Fixed-Target Opportunities at the (HL)LHC

J.P. Lansberg
IPN Orsay – Paris-Sud U./Paris Saclay U. –CNRS/IN2P3

Open Symposium - Update of the European Strategy for Particle Physics
13-16 May 2019, Granada, Spain
Part I

Introduction
Using the LHC beams in the fixed-target mode

Contributions to the ESPP update and other scientific sources
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3 ESPPU Contributions submitted in December [overall signed by 200+ physicists]

- Physics opportunities for a fixed-target programme in the ALICE experiment
  by F. Galluccio et al.: ID 47
- Community Support for A Fixed-Target Programme for the LHC by J.D. Bjorken et al.: ID 67
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Physics Beyond Colliders documents
- CERN-PBC-Notes: e.g. 2019-003,2019-002,2019-001,2018-008,2018-007,2018-003,2018-001
- Summary by the PBC LHC FT Working Group: yet to appear
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Physics Beyond Colliders documents

- Physics Beyond Colliders: QCD Working Group Report
  by the PBC QCD Working Group (A. Dainese et al.): arXiv:1901.04482
- Summary Report of Physics Beyond Colliders at CERN
- CERN-PBC-Notes: e.g. 2019-003, 2019-002, 2019-001, 2018-008, 2018-007, 2018-003, 2018-001
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Reviews, special issues

3 main research axes:
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**High-x gluon, antiquark and heavy-quark content in the nucleon & nucleus**

- Very large **gluon PDF** uncertainties for $x \gtrsim 0.5$.
- **Gluon** EMC effect to understand the quark EMC effect
- Proton **charm** content

$\leftrightarrow$ **high-energy neutrino & cosmic-ray physics**
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**Dynamics and spin of gluons and quarks inside (un)polarised nucleons**
- Possible missing contribution to the *proton spin: Orbital Angular Momentum* \( \mathcal{L}_{g,q} : \)
  \[
  \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + \mathcal{L}_g + \mathcal{L}_q
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- *Test of the QCD factorisation framework*
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**Heavy-ion collisions towards large rapidities**
- A complete set of heavy-flavour studies between SPS and RHIC energies
- Rapidity scan of the azimuthal asymmetries thanks to a broad rapidity reach
- Test the factorisation of cold nuclear effects from $p + A$ to $A + B$ collisions with Drell-Yan
Part II

Kinematics, Possible Implementations and Luminosities
Fixed-target collisions at the LHC: main kinematical features

Energy ranges similar to RHIC

Effect of boost: particularly relevant for high energy beams

LHC and the ALICE muon arm become backward detectors $y_c$. $m_s@/zero.fitted$

The ALICE central barrel becomes an extreme backward detector

With the reduced $s$, their acceptance for physics grows and nearly covers half of the backward region for most probes $x_F@/zero.fitted$

Allows for backward physics up to high $x$ uncharted for proton-nucleus coll.; most relevant for $pp$ with large $x$
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7 TeV proton beam on a fixed target

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2.76 TeV Pb beam on a fixed target

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Internal gas target (with or without storage cell)
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- can be installed in one of the existing LHC caverns, and coupled to existing experiments
- validated by LHCb with SMOG [their luminosity monitor used as a gas target]
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→ The beam line option is currently a little too ambitious (this could change with FCC)
→ The gas targets are the best polarised targets and satisfactory for heavy-ion studies
SMOG: more than a demonstrator?

Physics results now following in PRL. For fitting two fitted/two fitted (zero fitted/two fitted/nine fitted)...

Limited statistical samples (hundreds of $\Psi$ only) and no pH baseline yet. The physics reach is still currently very limited.

Approved installation of a storage cell [SMOG/two fitted] to increase the target local density.

Different options discussed for future LHCb upgrades. No decision taken yet.

