

# Heavy Flavour and Jet Production at HERA

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Martin Brinkmann, DESY  
for the H1 and ZEUS Collaborations



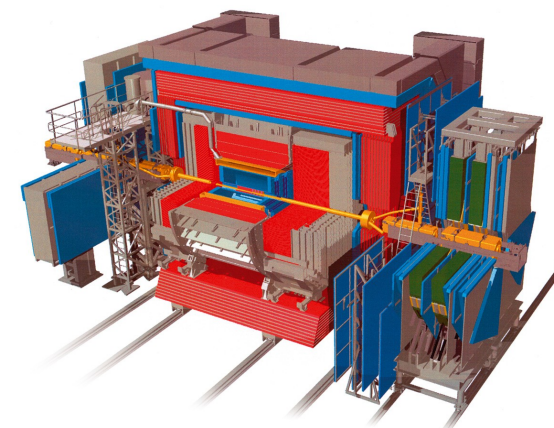
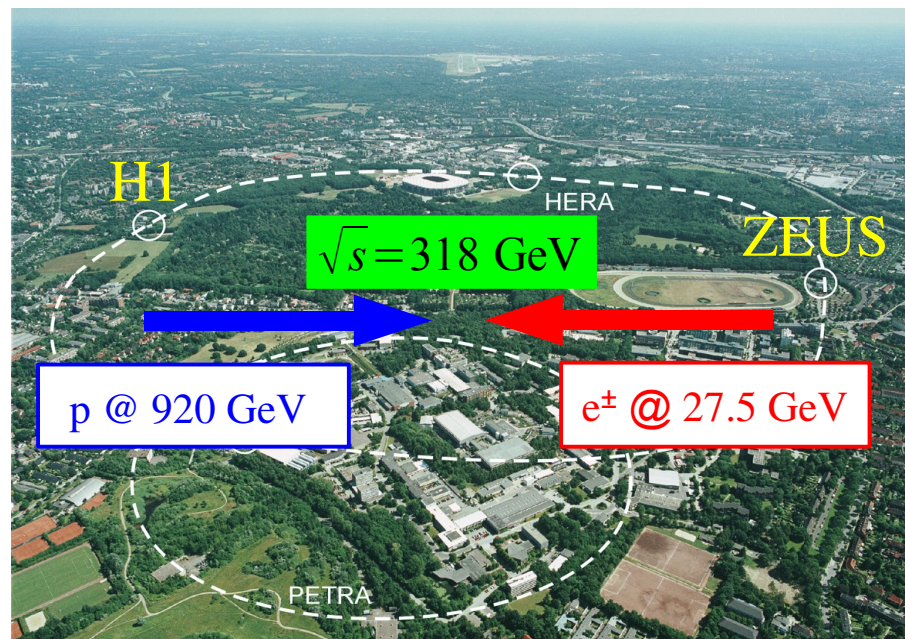
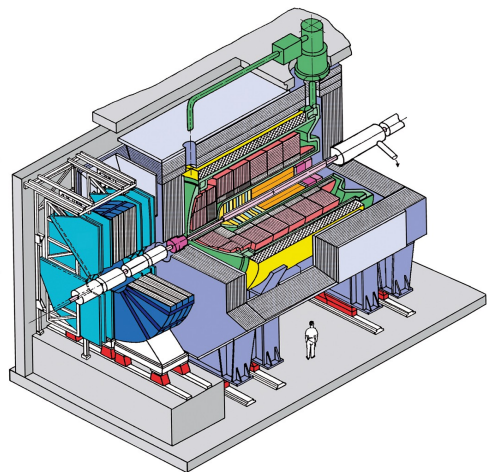
*XL International Symposium on Multiparticle  
Dynamics (ISMD 2010)*

21<sup>th</sup> - 25<sup>th</sup> September 2010

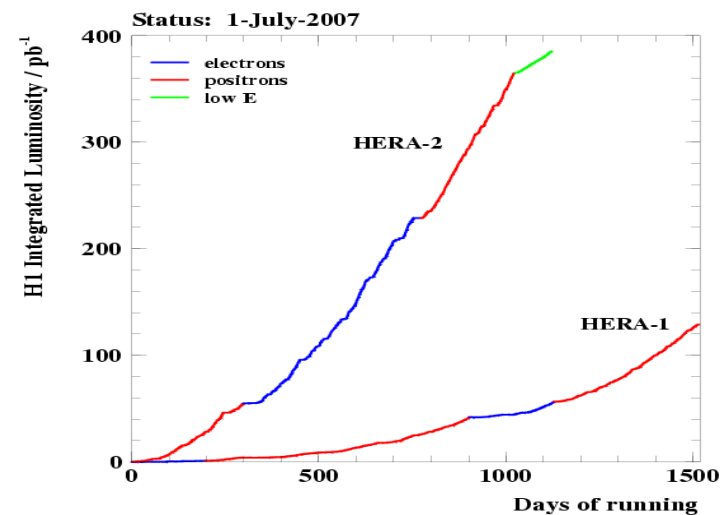




# HERA

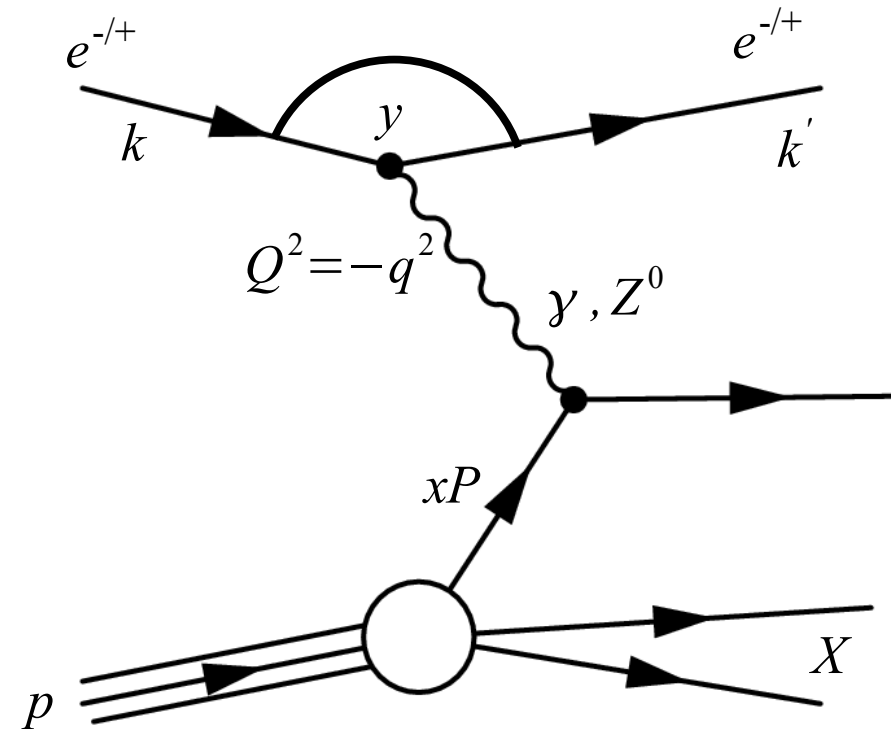


- HERA I: 1992-2000 and HERA II: 2003-2007
- $\sim 0.5 \text{ fb}^{-1}$  per experiment



## Kinematic Quantities:

- Center of mass Energy:  $s = (P + k)^2$
- Photon virtuality:  $Q^2 = -q^2 = (k - k')^2$
- Inelasticity:  $y = \frac{Pq}{Pk}$
- Bjorken Variable:  $x = \frac{Q^2}{2Pq}$



## Kinematic Regimes:

- $Q^2 \approx 0 \text{ GeV}^2$  : Photoproduction (PHP)
- $Q^2 \geq 1 \text{ GeV}^2$  : Deep inelastic scattering (DIS)

## QCD factorisation:

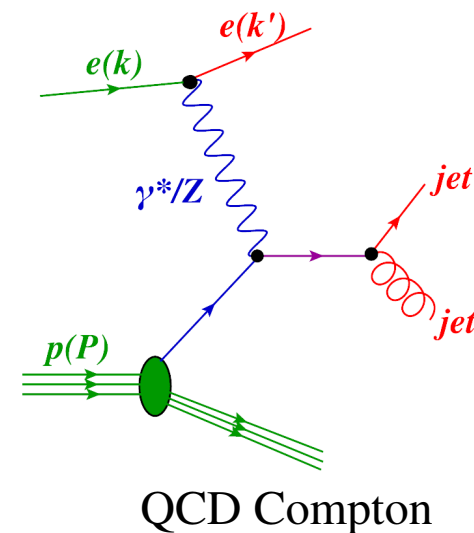
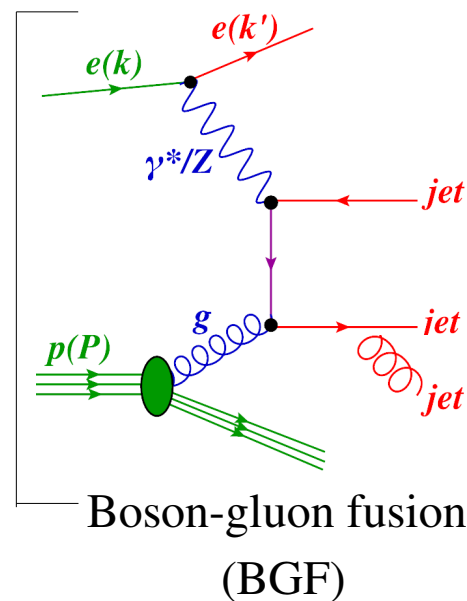
$$\sigma_{jet} \propto f_{p/\gamma} \otimes \hat{\sigma} \otimes (1 + \delta_{had})$$

- $f_{p/\gamma}$  : parton distribution functions (PDFs) for proton (and photon)
- $\hat{\sigma}$  : hard scattering matrix element
- $\delta_{had}$  : hadronisation correction

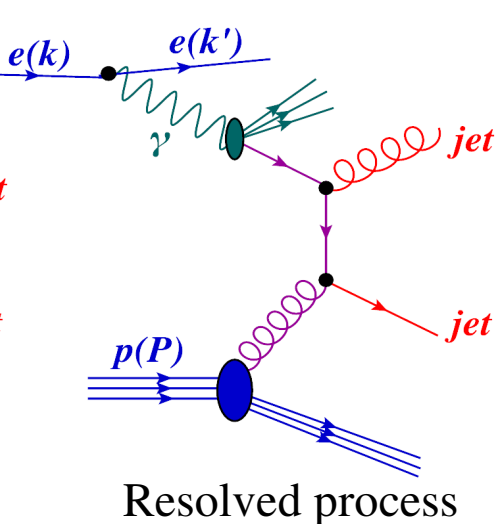
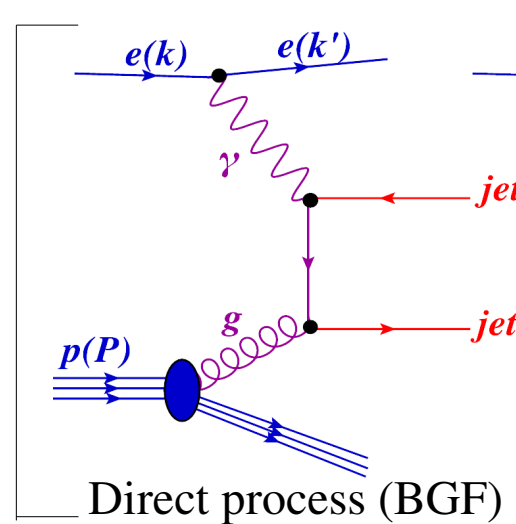
Measurement of jet production at HERA provides powerful tool for:

- Constraints on PDFs
- Testing ground of perturbative QCD
- Precision measurement of running strong coupling constant

