

# Heavy Flavour Production at HERA

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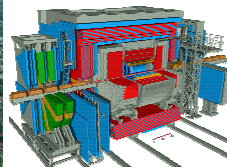
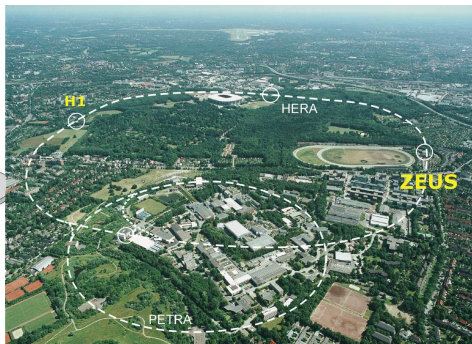
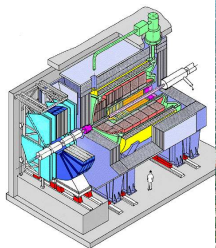
**Workshop on low-x physics, Crete 2008**  
**8<sup>th</sup> July 2008**



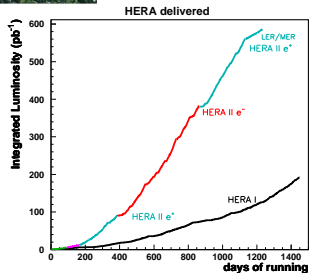
- Introduction
- Charm Production
- Beauty Production
- $F_2^{c\bar{c}}$  and  $F_2^{b\bar{b}}$



# H1 and ZEUS



- $27.5\text{ GeV } e^{\pm}$  colliding with  $920\text{ GeV } p$   
 $\rightarrow \sqrt{s} = 318\text{ GeV}$
- **HERAI:** 1992-2000 ( $\mathcal{L} \approx 150\text{ pb}^{-1}$ )
- **HERAII:** 2003-2007 ( $\mathcal{L} \approx 350\text{ pb}^{-1}$ )  
 $\rightarrow 0.5\text{ fb}^{-1}$  per experiment



# Motivation

Heavy Flavour production provides multiple hard scales:

- large mass  $m_b/m_c$
- large photon virtuality  $Q^2$
- high momenta  $p_T$

→ Should ensure reliable predictions

## Monte Carlo programs (leading order + parton shower)

- DGLAP evolution (collinear factorization)  
Rapgap (DIS)  
Pythia ( $\gamma p$ )
- CCFM evolution ( $k_t$ -factorization)  
Cascade (DIS+ $\gamma p$ )

## NLO Calculations

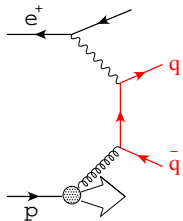
- HVQDIS (DIS)
- FMNR ( $\gamma p$ )

→ **Stringent probe for perturbative QCD**

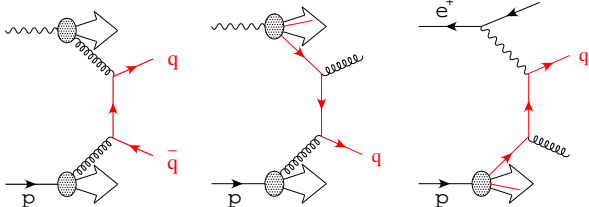
# Heavy Flavour Production Mechanism

Dominant process: **Boson-gluon fusion**

"direct"



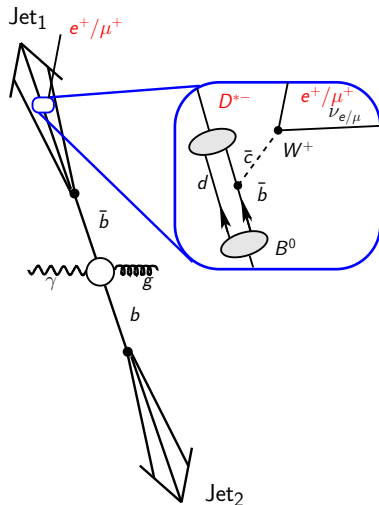
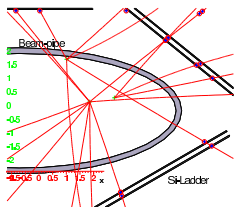
"resolved" (including flavour excitation)



