Heavy Flavor in Photoproduction at HERA

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O U T L I N E :

Production Mechanisms

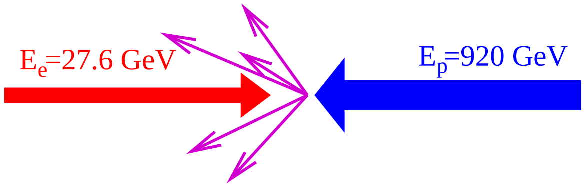
pQCD Predictions

Universality of Charm Fragmentation

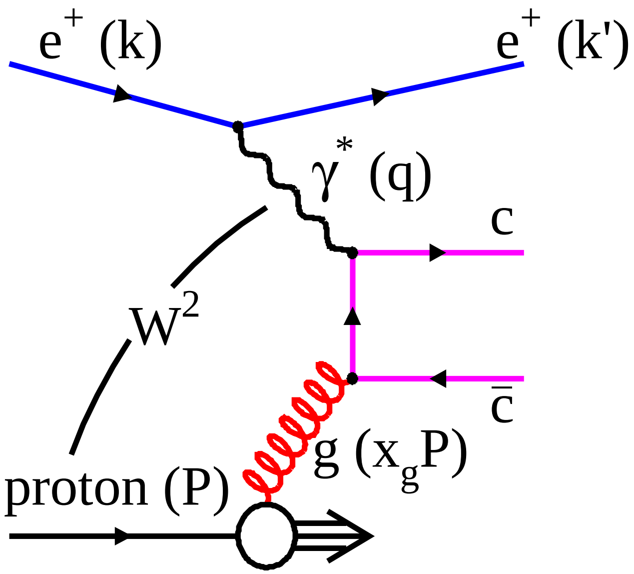
Charm and Beauty in Photoproduction vs pQCD

Summary and Outlook

Heavy Flavor Photoproduction Mechanisms at HERA



1992-1997 $E_p = 820\,\mathbf{GeV}$ $\sqrt{s} = 300\,\mathbf{GeV}$
1998-2000 $E_p = 920\,\mathbf{GeV}$ $\sqrt{s} = 318\,\mathbf{GeV}$



$$s = (P+k)^2$$

$$Q^2 = -q^2 = -(k-k')^2$$

Photoproduction $Q^2 \simeq 0\,GeV^2$

$$W^2 = (P+q)^2$$

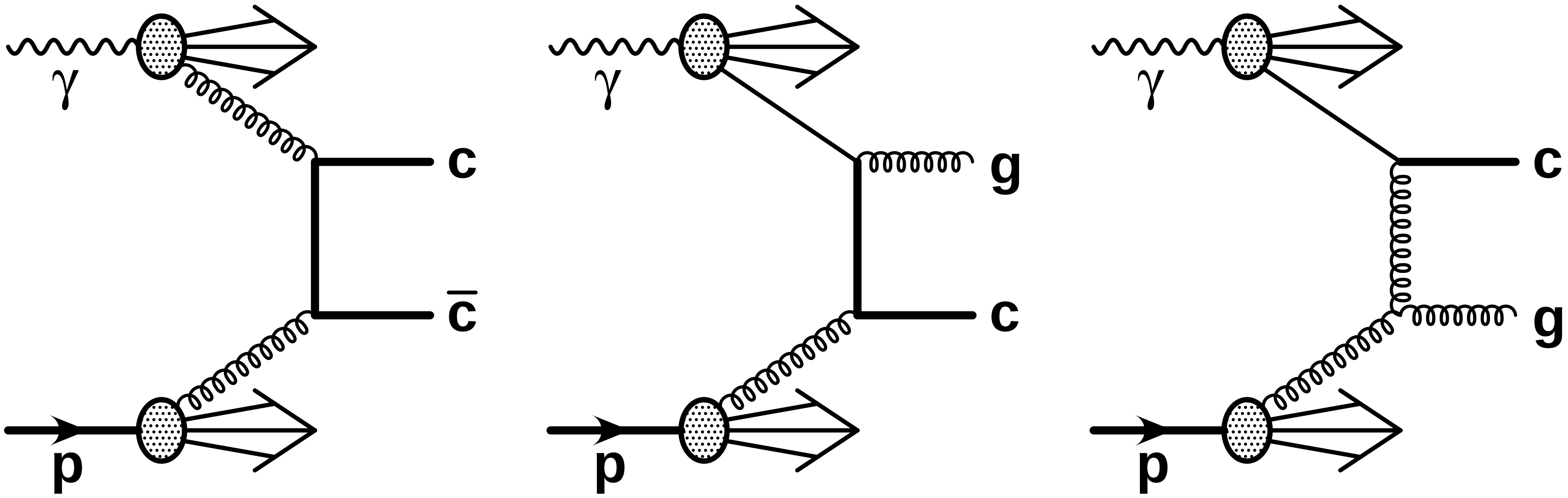
$$y = \frac{q \cdot P}{e \cdot P} \simeq \frac{W^2}{s}$$

direct γ : $\gamma g \to Q\bar{Q}$, Photon Gluon Fusion $\longleftarrow$ PGF

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

Heavy Flavor Photoproduction Mechanisms at HERA

Resolved γ processes: $x_\gamma < 1$



$gg \rightarrow Q\bar{Q}$

$Qg \rightarrow Qg$, Q excit. (q propagator)

$Qg \rightarrow Qg$, Q excit. (g propagator)

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 :

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

Perturbative QCD Calculations

Monte Carlo with LO matrix elements and parton showering :

AROMA (only direct γ)

HERWIG (direct and resolved)

PYTHIA (direct and resolved)

CASCADE (only PGF but with CCFM gluon)

NLO QCD calculations :

Fixed-order ("massive") approach:

Charm : $n_f = 3$: (u, d, s) are active flavors in p and γ
Beauty : $n_f = 4$: (u, d, s, c) are active flavors in p and γ

no explicit charm (beauty) excitation component
charm (beauty) is only produced dynamically

not valid for $p_\perp \gg m_Q$ (large logarithms $\frac{p_\perp}{m_Q}$)

Photoproduction : FMNR, S. Frixione et al.

Perturbative QCD Calculations

Resummed ("massless") approach:

Charm : $n_f = 4$: (u, d, s, c) are active flavors in p and γ
Beauty : $n_f = 5$: (u, d, s, c, b) are active flavors in p and γ

explicit charm (beauty) excitation component
large logarithms $(\frac{p_\perp}{m_Q})$ are resummed

valid only for $p_\perp \gg m_Q$

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

And matched/merged calculations (wait S. Frixione's talk)

From c(b)-quark to final state hadron (lepton)

Fragmentation fractions :

$$f(c \to D^{*+}) \;=\; 0.235 \pm 0.007 \pm 0.007(br.) \quad \text{(hep-ex/9912064)}$$
$$f(c \to D_s^{+}) \;=\; 0.101 \pm 0.009 \pm 0.025(br.) \quad \text{(hep-ex/9912064)}$$
$$f(b \to e^{-}) \;=\; 0.1073 \pm 0.0035 \;, \ldots \quad \text{(PDG)}$$

Fragmentation Functions :

Charm : Peterson's FF : $D_c(x) = N \frac{x(1-x)^2}{[(1-x)^2+\epsilon x]^2}$ $\quad x = \frac{p_{D^*}}{p_c}$

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

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

Resummed approach (LEP data fit):

