Heavy Flavour Production at HERA

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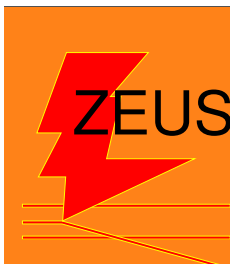
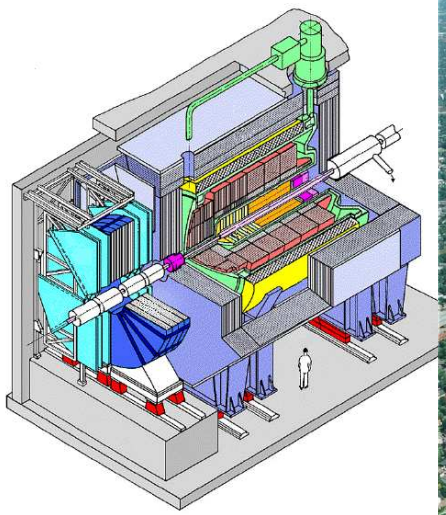
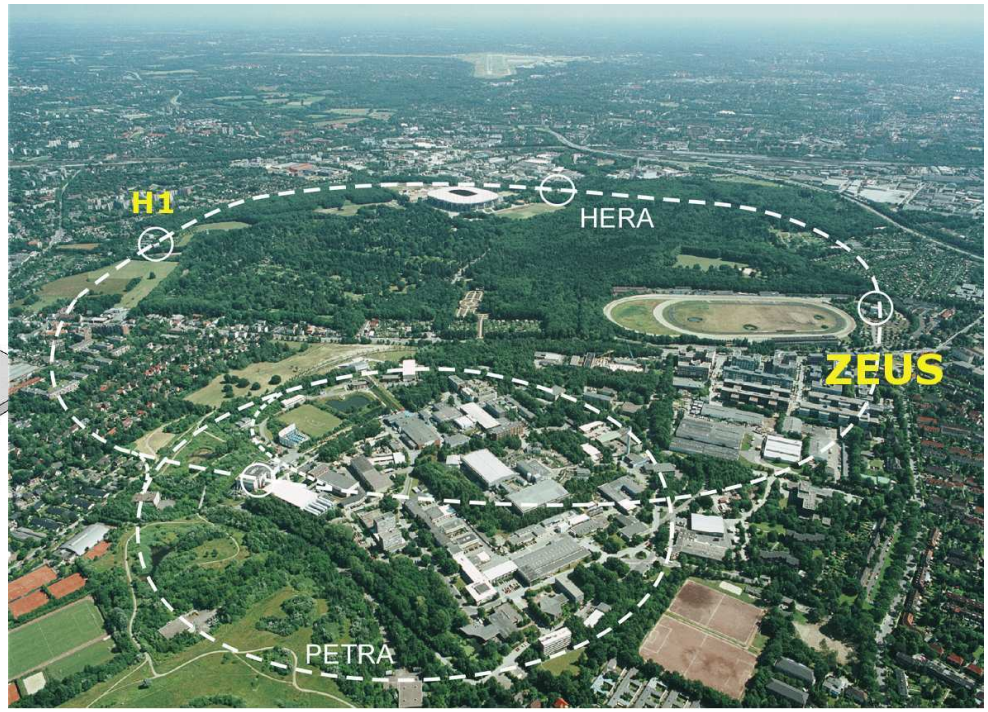
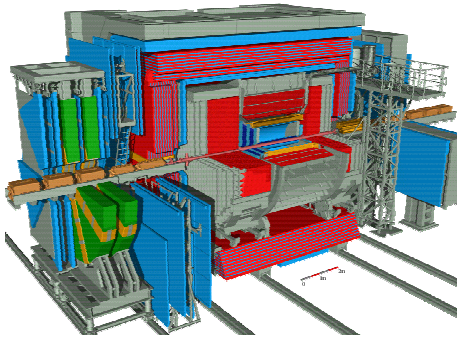


- Introduction
- Charm Production
- Beauty Production
- $F_2^{c\bar{c}}$ and $F_2^{b\bar{b}}$

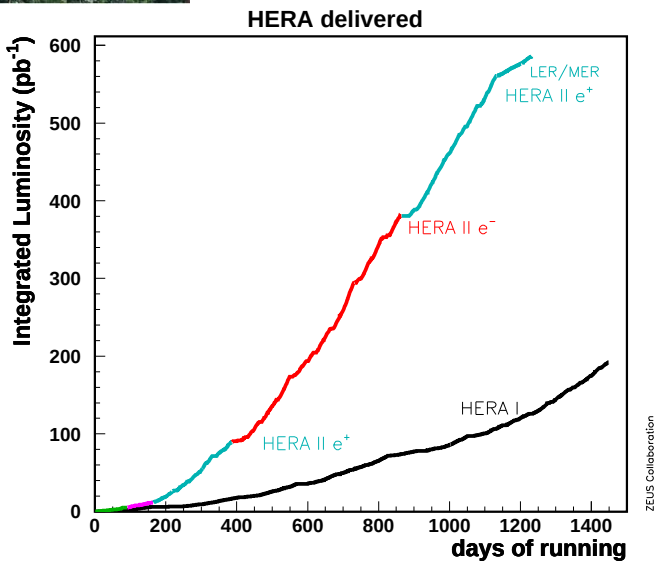
H1 and ZEUS







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

$\longrightarrow$ Should ensure reliable predictions

Monte Carlo programs (leading order + parton shower)

- DGLAP evolution (collinear factorization)
  Rapgap (DIS)
  Pythia (γp)
- CCFM evolution (k_t-factorization)
  Cascade (DIS+γp)

NLO Calculations

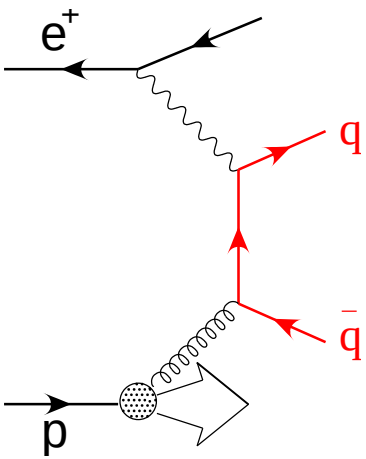
HVQDIS (DIS)
FMNR (γp)

$\longrightarrow$ **Stringent probe for perturbative QCD**

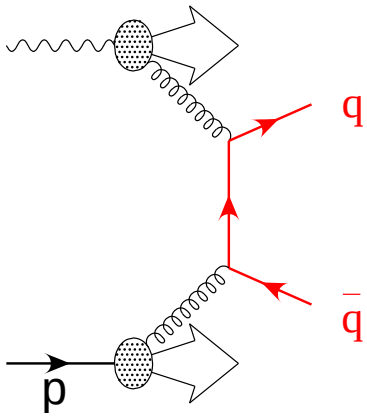
Heavy Flavour Production Mechanism

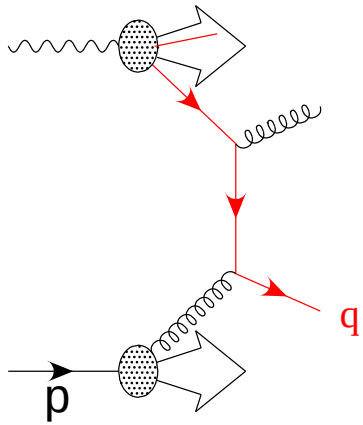
Dominant process: Boson-gluon fusion

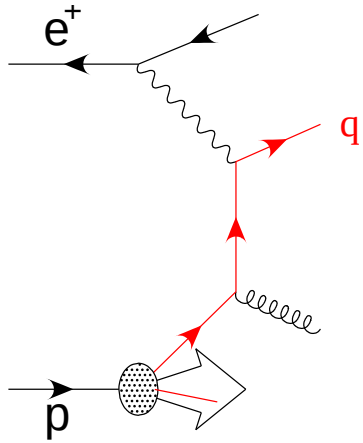
"direct"



"resolved" (including flavour excitation)



