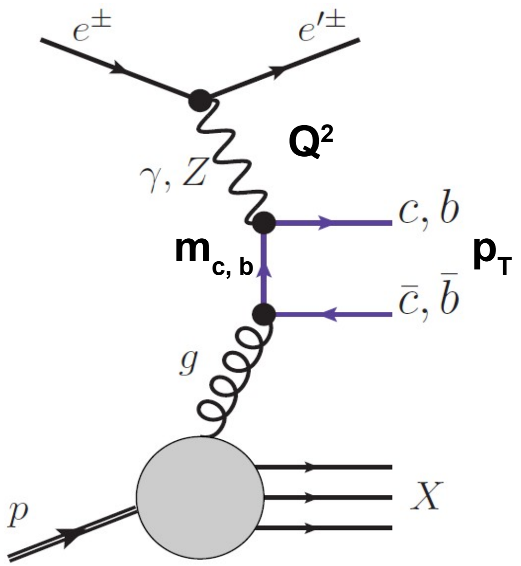
Charm and Beauty in Photoproduction at HERA

Monica Dobre on behalf of H1 and ZEUS Collaborations

Outline

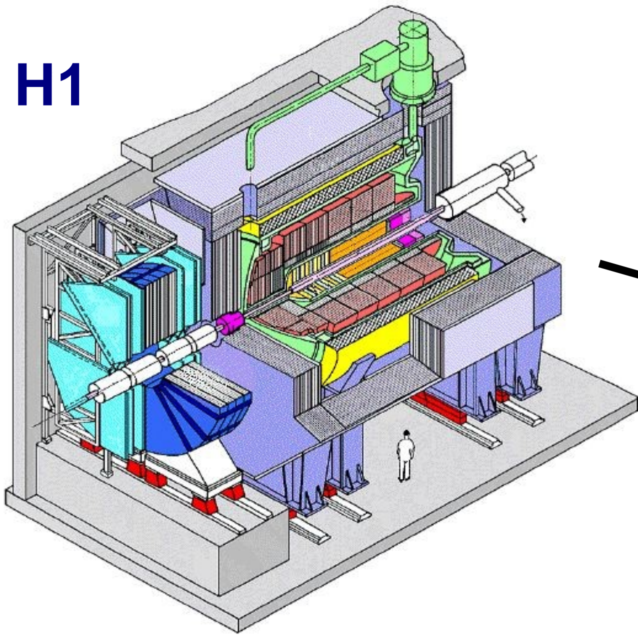
- HERA Collider
- Motivation
- QCD models
- Tagging methods
- Results



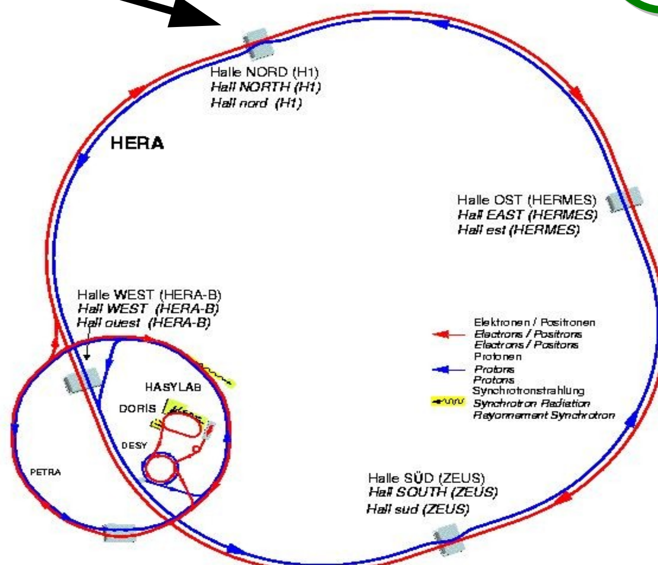
ICNFP 2013, Kolymbari, Greece

The HERA ep Collider (1992-2007)

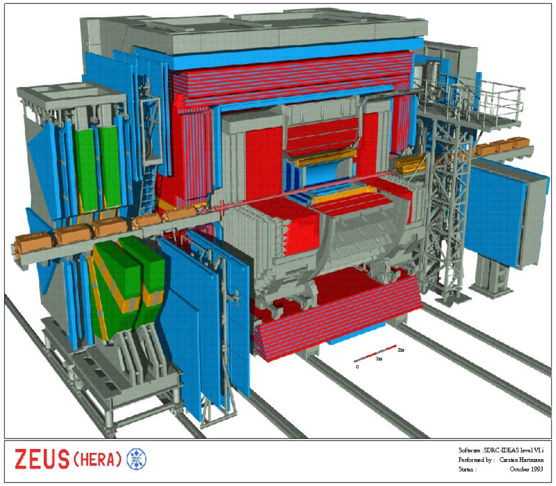
H1



- 27.6 GeV electrons/positrons
- 920 GeV protons
- 320 GeV center of mass energy



ZEUS

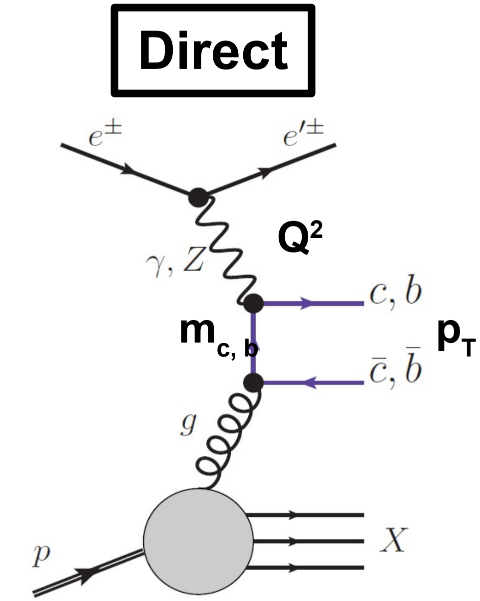


- Two general purpose collider experiments: H1 and ZEUS
- 0.5 fb^{-1} per experiment

Why Measure Heavy Flavour Production?

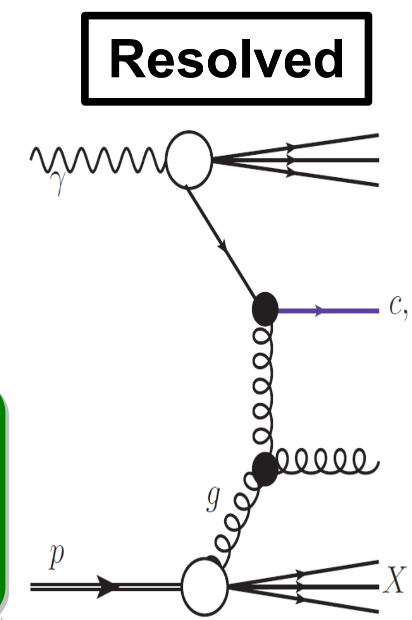
- Charm and beauty quarks are produced at HERA mainly through the photon-gluon fusion process
  → sensitive to the gluon density in the proton

Interpretation of Heavy Flavour measurements
→ use the pQCD calculations and
constrain the gluon density in the proton
→ take the gluon density from elsewhere and
test the consistency of the pQCD calculations



Two kinematic regimes:

- **Photoproduction**: $Q^2 \approx 0$ GeV^2
- Deep inelastic scattering: $Q^2 > 1$ GeV^2



- The large mass of the **c/b** quark provides a hard scale for the pQCD calculations, in addition to the p_T(HF quark)
  → **multi-scale problem**

QCD Models

QCD Scheme: massive fixed order QCD calculation FFNS
- **c**, **b** quarks generated dynamically via boson-gluon fusion
- **c**, **b** quarks treated as massive
- correct threshold treatment
- valid for small scales: $\mu^2 \approx O(m_c^{\,2}), O(m_b^{\,2})$

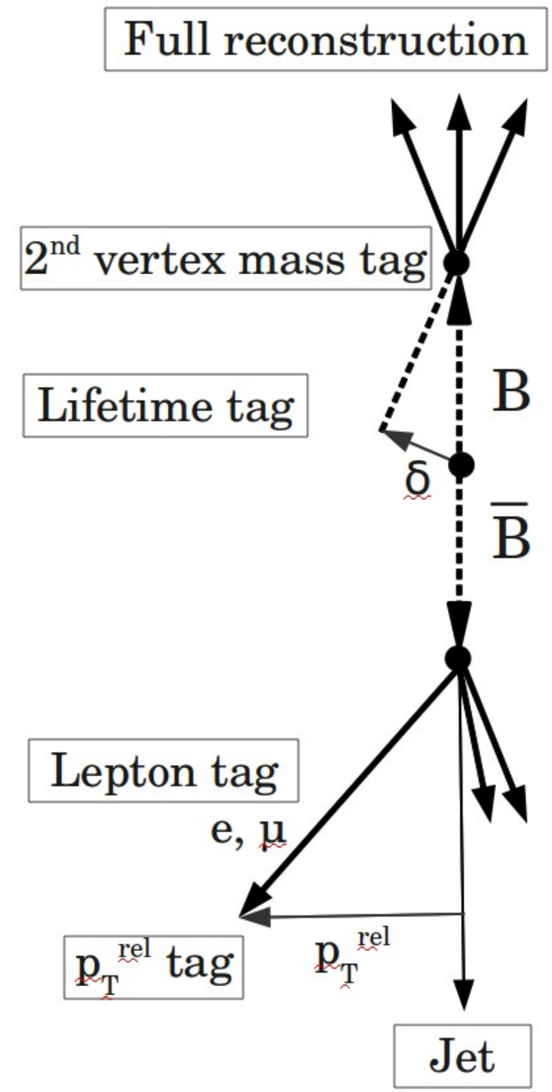
Monte Carlo Generators: QCD LO + parton showers
- PYTHIA: DGLAP evolution + Lund string fragmentation
- HERWIG: DGLAP evolution + cluster fragmentation
- CASCADE: CCFM evolution + Lund string fragmentation

