Town Meeting
Relativistic Heavy Ion Physics

LHCb
Future Plans

October 24, 2018

Burkhard Schmidt (CERN)
on behalf of the LHCb collaboration
Outline

- Introduction to the LHCb Detector and its SMOG system
  - Kinematic reach and data samples
  - Some recent results in Heavy Ion physics
- LHCb detector upgrade I and SMOG upgrade (LS2)
  - Short overview of the upgrade for Runs 3 and 4
  - Possibilities with the upgraded detector in Heavy Ion physics
- Further LHCb detector upgrade plans (upgrade II, LS4)
  - Possibilities in Heavy Ion physics with the upgrade II
- Summary and Conclusions
LHCb Detector

- Single arm spectrometer in the forward direction
  - designed for heavy flavour physics, but capable to address many other topics ...
  - fully instrumented in $2 < \gamma < 5$ with unique forward kinematics
  - Flexible trigger down to very low $p_T$

[ JINST 3 (2008) S08005 ]
[ IJMPA 30 (2015) 1530022 ]

Vertex Detector
reconstruct vertices
decay time resolution: 45 fs
IP resolution: 20 $\mu$m

Dipole Magnet
bending power: 4 Tm

RICH detectors
$K/\pi/p$ separation
$\epsilon(K\rightarrow K) \sim 95 \%$,
$\text{mis-ID } \epsilon(\pi\rightarrow K) \sim 5 \%$

Muon system
$\mu$ identification $\epsilon(\mu \rightarrow \mu) \sim 97 \%$,
$\text{mis-ID } \epsilon(\pi \rightarrow \mu) \sim 1\%$–3 %

Tracking system
momentum resolution
$\Delta p/p = 0.5\%–1.0\%$
(5 GeV/c – 100 GeV/c)

Calorimeters
energy measurement
e/$\gamma$ identification
$\Delta E/E = 1 \% \oplus 10 \%/\sqrt{E \,(\text{GeV})}$

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Town Meeting Relativistic Heavy Ion Collisions
**Fixed Target Physics with LHCb**

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

- Unique Fixed Target configuration at the LHC
- Inject noble gas (He, Ne, Ar) at $\sim 2 \times 10^{-7}$ mbar into the LHC vacuum around the interaction region.
- The gas spreads in the beam pipe around LHCb: collision vertices over $\sim 1$ m (usable range)

- Originally used to determine the luminosity, but since 2015 also to collect physics data.
- Allows to measure p-gas and Pb-gas interactions at between 69 - 110 GeV at central to backward rapidity (in nucleon-nucleon centre-of-mass system)
- Bridging the gap between the SPS (20 GeV) and RHIC (200 GeV) energy scales
Kinematic reach of LHCb

- Measurements at different $\sqrt{s}$ and in different setups allows to investigate:
  - The nucleon structure of free ($pp$) versus bound nucleons ($pA$) inside the nucleus
    - PDFs can be probed via quarkonia, electroweak bosons, Drell-Yan measurements
    - Access to very small $x$ (colliding beam mode) and large $x$ (fixed target mode)
  - Dynamics of hadronization process
    - Measurement of total cross sections, energy flow measurement, particle multiplicities
  - Complementary probes of QCD
    - Ultra-peripheral collisions: exclusive $\rho^0$ production, exclusive photo-production of $J/\psi$...

<table>
<thead>
<tr>
<th></th>
<th>$\sqrt{s}$ (GeV/c)</th>
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<tbody>
<tr>
<td>pp</td>
<td>$13$</td>
</tr>
<tr>
<td>p-Pb</td>
<td>$8$</td>
</tr>
<tr>
<td>p-SMOG</td>
<td>$110$</td>
</tr>
<tr>
<td>$W$, $Z$</td>
<td></td>
</tr>
<tr>
<td>$\Upsilon$</td>
<td></td>
</tr>
<tr>
<td>$J/\psi$</td>
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<table>
<thead>
<tr>
<th>$Q^2$ (GeV/c$^2$)</th>
<th>$Y_{MW}$</th>
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<tbody>
<tr>
<td>$10^{-6}$</td>
<td>$10^{5}$</td>
</tr>
<tr>
<td>$10^{-5}$</td>
<td>$10^{4}$</td>
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<tr>
<td>$10^{-4}$</td>
<td>$10^{3}$</td>
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<td>$10^{-3}$</td>
<td>$10^{2}$</td>
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<tr>
<td>$10^{-2}$</td>
<td>$10^{1}$</td>
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Data Samples acquired so far

