Community Support for
A Fixed-Target Programme for the LHC

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Abstract

This contribution aims at promoting the ground-breaking physics programme accessible with the multi-TeV LHC proton and ion beams used in the fixed-target mode. It can be realised in a parasitic mode for the LHC complex using existing detectors like those of the LHCb and ALICE collaborations or new dedicated systems during the LHC lifetime. It contains a brief description of the different technical implementations which are currently under investigation as well as the basic performances offered by the use of the ALICE and LHCb detectors in the fixed-target mode. In short, the multi-TeV LHC beams allow for the most energetic fixed-target experiment ever performed opening the way for unique studies of the nucleon and nuclear structure at high x, of the spin content of the nucleon and of the phases of the nuclear matter from a new rapidity viewpoint at seldom explored energies.

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1 Executive Summary

Fixed-target (FT) experiments have brought essential contributions to particle and nuclear physics. They have led to particle discoveries ($\Omega^-(sss)$, J/ψ, Υ,...) as well as evidence for the novel dynamics of quarks and gluons in heavy-ion collisions. In providing a unique access to the high Feynman x (denoted x_F) domain and in offering versatile options for polarised and unpolarised proton and nuclear targets, they have also led to the observation of unexpected QCD phenomena: the anomalous suppression of J/ψ in nucleus-nucleus collisions, unexpectedly large single- and double-spin asymmetries, higher-twist effects at high x_F, colour transparency, etc.

In the case of the multi-TeV LHC beams, the FT mode offers several unique assets [1–9] compared to the collider mode which are particularly relevant in the context of high-energy physics:

- **Accessibility** with the LHCb and ALICE detectors to the **far backward region** –thanks to the boost between the colliding-nucleon centre-of-mass system (cms) and the laboratory system. This region remains completely uncharted with hard reactions. An acceptance of $0 \le \eta_{\rm (lab)} \le 5$, combined with high luminosities, essentially allows one to measure any probe down to the very end of the backward phase space.
- **Target polarisation** offering uncountable opportunities to measure **single-spin asymmetries (SSA)** –at high $x^\uparrow$, where they are the largest. These have been the object of a growing attention in the recent years at RHIC, CERN and Fermilab. This includes polarised neutron studies with $^3\mathrm{He}^\uparrow$. Let us stress that the LHC beams cannot be polarised; this is thus the only option to make spin-physics measurements with the LHC complex.
- **Target-species versatility**, with the possibility to change them in a reduced amount of time for short runs to study the atomic-number dependence of nuclear effects. This also comprises deuteron and ^{3}He target allowing for unique isospin studies.
- **Energy range**. The cms energy per nucleon-nucleon collision ($\sqrt{s_{NN}}$) is identical for all 7 TeV proton- and 2.76 TeV lead-induced collisions, namely **115 GeV for *pp*, *pd*, *pA* systems** and **72 GeV for Pb*p*, Pb*d*, Pb*A* systems**[1]. For lead-induced collisions, this is half way between top SPS and RHIC energies. Having the same collision energies for various systems is particularly expedient for nuclear-modification measurements.
- **Outstanding luminosity** thanks to the high density of the target with an extracted beam or to the high current of the LHC beam, at no cost for the LHC collider-mode experiments. Both an internal gas target or a bent-crystal-extracted beam from the beam halo allow for yearly luminosities competitive or above those of similar machines, in particular RHIC, in the ballpark of the LHC and Tevatron collider luminosities. In case the ALICE and LHCb detectors are used, the luminosity limitation simply comes for the data-acquisition performance of the detectors.

It is instructive to recall that one of the scientific activities highlighted in the European Strategy for Particle Physics adopted by the CERN Council in 2006 directly concerned fixed-target experiments:

> 9. A variety of important research lines are at the interface between particle and nuclear physics requiring dedicated experiments; *Council will seek to work with NuPECC in areas of mutual interest, and maintain the capability to perform fixed target experiments at CERN.*

In this context, by this contribution, our community would like to emphasise that the potential offered by the use of the LHC beams –proton and heavy-ion– to perform a FT experiment should not be overlooked and that all the initiatives towards a full FT programme for the LHC should be prioritised given their high possible outcome at an extremely reduced cost. For instance, we would like to commend the recent publication in Physical Review Letters of the first LHCb analysis of pHe collisions in the FT mode [10] using the SMOG system.

Fully considering the aforementioned advantages of the FT mode compared to the collider mode, we have identified **three main topics for a strong physics case motivating a complete FT programme for the LHC**, denoted FTP4LHC in what follows. This programme should be understood with the use of one or more detectors, in particular that of the ALICE and LHCb collaborations. A new dedicated system probably would be for after the period covered by the European strategy update. The 3 main research axes of such a programme are:

- **High-momentum-fraction (x) frontiers** in nucleons and nuclei with a specific emphasis on the gluon and heavy-quark distributions, the transition between the inclusive and exclusive regimes of QCD and the implications for astroparticle physics including Ultra-High Energy (UHE) cosmic neutrinos.
- **Spin content of the nucleons** with a focus on transverse SSAs (STSAs) and azimuthal asymmetries from correlations between the spin and the transverse momenta of the partons. A global analysis of hadron-hadron reactions (to be studied within the FTP4LHC) and lepton-hadron reactions (to be studied at an EIC) is necessary to probe time-reversal symmetry of QCD.
- Ultra-relativistic **heavy-ion collisions** (HIC) in a **new rapidity and energy domain** with heavy-flavour (HF) observables (including quarkonia) as well as with identified light hadrons through a rapidity scan down to the target rapidity. The aim is to study the nature of the QCD phase transition to deconfined partons and to provide a global picture of HIC from SPS to LHC collider energies.

