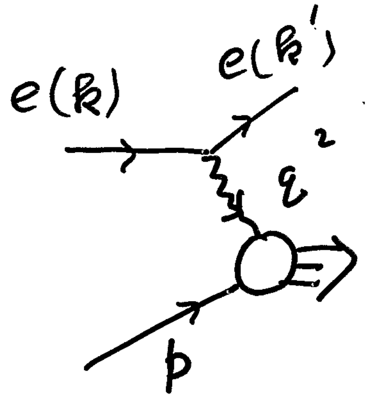
HEAVY FLAVOR ELECTROPRODUCTION

J. SMITH

STONY BROOK.

DEEP INELASTIC SCATTERING AT HERA



$$Q^2 = -q^2$$

$$x = \frac{Q^2}{2p\cdot q}.$$

$$y = \frac{p\cdot q}{p\cdot k} = 1 - \frac{p\cdot k'}{p\cdot k}.$$

$$\frac{d^2\sigma}{dx\,dy} = \frac{8\pi\alpha^2 ME}{(Q^2)^2}\left[\left(\frac{1+(1-y)^2}{2}\right)2xF_1(x,Q^2) + (1-y)\left[F_2(x,Q^2) - 2xF_1(x,Q^2)\right]\right]$$

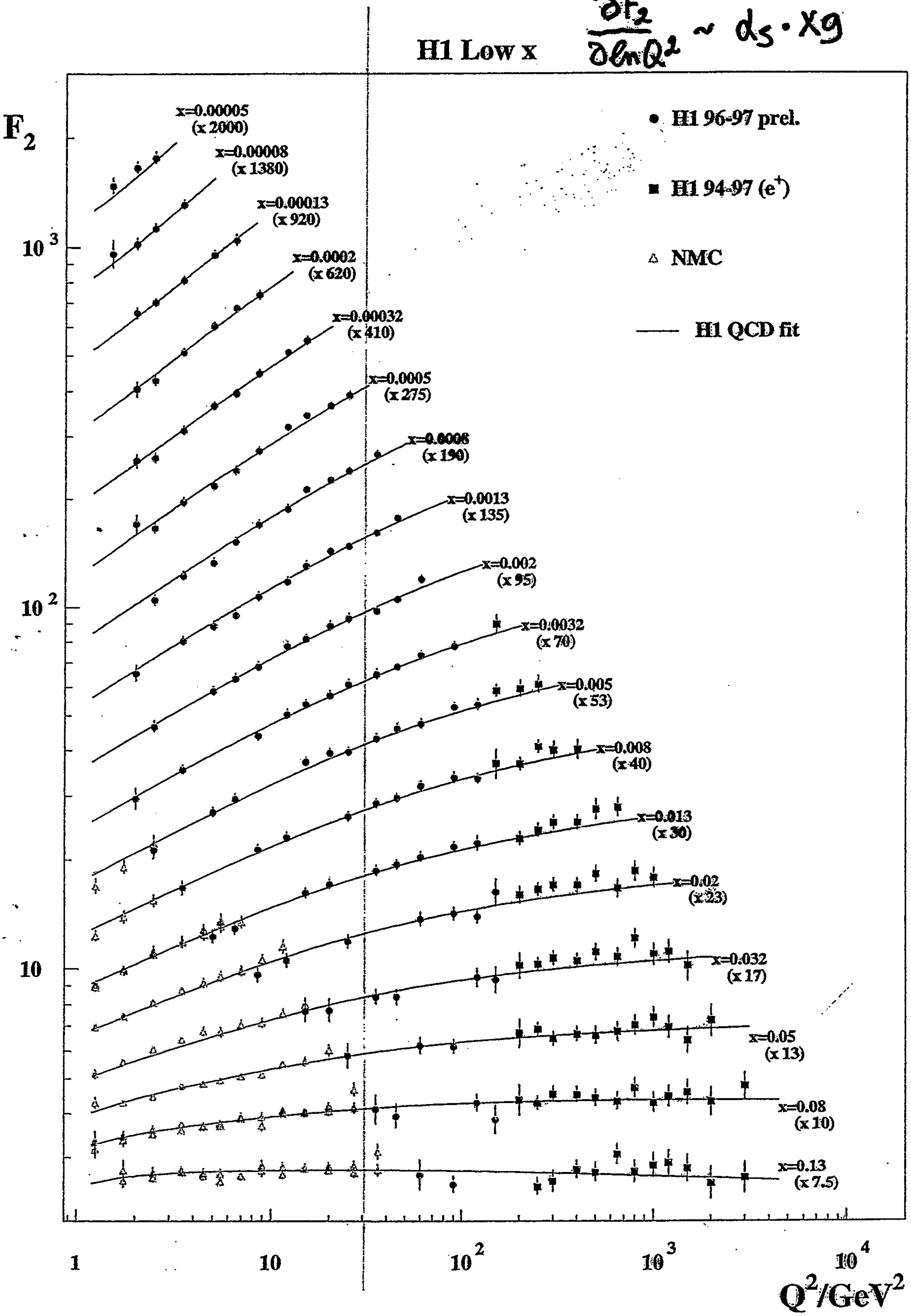
$$F_L(x,Q^2) = F_2(x,Q^2) - 2xF_1(x,Q^2)$$

$$= 0 \quad \text{IN LOWEST ORDER.}$$

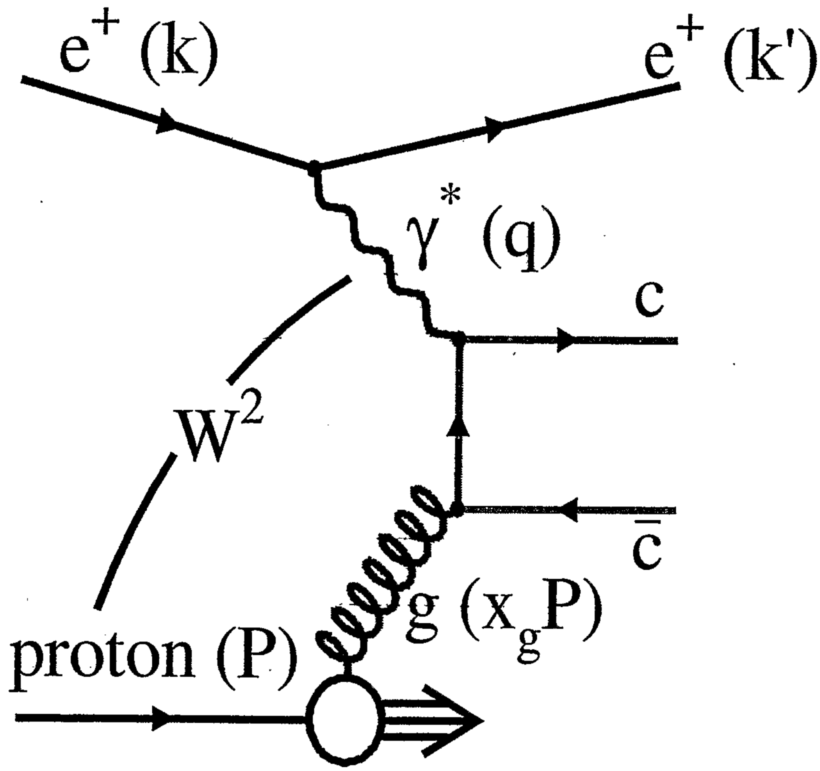
$$f\otimes g(x) = \int_0^1 dy\int_0^1 dz\ \delta(x-yz)\,f(y)\,g(z)$$

large scaling violations described by NLO DGLAP

$\frac{\partial F_2}{\partial \ln Q^2} \sim \alpha_s \cdot xg$



where is BFKL . $\ln 1/x$ terms ? cf. Proc. DIS99



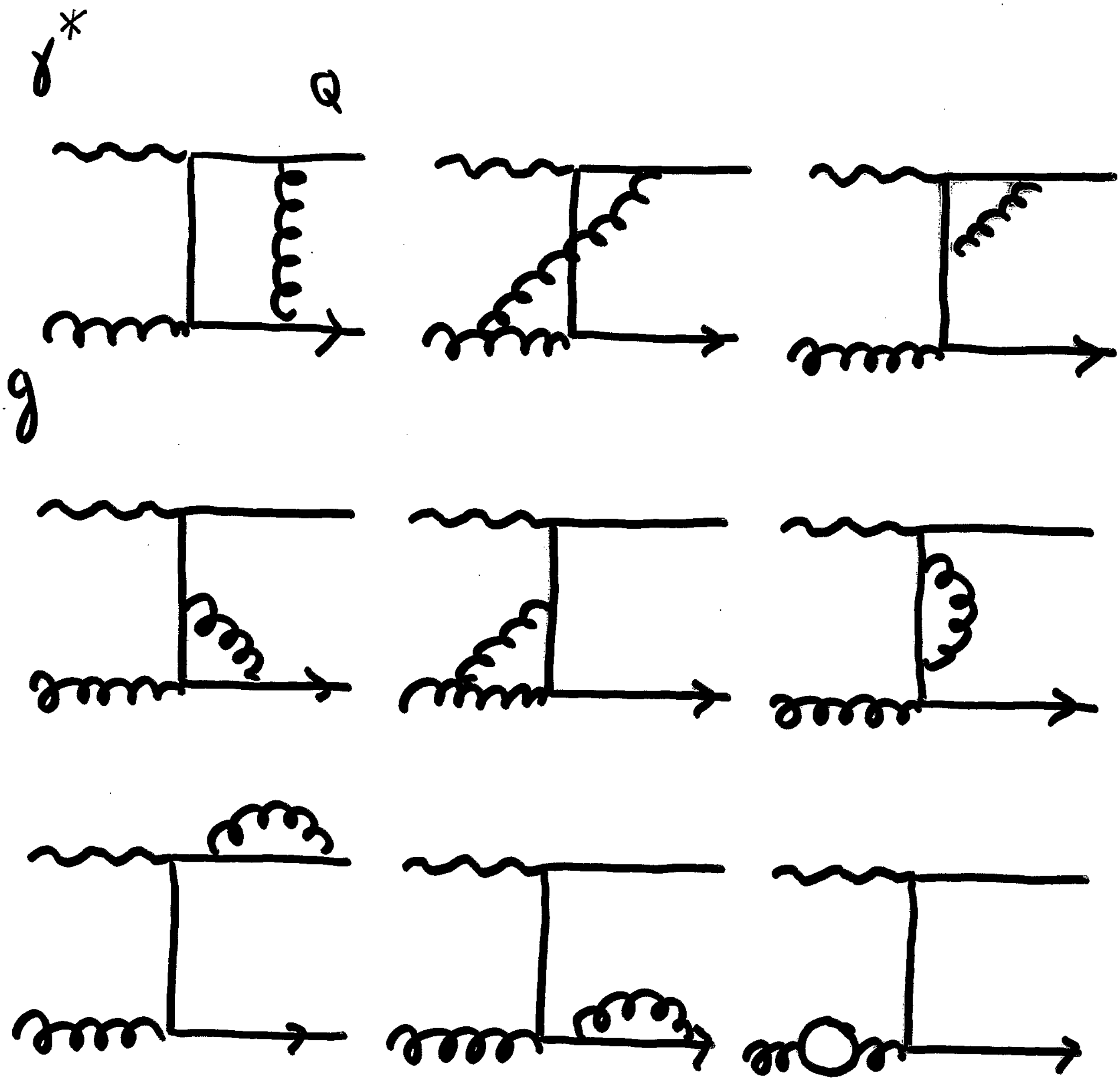
+ ....-

Figure 1: *Diagram of the boson-gluon-fusion process in* e^+p *collisions.*

+ NLO CORRECTIONS.

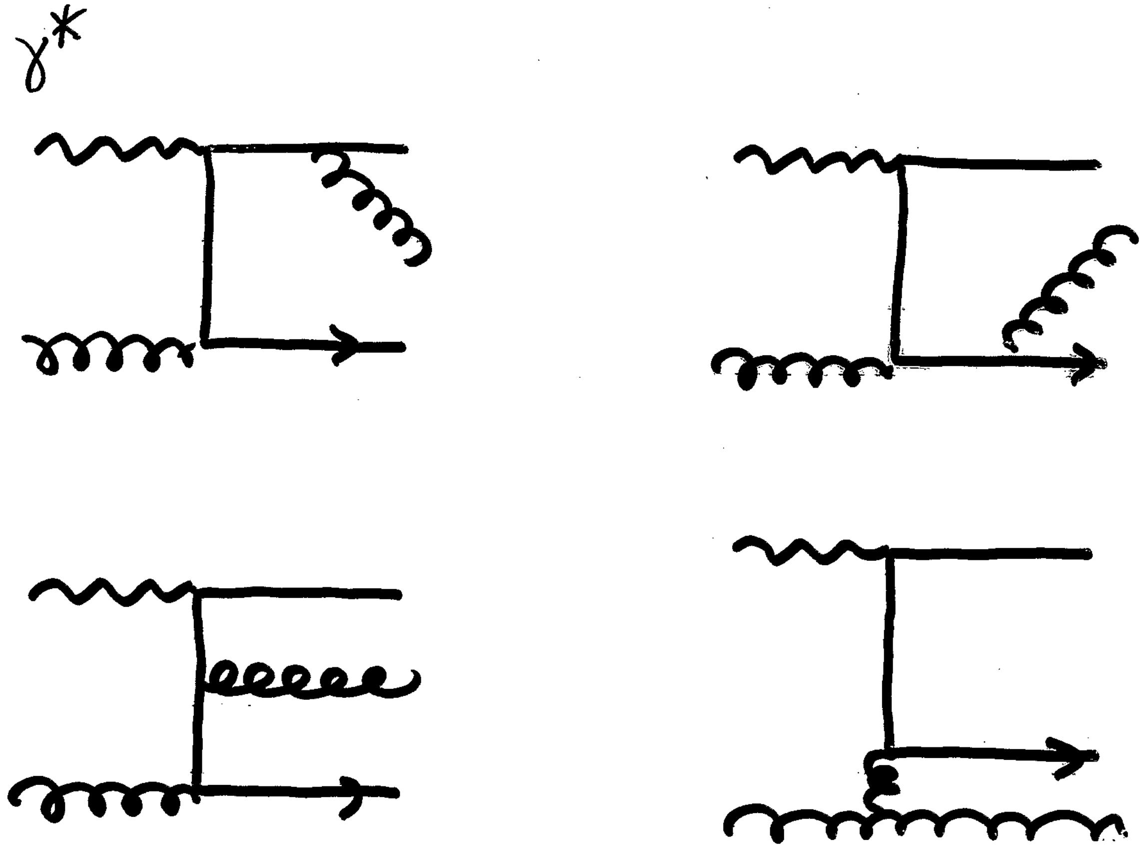
LAENEN, RIEMERSMA, SMITH, VAN NEERVEN (93)

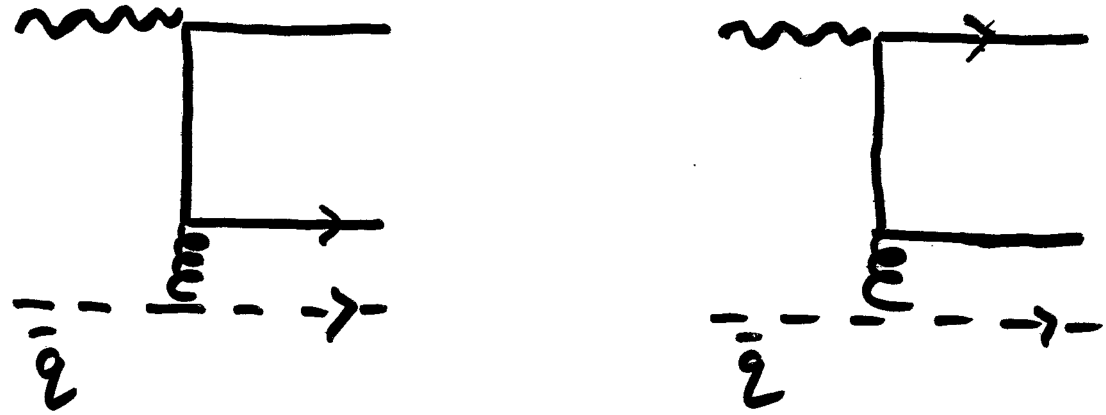
HARRIS & SMITH (HVQDIS) (95)



