Heavy Flavour Production at HERA

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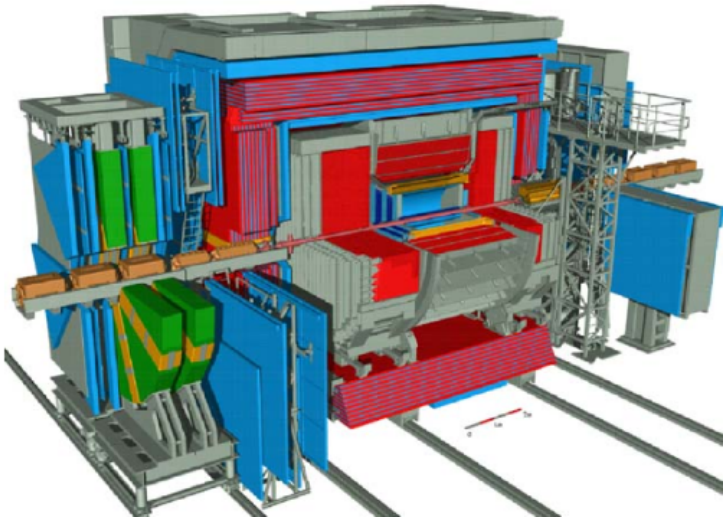
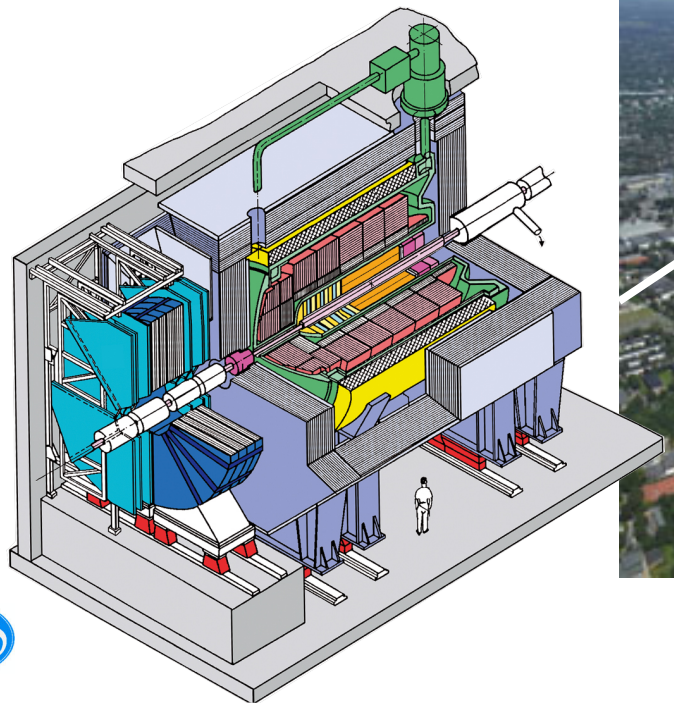
The HERA ep collider (1992 – 2007) at DESY in Hamburg

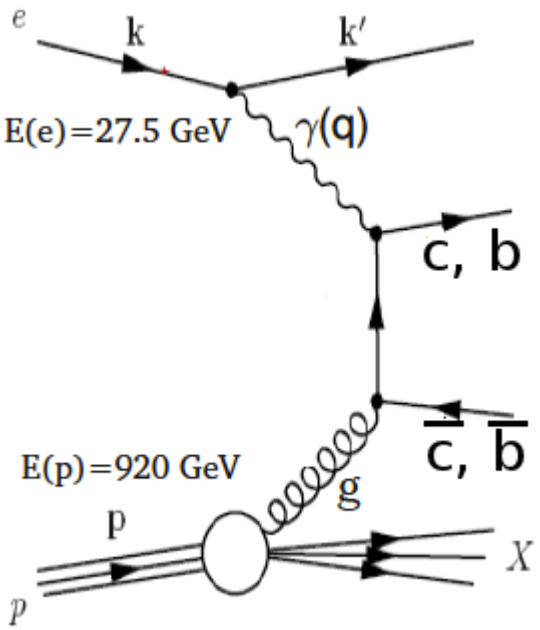
- ep collider:
- $e^{\pm}$ energy: 27.6 GeV
- p energy: 920 GeV
- Center of mass energy: 319 GeV
- 2 collider experiments: H1 and ZEUS
- Integrated luminosity: ~0.5 fb^{-1} (per experiment)





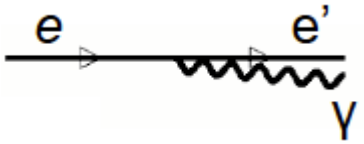
Motivation to measure heavy flavour production

- Charm and Beauty quarks at HERA are mainly produced in Boson-Gluon-Fusion.



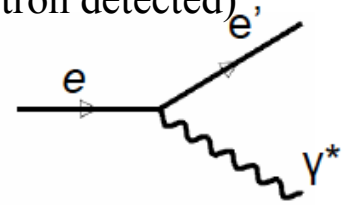
- Event kinematics:
  - Photon virtuality: $Q^2 = -q^2 = -(k-k')^2$
  - Inelasticity: $y = (q \cdot p) / (k \cdot p)$
  - Bjorken x: $x = Q^2 / (2\, p \cdot q)$

- Two kinematic regimes:
  - Photoproduction: $Q^2 \approx 0\ \mathrm{GeV}^2$



  - Deep Inelastic Scattering: $Q^2 > 1\ \mathrm{GeV}^2$

(scattered electron detected)



Motivation to measure heavy flavour production

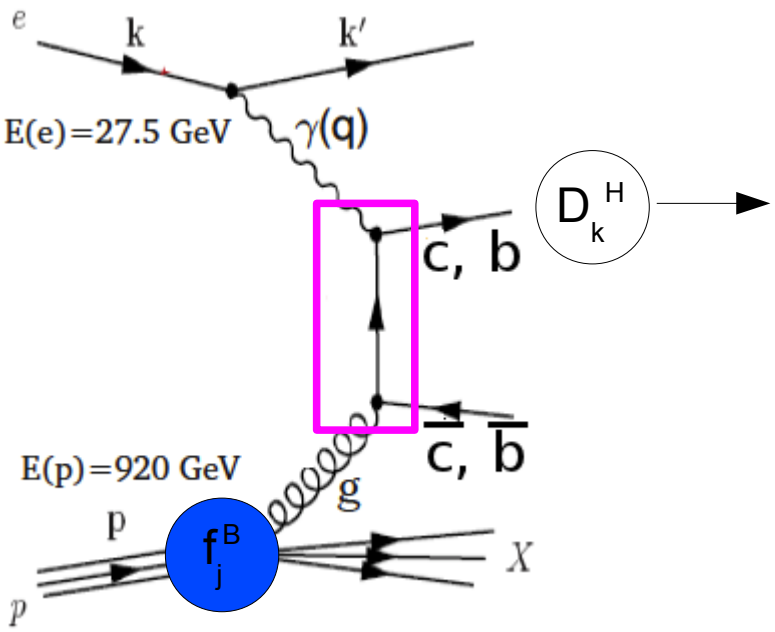
- Heavy Flavour cross sections can be calculated via the factorization ansatz:

$$d\sigma = \sum_{ijk} f_j^B(x, \mu_f) \otimes d\sigma_{ij \to kX} \otimes D_k^H(\mu_f)$$

Parton density function (from global fits)

pQCD matrix element

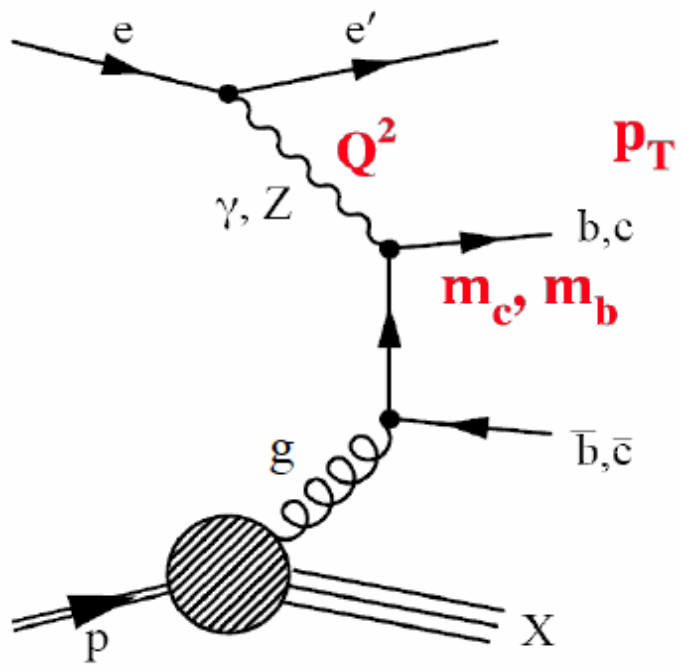
Fragmentation function (from ee data)



- Interpretation of Heavy Flavour measurements:
  - Use the pQCD calculations and constrain the gluon density of the proton.
  - Take the gluon density from elsewhere and test the consistency of the pQCD calculation.

Motivation to measure heavy flavour production

- Hard scales for perturbative QCD:
  - $m_{c,b}^2$, p_T^2, Q^2
    - multi-scale problem.
- Massive– Fixed flavour number scheme (FFNS):
  - c and b quarks generated dynamically via boson-gluon-fusion.
  - c and b quarks treated massive.
  - Expected to be valid for **small scales $\mu^2 \approx m_{b,c}^2$**
- Massless– Zero mass variable flavour number scheme (ZM-VFNS)
  - c and b quarks treated as massless partons in the proton and photon.
  - Expected to be valid for **large scales $\mu^2 \gg m_{b,c}^2$**
- Variable Flavour Number Scheme (GM-VFNS)
  - Interpolation between massive and massless model.
  - Massive at low scales.
  - Massless at high scales.



Monte Carlo generators

- QCD LO + Parton Shower MC:
  - Collinear factorization, DGLAP evolution (PYTHIA for photoproduction and RAPGAP for DIS).
  - k_T factorization, CCFM evolution (CASCADE).
  - Used for data corrections and model comparisons.

