Strange particle production in Monte Carlo generators in pp and pPb collisions at the LHC

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Abstract. Experimental data on strange particle production in p-Pb collisions and even in p-p scattering at several TeV show many similarities to the corresponding Pb-Pb results, the latter ones usually being interpreted in terms of hydrodynamic flow. We therefore analyse p-p and p-Pb data, comparing strange particle results to the simulations from various event generators: EPOS3, EPOS LHC, QGSJETII, SIBYLL, PHOJET, AMPT, PYTHIA6, PYTHIA8, HERWIG++, SHERPA. We show only selected results, a much more complete analysis can be found in [1].

Collective hydrodynamic flow seems to be well established in heavy ion (HI) collisions at energies between 200 and 2760 AGeV, whereas p-p and p-nucleus (p-A) collisions are often considered to be simple reference systems, showing "normal" behavior, such that deviations of HI results with respect to p-p or p-A reveal "new physics". Surprisingly, the first results from p-Pb at 5 TeV on the transverse momentum dependence of azimuthal anisotropies and particle yields are very similar to the observations in HI scattering [2, 3].

Do we see flow already in p-Pb or even in p-p collisions? In order to answer this question, we will analyse the predictions of different Monte Carlo generators, concerning identified (strange) particle production, a list of models is given in table 1. The EPOS3 approach [1] is the successor of EPOS2 [4, 5]. The main new ingredients: a more sophisticated treatment of nonlinear effects in the parton evolution by considering individual (per Pomeron) saturation scales [6], and a 3D+1 viscous hydrodynamical evolution. EPOS LHC [7] is a tune of EPOS1.99, containing flow put in by hand, parametrizing the collective flow at freeze-out. Both EPOS3 and EPOS LHC are based on initial conditions from Gribov-Regge multiple scattering [8]. The QGSJETII [9], SIBYLL [10], and PHOJET model [11] are also based on Gribov-Regge multiple scattering, but there is no fluid component. The main ingredients of the AMPT model [12] are a partonic cascade and a subsequent hadronic cascade, providing in this way some "collectivity" in nuclear collisions, but not in proton-proton. In addition, we will also show results from the so-called "general-purpose event generators for LHC physics" [13], as there are PYTHIA6 [14], PYTHIA8 [15], HERWIG++ [16], and SHERPA [17]. All these models are based on the factorization formula for inclusive cross sections, with a more or less sophisticated treatment of multiple scattering, whereas Gribov-Regge theory provides a multiple scattering scheme from the beginning.

There are few other studies of hydrodynamic expansion in proton-nucleus systems. In [18], fluctuating initial conditions based on the so-called Monte Carlo Glauber model (which is actually a wounded nucleon model) are employed, followed by a viscous hydrodynamical evolution. Also [19] uses fluctuating initial conditions, here based on both Glauber Monte Carlo

Model	Theoretical concept	Flow	Ref.
EPOS3	GR	hydro	[1]
EPOS LHC	GR	parametrized	[7]
QGSJETII	GR	no	[9]
SIBYLL	GR	no	[10]
PHOJET	GR	no	[11]
AMPT	PHC	partly	[12]
PYTHIA6	Fact	no	[14]
PYTHIA8	Fact	no	[15]
HERWIG++	Fact	no	[16]
SHERPA	Fact	no	[17]

Table 1. List of models used to analyse identified particle production. "GR" stands for Gribov-Regge approach, "PHC" for partonic and hadronic cascade, "Fact" for factorization approach.

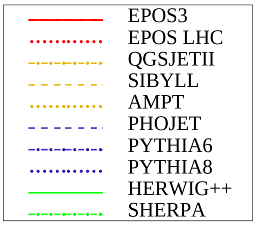

Table 2. (Color online) Line codes for the different models.

