Moriond QCD 2002 Les Arcs 18-03-2002

INFN

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Heavy quark production at HERA

Outline

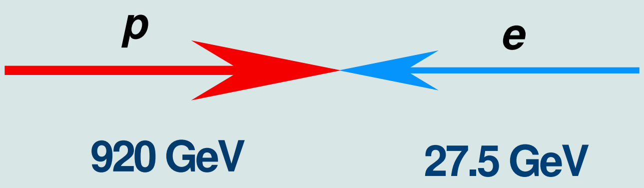
- ⋆ Heavy quark production mechanisms at HERA
- ⋆ Heavy quark tagging - charm fragmentation
- ⋆ Open charm in γp, dijet angular distributions
- ⋆ Open charm in DIS and $F_2^{c\bar{c}}$
- ⋆ Open beauty in photoproduction and DIS
- ⋆ Summary and Outlook

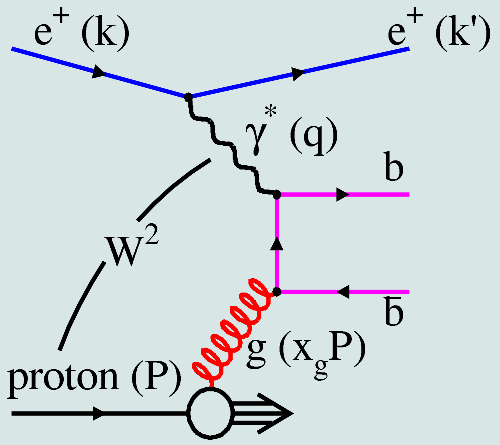
on behalf of

H1 and ZEUS collaborations

Introduction

$$\sqrt{s} \sim 320 \text{ GeV}$$



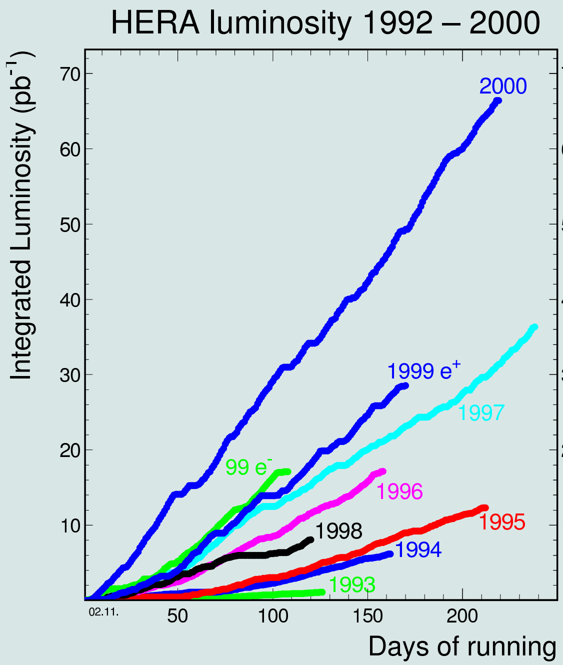


Kinematic variables

- ★ **4-momentum transfer:** $Q^2 = -q^2 = -(k-k')^2$
- ★ **Bjorken-x scaling variable:** $x = \frac{Q^2}{2P\cdot q}$
- ★ **Fraction of energy transfer:** $y = \frac{P\cdot q}{P\cdot k}$
- ★ γp **CMS energy:** $W_{\gamma p} = (P+q) \simeq \sqrt{4E_e E_p y}$

Two kinematic regimes

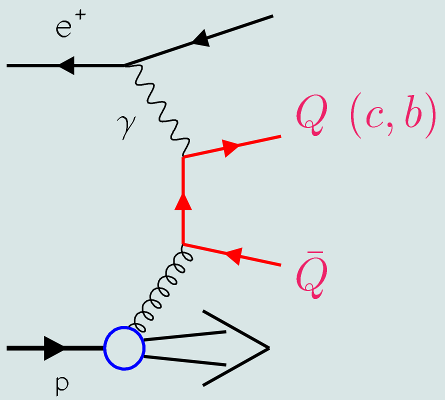
- ★ **Deep Inelastic Scattering (DIS)** $Q^2 > 1 \text{ GeV}^2$
  scattered e **visible in main detector**
- ★ **Photoproduction (PHP)** $Q^2 < 1 \text{ GeV}^2$; $\langle Q^2 \rangle \sim 3 \cdot 10^{-4}$
  no scattered e **in main detector** $\rightarrow$ **quasi-real** γ



$$\mathcal{L} \sim 120 \text{ pb}^{-1}$$

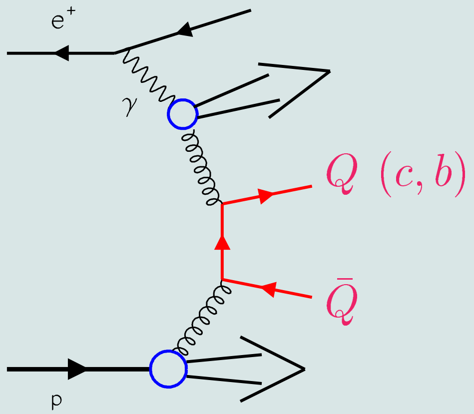
QCD LO contributions to open HQ production:

Boson gluon fusion BGF
"direct" (point-like) γ



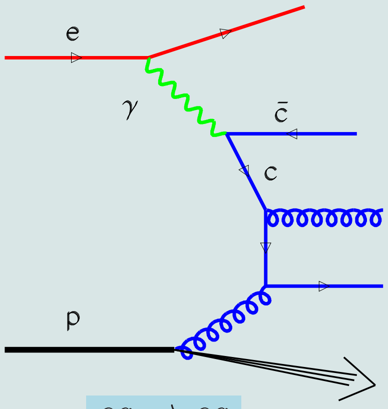
probe g in p $g_p(x, Q^2)$

"Resolved" γ



$gg \to Q\bar{Q}$

Charm excitation in γ



$cg \to cg$

$g^p(x, Q^2) \otimes g^\gamma(x, Q^2)$

Goal: study QCD dynamics with c and b quarks

- ★ Hard scale $m_Q >> \Lambda_{QCD}$ → pQCD calculations
- ★ Direct handle on
  - gluon density in p $xg(x)$ (via BGF diagram)
  - γ partonic structure (resolved γ)
- ★ HQ quark → hadron fragmentation universality

Next to leading order calculations ($\alpha\alpha_S^2$)

- ★ In NLO only sum of direct + resolved well defined
- ★ Full NLO calculations exist for HQ production in pp $\gamma\gamma$ and ep collisions

QCD Next to Leading Order calculations

★ **Fixed order ("massive") scheme**

- Only light quarks (u,d,s) are active flavours in p, γ
- No explicit c-excitation component
- Charm only produced dynamically via BGF
- Scheme valid for $Q^2, p_\perp^2 \sim m_Q^2$

★ **Resummed ("massless") scheme**

- u,d,s,c are active flavours in p, γ
- "massless" charm is part of a structure function $\Rightarrow$ calculation include c-excitation processes
- Large logarithms (Q/m_c $p_\perp/m_c$) are resummed
- Scheme valid for $Q^2, p_\perp^2 \gg m_Q^2$

... a "merged scheme" has been recently developed: **FONLL**

hadronization: Peterson function

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

Monte Carlo generators (LO+parton shower)

- **AROMA** direct only, DGLAP evolution
- **PYTHIA**, **HERWIG** direct + resolved, DGLAP
- **CASCADE** direct only, CCFM-like evolution (angular ordering, k_t dependent g-density)

HQ tagging methods

$\mathcal{L} = 127\ \mathrm{pb}^{-1}$

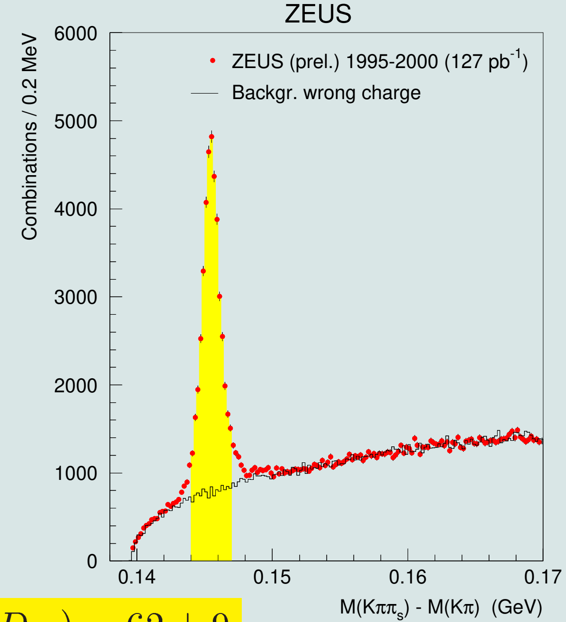
(ZEUS 95-00)

