Heavy Flavour Physics at HERA

HADRON'03

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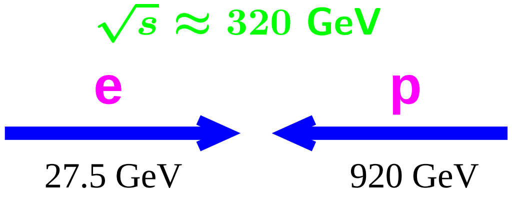
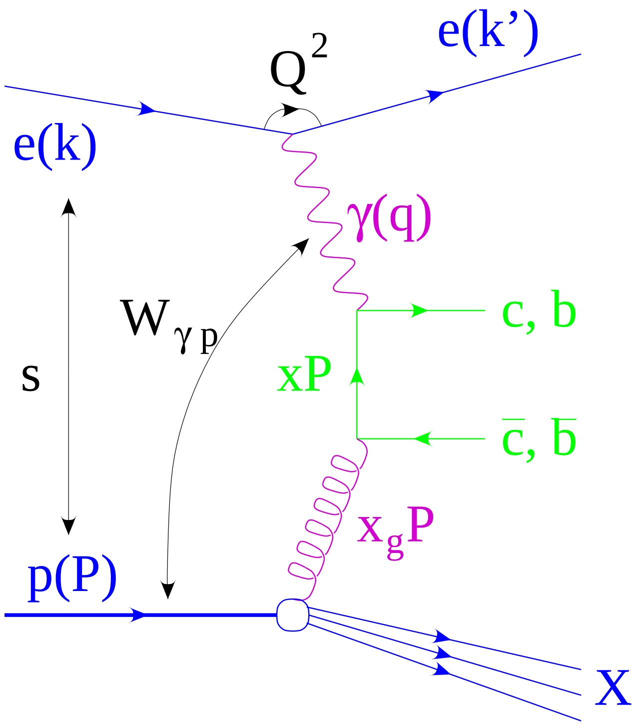
Introduction, theoretical Framework

- Charm Tagging, Fragmentation
- Charm (+jets) in DIS
- Charm (+jets) in Photoproduction
- Charmonium
  (not covered here)
- Beauty Tagging
- Beauty (+jets) in DIS and Photoproduction
- $D^* - \mu$ correlations
- Summary

HERA - Kinematics



Leading Order Picture:



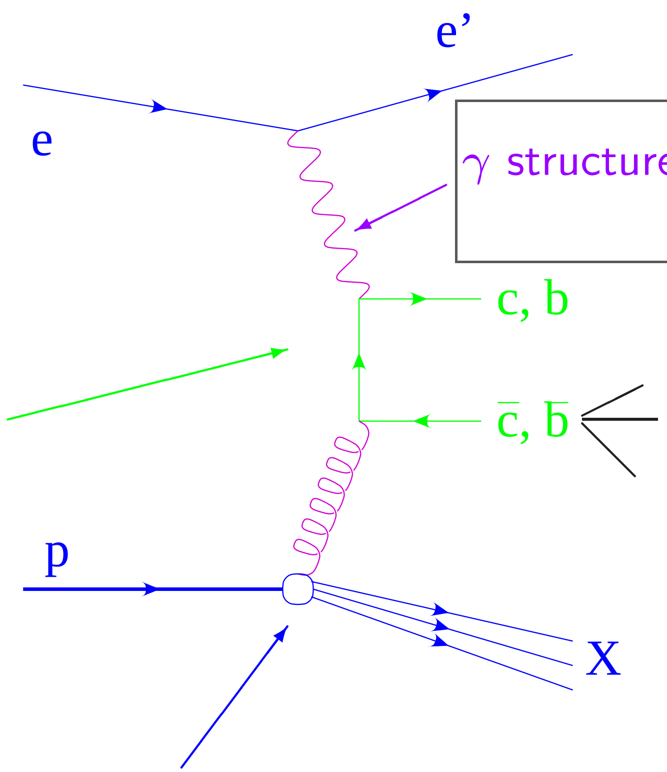
$s = (k + P)^2$
$\sqrt{s}$: **Center of mass energy**
$Q^2 = -(k - k')^2$: **Virtuality of** γ
y : **Relative energy loss of the** e **in the rest frame of the** p **(Inelasticity)**
x (x_g) : **Fraction of the parton (gluon) of the total p-momentum in the QPM**
$W_{\gamma p}$: **Center of mass energy of the** γp **system**

Two kinematic regimes:

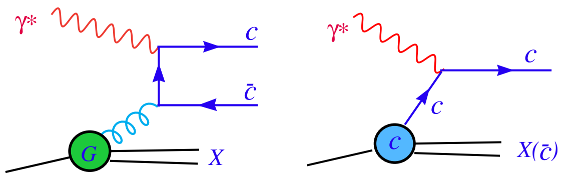
- ◇ $Q^2 \to 0$ GeV^2: Photoproduction (γp)
- ◇ $Q^2 > 2$ Gev^2: Electroproduction (DIS)

Heavy Flavour: Probing of QCD

Factorization Ansatz: p structure $\otimes$ Pert. QCD $\otimes$ γ structure $\otimes$ fragmentation



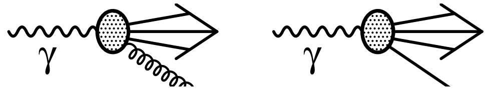
Pert. QCD:



$— \mu^2 \uparrow \rightarrow$

◇ Multi scale problem:
m_Q, p_T, Q^2, E_T^{jet}

γ structure:

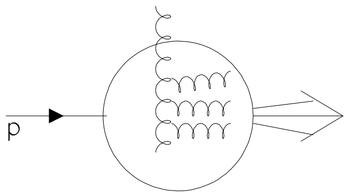


◇ Charm excitation

Fragmentation

◇ Universality

p structure:



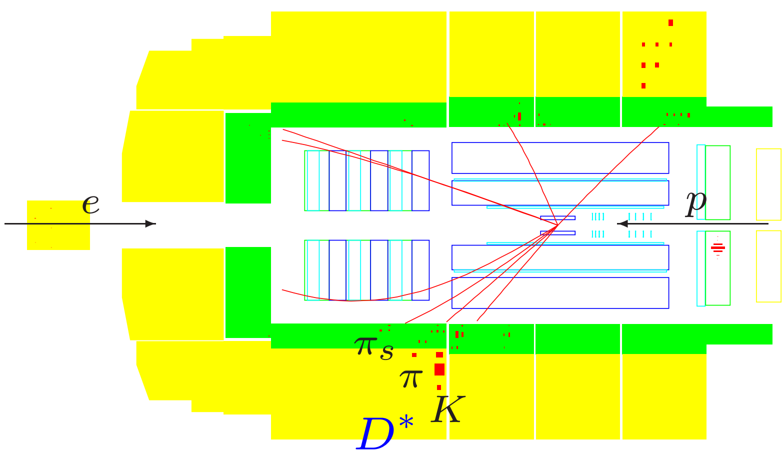
◇ Structure functions: F_2, F_2^c

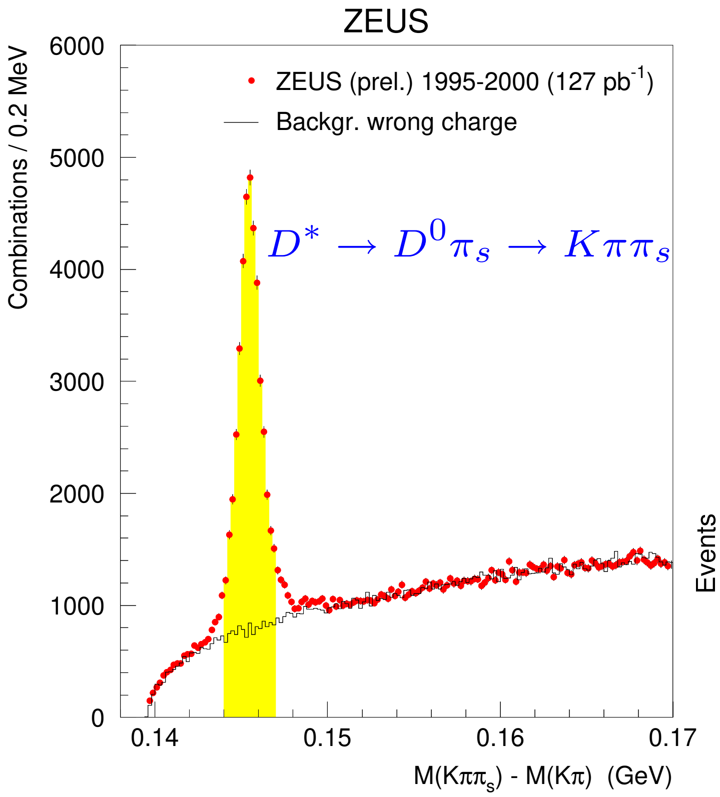
◇ Parton densities in p

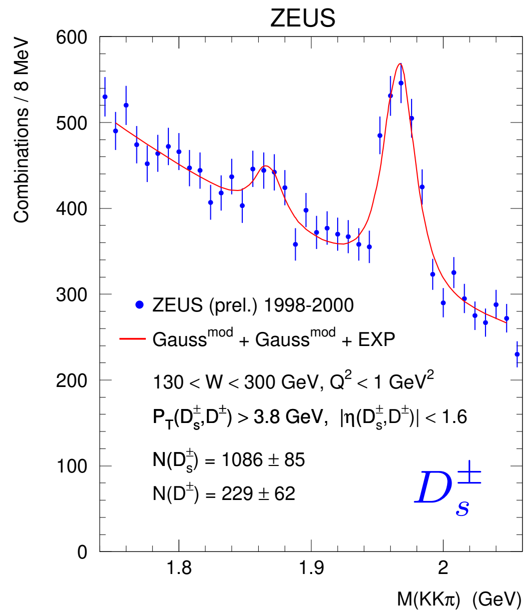
◇ Evolution models: DGLAP, BFKL, CCFM
(evolution in Q^2, evol. in x, unification)

