

# NAIVE DRELL-YAN AND ITS SUCCESSOR(S)

- SPECIAL THANKS TO DAVE SOPER
- REVIEWS
  - C. GROSSO-PILCHER + M. J. SHOCET  
ANN. NUCL. PART. SCI. 86
  - COLLINS + SOPER " " 87
  - \* STERMAN et al RMP 95
  - \* R. K. ELLIS, STERLING + WEBBER  
QCD AND COLLIDER PHYSICS 96
- SINCERE APOLOGY
  - ONLY VERY FEW NAMES  
MENTIONED

## OUTLINE

- NAIVE MODEL
- QCD IMPROVED
- COMPARISON WITH EXP'TS
- LEPTON PAIR AS PHYSICS TOOL

- IN THE BEGINNING 1970, 1973  
CHRISTENSON, HICKS, LEDERMAN,  
LIMON, POPE, & ZAVATINI

BNL:  $\rho + U \rightarrow \mu^+ \mu^- + X$

- $E_\rho$ : 22 - 29 GeV
- $M_{\mu\mu}$ : 1 - 6.7 GeV
- SHOULDER-LIKE STRUCTURE  
NEAR  $M_{\mu\mu} \sim 3$  GeV
- RAPID FALL-OFF FOR LARGE M
- LATER
  - 1974  $\pi/4$  BNL  
SLAC (SPEAR)
  - 1977  $\tau$  FERMILAB

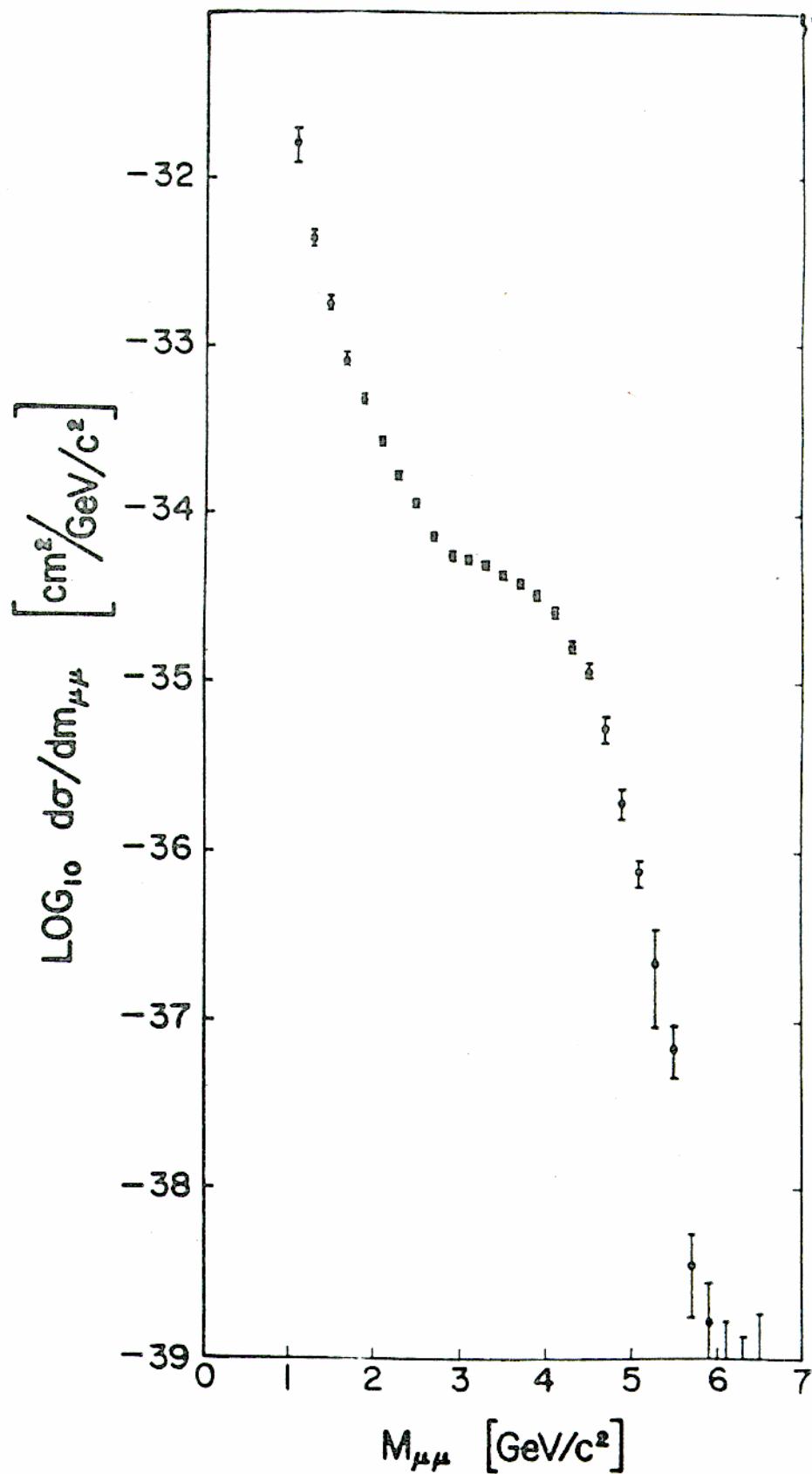
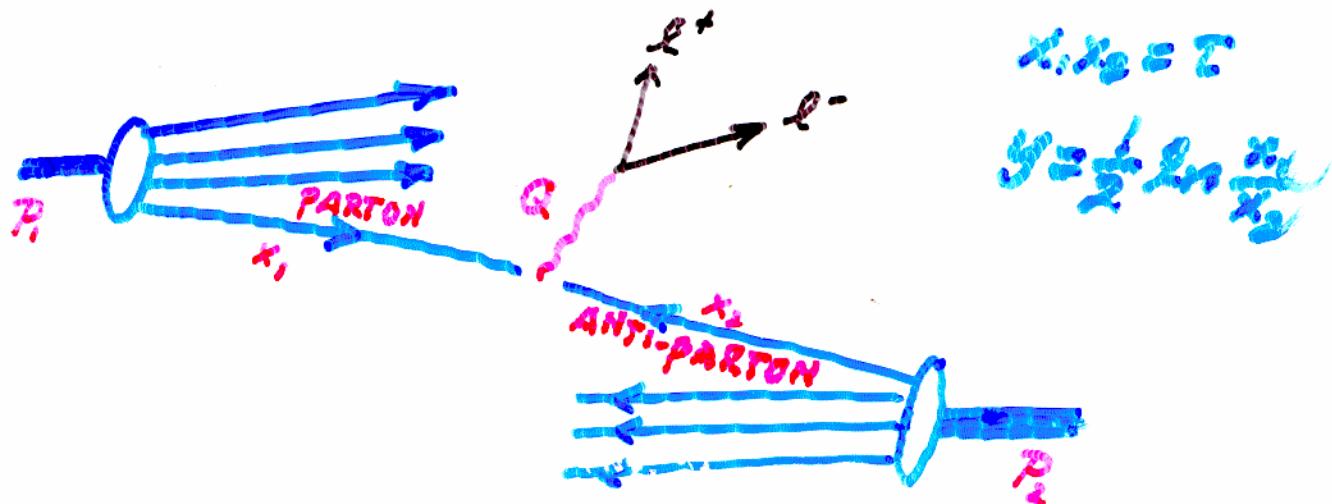


