AFTER @ LHC

The Spin Physics Program

Daniel Kikoła, Warsaw University of Technology

AFTER@LHC Study group:
http://after.in2p3.fr/after/index.php/Current_author_list
Outline

- Why a fixed-target experiment at the LHC?
- Physics motivation
- Fixed-target collisions at the LHC
- Selected spin physics cases
- Summary & status
Why a fixed-target experiment at the LHC?

- High luminosities
- Access to high Feynman $x_F$ domain ($|x_F| = |p_z|/p_{z\text{ max}} \to 1$)
- Variety of atomic mass of the target
- Polarization of the target $\rightarrow$ spin physics at the LHC
Why a fixed-target experiment at the LHC?

• High luminosities

• Access to high Feynman $x_F$ domain ($|x_F| = |p_z|/p_{z\,\text{max}} \rightarrow 1$)

• Variety of atomic mass of the target

• Polarization of the target → spin physics at the LHC

Can be realised at CERN in a parasitic mode with the most energetic beams ever!
Physics program
Broad physics program

- High-x gluon, antiquark and heavy-quark content in the nucleon & nucleus

Example:
Reducing unc. in high-energy neutrino & cosmic-rays physics

Energy spectrum of neutrino flux

![Energy spectrum graph]

Physics program

- Heavy-ion collisions

Figure adopted from: https://www.bnl.gov/newsroom/news.php?a=24281
Physics program

- High-x gluon, antiquark and heavy-quark content in the nucleon & nucleus

- Heavy-ion collisions
  - properties of partonic matter

- Transverse dynamics and spin of gluons inside (un)polarised nucleons
The Spin Physics Program

3D mapping of the parton momentum:

- Missing contribution to the proton spin: Gluon and Quark Orbital Angular Momentum $L_q$ and $L_g$

  $p+p^\uparrow \rightarrow$ (indirect) access to quark $L_q$, gluon $L_g$ and gluon TMDs
The Spin Physics Program

3D mapping of the parton momentum:

- Missing contribution to the proton spin: Gluon and Quark Orbital Angular Momentum $L_q$ and $L_g$

  $\rightarrow p+p^\uparrow \rightarrow$ (indirect) access to quark $L_q$, gluon $L_g$ and gluon TMDs

- Test of the QCD factorization framework
The Spin Physics Program

3D mapping of the parton momentum:

- Missing contribution to the proton spin: Gluon and Quark Orbital Angular Momentum $L_q$ and $L_g$

  $\rightarrow p+p^\uparrow \rightarrow \text{(indirect) access to quark } L_q, \text{ gluon } L_g \text{ and gluon TMDs}$

- Test of the QCD factorization framework

- Determination of the linearly polarized gluons in unpolarized protons

Phys. Rev. Lett. 112, 212001
Fixed-target collisions at LHC
Kinematics

- $p+p$ or $p+A$ with a 7 TeV $p$ on a fixed target

\[ \sqrt{s} = \sqrt{2m_N E_p} \approx 115 \text{ GeV} \]

\[ y_{CMS} = 0 \rightarrow y_{Lab} = 4.8 \]
Access to backward physics

Boost effect:

Hadron center-of-mass system

\[ x_1 \approx x_2 \]

\[ x_1 \ll x_2 \]

Target rest frame

\[ \sim 1^\circ \]

large angle
Access to backward physics

Boost effect:

\[ x_1 \approx x_2 \]

\[ x_1 \ll x_2 \]

backward physics = large-\( x_2 \) physics

( \( x_F < 0 \rightarrow \text{large } x^\uparrow \) )
Acceptance for LHCb-type detector

(1) fixed target, $\sqrt{s_{NN}} = 115$ GeV; (2) fixed target, $\sqrt{s_{NN}} = 72$ GeV;
(3) collider mode, $\sqrt{s} = 14$ TeV; (4) collider mode, $\sqrt{s_{NN}} = 5.5$ TeV,
(5),(6) $\sqrt{s_{NN}} = 8.8$ TeV
Fixed-target modes at LHC beams

- Internal target + existing detector
  - gas target (unpolarized/polarized) and full LHC beam
  - beam splitting by bent-crystal + internal (solid, pol.?) target

- Beam extraction by bent-crystal
  - new beam line + new experiment
Internal gas target

- Can be installed in existing LHC caverns or tunnel, and coupled to existing experiments
- Validated by LHCb via a luminosity monitor (SMOG)
- Takes the full LHC beam without loss in lifetime
SMOG-LHCb:
System for Measuring Overlap with Gas

