D^* and D_s Production at HERA
and comparison with NLO

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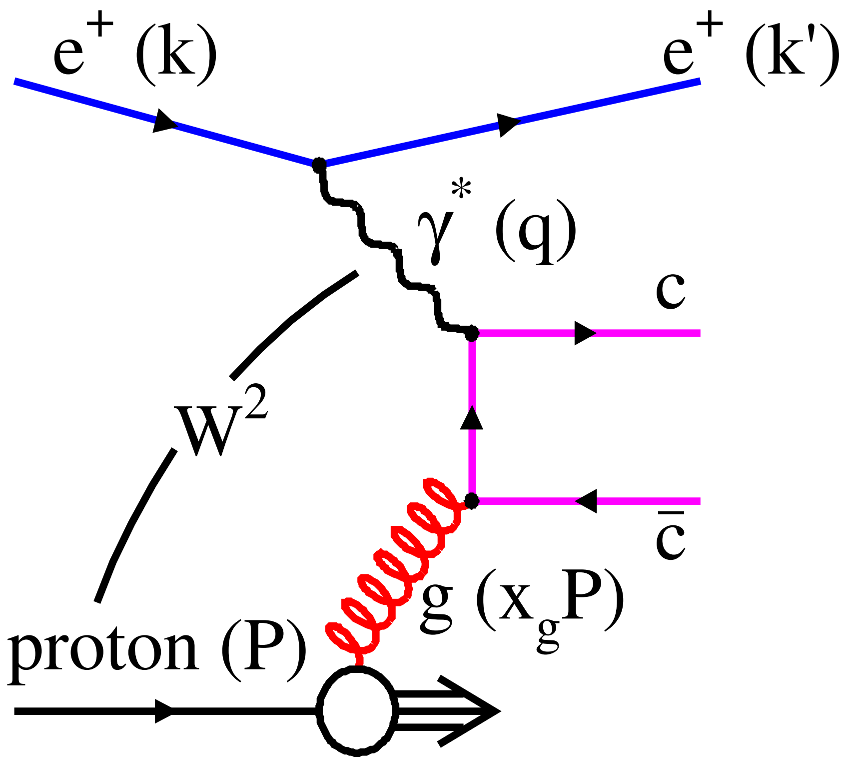
Charm Production Mechanisms

direct γ^* : $\gamma^* g \rightarrow c\bar{c}$ **(BGF)**



Photoproduction	$Q^2 \simeq 0\, GeV^2$
DIS	$Q^2 > 1\, GeV^2$

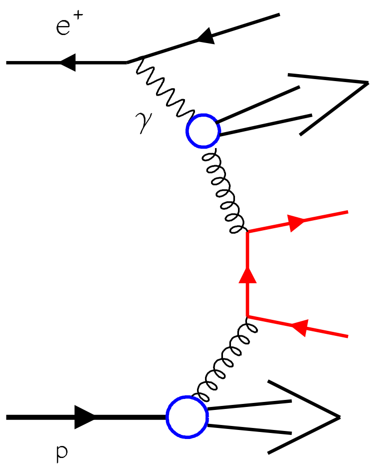
The entire photon momentum participates in hard interaction: $x_\gamma = 1$

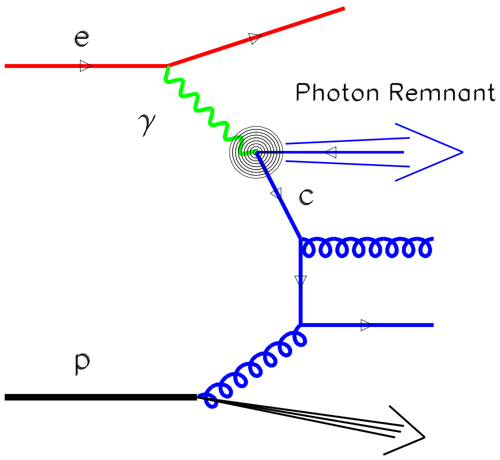
BGF dominates DIS charm production at HERA

Charm Production Mechanisms

In Photoproduction one can also expect
resolved γ : $gg \to c\bar{c}$, $cg \to cg$

Charm excitation





Only the fraction of photon momentum participates in hard interaction: $x_\gamma < 1$

This is a Leading Order picture

In all orders one can define x_γ^{OBS}, a fraction of the photon momentum participating in the dijet production :

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

From c-quark to hadron

What is the probability that a charm quark fragments into some hadron ?

recent compilation (hep-ex/9912064) of

CLEO, ARGUS,

ALEPH, DELPHI and OPAL data:

$$f(c \to D^{*+}) = 0.235 \pm 0.007 \pm 0.007(br.)$$

$$f(c \to D_s^+) = 0.101 \pm 0.009 \pm 0.025(br.)$$
$$f(c \to D^0) = 0.549 \pm 0.023 \pm 0.013(br.)$$
$$f(c \to D^+) = 0.232 \pm 0.010 \pm 0.015(br.)$$
$$f(c \to \Lambda_c^+) = 0.076 \pm 0.007 \pm 0.020(br.)$$

And $f(c \to D^0, D^+, D_s^+, \Lambda_c^+) \approx 96\,\%$
leaving a room for the fragmentation of a charm quark to Ξ_c **and** Ω_c

Charm Tagging: D^*

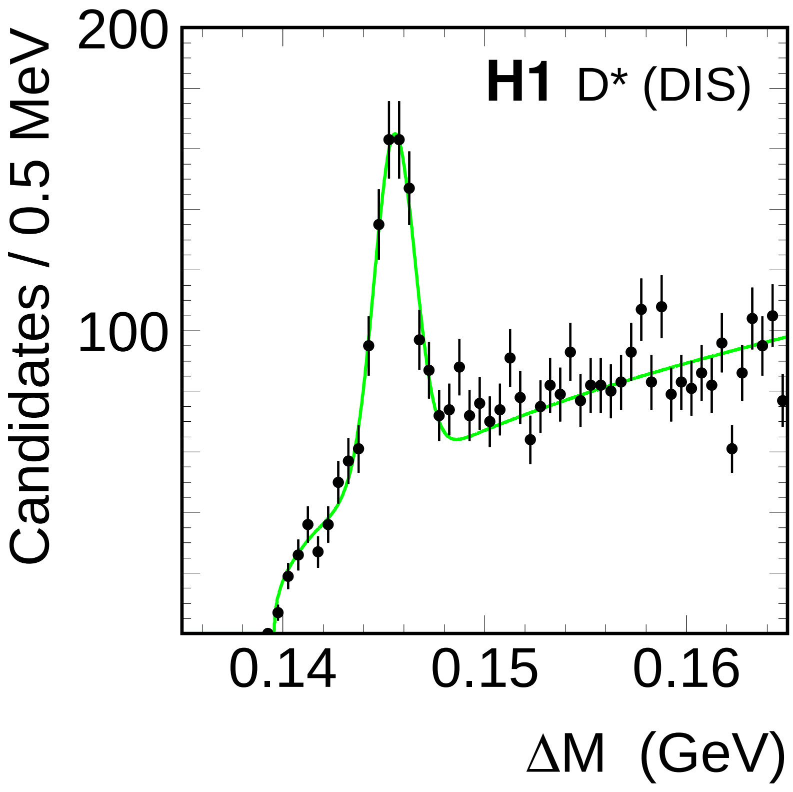
$D^{*\pm}(2010)$ Reconstruction :