$D^{*\pm} \to (K^{\mp}\pi^{\pm})\pi_s^{\pm}$

$p_T^{D^*} > 2\ \mathrm{GeV}$,

$|\eta^{D^*}| < 1.5$

$N(D^*) = 31350 \pm 240$



Charm production:

main tool: $D^*(2010)$ **reconstruction**

$f(c \to D^*) = 0.235 \pm 0.007 \pm 0.007$ **hep-ex/9912064**

Used D^* channels:

- ★ $D^{*+} \to D^0\pi_s^+ \to (K^-\pi^+)\pi_s^+$ $\mathcal{B} = (2.62 \pm 0.10)\%$
- ★ $D^{*+} \to D^0\pi_s^+ \to (K^-\pi^+\pi^+\pi^-)\pi_s^+$ $\mathcal{B} = (5.1 \pm 0.3)\%$

Clean tag: $m_{D^*} - (m_{D^0} + m_\pi) \sim 10\ \mathrm{MeV}$

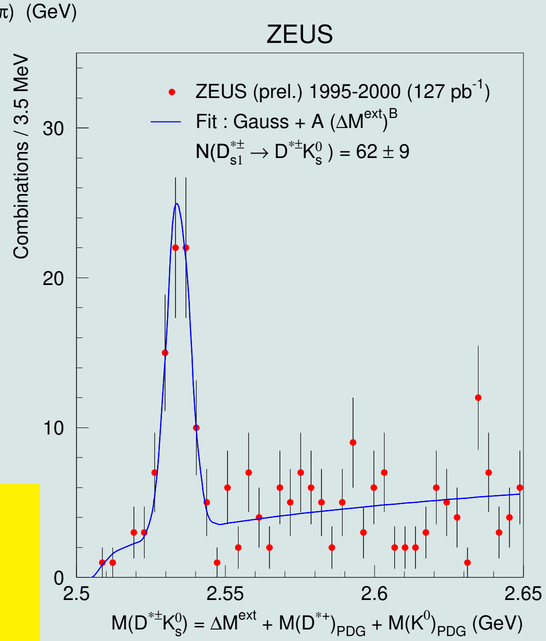
$D_{s1} \to D^* K_s(\to \pi\pi)$ $N(D_{s1}) = 62 \pm 9$

	$f(c \to D_{s1}^+)$
ep	$(1.24 \pm 0.18^{+0.08}_{-0.06} \pm 0.14)\ \%$
OPAL	$(1.6 \pm 0.4 \pm 0.3)\ \%$
ALEPH	$(0.94 \pm 0.22 \pm 0.07)\ \%$

$+$ **recent** P_V, γ_s **measurements** $\downarrow$

Consistent picture in ep and e^+e^-

charm fragmentation universality



Other open charm channels:

- $D_s \to \phi\pi^+ \to (K^+K^-)\pi^+$
- **semi-leptonic decays**
  $f(c \to e^+) = 0.098 \pm 0.009^{+0.006}_{-0.005}$

D^{**}, D_{s1} **are also measured**

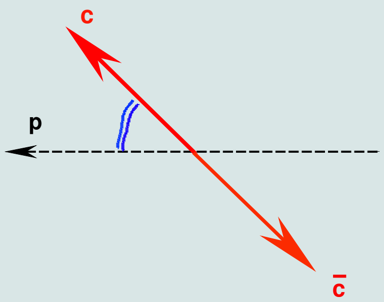
Beauty production:

- **semi-leptonic decays (open b)**

charm photoproduction: dijet angular distributions

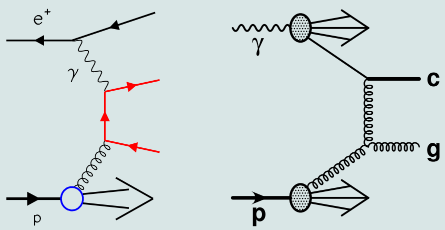
D^* + at least 2 **jets** with $E_T > 5$ GeV and $M_{jj} > 18$ GeV

In the dijet rest frame θ^* is the angle between jet-jet axis and beam axis



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

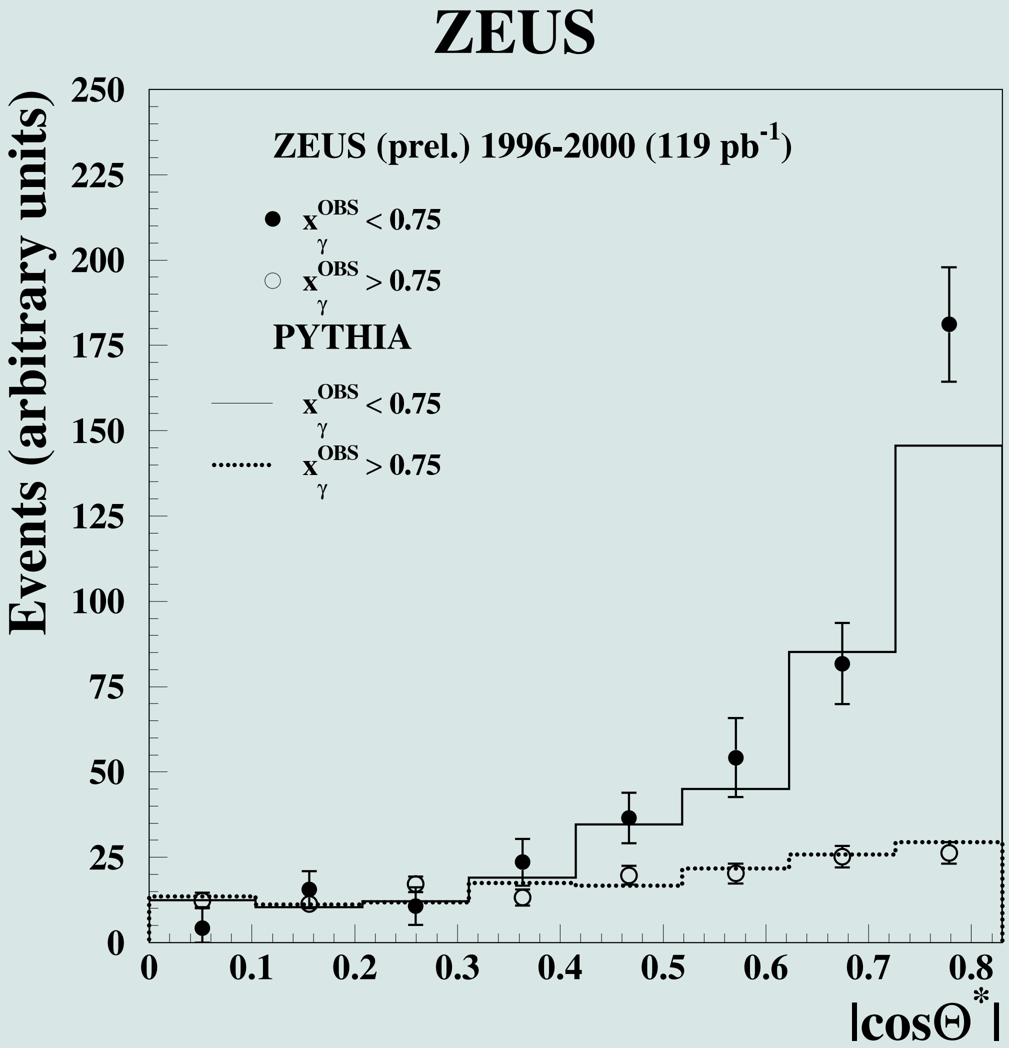
"q-propagator"
$\propto (1 - |\cos\theta^*|)^{-1}$
"g-propagator"
$\propto (1 - |\cos\theta^*|)^{-2}$



signature of gluon propagator

$\leftrightarrow$ c-**excitation**

this is still at event level ! be prepared for differential x-sections . . . CASCADE ? NLO ?



