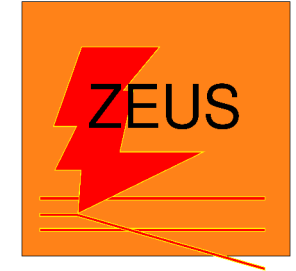


Heavy Quark Production in ep Collisions at HERA



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9th Conference on the Intersection
of Particle and Nuclear Physics

May 30th - June 03rd 2006

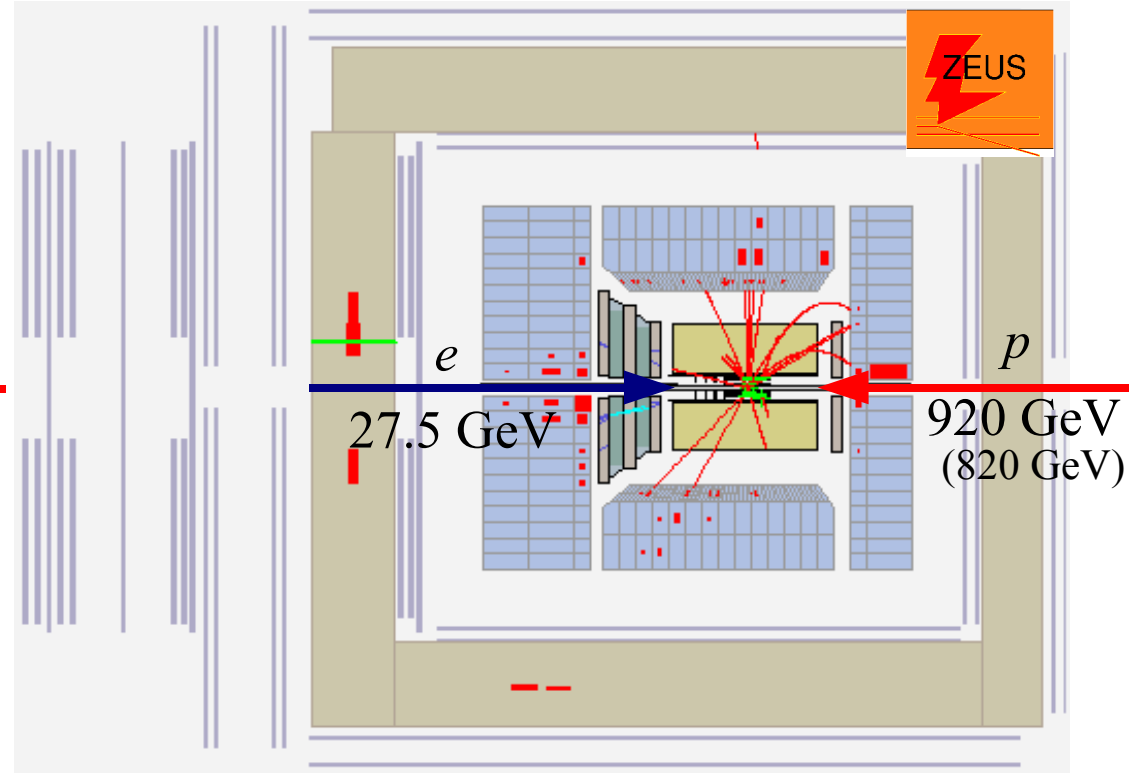
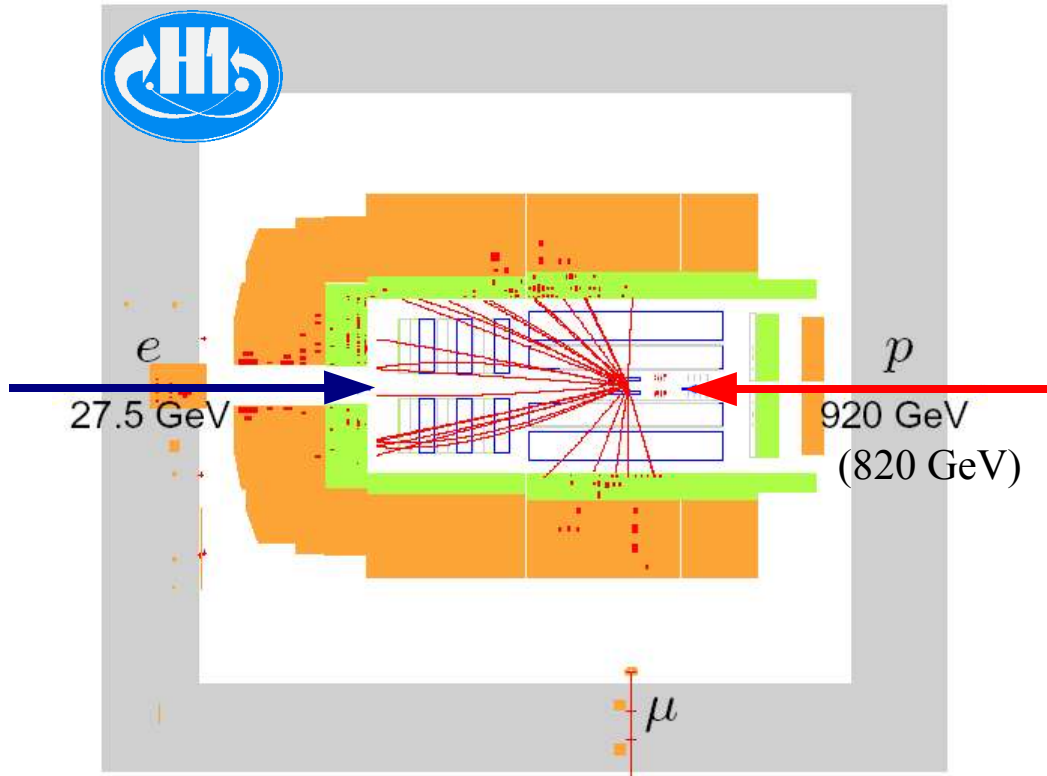
High Energy Hadron Physics

- Introduction & Theory
- Results:
 - Charm
 - Beauty
 - Inclusive $F_2^{c\bar{c}/b\bar{b}}$
- Summary & Outlook

HERA: ep collisions within H1 & ZEUS



HERA: ep collisions within H1 & ZEUS



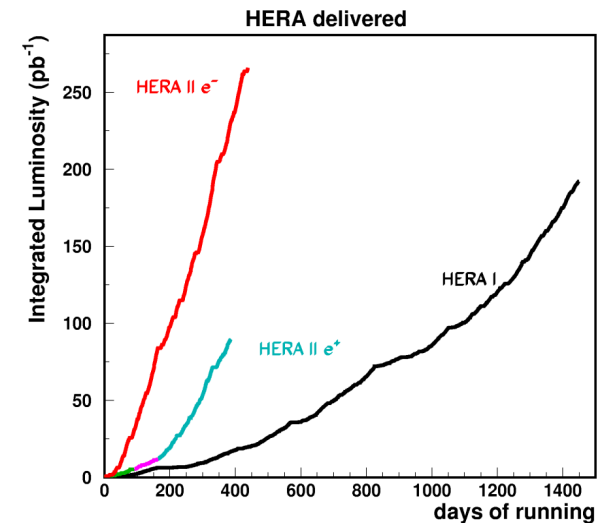
ep centre of mass energy:

1992 - 1997: 300 GeV

1998 - 2006: 318 GeV

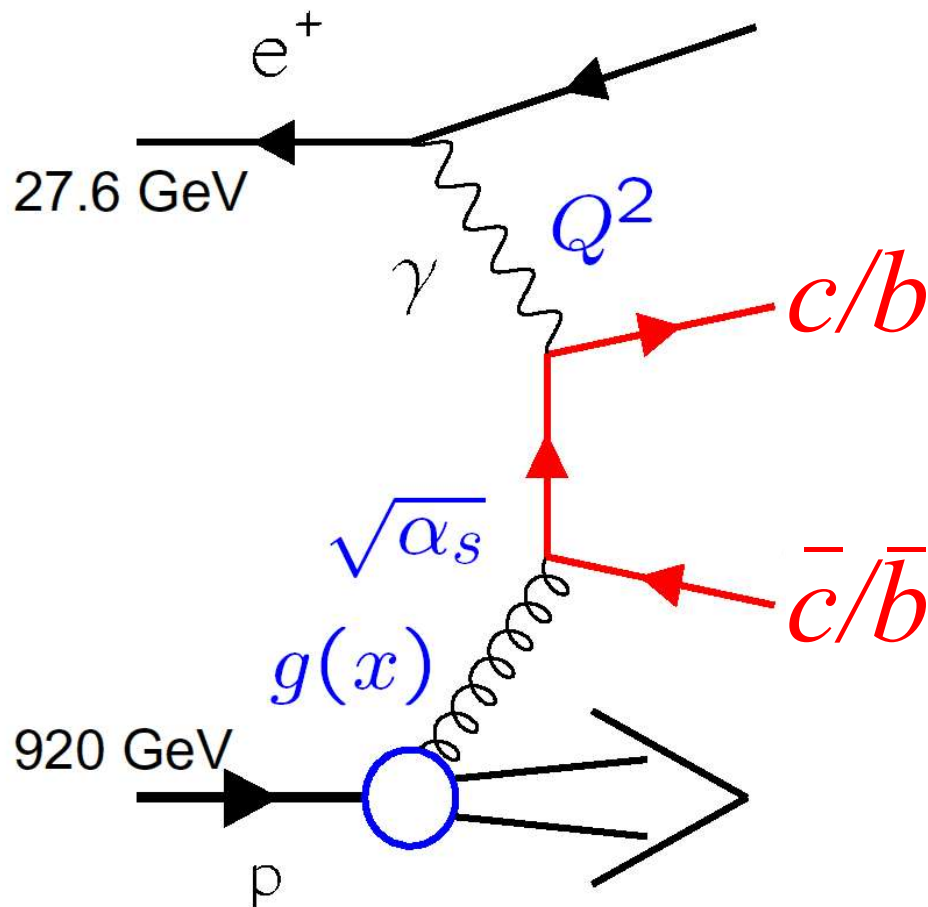
H1&ZEUS integrated Luminosity: 96-00 / 03-06

(per experiment) $e^{+/-} p$ scattering: $L \approx 115 / 240 \text{ pb}^{-1}$



Heavy Quark Production in ep collisions

Dominant process in ep collisions:
Boson-Gluon-Fusion



Multiple scales:

$$m_{c/b} \sim 1.5 / 5 \text{ GeV}$$

$$p_{T, c/b} \sim \text{typically few to } 50 \text{ GeV}$$

$$Q^2 \lesssim 1 \text{ GeV}^2 \text{ Photoproduction } (\gamma p)$$

$$\gtrsim 1 \text{ GeV}^2 \text{ Deep inelastic scattering (DIS)}$$

NLO calculations with different schemes depend on dominant scale:

- „massive scheme“ **FFNS**:

$$Q^2, p_{T, c/b}^2 \approx m_{c/b}^2$$

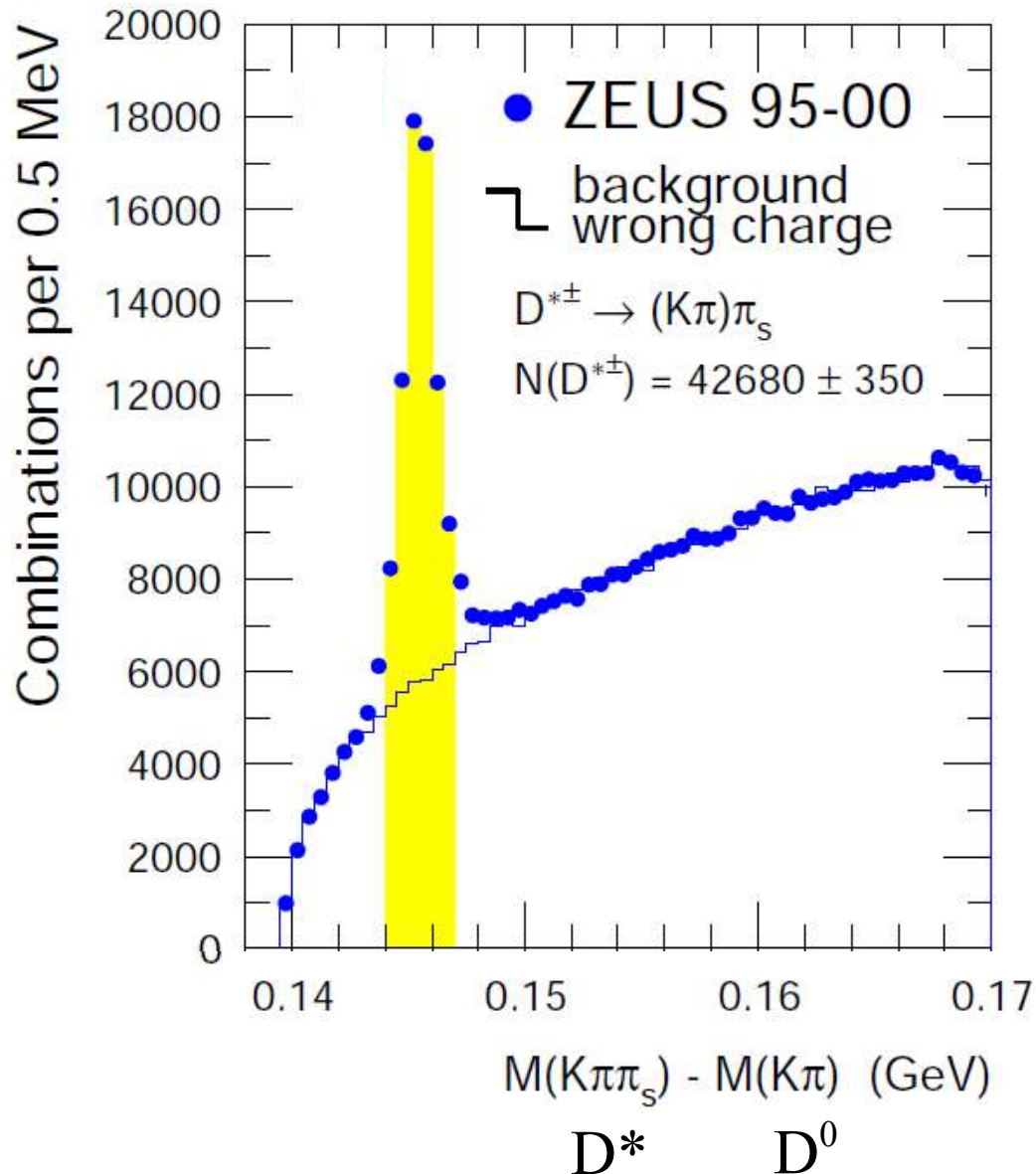
- „massless scheme“ **ZM-VFNS**:

$$Q^2, p_{T, c/b}^2 \gg m_{c/b}^2$$

- combined massive \otimes massless: **VFNS**

Charm production, D* tag

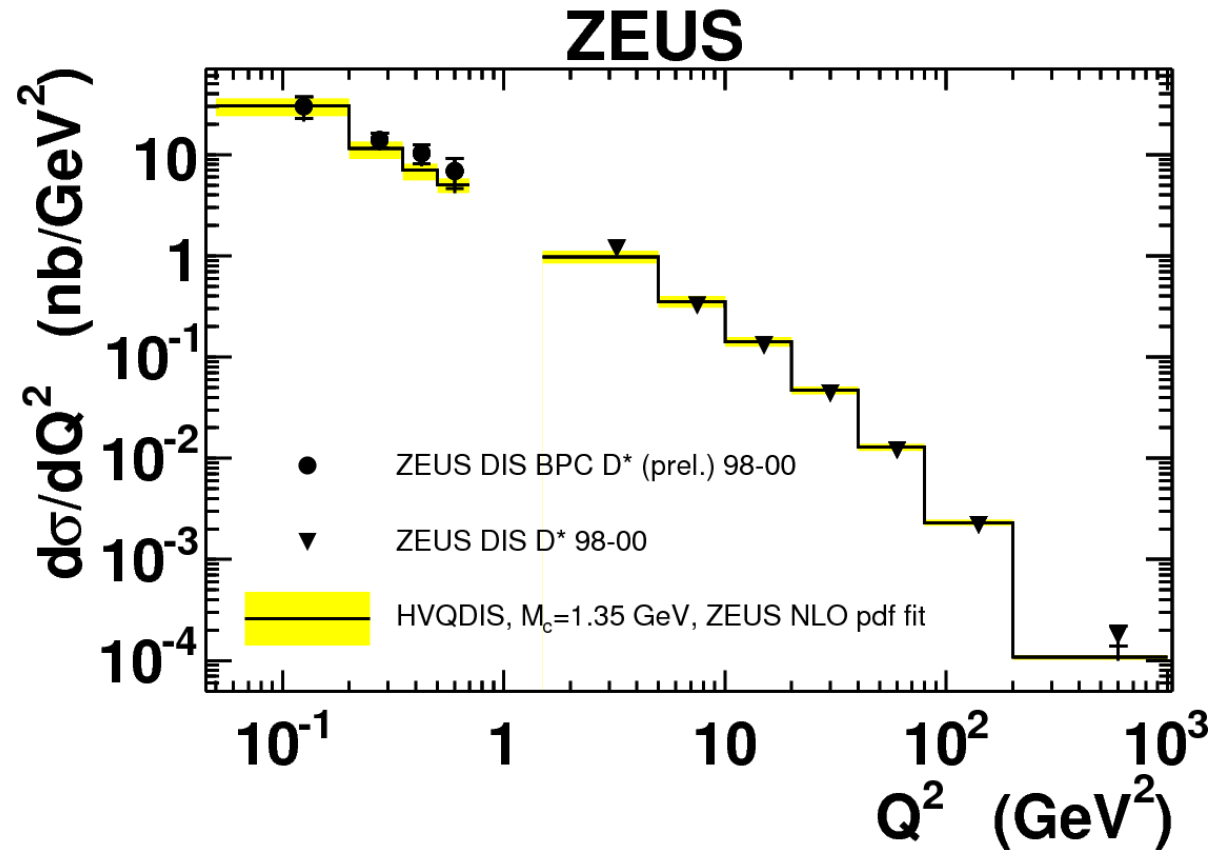
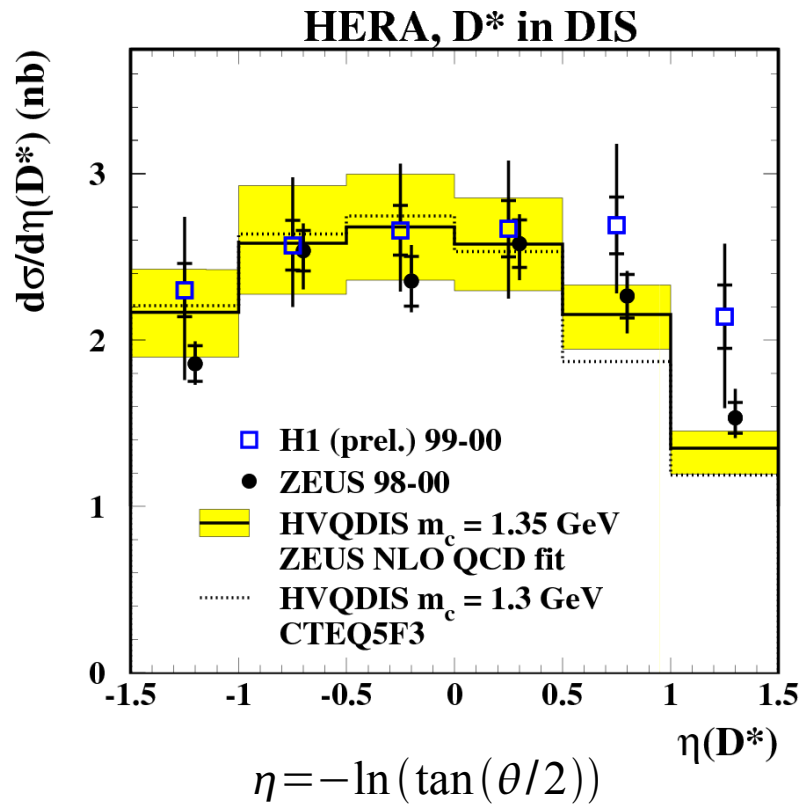
Tag Charm via:



- **exclusive final hadronic decay**
here $c \rightarrow D^* X \rightarrow D^0 \pi_s X \rightarrow (K\pi)\pi_s X$
- or
- impact parameter (later)

Clean signal tag with large statistics.