Fig. 26

## NAIVE DRELL-YAN MODEL

- MOTIVATION
  - APPLICATION OF PARTON MODEL OUTSIDE DIS
  - TO RECONCILE POINT-LIKE  $\sigma$  IN DIS WITH RAPID FALL-OFF OF  $\sigma$  WITH  $M_{\text{jet}}$
- KEY IDEA IMPULSE APPROX
  - JUDICIOUS CHOICE OF  $P \rightarrow \infty$  FRAME (TIME DILATION)
  - IN THIS FRAME  $\tau_{\text{PROBE}} \ll \tau_{\text{INT. STATES}}$
  - CONSTITUENTS FREE

IMPULSE APPROX.  $\Rightarrow$



- PREDICTIONS

- SCALING  $Q^4 \frac{d\sigma}{dQ^2} = F(\frac{Q^2}{s})$

- MAGNITUDE & SHAPE FIXED BY DIS

$$\frac{d\sigma}{dQ^2 dy} = \frac{4\pi\alpha^2}{3Q^4} \cdot \left(\frac{1}{N_c}\right) \sum_P e_p^2 x_1 f_p(x_1) x_2 f_{\bar{p}}(x_2)$$

- SMALL  $R_T \sim 300 - 500 \text{ MeV}$

- ANGULAR DISTRIBUTION IN  $\vec{Q} = 0$  FRAME

$$(1 + \cos^2 \theta)$$

- STRUCTURE FUNCTIONS FOR  $\pi, K, \dots$

- W PRODUCTION

## GENERALIZATIONS

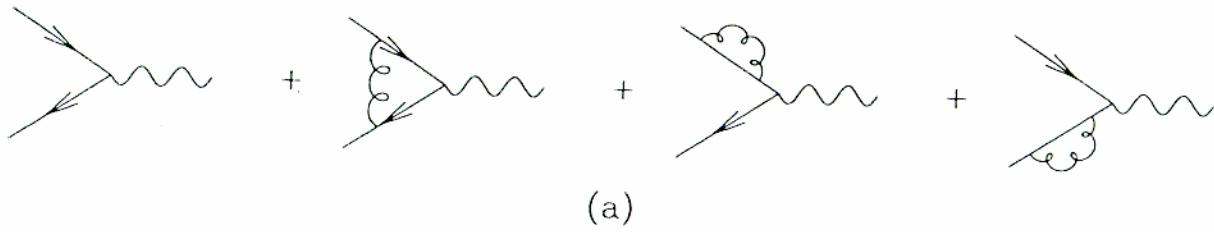
- LEPTON PAIR PRODUCTION
  - FIRST EXAMPLE OF HARD PROCESSES WITH 2 INITIAL HADRONS
  - NOT DOMINATED BY LIGHT CONE OR SHORT DISTANCES
- OTHER LARGE  $p_T$  PROCESSES
  - BERMAN, BJORKEN, & KOGUT 1971
  - $h + h \rightarrow h(\text{LARGE } p_T) + \text{ANYTHING}$
  - DEEP INELASTIC EM
  - PRECURSOR OF POINT-LIKE GLUON INTERACTION

## SUCCESSOR(S) QCD

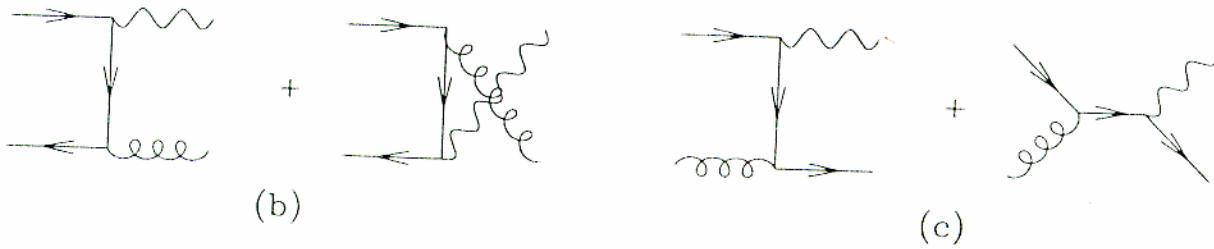
- PARTONS =  $q, \bar{q}, g$
- NUMBER OF COLOR  $N_c = 3$
- ASYMPTOTIC FREEDOM  $\Rightarrow$   
 $QCD = \text{PARTON MODEL} +$   
"SMALL" CORRECTIONS
- IMPULSE APPROXIMATION  
= FACTORIZATION
  - $\tau_{\text{PROBE}} \ll \tau_{\text{INT. STATES}} \iff Q \gg \Lambda_{\text{QCD}}$
  - (ALMOST) FREE CONSTITUENTS  
 $\sim$  LOGARITHMIC CORRECTIONS
  - $f_i(x) \Rightarrow f_i(x, \ln Q^2)$
  - DIS
    - OPE (K. WILSON)
    - SUSSKIND & KOGUT
    - GLAP

- FACTORIZATION IN LEPTON PAIR
- INITIAL & FINAL STATE INTERACTIONS MUST BE CONSIDERED
- SEE REVIEWS
  - COLLINS & SOPER ANN REV NUCL SC. 87
  - STERMAN et al RMP 95
  - R. ELLIS, STIRLING & WEBBER BOOK 96
- QCD PREDICTIONS
  - $f_i(x, Q^2)$  SAME AS IN DIS
  - $\langle k_L^2 \rangle = k_{\text{PRIMORDIAL}}^2 + \alpha_s(Q^2) S f(\zeta, \alpha_s(Q^2))$
  - K-FACTOR LARGE AT LOW  $Q^2$
  - $\sigma = \sigma_0 [1 + \frac{\alpha_s}{2\pi} \cdot \frac{4}{3}\pi^2] \rightarrow \sigma_0 e^{\frac{\alpha_s}{2\pi} \cdot \frac{4}{3}\pi^2}$   
 $\approx 1.8 \sigma_0$  ( $\alpha_s = 0.3$ )
  - KNOWN AS LEADING  $\pi$  SUMMATION  
 (ALTARELLI, ELLIS, & MARTINELLI 79  
 PARISI, 80)
  - ANG. DIST. COMPLICATED DUE TO  
 LARGE  $k_L$

# $O(\alpha_s)$ QCD CORRECTIONS



(a)



(b)

(c)

- (b) + (c) CONTRIBUTE TO LARGE  $k_L$
- $O(\alpha_s^2)$  CORRECTIONS HAVE BEEN DONE [HAMBERG, MATSUURA & VAN NEERVEN, 1990, 1991  
VAN NEERVEN, & ZIJLSTRA 1992]
- FACTORIZATION HAS BEEN PROVED TO ALL ORDERS IN  $\alpha_s$

## COMPARISON WITH EXP'TS

- SCALING
- ABSOLUTE RATES
- W AND Z PRODUCTIONS
- $k_L$
- ANG. DIST.

