Study of heavy-ion and proton interactions with nuclei on the LHC beams with fixed target.

N.S. Topilskaya and A.B. Kurepin
INR RAS, Moscow

1. Fixed target proposal.
2. Physical motivation.
3. Experimental situation.
4. Summary.

N.S. Topilskaya, ICPPA’17, 5 October 2017.
Proposal of fixed target experiments at the LHC

1. Fixed-target experiment with wire target at the LHC—energy between SPS and RHIC was proposed in 2005 and then in 2009 at CERN Workshop “New opportunities at CERN” by INR RAS. A.B.Kurepin, N.S.Topilskaya, M.B.Golubeva


2. Then proposal of experiment AFTER@LHC (A Fixed Target ExpeRiment at the LHC).

S.J.Brodsky, F.Fleuret, C.Hadjidakis and J.P.Lansberg

Physics Opportunities of a Fixed-Target Experiment using the LHC Beams Phys. Rept. 522 (2013) 239

3. Started at LHCb with low density gas target (SMOG)
Current study group of AFTER@LHC experiment


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Physics at a Fixed-Target Experiment Using the LHC Beams

Study and physical ideas

The Gluon Sivers Distribution: Status and Future Prospects,
D.Boer et al., ID 371396

Transverse Single-Spin Asymmetries in Proton-Proton Collisions at the AFTER@LHC Experiment in a TMD Factorization Scheme,
M.Anscelmino et al., ID 475040

A Gas Target Internal to the LHC for the Study of \( pp \) Single-Spin Asymmetries and Heavy Ion Collisions,
C.Barschel et al., ID 463141

Quarkonium Production and Proposal of the New Experiments on Fixed target at the LHC,
A.B.Kurepin and N.S.Topilskaya, ID 760840

Feasibility Studies for Quarkonium Production at a Fixed-Target Experiment Using the LHC Proton and Lead Beams (AFTER@LHC),
I.Massacrier et al., ID 986348
Advantages of the fixed target experiments

Four features:
- accessing the high $x$, $x_F = |p_z| / p_{z,max} \rightarrow 1$
- achieving high luminosities
- varying the beams and atomic mass of the target
- polarizing the target

Three physics reasons:
- Heavy-ion physics between SPS&RHIC energies towards large rapidities
  (Test of factorization of the cold nuclear matter effects from p+A to A+B collisions, study of quarkonia production and suppression depending on the phase transition of matter to quark-gluon phase)
- High $-x$ gluon, antiquark and heavy quark content in the nucleon&nucleus
  (Very large PDF uncertainties for $x>0.5$, could be crucial to characterize possible BSM discoveries)
- Transverse dynamics and spin of quarks/gluons inside (un)polarized nucleon
  (Possible missing contribution to the proton spin from quark/gluon orbital angular momentum)

All this can be realized at CERN without disturbing other experiments at the LHC with the beams of highest energy and luminosities

Note, that all accelerators with energy $E_p > 100$ GeV now have fixed target program: (Tevatron, HERA, SPS, RHIC)
Fixed target experiment at the LHC: main kinematical features

<table>
<thead>
<tr>
<th>Energy range</th>
<th>7 TeV proton beam on a fixed target</th>
<th>2.76 TeV Pb beam on a fixed target</th>
</tr>
</thead>
<tbody>
<tr>
<td>c.m.s. energy:</td>
<td>$\sqrt{s} = \sqrt{2m_N E_p} \approx 115$ GeV</td>
<td>$\sqrt{s_{NN}} = \sqrt{2m_N E_{Pb}} \approx 72$ GeV</td>
</tr>
<tr>
<td>Boost:</td>
<td>$\gamma = \sqrt{s} / (2m_N) \approx 60$</td>
<td>$\gamma \approx 40$</td>
</tr>
<tr>
<td>Rapidity shift:</td>
<td>$y_{c.m.s.} = 0 \rightarrow y_{lab} = 4.8$</td>
<td>$y_{c.m.s.} = 0 \rightarrow y_{lab} = 4.3$</td>
</tr>
</tbody>
</table>

