Particle rapidity distribution in proton-nucleus collisions using the proton-contributor reference frame

Ginés Martínez-García

1Subatech (CNRS/IN2P3 - Ecole des Mines de Nantes - Université de Nantes), Nantes, France

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Abstract

I define the proton-contributor reference frame in proton nucleus (p–A) collisions as the center of mass of the system formed by the proton and the participant nucleons of the nucleus. Assuming that the rapidity distribution of produced particles is symmetric in the proton-contributor reference frame, several measurements in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV can be described qualitatively. These include rapidity distributions of charged particles, $J/\psi$ and $Z$ bosons.

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I. INTRODUCTION

In proton-proton (pp) and nucleus-nucleus (A–A) collisions, the colliding system defines unambiguously the reference frame in which the rapidity distribution of particles produced in the collisions must be symmetric. In proton-nucleus (p–A) collisions, the situation is more complex since this rapidity distribution is not expected to be necessarily symmetric. Therefore we are used to consider the nucleon-nucleon center-of-mass frame, as for pp and A–A collisions. This is justified for high-energy p–A collisions which can be seen as a multiple interaction of parton pairs, one parton of the pair belonging to the proton and the other belonging to one of the nucleons of the nucleus. I propose hereafter an alternative reference frame, called the proton-contributor reference frame. The main assumption is that particles are produced in p–A collisions with a rapidity distribution identical to that in pp collisions, but shifted by the rapidity gap between the proton-nucleon and the proton-contributor reference frame. Under this simple hypothesis the centrality dependence of charged particle pseudo-rapidity distribution measured by the ATLAS collaboration, the suppression (enhancement) of the \( J/\psi \) at forward (backward) rapidity measured by the ALICE collaboration, and the Z boson backward-to-forward ratio measured by the CMS collaboration, are qualitatively understood.

II. TIME SCALE OF THE P–A COLLISION

Many of the numerous theoretical models aiming at describing heavy-ion or proton-nucleus collisions at RHIC and LHC energies assume that, at sufficiently low transferred momentum, the interaction takes place coherently with all the partons of the nuclei or nucleus. Such a coherent interaction will occur when the crossing time of the projectile and the target is smaller than the formation time of a given process. Let us consider the production of a probe involving a momentum transfer \( Q \). The formation time of the probe can be estimated as

\[
\tau_f \approx Q^{-1}. 
\tag{1}
\]

In a proton-nucleus collision, the crossing-time in the reference of the probe (centre of mass frame of the parton-parton interaction in 2→1 processes) can be estimated as

\[
\tau_c \approx R/\gamma_R 
\tag{2}
\]
FIG. 1: Formation times for $J/\psi$, $c\bar{c}$ pair and Z particles and the crossing time in p–Pb collisions at 5.02 TeV, as a function of the probe rapidity in the LHC reference frame.

where $R$ is the radius of the nucleus and $\gamma_R$ is the nucleus Lorentz factor in the probe reference frame. $\gamma_R$ can be expressed as

$$\gamma_R = \cosh (y - y_A)$$

where $y_A$ is the rapidity of the nucleus and $y$ the rapidity of the probe. In p–Pb collisions at 5.02 TeV and for $y = 0$, the crossing time $\tau_c$ is smaller than $\tau_f$ for $Q \lesssim 70$ GeV. Fig. 1 shows the formation times for $J/\psi$, $c\bar{c}$ pair and Z particles, compared to the crossing time in p–Pb collisions at 5.02 TeV as a function of the probe rapidity in the LHC reference frame.

III. THE PROTON-CONTRIBUTOR REFERENCE FRAME IN P–A COLLISIONS

We are used to consider the proton-nucleon reference frame to study the production of a probe in p–A collisions, namely when $\tau_c \gg \tau_f$. Indeed, the probe can be viewed as produced in a single collision of the proton with one of the nucleons of the nucleus. However, we
have seen in the previous section that most of the time $\tau_c \leq \tau_f$ at LHC energies. Therefore, the whole volume of the nucleus crossed by the proton (a cylinder of about $\sqrt{\sigma_{NN}/\pi} \approx 1.5$ fm radius, that I am calling contributor in this paper) will coherently contribute to the production of the probe. In addition, the Bjorken-$x$ ($x_{Bj}$) values of the partons involved in the hard collision are small ($x_{Bj} \leq 2 \cdot 10^{-2}$ for $Q \leq 100$ GeV/$c$ at $y=0$ and $\sqrt{s}=5$ TeV). One could wonder whether the belonging of a small $x_{Bj}$ parton to a given nucleon is not blurred by the presence of other nucleons contributing to the collision. This is the main physics motivation\textsuperscript{1} to make the extreme hypothesis that particles in p–A collisions at the LHC are produced with a rapidity differential cross section which is symmetric in the proton-contributor reference frame with a similar shape as in pp collisions:

$$\frac{dN_{pA(\Delta p)}}{dy}(y) = N \frac{dN_{pp}^{\text{probe}}}{dy}(y - (+)\Delta y_{pN-pC})$$

