Open Charm and Beauty at HERA

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On Behalf of

the H1 and ZEUS Collaborations

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Heavy Quark Physics
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Outline:

- Introduction
- Kinematic variables
- Motivations and definitions
- Results:
  - Charm in Deep Inelastic Scattering
  - Charm in Photoproduction
  - Beauty in Photoproduction
- Summary and outlook

Introduction

HERA collides positrons (electrons) and protons

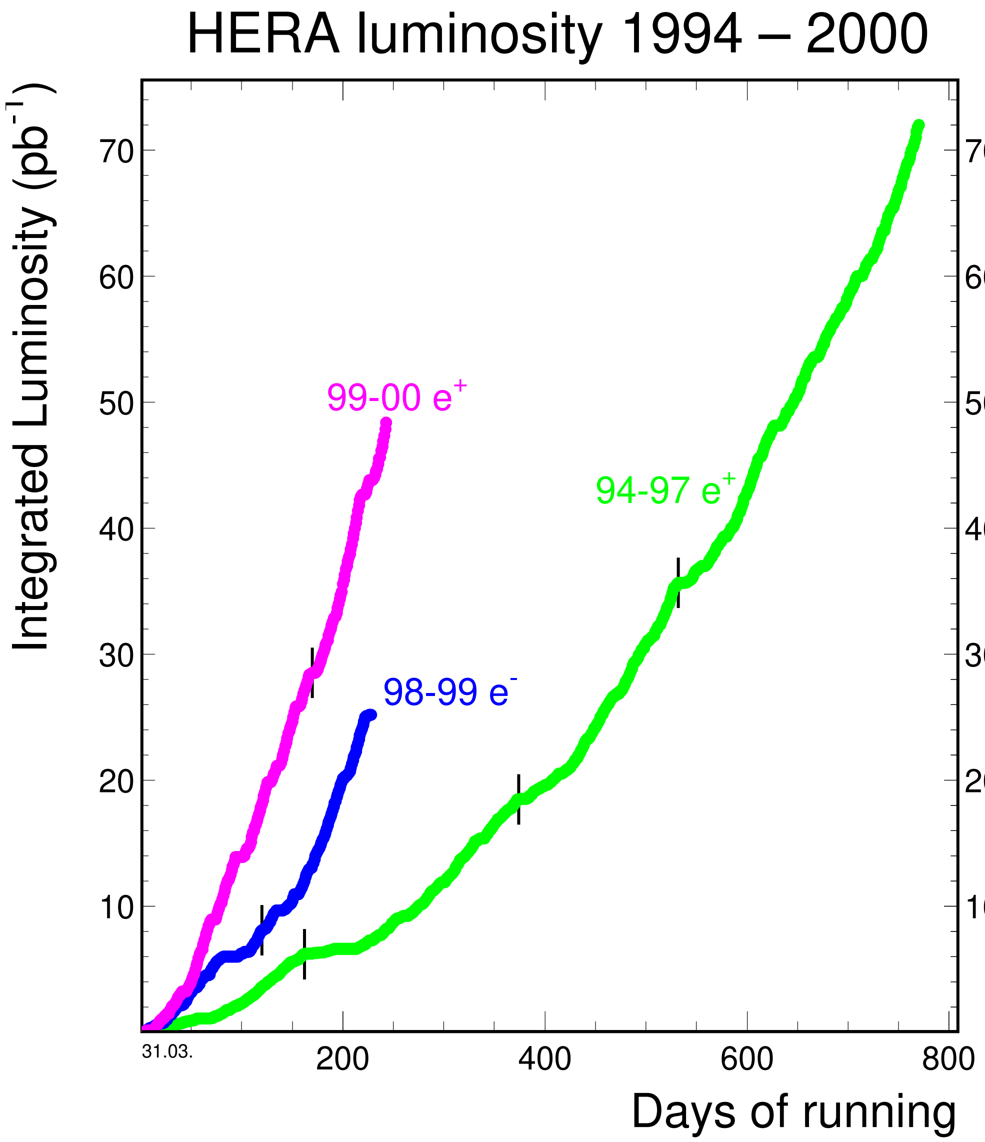
1994 - 1997 :

$\mathbf{27.5\ GeV}\ e \Rightarrow \sqrt{s} = 300\ \mathbf{GeV} \Leftarrow p\ 820\ \mathbf{GeV}$

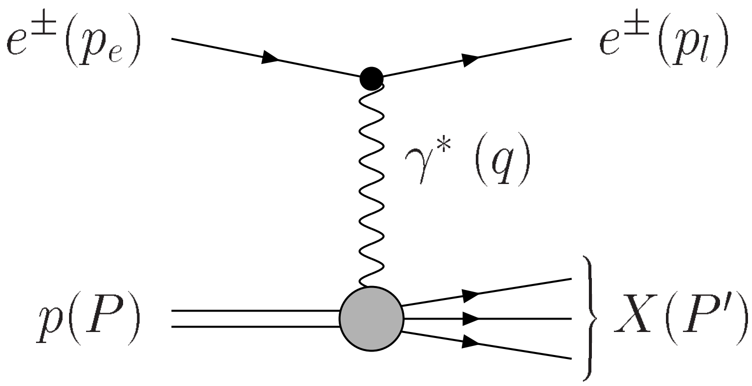
1998 - 1999 :

$\mathbf{27.5\ GeV}\ e \Rightarrow \sqrt{s} = 318\ \mathbf{GeV} \Leftarrow p\ 920\ \mathbf{GeV}$

$\Rightarrow \mathcal{L}_{\max} 1.9 \cdot 10^{31}\ \mathbf{cm^{-2}s^{-1}}$ [**design:** $1.5 \cdot 10^{31}\ \mathbf{cm^{-2}s^{-1}}$]



Kinematic variables



Energy $e\,p$ **c.m.:** $s = (p_e + P)^2$

Virtuality γ^***:** $Q^2 = -(p_e - p_l)^2 = -q^2$

Photoproduction: $Q^2 \simeq 0$

Deep Inelastic Scattering: $Q^2 > 1\ \mathrm{GeV}^2$

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

Fraction of E_e **lost (in the** p **rest frame)**

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

Fraction of P **carried by the struck quark:** $x = \frac{Q^2}{2p\cdot q}$

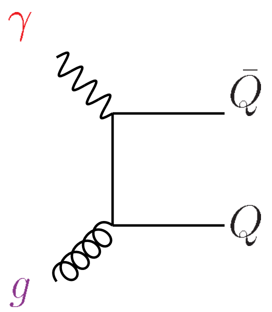
Pseudorapidity: $\eta = -\ln\left(\tan\frac{\theta}{2}\right)$

The angle θ **is measured w.r.t. proton direction**

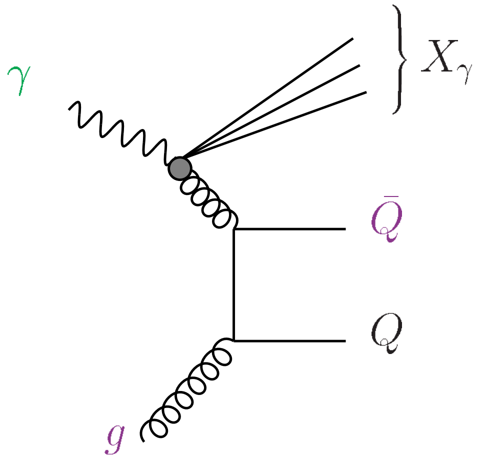
Motivations and interests:

- **Study of production mechanisms of heavy flavours;**
- **The larger the quark mass ($m_q \gg \Lambda_{\mathrm{QCD}}$) the more calculations within the perturbative-QCD are reliable;**
- **Study of proton and photon parton densities.**

At HERA 2 kind of diagrams:



direct photon process



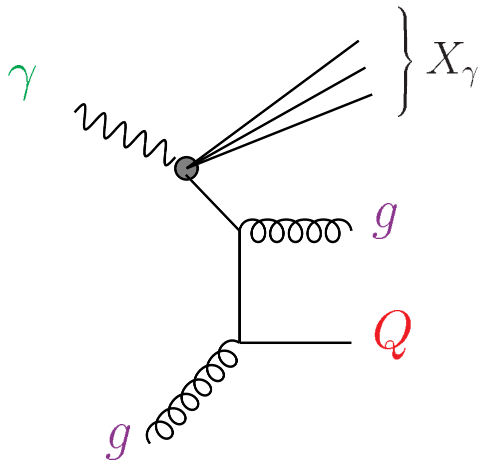
resolved photon process

- **In a direct photon event $\gamma^* g \to Q\bar{Q}$ (BGF): the photon participates in the scattering as a point-like object and all its energy is available in the reaction**

- **In a resolved photon event $gg \to Q\bar{Q}$, $Qg \to Qg$: the photon exhibits a structure: the hard scattering happens among partons of the γ and partons of the p, only part of the energy of the photon is available in the reaction**

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

Heavy Flavour Excitation:



process of Heavy Flavour excitation within the photon

Note: in the Heavy Flavour excitation process the heavy flavour contents of proton and photon are probed.

Such diagrams are included in resummed but not in fixed-order NLO calculations.

How to distinguish between direct and resolved processes?

We can measure the fraction of the photon momentum contribuiting to dijet production:

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

This observable can be measured and calculated at every order of pQCD.

NLO models

Fixed order (Massive) scheme

- $n_f = 3(u, d, s)$ **flavours in initial state**
- $c, [b]$ **produced dynamically from hard process**
- $p_\perp^q \approx m_q$
- **Peterson Fragmentation**

S. Frixione et al., ***Nucl. Phys.*** B454 (1997) 3.

B. Harris and J. Smith, ***Phys. Rev.*** D57 (1998) 2806.

Resummed (Massless) scheme

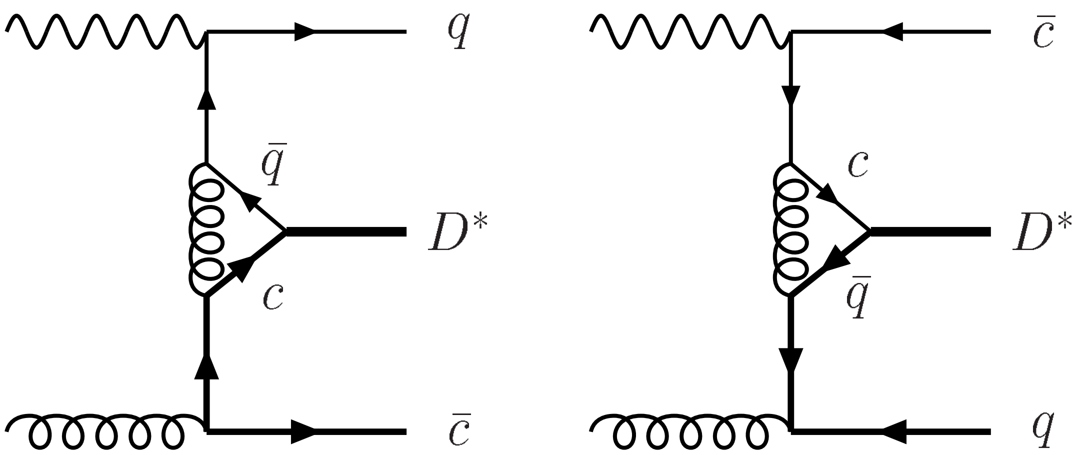
- $n_f = 4[5](u, d, s, c, [b])$ **flavours in initial state**
- $c, [b]$ **from hard process**
- $p_\perp^q \gg m_q$
- **Peterson Fragmentation**

J. Binnewies et al., ***Z. Phys.*** C76 (1997) 677.

M. Cacciari et al., ***Phys. Rev.*** D55 (1997) 2736.

BKL

Tree-level $\mathcal{O}(\alpha\alpha_s^3)$ calculation considers diagrams like:



Instead of fragmenting an isolated c-quark, a $(c, \bar{q})$-state is directly produced.

