Highlights from the LHCb Ion Physics Program

Michael Schmelling – MPI for Nuclear Physics
– on behalf of the LHCb collaboration –

Outline

- Introduction
- LHCb Detector and Physics Reach
- Proton-Lead Collisions
- Lead-Lead Collisions
- Fixed-Target Physics
- Summary and Outlook
1. INTRODUCTION

- theoretical understanding of strong interactions:
  - the QCD Lagrangian is well known and tested
  - many open questions in the non-perturbative regime
    - soft processes, bound states and high densities and temperatures

- an incomplete list of things to explore. . .
  - quark gluon plasma
  - cold nuclear matter effects
  - nucleon structure at large $x$
  - intrinsic charm in the nucleon
  - spin-structure of the nucleon
  - hadronization
  - diffractive scattering
Experimental approach

- **study hadronic collisions**
  - as a function of the centre-of-mass energy
  - for different beam-target combinations
  - reference given by pp collisions

Collider mode

Fixed target mode

\[ \sqrt{s_{NN}} = 8.2 \text{ TeV} \]

\[ \sqrt{s_{NN}} = 110 \text{ GeV} \]

\[ \sqrt{s_{NN}} = 5.0 \text{ TeV} \]

\[ \sqrt{s_{NN}} = 69 \text{ GeV} \]
2. LHCb Detector and Physics Reach

Vertexing, tracking, particle-ID and calorimetry in the forward region down to low $p_T$

**Vertex detector**
- IP resolution $\sim 20\mu m$
- Decay time resolution $\sim 45$ fs

**RICH:** $K/\pi/p$ separation
- $\varepsilon(K\rightarrow K) \sim 95\%$
- Mis-ID: $\varepsilon(\pi\rightarrow K) \sim 5\%$

**Muon system**
- $\mu$ identification: $\varepsilon(\mu\rightarrow \mu) \sim 97\%$
- Mis-ID: $\varepsilon(\pi\rightarrow \mu) \sim 1\%-3\%$

**Dipole magnet**
- Bending power 4 Tm

**Tracking system**
- $\Delta p/p = 0.5\% - 1.0\%$
  (5 GeV/c – 200 GeV/c)

**Electromagnetic + hadronic calorimeters**
Angular coverage of the LHC experiments

- ALICE
  - central
  - forward muon coverage

- ATLAS & CMS
  - central detectors

- LHCb
  - forward detector
  - tracking, particle-ID and calorimetry in full acceptance

**Legend:**
- hadron PID
- muon system
- lumi counters
- HCAL
- ECAL
- tracking

LHCb Highlights - LHCb detector and Physics Reach

M. Schmelling, SQM2016, June 27, 2016
Fixed-target physics with LHCb

**SMOG: System for Measuring Overlap with Gas**

- injection of gas into interaction region
- very simple robust system
- used for a precise luminosity determination

- possibility to inject (noble) gases: He, Ne, Ar (maybe Kr)
- fixed-target physics in pA and PbA configuration
Forward extension of the detector

→ HeRSCheL: High Rapidity Shower Counters for LHCb

- scintillators at large rapidities
- up to $\pm 114$ m from IP
- central region not covered
- coverage $5 < |\eta| < 9$

→ huge gain for diffractive physics and central exclusive production

LHCb simulation results for the efficiency to see charged pions

$p_T > 0.5\text{ GeV/c}$

$p_T > 1.5\text{ GeV/c}$
### available/upcoming LHCb running modes and $\sqrt{s_{NN}}$

<table>
<thead>
<tr>
<th>$E_{\text{beam}}(p)$</th>
<th>pp</th>
<th>p-Gas</th>
<th>p-Pb/Pb-p</th>
<th>Pb-Gas</th>
<th>Pb-Pb</th>
</tr>
</thead>
<tbody>
<tr>
<td>450 GeV</td>
<td>0.90 TeV</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.38 TeV</td>
<td>2.76 TeV</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.5 TeV</td>
<td>5 TeV</td>
<td>69 GeV$^{(1)}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.5 TeV</td>
<td>7 TeV</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.0 TeV</td>
<td>8 TeV</td>
<td>87 GeV$^{(2)}$</td>
<td>5 TeV</td>
<td>54 GeV$^{(3)}$</td>
<td></td>
</tr>
<tr>
<td>6.5 TeV</td>
<td>13 TeV</td>
<td>110 GeV$^{(4)}$</td>
<td>8.2 TeV</td>
<td>69 GeV$^{(5)}$</td>
<td>~5 TeV</td>
</tr>
</tbody>
</table>

