Physics case for a polarised target for A Fixed Target ExpeRiment @ the LHC (AFTER@LHC)

Jean-Philippe Lansberg
IPN Orsay, CNRS/IN2P3, Université Paris-Sud

The 2015 International Workshop on Polarized Sources, Targets & Polarimetry (PSTP2015)
14 - 18 September 2015

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

Why a new fixed-target experiment for High-Energy Physics now?
Decisive advantages of Fixed-target experiments

- Fixed-target experiments offer specific **advantages** that are still nowadays **difficult to challenge by collider experiments**
Decisive advantages of Fixed-target experiments

- Fixed-target experiments offer specific advantages that are still nowadays difficult to challenge by collider experiments.
- They exhibit 4 decisive features,
  - accessing the high Feynman $|x_F|$ domain ($x_F \equiv \frac{p_z}{p_{z_{\text{max}}}}$)
  - achieving high luminosities,
  - varying the atomic mass of the target almost at will,
  - polarising the target.

J.P. Lansberg (IPNO, Paris-Sud U.)
Decisive advantages of Fixed-target experiments

- Fixed-target experiments offer specific advantages that are still nowadays difficult to challenge by collider experiments.
- They exhibit 4 decisive features,
  - accessing the high Feynman $|x_F|$ domain ($x_F \equiv \frac{p_z}{p_{z\text{ max}}}$)
  - achieving high luminosities,
  - varying the atomic mass of the target almost at will,
  - polarising the target.
- which are essential assets to study
  - rare proton fluctuations at large $x$
  - vector boson production near threshold and other rare processes
  - nuclear dependence in heavy-ion collisions
  - observables involving gluons and the target proton spin
Why a fixed-target experiment at the LHC?

- **Advance our understanding of the large-x gluon, antiquark and heavy-quark content in the nucleon & nucleus**
Why a fixed-target experiment at the LHC?

- **Advance our understanding of the large-x gluon, antiquark and heavy-quark content in the nucleon & nucleus**
  - Very large PDF uncertainties for $x \gtrsim 0.5$.
    - [could be crucial to characterise possible BSM discoveries]
  - Proton **charm** content important to **high-energy neutrino & cosmic-rays physics**
  - **EMC effect** is an open problem; studying a possible **gluon** EMC effect is essential
  - Relevance of nuclear PDF to understand the **initial state of heavy-ion collisions**
  - Search and study **rare proton fluctuations**
    - where one gluon carries most of the proton momentum
Why AFTER@LHC?

Why a fixed-target experiment at the LHC?

- **Advance our understanding of the large-x gluon, antiquark and heavy-quark content in the nucleon & nucleus**
  - Very large PDF uncertainties for $x \gtrsim 0.5$.
    - [could be crucial to characterise possible BSM discoveries]
  - Proton charm content important to high-energy neutrino & cosmic-rays physics
  - EMC effect is an open problem; studying a possible gluon EMC effect is essential
  - Relevance of nuclear PDF to understand the initial state of heavy-ion collisions
  - Search and study rare proton fluctuations
    - where one gluon carries most of the proton momentum

- **Dynamics and spin of gluons inside (un)polarised nucleons**
Why a fixed-target experiment at the LHC?

- **Advance our understanding of the large-x gluon, antiquark and heavy-quark content in the nucleon & nucleus**
  - Very large PDF uncertainties for $x \gtrsim 0.5$. [could be crucial to characterise possible BSM discoveries]
  - Proton **charm** content important to high-energy neutrino & cosmic-rays physics
  - **EMC effect** is an open problem; studying a possible gluon EMC effect is essential
  - Relevance of nuclear PDF to understand the **initial state of heavy-ion collisions**
  - Search and study **rare proton fluctuations**
    - where one gluon carries most of the proton momentum

- **Dynamics and spin of gluons inside (un)polarised nucleons**
  - Possible missing contribution to the **proton spin: orbital angular momentum**
  - **Test** of the QCD **factorisation** framework
  - Determination of the **linearly polarised gluons** in unpolarised protons
Why a fixed-target experiment at the LHC?

- **Advance our understanding of the large-x gluon, antiquark and heavy-quark content in the nucleon & nucleus**
  - Very large PDF uncertainties for $x \gtrsim 0.5$.
  - [could be crucial to characterise possible BSM discoveries]
  - Proton charm content important to high-energy neutrino & cosmic-rays physics
  - EMC effect is an open problem; studying a possible gluon EMC effect is essential
  - Relevance of nuclear PDF to understand the initial state of heavy-ion collisions
  - Search and study rare proton fluctuations
    - where one gluon carries most of the proton momentum

- **Dynamics and spin of gluons inside (un)polarised nucleons**
  - Possible missing contribution to the proton spin: orbital angular momentum
  - Test of the QCD factorisation framework
  - Determination of the linearly polarised gluons in unpolarised protons

- **Heavy-ion collisions towards large rapidities**
Why AFTER@LHC?

Why a fixed-target experiment at the LHC?

- **Advance our understanding of the large-\(x\) gluon, antiquark and heavy-quark content in the nucleon & nucleus**
  - Very large PDF uncertainties for \(x \gtrsim 0.5\).
  - [could be crucial to characterise possible BSM discoveries]
  - Proton charm content important to high-energy neutrino & cosmic-rays physics
  - EMC effect is an open problem; studying a possible gluon EMC effect is essential
  - Relevance of nuclear PDF to understand the initial state of heavy-ion collisions
  - Search and study rare proton fluctuations
    - where one gluon carries most of the proton momentum

- **Dynamics and spin of gluons inside (un)polarised nucleons**
  - Possible missing contribution to the proton spin: orbital angular momentum
  - Test of the QCD factorisation framework
  - Determination of the linearly polarised gluons in unpolarised protons

- **Heavy-ion collisions towards large rapidities**
  - Explore the longitudinal expansion of QGP formation with new hard probes
  - Test the factorisation of cold nuclear effects from \(p + A\) to \(A + B\) collisions
  - Test the formation of azimuthal asymmetries: hydrodynamics vs. initial-state radiation

J.P. Lansberg (IPNO, Paris-Sud U.)
Part II

A fixed-target experiment using the LHC beam(s): AFTER@LHC
Generalities

- $pp$ or $pA$ collisions with a 7 TeV $p^+$ on a fixed target occur at a CM energy

$$\sqrt{s} = \sqrt{2m_N E_p} \approx 115 \text{ GeV}$$
Generalities

- $pp$ or $pA$ collisions with a 7 TeV $p^+$ on a fixed target occur at a CM energy
  \[ \sqrt{s} = \sqrt{2m_NE_p} \approx 115 \text{ GeV} \]

- In a symmetric collider mode, $\sqrt{s} = 2E_p$, i.e. much larger
A bit of kinematics with the 7 TeV proton beam

Generalities

- $pp$ or $pA$ collisions with a 7 TeV $p^+$ on a fixed target occur at a CM energy
  \[
  \sqrt{s} = \sqrt{2m_N E_p} \approx 115 \text{ GeV}
  \]
  
- In a symmetric collider mode, $\sqrt{s} = 2E_p$, i.e. much larger
  
- Benefit of the fixed target mode: boost: $\gamma_{CM}^{Lab} = \frac{\sqrt{s}}{2m_p} \approx 60$
Generalities

- _pp_ or _pA_ collisions with a 7 TeV _p_ on a fixed target occur at a CM energy
  \[ \sqrt{s} = \sqrt{2m Ne_p} \approx 115 \text{ GeV} \]

- In a symmetric collider mode, \( \sqrt{s} = 2E_p \), _i.e._ much larger

- Benefit of the fixed target mode: boost: \( \gamma_{CM}^{Lab} = \frac{\sqrt{s}}{2m_p} \approx 60 \)

- Rather soft particles in the CM are in principle detectable
Generalities

- *pp* or *pA* collisions with a 7 TeV *p* on a fixed target occur at a CM energy
  \[
  \sqrt{s} = \sqrt{2m_N E_p} \approx 115 \text{ GeV}
  \]

- In a symmetric collider mode, \(\sqrt{s} = 2E_p\), *i.e.* much larger

- Benefit of the fixed target mode: boost: \(\gamma_{CM} = \frac{\sqrt{s}}{2m_p} \approx 60\)

- Rather soft particles in the CM are in principle detectable

- Angle in the Lab. frame: \(\tan \theta = \frac{p_T}{p_{z,Lab}} = \frac{1}{\gamma \beta} \Rightarrow \theta \approx 1^\circ\).

  [Rapidity shift: \(\Delta y = tanh^{-1} \beta \approx 4.8\)]
Generalities

- **pp** or **pA** collisions with a 7 TeV **p** on a fixed target occur at a CM energy
  \[ \sqrt{s} = \sqrt{2m_NE_p} \approx 115 \text{ GeV} \]

- In a symmetric collider mode, \( \sqrt{s} = 2E_p \), *i.e.* much larger

- Benefit of the fixed target mode: boost: \( \gamma^{Lab}_{CM} = \frac{\sqrt{s}}{2m_p} \approx 60 \)

- Rather soft particles in the CM are in principle detectable

- Angle in the Lab. frame: \( \tan \theta = \frac{p_T}{p_z,Lab} = \frac{1}{\gamma \beta} \Rightarrow \theta \approx 1^\circ \).
  
  [Rapidity shift: \( \Delta y = tanh^{-1} \beta \approx 4.8 \)]

- The entire forward CM hemisphere (\( y_{CM} > 0 \)) within \( 0^\circ \leq \theta_{Lab} \leq 1^\circ \)
Generalities

- **pp** or **pA** collisions with a **7 TeV** **$p^+$** on a fixed target occur at a CM energy
  \[ \sqrt{s} = \sqrt{2m_N E_p} \approx 115 \text{ GeV} \]

- In a symmetric collider mode, \( \sqrt{s} = 2E_p \), *i.e.* much larger

- Benefit of the fixed target mode: **boost**:
  \[ \gamma_{CM}^{Lab} = \frac{\sqrt{s}}{2m_p} \approx 60 \]

- Rather soft particles in the CM are in principle detectable

- Angle in the Lab. frame:
  \[ \tan \theta = \frac{p_T}{p_z,Lab} = \frac{1}{\gamma \beta} \implies \theta \approx 1^\circ. \]
  [Rapidity shift: \( \Delta y = \tanh^{-1} \beta \approx 4.8 \)]

- The entire forward CM hemisphere (\( y_{CM} > 0 \)) within \( 0^\circ \leq \theta_{Lab} \leq 1^\circ \)

- **Good thing**: small forward detector \( \equiv \) large acceptance
Generalities

- *pp* or *pA* collisions with a 7 TeV *p* on a fixed target occur at a CM energy
  \[ \sqrt{s} = \sqrt{2m_N E_p} \approx 115 \text{ GeV} \]

- In a symmetric collider mode, \( \sqrt{s} = 2E_p \), i.e. much larger

- Benefit of the fixed target mode: boost: \( \gamma_{CM}^{Lab} = \frac{\sqrt{s}}{2m_p} \approx 60 \)

- Rather soft particles in the CM are in principle detectable

- Angle in the Lab. frame: \( \tan \theta = \frac{p_T}{p_z, Lab} = \frac{1}{\gamma \beta} \Rightarrow \theta \approx 1^\circ \).
  
  [Rapidity shift: \( \Delta y = \tanh^{-1} \beta \approx 4.8 \)]

- The entire forward CM hemisphere \( (y_{CM} > 0) \) within \( 0^\circ \leq \theta_{Lab} \leq 1^\circ \)

- **Good thing**: small forward detector \( \equiv \) large acceptance
Generalities

- **pp** or **pA** collisions with a 7 TeV **p⁺** on a fixed target occur at a CM energy
  \[ \sqrt{s} = \sqrt{2m_N E_p} \approx 115 \text{ GeV} \]

- In a symmetric collider mode, \( \sqrt{s} = 2E_p \), *i.e.* much larger

- Benefit of the fixed target mode: boost: \( \gamma_{CM}^{Lab} = \frac{\sqrt{s}}{2m_p} \approx 60 \)

- Rather soft particles in the CM are in principle detectable

- Angle in the Lab. frame: \[ \tan \theta = \frac{p_T}{p_{z,Lab}} = \frac{1}{\gamma \beta} \Rightarrow \theta \approx 1^\circ. \]
  [Rapidity shift: \( \Delta y = tanh^{-1} \beta \approx 4.8 \)]

- The entire forward CM hemisphere (\( y_{CM} > 0 \)) within \( 0^\circ \leq \theta_{Lab} \leq 1^\circ \)

- **Good thing**: small forward detector \( \equiv \) large acceptance

- **Bad thing**: high multiplicity \( \Rightarrow \) absorber \( \Rightarrow \) physics limitation
Boost effect: LHCb becomes a backward detector

- Because of the boost $y_{CM} = 0 \Rightarrow y_{Lab} \approx 4.8$
Boost effect: LHCb becomes a backward detector

- Because of the boost $y_{CM} = 0 \Rightarrow y_{Lab} \approx 4.8$
- The pseudo-rapidity coverage of LHCb, $2 \leq \eta \leq 5$, approximately translates to a rapidity coverage in the CM of roughly $-2.8 \leq y_{CM} \leq 0.2$
- LHC muon arm: $2.5 \leq \eta \leq 4 \Rightarrow -2.3 \leq y_{CM} \leq -0.8$
Boost effect: LHCb becomes a backward detector

- Because of the boost $y_{CM} = 0 \Rightarrow y_{Lab} \approx 4.8$
- The pseudo-rapidity coverage of LHCb, $2 \leq \eta \leq 5$, approximately translates to a rapidity coverage in the $CM$ of roughly $-2.8 \leq y_{CM} \leq 0.2$
- LHC muon arm: $2.5 \leq \eta \leq 4 \Rightarrow -2.3 \leq y_{CM} \leq -0.8$
- As a comparison, the PHENIX detector with its forward and backward muons arm *only* goes up to $|y_{CM}| \lesssim 2.2$
Boost effect: LHCb becomes a backward detector

- Because of the boost $y_{CM} = 0 \Rightarrow y_{Lab} \simeq 4.8$
- The pseudo-rapidity coverage of LHCb, $2 \leq \eta \leq 5$, approximately translates to a rapidity coverage in the CM of roughly $-2.8 \leq y_{CM} \leq 0.2$
- LHC muon arm: $2.5 \leq \eta \leq 4 \Rightarrow -2.3 \leq y_{CM} \leq -0.8$
- As a comparison, the PHENIX detector with its forward and backward muons arm only goes up to $|y_{CM}| \lesssim 2.2$
- In addition, there are advantages to go there:
  - reduced multiplicities at large(r) angles
  - access to partons with momentum fraction $x \rightarrow 1$ in the target
Boost effect: LHCb becomes a backward detector

- Because of the boost $y_{CM} = 0 \Rightarrow y_{Lab} \approx 4.8$
- The pseudo-rapidity coverage of LHCb, $2 \leq \eta \leq 5$, approximately translates to a rapidity coverage in the CM of roughly $-2.8 \leq y_{CM} \leq 0.2$
- LHC muon arm: $2.5 \leq \eta \leq 4 \Rightarrow -2.3 \leq y_{CM} \leq -0.8$
- As a comparison, the PHENIX detector with its forward and backward muons arm *only* goes up to $|y_{CM}| \lesssim 2.2$

In addition, there are advantages to go there:
- *reduced multiplicities at large(r) angles*
- *access to partons with momentum fraction $x \to 1$ in the target*

