Charm and Beauty Production from Secondary Vertexing at HERA

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for the H1 and ZEUS Collaborations

- Motivation and analysis method
- Heavy Flavour jets in photoproduction
- Heavy Flavour jets in Deep Inelastic Scattering
- Contribution of Heavy Flavours to proton structure

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Heavy Flavour Analyses

- In total ~500pb\(^{-1}\) of high energy data collected per experiment
- luminosity upgrade in 2001
- detectors adjusted
- ZEUS: silicon micro vertex detector

Many heavy flavour final analyses on full HERA I+II data. Working on publication of remaining preliminaries and combination of results
Production of Heavy Quarks

Contribution of quasi-real photons at low $Q^2$

Direct $\gamma$

Resolved $\gamma$ (flavour excitation)

$Q^2 < 1 \text{ GeV}^2$ Photoproduction, $Q^2 > 1 \text{ GeV}^2$ DIS

Predominantly via boson gluon fusion

Test of perturbative QCD:

multi-scale problem ($M$, $Q$, $p_T$)

Directly sensitive to gluon density in the proton (PDFs)
Heavy Quark Production

Number of theoretical approaches:

Massless (Zero Mass), massive (Fixed Flavour) and general mass (GM) flavour number schemes (combination of massless/massive should provide best theoretical model).

QCD Calculations:

- Fixed order - massive FFNS NLO($\alpha_s^2$) (FMNR, HVQDIS)
- GM-VFNS PDFs - used in latest PDF fits
  - MSTW08 to NLO ($\alpha_s^2$) and NNLO ($\alpha_s^3$)
  - CTEQ 6.6 to NLO ($\alpha_s$)

Monte-Carlo: LO ($\alpha_s$) + Parton shower:

Collinear factorisation, DGLAP (PYTHIA, RAPGAP)
HERA I+II result:

- fraction of total DIS cross section from charm and beauty
- large charm fraction (~30%). Has influence on PDFs!
- small beauty fraction (~%) (lower at low $Q^2$)
- mass thresholds visible
- good description by NNLO QCD
Tagging Heavy Quarks

Heavy quarks rarely produced, use properties of beauty hadrons:

- lifetime and mass
  - reconstruction of a secondary vertex
  - decay length and mass of tracks from secondary vertex
  - impact parameter

Vertex method allows measurement of all tracks to low $p_T$ – increase statistics and reduce extrapolations to full phase space. Can compare with other methods semi-leptonic (1163 Juengst), reconstruction of charmed meson decays (1160 Jung, 1162 Roloff)
**H1 and ZEUS vertex measurements**

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*Methods to discriminate heavy flavours from light quarks and to disentangle c from b are very similar for H1 and ZEUS*

*Highlight the important features here...*
Flavour Tagging - secondary vertex

- Use all tracks ("inclusive") with hits in silicon detectors $p_T > 0.3(0.5)$ GeV H1(ZEUS)
- 2D(3D) hits H1(ZEUS). Calculate 2D secondary vertex decay length and decay length significance $S_L = L/\sigma(L)$
- Sign of vertex given w.r.t jet axis
- Use also signed impact parameter $\delta$ of individual tracks

\[ \alpha < 90^\circ \rightarrow \delta = +|\delta| \]
\[ \alpha > 90^\circ \rightarrow \delta = -|\delta| \]
Flavour Separation

Significance \( S = \frac{\delta}{\sigma(\delta)} \)

For >2 tracks use NN

\( S_1 \) highest \( |S| \)
\( S_2 \) 2\textsuperscript{nd} highest \( |S| \)

Charm and beauty asymm. due to lifetime

Light flavours mostly symmetric

Photoproduction background small

\( S_1 \), \( S_2 \), \( S_3 \), \( S_L \) and number of silicon tracks
Fitting Flavour Fractions

Reduce contribution of lights by using “mirror image” i.e. subtract negative bins from positive.

