Measurement of beauty production from dimuon events (and other heavy flavour results) at HERA

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- Introduction
- Beauty tags at HERA
- Beauty from dimuons ZEUS-prel-18-006
- Reminder: combination of charm and beauty data in NC DIS
- Cross-reference: charm in CC DIS \rightarrow see talk J. Nam in WG1
- Conclusions
The HERA ep collider and experiments

HERA I: $\sim 130 \text{ pb}^{-1}$ (physics)

HERA II: $\sim 380 \text{ pb}^{-1}$ (physics)

combined: $\sim 2 \times 0.5 \text{ fb}^{-1}$

HERA: $318 \text{ GeV}$

\[ p (920 \text{ GeV}) \rightarrow e (27.6 \text{ GeV}) \]

DESY, Hamburg
Open beauty production in ep scattering

Dominant production process in $ep$-collisions: Boson-Gluon -Fusion

- Driven by gluons in the proton
- Relevant scales:
  \[ m_b \sim 5 \text{ GeV} \]
  \[ Q^2 \lesssim 1 \text{ GeV}^2 \rightarrow \gamma p \]
  \[ Q^2 \gtrsim 1 \text{ GeV}^2 \rightarrow \text{DIS} \]

 multiscale problem

\[ p_T^b \]

\[ \sqrt{\alpha_s} \]

\[ g(x) \]

\[ b \rightarrow b \]

\[ \alpha_s \ln \left( \frac{Q^2}{m_b^2} \right)^n, \quad \alpha_s \ln \left( \frac{p_T^2}{m_b^2} \right)^n, \quad \text{etc.} \]

in perturbative expansion \rightarrow potentially large th. errors
Fixed Flavour Number Scheme (FFNS)

- no beauty in proton
- full kinematical treatment of beauty quark mass
  (multi-scale problem: $Q^2, p_T, m_b \rightarrow \text{logs of ratios}$)
- no resummation of logs 😞
- no extra matching parameters 😊

$\sqrt{\alpha_s} \cdot g(x)$

\[ \mu^2 = m_b^2 + p_T^2 \quad (\gamma p) \]
\[ \mu^2 = Q^2 + 4m_b^2 \quad \text{(DIS)} \]

example: beauty

27.6 GeV

920 GeV

$e^+$

$\gamma\gamma$

$p_Tb$

$m_b$

+ NLO corrections,

“natural” scales:
multi-tagged $b\bar{b}$ events

- tag both $b$'s
  - explicitly measure $b\bar{b}$ correlations
- dimuon signature has low background
  - low muon $p_T$ cuts
  - sensitive even to $B$ mesons at the kinematic threshold (low $p_T$)
- almost full rapidity coverage
  (rear and forward muon chambers)
  - directly measure total $b\bar{b}$ cross section without any additional cuts
  ($DIS + \gamma p$)

here: two muons
Signal topologies: mass, charge

multi-tagged $b\bar{b}$ events

here: two muons

- muons from different $b$'s
  $\rightarrow$ like or unlike sign
  (secondary $c$ decays or $B^0\bar{B}^0$ mixing)
  opposite hemispheres
  high dimuon mass

- suited to measure $b\bar{b}$ correlations
Signal topologies: mass, charge

multi-tagged $b\bar{b}$ events

here: two muons

- muons from same $b$ (including $b \to J/\psi$)

  → unlike sign

  same hemisphere
  dimuon mass $< 4$ GeV

  (B mass - hadrons/neutrinos)

- useful contribution to total cross section

  → classify data into subsamples:

<table>
<thead>
<tr>
<th></th>
<th>low mass ($&lt; 4$ GeV)</th>
<th>high mass ($&gt; 4$ GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unlike sign</td>
<td></td>
<td></td>
</tr>
<tr>
<td>±/±</td>
<td>muons from same $b$</td>
<td>muons from diff. $b$ or $c$</td>
</tr>
<tr>
<td>$J/\psi, \psi'$ + light-flavour bg</td>
<td>$\Upsilon$, Bethe Heitler + light-flavour bg</td>
<td></td>
</tr>
<tr>
<td>Like sign</td>
<td></td>
<td></td>
</tr>
<tr>
<td>++/---</td>
<td>light flavour bg</td>
<td>muons from diff. $b$</td>
</tr>
<tr>
<td>+ few muons from diff. $b$</td>
<td>+ light-flavour bg</td>
<td></td>
</tr>
</tbody>
</table>