J.P. Lansberg (IPNO)
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J.P. Lansberg (IPNO)  
FT@HL-LHC  
May 14, 2019
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- A similar solution w/o storage cell like the RHIC H-jet polarimeter is an alternative
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Different options for the FT mode used with ALICE can be considered. An internal gas target is obviously one. Investigations are most advanced for a solid target coupled with a bent crystal for beam-halodeviation. ITS removal during EYETS target location at min. / four, fitted / eight, fitted m from the IP using the existing valve layout. A possible extraction layout worked out by the UA / nine, fitted collaboration. Extraction of these secondary proton halo is preferred. Luminosity reduction can be compensated by a thicker target. A gas-target layout will also be studied within STRONG / two, fitted / zero, fitted / two, fitted / zero, fitted. Gain of an additional tracker and TPC performance yet to be studied within STRONG / two, fitted / zero, fitted / two, fitted / zero, fitted.
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- An internal gas target is obviously one
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- ITS removal during EYETS ⇒ target location at min. -4.8m from the IP using the existing valve layout
- A possible extraction layout worked out by the UA9 collaboration
- Extraction of the secondary proton halo is preferred. Luminosity reduction can be compensated by a thicker target.
- A gas-target layout will also be studied within STRONG2020
- Gain of an additional tracker and TPC perf. yet to be studied within STRONG2020
Luminosity comparison

[with detector constraints]
Luminosity comparison

**LHCb ‘possible’**

**Assumption:** Rates only constrained by the DAQ (40 MHz for $pp$ coll.)

- $\mathcal{L}_{pH_2/H^+}$: 10 fb$^{-1}$ yr$^{-1}$
- $\mathcal{L}_{pXe}$: 300 pb$^{-1}$ yr$^{-1}$
- $\mathcal{L}_{PbXe}$: 30 nb$^{-1}$ yr$^{-1}$

---

**J.P. Lansberg (IPNO)**

FT@(HL)LHC

May 14, 2019
**Luminosity comparison**

### LHCb ‘possible’

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### LHCb ‘SMOG2’ baseline for Run3

**Assumption:** Storage cell installed, very parasitic mode

\[
\mathcal{L}_{p_{\text{beam}}}: 150 \text{ pb}^{-1} \text{ on H, 10 pb}^{-1} \text{ on D or 45 pb}^{-1} \text{ on Ar; } \mathcal{L}_{p_{\text{Pb beam}}}: 5 \text{ nb}^{-1} \text{ on Ar}
\]
Luminosity comparison

LHCb ‘possible’

Assumption: Rates only constrained by the DAQ (40 MHz for $pp$ coll.)

$L_{pH_2/H^+}: 10 \text{ fb}^{-1} \text{ yr}^{-1}$; $L_{pXe}: 300 \text{ pb}^{-1} \text{ yr}^{-1}$; $L_{PbXe}: 30 \text{ nb}^{-1} \text{ yr}^{-1}$

LHCb ‘SMOG2’ baseline for Run3

Assumption: Storage cell installed, very parasitic mode

$L_{p \text{ beam}}: 150 \text{ pb}^{-1}$ on H, $10 \text{ pb}^{-1}$ on D or $45 \text{ pb}^{-1}$ on Ar; $L_{p \text{ beam}}: 5 \text{ nb}^{-1}$ on Ar

ALICE ‘possible’ from Run4

Assumption: Readout rate: 50 kHz in PbPb coll. and possibly up to 1 MHz in $pp$ and $pA$ coll.

With internal gas target: $L_{pH_2/H^+}: 250 \text{ pb}^{-1}$; $L_{pXe}: 8 \text{ nb}^{-1}$

With beam splitting and solid target: $L_{PW}: 0.6 \div 6 \text{ pb}^{-1}$; $L_{PbW}: 3 \text{ nb}^{-1}$
Part III

Examples of Physics Studies
Unique acceptance (with a LHCb-liked detector) compared to existing DY pA data used for nuclear PDF/fit(E). Extremely large yields up to $x/2 \pm 1/2$ (plot made for pX with a Hermes-like target). Same acceptance for pp collisions. A single measurement (in pp coll.) at RHIC, recently released. Decrease of the proton PDF uncertainties: FoM using Bayesian reweighting as well as the nuclear PDF uncertainties. On-going theory study for $W$ production accounting for threshold resummation.
Drell-Yan

- Unique acceptance (with a LHCb-like detector) compared to existing DY $pA$ data used for nuclear PDF fit (E866 & E772 @ Fermilab).

