Heavy Flavour Production in ep Interactions

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for the ZEUS and H1 collaborations

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- Selected topics: open heavy flavour
  - Introduction
  - D^*/D^{+-} production
  - beauty production

- not covered:
  - fragmentation, structure functions, diffractive production, J/Ψ, Υ production

Why study heavy flavours at HERA?

- **HERA, Queen of the greek gods,** sister and wife of ZEUS, (sorry H1 ...) is known for her Beauty and Charm, but also for her guile ...
- Heavy quarks are heavy (m_b,m_c)

useful scale for perturbative QCD
=> reliable predictions (in principle ...)

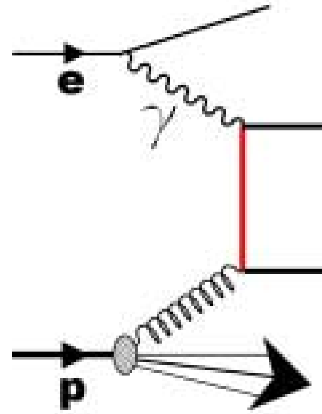
often multi-scale problem
=> large uncertainties (in practice ...)

- Study perturbative (production ...) and non-perturbative (fragmentation ...) aspects
- Tool to study heavy flavour (c,b) and/or gluon (g -> cc,bb) „content“ of γ, proton

Processes for Open Heavy Quark Production (Q = c,b)

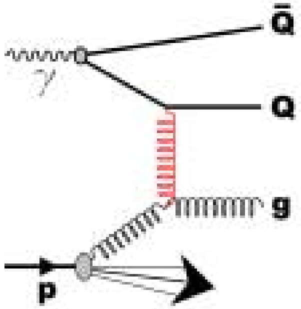
- dominant Leading Order (LO) QCD diagram:
  direct Boson(γ)-Gluon-Fusion (BGF)
  => heavy quark propagator

a)

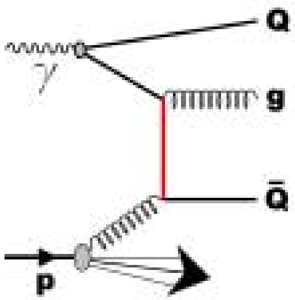


- „resolved“ photon (or p) contributions
  (in LO + parton shower (PS) picture)
  => gluon (dominant) + quark propagators

b)

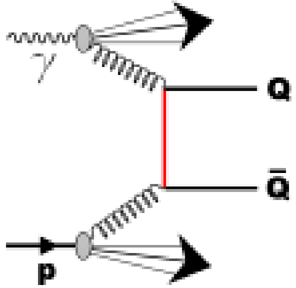


c)



+

d)



+ ...

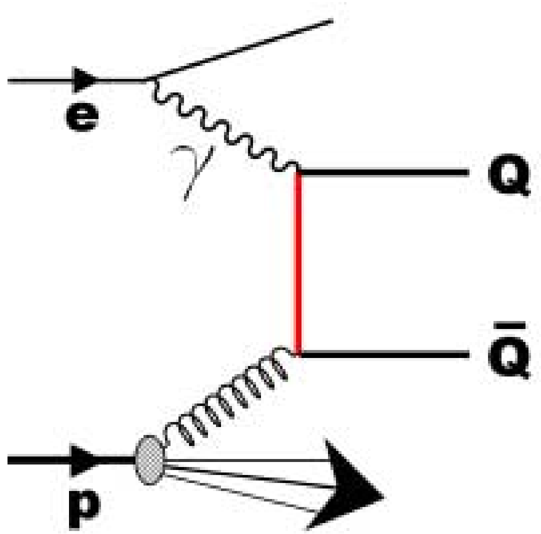
„Q-excitation“ in photon

hadron-like photon

alternative interpretations of b):

- LO excitation of „heavy quark in photon“ (+ parton shower evolution)
  LO+PS Monte Carlos (DGLAP), „massless“ QCD calculations
- NLO pointlike photon diagram (massive fixed order QCD calculations)
- LO BGF diagram + gluon cascade (CCFM, CASCADE Monte Carlo)

Kinematics of Heavy Quark Production at HERA



- Kinematic variables:

$\sqrt{s}$	= 300 (318) GeV	ep CM energy before (after) 1998
W	= $m(\gamma p)$	γp CM energy
Q^2	= $-q^2$	photon virtuality, squared momentum transfer
x	= $\frac{Q^2}{2Pq}$	Bjorken scaling variable, for $Q^2 \gg (2m_Q)^2$ (!): momentum fraction of p constituent
y	= $\frac{qP}{\ell P}$	Bjorken scaling variable, inelasticity, for $Q^2 \to 0$: γ energy fraction (of e)

- Kinematic regimes:
  - Photoproduction: γ quasi-real: $Q^2 < 1\ \mathrm{GeV}^2$, e escapes through beam pipe
  - Deep inelastic scattering (DIS): $1 < Q^2 < (300\ \mathrm{GeV})^2$, e visible in detector
- Beams and luminosity:
  - electrons + protons: (1998- mid 99) Luminosity ~ 15 pb^{-1}
  - positrons + protons: (mid 1994-97, mid 99 - 2000) Luminosity ~ 60-120 pb^{-1}

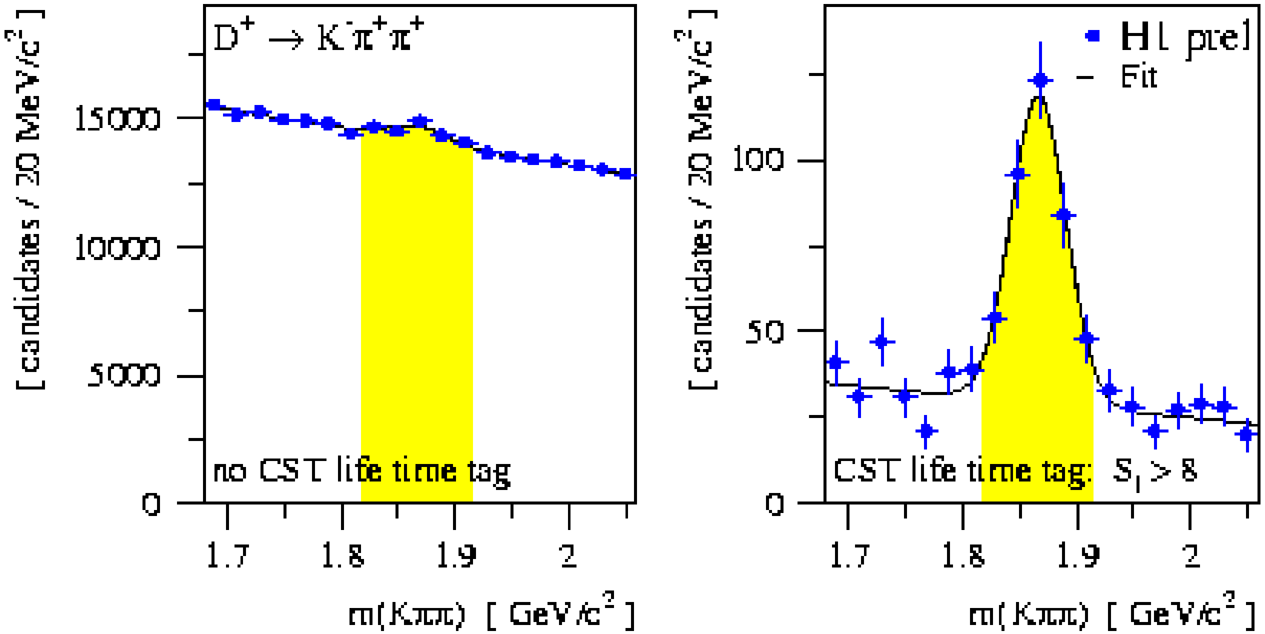
Charm tagging via decay length

Reconstruct exclusive final states via secondary vertex

Measure „lifetime"
($l=\gamma c\tau$) at 100 μm level,
e.g. H1 silicon tracker (CST)

