

# Production of heavy flavours in ep collisions at HERA



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***on behalf of the H1 and ZEUS Collaborations***



Motivation

Predictions

Tagging methods

Tests of QCD in PhP and DIS

Structure Functions and PDF of Proton

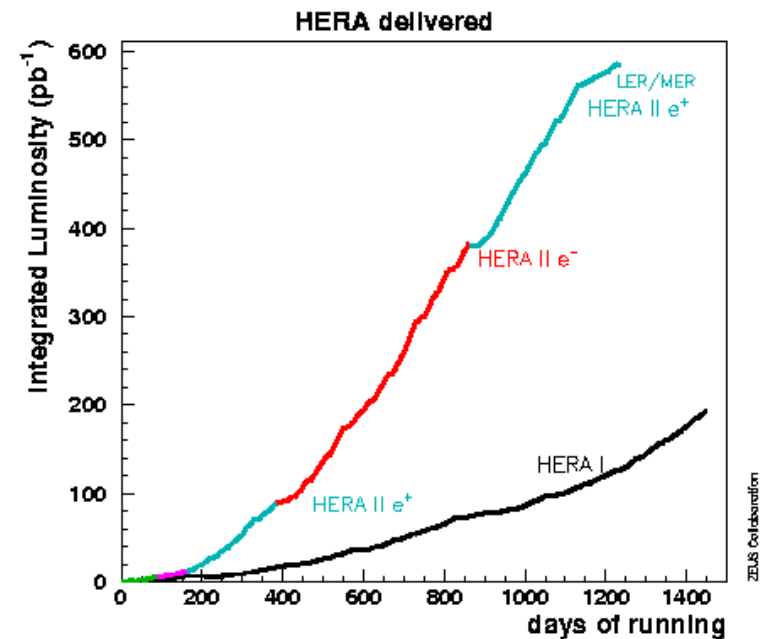
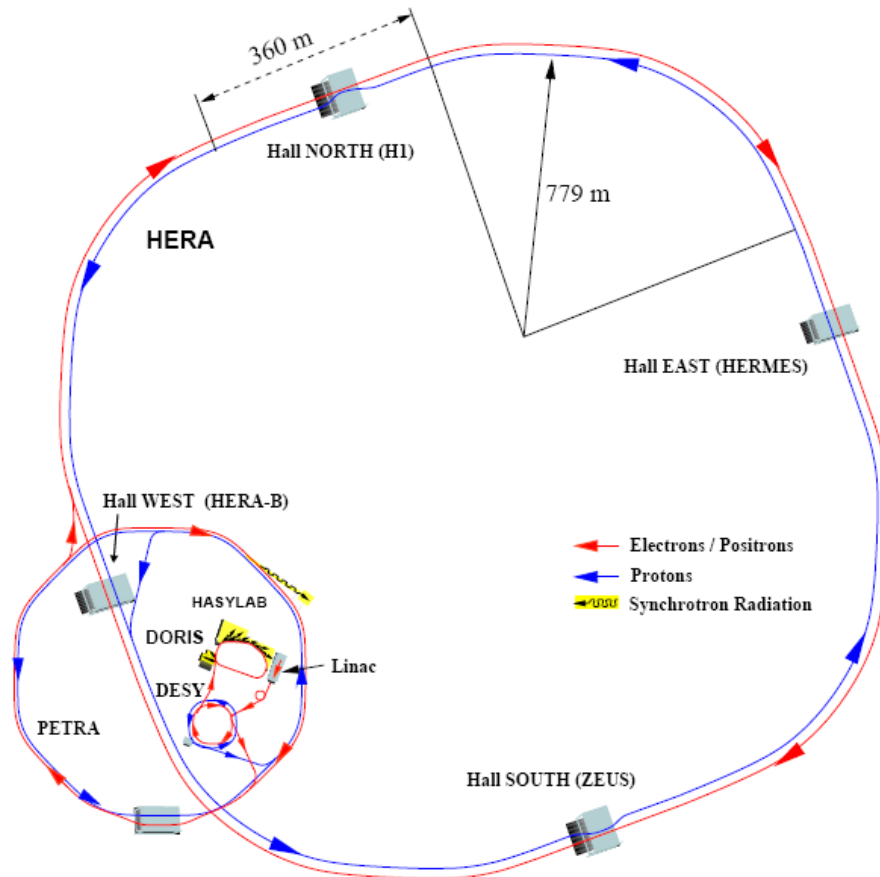
# The HERA Collider

$e^\pm$  energy 27.5 GeV

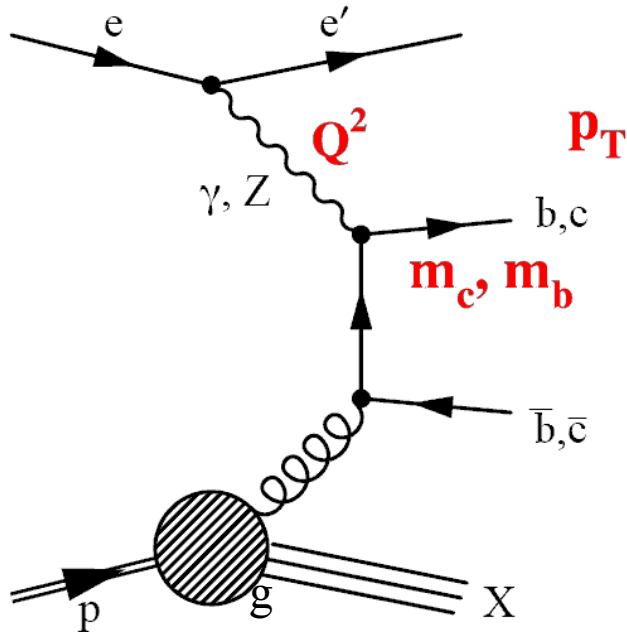
p energy 920 GeV

centre-of-mass energy 318 GeV

2 collider experiments: ZEUS and H1



# Heavy Quark production in ep interactions



## Boson Gluon Fusion (BGF)

dominating mechanism of heavy quark production

## invariant kinematical variables:

$s=(k+p)^2$  center-of-mass energy of ep system squared

$Q^2=-q^2=-(k-k')^2$  boson virtuality

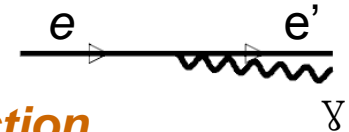
$x=Q^2/2pq$  Bjorken scaling variable

$y=pq/pk$  inelasticity – fraction of lepton energy transferred to the hadronic system in the proton rest frame

## Two kinematic regimes:

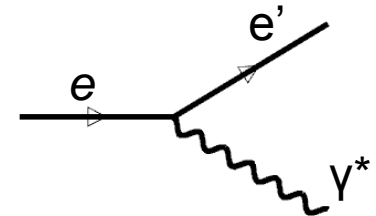
$Q^2 \approx 0 \text{ GeV}^2$

**Photoproduction**

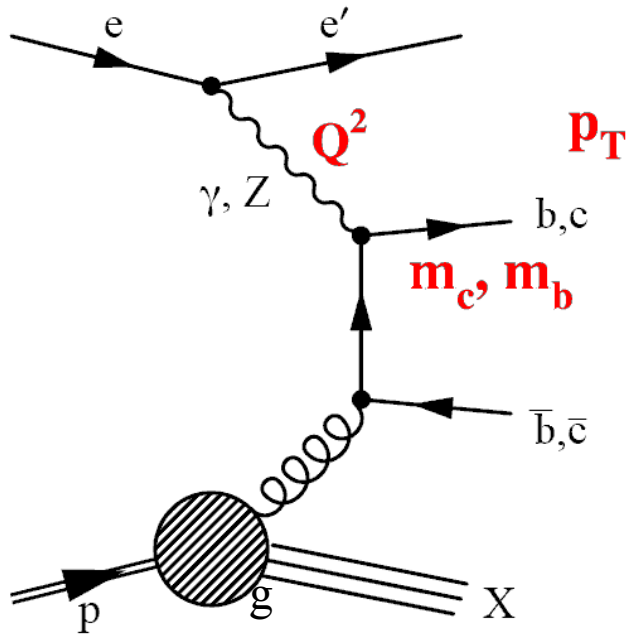


$Q^2 > 1 \text{ GeV}^2$

**Deep Inelastic Scattering**



## Motivation



c and b quarks provide a hard scale

-Tests of *pQCD* based models –  
scales  $Q^2, m_{HQ}, p_T$

BGF process is directly sensitive to  
the gluon density in the proton

-Measurement of charm and beauty  
contribution to the structure function  
of the proton –  $F_2^{cc}$  and  $F_2^{bb}$  and their  
impact on the protons PDF