This document is based on recently published scientific papers, as well as oral contributions presented during international conferences and workshops, and in the framework of the CERN Physics Beyond Colliders (PBC) working group of which 2 sub-working groups were dedicated to the potential and the feasibility of FT experiments with the LHC beams. In the next section, we review implementation and detector aspects. In the third section, we present the scope of the 3 research axes along with selected flagship measurements. It is then complemented by a brief discussion of additional ideas beyond these 3 subjects.

[1] $\sqrt{s_{NN}}$ for lighter ion beams remains on the order of 70 GeV.

2 Implementation and detectors

Several technological options are currently under investigation to perform dedicated FT experiments at the LHC. One can indeed initiate collisions of the LHC beams with nucleons or nuclei at rest:

- by letting the full LHC beam go through a (possibly polarised) gas target in the LHC beam pipe,
- by extracting halo particles by means of a bent-crystal deflector onto a target positioned inside the beam pipe or outside the beam pipe with a dedicated beam line,
- or by placing a wire/foil target intercepting the faint beam halo in the beam pipe.

The detailed descriptions of such implementations can be found in [9] and are also reviewed by the CERN PBC WG (see [11]). Tab. 1 qualitatively summarises the different solutions with regards to a number of decisional criteria and the reach in the 3 physics axes presented in the following section (see also [9] for the precise meaning of the stars).

Let us emphasise that the vast majority of the physics opportunities offered by the FT mode can be covered with the LHCb and ALICE detectors if they are coupled with the most suitable implementation. As explained in the box on the right, the rapidity boost typical of the FT mode strongly modifies their physical acceptance. It is both increased[2] and shifted to a region ($y_{\rm cms} < 0$) which is poorly known.

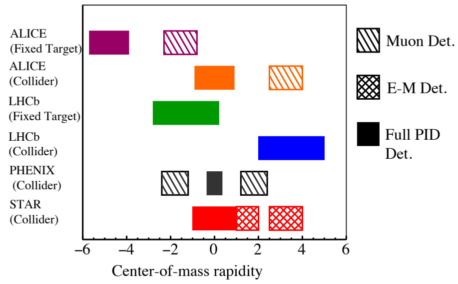
The impressive particle tracking and identification of the LHCb and ALICE detectors make them meet most of the FTP4LHC requirements. In this context, let us stress that first investigations indicate that the installation of a dedicated target system within or by these experiments is very well feasible. The first LHCb results [10, 12], with their SMOG luminosity system [13] used as internal gaseous target, further illustrate how well conventional (forward) collider detectors can perform in the FT mode, as well as with versatile targets[3]. However, it also highlights how crucial are the possible duration of the runs and the collected luminosities. So far, LHCb only collected hundreds of J/ψ or D^0 for instance –very far from the billions expected with dedicated systems– and currently no option for pp data exists –which is critical for many high-x studies (see later).

The FT implementation in ALICE and LHCb is actively studied. Dedicated documents were prepared as submission to the ESG (see also [14] for LHCb and the PBC documents). LHCb plans [15] a SMOG upgrade, called SMOG2, consisting in the installation of a storage cell. This may allow for H injection, which is crucial as aforementioned. Polarised gas injection in a storage cell is promoted by the LHCSpin group [16, 17]. Within ALICE, a solution with an internal solid target and a bent-crystal set-up is studied [18]. Other options (for example a gas-jet target in ALICE using the RHIC H-jet polarimeter [19]) should be envisioned and are part of the work packages of EU Horizon FP Integrated Initiative STRONG-2020.

A double-bent crystal solution was also proposed to study Magnetic and Electric Dipole Moments (M/E DM) of heavy baryons. The LHCb interaction point [20, 21] was identified as a suitable location. A main challenge is the limited coverage of LHCb in the very forward region, requiring a secondary crystal with a large bending exceeding 15 mrad. R&D is ongoing to assess the feasibility of the secondary crystal along other challenges (compatibility with the machine, operation mode, maximum reachable p flux, absorber design downstream the detector [11], etc.).

From forward to backward detectors

7 TeV protons on FT release a cms energy of 114.6 GeV ($\sqrt{2Em}$). For 2.76 TeV Pb beams, $\sqrt{s_{NN}}$ =72 GeV. The boost between the cms and the laboratory is respectively $\gamma^{\rm lab.}_{\rm cms} = \sqrt{s}/(2m) \simeq 60$ and 38, thus resulting in a rapidity shift, Δy, as large as $\mathrm{atanh}\,\beta^{\rm lab.}_{\rm cms} \simeq 4.8(4.3)$. The nominal acceptance of the LHCb and ALICE detectors are then shifted to negative $y_{\rm cms}$ down to rapidities very close to the target one in the case of the ALICE Central Barrel (CB). Physics wise, these detectors used in the FT mode probe backward physics which is of particular relevance for asymmetric collisions: proton-nucleus, nucleus (A) - nucleus (B) and proton-polarised proton. The figure below illustrates this situation with a comparison with the RHIC detectors operating in the same energy range.



Characteristics	Internal gas target SMOG	Internal gas target Gas Jet	Internal gas target Storage Cell	Internal solid target with beam halo	Beam splitting	Beam extraction
Run duration	★	★★	★★	★	★★	★★★
Parasiticity	★★	★★	★★	★	★★	★★★
Integrated luminosity	★	★★★	★★★	★	★★	★★★
Absolute luminosity determination	★	★★	★★	★	★★	★★★
Target versatility	★	★★	★★	★	★★	★★★
(Effective) target polarisation	-	★★★	★★	-	- / ★	★
Use of existing experiment	★★★	★★	★	★★	★★	-
Civil engineering or R&D	★★★★	★★★	★★	★★	★★	★
Cost	★★★	★★	★★	★★★	★★	★
Implementation time	★★★	★★	★★	★★★	★★	★
High x	★	★★★	★★★★	★	★★	★★★★
Spin Physics	-	★★★	★★★	-	- / ★★	★★★
Heavy-Ion	★	★★★	★★★	★★	★★	★★★★

Table 1: Qualitative comparison of various solutions for a FT program at the LHC. The "-" denotes an option currently considered as infeasible, an increasing number of stars points to an, a priori, better solution for a given objective. We refer to [9] for details.