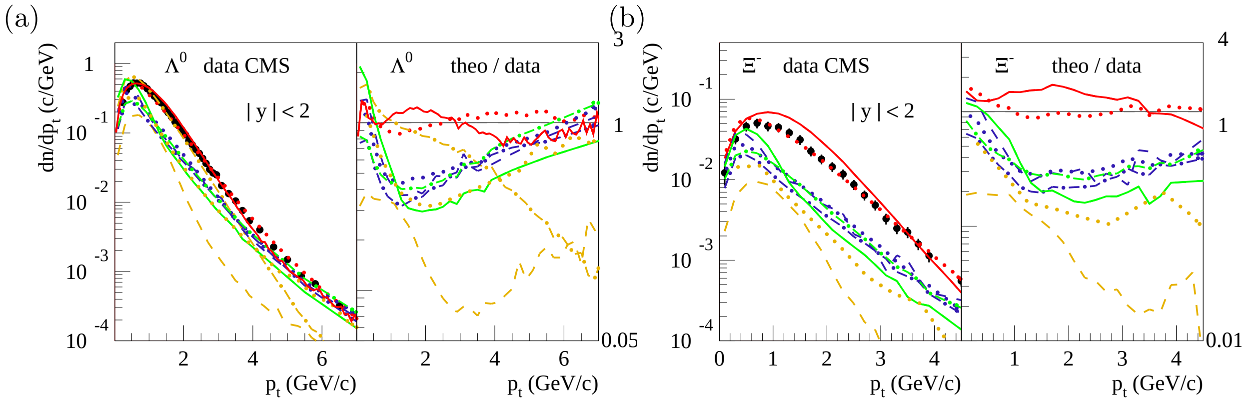

Figure 1. (Color online) **p-p scattering at 7 TeV:** Transverse momentum spectra and ratios "theory over data" of Λ baryons (a) and Ξ baryons (b). We show data from CMS [23, 24] (symbols) and simulations from the different models, using the line codes defined in tab. 2.

and Glasma initial conditions. Finally in [20], ideal hydrodynamical calculations are performed, starting from smooth Glauber model initial conditions.

We first study **p-p scattering at 7TeV**. We investigate the transverse momentum spectra of Λ baryons and Ξ baryons (see fig. 1), comparing simulations with data from CMS [23, 24], since for these particles the spectra from the different models are very different. One can distinguish three groups of models: (1) QGSJETII and SIBYLL are far off the data, they are simply not constructed to produce these kind of baryons. (2) The so-called QCD generators like PYTHIA, HERWIG, SHERPA etc show a profound "dip" in the region between 1 and 5 GeV/c, underpredicting the data by a factor of 4-5 for the Ξ baryons, and by a factor of around 3 for the Λ baryons. (3) The two EPOS versions are relatively close to the data. We recall that EPOS LHC contains collective flow (put in by hand) and EPOS3 hydrodynamic flow.

From the above study we conclude that flow seems to help to explain particle spectra. To understand better the flow contribution, we sketch in fig. 2(a) the core-corona procedure employed in EPOS to determine the flow contribution: String segments with high pt escape

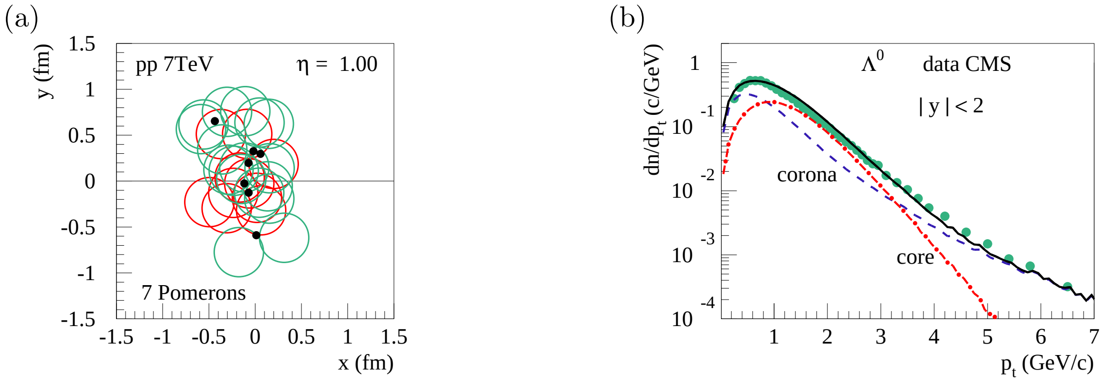

Figure 2. (Color online) **p-p scattering at 7 TeV:** (a) Core-corona separation. (b) Transverse momentum spectra of Λ baryons. We show data from CMS [23] (symbols) and simulations from EPOS3. The dashed line is the corona contributions, the dashed-dotted one the core contribution, the full line is the sums of all contributions.

(green circles, corona), the others form the "core" i.e. the initial condition for hydro (red circles). We plot in 2(b) again the transverse momentum spectra of Λ baryons, but this time only for EPOS3, also showing the corona and the core contribution. The core evolved hydrodynamically, and one can see clearly the intermediate p_t enhancement due to flow, as compared to "normal" production from (kinky) strings in the corona contributions. So we get huge flow effects for heavy particles like Λ (and Ξ) baryons.

