Excitation function of anti-baryon to baryon ratios using model simulations in pp collisions at LHC Energies

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Abstract

We study the excitation function of anti-baryon to baryon ratios ($\bar{p}/p$, $\bar{\Lambda}/\Lambda$ and $\bar{\Xi}^+ / \Xi^+$) in pp collisions at $\sqrt{s} = 0.9, 2.76, 7$ TeV from Pythia 8, EPOS1.99, EPOS-LHC and DPMJET-III model simulations. These computed ratios from model simulations are then compared with the experimental results from ALICE. LHC is taking high luminosity data in pp collisions at $\sqrt{s} = 13.6$ TeV this year. In order to study the predictions of these models at $\sqrt{s} = 13.6$ TeV, we also computed these ratios at this energy. The anti-baryon to baryon ratios are extremely important to study the baryon number transport mechanisms and are also helpful to determine the carrier of baryon number as well as to extract the baryon structure information itself. These ratios are independent of both transverse momentum ($p_T$) and rapidity ($y$). There is a good agreement between almost all the model simulations and data. The ratios extracted from DPMJET-III model perfectly describe the data at all energies. It is observed that the ratios converges to unity from lower to higher energies which is confirmed by various model predictions at $\sqrt{s} = 13.6$ TeV. This convergence in the anti-baryon to baryon ratios at higher energies indicates that these ratios follow the mass hierarchy. The ratio of hyperon species containing more valence quark ($\bar{p}/p$) approaches to unity later than the ratio of hyperon species containing less valence quarks ($\bar{\Lambda}/\Lambda$ and $\bar{\Xi}^+ / \Xi^+$). In other words, the increase in strangeness content results in the reduced contribution of the stopping related process of different beam particles constituents. As a result, the $B/B$ ratio becomes closer to unity as the strangeness content increases. Furthermore, an excess of baryon over anti-baryon is observed at lower energies and this effect vanishes at higher energies due to the baryon-anti-baryon pair production mechanism which is dominated at higher energies and the baryon-anti-baryon yields becomes equal. All the model describe the similar behaviour towards higher energies. We have also computed the asymmetry $A = \frac{N_{\bar{p}} - N_p}{N_{\bar{p}} + N_p}$ for protons using different model simulations. The asymmetry shows decreasing trend from lower to higher energies which is confirmed by the model predictions at $\sqrt{s} = 13.6$ TeV. These studies will certainly help to put possible constraints on these model calculations.

Keywords — simulations, baryon number transport, predictions, pair production, hyperon

1 Introduction

One of the most fundamental physical observables, which have been extensively measured and hence studied in cosmic-ray physics and hadronic colliders for many decades, is the yield and transverse momentum spectra ($p_T$) of identified particles produced in high energy hadronic interactions [1]. At partonic level, hadrons are produced from the soft and hard scattering processes at collider energies. The interaction of two partons with large momentum transfer is known as the hard scatterings which result in the production of high $p_T$ particles. Theoretically, the factorization theorem based perturbative Quantum Chromodynamics (pQCD) calculations explain this process [2].
At LHC, the lower $x$ region is probed by increasing the center of mass energy ($\sqrt{s}$) which results in the increase in contributions from the hard scattering processes. The dominant production of high-$p_T$ particles is from the fragmentation of gluons in the kinematic regions probed by these measurements [2,3]. On the other hand, the origin of the bulk of low $p_T$ ($p_T < 2$ GeV/$c$) particles are from soft scattering processes having a small amount of momentum transfer. The production of particles in this regime cannot be calculated from the first principle and therefore QCD inspired phenomenological models plays a significant role for these calculations. These models are then tuned for the comparison of previous measurements and hence, low $p_T$ measurements may be helpful to provide further important constraints on models. Furthermore, soft particle production studies are an important tool to understand the basic mechanisms involved in particle production at the low $p_T$ region.

