Heavy Flavour Production at HERA

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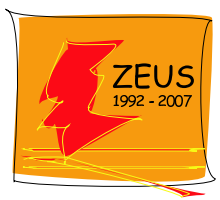


- Introduction
- Charm and beauty in photoproduction
- Charm and beauty in deep inelastic scattering

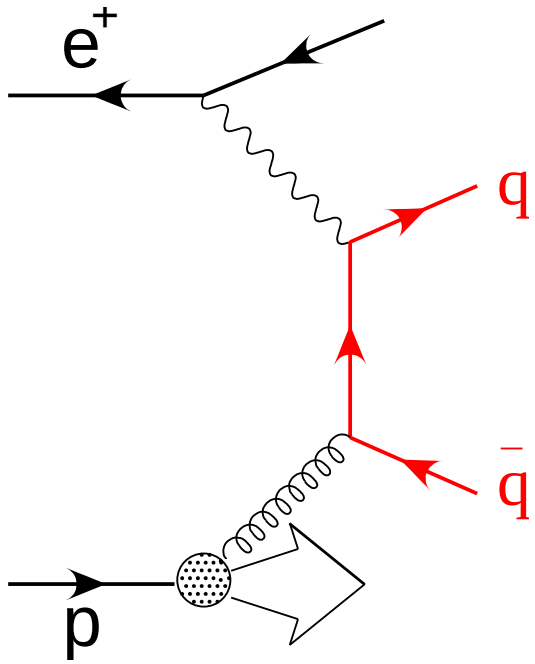
Introduction

Heavy Flavour production provides multiple hard scales:

- large masses m_b, m_c
- high momenta p_T
- four-momentum transfer Q^2

$\longrightarrow$ Should ensure reliable predictions?

$\longrightarrow$ **Test of perturbative QCD**



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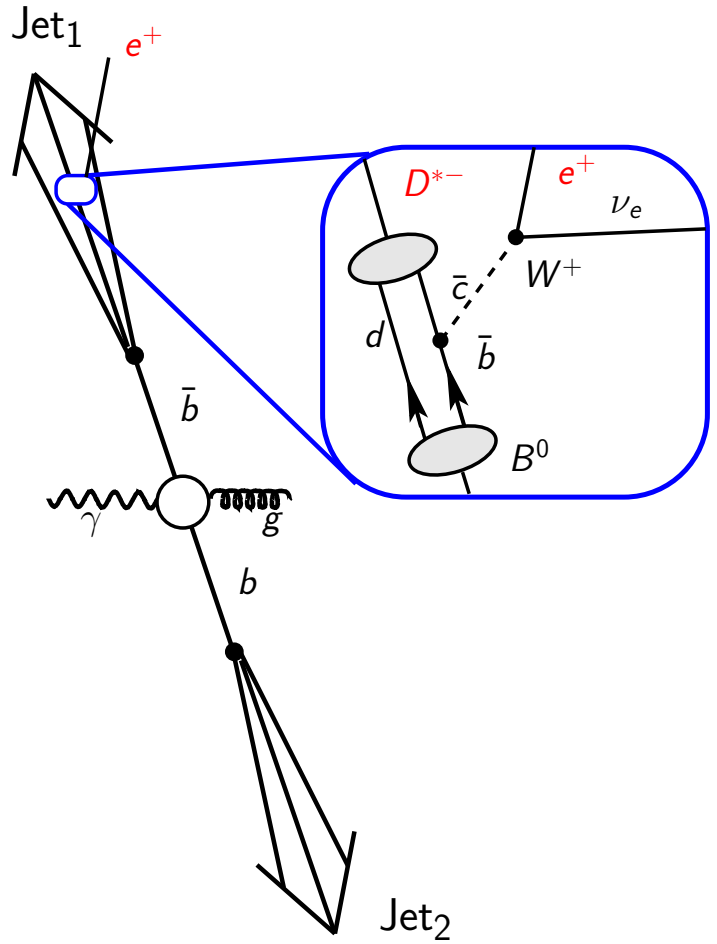
Different experimental techniques to use (combine) for heavy flavour tagging:

- Meson identification
  $D^{*\pm}$ tagging



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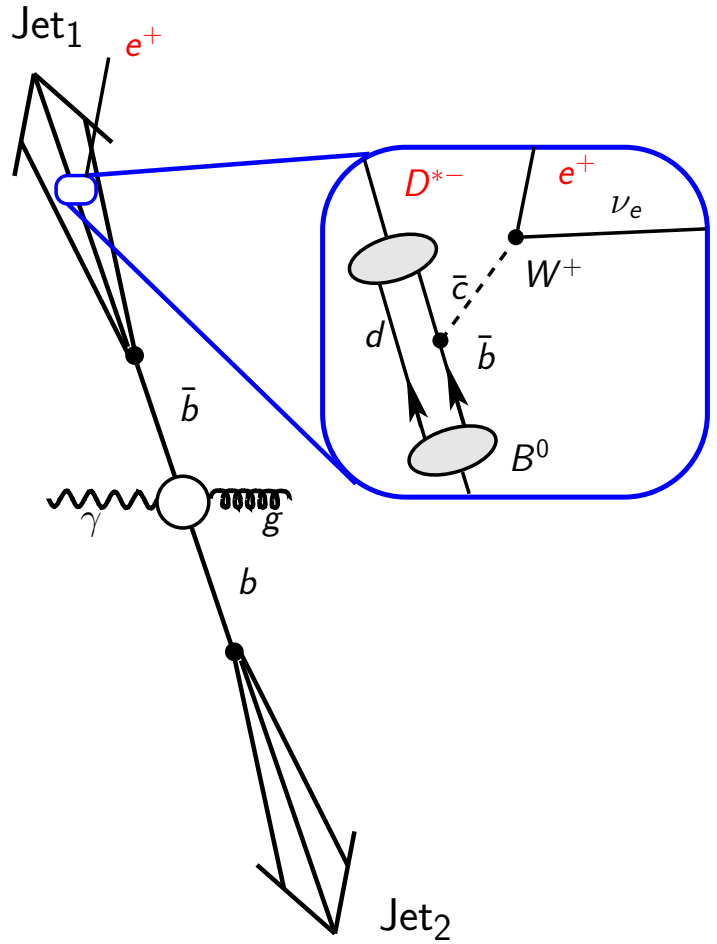
  p_T^{rel} of lepton to jet axis



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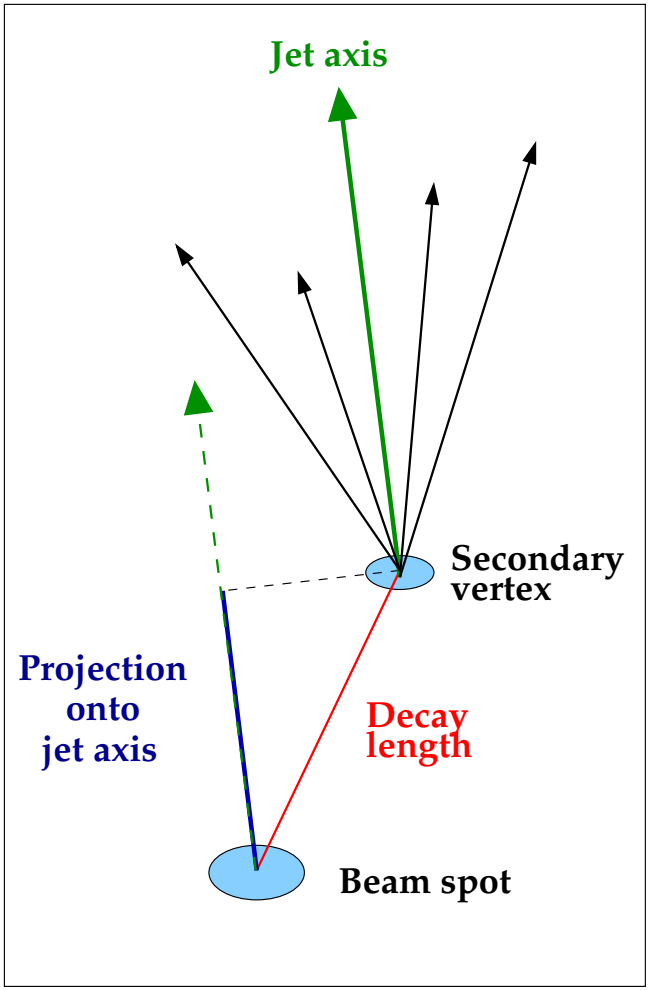
Different experimental techniques to use (combine) for heavy flavour tagging:

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



Charm and beauty in photoproduction

$(Q^2 \approx 0\,\mathrm{GeV}^2)$

Photoproduction of D^* and Jets

H1

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

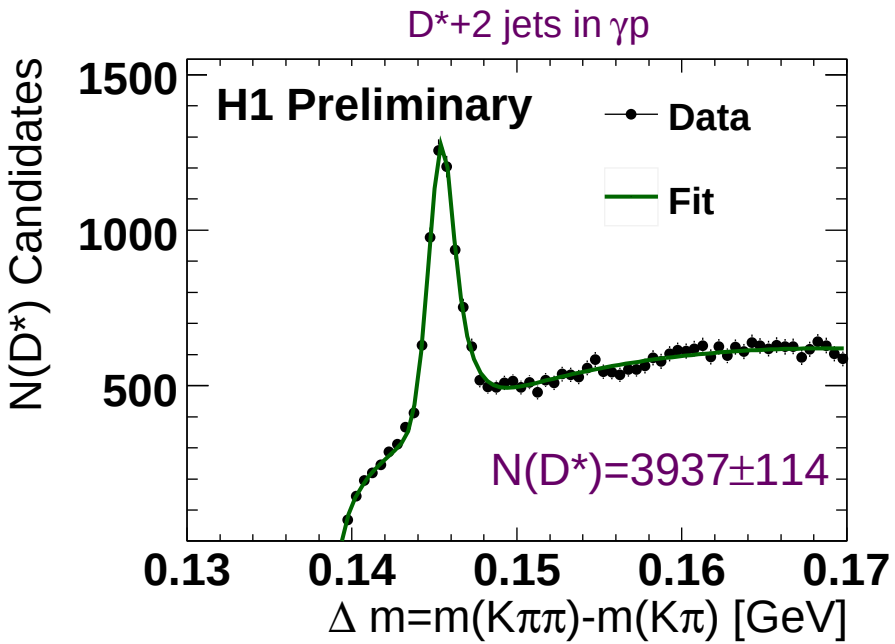
$$D^{*\pm} \rightarrow D^0 \pi^{\pm}_{\text{slow}} \rightarrow K^{\mp}\pi^{\pm}\pi^{\pm}_{\text{slow}}$$

Data: $\mathcal{L} \approx 93\,\text{pb}^{-1}$

Aim

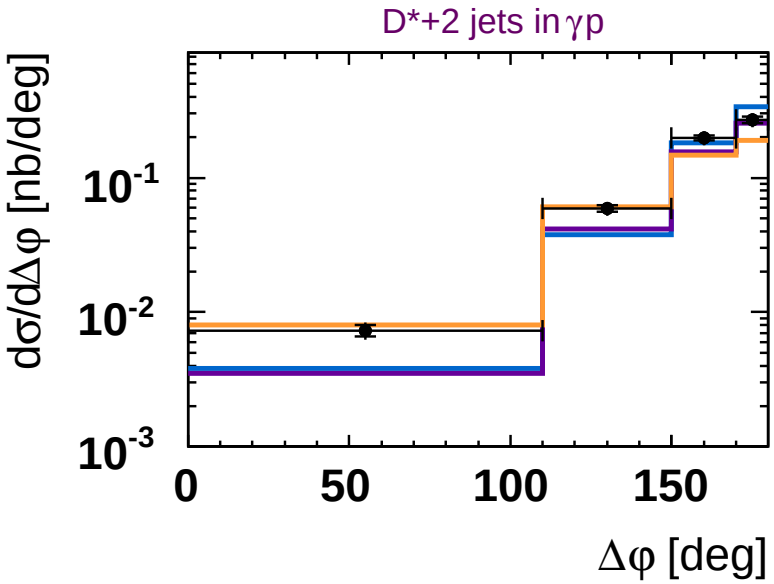
- Study correlations of both quarks by comparing D^* cross sections to different LO+PS and NLO MC models:
  - PYTHIA
  - CASCADE
  - MC@NLO
- Test sensitivity to direct and resolved contributions

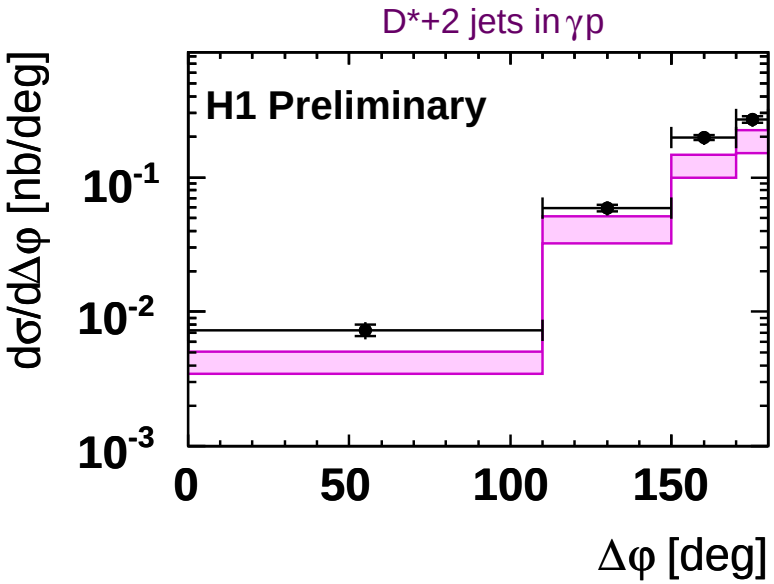
ΔM distribution for determination of number of D^* mesons



Photoproduction of D^* and Jets

H1





H1prelim-10-072

Data (H1 Prel.)

MC@NLO

Pythia Massless

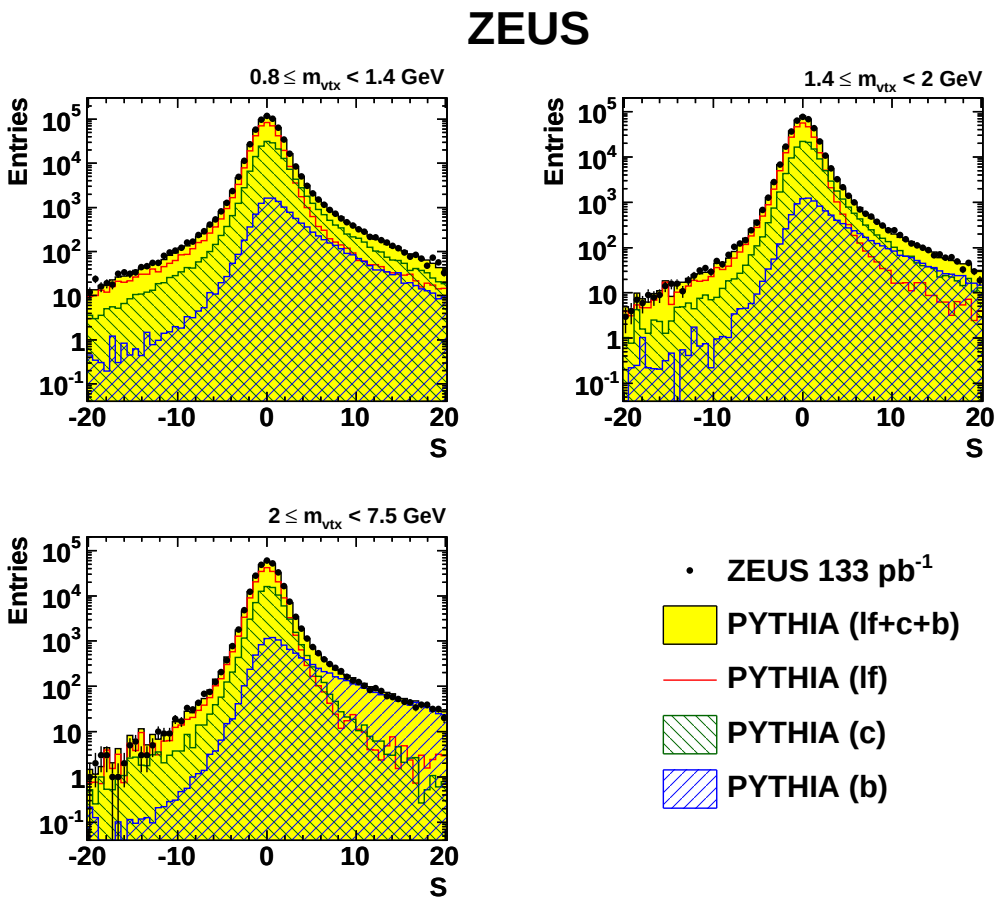
Pythia Massive

Cascade

- Kinematic quantities of the D^* and the jets well reproduced by all MC models (not shown here)
- Both LO+PS MC models fail to describe the data
- MC@NLO predictions below the data, direct contribution reasonably well-described