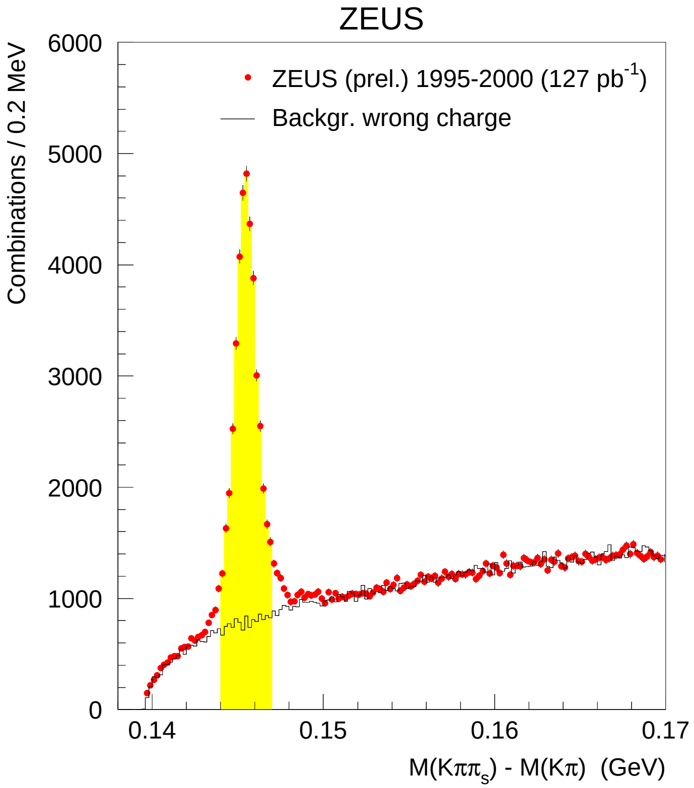
Kniehl et al. $\epsilon(D^*) = 0.116$

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

Beauty : $\epsilon_b \approx \epsilon_c \cdot (m_c/m_b)^2 \approx 0.0035$ for $b \to B$

and MC parameterization(s) for $B \to l$

Charm Tagging and Universality of Charm Fragmentation



$D^{*+} \to D^0 \pi_s^+ \to (K^- \pi^+) \pi_s^+ \;\; (+ \text{ c.c.})$

$\Delta M = M(D^{*+}) - M(D^0) \sim m_\pi$

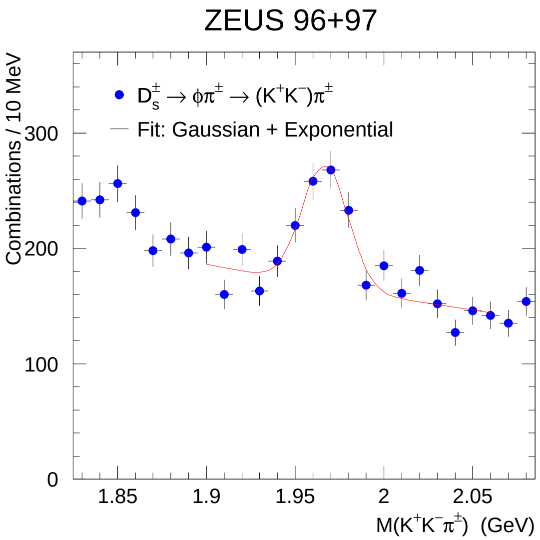
$P_\perp^{D^*} > 2\,\text{GeV}$ and $-1.5 < \eta^{D^*} < 1.5$

In the yellow band under background:

$\boxed{N(D^{*\pm}) = 31350 \pm 240}$ Budapest, abstr. 497

Is $f(c \to D^{*+})$, measured in e^+e^-, the same for e^+p ?

To answer measure other D mesons :



$D_s \to \phi\pi \to (K^- K^+)\pi$

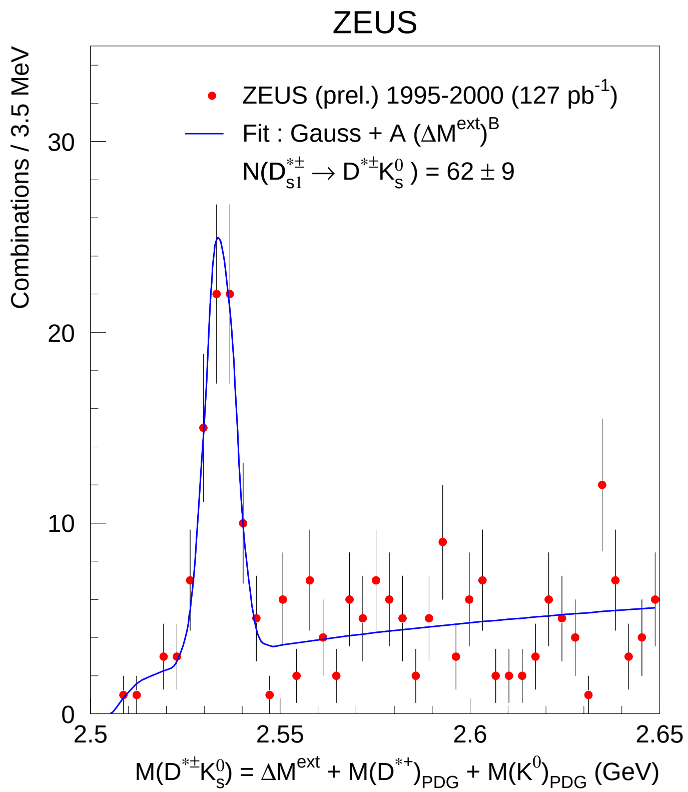
	e^+p	e^+e^-
D_s/D^*	$0.41 \pm 0.07^{+0.03}_{-0.05}$	0.43 ± 0.04
γ_s	0.27 ± 0.05	0.26 ± 0.03

γ_s is the strangeness-suppression factor

Universality of Charm Fragmentation, Excited D mesons

$D_1^0, D_2^{*0} \rightarrow D^{*\pm}\pi^{\mp}$ Osaka, abstr. 854

	$f(c \rightarrow D_1^0)$ [%]	$f(c \rightarrow D_2^{*0})$ [%]
ZEUS Prel. (Osaka, abstr. 854)	$1.46 \pm 0.18^{+0.33}_{-0.27} \pm 0.06$	$2.00 \pm 0.58^{+1.40}_{-0.48} \pm 0.41$
CLEO	1.8 ± 0.3	1.9 ± 0.3
OPAL	2.1 ± 0.8	5.2 ± 2.6
ALEPH Prel.	1.6 ± 0.5	4.7 ± 1.0
DELPHI Prel.	1.9 ± 0.4	4.7 ± 1.3