- **Colliding beam mode ($p$Pb and PbPb):**
  - 1.1 nb$^{-1}$ $p$Pb, 0.5 nb$^{-1}$ Pb$p$ at $\sqrt{s_{NN}} = 5.02$ TeV (2013)
  - 13.6 nb$^{-1}$ $p$Pb, 20.8 nb$^{-1}$ Pb$p$ at $\sqrt{s_{NN}} = 8.16$ TeV (2016)
  - 10 µb$^{-1}$ PbPb at $\sqrt{s_{NN}} = 5.02$ TeV (2015) and 0.4 µb$^{-1}$ XeXe (2017)
    - aim at factor 10-20 more luminosity for the 2018 PbPb run

- **Fixed Target mode (SMOG):**
  - $\sqrt{s_{NN}}$: 69 - 110 GeV
  - $\int L dt \sim 5 \text{ nb}^{-1} \times \frac{\text{pot}}{10^{22}} \times \frac{p_{gas}}{2 \times 10^{-7} \text{mbar}} \times \text{Exp\_Efficiency}$

![Graph](image)
Some recent LHCb results

- Charm production in fixed-target configuration
- Antiproton production in fixed-target configuration

- Heavy flavour production in pPb collisions:
  - $D^0$ at 5.02 TeV: LHCb-PAPER-2017-015, JHEP (2017) 090
  - $\Lambda_c^+$ at 5.02 TeV: LHCb-PAPER-2018-021, arXiv:1809.01404
  - $J/\psi$ at 8.16 TeV: LHCb-PAPER-2017-014, PLB774 (2017) 159
  - $B^+, B^0, \Lambda_b^0$ at 8.16 TeV: LHCb-CONF-2018-004
  - $\Upsilon(nS)$ at 8.16 TeV: LHCb-PAPER-2018-035, arXiv:1810.07655

- Exclusive photonuclear $J/\psi$ production in UPC of PbPb at 5 TeV
  - LHCb-CONF-2018-003
Charm Production in pA collisions

Motivation to perform fixed-target heavy ion physics at LHC:

- Access to nPDF in anti-shadowing region
- Access to intrinsic charm content in the nucleon

- Measurement of hidden and open charm production ($J/\psi, D^o \ldots$) down to low $p_T$
- Large rapidity coverage (~3 rapidity units) at large $x_{Bj}$
Charm production in pA collisions

- $J/\psi$ and $D^0$ inclusive cross section in $p$He collisions $\sqrt{s_{NN}} = 86.6$ GeV:
  - Cross section measured in $J/\psi \rightarrow \mu^+\mu^-$ and $D^0 \rightarrow K^-\pi^+$ decays

  \[
  \sigma_{J/\psi}^{86.6\text{ GeV}} = 1225.6 \pm 62.0(\text{stat.}) \pm 81.6(\text{syst.}) \text{ nb/nucleon}
  \]

  \[
  \sigma_{D^0}^{86.6\text{ GeV}} = 156.0 \pm 4.6(\text{stat.}) \pm 12.3(\text{syst.}) \text{ µb/nucleon}
  \]

- Scaling the $D^0$ cross-section with the global fragmentation ratio $f(c \rightarrow D^0) = 0.542 \pm 0.024$, the $c\bar{c}$ production cross section can be obtained:

  \[
  \sigma_{c\bar{c}}^{86.6\text{ GeV}} = 287.8 \pm 8.5(\text{stat.}) \pm 25.7(\text{syst.}) \text{ µb/nucleon}
  \]

- LHCb results in good agreement with NLO NRQCD fit ($J/\psi$, left) and NLO pQCD predictions ($c\bar{c}$, right) and other measurements

LHCb-PAPER-2018-023
arXiv:1810.07907
Measurements of light flavor hadrons

- Antiproton/proton ratio known with great precision in cosmic rays
  - AMS 2 result: [PRL 117, 091103 (2016)]
  - PAMELA result [JETP Letters 96 (2013) 621]
- Hint for a possible excess of the $\bar{p}/p$ ratio at high energies with less energy dependence than expected
- The prediction for $\bar{p}/p$ ratio from spallation of primary cosmic rays on interstellar medium (H and He) is limited by uncertainties on $\bar{p}$-production cross-sections, particularly for $p$-He
- Predictions from soft QCD models vary within a factor 2
  - The energy scale of LHCb in fixed target mode is well suited to measure the $p$-He cross-section
Data collected in 2016 in pHe collisions at $\sqrt{s_{NN}} = 110$ GeV

