Beauty Production at HERA

on behalf of the ZEUS and H1 Collaborations

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Outline

- ✓ HERA Collider and ZEUS/H1 detectors
- ✓ Heavy flavour production at HERA
- ✓ Latest beauty results at HERA

(Photoproduction PHP, $Q^2 \approx 0$, and Deep Inelastic Scattering DIS, $Q^2 \geq 1 \text{ GeV}^2$)

F_2^{bb} measurements

- ✓ PHP events with 2 jets + sec.vtx (ZEUS-prel-09-005)
- ✓ PHP events with 2 jets + 1μ (DESY-08-210, by ZEUS Coll.)
- ✓ DIS decays into μ 's (DESY-09-56 by ZEUS Coll.)
- ✓ DIS events using sec.vtx (H1-prel-08-173 by H1 Coll.)

The HERA Collider

HERA delivered

$$\begin{aligned} E_p &= 920 \text{ GeV} \\ E_e &= 27.5 \text{ GeV} \\ \sqrt{s} &\sim 318 \text{ GeV} \end{aligned}$$

Heavy Flavour Production

- Dominant production process in ep -collisions: **Boson-Gluon Fusion**

Why study heavy quark production at HERA?:

- ❖ **Test of perturbative QCD** due to the hard scale given by the heavy quark mass.
- ❖ **Study of multi-scale problem:** p_T, m^2, Q^2
- ❖ **Better understanding of structure of the proton:** direct sensitive to gluon content inside proton (PDF's) .
beauty measurements at high Q^2 relevant for LHC e.g. $bb \rightarrow H$

● Kinematic Variables:

$Q^2 = -q^2 = (k - k')^2$ Neg. squared momentum transfer
(virtuality of exchanged boson)

$s = (k + p)^2 \approx 4E_e E_p$ CM Energy, at HERA $\sqrt{s} = 318$ GeV

$x = Q^2 / 2p \cdot q$ Bjorken scaling variable: momentum fraction of parton interacting with lepton in infinite momentum frame (QPM)

$y = p \cdot q / p \cdot k$ Inelasticity: lepton momentum fraction transferred to boson in proton rest frame

pQCD approximations

(assuming one dominant hard scale)

Massive scheme/FO: $\rightarrow m_b$

(Fixed Flavour Number Scheme)

- b massive
- neglects $[\alpha_s \ln(Q^2/m_b^2)]^n \dots$
- reliable for $p_T \sim m_Q$
- **FMNR (PHP) and HVQDIS (DIS)**

Massless scheme/NLL:

$\rightarrow Q^2, p_T$

- b massless
- resums $[\alpha_s \ln(Q^2/m_b^2)]^n \dots$
- reliable for $p_T \gg m_Q$

Variable schemes:

(Variable Flavour Number Scheme)

- at small $Q^2 \rightarrow$ massive, at large $Q^2 \rightarrow$ massless
- **MRST, CTEQ...**

Beauty PHP from inc. secondary vertexing

The experimental method and data selection

$\mathcal{L} = 128 \text{ pb}^{-1}$ (06/07 $e^{\pm}p$ data)

- PHP selection:
veto on scattered $e^{\pm}$
 $0.2 < y_{\text{JB}} < 0.8$
- JET selection:
2 Jets (kt-algorithm, massive)
with $p_{\text{T}} > 7(6) \text{ GeV}$ and $|\eta| < 2.5$
- TRACK selection:
 $p_{\text{T}} > 0.5 \text{ GeV}$
- If ≥ 2 tracks associated to a jet
→ secondary vertex fitted
- $-1.6 < \eta_{\text{jet}} < 1.3$ for vtx-tagged jet

- Combining decay length significance ($S = L_{xy} / \sigma$) and mass of sec.vtx (m_{vtx}) provides very good discrimination between beauty and BG:
→ S divided in 3 mass bins

Beauty PHP from inc. secondary vertexing (cont'd)

