Advancing the precision of proton-proton and proton-nucleus collision studies with A Fixed-Target ExpeRiment at the LHC (AFTER@LHC)

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

3-7 April 2017, University of Birmingham

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

Assets, Kinematics, Possible Implementations and Luminosities
The fixed-target mode with TeV beams: why and what for?

achieving high luminosities, varying the atomic mass of the target at a target, polarising the target.

physics cases:

- High-xx gluon, antiquark and heavy-quark content in the nucleon & nucleus
- Transverse dynamics and spin of gluons inside (un)polarised nucleons
- Heavy-ion physics between SPS & RHIC energies towards larger rapidities

All this can be realised at CERN in a parasitic mode with the most energetic beams ever!

Nota: all (past) colliders with \(E_p\) have had a fixed-target program (Tevatron, HERA, SPS, RHIC)
The fixed-target mode with TeV beams: why and what for?

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- accessing the high $x$ frontier
- achieving high luminosities,
- varying the atomic mass of the target almost at will,
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\[ |x_F| \equiv \frac{|p_z|}{p_{z \text{ max}}} \rightarrow 1 \]
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Fixed-target collisions at the LHC: main kinematical features
### Energy range

**7 TeV proton beam on a fixed target**

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Such $\sqrt{s}$ allow, for the first time, for systematic studies of $W$ boson, bottomonia, $p_T$ spectra, associated production, ..., in the fixed target mode.
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- LHCb and the ALICE muon arm become **backward detectors** $[y_{c.m.s.} < 0]$ [particularly relevant for high energy beams]
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- 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 $x_{\text{target}}$ (≡ $x_2$) $[\text{uncharted for proton-nucleus; most relevant for } p-p^\uparrow \text{ with large } x^\uparrow]$.
LHCb acceptance for various colliding modes

(1) Fixed-target using p beam, $E_p = 7$ TeV

(2) Fixed-target using Pb beam, $E_{Pb} = 2.76$ A.TeV

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ALICE muon acceptance for various colliding modes

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Possible implementations

Nota: In most of the cases, the luminosity is limited by the detector or by the *parasiticity*.
Possible implementations

- **Internal gas target** (see next slide)
  - can be installed in one of the existing LHC caverns, and coupled to existing experiments
  - currently validated by the LHCb collaboration via a luminosity monitor (SMOG)
  - bears on the high LHC particle current
    - proton flux: $3.4 \times 10^{18} \text{ s}^{-1}$ & lead flux: $3.6 \times 10^{14} \text{ s}^{-1}$

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  - the most ambitious solution [civil engineering required]
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  - the LHC beam halo is recycled
    - proton flux: $5 \times 10^8 \text{ s}^{-1}$ & lead flux: $2 \times 10^5 \text{ s}^{-1}$

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- Similar luminosities with an internal gas target or a crystal-based solution

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<td>Lumi.</td>
<td>$\mathcal{O}(10 \text{ fb}^{-1}\text{yr}^{-1})$</td>
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Internal gas targets

SMOG(-like) system

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April 4, 2017
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The simulations showed in Part II are based on this set-up coupled to a LHCb like detector.
Beam splitting option

Proposed at the Physics Beyond Collider workshop Sept.2016 (S.Redaelli, W.Scandale)

- Crystal located ~ 100 m downstream the target to deflect the beam halo
- Solid target close to the nominal interaction point
- Absorber 100 m upstream for the non-interacting beam halo
Part II

A selection of projected performances

What is not covered by lack of time

- Heavy-ion physics case
- Azimuthal asymmetries
- Photon related observables
- $W$ boson
- Antiproton and related x-section measurements for astroparticle MC tuning
- $C$-even quarkonia
- Associated production (beyond double $J/\psi$)
Unique acceptance (with a LHCb-like detector) compared to existing DY pA data used for nuclear PDF/fit (E/eight.fitted/six.fitted&E/seven.fitted/seven.fitted/two.fitted@Fermilab).

