LHCb as a fixed-target experiment

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on behalf of the LHCb and LHCSpin Collaborations

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Reminder on LHCb Fixed Target

LHCb as a fixed target experiment, thanks to the SMOG internal gas target

pA collisions at unique energy scale
\[ \sqrt{s_{\text{NN}}} \sim 100 \text{ GeV} \]

Unique coverage for (n)PDF at large \( x \)


SMOG data samples

Final summary of fixed-target samples acquired with SMOG in Run 2

\[ \int \mathcal{L}dt \sim 5 \text{ nb}^{-1} \times \frac{pot}{10^{22}} \times \frac{p_{gas}}{2 \times 10^{-7} \text{ mbar}} \times \text{Exp\_Efficiency} \]

Largest sample (pNe 2017) \sim 100 \text{ nb}^{-1}

Main physics goals:

- charm production to investigate nuclear effects and (n)PDF at large $x$;
- studies of hadron production in novel kinematic regime and collision systems (notably proton - Helium), bringing crucial inputs to cosmic ray physics.

First two physics results submitted to PRL in 2018

antiprotons in pHe, PRL 121 (2018), 222001

charm production in pHe and pAr, arXiv:1810.07907, subm. to PRL
Cosmic Antiprotons

First measurement of antiproton production in pHe collisions, in kinematic range relevant for the measurement of cosmic antiprotons in space (production in collisions on interstellar gas is main background to search for possible dark matter signal)

Visible inelastic cross section compatible with EPOS LHC:

\[ \frac{\sigma_{\text{LHCb}}^{\text{vis}}}{\sigma_{\text{EPOS-LHC}}^{\text{vis}}} = 1.08 \pm 0.07 \pm 0.03 \]

\[ \Rightarrow \text{excess of } \bar{p} \text{ yield over EPOS LHC from } \bar{p} \text{ multiplicity} \]

Prospects:
- extend to \( \bar{p} \) from anti-hyperon decays (20-30% of production);
- repeat on 4 TeV beam data

\[ \Rightarrow \text{measure scaling violations} \]

Desiderata: also measure in \( pp \) with \( H_2 \) target, use \( D_2 \) target to constrain isospin violation for \( p/\bar{n} \) production, extend energy scan to lower energy

Result for prompt production compared to EPOS LHC

**EPOS LHC** PRC92 (2015) 034906
underestimating \( \bar{p} \) prod. by \( \sim 1.5 \)

**QGSJETII-04** PRD83 (2011) 014018
**QGSJETII-04m** Astr. J. 803 (2015) 54
**HIJING 1.38** Comp. Phys. Comm. 83 307
**PYTHIA 6.4** (2pp + 2pn) JHEP 05 (2005) 026
Charm production in fixed targets

First charm samples from pHe@69 GeV ($7.6 \pm 0.5 \text{ nb}^{-1}$) and pAr@110 GeV (few nb$^{-1}$)

First determination of $c \bar{c}$ cross-section at this energy scale
Sensitive to $x$ in target up to $\sim 0.5 \implies$ EMC effect, intrinsic charm

Desiderata: increase data size for better accuracy, access other heavy states, extend to other targets ($H_2$ for pp reference, heavier targets)
Goals for LHC Run 3/4

- Increase data size: better accuracy, access rarer states (including $b\bar{b}$), study QGP in PbA
- Extend target choice:
  - **Hydrogen** and **Deuterium** would allow to have $pp$ reference measurements, studies of GPDs/TMDs (through unpolarized observables), more $\bar{p}$ production for CR in space (production in $pp$ and isospin violation)
  - **Nitrogen/Oxygen** for atmospheric CR
  - **Heavier** gas (Kr, Xe?). Upgraded LHCb detector (from Run 3) will allow better reconstruction of central event

Implementation: the SMOG2 target upgrade

- contain gas in 20 cm long storage cell
  - $\Rightarrow$ up to x100 increase of target density for same gas flow;
  - SMOG $\sim 10^{-7}$ mbar on +/- 20 m
  - SMOG2 up to $10^{-3}$ mbar on 20 cm
  - VErtex LOcator sensors

- lower contamination of beam line $\Rightarrow$ more gas species possible;
- better control over injected gas density (better accuracy on absolute cross sections).

slide 7
Simultaneous operation of fixed target and p-p collisions is in principle possible, though challenging due to the critical trigger requirements.

