AFTER@LHC: A fixed-target programme at the LHC for heavy-ion, hadron, spin and astroparticle physics

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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 at the LHC

The fixed-target mode with TeV beams: why and what for?

Four fitted decisive features:

1. Accessing the high-x frontier

2. Achieving high luminosities, varying the atomic mass of the target at will, polarising the target.

Three fitted physics cases:

1. High-x gluon, antiquark and heavy-quark content in the nucleon & nucleus
2. Transverse dynamics and spin of gluons inside (un)polarised nucleons
3. 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!

Note: all (past) colliders with $E_{p}$C GeV have had a fixed-target program (Tevatron, HERA, SPS, RHIC).

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- achieving high luminosities,
- varying the atomic mass of the target almost at will,
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Fixed-target collisions at the LHC: main kinematical features

7 TeV proton beam on a fixed target
c.m.s. energy: Rapidity shift:
Boost:

Such allow, for the first time, for systematic studies of W boson, bottomonia, pT spectra, associated production,..., in the fixed-target mode

Effect of boost: [particularly relevant for high energy beams]

LHC and the ALICE muon arm become backward detectors [particularly relevant for high energy beams]

With the reduced acceptance for physics grows and nearly covers half of the backward region for most probes [particularly relevant for high energy beams]

Allows for backward physics up to high x target (particularly relevant for p-p with large x)
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**Energy range**

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Such options allow, for the first time, for systematic studies of $W$ boson, bottomonia, $p_T$ spectra, associated production, ... in the fixed-target mode.

Effect of boost: [particularly relevant for high energy beams] the LHC and the ALICE muon arm become backward detectors. With the reduced $s$, their acceptance for physics grows and nearly covers half of the backward region for most probes. Allows for backward physics up to high $x_T$ target (uncharted for proton-nucleus; most relevant for p-p with large $x_T$).
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Possible implementations

Internal gas target (seen next slide) can be installed in one of the existing LHC caverns and coupled to existing experiments currently validated by the LHCb collaboration via an luminosity monitor (SMOG) on the high LHC particle current.

Internal wire target [used by HERA-B at the nine fitted two fitted zero fitted GeV HERA p beam and by STAR at RHIC].

Beam line extracted by a bent crystal [see S. Radaelli's talk].

The most ambitious solution [civil engineering] provides a new facility with seven fitted TeV proton beam the LHC beam halo is recycled.

Beams split by a bent crystal intermediate option which reduces the civil engineering [see W. Scandale's & A. Stocchi's talk]. It might be coupled to an existing experiment similar fluxes.

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

- **Internal gas target (see next slide)**
  - can be installed in one of the existing LHC caverns, and coupled to existing experiments
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September 7, 2016
Internal gas targets

SMOG(-like) system

- Designed for precise luminosity determination
- Noblegas directly injected in the VELO
- $p(\text{He, Ne, Ar}), \text{Pb(Ne, Ar)}$ tested: completely parasitic [up to one week, so far]
- New pressure monitor to be installed

HERMES(-like) system

- No specific pumping system: limit in the gas injection [pressure and duration]
- No possibility to use polarised gases
- Gas flows in the beam pipe; pressure profile not optimised
- K and Xe maybe only at end of a run
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- **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

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AFTER@LHC

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![LHCb preliminary 2015 pNe data](image)

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![SMOG System Diagram](image)

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The simulations showed in Part III are based on this set-up coupled to a LHCb like detector
High-$x$ frontier

Advance our understanding of the high-$x$ gluon, antiquark and heavy-quark content in the nucleon & nucleus
High-\( x \) frontier

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- Very large PDF uncertainties for \( x \gtrsim 0.5 \).

[could be crucial to characterise possible BSM discoveries]
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- 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

Best to take data at large $x$ and small scale, than at large scale: advantage of low $E$; provided HT are under control.
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- 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

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3D mapping of the parton momentum

Advance our understanding dynamics and spin of gluons and quarks inside (un)polarised nucleons
3D mapping of the parton momentum

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- Possible missing contribution to the proton spin: Orbital Angular Momentum $L_{g,q}$:

$$\frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L_g + L_q$$

[First hint by COMPASS that $L_g \neq 0$]
3D mapping of the parton momentum

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  \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + \mathcal{L}_{g} + \mathcal{L}_{q}
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- Test of the QCD factorisation framework

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

  [beyond the DY $A_N$ sign change]
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  [First hint by COMPASS that $L_{g} \neq 0$]
- Test of the QCD factorisation framework
- Determination of the linearly polarised gluons in unpolarised protons
  [once measured, allows for spin physics without polarised proton, e.g. at the LHC]