![Diagram showing kinematics around the target rest frame and hadron center-of-mass system, illustrating the relationship between $x_1$ and $x_2$.]
Boost effect: LHCb becomes a backward detector

- Because of the boost $y_{CM} = 0 \Rightarrow y_{Lab} \approx 4.8$
- The pseudo-rapidity coverage of LHCb, $2 \leq \eta \leq 5$, approximately translates to a rapidity coverage in the CM of roughly $-2.8 \leq y_{CM} \leq 0.2$
- LHC muon arm: $2.5 \leq \eta \leq 4 \Rightarrow -2.3 \leq y_{CM} \leq -0.8$
- As a comparison, the PHENIX detector with its forward and backward muons arm only goes up to $|y_{CM}| \lesssim 2.2$
- In addition, there are advantages to go there:
  - reduced multiplicities at large($r$) angles
  - access to partons with momentum fraction $x \rightarrow 1$ in the target

\begin{align*}
x_1 &\approx x_2 \\
x_1 &\ll x_2
\end{align*}

**Hadron center-of-mass system**

**Target rest frame**

**backward physics = large-$x_2$ physics**
First systematic access to the target-rapidity region

\( (x_F \rightarrow -1) \)
First systematic access to the target-rapidity region ($x_F \rightarrow -1$)

$J/\psi$ suppression in $pA$ collisions

- $x_F$ systematically studied at fixed target experiments up to $+1$
First systematic access to the target-rapidity region

\( x_F \to -1 \)

\( J/\psi \) suppression in \( pA \) collisions

- \( x_F \) systematically studied at fixed target experiments up to +1
- Hera-B was the only one to really explore \( x_F < 0 \), up to -0.3
First systematic access to the target-rapidity region
($x_F \rightarrow -1$)

$J/\psi$ suppression in $pA$ collisions

- $x_F$ systematically studied at fixed target experiments up to $+1$
- Hera-B was the only one to really explore $x_F < 0$, up to $-0.3$
- PHENIX @ RHIC: $-0.1 < x_F < 0.1$ [could be wider with $\Upsilon$, but low stat.]
- CMS/ATLAS: $|x_F| < 5 \cdot 10^{-3}$; LHCb-collider: $5 \cdot 10^{-3} < x_F < 4 \cdot 10^{-2}$
First systematic access to the target-rapidity region

\( x_F \rightarrow -1 \)

\( J/\psi \) suppression in \( pA \) collisions

- \( x_F \) systematically studied at fixed target experiments up to +1
- Hera-B was the only one to really explore \( x_F < 0 \), up to -0.3
- PHENIX @ RHIC: \(-0.1 < x_F < 0.1 \)  
  [could be wider with \( \Upsilon \), but low stat.]
- CMS/ATLAS: \(|x_F| < 5 \cdot 10^{-3} \); LHCb-collider: \( 5 \cdot 10^{-3} < x_F < 4 \cdot 10^{-2} \)

J.P. Lansberg (IPNO, Paris-Sud U.)
First systematic access to the target-rapidity region

\( x_F \rightarrow -1 \)

\( J/\psi \) suppression in \( pA \) collisions

- \( x_F \) systematically studied at fixed target experiments up to +1
- Hera-B was the only one to really explore \( x_F < 0 \), up to -0.3
- PHENIX @ RHIC: \(-0.1 < x_F < 0.1\)  [could be wider with \( \Upsilon \), but low stat.]
- CMS/ATLAS: \(|x_F| < 5 \cdot 10^{-3}\); LHCb-collider: \( 5 \cdot 10^{-3} < x_F < 4 \cdot 10^{-2}\)
- If we measure \( \Upsilon (b\bar{b}) \) at \( y_{\text{cms}} \approx -2.5 \) \( \Rightarrow x_F \approx \frac{2m_\Upsilon}{\sqrt{s}} \sinh(y_{\text{cms}}) \approx -1 \)
Part III

Colliding the LHC beams on fixed targets: 2 options
The extracted-beam option

★ The LHC beam may be extracted using “Strong crystalline field”

without any decrease in performance of the LHC!

The extracted-beam option

★ The LHC beam may be extracted using “Strong crystalline field”

without any decrease in performance of the LHC!

The extracted-beam option

★ The LHC beam may be extracted using “Strong crystalline field”
without any decrease in performance of the LHC!


★ Illustration for collimation

A solid state primary collimator-scatterer

Bent-crystal as primary collimator
The extracted-beam option

★ The LHC beam may be extracted using “Strong crystalline field” without any decrease in performance of the LHC!


★ Illustration for collimation

★ Tests will be performed on the LHC beam:

LUA9 proposal approved by the LHCC
The extracted-beam option

★ The LHC beam may be extracted using “Strong crystalline field” without any decrease in performance of the LHC!


★ Illustration for collimation

★ Tests will be performed on the LHC beam:

LUA9 proposal approved by the LHCC

★ 2 crystals and 2 goniometers already installed in the LHC beampipe
The extracted-beam option

★ The LHC beam may be extracted using “Strong crystalline field” without any decrease in performance of the LHC!


★ Illustration for collimation

★ Tests will be performed on the LHC beam:

- LUA9 proposal approved by the LHCC
- 2 crystals and 2 goniometers already installed in the LHC beampipe
- CRYSBEM: ERC funded project to extract the LHC beams with a bent crystal (G. Cavoto - Rome)
Luminosities with extracted-proton beams

- Expected proton flux $\Phi_{beam} = 5 \times 10^8 \, p^+ \, s^{-1}$

<table>
<thead>
<tr>
<th>Target</th>
<th>$\rho$ (g.cm$^{-3}$)</th>
<th>$A_L$ ($\mu$b$^{-1}$s$^{-1}$)</th>
<th>$\int L$ (fb$^{-1}$yr$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1m Liq. H</td>
<td>0.07</td>
<td>1</td>
<td>2000</td>
</tr>
<tr>
<td>1m Liq. D</td>
<td>0.16</td>
<td>2</td>
<td>2400</td>
</tr>
<tr>
<td>1cm Be</td>
<td>1.85</td>
<td>9</td>
<td>62.62</td>
</tr>
<tr>
<td>1cm Cu</td>
<td>8.96</td>
<td>64</td>
<td>42.42</td>
</tr>
<tr>
<td>1cm W</td>
<td>19.1</td>
<td>185</td>
<td>31.31</td>
</tr>
<tr>
<td>1cm Pb</td>
<td>11.35</td>
<td>207</td>
<td>16.16</td>
</tr>
</tbody>
</table>

For $pp$ and $pd$ collisions: $L_{H} \sim D_{L} \sim f_b / y \sim 10^3$ orders of magnitude larger than RHIC (GeV)

J.P. Lansberg (IPNO, Paris-Sud U.)
Luminosities with extracted-proton beams

- Expected proton flux $\Phi_{beam} = 5 \times 10^8 \, p^+ \, s^{-1}$
- Instantaneous Luminosity:

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

[ $\ell$: target thickness (for instance 1cm)]
Luminosities with extracted-proton beams

- Expected proton flux $\Phi_{beam} = 5 \times 10^8 \text{ } p^+ \text{ s}^{-1}$
- Instantaneous Luminosity:

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

[ $\ell$: target thickness (for instance 1cm)]

- Integrated luminosity: $\int dt \mathcal{L}$ over $10^7$ s for $p^+$ and $10^6$ for Pb

[the so-called LHC years]
Luminosities with extracted-proton beams

- Expected proton flux $\Phi_{beam} = 5 \times 10^8 \ p^+ \ s^{-1}$
- Instantaneous Luminosity:

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

[ $\ell$: target thickness (for instance 1cm)]

- Integrated luminosity: $\int dt\mathcal{L}$ over $10^7$ s for $p^+$ and $10^6$ for Pb
[the so-called LHC years]

<table>
<thead>
<tr>
<th>Target</th>
<th>$\rho$ (g.cm$^{-3}$)</th>
<th>A</th>
<th>$\mathcal{L}$ (µb.s$^{-1}$)</th>
<th>$\int \mathcal{L}$ (fb$^{-1}$.yr$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1m Liq. H$_2$</td>
<td>0.07</td>
<td>1</td>
<td>2000</td>
<td>20</td>
</tr>
<tr>
<td>1m Liq. D$_2$</td>
<td>0.16</td>
<td>2</td>
<td>2400</td>
<td>24</td>
</tr>
<tr>
<td>1cm Be</td>
<td>1.85</td>
<td>9</td>
<td>62</td>
<td>.62</td>
</tr>
<tr>
<td>1cm Cu</td>
<td>8.96</td>
<td>64</td>
<td>42</td>
<td>.42</td>
</tr>
<tr>
<td>1cm W</td>
<td>19.1</td>
<td>185</td>
<td>31</td>
<td>.31</td>
</tr>
<tr>
<td>1cm Pb</td>
<td>11.35</td>
<td>207</td>
<td>16</td>
<td>.16</td>
</tr>
</tbody>
</table>
Luminosities with extracted-proton beams

- **Expected proton flux** $\Phi_{beam} = 5 \times 10^8 \ p^+ \ s^{-1}$
- **Instantaneous Luminosity**:

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

[ $\ell$: target thickness (for instance 1cm)]

- **Integrated luminosity**: $\int dt \mathcal{L}$ over $10^7$ s for $p^+$ and $10^6$ for Pb

<table>
<thead>
<tr>
<th>Target</th>
<th>$\rho$ (g.cm$^{-3}$)</th>
<th>A</th>
<th>$\mathcal{L}$ (µb$^{-1}$.s$^{-1}$)</th>
<th>$\int \mathcal{L}$ (fb$^{-1}$.yr$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1m Liq. H$_2$</td>
<td>0.07</td>
<td>1</td>
<td>2000</td>
<td>20</td>
</tr>
<tr>
<td>1m Liq. D$_2$</td>
<td>0.16</td>
<td>2</td>
<td>2400</td>
<td>24</td>
</tr>
<tr>
<td>1cm Be</td>
<td>1.85</td>
<td>9</td>
<td>62</td>
<td>.62</td>
</tr>
<tr>
<td>1cm Cu</td>
<td>8.96</td>
<td>64</td>
<td>42</td>
<td>.42</td>
</tr>
<tr>
<td>1cm W</td>
<td>19.1</td>
<td>185</td>
<td>31</td>
<td>.31</td>
</tr>
<tr>
<td>1cm Pb</td>
<td>11.35</td>
<td>207</td>
<td>16</td>
<td>.16</td>
</tr>
</tbody>
</table>

- For $pp$ and $pd$ collisions: $\mathcal{L}_{H_2/D_2} \approx 20 \ fb^{-1} yr^{-1}$

3 orders of magnitude larger than RHIC (200 GeV)
SMOG@LHCb: the first step towards an internal (polarised) target?
Colliding the LHC beams on fixed targets

SMOG@LHCb: the first step towards an internal (polarised) target?

Initially: low density Ne-gas injected into LHCb Vertex Locator

Short pilot runs: two fitted/zero fitted/one fitted/two fitted

Neat ° \text{s}

NN eight fitted/seven fitted/GeV

Pb Neat ° \text{s}

NN five fitted/four fitted/GeV

one fitted/two fitted hours of p Ne and eight fitted hours p He/two fitted/zero fitted/one fitted/five fitted

three fitted days of p Ar in/two fitted/zero fitted/one fitted/five fitted

three fitted weeks of Pb Ar/two fitted/zero fitted/one fitted/five fitted

Noblegasesfavoured

Target unpolarised with the current SMOG system

SMOG test: no decrease of LHC performances observed

J.P. Lansberg (IPNO, Paris-Sud U.)

A Polarised target for AFTER@LHC
Colliding the LHC beams on fixed targets

SMOG@LHCb: the first step towards an internal (polarised) target?

Initially: low density Ne-gas injected into LHCb Vertex Locator [LHCb-CONF-2012-034]
Initial: low density Ne-gas injected into LHCB Vertex Locator [LHCB-CONF-2012-034]

Short pilot runs: 2012 pNe at $\sqrt{s_{NN}} = 87$ GeV & 2013 PbNe at $\sqrt{s_{NN}} = 54$ GeV
SMOG@LHCb: the first step towards an internal (polarised) target?

- Initially: low density Ne-gas injected into LHCb Vertex Locator [LHCb-CONF-2012-034]
- Short pilot runs: 2012 $p$Ne at $\sqrt{s_{NN}} = 87$ GeV & 2013 PbNe at $\sqrt{s_{NN}} = 54$ GeV
- 12 hours of $p$Ne and 8 hours $p$He (09/2015); 3 days of $p$Ar in (10/2015)
- 3 weeks of PbAr (12/2015)
Colliding the LHC beams on fixed targets

SMOG@LHCb: the first step towards an internal (polarised) target?

Initially: low density Ne-gas injected into LHCb Vertex Locator [LHCb-CONF-2012-034]

- Short pilot runs: 2012 $p$Ne at $\sqrt{s_{NN}} = 87$ GeV & 2013 PbNe at $\sqrt{s_{NN}} = 54$ GeV
- 12 hours of $p$Ne and 8 hours $p$He (09/2015); 3 days of $p$Ar in (10/2015)
- 3 weeks of PbAr (12/2015)
- Noble gases favoured
SMOG@LHCb: the first step towards an internal (polarised) target?

- Initially: low density Ne-gas injected into LHCb Vertex Locator [LHCb-CONF-2012-034]
- Short pilot runs: 2012 $p$Ne at $\sqrt{s_{NN}} = 87$ GeV & 2013 PbNe at $\sqrt{s_{NN}} = 54$ GeV
- 12 hours of $p$Ne and 8 hours $p$He (09/2015); 3 days of $p$Ar in (10/2015)
- 3 weeks of PbAr (12/2015)
- Noble gases favoured
- Target unpolarised with the current SMOG system
SMOG@LHCb: the first step towards an internal (polarised) target?

- Initially: low density Ne-gas injected into LHCb Vertex Locator [LHCb-CONF-2012-034]
- Short pilot runs: 2012 $p$Ne at $\sqrt{s_{NN}} = 87$ GeV & 2013 PbNe at $\sqrt{s_{NN}} = 54$ GeV
- 12 hours of $p$Ne and 8 hours $p$He (09/2015); 3 days of $p$Ar in (10/2015)
- 3 weeks of PbAr (12/2015)
- Noble gases favoured
- Target unpolarised with the current SMOG system
- SMOG test: no decrease of LHC performances observed
Luminosities with the internal-gas-target option
Luminosities with the internal-gas-target option

- Instantaneous Luminosity: \( \mathcal{L} = \Phi_{\text{beam}} \times N_{\text{target}} = N_{\text{beam}} \times (\rho \times \ell \times N_A)/A \)
Luminosities with the internal-gas-target option

- **Instantaneous Luminosity**: \( \mathcal{L} = \Phi_{\text{beam}} \times N_{\text{target}} = N_{\text{beam}} \times (\rho \times \ell \times N_A)/A \)
- \( \Phi_{p^+} = 3.2 \times 10^{14} p^+ \times 11000\text{Hz} = 3.5 \times 10^{18} p^+ \text{ s}^{-1} \)
- \( \Phi_{\text{Pb}} = 4.2 \times 10^{10} p^+ \times 11000\text{Hz} = 4.6 \times 10^{14} \text{Pb s}^{-1} \)
Luminosities with the internal-gas-target option

- Instantaneous Luminosity: \( \mathcal{L} = \Phi_{\text{beam}} \times N_{\text{target}} = N_{\text{beam}} \times (\rho \times \ell \times N_A)/A \)
- \( \Phi_{p^+} = 3.2 \times 10^{14} p^+ \times 11000\text{Hz} = 3.5 \times 10^{18} p^+ \text{s}^{-1} \)
- \( \Phi_{\text{Pb}} = 4.2 \times 10^{10} p^+ \times 11000\text{Hz} = 4.6 \times 10^{14} \text{Pb s}^{-1} \)
- Usable gas zone \( \ell \), up to 100 cm
Luminosities with the internal-gas-target option

- Instantaneous Luminosity: \( \mathcal{L} = \Phi_{beam} \times N_{target} = N_{beam} \times (\rho \times \ell \times N_A)/A \)

- \( \Phi_{p^+} = 3.2 \times 10^{14} p^+ \times 11000 \text{Hz} = 3.5 \times 10^{18} p^+ \text{ s}^{-1} \) [1/2 Ampère !]