PYTHIA does a good job in the whole x_γ^{OBS} range

Charm contribution to DIS: $F_2^{c\bar{c}}(x, Q^2)$

Inclusive DIS

$$\frac{d^2\sigma^{ep\to ecX}}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}(1+(1-y)^2)\cdot F_2(x,Q^2)$$

Charm production in DIS

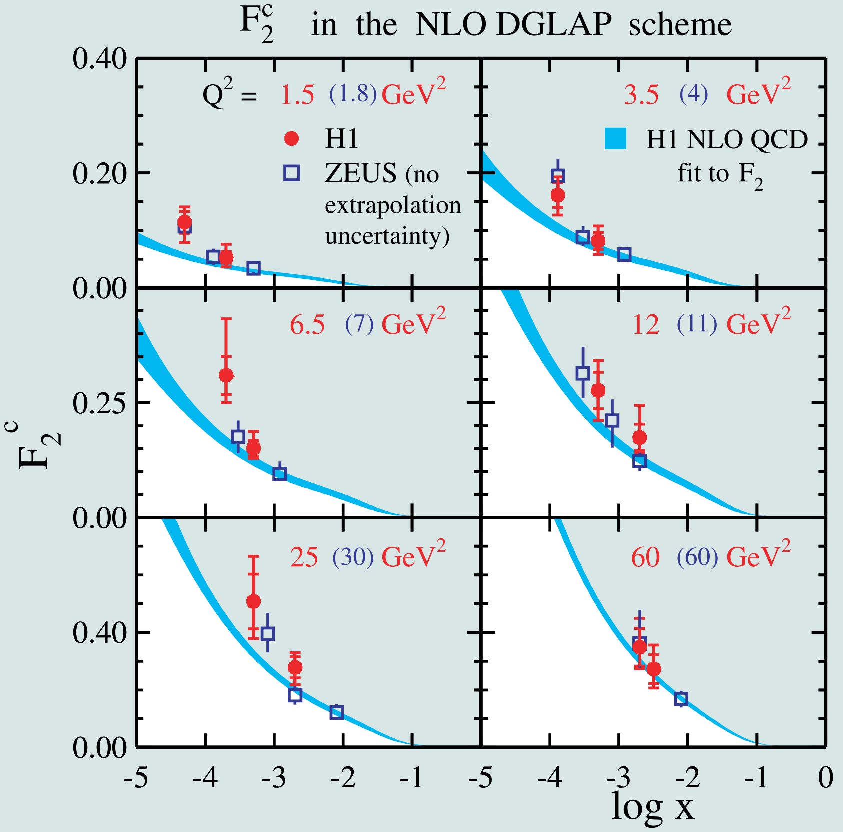
$$\frac{d^2\sigma^{ep\to eX}}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}(1+(1-y)^2)\cdot F_2^c(x,Q^2)$$

$1 < Q^2 < 100(600)$ GeV^2 $\quad 0.05(0.02) < y < 0.7$

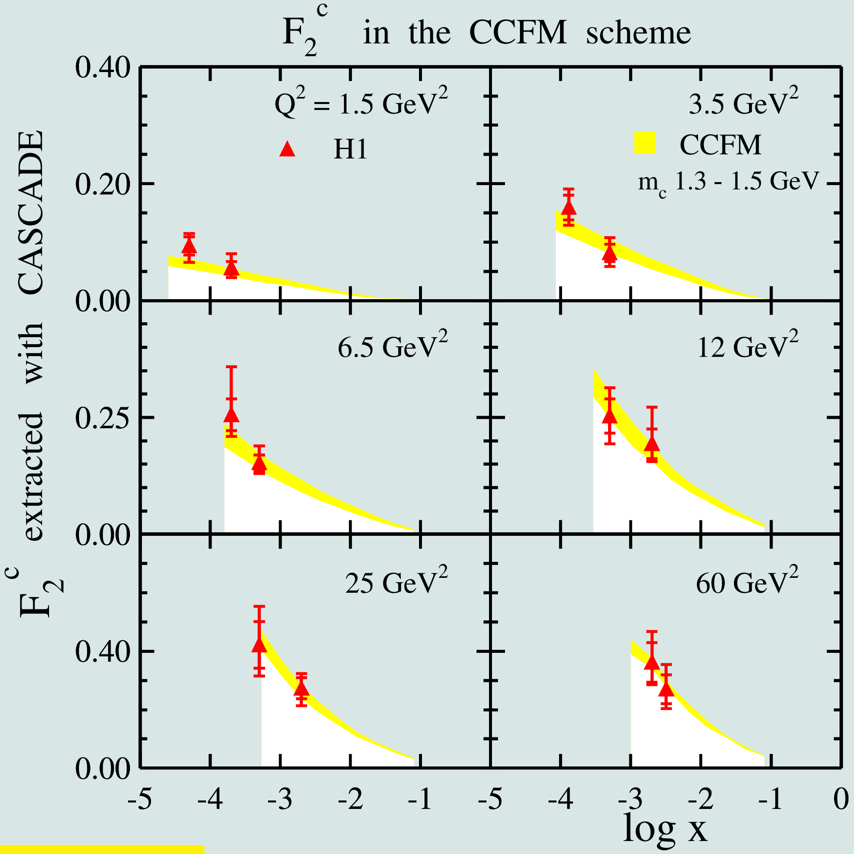
$1.5 < p_T^{D^*} < 15$ GeV/c $\quad |\eta^{D^*}| < 1.5$

$\sigma_{ep\to eD^*X}$ $\quad (8.37 \pm 0.41(\text{st.})^{+1.11}_{-0.82}(\text{sy.})^{+0.64}_{-0.39}(\text{th.}))$ nb

$(8.31 \pm 0.31(\text{st.})^{+0.3}_{-0.5}(\text{sy.}))$ nb



NLO DGLAP scheme



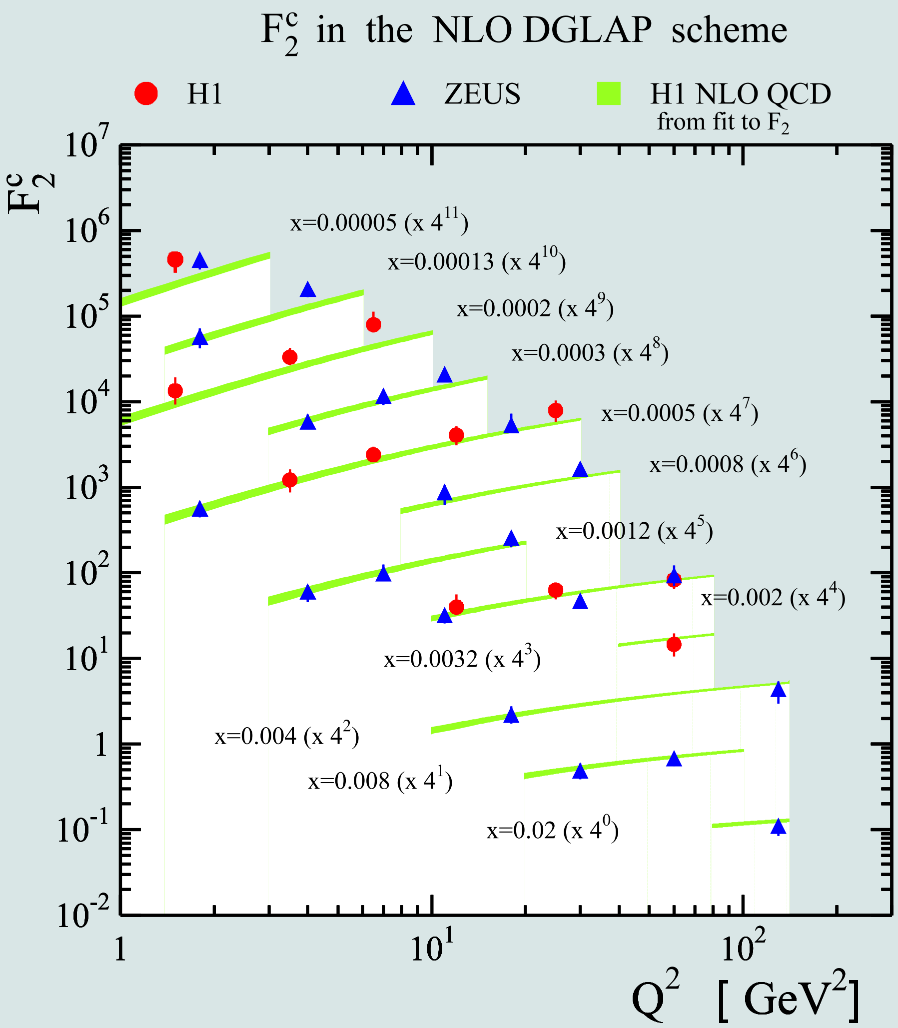
Strong rise towards low x: $F_2^{c\bar{c}} \propto xg(x)$ **(BGF)**

Good agreement between ZEUS and H1

Lowest x and Q^2: departure from DGLAP ?