- QCD NLO
  - Massive scheme, NLO(α_s^2):
    - FMNR, MC@NLO: Photoproduction.
    - HVQDIS: DIS.
  - Massless scheme, NLO(α_s^2):
    - ZM-VFNS
  - Used for comparisons and extrapolations to full heavy quark cross sections.

Tagging methods for heavy flavour physics at HERA

- Rates at HERA behaved like $\sigma(b) : \sigma(c) : \sigma(uds) \approx 1 : 50 : 2000$
- Charm and beauty enrichment is possible with:

1) Full reconstruction
   - Only possible for charm at HERA, eg. $D^* \rightarrow K\pi\pi$. No suitable beauty decay channels with high statistics.

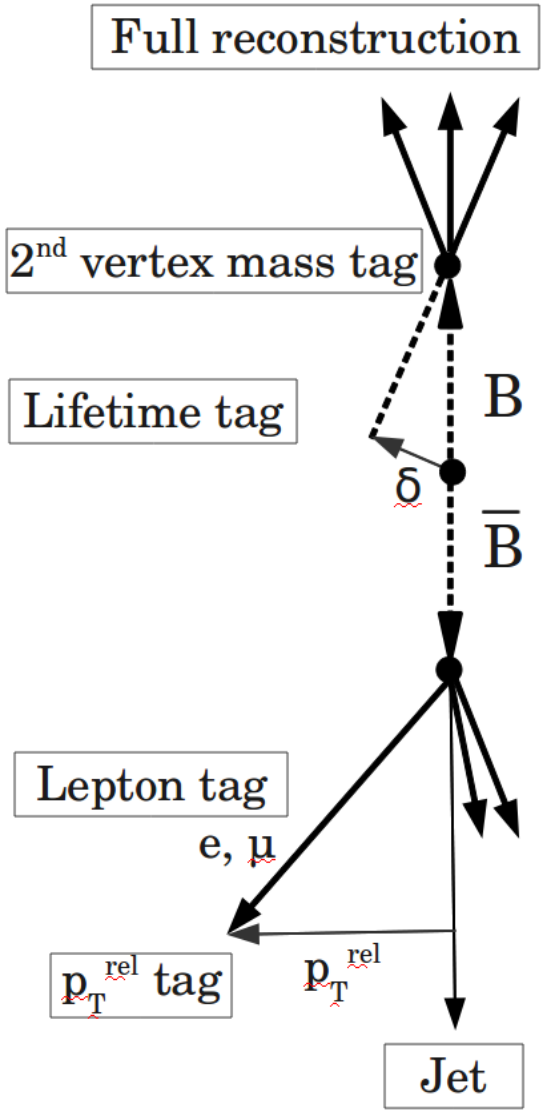
2) Lepton tagging
   - Use semileptonic b/c decay channels:
     - look for μ or e , high BR(c,b→ lepton + anything)

3) p_T^{rel} tagging
   - b/c quark have large masses:
     - look for decay leptons with a high transverse momentum w.r.t the b quark flight direction.

4) Lifetime tagging
   - b/c quark have long lifetimes:
     - look for displaced vertices.
     - look for tracks with large impact parameters δ.

5) Secondary vertex mass tagging
   - Use high b quark mass and long lifetimes:
     - look for high secondary vertex masses.

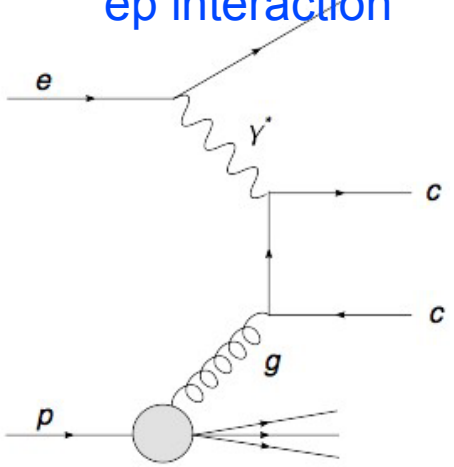
- Combination of different tagging methods.



Charm Fragmentation fraction

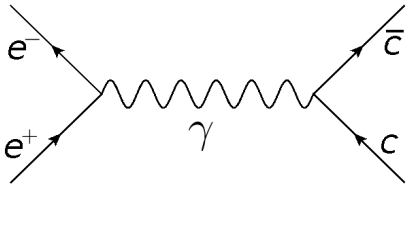
- Is the charm fragmentation fraction f universal?

ep interaction



$\rightarrow$ D^{*+}, D^{+}, D^{+}_{s}, D^{0}, Λ^{+}_{c}

ee interaction



$\rightarrow$ D^{*+}, D^{+}, D^{+}_{s}, D^{0}, Λ^{+}_{c}

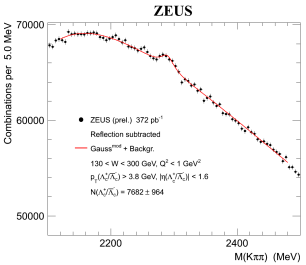
$f \rightarrow$ Probability of c-quark to hadronize into particular charm meson:

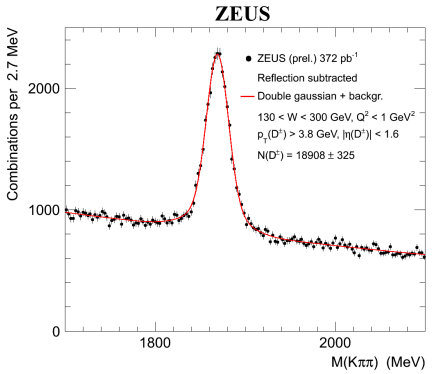
$$f(c \to D, \ldots, \Lambda_c) = \frac{\sigma_{D,\Lambda_c}}{\sigma_{gs}}$$

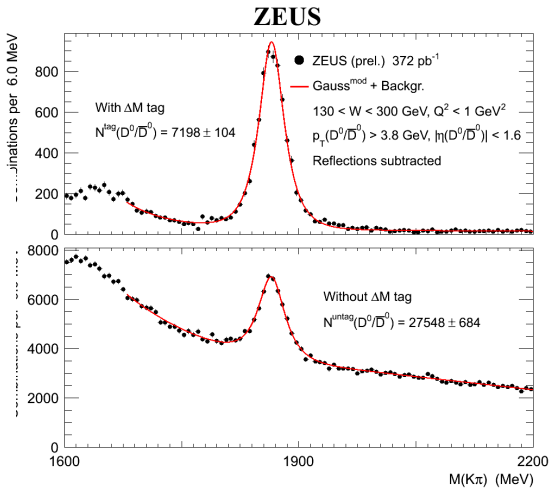
ZEUS-prel-12-003 $\quad \sigma_{gs} = \sigma^{eq}(D^+) + \sigma^{eq}(D^0) + \sigma(D_s^+) + \sigma(\Lambda_c^+) \cdot 1.14.$

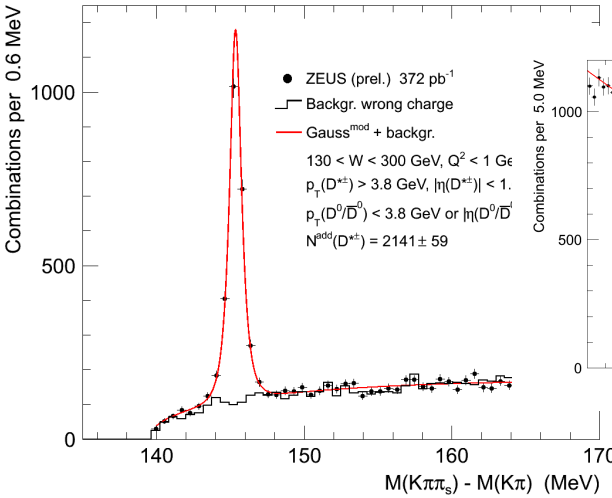
Analyzed channels:

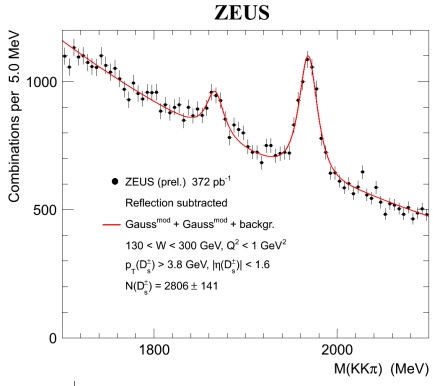
- $D^{+} \rightarrow K^{-}\pi^{+}\pi^{+}$
- $D^{*+} \rightarrow K^{-}\pi^{+}\pi^{+}$
- $D^{0} \rightarrow K\pi$
- $D^{+}_{s} \rightarrow K^{+}K^{-}\pi^{+}$
- $\Lambda^{+}_{c} \rightarrow pK^{-}\pi^{+}$