4.9.2019

DIS 2019, A. Geiser
Dimuon mass spectrum

ZEUS preliminary

muons mostly isolated

signal mainly nonisolated

very similar to HERA I analysis JHEP02 (2009) 032

almost 3 times larger statistics
Muon $p_T$ and $\eta$ distributions

nonisolated unlike sign muon pairs (low+high mass)

Charm bg fraction verified/confirmed by fit of inclusive secondary vertices (not shown)

acceptance down to very low $p_T$
very large $\eta$ range (-2.2 to +2.5)

$\textbf{b MC (x 1.85) agrees with data}$

$p_T$ of tagged $b$ quark:
ZEUS

~50% beauty

sensitive to total $b\bar{b}$ cross section!

ZEUS-prel-18-006
Total visible $bb \to \mu\mu + X$ cross section

Visible cross section: using lumi + MC acceptance + corrections

- HERA I paper: JHEP02 (2009) 032
  \[ \sigma_{\text{vis}} \, \text{ep} \to bbX \to \mu\mu X' = 55 \pm 7 \text{ (stat.)}^{+14}_{-15} \text{ (syst.) pb} \]

- HERA II preliminary: ZEUS-prel-18-006
  \[ \sigma_{\text{vis}} \, \text{ep} \to bbX \to \mu\mu X' = 43 \pm 3 \text{ (stat.)}^{+13}_{-11} \text{ (syst.) pb} \]

NLO QCD (same as HERA I paper):
  \[ \sigma_{\text{vis}} \, \text{ep} \to bbX \to \mu\mu X' = 33^{+14}_{-8} \text{ (NLO)}^{+5}_{-3} \text{ (frag+Br) pb} \]

scale $\mu^2 = \frac{1}{4}(m^2+p_T^2)$

details see backup

\(- \to \text{agreement within uncertainties}\)
Total beauty cross section in ep @ 318 GeV

Total cross section: using MC cross section x scale factor + corrections

- HERA I paper: JHEP02 (2009) 032
  \[ \sigma_{b\text{ tot}}^{ep \to bbX} (318 \text{ GeV}) = 13.9 \pm 1.5 \text{ (stat.)} ^{+4.0}_{-4.3} \text{ (syst.)} \text{ nb} \]

- HERA II preliminary: ZEUS-prel-18-006
  \[ \sigma_{b\text{ tot}}^{ep \to bbX} (318 \text{ GeV}) = 11.4 \pm 0.8 \text{ (stat.)} ^{+3.9}_{-2.9} \text{ (syst.)} \text{ nb} \]

NLO QCD predictions (same as HERA I paper):
FMNR+HVQDIS \[7.5^{+4.5}_{-2.1} \text{ nb}\] scale \( \mu^2 = \frac{1}{4}(m^2+p_T^2+Q^2) \)

-> agreement within (large) uncertainties
only measurement of its kind so far
any chance to get NNLO prediction?
(exists for pp and (almost) for DIS)

4.9.2019 DIS 2019, A. Geiser
Differential cross sections $bb \rightarrow \mu\mu + X$

**Good agreement with HERA I result, smaller data uncertainties.**
**Shape of NLO prediction agrees well with data.**
**Normalisation agreement better for reduced QCD scale**

(NNLO corrections, also to $bb$ correlations, potentially large)
**Differential cross sections** $\mathrm{bb} \rightarrow \mu\mu + X$

**in general:** similar conclusions as for muon $p_T$

LO+PS MC describes shape slightly better than NLO
Differential cross sections $bb\rightarrow \mu\mu+X$