Colour-singlet and octet states both contribute. Fit to published ZEUS D^* data yielded a ratio

$$O(8)/O(1) = 1.3$$

A. V. Berezhnoy, V. V. Kiselev and A. K. Likhoded, hep-ph/9905555.

Open Charm DIS production

How it is carried out? $\Rightarrow$ Kinematic reconstruction of charmed hadrons

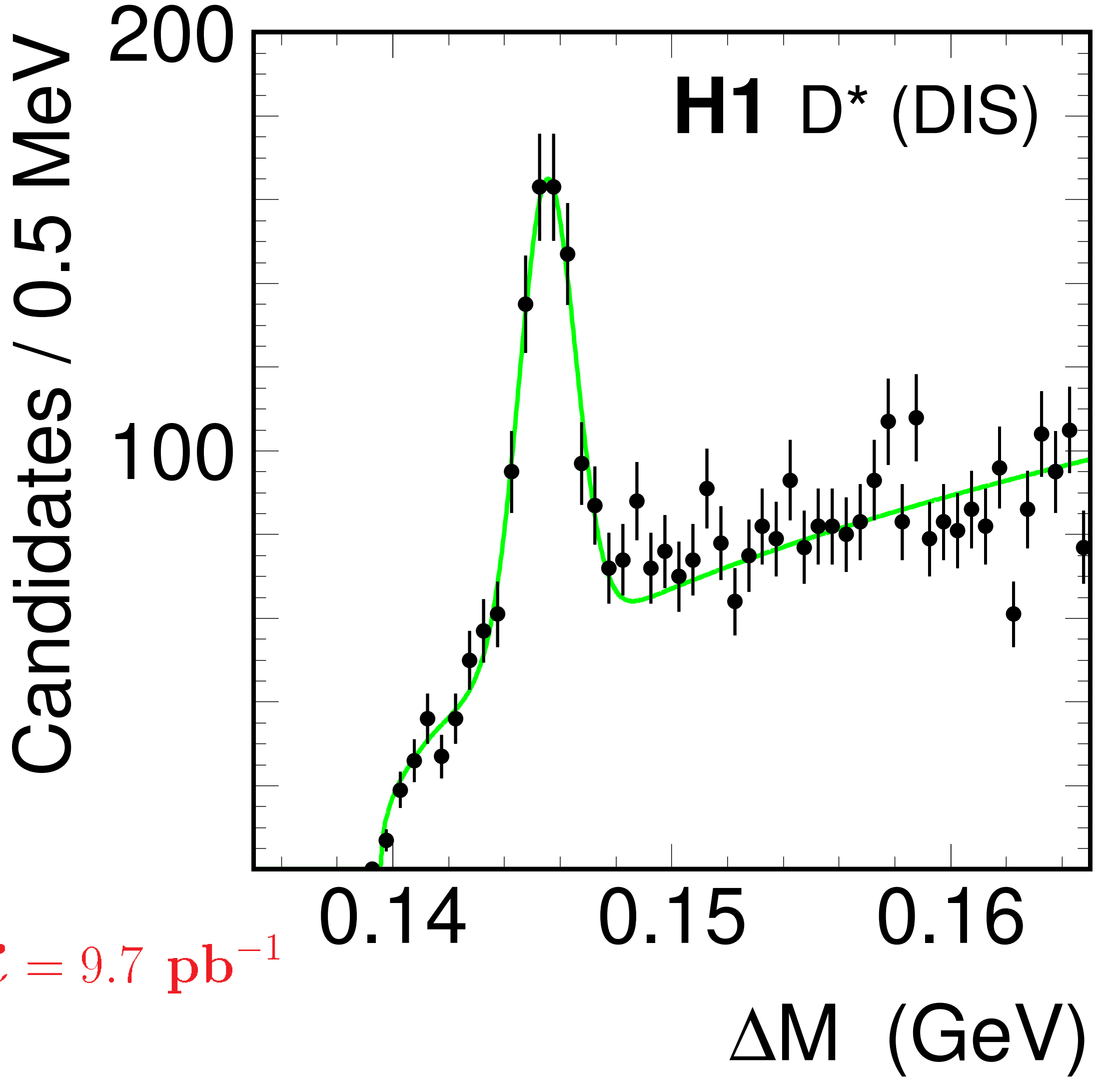
Example:

$$ep \to e \;\; c \;\; + X$$

$$c \;\to D^* \to (K^-\pi^+)\,\pi_s^+ \qquad \textbf{(H1, ZEUS)}$$

$$\to (K^-\pi^+\pi^+\pi^-)\,\pi_s^+ \qquad \textbf{(ZEUS)}$$

- $p_\perp^{D^*} > 1.5$ GeV, $\quad |\eta^{D_s}| < 1.5$
- $2 < Q^2 < 100$ GeV^2 $\quad 0.05 < y < 0.7$



$\mathcal{L} = 9.7$ **pb**$^{-1}$

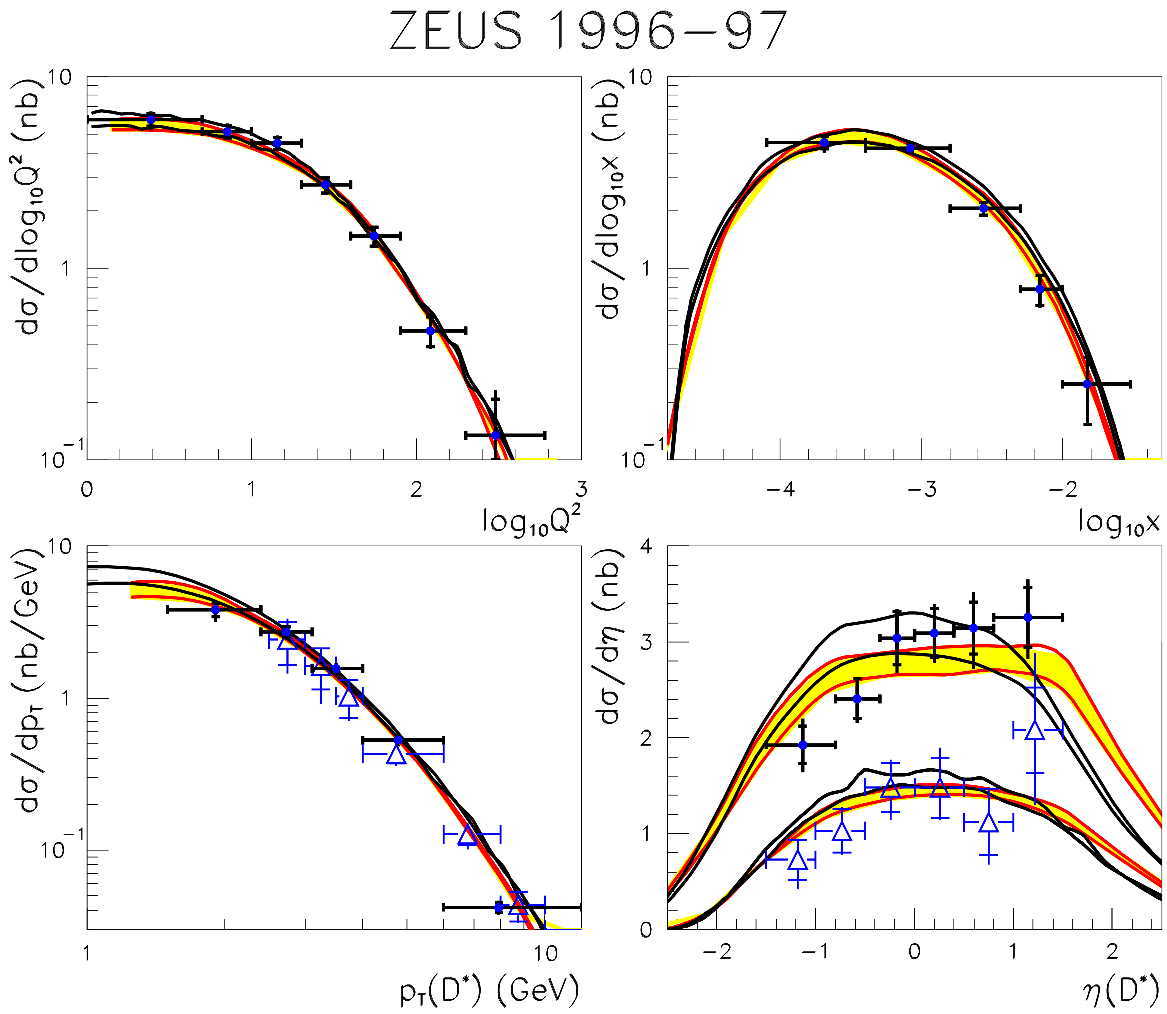
D^* Cross Section in DIS

In the experimentally accessed region:

$$1 < Q^2 < 600 \text{ GeV}^2 \qquad 0.02 < y < 0.7$$

$$D^* \to (K\pi)\pi_s \quad 1.5 < p_\perp^{D^*} < 15 \text{ GeV}, \quad \left|\eta^{D^*}\right| < 1.5$$

$$D^* \to (K3\pi)\pi_s \quad 2.5 < p_\perp^{D^*} < 15 \text{ GeV}, \quad \left|\eta^{D^*}\right| < 1.5$$



Compare with Fixed order NLO QCD HVQDIS

Open band: Peterson fragmentation ($\epsilon = 0.035$ **from** e^+e^-**), uncertainty on** m_c $[1.3; 1.5]$ GeV

Yellow band: LO MC fragmentation (JETSET)

Rapidity variable sensitive to fragmentation effects $\to$ **"beam drag"**

Good agreement $\to$ **extrapolate to full phase space**

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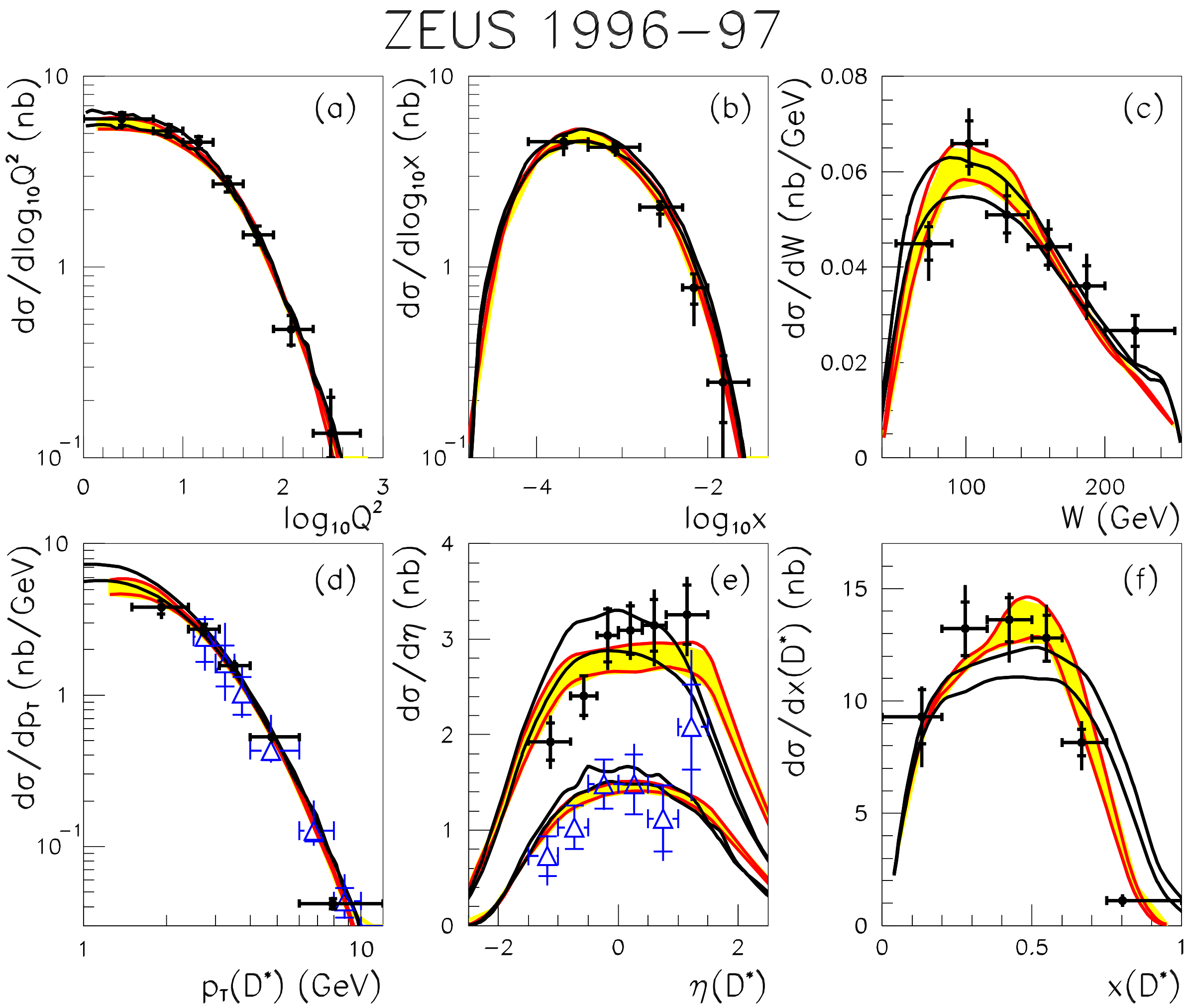


