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Slow nucleon detection with the ALICE ZDC to select centrality in pA colllisions

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Abstract:

The ALICE Zero Degree Calorimeters (ZDC) were originally designed to measure centrality in nucleus-nucleus collisions by detecting the non interacting energy carried by spectator nucleons. Lately the possibility to use such detectors to select centrality also in proton-nucleus collisions has been investigated. The proposed technique relies on the detection of the so called “slow” nucleons emitted by the excited nucleus. In the following the method proposed to perform the measurement will be presented, together with the results of a study on the physics performances of the detector for such measurement.

1 Introduction

Proton-nucleus collisions will provide a very important tool for the interpretation of nucleus-nucleus data; it would therefore be very useful to estimate event-by-event the centrality of the collision. The centrality in proton-nucleus collisions is typically defined through the number of nucleon-nucleon collisions, N_{coll}. The centrality determination can be based on charged particle multiplicity measurement. However the inclusive measurement of charged particle multiplicity can sometimes be poorly correlated with the number of collisions and in this case the method would not allow to perform a centrality selection. Anyway, since the charged particle distribution is studied as a function of centrality, it would be favorable to have an independent method to estimate the centrality.

The method proposed to select centrality relies on the detection of the "slow" nucleons produced in the interaction by means of the Zero-Degree Calorimeters (ZDC). The classification of the so called "slow"particles derives from pioneering emulsion works. The emitted particles were in fact defined, according to the grain density left in the detection material, as "black" ($p < 250\ MeV/c$) or "gray" ($250\ MeV/c\ < p < 1\ GeV/c$). These slow particles are produced by different mechanisms: while gray particles are essentially soft nucleons knocked out by wounded nucleons, black nucleons are emitted during the nucleus de-excitation processes. An exhaustive description of the measurements performed on slow particles in both emulsion and fixed target experiments, with different colliding systems, together with a summary of the obtained results can be found in reference [1].

At colliders, where the slow nucleons emitted in pA interactions are Lorentz-boosted, the ideal device for their detection is the Zero Degree Calorimeter (ZDC). The ZDC of the ALICE experiment were originally designed to measure centrality in nucleus-nucleus collisions by detecting the non interacting energy carried by spectator nucleons. These detectors are placed at about 116 m from the interaction point, where the distance between the two beam pipes allows to insert a device to detect spectator neutrons. Two different detectors will in fact detect spectator protons and spectator neutrons that are separated from the magnetic elements of the LHC beam line. Two identical systems of ZDC will be placed on both sides relative to the interaction point to reduce the background due to beam-gas interactions and to improve the resolution on the impact parameter measurement. Technical details about the detectors can be found in ref. [2], while the methods used to estimate the centrality from the measured spectator energy are described in ref. [3].

Simulations have been performed to evaluate the ZDC response for slow nucleon detection and to study the centrality determination in pA collisions. In the following the proposed model will be described and the obtained results will be presented.

2 Model for slow nucleon generation

The model we used to generate slow particles in pA interactions consists essentially in a parametrization of the experimental results included in ref. [1]. From past experimental results it comes out that the features of produced particles are highly independent from projectile energy in the range that goes from 1 GeV to 1 TeV. On the other hand, there is a clear indication that the emission of slow particles depends essentially on the nuclear geometry.

The distribution of the number of projectile collisions at a given impact parameter is calculated through the Glauber model, assuming a Wood-Saxon nuclear density distribution. The number distribution of gray particles (N_{gray}) and of the number of collisions (N_{coll}) have very similar distributions (see ref. [1]). Several models, with different assumptions for the relationship between N_{coll} and N_{gray}, have been used to reproduce the measured distributions. BNL-E910 experiment fitted its data assuming that N_{gray} is a second order polynomial function of N_{coll} and found that the coefficient of the second degree term is negligible [5]. This results is consistent with a simple geometric model. The average black nucleon multiplicity is assumed to depend linearly on the number of projectile collisions, being connected to the target excitation. This assumption is validated by the experimental observation that the number of black nucleons (N_{black}) is proportional to the number of gray nucleons emitted in the collision. The number distribution of both black and gray particles follow binomial distributions. Kinematical distributions can be described by independent statistical emission from a moving frame: black nucleons are emitted from a stationary source while gray nucleons from a frame moving slowly along the beam direction (for Pb nuclei $\beta_{gray} \sim 0.05$).