Quantum Chromodynamics (QCD) does not fully describe the production of baryons. It is still unclear whether the baryon number should be associated with the valence quark or with its gluonic field. The baryon in QCD is represented by the gauge-invariant state operator which further shed light on the string junction in which gluonic string joins three valance quarks at one point [4,5]. This depicts the association of baryon gluonic field with baryon number, i.e., with the string junction. It is important to point out that in this representation, the string junction is responsible for the production of baryon anti-baryon pair from vacuum while on the other hand a combination of sea quark-antiquark is produced along with the anti-string pair production. The anti-baryons are produced in baryon-baryon collisions through this mechanism. There is a possibility that a baryon may have the contributions of string junction or valence quarks, di-quarks of the incoming baryons. The significant diffusion of any constituents over the large rapidity results different (anti-) baryons spectrum at mid-rapidity [4,17].

The string junction of the baryons coming from the beam at large rapidity $\Delta y$, in Regge field theory [18,19], can be calculated using the expression $\exp[(\alpha_j - 1)\Delta y]$ [4], where, $\Delta y = y_{beam} - y, y_{beam} = \ln(\sqrt{s}/m_B) = $ incoming baryon rapidity and $y$ is string junction rapidity. The intercept of the string junction trajectory is represented by $\alpha_j$. Theoretically, at present, it is not possible to calculate the intercept $\alpha_j$ of the string junction which is non-pQCD object. At mid-rapidity, the (anti-) baryons spectra are expected to be different depending on the value of $\alpha_j$. At $\alpha_j \approx 1$, the string junction of incoming baryons does not show rapidity dependence at high values of $\Delta y$ as reported in Ref. [5]. However, at $\alpha_j = 0.5$, transport of string junction approaches to zero with the increase in $\Delta y$ [4].

Reggeon exchange with C-parity is another source that causes the difference in particle and anti-particle spectra [6]. $\omega$-reggeon is a known Regge pole with the value of intercept $\alpha_{\omega} \approx 0.5$ and the exchange of $\omega$-reggeon is also one of the main factors which may cause the difference in (anti-) particle spectra. Since the value of $\alpha_{\omega}$ is less than unity, therefore its contribution decreases at mid-rapidity with the increase in colliding energy. Another source, if exists, is the negative signature of Regge pole and $\alpha \approx 1$ which may also cause the difference in (anti-) particle in the mid-rapidity region. The information about the contributions of different mechanisms involved to study the baryon production from baryon and anti-baryon spectra in $pp$ collisions can be gathered. Particularly, the measurement of anti-baryon to baryon spectra and $\bar{B}/B$ ratios with different quark flavor for example $\Lambda(\bar{\Lambda}), \Xi^- (\Xi^+), \rho(\bar{p}),$ and $\Omega^- (\bar{\Omega}^+)$ is directly useful to find constraints on the mechanisms involved in baryon production. For example, the increase in strangeness content results in the reduced contribution of the stopping related process of different beam particles constituents. As a result, the $\bar{B}/B$ ratio becomes closer to unity as the strangeness content increases.

In this paper, a comprehensive simulation has been performed with different model-based event generators DPMJET-2019, EPOS 1.99, EPOS-LHC and Pythia 8 to study the different $\bar{B}/B$ ratios ($\Lambda(\bar{\Lambda}), \bar{p}/p, \Xi^- / \Xi^+$) at $\sqrt{s} = 0.9, 2.76, 7$ TeV and results are compared with that of published data from the ALICE experiment [20]. On the basis of previously published results, we also performed simulations at $\sqrt{s} = 13.6$ TeV to check the model predictions, where no data is available and LHC is currently running to take data in Run-3 this year. The paper is organized as follows: The description of models is discussed in section 2. The analysis details and results are presented in section 5. Finally, the summary and conclusion are presented in the last section.
2 Model Details

The models used for simulation are discussed in this section.

