Heavy Quark Production at HERA
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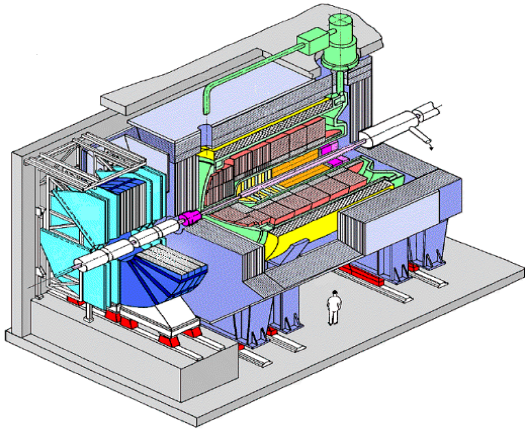
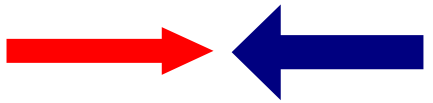
- HERA and heavy quark production
- Tagging heavy quarks
- Cross section measurements
- Heavy quark contribution to proton structure
- Charm fragmentation

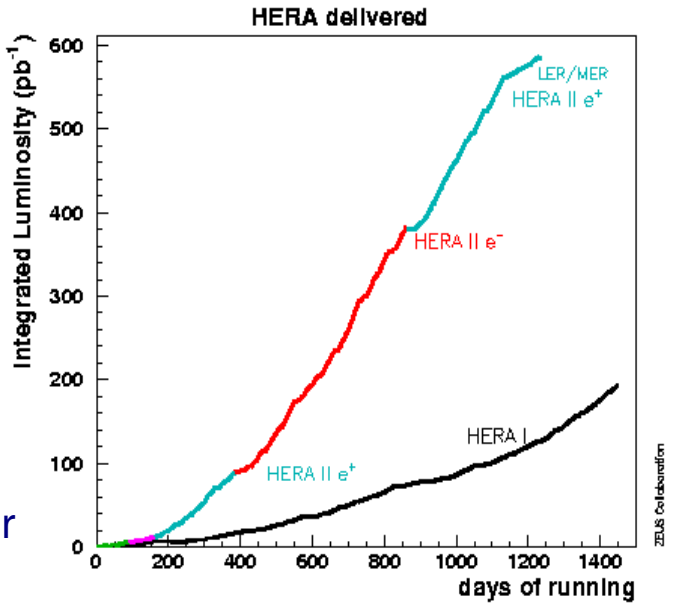
HERA - the world's only ep collider

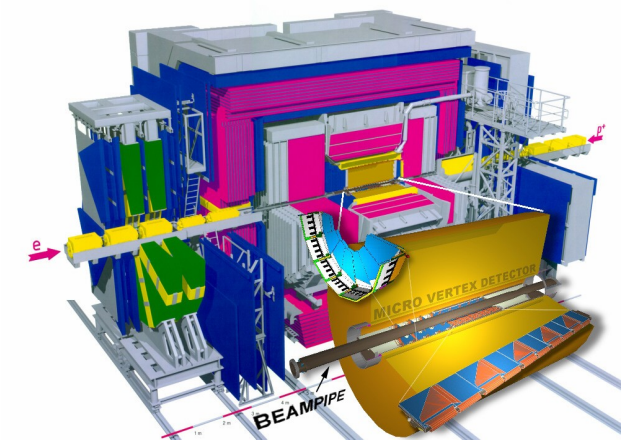
- HERA I (1996-2000): 130pb^{-1}
- HERA II (2003-2007): 380pb^{-1}
- Luminosity upgrade in 2001

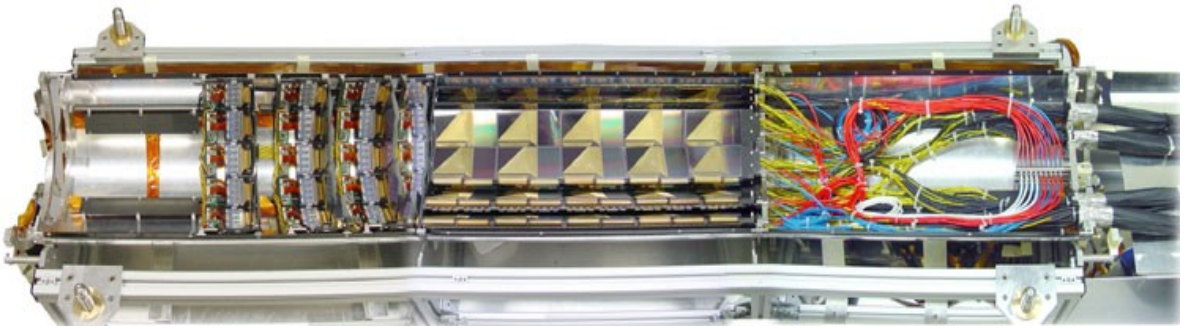




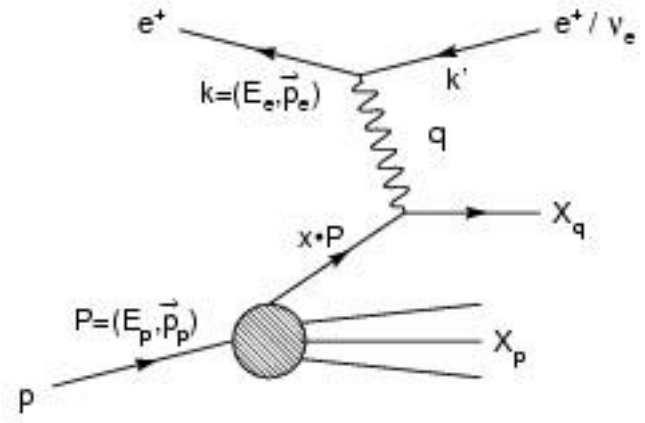
- ZEUS detector installed the MicroVertex detector (MVD)
- Enables precision heavy flavour measurements