- Control distributions of beauty-enriched region

The signal extraction

- To reduce systematic uncertainties:
→ mirrored distributions (S^+-S^-)
- Fractions of b , c and $l\bar{f}$ extracted using χ^2 -simultaneous fit to the 3 mass bins mirrored distributions

- Almost pure beauty sample:
➤ $m_{vtx} > 2$ GeV and $(S^+-S^-) > 8$

Beauty PHP from inc. secondary vertexing

The results

- FMNR NLO QCD predictions:

- $\mu = \mu_0, (\mu_0/4) < \mu < \mu_0, m_b = 4.75 \text{ GeV}, 4.5 \text{ GeV} < m_b < 5 \text{ GeV}$
- $\text{PDF}(p) = \text{CTEQ5}, \text{PDF}(\gamma) = \text{GRV-HO}, \epsilon_b = 0.0035$
- Hadronization corrections from PYTHIA

- Results: Good agreement with NLO QCD

Good agreement with previous HERA I results (DESY-03-212)

Completely different tagging technique → better precision achieved

Beauty PHP using decays into μ in dijet events

The experimental method

Final result DESY-08-210 published by JHEP

- Semi-leptonic decays: final state $\mu + 2$ jets
- Discriminant variables used :
 - P_T of muon relative to jet axis (P_T^{rel})
 - Muon impact parameter (δ)
- Combined $p_T^{\text{rel}} - \delta$ fit used
→ provides complementary information

The data selection

$\mathcal{L} = 125 \text{ pb}^{-1}$ (2005 e^+p data)

- PHP selection:
veto on scattered $e^\pm$, $0.2 < y_{\text{JB}} < 0.8$
- JET selection:
2 Jets (kt-algorithm, massive)
with $p_T > 7(6) \text{ GeV}$ and $|\eta| < 2.5$
- μ selection:
 $p_T^\mu > 1.5 \text{ GeV}$, $1.6 < \eta < 2.3$

Beauty PHP using decays into μ in dijet events

The results

● FMNR NLO QCD predictions:

- $\mu = \mu_o$, $0.5\mu_o < \mu < 2\mu_o$, $m_b = 4.75\text{GeV}$, $4.5\text{GeV} < m_b < 5\text{GeV}$
- $\text{PDF}(p) = \text{CTEQ5M}$, $\text{PDF}(\gamma) = \text{GRV-HO}$, $\epsilon_b = 0.0035$
- Hadronization corrections from PYTHIA

● Results:

- Good agreement with NLO QCD
- Good agreement with previous HERA I results (p_T^{rel} only)

$$x_{\gamma}^{jj} = \sum_{j1j2} (E - P_z) / \sum_h (E - P_z)$$

● at LO QCD x_{γ} is the fraction of photon's energy entering the hard interaction

● No serious discrepancy within the data and theory

Beauty PHP Summary

HERA

- Results obtained with different methods and by different experiments. Cross sections for b production extrapolated using NLO calculations.
- General good agreement with NLO QCD predictions

Measurements of F_2^{bb}

Beauty contribution to inclusive DIS

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

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

Use inclusive lifetime tagging to determine fraction of b quark events $\rightarrow F_2^{b\bar{b}}$

H1, for process $(ep \rightarrow ebbX)$

ZEUS, for process $(ep \rightarrow ebbX \rightarrow e\mu jX)$

Measurement of F_2^{bb} by H1

- Inclusive analysis: select all tracks with hits in silicon detector and $p_T > 0.3$ GeV.
- For each track: track significance $S = \delta / \sigma(\delta)$ with $\delta \equiv$ signed impact parameter
- For each reconstructed sec.vtx: significance $S_L = L_{xy} / \sigma(L_{xy})$
- For $N_{\text{track}} \geq 3$, Neural Network (NN) used for improved separation between b and c

Signal extracted in each $(y-Q^2)$ bin using χ^2 -simultaneous fit to subtracted S_1 , S_2 and NN distributions

