Interest in Heavy Flavour production:

- Perturbative QCD applicable due to large masses $m_c$, $m_b$
  - but often multi scale problem (i.e. additional scales $Q^2$, $p_t^2$, ...)
- Detailed understanding of the production mechanism sheds light on the underlying parton dynamics in QCD
- Dominant production process is boson gluon fusion
  - direct sensitivity to gluon density in proton
- Heavy-quark production provides core constraints in global fits on the parton distribution functions (PDFs)
  - reduced uncertainty
- Sizeable fraction of total cross section up to
  - 30% for charm and 2-3% for beauty
- Measurements relevant for interpretation of
  - LHC results (e.g. HQ treatment vs. $\sigma_{W/Z}$)
  - Cosmic Ray physics (UHE $\nu$ background)
Production of Heavy Flavour in ep Scattering

**Direct $\gamma$**

**Resolved $\gamma$**

**Flavour excitation**

Kinematics of ep scattering:

\[ Q^2 = -q^2 = -(k - k')^2 \]

\[
\begin{align*}
x &= \frac{Q^2}{2P \cdot q} & \text{momentum fraction} \\
y &= \frac{P \cdot q}{P \cdot k} & \text{inelasticity}
\end{align*}
\]

Two regimes:

- \( Q^2 \simeq 0 \text{ GeV}^2 \) Photoproduction (\(\gamma p\))
- \( Q^2 > 1 \text{ GeV}^2 \) Deep Inelastic Scattering (DIS)
Calculations and Monte Carlo programs used to describe Heavy Flavour production:

- **Monte Carlo Programs**
  - leading order (LO) + parton shower (PS) models available
    - DGLAP evolution (collinear factorization):
      - $\gamma p$: PYTHIA, HERWIG
      - DIS: RAPGAP
    - CCFM evolution ($k_t$ factorization) $\gamma p + \text{DIS}$: CASCADE

- **Theoretical Calculations**
  - full (massive) NLO calculations available
    - $\gamma p$: FMNR
    - DIS: HVQDIS
Tagging Heavy Flavour at HERA

Exploit properties of charm/beauty hadrons:

- **Full reconstruction**
  - At HERA only possible for charm, *e.g.* $D^* \rightarrow K\pi\pi$, $J/\Psi \rightarrow \mu\mu$, $ee$

- **Lepton tagging**
  - Use semileptonic b/c decay channels:
    - $\mu$ or $e$, high BR($c,b \rightarrow$ lepton + anything)

- **Lifetime tagging**
  - b/c hadrons have long lifetimes:
    - displaced vertices
    - tracks with large impact parameters $\delta$

- $p_t^{\text{rel}}$ tagging
  - b hadrons have large mass:
    - decay leptons with high transverse momentum w.r.t. b quark flight direction

- **Secondary vertex mass tagging**
  - exploit high b quark mass
    - high secondary vertex masses

- Compare/combine different tagging methods
**Photoproduction of D* and Jets**

- Charm tagging by reconstructing D* decay in "golden channel":
  \[ D^{*\pm} \rightarrow D^0 \pi^{\pm}_{\text{slow}} \rightarrow K^{\mp} \pi^{\pm} \pi^{\pm}_{\text{slow}} \]

- Measurements of jets gives access to both partons from hard process:
  - D* jet quantities expected to be closer to charm quark quantities than D* alone
  - study angular correlation in transverse plane \( \Delta \phi \)
  - sensitivity to resolved photons

- Models for comparison:
  - Pythia (DGLAP)
  - Cascade (CCFM)
  - MC@NLO (FMNR + Herwig)

---

Motivation

- D*: tag charm
- pQCD
- gluon density
dijets: measure both partons from hard process
  - correlations
  - parton evolution in proton

**H1 Preliminary**

\[ N(D^*) = 3937 \pm 114 \]

\[ \Delta m = m(K\pi\pi) - m(K\pi) \text{ [GeV]} \]

N(D*) Candidates

- Data
- Fit

---

**23rd Rencontres de Blois 2011: Heavy Flavour Production at HERA**
D* + Dijets in Photoproduction

resolved $\gamma$

direct enriched $\gamma$

$x_\gamma$: longitudinal momentum fraction of the photon carried by the jets

- LO Monte Carlo Pythia and Cascade
  - not able to reproduce $\Delta\varphi$ shape of the data
- MC@NLO
  - $\Delta\varphi$ shape reasonably well described
  - normalization too low at low $x_\gamma$
Inclusive Heavy Flavour Jets in Photoproduction

