Charm and Beauty Production at HERA

Outline

- Introduction
- Charm Production
- Beauty Production
- Summary and Outlook

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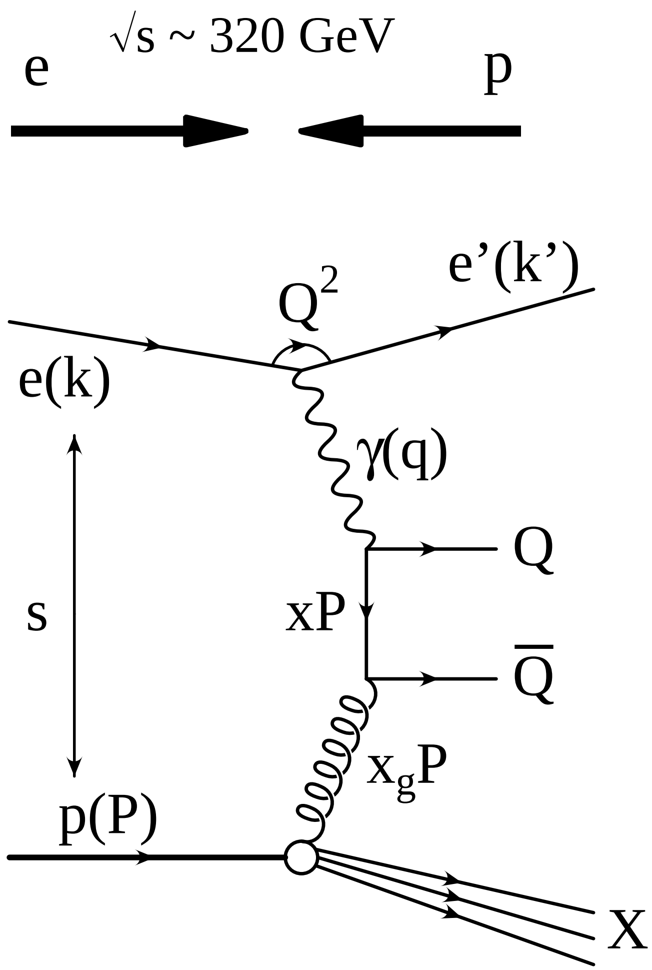
some selected results on charm and beauty production at HERA, mostly from the full HERA I dataset (~100/pb)

Heavy Quark Production at HERA



- two kinematical regions
  - photon almost on mass shell

    photoproduction (γp)
  - photon highly virtual

    deep inelastic scattering (DIS)
  - same production mechanism but real photons can behave as hadrons
- study pQCD dynamics in heavy quark production
- learn more about structure of proton and photon

QCD Calculations

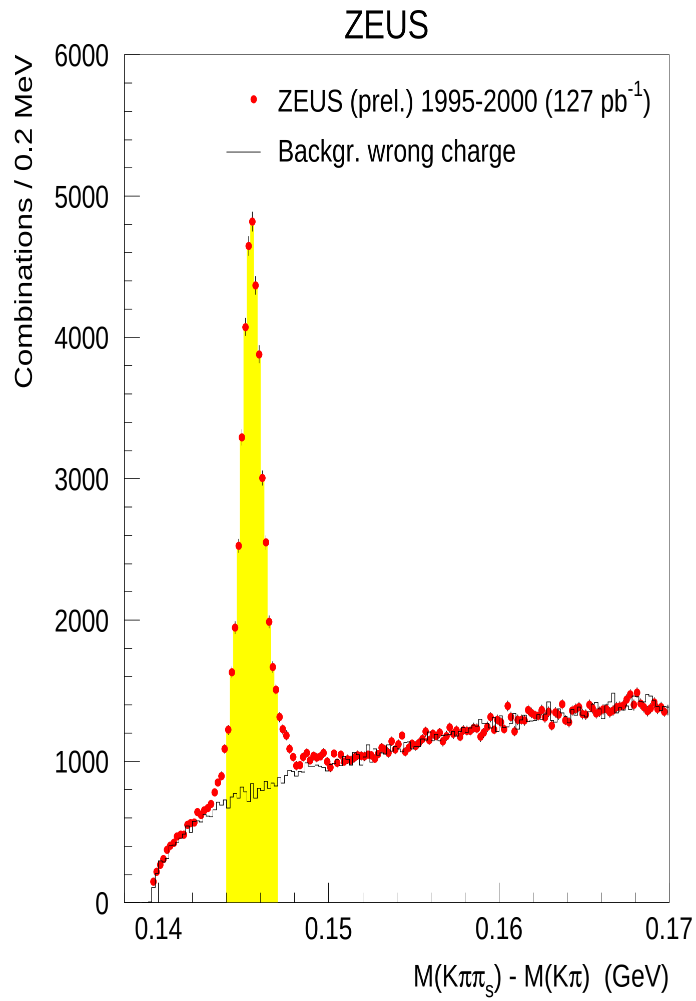
- LO + PS programs
  - AROMA
    - direct only, DGLAP evolution
  - HERWIG, PYTHIA
    - direct and resolved, DGLAP
  - CASCADE
    - direct only, CCFM−like evolution
- fixed (NLO) order (FO) calculations ("massive")
  - FMNR, HVQDIS
    - HQ mostly via BGF (quark masses taken into account)
    - valid for $Q, p_t \sim m_Q$
- resummed (RS) calculations ("massless")
  - Cacciari et al., Kniehl et al.
    - HQ part of parton densities (massless quarks)
    - resums contributions of large logarithms (Q/m_Q, p_t/m_Q)
    - valid for $Q, p_t \gg m_Q$
- matched calculations (FONLL)
  - Frixione, Nason
    - merges FO and RS calculations

Charm Tagging

- mass difference method, e.g.