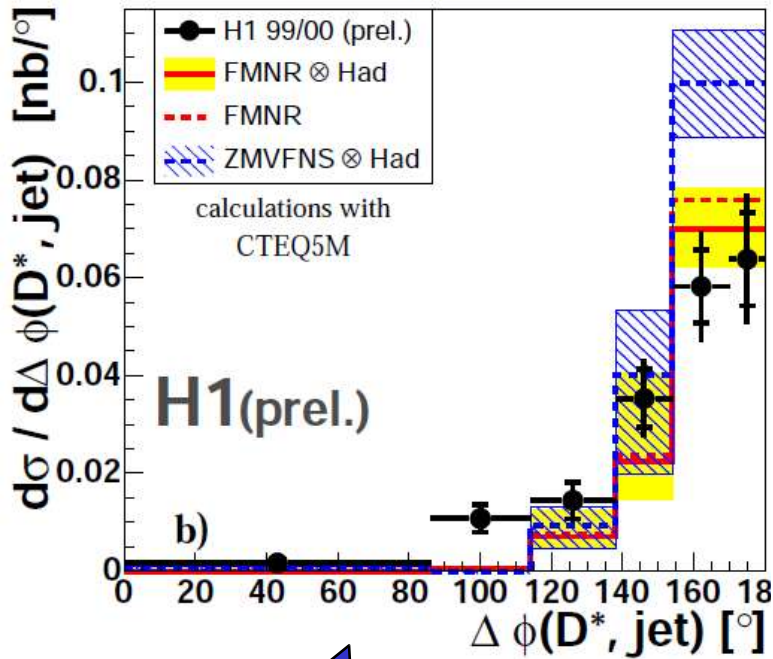
Charm production, D^* tag



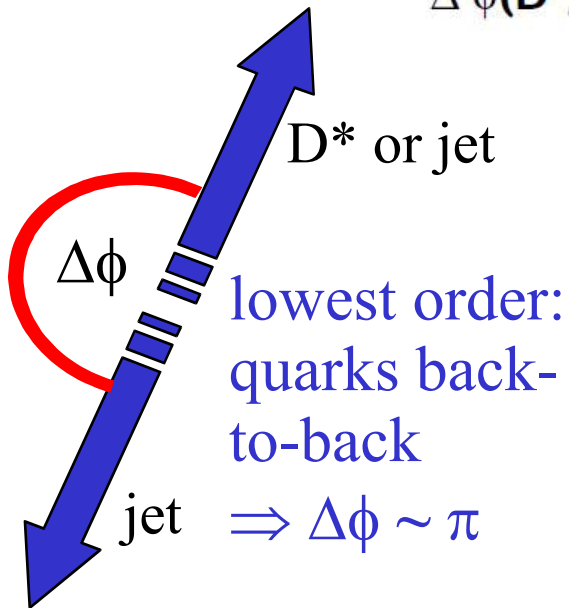
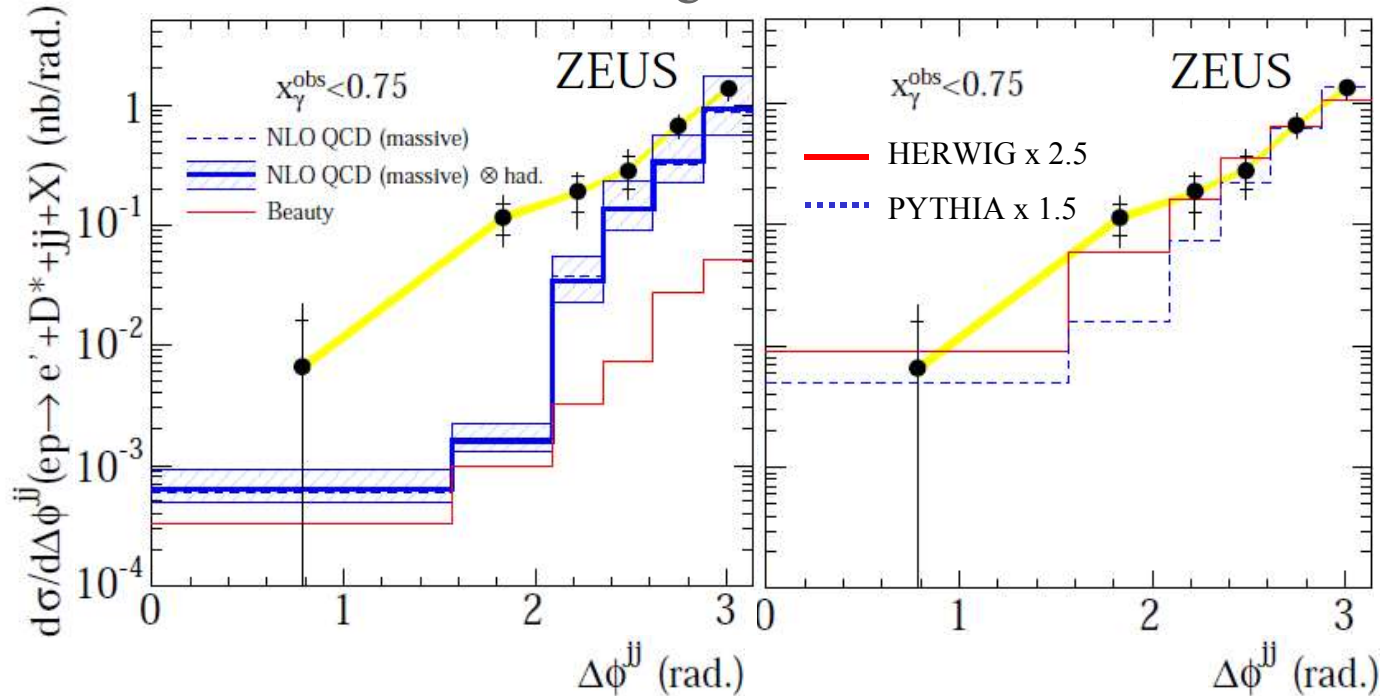
Data described by NLO QCD over 5 orders of magnitude.

Charm production, $D^* + \text{jet}(s)$ - higher order events

$D^* + \text{other jet}$



Enriched in higher-order like events



NLO: Shape not well reproduced.

LO+PS: Describes shape. Normalisation too low.

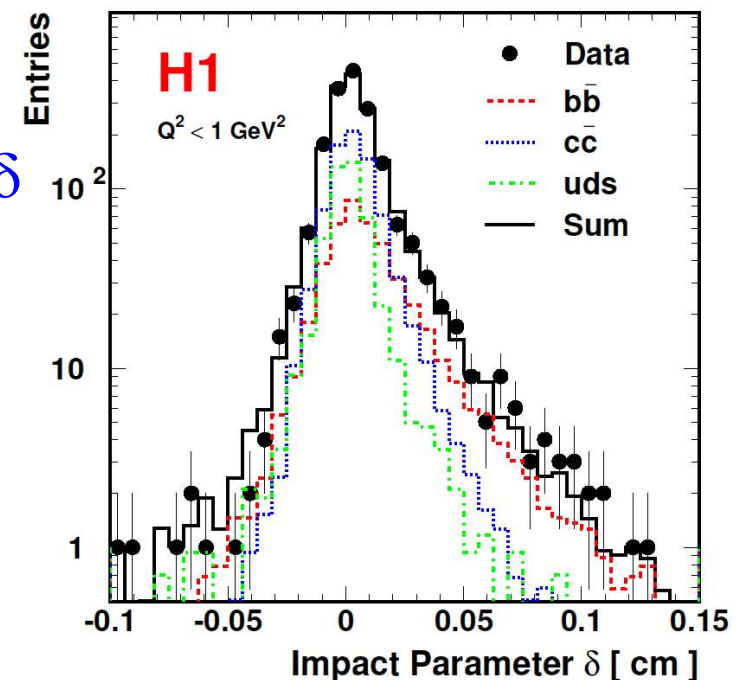
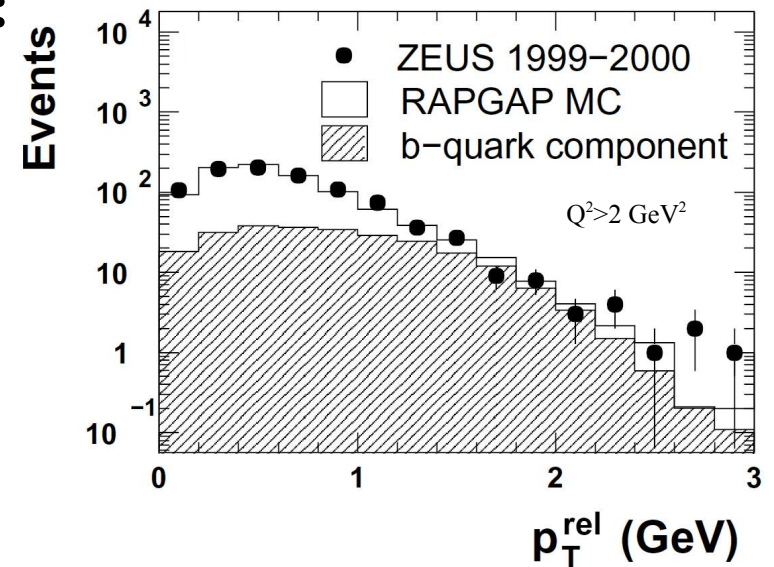
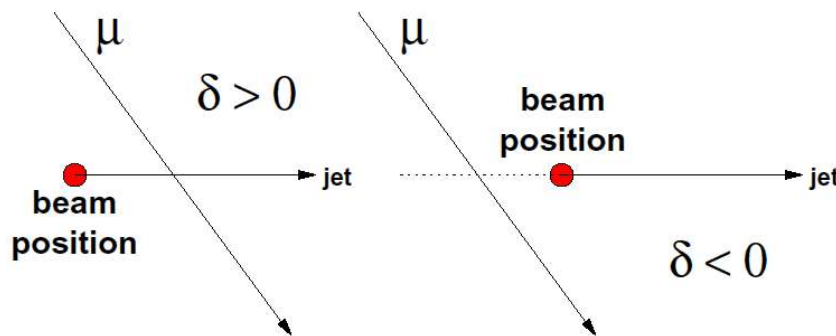
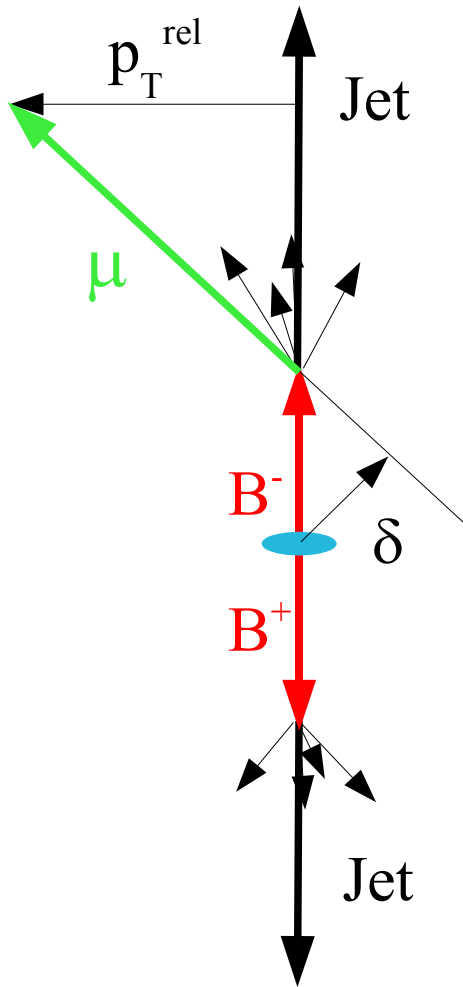
For high precision: Need parton showers in NLO (e.g. MC@NLO) or NNLO.