CASCADE provides better agreement (H1 data)

$F_2^{c\bar{c}}$ scaling violations and contribution to inclusive cross section (F_2^c/F_2)



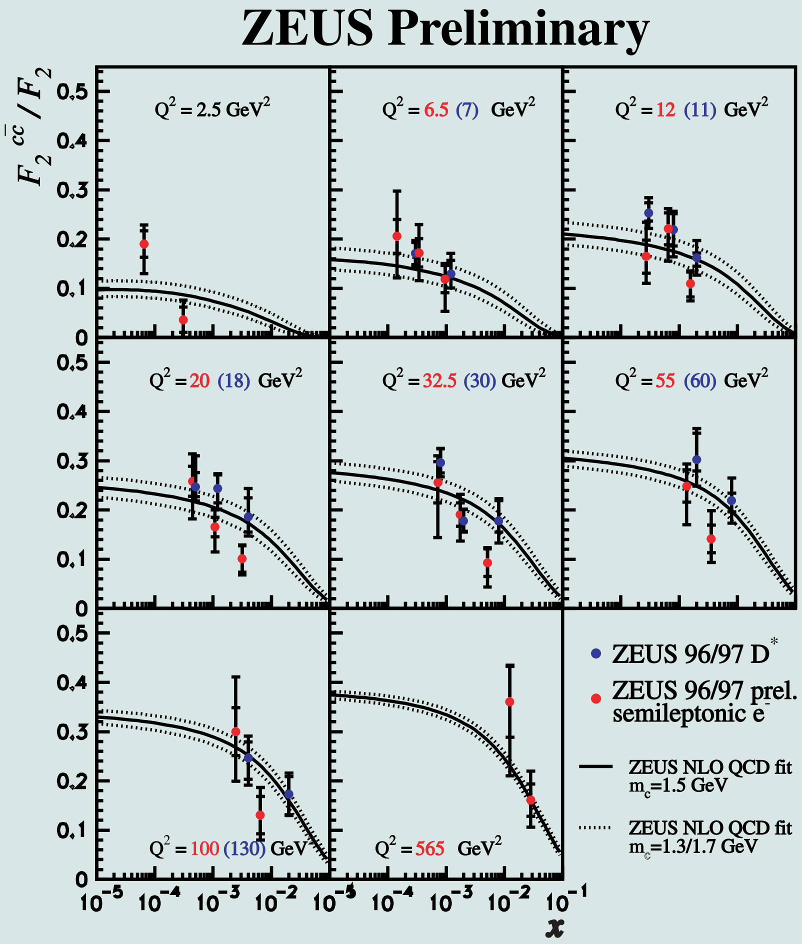
★ **High Q^2 →**

m **effects dumped: q counting**

$\frac{11}{4} \sim 0.36$

★ **High x →**

not enough gluons !



Pronounced scaling violations $(F_2(Q^2))$**:**

QCD radiation and gluonic component in the proton.

charm: $10\ \%$ **at small** Q^2

$30 - 40\ \%$ **at largest** Q^2 **and smallest** x **values**

Main uncertainties statistics and value of m_c

Open beauty production

⋆ Cross section predicted to be low: $\boxed{\sigma_{c\bar{c}} : \sigma_{b\bar{b}} = 200 : 1}$ (larger mass, half of the c-quark charge)

⋆ . . . but smaller theoretical uncertainties due to larger mass of b quark ($\rightarrow$ QCD scale)

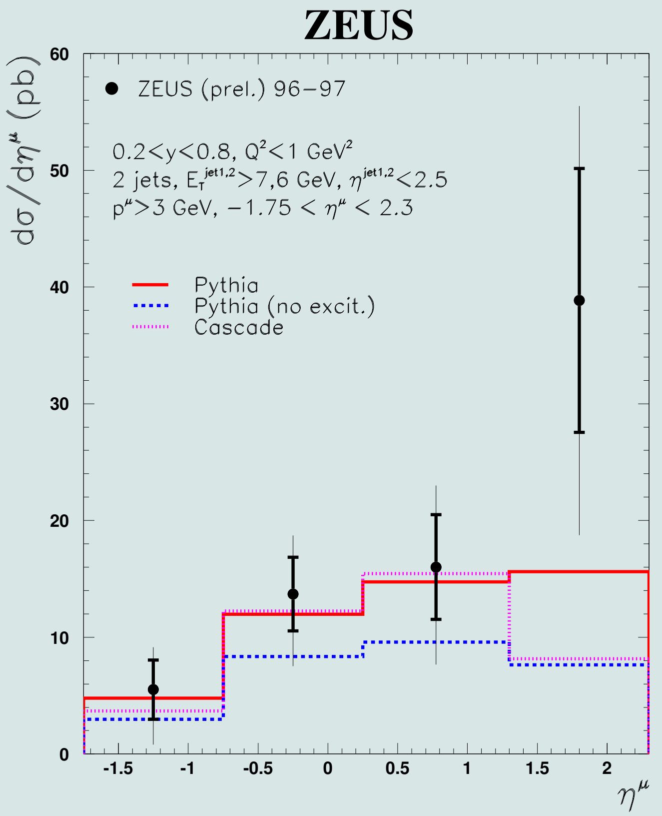
Beauty tagging

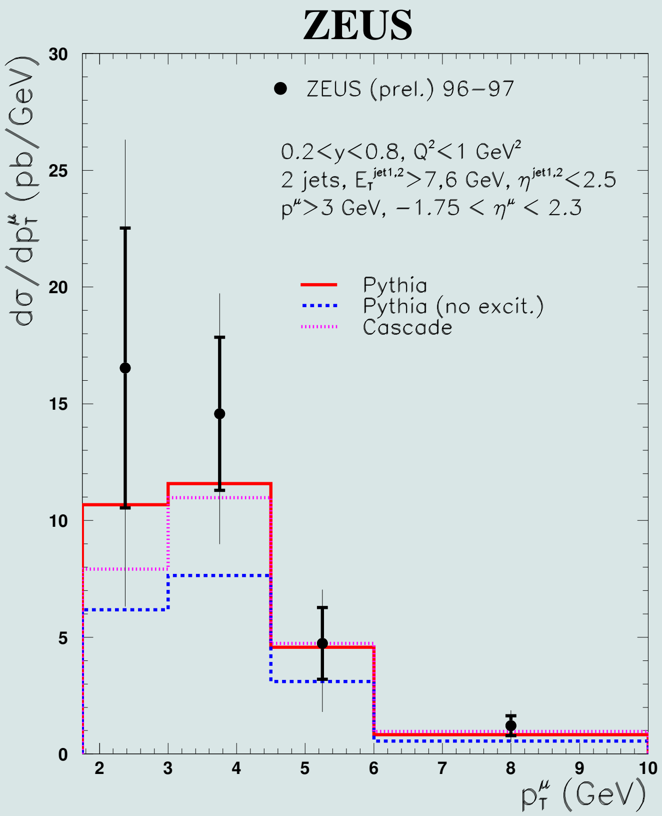
⋆ **Signature**: muons or electrons from b semi-leptonic decays ($\mathcal{B} \sim 10$ %) associated with jets $\rightarrow$ signal enhanced sample

⋆ **Signal extraction**: on a statistical basis by fitting the ditributions of sensitive variables:

- transverse momentum with respect to the closest jet (p_T^{rel}) (high b mass)
- lepton track impact parameter (δ) (long b lifetime)

ZEUS photoproduction $\mu - p_T^{rel}$: differential cross sections





96-97 data $\mathcal{L} = 37\ \mathrm{pb}^{-1}$

Visible cross sections

Reasonable description with PYTHIA with b-excitation and CASCADE

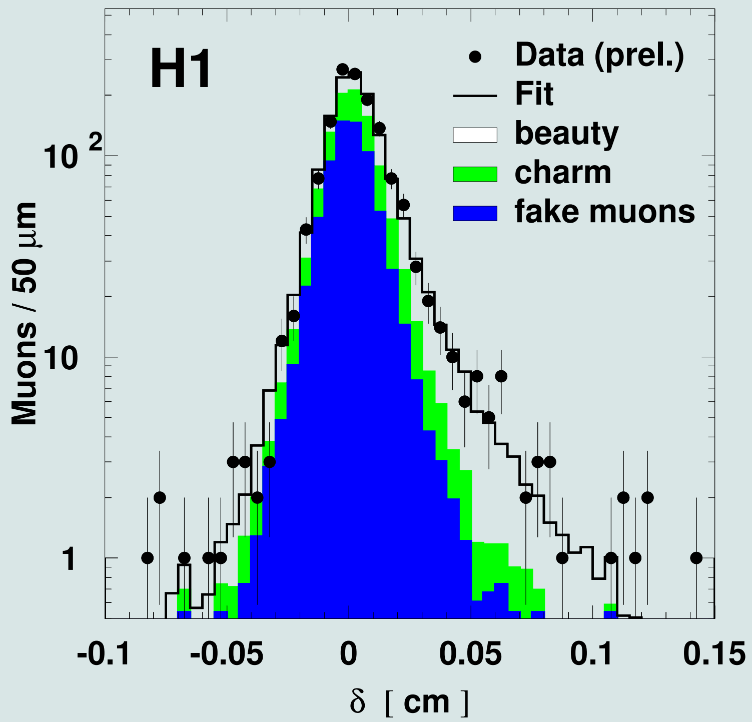
Possible excess in proton direction ?

the whole data sample is being analyzed

$Q^2 < 1\ \mathrm{GeV}^2$	$0.2 < y < 0.8$	$E_T^{jet\ 1(2)} > 7(6)\ \mathrm{GeV}$	$\vert\eta^{jet\ 1(2)}\vert < 2.5$
	forward μ	$p_\perp^\mu > 1.5\ \mathrm{GeV}$	$1.4 < \eta^\mu < 2.3$
	central-backward μ	$p^\mu > 3\ \mathrm{GeV}$	$-1.75 < \eta^\mu < 1.3$

