Introduction

Measurements using beauty tagging by

- muons and jets, HERA I + new HERA II
- lifetime information
- double tags: muon + D* or muon + muon

Comparisons and Summary
Various scales involved:

$Q^2 < 1 \text{ GeV}^2$ : Photoproduction ($\gamma P$)

$Q^2 > 1 \text{ GeV}^2$ : Deep Inelastic Scattering (DIS)

$M_b \sim 5 \text{ GeV}$ and $p_T^b \sim \text{ few GeV}$

- **Powerful tool** to test pQCD, measure g-density in proton and study **hadronic components** of photon.

Heavy quarks are dominantly produced via direct **photon-gluon fusion**: $\gamma g \rightarrow bb$

+ resolved contributions ...

"c/b-excitation"
QCD Calculations for Open Beauty

LO and PS programs:

- **PYTHIA**: direct and resolved (inc. flavour-excitation), DGLAP evolution
- **RAPGAP**: direct and resolved, CCFM-like evolution
- **CASCADE**: direct only, CCFM-like evolution

NLO calculations in pQCD used here:

- **FO = fixed order in** $\alpha_s$, **massive quarks** scheme: valid for $p_t \sim m_Q$
  - uses fixed number of active flavours in $p$ and $\gamma$ (FFNS),
    - **FMNR** in photoproduction (direct + resolved), with CTEQ5M + GRV-G HO pdfs: Frixione, Mangano, Nason, Ridolfi
    - **HVQDIS** in DIS (direct), with CTEQ5F4 pdf: Harris+Smith

**Jets** for NLO: run jet algorithm on partons, then correct to hadron level with MC [ O(5%) ]

**D*, µ** – final states: fold Q with fragmentation function (e.g. Peterson) and add semileptonic decays for $\mu$
Exploit large B-mass and long B-lifetime

- $p_{T}^{\text{rel}} = p_{T}$ of $\mu$ w.r.t. jet axis: large for $b$ due to $b$-mass
- $\delta = $ signed impact parameter of track (e.g. $\mu$) w.r.t. primary vertex (using Si-vertex detectors); sign defined by jet-direction
- $S = \delta / \sigma(\delta) :$ impact parameter significance
  - $S1 =$ highest $S, \ S2 =$ 2nd highest $S$ with same sign
  - positive tails for $b$ and $c$ due to lifetime
  - symmetric around zero for light-flavours

**Determination of $b$-cross section:**
- extract fractions of $b$, $c$- and $uds$- by fitting distributions ($p_{T}^{\text{rel}}, \delta, Si$) using MC templates for shape functions
Beauty Tagging
with muon and jets
Select events with muon and jet(s)

likelihood fit to \((p_t^{\text{rel}}, \delta)\) distributions; example below yields 30% b-fractions

Sum is described
**b-tag μ+2j: δ and $p_t^{\text{rel}}$ in $\gamma p: H1 + ZEUS$**

H1: 2D-fit to $p_t^{\text{rel}}$ and δ ($\sim 50$ pb$^{-1}$);

ZEUS: fit to $p_t^{\text{rel}}$ ($\sim 110$ pb$^{-1}$)

- General agreement between H1 and ZEUS
- NLO (FMNR): shape close, agreement within errors

H1 excess at low $p_t^{\mu}$
b-tag $\mu+2j$: $\delta$ and $p_t^{\text{rel}}$ in $\gamma p$: H1 + ZEUS

H1: $Q^2<1$ GeV$^2$, $0.2<y<0.8$; $p_t^{\text{jet}}>7(6)$ GeV, $|\eta_{\text{jet}}|<2.5$; $p_t^{\mu}>2.5$ GeV, $-0.55<\eta_{\mu}<1.2$;

ZEUS: $Q^2<1$ GeV$^2$, $0.2<y<0.8$; $p_t^{\text{jet}}>7(6)$ GeV, $|\eta_{\text{jet}}|<2.5$; $p_t^{\mu}>2.5$ GeV, $-1.6<\eta_{\mu}<1.3$;

$|p_t^{\mu}|>1.0$ GeV AND $p^{\mu}>4.0$ GeV in $1.48<\eta_{\mu}<2.3$

LO: Pythia fails at $x_\gamma=1$ in H1, Cascade fails at low $x_\gamma$ in ZEUS

NLO: reasonable agreement (large uncertainties)