Measurement of F_2^{bb} by H1

H1 BEAUTY CROSS SECTION IN DIS

Kinematic range:

$$5 < Q^2 < 650 \text{ GeV}^2, 0.0002 \leq x \leq 0.032$$

- Results compared to NLO QCD predictions and predictions based on CCFM parton evolution
- Data well described by predictions
- F_2^{bb} and F_2^{cc} extracted simultaneously
- Differences in theory are within mass and scale uncertainties (see slide 15)

Measurements of F_2^{bb} by ZEUS

- Semileptonic decay into muons: $P_T^\mu > 1.5 \text{ GeV}$ and $-1.6 < \eta^\mu < 2.3$
- Fraction of muons determined from simultaneous fit of 3 discriminating variables:
 - P_T^{rel} : P_T of muon relative to associated jet axis
 - δ : signed impact parameter of muon
 - $P_T^{\text{miss}||\mu}$: missing P_T parallel to the muon (sensitive to ν , high resolution HCAL needed)
- $F_2^{bb}(\mathbf{x}, Q^2) = [\sigma_{\text{measured}}^b / \sigma_{\text{NLO}}^b] \cdot F_{2, \text{NLO}}^{bb}(\mathbf{x}, Q^2)$ @NLO in FFNS using HVQDIS

Kinematic range:

$$Q^2 > 20 \text{ GeV}^2, 0.01 < y < 0.7$$

Measurements of F_2^{bb}

- Latest F_2^{bb} measurements using different techniques were performed at ZEUS and H1
- Good agreement between both coll.
- Good agreement between theory and data
- Different theory schemes agree well
- Data precision can be improved by:
 - Using the whole HERA data sample
 - Combining H1 and ZEUS data
 - Combining different tag methods

Conclusions

- First ZEUS dijet inclusive PHP measurement of beauty has been presented:
 - Good agreement with theory and better precision achieved than previous published result.
- Different beauty measurements from ZEUS and H1 since last summer:
 - Very good agreement between the results and with NLO QCD predictions
- The beauty contribution to the proton structure functions has been measured at ZEUS and H1:
 - Good agreement between the two collaborations, both using different methods for the analysis.
 - Good agreement between theory and data.

BACK-UP SLIDES

Measurements of F_2^{bb}

- Given the relation between double differential cross section and the proton structure functions:

$$d^2\sigma^{bb}/(dx \cdot dQ^2) = (2\pi\alpha^2/Q^4x) \{ [1 + (1-y)^2] F_2^{bb}(x, Q^2) - y^2 F_L^{bb}(x, Q^2) \}$$

→ The reduced b cross section can be defined from the double as

$$\tilde{\sigma}^{bb}(x, Q^2) = [d^2\sigma^{bb}/(dx \cdot dQ^2)] [xQ^4/(2\pi\alpha^2(1 + (1-y)^2))]$$

- F_2^{bb} can be calculated from the ratio of measured and theory cross sections:

$$F_2^{bb}(x, Q^2) = [\sigma_{\text{measured}}/\sigma_{\text{NLO}}] \cdot F_2^{bb}{}_{\text{NLO}}(x, Q^2)$$

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ZEUS, for process $(ep \rightarrow ebbX \rightarrow e\mu jX)$

Beauty PHP from inc. secondary vertexing

Control Distributions

Beauty PHP using decays into μ in dijet events

Control Distributions

- ZEUS 125pb⁻¹
- $b\bar{b}+c\bar{c}+LF$ MC
- - - LF MC
- ... $c\bar{c}$
- $b\bar{b}$

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List of results since last summer

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- ✓ DIS decays into μ 's (DESY-09-56 by ZEUS Coll.)
- ✓ DIS events using sec.vtx (H1-prel-08-173 by H1 Coll.)
 - PHP events with 2 jets + 1μ (H1-prel-08-071, by H1 Coll.)
 - PHP events with 2 jets + $1e$ (PRD 78,072001 (2008), by ZEUS Coll.)
 - Events with $1 D^* + 1\mu$ (EPJ C50 (2007) 299-314, by ZEUS Coll.)
 - Events with 2μ 's (JHEPo2 (2009) 032, by ZEUS Coll.)

F_2^{bb} measurements