# Heavy Flavour Tagging

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

- Meson identification  
 $D^{*\pm}$  tagging ("Golden Decay")
- Decay spectra  
 $p_T^{rel}$  of lepton to jet axis
- Lifetime information  
Measure impact parameter with respect to primary vertex (beamspot)



# Part I

## Charm Production

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/MC sets and NLO calculation:

### DIS

**Data:** 2004-2007 ( $\mathcal{L} = 347 \text{ pb}^{-1}$ )  
**LO:** Rapgap and Cascade  
**NLO:** HVQDIS

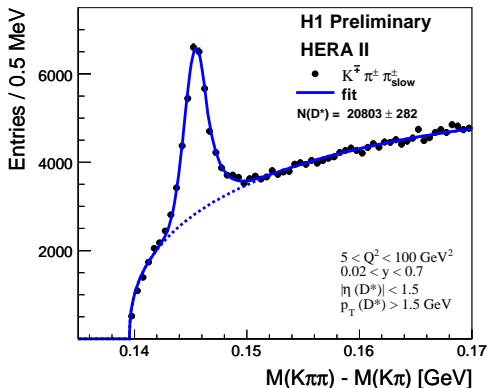
### PhP

**Data:** 2006-2007 ( $\mathcal{L} = 93 \text{ pb}^{-1}$ )  
**LO:** Pythia and Cascade  
**NLO:** FMNR

Kinematic range:

- $5 \text{ GeV}^2 < Q^2 < 100 \text{ GeV}^2$
- $0.02 < y < 0.7$
- $p_t(D^*) > 1.5 \text{ GeV}$
- $|\eta(D^*)| < 1.5$

- $Q^2 < 2 \text{ GeV}^2$
- $0.1 < y < 0.8$
- $p_t(D^*) > 1.8 \text{ GeV}$
- $|\eta(D^*)| < 1.5$



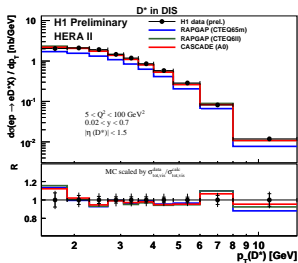
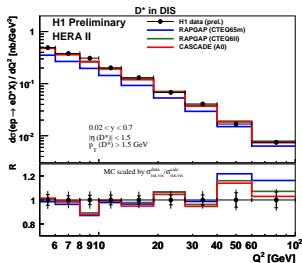
$\Delta M$  distribution for  
determination of  
number of D\* mesons

## Total visible cross-section

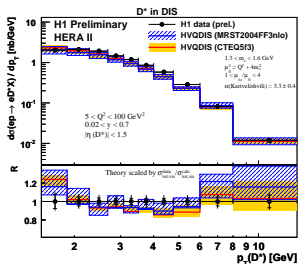
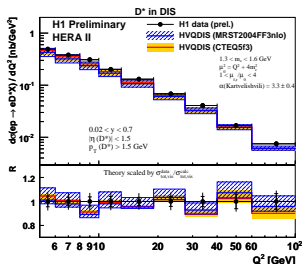
$$\sigma_{\text{vis}}^{\text{tot}}(e^\pm p \rightarrow e^\pm D^{*\pm} X) = 4.85 \pm 0.07 \text{ (stat.)} \pm 0.42 \text{ (syst.) nb}$$