$2 < \eta < 5$
SMOG-LHCb:

Gas injected into into beam vacuum

<table>
<thead>
<tr>
<th>Preferred target Gas</th>
<th>He</th>
<th>Ne</th>
<th>Ar</th>
<th>Kr</th>
<th>Xe</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>4</td>
<td>20</td>
<td>40</td>
<td>84</td>
<td>131</td>
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SMOG-LHCb:

Gas injected into beam vacuum

Preferred target Gas

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LHC beam traverses SMOG shielding (tube with 10 mm i.d. and 1 m long) with no effect on lifetime
SMOG-LHCb data

Successful p+A and A+A data taking
Good resolution, low background

https://twiki.cern.ch/twiki/bin/view/LHCb/LHCbPlots2015
Polarized target: HERMES-type system

HERMES-target in the HERA tunnel.

Source: http://www-hermes.desy.de/hedt/pictures/DESY_PR/
Polarized target: HERMES-type system

- Dedicated pumping system [turbo-molecular pumps]
- Polarised H and D injected ballistically in open-end storage cell with high polarisation ~80%
- Polarised $^3$He or unpolarised heavy gas (Kr, Xe) can also be injected

See talk by P. Lenisa for details
Beam splitting by bent-crystal

Motivation: beam collimation

→ Deflecting the beam halo at 7σ distance to the beam
→ Reduces the LHC beam loss
→ Beam extraction: civil engineering required, new facility with 7 TeV proton beam
→ Beam splitting: intermediate option, might be used with existing experiment

![Diagram showing standard collimation vs. crystal-based collimation](image.png)

*W. Scandale et al., JINST 6 T10002 (2011)*
Expected operation parameters at AFTER:

→ Luminosity $\int \mathcal{L} = 10 \text{ fb}^{-1} / \text{year}$

→ Target polarization $P \sim 80\%$

Avg. polarization $P = 80\%$ assumed based on the HERMES target performance
Sensitivity studies - assumptions

\[ \int \mathcal{L} = 10 \text{ fb}^{-1} / \text{year} \]

P = 60%

HERMES-type polarized target + LHCb – like acceptance and performance

\[ 2 < \eta < 5 \]

microvertexing, particle ID, \( \mu \) ID, electromagnetic and hadronic cal.
Spin physics cases at AFTER@LHC
Orbital angular momentum of quarks and gluons

- non-zero quark/gluon Sivers function $\rightarrow$ non-zero quark/gluon OAM

- Drell-Yan $A_N$ $\rightarrow$ access to $f_{1T}^q(x, \vec{k}_T^2)$

- Gluon Sivers effect
  - essentially unconstrained
  - access via $A_N$ of open charm & quarkonia, $J/\psi$-$J/\psi$, $J/\psi$+$\gamma$
Drell-Yan in AFTER

- large yields

DY studied also for
3 < y_{\mu\mu} < 4 and
4 < y_{\mu\mu} < 5
Drell-Yan in AFTER

- large yields & broad kinematic reach \((10^{-2} < x^< < 0.9)\)
Drell-Yan in AFTER

- Drell-Yan in AFTER
  - large yields & broad $x^\uparrow$ reach: $10^{-2} < x^\uparrow < 0.9$

- High $x^\uparrow \rightarrow$ largest $k_T$ – spin correlation, largest asymmetry expected
Drell-Yan $A_N$ in AFTER

Precision study of the quark Sivers function with Drell-Yan

$$A_N = \frac{1}{P} \frac{\sigma^\uparrow - \sigma^\downarrow}{\sigma^\uparrow + \sigma^\downarrow}$$

$P$ – effective target polarization

STSA predictions for the AFTER@LHC kinematics:
Open charm $A_N$

- Access to the tri-gluon correlation and (indirectly) the gluon Sivers effect ($\rightarrow L_g$)  
  [First hint by COMPASS that $L_g \neq 0$, J. Phys.: Conf. Ser. 678 012055]

- Unique study: $A_N$ of $D^0$ vs $\bar{D}^0$ → access to C-odd correlators

PRD 78, 114013 (2008)

$T_g^{(f)} = - T_g^{(d)}$

$T_g^{(f)} = T_g^{(d)} = 0$

$T_g^{(f)} = T_g^{(d)} -$ tri-gluon corr. functions
Open Heavy Flavour simulations

\[ D^0 \rightarrow K^- \pi^+ \]

- Huge yields
- Charm measured down to 0 p\_T
- Constraint the intrinsic charm in proton
Sensitivity predictions: Open charm $A_N$