# SCALING

1979-85

PROTON

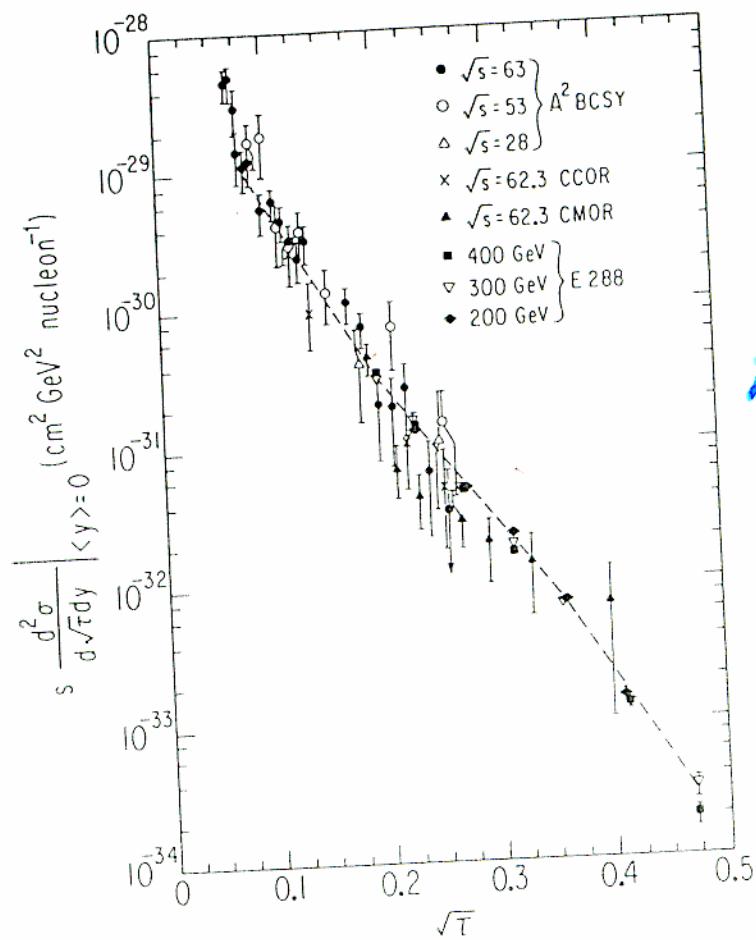


Figure 3 Test of scaling in proton-induced dilepton production (12-15). The curve is the Drell-Yan model prediction (6) scaled up by a factor of  $\sim 3$ .

PION

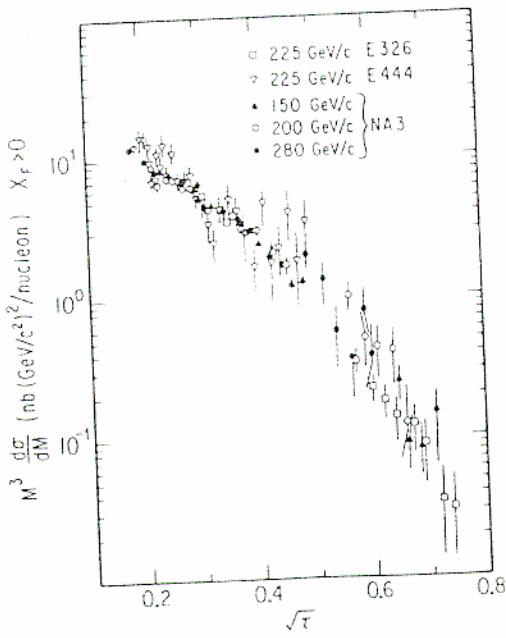


Figure 4 The scaling behavior of the pion-induced dimuon cross section (16-18). The E444 data have been renormalized by assuming an  $A^1$  dependence on the atomic mass of the target.

SCALING

1991

P + Cu

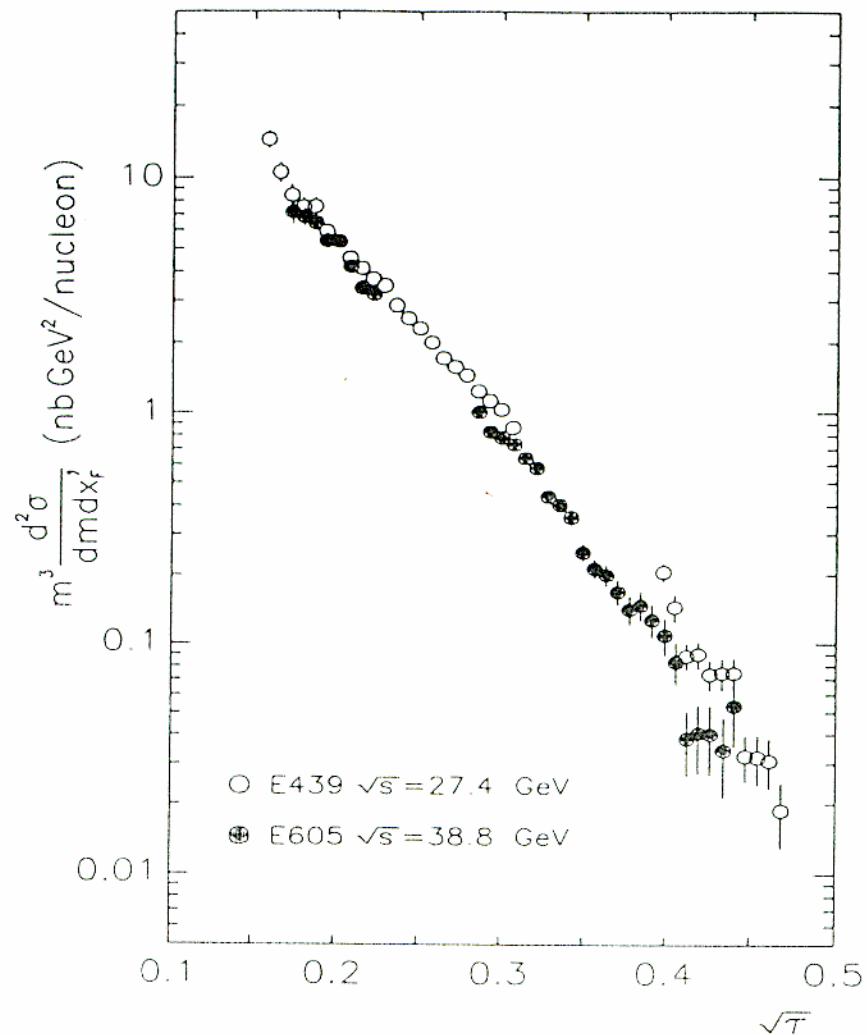


FIG. 12. Scaling form of the dimuon yield versus  $\sqrt{\tau}$  comparing this experiment with experiment E439 (Smith *et al.*, Ref. 31,  $\sqrt{s} = 27.4$  GeV) for the interval  $0 < x'_F < .2$ .

