On the application of “$Z^0 + jet$” events for determining the gluon distribution in a proton at the LHC.

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Abstract

It is shown that the samples of “$Z^0 + jet$” events, collected at the LHC with the integrated luminosity $L_{\text{int}} = 20$ fb$^{-1}$, may have enough statistics for determining the gluon distribution inside a proton in the region of $2 \cdot 10^{-4} \leq x \leq 1.0$ at $Q^2$ values in the interval of $0.9 \cdot 10^3 \leq Q^2 \leq 4 \cdot 10^4$ (GeV/c)$^2$. A possibility of the background events suppression by use of the “$Z^0 + jet$” events selection criteria is also demonstrated.

Key-words: proton, gluon distribution function, $Z^0$-boson

1. Introduction.

Many important predictions for the production processes of new particles at the LHC require a good knowledge of the gluon distribution function in a proton $f_{p g}(x, Q^2)$. Thus, determining the proton gluon density directly in the LHC experiments, especially in the region of small $x$ and high $Q^2$, would be very useful.

One of promising channels that can be used for measuring $f_{p g}(x, Q^2)$ is the direct photon production process in association with one jet $pp \rightarrow \gamma_{\text{dir}} + 1 \text{ jet} + X$. It was studied in detail in [1, 2, 3]¹.

Here for the same aim we consider the “$Z^0 + jet$” production process (see also [4, 5]), analogous to the “$\gamma_{\text{dir}} + jet$” process above:

$$pp \rightarrow Z^0 + 1 \text{ jet} + X.$$ (1)

The process (1) is caused at the parton level by two subprocesses: Compton-like scattering

$$qg \rightarrow q + Z^0$$ (2a)

and the annihilation process

$$q\bar{q} \rightarrow g + Z^0.$$ (2b)

Here we suppose that $Z^0$ boson decays in the following via leptonic channels $Z^0 \rightarrow \mu^+\mu^-$, $e^+e^-$, the signals from which can be well reconstructed by using electromagnetic calorimeter, tracker and muon system [7, 8, 9, 10]².

In the case of $pp \rightarrow Z^0/\gamma_{\text{dir}} + 1 \text{ jet} + X$ in the region of $P_{t,Z/\gamma} \geq 30$ GeV/c (where $k_T$ smearing effects are not important [6]) the cross section of “$Z^0 + jet$” production is expressed directly ³ in terms of parton distribution functions $f_{p a}(x_a, Q^2)$ and the cross sections of the elementary scattering subprocesses (e.g. see [11]):

¹see also [4]
²The estimations done here are based on the geometry of the CMS detector [7].
³In contrast to, for instance, the cross section of the inclusive photon production process, also used for the extraction of data on $f_{p g}(x, Q^2)$, that is expressed as integral over the proton momentum fractions $x_a$ multiplied by $f_{p a}(x, Q^2)$. 
\[
\frac{d\sigma}{d\eta_1 d\eta_2 dP_t^2} = \sum_{a,b} x_a f_a^p(x_a, Q^2) x_b f_b^p(x_b, Q^2) \frac{d\sigma}{d\hat{t}}(a b \to 1 2)
\]  
(3)

where the incident parton momentum fractions \(x_{a,b}\) can be found from the \(Z^0\) and jet parameters via

\[
x_{a,b} = P_t / \sqrt{s} \cdot (\exp(\pm \eta_1) + \exp(\pm \eta_2)).
\]  
(4)

We also used the following designations above: \(\eta_1 = \eta^Z\), \(\eta_2 = \eta^{jet}\); \(P_t = P_t^Z\); \(a, b = q, \bar{q}, g\); \(1, 2 = q, \bar{q}, g, Z^0\). Formula (3) and the knowledge of the results of independent measurements of \(q, \bar{q}\) distributions [4] allow the gluon distribution \(f_g^p(x, Q^2)\) to be determined in different \(x\) and \(Q^2\) intervals after a suppression of the background events contribution.

2. Definition of selection rules.

1. We shall select the events with \(Z^0\) boson\(^4\) and one jet with \(P_t^Z \geq 30\) GeV/c and \(P_t^{jet} \geq 25\) GeV/c.

