QCD03 Conference - Montpellier 04/07/2003

Heavy flavour production in ep collisions

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on behalf of

ZEUS and H1 collaborations

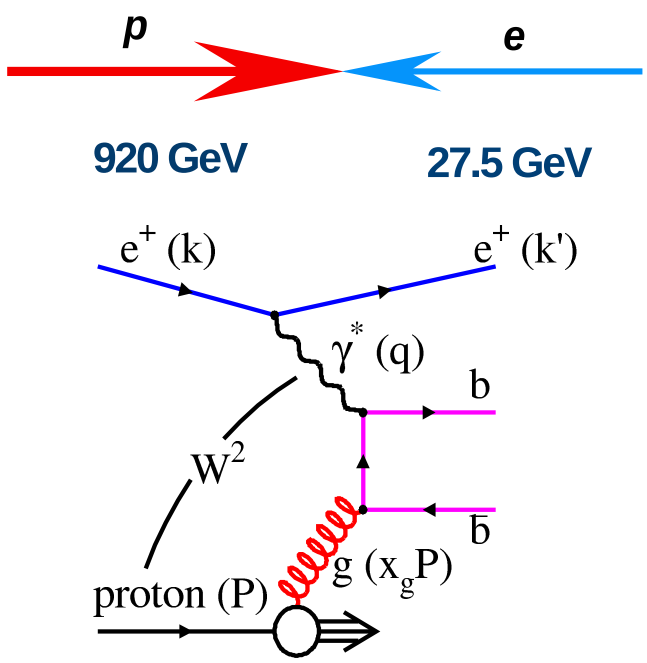
Outline (selected topics)

- HERA environment
- Theoretical framework
- D^* in photoproduction
- c dijet angular distributions
- c fragmentation studies
- c tagging via decay length: D^+ in DIS
- Open b production in DIS and PHP
- Summary and conclusions

Not covered: J/ψ, Υ, diffractive production, non pert. parameters, structure functions

HERA kinematics

$\sqrt{s} = 318$ GeV



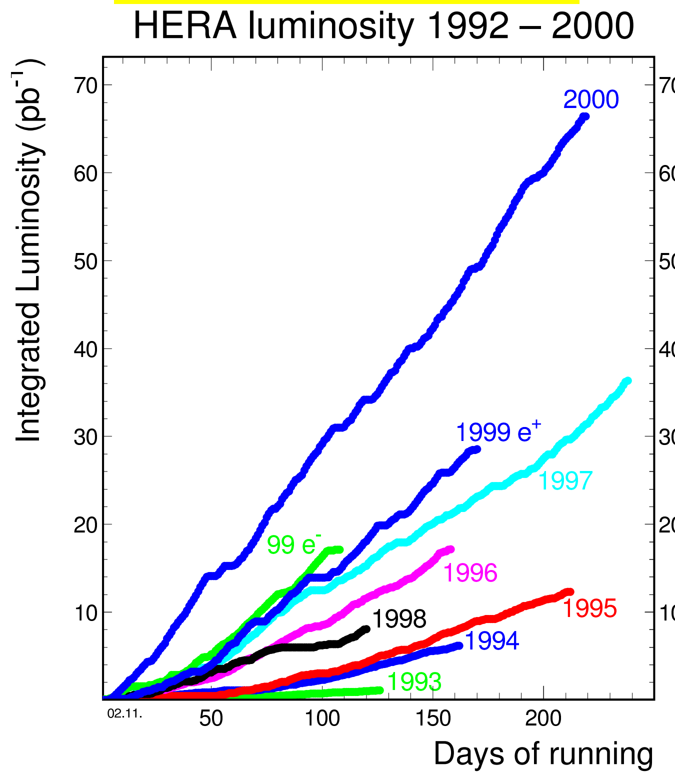
Kinematic variables

- ⋆ **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:** $W_{\gamma p} = (P+q) \simeq \sqrt{4E_eE_py}$

Kinematic regimes

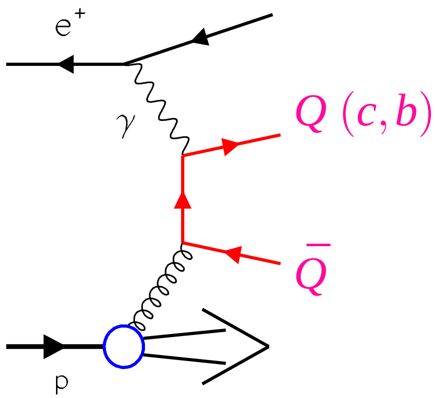
- ⋆ **Deep Inelastic Scattering (*DIS*)** $Q^2 > 1\ \mathrm{GeV}^2$
  scattered e ***visible in main detector***
- ⋆ **Photoproduction (*PHP*)** $Q^2 < 1\ \mathrm{GeV}^2$; $\langle Q^2 \rangle \sim 3\cdot 10^{-4}$
  no scattered e ***in main detector*** $\rightarrow$ ***quasi-real*** γ

$\mathcal{L}^{int}_{92-00} \sim 127\ \mathrm{pb}^{-1}$



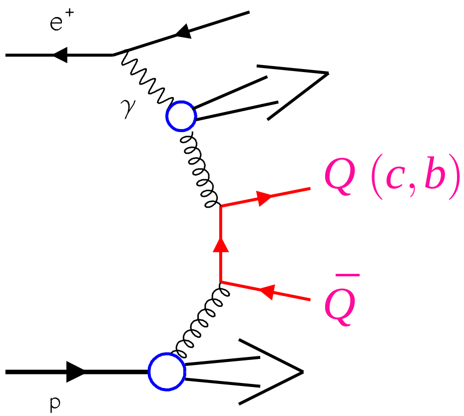
QCD LO contributions to open *HQ* production:

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



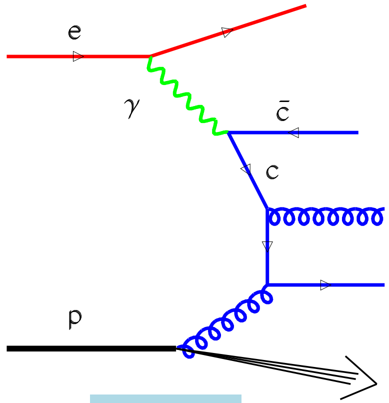
probe g in p $g_p(x,Q^2)$

"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 $m_Q >> \Lambda_{QCD} \to$ pQCD calculations
- ★ Direct handle on
  - gluon density in p $xg(x)$ (via *BGF* diagram)
  - γ partonic structure (resolved γ)
- ★ *HQ* quark $\to$ 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 flavour-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 flavour-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*

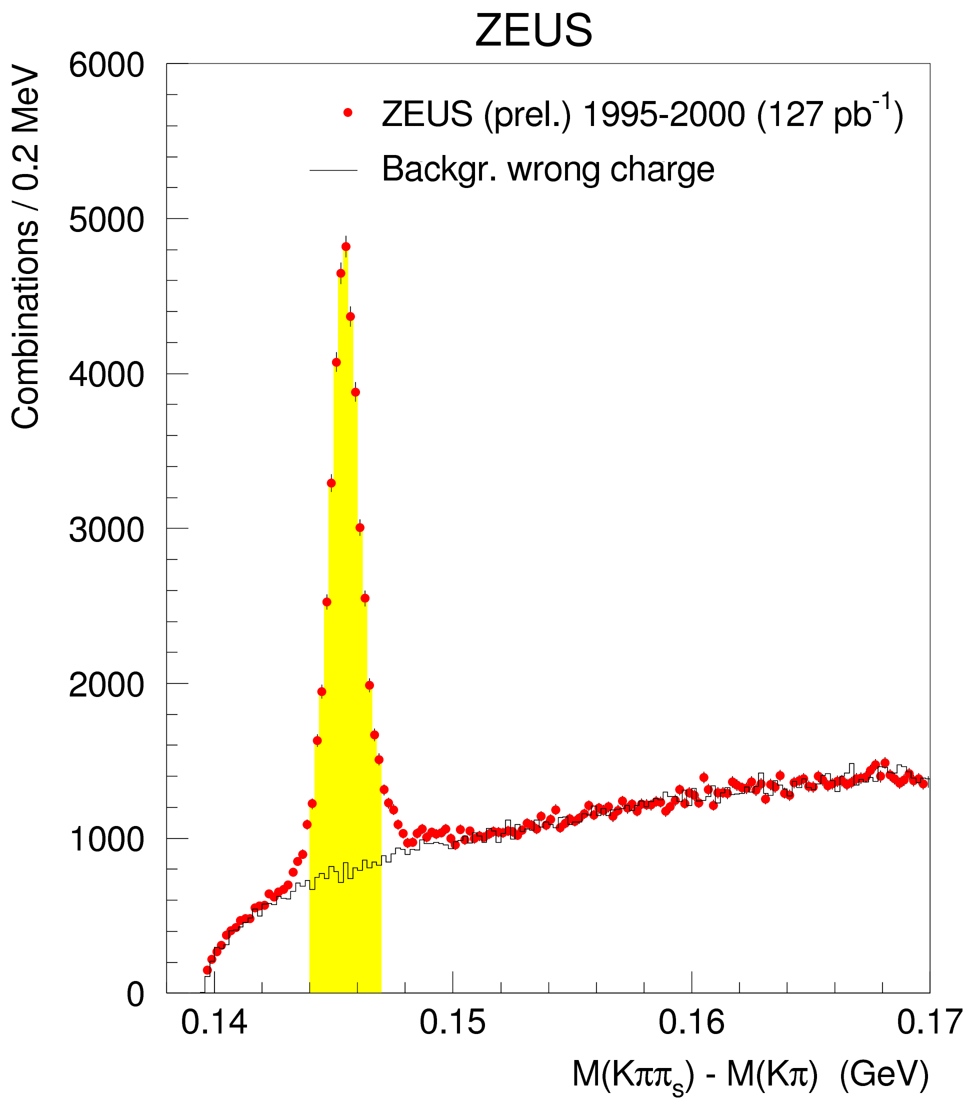
***hadronization*: Peterson function**

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

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)**

D^* in $\gamma^*\ p$: signal



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

$f(c \to D^*) = 0.235$

$\mathcal{B} = (2.62 \pm 0.10)\%$

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

$\mathcal{L} = 127\ \text{pb}^{-1}$ **(*ZEUS* 95-00)**

$p_T^{D^*} > 2$ GeV, $|\eta^{D^*}| < 1.5$

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

better than 1% stat. precision

D^* in $\gamma^*\ p$: comparison with QCD predictions

$\longrightarrow$ **FO NLO**, reasonable agreement, some deviations at forward η, low z ($z = \frac{(E-p_Z)(D^*)}{(E-p_Z)(\text{total})}$)