NLO Calculations:
- FMNR: collinear NLO calculation
- MC@NLO: collinear NLO calculation + parton showers and hadronisation
- GMVFNS (only for c → D*): uses the KKKS fragmentation for c → D*

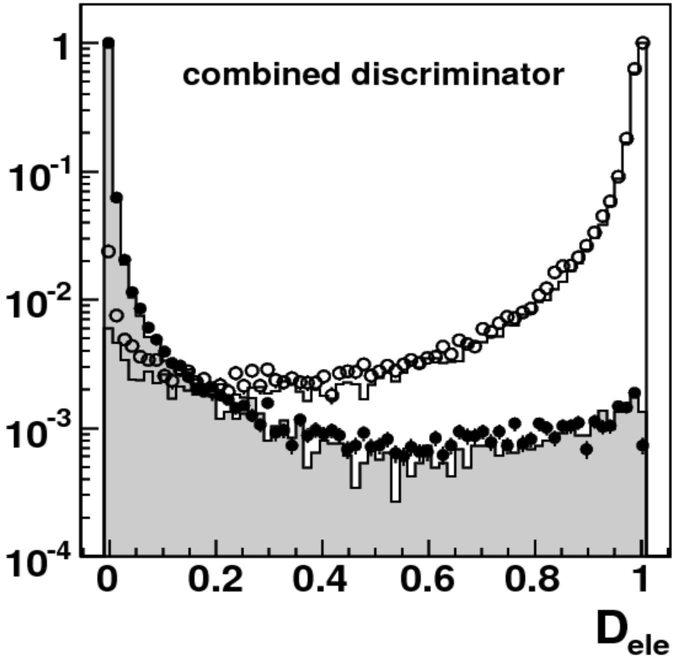
Heavy Flavour Tagging Methods

$\sigma(b) : \sigma(c) : \sigma(uds) \approx 1 : 50 : 2000$

- **Full reconstruction**
  – only charm mesons can be reconstructed at HERA
- **Semileptonic decays**
  – uses the semileptonic decay of a heavy quark into an electron or a muon
- **p_T^{rel} tagging**
  – p_T of the muon wrt the direction of the jet is a good discriminant of the b quark against uds and c
- **Lifetime tagging**
  – looks for displaced vertices and tracks with large impact parameters
- **Secondary vertex mass tagging**
  – considers the higher mass of the c and b quarks w.r.t. the uds quarks



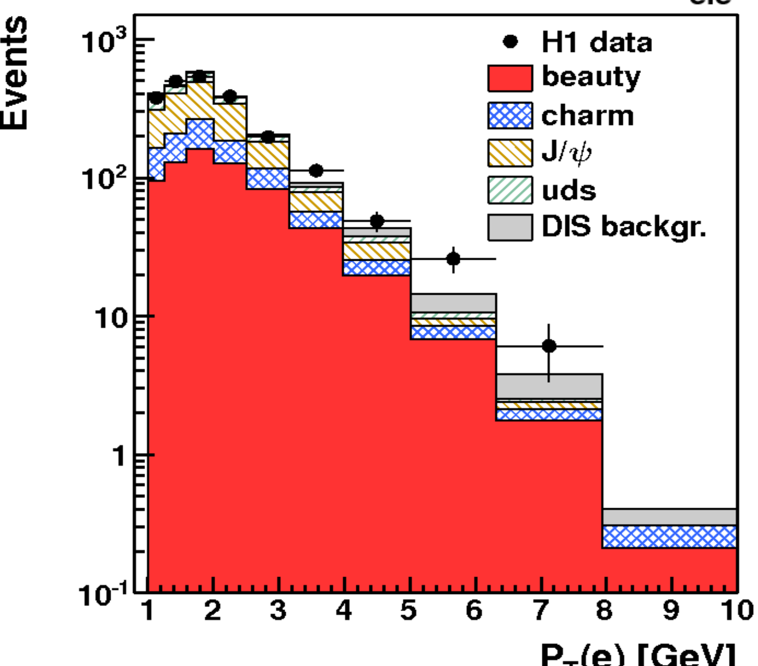
Beauty Photoproduction near Threshold Using Di-electron Events



Eur.Phys.J. C72 (2012) 2148

$$b\bar{b} \rightarrow eeX'$$

- Obtain the b quark cross section at threshold
- Online and offline electron identification of low p_T electrons
  p_T(e) > 1 GeV
- The dedicated offline electron discriminator suppresses hadrons by a factor > 100.



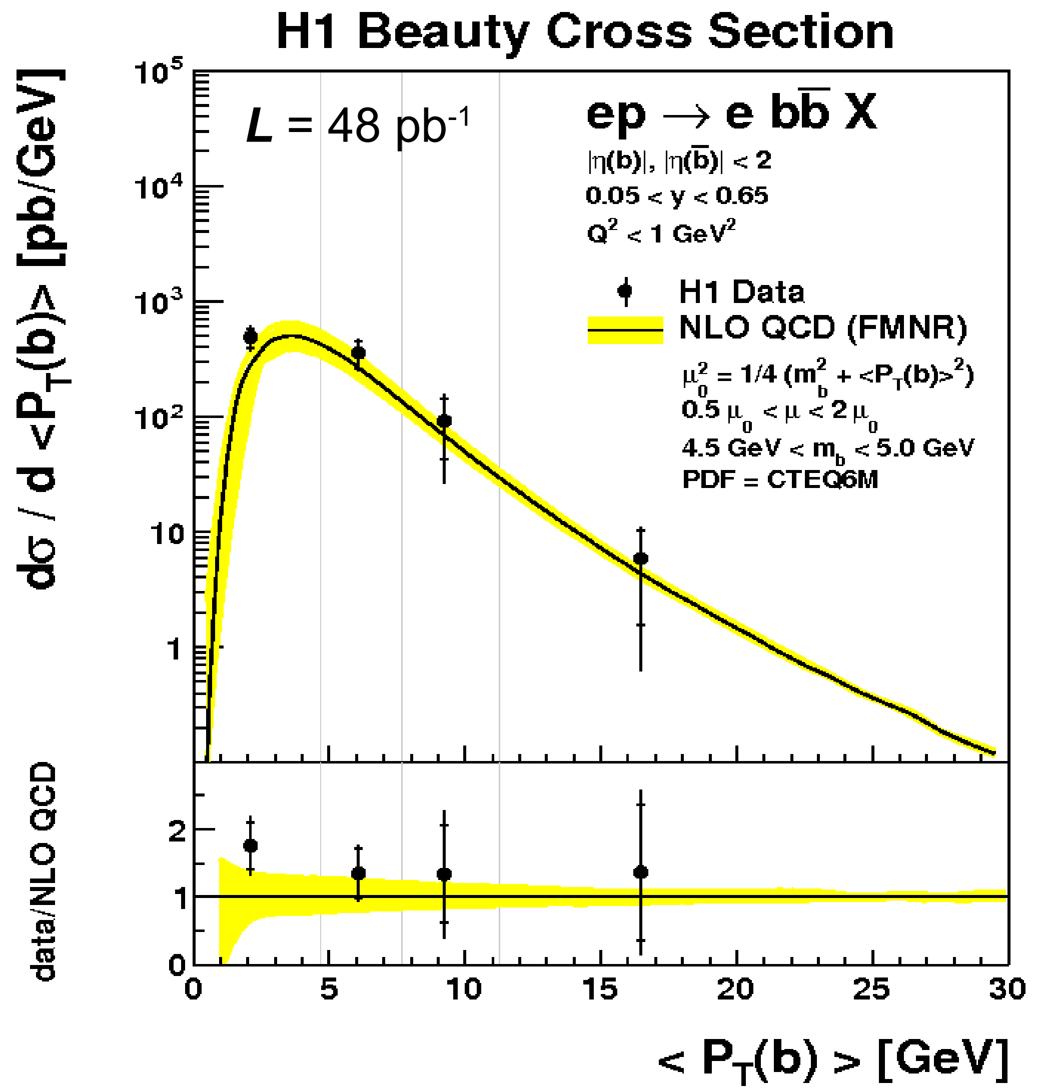
- The flavours are disentangled by using a template method
- The number of bkg events is determined using unfolding

Beauty Photoproduction near Threshold Using Di-electron Events

Eur.Phys.J. C72 (2012) 2148

The differential b quark cross section as a function of the mean b quark transverse momentum is in agreement with the NLO prediction.