[2] In the FT mode, LHCb covers 50% of the Υ-production phase space. This is far from being the case in the collider mode.

[3] So far, data have already been collected for pNe, pHe, pAr and PbAr collisions.

Target			ALICE		LHCb	
			p beam	Pb beam	p beam	Pb beam
			$\int \mathcal{L}$	$\int \mathcal{L}$	$\int \mathcal{L}$	$\int \mathcal{L}$
Internal gas target	Gas-Jet	$H^{\uparrow}$	43 pb^{-1}	0.56 nb^{-1}	43 pb^{-1}	0.56 nb^{-1}
		H_2	260 pb^{-1}	28 nb^{-1}	10 fb^{-1}	118 nb^{-1}
		$D^{\uparrow}$	43 pb^{-1}	0.56 nb^{-1}	43 pb^{-1}	0.56 nb^{-1}
		$^3He^{\uparrow}$	85 pb^{-1}	20 nb^{-1}	3.4 fb^{-1}	47 nb^{-1}
		Xe	7.7 pb^{-1}	8.1 nb^{-1}	310 pb^{-1}	23 nb^{-1}
	Storage Cell	$H^{\uparrow}$	260 pb^{-1}	28 nb^{-1}	9.2 fb^{-1}	118 nb^{-1}
		H_2	260 pb^{-1}	28 nb^{-1}	10 fb^{-1}	118 nb^{-1}
		$D^{\uparrow}$	140 pb^{-1}	22 nb^{-1}	5.6 fb^{-1}	88 nb^{-1}
		$^3He^{\uparrow}$	85 pb^{-1}	20 nb^{-1}	13 fb^{-1}	83 nb^{-1}
		Xe	7.7 pb^{-1}	8.1 nb^{-1}	310 pb^{-1}	30 nb^{-1}
Internal wired target with beam halo		Ti (500 μm)	14 pb^{-1}	0.28 nb^{-1}	14 pb^{-1}	0.28 nb^{-1}
Beam splitting	Polarised target	$NH_3^{\uparrow}$	0.26 fb^{-1}	14 nb^{-1}	0.72 fb^{-1}	14 nb^{-1}
	Unpolarised solid target	Ti (515 μm)	14 pb^{-1}	–	–	–
		Ti (5 mm)	–	2.8 nb^{-1}	140 pb^{-1}	2.8 nb^{-1}

Table 2: Summary table of the achievable integrated luminosities with the ALICE and LHCb detectors in the FT mode, accounting for the data-taking-rate capabilities. We refer to [9] for details.

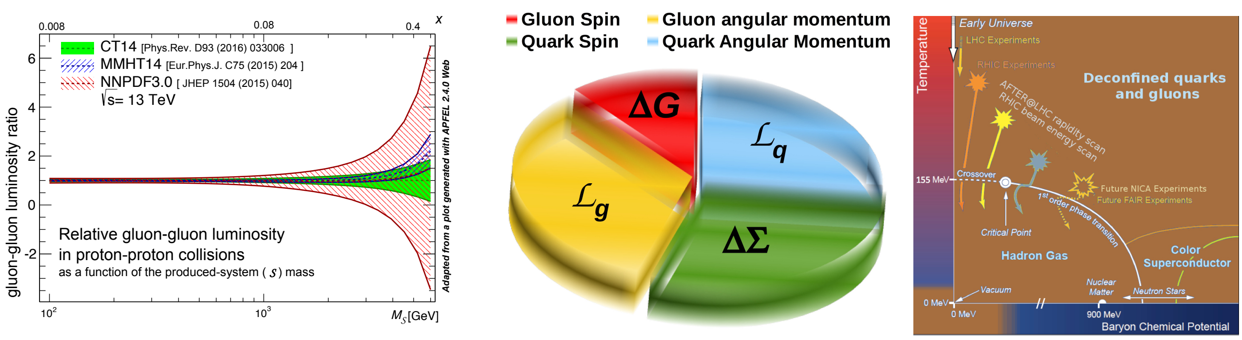
Tab. 2 summarises the achievable yearly luminosities with different implementations in both ALICE and LHCb accounting for detector constraints and limits on the particle beam used over a fill (see [9]). pp luminosities as high as 10 fb^{-1} and 250 pb^{-1} can be achieved with LHCb and ALICE. For pA, extremely high values on the order of 10÷100 pb^{-1} are easily reachable, whereas PbA values (for the yearly one-month Pb run) range between 0.3 and 30 nb^{-1}. This is highly competitive compared to the LHC collider values, in particular keeping in mind that the LHC beam is in some sense recycled when the FT mode is on. The physics case outlined below is based on these numbers considering that several years of data taking may be necessary for the different colliding systems to be studied.

For the double-crystal mode, a W target of $\approx$ 2 cm thickness hit by a proton flux of $\approx 10^7$ protons/s is the upper limit for a parallel detector operation not affecting LHCb data taking of pp collisions.