- (1) SMOG with $^{40}$Ar few h (2015)
- (2) SMOG with $^{20}$Ne 2.5 h (2012)
- (3) SMOG with $^{20}$Ne 30 min (2013)
- (4) SMOG with $^{4}$He 8 h (2015) + 2 d (2016), $^{20}$Ne 12 h (2015), $^{40}$Ar 3 d (2015)
- (5) SMOG with $^{40}$Ar 1.5 weeks (2015)

→ bridge the gap from SPS to LHC in a single experiment
**Phase space coverage of LHCb**

- **kinematic acceptance for $E_{\text{beam}}(p)$ between 450 GeV and 7 TeV**

$y^*$: rapidity in nucleon-nucleon centre-of-mass system, with forward direction (+ values) in direction of the proton/beam.
Access to parton densities

probe $x$ by inclusive particle production

mass $M$, rapidity $y$: $x_{1,2} \approx e^{\pm y} \frac{M}{\sqrt{s}}$

two $x$-values from nucleon/nuclear PDF for given $y$ and $Q^2 = M^2$

boost between lab and nucleon-nucleon centre-of-mass system

- $p$ on Pb: $\Delta y \approx 0.465$
- $p$ on gas: $\Delta y \approx 4.8$
- Pb on gas: $\Delta y \approx 4.3$
study nuclear effects:

nuclear modification factor:

\[ R_{pA}(y) = \frac{1}{A} \cdot \frac{d\sigma_{pA}/dy}{d\sigma_{pp}/dy} \]

forward-backward asymmetry:

\[ R_{FB}(y) = \frac{\sigma_{pA}(+|y|)}{\sigma_{pA}(-|y|)} \]

- pp cross-section and experimental systematics cancel in \( R_{FB} \)
- flip beam directions to measure both hemispheres

results from 1.6 \( \text{nb}^{-1} \) pPb-data recorded in 2013
$J/\psi$ and $\psi(2S)$ production in pPb collisions

- separate prompt and delayed components by a simultaneous fit of mass and pseudo-proper-time $t_z = (z_{J/\psi} - z_{PV}) \cdot M_{J/\psi}/p_z^{J/\psi}$

**pA collisions:**
- forward hemisphere
  - $1.5 < y < 4.0$
  - $p_T < 14$ GeV/c

**Ap collisions:**
- backward hemisphere
  - $-5.0 < y < -2.5$
  - $p_T < 14$ GeV/c
results require interpolation of pp cross-section to $\sqrt{s} = 5$ TeV

- $R_{pPb} \neq 1$: the nucleus is not a loose collection of independent nucleons
- tighter bound $B$-mesons less affected than prompt $J/\psi$
- $J/\psi$ data agree with “energy loss + NLO shadowing”
- consistent results from ALICE and LHCb for stronger $\psi(2S)$ suppression
- $J/\psi$ from b and $\psi(2S)$ from b expected to be consistent
$J/\psi$ and $\psi(2S)$ production in pPb collisions

$\rightarrow$ forward-backward asymmetries of $\psi(2S)$ versus $J/\psi$

- $\psi(2S)$ ratios closer to unity than $J/\psi$ ratios
- $J/\psi$ and $\psi(2S)$ consistent within uncertainties
- consistency expected by theoretical models
- resolve with 2016 pPb data (10x more than 2013)

Ferreiro et al. PRC88(2013)04791
Arleo, Peigne JHEP03(2013)122
Albacete et al. IJMPE22(2013)133007
Upsilon production in pPb collisions

- **statistics limited measurement**

- **kinematic range**: \( p_T < 15 \text{ GeV/c}, \ 1.5 < y < 4.0 \) and \(-5.0 < y < -2.5\)
- no differential measurements possible
- evidence for strong suppression of \( \Upsilon(2S) \) and \( \Upsilon(3S) \)
  - \( \Rightarrow 2016 \) data will allow a measurement
- study \( \Upsilon(1S) \) nuclear effects in common rapidity range \( 2.5 < |y| < 4.0 \)
Upsilon production in pPb collisions