$\longrightarrow$ **matched FONLL**, Similar to FO, Slighlty worse at large p_T

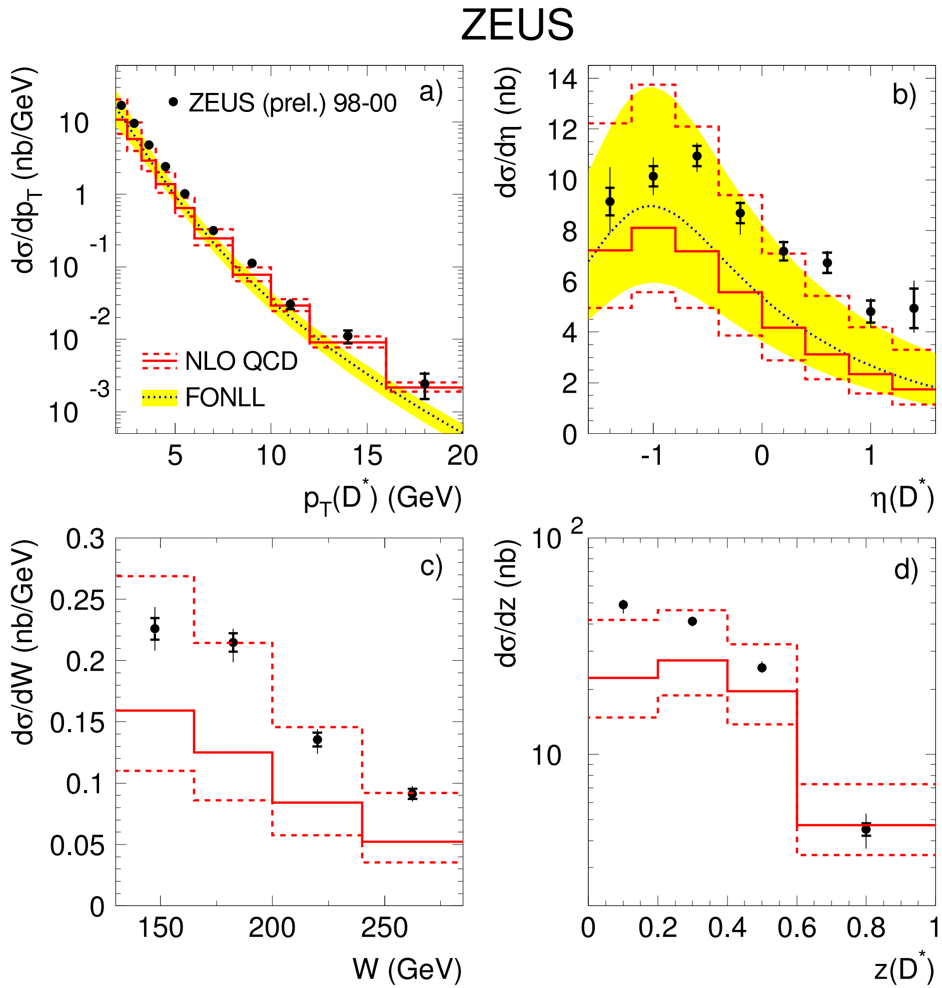
CTEQ5M1+AGF structure functions

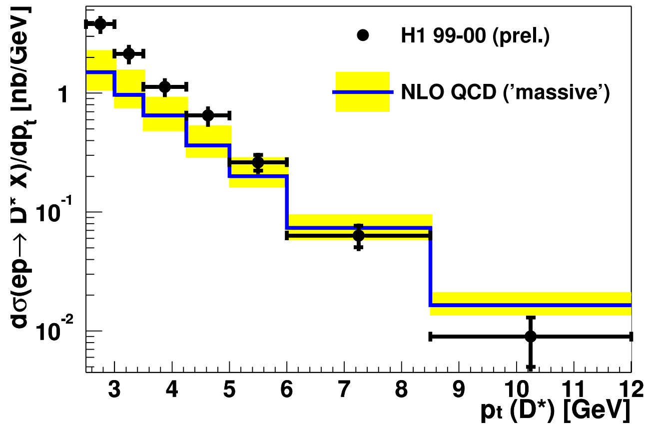
$m_c = 1.5 \pm 0.2$ GeV, $\mu_0 = \sqrt{m_c^2 + p_T^2}$

$\mu_R = \mu_F = \mu$, $\frac{\mu_0}{2} < \mu < 2 \cdot \mu_0$

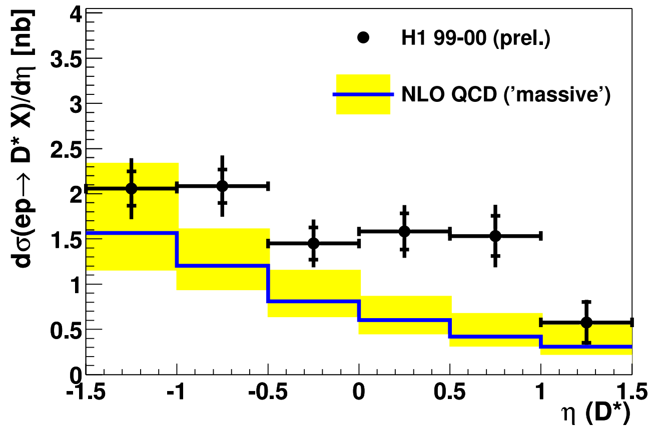
$f(c \to D^*) = 0.235$

$\varepsilon_{Peterson} = 0.035$ (FO NLO), 0.02 (FONLL)





H1

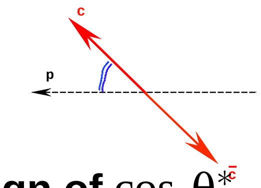


D^* in γ^* p: dijet angular distributions

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

- **Jet angle w.r.t. beam in dijet CM system:**

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



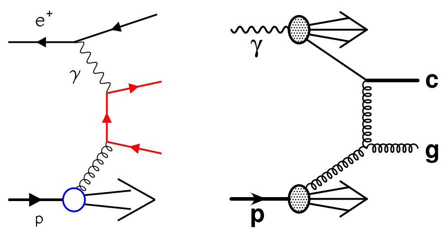
- **Associate D^* with charm jet → sign of $\cos\ \theta^*$**

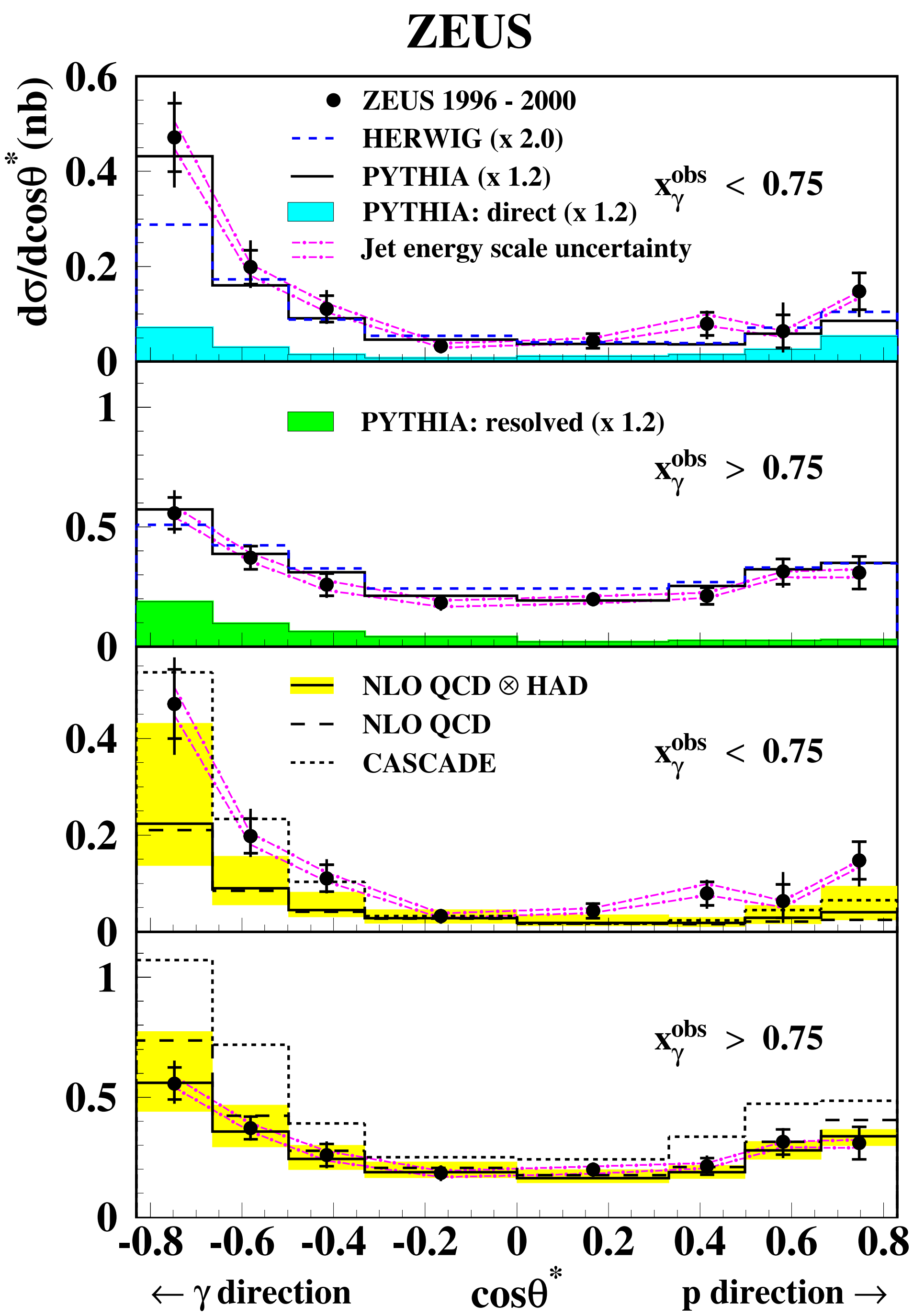
$$x_\gamma^{OBS} = \frac{\sum_{jets} E^T\ e^{-\eta}}{2yE_e}$$ ∼ **fraction of γ energy in the hard interaction**