$\Delta\phi^{\mu\mu}$ for $m^{\mu\mu} > 3.25$ GeV ($\mu$'s from different b's)

$\rightarrow$ directly sensitive to $bb\bar{b}$ correlations

Lower scale NLO prediction agrees better in both shape and normalisation
Differential cross sections $b\bar{b} \rightarrow \mu \mu + X$

agrees with LO+PS MC, NLO prediction not calculated yet

no previous measurement (statistics)
Beauty in photoproduction: summary

Data vs. NLO QCD: reasonable agreement

for theory-inspired motivation of QCD scale choice
see doi:10.3360/dis.2007.163

double-tag measurements have tendency to come out higher than single tag
Deep Inelastic ep Scattering at HERA

HERA:

\begin{align*}
(\ell) & \quad \text{Electron} \\
\gamma, Z & \quad \text{Photon, Z boson} \\
\text{q} & \quad \text{Quark or gluon}
\end{align*}

Proton (P)

Electron ($\ell'$)

kinematic variables:

\begin{align*}
Q^2 &= -q^2 \quad \text{photon (or Z) virtuality, squared momentum transfer} \\
X_{\text{Bj}} &= \frac{Q^2}{2Pq} \quad \text{Bjorken scaling variable} \\
\gamma &= \frac{qP}{\ell P} \quad \text{inelasticity, momentum fraction of p constituent} \\
q &= \ell - \ell' \\
\end{align*}
Heavy flavour contributions to $\sigma_r$ for $Q^2$, $x = Q^2/2pq$.

Detect

$\sigma_{bb}^{\text{cc}}$ or $\sigma_{cc}$

$\sigma_r(x_{Bj}, Q^2)$

Combine 16 H1+ZEUS input data sets!
QCD fit (DIS incl.+c+b): charm subset

already presented at DIS18

fully consistent with HERAPDF2.0 FF3A

under discussion in context of low x resummation

(see backup and talks J. Rojo and R. Yoshida)

\[ m_c(m_c) = 1.29^{+0.05}_{-0.04} \text{ exp/fit} +0.06_{-0.01} \text{ mod/scale} +0.00_{-0.03} \text{ par} \text{ GeV} \]

PDG: 1.27 ±0.03 GeV (lattice QCD + time-like processes)
QCD fit (DIS incl.+c+b): beauty subset

fully consistent with HERAPDF FF3A

new: \( m_b(m_b) = 4.05 \pm 0.10 \) GeV

ZEUS: \( m_b(m_b) = 4.07 \pm 0.14 \) GeV

PDG: \( 4.18 \pm 0.03 \) GeV (lattice QCD + time-like processes)
Charm in ep CC

First ever collider measurement, large uncertainties already advertised in talk C. Glasman:

Visible cross section:

\( \sigma_{c, \text{vis}}^+ = 4.0 \pm 2.8 \text{ (stat)} \pm 0.1 \text{ (syst)} \text{ pb} \)

\( \sigma_{c, \text{vis}}^- = -3.0 \pm 3.8 \text{ (stat)} \pm 0.5 \text{ (syst)} \text{ pb} \)

Sets the stage for future measurements at EIC/LHeC/...
Details see dedicated talk J. Nam tomorrow in WG1
Summary and conclusions

- Beauty cross sections in ep collisions have been measured from dimuons
dimuon tag covers full phase space -> allows extraction of total b cross section

- Good agreement with earlier measurements

- Total cross section somewhat larger than but in agreement with NLO QCD

- Differential cross sections in muon p_T, η, Δφ and ΔR test bbbar correlations,
agree very well with LO+PS MC shape

- NLO prediction: good agreement in shape
  normalisation agrees better with lower scale choice (motivated by theory)

- Large NLO uncertainties (mainly b mass + QCD scale dependence)
suggest significant NNLO corrections
  -> any chance for NNLO calculations soon?