H1 photoproduction: 1997 data, p_T^{rel} and lifetime analysis

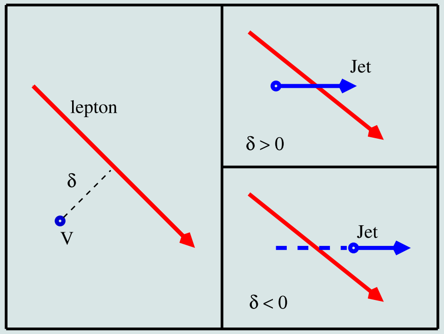
b production: impact parameter



1415 μ **candidates**

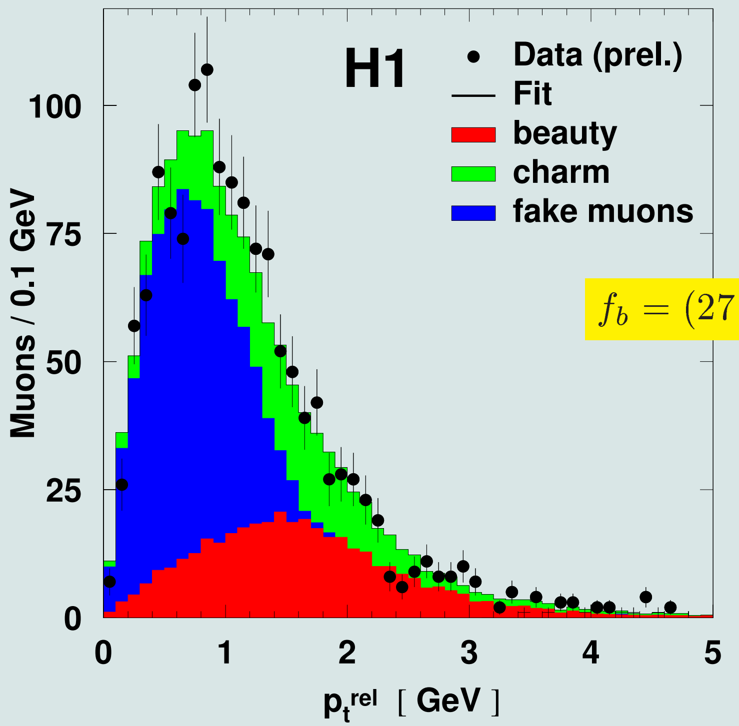
$\mathcal{L} = 14.7\ \mathrm{pb}^{-1}$

$f_b = (26 \pm 5)\ \%$



$E_T^{jets} > 5$ GeV

b production: p_t^{rel}



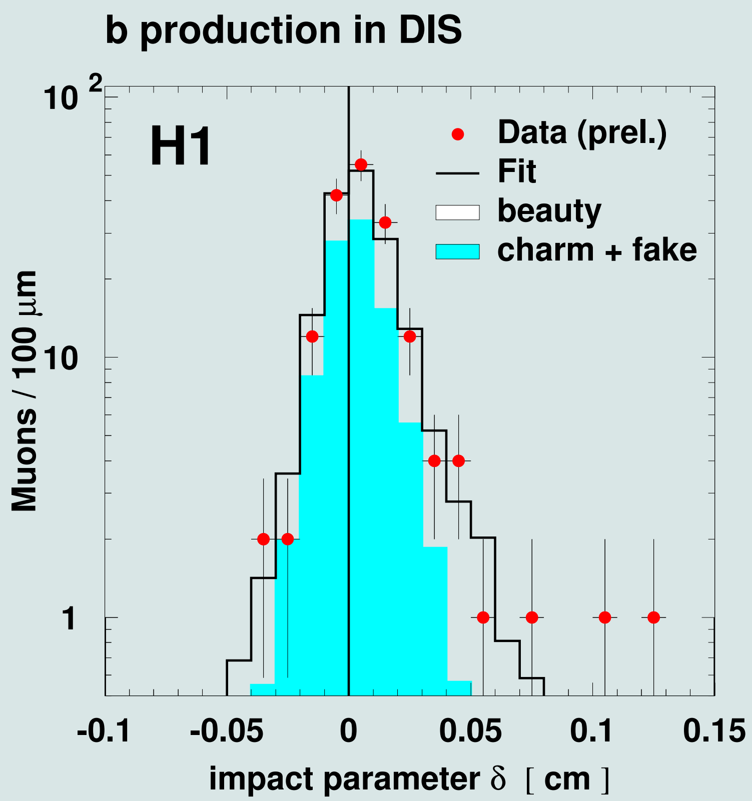
$f_b = (27 \pm 3)\ \%$

$Q^2 < 1\ \mathrm{GeV}^2 \qquad 0.1 < y < 0.8$

$p_T^{\mu} > 2\ \mathrm{GeV/c} \qquad 30^\circ < \theta^\mu < 135^\circ$

$\delta + p_T^{rel}$ **2D fit**	$\sigma_{vis} = 160 \pm 16(\mathrm{sta.}) \pm 29(\mathrm{sys.})$ pb
H1 combined	$\sigma_{vis} = 170 \pm 25$ pb
AROMA MC	$\sigma_{vis} = 38$ pb
CASCADE MC (CCFM)	$\sigma_{vis} = 67$ pb
NLO pQCD (FMNR)	$\sigma_{vis}^{NLO} = (54 \pm 9)$ pb

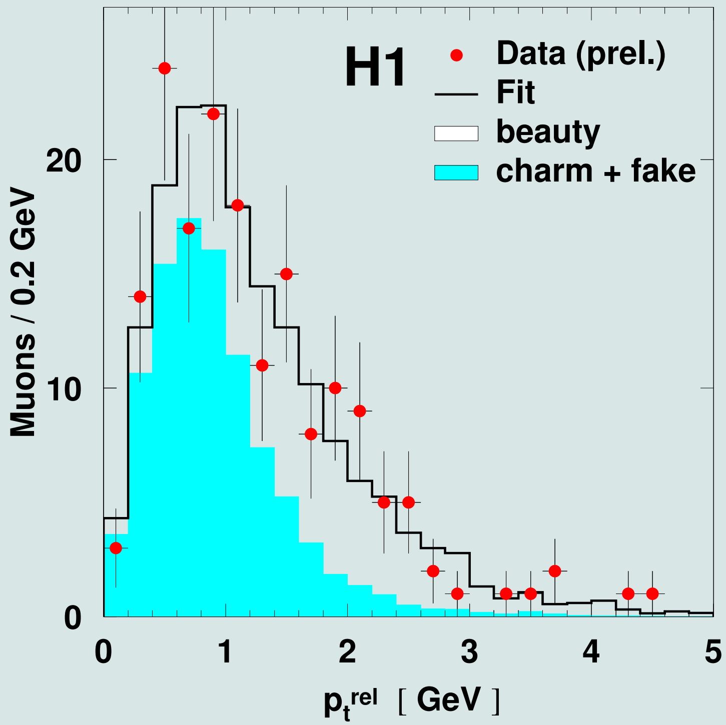
H1 DIS: 1997 data, p_T^{rel} and lifetime analysis