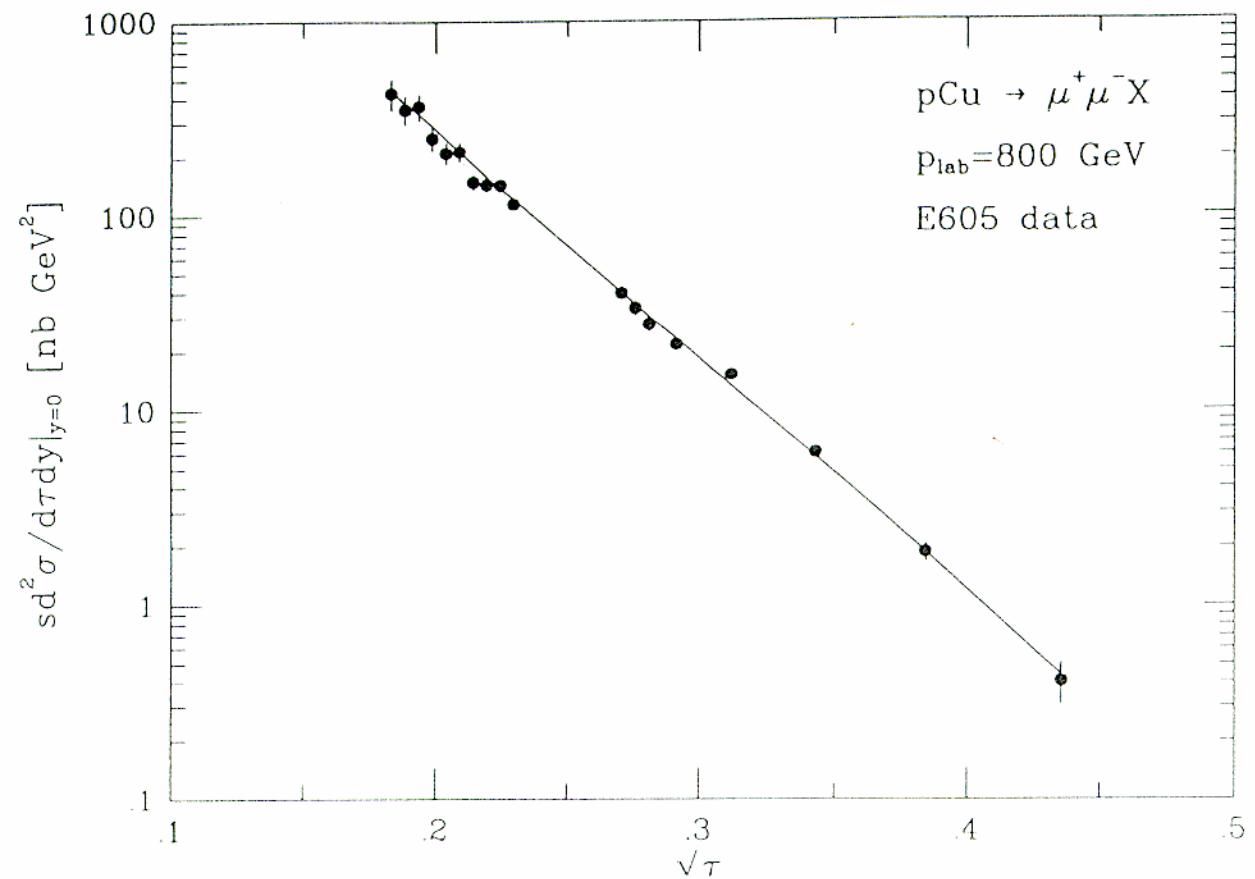


Fig. 9.4. The Drell-Yan cross section measured by the E605 collaboration [8] compared with the next-to-leading-order theoretical prediction.

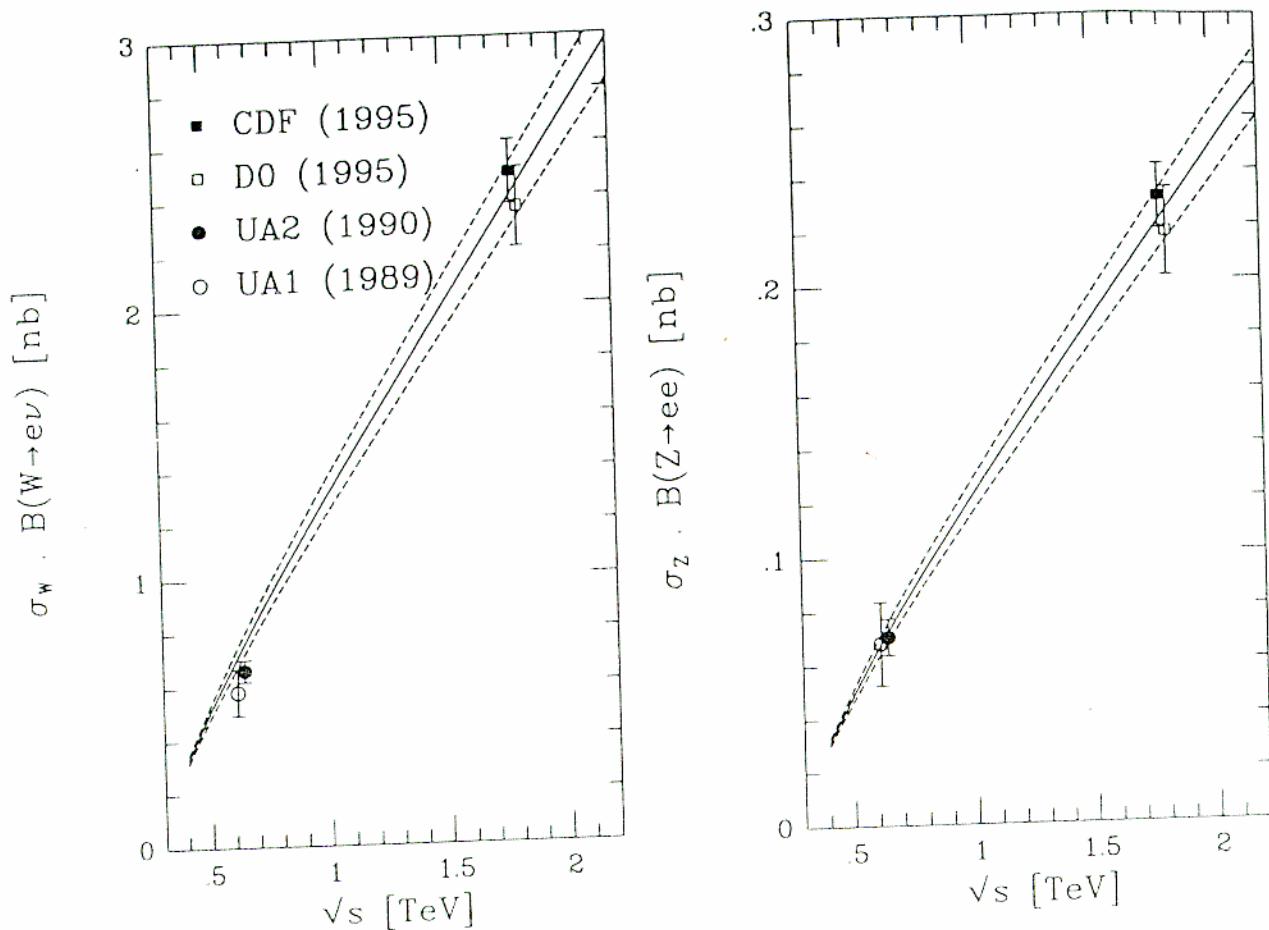


Fig. 9.6. Comparison of  $W$  and  $Z$  cross section measurements in  $p\bar{p}$  collisions with theoretical predictions. The systematic and statistical errors on the measurements have been combined in quadrature.