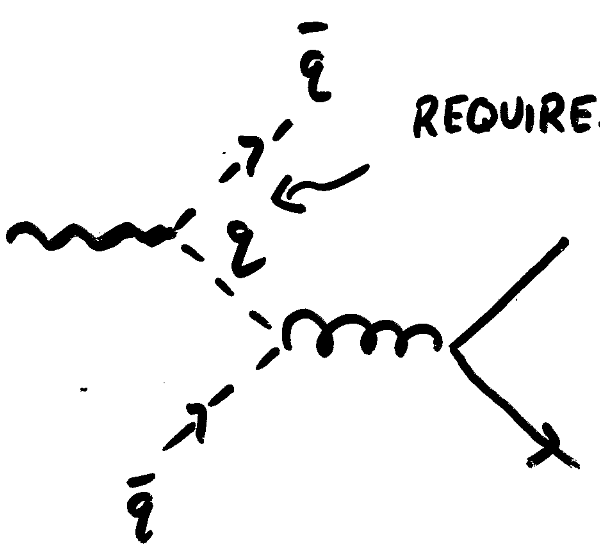
$Q^2 = 0$

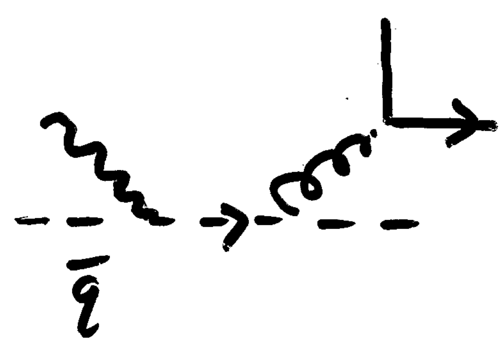
$Q^2 \neq 0$





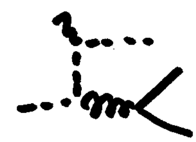
REQUIRES MASS FACTORIZATION IF $Q^2=$(





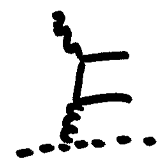
STRUCTURE FUNCTIONS

$$F_i(x, Q^2, m^2) = x \int_x^{z_{MAX}} \frac{dz}{z} \left[\frac{1}{n_f} \sum_{k=1}^{n_f} e_k^2 \right.$$



$$\left\{ \Sigma\left(\frac{x}{z}, \mu^2\right) \times L^S_{i,q}(z, Q^2, m^2, \mu^2) + G\left(\frac{x}{z}, \mu^2\right) L_{i,g}(z, Q^2, m^2, \mu^2) \right\}$$

$$\left. + \Delta\left(\frac{x}{z}, \mu^2\right) L^{NS}_{i,q}(z, Q^2, m^2, \mu^2) \right]$$



$$+ x e_H^2 \int_x^{z_{MAX}} \frac{dz}{z} \left\{ \Sigma\left(\frac{x}{z}, \mu^2\right) H_{i,q}(z, Q^2, m^2, \mu^2) \right.$$

$$\left. + G\left(\frac{x}{z}, \mu^2\right) H_{i,g}(z, Q^2, m^2, \mu^2) \right\}.$$

SINGLET Σ

NON-SINGLET Δ

GLUON G

Σ, Δ & G : PARTON DENSITIES.

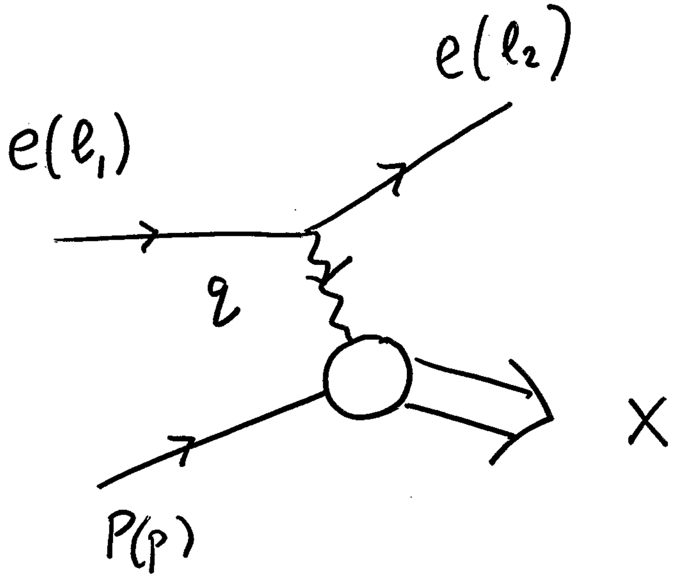
3 FLAVOUR SCHEME u, d, s, g

DEFINE $\eta = \dfrac{s - 4m^2}{4m^2}$, $\quad \xi = \dfrac{Q^2}{m^2}$. $\quad z = \dfrac{Q^2}{s + Q^2}$

$$= \left(\frac{1-z}{z}\right)\xi - 1 \, . \qquad z_{MAX} = \frac{Q^2}{Q^2 + 4m^2}.$$

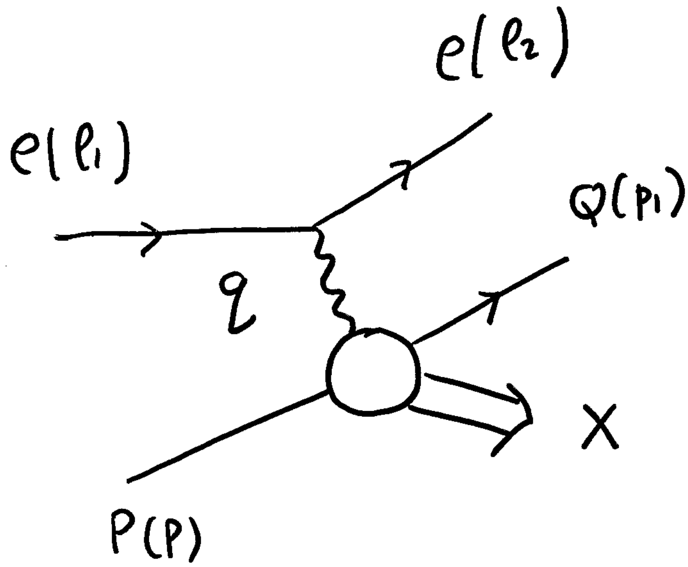
μ^2 : MASS FACTORIZATION SCALE.

I



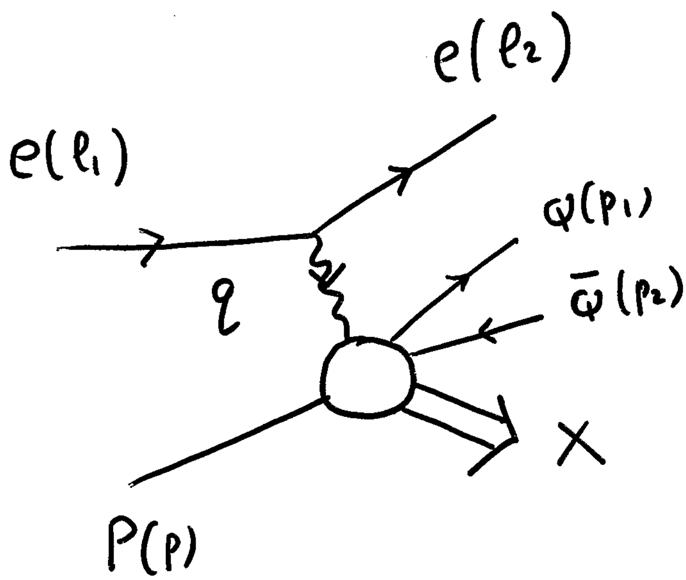
DIS

II



INCLUSIVE.

III



EXCLUSIVE

PART II

SINGLE PARTICLE INCLUSIVE DISTRIBUTIONS

IN P_T AND Y ARE ALSO AVAILABLE.

$$\frac{d F_2(x, Q^2, m^2)}{d P_t} \quad , \quad \frac{d F_2(x, Q^2, m^2)}{d Y} .$$

PART III

WHAT ABOUT MORE COMPLICATED CORRELATIONS?

$$\frac{d F_2(x, Q^2, m^2)}{d \varphi_{Q\bar{Q}}} \qquad \text{ETC}$$

OR EVENT RATES WITHIN A LIMITED PHASE SPACE REGION?

RETAIN INFORMATION LOST IN ANGULAR INTEGRATIONS IN $m = 4 + \varepsilon$ DIMENSIONS. NEED A 4-DIMENSIONAL RESULT FOR COMPUTER PROGRAM.

INCLUSIVE $\quad F_{2,c}(x,Q^2), \quad F_{L,c}(x,Q^2)$

E. LAENEN, S. RIEMERSMA, J. SMITH & W.L. VAN NEERVEN,

PHYS. LETTS. B 291 (1992) 325

NUCL. PHYS. B 392 (1993) 162, 229.

S. RIEMERSMA, J. SMITH & W.L. VAN NEERVEN,

~~PHYS LETTS~~ B 347 (1995) 143.

EXCLUSIVE

B.W. HARRIS & J. SMITH

NUCL. PHYS. B 452 (1995) 109; PHYS. LETTS. B 353 (1995) 535.

B.W. HARRIS, J. SMITH & R. VOGT

NUCL. PHYS. B 461 (1996) 181

DETECT $D^0 \to K^- \pi^+$ $\quad m_{D^0} \simeq 1.86\ \text{GeV}.$

$D^{*+} \to D^0 \pi^+ \to K^- \pi^+ \pi^+$ $\quad m_{D^*} = 2.01\ \text{GeV}.$

$m_{D^{*+}} - m_{D^0} = 145.4\ \text{MeV}$ SLOW PION.

$$B(D^0 \to K^- \pi^+) = \frac{\Gamma(D^0 \to K^- \pi^+)}{\Gamma(D^0 \to \text{ALL})} \simeq 0.040$$

$$B(D^{*+} \to D^0 \pi^+) \times B(D^0 \to K^- \pi^+) = 0.027$$

CROSS SECTIONS REQUIRE FRAGMENTATION FNS.

$P(c \to D^0)$; $P(c \to D^{*+})$

$$P(c \to D^0) . B(D^0 \to K^- \pi^+) = 0.0205 \pm 0.0011$$

$$P(c \to D^{*+}) . B(D^{*+} \to D^0 \pi^+) \times B(D^0 \to K^- \pi^+) = 0.0069 \pm 0.0005.$$

NUMBERS FROM CHARM PRODUCTION IN e^+e^- COLLISIONS.

$\therefore$ <u>LOW PROBABILITY</u> TO DETECT THESE CHARM STATES.

PLOT THE p_t DISTRIBUTION OF THE $D^*(D^0)$

AND EXTRAPOLATE TO MEASURE THE RATE.

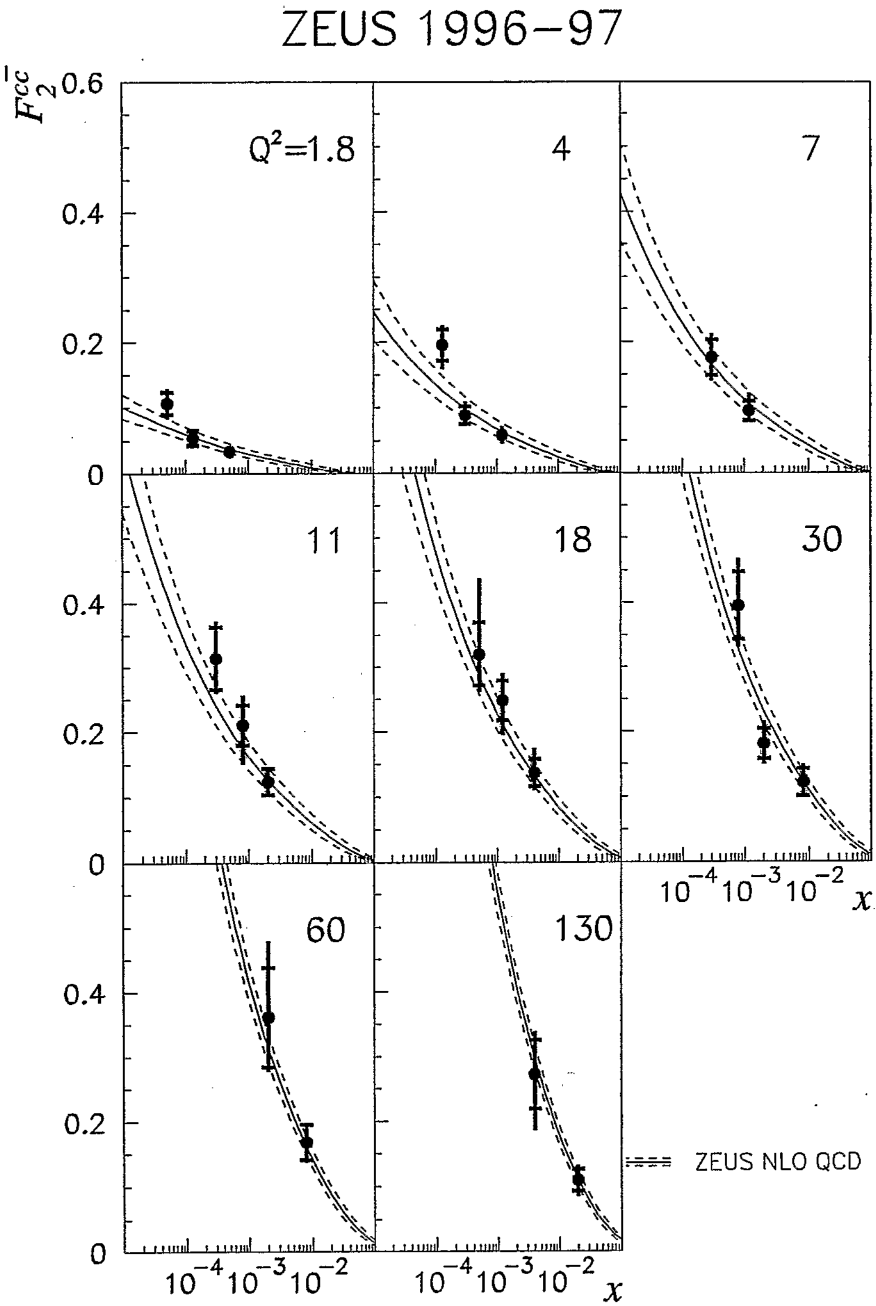
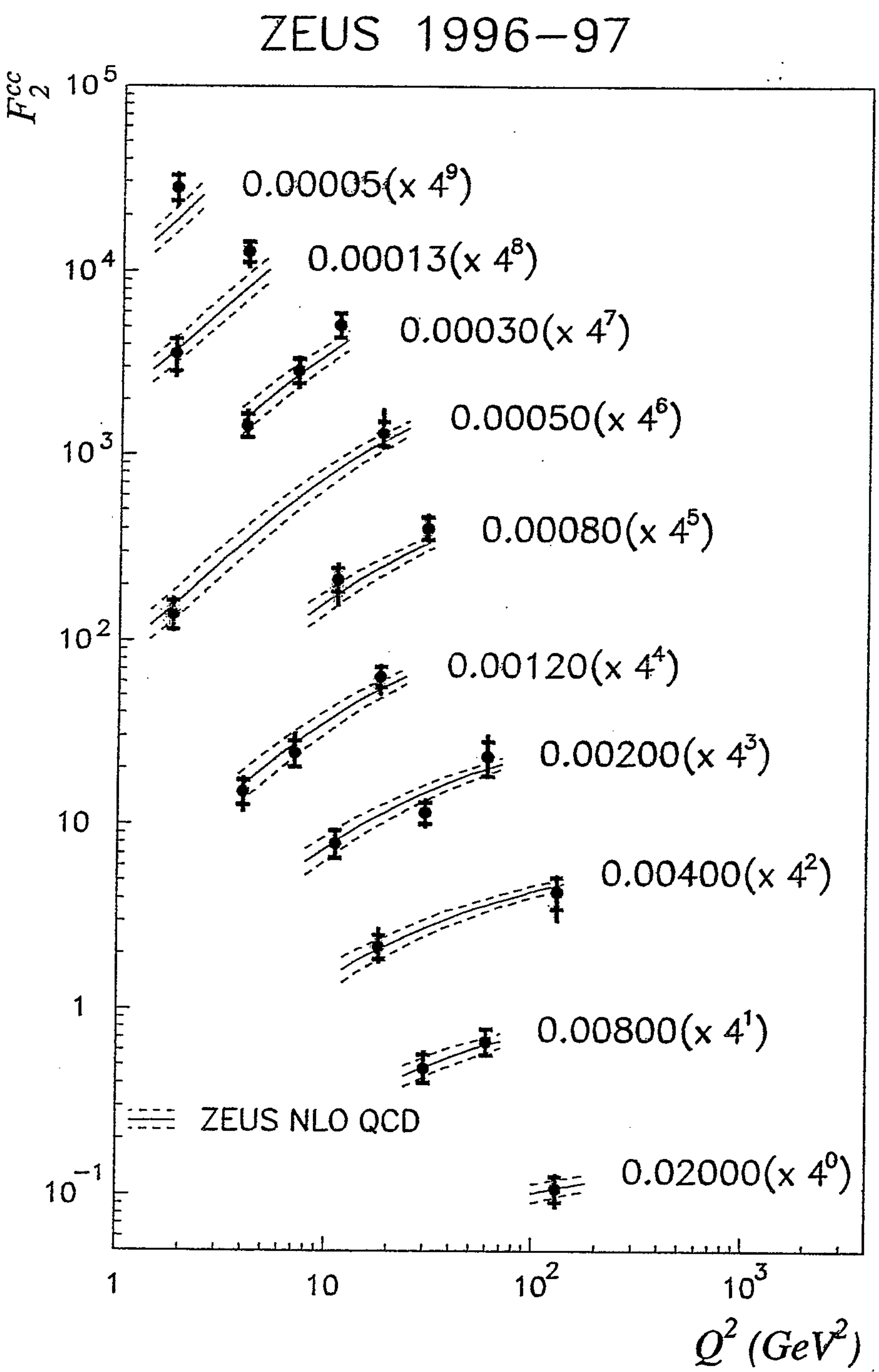


