Review of Measurements with HERA-B

Prospects for Early Measurements with LHCb

Michael Schmelling – MPI for Nuclear Physics
e-Mail: Michael.Schmelling@mpi-hd.mpg.de

Outline

- The HERA-B Experiment
- Setting the Stage for LHCb
- Selected Physics Topics
- Summary and Conclusions

Disclaimer

Cross sections and rates given below are order-of-magnitude estimates, (usually) NOT the result of detailed studies.
fixed target experiment at the HERA proton ring
C, Al, Ti, W target wires in the beam halo
forward spectrometer - layout similar to LHCb, except . . .
  ➔ only one RICH detector
  ➔ simpler ECAL system (no PS, no SPD)
  ➔ no HCAL
Kinematics

- angular coverage $10 - 220$ mrad
  - pseudorapidity very similar to range covered by LHCb
    $\eta = -\ln \tan \frac{\theta}{2} \sim [2.2 - 5.2] \sim 3.7 \pm 1.5$

- energy of the proton beam $E = 920$ GeV
  - nucleon-nucleon center-of-mass energy
    $\sqrt{s_{NN}} = \sqrt{2m_N E} \approx 42$ GeV
  - boost of center-of-mass system
    $\gamma = \frac{E}{M} \approx \frac{920}{42} \approx 22$
  - rapidity of center-of-mass system
    $y = \frac{1}{2} \ln \frac{E + p}{E - p} = \frac{1}{2} \ln \frac{(E + p)^2}{(E + p)(E - p)} \approx \ln \frac{2E}{M} \approx \ln 44 \approx 3.8$

- HERA-B is a central detector!
- study of $pA$ collisions at $\sqrt{s_{NN}} = 42$ GeV
compare particle flux in LHCb and HERA-B

rule of thumb: \( \Phi \sim \nu_{int} \cdot \ln s \cdot \Delta y \)

<table>
<thead>
<tr>
<th>Target</th>
<th>A</th>
<th>Wire</th>
<th>Run</th>
<th>triggers used</th>
<th>interactions</th>
<th>MC</th>
</tr>
</thead>
<tbody>
<tr>
<td>HERA-B nom.</td>
<td>42</td>
<td>Inner</td>
<td>14551</td>
<td>200,000</td>
<td>44,247 ± 464</td>
<td>21,489</td>
</tr>
<tr>
<td>HERA-B MinBias</td>
<td>42</td>
<td>Inner</td>
<td>14577</td>
<td>450,000</td>
<td>127,280 ± 414</td>
<td>39,997</td>
</tr>
<tr>
<td>LHCb 2008</td>
<td>14000</td>
<td>Inner</td>
<td>14606</td>
<td>150,000</td>
<td>21,928 ± 2069</td>
<td>13,679</td>
</tr>
<tr>
<td>LHCb nom.</td>
<td>14000</td>
<td>Upper</td>
<td>14639</td>
<td>300,000</td>
<td>28,520 ± 367</td>
<td>22,553</td>
</tr>
</tbody>
</table>

similar radiation loads for both experiments

→ pile-up events in nominal HERA-B operation

→ “clean” conditions for nominal LHCb running

the very first HERA-B data sets:
2. Setting the Stage for LHCb

How quickly can LHCb collect Minimum Bias events?

<table>
<thead>
<tr>
<th>Lumi</th>
<th>nr-bunches</th>
<th>pp-int/xing</th>
<th>non-empty rate</th>
<th>L0-YES</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1.1 \times 10^{29}$</td>
<td>* 4</td>
<td>0.15</td>
<td>6 kHz</td>
<td>3 kHz</td>
</tr>
<tr>
<td>$2.3 \times 10^{30}$</td>
<td>* 16</td>
<td>0.76</td>
<td>94 kHz</td>
<td>47 kHz</td>
</tr>
<tr>
<td>$2.6 \times 10^{31}$</td>
<td>936 (75 ns)</td>
<td>0.15</td>
<td>1.4 MHz</td>
<td>0.7 MHz</td>
</tr>
<tr>
<td>$2.0 \times 10^{32}$</td>
<td>2622 (25 ns)</td>
<td>0.4</td>
<td>10 MHz</td>
<td>1 MHz</td>
</tr>
</tbody>
</table>