Maximum allowed gas flow for the various species still to be determined:

- for H\textsubscript{2} and D\textsubscript{2}, possible limitations from embrittlement and, as for other getterable gases, from the integrity of the NEG coating in the vicinity of IP8;
- heavy noble gases Kr and Xe which will be cryosorbed at the warm-to-cold transitions of the triplet quadrupoles and cause an increase of the local secondary electron yield.
Given these caveats, an optimistic, still realistic, scenario for the fixed-target samples to be collected during the 3 years of Run3 is the following:

<table>
<thead>
<tr>
<th>System</th>
<th>$\sqrt{s_{NN}}$ (GeV)</th>
<th>$&lt;\text{pressure}&gt;$ (mbar)</th>
<th>$\mathcal{L}$ ($cm^{-2}s^{-1}$)</th>
<th>Rate (MHz)</th>
<th>Time (s)</th>
<th>$\int \mathcal{L}$ (pb$^{-1}$)</th>
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<td>$pH_2$</td>
<td>115</td>
<td>$4 \cdot 10^{-5}$</td>
<td>$6 \cdot 10^{31}$</td>
<td>4.6</td>
<td>$2.5 \cdot 10^6$</td>
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<tr>
<td>$pD_2$</td>
<td>115</td>
<td>$2 \cdot 10^{-5}$</td>
<td>$3 \cdot 10^{31}$</td>
<td>4.3</td>
<td>$0.3 \cdot 10^6$</td>
<td>9</td>
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<tr>
<td>$pAr$</td>
<td>115</td>
<td>$1.2 \cdot 10^{-5}$</td>
<td>$1.8 \cdot 10^{31}$</td>
<td>11</td>
<td>$2.5 \cdot 10^6$</td>
<td>45</td>
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<tr>
<td>$pKr$</td>
<td>115</td>
<td>$0.8 \cdot 10^{-5}$</td>
<td>$1.2 \cdot 10^{31}$</td>
<td>12</td>
<td>$2.5 \cdot 10^6$</td>
<td>30</td>
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<tr>
<td>$pXe$</td>
<td>115</td>
<td>$0.6 \cdot 10^{-5}$</td>
<td>$0.9 \cdot 10^{31}$</td>
<td>12</td>
<td>$2.5 \cdot 10^6$</td>
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<tr>
<td>$pHe$</td>
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<td>$2 \cdot 10^{-5}$</td>
<td>$3 \cdot 10^{31}$</td>
<td>3.5</td>
<td>$3.3 \cdot 10^3$</td>
<td>0.1</td>
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<tr>
<td>$pNe$</td>
<td>115</td>
<td>$2 \cdot 10^{-5}$</td>
<td>$3 \cdot 10^{31}$</td>
<td>12</td>
<td>$3.3 \cdot 10^3$</td>
<td>0.1</td>
</tr>
<tr>
<td>$pN_2$</td>
<td>115</td>
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<td>$1.5 \cdot 10^{31}$</td>
<td>9.0</td>
<td>$3.3 \cdot 10^3$</td>
<td>0.1</td>
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<td>$pO_2$</td>
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<td>$1 \cdot 10^{-5}$</td>
<td>$1.5 \cdot 10^{31}$</td>
<td>10</td>
<td>$3.3 \cdot 10^3$</td>
<td>0.1</td>
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<tr>
<td>$PbAr$</td>
<td>72</td>
<td>$8 \cdot 10^{-5}$</td>
<td>$1 \cdot 10^{29}$</td>
<td>0.3</td>
<td>$6 \cdot 10^5$</td>
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<tr>
<td>$PbH_2$</td>
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<td>$1 \cdot 10^{29}$</td>
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<tr>
<td>$pAr$</td>
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<td>11</td>
<td>$3 \cdot 10^5$</td>
<td>5</td>
</tr>
</tbody>
</table>
# Expected yields for some benchmark modes