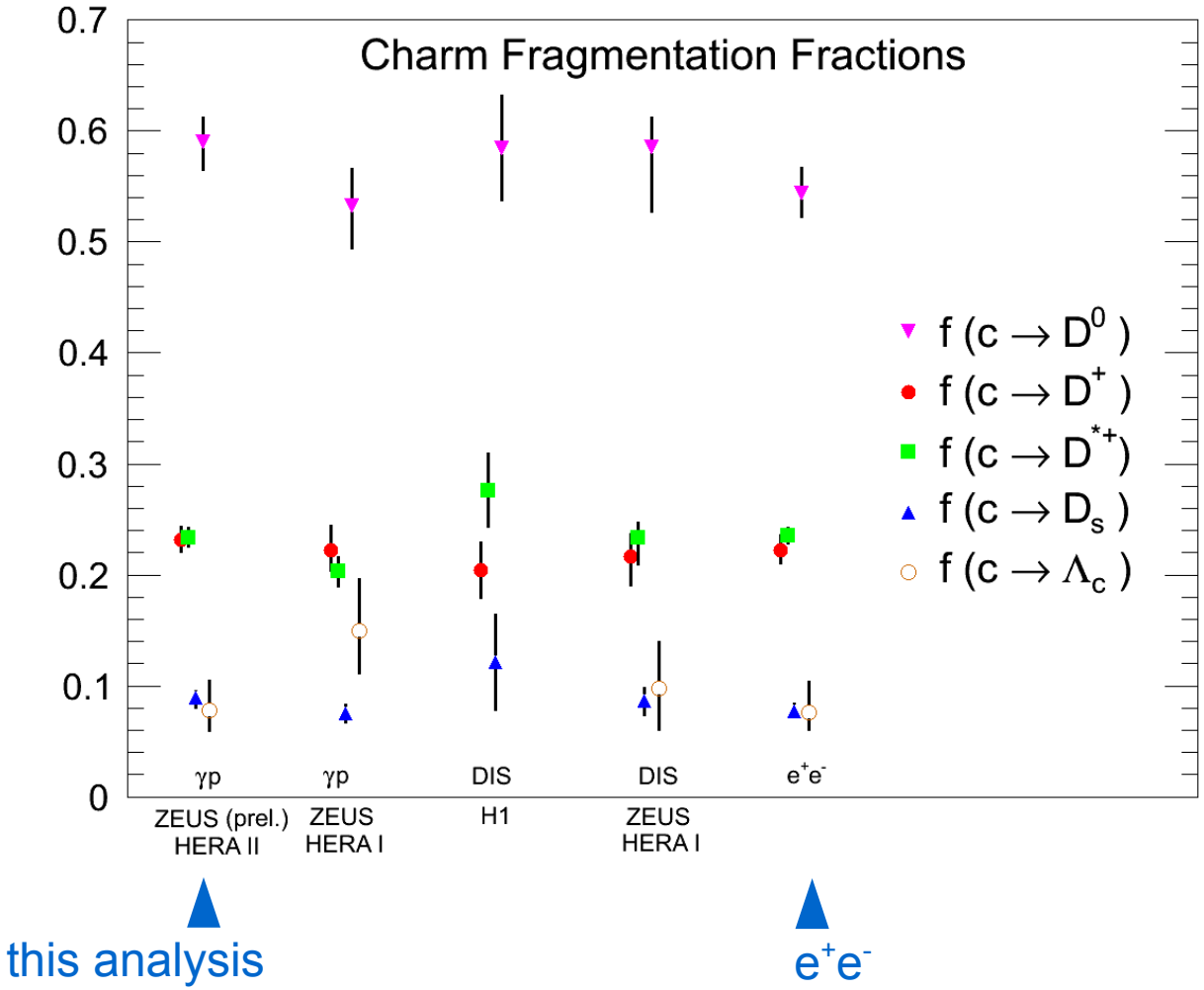








Charm Fragmentation fraction



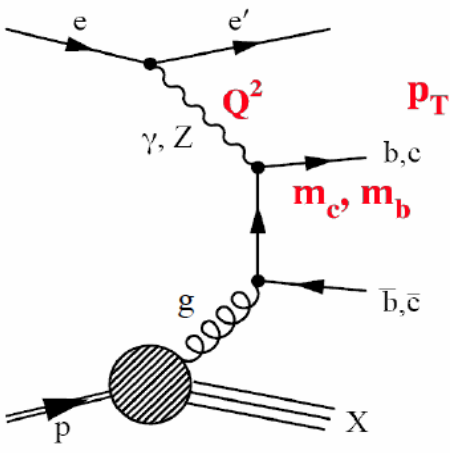
ZEUS-prel-12-003

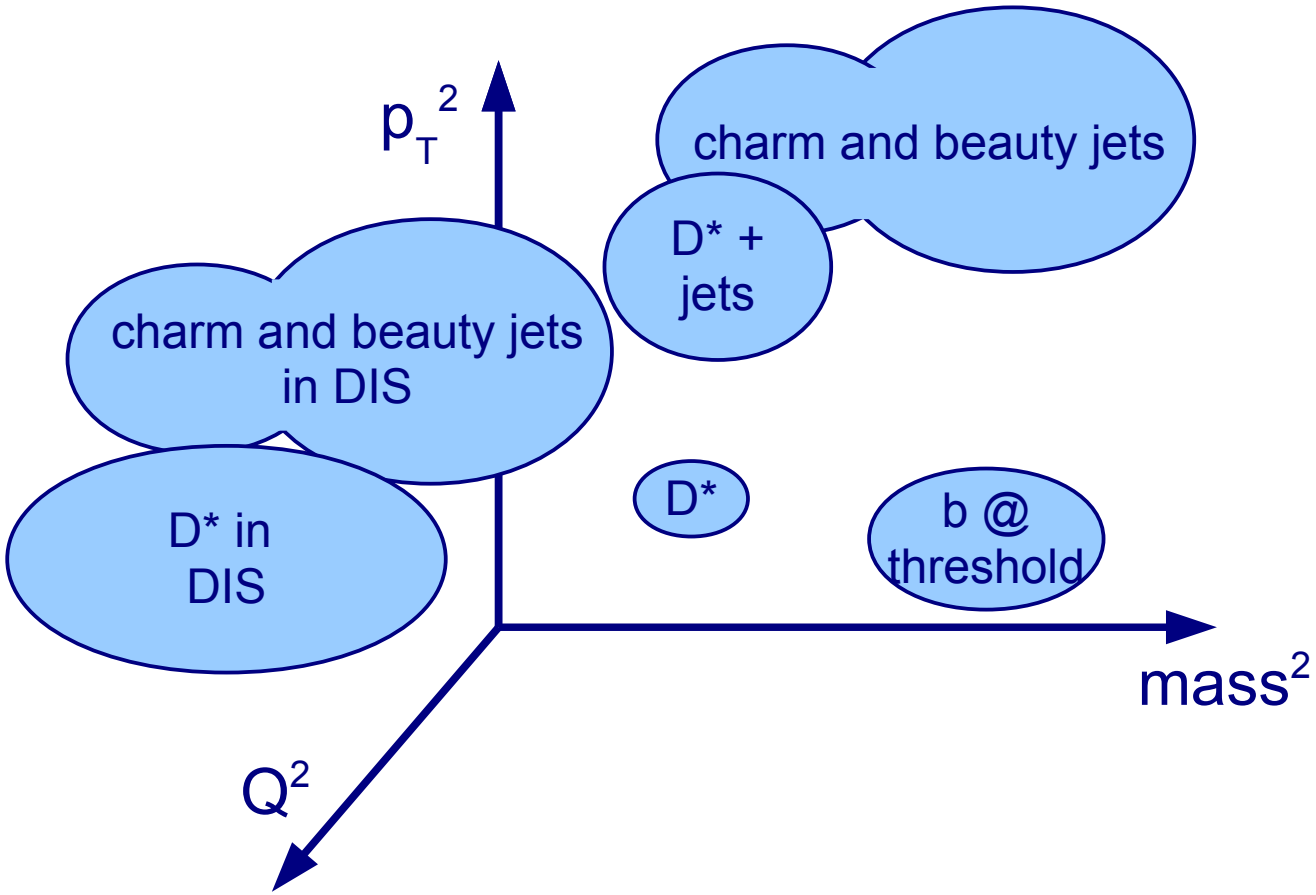
- Charm fragmentation universality confirmed.

Scales of the other measurements discussed in this talk:

7 new measurements test different scales relevant for perturbative QCD.

All references are listed in the backup.



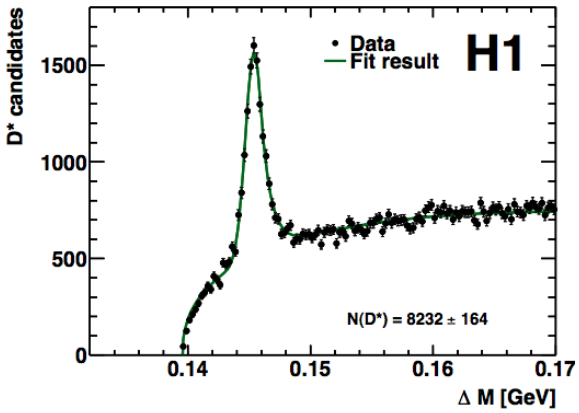


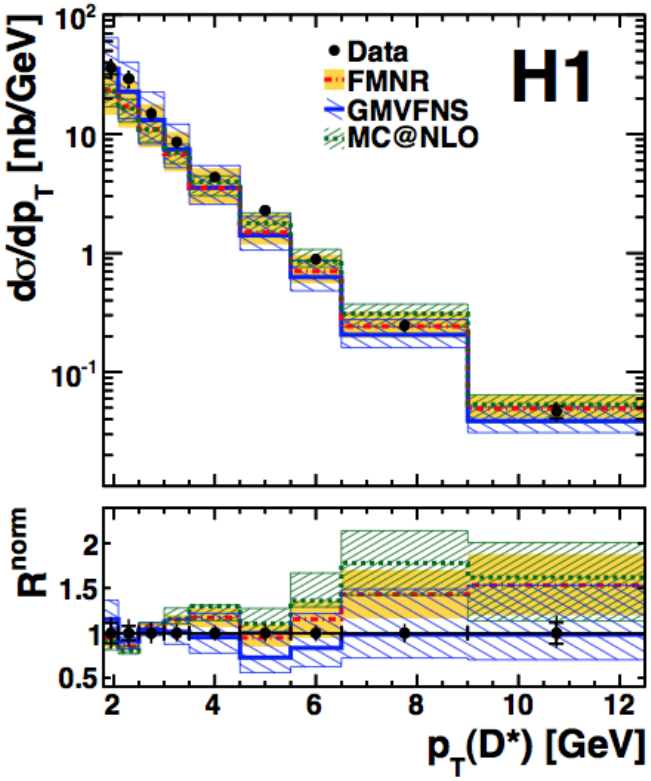
Data sample: $\mathcal{L}$=93 pb^{-1}

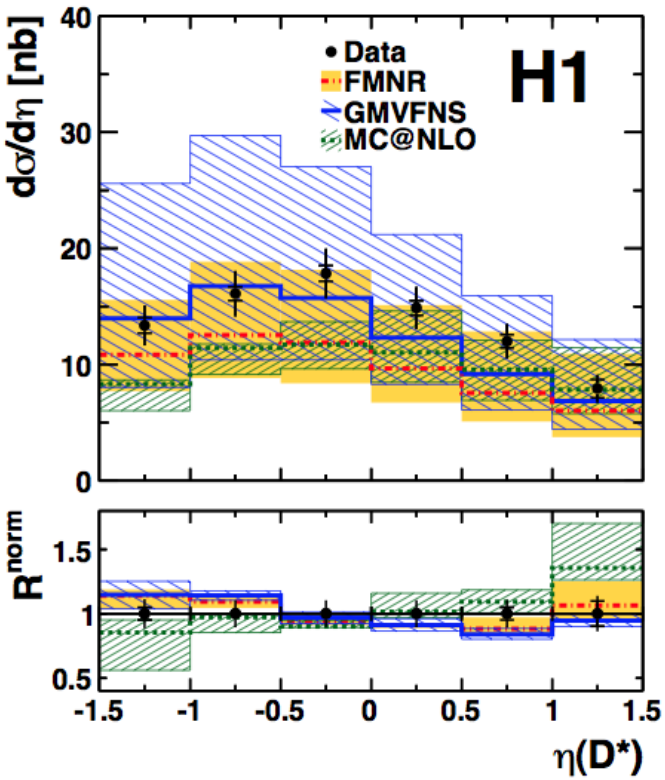
Phase Space
$Q^2 < 2$ GeV^2, $p_T^{D^*} > 1.8$GeV