Access to the lowest $p_T(b)$ values ever measured in ep collisions.



Inclusive D Meson Cross Section in Photoproduction*

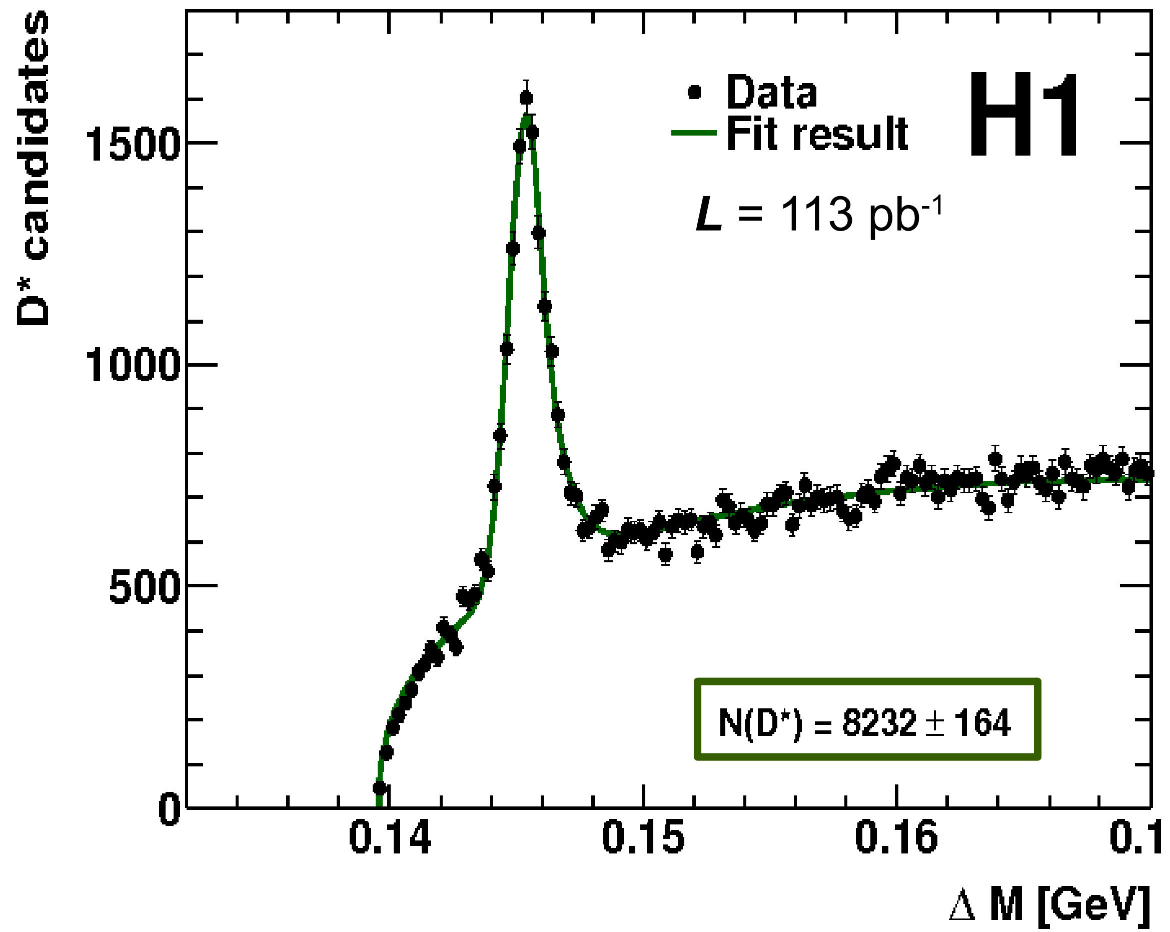
Eur.Phys.J. C72 (2012) 1995

Full reconstruction of the D* meson:

$$D^{*\pm} \longrightarrow D^0 \pi^\pm_{slow} \longrightarrow K^\mp \pi^\pm \pi^\pm_{slow}$$

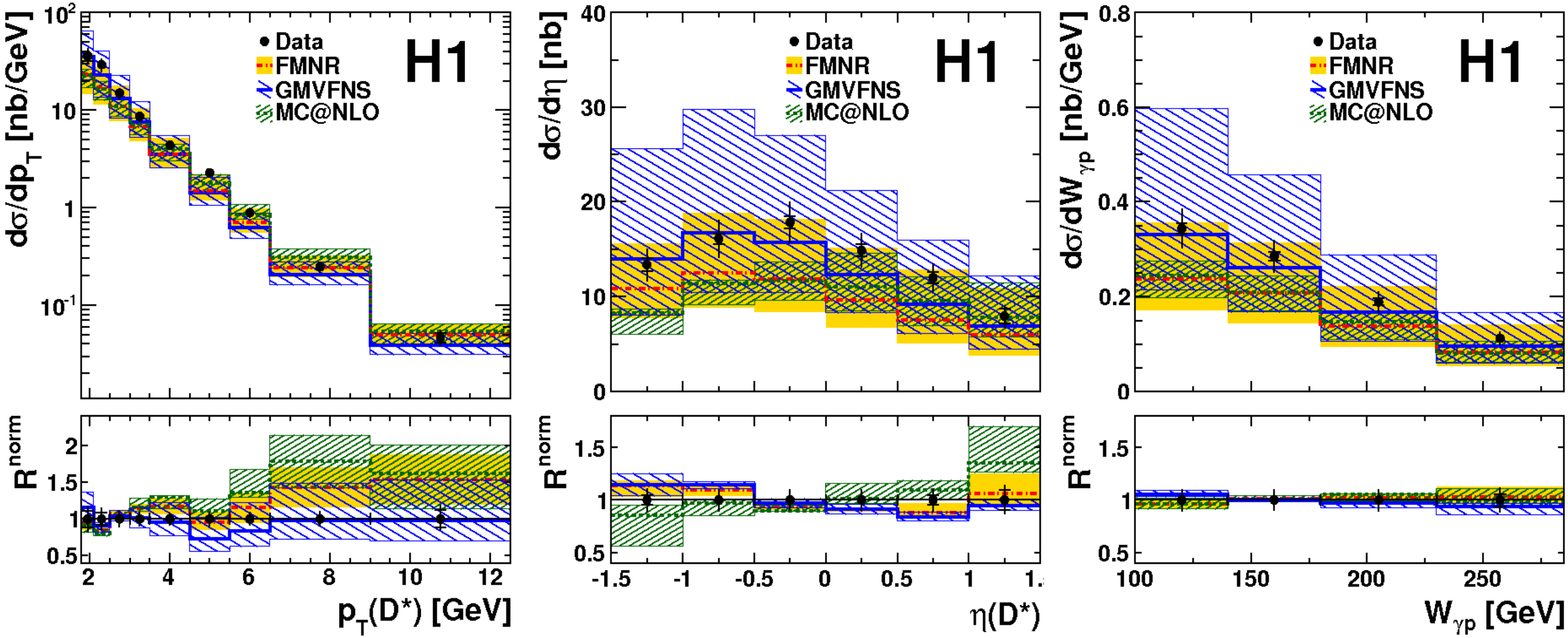
Phase Space	
Q^2	< 2 GeV^2
$p_T(D^*)$	> 1.8 GeV
$\mid \eta \mid$	< 1.5
$W_{\gamma p}$	(100, 285) GeV