# pQCD calculations

## Massive (FFNS)

*c and b generated dynamically*

*c and b massive*

*Neglects  $[\alpha_s \ln(\mu^2/m^2)]^n$*

*Valid for  $\mu^2 \approx m^2$*

*Programs: HVQDIS, FMNR(PhP)*

## Massless (ZM-VFNS)

*c and b massless partons in  
proton and photon*

*Resums  $[\alpha_s \ln(\mu^2/m^2)]^n$*

*Valid for  $\mu^2 \gg m^2$*

## Variable Flavour Number Scheme (GM-VFNS)

*Interpolation between massive and massless  
model*

*Massive at low  $Q^2$*

*Massless at high  $Q^2$*

*(eg. for prediction of  $F_2^{cc}$  and  $F_2^{bb}$ )*

# Monte Carlo Generators

**PYTHIA** – most frequently used for PhP at HERA for all quark flavours

PS – according DGLAP approximation of the evolution of PDF

fragmentation – Lund string model

**RAPGAP** – standard event generator for DIS

HQ production in the massive scheme

**CASCADE** – instead of DGLAP uses CCFM evolution equation

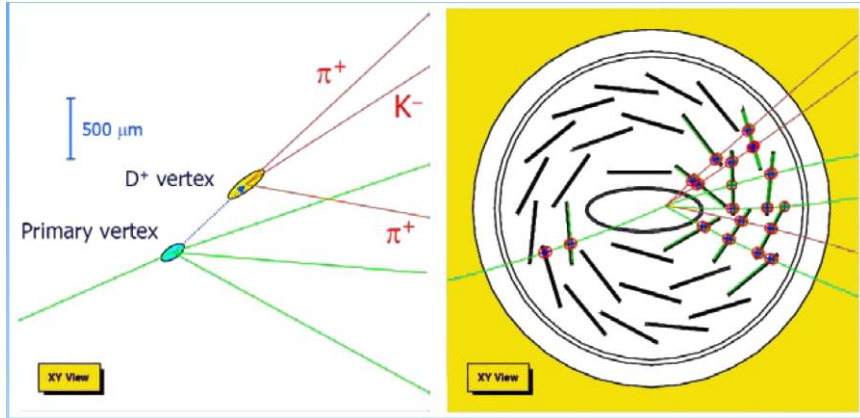
Can be used both for PhP and DIS

**MC@NLO** – NLO matrix elements for HQ production

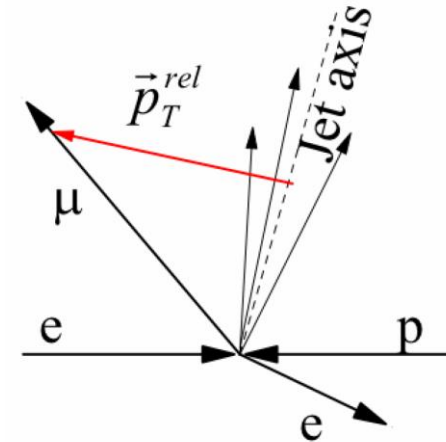
PS and hadronisation from MC

# Heavy quark tagging methods

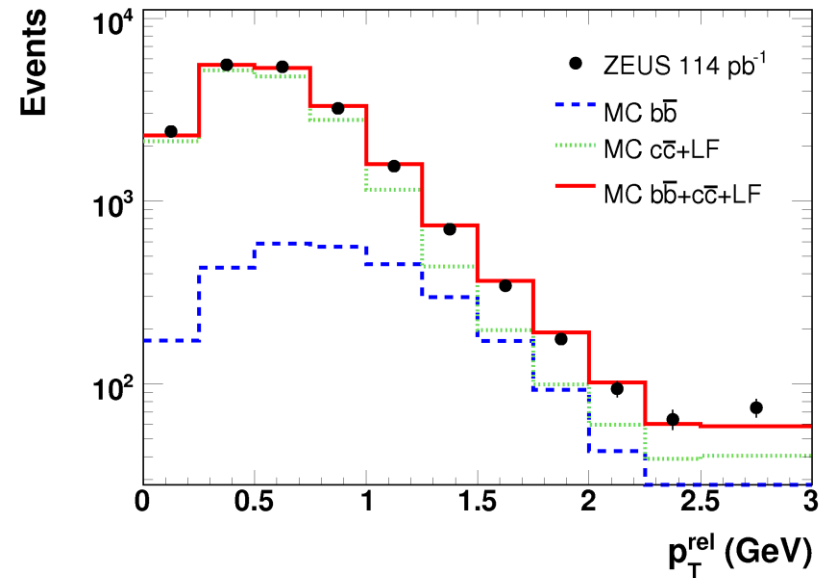
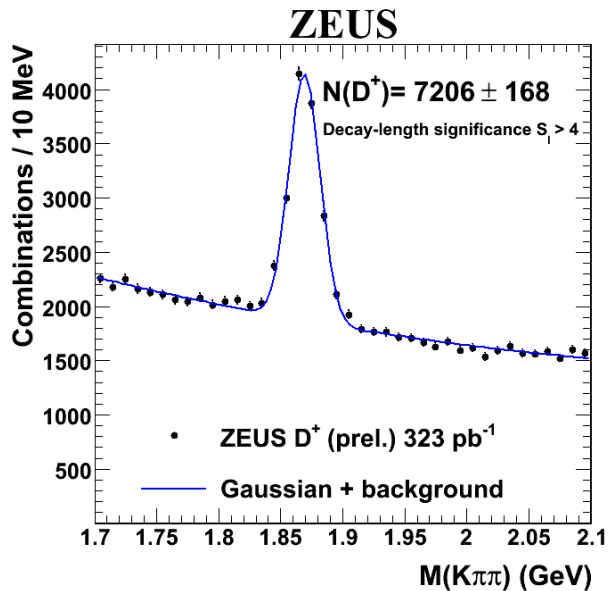
## Reconstruction of $D$ meson



## Semileptonic decay $c, b \rightarrow e$ or $c, b \rightarrow \mu$

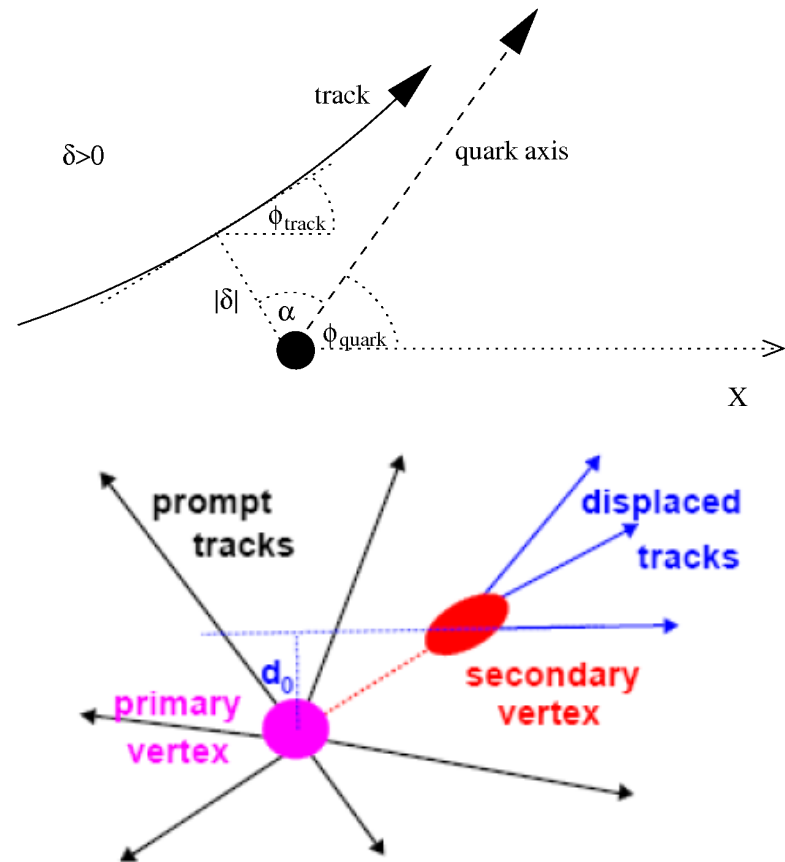
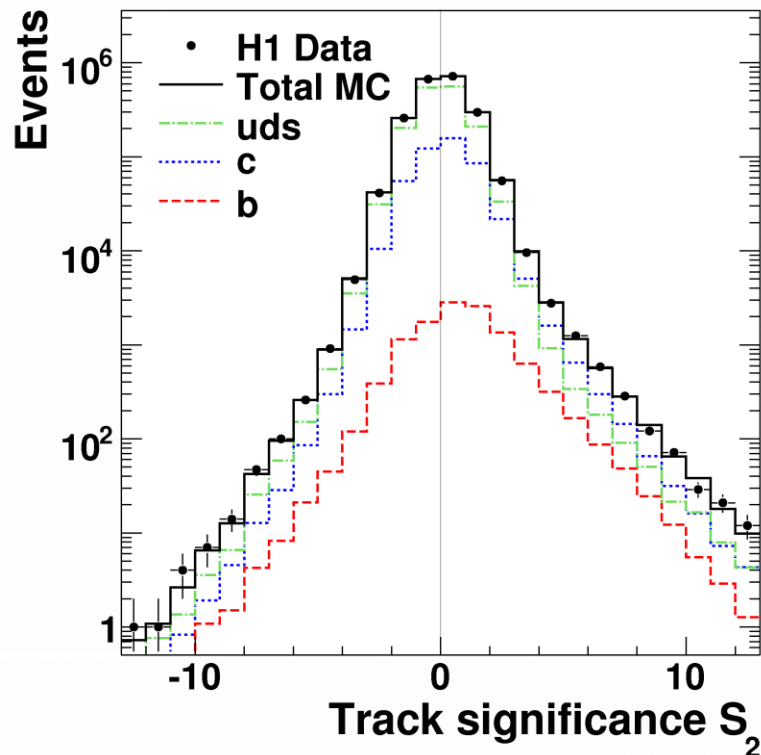


ZEUS



# Heavy quark tagging methods

*Inclusive method based on information from vertex detector and using long  $B$  and  $D$  lifetime*





# Charm *Photoproduction* using $D^*$ and dijets

data sample:  $93.4 \text{ pb}^{-1}$

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

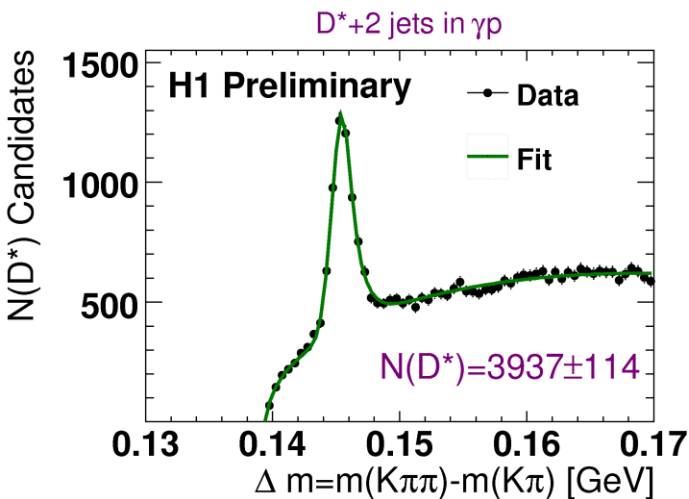
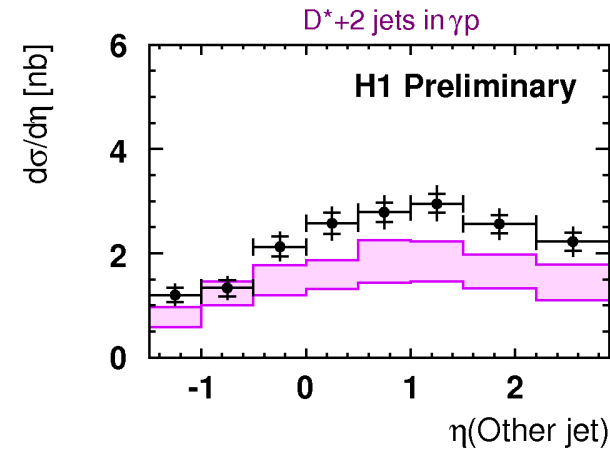
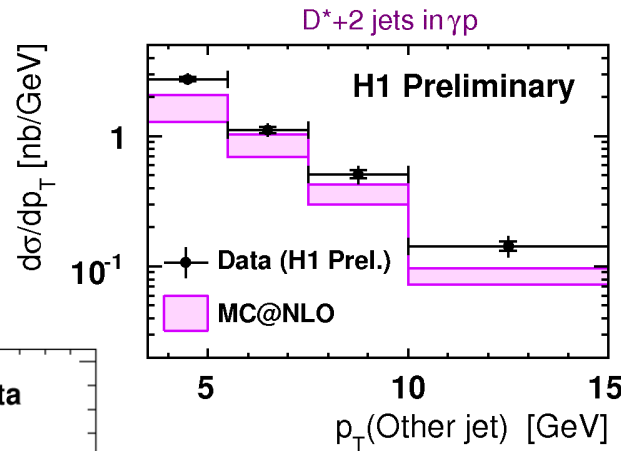
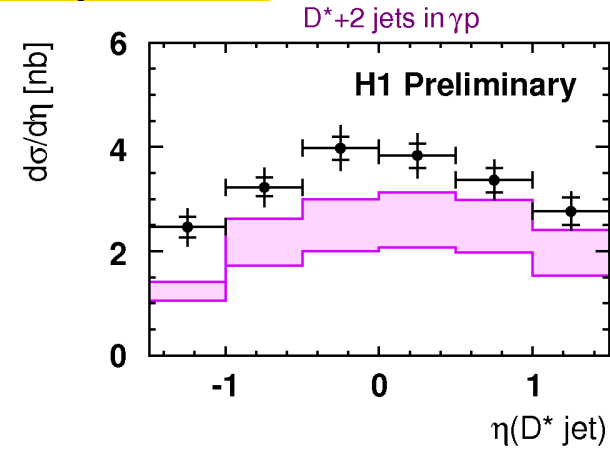
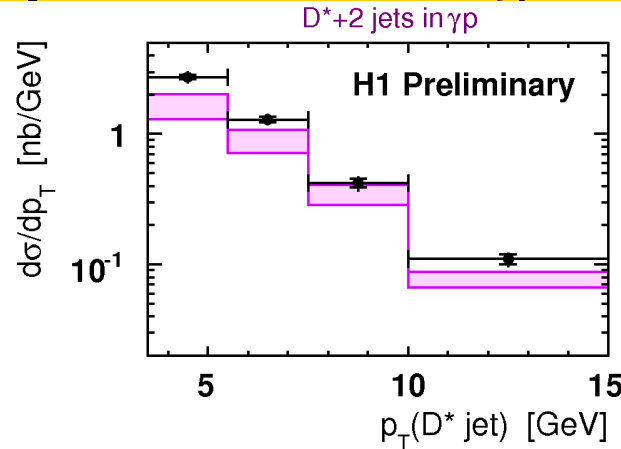
$D^*$  reconstructed in the  
golden decay channel