Charm Tagging

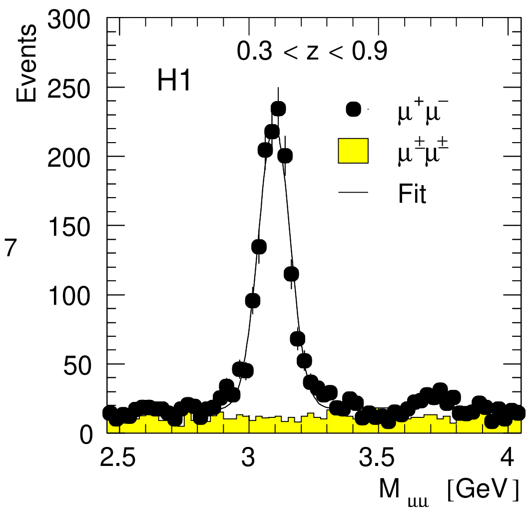
H1 Detector







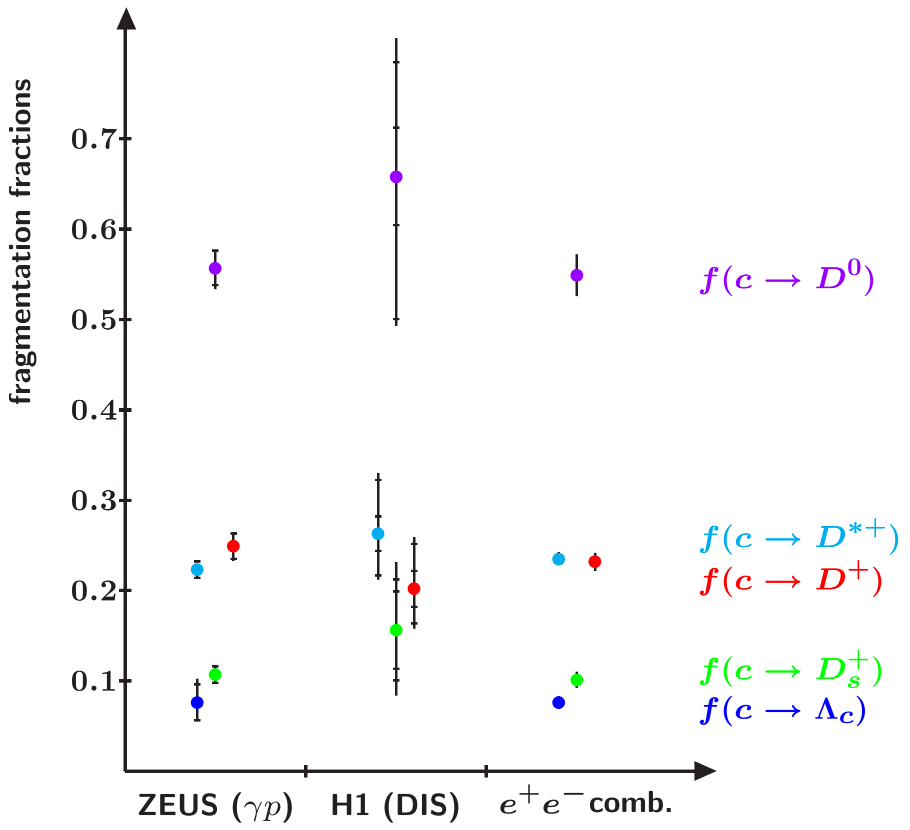
$J/\Psi \to \mu\mu$: not covered



Charm Fragmentation

Reconstruct all charm ground states:
$D^{\pm}$, D^0, $D_s^{\pm}$, $D^{*\pm}$, ($\Lambda_c^{\pm}$, ZEUS only)

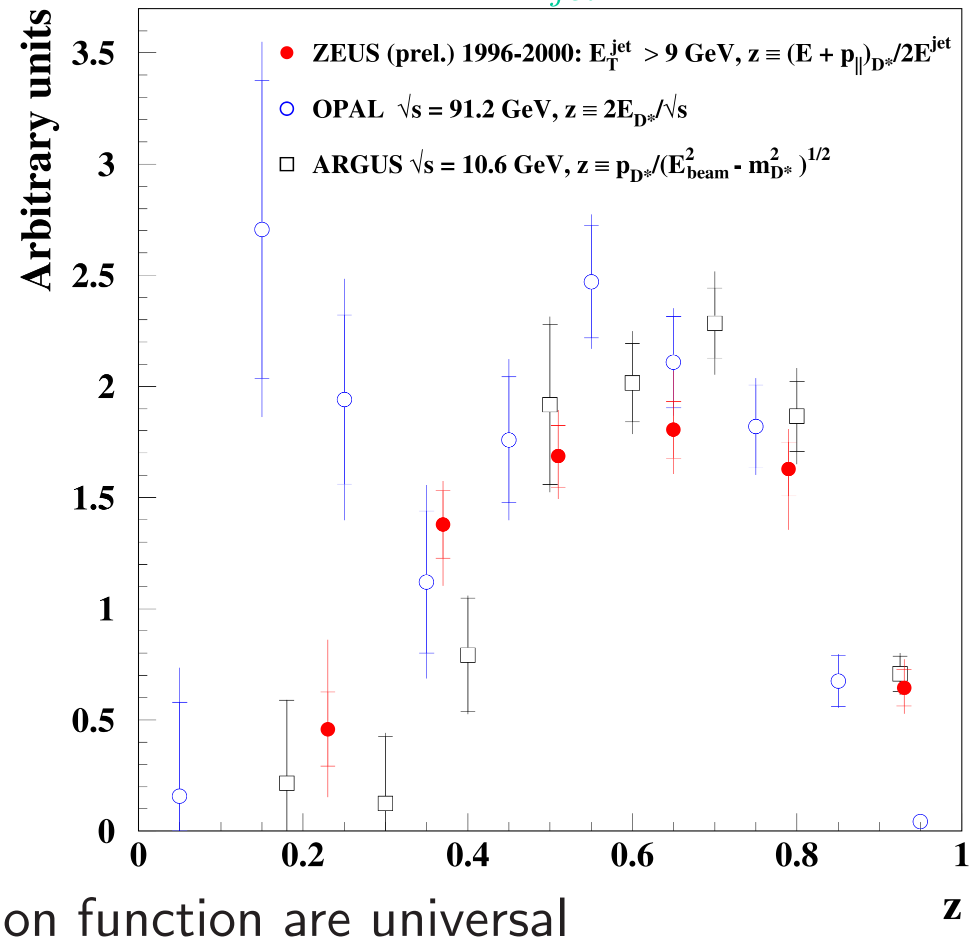
Fragmentation fractions



ZEUS: D^* + jet in γp

◇ $p_T^{D^*} > 2$ GeV, $E_T^{jet} > 9$ GeV, $|\eta^{jet}| < 2.4$

$$z = \frac{(E+p_{||})^{D^*}}{2E_{jet}}$$



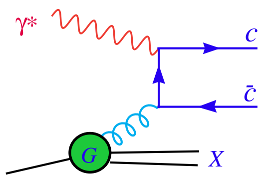
◇ Fragmentation fractions and fragmentation function are universal

Modelling Heavy Quark Production

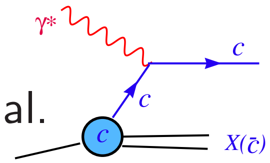
pQCD calculations in NLO:

(DGLAP evolution used)

- ◇ Fixed order *massive* scheme
  ($\mu^2 \approx m_Q^2$)
  γp: FMNR (Frixione et al.)
  DIS: HVQDIS (Harris et al.)



- ◇ *Massless* scheme
  ($\mu^2 >> m_Q^2$)
  γp: Cacciari et al., Kniehl et al.



- ◇ *Matched* scheme (FONLL)
  Cacciari et al.