- \( \Phi_{Pb} = 4.2 \times 10^{10} p^+ \times 11000 \text{Hz} = 4.6 \times 10^{14} \text{Pb s}^{-1} \)

- Usable gas zone \( \ell \), up to 100 cm

- Target density: \( \frac{\rho}{P} = c = \frac{A}{22400} \text{bar}^{-1} \text{ g cm}^{-3} \Rightarrow \mathcal{L} = \Phi_{beam} \times (\frac{N_A}{22400} \times P \times \ell) \)

[1 mole of a perfect gas occupies 22 400 cm³ at 273 K and 1 bar]
Luminosities with the internal-gas-target option

- Instantaneous Luminosity: \( \mathcal{L} = \Phi_{beam} \times N_{target} = N_{beam} \times (\rho \times \ell \times N_A)/A \)

- \( \Phi_{p^+} = 3.2 \times 10^{14} \text{ } p^+ \times 11000\text{Hz} = 3.5 \times 10^{18} \text{ } p^+ \text{ } \text{s}^{-1} \) [1/2 Ampère !]

- \( \Phi_{Pb} = 4.2 \times 10^{10} \text{ } p^+ \times 11000\text{Hz} = 4.6 \times 10^{14} \text{ } \text{Pb} \text{ } \text{s}^{-1} \)

- Usable gas zone \( \ell \), up to 100 cm

- Target density: \( \frac{\rho}{P} = \frac{c}{\frac{A}{22400}} \text{bar}^{-1} \text{g} \text{cm}^{-3} \Rightarrow \mathcal{L} = \Phi_{beam} \times (\frac{N_A}{22400} \times P \times \ell) \)

  [1 mole of a perfect gas occupies 22 400 cm\(^3\) at 273 K and 1 bar]

- For \( P = 10^{-9} \text{ bar} \) [7\(^x\) that of SMOG in 2015, the ‘vacuum’ is \( 10^{-12} \text{ bar} \)], \( \mathcal{L}_{pX(PbX)} = 10(10^{-3}) \mu \text{b}^{-1} \text{ } \text{s}^{-1} \)
Luminosities with the internal-gas-target option

- Instantaneous Luminosity: \( \mathcal{L} = \Phi_{beam} \times N_{target} = N_{beam} \times (\rho \times \ell \times N_A)/A \)
- \( \Phi_{p^+} = 3.2 \times 10^{14} p^+ \times 11000\text{Hz} = 3.5 \times 10^{18} p^+ \text{s}^{-1} \)
- \( \Phi_{\text{Pb}} = 4.2 \times 10^{10} p^+ \times 11000\text{Hz} = 4.6 \times 10^{14} \text{Pb s}^{-1} \)
- Usable gas zone \( \ell \), up to 100 cm
- Target density: \( \frac{\rho}{P} = c = \frac{A}{22400}\text{bar}^{-1}\text{g cm}^{-3} \Rightarrow \mathcal{L} = \Phi_{beam} \times (\frac{N_A}{22400} \times P \times \ell) \)
  [1 mole of a perfect gas occupies 22 400 cm\(^3\) at 273 K and 1 bar]
- For \( P = 10^{-9} \text{bar} \) [7x that of SMOG in 2015, the ’vacuum’ is \( 10^{-12} \text{bar} \)], \( \mathcal{L}_{pX(\text{PbX})} = 10(10^{-3}) \mu\text{b}^{-1} \text{s}^{-1} \)
- Provided that the runs can last as long, similar luminosities for \( pA \) than with the extracted beam options (up to 60 \( \mu\text{b}^{-1} \text{s}^{-1} \))
Luminosities with the internal-gas-target option

- Instantaneous Luminosity: \( \mathcal{L} = \Phi_{\text{beam}} \times N_{\text{target}} = N_{\text{beam}} \times (\rho \times \ell \times \mathcal{N}_A)/A \)

\[ \Phi_{p^+} = 3.2 \times 10^{14} \, \text{p}^+ \times 11000\text{Hz} = 3.5 \times 10^{18} \, \text{p}^+ \, \text{s}^{-1} \]

\[ \Phi_{\text{Pb}} = 4.2 \times 10^{10} \, \text{p}^+ \times 11000\text{Hz} = 4.6 \times 10^{14} \, \text{Pb} \, \text{s}^{-1} \]

- Usable gas zone \( \ell \), up to 100 cm

- Target density: \( \frac{\rho}{P} = c = \frac{A}{22400} \, \text{bar}^{-1} \, \text{g cm}^{-3} \Rightarrow \mathcal{L} = \Phi_{\text{beam}} \times \left( \frac{\mathcal{N}_A}{22400} \times P \times \ell \right) \)

  [1 mole of a perfect gas occupies 22 400 cm³ at 273 K and 1 bar]

- For \( P = 10^{-9} \, \text{bar} \) [7× that of SMOG in 2015, the ‘vacuum’ is \( 10^{-12} \, \text{bar} \)], \( \mathcal{L}_{pX(\text{PbX})} = 10(10^{-3}) \, \mu\text{b}^{-1} \, \text{s}^{-1} \)

- Provided that the runs can last as long, similar luminosities for \( pA \) than with the extracted beam options (up to 60 \( \mu\text{b}^{-1} \, \text{s}^{-1} \))

- To get 10 \( \text{fb}^{-1} \, \text{y}^{-1} \) for \( pp \), \( P \) should reach \( 10^{-7} \, \text{bar} \) ↔ target storage cell

  which could be polarised


- Simply scaled up, this would give for \( \text{PbP} \) or \( \text{PbA} \) 100 \( \text{nb}^{-1} \, \text{y}^{-1} \).

  \( \Rightarrow \) For \( \text{PbA} \), limitations would come first from the beam lifetime.
Luminosities with the internal-gas-target option

- **Instantaneous Luminosity:** \( \mathcal{L} = \Phi_{\text{beam}} \times N_{\text{target}} = N_{\text{beam}} \times (\rho \times \ell \times N_A)/A \)
- \( \Phi_{p^+} = 3.2 \times 10^{14} p^+ \times 11000\text{Hz} = 3.5 \times 10^{18} p^+ \text{s}^{-1} \) [1/2 Ampère !]
- \( \Phi_{\text{Pb}} = 4.2 \times 10^{10} p^+ \times 11000\text{Hz} = 4.6 \times 10^{14} \text{Pb s}^{-1} \)
- Usable gas zone \( \ell \), up to 100 cm
- Target density: \( \frac{\rho}{P} = c = \frac{A}{22400} \text{bar}^{-1} \text{g cm}^{-3} \Rightarrow \mathcal{L} = \Phi_{\text{beam}} \times (\frac{N_A}{22400} \times P \times \ell) \) [1 mole of a perfect gas occupies 22 400 cm³ at 273 K and 1 bar]
- For \( P = 10^{-9} \text{bar} \) [7× that of SMOG in 2015, the ‘vacuum’ is \( 10^{-12} \text{ bar} \)], \( \mathcal{L}_{pX(\text{PbX})} = 10 (10^{-3}) \mu\text{b}^{-1} \text{s}^{-1} \)
- Provided that the runs can last as long, similar luminosities for \( pA \) than with the extracted beam options (up to 60 \( \mu\text{b}^{-1} \text{s}^{-1} \))
- To get \( 10 \text{ fb}^{-1} \text{yr}^{-1} \) for \( pp \), \( P \) should reach \( 10^{-7} \text{ bar} \) ↔ target storage cell which could be polarised


- Simply scaled up, this would give for \( \text{Pb}p \) or \( \text{Pb}A \) 100 nb\(^{-1}\)\(\text{yr}^{-1}\).
  \( \Rightarrow \) For \( \text{Pb}A \), limitations would come first from the beam lifetime.
- A specific gas target could be a competitive alternative to the beam extraction
Part IV

AFTER@LHC: the case of spin physics
The quest for the orbital angular momentum of the quarks and gluons

Quark/Gluon Sivers function: distortion in the distribution of an unpolarised parton with momentum fraction $x$ and transverse momentum $k_T$ due to the proton transverse polarisation:

$$f_{\mathrm{q/g}}(x, k_T)\,\tilde{T}.$$ 

First suggested by D. Sivers to explain the large observed lepton single transverse spin asymmetries $A_N$ in $p p \pi X$ non-zero quark/gluon Sivers function

Process dependence predicted:

$$f_{\mathrm{q/g}}(x, k_T)\,\tilde{T}.$$ 

Drell-Yan

Semi-Inclusive DIS

Several experiments wish to measure $A_{\mathrm{Drell-Yan}}$ to extract $f_{\mathrm{q/g}}(x, k_T)\,\tilde{T}.$

COMPASS: valence quarks using a pion beam (one/fitted/six/fitted/zero/fitted GeV) on a polarised proton target (one/fitted/zero/fitted/seven/fitted: valence quarks using a polarised proton beam (one/fitted/two/fitted/zero/fitted GeV) on an unpolarised proton target (one/fitted/zero/fitted/three/fitted/nine/fitted: sea quarks using an unpolarised proton beam (one/fitted/two/fitted/zero/fitted GeV) on a polarised proton target.)
The quest for the orbital angular momentum of the quarks and gluons

- Quark/Gluon Sivers function: distortion in the distribution of an unpolarised partons with momentum fraction $x$ and transverse momentum $k_{\perp}$ due to the proton transverse polarisation: $f_{1T}^{\perp}(x, \vec{k}_{\perp}^2)$
The quest for the orbital angular momentum of the quarks and gluons

- Quark/Gluon Sivers function: distortion in the distribution of an unpolarised partons with momentum fraction $x$ and transverse momentum $k_\perp$ due to the proton transverse polarisation: $f_{1T}^ q(x, \vec{k}_\perp^2)$

- First suggested by D. Sivers to explain the large observed left-right single transverse spin asymmetries $A_N$ in $p^\uparrow p \rightarrow \pi X$
The quest for the orbital angular momentum of the quarks and gluons

- **Quark/Gluon Sivers function**: distortion in the distribution of an unpolarised partons with momentum fraction $x$ and transverse momentum $k_\perp$ due to the proton transverse polarisation: $f_{1T}(x, \bar{k}_\perp^2)$

- First suggested by D. Sivers to explain the large observed left-right single transverse spin asymmetries $A_N$ in $p^\uparrow p \rightarrow \pi X$

- non-zero quark/gluon Sivers function $\Rightarrow$ non-zero quark/gluon OAM
The quest for the orbital angular momentum of the quarks and gluons

- Quark/Gluon Sivers function: **distortion** in the distribution of an unpolarised partons with momentum fraction $x$ and transverse momentum $k_\perp$ due to the proton transverse polarisation: $f_{1T}^{\perp}(x, \vec{k}_\perp)$

- First suggested by D. Sivers to explain the large observed left-right single transverse spin asymmetries $A_N$ in $p^\uparrow p \rightarrow \pi X$

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

- Process dependence predicted: $f_{1T}^{\perp q}(x, \vec{k}_\perp)^{\text{Drell–Yan}} = -f_{1T}^{\perp q}(x, \vec{k}_\perp)^{\text{Semi–Inclusive DIS}}$
The quest for the orbital angular momentum of the quarks and gluons

- Quark/Gluon Sivers function: **distortion** in the distribution of an unpolarised partons with momentum fraction $x$ and transverse momentum $k_\perp$ due to the proton transverse polarisation: $f_{1T}^L(x, \bar{k}_\perp^2)$

- First suggested by D. Sivers to explain the large observed left-right single transverse spin asymmetries $A_N$ in $p^\uparrow p \rightarrow \pi X$

- **non-zero** quark/gluon Sivers function $\Rightarrow$ **non-zero** quark/gluon OAM

- Process dependence predicted: $f_{1T}^{\perp q}(x, \bar{k}_\perp^2)_{Drell-Yan} = -f_{1T}^{\perp q}(x, \bar{k}_\perp^2)_{Semi-Inclusive DIS}$

- Several experiments wish to measure $A_N^{Drell-Yan}$ to extract $f_{1T}^{\perp q}(x, \bar{k}_\perp^2)$
  - COMPASS: valence quarks using a pion beam (160 GeV) on a polarised proton target
  - P1027: valence quarks using a polarised proton beam (120 GeV) on an unpolarised proton target
  - P1039: sea quarks using an unpolarised proton beam (120 GeV) on a polarised proton target
Relevant parameters for existing and proposed polarized DY experiments.

<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 (low mass)</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</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>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>
<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>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 (low mass)</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>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 (1,2)</td>
<td>$p^\uparrow + p$</td>
<td>250</td>
<td>22</td>
<td>$0.2 \div 0.5$</td>
<td>$(2,60)$</td>
</tr>
</tbody>
</table>
SSA in Drell-Yan studies with AFTER@LHC

⇒ Relevant parameters for existing and proposed polarized DY experiments.


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

For AFTER, $\mathcal{L}$ corresponds to the Barschel et al. setup
or an equivalent of 50 cm liquid $H$ target ⇒ could yield up to 10 fb$^{-1}$ per year
SSA in Drell-Yan studies with AFTER@LHC

Relevant parameters for existing and proposed polarized DY experiments.


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

For AFTER, $\mathcal{L}$ corresponds to the Barschel et al. setup
or an equivalent of 50 cm liquid $H$ target ⇒ could yield up to 10 fb$^{-1}$ per year
It is admittedly an apple-to-pear comparison since the precision on $A_N$
depends on the polarisation of the target/beam and on the cross-sections.
Relevant parameters for existing and proposed polarized DY experiments.


<table>
<thead>
<tr>
<th>Experiment</th>
<th>particles</th>
<th>energy (GeV)</th>
<th>$\sqrt{s}$ (GeV)</th>
<th>$x_p^\uparrow$</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 ÷ 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 ÷ 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>~ 0.05</td>
<td>2</td>
</tr>
<tr>
<td>P1039</td>
<td>$p + p^\uparrow$</td>
<td>120</td>
<td>15</td>
<td>0.1 ÷ 0.3</td>
<td>400-1000</td>
</tr>
<tr>
<td>P1027</td>
<td>$p^\uparrow + p$</td>
<td>120</td>
<td>15</td>
<td>0.35 ÷ 0.85</td>
<td>400-1000</td>
</tr>
<tr>
<td>RHIC</td>
<td>$p^\uparrow + p$</td>
<td>collider</td>
<td>500</td>
<td>0.05 ÷ 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 ÷ 0.9</td>
<td>1000</td>
</tr>
<tr>
<td>PANDA (low mass)</td>
<td>$\bar{p} + p^\uparrow$</td>
<td>15</td>
<td>5.5</td>
<td>0.2 ÷ 0.4</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 ÷ 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 ÷ 0.8</td>
<td>0.001</td>
</tr>
<tr>
<td>RHIC Int. Target (1,2)</td>
<td>$p^\uparrow + p$</td>
<td>250</td>
<td>22</td>
<td>0.2 ÷ 0.5</td>
<td>(2,60)</td>
</tr>
</tbody>
</table>

- For AFTER, $\mathcal{L}$ corresponds to the Barschel et al. setup
- or an equivalent of 50 cm liquid $H$ target ⇒ could yield up to 10 fb$^{-1}$ per year
- It is admittedly an apple-to-pear comparison since the precision on $A_N$
- depends on the polarisation of the target/beam and on the cross-sections.
- Nota: At RHIC energy, Drell-Yan studies are very delicate (see later)
  [not yet done for unpolarised $pp$ collisions]
SSA in Drell-Yan studies with AFTER@LHC

Relevant parameters for existing and proposed polarized DY experiments.


