Lake Louise Winter Institute 2002

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Open Heavy Flavour Production at HERA

Jürgen Kroseberg (Universität Zürich)

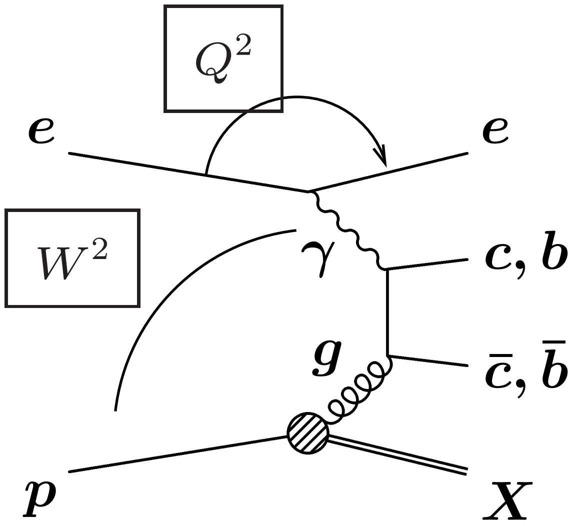
on behalf of the H1 and ZEUS collaborations

Testing QCD through measuring charm and beauty in high energy ep collisions.

Heavy Flavour Production at HERA

$\boxed{\text{27.5 GeV}}\ e^{\pm} \longrightarrow \boxed{\sqrt{s} \approx 318(300)\ \text{GeV}} \Longleftarrow p\ \boxed{\text{920(820) GeV}}$

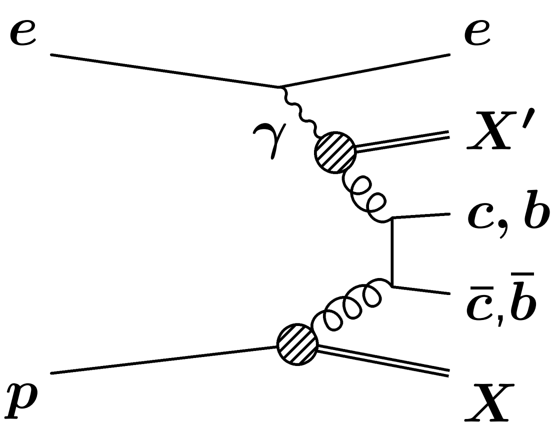
- necessary ingredient to
  understand proton structure
- quark mass provides hard scale:
  good **testing ground for pQCD**
- dominantly **gluon induced**
- **photoproduction dominates**
  ($Q^2 \approx 0$) over DIS ($Q^2 \gg 0$).



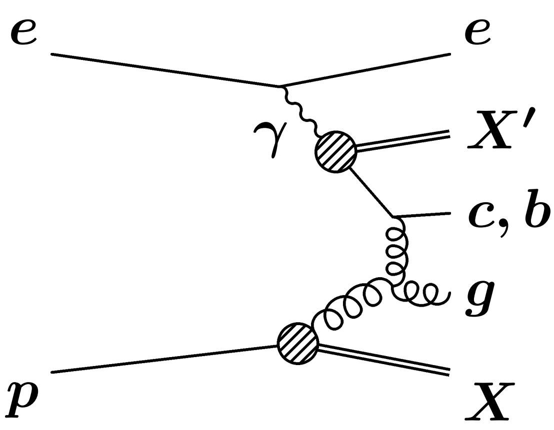
$$\boxed{Q^2 = -p_\gamma^2\ ,\ y = \frac{\mathbf{p_p \cdot p_\gamma}}{\mathbf{p_p \cdot p_e}}\ ,\ x = \frac{Q^2}{ys}}$$

Resolved Photon Processes

gluon-gluon fusion



heavy quark excitation



- resolve **hadronic structure of the photon**
- only fraction $x_\gamma < 1$ of γ momentum enters the interaction ($x_\gamma = 1 \rightarrow$ "direct" process)
- **resolved** $\leftrightarrow$ **direct** : **LO picture!**
- for all orders can define **jet based observable**:

$$\boxed{x_\gamma^{obs} = \frac{E_\perp^{jet1} e^{-\eta^{jet1}} + E_\perp^{jet2} e^{-\eta^{jet2}}}{2yE_e}}$$

QCD Tools

pQCD calculations in NLO:

- fixed order, **massive scheme**:
  HQ **produced dynamically**;
  reliable for $\boldsymbol{p_t \leq m_q}$
- resummed, **massless scheme**
  HQ **active parton** in p and γ;
  reliable for $\boldsymbol{p_t \gg m_q}$
- FONLL, **merged scheme**

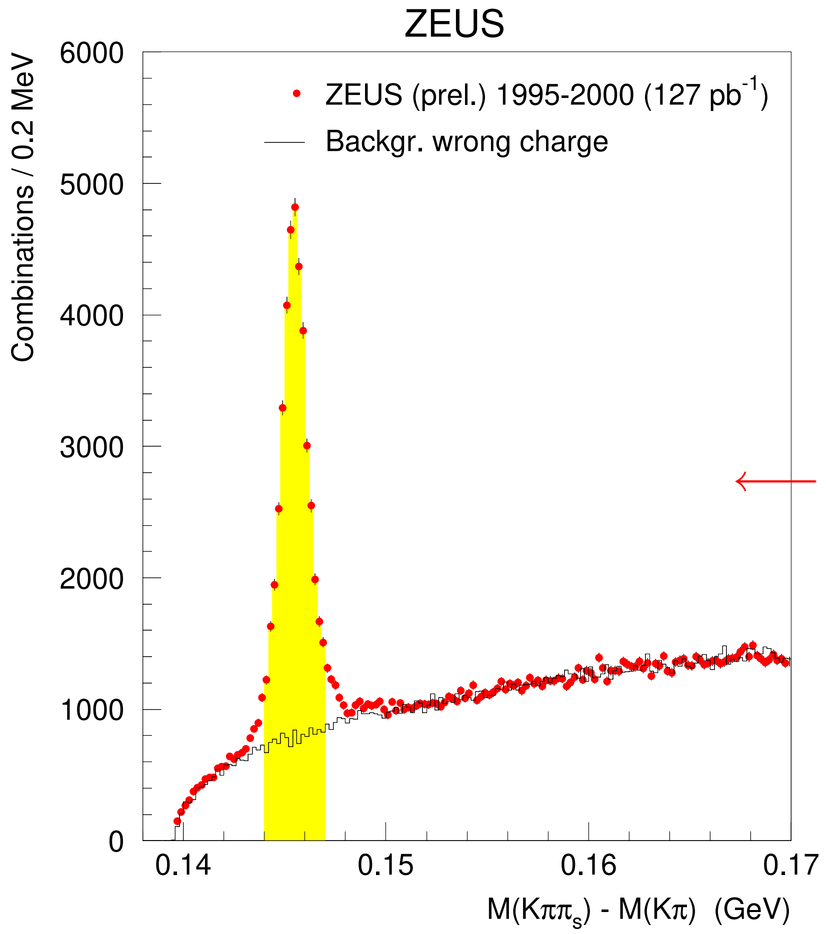
[. . .]

