Ultra-relativistic heavy-ion physics with AFTER@LHC

A. Rakotozafindrabe[a], R. Arnaldi[b], S.J. Brodsky[c], V. Chambert[d], J.P. Didelez[d], B. Genolini[d],
E.G. Ferreiro[e], F. Fleuret[f], C. Hadjidakis[d], J.P. Lansberg[d], P. Rosier[d], I. Schienbein[g], E. Scomparin[b],
U.I. Uggerhøj[h]

[a]*IRFU/SPhN, CEA Saclay, 91191 Gif-sur-Yvette Cedex, France*
[b]*INFN Sez. Torino, Via P. Giuria 1, I-10125, Torino, Italy*
[c]*SLAC National Accelerator Laboratory, Theoretical Physics, Stanford U., Menlo Park, CA 94025, USA*
[d]*IPNO, Université Paris-Sud, CNRS/IN2P3, F-91406, Orsay, France*
[e]*Departamento de Física de Partículas, Universidade de Santiago de C., 15782 Santiago de C., Spain*
[f]*Laboratoire Leprince Ringuet, École Polytechnique, CNRS/IN2P3, 91128 Palaiseau, France*
[g]*LPSC, Université Joseph Fourier, CNRS/IN2P3/INPG, F-38026 Grenoble, France*
[h]*Department of Physics and Astronomy, University of Aarhus, Denmark*

Abstract

We outline the opportunities for ultra-relativistic heavy-ion physics which are offered by a next generation and multi-purpose fixed-target experiment exploiting the proton and ion LHC beams extracted by a bent crystal.

1. Introduction

Before the advent of RHIC and the LHC, relativistic collisions of heavy ions have always been studied at fixed-target experiments. Clearly, the possibility to use heavy-ion colliders has opened new horizons in terms of the study of hard probes, which can only be produced abundantly at high energies. Yet, one should not overlook the critical advantages of the fixed-target mode for heavy-ion physics. Briefly, these advantages are

- extremely high luminosities thanks to the high density of the target,
- the unlimited versatility of the target species which allows for in-depth studies of yields as a function of the centrality through the A dependence or the nuclear length,
- the reduced constraints of the P_T and y of the studied particles due to the boost between the laboratory frame and the c.m.s.
- the possibility for thorough and ultra precise baseline studies in proton-nucleus collisions –and even in proton-proton collisions– at similar energies.

These assets are particularly striking in view of the first hard-probe studies at the LHC where

- the request for pA measurements necessarily conflicts with those for more run time to reach higher statistics for AA measurements,
- the low P_T region –probably the most important to understand– is not easily accessible for hard probes such as the J/ψ for the CMS and ATLAS experiments,
- the precision of centrality-dependent observables is challenged by our determination of the so-called centrality classes, etc.

In this context, it is well worth advertising the unprecedented possibilities offered by a fixed-target experiment using the proton and lead LHC beams extracted by a bent crystal [1]. We referred to such a project[1] of a next generation and multi-purpose fixed-target experiment as "AFTER", standing for "A Fixed Target ExperiRement @ LHC".

In the following, we outline the opportunities for ultra-relativistic heavy-ion physics, which AFTER can provide. In section 2 we present some generalities about the experiment during the LHC Pb run. In section 3 we elaborate on the more specific case of quarkonium production. Section 4 briefly summarises our conclusions.

2. A fixed-target experiment with the heavy-ion LHC beam extracted by a bent crystal

Bent-crystal beam extraction is a mature technique which offers an ideal way to obtain a clean and very collimated high-energy beam, without altering the performance of the LHC [2, 3, 4]. The multi-TeV LHC beams (E_p = 7 TeV and $E_{\rm Pb}$ = 2.76 TeV per nucleon) grant the most energetic fixed-target experiment ever performed to study PbA and PbH collisions at $\sqrt{s_{NN}} \simeq$ 72 GeV ($\sqrt{2E_{\rm beam}m_N}$) as well as pp, pd and pA collisions at $\sqrt{s_{NN}} \simeq$ 115 GeV. As regards the heavy ion case, first tests on lead-beam collimation/extraction at the SPS through a 50 mm bent crystal showed the feasibility of a large-angle deflection [5]. Recently, further tests of a small-angle deflection with a shorter crystal –2mm– have also been performed successfully [6]. In addition, a new technique to bend diamond crystal –thus extremely tolerant to high radiation doses– using laser ablation techniques has been shown to be successful [7].

The intensity of the extracted lead beam from the LHC by putting a bent crystal in the halo of the circulating beam can easily reach 2×10^5 Pb/s [2, 3]. Over a 10-hour fill, this corresponds to an extraction of about 15 % of the lead ions contained in the beam (4.1×10^{10}), which would be lost in the collimators anyway. The extracted beam will show a similar bunch structure as that of the one circulating in the beam and one expects to extract on average 0.03 ions from each bunch at each pass. No pile-up is therefore expected. Correspondingly, the typical instantaneous luminosities achievable in PbA mode with 1cm targets range from 7 mb^{-1}s^{-1} for Pb to 25 mb^{-1}s^{-1} for Be (Table 1 (a)). The yearly luminosity for PbPb (7 nb^{-1}) is thus twice as large as the one expected at RHIC [8] in AuAu at 200 GeV and 60 times that at 62 GeV. It is also more than 10 times that expected at the LHC. As discussed later, despite the smaller c.m.s energy, the hard-probe yields expected at AFTER in PbPb are also competitive with RHIC and LHC experiments.