**DPMJET-III** unifies all the features of DPMJETII [21], Dtnuc-2 [22 23] and Phojet1.12 [24] event generators into single code system. DPMJET model is based on multiple scattering Gribov-Glauber formalism and simulations of hadron-nucleus ($h - N$), hadron-hadron ($hh$), photon-hadron ($\gamma - h$), nucleus-nucleus ($NN$), photon-nucleus ($\gamma - N$) and photon-photon ($\gamma\gamma$) interactions can be studied from few GeV to highest cosmic ray energies [25]. The Dual Parton Model (DPM) on which DPMJET is based, describes the soft and multi-partonic interactions in high-energy interactions [25]. The soft processes are expressed by the exchange of pomerons under Reggeon field theory [26] and hard processes are described by the perturbative parton scattering approach. The assumptions of duality with Gribov’s Reggeon field theory [26] and the predictions of large $N_C$ and $N_f$ expansions of QCD [28] is combined in DPM. The production cross-sections, as well as total, (quasi) elastic calculations for different colliding systems, can be calculated under the framework of DPMJET at high energies [29]. The new feature of enhanced graph cuts in non-diffractive inelastic $h - N$ and $NN$ collisions is incorporated in DPMJET-III model. On the other hand, the hadronization of color-neutral strings is based on the Lund model as incorporated in Pythia [30 31]. Further detail of the model can be found in Ref. [25].

**Pythia** [25 30 32] simulate the particle production in high energy collisions over the wide range of energy scales in detail. Due to the complexity of hadron collisions and production, no comprehensive theory available can predict event properties over the full range of available collision energies. Pythia with a core based on the Lund string model of hadronization [33], addresses a large set of phenomenological problems in particle physics, astroparticle, nuclear, and neutrino physics. According to the string model, if two color charges are located at some large distance, the QCD-vacuum will expel color flux leading to a color-flux tube between color charges, which behaves as a string. In string fragmentation, these strings are broken to form hadrons. Pythia also includes a hybrid hadronization model [34] to accommodate heavy-ion collisions. For the historical evolution of Pythia see Ref. [35].

Pythia can simulate many Standard-Model processes, i.e., lepton-lepton, lepton-hadron and hadron-hadron, Beyond Standard Model (BSM) particle decays, Resonance decays with hadronization and final state showering, hadronization of partonic configuration, $AA$ collision for $\sqrt{s_{NN}} > 10$ GeV and astrophysical phenomenons. Pythia includes a large selection of QCD processes classified into three groups: (1) $2 \rightarrow 2$ (interaction of light quarks and gluons, i.e, $gg \rightarrow gg$, $gg \rightarrow q\bar{q}$ ), (2) $2 \rightarrow 2$ (Production of charm and bottom, i.e., $gg \rightarrow c\bar{c}$, $gg \rightarrow b\bar{b}$ ) and (3) $2 \rightarrow 3$ processes also involving light quarks and gluons. Electroweak processes in Pythia include prompt photon production ($qg \rightarrow q\gamma$, $gg \rightarrow g\gamma$), weak boson, single vector boson ($\gamma^*/Z$, $W^\pm$), photon collision ($\gamma\gamma \rightarrow q\bar{q}$, $c\bar{c}$, $b\bar{b}$ ). Pythia also provided with charmonium and bottomonium production using Non-Relativistic QCD (NRQCD) [36] including both color singlet and color octet configuration, Top, Higgs production, and also supersymmetric particles using Minimal Supersymmetric Simplified Model (MSSM) [37].

**EPOS-1.99/LHC** [38 40] In simple hadron-hadron interaction models at high energies, the inclusive cross-section is the convolution of the two parton distribution function (PDF) [41], which deduced from the pQCD and PDF from the deep inelastic scattering experiment. In EPOS after the hard scattering, the successive partons emission is termed as initial cascade or space-like cascade. These partons are generally off-shell and give rise to parton emission called final cascade or time-like cascade. This cascade of partons is called a parton ladder. Such parton ladders are split into the color strings which are fragmented into hadrons. This soft part of the parton ladder is parameterized in Regge pole fashion [42]. To complete the picture, remnants are also taken into account usually colorless excited quark-antiquark. Thus in EPOS, the hadron-hadron interaction is composed of two parts, inner contribution (from parton ladder) and outer contribution (from remnants). Remnants produce particles at large rapidities and parton ladders at central rapidities.