  $\Delta M = M(K^-\pi^+\pi^+) - M(K^-\pi^+)$

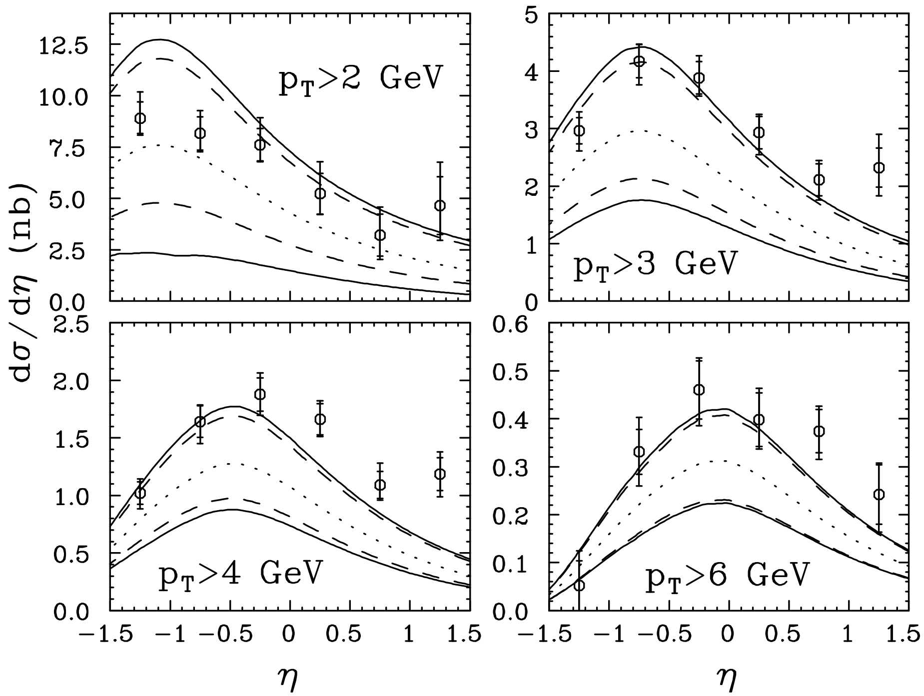
- other channels studied
  - D_S
  - D^0
  - excited charm states (D^{**}, $D_{s1}^{\pm}(2536)$)
  - semileptonic decays
  - ...



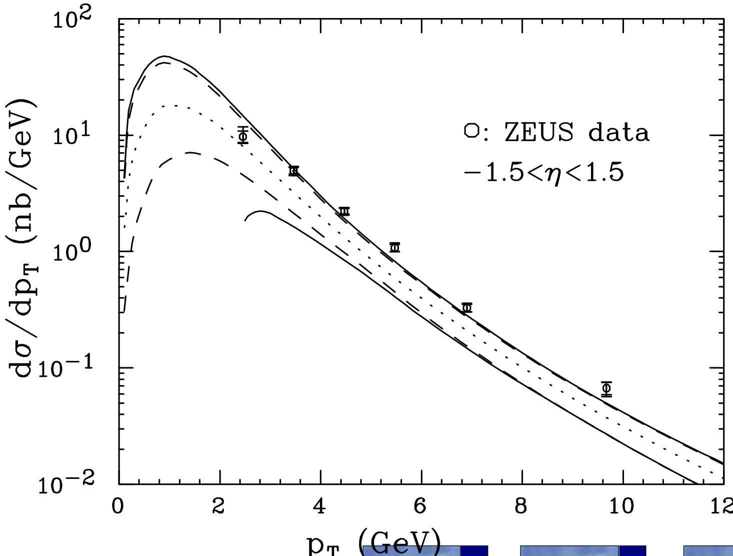
... an example: D* cross sections in photoproduction

Differential Cross sections

$\mathscr{L} \sim 40\ pb^{-1}$



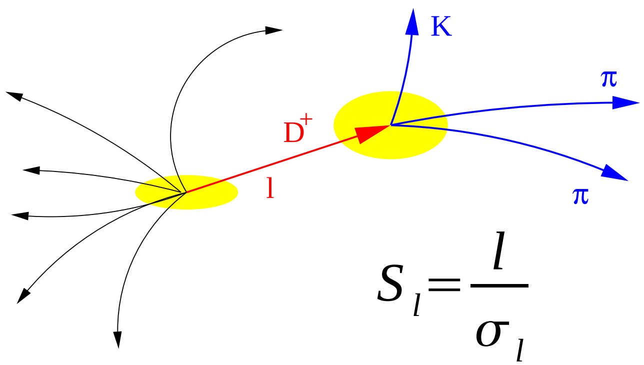
- comparison with FONLL
  - dotted curve: central prediction
  - solid curve: all uncertainties added linearly
  - dashed curve: without factorization scale uncertainty



- theoretical uncertainties very large (mainly renormalization scale)
- predictions marginally consistent with data: fragmentation, NNLO?

