Heavy Flavour Production at HERA

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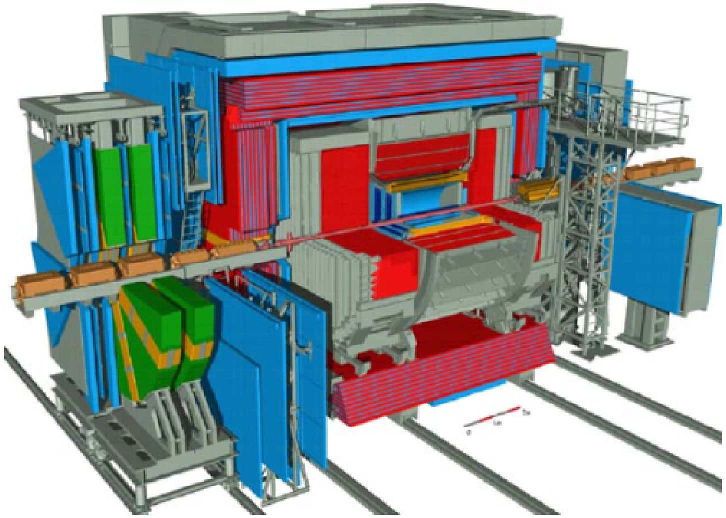
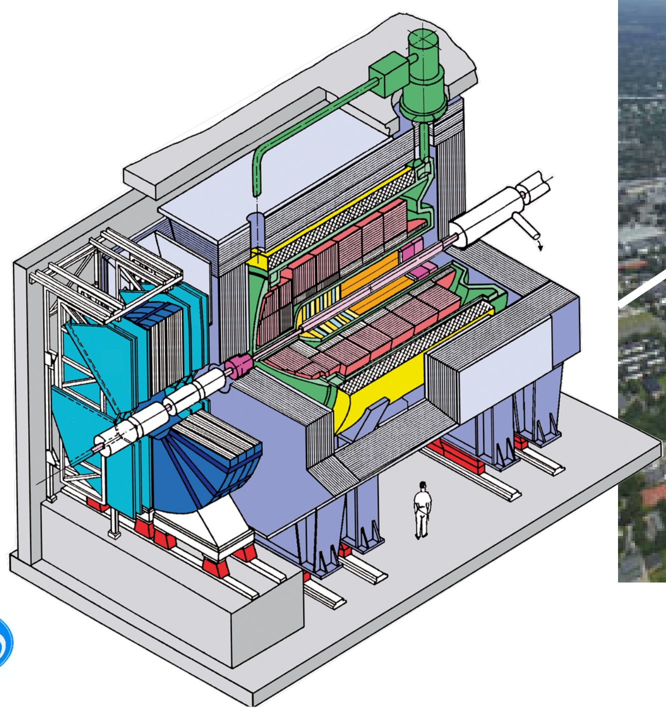
The HERA ep collider (1992 - 2007)

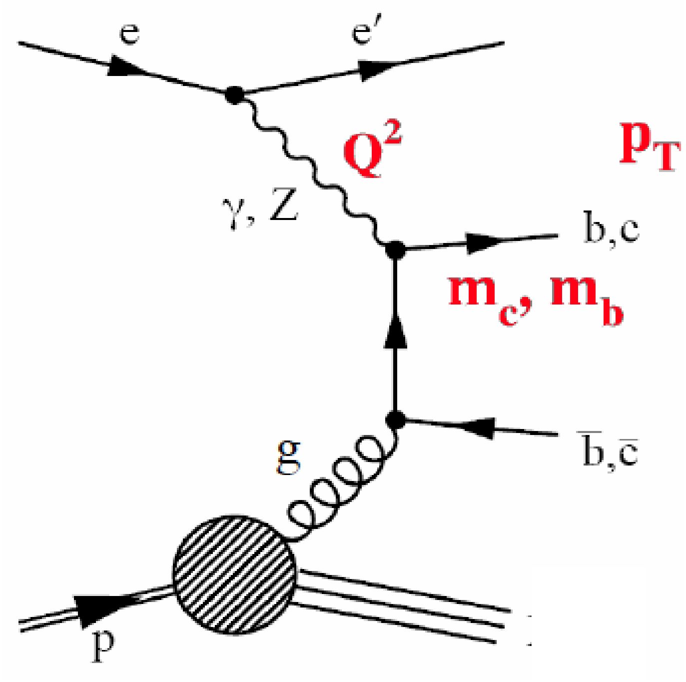
- ep collider:
- $e^{\pm}$ energy: 27.6 GeV
- p energy: 920 GeV
- Center of mass energy: 319 GeV
- 2 collider experiments: H1 and ZEUS
- Integrated luminosity: ~0.5 fb^{-1} (per experiment)





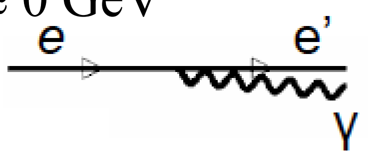
Motivation to measure heavy flavor production

- Charm and Beauty quarks at HERA are mainly produced in Photon-Gluon-Fusion → sensitive to the gluon in the proton.
- Hard scales for perturbative QCD:
  - $m_{c,b}^2$, p_T^2, Q^2
    - multi-scale problem.
- 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.

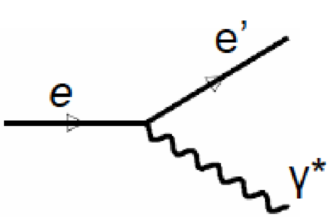


Two kinematic regimes:

- Photoproduction: $Q^2 \approx 0$ GeV^2



- Deep Inelastic Scattering: $Q^2 > 1$ GeV^2
  (scattered electron detected)



