Z plus jets production via double parton scattering in pA collisions at the LHC

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In this note we present results on $Zjj$ production via double parton scattering and discuss the feasibility of its observation in pA collisions at the LHC.

I. INTRODUCTION

The study of multiple parton interaction (MPI) and in particular of hard double parton scattering (DPS) reactions in pA collisions is important for our understanding of MPI in pp collisions. The theory of DPS in pA collisions was developed in [1, 2], where it was shown that there are two DPS contributions at work in such a case. First, there is the so-called DPS1 contribution, in which two partons from the incoming nucleon interact with two partons in the target nucleon in the nucleus, making such a process formally identical to DPS in the pp collisions [3–14]. Then there is a new type of contribution, often called DPS2, in which two partons from the incoming nucleon interact with two partons each of them belonging to the distinct nucleons in the target nucleus located at the same impact parameter. Recently a significant progress was achieved in the study of MPI, in particular of double parton scattering (DPS) in proton-nucleus collisions which were studied for a variety of final states [15–22] and implemented in PYTHIA Monte Carlo simulation [23].

Recently a new method was suggested [24] which could allow the observation of DPS2 in pA collisions. It was pointed out that the DPS2 has a different dependence on impact parameter than SPS and DPS1 contributions. Namely while the latter contributions are proportional to the nuclear thickness function $T(B)$, $B$ being the pA impact parameter, the DPS2 contribution is proportional to the square of $T(B)$. Therefore the cross section producing a given final state can be schematically written as:

$$
\frac{d^2\sigma_{pA}}{d^2B} = \left( \sigma_{pA}^{LT} + \sigma_{pA}^{DPS1} \right) \frac{T(B)}{A} + \sigma_{pA}^{DPS2} \frac{T^2(B)}{\int d^2B T^2(B)},
$$

where $T(B)$ is normalized to the atomic number $A$ of the nucleus. This observation gives the possibility to distinguish the DPS2 contribution in pA collisions from both the LT SPS and DPS1 contributions that are instead linear in $T(B)$. This strategy has been adopted by us in a couple of recently appeared papers where we have analyzed the associated production of electroweak $W$ boson and jets [25] and multijets production [26] via double parton scattering in pA collisions. There we have shown that, exploiting the experimental capability of measuring the centrality dependence of the cross section [27–29], one can separate the DPS2 and SPS mechanism exploiting the different dependence of the impact parameter $B$ of the pA collisions, and this can be achieved by using the pA data already recorded in 2016.

In this note we shall present the results for DPS2 production for $Zjj$ final state. We shall see that also for this final state we could separate the DPS2 contribution from the DPS1+SPS background.

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Although the calculations for $Zjj$ final state are very similar to those for $Wjj$ final state presented in [23], the study of $Zjj$ final state presents some advantages relative to $Wjj$ final state: despite the lower statistics, the determination of $Z$ kinematic is affected by smaller systematic uncertainties allowing its accurate reconstruction. This latter feature, and tiny K-factors for $Zjj$ final state arising from NLO corrections, make this channel ideal to explore longitudinal correlations in the proton, which are estimated to be of the order of 10-20% [2].

II. CALCULATION

In this note we consider proton-lead collisions at a per nucleon centre-of-mass energy $\sqrt{s_{pN}} = 8.16$ TeV, with proton energy $E_p = 6.5$ TeV and nucleon energy $E_N = 2.56$ TeV. The proton-nucleon centre-of-mass is boosted with respect to the laboratory frame by $\Delta y = 1/2 \ln E_p/E_N = 0.465$ in the proton direction, assumed to be at positive rapidity. Therefore the rapidity shift reads $y_{CM} = y_{lab} - \Delta y$. In all calculations, we consider proton-nucleon centre-of-mass rapidities. We consider the process:

$$pp \rightarrow Z + 2\text{jets} + X$$

where the $Z$ decays leptonically into electrons and muons and at least two jets are found in the final state. The production of $Z$ boson in proton-lead collisions has been measured at 5.02 TeV in Ref. [30] and it has been found to scale with the atomic number $A$ of the colliding nucleus to very good approximation. The associated production of jets associated with $Z$ boson in $pp$ at 7 TeV has been measured in Ref. [31]. In the present note we adopt the following cuts on the final state: for the $Z$ kinematics we require the leptons rapidities to lie in $|y_{l,j}| < 2.4$, their transverse momentum to be $p_T^l > 20$ GeV. We also require the invariant mass of the dilepton to be in the range $66$ GeV $< m_{ll} < 116$ GeV and the jet-lepton distance to be $\Delta R_{lj} > 0.5$. The dijet kinematics is restricted to jet rapidities $|y_{l,j}| < 4.4$ and jet transverse momenta $p_T^l > 20, 25, 30$ GeV with the interjet distance required to satisfy $\Delta R_{lj} > 0.7$. The corresponding DPS cross section (with $C = Z$ and $D = jj$) is written as [1, 2]:

$$\frac{d\sigma_{DPS}^{CD}}{d\Omega_1 d\Omega_2} = \sum_{i,j,k,l} \sum_{N=p,n} \sigma_{eff}^{-1} f^i_p(x_1) f^j_p(x_2) f^k_N(x_3) f^l_N(x_4) \frac{d\sigma_{ik}}{d\Omega_i} \frac{d\sigma_{jl}}{d\Omega_j} \int d^2B T_N(B),$$

$$+ \sum_{i,j,k,l} \sum_{N_3,N_4=p,n} f^i_p(x_1) f^j_p(x_2) f^k_{N_3}(x_3) f^l_{N_4}(x_4) \frac{d\sigma_{ik}}{d\Omega_i} \frac{d\sigma_{jl}}{d\Omega_j} \int d^2B T_{N_3}(B) T_{N_4}(B).$$

The first term corresponds to the so-called DPS1 mechanism, is linear in the thickness function $T_A$. It is calculated by assuming $\sigma_{eff} = 18$ mb, the average of experimental extracted value for similar final state [30, 31] in DPS analyses in $pp$ collisions. The second term corresponds to the so-called DPS2 mechanism and it is quadratic in the thickness function $T_A$ [1]. Quite importantly, it involves one double distribution integrated over the partonic relative interdistance and therefore is free of the inherent uncertainty introduced by $\sigma_{eff}$ which affects the DPS1 term. All double distributions are evaluated in mean field approximation, i.e. we assume the $y$ can be written as a product single parton distributions. Cross sections are calculated with ALPGEN [34] by using CTEQ6L1 [32] free proton parton distributions. Nuclear effects on the cross sections are estimated by using EPS09 nuclear parton distributions [36]. They are found to reduce the dijet cross sections less than 1% for $p_T > 20$ GeV and are neglected. We also mention that dijet and $Z$ cross sections are, to good accuracy, the same on target protons or neutrons. ALPGEN is used to calculate the SPS background from which we derive $(Z + 0j/Z + 2j) = 0.038$ in $pN$ ($N=proton$ or neutron) collisions.
TABLE I: Predictions for $Zjj$ DPS and SPS cross sections in $pA$ collisions in fiducial phase space, for different cuts on jets transverse momenta.

| $p_T^j$ | DPS1 [pb] | DPS2 [pb] | SPS [pb] | Sum [pb] | $\sigma(Zjj) / \sigma(Z)$ | $f_{DPS1}$ | $f_{DPS2}$ |
|---------|------------|------------|----------|----------|-----------------|-------------|-------------|
| $> 20$  GeV | 2983       | 7847       | 13170    | 24001    | 0.147           | 0.184       | 0.32        |
| $> 25$  GeV | 1277       | 3358       | 8878     | 13514    | 0.083           | 0.125       | 0.25        |
| $> 30$  GeV | 627        | 1649       | 6321     | 8597     | 0.053           | 0.090       | 0.19        |

TABLE II: Number of expected $Zjj$ and $Z$ events assuming $\int L dt = 0.1 \text{ pb}^{-1}$, integrated in bins of $T_A$ with $Z$ decaying into opposite sign electrons and muons. The Number of $Zjj$ is reported for three different cut on jet transverse momenta.

| $p_T^j$ | $T_{min}$ | $T_{max}$ | $N_{ev}^{Zjj}$ | $N_{ev}^{Zjj}$ | $N_{ev}^{Zjj}$ | $N_{ev}^{Z}$ |
|---------|------------|------------|----------------|----------------|----------------|--------------|
| $> 30$ GeV | 0.00 1.00  | 148        | 224            | 375            | 3160           |
| $> 25$ GeV | 1.00 1.40  | 142        | 221            | 387            | 2760           |
| $> 20$ GeV | 1.40 1.65  | 145        | 228            | 407            | 2710           |
| $> 15$ GeV | 1.65 1.83  | 143        | 228            | 410            | 2610           |
| $> 10$ GeV | 1.83 1.98  | 142        | 227            | 412            | 2530           |
| $> 5$  GeV | 1.98 2.10  | 140        | 224            | 409            | 2450           |

at $\sqrt{s_{pN}} = 8.16$ TeV with the above kinematic selection. The same ratio measured in $pp$ collisions at $\sqrt{s} = 7$ TeV with the same kinematic selection used in this note, is found to be 0.0309 [31].

