A Very Forward Hadron Spectrometer for the LHC. (Expression of Interest: Snowmass EF05,EF06)

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Abstract

We are developing a proposal to measure at the LHC the spectra high Feynman $x_F = p_z/p_{beam}$ charged hadrons, light nuclei and antinuclei ($\bar{d}$, $^3\bar{H}$, $^3\bar{H}e$), as well as decaying neutrals such as K^0, Λ^0, and charm: D^0 and Λ_c^+. Charged particles with $1 \lesssim p_z \lesssim 3$ TeV can be measured in low luminosity pp and light-ion runs behind an enlarged beam pipe ($R \sim$ 1 m, $L \sim 20$ m) with 96 m $< z <$ 116 m. It will also be possible to measure interactions ($\sigma_{inel}, N_{ch}, dn/d\eta$) of multi-TeV hadrons on hydrogen, carbon 0r other targets.

The focus of physics at hadron colliders, from the CERN $Sp\bar{p}S$ collider to the LHC, has been on physics in the central reqion, with pseudorapidity $\eta \lesssim 5$, appropriate for ElectroWeak physics and perturbative QCD. In inelastic p+p collisions at the LHC most produced hadrons have transverse momenta $p_T \lesssim 1$ GeV/c and much larger longitudinal momenta; those with $\eta \gtrsim 7$ are outside the coverage of all the central detectors[1].

The only LHC measurements of very forward particles are of neutral hadrons (mainly π^0 and neutrons) at $\theta \sim 0°$ in zero degree calorimeters, and elastic and diffractively scattered protons with Feynman $x_F \gtrsim 0.9$ in Roman pots. Charged hadron spectra in this x_F, p_T region have not been measured above $\sqrt{s} = 62.5$ GeV at the CERN ISR; the LHC at 14 TeV is 224 $\times$ higher. This is 50,000 $\times$ higher in fixed target equivalent energy as appropriate for cosmic ray showers. The only hadron collider observation of charm with $x_F > 0.1$ was of the Λ_c^+ at the ISR. High x_F charm production may be much higher than expected due to an intrinsic charm component in the proton. Precise measurements of hadron and $\mu^\pm$ spectra in the TeV region will not only allow the models to be improved, but may lead to fresh insights into QCD at the low-Q^2 frontier.

There are many reasons why it is important to measure the spectra of particles produced at the LHC in the very forward direction with momenta from hundreds of GeV to several TeV. Many models for this region have been developed, primarily to understand cosmic ray showers with values of $\sqrt{s}$ extending well above the LHC. When these models are used to predict meson production at high x_F they differ by factors $\gtrsim$10. Understanding very high energy cosmic rays depends on knowledge of forward hadron production. There is a puzzling excess of muons. Distinguishing high energy neutrinos from the cosmos (as in ICECUBE) from those produced by cosmic rays would also benefit.

Future measurements of TeV neutrino interactions depend for the flux normalization on knowing the spectra of $\pi^\pm, K^\pm$ and charmed hadrons; these have uncertainties of more than an order of

[1]Pseudorapidity η is not an appropriate variable at very small angles, rather x_F and p_T should be used.

magnitude. Forward muons can be measured in the spectrometer and those from sources other than $\pi^{\pm}$ and $K^{\pm}$ decays measured by subtraction, since those spectra will be known.

Estimates of Standard Model contibutions to a possible dark matter annihilation signal from the galactic center depend on the production of light antinuclei ($\bar{p}, \bar{d}, \bar{t}, \bar{He}^3$) which have only been measured at the LHC in the central region, primarily by ALICE.

With ion beams in the LHC a forward spectrometer can search for short lived (even $\tau \lesssim 1$ ns) nuclear fragments, including strangelets with abnormal charge:mass ratio.

We describe a spectrometer which could be a new subsystem for an existing experiment. In principle it could be an independent experiment, but that could lose the benefits of combining the forward and central data, and have other disadvantages.

