TMDs STUDIES WITH A FIXED TARGET EXPERIMENT USING THE LHC BEAMS

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OUTLINE

- Why a fixed-target experiment at the LHC?
- LHC beam extraction using a bent crystal
- Luminosities
- Physics highlights for AFTER@LHC
- TMDs studies with AFTER@LHC
- First simulations
WHY A FIXED TARGET EXPERIMENT AT THE LHC?

- Several advantages of the fixed-target mode wrt to the collider mode
  - Accessing the high Feynman $x_F$ domain ($x_F = p_z/p_{z\text{max}}$)
  - Achieving high luminosities thanks to dense targets
  - Easier to change the target type ($\neq$ atomic mass)
  - Possibility to polarize the target
    - Open the possibility for a spin physics program!

- Without affecting the LHC performances
  - Recycling of the beam loss by inserting a bent crystal in the halo ($7\sigma$) of the LHC beam
  - With an outstanding luminosity, yet without pile-up
  - With modern detection techniques
  - Virtually no limit on particle-species studies (except top quark)

AFTER@LHC would definitely be a unique experiment
WHY A FIXED TARGET EXPERIMENT AT THE LHC?

- Provide a novel testing ground for QCD in the high x frontier: $x = [0.3-1]$

- Entire CM forward hemisphere ($y_{CM} > 0$) within $0^\circ < \theta_{lab} < 1^\circ$ (small detector and high multiplicities $\rightarrow$ large occupancies)

- Backward physics ($y_{CM} < 0$): larger angle in the laboratory frame (low occupancies, no constraint from beam pipe). Access to parton with momentum fraction $x_2 \rightarrow 1$ in the target

7 TeV proton beam on a fixed target

<table>
<thead>
<tr>
<th>CMS energy: $\sqrt{s} = \sqrt{2m_N E_p} \approx 115$ GeV</th>
<th>Rapidity shift: $y_{CM} = 0 \rightarrow y_{lab} = 4.8$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boost: $\gamma = \sqrt{s} / (2m_p) \approx 60$</td>
<td></td>
</tr>
</tbody>
</table>

2.76 TeV Pb beam on a fixed target

<table>
<thead>
<tr>
<th>CMS energy: $\sqrt{s_{NN}} = \sqrt{2m_N E_{Pb}} \approx 72$ GeV</th>
<th>Rapidity shift: $y_{CM} = 0 \rightarrow y_{lab} = 4.3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boost: $\gamma \approx 40$</td>
<td></td>
</tr>
</tbody>
</table>
LHC BEAM EXTRACTION USING A BENT CRYSTAL

Standard collimation today

Crystal-based collimation (ideally)

To beam extraction
- CRYSBEAM (@SPS then LHC)
- AFTER@LHC

UA9 experiment @ SPS, 15/10/2014

Direct view of the channeled beam

S. Montesano, W. Scandale, Joint LUA9-AFTER meeting, Nov. 2013
LHC BEAM EXTRACTION USING A BENT CRYSTAL

Beam collimation @LHC: amorphous collimator, inefficiency of 0.2% (3.5TeV p beam) → Expected bent cristal inefficiency : 0.02%

**UA9**: test @SPS on the crystal with proton and ion beams
**LUA9** (beam bending experiment using crystal): approved by LHCC
- 2 bent crystals installed in IR7 during LS1
- 2015/2016 first tests with beams

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**Proton beam extraction:**
- Single or multi-pass extraction efficiency of 50%
- LHC beam loss ~ $10^9$ p/s → Extracted beam : $5 \times 10^8$ p/s
- Extremely small emittance:
  → beam size (in the extraction direction) 950m after the extraction: 0.3mm

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**Ion beam extraction:**
- Successfully tested at the SPS
- Should also work at the LHC
LUMINOSITIES IN $p\bar{p}$, $pA$ @ $\sqrt{S_{NN}} = 115$ GeV AND Pb-A $\sqrt{S_{NN}} = 72$ GeV

Instantaneous luminosity:  
$$L = \phi_{\text{beam}} \times N_{\text{target}} = \phi_{\text{beam}} \times (\rho \times l \times N_A) / A$$

With $l$ target thickness, $\phi_{\text{beam}} = 5 \times 10^8 \, p^+ \, s^{-1}$ (1/2 of the beam loss)

Integrated luminosity: assuming $10^7$ s of $p$ beam and $10^6$ s of Pb beam (LHC year)

