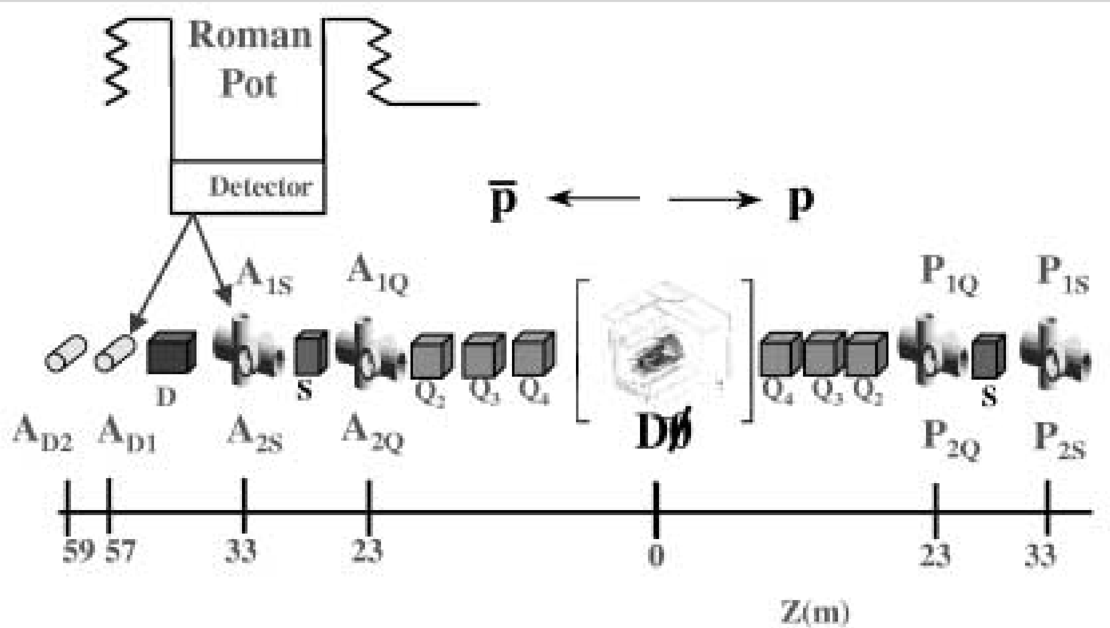
$$f_g = 0.54^{+0.16}_{-0.14}$$



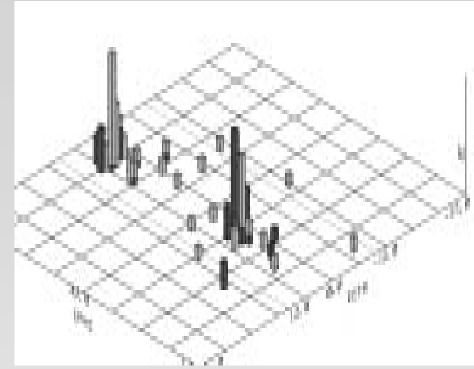




P fraction of pomeron

# Double Pomeron@RunII w/  DØ/CDF upgrades



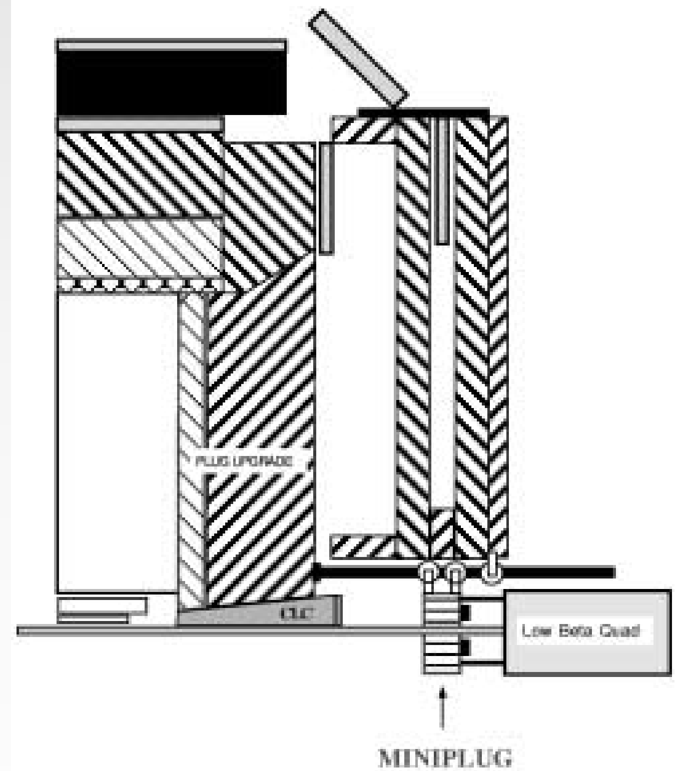

**DØ** Roman Pot Spectrometer



complete w/
p/p-bar arms – now installed

**CDF**

Pots on anti-proton side +
Beam shower counters
+ mini-plug
+double spectrometer proposal on the table…