$D^{*\pm} \rightarrow D^0 \pi^\pm \rightarrow (K \pi) \pi^\pm$

$p_t(D^*) > 2.1 \text{ GeV}$

$|\eta(D^*)| < 1.5$

$P_T^{\text{jet}} > 3.5 \text{ GeV}$

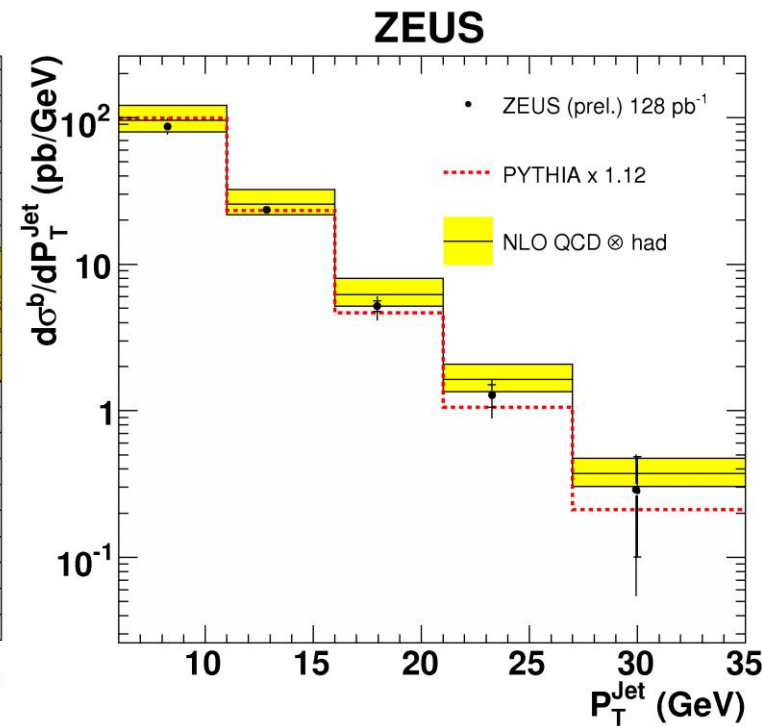
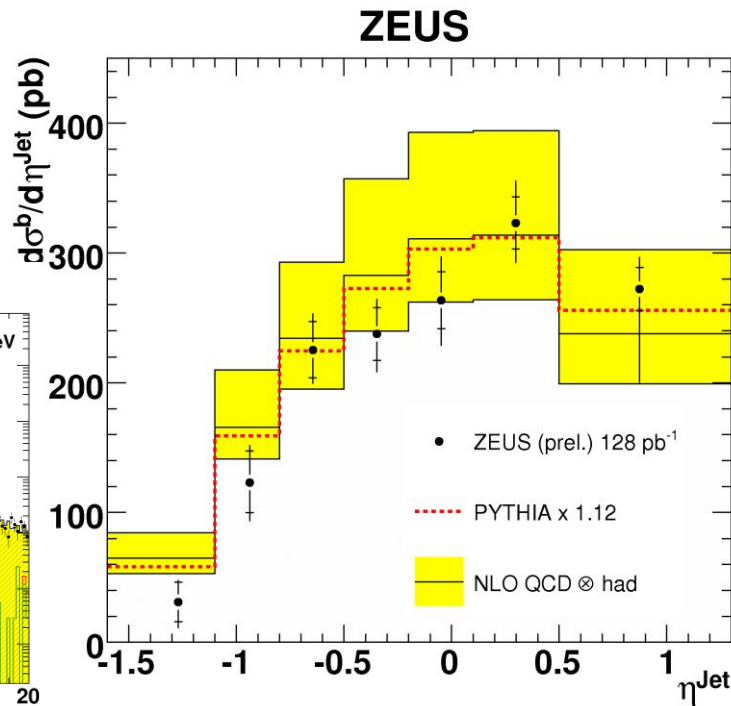
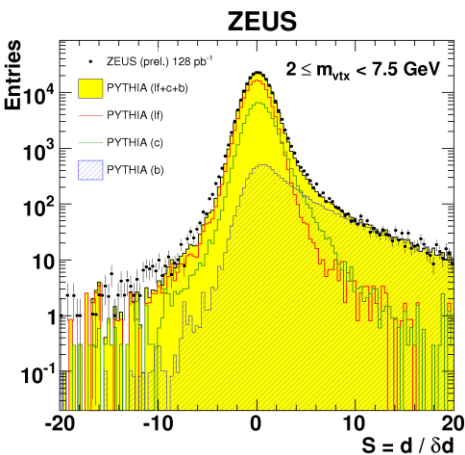


Reasonable agreement with MC@NLO

# Beauty in Photoproduction with jets

data sample: 128 pb<sup>-1</sup> (2006-07)

$Q^2 < 1 \text{ GeV}^2$   
 2 jets with  
 $p_T > 7(6) \text{ GeV}$   
 $|\eta^{\text{jet}}| < 2.5$

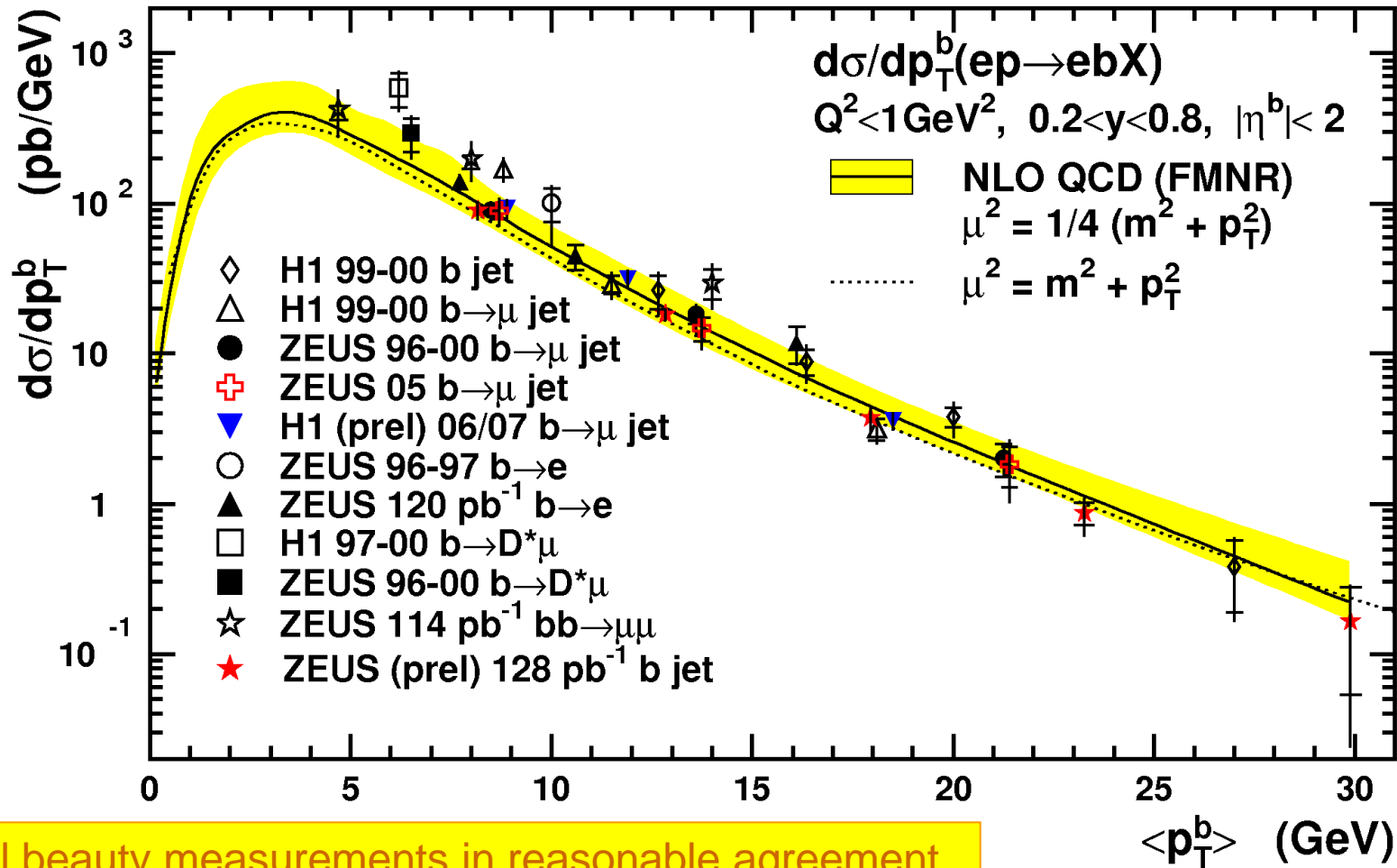


3D secondary vertices  
 reconstructed using  
 secondary vertex  
 information

Good agreement with NLO

## Beauty in Photoproduction with jets

## HERA

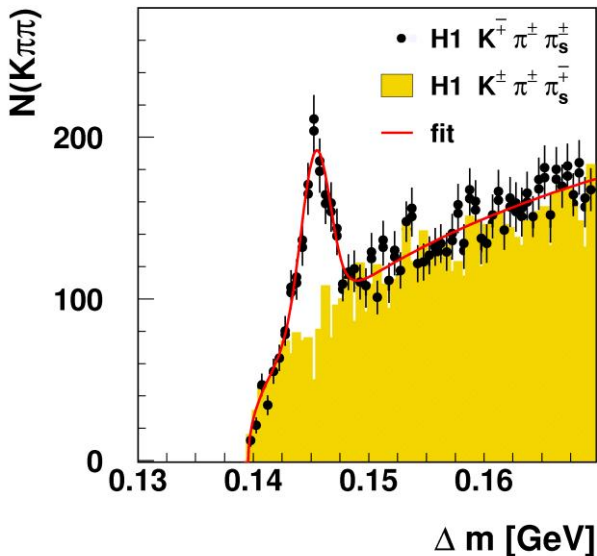
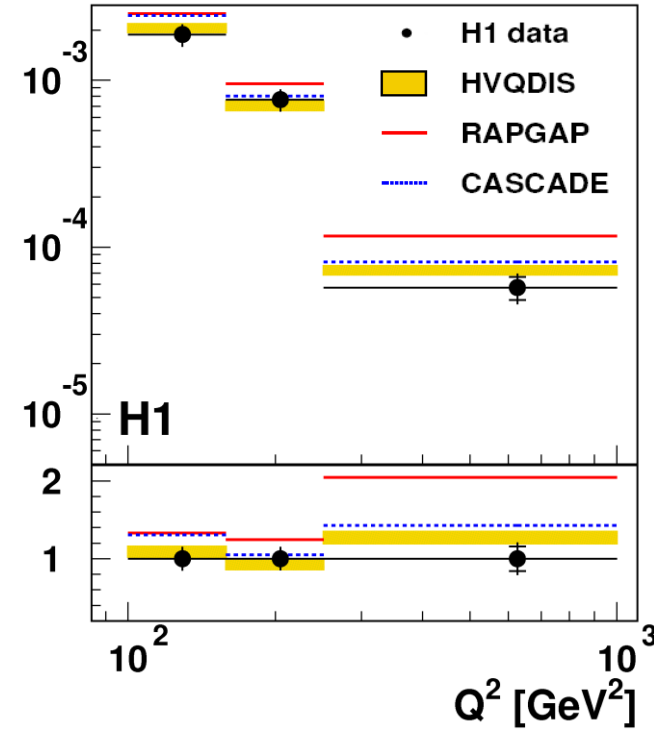
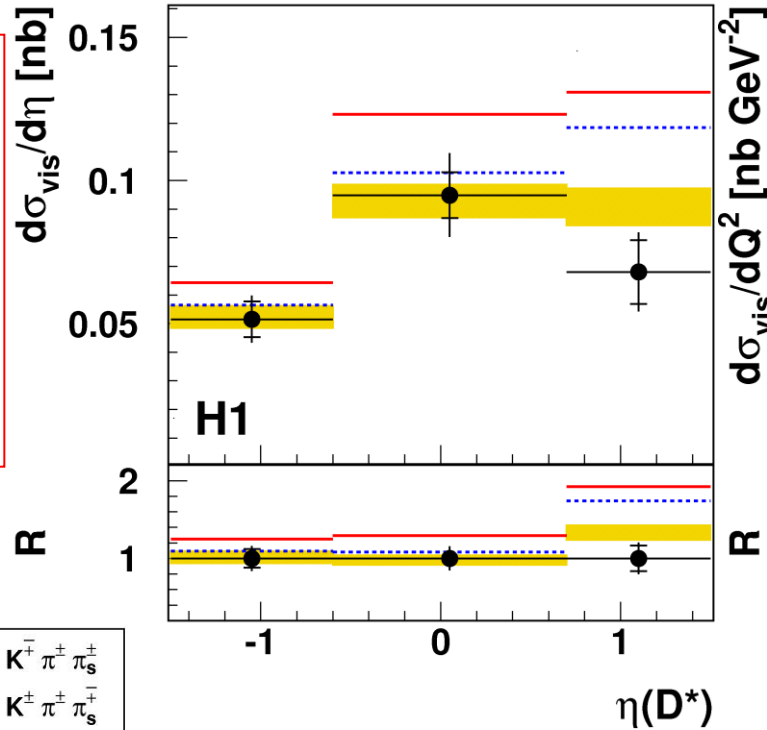


