The LHCspin project

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Outline

- Fixed-target program at LHCb
- The LHCspin project
- Physics opportunities
- The experimental setup
- Current status and conclusions
Fixed-target program at LHCb
The LHCb detector

- General purpose forward spectrometer
- $2 < \eta < 5$ rapidity coverage
- High performance in charge hadron identification
- Excellent momentum resolution over a wide momentum range
  $\frac{\sigma_p}{p} \sim 0.5 - 1.0\%$
  $p \in [2, 200]$ GeV

The LHCb fixed-target program: SMOG and SMOG2

- Injection of noble gases in the VELO
- Active program with several analyses ongoing
- SMOG2: openable storage cell
  - Precise density measurements (luminosity)
  - Significantly higher areal density
  - More gas species: H$_2$, D$_2$, He, N$_2$, O$_2$, Ne, Ar, Kr, Xe
  - High tracking efficiency despite displaced PVZ

[see poster]
Types of collisions and kinematic regions

**Collider mode**
- $\sqrt{s} = 14$ TeV
- $\sqrt{s_{NN}} = 8.16$ TeV
- $\sqrt{s_{NN}} = 5.5$ TeV

**Fixed-target mode**
- $\sqrt{s_{NN}} = 115$ GeV
- Large Lorentz boost in the laboratory system:
  \[ \gamma = \frac{\sqrt{s_{NN}}}{2m_p} \approx 60 \]
- Negative and mid rapidity in the CM:
  \[-3 \leq y_{CM} \leq 0\]
- High $x$ of the target nucleon at intermediate $Q^2$
- Large and negative $x_F$
- Run in parallel with collider mode (SMOG2)
The LHCspin project
The LHCspin project

First spin-physics program at LHC

Unpolarised physics program

Run in parallel with collider mode

Extending the fixed-target program in Run4

LHC + LHCb + transverse polarised target

$H^\uparrow, D^\uparrow$

Unique kinematic conditions
Physics opportunities
Physics opportunities: TMDs and GPDs

Spin-orbit correlations inside the nucleon

<table>
<thead>
<tr>
<th>$\mathcal{W}_X$</th>
<th>$U$</th>
<th>$L$</th>
<th>$T_x$</th>
<th>$T_y$</th>
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</thead>
<tbody>
<tr>
<td>$U$</td>
<td>$\langle 1 \rangle$</td>
<td>$\langle S_L^q \ell_L^q \rangle$</td>
<td>$\langle S_x^q \ell_x^q \rangle$</td>
<td>$\langle S_y^q \ell_y^q \rangle$</td>
</tr>
<tr>
<td>$L$</td>
<td>$\langle S_L^q \ell_L^q \rangle$</td>
<td>$\langle S_L S_L^q \ell_L^q \rangle$</td>
<td>$\langle S_x^q S_x^q \ell_x^q \ell_x^q \rangle$</td>
<td>$\langle S_y^q \ell_y^q \ell_y^q \rangle$</td>
</tr>
<tr>
<td>$T_x$</td>
<td>$\langle S_x^q \ell_x^q \rangle$</td>
<td>$\langle S_x^q S_x^q S_L^q \ell_L^q \rangle$</td>
<td>$\langle S_x^q \ell_x^q \rangle$</td>
<td>$\langle S_y^q \ell_y^q \ell_y^q \rangle$</td>
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<tr>
<td>$T_y$</td>
<td>$\langle S_y^q \ell_y^q \rangle$</td>
<td>$\langle S_y^q S_y^q S_L^q \ell_L^q \rangle$</td>
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<td>$\langle S_y^q \ell_y^q \ell_y^q \rangle$</td>
</tr>
</tbody>
</table>

$\xi = 0$

$\int d^2 \vec{k}_1$

GPD

<table>
<thead>
<tr>
<th>$U$</th>
<th>$H$</th>
<th>$E_T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L$</td>
<td>$\tilde{H}$</td>
<td>$\tilde{E}_T$</td>
</tr>
<tr>
<td>$T$</td>
<td>$E$</td>
<td>$\tilde{E}$</td>
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</table>

TMD

<table>
<thead>
<tr>
<th>$U$</th>
<th>$f_1$</th>
<th>$h_1^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L$</td>
<td>$g_{1L}$</td>
<td>$h_{1L}^+$</td>
</tr>
<tr>
<td>$T$</td>
<td>$f_{1T}$</td>
<td>$g_{1T}$</td>
</tr>
</tbody>
</table>

[from B. Pasquini DIS2021]

: accessible at LHCspin
Quark TMDs

Goal
- Boer-Mulders function \( h_{1}^{Lq}(x, p_{T}^2) \)
- Quark Sivers function \( f_{1T}^{Lq}(x, p_{T}^2) \)
- Nucleon tomography