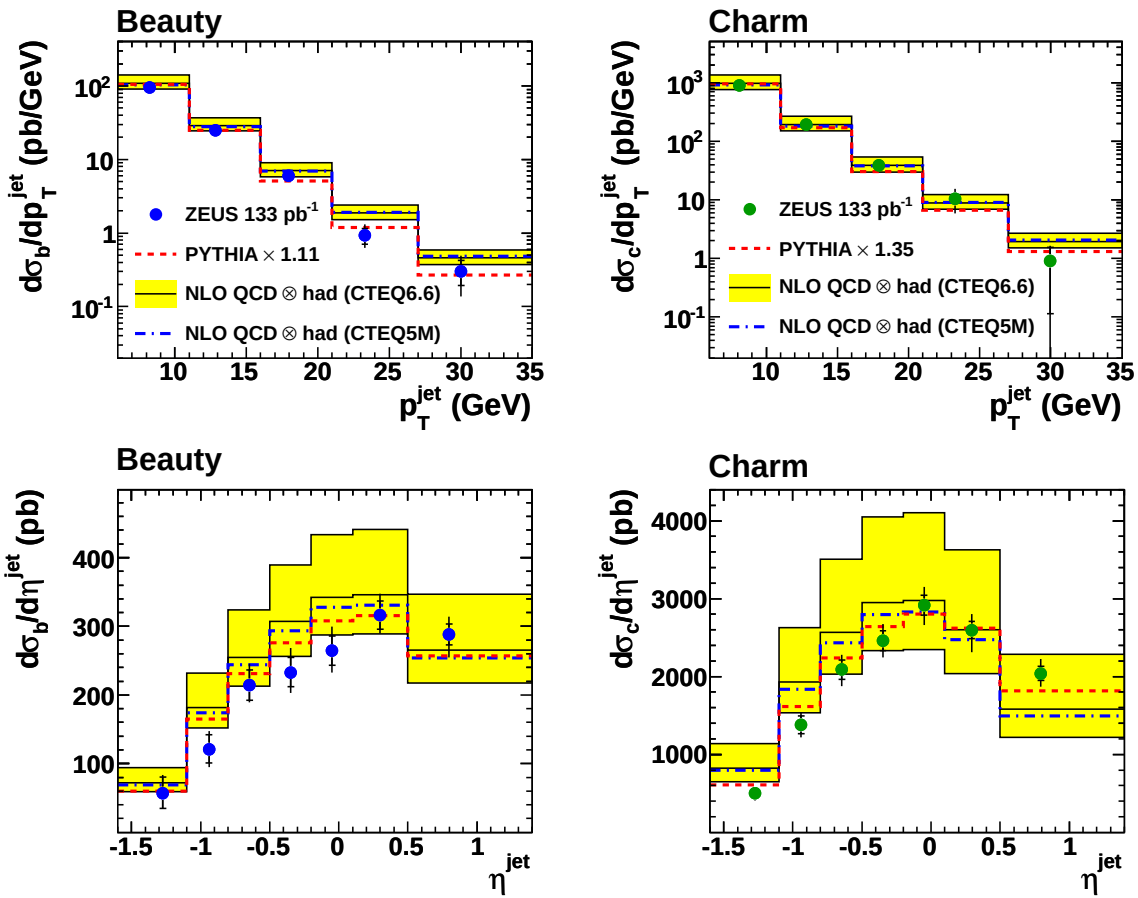
Inclusive heavy-quark jet photoproduction ZEUS

- Data: $\mathcal{L} \approx 130\,\mathrm{pb}^{-1}$
- Dijet PhP events with $p_T^{jet} > 7(6)\,\mathrm{GeV}$
- No specific decay channel $\rightarrow$ Inclusive analysis
- Simultaneous identification of beauty and charm content via reconstruction of secondary vertices

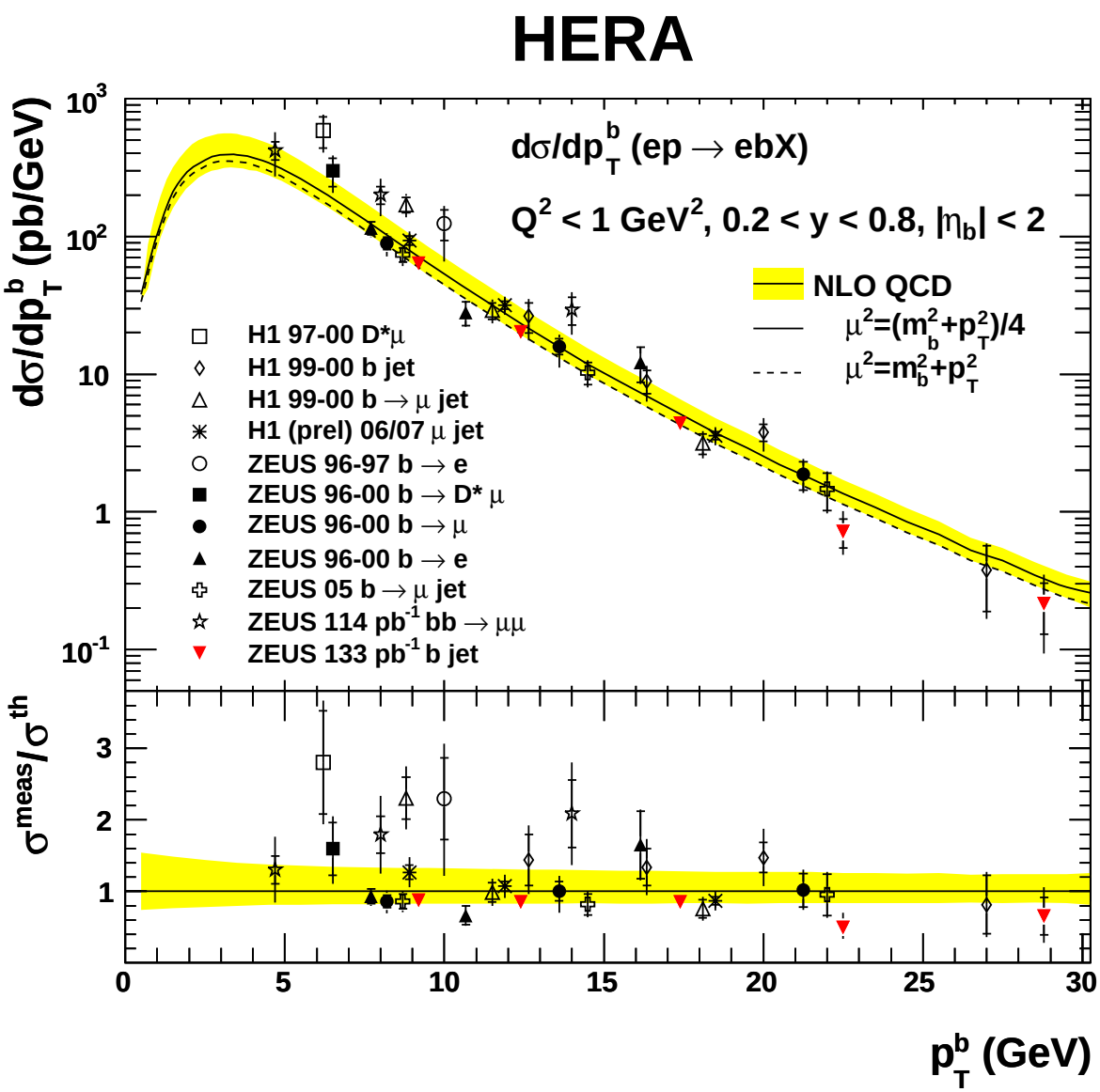


Separation variables: Decay-length significance $S = DL/\delta DL$ and invariant mass of sec. vertex tracks, m_{vtx}

To be submitted to EPJ C



- Differential cross sections as a function of p_T^{Jet} and η^{Jet}
- Good agreement between Data and PYTHIA / NLO (FMNR)



- Consistent picture of *b*-quark production at HERA over wide kinematic range
- Discussed measurement represents the most precise *b* in PhP measurement at HERA

Charm and beauty in deep inelastic scattering

$(Q^2 \gg 0\,\mathrm{GeV}^2)$

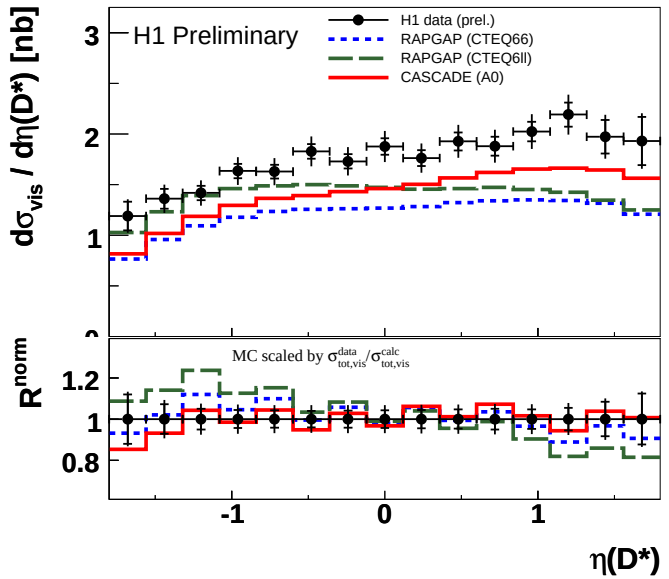
H1prelim-10-172

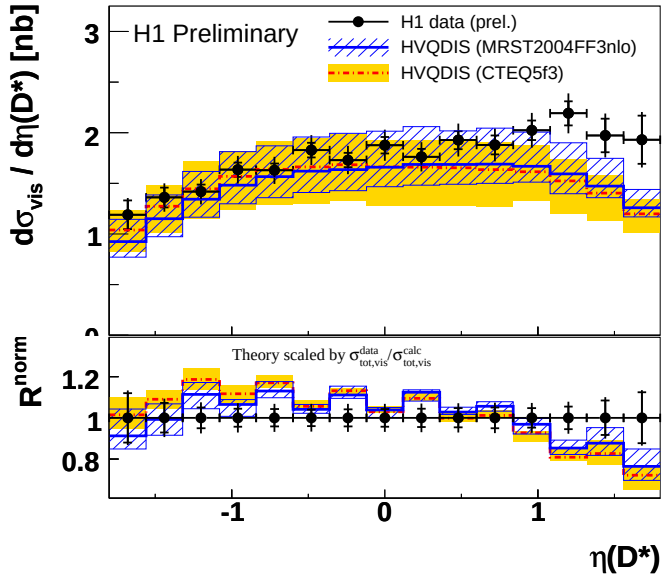
Charm quark tagged through reconstruction of a D^* meson
$D^{*\pm} \rightarrow D^0 \pi^{\pm}_{\text{slow}} \rightarrow K^{\mp}\pi^{\pm}\pi^{\pm}_{\text{slow}}$