**ABSOLUTE RATE: THEORY vs DATA**

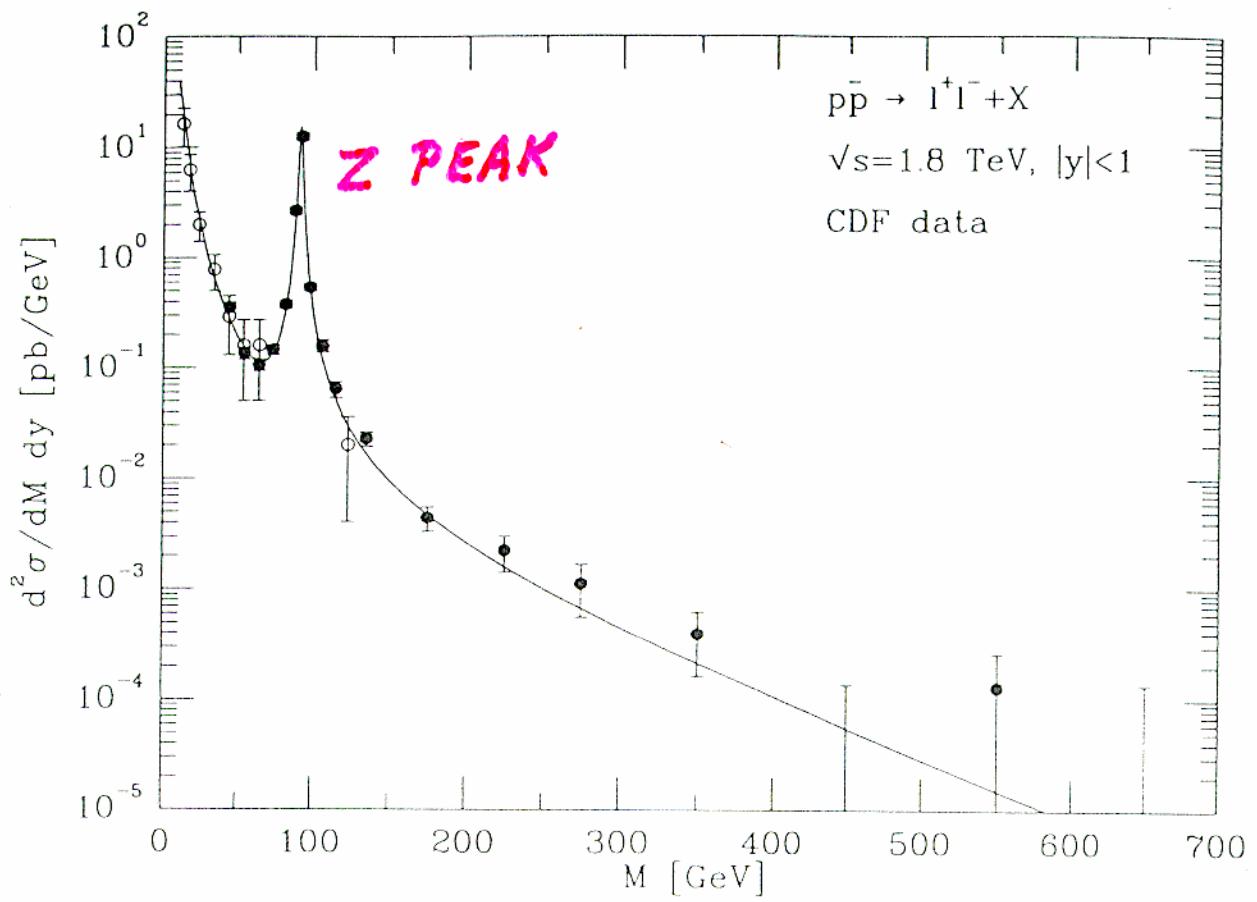


Fig. 9.5. The lepton pair cross section in  $p\bar{p}$  collisions at  $\sqrt{s} = 1.8$  TeV, with CDF data from ref. [12] (open circles) and ref. [13] (solid circles). The curve is the next-to-leading-order QCD prediction using the parton distributions from ref. [9].

RL

1981-84

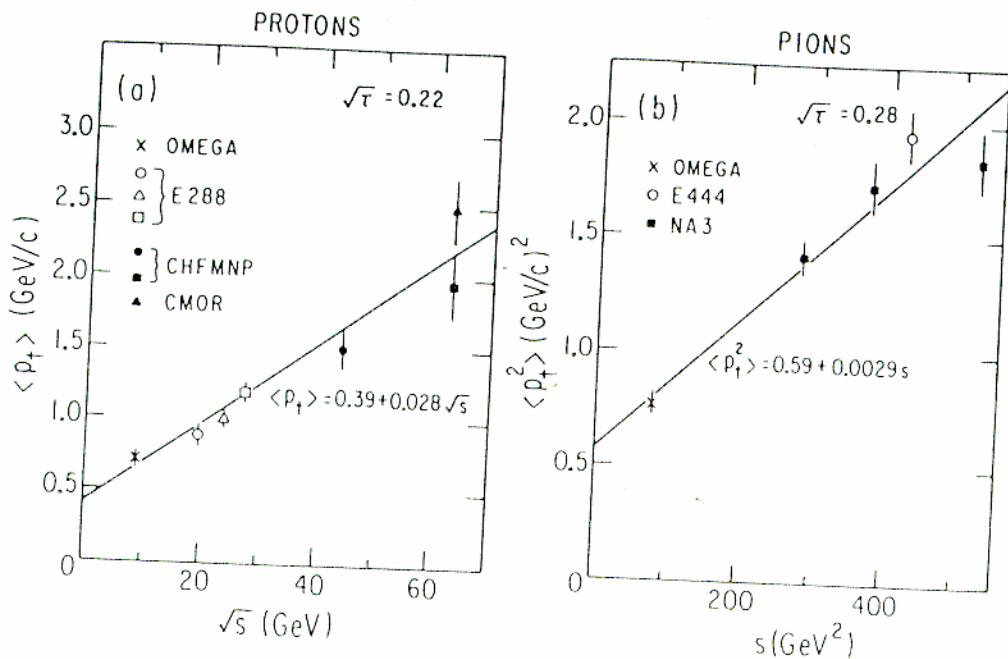


Figure 16 (a) The mean transverse momentum for proton-induced dilepton production as a function of  $\sqrt{s}$  (12, 14, 30). (b) The mean  $P_T^2$  as a function of  $s$  for dimuons produced in pion collisions (31, 35, 52).

1991

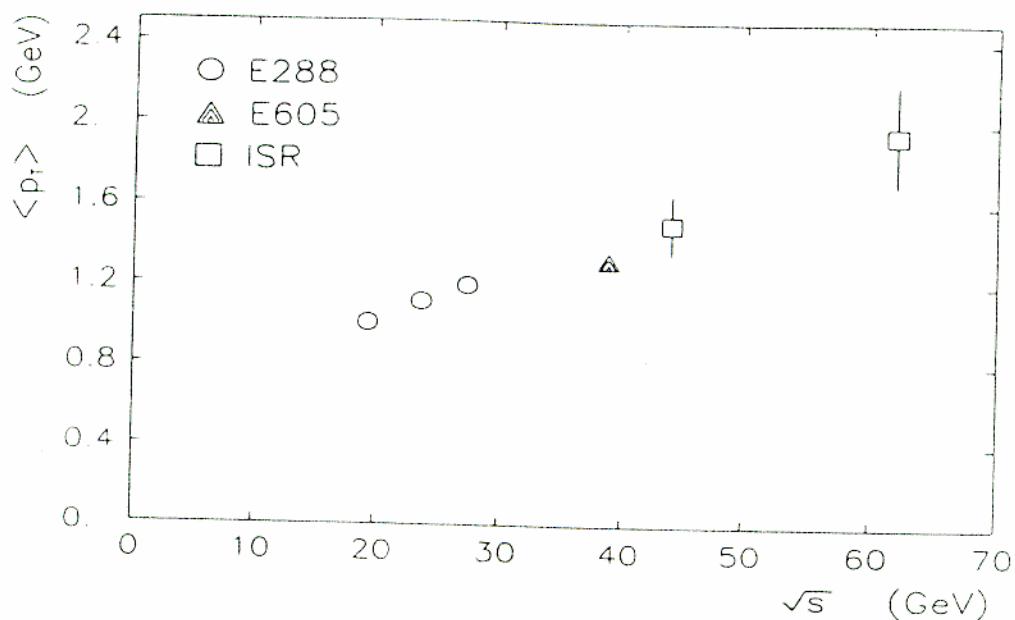


FIG. 15. Average transverse momentum of dimuons at  $\sqrt{\tau} \simeq 0.3$  versus  $\sqrt{s}$  for this experiment. Also shown are the data of Ref. 33 and Ref. 34.