MC generators:

(LO matrix element + parton showers)

DGLAP evolution:

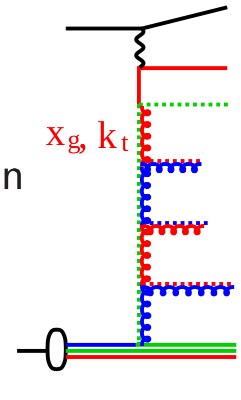
- ◇ Aroma: direct only
- ◇ Pythia, Rapgap, Herwig: direct + resolved

CCFM evolution:

- ◇ Cascade: direct; but contains implicitly contributions from c out of the photon

Differences:

- ◇ CCFM: no ordering in k_T required
- ◇ Gluon density and hard cross section are k_T dependent in CCFM model
- ◇ Evolution phase space larger for CCFM



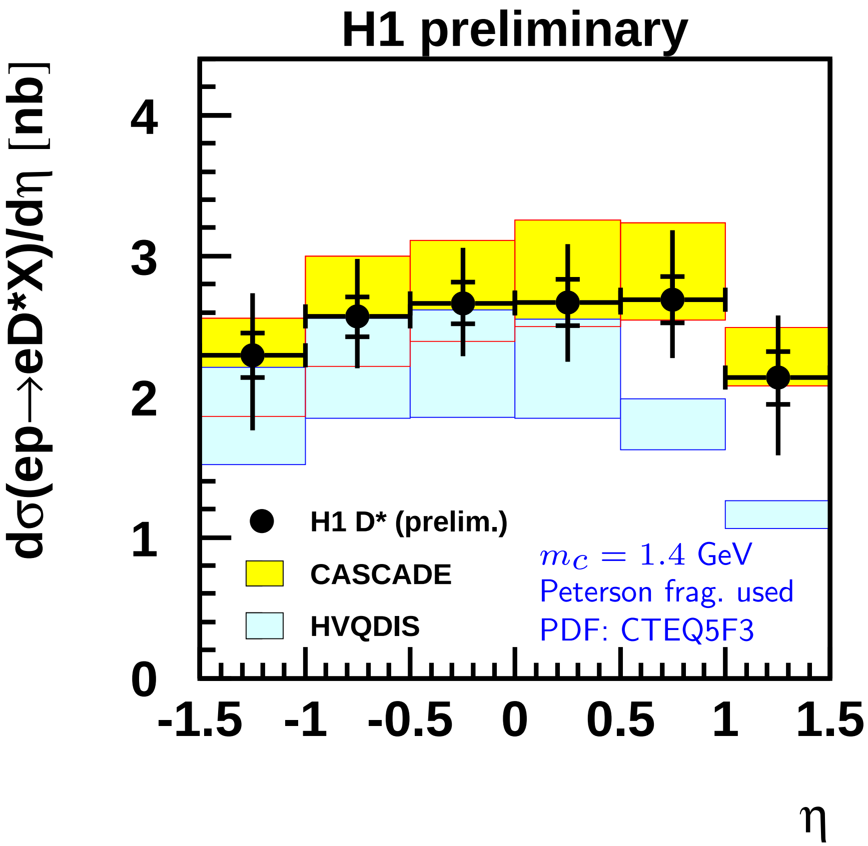
D^* in DIS

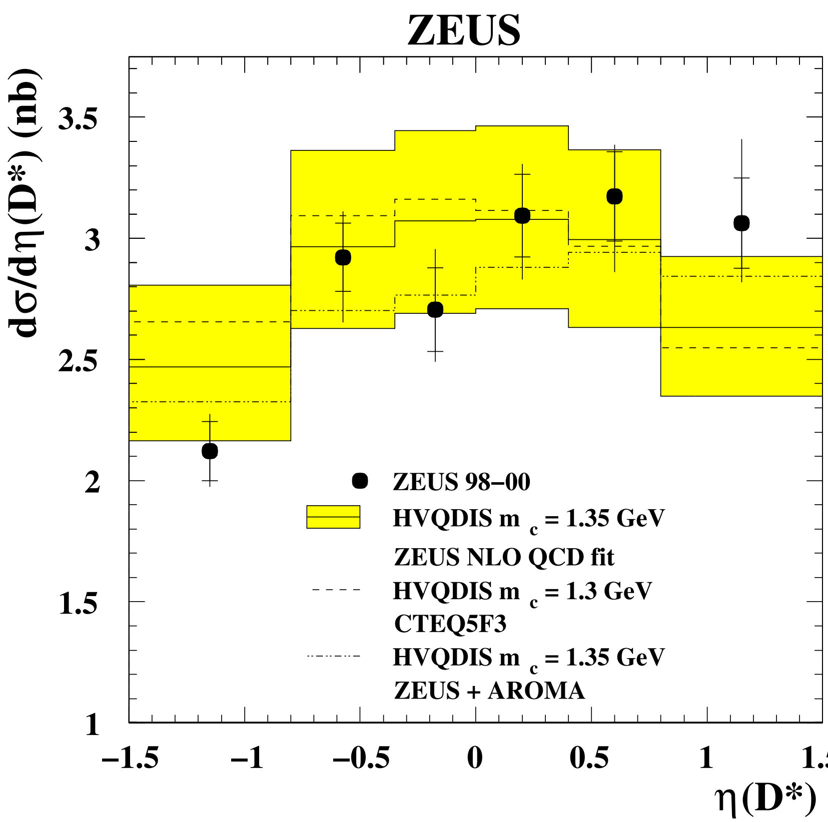
H1: $99e^+/00$, $\mathcal{L} = 47.0$ pb^{-1}

◇ $1.5 \le p_{t,D^*} \le 15$ GeV, $|\eta_{D^*}| \le 1.5$
$2 \le Q^2 \le 100$ GeV^2, $0.05 \le y \le 0.7$

ZEUS: $98-00$, $\mathcal{L} = 82$ pb^{-1}

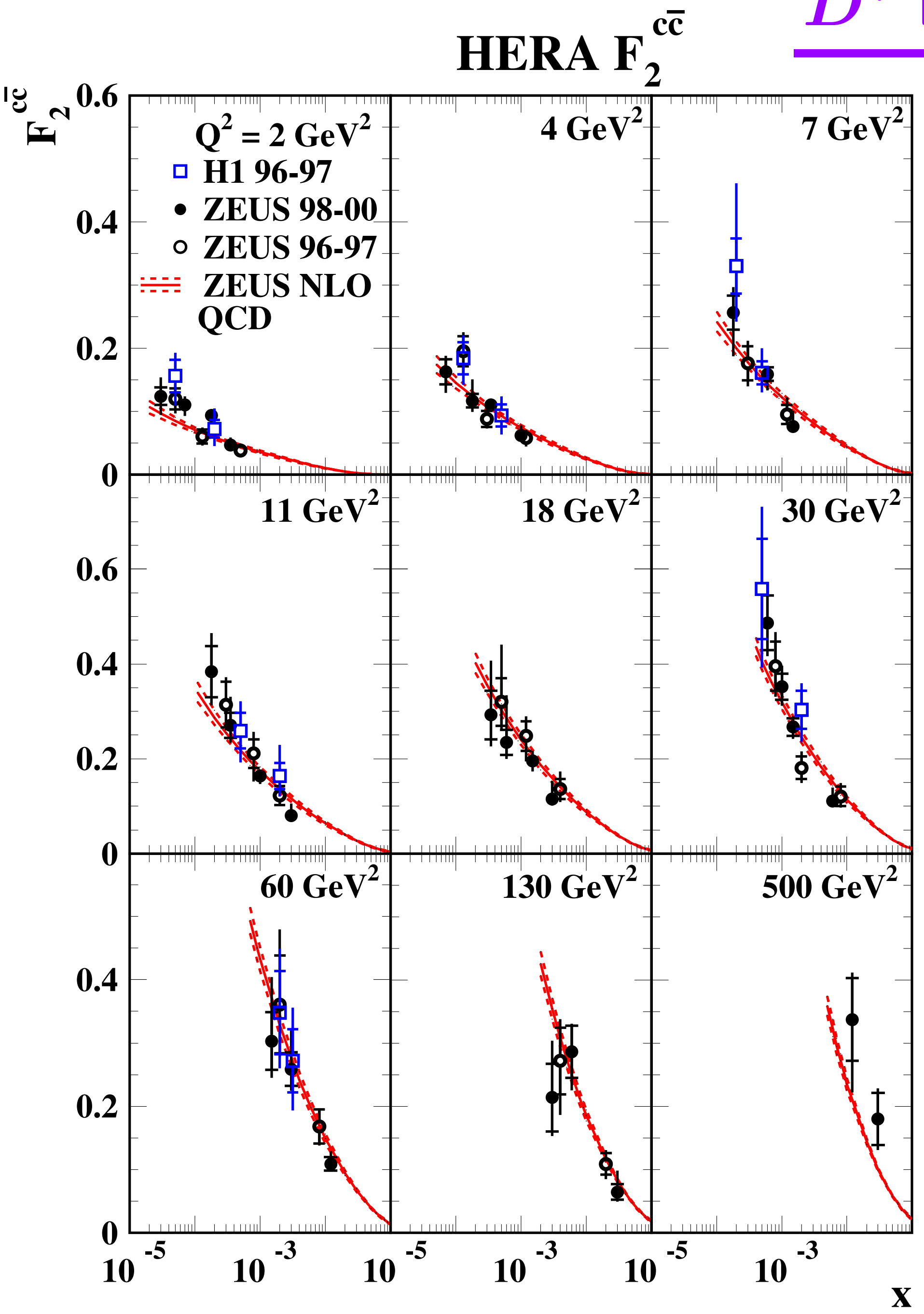
◇ $1.5 \le p_{t,D^*} \le 15$ GeV, $|\eta_{D^*}| \le 1.5$
$1.5 \le Q^2 \le 1000$ GeV^2, $0.02 \le y \le 0.7$