$D^* \to D^0\pi_s \to (K^-\pi^+)\pi_s$ $\quad$ $(\ BR = 0.0263 \pm 0.0008\ )$

$D^* \to D^0\pi_s \to (K^-\pi^+\pi^+\pi^-)\pi_s$ $\quad$ $(\ BR = 0.052 \pm 0.003\ )$

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

Clean signal in ΔM !



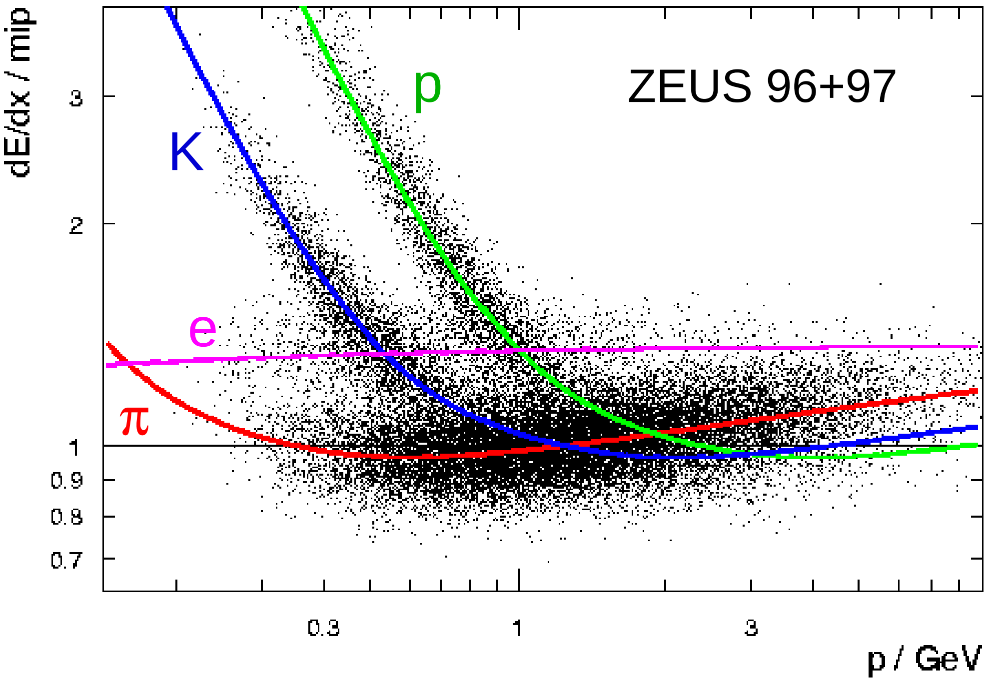
Signal is extracted using either fit or subtraction (wrong-charge or side-band)

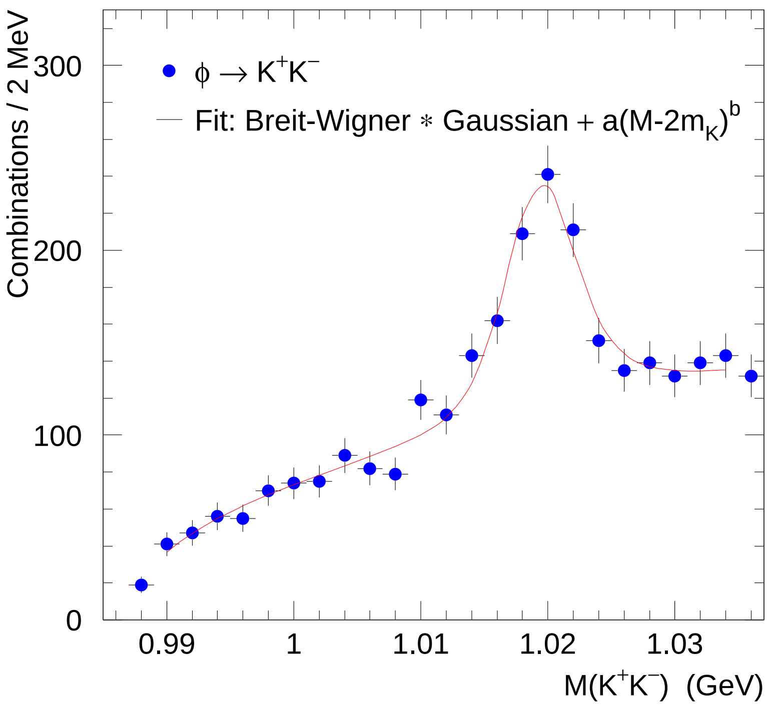
Charm Tagging: D_s

$D_s^{\pm}$ Reconstruction :

