Production and Properties of Heavy Flavours at HERA

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On Behalf of H1 and ZEUS Collaborations

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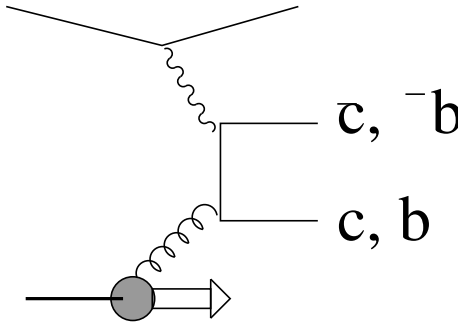
La Thuile Mar. 5 - 11, 2006

Overview:

- HERA Collider
- c/b production
- Charm Fragmentation
- Charm/Beauty Jet Cross Sections
- Charm and Beauty Contributions to the Proton Structure function F_2

Introduction

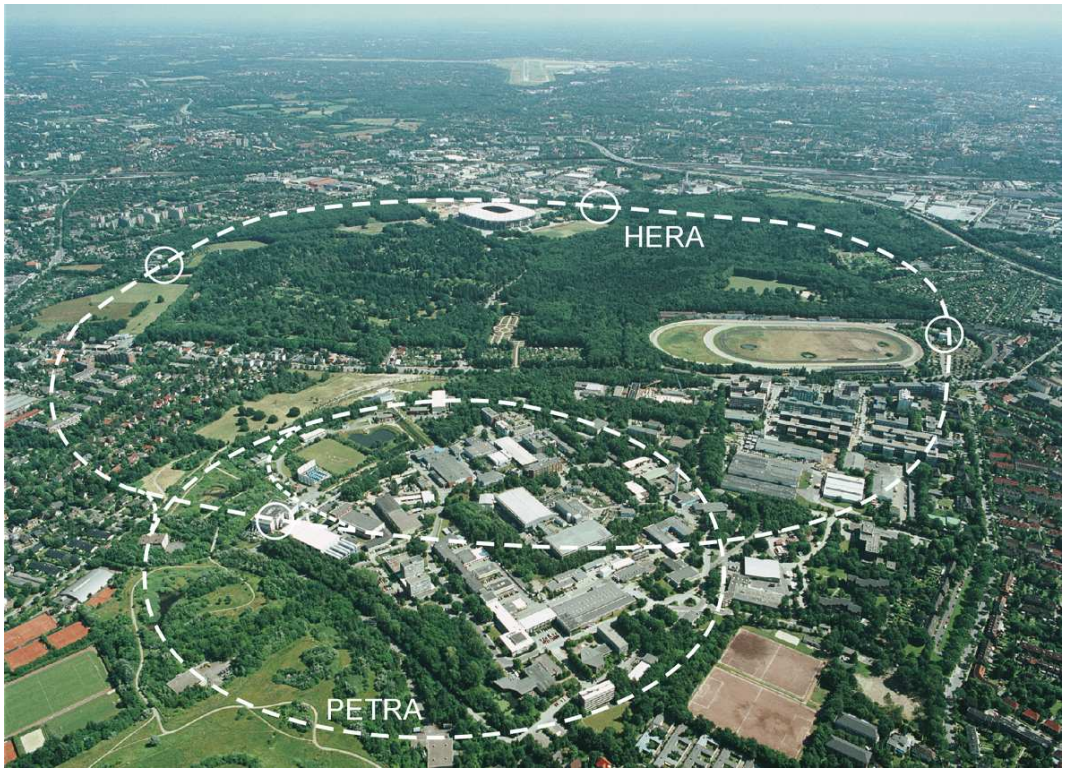


Why study heavy quark production at HERA?

- Heavy quark production can be used as a test of perturbative QCD due to the large mass scale of the quark
- Understanding heavy quark production will be useful for LHC experiments where beauty and charm will be produced at high rates as background

This talk will focus on a few of the most recent results.

The HERA Collider: H1 and ZEUS



HERA I

- 820/920 GeV proton beam, 27.5 GeV $e^{\pm}$ beam
- Beam spot 150×30 μm^2
- Integrated Lum. 135 pb^{-1} (94-00)

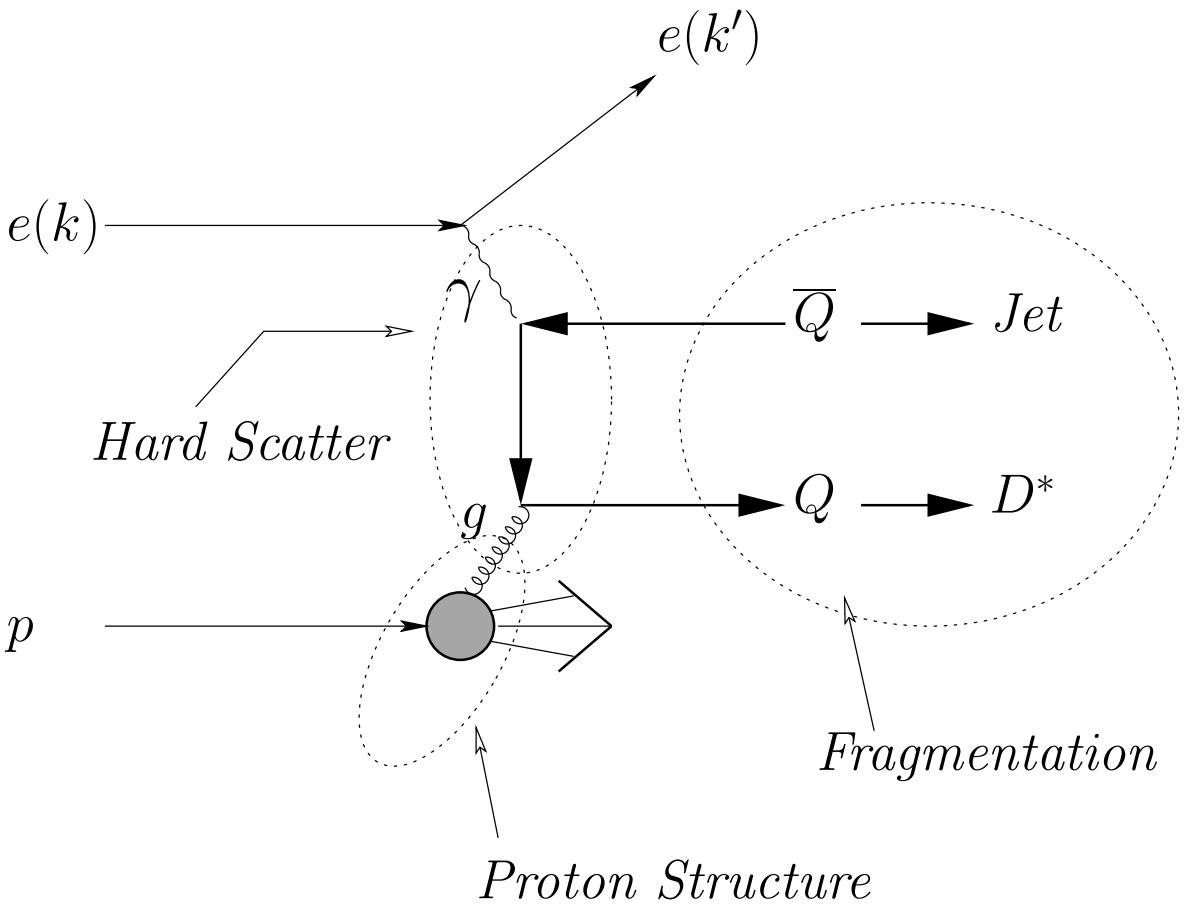
HERA II

- 920 GeV proton beam, 27.5 GeV $e^{\pm}$ beam
- Beam spot 80×20 μm^2
- Int. Lum. 160 pb^{-1} (03-05 More to come!)
- $e^{\pm}$ beam long. polarized ($\approx 30\%$)

H1 and ZEUS are two experiments at HERA studying these electron proton interactions

c/b Productions

At HERA charm/beauty production is dominated by Boson Gluon Fusion (BGF) $\gamma g \to Q\overline{Q}$.

