Subnuclear Physics: Past, Present and Future
Pontifical Academy of Sciences, Scripta Varia 119, Vatican City 2014
www.pas.va/content/dam/accademia/pdf/sv119/sv119-cifarelli.pdf

An Interesting Result in pp collisions at 7 TeV

A. Agostinelli[1,4], A. Alici[3], P. Antonioli[2], S. Arcelli[1], R. Baldini Ferroli[3], F. Bellini[1,4], G. Cara Romeo[2], L. Cifarelli[1,3,4], M. Colocci[1], A. De Caro[3], D. De Gruttola[4,5], S. De Pasquale[5], M. Fusco Girard[5], B. Guerzoni[1,4], D. Hatzifotiadou[2], A. Margotti[2], R. Nania[2], F. Noferini[3], P. Pagano[5], A. Pesci[2], R. Preghenella[3], E. Scapparone[2], G. Scioli[1,4], M.C.S. Williams[2,4], C. Zampolli[2,4], A. Zichichi[1,4]

[1] Dipartimento di Fisica dell'Università e Sezione INFN, Bologna
[2] Sezione INFN, Bologna
[3] Centro Fermi – Centro Studi e Ricerche e Museo Storico della Fisica "Enrico Fermi", Roma
[4] CERN, Geneva
[5] Dipartimento di Fisica "E.R. Caianiello" dell'Università e Gruppo Collegato INFN, Salerno

In this work we explore the possibility to perform 'effective energy' studies in very high energy collisions at the CERN Large Hadron Collider (LHC). In particular, we focus on the measurement of the 'quantum number flow' in pp collisions with the ALICE experiment, exploiting the capability of the Zero Degree Calorimeters (ZDCs) to measure the energy of the leading baryons in the very forward region with respect to the beam axis. Similar studies performed at lower centre-of-mass energies have shown that, once the appropriate physical variables are chosen, particle production is characterized by universal properties: no matter the nature of the interacting particles, the final states have identical features.

Introduction

In high-energy particle collisions, bulk event properties like the average charged particle multiplicity are regarded as experimental observables of fundamental interest, providing important information on the dynamics of the interaction. In particular, the average charged particle multiplicity in multihadronic final states has been measured in many different interacting systems (e^+e^- and $pp(\overline{p})$ collisions, DIS processes, etc.) and over a wide range of centre-of-mass energies. The data show a dependence on $\sqrt{s}$ which is apparently characteristic of the specific initial state under consideration. This kind of dependence disappears if the 'effective energy' is considered to characterize the system as proved in the past in a CERN ISR (Intersecting Storage Rings) experiment [1-6], performed using the SFM (Split Field Magnet) facility at energies of tens of GeV. The aim of this work is to address the possibility to carry out a similar study at energies of several TeV at the LHC and to measure the energy distribution of the so called 'quantum number flow' (QNF) particles, with the ALICE experiment [7-9]. In this respect ALICE (A Large Ion Collider Experiment) has excellent capabilities, thanks to the presence of several detectors for the measurement of particle multiplicity over a wide rapidity range [10,11]. Moreover, on both sides of the interaction point, the experiment is equipped with very forward hadronic calorimeters, the Zero Degree Calorimeters (ZDCs) [12], which allow to derive the effective energy on an event-by-event basis by detecting the outgoing leading nucleons.

Quantum number flow in pp collisions

The global properties of the final state in high-energy collisions are governed by the non-perturbative regime of QCD. This means that if the energy is high enough particles produced in the collision should not care about the nature of the colliding system but only on the energy effectively available for particle production. In e^+e^- collisions the annihilation process makes all the centre-of-mass energy available for the production of final state particles. In other systems, like pp or $p\overline{p}$ collisions, the main process is constrained by the conservation of the initial quantum numbers. We call quantum number flow (QNF) the component of the final state particles which conserves these numbers and therefore removes a sizeable fraction of the total centre-of-mass energy. In particular, in pp collisions, the initial non-zero baryon flow is expected to be manifest in the very forward rapidity region, where high (longitudinal) momentum and energy QNF baryons, often called leading baryons, can be detected. In this case it is necessary to define an effective energy to describe the system subtracting the QNF energy to the initial centre-of-mass energy ($\sqrt{s}$). For each hemisphere, defined with respect to the plane transverse to the beam axis, this effective energy is:

$$E_{had} = E_{inc} - E_{leading} \tag{1}$$

where $E_{inc} = \sqrt{s}/2$ and $E_{leading}$ equals the energy of the outgoing QNF particle in one hemisphere.

Once the proper variable is defined it is then possible to characterize the products of a collision in terms of the available energy of the system. It was demonstrated at ISR that the charged particle multiplicity measured in pp collisions is in very good agreement with the one measured in e^+e^- collisions when the effective energy is considered, as shown in Fig. 1 [5].

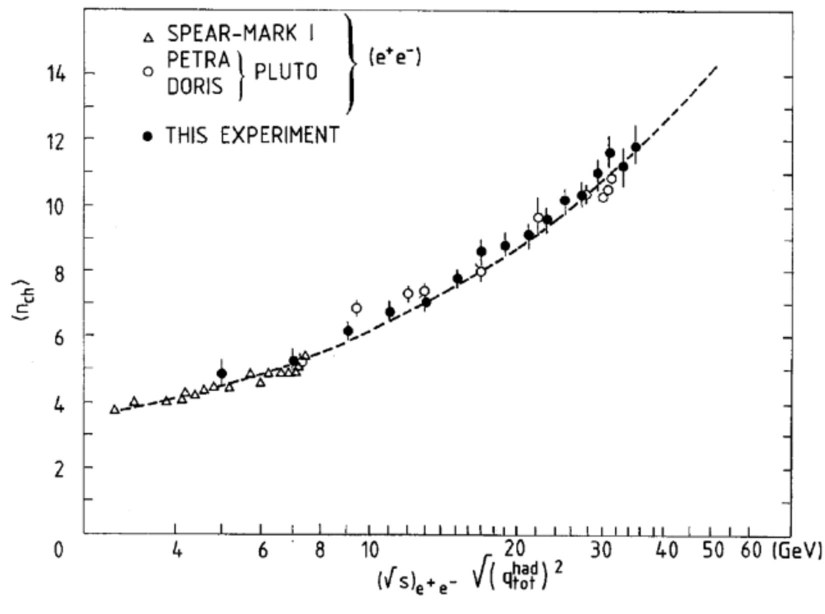

Fig. 1. Average charged multiplicity $\langle n_{ch} \rangle$ as a function of the effective energy (here indicated as $\sqrt{(q_{had}^{tot})^2}$, as measured in minimum bias pp collisions collected by the SFM experiment at the CERN ISR (full circles). The data from e^+e^- experiments are also shown (open circles and triangles) in terms of $\sqrt{s}$. A fit to ISR pp data is superimposed.

At the ISR it was also proved that the QNF effect happens in both hemispheres independently, as shown in Fig. 2 [6] for leading protons, where in each hemisphere their Feynman-x can be defined as $x_F^i = \frac{E_{leading}^i}{E_{inc}}$, with $i = 1, 2$.