Budapest, abstr. 497

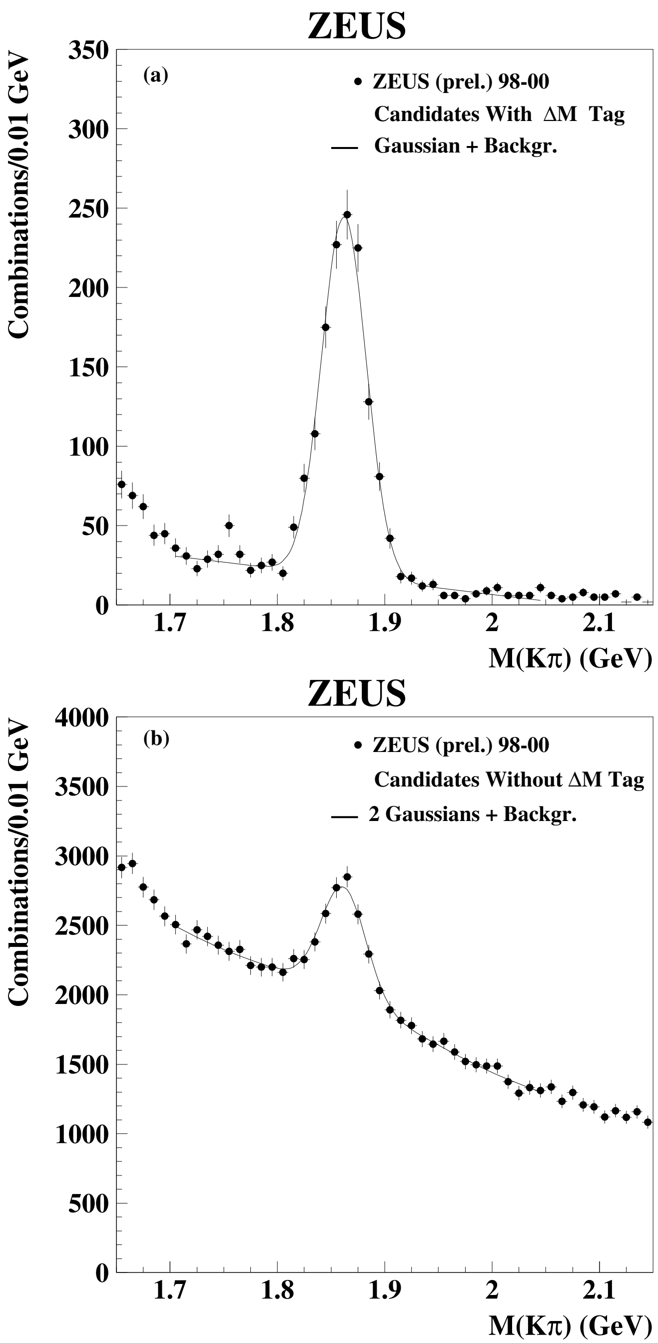
$D_{s1}^{\pm}(2536) \rightarrow D^{*\pm}K_S^0$, $K_S^0 \rightarrow \pi^+\pi^-$

$$\boxed{f(c \rightarrow D_{s1}^+) = 1.24 \pm 0.18(\text{stat.})^{+0.08}_{-0.06}(\text{syst.}) \pm 0.14(\text{br.})\%}$$

OPAL : $f(c \rightarrow D_{s1}^+) = 1.6 \pm 0.4 \pm 0.3\%$

The same amounts of excited D mesons in e^+e^- and e^+p data

Universality of Charm Fragmentation, P_v value



$D^{*\pm}$ and D^0 in PhP (Budapest, abstr. 501)

$$P_v = \frac{Vectro}{Vector+Pseudoscalar} = \frac{D^*}{D^*+D}$$

Assuming: a) $\sigma(D^{*0}) = \sigma(D^{*+})$

b) no sizable distortions from excited D mesons

$$P_v = (\sigma(D^0)/\sigma(D^{*+}) - B_{D^{*+}\rightarrow D^0\pi})^{-1}$$

Using : $N(D^0) = 5223 \pm 185$

$N(D^{*\pm}) = 1180 \pm 39$

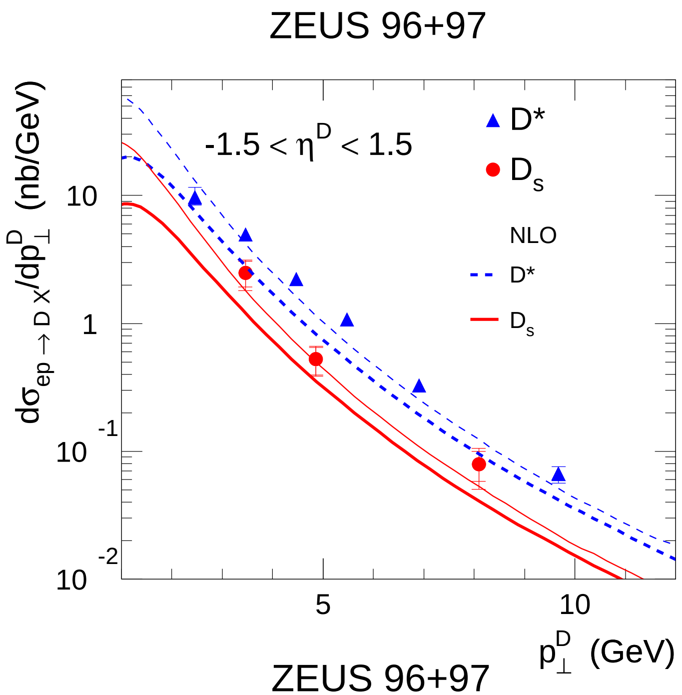
$$\boxed{P_v = 0.546 \pm 0.045(\text{stat.}) \pm 0.028(\text{syst.})}$$

OPAL : $P_v = 0.57 \pm 0.05$

ALEPH : $P_v = 0.595 \pm 0.045$

Charm Fragmentation Fractions are Universal

Charm in Photoproduction vs NLO



$D^{*\pm}$ and $D_s^{\pm}$ in PhP

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

NLO : FMNR, MRSG and GRV-G HO

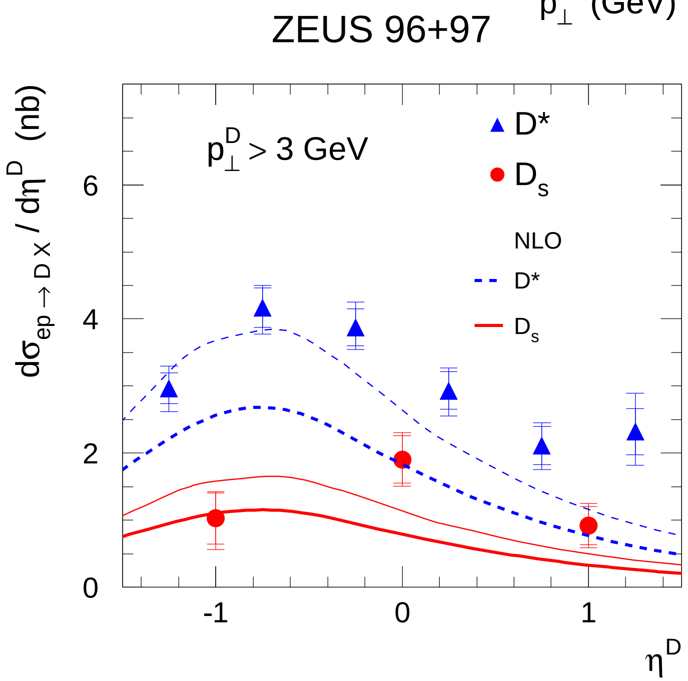
thick curves: $m_c = 1.5\,GeV,\ \mu_R = m_\perp, \mu_F = 2m_\perp$

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

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

extreme: still below the data

$p_\perp$ shape ? somewhat different (see D^* points)



disagreement is larger

in forward($\eta > 0$)