Measurement compared with EPOS LHC, EPOS 1.99, QGSJET-II, QGSJETII-04m, Hijing, PYTHIA 6.4. ICRC ’17: difference summary by T. Pierog

Uncertainties smaller than model spread

EPOS LHC tuned on LHC collider data underestimates $p$-production

Unique and precise: decisive contribution to shrink background uncertainties in dark matter searches in space

Prompt $D^0$ modification factor

- $D^0$ cross-section and modification factor in $pPb$ at $\sqrt{s} = 5.02$ TeV
- $D^0$ fully reconstructed through $D^0 \to K^- \pi^+$ decays

- $R_{pPb}$ suppressed in forward region (~30%), no suppression in backward region, hint of small excess at large at backward rapidity ($y^*<-4$)
- Measurements consistent with predictions using nPDFs or CGC framework
  

- At forward rapidity measurement also consistent with CGC models
  
In fwd region: up to 50% suppression at low $p_T$, converging to unity at high $p_T$

In bwd region: $R_{pPb}$ closer to unity, intriguing low values at low $p_T$

Overall agreement with models good, but some have large uncertainties

Results are compatible with LHCb results at 5 TeV  

$\Psi(2S)$ modification factor is coming soon
Pattern consistent with $R_{pA}$ of $D^0$ mesons

- Significant suppression ($\approx 25\%$) in fwd rapidity, suppression decreases at large $p_T$
- Consistent with unity at backward rapidity
- Measurements in good agreement with $J/\psi$-from-$b$ decay data and calculations using nPDF sets [JHEP 04 (2009) 065, EPJ C77 (2017) 1, CPC. 198 (2016) 238]
$Y(nS)$ production in $pPb$

- $Y(nS)$ suppression observed in PbPb and pPb/Pbp by CMS and ALICE at low-$p_T$
- LHCb observed clear $Y(3S)$ signal in both forward and backward rapidity
- $Y(1S)$ fwd suppressed by ~30%
- $Y(1S)$ bwd compatible with 1 within nPDF uncertainties
- $Y(2S)$ additional suppression confirmed

Models:
- EPS09: JHEP 04 (2009) 065
J/ψ photo-production in UPC

- Interaction between the electromagnetic field of the ions → Coherent J/ψ photo-production, sensitive to nPDF, ...
- Cross section for coherent J/ψ production:
  \[ \sigma = 5.3 \pm 0.2 \text{ (stat)} \pm 0.5 \text{ (syst)} \pm 0.7 \text{ (lumi)} \text{ mb} \]

- Phenomenological models:

- Measurement of \( \psi(2S) / J/\psi \) ratio planned with 2018 PbPb data
Centrality of PbPb collisions

- **LHCb centrality reach**
  - Measured by the calorimeter
  - Detector limitation: Saturation in the Vertex Locator and the Tracking System for the most central PbPb collisions

- **Current LHCb tracking algorithm efficient to up to 50% of centrality**
  - Present limit for studies of nuclear PbPb interactions
LHCb Detector Upgrade 1

- Better utilise LHC capabilities: collect > 50 fb\(^{-1}\) of \(pp\) data
- upgrade ALL sub-systems to 40 MHz FE-electronics; fully software trigger
- adapt sub-systems to increased occupancies due to 5 x higher luminosity
  ➔ Go from \(4 \times 10^{32}/\text{cm}^2/\text{s}\) to \(2 \times 10^{33}/\text{cm}^2/\text{s}\)

[CERN-LHCC-2012-007]

- New VELO (Vertex Locator)
- Calorimeters Replace R/O
- RICH Detectors: Replace photodetectors and change RICH1 optics
- New Tracking System
- Muon System Replace ODE
VELO upgrade

Upgrade challenge:
- withstand increased radiation
- handle high data volume
- improve current performance
  - lower materiel budget
  - enlarge acceptance

Technical choices:
- $55 \times 55 \, \mu m^2$ pixel sensors with micro channel CO$_2$ cooling
- 40 MHz VELOPIX
- replace RF-foil between detector and beam vacuum
  - reduce thickness from 300 $\mu$m $\rightarrow$ $\leq$ 250 $\mu$m
- move closer to the beam
  - reduce inner aperture from 5.5 mm $\rightarrow$ 3.5 mm
- better IP resolution due to reduced material budget
  - Figure: 3D IP resolution at $L = 2 \cdot 10^{33}$ cm$^{-2}$s$^{-1}$
T-stations upgrade: Fibre Tracker