- pessimistic/realistic scenario
  - only 4 colliding bunches at $L = 1.1 \times 10^{29} \text{cm}^{-2}\text{s}^{-1}$
  - no L0-trigger but proper timing
  - 2 kHz random trigger on filled bunches
  - 300 Hz non-empty minimum bias events to disk
  - $10^8$ events in approx. 100 hours of running
  - approx. 15 hours with L0 interaction-trigger
**Conclusion:**

Already in the first weeks after turn-on of the accelerator, LHCb should be able to log at least $10^8$ minimum bias events. Even without triggering, those should provide 10 million charm and 500,000 b-events.

- enough statistics for publishable results already at $10^{-6}$ fb$^{-1}$!
- examples will be discussed below
- remember: 2 fb$^{-1}$ per nominal LHCb year

**physics analyses**

- no existing data at $\sqrt{s} = 14$ TeV – everything is new . . .
  - interesting in its own right
  - stepping stones towards the LHCb b-physics program

**Note:**

Harvesting the initial physics already needs a working experiment, although neither ultimate precision in calibration nor HLT is required.
Check list for first data

**requirements**

- proper time alignment of all subdetectors
- data logging capabilities at the nominal rate of 2 kHz
- computing infrastructure for quasi-online reconstruction and analysis of $10^8$ Events (0.5% of the nominal annual data volume)

**calibration tasks**

- setting up and debugging of L0-trigger and HLT
  - initially run trigger offline or in transparent mode
- local and global alignment of tracking detectors
- calibration of the RICH detectors with identified particles
- ECAL calibration with $\pi^0$s
- systematic studies, for example
  - azimuthal symmetry of particle flow and charge ratios
- luminosity determination
- Monte Carlo tuning . . . not only for LHCb
**general considerations**

- $\sigma_{mb}$: $pp$ inelastic minimum bias cross section
- $N_{mb}$: number of minimum bias events recorded/scrutinized
- $\sigma$: cross section for a given signal
- $\varepsilon$: efficiency for seeing a signal event, which includes
  - limited phase space coverage of the experiment
  - detector efficiencies
  - BR for a specific decay channels of final state particles
  - selection cuts to suppress background
- the number of signal events $S$ then becomes
  \[ S = \frac{\sigma \varepsilon}{\sigma_{mb}} N_{mb} \]
- relation between signal and required minimum bias statistics
  \[ \log_{10} N_{mb} = \log_{10} S - \log_{10} \left( \frac{\sigma \varepsilon}{\sigma_{mb}} \right) \]
assume in the following $S = 100$ as “analysis threshold”, i.e.

$$\log_{10} N_{mb} = 2 - \log_{10} \left( \frac{\sigma \varepsilon}{\sigma_{mb}} \right)$$

significance $K$ in units of standard deviations of such a measurement depends on the number of background events $B$

$$K = \frac{S}{\sqrt{S + B}} = \frac{\sqrt{S}}{\sqrt{1 + B/S}}$$

- $B/S = 0 \Rightarrow K = 10$
- $B/S = 3 \Rightarrow K = 5$

try to get some estimates for $\sigma$ and $\varepsilon$ in various channels

- use published HERA-B data; apply scaling to cross sections
  - scale light flavours with inelastic $pp$-cross section
  - scale heavy flavours with $\sigma_{cc}$ and $\sigma_{bb}$

- LHCb DC04 results (mainly b-physics)
-> resulting (gu)estimates:

<table>
<thead>
<tr>
<th>process</th>
<th>$\sigma$/mb</th>
<th>$\varepsilon$</th>
<th>$\log_{10}(\sigma\varepsilon/\sigma_{mb})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$pp \rightarrow \pi^\pm X$</td>
<td>3000</td>
<td>0.1</td>
<td>0.48</td>
</tr>
<tr>
<td>$pp \rightarrow \pi^0 X$</td>
<td>1500</td>
<td>0.01</td>
<td>−0.82</td>
</tr>
<tr>
<td>$pp \rightarrow K^0 X$</td>
<td>23</td>
<td>0.02</td>
<td>−2.34</td>
</tr>
<tr>
<td>$pp \rightarrow \Lambda X$</td>
<td>11</td>
<td>0.01</td>
<td>−2.95</td>
</tr>
<tr>
<td>$pp \rightarrow \bar{\Lambda} X$</td>
<td>4.5</td>
<td>0.01</td>
<td>−3.35</td>
</tr>
<tr>
<td>$pp \rightarrow \Phi X$</td>
<td>2.5</td>
<td>0.004</td>
<td>−4.00</td>
</tr>
<tr>
<td>$pp \rightarrow D X$</td>
<td>6</td>
<td>0.0004</td>
<td>−4.62</td>
</tr>
<tr>
<td>$pp \rightarrow J/\psi X$</td>
<td>0.133</td>
<td>0.008</td>
<td>−4.97</td>
</tr>
<tr>
<td>$pp \rightarrow b\bar{b} \rightarrow J/\psi X$</td>
<td>0.133</td>
<td>0.008</td>
<td>−6.25</td>
</tr>
<tr>
<td>$pp \rightarrow \Upsilon X$</td>
<td>0.0002</td>
<td>0.01</td>
<td>−7.48</td>
</tr>
<tr>
<td>$pp \rightarrow B_d(J/\psi K_s)$</td>
<td>0.0002</td>
<td>0.0006</td>
<td>−8.92</td>
</tr>
</tbody>
</table>

with $\frac{\sigma_{LHCb}^{mb}}{\sigma_{HERA-B}^{mb}} = \frac{100 \text{ mb}}{40 \text{ mb}}$, $\frac{\sigma_{LHCb}^{cc}}{\sigma_{cc}^{HERA-B}} = \frac{10 \text{ mb}}{50 \text{ $\mu$b}}$ and $\frac{\sigma_{LHCb}^{bb}}{\sigma_{bb}^{HERA-B}} = \frac{500 \text{ $\mu$b}}{15 \text{ nb}}$
Overview

![Graph showing physics reach vs integrated luminosity]

- Trigger needed to go beyond $10^{11}$ events - i.e. to $b$-physics!
3. Selected Physics Topics

Preliminaries: Measurements without B-Field

- $\pi^0$ reconstruction
  - first signal seen by HERA-B
  - ECAL was the first detector able to take data
  - calibration of ECAL
  - mapping of radiation length
  - cross check GEANT
  - basis for all studies using photons or $\pi^0$

- search for $J/\psi \rightarrow e^+e^-$ signals
  - use a high-$p_T$ ECAL trigger
  - need at least partial coverage by ECAL plus overlap with some layers of the vtx-detector
  - use vertex-detector to veto photons
  - requires only lateral alignment in the sensitive coordinate
Compare production of positive and negative particles

- minimum requirement: working Main Tracker
- study ratios of single (or double) differential distributions

\[ R_\eta = \frac{dN^+/d\eta}{dN^-/d\eta} \]
\[ R_{p_T} = \frac{dN^+/dP_T^2}{dN^-/dP_T^2} \]
\[ R_\phi = \frac{dN^+/d\phi}{dN^-/d\phi} \]

- very simple measurement
- can be done with very low integrated luminosity
- vital for understanding charge asymmetries
- first check of the quality of the simulation
- important input for tuning of (minbias) Monte Carlo generators
Phase Space Coverage of HERA-B

- phase space coverage $\phi$ vs $\eta$ of charged tracks
- average number of reconstructed tracks
- average $p_t$ of reconstructed tracks
- comparison of data and Monte Carlo

tracks/event - Carbon

mean $p_t$ - Carbon

HERA-B and Prospects for LHCb – Selected Physics Topics

M. Schmelling / Neckarzimmern / March 12-14, 2008
Measurements of $V^0$ Production

- **neutral particles with weak decays into two charged tracks**

  - minimum requirement: working VeLo and Main Tracker
  - experimental signature:
    - secondary vertex
    - oppositely charged tracks
    - momentum pointing back to the primary vertex
  - most important $V^0$-signals:
    - $K^0_{(s)} \rightarrow \pi^+ \pi^-$
    - $\Lambda \rightarrow p \pi^-$
    - $\bar{\Lambda} \rightarrow \bar{p} \pi^+$