Deep Inelastic Scattering

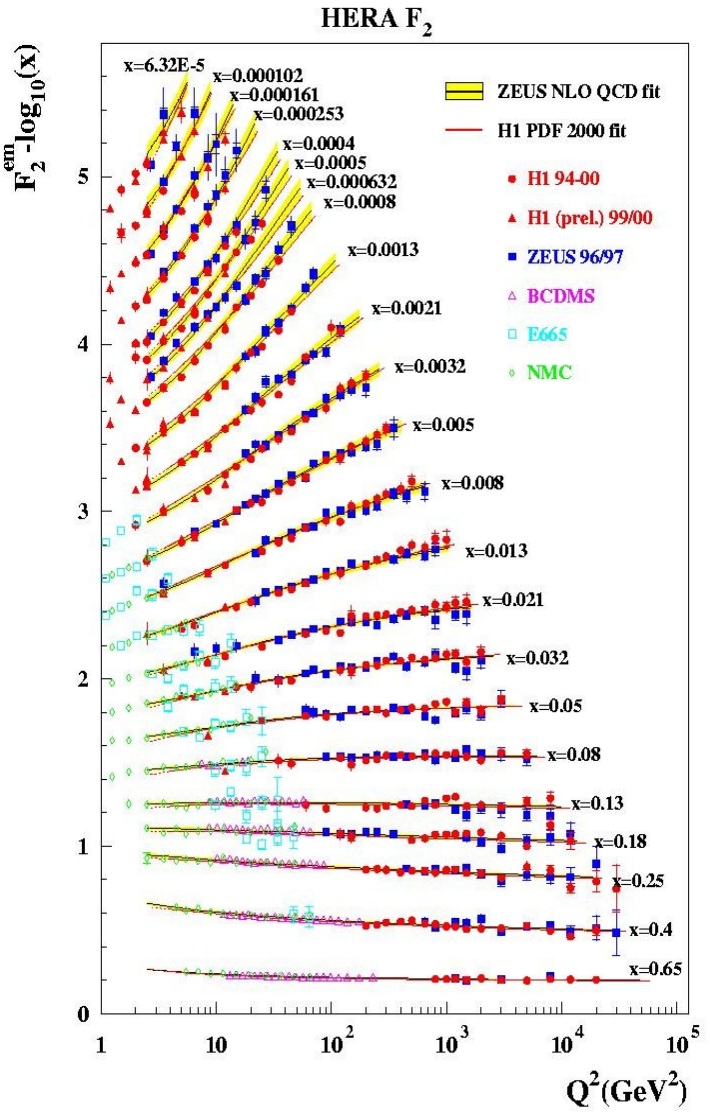


- $Q^2 = -q^2$
- $x = Q^2/2p.q$
- Kinematic Regimes:

  → $Q^2 > 1GeV^2$: DIS

  → $Q^2 \sim 0GeV^2$: Photoproduction

- Directly sensitive to quark content of the proton
- Gluons seen in scaling violations



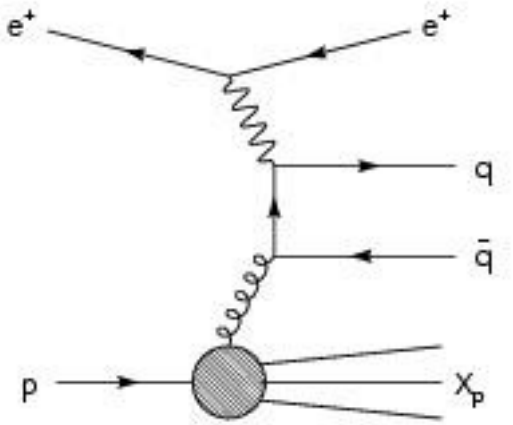
pQCD calculations

- pQCD calculations are performed in different ways:

- Massive (Fixed Flavour Number Scheme)
  - →Heavy quarks have mass and are not part of structure functions
  - →c and b are produced perturbatively in the hard interaction
  - →most appropriate for $Q^2 \sim M_Q^2$
  - →If $Q^2 >> M_Q^2$, large $\ln(Q^2/M_Q^2)$ appear
    - →DGLAP evolution is used to obtain the quark and gluon densities.
    - →Programs for Photoproduction: FMNR (Frixione et al.)
    - →DIS: HVQDIS (Harris+Smith)
- Massless (B. Kniehl et al)
  - →Heavy quark masses are neglected
  - →resummation is valid for $Q^2 >> M_Q^2$
- and a combined method (Variable Flavour Number Scheme)
  - →At small Q^2 uses massive, at large Q^2 uses massless
  - →(M. Cacciari et al).

Heavy Quark Production

Heavy quarks (c and b) predominantly by Boson-Gluon Fusion



PDF

Proton and Photon structure functions
Direct sensitivity to gluon density in proton

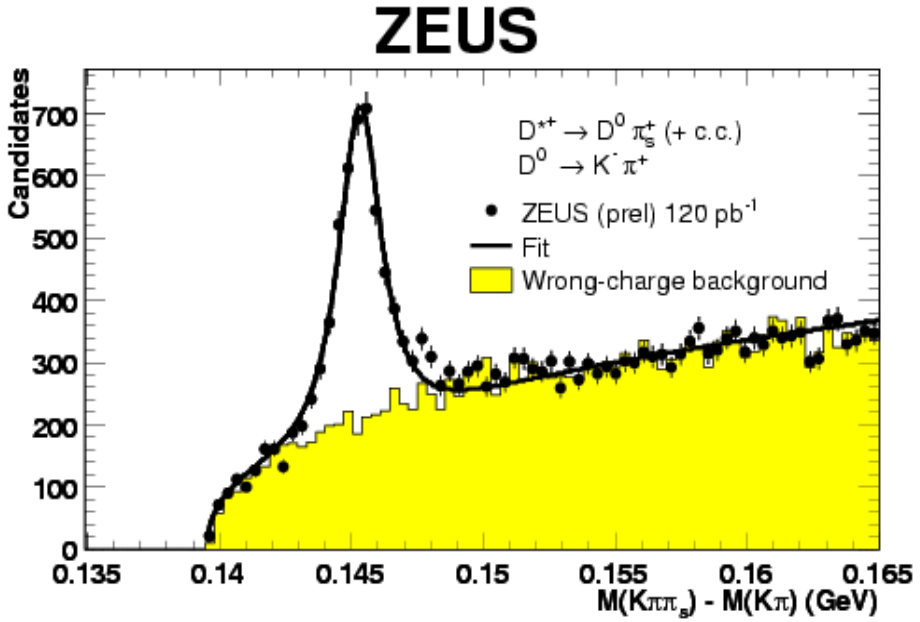
Hard Scatter

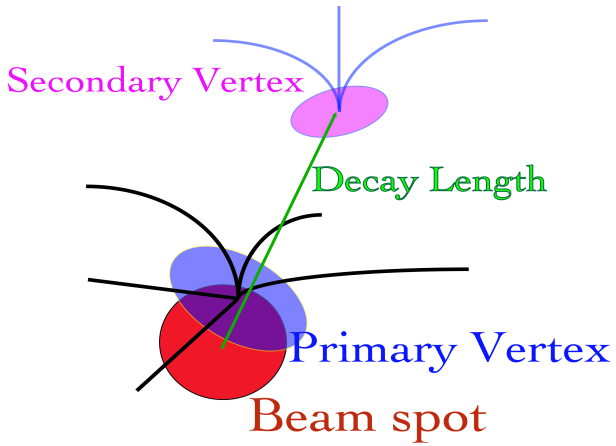
Dynamics of NLO QCD
Large quark mass allows pQCD calculations