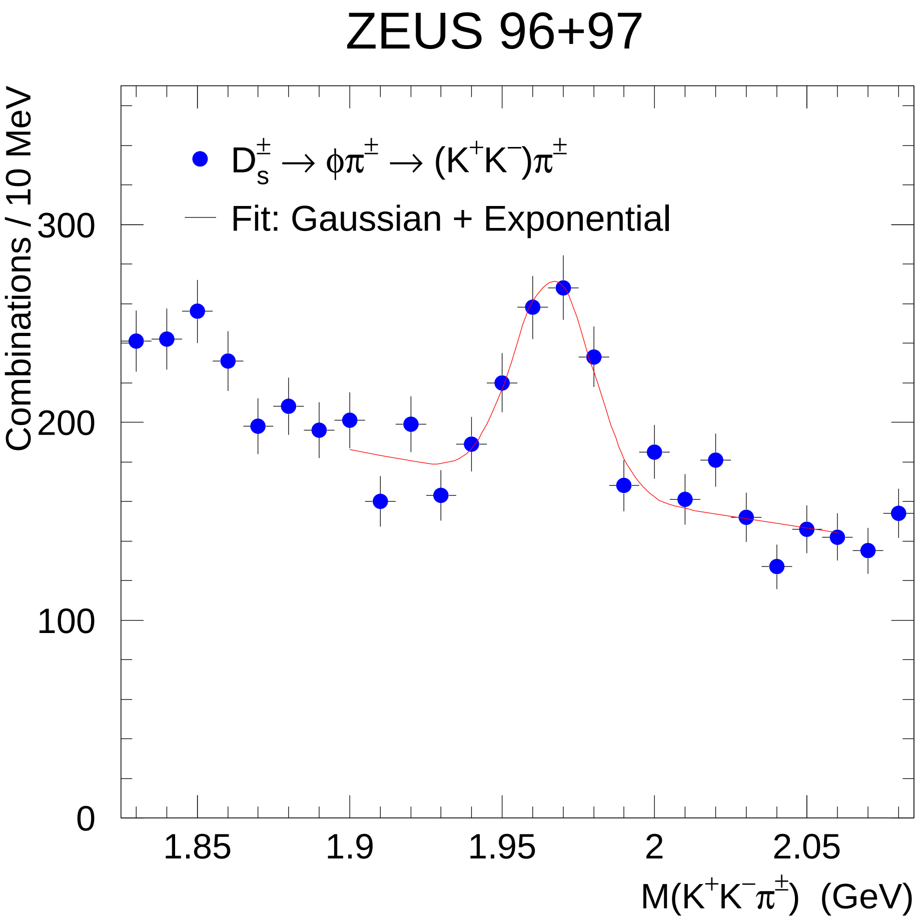
$D_s \to \phi\pi \to (K^- K^+)\pi$ $\quad\quad$ $(\ BR = 0.0177 \pm 0.0044 \ )$

Partial particle identification:





Charm Tagging: D_s



in the kinematic range:

$$Q^2 < 1\,\mathbf{GeV}^2,\ 130\,\mathbf{GeV} < W_{\gamma p} < 280\,\mathbf{GeV}$$

$$p_{\perp}(D_s, D^*) > 3.0\,\mathbf{GeV},\ -1.5 < \eta(D_s, D^*) < 1.5$$

$$\sigma_{ep\to D_s X} = 3.79 \pm 0.59(stat.)^{+0.26}_{-0.46}(syst.) \pm 0.94(br.) \quad nb$$

$$\sigma_{ep\to D_s X}/\sigma_{ep\to D^* X} = 0.41 \pm 0.07(stat.)^{+0.03}_{-0.05}(syst.) \pm 0.10(br.)$$

from this ratio using LUND model (PYTHIA), the strangeness-suppression factor:

$$\gamma_s = 0.27 \pm 0.05 \pm 0.07(br.)$$

Universality of Charm Fragmentation

Now the ratio $\sigma_{ep \to D_s X} / \sigma_{ep \to D^* X}$ and γ_s can be compared with the ratios $f(c \to D_s^+) \ / f(c \to D^{*+})$ and $2f(c \to D_s^+)/[f(c \to D^+) + f(c \to D^0)]$ measured in $e+e-$ annihilation:

	$e+p$	$e+e-$
D_s/D^*	$0.41 \pm 0.07^{+0.03}_{-0.05}$	0.43 ± 0.04
γ_s	0.27 ± 0.05	0.26 ± 0.03

Uncertainty in $BR(D_s \to \phi\pi)$ can be ignored in the comparison!

The comparison tends to support universality of charm fragmentation

Fragmentation parameters obtained with data on charm production in $e+e-$ annihilation can be used as input to pQCD calculations for $e+p$ case!

NLO QCD Calculations

Fixed-order ("massive") approach:

$n_f = 3$: (u, d, s) are active flavors in p and γ
no explicit charm excitation component
charm is only produced dynamically
not valid for $Q, p_\perp \gg m_c$

DIS : HVQDIS, B. Harris and J. Smith
Photoproduction : FMNR, S. Frixione et al.

Resummed ("massless") approach:

$n_f = 4$: (u, d, s, c) are active flavors
explicit charm excitation component
large logarithms $(\frac{Q}{m_c}, \frac{p_\perp}{m_c})$ are resummed
valid only for $Q, p_\perp \gg m_c$

Photoproduction : B. Kniehl et al.
M. Cacciari et al.

And matched/merged calculations in progress (see theoretical talks).

Non-perturbative Input

Fragmentation fractions :

$$f(c \to D^{*+}) = 0.235 \pm 0.007$$
$$f(c \to D_s^+) = 0.101 \pm 0.009$$

Peterson Fragmentation parameter:

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

Resummed approach (LEP data fit):

Kniehl et al. $\epsilon(D^*) = 0.116$

Cacciari et al. $\epsilon(D^*) = 0.020$

Fixed-order approach (P. Nason and C. Oleari):

$\epsilon(D^*) = 0.035$ ARGUS data $\Leftarrow$ Recommended !

What about $\epsilon(D_s)$?

Naive expectations: $\epsilon(D_s) \approx \epsilon(D^*)(\frac{m_s}{m_{u,d}})^2 \approx 0.085$

However recent NLO fit of C. Oleari to ARGUS D_s data: $\epsilon(D_s) \approx \epsilon(D^*) \approx 0.035$

