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Charm (and beauty) production in DIS at HERA

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on behalf of the H1 and ZEUS collaborations



Outline:

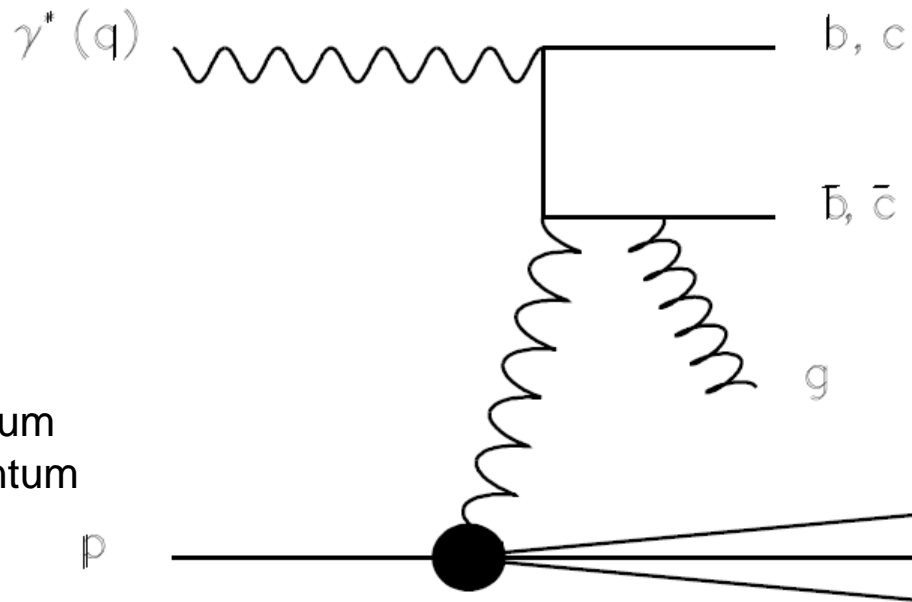
- HERA, H1 and ZEUS
- heavy quark production in DIS at HERA
- charm and beauty DIS cross section measurements
- conclusions

The HERA collider and the H1 and ZEUS detectors: short introduction



- HERA was an $e p$ collider; γp center of mass energy was up to 320 GeV (equivalent to a ~ 50 TeV e beam on fixed target)
- H1 and ZEUS were large multipurpose experiments
- running started in 1992 and ended in 2007 ... over time significant detector upgrades: like the silicon vertex detectors that boosted the charm and beauty performances
- integrated luminosity: $\sim 500 \text{ pb}^{-1}$ per experiment

Deep Inelastic Scattering (DIS) kinematic variables



P : proton 4-momentum
 k : electron 4-momentum

referring to the diagram shown above:

- $Q^2 = -q^2$

virtually of the exchanged γ

- $x = Q^2 / 2 P q$

fraction of the proton momentum taken by the incoming gluon

- $y = P q / P k$

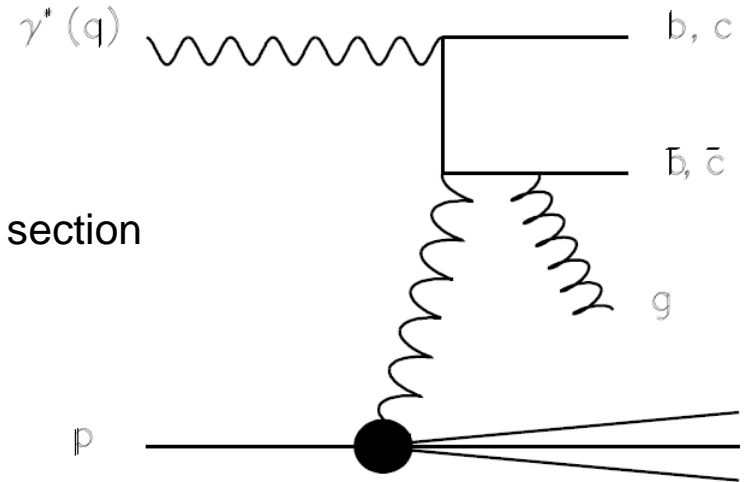
fraction of the electron momentum taken by the incoming γ

- DIS regime: $Q^2 > 1 \text{ GeV}^2$
- photoproduction regime: $Q^2 \sim 0 \text{ GeV}^2$

Heavy quark (charm and beauty) production in DIS at HERA

- important playground for pQCD: the large heavy quark mass provides a hard scale that allows pQCD calculations to be made ... be aware that other scales are also present ...
- dominant heavy quark production process in DIS: boson gluon fusion

cross section $\sigma = \text{gluon density} \otimes \text{hard sub-process cross section}$



hottest questions for pQCD:

- how accurate is the prediction of the hard sub-process cross section ?
- if you plug in the gluon density from inclusive DIS measurements do you get the right results for the heavy quark cross sections ?