◇ H1 and ZEUS data are consistent but small differences in theoretical interpretation

D^* in DIS: F_2^c



ZEUS: $1.5 < Q^2 < 1000$ GeV^2, $0.02 < y < 0.7$,
$1.5 < p_T^{D^*} < 15$ GeV, $|\eta_{D^*}| < 1.5$

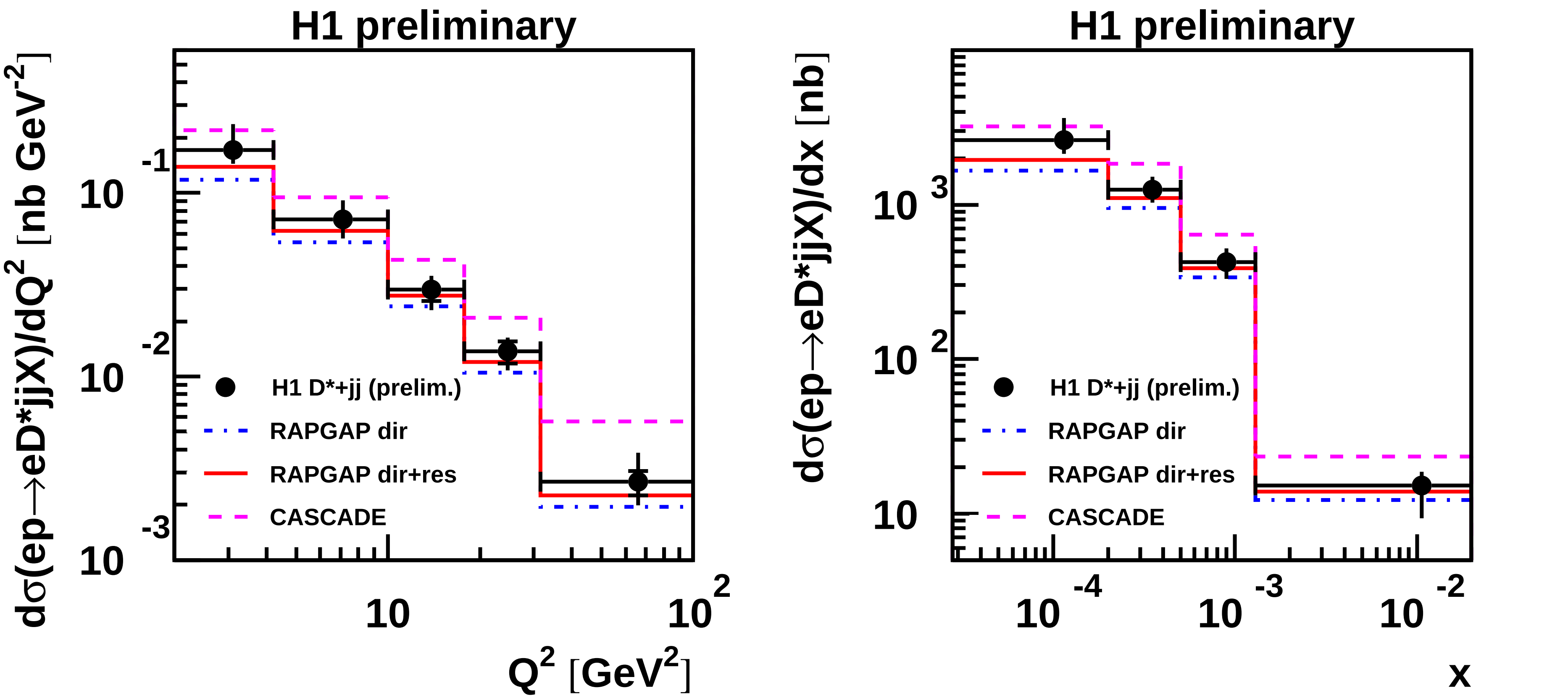
$$\boxed{\frac{d^2\sigma^{c\bar{c}}}{dx\,dQ^2} = \frac{2\pi\alpha^2}{xQ^4} \cdot \left(1 + (1-y)^2\right) \cdot F_2^{c\bar{c}}(x, Q^2)}$$

- Data extended to higher Q^2; Increased precision
- Measure D^* cross section in restricted kinematic range
  $\longrightarrow$ model dependent due to extrapolation

- ZEUS and H1 data are consistent
- Agreement between data and ZEUS NLO QCD fit over a wide rang in Q^2 and x
- Prediction of charm contribution to F_2 from scaling violations is consistent with F_2^c measurement

D^* + jet in DIS

H1: $D^* + 2$ jets; $E_t^{jet} \geq 3, 4$ GeV, $-1 \leq \eta_{lab\,jet\,1,2} \leq 2.5$



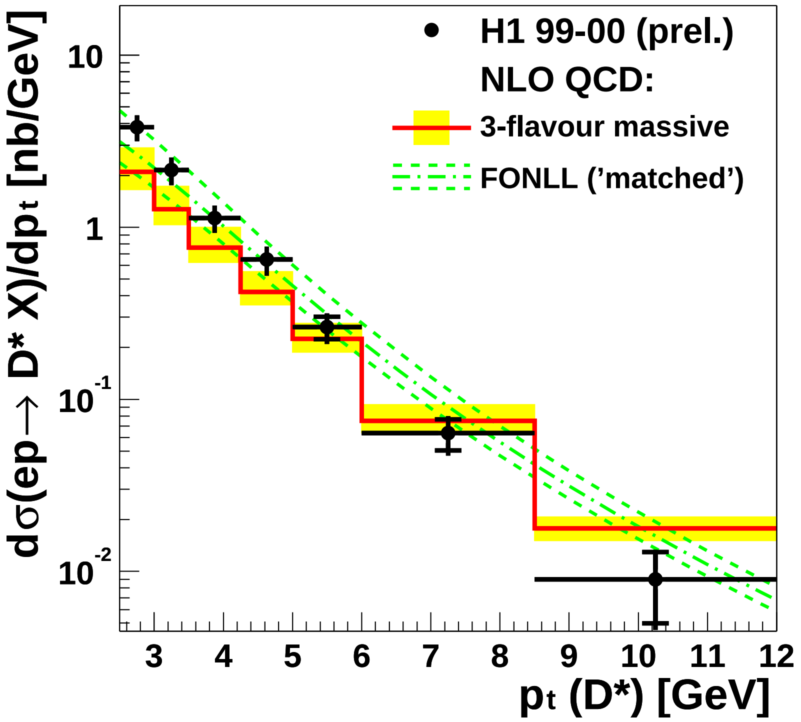
- ◇ Cascade (CCFM) above data, describes inclusive D^* (H1)
- ◇ Direct Rapgap (LO+PS,DGLAP) below data, improves with resolved component, direct + resolved is often above data for inclusive D^* (H1, not shown)

D^* in Photoproduction

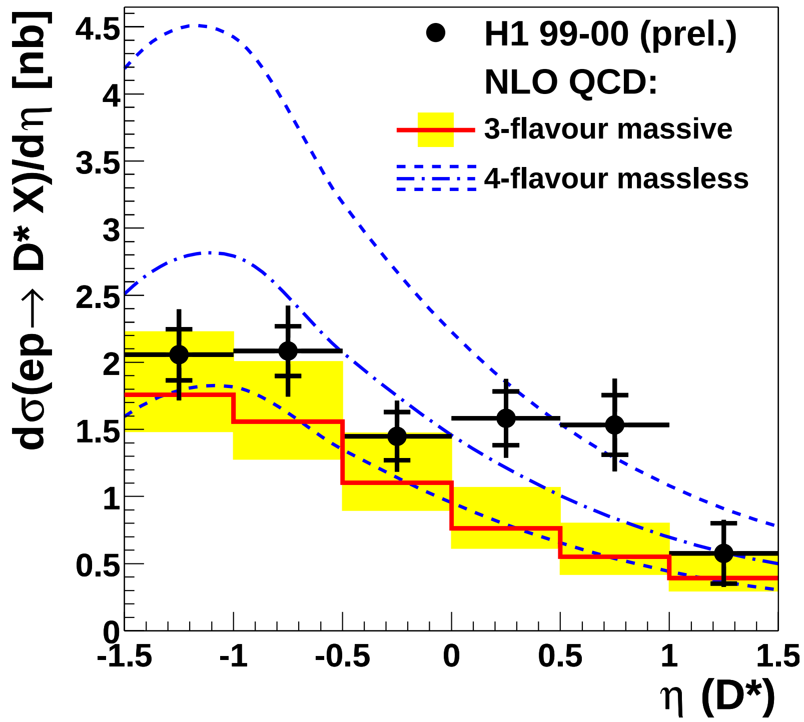
H1: D^* + tagged electron, $\mathcal{L} = 49$ pb^{-1}