<table>
<thead>
<tr>
<th>Experiment</th>
<th>particles</th>
<th>energy (GeV)</th>
<th>(\sqrt{s}) (GeV)</th>
<th>(x_p^\uparrow)</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 ÷ 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 ÷ 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>~0.05</td>
<td>2</td>
</tr>
<tr>
<td>P1039</td>
<td>(p + p^\uparrow)</td>
<td>120</td>
<td>15</td>
<td>0.1 ÷ 0.3</td>
<td>400-1000</td>
</tr>
<tr>
<td>P1027</td>
<td>(p^\uparrow + p)</td>
<td>120</td>
<td>15</td>
<td>0.35 ÷ 0.85</td>
<td>400-1000</td>
</tr>
<tr>
<td>RHIC</td>
<td>(p^\uparrow + p)</td>
<td>collider</td>
<td>500</td>
<td>0.05 ÷ 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 ÷ 0.9</td>
<td>1000</td>
</tr>
<tr>
<td>PANDA (low mass)</td>
<td>(\bar{p} + p^\uparrow)</td>
<td>15</td>
<td>5.5</td>
<td>0.2 ÷ 0.4</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 ÷ 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 ÷ 0.8</td>
<td>0.001</td>
</tr>
<tr>
<td>RHIC Int.Target (1,2)</td>
<td>(p^\uparrow + p)</td>
<td>250</td>
<td>22</td>
<td>0.2 ÷ 0.5</td>
<td>(2,60)</td>
</tr>
</tbody>
</table>

For AFTER, \(\mathcal{L}\) corresponds to the Barschel et al. setup
or an equivalent of 50 cm liquid \(H\) target ⇒ could yield up to 10 fb\(^{-1}\) per year
It is admittedly an apple-to-pear comparison since the precision on \(A_N\)
depends on the polarisation of the target/beam and on the cross-sections.
Nota: At RHIC energy, Drell-Yan studies are very delicate (see later)
[not yet done for unpolarised pp collisions]
AFTER could be the only project able to reach \(x^\uparrow = 10^{-2}\) and \(x^\uparrow > 0.4\)
SSA in Drell-Yan studies with AFTER@LHC

Expected asymmetries

The target-rapidity region (negative $x_F$) corresponds to high $x^\uparrow$
where the $k_T$-spin correlation is the largest.
SSA in Drell-Yan studies with AFTER@LHC

Expected asymmetries

The target-rapidity region (negative $x_F$) corresponds to high $x^\uparrow$
where the $k_T$-spin correlation is the largest

\[ p p^\uparrow \rightarrow l^+ l^- + X \]

\[ \sqrt{s}=115 \text{ GeV} \quad 4<M<9 \text{ GeV} \quad -4<y<1 \quad q_T<1.5 \text{ GeV} \]

SIDIS 1 (Sivers effect)

SSA in Drell-Yan studies with AFTER@LHC

Expected asymmetries

The target-rapidity region (negative $x_F$) corresponds to high $x^\uparrow$
where the $k_T$-spin correlation is the largest

\[ p p^\uparrow \rightarrow l^+ l^- + X \]

Experimental goal: to measure asymmetries on the order of 5-10 % at $x_F < 0$
With 10 fb$^{-1}$, one can expect up to $10^6$ DY events in $4 < M < 9$ GeV (see later)
The gluon OAM contribution to the proton spin

- **Gluon Sivers effect essentially unconstrained**

The gluon OAM contribution to the proton spin

- **Gluon Sivers effect essentially unconstrained**
- **It can be measured via** $A_N$ **of gluon sensitive probes** [as opposed to DY for quarks]

The gluon OAM contribution to the proton spin

- **Gluon Sivers effect** essentially unconstrained
  

- It can be measured via $A_N$ of **gluon sensitive probes** [as opposed to DY for quarks]

- Theoretical complications suggest to analyse **multiple probes**
The gluon OAM contribution to the proton spin

- **Gluon Sivers effect** essentially unconstrained


- It can be measured via $A_N$ of **gluon sensitive probes** [as opposed to DY for quarks]

- Theoretical complications suggest to analyse **multiple probes**

- **quarkonia** ($J/\psi$, $\Upsilon$, $\chi_c$, $\eta_c$, ...)

The gluon OAM contribution to the proton spin

- **Gluon Sivers effect** essentially unconstrained
  

- It can be measured via $A_N$ of **gluon sensitive probes** [as opposed to DY for quarks]

- Theoretical complications suggest to analyse **multiple probes**

- quarkonia ($J/\psi$, $\Upsilon$, $\chi_c$, $\eta_c$, ...)
  

- **$B$ & $D$ meson production**
  

- $p+p \rightarrow J/\psi + X$ at $\sqrt{s} = 200$ GeV
  
  $<p_T> = 1.6$ GeV/c (side points)
  $<p_T> = 1.5$ GeV/c (middle point)
The gluon OAM contribution to the proton spin

- **Gluon Sivers effect** essentially unconstrained
  

- It can be measured via $A_N$ of **gluon sensitive probes** [as opposed to DY for quarks]

- **Theoretical complications** suggest to analyse **multiple probes**

- **quarkonia ($J/\psi$, $\Upsilon$, $\chi_c$, $\eta_c$, ...)**
  

- **$B$ & $D$ meson production**
  

- **$\gamma$, $\gamma$-jet, $\gamma - \gamma$**
  
  J.W. Qiu, et al., PRL 107 (2011) 062001
The gluon OAM contribution to the proton spin

- **Gluon Sivers effect** essentially unconstrained
  

- It can be measured via $A_N$ of **gluon sensitive probes** [as opposed to DY for quarks]

- Theoretical complications suggest to analyse **multiple probes**

- **quarkonia** ($J/\psi$, $\Upsilon$, $\chi_c$, $\eta_c$, ...)
  

- **$B$ & $D$ meson production**
  

- **$\gamma$, $\gamma$-jet, $\gamma - \gamma$**
  

- **$J/\psi + \gamma$: the cleanest; sensitive to gluons up to $x^\uparrow \approx 0.5$**
  
Gluon contribution to the proton spin

**The gluon OAM contribution to the proton spin**

- **Gluon Sivers effect** essentially unconstrained
  

- It can be measured via $A_N$ of **gluon sensitive probes** [as opposed to DY for quarks]

- Theoretical complications suggest to analyse multiple probes

- **quarkonia** ($J/\psi$, $\Upsilon$, $\chi_c$, $\eta_c$, ...)

  

- **$B$ & $D$ meson production**


- $\gamma$, $\gamma$-jet, $\gamma - \gamma$

  
  - J.W. Qiu, et al., PRL 107 (2011) 062001

- $J/\psi + \gamma$: the cleanest; sensitive to gluons up to $x^\uparrow \approx 0.5$


- **All these measurements can be done with AFTER@LHC with the required precision**: $10^9 J/\psi$, $10^6 \Upsilon$, $10^8 B$, etc ...
Further studies of the Sivers effect

- $A_N^\gamma$ is predicted to have an **opposite sign** between the Generalised Parton Model (GPM) and the Collinear-Twist 3 (CT3) approach
  

- $A_N^\pi$: sign mismatch issue with $f_{1T,q}^\perp(x, \vec{k}_T^2)$ extracted from SIDIS
  
  - $A_N^{jet}$: complementary since no “contamination” (fragmentation Collins effect)
  - $A_N^\pi$ should be measured at larger $p_T$
Part V

First simulation results
First simulation: is the boost an issue?

First simulation: is the boost an issue?


- LHCb has successfully carried out $p$Pb and Pb$p$ analyses at 5 TeV
First simulation: is the boost an issue?


- LHCb has successfully carried out $p$Pb and Pb$p$ analyses at 5 TeV
- We have compared the multiplicity as function of $\eta$ in the collider mode ($\sqrt{s} = 5$ TeV) vs. that in fixed target mode ($\sqrt{s} = 115$ TeV) using EPOS
First simulation: is the boost an issue?

LHCb has successfully carried out $p$Pb and Pb$p$ analyses at 5 TeV

We have compared the multiplicity as function of $\eta$ in the collider mode ($\sqrt{s} = 5$ TeV) vs. that in fixed target mode ($\sqrt{s} = 115$ TeV) using EPOS

Despite the boost, the multiplicity in the LHCb acceptance [forward $\eta$] is lower in the fixed mode than in the collider mode (at higher $\sqrt{s}$)
First simulation: is the boost an issue?

LHCb has successfully carried out $p$Pb and Pb$p$ analyses at 5 TeV

We have compared the multiplicity as function of $\eta$ in the collider mode ($\sqrt{s} = 5$ TeV) vs. that in fixed target mode ($\sqrt{s} = 115$ TeV) using EPOS

Despite the boost, the multiplicity in the LHCb acceptance [forward $\eta$] is lower in the fixed mode than in the collider mode (at higher $\sqrt{s}$)

Simulation backed-up with a comparison of the number-of-track distribution between simulations at the detector level and data

Z. Yang, private comm.
Fast simulation using LHCb reconstruction parameters
Projection for a LHCb-like detector

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

Requirements:
- Momentum resolution: $\frac{\Delta p}{p} = 0.5\%$
- Muon identification efficiency: 98%

Cuts at the single muon level
- $2 < \eta_{\mu} < 5$
- $p_{T\mu} > 0.7 \text{ GeV}$

Muon misidentification:
- If $\pi$ and $K$ decay before the calorimeters (12m), they are rejected by the tracking
- otherwise a misidentification probability is applied following: F. Achilli et al, arXiv:1306.0249
Charmonium background & its rapidity dependence

Charmonium background & its rapidity dependence

Bottomonium background & signal reach


The dominant background is Drell-Yan

3 peaks well resolved
Bottomonium background & signal reach


The dominant background is Drell-Yan

3 peaks well resolved

$J/\psi$: $10^4$ events at $P_T \approx 12$ GeV
$\Upsilon$: 200 events at $P_T \approx 12$ GeV

$J/\psi$: reach cut by the detector acceptance

$\Upsilon$: 200 events at $y_{c.m.s.} \approx -2.1$, i.e. $x_2 \approx 0.7$
Drell-Yan background & signal reach

- At backward rapidities, quark-induced processes are favoured ⇒ Bkgd get smaller
Drell-Yan background & signal reach

- At backward rapidities, quark-induced processes are favoured $\Rightarrow$ Bkgd get smaller

- Charm and beauty background can be cut (2nd vertex) but interesting on their own
Drell-Yan background & signal reach

- At backward rapidities, quark-induced processes are favoured ⇒ Bkgd get smaller

- Charm and beauty background can be cut (2nd vertex) but interesting on their own

- Uncorrelated background can be subtracted by the mixing-event method
  [up to which $S/B$ depends on the systematics of the subtraction]
Drell-Yan background & signal reach

- At backward rapidities, quark-induced processes are favoured ⇒ Bkgd get smaller

- Charm and beauty background can be cut (2nd vertex) but interesting on their own

- Uncorrelated background can be subtracted by the mixing-event method
  [up to which $S/B$ depends on the systematics of the subtraction]

- Still 4000+ DY events left in $2 < Y < 3$ for $8 < M < 9$ GeV, i.e. at $x^\uparrow \approx 0.7$
Drell-Yan background & signal reach

- At backward rapidities, quark-induced processes are favoured ⇒ Bkgd get smaller

- Charm and beauty background can be cut (2nd vertex) but interesting on their own

- Uncorrelated background can be subtracted by the mixing-event method
  [up to which S/B depends on the systematics of the subtraction]

- Still 4000+ DY events left in $2 < Y < 3$ for $8 < M < 9$ GeV, i.e. at $x^+ \approx 0.7$

- Should yield to precise measurements of $A_N^{DY}$ at large $x$
Part VI

Further readings
Heavy-Ion Physics


Further readings

Spin physics

- Transverse single-spin asymmetries in proton-proton collisions at the AFTER@LHC experiment

- Transverse single-spin asymmetries in proton-proton collisions at the AFTER@LHC experiment in a TMD factorisation scheme

- The gluon Sivers distribution: status and future prospects

- Azimuthal asymmetries in lepton-pair production at a fixed-target experiment using the LHC beams (AFTER)

- Polarized gluon studies with charmonium and bottomonium at LHCb and AFTER
Further readings

Hadron structure

- **Double-quarkonium production at a fixed-target experiment at the LHC (AFTER@LHC).**

- **Next-To-Leading Order Differential Cross-Sections for Jpsi, psi(2S) and Upsilon Production in Proton-Proton Collisions at a Fixed-Target Experiment using the LHC Beams (AFTER@LHC)**

- **$\eta_c$ 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 $\Xi_{cc}$ at a fixed-target experiment at the LHC**
Further readings

Feasibility study and technical ideas


Generalities

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

Conclusion and outlooks
Conclusion

- **Three main themes push for a fixed-target program at the LHC**
  [without interfering with the other experiments]
Conclusion

- **Three main themes push for a fixed-target program at the LHC**
  [without interfering with the other experiments]
- The large $x$ frontier: new probes of the confinement
  and connections with astroparticles
Conclusion

- **Three main themes push for a fixed-target program at the LHC**
  - [without interfering with the other experiments]
  - The large $x$ frontier: new probes of the confinement and connections with astroparticles
  - The nucleon spin and the transverse dynamics of the partons
Three main themes push for a fixed-target program at the LHC
[without interfering with the other experiments]
- The large $x$ frontier: new probes of the confinement and connections with astroparticles
- The nucleon spin and the transverse dynamics of the partons
- The approach to the deconfinement phase transition:
  new energy, new rapidity domain and new probes
Conclusion

- **Three main themes push for a fixed-target program at the LHC**
  [without interfering with the other experiments]
  - The large $x$ frontier: new probes of the confinement and connections with astroparticles
  - The nucleon spin and the transverse dynamics of the partons
  - The approach to the deconfinement phase transition: new energy, new rapidity domain and new probes

- **2 ways towards fixed-target collisions with the LHC beams**
Conclusion

- **Three main themes push for a fixed-target program at the LHC**
  [without interfering with the other experiments]
  - The large $x$ frontier: new probes of the confinement and connections with astroparticles
  - The nucleon spin and the transverse dynamics of the partons
  - The approach to the deconfinement phase transition:
    new energy, new rapidity domain and new probes

- **2 ways towards fixed-target collisions with the LHC beams**
  - A slow extraction with a bent crystal
  - An internal gas target inspired from SMOG@LHCb/Hermes/H-jet@RHIC, ...
Conclusion

- **Three main themes push for a fixed-target program at the LHC**
  [without interfering with the other experiments]
  - The large $x$ frontier: new probes of the confinement
    and connections with astroparticles
  - The nucleon spin and the transverse dynamics of the partons
  - The approach to the deconfinement phase transition:
    new energy, new rapidity domain and new probes

- **2 ways towards fixed-target collisions with the LHC beams**
  - A slow extraction with a bent crystal
  - An internal gas target inspired from SMOG@LHCb/Hermes/H-jet@RHIC, ...