$\boxed{\Delta M = M(K\pi\pi_s) - M(K\pi)}$



Inclusive D Meson Cross Section in Photoproduction*

Eur.Phys.J. C72 (2012) 1995



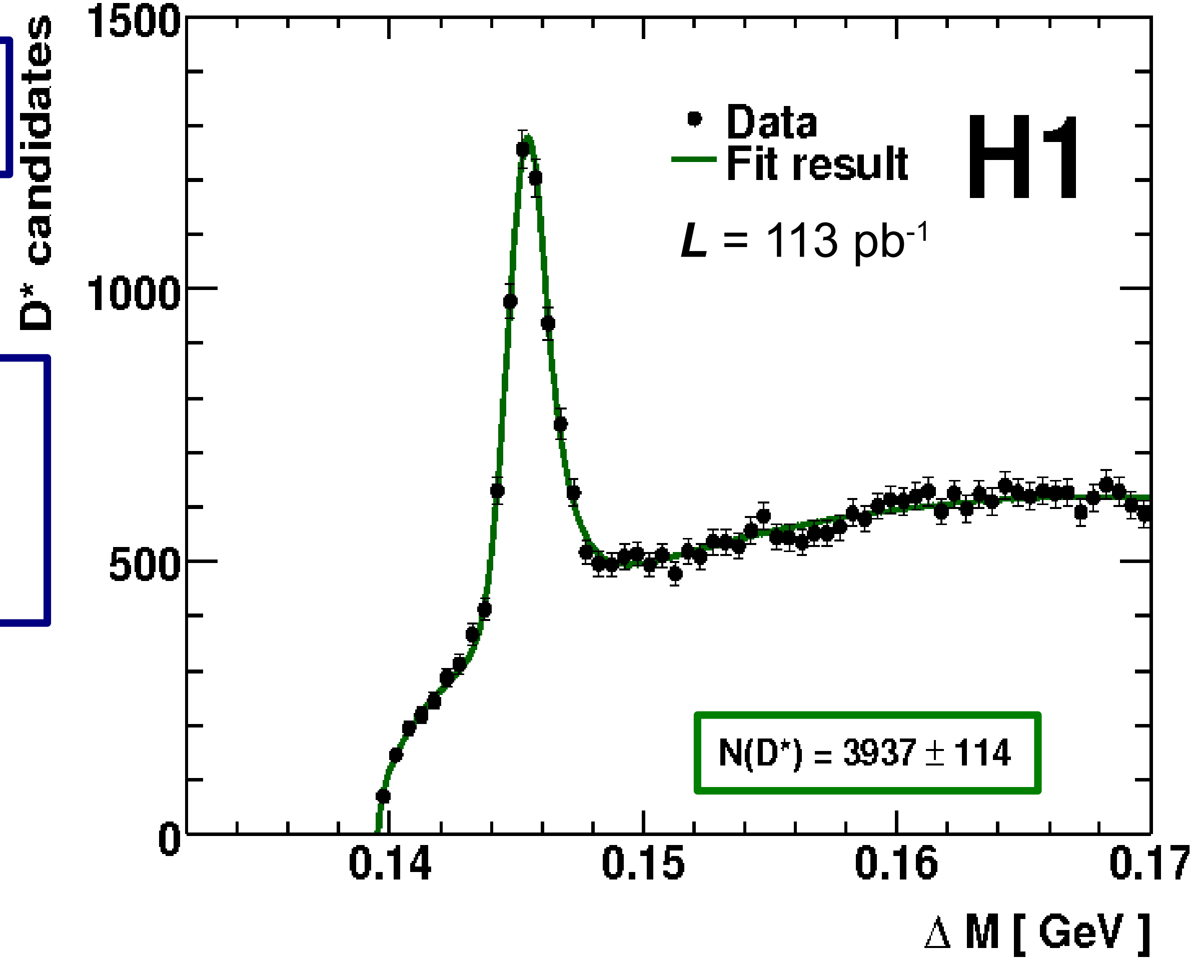
Large theoretical uncertainties

- Good description of the $W_{\gamma p}$ – data in general described
- D* kinematics reasonably well described

Dijet D Meson Cross Section in Photoproduction*

Eur.Phys.J. C72 (2012) 1995

At least two jets are required, at least one jet containing the D* candidate



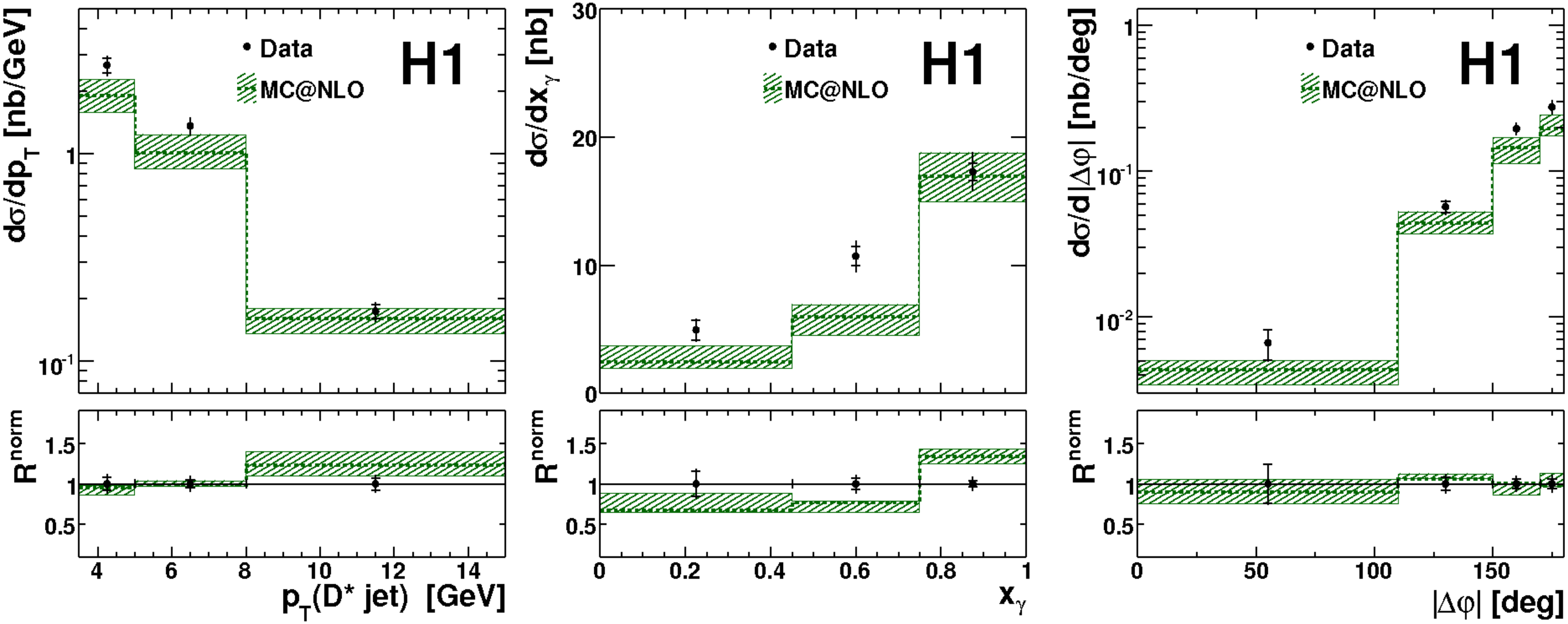
Correlations between the two jets used:
- azimuthal angular difference $\Delta\varphi$
- the longitudinal momentum fraction of the photon carried by the jets $\mathbf{x_\gamma}$

$$x_\gamma = \frac{\sum_{jets}(E-p_z)_i}{\sum_{HFS}(E-p_z)_j}$$

$x_\gamma \approx 1$ – direct processes dominate
$x_\gamma < 1$ – resolved processes dominate

Dijet D Meson Cross Section in Photoproduction*

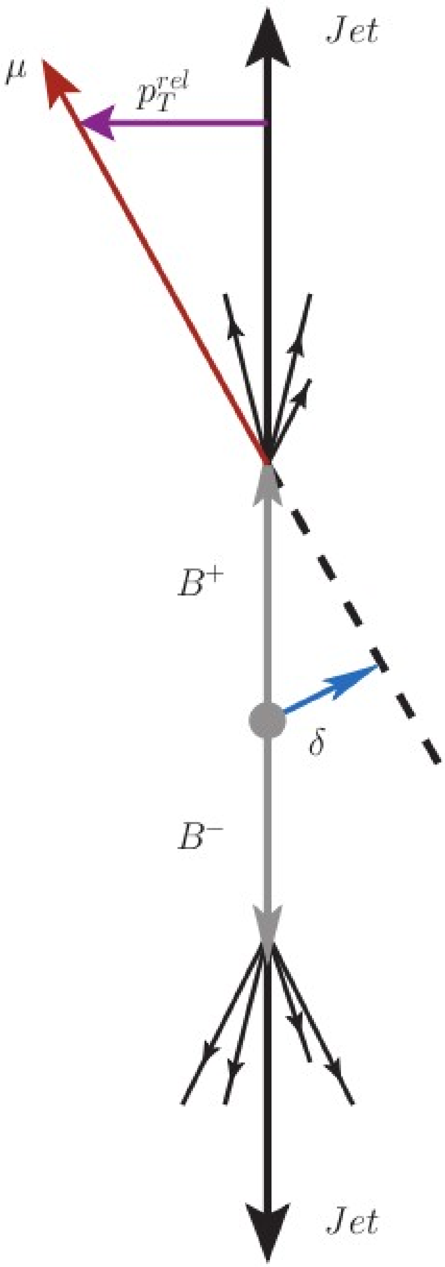
Eur.Phys.J. C72 (2012) 1995



p_T(jet) > 3.5 GeV

- Reasonably well described distributions
- The central value of the MC@NLO prediction tends to lie lower than the measured data