Charm in DIS vs NLO

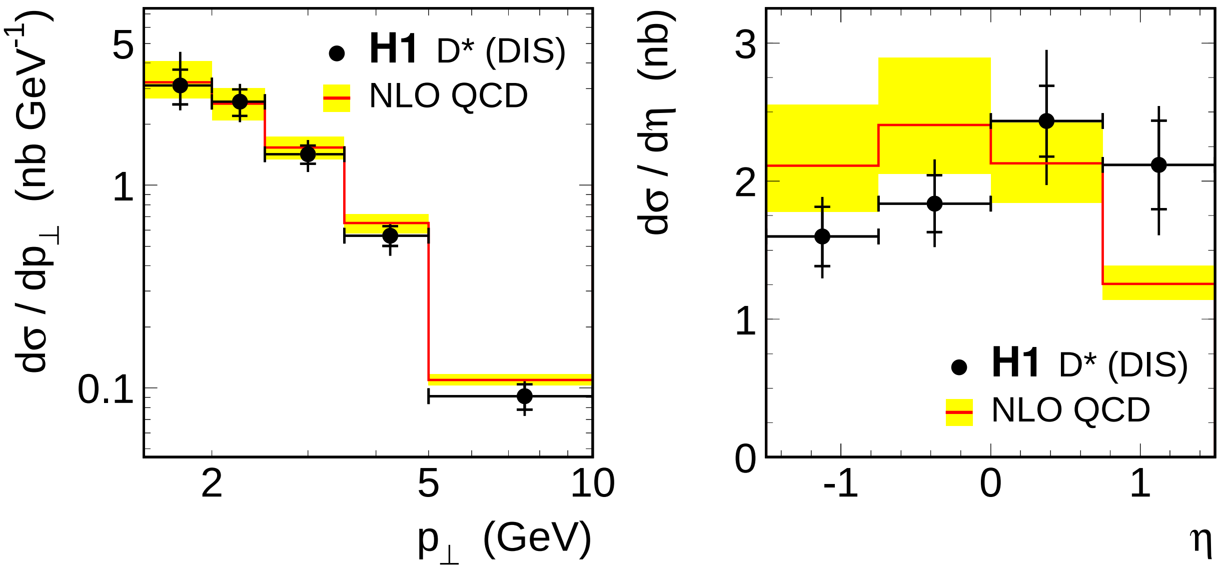
DATA: H1 D^* in DIS

$2 < Q^2 < 100\,GeV^2$, $0.05 < y < 0.7$

NLO : HVQDIS, CTEQ4F3

$m_c = 1.5\,GeV,\ \mu_F = \mu_R = \sqrt{4m_c^2 + Q^2}$

band: $m_c = 1.3 \div 1.7\,GeV$



Reasonable agreement in absolute normalization and in $p_\perp(D^*)$ shape

$\eta(D^*)$ shape is not described

Charm in DIS vs NLO

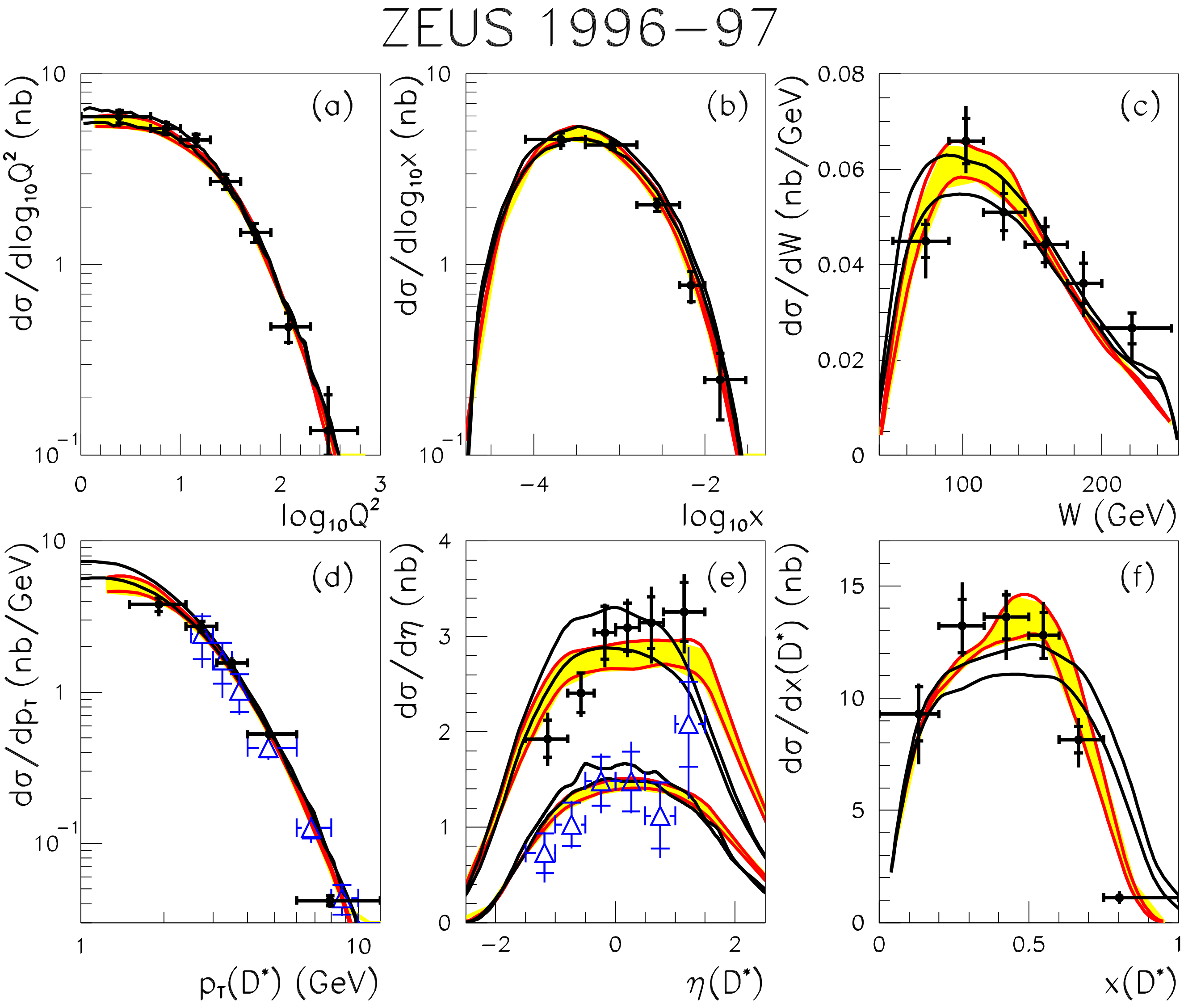
DATA: ZEUS D^* in DIS (two decay modes)

$1 < Q^2 < 600\,GeV^2$, $0.02 < y < 0.7$

$x(D^*)$ - energy fraction in $\gamma^* p$ system.

NLO : HVQDIS, ZEUS NLO part. distr.

$\mu_F = \mu_R = \sqrt{4m_c^2 + Q^2}$, bands: $m_c = 1.3 \div 1.5\,GeV$



open band: Peterson fragmentation

shaded band: RAPGAP fragmentation

(two dimensional $(p_\perp, \eta)$ projection from c-quark to D^*)

$\eta(D^*)$ and $x(D^*)$ $\Longleftrightarrow$ "beam-drag effect" !?