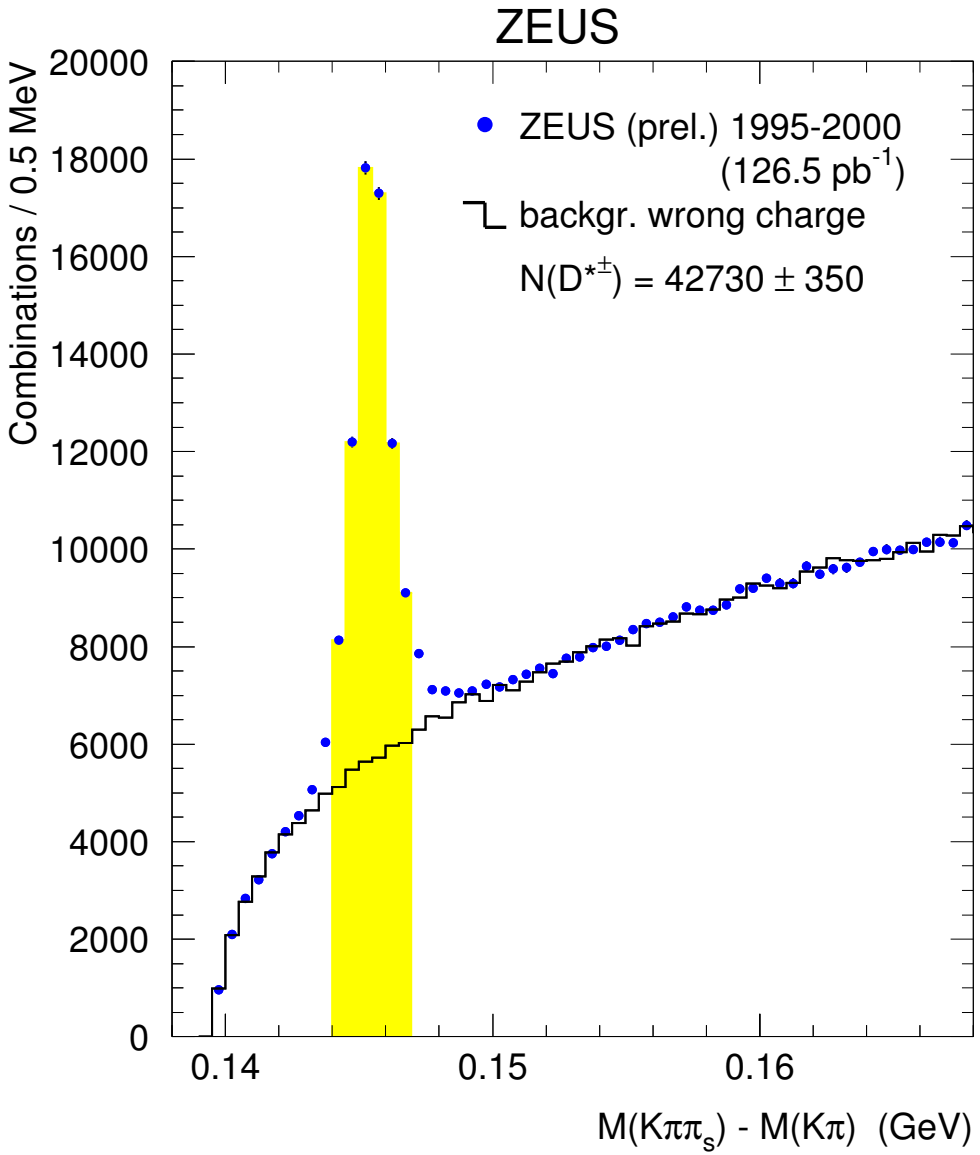


- γ from e and g from the proton *fuse* producing a $Q\overline{Q}$ pair
- x: Bjorken scaling variable (fractional momentum carried by struck parton)
- y: fraction of energy transferred from e to p (in p rest frame)
- $Q^2 = -q^2 = -(k - k')^2$
- Two kinematic regimes:
  - Photoproduction (γp), $Q^2 < 1$ GeV^2
  - Deep Inelastic scattering (DIS), $Q^2 > 1$ GeV^2

- Factorization

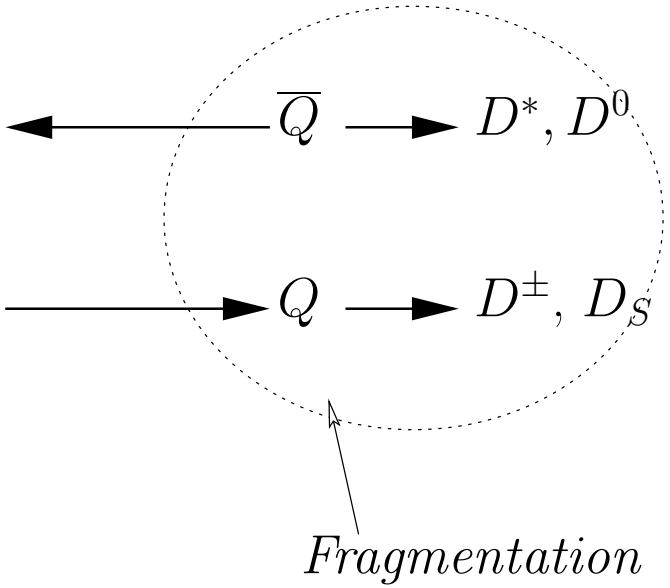
σ = proton PDF $\otimes\, \sigma_{\gamma g \to Q\overline{Q}} \otimes$ photon PDF $\otimes$ fragmentation process

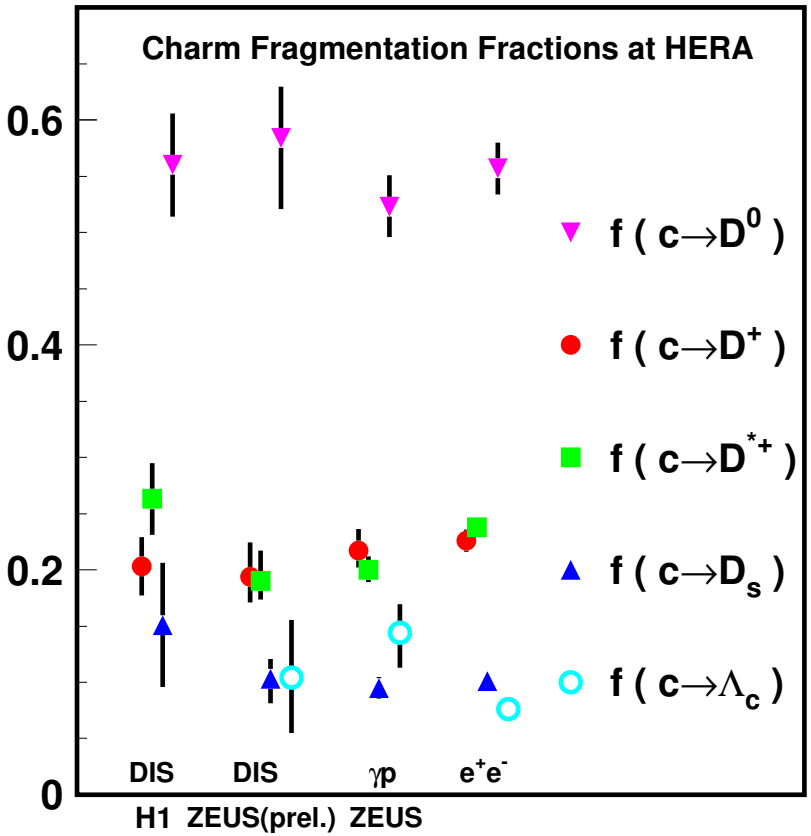
How is Charm Measured?



- The charm hadrons used to measure charm cross sections are D^0, D^+. D^*, D_S, Λ_C
- Left is the D^* signal measured at ZEUS
- Semileptonic decays ($c \rightarrow \mu X$) are also used
- An inclusive lifetime tag method is also used to measure charm (will be explained later)

Charm Fragmentation Fractions





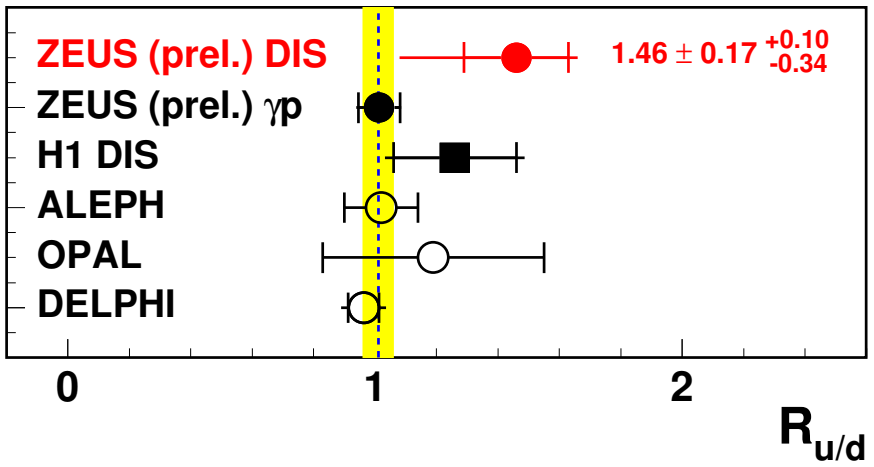
- $f(c \to H)$ is the fraction of c quarks ending in a specific hadronic state H (e.g. $D^{*\pm}$, D^0, etc.)
- Compare HERA results with e^+e^- (LEP):

Consistent with the universality assumption of charm fragmentation fractions.