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

Reduce background
via decay length
significance $S_l = l/\sigma_l$

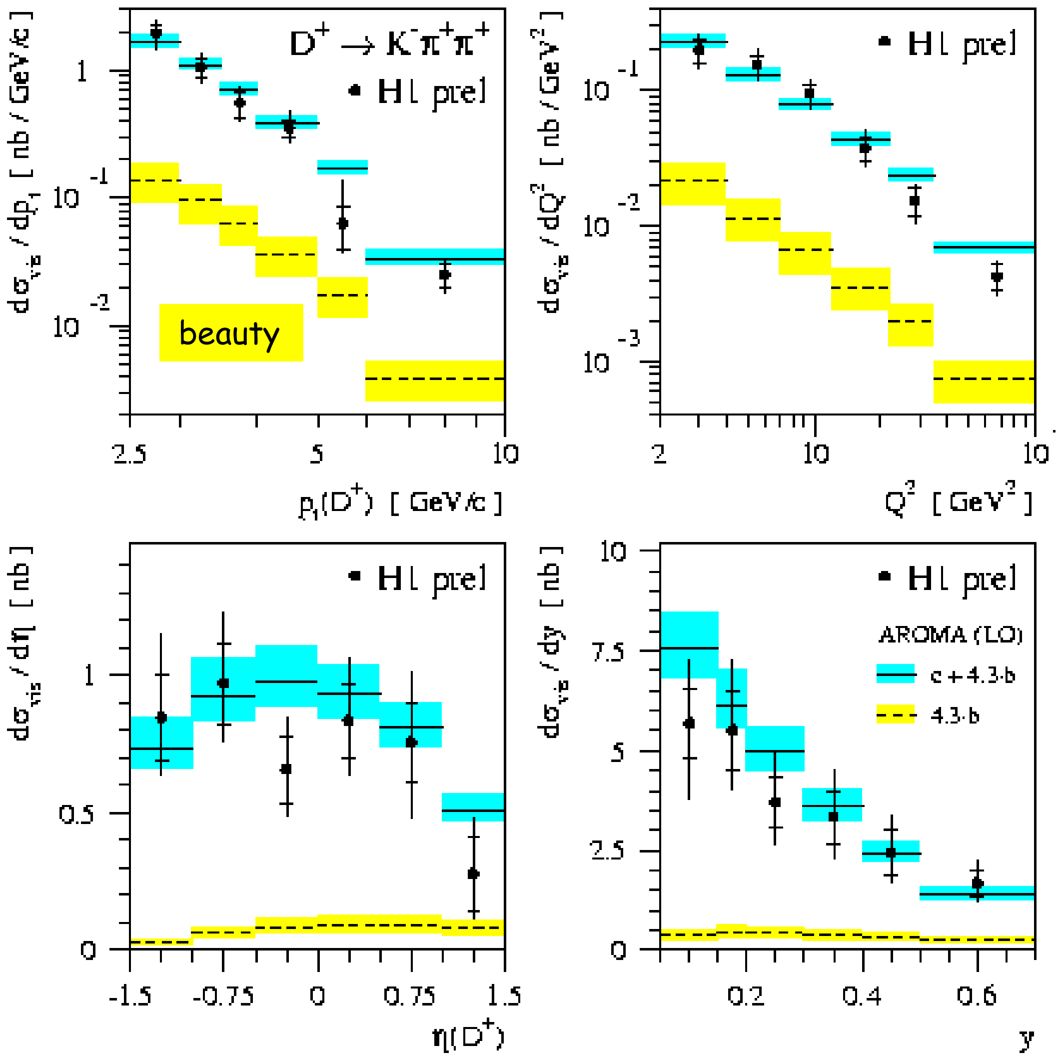


D^+ production in DIS

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

H1 data 1997/00, 48 pb^{-1}
$2 < Q^2 < 100$ GeV^2, $0.05<y<0.7$,
$p_T(D)>2.5$ GeV, $|\eta(D)|<1.5$

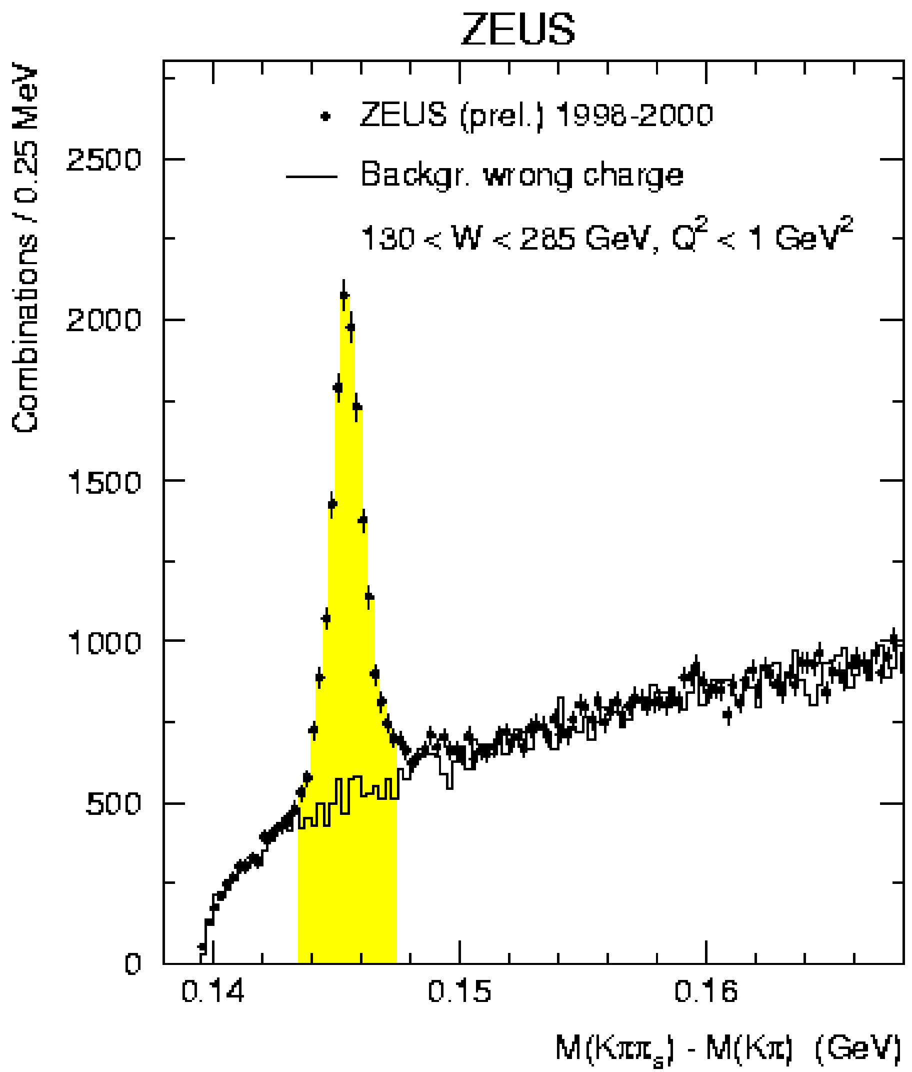
$\sigma(ep \to e\, D\, X) =$
$2.16 \pm 0.19\,(\text{stat})\,^{+0.46}_{-0.35}\,(\text{sys})$ nb