Monte Carlo generators

(**LO** + parton showers)

- **AROMA**:
  direct only, **DGLAP** evolution
- **PYTHIA, HERWIG**:
  direct **+ resolved**, DGLAP
- **CASCADE**:
  direct only, **CCFM**–like evolution,
  k_t dependent gluon density

Tagging Charm



"golden" channel:

$$\boxed{D^{*\pm} \rightarrow D^0\pi_s^\pm \rightarrow (K^\mp\pi^\pm)\pi_s^\pm}$$

$$\Delta M = m_{D^*} - m_{D^0} \approx m_\pi$$

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

$(p_t(D^*) > 2$ GeV, $-1.5 < \eta(D^*) < 1.5)$

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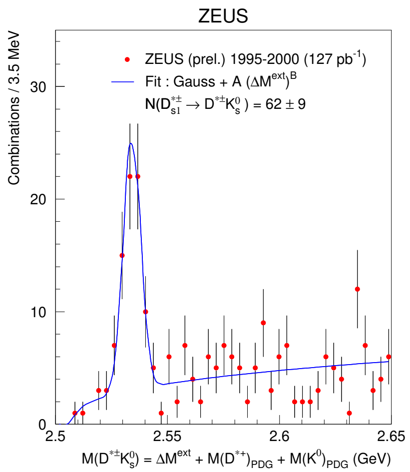
other channels, e.g.:

- $D^* \rightarrow (K\pi\pi\pi)\pi_s$, D_s
- e^- from semileptonic charm decays
- D^0, D^{**},D_{s1}^* seen

Production Ratios of Charmed Mesons

$\sigma(D_s)/\sigma(D^*) = 0.41 \pm 0.07^{+0.03}_{-0.05}$

$[\ e^+e^- \quad : \ 0.43 \pm 0.04\ ]$



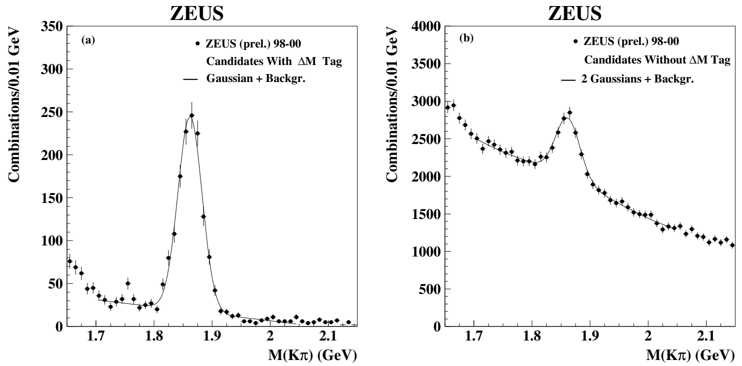
$f(c \to D_{s1}^+) = (1.24 \pm 0.18^{+0.08}_{-0.06} \pm 0.14)\%$

OPAL : $(1.6 \pm 0.4 \pm 0.3)\%$

ALEPH: $(0.94 \pm 0.22 \pm 0.07)\%$

vector/pseudoscalar meson production:

[assume $\sigma(D^{*\pm}) = \sigma(D^{*0})$]



$P_V = D^*/(D^* + D^0)$

ZEUS : $0.546 \pm 0.045 \pm 0.028$

OPAL : 0.57 ± 0.05

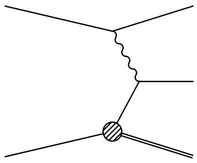
ALEPH: 0.595 ± 0.045

e^+e^- and ep results consistent; **charm fragmentation appears universal**

Charm Contribution to DIS

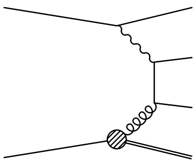
inclusive deep ineleastic scattering:

$$\frac{d^2\sigma(ep\to eX)}{dx\,dQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left(1+(1-y)^2\right) F_2(x,Q^2)$$

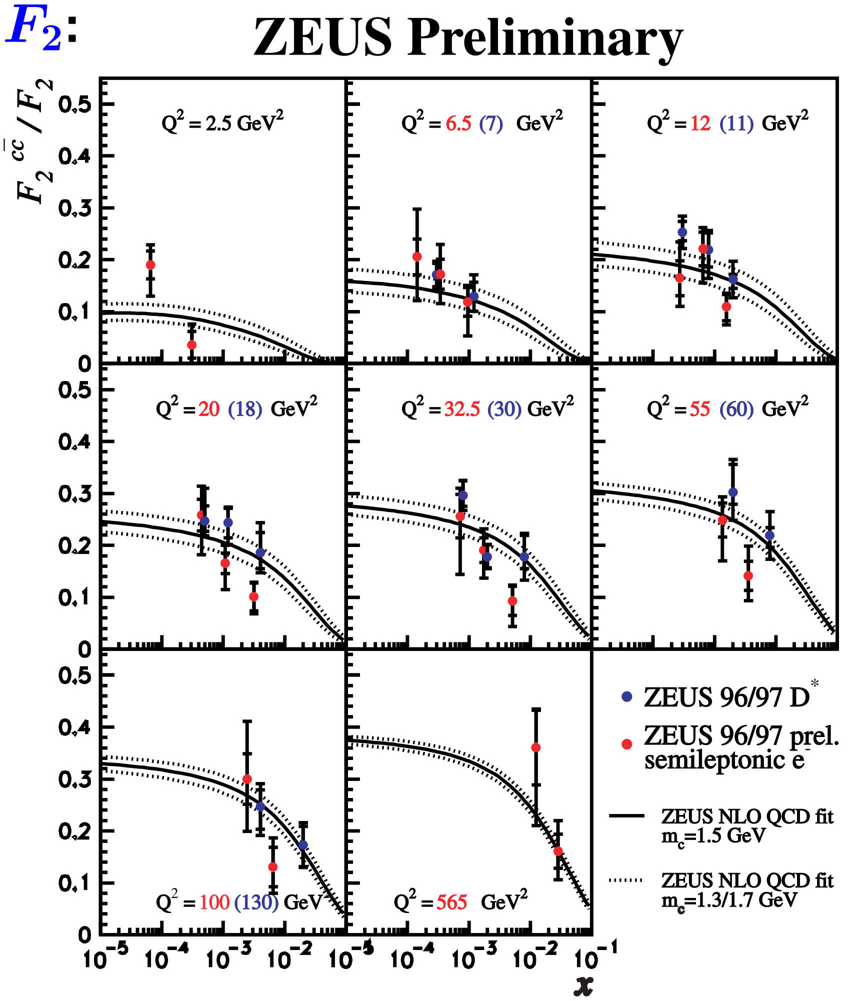


charm production in DIS:

$$\frac{d^2\sigma(ep\to cX)}{dx\,dQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left(1+(1-y)^2\right) F_2^c(x,Q^2)$$



ratio F_2^c/F_2:

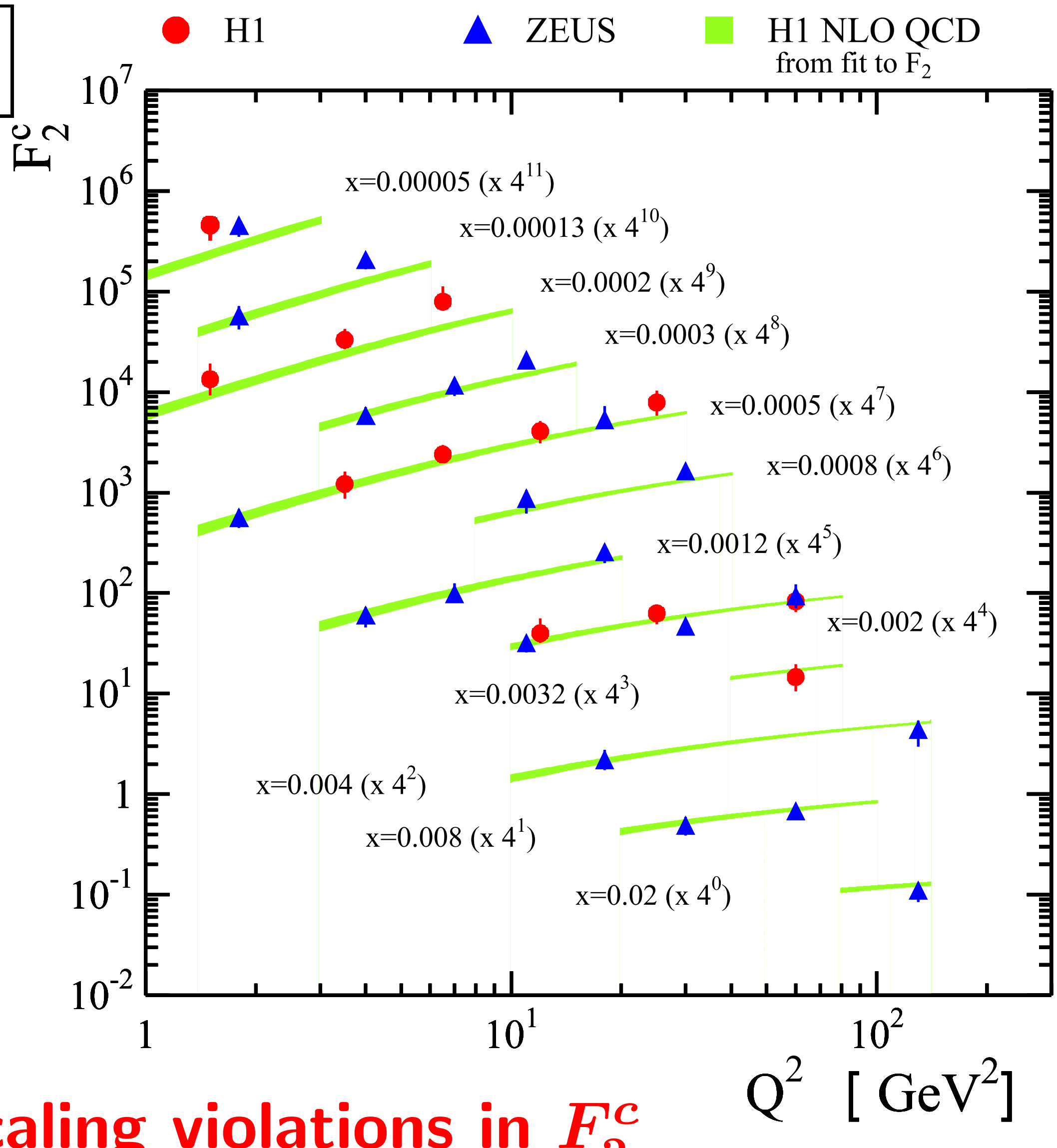


$\rightarrow$ F_2^c/F_2 large at low x and high Q^2

Scaling Violations in F_2^c

- naive **quark–parton model** for the proton:
  $\longrightarrow$ **scaling** of inclusive F_2
- QCD radiation, **gluonic proton component**
  $\longrightarrow$ **scaling violations** in F_2

$\boxed{F_2^c}$

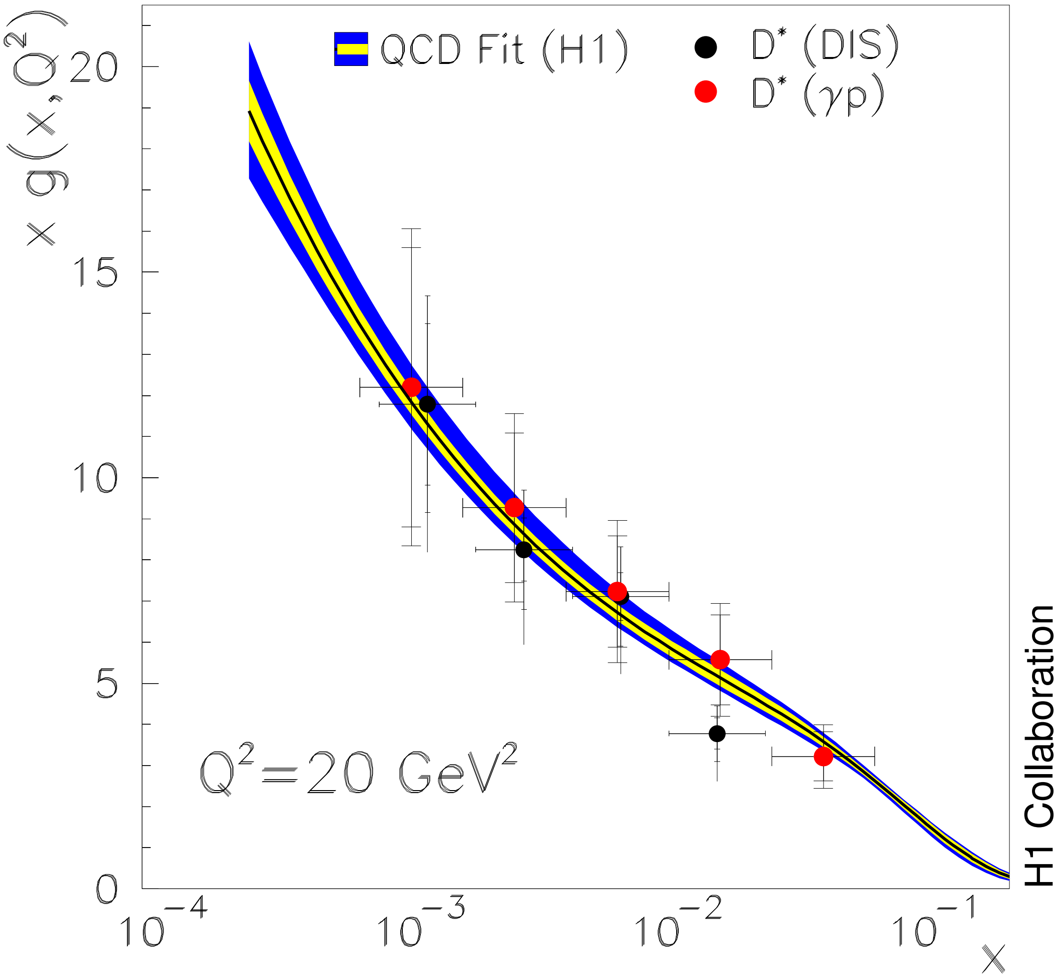


$\longrightarrow$ **scaling violations in F_2^c**
(more pronounced than in inclusive F_2)