EPOS 1.99 [40] released in 2009 was adjusted for indepth study of LHC data and was called EPOS-LHC [39]. EPOS-LHC can be tuned to reproduce different hadronic interaction $p - p$, $h - A$, and $A - A$, where $h$ can be $\pi$, $K$, $p$ and $A$ can be from 1 to 210 nucleons in the energy starting from 40 GeV in lab frame up-to 1000 TeV in center of mass frame. Collective hadronization in $p - p$ scattering is modified by introducing different parametrization of flow in EPOS-LHC due to very high-density matter formed in $pp$ collision in LHC. Such highly dense matter core
expands very quickly, requiring a unique radial flow algorithm used in EPOS-LHC.

3 Analysis, Results and Discussion

3.1 Data Set

We simulated 30 million pp collisions at $\sqrt{s} = 0.9$, 2.76 and 7 TeV using Pythia 8, EPOS1.99, EPOS-LHC and DPMJET-III. LHC is running to take high luminosity pp collisions data at $\sqrt{s} = 13.6$ TeV this year. In order to study the predictions of different models, we also simulated 30 million pp collisions at $\sqrt{s} = 13.6$ TeV. The simulations are then compared with the available published results from ALICE experiment [20]. Motivated by the ALICE experiment capabilities, the final state hyperons are considered to be in rapidity window $|y| < 0.5$ and $|y| < 0.5$ in case of $\bar{p}/p$. The particles having lifetime $c\tau > 10$ mm are considered as final state particles which can be tracked in the detector. The cuts used to calculate the transverse momentum and rapidity distributions are listed in Table 1.

Table 1: Rapidity and $p_T$ cuts used to study $\bar{B}/B$ ratios at LHC energies

| $\sqrt{s}$ (TeV) | $p/p$ | $\bar{\Lambda}/\Lambda$ | $\Xi^+ / \Xi^-$ |
|------------------|-------|--------------------------|------------------|
|                  | $p_T$ | $|y|$  | $p_T$ | $|y|$  | $p_T$ | $|y|$  |
| 0.9              | [0.45, 1.05] | < 0.5 | [0.5, 4.0] | < 0.8 | [0.5, 3.5] | < 0.8 |
| 2.76             | [0.45, 1.05] | < 0.5 | [0.5, 4.5] | < 0.8 | [0.5, 4.5] | < 0.8 |
| 7                | [0.45, 1.05] | < 0.5 | [0.5, 10.5] | < 0.8 | [0.5, 5.5] | < 0.8 |
| 13.6             | [0.45, 1.05] | < 0.5 | [0.5, 10.5] | < 0.8 | [0.5, 5.5] | < 0.8 |

3.2 Results

We studied the $\bar{B}/B$ ratios from different model simulations as a function of transverse momentum $p_T$ and rapidity $y$ at LHC energies. Due to insufficient statistics, the $\Xi^+ / \Omega^-$ ratio was not studied.

Figure 1 shows the $\bar{p}/p$ ratio vs $p_T$ in $pp$ collisions at $\sqrt{s} = 0.9$ TeV. The simulation results from Pythia 8, EPOS1.99, EPOS-LHC and DPMJET-III are compared with the experimental data from ALICE experiment [20]. The experimental data does not show $p_T$ dependence and $\bar{p}/p$ ratio is almost smooth around 0.95 for all $p_T$ intervals. In comparison to the experimental data, Pythia 8, EPOS1.99, and DPMJET-III models successfully reproduce the data and show no $p_T$ dependence at all. EPOS-LHC, on the other hand, slightly overpredict the ratio at higher $p_T$ bins ($p_T > 0.7$ GeV/c). The lower panel of Figure 1 shows the model-to-data ratio which shows the very good agreement of models with data.