Christoph Grab, ETHZ

Photon 2005
**b-tag \( \mu + j \): \( \delta \) and \( p_t^{\text{rel}} \) in DIS: H1**

H1: \( 2 < Q^2 < 100 \text{ GeV}^2 \), \( 0.1 < y < 0.8 \); \( p_t^{\mu} > 2.5 \text{ GeV} \), \( -0.55 < \eta_\mu < 1.2 \); \( p_t^{\text{jet}} > 6 \text{ GeV} \), \( |\eta_{\text{jet}}| < 2.5 \)

- **NLO (HVQDIS): norm low, in particular in forward direction**
- **Data softer**
- **NLO (HVQDIS): norm low at low pt**

\[ \frac{d\sigma}{d\eta^{\mu}} \text{[pb]} \]  

\[ \frac{d\sigma}{dp_t^{\mu}} \text{[pb/GeV]} \]
b-tag $\mu+j$: $\delta$ and $p_t^{\text{rel}}$ in DIS: H1

ZEUS: $Q^2 > 2 \text{ GeV}^2$, $0.05 < y < 0.7$; $p_t^{\mu} > 2.0 \text{ GeV}$ for $-0.9 < \eta_{\mu} < 1.3$; AND $p_t^{\mu} > 2.0 \text{ GeV}$ in $-1.6 < \eta_{\mu} < -0.9$; $E_t^{\text{jet}} > 6 \text{ GeV}$, $-2 < \eta_{\text{jet}} < 2.5$

Same general message …
Beauty tagging with muon and jets

ZEUS with MVD in HERA-II data
ZEUS Microvertex Detector at HERA-II

Barrel: 3 layers, double sided strips, 65 cm length, covering 30 - 150°

- Beam spot size: 110 x 30 µm².

D⁺ candidate

Lifetime effects $\Rightarrow$ asymmetric $\delta$
HERA-II results for 33 pb$^{-1}$ from a 2-D fit ($\delta, p_t^{\text{rel}}$) yield:

\[ f_b = (16.7 \pm 2.6)\% \quad f_c = (52 \pm 10)\% \]

- no excess seen at low $p_T^{\mu}$

- agreement with previous measurements (used $p_t^{\text{rel}}$)

- pQCD NLO (FMNR) including had. corrections describes data well
Beauty tagging using inclusive lifetime in $\gamma p$ 2 jets, no muon
New measurement without muons: fit to subtracted S1, S2 distributions, using MC shape templates

→ See SF-talks for details on method

Q^2_{<1 \text{ GeV}^2}; \ 0.15 < y < 0.8; \ p_T(jet) > 11(8) \text{ GeV}; \ -0.88 < \eta(jet) < 1.3; \text{ from 57.7 pb}^{-1}
Double tagging using $D^*$-muon correlations
Double Tagging

Tag BOTH b quarks by either a

- $D^* \rightarrow (K\pi) \pi$ and/or muon from semileptonic decay

A) $D^* \mu : H1, ZEUS$ : Correlate charges and azimuthal angular separation $\Delta \phi (D^*-\mu)$

B) $\mu\mu : ZEUS (prel)$ : Correlate charges and $M_{\text{inv}} (\mu\mu)$

→ Obtain $\sigma$ by fitting $b,c,LF$- fractions in 4 correlation regions

😊 Large phase-space for $b$:
- No jets required: reach lower $p_t(b)$
- Large $\mu$-acceptance in $\eta$ of ZEUS
**D*μ correlations in γp : H1**

Population of 4 corr. regions well described

- **Charm**: good agreement
- **Beauty**: NLO too low

**Charm**:

\[
\sigma_c^{\text{vis}}(ep \to e D^* \mu X) = 250 \pm 57 \pm 40 \text{ pb} 
\]

(NLO: \(286^{+159}_{-59}\text{ pb}\))

**Beauty**:\n
\[
\sigma_b^{\text{vis}}(ep \to e D^* \mu X) = 206 \pm 53 \pm 35 \text{ pb} 
\]

(NLO: \(52^{+14}_{-9}\text{ pb}\))

- \(Q^2 < 1 \text{ GeV}, \ 0.05 < y < 0.75;\)
- \(p_t^{\mu} > 2 \text{ GeV}, |\eta_{\mu}| < 1.735;\)
- \(p_t(D^*) > 1.5 \text{ GeV}, |\eta(D^*)| < 1.5\)
**D*μ correlations in γp : H1**