Process
- Transverse (un)polarised Drell-Yan

Observable
- Transverse single spin asymmetry (TSSA)
  \[
  A_{N}^{DY} = \frac{1}{P} \frac{\sigma_{DY}^\uparrow - \sigma_{DY}^\downarrow}{\sigma_{DY}^\uparrow + \sigma_{DY}^\downarrow}
  \]
  \[
  A_{cos2\phi}^{UU} \sim \frac{h_{1}^{Lq} \otimes h_{1}^{\bar{q}}}{f_{1}^{q} \otimes f_{1}^{\bar{q}}}
  \]
  \[
  A_{sin\phi_{S}}^{UT} \sim \frac{f_{1}^{q} \otimes f_{1T}^{\bar{q}}}{f_{1}^{q} \otimes f_{1}^{\bar{q}}}
  \]
  \[
  A_{sin(2\phi+\phi_{S})}^{UT} \sim \frac{h_{1}^{Lq} \otimes h_{1}^{\bar{q}}}{f_{1}^{q} \otimes f_{1}^{\bar{q}}}
  \]

Projections
- Clean process
- LHCb well suited to reconstruct di-\(\mu\) final state

[arXiv:1807.00603]

[JHEP 06 (2017) 081]
**gluon TMDs**

- Experimental access extremely limited
- LHCspin: a unique facility to study gTMDs
- gluon Sivers function $f_{1T}^{g}$

**Goal**

- Heavy quarks are mainly produced via gluon fusion
- Factorisation theorem ($p_T << M_q$)

**Process**

Transverse single spin asymmetry (TSSA)

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

**Observable**

$\psi^+$ production for the kinematics reachable at LHC in $-x_F < 0$-type GSF, in particular in the small-$x$ region (see the AFTER PROJECT).

**Projections**

Expected 0-10% asymmetry in $x_F < 0$

$pp^\uparrow \rightarrow J/\psi + X$

Predictions for polarised FT measurements at LHCb

[PRD 99, 036013 (2019)]

<table>
<thead>
<tr>
<th>nucleon pol.</th>
<th>$U$</th>
<th>Circ.</th>
<th>Lin.</th>
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</thead>
<tbody>
<tr>
<td>$U$</td>
<td>$f_{1T}^g$</td>
<td>$h_{1T}^g$</td>
<td></td>
</tr>
<tr>
<td>$L$</td>
<td>$g_{1L}^g$</td>
<td>$h_{1L}^g$</td>
<td></td>
</tr>
<tr>
<td>$T$</td>
<td>$f_{1T}^g$</td>
<td>$g_{1T}^g$, $h_{1T}^g$</td>
<td></td>
</tr>
</tbody>
</table>

**Shinichi Okamura**
The experimental setup
Overview of the setup

Development of a new generation of polarised targets based on HERMES experiment (DESY)

1 Atomic Beam Source (ABS)
   - Input: unpolarised molecules
   - Output: high intensity, collimated, polarised atomic beam

2 Target Cell (TC)
   - T-shaped openable storage cell
   - Dipole holding magnet (transverse polarisation)

3 Diagnostic system
   - Target Gas Analyser: atomic fraction
   - Breit-Rabi Polarimeter: polarisation degree

Input: unpolarised molecules
Output: high intensity, collimated, polarised atomic beam

Courtesy of V. Carassiti

[Ref: NIMA 540 (2005) 68-101]
Target cell and magnet

- Dipole magnet
  - Superconductive coils + iron yoke
  - Possibility to rapidly invert the polarity
  - \( B = 300 \text{ mT} \), to maintain transverse polarisation
  - Uniformity \( \Delta B / B \sim 10\% \), to suppress beam-induced depolarisation [PoS (SPIN2018)]

- Target Cell
  - Almost same position of the SMOG2 cell (\( L = 20 \text{ cm}, D = 1 \text{ cm} \))
  - Inject both unpolarised and polarised gas (only way to bring polarised physics at LHC)
  - \( P \approx 85\% \) achieved at HERMES
ABS and BRP

- R&D phase
- No need for additional detectors
- Design **compact ABS and diagnostic system** to fit inside the limited available space in the VELO alcove
  - Injected intensity of H-atoms: \(~6.5 \times 10^{16} \text{s}^{-1}\)
  - Achievable luminosity (HL-LHC): \(~8 \times 10^{32} \text{cm}^{-2} \text{s}^{-1}\)
- Interface with the LHC
  - Coating of the internal walls of the cell
    - Low molecular recombination rate
    - Low Secondary Electron Yield (SEY)
Conclusions

- Extend the LHCb fixed-target program
  - LHCb spectrometer well suited for fixed-target collisions
  - Unpolarised and polarised target
  - Poorly explored kinematic region

- Physics opportunities
  - Nucleon tomography in momentum space
  - First insights on gTMDs
  - Access to spin-dependent GPDs
  - Comparison with SIDIS experiments

- Setup and current status
  - HERMES-like polarised target setup
  - A challenging R&D but worth the effort!
Backup
Generalised Parton Distribution (GPD)

- Build a **3D maps in coordinate space**
- Exclusive quarkonia production in **ultra peripheral collisions** (UPC)
- Process dominated by the **EM interaction**
- Access to the **Parton Orbital Angular Momentum** (OAM) via the Ji sum rule

\[
\frac{1}{2} = J^q(\mu) + J^g(\mu) = \frac{1}{2} \Delta \Sigma(\mu) + L^q_z(\mu) + J^g(\mu)
\]

- **First measurements of J/ψ production** in UPC in PbPb collisions at LHCb