Figure 2 (left) depicts the $\bar{\Lambda}/\Lambda$ ratio vs $p_T$ in $pp$ collisions at $\sqrt{s} = 0.9$ TeV from ALICE experiment compared to the model results. The data seems to show slight $p_T$ dependence at $p_T > 2$ GeV/c. It is observed that EPOS1.99 and Pythia 8 is in good agreement with experimental data within uncertainties. However, at low $p_T$ ($p_T < 2$ GeV/c), DPMJET-III reasonably reproduce the data while overpredict at higher $p_T$ bins. EPOS-LHC, on the other hand, clearly overpredicts the data at almost all $p_T$ bins except for the last $p_T$ bin at which the model matches with data within uncertainties. The lower panel shows the model-to-data ratio, which shows a good agreement of model simulations with experimental data. The model-to-data ratio shows $< 10\%$ discrepancy except for the $p_T$ bin $3 - 3.5$ GeV/c in case of EPOS-LHC where the discrepancy is about $12\%$. Figure 2 (right) shows the $\bar{\Lambda}/\Lambda$ ratio as a function of $y$ in $pp$ collisions at $\sqrt{s} = 0.9$ TeV from ALICE experiment compared with the model simulations. It is observed that all of the models successfully reproduce the $\bar{\Lambda}/\Lambda$ ratio vs $y$ at all bins. The model-to-data discrepancy is $< 10\%$. Overall, EPOS1.99 perfectly describe the $\bar{\Lambda}/\Lambda$ ratio at all the $p_T$ and $y$ bins.

Figure 3 shows the $\Xi^+ / \Xi^-$ ratio vs $p_T$ in $pp$ collisions at $\sqrt{s} = 0.9$ TeV from ALICE compared with various model simulations. It is observed that the ratio is almost unity except $p_T > 2.5$ GeV/c where a sudden decrease is
Figure 1: $p_T$ dependent $\bar{p}/p$ ratio in $pp$ collisions at $\sqrt{s} = 0.9$ TeV compared with Pythia 8, EPOS1.99, EPOS-LHC and DPMJET-III models. The model-to-data ratio is shown in the lower panel.

Figure 2: $p_T$ dependent $\bar{\Lambda}/\Lambda$ ratio (left) and $y$ (right) in $pp$ collisions at $\sqrt{s} = 0.9$ TeV compared with Pythia 8, EPOS1.99, EPOS-LHC and DPMJET-III models. The model-to-data ratio is shown in the lower panel.

seen. However, the uncertainty in the last data point makes it difficult to make any final conclusion. On the other side, ratio computed from almost all of the models stays around unity at all $p_T$ bins. The uncertainty in the last two bins from model simulations is relatively larger as compared to previous bins which makes it harder to conclude the final statement. The observed model-to-data ratio is shown in the lower panel, where the uncertainty in the last two bins is 20% and around 22% respectively. Overall, all the models are in good agreement with experimental data.

Figure 4 shows the $p_T$ dependent $\bar{p}/p$ ratio in $pp$ collisions at $\sqrt{s} = 7$ TeV compared with Pythia 8, EPOS1.99,
Figure 3: $p_T$ dependent $\Xi^+/\Xi^-$ ratio in $pp$ collisions at $\sqrt{s} = 0.9$ TeV compared with Pythia 8, EPOS1.99, EPOS-LHC and DPMJET-III models. The model-to-data ratio is shown in the lower panel.

Figure 4: $p_T$ dependent $\bar{p}/p$ ratio in $pp$ collisions at $\sqrt{s} = 7$ TeV compared with Pythia 8, EPOS1.99, EPOS-LHC and DPMJET-III models. The model-to-data ratio is shown in the lower panel.