normalization and shape well described by LO+PS MC prediction

similar results for D*, D^0, D_s production

Charm: D* photoproduction



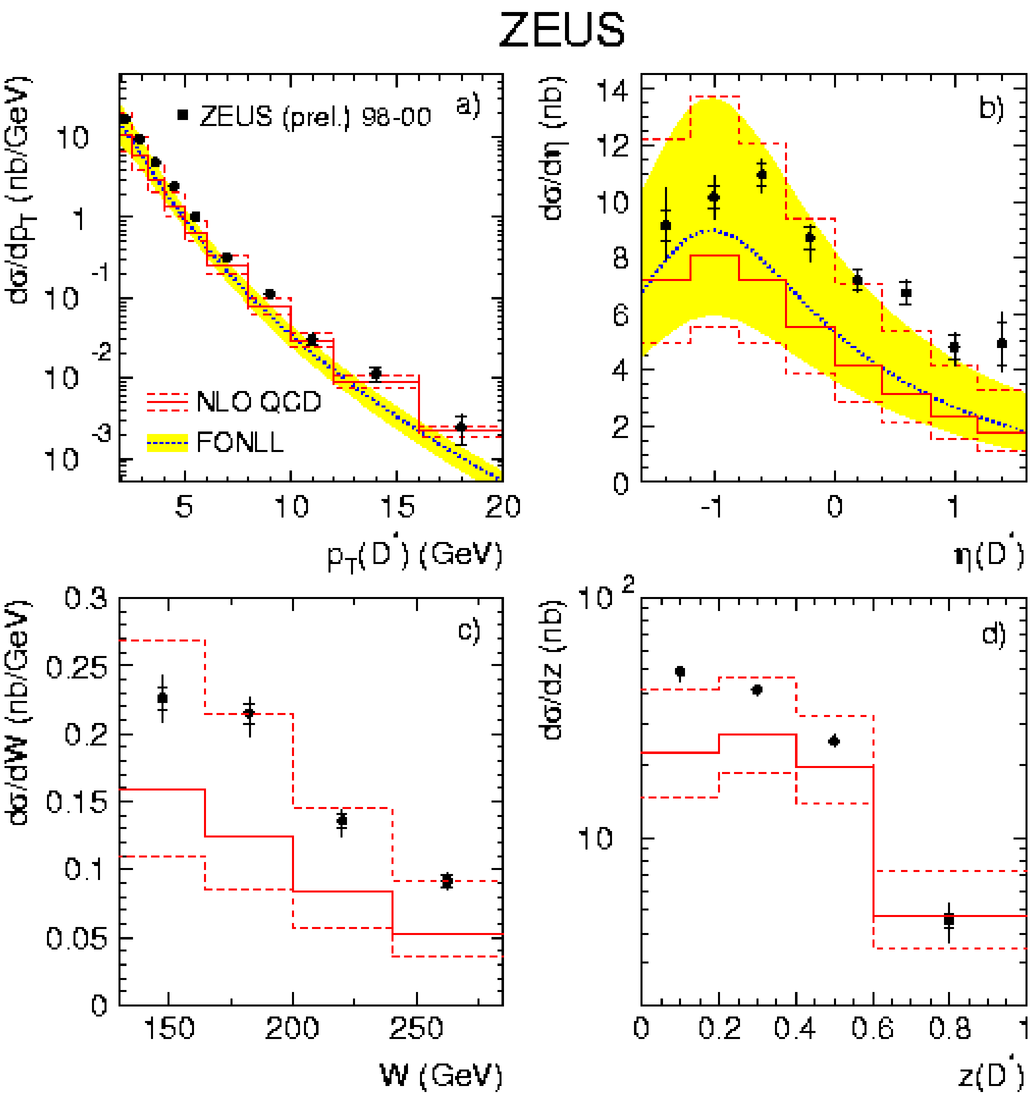
$D^{*+} \rightarrow D^0 \pi^+$ + c.c.
↳ $K^- \pi^+$

→ narrow peak in m(D*)-m(D^0)

ZEUS data 1998/00, 80 pb^{-1}
$Q^2 < 1$ GeV^2, 130<W<285 GeV,
1.9<p_T(D)<20 GeV, $|\eta(D)|$<1.6

~10000 D*s

D*in γp: Comparison with QCD predictions



QCD calculations using

CTEQ5M1 + AFG structure functions

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

$\mu_r = \mu_f = \mu$, $\mu_0/2 < \mu < 2\mu_0$

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

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

→ FO NLO

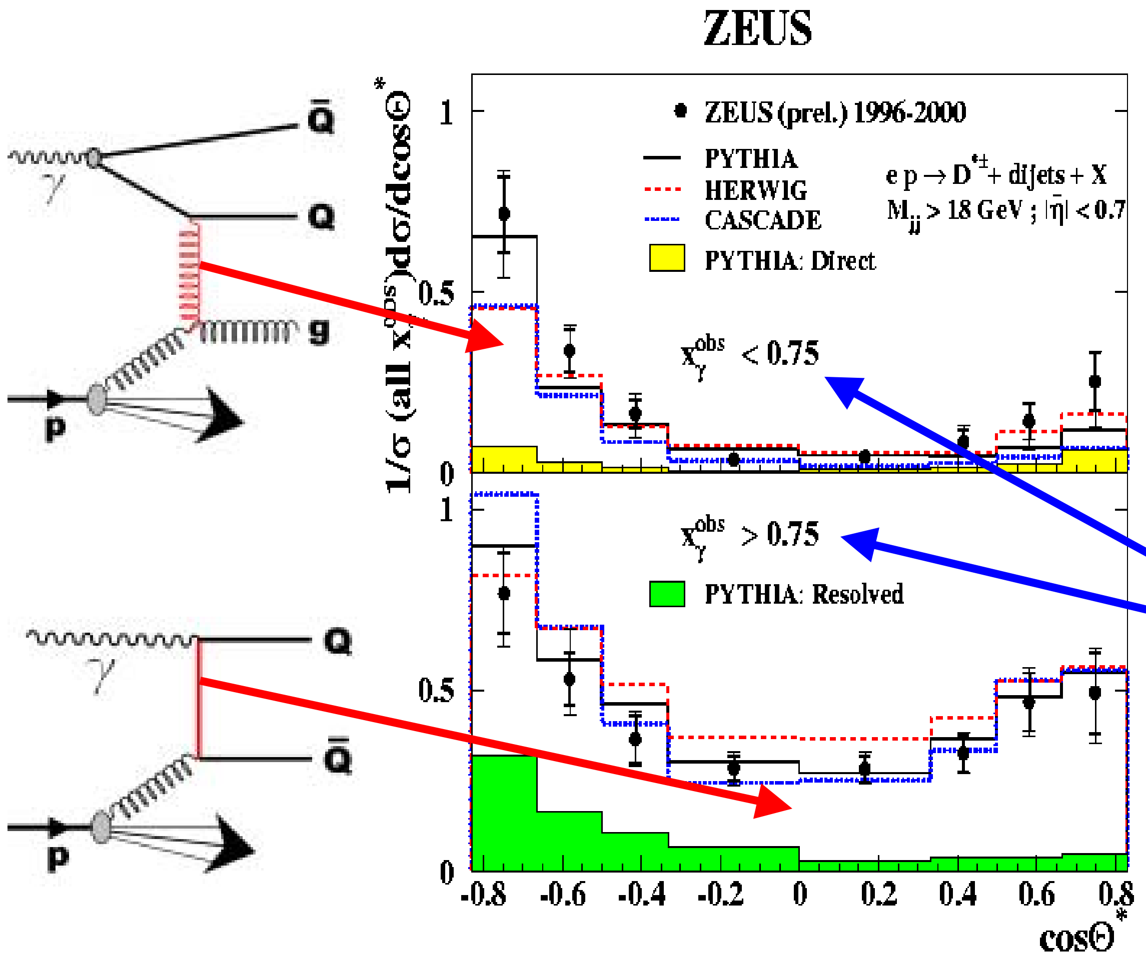
reasonable agreement
some deviations at forward η,
low z (z = E-p_z(D*)/E-p_z(total))