- **Split sample into**
  - **resolved enriched ($x_\gamma^{OBS} < 0.75$)**
  - **direct enriched ($x_\gamma^{OBS} > 0.75$)**

Strong asymmetric rise of cross section in γ direction

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





➡ **clear indication for gluon propagator contribution**

➡ **charm in the photon**

D^* in γ^* p: dijet angular distributions

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

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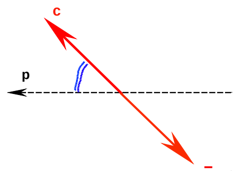

- Associate D^* with charm jet → sign of $\cos\ \bar{\theta}^*$

$$x_\gamma^{OBS} = \frac{\sum_{jets} E^T\ e^{-\eta}}{2yE_e}$$ ~ fraction of γ energy in the hard interaction

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Strong asymmetric rise of cross section in γ direction

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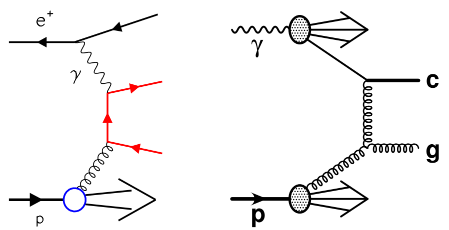
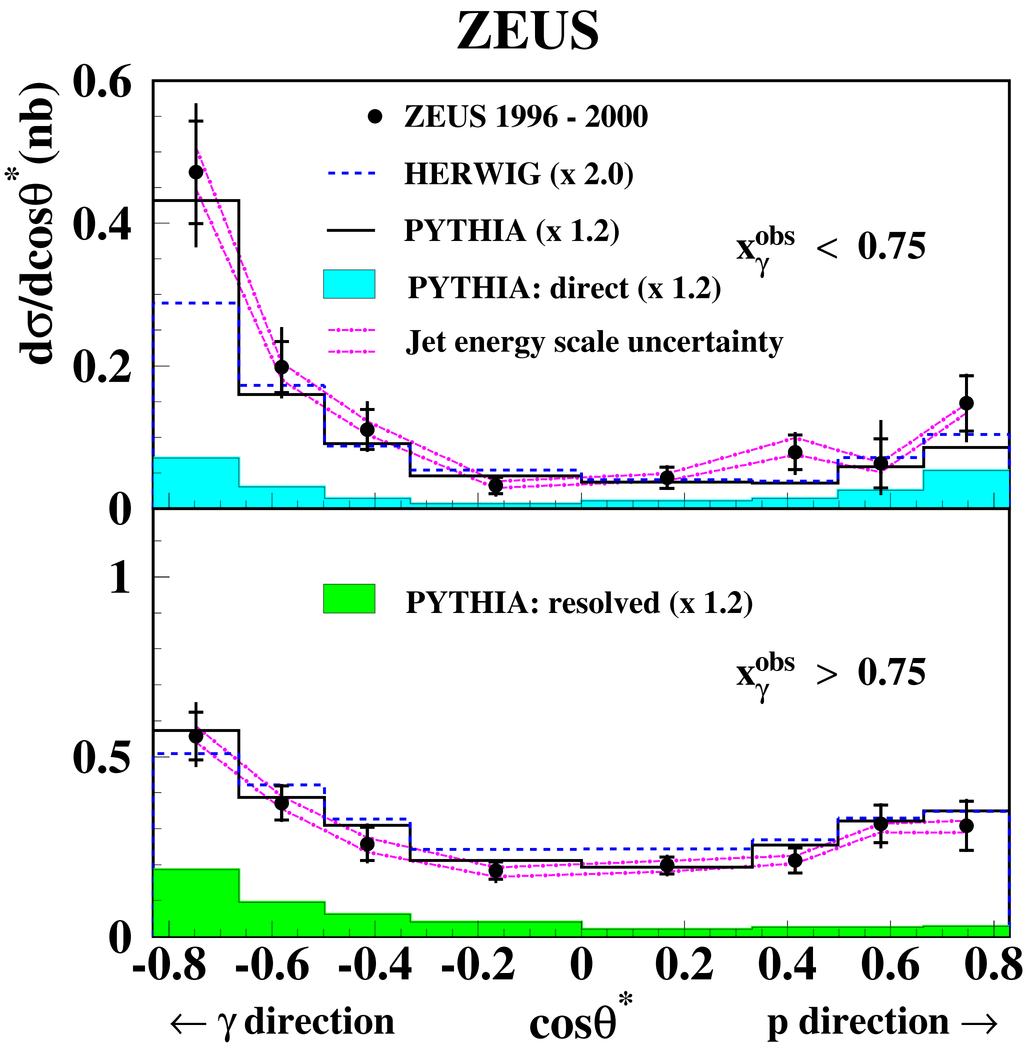




→ clear indication for gluon propagator contribution

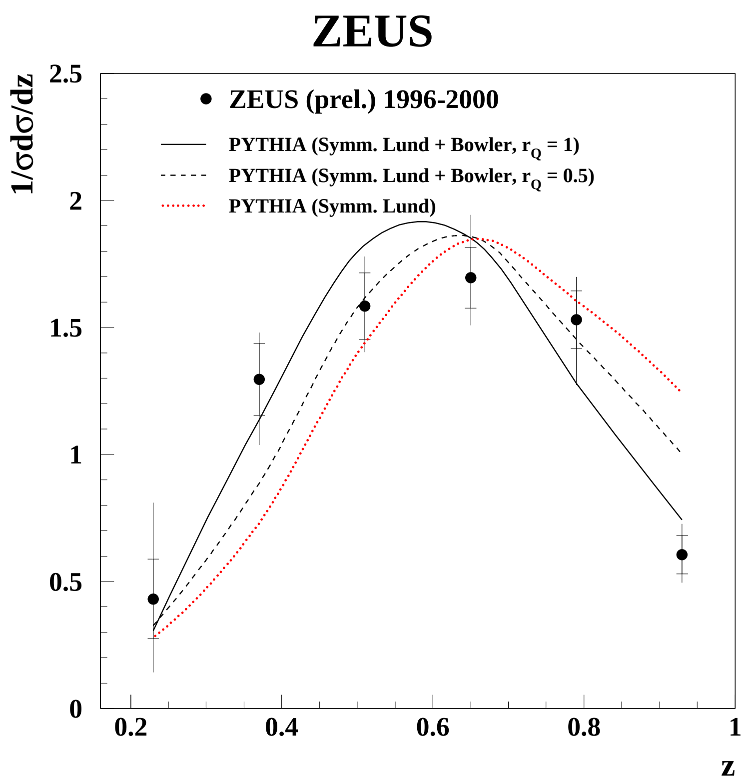
→ charm in the photon

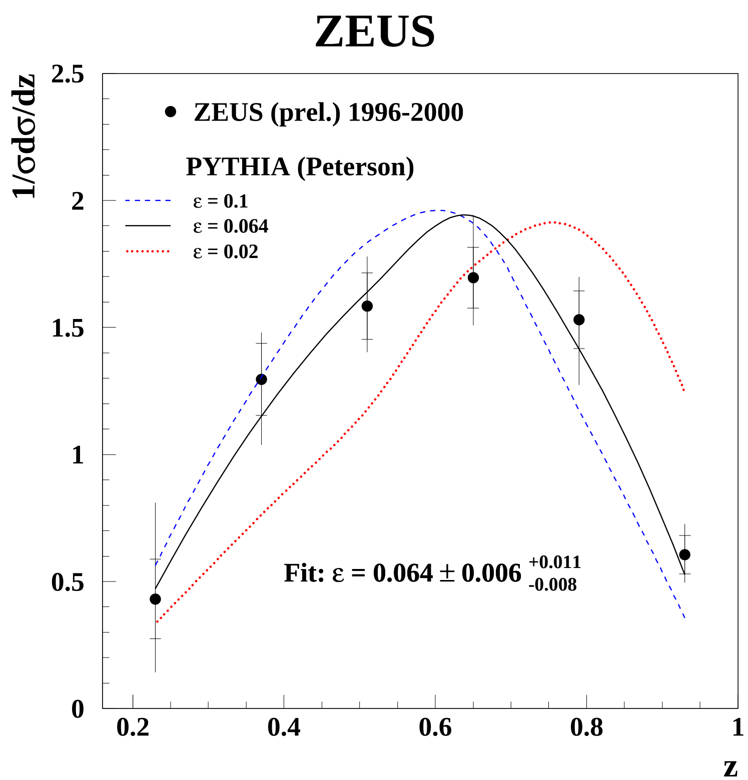
Charm fragmentation studies

$$Z = \frac{(E+p_{||})^{D^*}}{(E+p_{||})^{jet}}$$

Sensitive to fragmentation parameters.