## Differential cross-sections in $Q^2$ and $p_t(D^*)$

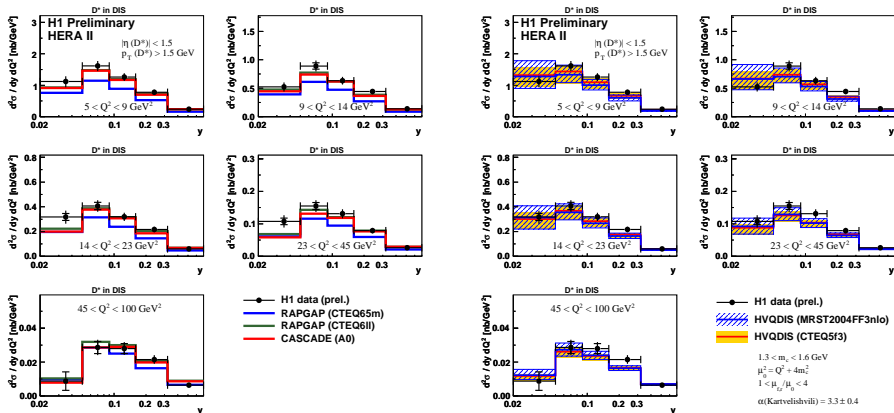


Data compared to  
Rapgap &  
Cascade MCs

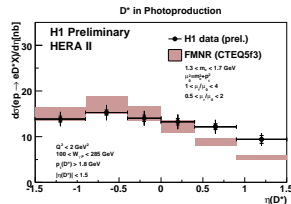
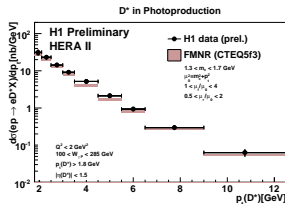
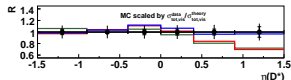
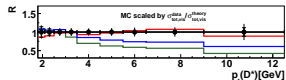
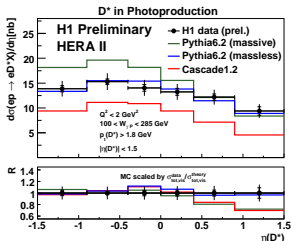
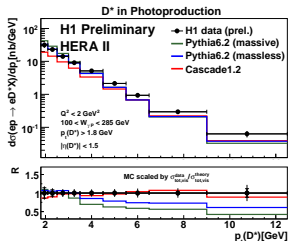


Data compared to  
HVQDIS

## Double-differential cross-sections in $y$ and $Q^2$



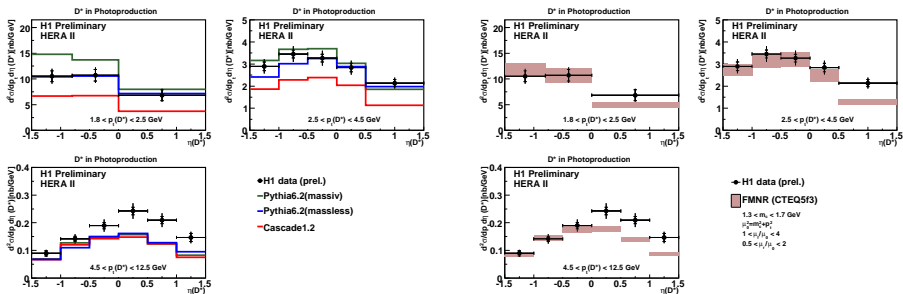
## Differential cross-sections in $p_t(D^*)$ and $\eta(D^*)$



Data compared to Pythia (massive), Pythia (massless) & Cascade MCs

Data compared to FMNR

## Double-differential cross-sections in $p_t(D^*)$ and $\eta(D^*)$

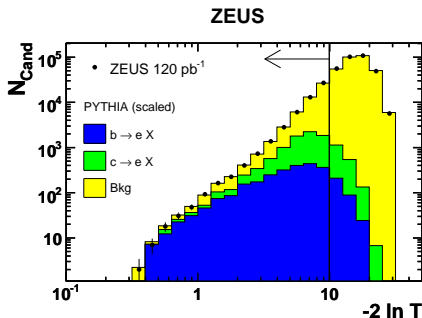
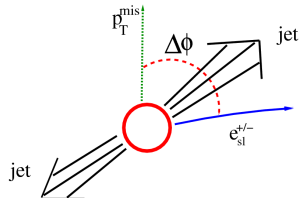