All beauty measurements in reasonable agreement  
 NLO prediction agrees with measurements  
 New measurement compatible with previous results

# $D^*$ production in **DIS** at $Q^2 > 100 \text{ GeV}^2$

data sample:  $351 \text{ pb}^{-1}$

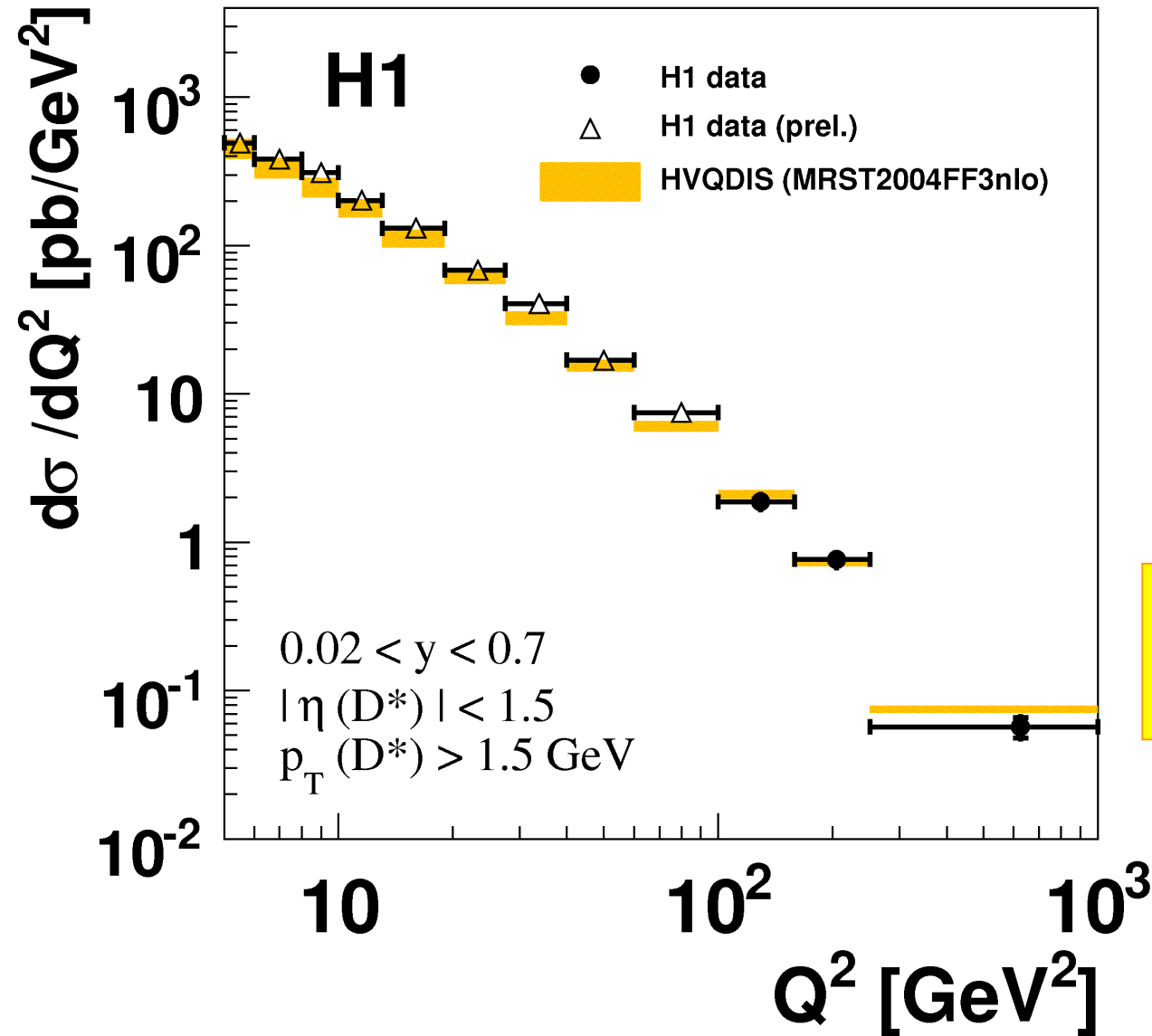
$100 < Q^2 < 1000 \text{ GeV}^2$   
 $D^*$  reconstructed in  
 the golden decay  
 channel  
 $D^{*\pm} \rightarrow D^0 \pi^\pm \rightarrow (K\pi) \pi^\pm$   
 $p_T(D^*) > 1.5 \text{ GeV}$   
 $|\eta(D^*)| < 1.5$   
 $0.02 < y < 0.7$



Good agreement with massive  
 NLO (despite  $Q^2 \gg m_c^2$ )  
 MC LO predictions do not  
 describe data well

# D\* production Cross Section in full Q<sup>2</sup> Range

## D\* production in DIS

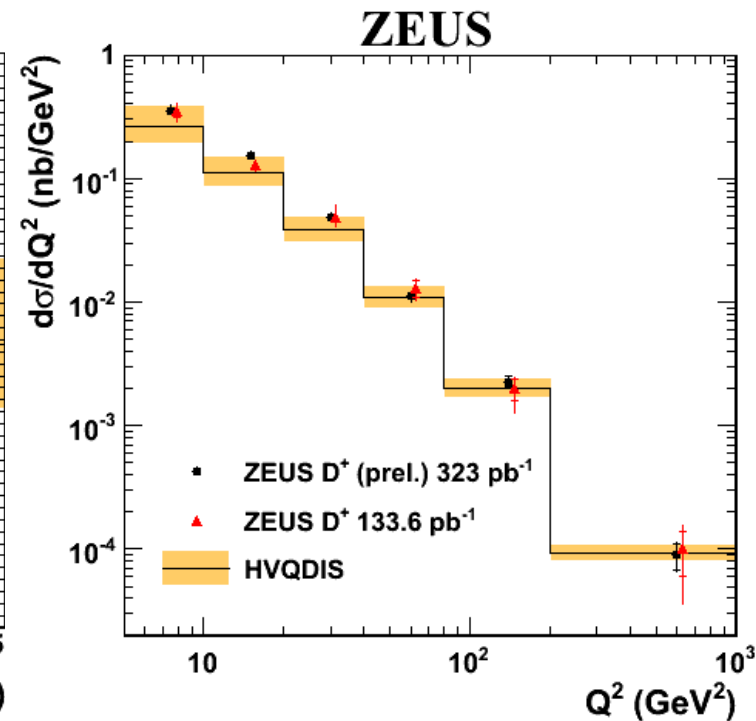
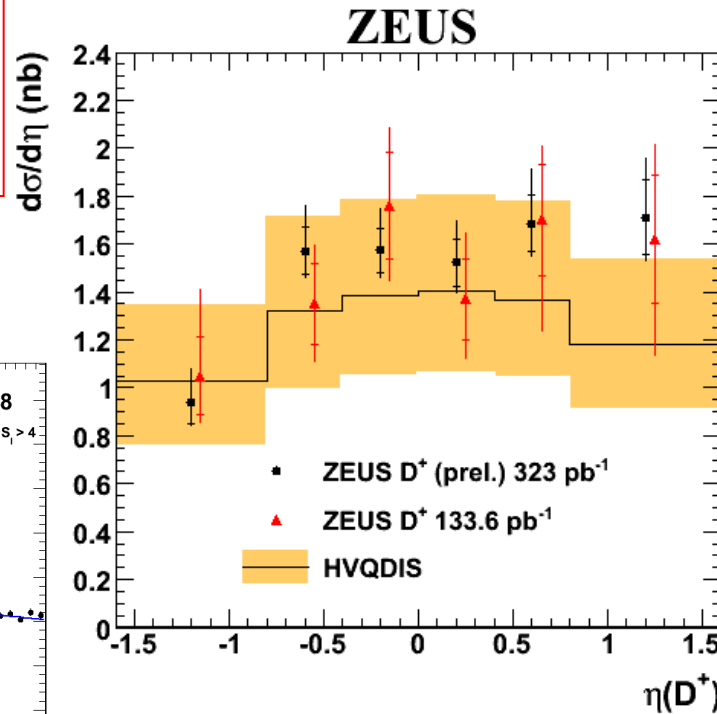
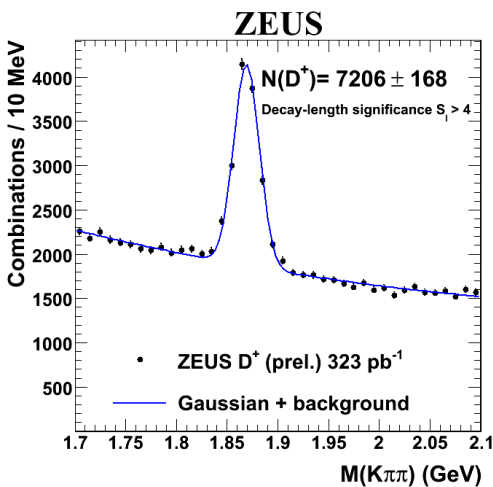


HVQDIS – describes data for whole kinematic region

# $D^\pm$ in DIS

data sample:  $323 \text{ pb}^{-1}$  (2005 -07)

$5 < Q^2 < 1000 \text{ GeV}^2$   
 $0.02 < y < 0.7$   
 $1.5 < p_T(D^+) < 15 \text{ GeV}$   
 $-1.6 < \eta^{jet} < 1.6$