From these considerations it comes out that the average numbers of black and gray nucleons in a minimum bias hadron-nucleus collisions are [1]:

$$\overline{N}_{black} \approx 0.08\ A \qquad \overline{N}_{gray} \approx 1.2\ A^{1/3}$$

For centrality selected collisions on Pb nuclei the average values per collision are [1]:

$$\overline{N}_{black} \approx 4\ N_{coll} \qquad \overline{N}_{gray} \approx 2\ N_{coll}$$

2.1 Saturation in black nucleons emission

It has been experimentally observed a saturation in the number of black nucleons as a function of the number of gray tracks for O and S targets ([6], [7]). This saturation occurs for $N_{gray} > 7$ and the saturated average value corresponds to about 12 black nucleons. Assuming that the number of emitted slow nucleons is proportional to the target nucleus thickness, we rescaled these values for Pb nuclei. In this case the saturation occurs for higher N_{gray} values: $\overline{N}_{black} \sim 28$ for $N_{gray} > 15$. However, since there are no experimental results on Pb nuclei, both the situations with and without saturation have been considered for the simulation.

2.2 Angular distribution of gray tracks

The angular distribution for black particles is essentially flat, coherently with the assumption that they are emitted isotropically from a very slowly moving frame. On the contrary, the angular distribution for gray tracks produced in pions and proton induced reactions on light ions (S and O) is forward peaked ([5] [6]). This experimental observation holds for different projectiles with different energies.

We used a parameterization of the angular distribution for gray tracks and we investigated the effect on our centrality selection. The used angular distribution is plotted in figure 1.

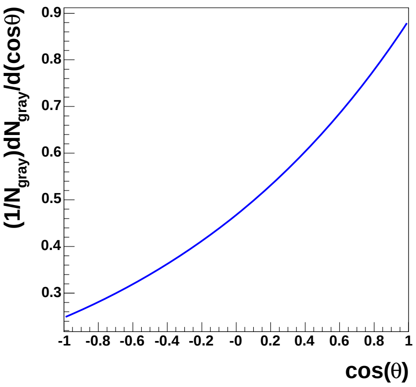

Figure 1: Normalized forward peaked angular distribution for gray tracks.

2.3 Model outputs

In figure 2 the distribution of the number of black and gray nucleons (for both protons and neutrons) as a function of the number of binary collisions can be seen. In figure 3 the average number of black particles as a function of gray spectators is shown both with and without including the saturation in black particle production. The relationship between the number of produced slow nucleons and the number of collisions in case of saturation is plot in figure 4. As can be seen in this figure, the black particle production begins to saturate for $N_{coll} \gtrsim 8$.