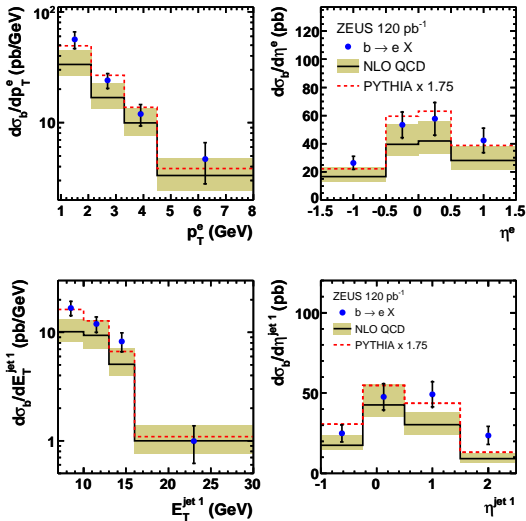
## Part II

# Beauty Production

**Data:** HERA I ( $\mathcal{L} = 120 \text{ pb}^{-1}$ )  
**LO:** Pythia  
**NLO:** FMNR

- Dijet events with  $E_T > 7(6) \text{ GeV}$
- Semileptonic decays to electrons
- Combine several discriminating variables in likelihood test function:
  - ▶ Electron identification:  $dE/dx$ , EMC fraction,  $E/p$
  - ▶ Decay identification:  $\Delta\phi$  and  $p_t^{\text{rel}}$





Differential cross-sections in  $p_T^e, \eta^e, E_T^{\text{jet}1}, \eta^{\text{jet}1}$

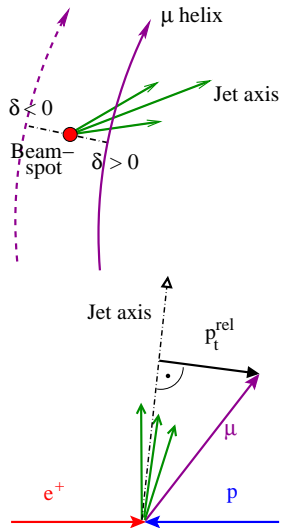
- NLO prediction consistent with Data
- Scaled MC distributions describe the shape well

**Data:** 2005 ( $\mathcal{L} = 124 \text{ pb}^{-1}$ )

**LO:** Pythia

**NLO:** FMNR

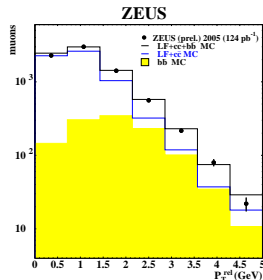
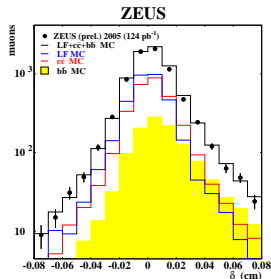
- Dijet PhP events with  $p_T^{\text{jet}} > 7(6) \text{ GeV}$
- Semileptonic decays to muons
  - ▶  $-1.6 < \eta^\mu < 2.3$
  - ▶  $p_t^\mu > 2.5 \text{ GeV}$
- Simultaneous fit of impact parameter and  $p_t^{\text{rel}}$

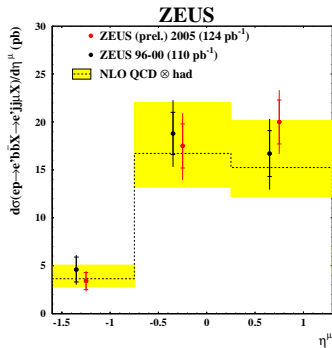
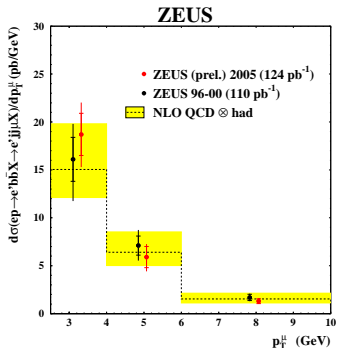