Ratio of u/d in Charm Fragmentation

$R_{u/d}$ is the ratio of the sum of direct neutral mesons (D^0, D^{*0}) production cross sections to the sum of the charged mesons ($D^{*\pm}$, $D^{\pm}$) production cross sections

$$R_{u/d} = \frac{c\overline{u}}{c\overline{d}}$$



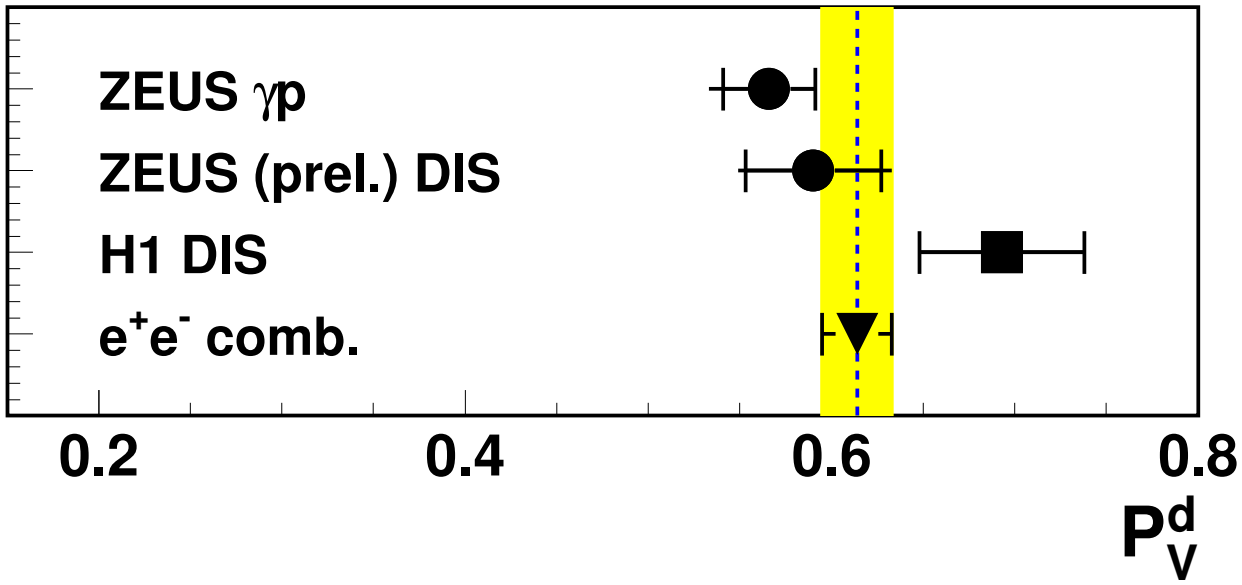
u and d quarks are produced equally in charm fragmentation.

$\rightarrow$ **Strong Isospin Invariance Holds**

Fraction of D Mesons in Vector State

- The vector to pseudoscalar fraction for charm is:

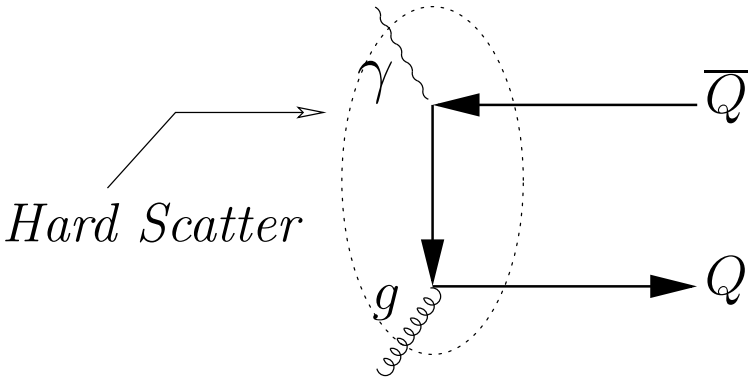
$$P_V^D = \frac{V}{V + PS}$$



- $P_V^D \neq 0.75$ **Simple Spin Counting Does NOT Work with Charm.**

To summarize fragmentation; the fragmentation fractions, ratio of u to d, and the vector to pseudoscalar ratio for D mesons are consistent with universality.

Calculations in pQCD



When looking at the hard scattering process, 2 schemes of calculating pQCD are:

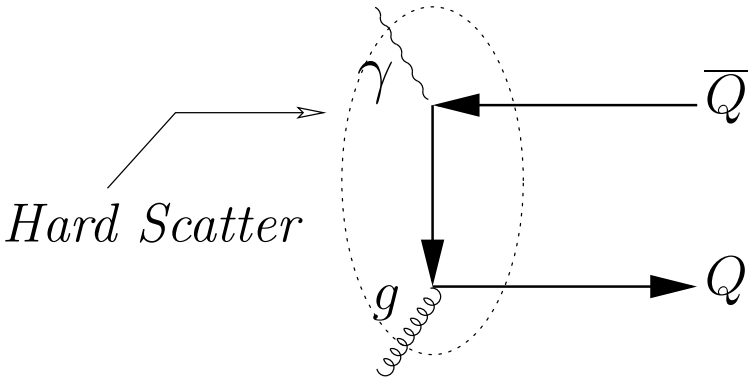
"Massive" Scheme

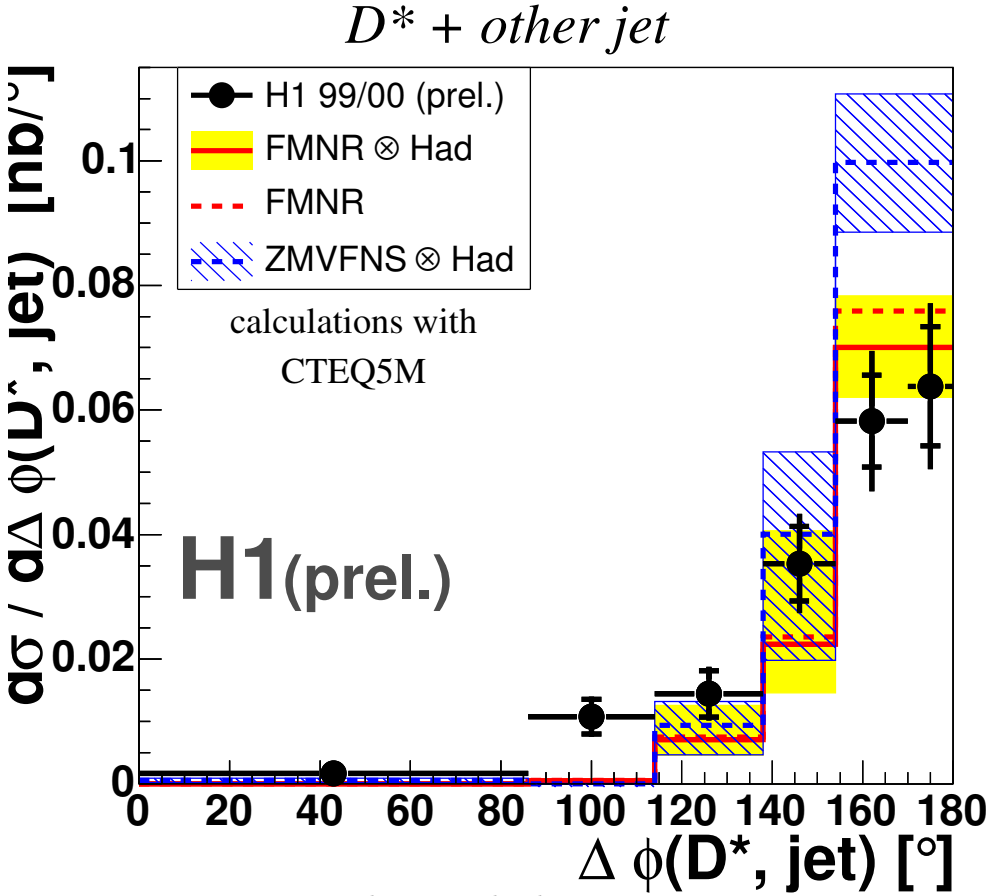
- c/b massive i.e $m_Q \neq 0$
- valid when $m_Q^2 \approx Q^2$
- Heavy quarks (HQ) NOT active flavours in parton distributions
- HQ produced in the hard scatter, e.g. $\gamma g \rightarrow Q\overline{Q}$

"Massless" Scheme

- c/b massless i.e. $m_Q = 0$
- valid when $p_T^2 \gg m_Q^2$
- HQ active flavours in parton distribution, i.e. charm and beauty are in the proton
- HQ can be produced in reactions such as $gQ \rightarrow gQ$

Charm Jet in Photoproduction





Why study Jets in addition to D^*s?

- Effects from fragmentation are reduced
- Jets are a good approximation of outgoing partons

The angle in the transverse plane between D^* and the other jet is $\Delta\phi$.

- To leading order (LO) jets should be back to back

Made with low p_T Jets.

- Large fraction of jets are not back to back indicating contributions from higher order QCD radiation.

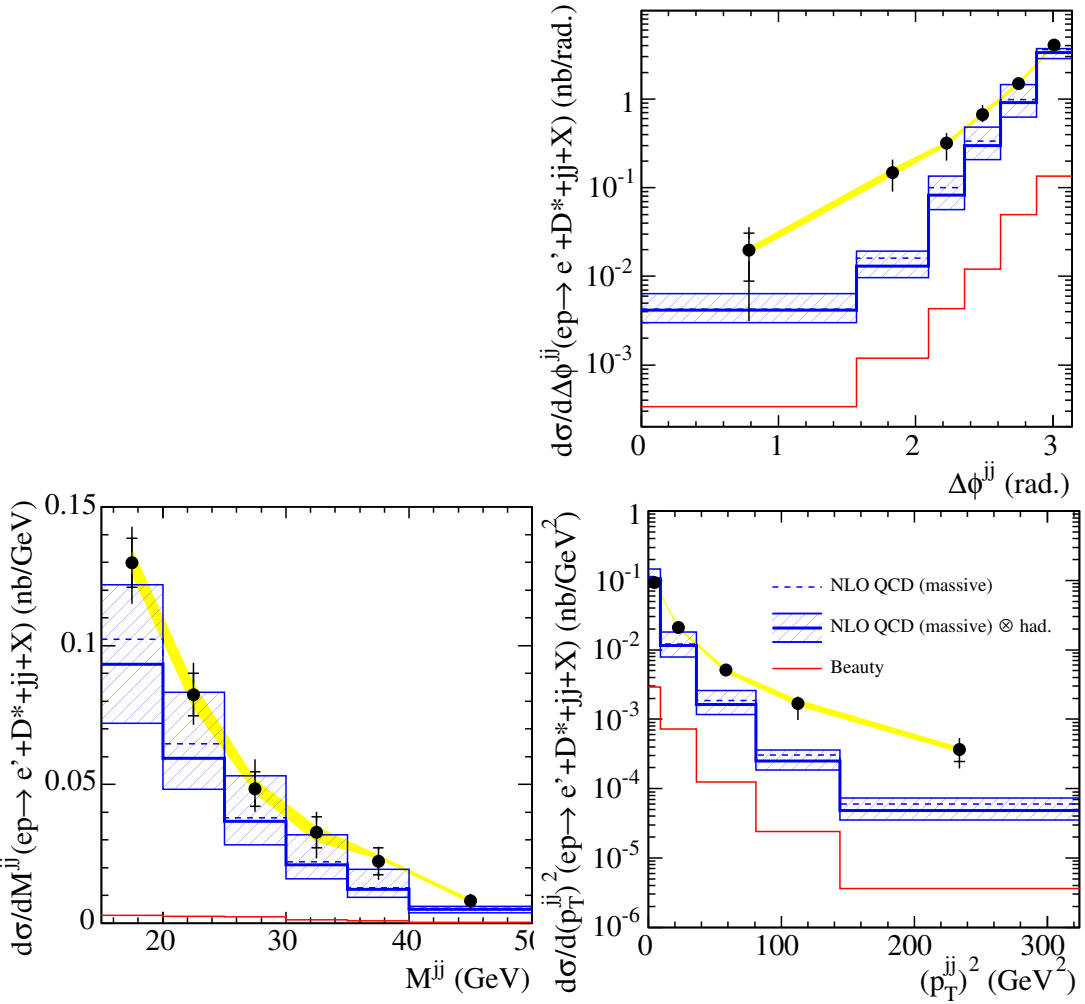
At $\Delta\phi < 120$ NLO predicts a smaller cross section than is observed.