Jet Production in DIS



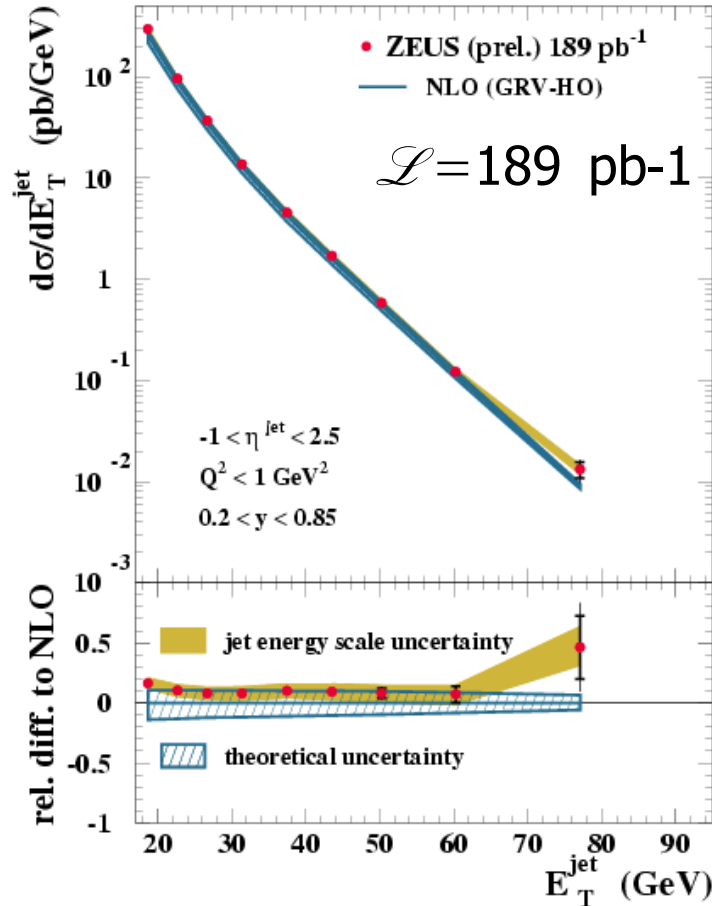
Jet Production in PHP



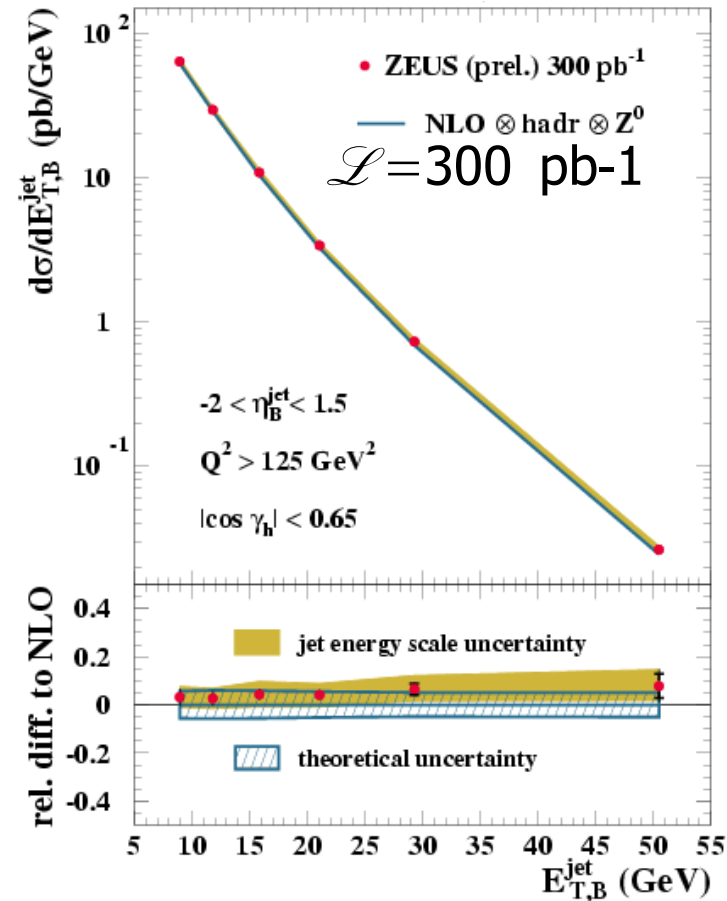
# Inclusive Jet Cross Sections



## Photoproduction



## Neutral current DIS



ZEUS-prel-10-002

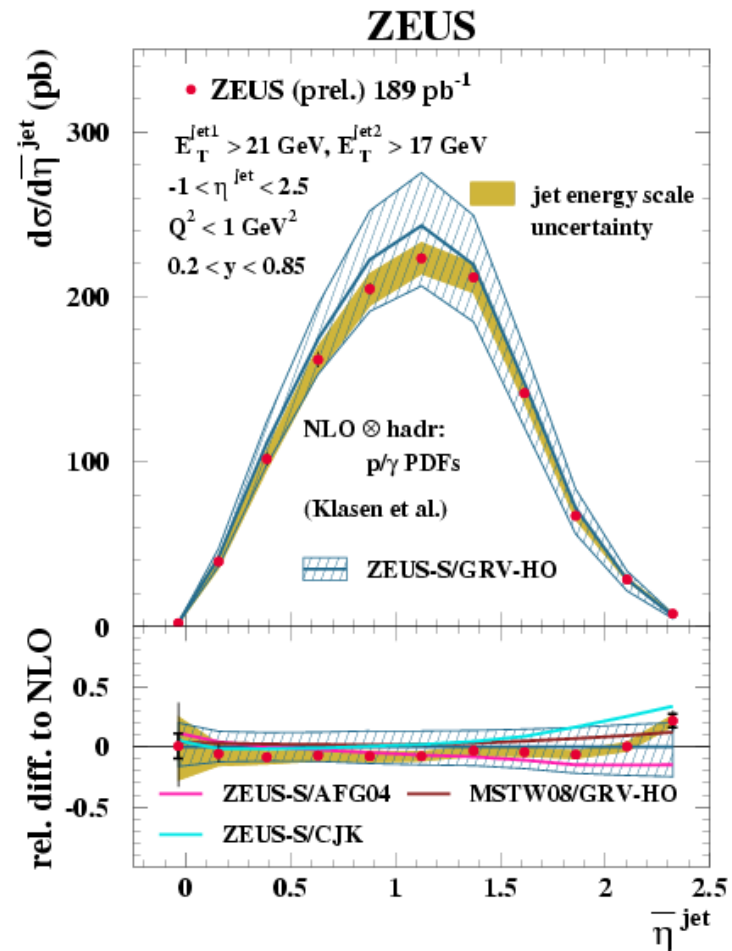
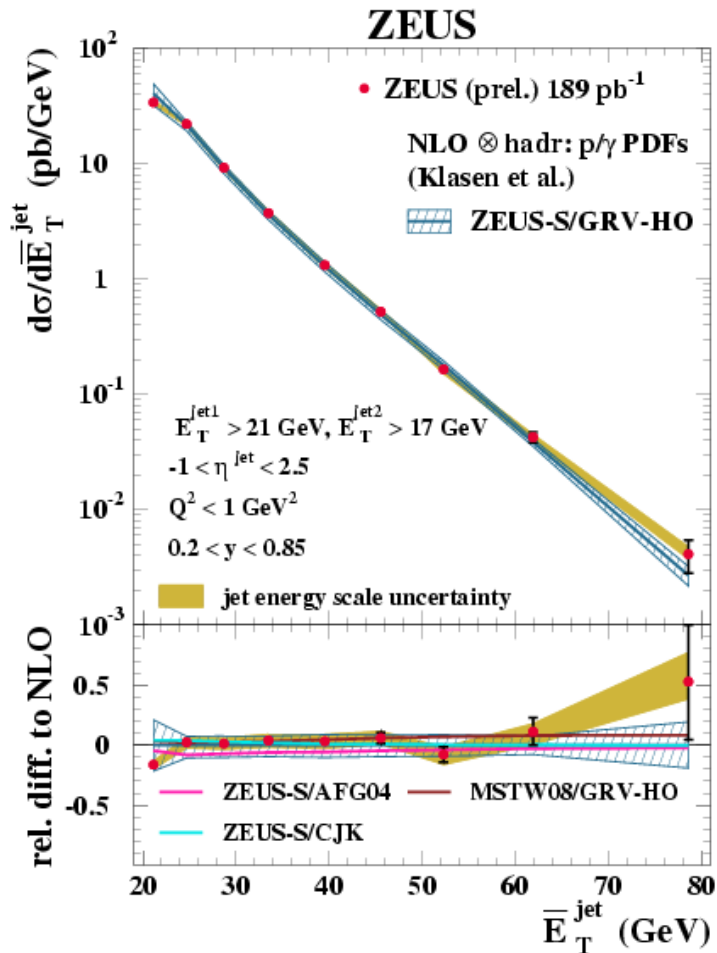
ZEUS-prel-10-003

- Cross sections well described by NLO predictions
- Measurements provide direct sensitivity to  $\alpha_s$
- Very precise data → stringent test of (p)QCD from  $Q^2 \sim 0 - 20000 \text{ GeV}^2$

# Dijets in Photoproduction



$\mathcal{L} = 189 \text{ pb}^{-1}$  ZEUS-prel-10-014



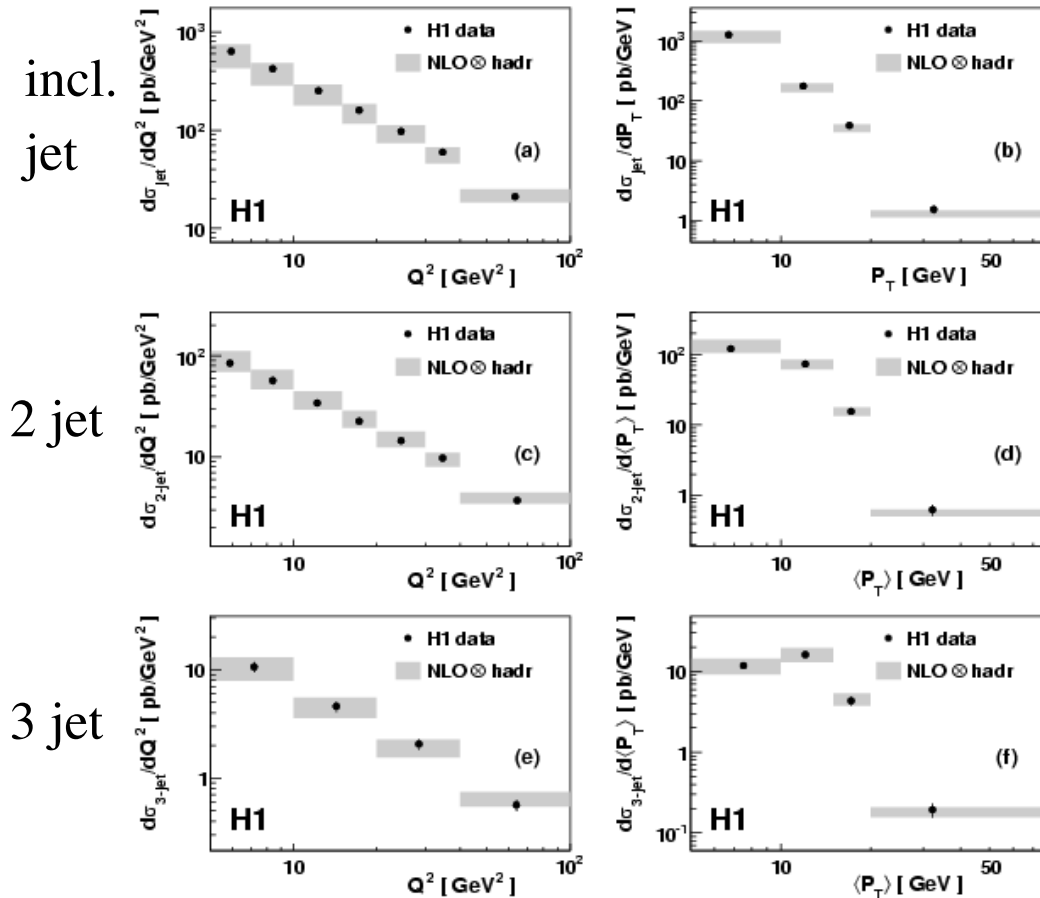
- Good description of data by NLO QCD in the whole measured range
- Sensitivity to photon (high  $\eta^{\text{jet}}$ ) PDFs

