Summary of Heavy Flavour Working Group

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WG3 convenors:
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contact persons: K. Lipka, U. Uwer

2nd HERA-LHC workshop, CERN, 9.6.06

- introduction
- open heavy flavour production
- parton density functions (joint with WG1)
- fragmentation
- inelastic quarkonium production ($J/\psi$)
- conclusions

thanks to WG3 speakers and O. Behnke for providing slides
The HERA ep collider and experiments

HERA I: $\sim 130 \text{ pb}^{-1}$ (physics)
HERA II so far:
$\sim 350 \text{ pb}^{-1}$
($\sim 230 \text{ pb}^{-1}$ physics)
goal:
$\sim 700 \text{ pb}^{-1}$ till 2007

$E_e = 27.6\text{GeV}, E_p = 920\text{GeV}$

$s = 2\sqrt{E_e E_p} = 319\text{GeV} \Leftrightarrow E_\beta = 54.1\text{TeV}$

polarisation: $P(e) = -0.5...0...+0.5$

$L_{\text{spec}} \approx 4...16 \cdot 10^{29} \text{cm}^{-2} \text{s}^{-1} mA^{-2}$

$I_e = 20...50 mA, I_p = 60...100 mA$
Design luminosity $L = 10^{34} \text{cm}^{-1}\text{s}^{-1}$
$\sim 100 \text{ fb}^{-1}/\text{year}$
Pile up $\sim 20$ collisions/crossing
40 MHz pp bunch-crossing rate

Start-up luminosity $L \approx 10^{33} \text{cm}^{-1}\text{s}^{-1}$
$\Rightarrow \sim 10 \text{ fb}^{-1}/\text{year}$

expected completion: mid 2007

<table>
<thead>
<tr>
<th>Beams</th>
<th>Energy</th>
<th>Luminosity</th>
</tr>
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<tbody>
<tr>
<td>LEP</td>
<td>$e^+ e^-$</td>
<td>200 GeV</td>
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<tr>
<td>LHC</td>
<td>p p</td>
<td>14 TeV</td>
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<td>Pb Pb</td>
<td>1312 TeV</td>
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</table>
b production at LHC

V. Andreev

- b production at hadron colliders
  - Huge cross section
  - Challenge for perturbative QCD
  - New physics searches: b jets as a signal feature
  - Dominant process: gg fusion
Fit results for b-jets in CMS

QCD events \( 120 < P_{t} < 170 \) GeV/c

Muon \( P_{t} \) w.r.t. the closest B jet

after muon + vertex tag

Fit:

\[ \begin{align*}
Nb &= 2750 \pm 346 \\
Nc &= 702 \pm 513 \\
Nudsg &= 329 \pm 235
\end{align*} \]

---

V. Andreev

\[ \begin{align*}
Nb &= 2503 \ (66\%) \\
Nc &= 965 \ (26\%) \\
Nudsg &= 299 \ (8\%)
\end{align*} \]

3767 events

3781 events
Open Heavy Flavour production in $ep$ scattering

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

- Driven by gluons in the proton
- Relevant scales:
  \[ m_b \sim 5 \text{ GeV}, \quad m_c \sim 1.5 \text{ GeV} \]
  \[ Q^2 \lesssim 1 \text{ GeV}^2 \rightarrow \gamma p \]
  \[ > 2 \text{ GeV}^2 \rightarrow \text{DIS} \]
  \[ p_T^{b,c} \]
  Event selection: $p_T^{\text{jet}} > 6$ or $7 \text{ GeV}$

multiscale problem

- terms $[\alpha_s \ln (Q^2/m_Q^2)]^n$, $[\alpha_s \ln (p_T^2/m_Q^2)]^n$, etc.
- in perturbative expansion $\rightarrow$ potentially large th. errors
pQCD approximations

assume one dominant hard scale:

**Massive scheme:** \( \rightarrow m_b \)
- \( b \) massive
- neglects \([\alpha_s \ln(Q^2/m_b^2)]^n\)

\( \rightarrow \) Perturbative production:

\[\begin{array}{c}
\text{e}^+ \\
\gamma \\
\sqrt{\alpha_s} \\
g \rightarrow \ \text{c, b} \\
p \\
\text{c, b} \\
\text{FONLL or GM-VFNS}
\end{array}\]

**Massless scheme:** \( \rightarrow p_T, Q^2 \)
- \( b \) massless!!!
- Resums \([\alpha_s \ln(Q^2/m_b^2)]^n\)

\( \rightarrow b \) also in Proton and Photon!

