LHC Run 3 and Run 4 prospects for heavy-ion physics with LHCb

Pasquale Di Nezza

on behalf of the LHCb collaboration

Wuhan, 05/11/19
LHCb, specialized in heavy flavour precision physics, discovered its potentialities in HI in 2015:

- forward region $2<\eta<5$ fully instrumented
- precise vertexing: separation of prompt production from HF decay products
- precise tracking: reconstruction down to $p_T=0$
- particle identification: full reconstruction of hadronic decays of charm and beauty
- low pileup, ideal for recording high multiplicities

PbPb Data Sets:
- $\sqrt{s_{NN}} = 5$ TeV in 2015: $10 \mu b^{-1}$
- $\sqrt{s_{NN}} = 5$ TeV in 2018: $210 \mu b^{-1}$

pPb/Pbp Data Sets:
- $\sqrt{s_{NN}} = 5$ TeV in 2015: $1.6$ nb$^{-1}$
- $\sqrt{s_{NN}} = 8.16$ TeV in 2018: $30$ nb$^{-1}$
## Published results

<table>
<thead>
<tr>
<th>Title</th>
<th>Details</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Status and Prospects for Fixed Target Physics (PBC)</td>
<td>LHCB-PUB-2018-015</td>
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<tr>
<td>SMOG2 Technical Design Report</td>
<td>LHCB-TDR-020</td>
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<tr>
<td>Projections for pPb analyses in Run 3 and Run 4</td>
<td>LHCB-CONF-2018-005</td>
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<tr>
<td>First measurements of charm production fixed-target configuration at the LHC</td>
<td>PAPER-2018-023</td>
<td>PRL 122 (2019) 132002</td>
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<tr>
<td>Study of Upsilon production in pPb collisions at sqrt(sNN)=8 TeV</td>
<td>PAPER-2018-035</td>
<td>JHEP11(2018)194</td>
</tr>
<tr>
<td>Prompt Lc production in pPb collisions at sqrt(sNN)=5.02 TeV</td>
<td>PAPER-2018-021</td>
<td>JHEP 02 (2019) 102</td>
</tr>
<tr>
<td>Measurement of antiproton production in pHe collisions at sqrt(sNN)=110 GeV</td>
<td>PAPER-2018-031</td>
<td>PRL 121 (2018) 222001</td>
</tr>
<tr>
<td>Study of prompt D0 meson production in pPb collisions at sqrt(sNN)=5 TeV</td>
<td>PAPER-2017-015</td>
<td>JHEP 10 (2017) 090</td>
</tr>
<tr>
<td>Prompt and nonprompt J/ψ production and nuclear modification in pPb collisions at sqrt(sNN)=8.16 TeV</td>
<td>PAPER-2017-014</td>
<td>PLB 774 (2017) 159</td>
</tr>
<tr>
<td>Study of η(2S) production and cold nuclear matter effects in pPb collisions at 5 TeV</td>
<td>PAPER-2015-058</td>
<td>JHEP 03 (2016) 133</td>
</tr>
<tr>
<td>Measurements of long-range near-side angular correlations in sqrt(sNN)=5 TeV proton-lead collisions in the forward region</td>
<td>PAPER-2015-040</td>
<td>PLB 762 (2016) 473</td>
</tr>
<tr>
<td>Observation of Z production in proton-lead collisions at LHCb</td>
<td>PAPER-2014-022</td>
<td>JHEP 09 (2014) 030</td>
</tr>
<tr>
<td>Study of Y production and cold nuclear matter effects in pPb collisions at 5 TeV</td>
<td>PAPER-2014-015</td>
<td>JHEP 07 (2014) 094</td>
</tr>
<tr>
<td>Study of J/ψ production and cold nuclear matter effects in pPb collisions at 5 TeV</td>
<td>PAPER-2013-052</td>
<td>JHEP 02 (2014) 72</td>
</tr>
</tbody>
</table>

### Ongoing analyses:

- Flow analysis
- Low/intermediate mass dileptons (thermal radiations) analysis
- Correlations: Double J/ψ, double-D, ...
- Drell-Yan
- ...