\(\)  
(5)

The jet is defined according to the PYTHIA [15] jetfinding algorithm LUCELL having the cone radius counted from the jet initiator cell \((\Delta \eta^2 + (\Delta \phi)^2)^{1/2} = 0.7\). A jet pseudorapidity \(|\eta^{jet}|:\) is limited by 5.0 according to the CMS detector geometry.

2. To guarantee a clear track identification of a lepton from the decays of \(Z^0 \to \mu^+ \mu^-, e^+ e^-\) in the tracker and muon systems and most precise determination of its parameters we put the following restrictions on leptons\(^5\):

(a) on the transverse momentum value \(P_t^l\) of any considered lepton:

\[
P_t^l \geq 10\) GeV/c;
\]  
(6)

(b) on the \(P_t\) value of the most energetic lepton in a pair:

\[
P_t^{l_{max}} \geq P_{t_{CUT}}^l
\]  
(7)

This cut depends on the energy scale\(^[10]\). So, we have taken \(P_{t_{CUT}}^l = 20\) GeV/c for events with \(P_t^Z \geq 40\) GeV/c and \(P_{t_{CUT}}^l = 50\) GeV/c for events with \(P_t^Z \geq 100\) GeV/c.

(c) on the value of the ratio of \(P_t^{isol}\), i.e. the scalar sum of \(P_t\) of all particles surrounding a lepton, to \(P_t^l\) (\(P_t^{isol}/P_t^l\)) in the cone of radius \(R = 0.3\) and on the value of maximal \(P_t\) of a charged particle surrounding a lepton in this cone:

\[
P_t^{isol}/P_t^l \leq 0.10, \quad P_t^{ch} \leq 2\) GeV/c.
\]  
(8)

The isolated high-\(P_t\) tracks (what takes place in case of the leptonic \(Z^0\) decays) should be reconstructed with a higher efficiency and with generation of a lower number of fake and ghost tracks\(^[8,9]\).

3. A lepton is selected in the acceptance region\(^[8,9]\):

\[
|\eta^l| < 2.4.
\]  
(9)

\(^4\)Here and below in the paper speaking about \(Z^0\) boson we imply a signal reconstructed from the lepton pair with leptons selected by the criteria 2 – 4 of this section.

\(^5\)Most of the \(e, \mu\) selection cuts are taken from\(^[8,9]\).
4. To select lepton pairs only from $Z^0$ decay we limit the value of the lepton pair invariant mass $M_{inv}^{ll}$ by:

$$|M^Z - M_{inv}^{ll}| \leq 5 \text{ GeV/c}^2.$$  (10)

with $M^Z$ taken to be 91.2 GeV/c$^2$.

5. We select the events with the vector $\vec{P}_{t\,\text{jet}}$ being “back-to-back” to the vector $\vec{P}_t^{Z}$ (in the plane transverse to the beam line) within the azimuthal angle interval $\Delta \phi$ defined by the equation:

$$\phi_{(Z,\text{jet})} = 180^\circ \pm \Delta \phi$$  (11)

where $\phi_{(Z,\text{jet})}$ is the angle between the $\vec{P}_t^{Z}$ and $\vec{P}_{t\,\text{jet}}$ vectors: $\vec{P}_t^{Z} \vec{P}_{t\,\text{jet}} = P_t^Z P_{t\,\text{jet}} \cos(\phi_{(Z,\text{jet})})$, with $P_t^Z = |\vec{P}_t^{Z}|$, $P_{t\,\text{jet}} = |\vec{P}_{t\,\text{jet}}|$. Here we limit $\Delta \phi$ values by 15$^\circ$.