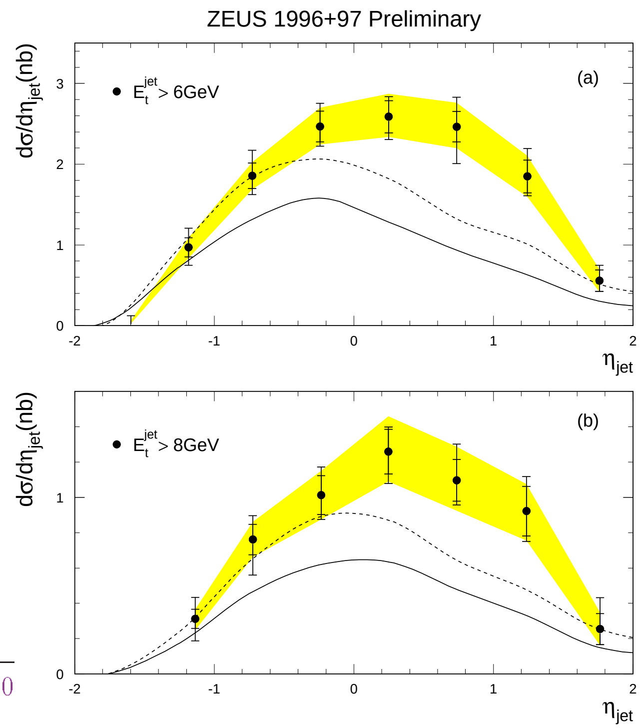
direction

$\longleftarrow$

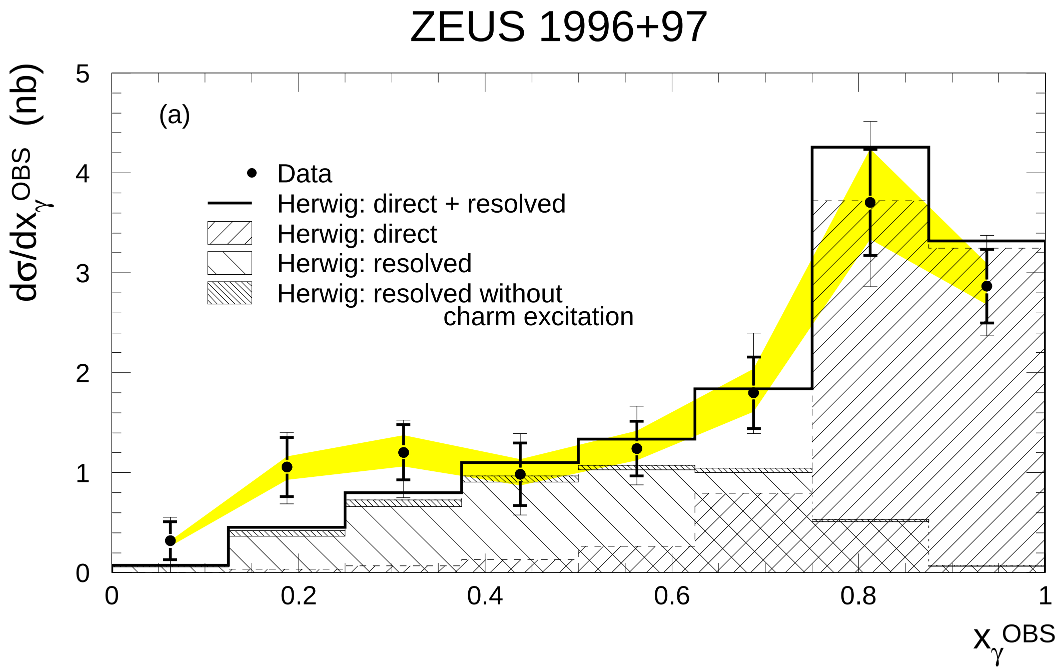
"beam-drag effect" ?

But charm jets

show the same $\longrightarrow$



Charm Dijet Photoproduction vs LO and NLO



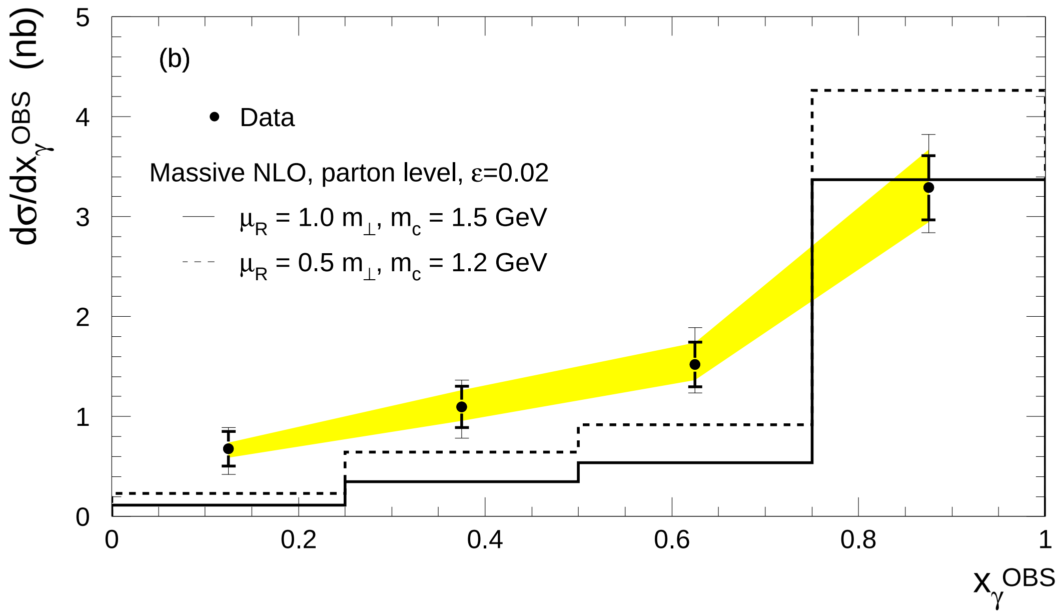
$D^{*\pm}$ in PhP

with at least 2 jets

$E_T^{jet1,2} > 7, 6\,\mathrm{GeV}$

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

$\longleftarrow$ (DGLAP) LO charm excitation in photon (≈ 40 %)



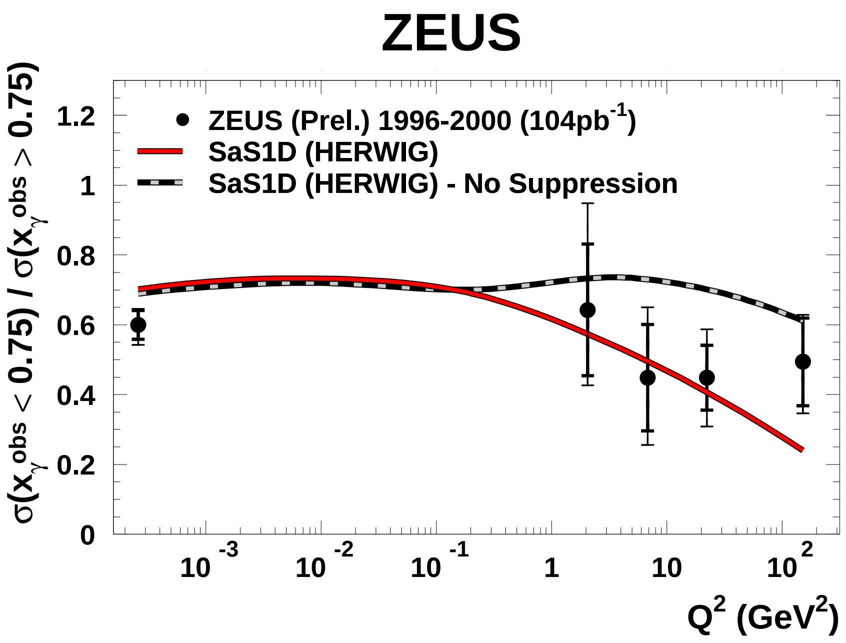
$\longleftarrow$ fixed-order NLO are below data at low x_γ^{OBS}

NNLO describes better ?

Resolved γ or CCFM gluon ?