(4)

where $dN/dy$ are the probe yields, $N$ is a normalisation parameter, and $\Delta y_{pN-pC}$ is the rapidity gap between the proton-nucleon and proton-contributor frames, which is defined below.

The mass and momentum of the contributor can be obtained using the Glauber model:

$$m_C = N_{\text{coll}}(b) \times m_N$$

(5)

$$P_C = N_{\text{coll}}(b) \times P_{Pb}$$

(6)

where $m_N$ is the mass of the nucleon (here 931 MeV/$c^2$), $P_{Pb}$ is the momentum per nucleon of the Pb LHC beam and $b$ the impact parameter.

The total energy of the proton-contributor system is given by:

$$E_{pC} = \sqrt{P_p^2 + m_p^2} + \sqrt{P_C^2 + m_C^2}$$

(7)

where $P_p$ is the momentum of the LHC proton beam, and $m_p$ is its mass (938 MeV/$c^2$). The total momentum (positive value in the direction of the proton beam) is

$$P_{pC} = P_p - P_C.$$  

\textsuperscript{1} I agree that this physics motivation is weak, as my colleague Stéhane Peigné already told me. Indeed, the main motivation to formulate the proton-contributor hypothesis is the successful explanation of several different phenomenological observations in p–A collisions at LHC energy as it is discussed in the present draft.
Finally, the rapidity of the proton-contributor in the laboratory frame is given by

\[ y_{pC} = \tanh^{-1}\left(\frac{p_{pC}}{E_{pC}}\right) \] (9)

Assuming \( N_{\text{coll}}=1 \), the rapidity becomes \( y_{pC} = 0.465 \), which is equal to the rapidity of the proton-nucleon frame. In minimum bias p–Pb collisions at 5.02 TeV, the average number of collisions in the nucleonic tube is \( \approx 6 \), therefore the rapidity of the proton-contributor system is \( y_{pC} = -0.430 \). The rapidity gap between the proton-nucleon and proton-contributor is close to one unit of rapidity, \( \Delta y_{pN-pC} = 0.896 \). For the most central p–A collisions (\( N_{\text{coll}} = 17 \)), the rapidity is \( y_{pC} = -0.951 \).

**IV. CENTRALITY DEPENDENCE OF THE CHARGED PARTICLE PSEUDO-RAPIDITY DISTRIBUTION IN P-PB COLLISIONS AT 5.02 TEV**

Let us assume that the charged particle rapidity density \( dN_{\text{ch}}^{pp}/dy \) exhibits a Gaussian shape with a width \( \sigma \) of 3.2 rapidity units\(^2\). The charged particle rapidity density as a function of the centrality in p–A collisions \( dN_{\text{ch}}^{pA}/dy \) can be obtained applying Eq.4.

The pseudo-rapidity density is then given by:

\[ \frac{dN_{\text{ch}}}{d\eta} = \frac{dN_{\text{ch}}}{dy} \times \frac{dy}{d\eta} \] (10)

where

\[ \theta = 2 \cdot \arctan(e^{-\eta}) \] (11)

\[ m_T = \sqrt{p_T^2 + m^2} \] (12)

\[ p_x = \frac{p_T}{\tan \theta} \] (13)

and

\[ y = \sinh^{-1}\left(\frac{p_x}{m_T}\right) \] (14)

The Jacobian depends on the particle mass and transverse momentum. For simplicity, I have assumed a mean charged particle mass of 450 MeV/c\(^2\) and a mean transverse momentum of 700 MeV/c\(^3\). The charged particle pseudo-rapidity densities as obtained from Eq.10

\(^2\) The \( \sigma \) parameter of the charged particle rapidity Gaussian distribution has been chosen arbitrarily to reproduce with ATLAS measurement of the charged particle pseudo-rapidity distribution ratios \([1]\).