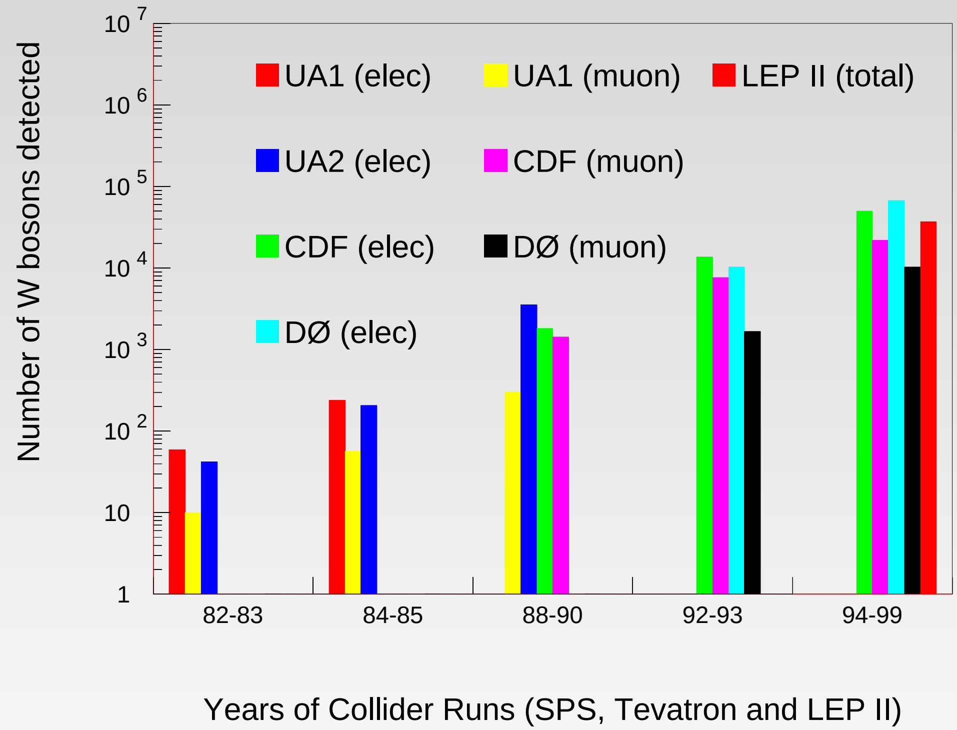



DoublePom in RunII: Valuable measure for understanding structure/nature of diffractive processes

# ElectroWeak (W/Z) Physics at the Tevatron

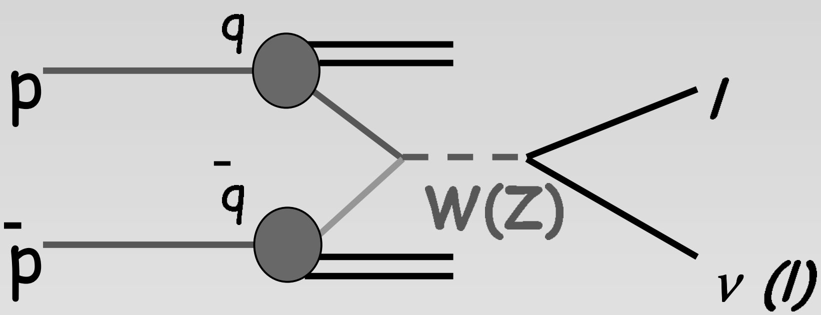
- – General Features of Production
- – Inclusive Cross Section
- – W Boson Width
- – W Boson Mass
- – Trilinear Gauge Boson Couplings

W Bosons Detected:




Top is discussed in the talk by E. Barberis at this conference

# General Features of W&Z Production




$$\sigma\left(p\bar{p} \to W + X \to \ell\nu + X\right) \approx 2\,\mathrm{nb}$$

$$\sigma\left(p\bar{p} \to Z + X \to \ell\bar{\ell} + X\right) \approx 0.2\,\mathrm{nb}$$

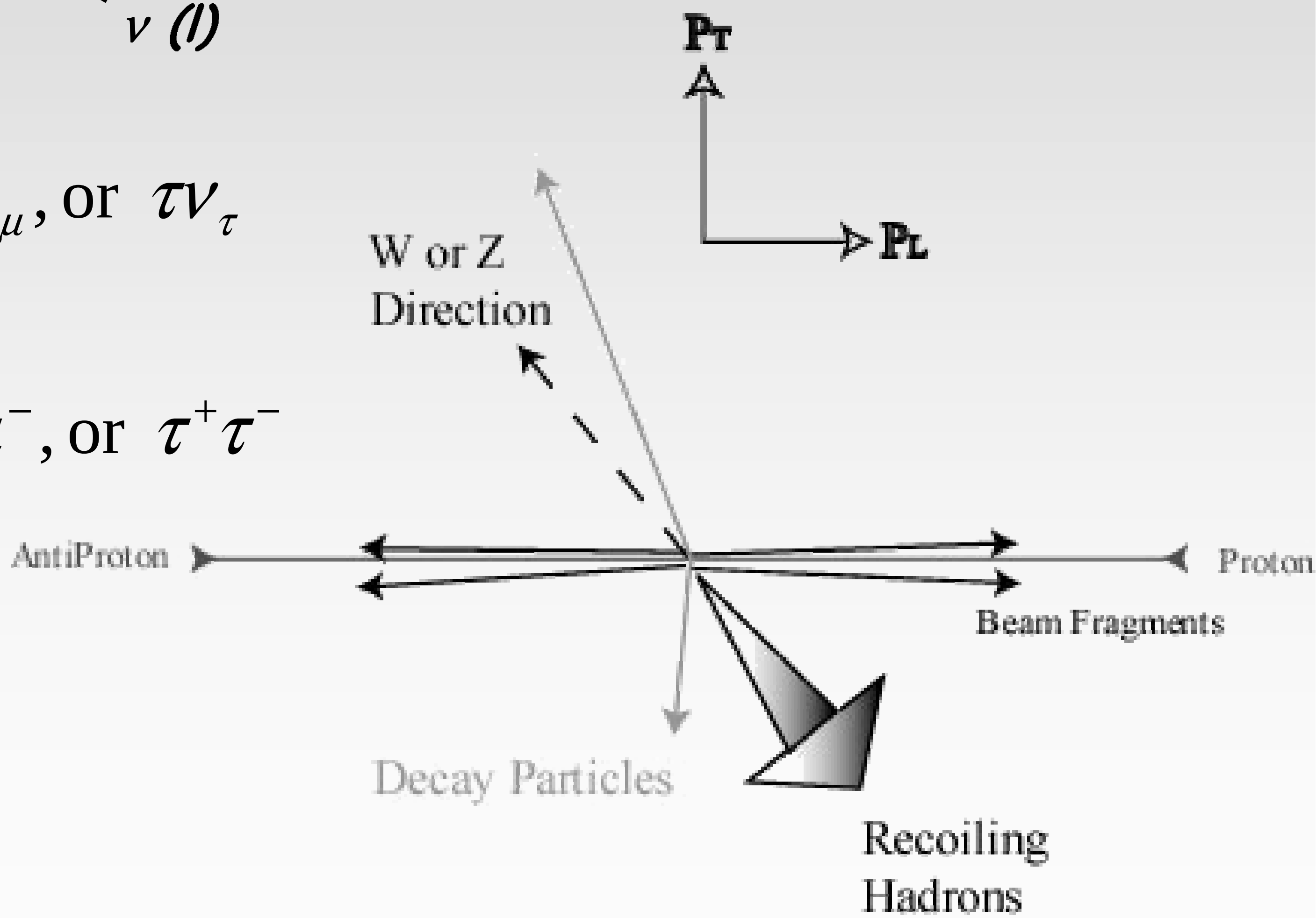
$$\mathrm{W}^{\pm} \xrightarrow{10.6\%} \mathrm{e}\nu_{\mathrm{e}}, \mu\nu_{\mu}, \text{or } \tau\nu_{\tau}$$