Fragmentation

Describes parton-hadron transition
Non-perturbative

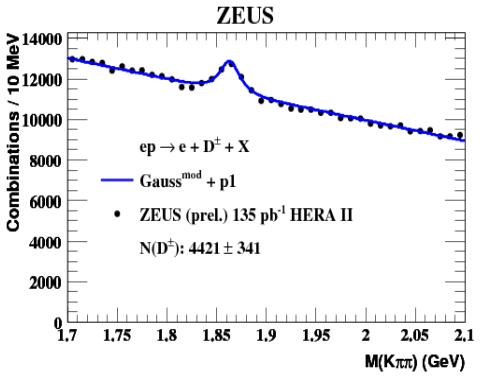
Heavy Flavour Quark Tagging

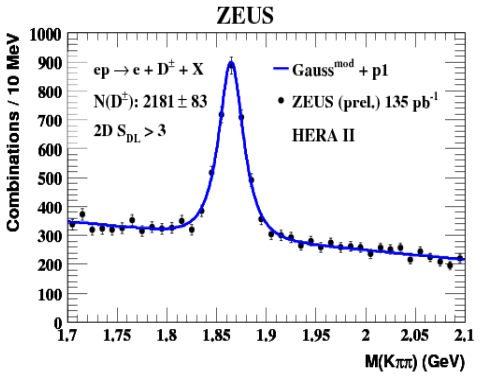




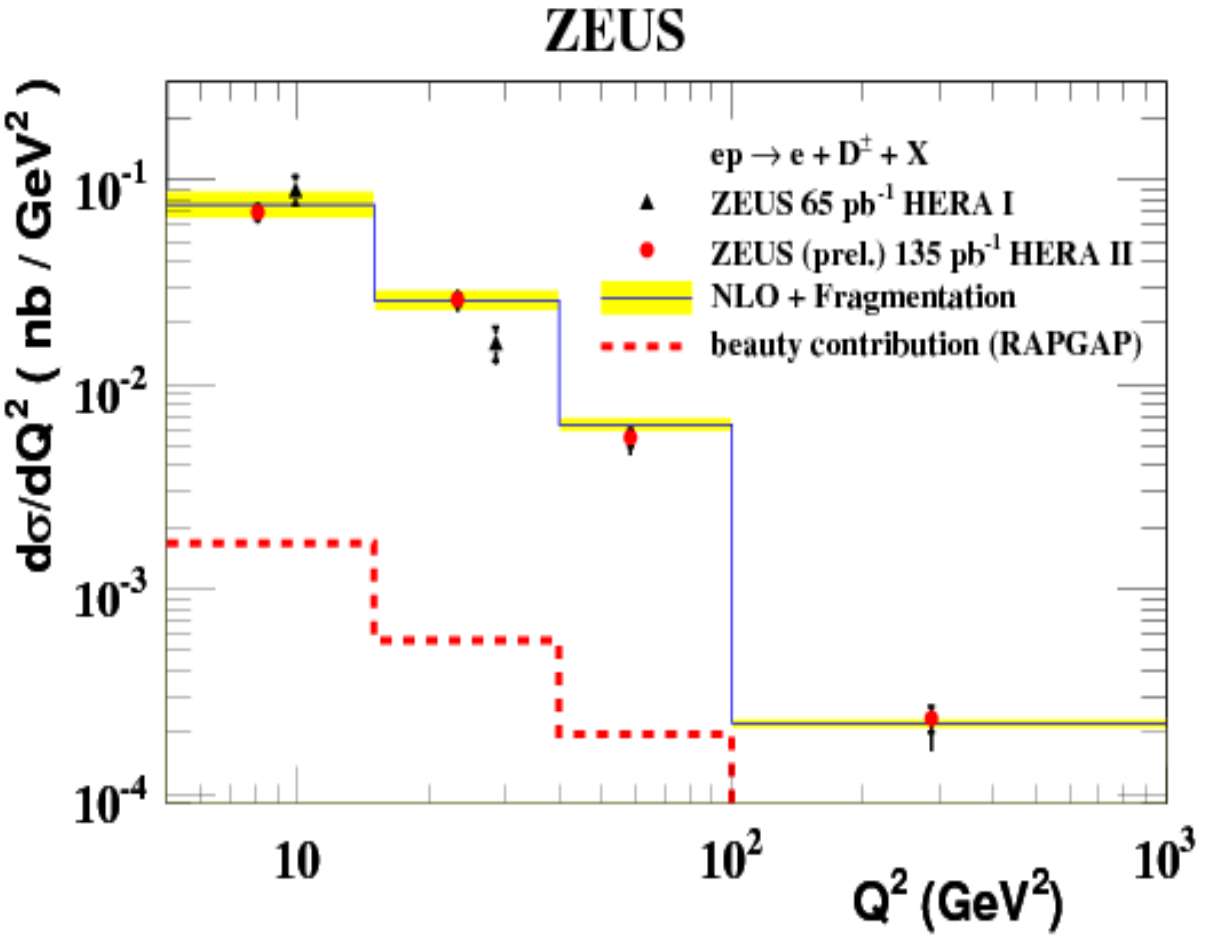
Resonance tagging:

- To tag charmed mesons
- Mass difference to tag D*
- Decay length significance cut: $\delta/\sigma(\delta)$





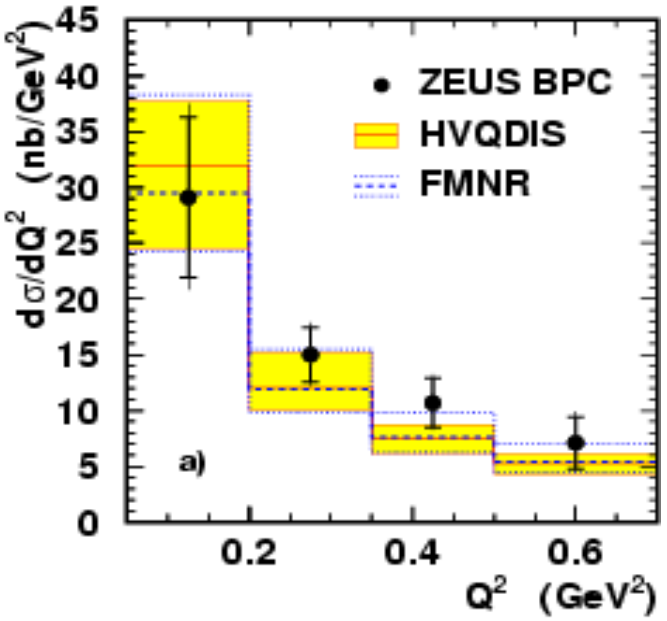
D± and other charm hadron cross sections