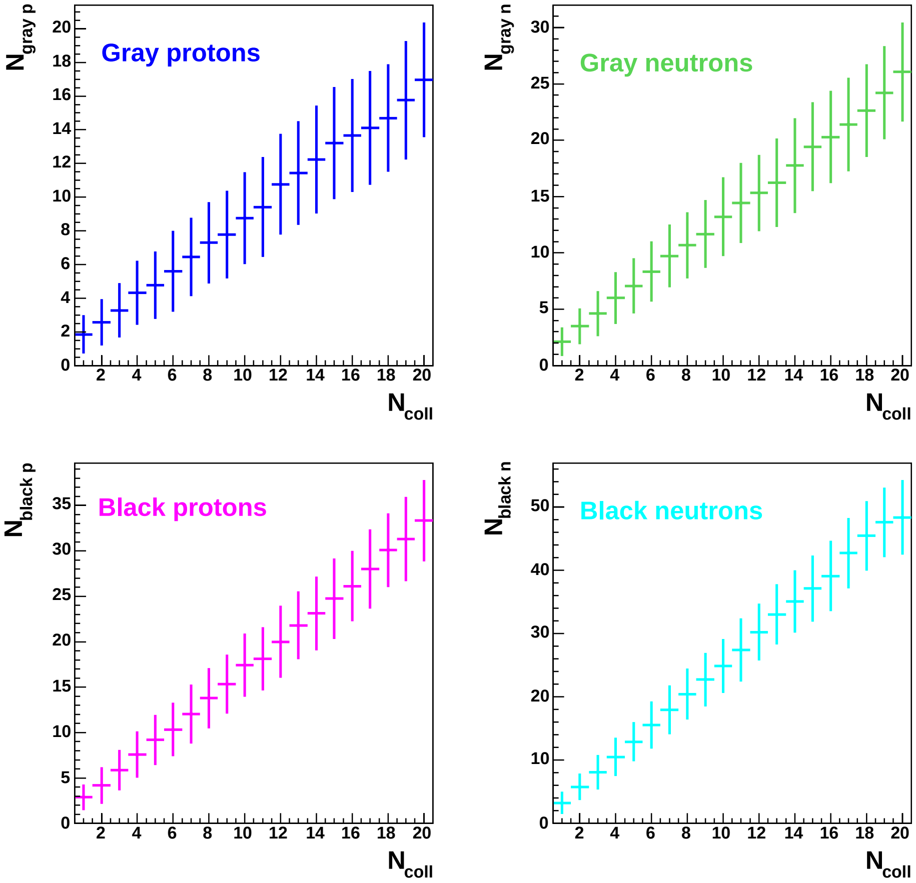

Figure 2: Number of slow nucleons produced vs. number of collisions in pPb collisions at $\sqrt{s} = 14\ TeV\sqrt{Z/A}$.

3 Slow nucleons detection in the ZDC

To evaluate the response of the ZDC for slow nucleons detection we generated 5000 pPb events using HIJING. The slow generator model has been implemented into an AliRoot generator (AliGenSlowNucleon). The generated slow particles have then been tracked through the ALICE setup to the ZDC location.

First of all we studied the case with no saturation in N_{black} and assuming a flat angular distribution for gray particle production. The impact point of slow protons and neutrons over the calorimeter front faces is reported in figure 5. The ZDC have full acceptance for black nucleons and for gray neutrons, while a few percent of gray protons is outside ZDC acceptance. It can be noticed that, as expected, black particles have narrower impact areas over the detector front faces. However, looking at the plot it is clear

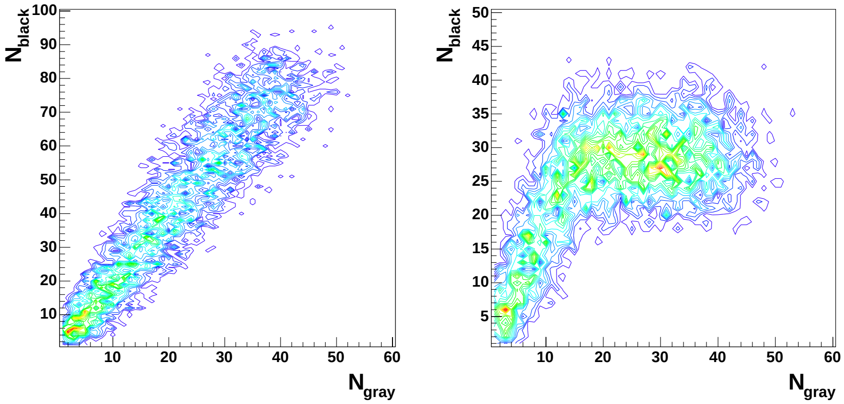

Figure 3: Black vs. gray nucleons without (left) and with (right) saturation in the average number of black tracks.

that, even if the detectors are segmented, it is not possible to separate the contribution due to gray particles from the one given by black nucleons since the spots are superimposed.

In simulation the separate contribution due to black and gray particles can be studied. The signals of the ZDC for black/gray protons and neutrons are shown in figure 6. The energy resolution of both proton and neutron calorimeters (about 9% for a single 2.7 TeV nucleon hitting the center of the detector front face) allows to separate the peaks due single black nucleons (see bottom plots in figure 6).

The ZDC signal for incident protons and neutrons as a function of the number of slow particles and as a function of the number of collisions is shown in figure 7. The signal is expressed in number of produced photoelectrons, the detected energy can be obtained knowing that for both detectors 300 photoelectrons corresponds to an energy of about 1 TeV.

Experimentally the two quantities that will be measured are the total energy carried respectively by slow neutrons and slow protons. The spectra of the neutron and proton ZDC are shown in figure 8.