(CASCADE is close in shape)

Charm Dijet Photoproduction vs LO and NLO

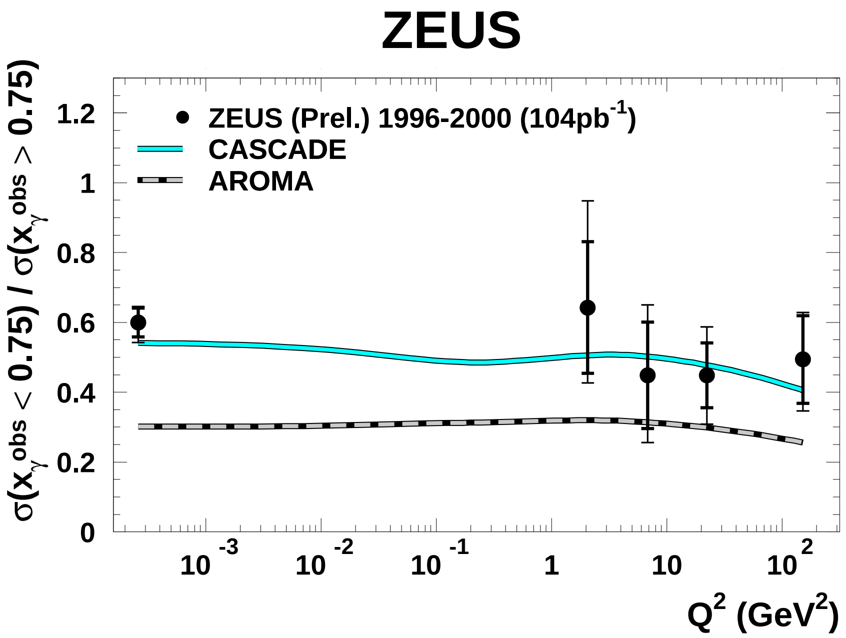


x_γ^{OBS} for $D^{*\pm}$ in PhP and DIS

$$\frac{\sigma(x_\gamma^{OBS}<0.75)}{\sigma(x_\gamma^{OBS}>0.75)} \text{ vs } Q^2$$

small (if any) suppression with Q^2

HERWIG with SaS1D agrees

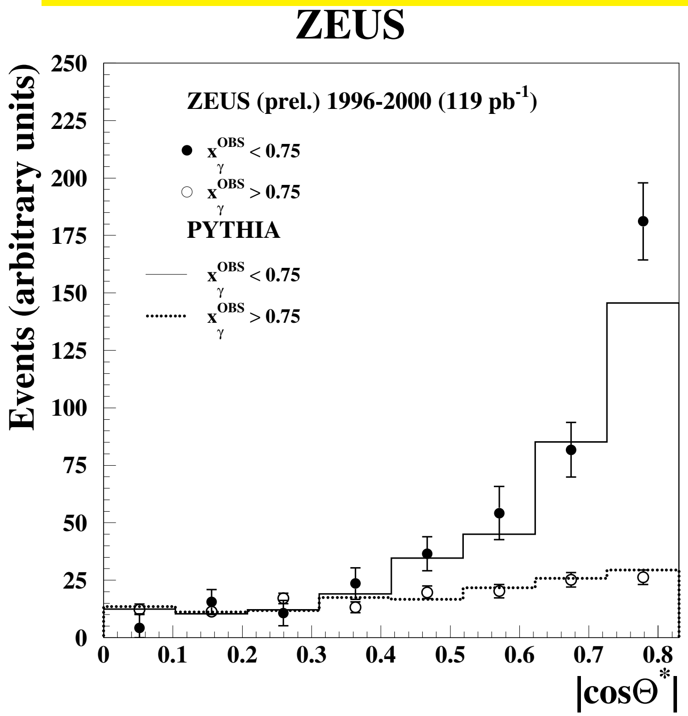


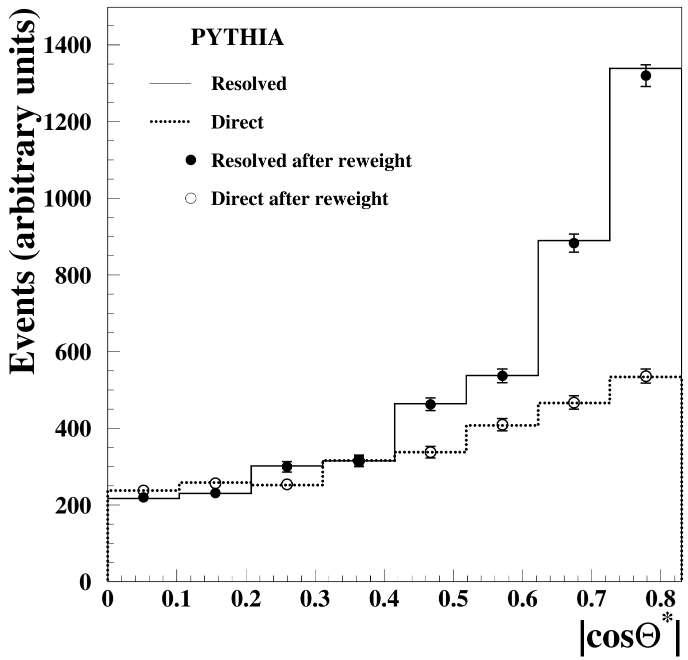
AROMA is too low (no resolved γ)

CASCADE describes w/o explicit resolved γ component

(Budapest, abstr. 495)

Dijet Angular Distributions for Charm in Photoproduction





$D^{*\pm}$ in PhP (Budapest, abstr. 499)

with at least 2 jets

$E_T^{jet1,2} > 5\,\text{GeV}$ and $M_{jj} > 18\,\text{GeV}$

Observable: the angle between jet-jet axis and the beam axis in the dijet rest frame :

