Novel high-luminosity fixed-target experiment at the LHC

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The Large Hadron Collider
The collider mode at LHC

Collider Mode

proton \quad 7 \text{ TeV} \quad 7 \text{ TeV} \quad \text{proton}

\sqrt{s} = 14 \text{ TeV}

\text{lead ion} \quad 2.76 \text{ TeV} \quad 2.76 \text{ TeV}

\sqrt{s_{NN}} = 5.5 \text{ TeV}

\text{proton} \quad \text{lead ion}

\sqrt{s_{NN}} = 8.2 \text{ TeV}
The collider mode at LHC

**ALICE**

**LHCb**

Collider Mode

- **proton**: 7 TeV
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A fixed-target mode at LHC

→ Energy range

Fixed-target Mode

proton

7 TeV

lead ion

2.76 TeV
A fixed-target mode at LHC

**Energy range**

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**Fixed-target Mode**

- **7 TeV** proton beam on a fixed target with $\sqrt{s_{NN}} = 115$ GeV
- **2.76 TeV** Pb beam on a fixed target with $\sqrt{s_{NN}} = 72$ GeV
A fixed-target mode at LHC (2)

→ Effect of boost

7 TeV proton beam on a fixed target

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• $y_{cms} > 0$

Entire forward hemisphere within $1^\circ$
A fixed-target mode at LHC (2)

→ Effect of boost

7 TeV proton beam on a fixed target

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\begin{array}{|c|c|}
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2.76 TeV Pb beam on a fixed target

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Rapidity shift:

\[
y_{\text{c.m.s.}} = 0 \rightarrow y_{\text{lab}} = 4.3
\]

- \( y_{\text{cms}} > 0 \)
  - Entire forward hemisphere within 1°
- \( y_{\text{cms}} < 0 \)
  - Easy access to (very) large CM backward rapidity range,
  - And large parton momentum fraction \( x_2 \rightarrow 1 \) \( (x_F \rightarrow -1) \)

\[ |x_F| \equiv \frac{|p_1|}{P_{\text{max}}} \rightarrow 1 \]
A fixed-target mode at LHC (2)

➔ Effect of boost

7 TeV proton beam on a fixed target

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Boost: \( \gamma = \sqrt{s}/(2m_N) \approx 60 \)

2.76 TeV Pb beam on a fixed target

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Boost: \( \gamma = 40 \)

- \( y_{\text{c.m.s.}} > 0 \)
  - Entire forward hemisphere within 1°
- \( y_{\text{c.m.s.}} < 0 \)

Easy access to (very) large CM rapidity range, and large parton momentum fraction \( x_2 \rightarrow 1 \) (\( x_F \rightarrow -1 \))

[\([x_F] \equiv \frac{p_F}{p_{F\text{max}}} \rightarrow 1\)]

Advantages of a fixed-targeted mode at the LHC

- Accessing high-x frontier
- Achieving high luminosities
- Varying atomic mass number of the target
- Possibility of the target polarisation
Possible implementations

- **Internal gas target**
  - Full LHC beam flux on internal gas target
  - Feasibility demonstrated by SMOG at LHCb
  - Storage cell target (HERMES-like) or gas-jet system (RHIC H-jet polarimeter) for (un)polarised gases
  - Can be coupled with an existing experiment

- **Internal wire/foil target**
  - Beam halo recycled directly on internal solid target
  - As HERA-B and STAR, heavy-nucleus targets
Possible implementations (2)

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➢ **Beam line extracted with a bent crystal**
  - Beam halo deflected onto an external target
  - Thick (un)polarised and cryogenic polarised targets
  - Considerable amount of civil engineering

➢ **Beam “split” by a bent crystal**
  - Beam halo deflected onto an internal solid or gas target
  - Inside beam pipe of an existing LHC experiment
Possible implementations: ALICE

- **Beam splitting with bent crystal + internal target**
  - Crystal installed prior the IP2, deviates the beam halo onto a target
  - Pneumatic motion system with two position, IN and OUT of the beam pipe
  - Various target type: from Be to W
  - Target length from \( \sim 100\,\mu\text{m} \) to 1 cm
  - **Feasibility studies ongoing**

- **Gas storage cell target**
  - **Under study**
Acceptance in centre-of-mass $y$

- With 7 TeV proton beam
- $\Delta y = 4.8$

STAR
PHENIX
ALICE
LHCb

ALICE $z_{\text{target}} = -4.7m$
ALICE $z_{\text{target}} = 0$
LHCb $z_{\text{target}} = -1.5m$
LHCb $z_{\text{target}} = -0.4m$
LHCb $z_{\text{target}} = 0$
Physics motivations

- Advance our understanding of the **high-x frontier in nucleons and nuclei** (gluon and heavy-quark content) **and its connection to astroparticle physics**

Gluon nuclear PDF uncertainties in lead nuclei

![Gluon nuclear PDF uncertainties in lead nuclei](chart)