Such energy allow systematic studies of quarkonia, $p_T$ spectra, associated production and W-boson production in a fixed target mode

- LHCb and the ALICE muon arm become backward detectors $[y_{c.m.s.} < 0]$
- With the reduced $\sqrt{s}$, their acceptance for physics grows and nearly covers half of the backward region for most probes $[-1 < x_F < 0]$
- Allows for backward physics up to high $x_{\text{target}} (\equiv x_2)$ [uncharted for proton-nucleus; most relevant for p-p$^\uparrow$ with large $x^\uparrow$]

J.P. Lansberg (IPNO, Paris-Sud U.)
The new target rapidity region

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
- PHENIX @ RHIC: \(-0.1 < x_F < 0.1\) [could be wider with \( Y \), 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 \( Y(b\bar{b}) \) at \( y_{\text{cms}} \approx -2.5 \) \( \Rightarrow x_F \approx \frac{2m_Y}{\sqrt{s}} \sinh(y_{\text{cms}}) \approx -1 \)
Rapidity shift and kinematical coverage in experiment AFTER

(1) fixed-target mode with 7 TeV p beam
(2) fixed-target mode with 2.76 TeV Pb beam
(3) collider mode with 7 TeV p beams

ALICE acceptance at $z_{\text{target}}=0$

- With a forward detector, access mid- to backward-rapidity region ($y_{\text{CM}} < 0$)
- With mid-rapidity detector, probe very backward-rapidity region (end of phase space)
Three possibilities for fixed target experiment:

1. To use extracted with bent crystal part of the beam and then put fixed target
   – Beam “split” with a bent crystal
     • beam halo is deflected by a bent crystal on a solid target internal to the LHC beam pipe
     • expected proton flux $\sim 5 \times 10^8$ p/s (LHC beam loss: $\sim 10^9$ p/s), Pb flux $\sim 2 \times 10^5$ Pb/s
     → beam halo on dense target

2. To put the internal gas target like SMOG at LHCb
   – Internal gas target similar to SMOG at LHCb / inspired by HERMES at HERA
     • full LHC proton flux: $3.4 \times 10^{18}$ p/s and Pb flux: $3.6 \times 10^{14}$ Pb/s on internal gas target
     • currently used by the LHCb collaboration via the luminosity monitor (SMOG) at low gas density
     → high intensity beam on gas target

3. To use wire target in the beam halo
   – Internal wire/foil target
     • beam halo is recycled directly on internal solid targets (HERA-B, STAR)

At the LHC the possible technical implementation are discussed within the **Physics Beyond Collider Fixed-Target working group.**
Conveners: S.Redealli and M.Ferro-Luzzi
http://pbc.web.cern.ch
Spin physics in AFTER@LHC

The orbital angular momentum (OAM) of the quarks and gluons

- Missing knowledge on the contribution of the orbital angular momentum (OAM) $L_g$ and $L_q$ to the proton spin
  - In fixed-target experiment is possible to use polarized target.
  - The polarization can be longitudinal and transverse.
  - Single Transverse Spin Asymmetries connected with the correlations between parton $k_T$ and the proton spin
    → information about orbital motion of partons in the proton
  - Quark/Gluon Sivers function: distortion in the distribution of an unpolarized partons with momentum fraction $x$ and transverse momentum $k_\perp$ due to the proton transverse polarization: $f_{1T}^\perp(x, k_\perp^2)$
  - First suggested by D.Sivers to explain the large observed left-right single transverse spin asymmetries $A_N$ in $p^\uparrow p \to \pi X$
  - Non-zero quark/gluon Sivers function → non-zero quark/gluon OAM
The gluon PDF

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

  - gluon PDF experimentally unknown for neutron (via deuteron target)

  - gluon PDF at high $x$:
    - with large uncertainties for proton
    - need high luminosity to reach large $x$