- 3 stations of X-U-V-X (±5° stereo angle) scintillating fibre planes
- every plane made of 5 layers of Ø=250 µm fibres, 2.5 m long
- x-position resolution of 50 – 75 µm;

**Benefits of SciFi concept:**
- a single technology with uniform material budget
- SiPM + infrastructure outside acceptance
- fast pattern recognition for HLT

**Efficiency for B_s → ΦΦ events:**
(under upgrade conditions)

→ improved tracking performance at upgrade luminosity with Fibre Tracker

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[CERN-LHCC-2014-001]
Current LHCb fixed-target setup is planned to be upgraded for Run 3
- Insert a storage cell, placed upstream of the VELO during LS2
- Injection of noble gases but also $H_2$, $D_2$ as references
- 10–100 times larger instantaneous luminosity per unit length
- Other upgrades (crystal target, polarised target, wire target) under discussion
Fixed Target scenario for Run 3

Planned data-sets for Run 3:
- Extended gas choice: $p$H$_2$, $p$D$_2$, $p$O$_2$ at 115 GeV
- Large dataset of $p$Ar foreseen at 115 GeV: $\sim$ 10/pb
- PbAr at 72 GeV $\sim$ 5/nb; $p$Ar at 72 GeV $\sim$ 1/pb

Physics reach:

<table>
<thead>
<tr>
<th>Current SMOG result</th>
<th>SMOG largest sample</th>
<th>SMOG2 example</th>
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</thead>
<tbody>
<tr>
<td>pHe@86 GeV</td>
<td>pNe@68 GeV</td>
<td>pAr@115 GeV</td>
</tr>
<tr>
<td>Int. Lumi.</td>
<td>7.6/nb</td>
<td>$\sim$ 100/nb</td>
</tr>
<tr>
<td>syst. error on $J/\psi$ x-sec.</td>
<td>7%</td>
<td>6 - 7%</td>
</tr>
<tr>
<td>$J/\psi$ yield</td>
<td>400</td>
<td>15k</td>
</tr>
<tr>
<td>$D^0$ yield</td>
<td>2000</td>
<td>100k</td>
</tr>
<tr>
<td>$\Lambda_c$ yield</td>
<td>20</td>
<td>1k</td>
</tr>
<tr>
<td>$\psi'$ yield</td>
<td>neglig.</td>
<td>150</td>
</tr>
<tr>
<td>$\Upsilon(1S)$ yield</td>
<td>neglig.</td>
<td>10</td>
</tr>
<tr>
<td>$DY \mu^+\mu^-$ yield</td>
<td>neglig.</td>
<td>10</td>
</tr>
<tr>
<td>($5 &lt; M &lt; 9$ GeV)</td>
<td></td>
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</table>

Comments:
- The above list is far from being exhaustive;
- extrapolations are crude estimates, just to provide figures of merit;
- smaller systematic uncertainties with SMOG2 are expected from the reduction of the dominant uncertainty on the luminosity (6%) for SMOG data.
UPC physics:

- Measure cross-section for photo-produced $J/\psi$ in Fix-Target mode
- $\sim 300 \text{ pb}^{-1}$ in $p\text{Ar}$ can complement studies ongoing by LHCb in collision mode ($pp$, $p\text{Pb}$, $\text{PbPb}$) [JHEP 1509 (2015) 087; arXiv:1709.09044, arXiv:1802.04713]

Potential to study elliptic flow over 3 units of pseudorapidity with full instrumentation at unique energy scale

- Di-hadron correlation studies already demonstrated by LHCb in $p\text{Pb}$
- no studies in Fix Target mode performed yet
- yields with SMOG2 could allow flow studies with charmed particles
Possibilities with more $p$Pb data

- LHCb looks forward to $p$Pb collisions in Run 3 and Run 4 at $\sqrt{s_{NN}} = 8.8$ TeV with integrated luminosities of 250 nb$^{-1}$ in each beam configuration.
- Precise measurements at low-$Q^2$ and low-$x_{Bj}$: crucial to constrain the nPDFs in the low-$x$ regime.