→ matched FONNL

similar to FO
slightly worse at large p_T

D*in γp: Dijet angular distributions

$p_T(D) > 3$ GeV, $|\eta(D)| < 1.5$, **two jets** $E_T > 5$ GeV, $|\eta|<2.4$



γ direction p direction

determine jet angle w.r.t. beam in dijet CM system: $\cos\theta^*$

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

using $x_\gamma^{obs} = \dfrac{\sum_{jets} E_T e^{-\eta}}{2yE_e}$

(~ fraction of γ energy participating in interaction)

split sample into

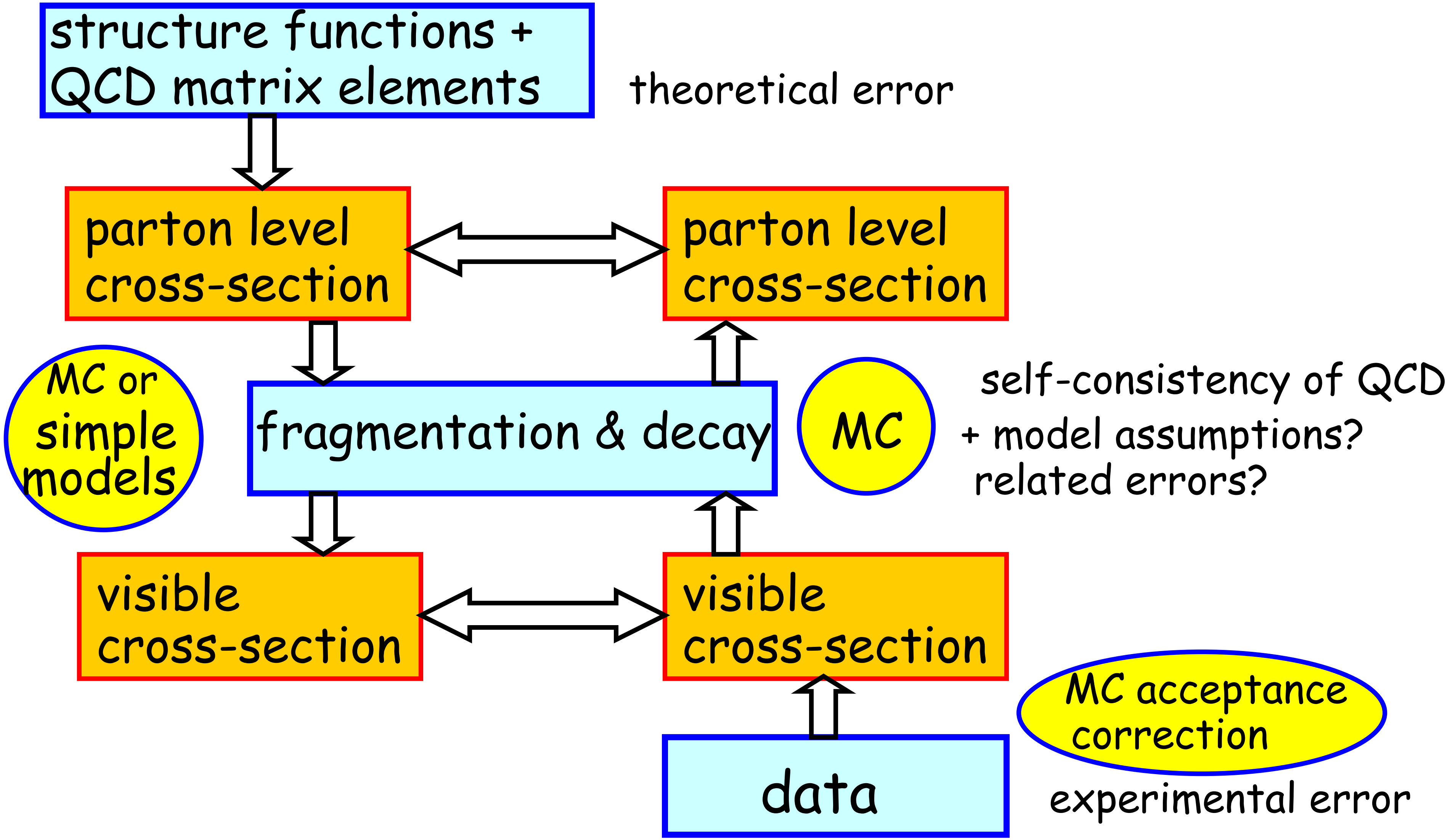
resolved-enriched ($x_\gamma^{obs} < 0.75$)

BGF-enriched ($x_\gamma^{obs} > 0.75$)

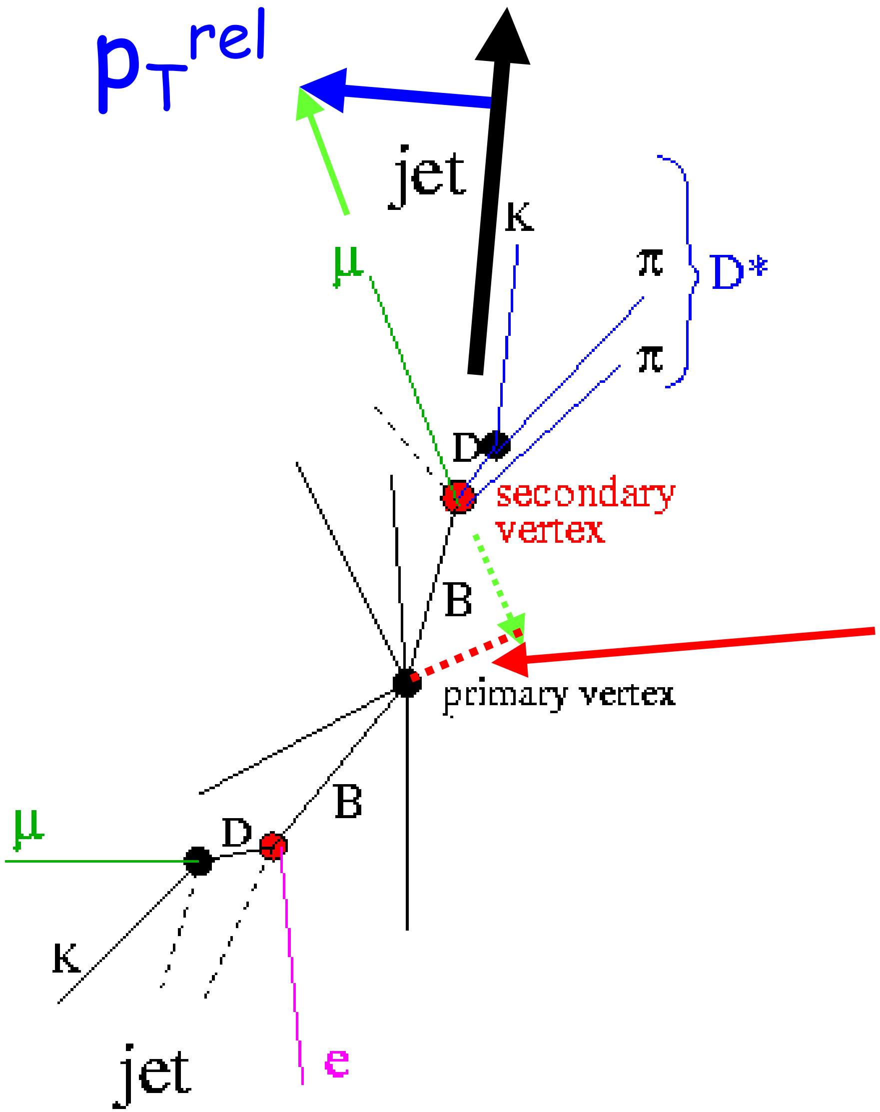
strong asymmetric rise of cross section in photon direction

