Heavy Flavour Production at HERA

BEACH 2012 Conference

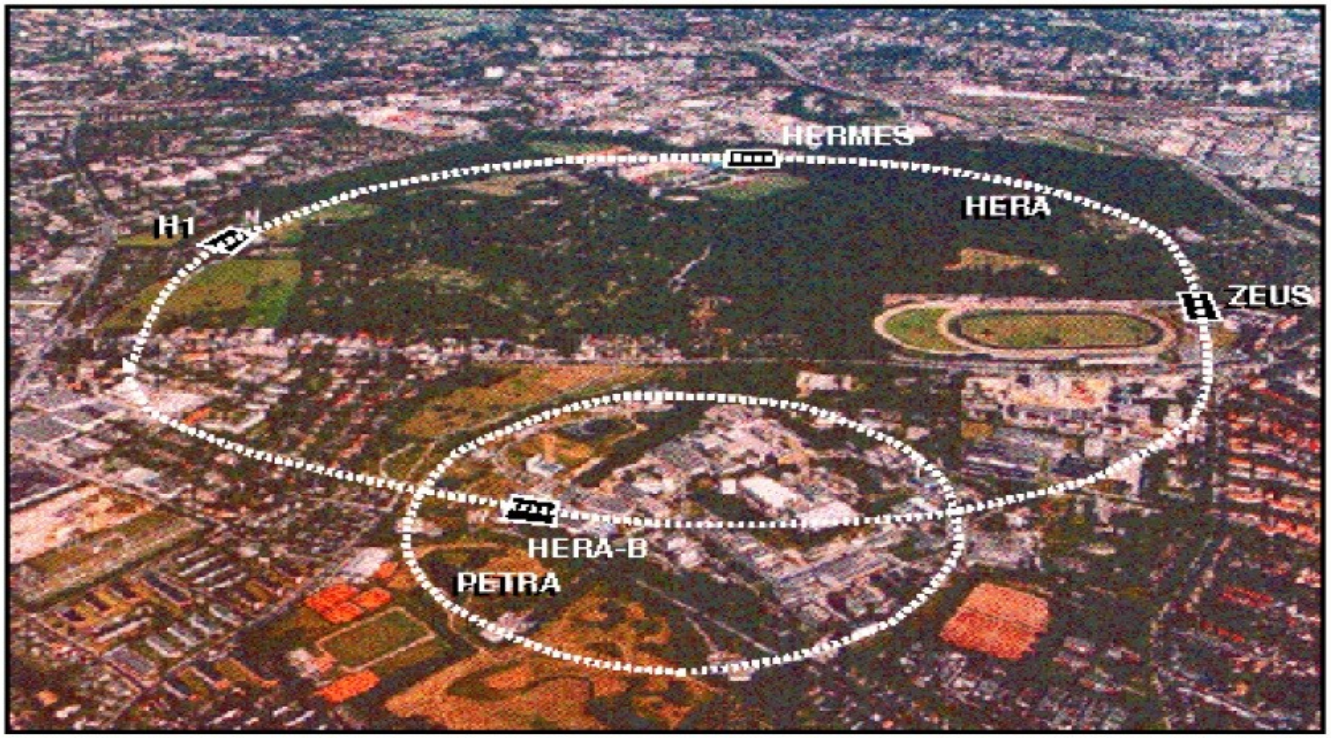
Kenan Mujkic

24 July 2012

Outlook

- Introduction
- Photoproduction
- Deep Inelastic Scattering (DIS)
- Summary

HERA Accelerator



- HERA world's first and to date only lepton proton collider
- ep interactions at centre-of-mass energy of 320 GeV^2

Motivation

Why studying heavy flavour physics at HERA ?

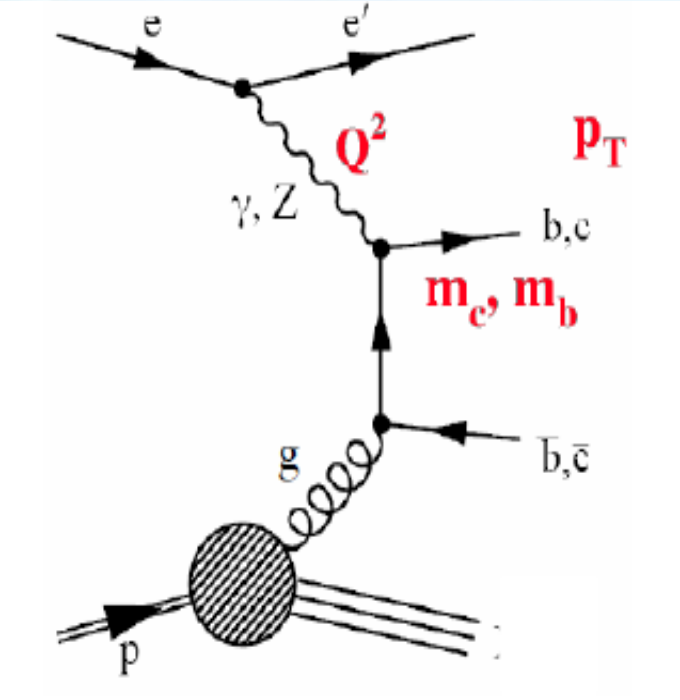
- HERA physics allows for precision tests of perturbative QCD and constrains quark and gluon density inside the proton
- Heavy Quark Production might help to distinguish between different theoretical approaches to include mass effects in perturbative QCD
- Heavy Quark Cross Sections constitute a significant Standard Model background to searches for new physics at the LHC

Heavy Flavour Production at HERA

- At HERA Boson-Gluon-Fusion (BGF) dominant production mechanism for heavy flavours

- Event Kinematics:

$$Q^2 = -q^2 = -(k-k')^2$$
$$y = (q \cdot p) / (k \cdot p)$$
$$x = Q^2 / (2\, p \cdot q)$$



- Kinematic Regimes:

Photoproduction: $Q^2 \approx 0\ \mathrm{GeV}^2$

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

Motivation to Measure Heavy Flavour Production

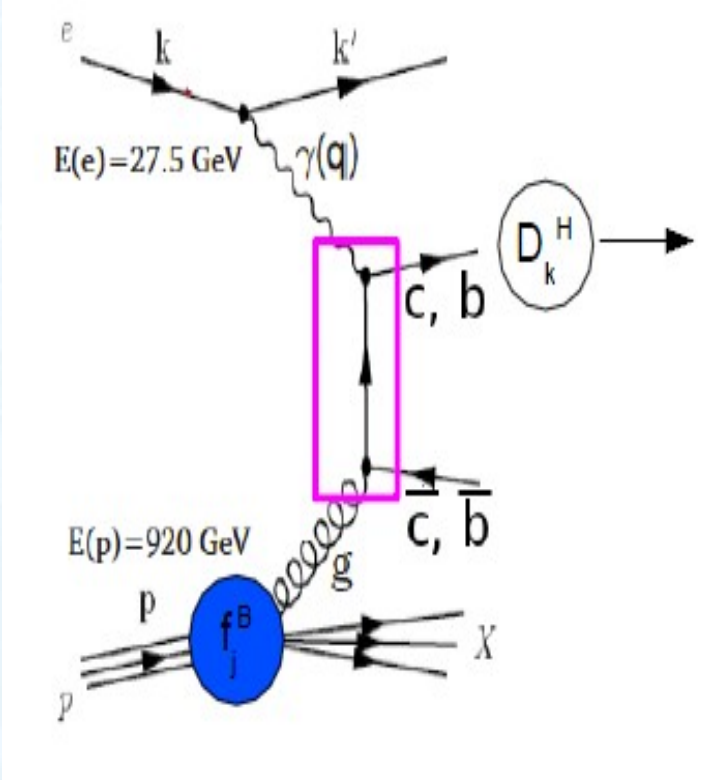
- Factorisation Theorem:

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

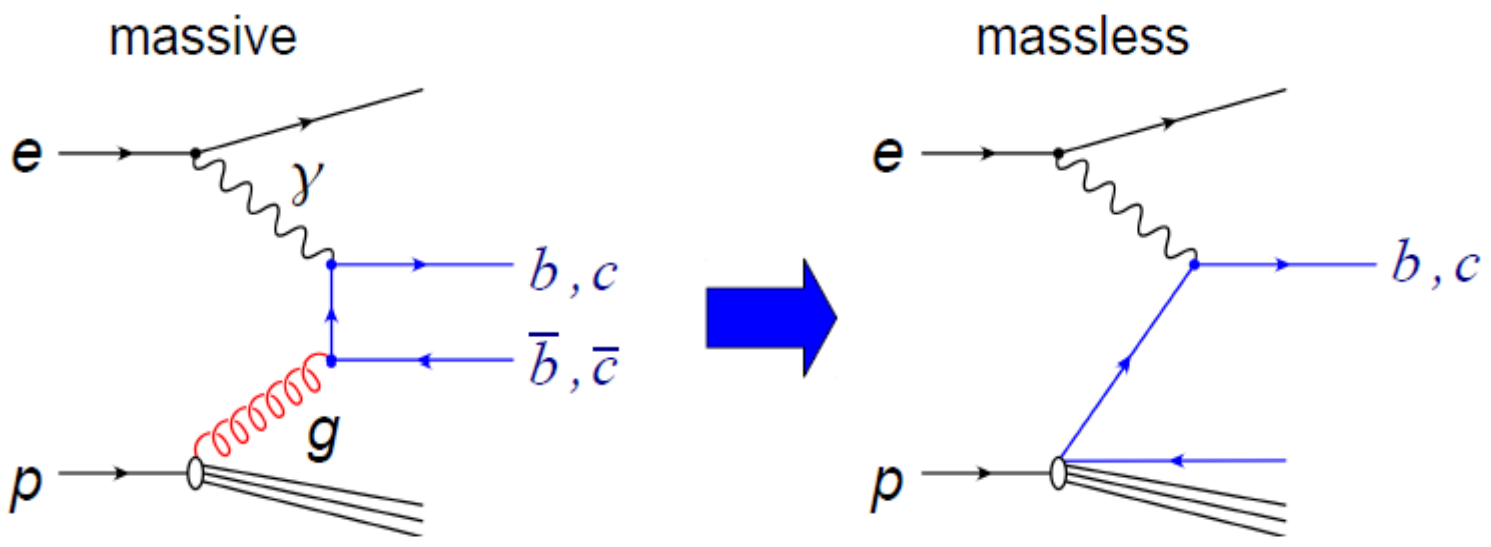
Parton density function (from global fits) — pQCD matrix element — Fragmentation function (from ee data)

- HFL production constrains quark and gluon density inside the proton

- For a given parton density HFL measurements constitute precision tests of QCD



Mass treatment in pQCD



Fixed Flavour Number Scheme	General Mass Variable Flavour Number Scheme	Zero Mass Variable Flavour Number Scheme
valid at low Q^2	transition	valid at high Q^2