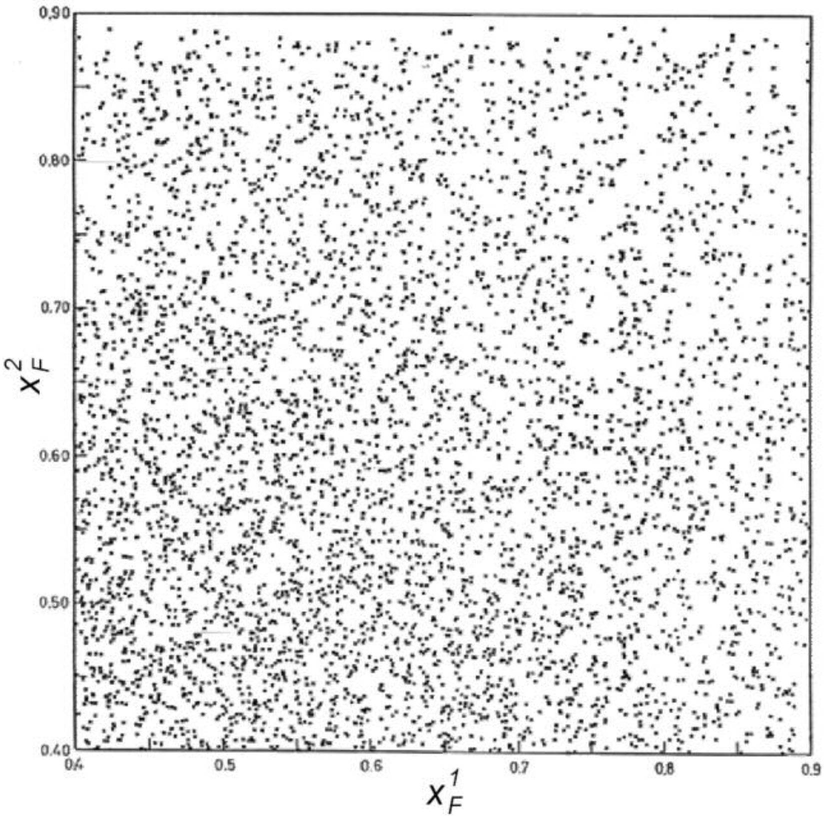

Fig. 2. Independency of the two hemispheres as seen in pp ($\sqrt{s} = 62$ GeV) at ISR, in terms of x_F^1 vs. x_F^2 for leading baryons (protons). The data correspond to about 2 x 10^5 pp events.

For this reason it is also possible to define a global effective energy involving both hemispheres:

$$q_{had}^{tot} = \sqrt{s(1 - x_F^1)(1 - x_F^2)}. \quad (2)$$

It has been demonstrated at the ISR that using both $2E_{had}$ and q_{had}^{tot} leads to the same observations in terms of particle production in a wide range of $\sqrt{s}$ and x_F values. It should be stressed here that, from the experimental point of view, using the first definition (Eq. 1) allows to collect larger statistics as only one leading QNF particle needs to be detected. However, using the second approach (Eq. 2) does not require to distinguish particles in the two hemispheres .

This important results was recently reviewed on the occasion of the 40th anniversary of the ISR [13] and it will be further studied at the LHC in a new energy domain by the ALICE experiment, as foreseen in the ALICE Physics Performance Report in 2007 [10, 11] and as described in the next sections.

The ALICE Zero Degree Calorimeter

Although the programme of the ALICE experiment has its main focus on heavy-ion physics, the detector has also excellent capabilities to study pp collisions. In particular, this applies to the analysis we are presenting in this paper.

The ALICE experiment started collecting data at the end of 2009 and both pp and PbPb data are available. pp data have been collected by ALICE with full-apparatus data acquisition at the energies of 900 GeV, 2.76 TeV and 7 TeV. A small sample of events was collected in 2009 at a centre-of-mass energy of 2.36 TeV but only few subdetectors were included in the data taking. Also PbPb collisions were collected in ALICE at the energy of 2.76 TeV per nucleon pair. In this paper we will focus on pp collisions at 7 TeV.

In Fig. 3 a summary of centre-of-mass energies with respect to effective energy ranges accessible by ALICE is reported and compared with the one corresponding to the ISR.

