Open Charm Production at HERA

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OUTLINE

1 Introduction and Kinematics

2 Charm Photoproduction

3 Dijet Analysis

4 F_2^{charm} Measurement

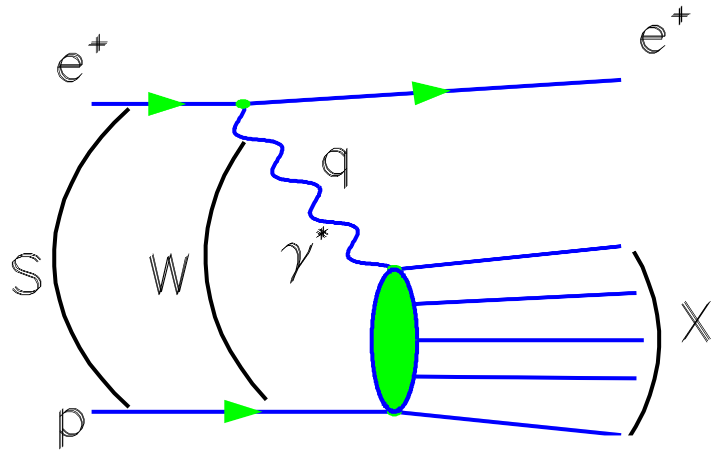
5 Gluon Density Extraction

6 Summary and Outlook

Kinematic Variables

HERA collides positrons (electrons) and protons

27.5 GeV $e \Longrightarrow \quad \sqrt{s} = 300$ GeV $\quad \Longleftarrow p$ 820 GeV



ep c.m.energy $\quad s = (P + e)^2$

γ^* virtuality $\quad Q^2 = -q^2 = -(e - e')^2$

Photoproduction $\qquad Q^2 \simeq 0$

DIS $\qquad Q^2 > 1GeV^2$

$\gamma^* p$ c.m.energy $\quad W^2 = (P + q)^2$

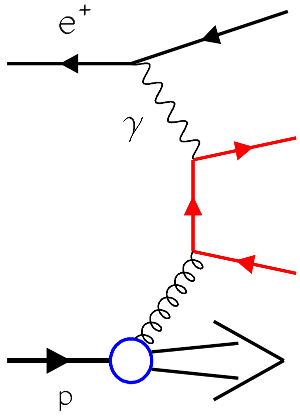
fraction of the E_e lost in the p.r. syst.

$$y = \frac{q \cdot P}{e \cdot P} = \frac{E_e - E_{e'}}{E_e} \cong \frac{W^2}{s}$$

fraction of the proton mom. $\quad x = \frac{Q^2}{2P \cdot q}$

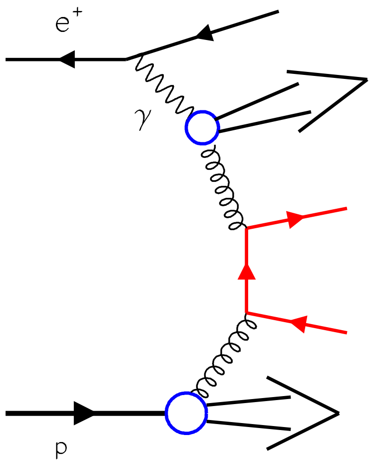
Production Mechanism

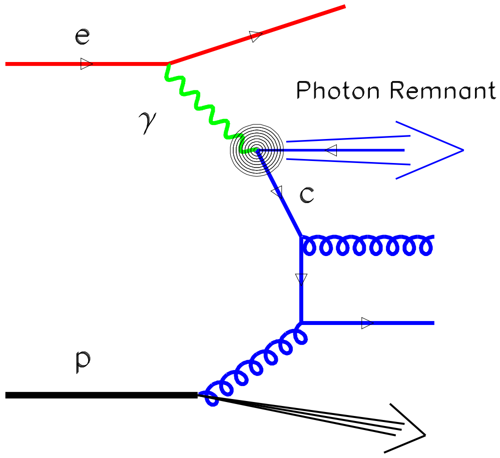
- direct γ^* - $\gamma^* g \to c\bar{c}$ (BGF)



- resolved γ^* - $gg \to c\bar{c}$, $cg \to cg$

Charm excitation





In NLO pQCD only sum of direct and resolved photon contributions is unambiguously defined

Charm Tagging

$f(c \to D^{*+}) = 0.222 \pm 0.014 \pm 0.014$ (OPAL)

$D^{*\pm}(2010)$ Reconstruction

D^* mesons are reconstructed through the decay modes :

$D^* \to D^0\pi_s \to (K^-\pi^+)\pi_s$ ($Br = 0.0262 \pm 0.0010$)

$D^* \to D^0\pi_s \to (K^-\pi^+\pi^+\pi^-)\pi_s$ ($Br = 0.051 \pm 0.003$)

Mass difference method of Nussinov (1975)

$M(D^*) = 2.010 \pm 0.0005\,\mathrm{GeV}$

$M(D^0) = 1.8645 \pm 0.0005\,\mathrm{GeV}$

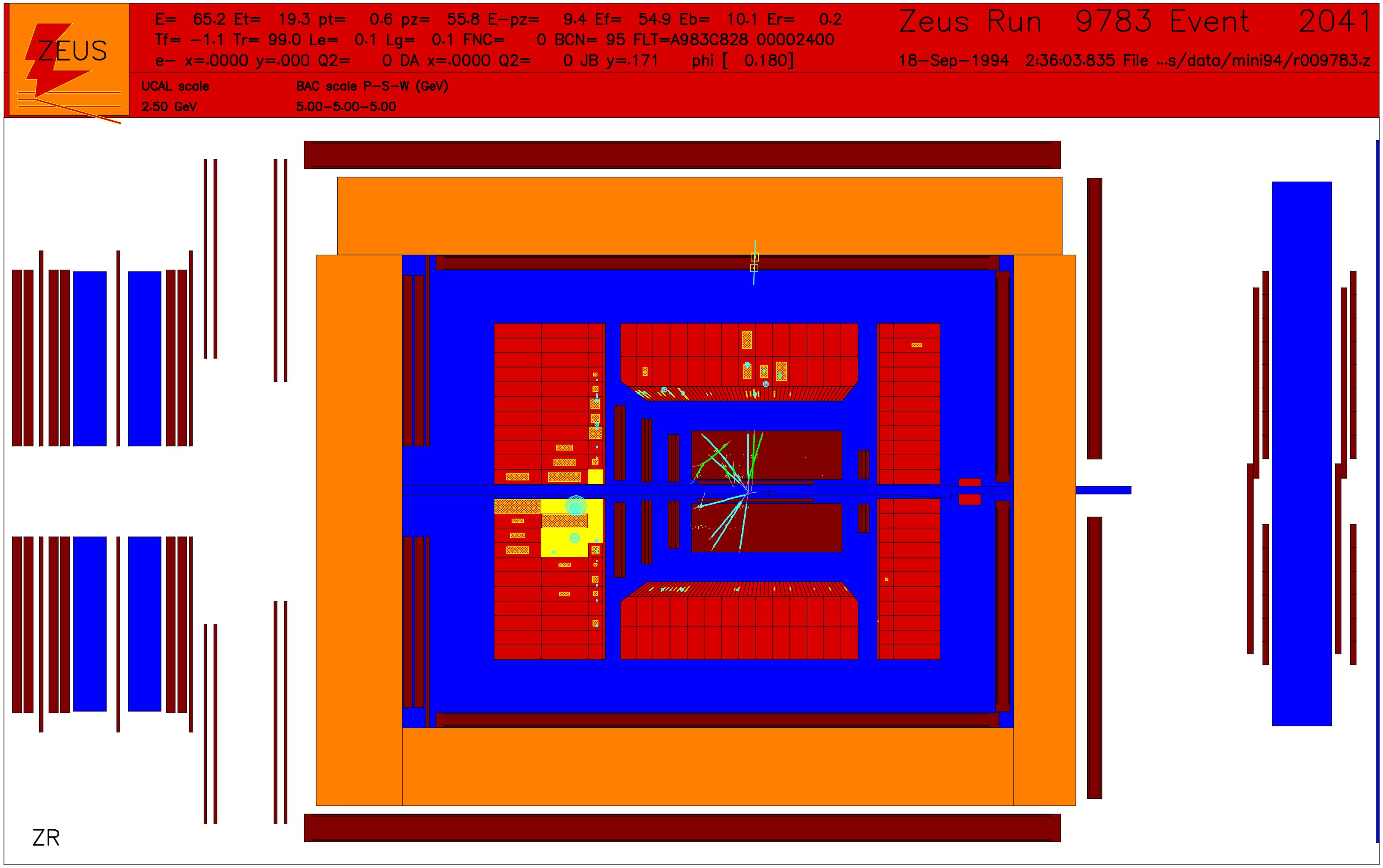
$\Delta M = M(D^*) - M(D^0) = 0.14542\,\mathrm{GeV} \sim m_\pi$