- analysis:
  - select oppositely charge tracks
  - require secondary vertex
  - require momentum to point back to the primary vertex
  - assign masses according to decay channel
  - histogram invariant masses
First $V^0$-Signals seen by HERA-B
**good topic for a first physics paper**

- simple early measurement, though not trivial
- can evolve quickly with improving understanding of alignment
- cross section ratios don’t require luminosity
  \[
  \frac{\sigma(\Lambda)}{\sigma(\bar{\Lambda})}(y, p_T)
  \]

  ➔ important input for models of strangeness production
  ➔ stepping stones towards \(c\)- and \(b\)-physics

- important for RICH calibration since particle-ID is done by relativistic kinematics
  ➔ consider \(\pm\)-pairs (with detached vertex)
  ➔ take the common direction of flight
  ➔ plot transverse momentum versus
  ➔ asymmetry of longitudinal momenta
  ➔ identify regions of phase space with enhanced \(p\) or \(\bar{p}\)-content

 ➔ “Armenteros-Podolanski plot”
Particle identification by relativistic kinematics

- two-body decay of a heavy particle with mass $M$
- energy-momentum conservation determines the absolute value of the center-of-mass momenta of the daughter particles
- Lorentz-transformation yields lab-momenta of the daughter particles as a function of the decay-angle $\theta$

basic relations:

\[
M = \sqrt{p_{cm}^2 + m_1^2} + \sqrt{p_{cm}^2 + m_2^2}
\]

\[
p_L = \gamma p_{cm}^L + \gamma \beta E_{cm}
\]

\[
p_T = p_{cm}^T
\]

\[
E_{cm}^2 = m^2 + p_{cm}^2
\]

\[
p_{cm}^L = \pm p_{cm} \cdot \cos \theta
\]

\[
p_{cm}^T = p_{cm} \cdot \sin \theta
\]
initial results:

\[ p_{cm}^2 = \frac{1}{4M^2} (M^4 + m_1^4 + m_2^4 - 2m_1^2M^2 - 2m_2^2M^2 - 2m_1^2m_2^2) \]

\[ E_{1cm}^c = \frac{1}{2M} (M^2 + m_1^2 - m_2^2) \]

\[ E_{2cm}^c = \frac{1}{2M} (M^2 - m_1^2 + m_2^2) \]

next, consider the asymmetry of the longitudinal momenta:

\[ \alpha = \frac{p_L^{(1)} - p_L^{(2)}}{p_L^{(1)} + p_L^{(2)}} = \frac{(p_{cm} \cos \theta + \beta E_{1cm}^c) - (-p_{cm} \cos \theta + \beta E_{2cm}^c)}{(p_{cm} \cos \theta + \beta E_{1cm}^c) + (-p_{cm} \cos \theta + \beta E_{2cm}^c)} = \frac{2p_{cm} \cos \theta + \beta (E_{1cm}^c - E_{2cm}^c)}{\beta (E_{1cm}^c + E_{2cm}^c)} = \frac{2p_{cm} \cos \theta + \frac{E_{1cm}^c - E_{2cm}^c}{M}}{\beta M} = \frac{2p_{cm}}{\beta M} \cos \theta + \frac{m_1^2 - m_2^2}{M^2} \]

result:

\[ \alpha = \alpha_0 + \frac{r_{\alpha}}{\beta} \cos \theta \quad \text{with} \quad \alpha_0 = \frac{m_1^2 - m_2^2}{M^2} \quad \text{and} \quad r_{\alpha} = \frac{2p_{cm}}{M} \]
consider the relativistic limit $\beta \to 1$

The asymmetry of the longitudinal momenta of the daughters is bounded:

$$\alpha_0 - r_\alpha < \alpha < \alpha_0 + r_\alpha$$

A combined view of $\alpha$ and $p_T$ suggests itself. One has

$$\frac{\alpha - \alpha_0}{r_\alpha} = \cos \theta \quad \text{and} \quad \frac{p_T}{p_{cm}} = \sin \alpha$$

and thus

$$\frac{(\alpha - \alpha_0)^2}{r^2_\alpha} + \frac{p^2_T}{p^2_{cm}} = 1$$

i.e. in the $(\alpha, p_T)$-plane particles from a two-body decay define an ellipse.