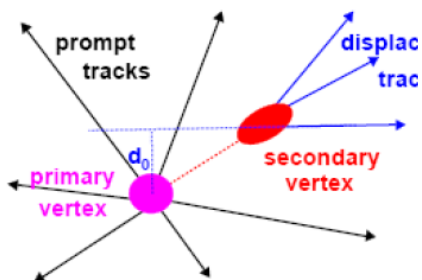


Reduction of background  
 using secondary vertex  
 information

Good agreement with  
 HVQDIS NLO QCD

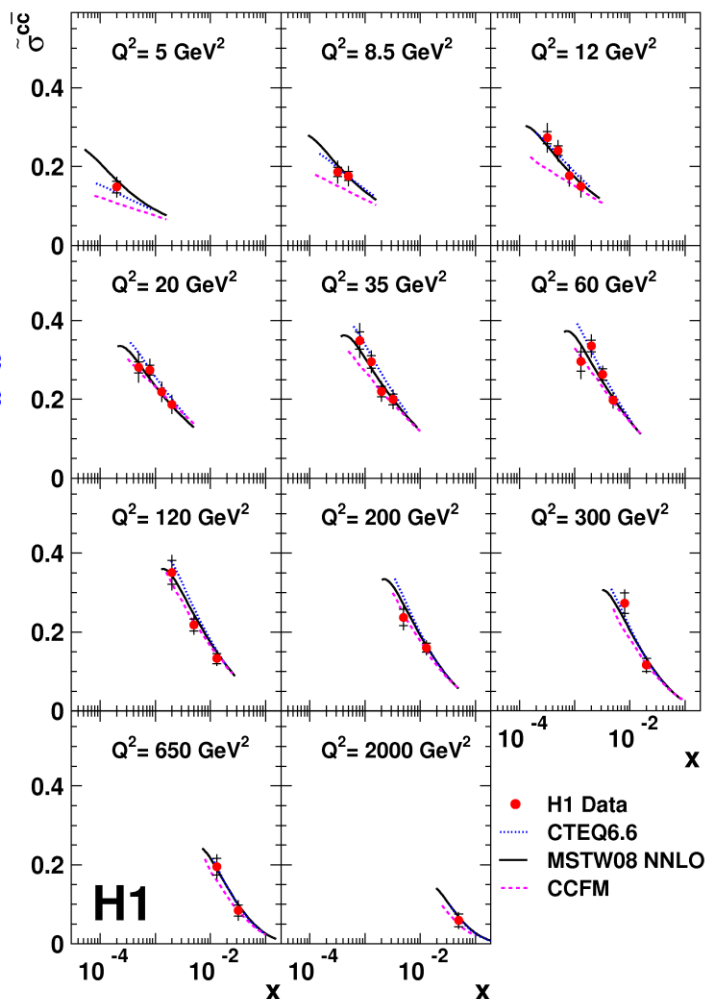
# Inclusive charm & beauty in DIS

data sample:  
189 pb<sup>-1</sup> (2006-07)

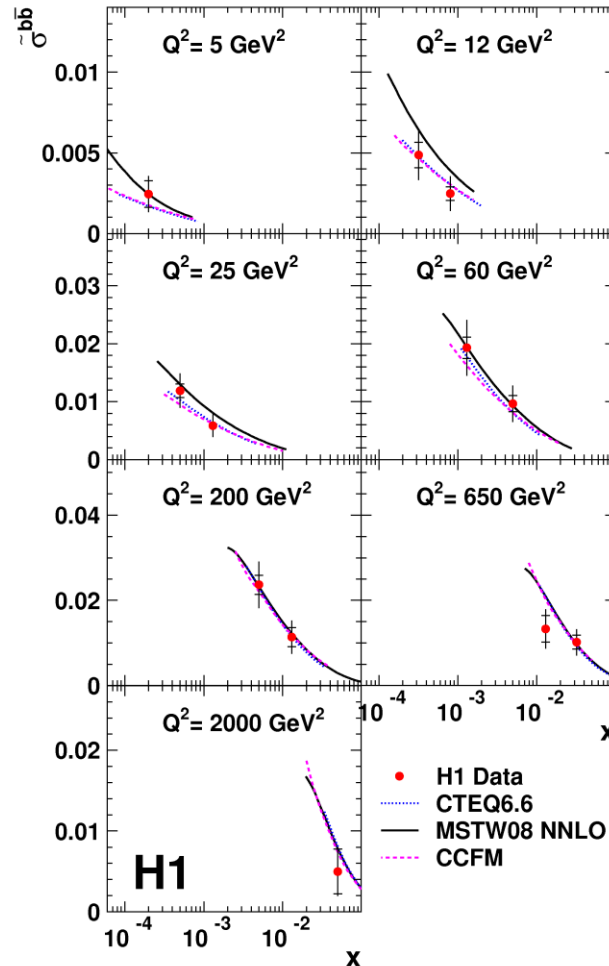


Measurement  
using VTX  
detector

## H1 CHARM CROSS SECTION IN DIS



## H1 BEAUTY CROSS SECTION IN DIS



Predictions reasonably describe the data

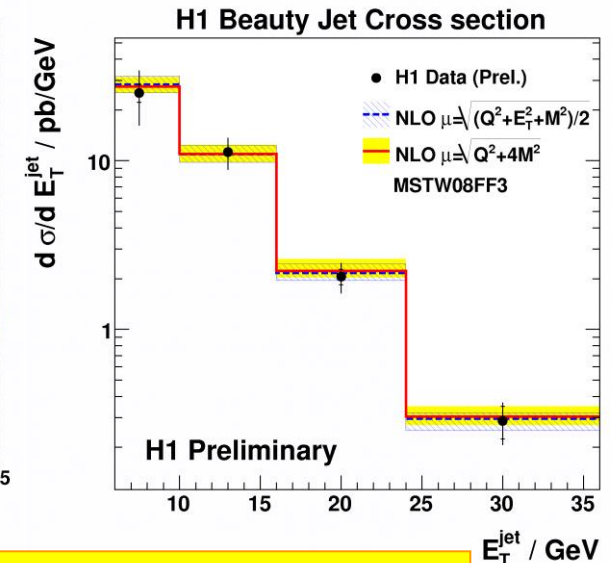
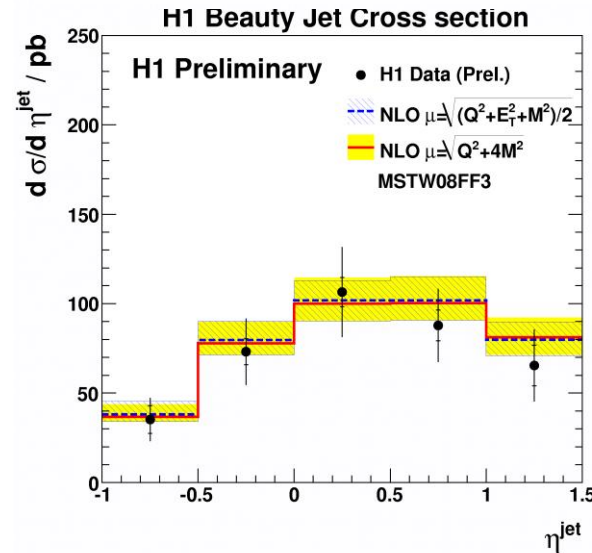
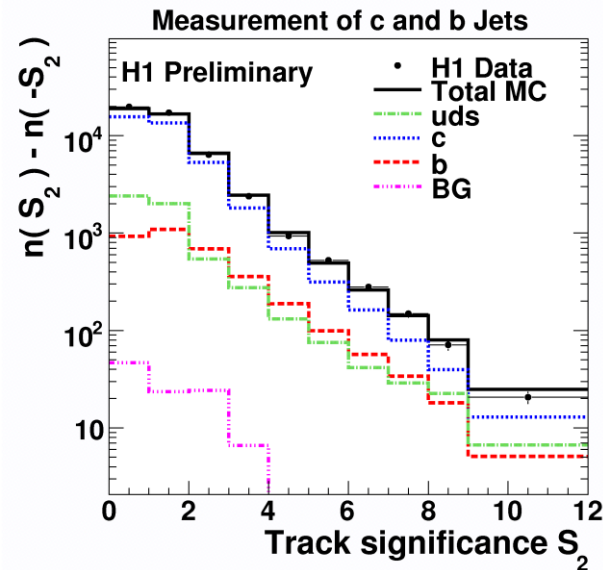
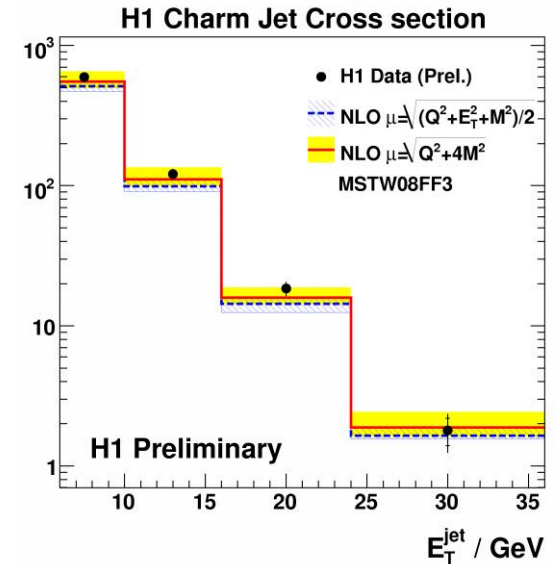
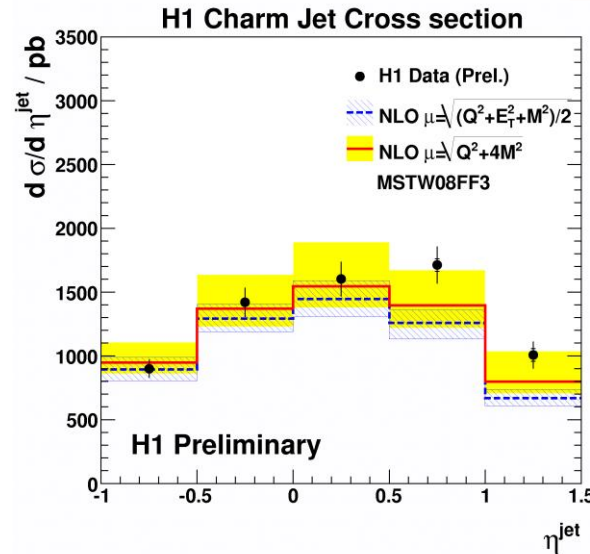
$$\tilde{\sigma}^{c\bar{c}}(x, Q^2) = \frac{d^2\sigma^{c\bar{c}}}{dx dQ^2} \frac{xQ^4}{2\pi\alpha^2(1 + (1 - y)^2)}$$

# charm & beauty in DIS with Jets

Good agreement with NLO

$6 < Q^2 < 1000 \text{ GeV}^2$   
 $0.07 < y < 0.625$   
 $E_T^{\text{jet}} > 6 \text{ GeV}$   
 $-1 < \eta^{\text{jet}} < 1.5$

Requiring a high  $E_T$   
 jet introduces  
 another hard scale

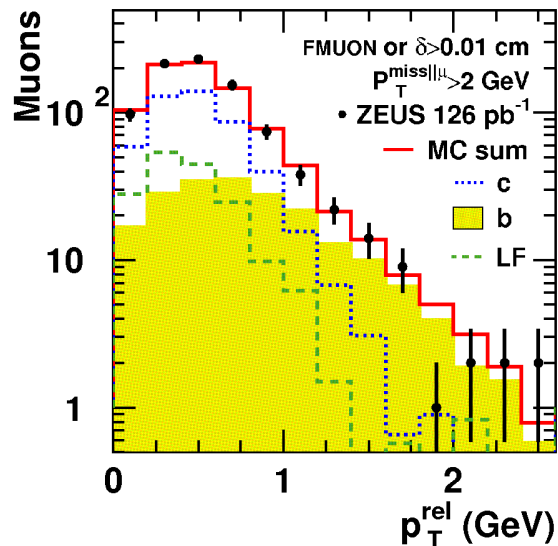


Beauty less sensitive to scale choice than charm

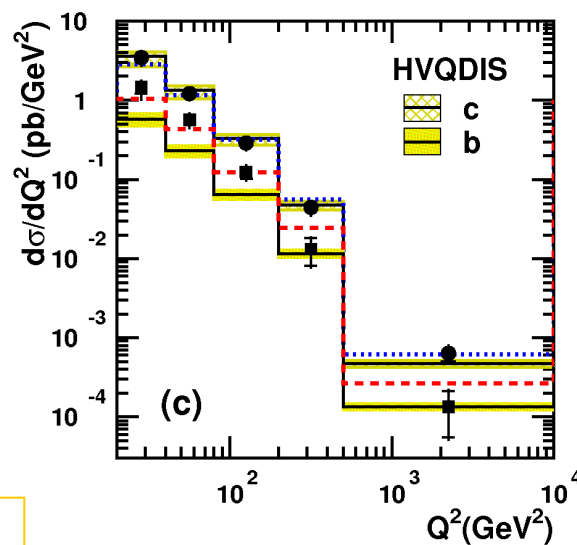
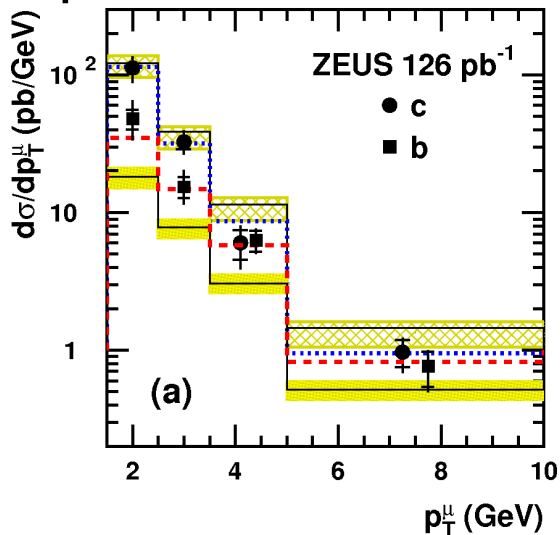


charm & beauty  $\rightarrow \mu$  in DISdata sample: 126 pb<sup>-1</sup> (2005)

