

# Heavy Flavour Production at HERA

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**Lake Louise Winter Institute  
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- Introduction
- Charm and beauty in photoproduction
- Charm and beauty in deep inelastic scattering



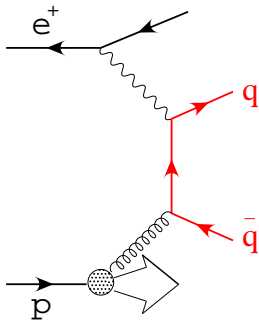
# Introduction

Heavy Flavour production provides multiple hard scales:

- large masses  $m_b, m_c$
- high momenta  $p_T$
- four-momentum transfer  $Q^2$

→ Should ensure reliable predictions?

→ **Test of perturbative QCD**



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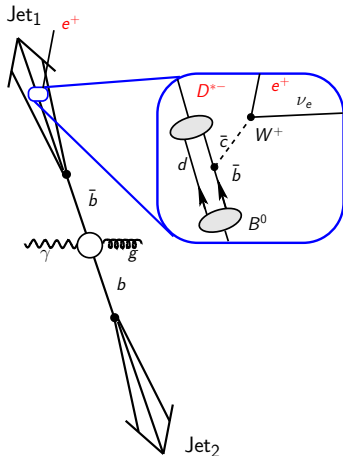
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Different experimental techniques to use (combine) for heavy flavour tagging:

- Meson identification  
 $D^{*\pm}$  tagging



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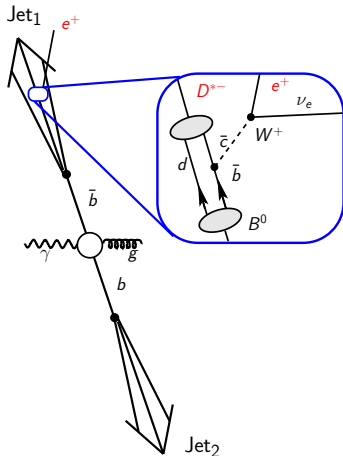
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 $p_T^{\text{rel}}$  of lepton to jet axis



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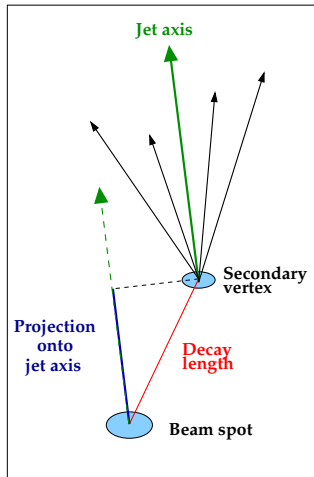
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Different experimental techniques to use (combine) for heavy flavour tagging:

- Meson identification  
 $D^{*\pm}$  tagging
- Decay spectra  
 $p_T^{\text{rel}}$  of lepton to jet axis
- Lifetime information  
Measure impact parameter of tracks or decay length (significance) with respect to primary vertex



# Charm and beauty in photoproduction

$$(Q^2 \approx 0 \text{ GeV}^2)$$

Charm quark tagged by a  $D^*$  meson decaying in the **golden channel**

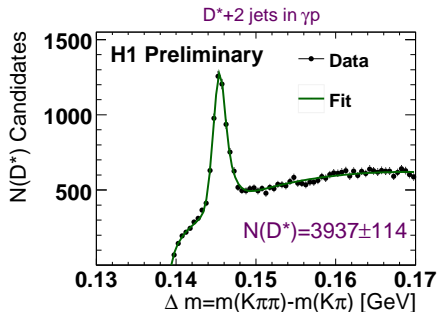
$$D^{*\pm} \rightarrow D^0 \pi_{\text{slow}}^{\pm} \rightarrow K^{\mp} \pi^{\pm} \pi_{\text{slow}}^{\pm}$$

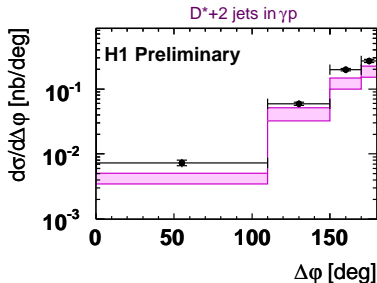
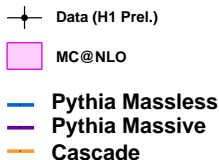
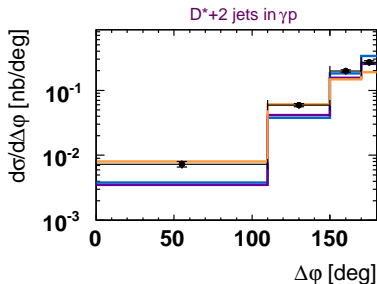
**Data:**  $\mathcal{L} \approx 93 \text{ pb}^{-1}$