$\mathcal{L} = 120\ pb^{-1}$





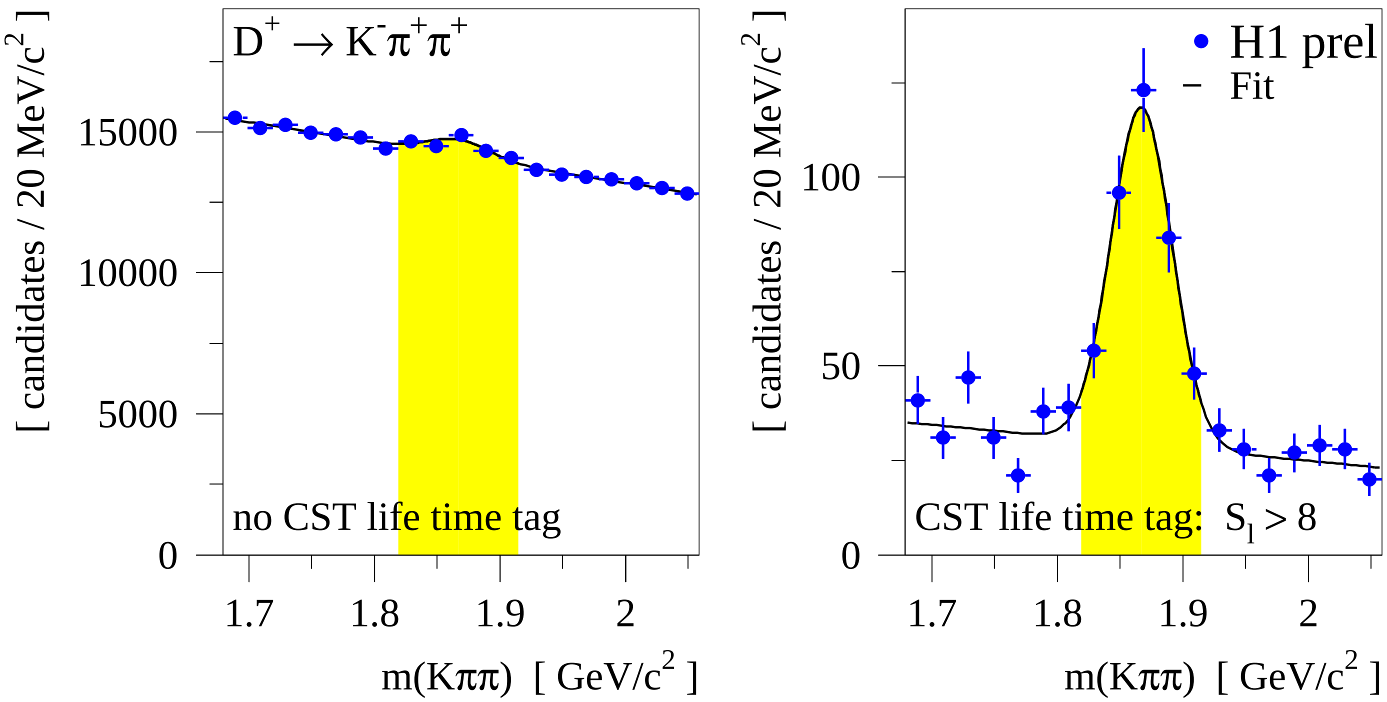
- k_t **clustering jets:** $E_T^{jet} > 9$ **GeV,** $|\eta^{jet}| < 2.4$
- $D^* \to K\pi\pi_s$: $p_T^{D^*} > 2$ **GeV** $|\eta^{D^*}| < 1.5$
- D^***-jet association: distance in** $\eta - \phi < 0.6$

- **Peterson best fit :** $\varepsilon = 0.064 \pm 0.006^{+0.011}_{-0.008}$ **(PYTHIA def.=0.05,**e^+e^-**:0.053)**
- **Bowler best fit:** $r_Q = 1$ **(default) (for** $a = 0.3$, $b = 0.58\ GeV^{-2}$ **fixed)**

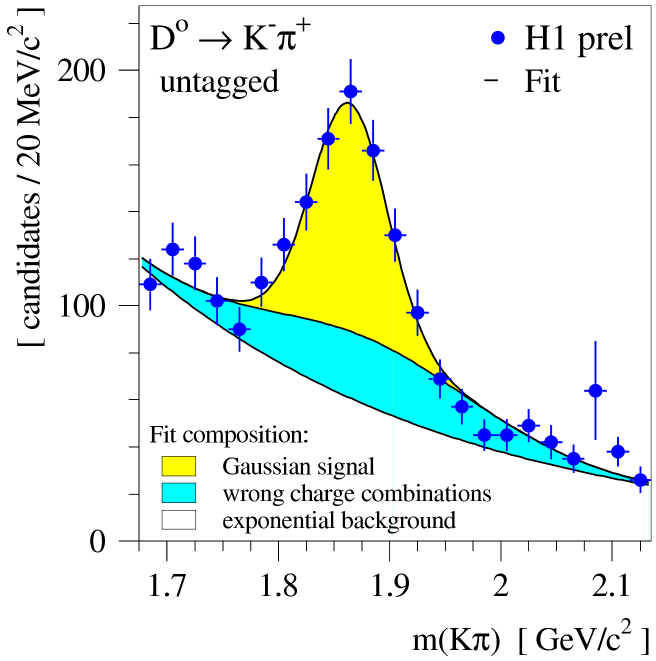
Charm tagging via decay length

- HERA I data (48 pb^{-1})
- No particle identification applied

$D^+ \to K^- \pi^+ \pi^+$



$D^0 \to K^- \pi^+$



- Measure "lifetime" ($l = \gamma c \tau$) at **100 μm** level

e.g. H1 silicon tracker (CST)

- Reduce background via decay length significance $S_l = \frac{l}{\sigma_l}$

$Bckg \downarrow \times O(300)$ $Sign/Bckg \uparrow \times O(50)$

D^+ production in DIS

$D^+ \rightarrow K^- \pi^+ \pi^+$

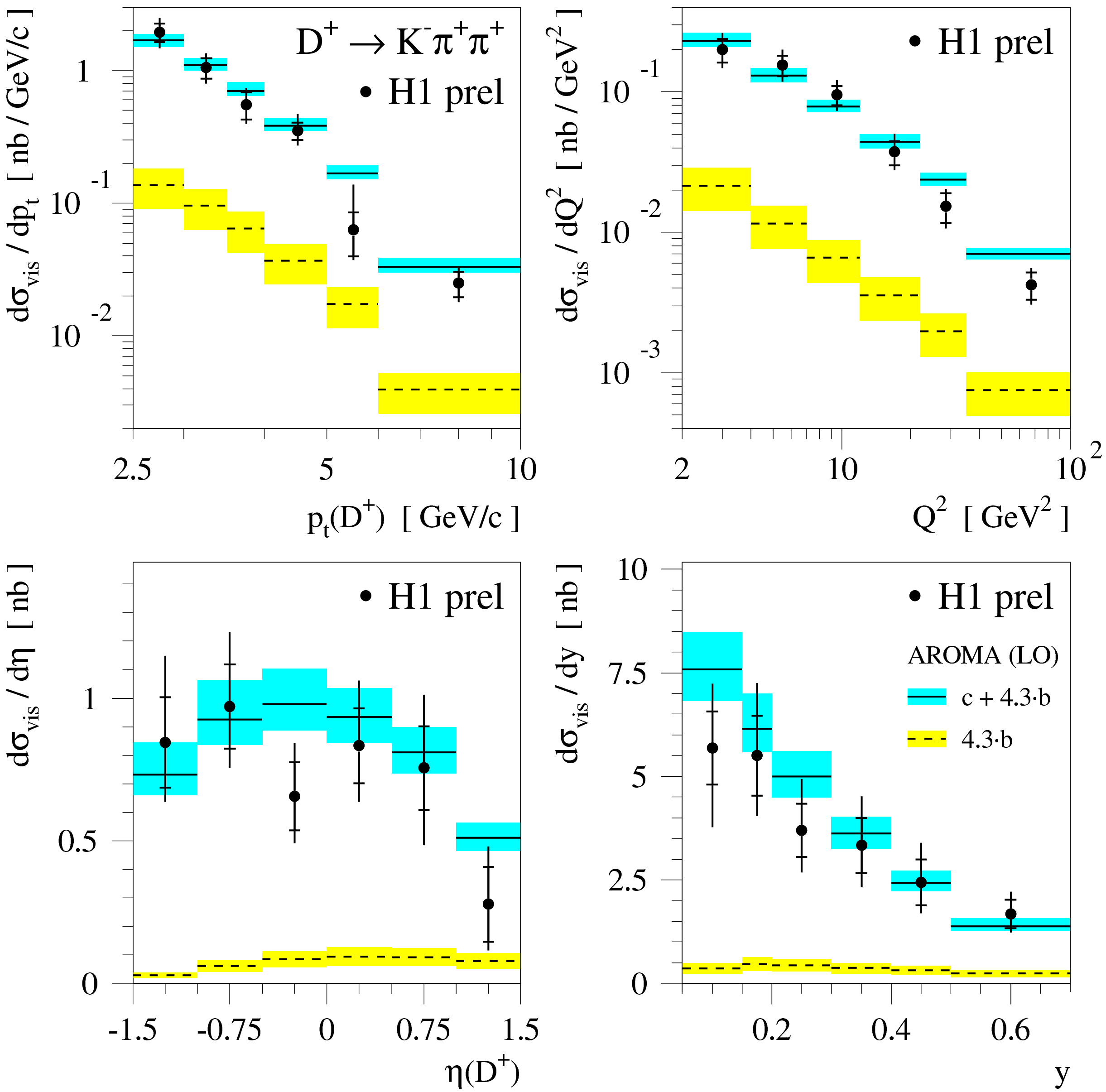
H1 data 1997/00, 48 pb^{-1}

$2 < Q^2 < 100$ **GeV^2**, $0.05 < y < 0.7$
$p_T^{D^+} > 2.5$ **GeV,** $|\eta^{D^+}| < 1.5$