Events corresponding to different centralities can be selected by cutting the ZDC energy spectra. Each selected class will correspond to a well defined fraction of the total pPb cross section. We selected three centrality bins. The events from each class have different distributions of the number of collisions. The three obtained distributions are shown in figure 9. In table 1 the E_{ZDC} cut values and the corresponding N_{coll} mean values (and RMS) are reported.

The obtained results show that we are able to separate events from the three different centrality classes since there is no significant superposition of events from different bins.

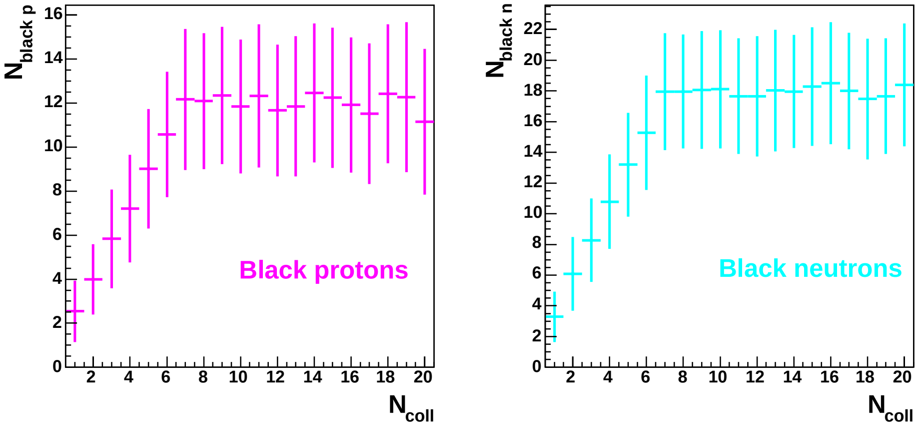

Figure 4: Number of black protons (left) and neutrons (right) emitted as a function of the number of collisions when saturation is included.

$\%\sigma_{TOT}$	E_{ZP} (TeV)	$\overline{N}_{coll}$ from ZP	E_{ZN} (TeV)	$\overline{N}_{coll}$ from ZN
0÷5	>105	15.1 (2.1)	>155	15.4 (1.9)
5÷50	34÷105	8.7 (3.1)	50÷155	9.3 (3.5)
50÷100	0÷35	2.3 (1.5)	0÷50	2.2 (1.3)

Table 1: Mean values (and RMS) of N_{coll} distributions for the 3 selected centrality bins.

3.1 Black particles saturation

We investigated the effect of the saturation in black nucleons production. The energy detected in the ZDC does not saturate with increasing centrality since the signal is due to both saturating (black) and not saturating (gray) components, but the slope of the dependence changes when saturation occurs. In figure 10 the ZDC signals are shown as a function of the number of collisions and it can be seen that the saturation effects begins to play a role for $N_{coll} \gtrsim 8$. The spectra for proton and neutron ZDC are shown in figure 11.

The saturation introduces further smearing in the distribution of the number of collisions. In this case it can be helpful to sum the spectra of the two detectors and perform the event selection applying the cuts on the ZDC (ZN+ZP) spectrum (shown in figure 11). In this case defined four centrality bins. The N_{coll} distributions are plotted in figure 11 and the E_{ZDC} cut values together with the mean N_{coll} values (and RMS) from each class are reported in table 2.