◇ $Q^2 < 0.01$ GeV^2, $171 < W_{\gamma p} < 256$ GeV, $p_T^{D^*} > 2.5$ GeV, $|\eta_{D^*}| < 1.5$

p_T: massive versus matched



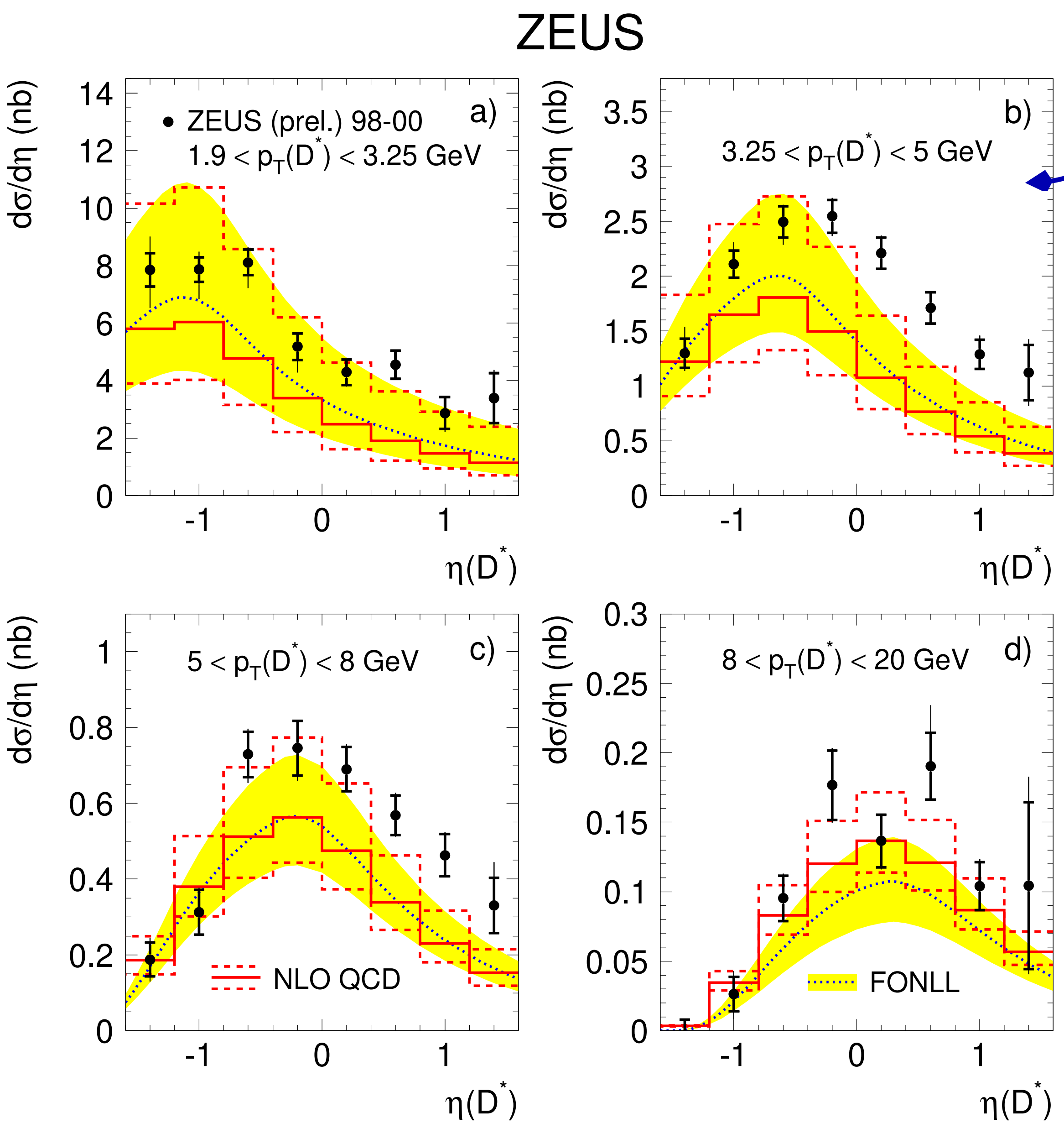
η: massive versus massless



◇ Massive NLO below data; Massless NLO reasonable agreement; FONLL matched calculation reasonable in p_T

◇ Theories have larger errors than data → Improvements on theory side are needed

D^* in γp: Double Diff. Cross Sections



η distributions in bins of p_T

ZEUS: No electron tag

- 98-00, $\mathcal{L} = 79$ pb^{-1}
- $Q^2 < 1$ GeV^2, $130 < W_{\gamma p} < 280$ GeV
- $p_T^{D^*} > 1.9$ GeV, $|\eta_{D^*}| < 1.6$

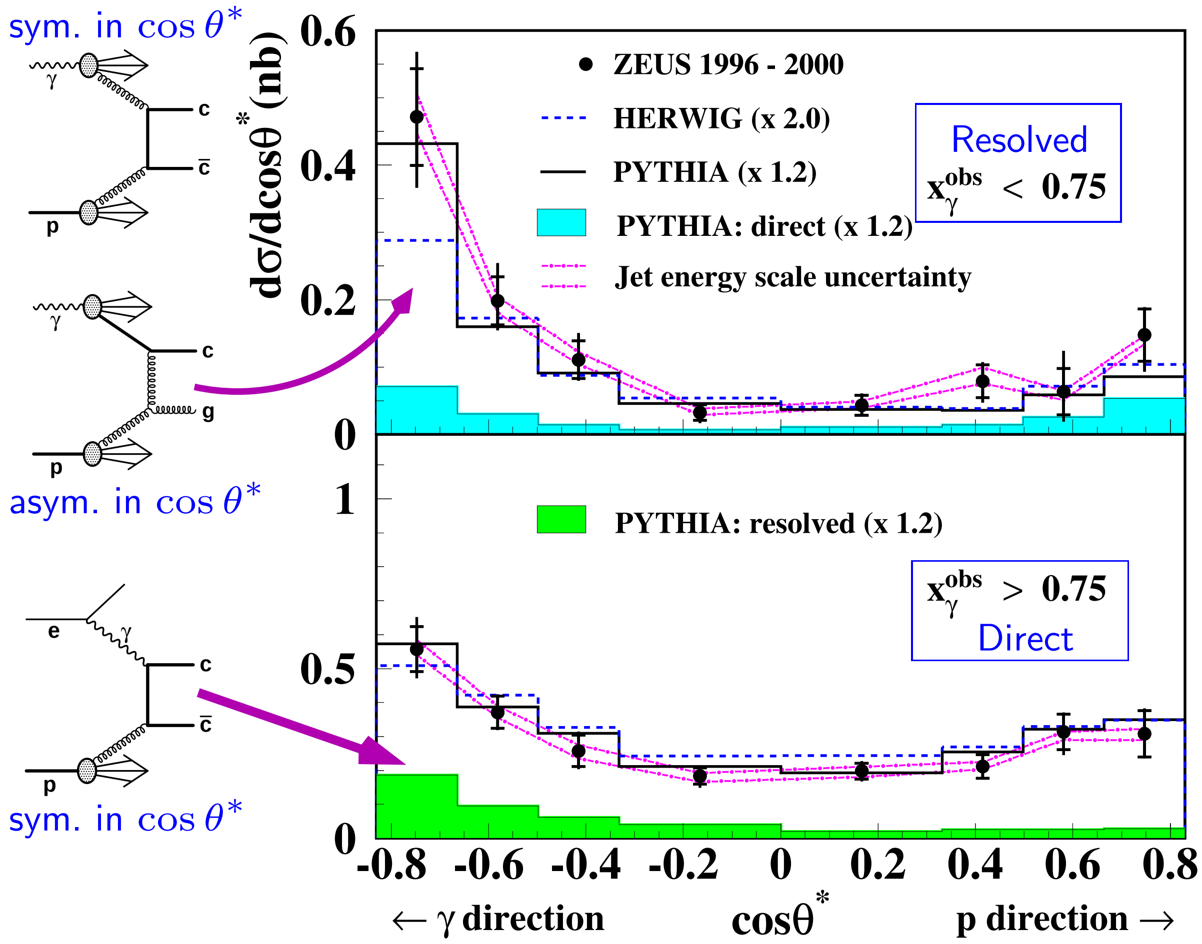
- NLO below data at medium $p_T^{D^*}$ and high η_{D^*}
- FONLL close to data only at low $p_T^{D^*}$