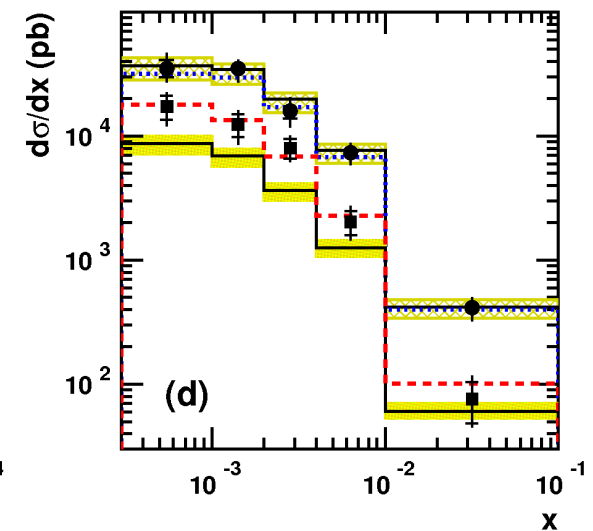
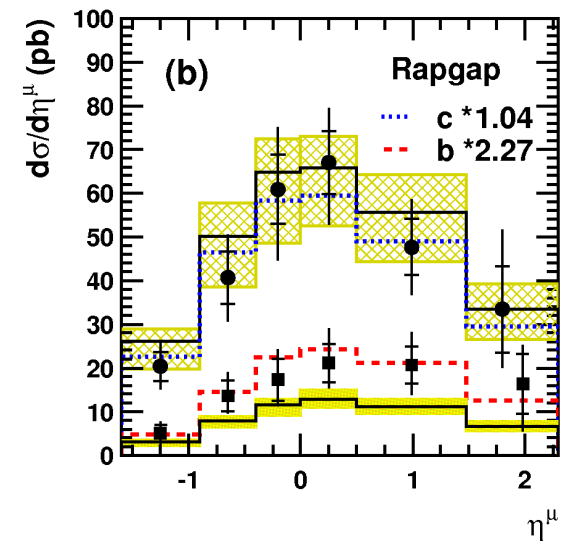
$$\begin{aligned}
 &Q^2 > 20 \text{ GeV}^2 \\
 &0.01 < y < 0.7 \\
 &-1.6 < \eta_\mu < 2.3 \\
 &p_T^\mu > 1.5 \text{ GeV} \\
 &p_T^{\text{jet}} > 2.5 \text{ GeV}
 \end{aligned}$$



3-dimensional fit of  $p_T^{\text{rel}}$ , missing pt and impact parameter  $\delta$  of muon using MC templates



## ZEUS



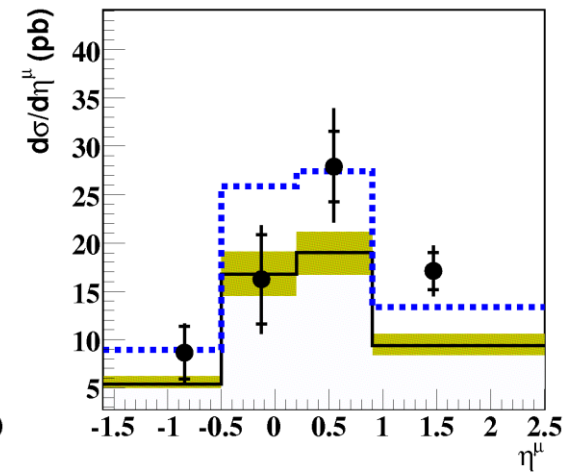
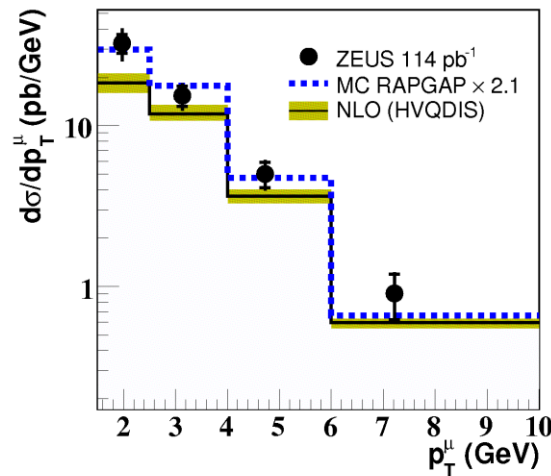
Charm: agreement with HVQDIS and RAPGAP  
Beauty: predictions below the data at low  $Q^2$

# Beauty $\rightarrow \mu$ in DIS (HERA I)

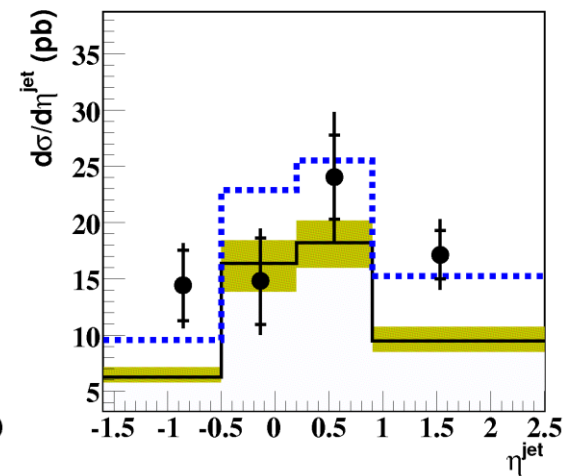
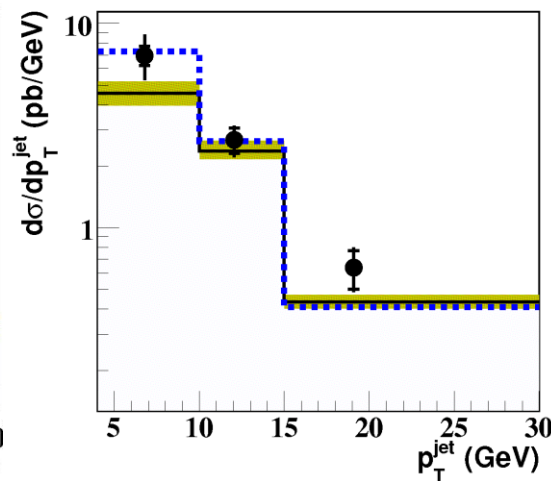
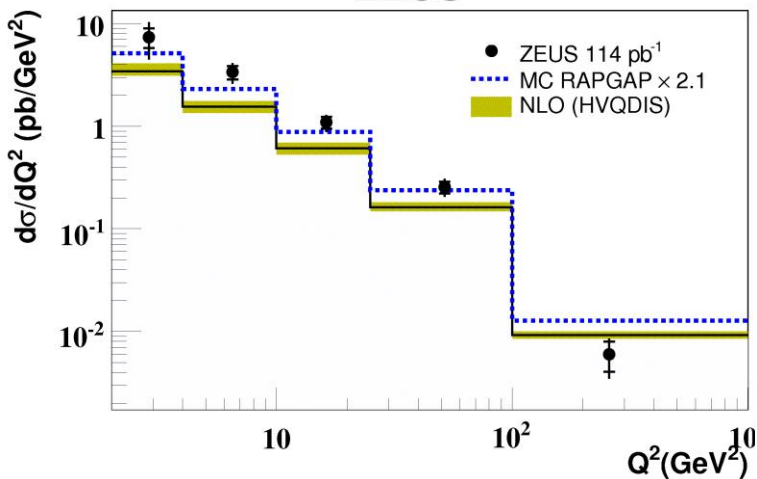
## ZEUS

data sample: 114 pb<sup>-1</sup> (1996-2000)

$Q^2 > 2 \text{ GeV}^2$   
 $0.05 < y < 0.7$   
 $\eta^\mu > -1.6$   
 $p_T^\mu > 1.5 \text{ GeV}$   
 $E_T^{\text{jet}, \text{lab}} > 5 \text{ GeV}$   
 $-2 < \eta^{\text{jet}} < 2.5$



## ZEUS

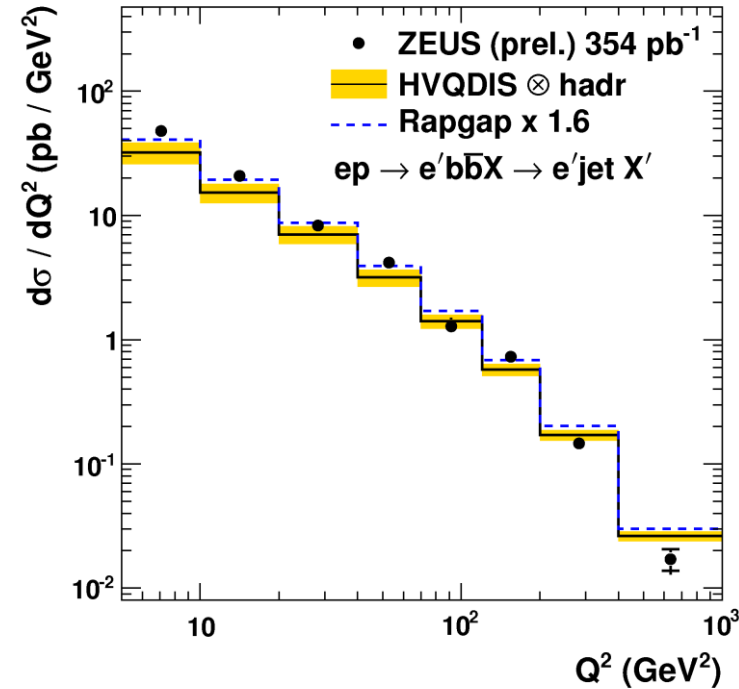
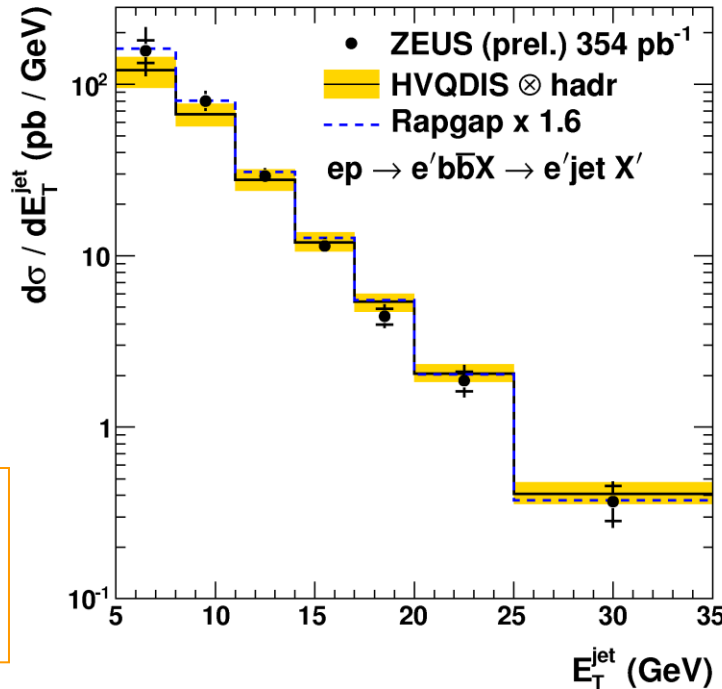


