AFTER @ LHC

A Fixed-Target Experiment using the proton and lead LHC beams

Jean-Philippe Lansberg
IPN Orsay, Université Paris-Sud

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on behalf of F. Fleuret (LLR), S.J. Brodsky (SLAC), C. Hadjidakis (IPN), R. Arnaldi (Torino), V. Chambert (IPN), J.P. Didelez (IPN), B. Genolini (IPN), E.G. Ferreiro (USC), A. Rakotozafindrabe (CEA), P. Rosier (IPN), E. Scomparin (Torino), and U.I. Uggerhøj (Aarhus) + M. Anselmino, I. Schienbein

J.P. Lansberg (IPNO, Paris-Sud U.)
The European strategy for particle physics
Approved by the CERN council at the special Session held in Lisbon on 14 July, 2006

Using the LHC beams, for the first time, the 100-GeV frontier can be broken at a fixed target experiment, without affecting the LHC performance with an extracted beam line using a bent crystal with the possibility of polarising the target without target-species limitation with an outstanding luminosity with virtually no limit on particle-species studies (except top quark) with modern detection techniques.
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Part I

A fixed-target experiment using the LHC beam(s): generalities
A Fixed Target Experiment using the LHC beams

Generalities

- \( pp \) or \( pA \) with a 7 TeV \( p \) beam: \( \sqrt{s} \sim 115 \text{ GeV} \)
- For \( pA \), a Fermi motion of 0.2 GeV would induce a spread of 10% of \( \sqrt{s} \)

S. Fredriksson, NPB 94 (1975) 337
**A Fixed Target Experiment using the LHC beams**

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- Boost: $\gamma_{CM}^{lab} = \frac{\sqrt{s}}{2m_p} \simeq 60$; rapidity shift: $\Delta y = \tanh^{-1} \beta_{CM}^{lab} \simeq 4.8$

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Pb p or Pb A with a 2.75 TeV Pb beam: $\sqrt{s}_{NN} \simeq 72$ GeV

Crystal channeling is also possible for heavy-ion beams

Recent test with Pb at SPS: W. Scandale et al., PLB 703 (2011) 547

If required, bent diamonds may provide a crystal highly resistant to radiations

Diamond bending by laser ablation: P. Ballin et al., NIMB 267 (2009) 2952

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A few figures on the (extracted) proton beam

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Revolution frequency: Each bunch passes the extraction point at a rate of $3 \times 10^5 \, km.s^{-1}$ or $\frac{27 \, km}{11 \, kHz}$

Extracted “mini” bunches: the crystal sees $2808 \times 11000 \, s^{-1} \approx 3 \times 10^7 \, bunched \, s^{-1}$ one extracts $5 \times 10^8 / 3 \times 10^7 \approx 16 \, p^+$ from each bunch at each pass

Provided that the probability of interaction with the target is below 5%... no pile-up...

Extraction over a 10h fill: $5 \times 10^8 \, p^+ \times 3600 \, s \times 10^{-1} \times 10 \, h = 1.8 \times 10^{13} \, p^+$ fill

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!

Similar figures for the Pb-beam extraction
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Luminosities

- Instantaneous Luminosity:
  \[ \mathcal{L} = \Phi_{beam} \times N_{target} = N_{beam} \times (\rho \times \ell \times N_A) / A \]
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- **Integrated luminosity**
  \[
  \int dt \mathcal{L} = \mathcal{L} \times 10^{7(6)} \text{ s } p^+ \text{ (or Pb)}
  \]

Using \(NA51\)-like 1.2m-long liquid \( \text{H}_2 \) & \( \text{D}_2 \) targets, \[
\mathcal{L}_{\text{H}_2 / \text{D}_2} \simeq 20 \text{ fb}^{-1} \text{ yr}^{-1}
\]

Planned lumi for PHENIX Run14pp 12 pb\(^{-1}\) and Run14 \(d\)\(Au\) 0.15 pb\(^{-1}\)