$\Rightarrow$ Theories are not able to describe all aspects observed in data

Charm: Dijet Angular Distributions in Photoproduction

ZEUS: $D^* + 2$ jets, 96-00, $\mathcal{L} = 120$ pb^{-1}

◇ $p_T^{D^*} > 3$ GeV, $E_T^{jet} > 5$ GeV, $|\eta^{jet}| < 2.4$, $M_{jj} > 18$ GeV



Momentum fraction of photon from jets:

$$x_\gamma^{obs} = \frac{\sum_{j_1,j_2}(E_T^j \cdot e^{-\eta^j})}{2yE_e}$$

θ^*: Angle between proton and D^*-jet (LO)

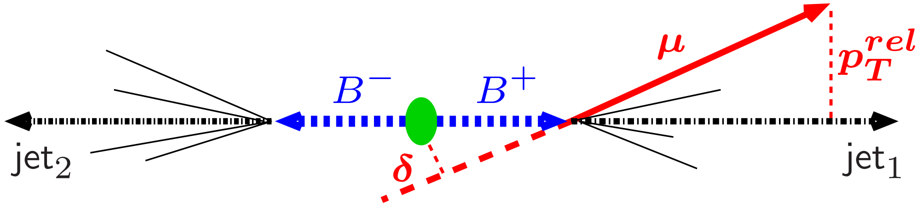
- ◇ Significant resolved contribution ($\approx 40\%$)
- ◇ Evidence for charm as an active flavour in the photon
- ◇ NLO DGLAP o.k. for $x_\gamma^{obs} > 0.75$, but too low for $x_\gamma^{obs} < 0.75$ (not shown)
- ◇ CCFM o.k. in shape but too high in cross section (not shown)

Summary Charm Production

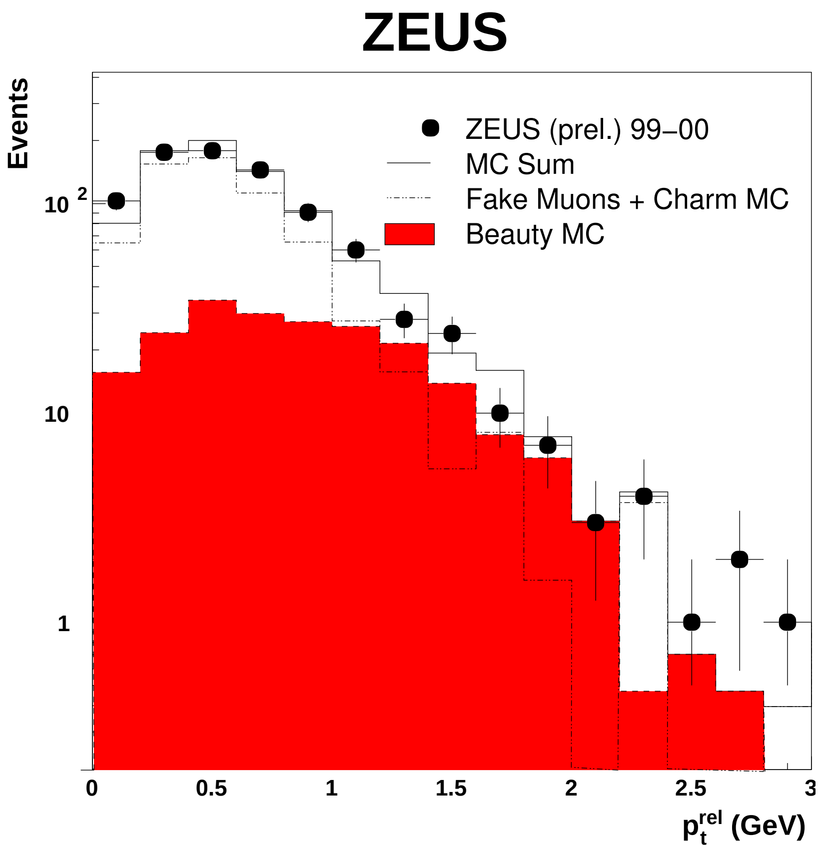
- **Fragmentation fractions and functions:**
  - Fragmentation of charm is independent of the hard physics
- **Electroproduction (DIS):**
  - D^*, QCD models still have some problems to describe data
  - Agreement in F_2^c between data and NLO QCD fit over a wide range in Q^2 and x
- **Photoproduction:**
  - NLO QCD has some problems to describe inclusive D^* cross sections
  - Confirmation of large charm content in the photon (LO picture)

Beauty tagging: μ analyses

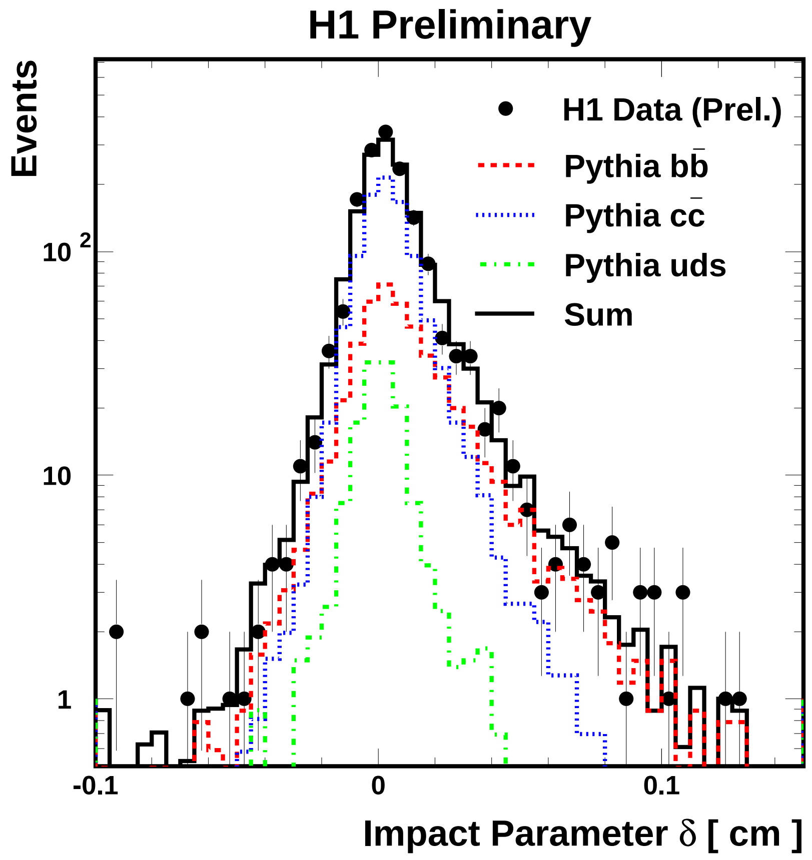
- $\sigma(b\bar{b})$: Factor ~ 200 smaller than $\sigma(c\bar{c})$
- Use semileptonic $b \to \mu$ decays
  $\longrightarrow$ Two separation variables



High B-mass $\Rightarrow p_T^{rel}$



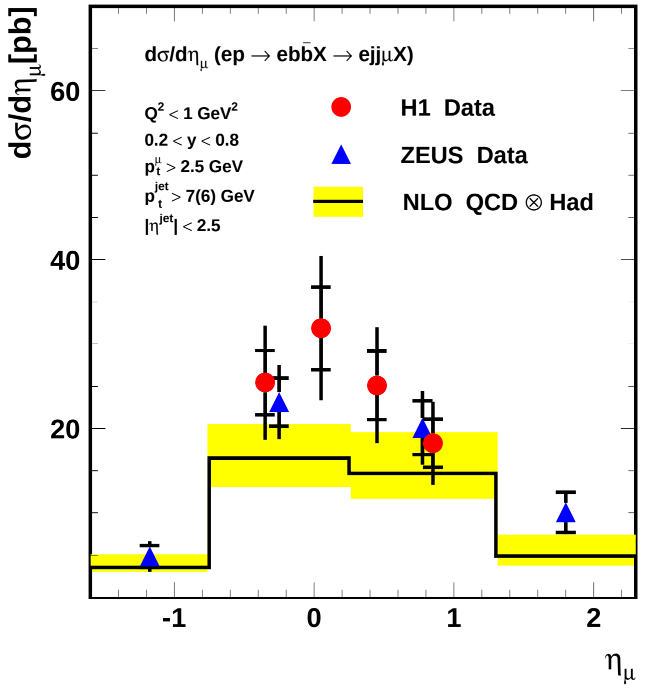
Long B-Lifetime $\Rightarrow \delta$



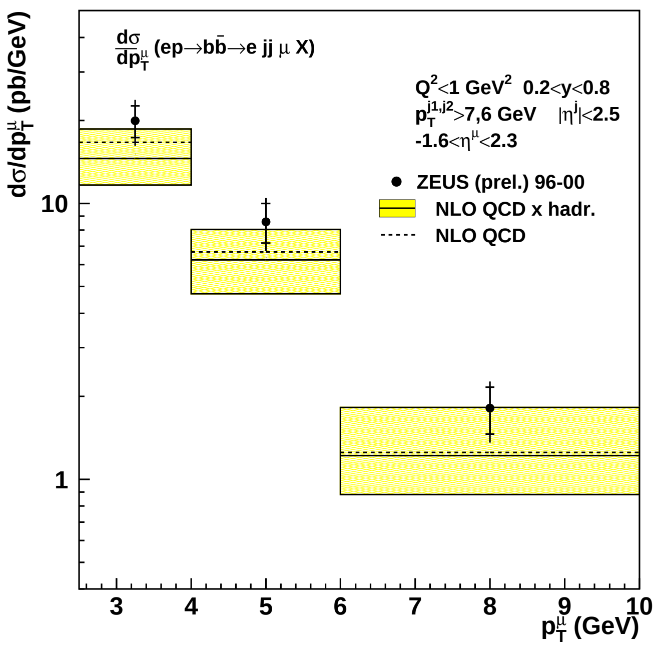
Beauty Production in Photoproduction

ZEUS: p_T^{rel} method ($\mathcal{L} = 98$ pb^{-1}), H1: p_t^{rel} and δ combined ($\mathcal{L} = 48$ pb^{-1})