Signals in ΔM and $M(D^0)$

D^* kinematic variables

$p_\perp(D^*)$, wrt to beam axis

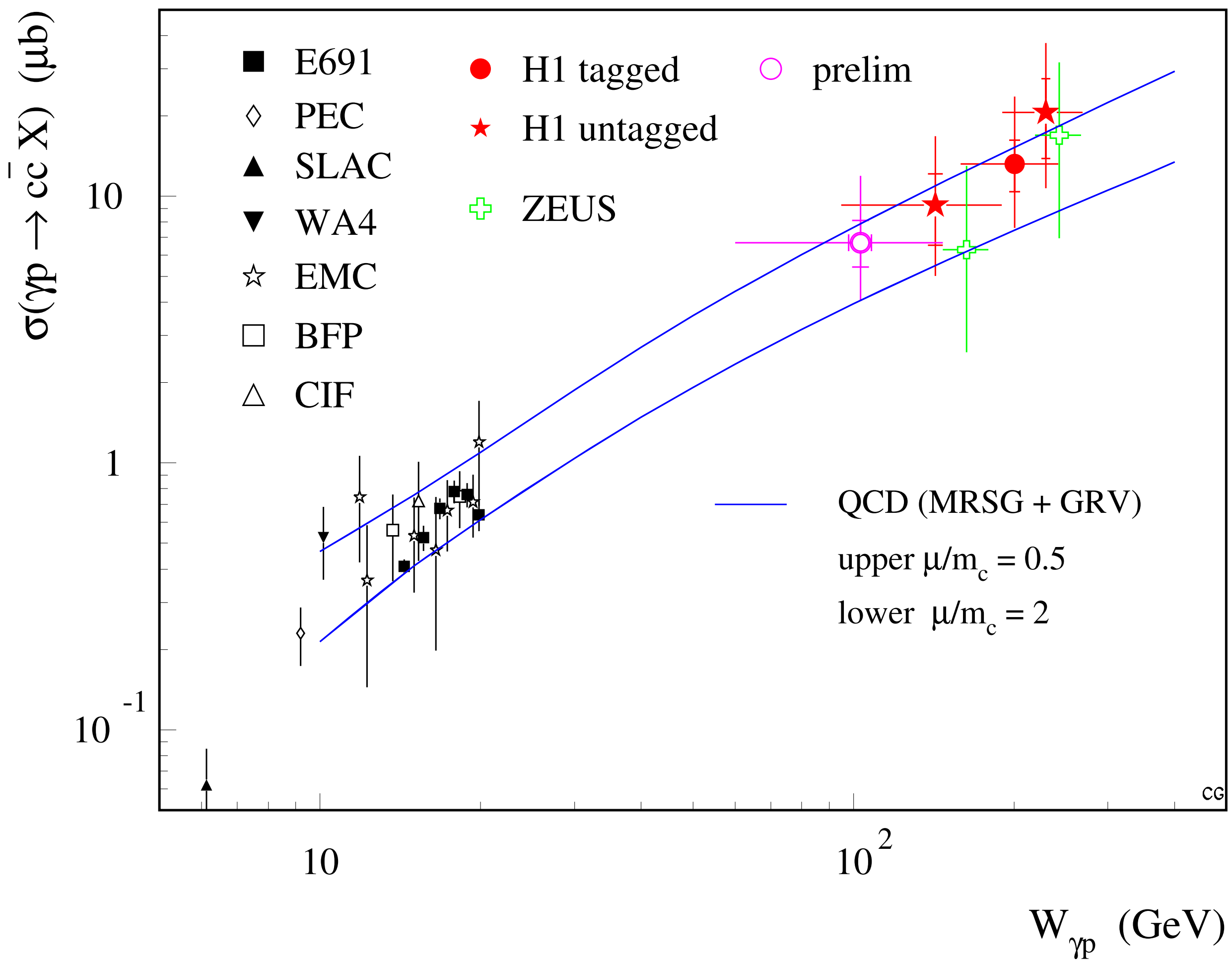
$\eta(D^*)$, $\eta = -\ln\left(tan\frac{\theta}{2}\right)$
and θ is taken wrt to the proton beam direction



ZEUS
E= 65.2 Et= 19.3 pt= 0.6 pz= 55.8 E−pz= 9.4 Ef= 54.9 Eb= 10.1 Er= 0.2
Tf= −1.1 Tr= 99.0 Le= 0.1 Lg= 0.1 FNC= 0 BCN= 95 FLT=A983C828 00002400
e− x=.0000 y=.000 Q2= 0 DA x=.0000 Q2= 0 JB y=.171 phi [0.180]
Zeus Run 9783 Event 2041
18−Sep−1994 2:36:03.835 File ...s/data/mini94/r009783.z
UCAL scale
2.50 GeV
BAC scale P−S−W (GeV)
5.00−5.00−5.00
ZR

Total $\gamma p \to c\bar{c}X$ cross section.

visible $\sigma_{ep\to D^*X}$ $\to$ full p_T, η $\sigma_{ep\to D^*X}$ (extrapolation)
$\to$ $\sigma_{\gamma p\to c\bar{c}X}$ (EPA formula)



- W increases one order of magnitude wrt fixed target experiments
- Cross section is also one order larger, singular gluon distribution in the proton
- QCD NLO calculation of Frixione *et al.* in general agreement with the data
- Large uncertainties due to extrapolation to full p_T, η range

NLO pQCD Calculations:

"massive charm" approach:

S.Frixione et al. NPB 454(1995)3

$n_f = 3$: (u, d, s) are the active flavours in p and γ

charm is only produced dynamically

"massless charm" approach:

B.A.Kniehl et al. ZPC 76(1997)689

M.Cacciari et al. PRD 55(1997)2736

$n_f = 4$: (u, d, s) and (c) are the active flavours in p and γ

Both approaches:

f_p = MRS(G) (CTEQ4M)

f_γ = GRV-G HO (GS-G HO , AFG-G HO)

$m_c = 1.5$ GeV , $\mu = m_\perp = \sqrt{m_c^2 + p_\perp^2}$

$\mu_r = \mu$, $\mu_f = 2\ \mu$

Fragmentation

Massive calculation, Peterson Fragmentation

$$D_c(x) = N \frac{x(1-x)^2}{[(1-x)^2 + \epsilon x]^2} \qquad x = \frac{p_{D^*}}{p_c}$$

$\epsilon = 0.060$ J.Chrin, ZPC36(1987)163

$\epsilon = 0.035$ OPAL fit

$\epsilon = 0.020$ suggested by M.Cacciari et al., for NLO massive calculations

Massless scheme (LEP1 data fit)

Fragmentation Function is parameterized at the starting scale $\mu_o = 2m_c$ by the Peterson FF and evolved via Altarelli-Parisi equation to higher scales.

Kniehl et al. $\epsilon = 0.116$

Cacciari et al. $\epsilon = 0.020$

Determination of ϵ in NLO fit to e^+e^- data is scheme dependent !