Acceptable description by HVQDIS  
 Similar differences as in previous analysis

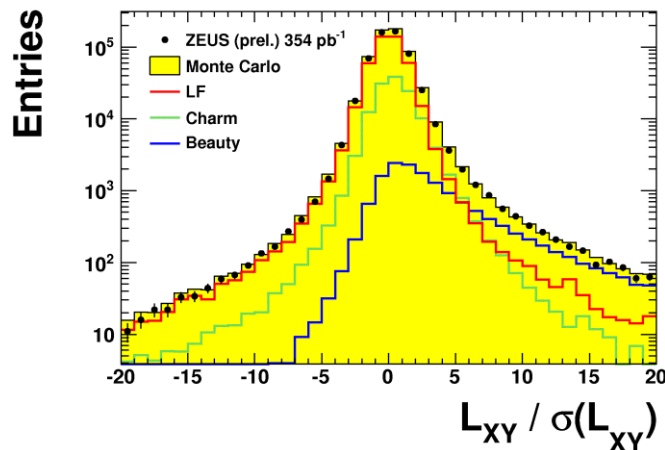
# Beauty using secondary vertices

data sample: 354 pb<sup>-1</sup> (2004 -07)

$5 < Q^2 < 1000 \text{ GeV}^2$   
 $0.02 < y < 0.7$   
 $E_T^{\text{jet}, \text{lab}} > 5 \text{ GeV}$   
 $-1.6 < \eta^{\text{jet}} < 2.2$



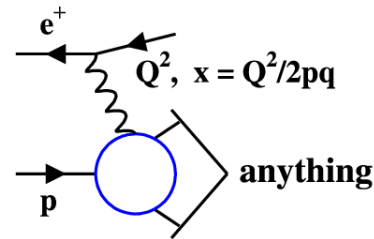
Measurement  
using secondary  
vertices



Good agreement with HVQDIS NLO QCD

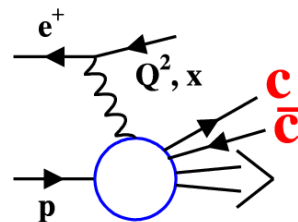
# $F_2^{bb}$ and $F_2^{cc}$ contributions to the proton structure function $F_2$

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

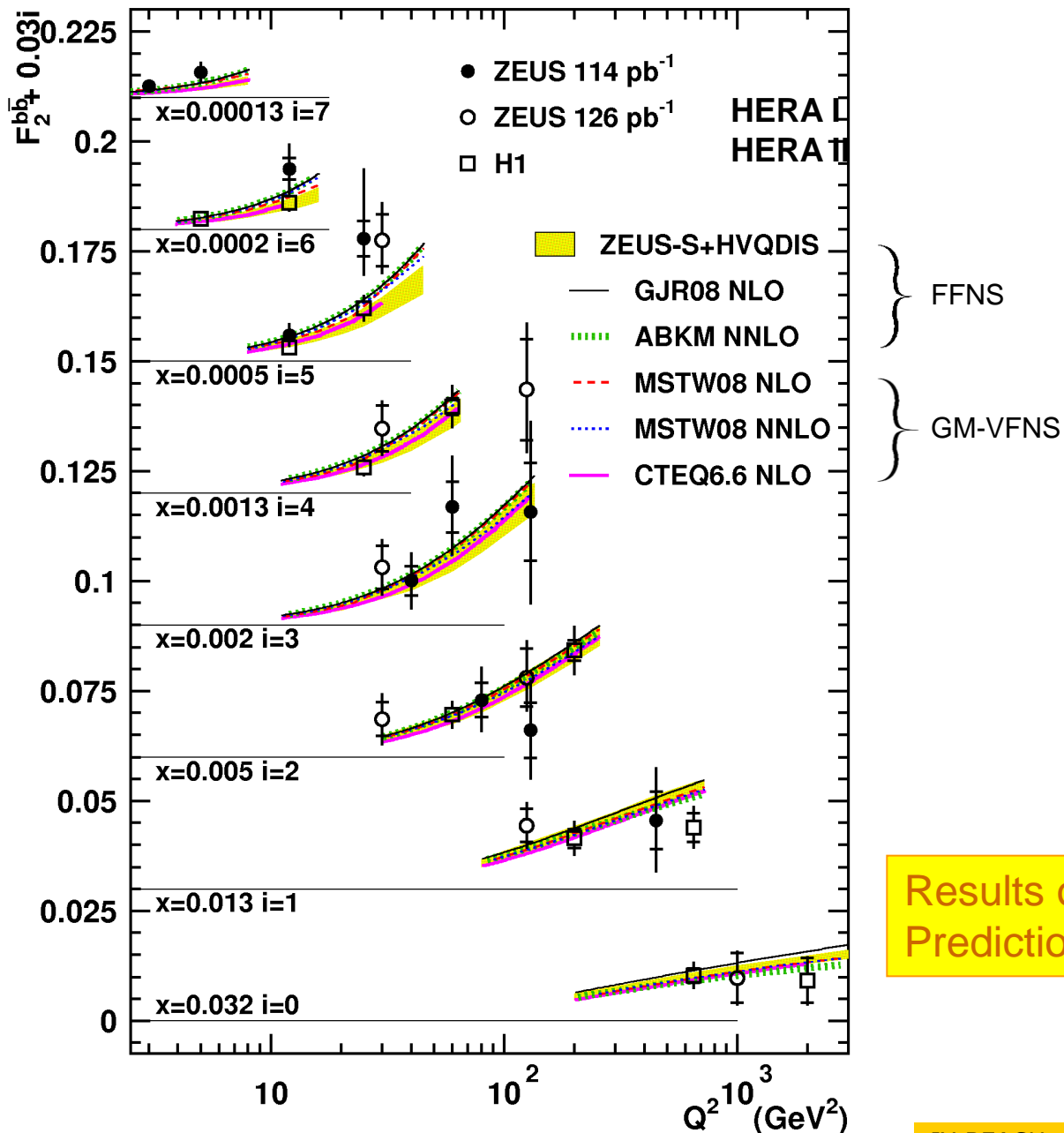


$$\frac{d^2\sigma^{ep}}{dQ^2 dx} \propto F_2(x, Q^2)$$

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



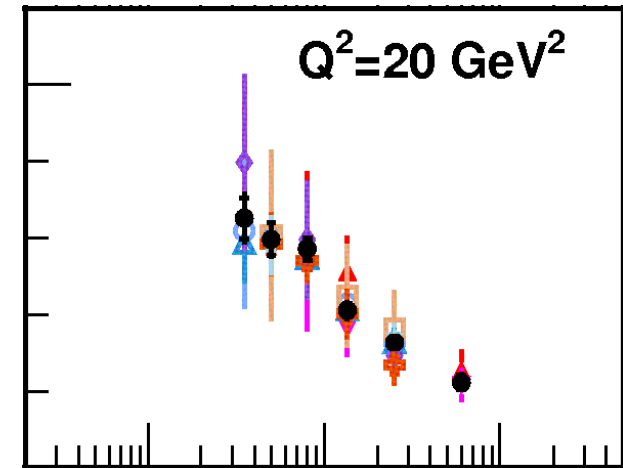
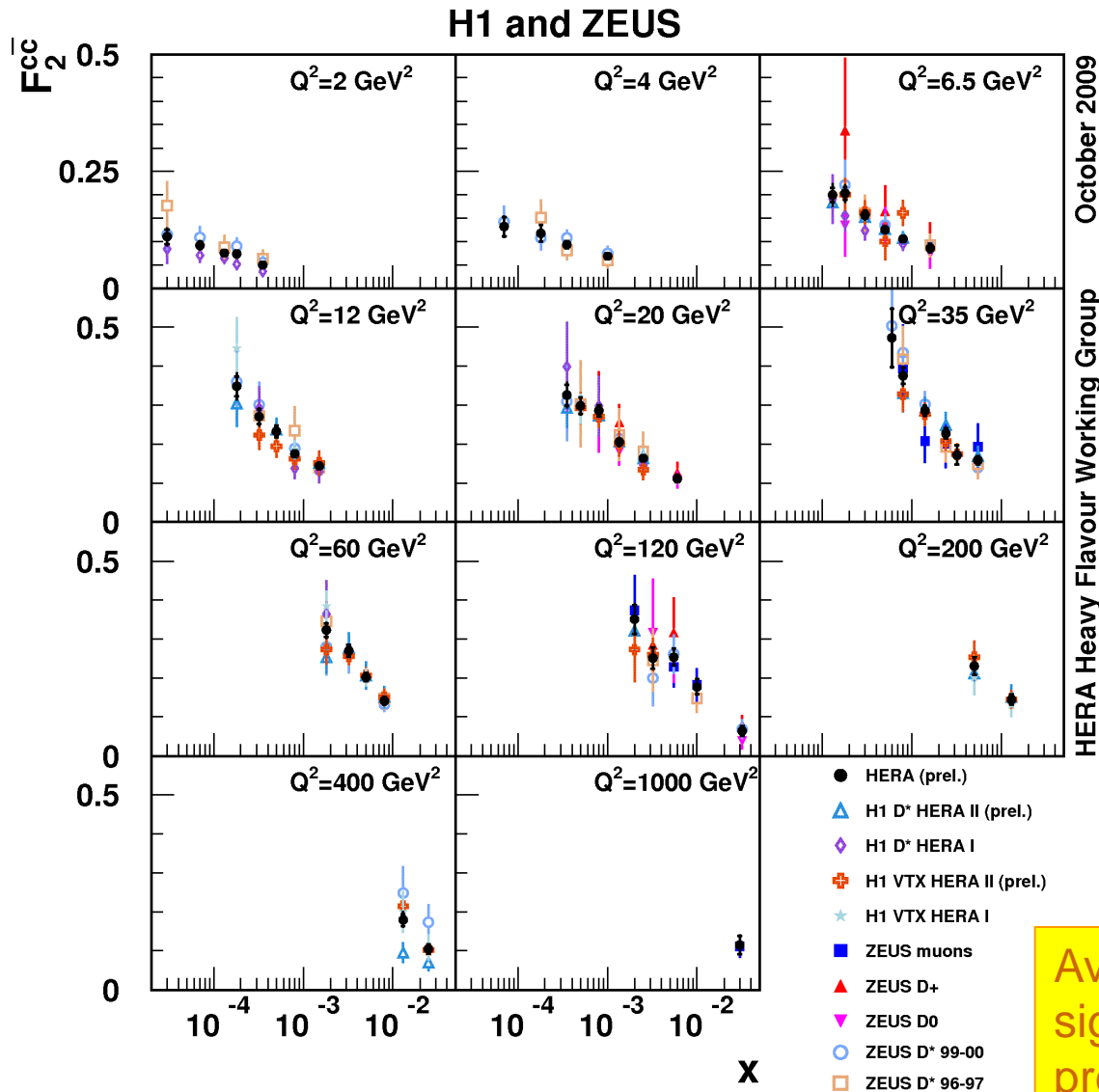
$$\frac{d^2\sigma^{ep \rightarrow c\bar{c}x}}{dQ^2 dx} \propto F_2^{c\bar{c}}(x, Q^2)$$