ZEUS fit $S_L$ in bins of $M_{VTX}$, H1 fit $S_1$, $S_2$ and NN output

Perform $l,c,b$ fits in bins of e.g. $p_T^{jet}$ or $x,Q^2$ to extract $F_2^{bb}$.  

ZEUS-prel-09-005

Lights suppressed

b dominates

ZEUS (prel.) 120 pb$^{-1}$  PYTHIA (b+c+fl)  PYTHIA (b)  PYTHIA (c)  PYTHIA (fl)
Photoproduction $b$ Dijets (ZEUS)

$Q^2<1$ GeV$^2$, $P_{T^{Jet}}>7(6)$ GeV, $-1.6 < \eta^{Jet}<1.3$

Beauty jet cross section vs $p_{T^{Jet}}$, $\eta^{Jet}$

Well described by (massive) NLO QCD

Agreement found with measurements from muon tagging (864 Geiser)
Beauty Jets In DIS (H1)

Q2 > 6 GeV², P_T^jet > 6 GeV, -1 < η^jet < 1.5

Beauty jet cross sections vs E_T^jet and η^jet

Well described by (massive) NLO QCD

Good description (as for H1 γp analysis hep-ex/0605016)

DESY 10-083
Beauty jet cross sections vs $Q^2$ and $x$. Agreement with NLO QCD, although QCD lower at low $Q^2$ and low $x$
Charm Jets In DIS (H1)

$Q^2 > 6 \text{ GeV}^2$, $P_T^{\text{jet}} > 6 \text{ GeV}$, $-1 < \eta^{\text{jet}} < 1.5$

Charm jet cross sections vs $E_T^{\text{jet}}$ and $\eta^{\text{jet}}$

Sensitivity to scale choice. Reasonable description with scale choice.

DESY 10-083
Measurement of $F_{2}^{cc}$ and $F_{2}^{bb}$

$$F_{2,\text{meas}}^{b}(x, Q^{2}) = \frac{\sigma_{\text{meas},i}}{\sigma_{\text{theo},i}} \times F_{2,\text{theo}}^{b}(x, Q^{2})$$

- Extraction of inclusive structure functions ($F_{L}$ is small)
- Double differential cross section
- Use HVQDIS to calculate theoretical predictions
- Extrapolation to full phase space small for beauty
- Larger for charm, but reduced compared to exclusive methods because of low $p_T$ track acceptance
Measurement of $F_2^{bb}$

- Beauty structure function versus $Q^2$ for fixed $x$
- Vertex methods between H1 and ZEUS agree
- Agreement also found with semi-leptonic analyses
- NNLO predictions available
- Some differences between theories
- Data well described
Measurement of $F_2^{cc}$

- Charm structure function vs $Q^2$ for fixed $x$
- Higher precision tests theory
- Differences between MSTW NNLO and NLO predictions for charm. NNLO somewhat better description than NLO
- CTEQ NLO describes data
- Data being used to complement D meson and semi-leptonic measurements in combination of HERA data (1159 Corradi)
Summary

- Heavy Flavour production at HERA is a vital testing ground for perturbative QCD
- Vertex detectors are a powerful tool to extract heavy flavour cross sections
- In general a good description is provided by pQCD
- The vertexing method allows to make measurements of the contribution of heavy flavours to the proton structure function. Charm data precision provides constraint for theory. Beauty well described.
- Better discrimination to come from combination of results.
Extra Slides
Flavour Tagging - Vertex Detectors

H1 and ZEUS vertex detectors:

- Multi-layered single and double sided silicon microstrip detectors
- Combine precise spatial information from vertex detectors with tracks from central drift chambers
- Resolution of impact parameter in transverse plane < 100 μm
Fitting Flavour Fractions

ZEUS

Example of ZEUS 2D $M_{VTX}$ and $S_L$ fitting for DIS
Measurement of $F_2^{bb}$

Comparison of vertexing results with semi-leptonic
Comparison with Muon Tagged Data

- Extrapolate muon data to full phase space (small uncertainty)
- H1 and ZEUS data from muon tagging lie systematically above vertex data at either high or low $Q^2$