3 The physics case

This section outlines the scope of the physics reach for the 3 research axes and shows some highlight plots demonstrating the uniqueness of the FTP4LHC:

- **High-momentum-fraction (*x*) frontiers** in nucleons and nuclei with a specific emphasis on the gluon and heavy-quarks and a strong implication for astroparticle physics, including UHE cosmic neutrinos. Precisely accessing the high-x region, barely experimentally explored up to now, will have a great impact on several fronts, like improving the accuracy of the gluon parton distribution function (see Fig. 1a) thanks to modern theory tools. Quarkonia [22] and, in general, HF [23] can be highly beneficial towards this objective.
- **Spin content of the nucleons** with a focus on STSAs and azimuthal asymmetries generated by parton-hadron momentum-spin correlations. The FTP4LHC spin-physics case will provide unique measurements of the 3-dimensional parton dynamics, i.e., their contribution to the nucleon spin through their Orbital Angular Momentum (OAM) (see Fig. 1b). To test QCD time-reversal symmetries encapsulated in STSA sign changes, it is mandatory to collect both hadron- and lepton-induced data and to confront them.
- Ultra-relativistic **heavy-ion collisions** in a **new rapidity and energy domain** using novel HF observables and identified light hadrons via a rapidity scan down to the target rapidity (see Fig. 1c). This energy range, between those of SPS and RHIC, will help clarify the picture of the quarkonium sequential suppression, whereas the rapidity range will directly complement the phase diagram exploration of the RHIC Beam-Energy Scan (BES).



(a) (b) (c)

Figure 1: 3 of the main goals of the FTP4LHC: (a) gluons at high x, (b) nucleon-spin decomposition and (c) nuclear-matter phase diagram.

3.1 High-x frontier for particles and astroparticles

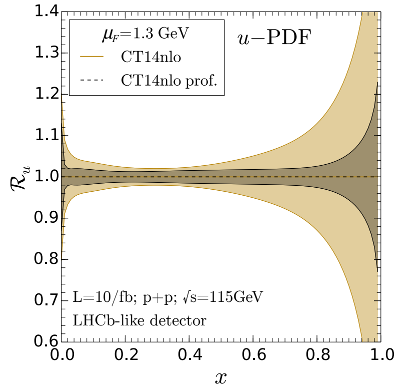
The FTP4LHC high-x axis addresses long-standing puzzles such as the origin of the nuclear EMC effect in nuclei or a possible non-perturbative intrinsic charm or beauty content in the proton at high x. Collecting such FT data will allow one to drastically reduce the uncertainty of the nuclear gluon distribution; this is imperative to use hard probes of the Quark-Gluon Plasma (QGP). A similar reduction in the proton case will directly benefit searches of new heavy particles at hadron colliders (LHC, HE-LHC, FCC-hh). With an extensive coverage of the backward region ($y_{\rm cms} < 0$) corresponding to high x in the target, FTP4LHC is probably the best for such physics with hadron beams, complementing the scope of the US EIC.

Fig. 2a clearly displays the impact of pp Drell-Yan (DY) pair data, taken in the FT mode using LHCb, on the proton u-quark PDF. We see a remarkable uncertainty reduction at high x; a similar effect is also observed for the nuclear valence PDFs for the pXe case [9]. As said above, a better determination of high-x PDFs can be crucial for future searches for new heavy particles. Moreover, improved measurements of the d/u PDF ratio for $x \to 1$ can tell which picture is valid among an SU(6) symmetric one where $d/u \to 1/2$, the dominance of a quark-scalar diquark where $d/u \to 0$, quark-hadron duality where $d/u \to 0.42$ or a simple perturbative QCD one where $d/u \to 1/5$. Imposing direct constraints on PDFs at such high x are challenging but they will certainly shed new light on the transition between the inclusive and exclusive regimes of QCD. For instance, the observation of HT corrections would signal correlations between valence quarks and thus give us information on their confinement.

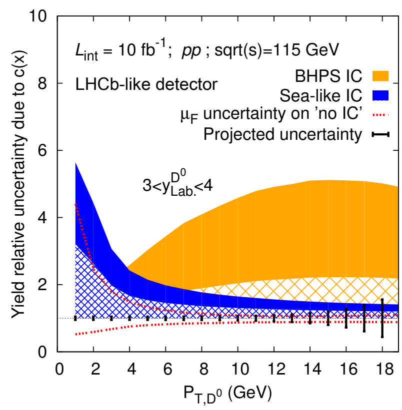
Due to the large boost between the laboratory and cms frames, the LHC FT mode is the ideal set-up to uncover a non-perturbative excess of charm at high x, referred to as intrinsic charm (IC). Fig. 2b clearly illustrates this with expected deviations –as large as a factor of 5– in inclusive-D^0-meson production. The projected uncertainties, even up to $P_T \simeq 15$ GeV, are sufficient to pin down IC or to constrain it by up to an order of magnitude. This is truly important to compute atmospheric-neutrino fluxes, which are the main background for the observation of e.g. the cosmic neutrinos in the PeV range seen by IceCube [24].

The FTP4LHC also comprises unique studies of the high-x nuclear gluon PDF –the least known nuclear PDF (nPDF). Let us highlight HF production, shown in Fig. 2c for $B^\pm$ production in pXe collisions with LHCb. A significant reduction of the nPDF uncertainty in the EMC region is expected to be seen, similar to that observed in the shadowing region in the collider mode [25]. In such data, final-state effects may come into play. Yet, the study of the mass and P_T dependence of HF production should allow one to separate them out from the initial-state nPDF ones. The antishadowing flavour dependence can also be studied [26]. Finally, off-shell W could be detected with luminosities of 10 fb^{-1}, providing data at high x and reasonably large scales in a poorly known region with limited HT contamination.

