PHYSICS OF pO COLLISIONS AT THE LHC WITH PROTON AND NEUTRON TAGGING*

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A short run of proton–oxygen (pO) collisions is planned at the Large Hadron Collider at CERN to improve the modeling of air showers, which are described using hadronic Monte Carlo simulations. The very forward proton and neutron detectors introduced by the ATLAS and CMS experiments could provide a unique opportunity to study elastic and diffractive interactions in pO collisions for the first time at center-of-mass energies above the TeV scale. In these proceedings, we will present the impact of proton and neutron tagging on the measurement of the diffractive components and discuss the perspectives of measuring decay products of oxygen ions after dissociation.

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1. Introduction

Oxygen ions are planned to be injected and collide at the Large Hadron Collider (LHC) for the first time during LHC Run 3, with a duration of a few days and include both oxygen–oxygen (OO) and proton–oxygen (pO) collisions [1]. The primary goal of the pO run is to provide inputs for modeling high-energy cosmic ray protons interacting with the atmospheric nuclei. These measurements are crucial to improving the accuracy of air-shower simulations, which rely on hadronic interaction models at energies well beyond those accessible in fixed-targeted experiments.

The physics program of the OO and pO runs was outlined during a dedicated workshop and summarized in [2], and is of particular interest to the LHCb and LHCf experiments. The latter is aimed to measure

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neutral particles, such as photons and neutrons, produced almost collinearly with the proton beam axis. Meanwhile, LHCb is aimed at the study of charged-particle production in the forward rapidity region, which is crucial to understanding the development of cosmic-ray showers.

In addition to the standard research program, we propose utilizing the forward proton and neutron detectors of the CMS and ATLAS experiments to significantly expand the probed phase space. These detectors, which are capable of tagging diffractive events, would allow for the study of these processes in pO collisions and the measurement of central particle production in association with high-energy nucleons at extreme forward rapidities. They may also lead to improvements in the constraints on the hadronic models of pO interactions. Forward neutron and proton detectors can tag collision events with a proton or a neutron in the final state, which carries a large fraction of the energy. These events are typically associated with low hadronic activity and are weakly constrained in the LHC experiments (*e.g.*, the modeling of the event shape variables in proton–proton collisions [3]). Representative diagrams of pO interactions involving a forward proton or neutron are depicted in figure 1.

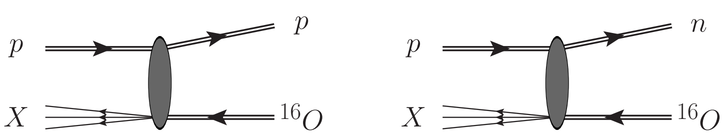

Fig. 1. Schematic diagrams of pO collisions with an intact proton (left) or a neutron (right) produced at very forward rapidities.

The proposed program would greatly expand the scientific potential of the pO run. By leveraging the unique capabilities of forward neutron and proton detectors, the LHC can provide a more comprehensive understanding of these interactions, benefiting the high-energy physics, nuclear physics, and cosmic-ray communities.

2. Forward proton and neutron tagging at the LHC

Two experiments at the LHC, ATLAS and CMS, are equipped with both forward neutron and proton detectors. The forward neutron detectors, known as Zero Degree Calorimeters (ZDCs), are designed to detect neutral particles produced in ion–ion or proton–ion collisions [4, 5] at very high rapidities. The detectors positioned in the Target Absorber for Neutrals are approximately 140 meters from the Interaction Point (IP). The ZDC detectors have rapidly evolved, culminating in the HL-LHC design, which comprises an Electromagnetic (EM) section of about 30 radiation lengths;

a Reaction Plane Detector, aiming to measure the transverse profile of neutron showers; and a hadronic section, which comprises three modules of 1.15 interaction lengths each.

The Precision Proton Spectrometer (a CMS subdetector) [6] and the ATLAS Forward Proton detector [7] are near-beam detectors positioned approximately 220 meters from the IP. Beam protons that lose a fraction of their momentum during an interaction are deflected from the beam trajectory and can be measured by the forward proton detectors. The typical acceptance of those detectors ranges from 2.5% to 15% of proton momentum loss (*e.g.*, [8]), with the exact range being determined by the LHC collimation scheme.

3. Constrain models of hadronic interactions

Events associated with the production of high-energy protons and neutrons provide valuable insights into the underlying physics of such collisions. Event kinematics, such as track multiplicity in the central region ($|\eta| < 2.5$), serve as key observables to constrain hadronic interaction models. Diffractive events, which account for about 20% of the total cross section, are of particular interest. These events are characterized by the presence of an intact proton and are typically associated with a low number of tracks in the central region. Figure 2 illustrates the track multiplicity for an inclusive selection of pO events and for events requiring a tagged forward proton obtained by using different MC hadronic models: EPOS LHC [9], DPMJet-III 2019.1 [10], Sibyll 2.3d [11], and QGSJETII-04 [12].

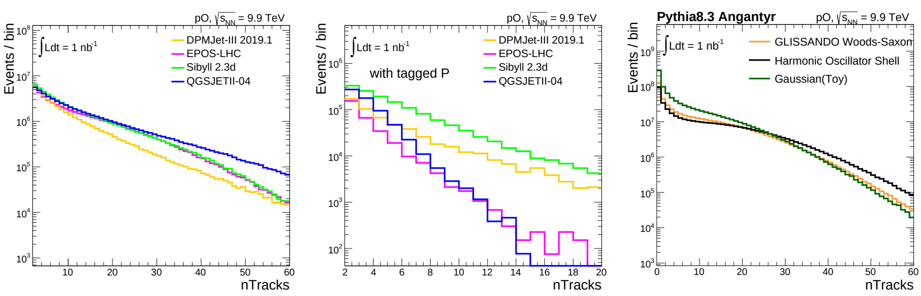

Fig. 2. Charged particle multiplicity in the central region ($|\eta| < 2.5$) for particles with transverse momentum (p_{T}) above 1 GeV for inclusive event selection (left), for events with a tagged proton (middle), and for different radial density functions of oxygen ions (right).