$\sigma(ep \rightarrow eDX) = (2.16 \pm 0.19(\text{stat.})^{+0.46}_{-0.35}(\text{syst.}))$ **nb**

- **Normalization and shape well described by LO+PS MC prediction**
- **Similar results for D^* D^0 D_s production**

Fragmentation parameters: R_{ud}, P_V, γ_s also measured and found to be in agreement with values in e^+e^- (test of c–fragmentation universality)



Open beauty production

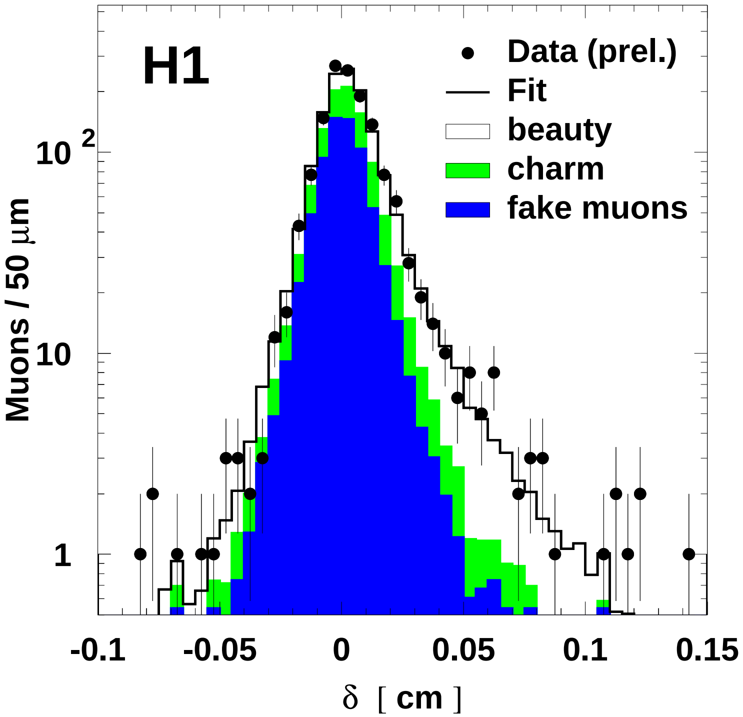
- **Cross section predicted to be low:** $\sigma_{c\bar{c}} : \sigma_{b\bar{b}} = 200 : 1$
  (larger mass, half of the c-quark charge)
- **. . . but smaller theoretical uncertainties due to larger mass of b quark ($\longrightarrow$ QCD scale)**

Beauty tagging at HERA

- **Signature: muons or electrons from b semi-leptonic decays ($\mathcal{B} \sim 10$ %) associated with jets $\longrightarrow$ signal enhanced sample**
- **Signal extraction: on a statistical basis by fitting the ditributions of sensible variables:**
  - **transverse momentum with respect to the closest jet (p_T^{rel}) (high b mass)**
  - **lepton track impact parameter (δ) (long b lifetime)**
  - **charge angle correlations with D^* (double tag tecnique) ($\Delta R(\mu - D^*)$) (decay kinematics)**

Beauty in photoproduction (H1)

b production: impact parameter

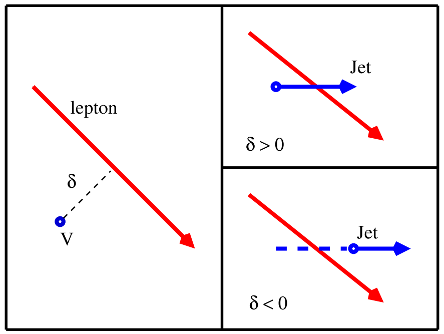


$1415\ \mu$ **candidates**

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

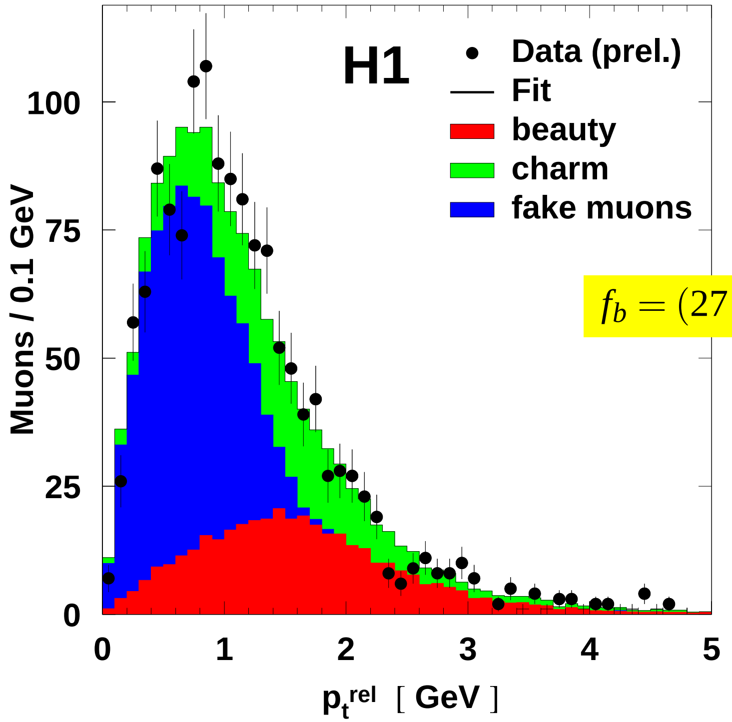
H1 1997 data

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



$E_T^{jets} > 5\ \text{GeV}$

b production: p_t^{rel}



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

p_T^{rel} **and lifetime analysis**

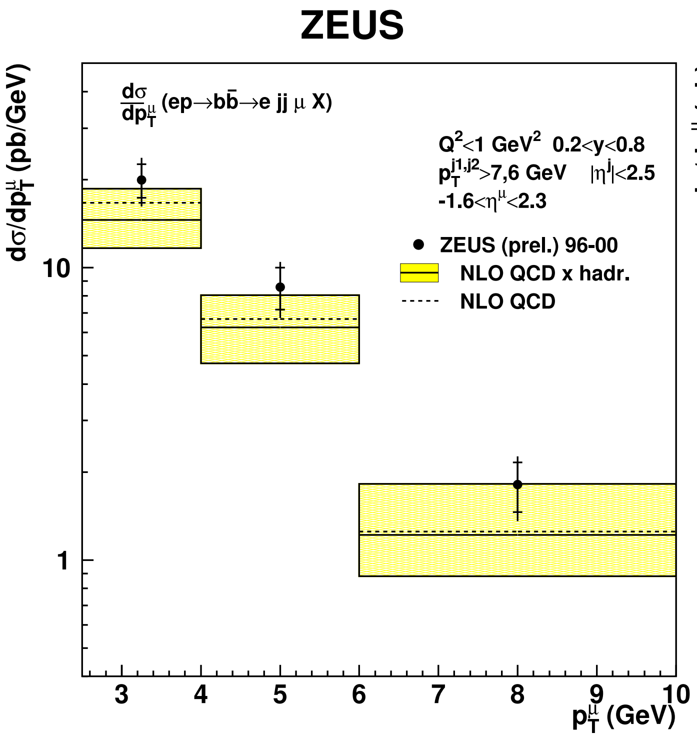
$Q^2 < 1\ \text{GeV}^2 \qquad 0.1 < y < 0.8$