EPOS-LHC and DPMJET-III model simulations. No $p_T$ dependence is observe for the ratio computed from models, similar to the experimental measurements. It is observed that all the models perfectly describe the experimental data. The $\bar{p}/p$ as a function of $p_T$ is close to unity from all the model simulations as well as data which explains the production of anti-particle and particle is the same. The model-to-data ratio which is shown in the lower panel where a nice comparison of data with model simulations can be seen.

Figure 5 (left) depicts the the $\Lambda/\bar{\Lambda}$ ratio vs $p_T$ in $pp$ collisions at $\sqrt{s} = 7$ TeV from ALICE experiment. The data is then compared with Pythia 8, EPOS1.99, EPOS-LHC and DPMJET-III models. The experimental data
suggest that the $\Lambda/\Lambda$ ratio is unity for all $p_T$ bins particularly at higher $p_T$ within uncertainties. A good agreement is observed with the experimental data for all the model simulations. The statistical fluctuation at high $p_T$ ($p_T > 7$ GeV/$c$) can be seen in case of models as well as data. It is difficult to make a solid conclusion that the discrepancy is 40% or lower due to large error bars. The model-to-data ratio is presented at the lower panel of the figure which also supports the statement of good agreement. The difference in model/data comparison at $p_T > 7$ GeV/$c$ is higher as compared to lower $p_T$ bins which may arise due to the statistical fluctuations. A sub-figure is drawn to show a clear view of the comparison of data with different models at $p_T \leq 6$ GeV/$c$. $\Lambda/\Lambda$ ratio as a function of $y$ is shown in Figure 5 (right). It can be seen that all models describe the experimental data very well at all rapidity bins. All the models are independent of the rapidity similar to the experimental data.

Figure 6 (left) shows the $\Xi^+ / \Xi^-$ ratio vs $p_T$ in $pp$ collisions at $\sqrt{s} = 7$ TeV from ALICE experiment to compare with Pythia 8, EPOS1.99, EPOS-LHC and DPMJET-III model simulations. There is a good agreement of data with that of all model simulations within uncertainties at higher $p_T$ bins. The fluctuation at higher $p_T$ bins ($p_T > 3$ GeV/$c$) is due to statistics. Overall, EPOS1.99 best describes the data for all $p_T$ bins. The $\Xi^+ / \Xi^-$ ratio as a function of $y$ is shown in Figure 6 (right). The experimental data is consistent with unity within uncertainties for the whole rapidity range. The computed ratio from different models is also consistent to unity within uncertainties of experimental data. EPOS1.99 gives a very good description of data at all $y$ bins.

4 Discussion

In DPMJET-III, the Glauber sea quark mechanism of baryon stopping (GSQBS) is implemented and the dip in the rapidity distribution of baryons at mid-rapidity is filled with the help of this mechanism. In addition to GSQBS mechanism, the unitary sea quark mechanism (USQBS) of baryon stopping is also implemented in DPMJET-III which leads to baryon stopping in $pp$ collisions at collider as well as cosmic ray energies. Kharzeev [14] and Capella and Kopeliovich [11–13] diquark breaking diagrams which were first discussed by Ranft [21–24] are also implemented in the DPMJET-III model. Initial fragmentation of a diquark has two possibilities, either a baryon containing both quarks of the diquark and the string junction is produced first or a meson with only one of the two quarks is produced. This is known as popcorn fragmentation which was implemented in the Lund chain fragmentation model JETSET [44] which is currently used in DPMJET-III. The net-baryon distributions from
experimental data are then compared with the DPMJET-III model in order to determine the optimum values of these new parameters. The used values for both GSQBS and USQBS parameters are 0.6. In $NN$ collisions, two baryon stopping mechanisms are involved. In addition to GSQBS, the baryon stopping mechanism is the outcome as a side effect of the chain fusion, for example, a $qq - q$ and $\bar{q} - \bar{q}$ chains can be fused to a $q - qq$ chain \cite{45}. Pythia, on the other hand, is a pure multi-parton interaction model. The enhanced baryon transfer is included in Pythia, and it does not consider the junction-stopping mechanisms. The chain fragmentation pairs of diquark and anti-diquark can possibly be exchanged at any position except for close to chain end diquark \cite{45}. EPOS model is based on Regge theory and gives good agreement with experimental data.