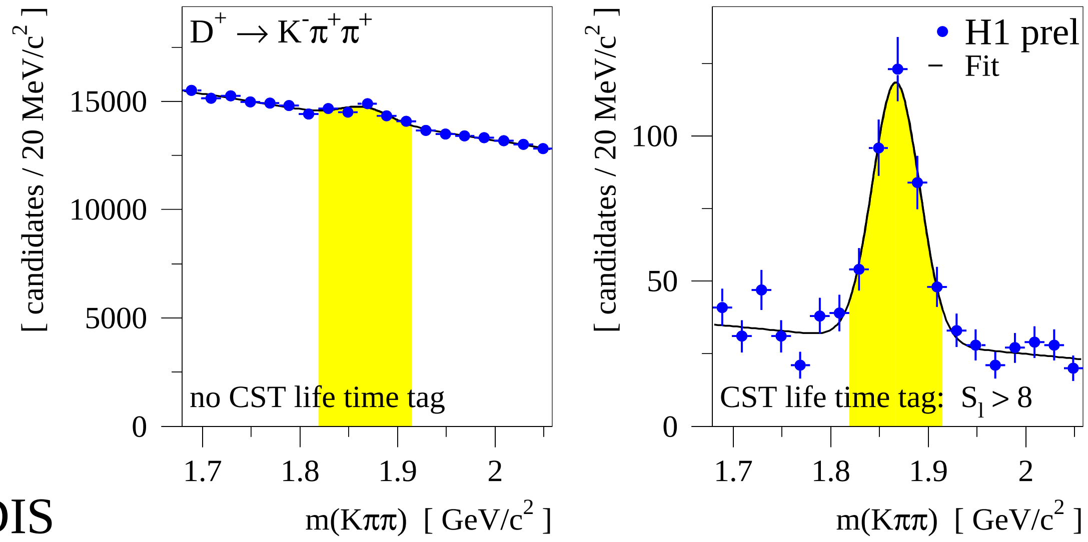
CHARM TAGGING … REVISITED

- vertex tagging (H1 silicon vertex detector, ZEUS micro vertex detector at HERA II)



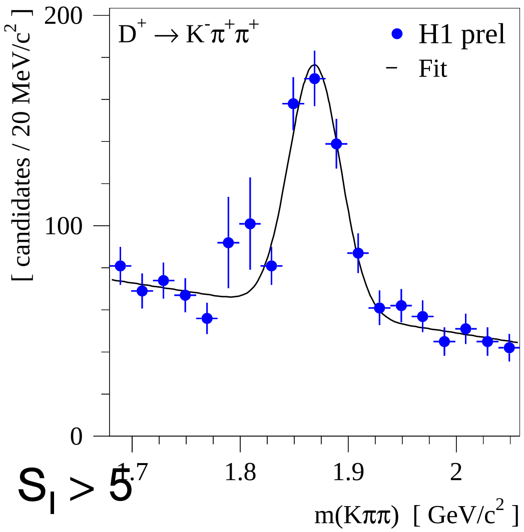
$$S_l = \frac{l}{\sigma_l}$$

- study production of various charm hadrons in DIS (D^{*+}, D^+, D^0, D_S^+)
  - independent cross section measurements
  - fragmentation fractions



… an example: D^+ production in DIS

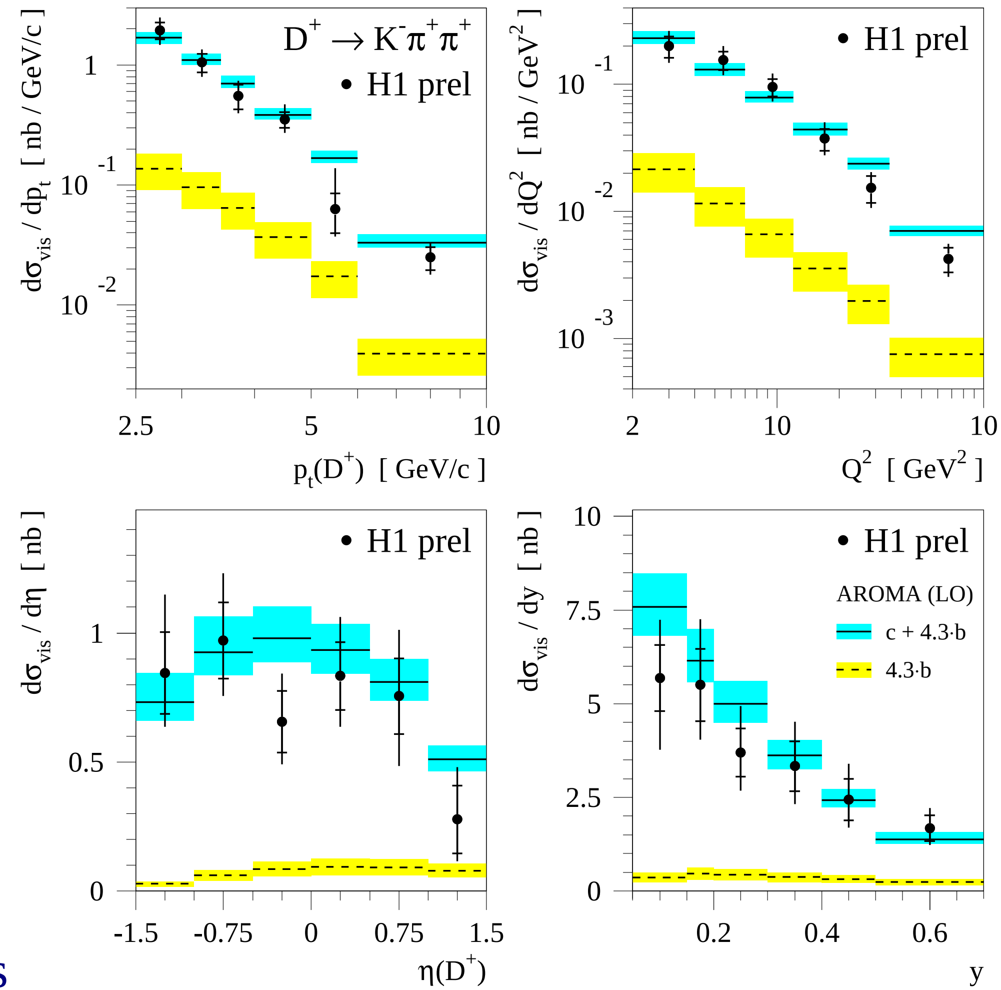
D+ Production (DIS)