Heavy quark tagging

- large lifetime of the produced heavy hadrons
- semileptonic electron decay mode
- semileptonic muon decay mode
- complete reconstruction of the heavy hadron (mostly D mesons at HERA)

DIS selection highlights:

- $Q^2 > 6 \text{ GeV}^2$
- $0.07 < y < 0.625$

lab. frame jet reco. highlights:

- input: HFS particles
- k_T algo. (massless P_T recombination scheme, $R_0=1$)
- $E_T^{\text{jet}} > 6 \text{ GeV}^2$
- $-1 < \eta^{\text{jet}} < 1.5$

Breit frame jet reco. highlights:

as for lab. frame jets but in the Breit frame

jet flavor separation:

$$S_i = \delta_i / \sigma(\delta_i)$$

sign of δ_i for to the relative position of the jet axis vs (DCA – primary vertex) axis in xy

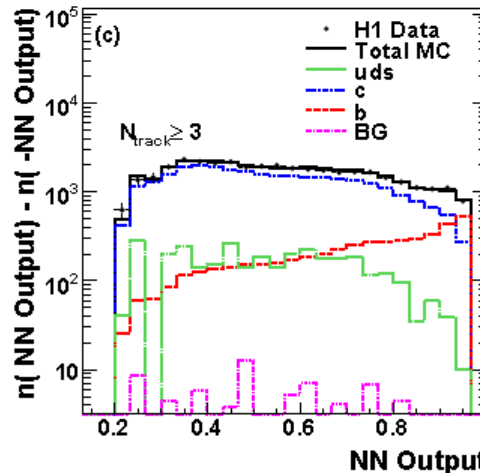
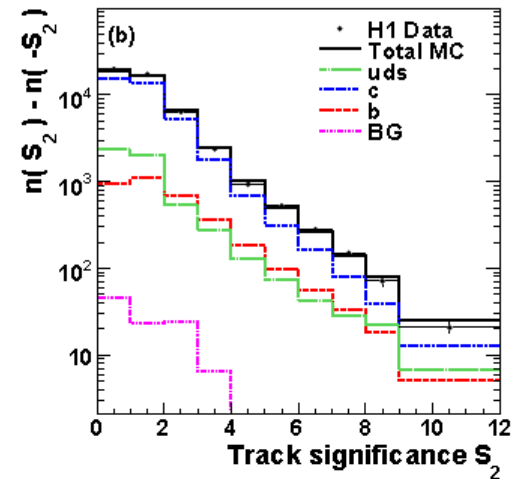
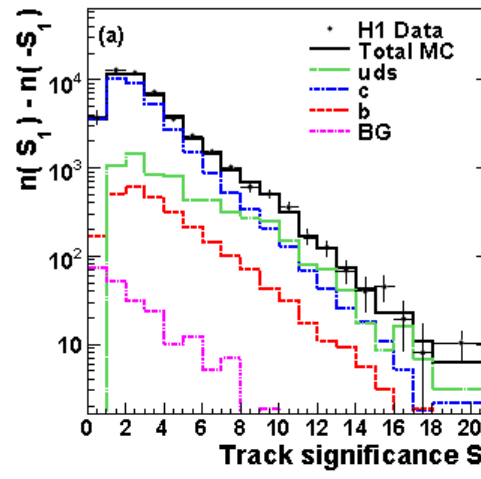
$$S_1 > S_2 > \dots$$

as many as you have tracks in the jet

template fit for:

uds **c** and **b**

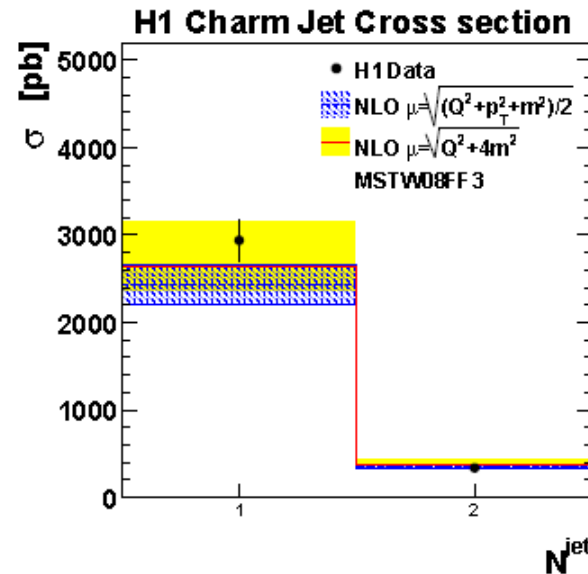
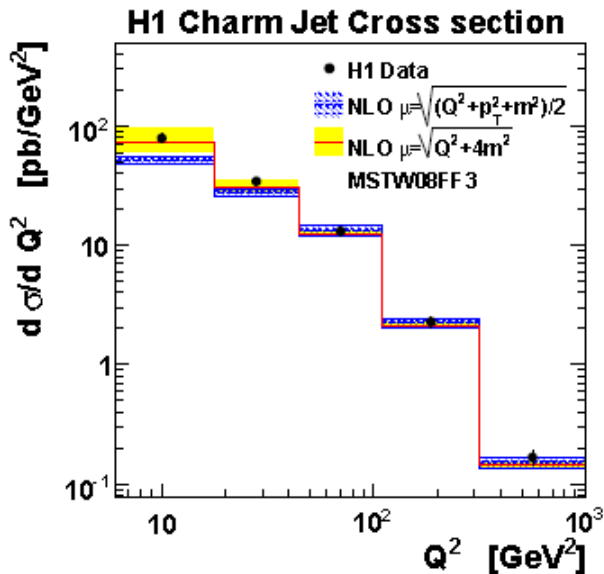
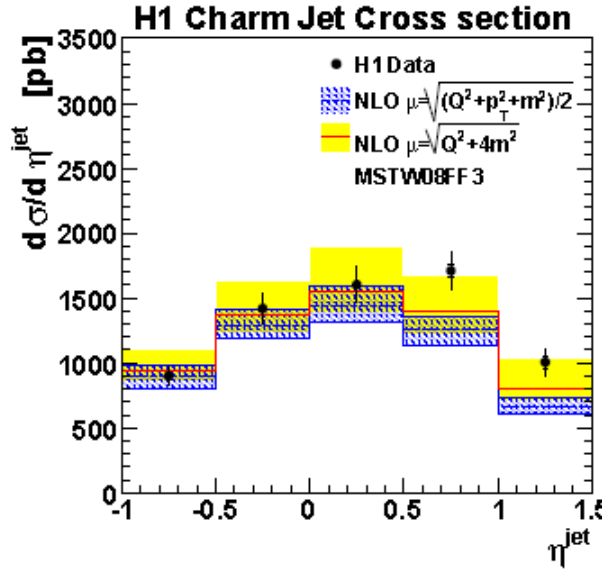
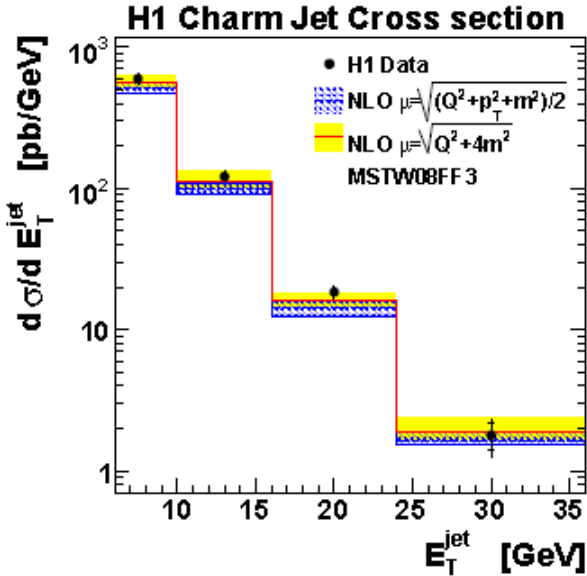
BG: photoproduction background



≥ 3 tracks:
feed a NN with all the useful observables of the event

Charm jet cross section (lab. frame)