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- **Expected luminosities with** \( 5 \times 10^8 \, \text{p}^+ \text{s}^{-1} \) **extracted** (1 cm-long target)

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  \( \Phi_{beam} = 5 \times 10^8 p^+ s^{-1} \), \( \ell = 1 \text{ cm} \) (target thickness)

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  \[ \int dt L = L \times 10^7(6) s p^+ \text{ (or Pb)} \]

- **Expected luminosities with** \( 5 \times 10^8 p^+ s^{-1} \) extracted (1 cm-long target)

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- **Using NA51-like 1.2m-long liquid \( H_2 \) & \( D_2 \) targets,** \( L_{H_2/D_2} \approx 20 \text{ fb}^{-1}\text{y}^{-1} \)
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- **Lumi for Pb runs in the backup slides**
Beam extraction

**Beam extraction @ LHC**

... there are extremely promising possibilities to extract 7 TeV protons from the circulating beam by means of a bent crystal.

... The idea is to put a bent, single crystal of either Si or Ge (W would perform slightly better but needs substantial improvements in crystal quality) at a distance of \( \sim 7 \sigma \) to the beam where it can intercept and deflect part of the beam halo by an angle similar to the one the foreseen dump kicking system will apply to the circulating beam.

... ions with the same momentum per charge as protons are deflected in a crystal with similar efficiencies.

If the crystal is positioned at the kicking section, the whole dump system can be used for slow extraction of parts of the beam halo, the particles that are anyway lost subsequently at collimators.
Part II

AFTER: a couple of flagships measurements
Key studies

- **Gluon distribution** at mid, high and ultra-high $x_B$ in the
Key studies

- **Gluon distribution** at mid, high and ultra-high $x_B$ in the proton

![Graph showing gluon distribution for $\mu = 100$ GeV]
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- Gluon distribution at mid, high and ultra-high $x_B$ in the proton
- neutron (via deuteron target) unique measurement!
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with
- quarkonia
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  - jets (we should access $P_T \in [20, 40]$ GeV)
Key studies

- Heavy-quark distributions (at high $x_B$)
Key studies

- **Heavy-quark distributions (at high $x_B$)**
- Pin down *intrinsic* charm, ... at last

![Graphs showing charm distributions for DGLAP, BHPS, and Sea-like models.](Image)

All 3 compatible with DIS data (Pumplin *et al.*)

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July 7, 2012
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requires

- several complementary measurements

DGLAP

BHPS

Sea-like

All 3 compatible with DIS data (Pumplin et al.)
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- good coverage in the target-rapidity region

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- Total open charm and beauty cross section (down to $P_T \to 0$)

requires

- several complementary measurements
- good coverage in the target-rapidity region
- high luminosity to reach large $x_B$

All 3 compatible with DIS data (Pumplin et al.)
Key studies

- **Gluon Sivers effect**: correlation between the gluon transverse momentum & the proton spin
Key studies

- Gluon Sivers effect: correlation between the gluon transverse momentum & the proton spin
- Transverse single spin asymmetries using gluon sensitive probes

<table>
<thead>
<tr>
<th>Fx</th>
<th>0.15</th>
<th>0.1</th>
<th>0.05</th>
<th>0</th>
<th>0.05</th>
<th>0.1</th>
<th>0.15</th>
</tr>
</thead>
<tbody>
<tr>
<td>NA</td>
<td>-0.2</td>
<td>-0.15</td>
<td>-0.1</td>
<td>-0.05</td>
<td>0</td>
<td>0.05</td>
<td>0.1</td>
</tr>
</tbody>
</table>

= 200 GeV

+X  at ψ J/→p+p

>=1.6 GeV/c (side points)

T<p

>=1.5 GeV/c (middle point)

2006

2008

2006+2008

B & D meson production


the target-rapidity region corresponds to high x↑ where the kT-spin correlation is the largest