→ clear indication for gluon propagator contribution

caveats for data - theory comparison



Tagging semileptonic beauty decays



1) p_T^{rel} :

p_T of μ with respect to jet axis

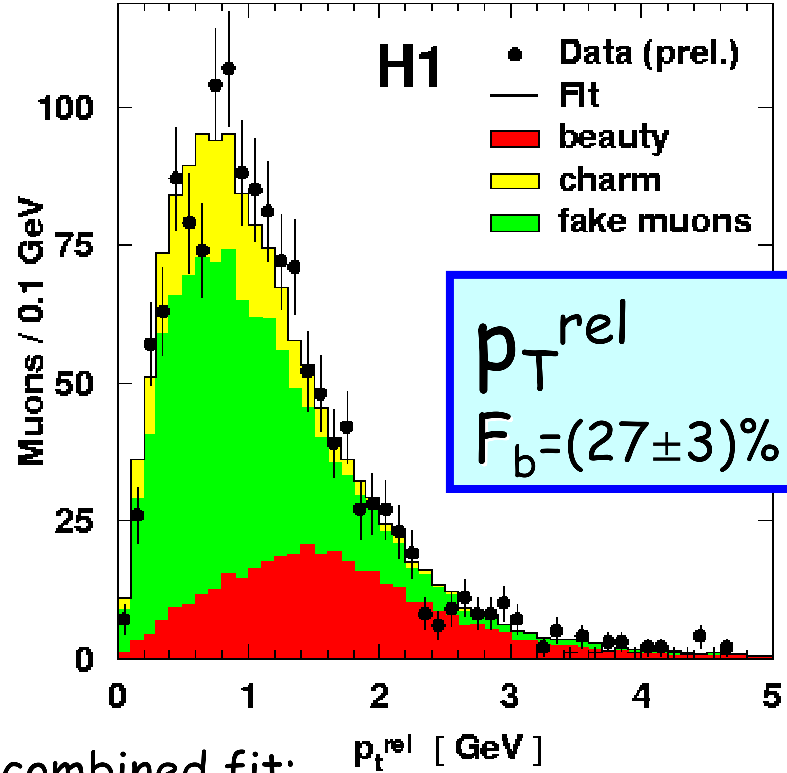
2) impact parameter

of μ with respect to primary vertex

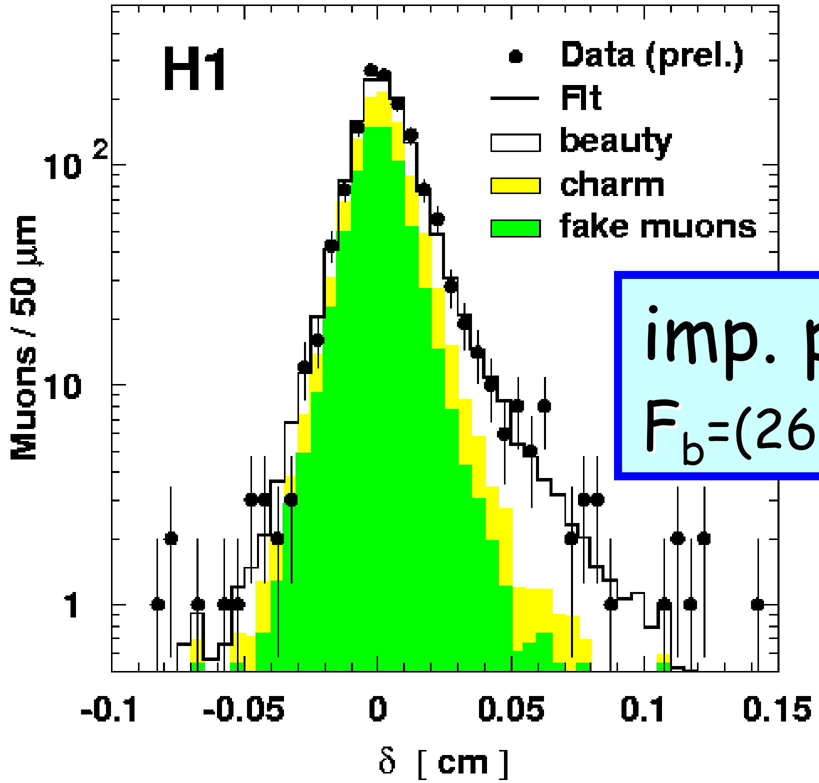
3) D* μ correlations

Beauty in photoproduction

H1 data 1997, ~15 pb^{-1}, $Q^2 < 1$ GeV^2, $0.1<y<0.8$, muon with $p_T>2$ GeV, $35^\circ<\theta<130^\circ$



p_T^{rel}
$F_b=(27\pm3)\%$



imp. par.
$F_b=(26\pm5)\%$

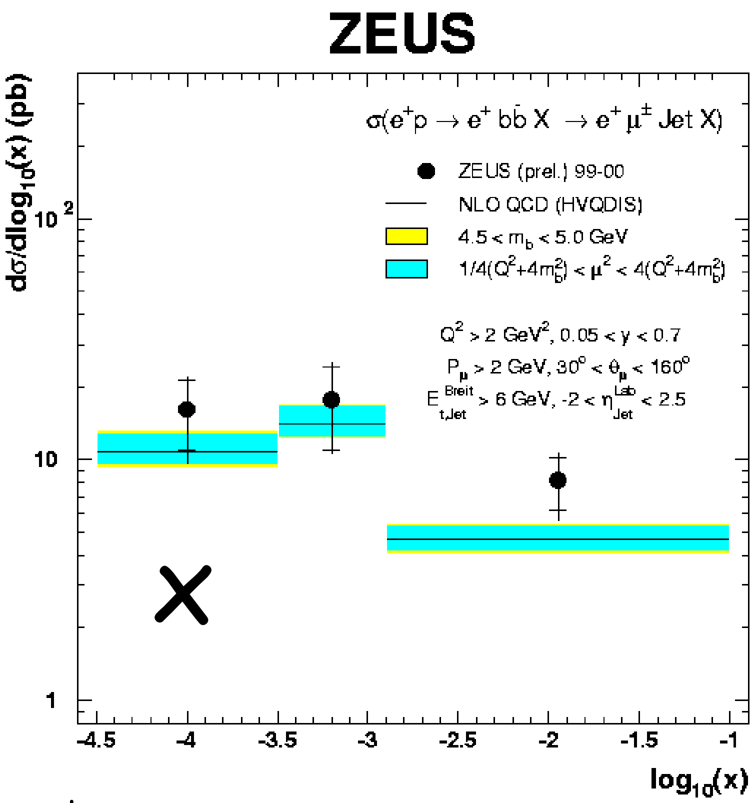
combined fit:

$\sigma(ep \rightarrow b\bar{b}\,X \rightarrow \mu\,X) = 160 \pm 16$ (stat) ± 29 (sys) pb
96 data (p_T^{rel} only): 176 ± 16 (stat) $^{+27}_{-17}$ (sys) pb