\[\begin{array}{c}
\text{e}^+ \\
\gamma \\
\sqrt{\alpha_s} \\
g \rightarrow \ \text{c, b} \\
p \\
\text{c, b} \\
\text{NLL or ZM-VFNS}
\end{array}\]

which describes HERA data best?
Charm tags

- $\sigma_{uds} : \sigma_{charm} : \sigma_{beauty} \sim 2000 : 200 : 1$
- \text{\bf HERA is charm factory}
- meson tag, e.g. $D^* \rightarrow K \pi \pi$
- lifetime tag, e.g. $D^+$ (or inclusive)

\[ \text{always } p_{Tc} > m_c! \]
Charm in photoproduction

QCD calculations using
CTEQ5M1 + AFG structure functions
\( m_c = 1.5 \pm 0.2 \text{ GeV}, \quad \mu_0^2 = m_c^2 + p_T^2, \)
\( \mu_r = \mu_f = \mu, \quad \mu_0/2 < \mu < 2\mu_0 \)
\( f(c \rightarrow D^*) = 0.235 \)
\( e_{\text{Peterson}} = 0.035 \text{ (FO NLO), 0.02 (FONLL)} \)

- **NLO** (FMNR)  reasonable agreement
  some deviations at forward \( \eta \)

- **FONNL** (Cacciari et al.)  similar, not better at large \( p_T \)

- **NLL** (Kniehl et al.)  larger norm., shape not better

\[ p_T(D^+) \quad (\text{GeV}) \]
\[ \eta(D^+) \]

13. 12. 05  A. Geiser,  WG3 summary, HERA-LHC workshop
ALICE heavy-flavour potential

- ALICE combines electronic ($|\eta|<0.9$), muonic (-4<$\eta$<-2.5), hadronic ($|\eta|<0.9$) channels

- ALICE covers low-$p_T$ region (similar to HERA)

- ALICE covers central and forward regions

1 year pp 14 TeV @ nominal lumin.
Model comparisons

\[ \text{charm} \]

- FO NLO (MNR)
- \( k_T \text{ fact. (CASCADE)} \)
- FONLL

\[ \text{beauty} \]

- FO NLO (MNR)
- \( k_T \text{ fact. (CASCADE)} \)
- FONLL

\[ |y| < 2.5 \]

\[ \begin{align*}
d\sigma/dp_T & [\text{mb/GeV}] \\
|y| < 2.5 &
\end{align*} \]

Good agreement between FO NLO and FONLL

\[ k_T \text{ factorization} + \text{LO (CASCADE)} \] higher at large \( p_T \)
Conclusions for HERA/LHC

- **LHC**: b production at LHC kinematically similar to c production at HERA. 
  spread of predictions between NLO and NLL schemes gives indication of theoretical uncertainties

- **HERA**: both NLO and NLL schemes give reasonable predictions 
  need more statistics at high pT 
  need reduction of theoretical uncertainties
NLO vs. LO + parton shower at HERA

"direct $\gamma$"

"resolved $\gamma$"
NLO vs. LO + parton shower

**direct enriched**

**resolved enriched**

**ZEUS**

NLO

norm. OK

shape X

data:

charm + dijet

LO+PS

shape OK

norm. X

need

NNLO

or

NLO+PS (MC@NLO)

J. Loizides
Conclusions for HERA/LHC

LHC: MC@NLO (NLO+PS) exists, whenever higher order topologies are important, use it!

HERA: MC@NLO being worked on (T. Toll)
-> hope for progress by next meeting
-> will greatly enhance possibilities for comparisons with perturbative QCD
• $S_1$ significance of highest significance track (1 track events)

• $S_2$ significance of 2nd highest significance track with same sign as $S_1$ ($\geq 2$ track events)

⇒ $S_2$ provides separation power between charm and beauty
Charm in photoproduction

NLO calculation describes data reasonably well

PYTHIA is too low

CASCADE is too low at small $x_{\gamma}^{obs}$
**Beauty in photoproduction**

K. Krüger

### NLO Calculation
- NLO calculation is somewhat too low, mainly at small $x_{\gamma}^{\text{obs}}$ (resolved)
- **Pythia** is too low
- **Cascade** is too low

### OK
- **H1**
- Shape OK
- $x_{\gamma}^{\text{obs}} > 0.85$
Beauty in HERA II data

First preliminary results using new ZEUS MVD:

- first 30 pb\(^{-1}\) of HERA II data
- combine muon \(p_{T_{\text{rel}}}\) with impact parameter (muon+dijet events)

Outlook: improve by ~ order of magnitude + new double differential measurements
Conclusions for HERA/LHC

- **LHC**: perturbative QCD should yield reasonably reliable predictions of $b$ production, in particular for "leading order" topologies.