Kinematics $\mathcal{L} \approx 350\,\text{pb}^{-1}$

- $5\,\text{GeV}^2 < Q^2 < 100\,\text{GeV}^2$
- $p_T(D^*) > 1.25\,\text{GeV}$
- $|\eta(D^*)| < 1.8$

- Differential cross sections as a function of $\eta(D^*)$
- General agreement with LO (in shape) and NLO predictions except for forward η region





$D^{\pm}$ production and $F_2^{c\bar{c}}$

ZEUS

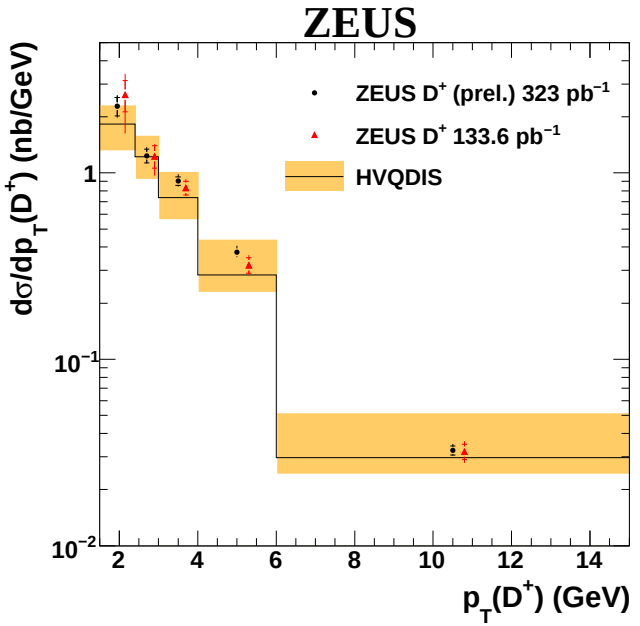
Charm quark tagged through reconstruction of a $D^{\pm}$ meson
$D^{\pm} \to K^{\mp}\pi^{\pm}\pi^{\pm}$

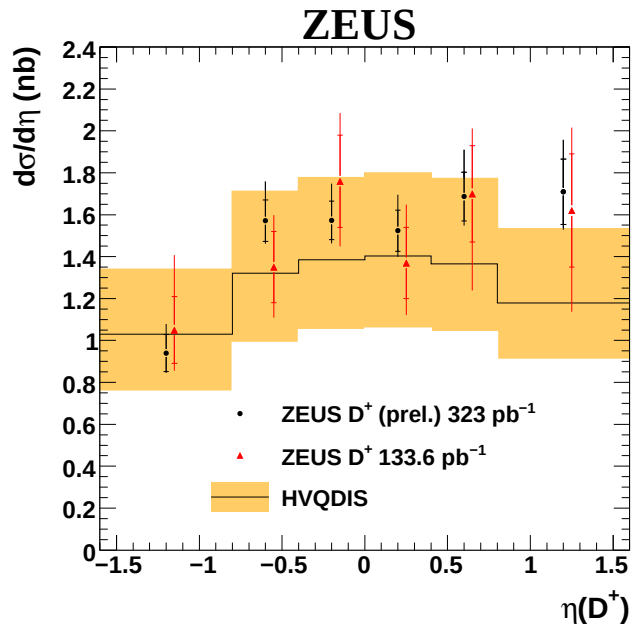
Purity of the D meson signal increased by including lifetime information

Kinematics $\mathcal{L} \approx 320\,\mathrm{pb}^{-1}$

- $5\,\mathrm{GeV}^2 < Q^2 < 1000\,\mathrm{GeV}^2$
- $1.5\,\mathrm{GeV} < p_T(D^{\pm}) < 15\,\mathrm{GeV}$
- $|\eta(D^{\pm})| < 1.6$

Improved precision with respect to previous measurement and good agreement with NLO prediction





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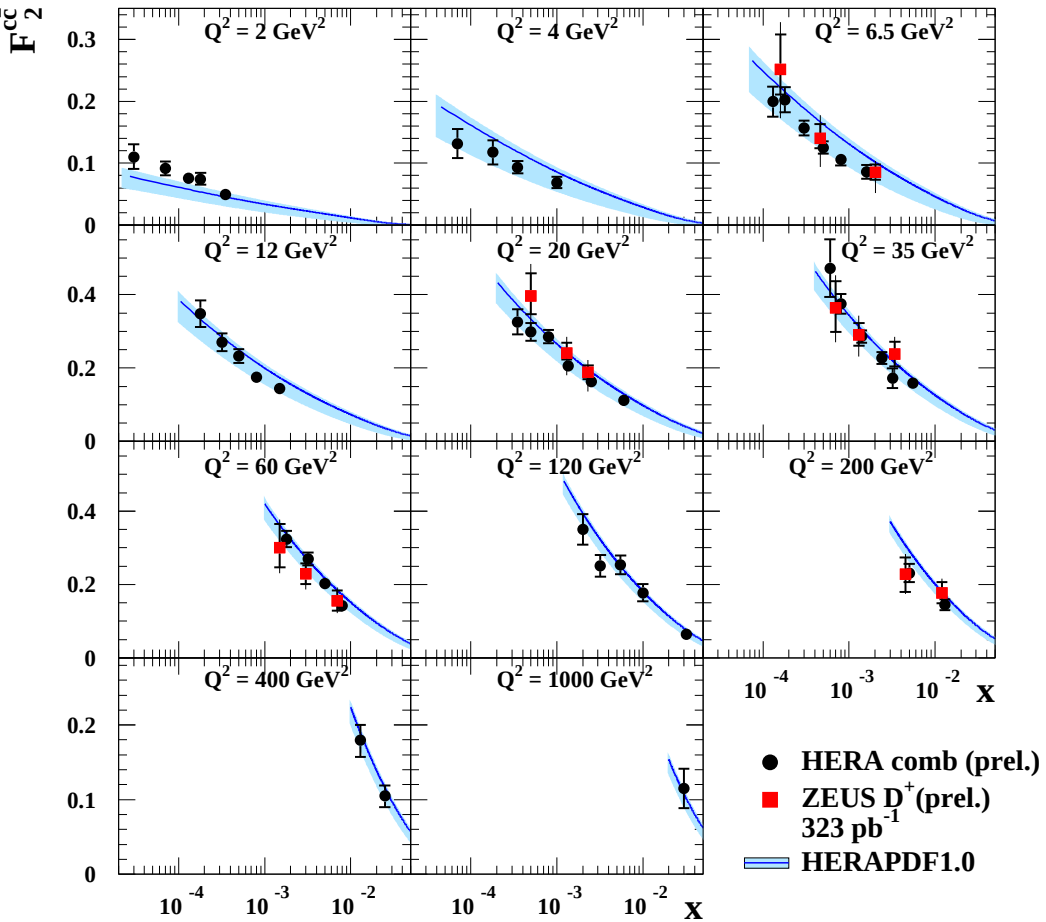
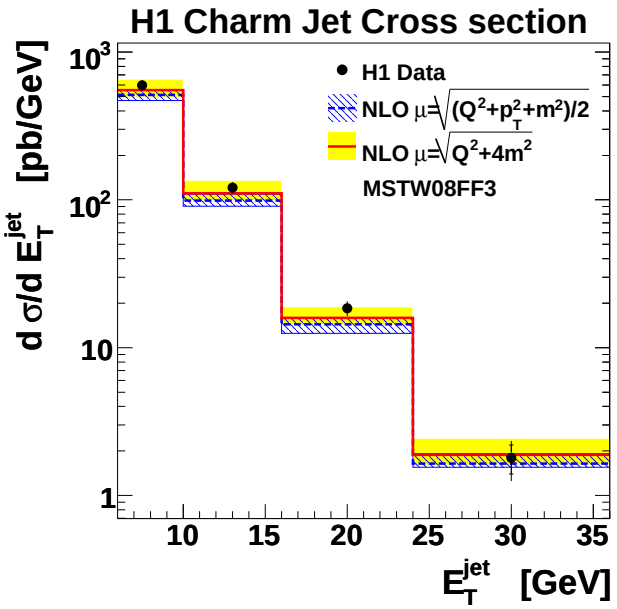


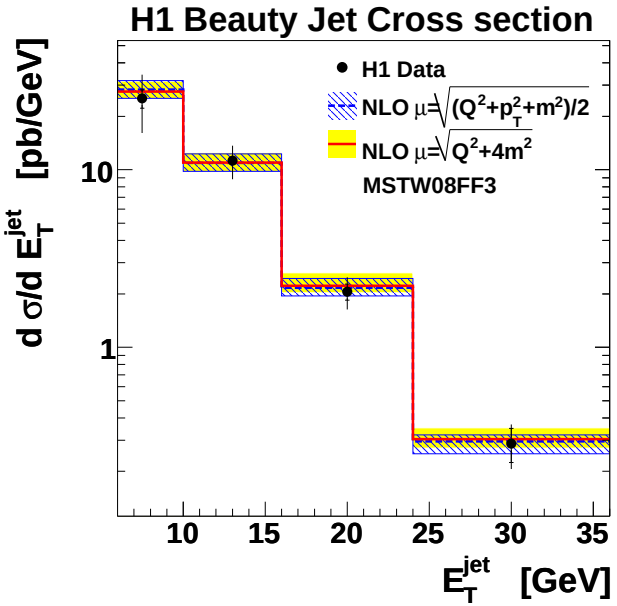
- Differential cross sections
  $\longrightarrow$ Good agreement with NLO prediction
- Double-differential cross sections as a function of x and Q^2 (not shown here)
- Extraction of $F_2^{c\bar{c}}$ and comparison with ZEUS-H1 combined results
  $\longrightarrow$ Good agreement between measurements and with NLO predictions