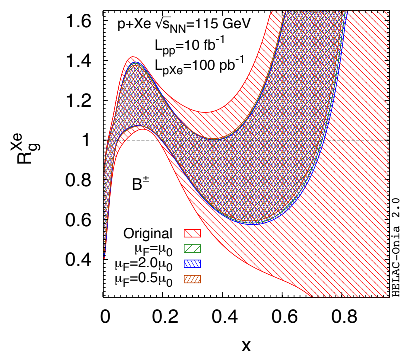
Predicting the cosmic $\bar{p}$ spectrum requires knowing their production cross section for different nuclear channels and kinematics [27, 28]. The first LHCb FT data [10] showed the discriminating power between current cross-section parametrisations [28]. For $E_{\bar{p}} > 10$ GeV, theory still exhibits 20% uncertainties for the $\bar{p}$ flux which increase fast at lower $E_{\bar{p}}$ [28]. Studies with ALICE of slow $\bar{p}$ (below few GeV) will thus complement the LHCb ones. Indeed, cosmic $\bar{p}$ data are extremely precise [29] at small $E_{\bar{p}}$ and will be even more so with the GAPS experiment [30]. Collecting positrons and gamma-ray cross sections [31] is also of interest and is possible with ALICE and LHCb in the FT mode. Let us add that the ALICE CB can measure large $E_{\bar{p}}$, close to the beam energy, in the inverse kinematics when the slow $\bar{p}$ emitted by the target is seen from the projectile rest frame as an ultra-fast one. Moreover, light-nuclei-production cross sections are also needed for galactic-transport-model calibration [32]. These can in principle be measured by the ALICE CB.



(a) u-quark PDF uncertainty projection after including DY-pair production pseudo-data. The CT14 PDFs [33] were used and the projections were done using the profiling method [34, 35].



(b) Impact of the charm PDF uncertainty on the D^0 yield vs. p_T compared to projected uncertainties. The orange and blue zones correspond to yields computed with IC PDFs [36, 37] The dashed-red curves indicate the μ_F uncertainty on the “no-IC” yield.



(c) Relative uncertainties of the gluon in Xe (R_g^{Xe}) at $\mu_F = 2$ GeV in the nCTEQ15 nPDFs [38] before (red) and after reweighting using $B^\pm$ pp and pXe pseudo-data.

Figure 2: Representative projections of the high-x FTP4LHC.

3.2 Spin and 3D nucleon structure

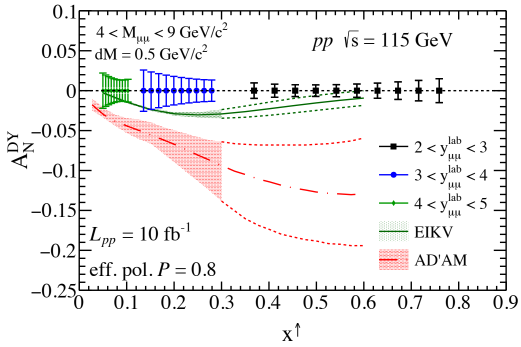
The spin part of the FTP4LHC bears on two pillars: STSA measurements with a polarised target and azimuthal-modulation studies. Both allow one to investigate the tri-dimensional (3D) complexity of partons confined in hadrons, and help unravel how quarks and gluons are bound in a spin-1/2 nucleon. In particular, DY STSA measurements will contribute to the worldwide effort towards the verification of the Sivers-asymmetry [39] sign change [40, 41] between DY and semi-inclusive deep-inelastic scattering (SIDIS). Corresponding extractions in the gluon sector would simply be ground-breaking owing to their expected precision. In addition, looking for azimuthal modulations in DY and pair-particle production will provide novel ways to study the correlations between the parton momentum and their own spin.

Fig. 3a shows two theoretical predictions of the DY STSA (A_N) compared to the projected statistical precision using the LHCb in the FT mode. This can clearly put strict constraints on the quark Sivers effect and the related 3-parton correlation functions [42, 43], help discriminate among different approaches, and test the time-reversal symmetry of QCD, realised through the relevant initial/final state interactions for DY and SIDIS. We note how crucial it is to be able to access the rapidity region $2 < y_{\rm lab} < 3$ to access the high $x^{\uparrow}$ region [7]. In addition, as shown in Fig. 3b, the projected statistical precision for several other asymmetries in DY production is expected to be as good as a few percent. They would for the first time offer the opportunity to constrain even less known transverse-momentum distributions, such as h_1^q, $h_1^{\perp q}$ and $h_{1T}^{\perp q}$, which encapsulate more information on the quark-hadron momentum-spin correlations, and thus indirectly on the quark orbital angular momentum (OAM) (see [9] for more details).

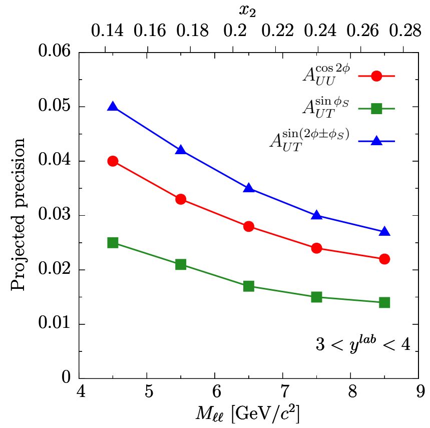
Besides, a major strength of the LHC FT mode is the large production rates for open heavy-flavour mesons and quarkonia (roughly 10^6 Υ and 10^9 J/ψ for a single year of data taking [6, 44]). These processes are very useful probes to precisely access and constrain the gluon Sivers effect, still essentially unknown [45]. For instance, Fig. 3c shows the projected statistical precision with ALICE in the FT mode for J/ψ A_N, compared to the existing measurements [46, 47] and theoretical predictions [48].

