Beauty Production at HERA

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Kinematic Quantities:

- Center of mass Energy squared: \( s = (P + k)^2 \)
- Photon virtuality: \( Q^2 = -q^2 = (k - k')^2 \)
- Inelasticity: \( y = \frac{Pq}{Pk} \)
- Bjorken Variable: \( x = \frac{Q^2}{2Pq} \)

Kinematic Regimes:

- \( Q^2 \approx 0 \text{ GeV}^2 \) : Photoproduction (PHP)
- \( Q^2 \geq 1 \text{ GeV}^2 \) : Deep inelastic scattering (DIS)
Production of Beauty Quarks

- Predominantly via boson gluon fusion

- Always hard scale given by mass (in addition to $Q^2$, $p_t^2$, ...)

- Problem in pQCD with more than one hard scale $\rightarrow$ need different schemes in pQCD to consider scales

QCD factorisation:

$$\sigma_B \propto \text{PDF} \otimes \text{hard ME} \otimes \text{fragmentation}$$
• Fractions shown here from a H1 lifetime tag analysis

• Beauty fraction of total cross section only 0.001 – 0.01

• Beauty analyses at HERA statistically limited (cross section measurements via full reconstruction of B hadrons not possible)
Methods for Beauty Tagging

Semileptonic decay:
• Reconstruction of decay leptons with particle identification

Large Mass:
• Make use of mass effects of b quark: decay leptons with high \( p_{t,rel} \) (lepton, jet), high \( m_{jet} \),...

Long lifetime:
• Reconstruct secondary vertex and use decay length significance: \( S_d = d/\sigma_d \)
• Impact parameter significance of displaced tracks \( S_\delta = \delta/\sigma_\delta \)
Tagging of beauty:

- Reconstruct two low $p_t$ electrons from semileptonic decays ($1 \text{ GeV} < p_t^e < 5 \text{ GeV}$)
- Analysis possible due to very good electron identification at all ($\pi$ misidentification rate only a few per mille!)

→ Access to lowest $p_t(b)$ values ever measured in $ep$
→ Agreement between data and NLO calculation (FMNR)
Beauty in PHP using Secondary Vertex

- Reconstruction of secondary vertices (belonging to jet)
- Use decay length significance and invariant mass of tracks

\[ \mathcal{L} = 133 \text{ pb}^{-1} \]

- Predicted Cross sections from NLO QCD calculation (FMNR) in \( p_T^{\text{jet}} \) and \( \eta^{\text{jet}} \)
  in agreement with data
- Theoretical uncertainties larger than experimental ones

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→ Measurements consistent with each other over a wide $p_t(b)$ range

→ In general good agreement between data and NLO calculation (FMNR)
Beauty Jets in DIS

$\mathcal{L} = 189 \text{ pb}^{-1}$

- Use sensitivity to lifetime
- Compare data with NLO calculation

• HVQDIS

$Q^2 > 6 \text{ GeV}^2, \ 0.07 < y < 0.6$

$E_T^{\text{jet}} > 6 \text{ GeV}, -1 < \eta^{\text{jet}} < 1.5$

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$E_T^{\text{jet}} > 6 \text{ GeV}, -1 < \eta^{\text{jet}} < 1.5$

- NLO QCD calculation describes data well for both scales
Beauty in DIS using Secondary Vertex

\[ \mathcal{L} = 354 \text{ pb}^{-1} \]

- Compare data with LO MC RAPGAP and NLO calculation HVQDIS

- Reasonable agreement with NLO QCD (except low \( Q^2 \) and low \( x \))
Beauty in DIS using $b \rightarrow e$ Decays

$\mathcal{L} = 363$ pb$^{-1}$

$Q^2 > 10$ GeV$^2$, $0.05 < y < 0.7$

$0.9 < p_t^e < 8$ GeV, $|\eta^e| < 1.5$

Tagging of beauty:

- Reconstruction of a jet ($p_t^{\text{jet}} > 2.5$ GeV) together with secondary vertex
- Requirement of electron candidate associated with the jet ($p_t^{\text{jet}} > 2.5$ GeV)

$\rightarrow$ Good agreement between data and NLO QCD calculation (HVQDIS) observed

$\rightarrow$ Also LO + PS MC RAPGAP describes data well in shape
Beauty in DIS using $b \rightarrow \mu$ Decays

$\mathcal{L} = 114$ pb$^{-1}$

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

$E_{t,\text{jet}} > 5 \text{ GeV}$, $-2 < \eta^{\text{jet}} < 2.5$

$p_{t,\mu} > 1.5 \text{ GeV}$, $\eta^{\mu} > -1.6$, belonging to jet

Tagging of beauty:

- Reconstruction of a jet ($p_{t,\text{jet}} > 5 \text{ GeV}$)
- Requirement of a muon candidate in cone of $\Delta R < 0.7$ around jet axis

→ Reasonable agreement between data and NLO QCD calculation (HVQDIS) within errors
One way to summarize beauty measurements

Definition of $F_2^{bb}$:

\[
\frac{d^2 \sigma^{bb}}{dx dQ^2} = \frac{2 \pi \alpha_{em}^2}{Q^4 x} \left[ (1 + (1 - y)^2) F_2^{bb}(x, Q^2) - y^2 F_L^{bb}(x, Q^2) \right]
\]

Extracted from measured double differential cross sections

Measurements consistent with each other and with NLO QCD predictions

Gain in precision with HERAII - data

Contribution of $F_L^{bb}$ small!
Summary

- Beauty cross sections measured in PHP and DIS from different final states

- Measurements in good agreement with each other where for PHP differential cross sections in $p_t^b$ and for DIS $F_2^{bb}$ are compared

- Predictions from NLO QCD calculations describe measurements well