$$\xrightarrow{68.5\%} q\bar{q}'$$

$$\mathrm{Z}^{0} \xrightarrow{3.4\%} \mathrm{e}^{+}\mathrm{e}^{-}, \mu^{+}\mu^{-}, \text{or } \tau^{+}\tau^{-}$$

$$\xrightarrow{20.0\%} \nu\bar{\nu}$$

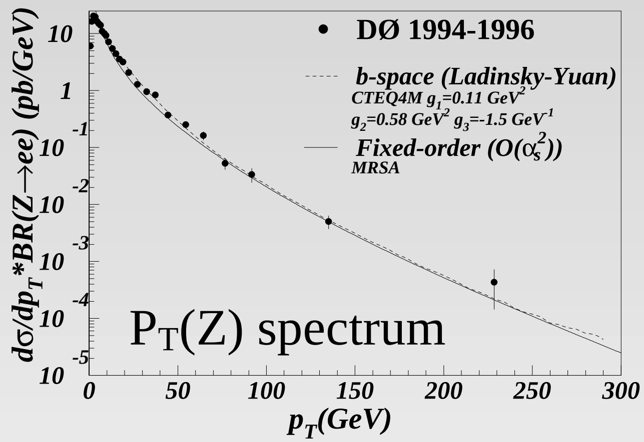
$$\xrightarrow{69.9\%} q\bar{q}$$



# W Boson Mass

- **Input from theorist's calculations tuned by our measurements.**

## Sampling of our published results:

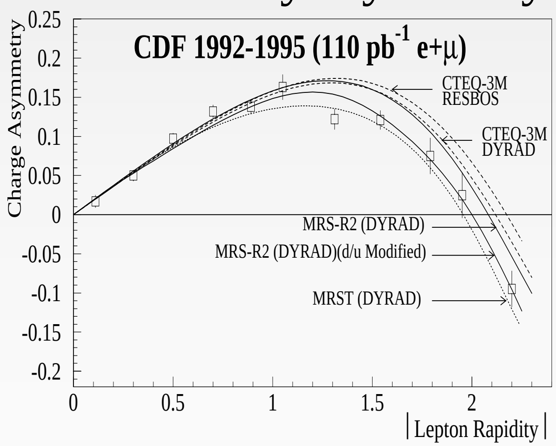


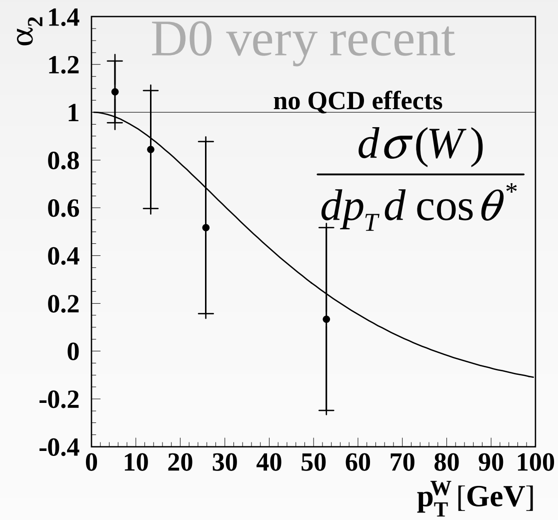

PT(W) Ladinsky-Yuan

W Boson Production & Decay Model

PDF's

W DecayAsymmetry




W Spin Orientation

E. Mirkes. (1992)

# W Boson Mass

- **W Mass measurements from**
  - **$M_T(W)$ @ CDF+D0**
  - **$P_T$(lepton) @ D0**
  - **$E_T(\nu)$ @ D0**
- **Using**
  - **electron channels @ CDF+D0**
  - **muon channels @ CDF**