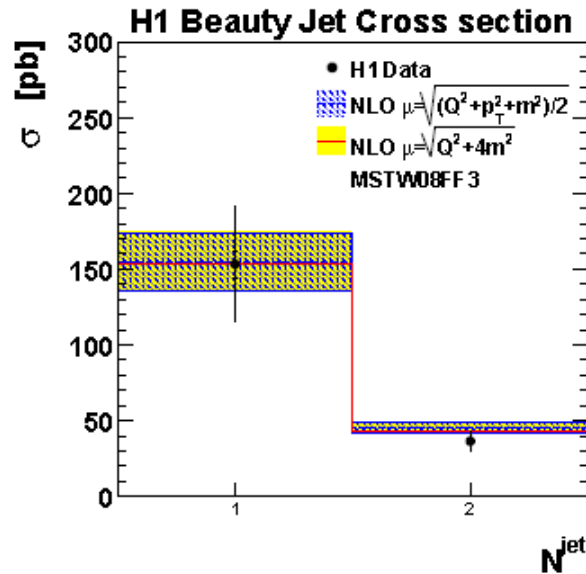
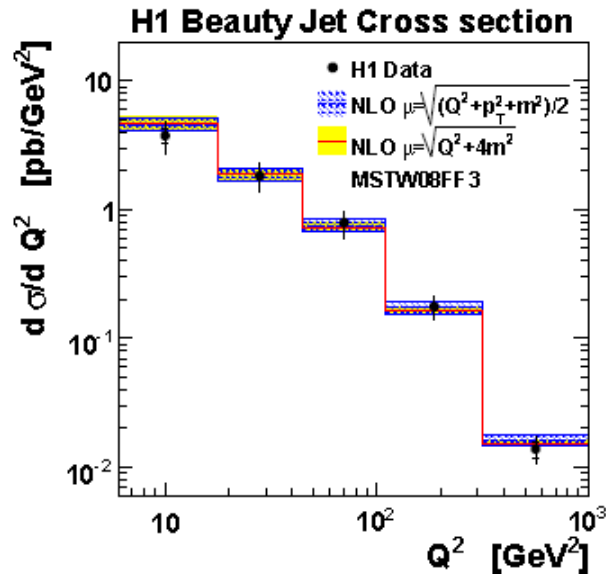
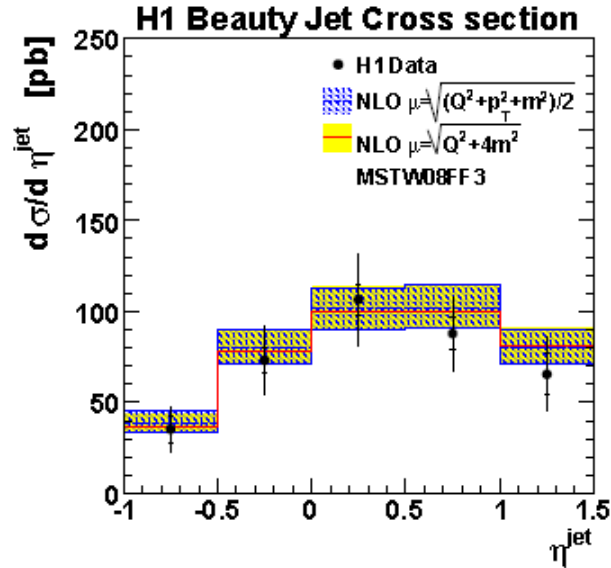
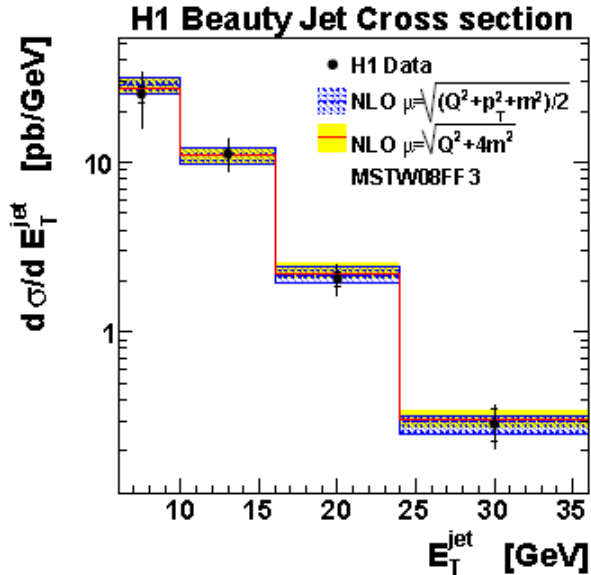
cross section calculation: simultaneous template fits to (S_1, S_2, NN) IN EACH bin



- data: from H1
- theory: HVQDIS (NLO) + hadron level corrections
- scale:
- $Q^2, m_c^2, p_T^2(c)$?
- not uniquely defined ...

- ✓ variations due to the scale choice are as large as the data uncertainties
- ✓ obtain a very good description of the data with the second scale and a significantly worse description with the first scale

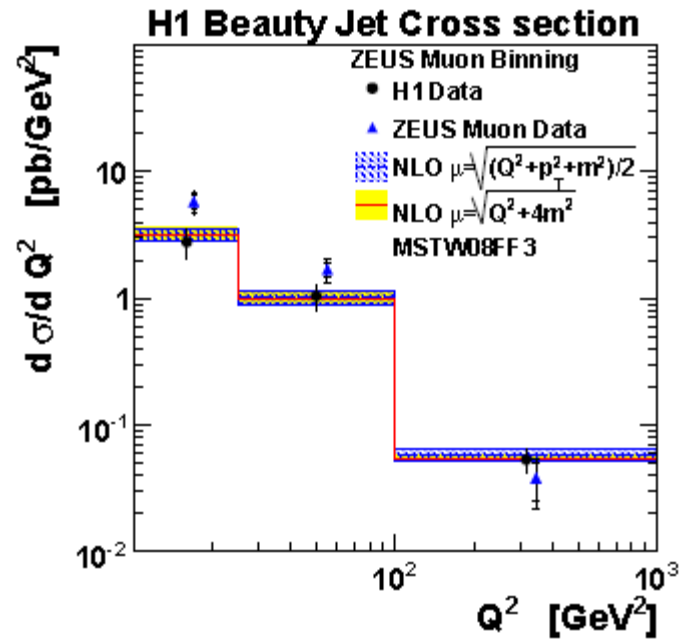
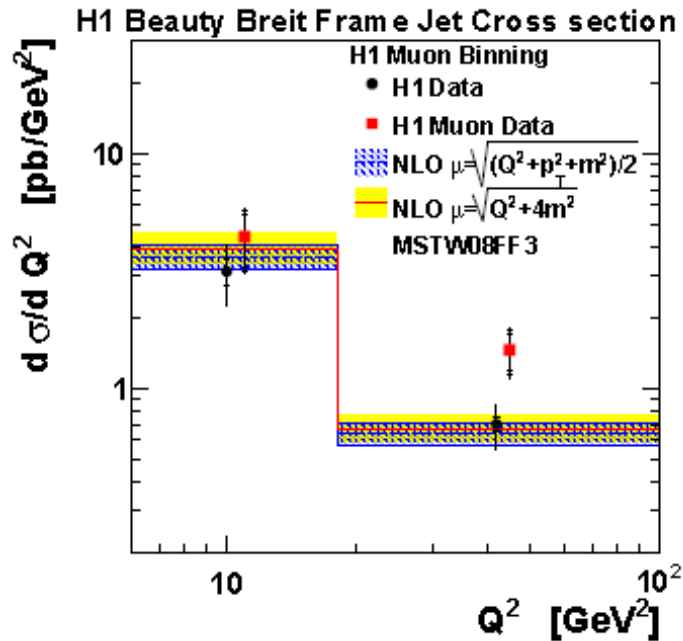
Beauty jet cross section (lab. frame)