Charm in Photoproduction vs NLO

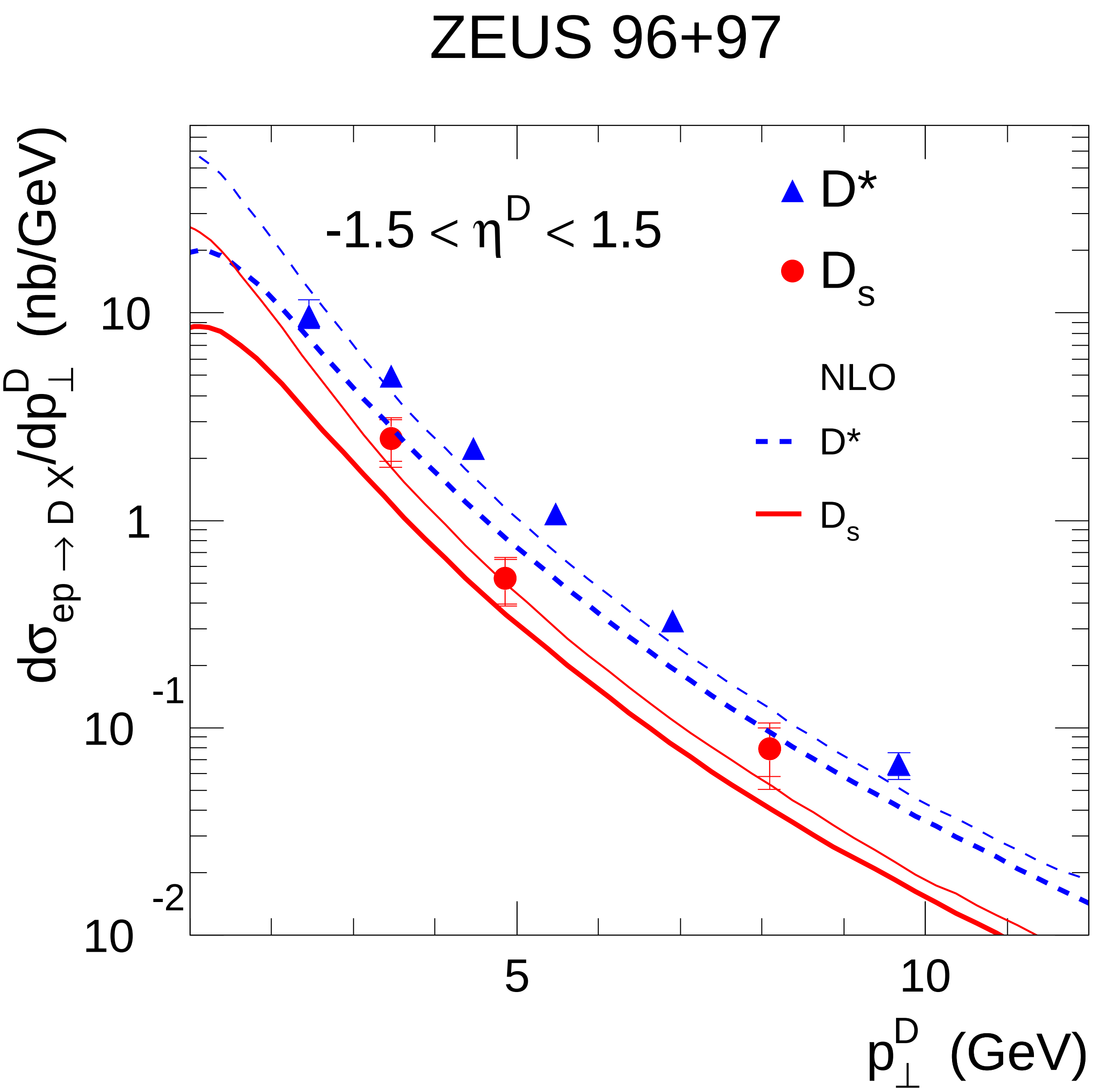
DATA: ZEUS D^* and D_s in PHP

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

NLO : FMNR, MRSG and GRV-G HO

thick curves: $m_c = 1.5\,GeV$, $\mu_R = m_\perp, \mu_F = 2m_\perp$

thin curves: $m_c = 1.2$ and $\mu_R = 0.5m_\perp$ $\leftarrow$ extreme ?!



nominal: underestimate x-sections $\approx$ 1.8 times

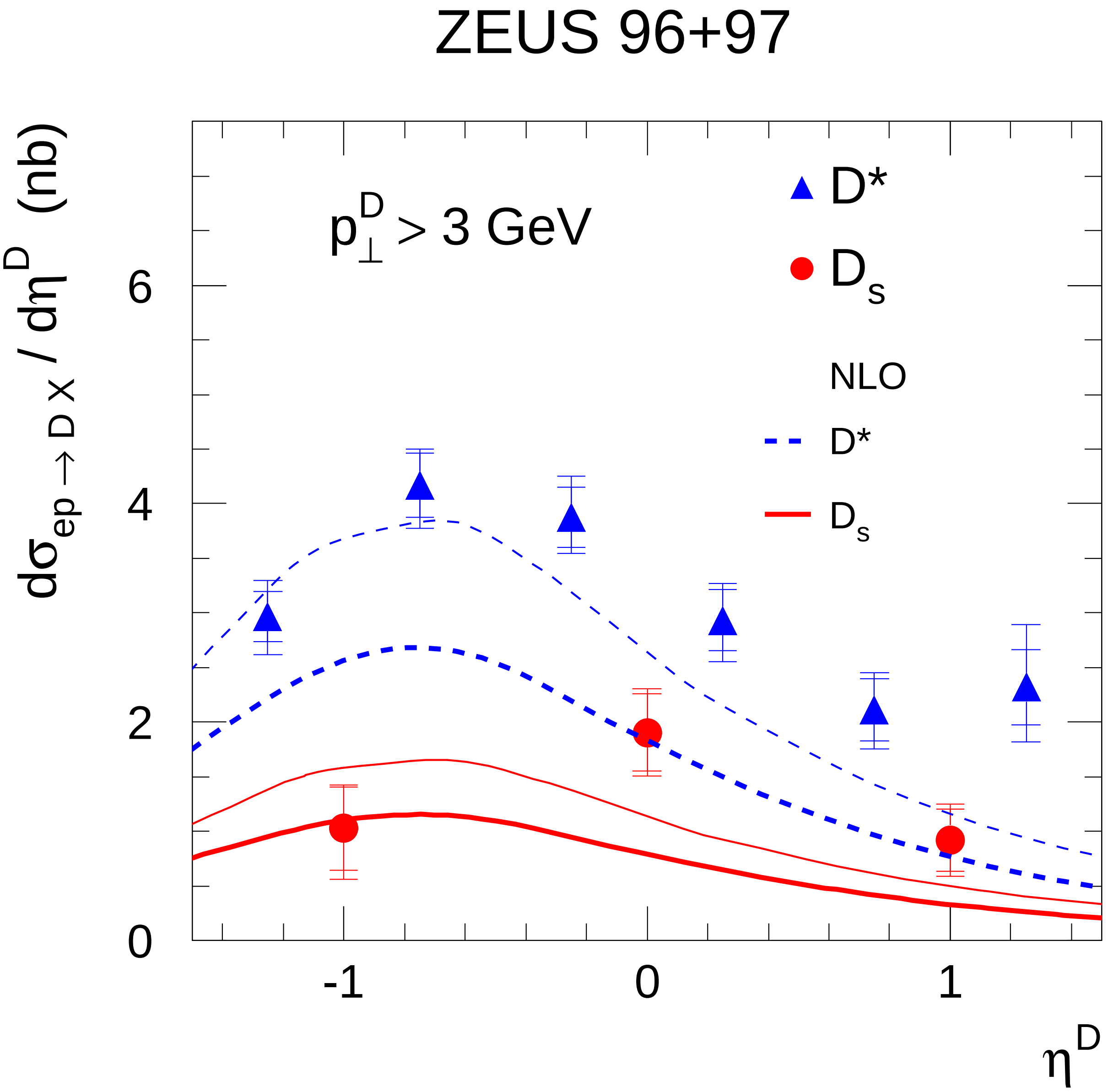
extreme: still below the data

$p_\perp$ shape ? not really correct (see D^* points)