In $p\bar{p}$ and $pA$ (115 GeV/c)

<table>
<thead>
<tr>
<th>Target</th>
<th>$\rho$ (g.cm$^{-3}$)</th>
<th>A</th>
<th>$L$ (µb$^{-1}$.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>

Luminosity comparable to the LHC itself (with 1m long H$_2$ (D$_2$) target)  
3 orders of magnitude larger than PHENIX@RHIC  
(run14pp@200GeV: 12pb$^{-1}$, run14dAu@200GeV: 0.15pb$^{-1}$)
PHYSICS HIGHLIGHTS FOR AFTER@LHC

p-p and p-A @ $\sqrt{s_{NN}} = 115$ GeV

Nucleon partonic structure

- Gluon PDF in the proton $\rightarrow$ large uncertainty at large $x$. DIS not ideal
- $g_n(x) = g_p(x)$?
- Experimental probes: quarkonia, isolated photons, high $p_T$ jets
- Multiple probes essential to check factorization

Heavy quark distribution at large $x$ in the proton

- Intrinsic charm?
- Experimental probes: open heavy flavors

Spin Physics

Gluon Sivers effect
- Linearly polarized gluons: $h_T^{Lg}$
- Single Spin Asymmetry in HF and DY studies

W and Z bosons production near threshold?

Pb-A @ $\sqrt{s_{NN}} = 72$ GeV

Gluon distribution in nucleus at large $x$

- Large uncertainty at high $x$
- EIC, LHeC experiments do not help much

Quark Gluon Plasma

- $Y$ sequential suppression
- Quarkonium excited state suppression
  - Jet-HF quenching
  - Direct photons

Ultra-peripheral collisions
Physics opportunities of a fixed-target experiment using LHC beams

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TMDs STUDIES IN AFTER@LHC (WITH A POLARIZED TARGET)

See also presentation by J.P. Lansberg, Gluon TMDs and Quarkonium production in unpolarised and polarised Proton-Proton collisions, on Monday 20th October, s1, 16:30

(Gluon) Sivers effects with a transversely polarized target

Gluon Sivers effect: correlation between the gluon transverse momentum $k_T$ and the proton spin

- The target rapidity region ($x_F < 0$) corresponds to high $x^+$ ($x_F \to -1$) where the $k_T$ - spin correlation is the largest
- Transverse single spin asymmetries studied using **gluon sensitives probes**:  
  - quarkonia ($J/\psi$, $\Upsilon$, $\chi_c$)  
  - B & D mesons production  
  - $\gamma$, $\gamma$-jet, $\gamma\gamma$ also $J/\psi\gamma$
TMDs STUDIES WITH AFTER@LHC (WITH A POLARIZED TARGET)

