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Events with a leading forward neutron have been observed in *ep* collisions at HERA as well as in *pp* collisions at the ISR and in Fermilab. It is shown that it is possible to study this class of events with the ALICE detector during *pp* running mode using the capabilities of the neutron ZDC and some of the physics potential of this class of events is discussed.

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Abstract

Events with a leading forward neutron have been observed in *ep* collisions at HERA as well as in *pp* collisions at the ISR and in Fermilab. It is shown that it is possible to study this class of events with the ALICE detector during *pp* running mode using the capabilities of the neutron ZDC and some of the physics potential of this class of events is discussed.

Events with a leading neutron have been studied in the context of *ep* [1, 2] and *pp* [3, 4] collisions. These events open a window to very interesting physics topics. In this note it is shown that ALICE can tag these events using the capabilities of the neutron ZDC (nZDC) detectors.

The note is organized as follows. First a brief overview of selected experimental results is presented in Section 1. One way to interpret this events is within the one pion exchange model (OPE) which will be discussed in Section 2. Using a neutron flux from the OPE model the response of the neutron ZDC is evaluated in Section 3. Finally, in Section 4 some of the physics potential of this class of events are discussed.

1 Leading forward neutrons

Both HERA experiments have recently measured and studied a class of events with a leading forward neutron the deep inelastic as well as in the photoproduction regime of *ep* collisions [1, 2]. This class of events has also been

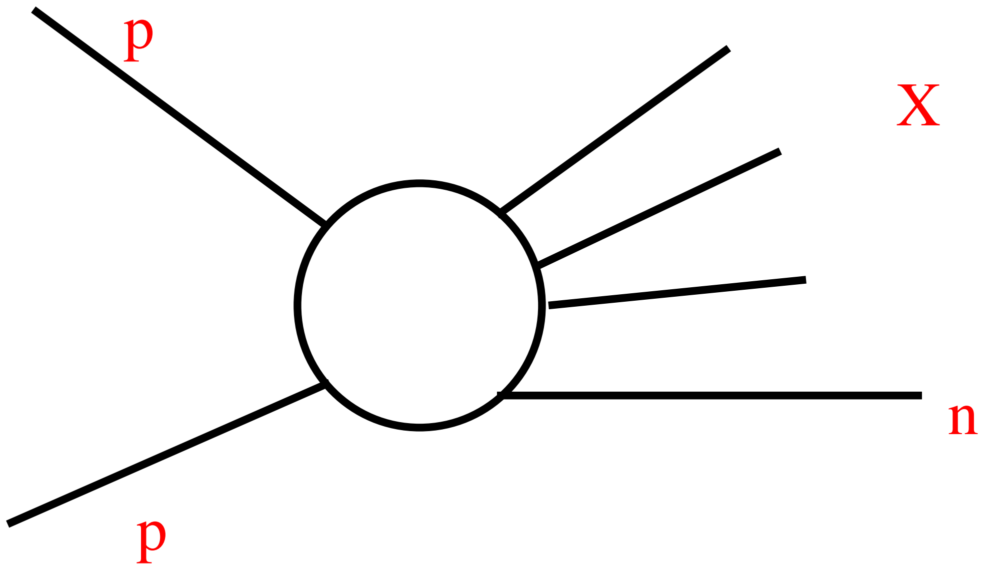

Figure 1: Two protons collide and produce a neutron and an indetermined system X. The neutron retains the direction of one of the incoming protons and carries away almost all of its energy.

observed in the ISR [3] and Fermilab [4] in pp collisions. It is interesting to note that these events are quite frequent. At HERA one measures approximately 1 event in each 10 deep inelastic collisions and 1 event in each 30 collisions in the photoproduction regime [1, 2].

With a leading forward neutron it is meant a neutron carrying a sizable fraction of the energy of the incoming proton and being produced with a rapidity very close to that of the incoming proton. This is illustrated in Figure 1 where two protons collide in the CMS with a total energy $\sqrt{s_{pp}} = 2E_p$, where E_p is the energy of the incoming protons. The neutron is produced with an energy $E_n = xE_p$ such that $x \approx 1$ and at a very forward rapidities $\eta_n \approx \eta_p$.