Figure 7 shows the $B/B$ spectra ratios integrated for the measured spectra range in $pp$ collisions at $\sqrt{s} = 0.9$, 2.76, 7 TeV from various model simulations. These ratios are then compared to the measured ratios from data of ALICE experiment \cite{20}. LHC is taking Run-III data this year from $pp$ collisions at $\sqrt{s} = 13.6$ TeV. In order to check the predictions of these models, we also computed the $B/B$ ratios at $\sqrt{s} = 13.6$ TeV. The cuts used to compute ratios at $\sqrt{s} = 13.6$ TeV are similar to those used for $\sqrt{s} = 7$ TeV. All the models reasonably reproduce the data at all energies. In the case of $\bar{p}/p$ ratio at $\sqrt{s} = 13.6$ TeV, the DPMJET-III model predicts the value of the ratio to unity while EPOS-LHC, EPOS1.99, and Pythia 8 predict the yield slightly less than unity. In case of $\Lambda/\Lambda$ and $\Xi^+/\Xi^-$ ratios, almost all the models predict the ratio to unity. It is observed that the ratios converge to unity with the increase in energy. The convergence of the ratios to unity as a function of energy follows the mass hierarchy; the more massive hyperon species achieve the saturation value of 1 earlier as compared to light hyperons. The hyperon containing less light valence quarks reaches unity earlier as compared to the one containing more light valence quarks. The $\Lambda$ hyperon contains 2 light valence quarks whereas, $\Xi$ contains 1 light valence quark which may be remnants from the incoming beam nucleons. In other words, the increase in strangeness content results in the reduced contribution of the stopping related process of different beam particles constituents. As a result, the $B/B$ ratio becomes closer to unity as the strangeness content increases. Furthermore, at lower energies, an excess of baryons is observed over anti-baryons and an equal number of baryons and anti-baryons results in the convergence of ratios to unity at higher energies. The equal yields of (anti-) baryons at mid-rapidity are due to the pair production of baryon and anti-baryon pairs. The more baryon produced as compared to anti-baryons is therefore directly related to the baryon number transfer from the incoming beam. The computed ratios from almost all the models suggest the saturation towards higher energies.
Figure 7: $\bar{B}/B$ ratio at $\sqrt{s} = 0.9, 2.76$ and $7$ TeV in comparison with Pythia 8, EPOS1.99, EPOS-LHC and DPMJET-III models. Open squares of different colors are the prediction of various models at $\sqrt{s} = 13.6$ TeV.

Figure 8 summarises the computed ratios for $p/p, \Lambda/\Lambda$ and $\Xi^+/\Xi^-$ from various models in comparison with the data from different experiments at mid-rapidity as a function of $y_{beam}$. The ratios computed from different models are compared with the previous published results from different experiments at lower $y_{beam}$ [46–58]. The ratios from different model simulations were estimated at higher $y_{beam}$ are converging to unity and are in good agreement with the experimental data from ALICE experiment [20]. There are certain possible ways for the production of baryons, either from pair production of baryon and anti-baryon from vacuum or contain quark di-quark or can be string junction, similarly can be a combination of the latter three of the incoming proton beam. With the decrease in $|y|$, there is an exponential decrease in the production probability of baryon containing valence or di-quark. The pair production mechanisms of (anti-) baryon are responsible for anti-baryon production. The (anti-) baryon yields are expected to be similar at higher energies and mid-rapidity, if the quarks and gluons from the proton beam do not contribute at large rapidity intervals from the beam. It can be seen from fig. 8 that the experimental data and various model simulations favor this scenario.