Gluon Density in the Proton

- $x_g g(x_g, Q^2)$ from differential charm cross section

  (unfolding using FO NLO QCD)

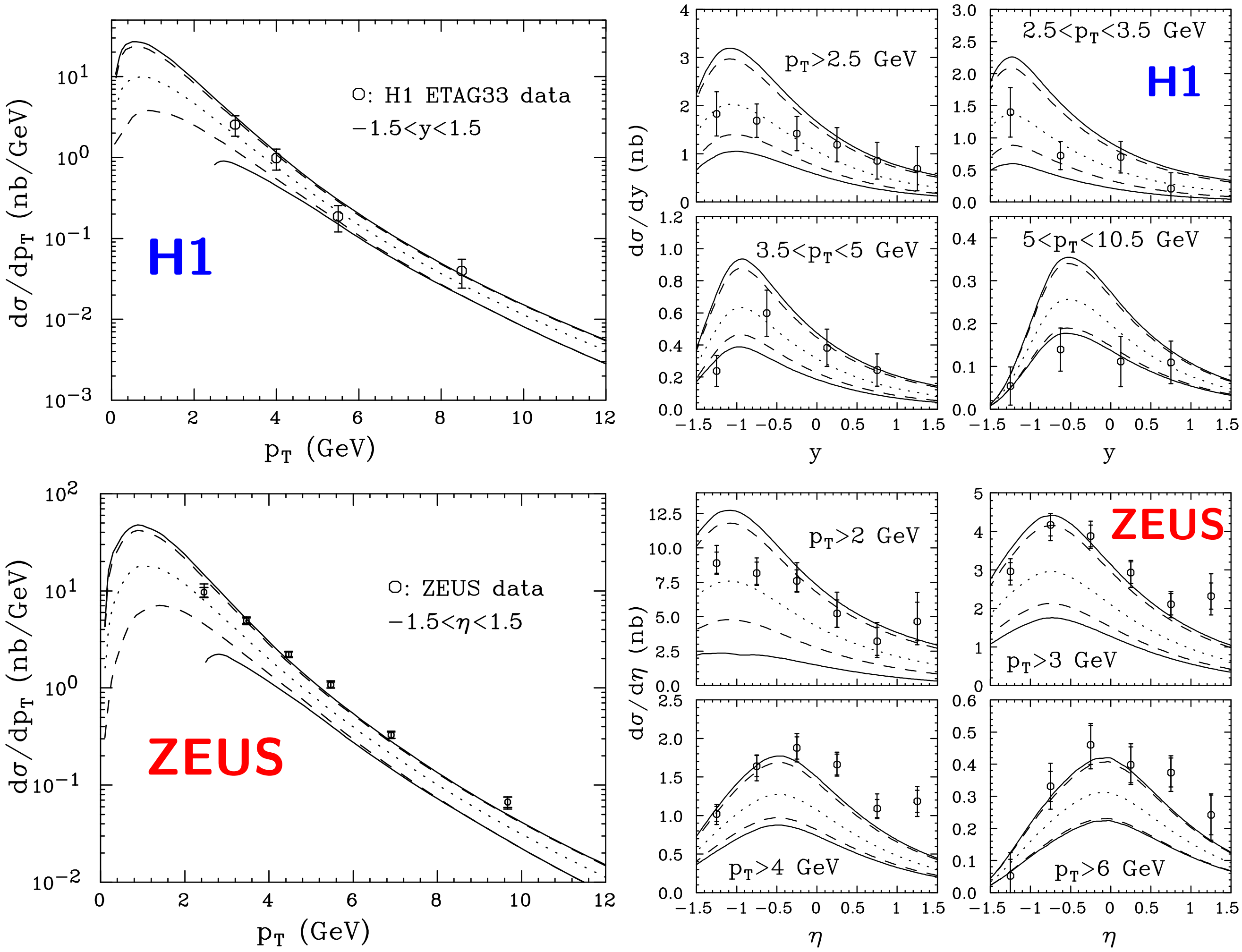


consistent with inclusive scaling violation analysis

Differential D^* Cross Sections

Comparison of HERA γp data with FONLL QCD:

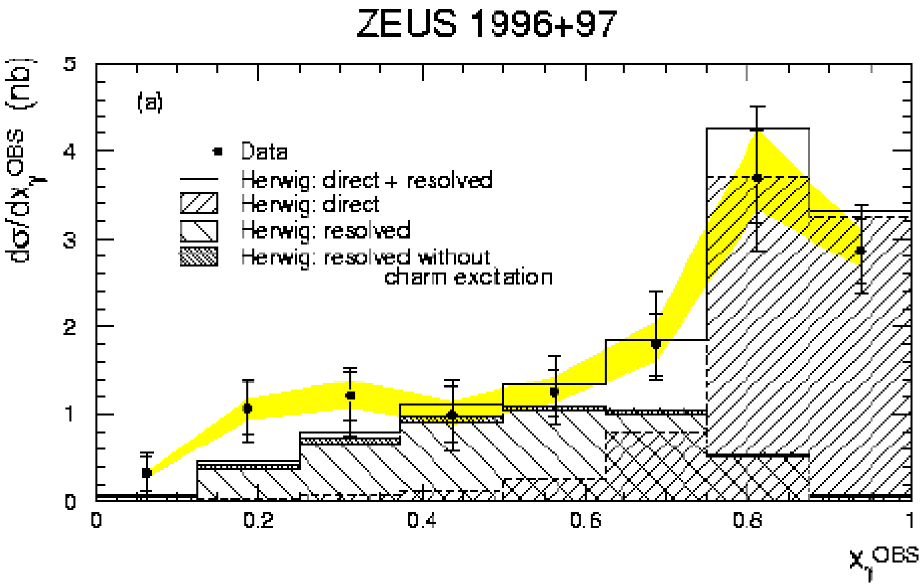
[S. Frixione, P. Nason: hep-ph/0201281]



- after **parameter tuning**: acceptable agreement
- rather **large theoretical uncertainties**
- **H1 data:** no discrepancies within errors.
- **ZEUS data:** somewhat harder p_t spectrum and hint for excess at $\eta > 0$.

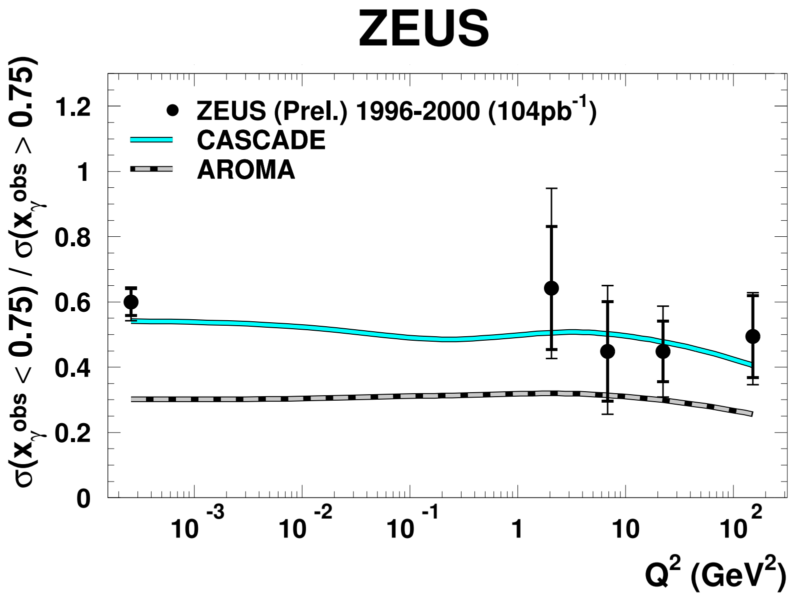
Resolved γ in Charm Production (I)