$x_D = p(D^*)/W$ **fractional momentum of D^* in $\gamma^* p$ frame**

Compare with Fixed order NLO QCD HVQDIS program

Open band: Peterson fragmentation ($\epsilon = 0.035$ from e^+e^-), uncertainty on m_c $[1.3; 1.5]$ GeV

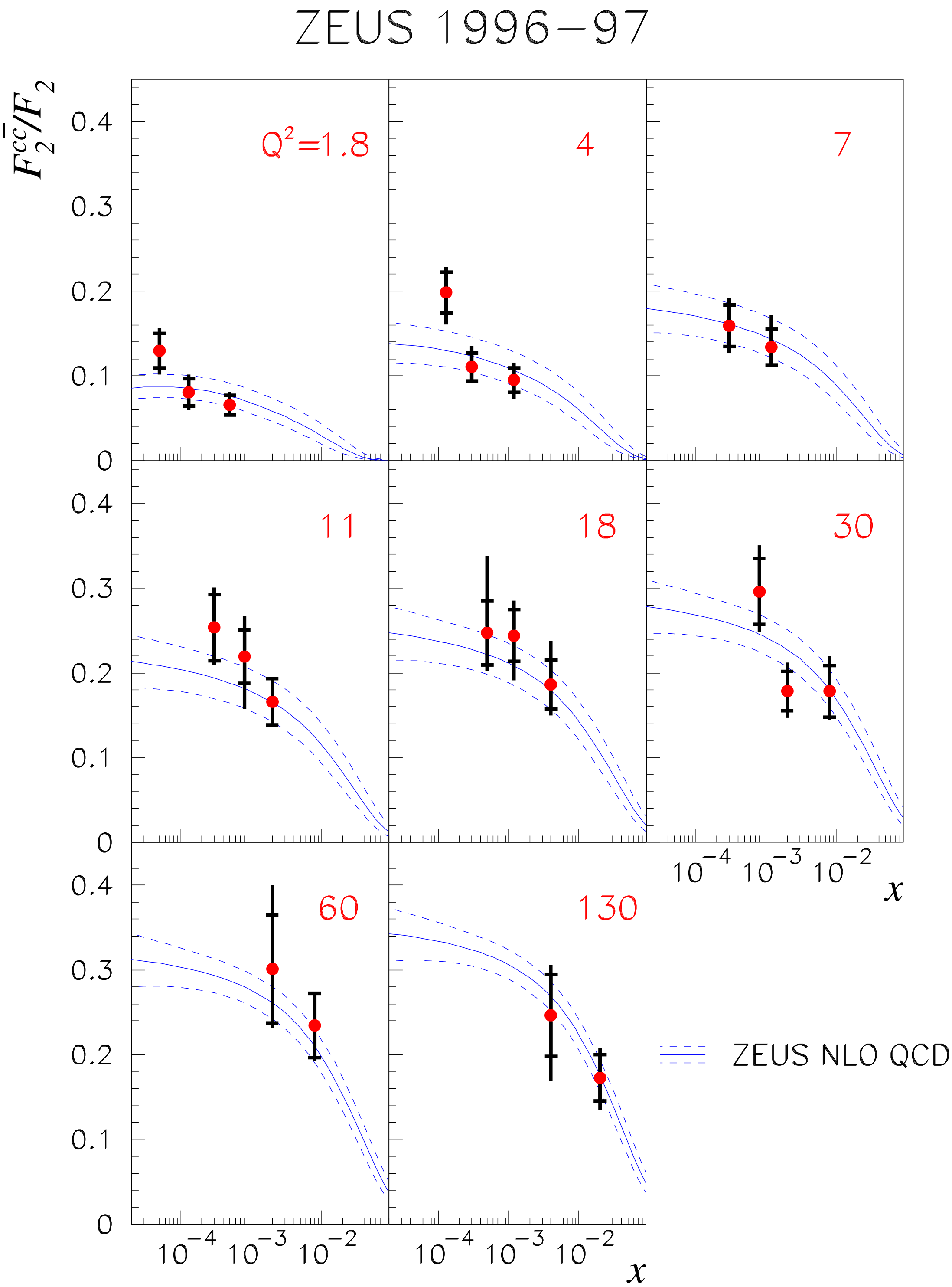
Yellow band: LO MC fragmentation (JETSET)

Rapidity (and x_D) variable sensitive to fragmentation effects $\to$ “beam drag”

Good agreement $\to$ extrapolate to full phase space

$F_2^{c\bar{c}}/F_2$ ratio measurement

- D^* cross section extrapolated to full kinematic range can be converted to $F_2^{c\bar{c}}$

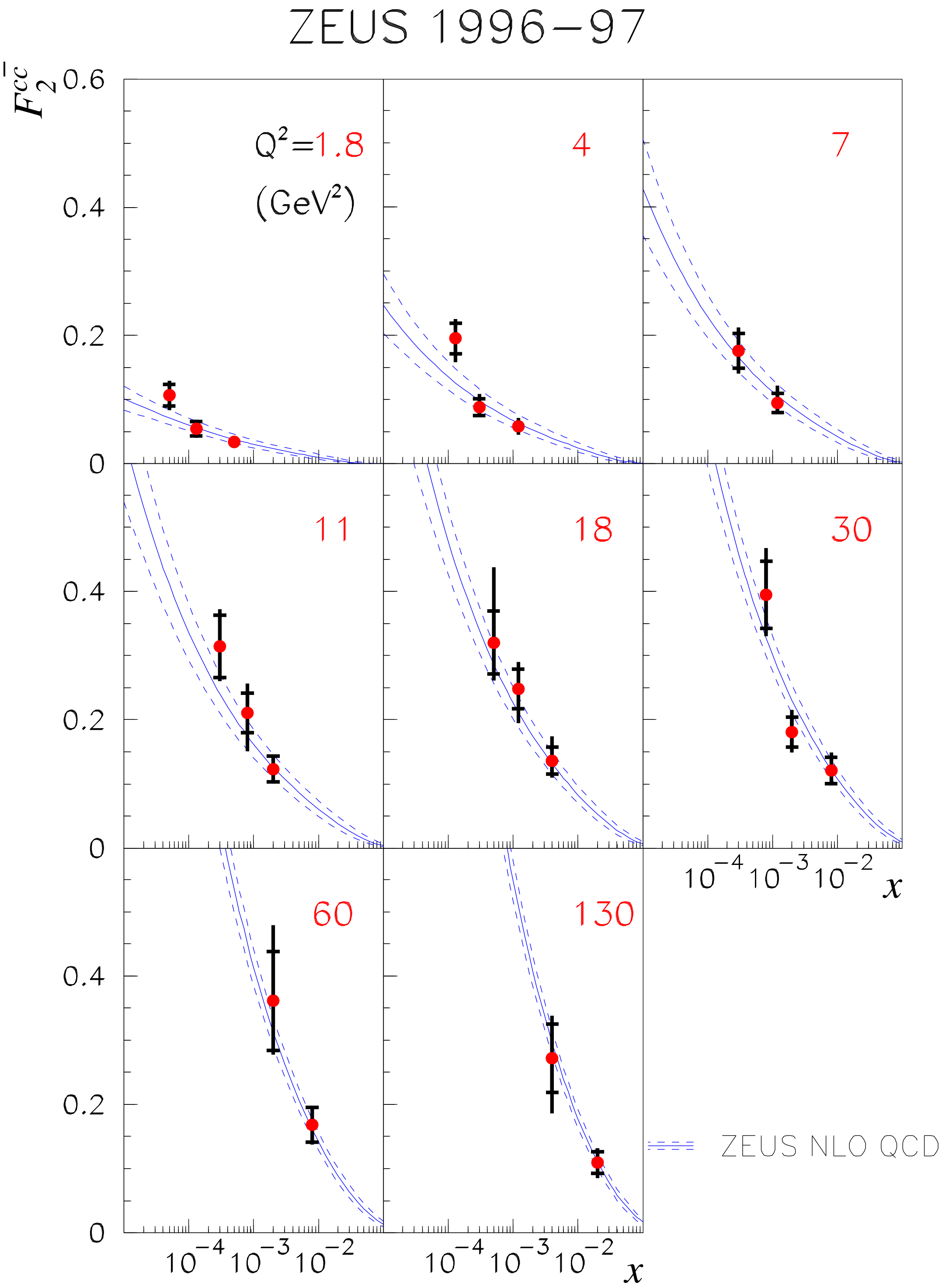


- charm contribution is large (up to 30%) at low x and high Q^2

$F_2^{c\bar{c}}$ measurement

- D^* cross section extrapolated to full kinematic range can be converted to $F_2^{c\bar{c}}$

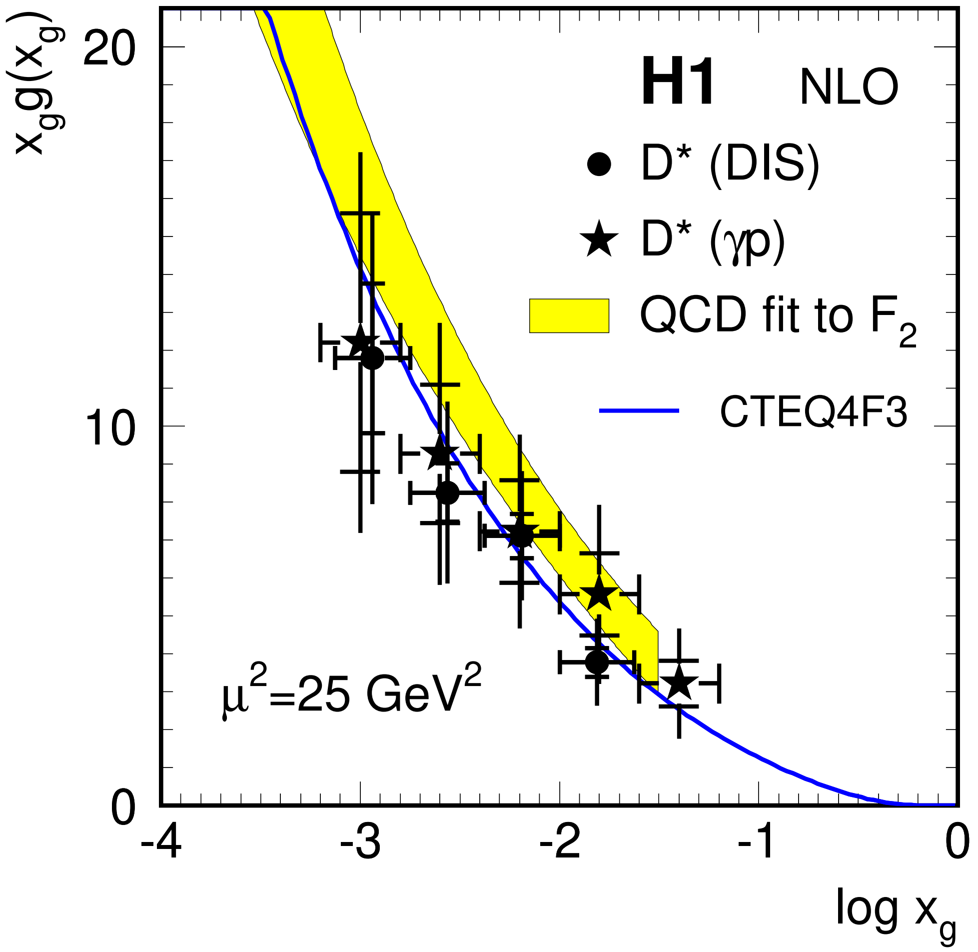
$$\frac{d^2\sigma^{c\bar{c}}}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[1+(1-y)^2\right]F_2^{c\bar{c}}(x,Q^2)$$