$\mathcal{L}=44 \text{ pb}^{-1}$  H1: Eur Phys J. C67 (2010) 1

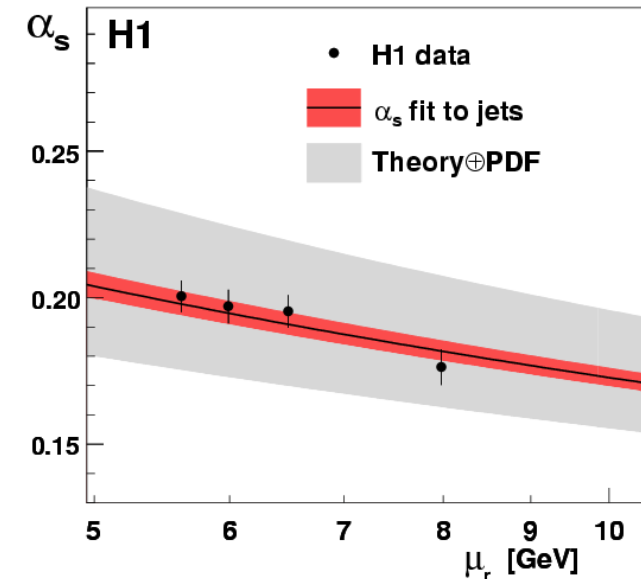
- Multijet cross sections as a function of  $Q^2$  and  $p_t^{\text{jet}}$

$5 < Q^2 < 100 \text{ GeV}^2, 0.2 < y < 0.7$   
 $p_t^{\text{jet}} > 5 \text{ GeV}, -1 < \eta_{\text{lab}} < 2.5$

Inclusive Jet, 2-Jet and 3-Jet Cross Sections



$\alpha_s$  from Jet Cross Sections



→ Good description of data by NLO predictions

- Extract  $\alpha_s$  from a simult. Fit of inclusive, dijet and trijet measurements
- Data much more precise than theory

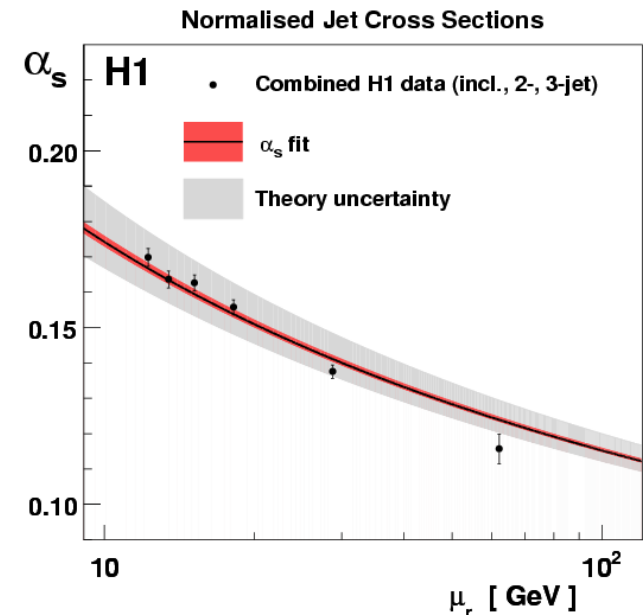
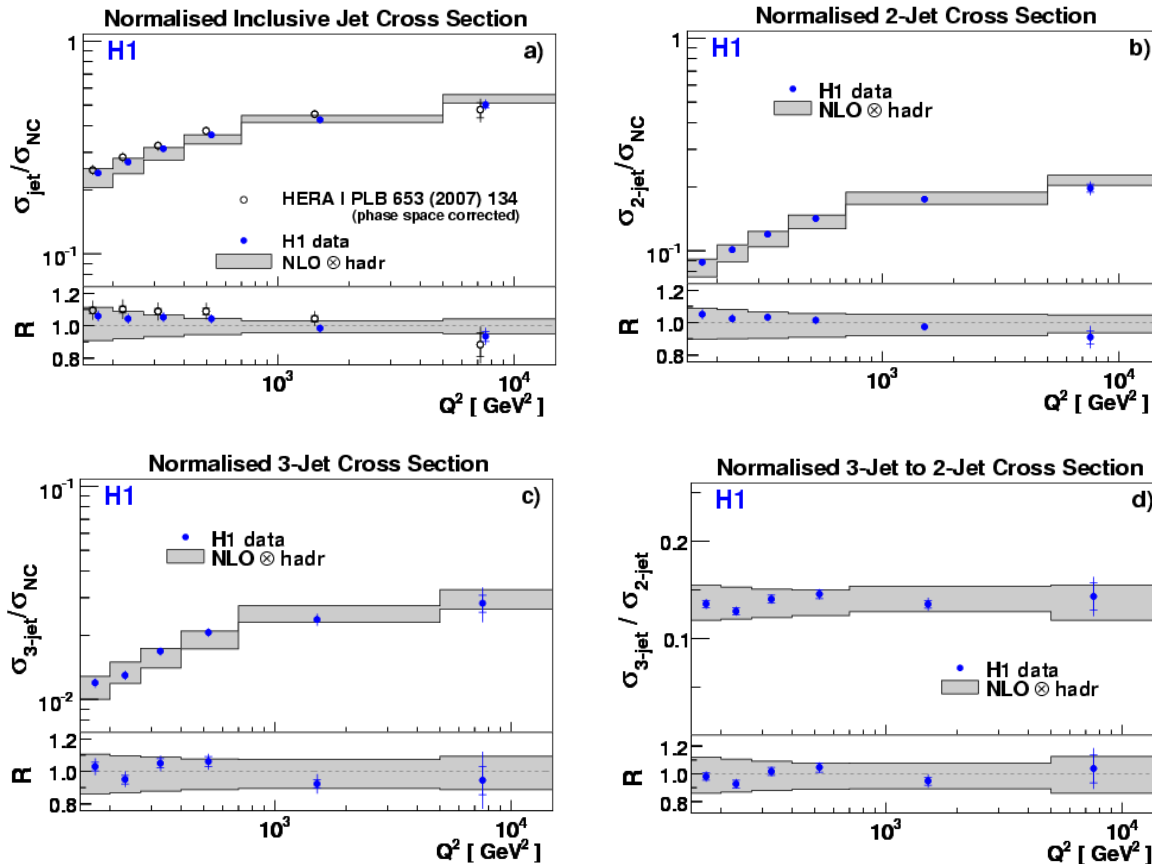


# Multijets at high $Q^2$

$\mathcal{L} = 395 \text{ pb}^{-1}$  H1: Eur Phys J. C65 (2010) 363

- Cross sections normalised to DIS cross section

$150 < Q^2 < 15000 \text{ GeV}^2, 0.2 < y < 0.7$   
 $p_t^{\text{jet}} > 7(5) \text{ GeV}, -0.8 < \eta_{\text{lab}} < 2$



→ Good description of data by NLO predictions

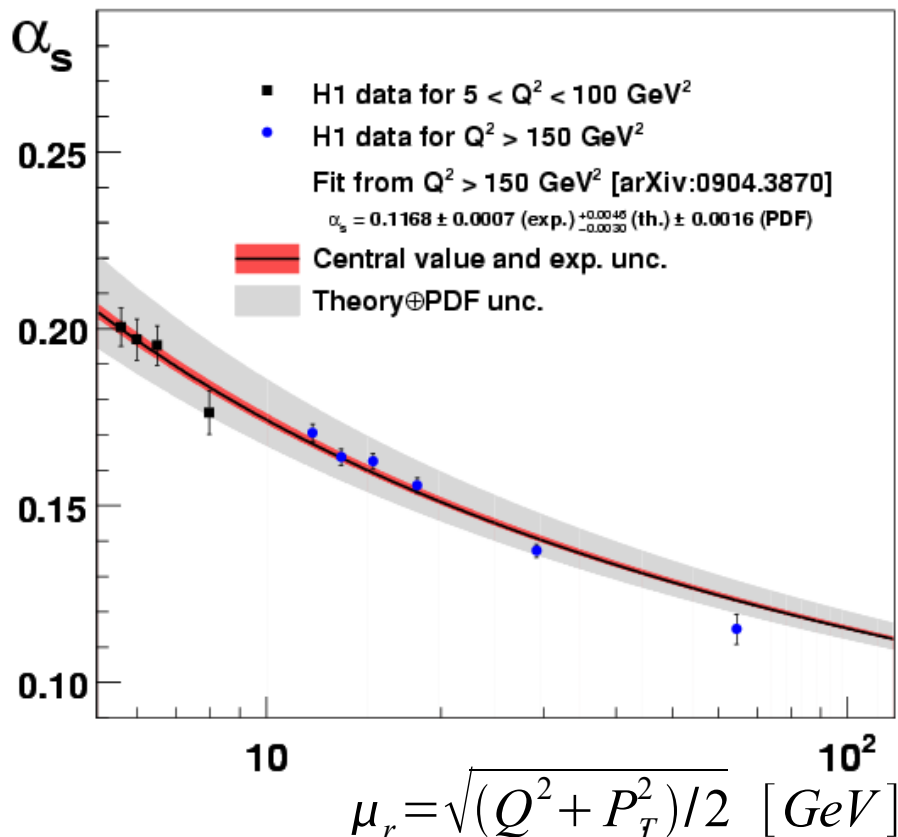
- Simultaneous fit of all norm. jet cross sections
- Smaller theoretical uncertainties due to higher scale



H1: Eur Phys J. C67 (2010) 1

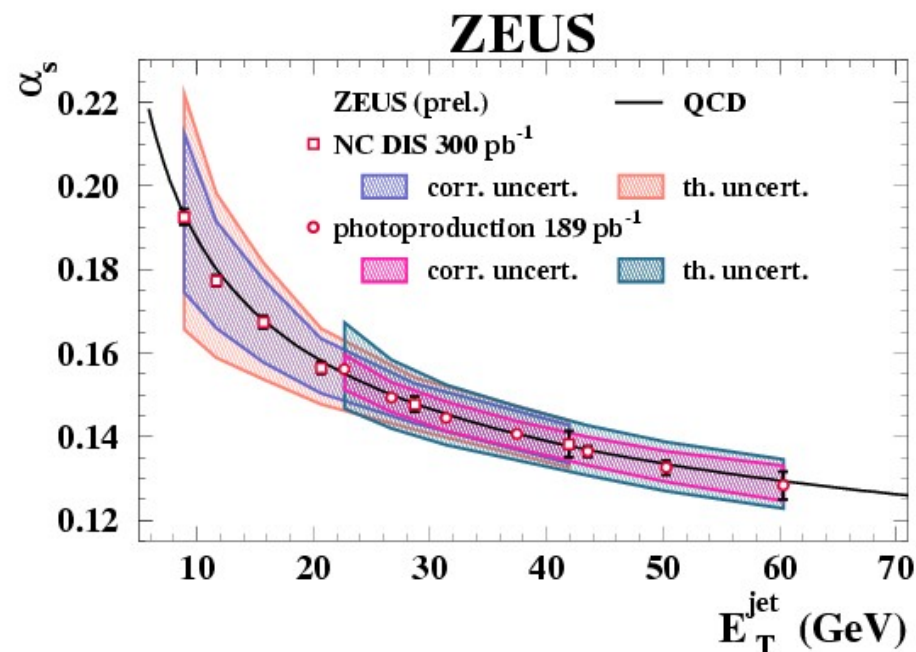
H1: Eur Phys J. C65 (2010) 363

## $\alpha_s$ from Jet Cross Sections in DIS



ZEUS-prel-10-002

ZEUS-prel-10-003



→ Very good agreement of extraction of  $\alpha_s(\mu_r)$  at low and high  $Q^2$