- **HERA**: exploit HERA II potential for more precise comparisons.
Small-$x$ Effects

\[ x < 10^{-4}, Q^2 \text{ in perturbative regime} \]

GLRMQ

DGLAP + non-linear $g$ recombination

→ enhanced gluon

→ enhanced $b$ production at LHC

KKMS

DGLAP + BK saturation effects

$k_T$-factorization (unintegrated PDF)

→ suppressed gluon

→ suppressed $b$ production at LHC?

accessible with HQ at HERA
Forward $J/\psi$ production at ALICE

D. Stocco

$gg$ contribution dominant

normalized to 1

$\Rightarrow$ study shape only

\[ \frac{d\sigma}{dy} \]

\[ y \]

\[ 0.9 \]

\[ 0.8 \]

\[ 0.7 \]

\[ 0.6 \]

\[ 0.5 \]

\[ 0.4 \]

\[ 0.3 \]

\[ 0.2 \]

\[ 0.1 \]

\[ 0 \]

\[ 2.4 \]

\[ 2.6 \]

\[ 2.8 \]

\[ 3 \]

\[ 3.2 \]

\[ 3.4 \]

\[ 3.6 \]

\[ 3.8 \]

\[ 4 \]

...put some constraints on gluon distribution functions in the low $x$ region
Conclusions for HERA/LHC

- **LHC:** low $x$ effects potentially very important for heavy flavour production

- **HERA:** exploit non-heavy flavour measurements to investigate this region (see WG1 and WG2)
Double tagging of $b\bar{b}$ pair

- Two direct flavour tags, e.g. $D^*\mu$ or $\mu+\mu$
- Large bg reduction, do not need jets
- Access low $p_T$ and forward regions (proton direction)

$\sim 50\%$ beauty

- Measure total beauty production cross section at HERA:

\[
\sigma(ep \rightarrow b\bar{b} + \text{anything}) = 16.1 \pm 1.8_{\text{stat}}^{+5.3}_{-4.8,\text{sys}} \text{ nb}
\]

\[
\sigma_{\text{NLO}} = 6.8^{+3.0}_{-1.7} \text{ nb} \quad (\text{FMNR+HVQDIS})
\]
New interface FMNR NLO -> PYTHIA for complicated final states

Results

Visible Beauty cross sections from $\mu\mu$

- Shape well described

NLO low, but still compatible
Beauty cross sections vs. $p_{Tb}$

$p_{Tb} \gg m_b$
better described than
$p_{Tb} \sim m_b$?
Conclusions for HERA/LHC

- **HERA:** improve both measurements (statistics) and theory (fragmentation, HO corrections) for b production near threshold

- **LHC:** top at LHC kinematically similar to b at HERA. any lessons to be learnt from this? e.g. threshold effects?
The structure of the proton

- Measure cross section

\[
\frac{d^2\sigma}{dx\,dQ^2} = \frac{2\pi\alpha^2}{Q^4x} \left\{ \left[ 1 + (1 - y)^2 \right] F_2(x, Q^2) - y^2 F_L(x, Q^2) + \ldots x F_3 \right\}
\]

\text{at high } Q^2

\text{to 0th order QCD} \ (Q^2 \gg m_q \ \text{only}!!):

- Parton distribution functions (PDF) in pQCD

\[
F_2^{\text{em}}(x, Q^2) = x \sum_i e_i^2 [q_i(x, Q^2) + \bar{q}_i(x, Q^2)]
\]

\(q_i\) – probability to find quark with flavour \(i\) in proton

\(b,c\) pair production is "higher" order QCD correction

in general: \(F_2\) structure function is not PDF

13. 12. 05

A. Geiser, WG3 summary, HERA-LHC workshop
Beauty contribution to $F_2$

**Beauty contribution to inclusive DIS**

\[
\frac{d^2\sigma^{ep}}{dQ^2 dx} \propto F_2(x, Q^2)
\]

\[
\frac{d^2\sigma^{ep\rightarrow b\bar{b}x}}{dQ^2 dx} \propto F_2^{b\bar{b}}(x, Q^2)
\]

*Use inclusive lifetime tagging to determine fraction of $b$ quark events $\rightarrow F_2^{b\bar{b}}$*
Beauty contribution to $F_2$