Figure 7: *The measured $F_2^{c\bar{c}}$ at Q^2 values between 1.8 and 130* GeV^2 *as a function of x. The inner error bars show the statistical uncertainty and the outer ones show the statistical and experimental systematic uncertainties summed in quadrature. The curves correspond to the NLO QCD calculation [7, 46] using the result of the ZEUS NLO QCD fit to F_2 [41]. The solid curves correspond to the central values and the dashed curves give the uncertainty due to the parton distributions from the ZEUS NLO fit. The overall normalization uncertainties arising from the luminosity measurement (±1.65%), the $D^{*\pm}$ and D^0 decay branching ratios, the charm hadronization fraction to D^{*+} (±9%) and the extrapolation uncertainties (see text) are not included.*

charm structure function.

ZEUS $D^* \to K2\pi, K4\pi$. $37 pb^{-1}$. DESY 99-101 hep-ex/9908012



Scaling violations

m_c 1.2..1.6 GeV dominantly.

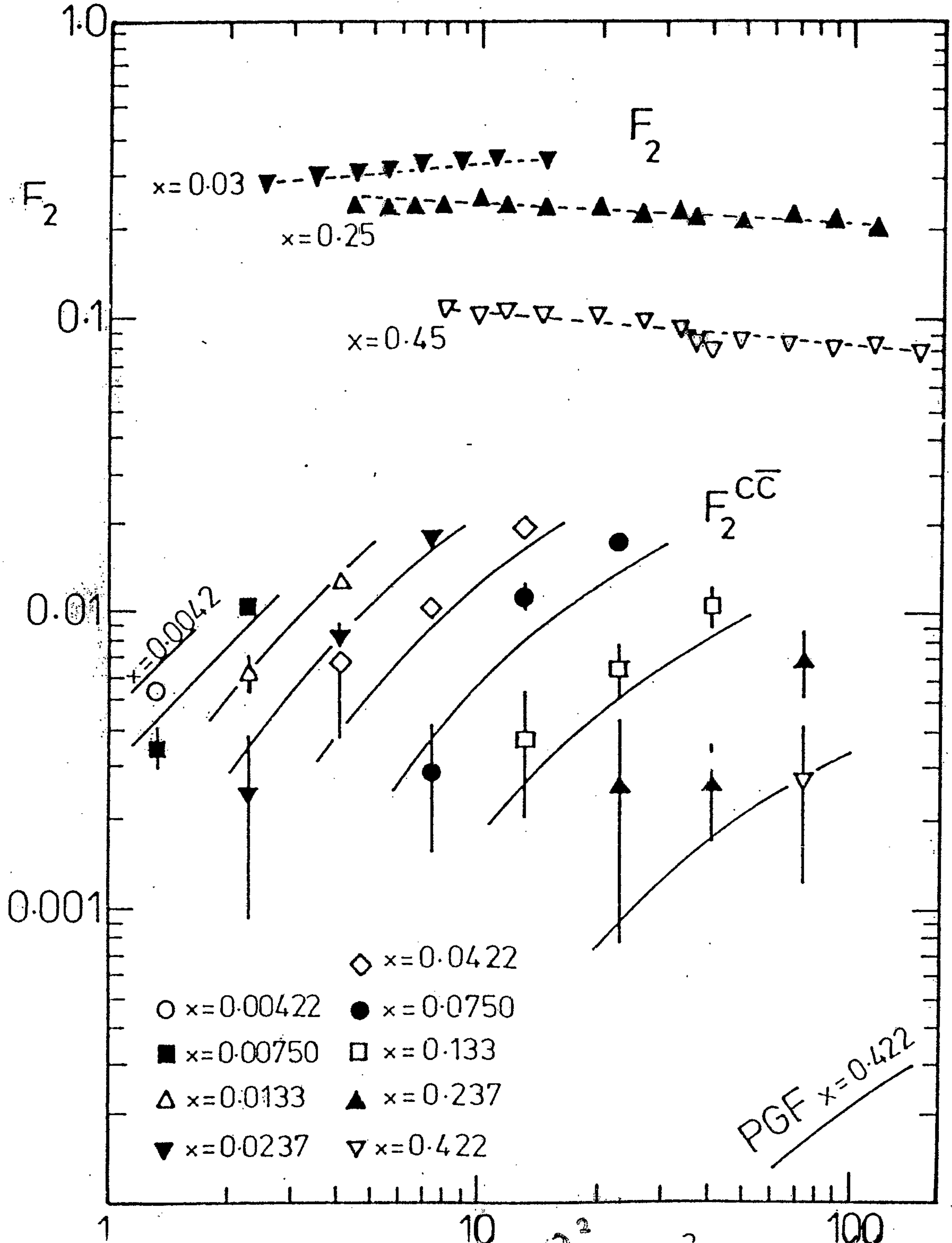
thy: 4 flavours, $Q^2 \gg m_c^2$

3 flavour + bg fusion $Q^2 \gtrsim m_c^2$ Laenen, vNeerven, Smith, Riemersma

variable flavour scheme J Smith DIS 99

J.J. Aubert et al. / Production of charmed particles

N.P. B213 (1983), 31.



WHAT HAPPENS IN N.L.O. ?

NLO I.C.

E. HOFFMANN & R. MORE

Z. PHYS C 20 (1983) 71.

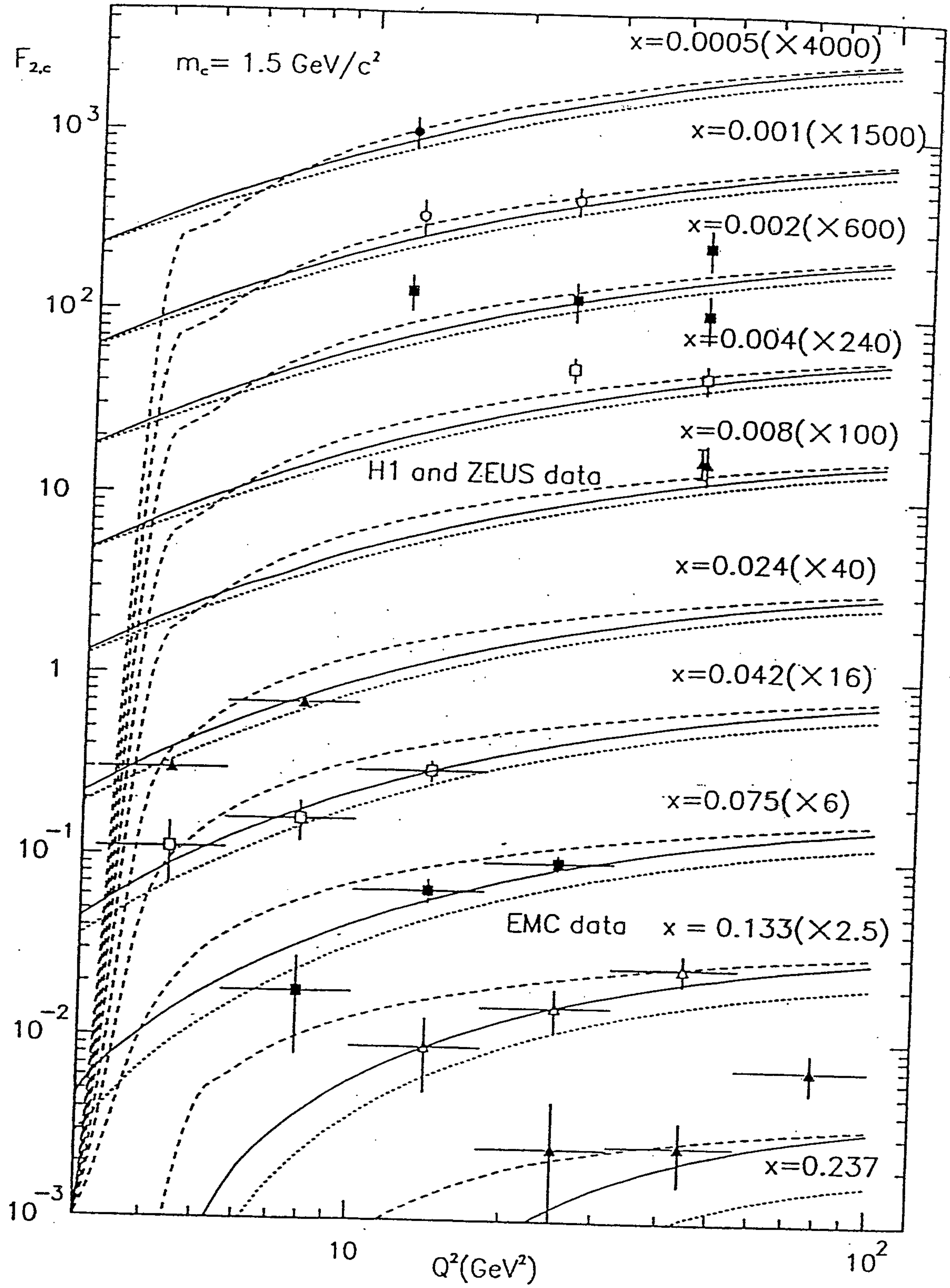
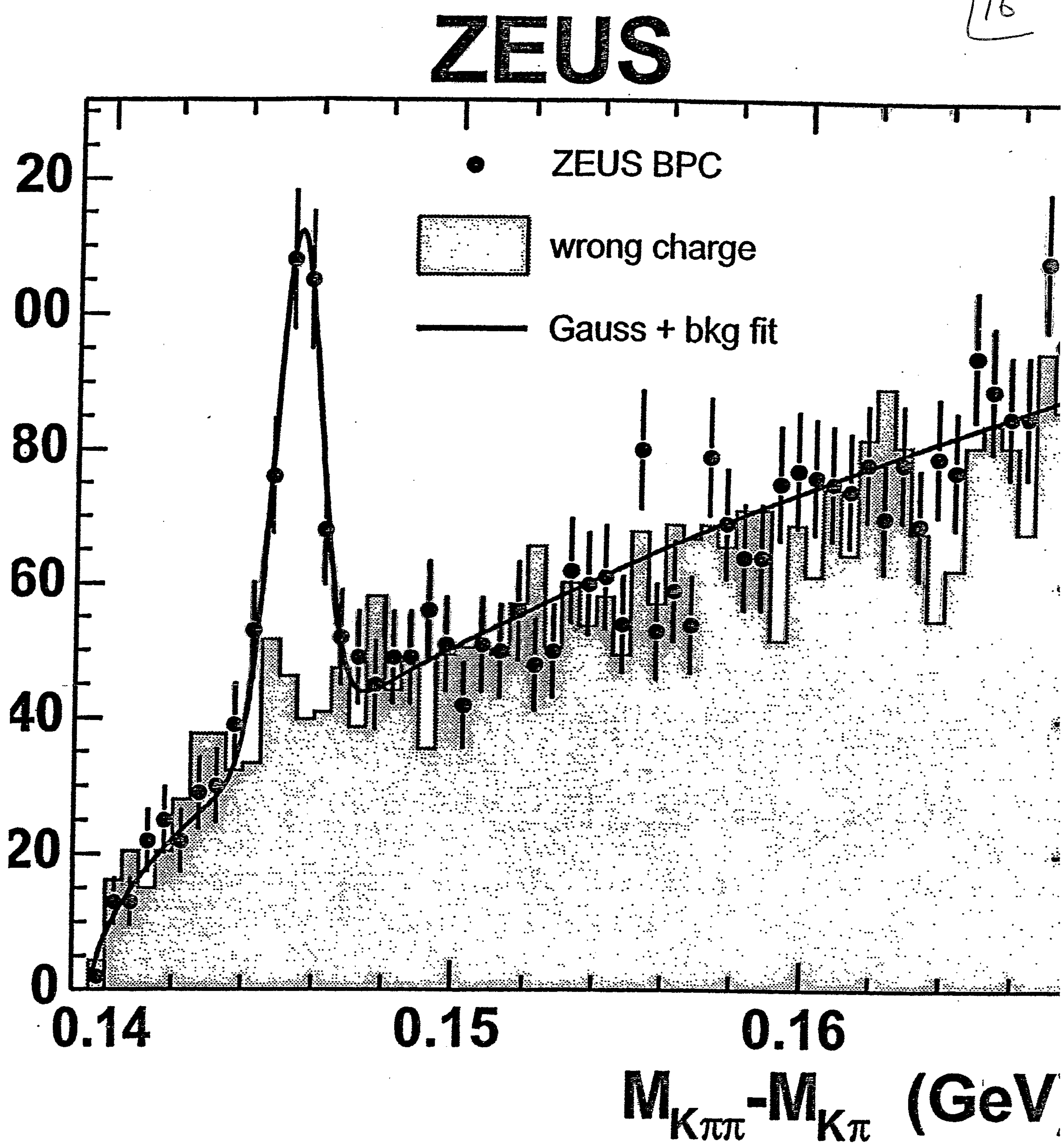
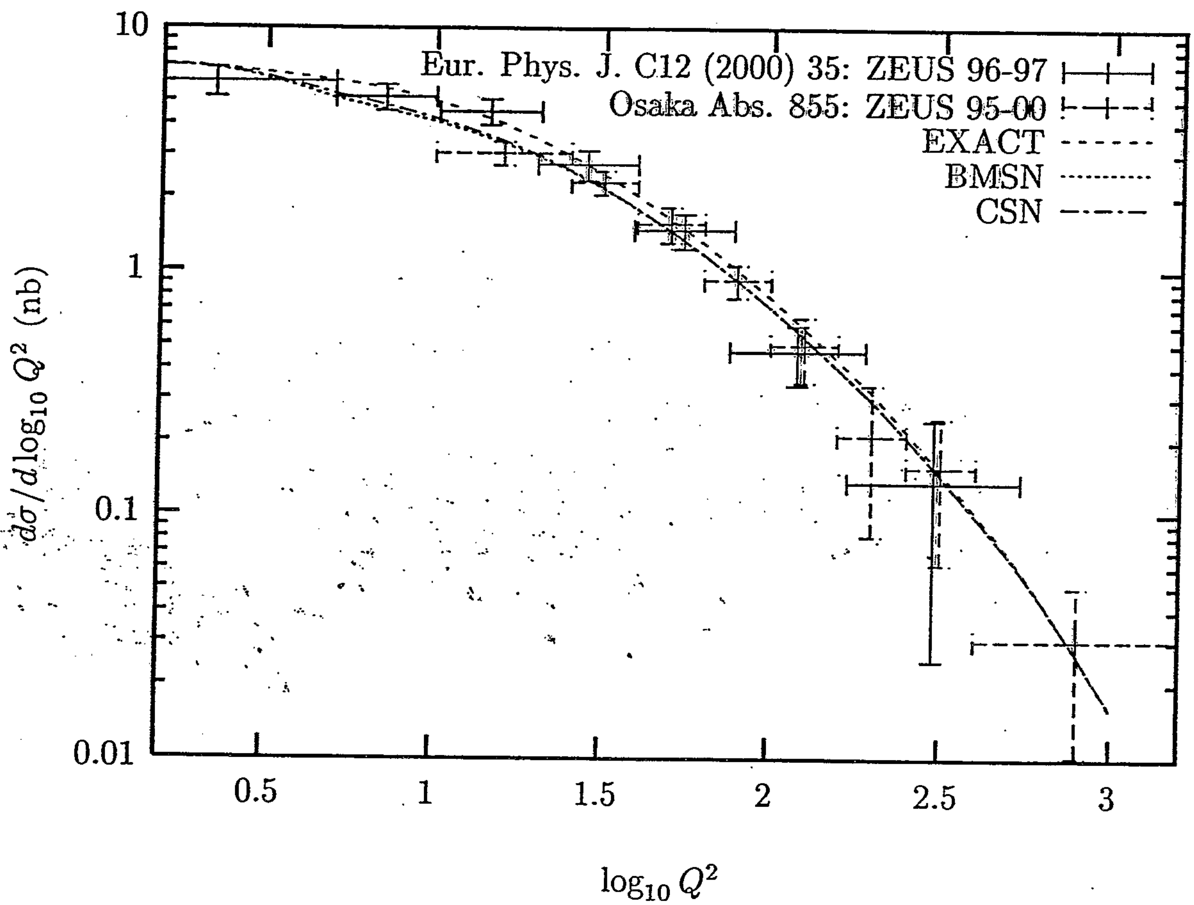
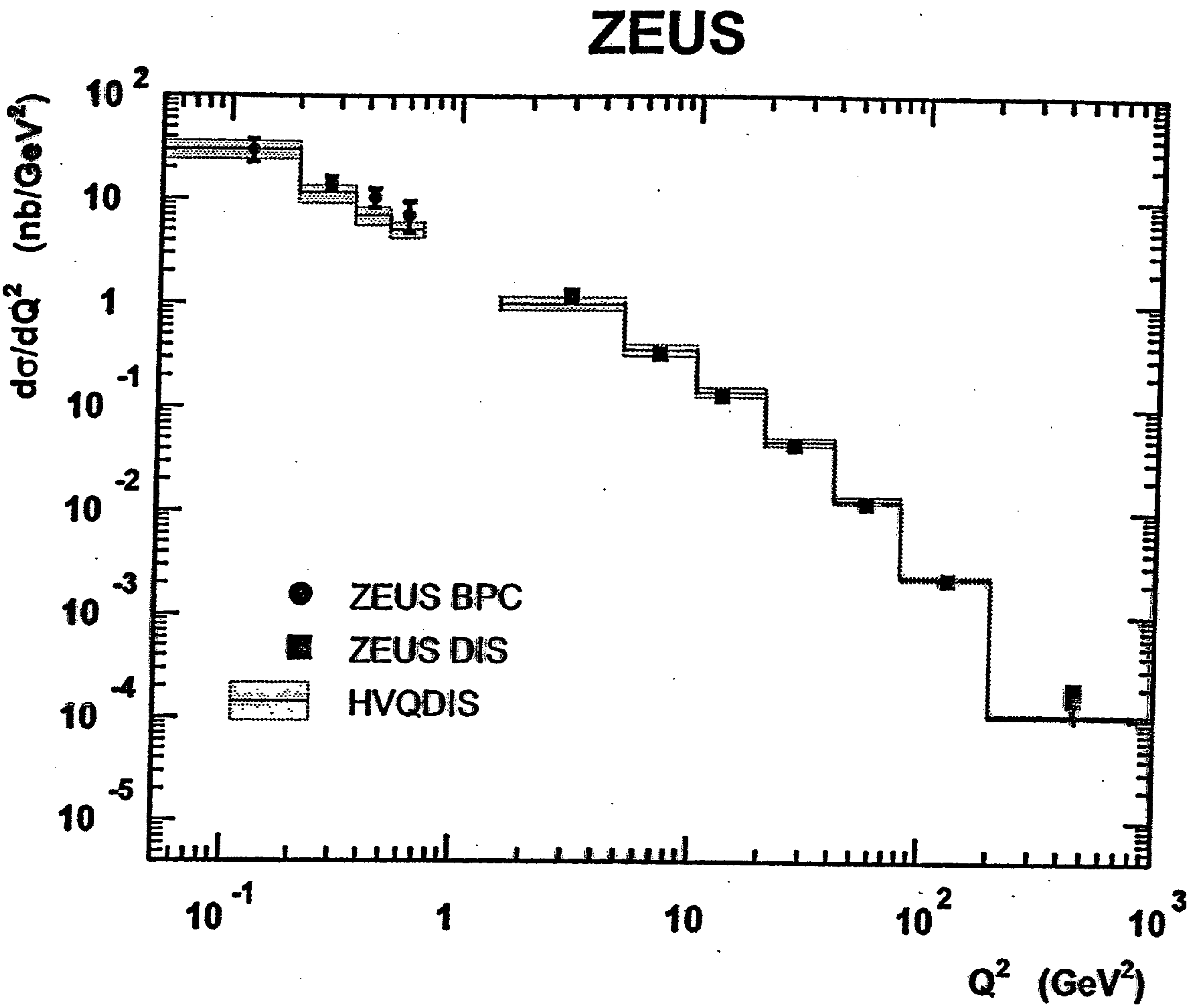