New $D^*(2010)$ in PHP results

Data collected at ZEUS, 96+97; $\mathcal{L} = 36.9 \pm 0.5\,\mathrm{pb}^{-1}$

Kinematic region of ZEUS measurement

- $Q^2 < 1\,\mathrm{GeV}^2$,
  median $Q^2 \approx 3 \cdot 10^{-4}\,\mathrm{GeV}^2$
- $130\,\mathrm{GeV} < W_{\gamma p} < 280\,\mathrm{GeV}$
- $p_\perp(D^*) > 2.0\,\mathrm{GeV}$
- $-1.5 < \eta(D^*) < 1.5$

Differential $ep \to D^{*\pm}X$ Cross Sections

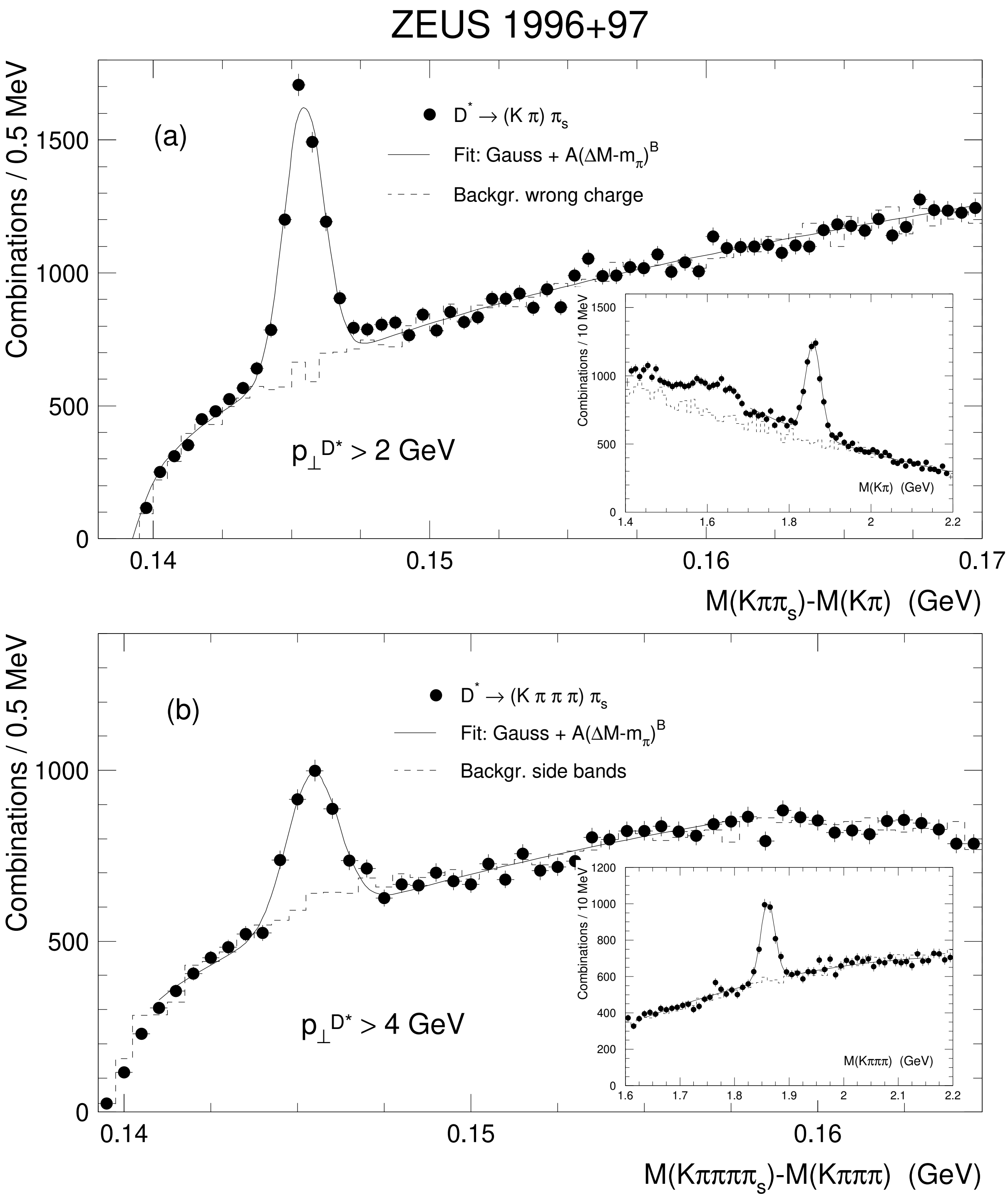
- $d\sigma/dp_\perp$

  $-1.5 < \eta(D^*) < 1.5$

- $d\sigma/d\eta$

  $p_\perp(D^*) > 2\,\mathrm{GeV}$
  $p_\perp(D^*) > 3\,\mathrm{GeV}$
  $p_\perp(D^*) > 4\,\mathrm{GeV}$
  $p_\perp(D^*) > 6\,\mathrm{GeV}$