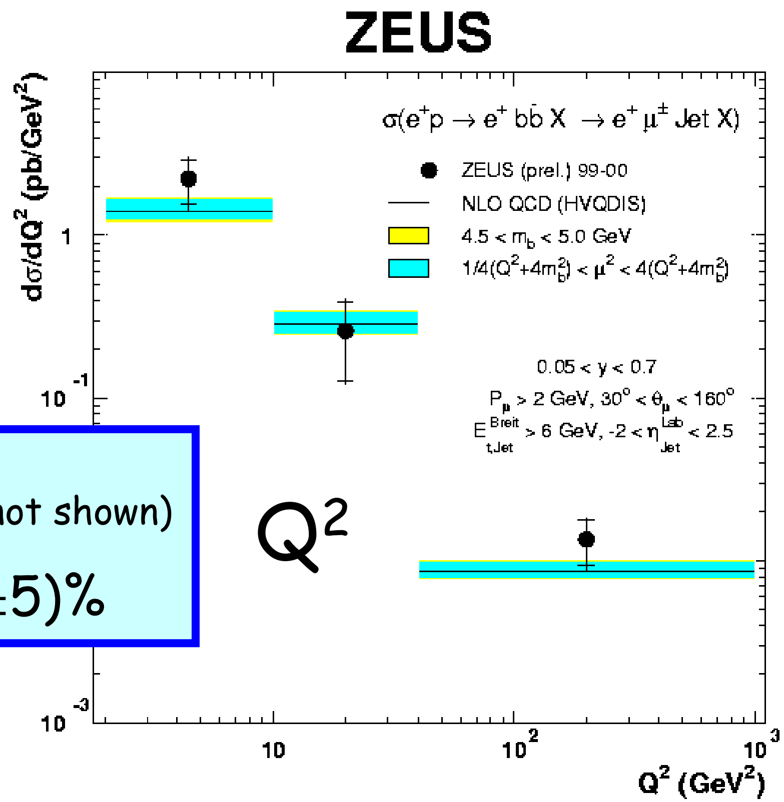
NLO QCD (FMNR):
54 ± 9 pb

Beauty in DIS

ZEUS data 1999/00, ~60 pb^{-1}, $Q^2 > 2$ GeV^2, 0.05<y<0.7, muon with p>2 GeV, **30° < θ < 160°**
at least one jet with $E_T^{Breit} > 6$ GeV in γ*p frame, $-2 < \eta^{Lab} < 2.5$



p_T^{rel} (not shown)
F_b=(25±5)%



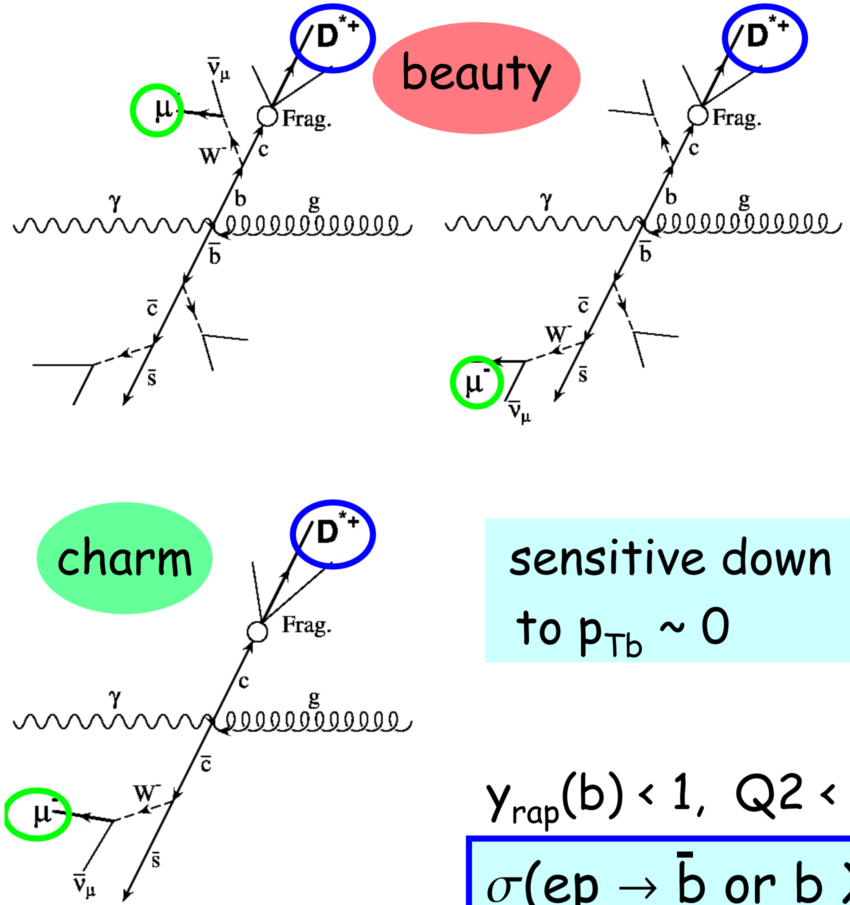
p_T^{rel} fit:

$\sigma(ep \to eb\bar{b}\ X \to e\mu\ jetX) = 38.7 \pm 7.7\ (stat)\ ^{+6.1}_{-5.0}\ (sys)$ pb

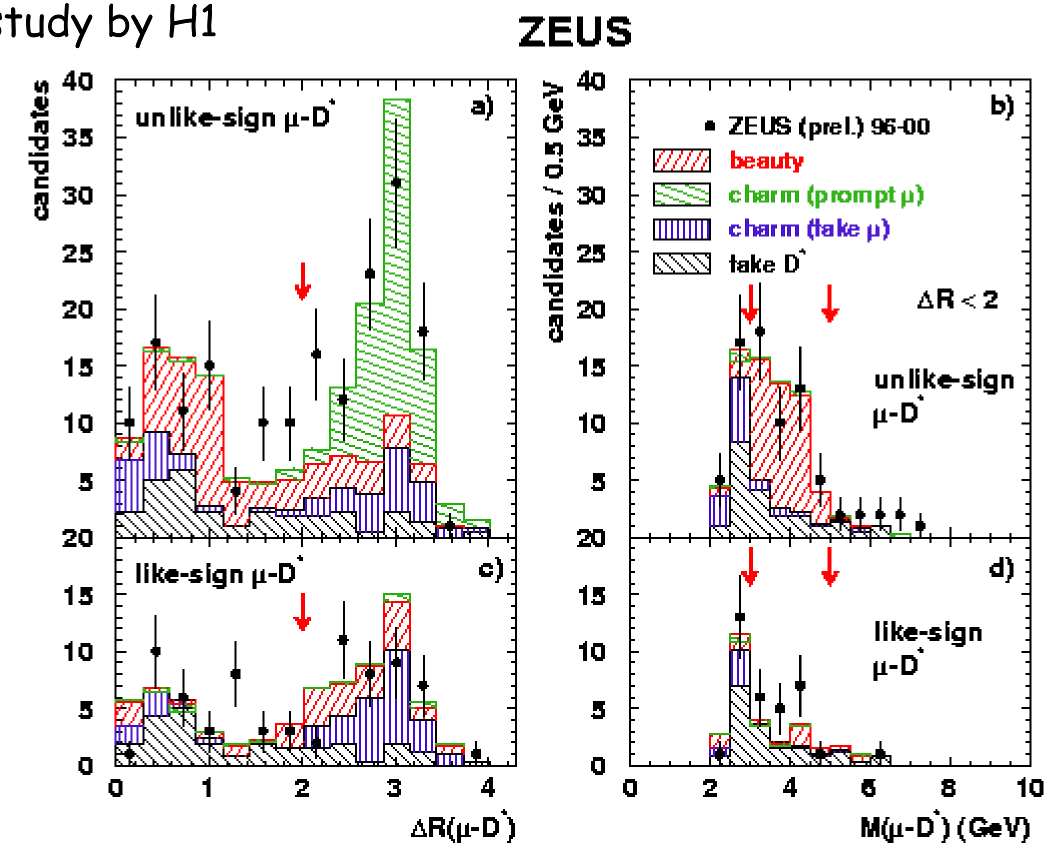
NLO QCD (HVQDIS):
28.1 + 5.3 -3.5 pb

Beauty cross-section from D*+ μ final state

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



sensitive down to $p_{Tb} \sim 0$



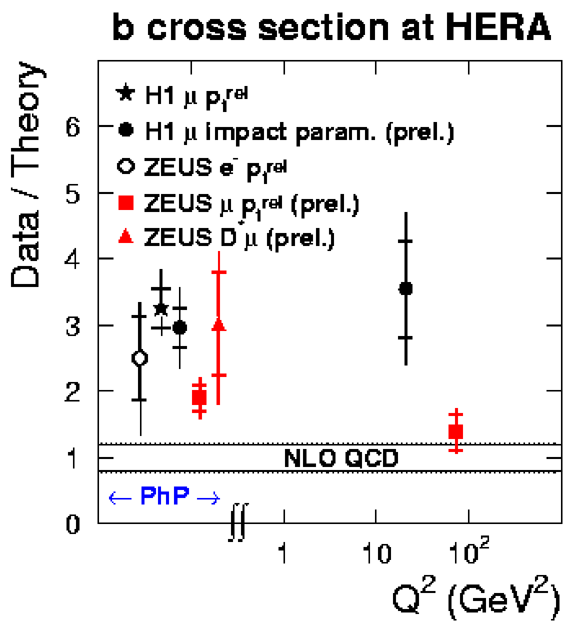
$y_{rap}(b) < 1$, $Q2 < 1$ GeV2, $0.05<y<0.85$