Direct Measurement of Gluon Density

• Reconstruct gluon momentum from D^* and scattered e

• Correct for higher order contributions and fragmentation by unfolding with NLO QCD programs



• Gluon distribution universal

Direct Measurement of Gluon Density

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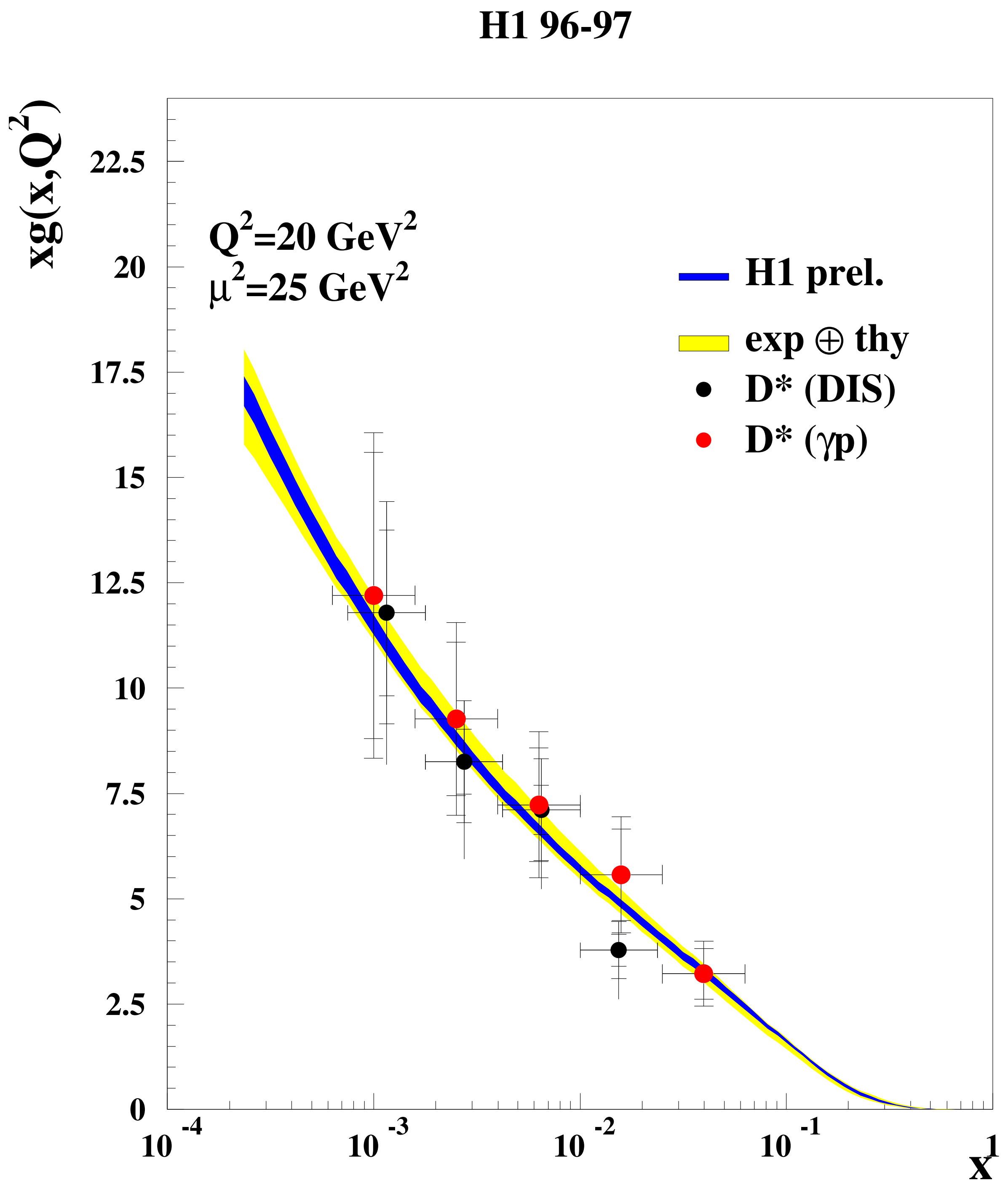


- Gluon distribution universal

Open Charm photoproduction

How it is carried out? $\Rightarrow$ Kinematic reconstruction of charmed hadrons

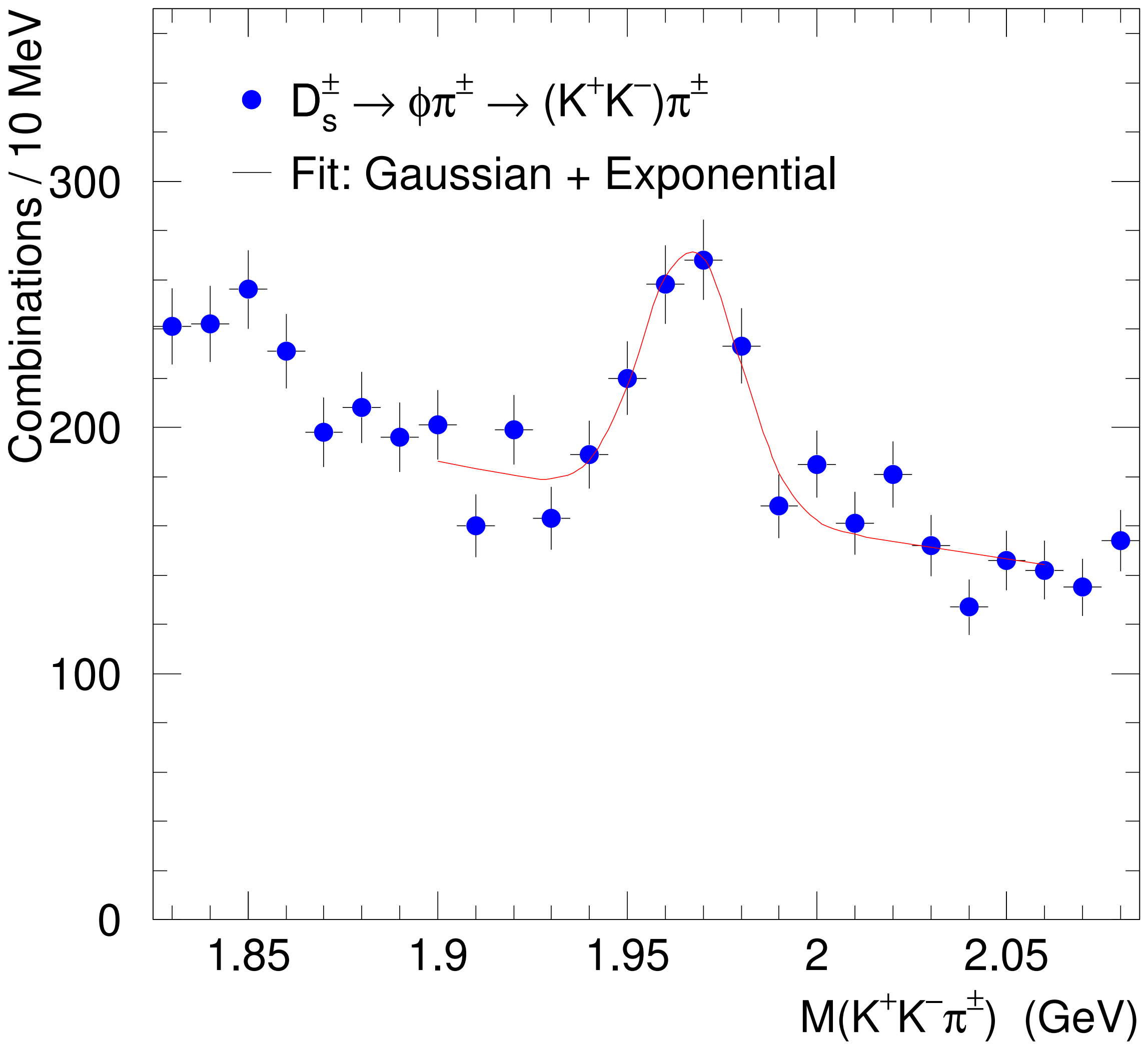
Example:

$$\begin{aligned} ep &\to \; c \; + X \\ & \quad\;\; c \; \to D_s \to \phi\pi \to (K^+K^-)\pi \end{aligned}$$

(But also: $D^* \to (K\pi)\pi_s$ **or** $D^* \to (K3\pi)\pi_s$**)**

- $3 < p_\perp^{D_s} < 12$ GeV, $\quad |\eta^{D_s}| < 1.5$
- $Q^2 < 1$ GeV^2 $\quad 130 < W < 280$ GeV