Charm Dijets in Photoproduction

Comparison with higher E_T Jets:

- Dijet mass (M^{jj}) well described by the massive NLO QCD prediction
- $\Delta\phi^{jj}$ and $(p_T^{jj})^2$ show a large deviation from NLO at low $\Delta\phi^{jj}$ and at high $(p_T^{jj})^2$
- These regions are expected to be sensitive to higher order effects

(ZEUS 98-00 data, the jet energy scale uncertainty indicated in yellow)



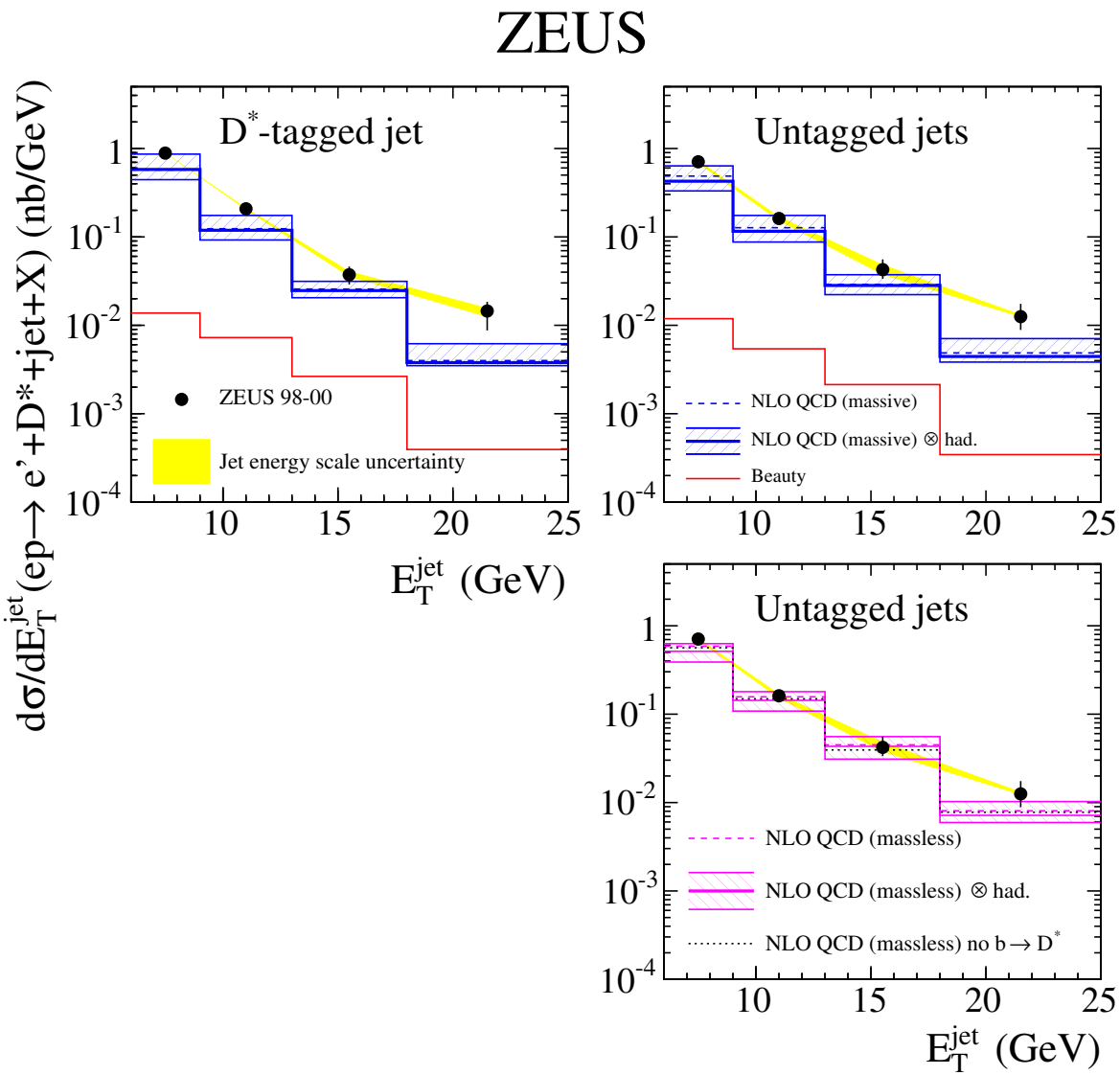
Good agreement of data to NLO except in phase space regions where higher orders are enhanced

$D^{*\pm}$ Dijets in Photoproduction

- Jets are considered $D^{*\pm}$ tagged when $\Delta R < 0.6$ where

$$\Delta R = \sqrt{(\eta^{Jet} - \eta^{D^{*\pm}})^2 + (\phi^{Jet} - \phi^{D^{*\pm}})^2}$$

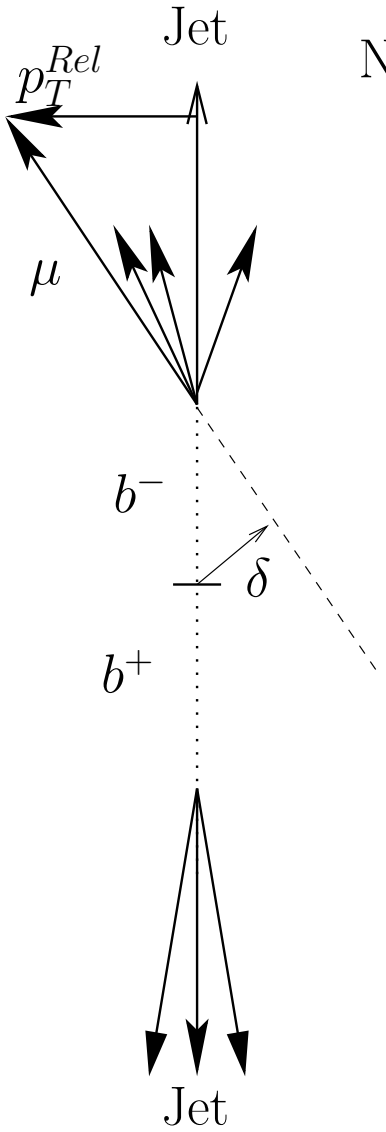
- The upper cross sections compare NLO QCD in a massive scheme to data
- The lower is a massless scheme comparison to data



Jets summary:

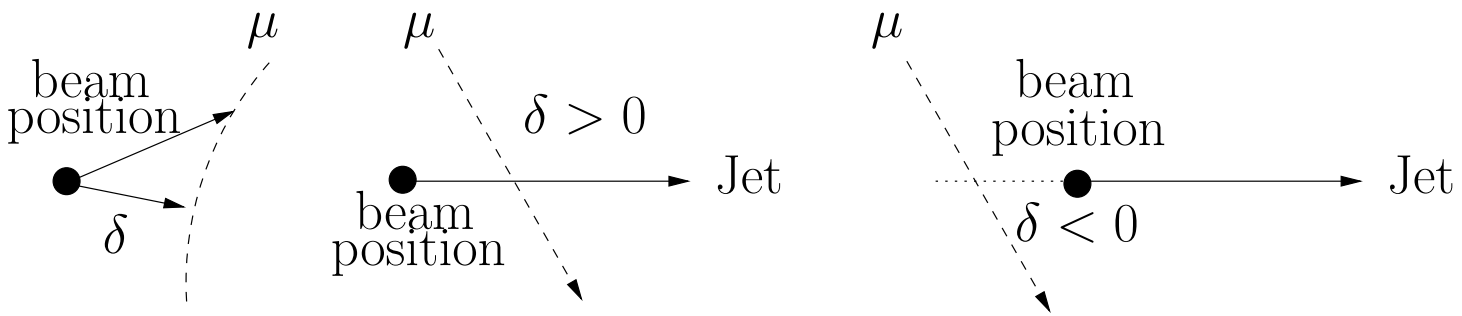
Both massive and massless pQCD give a good description of the data