→ center of the ellipse:

$$(\alpha_0, 0) = \left( \frac{m^2_1 - m^2_2}{M^2}, 0 \right)$$

→ radii of the ellipse:

$$(r_\alpha, r_{p_T}) = \left( \frac{2 p_{cm}}{M}, p_{cm} \right)$$
**Example:** $V^0$-decays

- $K^0$-decay
  \[ M = 0.498 \text{ GeV} \]
  \[ m_{1,2} = 0.140 \text{ GeV} \]
  \[ p_{cm} = 0.206 \text{ GeV} \]
  \[ \alpha_0 = 0 \]
  \[ r_\alpha = 0.827 \]

- $\Lambda$-decay
  \[ M = 1.116 \text{ GeV} \]
  \[ m_1 = 0.938 \text{ GeV} \]
  \[ m_2 = 0.140 \text{ GeV} \]
  \[ p_{cm} = 0.101 \text{ GeV} \]
  \[ \alpha_0 = \pm 0.691 \]
  \[ r_\alpha = 0.181 \]
Hyperon Production at HERA-B

- systematic study of strangeness production
  - as a function of the number of strange quarks
  - as a function of target mass
  - as a function of the kinematics $x_F, y, p_T$
- further topics: polarization, correlations between strange particles, . . .
- can also be done to LHCb
$D^0 \rightarrow K\pi$

$J/\psi \rightarrow \mu^+\mu^-$

- 200 million minimum bias events recorded
- small, but significant signals seen
- $D$-signals require working RICH
- still among the best results for absolute cross sections
- needed as normalization e.g. for $J/\psi$ triggered events
Vector-Meson Production and Cronin Effect

- requirement: working RICH and Main Tracker
- important building block for advanced analyses
- single Kaon tagging is sufficient to find the $\phi$-signal
  - also interesting for RICH calibration
- at HERA-B first seen for $K^*$: Cronin-Effect
  \[ \sigma_{pA} = \sigma_{pp} A^\alpha \]  
  \[ \text{with } \alpha = f(p_T) \]
- only phenomenological explanations
  - e.g. recattering in nucleus
 → Another good candidate for an early physics paper

- measurement of $J/\psi \to \mu^+\mu^-$-cross section
- minimum requirement: working MUON-system and Main Tracker
- production ratios for open charm, based on $D^0 \to K\pi$, $D^\pm \to K\pi\pi$
- requirement: RICH plus perfectly calibrated VeLo

 önemli building blocks for many CP and rare decay analyses!

expected signal from opposite charge di-muon candidates in $10^8$ min-bias events

DC04-analysis with tight cuts based on $1.28 \times 10^7$ min-bias events
- minimum requirement: working MUON-system, Main Tracker and VeLo
- reconstruct $J/\psi \rightarrow \mu^+\mu^-$
- disentangle fractions of prompt and detached $J/\psi$s
- relate $J/\psi$ yield to primary $c\bar{c}$ and $b\bar{b}$ cross sections, using as input fragmentation functions measured e.g. at LEP

(plot by Wenbin Qian)
Result from HERA-B

**Measurement of $b\bar{b}$-cross section at $\sqrt{s} = 42$ GeV**

scatter plot of invariant mass vs decay length and resulting cross section

**Other Measurements in the $c\bar{c}$ System**

- $J/\psi$ production via $\chi_c \to J/\psi\gamma$ decays ($J^{PC}(\chi_c) = \{0, 1, 2\}^{++}$)
- $J/\psi$ spin alignment
- $\psi' \to J/\psi\gamma$
proposed new states of 4-quarks and 1 antiquark

for example:

$$\Theta^+ (uudd\bar{s}) \rightarrow pK_s^0$$

$$\Xi^{-} (ddss\bar{u}) \rightarrow \Xi^- \pi^-$$

HERA-B results:

- based upon min-bias
  - $200 \cdot 10^6$ events
  - $2.2 \cdot 10^6 K_s^0$
  - $4.7 \cdot 10^3 \Xi^-$
- no signal found!
A quick look into single lepton triggered data... 