- data: from H1
- beauty = 1/20 charm !
- theory: HVQDIS (NLO) + hadron level corrections
- scale:
 - _ $Q^2, m_b^2, p_T^2(b)$?
 - _ not uniquely defined ...

- ✓ effect from the choice of the scale is now small
- ✓ obtain a very good description of the data
- ✓ $m_b > m_c$ seems to play a relevant role also at “large” Q^2 values

Beauty jet cross section: comparison between different tagging techniques



- this measurement: inclusive (all decay modes) beauty tagging using the large lifetime
- other measurements: semileptonic muon beauty decay mode only
- ✓ agreement between different experimental techniques is not overwhelmingly good
- ✓ muon data above inclusive data (probe different phase space)

DIS selection highlights:

- $Q^2 > 10 \text{ GeV}^2$
- $0.05 < y < 0.7$

electron selection highlights:

- $0.9 < p_T^e < 8 \text{ GeV}$
- complementary to muon selections
- $|\eta^e| < 1.5$

lab. frame jet reco. highlights:

- basically as for H1

electron jet association:

- $\Delta R(e, \text{jet}) < 1$

$T = (\text{electron from beauty})$ discriminating test-function variable

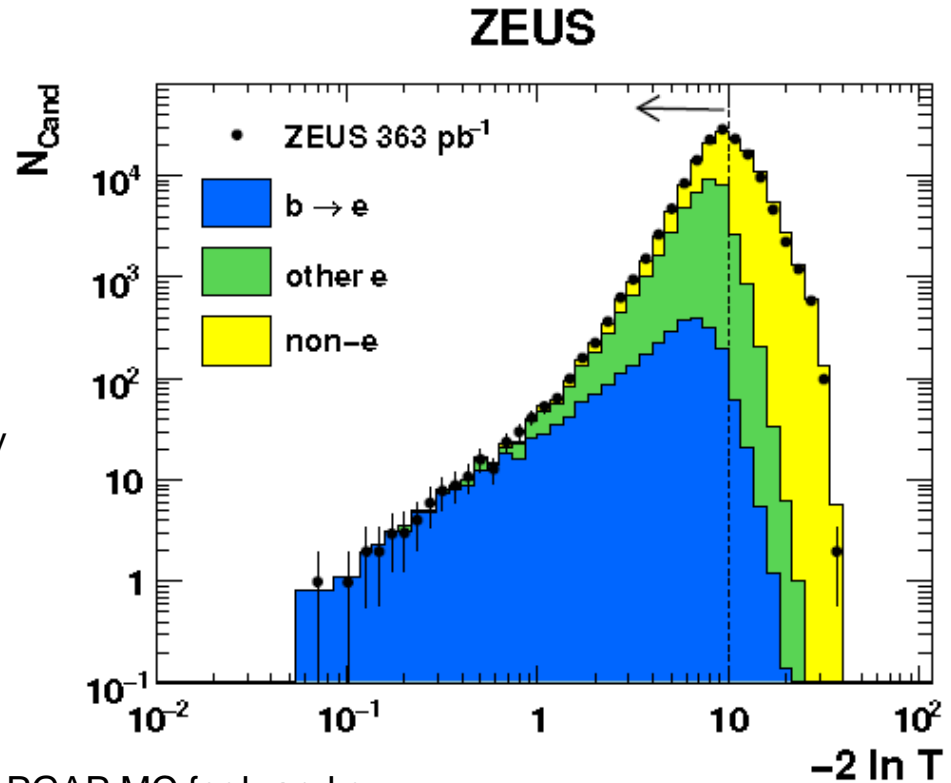
likelihood ratio technique

dE/dx ; $E_{\text{CAL}}/p_{\text{track}}$; d_{cell} (depth of the central energy deposit)

p_T^{rel}

$$\Delta\phi = |\phi(\vec{p}_e) - \phi(\vec{p}_T)|$$

$S = d / \delta d$ (with sign)