Measurement techniques - μ +jets

Tag μ +jets Beauty (Charm) events by exploiting:

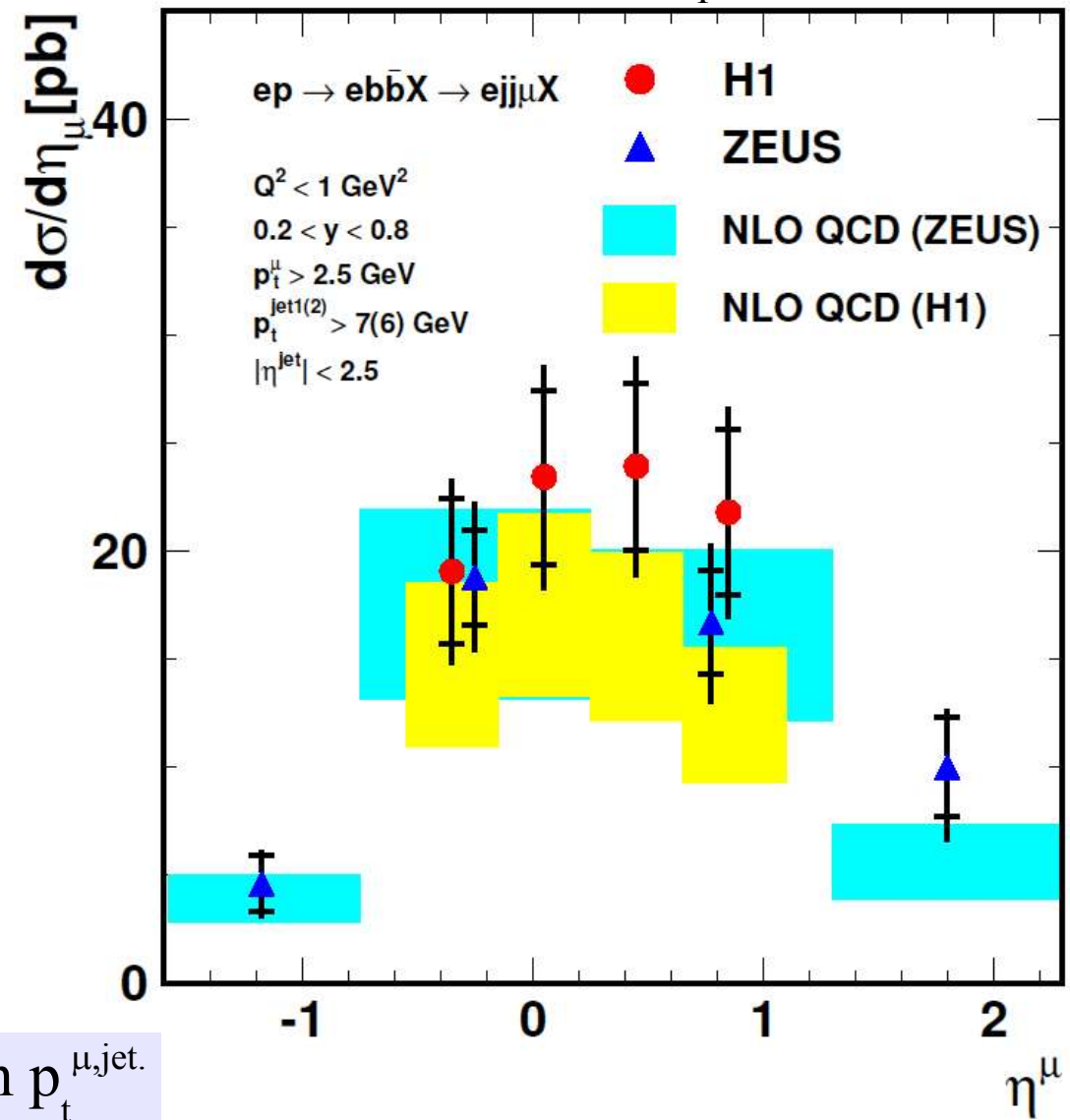
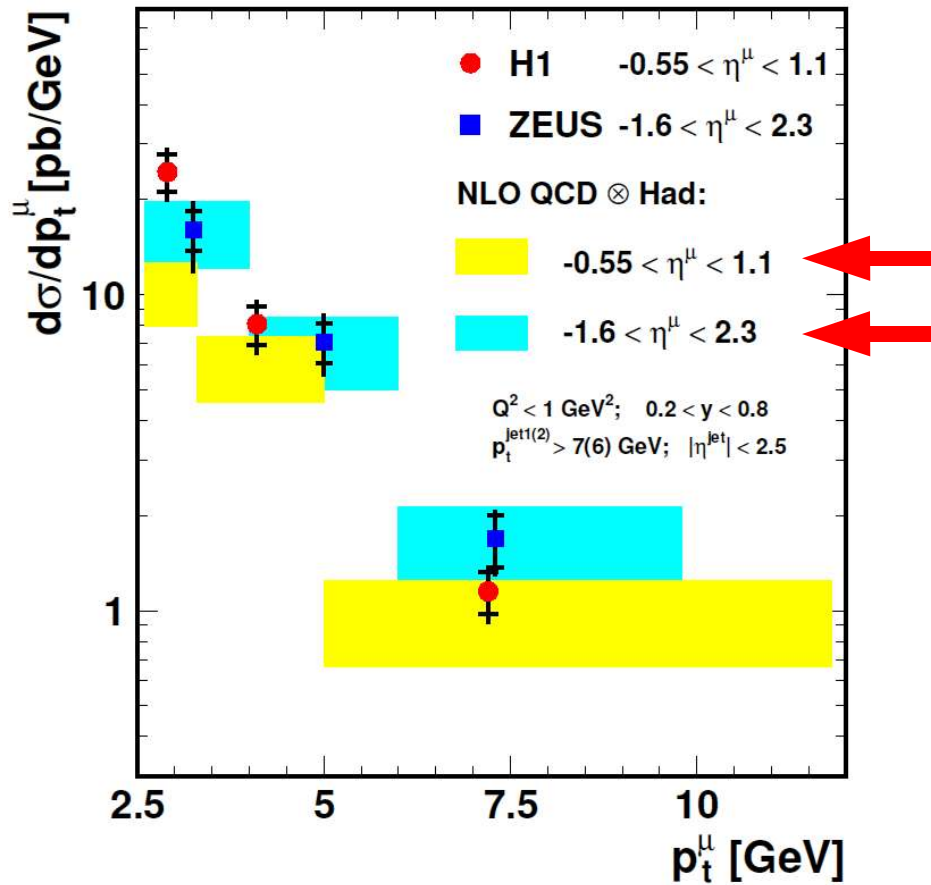
large B mass - μ -momentum relative to associated jet, $\mathbf{p}_T^{\text{rel}}$

"long" lifetime - signed impact parameter relative to vertex/beamspot, δ



Beauty in γp , μ +jets and δ

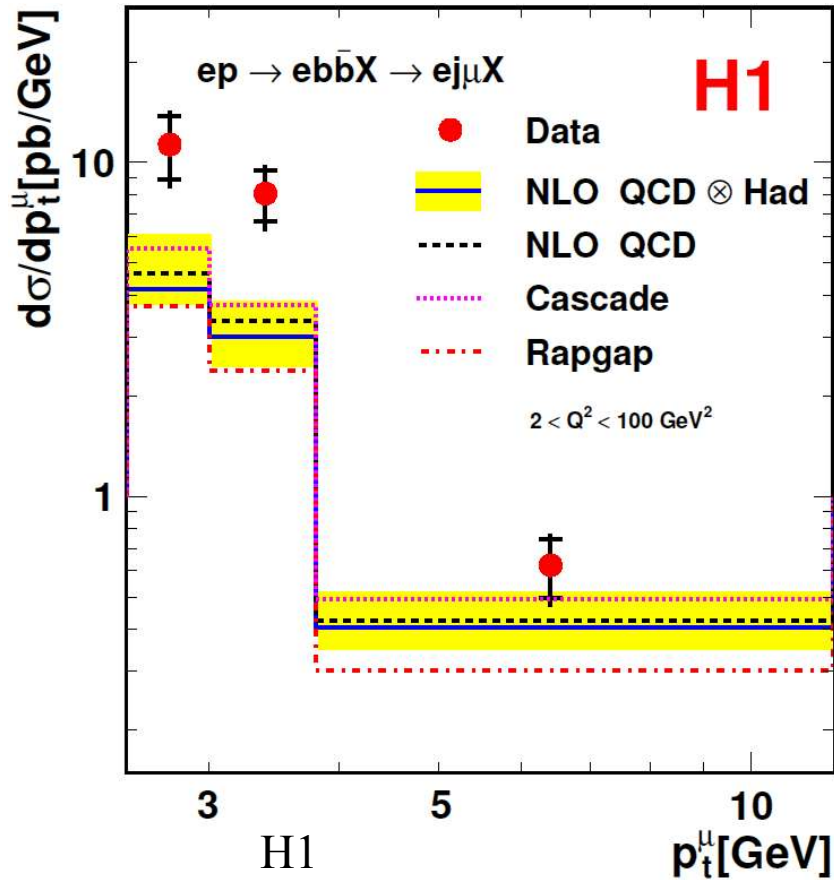
Typical $p_T^b \sim 10$ GeV



NLO agrees, H1 data slightly steeper in $p_t^{\mu, \text{jet}}$.

Agreement within errors of H1 and ZEUS.

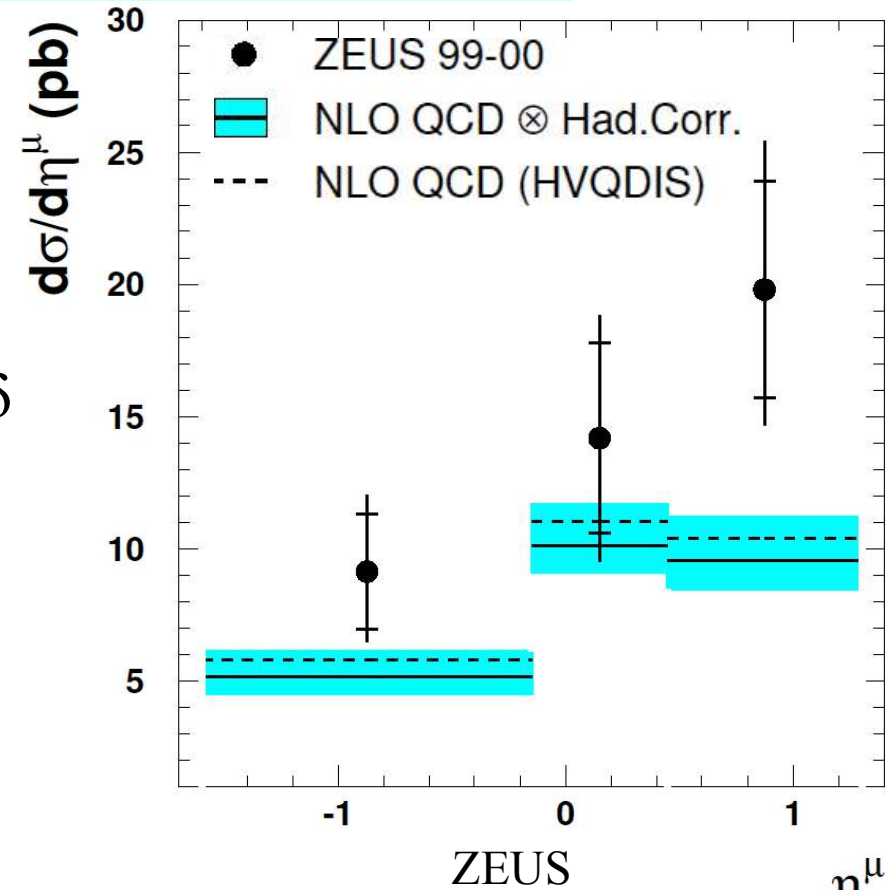
Beauty in DIS, μ +jet and δ



H1
 $Q^2 \in [1, 100] \text{ GeV}^2$
 $y \in [0.1, 0.7]$
 $p_T^\mu > 2.5 \text{ GeV}$
 $\eta^\mu \in [-0.75, 1.15]$

Data higher at low p_T^μ as for the H1 γp measurement.