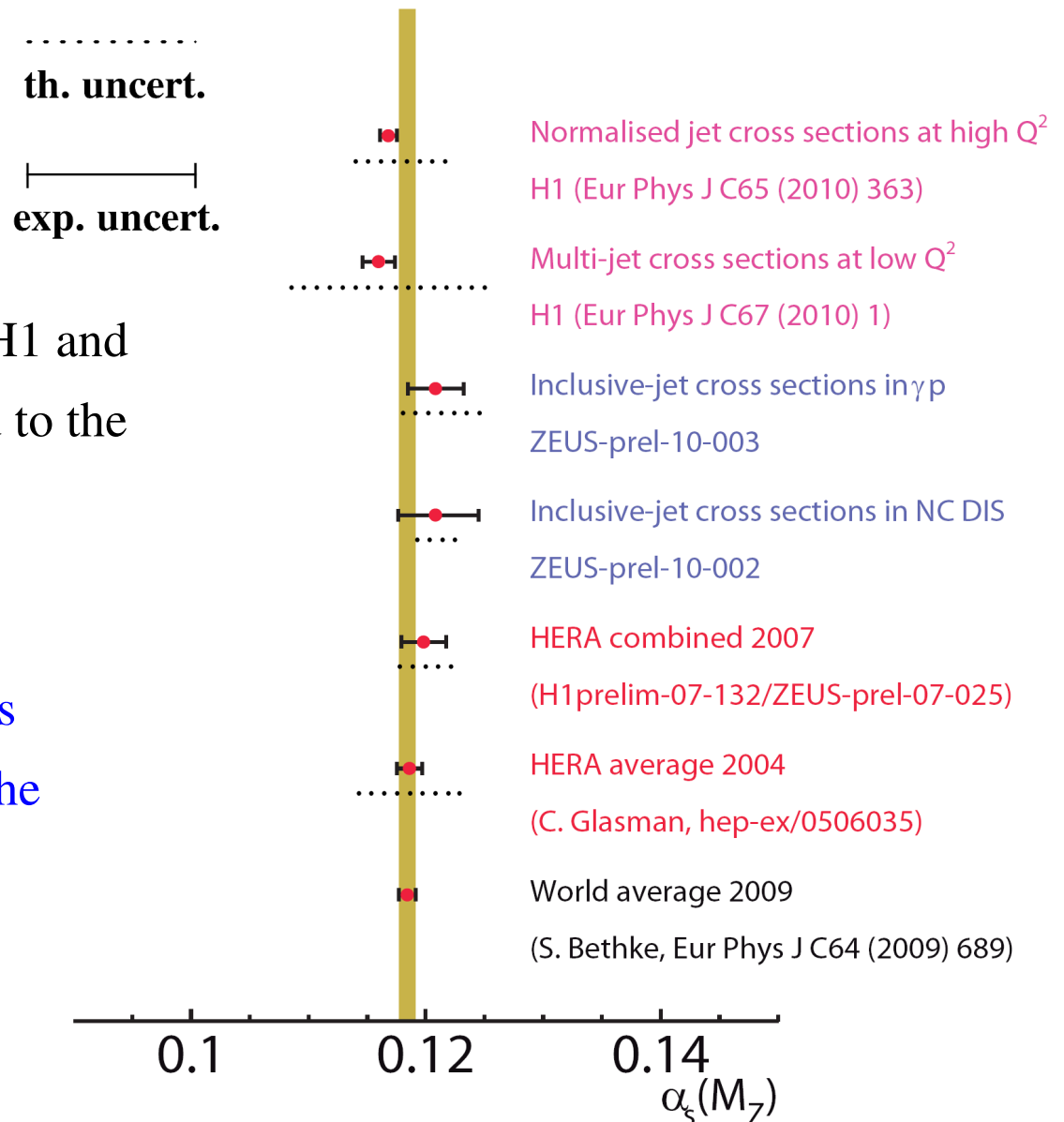
→ Running of  $\alpha_s$  tested over wide range of scale



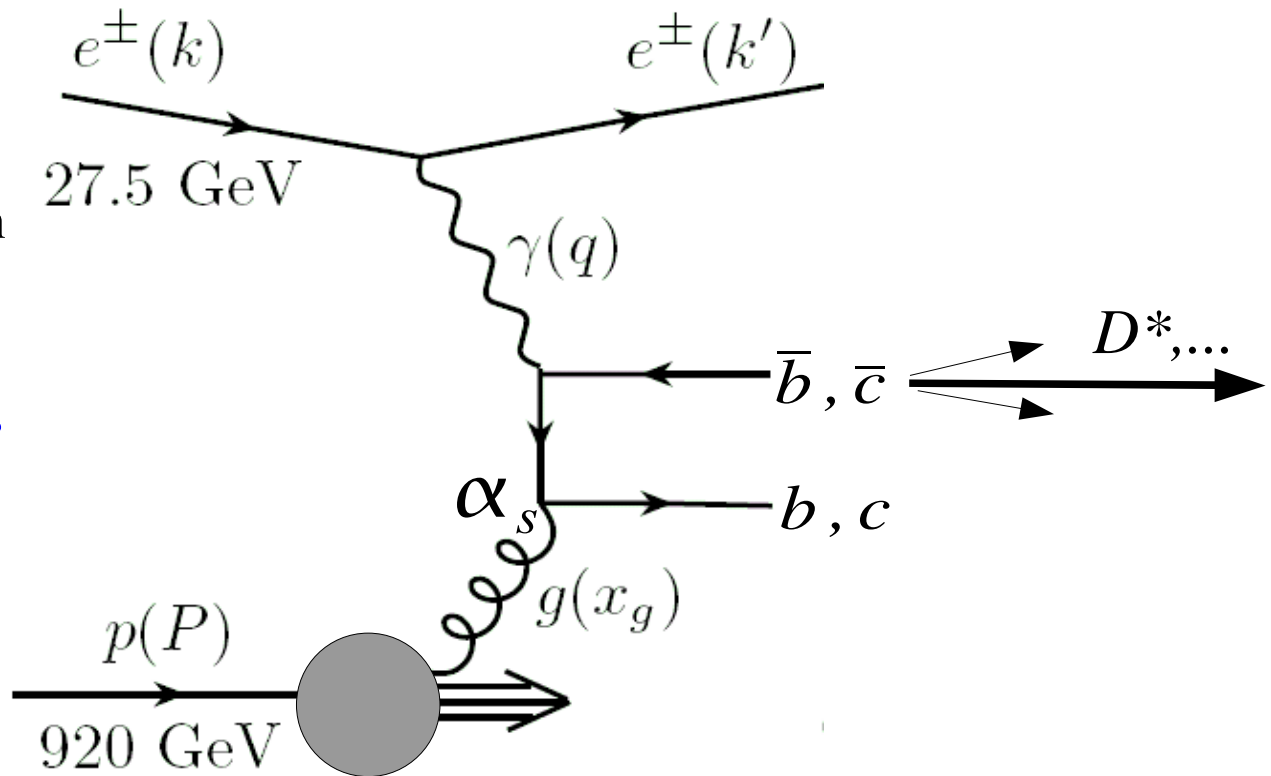
# $\alpha_s(M_Z)$ from H1 and ZEUS



- Results of  $\alpha_s(M_Z)$  from recent H1 and ZEUS measurements compared to the world average
- Results of  $\alpha_s(M_Z)$  measurements consistent with each other and the world average



- Predominantly via boson gluon fusion
- Additional scale given by mass
- High contribution to inclusive cross section



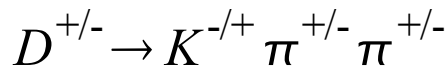
## QCD factorisation:

$$\sigma_{D^*} \propto f_{p/\gamma} \otimes \hat{\sigma} \otimes D_c^{D^*}(z)$$

parton density function (non-perturbative)    parton scattering cross section (perturbative)    fragmentation function (non-perturbative)

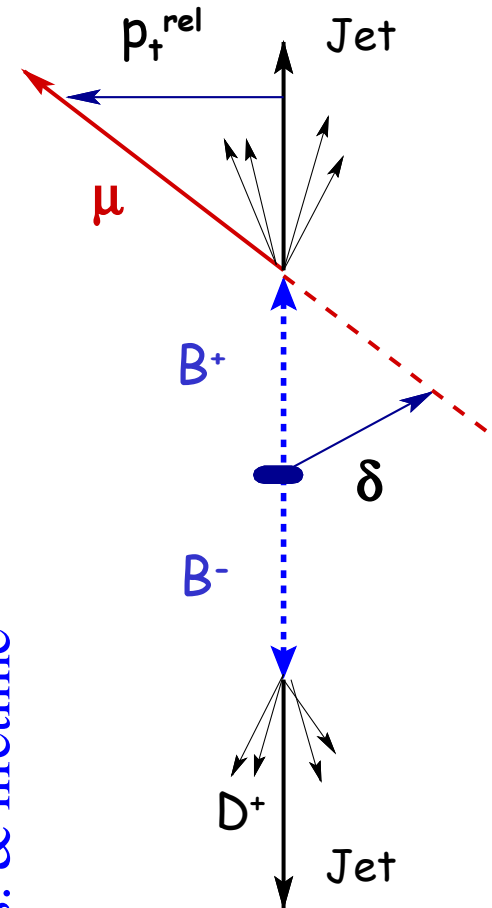
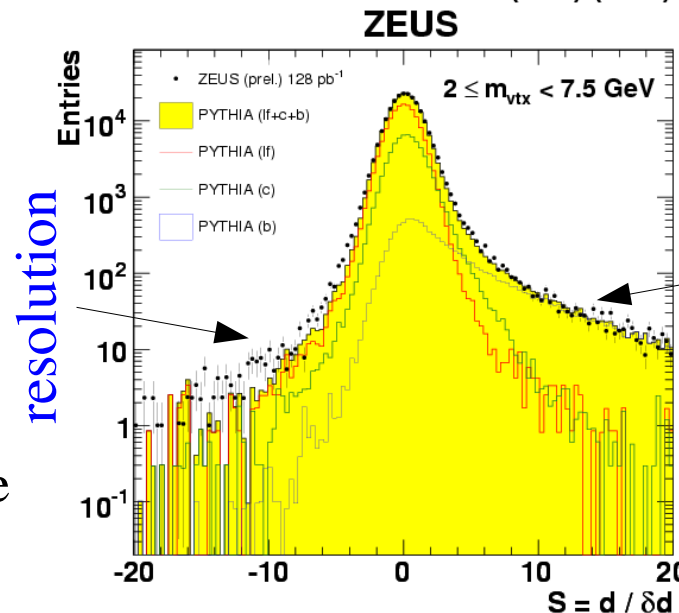
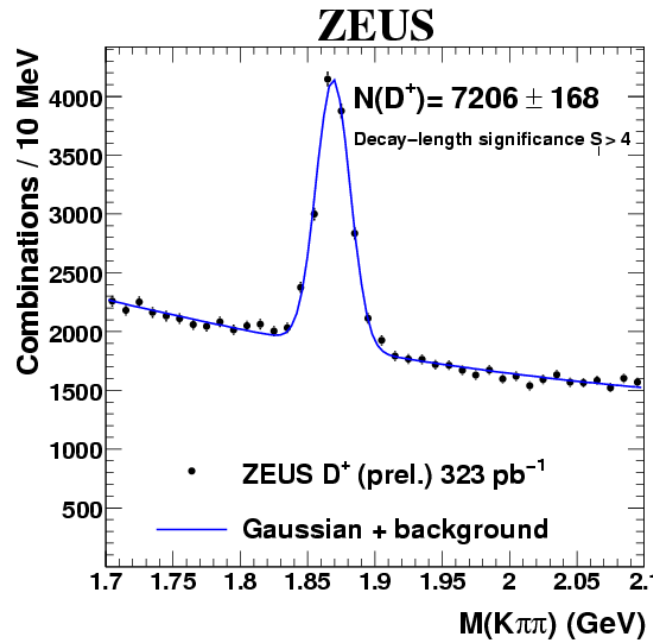
## Meson identification:

- Full reconstruction from decay tracks:



## Lifetime tag:

- Reconstruct secondary vertex (with jet)
- Project decay length on jet axis
- Use decay length significance:  $S = d / \delta d$
- Impact parameter significance of tracks



res. & lifetime

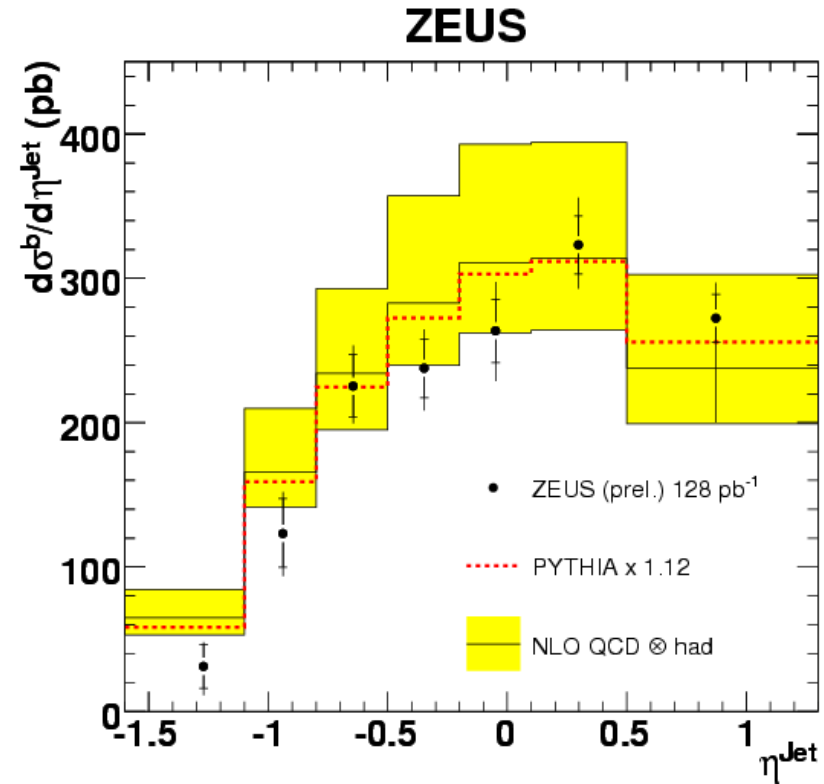
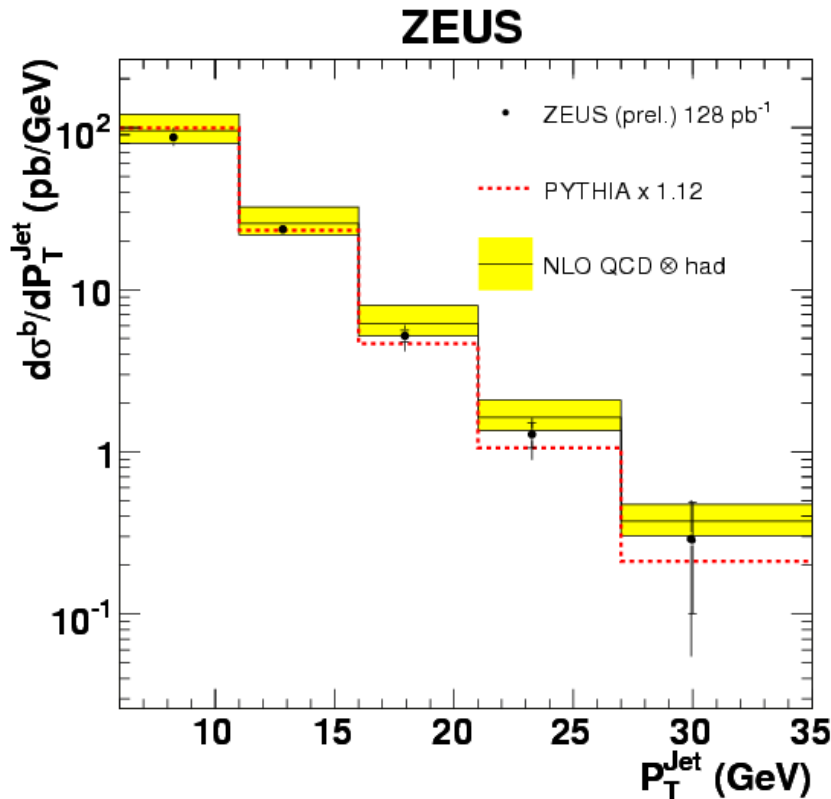
# Beauty in PHP using Secondary Vertex



$\mathcal{L} = 128 \text{ pb}^{-1}$

$Q^2 < 1 \text{ GeV}^2, 0.2 < y < 0.8$   
 $p_t^{\text{jet}} > 7(6) \text{ GeV}, |\eta_{\text{jet}}| < 2.5$

ZEUS-prel-09-005



- Cross sections in  $P_T^{\text{jet}}$  and  $\eta_{\text{jet}}$  in good agreement with LO MC (Pythia) and NLO QCD calculation (FMNR)
- Theoretical uncertainties larger than experimental ones



# Beauty Jets in DIS

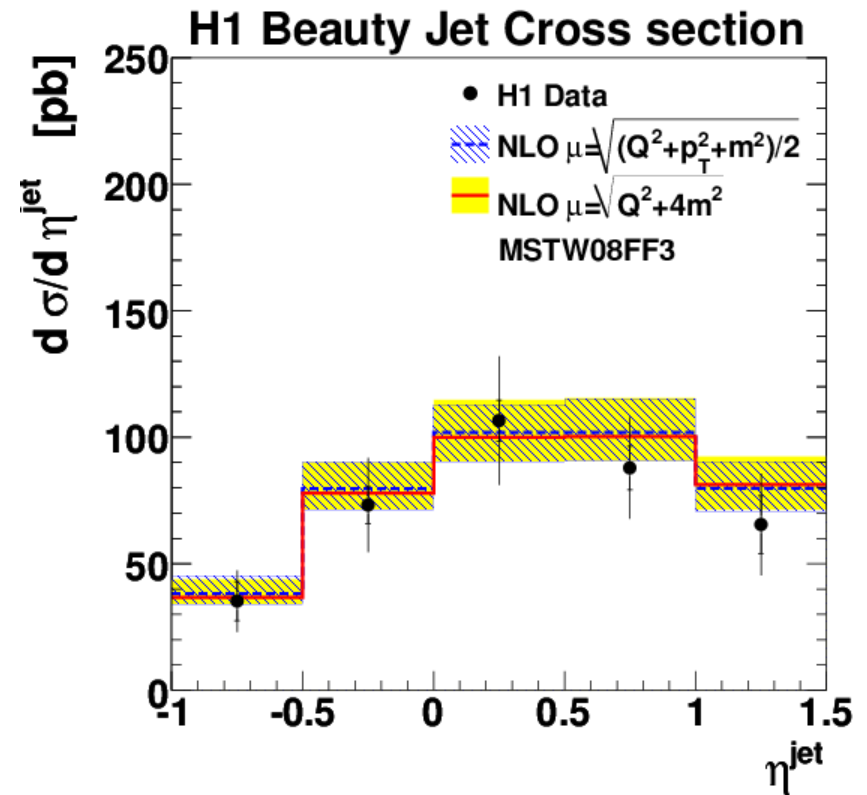
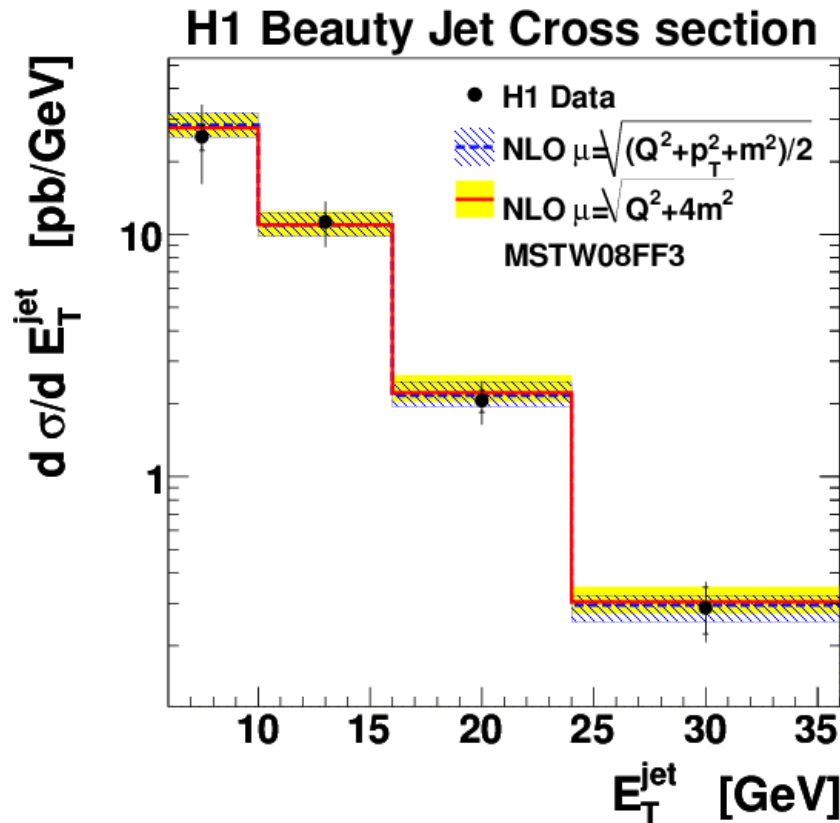
$\mathcal{L} = 189 \text{ pb}^{-1}$

$Q^2 > 6 \text{ GeV}^2, 0.07 < y < 0.6$   
 $E_t^{\text{jet}} > 6 \text{ GeV}, -1 < \eta_{\text{jet}} < 1.5$

H1: DESY-10-083

- Use sensitivity to lifetime
- Compare data with NLO calculation

HVQDIS



→ NLO QCD calculation describes data well for both scales

# Beauty in DIS using Secondary Vertex



$\mathcal{L} = 354 \text{ pb}^{-1}$

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

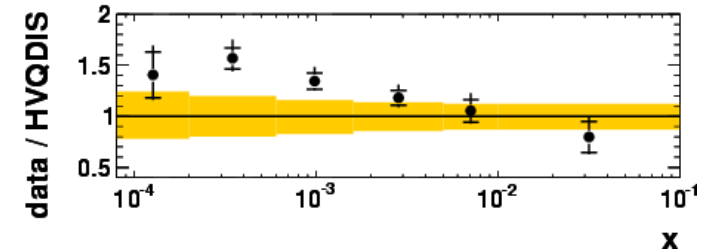
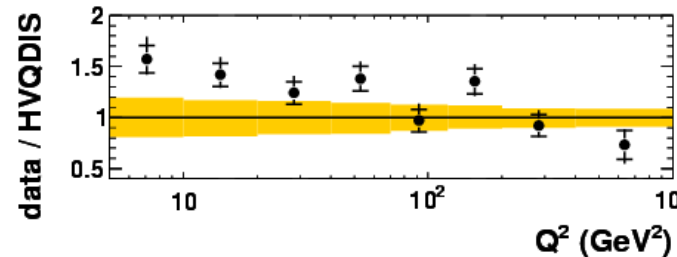
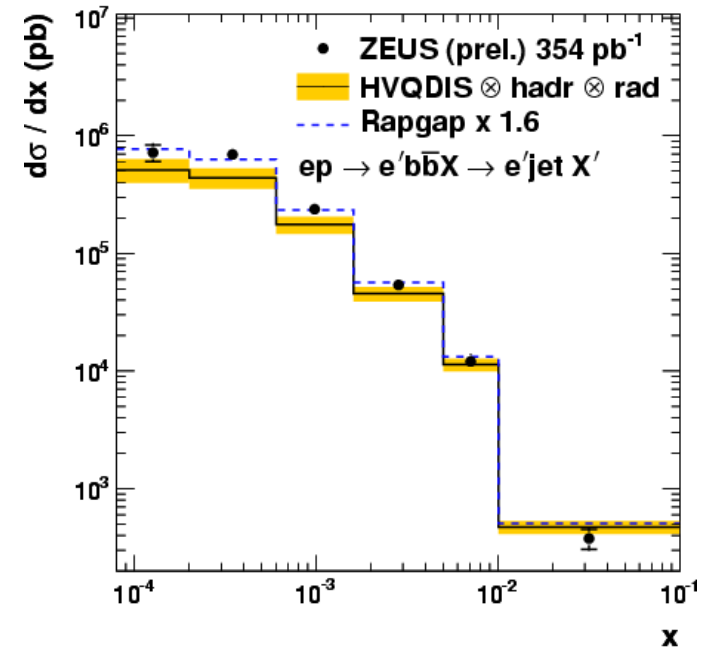
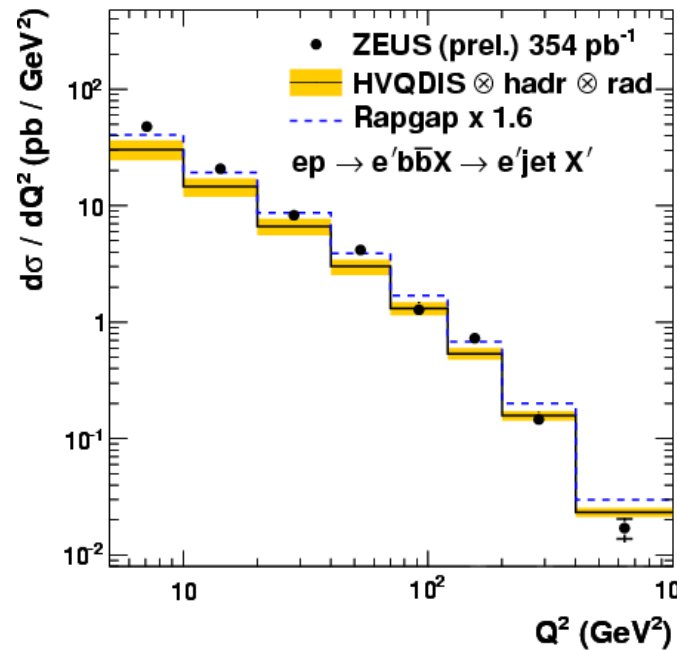
ZEUS-prel-10-004