DESY-10-083

- $\mathcal{L} \approx 190\,\mathrm{pb}^{-1}$
- $E_T^{\mathrm{jet}} > 6\,\mathrm{GeV}$ and $-1.0 < \eta^{\mathrm{jet}} < 1.5$
- Identification of heavy quarks through properties of tracks associated to jets
- Use of several variables providing lifetime information
- Extraction of heavy-quark content through simultaneous fit

- Charm and beauty jet cross sections as a function of E_T^{jet}
- Comparison with NLO predictions shows good agreement with little dependence on scale parametrisation



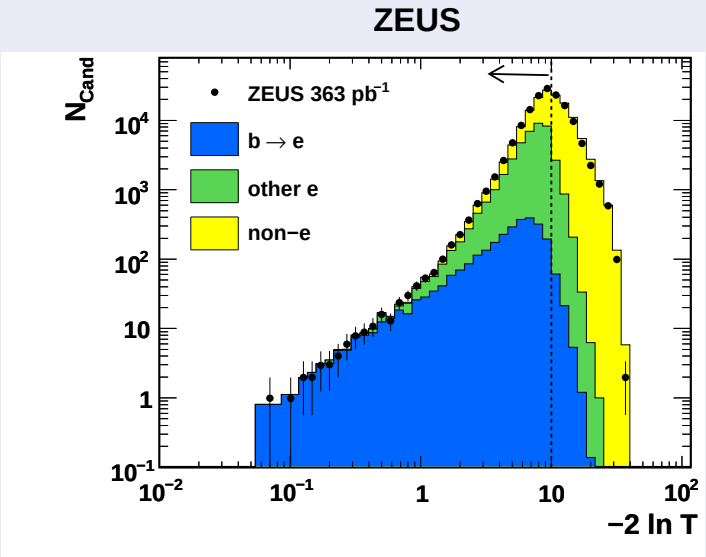


Beauty production in DIS and $F_2^{b\bar{b}}$

ZEUS

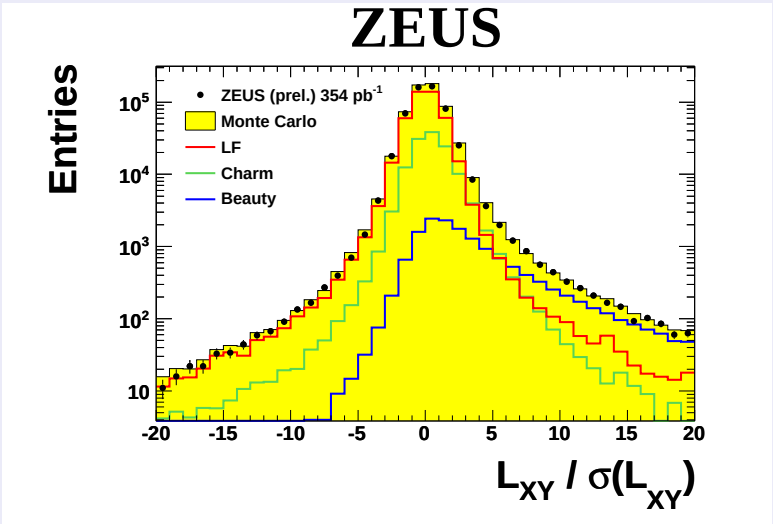
Exclusive: $b \rightarrow e$

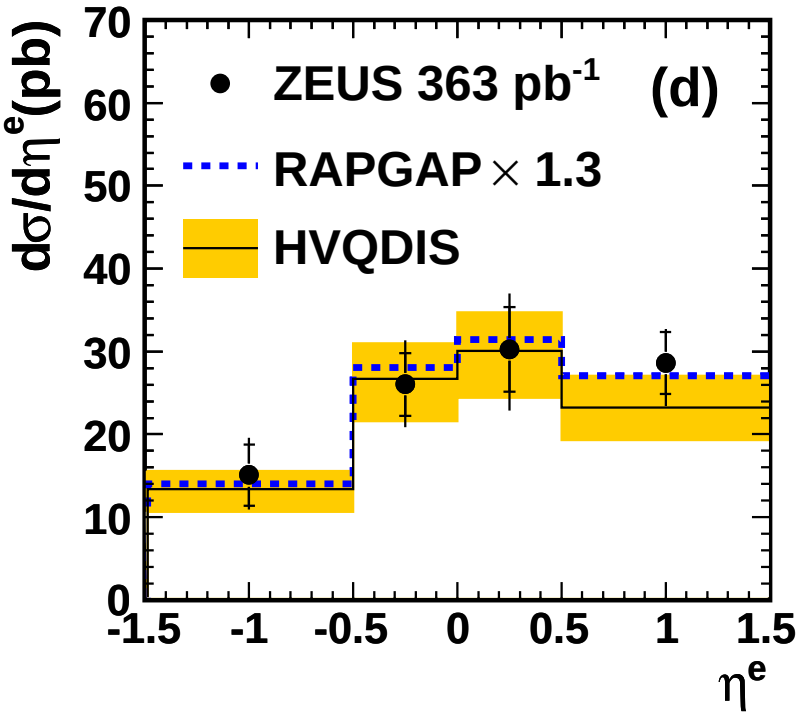
- Extraction of beauty content from semileptonic decays into electrons
- Separation variables:
  - p_T^{rel}
  - $\Delta\phi$ between p_T^{miss} and electron
  - Decay-length significance
- Combination in likelihood test function and fit of MC templates

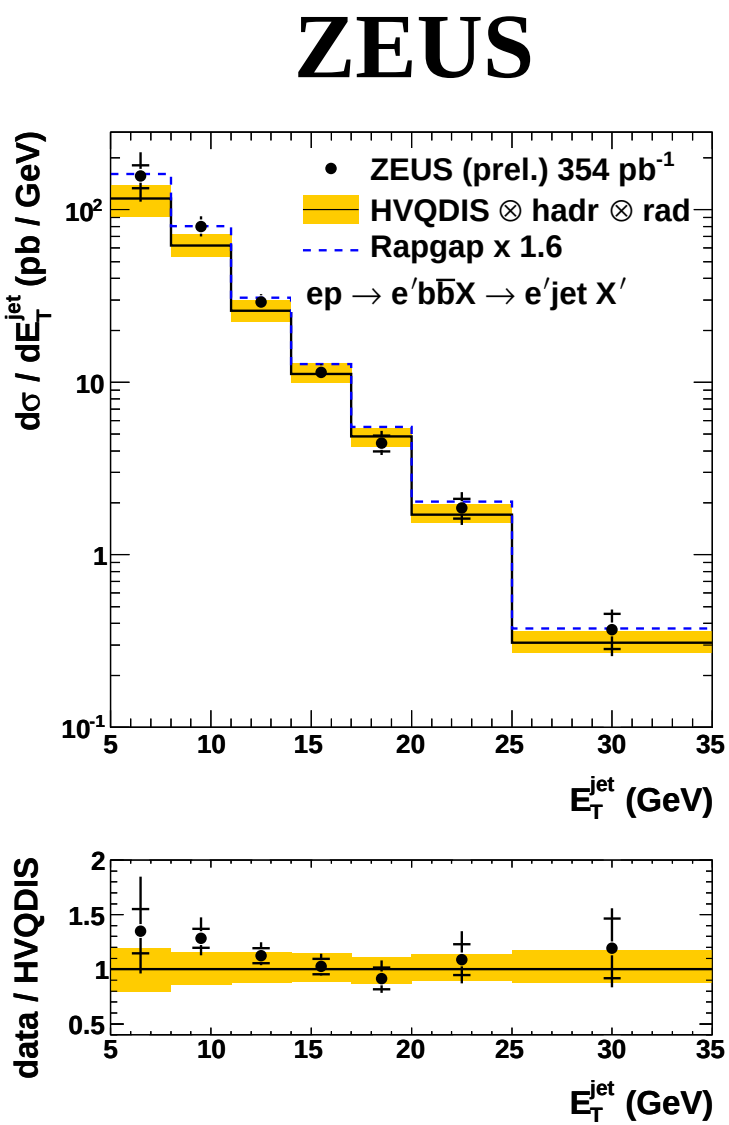


Inclusive measurement

- Extraction of beauty (charm) content through reconstruction of decay vertices
- Separation variables:
  - Decay-length significance
  - Invariant sec. vertex mass
- χ^2 fit of MC templates to data