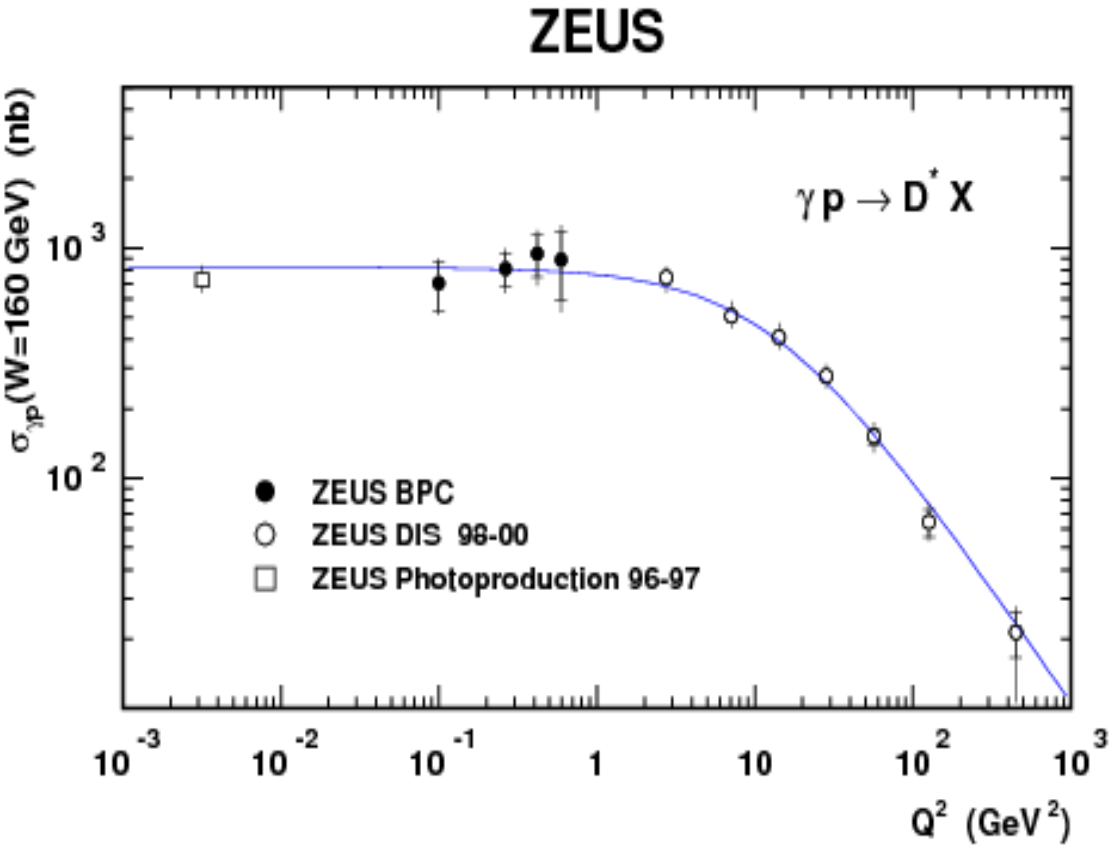


- Decay length significance cut used to enhance traditional D* tagging technique
- More precise measurement made with HERA II. Agrees well with HERA I data and NLO calculation

D*± Meson Production in DIS

- In general good agreement is seen between data and NLO prediction in DIS and PHP
- First measurement which tests NLO charm production across the transition region.
- Do the theories remain valid?



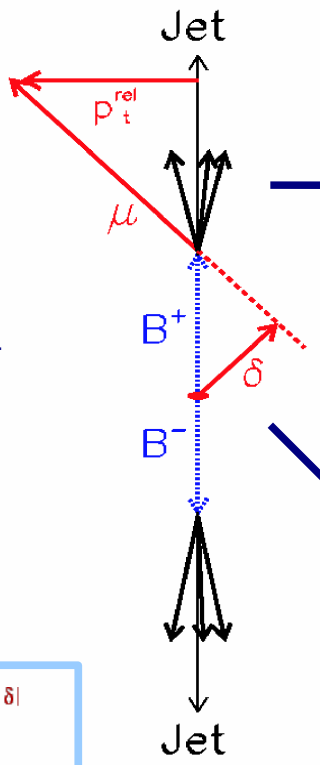


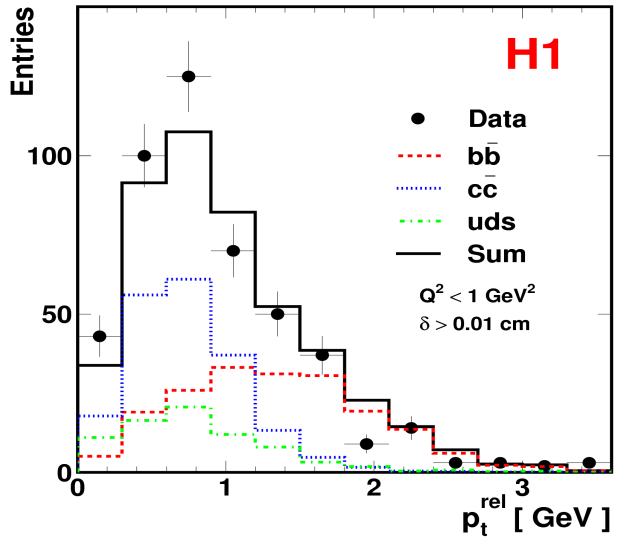
function $\sigma(Q^2) = SM^2/(Q^2+M^2)$
S is photoproduction cross section at $Q^2=0$
M is scale at which cross section changes from photoproduction to DIS $1/Q^2$ behaviour