$$\cos\theta^* = \tanh\frac{\eta^{jet1} - \eta^{jet2}}{2}$$

"q propagator" $\propto (1 - |\cos\theta^*|)^{-1}$

"g propagator" $\propto (1 - |\cos\theta^*|)^{-2}$

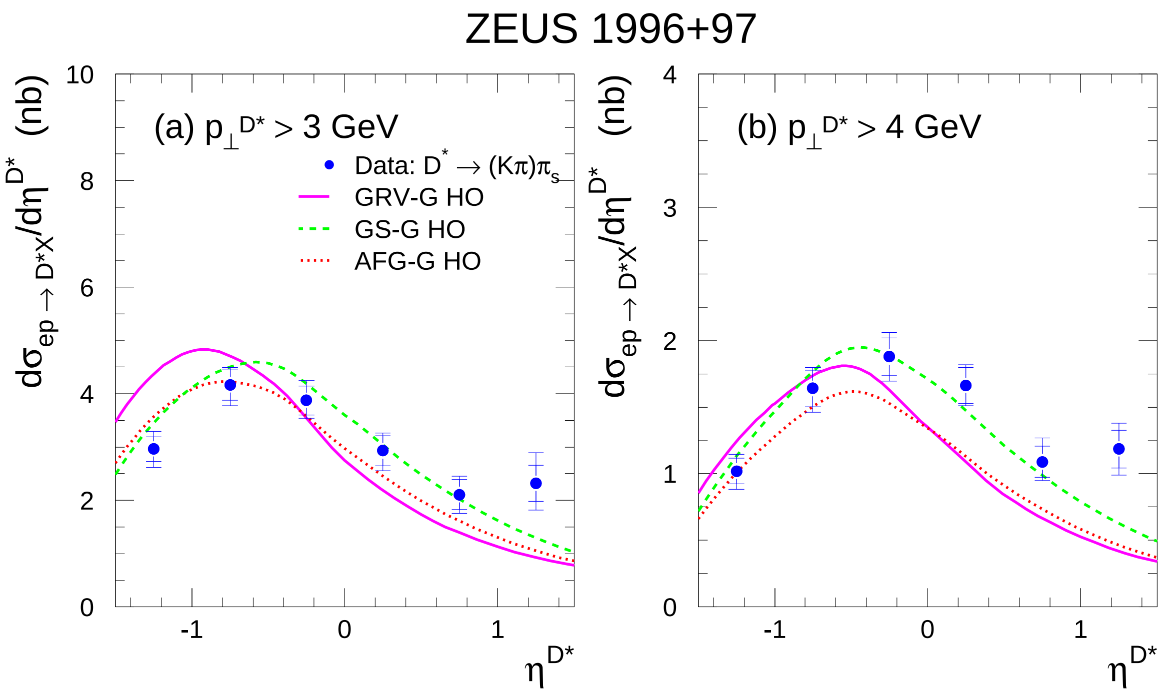
A signature of g propagator

No bias from $M_{jj} > 18\,\text{GeV}$ cut

PYTHIA describes both $x_\gamma > 0.75$ and < 0.75

CASCADE ? NLO ?

Charm in PhP in comparison with Resummed NLO



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

NLO : Kniehl et al., CTEQ4M, $m_c = 1.5\,GeV,\ \mu_R = m_\perp, \mu_F = 2m_\perp$

(resummed NLO from Cacciari et al. is $\approx$ 1.5 lower)

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 $m_\perp \approx 4.5\,GeV$?

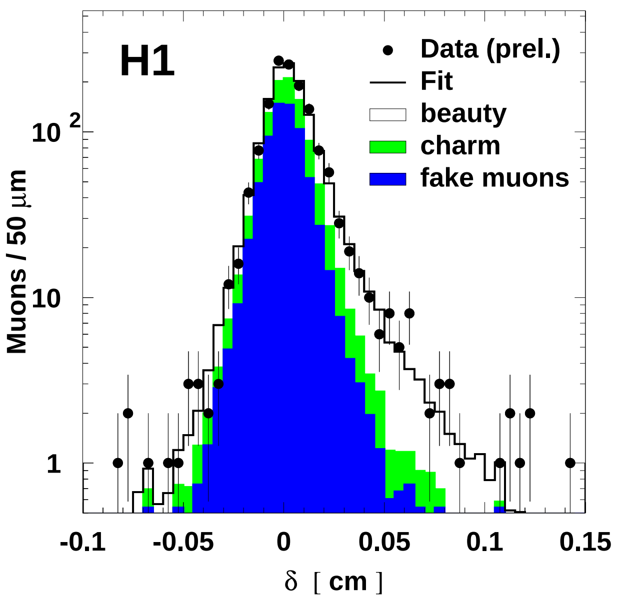
(Is $p_\perp$ large enough ?)

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

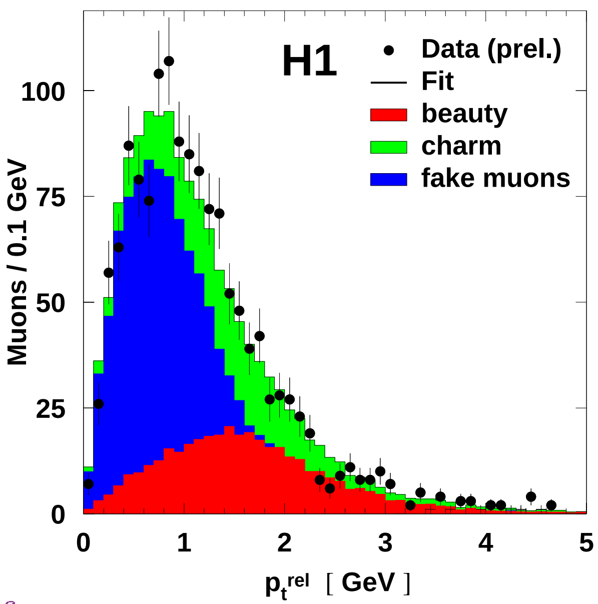
Beauty in Photoproduction, H1 muon analysis

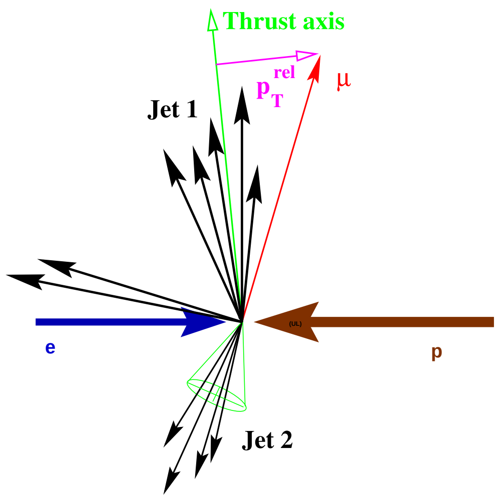
Budapest, abstr. 790

b production: impact parameter



b production: p_t^{rel}





Select dijet events with $E_T^{jets} > 5\,\mathrm{GeV}$ and measure P_T^{rel} w.r.t a jet

Use 2-D fit in (δ, P_T^{rel}) plane: $f_b = 27 \pm 3\%$

Correct for dijet selection with MC to the kinematic range :

$Q^2 < 1\,\mathrm{GeV}^2$; $0.1 < y < 0.8$; $P_\perp^\mu > 2\,\mathrm{GeV}$; $35^\circ < \theta^\mu < 130^\circ$

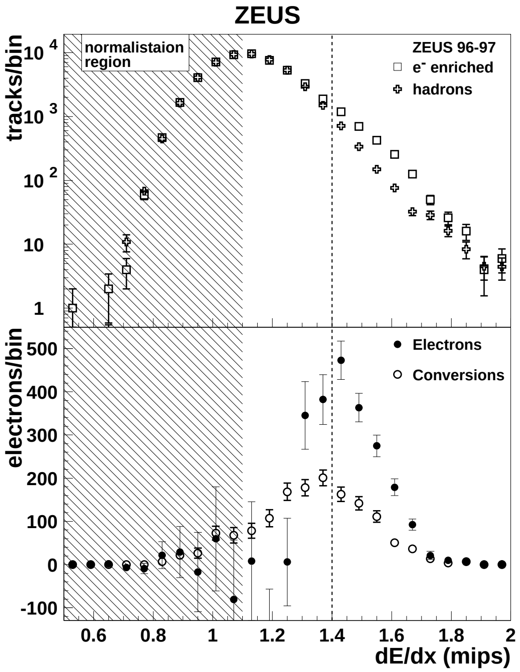
$\boxed{\sigma_{vis}(e + p \rightarrow b\bar{b}X \rightarrow \mu^\pm X) = (170 \pm 25)\,\mathrm{pb}}$ (H1 publ. + prel.)