Charm tagging
D* meson reconstruction via:

$D^{*\pm} \rightarrow D^0 \pi^{\pm}_{slow} \rightarrow K^{\mp} \pi^{\pm} \pi^{\pm}_{slow}$







- Very high precision of the data, compared to the uncertainties of the NLO predictions.
- NLO predicted shapes less sensitive to theoretical uncertainties, generally show a reasonable agreement with the data.

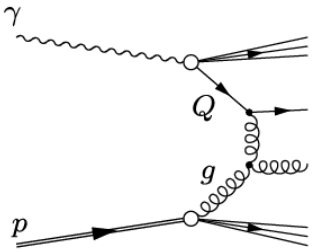
DESY-11-248, Eur. Phys. J. C72 (2012) 1995

Photoproduction of D* and two jets

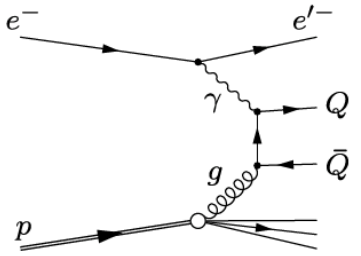
hard scales: p_T of jets, m_c

Data sample: $\mathcal{L}$=93 pb^{-1}

Phase Space
$Q^2 < 2\text{GeV}^2$, $p_T^{D^*} > 2.1\text{GeV}$
2 jets with: $p_T^{\text{jet 1}} > 3.5$ GeV

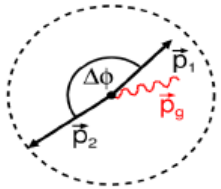


resolved enhanced



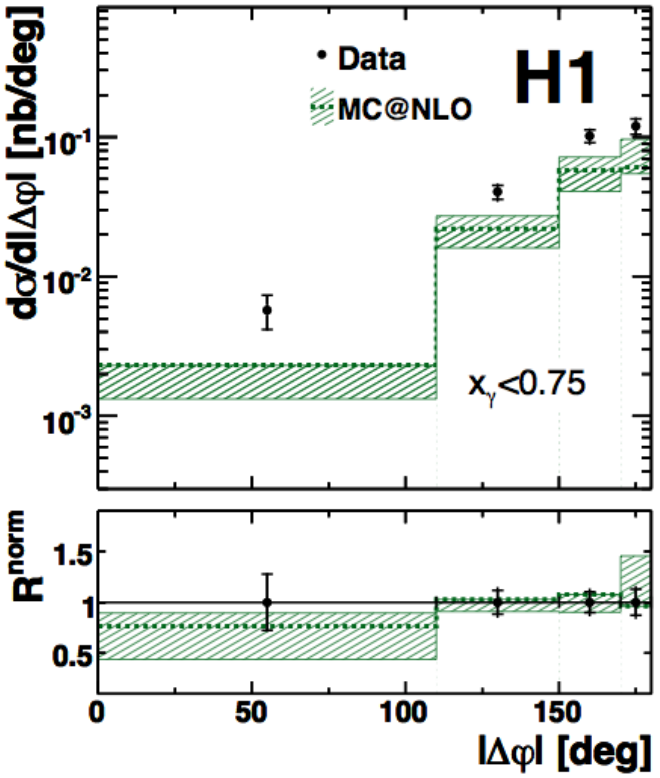
direct enhanced

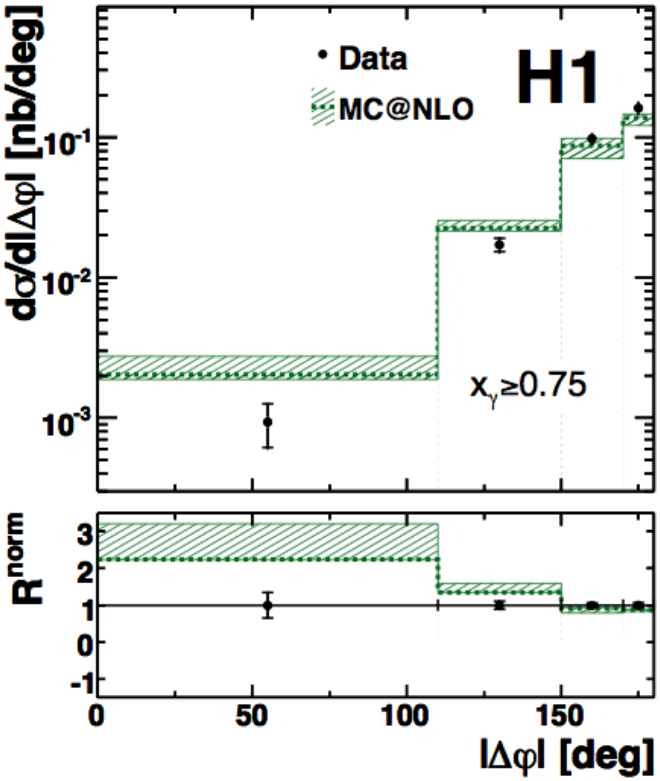
- Azimuthal correlation between the two jets, ΔΦ :



- Fraction of the photon energy entering the hard interaction (direct vs resolved), x_γ^{obs} :

$$x_\gamma^{obs} = \frac{\sum_{Jet1}(E - p_z) + \sum_{Jet2}(E - p_z)}{\sum_h (E - p_z)}$$





- MC@NLO predictions below the data for resolved photons, direct contribution reasonably well-described in normalization, shape not well described.

DESY-11-248, Eur. Phys. J. C72 (2012) 1995

Inclusive heavy quark jets in photoproduction

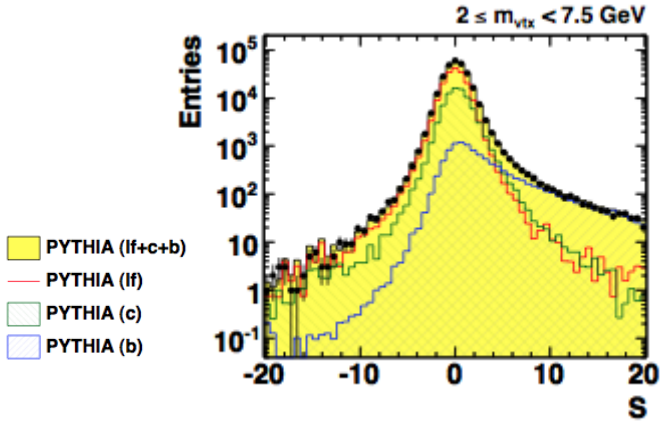
hard scales: p_T of jets, m_c, m_b

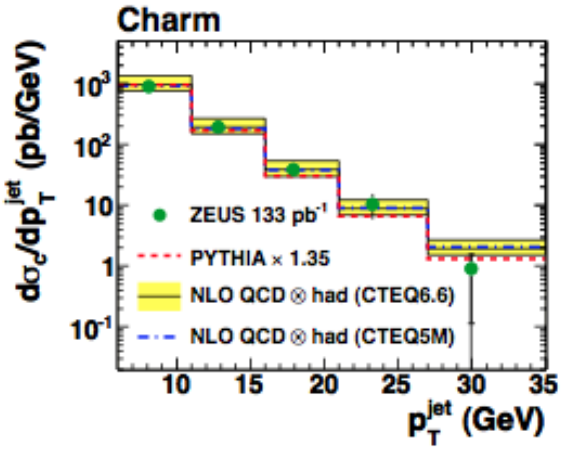
Data sample: $\mathcal{L}$=130 pb^{-1}

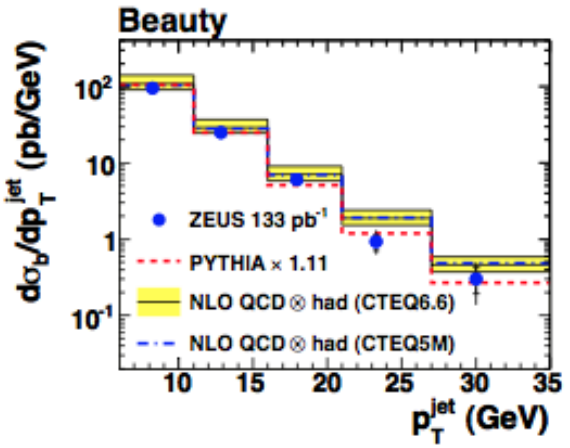
Phase Space
Events with 2 jets with:
$p_T^{\text{jet 1(2)}} > 7\ (6)$ GeV

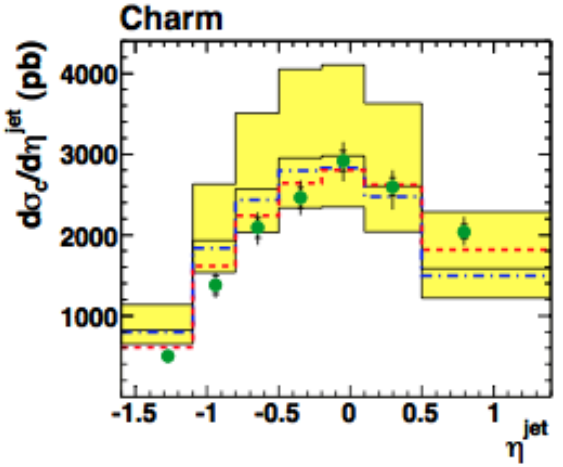
Heavy Quark tagging
Reconstruction of secondary vertices:

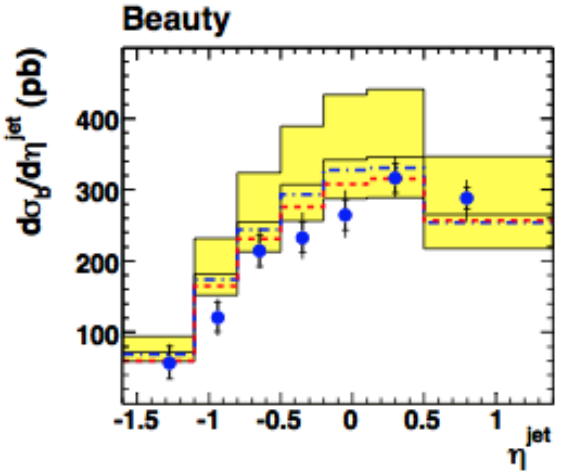
- Decay length significance
  $S = DL / \sigma(DL)$
- Mass of tracks associated with the secondary vertex, m_{vtx}
- 2d template fit











- Simultaneous measurement of c- and b-jets .
- Good agreement with LO MC (Pythia, scaled) and NLO QCD calculation (FMNR).