Even if the black particle production is supposed to saturate, the cen-

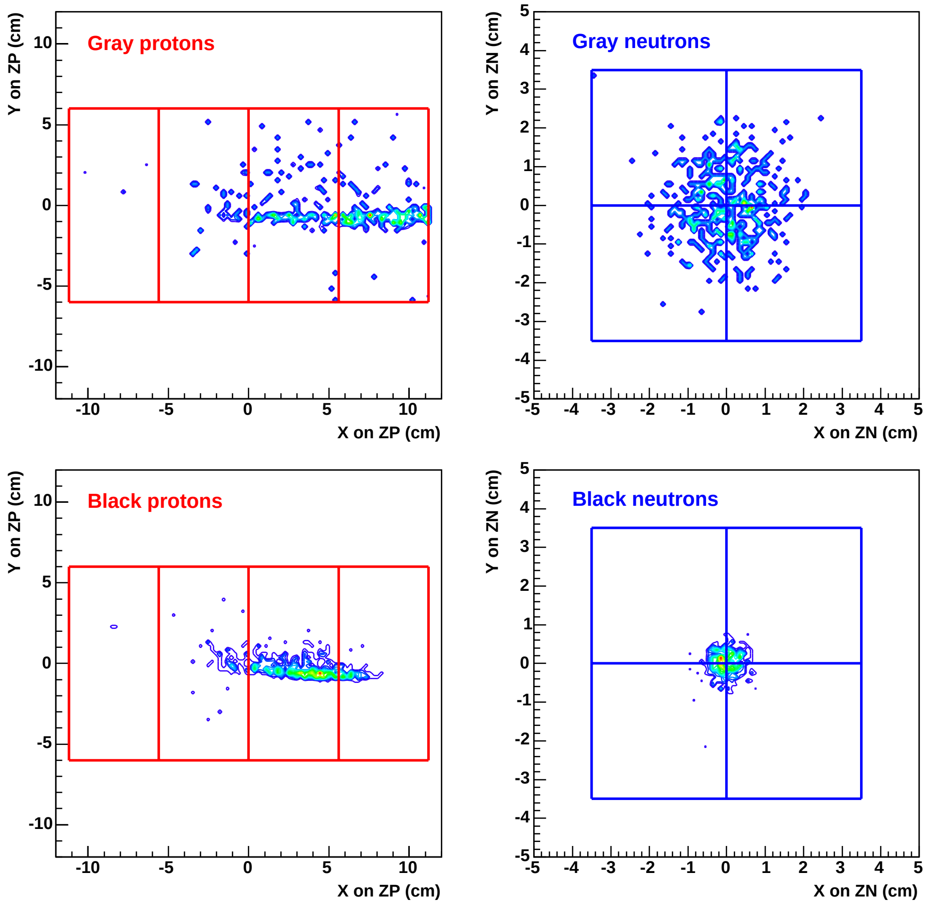

Figure 5: Left: impact point for gray (top) and black (bottom) protons over the proton ZDC front face (dimensions: 22.4 cm x 12 cm). Right: impact point over the neutron front face (dimensions: 7.04 cm x 7.04 cm) for the gray (top) and black (bottom) neutrons generated in pPb collisions.

trality bins defined do not superimpose significantly.

3.2 Forward peaked angular distribution

Finally, we introduced the anisotropy for gray particle angular distribution. It turned out that the forward peaked angular distribution plays a role for gray protons that are affected by the beam line magnetic fields, as can be seen by comparing figures 5 and 12. The results concerning the centrality selection do not depend on the angular distribution since both detector responses do not change significantly.

However if the angular anisotropy for gray tracks is considered, the spatial distribution of slow nucleons over the ZDC front face allows to separate