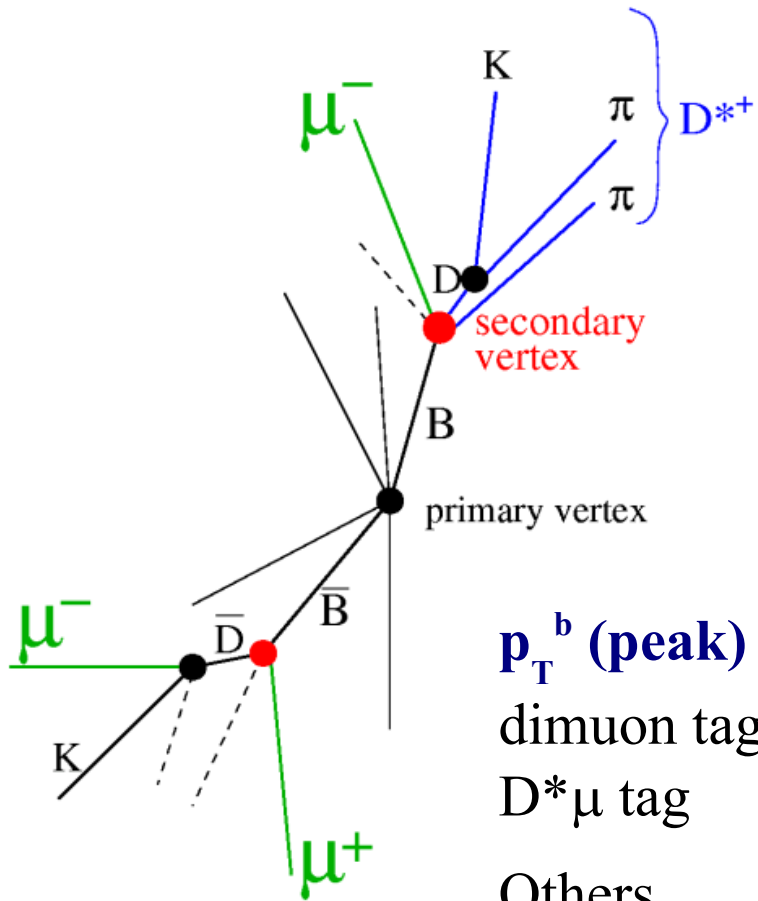
Higher data **also in forward η** .



ZEUS
 $Q^2 \in [1, 1000] \text{ GeV}^2$
 $y \in [0.05, 0.7]$
 $p_T^\mu > 2.0 \text{ GeV}$
 $\eta^\mu \in [-1.6, 1.3]$

A trend? Extend η and p_T range:

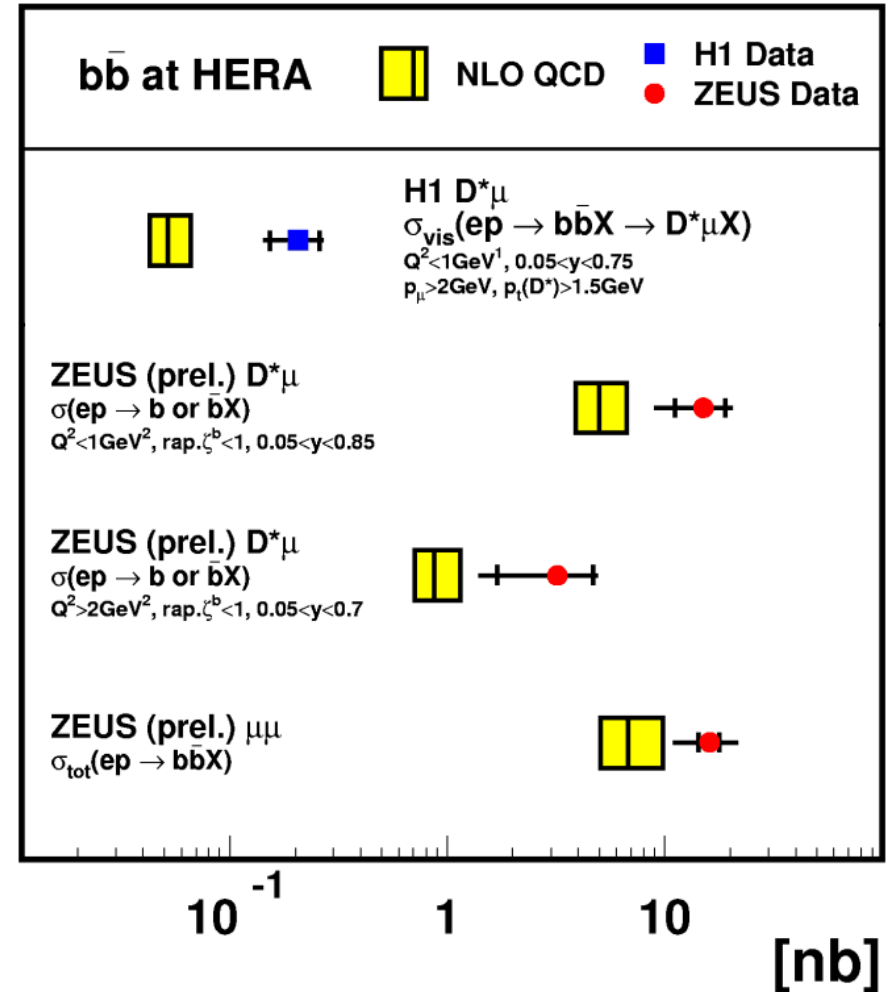
$b \rightarrow D^* \mu$ and $b \rightarrow \mu \mu$ measurements: sensitive to low p_T^b



Exploit correlations, no jet cuts, threshold prod.

p_T^b (peak) of tagged b-quarks:

- dimuon tag $\sim 4 \text{ GeV}$
- $D^* \mu$ tag $\sim 6 \text{ GeV}$
- Others $> 6 \text{ GeV}$



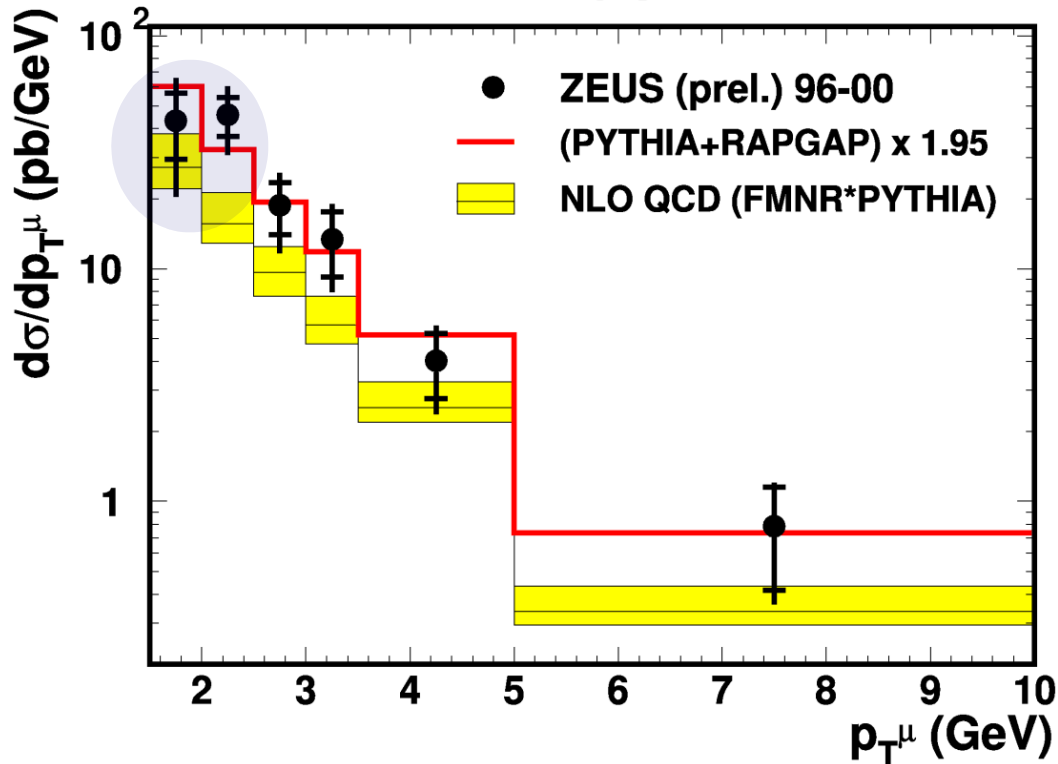
At low p_T - same trend: Massive NLO underestimates data,

ZEUS: NLO compatible within errors.

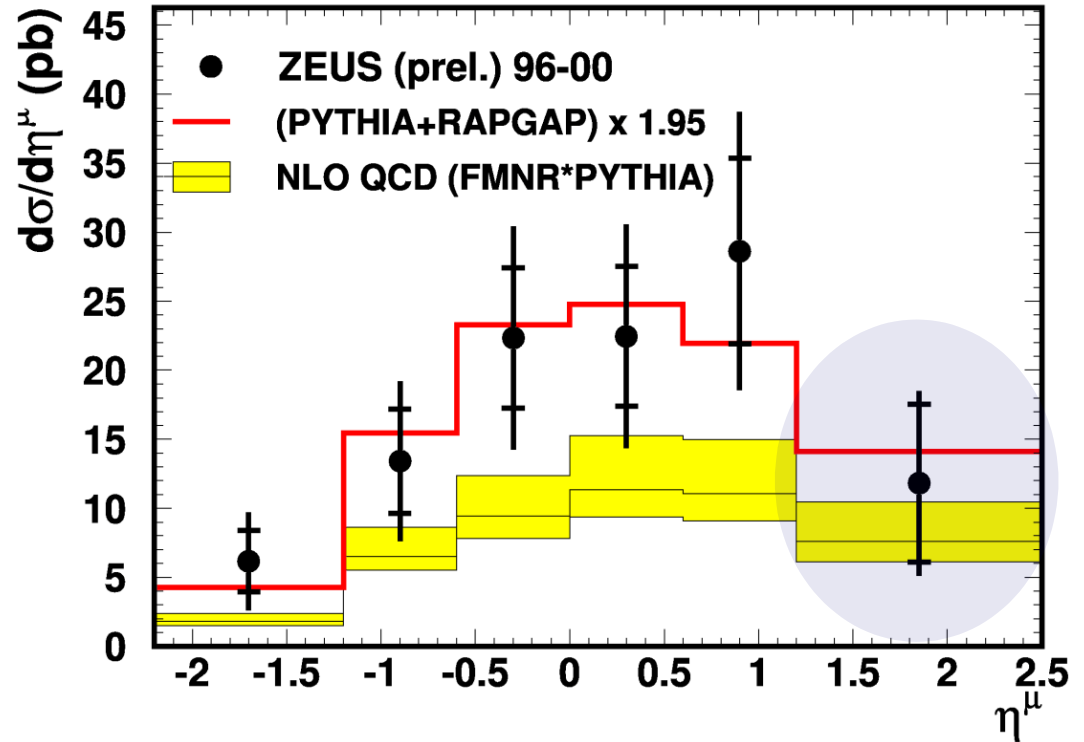
Trend at forward η and low p_T ?