**Effects of higher orders (LO vs NLO) expected:**

- $p_t(D^*μ)$: flatter
- $Δφ(D^*μ)$: more spread out at 180°

visible and in agreement with NLO
Beauty tagging with muon-muon correlations
Two muon event measured with ZEUS detector
\textbf{\(\mu\mu\) correlations : ZEUS signal}

- Take all \(\mu\mu\) invariant masses, fit the (unlike-sign – like-sign –BG) data
- Exploit data for background determination/suppression:
  - use non-isolated muon pairs to reduce \(J/\psi, \psi', \) Bethe-Heitler \(\mu\mu\)-pair background
  - remove fake \(\mu\)-background by taking difference between unlike-sign and like-sign samples (light flavour cancels, if assumed equal in ++ and +-)
  - charm contribution (to unlike-sign only) estimated from \(D^*\mu\) sample (no charm in like-sign high-mass) and fixed in fit

\begin{itemize}
  \item \(\mu\) pairs: unlike-sign (non-isolated), all masses (low+high)
  \item breakdown: MC agrees
\end{itemize}
**μμ correlations in γp + DIS: ZEUS**

(For differential $d\sigma$: cuts on $\mu$: $p_T(\mu)>1.5$ GeV, $-2.2<\eta(\mu)<2.5$)

$M_{\mu\mu}>3.25$ GeV leaves two $\mu$'s from different $b$'s

**LO**: shapes agree, norm 2x too low

**NLO**: (FMNR) agrees within errors
Double tag: $D^*\mu$ and $\mu\mu$ vs NLO: H1&ZEUS

D$^*$\mu H1 PHP (visible)

D$^*$\mu ZEUS PHP [ $\eta(b)<1$, $y$ ]

D$^*$\mu ZEUS DIS [ $\eta(b)<1$, $y$ ]

\(\mu\mu\) ZEUS all $Q^2$: total inclusive [ large $b$-phase space down to $p_t(b)\approx 0$ ]

NLO: normalisation still below data in ALL cases!
Comparison of various results with theory
Comparison with pQCD NLO: \( \text{FMNR}(\gamma p) + \text{HVQDIS (DIS)} \)

- NLO predictions are still below data…
  … both in \( \gamma p \) and DIS

To be settled in NLO:
- improve description of hadronisation
- resolved part is incomplete (no excitation graphs…)
- Possibly MC@NLO will help … ?
Summary

Beauty with jets and muons: discrepancies dwindle away…
- New measurements do not confirm the large excess seen earlier, BUT NLO predictions lie still below data, both in $\gamma p$ and DIS
- Differential shapes deviate only in a few regions (low $p_t$, forward $\eta$, low $x_\gamma$), seen in different measurements.

Measurements with double tags: $D^* - \mu$ and $\mu - \mu$ correlations:
- statistically still limited
- allow access to lower $p_t$ and lower $E_{\text{cms}}$
- exhibit effects of higher orders in shapes

HERA-II: impressive first measurements …

With new HERA-II statistics, we hope to reach similar precision in $b$ as we have in charm …
Optional Slides
\( \mu + \text{jets} : \text{H1 selection} + \text{errors (opt)} \)

- Select \( \geq 1 \) muon with 2 CST-hits, with \( p_t > 2.5 \text{ GeV}, \ -0.55 < \eta < 1.1 \)
- Select jets, using incl. \( k_T \)-algorithm
- Photoproduction: \( Q^2 < 1 \text{ GeV}; \ 0.2 < y < 0.8 \)
  - \( \geq 2 \) jets (in lab-frame): \( p_t(jet) > 7(6) \text{ GeV}, \ |\eta| < 2.5 \)
  - FMNR: \( m_b = 4.75; \ CTEQ5M + GRVG-HO; \ \epsilon = 0.0033 \)
    - variation: \( \Delta \sigma (m_b + \text{scale}) = 25\%; \ \Delta \sigma (\epsilon + 25\%) = 3\%; \ \Delta \sigma (\text{PDF}) < 8\%; \)
    - hadronisation corrections: -30\% to +5\%