To identify baryons in experimental measurements the value of $p_T$ cut-off used is higher than the mean $p_T$ of the produced baryons [20]. The Regge models are helpful to derive the $y$ and $y_{beam}$ dependencies of the ratios. It is important to point out that the Pomeron exchange implemented in EPOS is responsible for the pair production of baryons at very high energies in the phenomenological approach. This is also observed in the current study as most of the models used are based on Regge theory. Furthermore, the asymmetry is defined as $A = \frac{N_p - N_{\bar{p}}}{N_p + N_{\bar{p}}}$ of baryons in $pp$ collisions at $\sqrt{s} = 0.9, 2.76, 7$ and $13.6$ TeV is also computed with different models are listed in table 2. The string junction transport is used to express the asymmetry between baryons and anti-baryons with an exchange of negative C-parity which corresponds to $\omega$ exchange. In the conclusion, any significant contribution to $\bar{B}/B$ ratios at mid-rapidity due to exchange is disfavoured and this contribution is not suppressed with the increase in rapidity interval. The asymmetry of protons shows decreasing trend towards higher energies which is also confirmed by the predictions of different models at $\sqrt{s} = 13.6$ TeV and are consistent with the previously available measurements.
Table 2: The asymmetry $A$ of proton computed from different models at LHC energies.

| Proton   | 0.9 TeV | 2.76 TeV | 7 TeV  | 13.6 TeV |
|----------|---------|----------|--------|----------|
| DPMJET-III | 0.0176  | 0.0070   | 0.0090 | 0.0020   |
| EPOS-LHC  | 0.0162  | 0.0114   | 0.0060 | 0.0060   |
| EPOS-199  | 0.0320  | 0.0172   | 0.0113 | 0.0090   |
| Pythia8   | 0.0195  | 0.0104   | 0.0098 | 0.0061   |

5 Summary

We have computed the $\bar{p}/p$, $\Lambda/\Lambda$, $\Xi^{+}/\Xi^{-}$ ratios from Pythia 8, EPOS1.99, EPOS-LHC and DPMJET-III simulations in $pp$ collisions at $\sqrt{s} = 0.9$, 2.76 and 7 TeV. Furthermore, we also computed these ratios to check the predictions of different models in $pp$ collisions at $\sqrt{s} = 13.6$ TeV which is important due to the fact that LHC...
is taking high luminosity data at this energy this year. These ratios $(\bar{p}/p, \bar{\Lambda}/\Lambda$ and $\Xi^+/\Xi^−)$ are independent of both transverse momentum $(p_T)$ and rapidity $(y)$. The previously published results are then compared with these simulations and it is observed that all the models are in very good agreement with the experimental data. In the string models, the information of baryon number is carried by the vortex lines which in fact plays an important role in the string structure, therefore, the understanding of baryon and particularly net baryon production is significantly important. These ratios are approaching unity reflecting the mass hierarchy. The ratio of hyperon containing fewer light quarks $(\Xi^+/\Xi^−)$ approaches unity earlier than those containing more light quarks $(\bar{p}/p)$. The increase in strangeness content results in the reduced contribution of the stopping related process of different beam particles constituents. At lower energies, an excess of baryons is also observed over anti-baryons, however, this effect is negligible at higher energies due to baryon and anti-baryon pair production. The increase in the number of baryons in comparison with anti-baryons is directly related to the baryon number transfer from the incoming beam. The model simulations at higher energies also suggest the saturation towards higher energies. The model simulations predict the similar spectra of baryons and anti-baryons at large $\Delta y$ ($\Delta y > 8$) in $pp$ collisions. We also study the predictions of asymmetry for these hyperon from different models in $pp$ collisions at $\sqrt{s} = 0.9, 2.76, 7$ and $13.6$ TeV. The asymmetry shows decreasing trend towards higher energies which is consistent with the previously available measurements. These studies will certainly help to put possible constraints on these model calculations.

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Availability of Data and Material
The authors declare that all the supported data of this study are available within the article.

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