Two distinct groups of generators can be identified based on their predictions of track multiplicity in diffractive pO events: EPOS LHC and QGSJET exhibit a steep drop in track multiplicity, while Sibyll and DPMJet predict a slightly higher track multiplicity for such events.

Forward neutrons can originate from the colliding proton, either directly through pion exchange or due to the underlying event. As such, forward neutron multiplicities serve as an additional observable for studying hadronic interactions. Figure 3 shows the neutron multiplicity at the generator level and the reconstructed spectrum in the ZDC. The reconstructed spectrum includes a ZDC energy resolution of 17%.

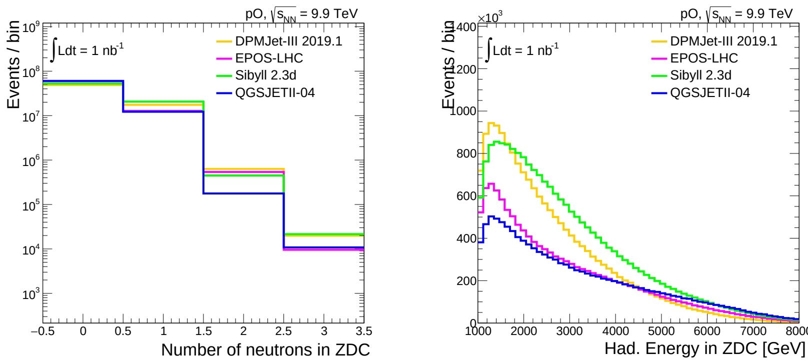

Fig. 3. Neutron multiplicity (left) and the energy spectra in the ZDC (right) for neutrons with energy above 1 TeV and rapidity above 8.5, assuming 17% energy resolution.

4. Nuclear geometry determination

The geometry of an ion can be reflected in various observables, such as the kinematics of neutrons emitted from oxygen ions or the event kinematics measured in the central region. For instance, charged-particle multiplicity in the central region is sensitive to the nuclear geometry. In figure 2, track multiplicity for nucleons with different radial-density distributions within the nucleus is shown. These distributions are based on models of ion geometry implemented in the PYTHIA MC event generator [13] and the Angantyr model [14], including different radial densities of oxygen ions: the GLISSANDO Woods–Saxon model [15, 16], commonly used for larger nuclei; the Harmonic Oscillator Shell model, often applied to lighter nuclei; and a simple Gaussian model with a nuclear charge radius of 7.7 fm. It is evident that the variations in track-multiplicity distributions across different nuclear geometries are of the same order as those predicted by the different hadronic

Monte Carlo models discussed in Section 3. Consequently, the suggested observables exhibit significant ambiguity in distinguishing between hadronic interaction models and ion geometries.

4.1. Ion geometry through ion tagging

The concept of tagging ion fragments has been explored in previous studies in the case of heavy-ion collisions [17, 18] and has very recently been discussed for light-ion collisions [19]. In pO collisions, the breakup of oxygen ions results in protons, neutrons, and various nuclear fragments. The ZDC is very efficient in measuring neutrons, but protons do not reach forward proton detectors due to their low longitudinal-momentum fraction ($x_\mathrm{L} \sim 0.5$). Ions with varying A/Z ratios are deflected away from the beam center, and they behave as particles carrying approximately $(A/Z)50\%$ of their momentum relative to the steering magnets, which is a function of their charge-to-mass ratio. The primary factor affecting resolution is the Fermi energy smearing, caused by the emitted nucleons and protons. However, for certain isotopes, this effect is relatively minor. For instance, in the case of single-neutron emission due to ion de-excitation, the resulting oxygen isotope ^{15}O will be deflected similarly to protons with $x_\mathrm{L} \sim 0.9375$. Here, the smearing due to the Fermi fluctuations is suppressed by a factor of 16, resulting in a narrow peak that can be measured in the forward proton detector.

Measurements of ion species resulting from oxygen disintegration could provide insights into the geometry of oxygen nuclei, particularly in the case of alpha clustering. For instance, tagging ^{11}C may reveal such structures. Hits from carbon-11 are expected to overlap with those from ^{15}O, since the mean $x_\mathrm{L} \sim 0.917$. However, the ^{15}O peak will be suppressed in events with high neutron multiplicity. A key question concerns the fraction of carbon-11 ions that pass the event selection criteria for high- or low-neutron multiplicity. The migration between these regions could indicate the production of neutrons bound with protons in alpha particles, which retain a nominal beam energy and escape detection in forward proton detectors. Such observations could provide valuable hints about alpha clustering in oxygen ions.

5. Conclusion

Including the forward proton and neutron detectors during the upcoming pO collisions at the LHC may lead to significant improvements in modeling the kinematics of diffractive interactions. It also provides access to a complementary phase space compared with the standard program. In addition, forward proton detectors, being sensitive to ion remnants, present an opportunity to explore the disintegration of ions through combined measurements with neutron detectors. Such measurements could provide insights into ion breakup dynamics at energies above the TeV scale. However, this approach faces challenges, including tracking under high Q, multiple scattering effects, and identifying appropriate beam settings for the LHC so that it can enable these studies.

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