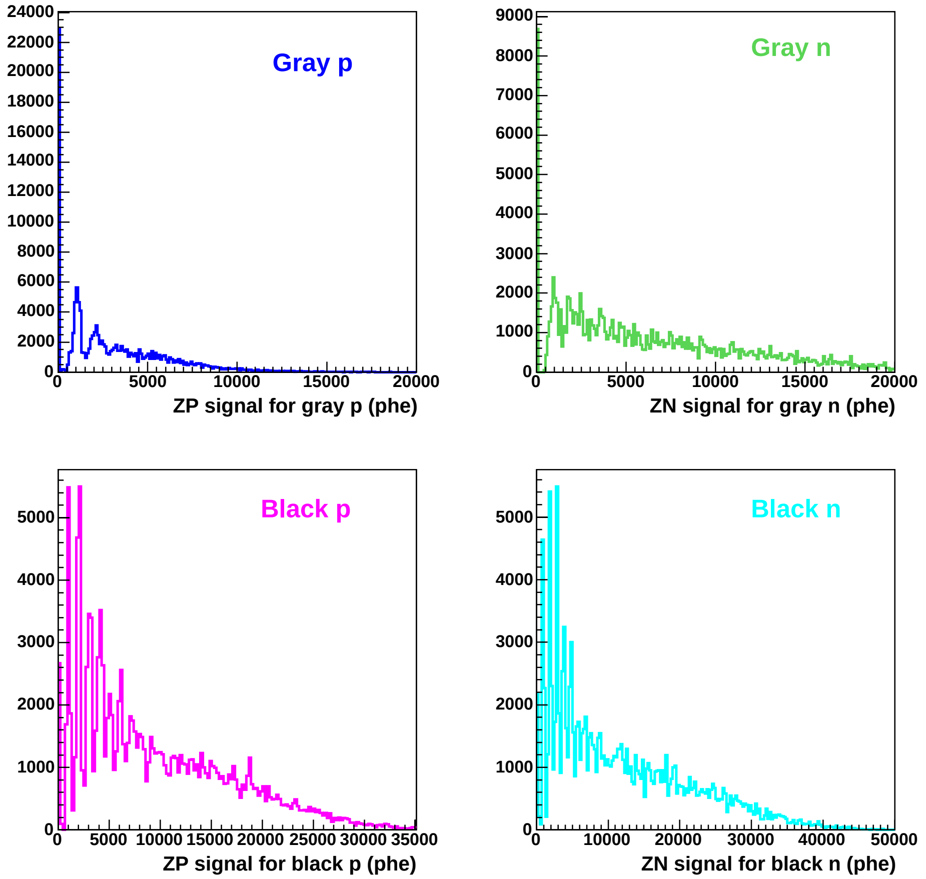

Figure 6: ZDC signal for slow nucleon detection.

the contribution due to gray protons from the one given by black nucleons. This could allow, in case of saturation, to select very central events using only the signal due to gray protons that does not saturate.

4 Conclusions

It has been shown the possibility to select centrality in proton-nucleons collisions by detecting slow particles emitted by the nucleus with the ALICE ZDC. The reached accuracy only depends on the ZDC energy resolution. We took into account all the possible effects that could play a role in slow particle production (i.e., saturation for black particles, forward peaked angular distribution for gray tracks). It is in any case possible to define at least three centrality bins without significant superimposition of the distribution of the number of collisions. We can conclude that the ALICE ZDC is well suited for centrality selection in pA collisions at the LHC.

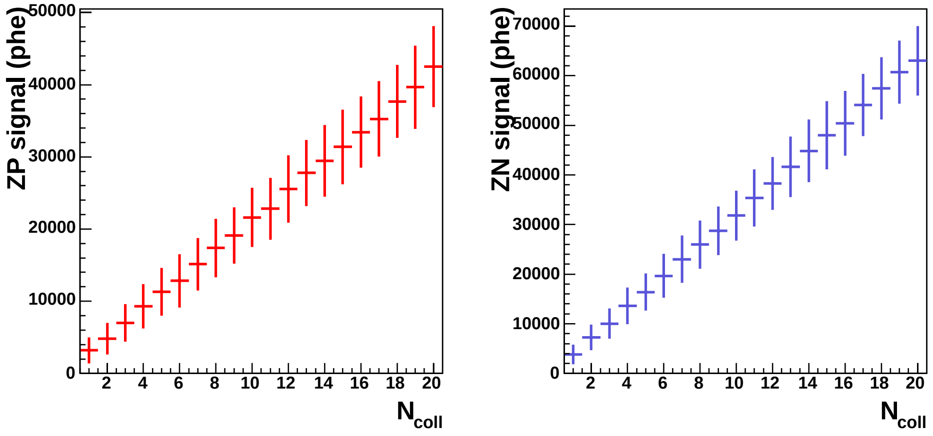

Figure 7: Proton (left) and neutron (right) ZDC signal vs. number of collisions.

$\%\sigma_{TOT}$	E_{ZDC} (TeV)	$\overline{N}_{coll}$
0÷5	>174	14.2 (2.8)
5÷25	134÷174	10.8 (2.8)
25÷100	83÷134	7.2 (2.5)
50÷100	0÷83	2.1 (1.3)

Table 2: Mean values (and RMS) of N_{coll} distributions for the 4 centrality bins selected from the summed ZDC spectrum in case of saturation.