## Aim

- Study correlations of both quarks by comparing  $D^*$  cross sections to different LO+PS and NLO MC models:
  - ▶ PYTHIA
  - ▶ CASCADE
  - ▶ MC@NLO
- Test sensitivity to direct and resolved contributions

$\Delta M$  distribution for determination of number of  $D^*$  mesons



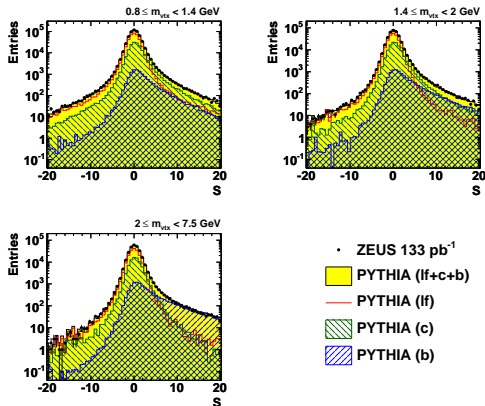
H1prelim-10-072


- Kinematic quantities of the  $D^*$  and the jets well reproduced by all MC models (not shown here)
- Both LO+PS MC models fail to describe the data
- MC@NLO predictions below the data, direct contribution reasonably well-described



- Data:  $\mathcal{L} \approx 130 \text{ pb}^{-1}$
- Dijet PhP events with  $p_T^{\text{jet}} > 7(6) \text{ GeV}$
- No specific decay channel  
→ Inclusive analysis
- Simultaneous identification of beauty and charm content via reconstruction of secondary vertices

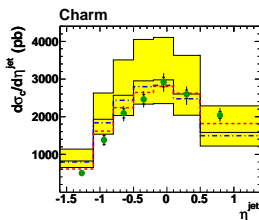
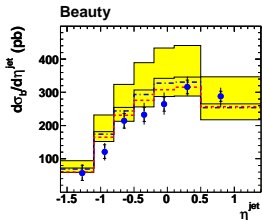
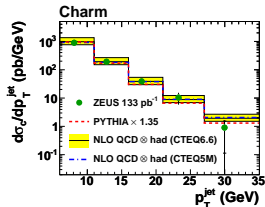
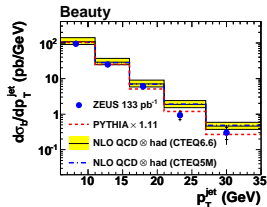
ZEUS



**Separation variables:** Decay-length significance  $S = DL/\delta DL$  and invariant mass of sec. vertex tracks,  $m_{\text{vtx}}$

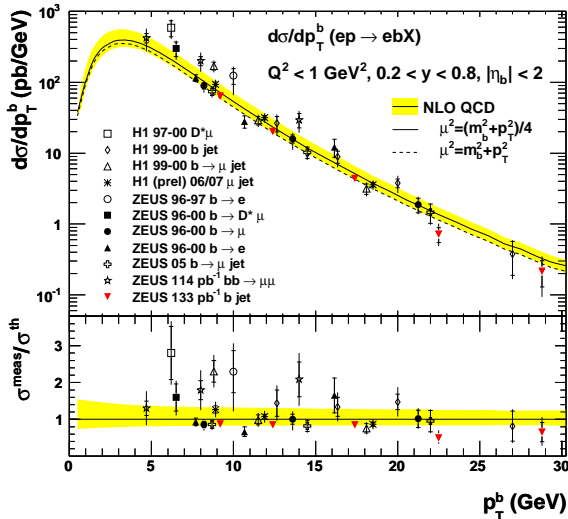
To be submitted  
to EPJ C

## ZEUS



- Differential cross sections as a function of  $p_T^{\text{Jet}}$  and  $\eta^{\text{Jet}}$
- Good agreement between Data and PYTHIA / NLO (FMNR)

## HERA



- Consistent picture of  $b$ -quark production at HERA over wide kinematic range
- Discussed measurement represents the most precise  $b$  in PhP measurement at HERA