$F_2^{b\bar{b}}$ vs $x$ in bins of $Q^2$

- First measurements at all!
- Rise towards smaller $x$ and larger $Q^2$ $\leftrightarrow$ gluon density
- MRST04 and CTEQ6HQ differ up to factor two!
- Data described well by calculations
**Beauty contribution to $F_2$**

$F_2^{b\bar{b}}$ vs $Q^2$ in bins of $x$

- Large scaling violations
- First NNLO calculation, from Robert Thorne:
  → mostly lower than NLO (max. 40%)
- Data in agreement also with NNLO

$Q^2 \gg m_b^2$
Conclusions for HERA/LHC

- **HERA:** first measurement of $F_{2}^{bb}$ achieved
to do: improve with HERA II,
derive $b$ PDF from high $Q^2$ ($\gg m_b^2$) data

- **LHC:** $b$ PDF important input for $H$ and $Z$ production at LHC
charm contribution to $F_2$

$\rightarrow$ test/ constrain gluon density

or

$(Q^2 \gg m_c^2)$

$\rightarrow$ obtain virtual charm content (PDF) of proton
Conclusions for HERA/LHC

- HERA: to do: converge towards quantitative direct measurement of gluon distribution from charm production

- LHC: gluon distribution determined by HERA is basis for many cross section predictions
Charm fragmentation fractions

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<tbody>
<tr>
<td>$p_T(D, \Lambda_c) &gt; 3.8$ GeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$</td>
<td>\eta(D, \Lambda_c)</td>
<td>&lt; 1.6$</td>
</tr>
<tr>
<td>$f(c \rightarrow D^+)$</td>
<td>stat.</td>
<td>syst.</td>
</tr>
<tr>
<td>0.217 $\pm$ 0.014 $^{+0.013}_{-0.005}$</td>
<td>0.226 $\pm$ 0.010 $^{+0.016}_{-0.014}$</td>
<td>0.203 $\pm$ 0.026</td>
</tr>
<tr>
<td>$f(c \rightarrow D^0)$</td>
<td>0.523 $\pm$ 0.021 $^{+0.018}_{-0.017}$</td>
<td>0.557 $\pm$ 0.023 $^{+0.014}_{-0.013}$</td>
</tr>
<tr>
<td>$f(c \rightarrow D_s^+)$</td>
<td>0.095 $\pm$ 0.008 $^{+0.005}_{-0.005}$</td>
<td>0.101 $\pm$ 0.009 $^{+0.034}_{-0.020}$</td>
</tr>
<tr>
<td>$f(c \rightarrow \Lambda_c^+)$</td>
<td>0.144 $\pm$ 0.022 $^{+0.013}_{-0.022}$</td>
<td>0.076 $\pm$ 0.007 $^{+0.027}_{-0.016}$</td>
</tr>
<tr>
<td>$f(c \rightarrow D^{*+})$</td>
<td>0.200 $\pm$ 0.009 $^{+0.008}_{-0.006}$</td>
<td>0.238 $\pm$ 0.007 $^{+0.003}_{-0.003}$</td>
</tr>
</tbody>
</table>

Table 4: The fractions of c quarks hadronising as a particular charm hadron, $f(c \rightarrow D, \Lambda_c)$. The fractions are shown for the $D^+$, $D^0$, $D_s^+$ and $\Lambda_c^+$ charm ground states and for the $D^{*+}$ state.

- consistent with universality of charm fragmentation
- HERA competitive with $e^+e^-$
Charm fragmentation functions

Z. Rurikova

Comparison of Experimental results I

\[ z_{\text{hem}} = \frac{(E+p_L)_{D^*}}{\sum_{\text{hem}} (E+p)} \]

\[ \text{CLEO } \sqrt{s} = 10.6 \text{ GeV}, \]
\[ z = p_{D^*}/p_{\max} \]

\[ \text{OPAL } \sqrt{s} = 91.2 \text{ GeV}, \]
\[ z = 2E_{D^*}/\sqrt{s} \]

\[ \text{ALEPH } \sqrt{s} = 91.2 \text{ GeV}, \]
\[ z = 2E_{D^*}/\sqrt{s} \]

▶ different observable definitions
▶ different center of mass energies, thus different pert. components as well

\[ \implies \text{Direct shape comparison impossible!} \]
Conclusions for HERA/LHC

- **HERA:** more work needed on the influence of the perturbative part of heavy quark fragmentation, where universality is NOT expected

- **LHC:** universality of nonperturbative part can be safely assumed
Fragmentation at NNLO?