References

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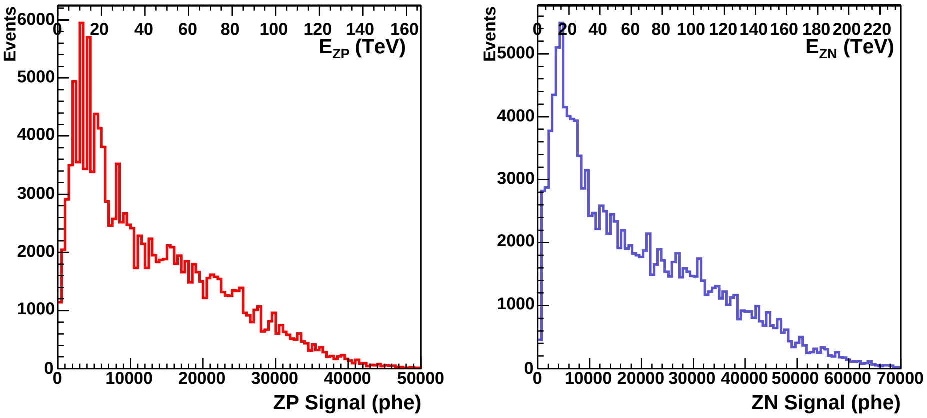

Figure 8: Proton (left) and neutron (right) ZDC spectra for slow particles detection.

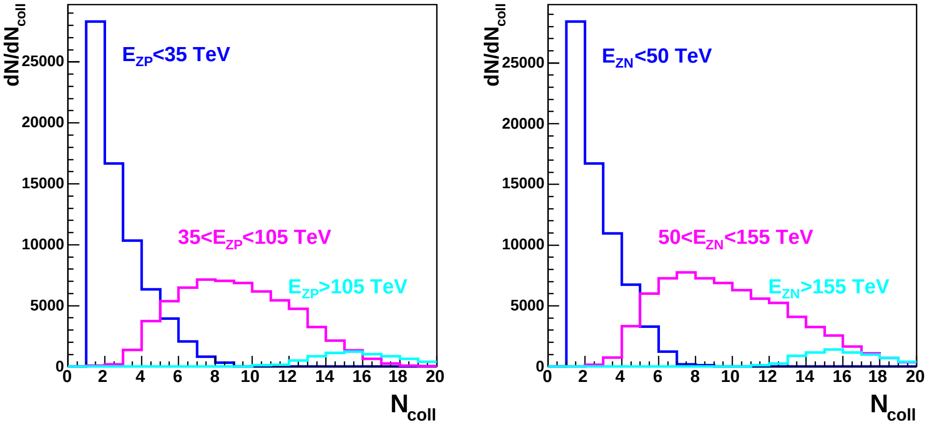

Figure 9: N_{coll} distributions in three centrality bins. Left: events from proton ZDC, right: events from neutron ZN.

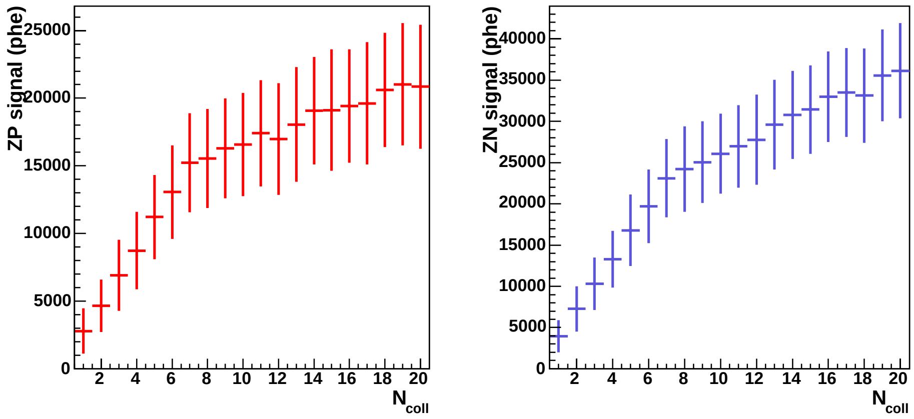

Figure 10: ZDC signal vs. N_{coll} for protons (left) and neutrons (right) when the saturation effect in N_{black} is included in the generator.