Beauty and Charm in Dijet Events with Semi-muonic Decays



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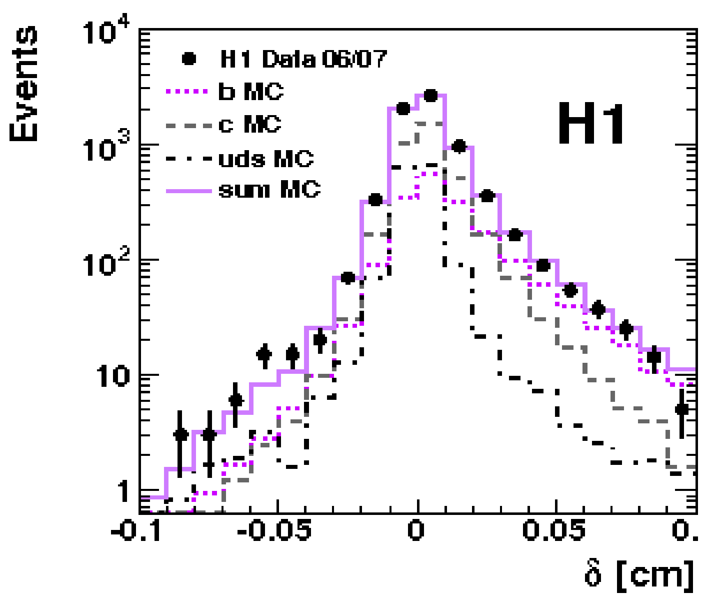
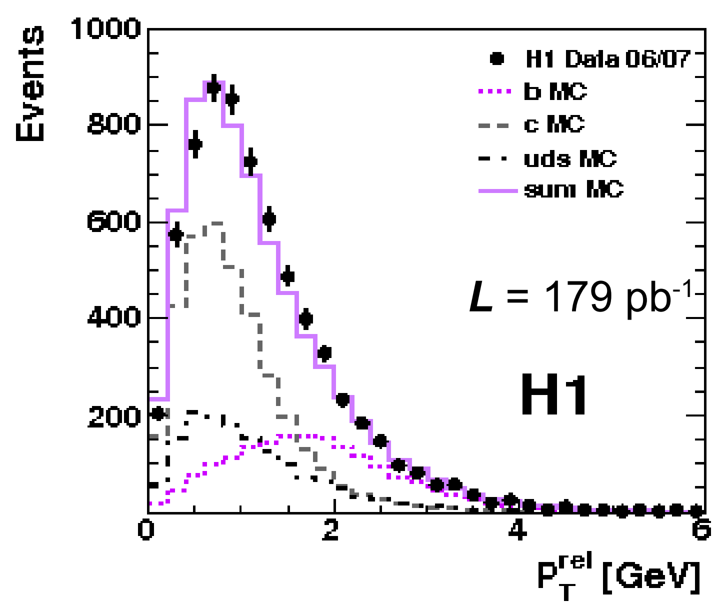
- A binned-likelihood fit in the δ-p_T^{rel} plane is performed to obtain the fractions of events with b, c and light flavours.

beauty: (26.0 ± 1.2) %

charm: (48.6 ± 2.5) %

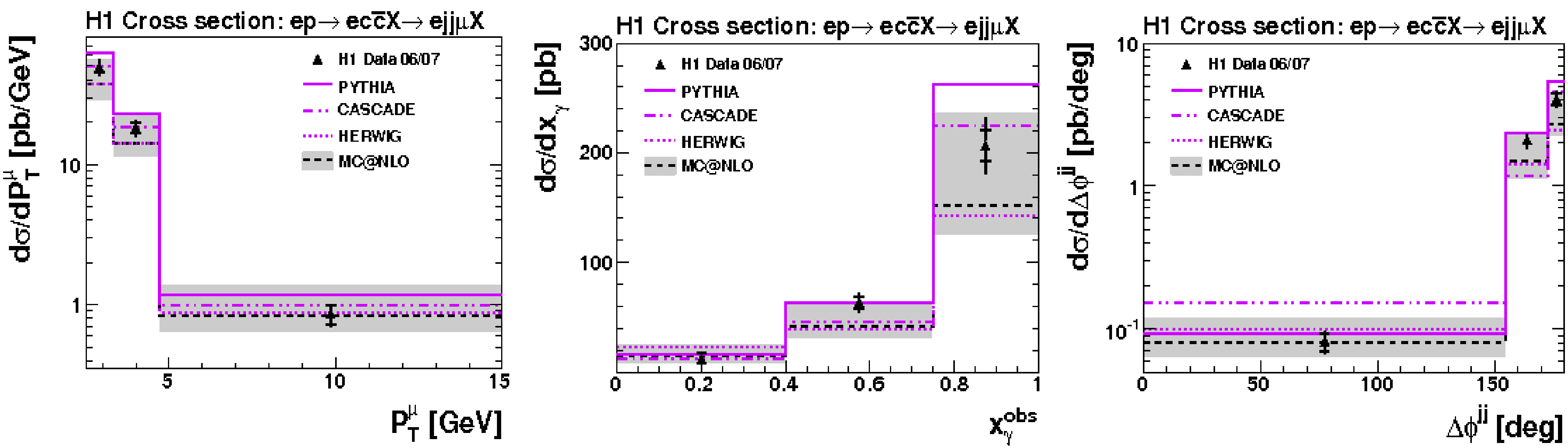
uds: (25.3 ± 2.6) %





Beauty and Charm in Semi-muonic Decays in Dijet Events

Eur.Phys.J. C72 (2012) 2047



p_T(jet 1(2)) > 7(6) GeV

$p_T(\mu)$ > 2.5 GeV

- Reasonably well described distributions
- The central value of the MC@NLO prediction tends to lie lower than the measured data

***Beauty* and Charm in Semi-muonic Decays in Dijet Events**

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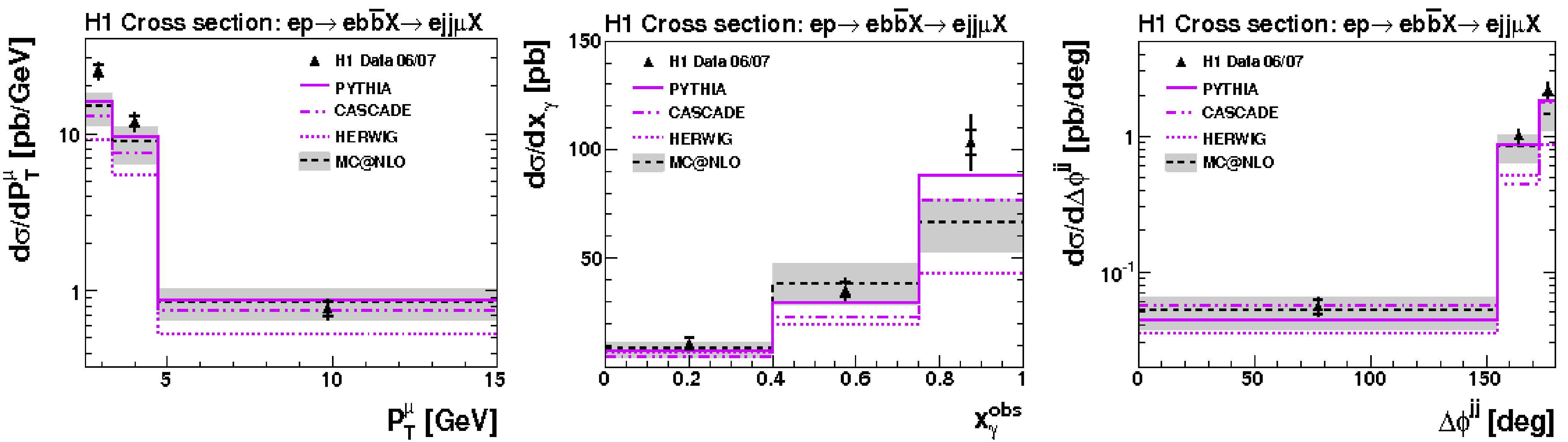