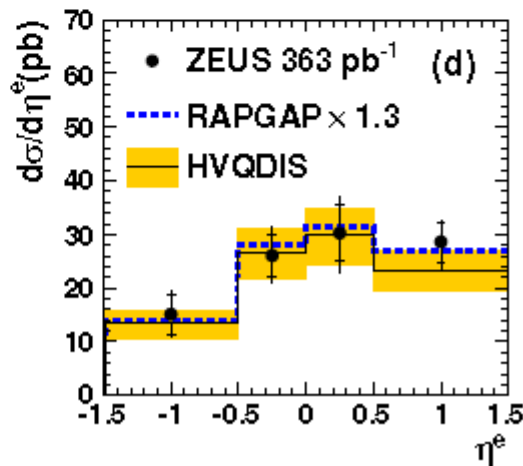
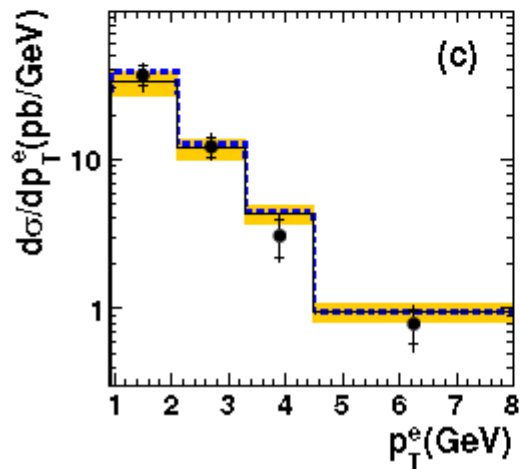
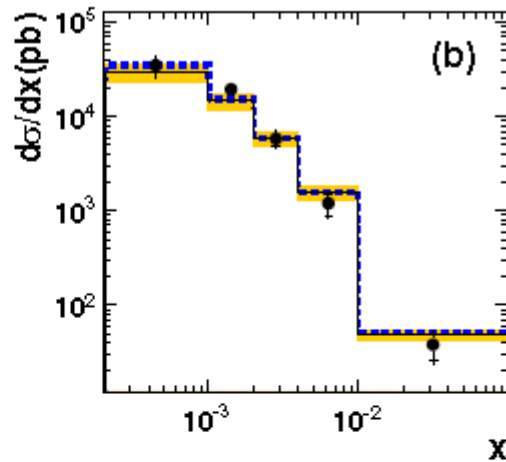
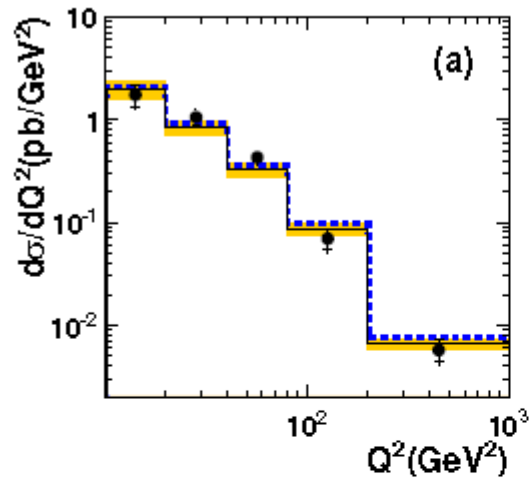
RAPGAP MC for b and c

DJANGO+ARIADNE MC for the inclusive sample

Beauty jet cross section (lab. frame)