QM19

4 talks + 5 posters
LHCb upgrade schedule

Improvements in the phase I

- Collision rate at 40 MHz
- Pile-up factor $\mu \approx 5$
- Remove L0 triggers (software trigger)
- Read out the full detector at 40 MHz
- Replace the entire tracking system

substantial improvements to HI, mainly for the possibility to reach more central PbPb collisions (up to 30%)

New Tracking system:
- Silicon upstream detector (UT)
- Scintillating Fiber Tracker (SciFi)

New electronics for muon and calorimeter systems

New pixel VELO

New RICH optics and photodetectors
3. Detector upgrade

- LHCb Upgrade 1a
  - Upgrade based on pp collision requirements:
    - Collision rate at 40 MHz.
    - Pile-up factor $\mu \approx 5$.
    - Remove L0 triggers (software trigger).
    - Read out the full detector at 40 MHz.
    - Replace the entire tracking system.

- Benefit for heavy ion physics
  - Can reach more central PbPb collisions.

- New electronics for muon and calorimeter systems
  - New Tracking system:
    - Silicon upstream detector (UT)
    - Scintillating Fiber Tracker (SciFi)
  - New RICH optics and photodetectors
  - New pixel VELO

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LHCb upgrade schedule

Run 2

- 60% less central
- 40% more central

Due to the VELO saturation, reconstruction limited to 60% less central

Run 3

- New Vertex Locator does not saturate
- Expect SciFi to saturate in most central collisions
Improvements in the phase I

- Collision rate at 40 MHz
- Pile-up factor $\mu \approx 5$
- Remove L0 triggers (software trigger)
- Read out the full detector at 40 MHz
- Replace the entire tracking system

substantial improvements to HI, mainly for the possibility to reach more central PbPb collisions (up to 30%)

- LS3 (2024 – 2026) Upgrade 1b for Run 4
  Proposal for a new tracker (stage 1): Inner tracker – 100 $\mu$m X 500 $\mu$m pixels or 0.1 mm X 100 mm strips
- LS4 (2030 – 2031) Upgrade 2 for Run 5, ...
  Proposal for a new tracker (stage 2): Inner tracker + Middle tracker
Possible LHC Run3 and Run4 schedule

<table>
<thead>
<tr>
<th>Year</th>
<th>Systems, $\sqrt{s_{\text{NN}}}$</th>
<th>Time</th>
<th>$L_{\text{int}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2021</td>
<td>Pb–Pb 5.5 TeV pp 5.5 TeV</td>
<td>3 weeks</td>
<td>2.3 nb$^{-1}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 week</td>
<td>3 pb$^{-1}$ (ALICE), 300 pb$^{-1}$ (ATLAS, CMS), 25 pb$^{-1}$ (LHCb)</td>
</tr>
<tr>
<td>2022</td>
<td>Pb–Pb 5.5 TeV O–O, p–O</td>
<td>5 weeks</td>
<td>3.9 nb$^{-1}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 week</td>
<td>500 $\mu$b$^{-1}$ and 200 $\mu$b$^{-1}$</td>
</tr>
<tr>
<td>2023</td>
<td>p–Pb 8.8 TeV pp 8.8 TeV</td>
<td>3 weeks</td>
<td>0.6 pb$^{-1}$ (ATLAS, CMS), 0.3 pb$^{-1}$ (ALICE, LHCb)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>few days</td>
<td>1.5 pb$^{-1}$ (ALICE), 100 pb$^{-1}$ (ATLAS, CMS, LHCb)</td>
</tr>
<tr>
<td>2027</td>
<td>Pb–Pb 5.5 TeV pp 5.5 TeV</td>
<td>5 weeks</td>
<td>3.8 nb$^{-1}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 week</td>
<td>3 pb$^{-1}$ (ALICE), 300 pb$^{-1}$ (ATLAS, CMS), 25 pb$^{-1}$ (LHCb)</td>
</tr>
<tr>
<td>2028</td>
<td>p–Pb 8.8 TeV pp 8.8 TeV</td>
<td>3 weeks</td>
<td>0.6 pb$^{-1}$ (ATLAS, CMS), 0.3 pb$^{-1}$ (ALICE, LHCb)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>few days</td>
<td>1.5 pb$^{-1}$ (ALICE), 100 pb$^{-1}$ (ATLAS, CMS, LHCb)</td>
</tr>
<tr>
<td>2029</td>
<td>Pb–Pb 5.5 TeV</td>
<td>4 weeks</td>
<td>3 nb$^{-1}$</td>
</tr>
<tr>
<td>Run-5</td>
<td>Intermediate AA pp reference</td>
<td>11 weeks</td>
<td>e.g. Ar–Ar 3–9 pb$^{-1}$ (optimal species to be defined)</td>
</tr>
</tbody>
</table>