p_T(jet 1(2)) > 7(6) GeV

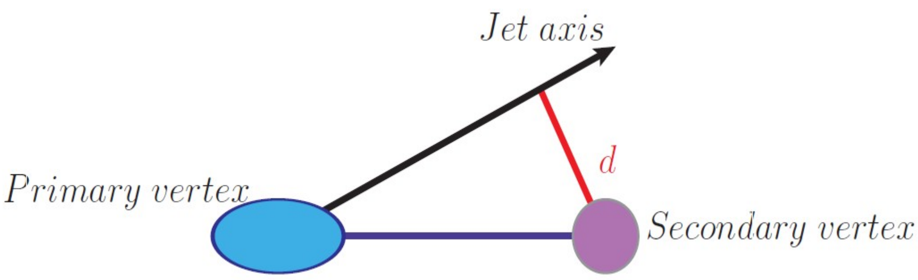
$p_T(\mu)$ > 2.5 GeV

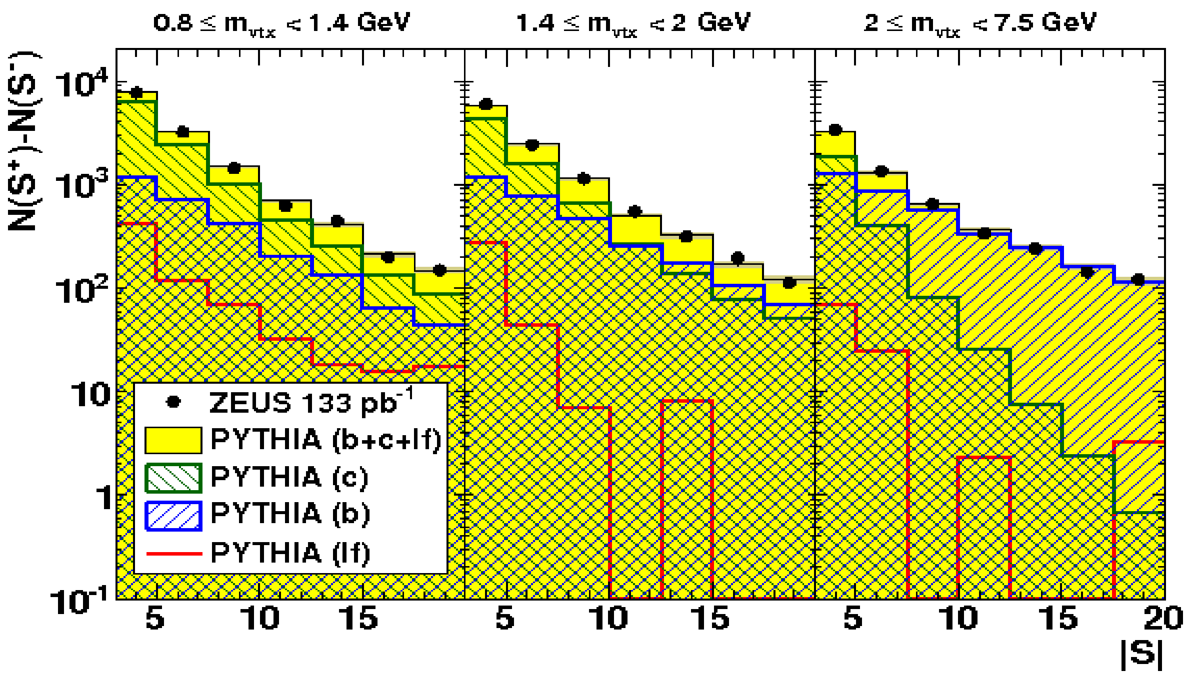
- Reasonable agreement between the measurement and the predictions
- The excess in the first $p_T(\mu)$ bin is within 2σ of the experimental and theoretical uncertainty
- Theoretical uncertainties exceed the experimental ones

Heavy-Quark Jet Photoproduction

Eur.Phys.J. C71 (2011) 1659

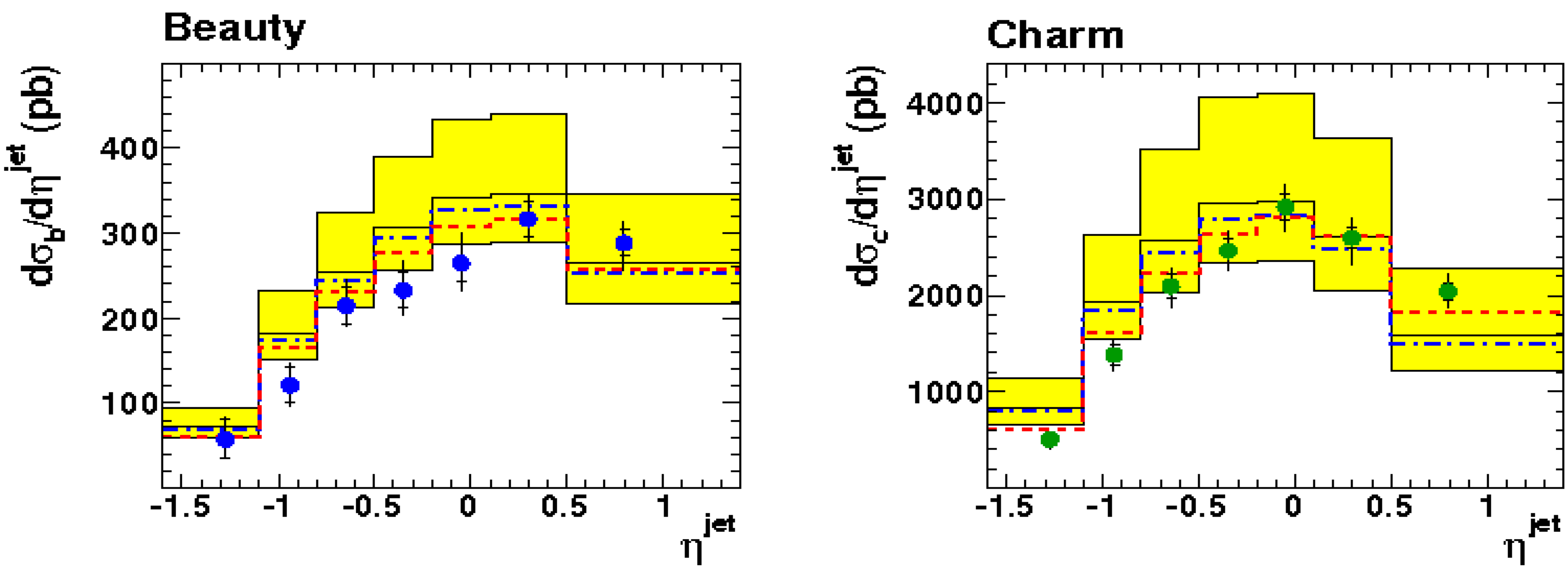
- Analysis exploits the large masses and the large lifetimes of HF hadrons
- S=d/δd used to suppress the LF bkg
- **c** and **b** contributions were obtained by fitting the S distributions in the three vertex mass bins
- ***L*** = 133 pb^{-1}





Heavy-Quark Jet Photoproduction

Eur.Phys.J. C71 (2011) 1659

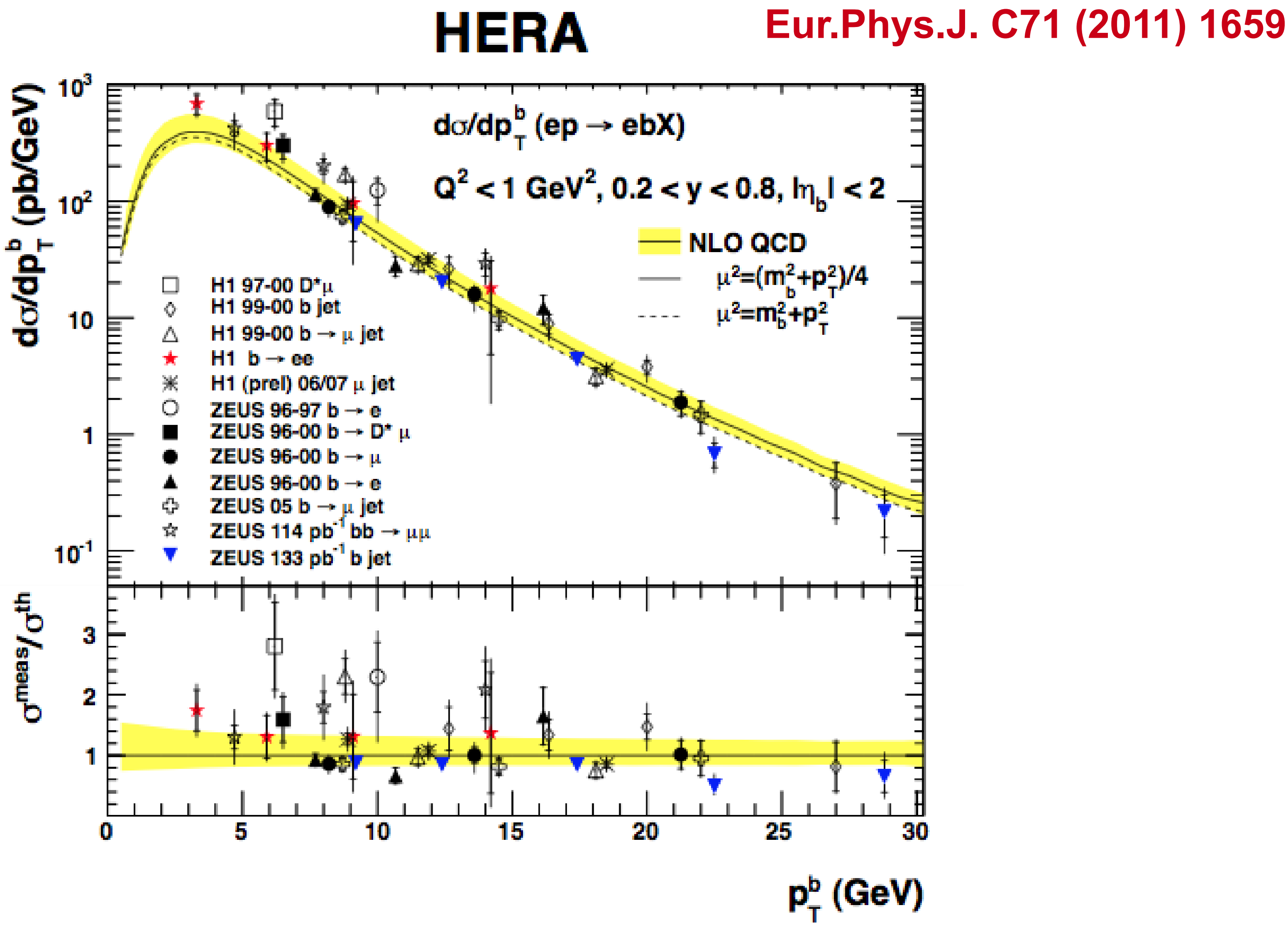


p_T(jet 1(2)) > 7(6) GeV

p_T(track 2nd vertex) > 0.5 GeV

- Good agreement between NLO QCD predictions and the measurements, both for the charm and for the beauty