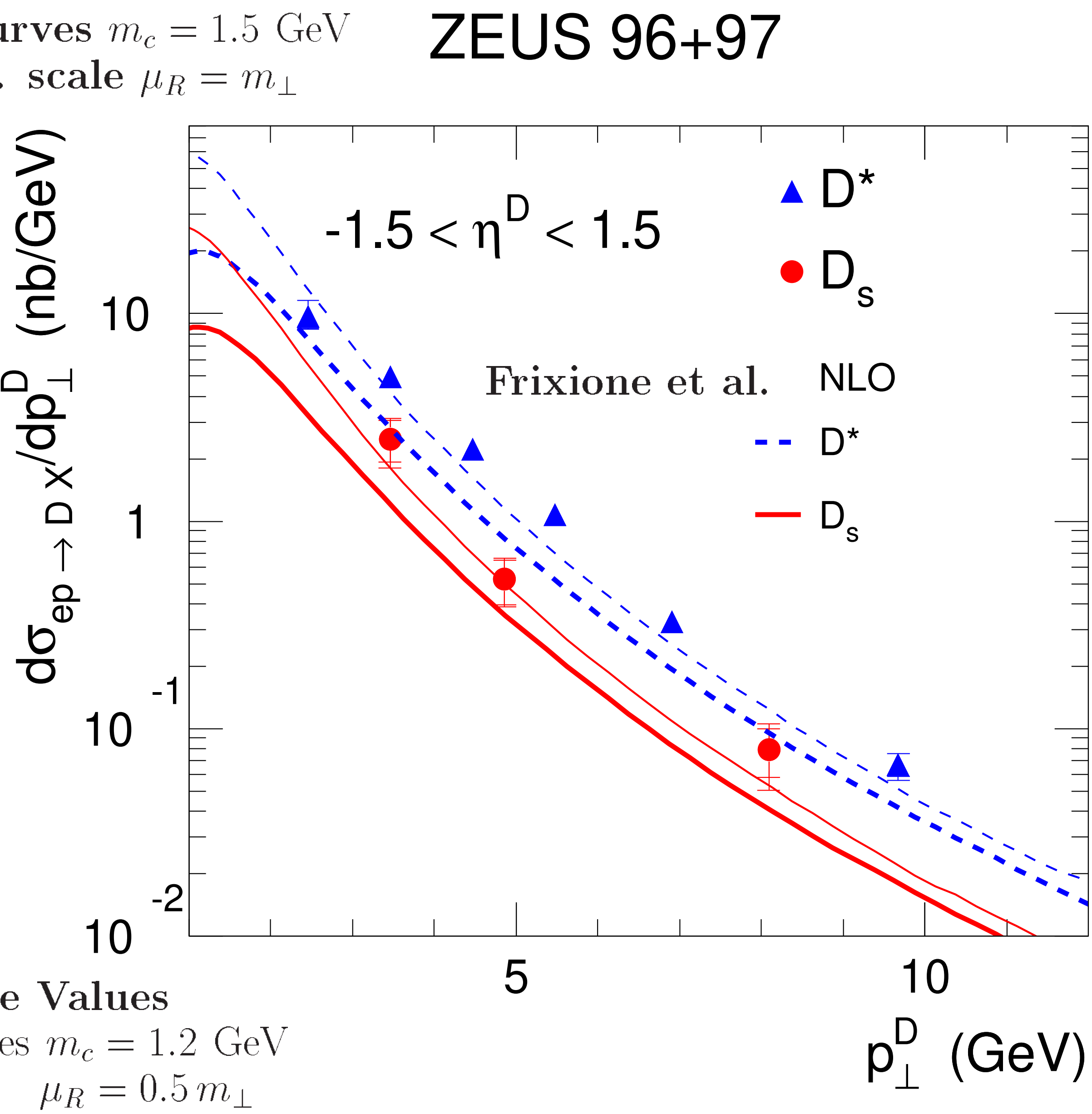
ZEUS 96+97



$D^*\&D_s$ Cross Section in Photoproduction

$Q^2 < 1$ GeV^2
$130 < W < 280$ GeV

Nominal Values
thick curves $m_c = 1.5$ GeV
renorm. scale $\mu_R = m_\perp$



Extreme Values
thin curves $m_c = 1.2$ GeV
$\mu_R = 0.5\, m_\perp$

- **NLO** **generally below** **data even for extreme choice of parameters**

$D^*\&D_s$ Cross Section in Photoproduction

$Q^2 < 1\ \mathrm{GeV}^2$
$130 < W < 280\ \mathrm{GeV}$

Nominal Values
thick curves $m_c = 1.5\ \mathrm{GeV}$
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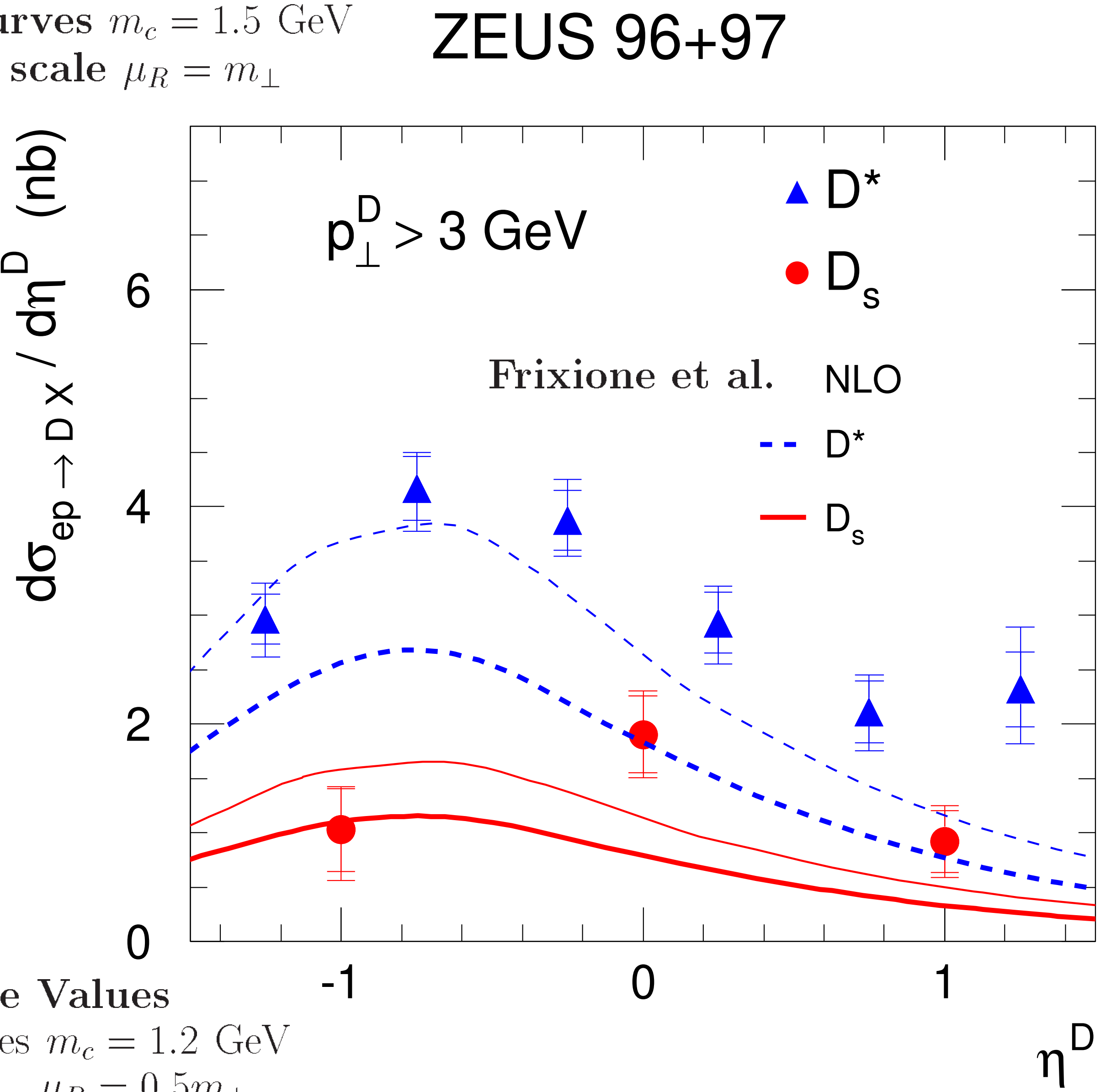


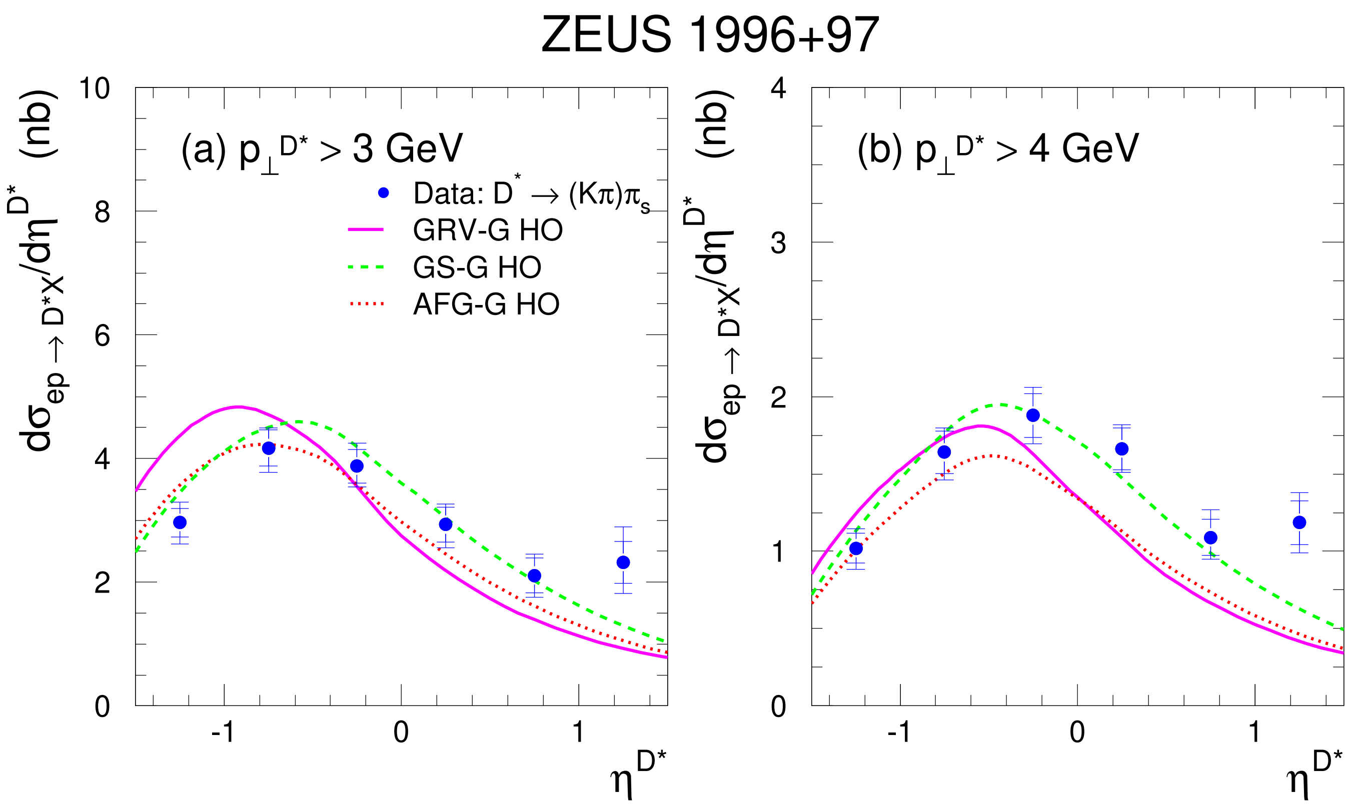
Extreme Values
thin curves $m_c = 1.2\ \mathrm{GeV}$
$\mu_R = 0.5 m_\perp$