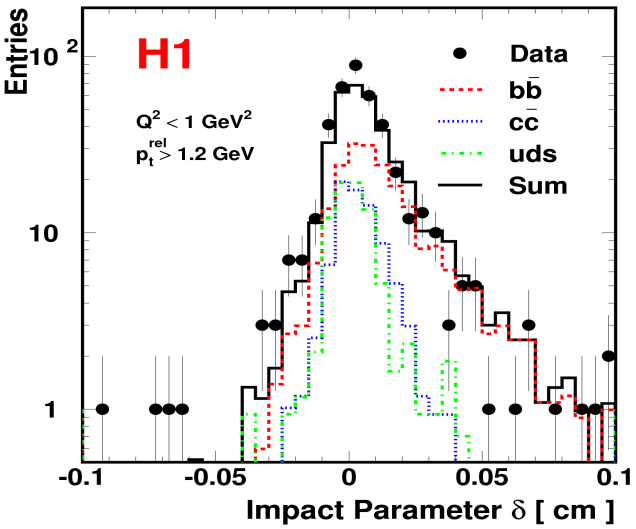
Heavy Flavour Quark Tagging

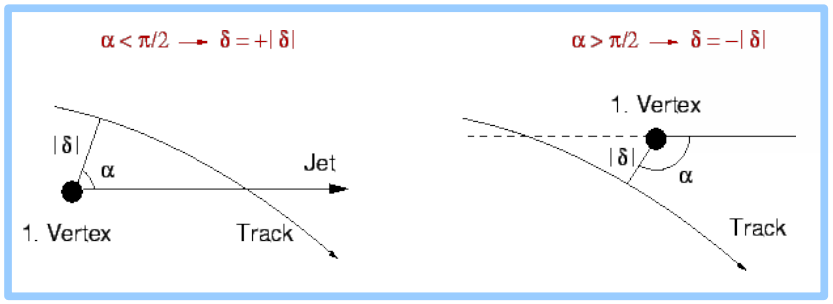
Decay tagging methods:

- Large Mass:
  - p_T of muon relative to jet, $p_T^{rel.}$
- Long Lifetime:
  - Signed Impact parameter, δ



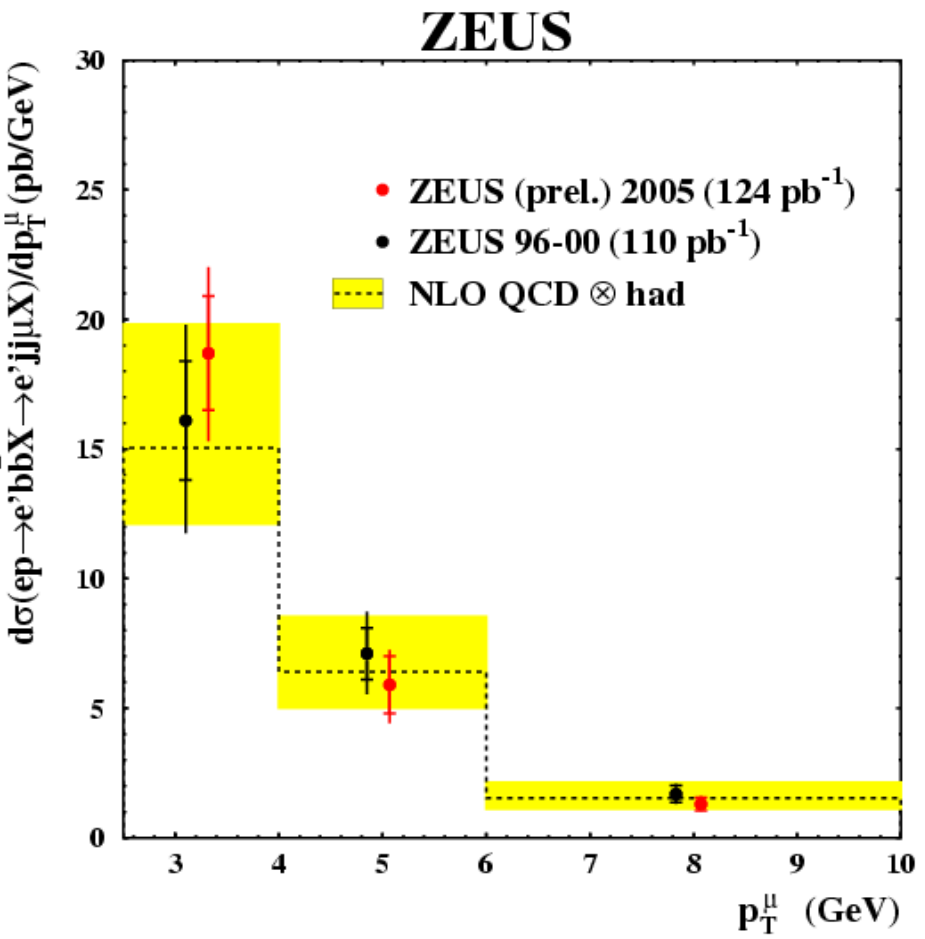






Differential beauty cross sections

- Large beauty mass means predictions should be reliable
- Beauty production is a stringent test of pQCD
- Some measurements observe an excess at low pT
- Measured at ZEUS and H1 in electron and muon decays and inclusively
- Double tagging techniques (δ and $p_T^{rel.}$) enable more precise measurements
- NLO (FMNR) agrees reasonably well with most precise measurements
- In this measurement the double tagging technique was used to measure cross section using semi-leptonic muon decay