# ANGULAR DISTRIBUTION FROM Z DECAY

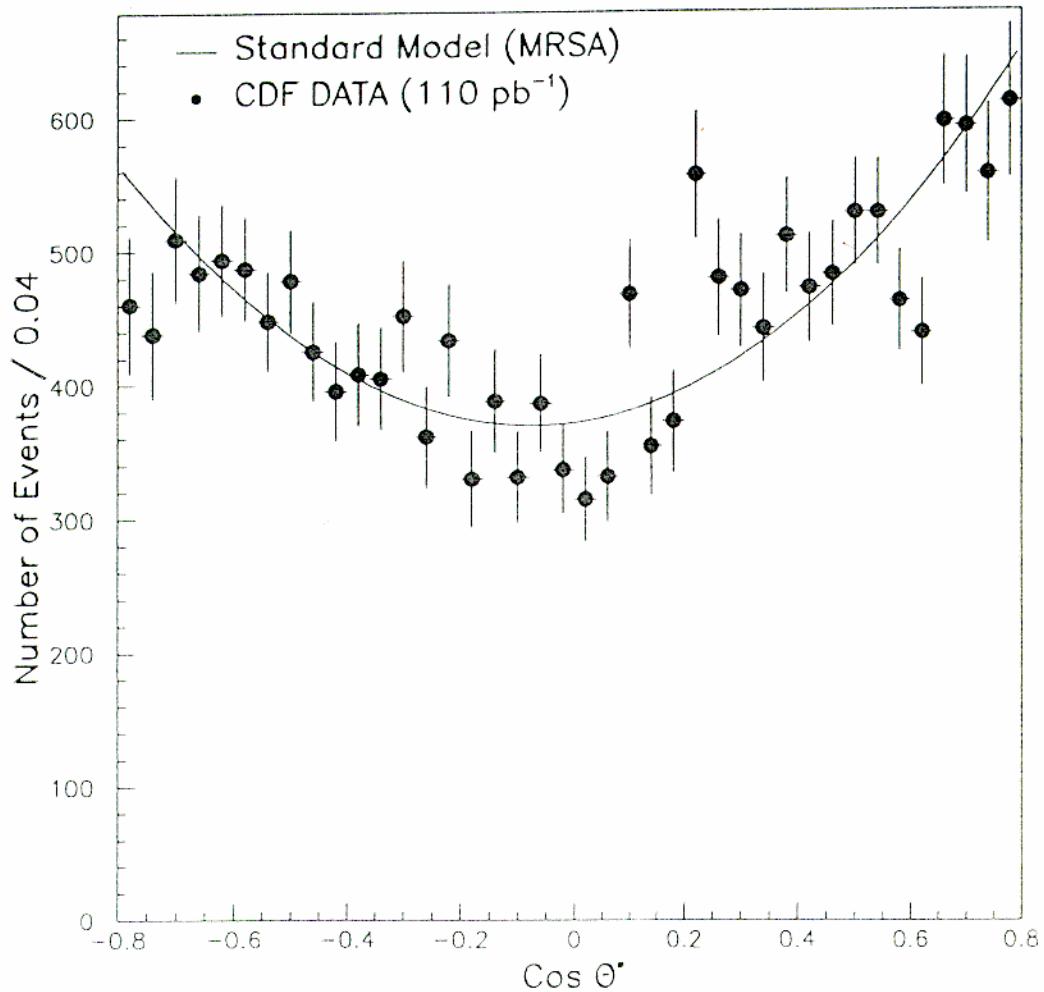


Fig. 9.9. Angular distribution of leptons from  $Z$ -boson decay measured by the CDF collaboration. Figure from ref. [23].

$\pi C$     $E = 225 \text{ GeV}$    K.J. ANDERSON et al  
 PRL, 1979

ANG. DIST.  
 $\sim 1 + \alpha \cos^2 \theta$

$\alpha$

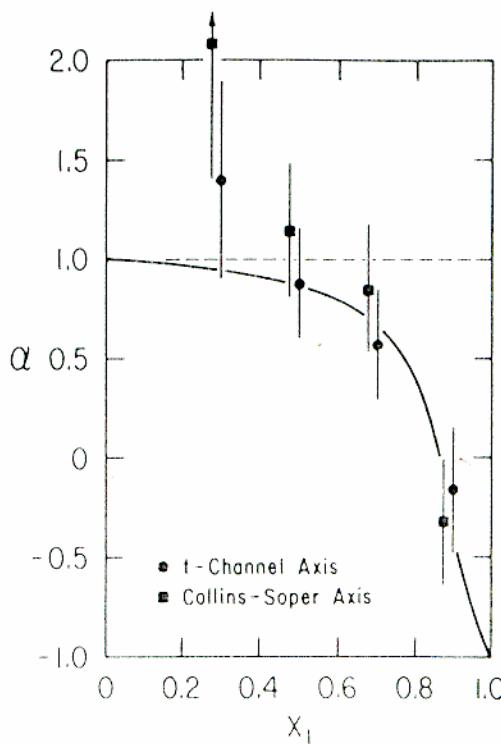


FIG. 2. The dependence of  $\alpha$  on  $x_1$  for data with  $M > 4$  GeV. The dashed line is the expected result for the naive Drell-Yan model. The solid curve is the QCD prediction of Berger and Brodsky (Ref. 8).

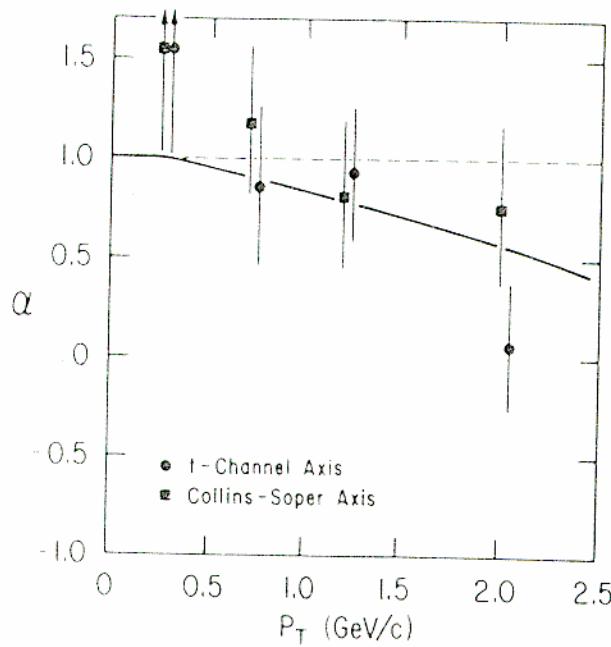
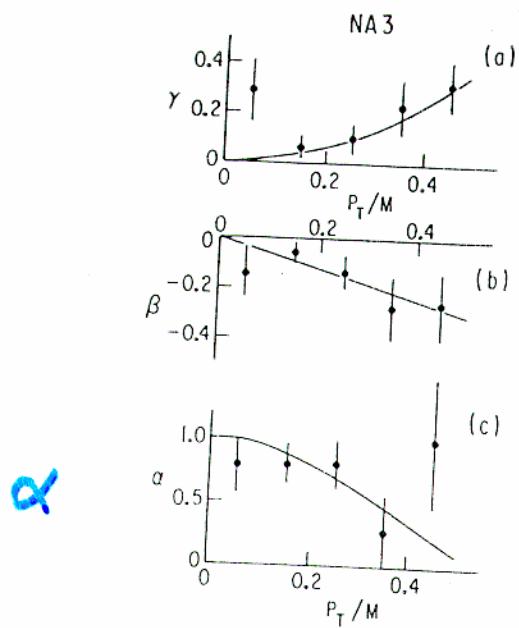


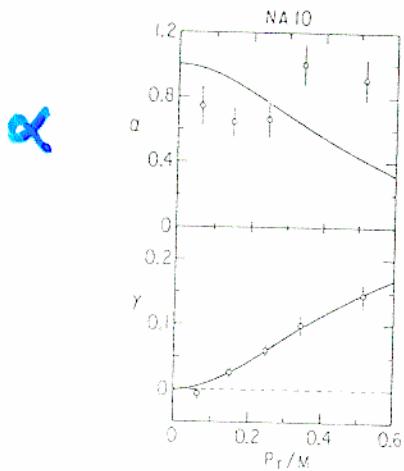
FIG. 3. The dependence of  $\alpha$  on  $P_T$  for data with  $M > 4$  GeV. The smooth curve is the QCD prediction from Kajantie et al. (Ref. 7). These authors consider only  $x_F = 0$  while the data are integrated over  $x_F$ .