cross section calculation: simultaneous template fits to T IN EACH bin

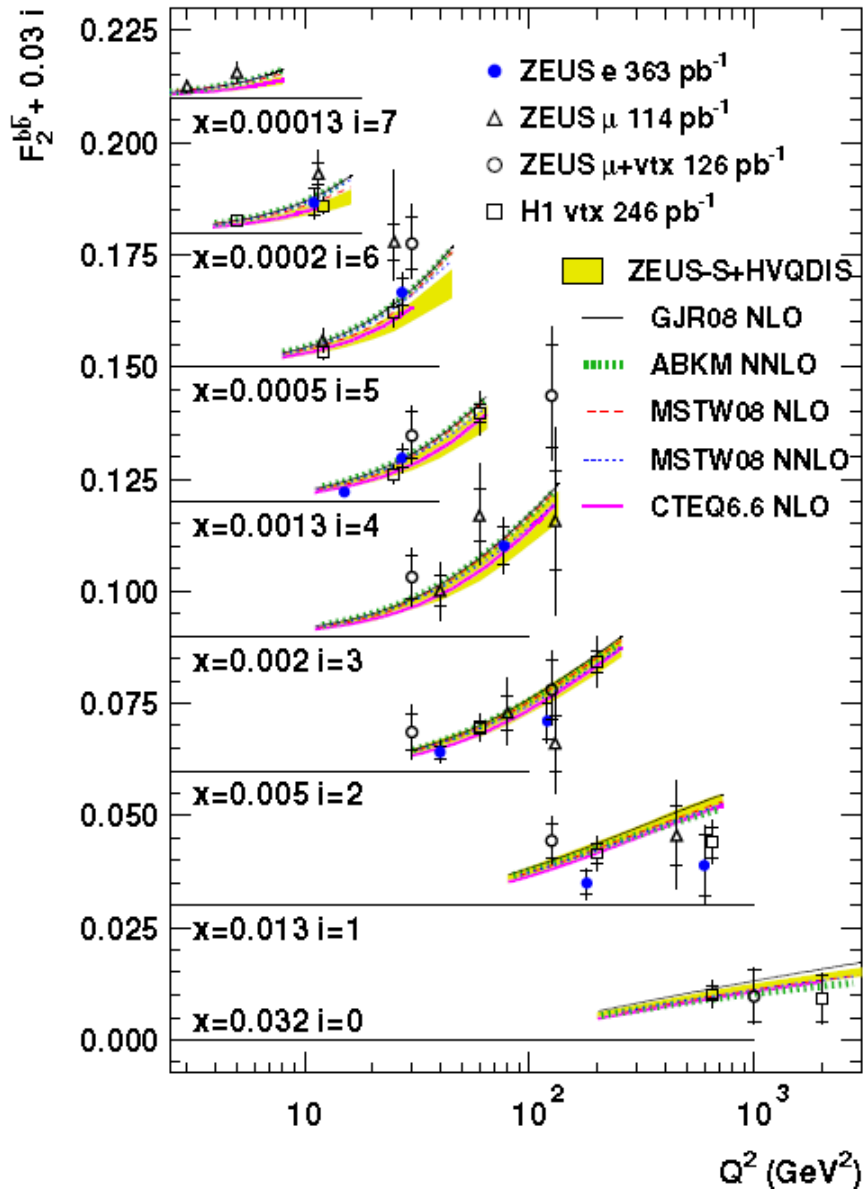
ZEUS



- data: from ZEUS
- theory:
 - RAPGAP MC (LO)
 - HVQDIS (NLO)

- ✓ data and theory have uncertainties of the same size
- ✓ good agreement between data and theory

ZEUS



definition:

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

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

measurement:

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

measure

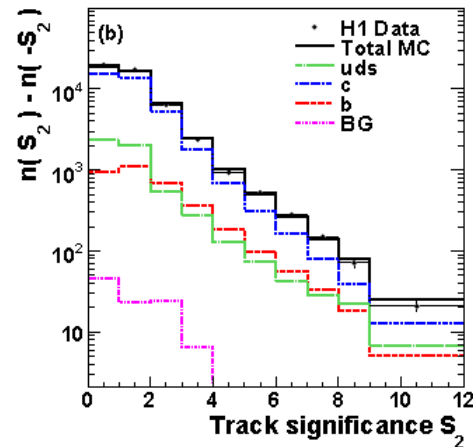
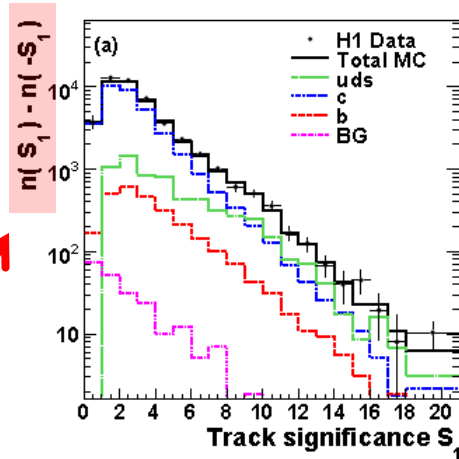
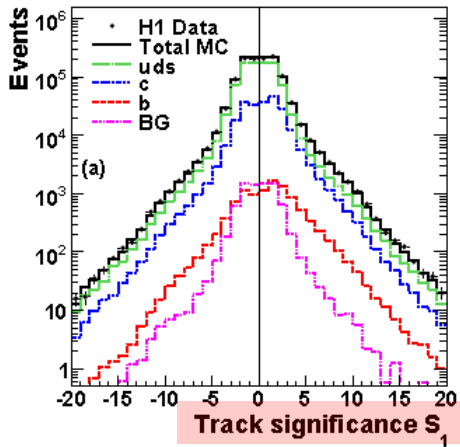
- data: from ZEUS and H1, this b to e analysis is shown in blue
- theory:
 - ZEUS-S NLO pdf fit
 - other popular NLO pdf
 - NNLO predictions also available !
- ✓ different techniques giving the same result !
- ✓ all predictions are rather similar and provide a good description of the data

Conclusions

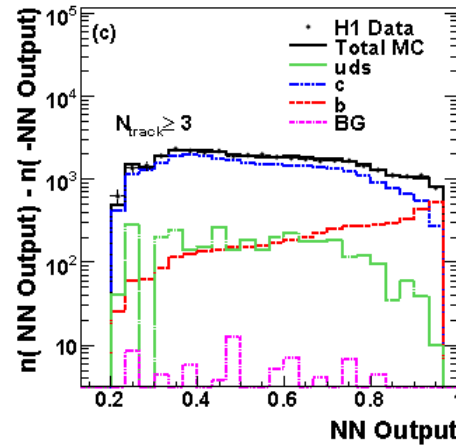
- accurate charm and beauty cross section measurements have been performed by the H1 and ZEUS collaborations
- same measurements are performed using different experimental techniques ... each technique has its own advantages and disadvantages ...
- charm data are significantly more precise than NLO predictions which suffers from large scale variation uncertainties ... **we need NNLO for charm !!!**
- beauty data and NLO predictions are of the same accuracy, data and NLO predictions are in good agreement ... **nice consistency test for QCD !!!**
- have already started to combine:
 - _ different experimental techniques
 - _ H1 and ZEUS resultsto achieve the best accuracy