$171\ \mu$ **candidates**

$\mathcal{L} = 10.5\ \mathrm{pb}^{-1}$

$f_b = (43 \pm 8)\ \%$

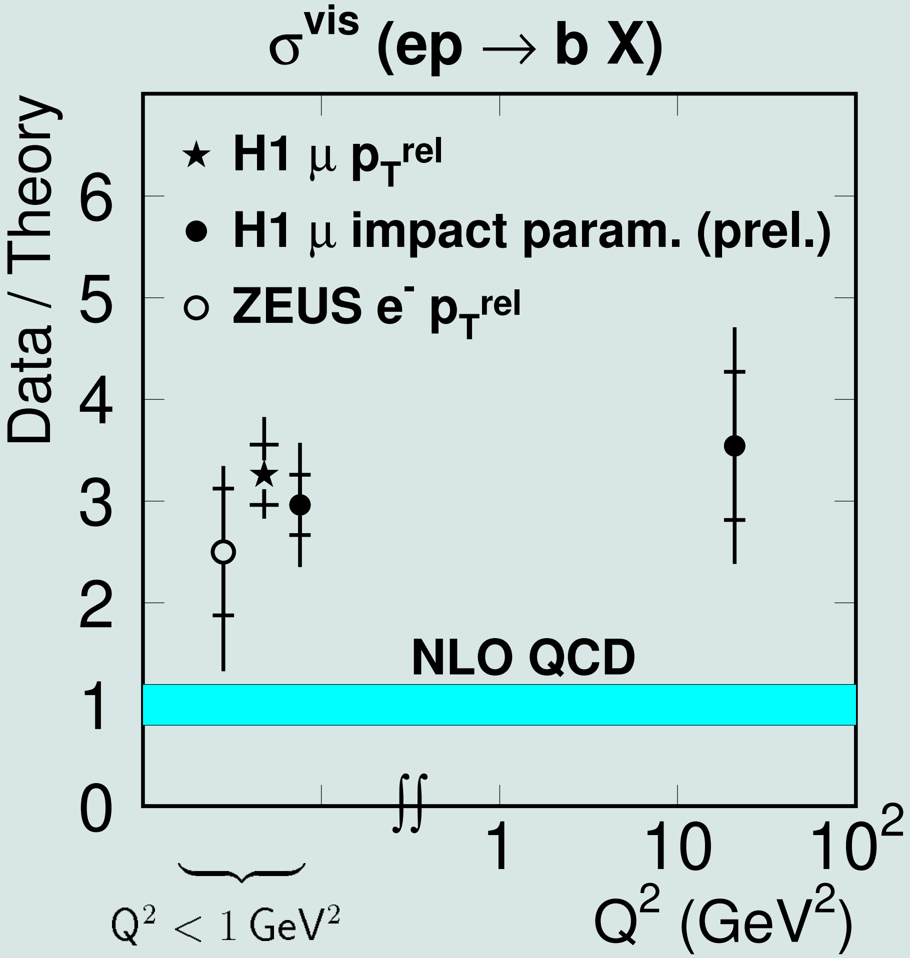


$2 < Q^2 < 100\ \mathrm{GeV}^2$ $\quad 0.05 < y < 0.7$

$p_T^{\mu} > 2\ \mathrm{GeV/c}$ $\quad 30° < \theta^{\mu} < 135°$

$\delta + p_T^{rel}$ **2D fit**	$\sigma_{vis} = 39 \pm 8(\mathrm{sta.}) \pm 10(\mathrm{sys.})\ \mathrm{pb}$
AROMA MC	$\sigma_{vis} = 9\ \mathrm{pb}$
CASCADE MC (CCFM)	$\sigma_{vis} = 15\ \mathrm{pb}$
NLO-DGLAP (HVQDIS)	$\sigma_{vis}^{NLO} = (11 \pm 2)\ \mathrm{pb}$

Overview on b-production at HERA. NLO - data



- Measurements **above NLO**
- Studied by **both experiments**
- Two channels ($e - \mu$) and methods (**mass-lifetime**)
- Both in γp **and DIS**

That's interesting !

Summary

⋆ Open charm

- **large statistics** ($\sim 0.1\ \mathrm{fb}^{-1}$) allow precise measurements (i.e. $c-$**fragmentation universality** - $e^+e^- \sim ep$)
- $\cos\theta^*$ provides a clear signature of **gluon propagator** for events with $x_\gamma^{OBS} < 0.75$
- In DIS c-production amounts to $\sim 30 - 40\%$ of σ^{tot} at low x and high Q^2. **NLO describes well**

⋆ Open beauty

- Also in ep production (DIS (recent) and PHP) measured cross sections are surprisingly **higher than NLO**
- H1 **"Impact parameter analysis"** confirms results of "p_T^{rel}" approach
- Need to look at **differential cross sections** with more statistics. Analysis of **new data** under way.

Outlook

- $\star$ Complete analysis of the whole 95/00 data–set.
- $\star$ Luminosity upgrade finished (hope for $1\ \mathrm{fb}^{-1}$ in 2006 $\equiv 10\ \times$)
- $\star$ Generally improved tracking (new Si-micro-vertex for ZEUS)

A lot of interesting heavy flavour physics from HERA in the near future

Spare tranparencies

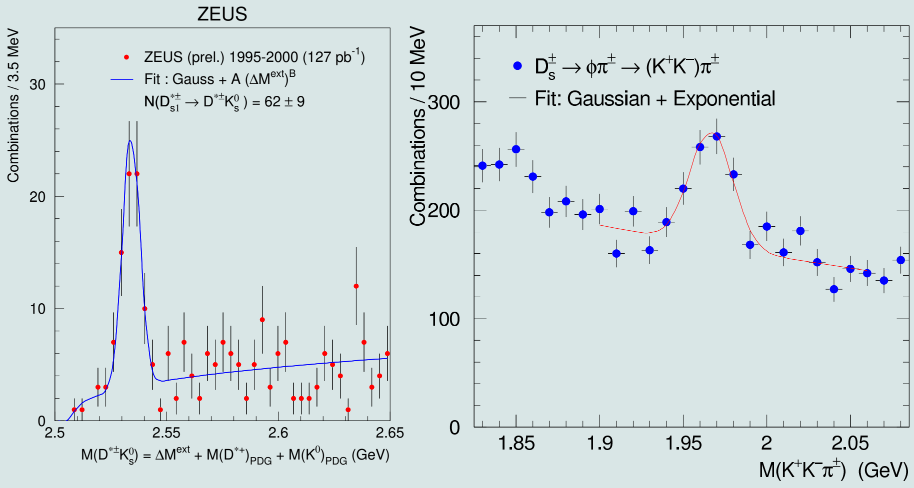
Charm fragmentation: γ_s D^+_{s1} p_V

	ep	e^+e^-
$\frac{\sigma(D_s)}{\sigma(D^*)}$	$0.41 \pm 0.07^{+0.02}_{-0.05}$	0.43 ± 0.04
$\gamma_s = P_s/P_{u,d}$	0.27 ± 0.05	0.26 ± 0.03

$\frac{\text{vector}}{\text{pseudoscalar}}$ **meson production**

$$p_V = \frac{D^*}{D^* + D^0}$$

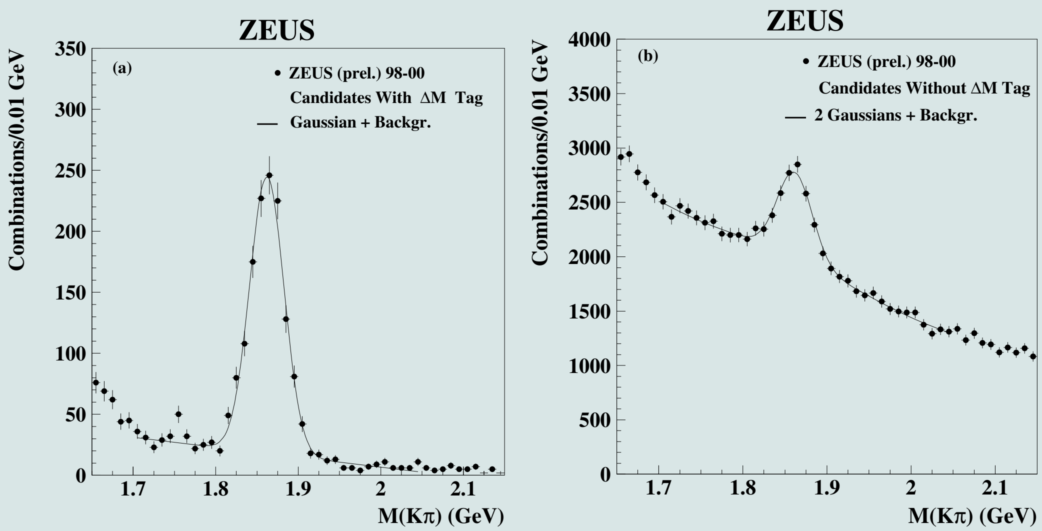
ep	$0.546 \pm 0.045 \pm 0.028$
OPAL	0.57 ± 0.05
ALEPH	0.595 ± 0.045



$D_{s1} \to D^* K_s$ $\qquad$ $D_s \to \phi(\to K^+K^-)\pi$

$$f(c \to D^+_{s1})$$

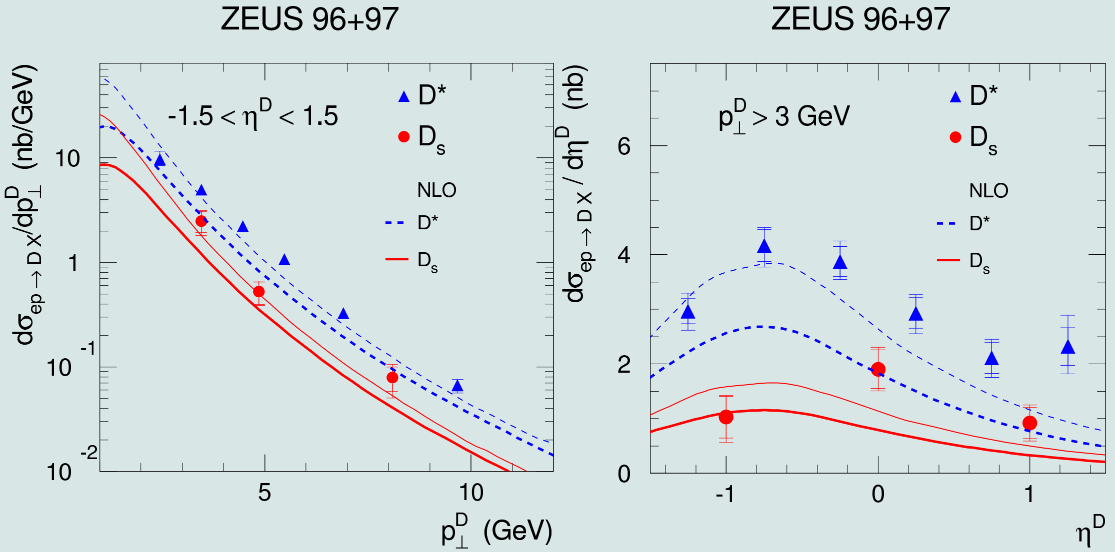
ep	$(1.24 \pm 0.18^{+0.08}_{-0.06} \pm 0.14)$ %
OPAL	$(1.6 \pm 0.4 \pm 0.3)$ %
ALEPH	$(0.94 \pm 0.22 \pm 0.07)$ %