DESY-11-067, Eur. Phys. J C72 (2011) 1659

Photoproduction of b- and c-jets with muons

hard scales: p_T of jets, m_c, m_b

Data sample: $\mathcal{L}$=179 pb^{-1}

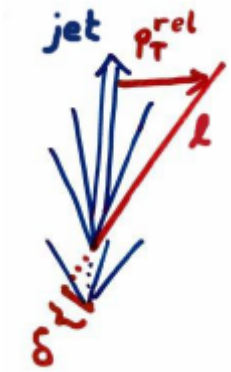
Phase Space

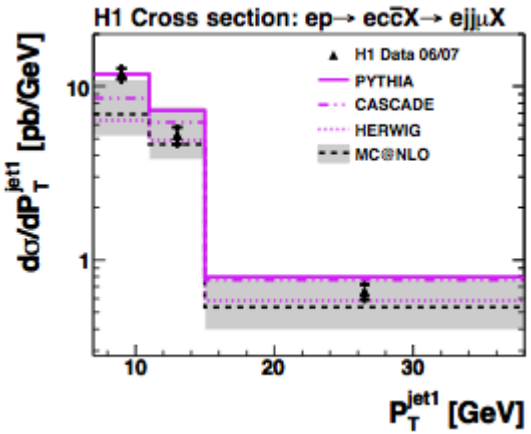
$Q^2 < 2.5$ GeV^2 , 1 muon $p_T^{\mu} > 2.5$ GeV, 2 jets $p_T^{\text{jet 1(2)}} > 7\ (6)$ GeV

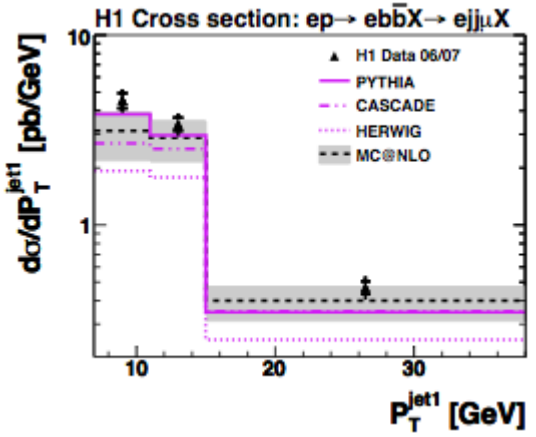
Heavy Quark tagging

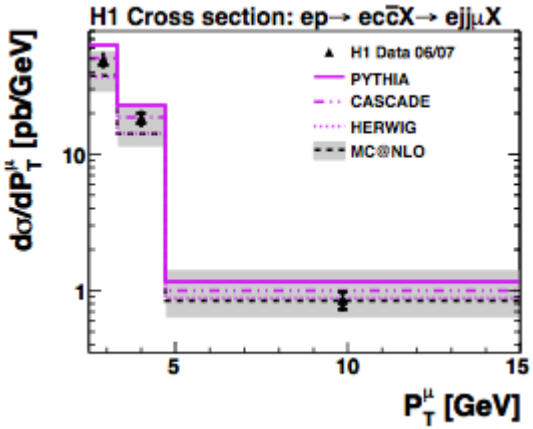
Reconstruction of a muon with:

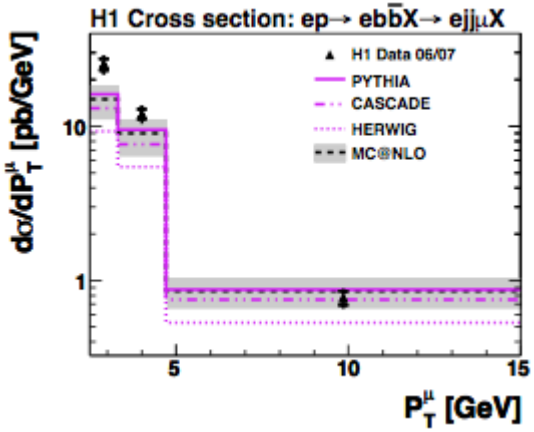
- Large momentum relative to the jet, p_T^{rel}.
- Large impact parameter δ.
- 2d template fit











- Simultaneous measurement of c- and b-jets.
- The data are in agreement with NLO calculation (MC@NLO).