Heavy Flavour Tagging

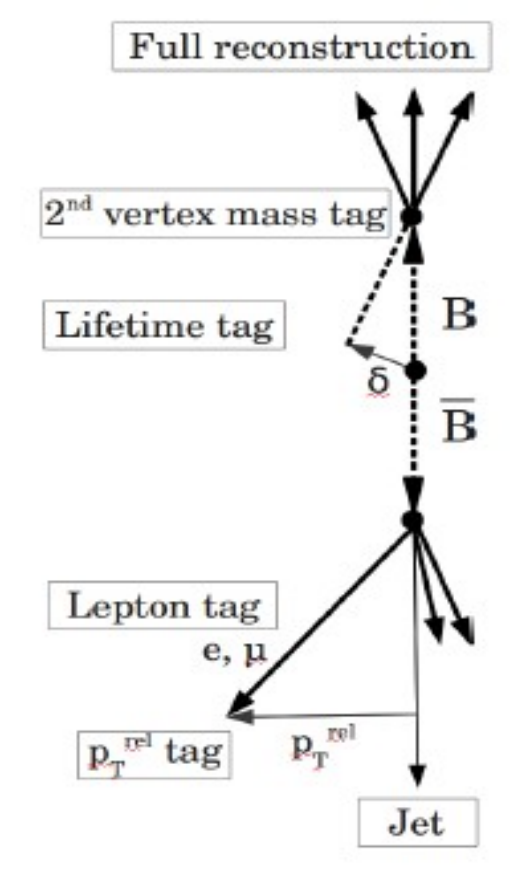
- Production rates behave like:
  $\sigma(b) : \sigma(c) : \sigma(uds) \approx 1 : 50 : 2000$

- Charm and beauty enrichment requires the application of various techniques:

  1.) Full reconstruction
  2.) Lepton tagging
  3.) pT(rel) tagging
  4.) Lifetime tagging
  5.) Vertex mass tagging

- Analyses discussed today include:

  1.) D*: full reconstruction
  2.) Low pT analysis: electron tagging
  3.) Muon analysis: lifetime techniques
  4.) Inclusive analysis: combined techniques

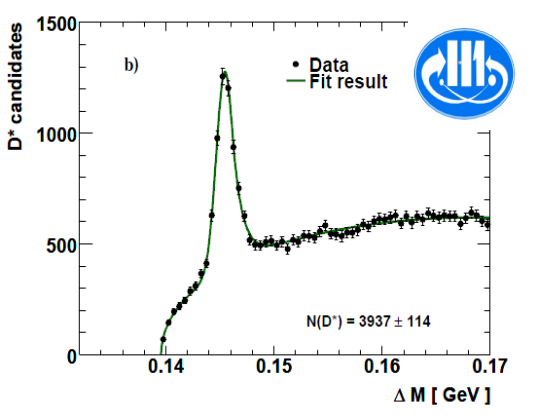


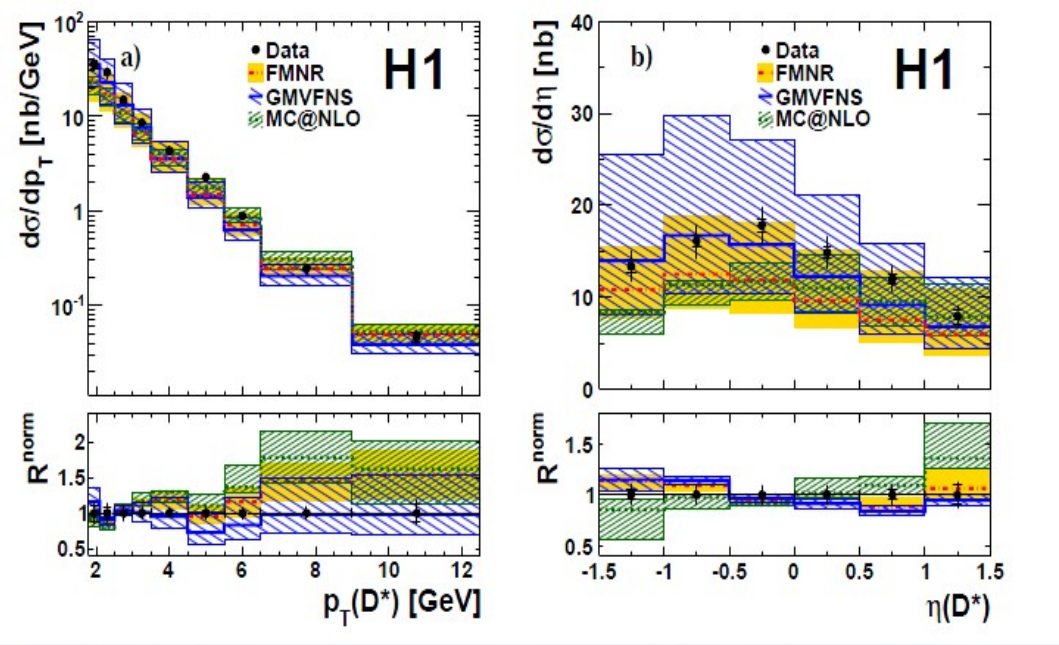
Charm in photoproduction with D*

Charm Tagging:

- Full reconstruction of decay:

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





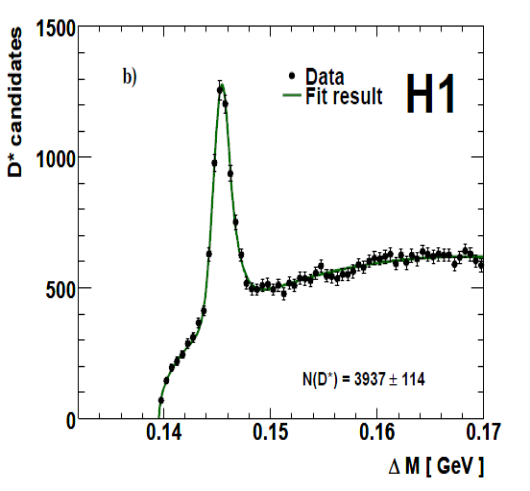
- High precision of data compared to MC simulation and NLO predictions

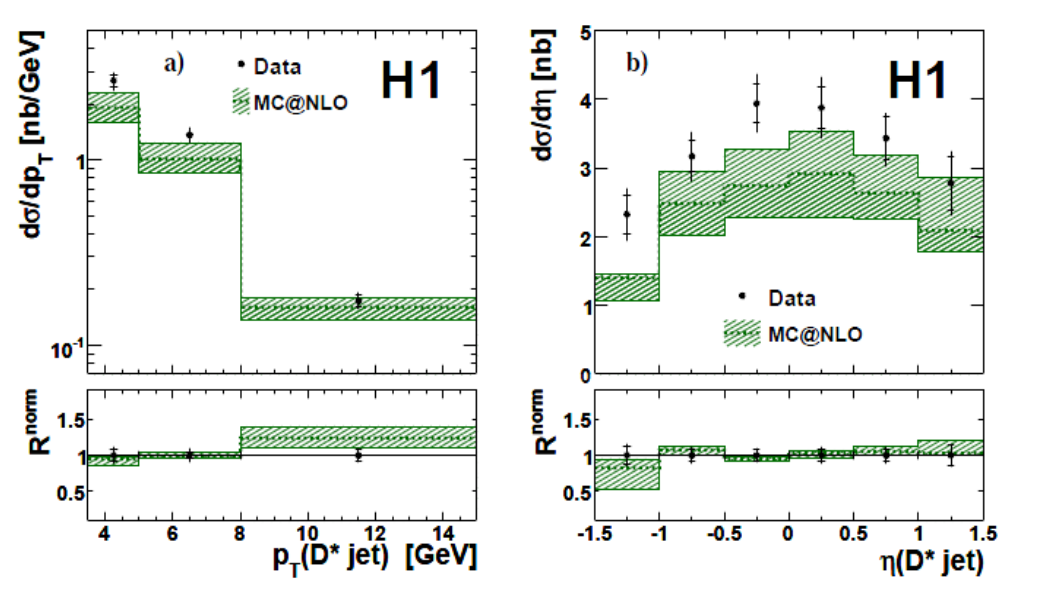
Eur. Phys. J. C72 (2012) 1995

Charm in photoproduction with D* and dijets

Charm Tagging:

- Full reconstruction of D* candidate
- Require 2 jets with pT(jet1) > 3.5 GeV





Data tends to overshoot NLO predictions, reasonable agreement within uncertainties

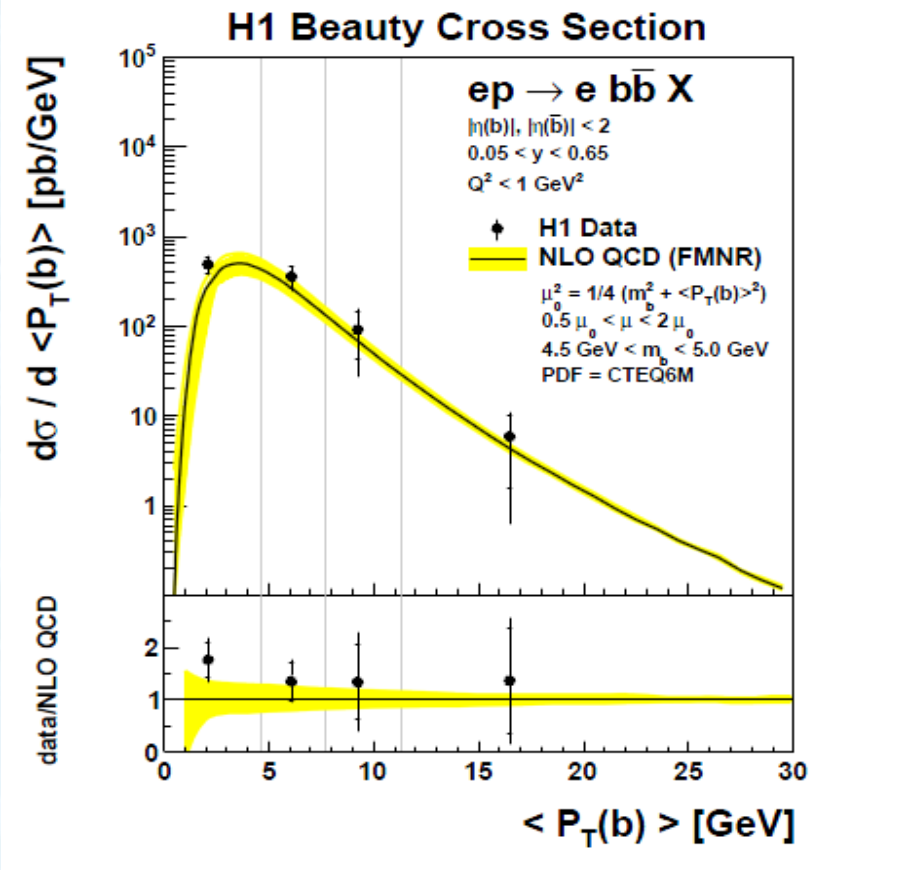
Eur. Phys. J. C72 (2012) 1995

Beauty with di-electrons in photoproduction near threshold

Focus of analysis:

- Low pT(b-quark)
- b-tagging with two low pT electrons

- Good agreement with NLO QCD predictions
- Measurement of cross section extends to lowest pT(b) values ever measured in ep collisions

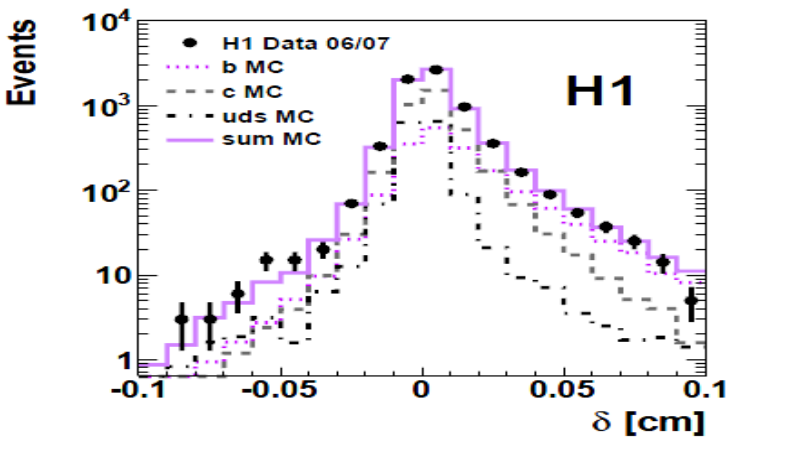


DESY 12-072, submitted to EPJC

Beauty in photoproduction with dijets and muons

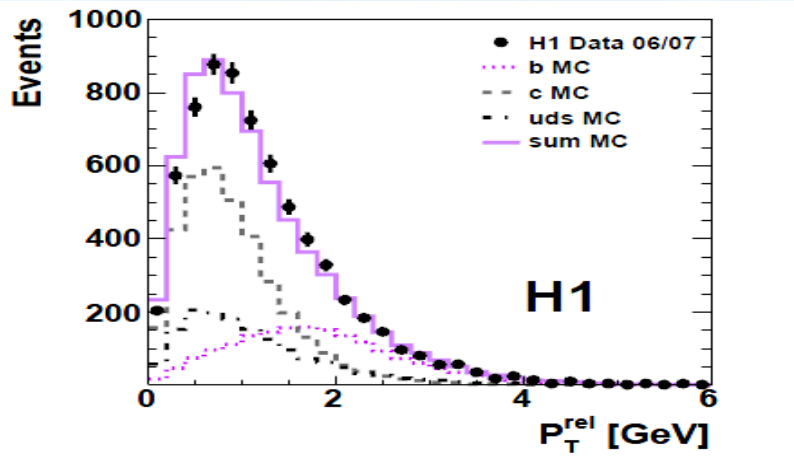
Signal Extraction:

- pT(rel) to muon jet
- Impact parameter
- 2D template fit

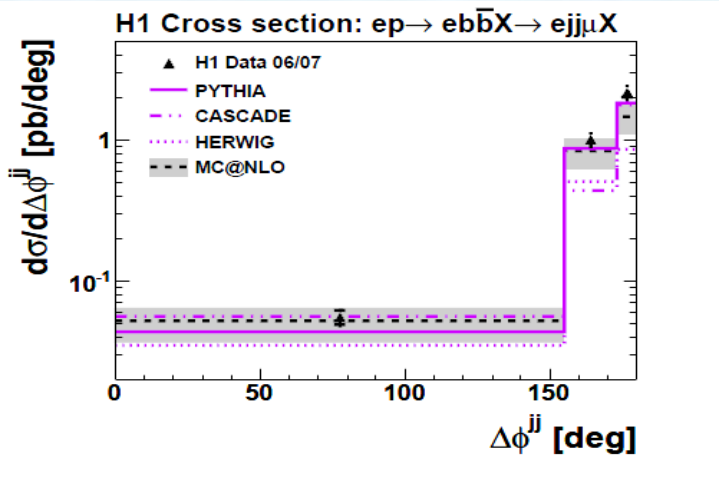


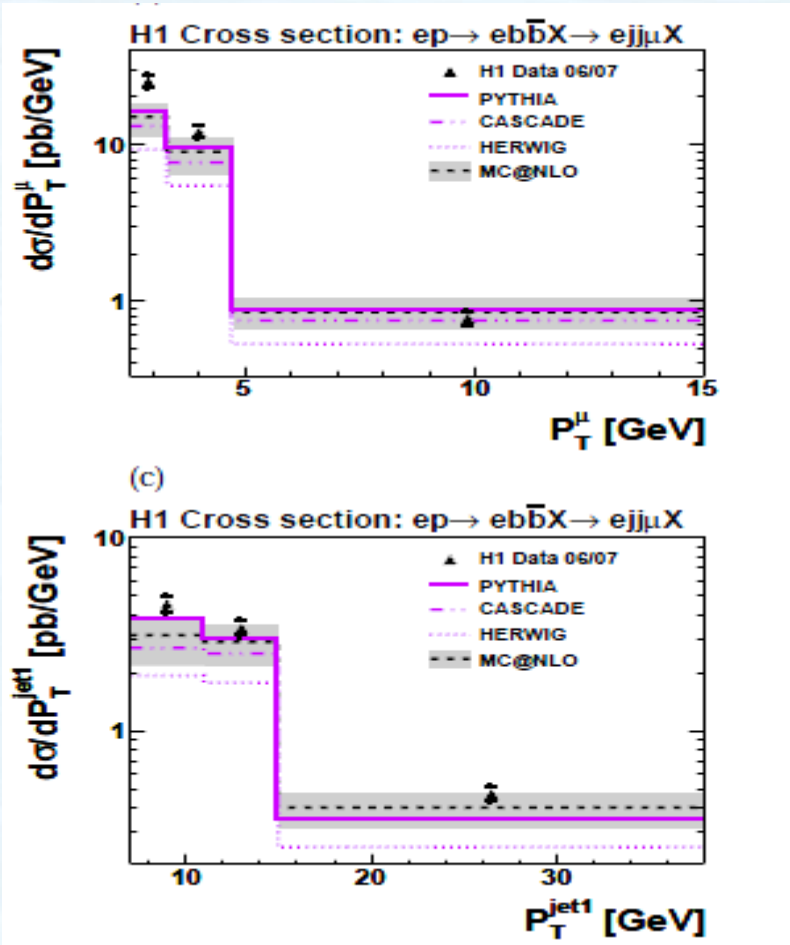
Event selection:

- 2 jets pT(jet) > 7(6) GeV
- 1 muon, pT(rel) > 2.5 GeV



Beauty in photoproduction with dijets and muons





- Data in agreement with NLO and MC predictions
- dphi sensitive to higher orders in pQCD

DESY 12-059, accepted by EPJC

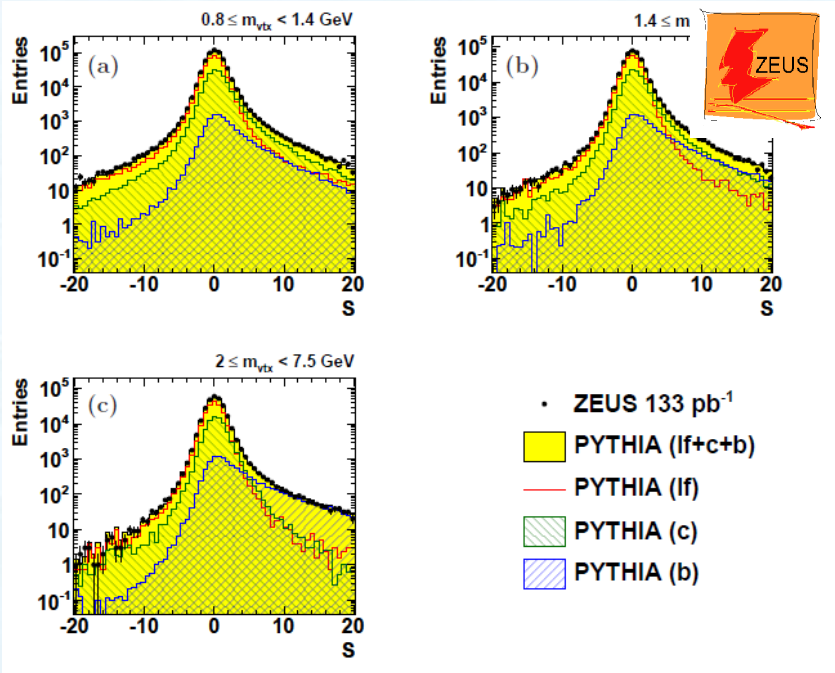
Beauty with dijets and secondary vertices in photoproduction

Heavy Flavour Tagging:

- Decay length significance
- Secondary vertex mass

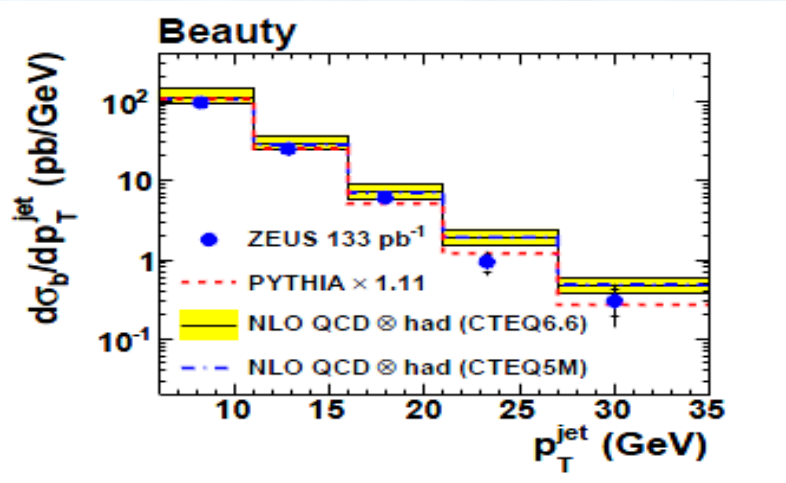
Event Selection:

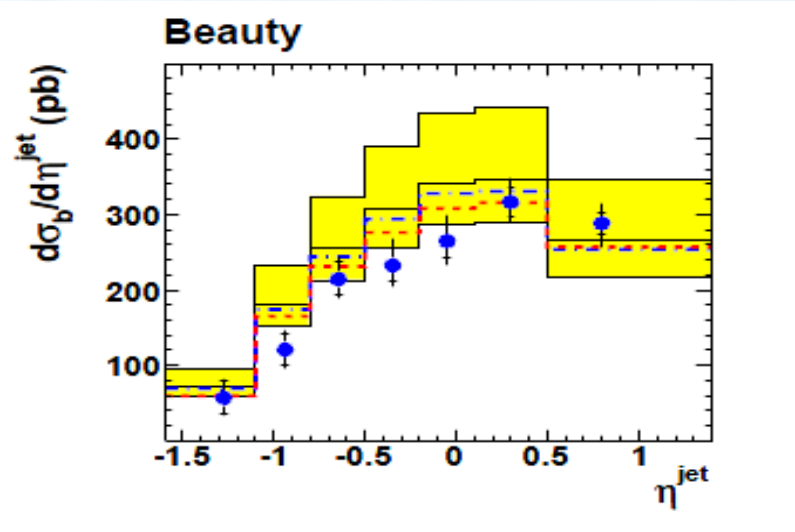
- Require at least 2 jets with pT(jet) > 7(6) GeV



Eur. Phys. J. C. (2011) 71:1659

Beauty with dijets and secondary vertices in photoproduction

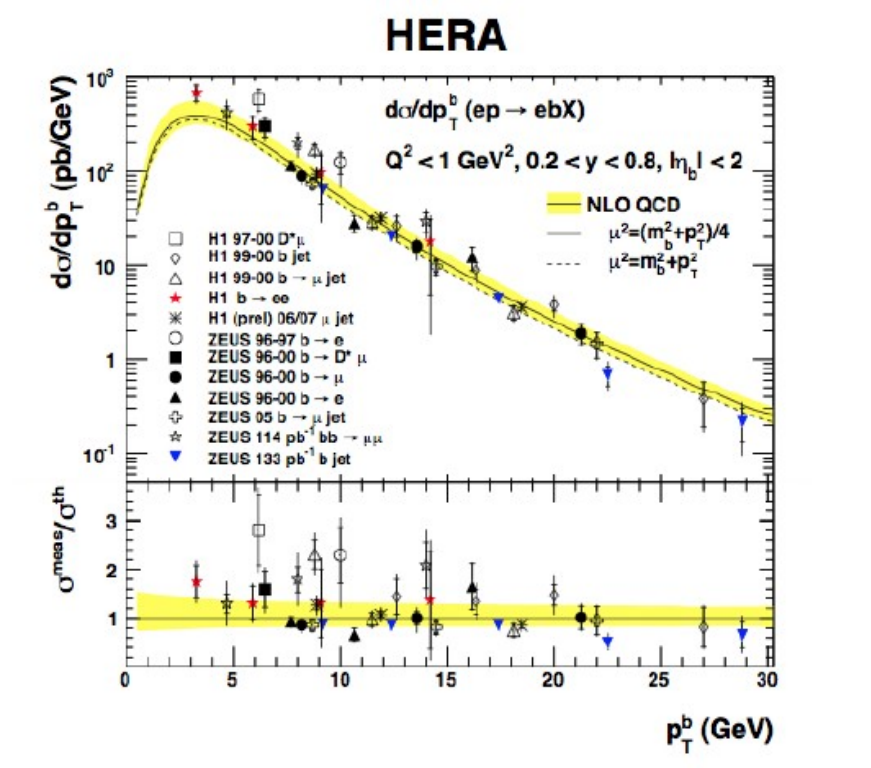




- Data and MC agree within large theory uncertainties

- Renormalisation scale dominant uncertainty for NLO QCD predictions

Beauty with dijets and secondary vertices in photoproduction



Eur. Phys. J. C. (2011) 71:1659

- Good agreement with previous measurements and NLO predictions for both scales

- *Note*: Extension of measurement to lower values of <pT(b)> than previous measurements

Charm from D+ and Λ+ decays at low pT in Deep Inelastic Scattering

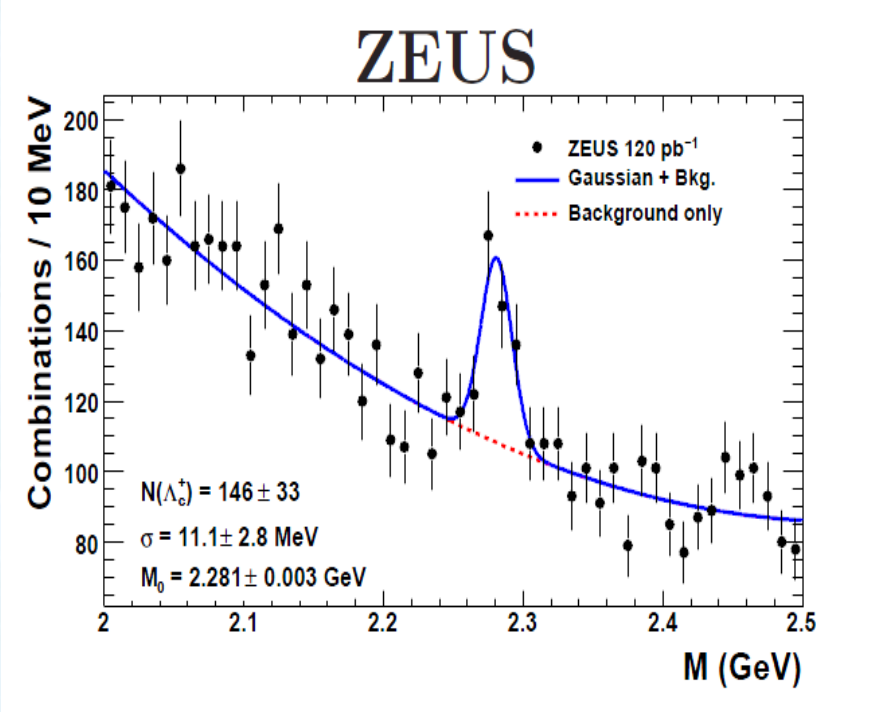
Full reconstruction:

$$D^+ \rightarrow K_S^0 \pi^+$$

$$\Lambda_c^+ \rightarrow p K_S^0 \qquad \Lambda_c^+ \rightarrow \Lambda \pi^+$$

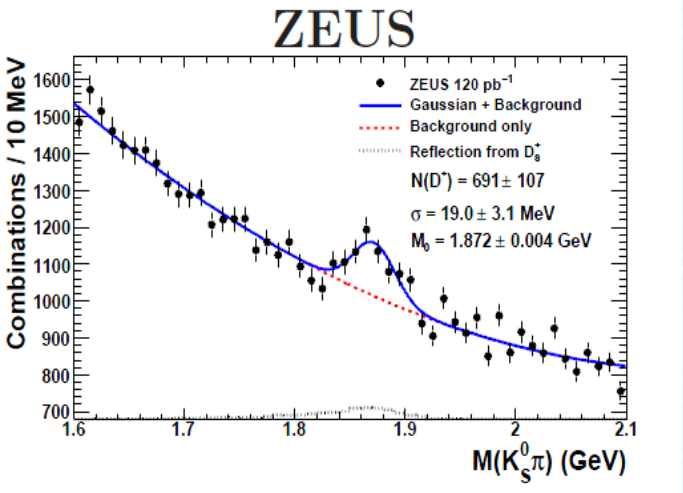
Event Selection:

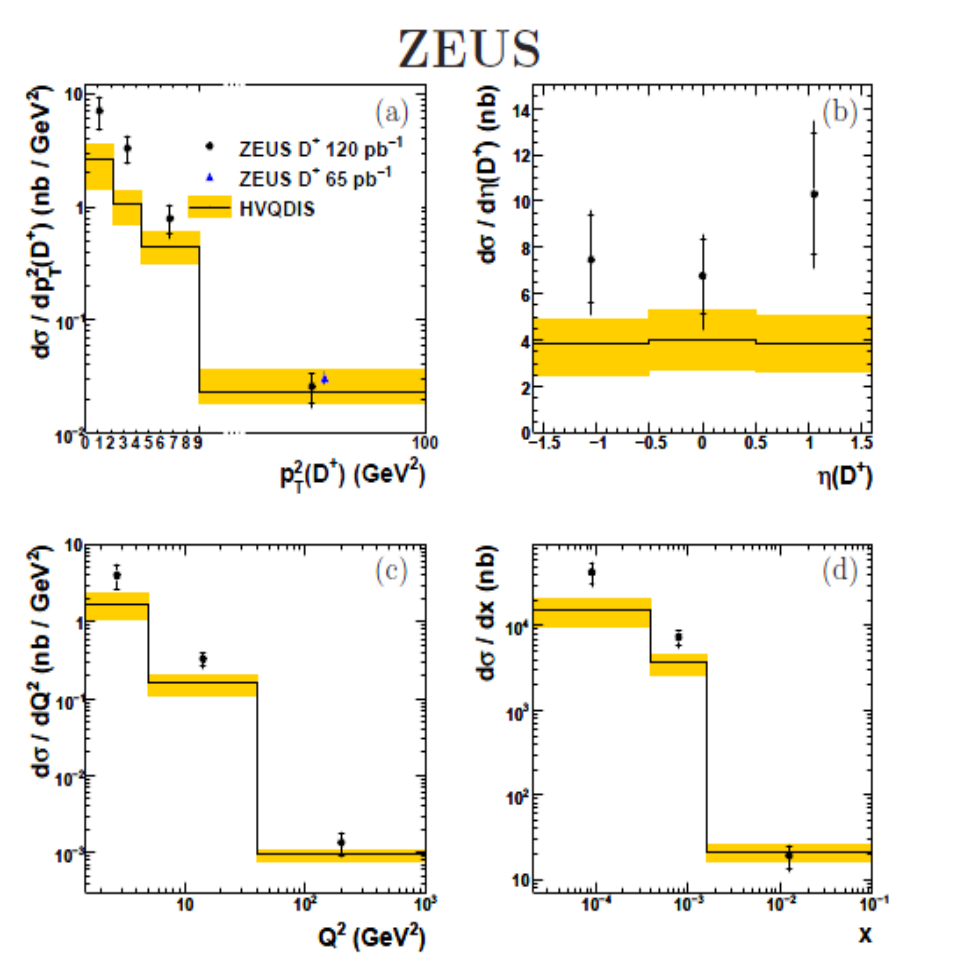
- Q^2 > 1 GeV^2 (DIS)
- 0 < pT(D+, Λ+) < 10 GeV



Note: Presence of neutral strange particle allows for extensions towards low pT region