![Drell-Yan plot](image)

- $\sqrt{s} = 115$ GeV, $2 < Y_{\mu\mu}^{lab} < 5$, $p_T^{\mu} > 1.2$ GeV/c, $L = 100$ pb$^{-1}$

J.P. Lansberg (IPNO)

FT@(HL)LHC

May 14, 2019
Drell-Yan

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Drell-Yan

- Unique acceptance (with a LHCb-like detector) compared to existing DY $pA$ data used for nuclear PDF fit (E866 & E772 @ Fermilab).
- Extremely large yields up to $x_2 \rightarrow 1$ [plot made for $pXe$ with a Hermes like target]
- Same acceptance for $pp$ collisions

---

**Drell-Yan, $\sqrt{s} = 115$ GeV , $2 < Y_{\mu\mu}^{lab} < 5$, $p_T^{\mu} > 1.2$ GeV/c, $L = 10$ fb$^{-1}$**

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- Decrease of the proton PDF uncertainties : FoM using Bayesian reweighting

**\( pp \) case**

![Graphs showing PDFs for different cases](image-url)
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$pp$ case

- $Q = 1.3$ GeV
- $u-$PDF
- $d-$PDF
- $\bar{u}-$PDF
- $\bar{d}-$PDF

$R_u = 1.3$ GeV

CT14nlo
CT14nlo prof.
**Drell-Yan**

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- Same acceptance for $pp$ collisions
- A single measurement (in $pp$ coll.) at RHIC, recently released
- Decrease of the proton PDF uncertainties: FoM using Bayesian reweighting
- as well as the nuclear PDF uncertainties

**$pW$ case**
Unique acceptance (with a LHCb-like detector) compared to existing DY $pA$ data used for nuclear PDF fit (E866 & E772 @ Fermilab).

Extremely large yields up to $x_2 \rightarrow 1$ [plot made for $pXe$ with a Hermes like target]

Same acceptance for $pp$ collisions

A single measurement (in $pp$ coll.) at RHIC, recently released

Decrease of the proton PDF uncertainties: FoM using Bayesian reweighting as well as the nuclear PDF uncertainties

On-going theory study for $W^\pm$ production accounting for threshold resummation
Drell-Yan performances for spin analyses  [LHCb-like detector]

C. Hadjidakis et al., 1807.00603; D. Kikola et al. Few Body Syst. 58 (2017) 139
Drell-Yan performances for spin analyses

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- DY pair production on a transversely polarised target
Drell-Yan performances for spin analyses

- DY pair production on a transversely polarised target
- Check the sign change in $A_N$ DY vs SIDIS: hot topic in spin physics!

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Drell-Yan performances for spin analyses

C. Hadjidakis et al.

1. DY pair production on a transversely polarised target
2. Check the sign change in \( A_N \) DY vs SIDIS: hot topic in spin physics!
3. From an exploration phase to a consolidation phase

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\( L_{pp} = 10 \text{ fb}^{-1} \)

**Diagram:**

- \( 4 < M_{\mu\mu} < 9 \text{ GeV/c}^2 \)
- \( dM = 0.5 \text{ GeV/c}^2 \)
- \( pp\ \sqrt{s} = 115 \text{ GeV} \)
- \( 2 < y_{\mu\mu} < 3 \)
- \( 3 < y_{\mu\mu} < 4 \)
- \( 4 < y_{\mu\mu} < 5 \)

\( A_N \) vs. \( x^\uparrow \) with different regions for \( L_{pp} \).

J.P. Lansberg (IPNO)
Drell-Yan performances for spin analyses

- DY pair production on a transversely polarised target
- Check the sign change in $A_N$ DY vs SIDIS: hot topic in spin physics!
- From an exploration phase to a consolidation phase
- $^3\text{He}^\uparrow$ target → quark Sivers effect in the neutron via DY: unique!