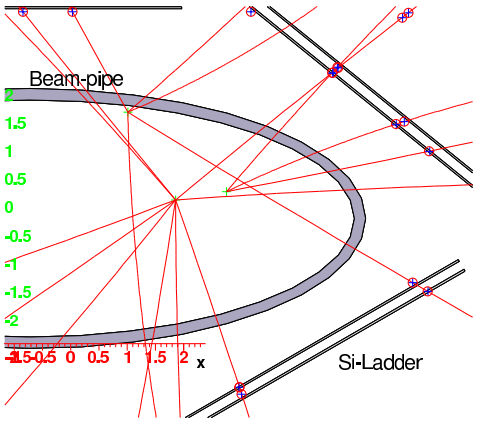


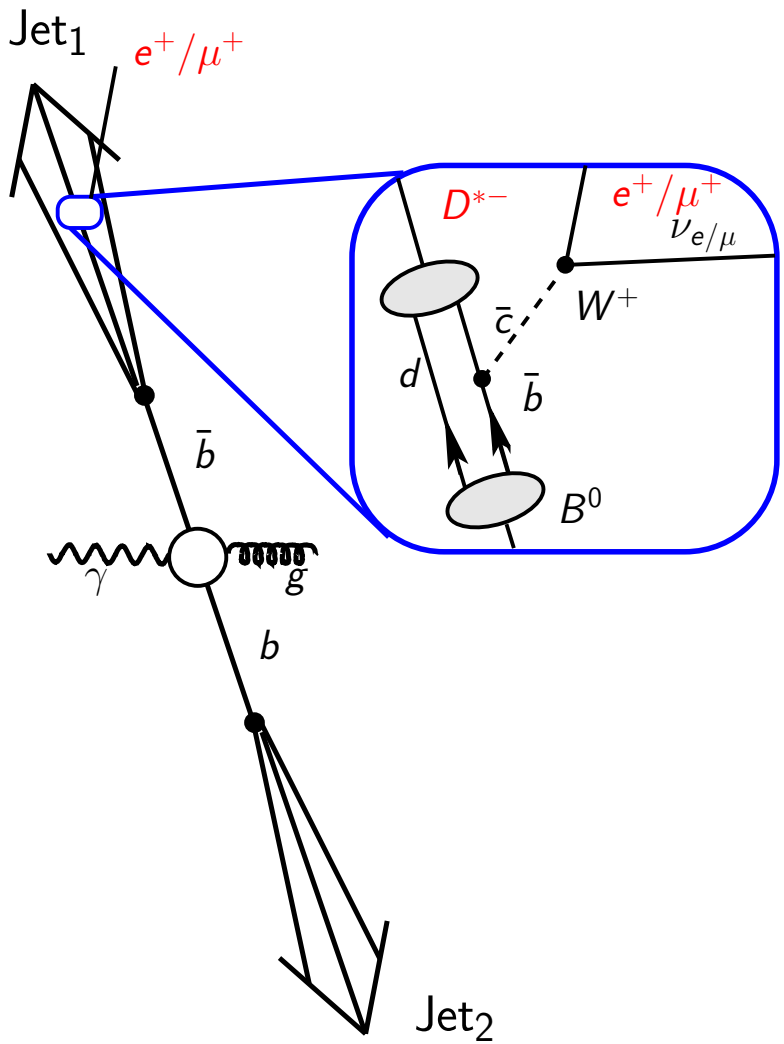


Heavy Flavour Tagging

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

D^* production in DIS & PhP

H1

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

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

Data/MC sets and NLO calculation:

DIS

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

PhP

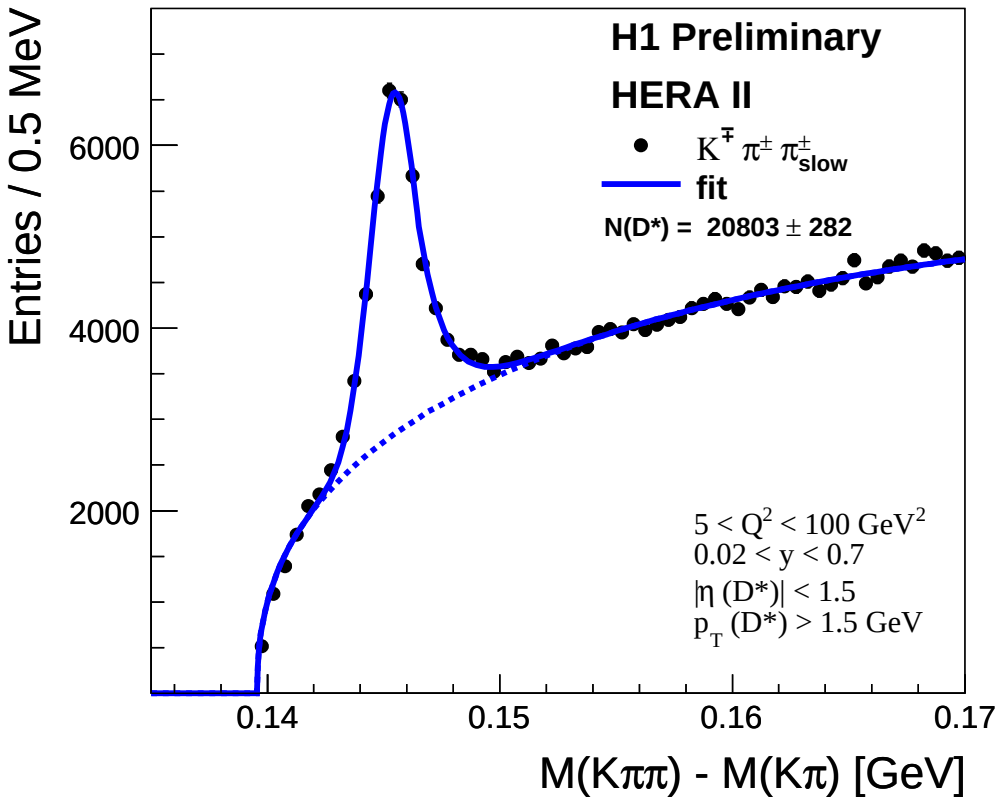
Data: 2006-2007 ($\mathcal{L} = 93\,\text{pb}^{-1}$)
LO: Pythia and Cascade
NLO: FMNR

Kinematic range:

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

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

D^* production in DIS

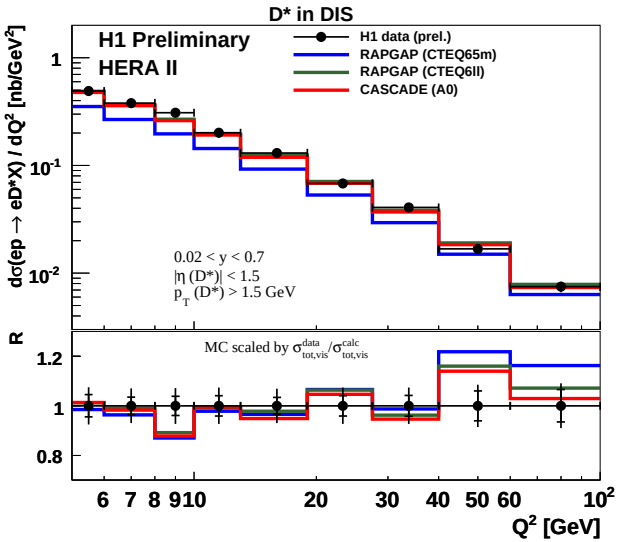


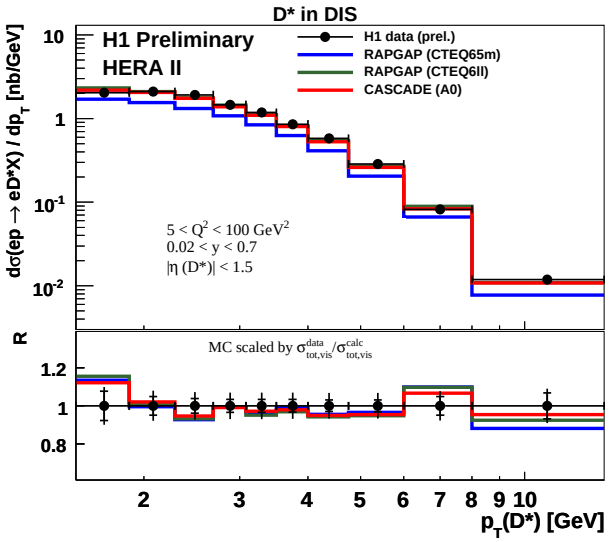
ΔM distribution for determination of number of D^* mesons

Total visible cross-section

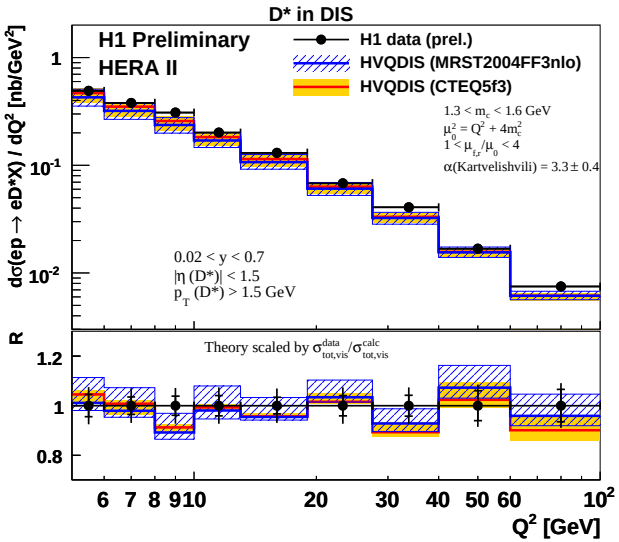
$$\sigma^{\text{tot}}_{\text{vis}}(e^{\pm}p \to e^{\pm}D^{*\pm}X) = 4.85 \pm 0.07\,(\text{stat.}) \pm 0.42\,(\text{syst.})\,\text{nb}$$