Charm from D+ and Λ+ decays at low pT in Deep Inelastic Scattering

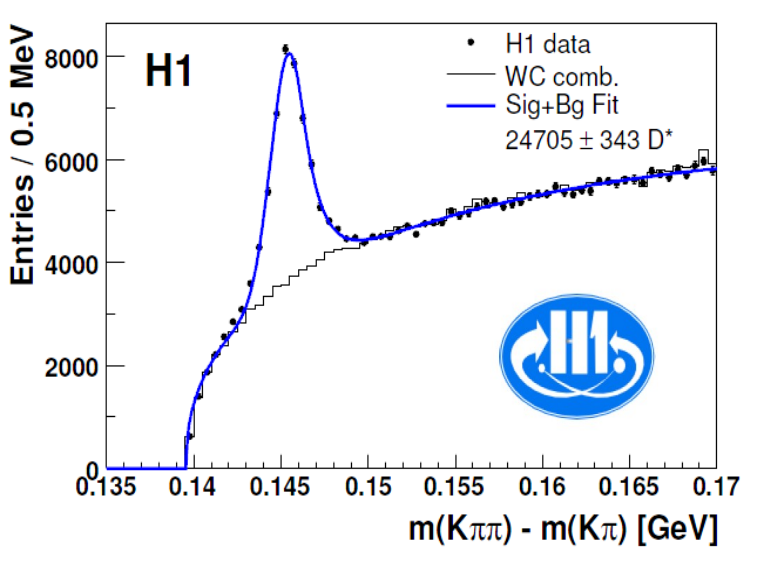


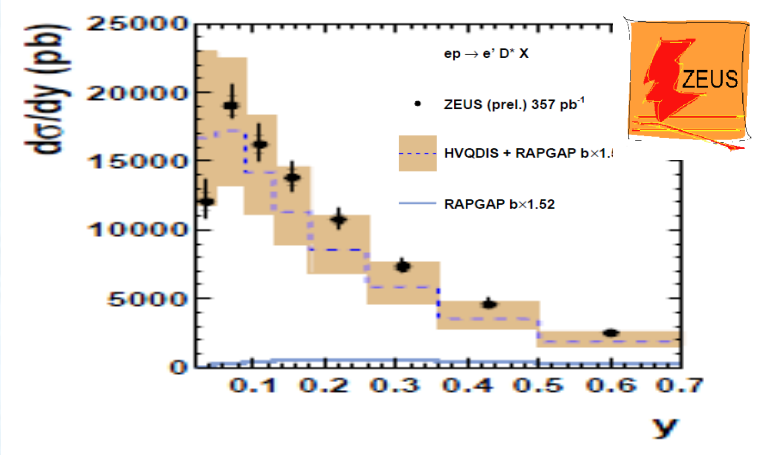


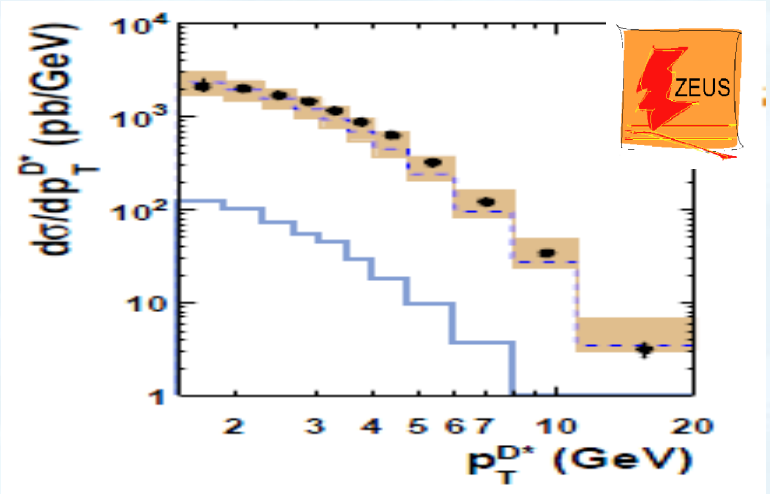
- Differential cross sections in reasonable agreement with NLO predictions