2 The one pion exchange model

Normally the structure of hadrons, in particular that of the proton, is described perturbatively in terms of quarks and gluons, but there are indications that non perturbative contributions may be sizable in some parts of phase space.

In this context one can picture the bare proton surrounded by a cloud of virtual particles. In this approach the wave function of the proton is expressed by the different possible Fock states allowed by the proton quantum numbers:

$$|p\rangle = \alpha|p\rangle_{\rm bare} + \beta|\pi n\rangle + \cdots \quad (1)$$

2.1 The OPE

There is experimental evidence that in a specific part of phase space the second term in the right hand side of equation 1 is the dominant contribution [5]. In this region the process $pp \to nX$, depicted in Figure 1, can be interpreted as shown in Figure 2 where the process happens now in two stages. In a first step the proton fluctuates to a $\pi n\rangle$ state[1] and afterwards the pion interacts with the counter rotating proton while the neutron continues his trajectory untouched. The momentum transfered in the $p\pi n$ vertex is given by t through:

$$t = -\frac{p_T^2}{x} - \frac{1-x}{x}(m_n^2 - xm_p^2), \quad (2)$$

where p_T is the transverse momentum of the neutron, x is the fraction of the proton energy carried by the neutron and m_n and m_p are the masses of the neutron and proton respectively.

In this case the process factorizes into two terms: a flux $f_{n/p}$ of neutrons in the proton and the $p\pi$ scattering. Hence the cross section can be written as

$$E_n \frac{d^3\sigma(pp \longrightarrow nX)}{d^3p} = f_{n/p}(x, p_T)\sigma_{\pi p}(s_{\pi p}) \quad (3)$$

where E_n is the energy of the neutron and $s_{p\pi} = s_{pp}(1-x)$.

[1] As a matter of fact, the proton can fluctuate into a number of states. Here we will concentrate in the fluctuation into a πn state, which is the dominant process in the region of phase space we are interested in

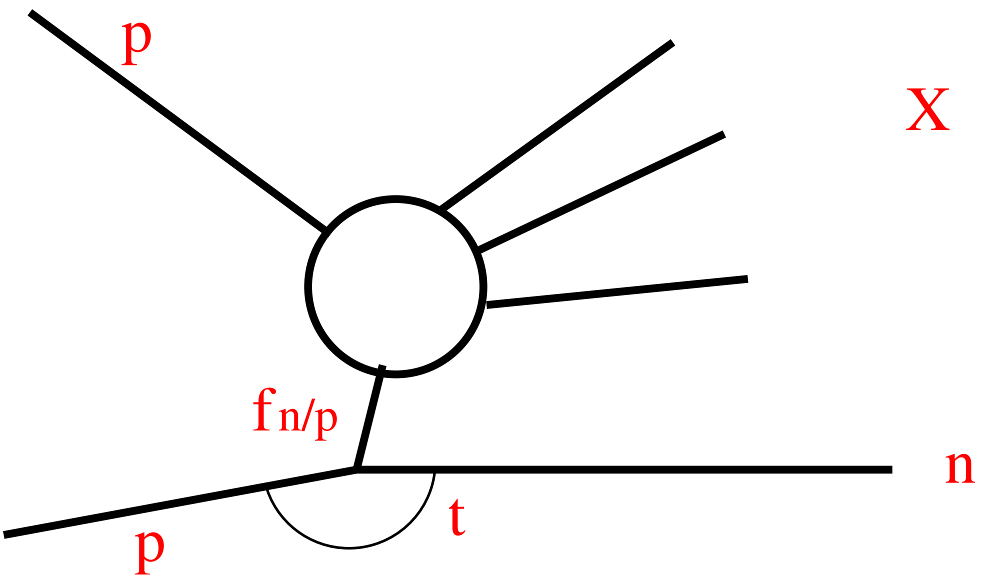

Figure 2: The collision of two protons happens in two steps. First one of the protons fluctuates into a neutron-pion state, and then the meson interacts with the other proton, while the neutron carries away most of the energy of the first proton.