# Charm and beauty in deep inelastic scattering

$$(Q^2 \gg 0 \text{ GeV}^2)$$

## H1prelim-10-172

Charm quark tagged through reconstruction of a  $D^*$  meson

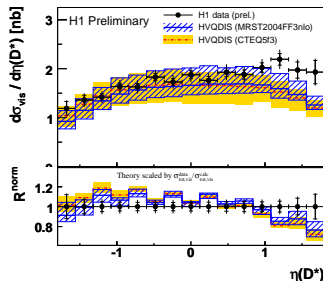
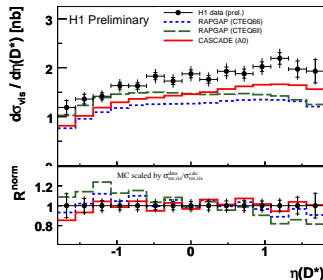
$$D^{*\pm} \rightarrow D^0 \pi_{\text{slow}}^{\pm} \rightarrow K^{\mp} \pi^{\pm} \pi_{\text{slow}}^{\pm}$$

### Kinematics

$$\mathcal{L} \approx 350 \text{ pb}^{-1}$$

- $5 \text{ GeV}^2 < Q^2 < 100 \text{ GeV}^2$
- $p_T(D^*) > 1.25 \text{ GeV}$
- $|\eta(D^*)| < 1.8$

- Differential cross sections as a function of  $\eta(D^*)$
- General agreement with LO (in shape) and NLO predictions except for forward  $\eta$  region



Charm quark tagged through reconstruction of a  $D^\pm$  meson

$$D^\pm \rightarrow K^\mp \pi^\pm \pi^\pm$$

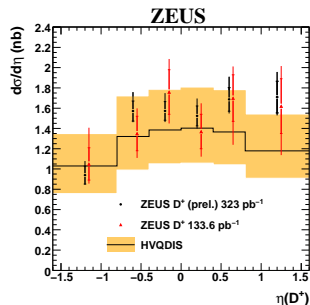
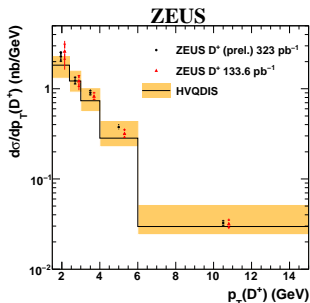
Purity of the  $D$  meson signal increased by including lifetime information

## Kinematics

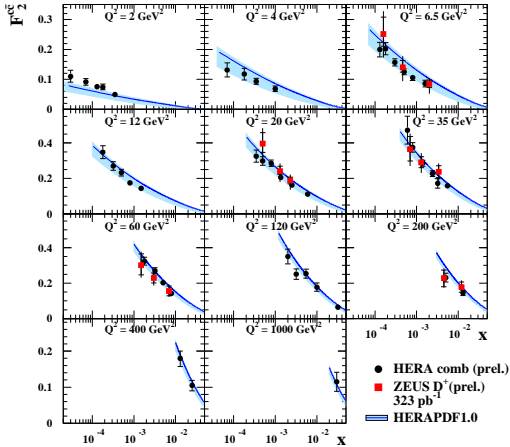
$$\mathcal{L} \approx 320 \text{ pb}^{-1}$$

- $5 \text{ GeV}^2 < Q^2 < 1000 \text{ GeV}^2$
- $1.5 \text{ GeV} < p_T(D^\pm) < 15 \text{ GeV}$
- $|\eta(D^\pm)| < 1.6$

Improved precision with respect to previous measurement and good agreement with NLO prediction



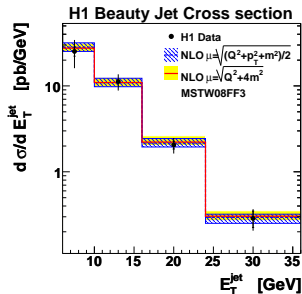
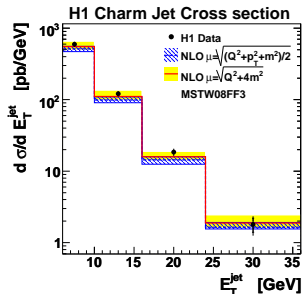
ZEUS-prel-10-005



- Differential cross sections  
→ Good agreement with NLO prediction
- Double-differential cross sections as a function of  $x$  and  $Q^2$  (not shown here)
- Extraction of  $F_2^{c\bar{c}}$  and comparison with ZEUS-H1 combined results  
→ Good agreement between measurements and with NLO predictions