$\Upsilon(1S)$ nuclear modification factor and forward-backward asymmetry

- large uncertainties
- Upsilon consistent with $J/\psi$ from b
- backward data consistent with expectations of “anti-shadowing”

- more data needed for firm conclusions
Forward production of prompt open charm in pA collisions

- $L = 0.11 \text{ nb}^{-1}$ (forward) and $L = 0.05 \text{ nb}^{-1}$ (backward)
- reconstruction in $D^0 \rightarrow K^−\pi^+ + \text{CC}$ decays
  - kinematic range: $p_T < 8 \text{ GeV/c}$, $1.5 < y^* < 4.0$ and $-5.0 < y^* < -2.5$
  - simultaneous fit of impact parameter and invariant mass
  - extraction of prompt yields down to $p_T \rightarrow 0$
**D^0** production in **pPb** collisions

→ **differential cross-sections**

- similar \( p_T \) slopes in beam and target hemispheres
- more forward production in target hemisphere
significant deviations from unity, consistent with expectations
- theoretical uncertainties larger than experimental ones
- analysis is being updated to include full statistics
- measurement of nuclear modification factor will use 5 TeV pp data
clean signals: 4 backward-candidates, 11 forward-candidates

muon selection
- $p_T > 20\,\text{GeV}/c$, $2.0 < \eta < 4.5$
- $60 < M(\mu^+\mu^-) < 120\,\text{GeV}/c^2$

cross-section results

- $\sigma_{\text{fwd}} = 13.5 \pm 5.4_{4.0}^{5.0} \,(\text{stat}) \pm 1.2 \,(\text{syst}) \,\text{nb}$
- $\sigma_{\text{bwd}} = 10.7 \pm 8.4_{5.1}^{5.1} \,(\text{stat}) \pm 1.0 \,(\text{syst}) \,\text{nb}$

(expect $\sim 250 \, Z \rightarrow \mu^+\mu^- \, \text{in 2016}$)
Two-particle correlations in pPb collisions

- measure “per trigger-particle associated yield”
  - 2-dim correlation functions of prompt particles in \((\Delta \eta, \Delta \phi)\)
  - select particles in fixed \(p_T\)-range as “trigger”
  - study all pairs of particles with the “trigger”
  - compare associated yields per trigger
    - within an event \((S(\Delta \eta, \Delta \phi))\)
    - with random combinations \((B(\Delta \eta, \Delta \phi))\) from mixed events

- definition of the experimental observable

\[
\frac{1}{N_{\text{trig}}} \frac{d^2 N_{\text{pair}}}{d\Delta \eta \, d\Delta \phi} = \frac{S(\Delta \eta, \Delta \phi)}{B(\Delta \eta, \Delta \phi)} \times B(0, 0)
\]

- \(L = 0.46 \text{nb}^{-1}\) (forward) and \(L = 0.30 \text{nb}^{-1}\) (backward)
- measurement in \(1.5 < y^* < 4.4\) and \(-5.4 < y^* < -2.5\)
- as function of relative and absolute activity in the acceptance
Two-particle correlations in pPb collisions

LHCb \( p+\text{Pb} \) \( \sqrt{s_{NN}} = 5 \text{ TeV} \)
1.0 < \( p_T < 2.0 \) GeV/c
Event class 50-100%

LHCb \( \text{Pb}+p \) \( \sqrt{s_{NN}} = 5 \text{ TeV} \)
1.0 < \( p_T < 2.0 \) GeV/c
Event class 50-100%

LHCb \( p+\text{Pb} \) \( \sqrt{s_{NN}} = 5 \text{ TeV} \)
1.0 < \( p_T < 2.0 \) GeV/c
Event class 0-3%

LHCb \( \text{Pb}+p \) \( \sqrt{s_{NN}} = 5 \text{ TeV} \)
1.0 < \( p_T < 2.0 \) GeV/c
Event class 0-3%

d\( N/d\Delta\eta/d\Delta\phi \)
d\( N/d\Delta\eta/d\Delta\phi \)

arXiv:2015.00439

low activity

high activity
Two-particle correlations in pPb collisions

quantitative results: growing near-side ridge with activity

- integrated yields vs $\Delta \phi$ outside jet peak

$$Y(\Delta \phi) = \frac{1}{0.9} \int_{2.0}^{2.9} d\Delta \eta \frac{1}{N_{\text{trig}}} \frac{d^2 N_{\text{pair}}}{d\Delta \eta d\Delta \phi}$$