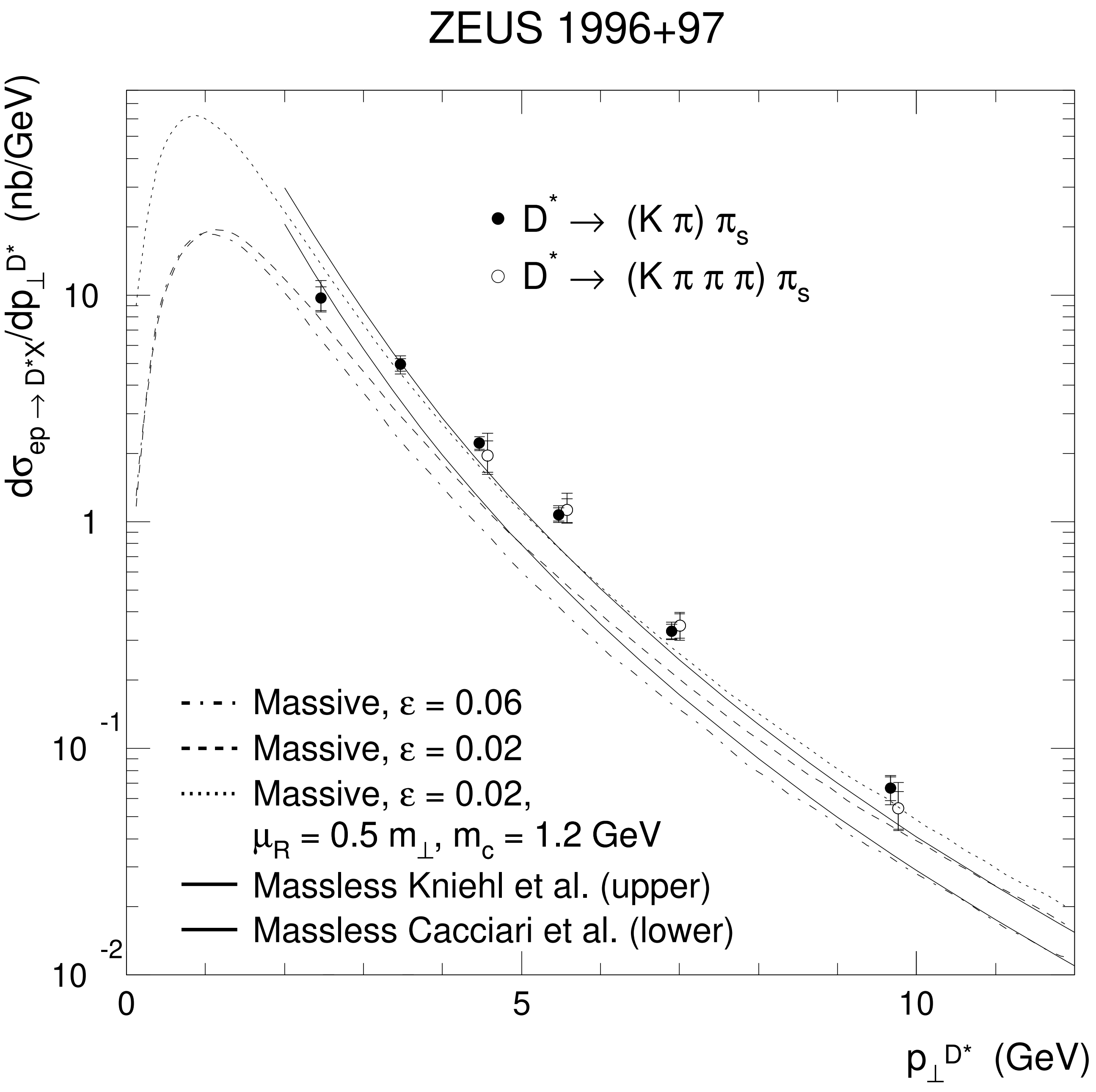
$D^*(2010)$ Tagging



$$N(D^* \to (K\pi)\pi_s) = 3702 \pm 136$$

$$N(D^* \to (K\pi\pi\pi)\pi_s) = 1397 \pm 108$$

Inclusive $d\sigma/dp_T(D^*)$ Cross-Section

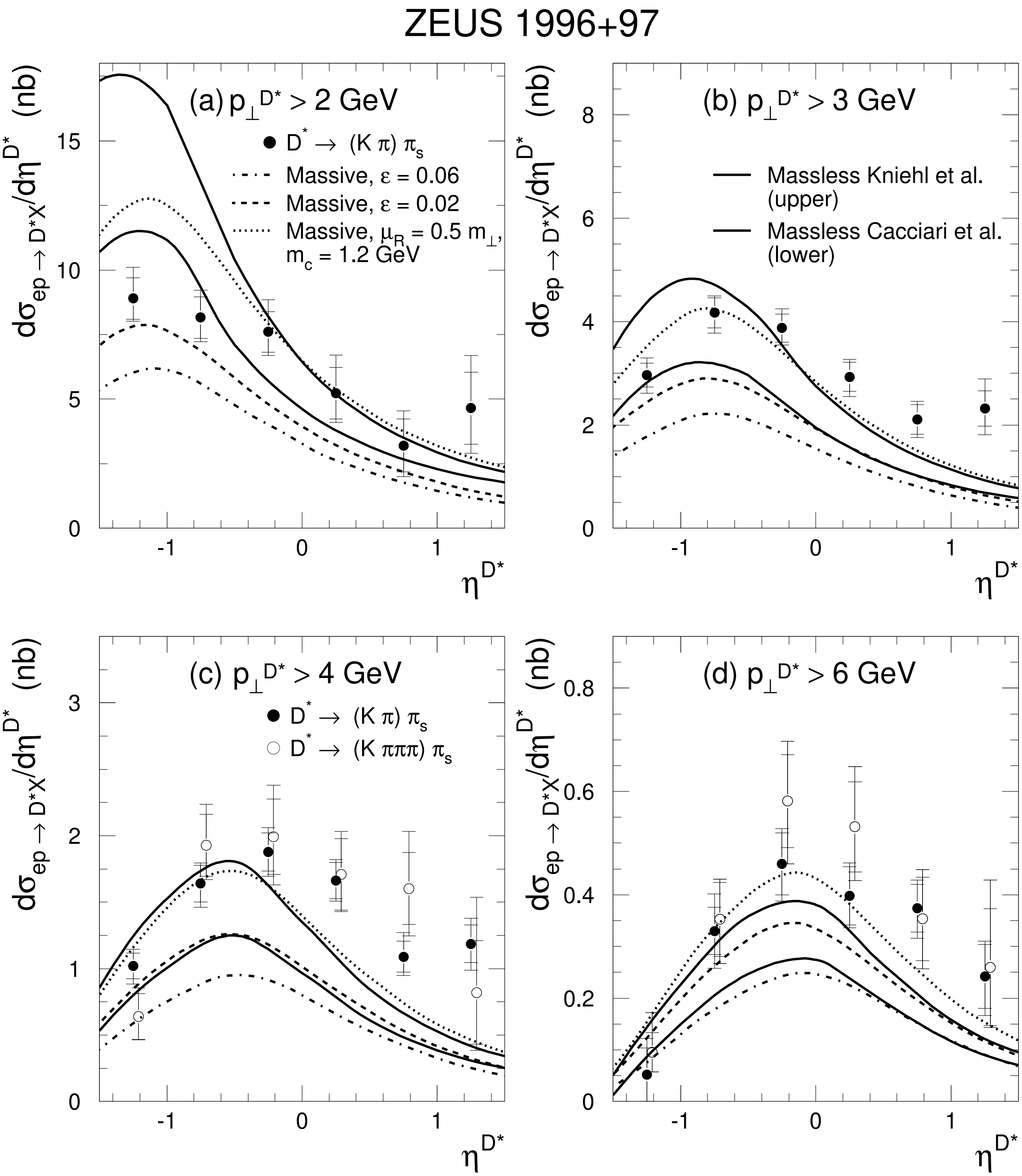


NLO Predictions are generally below the data

Shape is not well reproduced

Extreme choice of parameters is needed
for massive calculations
to make their results closer to DATA

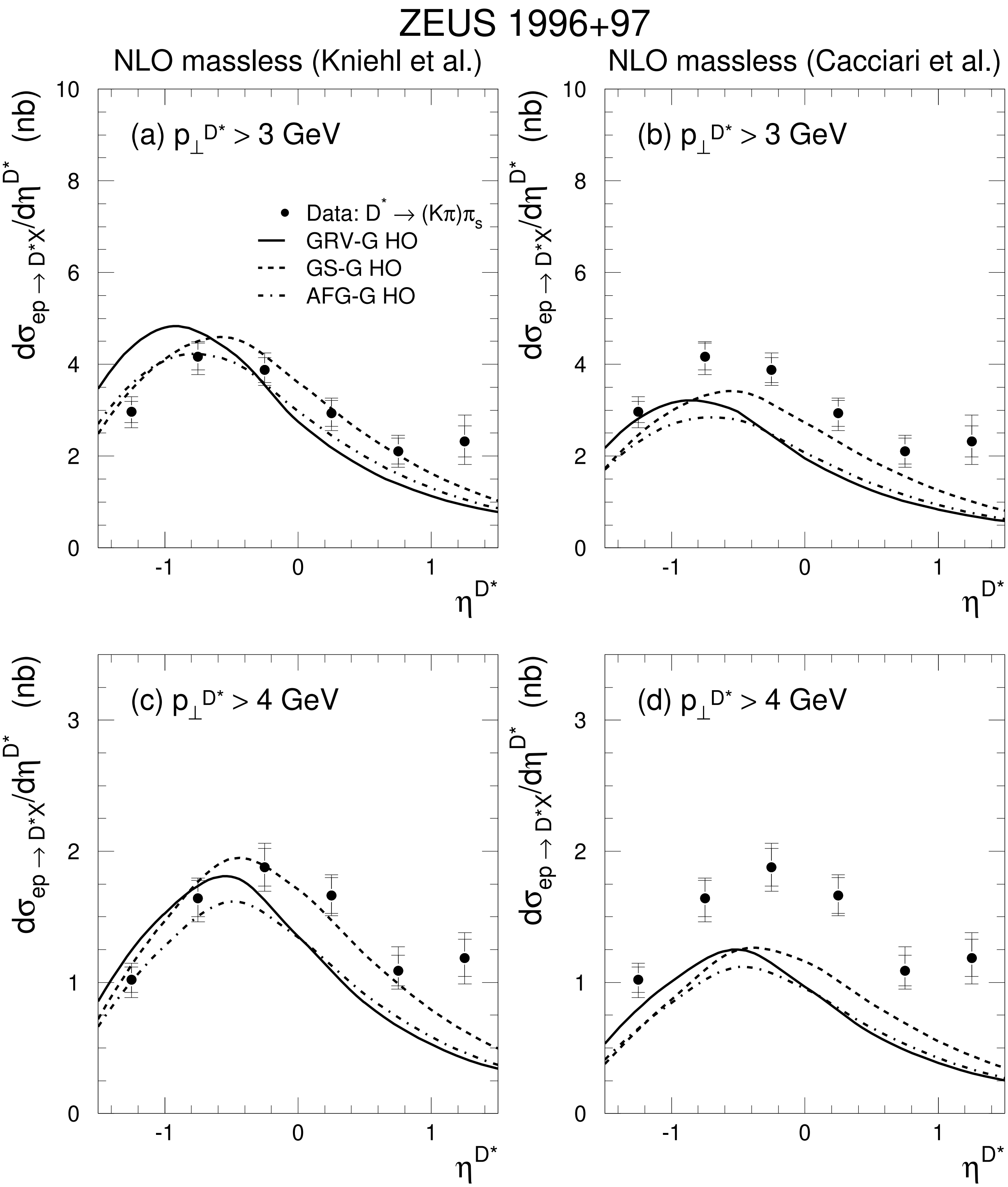
Inclusive $d\sigma/d\eta(D^*)$ Cross-Section



NLO Predictions do not describe the forward region $\eta(D^*) > 0$

Inclusive $d\sigma/d\eta(D^*)$ Cross-Section

Comparison with NLO Massless Predictions using Different Parton Density Functions of the Photon



Massless calculations of Kniehl et al. with $GS - G\ HO$ are closest to the DATA

However in the $GS - G\ HO$: $c = u$???