6. The initial and final state radiations manifest themselves most clearly as some final state mini-jets or clusters activity \[10, 13, 14\]. To suppress it, we impose a new cut condition that was not formulated in an evident form in previous experiments: we select the “$Z^0 + \text{jet}$” events that do not have any other jet-like or cluster high $P_t$ activity by taking values of $P_{t\,\text{clust}}$ value, i.e. we select the events with

$$P_{t\,\text{clust}} \leq P_{t\,\text{clust,CUT}}.$$  (12)

7. We limit the value of the modulus of the vector sum of $\vec{P}_t$ of all particles that do not belong to the “$Z^0 + \text{jet}$” system but fit into the region $|\eta| < 5$ covered by the calorimeter system, i.e., we limit the signal in the cells “beyond the jet and $Z^0$” regions by the following cut:

$$\left| \sum_{i \notin \text{jet}, Z^0} \vec{P}_t^i \right| \equiv P_{t\,\text{out}} \leq P_{t\,\text{out,CUT}}, \ |\eta_i| < 5.$$  (13)

The importance of $P_{t\,\text{out,CUT}}$ and $P_{t\,\text{clust,CUT}}$ for selection of events with a good balance of $P_t^Z$ and $P_{t\,\text{jet}}$ was already shown in \[10, 13, 14\]. In this paper they are fixed as $P_{t\,\text{out,CUT}} = 10 \text{ GeV/c}$ and $P_{t\,\text{clust,CUT}} = 10 \text{ GeV/c}$.

As we show below the presented selection criteria guarantee practically a complete suppression of the background events.

3. The study of background suppression.

In principle, there is a probability, that some combination of $\mu^+\mu^-$ or $e^+e^-$ pairs in the events, based on the QCD subprocesses with much larger cross sections (by about 5 orders of magnitude) than ones of the signal subprocesses (2a) and (2b), can be registered as the $Z^0$ signal. Firstly, to study a rejection possibility of such type of events by about 40 million events with a mixture of all QCD and SM subprocesses with large cross sections existing in PYTHIA \[7\] including also the signal subprocesses \[8\] were generated with the only $Z^0$ decay mode allowed: $Z^0 \rightarrow \mu^+\mu^-$. Three generations were performed with different minimal $P_t$ of the hard $2 \rightarrow 2$ subprocess \[9\] values: $\hat{p}_{\min}^2 = 40$, 70 and 100 GeV/c. The cross sections of different subprocesses serve in simulation as weight factors and, thus, determine the final statistics of the corresponding

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\[6\] A narrower mass window can be used with the statistics growth.

\[7\] Namely, having ISUB=11–20, 28–31, 53, 68 in PYTHIA \[15\].

\[8\] ISUB=15 and 30 in PYTHIA \[15\].

\[9\] i.e. CKIN(3) parameter in PYTHIA \[15\].
physical events. The generated events were analyzed by use of the cuts given in Table 1 (see also Section 2).

| Selection | Signal | Bkgd | $E_{ff}S(\%)$ | $E_{ff}B(\%)$ | $S/B$ |
|-----------|--------|------|-------------|-------------|------|
| 0         | 401    | 850821 | 100.00±0.00 | 100.00±0.000 | 0.02 |
| 1         | 226    | 15842 | 92.24±8.51  | 2.948±0.138  | 0.5  |
| 2         | 99     | 467   | 40.41±4.81  | 0.076±0.022  | 8.3  |
| 3         | 81     | 12    | 33.00±4.24  | 0.063±0.020  | 8.1  |
| 4         | 72     | 10    | 29.39±3.94  | 0.025±0.013  | 18.0 |
| 5         | 62     | 0     | 25.31±3.60  | 0.000±0.000  | –    |

We see from Table 2 that initial ratio of $\mu^+\mu^-$ pairs in signal and background events is very small (5 · 10$^{-4}$). A weak restriction of the muon transverse momentum and pseudorapidity in the first selection increase $S/B$ by about 2 order (as 5 · 10$^{-4}$ → 2 · 10$^{-2}$). The invariant mass criterion and one-jet events selection make $S/B = 18.0$ and the last criterion on the azimuthal angle between $Z^0$ and jet ($\Delta\phi < 15^\circ$) suppresses the background events completely.