Unique potentialities in pPb/Pbp at forward rapidities:
• in pPb/Pbp: L $\sim$ 30 nb$^{-1}$ in Run2 (~1M J/$\psi$, ~8M D$^0$) — L$\sim$300 nb$^{-1}$ in Run3 — 300 nb$^{-1}$ in Run4

Great potentialities in PbPb at forward rapidity:
• will benefit from detector upgrade
Drell–Yan production in pPb collisions at low dimuon mass and at forward rapidity can probe the gluon nPDF at small Bjorken-x, where gluon saturation could be observed.
Selection of few HI highlights for Run3+4

- Drell–Yan production in pPb collisions at low dimuon mass and at forward rapidity can probe the gluon nPDF at small Bjorken-x, where gluon saturation could be observed.

![Graph showing the coverage of LHCb (red), ATLAS/CMS (purple), ALICE (blue), and ALICE Muon (blue) in different collision systems](image)

Gluon saturated region

Large phase space coverage

- Can reach $x \sim 10^{-6}$ with the installation of the Magnet Tracking Station in Run4.

arXiv:1904.04130
Drell–Yan production in pPb collisions at low dimuon mass and at forward rapidity can probe the gluon nPDF at small Bjorken-x, where gluon saturation could be observed.

- **pPb:** \(L_{\text{total}} = 500 \text{ nb}^{-1}\) (4 weeks)
- **pp reference:** \(L_{\text{total}} = 104 \text{ pb}^{-1}\) (much shorter time)

At **forward rapidity** and low dimuon mass, a clear suppression is expected due to shadowing effect at low Bjorken-x.

DY production in this region is indirectly sensitive to the gluon nPDF at low \(x\), which is largely unconstrained by data except for heavy-flavour production, which might be affected by other nuclear effects.

At **backward rapidity**, the EMC effect appears, whose origin remains an active field of research.

*Already with a limited data taking period, these projections will provide valuable input for nPDF fits*. 

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**EPPS16 nPDF prediction at NLO**
Selection of few HI highlights for Run3+4

- **Drell–Yan** production in pPb collisions at low dimuon mass and at forward rapidity can probe the gluon nPDF at small Bjorken-x, where gluon saturation could be observed.

- Correlations between pairs of charm and beauty hadrons in pp and pPb. The angular distribution can be used to disentangle the contributions from different production mechanisms revealing intrinsic transverse momentum $k_T$, which may be related to the saturation scale.

The shape of the away-side peak at $\Delta \phi = \pi$ provides $k_T$ information, and is expected to be different in pPb and pp collisions.

Near $\Delta \phi = 0$ the NLO production process via gluon splitting becomes dominant and is responsible for the peaking structure.

The relative importance of these two contributions affects the initial momentum distribution of charm quarks, which is important for modelling charm thermalisation in nucleus-nucleus collisions.
Selection of few HI highlights for Run3+4

- **Drell–Yan** production in pPb collisions at low dimuon mass and at forward rapidity can probe the gluon nPDF at small Bjorken-x, where gluon saturation could be observed.

- Correlations between pairs of charm and beauty hadrons in pp and pPb. The angular distribution can be used to disentangle the contributions from different production mechanisms revealing intrinsic transverse momentum $k_T$, which may be related to the saturation scale.

- **Beauty hadron production** has negligible high-order corrections wrt charm. The production mechanism in pPb collisions provides an important reference for the study of HI collisions.

![LHCb projection](image)

Precise measurements of nuclear modification in the beauty sector will potentially enable disentangling whether these effects are due to PDF modifications or other effects, such as coherent energy loss.

The projected statistical uncertainty on the $B^+$ production cross-section is scaled using the inverse of the square root of the expected luminosity increase. The $B^+$ meson $R_{pPb}$ projection is based on the $B^+$ production cross-section measurement in pPb collisions at 8.16 TeV. The production cross-section of $B^+$ mesons is measured using two decay channels: $B^+ \rightarrow J/\psi K^+$ and $B^+ \rightarrow D^0 K^+$. 

The study of $B$ mesons is measured using two decay channels: $B^+ \rightarrow J/\psi K^+$ and $B^+ \rightarrow D^0 K^+$. 

Table 9: Numerical values of by the LHCb upgrade to study the emergent properties of QCD. These projections demonstrate the unique potential provided for the nuclear modification of heavy-flavour production, and potentially provide a new test of the saturation scale.
**System for Measuring Overlap with Gas (SMOG)** has been thought for precise luminosity measurements by beam gas imaging, but then it served as a “pseudo-target” producing interesting results.