- subtract offset (Zero-Yield-At-Minimum)

→ near-side ridge largest at $1 < p_T < 2$ GeV/c

→ equal relative activity:
  stronger correlation in Pb-hemisphere

→ equal absolute activity:
  similar correlation in both hemispheres
4. **LEAD-LEAD COLLISIONS**

➔ *first participation in Pb-Pb running by LHCb in December 2015*

- 24 colliding bunches, \( L = 3 - 5 \mu b^{-1} \),
- minimum bias trigger - i.e. all inelastic interactions recorded

![PbPb collision with a \( J/\psi \) candidate in 1130 reconstructed tracks](image)
Centrality determination

**ongoing work . . .**

- experimental observable: ECAL or HCAL energy sum
  - no saturation even for most central collisions
  - minimal correlation with particle production measurements

**first step: event classification in terms of ECAL activity**
- tracking may be possible up to ~15k VELO hits
- corresponding activity range: 100% - 50%

[first look at the data](https://twiki.cern.ch/twiki/bin/view/LHCb/LHCbPlots2015)
\( J/\psi \) and open charm in PbPb collisions

\[ J/\psi \rightarrow \mu^+ \mu^- \text{ decays} \]

\[ D^0 \rightarrow K^- \pi^+ + \text{CC decays} \]

[Graphs showing the distribution of candidates per 8.0 MeV/c for different mass ranges and event activity conditions.]

https://twiki.cern.ch/twiki/bin/view/LHCb/LHCbPlots2015

LHCb Highlights - Lead-Lead Collisions

M. Schmelling, SQM2016, June 27, 2016
Strangeness production in PbPb collisions

$K_S^0 \rightarrow \pi^+ \pi^-$ decays

$L \rightarrow p \pi^- + CC$ decays
**$J/\psi$ production in ultra-peripheral collisions**

→ **QED with extreme field strengths and large cross-sections**

- events containing only two tracks in the spectrometer
- coherent photoproduction of $J/\psi$ mesons

![Graph showing $M(\mu\mu)$ and $p_T(\mu\mu)$ distributions](https://twiki.cern.ch/twiki/bin/view/LHCb/LHCbPlots2015)

→ very clean signature
→ very soft transverse momentum spectrum

https://twiki.cern.ch/twiki/bin/view/LHCb/LHCbPlots2015
→ strangeness production in pNe collisions (2012) at $\sqrt{s_{NN}} = 87$ GeV
J/ψ and open charm production

charm production in pNe collisions (2015) at $\sqrt{s_{NN}} = 110$ GeV

- clean signals
- next: luminosity determination based on elastic $pe^-$ scattering
- goal: cross-section measurements for He, Ne and Ar targets

https://twiki.cern.ch/twiki/bin/view/LHCb/LHCbPlots2015
Links to other communities

- *cosmic ray physics and cosmology*
  - understanding of extensive air showers → MC tuning
  - understanding the AMS antiproton/proton ratio

AMS $\bar{p}/p$ results and modeling

use fixed-target measurements to clarify: QCD or Dark Matter annihilation
6. SUMMARY AND OUTLOOK

LHCb is much more than a pp heavy flavour experiment . . .

- participation in pp, pPb and since 2015 also PbPb running
- fixed-target physics program with (so far) \{p,Pb\} on \{He,Ne,Ar\}
- analyses of pPb collisions
  - probe nuclear effects with $J/\psi$, $\psi(2S)$ (prompt & from b), $\Upsilon$, $D^0$ and $Z$
  - 2-particle near-side ridge correlations vs relative and absolute activity
- analysis of PbPb and fixed-target data starting
  - PbPb physics results expected up to centralities around 50%
  - promising signals for large-$x$ fixed-target physics
- significantly enlarged physics reach with 2016 pPb data
  - 10x more statistics to address open issues
  - Drell-Yan production to disentangle energy loss and shadowing
  - associated $J/\psi-D^0$ production

Stay tuned to the LHCb ion physics and fixed-target program!