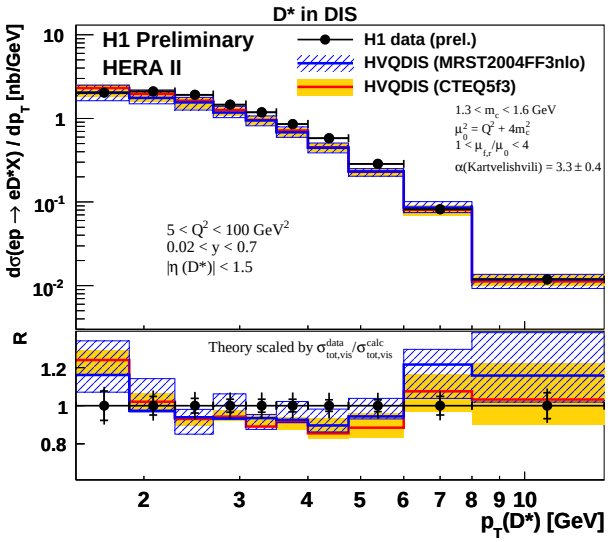
Differential cross-sections in Q^2 and $p_t(D^*)$





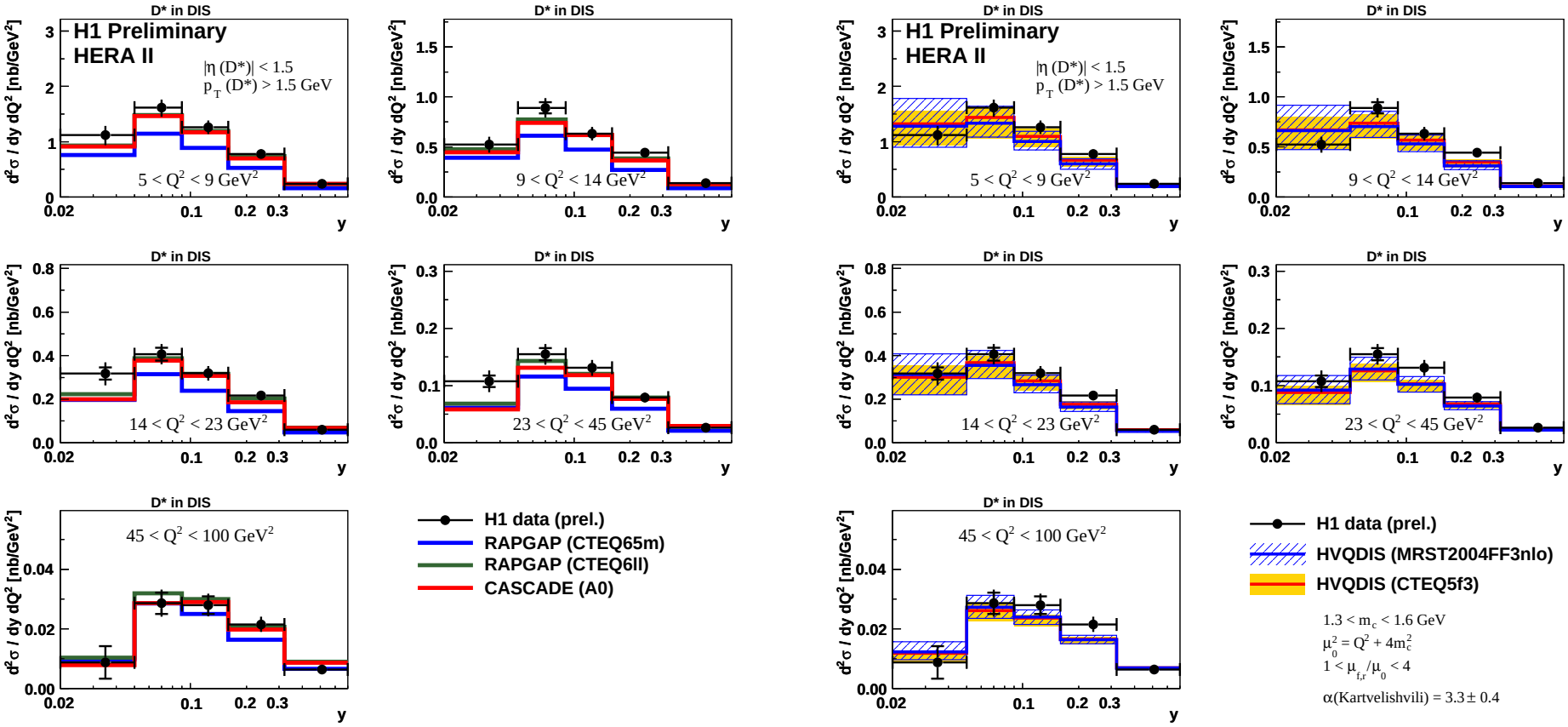
Data compared to Rapgap & Cascade MCs





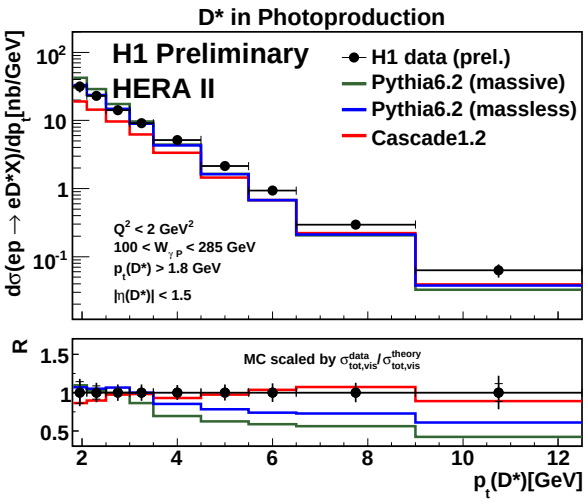
Data compared to HVQDIS

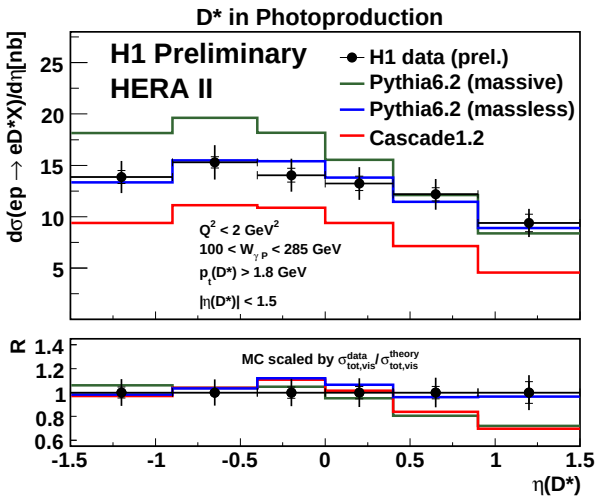
Double-differential cross-sections in y and Q^2



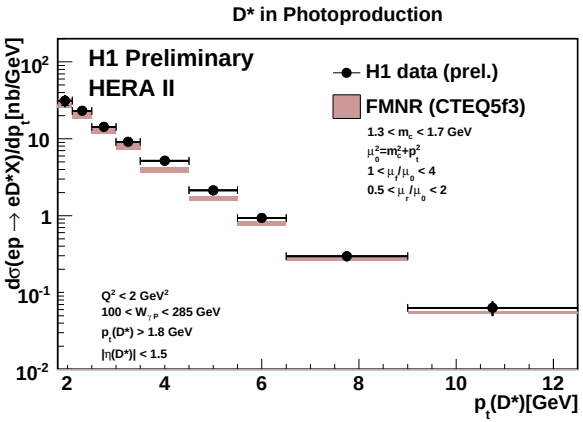
D^* production in PhP

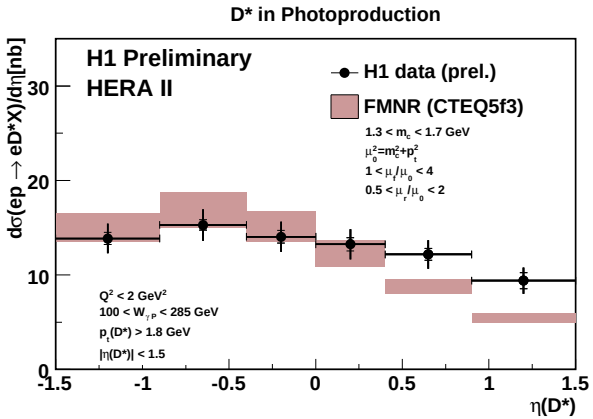
Differential cross-sections in $p_t(D^*)$ and $\eta(D^*)$