The boost between the c.m.s. and the laboratory system is rather large, $\gamma_{\rm c.m.s.}^{\rm lab} = \sqrt{s}/(2m_p) \simeq$ 38, and the rapidity shift is $\tanh^{-1}\beta_{\rm c.m.s.}^{\rm lab} \simeq 4.3$. The c.m.s. central-rapidity region –where the QGP is expected to be formed–, $y_{\rm c.m.s.} \simeq 0$, is thus highly boosted at an angle of 1.6 degrees with respect to the beam axis in the laboratory frame. The entire backward c.m.s. hemisphere ($y_{\rm c.m.s} < 0$) is easily accessible with standard experimental techniques. The forward hemisphere is less easily accessible because of the reduced distance from the (extracted) beam axis which requires the use of highly segmented detectors to deal with the large particle density. One should be able to access the region $-4.8 \leq y_{\rm c.m.s.} \leq 1$ without specific difficulty. The main part of the particle yields could then be detected as well as high precision measurements in the whole backward hemisphere, down to the target rapidity. In particular, this should allow for a survey of observables at $y \simeq y_{\rm Pb\ target}$ in order to deepen our understanding of the extended longitudinal scaling observed by Phobos [9].

---

[1]See http://after.in2p3.fr

	(a) Instantaneous and yearly luminosities				(b) J/ψ and Υ inclusive yields		
Target	ρ (g cm^{-3})	A	$\mathcal{L}$ (mb^{-1} s^{-1})	$\int \mathcal{L}$ (nb^{-1} yr^{-1})	Target	$N_{J/\psi}$ (yr^{-1})	N_{Υ} (yr^{-1})
10 cm liquid H	0.068	1	80	80	10 cm liquid H	3.4 10^5	6.9 10^2
10 cm liquid D	0.16	2	100	100	10 cm liquid D	8.0 10^5	1.6 10^3
1cm Be	1.85	9	25	25	1 cm Be	9.1 10^5	1.9 10^3
1cm Cu	8.96	64	17	17	1 cm Cu	4.3 10^6	0.9 10^3
1cm W	19.1	185	13	13	1 cm W	9.7 10^6	1.9 10^4
1cm Pb	11.35	207	7	7	1 cm Pb	5.7 10^6	1.1 10^4
dAu (200 GeV)	–	–	–	150	dAu (200 GeV)	2.4 10^6	5.9 10^3
dAu (62 GeV)	–	–	–	3.8	dAu (62 GeV)	1.2 10^4	1.8 10^1
AuAu (200 GeV)	–	–	–	2.8	AuAu (200 GeV)	4.4 10^6	1.1 10^4
AuAu (62 GeV)	–	–	–	0.13	AuAu (62 GeV)	4.0 10^4	6.1 10^1
pPb (8.8 TeV)	–	–	100	100	pPb (8.8 TeV)	1.0 10^7	7.5 10^4
PbPb (5.5 TeV)	–	–	0.5	0.5	PbPb (5.5 TeV)	7.3 10^6	3.6 10^4

Table 1: (a) Luminosities obtained with an extracted beam of 2×10^5 Pb/s for various target. (b) Yields per unit of rapidity expected per LHC year with AFTER at mid rapidity with a 2.76 TeV Pb beam on various targets. Both are compared to the projected nominal luminosities and yield in Pbp and PbPb runs of the LHC at 8.8 and 5.5 TeV as well as in dAu and AuAu collisions at 200 GeV and 62 GeV at PHENIX [8] at RHIC. The yields are per LHC/RHIC year.

In addition, let us emphasise that the luminosities in the pp and pA mode [1, 10] surpass those of RHIC by more than 3 orders of magnitude and are comparable to those of the LHC in the collider mode. In pA, the nuclear target-species versatility provides a unique opportunity to study cold nuclear matter versus the features of the hot and dense matter formed in heavy-ion collisions, including the formation of the quark-gluon plasma.

3. One example of physics studies: heavy quarkonia

Even when these luminosities are translated in terms of yields for hard probes, AFTER is still competitive compared to the LHC in the collider mode despite the significantly lower c.m.s energy. Table 1(b) displays the expected J/ψ and Υ yields using the 2.76 TeV Pb beam on various targets. They are compared to those expected nominally[2] per year at RHIC in dAu and AuAu, at the LHC in Pbp and in PbPb. As regards the AA collisions, one sees that the yields in PbPb at $\sqrt{s_{NN}} = 72$ GeV are about equal to those expected in a year at RHIC for AuAu at $\sqrt{s_{NN}} = 200$ GeV. They are 100 times larger than those expected at 62 GeV and also similar (20% lower, to be precise) to that to be obtained during one LHC PbPb run at 5.5 TeV. The same global picture also applies for other quarkonium states –as well as for most of the hard probes for QGP studies, in particular open-charm and open-beauty.