Dijet Analysis

The fraction of the photon momentum which participates in the dijet production :

$$x_\gamma^{OBS} = \frac{E_T^{jet1} e^{-\eta^{jet1}} + E_T^{jet2} e^{-\eta^{jet2}}}{2yE_e}$$

In LO QCD direct photon events at the parton level have $x_\gamma^{OBS} = 1$, while resolved photon events populate low value of x_γ^{OBS}.

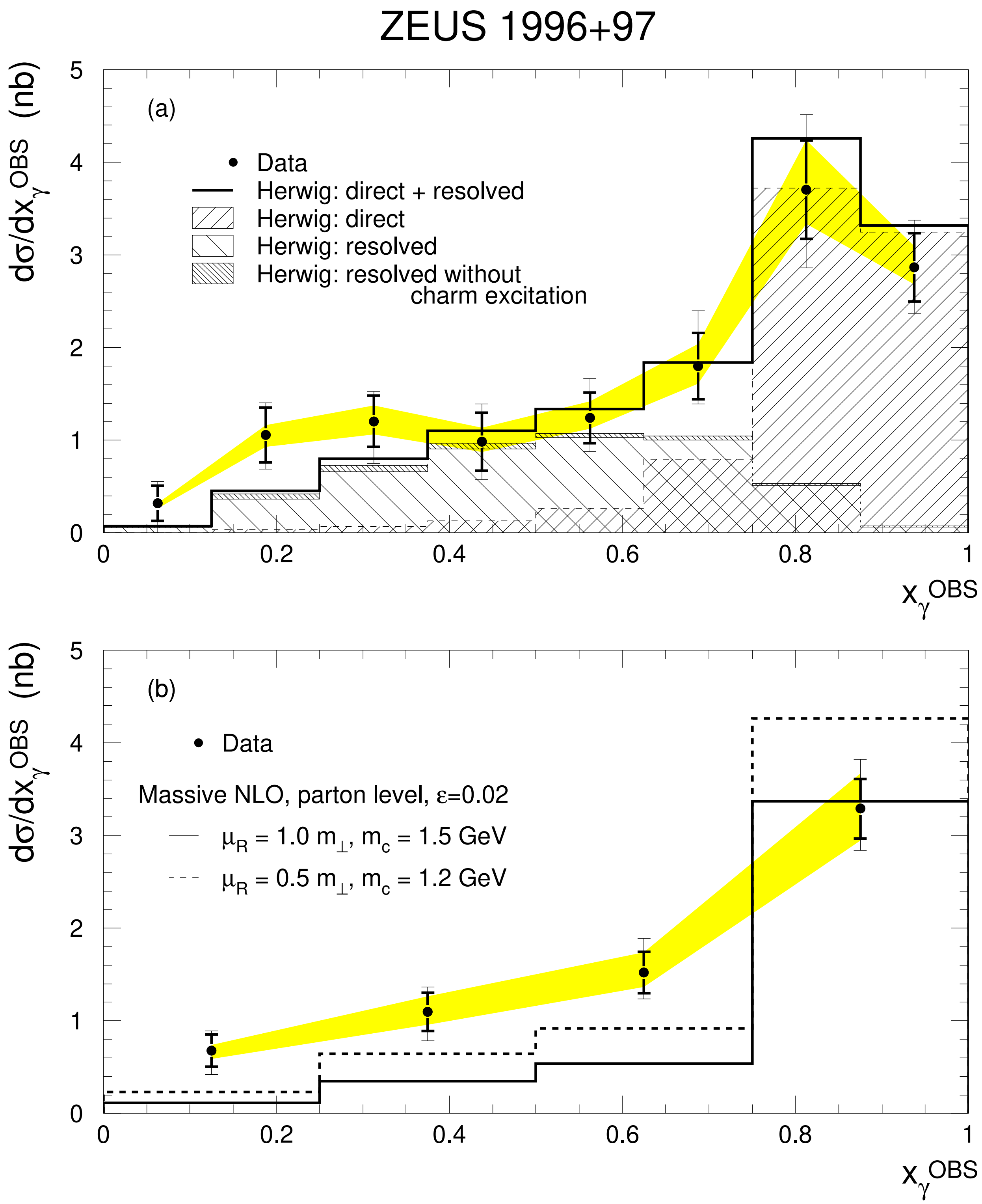
- $p_\perp(D^*) > 3\,\mathrm{GeV}$, $-1.5 < \eta(D^*) < 1.5$
- at least two jets with $\eta_{jet} < 2.4$, $E_T^{jet1} > 7.0\,\mathrm{GeV}$ and $E_T^{jet2} > 6.0\,\mathrm{GeV}$
- calculate x_γ^{OBS} for two highest E_T^{jet} jets
- kt algorithm
  KTCLUS: Nucl. Phys. B406 (1993) 187.

Theoretical Predictions :

- LO Monte Carlo (Herwig, Pythia)
- Massive QCD NLO double inclusive calculations, $\mu = m_\perp = \sqrt{m_c^2 + < p_\perp^2 >}$, where $< p_\perp^2 >$ is the average $p_\perp^2$ of the two charm quarks