In general, one can carry out an extensive spin-physics program

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Key studies

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

![Graph showing $A_N$ vs. $x_F$ with data points for different dilepton masses: $<p_T>$=1.6 GeV/c (side points), $<p_T>$=1.5 GeV/c (middle point), 2006, 2008, and 2006+2008.](image)
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- **\(\gamma\) and \(\gamma\)-jet**

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- **B & D meson production**

- **\(\gamma\) and \(\gamma\)-jet**

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

\[F_x = -0.15 \quad -0.1 \quad -0.05 \quad 0 \quad 0.05 \quad 0.1 \quad 0.15\]

\[N_A = -0.2 \quad -0.15 \quad -0.1 \quad -0.05 \quad -0 \quad 0.05 \quad 0.1 \quad 0.15 \quad 0.2\]

\[p+p \rightarrow J/\psi + X \text{ at } \sqrt{s} = 200 \text{ GeV}\]

\(\langle p_T \rangle = 1.6 \text{ GeV/c (side points)}\)

\(\langle p_T \rangle = 1.5 \text{ GeV/c (middle point)}\)

\[A_N\]

Key studies

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- **Transverse single spin asymmetries** using gluon sensitive probes
- **Quarkonia** ($J/\psi$, $\Upsilon$, $\chi_c$, \ldots)
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Key studies

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- Unique opportunity to measure QCD/threshold effects on $W/Z$ production.

If $W'/Z'$ exist, their production may share similar threshold corrections as that of $W/Z$, but at LHC energies. Reconstructed rates are most likely between a few dozen to a few thousand per year.

Multiply heavy baryons: discovery potential? ($\Omega^{++}(cc)$, ...).

Very forward (backward) physics: semi-diffractive events, ultra-peripheral collisions, etc.
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  - Ultra-peripheral collisions, etc.
Overall

Log (x^{-1})

Fixed Target @ LHC

x \leq 1 \ x \rightarrow 1

Non perturbative regime

EMC effect

Nuclear fermi motion

Dilute system

DGLAP

BFKL

saturation

Q^2 = Q^2_s(x)

BK-JIMWLK

saturation

log (x-1)

log (Q^2)

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Overall

Fixed Target @ LHC

- Non perturbative regime
- DGLAP
- BFKL
- BK-JIMWLK
- Drell-Yan
- EMC effect
- Nuclear fermi motion

$x \rightarrow 1$ $x \rightarrow 1$

$log (Q^2)$

$log (x^{-1})$
**Fixed Target @ LHC**

- **Non perturbative regime**
  - $x > 1$
  - $x \rightarrow 1$

- **Dilute system**
  - **BK-JIMWLK**
  - **DGLAP**

- **Fixed Target@LHC**

- **Quarkonia**

- **Drell-Yan**

- **EMC effect**

- **Nuclear fermi motion**

- **$Q^2 = Q^2_s(x)$**

- **$\log (x^{-1})$**

- **$\log (Q^2)$**

---

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Overall

\[ \log(x^{-1}) \quad \text{Fixed Target @ LHC} \]

- Non perturbative regime
- Fixed Target @ LHC
- $x > 1 \rightarrow x \rightarrow 1$
- $Q^2 = Q^2_s(x)$
- Saturation
- BK-JIMWLK
- Dilute system
- Drell-Yan
- Quarkonia
- EMC effect
- Nuclear fermi motion
- W/Z

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Overall

Fixed Target @ LHC

log (x⁻¹)

log (Q²)

Non perturbative regime

Quarkonia

High-p_T jet

W/Z

Dillute system

DGLAP

BFKL

saturation

BK-JIMWLK

Drell-Yan

Nuclear fermi motion

EMC effect

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AFTER: A fixed-target experiment at LHC

July 7, 2012
Physics Opportunities of a Fixed-Target Experiment using the LHC Beams

S.J. Brodsky\textsuperscript{1}, F. Fleuret\textsuperscript{2}, C. Hadjidakis\textsuperscript{3}, J.P. Lansberg\textsuperscript{3}