Consistent picture in ep and e^+e^-

charm fragmentation universality

D^* and D_s



Charm in photoproduction vs NLO

$Q^2 < 1\ \mathrm{GeV}^2 \quad 130 < W < 180\ \mathrm{GeV}$

★ **NLO: fixed order (FNMR) MRSG (p); GRV-G HO (γ)**

★ $\mu_F = 2m_\perp$

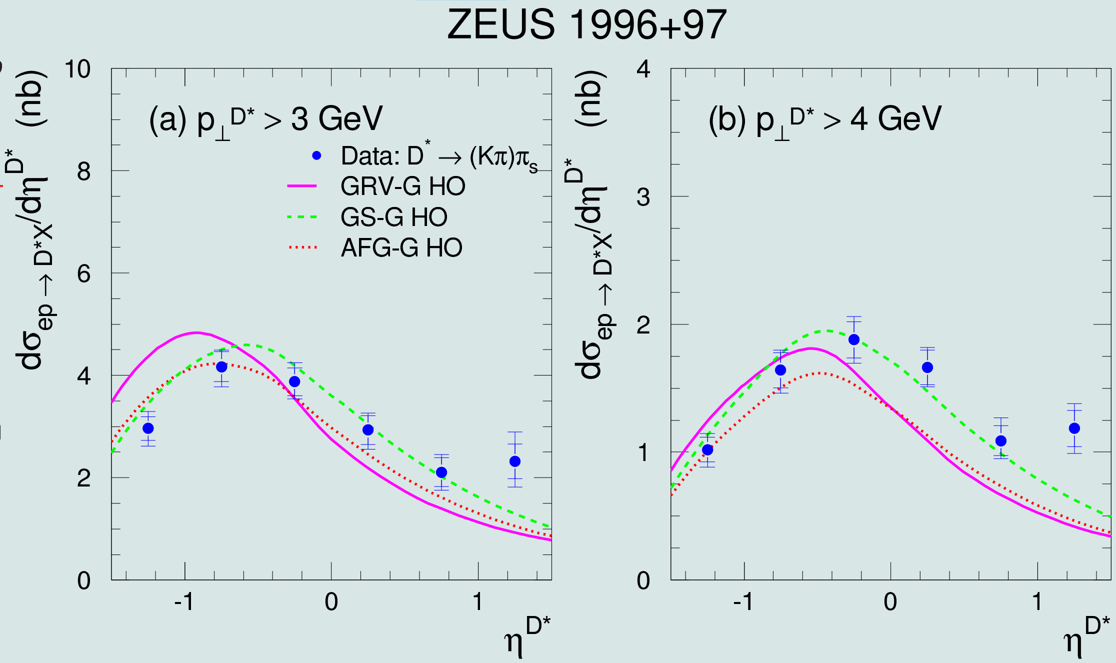
thick curves : $\mu_R = m_\perp \quad m_c = 1.5$ GeV

thin curves : $\mu_R = 0.5\ m_\perp \quad m_c = 1.2$ GeV

nominal: $\sim 1.8 \times$ **below; extreme: still below**

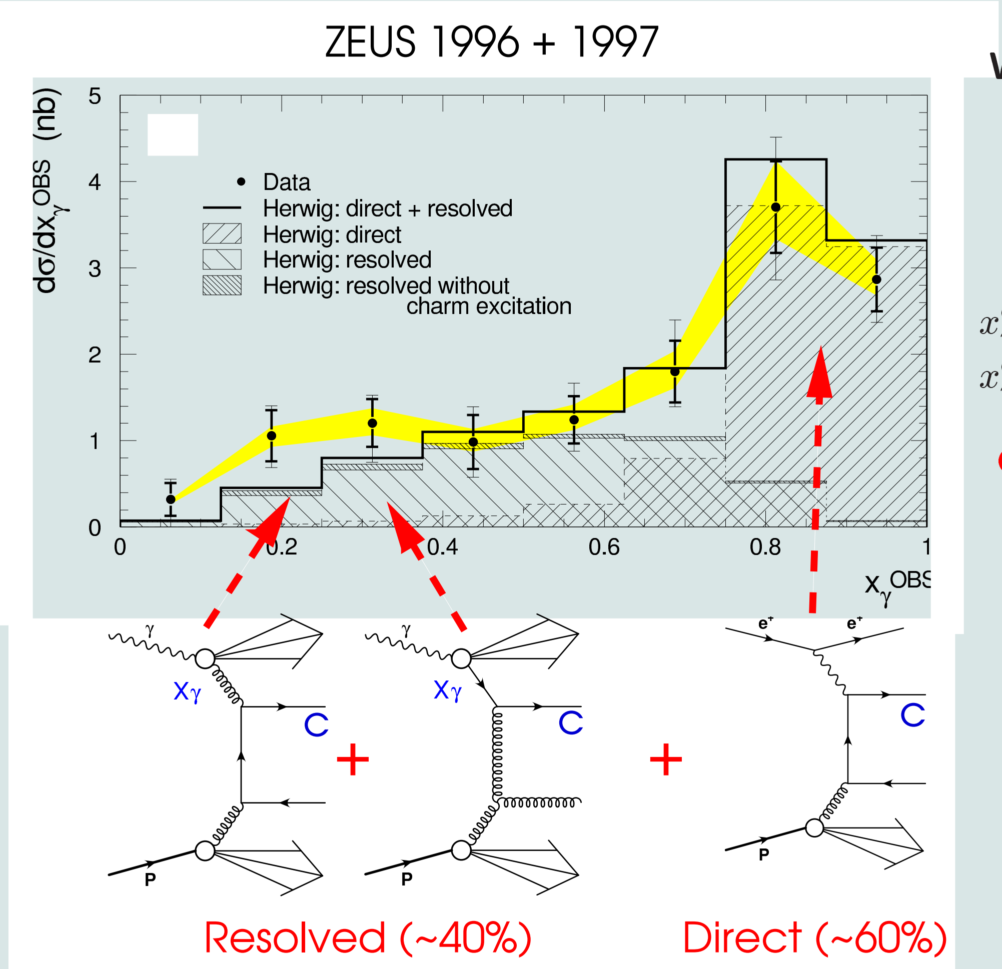
$p_\perp$ **shape ? data over NLO predictions for** D**-meson in** p **direction**

D^*



- **NLO: resummed CTEQ4M (p), 3 γ pdfs**
- $m_c = 1.5$ GeV, $\mu_R = m_\perp$, $\mu_F = 2m_\perp$
- **GS-G HO close to data . . . but c and u quarks in γ on the same footing already at $m_\perp \simeq 4.5$ GeV ?**

Photon structure in presence of charm



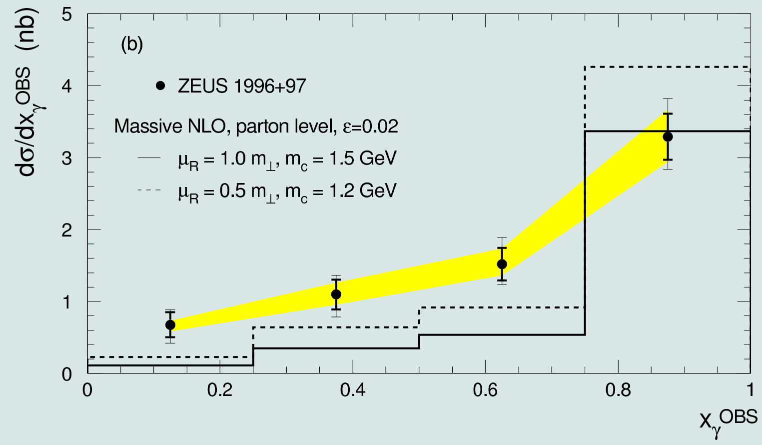
We can use the D^* **photoproduction** data also to study the **photon structure**, in particular its **charm content**.