- visible cross section (H1 Prelim.)

$$\sigma(ep \rightarrow eDX) = (2.16 \pm 0.19 {}^{+0.46}_{-0.36})\,nb$$

- in good agreement with LO + PS prediction ((2.45±0.30) nb)
- shapes well reproduced by LO + PS Monte Carlo (AROMA)
- similar results for other charm states



Fragmentation Ratios

- vector to pseudoscalar ratio (expect about 0.75 from counting spin states)

$$P_V = \left(0.693 \pm 0.045(stat) \pm 0.004(syst) \pm 0.009(theo)\right)$$ H1 preliminary

$$P_V = \left(0.546 \pm 0.045(stat) \pm 0.028(syst)\right)$$ Zeus preliminary

- u to d ratio (expect about 1 from isospin invariance)

$$R_{u/d} = \left(1.26 \pm 0.061(stat) \pm 0.033(syst) \pm 0.008(theo)\right)$$ H1 preliminary

- strangeness suppression factor (expect about 0.3 from strange quark mass)

$$\gamma_s = \left(0.36 \pm 0.10(stat) \pm 0.01(syst) \pm 0.08(theo)\right)$$ H1 preliminary

$$\gamma_s = \left(0.27 \pm 0.05\right)$$ Zeus published

consistent with measurements in e^+e^-, ...

$\Rightarrow$ consistent with charm fragmentation universality

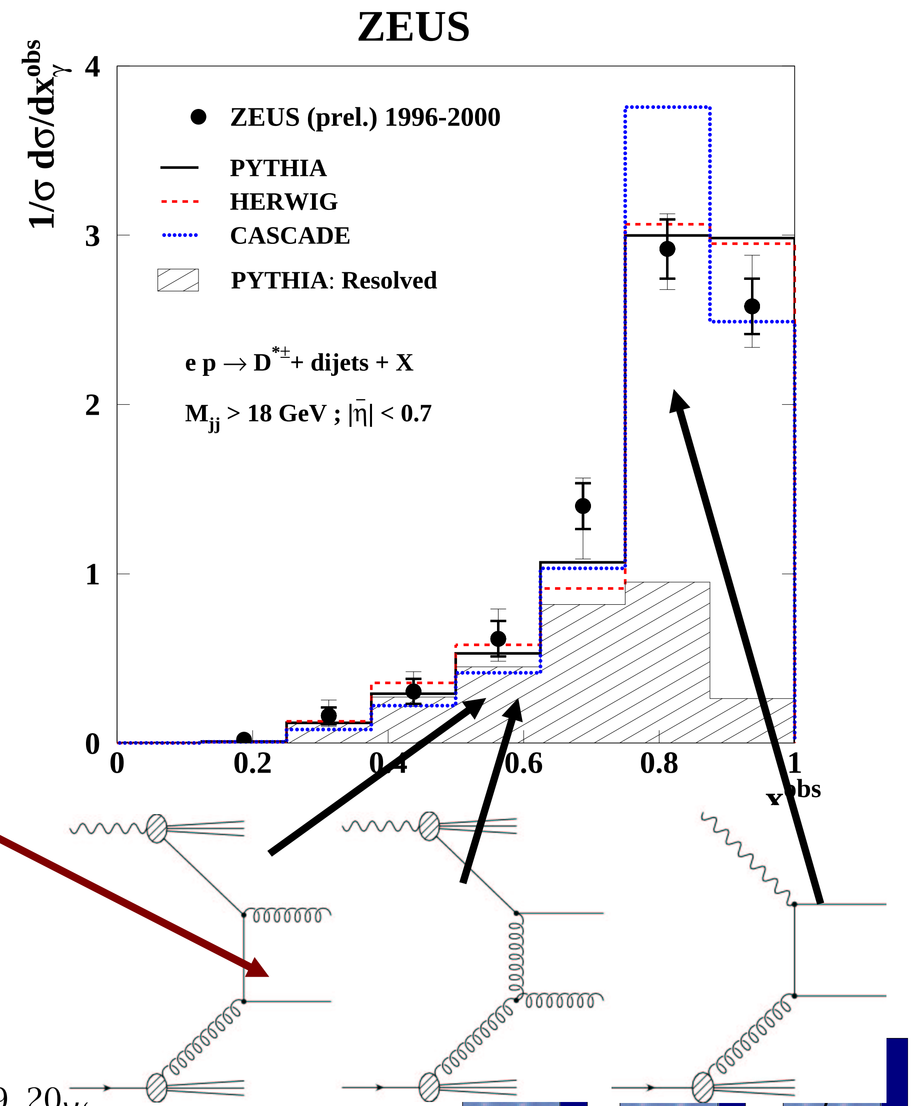
Photon Structure

- charm production used to study photon structure: D* tagged di−jet events
- fraction of photon momentum entering in charm production

$$x_\gamma^{obs} = \frac{\sum (E_t e^{-\eta})}{2yE_e}$$

- LO generators (PYTHIA, HERWIG) with charm excitation (perturbative part of parton densities) describe shape of data well