$\sigma(ep \rightarrow \bar{b} \text{ or } b\ X) = 15.1 \pm 3.9\ (stat)\ ^{+3.8}_{-4.7}\ (sys)$ pb

NLO QCD (FMNR): 5.7 +1.7 -1.1 pb

Summary and Conclusions

- Heavy Flavour production in e-p collisions is good testing ground for perturbative QCD
- Charm production in reasonable agreement with expections, some aspects need further clarification (more statistics, is charm mass heavy enough for pQCD?)
- NLO QCD predictions start to agree with some of the new beauty production results, but not yet fully consistent picture (different kinematic ranges, different approaches to perturbative calculations, fragmentation, decay, acceptance corrections)
  -> need more work, more data



- higher luminosity, and new detectors (e.g. ZEUS Micro-Vertex-Detector) will contribute to resolve remaining issues

Perturbative QCD calculations for open heavy flavour (opt)

Monte Carlo Programs

main purpose: efficiency calculations and qualitative QCD predictions

- LO matrix elements + parton shower (leading log), DGLAP (collinear) parton evolution:
  PYTHIA, HERWIG, RAPGAP (direct + resolved), AROMA (direct only)
- BGF matrix element + gluon cascade, CCFM (angular ordered) gluon evolution:
  CASCADE

NLO QCD calculations

main purpose: quantitative QCD predictions

- Fixed Order ($\alpha\alpha_s^2$, α_s^3), massive (FO): heavy quarks produced at perturbative level, reliable for $p_T \sim m_Q$ (FMNR, HVQDIS: Frixione et al., Harris + Smith)
- ReSummed, massless approach (RS): „massless" heavy quarks are active constituents of p and γ, masses only used for final state kinematics, resums next-to-leading log (NLL) contributions of large logs in Q/m_Q, p_T/m_Q to all orders, reliable for $p_T \gg m_Q$ (Kniehl, Kramer, Cacciari, ...)
- matched calculations of both schemes (FONLL): FO at low p_T, RS at large p_T (Frixione, Nason, Cacciari)

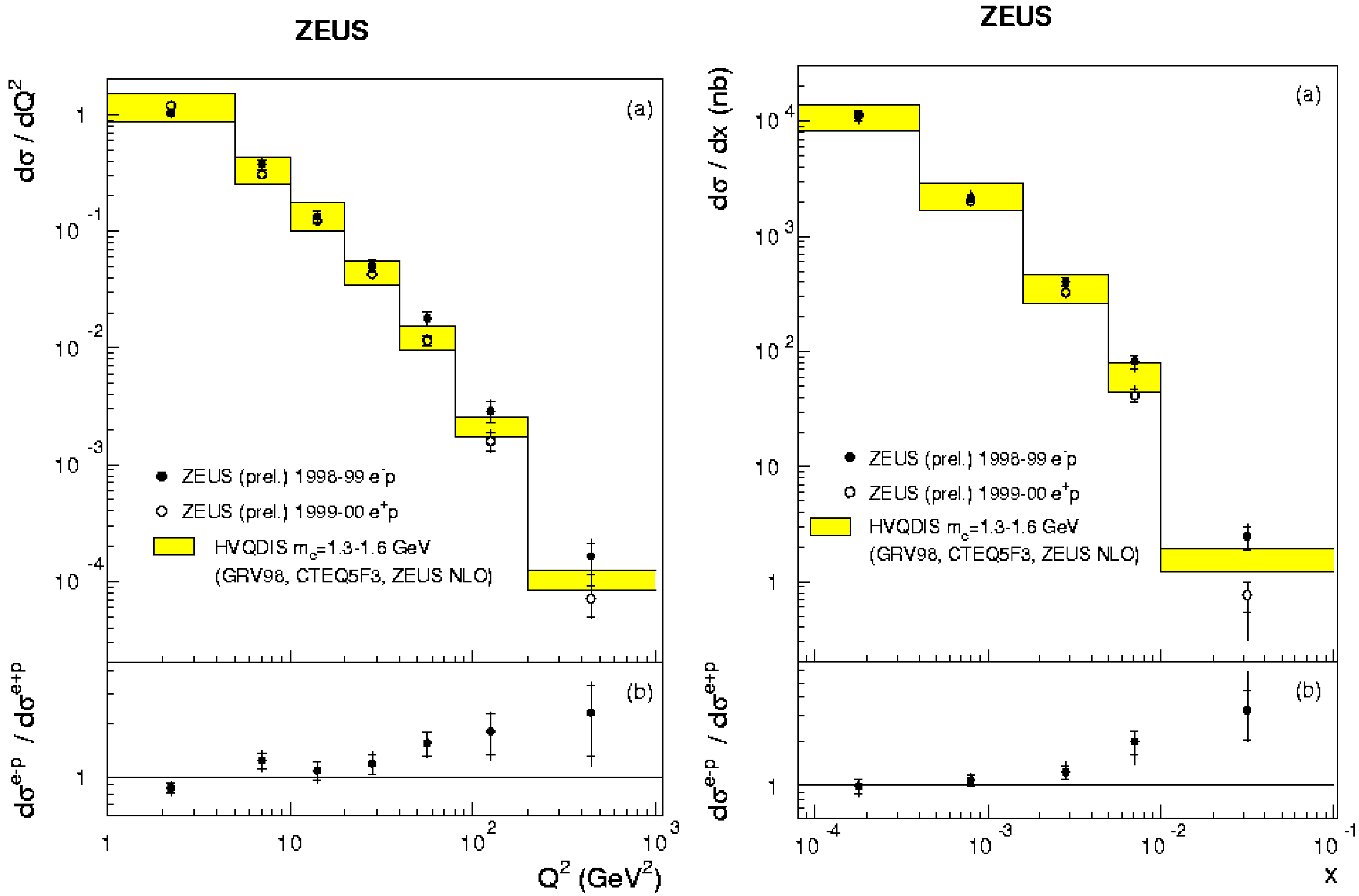
e^-p vs e^+p D* production in DIS (opt)