Drell-Yan measurement in pPb

- Clean indirect probe of the gluon nPDF at small $x_{Bj}$
- Reference measurement to clarify the dominant source of nuclear modification observed for heavy-flavour production

- For the Drell-Yan measurement, the precision of the VELO and the forward acceptance allow to control the background from semi-leptonic heavy-flavour decays.

[LHCb-CONF-2018-005]
Possibilities with more pPb data

- **$D^0D^0$ correlation measurement**
  - disentangle the contributions from different production mechanisms through the angular distribution
  - angular correlation is sensitive to intrinsic transverse momentum, which may be related to the saturation scale.
  - crucial piece of information for charm and beauty thermalisation within the QGP

- Azimuthal angular correlation $\Delta \phi$ between $D^0$ and $\bar{D}^0$ in $D^0 \rightarrow K^- \pi^+$ decays

\[
\frac{d\sigma}{d\Delta \phi} = \frac{N_{D\bar{D}}(\Delta \phi)}{N_{D\bar{D}}(\text{tot})}
\]

[LHCb-CONF-2018-005]
Further LHCb upgrades (Ib & II)

- To fully exploit the flavour physics potential of the HL-LHC, LHCb proposes an upgrade II in LS4. Target Luminosity: $> 300 \text{ fb}^{-1} \ (pp)\ at\ 1-2 \times 10^{34} \ \text{ /cm}^2/\text{s}$ [CERN-LHCC-2017-003]
- The upgrade II detector will have improved granularity and resolutions
  - This offers the opportunity of a general purpose Heavy Ion experiment suited also for the most central PbPb collisions at forward rapidity.
- The main limitation will come from the SciFi Tracker, which would need to be upgraded: add Si-trackers (with two different granularities)

<table>
<thead>
<tr>
<th>Detector</th>
<th>Maximum occupancy in most central PbPb at $\sqrt{s_{NN}} = 5 \ \text{TeV}$</th>
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<tbody>
<tr>
<td>Velo (Upgrade I)</td>
<td>4 %</td>
</tr>
<tr>
<td>Velo upgrade (Upgrade II)</td>
<td>1 %</td>
</tr>
<tr>
<td>SciFi (Upgrade II)</td>
<td>25%</td>
</tr>
</tbody>
</table>

Smaller upgrades are planned already for LS3:
Improve tracking acceptance for low momentum particles
- Install tracking stations on the dipole magnet internal sides
  - e.g. $D^{*+} \rightarrow D \pi^+_s$, 40% extra slow pions
At upgrade II luminosities, the number of tracks in \( pp \) collisions will be close to that observed in central \( \text{Pb-Pb} \) collisions (dedicated studies are needed).

**Quarkonium and open heavy flavour:**
- \( \psi(2S) \) yield at low \( p_T \) remain statistically limited after Run 3+4, with low signal over noise ratio
- \( P \)-wave states like \( \chi_c \) states are challenging and particularly interesting to study colour charges
  - Main limitation for LHCb: integrated luminosity

**Low-mass di-leptons and photons**
- \( \rho^0 \) meson sensitive to chiral symmetry restoration in the QGP
- thermal radiation in the intermediate mass region
- LHCb Upgrade II has the potential to measure precisely di-lepton production in the di-muon channel at the LHC.
- VELO detector allows for suppression of heavy flavour background

**Drell-Yan, \( c\bar{c} \) and \( b\bar{b} \) in \( pA \) or \( AA \) collisions in view of nuclear PDFs and saturation**
- Precise low mass Drell-Yan (below masses of 10 GeV/c\(^2\)) or low-\( p_T \) below 10 GeV/c\(^2\) photon measurements are world-leading unique opportunities
Summary and Conclusions

- The LHCb detector has unique capabilities for heavy flavour measurements at LHC in collider and fixed-target modes.

- The ongoing and proposed future upgrades of the detector will enhance the centrality reach of the LHCb experiment:
  - Upgrade 1: potentially up to 20-30% centrality (to be studied carefully)
  - Upgrade 2: intention to reach full centrality in PbPb (design phase is ongoing)

- The LHCb Upgrade II offers the opportunity of a general purpose heavy-ion experiment suited from pA up to most central AA collisions at forward rapidity.

- The SMOG2 proposal opens great possibilities for a substantial increase of data size and choice of gas species with respect to the current SMOG program already for Run3.

- Other upgrades for Fixed Target physics are under discussion: crystal target, polarised gas target, wire target.