Tagging Beauty via Muons

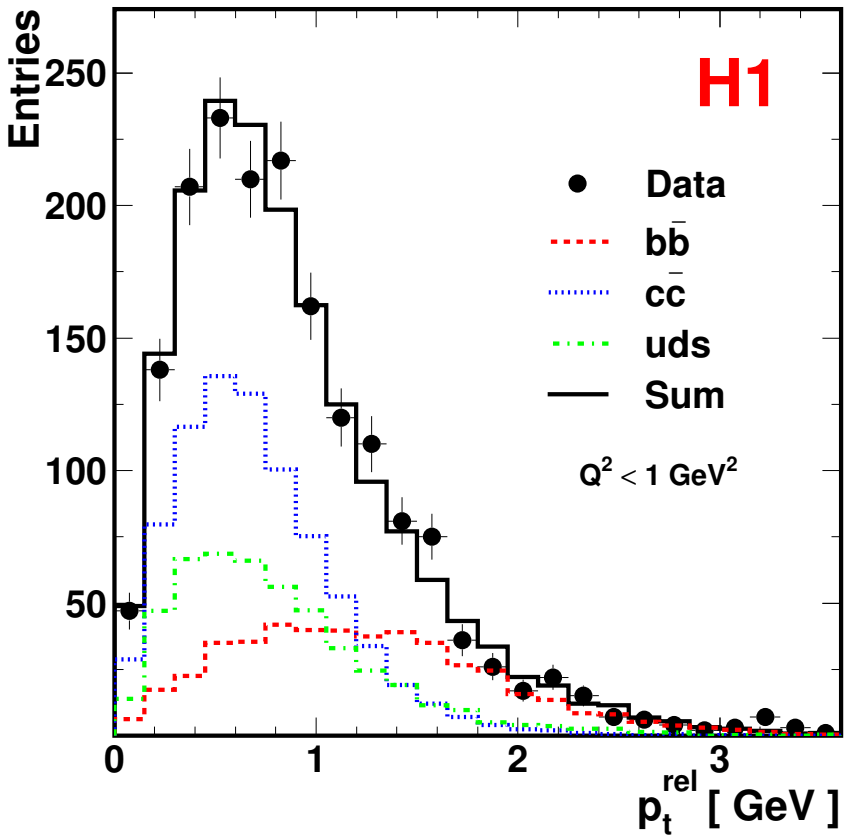


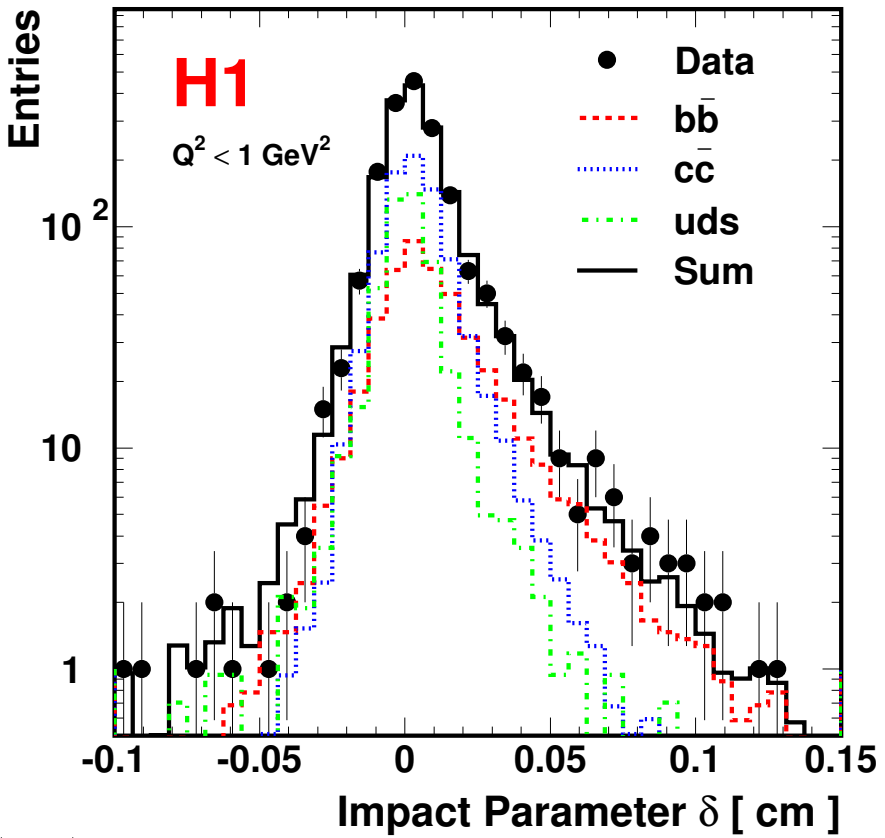
Now onto beauty. How is beauty measured?

- The process $ep \rightarrow eb\bar{b}X \rightarrow ejj\mu X$, where beauty decays via $b \rightarrow \mu X$ is used to tag beauty
- Due to large beauty mass, muons will have a high p_t relative to the beauty jet direction (p_T^{Rel})
- Due to the long b lifetime, the muon will have a large impact parameter (δ)
- Impact parameters are signed as seen below:



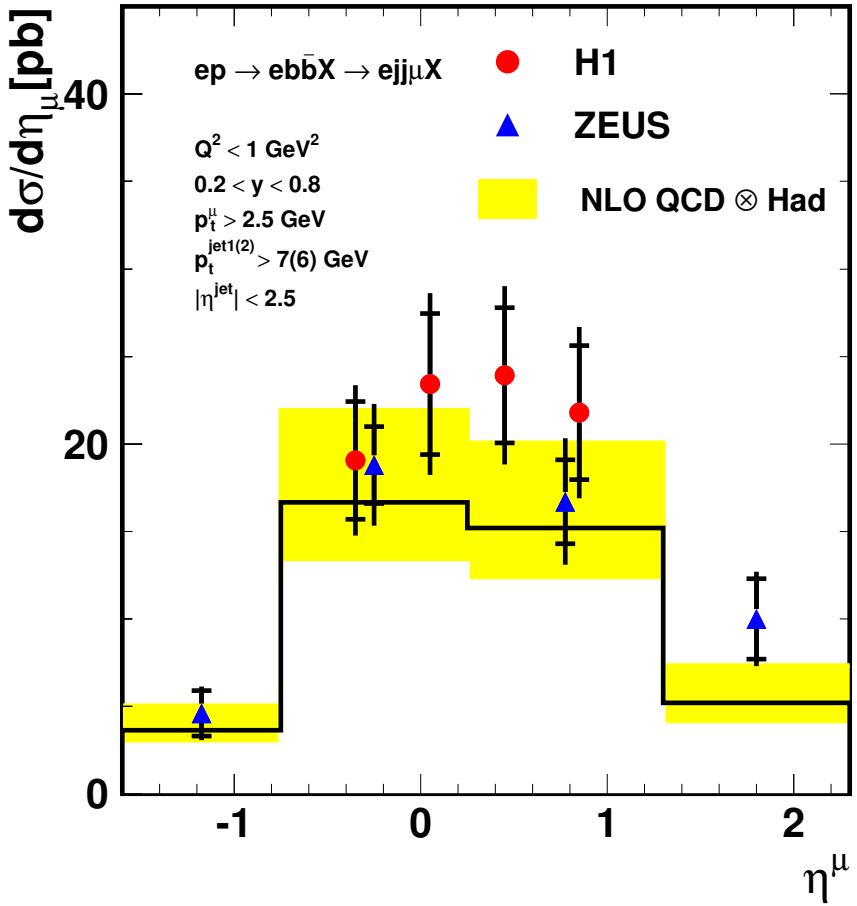
Beauty from p_T^{Rel} and Impact Parameters

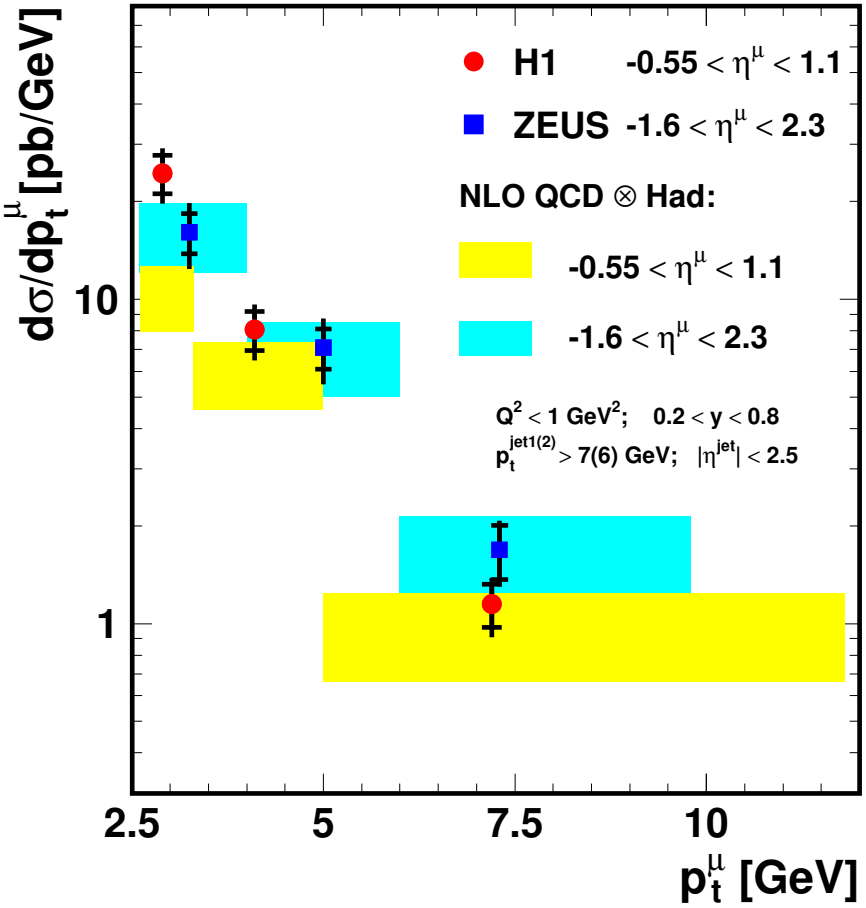




- The fractions of b, c, and light flavours (LF) are determined from a likelihood fit to the 2D distributions (p_T^{Rel}, δ)
- At higher p_T^{Rel}, the contribution from beauty falls off less rapidly than that of the LF
- The same beauty to LF fall off feature occurs for higher positive impact parameters
- (δ LF $\approx$ symmetric about zero)