- Compare data with LO MC RAPGAP and NLO calculation HVQDIS

→ Reasonable agreement with NLO QCD (except low  $Q^2$  and low  $x$ )

ZEUS

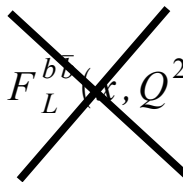
ZEUS



- One way to summarize beauty measurements
- Definition of  $F_2^{bb}$ :

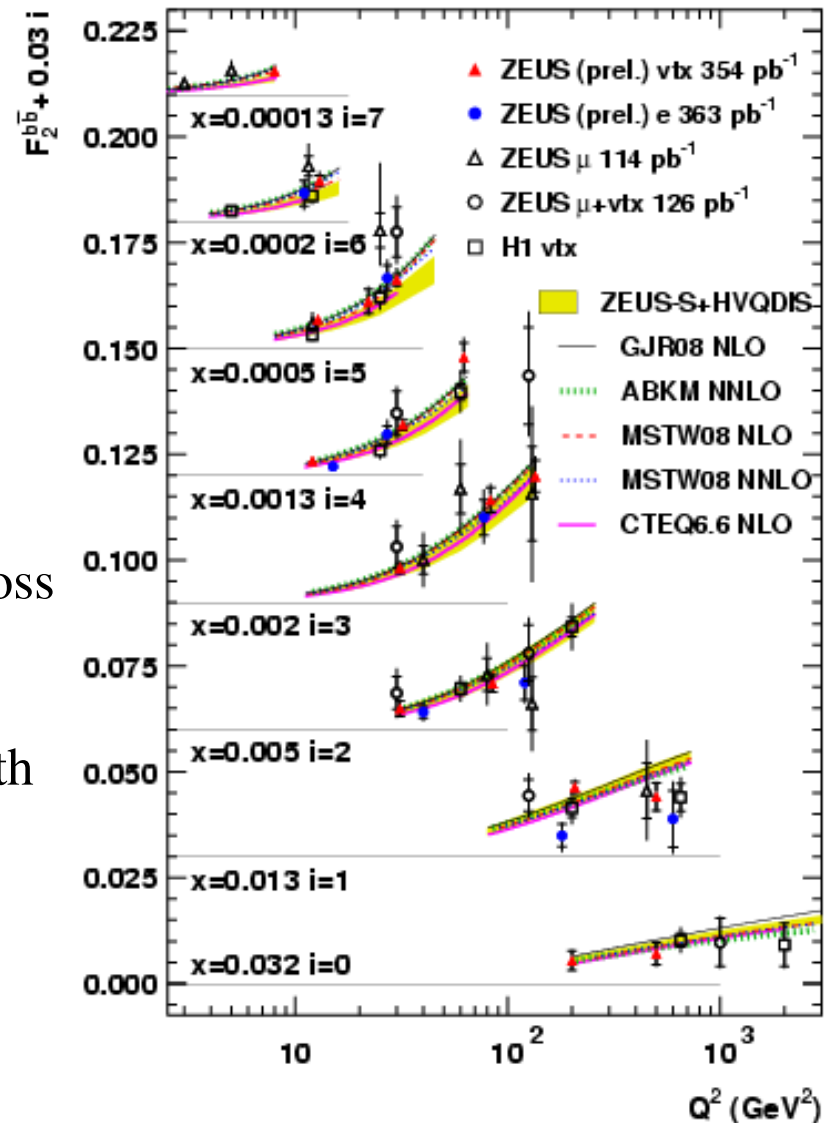
$$\frac{d^2 \sigma^{b\bar{b}}}{dx dQ^2} = \frac{2\pi\alpha_{em}^2}{Q^4 x} \left[ (1+(1-y)^2) F_2^{b\bar{b}}(x, Q^2) - y^2 F_L^{b\bar{b}}(x, Q^2) \right]$$

Contribution of  $F_1^{bb}$  neglected !



- Estimation from measured double differential cross sections
- Measurements consistent with each other and with NLO QCD predictions
- Gain in precision with HERAII - data

$F_2^{bb}$  at HERA





# Charm ( $D^\pm$ ) in DIS



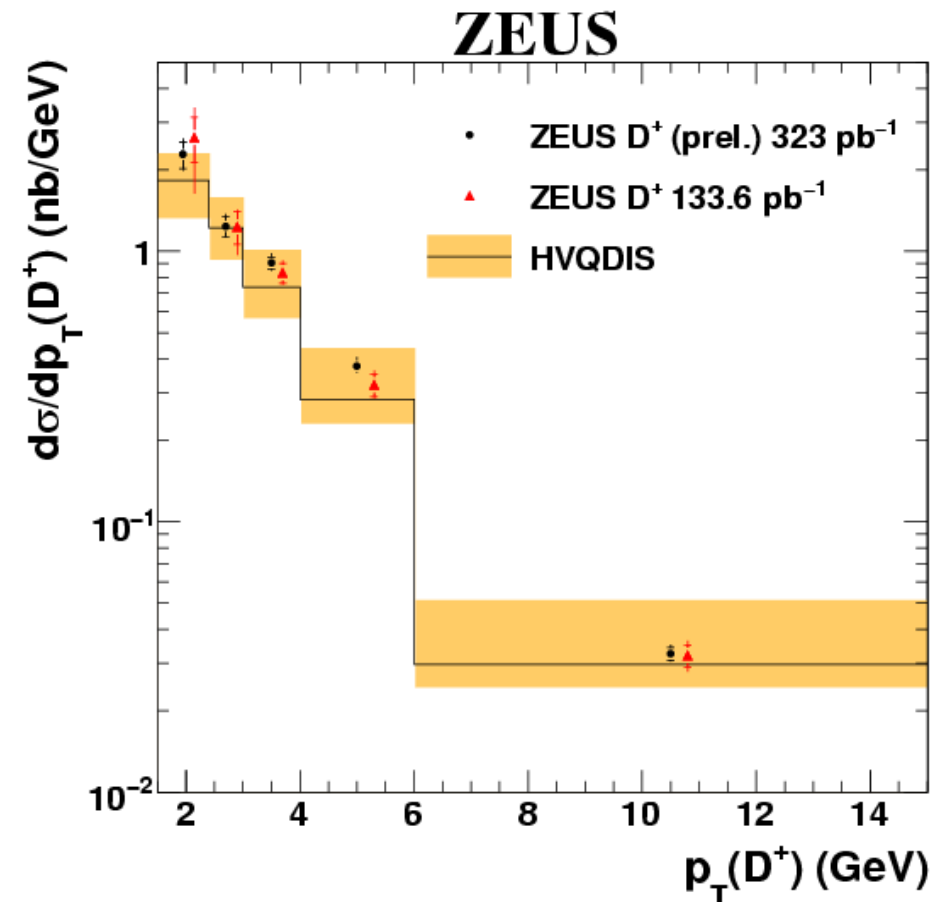
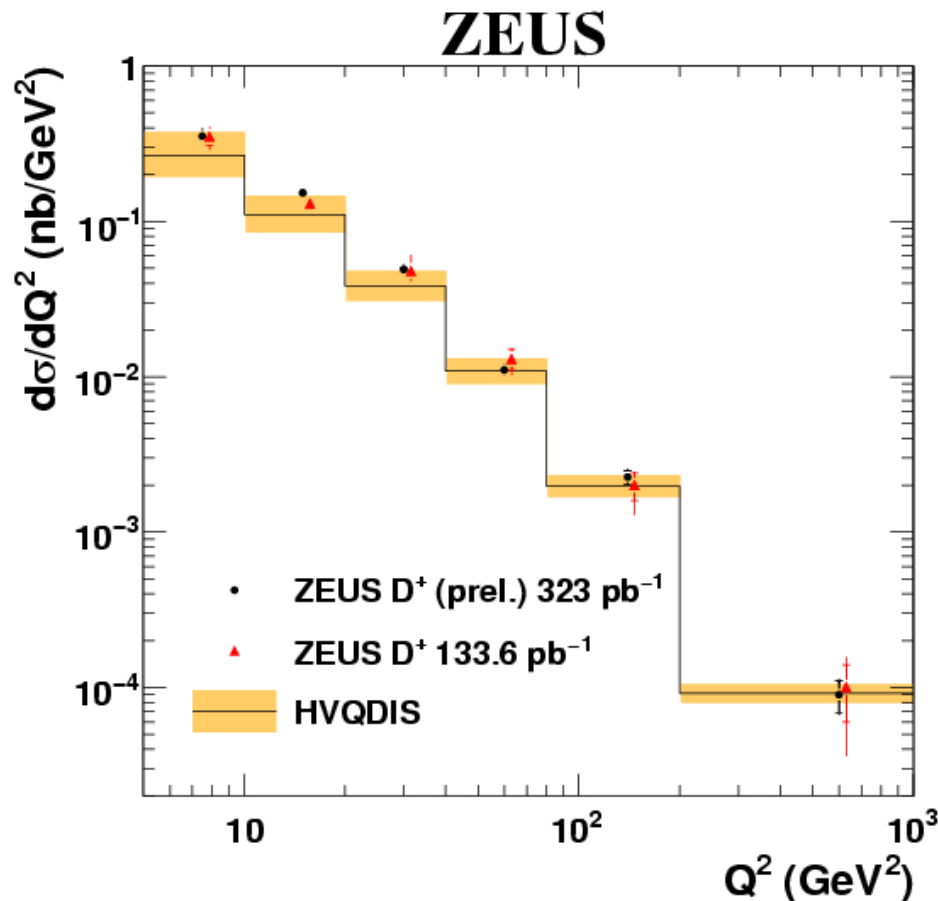
$\mathcal{L} = 323 \text{ pb}^{-1}$