... further insight by investigating di−jet angular distributions



Di - Jet Angular Distributions

- angle between jet−jet axis and beam direction sensitive to propagator type (quark/gluon)

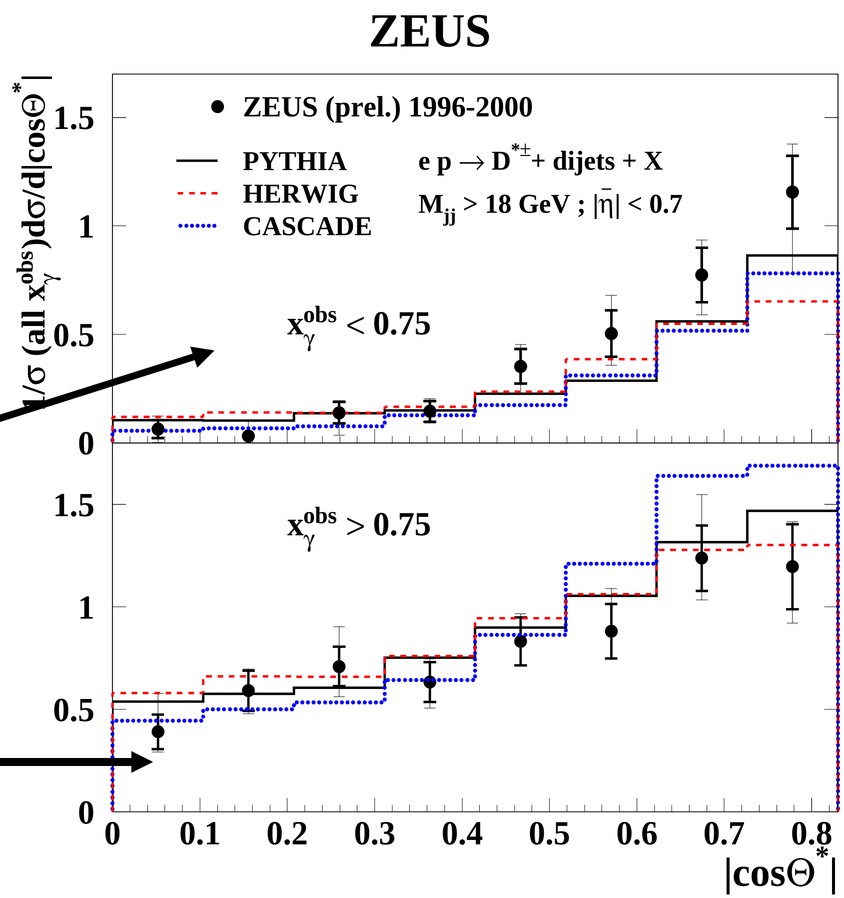
$$\cos\Theta^* = \tanh\left(\frac{\eta^{jet1}-\eta^{jet2}}{2}\right)$$

- resolved contribution is dominated by gluon exchange: cross section rises steeply at large $|\cos\Theta^*|$

$$(1-|\cos\Theta^*|)^{-2}$$

- direct contribution (LO) is quark exchange: cross section rises mildy with $|\cos\Theta^*|$