## DESY-10-083

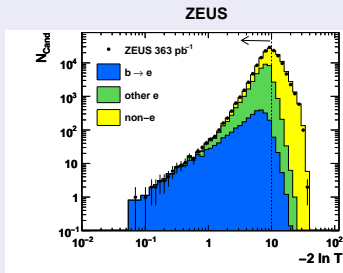
- $\mathcal{L} \approx 190 \text{ pb}^{-1}$
  - $E_T^{\text{jet}} > 6 \text{ GeV}$  and  $-1.0 < \eta^{\text{jet}} < 1.5$
  - Identification of heavy quarks through properties of tracks associated to jets
  - Use of several variables providing lifetime information
  - Extraction of heavy-quark content through simultaneous fit
- 
- Charm and beauty jet cross sections as a function of  $E_T^{\text{jet}}$
  - Comparison with NLO predictions shows good agreement with little dependence on scale parametrisation





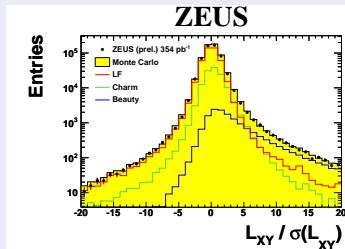
Exclusive:  $b \rightarrow e$ 

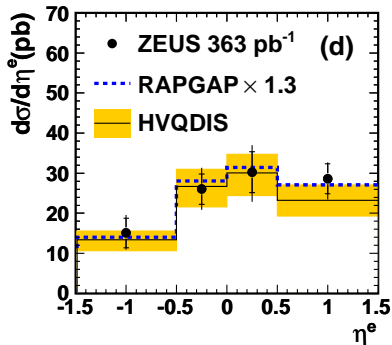
- Extraction of beauty content from semileptonic decays into electrons
- Separation variables:
  - ▶  $p_T^{\text{rel}}$
  - ▶  $\Delta\phi$  between  $p_T^{\text{miss}}$  and electron
  - ▶ Decay-length significance
- Combination in likelihood test function and fit of MC templates



## Inclusive measurement

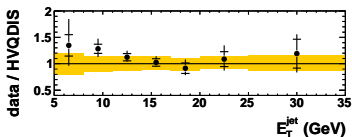
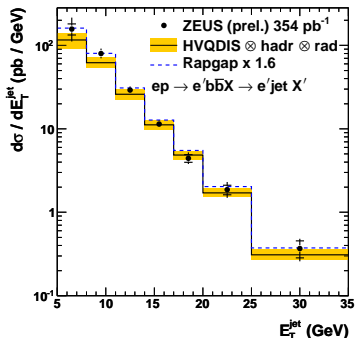
- Extraction of beauty (charm) content through reconstruction of decay vertices
- Separation variables:
  - ▶ Decay-length significance
  - ▶ Invariant sec. vertex mass
- $\chi^2$  fit of MC templates to data



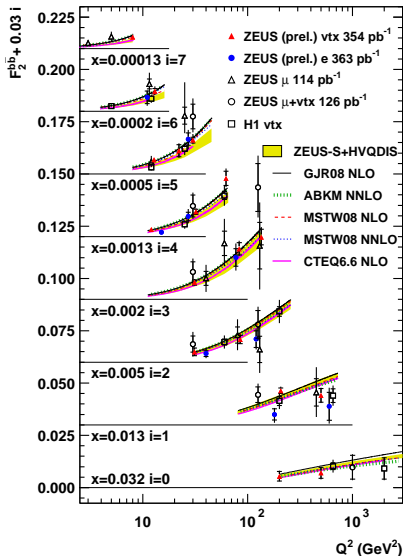


Good agreement with NLO predictions

## ZEUS



## ZEUS



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

- Double-differential cross sections as a function of  $x$  and  $Q^2$  (not shown here)
- Extraction of  $F_2^{b\bar{b}}$  and comparison with other measurements
  - Good agreement between measurements and with NLO/NNLO predictions

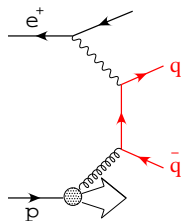
- Latest results of heavy flavour production at HERA presented
  - Measurements with complete HERA II statistics and well-understood detectors provide best precision
- 
- Various H1 and ZEUS measurements using different experimental techniques in very good agreement
  - General agreement with NLO QCD predictions

# BACKUP

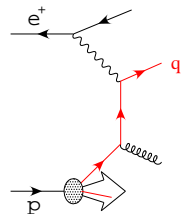
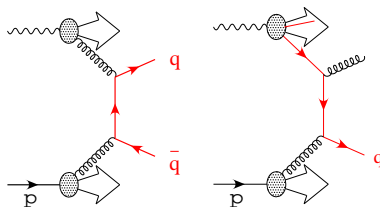
# Heavy Flavour Production Mechanism