Figure 5: The functions $F_{2,c}^{\mathrm{PDF},(2)}(4,x,Q^2)$ dashed line, $F_{2,c}^{\mathrm{VFNS},(2)}(x,Q^2,m^2)$ solid line and $F_{2,c}^{\mathrm{EXACT},(2)}(3,x,Q^2,m^2)$ dotted line, plotted as a functions of Q^2 for fixed x. The data points are from the EMC, H1 and ZEUS experiments.

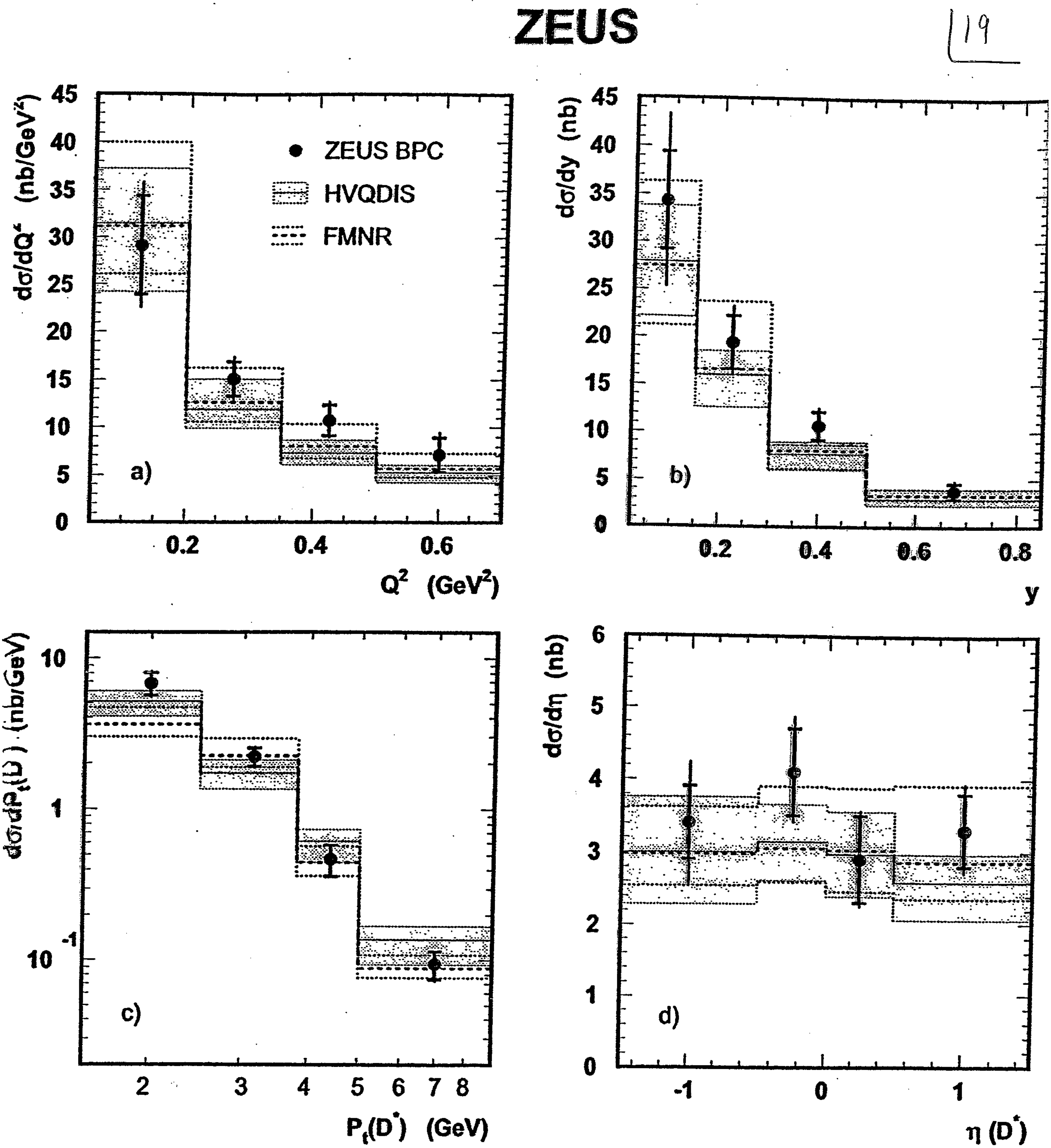

ZEUS
ZEUS BPC
wrong charge
Gauss + bkg fit
20
00
80
60
40
20
0
0.14
0.15
0.16
$M_{K\pi\pi}$-$M_{K\pi}$ (GeV



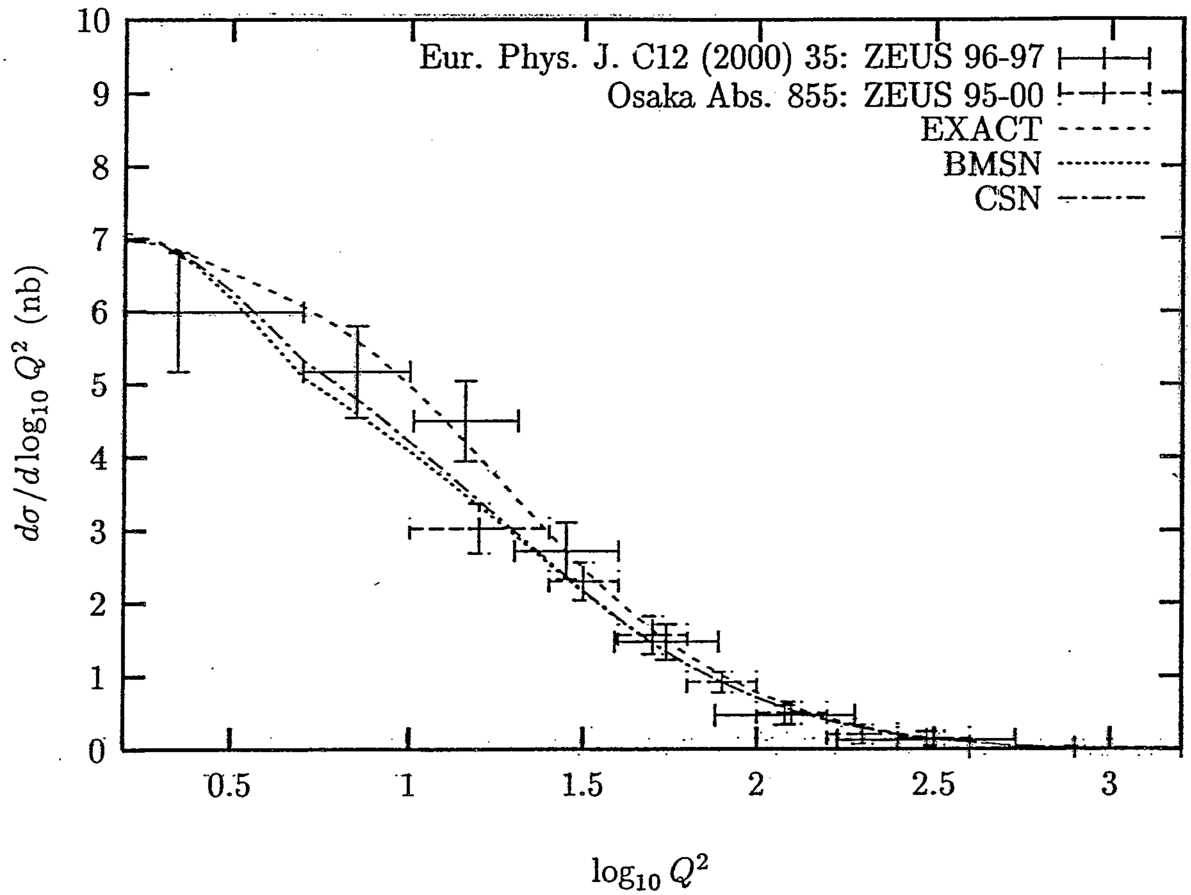
Eur. Phys. J. C12 (2000) 35: ZEUS 96-97
Osaka Abs. 855: ZEUS 95-00
EXACT
BMSN
CSN
10
1
0.1
0.01
0.5
1
1.5
2
2.5
3
$d\sigma/d\log_{10}Q^2$ (nb)
$\log_{10}Q^2$