- DIS: \( 2 < Q^2 < 100 \text{ GeV} ; \ 0.1 < y < 0.8 \) (\( e-\Sigma \)-method)
  - \( \geq 1 \) jet (in Breit-frame): \( p_t (jet) > 6 \text{ GeV}, \ |\eta| < 2.5 \)
  - HVQDIS:
    - \( m_b = 4.75; \ CTEQ5F4; \ \epsilon = 0.0033 \)
    - variations: \( \Delta \sigma (m_b + \text{scale}) = 15-20\%; \)

- major sys.error: track/\( \delta \) resolution = 7\%; fragmentation uncertainty (Lund/Peter)=7\%
μ + jets : ZEUS selection + errors (opt)

- Select ≥1 muon with $p_t^\mu > 2.5$ GeV in $-1.6 < \eta_\mu < 1.3$;
  
  \[ p_t^\mu > 1.0 \text{ GeV AND } p^\mu > 4.0 \text{ GeV in } 1.48 < \eta_\mu < 2.3 \]

- Photoproduction: $Q^2 < 1$ GeV; 0.2 < y < 0.8
  
  - ≥ 2 jets (in lab-frame) : $p_t(jet) > 7(6)$ GeV, $|\eta| < 2.5$
  
  - FMNR:
    - $m_b=4.75$; CTEQ5M + GRVG-HO; eps=0.0035
    - variation $\Delta\sigma (m_b+\text{scale}) = +34\%/-22\%$; $\Delta\sigma (\text{eps}) < 3\%$; $\Delta\sigma (\text{PDF}) < 4\%$;
    - hadronisation corrections: -20\% in rear-30\% to -3\% in fwd
H1 Vertex detector (opt)

Forward, Central and Backward Silicon Trackers

CST is used in this analysis:

- Two layers, cylindrical (Hera-I) at 5.7 and 9.7 cm radii; double sided strips
- $30 < \theta < 150^\circ$ polar angles
- Hit resolution: $12 \ (25) \ \mu m$ in r-phi (z)
- Efficiency to link 2 CST-hits: 72%
- Tracks with 2 CST-hits:
  - DCA-resolution = $33 +90/p_t \ [\mu m / GeV]$
  - Beamspot: $145 \times 25 \ \mu m^2$ measured with $5 \ \mu m$ accuracy
Exploit correlations: charges $Q(D^*, \mu)$ and azimuthal separation $\Delta \phi(D^*, \mu)$

<table>
<thead>
<tr>
<th>$Q(D^*) = Q(\mu)$</th>
<th>$\Delta \phi \approx 0^\circ$</th>
<th>$Q(D^*) = -Q(\mu)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta \Phi &lt; 90^\circ$</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>charm (%)</td>
<td>3.8</td>
<td>20.4</td>
</tr>
<tr>
<td>beauty (%)</td>
<td>6.0</td>
<td>50.0</td>
</tr>
</tbody>
</table>

Beauty in regions II, II, IV:
- $\Delta \phi \approx 180^\circ$; $Q(D^*) = -Q(\mu)$ (IV)
- $\Delta \phi \approx 180^\circ$; $Q(D^*) = +Q(\mu)$ (II)
- $\Delta \phi \approx 0^\circ$; $Q(D^*) = -Q(\mu)$ (III)

Charm in region IV (mostly):
- $\Delta \phi \approx 180^\circ$; $Q(D^*) = -Q(\mu)$
- no $c$ in like-sign regions

u,d,s: dominate I
- $\Delta \phi \approx 0^\circ$; $Q(D^*) = Q(\mu)$
D*\(\mu\) correlations in \(\gamma p\) : \(\sigma_{c,b}^{\text{vis}}\) (opt)

Cross sections in D*\(\mu\) variables:
- \(M(D^*\mu)\) : reflects \(E_{\text{cm}}\) (quark-pair)
- \(y(D^*\mu)\) : reflects E-ratio of quark-pair (from p or photon)

QCD : Reasonable description by both LO and NLO
μ−μ Correlations (opt)

- Mass + charge:
  - 4 regions

- Unlike-sign
  - $m_{\mu\mu} < 4$ GeV
  - $m_{\mu\mu} > 4$ GeV

- Like-sign
  - $m_{\mu\mu} < 4$ GeV
  - $m_{\mu\mu} > 4$ GeV

- $B^0\bar{B}^0$ mixing

- 4 GeV ~ $B$ mass – hadrons / vs

Mainly light flavour background

A. Longhin, INFN Padova

ZEUS: $b$ production with $\mu\mu$ correlations

DIS05 Madison (Wisconsin) 29/04/2005
μμ correlations: ZEUS selections (opt)