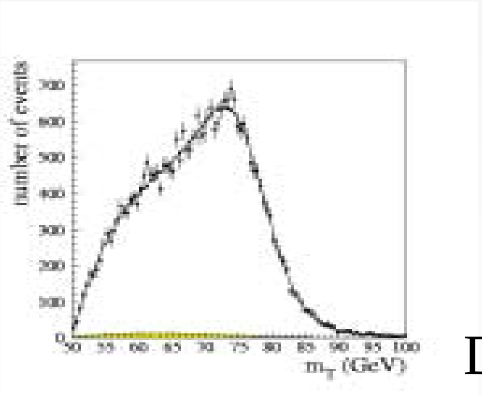
- **CDF (e+μ) combined (2000)**

$$M(W) = 80.433 \pm 0.079 \ \text{GeV/c}^2$$

- **D0 Run 1 (e) Result (2000)**

$$M(W) = 80.482 \pm 0.091 \ \text{GeV/c}^2$$

$$\boxed{\begin{array}{c} M(W) = 80.436 \pm 0.037 \ \text{GeV/c}^2 \ @ \\ \text{UA2} + \text{CDF} + \text{D0} + \text{LEP(12/2000)} \end{array}}$$




D0 CC electron channel

# Scaling of uncertainties – example from CDF

## Uncertainties that scale w/ statistics

(CDF IB preliminary)

| Source | $\delta M_W$ (MeV) | | $\delta\Gamma_W$ (MeV) | |
|---|---|---|---|---|
| | $e\nu$ | $\mu\nu$ | $e\nu$ | $\mu\nu$ |
| Statistics | 65 | 100 | 125 | 195 |
| Letpon $E,p$ scale | 75 | 85 | 63 | 16 |
| Letpon $E,p$ resolution | 25 | 20 | 10 | 20 |
| Recoil energy | 37 | 35 | 60 | 90 |
| Selection | – | 18 | 30 | 40 |
| Background | 5 | 25 | 50 | 50 |
| Total | 109 | 141 | 163 | 226 |

## Systematics to attack

Uncertainties that may not scale with statistics

(CDF, D0 Run IB)

| Source | $\delta M_W$ (MeV) | | $\delta\Gamma_W$ (MeV) | |
|---|---|---|---|---|
| | stat. | theo. | stat. | theo. |
| EWK Rad. | | 10 – 20 | | 10 |
| $p_T^W$ | 10 – 20 | $\lesssim$ 5 | 55 – 70 | |
| PDFs | 15 – 20 | | 15 | |

- Need Better Generators for
  - → Electroweak radiative corrections WGRAD
  - → $p_T^W$ NLO Showering, etc
- Need Better Way of Estimating PDF Uncertainty

$$2\ fb^{-1} : \delta M(W) < 30\ \mathrm{MeV/c^2}\ \text{(per exp.)}$$

# W/Z Mass Ratio

**Alternate Measurement of M_W**

Ratio of W and Z distributions
That are correlated to IVB mass.

- Treat Z→ ee as W → eν by discarding one of the two Z electrons

- The scale factor between equivalent Z and W distributions gives M_W / M_Z

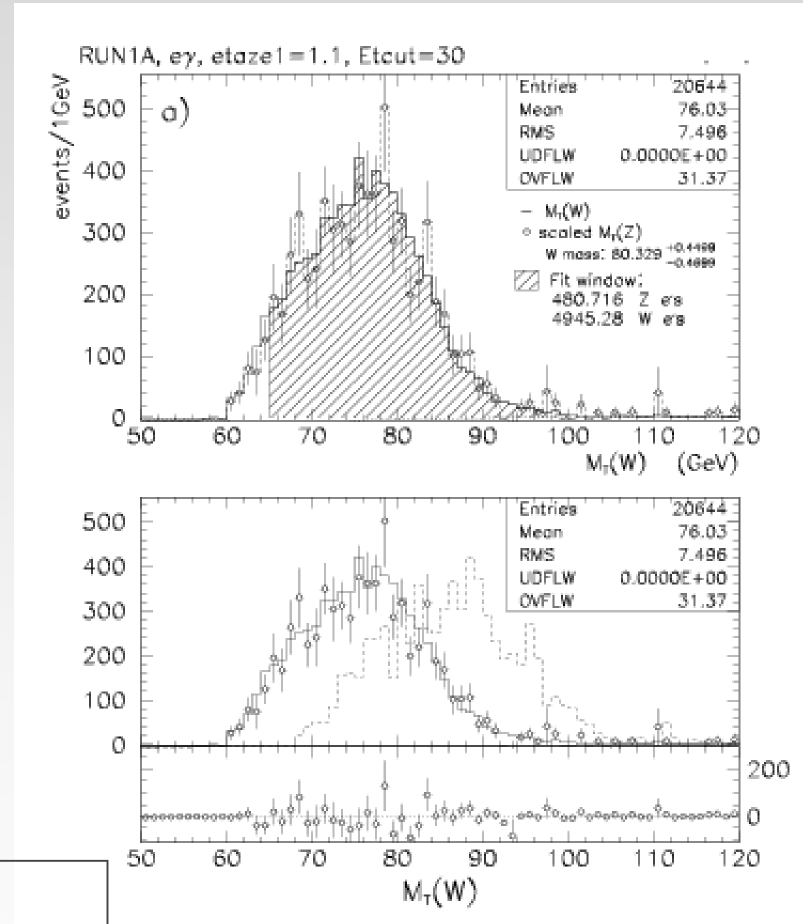
Possible Distributions:

- $M_T$
- $P_T^e$
- $P^e$

Stat Sys

DØ Run 1a W Mass
M_T: 80.350 +- 0.140 +- 0.165 +- 0.160
Ratio: 80.160 +- 0.360 +- 0.075

Extraction of W Mass from W/Z $M_T$ ratio



# W Boson Width

**Precisely predicted in SM: $2.093 \pm 0.002$ (GeV)**

- **Indirect Method**

Form ratio:

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

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

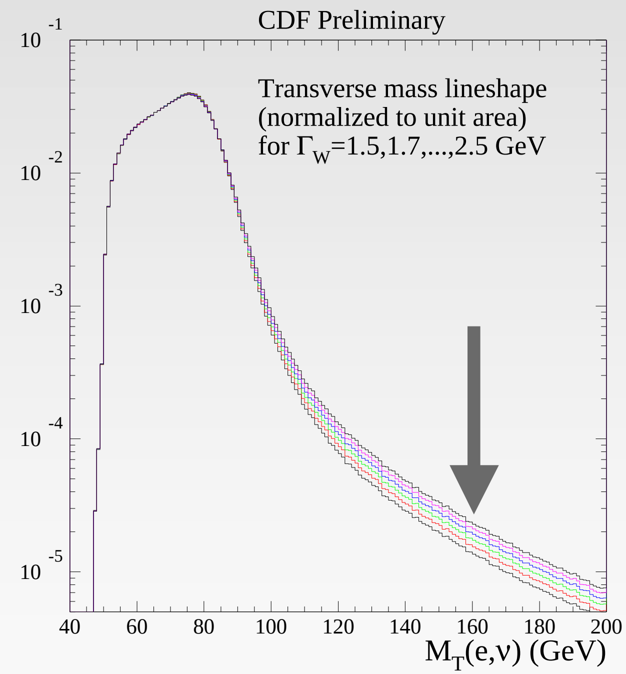
**Perturbative QCD** **LEP** **SM EW**

$$\Gamma_W(GeV) = 2.171 \pm 0.021(stat) \pm 0.047(sys)$$

CDF+D0 combined

Final RunII (10 fb-1) sensitivity ~ 10MeV

- **Direct Method (CDF)**
  - **Model independent**
  - **Study high-end tail of $M_T(l\nu)$.**



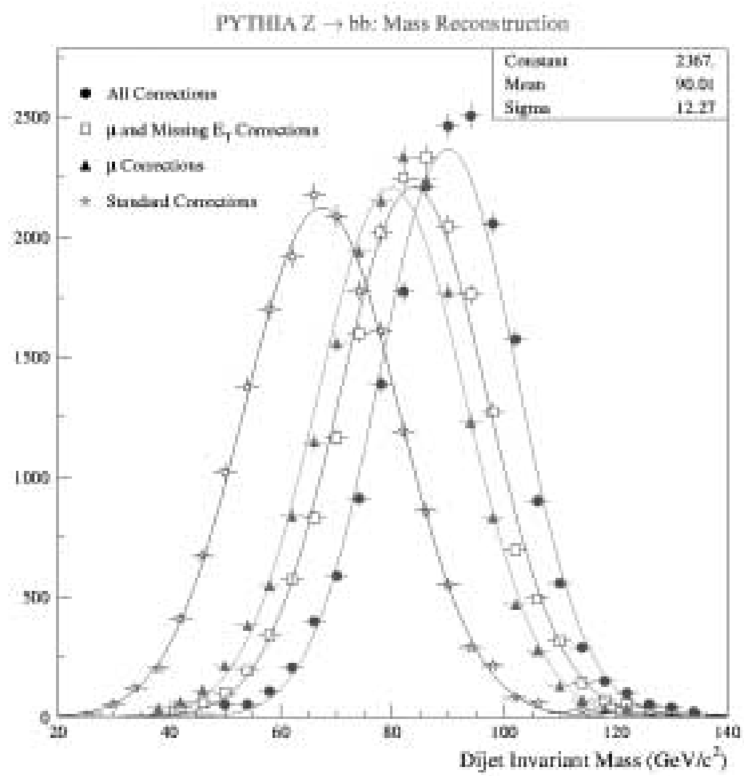

$$\Gamma_W(GeV) = 2.055 \pm 0.100(stat) \pm 0.075(sys)$$

**(LEP combined: $2.12 \pm 0.11$)**

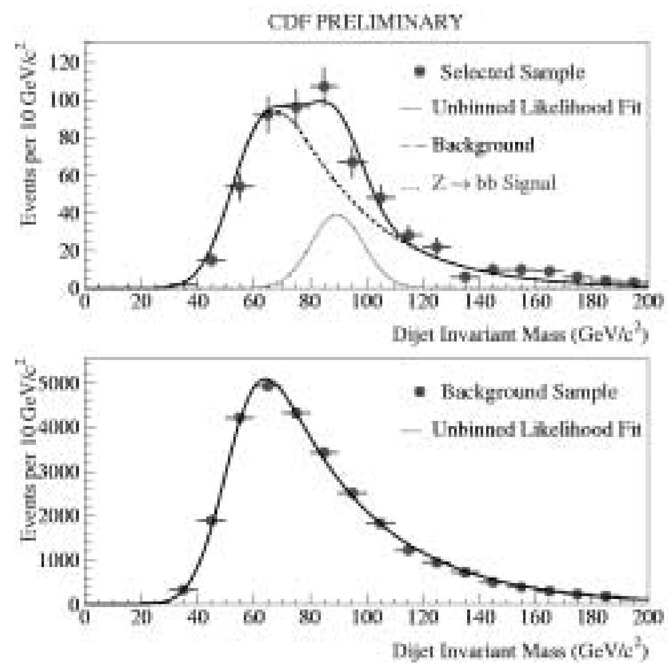
# Hadronic Decays of W/Z

CDF studies of
b b-bar mass resolution

200K W/Z → jj could offer a 1% check on jet escale (as seen in toy MC studies)