Low p_T^b $b \rightarrow \text{dimuon}$ cross sections:

ZEUS



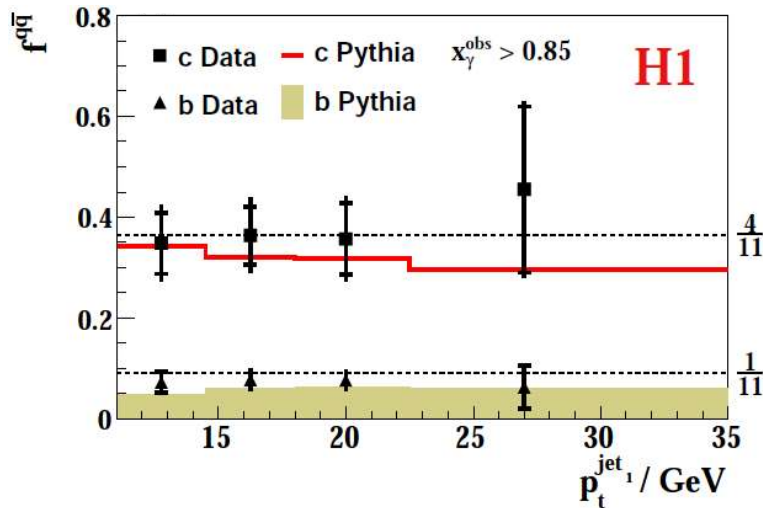
ZEUS



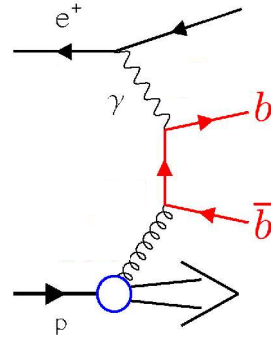
No evidence for trend at low p_T and forward η **to continue.**

Beauty and Charm - δ +jets (High p_T , γp)

Inclusive final state, **simultaneous determination of Beauty and Charm.**



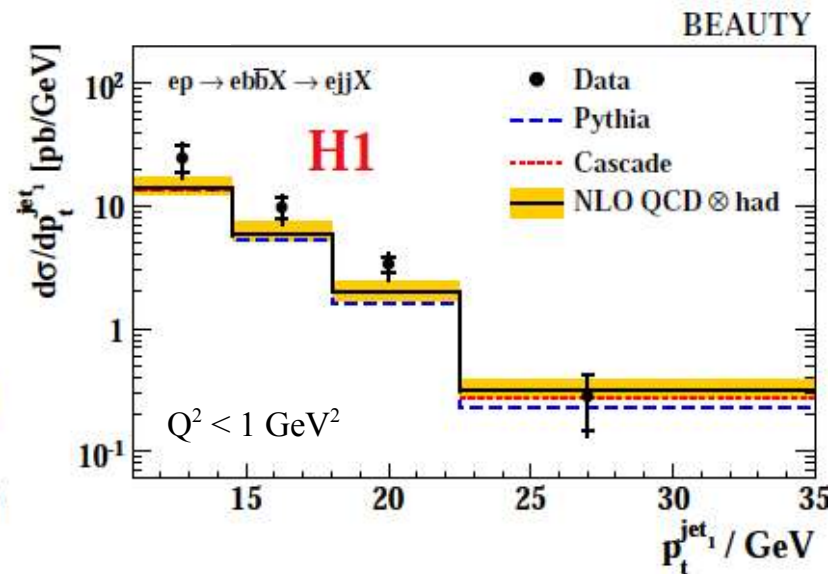
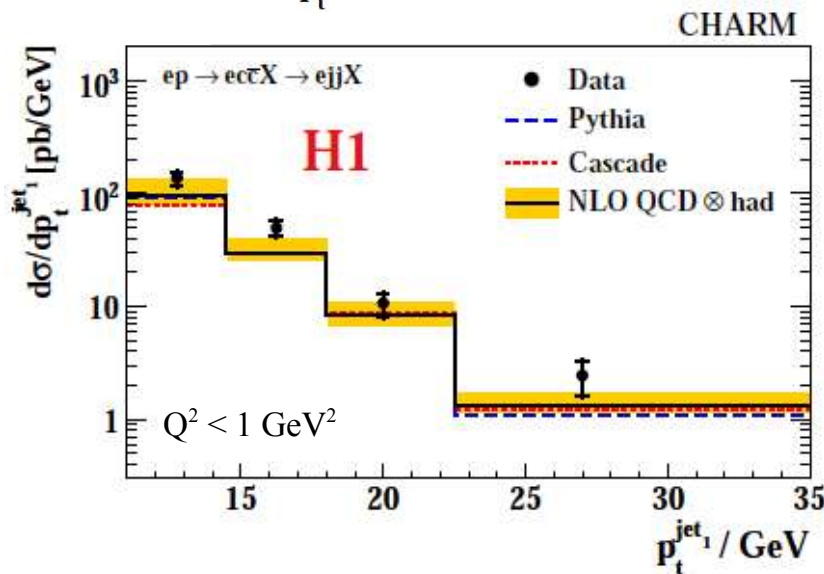
$f^{q\bar{q}}$: c or b fraction of total $ep \rightarrow ejjX$ cross section.



Simple quark charge counting:

$$f^{c\bar{c}} = 4/11,$$

$$f^{b\bar{b}} = 1/11$$

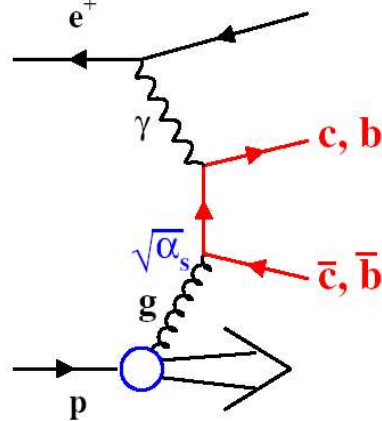


Overall good description of the data at high p_T^b .

$F_2^{q\bar{q}}$ in DIS at low and high Q^2 - Charm

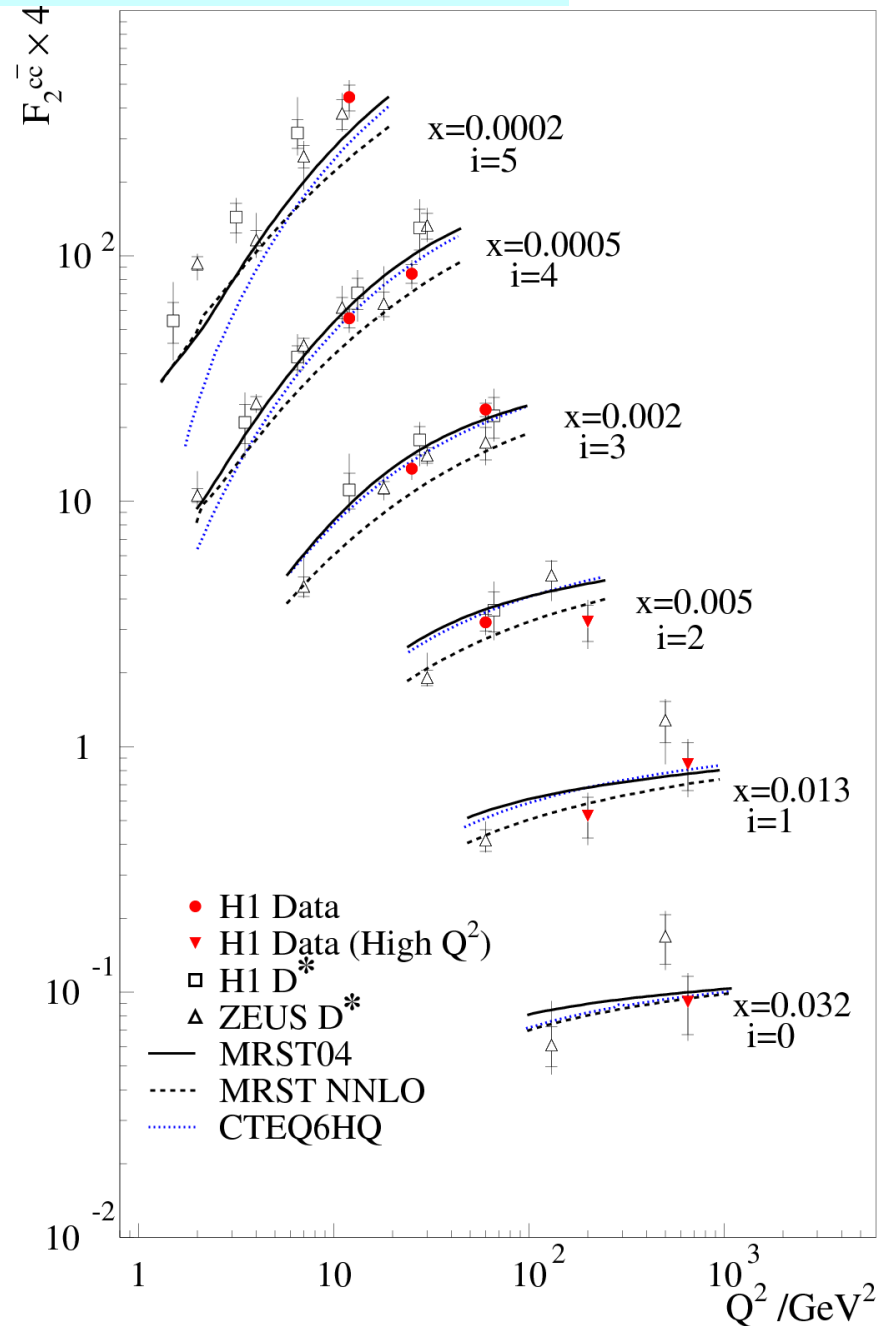
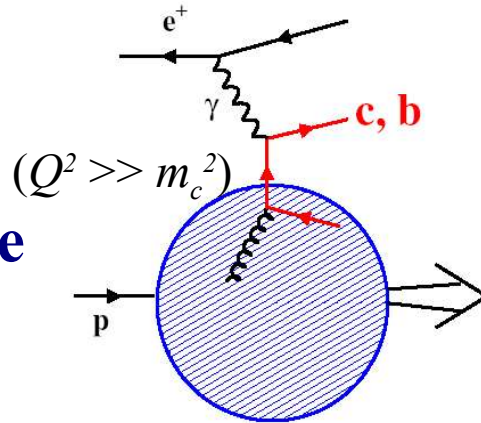
$F_2^{q\bar{q}}$ measurement allows to