$1 < Q^2 < 1000$ GeV^2

$0.02 < y < 0.8$

$15 < p_T(D) < 15$ GeV

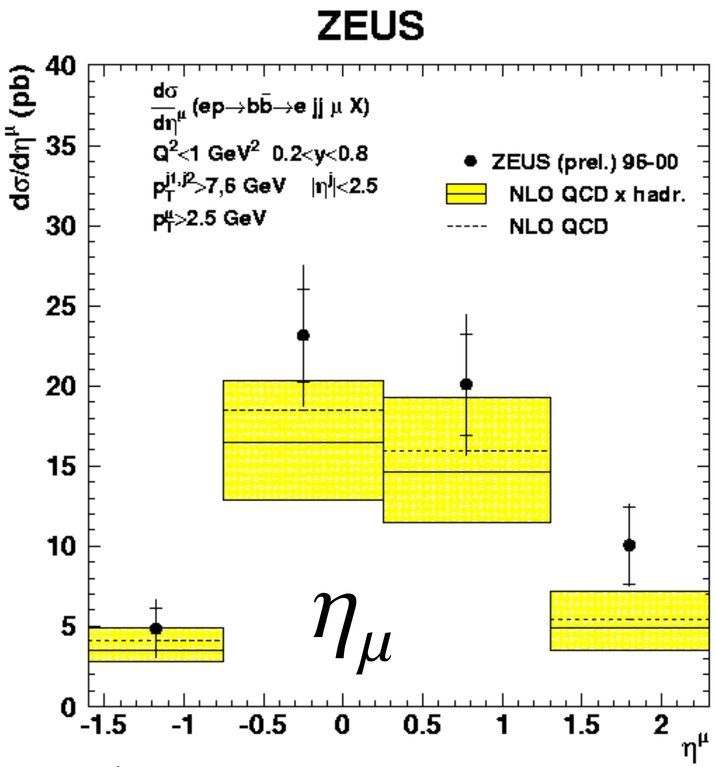
$|\eta(D)| < 1.5$



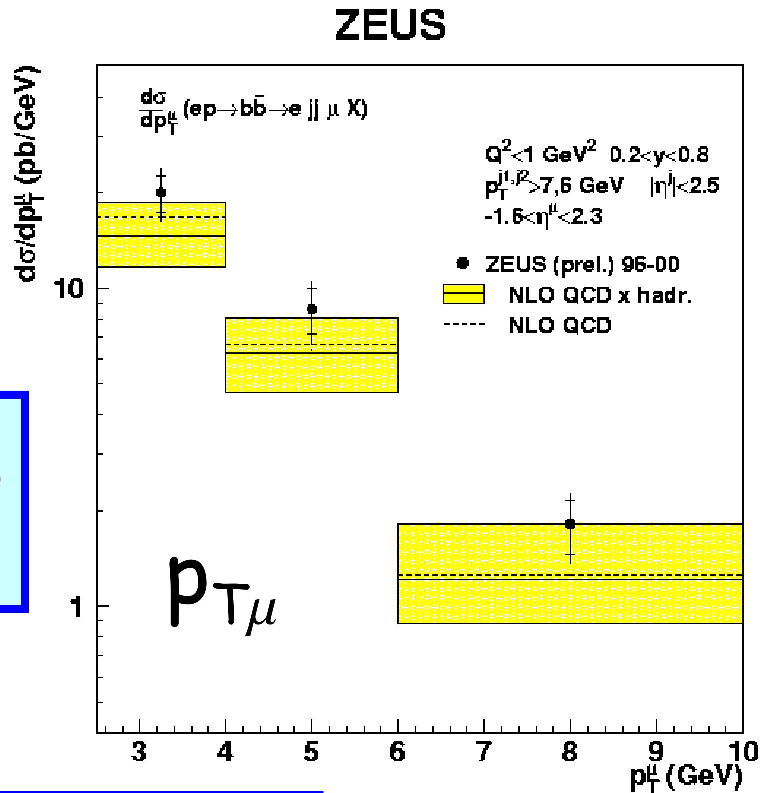
difference between e^-p and e^+p at large x, Q^2; unexpected, not explained, statistical fluctuation??

Beauty in photoproduction (opt)

ZEUS data 1996/00, ~98 pb^{-1}, $Q^2 < 1$ GeV^2, $0.2<y<0.8$, muon with $p_T>2$ GeV, $-1.6<\eta<2.3$,
at least two jets with $p_{T,Jet1(Jet2)} > 7$ (6) GeV, $|\eta|<2.5$



p_T^{rel} (not shown)
$F_b=(27\pm3)\%$

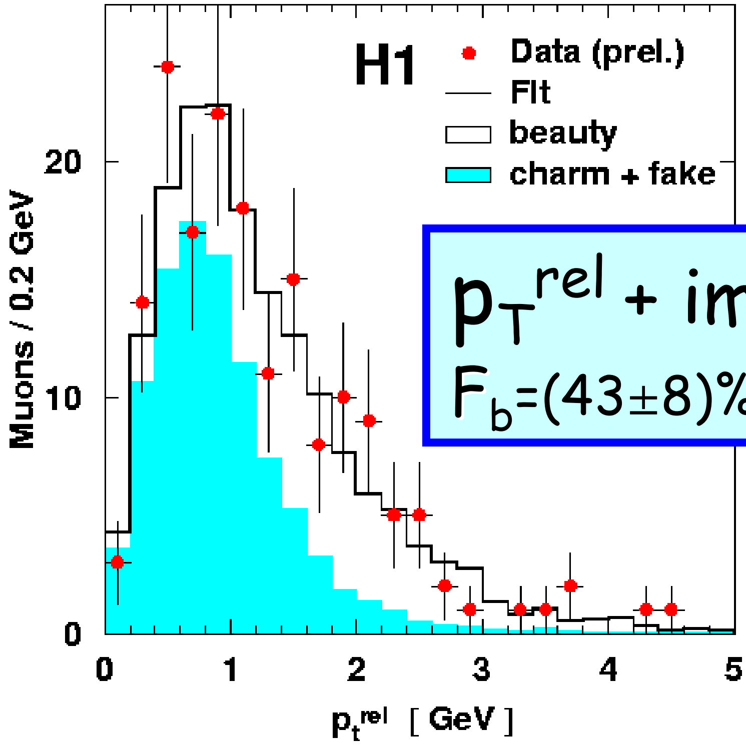


p_T^{rel} fit:

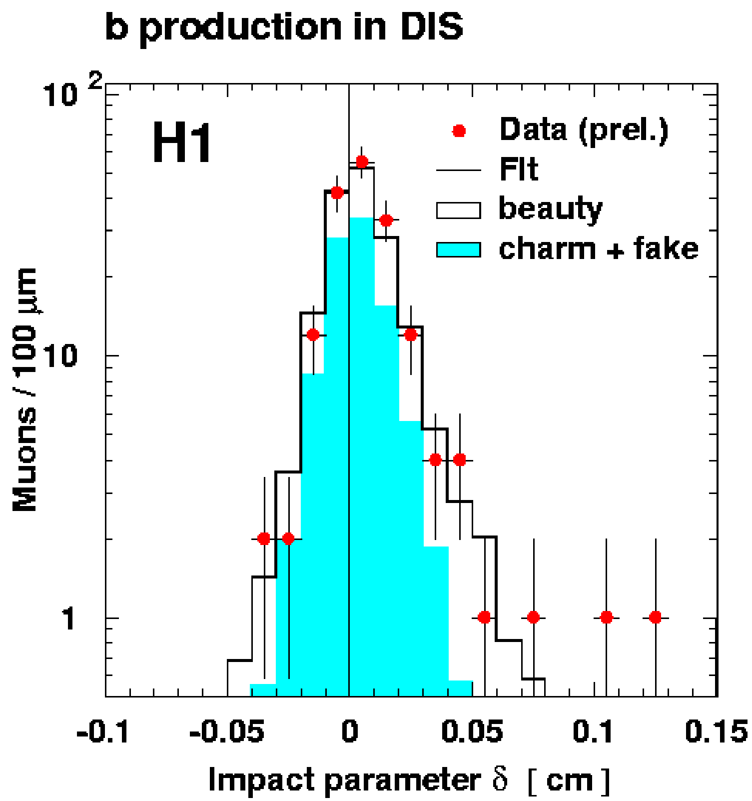
$\sigma(ep \rightarrow bb\ X \rightarrow \text{Jet Jet}\ \mu\ X) = 733 \pm 61\ (\text{stat}) \pm 104\ (\text{sys})$ pb
NLO QCD (FMNR): $381\ {+117}\ {-78}$ pb

Beauty in DIS (opt)

H1 data 1997, ~10 pb^{-1}, 2< Q^2 < 100 GeV^2, 0.05<y<0.7, muon with p_T>2 GeV, $35^o < \theta < 130^o$



p_T^{rel} + imp. par.
F_b=(43±8)%



combined fit:

$\sigma(ep \rightarrow bb\ X \rightarrow \mu\ X)$ = 39 ± 8 (stat) ± 10 (sys) pb

NLO QCD (FMNR):
11 ± 2 pb