$d\sigma/dx_\gamma^{obs}$ for D^*+dijet events:



→ **LO DGLAP picture (HERWIG):**
≈ 40% resolved contribution
(charm excitation in the photon)

$\sigma(x_\gamma^{obs} < 0.75)/\sigma(x_\gamma^{obs} > 0.75)$:



→ **no significant Q^2 dependence**
→ **k_t dependent g (CASCADE) gives good description**

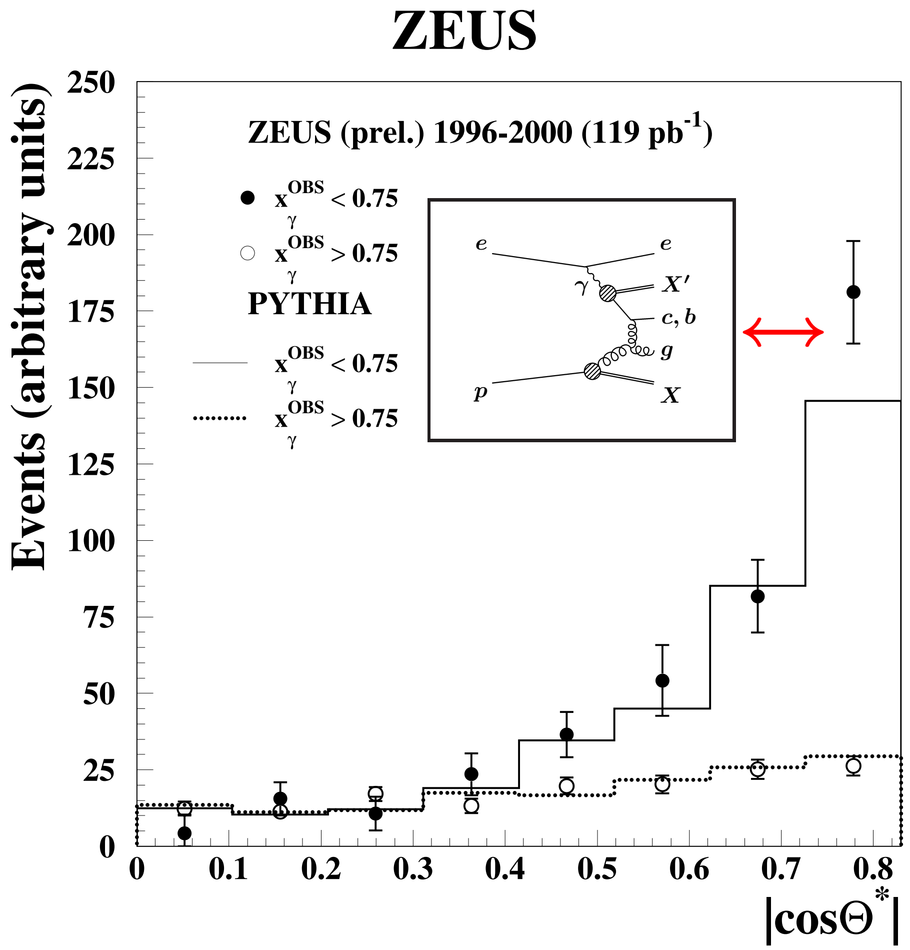
Resolved γ in Charm Production (II)

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

[∠ (jet–jet axis, beam) in dijet rest frame]

quark propagator $\sim (1-|\cos\theta^*|)^{-1}$

gluon propagator $\sim (1-|\cos\theta^*|)^{-2}$



→ **gluon propagator signature in resolved sample ($x_\gamma^{obs} < 0.75$)** $\leftrightarrow$ **c excitation**

Open Charm Summary

▷ becoming **precise tool to test QCD**
with two scales

▷ all in all **pQCD works quite well**:
$\longrightarrow$ **DIS** data well described
$\longrightarrow$ acceptable description of γp data

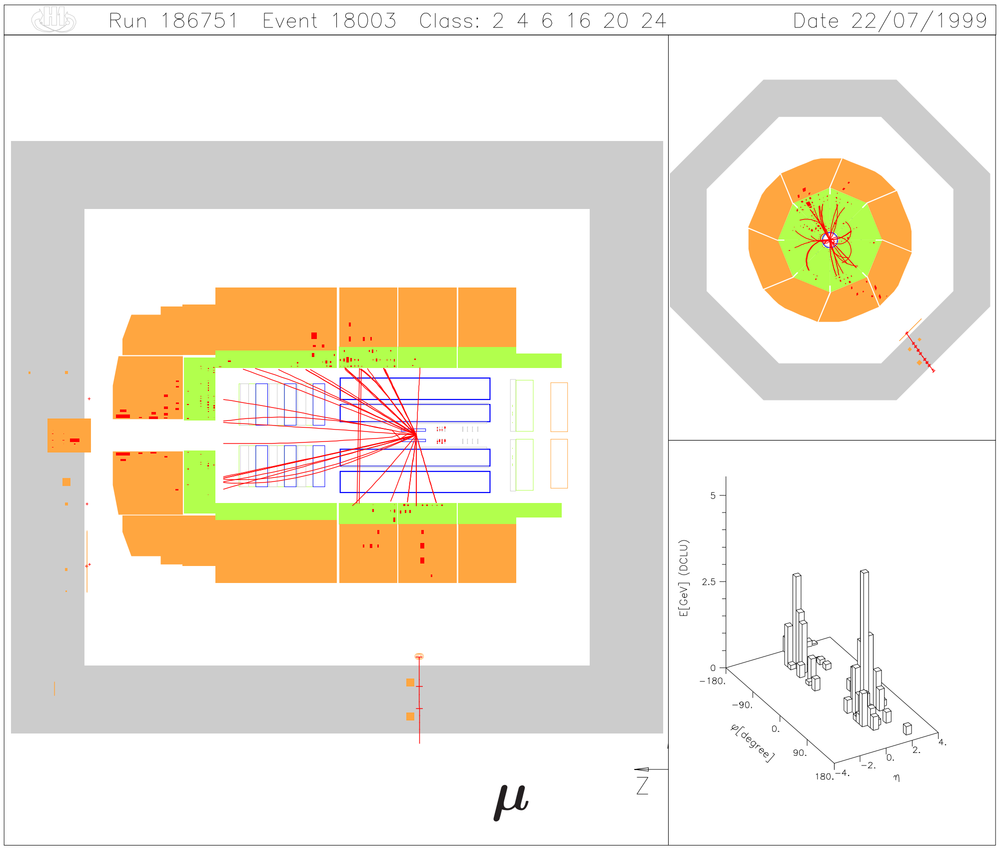
▷ analyses of **more data** to come

▷ will use **refined methods**,
e.g. **double tags**

Beauty Production

- even more **attractive** for QCD tests: $m_b > m_c$
- but also **rare:** $\sigma_b : \sigma_c : \sigma_{uds} \approx 1 : 200 : 2000$
- **need clear experimental starting point**:

  $\longrightarrow$ use **semileptonic decay** (BR $\approx 10\%$)

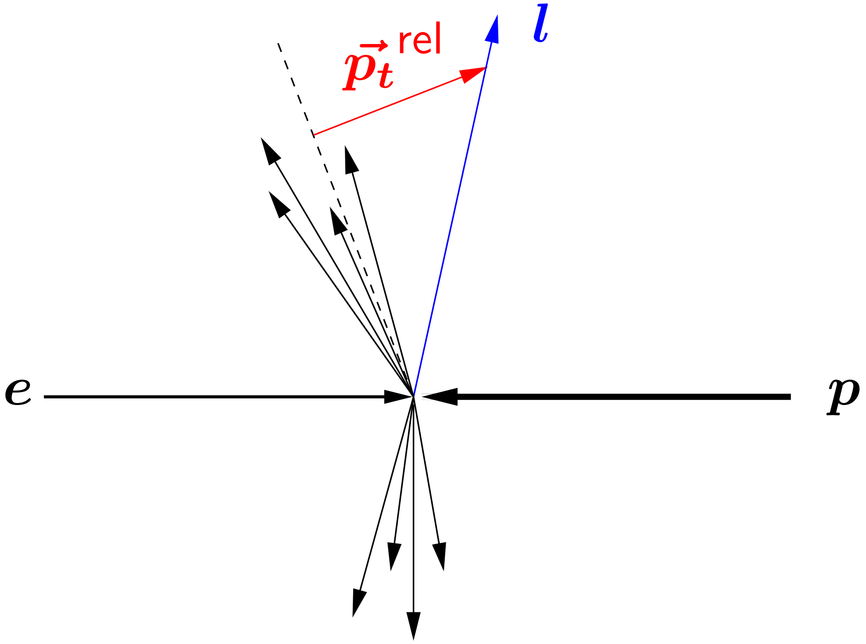


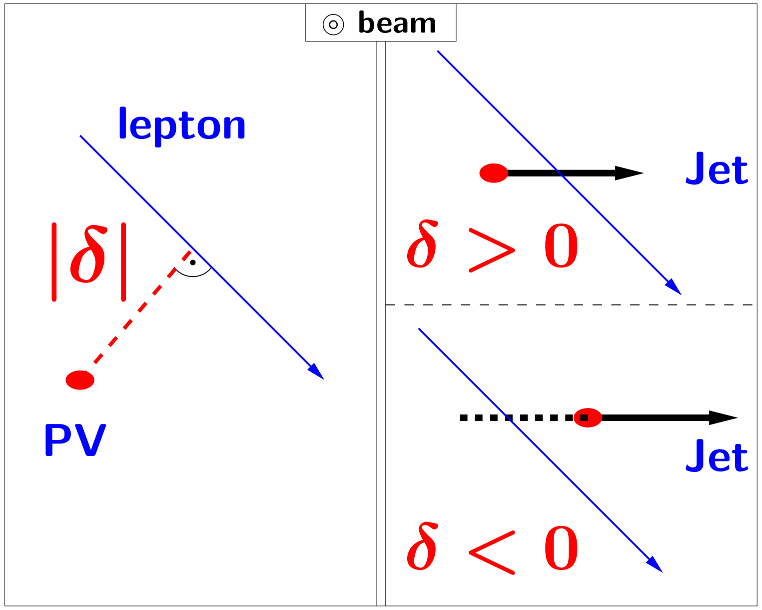
$\longrightarrow$ select dijet events with high p_t lepton