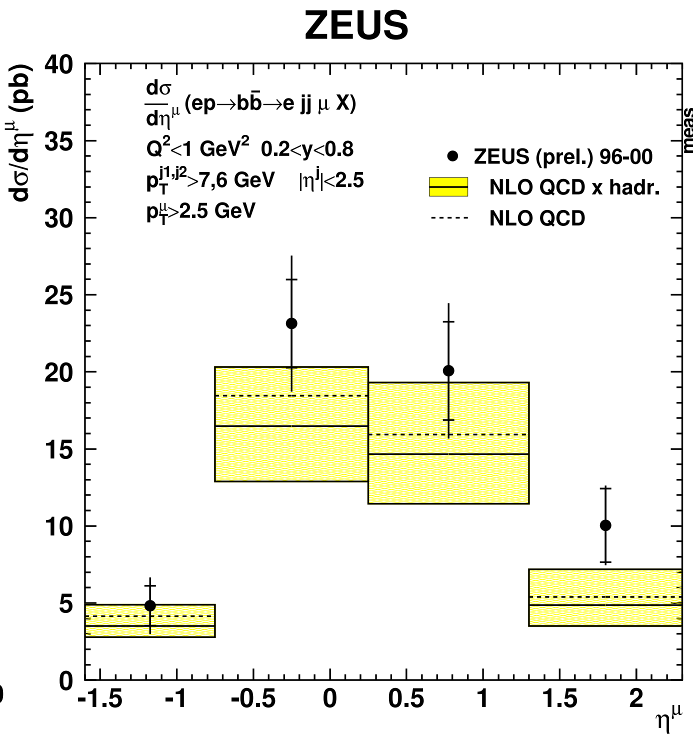
$p_T^{\mu} > 2\ \text{GeV/c} \qquad 30^\circ < \theta^{\mu} < 135^\circ$

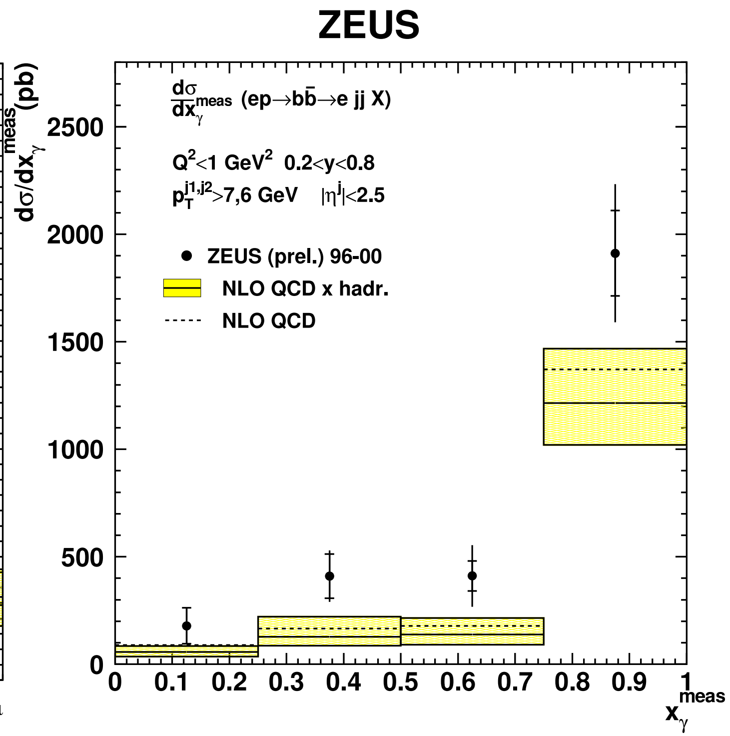
$\delta + p_T^{rel}$ ***2D* fit**	$\sigma_{vis} = 160 \pm 16(\text{sta.}) \pm 29(\text{sys.})\ \text{pb}$
***H1* combined**	$\sigma_{vis} = 170 \pm 25\ \text{pb}$
AROMA MC	$\sigma_{vis} = 38\ \text{pb}$
CASCADE MC (CCFM)	$\sigma_{vis} = 67\ \text{pb}$
NLO pQCD (FMNR)	$\sigma_{vis}^{NLO} = (54 \pm 9)\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

b in PHP: differential cross sections (ZEUS)

$ep \to b\bar{b} \to e\,j\,j\,\mu X$ $\qquad\qquad$ $ep \to b\bar{b} \to e\,j\,j\,X$







p_T^{rel} **analysis**

$\mathcal{L} = 98\ \mathrm{pb}^{-1}$

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

P_T^{rel} **fit separately in each bin**

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

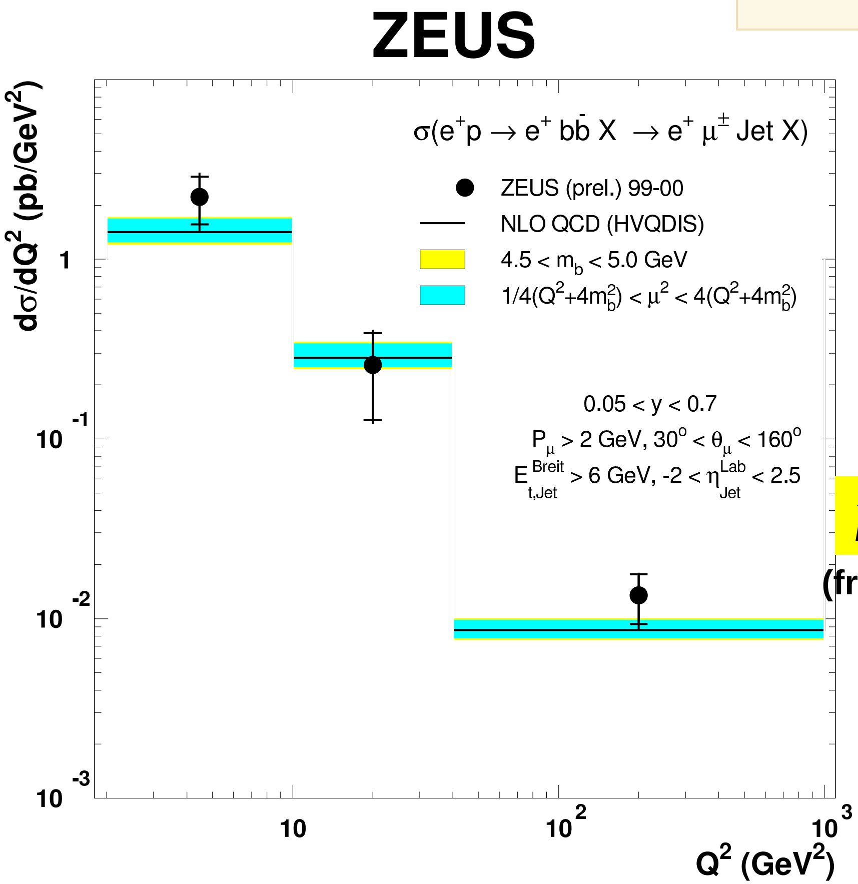
$p_T^\mu > 2.5\ \mathrm{GeV} \qquad -1.6 < \eta^\mu < 2.3$

$p_T^{jet1,(2)} > 7,(6)\ \mathrm{GeV}$

$\sigma_{vis}(ep \to b\bar{b} \to Jet\ Jet\ \mu\ X) = (733 \pm 61(\mathrm{stat.}) \pm 104(\mathrm{syst.}))\ \mathrm{pb}$

NLO pQCD (FMNR) $\qquad \sigma_{vis}^{NLO} = (381^{+117}_{-78})\ \mathrm{pb}$

Beauty in DIS



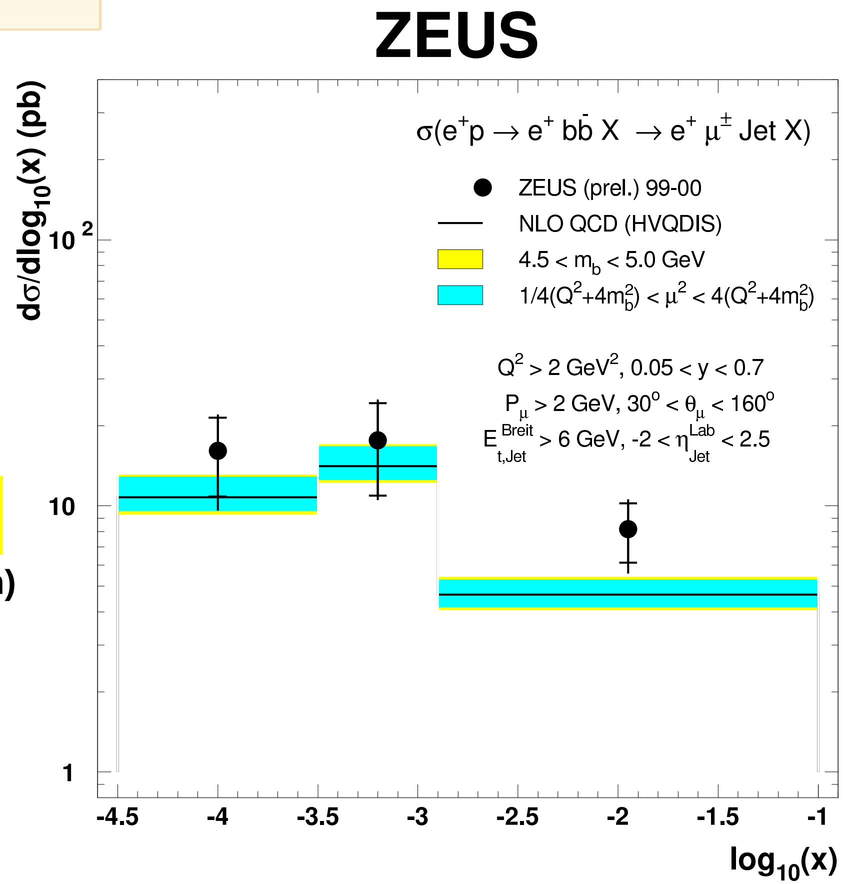
210 μ **candidates**

$\mathcal{L} = 60\ \mathrm{pb}^{-1}$

ZEUS 99-00 data

$f_b = (25 \pm 5)\ \%$

(from P_T^{rel} fit - not shown)



p_T^{rel} analysis

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

$p^\mu > 2\ \mathrm{GeV}$ $\quad 30^\circ < \theta^\mu < 160^\circ$

+ at least 1 jet in the Breit frame with:

$E_T^{Breit} > 6\ \mathrm{GeV}$ $\quad -2 < \eta^{LAB} < 2.5$

$$\sigma_{vis}(ep \to eb\bar{b}X \to e\mu jetX) = 38.7 \pm 7.7(\mathrm{sta.})^{+6.1}_{-5.0}(\mathrm{syst.})\ \mathrm{pb}$$

CASCADE MC (CCFM) $\quad \sigma_{vis} = 35\ \mathrm{pb}$

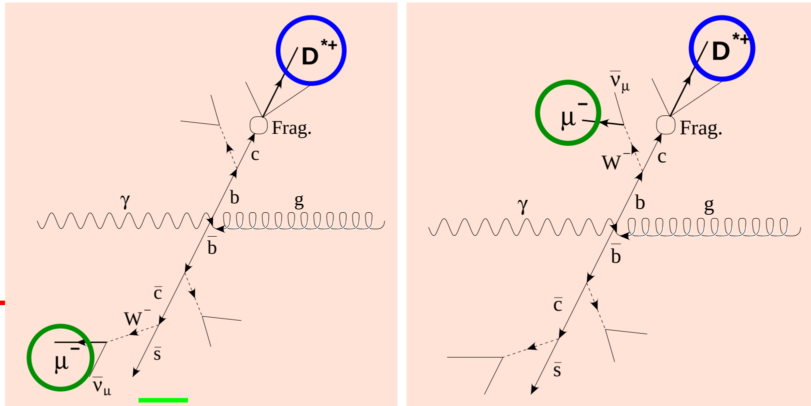
NLO-DGLAP (HVQDIS) $\quad \sigma_{vis}^{NLO} = (28.1^{+5.3}_{-3.5})\ \mathrm{pb}$

Beauty cross section from $D^* + \mu$ final state

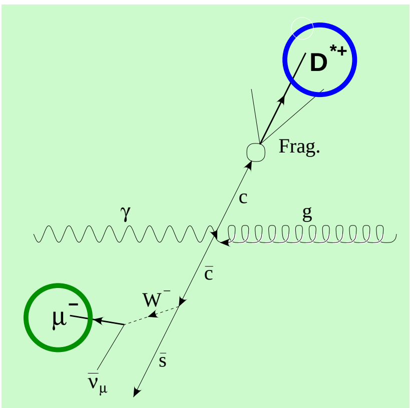
ZEUS data 1996/00, 114 pb^{-1}, similar study by H1.

method sensitive down to $p_T^b \sim 0$

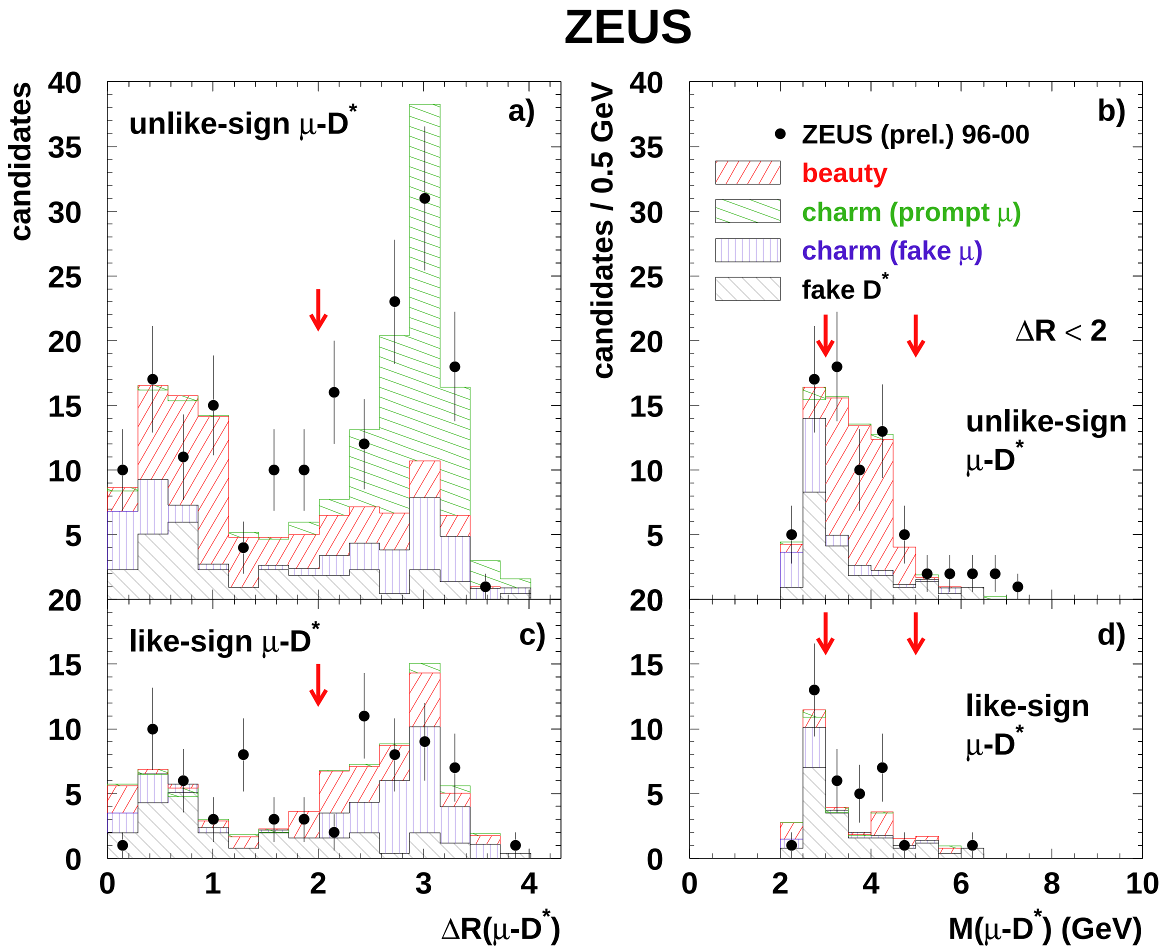
$b\bar{b}$



$c\bar{c}$



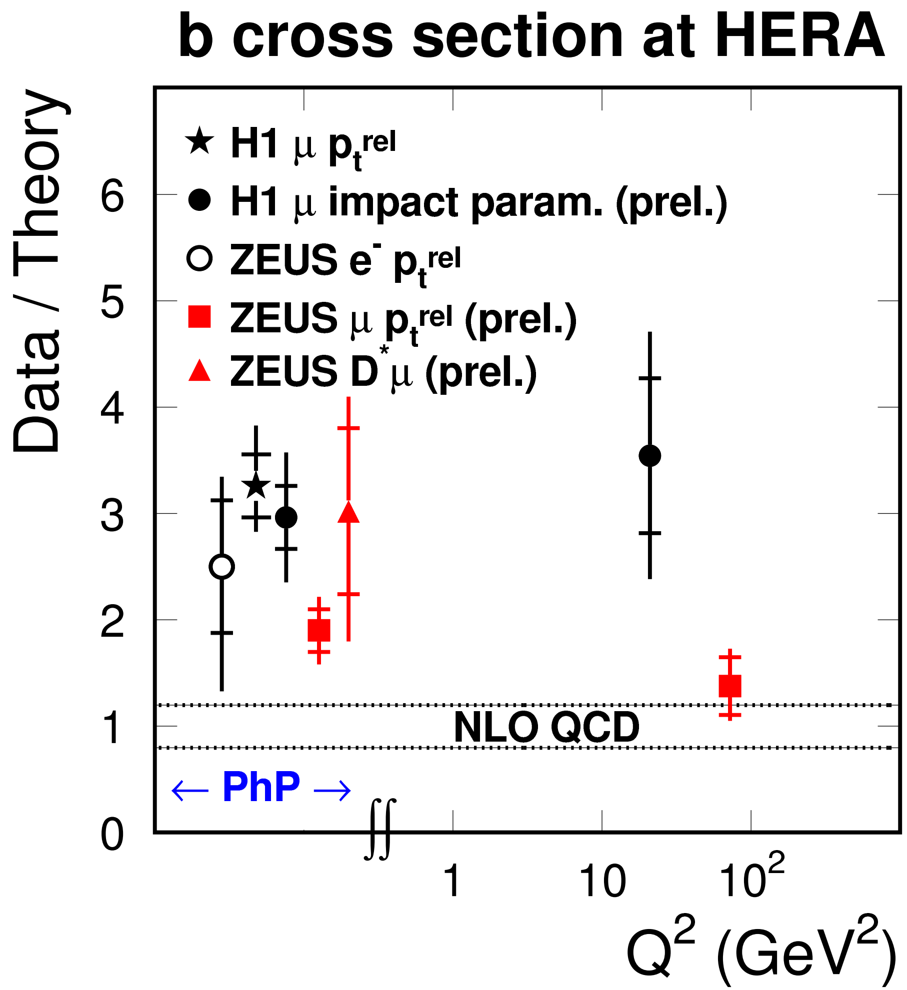
Exploits signal extraction by studying $\mu - D^*$ correlations (angle and charge)



$$\sigma(ep \to b \text{ or } \bar{b}X,\ y_{rap}(b) < 1,\ Q^2 < 1\ GeV^2,\ 0.05 < y < 0.85) = (15.1 \pm 3.9\ (\text{stat})^{+2.7}_{-4.5}(\text{sys}))\ \textbf{nb}$$