Charm in Photoproduction vs NLO

DATA: ZEUS D^* and D_s in PHP
$Q^2 < 1\,GeV^2$, $130 < W < 280\,GeV$

NLO : FMNR, MRSG and GRV-G HO
thick curves: $m_c = 1.5\,GeV$, $\mu_R = m_\perp, \mu_F = 2m_\perp$
thin curves: $m_c = 1.2$ and $\mu_R = 0.5m_\perp$ $\leftarrow$ **extreme ?!**



disagreement is larger in forward (proton) direction $\Longleftrightarrow$ "beam-drag effect" ?

Charm in Photoproduction vs NLO

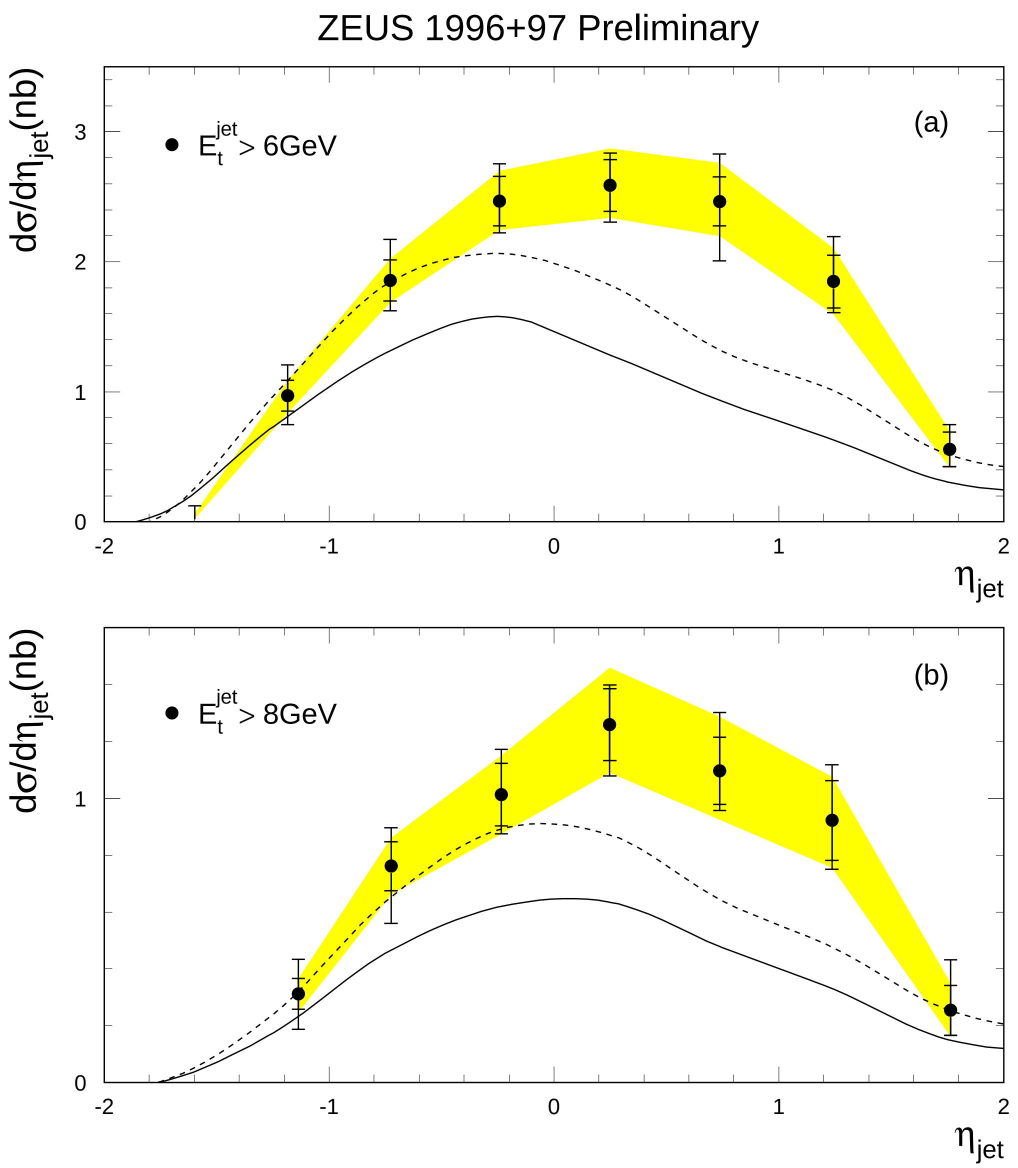
DATA: ZEUS D^* and Jet(s) in final state

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

NLO : FMNR, MRSG and GRV-G HO

solid curves: $m_c = 1.5\,GeV$, $\mu_R = m_\perp, \mu_F = 2m_\perp$

dashed curves: $m_c = 1.2$ and $\mu_R = 0.5m_\perp$ $\leftarrow$ extreme ?!