Cross-Section $d\sigma(ep \rightarrow D^{*\pm}X)/dx_\gamma^{OBS}$

$E_T^{jet1} > 7.0\,GeV$ and $E_T^{jet2} > 6.0\,GeV$



LO Charm Excitation in the Photon

Massive NLO are below the DATA at $x_\gamma^{OBS} < 0.75$

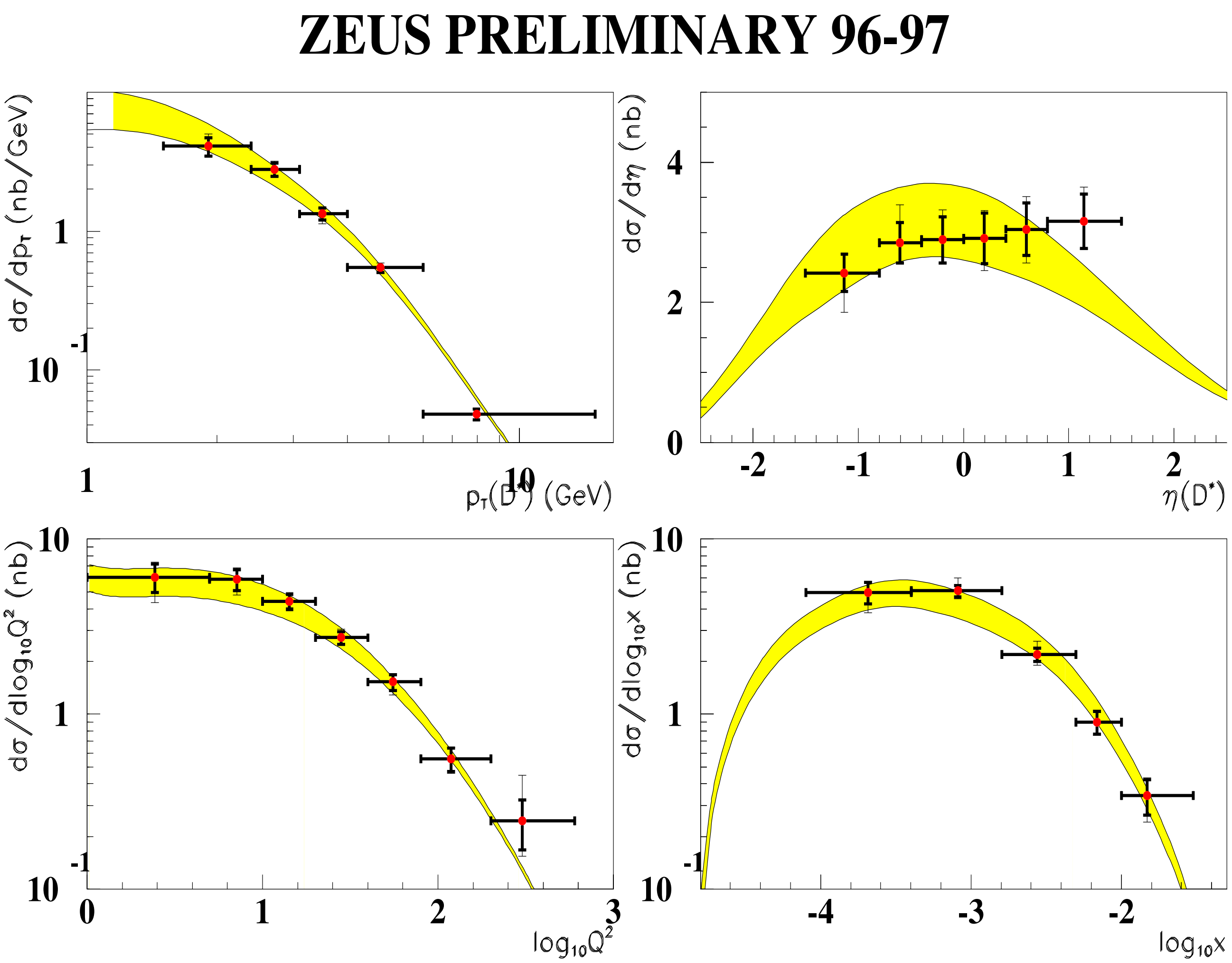
Summary Charm Photoproduction

- Differential photoproduced D^* cross sections have been measured with high precision
- QCD NLO calculations are generally below the data, in paticular in the forward direction
- The results are sensitive to the photon SF used for cross section calculations in the massless charm scheme
- A comparison of the x_γ^{OBS} distribution to LO Monte Carlo simulations indicates the existance of charm excitation in the photon parton density
- The data at ($x_\gamma^{OBS} < 0.75$) are higher than a NLO massive charm calculation at the parton level

D^* Cross Sections in DIS

In the experimentally accessed region:

$$1 < Q^2 < 600 \text{ GeV}^2, 0.02 < y < 0.7$$
$$1.5 < p_T(D^{*\pm}) < 15 \text{ GeV}, |\eta(D^{*\pm})| < 1.5$$

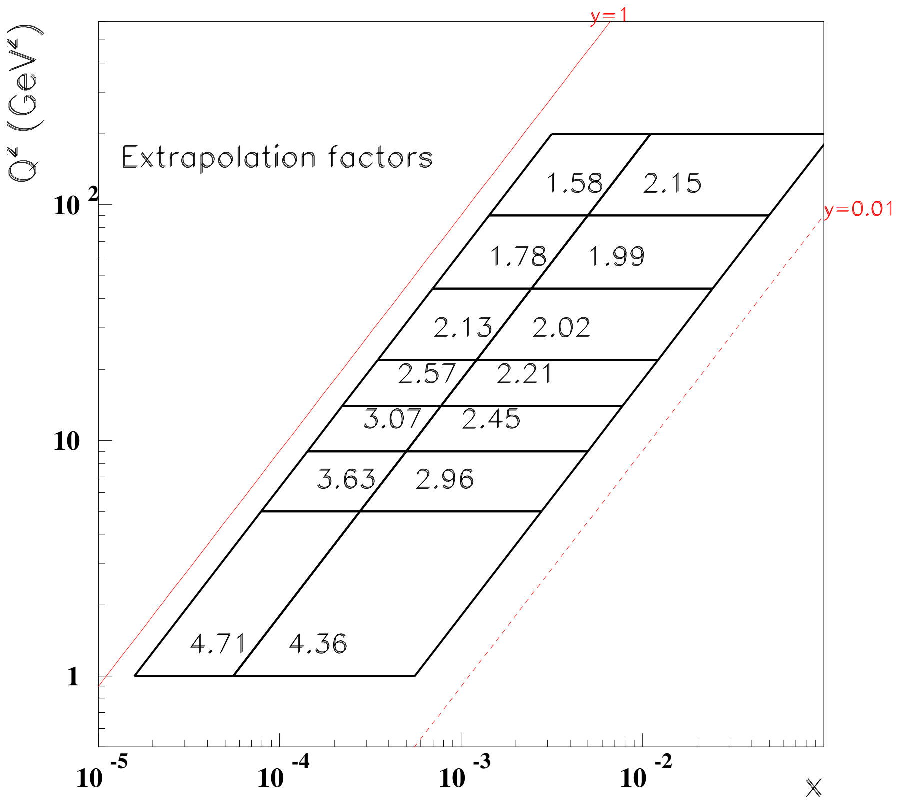


Theory: Harris-Smith program HVQDIS
(NLO QCD BGF), f_p = GRV94 HO
upper (lower) curve $m_c = 1.3$ GeV ($m_c = 1.7$ GeV)
Peterson FF : $\epsilon = 0.035$ (OPAL)

NLO QCD (BGF) predictions are in general agreement with data

From D^* Cross Sections to F_2^{charm}

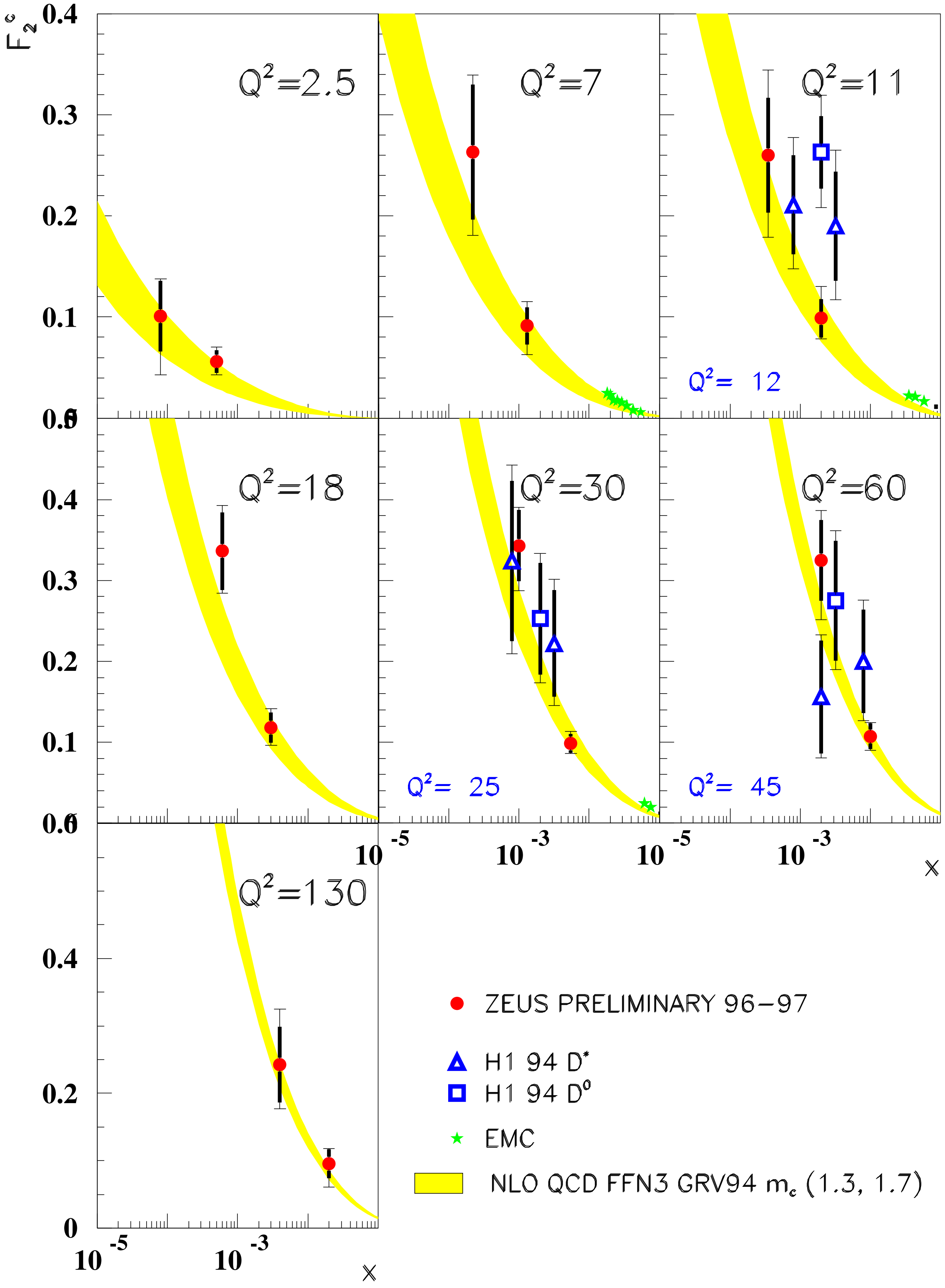
- D^* cross sections are measured in the restricted $p_T(D^*), \eta(D^*)$ region in y, Q^2 bins
- Extrapolation outside this region using NLO QCD calculation (including D^* fragmentation) implemented in HVQDIS