(Quark) Sivers effects with a transversely polarized target

- Can be probed with the Drell-Yan process

<table>
<thead>
<tr>
<th>Experiment</th>
<th>particles</th>
<th>energy (GeV)</th>
<th>( \sqrt{s} ) (GeV)</th>
<th>( x_p )</th>
<th>( \mathcal{L} ) (nb(^{-1})s(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>AFTER</td>
<td>( p + p^\uparrow )</td>
<td>7000</td>
<td>115</td>
<td>0.01 ( \div ) 0.9</td>
<td>1</td>
</tr>
<tr>
<td>COMPASS</td>
<td>( \pi^\pm + p^\uparrow )</td>
<td>160</td>
<td>17.4</td>
<td>0.2 ( \div ) 0.3</td>
<td>2</td>
</tr>
<tr>
<td>COMPASS (low mass)</td>
<td>( \pi^\pm + p^\uparrow )</td>
<td>160</td>
<td>17.4</td>
<td>( \sim ) 0.05</td>
<td>2</td>
</tr>
<tr>
<td>RHIC</td>
<td>( p^\uparrow + p )</td>
<td>collider</td>
<td>500</td>
<td>0.05 ( \div ) 0.1</td>
<td>0.2</td>
</tr>
<tr>
<td>J–PARC</td>
<td>( p^\uparrow + p )</td>
<td>50</td>
<td>10</td>
<td>0.5 ( \div ) 0.9</td>
<td>1000</td>
</tr>
<tr>
<td>PANDA</td>
<td>( \bar{p} + p^\uparrow )</td>
<td>15</td>
<td>5.5</td>
<td>0.2 ( \div ) 0.4</td>
<td>0.2</td>
</tr>
<tr>
<td>PANDA (low mass)</td>
<td>( \bar{p} + p^\uparrow )</td>
<td>15</td>
<td>5.5</td>
<td>( \sim ) 0.05</td>
<td>0.2</td>
</tr>
<tr>
<td>PAX</td>
<td>( p^\uparrow + \bar{p} )</td>
<td>collider</td>
<td>14</td>
<td>0.1 ( \div ) 0.9</td>
<td>0.002</td>
</tr>
<tr>
<td>NICA</td>
<td>( p^\uparrow + p )</td>
<td>collider</td>
<td>20</td>
<td>0.1 ( \div ) 0.8</td>
<td>0.001</td>
</tr>
<tr>
<td>RHIC Int. Target 1</td>
<td>( p^\uparrow + p )</td>
<td>250</td>
<td>22</td>
<td>0.2 ( \div ) 0.5</td>
<td>2</td>
</tr>
<tr>
<td>RHIC Int. Target 2</td>
<td>( p^\uparrow + p )</td>
<td>250</td>
<td>22</td>
<td>0.2 ( \div ) 0.5</td>
<td>60</td>
</tr>
<tr>
<td>P1027</td>
<td>( p^\uparrow + p )</td>
<td>120</td>
<td>15</td>
<td>0.35 ( \div ) 0.85</td>
<td>400-1000</td>
</tr>
<tr>
<td>P1039</td>
<td>( p + p^\uparrow )</td>
<td>120</td>
<td>15</td>
<td>0.1 ( \div ) 0.3</td>
<td>400-1000</td>
</tr>
</tbody>
</table>

Relevant parameters for the future proposed polarized DY experiments


Prediction for AFTER

M. Anselmo, ECT*, Feb. 2013
(Courtesy U. d’Alessio)

Asymmetry up to 10% predicted in DY for the target rapidity region \( (x_F < 0) \)
TMDs STUDIES WITH AFTER@LHC (WITHOUT A POLARIZED TARGET)

Access to the distribution of linearly polarized gluons ( $h_{1g}^\perp$ )

« Boers-Mulder » effect: correlation between the parton $k_T$ and its spin
For gluons, it is encoded in $h_{1g}^\perp$

- Low-$p_T$ C-even quarkonium production is a good probe of the gluon TMDs.
- The low-$p_T$ spectra of scalar and pseudo-scalar quarkonium ($\chi_{c0}$, $\chi_{b0}$, $\eta_c$, $\eta_b$) are affected differently by the linearly polarized gluons in unpolarized nucleons
  - Boost: better access to low-$p_T$ C-even quarkonia
  - Still challenging experimentally (first study of $\eta_c$ in collider by LHCb for $p_T > 6$ GeV/c)
- If possible somewhere, it is at AFTER@LHC
- Back-to-back $J/\psi + \gamma$ is also a good probe of gluon TMDs

Boer, Pisano, PRD 86 (2012) 094007

Den dunnen et al., PRL 112 (2014) 212001,
J. P. Lansberg, Transversity 2014

Den dunnen et al., PRL 112 (2014) 212001,
J. P. Lansberg, Transversity 2014
Simulations of a 7 TeV proton beam on a Pb target ($\sqrt{s_{NN}} = 115$ GeV)

- Full LHCb simulation and standard reconstruction
- Study the resolution at vertex, the occupancy in the pixels…
- Compare multiplicities in AFTER with LHCb pA run

- Simulations with HIJING version 1.383bs.2
- 10 000 events generated, no pile-up

Z. Yang, AFTER workshop les Houches, January 2014

\[ \frac{dN}{d\eta} \sim 13 \]
Generated charged particles in LHCb acceptance
Simulations of a 7 TeV proton beam on a Pb target ($\sqrt{s_{NN}} = 115$ GeV)

Z. Yang, AFTER workshop les Houches, January 2014

- Probability for high track multiplicity in AFTER (pPb @ 115 GeV) is lower than the one measured by LHCb (pPb/Pbp @ 5.02 TeV)

- No problem for a LHCb-like detector to cope with the multiplicity of pPb collisions at $\sqrt{s_{NN}} = 115$ GeV in $2 < \eta < 5$
**In pH and pA (115 GeV)**