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J.P. Lansberg (IPNO)
Kinematical coverage for heavy flavours

**LHCb**

- 

\[
p_{\text{T}} < 15 \text{ GeV/c (bottomonium)}
\]

- 

\[
p_{\text{T}} < 18 \text{ GeV/c (charmonium)}
\]

- 

\[
p_{\text{T}} < 20 \text{ GeV/c (D meson)}
\]

- 

\[
p_{\text{T}} < 16 \text{ GeV/c (B meson)}
\]

**ALICE**

- 

\[
p_{\text{T}} < 8 \text{ GeV/c (bottomonium)}
\]

- 

\[
p_{\text{T}} < 12 \text{ GeV/c (charmonium)}
\]

- 

\[
p_{\text{T}} < 12 \text{ GeV/c (charm)}
\]

J.P. Lansberg (IPNO)
Kinematical coverage for heavy flavours

- **pp** \( \sqrt{s_{NN}} = 115 \text{ GeV}, \text{AFTER@LHCb} \)
  - Green: bottomonium, \( p_T < 15 \text{ GeV/c} \)
  - Blue: charmonium, \( p_T < 18 \text{ GeV/c} \)
  - Red: D meson, \( p_T < 20 \text{ GeV/c} \)
  - Yellow: B meson, \( p_T < 16 \text{ GeV/c} \)
  - \( 2 < y_{\text{lab}} < 5 \)

- **pp** \( \sqrt{s_{NN}} = 115 \text{ GeV}, \text{AFTER@ALICE} \) (\( z=0 \))
  - Green: bottomonium, \( p_T < 8 \text{ GeV/c} \)
  - Blue: charmonium, \( p_T < 12 \text{ GeV/c} \)
  - Red: \( \mu \) from charm, \( 4 < p_T^{\mu} < 12 \text{ GeV/c} \)
  - \( 2.5 < y_{\text{lab}} < 4 \)

ALICE could extend its coverage with \( \eta \) for quarkonia into dileptons with one muon in the muon arm and another in the central barrel.

Both for LHCb and ALICE, the coverage depends on the target position. Access towards large \( x \) is crucial: EMC effect, spin, and UHE neutrinos.

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J.P. Lansberg (IPNO)
Kinematical coverage for heavy flavours

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J.P. Lansberg (IPNO)
Quarkonium Projections for spin asymmetries

C. Hadjidakis et al., 1807.00603; D. Kikola et al. Few Body Syst. 58 (2017)
Quarkonium Projections for spin asymmetries

- $A_N$ for all quarkonia ($J/\psi$, $\psi'$, $\chi_c$, $\Upsilon(nS)$, $\chi_b$ & $\eta_c$) can be measured

[So far, only $J/\psi$ by PHENIX with large uncertainties]

\[ \text{Stat. unc. projection} \]

Stat. unc. projection

\[ A_N \]

\[ p+p \; (s = 115 \text{ GeV}) \]

\[ L_{pp} = 10 \text{ fb}^{-1} \]

eff. pol. $P = 0.8$

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eff. pol. $P = 0.8$
Quarkonium Projections for spin asymmetries

$A_N$ for all quarkonia ($J/\psi, \psi', \chi_c, \Upsilon(nS), \chi_b \& \eta_c$) can be measured

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\[
\psi \text{di}-J/\psi \text{ allow one to study the } k_T \text{ dependence of the gluon Sivers function for the very first time!}
\]
Heavy ions: rapidity scan & heavy-flavour precision studies

Rapidity scan through $\mu$ & $T$ with a good PID (LHC band ALICE). At backward rapidities, lower backgrounds handle on more quarkonium states (e.g. $\chi_c$, $b$, $\eta_c$) and on open charm and beauty. FoMs for $\chi_c$, $b$ and $\eta_c$ to be done in cooperation with the LHC band ALICE collaborations with advanced simulations.
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- Energy domain: between SPS and RHIC

![Diagram of quark-gluon plasma phase transitions](image-url)
Heavy ions: rapidity scan & heavy-flavour precision studies