    **exp. probes**:
    - heavy quarkonia (gg fusion at high energy)
    - isolated photons (gq fusion)
    - high $p_T$ jets ($p_T > 20$ GeV, accessible up to 40 GeV)

---

Pioneering measurement by E866 @ Fermilab:
- using $\Upsilon$
- at $Q^2 \sim 100$ GeV$^2$ similar gluon distribution in proton and neutron
  - could be extended using $J/\Psi$:
    - to ($\sim 10x$) lower $x$
    - to lower $Q^2$

Need high luminosity.
The gluon nPDF

- A dependence thanks to target versatility
- Nuclear PDF from intermediate to high $x$: antishadowing, EMC region, Fermi motion
- Extraction using quarkonia, isolated photons, photon-jet correlation

- Experimental probes @ AFTER
  - Quarkonia
  - Isolated photons
  - High $p_T$ jets ($p_T > 20$ GeV/c)
    → to access target $x_g = 0.3 - 1$ (>1 Fermi motion in nucleus)

- Target versatility
  - Probing the A-dependence of shadowing and nuclear matter effects
Heavy-ion physics

• QGP studies between SPS and RHIC energies (e.g. with quarkonia)

- At 72 GeV, $Y(3S)$ and $Y(2S)$ are expected to melt: perform the same study as CMS at low energy
Heavy-ion collisions towards large rapidities

A complete sets of quarkonium studies between SPS and RHIC energies (calibration of quarkonium thermometer \([J/\psi, \psi', \chi_c, \Upsilon, D, J/\psi \rightarrow b + \text{pairs})\])

Test on the formation of azimuthal asymmetries: hydrodynamics vs initial-state radiation

Investigation of the longitudinal expansion of QGP formation

Factorization of cold nuclear matter effects from \(p+A\) to \(A+B\) collisions in new energy and kinematical ranges
Fixed-target charmonium data (SPS, FNAL, HERA)

**AA collisions**

S-U 200 GeV/nucleon, 0<y<1, √s=19.4 GeV

Pb-Pb 158 GeV/nucleon, 0<y<1, √s=17.3 GeV

In-In 158 GeV/nucleon, 0<y<1, √s=17.3 GeV

**pA collisions**

HERA-B

p-Cu,(Ti),W 920 GeV, -0.34<xF<0.14, √s=41.6 GeV

E866

p-Be, Fe, W 800 GeV, -0.10<xF<0.93, √s=38.8 GeV

NA50

p-Be,Al,Cu,Ag,W,Pb 400/450 GeV, -0.1<xF<0.1, √s=27.4/29.1 GeV

NA51

p-p, d 450 GeV, -0.1<xF<0.1, √s=29.1 GeV

NA3, NA38

p-p,Pt, Cu,U 200 GeV, 0<xF<0.6, √s=19.4 GeV

NA60

p-Be,Al,Cu,In,W,Pb,U 158/400 GeV, -0.1<xF<0.35, √s=17.3/27.4 GeV
Colliders (RHIC, LHC)

**AA collisions**
- RHIC CuCu, AuAu $\sqrt{s} = 39, 62, 130$ GeV, 200 GeV
- UU $\sqrt{s} = 193$ GeV
- LHC PbPb $\sqrt{s} = 2.76, 5.02$ TeV (max 5.5 TeV)

**pA collisions**
- RHIC pp, dAu $\sqrt{s} = 130, 200$ GeV
- LHC pp $\sqrt{s} = 2.76, 7, 8, 13$ TeV (max 14 TeV)
- pPb $\sqrt{s} = 5.02, 8.16$ TeV

**Fixed target experiment at LHC**
- AA collisions
  - Pb-Pb 2.75 TeV/nucleon, $\sqrt{s} = 72$ GeV

- pA collisions
  - p-A 7.0 TeV, $\sqrt{s} = 115$ GeV
  - (5.0 TeV, $\sqrt{s} = 97$ GeV)
The quarkonium study in experiment AFTER