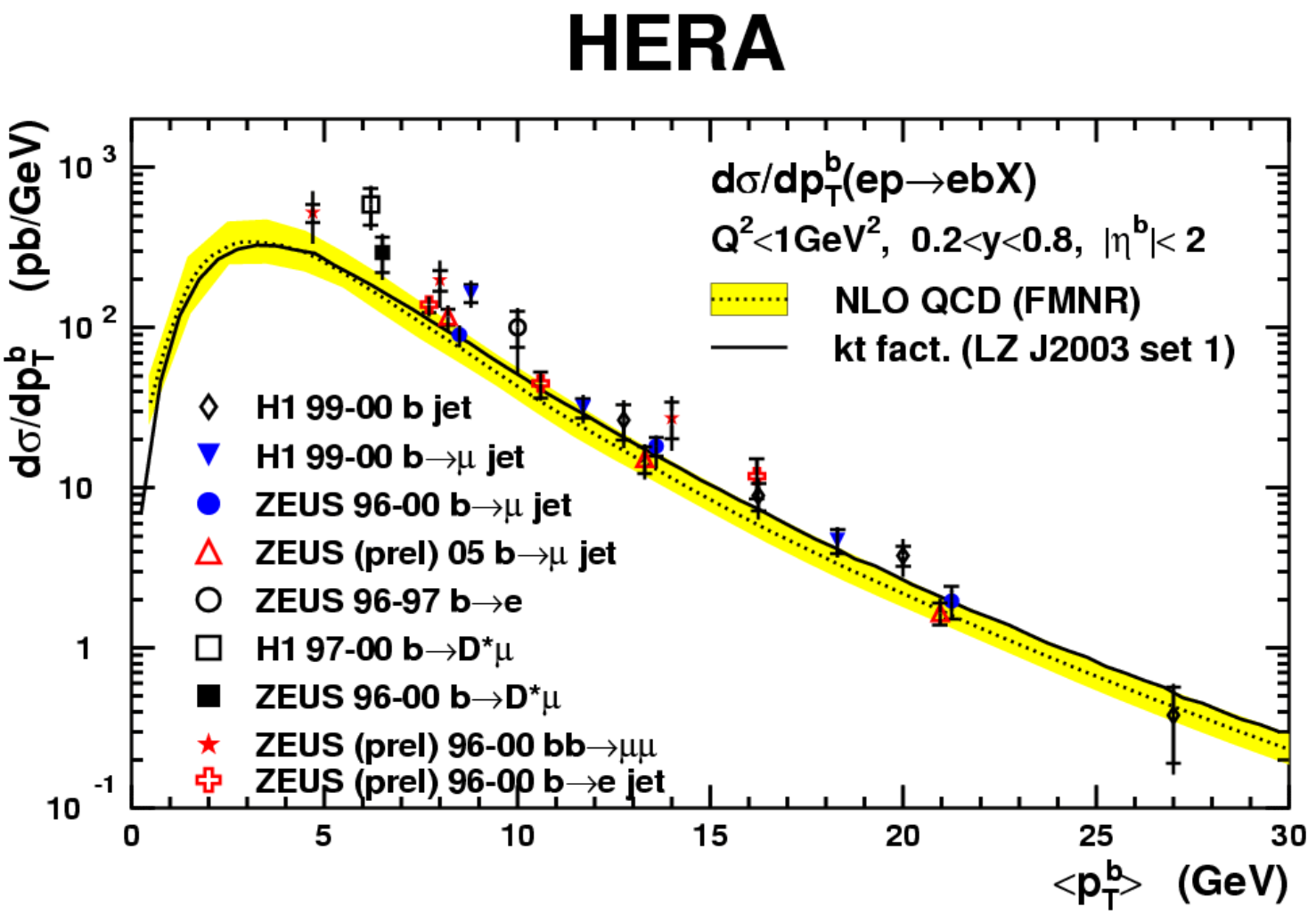


Total visible cross section:

$$\sigma_{bb} = 46.8 \pm 4.0\,(\text{stat.}) \pm {}^{6.1}_{7.2}\,(\text{syst.})\,\text{pb}$$

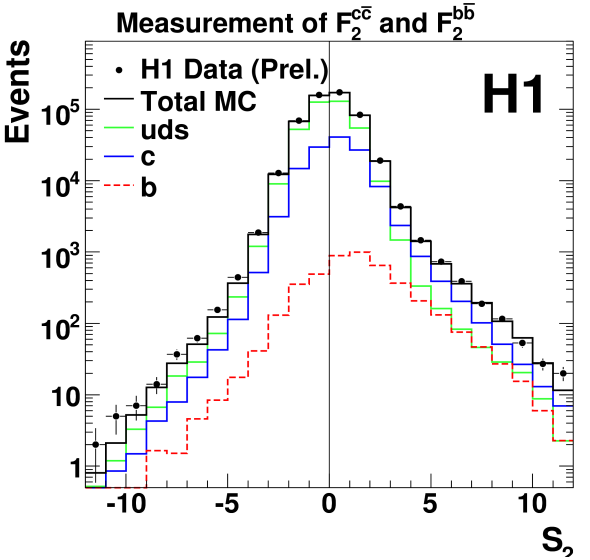
$$\sigma_{NLO} = 41.5 \pm {}^{13.9}_{8.9}\ \text{pb}$$

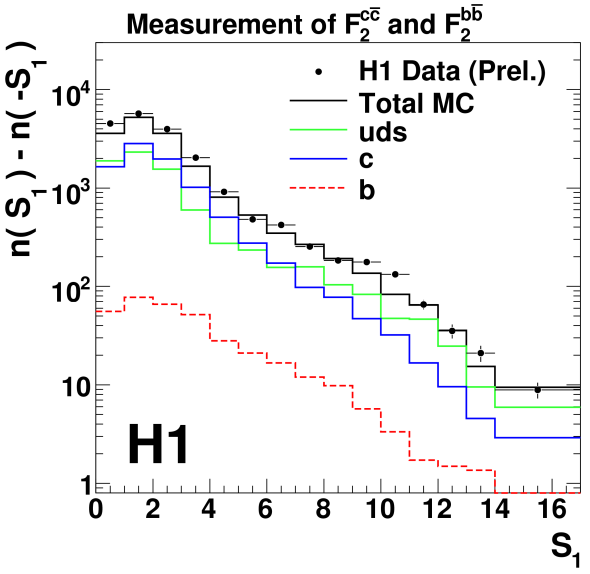
Compilation of beauty photoproduction results

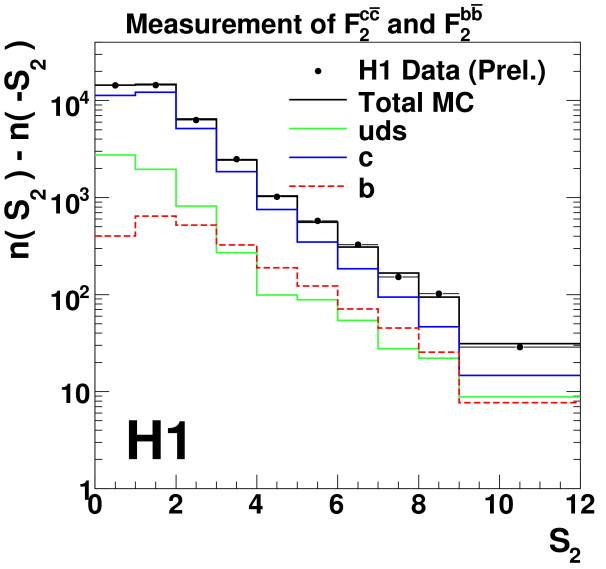


F_2^{cc} and F_2^{bb} : Impact Parameter Significance Tag

- Inclusive Method: use all tracks
- Charm and Beauty fractions extracted using impact parameter significance $\delta/\sigma(\delta)$.
- Allows separation of beauty, charm and light quarks
- Fit distributions of significance with negative impact parameter subtracted from both sides.