$$(1-|\cos\Theta^*|)^{-1}$$



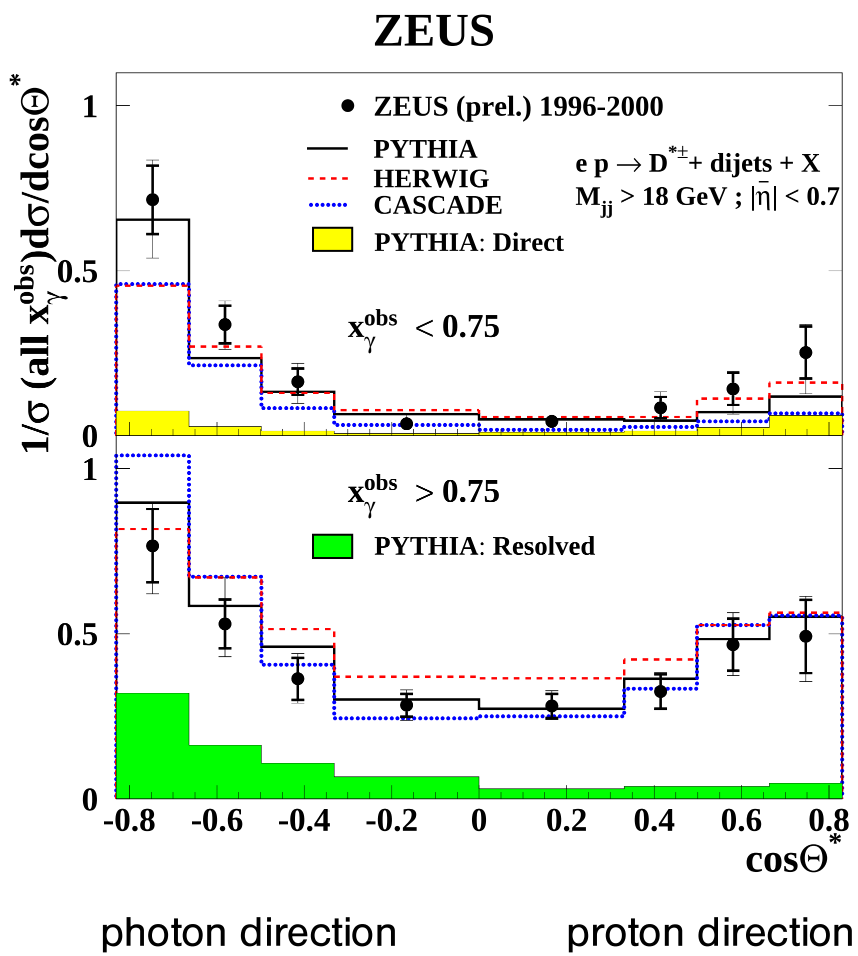
⇒ signature of gluon exchange

Di - Jet Angular Distributions

- identify charm jet by matching jets with a D*
  - D* jet mostly found in photon direction
  - contribution of resolved to $x_\gamma > 0.75$ explains asymmetric distribution in $\cos\theta^*$

⇒ evidence for charm content of photon

... comparison with NLO shortly

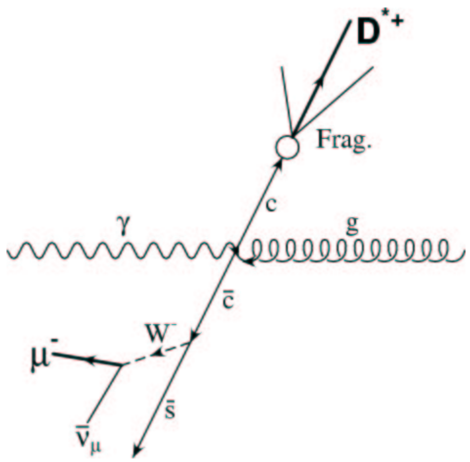


Double Tags

- tag both charm (beauty) quarks to completely reconstruct the hadronic final state, e.g.

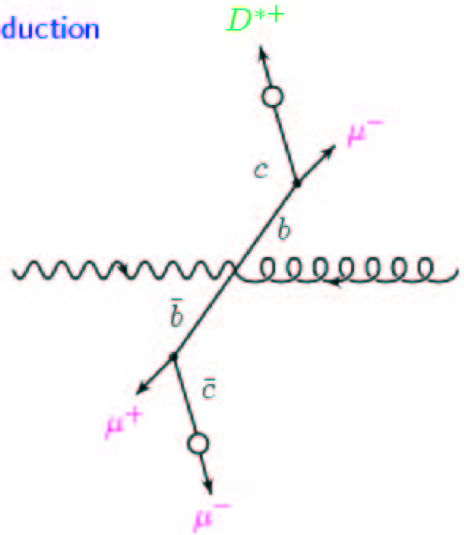
  $D^{*\pm}\ l^{\mp}$, $D^{*+}\ D^{*-}$, l^+l^-, $l = e, \mu$

  - measurement of the gluon density
  - sensitive to higher orders and non−perturbative effects

