Charm Production in $ep$ collisions

$XXXXth$ Recontres de Moriond

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- Introduction, theoretical Framework
- $D$ mesons - Fragmentation
- Proton structure function: $F_2^c$
- $D^*$ (+jets)
- $D^*$ + muon: Double tag
Center of mass energy ($\sqrt{s}$):

$$s = (k + P)^2$$

Virtuality of $\gamma$:

$$Q^2 = -q^2 = -(k - k')^2$$

$x$ ($x_g$): Fraction of the parton (gluon) of the total p-momentum in the QPM

$$x = Q^2 / (2 \cdot P \cdot q)$$

Two kinematic regimes:

- $Q^2 \to 0$ GeV$^2$: Photoproduction ($\gamma p$)
- $Q^2 \geq 2$ GeV$^2$: Electroproduction (DIS)
Production of Heavy Quarks at HERA

Dominant process ($\text{PhotonGluonFusion}$):

**Fragmentation:**
- Universality

**$p$ structure:**
- Proton structure function: $F_2^c$

**Production mechanism:**
- Contributing processes

**Factorisation:**

$p$ structure $\otimes$ hard process $\otimes$ fragmentation
Charm Tagging

ZEUS

$D^* \rightarrow D^0 \pi_s \rightarrow K \pi \pi_s$

- ZEUS (prel.) 1995-2000 (127 pb$^{-1}$)
- Backgr. wrong charge

$D_s \rightarrow \phi \pi \rightarrow KK\pi$

- ZEUS (prel.) 1998-2000
- Gauss$^{mod}$ + Gauss$^{mod}$ + EXP

$130 < W < 300$ GeV, $Q^2 < 1$ GeV$^2$
$P_T(D_s^-D^0) > 3.8$ GeV, $|\eta(D_s^-D^0)| < 1.6$

$N(D_s^0) = 1086 \pm 85$
$N(D_s^-) = 229 \pm 62$

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Charm Fragmentation

Reconstruction of charmed mesons: $D^\pm$, $D^0$, $D_s^\pm$, $D^{*\pm}$, ($\Lambda_c^\pm$, ZEUS only)

Universal fragmentation ansatz reasonable
(independent of hard scat. process and of c prod. scale)

Similar shapes for different $D$ mesons
Fragmentation Ratios

- \( R_{u/d} = c\bar{u}/c\bar{d} \)
  - Ratio of \( u \) to \( d \)
  - \( R_{u/d} \sim 1 \rightarrow \) Confirmation of isospin invariance

- \( \gamma_s = 2c\bar{s}/(c\bar{u} + c\bar{d}) \)
  - Strangeness suppression factor \((u:d:s=1:1:\gamma_s)\)
  - \( s \) suppressed by a factor 3-4

- \( P_v = VM/(VM + PS) \)
  - Fraction of \( D \) mesons produced as VM
  - Naive spin counting \((P_v = 3/4)\) does not work

Good agreement between data and world average
Precision comparable with LEP (DELPHI)
Charm contribution to $F_2$: $F_2^{c\bar{c}}$

$F_2$: Proton structure function

Extraction of $F_2^{c\bar{c}}$:
- $D^*$ cross section in visible range
  → Large extrapolation
- Inclusive $c$ tagging (vertex detector, VTX)
  → Almost no extrapolation

- Agreement between data and ZEUS NLO QCD fit over a wide rang in $Q^2$ and $x$
- Prediction of charm contribution to $F_2$ from scaling violations is consistent with $F_2^{c\bar{c}}$ measurement
Modelling Heavy Quark Production

**pQCD calculations in NLO:** (DGLAP evolution used for PDF’s)

- **Fixed order massive scheme** (scale $\mu^2 \approx m_Q^2$)
  - $\gamma p$: FMNR (Frixione et al.)
  - DIS: HVQDIS (Harris et al.)

- **Massless scheme** ($\mu^2 \gg m_Q^2$)
  - $\gamma p$: Cacciari et al., Kniehl et al.

**MC generators:** (LO matrix element + parton showers)

- **PYTHIA** (DGLAP evol.), **CASCADE** (CCFM evol.)

*Evolution models for PDF:* (PDF known at $\mu_0^2$ $\rightarrow$ PDF at $\mu^2$)
Inclusive $D^*$ Events

**DIS and Photoproduction**

Extension of $Q^2$ distribution towards low values using the beam pipe calorimeter (BPC)

![Graph showing $d\sigma/dQ^2$ vs $Q^2$](image)

- Massive NLO calculation consistent with data
- Massive and matched (FONLL) NLO calculations do not describe all details of the data

**Photoproduction**

$3.25 < p_T(D^*) < 5$ GeV

![Graph showing $d\sigma/d\eta$ vs $\eta(D^*)$](image)

- ZEUS (prel.) 98–00
- HVQDIS, $M_{c}=1.35$ GeV, ZEUS NLO pdf fit

![Line plot showing $d\sigma/dQ^2$ vs $Q^2$](image)

- ZEUS DIS BPC D* (prel.) 98-00
- ZEUS DIS D* 98-00

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9/13
Jet requirement →
Additional scale $E_T^{jet}$

At high $E_T^{jet}$:
'Massive' NLO calculation below data
'Massless' NLO calculation better here

Theories have large uncertainties
Double Tag - $D^* + \text{muon}$

- **Charge and angle correlation:**
  - Separation of charm and beauty (not shown)
  - Selection of double tagged events (90% charm, 10% beauty)

- **Double tag:**
  - Sensitive to details of production mechanism (e.g. NLO effects - LO: $p_T(QQ) = 0$)
  - Correlation between $D^*\mu$ and $QQ$
    - $x_g^{obs}(D^*\mu) = M^2(D^*\mu) \cdot x/Q^2$ approximates $x_g$ well
    - Correlation between $p_T(D^*\mu)$ and $k_T$ worse

- Require muon in addition to $D^*$
$D^* + \text{muon in Photoproduction}$

- All calculations give a reasonable description of the data
- LO FMNR is too soft, while NLO FMNR fits the data well
- Differences between PYTHIA (DGLAP evol.) and CASCADE (CCFM evol.) small
Summary

- **Fragmentation - fractions and ratios:**
  - Fragmentation of charm is independent of the hard physics

- **Proton structure -** $F_2^{c\bar{c}}$:
  - $c$ contribution to $F_2$ predicted from scaling violations consistent with $F_2^{c\bar{c}}$ measurement $\rightarrow$ QCD does a good job

- **Production mechanism:**
  - $D^* (+$ Jets) in photoproduction:
    - NLO QCD calculations have some problems to describe data
  - $D^* +$ muon - double tag:
    - NLO effects clearly seen