<table>
<thead>
<tr>
<th>Target</th>
<th>A</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>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:
  - $\chi_c$ measurement in $pA$ via $J/\psi + \gamma$ (extending Hera-B studies)
  - Polarisation measurement as the centrality, $y$ or $P_T$
  - Ratio $\psi'$ over direct $J/\psi$ measurement in $pA$
  - not to mention ratio with **open charm**, Drell-Yan, etc...
J/ψ suppression at SPS

**NA50**

Suppression (~40%); 
ψ’ suppression is measured

\[ \sigma_{\text{abs}} \text{ depends on energy; } \]

**NA60**

Suppression (~20-30%);

\[ \sigma_{\text{abs}} \text{ J/ψ (158 GeV) = 7.6 ± 0.7 ± 0.6 mb } \]

\[ \sigma_{\text{abs}} \text{ J/ψ (400 GeV) = 4.3 ± 0.8 ± 0.6 m } \]
Comparison of SPS and RHIC $J/\psi$ data at mid rapidity

$R_{AA}$ as a function of multiplicity ($\sim \varepsilon$)

$R_{AA}$ as a function of $N_{\text{part}}$

Which dependence to choose?

With NA60 data ($\sigma_{\text{abs}}$ depends on energy) suppression of charmonium production at PHENIX larger that at NA50

N.Brambilla et al., EPJ C71 (2011) 1534
Quarkonium production at LHC: ALICE, ATLAS, CMS and LHCb.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Selection Criteria</th>
<th>$p_T$ Coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALICE</td>
<td>$J/\psi \rightarrow \mu^+\mu^-$</td>
<td>$2.5 &lt; y &lt; 4$</td>
</tr>
<tr>
<td></td>
<td>$J/\psi \rightarrow e^+e^-$</td>
<td>$</td>
</tr>
<tr>
<td>ATLAS</td>
<td>$J/\psi \rightarrow \mu^+\mu^-$</td>
<td>$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(separation between B and prompt $J/\psi$)</td>
<td></td>
</tr>
<tr>
<td>CMS</td>
<td>$J/\psi \rightarrow \mu^+\mu^-$</td>
<td>$</td>
</tr>
<tr>
<td></td>
<td>(separation between B and prompt $J/\psi$)</td>
<td></td>
</tr>
<tr>
<td>LHCb</td>
<td>$J/\psi \rightarrow \mu^+\mu^-$</td>
<td>$2.5 &lt; y &lt; 4$</td>
</tr>
<tr>
<td></td>
<td>(separation between B and prompt $J/\psi$)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(no heavy ion physics program)</td>
<td></td>
</tr>
</tbody>
</table>

Now they have HI program.
Suppression for forward rapidity at all centralities and low pt at ALICE lower than at PHENIX.
Different behavior between RHIC and LHC data.

Models with all J/ψ produced at hadronization or models including large fraction (>50% in central collisions) of J/ψ produced from recombinations can describe ALICE results.
$R_{AA} (\text{PbPb})$ for forward rapidity vs transverse momentum without shadowing and CNM effects

At low transverse momentum $J/\psi$ are produced with indication on enhancement in agreement with regeneration model. At high transverse momentum strong suppression is seen – QGP formation?

Final state effects
J/ψ and ψ(2S) production in pPb-collisions at 5.02 TeV

- Different behavior for J/ψ and ψ(2S) production.
- ψ(2S) is more suppressed than J/ψ.

more pronounced in Pb-going direction than in p-going

Final state effects?

At LHC - some evidence for collective behavior in high-multiplicity p-Pb and pp collisions
No theoretical model that could reproduce all data.