Heavy-Quark Jet Photoproduction

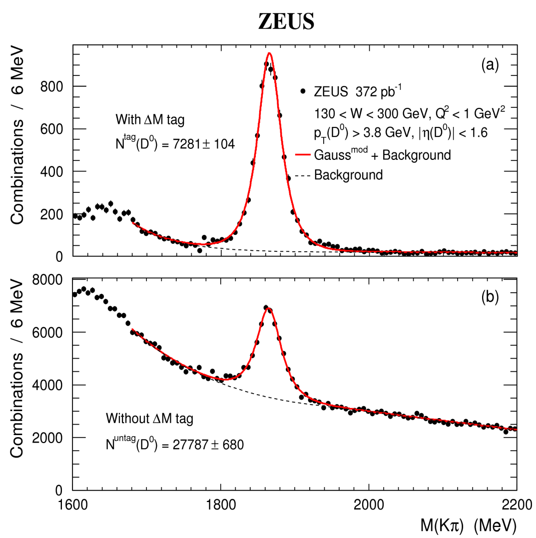


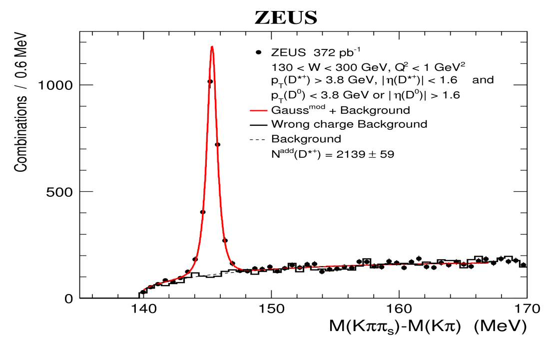
Several measurements consistent with one another and well described by NLO QCD

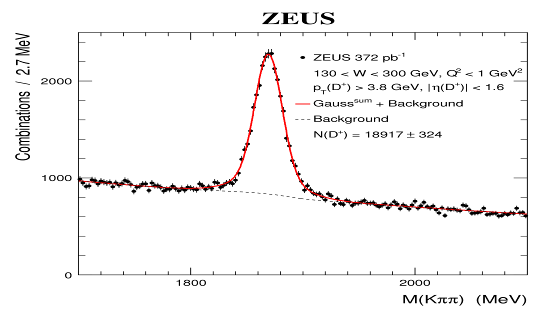
Charm Fragmentation Fractions

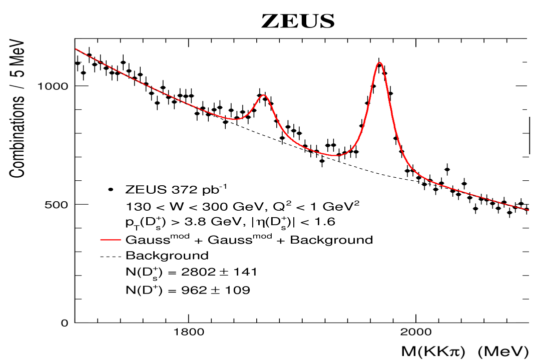
arXiv:1306.4862

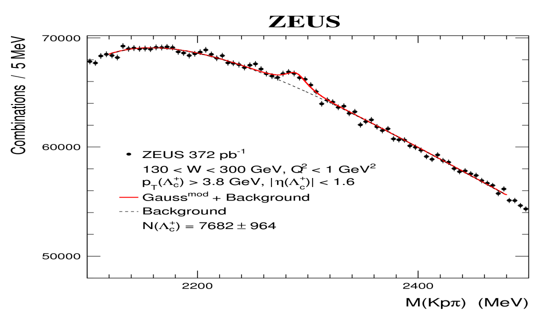
L = 372 pb^{-1}











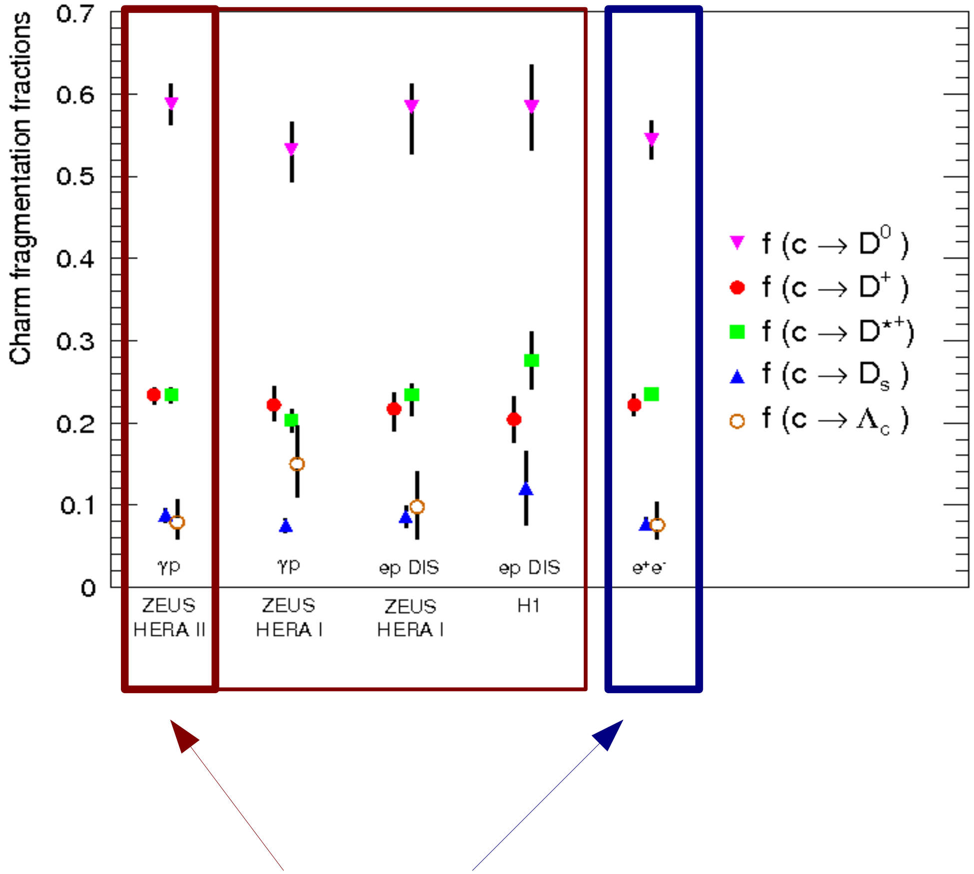
Analyzed channels:

- $D^+ \to K^- \pi^+ \pi^+$
- $D^{*+} \to K^- \pi^+ \pi^+$
- $D^0 \to K \pi$
- $D^+ \to K^+ K^- \pi^+$
- $\Lambda_c^+ \to p K^- \pi^+$

Is charm fragmentation fraction universal?

Charm Fragmentation Fractions

arXiv:1306.4862



	ZEUS (γp) HERA II		
	stat.	syst.	br.
$f(c \to D^+)$	0.234 ± 0.006	$^{+0.004}_{-0.006}$	$^{+0.006}_{-0.008}$
$f(c \to D^0)$	0.588 ± 0.017	$^{+0.011}_{-0.006}$	$^{+0.012}_{-0.018}$
$f(c \to D_s^+)$	0.088 ± 0.006	$^{+0.002}_{-0.007}$	$^{+0.005}_{-0.005}$
$f(c \to \Lambda_c^+)$	0.079 ± 0.013	$^{+0.005}_{-0.009}$	$^{+0.024}_{-0.014}$
$f(c \to D^{*+})$	0.234 ± 0.006	$^{+0.004}_{-0.004}$	$^{+0.005}_{-0.007}$

Data from **ep** and **e^+e^-** are in agreement → the fragmentation fractions of charm quarks are **independent of the production process**

Precision of this measurement is comparable with the precision of the combination of all LEP analyses.