- **Data well above the massive NLO calculations**

D^* Cross Section in Photoproduction

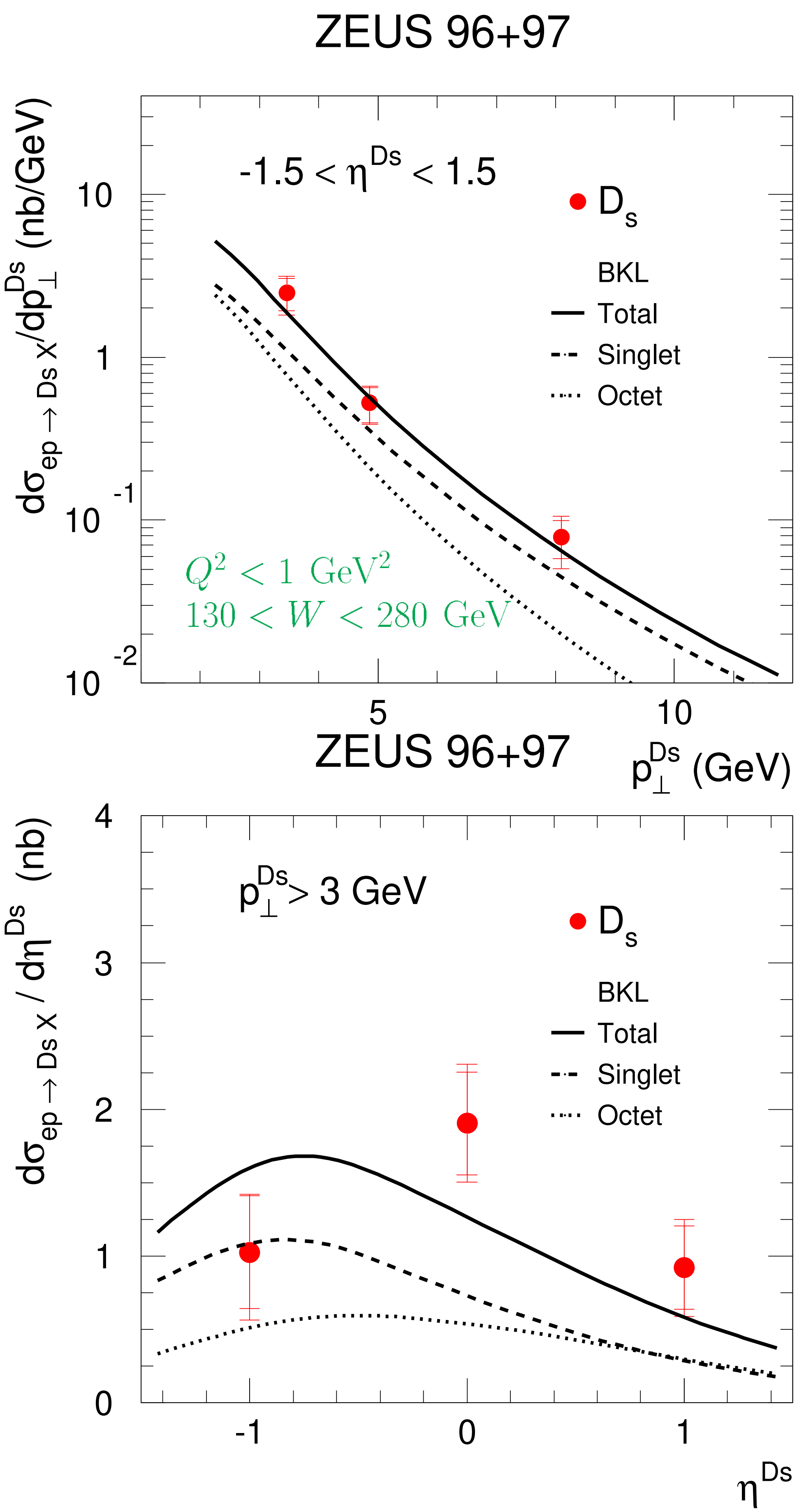
$Q^2 < 1$ GeV^2

$130 < W < 280$ GeV



- **Resummed (massless) NLO scheme**
- **GS-G HO gives the best agreement, this is an Extreme choice ($u = c$)**

D_s Cross Section in Photoproduction

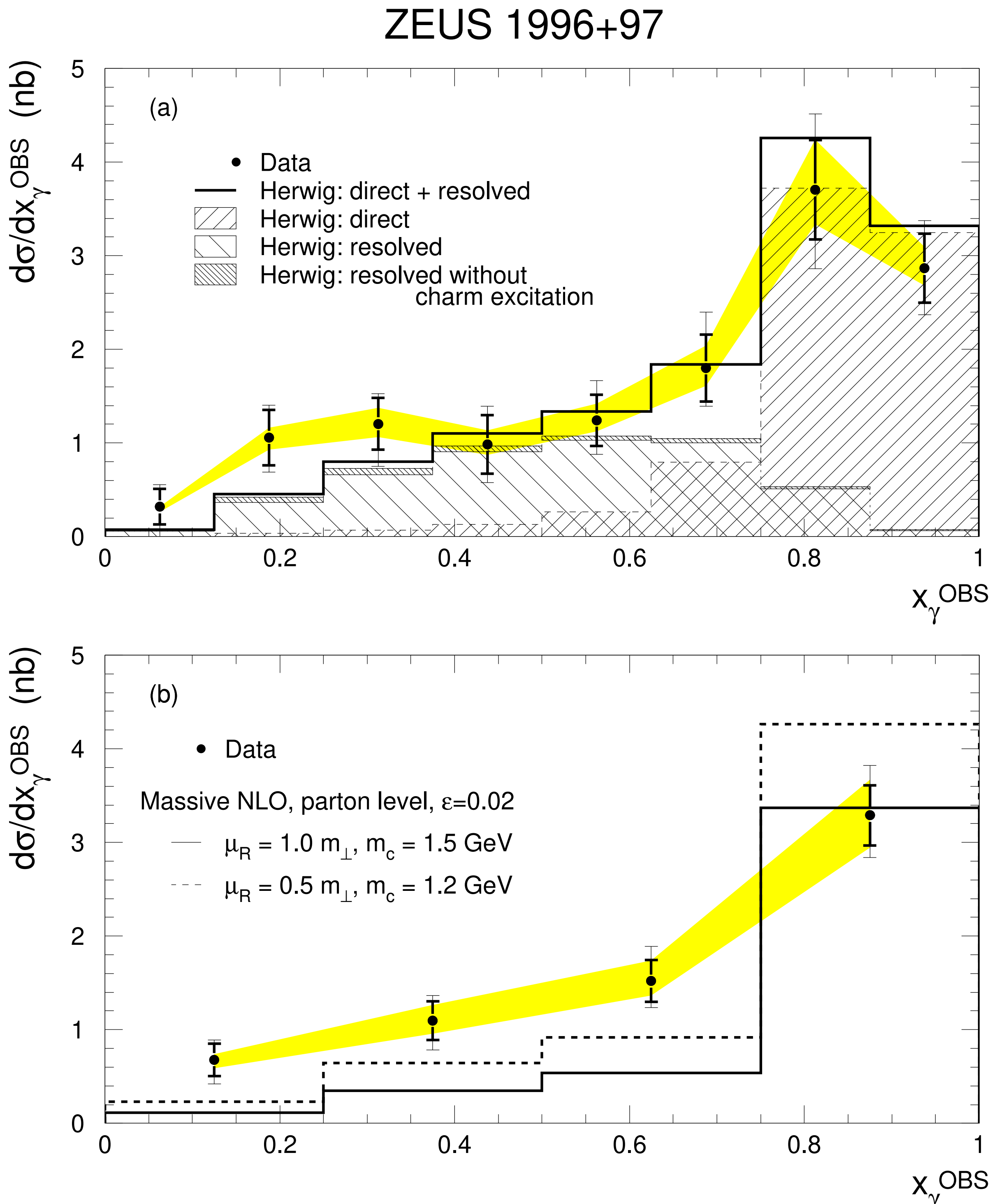


- **Large** contribution of color octet which contributes **mostly** in the forward direction

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

$E_T^{\mathrm{jet1}} > 7.0$ GeV, $E_T^{\mathrm{jet2}} > 6.0$ GeV $\quad Q^2 < 1$ GeV^2

$130 < W < 280$ GeV $\quad p_\perp^{D^*} > 3$ GeV $\quad \left|\eta^{D^*}\right| < 1.5$



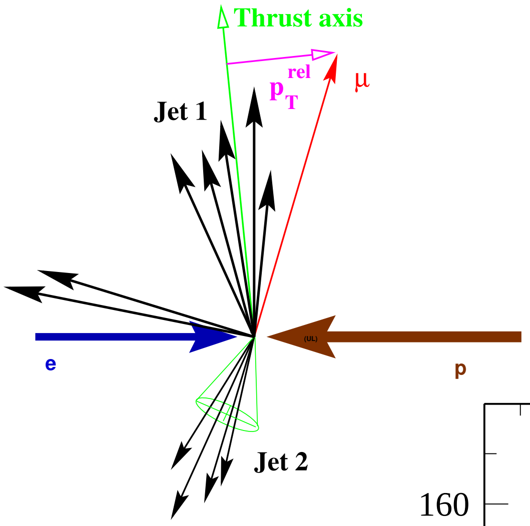
$\Rightarrow$ **LO resolved component required, mostly** c **excitation in the photon**

$\Rightarrow$ **massive NLO parton level calculation underestimate the low** $x_\gamma{}^{\mathrm{OBS}}$ **tail**

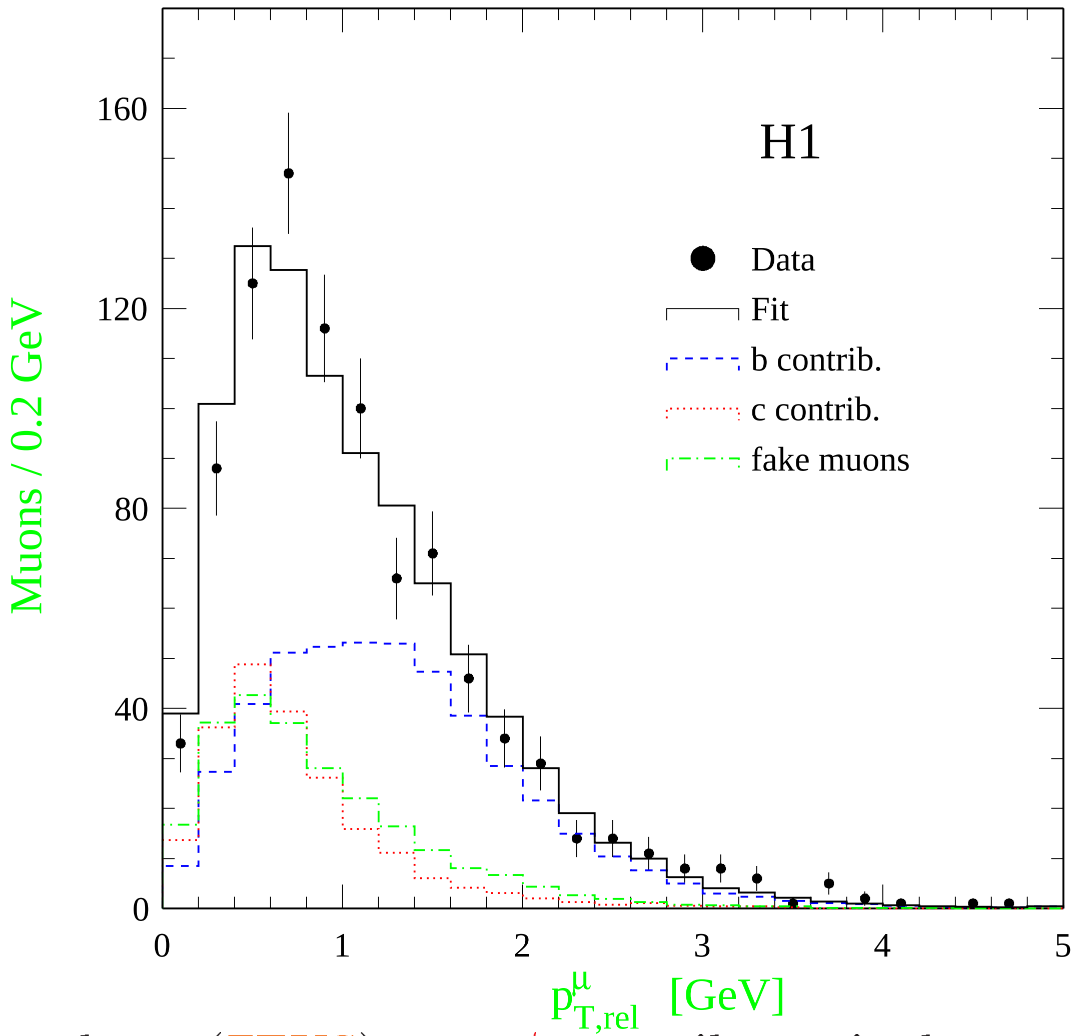
Open Beauty in Photoproduction

How it is carried out? $\Rightarrow$ Fit to p_T^{rel} Distribution

- $ep \to eb\bar{b}X \to e\mu X'$
- $Q^2 < 1\ \mathrm{GeV}^2 \qquad 0.1 < y < 0.8$
- $p_T^{\mu} > 2\ \mathrm{GeV} \qquad 35^\circ < \theta^{\mu} < 130^\circ$
- **At least two cone ($R = 1$) Jets:**
  $|\eta^{\mathrm{jet}}| < 2.5 \qquad E_T^{\mathrm{jet}} > 6.0\ \mathrm{GeV}$