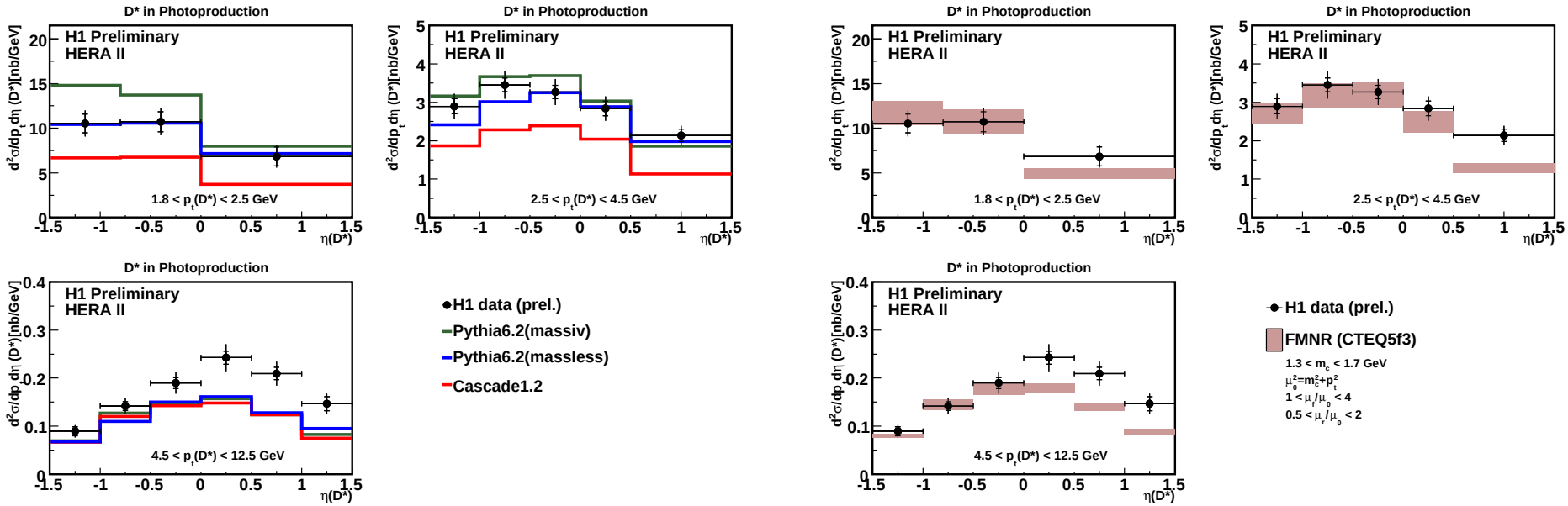
Data compared to Pythia (massive), Pythia (massless) & Cascade MCs





Data compared to FMNR

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



Part II

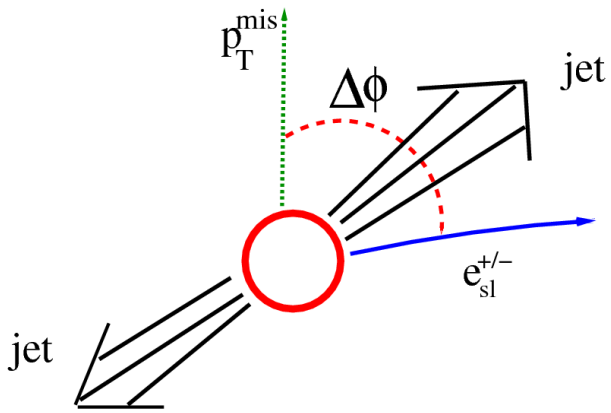
Beauty Production

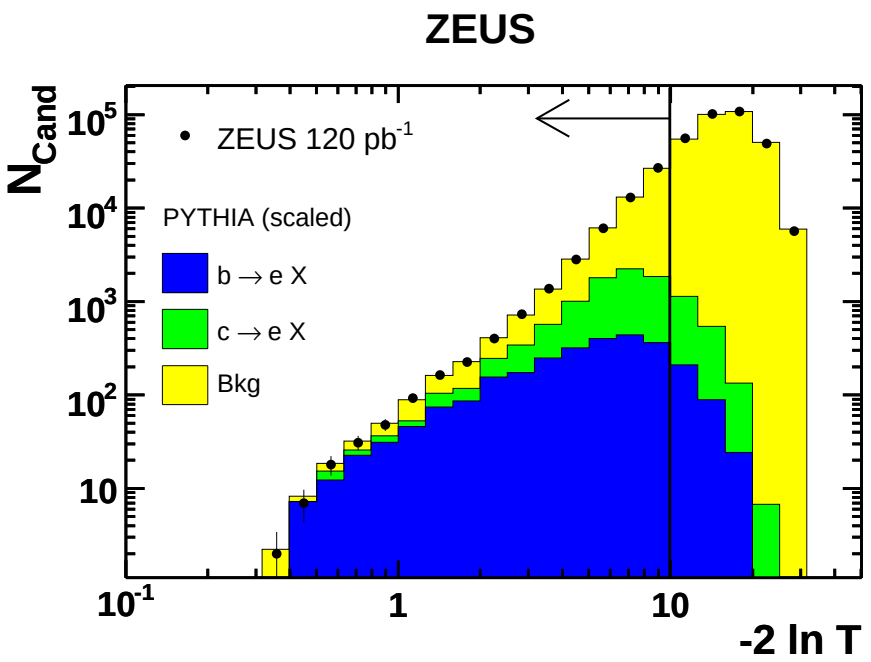
Beauty in Dijet PhP using electrons

ZEUS

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

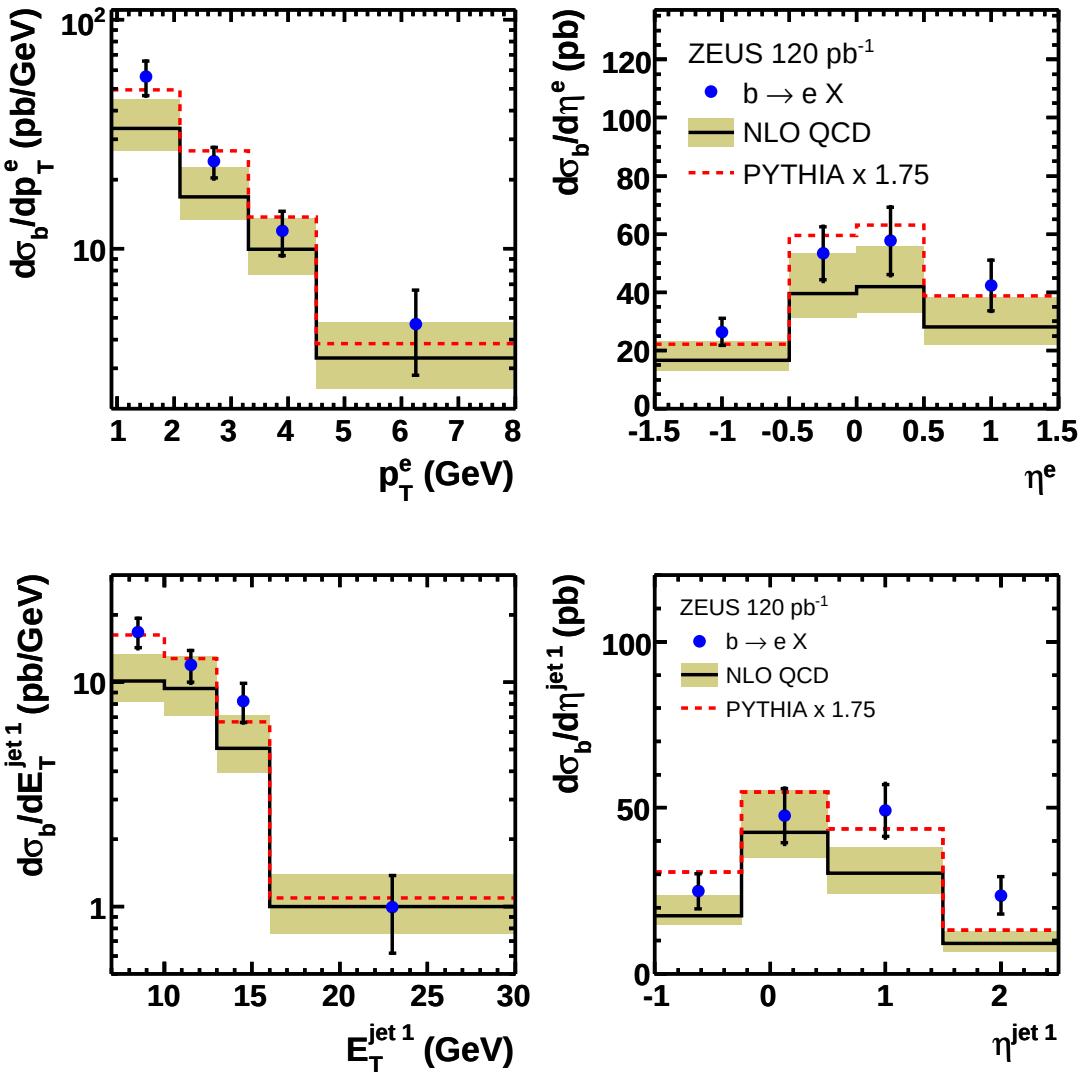
- Dijet events with $E_T > 7(6)\,\mathrm{GeV}$
- Semileptonic decays to electrons
- Combine several discriminating variables in likelihood test function:
  - Electron identification: dE/dx, EMC fraction, E/p
  - Decay identification: $\Delta\phi$ and p_t^{rel}