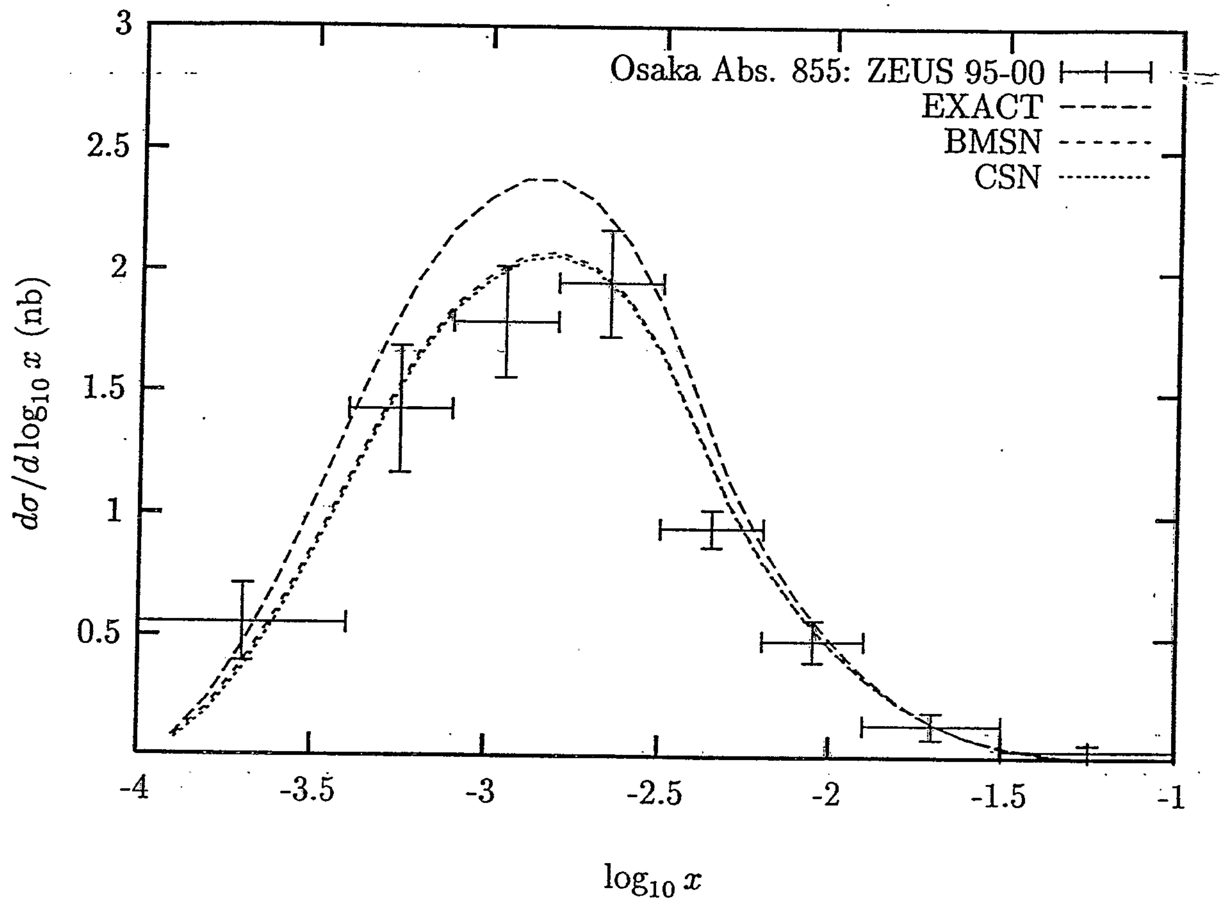
ZEUS
dσ/dQ² (nb/GeV²)
10²
10
1
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
ZEUS BPC
ZEUS DIS
HVQDIS
10⁻¹
1
10
10²
10³
Q² (GeV²)


ZEUS
ZEUS BPC
HVQDIS
FMNR
dσ/dQ² (nb/GeV²)
Q² (GeV²)
a)
dσ/dy (nb)
y
b)
dσ/dP_t(D*) (nb/GeV)
P_t(D*) (GeV)
c)
dσ/dη (nb)
η (D*)
d)

20

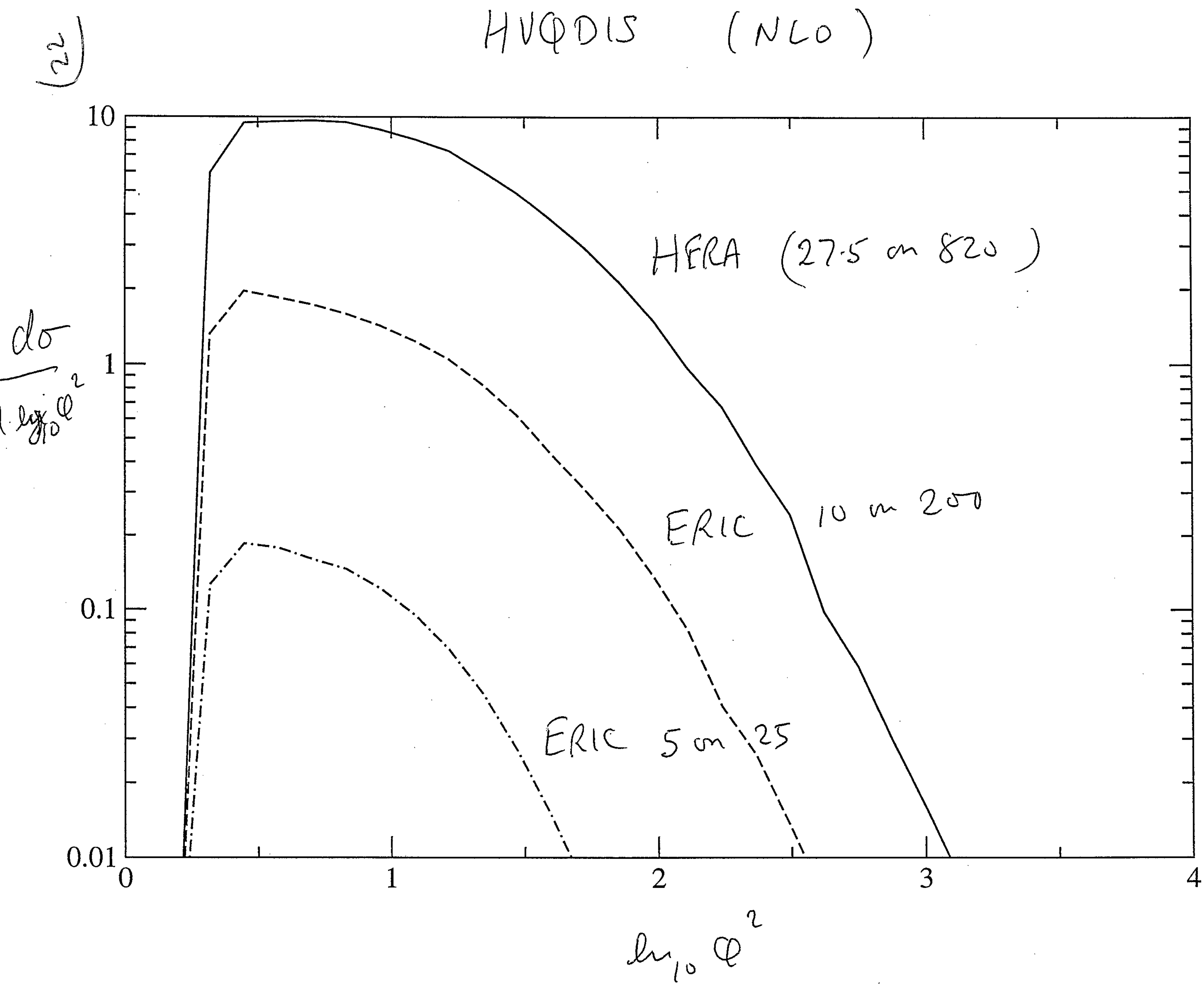


Eur. Phys. J. C12 (2000) 35: ZEUS 96-97
Osaka Abs. 855: ZEUS 95-00
EXACT
BMSN
CSN
$d\sigma/d\log_{10}Q^2$ (nb)
$\log_{10}Q^2$
0
1
2
3
4
5
6
7
8
9
10
0.5
1
1.5
2
2.5
3

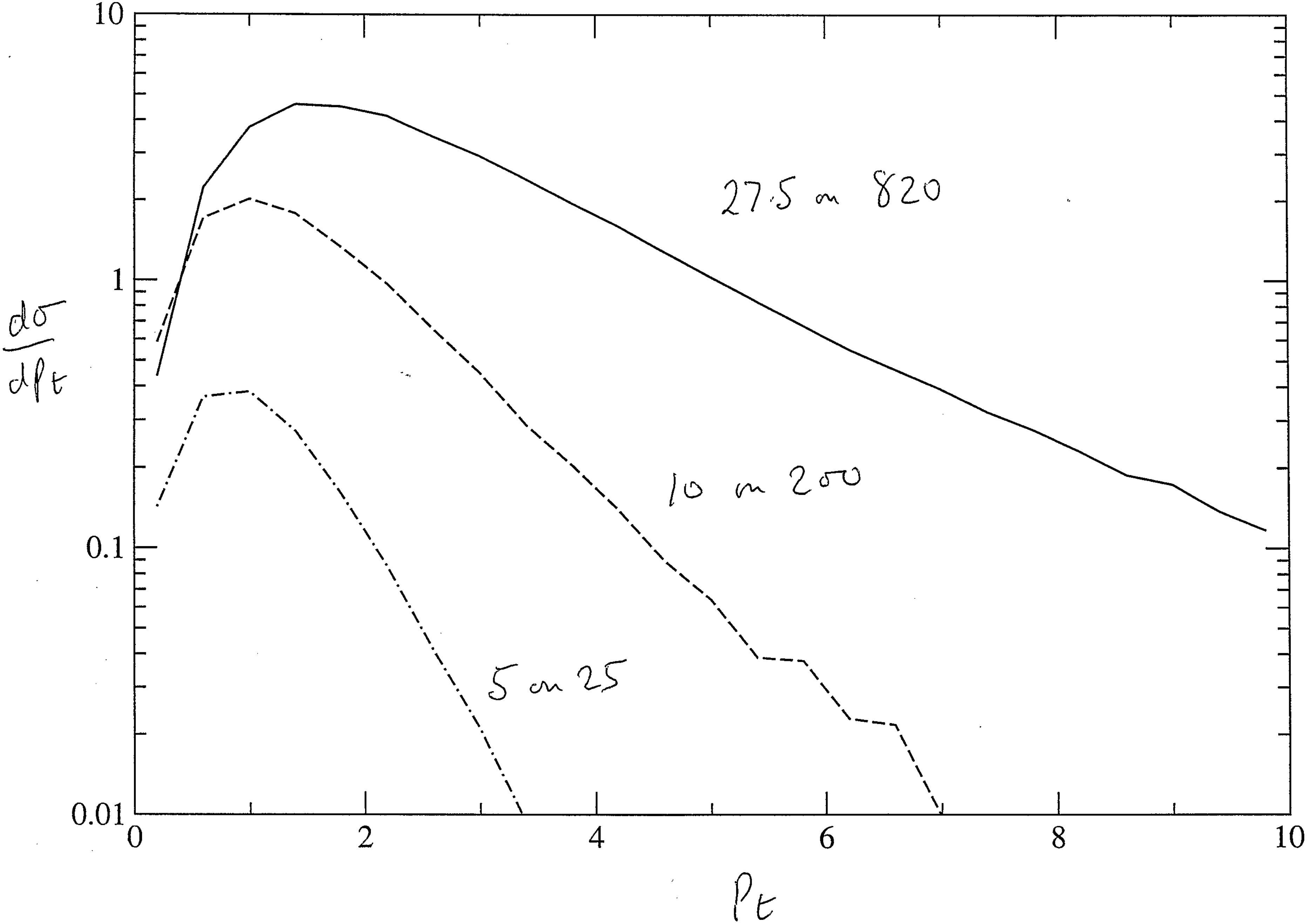


Osaka Abs. 855: ZEUS 95-00
EXACT
BMSN
CSN
$d\sigma/d\log_{10}x$ (nb)
$\log_{10}x$
3
2.5
2
1.5
1
0.5
-4
-3.5
-3
-2.5
-2
-1.5
-1

(22)

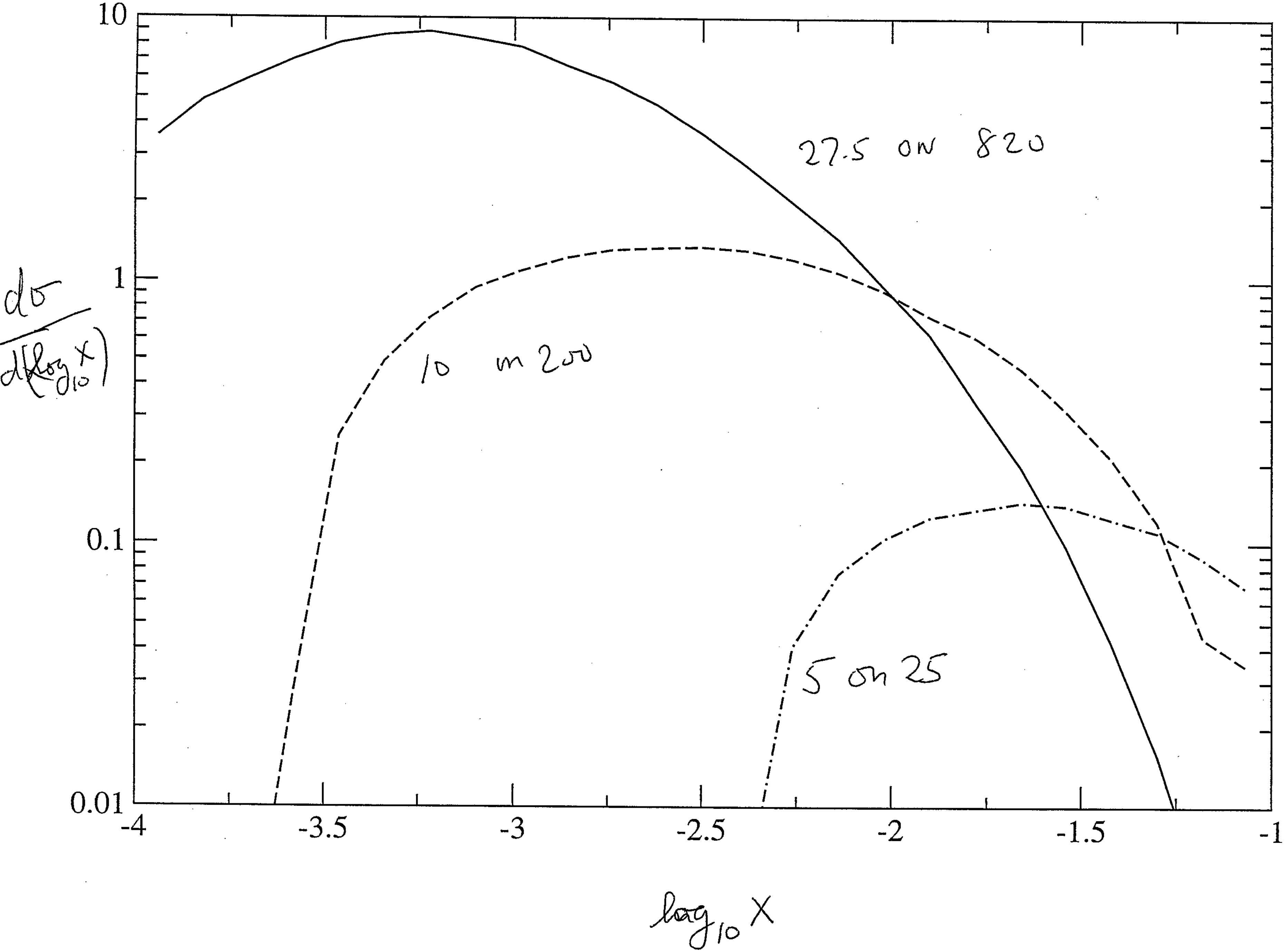

HVQDIS (NLO)
HERA (27.5 on 820)
ERIC 10 on 200
ERIC 5 on 25
10
1
0.1
0.01
0
1
2
3
4
dσ / d log10 Q^2
log10 Q^2

HVQDIS (NLO)