NA3 1981

Figure 18 The dimuon angular distribution parameters as measured by the NA3 group (59). The curves for  $\beta$  and  $\gamma$  are fits to the simple kinematic forms described in the text. The  $\alpha$  curve assumes the relation  $1 - \alpha = 4\gamma$ .

$\pi P_t$   $E = 150 \text{ GeV}$



NA10 1985

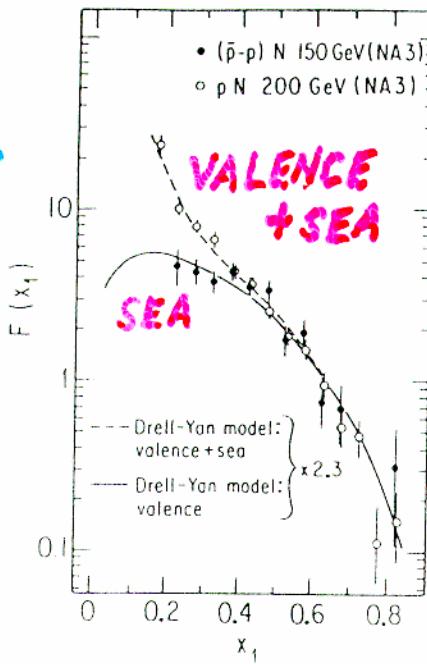
Figure 19 The dimuon angular distribution obtained by NA10 (60). The curve for  $\gamma$  is a fit to the theoretically expected form. The curve for  $\alpha$  results from the relation  $1 - \alpha = 4\gamma$ .

$\pi W$   $E = 194 \text{ GeV}$

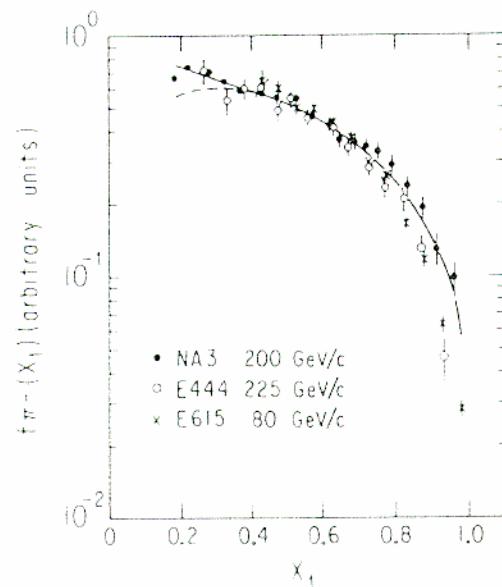
## PHYSICS TOOLS

- PROCESS WELL UNDERSTOOD IN PQCD  
⇒ POWERFUL TOOL FOR NEW INFO
- EXTRACTION OF  $\pi$  STRUCTURE FCTN
- COMPLEMENTARY INFO ON NUCLEON STRUCTURE FCTN  
(ESPECIALLY  $\bar{q}(x, Q^2)$ )
- DISCOVERY OF W & Z AT CERN
- PRECISE MEASUREMENTS OF W MASS AT FERMILAB
- LEPTON & QUARK SIZE
- E-W INTERFERENCE ⇒ FORWARD-BACK ASYMMETRIES ⇒ DIAGNOSTICS FOR Z'
- POLARIZED TARGET/BEAM

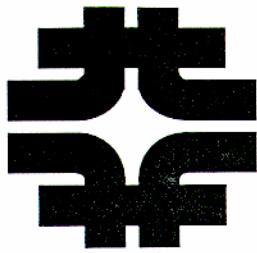
# NUCLEON STRUCT. FCN



*Figure 7* The nucleon structure function measured by experiment NA3 (27). The full circles are obtained from  $(\bar{p}$ - $p$ )N data and measure the valence distribution. The open circles are pN data, which measure the valence plus sea distribution. The curves are the Drell-Yan model predictions multiplied by 2.3.

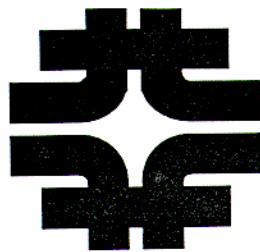


*Figure 9* The measured pion structure function (32, 44, 45). The solid line is the NA3 fit for the valence plus sea distribution. The dashed line is their result for the valence alone.



# Combined Results

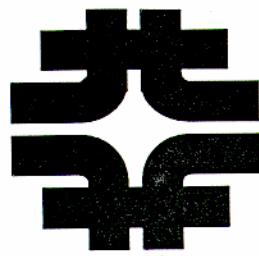
- ▷ Tevatron
  - ▷ DØ 1992-93(e) and 94-95(e)
    - ⇒  $M_W = 80.43 \pm 0.11 \text{ GeV}$
  - ▷ CDF 1989(e/μ), 92-93(e/μ), and 94-95(μ)
    - ⇒  $M_W = 80.38 \pm 0.12 \text{ GeV}$
- ▷ DØ, CDF, and UA2
  - ▷  $M_W = 80.405 \pm 0.090 \text{ GeV}$ 
    - ⇒ 50 MeV common error
- ▷ LEP2: CERN-PPE/97-154
  - ▷  $M_W = 80.48 \pm 0.14 \text{ GeV}$
- ▷ World Average
  - ▷  $M_W = 80.425 \pm 0.075 \text{ GeV}$