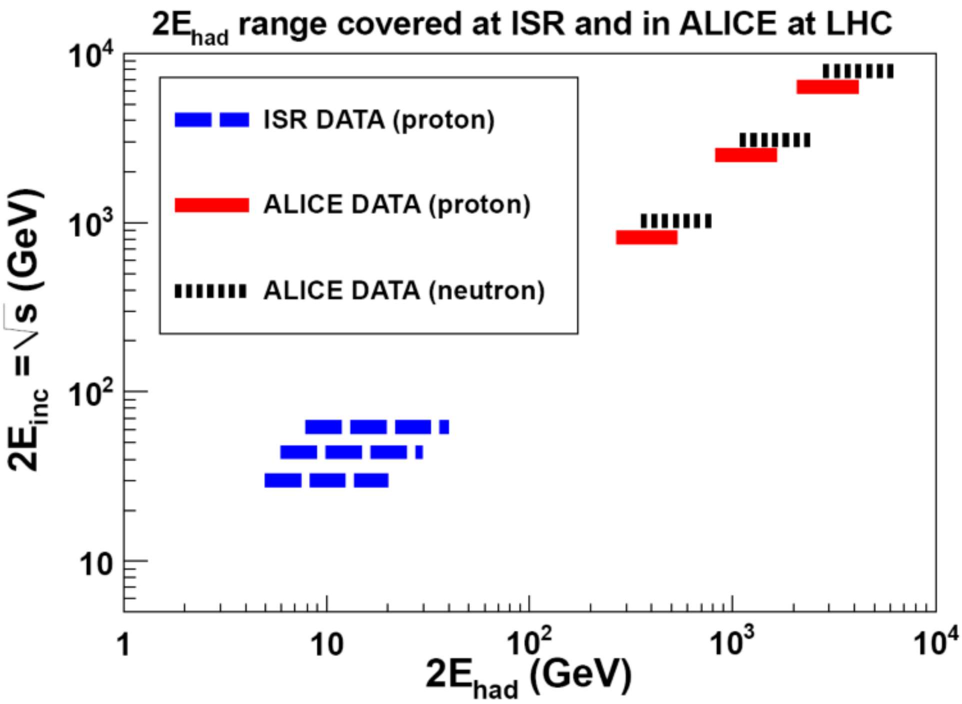

Fig. 3. Effective energy range (here indicated as $2E_{had}$ range) covered at ISR and LHC as a function of $\sqrt{s}$.

Two sets of Zero Degree Calorimeters (ZDCs) are located in the very forward region on both sides (called side A and side C) of the interaction point. They have been designed to provide a measurement of the centrality of nuclear collisions by measuring the energy of the spectator nucleons not participating in the collision. The same apparatus can be used in pp collisions to detect the leading baryons, both charged and neutral, thus allowing the measurement of the QNF energy on an event-by-event basis.

A scheme of the ZDC apparatus is shown in Fig. 4; it consists of two identical sets of detectors, placed on both sides of the interaction vertex at a distance of 116 m. Each set consists of two calorimeters, one for leading neutrons (ZDCN) and one for leading protons (ZDCP). Charged particles produced at very forward rapidity (leading protons) are slightly deflected by the LHC optics, therefore only those produced with 0.30 < x_F < 0.64 actually impinge on the ZDCP. For neutral particles such constraints are not present. Each calorimeter is segmented in 4 towers and two different geometries are used for ZDCN and ZDCP: 4 quadrants for the former and for 4 towers placed along the orizontal axis ortogonal to the beam direction for the latter. A more detailed description of the calorimeters is given elsewhere [12].

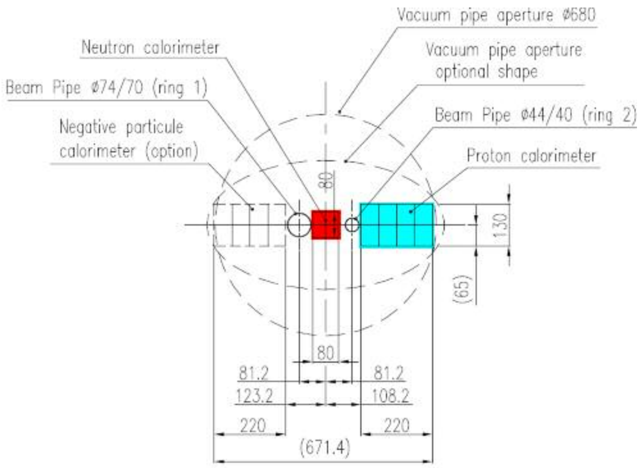

Fig. 4. Transverse section of the LHC beam line at a distance of 116 m from the interaction vertex. The location of the two ZDC calorimeters for protons and neutrons is also shown.