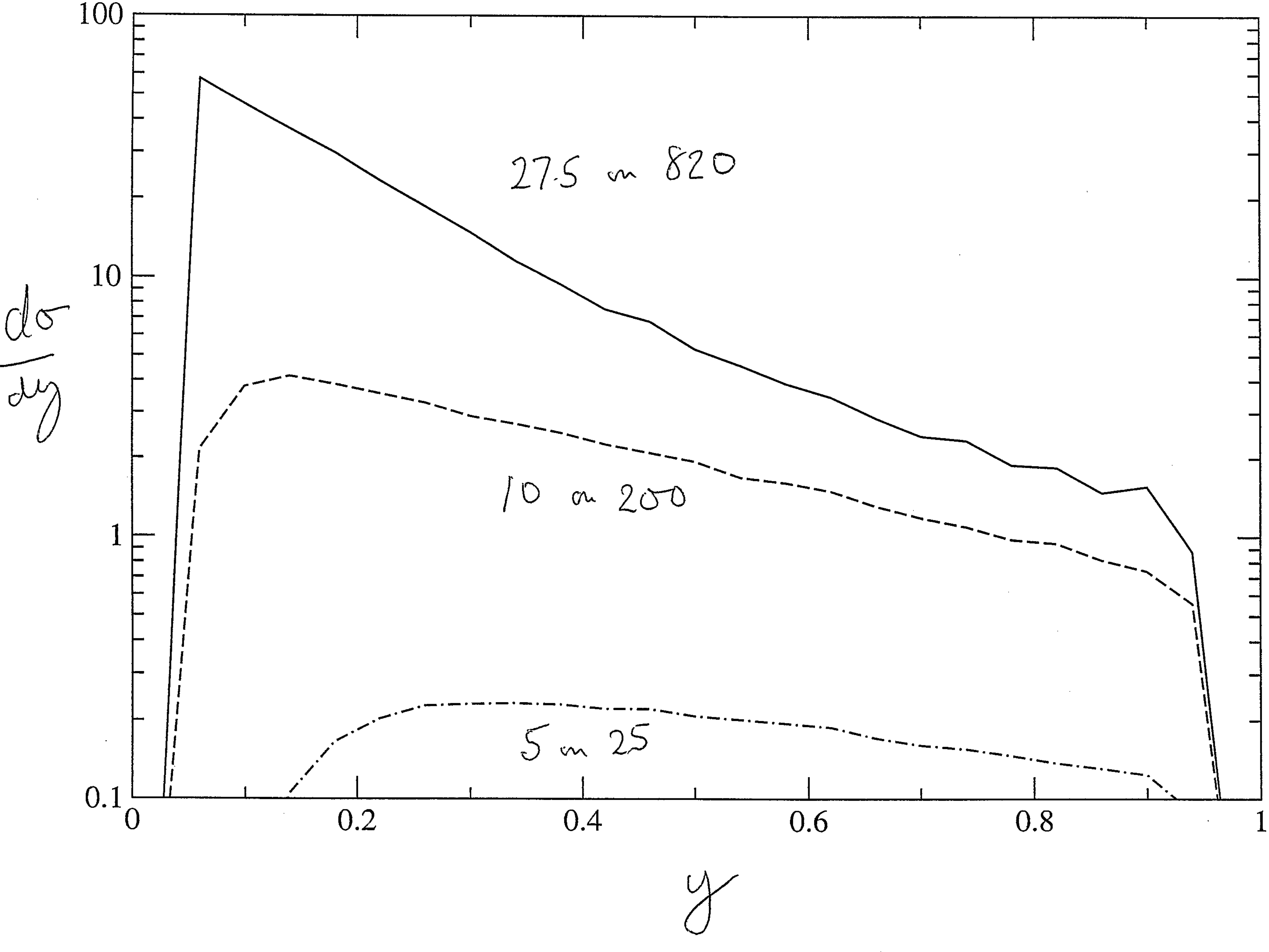
27.5 on 820
10 on 200
5 on 25
$\frac{d\sigma}{dp_t}$
p_t
10
1
0.1
0.01
0
2
4
6
8
10

HVQDIS (NLO)



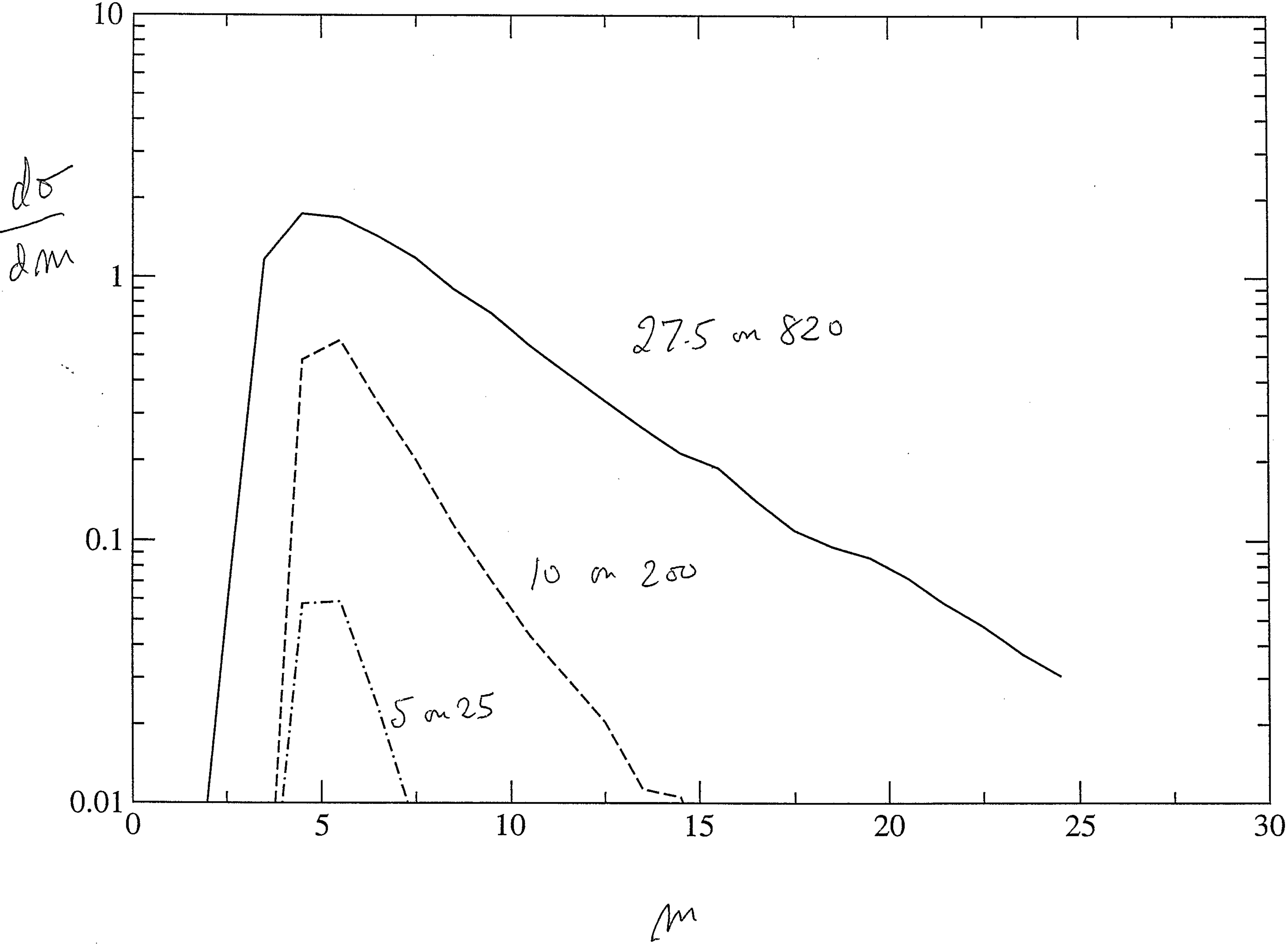
27.5 on 820
10 on 200
5 on 25
10
1
0.1
0.01
-4
-3.5
-3
-2.5
-2
-1.5
-1
$\frac{d\sigma}{d(\log_{10} x)}$
$\log_{10} x$

HVQDIS (NLO)



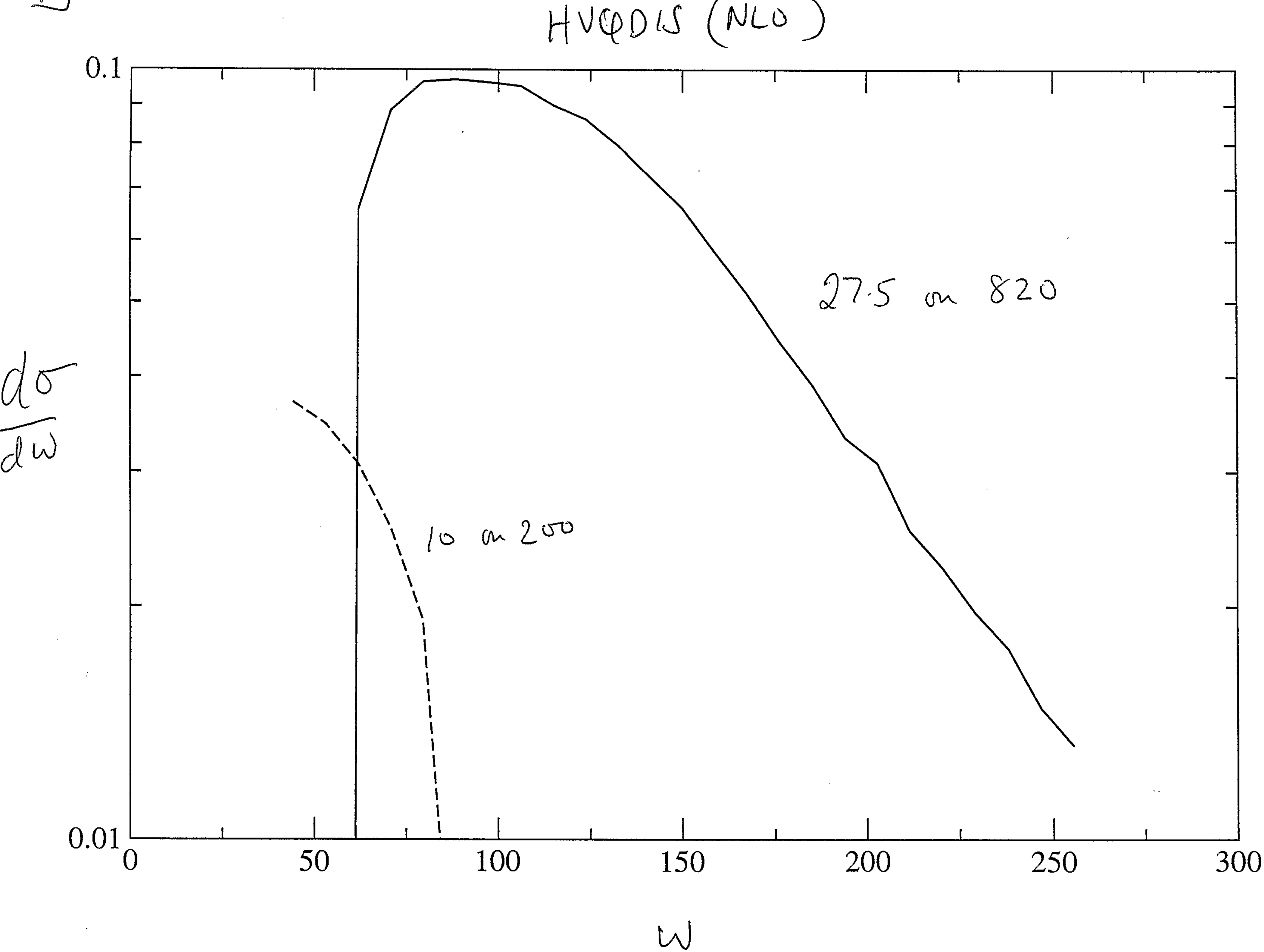
27.5 on 820
10 on 200
5 on 25
100
10
1
0.1
0
0.2
0.4
0.6
0.8
1
$\frac{d\sigma}{dy}$
y

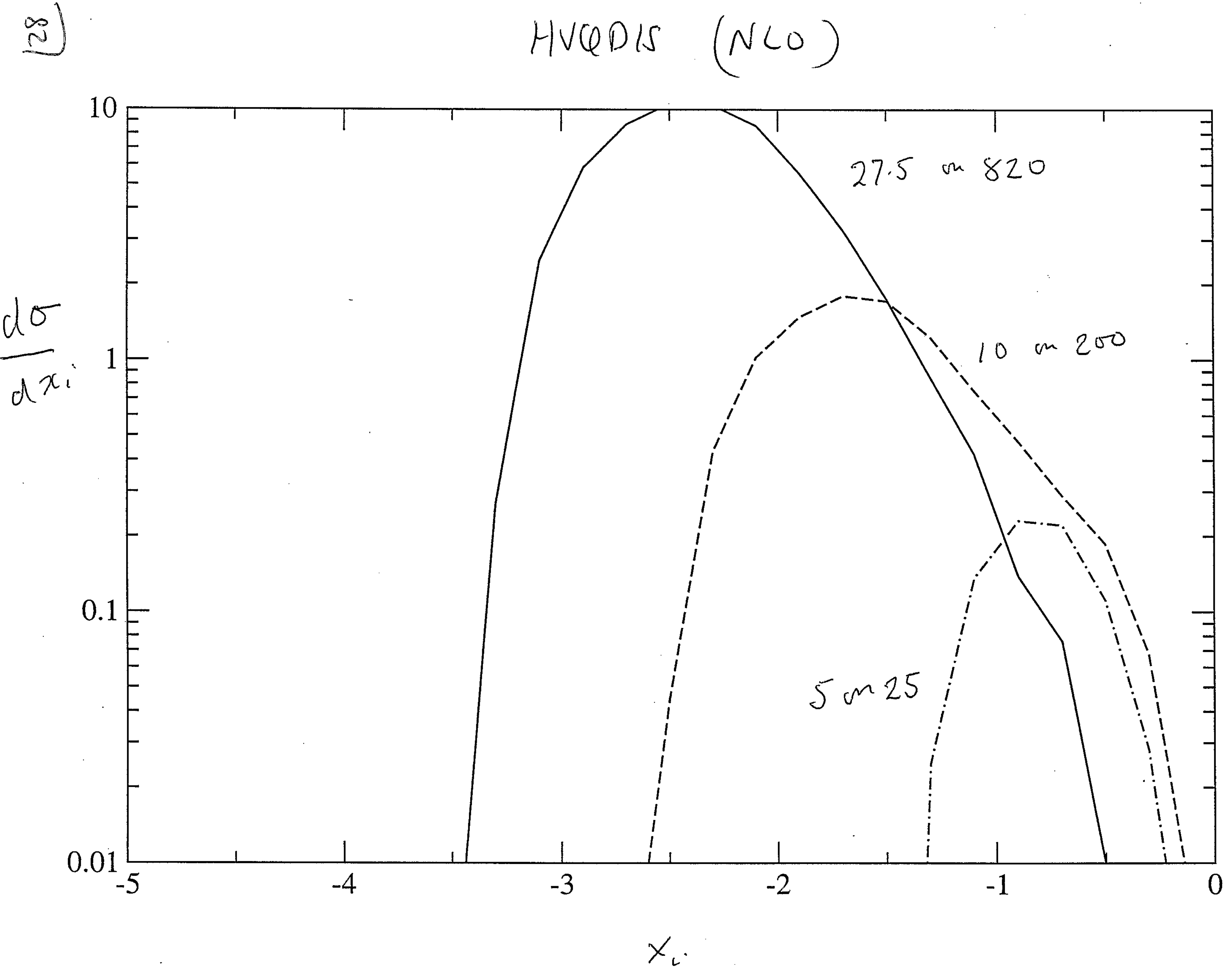
HVQDIS (NLO)