Tagging Beauty

mass lepton p_t w.r.t. jet

lifetime impact parameter

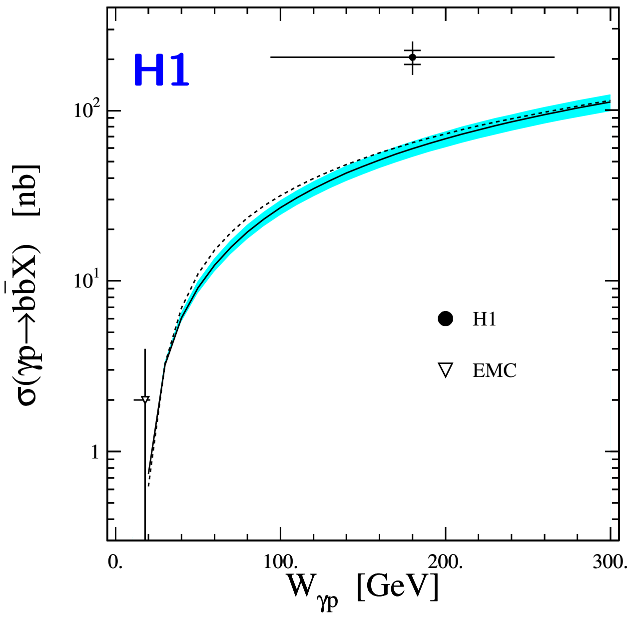


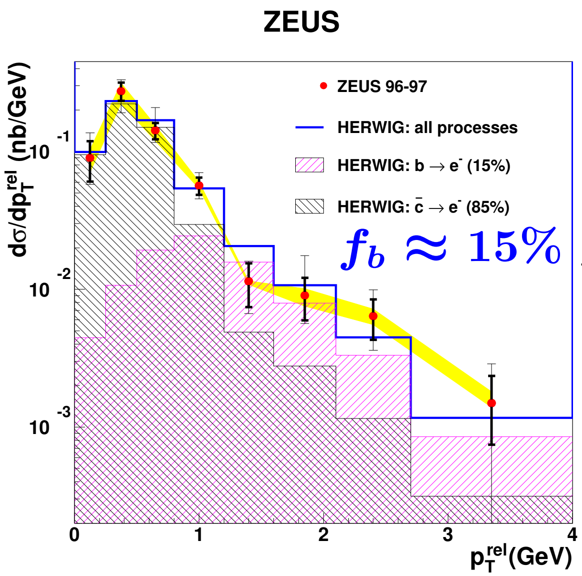


Beauty in Photoproduction: p_t^{rel} Analyses

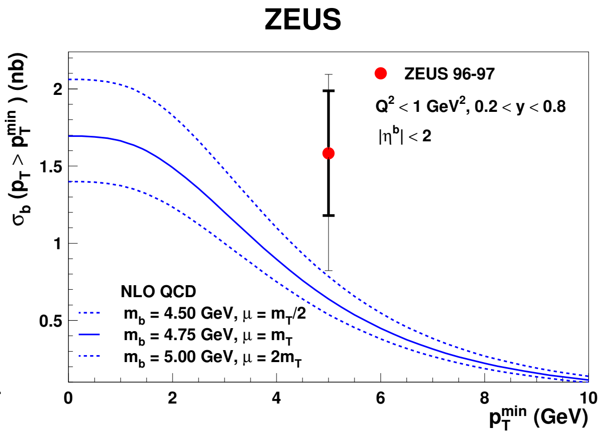
$b \longrightarrow \mu$

$b \longrightarrow e$





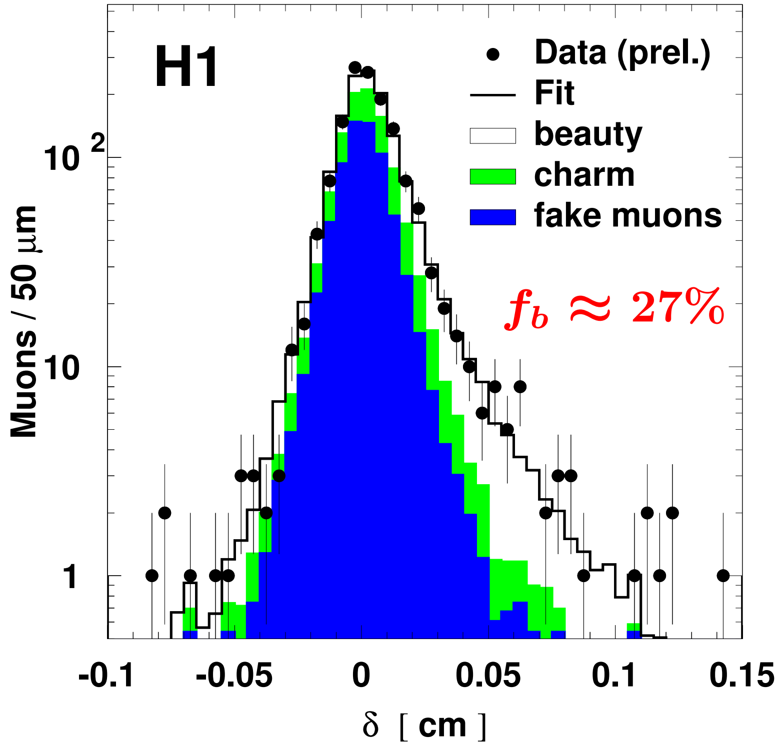
extrapolate to parton level:



$\longrightarrow$ **NLO QCD significantly below data**

$\longrightarrow$ **NLO QCD somewhat below data**

Beauty in Photoproduction: Impact Parameter Analysis



→ **confirms earlier H1 result using independent method and data**

- **establish consistency** $\delta \leftrightarrow p_t^{rel}$
- **combine both observables** in 2D fit
- **combine with earlier H1 result**

$$\Downarrow$$

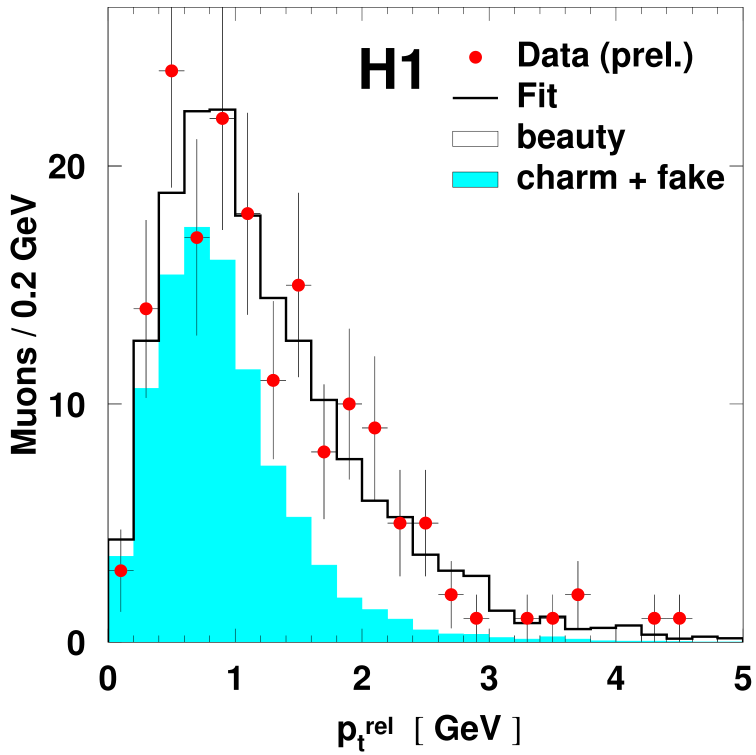
$$\boxed{\boldsymbol{\sigma_{vis} = (170 \pm 25)\ \text{pb}}}$$

$Q^2 < 1\ \text{GeV}^2$, $0.05 < y < 0.7$, $35^\circ < \theta^\mu < 130^\circ$, $p_t^\mu > 2\ \text{GeV}$