- arXiv: 1807.00603
- B.Trzeciak, kcsf2020
Physics motivations

- Advance our understanding of the **high-x frontier in nucleons and nuclei** (gluon and heavy-quark content) and its connection to astroparticle physics
- Unravel the **spin of the nucleon**: dynamics and spin distributions of quarks and gluons inside (un)polarised nucleons

Gluon nuclear PDF uncertainties in lead nuclei

\[
\frac{f_g^P}{f_g^P} \quad \text{for } Q = 2 \text{ GeV}
\]

\[
\frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L_g + L_q
\]

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Physics motivations

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- Unravel the spin of the nucleon: dynamics and spin distributions of quarks and gluons inside (un)polarised nucleons

- Studies of the quark-gluon plasma in heavy-ion collisions at a new energy domain down to the target-rapidity region

Gluon nuclear PDF uncertainties in lead nuclei
High-x PDF and nPDF

- Structure of nucleon and nuclei at high-x (>0.5) is poorly known, both at low and high scales
- Intrinsic (non-perturbative) charm (beauty) content of proton? Important for reducing uncertainties of the neutrino flux

u quark PDF uncertainties

<table>
<thead>
<tr>
<th>Q</th>
<th>PDF</th>
<th>L (fb⁻¹)</th>
</tr>
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<tbody>
<tr>
<td>1.3 GeV</td>
<td>CT14nlo</td>
<td>10</td>
</tr>
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<td>1.3 GeV</td>
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After @LHC
Drell–Yan pp
\( \sqrt{s} = 115 \text{ GeV} \)

GLP15/CT14, Q=2GeV

 gluon nuclear PDF uncertainties

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<tr>
<th>p+Xe</th>
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<tr>
<td>L_{pp} = 10 fb⁻¹</td>
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<td>L_{pXe} = 100 pb⁻¹</td>
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nCTEQ15/CT14, Q=2GeV
Spin of nucleon

- Unravel the **spin of the nucleon**: dynamics and spin distributions of quarks and gluons inside (un)polarised nucleons
  - 3D mapping of the proton momentum
  - How quarks and gluons bind into a spin-1/2 object

\[
\frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + \mathcal{L}_g + \mathcal{L}_q
\]

- quark spin: 25%
- gluon spin
- quark and gluon OAM

- quark/anti-quark: \(\sim\)30% of proton longitudinal spin
- gluons: even up to 40%

- Missing contribution to the proton spin from the **transverse dynamics of quarks and gluons**
  - gluon and quark Orbital Angular Momentum \(\mathcal{L}_{g,q}\)

*arXiv: 1807.00603*
Spin of nucleon

- Unravel the **spin of the nucleon**: dynamics and spin distributions of quarks and gluons inside (un)polarised nucleons

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\[ \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L_g + L_q \]

- quark/anti-quark: ~30% of proton longitudinal spin
- gluons: even up to 40%

- Missing contribution to the proton spin from the transverse dynamics of quarks and gluons

  - gluon and quark Orbital Angular Momentum \( L_{g,q} \)

- **Single Transverse Spin Asymmetries**
  (with transversely polarised target) → orbital motion of partons inside hadron: **Sivers effect**

- **Non-zero quark/gluon Sivers functions**
  → non-zero OAM

  \[ f_{1T}^{\perp} = \frac{1}{P_{\text{eff}}} (\sigma^\uparrow - \sigma^\downarrow) \]

\[ A_N = \frac{1}{P_{\text{eff}}} (\sigma^\uparrow + \sigma^\downarrow) \]

**arXiv: 1807.00603**
Study of the quark-gluon plasma between SPS and top RHIC energies of $\sqrt{s_{NN}} = 72$ GeV over broad rapidity range

Complete studies as a function of rapidity, centrality and system size → scan in $\mu_B$

complementary to RHIC BES programme


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Precise measurements of soft and hard probes of the QGP

*arXiv: 1807.00603*
Summary

➔ AFTER@LHC: **high-statistics measurements in an energy domain between the SPS and top RHIC**, in an unexplored rapidity domain

➔ Three main physics motivations:
  ➔ **High-x frontier**: nucleon and nuclear structure
  ➔ **Spin of the nucleon** and the transverse dynamics of partons
  ➔ **Quark-gluon plasma** over broad rapidity domain

➔ Experimental implementation possible based on the existing LHCb and ALICE detectors, two promising technical implementations:
  ➔ **Internal gas target**
  ➔ Beam halo extraction with a **bent crystal on an internal target**

A Fixed-Target Programme at the LHC:
arXiv: 1807.00603
*Submitted to Physics Report*
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This work was supported by grant from The Czech Science Foundation, grant number: GJ20-16256Y
Backup
Detector requirements