- Access to the tri-gluon correlation and the gluon Sivers effect ($\rightarrow L_g$)
- Differences in $A_N D^0$ and $A_N \overline{D^0}$ gives access to C-odd correlators

Precision at the per cent level
Typically $10^9$ charmonia, $10^6$ bottomonia per year
Typically $10^9$ charmonia, $10^6$ bottomonia per year
Quarkonia $A_N$

- Unique access to C-even quarkonia ($\chi_{c,b}$, $\eta_c$) + associated production
- $A_N$ for all quarkonia (J/$\psi$, $\psi'$, $\chi_c$, $\Upsilon(nS)$, $\chi_b$ & $\eta_c$) can be measured

New perspectives to study the gluon Sivers effect (and beyond → L$_g$)
Gluon Sivers effect via associated production

- J/ψ-ψ production (also J/ψ+γ, photon-pair)
  - clean probe of gluon TMD sector → gluon-induced process
  - produced colourless at low momenta
Gluon Sivers effect via associated production

- $J/\psi$-$J/\psi$ production (also $J/\psi+\gamma$, photon-pair)
  - large yields, precise $A_N^{J/\psi-J/\psi}$
  - $A_N (p_T^{J/\psi-J/\psi}) \rightarrow k_T$ dependance of gluon Sivers function
Distribution of linearly polarised gluons in unpolarised protons: $h_{1\perp g}$

- Access via:
  - back-to-back $J/\psi+\gamma$ production
  - low $p_T$ C-even quarkonium

\[ \frac{1}{\sigma} \frac{d\sigma(\eta_Q)}{dq_T^2} \propto 1 - R(q_T^2) \quad \text{and} \quad \frac{1}{\sigma} \frac{d\sigma(\chi_{0,Q})}{dq_T^2} \propto 1 + R(q_T^2) \]

(R involves $f_1^g(x, k_T, \mu)$ and $h_{1\perp g}(x, k_T, \mu)$)

**AFTER@LHC:**
possible to measure C-even quarkonia down to 0 $p_T$ and $J/\psi+\gamma$ and $J/\psi+J/\psi$

$\rightarrow$ determination of $h_{1\perp g}$
Other promising spin studies

- Azimuthal anisotropies beyond $A_N$ (e.g. transversity)
- Direct photon related observables
- Off-shell W production
- Ultra-peripheral collisions
Summary & status

- A fixed-target program at the LHC can be implemented without interfering with the other experiments
- SMOG-LHCb → success story of an internal gas target at the LHC

- **Unique transverse spin program**
  - gluon transverse dynamics via heavy flavor probes
  - precision study of Sivers effect for quarks via Drell-Yan

- An Expression of Interest to be submitted to the LHC Experiments Committee (LHCC) is being written

- AFTER @ LHC: [http://after.in2p3.fr](http://after.in2p3.fr)
Backup slides
Physics opportunities in AFTER @ LHC

Physics opportunities of a fixed-target experiment using LHC beams

*Physics Reports 522 (2013) 239*

Ideas for a fixed target experiment at LHC in a Special Issue in Advances in High Energy Physics:

*Advances in High Energy Physics, Volume 2015 (2015)*

- Heavy-ion physics
- Exclusive reactions
- Spin physics studies
- Hadron structure
- Feasibility study and technical ideas
Further readings: Spin physics


Further readings: Feasibility study and technical ideas


Further readings: Hadron structure


Further readings: Heavy-Ion Physics


- Lepton-pair production in ultraperipheral collisions at AFTER@LHC By J.P. Lansberg, L. Szymanowski, J. Wagner. JHEP 1509 (2015) 087

Acceptance for LHCb-type detector

\begin{align*}
2 < \eta_{\text{lab}} < 5
\end{align*}

\begin{enumerate}
\item p+A, fixed target, $\sqrt{s_{NN}} = 115$ GeV;
\item Pb+A, fixed target, $\sqrt{s_{NN}} = 72$ GeV;
\item p+p, collider mode, $\sqrt{s} = 14$ TeV;
\item Pb+Pb, collider mode, $\sqrt{s_{NN}} = 5.5$ TeV;
\item p+Pb, collider mode, $\sqrt{s_{NN}} = 8.8$ TeV;
\item Pb+p, collider mode, $\sqrt{s_{NN}} = 8.8$ TeV.
\end{enumerate}
Twist-3 predictions

TMD predictions

\[ x_F = x_1 - x_2, \quad x_1 = e^y m_T/\sqrt{s}, \quad x_2 = e^{-y} m_T/\sqrt{s}, \quad m_T^2 = m^2 + p_T^2 \]