Eur. Phys. (2012) 009

Charm with D* at low Q2 in Deep Inelastic Scattering

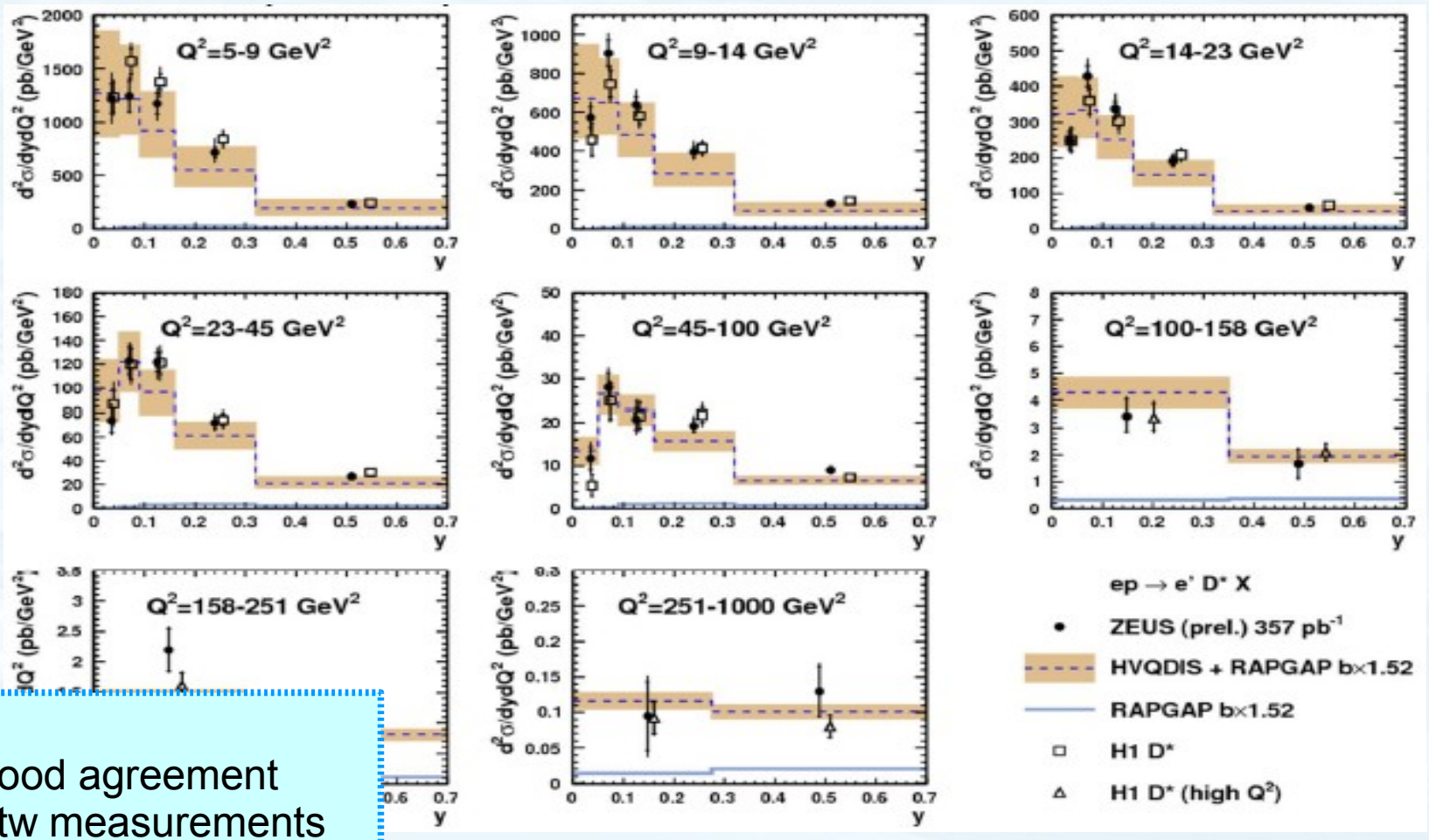






- H1 publication: DESY 14-066
- Zeus-prel-12-003
- Good agreement with NLO

Charm with D* at low Q2 in Deep Inelastic Scattering

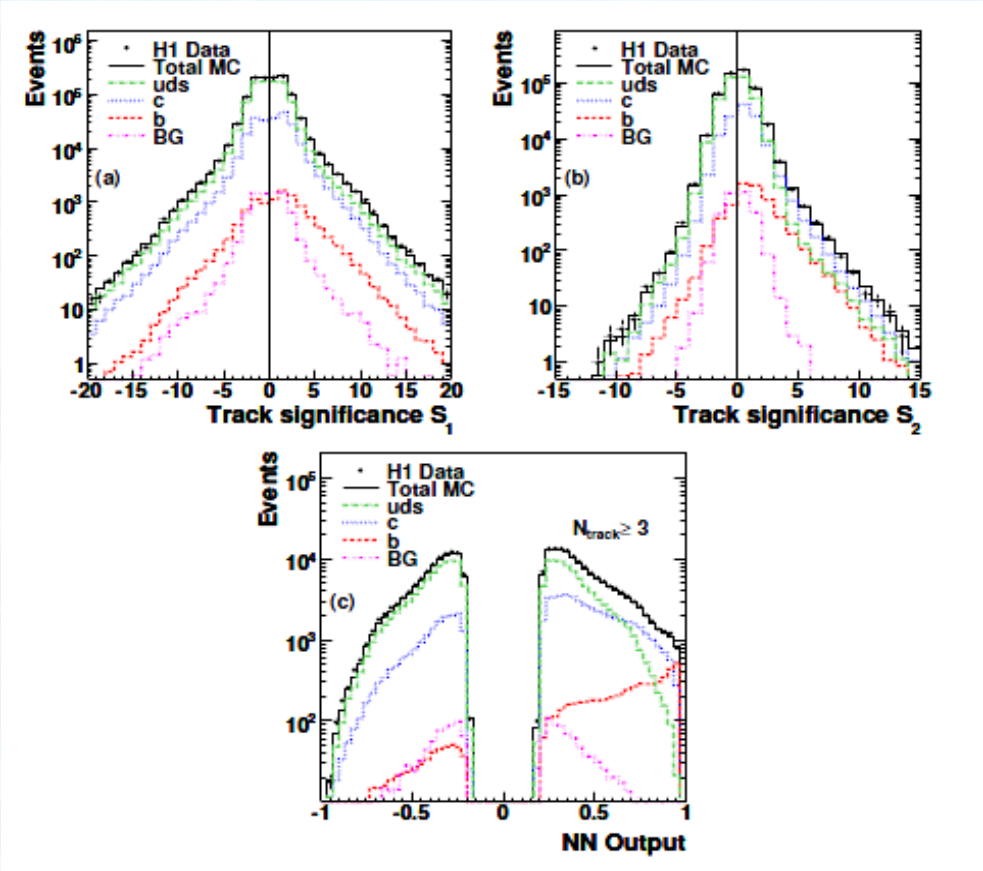


Good agreement
btw measurements

Inclusive measurements of charm jets in Deep Inelastic Scattering

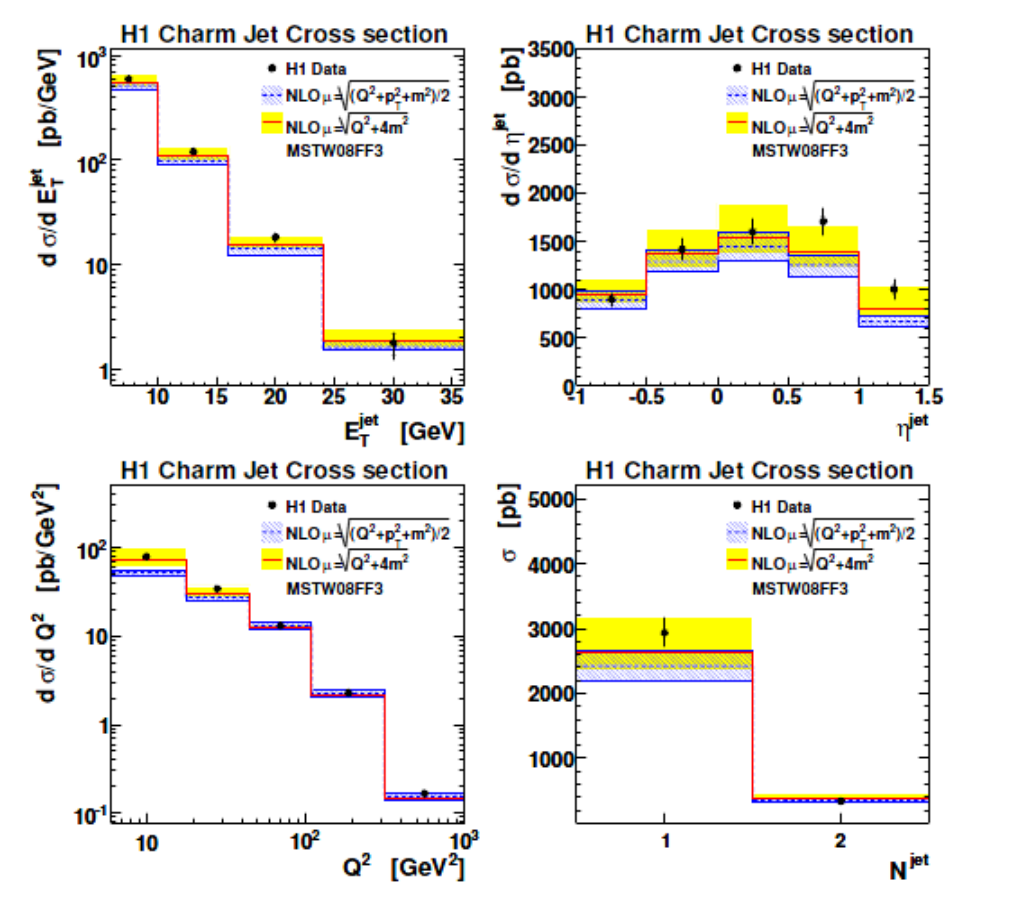
Event Selection:

- Impact parameter
- Neural network output



Eur. Phys. J. C71 (2011) 1509

Inclusive measurements of charm jets in Deep Inelastic Scattering



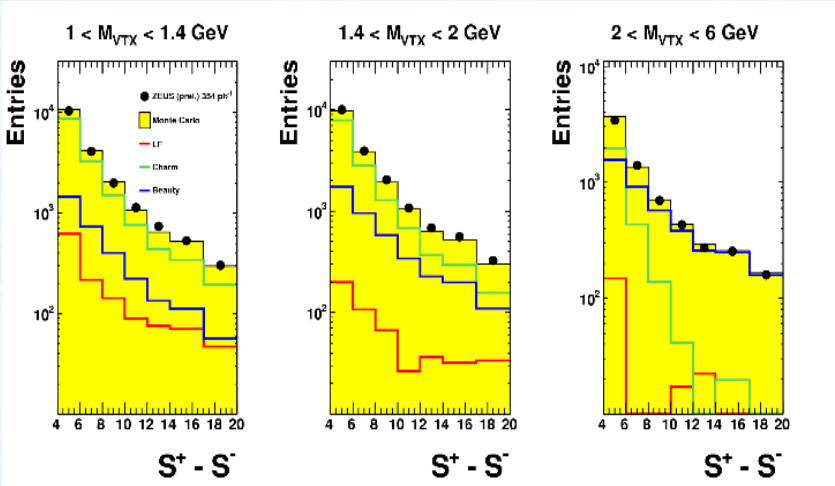
- Agreement between data and NLO prediction depends on choice of renormalisation scale

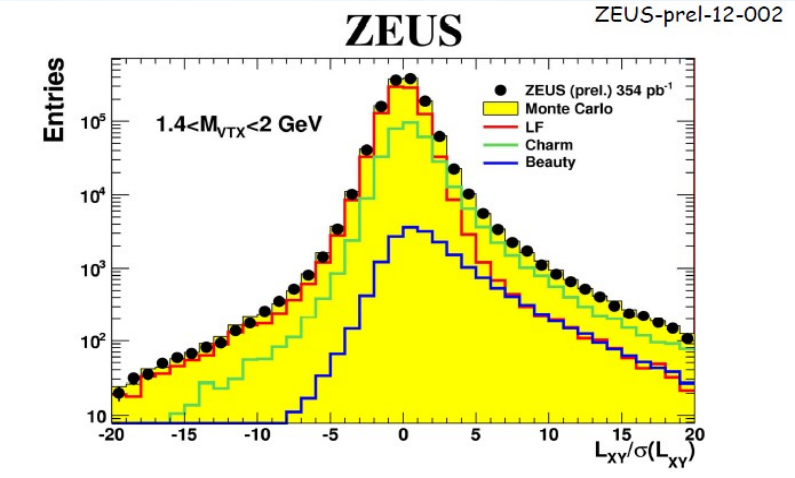
- High precision of data compared to theoretical uncertainties from NLO QCD calculations => data constrains theory

Charm jets from inclusive secondary vertices in Deep Inelastic Scattering

Signal Extraction:

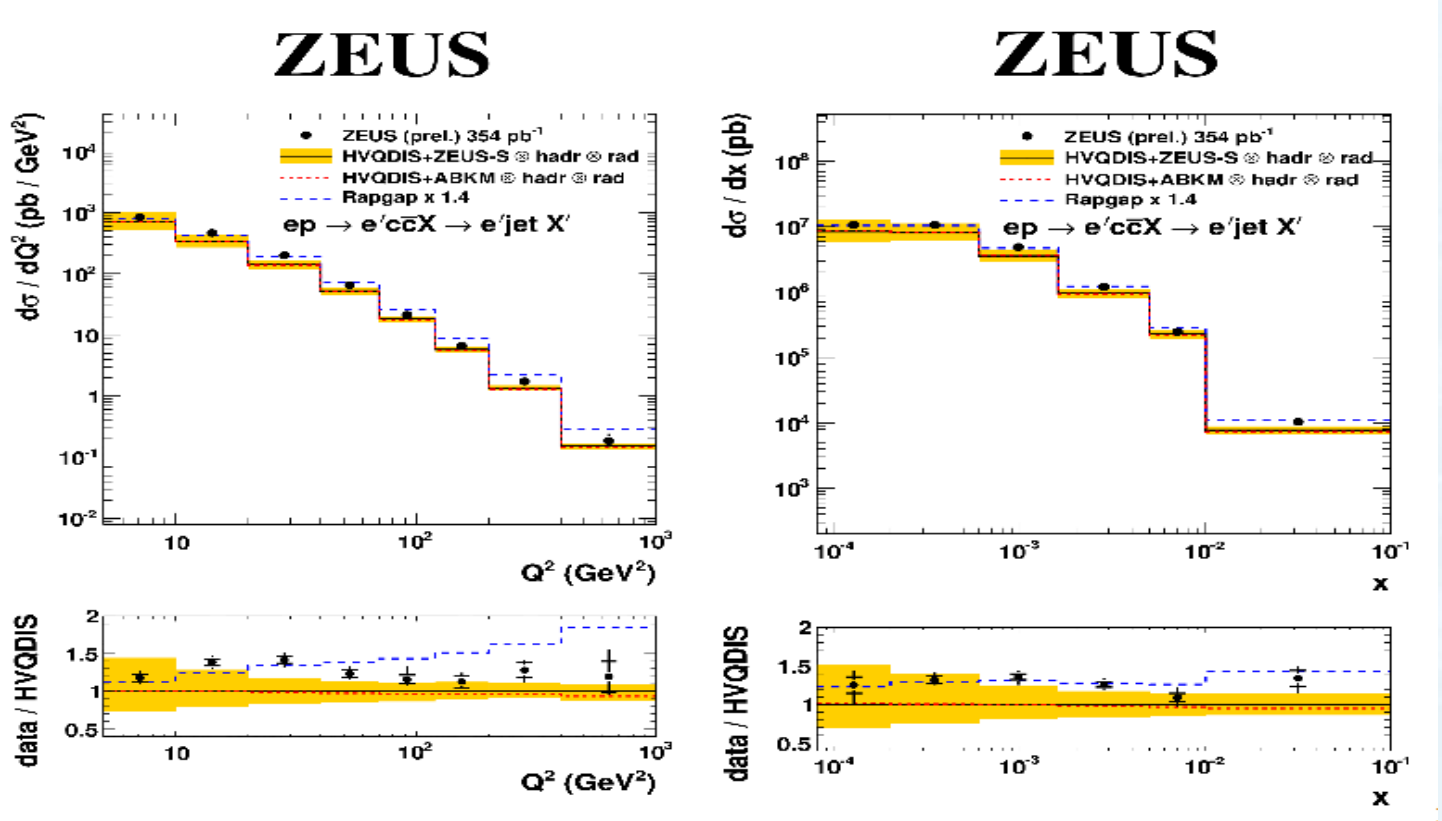
- Secondary vertex decay length
- Secondary vertex mass