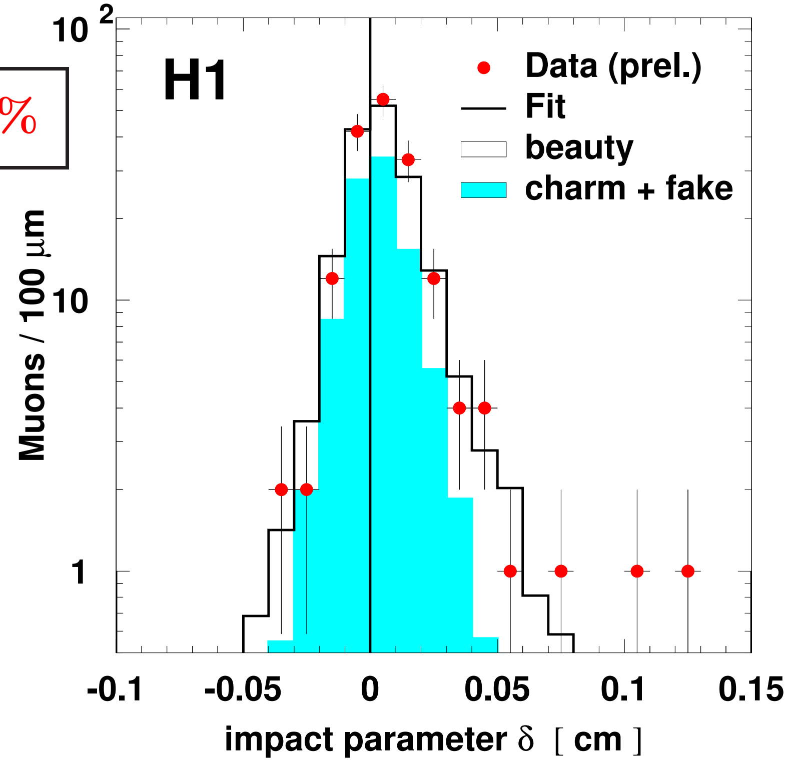
NLO QCD : $(\mathbf{54 \pm 9})$ **pb**

AROMA : 38 pb
CASCADE : 67 pb

First Measurement of Open Beauty in DIS



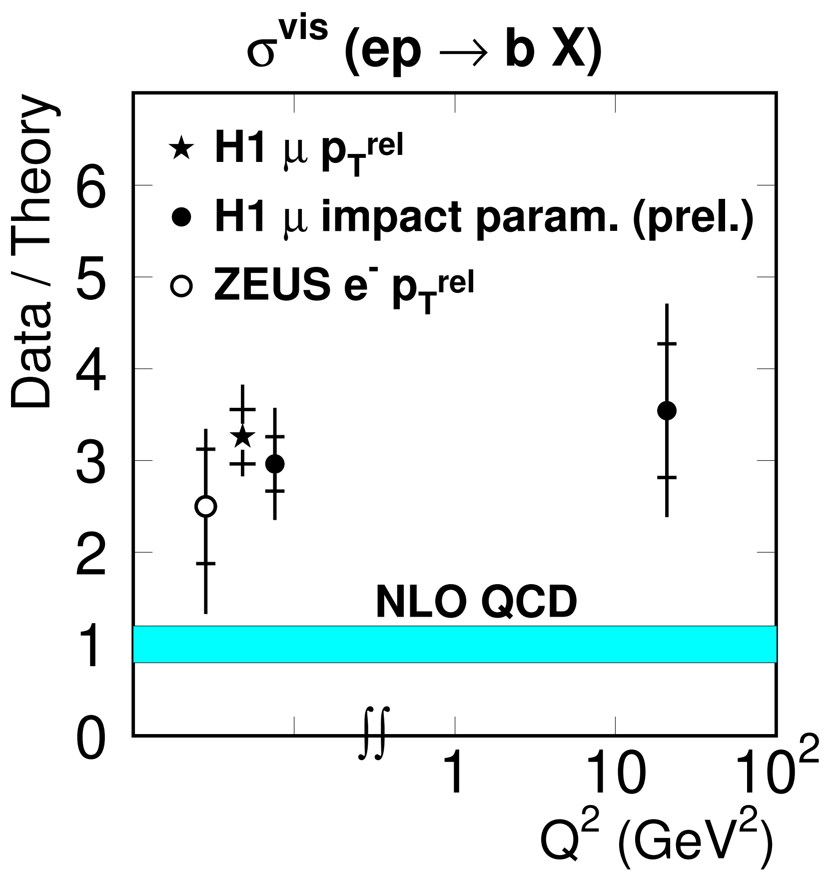
$f_b \approx 43\%$



2D fit $\rightarrow$ $\boxed{\boldsymbol{\sigma_{vis} = [39 \pm 8 \pm 10\,]\ \mathrm{pb}}}$ NLO QCD: $\sigma_{vis} = (11 \pm 2)\ \mathrm{pb}$

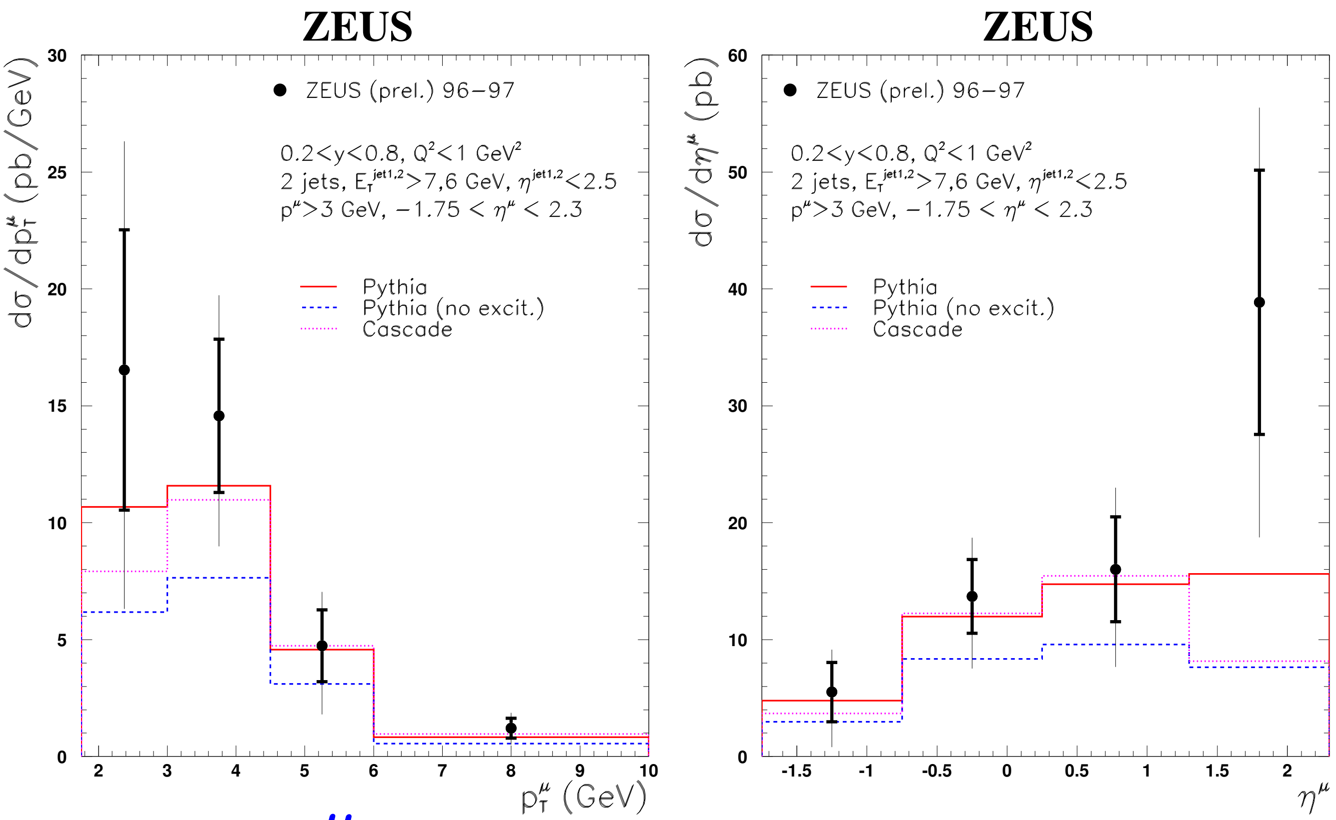
$$\left(2\ \mathrm{GeV}^2 < \mathrm{Q}^2 < 100\ \mathrm{GeV}^2,\ 0.05 < y < 0.7,\ 35^\circ < \theta^\mu < 130^\circ,\ p_t^\mu > 2\ \mathrm{GeV}\right)$$

Overview: HERA Beauty Results



- all **measurements above NLO QCD**
- seen by **both experiments**
- seen in **two channels** (e and μ)
- seen with **two methods** (mass and lifetime tag)
- seen in **photoproduction and DIS**

Differential $b \to \mu$ (γp) cross sections



p_t^μ η^μ

(NB: LO comparison!)

visible cross sections in two different η^μ regions:

(central: $-1.75 < \eta < 1.3$, forward: $1.4 < \eta < 2.4$)

	σ(pb)	Herwig	Pythia	Cascade
central μ	$36.4 \pm 5.2^{+10.4}_{-9.1}$	12	30	24.5
forward μ	$20.5 \pm 6.5^{+6.3}_{-5.7}$	4.1	9.6	5.9

(consistent with

central e $\quad 24.9 \pm 6.4^{+4.2}_{-7.3}$ $\quad$ 16.2 $\quad$ 19.5 $\quad$ 20.3)

Open Beauty Summary

▷ surprisingly **NLO QCD does not work well**:
all measured cross sections above prediction
[now **seen in pp, γp, $\gamma\gamma$ and ep** processes]

▷ **need** to look at **differential cross sections**
using more statistics

▷ analyses of **additional data/channels underway**

▷ HERA **luminosity upgrade**

▷ **detector upgrades** including **improved tracking**
e.g. **ZEUS vertex detector**