<table>
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<tr>
<th></th>
<th>SMOG released result</th>
<th>SMOG largest sample</th>
<th>SMOG2 example</th>
</tr>
</thead>
<tbody>
<tr>
<td>pHe@87 GeV</td>
<td>7.6 nb$^{-1}$</td>
<td>$\sim 100$ nb$^{-1}$</td>
<td>$\sim 45$ pb$^{-1}$</td>
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<tr>
<td>pNe@69 GeV</td>
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<tr>
<td>pAr@115 GeV</td>
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</tbody>
</table>

- Integrated luminosity
- syst. error on $J/\psi$ x-sec.
- $J/\psi$ yield
- $D^0$ yield
- $\Lambda_c^+$ yield
- $\psi(2S)$ yield
- $\Upsilon(1S)$ yield
- Low-mass ($5 - 9$ GeV) Drell-Yan

<p>| | | | |</p>
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<tr>
<td>$7%$</td>
<td>6 - 7%</td>
<td>2 - 3%</td>
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<td>400</td>
<td>15k</td>
<td>15M</td>
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<tr>
<td>2000</td>
<td>100k</td>
<td>150M</td>
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<tr>
<td>20</td>
<td>1k</td>
<td>1.5M</td>
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<tr>
<td>negl.</td>
<td>150</td>
<td>150k</td>
<td></td>
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<td>negl.</td>
<td>4</td>
<td>7k</td>
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</tr>
<tr>
<td>negl.</td>
<td>5</td>
<td>9k</td>
<td></td>
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</tbody>
</table>

### Notes:
- list is far from being exhaustive;
- extrapolations are crude estimates, just to provide figures of merit;
UPC physics: interesting cross-section for photoproduced $J/\psi$ and $\eta_c$ (sensitive to odderon) in LHCb-FT, can complement studies made/ongoing by LHCb in collisions ($pp, pPb, PbPb$)


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

- dihadron correlation studies already demonstrated by LHCb in pPb
- yields with SMOG2 could allow flow studies with charmed particles
- no studies in FT performed yet

A polarization induced by vorticity in HI collisions

(see Becattini et al., PRC 88, 034905 (2013), STAR results on [Nature 548, 62-65](https://www.nature.com))

Fixed target collisions have the correct energy scale (effect too small at TeV scale)

Polarization measurements for $\Lambda_c^+$ and other heavy hadrons in pA are also a needed ingredient for the MDM/EDM proposed experiment

(see talk on LHCb-FT CRYSTAL by N. Neri)
Understanding of lateral profile of Extensive Air Showers (muon puzzle).
Large spread for muon flux predictions among different models, mostly from uncertainty on baryon production ($\sim 70\%$). Measurements at 10\% accuracy would greatly help constraining the models.
Production in pN and pO at 115 GeV could be directly measured, complementing studies at beam-beam collision energy (notably in pO collisions if such run will be performed)

Drell-Yan and heavy flavour channels with H$_2$ and D$_2$ targets will also give access to spin-independent nucleon TMDs as the Boer-Mulders functions in a novel kinematic range
Physics opportunities with the fixed-target program of the LHCb experiment using an unpolarized gas target

Abstract

The LHCb experiment pioneered fixed-target physics with LHC beams, thanks to the SMOG internal gas target. Collisions of proton and heavy ion beams on targets with different nuclear size can be recorded at a center-of-mass energy of $\sqrt{s_{NN}} \sim 100$ GeV. This note summarises the physics opportunities offered by the current fixed-target setup and its upgrade envisaged for the LHC Run 3. Unique measurements are being performed with Run 2 data, covering in particular heavy flavour production in nuclear collisions on a wide Feynman-$x$ range and light particle production of particular interest to cosmic ray physics. The increase of luminosity and extension of the choice of target material, which are being pursued for Run 3, open many new possibilities which are reviewed in this document.
SMOG2 Technical Proposal