Photoproduction with μ + Jets





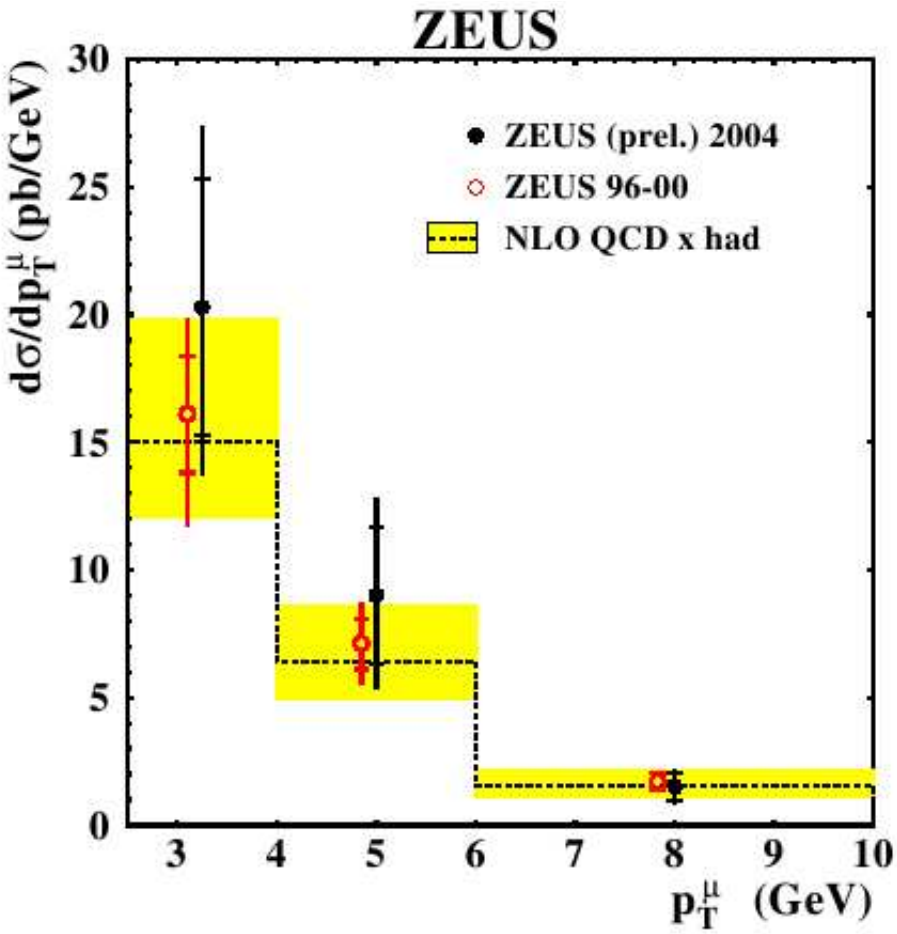
Agreement between H1 and ZEUS

- ZEUS: Good agreement with NLO pQCD
- H1: Excess data/NLO at low p_T^μ

Photoproduction μ + Jets

The p_T cross sections for muons created in the process $ep \to eb\bar{b}X \to ejj\mu X$ is shown:

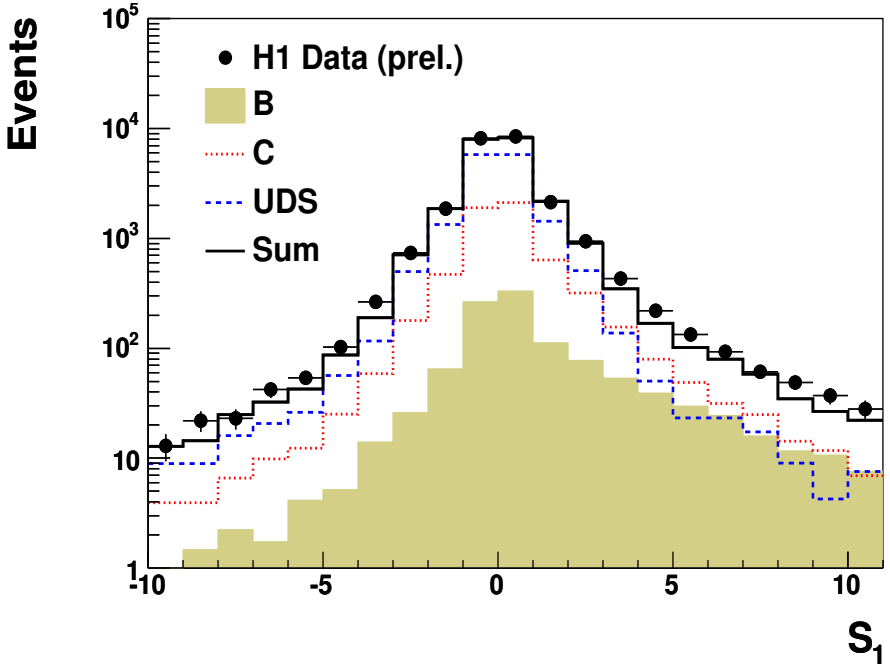
- This measurement utilizes the added ZEUS silicon Micro Vertex Detector (MVD)
- In good agreement with ZEUS HERA I data, and to the NLO QCD prediction from FMNR
- First beauty result from HERA II
- Measurement made with only 20% of present data

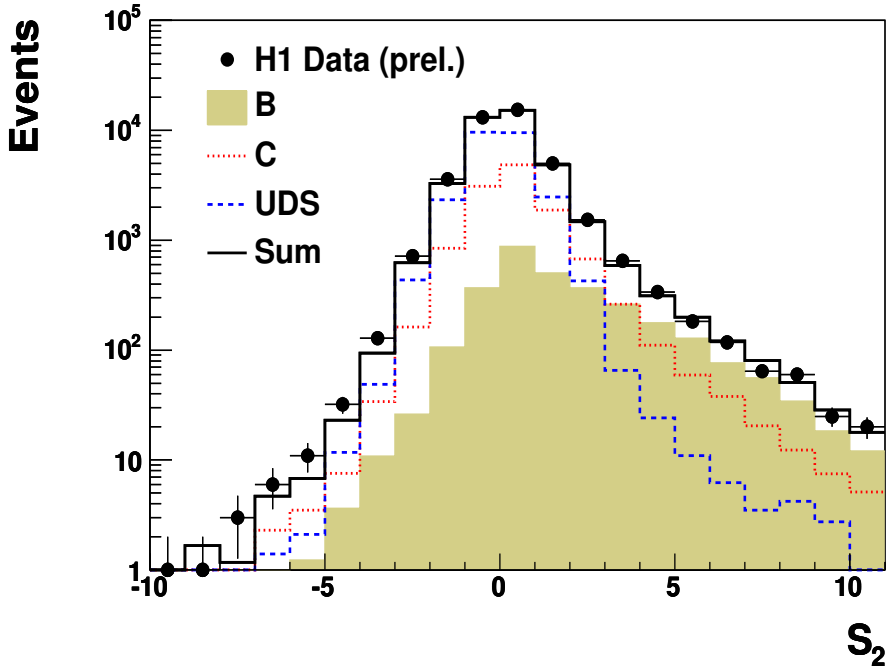


Much more to come!

Inclusive Lifetime Tag

An inclusive method to measure beauty and charm utilizes the significance of the signed impact parameter $S = \delta/\sigma(\delta)$.