Same acceptance for pp collisions

Extremely large yields up to $x/one.fitted[plot made for pX with a Hermes-like target]

No existing measurements at RHIC (per 0.10)

$M (GeV)$ (per 0.50)

$\mu T < 5$, $p_{lab} = 115$ GeV, $2 < Y_s$ Drell-Yan, pXe@FNAL-E866

FNAL-E772

AFTER@LHC sim

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Drell-Yan

- Unique acceptance (with a LHCb-like detector) compared to existing DY \( pA \) data used for nuclear PDF fit (E866 & E772 @ Fermilab).

![Drell-Yan, pXe@ \( \sqrt{s} = 115 \) GeV, \( 2 < Y_{\mu\mu}^{\text{lab}} < 5 \), \( p_T^{\mu} > 1.2 \) GeV/c, \( L = 100 \) pb\(^{-1}\)](image-url)
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No existing measurements at RHIC
Drell-Yan performances for spin analyses [LHCb-like detector]


DY pair production on a transversely polarised target is the aim of several experiments (COMPASS, E/one.fitted/zero.fitted/three.fitted/nine.fitted, STAR, E/one.fitted/zero.fitted/two.fitted/seven.fitted).

Check the sign change in $A_{\text{DY}}$ vs $A_{\text{SIDIS}}$: hot topic in spin physics!

With a highly polarised gas target, from an exploration phase to a consolidation phase.

With a $^{3}$He target, access to the quark Sivers effect in the neutron via DY: unique!

\begin{align*}
\text{SIDIS 1 (Sivers effect)} & < 3 \\
\mu \mu & < y < 4 \\
\mu \mu & < y < 5 \\
\mu \mu & < y^2 < 9 \text{ GeV/c} \\
\mu \mu & < M^2 \text{ d}M = 1 \text{ GeV/c} = 115 \text{ GeV/s} \\
p+p & -1 \\
\text{L} & = 0.8 \\
P_{\text{eff. pol.}} & = 10 \text{ fb} \\
p+p & L = 0.8 \\
P_{\text{eff. pol.}} & = 0.25 \text{ fb} \\
\text{L} & = 0.7/3 \\
P_{\text{eff. pol.}} & = 115 \text{ GeV} \\
\end{align*}
DY pair production on a transversely polarised target is the aim of several experiment (COMPASS, E1039, STAR, E1027)
Drell-Yan performances for spin analyses

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- Check the sign change in $A_N$ DY vs SIDIS: hot topic in spin physics!

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<th>$\sqrt{s}$ (GeV)</th>
<th>$x^F$</th>
<th>$\mathcal{L}$ (cm$^{-2}$s$^{-1}$)</th>
<th>$\mathcal{P}_\text{eff}$</th>
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<td>AFTER@LHCb $p + p^\uparrow$</td>
<td>7000</td>
<td>115</td>
<td>0.05 $\pm$ 0.95</td>
<td>$1 \cdot 10^{13}$</td>
<td>80%</td>
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J.P. Lansberg (IPNO, Paris-Sud U.)

AFTER@LHC

April 4, 2017
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- With a highly polarised gas target, from an exploration phase to a consolidation phase
- With a $^3$He$^+$ target, access to the quark Sivers effect in the neutron via DY: unique!