The information on other intervals (i.e. on the event generations with $\hat{p}_\perp^{\text{min}} = 40$ and $\hat{p}_\perp^{\text{min}} = 100$ GeV/c) is presented in Table 3. Line “Preselection (1)” corresponds to the first cuts in Table 1 ($P^\mu_1 > 10$ GeV/c, $|\eta^\mu| < 2.4$) while line “Main (1 - 5)” corresponds to the result of application of criteria from 1 to 5 of Table 1. After application of all six criteria of Table 1 we

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10 Notice, that the cuts used in Table 1 are weak enough. For instance, they do not limit (directly) $P^Z_t$, $P^\text{out}$ of the most energetic lepton in the pair (as well as they do not include $P^\text{cut}_{Z}\text{cut}$ and $P^\text{cut}_{\text{out}}$).

11 The number of events after the first cuts is taken as 100%.

12 That is mainly due to the huge difference in the cross sections of “$Z^0 + \text{jet}$” events (from subprocesses (2a), (2b)) and the QCD events.
have observed no background events in all of the $P_t^Z$ intervals with the signal events selection efficiency of 25 − 33%.

Analogous simulations in PYTHIA were done to estimate a background to the “$Z^0 + jet$” events with the subsequent $Z^0$ decay via $e^+e^-$ channel. By about 20 million events were generated at $\hat{p}_\perp^{min}= 40, 70$ and $100$ GeV/$c$ with a mixture of all QCD and SM subprocesses. The results are given in Table 3. As in the case of $Z^0 \rightarrow \mu^+\mu^-$, no background events were found after application of all criteria of Table 1.

| $\hat{p}_\perp^{min}$ (GeV/$c$) | Selections | Signal | Bkgd | $Eff_S$(%) | $Eff_B$(%) | $S/B$ |
|---------------------------------|------------|--------|------|-----------|-----------|------|
| 40                              | Preselected (1) | 48     | 1404 | 100.00±0.00 | 100.00±0.00 | 0.03  |
|                                 | Main (1−5)   | 20     | 3    | 41.67±11.09 | 0.214±0.123 | 6.7   |
| 70                              | Preselected (1) | 95     | 5396 | 100.00±0.00 | 100.00±0.00 | 0.02  |
|                                 | Main (1−5)   | 35     | 2    | 36.32±7.32  | 0.037±0.026 | 17.5  |
| 100                             | Preselected (1) | 191    | 18158| 100.00±0.00 | 100.00±0.00 | 0.01  |
|                                 | Main (1−5)   | 61     | 2    | 31.68±4.67  | 0.008±0.007 | 30.5  |

The practical absence of a background to the “$Z^0 + jet$” events allow to use them for an extraction of the gluon distribution in a proton $f^p_g(x, Q^2)$.

### 4. Estimation of rates for gluon distribution determination.

In Table 3 we present the distribution of the number of the events, based on the subprocesses $qq \rightarrow Z^0 + q$ and $q\bar{q} \rightarrow g + Z^0$ (with the decays $Z^0 \rightarrow \mu^+\mu^-, e^+e^-$), at integrated luminosity $L_{int} = 20 fb^{-1}$ in different $x$ (defined by (4)) and $Q^2(\equiv (P_t^Z)^2)$ intervals. These events satisfy the cuts (5)−(13) of Section 2. We see that at $L_{int} = 20 fb^{-1}$ one can collect about half a million of “$Z^0 + jet$” events in the interval of $30 \leq P_t^Z \leq 200$ GeV/$c$.

The contributions (in %) of the events originated from the subprocesses (2a) and (2b) as functions of $P_t^Z$ are presented in Fig. 1. From this figure one can see that the fraction of the “gluonic” events originated from the Compton scattering (2a) noticeably dominates over all considered $P_t^Z$ interval and varies from about 60% at $P_t^Z \approx 30$ GeV/$c$ to about 85% at $P_t^Z \geq 100$ GeV/$c$.