ZEUS-prel-12-002

Charm jets from inclusive secondary vertices in Deep Inelastic Scattering



Reasonable agreement with NLO QCD predictions

Charm jets from inclusive secondary vertices in Deep Inelastic Scattering

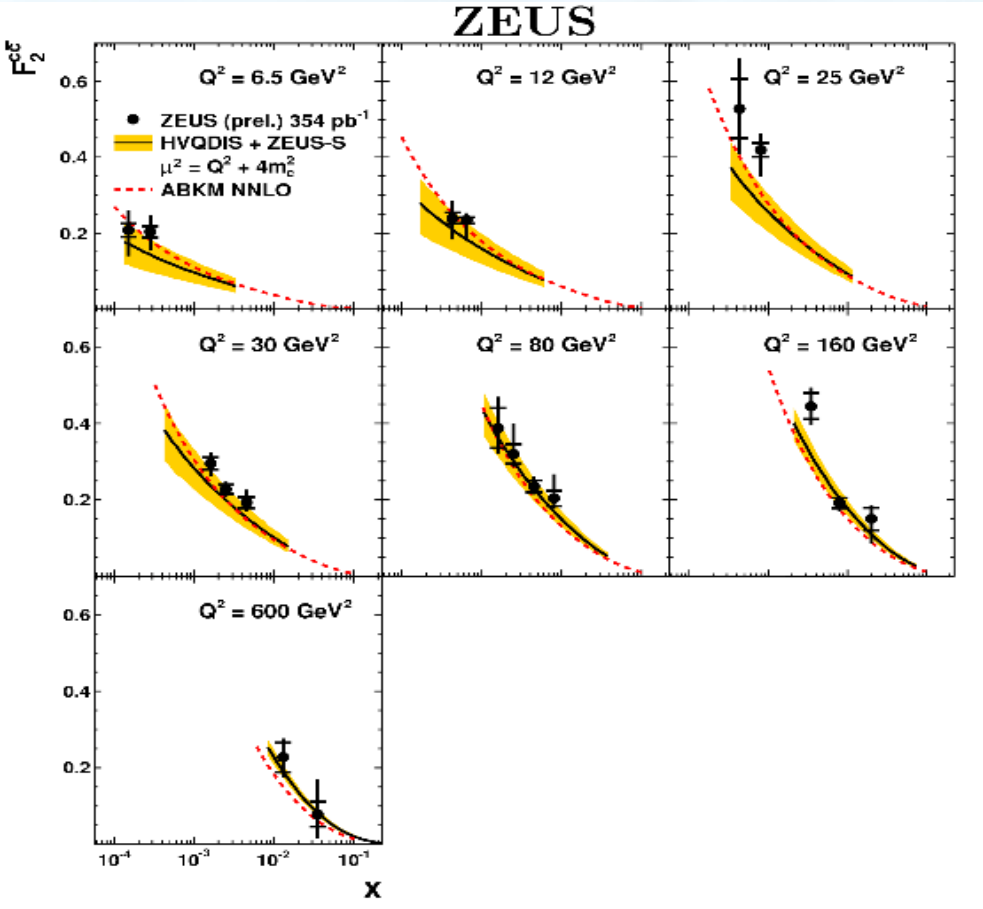
- Charm Contribution to the Proton Structure Functions:

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

- NLO predictions used for extrapolation from visible cross sections to full phase space:

$$F_2^{c\bar{c}}(\exp)=\frac{\sigma_{vis}(\exp)}{\sigma_{vis}(theory)}F_2^{c\bar{c}}(theory)$$

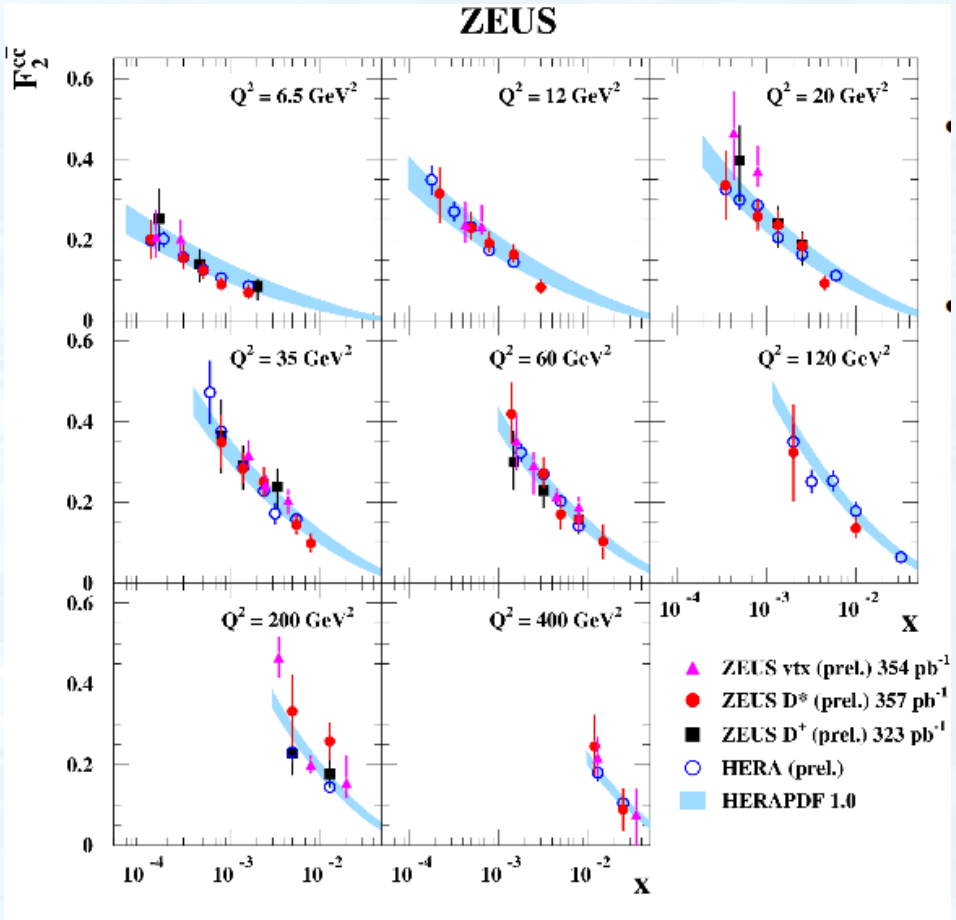
Charm jets from inclusive secondary vertices in Deep Inelastic Scattering



- Good agreement with NLO predictions
- Highest precision in middle x and Q^2 range
- Large extrapolation uncertainties at low Q^2

ZEUS-prel-12-002

Charm jets from inclusive secondary vertices in Deep Inelastic Scattering



- Comparison with previous measurements shows reasonable agreement
- Results will contribute to H1 and ZEUS combination

ZEUS-prel-12-002

Fragmentation Fractions

Fragmentation describes the transition from partons to hadrons.

The fragmentation fraction

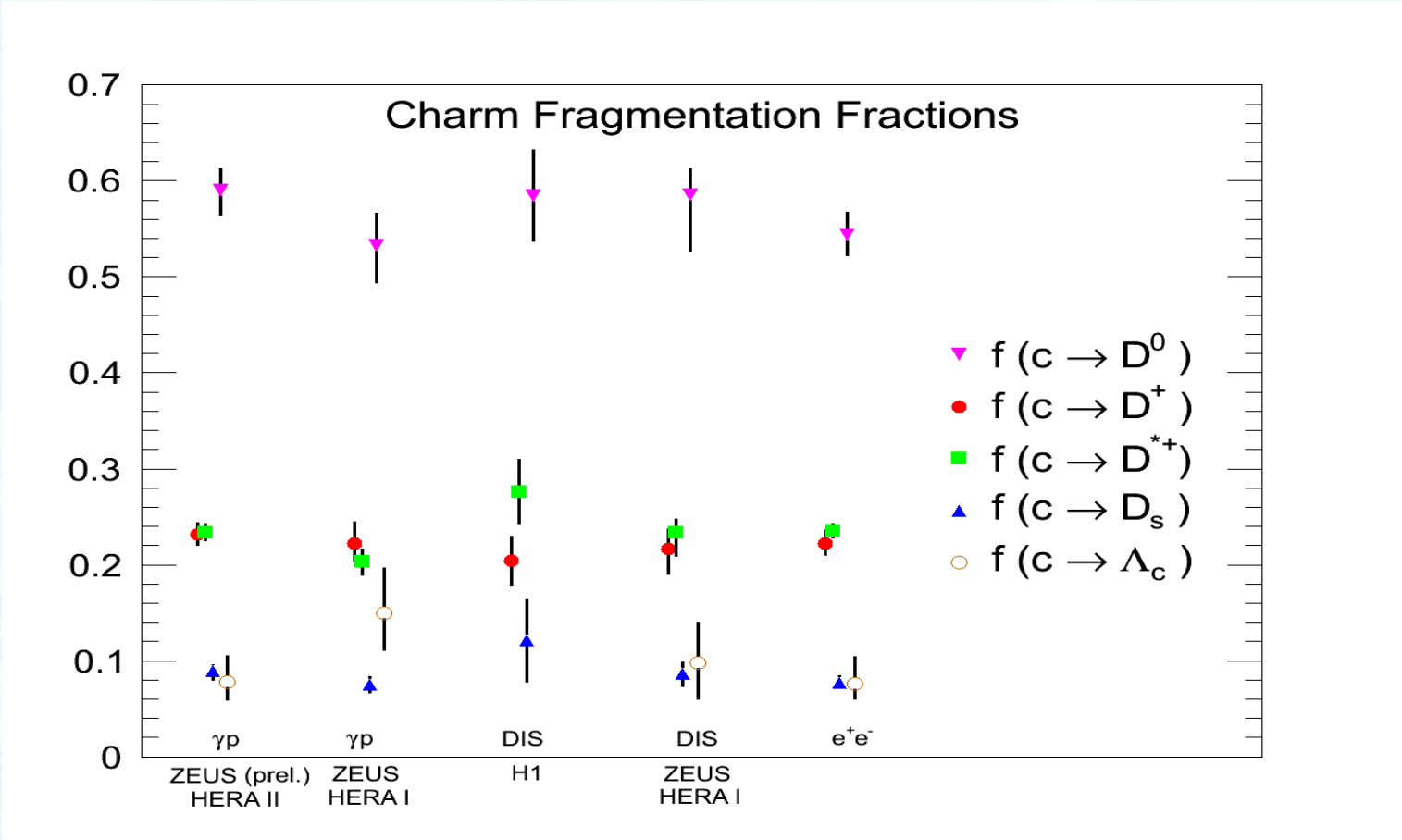
$$f(c \to D, ..., \Lambda) = \frac{\sigma_{D,...,\Lambda}}{\sigma_{gs}}$$

describes the probability of the charm quark to hadronise into a particular charm meson, where

- $\sigma_{D,...,\Lambda}$ denotes production cross section for hadron $D, ..., \Lambda$
- σ_{gs} denotes sum of all production cross sections of weakly decaying charm mesons

Question: Are the fragmentation fractions universal?