- Other HERA heavy flavour results include H1+ZEUS charm and beauty data
  combination in DIS (presented in detail last year) and charm in CC by ZEUS
  (see dedicated talk J. Nam)

- In general, 6 new ZEUS preliminaries and 2 new papers since last DIS (2 on HFL)
  -> ZEUS team is small, but alive and well, new collaborators and ideas welcome
Backup slides
Selection cuts and MC

data samples:
- HERA II, 03-07, L ~ 377 pb^{-1}

event selection:
- \text{CAL } E_T > 8 \text{ GeV} \ (\approx 2 \text{ m}_b - \text{missing neutrinos, proton remnant and DIS } e \text{ cand. removed})
- cut on muon } E_T \text{ fraction } (0.1 < p_T^{\mu\mu}/E_T < 0.7_{\text{high } m} / 0.5_{\text{low } m})
- |zvtx| < 30 \text{ cm}, \sqrt{(xvtx^2+yvtx^2)} < 3 \text{ cm}, \text{muon } p_T \text{ asym. } < 0.7, \ \Delta \eta^{\mu\mu} < 3, \ \text{anti-cosmic cuts}
- ‘or’ of muon, hadronic charm, and dijet triggers

muon selection:
- two muons, \( m^{\mu\mu} > 1.5 \text{ GeV} \)
- \( p_T^{\mu} > 0.75 \text{ GeV} \) for high muon quality \( \geq 5 \), \( p_T^{\mu} > 1.5 \text{ GeV} \) for low muon quality
- simplified for differential cross sections: \( p_T^{\mu} > 1.5 \text{ GeV} \) for both muons

MC samples:
- \textbf{beauty and charm: } RAPGAP (\( Q^2 > 1 \text{ GeV}^2 \)) and PYTHIA (\( Q^2 < 1 \text{ GeV}^2 \))
- \( J/\psi, \ psi', \text{Upsilon}, \text{Bethe-Heitler}, \) each DIS/\gamma p from various generators
- \( J/\psi (p_T) \) and Upsilon (\( Q^2 \)) MCs reweighted to data distributions
- muon efficiency corrections applied (from independent data set)
**Theoretical tools**

identical to HERA I

**FMNR**
- Fixed order NLO in the massive mode (PHP regime)
- Mass of the \( b \) quark \( m_b = 4.75 \text{ GeV} \), \( (4.5 - 5.0) \)
- \( \mu_R \) and \( \mu_F : \) \[ \mu^2 = m_b^2 + p_{Tb}^2 \] \( (\mu/2 - 2\mu) \)
- Proton: CTEQ5M  Photon: GRV-G-HO
  (PDF error \( << \) scale/mass error \( \rightarrow \) neglected)

For visible cross sections - identical procedure as for \( b \rightarrow D^*\mu \) paper:

**FMNR + Pythia**


- In FMNR weighted events with positive and negative weights spanning over 8 orders of magnitude \( \rightarrow \) “naive” interface very inefficient, not practical
- Use weight range reduction (**REDSTAT**) to \( \sim 1 \) order of magnitude preserving NLO accuracy
  - events with large + and – weights but similar topologies are “averaged”
QCD fit with $x_{Bj} > 0.01$ for inclusive data

charm and beauty mass floating

gluon at $x < 0.01$ inconsistent with inclusive fit
FONLL-C fit of inclusive data

arXiv:1802.00064 (XFitter team):
FONLL-C inclusive fit with and without NLLx resummation

personal remark:
FONLL-C inclusive fit with NLLx qualitatively consistent with FF charm
+ x > 0.01 inclusive fit (compare previous slide)
→ combine both worlds by applying NLLx to light flavours only in FF scheme?

Figure 3: The up valence PDF $xu_u$, the gluon PDF $xg$ and the total singlet PDF $xΣ$ for the final fits with (NNLO+NLLx) and without (NNLO) $\ln(1/x)$ resummation.
beauty from inclusive dijets + vtx

use significance of secondary vertex

simultaneous fit of mirrored significance for three different mass ranges
NLO vs. LO + parton shower

"direct $\gamma$"

"resolved $\gamma$"