- $\sigma_{e^+p\to e^+D^*X} \Longrightarrow \sigma_{e^+p\to e^+c\bar{c}X}$ using $c \to D^{*+}$ from LEP

$$\frac{d\sigma_{c\bar{c}}(x,Q^2)}{dxdQ^2} = \frac{2\pi\alpha^2[1+(1-y)^2]}{xQ^4} \quad F_2^c(x,Q^2)$$

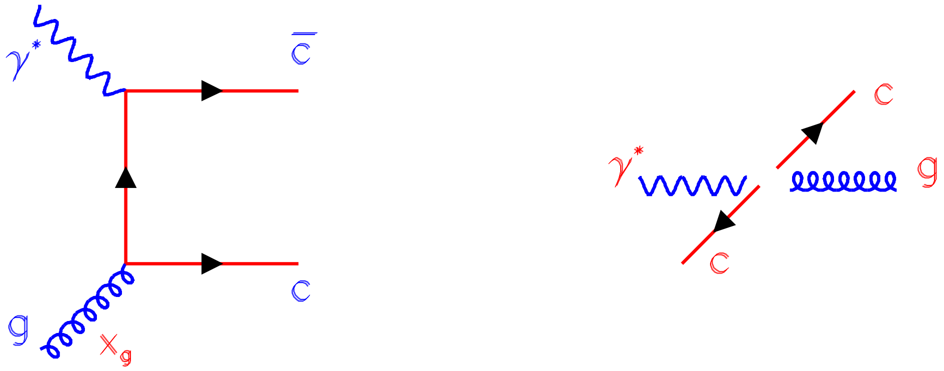
Latest F_2^c from H1 and ZEUS



$F_2^c/F_2 \sim 25\%$

BGF is in agreement with data

Gluon Density Extraction



$x_g = (\hat{s} + Q^2)/ys$, where

$\hat{s} = (p_\perp^{*2} + m_c^2)/z(1-z)$, where

$z = Pp/Pq = (E - P_z)^c/2yE_e$

- Reconstruct an observed x_g^{OBS} from the measured electron and tagged D^*

  $z \rightarrow z^{OBS} = (E - P_z)^{D^*}/2yE_e$

  $p_\perp^{*2}(c) \rightarrow p_\perp^{*2}(D^*)$

- Measure a $\sigma(x_g^{OBS})$ only in restricted $p_\perp(D^*), \eta(D^*) region$
- Unfold $x_g^{OBS} \rightarrow x_g$ using

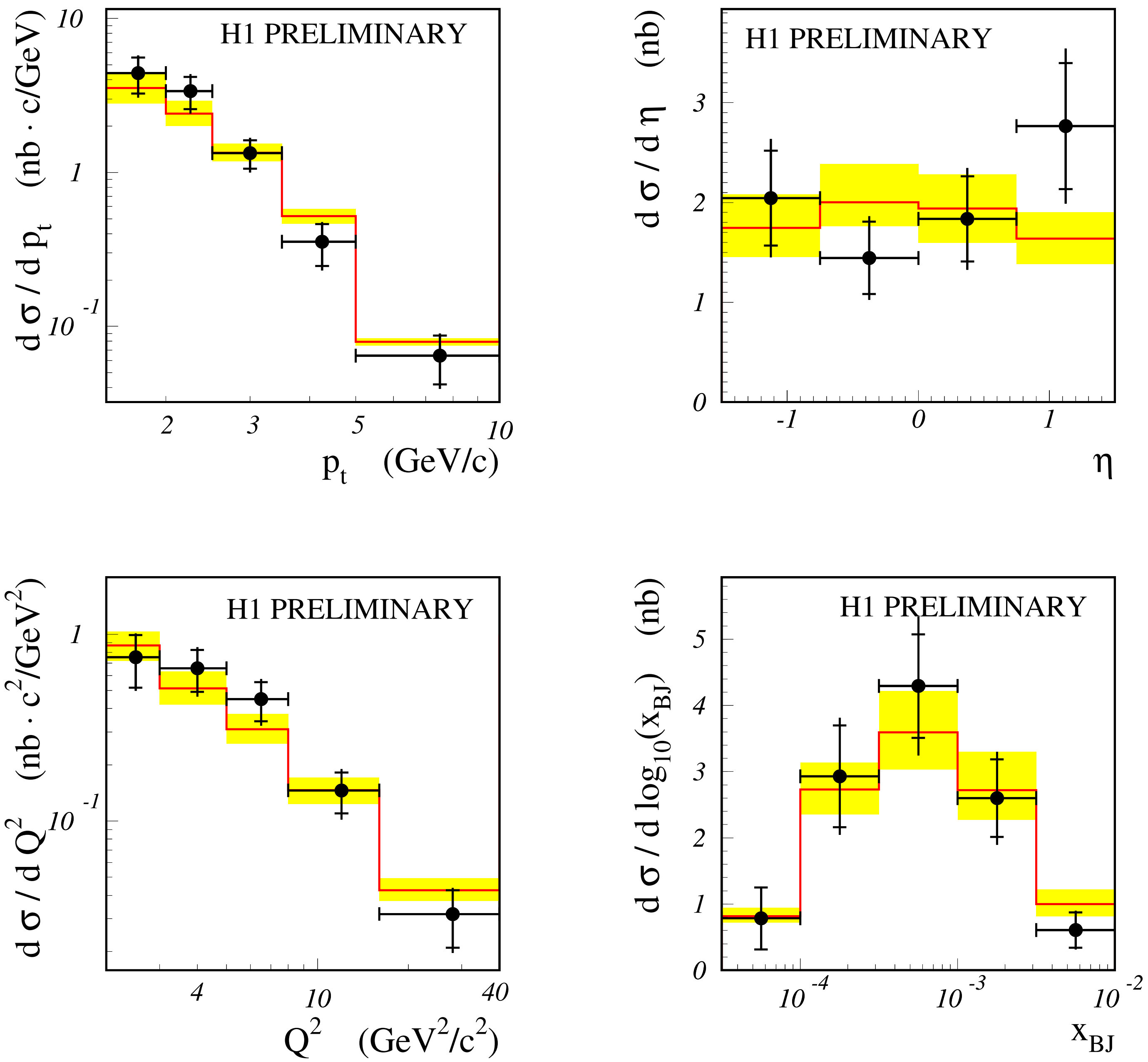
  Iterative unfolding procedure (d'Agostini)

  QCD NLO model

  Peterson fragmentation in the model

$$\sigma(x_g^{OBS}) = \int_{x_g^{min}}^1 f_{g/p}(x_g, \mu^2)\hat{\sigma}(x_g, \mu^2)A(x_g^{OBS}, x_g)dx_g$$