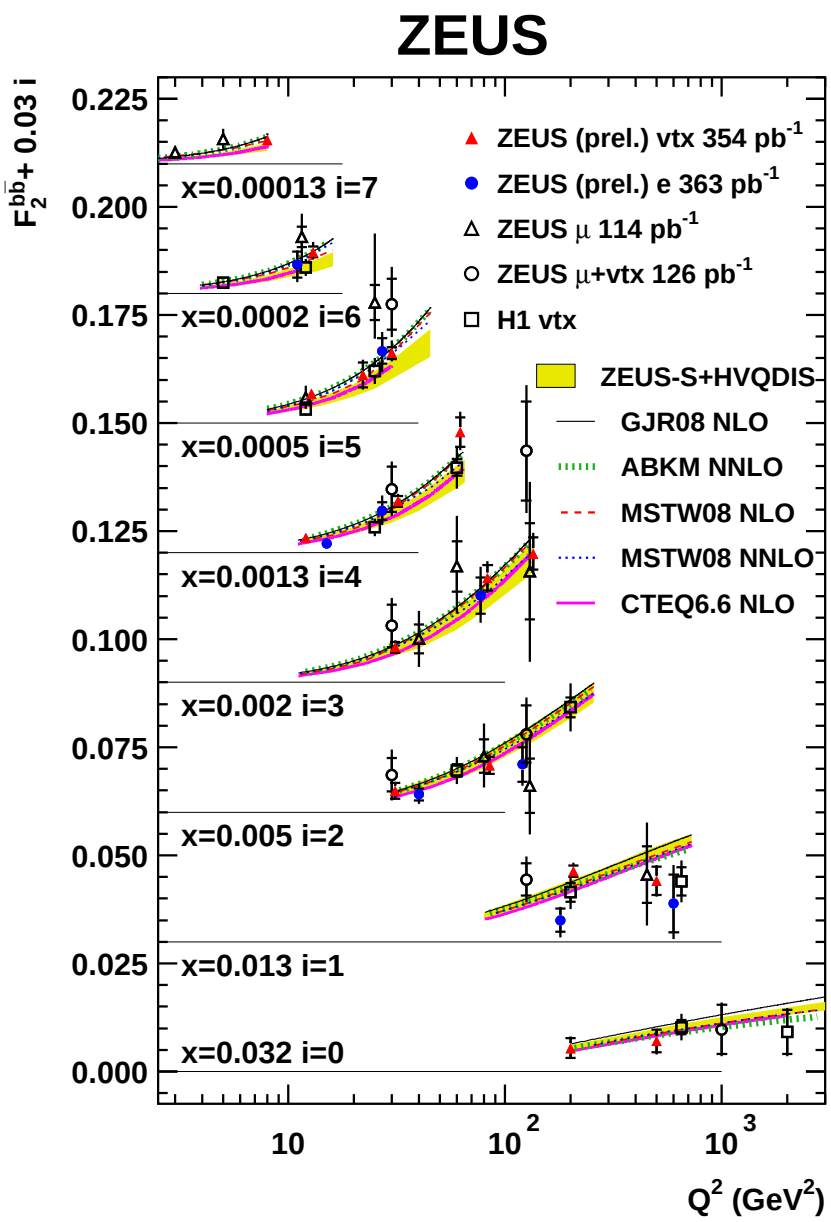




Good agreement with NLO predictions

Beauty production in DIS and $F_2^{b\bar{b}}$

ZEUS



DESY-11-005
ZEUS-prel-10-004

- Double-differential cross sections as a function of x and Q^2 (not shown here)
- Extraction of $F_2^{b\bar{b}}$ and comparison with other measurements
  $\rightarrow$ Good agreement between measurements and with NLO/NNLO predictions

Summary

- Latest results of heavy flavour production at HERA presented
- Measurements with complete HERA II statistics and well-understood detectors provide best precision

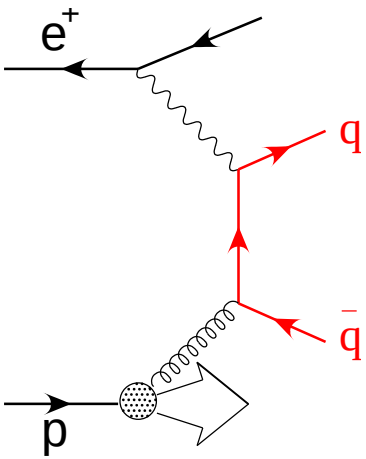
- Various H1 and ZEUS measurements using different experimental techniques in very good agreement
- General agreement with NLO QCD predictions

BACKUP

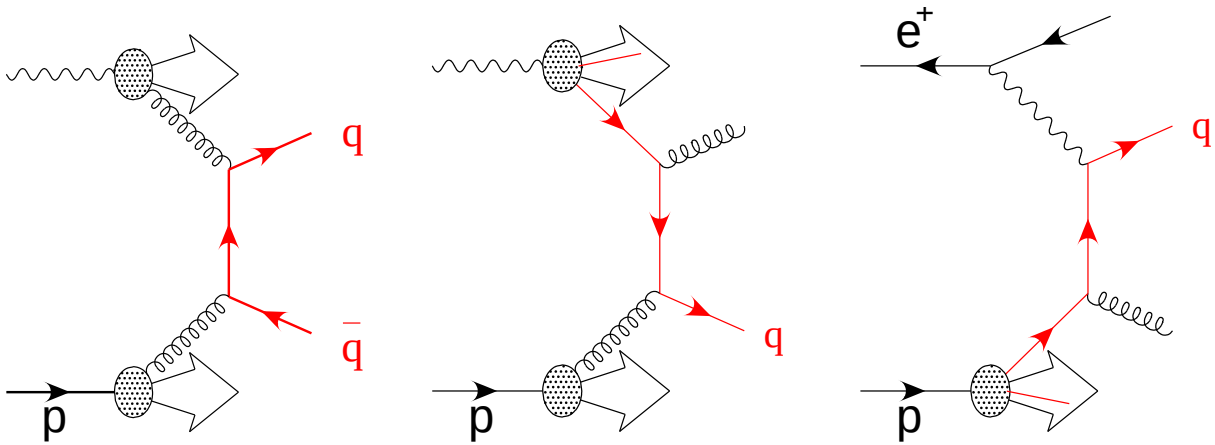
Heavy Flavour Production Mechanism

Dominant process: Boson-gluon fusion

"direct"



"resolved" (including flavour excitation)