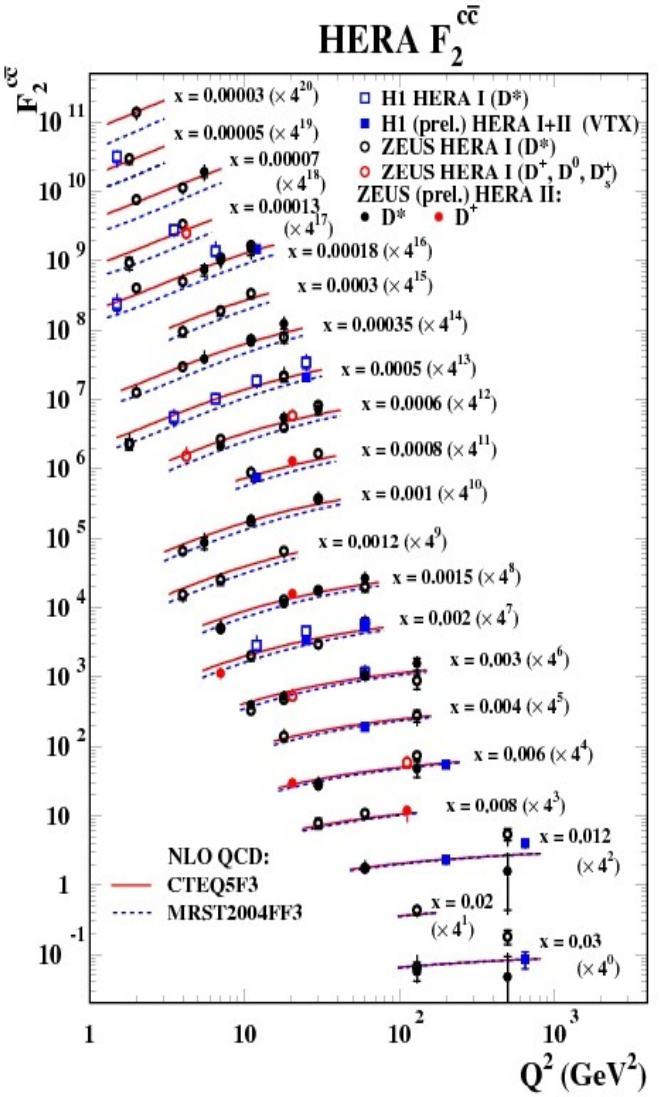






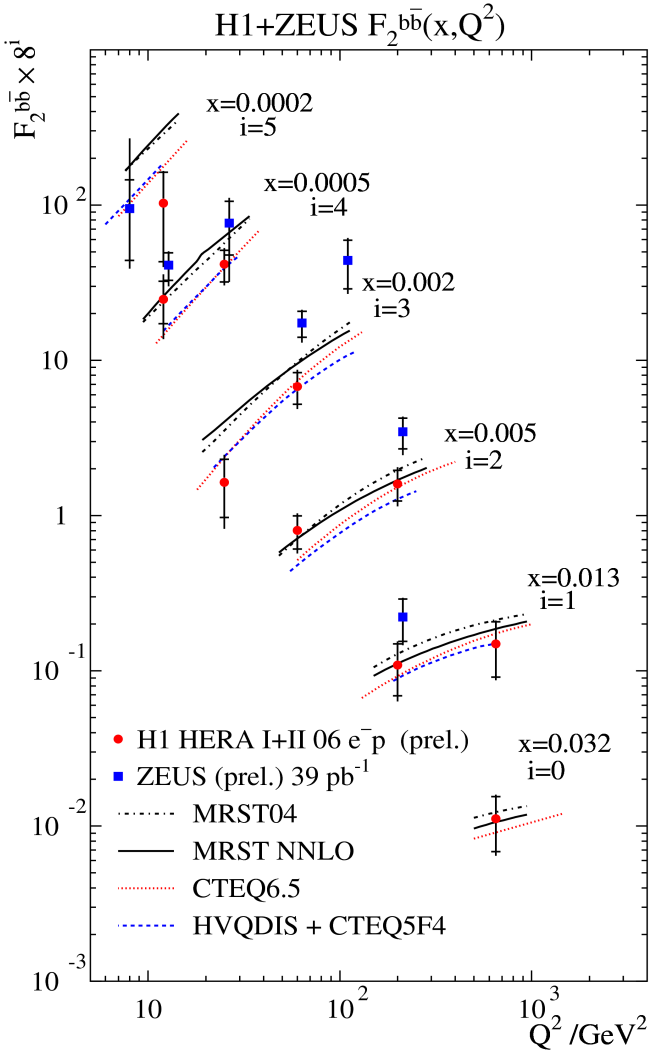
F_2^{cc}

- Charm contribution to proton structure function is determined over large range of x and Q^2
- Values of F_2^{cc} as a function of x at fixed values of Q^2
- Demonstrates scaling violation in charm production
- Reasonably good agreement in found between measurement and NLO QCD predictions
- Notable differences between theoretical predictions at low x



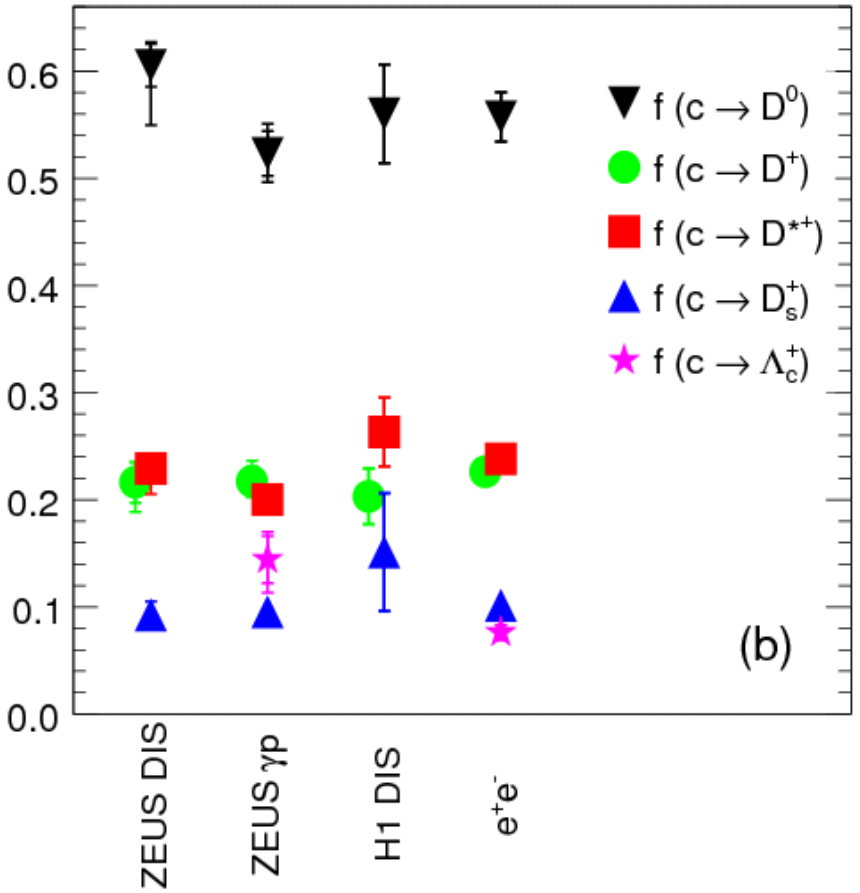
F_2^{bb}

- World's first F_2^{bb} measurements
- Different tagging techniques:
  - ZEUS: $p_T^{rel.}$
  - H1: Inclusive Lifetime
- Experimental errors too large to distinguish theories
- More data to analyse