But of particular interest is Z→b-bbar…



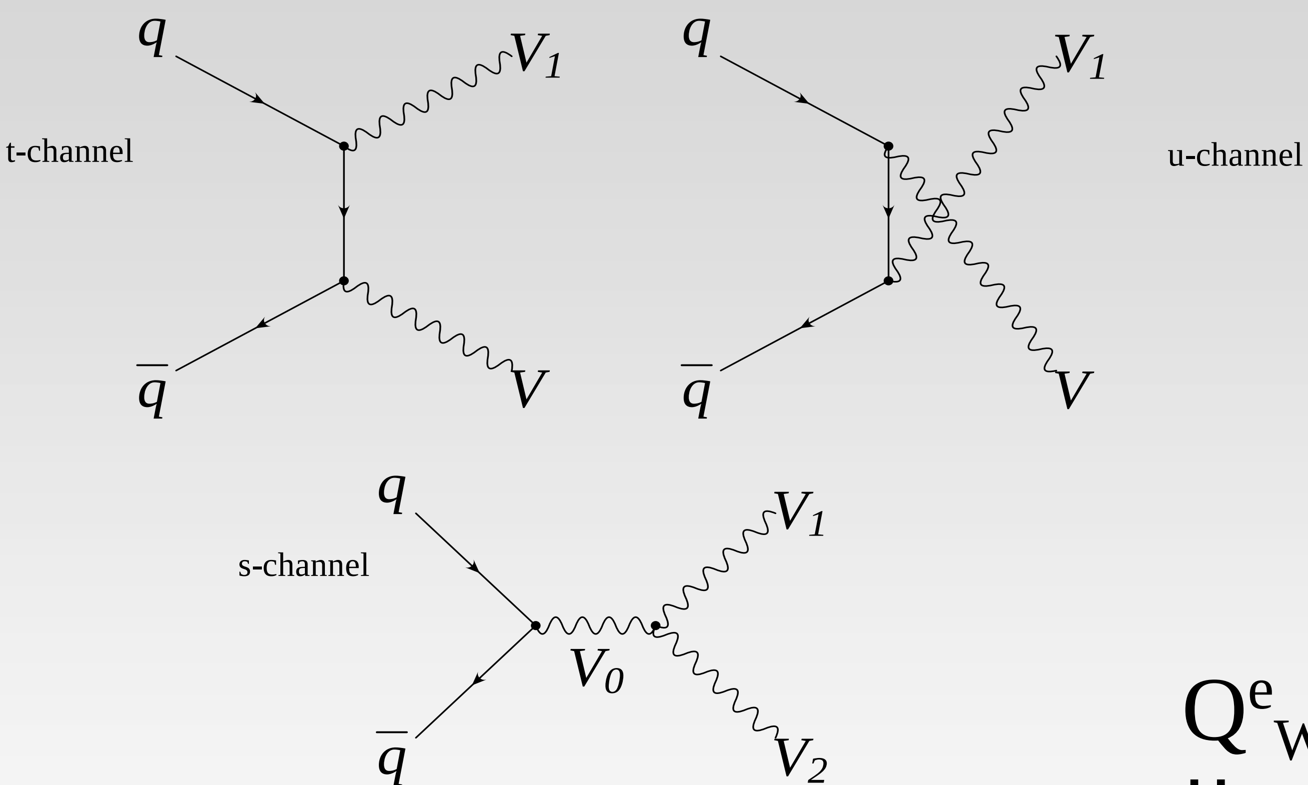

2E6 events →
588 after cuts
Vertex tagging + event energy profile
Mz = 90+-2.4

20x the data →
1% accuracy on b-scale

Bbbar useful for improving mass resol studies,
→ Higgs!!!

Good stats for absolute b-jet scale in the energy range we need for **top**!

# Gauge Boson Self-Interactions




- **Self-interactions are a direct consequence of the non-Abelian $SU(2)_L \times U(1)_Y$ gauge symmetry.**
- **SM makes specific predictions for the strength of the couplings.**

$$Q^e_W = -\, e\, (\kappa - \lambda) \,/\, M^2_W$$
$$\mu_W = e(1+\kappa+\lambda) \,/\, 2M_W$$

We study gauge boson couplings by investigating properties of vector boson pair production: Wγ, WW, WZ, Zγ, ZZ in various final states