We report in Tab. I the various contributions to the $Zjj$ fiducial cross section for three different transverse momentum cuts on the jets. In the last three columns we report the following ratios: 1) the $Zjj$ (SPS+DPS) over inclusive $Z$ cross section ratio, 2) the DPS1 fraction over (DPS1+SPS) events, for easy comparison with $f_{DPS}$ measured in $pp$ collisions and 3) DPS2 over total $Zjj$ cross section (DPS+SPS) ratio.

We present in the left panel of Fig. I the various contributions to the $Zjj$ cross section as a function of $B$. In the right panel of the same plot we present the expected number of events assuming an integrated luminosity of $\int L dt = 0.1 \text{ pb}^{-1}$, a value in line with data recorded in 2016 $pA$ runs, integrated in bins of $T$. In addition we present in Tab. II the expected number of events, $N_{ev}$, as a function of $T$, with binning chosen as to evenly distribute the events across the whole $T$ range. With these numbers at our disposal we may exploit the different dependence on $T$ of the various DPS and SPS contributions. For this purpose we consider the ratio $R_Z$ between the total number (DPS+SPS) of $Zjj$ events over those for $Z$ production as a function of $T_A(B)$:

$$R_Z(T) = \frac{N_{Zjj}(T)}{N_Z(T)}.$$  \hfill (3)

In such a ratio, $N_Z(T)$ is linear in $T_A(B)$, as well as the SPS background and DPS1 mechanisms contributing to $N_{Zjj}$. Therefore, in absence of the quadratic DPS2 contribution, the ratio would be a constant. Its deviation from such a behaviour will be just due to DPS2 contribution, which will determine the slope of its linear increase. The resulting distribution is presented in Fig. 2.
FIG. 1: $Z_{jj}$ cross sections (left panel) and expected number of events (right panel) as a function of $B$ for $\int L \, dt = 0.1 \, pb^{-1}$. In both plots we adopt $p_T^j > 30$ GeV.

FIG. 2: The ratio $R_Z$ defined in eq. (3) as a function of $T$ (left) and integrated in bins of $T$ (right).
associated to higher order corrections to the dijet cross section. Upon noting that the K-factor for dijet production is larger than one, and the dijet cross section is appearing in the numerator, this LO estimate of the ratio it is expected to represent its lower bound.

The knowledge of higher order corrections for all the processes involved in the determination of the signal and background and the possibility to accurately reconstruct the kinematics of the final state makes this final state valuable to explore longitudinal correlations in the proton. Indeed, as it was shown in [2], the DPS2 contribution has a correction to a factorised form of the type \( G(x_1, x_2, p_1^2, p_2^2, \vec{0}) / (f(x_1, p_1^2)f(x_2, p_2^2)) - 1 \). Here \( f(x, p^2) \) are the proton parton distributions and \( G(x_1, x_2, p_1^2, p_2^2, \vec{0}) \) is the two particle GPD of the proton (see e.g. the review [3] for the discussion of its properties and definitions) taken at the momentum \( \Delta = 0 \), being \( \vec{0} \) the transverse momentum imbalance conjugated to the transverse distance between initial partons in DPS. Both distributions are evaluated at the transverse scales \( p_1^2 \) and \( p_2^2 \) of the hard DPS processes. Therefore the comparison of theoretical predictions of DPS2 contribution, which make use of the aforementioned factorized assumption for \( G \) in Eq. (2), with experimental data will make it possible to determine longitudinal correlations in the proton.

III. CONCLUSIONS

In this letter we have calculated cross sections for \( Zjj \) final state in \( pA \) collisions at the LHC with the aim of studying the so called DPS2 contribution to the cross section. The latter has large enough cross sections to allow its determination already with data recorded in 2016 in dedicated \( pA \) runs.

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