The System for Measuring Overlap with Gas (SMOG) allows to inject small amount of noble gas (He, Ne, Ar, ...) inside the LHC beam around (\(\pm 20\) m) the LHCb collision region. Expected pressure is \(2 \times 10^{-7}\) mbar. Originally conceived for the luminosity determination with beam gas imaging, SMOG became the LHCb internal gas target for a rich and varied fixed target physics program.

- Low intensity noble gas injected in the VELO vessel (~10\(^{-7}\) mbar)
- Gas pressure 2 orders of magnitude higher than LHC vacuum

Data taking SMOG 2015-2018

<table>
<thead>
<tr>
<th>Year</th>
<th>2015</th>
<th>2016</th>
<th>2017</th>
<th>2018</th>
</tr>
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<td>PNe</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>pHe</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>pAr</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>10</td>
</tr>
<tr>
<td>pAr</td>
<td>11</td>
<td>12</td>
<td>13</td>
<td>14</td>
</tr>
<tr>
<td>PbAr</td>
<td>15</td>
<td>16</td>
<td>17</td>
<td>18</td>
</tr>
<tr>
<td>He</td>
<td>19</td>
<td>20</td>
<td>21</td>
<td>22</td>
</tr>
<tr>
<td>fHe</td>
<td>23</td>
<td>24</td>
<td>25</td>
<td>26</td>
</tr>
<tr>
<td>Ne</td>
<td>27</td>
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<td>PbNe</td>
<td>35</td>
<td>36</td>
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<td>38</td>
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</tbody>
</table>

2 papers published on PRL + other released results:

The first fixed target at the LHC

System for Measuring Overlap with Gas (SMOG) has been thought for precise luminosity measurements by beam gas imaging, but then it served as a “pseudo-target” producing interesting results.

- Low intensity noble gas injected in the VELO vessel (~10^{-7} mbar)
- Gas pressure 2 orders or magnitude higher than LHC vacuum

2 papers published on PRL + other released results:
- antiproton production in p-He collisions @ 110 GeV

During the LS2 a real storage cell will be installed
Ready to take data from Run3

The SMOG apparatus is equipped with a gas feed system, shown in Fig. 2, which allows to inject gas into the VELO vessel, Fig. 5. This system has only one feed line (used for different noble gases), and cannot provide accurate determination of the injected gas flow rate $Q$.

For SMOG2 a new GFS, schematically shown in Fig. 36, has been designed. This system includes an additional feed line directly into the cell center via a capillary, Fig. 29. The amount of gas injected can be accurately measured in order to precisely compute the target densities from the cell geometry and temperature.

Beyond the constraints requested by LHC and LHCb, the scheme shown in Fig. 36 is a well established system, operated by the proponents in previous experiments [32, 33].

7.1 Overview

The system consists of four assembly groups, Fig. 36.

(i) GFS Main Table: Table which hosts the main components for the injection of calibrated gas flow (volumes, gauges, and electro–pneumatic valves), to be located on the balcony at the P8 cavern;

SMOG2 can potentially run in synergy with the pp physics at 13 TeV
Unique kinematic region

At the LHC fixed target pp, pA, Pb-p or Pb-A collisions one has unique kinematic conditions at the poorly explored energy of $\sqrt{s} \sim 115$ GeV

$\sqrt{s} = \sqrt{2m_NE_p} = 115$ GeV

$-3.0 \leq y_{CMS} \leq 0 \rightarrow 2 \leq y_{lab} \leq 5$

$\sqrt{s_{NN}} \approx 72$ GeV

$y_{CMS} = 0 \rightarrow y_{lab} = 4.3$

Boost effect $\gamma = \frac{\sqrt{s}}{2m_p} \sim 60$

access to large $x_2$ physics ($x_F<0$)

\[ y_{CMS} = 0 \rightarrow \theta \sim 1^\circ \]

\[ y_{CMS} = -3 \]
Statistics in full synergy mode (1 yr data taking)

SMOG2 example pAr @115 GeV

### Table 1: Typical gas fluxes, peak densities, areal densities, annual running time and integrated luminosity with proton beams for different gas types.