Luminosities in p+p and p+A at 115 GeV

### Instantaneous luminosity:

\[ \mathcal{L} = \Phi_{\text{beam}} \times N_{\text{target}} = N_{\text{beam}} \times (\rho \times \ell \times N_A)/A \]

\( I \) is a target thickness

#### Extracted beam

<table>
<thead>
<tr>
<th>Target</th>
<th>( \rho ) (g.cm(^{-3}))</th>
<th>A</th>
<th>( L ) ((\mu)b(^{-1}).s(^{-1}))</th>
<th>( \int L ) (pb(^{-1}).yr(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liq H(_2) (1m)</td>
<td>0.07</td>
<td>1</td>
<td>2000</td>
<td>20000</td>
</tr>
<tr>
<td>Liq D(_2) (1m)</td>
<td>0.16</td>
<td>2</td>
<td>2400</td>
<td>24000</td>
</tr>
<tr>
<td>Be (1cm)</td>
<td>1.85</td>
<td>9</td>
<td>62</td>
<td>620</td>
</tr>
<tr>
<td>Cu (1cm)</td>
<td>8.96</td>
<td>64</td>
<td>42</td>
<td>420</td>
</tr>
<tr>
<td>W (1cm)</td>
<td>19.1</td>
<td>185</td>
<td>31</td>
<td>310</td>
</tr>
<tr>
<td>Pb (1cm)</td>
<td>11.35</td>
<td>207</td>
<td>16</td>
<td>160</td>
</tr>
</tbody>
</table>

#### Internal gas target

<table>
<thead>
<tr>
<th>Beam</th>
<th>Target</th>
<th>Usable gas zone (cm)</th>
<th>Pressure (Bar)</th>
<th>( L ) ((\mu)b(^{-1}).s(^{-1}))</th>
<th>( \int L ) (pb(^{-1}).yr(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>Perfect gas</td>
<td>100</td>
<td>10(^{-9})</td>
<td>10</td>
<td>100</td>
</tr>
</tbody>
</table>

With pressure of 10\(^{-6}\) mbar - 3 times SMOG - one gets 100 pb\(^{-1}\) yr\(^{-1}\)

\[ \rightarrow \text{target storage cell that can be polarised} \]

\[ P = 10^{-4} \text{ mbar} \]

### Integrated luminosities with 10\(^7\) s (LHC year - 9 months of running)

For 1m long H\(_2\) target

\[ \int \mathcal{L} = 20 \text{ fb}^{-1}\text{yr}^{-1} \]

Large luminosities comparable to LHC, 3 orders of magnitude larger than at RHIC

\[ \int \mathcal{L} = 10 \text{ fb}^{-1}\text{yr}^{-1} \quad \text{for } P = 10^{-4} \text{ mbar} \]

Similar integrated luminosities in pA in the target storage cell case as with the extracted beam option

B. Trzeciak, SQM 2016
Luminosities in A+A at 72 GeV

Instantaneous luminosity:

\[ \mathcal{L} = \Phi_{beam} \times N_{target} = N_{beam} \times \left( \rho \times \ell \times N_A \right) / A \]

\[ l \text{ is a target thickness} \]

**Extracted beam**

<table>
<thead>
<tr>
<th>Target</th>
<th>( \rho ) (g.cm(^{-3}))</th>
<th>( A )</th>
<th>( L ) (( \mu b^{-1}.s^{-1} ))</th>
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<td>Liq D(_2) (1m)</td>
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<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Be (1cm)</td>
<td>1.85</td>
<td>9</td>
<td>0.025</td>
<td>0.025</td>
</tr>
<tr>
<td>Cu (1cm)</td>
<td>8.96</td>
<td>64</td>
<td>0.017</td>
<td>0.017</td>
</tr>
<tr>
<td>W (1cm)</td>
<td>19.1</td>
<td>185</td>
<td>0.013</td>
<td>0.013</td>
</tr>
<tr>
<td>Pb (1cm)</td>
<td>11.35</td>
<td>207</td>
<td>0.007</td>
<td>0.007</td>
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**Internal gas target**

<table>
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<tr>
<th>Beam</th>
<th>Target</th>
<th>Usable gas zone (cm)</th>
<th>Pressure (Bar)</th>
<th>( L ) (( \mu b^{-1}.s^{-1} ))</th>
<th>( \int L ) (pb(^{-1}.yr^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pb</td>
<td>Perfect gas</td>
<td>100</td>
<td>( 10^{-6} )</td>
<td>0.001</td>
<td>0.001</td>
</tr>
</tbody>
</table>

\[ P = 10^{-6} \text{ mbar} \]

\[ \rightarrow \text{ target storage cell that can be polarised} \]