- Inclusive selection
  - 2 jets [$p_{T\text{jet}} > 7(6) \text{ GeV}$]
  - secondary vertex
    - decay length significance
    - mass of tracks from 2nd vertex
- Compares well with scaled LO MC and NLO QCD predictions (FMNR)
  - large theory uncertainty
  - small dependence on proton PDF

Significance:

\[ S = \frac{d}{\delta d} \]
Large variety of measurement techniques yields consistent picture of b-quark photo-production at HERA over wide kinematic range

- most recent measurements have improved precision and lead to extension of accessible $p_T$ range in both directions
  - Lepton tag $b \to ee$ analysis [★]
    - exploits product $m_{e1,e2} q_{e1} q_{e2}$ to extend phase space towards b-quark production threshold

Good description by massive NLO calculation (FMNR) over entire $p_T$ range

HERA

$\frac{d\sigma}{dp_T^b} (ep \to ebX)$

$Q^2 < 1 \text{ GeV}^2$, $0.2 < y < 0.8$, $|t_b| < 2$

NLO QCD

$\mu^2 = (m_b^2 + p_T^2)/4$

$\mu^2 = m_b^2 + p_T^2$

Lepton tag $H1prelim-11-071$
D* Production in DIS at low Q²

- D* reconstruction in golden decay channel: \( D^{* \pm} \rightarrow D^0 \pi_{\text{slow}}^\pm \rightarrow K^\mp \pi^\pm \pi_{\text{slow}}^\pm \)
- Data reasonably well described by NLO calculation HVQDIS
- In forward direction predictions slightly undershoot data
  - from double differential distribution: excess mainly at low \( p_T(D^*) \)
- Double differential cross section \( d^2\sigma/dy dQ^2 \) is used to extract charm contribution \( F_{2cc}(x,Q^2) \) to proton structure function \( F_2 \):
  \[
  \frac{d^2\sigma^{cc}}{dx \, dQ^2} = \frac{2\pi\alpha^2}{Q^4x} \left[ (1 + (1 - y)^2) \cdot F_{2}^{cc}(x, Q^2) - y^2 F_{L}^{cc} \right]
  \]
Combination of 9 results based on different charm tagging methods
- averaging procedure leads to significant reduction of cross-correlated systematic uncertainties
- resulting precision of 5 - 10%

Data can be used to study differences in available flavour number schemes
- [massless (Zero Mass)]
- massive (Fixed Flavour)
- general mass (GM)
Charm and beauty cross section as function of $E_{T}^{jet}$ well described by NLO QCD calculation (HVQDIS)
- only little dependence on scale choice

Comparison with results from $\mu$-tagging
- relatively large extrapolation factors
- ratio of the muon data to the lifetime tagged data $\approx 2$, but in agreement within full error
Extraction of beauty content from semileptonic decays into electrons

\[ ep \rightarrow e'b\bar{b} \rightarrow e'eX \]

Construct likelihood discriminator \( T \) and fit to MC templates

Good description of data by
- scaled LO prediction (RAPGAP)
- NLO QCD calculation (HVQDIS)
Inclusive Beauty Production in DIS

- Measurement of beauty production using inclusive secondary vertices
- Single differential cross sections in reasonable agreement with NLO QCD predictions (HVQDIS)
- $F_{2}^{bb}$ extracted from double-differential cross sections
  - extrapolation factors to full phase space typically quite small 1.0-1.3

$$
\frac{d^2\sigma^{ep\rightarrow b\bar{b}X}}{dx\,dQ^2} = \frac{2\pi\alpha^2}{Q^4x} \left[(1 + (1 - y)^2) \cdot F_{2}^{bb}(x, Q^2) - y^2 F_L^{bb}\right]
$$

$$
F_{2}^{bb}(\text{exp}) = \frac{\sigma_{vis}(\text{exp})}{\sigma_{vis}(\text{theo})} F_{2}^{bb}(\text{theo})
$$
Large variety of different experimental methods to extract $F_2^{bb}$

Measurements are compatible with each other within uncertainties

NLO QCD predictions based on HVQDIS describe the data well
Summary

- Wealth of heavy flavour results exploiting complete HERA statistics
  - increased precision
  - extended phase space

- Large variety of very different experimental techniques allow non-trivial cross checks to be made
  - measurements generally very well consistent with each other

- Reasonable description of data by up-to-date NLO QCD predictions