Beauty in Dijet PhP using electrons

ZEUS



Differential cross-sections in p_T^e, η^e, E_T^{jet1}, η^{jet1}

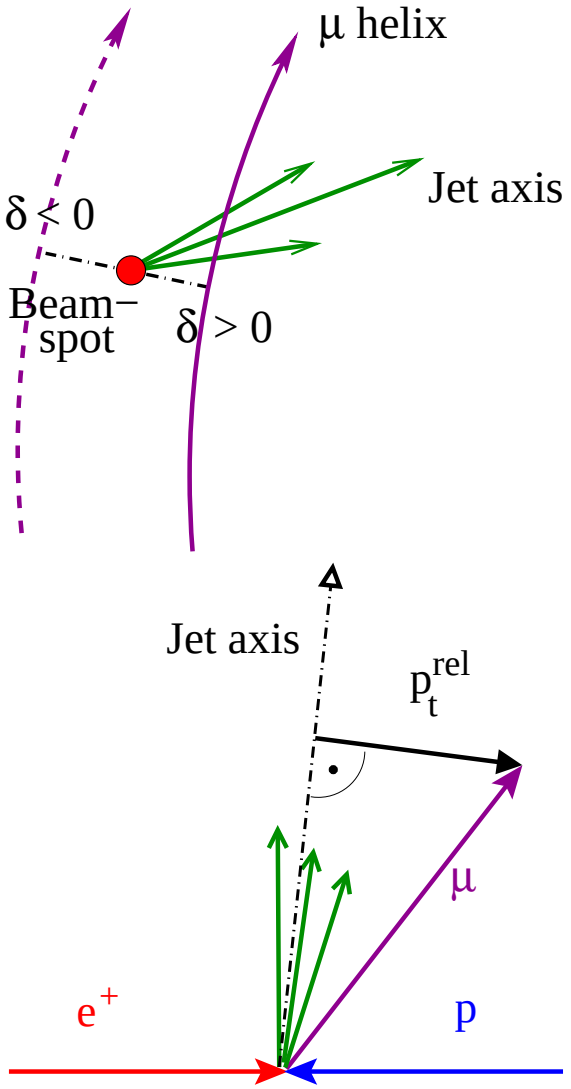
- NLO prediction consistent with Data
- Scaled MC distributions describe the shape well

Beauty in Dijet PhP using muons

ZEUS

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

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



Beauty in Dijet PhP using muons

ZEUS

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

- Dijet PhP events with $p_T^{jet} > 7(6)\,\mathrm{GeV}$
- Semileptonic decays to muons
  - $-1.6 < \eta^{\mu} < 2.3$
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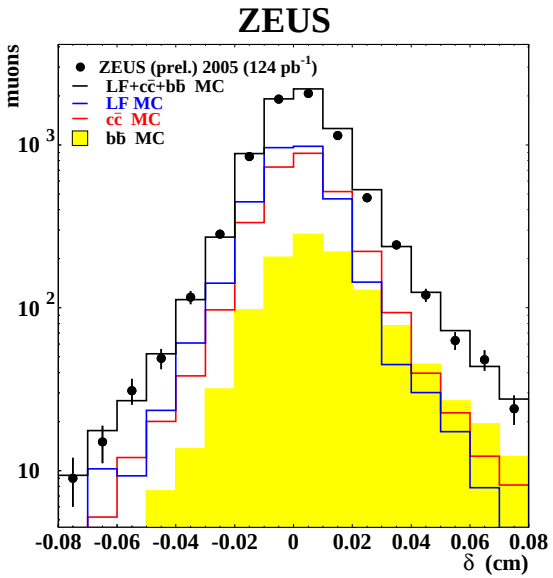
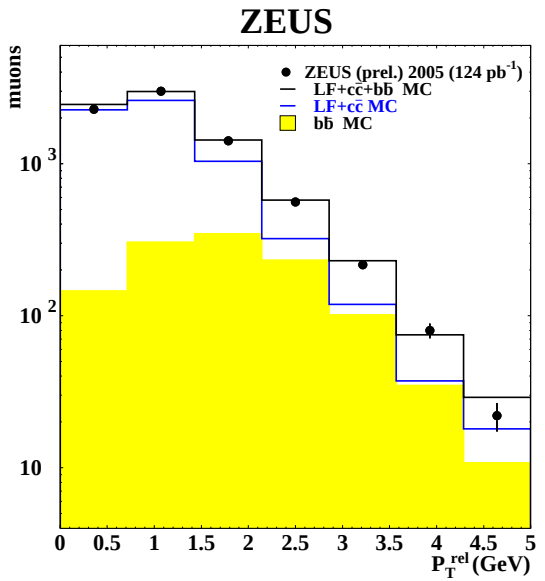
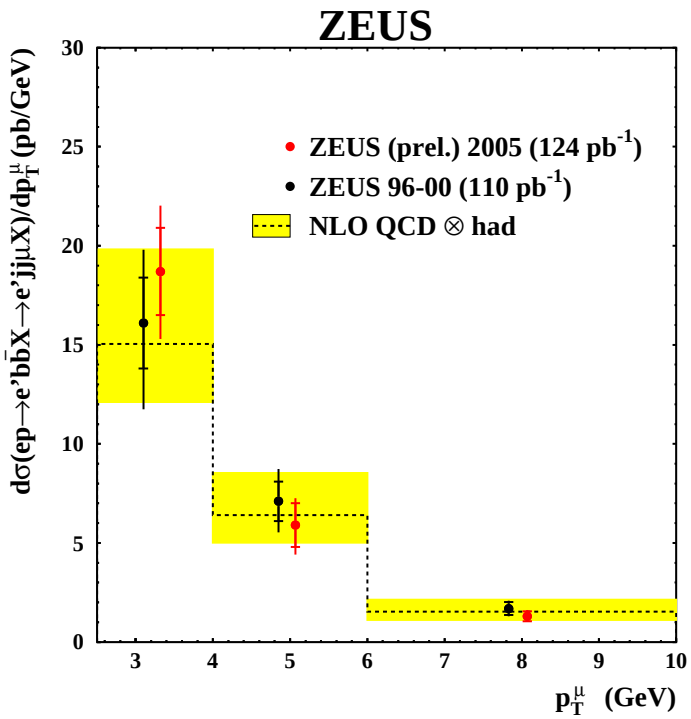
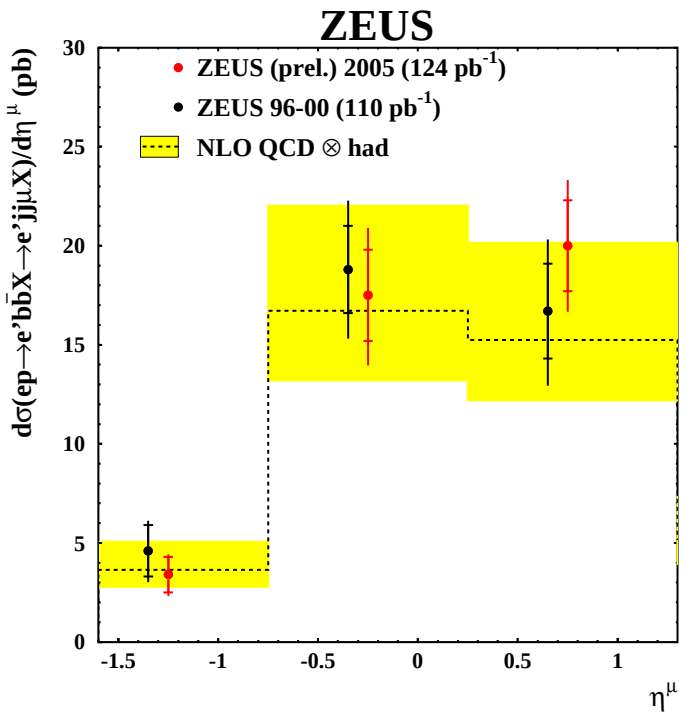