- **Large potential for spin physics with**
Conclusion

- **Three main themes push for a fixed-target program at the LHC**
  [without interfering with the other experiments]
  - The large $x$ frontier: new probes of the confinement and connections with astroparticles
  - The nucleon spin and the transverse dynamics of the partons
  - The approach to the deconfinement phase transition: new energy, new rapidity domain and new probes

- **2 ways towards fixed-target collisions with the LHC beams**
  - A slow extraction with a bent crystal
  - An internal gas target inspired from SMOG@LHCb/Hermes/H-jet@RHIC, ...

- **Large potential for spin physics with**
  - extracted beam + polarised target as COMPASS, P1039, JLab ...
  - polarised gas target
Conclusion

- **Three main themes push for a fixed-target program at the LHC**
  - [without interfering with the other experiments]
  - The large $x$ frontier: new probes of the confinement and connections with astroparticles
  - The nucleon spin and the transverse dynamics of the partons
  - The approach to the deconfinement phase transition: new energy, new rapidity domain and new probes

- **2 ways towards fixed-target collisions with the LHC beams**
  - A slow extraction with a bent crystal
  - An internal gas target inspired from SMOG@LHCb/Hermes/H-jet@RHIC, ...

- **Large potential for spin physics with**
  - extracted beam + polarised target as COMPASS, P1039, JLab ...
  - polarised gas target

- We have started to draft an Expression of Interest to be submitted to the LHCC
Conclusion

- **Three main themes push for a fixed-target program at the LHC**
  - [without interfering with the other experiments]
  - The large $x$ frontier: new probes of the confinement and connections with astroparticles
  - The nucleon spin and the transverse dynamics of the partons
  - The approach to the deconfinement phase transition: new energy, new rapidity domain and new probes

- **2 ways towards fixed-target collisions with the LHC beams**
  - A slow extraction with a bent crystal
  - An internal gas target inspired from SMOG@LHCb/Hermes/H-jet@RHIC, ...

- **Large potential for spin physics with**
  - extracted beam + polarised target as COMPASS, P1039, JLab ...
  - polarised gas target

- We have started to draft an Expression of Interest to be submitted to the LHCC
- Your contribution is welcome especially on the polarised target
Conclusion

- **Three main themes push for a fixed-target program at the LHC**
  - [without interfering with the other experiments]
  - The large x frontier: new probes of the confinement and connections with astroparticles
  - The nucleon spin and the transverse dynamics of the partons
  - The approach to the deconfinement phase transition: new energy, new rapidity domain and new probes

- **2 ways towards fixed-target collisions with the LHC beams**
  - A slow extraction with a bent crystal
  - An internal gas target inspired from SMOG@LHCb/Hermes/H-jet@RHIC, ...

- **Large potential for spin physics with**
  - extracted beam + polarised target as COMPASS, P1039, JLab ...
  - polarised gas target

- We have started to draft an Expression of Interest to be submitted to the LHCC
- Your contribution is welcome especially on the polarised target
Part VIII

Backup slides
Overall

\[ \log (x^{-1}) \uparrow \]

Fixed Target @ LHC

Non perturbative regime

Dilute system

\[ Q^2 = Q^2_s(x) \]

BK-JIMWLK

DGLAP

EMC effect

Nuclear fermi motion

Fixed Target @ LHC

J.P. Lansberg (IPNO, Paris-Sud U.)

A Polarised target for AFTER@LHC

September 15, 2015 34 / 32
Overall

Fixed Target @ LHC

\[ \log(x^{-1}) \uparrow \]

Non perturbative regime

\[ x \rightarrow 1, x \rightarrow 1 \]

Dilute system

\[ \log(Q^2) \]

Non perturbative regime

\[ Q^2 = Q^2_s(x) \]

log (x-1)

log (Q^2)

BKL-JIMWLK saturation

Drell-Yan

DGLAP

EMC effect

Nuclear fermi motion

\[ ? \rightarrow ? \rightarrow ? \rightarrow ? \rightarrow ? \rightarrow ? \rightarrow \]
Overall

\[ Q^2 = Q^2_s(x) \]

\[ \log(x^{-1}) \uparrow \]

Non perturbative regime

\[ x \geq 1 \] \rightarrow \[ x \rightarrow 1 \]

Fixed Target @ LHC

Fixed Target @ LHC

BKH-JIMWLK

Dilute system

Quarkonia

EMC effect

Drell-Yan

Nuclear fermi motion

DGLAP

J.P. Lansberg (IPNO, Paris-Sud U.)

A Polarised target for AFTER@LHC

September 15, 2015
J.P. Lansberg (IPNO, Paris-Sud U.)

A Polarised target for AFTER@LHC

September 15, 2015
Overall

DGLAP
BFKL
saturation
Dilute system

\[ Q^2 = Q^2_s(x) \]

log (x⁻¹)

Fixed Target @ LHC

log (Q²)

x \geq 1 \rightarrow \log (x-1)

DKLAP

W/Z

Fixed Target @ LHC

Non perturbative regime

BK-JIMWLK

Drell-Yan

Quarkonia

High-p_T jet

EMC effect

Nuclear fermi motion

J.P. Lansberg (IPNO, Paris-Sud U.)

A Polarised target for AFTER@LHC

September 15, 2015
Tabelle 1: Vergleich von Gaszielen in Speicherringen mit einem hypothetischen Ziel für die geplante AFTER@LHC Initiative [1, 2]. Das Zielgas $^1$H, $^2$D, oder $^3$He wird als spinpolariert angenommen.

<table>
<thead>
<tr>
<th>Speicherring</th>
<th>Teilchen</th>
<th>$E_{\text{max}}$ [GeV]</th>
<th>Zieltyp</th>
<th>$L$ [m]</th>
<th>$T$ [K]</th>
<th>$L_{\text{max}}$ [1/cm$^2$/s]</th>
<th>Anmerkungen</th>
<th>Bezug</th>
</tr>
</thead>
<tbody>
<tr>
<td>HERA-e DESY (term. 2007)</td>
<td>$e^\pm$ pol.</td>
<td>27.6</td>
<td>Cell $^1$H, $^2$D, $^3$He</td>
<td>0.4</td>
<td>100</td>
<td>$2.5 \cdot 10^{31}$ $2.5 \cdot 10^{32}$</td>
<td>HERMES exp. 1995–2007</td>
<td>[9]</td>
</tr>
<tr>
<td>RHIC-p BNL</td>
<td>p pol.</td>
<td>250</td>
<td>Jet</td>
<td>—</td>
<td>—</td>
<td>$1.7 \cdot 10^{30}$</td>
<td>Absolute p polarimeter</td>
<td>[10]</td>
</tr>
<tr>
<td>COSY FZ Jülich</td>
<td>p, d pol.</td>
<td>3.77</td>
<td>Cell $^1$H, $^2$D</td>
<td>0.4</td>
<td>300</td>
<td>$10^{29}$ $2.75 \cdot 10^{29}$</td>
<td>ANKE exp. PAX exp.</td>
<td>[4, 5]</td>
</tr>
<tr>
<td>LHC CERN (proposed)</td>
<td>p unpol. heavy ions</td>
<td>7,000, 2,760 · $A$</td>
<td>Cell $^1$H, $^2$D $^\text{Xe}$ $M \approx 131$</td>
<td>1.0</td>
<td>$\geq 100$</td>
<td>$10^{33}$ $10^{27} - 10^{28}$</td>
<td>Based on techn. of HERMES target</td>
<td>this paper</td>
</tr>
</tbody>
</table>

$\rightarrow$ Strahllebenszeit mit $L_{\text{pp}} = 10^{33}$ cm$^{-2}$ s$^{-1} = 10$ nb$^{-1}$ s$^{-1}$ of $2 \times 10^6$ s (or 23 days).
Accessing the large $x$ glue with quarkonia:

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
MSTW PDF
- only for the gluon content of the target
- assuming

$$x_g = M_{J/\Psi} / \sqrt{s} \ e^{-y_{CM}}$$

$J/\Psi$

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

Assuming that we understand the quarkonium-production mechanisms

$Y$: larger $x_g$ for same $y_{CM}$

$y_{CM} \sim 0 \rightarrow x_g = 0.08$
$y_{CM} \sim -2.4 \rightarrow x_g = 1$

⇒ Backward measurements allow to access large $x$ gluon pdf
Distribution of linearly polarised gluons in unpolarised protons
Distribution of linearly polarised gluons in unpolarised protons

PHYSICAL REVIEW D 86, 094007 (2012)
Polarized gluon studies with charmonium and bottomonium at LHCb and AFTER

Daniël Boer
理论集团, KVI, 乌得勒支大学, Zernikeplein 25, NL-9747 AA Groningen, The Netherlands
Cristian Pisano
Istituto Nazionale di Fisica Nucleare,  C.P. 170, I-09042 Monserrato (CA), Italy

A Polarised target for AFTER@LHC

J.P. Lansberg (IPNO, Paris-Sud U.)
Distribution of linearly polarised gluons in unpolarised protons

- Low $P_T$ C-even quarkonium production is a good probe of the distribution of linearly polarised gluons in unpolarised protons: $h_{1Lg}$
Low $P_T$ C-even quarkonium production is a good probe of the distribution of linearly polarised gluons in unpolarised protons: $h_{1}^{Lg}$

Affect the low $P_T$ spectra:

$$\frac{1}{\sigma} \frac{d\sigma(\eta_Q)}{dq_T^2} \propto 1 - R(q_T^2) \quad \& \quad \frac{1}{\sigma} \frac{d\sigma(\chi_{0,Q})}{dq_T^2} \propto 1 + R(q_T^2)$$

($R$ involves $f_1^g(x, k_T, \mu)$ and $h_{1}^{Lg}(x, k_T, \mu)$)
Low $P_T$ C-even quarkonium production is a good probe of the distribution of linearly polarised gluons in unpolarised protons: $h_{1}^{Lg}$

Affect the low $P_T$ spectra:

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

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

The boost is of great help to access low $P_T$ P-wave quarkonia.

Overall Distribution of linearly polarised gluons in unpolarised protons
Low $P_T$ C-even quarkonium production is a good probe of the distribution of linearly polarised gluons in unpolarised protons: $h_{1,Lg}$

Affect the low $P_T$ spectra:

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

($R$ involves $f_{1g}^2(x, k_T, \mu)$ and $h_{1,Lg}^g(x, k_T, \mu)$)

The boost is of great help to access low $P_T$ $P$-wave quarkonia

$h_{1,Lg}$ is connected to the Higgs transverse-momentum distribution D. Boer, et al. PRL 108 (2012) 032002
Access to $h_1^{lg}$: II
Accessing the Transverse Dynamics and Polarization of Gluons inside the Proton at the LHC

Wilco J. den Dunnen,1,* Jean-Philippe Lansberg,2,† Cristian Pisano,3,‡ and Marc Schlegel1,§

1Institute for Theoretical Physics, Universität Tübingen, Auf der Morgenstelle 14, D-72076 Tübingen, Germany
2IPNO, Université Paris-Sud, CNRS/IN2P3, F-91406, Orsay, France
3Nikhef and Department of Physics and Astronomy, VU University Amsterdam,
   De Boelelaan 1081, NL-1081 HV Amsterdam, The Netherlands

Accessing the Transverse Dynamics and Polarization of \( h_1^{gl} \): II
Access to $h_1^{1g}: \text{II}$

Gluon B-M can also be accessed via back-to-back $\psi/\Upsilon + \gamma$ associated production at the LHC. Also true at AFTER@LHC!
Access to $h_1^{1g}$: II

Gluon B-M can also be accessed via back-to-back $\psi/\Upsilon + \gamma$ associated production at the LHC. Also true at AFTER@LHC!

Smaller yield (14 TeV $\rightarrow$ 115 GeV) compensated by an access to lower $P_T$
**Gluon B-M can also be accessed via back-to-back $\psi/\Upsilon + \gamma$ associated production at the LHC. Also true at AFTER@LHC!**

**Smaller yield (14 TeV $\rightarrow$ 115 GeV) compensated by an access to lower $P_T$**

---

**Accessing the Transverse Dynamics and Polarization of Gluons inside the Proton at the LHC**

Wilco J. den Dunnen,1,* Jean-Philippe Lansberg,2,† Cristian Pisano,3,‡ and Marc Schlegel1,§

1Institute for Theoretical Physics, Universität Tübingen, Auf der Morgenstelle 14, D-72076 Tübingen, Germany
2IPNO, Université Paris-Sud, CNRS/IN2P3, F-91406, Orsay, France
3Nikhef and Department of Physics and Astronomy, VU University Amsterdam, De Boelelaan 1081, NL-1081 HV Amsterdam, The Netherlands

---

**Direct back-to-back $J/\psi + \gamma$ at $\sqrt{s}=115$ GeV**

- $|Y| < 0.5; |\cos\theta_{CS}| < 0.45$
- $-1.5 < Y < -0.5; |\cos\theta_{CS}| < 0.45$
- $-2.5 < Y < -1.5; |\cos\theta_{CS}| < 0.45$

- $<O^{q\bar{q}}(J/\psi)>=0.02$ GeV$^3$
- $<O^{gg}(J/\psi)>=0.002$ GeV$^3$

**Legend:**
- $gg$: Color Singlet
- $gg$: Color Octet
- $qq$: Color Singlet
- $qq$: Color Octet

---

J.P. Lansberg (IPNO, Paris-Sud U.)

A Polarised target for AFTER@LHC

September 15, 2015 38 / 32
Gluon B-M can also be accessed via back-to-back $\psi/Y + \gamma$ associated production at the LHC. Also true at AFTER@LHC!