Summary

- Many methods available for measuring the heavy flavour in photoproduction.
- NLO QCD tested to high precision – in general, good agreement between data and theory.
- The uncertainties on the measurements are smaller than the theoretical ones.
- The fragmentation fractions of the charm quarks measured at HERA are similar to the ones measured at LEP

  → universality of the fragmentation fractions is confirmed.

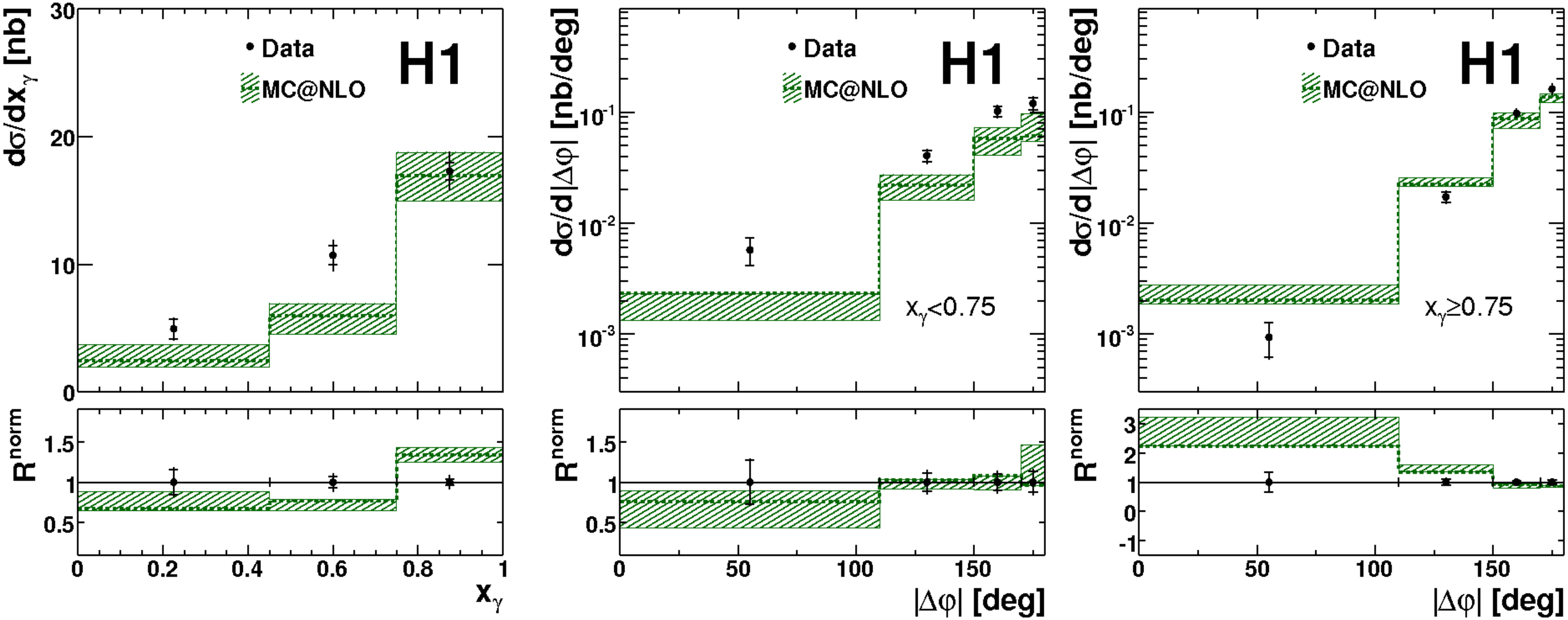
Backup

References

- beauty in di-electron events: **Eur.Phys.J. C72 (2012) 2148**
- charm in the D* golden channel: **Eur.Phys.J. C72 (2012) 1995**
- charm in dijet events, with a D*-tagged jet: **Eur.Phys.J. C72 (2012) 1995**
- c and b in events with semi-muonic decays: **Eur.Phys.J. C72 (2012) 2047**
- c and b in events tagging secondary vertices: **Eur.Phys.J. C71 (2011) 1659**
- charm fragmentation fractions: **arXiv: 1306.4862**

Dijet D Meson Cross Section in Photoproduction*

Eur.Phys.J. C72 (2012) 1995



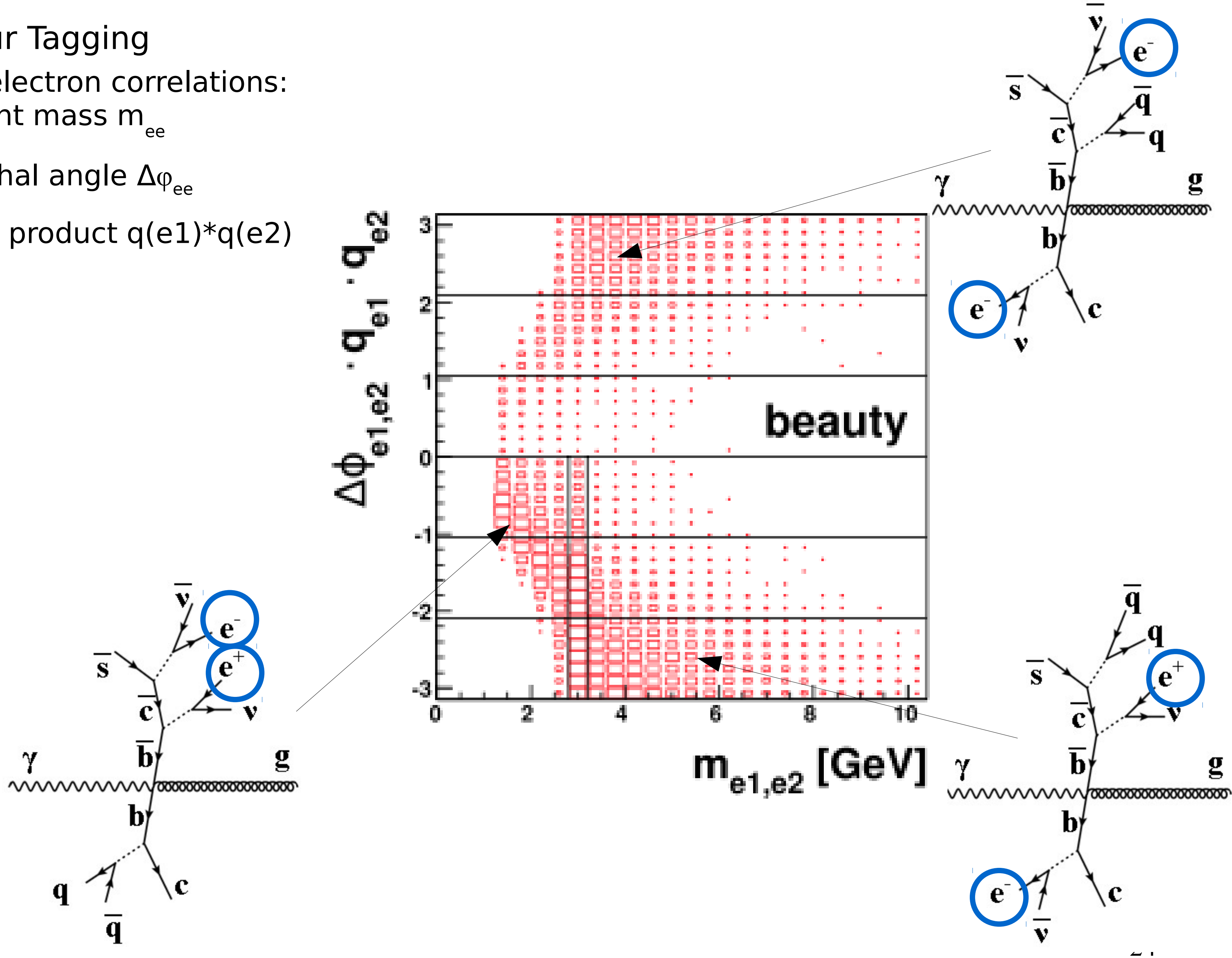
- MC@NLO fails to describe the region with resolved photons, whereas reasonable agreement is observed for the description of the direct process.

- Non-negligible contributions from higher order QCD radiation or k_T of the partons in the initial state are needed to describe the cross section for the regions away from back-to-back configurations.

Beauty in photoproduction at low $p_T(b)$

Heavy Flavour Tagging

- Exploit di-electron correlations:
  - Invariant mass m_{ee}
  - Azimuthal angle $\Delta\varphi_{ee}$
  - Charge product q(e1)*q(e2)



Beauty in photoproduction at low $p_T(b)$

Heavy Flavour Tagging

- Exploit di-electron correlations:
  - Invariant mass m_{ee}
  - Azimuthal angle $\Delta\varphi_{ee}$
  - Charge product q(e1)*q(e2)
- An additional background region (open electron identification cuts) constrains uds.
- Matrix unfolding of the differential beauty cross section (similar to 2d template fit).