**Fixed target** experiment at **LHC** for quarkonium production at the energy range between **SPS** and **RHIC** in p-A and A-A collisions with planning proton beam at **T=7 TeV** \((\sqrt{s} = 114.6 \text{ GeV})\) and Pb beam at **2.75 TeV** \((\sqrt{s} = 71.8 \text{ GeV})\) with high statistics is possibility to clarify the mechanism of quarkonium \((J/\psi, \psi(2S), \Upsilon(1S,2S,3S)\text{ and } \chi_c)\) production, to investigate the contribution of recombination.

proton and lead beams, different targets, possible scan of the energy
Luminosities for 500 μm target length

<table>
<thead>
<tr>
<th>LHC beam</th>
<th>Target species</th>
<th>Density $\rho$ [g cm$^{-3}$]</th>
<th>M [g mol$^{-1}$]</th>
<th>Thickness $\ell$ [μm]</th>
<th>$\theta_{\text{target}}$ [cm$^{-2}$]</th>
<th>beam flux [s$^{-1}$]</th>
<th>$\mathcal{L}$ [cm$^{-2}$s$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p$</td>
<td>C</td>
<td>2.25</td>
<td>12</td>
<td>500</td>
<td>$5.6 \cdot 10^{21}$</td>
<td>$5 \times 10^{8}$</td>
<td>$2.8 \cdot 10^{30}$</td>
</tr>
<tr>
<td>$p$</td>
<td>Ti</td>
<td>4.43</td>
<td>48</td>
<td>500</td>
<td>$2.8 \cdot 10^{21}$</td>
<td>$5 \times 10^{8}$</td>
<td>$1.4 \cdot 10^{30}$</td>
</tr>
<tr>
<td>$p$</td>
<td>W</td>
<td>19.25</td>
<td>184</td>
<td>500</td>
<td>$3.1 \cdot 10^{21}$</td>
<td>$5 \times 10^{8}$</td>
<td>$1.6 \cdot 10^{30}$</td>
</tr>
<tr>
<td>Pb</td>
<td>C</td>
<td>2.25</td>
<td>12</td>
<td>500</td>
<td>$5.6 \cdot 10^{21}$</td>
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</table>

Typical luminosities integrated over a month ($10^6$ s): $L_{\text{PbW}}$ (72 GeV) = 0.3/nb
Charge particle multiplicities

- Charge particle multiplicities for all fixed target modes: p+Pb at 115 GeV and Pb+H at 72 GeV (left) and Pb+Pb, Pb+Xe, Pb+Ar at 72 GeV (right)
- Multiplicities smaller than reached in collider mode for $\eta_{\text{lab}} < 6$
- ALICE would be possible to use such multiplicities

Large yields expected for charmonia
Experiment AFTER

AFTER:

- Offers a wide physical program.
- Possibility to use different targets with high thickness – higher luminosity (20 times more for 1 cm target vs 500 µm)
- Possibility to use 1 meter-long liquid H$_2$ and D$_2$ targets: extremely high luminosity $\sim 20$ fb$^{-1}$ yr$^{-1}$ -compatible to LHC.
  But – high cost.

Fixed target experiment with the target in the form of thin ribbon:

- Only after beam tuning with the aid of rotation system-put in the working position
- Used only halo of the beam (and may be used as extra collimator)
- May be placed at existing experimental installation (for example, ALICE and/or LHCb)
- Possibility to measure charmonium production with rather high statistics on different targets in pA and PbA.

First step?
Conclusions

- **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

The measurement in energy range for fixed target experiment between SPS and RHIC with high statistics gives important additional information for quarkonium (J/ψ, ψ(2S), Υ(1S,2S,3S) and χc) production.

- Proton and lead beams, different targets, possible scan of energy

- **The possible technical implementation are discussed at the LHC:**
  - Internal gas target, beam extraction with bent crystal or internal wire target

- **The Expression of Interest is preparing to be sent to the CERN LHCC**
Backup
Fixed target experiment at the LHC: main kinematical features

- Entire center-of-mass forward hemisphere ($y_{CM} > 0$) within 1 degree
- Large angle gives access to large parton momentum fraction ($x_2$) of the target

- LHCb and the ALICE muon arm become backward detectors

- With the reduced $\sqrt{s}$, their acceptance for physics grows and nearly covers half of the backward region for most probes [$-1 < x_F < 0$]