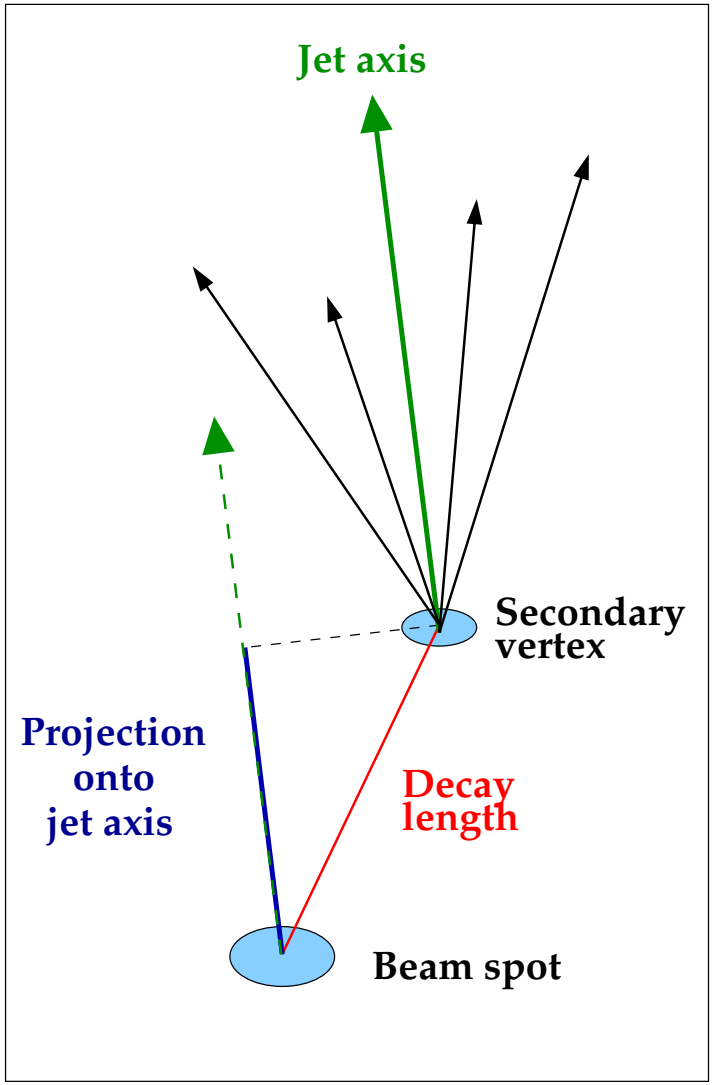


LO and NLO MC models

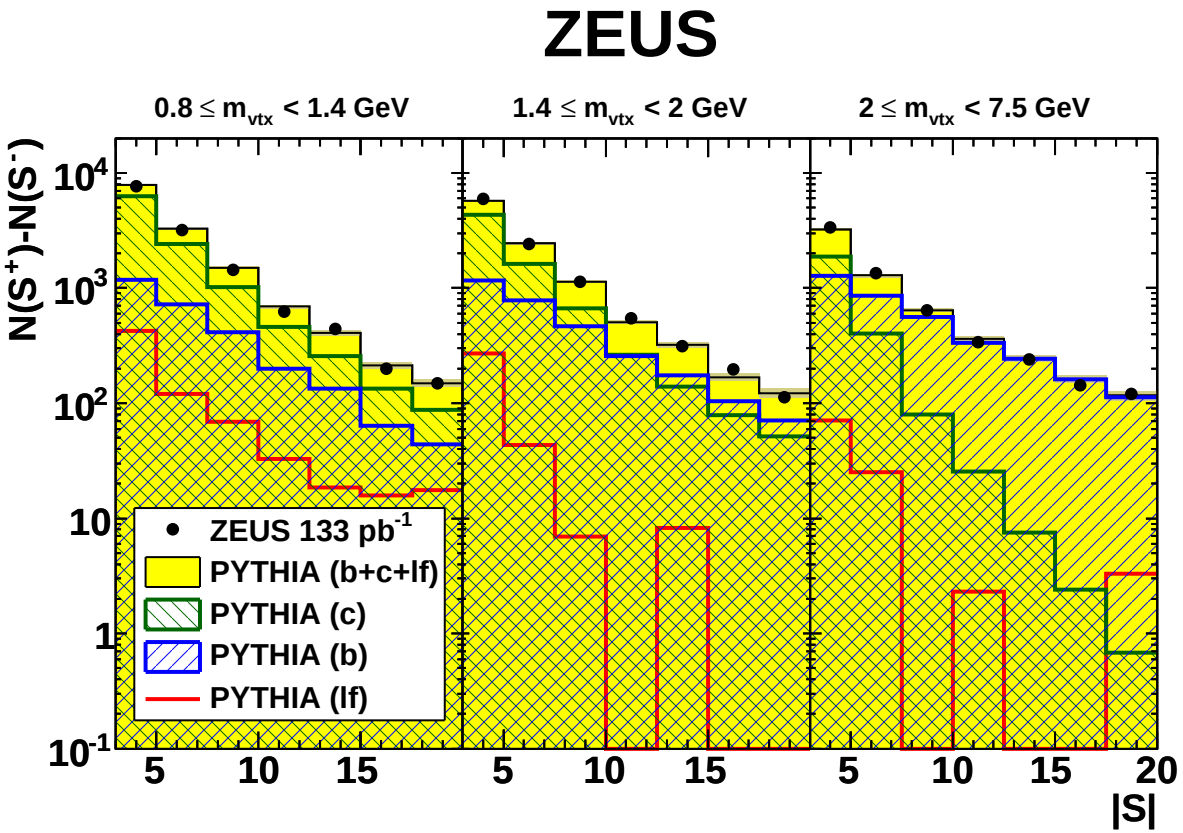
- **PYTHIA:**
  PS according to DGLAP evolution equations,
  LO matrix elements calculated for massless or massive quarks
- **CASCADE:**
  PS according to CCFM evolution equations
- **RAPGAP:**
  PS according to DGLAP evolution equations
- **MC@NLO:**
  PS according to DGLAP evolution equations,
  NLO matrix elements matched with parton showers

Data: $\mathcal{L} = 133\,\mathrm{pb}^{-1}$

- Dijet PhP events with $p_T^{jet} > 7(6)\,\mathrm{GeV}$
- No specific decay channel
  $\rightarrow$ Inclusive measurement
- Secondary vertexing:
  - Associate tracks to jets and fit secondary vertices
  - Calculate 2D decay length as distance between beam spot and secondary vertex in x-y (projected onto jet axis)

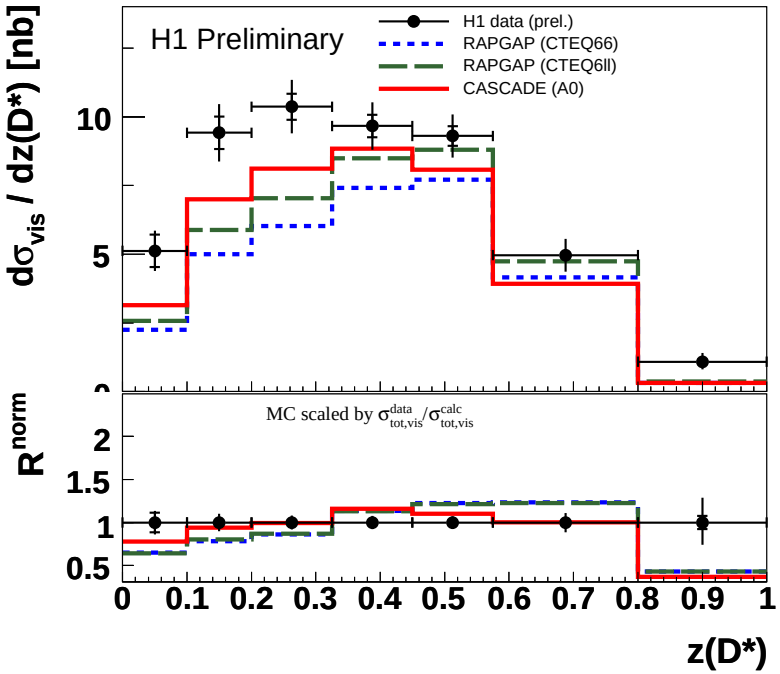


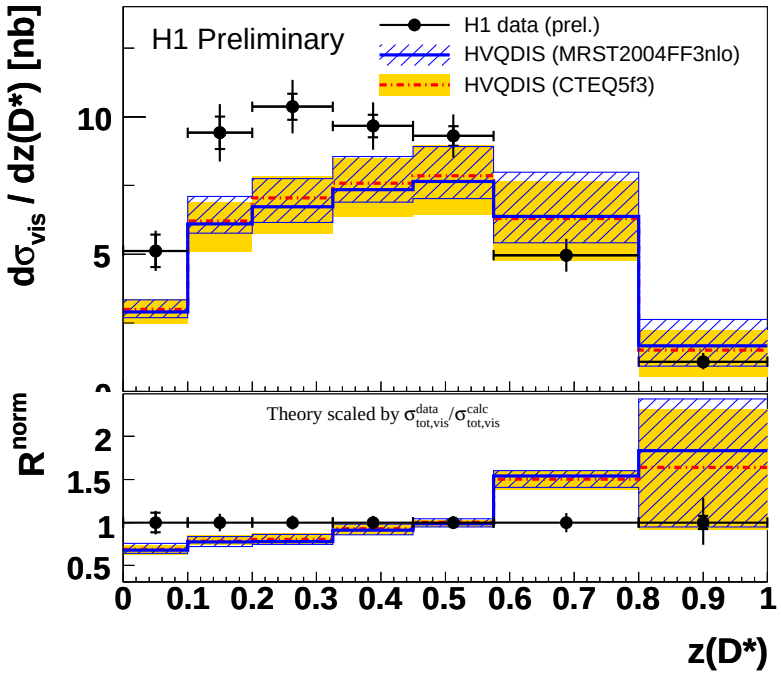
Mirrored decay-length significance in m_{vtx} bins:



D^* production at low Q^2

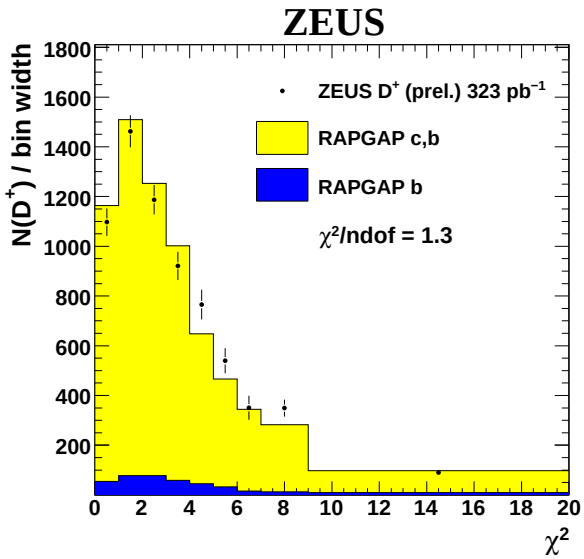
H1

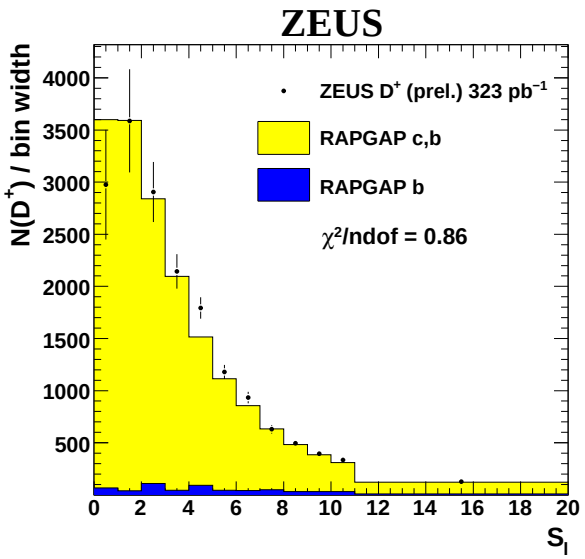


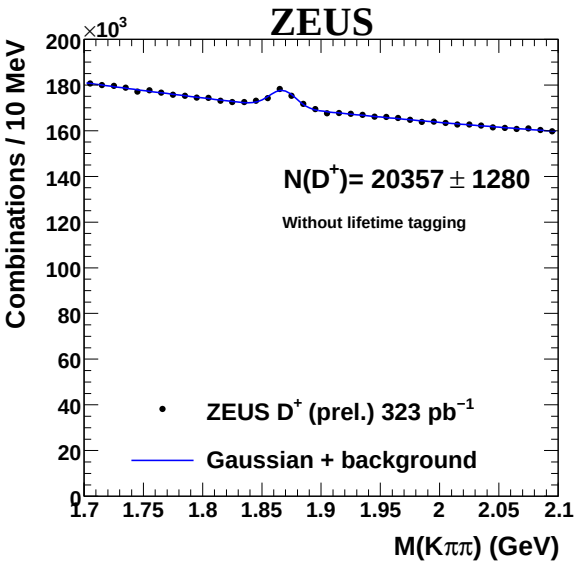


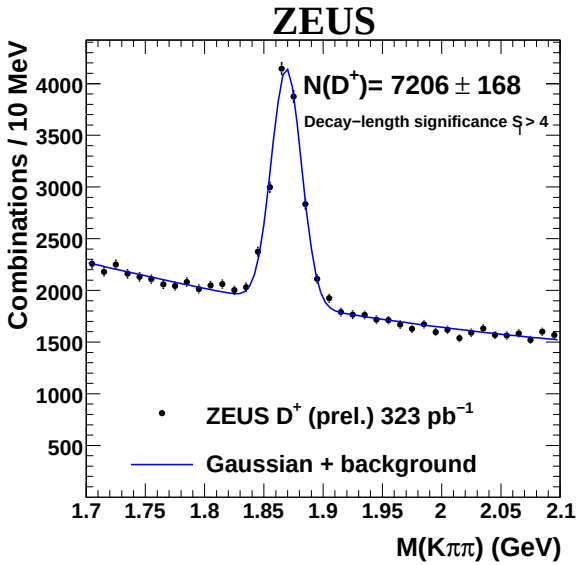
$$R^{\text{norm}} = \frac{1/\sigma^{\text{calc}}_{tot,vis} \cdot \frac{d\sigma^{\text{calc}}}{dQ^2}}{1/\sigma^{\text{data}}_{tot,vis} \cdot \frac{d\sigma^{\text{data}}}{dQ^2}}$$

- Diff. cross sections as a function of the fragmentation variable z
- Shape fairly well modelled by CASCADE
- General discrepancies at low z

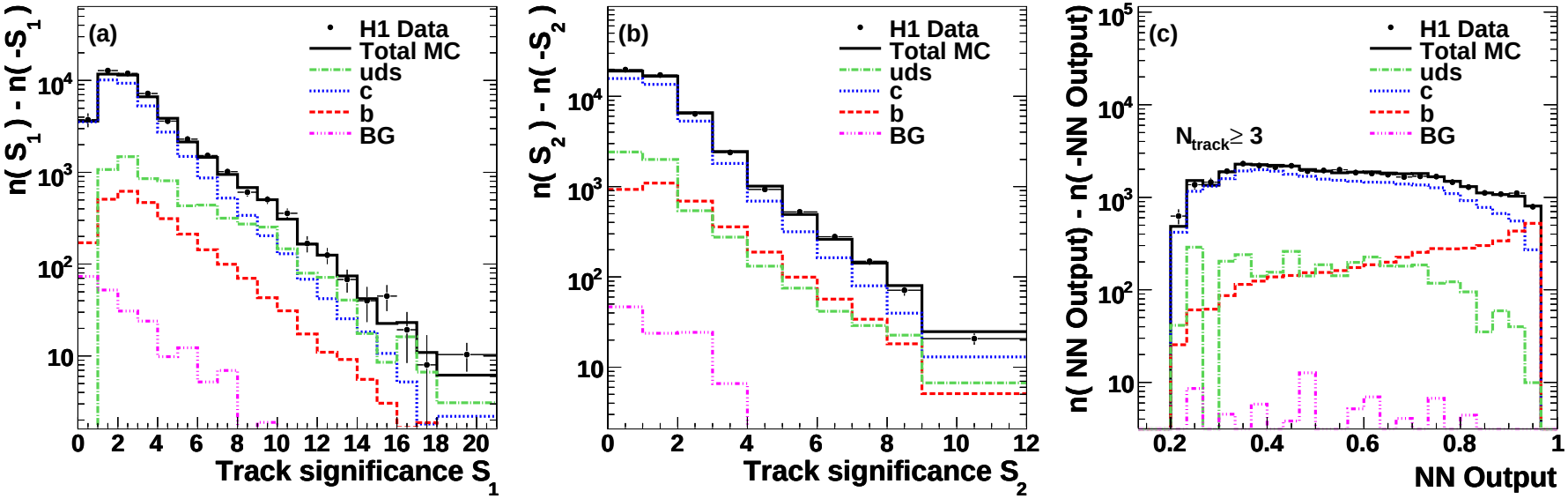








- Control plots for χ^2 and decay-length significance, S_l
- $K\pi\pi$ mass distribution without and with S_l cut



Split data into 3 subsamples:

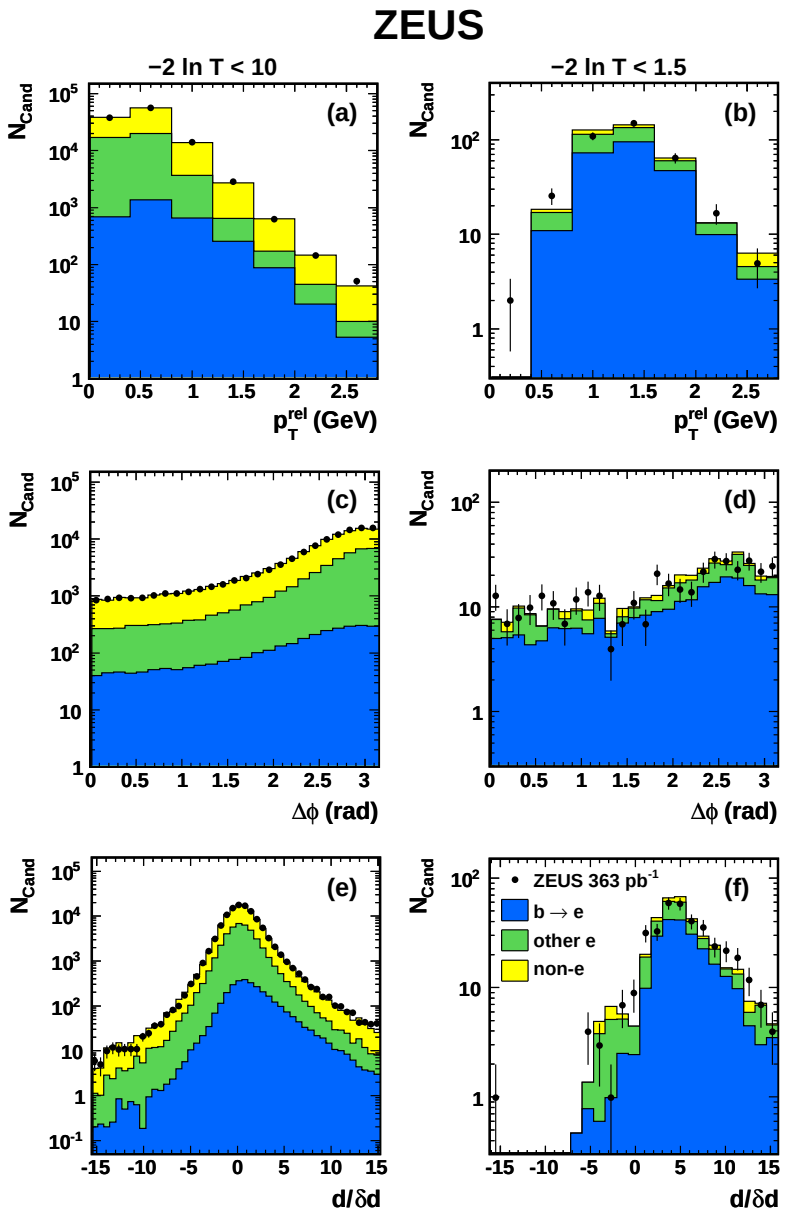
1. Use S_1: $N_{\text{track}} = 1$ or $N_{\text{track}} \geq 2$, S_1 and S_2 have opposite signs
2. Use S_2: $N_{\text{track}} = 2$, S_1 and S_2 have same signs or
   $N_{\text{track}} \geq 3$, S_3 has different sign than S_1, S_2
3. Use NN combining S_1, S_2, S_3 and several track / decay vertex properties:
   $N_{\text{track}} \geq 3$ and S_1, S_2, S_3 have the same sign,
   NN signed according to S_1

Variables for electron identification

- energy loss in the CTD, dE/dx
- $E^{\mathrm{CAL}}/p^{\mathrm{track}}$
- depth of the central energy deposit within the CAL, d_{cell}

Variables for decay identification

- p_T^{rel} w.r.t. jet axis
- $\Delta\phi$ between p_T^{miss} and electron
- Decay-length significance



Definition of $F_2^{b\bar{b}}$ in terms of the inclusive double-differential cross section as a function of the Bjorken scaling variable, x, and the four-momentum transfer, Q^2:

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

with $Y_+ = 1 + (1-y)^2$.
Extraction of $F_2^{b\bar{b}}$ at a reference point in the x–Q^2 plane:

$$F_2^{b\bar{b}}(x,Q^2) = \frac{\mathrm{d}^2\sigma_{b\to e}}{\mathrm{d}x\,\mathrm{d}Q^2} \cdot \frac{F_2^{b\bar{b},\mathrm{NLO}}(x,Q^2)}{\mathrm{d}^2\sigma_{b\to e}^{\mathrm{NLO}}/\mathrm{d}x\,\mathrm{d}Q^2}$$