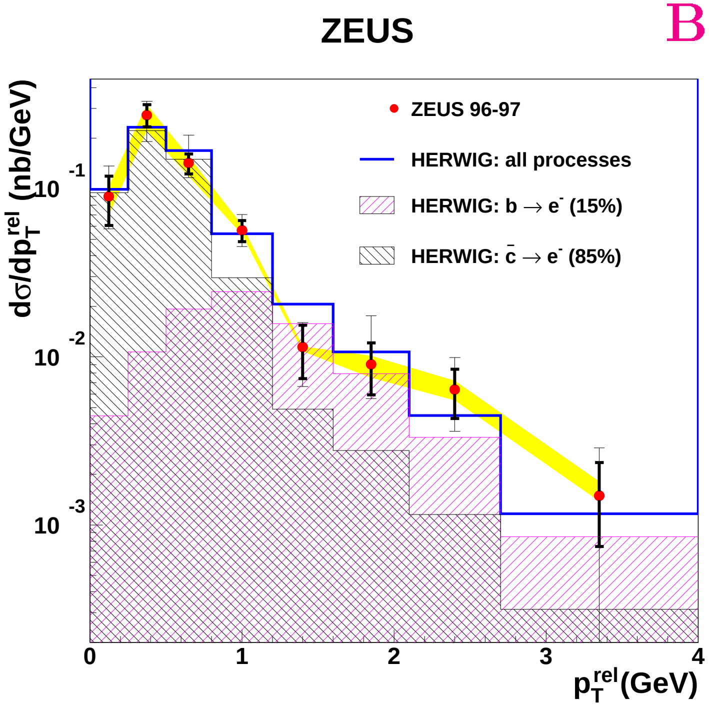
NLO (FMNR) : $(54 \pm 9)\,\mathrm{pb}$ (recent H1 update) too low

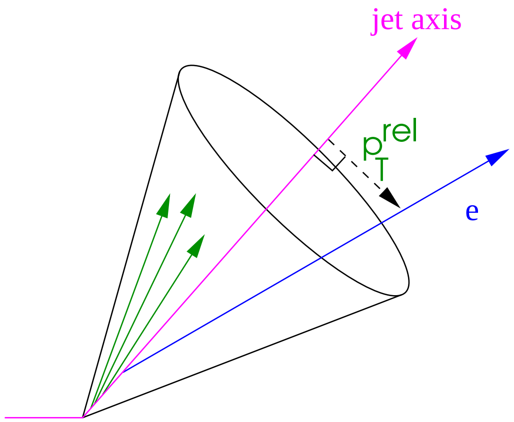
AROMA : 38 pb CASCADE : 67 pb

Beauty in Photoproduction, ZEUS electron analysis

Budapest, abstr. 487







Use calorimeter and dE/dx in central tracker to identify 943 ± 69 e^- from s-l decays

Fit P_T^{rel} w.r.t a jet : $f_b = 14.7 \pm 3.8\%$ (HERWIG, PYTHIA : 16%, 19%)

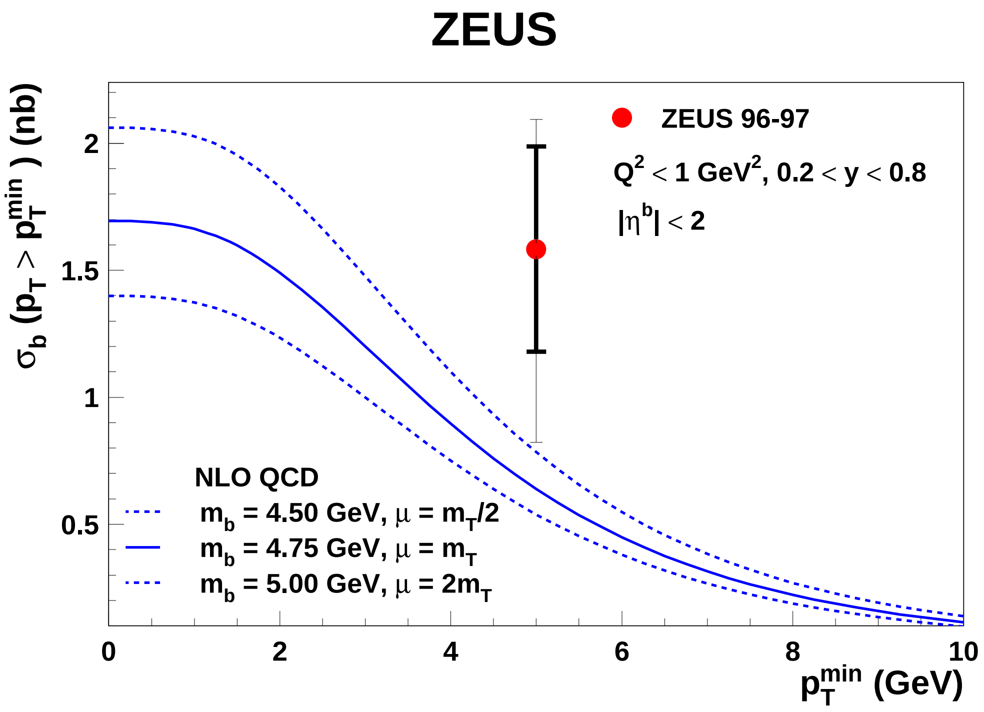
Kinematic range : $Q^2 < 1\,\mathrm{GeV}^2$; $0.2 < y < 0.8$; $P_\perp^e > 1.6\,\mathrm{GeV}$; $|\eta^e| < 1.1$

≥ 2 Jets ; $E_T^{jet1,2} > 7,6\,\mathrm{GeV}$; $\eta^{jet1,2} < 2.4$

$$\boxed{\sigma^{b\to e^-}_{e^+p\to e^+ + dijet + e^- + X} = 24.9 \pm 6.4(stat.)^{+4.2}_{-7.3}(syst.)\,\mathrm{pb}}$$

HERWIG : 8 pb PYTHIA : 18 pb CASCADE : 18 pb

Beauty in Photoproduction, ZEUS electron analysis



Use MC to extrapolate to :

$Q^2 < 1\,\mathrm{GeV}^2$; $0.2 < y < 0.8$

$P_\perp^b > 5\,\mathrm{GeV}$; $|\eta^b| < 2$

$$\boxed{\sigma^{ext}_{e^+p\to e^+bX} = (1.6 \pm 0.4(\mathrm{stat.})^{+0.3}_{-0.5}(\mathrm{syst.})^{+0.2}_{-0.4}(\mathrm{ext.})\ \mathrm{nb}}$$

NLO (FMNR) : $(0.64^{+0.14}_{-0.10})$ nb — somewhat below

CASCADE : (0.88 ± 0.08) nb — more or less o.k.

Beauty in Photoproduction, ZEUS muon analysis

Tampere, abstr. 498 ; Budapest, abstr. 496

Use muon detectors and P_T^{rel} w.r.t. jet :

Kinematic range : $Q^2 < 1\,\mathrm{GeV}^2$; $0.2 < y < 0.8$

≥ 2 Jets ; $E_T^{jet1,2} > 7, 6\,\mathrm{GeV}$; $\eta^{jet1,2} < 2.4$

1. Central region :

$P^\mu > 3\,\mathrm{GeV}$; $-1.75 < \eta^\mu < 1.3$

$$\boxed{\sigma_{b\bar{b}}^{vis}(e^+p \rightarrow dijet + \mu^\pm + X) = 36.4 \pm 5.2(stat.)^{+10.4}_{-9.1}(syst.)\,\mathrm{pb}}$$