AFTER is even more competitive for hard probe yields in pp and pA (see [1, 11]). This provides a quarkonium and heavy-flavour observatory in pp and pA collisions where, by instrumenting the target-rapidity region, gluon and heavy-quark distributions of the proton, the neutron and the nuclei can be accessed at large x – even larger than unity in the nuclear case. For the first

---

[2]In both cases, the numbers hold for one unit of rapidity with the branching into di-lepton but without any acceptance nor efficiency corrections and without any suppression due to nuclear effects.

time, the far negative x_F region can be accessed where novel effects, such as those observed at large positive x_F (see *e.g.* [12]), may be uncovered.

With the advent of modern detection technologies –such as those developed for instance for the ILC [13]–, one can be very hopeful that the study of all the quarkonium excited states is at reach. This is particularly true for the χ_c and χ_b resonances, even in the challenging high-multiplicity environment of pA and PbA collisions. Potential synergies with the project CʜɪC [14] could therefore be very fruitful. The recent results on excited quarkonium states obtained at the LHC [15, 16] are particularly motivating for such studies at lower energies.

High-statistics data from PbA, pA and pp will be of great help to improve our understanding of heavy-quark and quarkonium production [17], to unravel cold from hot nuclear effects [18] and to restore the status of heavy quarkonia as a golden-plated test [19] of lattice QCD in terms of dissociation temperature predictions at a $\sqrt{s_{NN}}$ where the procees of heavy-quark recombination is expected to have a small impact.

4. Summary

The physics reach of the most energetic heavy-ion accelerator ever built, the CERN-LHC, can be significantly augmented by extracting a small fraction of its content –which would be lost in the collimators anyway– with a bent crystal and by colliding it on a fixed target. The resulting energy in the c.m.s. amounts to $\sqrt{s_{NN}}$ = 72 GeV in PbA collisions and $\sqrt{s_{NN}}$ = 115 GeV in pA collisions. Hydrogen and deuterium targets also allow for pp and pd collisions to be studied with an extreme accuracy. As expected for a fixed-target experiment, the resulting luminosities surpass those of the existing relativistic heavy-ion colliders, *i.e.* RHIC and the LHC itself.

Such a fixed-target experiment, AFTER, would be a key actor in the study of the formation of the quark-gluon plasma under scrutiny with these heavy ion collisions. Among the large number of proposed observables, probes such as the suppression of quarkonia, the quenching of jets or the production of direct photons could easily be accessed. Finally, let us stress that a fixed-target set-up also offers the novel opportunity of studying the QGP formation from the viewpoint of one of the colliding nuclei.

References

References

[1] S. J. Brodsky, F. Fleuret, C. Hadjidakis, J. P. Lansberg, Phys. Rep. (2012), 10.1016/j.physrep.2012.10.001.
[2] E. Uggerhoj and U. I. Uggerhoj, Nucl. Instrum. Meth. B **234** (2005) 31.
[3] U. I. Uggerhoj, Rev. Mod. Phys. **77** (2005) 1131.
[4] W. Scandale, *et al.* [LUA9], CERN-LHCC-2011-007, 2011.
[5] G. Arduini, , *et al.* Phys. Rev. Lett. **79** (1997) 4182.
[6] W. Scandale, *et al.* Phys. Lett. B **703** (2011) 547.
[7] P. Balling, *et al.* Nucl. Instrum. Meth. B **267** (2009) 2952.
[8] PHENIX collaboration, "The PHENIX Experiment at RHIC, Decadal Plan 2011-2020", [available online].
[9] B. B. Back, *et al.*, Nucl. Phys. **A757** (2005) 28.
[10] J. P. Lansberg, *et al.* PoS QNP **2012** (2012) 049 [arXiv:1207.3507 [hep-ex]].
[11] J. P. Lansberg, S. J. Brodsky, F. Fleuret, C. Hadjidakis, Few Body Syst. **53** (2012) 11
[12] P. Hoyer, M. Vanttinen and U. Sukhatme, Phys. Lett. B **246** (1990) 217.
[13] M. A. Thomson, Nucl. Instrum. Meth. A **611** (2009) 25.
[14] F. Fleuret *et al.*, EoI for "An experiment to measure χ_c suppression at the SPS: CHIC", CERN-SPSC-2012-031
[15] S. Chatrchyan *et al.* [CMS], Phys. Rev. Lett. **107** (2011) 052302; C. Mironov, talk at Hard Probes 2012.
[16] R. Arnaldi *et al.* [ALICE], these proceedings.

[17] N. Brambilla, *et al.*, Eur. Phys. J. C **71** (2011) 1534; J. P. Lansberg, Int. J. Mod. Phys. A **21** (2006) 3857

[18] Z. Conesa del Valle, *et al.*, Nucl. Phys. Proc. Suppl. **214** (2011) 3 [arXiv:1105.4545 [hep-ph]].

[19] T. Matsui and H. Satz, Phys. Lett. B **178** (1986) 416.