**Integrated luminosities with** \( 10^6 \) s (Pb LHC year – 1 months of running)

**For 1m long H\(_2\) target**

\[ \int \mathcal{L} = 0.8 \text{ pb}^{-1}.\text{yr}^{-1} \]

**For 1cm long Pb target**

\[ \int \mathcal{L} = 7 \text{ nb}^{-1}.\text{yr}^{-1} \]

Nominal LHC collider luminosity for PbPb: 0.5 nb\(^{-1}\)
SMOG-LHCb data

p+Ne pilot run at $\sqrt{s_{NN}} = 87$ GeV (2012) $\sim$ 30 min
Pb+Ne pilot run at $\sqrt{s_{NN}} = 54$ GeV (2013) $\sim$ 30min
p+Ne run at $\sqrt{s_{NN}} = 110$ GeV (2015) $\sim$ 12h
p+He run at $\sqrt{s_{NN}} = 110$ GeV (2015) $\sim$ 8h
p+Ar run at $\sqrt{s_{NN}} = 110$ GeV (2015) $\sim$ 3 days
p+Ar run at $\sqrt{s_{NN}} = 69$ GeV (2015) $\sim$ few hours
Pb+Ar run at $\sqrt{s_{NN}} = 69$ GeV (2015) $\sim$ 1.5 week
p+He run at $\sqrt{s_{NN}} = 110$ GeV (2016) $\sim$ 2 days
HERMES-type system

From left to right: Atomic Beam Source (ABS), target chamber with cell and SC magnet coils, diagnostic system of target gas analyzer (TGA), and Breit-Rabi polarimeter (BRP).

## Available Luminosities

<table>
<thead>
<tr>
<th>Beam</th>
<th>Target</th>
<th>$A$</th>
<th>Areal density ($\theta$) $(\text{cm}^{-2})$</th>
<th>$\mathcal{L}$ $(\mu\text{b}^{-1}.\text{s}^{-1})$</th>
<th>$\int \mathcal{L}$ $(\text{fb}^{-1}.\text{y}^{-1})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p$</td>
<td>H</td>
<td>1</td>
<td>$2.5 \times 10^{14}$</td>
<td>900</td>
<td>9</td>
</tr>
<tr>
<td>$p$</td>
<td>D</td>
<td>2</td>
<td>$3.2 \times 10^{14}$</td>
<td>1200</td>
<td>12</td>
</tr>
</tbody>
</table>

(b) Polarised internal-gas-target option
Layout for the measurement of Short Living Baryon Magnetic Moment using Bent Crystals at LHC.

All devices placed in available slots in IR8

The crystal 1 is at 5.0 $\sigma$ from the center-line, whilst the collimation system has the 2016 nominal settings, with the primary TCP at 5.5 $\sigma$. 

W. Scandale, Physics Beyond Colliders, CERN, 06/09/2016
Example: J/ψ

Typically $10^9$ charmonia, $10^6$ bottomonia per year

Kinematics

- p+p or p+A with a 7 TeV p on a fixed target

\[ \sqrt{s} = \sqrt{2m_N E_p} \approx 115 \text{GeV} \]
\[ y_{CMS} = 0 \rightarrow y_{Lab} = 4.8 \]

- A+A collisions with a 2.76 TeV Pb beam

\[ \sqrt{s} \approx 72 \text{GeV} \]
\[ y_{CMS} = 0 \rightarrow y_{Lab} = 4.3 \]
Beam splitting by a bent crystal

→ intermediate option, reduces the civil engineering
→ similar fluxes as for beam extraction (new beam line)
→ might be coupled to an existing experiment

S. Redaelli, Physics Beyond Colliders, CERN, 06/09/2016
Drell-Yan production

$p+p, \ \sqrt{s} = 115 \text{ GeV}$

$L = 10 \text{ fb}^{-1}$

$p_T^\mu > 1.2 \text{ GeV}/c$

$2 < Y_{\mu\mu} < 3$

Counts per 100 MeV/c$^2$

$M_{\mu\mu}$ (GeV/c$^2$)

$\times_F$

$\text{DY signal}$

$\text{ccbar}$

$\text{bbar}$

$\text{sum - MB bkg}$

Counts per 100 MeV/c$^2$

$M_{\mu\mu}$ (GeV/c$^2$)

$\times_F$

$\text{DY signal}$

$\text{ccbar}$

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