$$f_b = 50.8 \pm 4.9\%$$

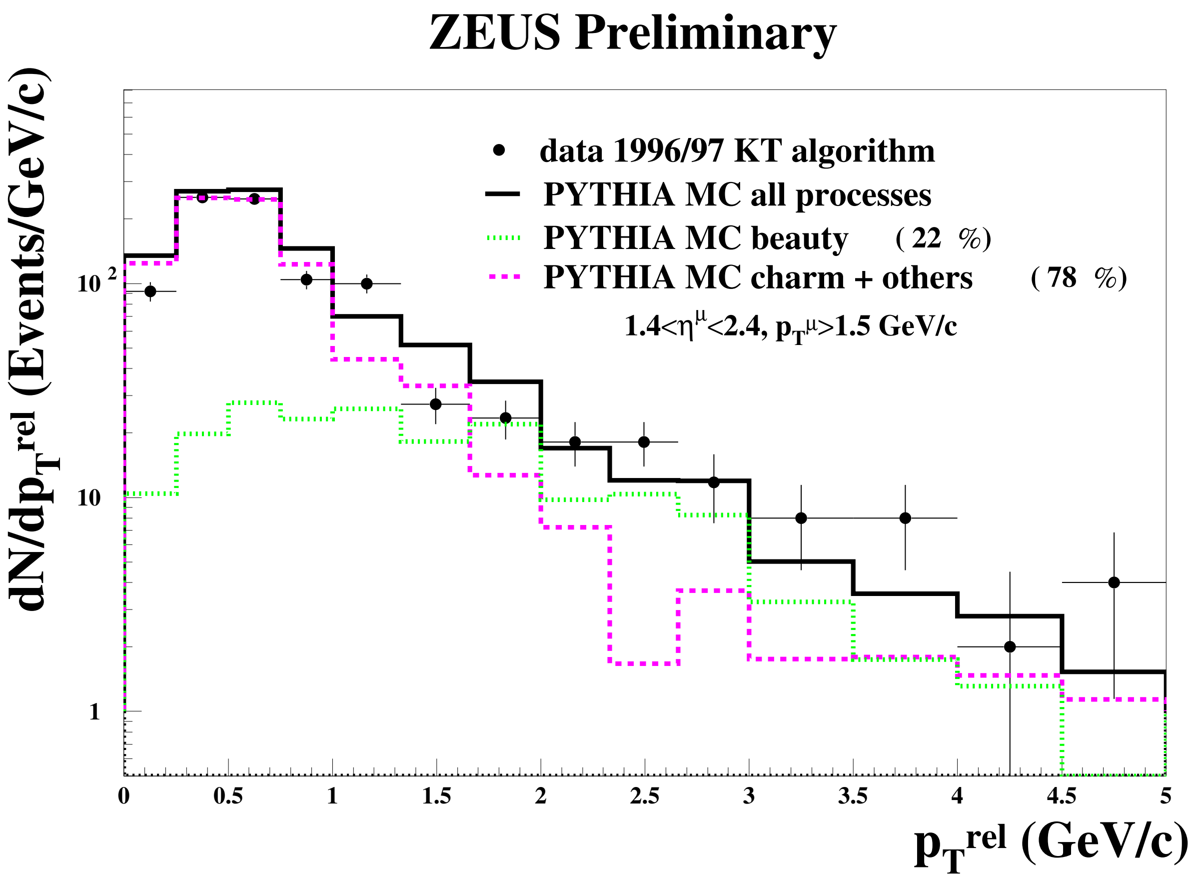


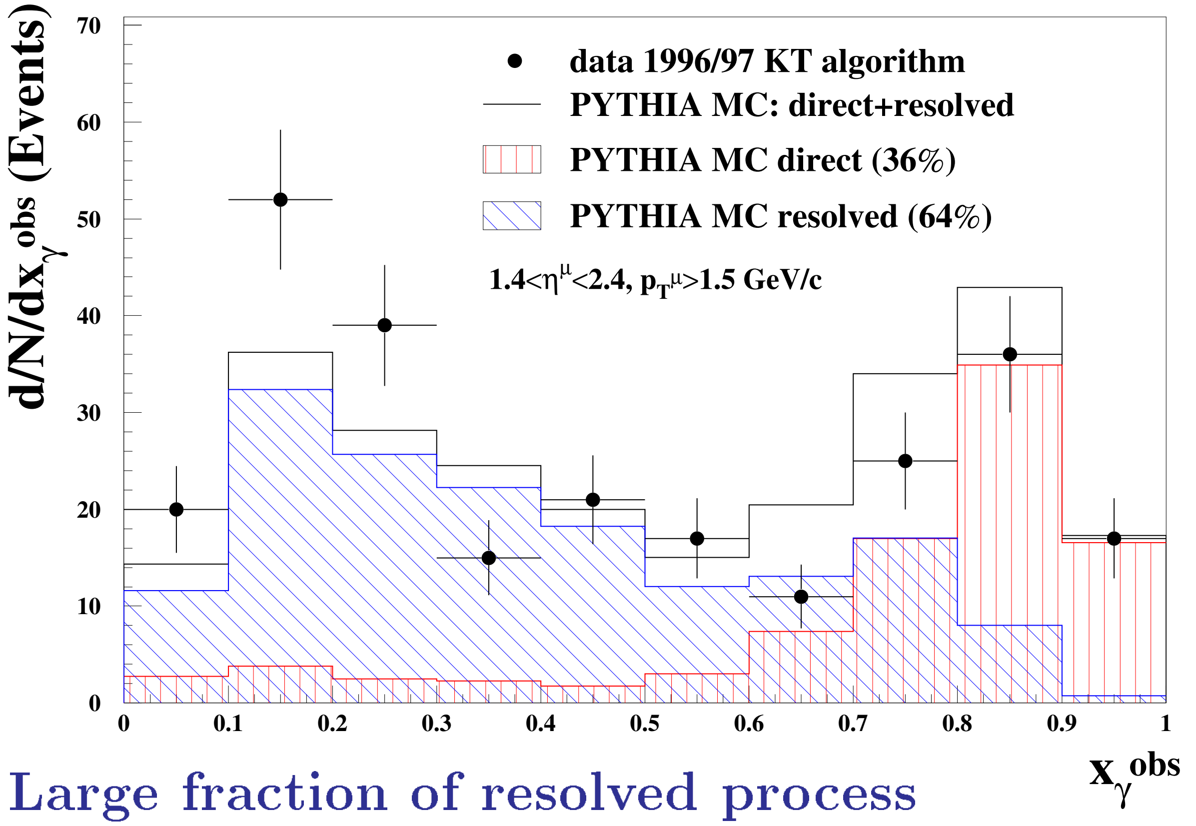
- **Other analyses (ZEUS) use μ/e^- semileptonic decay to extract the signal (p_T^{rel} vs jet axis)**

Open Beauty in Photoproduction (Forward region)

First Measurement

$E_T^{\text{jet1}} > 7.0$ GeV, $E_T^{\text{jet2}} > 6.0$ GeV $\quad \eta^{\text{jet}} < 2.4$