2.2 The flux

The flux of neutrons $f_{n/p}$ is not perturbatively calculable. There are many prescriptions to compute it within different models based on the OPE idea. Here I use the formula advocated in [5] and given by

$$f_{n/p}(x, p_T^2) = \frac{g_{pn\pi}^2}{16\pi^3} \frac{(1-x)^2 m_n^2 + p_T^2}{[m_n^2 - M_{n\pi}^2(x, p_T^2)]^2} \frac{|G_{pn\pi}(x, p_T^2)|^2}{x(1-x)}, \tag{4}$$

where

$$M_{n\pi}^2(x, p_T^2) = \frac{m_n^2 + p_T^2}{x} + \frac{m_\pi^2 + p_T^2}{1-x}, \tag{5}$$

$$G_{pn\pi}(x, p_T^2) = \exp\left[\frac{m_n^2 - M_{n\pi}^2(x, p_T^2)}{2\Lambda^2}\right] \tag{6}$$

with $g_{pn\pi}^2/4\pi = 27.2$, and $\Lambda = 1.10 \pm 0.05$ GeV.

The only non perturbative parameter is Λ whose value has been extracted from previous experiments. Note that within the OPE model the flux is a a universal quantity. This means that once it is determined it can be used in any other context.

The flux given by equation (4) is shown in Figure 3. It is clear that most of the produced neutrons carry approximately 80% of the incoming proton and that they are produced with transverse momentum close to zero. It is also important to notice that the flux is negligible for $p_T > 1GeV$.

2.3 Validity of OPE

The OPE has been successfully tested at HERA [1, 2], the ISR [3] and Fermilab [4]. It also has some predictive power. For example it has been invoked to predict the $\bar{u} - \bar{d}$ asymmetry [6] which was then measured by NA51 Drell-Yan experiment [7]. In summary it is a mature technique which provides interesting insight into the inner structure of hadrons.

3 The neutron ZDC

Having the main kinematic characteristics of the produced neutron, it is possible to explore the possibility to tag this class of events using the neutron ZDC detectors.

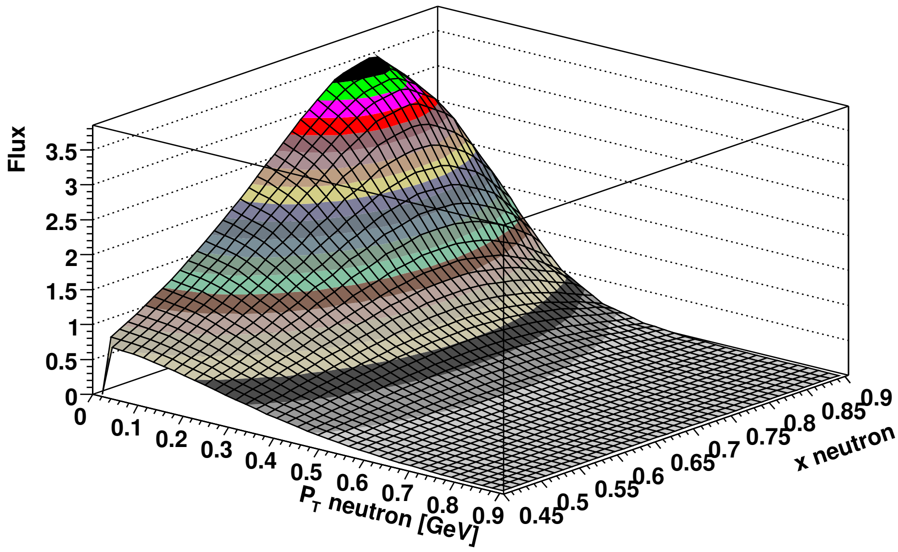

Figure 3: Flux of neutrons in the proton as a function of the fraction of the proton energy carried by the neutron and its transverse momentum. See equation (4).