<table>
<thead>
<tr>
<th>Storage cell assumptions</th>
<th>gas type</th>
<th>gas flow (s⁻¹)</th>
<th>peak density (cm⁻³)</th>
<th>areal density (cm⁻²)</th>
<th>time per year (s)</th>
<th>int. lum. (pb⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SMOG2 SC</td>
<td>He</td>
<td>1.1 × 10⁻¹⁶</td>
<td>10¹²</td>
<td>10¹³</td>
<td>3 × 10⁴</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>Ne</td>
<td>3.4 × 10⁻¹⁵</td>
<td>10¹²</td>
<td>10¹³</td>
<td>3 × 10³</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>Ar</td>
<td>2.4 × 10⁻¹⁵</td>
<td>10¹²</td>
<td>10¹³</td>
<td>2.5 × 10⁶</td>
<td>80</td>
</tr>
<tr>
<td></td>
<td>Kr</td>
<td>8.5 × 10⁻¹⁴</td>
<td>5 × 10¹¹</td>
<td>5 × 10¹²</td>
<td>1.7 × 10⁶</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>Xe</td>
<td>6.8 × 10⁻¹⁴</td>
<td>5 × 10¹¹</td>
<td>5 × 10¹²</td>
<td>1.7 × 10⁶</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>H₂</td>
<td>1.1 × 10⁻¹⁶</td>
<td>10¹²</td>
<td>10¹³</td>
<td>5 × 10⁶</td>
<td>150</td>
</tr>
<tr>
<td></td>
<td>D₂</td>
<td>7.8 × 10⁻¹⁵</td>
<td>10¹²</td>
<td>10¹³</td>
<td>3 × 10⁵</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>O₂</td>
<td>2.7 × 10⁻¹⁵</td>
<td>10¹²</td>
<td>10¹³</td>
<td>3 × 10³</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>N₂</td>
<td>3.4 × 10⁻¹⁵</td>
<td>10¹²</td>
<td>10¹³</td>
<td>3 × 10³</td>
<td>0.1</td>
</tr>
</tbody>
</table>

SMOG2 example pAr @115 GeV

- Int. Lumi. = 80 pb⁻¹
- Sys.error of $J/\Psi$ xsection = ~3%
- $J/\Psi$ yield = 28 M
- $D^0$ yield = 280 M
- $\Lambda_c$ yield = 2.8 M
- $\Psi'$ yield = 280 k
- $Y(1S)$ yield = 24 k
- $D\gamma \mu^+\mu^-$ yield = 24 k
Selection of few HI highlights for FT Run3+4

To reduce the uncertainties on (n)PDFs goes beyond the "simple" knowledge. Among others, it is a crucial ingredient for HEP measurements and predictions of physics processes BSM (e.g. heavy partners of the gauge bosons), fundamental input to Cosmic Ray physics, etc...

Substantial improvement of the uncertainties
Selection of few HI highlights for FT Run3+4

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- QGP and phase transition

3 experimental degrees of freedom: rapidity scan, different colliding systems, centrality dependence
LHCb @72 GeV with FT can complement the RHIC beam energy scan
Selection of few HI highlights for FT Run3+4

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- QGP and phase transition

- Color screening, sequential suppression and QGP tomography

**c\bar{c}** bound states: \(J/\psi, \chi_c, \psi', \ldots\) different binding energy, different dissociation temperature

Sequential suppression pattern

Probing:
- the longitudinal extension of the hot medium (high rapidities)
- the colliding systems of different sizes
- the centrality dependence
- with and w/o HF probes

T dependence of \(\eta/s\) by measuring the rapidity dependence of the anisotropic flow

3D+1 viscous hydrodynamic calculations
Deep in the hadronic structure

Exclusive meson production

GPDs

Photon flux $Z^2$ $J/\psi, \Upsilon$

Timelike Compton scattering

One of the objectives:
3D pictures in coordinate (impact parameter) space

GPDs

Exclusive meson production

$\gamma p$ c.m.

Already interesting results presented at this conference
With high statistics, new frontiers for the exclusive physics at LHC
Conclusions

- LHCb developed a lively and fast growing Heavy-Ion physics program, which benefits of the peculiar capabilities of the spectrometer.

- Fixed target collisions represent a real laboratory for QCD and QGP, exploiting unexplored kinematic conditions provided by a TeV-scale beam and a fully instrumented forward spectrometer.

Pasquale Di Nezza
Conclusions

- LHCb developed a lively and fast growing Heavy-Ion physics program, which benefits of the peculiar capabilities of the spectrometer.

- Fixed target collisions represent a real laboratory for QCD and QGP, exploiting unexplored kinematic conditions provided by a TeV-scale beam and a fully instrumented forward spectrometer.

In the realistic time schedule of Run3 and Run4, LHCb will give unique and groundbreaking insights on the intrinsic properties of the HI physics.