Results of different analyses agree  
Predictions agree with data

# $F_2^{\text{cc}}$ combined measurement

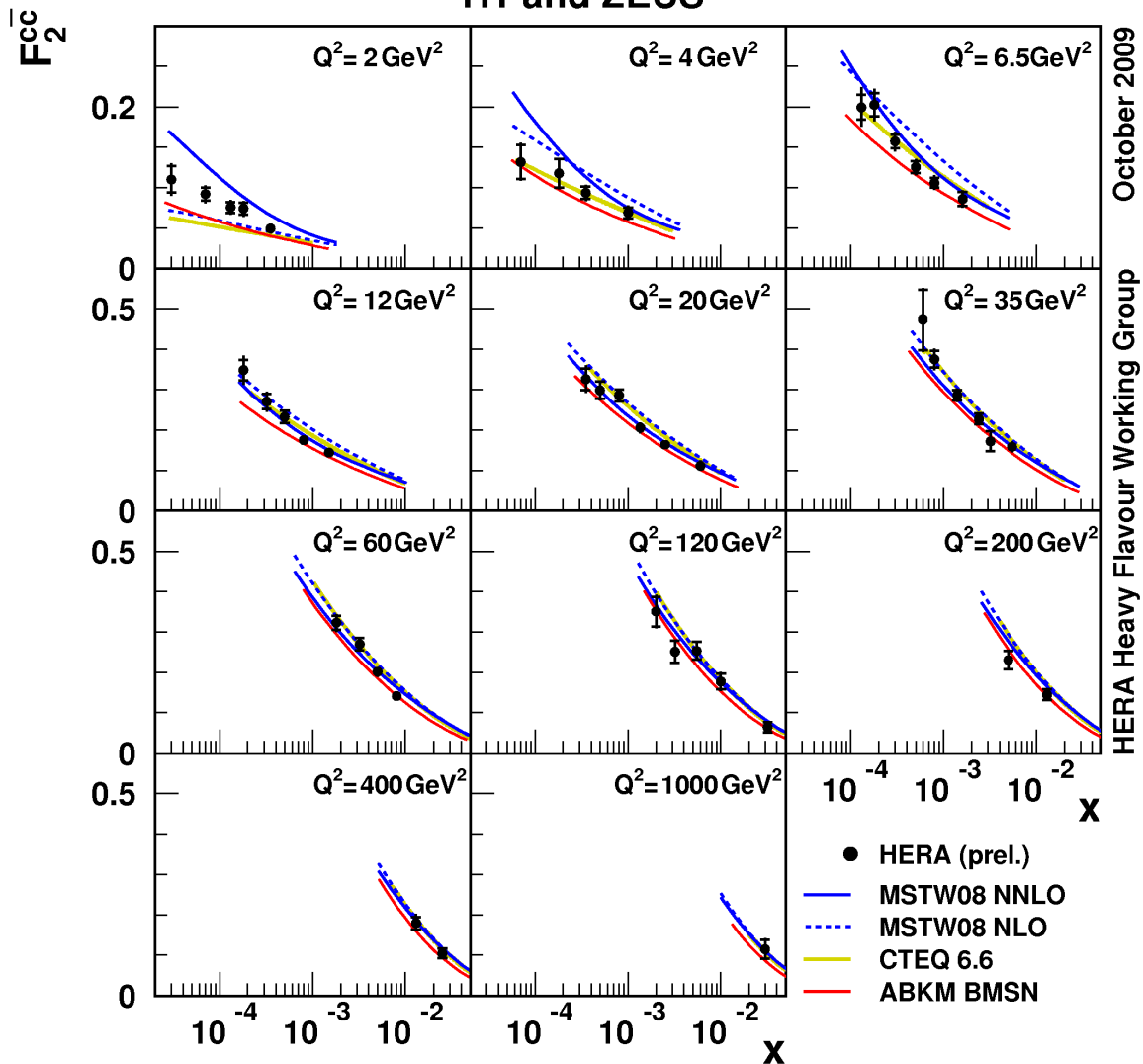
H1prelim-09-171  
ZEUS-prel-09-015



Averaging 9 different analyses:  
significantly smaller error,  
precision 5÷10%

# $F_2^{\text{cc}}$ combined measurement

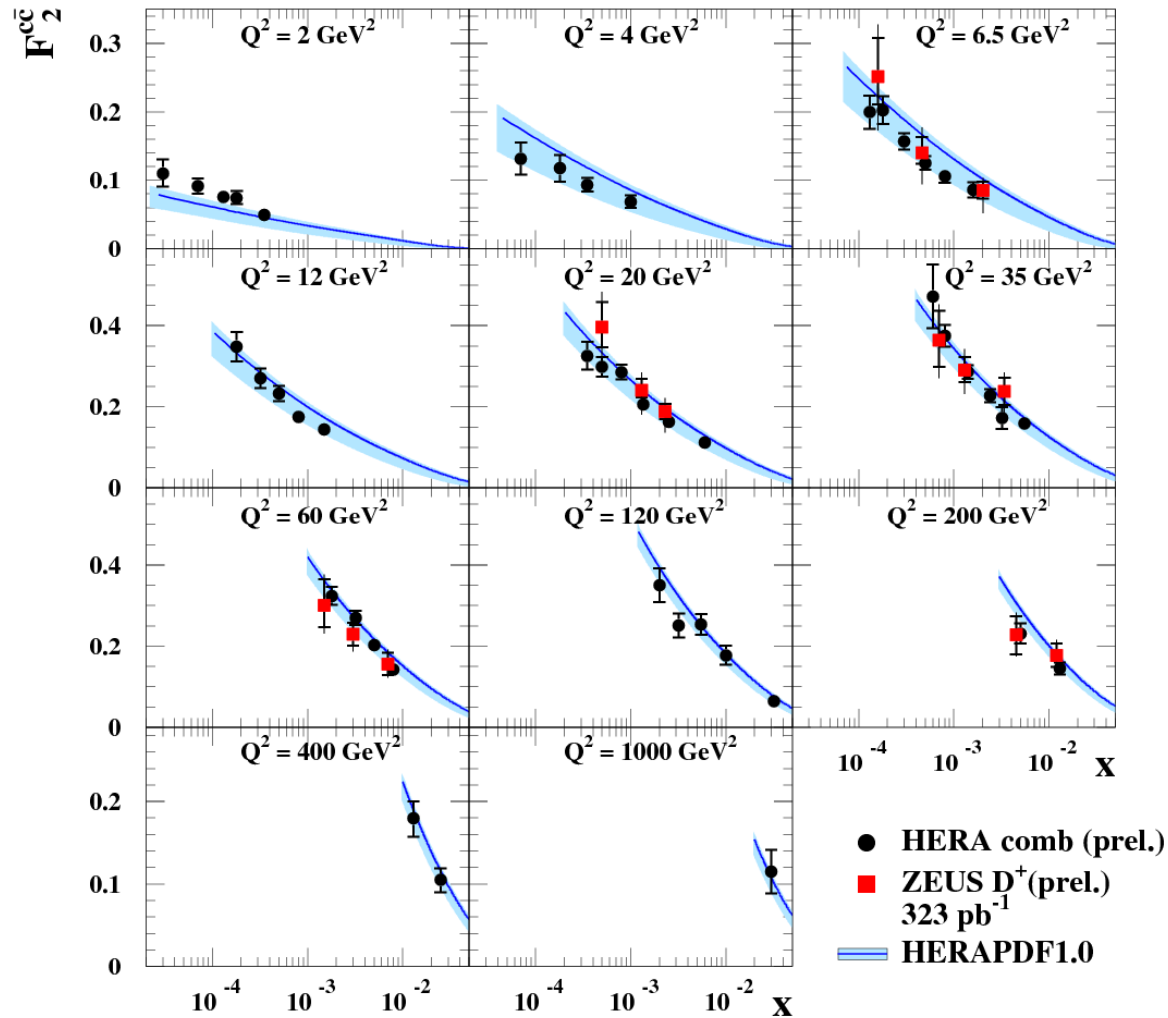
H1 and ZEUS



Comparison with  
GM-VFNS: precision  
of the data is smaller  
than variation of  
different predictions

# $F_2^{\text{cc}}$ combined measurement

ZEUS

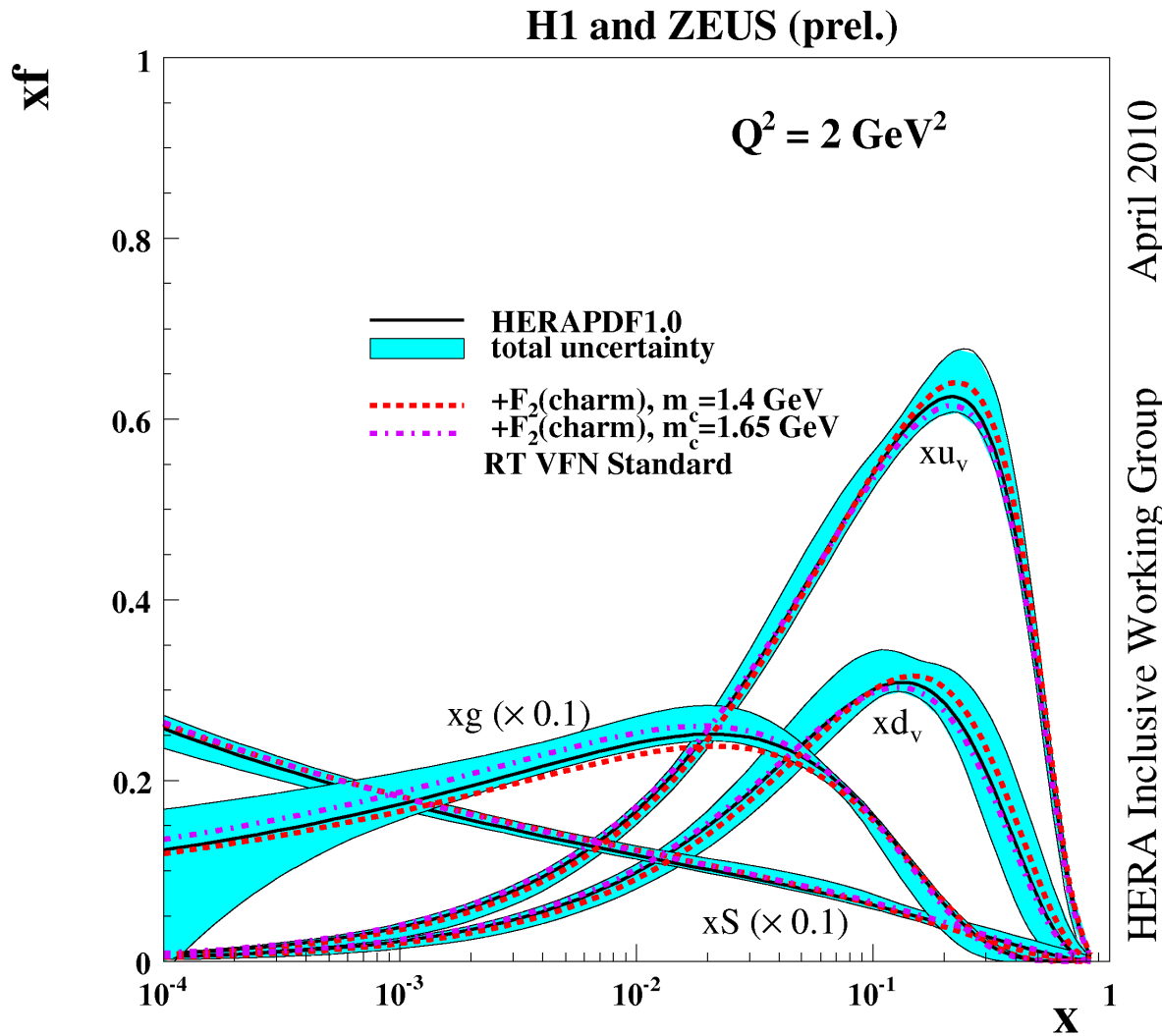


Agreement with independent measurement of HERAPDF1.0

ZEUS  $D^\pm$  (red): result of new analysis compatible with the combined result



# Proton PDF fits including combined $F_2^{cc}$



Using combined  $F_2^{cc}$  measurement makes the PDF fit more stable against different treatment of charm mass

# Summary and conclusions

Some of the latest Heavy Flavour analyses from H1 and ZEUS presented

General agreement with QCD predictions

$F_2^{bb}$  and  $F_2^{cc}$  - different measurements compatible

Charm measurement is about to be included in the global PDF fit