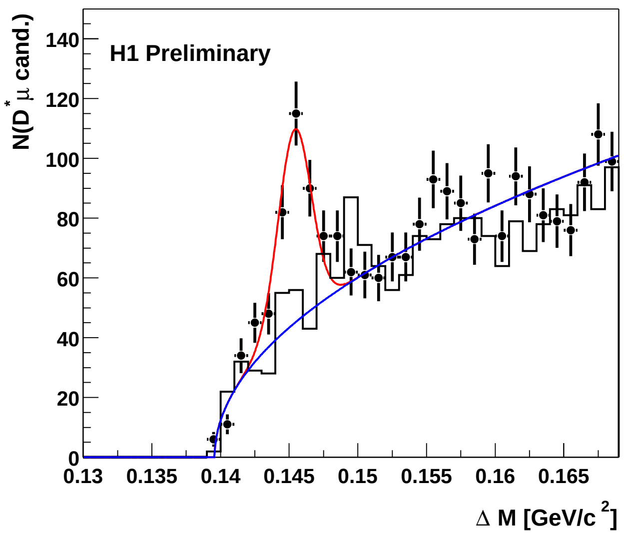


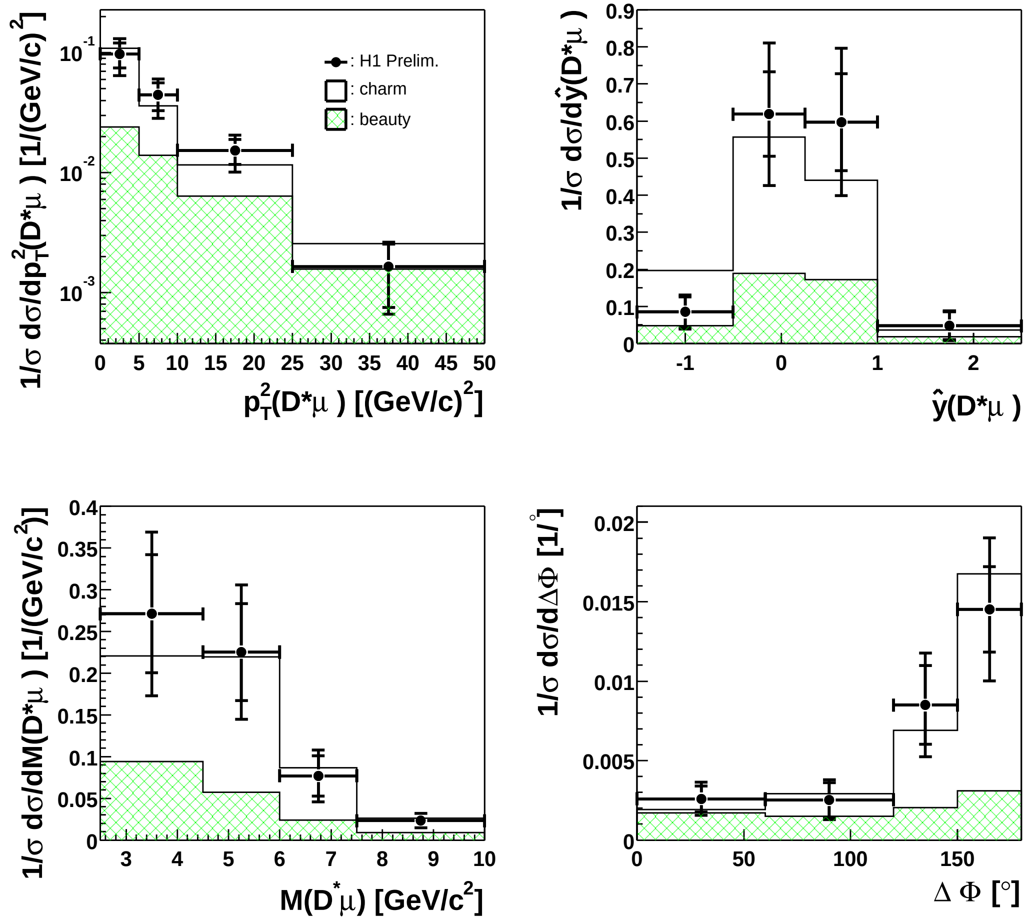
- example: $D^{*\pm}\ \mu^{\mp}$ analysis
  - exploit charge and angular correlations to separate charm and beauty
    - measurements of total cross sections compatible with previous results
    - measure differential distributions ...

Beauty production



Double Tags (DIS and γP)





- good agreement with LO+PS prediction
- large potential for HERA II

Charm Conclusions

- charm production at HERA
  - pQCD calculations in NLO about consistent with data, but
    - parameters in the calculations have to be stretched within their uncertainties
    - theoretical uncertainties rather large
    - experimental uncertainties typically smaller but still large
  - some puzzling details need to be understood
    - better agreement using NNLO calculations, ...
  - a consistent picture of the (gluonic) structure of the proton and the photon emerges

... what about the next heavier quark ?

Beauty Production

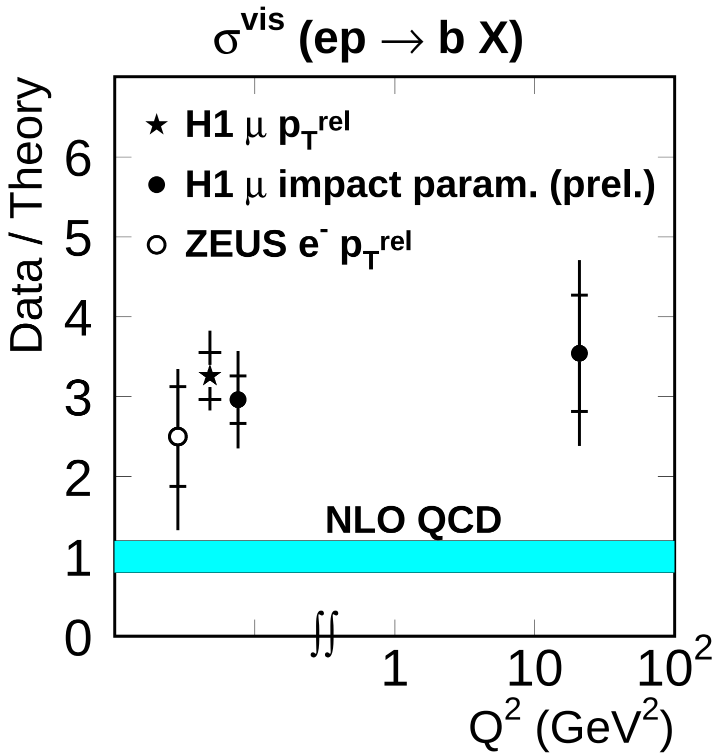
- beauty cross sections expected to be smaller than charm cross sections by a factor of 200 (larger mass, smaller charge)
- theoretical predictions expected to be more reliable (due to larger mass)
- beauty tagging exploits the large mass and the long lifetime of b hadrons
  - muons or electrons from semi−leptonic decays associated with jets
  - signal extracted by fitting distributions of sensitive variables
    - transverse momentum of leptons with respect to the jet axis (high b mass) $p_{t,rel}$
    - track impact parameter of leptons (long b lifetime) δ

