Measurement of the photoproduction of b-quarks at threshold at HERA

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Measurement of the photoproduction of b-quarks with a special focus on small b-quark momenta.

“The transverse momentum of bottom quark at HERA can be predicted by perturbative QCD quite accurately. … The comparison of this prediction with the data would be extremely useful … “.

“The differential spectra indicate that the data tend to lie above the predictions more significantly towards small b-quark momenta… “.
The HERA ep collider (1992 - 2007)

- ep collider:
- $e^\pm$ energy: 27.6 GeV
- $p$ energy: 920 GeV
- Center of mass energy: 319 GeV
- 2 collider experiments: H1 and ZEUS
- Integrated luminosity: $\sim0.5\text{ fb}^{-1}$ (per experiment)
Motivation to measure heavy flavor production

- Beauty quarks in ep interactions at HERA are mainly produced in Photon-Gluon-Fusion.

- Hard scales for perturbative QCD:
  - \( m_b, p_T, Q^2 \)
  - multi-scale problem.

- pQCD approximations:
  - Massive scheme:
    - b quarks treated massive.
    - Valid for small scales \( \mu^2 \approx m_b^2 \)
  - Massless scheme:
    - b quarks treated as massless partons in the proton and photon.
    - Valid for large scales \( \mu^2 \gg m_b^2 \)

Two kinematic regimes:

- Photoproduction: \( Q^2 \approx 0 \text{ GeV}^2 \)
- Deep Inelastic Scattering: \( Q^2 > 1 \text{ GeV}^2 \)
  (scattered electron detected)
Concept of this analysis

- What happens if the only experimental hard scale is $m_b$?

- Experimental implications:
  - Measure in photoproduction: $Q^2 \approx 0 \text{ GeV}^2$
  - Avoid jets (no $p_T^{\text{jet}}$-cut off) and enrich beauty with two low $p_T$-leptons from semileptonic decays: $p_T \approx 0 \text{ GeV}$
  - Low $p_T$-leptons: use electrons and not muons (electrons have lower experimental $p_T$ thresholds).

- Chosen beauty-tag:
  - 2 electrons from semileptonic decays:
    $$b \bar{b} \rightarrow e e X$$
Online electron identification

**Calorimeter Trigger (JT)**
16 highest **energy depositions** in calorimeter (within 2.3 µs)

**Fast Track Trigger (FTT)**
Fits up to 48 **tracks** (within 20 µs)

**Electron Trigger:** Combine information from FTT and JT (within 100 µs):
- Topological match: cut on $\Delta \phi$, $\Delta \theta$.
- Cut on $E_{T,\text{JT}}/p_{T,\text{FTT}}$ (enrich electrons).

Online measured $E_{T,\text{JT}}/p_{T,\text{FTT}}$

**Measured data set:** 47.6 pb$^{-1}$

2) doi:10.3929/ethz-a-005977487.
Offline electron identification

Requirements:
- High efficiency.
- Good background rejection (pions).
- Low $p_T$ threshold.

Implementation:
- Neural Network (NN) based on 5 variables using input from the calorimeter (shower profile) and tracker information. The NN discriminate electrons from background (pions).
- Normalized dEdx-likelihood:
  \[ Lkh_{dEdx} = \frac{P_{dEdx}(e)}{P_{dEdx}(e) + P_{dEdx}(\pi)} \]
- Combination of NN with normalized dEdx-likelihood to a common electron pion discriminator $D$.

Excellent separation between electrons (signal) and pions (background).
Overview on the data analysis

**Di-electron Selection:**
- Trigger selection.
- Selection of 2 electron candidates with
  - $1 \text{ GeV} < p_T(e) < 5 \text{ GeV}$, $20 < \theta < 140$

- Rejection of background.
  - Rejection of non-ep background.
  - Loose isolation-criterion (better electron discriminator performance).

- Rejection of real electrons from
  - DIS events (including beam electrons).
  - $\gamma$-conversion.