<table>
<thead>
<tr>
<th>Target</th>
<th>$\int L,(fb^{-1}\cdot yr^{-1})$</th>
<th>$N(J/\Psi),yr^{-1}$</th>
<th>$N(\Upsilon),yr^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 m Liq. H$_2$</td>
<td>20</td>
<td>$4.0 \times 10^8$</td>
<td>$8.0 \times 10^5$</td>
</tr>
<tr>
<td>1 m Liq. D$_2$</td>
<td>24</td>
<td>$9.6 \times 10^8$</td>
<td>$1.9 \times 10^6$</td>
</tr>
<tr>
<td>LHC pp 14 Tev (low pT)</td>
<td>0.05 (ALICE) 2 LHCb</td>
<td>$3.6 \times 10^7$</td>
<td>$1.4 \times 10^6$</td>
</tr>
<tr>
<td>RHIC pp 200GeV</td>
<td>$1.2 \times 10^{-2}$</td>
<td>$4.8 \times 10^5$</td>
<td>$1.2 \times 10^3$</td>
</tr>
</tbody>
</table>

**In PbA (72 GeV)**

<table>
<thead>
<tr>
<th>Target</th>
<th>$\int L,(nb^{-1}\cdot yr^{-1})$</th>
<th>$N(J/\Psi),yr^{-1}$</th>
<th>$N(\Upsilon),yr^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 m Liq. H$_2$</td>
<td>800</td>
<td>$3.4 \times 10^6$</td>
<td>$6.9 \times 10^3$</td>
</tr>
<tr>
<td>1 cm Be</td>
<td>25</td>
<td>$9.1 \times 10^5$</td>
<td>$1.9 \times 10^3$</td>
</tr>
<tr>
<td>1 cm Cu</td>
<td>17</td>
<td>$4.3 \times 10^6$</td>
<td>$0.9 \times 10^3$</td>
</tr>
<tr>
<td>1 cm W</td>
<td>13</td>
<td>$9.7 \times 10^6$</td>
<td>$1.9 \times 10^4$</td>
</tr>
<tr>
<td>1 cm Pb</td>
<td>7</td>
<td>$5.7 \times 10^6$</td>
<td>$1.1 \times 10^4$</td>
</tr>
<tr>
<td>LHC PbPb 5.5 TeV</td>
<td>0.5</td>
<td>$7.3 \times 10^6$</td>
<td>$3.6 \times 10^4$</td>
</tr>
<tr>
<td>RHIC AuAu 200GeV</td>
<td>2.8</td>
<td>$4.4 \times 10^6$</td>
<td>$1.1 \times 10^4$</td>
</tr>
<tr>
<td>RHIC AuAu 62GeV</td>
<td>$0.13$</td>
<td>$4.0 \times 10^4$</td>
<td>61</td>
</tr>
</tbody>
</table>

*pp:* 1000 times more statistics than at RHIC ($\sqrt{s} = 200$ GeV) and comparable statistics to LHCb with a 1m H$_2$ target

*pA:* 100 times more statistics than at RHIC (dAu $\sqrt{s} = 200$ GeV) with a 1cm Pb target

PbA: similar statistics as at RHIC (Au-Au $\sqrt{s}_{NN} = 200$ GeV) and 2 orders of magnitude larger than at RHIC (Au-Au $\sqrt{s}_{NN} = 62$ GeV) with a 1cm thick Pb target

Detailed study of quarkonium production and nuclear effects
FAST SIMULATIONS FOR QUARKONIA (pp $\sqrt{s} = 115$ GeV) USING LHCb RECONSTRUCTION PARAMETERS

- Simulations with Pythia 8.185
- LHCb detector is NOT simulated but LHCb reconstruction parameters are introduced in the fast simulation (resolution, analysis cuts, efficiencies...)

Requirements
Momentum resolution: $\Delta p/p = 0.5$
Muon identification efficiency: 98%

Cuts at the single muon level
$2 < \eta_\mu < 5$
$p_T^{\mu} > 0.7$ GeV/c

Muon misidentification
If $\pi$ and K decay before the calorimeters (12m), they are rejected by the tracking
Otherwise a misidentification probability is applied

Performance of the muon identification at LHCb, F. Achilli et al, arXiv:1306.0249
J/Ψ → μ⁺μ⁻ IN MINIMUM BIAS pp COLLISIONS @ 115 GeV

- For 1m of H target and 10 seconds of data taking!