TOTAL CROSS SECTIONS

- new measurement using D*μ double tags

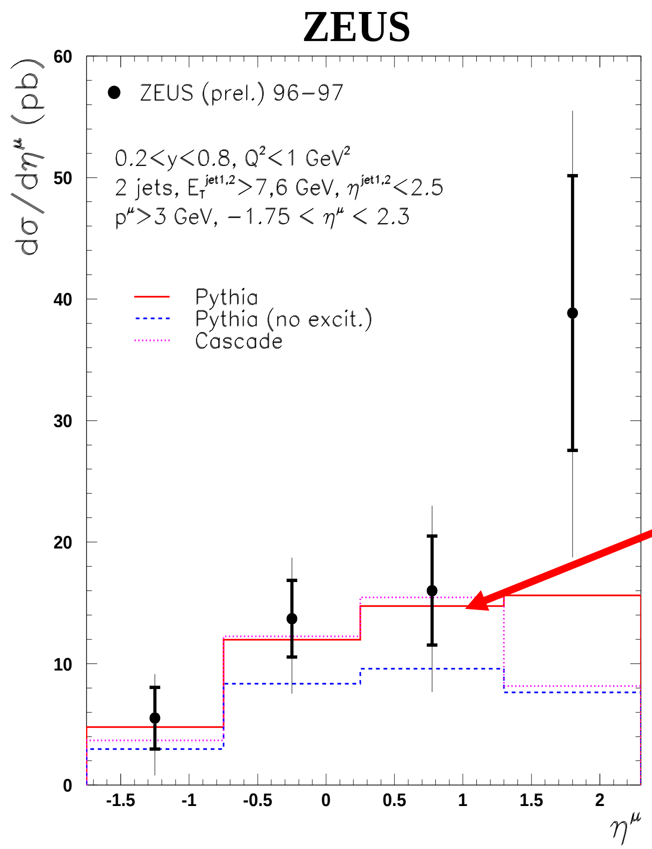
  $$\sigma^{b}(e\,p \rightarrow e\,D\,\mu\,X) = (380 \pm 120 \pm 130)\,pb$$

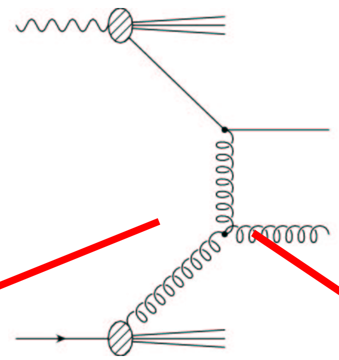
  - about factor 4 larger than LO + PS prediction
- measurements above NLO QCD predictions
  - both in γp, DIS
  - also observed in pp, e^+e^- (γγ) scattering
  - NNLO, .. ?
- new and more precise measurements soon

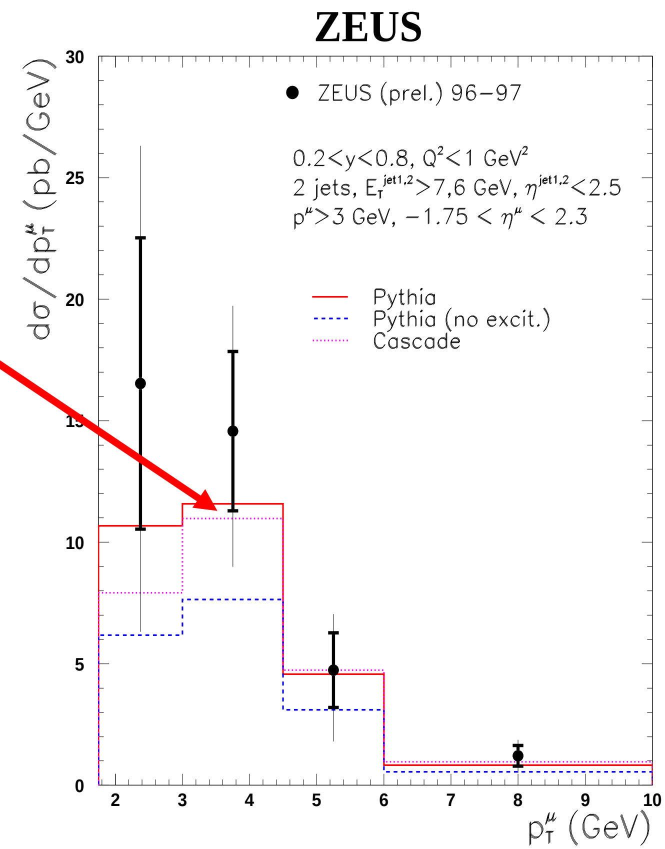


... can a more differential study shed more light on this effect ?

Differential Cross Sections







- LO + PS Monte Carlo describes the data rather well
  - indication that b excitation component maybe needed (as in charm production)
- experimental uncertainties still very large

Conclusions - Beauty

- measurements above NLO, shape about okay
- two channels (e, μ) and two methods (mass, lifetime)
- two kinematical regimes (DIS and γp)
- interesting !
  - new theoretical developments are promising (NLO, FONLL, fragmentation, CCFM−like evolution, ...)
  - high precision measurements will help to clarify

... more to come soon !

Conclusions and Outlook

- HERA I has made (and will still make) substantial contributions to
  - understand the production of charm and beauty
  - improve our knowledge about the structure of the proton and the photon
- Uncertainties of theoretical predictions are still very large
  - more precise calculations are very desirable (NNLO, ...)
- HERA II with its considerable (about factor 10) increase in luminosity and the improved H1 and ZEUS detectors will allow even deeper insight into these important topics of QCD
- a lot of interesting heavy flavour phyiscs from HERA in the near future