Ultraperipheral collisions in the FT mode [51] offer access to photoproduction in hadron-hadron interactions [52]. Such exclusive reactions can help study the 3D “tomography” in position space of hadrons in terms of generalised parton distributions (GPDs) [53–57], directly related to the parton OAM. It remains to be studied whether additional detectors will be required to trigger on these exclusive reactions. In particular, Timelike Compton Scattering [58], via lepton-pair photoproduction [51] and J/ψ photoproduction [59], might provide additional information on GPDs.

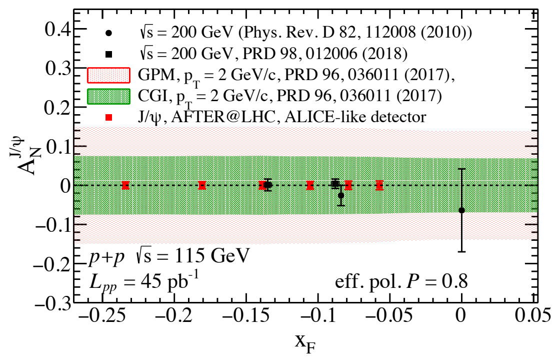
Finally, at the LHC in the FT mode one can also access the distributions of longitudinally polarised (anti)quarks inside a nucleon, which are not well known (see e.g. [60]), through the measurement of the longitudinal spin transfer D_{LL} from a longitudinal polarised target to Λ or $\bar{\Lambda}$ hyperons, for which only limited experimental results exist [61–63]. Specifically, the understanding of the distribution of polarised strange and anti-strange quark distributions, and their possible asymmetry, is a very intriguing open question



(a) Two predictions (AD'AM [49] and EIKV [50]) of the DY A_N at LHCb in the FT mode, compared to the projected precision of the measurement [7]. Bands are filled in the region where the fits use existing SIDIS data and hollow where they are extrapolations.



(b) Projected statistical uncertainty on asymmetries in DY production with LHCb (the rapidity is integrated over, as well as the mass in bins of dM = 1 GeV/c^2).



(c) Projected precision for J/ψ A_N compared to existing measurements [46, 47] using the ALICE Muon Spectrometer.

Figure 3: Representative projections of the spin FTP4LHC.

in hadronic physics. Moreover, similar measurements can be carried out for the transverse spin transfer D_{TT} to hyperons, with a similar precision to that for D_{LL}, giving access to the integrated quark transversity (also called the nucleon tensor charge). This quantity is a useful input in the search for new physics and is now studied on the lattice [64]. In general, any additional data at high x can reduce the uncertainties in the determination of (un)polarised parton distributions, so the FTP4LHC can provide unmatched opportunities for such studies.

3.3 Heavy-ion physics

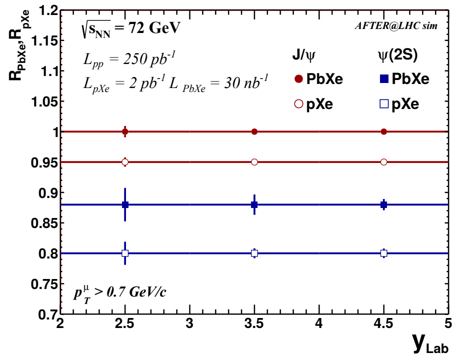
Despite the considerable progress achieved in the last decades to understand the hadronic-matter properties at extreme conditions, key aspects remain challenging [65]. The clarification of crucial properties of the QCD phase structure requires a facility to study HIC spanning energy and rapidity regimes not covered by the existing AA, pA and pp programmes. This is the scope of the FTP4LHC HIC research axis, in which we propose to measure, at an energy between RHIC and SPS:
(i) The suppression of the entire bottomonium family.
(ii) A complete set of charm observables down to low P_T (e.g. ψ, χ_c, D, $D+D$, $\psi+D$ and their ratios), complemented by bottom production observables.
(iii) The DY process in pA, Pbp and PbA collisions to check –for the first time– the collinear factorisation in HIC.
(iv) Particle yields and azimuthal asymmetries over the entire negative $y_{\rm cms}$ to perform a *rapidity scan* complementary to the *beam-energy scan* of RHIC whose primary goals are to probe the temperature dependence of the shear viscosity and look for the QCD critical point.

As for charmonia, the precision data will be sufficient to greatly contribute to the resolution of the long-standing charmonium-suppression puzzle [22,23,66]. Fig. 4a shows the projected statistical precision of the J/ψ and $\psi(2S)$ nuclear modification factor vs $y_{\rm lab.}$ in PbXe ($R_{\rm PbXe}$) and pXe ($R_{p\rm Xe}$) collisions in the FT mode. It clearly shows that the per-cent level precision is within reach for the LHCb detector. Similar performances are expected with the ALICE muon arm owing to the background reduction from the absorber. Such measurements along with χ_c and open HF ones should allow one to uncover the charmonium sequential pattern predicted by Matsui and Satz more than 30 years ago [67]. Moreover, the 3 $\Upsilon(nS)$ states will be measurable [6, 8, 9], complementing the CMS LHC collider studies. These hinted at a sequential suppression, whose interpretation however remains unclear with the recent observation of a similar relative $\Upsilon(nS)$ suppression in pPb collisions [23]. The FTP4LHC will address this issue.