**Data:** 2005 ( $\mathcal{L} = 124 \text{ pb}^{-1}$ )  
**LO:** Pythia  
**NLO:** FMNR

- Dijet PhP events with  $p_T^{\text{jet}} > 7(6) \text{ GeV}$
- Semileptonic decays to muons
  - ▶  $-1.6 < \eta^\mu < 2.3$
  - ▶  $p_t^\mu > 2.5 \text{ GeV}$
- Simultaneous fit of impact parameter and  $p_t^{\text{rel}}$





$$\sigma^{vis} = 46.8 \pm 4.0 \text{ (stat.)}_{-7.2}^{+6.1} \text{ (syst.) pb}$$

$$\sigma^{NLO} = 41.5_{-8.9}^{+13.9} \text{ pb}$$

**Data:** Hera I ( $\mathcal{L} = 114 \text{ pb}^{-1}$ )

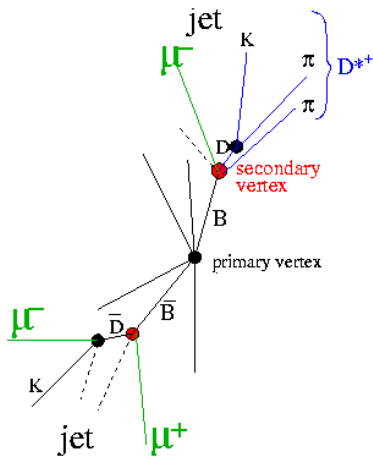
**LO:** Pythia + Rapgap

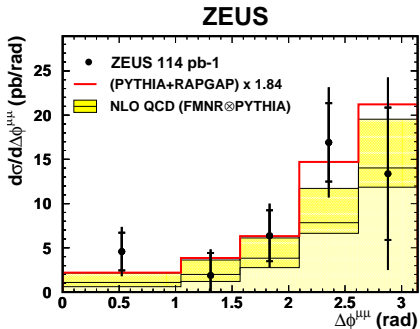
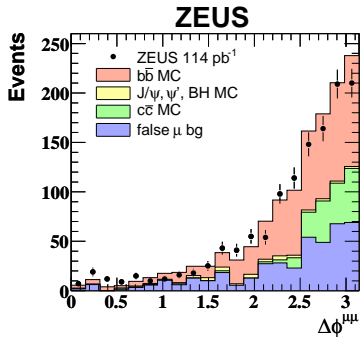
**NLO:** FMNR

- PhP and DIS
- Two identified muons in the final state
- Extract b fraction from difference between unlike-sign and like-sign distributions

#### Advantages:

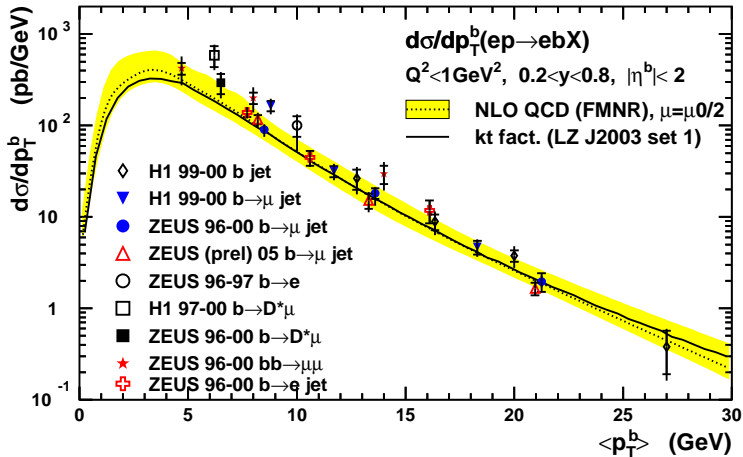
- No jet requirements
- Low  $p_t^\mu$  thresholds
- Measure bb correlations





- $\Delta\phi^{\mu\mu}$  = angle between muons from different quarks
- Correlations expected to show higher order effects  
→ Good description, but large uncertainties