Because of the presence of two beam collimators in front of the ZDC neutron calorimeters, the experimental setup conditions in 2010 and 2011 pp data were not optimized. In this particular configuration an accurate estimate of the acceptance could not be achieved. In view of 2012 pp data taking, these two collimators have been moved behind the ZDCs and this will provide a cleaner experimental environment. For these reasons the results presented hereafter are not corrected for acceptance and efficiency factors, which will instead be possible with the forthcoming 2012 data.

In the next section we focus on the feasibility of the effective energy study in pp interactions at LHC using Monte Carlo simulations and we report the first results which are observed to be only weakly dependent on the acceptance corrections.

The analysis scheme and a first interesting result

The performance of the ALICE ZDC calorimeters was first checked through detailed Monte Carlo simulations using the PYTHIA generator [14] to mimic the physics expected in pp collisions. More detail on the leading baryon behaviour described by PYTHIA can be found in a previous study in [15].

As already mentioned, due to the beam optics the ZDC acceptance is restricted to protons with energies in the range 1.1 < E < 2.25 TeV, while in the case of neutrons the whole range of energy is accessible. The GEANT3

[16] package and the ALICE simulation and reconstruction software, AliRoot [17], were used for the simulation of the detector response, and to perform realistic digitization and reconstruction in the ZDC calorimeters.

The full simulation allows to estimate the energy responses of the calorimeters for the different components (photons, baryons, etc.) and the corresponding resolutions. As mentioned before the estimate of the acceptance is still problematic because of the current difficulties in describing the influence of the beam collimator in a satisfactory way.

In Fig. 5 the neutral leading distribution is reported, in terms of x_F, for one tower of the ZDCN. The black points represent the reconstructed distribution including all detector effects. As it can be noted the 'measured' distribution is non-zero also for x_F larger than one because of resolution effects. Actually the energy resolution at the highest energy is about 20%. The red line is a global function used to fit the distribution. Two components are used in the fit: the baryon component which is described by a polynomial Legendre function convoluted with the detector resolution, and the photon component which is represented by an exponential convoluted with the detector resolution. Both the components are forced to be zero for $x_F = 0$ according to the expected acceptance behaviour. This model fits the data very well, thus allowing to extract separately the baryon and photon distributions already unfolded from resolution effects. The 'reconstructed' distributions, respectively blue and green line for baryon and photon components, are compared with the 'true' ones (open squares), as generated by the Monte Carlo enabling to validate the procedure. A good agreement is obtained, although the method can be further refined, which shows that the technique is very promising to perform such a measurement.