The charged particles discussed in this EoI have remained in the LHC beam pipe until the exit of the new (for Run 4) superconducting 35 Tm beam separation dipole D1 at $z = 82$ m in IR1 (ATLAS region) and IR5 (CMS region). (IR3 and IR7 will have a different configuration.) The quadrupoles Q1 − Q3 and the dipole D1 are here used as spectrometer magnets, D1 deflecting charged particles to the left and right of the outgoing beam.

As presently planned the straight beam pipe (containing both incoming and outgoing beams) has a radius increasing from R = 7.5 cm at the exit of D1 to R = 12.5 cm at the entrance to the TAXN. Positive particles with $x_F \gtrsim 0.4$ are still in the beam pipe as it enters the TAXN. Most of those with lower momenta *would* hit the sides of the planned beam pipe at glancing angles, but this can be avoided by increasing the aperture of that pipe to $R = 40$ - 50 cm, terminated with a thin perpendicular metal window at $z = 116$ m, there making a transition to an R = 12.5 cm pipe entering the TAXN absorber at $z = 127$ m. The effect of the change in the pipe diameter on the beams may be mitigated by an internal conical wire grid, for example.

The main set of detectors are behind the thin steel window between $z = 116$ m and 126 m, with tracking, transition radiation detectors, calorimetry and muon chambers in a magnetised iron toroid. The detecttors need only cover the left and right quadrants, see Fig.1, but the enlarged beam pipe should be circular as prefered by LHC considerations and the possibility of searching for new long-lived particles, LLPs, the subject of a different Snowmass EoI[3].

Fig. 1 shows that the spectrometer described here has acceptance for $D^0 \to K^{\pm}\pi^{\mp}$ and $\Lambda_c^+ \to p\, K^-\pi^+$; detecting them requires excellent momentum resolution and $\pi^{\pm}, K^{\pm}$, p discrimination.

From the exit of D1 to the spectrometer there is only vacuum and no magnetic field, providing a long lever arm for precise track measurement. For particles coming from the primary collision, whose location also in z will be known from the central event, the momenta will be well measured[2]. Backgrounds from beam-pipe interactions need to be studied.

Cherenkov counters at not practical at such high momenta, but transition radiation detectors, TRD, are being developed that should be suitable[1]. TRDs use a large number of interfaces between materials that have different plasma frequencies resulting in the emission of X-rays with a yield growing like $\gamma = E/m$ before saturating, and are typically used to distinguish $e^{\pm}$ from hadrons. We plan to develop a suitable system, for a range $\gamma = 10^3$ (1 TeV protons) to $\gamma = 2.5 \times 10^4$ (3.5 TeV pions). A Snowmass EoI to the Instrumentation Frontier [2] addresses TRD development for TeV hadron identification for this and other future projects.

Between the TRD and the calorimeter it would be possible to insert thin targets (e.g. of carbon and polyethylene) followed by pixel detectors to make measurements of σ_{inel}, n_{ch} and $dN/d\eta$ for identified TeV hadrons on H and C. If necessary extra space can be provided for this at the expense of calorimeter length (e.g.).

The fluxes of primary particles in this spectrometer are expected to be less than one per pp interaction, by DPMJET+FLUKA calculations. However even at low luminosity with no pile-up, high statistics data can be collected in runs of order 100 hours, even for light antinuclei and charm. It is also important for the cosmic ray frontier to have data with ion beams, preferably p + O and O + O runs. Any pile-up background could dilute charm signals, e.g. with $K^{\pm}$ and $\pi^{\mp}$ from different interactions. With a single interaction in the bunch crossing the central detectors can be read out to study full event structures with leading particles, including low mass diffraction to $p\pi^+\pi^-, n\pi^+$ (in combination with a zero degree calorimeter detecting a neutron).

The beam crossing angle and the quadrupole fields distort the x, y distribution of the particles at $z = 116$ m, as seen Fig.1 (vertical crossing), but most of the UP+DOWN quadrants are not

[2] A 5 TeV D^0 has a mean decay length of $c.\tau = 33$ cm; this may be an asset or a liability.

populated by either charged particles or direct neutrals[3].