\textsuperscript{1}SLAC National Accelerator Laboratory, Theoretical Physics, Stanford University, Menlo Park, California 94025, USA
\textsuperscript{2}Laboratoire Leprince-Ringuet, Ecole polytechnique, CNRS/IN2P3, 91128 Palaiseau, France
\textsuperscript{3}IPNO, Université Paris-Sud, CNRS/IN2P3, 91406 Orsay, France

Abstract

We outline the many physics opportunities offered by a multi-purpose fixed-target experiment using the proton and lead-ion beams of the LHC extracted by a bent crystal. In a proton run with the LHC 7-TeV beam, one can analyze $pp$, $pd$ and $pA$ collisions at center-of-mass energy $\sqrt{s_{NN}} \approx 115$ GeV and even higher using the Fermi-motion of the nucleons in a nuclear target. In a lead run with a 2.76 TeV-per-nucleon beam, $\sqrt{s_{NN}}$ is as high as 72 GeV. Bent crystals can be used to extract about $5 \times 10^8$ protons/sec; the integrated luminosity over a year would reach 0.5 fb$^{-1}$ on a typical 1 cm-long target without nuclear species limitation. We emphasize that such an extraction mode does not alter the performance of the collider experiments at the LHC. By instrumenting the target-rapidity region, gluon and heavy-quark distributions of the proton and the neutron can be accessed at large $x$ and even at $x$ larger than unity in the nuclear case. Single diffractive physics and, for the first time, the large negative-$x_F$ domain can be accessed. The nuclear target-species versatility provides a unique opportunity to study nuclear matter versus the features of the hot and dense matter formed in heavy-ion collisions, including the formation of the Quark-Gluon Plasma (QGP), which can be studied in $PbA$ collisions over the full range of target rapidities with a large variety of nuclei. The polarization of hydrogen and nuclear targets allows an ambitious spin program, including measurements of the QCD lensing effects which underlie the Sivers single-spin asymmetry, the study of transversity distributions and possibly of polarized parton distributions. We also emphasize the potential offered by $pA$ ultra-peripheral collisions where the nucleus target $A$ is used as a coherent photon source, mimicking photoproduction processes in $ep$ collisions. Finally, we note that $W$ and $Z$ bosons can be produced and detected in a fixed-target experiment and in their threshold domain for the first time, providing new ways to probe the partonic content of the proton and the nucleus.

Keywords: LHC beam, fixed-target experiment
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Part III

Conclusion and outlooks
Conclusion

Both \( p \) and \( Pb \) LHC beams can be extracted without disturbing the other experiments.

Extracting a few per cent of the beam \( \rightarrow 5 \times 10^8 \) protons per sec allows for high luminosity \( pp, pA, \) and \( PbA \) collisions at \( \sqrt{s} = 115 \text{ GeV} \) and \( \sqrt{s_{NN}} = 72 \text{ GeV} \).

Example: precision quarkonium studies taking advantage of high luminosity (reach in \( y, P_T, \) small BR channels) target versatility (nuclear effects, strongly limited at colliders) modern detection techniques (e.g. \( \gamma \) detection with high multiplicity).

This would likely prepare the ground for \( g(x, Q^2) \) extraction.

A wealth of possible measurements: \( DY, \) Open \( b/c, \) jet correlation, UPC...

(Not mentioning secondary beams)

Planned LHC long shutdown (<2020 ?) could be used to install the extraction system.

Very good complementarity with electron-ion programs.
Conclusion

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Do not hesitate to contact us

Webpage:  
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First paper on AFTER: T. Liu, B.Q. Ma, EPJC (2012) 72:2037

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Part IV

Backup slides
Luminosities

- 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})) = ( \int \mathcal{L} ) (nb(^{-1}).yr(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sol. H(_2)</td>
<td>0.09</td>
<td>1</td>
<td>11</td>
</tr>
<tr>
<td>Liq. H(_2)</td>
<td>0.07</td>
<td>1</td>
<td>8</td>
</tr>
<tr>
<td>Liq. D(_2)</td>
<td>0.16</td>
<td>2</td>
<td>10</td>
</tr>
<tr>
<td>Be</td>
<td>1.85</td>
<td>9</td>
<td>25</td>
</tr>
<tr>
<td>Cu</td>
<td>8.96</td>
<td>64</td>
<td>17</td>
</tr>
<tr>
<td>W</td>
<td>19.1</td>
<td>185</td>
<td>13</td>
</tr>
<tr>
<td>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\(^{-1}\)
A Fixed Target Experiment: e.g. a quarkonium observatory in $pp$