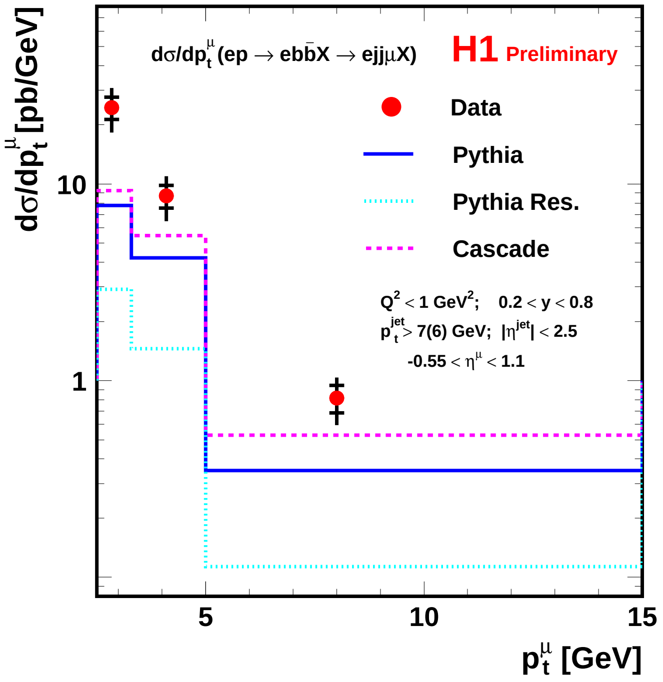
H1,ZEUS: η_μ - comp. with NLO



ZEUS: p_T^μ - comp. with NLO



H1: p_T^μ - comp. with LO+PS



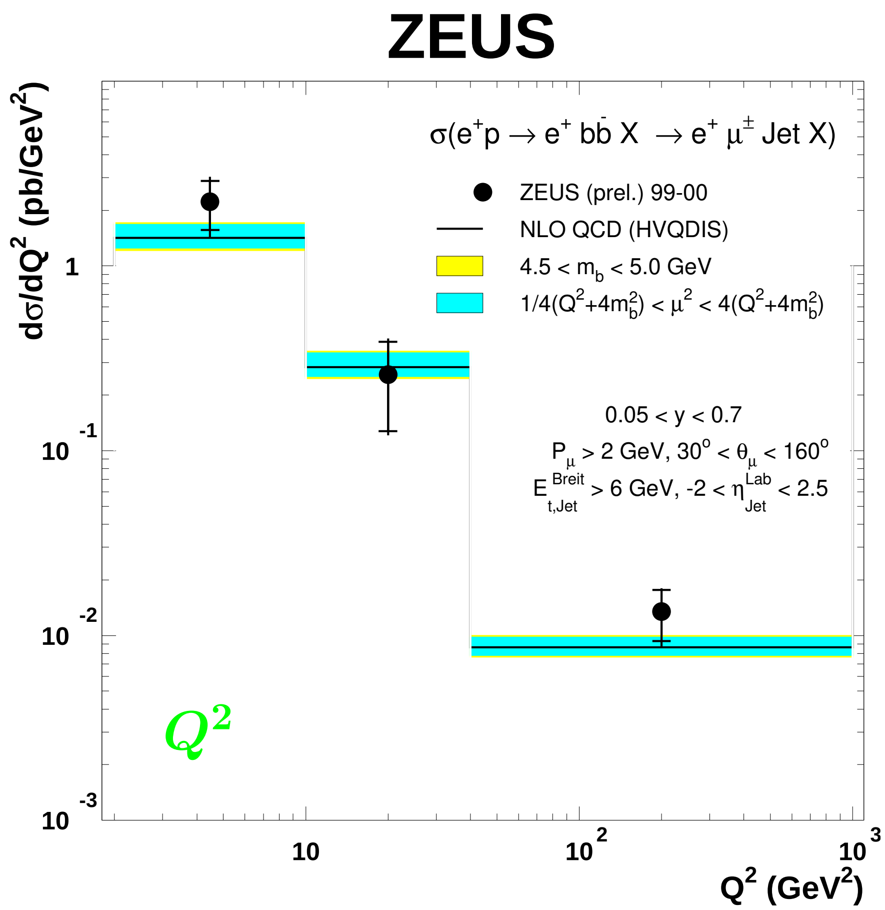
◇ H1 and ZEUS data are consistent

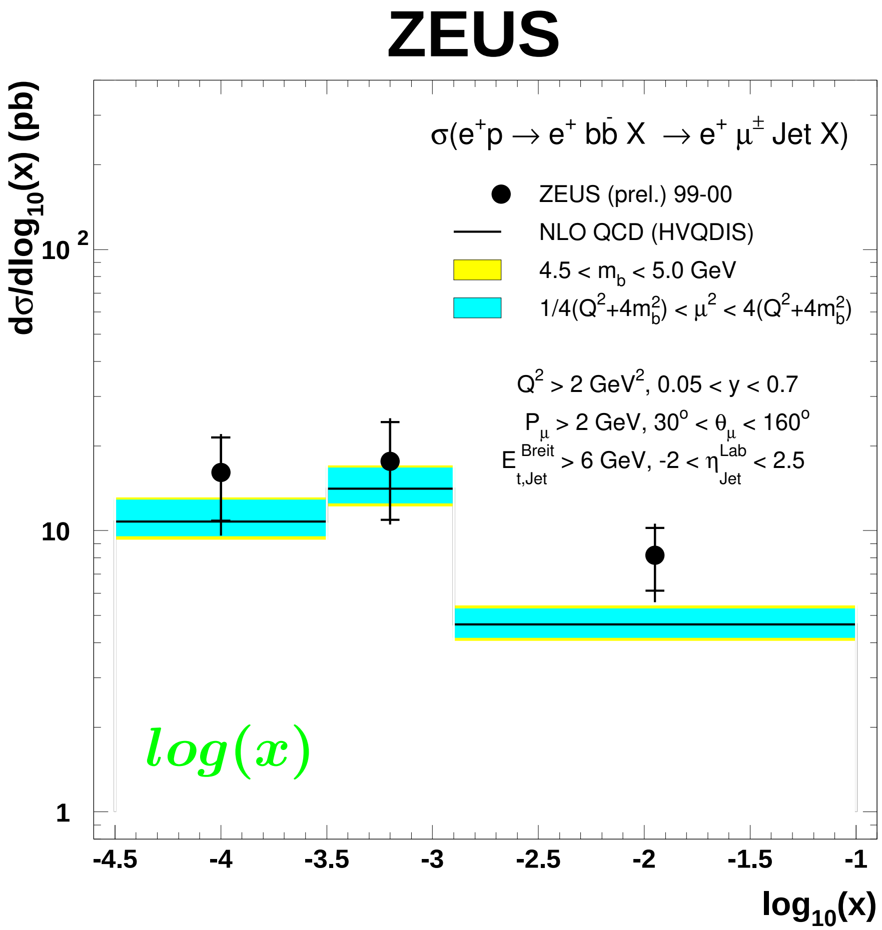
◇ NLO QCD: Normalisation somewhat below data, shapes reasonably well described

◇ LO+PS QCD models: Low in normalisation

Beauty production in DIS

ZEUS ($\mathcal{L} = 60$ pb^{-1}): $Q^2 > 2$ GeV^2, $0.05 < y < 0.7$, $p_T^\mu > 2$ GeV, $E_T^{Breit} > 6$ GeV