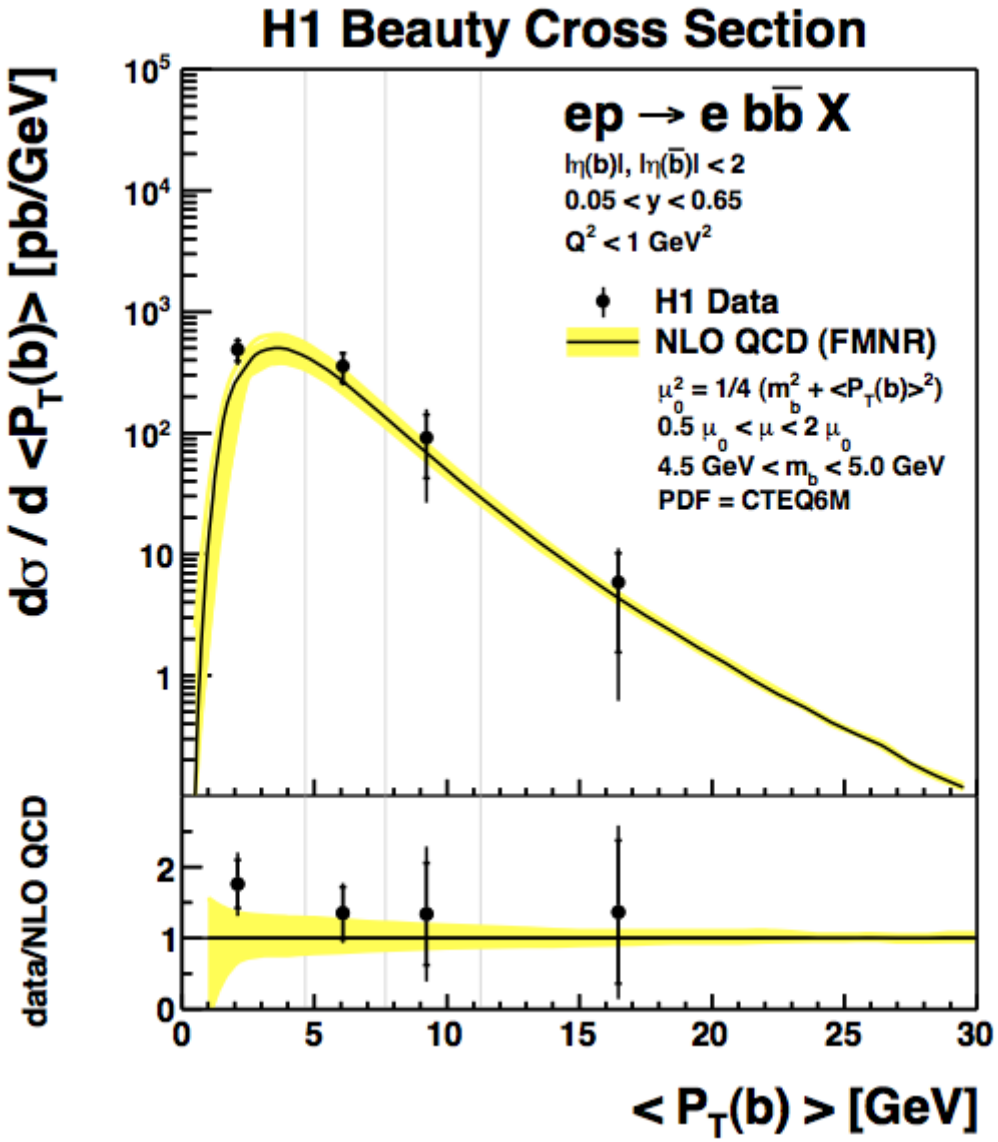
DESY-12-059, Accepted by EPJC

Data sample: $\mathcal{L}$=48 pb^{-1}

Phase Space
Events with 2 low p_T-electrons with
$p_T(e) \gtrsim 1$GeV

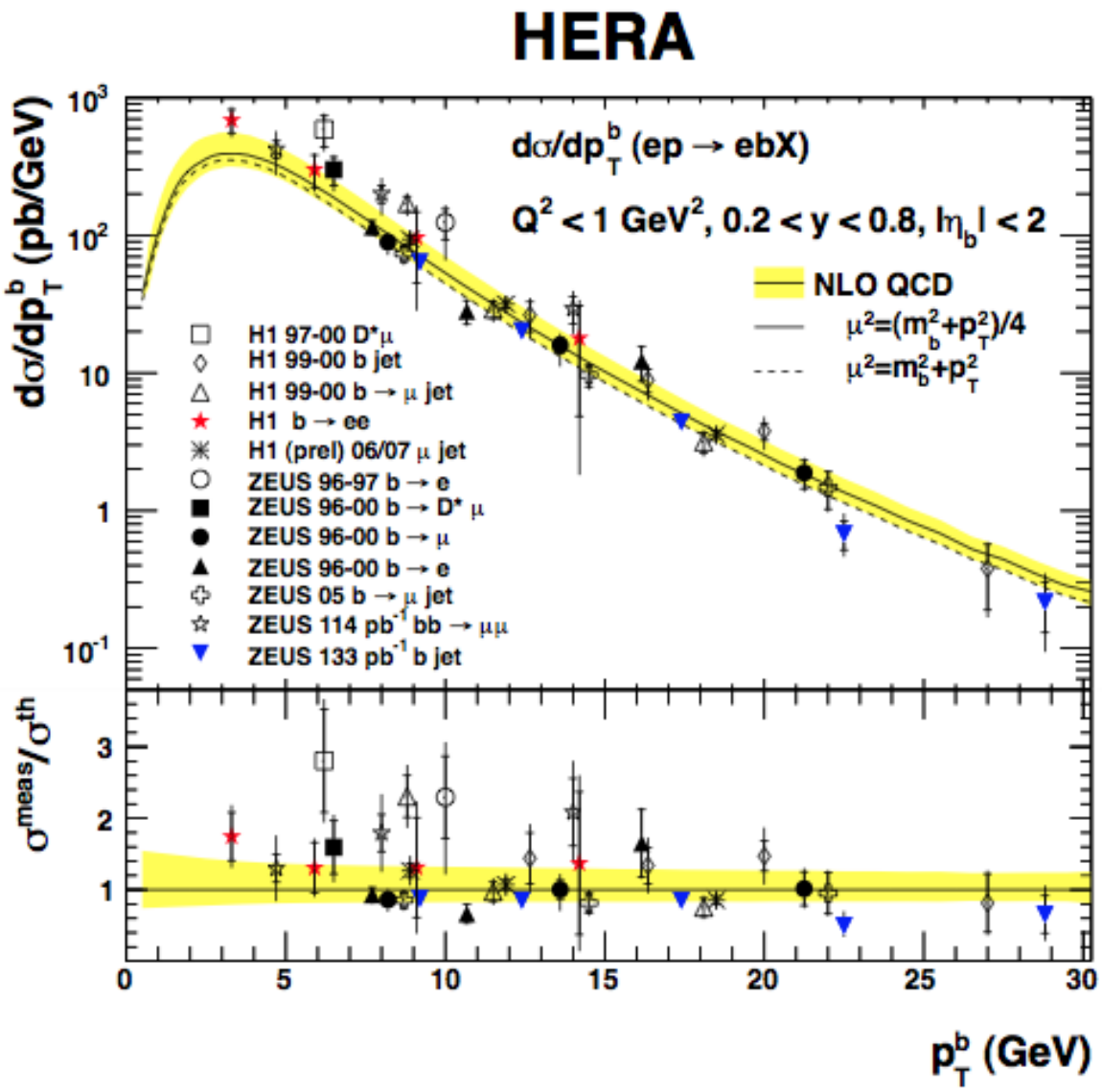
Beauty tagging
Two low p_T electrons from semileptonic decays:

- Exploit di-electron correlations:
  - Invariant mass m_{ee}
  - Azimuthal correlation $\Delta\Phi_{ee}$
  - di-electron charge product: q(e1)*q(e2)



- Access to lowest $p_T(b)$ values ever measured in ep.
- Agreement between data and NLO calculation (FMNR).

DESY-12-072, Submitted to EPJC



- Many measurements confirming each over a wide $p_T(b)$ range.
- General good agreement between data and NLO calculation (FMNR).

D* production in DIS

hard scales: m_c, Q^2

Data Samples: $\mathcal{L} \sim 350\ pb^{-1}$

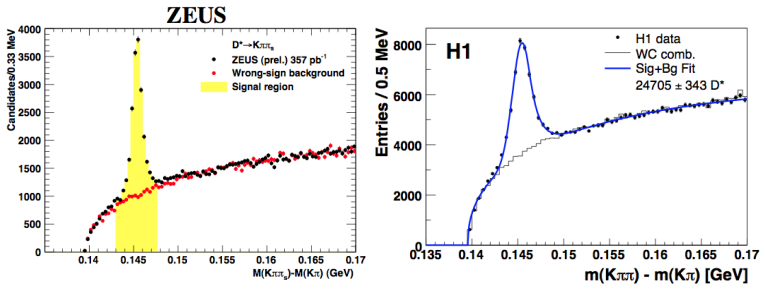
Phase Spaces (H1 / ZEUS)

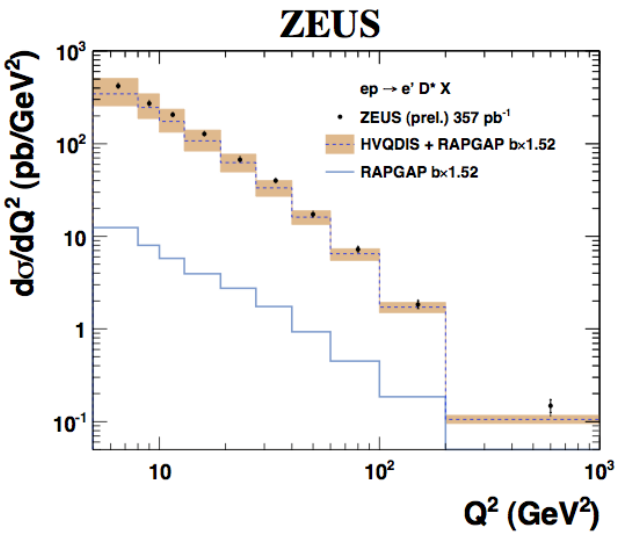
Q^2 :	5-100 GeV^2	5-1000 GeV^2
$P_T^{D^*}$	> 1.25 GeV	>1.5 GeV
$\lvert\eta^{D^*}\rvert$	< 1.8	< 1.5

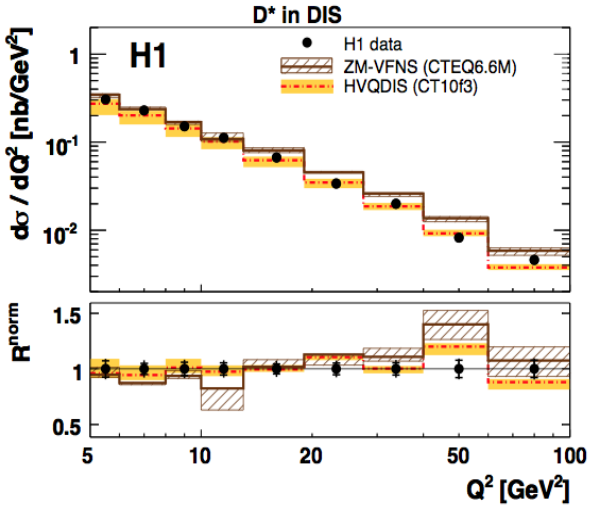
Charm tagging

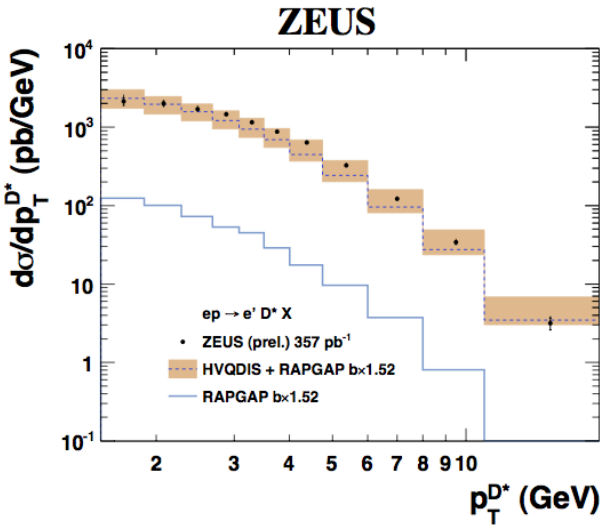
Reconstruction of a D* meson decaying in the golden channel:

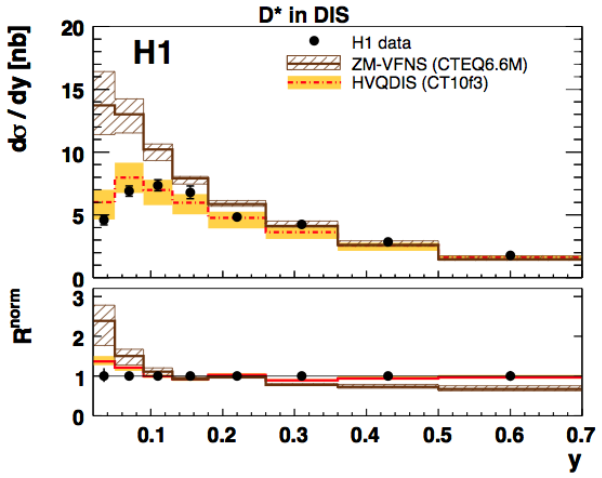
$$D^{*\pm} \rightarrow D^0 \pi^{\pm}_{slow} \rightarrow K^{\mp}\pi^{\pm}\pi^{\pm}_{slow}$$











- General good agreement with massive NLO calculation (HVQDIS) over a wide range in y and Q^2.
- The ZM-VFNS calculation overshoots the data at low y.