Interpolating the world data set:

<table>
<thead>
<tr>
<th>Target</th>
<th>$\int L , (fb^{-1} \cdot yr^{-1})$</th>
<th>$N(J/\Psi) , yr^{-1}$</th>
<th>$N(\Upsilon) , yr^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 m Liq. $H_2$</td>
<td>20</td>
<td>$4.0 \times 10^8$</td>
<td>$8.0 \times 10^5$</td>
</tr>
<tr>
<td>1 m Liq. $D_2$</td>
<td>24</td>
<td>$9.6 \times 10^8$</td>
<td>$1.9 \times 10^6$</td>
</tr>
<tr>
<td>LHC pp 14 Tev (low pT)</td>
<td>0.05 (ALICE) 2 LHCb</td>
<td>$3.6 \times 10^7$</td>
<td>$1.8 \times 10^5$</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 $y$ about 0

Unique access in the backward region

Probe of the (very) large $x$ in the target

1000 times higher than at RHIC; comparable to ALICE/LHCb at the LHC
**A Fixed Target Experiment: e.g. a quarkonium observatory in pp**

- Interpolating the world data set:

<table>
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<tr>
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- Probe of the (very) large $x$ in the target
**AFTER: also a quarkonium observatory in pA**

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### AFTER: also a quarkonium observatory in $p\Lambda$

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- not to mention ratio with **open charm, Drell-Yan**, etc ...  
- Remember that we can change $A$ ...
AFTER: also an heavy-flavour observatory in \textit{PbA}

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

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<th>$\int L$ (nb$^{-1}$ yr$^{-1}$)</th>
<th>$N(J/\Psi)$ yr$^{-1}$ = $ABLB\sigma_{\Psi}$</th>
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<td>1 cm Be</td>
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Yields similar those of RHIC at 200 GeV and LHC at 5.5 TeV, 100 times those of RHIC at 62 GeV

Also very competitive compared to the LHC.
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  \( \left( \sqrt{s_{\text{NN}}} = 72 \text{ GeV} \right) \)

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<thead>
<tr>
<th>Target</th>
<th>A.B</th>
<th>( \int \mathcal{L} ) (nb(^{-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. ( \text{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>
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</tr>
<tr>
<td>1 cm Pb</td>
<td>207.207</td>
<td>7</td>
<td>5.7 ( 10^6 )</td>
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</tr>
<tr>
<td>LHC PbPb 5.5 TeV</td>
<td>207.207</td>
<td>0.5</td>
<td>7.3 ( 10^6 )</td>
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</tr>
<tr>
<td>RHIC AuAu 200GeV</td>
<td>198.198</td>
<td>2.8</td>
<td>4.4 ( 10^6 )</td>
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</tr>
<tr>
<td>RHIC AuAu 62GeV</td>
<td>198.198</td>
<td>0.13</td>
<td>4.0 ( 10^4 )</td>
<td>61</td>
</tr>
</tbody>
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- Yields similar those of RHIC at 200 GeV and LHC at 5.5 TeV, 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 ($\sqrt{s_{NN}} = 72$ GeV)

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- Also very competitive compared to the LHC.

The same picture also holds for open heavy flavour
Accessing the large $x$ glue

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

Statistical relative uncertainty
Large statistics allow to access very backward region

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

\( J/\Psi \)
\[ y_{CM} \sim 0 \rightarrow x_g = 0.03 \]
\[ y_{CM} \sim -3.6 \rightarrow x_g = 1 \]

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

⇒ Backward measurements allow to access large $x$ gluon pdf