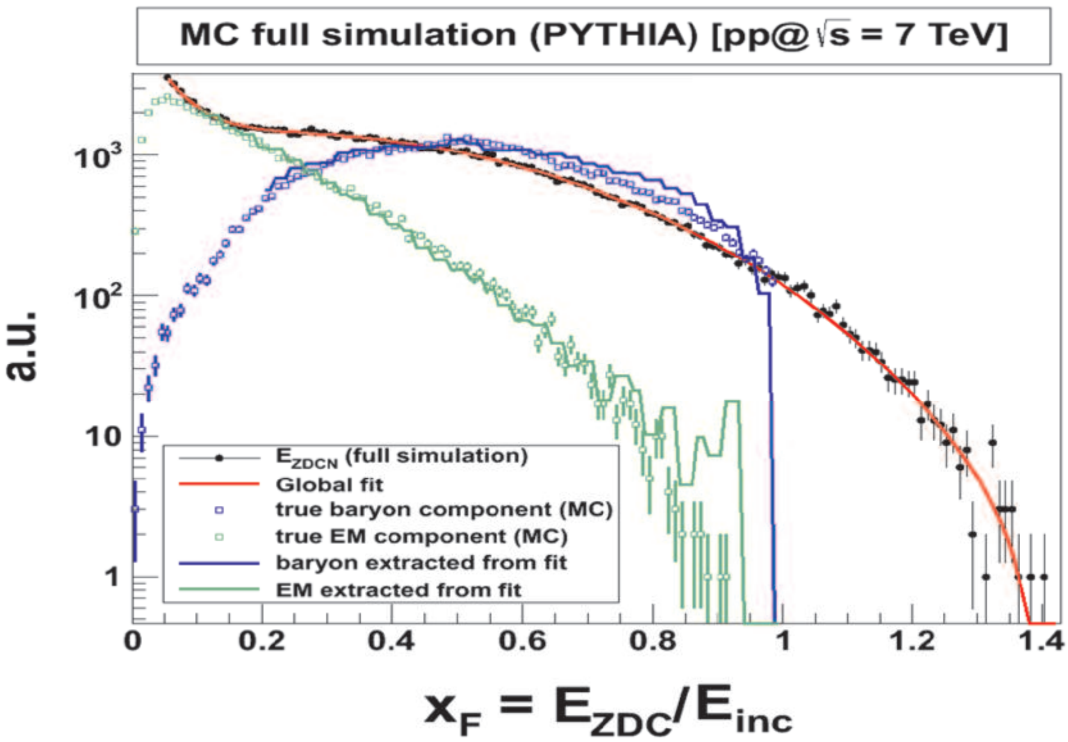

Fig. 5. Global fit to the leading neutron x_F distribution in Monte Carlo (MC) simulations. This procedure allows to disentangle the photon and baryon components and to remove the ZDC resolution effect through a deconvolution.

The same procedure has to be applied to the data and therefore a calibration of the ZDC channels is needed to convert the ADC charge into the energy of particle hits the calorimeter.

A very clean signal to calibrate the ZDC is provided by electromagnetic dissociation processes in PbPb collisions. To this purpose the data sample at $\sqrt{s}$ = 2.76 GeV has been used. These processes consist in the emission of one ore more nucleons which escape from the nucleus and continue to propagate approximately with the same energy (1.38 TeV). The signal expected in the calorimeter has a discrete spectrum of Gaussians corresponding to the case of 1, 2 or more nucleons recovered, as clearly visible in Fig. 6 where each peak corresponds to a known value of the energy.

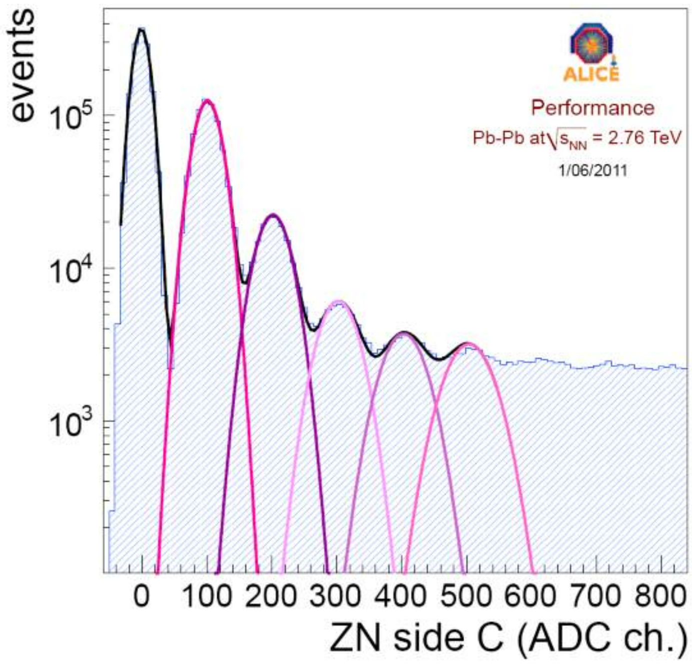

Fig. 6. Fit to the ZDCN (C side) energy distribution for electromagnetic dissociation processes in PbPb collisions ($\sqrt{s_{NN}}$ = 2.76 TeV).