HERWIG : 12 pb PYTHIA : 30 pb CASCADE : 24.5 pb

2. Forward ($\eta > 0$) region :

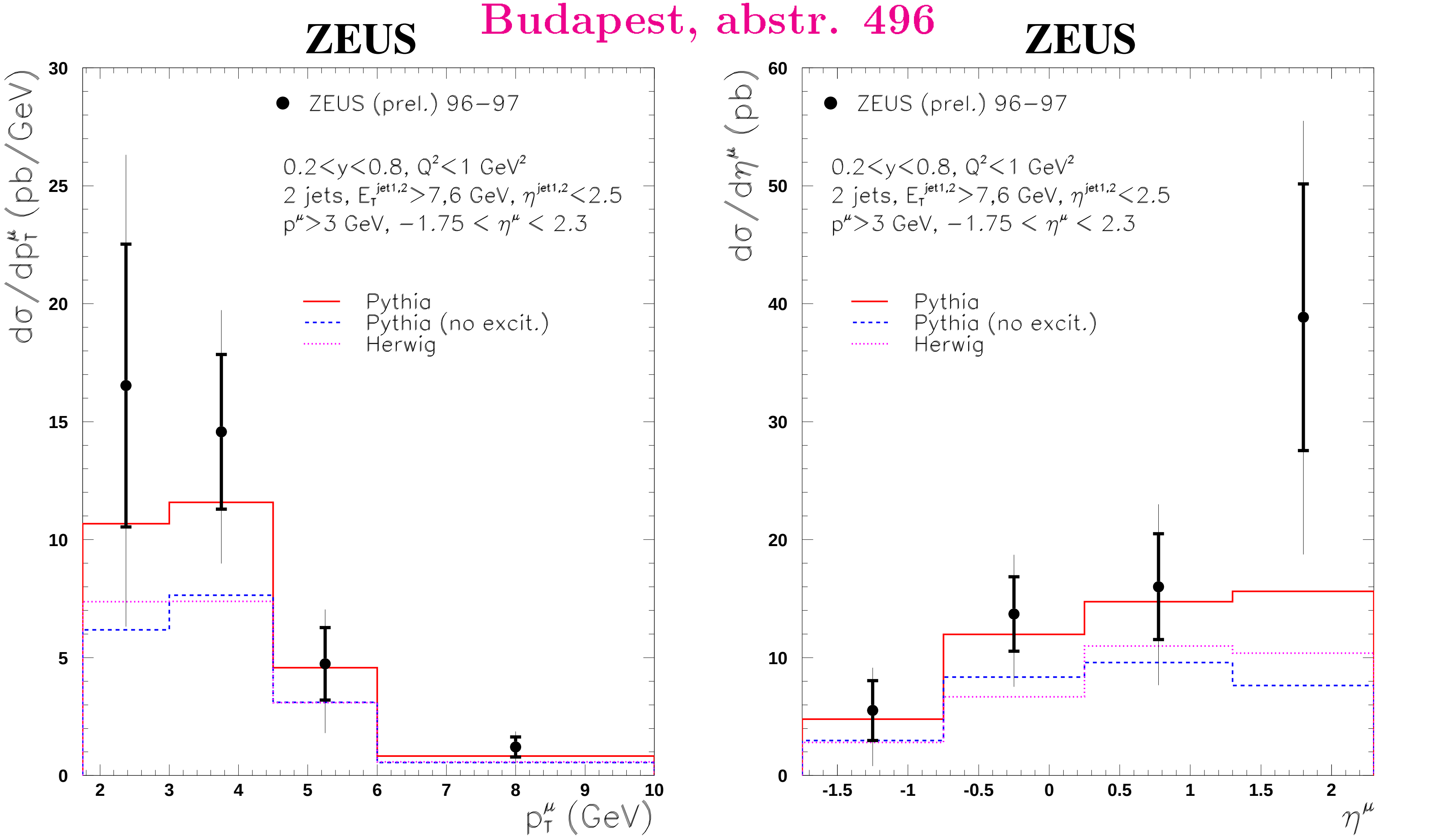
$P_\perp^\mu > 1.5\,\mathrm{GeV}$; $1.4 < \eta^{mu} < 2.4$

$$\boxed{\sigma_{b\bar{b}}^{vis}(e^+p \rightarrow dijet + \mu^\pm + X) = 20.5 \pm 6.5(stat.)^{+6.3}_{-5.7}(syst.)\,\mathrm{pb}}$$

HERWIG : 4.1 pb PYTHIA : 9.6 pb CASCADE : 5.9 pb

Differential Cross Sections for Beauty in Photoproduction

Budapest, abstr. 496



PYTHIA with b-excitation component describes (reasonably well)

In forward (proton) direction data are above PYTHIA and HERWIG

Will NLO describe the cross sections ?

Summary

- HERA has provided wide spectrum of charm and first beauty measurements. In charm sector experimental errors are typically smaller than theoretical uncertainties.

- Measurements of strangeness-suppression factor, value of P_v and excited D meson fragmentation fractions justify universality of charm fragmentation.

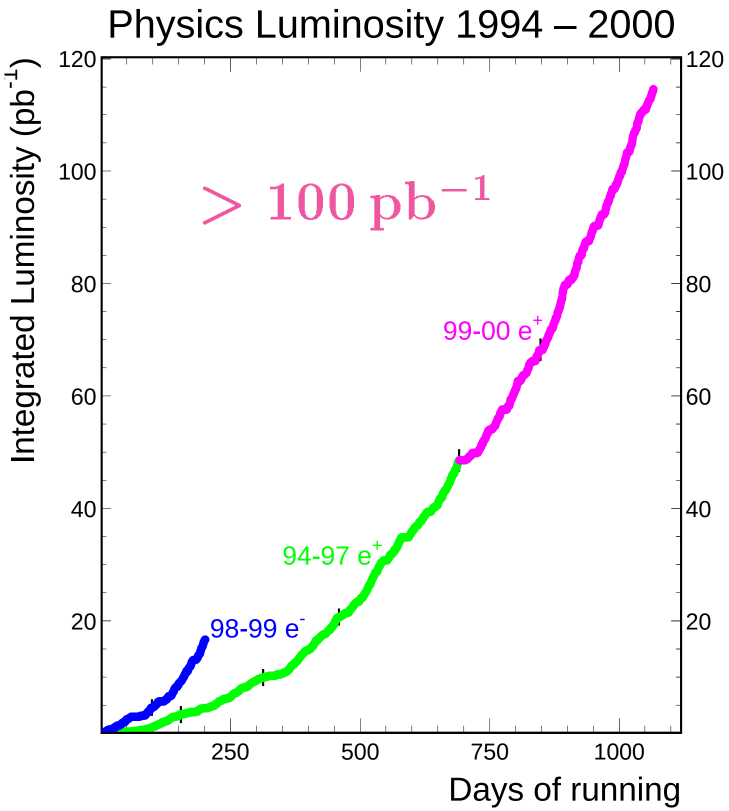
- Charm and beauty photoproduction x-sections are underestimated by fixed-order NLO.

- x_γ^{OBS} distr. indicates large (DGLAP) LO resolved γ (c excitation) component. However, CASCADE (CCFM gluon) shows realistic low x_γ^{OBS} fraction w/o explicit resolved γ component. Fixed-order NLO are below the data at low x_γ^{OBS} values.

- $\cos\theta^*$ distribution for dijet events with a $D^{*\pm}$ shows a signature of the gluon propagator for events with $x_\gamma^{OBS} < 0.75$

- Resummed NLO calculations from Kniehl et al. with GS-G HO are close to data. However, $c = u$ in this photon SF. There are still no resummed NLO calculations for x_γ^{OBS}.

Outlook



	HERA I	HERA II
	1992-2000	2001-2006
$\sqrt{s}$	320 (300)	320 GeV
$\mathcal{L}$	$1.5 \cdot 10^{31}$	$7 \cdot 10^{31}\, cm^{-2}\, s^{-1}$
$\mathcal{L}_{int}$	0.1	$1\, fb^{-1}$

And Detectors Upgrades

(Si, forward tracking)

In 3-6 months production x-sections with all data from HERA I

In 3-6 years results with $\approx 1\,\mathrm{fb}^{-1}$ from HERA II

Be prepared !