\(^3\) These values represent a first approximation, which could be improved considering realistic particle ratios and realistic particle transverse momentum distributions.
for a Gaussian rapidity distribution, are plotted in Fig. 2 top. The $dN_{chA}^y/dy$ distributions are normalized ($N$ parameter) to the charged particle pseudo-rapidity density at $\eta = 0$ measured by the ATLAS collaboration [1]. We observe that the shape of $dN_{ch}^y/d\eta$ becomes progressively more asymmetric in the Pb-going direction, in accordance with the increase of the contributor size and therefore the increase of the rapidity shift between proton-contributor frame in more central collisions and the proton-contributor frame in the peripheral 60%-90% centrality bin. In Fig. 2 bottom, the ratio of the pseudo-rapidity densities with respect to that in 60%-90% centrality bin is presented. The double peak structure present in the distributions in Fig. 2 top disappears in the ratios. The ratios are observed to grow nearly linearly with pseudo-rapidity, and the slope increases from peripheral to central collisions.

The ATLAS collaboration presented at the Quark Matter Conference in Darmstadt, the charged particle pseudo-rapidity distribution in p–Pb collisions at 5.02 TeV as a function of the collision centrality [1, 2]. A linear dependence of the charged particle pseudo-rapidity ratios with a slope increasing from peripheral to central p–Pb collisions, is observed (see Fig. 8 in [1]), qualitatively agreeing the predictions presented in Fig. 2 bottom, obtained with the hypothesis in Eq. 4.

V. CENTRALITY DEPENDENCE OF THE $J/\psi$ PRODUCTION IN P–PB COLLISIONS

Recently, the ALICE collaboration has published results on $J/\psi$ production and nuclear effects in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [3]. Let us assume a $J/\psi$ rapidity distribution according to the phenomenological parameterization introduced in [4]:

$$\frac{d\sigma}{dy} / \frac{d\sigma}{dy}|_{y=0} = e^{-(y/y_{\text{max}})^2/2\sigma_y^2}$$

(15)

where $y_{\text{max}} = \ln (\sqrt{s}/m_{J/\psi})$ and $\sigma = 0.38$ for pp collisions. In p–A collisions, I am assuming that the rapidity distribution is shifted by the rapidity gap between the proton-nucleon and the proton-contributor frames following Eq. 4. The $J/\psi$ nuclear modification factor is then obtained from the ratio of the two Gaussian distributions. The normalization factor $N$ is determined assuming binary scaling and an additional shadowing-like factor of 0.85$^4$.

$^4$ The only motivation of this shadowing-like factor is to fit the experimental data. Note that shadowing is expected to be almost constant as a function of rapidity and the 0.85 shadowing factor agrees very well
FIG. 2: Top $dN_{ch}/d\eta$ in different centrality classes, assuming a charged particle rapidity distribution with a Gaussian shape ($\sigma = 3.2$) in the proton-contributor reference frame. Bottom: Ratios of $dN_{ch}/d\eta$ distributions in different centrality classes, with respect to $dN_{ch}/d\eta$ distribution in the peripheral (60%-90%) centrality interval.
FIG. 3: Nuclear modification factor of $J/\psi$ in p–Pb collisions at 5.02 TeV assuming that the rapidity distribution shape is identical to that in pp, but shifted by the rapidity gap between the proton-nucleon and the proton-contributor frames. A suppression factor of 0.85 has been considered to mimic shadowing effect. The $R_{pA}$ for $N_{\text{coll}} = 6$ is compared with the measurement performed by the ALICE collaboration. The $R_{pA}$ for $N_{\text{coll}} = 2$ (peripheral p–Pb collision) and $N_{\text{coll}} = 14$ (central p–Pb collisions) are also shown.

This is shown in Fig.3 together with the ALICE measurements. As it can be seen, the simple assumption of a $J/\psi$ rapidity distribution in p–A collisions shifted with respect to that in pp collisions allows to describe the observed $J/\psi$ suppression (enhancement) at forward (backward) rapidity. The rapidity gap between the proton-nucleon and proton-contributor frames, would explain the observed $J/\psi$ suppression at forward rapidity and the enhancement at backward rapidities. As shown in Fig.3, the previous pattern is enhanced in central p–Pb collisions since the contributor size increases, thus increasing the rapidity gap. This is in qualitative agreement with results from the ALICE collaboration showing that the $J/\psi$ nuclear modification factor decreases with centrality at forward rapidity, while
VI. PRODUCTION OF Z IN P–A COLLISIONS AT 5.02 TEV

Recently, the ATLAS and CMS collaboration have reported the measurement of the Z differential cross section in p–Pb collisions at 5.02 TeV [7–10]. ATLAS claimed that the rapidity differential cross section shows a significant asymmetry compared to the simple model based on binary scaling with respect to nucleon-nucleon collisions. Indeed, a relative excess in the Z differential cross section is seen in the backward (Pb-going) part of the rapidity distribution [7]. CMS interpreted such an asymmetry as a consequence of the modification of the parton distribution functions (PDF) in the nucleus and claimed that this measurement is providing new data points in a previously unexplored region of phase space for constraining nuclear PDF fits [8]. Furthermore, ATLAS observed a more pronounced asymmetry in central events, while the asymmetry is apparently absent in peripheral events.