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J.P. Lansberg (IPNO, Paris-Sud U.)
Drell-Yan performances for nuclear matter analysis

Statistical uncertainties smaller than PDF: discriminating power

LHCb

L

pp

L

pp

pA

L

pA

L

pp/

one.fitted

zero.fitted/

one.fitted

L

pA

Pb

L

pA

Pb

one.fitted/

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one.fitted

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AFTER@LHC

April 4, 2017

13 / 21
Drell-Yan performances for nuclear matter analysis

- New constraints on quark nPDF with DY in pA collisions
Drell-Yan performances for nuclear matter analysis

- New constraints on quark nPDF with DY in $pA$ collisions
- Stat. uncertainties smaller than nPDF: discriminating power

[only 1 bin out of 5 shown; global syst. : $pp$ vs $pA$ lumi.]

\[
L_{pp} = 10 \text{ fb}^{-1}; \quad L_{pPb} = 100 \text{ pb}^{-1}
\]
Open/Closed heavy flavour: kinematical coverage

\[ \mu = 100 \text{ GeV} \]

\[ 2 \leq x \leq 10 \]

\[ 1 \leq y_{\text{Lab}} \leq 5 \]

\[ m_T (\text{GeV}/c^2) \]

\[ \sqrt{s_{\text{NN}}} = 115 \text{ GeV} \]

- bottomonium, \( p_T < 15 \text{ GeV}/c \)
- charmonium, \( p_T < 18 \text{ GeV}/c \)
- D meson, \( p_T < 20 \text{ GeV}/c \)
- B meson, \( p_T < 16 \text{ GeV}/c \)
Open heavy flavour: charm

Extremely good prospects to measure charm down to zero over a wider rapidity coverage with extremely high statistical precision in pp, pA and AA collisions.

With a LHCb-like detector, the background is well under control (see below).

Looking at D Kπ gives direct access to charm–anticharm asymmetries.

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<th>D0 yield per year [per 1 GeV bin]</th>
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![Graph showing $D^0$ yield per year vs. $P_{T,D^0}$ (GeV)]

$10 \text{ fb}^{-1}$ of $pp$ collisions at $\sqrt{s}=115$ GeV
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Same yields for $D^-$
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![Graph showing $D^0$ yields per year](image)

**LHCb preliminary**

$\sqrt{s_{NN}} = 110$ GeV $pA$

$N_{D^0} = 6451 \pm 90$

$\sigma \sim 8$ MeV/$c^2$
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Longstanding debate in the QCD community: perturbative vs. non-perturbative origin
Relevant for cosmic neutrinos [not well constrained by lack of inputs]

Yield relative uncertainty due to c(x)

10 fb$^{-1}$ of pp collisions at $\sqrt{s} = 115$ GeV

Syst. : 5%, $\varepsilon > 10\%$; 2 < y $D_0$ < 3, Br$_{K\pi} = 3.93\%

Coloured curves: yield uncertainty from IC central c(x) with scale uncertainty.
AFTER at LHC projected uncertainty

D. Kikola et al. arXiv:/one.fitted/seven.fitted/zero.fitted/two.fitted/.zero.fitted/one.fitted/five.fitted/four.fitted/six.fitted

Can also be collected with a transversely polarised target [Never measured]
Gives access to the tri-gluon correlation and the gluon Sivers effect [related to $L_g$]

Differences in $A_{D^0}$ and $A_{\bar{D}^0}$ gives access to C-odd correlators [No other facility can directly measure this; PHENIX via charged muons]

Precision at the percent level with AFTER@LHC

[ Beware of the unconventional definition of $x_F$ at RHIC which does not correspond to $x$ in the fixed target mode]
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- This huge data sample over a wide kinematical coverage gives a unique handle on the charm content in the proton at high $x$ [Only 1 bin shown]
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Quarkonium Projections

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\[ \Upsilon : 200 \text{ events at} \ P_T \simeq 12 \text{ GeV} \]

\[ J/\psi: \text{ reach cut by the detector acceptance} \]

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- Full background simulations show very good prospects in all systems

$J/\psi$: $10^4$ events at
$P_T \approx 12$ GeV
$\Upsilon$: 200 events at
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Quarkonium Projections 2

\[ \text{forallquarkonia}(J \sim \psi, \psi, \Upsilon, \Upsilon^\dagger, \chi_c, b, \eta_c) \text{can be measured} \]