- Allows for backward physics up to high $x_{\text{target}}$ ($\equiv x_2$)
  [uncharted for proton-nucleus; most relevant for $p-p^\uparrow$ with large $x^\uparrow$]
Spin physics in AFTER@LHC

• Unraveling the spin of the nucleon

• Possible missing contribution to the proton spin: Orbital Angular Momentum $\mathcal{L}_{g;q}$:

  \[ \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + \mathcal{L}_{g} + \mathcal{L}_{q} \]

  [First hint by COMPASS that $\mathcal{L}_{g} \neq 0$]

• Test of the QCD factorisation framework

  [beyond the DY $A_N$ sign change]
The quarks orbital angular momentum (OAM).

Single spin asymmetry (STSA) 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.

Experimental goal: to measure asymmetries on the order of 5-10% at $x_F < 0$.

Transverse Single-Spin Asymmetries in Proton-Proton Collisions…

Black points – calculated AFTER@LHC values.
The gluon orbital angular momentum (OAM) contribution to the proton spin in J/ψ production.

Single transverse spin asymmetry (STSA) for J/ψ production.

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

The three red points correspond to $2<\gamma_{lab}<3$, $3<\gamma_{lab}<4$ and $4<\gamma_{lab}<5$ PHENIX data, with average central value $A_N(J/\psi) = -0.025$.

Black points – calculated AFTER@LHC values.
The dilepton study

- 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
In the frame of AliRoot fast simulation we calculated the geometrical acceptances for fixed target experiment at LHC with the target in the form of thin ribbon placed around the main orbit for charmonium production at the energy range between SPS and RHIC in p-A and A-A collisions with planning proton beam at $T=7$ TeV ($\sqrt{s} = 114.6$ GeV) and Pb beam at $2.75$ TeV ($\sqrt{s} = 71.8$ GeV) at IP $z=0$ and at $z= -50$cm.

Then - luminosity and counting rate estimation for $J/\psi$ production.
Luminosity, cross sections ($x_F > 0$), counting rates

<table>
<thead>
<tr>
<th>System</th>
<th>$\sqrt{s}$ (TeV)</th>
<th>$\sigma_{nn}$ (µb)</th>
<th>$\sigma_{pA} = \sigma_{nn} \cdot A^{0.92}$ (µb)</th>
<th>I (%)</th>
<th>Rate (µb)</th>
<th>$I \cdot B \cdot \sigma_{pA}$ (µb)</th>
<th>$L$ (cm$^{-2}$s$^{-1}$)</th>
<th>Rate (hour$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>pp</td>
<td>14</td>
<td>32.9</td>
<td>32.9</td>
<td>4.7</td>
<td>0.091</td>
<td>5·10$^{30}$</td>
<td>1635</td>
<td></td>
</tr>
<tr>
<td>pp$_{RHIC}$</td>
<td>0.200</td>
<td>2.7</td>
<td>2.7</td>
<td>3.59</td>
<td>0.0057</td>
<td>2·10$^{31}$</td>
<td>410</td>
<td></td>
</tr>
<tr>
<td>pPb$_{fixed}$</td>
<td>0.1146</td>
<td>0.65</td>
<td>88.2</td>
<td>5.98</td>
<td>0.310</td>
<td>1·10$^{29}$ (*)</td>
<td>112</td>
<td></td>
</tr>
<tr>
<td>pPb$_{fixed}$</td>
<td>0.0718</td>
<td>0.55</td>
<td>74.6</td>
<td>7.97</td>
<td>0.349</td>
<td>1·10$^{29}$</td>
<td>126</td>
<td></td>
</tr>
<tr>
<td>pPb$_{NA50}$</td>
<td>0.0274</td>
<td>0.19</td>
<td>25.8</td>
<td>14.0</td>
<td>0.212</td>
<td>7·10$^{29}$</td>
<td>535</td>
<td></td>
</tr>
<tr>
<td>PbPb$_{fixed}$</td>
<td>0.0718</td>
<td>0.55</td>
<td>11970</td>
<td>7.97</td>
<td>47.9</td>
<td>2.2·10$^{27}$ (**)</td>
<td>378</td>
<td></td>
</tr>
</tbody>
</table>