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Abstract

A proposal for an upgraded version of the existing gas injection system for the LHCb experiment (SMOG) is presented. The core idea of the project, called SMOG2, is the use of a storage cell for the injected gas to be installed upstream of the VELO detector. The main advantage of the proposed system is to increase by up to two orders of magnitude the effective target areal density, thus resulting in a significant increase of the luminosity for fixed-target collisions. Other important advantages are the possibility to inject additional gas species, including H₂ and D₂, a better defined interaction region, displaced with respect to the nominal interaction point, and thus possibly compatible with running in parallel to the collider mode (resulting in a further huge increase in luminosity). A technical design of the target system is presented together with a description of the installation procedure. Impedance properties and Electron Cloud effects have been studied for the proposed system, and the possible beam instabilities estimated. The geometry of the system has been integrated into the GEANT4 model of the LHCb detector in order to validate the target design with reliable simulation studies, and to ensure that the near-beam material budget has negligible effects in terms of beam-induced background. The loss in reconstruction efficiency with respect to SMOG for selected physics channels, due to the displaced interaction region with respect to the nominal interaction point, is found to be of the order 10%, thus largely over-compensated by the expected increase in luminosity. The installation of the system is proposed for the LHC Long Shutdown 2. This will open new physics frontiers at LHCb already from the LHC Run-3.
Beam pipe

Target Cell

VELO vessel
Fits into the space now taken by the upstream WFS
STORAGE CELL

FIXED HALF CELL SUPPORT CONNECTED TO THE DETECTOR BOX

FLOATING HALF CELL SUPPORT CONNECTED TO THE DETECTOR BOX

STORAGE CELL SUSPENSIONS

ELECTRICAL CONTINUITY BETWEEN CELL AND RF FOIL

GAS FEED TUBE IN THE CELL CENTER

CONICAL TRANSITION

FLEXIBLE WAKE FIELD SUPPRESSOR

FIXED HALF CELL SUPPORT CONNECTED TO THE DETECTOR BOX
MODIFIED SPOKE INSTALLATION

CF200 SERVICE FLANGE: GAS FEED-THROUGH AND THERMOCOUPLES CONNECTION
R&D basically completed
R&D basically completed

* Interaction with LHC:
R&D basically completed

* Interaction with LHC:
  - vacuum
  (G. Bregliozzi, P.M. Gebolis, G. Pigny)

The new Gas Feed System to be positioned in a low-radiation area

A precise measurement of the flow rate and the temperature of the gas allows for a determination of the luminosity to a couple of %
R&D basically completed

- Interaction with LHC:
  - vacuum
  - impedance

(B.K. Popovic, B. Salvant, C. Vollinger, C. Zannini)

LHC impedance group:
- there is no indication that the replacement of the upstream WFS by the SMOG2 system alters longitudinal and transverse resonant modes significantly in both open and closed positions

- the additional contribution to the low frequency broadband impedance due to the SMOG2 remains small compared to the VELO

- with or without the SMOG2, the expected local power loss can reach up to of the order of 1.5 kW if the worst mode (∼380 MHz, Rs ∼ 1.5 kOhm) is hit by one of the main spectral lines of the HL-LHC beam (2748 bunches with 2.2 · 10^{11} p/b).

This means that, in the open cell configuration, there will be a DT~60 K. Simulations and measurements are going on, however the system is robust enough for such a temperature variation.
R&D basically completed

* Interaction with LHC:
  - vacuum
  - impedance
  - aperture

(C. Boscolo Meneguolo, R. Bruce)
R&D basically completed

* Interaction with LHC:
  - vacuum
  - impedance
  - aperture
  - coating and beam stability (SEY)

(G. Iadarola, L. Mether)

For the coating the amorphous carbon solution has been chosen. This has been already adopted at the SPS and at the vacuum pilot sector of the LHC.