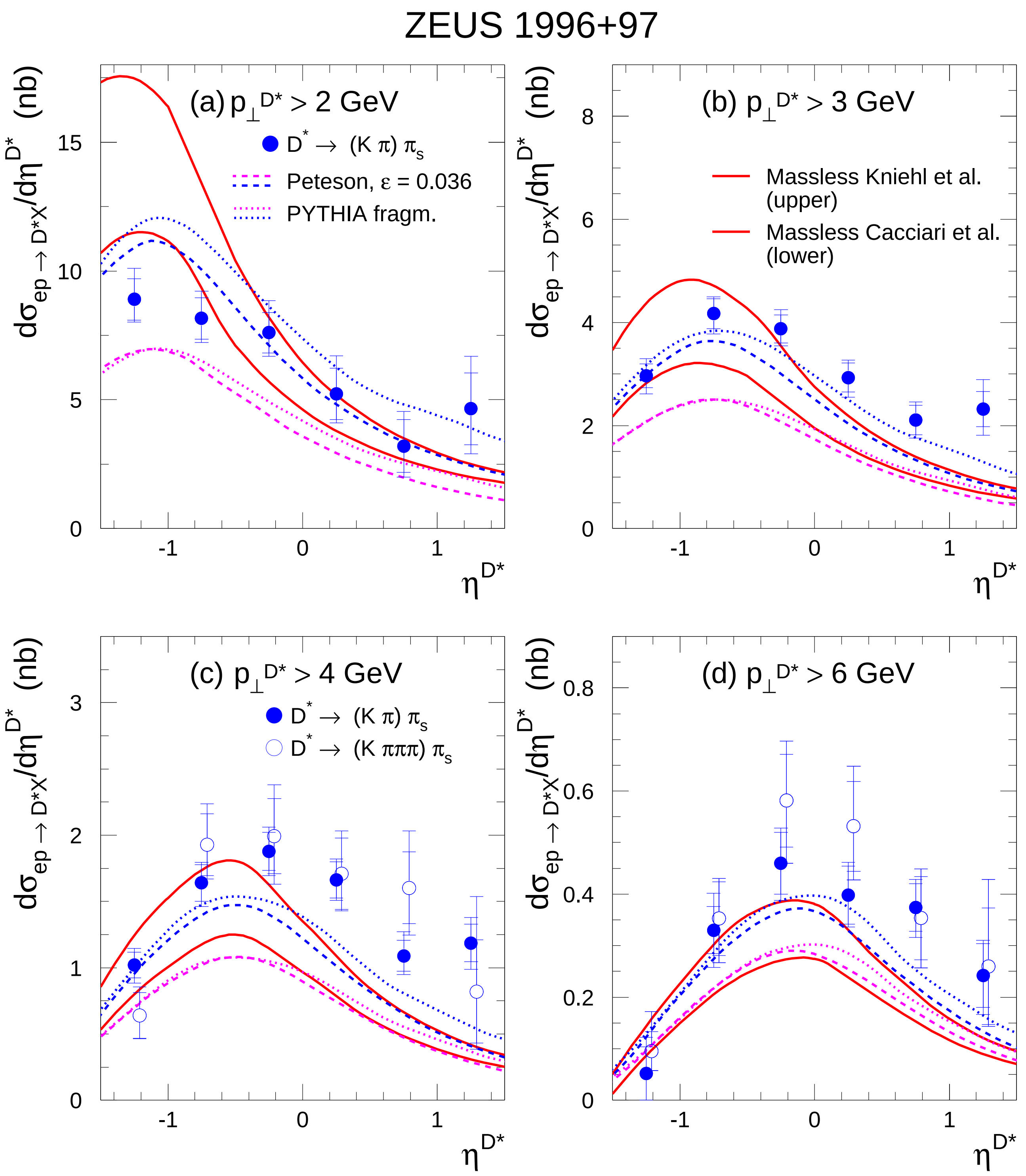


η_{jet} distribution is rather insensitive to fragmentation

similar disagreement as for inclusive D^*

Charm in Photoproduction vs NLO

DATA: ZEUS D^* in PHP (two decay modes)



PYTHIA fragmentation (projection in η) helps but does not fix the problems

Two resummed calculations are very different !?

(BTW, is $p_\perp$ large enough ?)