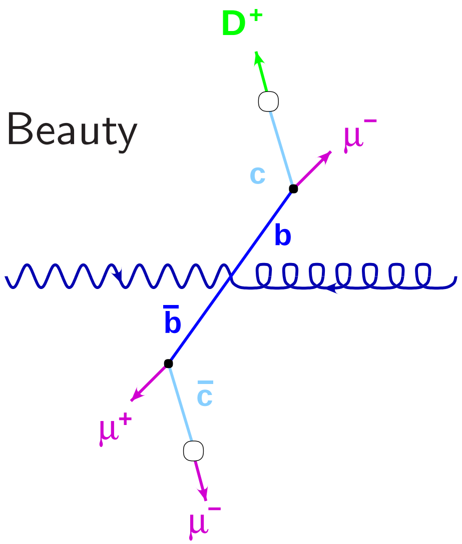




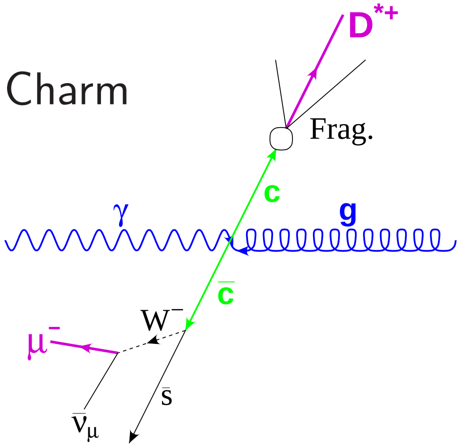
◇ Data and NLO agree

Heavy-Flavour Double-Tag: $D^*\mu$-Correlations

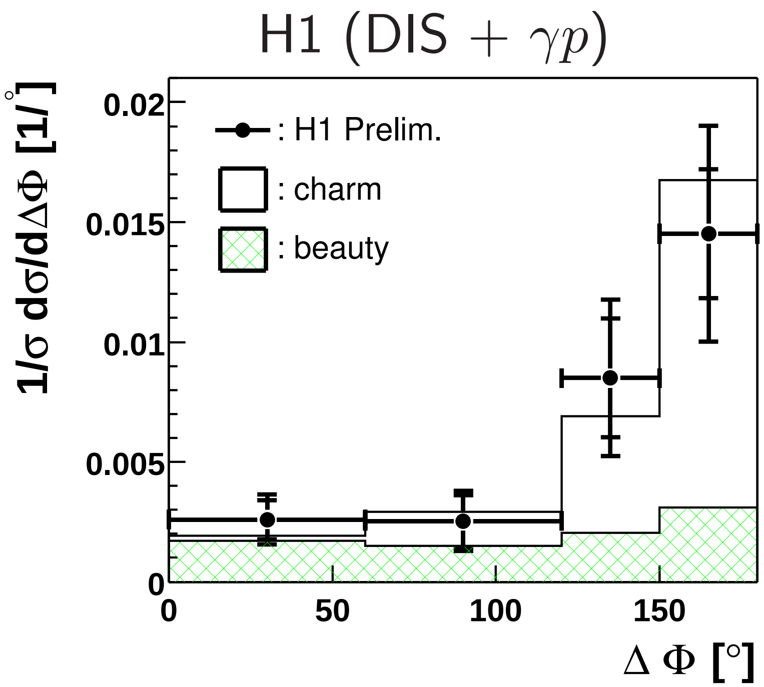
Beauty



Charm



c-b separation using charge and angular correlations

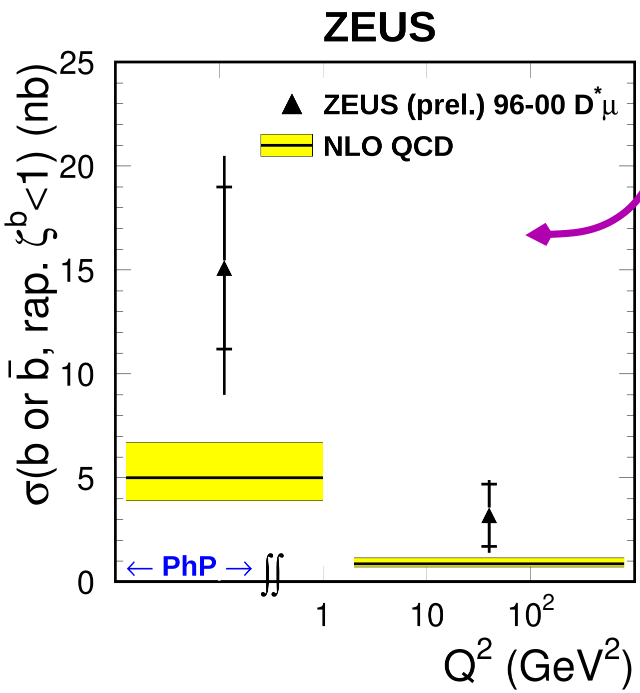


- LO $Q\bar{Q}$ picture:
  $\Delta\Phi = 0°$ (c)
  $\Delta\Phi = 0°$ or $180°$ (b)
- Smearing due to NLO and fragmentation

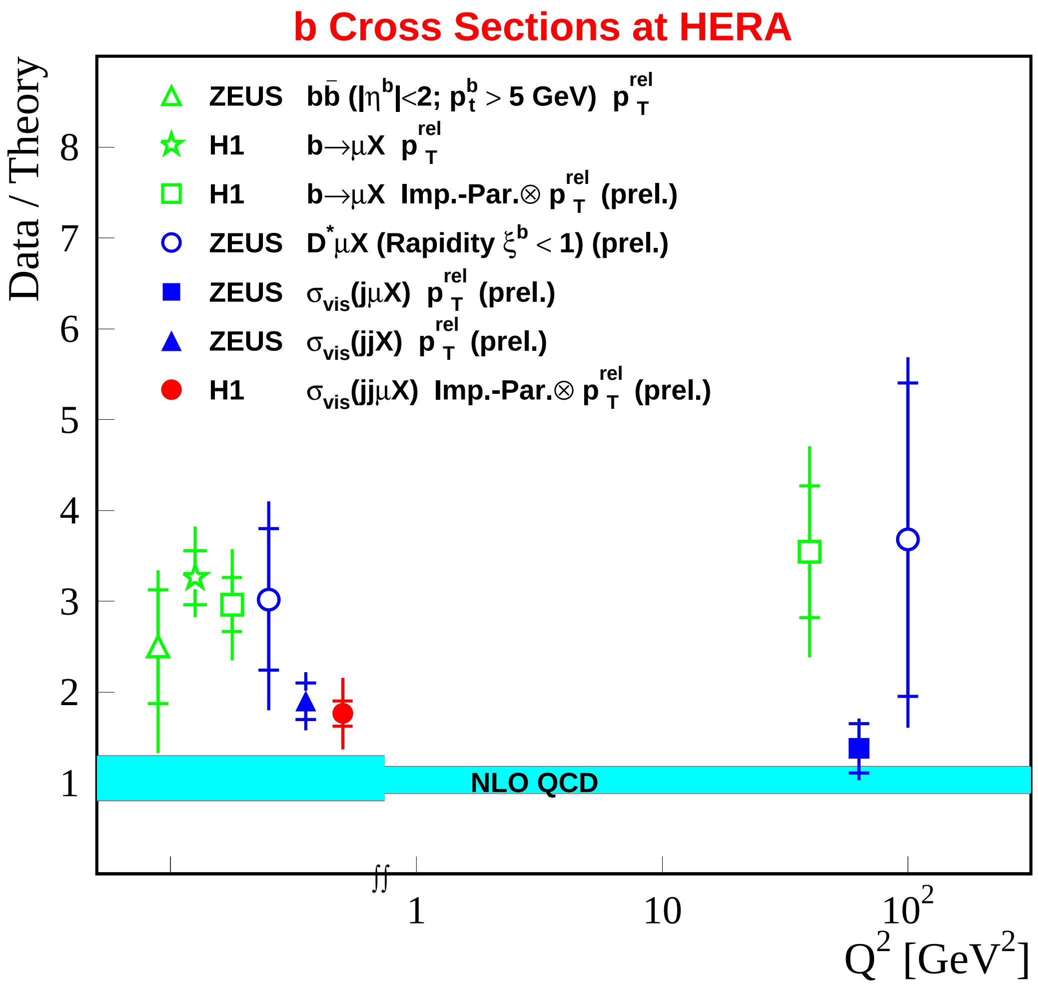
Data $>$ NLO QCD, but large errors

Data versus NLO QCD:

b or $\bar{b}$ cross section



Summary Beauty Production



- New precise differential b-cross section measurements
- H1 and ZEUS data agree
- Data points mostly above NLO QCD predictions:
  - Discrepancies $\lesssim 1.5\ \sigma$ for each measurement
  - New measurements are consistent with older data points, if extrapolated with LO MC
  - Better description towards large Q^2, p_T^μ (?)
- LO+PS QCD predictions too low

Summary and Outlook

- Many new results on the heavy flavours at HERA
- Much more will come:

  $\Rightarrow$ Work is ongoing to finalize analyses on HERA I data

  $\Rightarrow$ First HERAII data coming soon

  - $\triangleright$ Improved detectors (Silicon, trigger,..)

    $\Rightarrow$ New kinematic regions (forward region)

  - $\triangleright$ Increased statistics ($\approx$ factor 5 in luminosity)

    $\Rightarrow$ More precise measurements: F_2^b, double tagging, ...