non standard couplings → increased cross section and harder $p_T$ spectrum

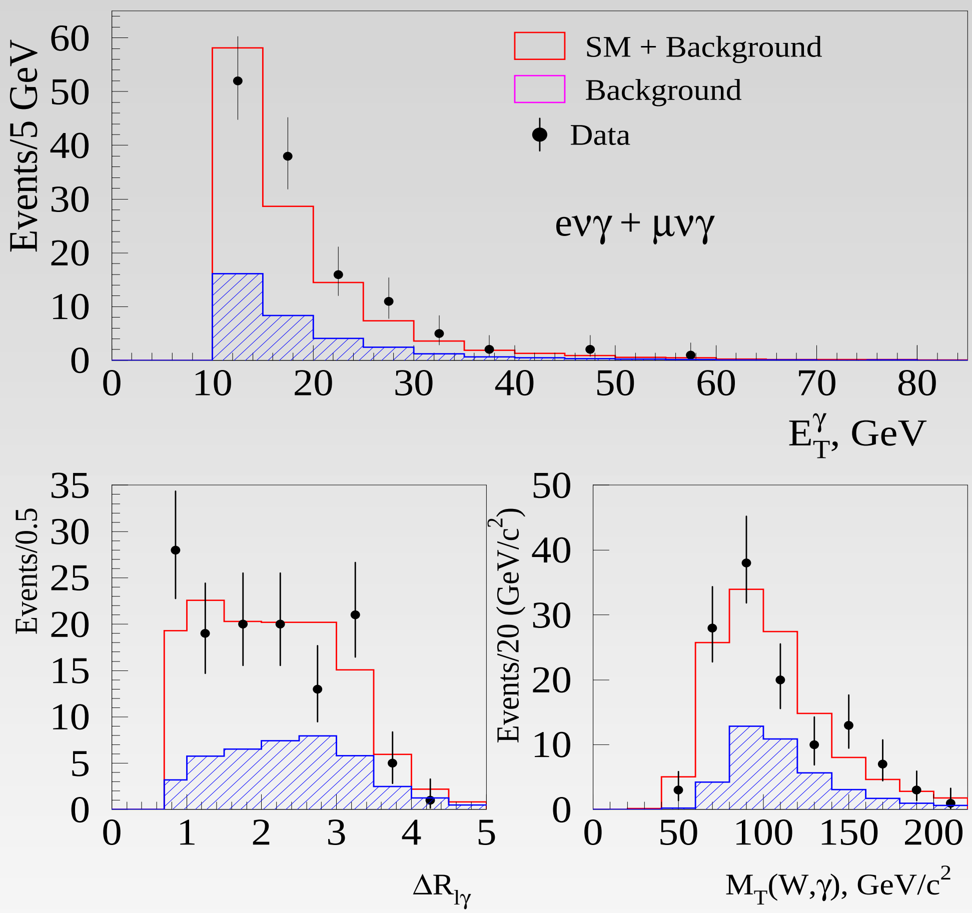
# WWγ and WWZ Couplings

- **In Run 1:**
  - **Established the EW coupling of W to γ and W to Z.**
  - **The Wγ and WW processes were observed. Candidate WZ events observed.**

$$\sigma(p\bar{p} \rightarrow WW + X) = 10.2^{+6.5}_{-5.1} \pm 1.6\, pb \quad (CDF)$$

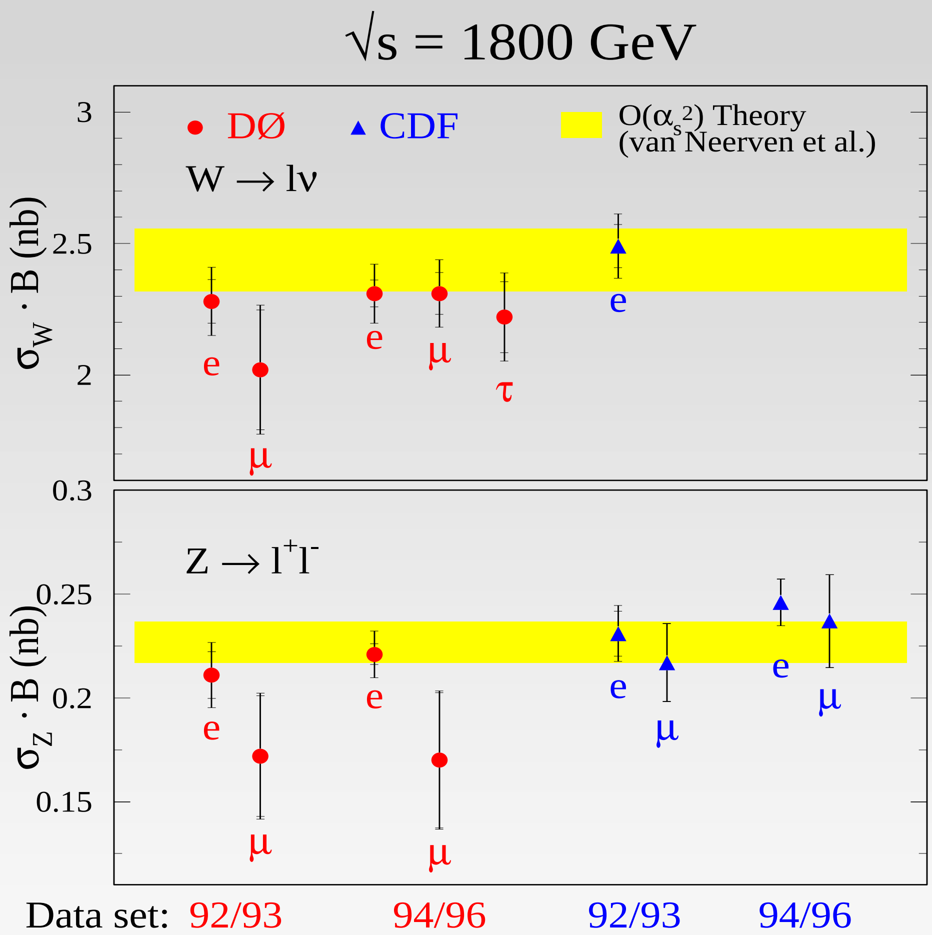
  - **Anomalous Coupling Limits Wγ, WW, and combined WZ results from DØ (equal γ+Z couplings):**

$$-0.25 \leq \Delta\kappa \leq 0.31\ (\lambda = 0)$$
$$-0.18 < \lambda < 0.18\ (\Delta\kappa = 0)\ \ at\ \ 95\%\ CL$$