## HERA



## Part III

$F_2^{c\bar{c}}$  and  $F_2^{b\bar{b}}$

**Data:** 2006 ( $\mathcal{L} \approx 54 \text{ pb}^{-1}$ )

**LO:** Rapgap, Cascade

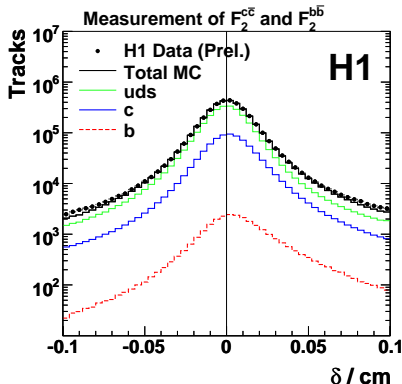
**Kinematic region:**

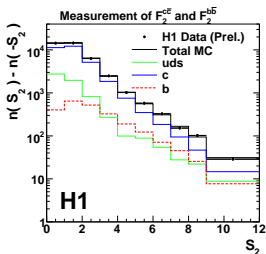
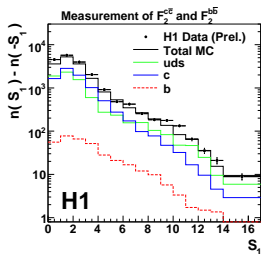
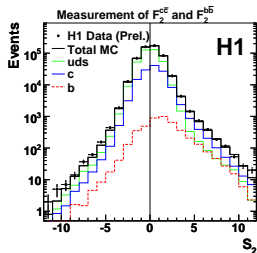
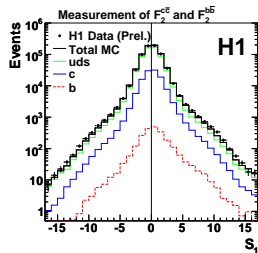
$$12 < Q^2 < 650 \text{ GeV}^2$$

$$0.0002 \leq x \leq 0.032$$

$$p_T^{\text{track}} > 0.5 \text{ GeV}$$

- **Aim:** Measure charm and beauty contribution to inclusive proton structure function  $F_2$  in DIS
- Use impact parameter significance  $\delta/\sigma(\delta)$  to extract beauty and charm fractions





- Significance  $\delta/\sigma(\delta)$  for highest significant track  $S_1$  and second highest significant track  $S_2$
- Simultaneous fit of the subtracted  $S_1$  and  $S_2$  distributions



- Calculation of  $F_2^{c\bar{c}}$  via **reduced cross-section**

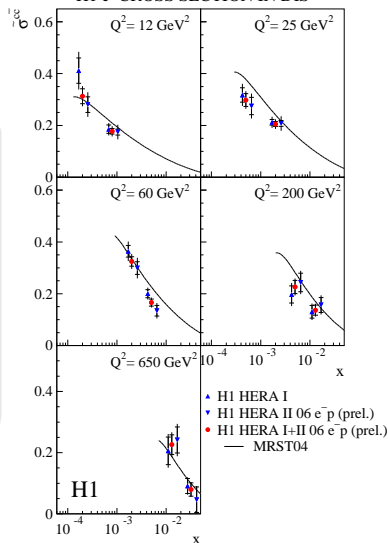
$$\tilde{\sigma}^{c\bar{c}}(x, Q^2) = \frac{d^2\sigma^{c\bar{c}}}{dx dQ^2} \frac{xQ^4}{2\pi\alpha^2(1+(1-y)^2)}$$