- select opposite charge pairs
  - secondary vertex downstream of the primary vertex
  - assign pion masses
  - invariant mass consistent with $K^0_s$
- combine with another positive track
  - assign proton mass
  - construct invariant mass with the $V^0$
- highly significant signal at the $\Theta^+\text{-mass}$
A quick look into single lepton triggered data...

- select opposite charge pairs
  - secondary vertex downstream of the primary vertex
  - assign pion masses
  - invariant mass consistent with $K^0_s$
- combine with another positive track
  - assign proton mass
  - construct invariant mass with the $V^0$
- highly significant signal at the $\Theta^+$-mass

-but:
- the “signal” was fake
- the positive track was used twice
- could also be caused by a feature of the track finding program which splits a single true track into two independent ones...
Yet Another “Signal” . . .

**HERA-B data with a single high-**$p_T$** lepton trigger**

- study invariant mass spectrum of $\pi^+\pi^-$-pairs
- “clear” $B_0 \rightarrow \pi^+\pi^-$ signal . . .
  - $m(B_0) = 5.279$ GeV
  - $\text{BR}(B_0 \rightarrow \pi^+\pi^-) = 4.6 \times 10^{-6}$
  - approx. 3 million triggered events . . .

![Graph showing invariant mass spectrum](image)

- fluctuations do happen!
**Prospects for B-Physics at LHCb**

- **Integrated luminosity for first $5\sigma$ signals**
  - Based on DC04 studies (numbers by Olivier Schneider):
    - [www.cern.ch/lhcb-phys/DC04_physics_performance](http://www.cern.ch/lhcb-phys/DC04_physics_performance)

<table>
<thead>
<tr>
<th>Lumi(pb$^{-1}$)</th>
<th>Channel</th>
<th>MinBias events</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.009</td>
<td>$B_d \to D^{*-} \mu^+\nu$</td>
<td>$9.0 \cdot 10^8$</td>
</tr>
<tr>
<td>0.039</td>
<td>$B_u \to J/\psi(\mu^+\mu^-)K^+$</td>
<td>$3.9 \cdot 10^9$</td>
</tr>
<tr>
<td>0.046</td>
<td>$B_d \to D^+\pi^-$</td>
<td>$4.6 \cdot 10^9$</td>
</tr>
<tr>
<td>0.062</td>
<td>$B_d \to J/\psi(\mu^+\mu^-)K^{*0}$</td>
<td>$6.2 \cdot 10^9$</td>
</tr>
<tr>
<td>0.418</td>
<td>$B_d \to K^+\pi^-$</td>
<td>$4.2 \cdot 10^{10}$</td>
</tr>
<tr>
<td>0.427</td>
<td>$B_s \to J/\psi(\mu^+\mu^-)\phi$</td>
<td>$4.3 \cdot 10^{10}$</td>
</tr>
<tr>
<td>0.500</td>
<td>$B_s \to D_s^-\pi^+$</td>
<td>$5.0 \cdot 10^{10}$</td>
</tr>
<tr>
<td>1.176</td>
<td>$B_d \to K^{*}\gamma$</td>
<td>$1.2 \cdot 10^{11}$</td>
</tr>
<tr>
<td>1.490</td>
<td>$B_s \to K^+K^-$</td>
<td>$1.5 \cdot 10^{11}$</td>
</tr>
<tr>
<td>2.101</td>
<td>$B_d \to \pi^+\pi^-$</td>
<td>$2.1 \cdot 10^{11}$</td>
</tr>
</tbody>
</table>

→ B-Physics with exclusive decays requires HLT
Interesting LHC physics possible already with $10^8$ minimum bias events

**many use cases . . .**

- calibration of detector components
- (final) commissioning of trigger system
- first luminosity determination
- full test of computing model with real data
- first steps on the road to b-physics
- basis for tuning of (minbias) Monte Carlo
- first physics papers, such as
  - particle ratios and $V^0$-production and heavier hyperons
  - $\phi$-crosss section and other vector meson resonances
  - studies of the charmonium system and open charm
  - measurement of $c\bar{c}$ and $b\bar{b}$ cross sections, . . .