test/constrain the proton gluon density

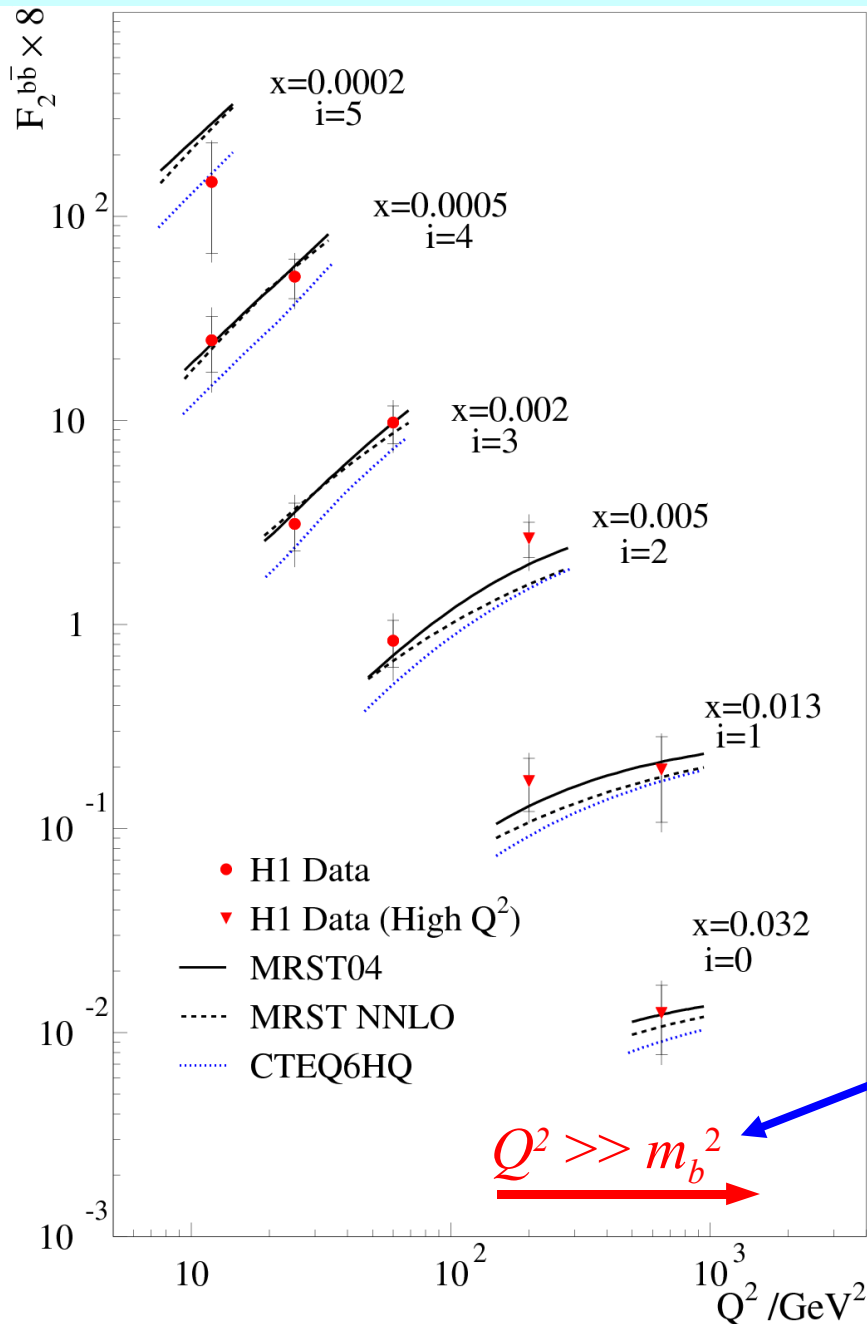


OR

obtain the virtual Charm content of the proton



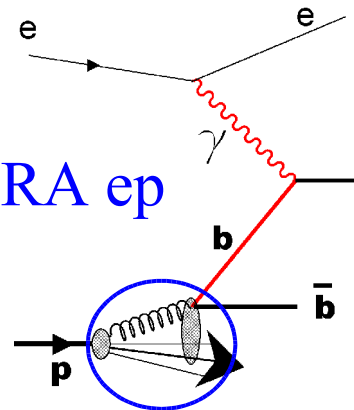
$F_2^{q\bar{q}}$ in DIS at low and high Q^2 - Beauty



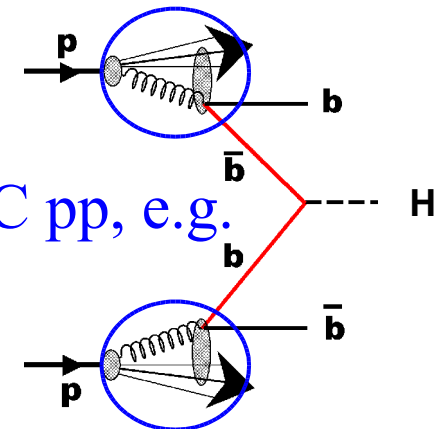
$$F_2^{b\bar{b}}(x, Q^2)$$

- first measurement
- scaling violation steeper at lower x
- **data are described well by VFNS (massive \oplus massless) NLO calculations**

HERA ep

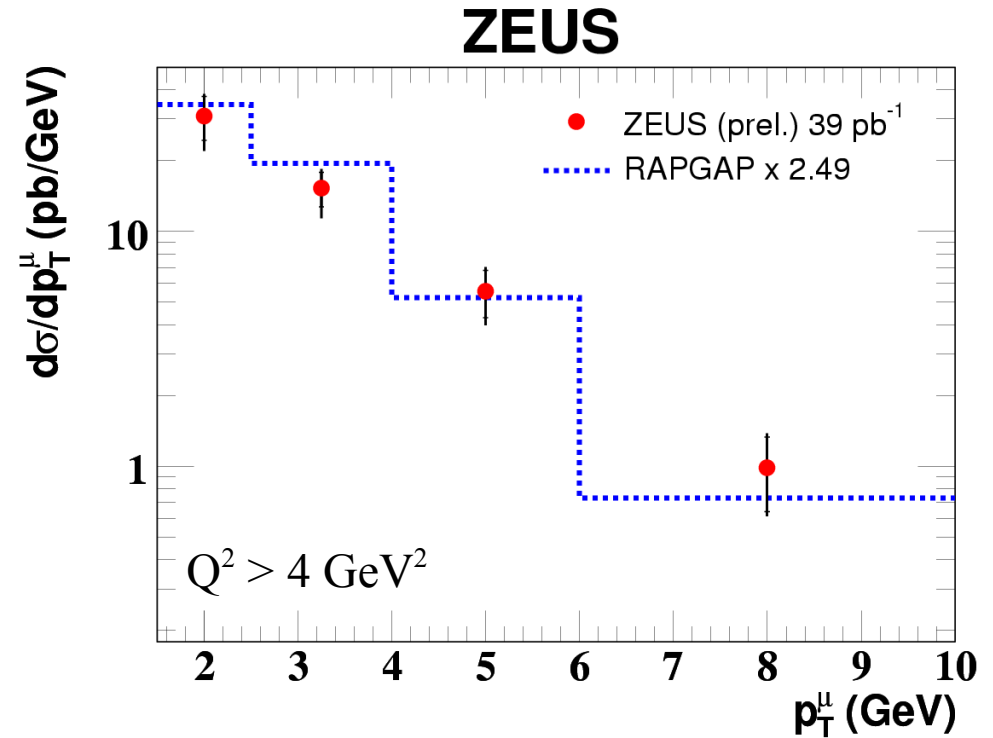
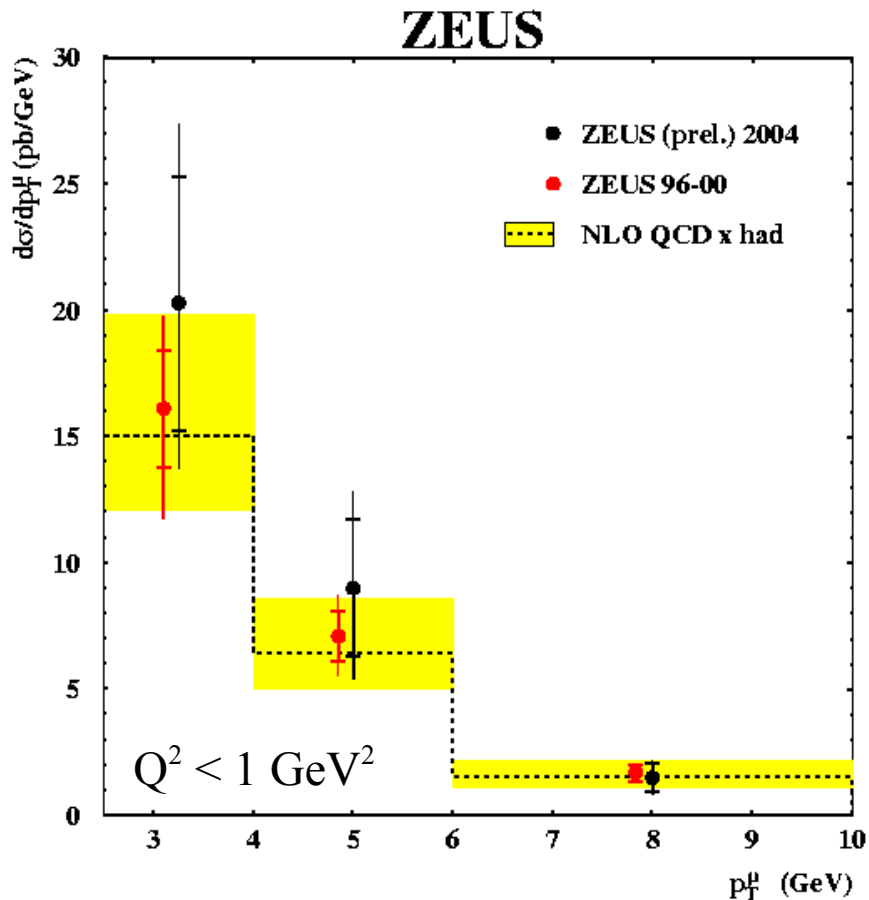


LHC pp, e.g.