This technique allows to calibrate the common channel (i.e. corresponding to the OR of all single-tower signals of the calorimeter) and after that the relative calibration of the single-tower channels can be obtained with respect to the common one. Therefore, even if it is not possible at the moment to derive a QNF energy distribution from the data because of the still large uncertainties in the acceptance, there are some observations that can be already made. In fact the correlation between the QNF energies of the two hemispheres can be investigated and this is one of the key features in the particle production mechanism as observed in the past at ISR.

The question is whether the independency of the two hemispheres still holds true when moving at much higher energy above $\sqrt{s}$ = 62 GeV. We performed this measurement at the maximum LHC energy available so far, i.e. $\sqrt{s}$ = 7 TeV, using the neutral component of the QNF in order to cover the same x_F range as in the ISR experiment. In Fig. 7 and Fig. 8 (right panel) the independency of the QNF in the two hemispheres is clearly visible for $0.4 < x_F < 0.9$, thus established at an unprecedented centre-of-mass energy. Furthermore, by comparing the data at $\sqrt{s}$ values which differ by more than a factor 10^2, one can clearly see (Fig. 8) that this non-correlation of the two hemispheres is energy independent. It should be noted that although the LHC data were not corrected for acceptance and efficiency, such a correction is negligible in the x_F range considered in this analysis. This result opens the way to a detailed study of a phenomenology similar to what observed at the ISR.

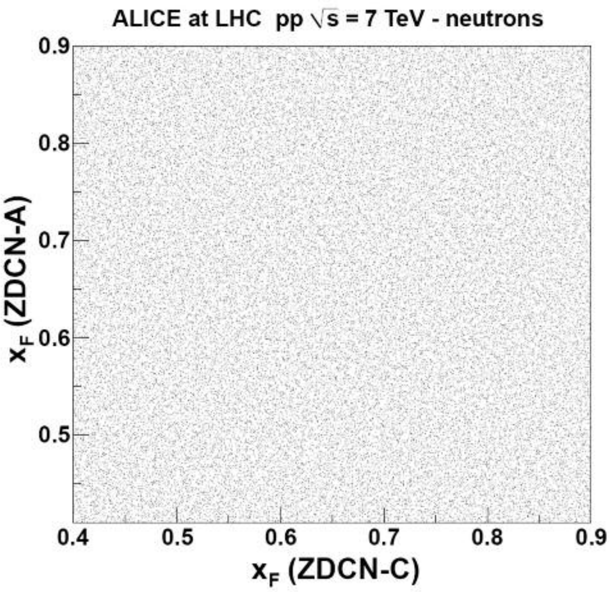

Fig. 7. Independency of the two hemispheres as seen in pp ($\sqrt{s}$ = 7 TeV) by ALICE at LHC, in terms of x_F^1 vs. x_F^2 for leading baryons (neutrons). The data correspond to about 2 x 10^7 pp events.