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Rapidity scan
Illustration of the ALICE-LHCb complementarity

C. Hadjidakis et al., 1807.00603
Quarkonium Projections: heavy-ion collisions

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- Like for nPDF studies (see later), **multiple quarkonium studies are needed**
Quarkonium Projections: heavy-ion collisions


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Quarkonium Projections: heavy-ion collisions

- Like for nPDF studies (see later), multiple quarkonium studies are needed
- Clear need for a reliable $pA$ baseline
- Statistical-uncertainty projections (accounting for background subtraction)

\[
\sqrt{s_{NN}} = 72 \text{ GeV}
\]

\[
L_{pp} = 250 \text{ pb}^{-1}
\]

\[
L_{pXe} = 2 \text{ pb}^{-1}
\]

\[
L_{PbXe} = 30 \text{ nb}^{-1}
\]

\[
J/\psi, \ 
\psi(2S)
\]

\[
p_T > 0.7 \text{ GeV/c}
\]

\[
3 < y_{lab} < 5 \text{ LHCb-like}
\]
Gluons at the high-x frontier using precision heavy-flavour-production data

C. Hadjidakis et al., 1807.00603
Gluons at the high-$x$ frontier using precision heavy-flavour-production data

- Extremely promising first projections using Bayesian reweighting
  [esp. since initial nPDF uncertainties for $x > 0.1$ (red band) are underestimated; simply no data exist there. See *PRL* 121 (2018) 052004]
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**Reward:** unique constraints on gluon (n)PDFs at high $x$ and low scales
Part IV

Conclusions and recommendation
Conclusions and recommandation

- **Three main themes push for a fixed-target program at the LHC**

- Conclusions and recommendations for future research in high-energy physics, focusing on the LHC and its potential for extending the physics reach with fixed-target programs.

- The CERN laboratory should support the efforts of existing LHC experiments to implement such programs, including specific R&D actions on the LHC.

- The LHC, with its new energy, new rapidity domain, and new probes, offers opportunities beyond QCD and EDM of heavy baryons.

- Beyond QCD, the physics reach of the LHC complex can greatly be extended at a very limited cost with an ambitious and long-term research program using the LHC beams in the fixed-target mode.

- Three main themes push for a fixed-target program at the LHC, aiming to advance our understanding of fundamental physics and particle interactions.
Conclusions and recommandation

- **Three main themes push for a fixed-target program at the LHC**
- **The high $x$ frontier**: new probes of the confinement and connections with astroparticles

---

J.P. Lansberg (IPNO)
Conclusions and recommandation

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- A slow extraction with a bent crystal
- An internal gas target inspired from SMOG@LHCb/Hermes/H-Jet, ...

J.P. Lansberg (IPNO)

FT@(HL)LHC
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Part V

Backup slides
Qualitative comparison

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Internal gas target</th>
<th>Internal solid target with beam halo</th>
<th>Beam splitting</th>
<th>Beam extraction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SMOG</td>
<td>Gas Jet</td>
<td>Storage Cell</td>
<td></td>
</tr>
<tr>
<td>Run duration</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>★</td>
</tr>
<tr>
<td>Parasiticity</td>
<td>★★</td>
<td>★</td>
<td>★</td>
<td>★</td>
</tr>
<tr>
<td>Integrated luminosity</td>
<td>★</td>
<td>★★</td>
<td>★★★</td>
<td>★</td>
</tr>
<tr>
<td>Absolute luminosity determination</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>★</td>
</tr>
<tr>
<td>Target versatility</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>★</td>
</tr>
<tr>
<td>(Effective) target polarisation</td>
<td>-</td>
<td>★</td>
<td>-</td>
<td>- / ★</td>
</tr>
<tr>
<td>Use of existing experiment</td>
<td>★★★</td>
<td>★</td>
<td>★</td>
<td>★</td>
</tr>
<tr>
<td>Civil engineering or R&amp;D</td>
<td>★★★★</td>
<td>★★</td>
<td>★</td>
<td>★</td>
</tr>
<tr>
<td>Cost</td>
<td>★★★☆</td>
<td>★</td>
<td>★</td>
<td>★</td>
</tr>
<tr>
<td>Implementation time</td>
<td>★★★☆</td>
<td>★</td>
<td>★</td>
<td>★</td>
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<tr>
<td>High x</td>
<td>★</td>
<td>★★★</td>
<td>★★★☆</td>
<td>★</td>
</tr>
<tr>
<td>Spin Physics</td>
<td>-</td>
<td>★★★</td>
<td>-</td>
<td>- / ★★</td>
</tr>
<tr>
<td>Heavy-Ion</td>
<td>★</td>
<td>★★★</td>
<td>★</td>
<td>★</td>
</tr>
</tbody>
</table>
Bent crystals proposal