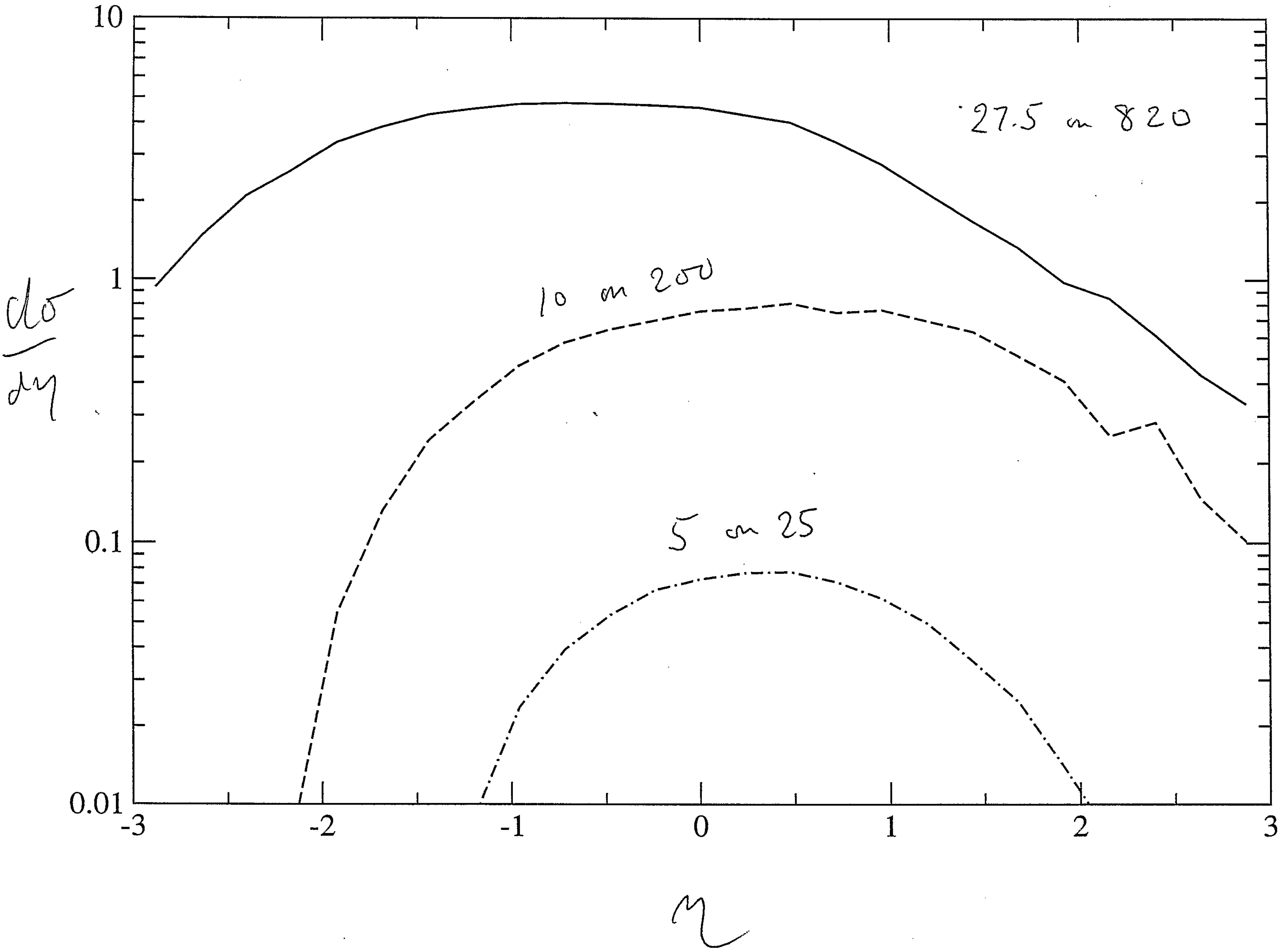
10
1
0.1
0.01
0
5
10
15
20
25
30
$\frac{d\sigma}{dm}$
m
27.5 on 820
10 on 200
5 on 25

DUE TO CUTS NO DIST FOR 5 on 25.




HVQDIS (NLO)
27.5 on 820
10 on 200
5 on 25
$\frac{d\sigma}{dx_i}$
x_i
10
1
0.1
0.01
-5
-4
-3
-2
-1
0

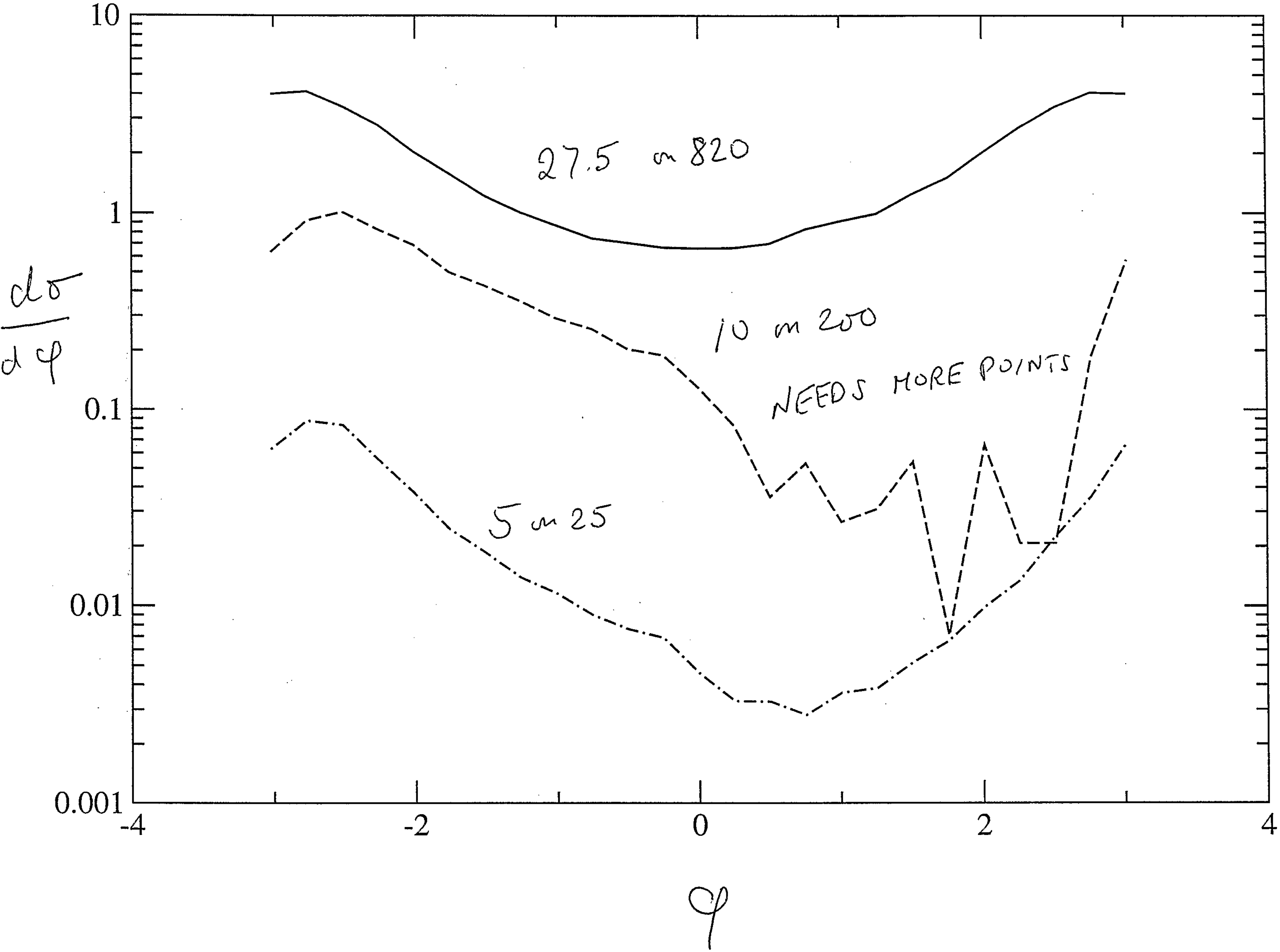
HVQDIS (NLO)



10
1
0.1
0.01
-3
-2
-1
0
1
2
3
$\frac{d\sigma}{d\eta}$
η
27.5 on 820
10 on 200
5 on 25

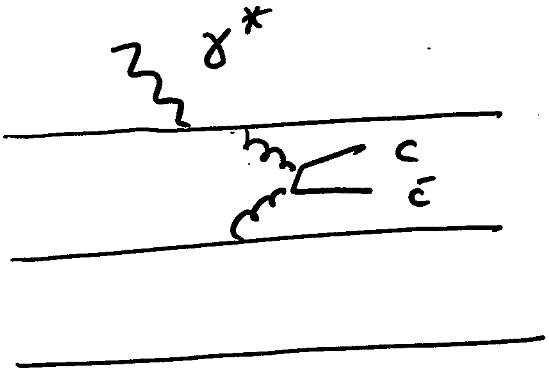
30

HVQDIS (NLO)



ALTERNATIVE DESCRIPTION

INTRINSIC PRODUCTION BRODSKY, MUELLER . . .



THIS MECHANISM INVOLVES MORE THAN ONE QUARK IN THE PROTON, SO ONE

NEEDS INPUT ABOUT THE PROTON WAVEFUNCTION.

HIGHER TWIST : NOT NORMAL (FACTORIZABLE) QCD.

NO CALCULATION FROM FIRST PRINCIPLES.

EVOLUTION EQUATION ?

PROBABLY EXISTS AT LARGE $x_F = \dfrac{2 P_{L,(c\bar{c})}}{\sqrt{s}}$.

DATA FROM <u>EMC</u> EXPERIMENT AT CERN

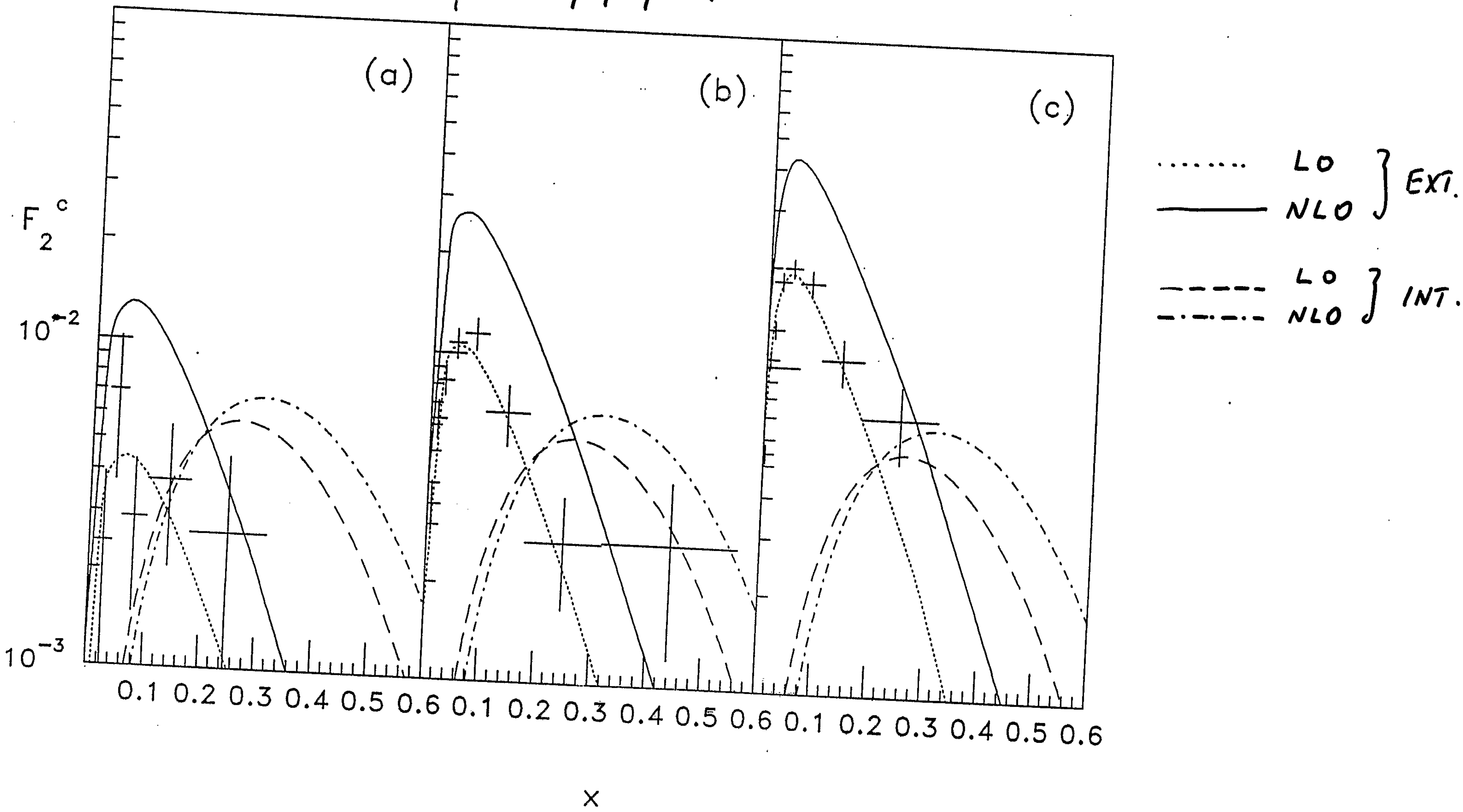
B.W. HARRIS, J. SMITH & R. VOGT NP B <u>461</u> (1996) 181.

SEE LATER.

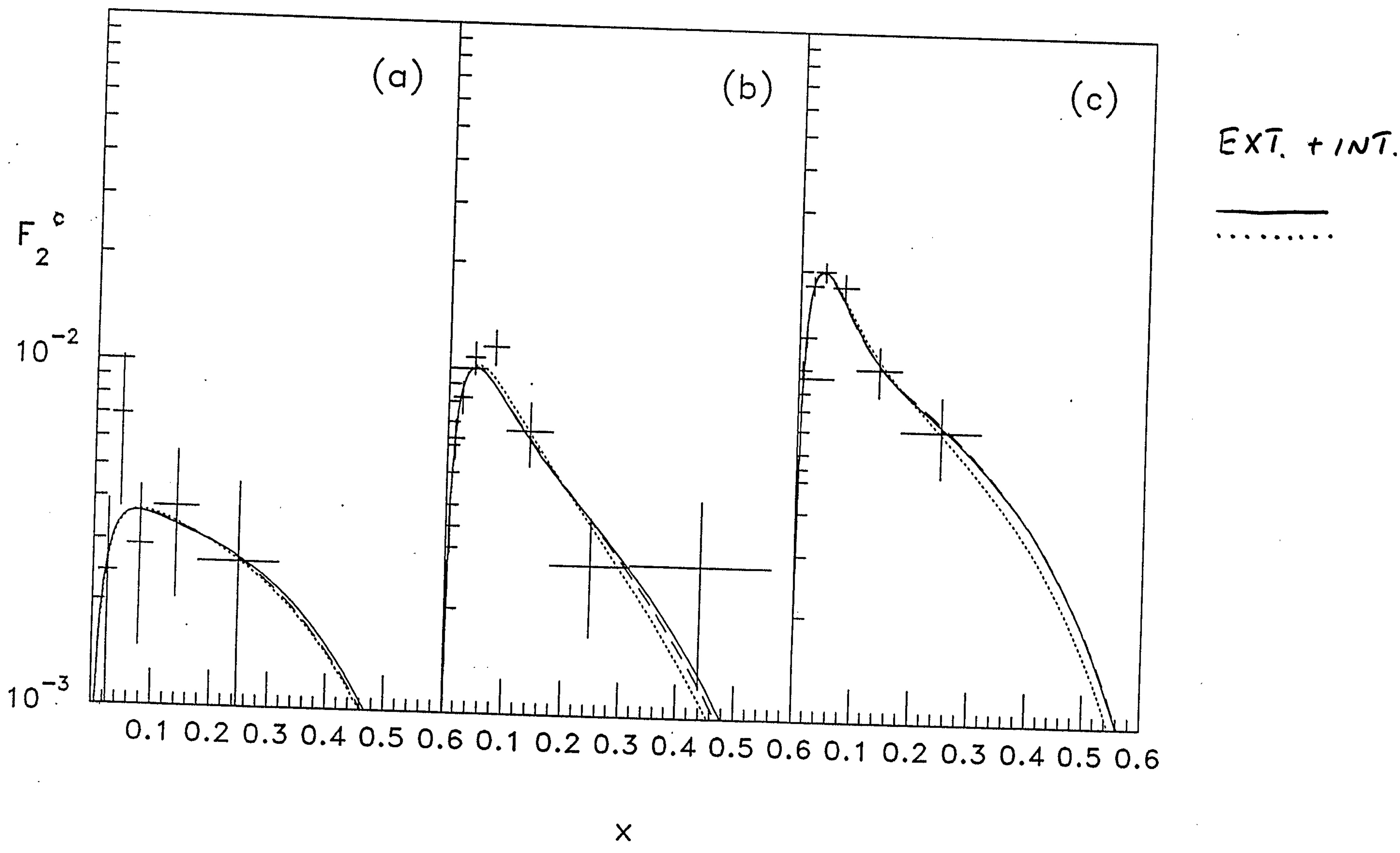
B.W. Harris, J. Smith & R. Vogt, N.P. B 461 (1996) 181

EMC DATA ON OPEN CHARM

$\mu N \to \mu \mu^+ \mu^- N.$



RECENT PARTON DENSITIES



(4) FIXED ORDER PERTURBATION THEORY

WHAT HAPPENS IF $Q^2 \gg m^2$? NLO

WHEN SHOULD WE TREAT THE CHARM QUARK AS A NORMAL "MASSLESS" QUARK LIKE u, d, s.