(*) pPb$_{fixed}$, 500 µ wire, $3.2 \cdot 10^{11}$ protons/60 min
(** PbPb$_{fixed}$, 500 µ wire, $6.8 \cdot 10^{8}$ ions/60 min
The luminosity for extracted proton beam in experiment AFTER

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

- Expected proton flux \( \Phi_{beam} = 5 \times 10^8 \, p^+ \, s^{-1} \)
- Instantaneous Luminosity:
  \[ L = \Phi_{beam} \times N_{target} = N_{beam} \times (\rho \times \ell \times N_A) / A \]
  \[ \{ \ell: \text{target thickness (for instance 1cm)} \}\]
- Integrated luminosity: \( \int dt L \) 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} ) (fb(^{-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>0.62</td>
</tr>
<tr>
<td>1cm Cu</td>
<td>8.96</td>
<td>64</td>
<td>42</td>
<td>0.42</td>
</tr>
<tr>
<td>1cm W</td>
<td>19.1</td>
<td>185</td>
<td>31</td>
<td>0.31</td>
</tr>
<tr>
<td>1cm Pb</td>
<td>11.35</td>
<td>207</td>
<td>16</td>
<td>0.16</td>
</tr>
</tbody>
</table>

- For \( pp \) and \( pd \) collisions: \( \mathcal{L}_{H_2/D_2} \simeq 20 \, \text{fb}^{-1}\text{yr}^{-1} \)
  3 orders of magnitude larger than RHIC (200 GeV)
The luminosity for extracted lead beam in experiment AFTER

- $Pbp$ or $PbA$ with a 2.75 TeV Pb beam: $\sqrt{s_{\text{NN}}} \approx 72$ GeV
- Crystal channeling is also possible (to extract a fraction of the beam)
- May require crystals highly resistant to radiations: bent diamonds?

P. Ballin et al., NIMB 267 (2009) 2952

Expected luminosities with $2 \times 10^5$ Pb/s extracted (1 cm-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$^{-1}$
The quarkonium study in experiment AFTER

<table>
<thead>
<tr>
<th>Target</th>
<th>A</th>
<th>( \int \mathcal{L} , (fb^{-1}.yr^{-1}) )</th>
<th>( N(J/\Psi) , yr^{-1} = \frac{ALB \sigma_{\psi}}{A} )</th>
<th>( N(\Upsilon) , yr^{-1} = \frac{ALB \sigma_{\Upsilon}}{A} )</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)
  - Polarisation measurement as the centrality, \(y\) or \(P_T\)
  - Ratio \(\psi'\) over direct \(J/\psi\) measurement in \(pA\)
  - not to mention ratio with open charm, Drell-Yan, etc...
Internal gas targets

SMOG(-like) system
- SMOG: System for Measuring Overlap with Gas
- Designed for precise luminosity determination
- Noble gas directly injected in the VELO
- p(He,Ne,Ar), Pb(Ne,Ar) tested: completely parasitic
  - [up to one week, so far]
- New pressure monitoring to be installed
- Could be coupled to ALICE: ideal demonstrator
- No specific pumping system: limit in the gas inject
  - [pressure and duration]
- No possibility to use polarised gases
- Gas flows in the beampipe; pressure profile not optimised
- Kr and Xe maybe only at end of a run

HERMES(-like) system
- Injection of gas in an open-end storage cell
- Used e.g. at DESY for 10 years
- Dedicated pumping system [turbo-molecular pumps]
- Pressure in the cell significantly higher
  - [diameter ≤ 2cm in the closed position]
- Polarised H and D can be injected ballistically with high polarisation
- Polarised $^3$He or unpolarised heavy gas (Kr, Xe) can also be injected
- Not compatible with an injection inside ALICE; only upstream
- May need complementary vertexing capabilities

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