- Magnetic (MDM) and electric (EDM) dipole moments of short-lived particles, i.e. charm, beauty baryons, $\tau$ lepton, have never been measured
- A tool for SM and BSM physics
- Exploit the high electric field between Si or Ge crystallographic planes to induce spin precession

Extracted $p$ beam is directed on W target paired to a 2nd bent crystal ($\approx$15 mrad) for spin precession

Heavy baryons are deflected inside the detector to be reconstructed and measure the angular distribution

A 1st bent crystal ($\approx$150 $\mu$rad) extracts 7 TeV protons from LHC beam halo

Non-interacting protons, non-channeling particles and most secondary interactions outside acceptance, to be absorbed downstream the detector
Bent crystals proposal

Ongoing activities:

**LHC Collimation**: layout, simulations, beam extraction, collimators, absorbers

**SELDOM** project & **LHCb** experiment: exp. techniques, physics program, preparatory measurements, R&D on long bent crystals

**UA9** experiment: bent crystals, channeling, layout, LHC beam extraction, double-crystal scheme studies at SPS, physics studies

Aiming for:

- **1st phase** installation at IR8 (LHCb) in YETS Run3:
  - Up to $\sim 10^{15}$ PoT (5 mm W target)
  - e.g. for $\Lambda_c^+$, MDM $\sim 10^{-3}$ $\mu_N$ and EDM $\sim 10^{-17}$ e cm
  - JHEP 1708 (2017)

- **2nd phase** (high lumi) in dedicated experiment (e.g. IR7 or IR3, longer term)
  - e.g. for $\tau$ lepton, $\sim 10^{17}$ PoT for $g-2\sim 10^{-3}$ (SM) and EDM $\sim 10^{-17}$ e cm
  - JHEP 1903 (2019) 156
Further readings

Heavy-Ion Physics


- *Rapidity scan in heavy ion collisions at* $\sqrt{s_{NN}} = 72$ GeV *using a viscous hydro + cascade model* by I. Karpenko: arXiv:1805.11998 [nucl-th]

- *Gluon shadowing effects on* $J/\psi$ *and* $\Upsilon$ *production in* $p+Pb$ *collisions at* $\sqrt{s_{NN}} = 115$ GeV *and* $Pb+p$ *collisions at* $\sqrt{s_{NN}} = 72$ GeV *at* AFTER@LHC *by* R. Vogt. Adv.Hi.En.Phys. (2015) 492302.


- *Lepton-pair production in ultraperipheral collisions at* AFTER@LHC

Further readings

Spin physics


Further readings

Hadron structure


- *ηc production in photon-induced interactions at a fixed target experiment at LHC as a probe of the odderon*  

- *A review of the intrinsic heavy quark content of the nucleon*  

- *Hadronic production of Ξ_{cc} at a fixed-target experiment at the LHC*  
Further readings

Feasibility study and technical ideas


- Heavy-ion Physics at a Fixed-Target Experiment Using the LHC Proton and Lead Beams (AFTER@LHC): Feasibility Studies for Quarkonium and Drell-Yan Production by B. Trzeciak et al. [arXiv:1703.03726 [nucl-ex]] Few Body Syst. 58 (2017) 148


Generalities

- Physics Opportunities of a Fixed-Target Experiment using the LHC Beams