$Q^2 > 6 \text{ GeV}^2, 0.07 < y < 0.6$

$1.5 < p_T(D^+) < 15 \text{ GeV}, |\eta(D^+)| < 1.6$

ZEUS-prel-10-005

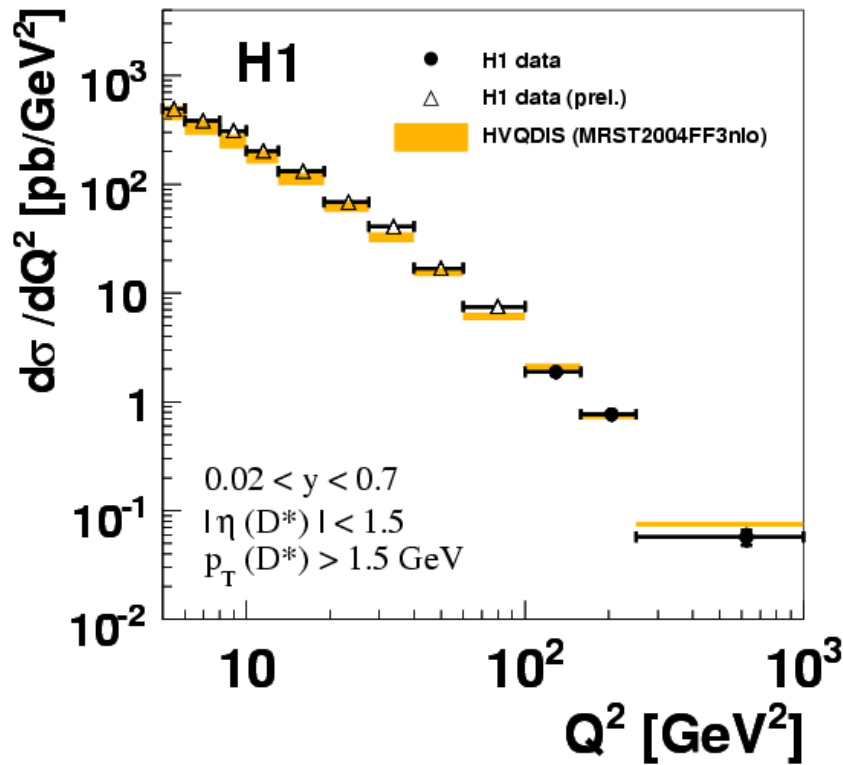
- Reconstruction:  $D^+ \rightarrow K^- \pi^+ \pi^+$  using lifetime information (secondary vertex)



→ NLO calculation HVQDIS describes data well

H1prelim-08-072

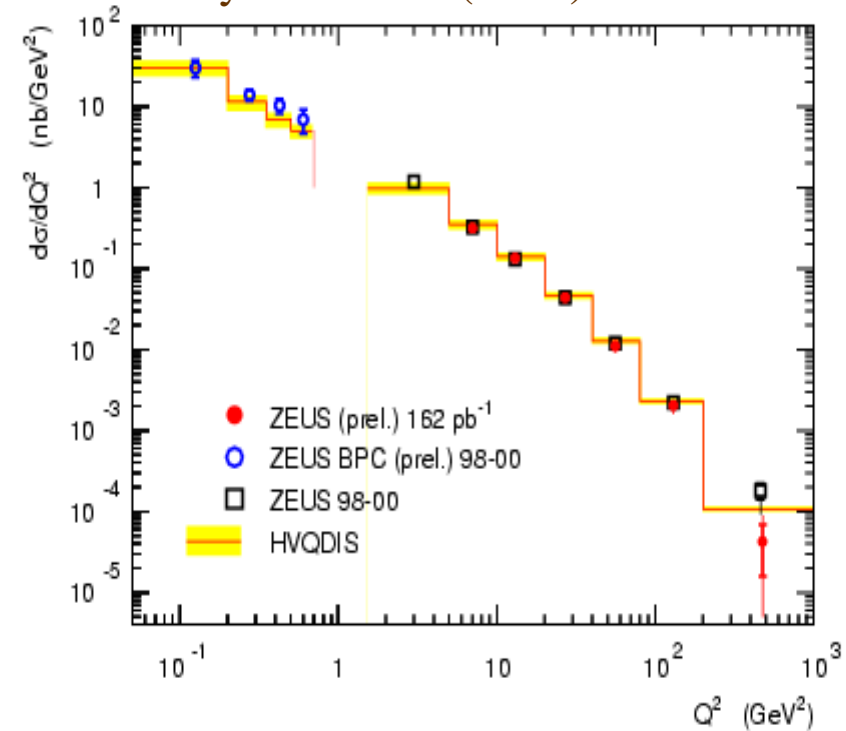
H1: Phys. Lett. B686 (2010) 91



Phys.Lett.B649 (2007) 111

ZEUS-prel-06-021

Phys.Rev.D69 (2004) 012004

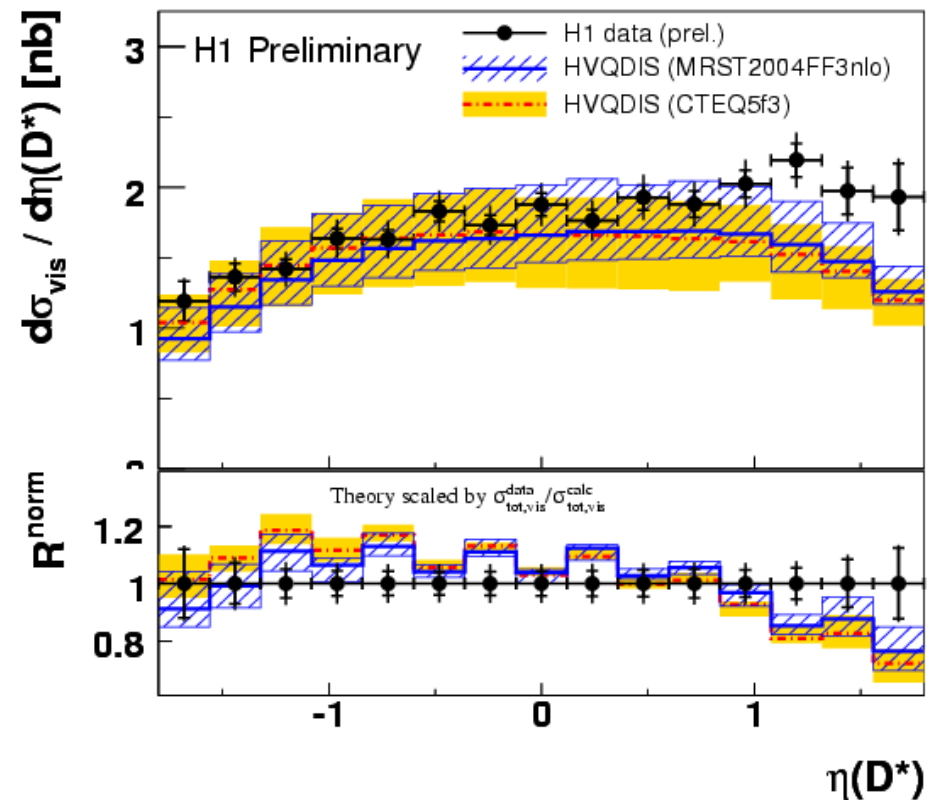
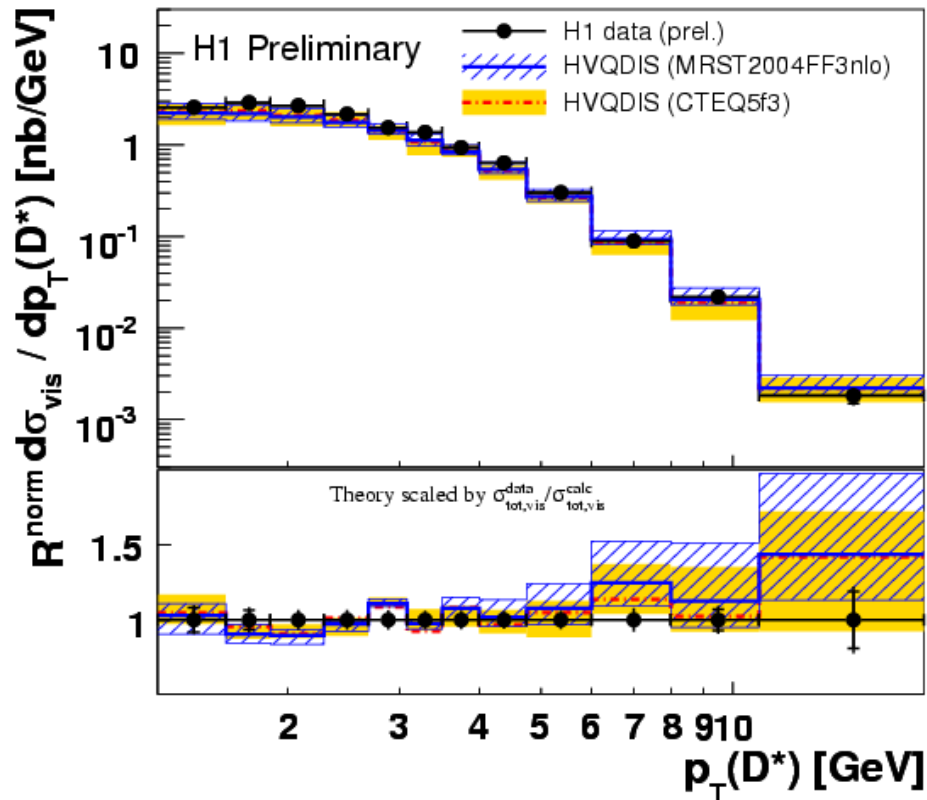


- Good description of data by NLO calculation (HVQDIS) over four orders of magnitude in  $Q^2$

$\mathcal{L} = 347 \text{ pb}^{-1}$

$5 < Q^2 < 100 \text{ GeV}^2, 0.02 < y < 0.7$   
 $p_t(D^*) > 1.25 \text{ GeV}, |\eta(D^*)| < 1.8$

H1Prelim-10-172



→ NLO calculations describe measured cross sections reasonably well



# Charm Jet Cross Sections DIS

- Flavour separation: combine secondary vertex and impact parameter information
- Compare data with NLO calculation

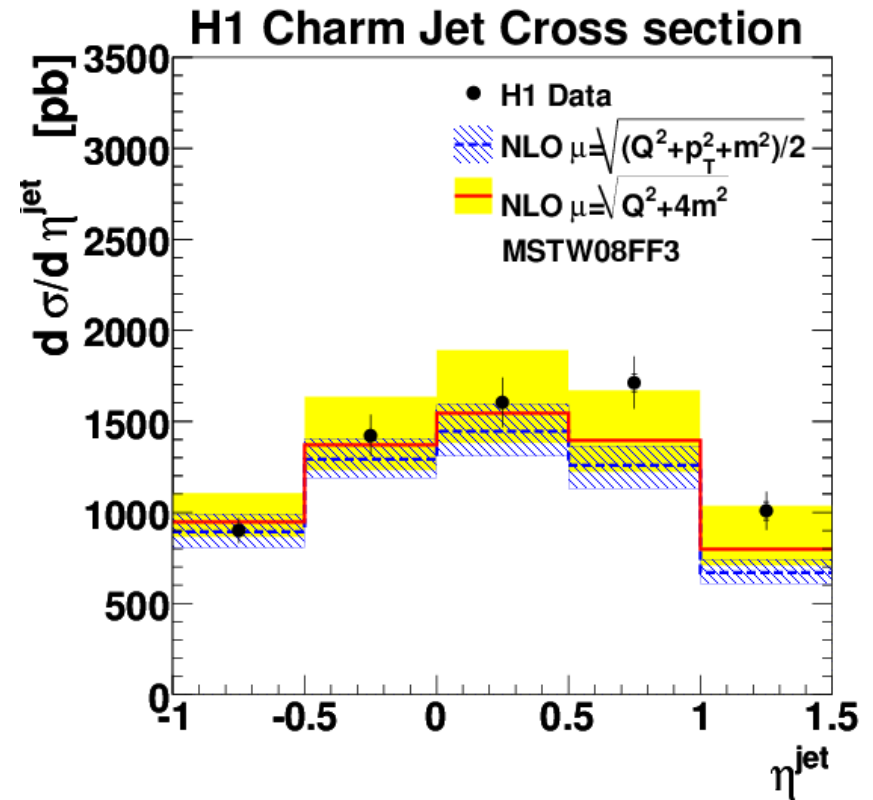
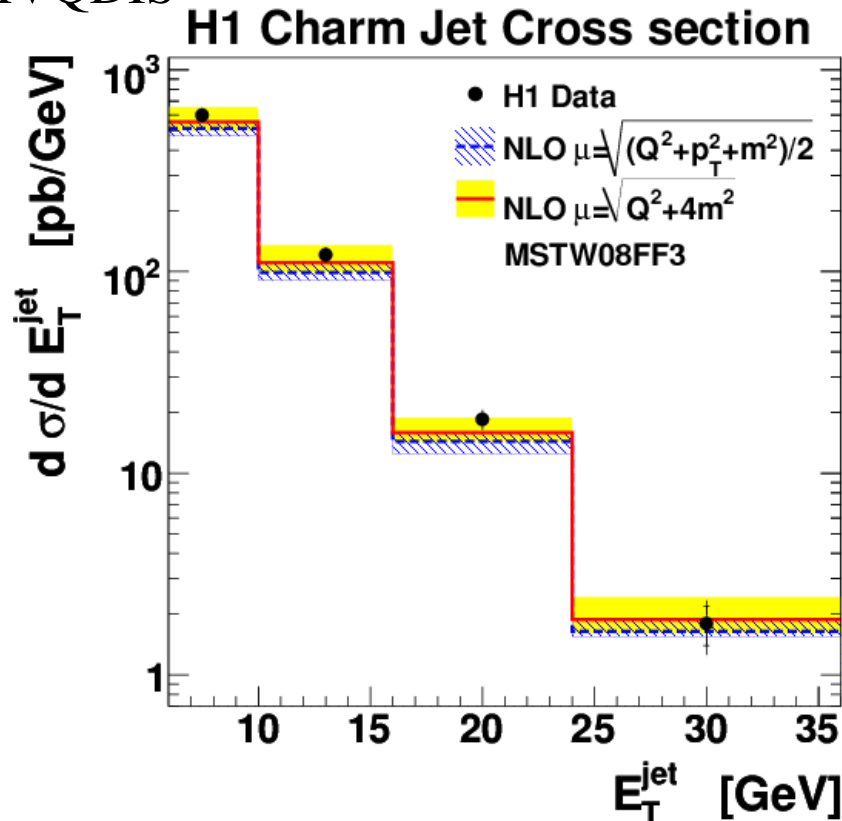
$$Q^2 > 6 \text{ GeV}^2, 0.07 < y < 0.6$$