pQCD approximations

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

Monte Carlo generators

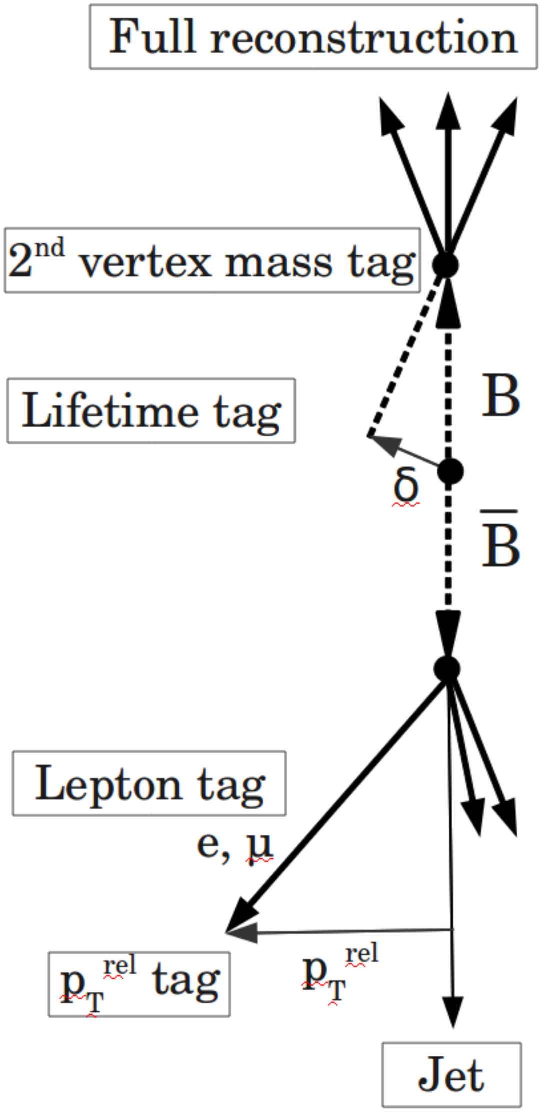
- QCD LO + Parton Shower MC:
  - Collinear factorization, DGLAP evolution (PYTHIA for photoproduction and RAPGAP for DIS).
  - k_T factorization, CCFM evolution (CASCADE).
  - Used for data corrections and model comparisons.

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

- Rates at HERA behaved like σ(b) : σ(c) : σ(uds) ≈ 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.

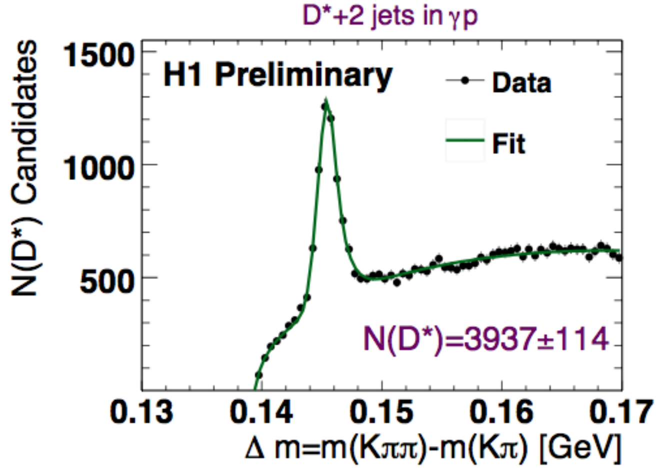


Charm and beauty in photoproduction

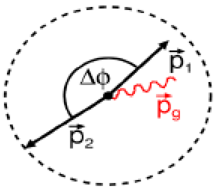
Data sample: $\mathcal{L}$=93 pb^{-1}

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

Charm tagging
D* meson reconstruction via: $D^{*\pm} \rightarrow D^0 \pi^{\pm}_{slow} \rightarrow K^{\mp} \pi^{\pm} \pi^{\pm}_{slow}$



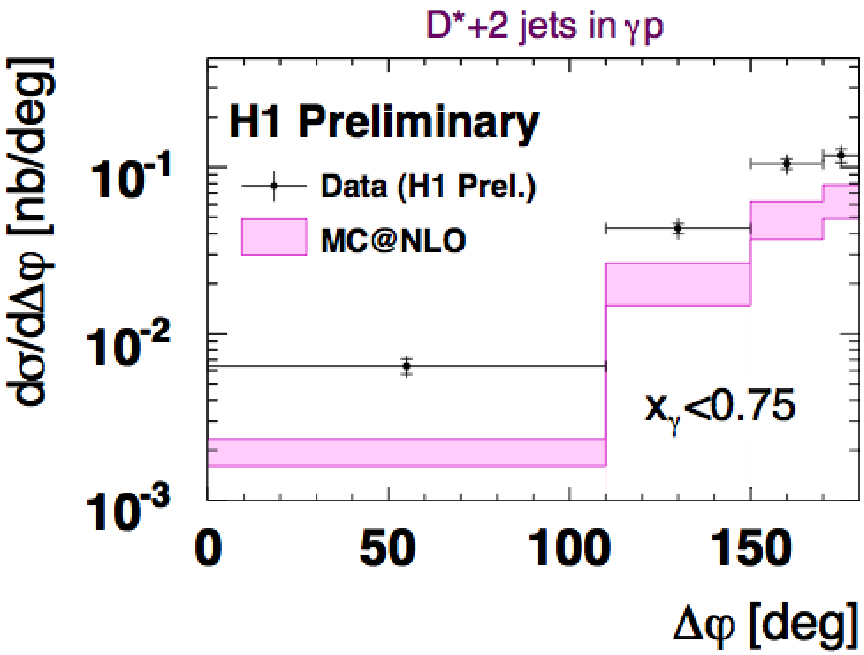
- Azimutal correlation between the two jets, ΔΦ :

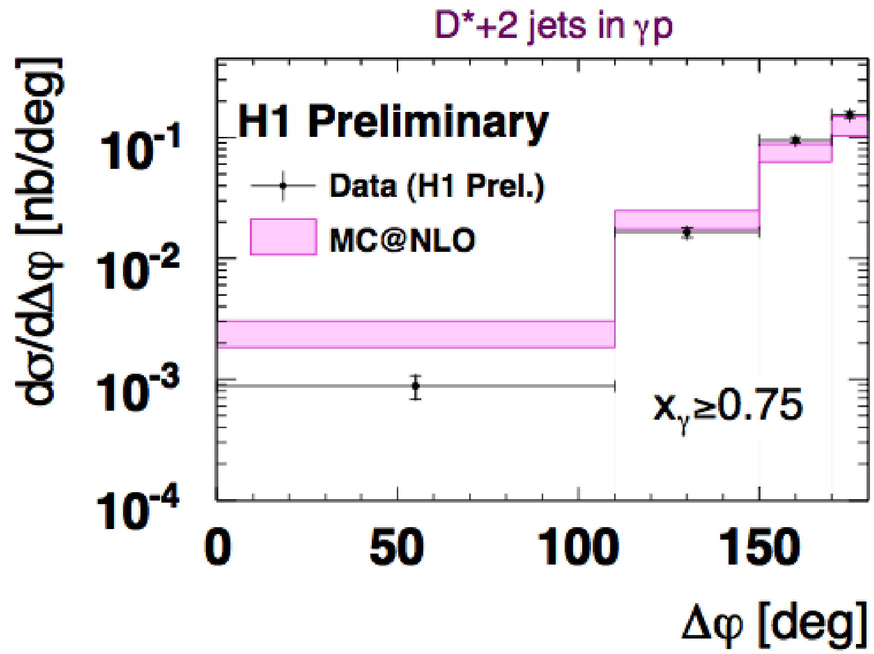


- Fraction of the photon energy entering the hard interaction (direct vs resolved), x_γ^{obs} :