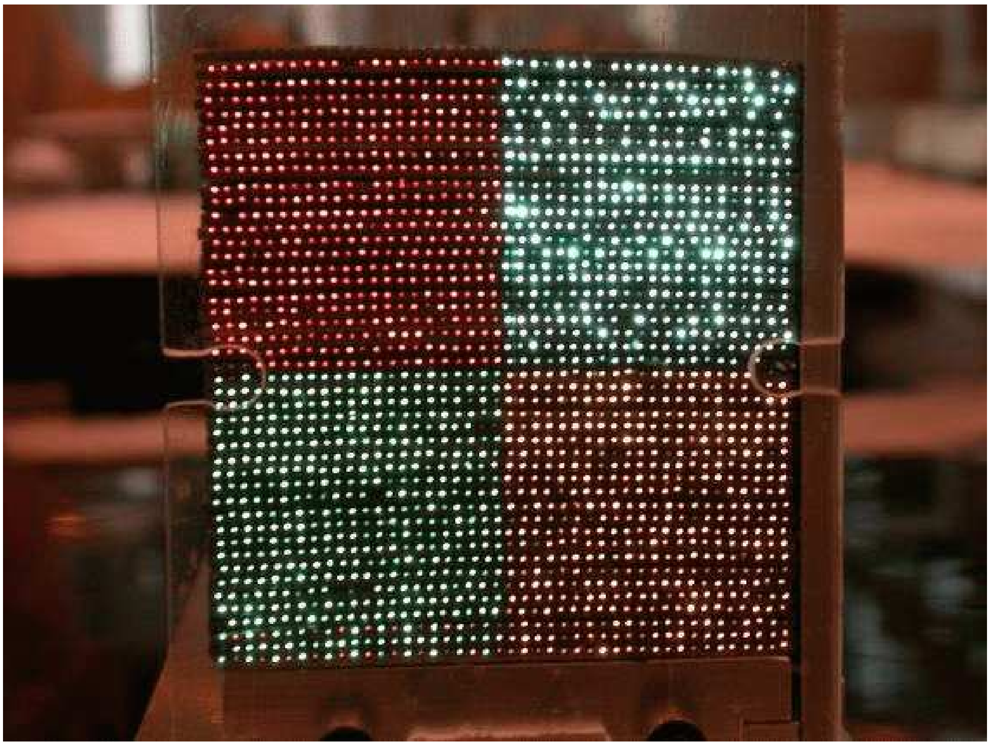

Figure 4: Frontal view of th nZDC. The four modules and the fibers are clearly seen.

3.1 Description of the detector

The neutron ZDC detector is described in detail in [8]. Here only the main features needed for the analysis are explained. The ALICE detector has two neutron ZDC detectors positioned at $\pm$ 116 m away from the nominal interaction point along the direction of the incoming proton beams.

Each detector is composed of 44 grooved W-alloy slabs and the sensitive material is formed by 1936 quartz fibers. The dimension of the front face is a square of 7.2 cm^2 and has a depth of 100 cm corresponding to 8.5 interaction lengths (see Figure 4). It is read via PMTs and segmented in 4 modules. The read out has 5 channels (for details see [8]) which may open up the possibility of measuring the transverse position of the impact point of the neutron and to deduce from it the transverse momentum of the neutron which in turn helps to determine the momentum transfered in the $p\pi n$ vertex.

3.2 Efficiencies, acceptance and background

Note that the geometric acceptance for neutrons given by the position and geometry of the detector covers the neutron transverse momentum p_T form zero up to approximately 1.6 GeV which allows in principle to use all the flux shown in Figure 3.

Given that the spectrum is peaked at $p_T \approx 0$ single neutron events have been generated with the AliRoot class **AliGenZDC** with $p_T = 0$ and no Fermi motion, but taking into account the crossing angle of the interacting beams. The events have been generated with fixed E_n at values of x going from 0.45 to 0.95 in steps of 0.05.

No x dependence have been found in the efficiency to tag the leading neutrons ($\approx 90\%$), nor in the calibration factor to get back the neutron energy ($E_n = E_{\mathrm{nZDC}}/0.43$), nor in the Energy resolution ($\approx 9\%$). This is shown in Figure 5

To evaluate possible background from inelastic non diffractive collisions Pythia events have been generated. The corrected energy spectra of neutrons in the nZDC is shown in Figure 6. Most of the events have no energy deposition in the nZDC. The same figure show the contribution from the OPE model with solid and empty bullets. The normalization is such that the contribution from OPE in the case of solid bullets is equal to the contribution of the background for a value of x neutron around 0.4 as found by the ZEUS Collaboration [2] for the photoproduction regime. The contribution from OPE depicted with the empty bullets is the same as the solid bullets but suppressed by an additional factor of five. Even-though the normalization is somewhat arbitrary and there is a big question mark regarding the hadronization in the forward direction from Pythia, the conclusion of this study is that the contribution from the background can be controled in the analysis of leading neutron production in the diffractive case.