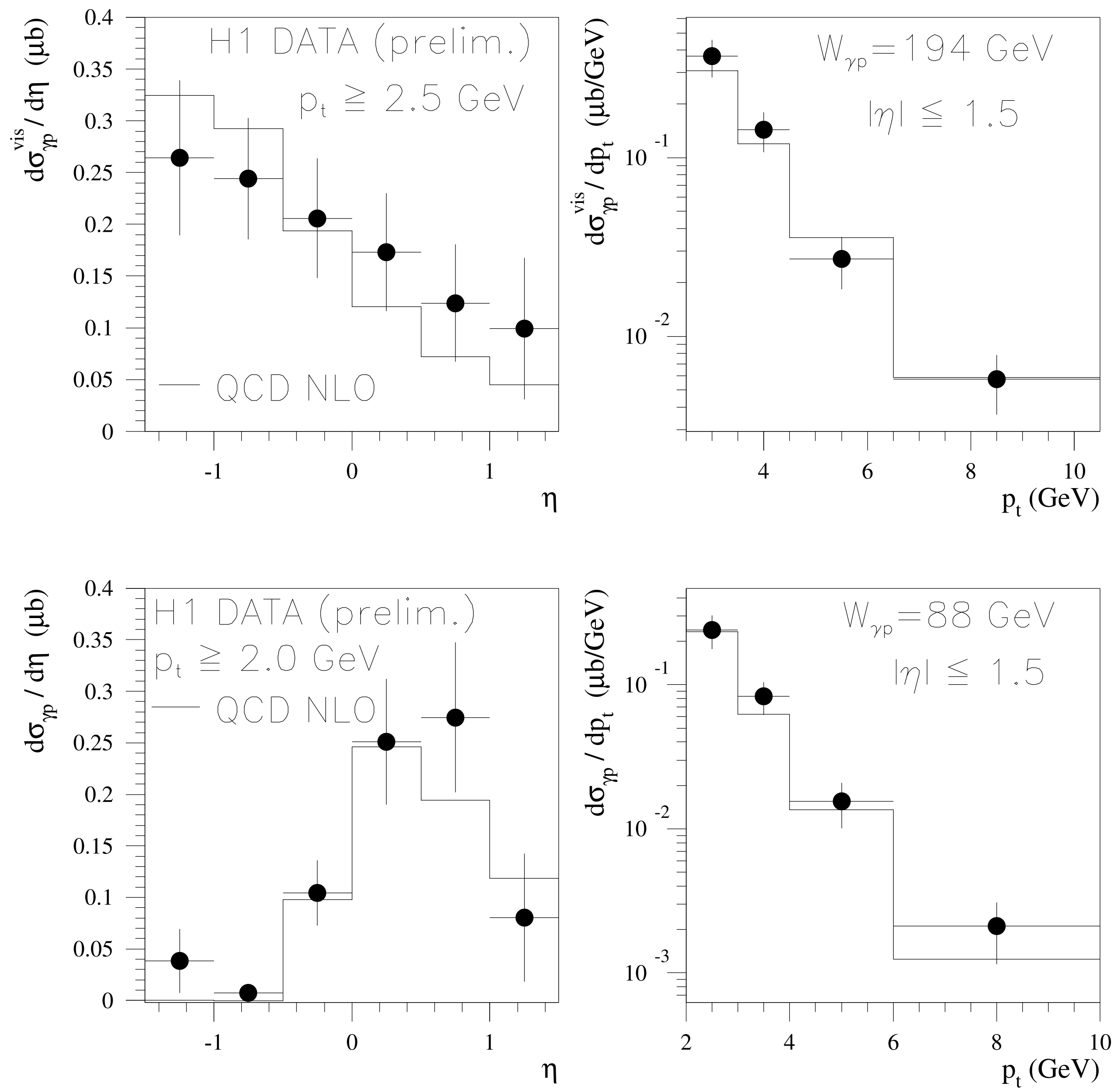
D^* in DIS Cross Sections used for $x_g f_{g/p}(x_g)$



$2 < Q^2 < 100$ GeV^2, $0.01 < y < 0.7$
$p_T(D^{*\pm}) > 1.5$ GeV, $|\eta(D^{*\pm})| < 1.5$

Theory : HVQDIS

D^* in PHP Cross Sections used for $x_g f_{g/p}(x_g)$



tagged photoproduction : $Q^2 < 0.01$

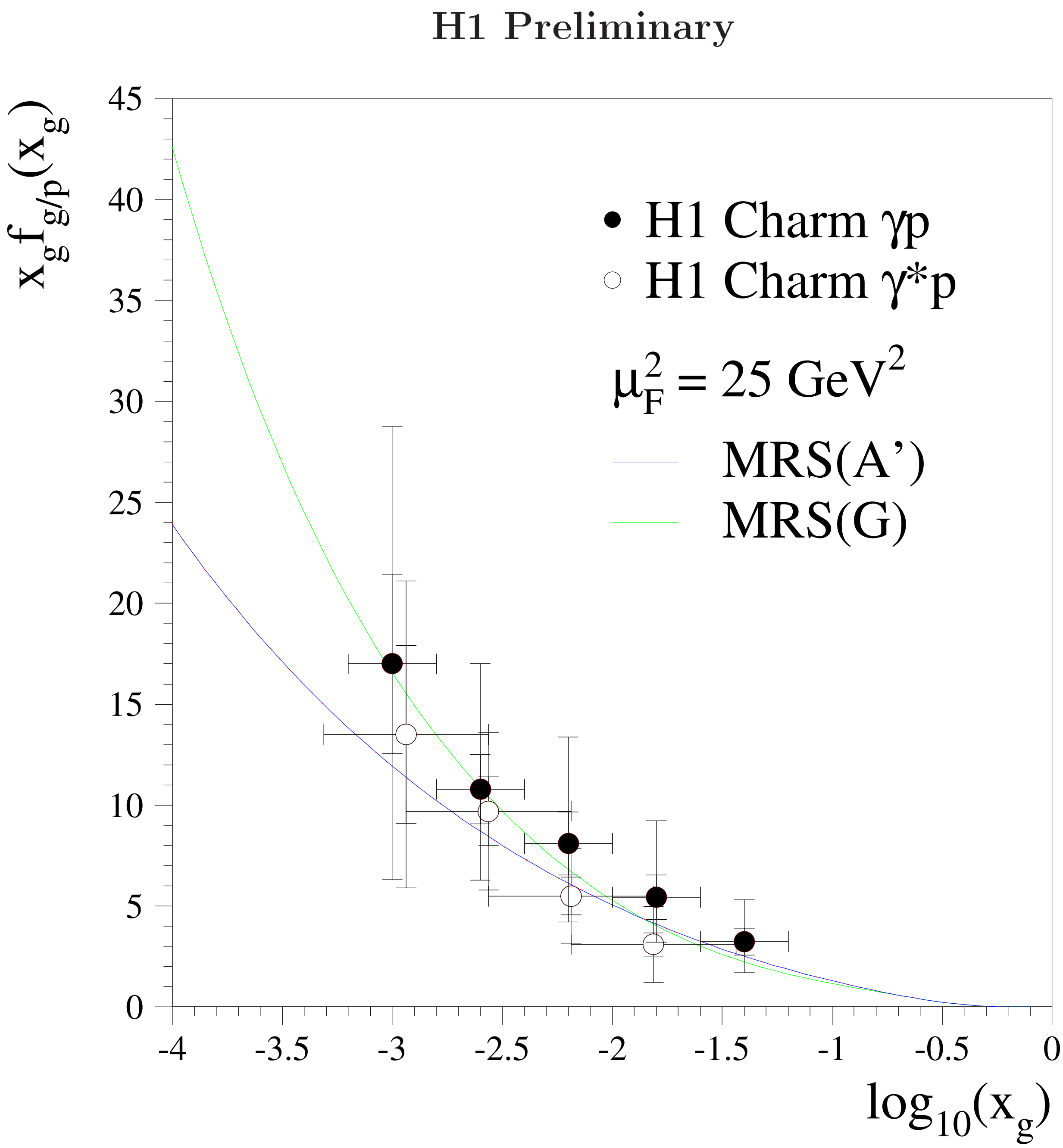
$\mathcal{L} \simeq 10.5\ pb^{-1}$

Errors : statistical only

to suppress resolved : $\eta(D^*) < 0.5$ (< 1.0)

Theory : Massive QCD NLO (Frixione et al.)

First $x_g f_{g/p}(x_g)$ from charm



DIS and PHP results are in good agreement

Dominant uncertainty : scale in QCD NLO

Other uncertainties : m_c , fragmentation, struct.function, resolved contribution

Summary DIS Charm Production

- Differential D^* cross sections in the experimentally accessible region are described by NLO QCD
- Large contribution of F_2^c to F_2 ($\sim 25\%$)
- F_2^c component of the proton SF is consistent with BGF
- First measurements of gluon density with charm in DIS and Photoproduction are in good agreement

Summary and Outlook

- Both H1 and ZEUS Collaborations have collected large samples of charm events produced at HERA in 93-97
- Many new results have been obtained, in particular :
  - Total $\gamma p \rightarrow c\bar{c}X$ cross section
  - differential cross sections of D^* in PHP and DIS
  - F_2^{charm} measurement
  - gluon density extraction
- Experimental results have been confronted with QCD NLO predictions. In general QCD makes some reasonable work for charm production at HERA. However differential cross sections of D^* in PHP are not well reproduced. This highlights a few theoretical problems :
  - different predictions from different theoretical group ("massive" vs "massless")
  - charm component in photon structure functions
  - unperturbative input treatment ($c \rightarrow D^*$)

- An era of beauty studies at HERA has started also ! (just wait for a talk of S.Passaggio)
- We are looking forward :
  - complex analysis of present data
  - high-lumi upgrade of HERA(2000)
  - detector's upgrades

  A lot of more interesting Heavy Flavour Physics to come from HERA