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

resolved enhanced





- MC@NLO predictions below the data for resolved photons, direct contribution reasonably well-described

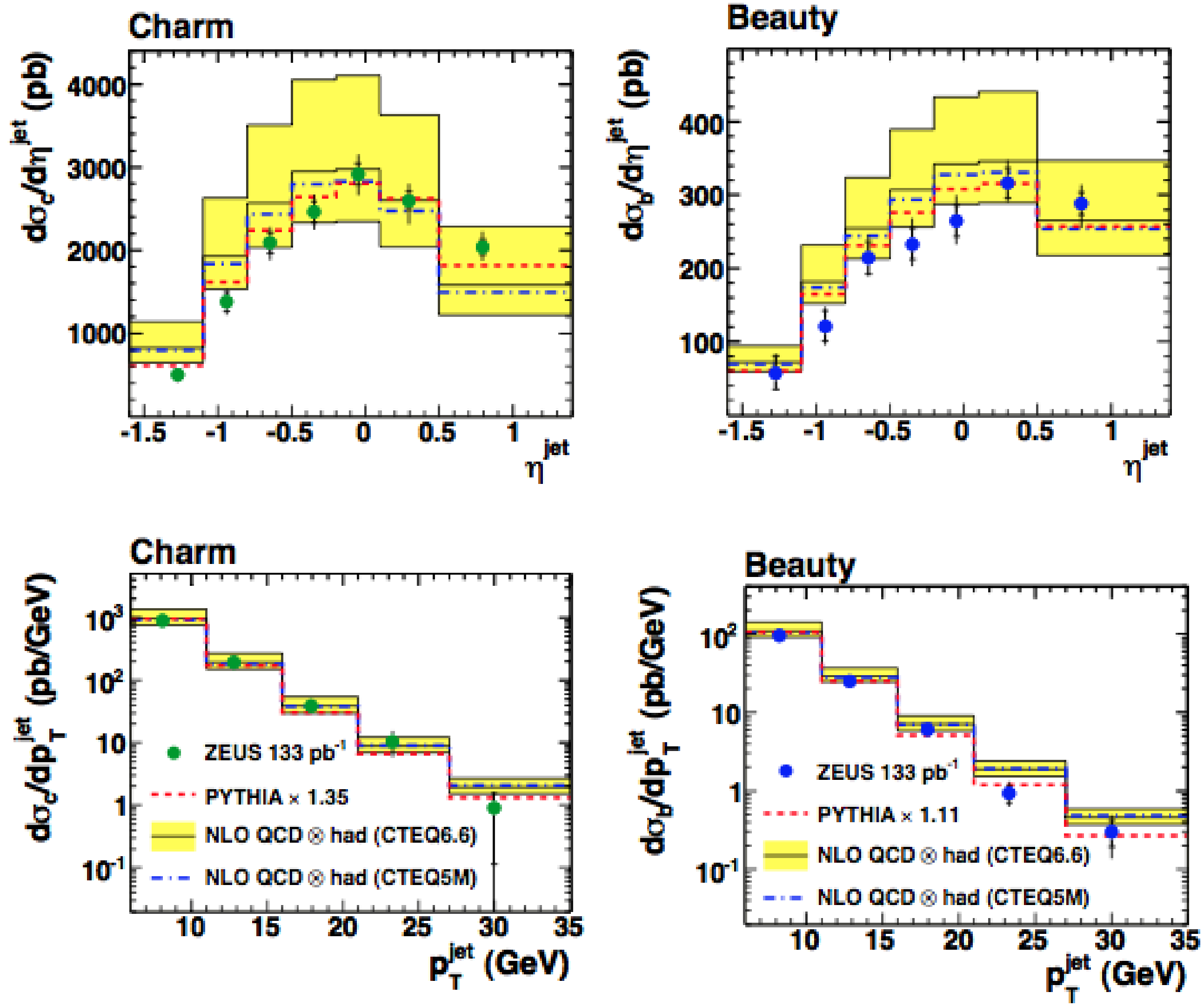
H1prelim-10-072

High p_T jet adds a hard scale

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

Phase Space

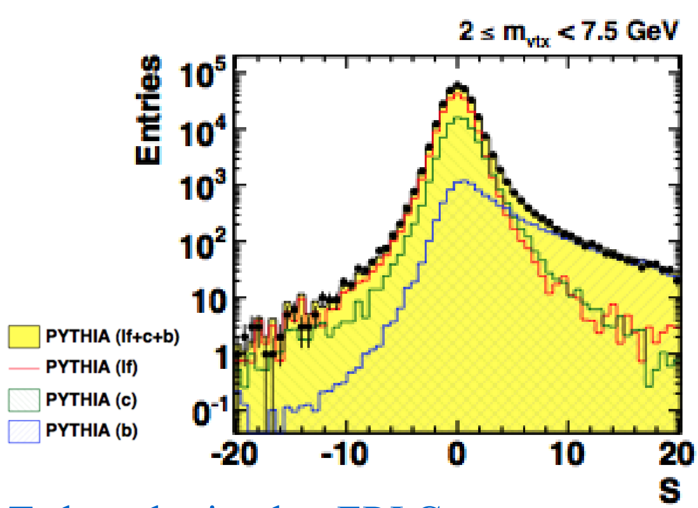
Events with least 2 jets with:
$p_T^{\text{jet } 1(2)} > 7\ (6)$ GeV



Heavy Quark tagging

Reconstruction of secondary vertices:

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



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

To be submitted to EPJ C

Data sample: $\mathcal{L}$=46 pb^{-1}

Phase Space

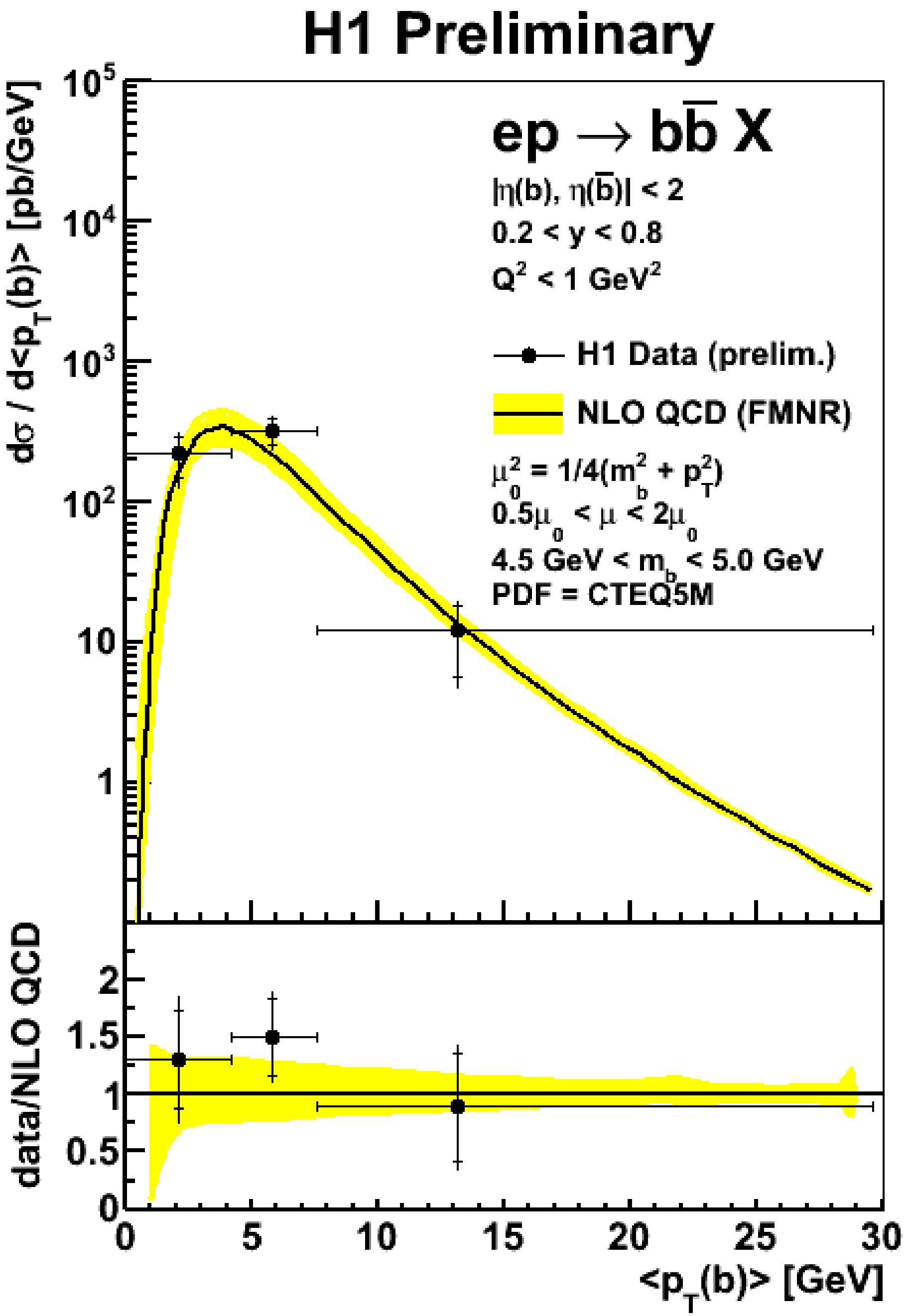
Events with 2 low p_T-electrons with

1 GeV^2 < p_T^e < 5 GeV^2

Beauty tagging

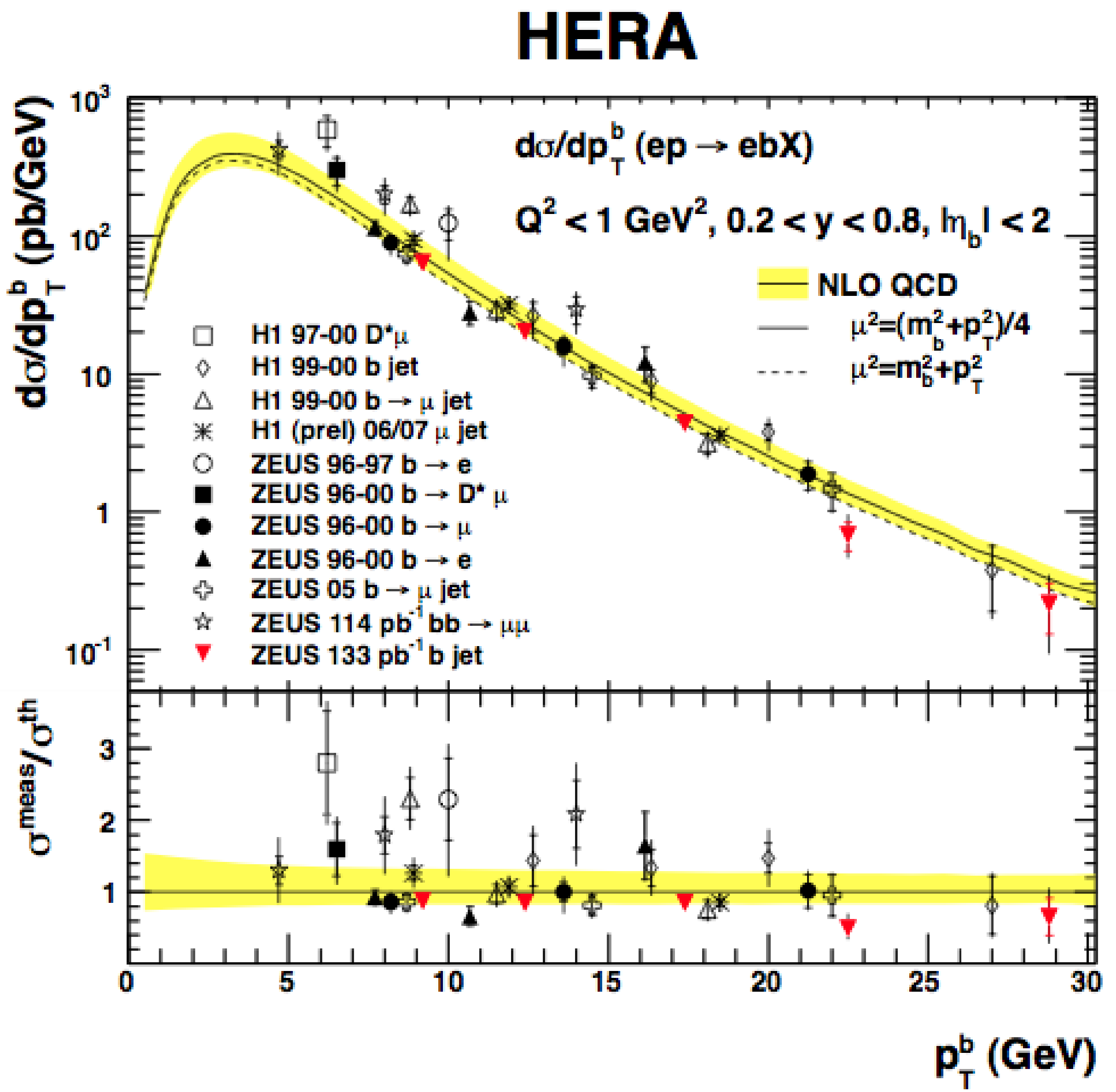
Two low p_T electrons from semileptonic decays:

- Invariant di-electron mass times di-electron charge product: m_{ee}*q(e1)*q(e2)



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

H1prelim-11-071



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

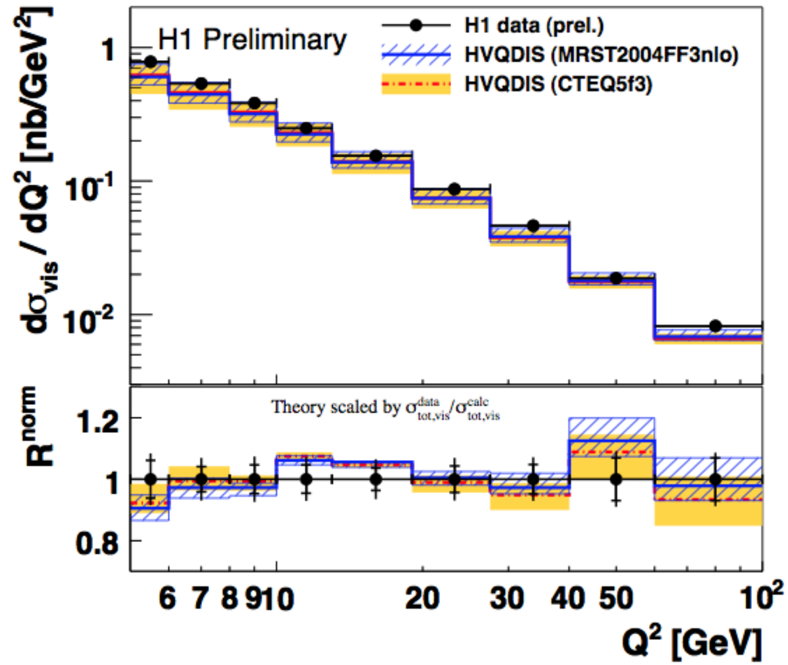
Charm and beauty in deep inelastic scattering

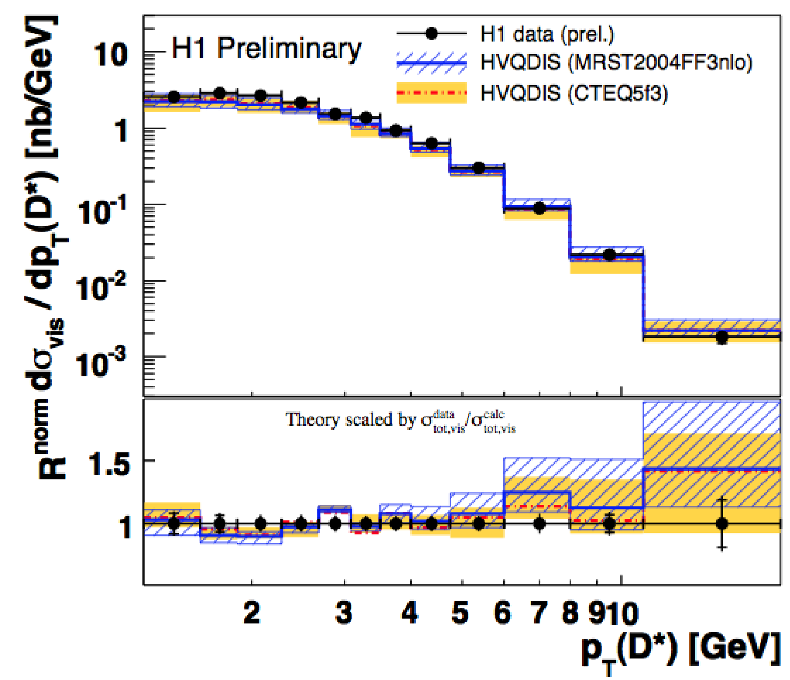
D* production at low Q^2 in DIS

Data Sample: $\mathcal{L}$=350 pb^{-1}

Phase Space
$5 GeV^2 < Q^2 < 100 GeV^2$
$p_T^{D*} > 1.25$ GeV
$|\eta^{D*}| < 1.8$

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 NLO calculations over a wide range in $p_T(D^*)$ and Q^2.