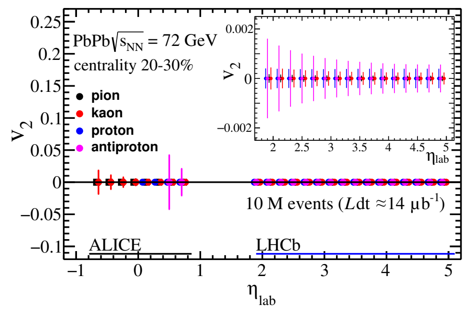
The study of QCD collective effects is another domain where the FTP4LHC can have a considerable impact. Fig. 4b displays the projected statistical uncertainties for the elliptic flow (v_2) measurements for identified hadrons using as low as 10 million 20-30% central PbPb events, i.e., for an integrated luminosity of 14/μb with the ALICE CB and LHCb detectors. Altogether, they could cover as much as 6 units of rapidity! This clearly indicates the reach for v_2 (and v_n in fact [9]) precision studies over a very broad rapidity range. These will then yield to an accurate determination of the temperature dependence of the shear viscosity to entropy ratio η/s complementing existing v_n studies.

Fig. 4c shows how a *rapidity scan* at 72 GeV can complement the RHIC *beam-energy scan* from 62.4 GeV down to 7.7 GeV for $y_{\rm cms}$ close to zero, and help us better understand the interplay between the baryon chemical potential μ_B, the temperature T and the rapidity. In fact, recent calculations show [68, 69] that, in PbPb collisions in the LHC FT mode, μ_B does vary with rapidity in the range accessible by ALICE and LHCb. This μ_B range covers a large fraction of that accessible at the RHIC BES program [70]. Correlation and fluctuation measurements of conserved quantities in small rapidity bins provide new ways to search for the QCD critical point and to probe the nature of the phase transition to confined partons. The large rapidity coverage of the LHC FT mode, combined with the excellent particle identification capabilities of ALICE and LHCb, makes it a perfect place for such a rapidity scan.

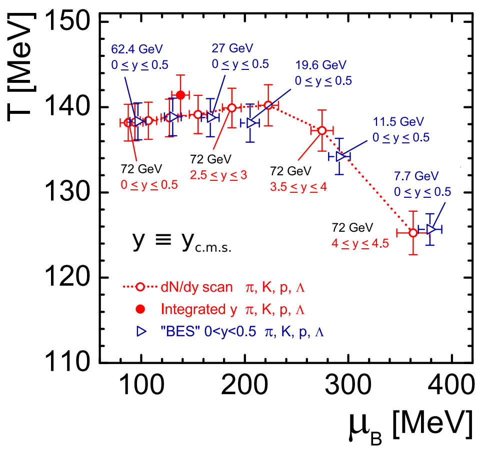
Finally, the LHC in the FT mode offers a unique playground to probe initial-state effects on quarks via DY measurements in different collision species. This will allow one to check whether such initial-state effects in AA collisions, usually embedded in nuclear PDF defined within the collinear factorisation, can be extrapolated from pA and eA collision data. One indeed usually assumes that they linearly factorise, although some effects [71] may break this linearity. DY measurements in AA collisions will be accessible in the backward region thanks to a smaller background compared to the collider mode [8].



(a) Projected statistical precision of $R_{\rm PbXe}$ and $R_{p\rm Xe}$ vs $y_{\rm lab.}$ for $\psi(nS)$ using LHCb in the FT mode [8, 9].



(b) Projected statistical precision for elliptic flow measurements of various light hadrons vs $\eta_{\rm lab.}$ with the ALICE CB and the LHCb detectors used in the FT mode [9].



(c) Illustration of the similarity between a beam-energy scan at RHIC and a rapidity scan in the LHC FT mode in terms of values of T and μ_B probed [68].

Figure 4: Representative projections of the heavy-ion FTP4LHC.

3.4 Going further

3.4.1 Magnetic and Electric Dipole Moments

Until now, MDM and EDM of charm and beauty baryons have been experimentally elusive. They play a special role in QCD since the heavy-quark mass brings simplifications due to heavy-quark symmetry. As such, direct MDM measurements of heavy baryons at few per-cent level would add new constraints for low-energy QCD calculations and will help discriminate between some model predictions [72–74]. The possibility to measure the MDM and EDM of heavy and strange baryons at the LHC has been explored in recent years [75–83]. The idea relies on a bent crystal to extract protons from the LHC beam halo. These protons then hit a dense target and produce charged baryons that will then be channelled in bent crystals positioned in front of the detector. The intense electric field between the crystal atomic planes induces a sizeable spin precession during the lifetime of the particle. The EDM, along with the MDM, can be determined by analysing the angular distribution of the decay particles.

About 2.4×10^{14} p on target could be reached with three years of data taking after the installation during an LHC technical stop during Run 3, either with two weeks per year of dedicated detector running at 10^{8} p/s or with parallel detector operation at 10^{7} p/s. This would lead to MDM and EDM sensitivities of roughly $10^{-4} \div 10^{-1}$ and $10^{-18} \div 10^{-13}$, respectively [80]. Extending the detector coverage down to 10 mrad along with an increase of the proton flux during LHC Runs 4 and 5, either at LHCb or at a dedicated experiment, would improve sensitivity by about one order of magnitude, challenging the physics of and beyond the SM.

3.4.2 Opportunities with secondary beams

If a dedicated beam line fed by bent-crystal extraction were to be built, TeV secondary beams of π, K could be created by impinging 7 TeV p beam on a primary target. The πN DY COMPASS program [84] has lately re-emphasised the importance of pion-beam facilities to measure the Boer-Mulders functions. Meson beams are particularly interesting owing to their valence antiquark. Beyond meson beams, e^+/e^- tertiary beams with an energy up to 4 TeV could be considered [85] with an efficiency up to 10^{-5}. The creation of hundred-GeV neutrino beam is another option to be explored despite the likely significant civil engineering. It would allow for ν DIS studies at small x (see [86]).

3.4.3 Diffraction studies and forward detectors

As mentioned above, the Pb beam can be used as an effective photon source to study photoproduction process. It can also be used to study the diffractive dissociation of the proton into three jets and tests of colour transparency [87].