From the previous HERA-LHC workshop hep-ph/0601164 …

fragmentation is second largest uncertainty

QCD predictions from NLO QCD (fixed order only)
Mangano, Nason, Ridolfi (1992)
Conclusions for HERA/LHC

- expect improved predictions, in particular for LHC
  $p_{Tb}$ distributions
  top mass measurements

- test at HERA
Baryon asymmetries

\[ \frac{\Lambda^0}{\bar{\Lambda}^0} \text{ asymmetry} \]

\[ \frac{\Lambda_c}{\bar{\Lambda}_c} \text{ asymmetry should be the same!} \]
Conclusions for HERA/LHC

- try to measure Lambda_c asymmetry at HERA

- LHC can discriminate even better
**J/ψ production at Tevatron->LHC**  

**Measurements done at CDF are not consistent with the predictions of the J/ψ polarization $P_T$ dependence.**

*Recent measurements April 28, 2005*  

**LHC can improve this!**

13. 12. 05  
A. Geiser, WG3
Cross Sections \((g+g\rightarrow J/\Psi +g)\)

The prompt \(J/\Psi\) direct production using 3 different parton distribution functions.
- CTEQ3L-Green
- CTEQ5L-Red
- CTEQ6M-Blue

- Trigger efficiency (low luminosity) to select \(pp\rightarrow J/\Psi\rightarrow \mu(6\text{GeV})\mu(3\text{GeV})\) is~10\(^9\)
- Reconstruction algorithm efficiency ~6
- First year run ~ 100 days

\[10^{33}[\text{bar}^{-1}\text{sec}^{-1}] \cdot 10^{-24}[\text{particles/cm}^2] \cdot 10^{-8}[\text{bar}] \cdot 10^7[\text{sec/run\_year}] = 10^8[\text{events/year}]\]

\[10^8[\text{events/year}] \times 0.1 \times 0.6 \approx 6 \times 10^6[\text{events/year}]\]

After one year we expect 6 million events of \(pp\rightarrow J/\Psi\rightarrow \mu^+\mu^-\)
(a) leading-order colour-singlet:

direct $\gamma$: $\gamma + g \rightarrow c\bar{c}[^3S_1^{(1)}] + g$

(b) inelastic colour-octet:

direct $\gamma$: $\gamma + g \rightarrow c\bar{c}[^1S_0^{(8)}, ^3P_J^{(8)}] + g$

- **Colour Singlet (CS) contribution**
  
directly calculable
  (see e.g. talk G. Bodwin)
  available at LO and NLO

- **Colour Octet (CO) contribution**
  introduced in NRQCD to describe Tevatron data,
  not directly calculable,
  parametrized from Tevatron
  -> prediction for HERA, LO only
inelastic $J/\psi$ photoproduction

$\frac{d\sigma}{dp_T^2} (\text{nb}/\text{GeV}^2)$

- ZEUS (38 pb$^{-1}$)
- H1 (80 pb$^{-1}$) (scaled)
- KZSZ (NLO, CS)

$0.117 < \alpha_s(M_Z) < 0.121$

$1.3 < m_c < 1.6 \text{ GeV}$

- KZSZ (LO, CS)

$z$ = fraction of $\gamma$ energy carried by $J/\psi$ (in $p$ rest frame)

CS LO $\rightarrow$ NLO $\sim$ factor 3-10!
**inelastic $J/\psi$ electroproduction**

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**LO CS + CO**

**NLO CS**

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**p_T*(J/\psi) > 1 GeV**

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*Color Octet contribution not really needed to describe HERA data*

*Does NLO CS contain part of CO?*
Conclusions for HERA/LHC

HERA: status of CO contribution (NRQCD) unclear -> need HERA II measurements

LHC: since J/ψ production mechanism potentially not yet fully understood: can theoretical predictions (extrapolation Tevatron -> LHC) be trusted?
Summary and Conclusions

- Heavy Flavour production in ep and pp collisions is good testing ground for perturbative QCD

- Charm production: reasonably described, no clear preference between "massive" NLO and "massless" NLL calculations. NNLO or NLO+PS needed for some regions of phase space. HERA charm fragmentation measurements competitive with e+e-.

- Beauty production: reasonable description at high p_{Tb} -> OK for LHC getting worse (but still acceptable) at low p_{Tb}? problem with „resolved“ region? -> higher orders!

- DIS (F_2): both charm and beauty well described first measurement of F_2^{bb} -> extract b and gluon for LHC

- Inelastic J/ψ production at HERA: data acceptably described by both LO CS+CO, and NLO CS only. CO not really needed. LHC??

- HERA II performing well. Expect improved results soon!