H1prelim-10-172

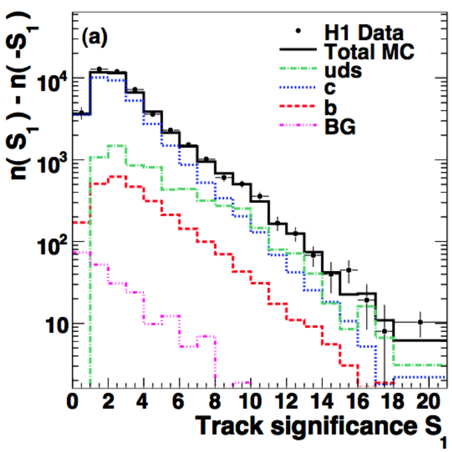
High E_T jet adds an additional scale

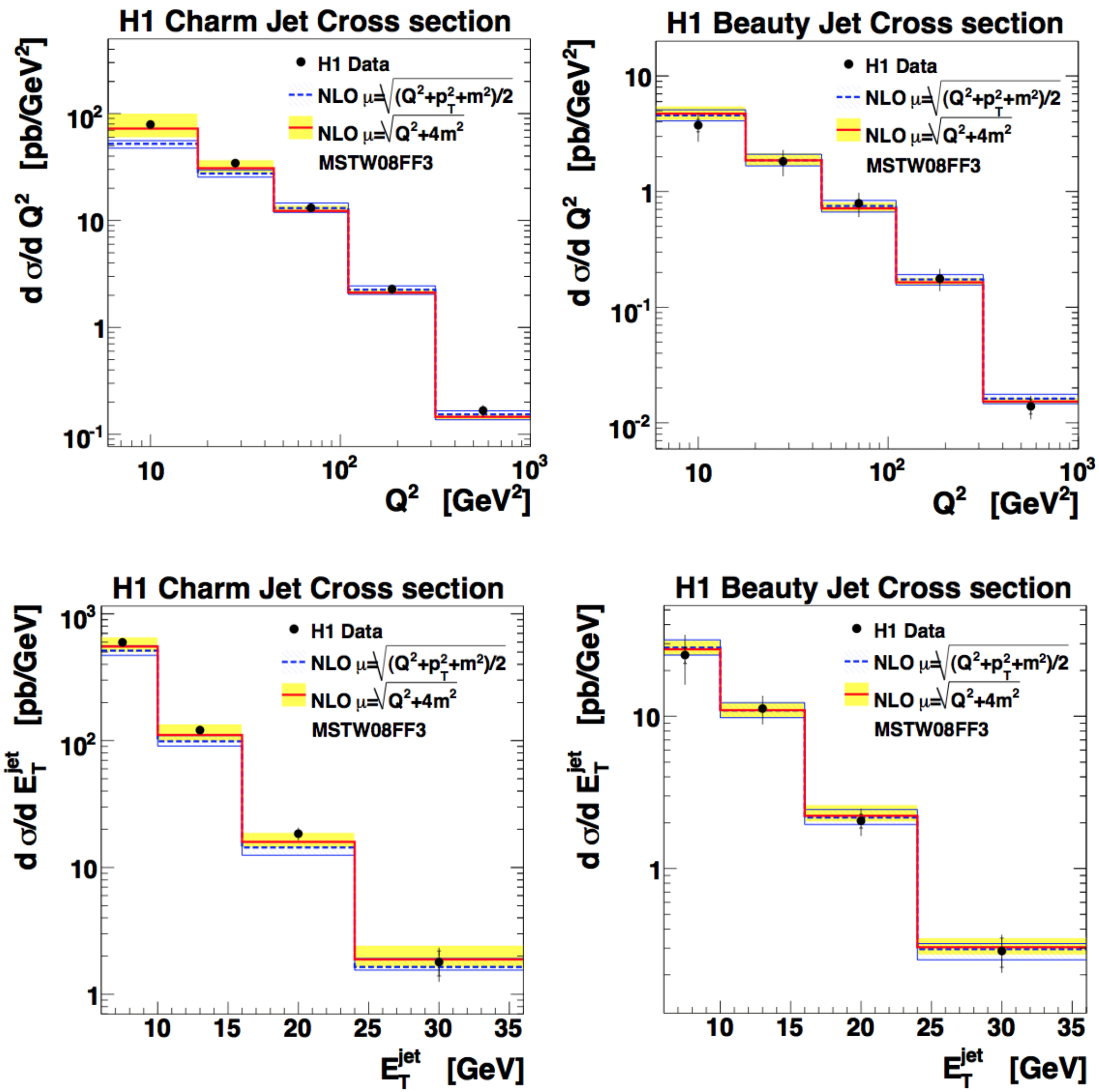
Data Sample: $\mathcal{L}$=189 pb^{-1}

Phase Space
$6GeV^2 < Q^2$, $0.07 < y < 0.625$
At least on jets with:
$E_T^{jet} > 6$ GeV, $-1 < \eta^{jet} < 1.5$

Heavy Quark tagging

Reconstruction of secondary vertex.
Displaced tracks.

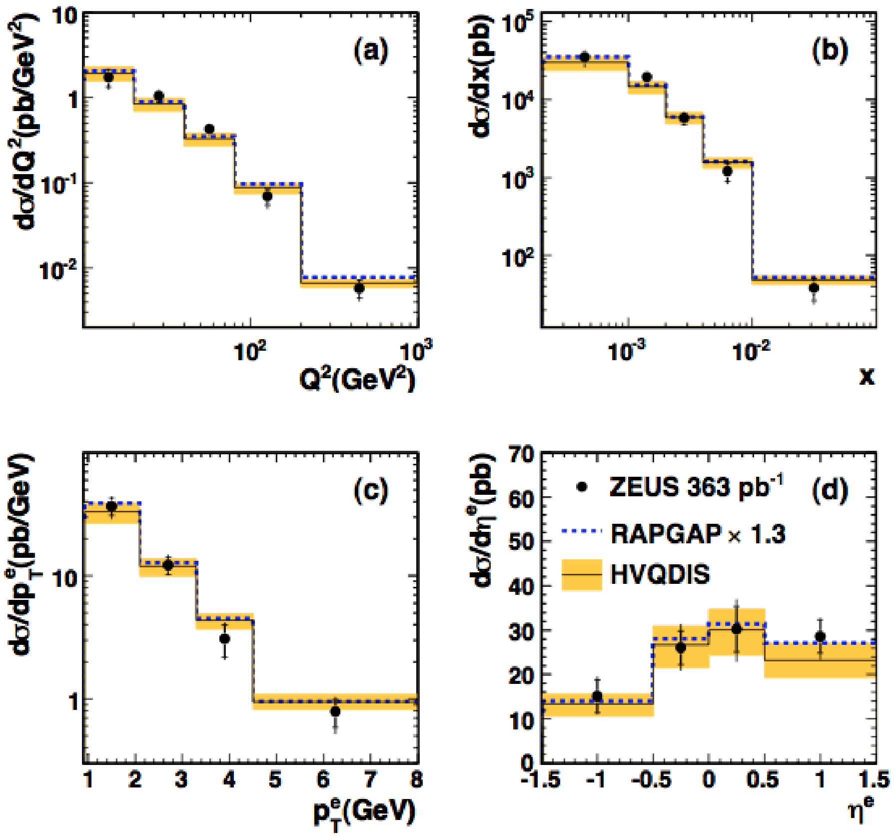




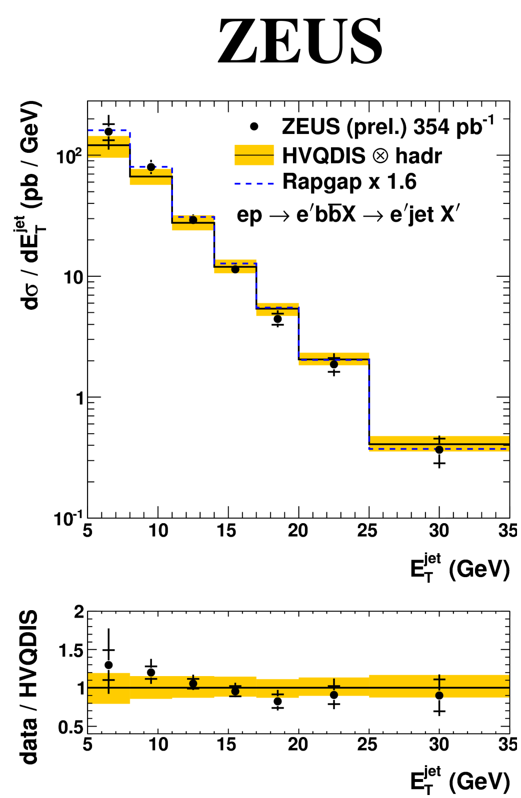
- Charm and Beauty in good agreement with NLO.