Dominant process: **Boson-gluon fusion**

"direct"



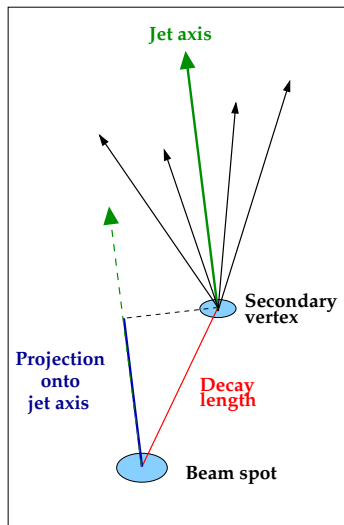
"resolved" (including flavour excitation)



- **PYTHIA:**  
PS according to DGLAP evolution equations,  
LO matrix elements calculated for massless or massive quarks
- **CASCADE:**  
PS according to CCFM evolution equations
- **RAPGAP:**  
PS according to DGLAP evolution equations
- **MC@NLO:**  
PS according to DGLAP evolution equations,  
NLO matrix elements matched with parton showers

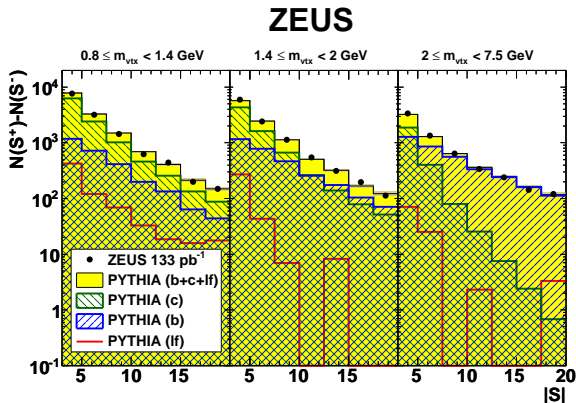
**Data:**  $\mathcal{L} = 133 \text{ pb}^{-1}$

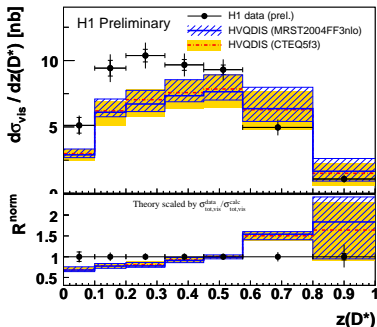
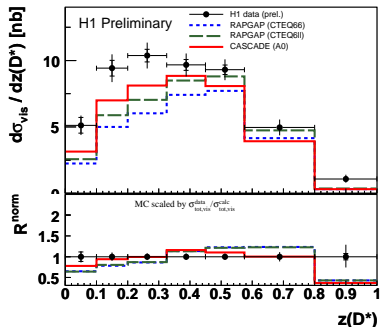
- Dijet PhP events with  $p_T^{\text{jet}} > 7(6) \text{ GeV}$
- No specific decay channel  $\rightarrow$  Inclusive measurement
- Secondary vertexing:
  - ▶ Associate tracks to jets and fit secondary vertices
  - ▶ Calculate 2D decay length as distance between beam spot and secondary vertex in x-y (projected onto jet axis)





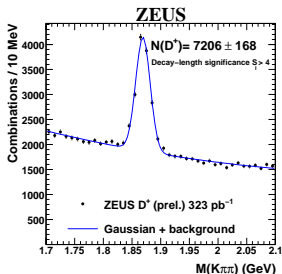
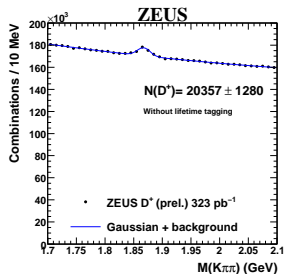
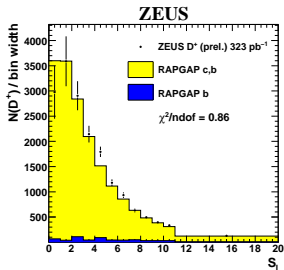
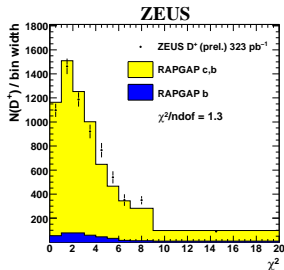
Mirrored decay-length significance in  $m_{\text{vtx}}$  bins:



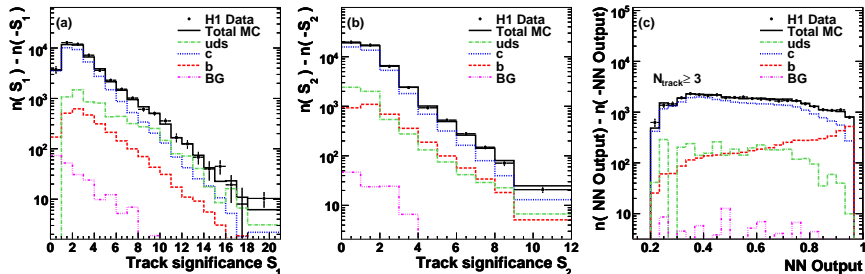


$$R^{\text{norm}} = \frac{1/\sigma_{\text{tot,vis}}^{\text{calc}} \cdot \frac{d\sigma^{\text{calc}}}{dQ^2}}{1/\sigma_{\text{tot,vis}}^{\text{data}} \cdot \frac{d\sigma^{\text{data}}}{dQ^2}}$$

- Diff. cross sections as a function of the fragmentation variable  $z$
- Shape fairly well modelled by CASCADE
- General discrepancies at low  $z$



- Control plots for  $\chi^2$  and decay-length significance,  $S_1$
- $K\pi\pi$  mass distribution without and with  $S_1$  cut



Split data into 3 subsamples:

- 1 Use  $S_1$ :  $N_{\text{track}} = 1$  or  $N_{\text{track}} \geq 2$ ,  $S_1$  and  $S_2$  have opposite signs
- 2 Use  $S_2$ :  $N_{\text{track}} = 2$ ,  $S_1$  and  $S_2$  have same signs or  $N_{\text{track}} \geq 3$ ,  $S_3$  has different sign than  $S_1, S_2$
- 3 Use NN combining  $S_1, S_2, S_3$  and several track / decay vertex properties:  $N_{\text{track}} \geq 3$  and  $S_1, S_2, S_3$  have the same sign, NN signed according to  $S_1$

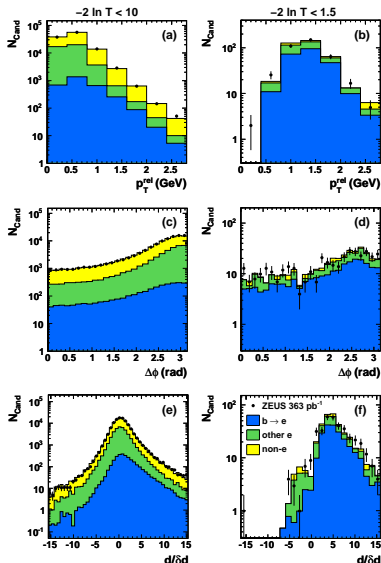
## Variables for electron identification

- energy loss in the CTD,  $dE/dx$
- $E^{\text{CAL}}/p^{\text{track}}$
- depth of the central energy deposit within the CAL,  $d_{\text{cell}}$

## Variables for decay identification

- $p_T^{\text{rel}}$  w.r.t. jet axis
- $\Delta\phi$  between  $p_T^{\text{miss}}$  and electron
- Decay-length significance

## ZEUS



Definition of  $F_2^{b\bar{b}}$  in terms of the inclusive double-differential cross section as a function of the Bjorken scaling variable,  $x$ , and the four-momentum transfer,  $Q^2$ :

$$\frac{d^2\sigma_{b\bar{b}}}{dx dQ^2} = \frac{Y_+(2\pi\alpha_{\text{em}}^2)}{xQ^4} \left[ F_2^{b\bar{b}}(x, Q^2) - \frac{y^2}{Y_+} F_L^{b\bar{b}}(x, Q^2) \right]$$

with  $Y_+ = 1 + (1 - y)^2$ .

Extraction of  $F_2^{b\bar{b}}$  at a reference point in the  $x$ - $Q^2$  plane:

$$F_2^{b\bar{b}}(x, Q^2) = \frac{d^2\sigma_{b \rightarrow e}}{dx dQ^2} \cdot \frac{F_2^{b\bar{b}, \text{NLO}}(x, Q^2)}{d^2\sigma_{b \rightarrow e}^{\text{NLO}}/dx dQ^2}$$