Beauty in Dijet PhP using muons

ZEUS





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

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

Beauty in PhP - double tag

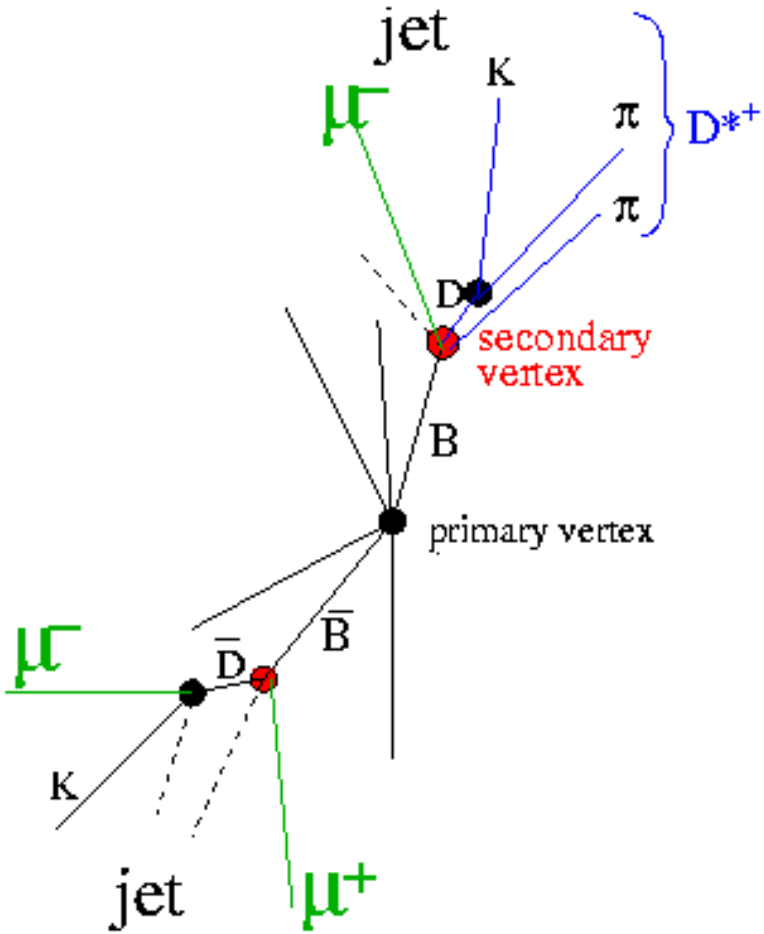
ZEUS

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

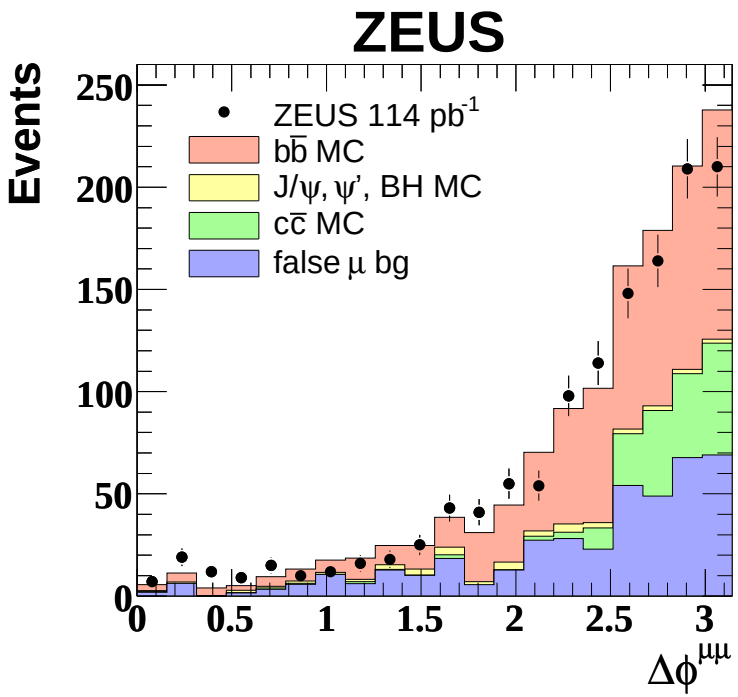
Advantages:

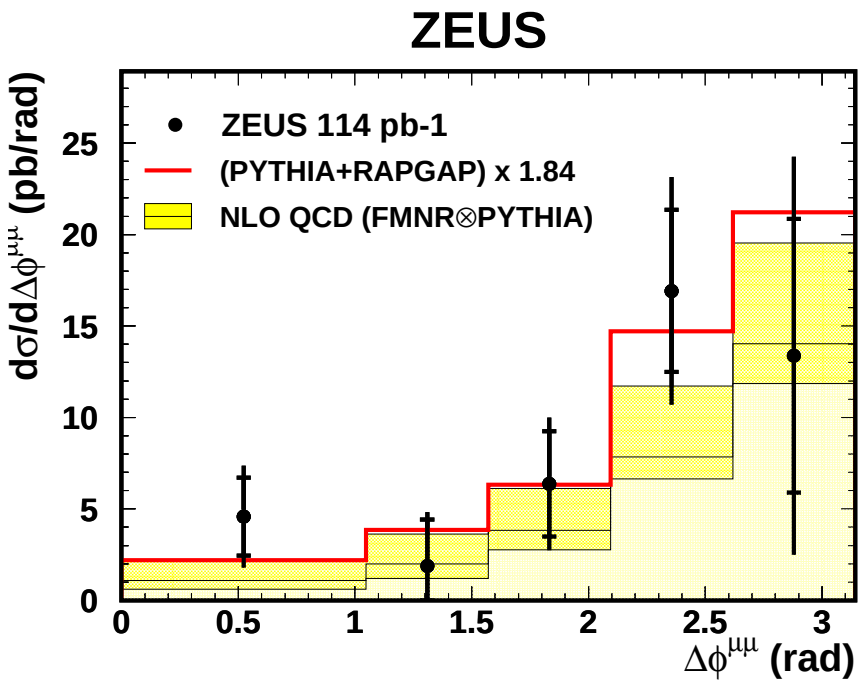
- No jet requirements
- Low p_t^{μ} thresholds
- Measure bb correlations



Beauty in PhP - double tag

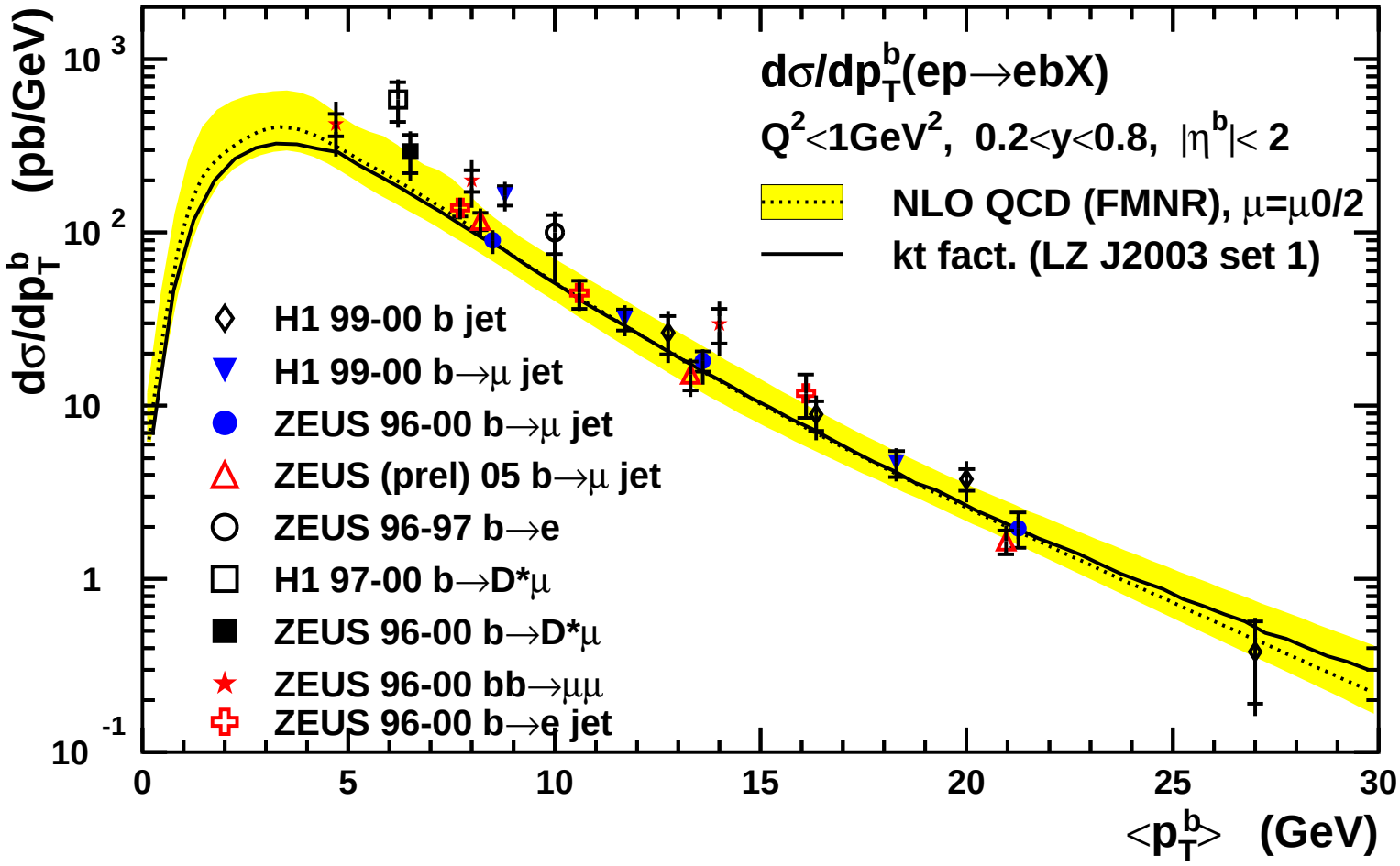
ZEUS





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

HERA


dσ/dp_T^b (pb/GeV)
10^3
10^2
10
1
10^-1
0
5
10
15
20
25
30
<p_T^b> (GeV)
dσ/dp_T^b(ep→ebX)
Q^2<1GeV^2, 0.2<y<0.8, |η^b|< 2
NLO QCD (FMNR), μ=μ0/2
kt fact. (LZ J2003 set 1)
H1 99-00 b jet
H1 99-00 b→μ jet
ZEUS 96-00 b→μ jet
ZEUS (prel) 05 b→μ jet
ZEUS 96-97 b→e
H1 97-00 b→D*μ
ZEUS 96-00 b→D*μ
ZEUS 96-00 bb→μμ
ZEUS 96-00 b→e jet