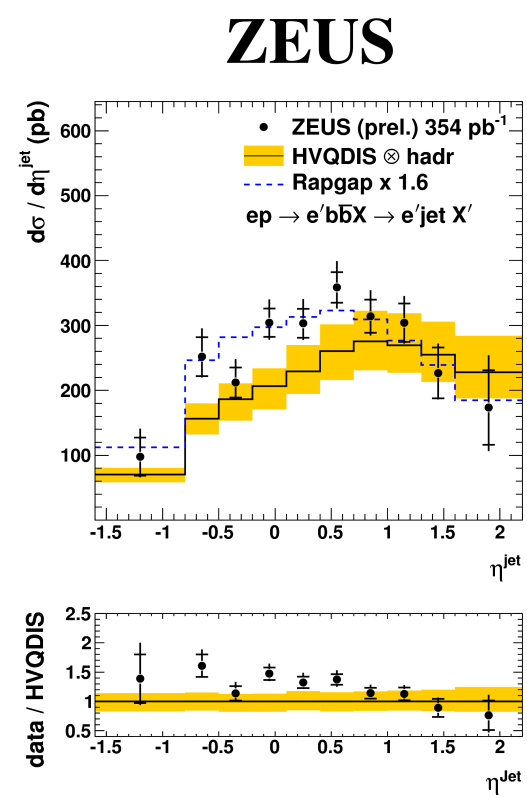
DESY-10-083

- Exclusive: b → e



- Inclusive measurement:





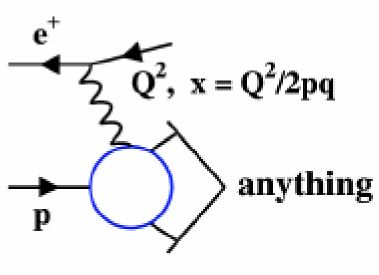
- Good agreement between data and NLO QCD calculation (HVQDIS) observed in different kinematical regions.

DESY-11-005, ZEUS-prel-10-004

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

- F_2 structure function of the proton:

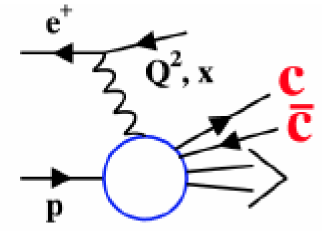
$$\frac{d^2\sigma}{dx\,dQ^2} = \frac{2\pi\alpha^2}{x\,Q^4}\cdot[(1+(1-y)^2)F_2 - y^2 F_L]$$



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

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

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



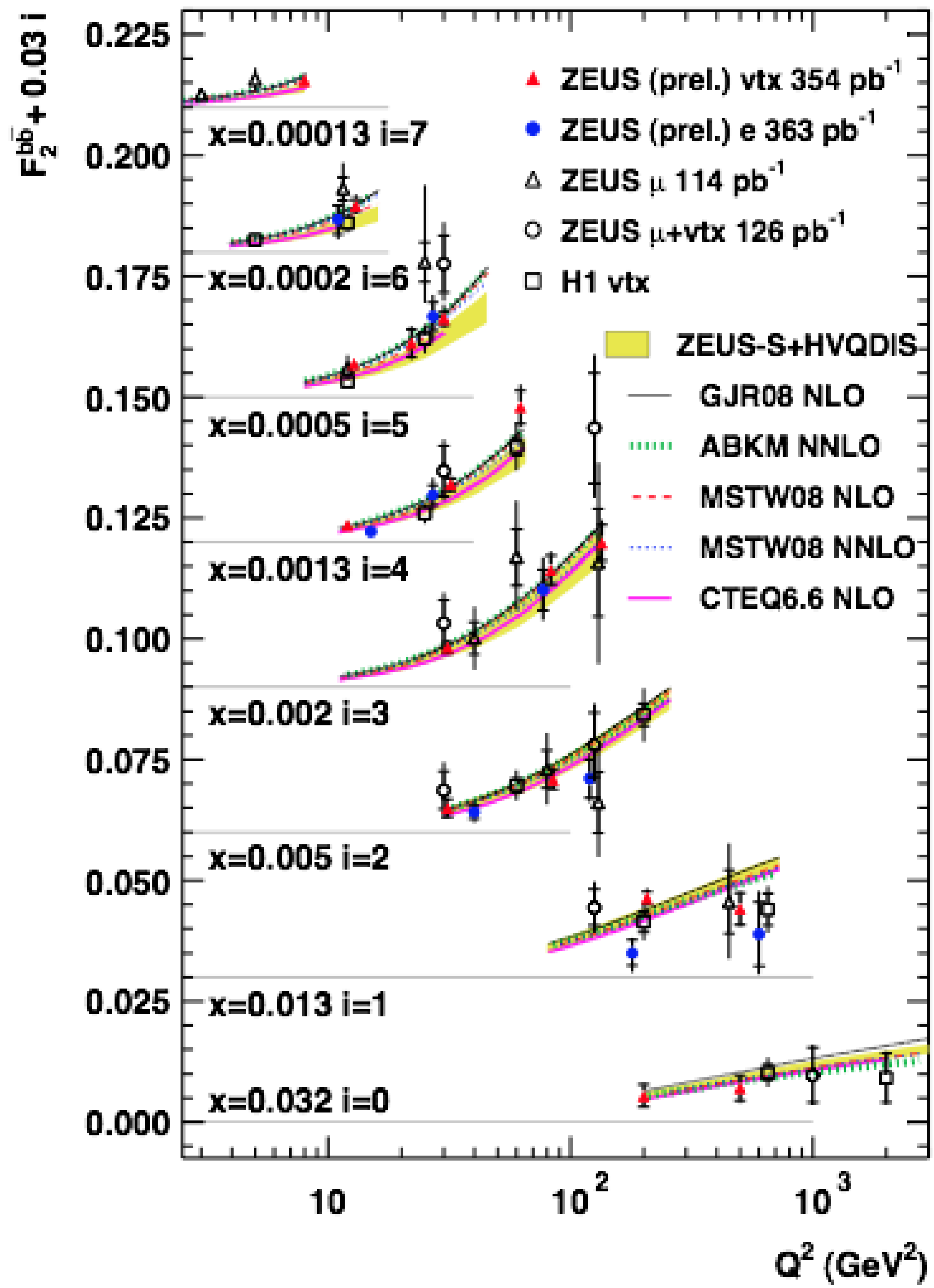
$$\frac{d^2\sigma^{ep\to c\bar{c}x}}{dx\,dQ^2} \propto F_2^{c\bar{c}}(x, Q^2)$$