3D mapping of the parton momentum

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Heavy-ion collisions from one colliding nucleus rest frame

Heavy-ion collisions towards large rapidities
Heavy-ion collisions towards large rapidities

- A complete set of heavy-flavour studies between SPS and RHIC energies
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J.P. Lansberg (IPNO, Paris-Sud U.)
Heavy-ion collisions towards large rapidities

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- Test the factorisation of cold nuclear effects from $p + A$ to $A + B$ collisions
Part III

A selection of projected performances

- Azimuthal anisotropies [Heavy-Ion, Spin]
- Photon related observables [High-x, Spin, Heavy-Ion]
- $W$ boson [High-x, Spin]
- Antiproton and related x-section measurements for astroparticle MC tuning [High-x]
- C-even quarkonia [High-x, Spin, Heavy-Ion]
- Associated production [Spin, Heavy-Ion]
- Ultra-peripheral collisions [Spin, High-x]
Drell-Yan simulation

Unique acceptance (with a LHCb-like detector) compared to existing DY pA data used for nuclear PDF/fitted/six.fitted & seven.fitted/two.fitted@Fermilab. Same acceptance for pp collisions. Extremely large yields up to x/two.fitted/one.fitted[plot made for pXe with a Hermes-like target]. Combinatorial background well under control. Combinatorial background easily subtracted using the large like-sign yields [although accessible by other means]. One could re/fit with mixing event techniques [needed for PbAs systems]. No existing measurements at RHIC (per 0.10)

![Graph](image_url)

Counts per 100 MeV/c

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After@LHC

J.P. Lansberg (IPNO, Paris-Sud U.)
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\begin{itemize}
  \item Drell-Yan, $pXe$, $\sqrt{s} = 115$ GeV, $2 < Y_{\mu\mu}^{lab} < 5$, $\mu_T > 1.2$ GeV/c, $L = 100$ pb$^{-1}$
  \item $p+Xe$, $\sqrt{s} = 115$ GeV, $L = 100$ pb$^{-1}$, $p_T^{\nu} > 1.2$ GeV/c, $2 < Y_{\mu\mu} < 3$
  \item Comb - MB bkg

\end{itemize}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{Drell-Yan_simulation}
\caption{Drell-Yan simulation for $pXe$, $\sqrt{s} = 115$ GeV, $L = 100$ pb$^{-1}$, $2 < Y_{\mu\mu}^{lab} < 5$, $\mu_T > 1.2$ GeV/c, $L = 100$ pb$^{-1}$, $p_T^{\nu} > 1.2$ GeV/c, $2 < Y_{\mu\mu} < 3$.}
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![Graph showing Drell-Yan simulation results](image-url)
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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/three.fitted/nine.fitted). [See O. Denisov's talk]

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

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

Novel constraints on the quark nuclear PDF with DY in $pA$ collisions. Statistical uncertainties smaller than PDF: discriminating power [only one fitted bin out of five fitted shown; global system: $pp$ vs $pA$ luminosity].

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

AFTER@LHC September 7, 2016 13 / 19
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Open heavy flavour: charm

Extremely good prospects to measure charm down to zero.

Total section over a wider rapidity coverage with extremely high statistical precision in pp, pA, and AA collisions.

With a LHCb-liked detector, the background is well under control. See below.

Looking at $D K \pi$ gives direct access to charm–anticharm asymmetries.

1e+06

$D_0$ yield per year [per 1 GeV bin]

$P_T, D_0$ (GeV)

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

$\langle \varepsilon \rangle = 10\%$; $Br_{K\pi}=3.93\%$

Same yields for $D_0^-$

$2<y_{lab} < 3$

$3< y_{lab} < 4$

$4< y_{lab} < 5$

$K$ invariant mass (MeV/c)

1750

1800

1850

1900

1950

2000

2 entries / 8 MeV/c

LHCb preliminary 2015 pNe data
Open heavy flavour: charm

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![Graph showing $D^0$ yield per year vs $P_T,D^0$ (GeV)]

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LHCb preliminary 2015 pNe data

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

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)

$|P|_{T,D}^0$ (GeV)

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

$\epsilon$ = 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

Differences in $A_{D/zero.fitted}^N$ and $A_{\bar{D}/zero.fitted}^N$ gives access to $C_{-odd}$ correlators [No other facility can measure this]

Precision at the percent level [GeV/c] $T_p$

Stat. unc. projection $q$ [PRD 72 (2005)] $g$ [JHEP 09 (2016)] $g$ [pos. bound] $-1 = 10 \text{ fb}^{-1}$ pp at $L = 115$ GeV $s_{p+p} = 2.25$, CMS $y = 0.03 \pm 0.6$ $P_{\text{eff. pol.}}$ SIDIS1

As for $AA$ collisions, nuclear modification factors vs $p_T$, $y$, centrality as well as azimuthal anisotropies ($v_{two.fitted}$) can be of course measured [not time to cover them]
Open charm projections

- This huge data sample over a wide kinematical coverage gives a unique handle on the charm content in the proton at high $x$
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J.P. Lansberg (IPNO, Paris-Sud U.)