DESY-11-066, Phys.J.C71 (2011) 1769
ZEUS-prel-11-012

Inclusive heavy quark jets in DIS

hard scales: p_T of jets, m_c, m_b, Q^2

Phase Space

$5\text{GeV}^2 < Q^2 < 100\ \text{GeV}^2$

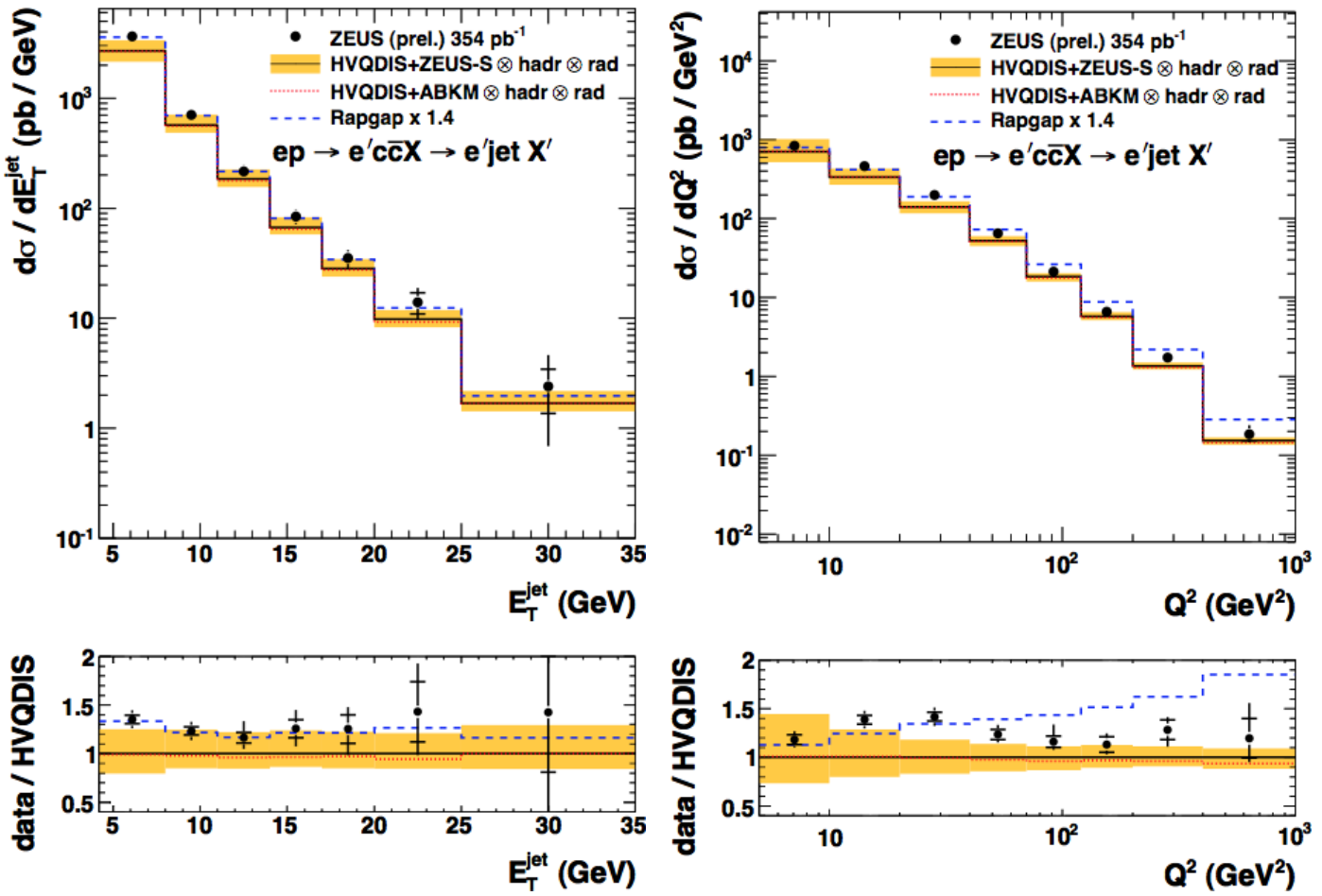
Events with ets with:

$E_T^{\text{jet 1(2)}} > 4.2$ GeV

Heavy Quark tagging

Reconstruction of secondary vertices:

- Decay length significance $S = DL / \sigma(DL)$
- Mass of tracks associated with the secondary vertex, m_{vtx}



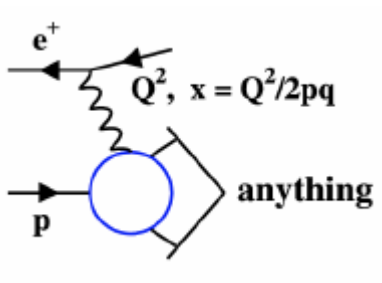
- Good agreement between data and NLO QCD calculation (HVQDIS) observed in different kinematical regions.

ZEUS-prel-11-012

F_2^{bb} and F_2^{cc} contributions to the proton structure function F_2

- F_2 structure function of the proton:

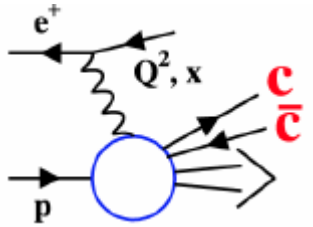
$$\frac{d^2\sigma}{dx\,dQ^2} = \frac{2\pi\alpha^2}{xQ^4}\cdot[(1+(1-y)^2)F_2 - y^2 F_L]$$



$$\frac{d^2\sigma^{ep}}{dx\,dQ^2} \propto F_2(x, Q^2)$$

- F_2^{cc} structure function of the proton: (identical for F_2^{bb})

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



$$\frac{d^2\sigma^{ep\to c\bar{c}x}}{dx\,dQ^2} \propto F_2^{c\bar{c}}(x, Q^2)$$

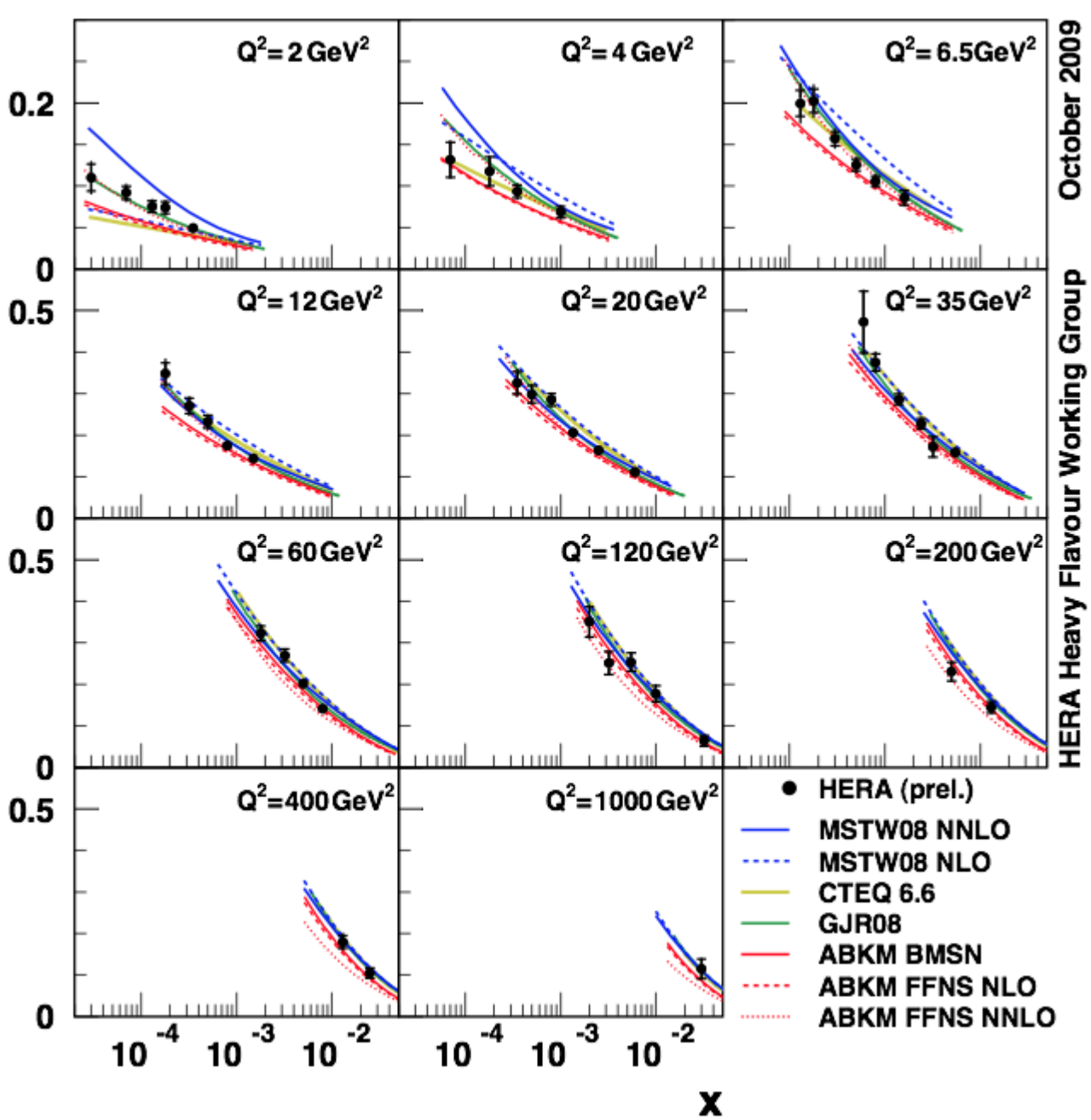
- The good agreement of the data and NLO calculations in the visible phase (given by the heavy quark tagging) allow to extrapolate to the full phase space and to measure F_2^{cc} (and identical F_2^{bb}) :

$$F_2^{c\bar{c},\,meas}(x, Q^2) = \sigma_{vis,\,bin}^{meas} \frac{F_2^{c\bar{c},\,model}(x, Q^2)}{\sigma_{vis,\,bin}^{model}}$$

Combination of charm measurements at HERA to common (x,Q^2) points allow highest precision in the data.

Comparison to different pQCD predictions, based on different PDFs give a consistent picture:

- The data can be used to further constrain the gluon density.