Part III

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

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

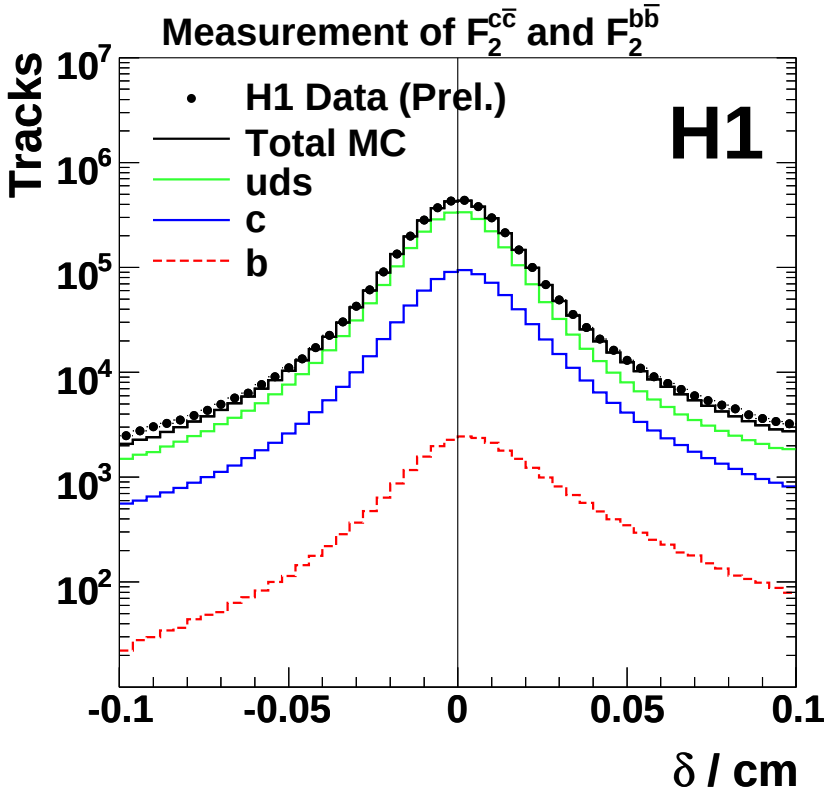
H1

Data: 2006 ($\mathcal{L} \approx 54\,\mathrm{pb}^{-1}$)
LO: Rapgap, Cascade

Kinematic region:

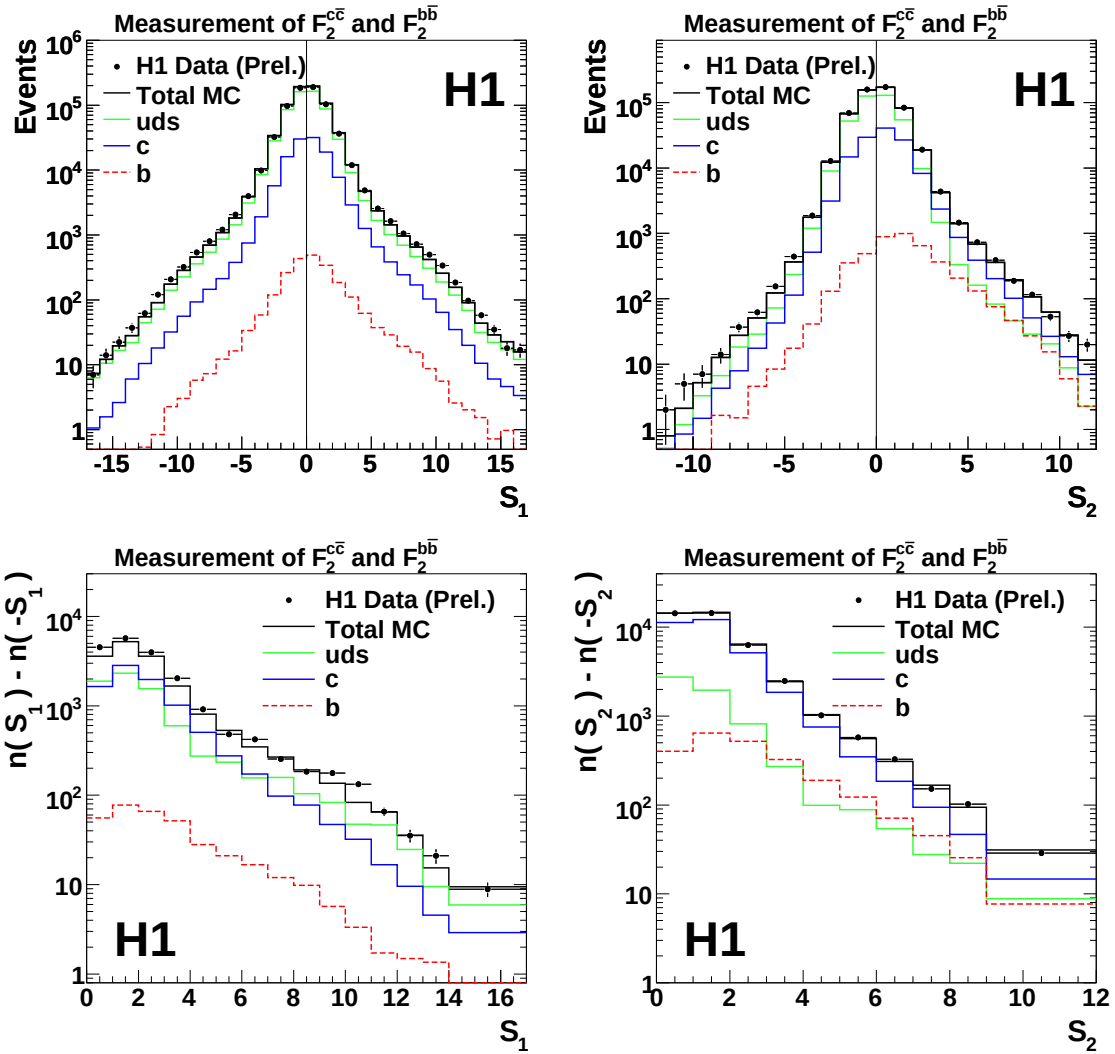
$12 < Q^2 < 650\,GeV^2$
$0.0002 \leq x \leq 0.032$
$p_T^{track} > 0.5\,GeV$

- 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



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

H1



- Significance $\delta/\sigma(\delta)$ for highest significant track S1 and second highest significant track S2
- Simultaneous fit of the subtracted S1 and S2 distributions

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

H1

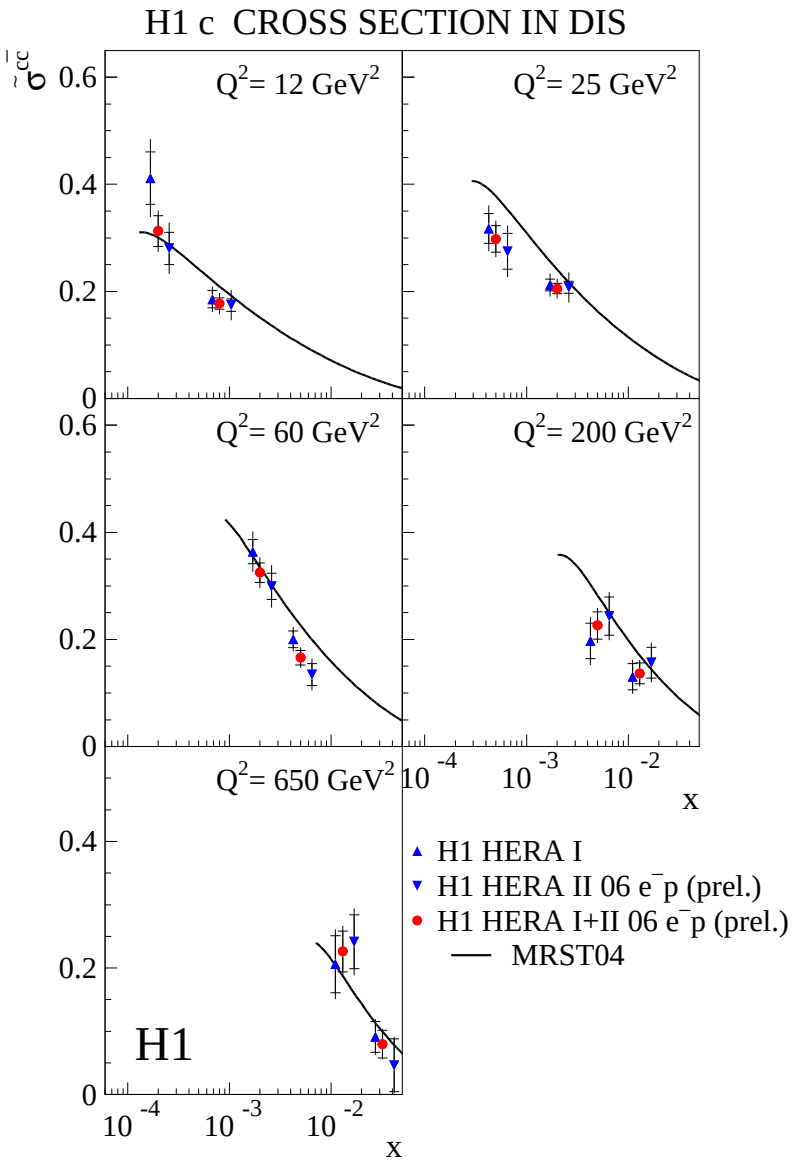
- Calculation of $\mathbf{F_2^{c\bar{c}}}$ via **reduced cross-section**