D. Kikola et al. /one.fitted/seven.fitted/two.fitted./zero.fitted/one.fitted/five.fitted/four.fitted/six.fitted

[Sofar, only \( J \sim \psi \) by PHENIX with large uncertainties]

Also access on polarised neutron (He) at the percent level!

\[ \begin{array}{c} 0.3 \\ -0.25 \\ -0.2 \\ -0.15 \\ -0.1 \\ -0.05 \\ -0 \\ 0.05 \\ 0.1 \\ \end{array} \]

\[ \begin{array}{c} \psi \\ J/ N \\ A \end{array} \]

\[ \begin{array}{c} 0.2 \\ -0.15 \\ -0.1 \\ -0.05 \\ -0 \\ 0.05 \\ 0.1 \\ 0.15 \end{array} \]

\[ = 200 \text{ GeV} \] (Phys. Rev. D 82, 112008 (2010))

\[ \text{Stat. unc. projection} = 115 \text{ GeV} \]

\[ p+p^{-1} = 10.00 \text{ fb} \]

\[ \text{pp} \]

\[ L = 0.8 \]

\[ P_{\text{eff. pol.}} = 0.8 \]

\[ \begin{array}{c} 0.4 \\ -0.35 \\ -0.3 \\ -0.25 \\ -0.2 \\ -0.15 \\ -0.1 \\ -0.05 \\ -0 \\ 0.05 \\ 0.1 \\ \end{array} \]

\[ \begin{array}{c} N \\ A \\ 0.6 \\ -0.4 \\ -0.2 \\ -0 \\ 0.2 \\ 0.4 \\ 0.6 \end{array} \]

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[4 bins with equal yields]
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- $A_N$ for all quarkonia ($J/\psi$, $\psi'$, $\Upsilon(nS)$, $\chi_{c,b}$ & $\eta_c$) can be measured

D. Kikola et al. 1702.01546 [hep-ex]

[So far, only $J/\psi$ by PHENIX with large uncertainties]
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  [So far, only $J/\psi$ by PHENIX with large uncertainties]

\begin{align*}
\text{Stat. unc. projection} & = 115 \text{ GeV} \\
\text{eff. pol. } P & = 0.8 \\
\text{Eff. pol. } P & = 0.6
\end{align*}
Quarkonium Projections 2

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- Completely new perspectives to study the gluon Sivers effect [and beyond \( \mathcal{L}_g \)]

\[ \begin{align*}
A_N^{J/\psi} & = \frac{0.2}{0.5} \text{ at } \sqrt{s} = 200 \text{ GeV} \quad \text{(Phys. Rev. D 82, 112008 (2010))} \\
A_N^{\Upsilon(1S)} & = \frac{0.4}{1} \text{ at } \sqrt{s} = 115 \text{ GeV} \quad \text{(Stat. unc. projection)}
\end{align*} \]
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- Completely new perspectives to study the gluong Sivers effect \cite{Lansberg2017}
  [and beyond $\rightarrow L_g$]
- Di-$J/\psi$ allow one to study the $k_T$ dependence of the gluong Sivers function for the very first time!
UPC in the fixed target mode and $J/\psi$ production

JPL, L. Massacrier, L. Szymanowski, J. Wagner, in progress
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- $\gamma_p^{\text{beam}} \approx 7450 \ (E_p = 7000 \text{ GeV})$
- $\gamma_{\text{Pb beam}} \approx 2940 \ (E_{\text{Pb}} = 2760 \text{ GeV})$
- $E_{\gamma}^{\text{max}} \approx \gamma_{\text{lab}}^{\text{beam}} \times 30 \text{ MeV} \ (1/(R_{\text{Pb}} + R_p) \approx 30 \text{ MeV})$
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In the LHCb acceptance (muon cuts):