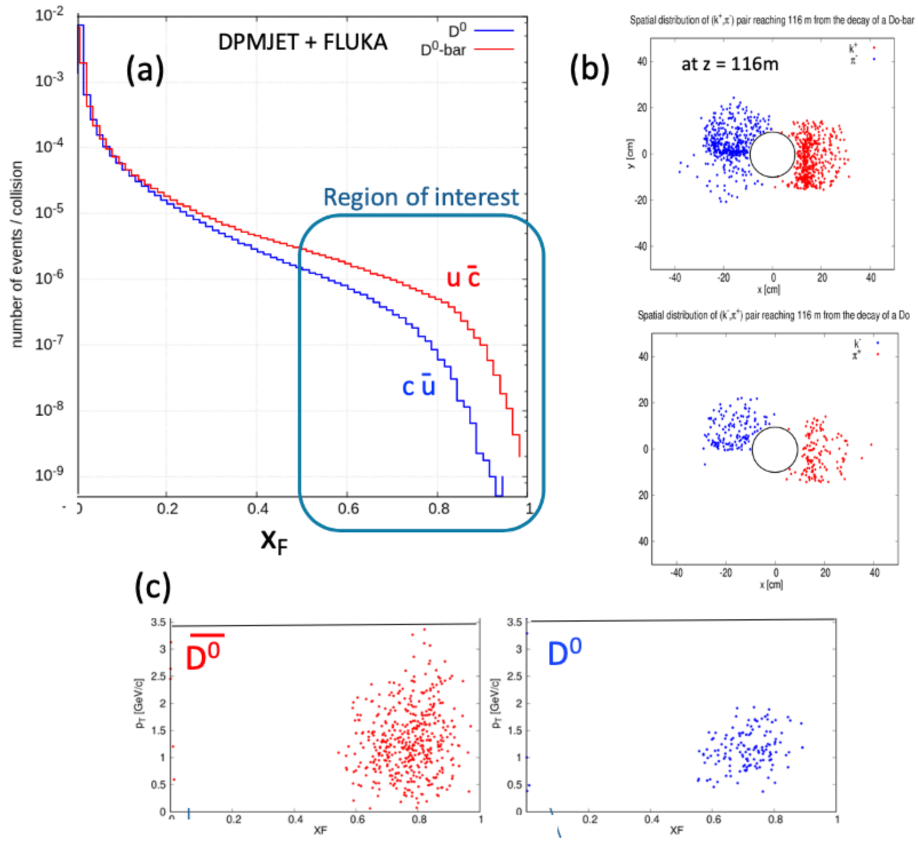

Figure 1: (a) Predictions by DPMJET+FLUKA of D^0 and $\bar{D}^0$ production vs. Feynman x_F. (b) Distribution in (x, y) of K and π from D^0 and $\bar{D}^0$ decays at $z = 116$ m. (c) Distributions in p_T and x_F of accepted D^0 and $\bar{D}^0$.

We plan to develop these ideas into a Snowmass White Paper by April 2021. A design study is needed, possibly using "clones" of upgrade detectors (but with an area only $\lesssim 0.5$ m^2) together with a novel TRD, and simulations need to be done. Such a spectrometer would enable a broad physics program in a largely unexplored region of phase space, impacting QCD, neutrino studies at the LHC, dark matter in the Galaxy, and more. We invite interested experimenters and theorists to participate in developing this idea. We thank CERN LHC staff F. Cerutti, V. Baglin, M. Sabaté-Gilarte for invaluable calculations (including FLUKA) and discussions.

References

[1] Development of Transition Radiation Detectors for hadron identification at TeV energy scale, N. Belyaev *et al.*, J.Phys.Conf.Ser 1390 (2019) 1, 012126 (Contribution to ICPPA 2018).

[2] C.Rembser *et al.*, Snowmass Instrumention Frontier EoI for TRD development.

[3] A Long-Lived Particle and Dark Matter Search at the LHC, D.Cerci *et al.* LoI to Snowmass EF08, EF09 and EF10.

[3] The UP+DOWN quadrants are ideal for searching for penetrating long-lived particles, the subject of a different Snowmass EoI.