$$E_T^{\text{jet}} > 6 \text{ GeV}, -1 < \eta_{\text{jet}} < 1.5$$

H1: DESY-10-083

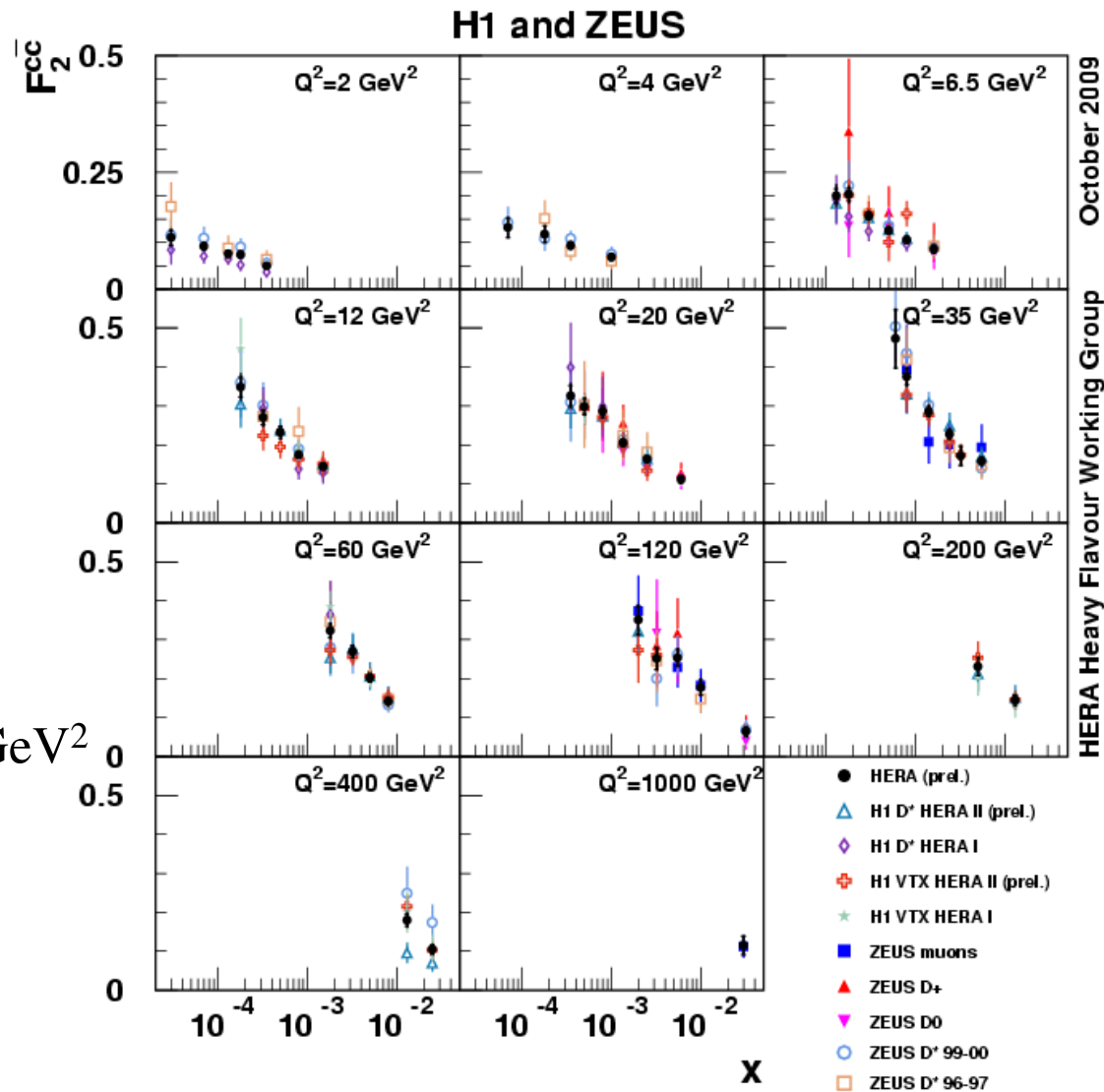
$\mathcal{L} = 189 \text{ pb}^{-1}$

HVQDIS



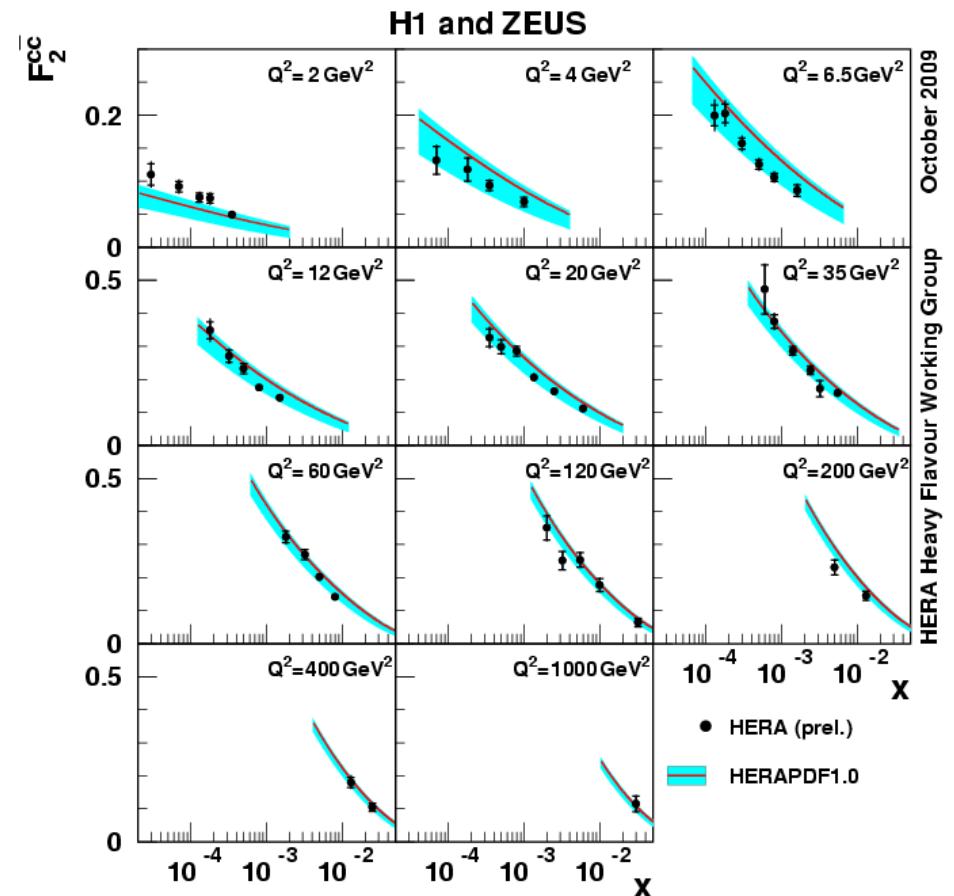
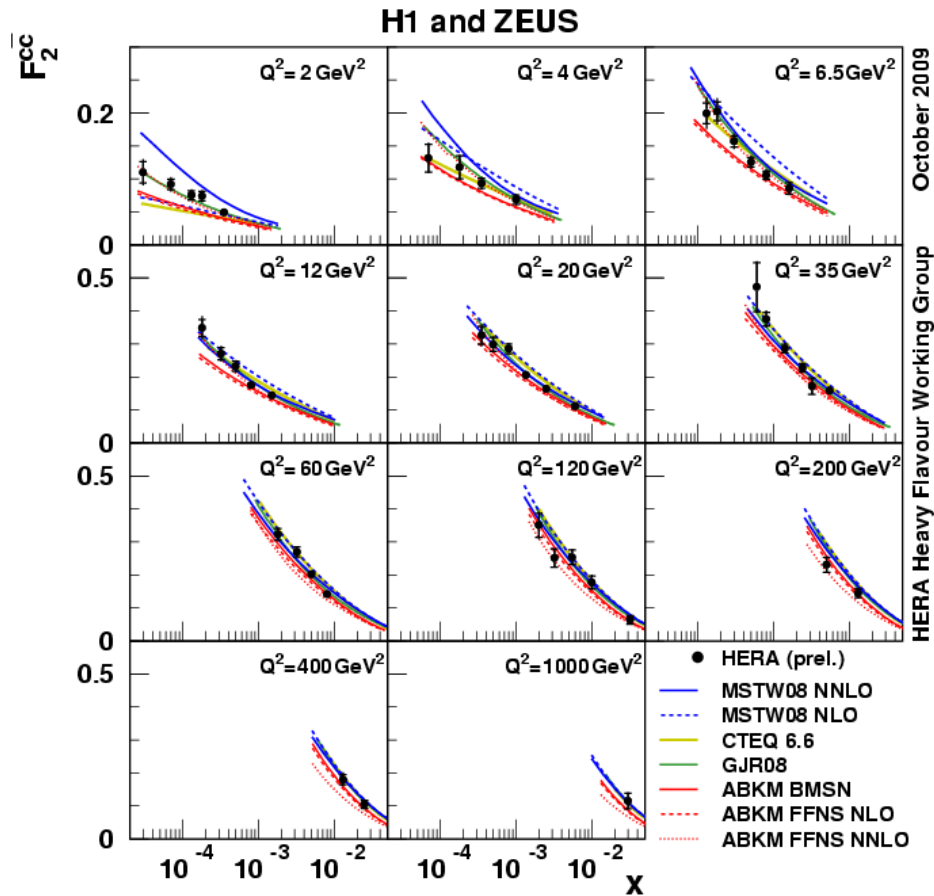
- NLO QCD calculation provides reasonable description of data
- Slight sensitivity to scale (large  $\eta$ )

- Combined  $F_2^{cc}$  compared to single measurements from H1 and ZEUS
- For combination take correlated systematic uncertainties into account
- Precision 5 – 10% for  $6.5 < Q^2 < 60 \text{ GeV}^2$



- Combined  $F_2^{cc}$  compared to NLO and NNLO calculations

- Combined  $F_2^{cc}$  compared to HERAPDF 1.0



→ Precision in data good enough to discriminate between different theory predictions



# Summary



- Jet physics at HERA provides precision measurements to understand QCD
- Precise and consistent extraction of strong coupling constant and its running over wide range of scale in one experiment
- Measured charm and beauty cross sections in general in good agreement with NLO QCD
- Different beauty measurements provide consistent results of  $F_2^{bb}$
- Predictions from NLO QCD describe measured  $F_2^{bb}$
- Combining H1 and ZEUS  $F_2^{cc}$  measurements provide a precision of 5 – 10 % on a wide kinematic range