- $\sigma [Pb \to^{1-\gamma} (\text{Pb}) J/\psi (p) \times \text{Br}(J/\psi \to \mu\mu)]$ via 1-photon exchanges: 16 nb
- $\sigma [p p \to^{1-\gamma} (p) J/\psi (p) \times \text{Br}(J/\psi \to \mu\mu)]$ via 1-photon exchanges: 34 pb
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  - $\sigma[pp^{1-\gamma} \rightarrow (p)J/\psi(p) \times \text{Br}(J/\psi \rightarrow \mu\mu)]$ via 1-photon exchanges : 34pb
  - 1600 dimuon events with the Pb beam [which we know for sure to be the $\gamma$ emitter]
  - 340 000 dimuon events with the $p$ beam [each $p$ can emit; possible $\Omega\overline{\Omega}$P contributions]
Conclusions

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

For the update of the Strategy for Particle Physics, CERN has triggered the creation of a working group for the “Physics Beyond Colliders” whose mandate is to explore the opportunities offered by the CERN accelerator complex to address some of today's outstanding questions in particle physics through experiments complementary to high-energy colliders and other initiatives in the world.

The kick-off workshop took place last September at CERN after LHC was one of the proposed ideas (one talk). Very recent outcome: creation of two fitted WGs – after LHC considered as a core project.

Accelerator [to study possible implementation of the project at CERN] and Physics [to study the physics case [...]] and optimized detectors including siting options.

Creation of five fitted Accelerator sub-WGs: Beam Dump Facility, EDM ring, Conventional beams, LHC Fixed Target, Technology. Thus, one uniquely devoted to LHC Fixed-Target whose goal is a CDR putting together UA nine fitted, LHC Collimation, after...

The physics of after LHC is also included in the physics sub-WG for QCD [the other is for BSM].

Two fitted after LHC representatives named (C.Hadjidakis for the Accelerator WG; myself for the physics one) + contact persons for ALICE (A.Dainese) and for LHCb (M.Ferro-Luzzi).

In parallel, we pursue our effort to finalize the Expression of Interest. Inputs are still welcome until June.
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Part III

Backup slides
Further quarkonium projections

Hint from $\Upsilon$ data at RHIC
Strongly limited in terms of statistics

A quest for the gluon EMC effect with $J/\psi$ statistical uncertainties are not even visible

A quest for the gluon EMC effect for bottom (onium)


One could access to $\eta_c$ production in $pA$ collisions for the first time

High stat. quarkonium polarization in $pA$ and $AA$ collisions
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J.P. Lansberg (IPNO, Paris-Sud U.)
Further readings

**Heavy-Ion Physics**


- **Lepton-pair production in ultraperipheral collisions at AFTER@LHC**

Spin physics


Further readings

Hadron structure

- **Double quarkonium production at high Feynman-x**

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

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

- **ηc 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 Ξcc at a fixed-target experiment at the LHC**
Further readings

Feasibility study and technical ideas

- **Heavy-ion Physics at a Fixed-Target Experiment Using the LHC Proton and Lead Beams (AFTER@LHC): Feasibility Studies for Quarkonium and Drell-Yan Production**

- **Feasibility Studies for Single Transverse-Spin Asymmetry Measurements at a Fixed-Target Experiment Using the LHC Proton and Lead Beams (AFTER@LHC)**

- **Feasibility studies for quarkonium production at a fixed-target experiment using the LHC proton and lead beams (AFTER@LHC)**
  by L. Massacrier, B. Trzeciak, F. Fleuret, C. Hadjidakis, D. Kikola, J.P.Lansberg, and H.S. Shao

- **A Gas Target Internal to the LHC for the Study of pp Single-Spin Asymmetries and Heavy Ion Collisions**

- **Quarkonium production and proposal of the new experiments on fixed target at LHC**
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: $\Delta p/p = 0.5\%$
- Muon identification efficiency: 98%

Cuts at the single muon level
- $2 < \eta_\mu < 5$
- $p_T\mu > 0.7$ GeV

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