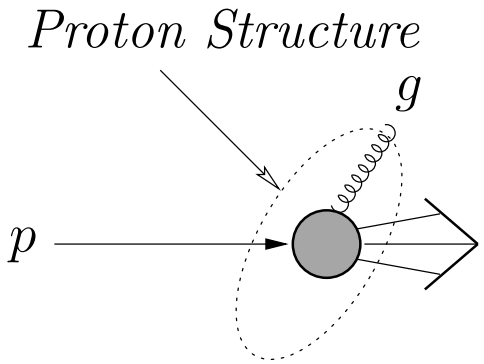




- The (positive) tail of the 1st most significant track (S_1) shows the charm to LF ratio increase
- Now the (positive) tail of the S_2 shows the beauty to LF ratio increase

Beauty and charm cross sections are obtained from likelihood fits to data

Extraction of $F_2^{\overline{Q}Q}$



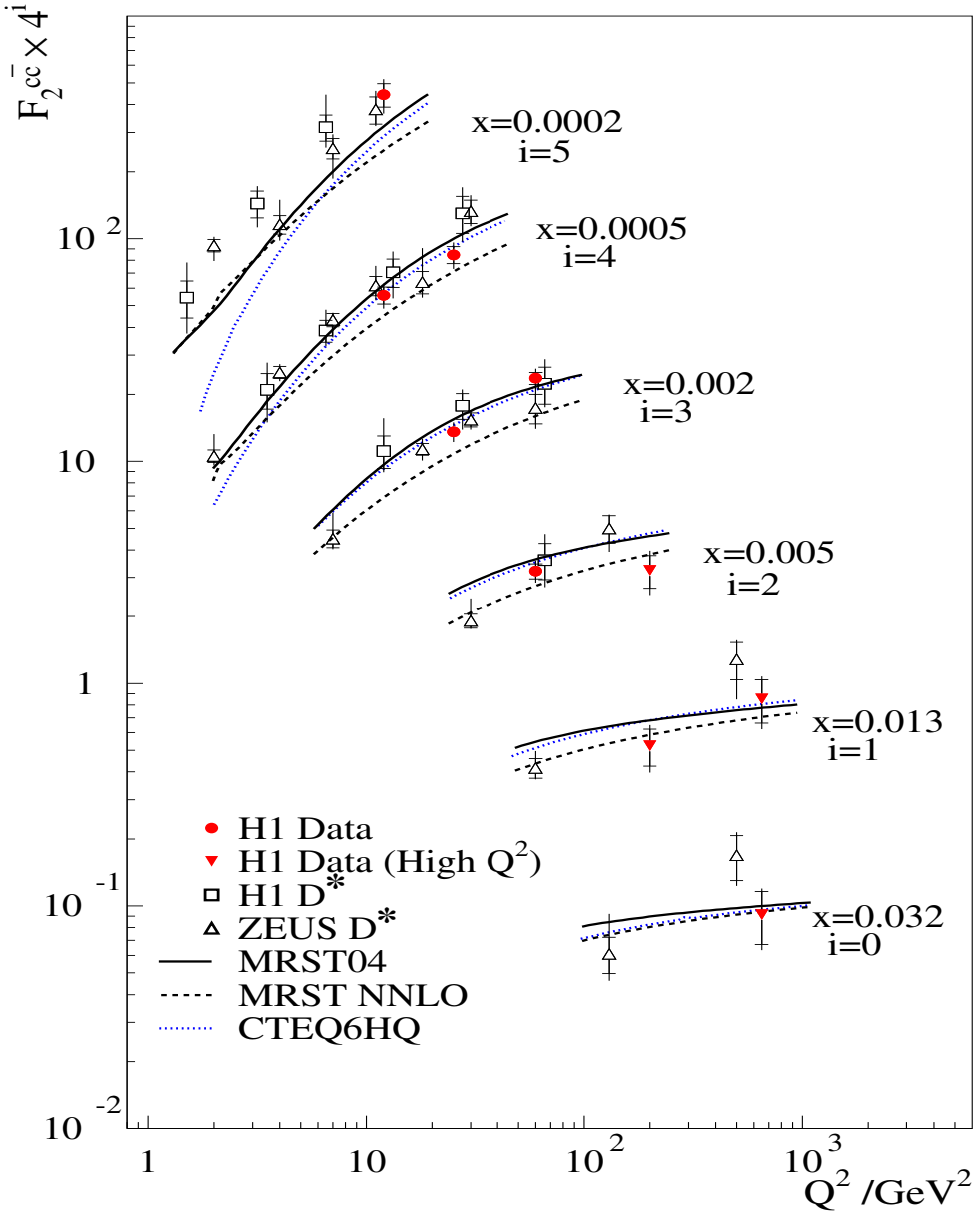
$F_2^{\overline{Q}Q}$ is extracted from the charm/beauty double differential cross sections:

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

- F_L only significant at large y
- F_2 depends on Q^2 only because gluons are present in the proton
- Previous measurements used D^* cross sections to determine $F_2^{\overline{c}c}$
- New (H1) $F_2^{\overline{c}c}$ measurement uses inclusive lifetime tag
- $F_2^{\overline{b}b}$ uses inclusive lifetime tag measurements

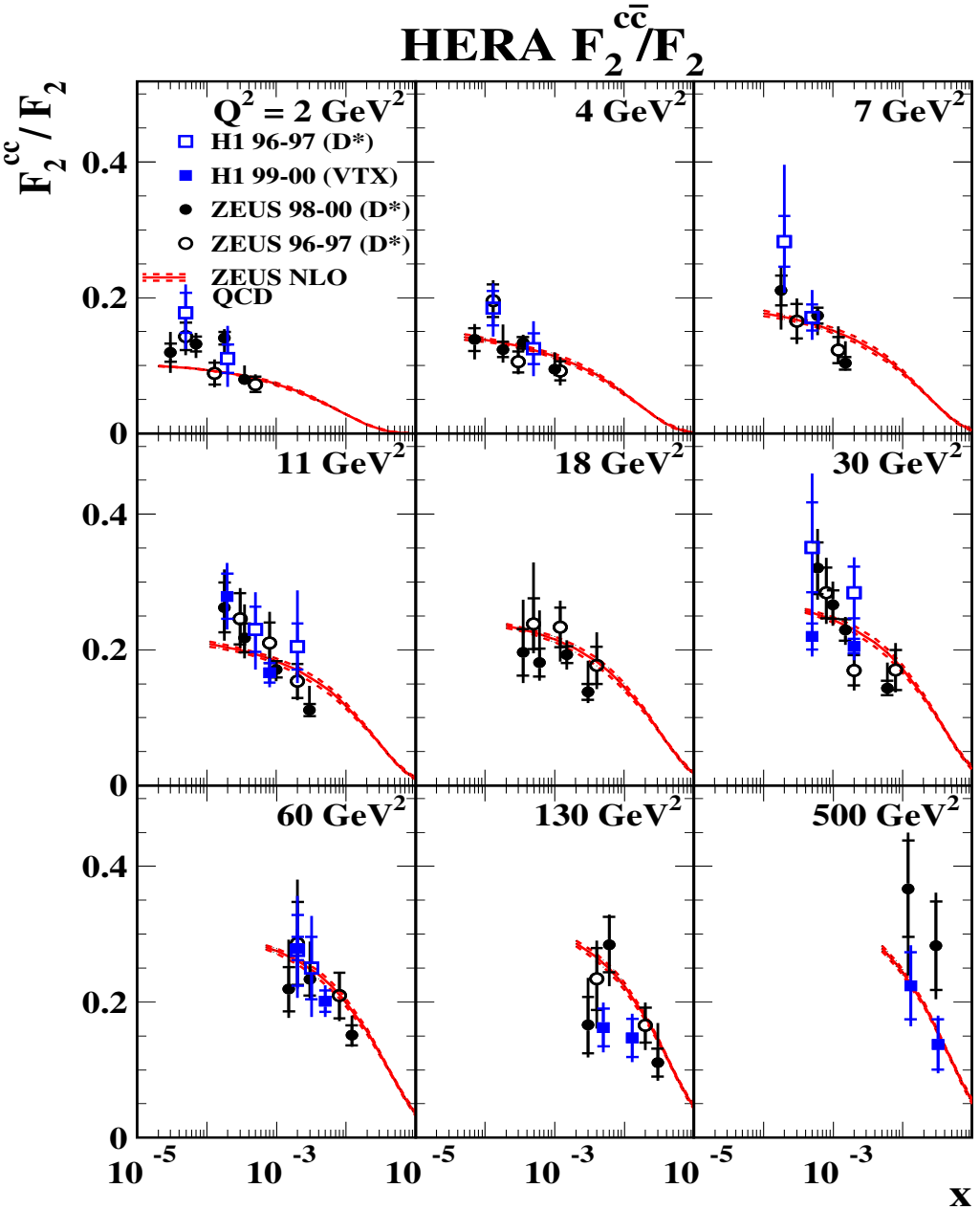
$F_2^{c\bar{c}}$

- QCD calculations fit the data reasonably well
- NNLO calculations now available
- scaling violation