Smaller yield (14 TeV $\rightarrow$ 115 GeV) compensated by an access to lower $P_T$
Luminosities with extracted-lead beams
Luminosities with extracted-lead beams

- **Instantaneous Luminosity:**
  \[
  \mathcal{L} = \Phi_{beam} \times N_{\text{target}} = N_{beam} \times (\rho \times \ell \times N_A)/A
  \]
  \[
  \Phi_{beam} = 2 \times 10^5 \text{ Pb s}^{-1}, \quad \ell = 1 \text{ cm (target thickness)}
  \]
Luminosities with extracted-lead beams

- **Instantaneous Luminosity:**
  \[ \mathcal{L} = \Phi_{beam} \times N_{target} = \frac{N_{beam} \times (\rho \times \ell \times N_A)}{A} \]
  \[ \Phi_{beam} = 2 \times 10^5 \text{ Pb s}^{-1}, \quad \ell = 1 \text{ cm (target thickness)} \]

- **Integrated luminosity**
  \[ \int dt \mathcal{L} = \mathcal{L} \times 10^6 \text{ s for Pb} \]
Luminosities with extracted-lead beams

- Instantaneous Luminosity:
  \[ \mathcal{L} = \Phi_{beam} \times N_{target} = N_{beam} \times (\rho \times \ell \times N_A)/A \]
  \[ \Phi_{beam} = 2 \times 10^5 \text{ Pb s}^{-1}, \quad \ell = 1 \text{ cm (target thickness)} \]

- Integrated luminosity \( \int dt\mathcal{L} = \mathcal{L} \times 10^6 \text{ s for Pb} \)

- Expected luminosities with \( 2 \times 10^5 \text{Pb s}^{-1} \) extracted (1cm-long target)

<table>
<thead>
<tr>
<th>Target</th>
<th>( \rho ) (g.cm(^{-3}))</th>
<th>A</th>
<th>( \mathcal{L} ) (mb(^{-1}).s(^{-1})) = ( \mathcal{L} ) (nb(^{-1}).yr(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1m Liq. H(_2)</td>
<td>0.07</td>
<td>1</td>
<td>800</td>
</tr>
<tr>
<td>1m Liq. D(_2)</td>
<td>0.16</td>
<td>2</td>
<td>1000</td>
</tr>
<tr>
<td>1cm Be</td>
<td>1.85</td>
<td>9</td>
<td>25</td>
</tr>
<tr>
<td>1cm Cu</td>
<td>8.96</td>
<td>64</td>
<td>17</td>
</tr>
<tr>
<td>1cm W</td>
<td>19.1</td>
<td>185</td>
<td>13</td>
</tr>
<tr>
<td>1cm Pb</td>
<td>11.35</td>
<td>207</td>
<td>7</td>
</tr>
</tbody>
</table>
Luminosities with extracted-lead beams

- **Instantaneous Luminosity:**
  \[ \mathcal{L} = \Phi_{beam} \times N_{target} = \frac{N_{beam} \times (\rho \times \ell \times \mathcal{N}_A)}{A} \]
  \[ \Phi_{beam} = 2 \times 10^5 \text{ Pb s}^{-1}, \quad \ell = 1 \text{ cm (target thickness)} \]

- **Integrated luminosity** \[ \int dt \mathcal{L} = \mathcal{L} \times 10^6 \text{ s for Pb} \]

- **Expected luminosities with** \[ 2 \times 10^5 \text{Pb s}^{-1} \text{ extracted (1cm-long target)} \]

<table>
<thead>
<tr>
<th>Target</th>
<th>( \rho ) (g.cm(^{-3}))</th>
<th>( A )</th>
<th>( \mathcal{L} ) (mb(^{-1}).s(^{-1}))=( \int \mathcal{L} ) (nb(^{-1}).yr(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1m Liq. ( \text{H}_2 )</td>
<td>0.07</td>
<td>1</td>
<td>800</td>
</tr>
<tr>
<td>1m Liq. ( \text{D}_2 )</td>
<td>0.16</td>
<td>2</td>
<td>1000</td>
</tr>
<tr>
<td>1cm Be</td>
<td>1.85</td>
<td>9</td>
<td>25</td>
</tr>
<tr>
<td>1cm Cu</td>
<td>8.96</td>
<td>64</td>
<td>17</td>
</tr>
<tr>
<td>1cm W</td>
<td>19.1</td>
<td>185</td>
<td>13</td>
</tr>
<tr>
<td>1cm Pb</td>
<td>11.35</td>
<td>207</td>
<td>7</td>
</tr>
</tbody>
</table>

- **Planned lumi for PHENIX Run15AuAu 2.8 nb\(^{-1}\) (0.13 nb\(^{-1}\) at 62 GeV)

- **Nominal LHC lumi for PbPb 0.5 nb\(^{-1}\)**
The beam extraction with a bent crystal

- Inter-crystalline fields are huge

![Graph showing deflection efficiency vs. deflection angle for Ge (110), 450 GeV protons.](image)

**Overall**

A Polarised target for *AFTER@LHC*
The beam extraction with a bent crystal

- Inter-crystalline fields are huge
- The channeling efficiency is high for a deflection of a few mrad

![Graph showing deflection efficiency vs. deflection angle for Ge (110), 450 GeV protons]

2000 T!
The beam extraction with a bent crystal

- Inter-crystalline fields are huge

- The channeling efficiency is high for a deflection of a few mrad
- One can extract a significant part of the beam loss \((10^9 p^+ s^{-1})\)
The beam extraction with a bent crystal

- Inter-crystalline fields are huge

![Graph showing deflection efficiency vs. deflection angle](image)

- The channeling efficiency is high for a deflection of a few mrad
- One can extract a significant part of the beam loss ($10^9 p^+ s^{-1}$)
- Simple and robust way to extract the most energetic beam ever:
The beam extraction: news

Goal: assess the possibility to use bent crystals as primary collimators in hadronic accelerators and colliders.

Prototype crystal collimation system at SPS:

- local beam loss reduction (5-20x reduction for proton beam)
- beam loss map show average loss reduction in the entire SPS ring
- halo extraction efficiency 70±80% for protons (50±70% for Pb)

UA9 installation in the SPS

[S. Montesano, Physics at AFTER using LHC beams, ECT* Trento, Feb. 2013]
The beam extraction: news

Goal: assess the possibility to use bent crystals as primary collimators in hadronic accelerators and colliders

Prototype crystal collimation system at SPS:
- local beam loss reduction (5–20x reduction for proton beam)
- beam loss map show average loss reduction in the entire SPS ring
- halo extraction efficiency 70–80% for protons (50–70% for Pb)
The beam extraction: news

Goal: assess the possibility to use bent crystals as primary collimators in hadronic accelerators and colliders.

Prototype crystal collimation system at SPS:
- local beam loss reduction (5-20x reduction for proton beam)
- beam loss map show average loss reduction in the entire SPS ring
- halo extraction efficiency 70-80% for protons (50-70% for Pb)

Towards an installation in the LHC: propose and install during LS1 a min. number of devices
- 2 crystals

Long term plan is ambitious: propose a collimation system based on bent crystals for the upgrade of the current LHC collimation system.
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 μs, $1.1 \times 10^{11}$ 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
A few figures on the (extracted) proton beam

- Beam loss: $10^9 \, p^+ s^{-1}$
- Extracted intensity: $5 \times 10^8 \, p^+ s^{-1}$ (1/2 the beam loss)

A few figures on the (extracted) proton beam

- Beam loss: $10^9 p^+ s^{-1}$
- Extracted intensity: $5 \times 10^8 p^+ s^{-1}$ (1/2 the beam loss)
- Number of $p^+$: 2808 bunches of $1.15 \times 10^{11} p^+ = 3.2 \times 10^{14} p^+$
A few figures on the (extracted) proton beam

- Beam loss: $10^9 \, p^+ s^{-1}$
- Extracted intensity: $5 \times 10^8 \, p^+ s^{-1}$ (1/2 the beam loss)
- Number of $p^+$: 2808 bunches of $1.15 \times 10^{11} p^+ = 3.2 \times 10^{14} p^+$
- Revolution frequency: Each bunch passes the extraction point at a rate of $3 \times 10^5 \, km.s^{-1}/27 \, km \approx 11 \, kHz$
A few figures on the (extracted) proton beam

- Beam loss: $10^9 p^+ s^{-1}$
- Extracted intensity: $5 \times 10^8 p^+ s^{-1}$ (1/2 the beam loss)
- Number of $p^+$: 2808 bunches of $1.15 \times 10^{11} p^+ = 3.2 \times 10^{14} p^+$
- Revolution frequency: Each bunch passes the extraction point at a rate of $3.10^5$ km.s$^{-1}$/27 km $\sim$ 11 kHz
- Extracted “mini” bunches:
  - the crystal sees $2808 \times 11000$ s$^{-1} \simeq 3.10^7$ bunches s$^{-1}$
  - one extracts $5.10^8/3.10^7 \simeq 15 p^+$ from each bunch at each pass
  - Provided that the probability of interaction with the target is below 5%, 
    
    **pile-up is not an issue**
A few figures on the (extracted) proton beam

- Beam loss: $10^9 p^+ s^{-1}$
- Extracted intensity: $5 \times 10^8 p^+ s^{-1}$ (1/2 the beam loss)
- Number of $p^+$: 2808 bunches of $1.15 \times 10^{11} p^+ = 3.2 \times 10^{14} p^+$
- Revolution frequency: Each bunch passes the extraction point at a rate of $3.10^5 \text{ km.s}^{-1}/27 \text{ km} \approx 11 \text{ kHz}$
- Extracted “mini” bunches:
  - the crystal sees $2808 \times 11000 \text{ s}^{-1} \approx 3.10^7 \text{ bunches s}^{-1}$
  - one extracts $5.10^8/3.10^7 \approx 15 p^+$ from each bunch at each pass
  - Provided that the probability of interaction with the target is below 5%,
  - Extraction over a 10h fill:
    - $5 \times 10^8 p^+ \times 3600 \text{ s h}^{-1} \times 10 \text{ h} = 1.8 \times 10^{13} p^+ \text{ fill}^{-1}$
    - This means $1.8 \times 10^{13}/3.2 \times 10^{14} \approx 5.6\%$ of the $p^+$ in the beam
      - These protons are lost anyway!

pile-up is not an issue
A few figures on the (extracted) proton beam

- Beam loss: $10^9 p^+ s^{-1}$
- Extracted intensity: $5 \times 10^8 p^+ s^{-1}$ (1/2 the beam loss)
- Number of $p^+$: 2808 bunches of $1.15 \times 10^{11} p^+ = 3.2 \times 10^{14} p^+$
- Revolution frequency: Each bunch passes the extraction point at a rate of $3.10^5 \text{ km.s}^{-1}/27 \text{ km} \approx 11 \text{ kHz}$
- Extracted “mini” bunches:
  - the crystal sees $2808 \times 11000 \text{ s}^{-1} \approx 3.10^7$ bunches s$^{-1}$
  - one extracts $5.10^8/3.10^7 \approx 15p^+$ from each bunch at each pass
  - Provided that the probability of interaction with the target is below 5%,
- Extraction over a 10h fill:
  - $5 \times 10^8 p^+ \times 3600 \text{ s h}^{-1} \times 10 \text{ h} = 1.8 \times 10^{13} p^+ \text{ fill}^{-1}$
  - This means $1.8 \times 10^{13}/3.2 \times 10^{14} \approx 5.6\%$ of the $p^+$ in the beam
  - pile-up is not an issue
  - These protons are lost anyway!
- similar figures for the Pb-beam extraction
AFTER@LHC: A dilepton observatory?

Region in $x$ probed by dilepton production as function of $M_{\ell\ell}$
AFTER@LHC: A dilepton observatory?

- Region in $x$ probed by dilepton production as function of $M_{\ell\ell}$
- Above $c\bar{c}$: $x \in [10^{-3}, 1]$
- Above $b\bar{b}$: $x \in [9 \times 10^{-3}, 1]$

Note:
- $x$ target
- $x$ projectile

"backward" region

\textit{sea-quark asymmetries via $p$ and $d$ studies - at large $x$: backward ("easy")
- at small $x$: forward (need to stop the (extracted) beam)

Todo: to look at the rates to see how competitive this will be

Interesting to check the negligible cos/two.fitted/uni03D5 dependence in $pd$ compared to $\pi$ induced $DY$
AFTER@LHC: A dilepton observatory?

- Region in $x$ probed by dilepton production as function of $M_{\ell \ell}$
  - Above $c\bar{c}$: $x \in [10^{-3}, 1]$
  - Above $b\bar{b}$: $x \in [9 \times 10^{-3}, 1]$

Note: $x_{\text{target}} \approx x_{\text{projectile}}$

- "backward" region
- sea-quark asymmetries via $p$ and $d$ studies
- at-large $x$ (easy)
- at-small $x$ (need to stop the (extracted) beam)

Todo: to look at the rate to see how competitive this will be

Interesting to check the negligible $\cos^2$ dependence in $p d$ compared to $\pi$ induced $D_\gamma$.
AFTER@LHC: A dilepton observatory?

- Region in $x$ probed by dilepton production as function of $M_{\ell\ell}$
  - Above $c\bar{c}$: $x \in [10^{-3}, 1]$
  - Above $b\bar{b}$: $x \in [9 \times 10^{-3}, 1]$

**Note:** $x_{\text{target}} (\equiv x_2) > x_{\text{projectile}} (\equiv x_1)$

“backward” region
AFTER@LHC: A dilepton observatory?

- Region in $x$ probed by dilepton production as function of $M_{\ell\ell}$
  - Above $c\bar{c}$: $x \in [10^{-3}, 1]$
  - Above $b\bar{b}$: $x \in [9 \times 10^{-3}, 1]$

**Note:** $x_{\text{target}}$ (≡ $x_2$) > $x_{\text{projectile}}$ (≡ $x_1$) “backward” region

- **sea-quark asymmetries** via $p$ and $d$ studies
  - at large(est) $x$: backward (“easy”)
  - at small(est) $x$: forward (need to stop the (extracted) beam)
AFTER@LHC: A dilepton observatory?

→ Region in $x$ probed by dilepton production as function of $M_{\ell\ell}$

→ Above $c\bar{c}$: $x \in [10^{-3}, 1]$

→ Above $b\bar{b}$: $x \in [9 \times 10^{-3}, 1]$

**Note:** $x_{\text{target}} (\equiv x_2) > x_{\text{projectile}} (\equiv x_1)$

“backward” region

→ sea-quark asymmetries via $p$ and $d$ studies

- at large(est) $x$: backward (“easy”)

- at small(est) $x$: forward (need to stop the (extracted) beam)

→ To do: to look at the rates to see how competitive this will be
**AFTER, among other things, a quarkonium observatory in $pp$**

Interpolating the world dataset:

<table>
<thead>
<tr>
<th>Target</th>
<th>$\int L \ (fb^{-1}.yr^{-1})$</th>
<th>$N(J/\Psi) \ yr^{-1} = ALB\sigma_{\Psi}$</th>
<th>$N(\Upsilon) \ yr^{-1} = ALB\sigma_{\Upsilon}$</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>$1.8 \times 10^5$</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>

Numbers are for only one unit of rapidity about/zero.fitted

Unique access in the backward region

Probe of the (very) large $x$ in the target
AFTER, among other things, a quarkonium observatory in \( pp \)

- Interpolating the world data set:

<table>
<thead>
<tr>
<th>Target</th>
<th>( \int \mathcal{L} : (\text{fb}^{-1} \cdot \text{yr}^{-1}) )</th>
<th>( N(J/\Psi) : \text{yr}^{-1} = A \mathcal{L} B \sigma_{\Psi} )</th>
<th>( N(\Upsilon) : \text{yr}^{-1} = A \mathcal{L} B \sigma_{\Upsilon} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 m Liq. ( \text{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. ( \text{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>( 1.8 \times 10^5 )</td>
</tr>
<tr>
<td>RHIC pp 200 GeV</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>

- 1000 times higher than at RHIC; comparable to ALICE/LHCb at the LHC
AFTER, among other things, a quarkonium observatory in pp

- Interpolating the world data set:

<table>
<thead>
<tr>
<th>Target</th>
<th>$\int L \ (fb^{-1}.yr^{-1})$</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>$4.0 \ 10^8$</td>
<td>$8.0 \ 10^5$</td>
</tr>
<tr>
<td>1 m Liq. $D_2$</td>
<td>24</td>
<td>$9.6 \ 10^8$</td>
<td>$1.9 \ 10^6$</td>
</tr>
<tr>
<td>LHC pp 14 TeV (low pT)</td>
<td>0.05 (ALICE) 2 LHCb</td>
<td>$3.6 \ 10^7$</td>
<td>$1.8 \ 10^5$</td>
</tr>
<tr>
<td>RHIC pp 200GeV</td>
<td>$1.2 \ 10^{-2}$</td>
<td>$4.8 \ 10^5$</td>
<td>$1.2 \ 10^3$</td>
</tr>
</tbody>
</table>