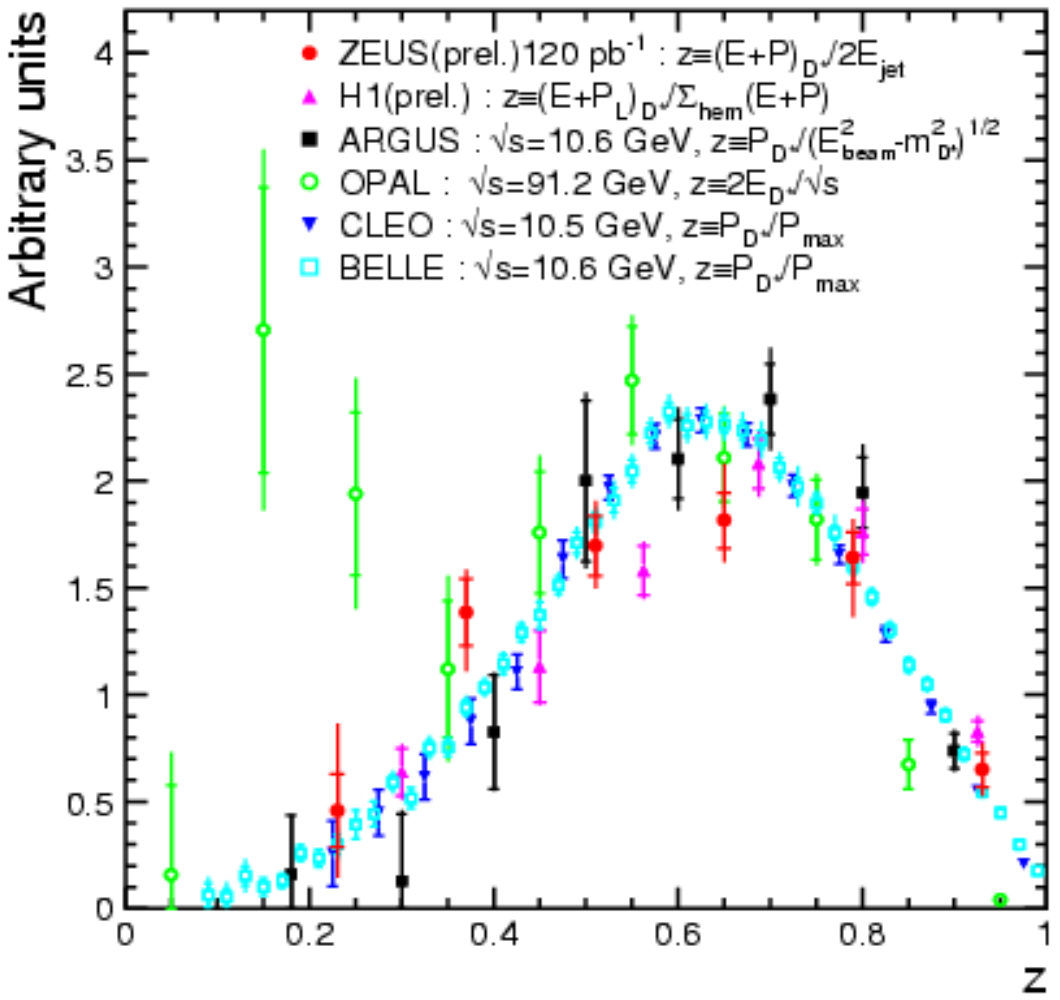
Fragmentation Fractions

- Fraction of c-quarks hadronising into a particular D meson
- Agreement is seen between HERA experiments and e^+e^- data
- This supports the hypothesis that fragmentation is independent of the hard sub-process



Fragmentation Functions

- Fraction of c-quark energy taken by charmed meson $z = E_{D^*} / E_c$
- Important to measure in environment other than e^+e^- collisions
- e^+e^- machines: $z = E_{D^*} / E_{beam}$
- In ep collisions it's not so simple
- Despite different z definitions:
  - ZEUS: $z = (E+P)_{D^*} / 2E_{jet}$
  - H1: $z = (E+P_L)_{D^*} / \Sigma_{hem}(E+P)$
- ..... spectra are similar in shape across all experiments



Summary

- Heavy flavour production at HERA allows the study of:

  - gluon density of the proton
  - pQCD calculations

- In general a reasonable description of the data is given by NLO calculations

- Sensitive to fragmentation parameters

- Outlook..... analyses using full HERA statistics

- There will be no more collisions at HERA but analysis of its data will continue

Back up – extraction of F_2^{cc}

$$\frac{d^2\sigma^{c\bar{c}}(x,Q^2)}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}\{[1+(1-y)^2]F_2^{c\bar{c}}(x,Q^2) - y^2 F_L^{c\bar{c}}(x,Q^2)\}$$

ZEUS extracts F_2^{cc} from *D* mesons cross sections, using HVQDIS to extrapolate to the full meson phase space:

$$F_{2,\mathrm{meas}}^{c\bar{c}}(x_i,Q_i^2) = \frac{\sigma_{i,\mathrm{meas}}(ep\to D^*X)}{\sigma_{i,\mathrm{theo}}(ep\to D^*X)} F_{2,\mathrm{theo}}^{c\bar{c}}(x_i,Q_i^2)$$

H1 measures charm inclusively:

$$\tilde{\sigma}^{c\bar{c}}(x,Q^2) = \tilde{\sigma}(x,Q^2)\frac{P_c N_c^{\mathrm{MCgen}}}{P_c N_c^{\mathrm{MCgen}} + P_b N_b^{\mathrm{MCgen}} + P_l N_l^{\mathrm{MCgen}}}\delta_{\mathrm{BCC}}$$

Where $P_{c,b,l}$ are the fraction of charm, beauty, LF from the fit and σ is the inclusive reduced cross section.