Fragmentation Fractions



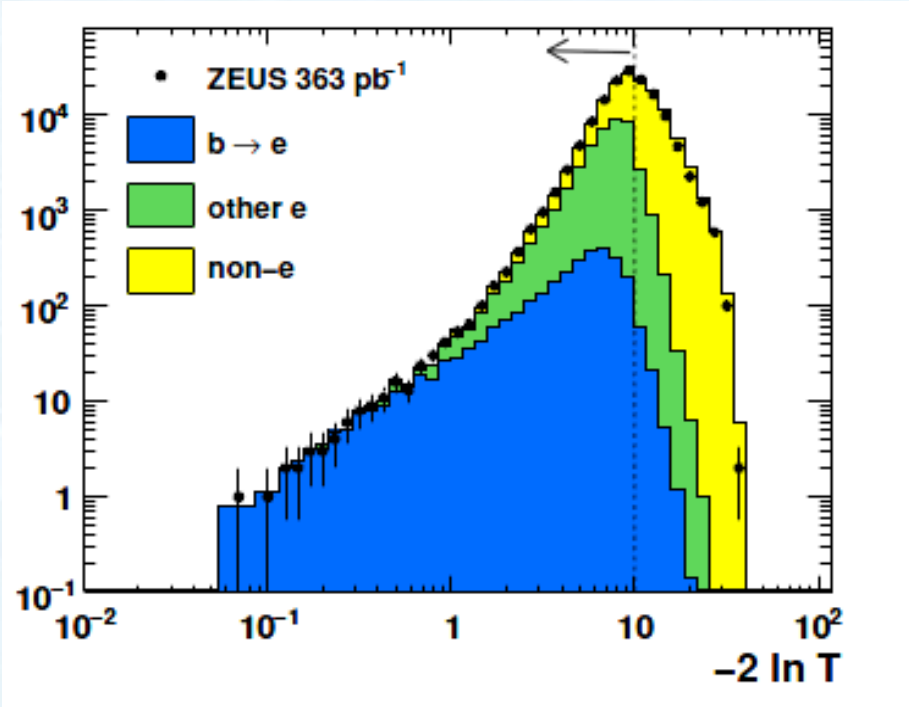
Zeus-prel-12-003

Beauty from decays into electrons in Deep Inelastic Scattering

Signal Extraction:

- Reconstruction of b-decays into electrons
- Likelihood ratio technique

- Electron decay mode allows for extensions towards low pT region

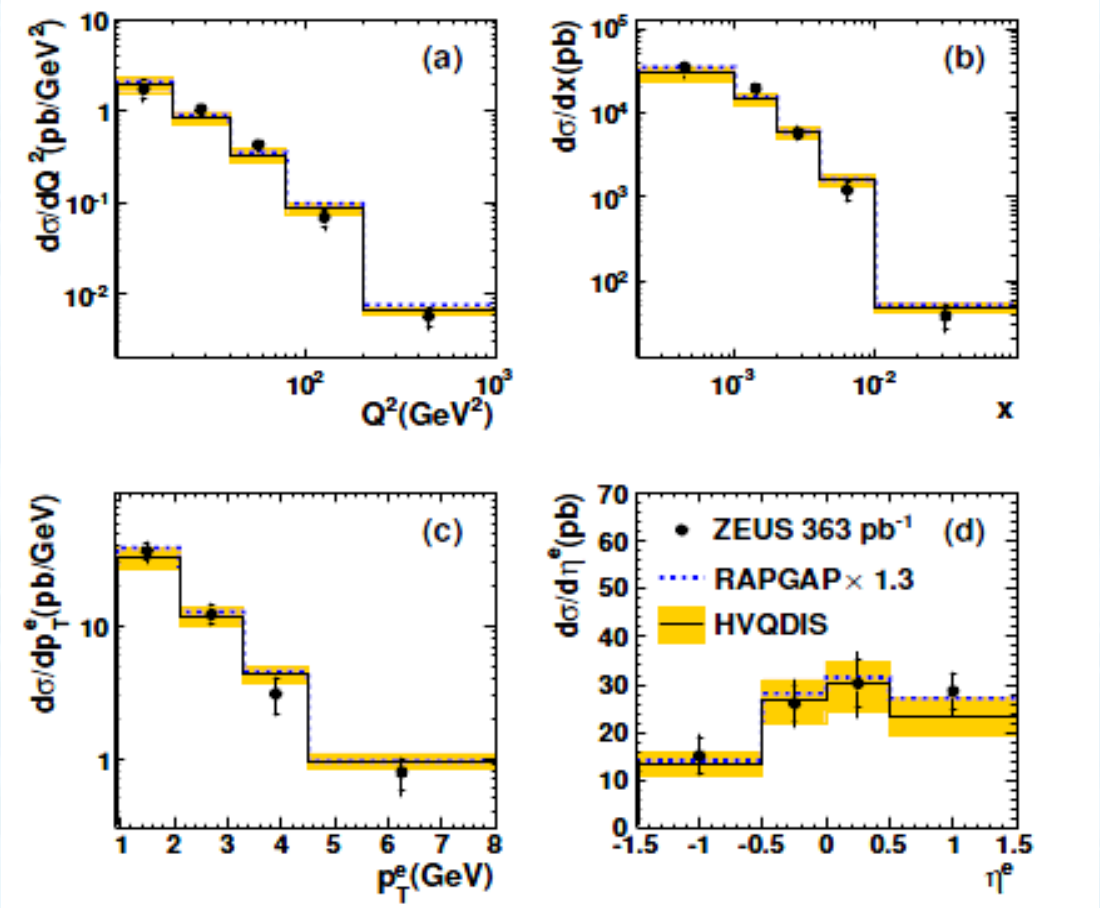


Eur. Phys. J. C. (2011) 71:1573

Beauty from decays into electrons in Deep Inelastic Scattering

- NLO predictions describe the data reasonably

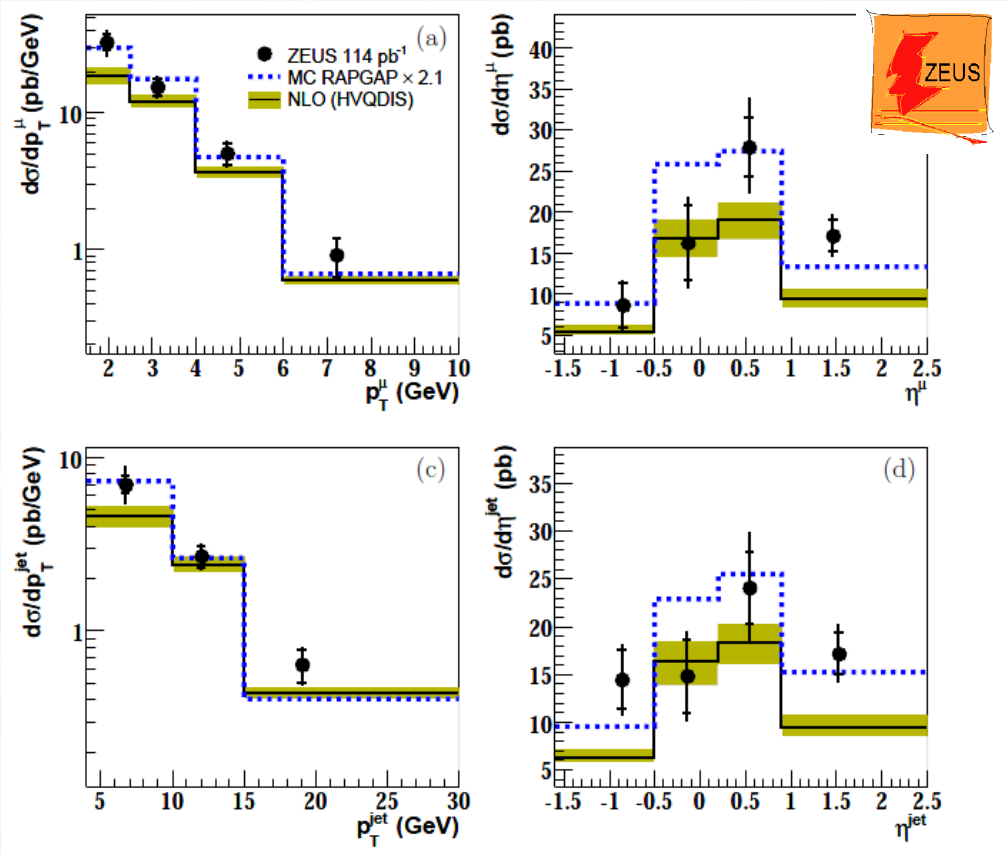
- Analysis benefited from improved tracking and reconstruction of decay length of b-hadrons



Beauty with muon and jets in Deep Inelastic Scattering

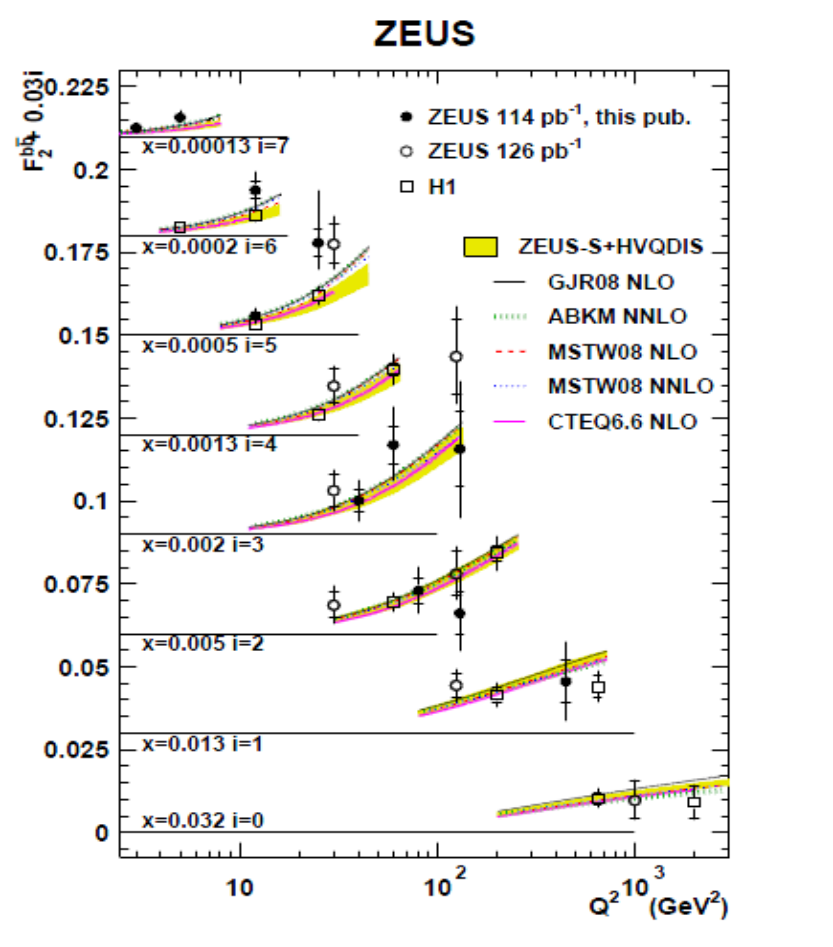
- Require muon and jet
- use pT(muon) rel to jet

- Data in reasonable agreement with MC and NLO predictions
- At low Q^2 HVQDIS tends to underestimate the data => mass effects play a role



Eur. Phys. 9.C (2012) 69:347-360

Beauty with muon and jets in Deep Inelastic Scattering



- Extracted values extend the kinematic region towards lower Q^2 and x, compared to previous measurements

- Reasonable agreement with QCD predictions, whose spread is smaller than current experimental uncertainty

Eur. Phys. 9.C (2012) 69:347-360

Conclusions

- Charm and beauty production has been measured in Photoproduction and Deep Inelastic Scattering over a wide kinematic range

- NLO predictions in massive schemes describe the data well within large theoretical uncertainties

- In comparison to NLO QCD predictions the measured heavy flavour cross sections are more precise

  => NNLO predictions would give better predictions and allow for precision tests of pQCD

- Universality of charm fragmentation fractions has been confirmed

Backup