- 1000 times higher than at RHIC; comparable to ALICE/LHCb at the LHC
- Numbers are for only one unit of rapidity about 0
AFTER, among other things, a quarkonium observatory in $pp$

- Interpolating the world data set:

<table>
<thead>
<tr>
<th>Target</th>
<th>$\int L\ (fb^{-1}.yr^{-1})$</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>$1.8 \times 10^5$</td>
</tr>
<tr>
<td>RHIC $pp\ 200 GeV$</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>

- 1000 times higher than at RHIC; comparable to ALICE/LHCb at the LHC
- Numbers are for only one unit of rapidity about 0
- Unique access in the backward region
AFTER, among other things, a quarkonium observatory in \( pp \)

- Interpolating the world data set:

<table>
<thead>
<tr>
<th>Target</th>
<th>( \int \mathcal{L} ) (( fb^{-1}.yr^{-1} ))</th>
<th>( N(J/\Psi) ) yr(^{-1} ) = ( ALB\sigma_{\Psi} )</th>
<th>( N(\Upsilon) ) yr(^{-1} ) = ( ALB\sigma_{\Upsilon} )</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>( 1.8 \times 10^5 )</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>

- 1000 times higher than at RHIC; comparable to ALICE/LHCb at the LHC
- Numbers are for only one unit of rapidity about 0
- Unique access in the backward region
- Probe of the (very) large \( x \) in the target
Need for a quarkonium observatory

- Many hopes were put in quarkonium studies to extract gluon PDF
Need for a quarkonium observatory

- Many **hopes** were put in **quarkonium studies** to extract **gluon PDF**
  - in photo/lepto production (DIS)
  - but also **$pp$** collisions in **$gg$-fusion process**
  - mainly because of the presence of a natural “hard” scale: $m_Q$
  - and the good detectability of a dimuon pair
Overall

Need for a quarkonium observatory

- Many **hopes** were put in **quarkonium studies** to extract gluon PDF
  - in photo/lepto production (DIS)
  - but also $pp$ collisions in $gg$-fusion process
  - mainly because of the presence of a natural “hard” scale: $m_Q$
  - and the good detectability of a dimuon pair
Need for a quarkonium observatory

- Many hopes were put in quarkonium studies to extract gluon PDF
  - in photo/lepto production (DIS)
  - but also $pp$ collisions in $gg$-fusion process
  - mainly because of the presence of a natural “hard” scale: $m_Q$
  - and the good detectability of a dimuon pair

Production puzzle → quarkonium not used anymore in global fits
Need for a quarkonium observatory

- Many hopes were put in quarkonium studies to extract gluon PDF
  - in photo/lepto production (DIS)
  - but also $pp$ collisions in $gg$-fusion process
  - mainly because of the presence of a natural “hard” scale: $m_Q$
  - and the good detectability of a dimuon pair

Production puzzle $\rightarrow$ quarkonium not used anymore in global fits
With systematic studies, one would restore its status as gluon probe
AFTER: also a quarkonium observatory in $pA$

<table>
<thead>
<tr>
<th>Target</th>
<th>A</th>
<th>$\int L$ (fb$^{-1}$yr$^{-1}$)</th>
<th>$N(J/\Psi)$ yr$^{-1}$ = $A\mathcal{L}B\sigma_\Psi$</th>
<th>$N(\Upsilon)$ yr$^{-1}$ = $A\mathcal{L}B\sigma_\Upsilon$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1cm Be</td>
<td>9</td>
<td>0.62</td>
<td>$1.1 \times 10^8$</td>
<td>$2.2 \times 10^5$</td>
</tr>
<tr>
<td>1cm Cu</td>
<td>64</td>
<td>0.42</td>
<td>$5.3 \times 10^8$</td>
<td>$1.1 \times 10^6$</td>
</tr>
<tr>
<td>1cm W</td>
<td>185</td>
<td>0.31</td>
<td>$1.1 \times 10^9$</td>
<td>$2.3 \times 10^6$</td>
</tr>
<tr>
<td>1cm Pb</td>
<td>207</td>
<td>0.16</td>
<td>$6.7 \times 10^8$</td>
<td>$1.3 \times 10^6$</td>
</tr>
<tr>
<td>LHC pPb 8.8 TeV</td>
<td>207</td>
<td>$10^{-4}$</td>
<td>$1.0 \times 10^7$</td>
<td>$7.5 \times 10^4$</td>
</tr>
<tr>
<td>RHIC dAu 200GeV</td>
<td>198</td>
<td>$1.5 \times 10^{-4}$</td>
<td>$2.4 \times 10^6$</td>
<td>$5.9 \times 10^3$</td>
</tr>
<tr>
<td>RHIC dAu 62GeV</td>
<td>198</td>
<td>$3.8 \times 10^{-6}$</td>
<td>$1.2 \times 10^4$</td>
<td>18</td>
</tr>
</tbody>
</table>

- In principle, one can get 300 times more $J/\psi$ –not counting the likely wider $\Upsilon$ coverage– than at RHIC, allowing for
AFTER: also a quarkonium observatory in $pA$

<table>
<thead>
<tr>
<th>Target</th>
<th>$A$</th>
<th>$\int \mathcal{L} \ (fb^{-1}.yr^{-1})$</th>
<th>$N(J/\Psi) \ yr^{-1}$</th>
<th>$N(\Upsilon) \ yr^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1cm Be</td>
<td>9</td>
<td>0.62</td>
<td>1.1 $10^8$</td>
<td>2.2 $10^5$</td>
</tr>
<tr>
<td>1cm Cu</td>
<td>64</td>
<td>0.42</td>
<td>5.3 $10^8$</td>
<td>1.1 $10^6$</td>
</tr>
<tr>
<td>1cm W</td>
<td>185</td>
<td>0.31</td>
<td>1.1 $10^9$</td>
<td>2.3 $10^6$</td>
</tr>
<tr>
<td>1cm Pb</td>
<td>207</td>
<td>0.16</td>
<td>6.7 $10^8$</td>
<td>1.3 $10^6$</td>
</tr>
<tr>
<td>LHC pPb 8.8 TeV</td>
<td>207</td>
<td>$10^{-4}$</td>
<td>1.0 $10^7$</td>
<td>7.5 $10^4$</td>
</tr>
<tr>
<td>RHIC dAu 200GeV</td>
<td>198</td>
<td>1.5 $10^{-4}$</td>
<td>2.4 $10^6$</td>
<td>5.9 $10^3$</td>
</tr>
<tr>
<td>RHIC dAu 62GeV</td>
<td>198</td>
<td>3.8 $10^{-6}$</td>
<td>1.2 $10^4$</td>
<td>18</td>
</tr>
</tbody>
</table>

- In principle, one can get 300 times more $J/\psi$ –not counting the likely wider $\Upsilon$ coverage– than at RHIC, allowing for
  - $\chi_c$ measurement in $pA$ via $J/\psi + \gamma$ (extending Hera-B studies)
### AFTER: also a quarkonium observatory in $p\bar{A}$

<table>
<thead>
<tr>
<th>Target</th>
<th>$A$</th>
<th>$\int \mathcal{L} \ (fb^{-1}.yr^{-1})$</th>
<th>$N(J/\Psi) \ yr^{-1}$</th>
<th>$N(\Upsilon) \ yr^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1cm Be</td>
<td>9</td>
<td>0.62</td>
<td>$1.1 \ 10^8$</td>
<td>$2.2 \ 10^5$</td>
</tr>
<tr>
<td>1cm Cu</td>
<td>64</td>
<td>0.42</td>
<td>$5.3 \ 10^8$</td>
<td>$1.1 \ 10^6$</td>
</tr>
<tr>
<td>1cm W</td>
<td>185</td>
<td>0.31</td>
<td>$1.1 \ 10^9$</td>
<td>$2.3 \ 10^6$</td>
</tr>
<tr>
<td>1cm Pb</td>
<td>207</td>
<td>0.16</td>
<td>$6.7 \ 10^8$</td>
<td>$1.3 \ 10^6$</td>
</tr>
<tr>
<td>LHC pPb 8.8 TeV</td>
<td>207</td>
<td>$10^{-4}$</td>
<td>$1.0 \ 10^7$</td>
<td>$7.5 \ 10^4$</td>
</tr>
<tr>
<td>RHIC dAu 200GeV</td>
<td>198</td>
<td>$1.5 \ 10^{-4}$</td>
<td>$2.4 \ 10^6$</td>
<td>$5.9 \ 10^3$</td>
</tr>
<tr>
<td>RHIC dAu 62GeV</td>
<td>198</td>
<td>$3.8 \ 10^{-6}$</td>
<td>$1.2 \ 10^4$</td>
<td>$18$</td>
</tr>
</tbody>
</table>

- In principle, one can get **300 times more $J/\psi$** –not counting the likely wider $\gamma$ coverage– than at RHIC, allowing for:
  - $\chi_c$ measurement in $p\bar{A}$ via $J/\psi + \gamma$ (extending Hera-B studies)
  - Polarisation measurement as the centrality, $\gamma$ or $P_T$
**AFTER: also a quarkonium observatory in $pA$**

<table>
<thead>
<tr>
<th>Target</th>
<th>A</th>
<th>$\int L (fb^{-1}.yr^{-1})$</th>
<th>N($J/\Psi$) yr$^{-1}$ = $A \ell B \sigma_{\Psi}$</th>
<th>N($\Upsilon$) yr$^{-1}$ = $A \ell B \sigma_{\Upsilon}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1cm Be</td>
<td>9</td>
<td>0.62</td>
<td>1.1 $10^8$</td>
<td>2.2 $10^5$</td>
</tr>
<tr>
<td>1cm Cu</td>
<td>64</td>
<td>0.42</td>
<td>5.3 $10^8$</td>
<td>1.1 $10^6$</td>
</tr>
<tr>
<td>1cm W</td>
<td>185</td>
<td>0.31</td>
<td>1.1 $10^9$</td>
<td>2.3 $10^6$</td>
</tr>
<tr>
<td>1cm Pb</td>
<td>207</td>
<td>0.16</td>
<td>6.7 $10^8$</td>
<td>1.3 $10^6$</td>
</tr>
<tr>
<td>LHC pPb 8.8 TeV</td>
<td>207</td>
<td>$10^{-4}$</td>
<td>1.0 $10^7$</td>
<td>7.5 $10^4$</td>
</tr>
<tr>
<td>RHIC dAu 200GeV</td>
<td>198</td>
<td>$1.5 \times 10^{-4}$</td>
<td>2.4 $10^6$</td>
<td>5.9 $10^3$</td>
</tr>
<tr>
<td>RHIC dAu 62GeV</td>
<td>198</td>
<td>$3.8 \times 10^{-6}$</td>
<td>1.2 $10^4$</td>
<td>18</td>
</tr>
</tbody>
</table>

- In principle, one can get **300 times more $J/\psi$** –not counting the likely wider $\Upsilon$ coverage– than at RHIC, allowing for
  - $\chi_c$ measurement in $pA$ via $J/\psi + \gamma$ (extending Hera-B studies)
  - Polarisation measurement as the centrality, $\Upsilon$ or $P_T$
  - Ratio $\psi'$ over direct $J/\psi$ measurement in $pA$
In principle, one can get 300 times more $J/\psi$ – not counting the likely wider $\gamma$ coverage – than at RHIC, allowing for

- $\chi_c$ measurement in $pA$ via $J/\psi + \gamma$ (extending Hera-B studies)
- Polarisation measurement as the centrality, $\gamma$ or $P_T$
- Ratio $\psi'$ over direct $J/\psi$ measurement in $pA$
- not to mention ratio with open charm, Drell-Yan, etc ...

<table>
<thead>
<tr>
<th>Target</th>
<th>A</th>
<th>$\int \mathcal{L} \text{ (fb}^{-1}.\text{yr}^{-1})$</th>
<th>$N(J/\Psi) \text{ yr}^{-1}$</th>
<th>$N(\Upsilon) \text{ yr}^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1cm Be</td>
<td>9</td>
<td>0.62</td>
<td>1.1 $10^8$</td>
<td>2.2 $10^5$</td>
</tr>
<tr>
<td>1cm Cu</td>
<td>64</td>
<td>0.42</td>
<td>5.3 $10^8$</td>
<td>1.1 $10^6$</td>
</tr>
<tr>
<td>1cm W</td>
<td>185</td>
<td>0.31</td>
<td>1.1 $10^9$</td>
<td>2.3 $10^6$</td>
</tr>
<tr>
<td>1cm Pb</td>
<td>207</td>
<td>0.16</td>
<td>6.7 $10^8$</td>
<td>1.3 $10^6$</td>
</tr>
<tr>
<td>LHC pPb 8.8 TeV</td>
<td>207</td>
<td>$10^{-4}$</td>
<td>1.0 $10^7$</td>
<td>7.5 $10^4$</td>
</tr>
<tr>
<td>RHIC dAu 200GeV</td>
<td>198</td>
<td>$1.5 \times 10^{-4}$</td>
<td>2.4 $10^6$</td>
<td>5.9 $10^3$</td>
</tr>
<tr>
<td>RHIC dAu 62GeV</td>
<td>198</td>
<td>$3.8 \times 10^{-6}$</td>
<td>1.2 $10^4$</td>
<td>18</td>
</tr>
</tbody>
</table>
What for?

- The **target versatility** of a fixed-target experiment is undisputable.
What for?

- The **target versatility** of a fixed-target experiment is undisputable

- A **wide rapidity coverage** is needed for:
  - a precise analysis of gluon nuclear PDF: \( y, p_T \leftrightarrow x_2 \)
  - a handle on **formation time effects**
What for?

- The **target versatility** of a fixed-target experiment is undisputable

- A **wide rapidity coverage** is needed for:
  - a precise analysis of **gluon nuclear PDF**: \( y, p_T \leftrightarrow x_2 \)
  - a handle on **formation time effects**

- **Strong need for cross checks from various measurements**
What for?

- The **target versatility** of a fixed-target experiment is undisputable

- A **wide rapidity coverage** is needed for:
  - a precise analysis of **gluon nuclear PDF**: $y, p_T \leftrightarrow x_2$
  - a handle on **formation time effects**

- **Strong need for cross checks from various measurements**

- The **backward kinematics** is very useful for large-$x_{target}$ studies
**What for?**

- The **target versatility** of a fixed-target experiment is undisputable

- A **wide rapidity coverage** is needed for:
  - A precise analysis of gluon nuclear PDF: $y, p_T \leftrightarrow x_2$
  - A handle on formation time effects

- Strong need for **cross checks** from various measurements

- The **backward kinematics** is very useful for large-$x_{\text{target}}$ studies
  - What is the amount of Intrinsic charm? Is it color filtered?
What for?

- The **target versatility** of a fixed-target experiment is undisputable

- A **wide rapidity coverage** is needed for:
  - a precise analysis of gluon nuclear PDF: $y, p_T \leftrightarrow x_2$
  - a handle on **formation time effects**

- Strong need for **cross checks** from various measurements

- The **backward kinematics** is very useful for large-$x_{target}$ studies
  - What is the amount of Intrinsic charm? Is it color filtered?
  - **Is there an EMC effect for gluon?** (reminder: EMC region $0.3 < x < 0.7$)
What for ?