B. Trzeciak, July 2014, Orsay

Misidentified pions is the dominant source of background
$J/\Psi \rightarrow \mu^+\mu^-$ IN MINIMUM BIAS pp COLLISIONS @ 115 GEV (BINS IN RAPIDITY)

For 1m of H target and 1.5 minute of data taking

B. Trzeciak, July 2014, Orsay
Preliminary studies of the $\chi_c$ also started
L_{int} = 192 nb^{-1}, for 1m of H target and 1.5 minute of data taking

- Hope to be able to reach $p_T$ of the $\chi_c$ down to 0
- $\chi_{c1}$ and $\chi_{c2}$ separation

B. Trzeciak, July 2014, Orsay
AFTER@LHC provides a novel testing ground for QCD in the high x frontier

High luminosities are achievable in pp, pA @ 115 GeV and PbA @ 72 GeV using dense targets and without affecting the LHC beam

TMDs studies can be performed with/without polarizing the target thanks to e.g. low-p_T quarkonia

First fast simulations with LHCb like setup are promising

What’s next:
- Special issue in Advances in High Energy Physics (submission deadline in March 2015)
  Everybody is welcome to contribute
  - Expression of interest expected in 2015
  - AFTER week @ CERN, 17-21 November 2014

The AFTER web page: after.in2p3.fr
BACK UP
NUMBER OF CHARGED PARTICLES IN MB pp @ $\sqrt{s} = 115$ GEV

**EPOS 1.6.5**  
Number of generated events: 1000  
\[
dN_{\text{ch}} / d\eta \big|_{\eta = 0} \approx 3
\]

**PYTHIA 8.170**  
Number of generated events: $10^6$  
\[
dN_{\text{ch}} / d\eta \big|_{\eta = 0} \approx 3.5
\]

Rapidity shift:  
\[
\Delta y = \tan^{-1}\beta \approx 4.8  
y_{CM} = 0 \rightarrow y_{lab} \approx 4.8
\]
For 1m of H target and 2 weeks of data taking

Large statistics allow one:
- To reach large $p_T$
- Large $y_{lab}$ acceptance $2 < y_{lab} < 5$
ACCESSING THE LARGE $x$ GLUON PDF

PYTHIA simulation
$\sigma(y) / \sigma(y=0.4)$
statistics for one month
5% acceptance considered

Statistical relative uncertainty
Large statistics allow to access very backward region

Gluon uncertainty from MSTWPDF
- only for the gluon content of the target
- assuming
  $x_g = \frac{M_{J/\Psi}/\sqrt{s}}{e^{-y_{CM}}}$

$J/\Psi$
$y_{CM} \sim 0 \rightarrow x_g = 0.03$
$y_{CM} \sim -3.6 \rightarrow x_g = 1$

$Y$: larger $x_g$ for same $y_{CM}$
$y_{CM} \sim 0 \rightarrow x_g = 0.08$
$y_{CM} \sim -2.4 \rightarrow x_g = 1$

$\Rightarrow$ Backward measurements allow to access large $x$ gluon pdf
Crystal resistance to irradiation

- **IHEP U-70** (Biryukov et al, NIMB 234, 23-30):
  - 70 GeV protons, 50 ms spills of $10^{14}$ protons every 9.6 s, several minutes irradiation
  - equivalent to 2 nominal LHC bunches for 500 turns every 10 s
  - 5 mm silicon crystal, channeling efficiency unchanged

- **SPS North Area - NA48** (Biino et al, CERN-SL-96-30-EA):
  - 450 GeV protons, 2.4 s spill of $5 \times 10^{12}$ protons every 14.4 s, one year irradiation, $2.4 \times 10^{20}$ protons/cm$^2$ in total,
  - equivalent to several year of operation for a primary collimator in LHC
  - $10 \times 50 \times 0.9$ mm$^3$ silicon crystal, $0.8 \times 0.3$ mm$^2$ area irradiated, channeling efficiency reduced by 30%.

- **HRMT16-UA9CRY** (HiRadMat facility, November 2012):
  - 440 GeV protons, up to 288 bunches in 7.2 $\mu$s, $1.1 \times 10^{11}$ protons per bunch ($3 \times 10^{13}$ protons in total)
  - energy deposition comparable to an asynchronous beam dump in LHC
  - 3 mm long silicon crystal, no damage to the crystal after accurate visual inspection, more tests planned to assess possible crystal lattice damage
    - accurate FLUKA simulation of energy deposition and residual dose