$$\sigma^{NLO} = 5.0^{+1.7}_{-1.1}(\text{th.})\ \text{nb}$$

Overview: b-production at HERA : *NLO* - data



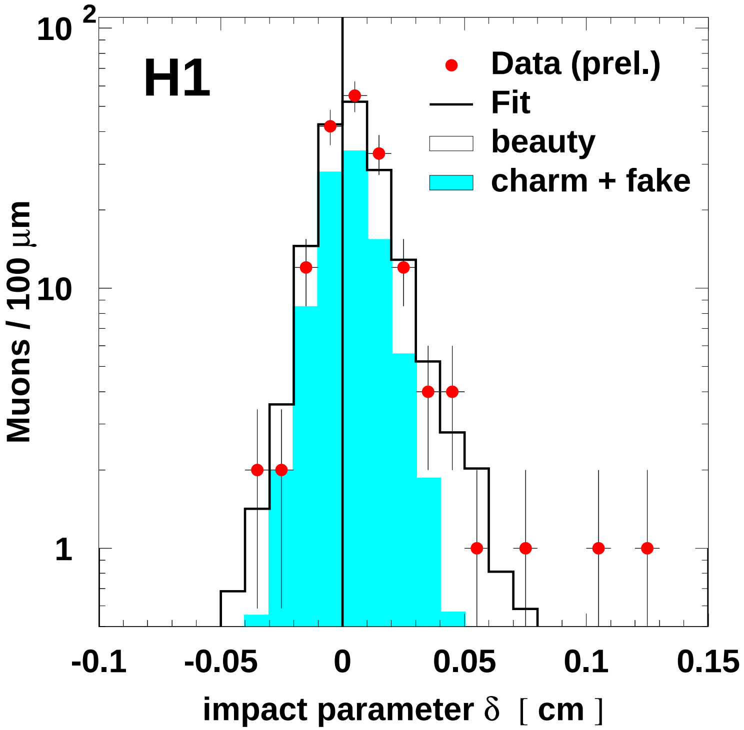
- Studied by both experiments
- Two channels ($e - \mu$) and methods ("p_T^{rel}", lifetime, double tag)
- Both in γp and *DIS*
- NLO QCD predictions start to agree with some of the new beauty production results,but not yet fully consistent picture (CAVEAT ! different kinematic ranges, different approaches to perturbative calculations, decay, acceptance corrections)
- Still some HERA I data to be analyzed
- More precise measurements expected from HERA II data !

Summary and conclusions

- **Heavy flavour production in ep collisions is a good testing ground for pQCD**
- **Charm production in reasonable agreement with expectations , some aspects need further clarification (theory failing in certain phase space regions).**
- **HERA II higher luminosity and new detectors in both H1 and ZEUS (better tracking, coverage of forward region) will contribute to resolve remaining issues.**

Beauty in DIS (H1) (opt.)

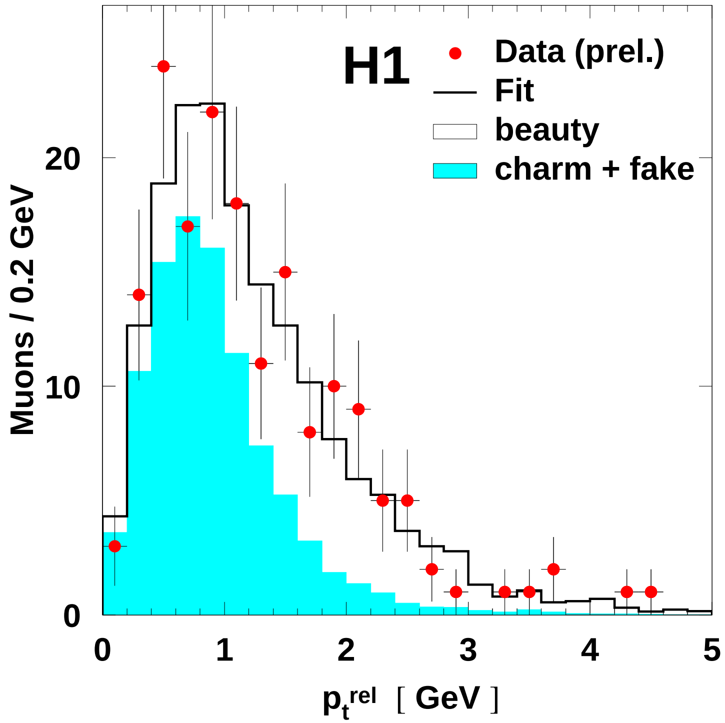
b production in DIS



171 μ **candidates**

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

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



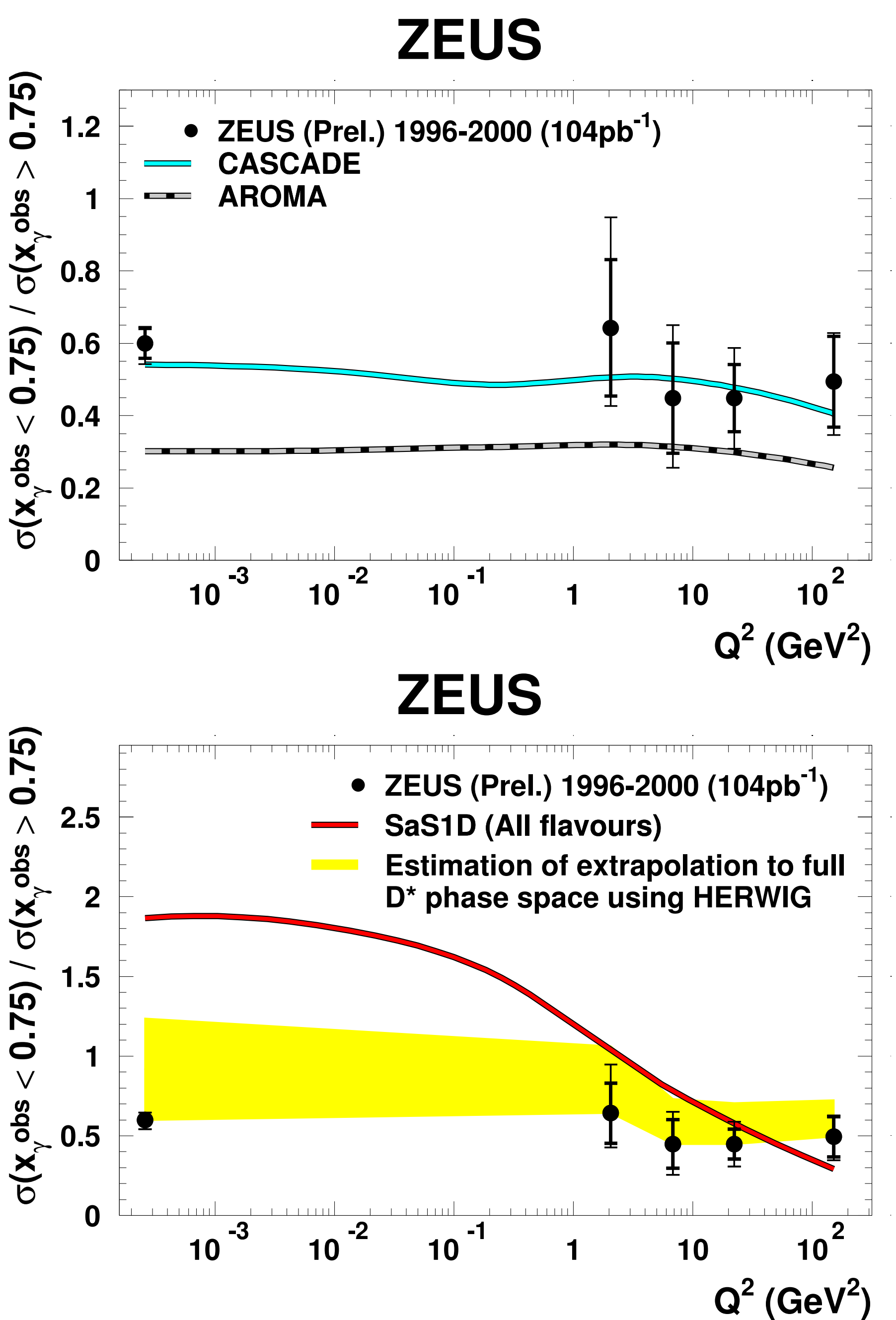
$2 < Q^2 < 100\ \mathrm{GeV}^2 \qquad 0.05 < y < 0.7$

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

$\delta + p_T^{rel}$ ***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)	$\sigma_{vis}^{NLO} = (11 \pm 2)\ \mathrm{pb}$

Resolved γ in charm (opt.)

- $x_\gamma^{OBS} = \frac{\sum_{jets} E^T\ e^{-\eta}}{2yE_e}$ $\sim$ **fraction of γ energy in the hard interaction**
- **Study the ratio of resolved/direct:** $\frac{\sigma(x_\gamma^{OBS}<0.75)}{\sigma(x_\gamma^{OBS}>0.75)}$ **vs Q^2 in presence of charm**
- **no significant Q^2 dependance** **(differently from inclusive case !)**
- k_t **dependent** g **(CASCADE) gives good description**
- **Suppression of resolved w.r.t. direct due to m_c and Q^2 appear NOT to be independent**



D^* in DIS and associated di-jet production (opt.)

$\mathcal{L} = 47\ \text{pb}^{-1}$

H1 99-00 data

$Q^2 > 2$ **GeV**^{2}, $0.05 < y < 0.7$

$p_T^{D^*} > 1.5$ **GeV**, $|\eta^{D^*}| < 1.5$

- **NLO QCD** **(HVQDIS) low**
- **CASCADE** **(CCFM) better (i.e.** η, z**)**