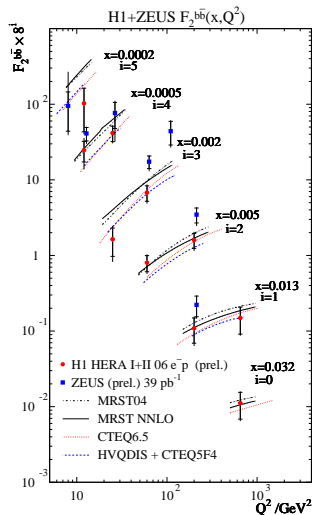
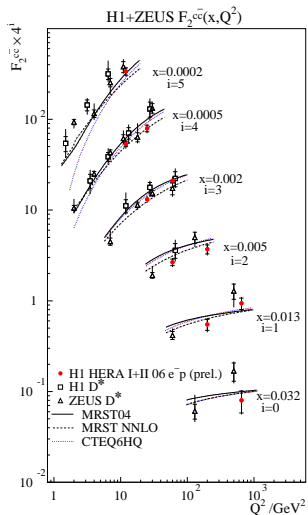
- $F_2^{c\bar{c}}$  evaluated after corrections for the longitudinal structure function  $F_L^{c\bar{c}}$ :

$$\tilde{\sigma}^{c\bar{c}} = F_2^{c\bar{c}} - \frac{y^2}{1+(1-y)^2} F_L^{c\bar{c}}$$

- Combine with HERA I result

H1 c CROSS SECTION IN DIS





# Summary

- Latest results of heavy flavour production at HERA presented
  - HERA II data provide large increase in statistics
  - New methods used and improved (lifetime tagging)
- 
- Shapes well described by LO MCs
  - General agreement with NLO QCD predictions
  - Beauty production summary plot shows reasonable agreement between various measurements and NLO prediction
  - $F_2^{c\bar{c}}$  and  $F_2^{b\bar{b}}$  measured over a wide range of  $Q^2$  and Bjorken  $x$

# BACKUP

Selection cuts:

### in DIS

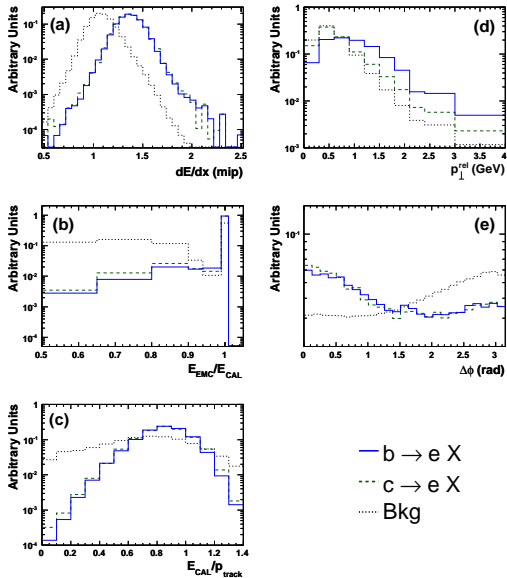
- $p_t(K) > 0.3 \text{ GeV}$
- $p_t(\pi) > 0.3 \text{ GeV}$
- $p_t(\pi_{slow}) > 0.12 \text{ GeV}$
- $p_t(K) + p_t(\pi) > 2.0 \text{ GeV}$
- $|M(K\pi) - M(D^0)| < 0.08 \text{ GeV}$

### in PhP

- $p_t(K) > 0.5 \text{ GeV}$
- $p_t(\pi) > 0.3 \text{ GeV}$
- $p_t(\pi_{slow}) > 0.12 \text{ GeV}$
- $p_t(K) + p_t(\pi) > 2.2 \text{ GeV}$
- $|M(K\pi) - M(D^0)| < 0.08 \text{ GeV}$

### Cross-section determination

$$\sigma_{\text{vis}}^{\text{tot}} = \frac{N_{D^*} \cdot (1-r)}{\mathcal{L} \cdot \mathcal{B}(D^* \rightarrow K\pi\pi_{\text{slow}}) \cdot \epsilon \cdot (1-\delta_{\text{rad}})}$$



## Discriminating variables

- $dE/dx$
- $p_t^{rel}$
- EMC fraction
- $\Delta\phi$
- $E/p$

## Method

- Sample split into different charge combinations
- 2 muons from same b quark
  - Unlike-sign muon pair
- 2 muons from different b quarks
  - Like-sign or unlike-sign muon pair
- Use difference between unlike-sign and like-sign distributions to extract beauty contribution
  - Almost free from false-muon background
  - Other background sources: Charm, heavy vector mesons, Bethe-Heitler