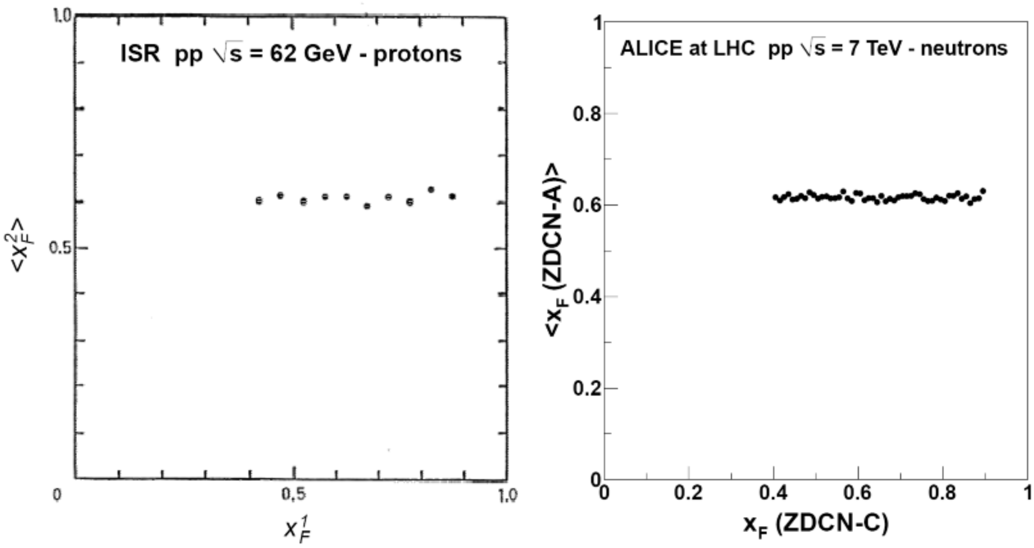

Fig. 8. Independency of the two hemispheres as seen at ISR (left panel) and by ALICE at LHC (right panel), for leading baryons (i.e. protons and neutrons, respectively). These plots are obtained by slicing those shown in Fig. 2 and Fig. 7.

Conclusion

In this work we have shown the feasibility to extend the ISR physics programme up to LHC energies with the ALICE detector and its capability to detect final state baryons in the very forward region. Following the ISR guide lines, the properties of pp collisions and in particular of multihadron production will be soon characterized using the effective energy approach (QNF effect subtracted), for three new values of energy: $\sqrt{s} = 0.9, 2.76, 7\ \mathrm{TeV}$. The measurement of the QNF neutron and proton distribution is ongoing. The independence of the two hemispheres is now proved also at LHC energies similarly to ISR observation. These results represent a further interesting frontier of the LHC research programme.

References

1. M. Basile *et al.*, Phys. Lett. B **92** (1980) 367
2. M. Basile *et al.*, Phys. Lett. B **95** (1980) 311
3. M. Basile *et al.*, Nuovo Cim. A **67** (1982) 244
4. M. Basile *et al.*, Nuovo Cim. A **79** (1984) 1
5. M. Basile *et al.*, Lett. Nuovo Cim. **38** (1983) 359
6. M. Basile *et al.*, Nuovo Cim. A **73** (1983) 329
7. ALICE Collaboration, "ALICE: Technical Proposal for A Large Ion Collider Experiment at the CERN LHC" CERN/LHCC 95–71 (1995)
8. ALICE Collaboration, "ALICE: Technical Proposal for A Large Ion Collider Experiment at the CERN LHC (addendum 1)" CERN/LHCC 96–32 (1996)
9. ALICE Collaboration, "ALICE: Technical Proposal for A Large Ion Collider Experiment at the CERN LHC (addendum 2)" CERN/LHCC 99–13 (1999)
10. F. Carminati *et al.*, J. Phys. G **30** (2004) 1517
11. F. Carminati *et al.*, J. Phys. G **32** (2006) 1295
12. ALICE Collaboration, "ALICE Technical Design Report of the Zero Degree Calorimeter (ZDC)" CERN/LHCC 99–5 (1999)
13. A. Zichichi, Nuovo Saggiatore **27** n. 3-4 (2011) 48
14. T. Sjostrand, S. Mrenna and P. Skands, JHEP **605** (2006) 826
15. A. Akindinov *et al.*, Eup. Phys. J. C **50** (2007) 341
16. R. Brun, F. Bruyant, M. Maire, A. C. McPherson and P. Zanarini, "GEANT3" CERN-DD/EE 84–1 (1987)
17. ALICE Collaboration, http://aliweb.cern.ch/Offline/