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

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

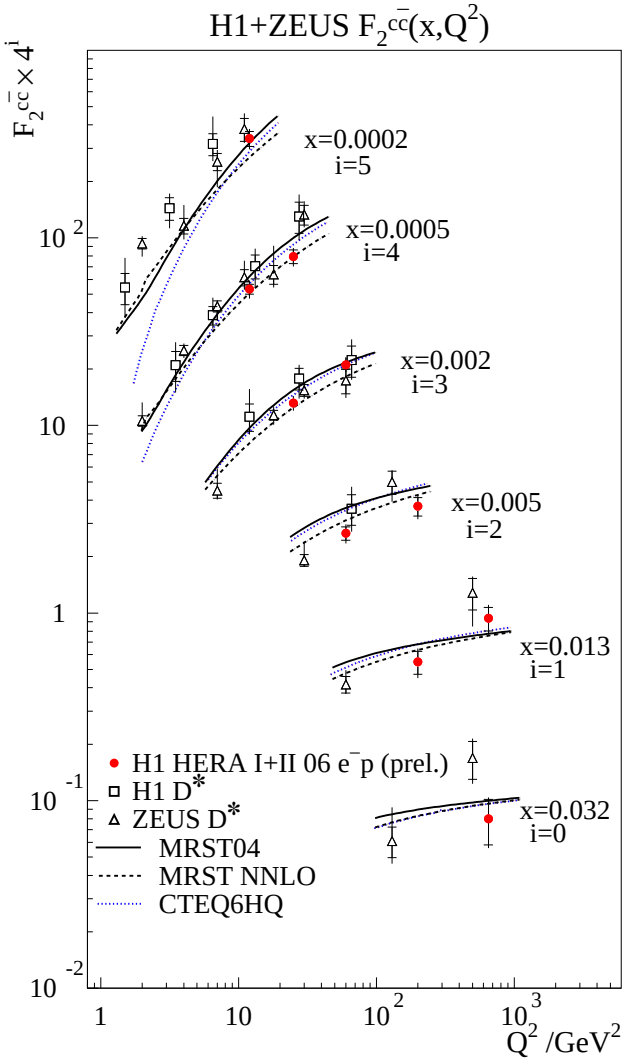
$$\tilde{\sigma}^{c\bar{c}} = F_2^{c\bar{c}} - \frac{y^2}{1+(1-y)^2}F_L^{c\bar{c}}$$

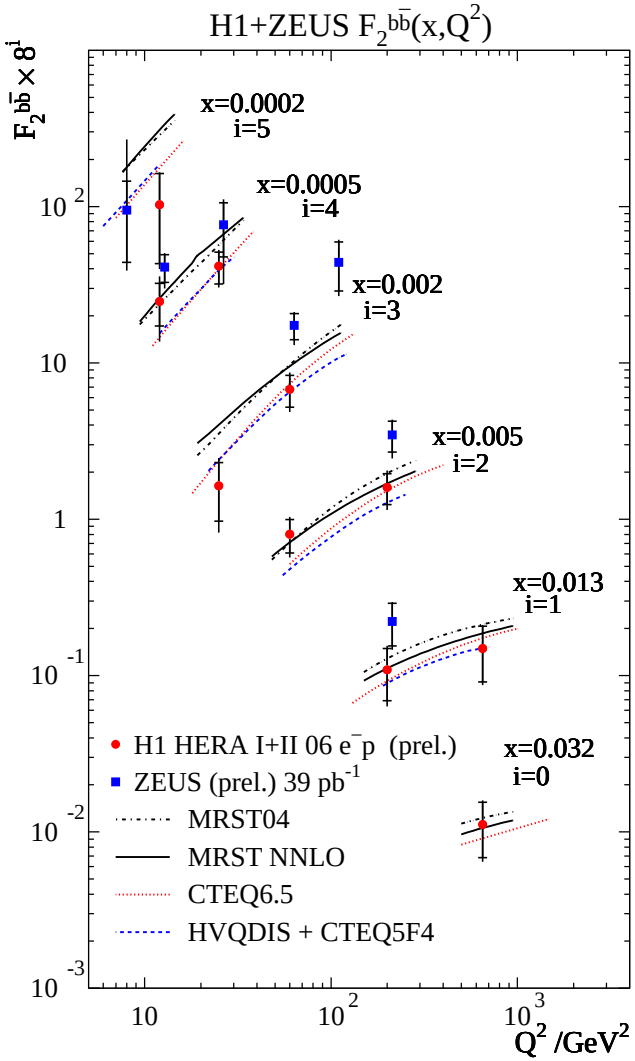
- Combine with HERA I result



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

H1 + ZEUS





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

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

in PhP

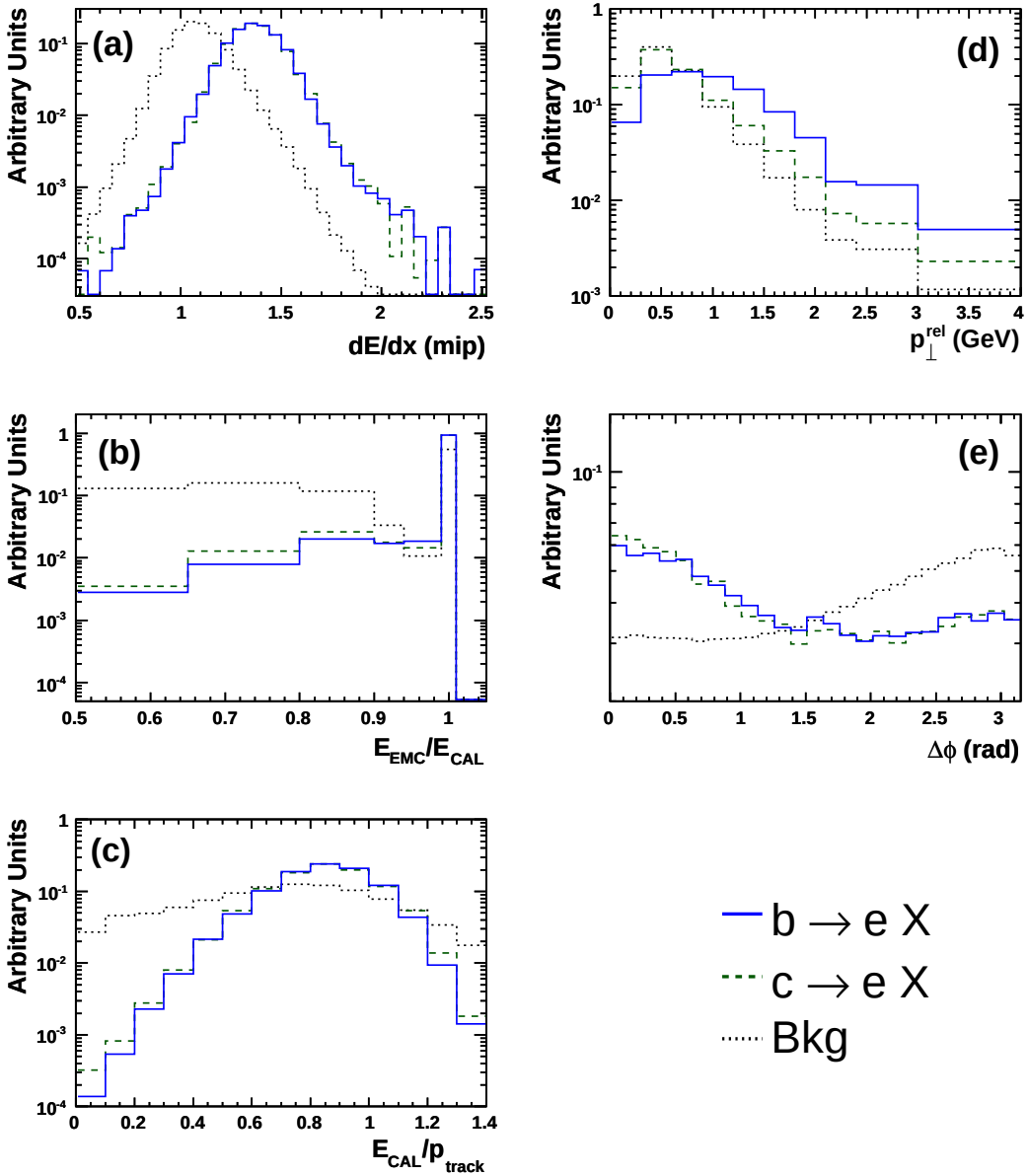
- $p_t(K) > 0.5\,\mathrm{GeV}$
- $p_t(\pi) > 0.3\,\mathrm{GeV}$
- $p_t(\pi_{slow}) > 0.12\,\mathrm{GeV}$
- $p_t(K) + p_t(\pi) > 2.2\,\mathrm{GeV}$
- $|M(K\pi) - M(D^0)| < 0.08\,\mathrm{GeV}$

Cross-section determination

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

Beauty in Dijet PhP using electrons

ZEUS



Discriminating variables

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

Beauty in PhP - double tag

ZEUS

Method

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