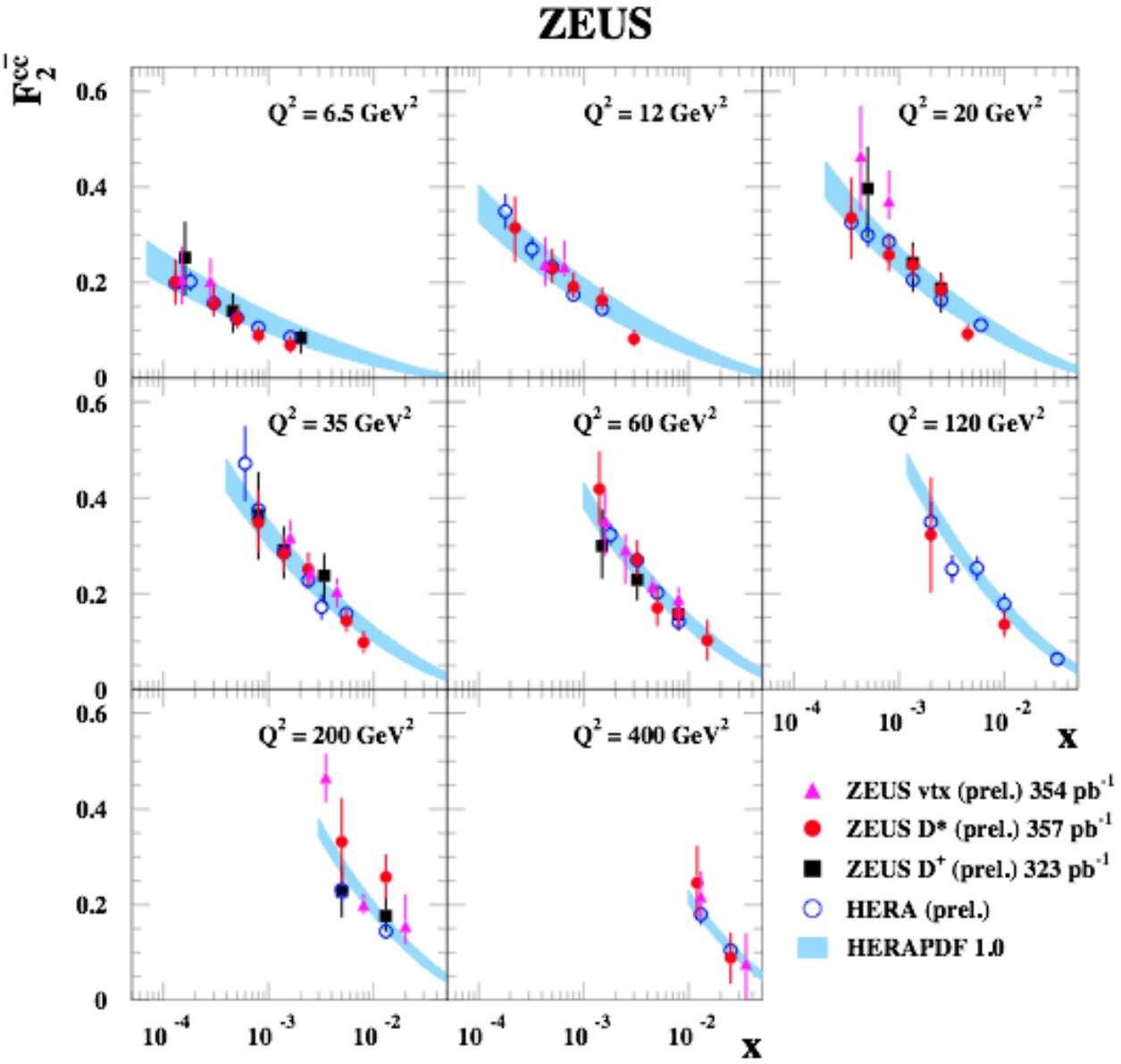
H1prelim-09-171,
ZEUS-prel-09-015

F_2^{cc} from recent preliminary ZEUS measurements (HERAII)

Comparison to combined F_2^{cc} and HERAPDF 1.0 .

Comment:

- The combined F_2^{cc} does not contain prelim. ZEUS D*, D^+ and vertex data for HERAII.



H1prelim-09-171,
ZEUS-prel-09-015,
ZEUS-prel-11-012,
ZEUS-prel-12-002

Summary and Conclusions

- Selection of recent HERA heavy flavour measurements presented:
  - Charm fragmentation
  - Beauty photoproduction near threshold
  - D* in photoproduction and DIS
  - Beauty and charm jets in photoproduction and DIS
  - Structure function F_2^{cc}

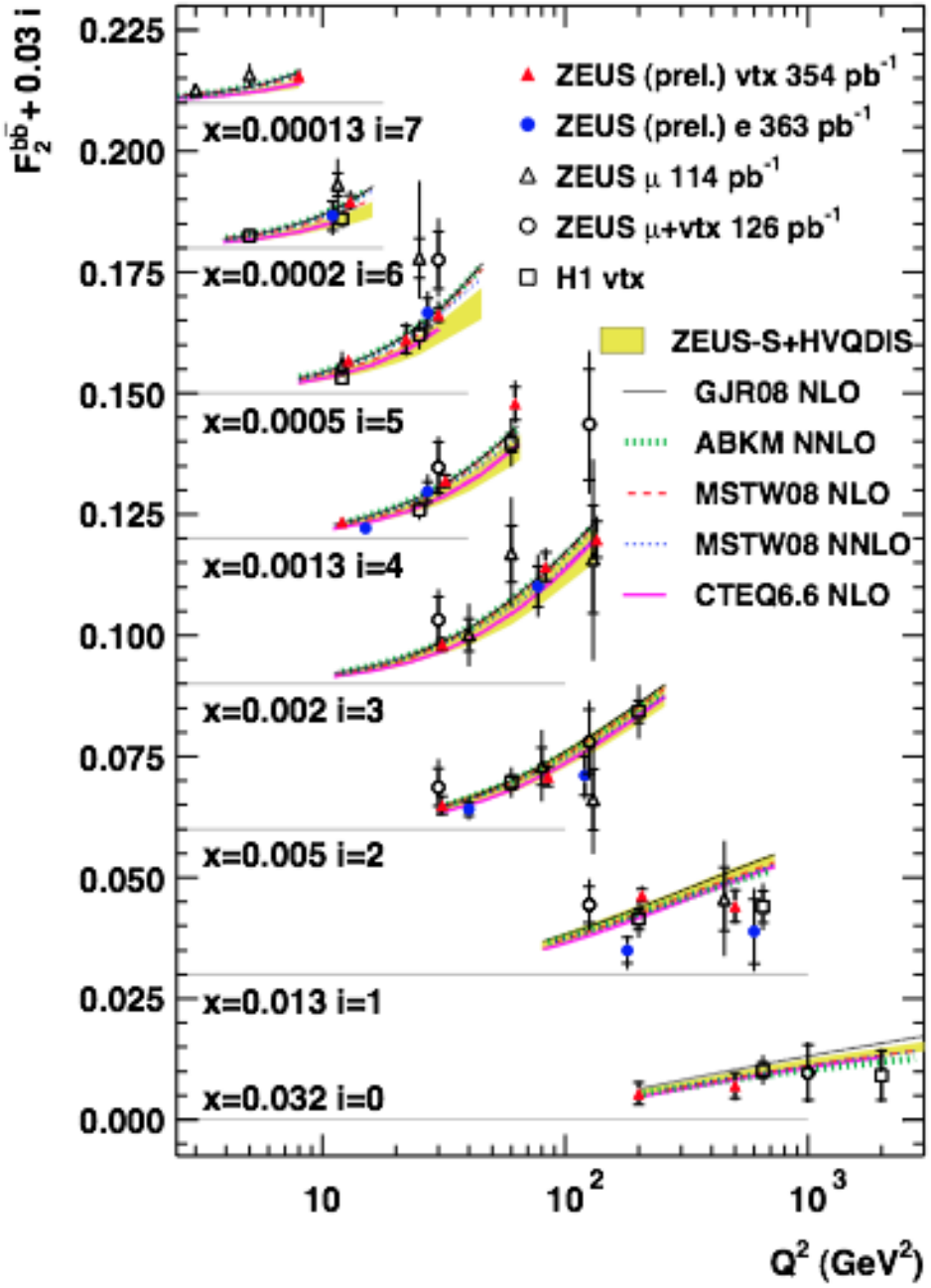
- In general a good agreement with NLO pQCD predictions is observed.

backup

Heavy Flavor Measurements discussed in this talk:

- Photoproduction:
  - "Measurement of Inclusive and Dijet D* Meson Cross Sections in Photoproduction at HERA"
    DESY-11-248, H1 Collab., F.D. Aaron et al., Eur. Phys. J. C72 (2012) 1995
  - "Measurement of heavy-quark jet photoproduction at HERA"
    DESY-11-067, ZEUS Collaboration; H. Abramowicz et al., Eur. Phys. J C72 (2011) 1659
  - "Measurement of Beauty and Charm Photoproduction using Semi-muonic Decays in Dijet Events at HERA"
    DESY-12-059, H1 Collab., F.D. Aaron et al., Accepted by EPJC
  - "Measurement of Beauty Photoproduction near Threshold using Di-electron Events with the H1 Detector at HERA"
    DESY-12-072, H1 Collab., F.D. Aaron et al., Submitted to EPJC
- Deep Inelastic Scattering:
  - "Measurement of D* Meson Production and Determination of F2cc at low Q2 in Deep-Inelastic Scattering at HERA "
    DESY-11-066, H1 Collab., F.D. Aaron et al., Eur. Phys.J.C71 (2011) 1769
  - "Measurement of charm production in DIS with D* mesons"
    ZEUS-prel-11-012, http://www-zeus.desy.de/public_results/functiondb.php?id=ZEUS-prel-11-012
  - "Charm production in DIS using inclusive secondary vertices and extraction of F2cc"
    ZEUS-prel-12-002, http://www-zeus.desy.de/public_results/functiondb.php?id=ZEUS-prel-12-002
  - "Combination of F2cc from DIS measurements at HERA "
    H1prelim-09-171, ZEUS-prel-09-015, http://www-h1.desy.de/publications/H1preliminary.short_list.html
- Charm Fragmentation
  - "Charm fragmentation fractions in Photoproduction"
    ZEUS-prel-12-003, http://www-zeus.desy.de/public_results/functiondb.php?id=ZEUS-prel-12-003

- Summary of H1 and ZEUS F_2^{bb} measurements.
- Comparison with different pQCD predictions.



- Data are compatible within uncertainties.
- NLO predictions able to describe the data.

DESY-09-096, DESY-11-005, ZEUS-prel-10-010