3.3 Some comments on a trigger for leading forward neutrons

It is envisioned that the ZDC has the necessary capabilities to trigger on different centrality classes during $Pb--Pb$ collisions. From this point of view it could be argued that, in principle, a trigger for leading neutrons could be implemented. The main problem is that one would probably need the ZDC signal already at the level zero of the trigger.

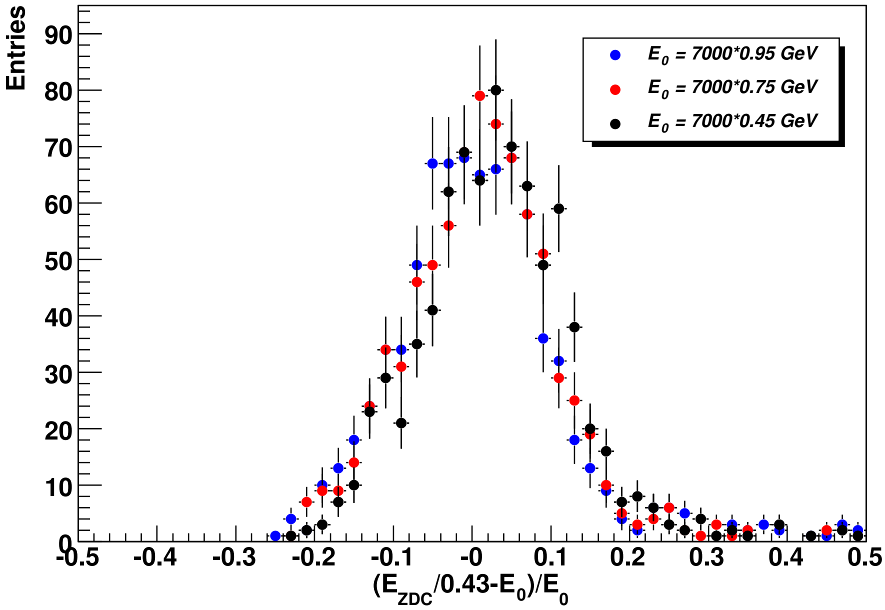

Figure 5: Quality of the measurement of single neutrons shot from the nominal interaction point in ALICE towards the neutron ZDC with different initial energies E_0. The energy deposited in the nZDC is denoted with E_{ZDC} and the factor 0.43 is the calibration correction factor to convert the measured energy to the energy of the neutron.