... backup slides ...

jet flavor separation:

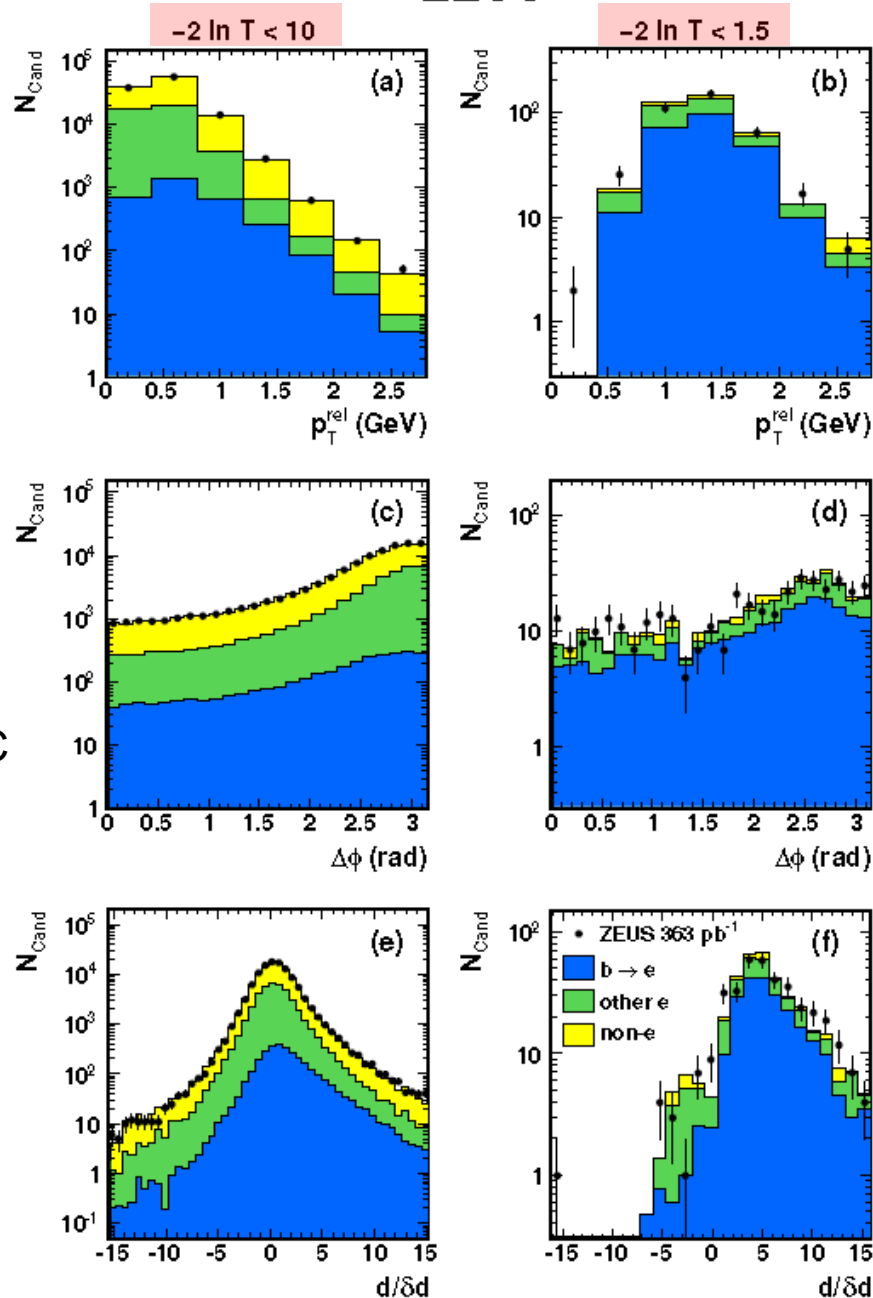


$S_i = \delta_i / \sigma(\delta_i)$
 sign of δ_i for to the relative position of the jet axis vs (DCA – primary vertex) axis in xy
 $S_1 > S_2 > \dots$
 as many as you have tracks in the jet



≥ 3 tracks:
 feed a NN with: S_i $i=1,3$,
 significance of the transverse distance between 1ary and 2ary vtx, max $p_{t,i}$ $i=1,2$,
 number of jet tracks and
 number of 2ary vtx tracks

ZEUS



nominal selection for cross section measurements:
 $-2 \ln T < 10$
 ✓ good agreement between data and MC (mostly inclusive)

harder selection, beauty enriched sample:
 $-2 \ln T < 1.5$
 ✓ good agreement between data and MC (mostly beauty)