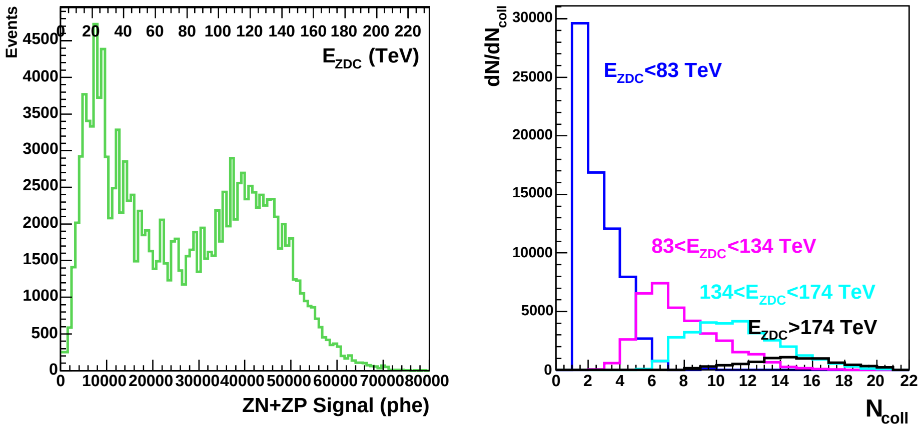

Figure 11: Left: Summed proton and neutron spectrum. Right: N_{coll} distributions for the selected centrality bins (see text).

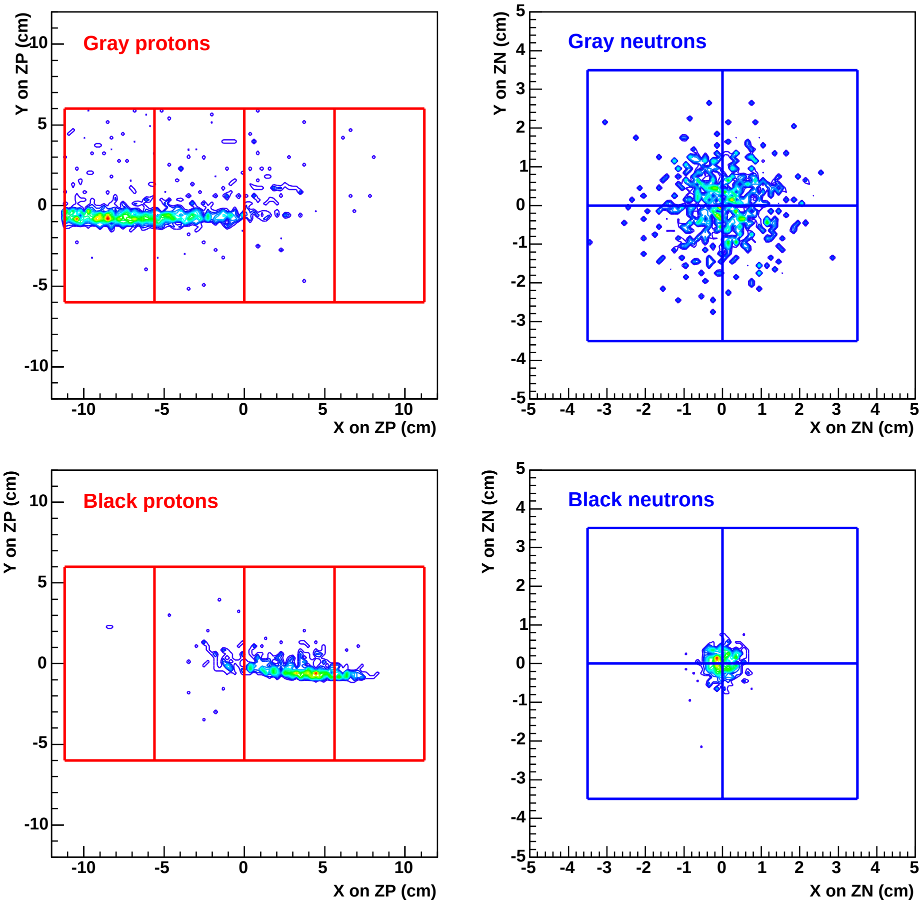

Figure 12: Left: impact point of gray (top) and black (bottom) protons over the proton ZDC front face. Right: impact point over the neutron front face for the gray (top) and black (bottom) neutrons generated in p-Pb collisions.The angular distribution for gray particles is forward peaked.