Fraction of γ momentum participating in the dijet production

$x_\gamma^{OBS} = 1$ for **direct** γ,
$x_\gamma^{OBS} < 1$ for **resolved** γ

$$x_\gamma^{OBS} = \frac{\sum_{jets} E_T e^{-\eta}}{2yE_e}$$

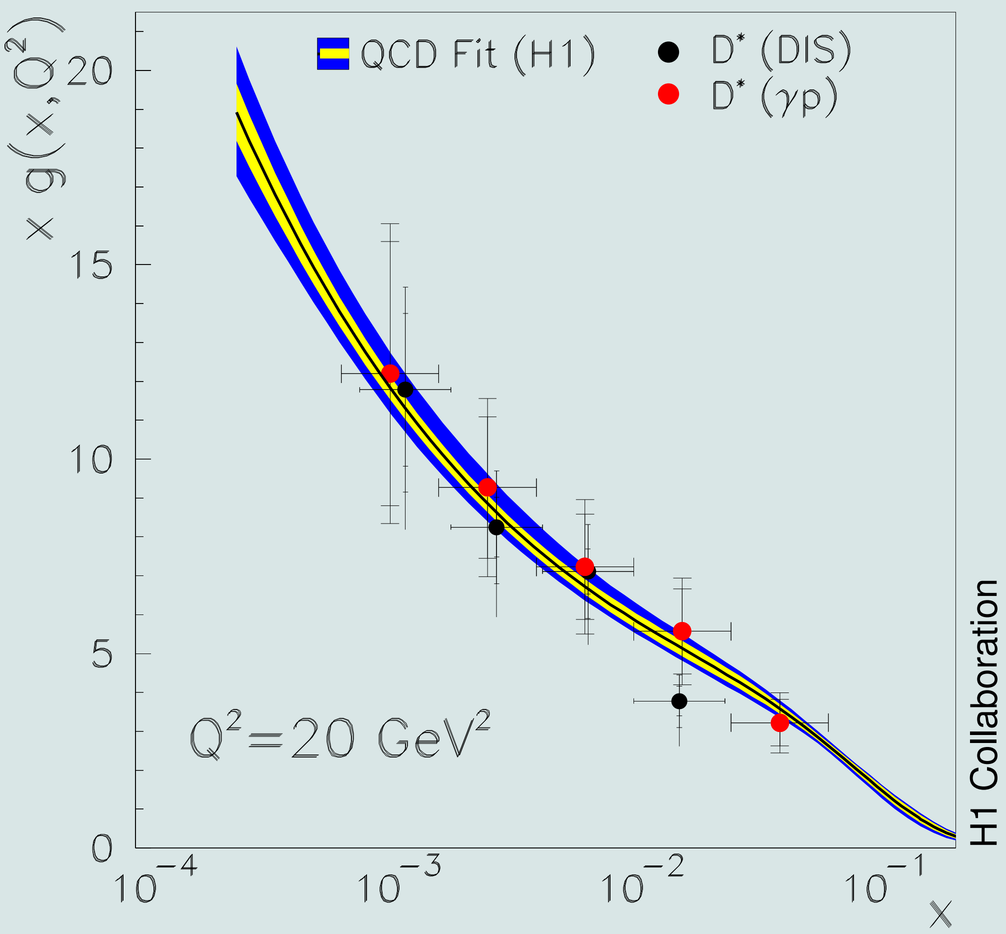
- **DGLAP LO MC: Excitation in γ ($\sim 40\ \%$)**



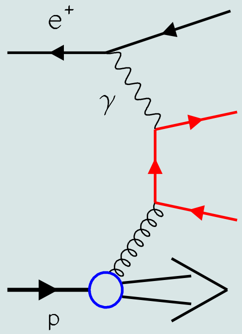
- **Fixed order NLO (no excitation in): poor description of low x_γ tail**

Gluon density extraction

H1 analysis $\mathcal{L} \simeq 10\ \mathrm{pb}^{-1}$



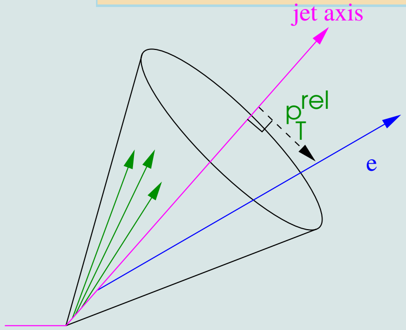
D^* data can be used to directly extract the proton g-density $x_g g(x_g)$, via BGF diagram



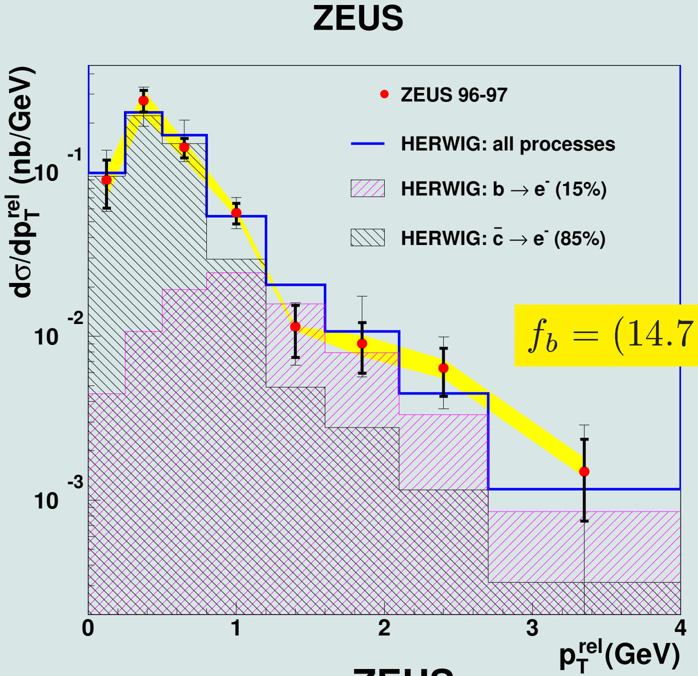
- ★ **Reconstruct x_g from D^* and scattered $e^{\pm}$**
- ★ **Correct for higher order contributions and fragmentation by unfolding with NLO QCD**

- **DIS and PHP results are in good agreement**
- **Result consistent with inclusive F_2 scaling violation analysis**
- **Error dominated by statistics and fragmentation uncertainties**

ZEUS photoproduction: 1996/97 data, p_T^{rel} electron analysis



$943 \pm 69\ e^-$ **from s-l decay selected using** dE/dx **and calorimeter information**



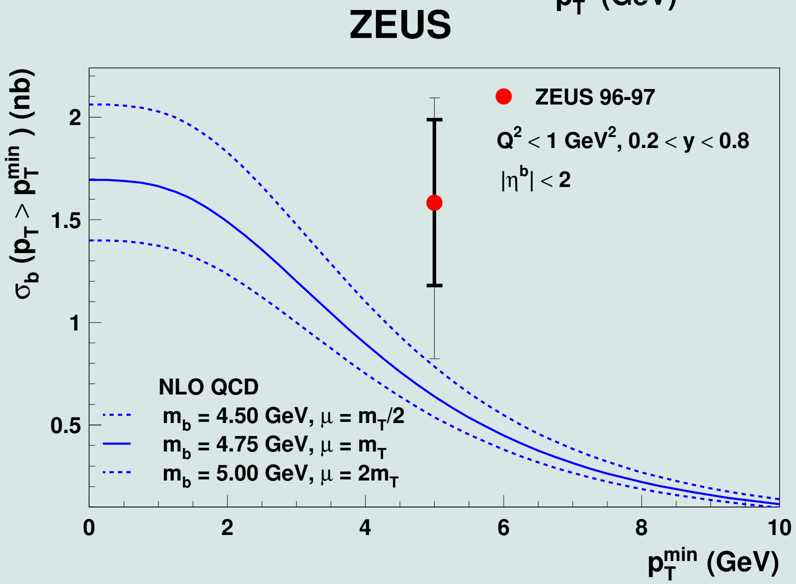
$f_b = (14.7 \pm 3.8)\ \%$

Kinematical region

$Q^2 < 1\ \text{GeV}^2$	$0.2 < y < 0.8$	$E_T^{jet\ 1(2)} > 7(6)\ \text{GeV}$
$\lvert\eta^{jet\ 1(2)}\rvert < 2.4$	$p_T^{e^-} > 1.6\ \text{GeV}$	$\lvert\eta^{e^-}\rvert < 1.1$

$$\sigma^{b\to e^-}_{e^+p\to e^+\text{dijet}e^-X} = (24.9 \pm 6.4(\text{st.})^{+4.2}_{-7.3}\ (\text{sys.})\ \text{pb})$$

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



MC extrapolation at parton level

$$\sigma^{ext}_{e^+p\to e^+bX} = (1.6 \pm 0.4(\text{st.})^{+0.3}_{-0.5}\ (\text{sys.})^{+0.2}_{-0.4}\ (\text{ext.})\ \text{nb})$$

NLO (FMNR): $(0.64^{+0.14}_{-0.10})$ **nb** **CASCADE:** (0.88 ± 0.08) **nb**