- 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}) :

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

F_2^{bb} measurement

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



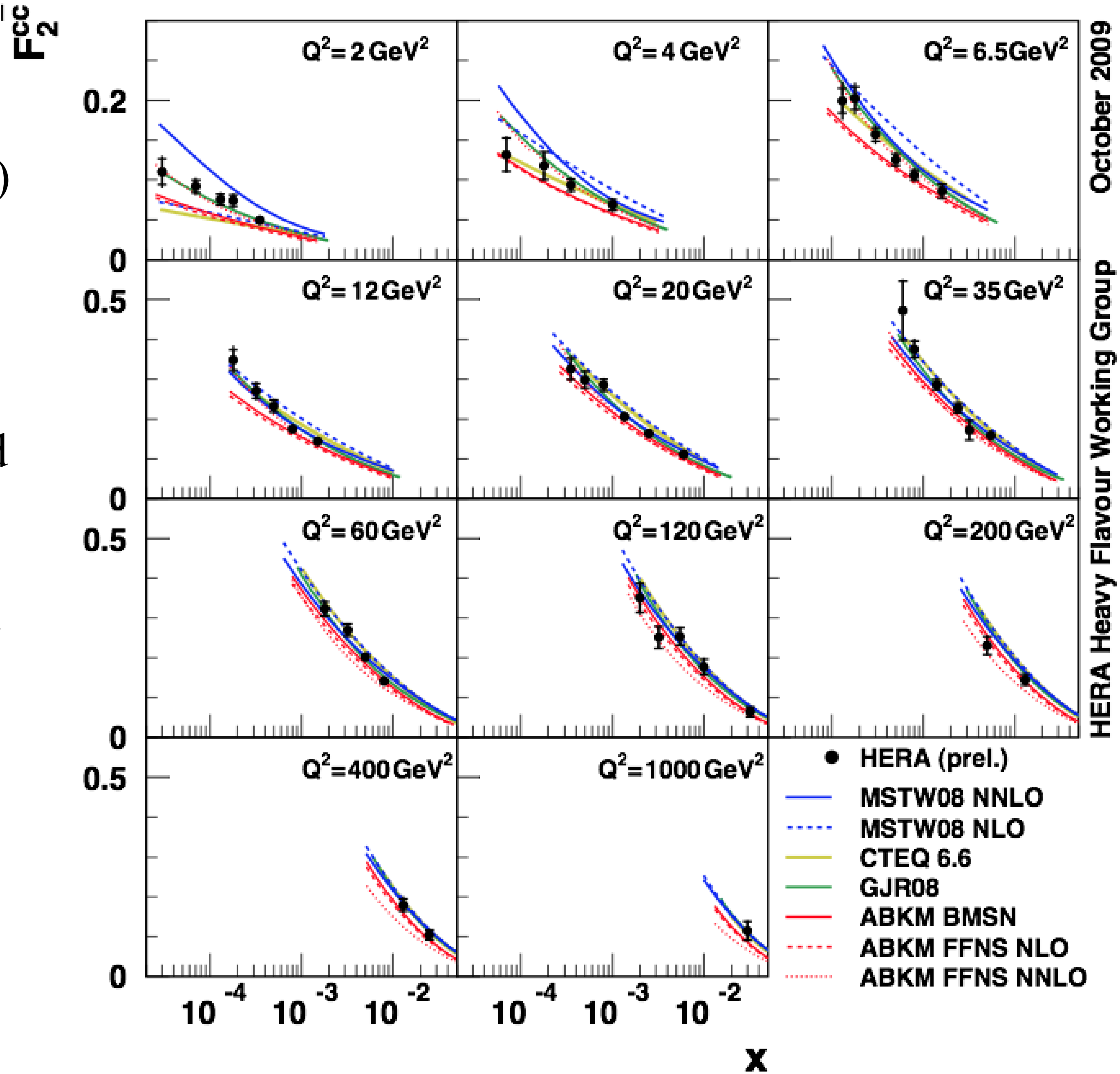
- Data are compatible within uncertainties.
- NLO predictions able to describe the data.

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

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

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

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



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

Summary

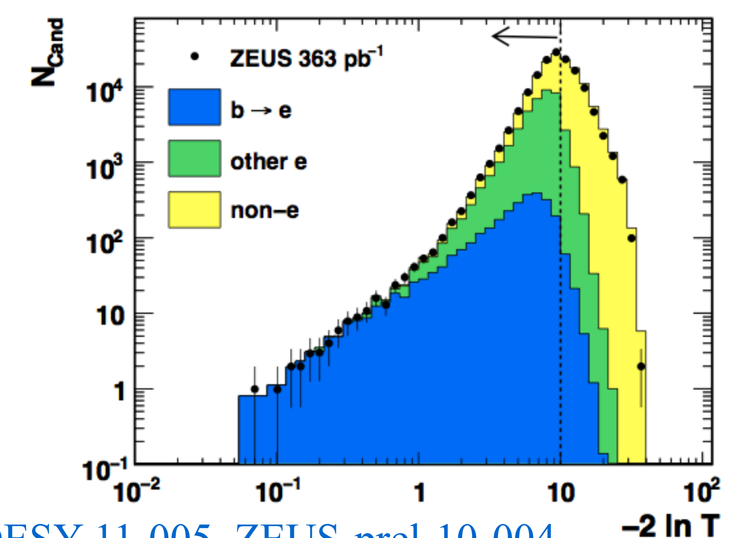
- Heavy flavour production at HERA allows to test QCD at different scales.
- The heavy flavor measurements of ZEUS and H1 using different experimental techniques and having different systematics are in good agreement.
- The data is in general in a good agreement with NLO pQCD predictions.

Backup

- Exclusive: b → e

Phase Space
$10\ GeV^2 < Q^2$
Events with a jet and an electron with:
$0.9\ GeV^2 < p_T^e < 8\ GeV^2$

Heavy Quark tagging:
Semileptonic decays
Likelihood test function T based on:
- Decay length significance
- p_T of electrons w.r.t. Jet
- $\Delta\phi$ between p_T^{miss} and electron



DESY-11-005, ZEUS-prel-10-004

- Inclusive measurement.

Phase Space
$5GeV^2 < Q^2 < 1000GeV^2$, $0.02 < y < 0.7$
Events with least 2 jets with:
$E_T^{jet} > 5\ GeV$

Heavy Quark tagging:
Reconstruction of secondary vertices:
- Decay length significance
- Mass of tracks associated with the secondary vertex, m_{vtx}