LHC Beam Stability Group

The integrated gas densities foreseen for SMOG2 are at least two orders of magnitude lower than in the 16L2 case (where the gas was generated by sublimation of flakes released off the pipe).

The $\beta$ function at the SMOG2 location is at least one order of magnitude smaller than in the LHC arcs, thus disfavoring the occurrence of fast instabilities.
R&D basically completed

- Interaction with LHC:
  - vacuum
  - impedance
  - aperture
  - coating and beam stability (SEY)

- Target prototypes and tests

- Induced heating and bake-out stress

- WFS prototypes and stress test (15,000 cycles)
R&D basically completed

- **Interaction with LHC:**
  - vacuum
  - impedance
  - aperture
  - coating and beam stability (SEY)

- **Target prototypes and tests**

- **Induced heating and bake-out stress**

- **WFS prototypes and stress test (15,000 cycles)**

- **Material budget and Machine Background Induced on LHCb**

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<tr>
<th>Config.</th>
<th>MIB-TCT (μ=0.0238)</th>
<th>MIB-LSS (μ=0.0019)</th>
<th>pp</th>
<th>pp + μ MIB</th>
<th>$\Delta^{MIB-TCT}$</th>
<th>$\Delta^{MIB-LSS}$</th>
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<td>5. GFS table construction and test in laboratory</td>
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<td>6. Tests of surface coatings</td>
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<td>7. Final target construction (including 1 spare parts)</td>
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<td>8. Target installation</td>
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<td>11. Trigger coding</td>
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</table>
SMOG2 not only a project itself

Phase II transversely polarised H and D target

R&D
PGT experimental set-up

Design follows the successful HERMES Polarised Gas Target which ran at HERA 1996 – 2005, and the follow-up PAX target operational at COSY (FZ Jülich)

\[ I_H (100 \% \text{ HERMES ABS flow}) = 6.5 \cdot 10^{16}/s \text{ by a cell 30 cm long, 1.0 cm i.d., at 100K, with feed tube 10 cm long, 1.0 cm i.d.} \]

The resulting 100% PGT density is \[ \theta = 1.2 \cdot 10^{14} \text{ cm}^{-2} \]

For the future HL-LHC-25ns, the maximum Luminosity would be up to \[ 8.3 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1} \]
New groups (US, Russia, Germany, ...) joined the R&D and are developing the drawings and simulations.

Ongoing R&D on coating and on spin holding transverse magnet

Beam Induced Depolarization calculation already investigated: CERN-PBC-Notes-2018-001

The goal is to install the system during the LS3
Improvement of the VELO upstream sector

First ideas: Arrangement in the tunnel

Present view of the target area:
• beam tube in the foreground;
• in green: pneumatic cylinder of all-metal valve GV302 /SMOG. To be replaced next shutdown by flat gate valve.

Available space upstream of the VELO vessel:
• Along the beam about 1m, limited by shielding wall. Could be moved, but important for the PGT to stay as close to the VELO as possible!
• In transverse direction: enough to place ABS and diagnostics in the horizontal plane (→ B guide vertical)

OLD

NEW

New gate valve
New compact pump
Conclusions

- LHCb demonstrated the possibilities for fixed target physics at the LHC using internal gas targets in existing detectors
- First two physics results on PRL, much more to come from Run 2 samples
- SMOG2 upgrade, approved by LHCb, opens great possibilities for a substantial increase of data size and choice of target gas species wrt the current SMOG program already for Run3
- The LHCspin group is working on a polarized target proposal allowing for a further upgrade for Run4/Run5
- We plan to continue developing the evaluations of the physics reach with detailed simulations, in parallel with the exploitation of the available data samples