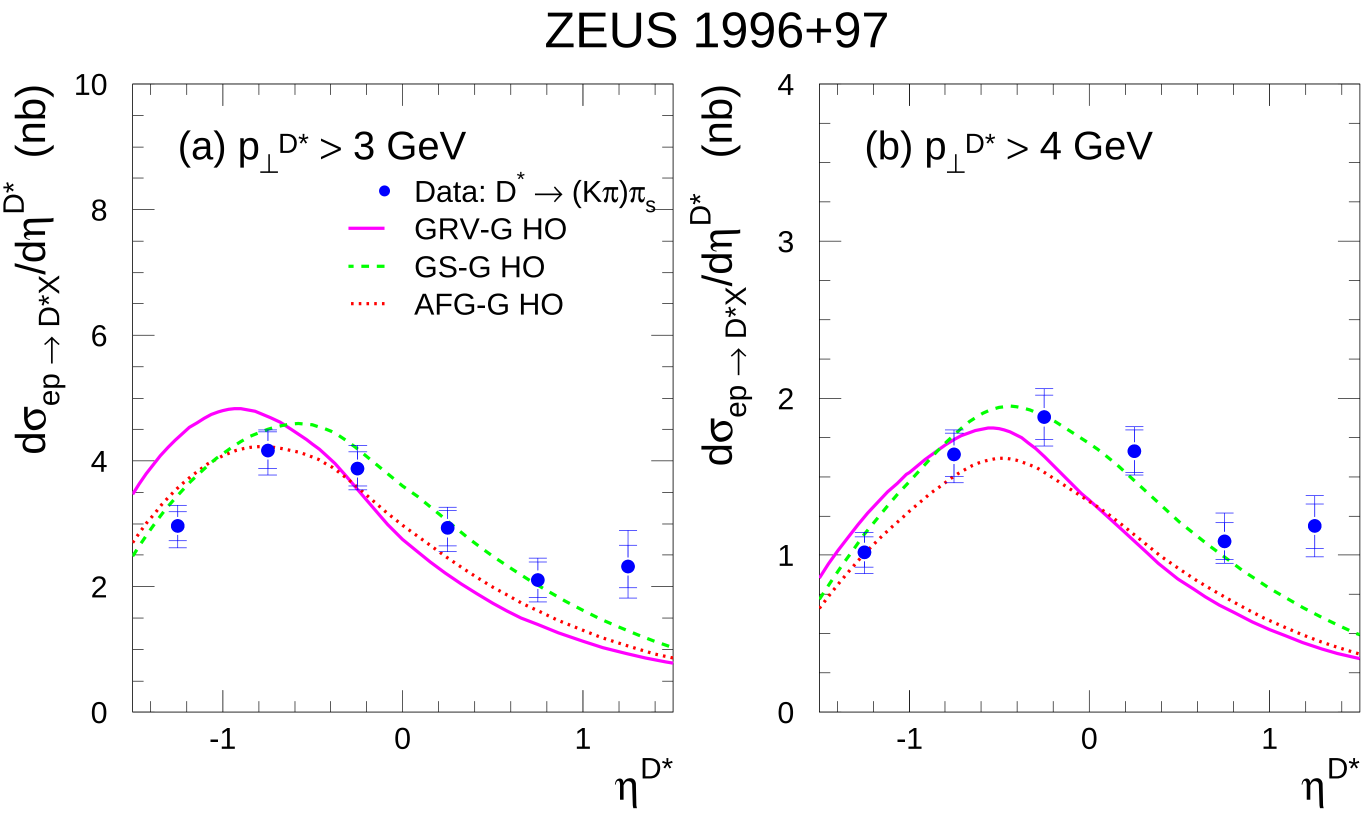
Charm in Photoproduction vs NLO

DATA: ZEUS D^* in PHP

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

NLO : Kniehl et al., CTEQ4M

$m_c = 1.5\,GeV$, $\mu_R = m_\perp$, $\mu_F = 2m_\perp$



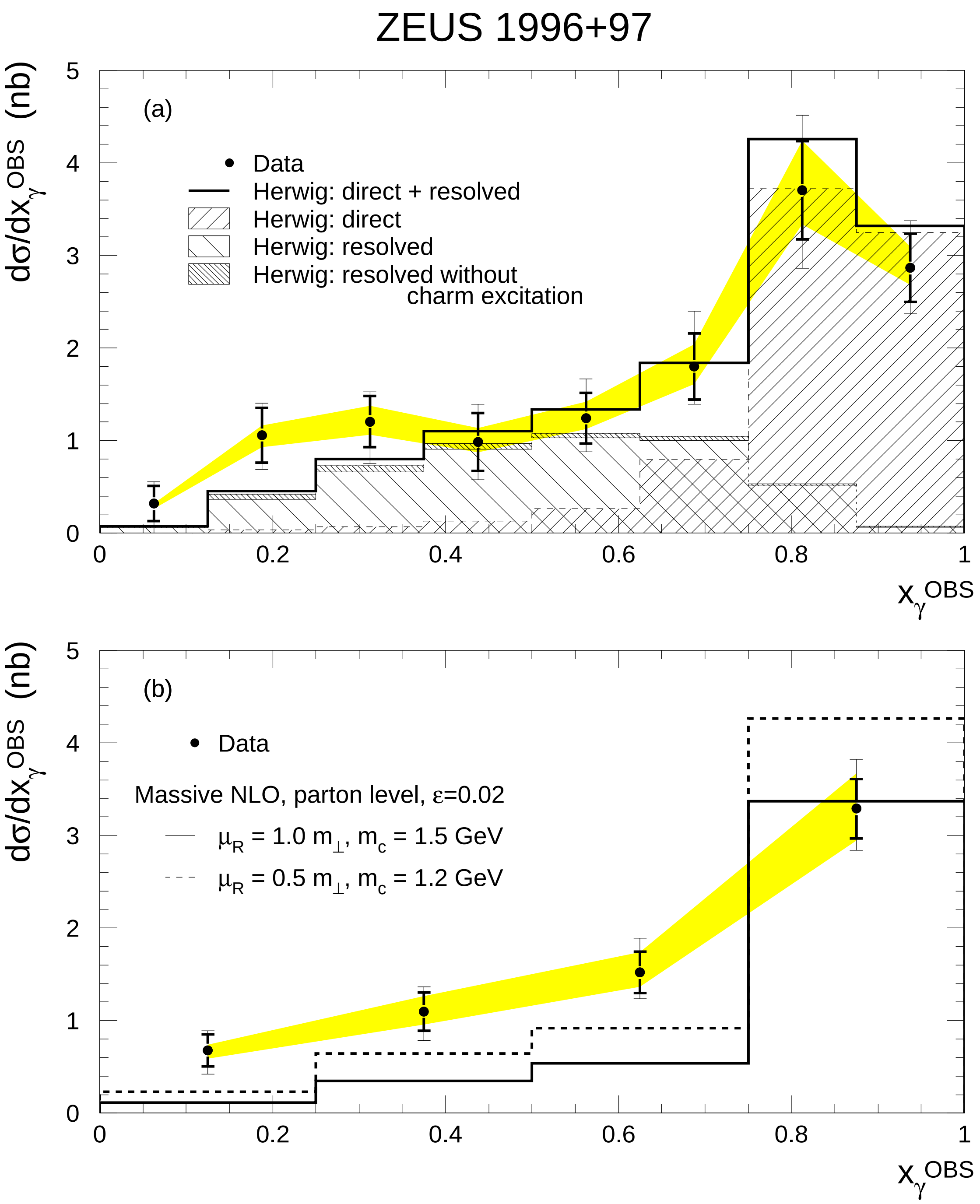
Predictions with GS-G HO are close to data !
However, $c = u$ in this photon SF !?

Can light contain the same amounts of c and u already at $m_\perp \approx 4.5\,GeV$?

BTW, $\Lambda_5^\gamma \neq \Lambda_5^p$. Can we trust hadronic (resolved) component calculations with Λ_5^p ?

Charm in Photoproduction vs NLO

DATA: ZEUS D^* and two jets in final state
NLO : FMNR, MRSG and GRV-G HO



LO charm excitation in photon (≈ 45 %) !
Fixed-order NLO are below data at low x_γ^{OBS}
Where are resummed predictions ?

Summary

- HERA has already provided wide spectrum of D^* and first D_s results.
- D_s/D^* cross-section ratio and γ_s are in good agreement with those obtained in charm production in $e+e-$ annihilation.
- D^* in DIS ($Q^2 > 1\,GeV^2$) cross sections are reasonably well described by fixed-order NLO calculations in absolute normalization.
- Differential D^* in DIS cross sections in $\eta(D^*)$ and $x(D^*)$ are not described if Peterson fragmentation is used. They can be described using LO Monte Carlo fragmentation.
- D^* and D_s photoproduction ($Q^2 < 1\,GeV^2$) cross sections are underestimated by fixed-order NLO calculations. Shapes of differential cross sections ($p_\perp$ and η) are also not described. LO Monte Carlo fragmentation improves agreement but does not fix the problems.
- x_γ^{OBS} distribution indicates large LO resolved (charm excitation) component in D^* photoproduction. Fixed-order NLO are below the data at low x_γ^{OBS} values where resolved photon contribution is significant.
- Resummed NLO calculations from Kniehl et al. with GRV-G HO are close to data. However, $c = u$ in this photon SF. There are still no resummed NLO calculations for x_γ^{OBS}.

Two shopping lists

Experimental shopping list:

- **Further fragmentation studies. HERA measurements for P_v, D^{**}, $f(c \to D^{*+})$.**
- **Cross section measurements in wider kinematic ranges (Q^2, $p_\perp(D^*)$, $\eta(D^*)$, $W_{\gamma p}$).**
- **Measurements with smaller statistical (0.1 fb^{-1} is already available) and systematic errors.**
- **Double tagged measurements.**

Theoretical shopping list:

- **Resummed calculations for x_γ^{OBS}.**
- **Further developments of merged/matched NLO calculations.**
- **Inclusion of "beam-drag effect" in NLO codes. NLO Monte Carlo.**
- **NNLO calculations for charm at HERA.**

Can the program be realized in, say, one year ?