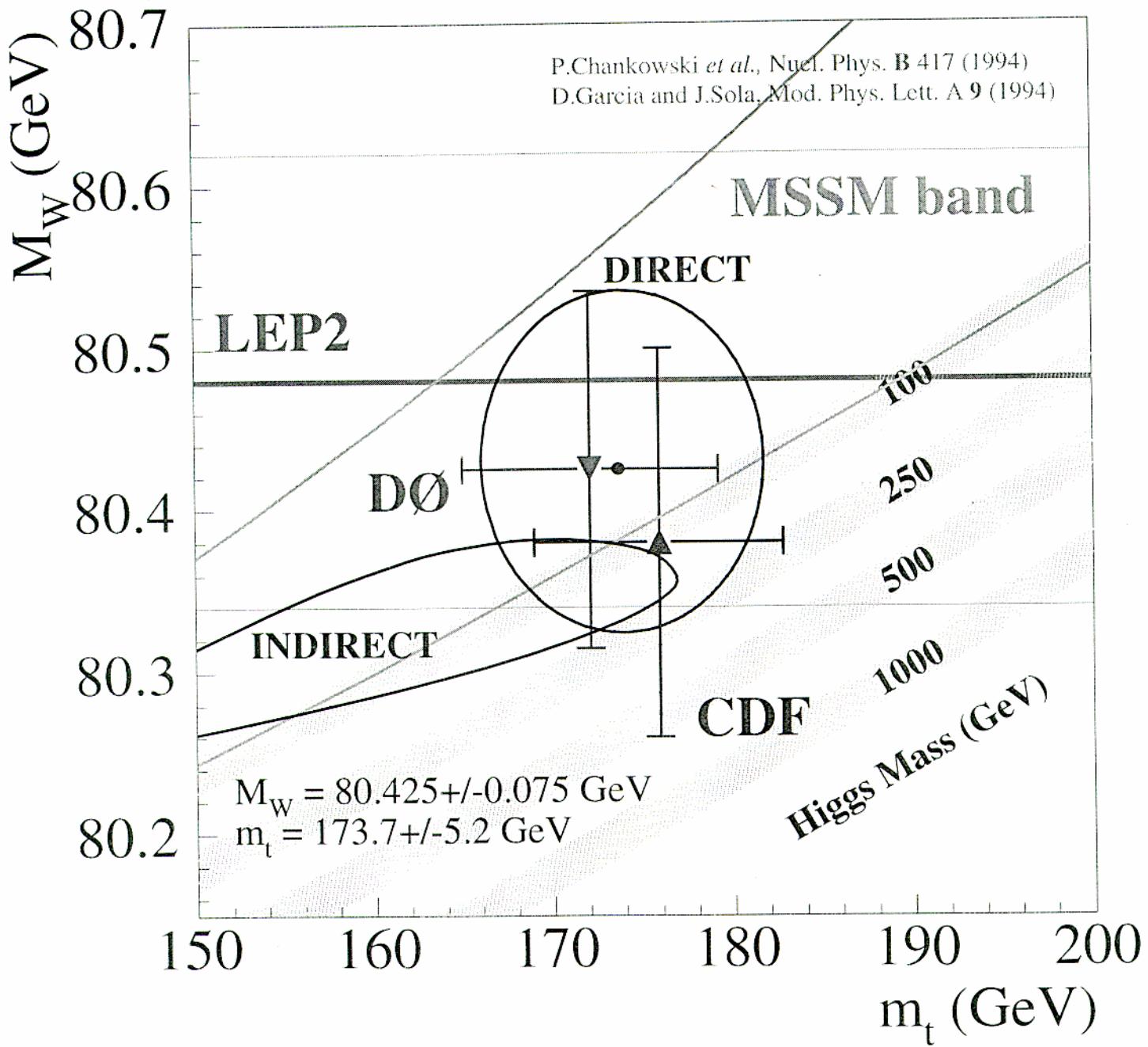
# Prospects from the Tevatron Collider

- ▷ Data continues to be analyzed from Run 1:  $\sim 100 \text{ pb}^{-1}$ 
  - ▷ CDF
    - ⇒ electron/muon channel
      - ⇒  $\Delta M_W \sim 90 \text{ MeV}$
  - ▷ DØ
    - ⇒ electron channel in the forward calorimeters
      - ⇒  $\Delta M_W \sim 100 \text{ MeV}$
  - ▷ Tevatron
    - ⇒  $\Delta M_W \sim 70 \text{ to } 80 \text{ MeV}$
- ▷ Run 2:  $\sim 2 \text{ fb}^{-1}$ 
  - ⇒  $\Delta M_W \sim 40 \text{ MeV}$
- ▷ TeV33:  $\sim 30 \text{ fb}^{-1}$ 
  - ⇒  $\Delta M_W \sim 20 \text{ MeV}$

*Eric Flattum - Fermilab*



# Higgs



Eric Flattum - Fermilab

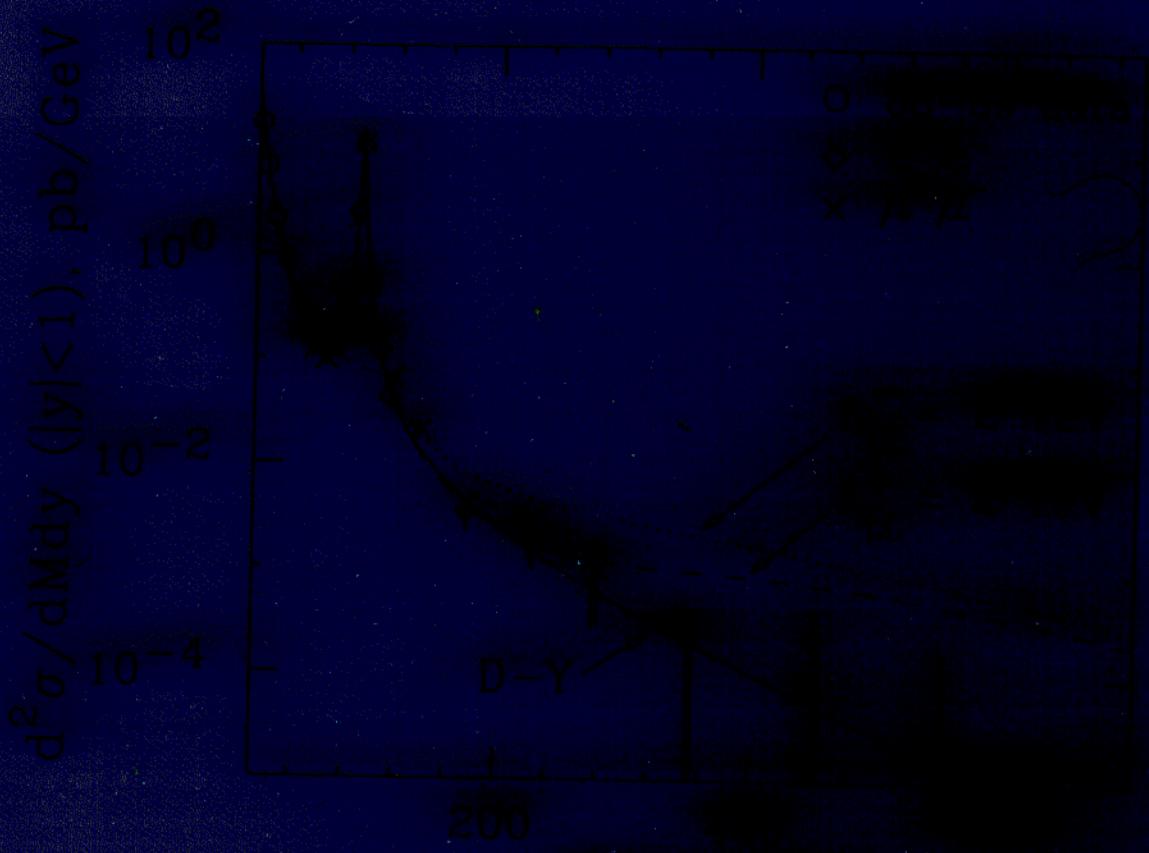


FIG. 1.  $d^2\sigma/dMdy(y < 1)$ , pb/GeV vs.  $M$  in GeV. Open circles ( $M < 50$  GeV) and crosses ( $M > 50$  GeV) are experimental data normalized to  $y = 1$ . Above 110 GeV, the crosses are not normalized. The  $D-Y$  curve is a simulation. Superimposed are  $LL$  model calculations.

E. EICHEN, K. LANE, & M. R.  
PRL, 50, 811 (1983)

$$\mathcal{L} = \xi_{LL} (\bar{E}_L \gamma^\mu E_L) (\bar{Q}_L \gamma_\mu Q_L)$$

$$E = (\nu_e, e^-) \quad Q = (u, d)$$

$$\xi_{LL} = \pm \frac{4\pi}{(A_{LL}^\pm)^2}$$

## CONCLUSIONS

- NAIVE MODEL IMPROVED BY QCD
- IMPORTANT ARENA FOR PQCD
  - INFRARED DIVERGENCES
  - COLLINEAR " "
  - FACTORIZATION
- GOOD AGREEMENT WITH EXPT
  - $N_c = 3$
  - K-FACTOR  $\sim 2$
- POWERFUL PHYSICS TOOL

THEOREM

NAIVE DRELL =

A MAN OF WISDOM,  
WARMTH, AND  
KINDNESS