13 and passed selection cuts (5)−(13)
Table 5: Numbers of “$Z^0 + jet$” events (with $Z^0 \to \mu^+\mu^-$, $e^+e^-$) in $Q^2$ and $x$ intervals for $L_{int} = 20 \, fb^{-1}$.

| $Q^2$ (GeV/c$^2$) | $x$ values of a parton | All $x$ | $P_{tZ}$ (GeV/c) |
|------------------|------------------------|---------|-----------------|
| 20000-40000      | 0                      | 0       | 0               |
| 14000-20000      | 0                      | 0       | 0               |
| 10000-14400      | 38                     | 1816    | 1438            |
| 6400-8100        | 341                    | 8476    | 10860           |
| 2500-3600        | 4957                   | 33148   | 38029           |
| 3600-5000        | 2195                   | 20812   | 25882           |
| 5000-6400        | 454                    | 11693   | 13887           |
| 6400-8100        | 341                    | 8476    | 10860           |
| 8100-10000       | 38                     | 5979    | 8098            |
| 10000-14400      | 38                     | 5638    | 9157            |
| 14400-20000      | 0                      | 2800    | 5562            |
| 900-1600         | 36818                  | 91689   | 94905           |
| 1600-2500        | 14833                  | 56722   | 57403           |
| 2500-3600        | 4957                   | 33148   | 38029           |
| 3600-5000        | 2195                   | 20812   | 25882           |
| 5000-6400        | 454                    | 11693   | 13887           |

The $x - Q^2$ kinematic area in which one can study the gluon distribution $f^p_g(x, Q^2)$ by selecting “$Z^0 + jet$” events (with the leptonic decay modes of $Z^0$) is also shown in Fig. 2. From this figure (and Tables 5) it is seen that during first two years of LHC running at low luminosity ($L = 10^{33} \, cm^{-2}s^{-1}$) it would be possible to extract an information for determination of $f^p_g(x, Q^2)$ in the region of $0.9 \cdot 10^3 \leq Q^2 \leq 4 \cdot 10^4 \, (GeV/c)^2$ with as small $x$ values as accessible at HERA but at higher $Q^2$ values (by 1–2 orders of magnitude). It is also worth emphasizing that the sample of the “$Z^0 + jet$” events selected for this aim can be used to perform a cross-check of $f^p_g(x, Q^2)$ determination by using “$\gamma + jet$” events [1, 2, 3]. It is especially important in the region of lower $Q^2$ where we have quite a sufficient statistics of “$Z^0 + jet$” events, on the one hand, and a higher background contribution to the “$\gamma + jet$” events, on the other hand. The area that can be covered with “$\gamma + jet$” events is also shown in Fig. 2 by dashed lines.

Fig. 1: The contributions of the events originated from the subprocesses (2a) and (2b) as a function of $P_{tZ}$. Full line corresponds to the “$qg \rightarrow q + Z^0$” events, dashed line – to the “$q\bar{q} \rightarrow g + Z^0$” events.
Fig. 2: LHC \((x, Q^2)\) kinematic region for the process \(pp \to Z^0 + \text{jet} + X\) (with \(Z^0 \to \mu^+\mu^-, e^+e^-\)).

5. Summary.

It is shown that the samples of \(Z^0 + \text{jet}\) events with a clean topology, most suitable for the absolute jet energy scale setting \(^\text{14}\) \cite{10} and with the suppressed combinatorial background contribution from the QCD events, can provide an useful information for the gluon density determination inside a proton. The corresponding measurements can be done in a new kinematic region, not covered in any previous experiments, of \(2 \times 10^{-4} \leq x \leq 1.0\) with \(0.9 \times 10^3 \leq Q^2 \leq 4 \times 10^4 (\text{GeV}/c)^2\). The study of gluon distribution \(f_p^g(x, Q^2)\) obtained from the analysis of \(Z^0 + \text{jet}\) events can be used as the independent cross-check of the \(f_p^g(x, Q^2)\) determination from the \(\gamma^{\text{dir}} + \text{jet}\) events \(^\text{1, 2, 3}\) as well as from the analytical solutions of the DGLAP equations describing the \(Q^2\) evolution of parton distributions at small \(x\) \cite{16}.

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\(^\text{14}\) As was shown in \cite{10}, the chosen cut conditions noticeably suppress initial and final state radiations, i.e. the contributions from the events caused by next-to-leading order diagrams.

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