NEED TO INTRODUCE A CHARM DENSITY TO ABSORB THE MASS-SINGULAR TERMS IN THE PERTURBATION THEORY.

HOWEVER THE CHARM DENSITY IS NOT JUST A FUNCTION FITTED TO THE DATA.

WE CAN CALCULATE IT! $O(\alpha_s^2)$

BUZA ET AL. (DESY 96-258)

HEAVY QUARKS c, b, t IN QCD.

1. DEEP INELASTIC SCATTERING (HERA) NEUTRAL CURRENT (γ^*).

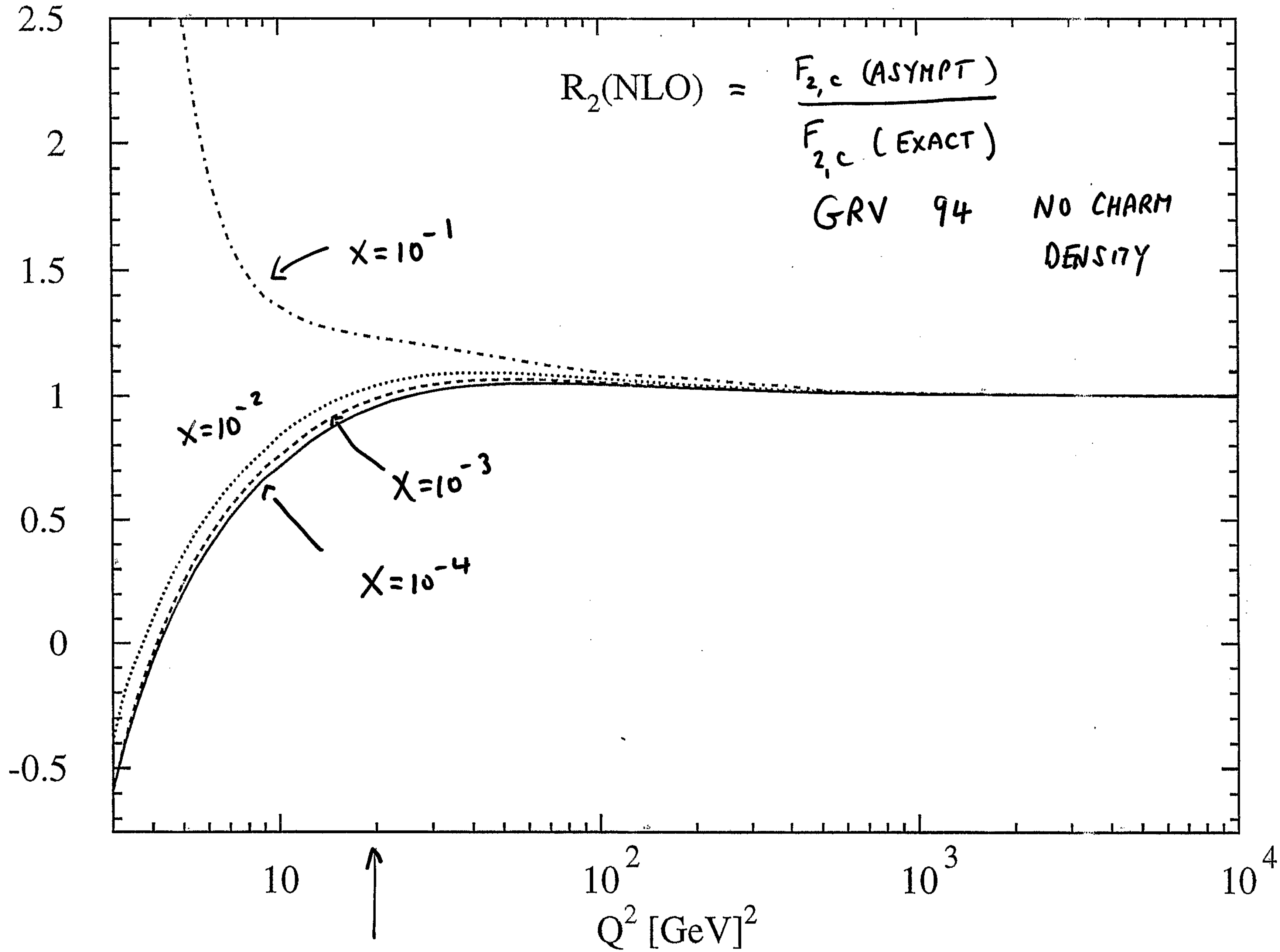
2. FIXED NUMBER OF LIGHT FLAVORS (3)

   u, d, s ONE EXTRA HEAVY QUARK c ($+\bar{c}$)

3. FIXED NUMBER OF LIGHT FLAVORS (4)

   u, d, s, c.

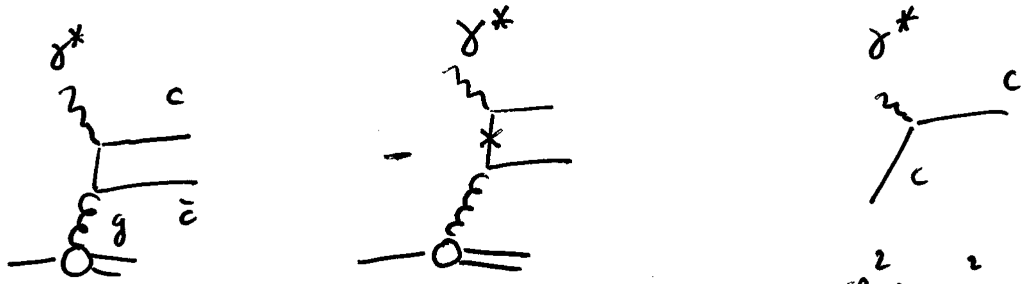
4. VARIABLE FLAVOR SCHEMES INTERPOLATE BETWEEN THEM.



ABOVE $Q^2 = 20$ LOGS DOMINATE AND WE CAN DEFINE A CHARM DENSITY.

IMPLEMENT THE VARIABLE FLAVOUR SCHEME IN L.O.

AIVAZIS, COLLINS, OLNESS & TUNG
PHYS. REV D 50 (1995) 3102. → CTEQ4HQ



$Q^2 \simeq m^2$ 0 $Q^2 \gg m^2$

MASSLESS CHARM DENSITY $= 0$ AT $Q^2 = M^2 = (1.6)^2$.

$$F_{2,c}^{ACOT} = f_g \otimes \omega^1 - f_g \otimes f_{Q/g} \otimes \omega^0 + f_Q \otimes \omega^0.$$

↓ GLUON FUSION — OK NEAR THRESHOLD $M \neq 0$

↓ SUBTRACTION TERM — KEEP MASS FOR CHARM. OK IN L.O.

↓ CHARM DENSITY.

WHAT HAPPENS IN HIGHER ORDER ?

ALSO NEW PARTON DENSITY SETS

CTEQ4F3 → GRV94

CTEQ4F4   4 FLAVOUR SET.

WHAT ABOUT HEAVY QUARKS?

CALCULATE

$$\hat{\sigma}_{ij}\left(\varepsilon, \frac{Q^2}{m^2}, z\right), \qquad z = \frac{Q^2}{2k_1 \cdot q} \qquad Q^2 \gg m^2$$

REGULARIZE BY BOTH $\frac{1}{\varepsilon}$ AND $\ln m^2$.

① REMOVE $\frac{1}{\varepsilon}$ POLES

$$\hat{\sigma}_{ij}\left(\varepsilon, \frac{Q^2}{m^2}\right) = \Gamma_{kj}(\varepsilon) \otimes H_{ik}\left(\frac{Q^2}{m^2}, \frac{m^2}{\mu^2}\right)$$

② REMOVE $\ln m^2$ TERMS

$$H_{ik}\left(\frac{Q^2}{m^2}, \frac{m^2}{\mu^2}\right) = A_{lk}\left(\frac{m^2}{\mu^2}\right) \otimes C_{il}\left(\frac{Q^2}{\mu^2}\right)$$

A_{lk}: NEED THESE OME'S.

C_{il}: KNOWN

FROM THE RGE WE HAVE GOOD CHECKS ON THE RESULTS.

IN $\overline{MS}$ SCHEME.

$$A^{(1)}_{Qg} = -\frac{1}{2} P^{(0)}_{qg} \ln \frac{m^2}{\mu^2} + \underline{a^{(1)}_{Qg}}$$

$$A^{(2)}_{Qg} = \left\{ \frac{1}{8} P^{(0)}_{qg} \otimes \left(P^{(0)}_{qq} - P^{(0)}_{gg} \right) + \frac{1}{4} \beta_0 P^{(0)}_{qg} \right] \underline{\underline{\ln^2 \frac{m^2}{\mu^2}}}.$$

$$+ \left\{ -\frac{1}{2} P^{(1)}_{qg} - \beta_0 a^{(1)}_{Qg} + \frac{1}{2} a^{(1)}_{Qg} \otimes \left(P^{(0)}_{gg} - P^{(0)}_{qq} \right) \right\} \underline{\underline{\ln \frac{m^2}{\mu^2}}}.$$

$$+ 2\beta_0 \bar{a}^{(1)}_{Qg} + \bar{a}^{(1)}_{Qg} \otimes \left(P^{(0)}_{qq} - P^{(0)}_{gg} \right) + \underline{a^{(2)}_{Qg}}$$

TO FIND THE UNDERLINED TERMS WE HAVE TO CALCULATE THE OME's.

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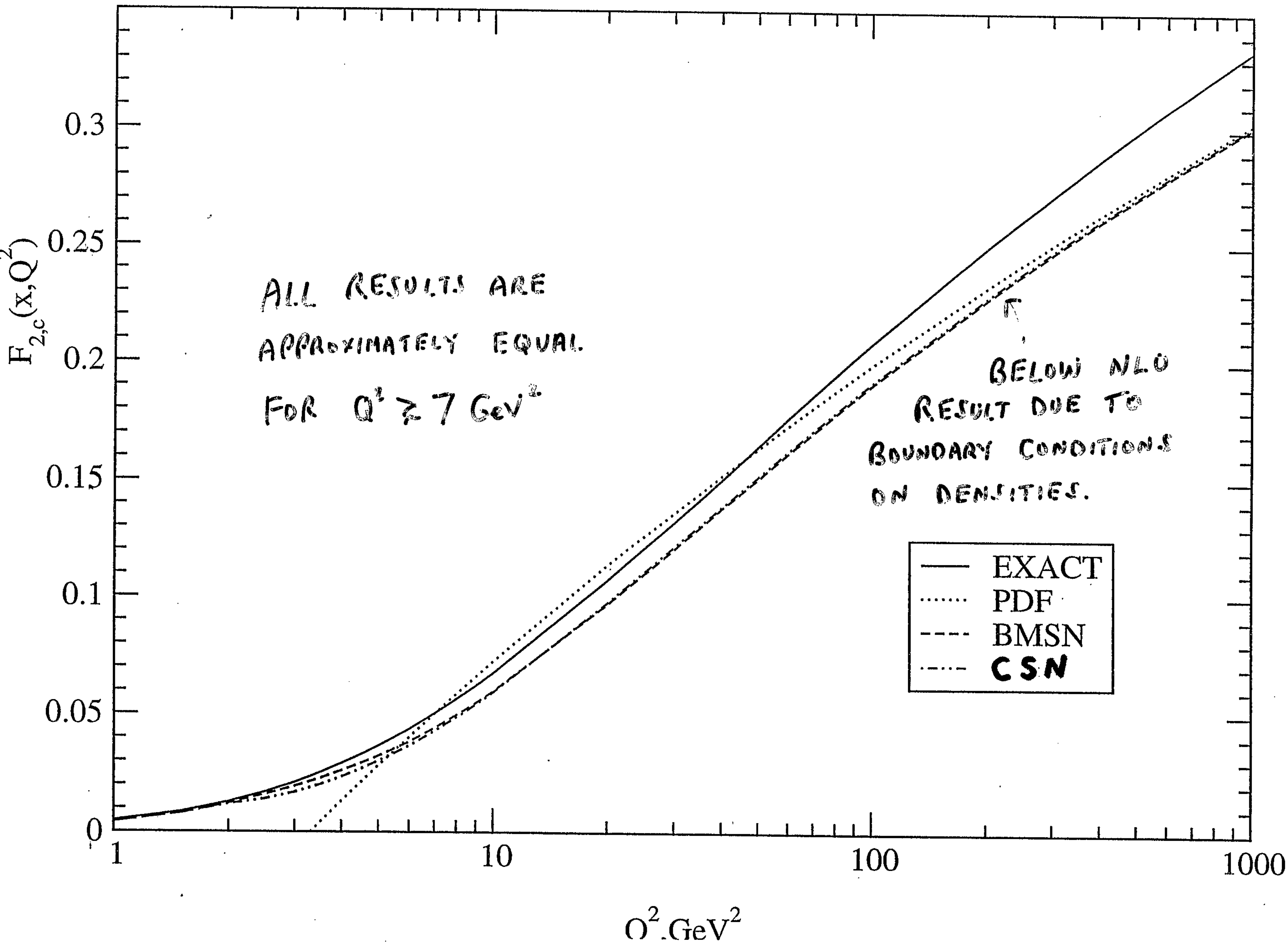
$X = 5 \times 10^{-3}$

Fig 12



CONCLUSIONS

DEEP INELASTIC PRODUCTION OF CHARM IS UNDER INTENSE STUDY IN HERA AS IT CONTRIBUTES ABOUT 25% OF $F_2(x, Q^2)$ FOR $x \simeq 10^{-3}$, $Q^2 \simeq 25.\ \mathrm{GeV}^2$.

CHARM DISTRIBUTIONS FIT NLO QUITE WELL (u, d, s, g PARTON DENSITIES GRV94, CTEQ4F3)

CONFUSION ABOUT NEW CHARM DENSITIES FROM MRRS AND CTEQ4HQ.

MATHEMATICAL PROBLEM HOW TO MASS FACTORIZE NLO CHARM (PHOTON-GLUON FUSION) INTO $\tilde{u}, \check{d}, \tilde{s}, \acute{g}$ AND c SOLVED IN $\overline{MS}$ SCHEME TO ALL ORDERS IN PERTURBATION THEORY.

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SMITH
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