- **Wide rapidity coverage** of backward and mid-rapidity in $y_{\text{c.m.s.}}$.
  - p beam: $y_{\text{lab.}}$ range 0 – 4.8
  - Pb beam: $y_{\text{lab.}}$ range 0 – 4.2
- With (low $p_T$) **PID and vertexing** capabilities
- Heavy-ion: good performance in **high-multiplicity events**, up to 600 – 700 charged tracks per unit of rapidity at $\eta_{\text{lab}} \sim 4.2$
- Readout **rate similar to LHC** collider
- Polarised target requires space e.g. for pumping system
Spin projections

- Transversely polarised target
- Gluon Sivers effect:
  - With $D^0$– difference in $A_N$ of $D^0$ vs $D^0$ gives $A_N$ of $D^0$ vs $D^0$ access to C-odd correlators (PHENIX: 1703.09333)
  - Quarkonia ($\Upsilon$ never measured) and di-$J/\psi$ – access to $k_T$ dependence of the gluon Sivers function for the first time

\[ A_N = \frac{1}{\mathcal{P}_{\text{eff}}} \frac{\sigma^\uparrow - \sigma^\downarrow}{\sigma^\uparrow + \sigma^\downarrow} \]
charm PDF (IC) with D

- Extremely good prospects for charm
- Down to 0 $p_T$ → total charm x-section
- Wide rapidity coverage, $x_F \rightarrow -1$
- High statistical precision in pp, p-A, A-A
- With LHCb background well under control
- Intrinsic charm modifies significantly D meson yields at large $p_T$ or forward rapidity
- Large-$x$ → large charm PDF uncertainty
  - Perturbative via gluon splitting vs non-perturbative from intrinsic charm
- Impact on neutrino flux and cosmic-ray physics

arXiv: 1807.00603
Constraining gluon nPDF with D, B and quarkonium measurements

Almost unknown for $x > 0.1$; anti-shadowing, EMC effect?

Reweigting analysis with pseudo data on $R_{pA}$

Large reduction on the gluon nPDF uncertainty: unique constraints at large $x$ and low scales

Other nuclear effects in play: nuclear absorption, ...

Impact on gluon nPDFs

$LHCb$-like

$nCTEQ15$

arXiv: 1807.00603
Quarkonium measurements

- Determination of the QGP thermodynamic properties
  - Measurements of $\psi$ and $\Upsilon(nS)$ states down to 0 $p_T$, in pp, pA and PbA
  - Negligible contribution from recombination
Quarkonium $R_{AA}$

- Precise measurements of charmonium states vs rapidity
- Measurement of the 3 $\Upsilon(nS)$ state suppression

- Possibility to access $\chi_C$ and $\eta_C$, $J/\psi - J/\psi$ and $J/\psi - D$ correlations

Few Body Syst. 58 (2017) 5, 148
arXiv: 1807.00603
Open HF in small systems

- p-A collisions: cold nuclear matter effects, collectivity in small systems, QGP?
- Simultaneous measurements of D meson elliptic flow and nuclear modification factor, in different systems

- ALICE: target at $z = -4.7$ m, with 1cm long solid targets
- Similar precision expected in 10-20, 20-40% centrality intervals
- Quarkonia and HF $\mu$ can be studied with ALICE muon arms at: $-1.6 < y_{CMS} < -0.5$
QGP: Open Heavy-Flavour

- Open heavy-flavour in A-A → heavy-quark energy loss in the medium
- Precise suppression measurements of charm and beauty vs rapidity and $p_T$ → medium transport coefficient
- Useful reference for charmonium studies
- $p$-A: study collective-like effects in small systems
- Precise D meson $v_2$ measurement
  - Studies vs $y$ and different target type
Possible implementation: ALICE

Beam splitting with bent crystal + internal target
- Crystal installed prior of the IP2 (ALICE), at ~70m
- Deviates the beam halo onto a solid target in L3 magnet
- Target z position < 4.8m

Gas storage cell target
- Under study
Possible implementation: LHCb

Several investigations/projects:
- Unpolarised storage cell gas target: SMOG2
- Polarized storage cell gas target: LHCSpin, R&D needed with possible installation in LS3
- Beam split and internal W solid gas (with a second crystal)

LHCb:
- Forward detector with full PID, $2 < \eta_{lab} < 5$
- Precision tracking system, vertex locator
- Limitation in high-multiplicity event reconstruction
- New VELO: high readout rate, higher multiplicities
Possible implementations

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**SMOG@LHCb**
*System for Measuring Overlap with Gas*

**VELO (+SMOG)**
*Dynamic vacuum: sketch*

- Unpolarised noble gases
- Gas injected into vertex locator (VELO) vacuum
- Low gas pressure

**Target cell for polarised gas**
*HERMES-like*

- High pressure
- Polarised H and D ($^3$He)
- Unpolarised Kr, Xe

**H-jet system at BNL-RHIC**

- Measures proton beam polarisation at RHIC
- Polarised gas: H, D and He possible