AFTER@LHC

September 7, 2016

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Syst. : 5%, $\langle \varepsilon \rangle = 10\%$, $2<y_D<3$, Br$_{K\pi}=3.93\%$

Coloured curves: yield uncert. from IC
AFTER at LHC projected uncertainty

$A_{N}^{D^0}$ vs. $p_T$ at CMS $\sqrt{s}=115$ GeV, $y_{eff.\ pol.}=0.6 \pm 0.03$

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Our aim is to measure a complete set of heavy-flavours to use them as tools [gluon luminometers (TMDs, PDFs, nPDFs), QGP effects]
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- In PbA collisions, one can repeat the celebrated $\Upsilon(nS)$ CMS analysis in a new energy domain

![Graph for PbXe, $L = 7$ nb$^{-1}$, $p_T^\mu > 0.7$ GeV/c, $2 < Y_{\mu\mu} < 5$]

![Graph for PbXe, $L = 7$ nb$^{-1}$, $3 < Y_{\mu\mu} < 5$, $p_T^\mu > 0.7$ GeV/c]
forall quarkonia (J ~ ψ, ψœ, χc, Υ^nS, χb, ηc) can be measured [So far, only ~ψ by PHENIX with large uncertainties].

Completely new perspectives to study the gluon Sivers effect and beyond.

\( \psi \rightarrow J/\psi \rightarrow B \)

\( R = 0.7, 0.8, 0.9, 1, 1.1, 1.2, 1.3, 1.4 \)

EPS09 central

EPS09 min./max. shadowing

EPS09 min./max. EMC effect

\( s = 115 \text{ GeV} \)
Quarkonium Projections 2

- $A_N$ for all quarkonia ($J/\psi$, $\psi'$, $\chi_c$, $\Upsilon(nS)$, $\chi_b$ & $\eta_c$) can be measured

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- pA: constrain the gluon antishadowing and EMC effects; $pD$: $g_n(x) \equiv g_p(x)$
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- Completely new perspectives to study the gluon Sivers effect
  [and beyond $\rightarrow L_g$]

- $pA$: constrain the gluon antishadowing and EMC effects; $pD$: $g_n(x) \neq g_p(x)$

- One could access $\eta_c$ production in $pA$ collisions for the first time
A_N for all quarkonia (J/ψ, ψ', χ_c, Υ(nS), χ_b & η_c) can be measured
[So far, only J/ψ by PHENIX with large uncertainties]
Completeness new perspectives to study the gluon Sivers effect [and beyond → L_g]

pA: constrain the gluon antishadowing and EMC effects; pD : g_n(x) ≠ g_p(x)
One could access η_c production in pA collisions for the first time
High stat. → quarkonium polarisation in pA and AA collisions [→ production/suppression mechanisms]
Part IV

Conclusion and outlooks
Conclusions

**Three main themes push for a fixed-target program at the LHC**

[without interfering with the other experiments]
Conclusions

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

- The high $x$ frontier: new probes of the confinement and connections with astroparticles
Conclusions

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

As a slow extraction with a bent crystal

An internal gas target inspired from SMOG@LHC/Hermes/H-jet@RHIC,...

An expression of interest to be submitted to the LHCC is being written
Conclusions

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  [without interfering with the other experiments]
- **The high $x$ 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
Conclusions

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

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

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AFTER@LHC

September 7, 2016
Conclusions

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Part V

Backup slides
LHCb acceptance as a function of the colliding modes

\[ y_{\text{beam}} = \ln \left( \frac{\sqrt{s}}{m_{\psi}} \right) \]

Notas: similar for the ALICE spectrometer
Further readings

**Heavy-Ion Physics**


- Lepton-pair production in ultraperipheral collisions at AFTER@LHC By J.P. Lansberg, L. Szymanowski, J. Wagner. JHEP 1509 (2015) 087

Further readings

Spin physics


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)**

- **η_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 Ξ_{cc} at a fixed-target experiment at the LHC**
Further readings

Feasibility study and technical ideas


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