- The **target versatility** of a fixed-target experiment is undisputable

- A **wide rapidity coverage** is needed for:
  - a precise analysis of gluon nuclear PDF: $y, p_T \leftrightarrow x_2$
  - a handle on formation time effects

- Strong need for **cross checks from various measurements**

- The **backward kinematics** is very useful for large-$x_{target}$ studies
  - What is the amount of Intrinsic charm? Is it color filtered?
  - Is there an EMC effect for gluon? (reminder: EMC region $0.3 < x < 0.7$)

- One should be careful with factorization breaking effects:
  
  This calls for **multiple measurements to (in)validate factorisation**
AFTER: also an heavy-flavour observatory in PbA

- Luminosities and yields with the extracted 2.76 TeV Pb beam

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

\[
\begin{array}{|c|c|c|c|c|}
\hline
\text{Target} & \text{A.B} & \int L \ (\text{nb}^{-1}\cdot\text{yr}^{-1}) & N(J/\Psi) \text{ yr}^{-1} = ABLB\sigma_{\Psi} & N(\Upsilon) \text{ yr}^{-1} = ABLB\sigma_{\Upsilon} \\
\hline
1 \text{m Liq. } H_2 & 207.1 & 800 & 3.4 \times 10^6 & 6.9 \times 10^3 \\
1 \text{cm Be} & 207.9 & 25 & 9.1 \times 10^5 & 1.9 \times 10^3 \\
1 \text{cm Cu} & 207.64 & 17 & 4.3 \times 10^6 & 0.9 \times 10^3 \\
1 \text{cm W} & 207.185 & 13 & 9.7 \times 10^6 & 1.9 \times 10^4 \\
1 \text{cm Pb} & 207.207 & 7 & 5.7 \times 10^6 & 1.1 \times 10^4 \\
\text{LHC } PbPb \ 5.5 \text{ TeV} & 207.207 & 0.5 & 7.3 \times 10^6 & 3.6 \times 10^4 \\
\text{RHIC } AuAu \ 200\text{GeV} & 198.198 & 2.8 & 4.4 \times 10^6 & 1.1 \times 10^4 \\
\text{RHIC } AuAu \ 62\text{GeV} & 198.198 & 0.13 & 4.0 \times 10^4 & 61 \\
\hline
\end{array}
\]
AFTER: also an heavy-flavour observatory in PbA

- Luminosities and yields with the extracted 2.76 TeV Pb beam

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

<table>
<thead>
<tr>
<th>Target</th>
<th>A.B</th>
<th>( \int L \text{ (nb}^{-1}\text{.yr}^{-1}) )</th>
<th>( N(J/\Psi) \text{ yr}^{-1} = ABLB\sigma_{\Psi} )</th>
<th>( N(\Upsilon) \text{ yr}^{-1} = ABLB\sigma_{\Upsilon} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 m Liq. H_2</td>
<td>207.1</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>207.9</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>207.64</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>207.185</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>207.207</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>207.207</td>
<td>0.5</td>
<td>7.3 \times 10^6</td>
<td>3.6 \times 10^4</td>
</tr>
<tr>
<td>RHIC AuAu 200 GeV</td>
<td>198.198</td>
<td>2.8</td>
<td>4.4 \times 10^6</td>
<td>1.1 \times 10^4</td>
</tr>
<tr>
<td>RHIC AuAu 62 GeV</td>
<td>198.198</td>
<td>0.13</td>
<td>4.0 \times 10^4</td>
<td>61</td>
</tr>
</tbody>
</table>

- Yields similar to those of RHIC at 200 GeV, 100 times those of RHIC at 62 GeV
AFTER: also an heavy-flavour observatory in PbA

- Luminosities and yields with the extracted 2.76 TeV Pb beam

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

<table>
<thead>
<tr>
<th>Target</th>
<th>A.B</th>
<th>( \int L ) (nb(^{-1}).yr(^{-1}))</th>
<th>( N(J/\psi) ) yr(^{-1}) = ( ABLB\sigma_{\psi} )</th>
<th>( N(\Upsilon) ) yr(^{-1}) = ( ABLB\sigma_{\Upsilon} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 m Liq. H(_2)</td>
<td>207.1</td>
<td>800</td>
<td>3.4 ( 10^6 )</td>
<td>6.9 ( 10^3 )</td>
</tr>
<tr>
<td>1 cm Be</td>
<td>207.9</td>
<td>25</td>
<td>9.1 ( 10^5 )</td>
<td>1.9 ( 10^3 )</td>
</tr>
<tr>
<td>1 cm Cu</td>
<td>207.64</td>
<td>17</td>
<td>4.3 ( 10^6 )</td>
<td>0.9 ( 10^3 )</td>
</tr>
<tr>
<td>1 cm W</td>
<td>207.185</td>
<td>13</td>
<td>9.7 ( 10^6 )</td>
<td>1.9 ( 10^4 )</td>
</tr>
<tr>
<td>1 cm Pb</td>
<td>207.207</td>
<td>7</td>
<td>5.7 ( 10^6 )</td>
<td>1.1 ( 10^4 )</td>
</tr>
<tr>
<td>LHC PbPb 5.5 TeV</td>
<td>207.207</td>
<td>0.5</td>
<td>7.3 ( 10^6 )</td>
<td>3.6 ( 10^4 )</td>
</tr>
<tr>
<td>RHIC AuAu 200 GeV</td>
<td>198.198</td>
<td>2.8</td>
<td>4.4 ( 10^6 )</td>
<td>1.1 ( 10^4 )</td>
</tr>
<tr>
<td>RHIC AuAu 62 GeV</td>
<td>198.198</td>
<td>0.13</td>
<td>4.0 ( 10^4 )</td>
<td>61</td>
</tr>
</tbody>
</table>

- Yields similar to those of RHIC at 200 GeV,
- 100 times those of RHIC at 62 GeV
- Also very competitive compared to the LHC.
AFTER: also an heavy-flavour observatory in PbA

- Luminosities and yields with the extracted 2.76 TeV Pb beam 
  \( (\sqrt{s_{NN}} = 72 \text{ GeV}) \)

<table>
<thead>
<tr>
<th>Target</th>
<th>A.B</th>
<th>( \int \mathcal{L} ) (nb(^{-1}).yr(^{-1}))</th>
<th>( N(J/\Psi) ) yr(^{-1}) = ( ABLB\sigma_{\Psi} )</th>
<th>( N(\Upsilon) ) yr(^{-1}) = ( ABLB\sigma_{\Upsilon} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 m Liq. H(_2)</td>
<td>207.1</td>
<td>800</td>
<td>3.4 ( 10^6 )</td>
<td>6.9 ( 10^3 )</td>
</tr>
<tr>
<td>1 cm Be</td>
<td>207.9</td>
<td>25</td>
<td>9.1 ( 10^5 )</td>
<td>1.9 ( 10^3 )</td>
</tr>
<tr>
<td>1 cm Cu</td>
<td>207.64</td>
<td>17</td>
<td>4.3 ( 10^6 )</td>
<td>0.9 ( 10^3 )</td>
</tr>
<tr>
<td>1 cm W</td>
<td>207.185</td>
<td>13</td>
<td>9.7 ( 10^6 )</td>
<td>1.9 ( 10^4 )</td>
</tr>
<tr>
<td>1 cm Pb</td>
<td>207.207</td>
<td>7</td>
<td>5.7 ( 10^6 )</td>
<td>1.1 ( 10^4 )</td>
</tr>
<tr>
<td>LHC PbPb 5.5 TeV</td>
<td>207.207</td>
<td>0.5</td>
<td>7.3 ( 10^6 )</td>
<td>3.6 ( 10^4 )</td>
</tr>
<tr>
<td>RHIC AuAu 200 GeV</td>
<td>198.198</td>
<td>2.8</td>
<td>4.4 ( 10^6 )</td>
<td>1.1 ( 10^4 )</td>
</tr>
<tr>
<td>RHIC AuAu 62 GeV</td>
<td>198.198</td>
<td>0.13</td>
<td>4.0 ( 10^4 )</td>
<td>61</td>
</tr>
</tbody>
</table>

- Yields similar to those of RHIC at 200 GeV, 
  100 times those of RHIC at 62 GeV 
- Also very competitive compared to the LHC.

The same picture also holds for open heavy flavour
What for?

Observation of $J/\psi$ sequential suppression seems to be hindered by

- the **Cold Nuclear Matter effects**: non trivial and

... not well understood
Observation of $J/\psi$ sequential suppression seems to be hindered by
- the **Cold Nuclear Matter effects**: non trivial and
  ... not well understood
- the difficulty to observe directly the **excited states**
  which would melt before the ground states
  - $\chi_c$ never studied in $AA$ collisions
  - $\psi(2S)$ not yet studied in $AA$ collisions at RHIC
What for?

Observation of $J/\psi$ sequential suppression seems to be hindered by

- the Cold Nuclear Matter effects: non trivial and ... not well understood

- the difficulty to observe directly the excited states which would melt before the ground states

  - $\chi_c$ never studied in $AA$ collisions
  - $\psi(2S)$ not yet studied in $AA$ collisions at RHIC

- the possibilities for $c\bar{c}$ recombinations

  - Open charm studies are difficult where recombinations matters most
    i.e. at low $P_T$
  - Only indirect indications –from the $y$ and $P_T$ dependence of $R_{AA}$ – that recombinations may be at work
  - CNM effects may show a non-trivial $y$ and $P_T$ dependence …
SPS and Hera-B

− $J/\psi$ data in $pA$ collisions
SPS and Hera-B

- $J/\psi$ data in $pA$ collisions
- $\chi_c$ data in $pA$ collisions

HERA-B PRD 79 (2009) 012001, and ref. therein
LHB

Our idea is not completely new

North-Holland

LHB, a fixed target experiment at LHC to measure CP violation in B mesons
Flavio Costantini
University of Pisa and INFN, Italy

A fixed target experiment at LHC to measure CP violation in B mesons is presented. A description of the proposed apparatus is given together with its sensitivity on the CP violation asymmetry measurement for the two benchmark decay channels \( B^0 \rightarrow J/\psi + K^0_s \), \( B^0 \rightarrow \pi^+\pi^- \). The possibility of obtaining an extracted LHC beam hinges on channeling in a bent silicon crystal. Recent results on beam extraction efficiencies measured at CERN SPS based on this technique are presented.
LHB

Our idea is not completely new

1. Introduction

... 

This paper presents a fixed target experiment to measure CP violation in the B system based on the possibility of extracting the 8 TcV LHC proton beam using a bent silicon crystal [4]. A 10% extraction efficiency of the LHC beam halo will give an extracted beam intensity of about $10^8$ protons/s allowing the production of as many as $10^{10}$ $\bar{B}B$ pairs per year, i.e. about two orders of magnitude more than what could be produced by an $e^+e^-$ asymmetric B factory with $10^{34}$ cm$^{-2}$s$^{-1}$ luminosity [5].
1. Introduction

This paper presents a fixed target experiment to measure CP violation in the B system based on the possibility of extracting the 8 TeV LHC proton beam using a bent silicon crystal [4]. A 10% extraction efficiency of the LHC beam halo will give an extracted beam intensity of about $10^8$ protons/s allowing the production of as many as $10^{10}$ $B\bar{B}$ pairs per year, i.e. about two orders of magnitude more than what could be produced by an $e^+e^-$ asymmetric B factory with $10^{34}$ cm$^{-2}$s$^{-1}$ luminosity [5].

- $B$-factories: 1 ab$^{-1}$ means $10^9 B\bar{B}$ pairs

Overall

LHB

Our idea is not completely new
1. Introduction

This paper presents a fixed target experiment to measure CP violation in the B system based on the possibility of extracting the 8 TeV LHC proton beam using a bent silicon crystal [4]. A 10% extraction efficiency of the LHC beam halo will give an extracted beam intensity of about $10^8$ protons/s allowing the production of as many as $10^{10}$ $B\bar{B}$ pairs per year, i.e. about two orders of magnitude more than what could be produced by an $e^+e^-$ asymmetric B factory with $10^{34}$ cm$^{-2}$s$^{-1}$ luminosity [5].

- $B$-factories: 1 ab$^{-1}$ means $10^9 B\bar{B}$ pairs
- For LHCb, typically 1 fb$^{-1}$ means $\approx 2 \times 10^{11} B\bar{B}$ pairs at 14 TeV
LHB

Our idea is not completely new

1. Introduction

This paper presents a fixed target experiment to measure CP violation in the B system based on the possibility of extracting the 8 TeV LHC proton beam using a bent silicon crystal [4]. A 10% extraction efficiency of the LHC beam halo will give an extracted beam intensity of about $10^8$ protons/s allowing the production of as many as $10^{10}$ \( B\bar{B} \) pairs per year, i.e. about two orders of magnitude more than what could be produced by an \( e^+e^- \) asymmetric B factory with $10^{34}$ cm\(^{-2}\)s\(^{-1}\) luminosity [5].

- \( B \)-factories: 1 ab\(^{-1}\) means $10^9 B\bar{B}$ pairs
- For LHCb, typically 1 fb\(^{-1}\) means \( \simeq 2 \times 10^{11} B\bar{B} \) pairs at 14 TeV
- LHB turned down in favour of LHCb mainly because of the fear of a premature degradation of the bent crystal due to radiation damages.
LHB

Our idea is not completely new

1. Introduction

...  

This paper presents a fixed target experiment to measure CP violation in the B system based on the possibility of extracting the 8 TeV LHC proton beam using a bent silicon crystal [4]. A 10% extraction efficiency of the LHC beam halo will give an extracted beam intensity of about $10^{8}$ protons/s allowing the production of as many as $10^{10}$ $B\bar{B}$ pairs per year, i.e. about two orders of magnitude more than what could be produced by an $e^+ e^-$ asymmetric B factory with $10^{34}$ cm$^{-2}$s$^{-1}$ luminosity [5].

- $B$-factories: 1 ab$^{-1}$ means $10^{9} B\bar{B}$ pairs
- For LHCb, typically 1 fb$^{-1}$ means $\sim 2 \times 10^{11} B\bar{B}$ pairs at 14 TeV
- LHB turned down in favour of LHCb mainly because of the fear of a premature degradation of the bent crystal due to radiation damages.
- Nowadays, degradation is known to be $\sim 6\%$ per $10^{20}$ particles/cm$^{2}$
- $10^{20}$ particles/cm$^{2}$ : one year of operation for realistic conditions
Our idea is not completely new

1. Introduction

This paper presents a fixed target experiment to measure CP violation in the B system based on the possibility of extracting the 8 TcV LHC proton beam using a bent silicon crystal [4]. A 10% extraction efficiency of the LHC beam halo will give an extracted beam intensity of about $10^8$ protons/s allowing the production of as many as $10^{10}$ $B\bar{B}$ pairs per year, i.e. about two orders of magnitude more than what could be produced by an $e^+e^-$ asymmetric B factory with $10^{34}$ cm$^{-2}$s$^{-1}$ luminosity [5].

- $B$-factories: 1 ab$^{-1}$ means $10^9 B\bar{B}$ pairs
- For LHCb, typically 1 fb$^{-1}$ means $\approx 2 \times 10^{11} B\bar{B}$ pairs at 14 TeV
- LHB turned down in favour of LHCb mainly because of the fear of a premature degradation of the bent crystal due to radiation damages.
- Nowadays, degradation is known to be $\approx 6\%$ per $10^{20}$ particles/cm$^2$
- $10^{20}$ particles/cm$^2$: one year of operation for realistic conditions
- After a year, one simply moves the crystal by less than one mm ...