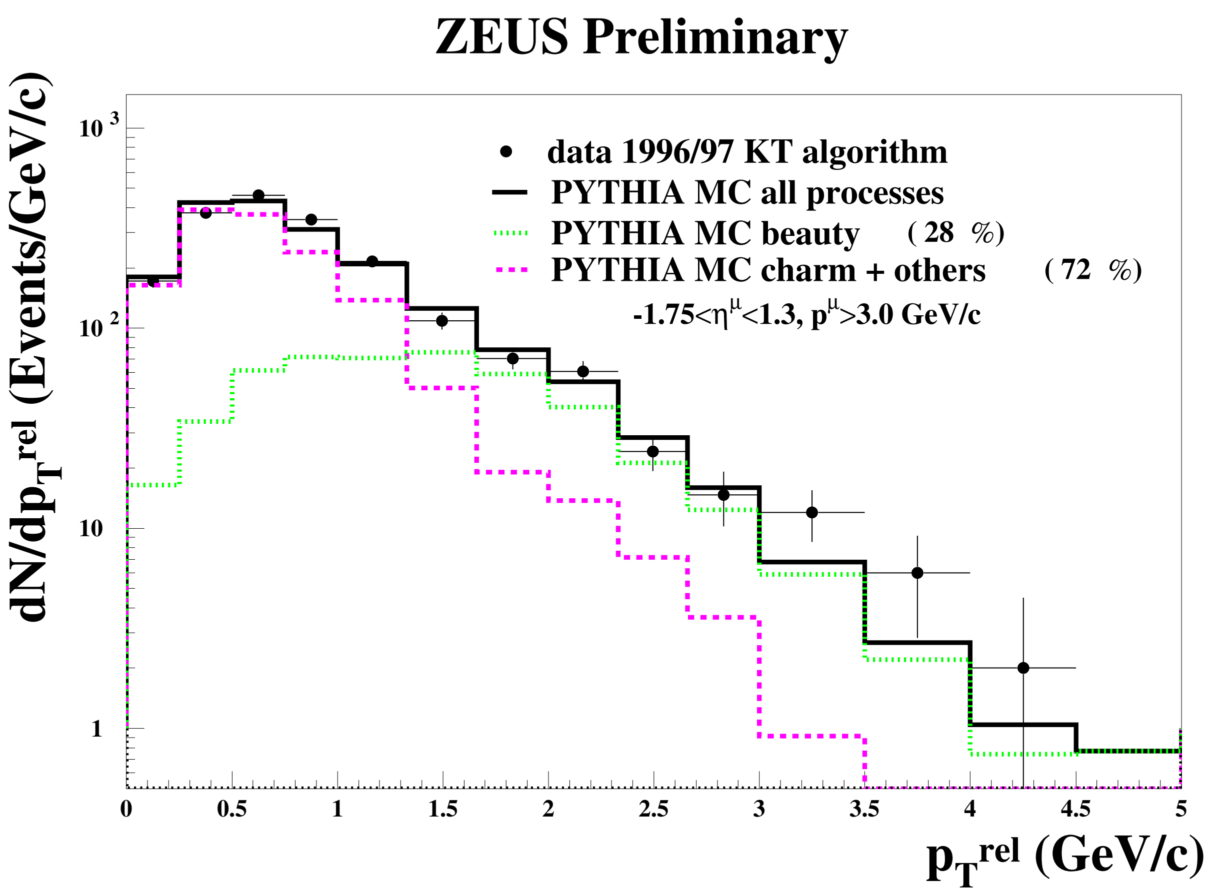


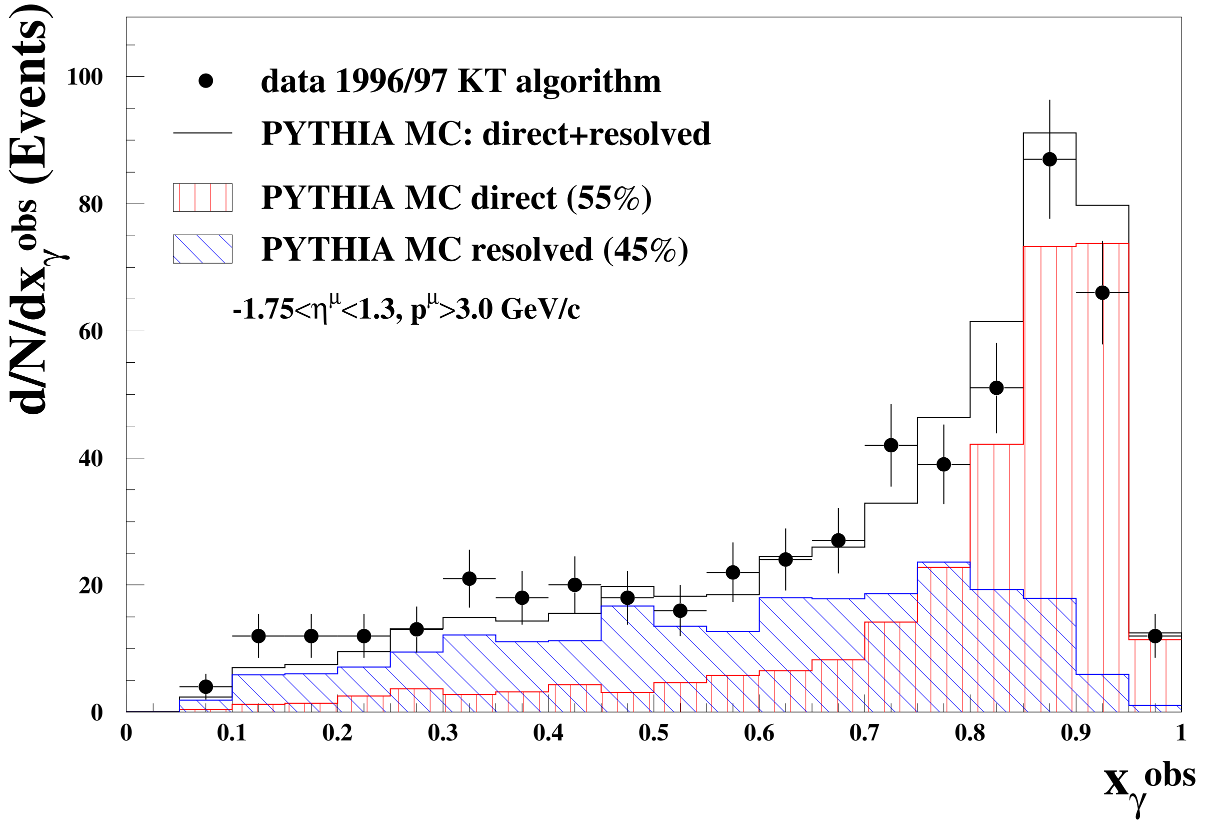


- Large fraction of resolved process

Open Beauty in Photoproduction (Central and Rear Regions)

$E_T^{\rm jet1} > 7.0$ GeV, $E_T^{\rm jet2} > 6.0$ GeV $\quad \eta^{\rm jet} < 2.4$





Measured visible Open Beauty Cross sections $Q^2 < 1$ GeV^2

H1 ($\mathcal{L} = 6.6$ pb^{-1}): $0.1 < y < 0.8$

Central muon $p_\perp^\mu > 2$ GeV $35^\circ < \theta^\mu < 130^\circ$

$\sigma_{b\bar{b}}^{\text{vis}}(ep \to \mu X) = 176 \pm 16^{+26}_{-17}$ **pb**

AROMA (38 pb), Fixed Order NLO (104 pb)

ZEUS ($\mathcal{L} = 37$ pb^{-1}) $0.2 < y < 0.8$

$E_T^{\text{jet1}} > 7.0$ GeV, $E_T^{\text{jet2}} > 6.0$ GeV $\eta^{\text{jet}} < 2.4$

Central electron $\left|\eta^{e^-}\right| < 1.1$ $p_T^{e^-} \geq 1.6$ GeV

$f_b = 20 \pm 6^{+12}_{-7}\%$

$\sigma_{b\bar{b}}^{\text{vis}}(e^+p \to e^- + \textbf{dijet} + X) = 39 \pm 11^{+23}_{-16}$ **pb**

Herwig **(9.3 pb)**, Pythia **(22 pb)**

Central-Rear muon $-1.75 < \eta^\mu < 1.3$ $p^\mu \geq 3$ GeV

$f_b = 28 \pm 5\%$

$\sigma_{b\bar{b}}^{\text{vis}}(e^+p \to \mu + \textbf{dijet} + X) = 36.4 \pm 5.2^{+10.4}_{-9.1}$ **pb**

Herwig **(12 pb)**, Pythia **(30 pb)**

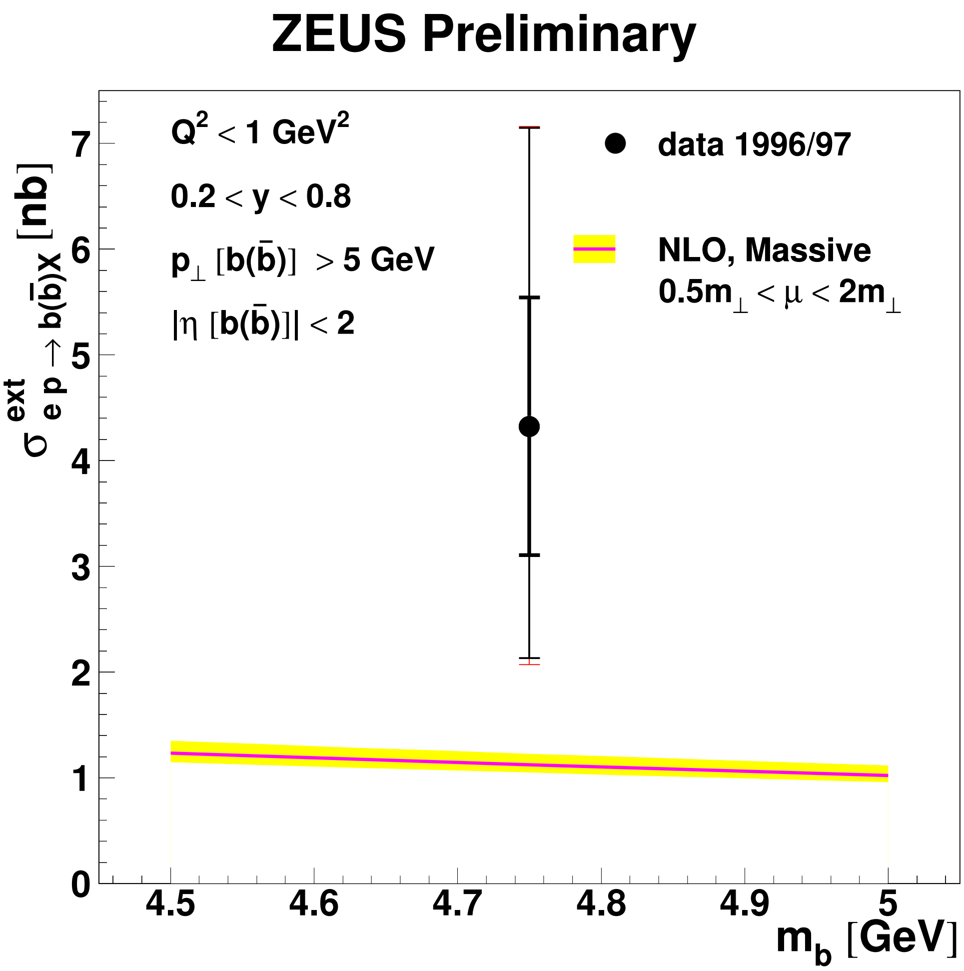
Forward muon $1.4 < \eta^\mu < 2.4$ $p_T^\mu \geq 1.5$ GeV

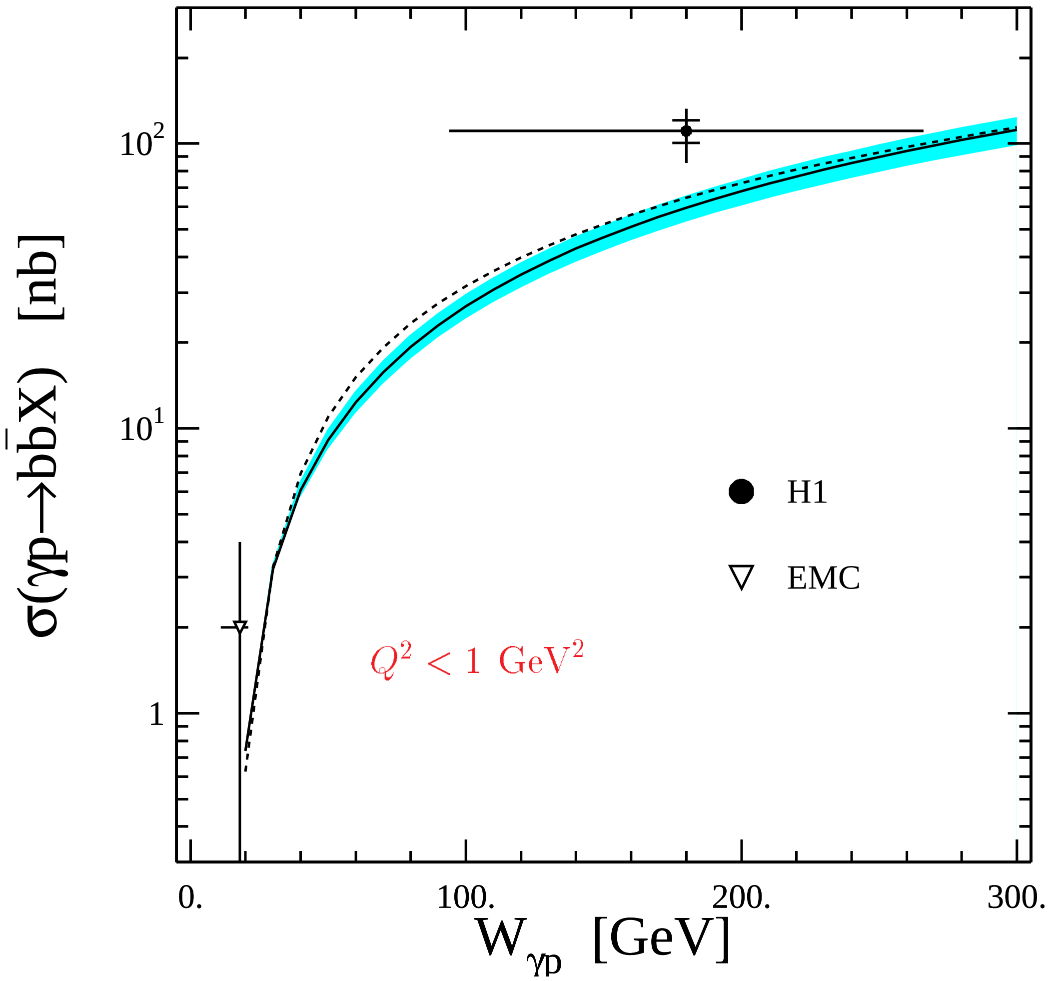
$f_b = 22 \pm 7\%$

$\sigma_{b\bar{b}}^{\text{vis}}(e^+p \to \mu + \textbf{dijt} + X) = 20.5 \pm 6.5^{+6.3}_{-5.7}$ **pb**

Herwig **(4.1 pb)**, Pythia **(9.6 pb)**

Open Beauty photoproduction vs NLO





Summary and outlook

- Open Charm Deep Inelastic Scattering
  - NLO calculations describe cross sections reasonably
  - $F_2^{c\bar{c}}$ up to 30% of F_2 at large Q^2 and small x
- Open Charm Photoproduction
  - NLO calculations are generally below the data, particularly, in the forward (proton) direction
  - The BKL model needs large color octet contribution to describe the forward (proton) region
  - large resolved component is needed (45%) to describe the observed $x_\gamma{}^{\mathrm{OBS}}$ distribution HERA has enlightened the need to consider such contributions throught studies carried on with charm enriched samples
- Open Beauty Production
  - Semi-leptonic b decays ($b \to e^-$ and $\mu^\pm$)
  - NLO and LO MC predictions underestimates the data
- In the year 2000
  - Accelerator upgrade $\mathcal{L} \sim 1$ fb^{-1} before 2005;
  - Experiments upgrades silicon vertex detector
- A lot of new physics results yet to come