Selection to enhance beauty:  in HERA-I data of  \( L = 121 \) pb⁻¹;

- \( E_T(\text{all}>10.\text{deg} - \text{elec}) > 8 \) GeV
- Muon: \( \text{pt} > 0.75/1.5 \) GeV in \(-2.2 < \eta < 2.5\)
- Isolation cut: mu from b accompanied by hadrons are NOT isolated
  reduces J/ψ, ψ', Bethe-heitler di-muon production

Background reduction, (yields 40-50% b-purity):

- Open charm: MC-sample normalised to D⁻-µ data sample
- Light-flavour LF-BG:
  - Assume LF-BG is same in like-sign and unlike-sign data
  - like-sign high-mass has NO charm --> LF-BG = data − b-MC

Normalisation of signal: beauty

- Fix contributions of (charm+BH+J/ψ+ψ') and extract b-contributions
  from fit of unlike-sign data
Mu-Mu Correlations : ZEUS $\sigma_{\text{tot}}$ numbers (opt)

Visible range: 1$^{\text{st}}$ $\mu$: $p_{t\mu}>1.5$ GeV, $-2.2<\eta_{\mu}<2.5$
2$^{\text{nd}}$ $\mu$: $p_{t\mu}>0.75$ GeV, $-2.2<\eta_{\mu}<2.5$ AND $p_{\mu}>1.8$ for $\eta_{\mu}<0.6$ or $p_{\mu}>1.8$ for $\eta_{\mu}>0.6$

Prelim. visible cross section: $\sigma_{\text{vis}} = (44\pm 5 +14.1 -12.3) \text{ pb}$
extrapolate (by 300x) to full $p_{t},\eta$ range of $\mu$, all $Q^2$

Data ZEUS : $\sigma_{\text{tot}}(ep \rightarrow bbX) = (16.1 \pm 1.8 +5.3 -4.8) \text{ nb}$

- LO MC (Pythia 6.89 [Q$^2<1$] + Rapgap 0.92 ) = 7.81 nb
- NLO (FMNR 5.8 + HVQDIS 1.0) = (6.8 +3. -1.7) nb

$\Rightarrow$ LO and NLO well below data !

Main systematics of (+33% -30%): $\mu$ -efficiency, bg-subtraction, variation of pt-shape
# References for new results (opt)

<table>
<thead>
<tr>
<th>Region</th>
<th>Method</th>
<th>Collab</th>
<th>Reference</th>
<th>Published</th>
</tr>
</thead>
<tbody>
<tr>
<td>Php + DIS</td>
<td>Incl. lifetime tag</td>
<td>H1</td>
<td>Prel. 04-173</td>
<td></td>
</tr>
<tr>
<td>Php + DIS</td>
<td>D* - mu correlation</td>
<td>H1</td>
<td>DESY 05-040</td>
<td></td>
</tr>
<tr>
<td>Php + DIS</td>
<td>Mu + jets</td>
<td>H1</td>
<td>DESY 05-004</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Dijet, inclus.vtx</td>
<td>H1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DIS</td>
<td>Impact param, F_2bb</td>
<td>H1</td>
<td>DESY 04-209</td>
<td>E.J.Phys. C40 (05) 349</td>
</tr>
<tr>
<td>Low Q2</td>
<td>Impact param, F_2bb</td>
<td>H1</td>
<td>DESY 05-110</td>
<td></td>
</tr>
<tr>
<td>PHP</td>
<td>Mu + jets</td>
<td>ZEUS</td>
<td>DESY 03-212</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mu + jets; Hera-II MVTX</td>
<td>ZEUS</td>
<td>Prel- CHEP04</td>
<td></td>
</tr>
<tr>
<td></td>
<td>D* - mu correlation</td>
<td>ZEUS</td>
<td>Prel- EPS-03</td>
<td></td>
</tr>
<tr>
<td>Php + DIS</td>
<td>Mu + mu correlation</td>
<td>ZEUS</td>
<td>Prel; Cont. DIS05</td>
<td></td>
</tr>
<tr>
<td>DIS</td>
<td>Mu + jets; Q&gt;2</td>
<td>ZEUS</td>
<td>DESY 04-070</td>
<td>PL B599 (04) 174</td>
</tr>
</tbody>
</table>