- **In 2 fb$^{-1}$:**
  - **2000 eνγ+μνγ events per exp.**
  - **Observe "radiation zero"**
  - **Sensitivity to anomalous couplings ~2-3X better.**

# Inclusive Cross Sections




**Luminosity:**
**L(D0) = 1.062 x L(CDF)**
**D0 uses world avg. σ(pp)$_{inel}$,**
**CDF uses CDF measurement**

- σB(W–> ℓ ν) ~ 2.2 nb
- σB(Z–> ℓ+ ℓ–) ~ 0.22 nb
- Cross section measurement uncertainty:

  Stat ⊕ Sys ~ 2%,

  Luminosity error ~ 4%

- Theory prediction uncertainty:

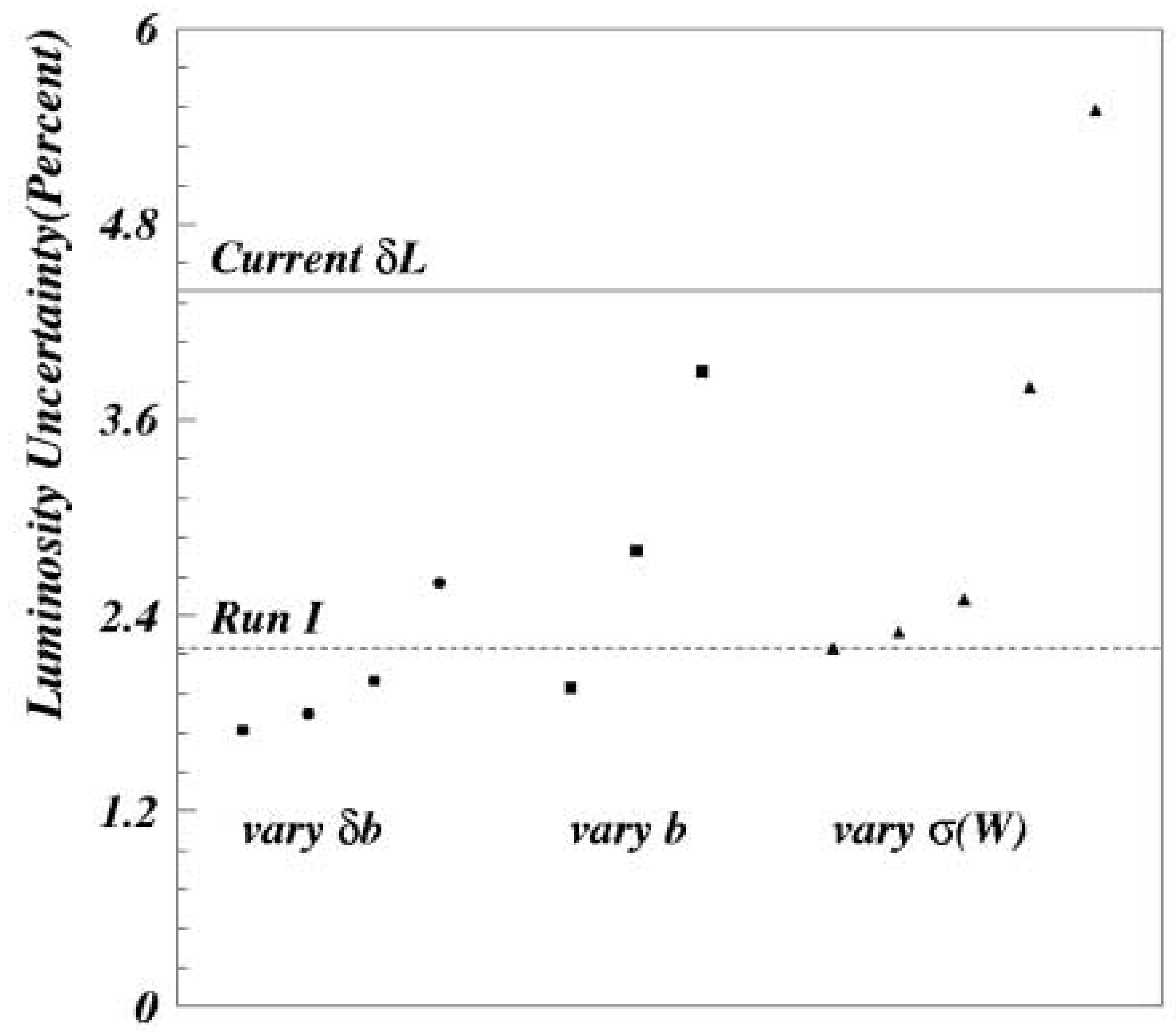
  ~ 3%, NNLO, O($\alpha_s^2$)

Dominated by PDF’s at NLO…

# Another prospect for RunII

## The W cross section as a luminosity monitor

Exp. uncertainties dominated by background fraction and background uncertainty
Calculated Sigma_w most important, dominated by pdf uncertainties



# Concluding Remarks

**The higher energy (1.96 TeV) and 🕘$\mathcal{L}$ (2fb$^{-1}$)+ of Run 2 will make the Tevatron a very exciting place to be for the next many years!**

**Summary of results will be increasingly more work!**

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There are currently many great postdoc opportunities to explore fundamental physics at the world's highest energy collider with DØ collaborating institutions !!!

- Fermilab
- Lawrence Berkeley Lab
- Lancaster University
- Manchester University
- Swedish Consortium

} *As of two weeks ago*

Many located full time at Fermilab at DØ.