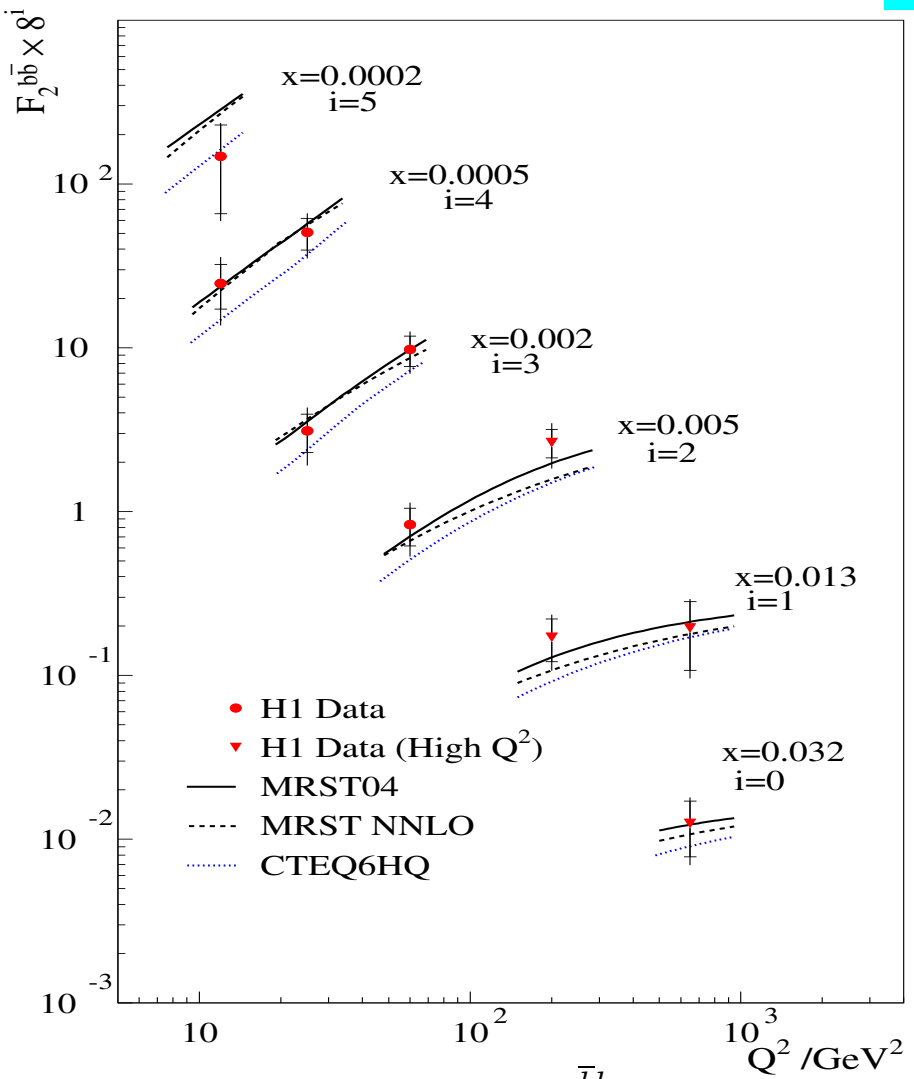


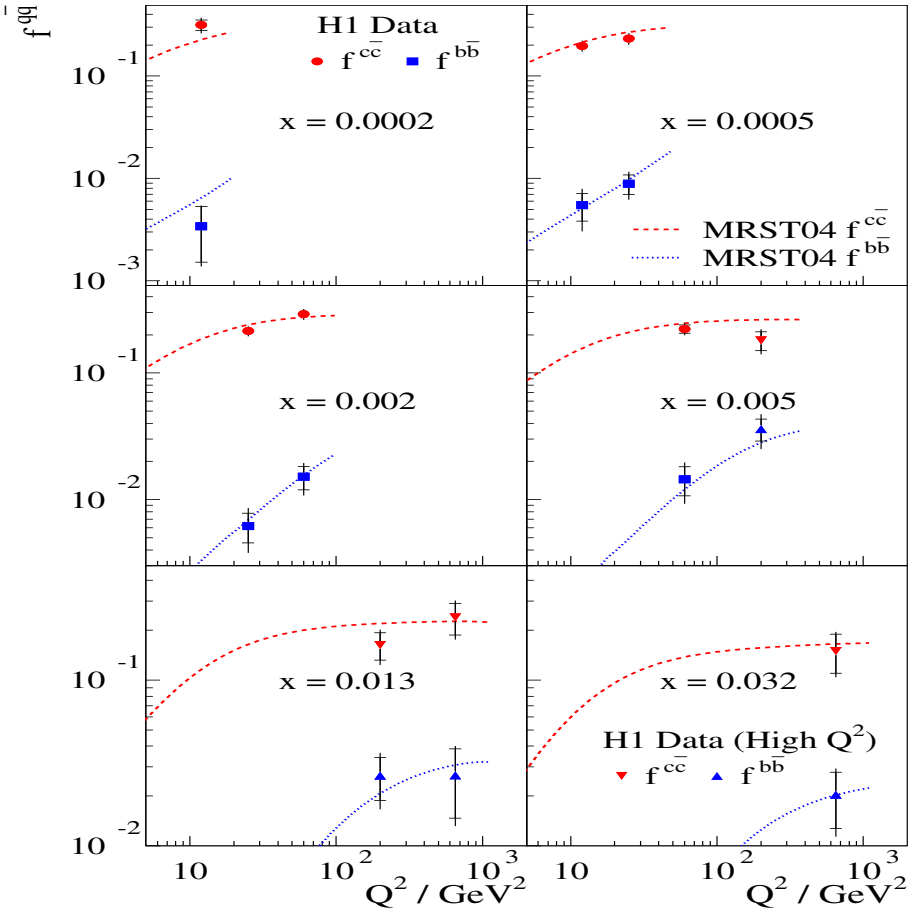
$F_2^{\bar{c}c}/F_2$

- $F_2^{\bar{c}c}$ increases with Q^2 for same x
- Contributions from $F_2^{\bar{c}c}$ can be as high as 30%
- Good description by NLO QCD calculation



$F_2^{b\bar{b}}$





Beauty contributes a small fraction to the total F_2

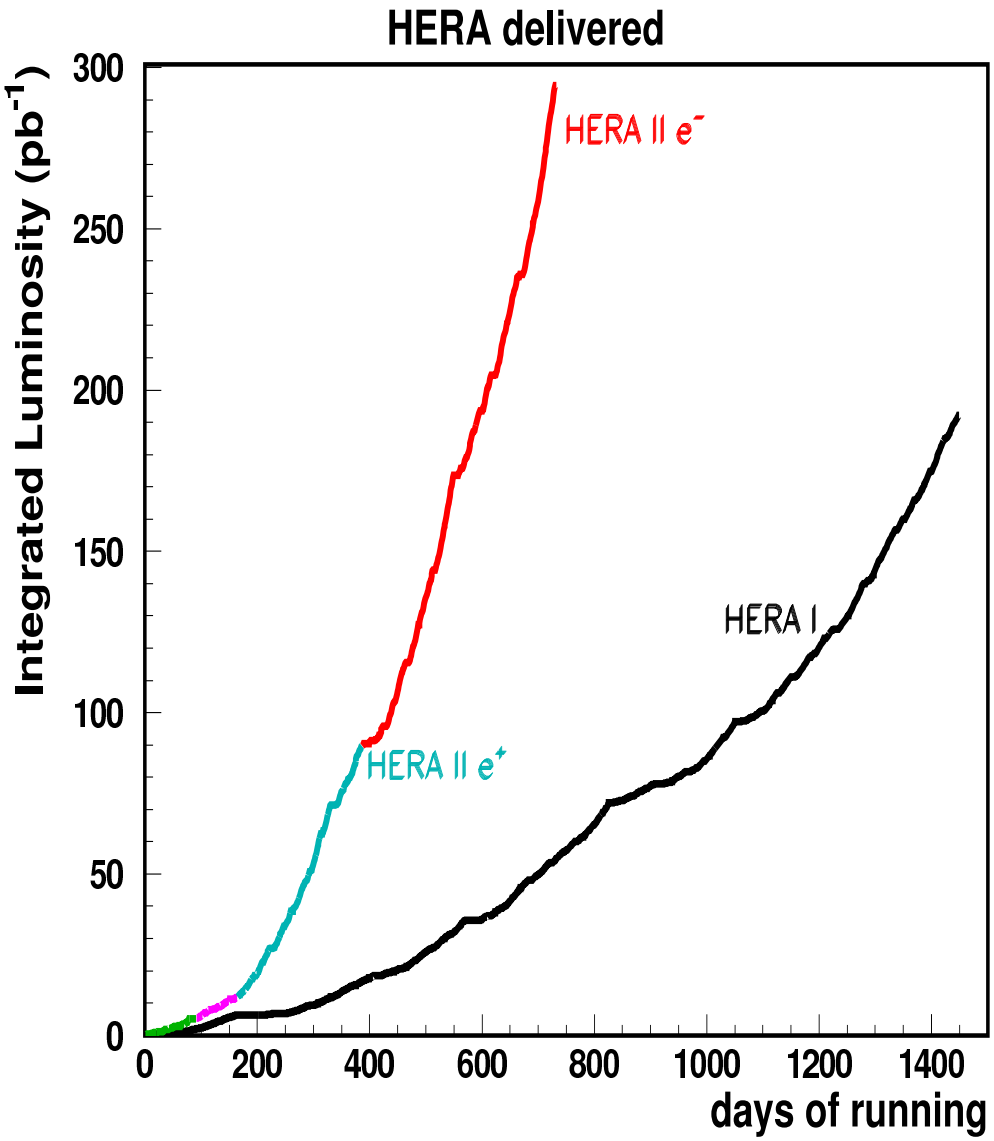
- First measurement of $F_2^{b\bar{b}}$
- Improved precision expected from HERA II
- Compared to NNLO as well

Summary

- HERA results consistent with universality of charm fragmentation
- Cross sections reasonably well described by NLO pQCD
  - Higher order calculations needed in some regions
- Both c and b contribution to F_2 have been measured

Outlook

- HERA II luminosity exceeds HERA I, 160 pb^{-1} thus far, 240 pb^{-1} to come (optimistically 500 pb^{-1} by end of running in 2007)
- Most HERA data not yet analyzed
- Many more results from HERA to come!



Combined Fit of p_T^{Rel} and δ

ZEUS measured similar p_T^{Rel} and δ distributions.

- p_T^{Rel} is plotted in bins of δ
- Minimization of χ^2 fits resulted in fractions f_b and f_c
- $\chi^2 = \frac{\Sigma_i (N_i^{data} - N_i^{fit})^2}{D.O.F}$
- where $N_i^{fit} = \frac{f_b N_i^b + f_c N_i^c + f_{LF} N_i^{LF}}{f_b + f_c + f_{LF}}$
- The three contours indicate regions of 68% probability that the charm and beauty fractions are $f_b = 0.166 \pm 0.026$ and $f_c = 0.518 \pm 0.098$
- Three MC samples (for b, c, and LF) were adjusted in MC to reproduce the data