Assuming Z production with a rapidity distribution symmetric in the proton-contributor reference frame (see Eq. 4) can provide a phenomenological explanation to the observation made by the ATLAS and CMS collaborations. As it was quoted above, the rapidity of the proton-contributor reference frame for p–Pb ($N_{\text{coll}} \approx 6$) is -0.430 in the LHC reference frame. It is, indeed, observed (see Fig.4 of [7]) that the measured Z rapidity distribution exhibits a maximum around this value. Hence, the Z rapidity distributions for 0%-10% ($N_{\text{coll}} \approx 14$), 10%-40% ($N_{\text{coll}} \approx 10$) and 40%-90% ($N_{\text{coll}} \approx 4$) should be centred at $y_Z$ equal to -0.85, -0.69 and -0.23, thus qualitatively agreeing with the experimental observations (see Fig.9 of [7]). At Quark Matter Conference, the CMS collaboration presented the backward-to-forward ratio of the Z rapidity distribution in the proton-nucleon centre of mass [10, 11]. A Gaussian rapidity distribution with a width equal to 3 (solid line of Fig.4 top), can be considered to model the Powheg-Pythia predictions presented in Fig.2 of reference [8, 12]. Assuming that the Z rapidity distribution in p–Pb collisions has the same shape but is centred at the rapidity of the proton-contributor reference frame ($y_{pC} - y_{pN}$), the dashed curve plotted in Fig.4 top is obtained. The backward-to-forward ratio can then been easily calculated as the ratio of the dashed and solid curve in Fig.4 top and it is plotted in Fig.4 bottom. This prediction is in agreement with the backward-to-forward ratio measured by the CMS collaboration [8].
FIG. 4: Top: Z rapidity distributions in the proton-nucleon centre of mass frame. The solid curve models the Powheg-Pythia predictions (open symbols) presented in Fig.2 of \cite{8, 12}. The dashed curve is the same distribution but is centred at the proton-contributor rapidity. Bottom: The ratio of the dashed and solid curve allows to estimate the backward-to-forward ratio of the Z production in the proton-nucleon centre of mass. Open circles represent the backward-to-forward ratio measured by CMS, extracted from the pdf file, Fig.3 of \cite{8}.
VII. SUMMARY AND OUTLOOKS

I have defined the proton-contributor the proton-contributor system in p–A collisions as the system formed by the proton and the nucleons of the nucleus participating to the collisions, which is determined with the Glauber model. Assuming that the particle rapidity distribution is identical to that in pp collisions but centred at the rapidity of the proton-contributor system,

- the pattern of the pseudo-rapidity distribution ratios of charged particles as a function of the collision centrality in p–Pb at 5.02 TeV, measured by the ATLAS collaboration [1, 2],
- the nuclear modification of J/ψ at forward and backward rapidity in p–Pb collisions at 5.02 TeV measured by the ALICE collaboration [3, 6], and
- the backward-to-forward ratio of Z bosons in p–Pb collisions at 5.02 TeV measured by the CMS collaboration [8, 10]

can be understood.

This phenomenological observation might trigger new theoretical ideas on the physics underlying the present hypothesis of the proton-contributor frame. Seemingly, this hypothesis could be also applied to RHIC results in d-Au collisions and to other observables in p–Pb collisions, like Υ or W production. Finally, one could imagine new experimental observables taking into account the rapidity gap \( \Delta y_{pN–pC} \) between the proton-nucleon and the proton-contributor systems, like the the backward-to-forward ratio in the proton-contributor frame or a proton-contributor nuclear modification factor that would be defined as:

\[
R_{pC}^{pA}(y) = \frac{Y_{pA}(y)}{\langle N_{\text{coll}} \rangle Y_{pp}(y - \Delta y_{pN–pC})} \tag{16}
\]

This is a preliminary draft and comments and suggestions are welcome. I plan to make an oral presentation during the [Rencontres QGP-France September 15th-18th 2014 in Etretat](#).

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