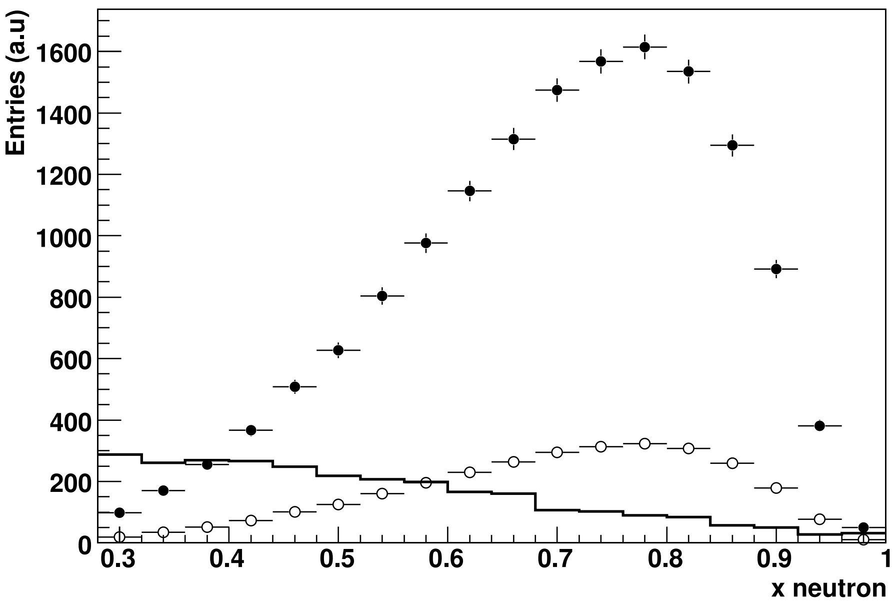

Figure 6: The contribution of non diffractive events, according to Pythia, to neutrons measured in the ZDC (solid line) is compared to the OPE model normalized such that signal and background are the same around 0.4 (full bullets) and the same OPE result suppressed by an additional factor of five (empty bullets).

It has to be stressed that one would expect a big rate of this type of events, so even keeping only the minimum bias triggered events one should be able to have nice statistics to do first studies of this kind of events and evaluate the need of a dedicated trigger setting.

Other argument to investigate the possibility to use the neutron ZDC as a triggering device is furnished by the interest on ultra-peripheral collisions (UPC) [9, 10] which can be tagged asking for very small multiplicities in the central detector and the presence of neutrons at forward rapidities. Leading forward neutrons in *pp* collisions would also serve to test and commission a trigger for UPC.

4 Physics potential

If it turns out that these events are also present at LHC energies the first step would be to check that the OPE is a valid approach in this new kinematic domain. This means to measure the flux and see if it has the predicted shape. One can also define a class of events, for example events with two jets in the central detector an a neutron in the ZDC and check that the neutron spectra is indeed independent of the two jet production as a function of, say, the transverse momentum of the jets in the partonic CMS of the hard scattering.

If the OPE is found to be a reasonable model for the data, one could go a step forward and try to measure the pion regge trajectory. Even if this measurement is not possible, if there is a region of phase space at LHC where the OPE formalism is validated, then a whole new horizon of physics topics opens up. One would have access to effective proton-pion and pion-pion collisions at LHC energies. Indeed, every analysis one can think to perform for proton-proton collisions, can be then also performed in these other two effective systems. These include for example constrains to effective pion PDFs and possible extraction of effective strangeness, charm, and beauty content of the pion.

These type of events have also been used to generate the $\bar{d}-\bar{u}$ asymmetry and it would be interesting to explore the possibility of this type of analysis comparing events with zero, one and two tagged forward neutrons.

There is though a potential problem in the case of the ALICE detector. How to be sure that these are real diffractive events; i.e., that there are no more particles produced near the forward neutron. The experimental solution would be to put some counters around the ZDC to be sure that there is a large rapidity gap between the neutron and any other particle. This solution looks quite complicated given the amount of material from the LHC accelerator present in the region where the nZDC will be installed. Another option could be that the theoreticians compute an upper limit to the contribution from other kinds of events to see if one can extract the signal. Given that at HERA it is possible to measure the presence of large rapidity gaps, and that the events compatible with the OPE are quite frequent, it can be argued that the contribution from other sources at large neutron x are small.

Even if the OPE approach can not be fully validated, one would have access to classes of events with zero, one and two units of baryon number tagged at very forward rapidities. The comparison of these three classes of events looks to be an ideal playground to test the different hadronization models, specifically the hadronization of mesons with respect to that of baryons and eventually to shed some light in the process of transport of baryon number to central rapidities.

5 Summary, conclusions and outlook

It has been shown that using the capabilities of the neutron ZDC detectors of ALICE, the special class of events with one or two leading forward neutrons can be tagged and then studied using the central ALICE detector. The efficiency to tag these events is quite high and there is not much background expected. It has also been argued that these events would expand the *pp* physics program of the ALICE Collaboration.

Two interesting aspects which one should explore further are first the capabilities to measure the transverse momentum of the leading neutron and second the capabilities of the neutron ZDC as a triggering detector. This second point has also repercussions for the study of ultra peripheral collisions as part of the physics program for heavy ion collisions.

It would also be quite important to draw the attention of theoreticians potentially interested in this kind of physics to invite them to propose topics attractive to them which could potentially be measured in ALICE.

Acknowledgments

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