**Unfolding Procedure:**
- Deconvolution of the $p_T(b)$ cross section.
- Determination of remaining background: $J/\psi$, charm, electron misidentification.
Measurement of $<p_T(b)>$ via the thrust axis-method

Definition of mean transverse beauty mass:
$$<m_T(b)> = \sqrt{m_b^2 + <p_T(b)>^2}$$

- Measurement of $<m_T(b)>$ allows measurement of $<p_T(b)>$.

Estimator for mean transverse beauty mass:

1) Determine thrust axis in transverse plane:

2) Divide event in upper part, lower part (defined by thrust axis) and proton remnant ($\vartheta < 15$).

3) Determine estimator for mean transverse beauty mass $m_{T,est}$, based on the vectorial sum of the energy flow in the upper and the lower part.

Measurement of $<m_T(b)>$ at threshold.

$p_T(b)=0 \rightarrow <m_T(b)> = m_b$
Unfolding of the differential cross section

**Purpose:**
- Deconvolution of the $p_T(b)$ cross section from the detector response.
- Determination of remaining the **background**.

**Method:**
- Relate measured quantities with the mean transverse b-quark momentum $<p_T(b)>$:

\[ y = Ax + b \quad (1) \]

- Solve equation (1) with **regularized unfolding**:
  - Determine an estimator for $x$ by minimizing a standard $\chi^2$-function with additional side conditions on the smoothness and the normalization.
  - The regularization parameter is chosen to minimize the correlations among the bins of $x$.
  - Bins of $x$ are further combined, such that the resulting signal bins have almost **no** correlations.

For literature on unfolding: http://www.desy.de/~blobel/unfold.html
and the book of G. Cowan
Structure of the response matrix

\[ y = Ax + b \]

- \( y \): reconstructed vector
- \( A \): number of bins
- \( x \): true vector
- \( b \): remaining DIS background. Normalization estimated from MC and subtracted from \( y \).

Substructure of single bin
Used to separate beauty from charm, \( J/\Psi \) and \( \gamma p \)-background.
\[ m_{ee \ sgn} := m_{ee} * q(e1) * q(e2) \]
Control distribution: substructure in $y$

side bins sensitive to $\gamma p$-background

$m_{ee} q(e1) q(e2)$: discrimination of beauty against charm and $J/\psi$. 
Fractions of beauty, charm, J/ψ, γp backgr. determined by the unfolding procedure.
Control distribution: $p_T$ track distributions

Good description in all control distributions.
Differential cross section

H1 Preliminary

\[ \text{ep} \rightarrow b\bar{b} X \]

- Access to lowest \( p_T(b) \) values ever measured in ep.
- Agreement between data and NLO calculation (FMNR).
Comparison to other measurements

- Many measurements confirming each other over a wide $p_T(b)$ range.
- This analysis extends the measured differential cross section to lowest $p_T(b)$ values.
- General good agreement between the data and the NLO calculation (FMNR).
Summary

- Measurement of beauty photoproduction using di-electron events.
- Measurement is consistent with other measurements.
- Good agreement between data and NLO.
- Measurement of beauty photoproduction at the $p_T(b)$-production threshold.
Differential cross section

- The indicated bin centers of the data points are corrected in $\langle p_T(b) \rangle$, according to the expected distribution. Correction done, such that:

$$\int_{\delta p_T} d\sigma_{\text{FMNR}} / dp_T = \frac{d\sigma_{\text{FMNR}}}{dp_T}(p_{T, b.c.}) \cdot \delta p_T$$

- The errors in $p_T(b)$ indicate the bin width $\delta p_T$.
- The ratios is based on the full bin width $\delta p_T$:

$$R = \frac{\delta \sigma_{\text{measured}} / \delta p_T}{\delta p_T / \int_{\delta p_T} d\sigma_{\text{FMNR}} / dp_T}$$

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