Most of the above physics discussion focused on the physics reach with detector covering up to $\eta_{\rm lab.} \sim 5$. In the case of pH, pA and PbH collisions, it is possible to instrument the more forward region with roman pots to strengthen the physics case for exclusive and diffractive studies. This may allow one for instance to improve the tagging of UPCs by looking at forward neutron emissions or to make sure that the colliding particles remained intact after the scattering. The corresponding feasibility studies remain to be done. In the case of LHCb, the HeRSChel detector may offer new physics opportunities yet unexplored.

3.4.4 Beyond unity

The domain $x > 1$ in a nuclear target, which can be accessed in the most backward region, can probe specific aspects of the nuclear wavefunction such as the hidden-color excitations of the deuteron [88,89] effectively corresponding to six-quark Fock states. With liquid or gaseous deuteron targets, one can probe these in inclusive reactions requiring high x (≥ 1) and by studying the diffractive dissociation of the deuteron in its rapidity domain [90] in Pbd collisions. In Pbd UPCs, one could also measure the deuteron GPDs [91].

Gluon and heavy-quark distributions are essentially unknown for $x \geq 1$ (see [92] for a recent theory study for the deuteron). Their study for deuterium or helium targets is clearly challenging but would give us new means to probe $n > 3$ partonic Fock states in light nuclei and thus the strong interaction in these systems.

3.4.5 Multiply-heavy baryons

Similar to the *leading-particle* effect for light quarks, the possibility for IC in the proton can lead to an excess of charmonium production at large x. Along the same lines, the kinematics of the FT mode coupled with large luminosities and very good detector PID, may lead to the detections of very heavy baryons such as Ω_{ccc}, Ω_{bbb}, Ξ^{+}_{ccb}, ..., as well as single and double heavy-quark meson production such as B_c in diffractive and non-diffractive channels. Such studies may be crucial to clear up the long-standing debate about the production mechanism of double-charm baryons and their nature: the FT-based SELEX collaboration found what is considered to be the Ξ^{+}_{cc} [93,94], which however was neither seen in e^+e^- reactions by Babar [95] nor in the collider mode by LHCb [96] and the mass splitting between the Ξ^{+}_{cc} and the Ξ^{++}_{cc} recently discovered by LHCb [97] challenges many models.

3.4.6 Beyond the LHC

The FT mode with future UHE hadron machines like the HE-LHC, the SppC and the FCC-hh has been discussed in the context of high luminosity studies of $W^{\pm}$, Z^0 and H^0 production at cms energies from 176 to 307 GeV [98, 99]. Correspondingly the boost between the laboratory and the cms frame ranges between 94 and 163 with a rapidity shift between 5.2 and 5.8. This energy range corresponds to that of RHIC and would certainly allow one to pursue QCD studies initiated at RHIC in the coming decades. It is thus important not to reproduce the current situation of the LHC for which no FT program was planned, neither during the machine nor the detector designs.

3.4.7 Rapidity target studies

Accessing the entire backward hemisphere (in the cms system) at the LHC in FT mode, together with precise DY measurements, would allow one to study the target fracture functions [100]. Measuring recoil particles may also allow to measure missing masses to select (quasi-)elastic scatterings. In addition, the good PID in the target region will allow one to study the limiting fragmentation (or extended longitudinal scaling) and cumulative effects, both examples of enhancements of particle production on nuclear targets at large x, which extend into regions which are kinematically forbidden in scattering on free nucleons.

4 Conclusions

Unlike the Tevatron collider at Fermilab and the HERA collider at DESY (with proton beams in the TeV range), no fixed-target (FT) programme was planned for the LHC. In view of the forthcoming update of the European strategy for particle physics and of the fruitful discussions that took place within the Physics Beyond Colliders working group in the last two years, this document promotes an ambitious FT programme for the LHC (FTP4LHC) and gathers the community in support of it.

The physics opportunities offered by the LHC FT mode are compiled under the appellation "FTP4LHC", supporting all the experimental proposals for a FT configuration submitted for the strategy update and the possible implementations relying on different detectors (e.g., LHCb, ALICE or a new system). The FTP4LHC will significantly extend the physics capabilities of the LHC complex and critically complement the reach of other successful hadronic collider and FT programmes, such as the COMPASS experiment at the CERN SPS and the FT experiments at Fermilab.

It will also add on to the achievements of RHIC and JLAB and support the new physics directions explored by a future US EIC [101] and by LHeC [102]. Let us cite the global efforts to test QCD-based predictions of spin-asymmetry-sign changes between specific hadron- and lepton-induced reactions. This stems from the unique features [1, 9] of the FT mode compared to the collider mode used with the most energetic proton and nuclear beam ever: the accessibility of the backward-rapidity regions, the target polarisation, the target-species versatility, the energy range, and the outstanding luminosity.

The physics case presented in this document is equally relevant for both the multi-TeV proton and ion LHC beams. It relies on extensive theoretical works [44, 45, 49, 51, 68, 69, 92, 100, 100, 103–111] and projection studies [5–9, 112, 113] which have been based on the LHCb and ALICE performances. It clearly indicates that unprecedented precision measurements in the backward hemisphere of pp, pA and AA collisions are within reach. The projections cover the nucleon and nucleus structure at high x, the nucleon-spin decomposition in terms of the partonic degrees of freedom, cross sections relevant for galactic cosmic rays and UHECR astroparticle physics and the properties of the nuclear matter at extreme conditions, such as those resulting from ultra-relativistic heavy-ion collisions. Overall, a complete FT program can certainly and fruitfully be carried out at the LHC, with a great impact on the European and world-wide science in the near future.

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