Beauty with μ +jet, HERA II

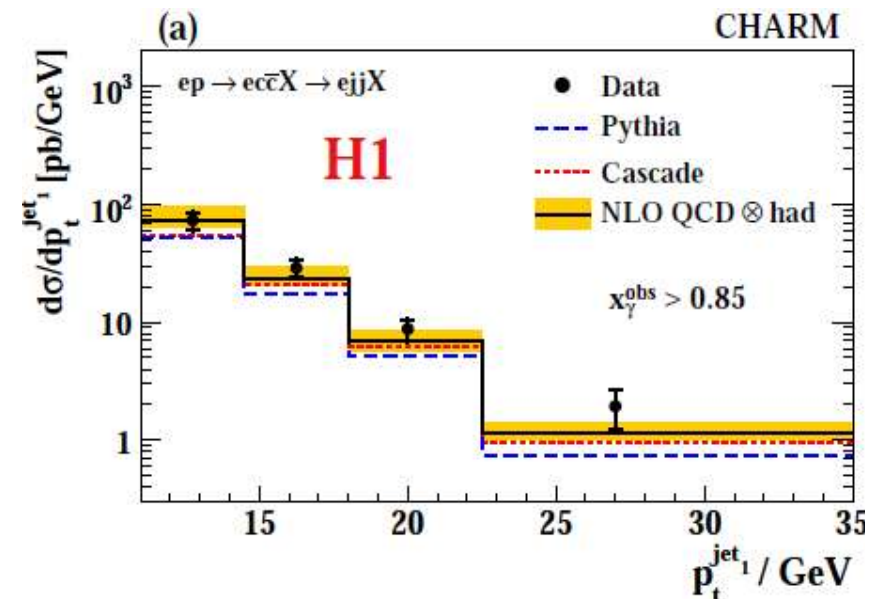
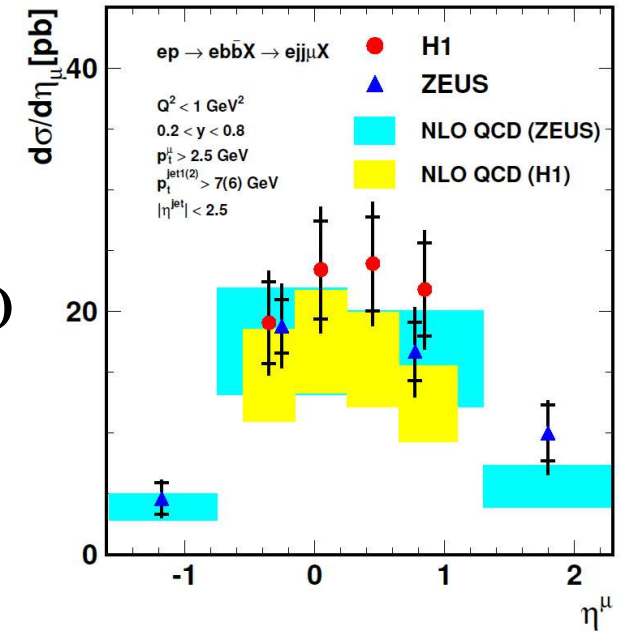
- Preliminary Beauty p_t^{rel} (+ δ) results:
 - small fraction of HERA II data
 - jet+muon: p_t^{rel} as well as $p_t^{rel} + \delta$



- Outlook:
 - Improve by \sim order of magnitude.
 - New double differential measurements possible, as well as extraction of $F_2^{b\bar{b}}$

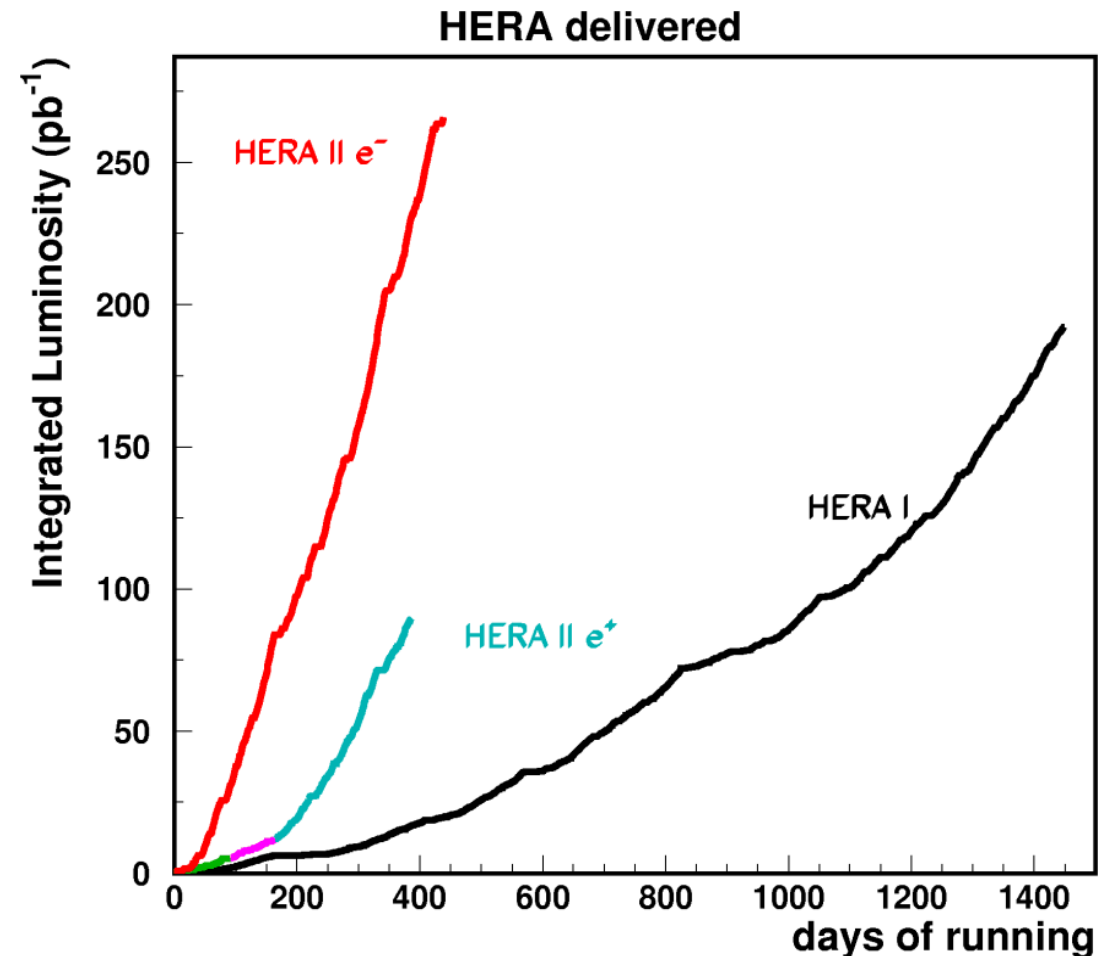
Summary

- H1 and ZEUS heavy flavour measurements agree
- Beauty and Charm data in general agreement with NLO
- Beauty data partially slightly higher
- inclusive γp impact parameter measurements in good agreement with NLO prediction
- Beauty and Charm contribution to proton structure $F_2^{\bar{c}c/\bar{b}b}$ measured
 - well described by NLO



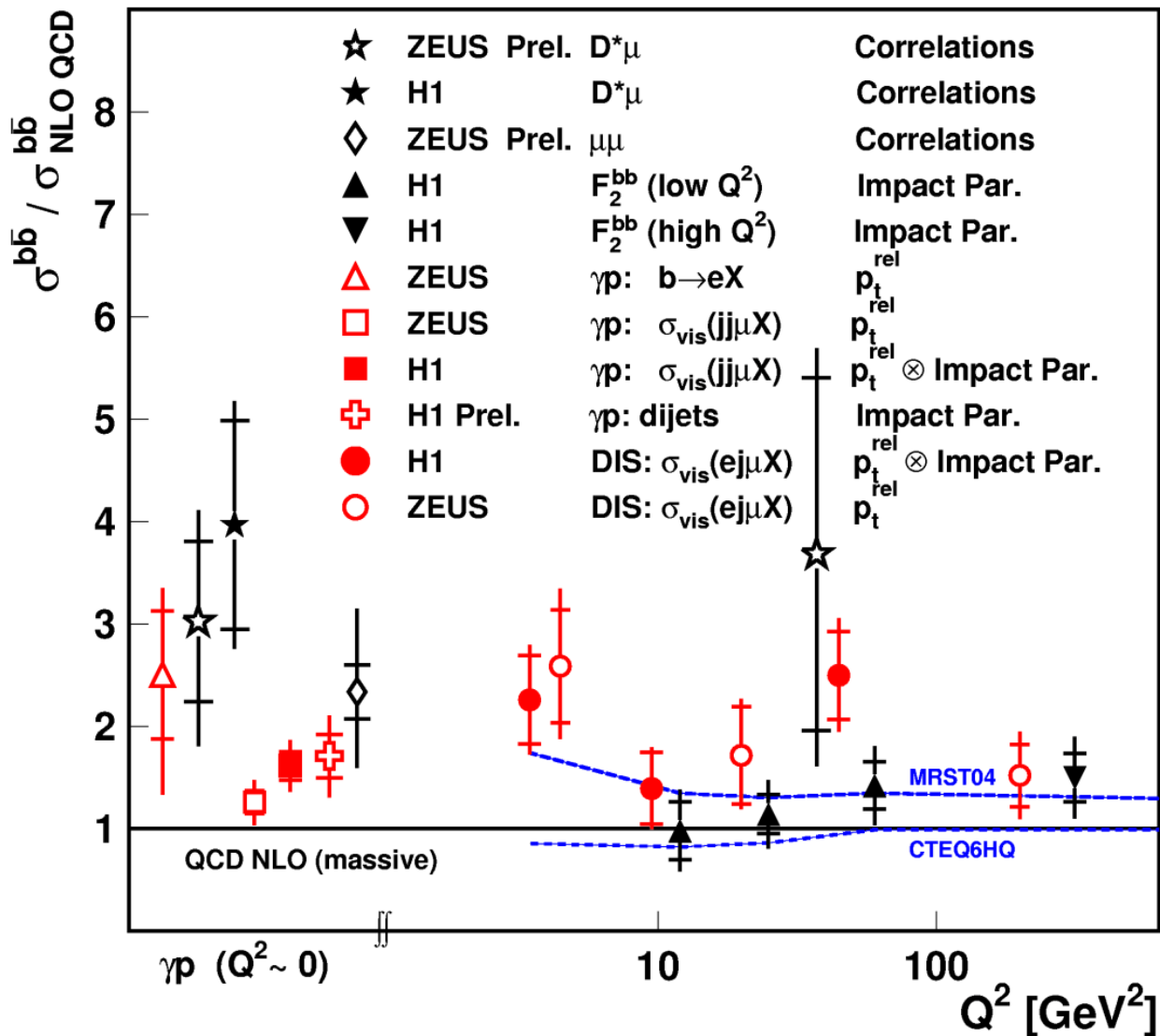
Outlook

- **HERA II is running smoothly**
 - already accumulated more data than during HERA I
- **upgraded detectors performing well**
- **expect higher precision results.**



backup slides follow

Backup: Data - NLO ratio



This is just a rough comparison. Q^2 is not the driving scale in the whole range!

Main caveats:

- NLO has been extrapolated to hadron level using different approaches
- NLO has been calculated for different sets of scales and parameters, same for the uncertainty
- Cross section definitions and kinematic ranges somewhat different