We will now turn to **p-Pb scattering**. The CMS collaboration published a detailed study [2] of the multiplicity dependence of (normalized) transverse momentum spectra in p-Pb scattering at 5.02 TeV. The multiplicity (referred to as N_{track}) counts the number of charged particles in

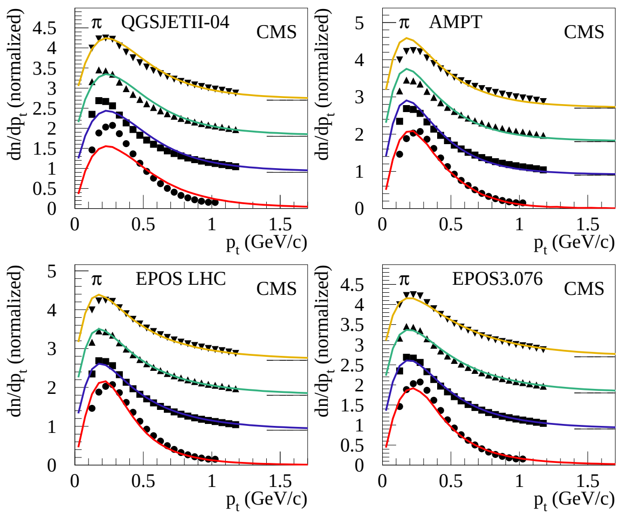

Figure 3. (Color online) Transverse momentum spectra of pions in p-Pb scattering at 5.02 TeV, for four different multiplicity classes with mean values (from bottom to top) of 8, 84, 160, and 235 charged tracks.

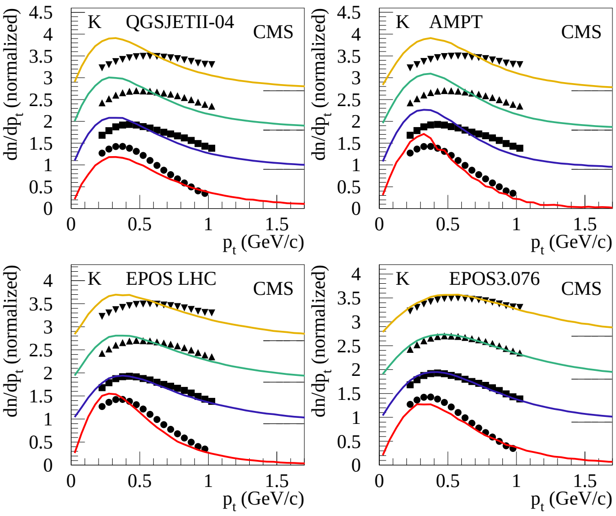

Figure 4. (Color online) Same as fig. 3, but for kaons. We show data from CMS [2] (symbols) and simulations from QGSJETII, AMPT, EPOS LHC, and EPOS3, as indicated in the figures.

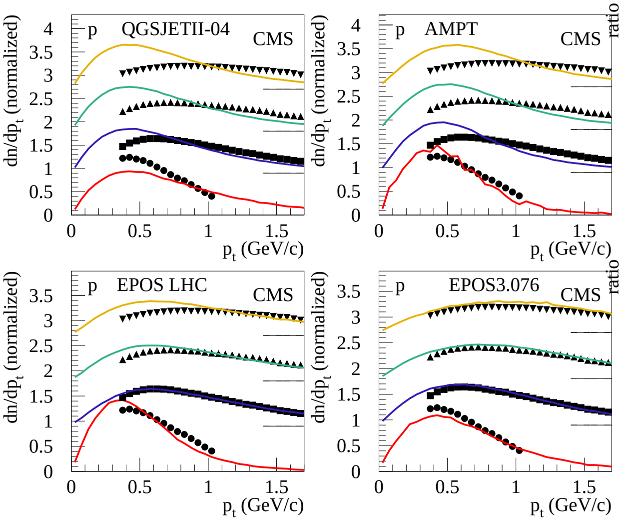

Figure 5. (Color online) Same as fig. 3, but for protons.

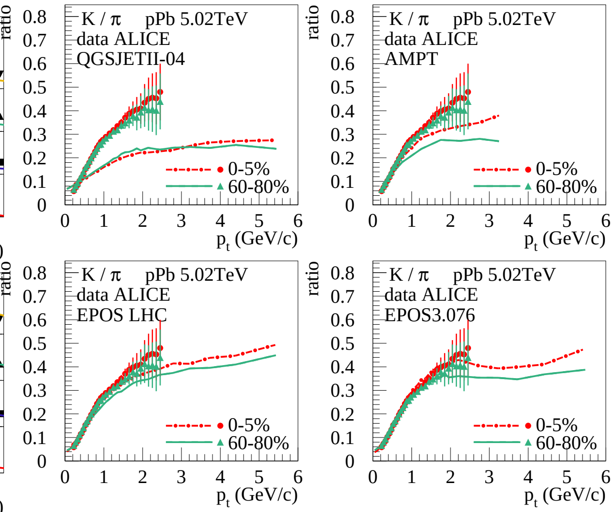

Figure 6. (Color online) Kaon over pion ratio as a function of transverse momentum in p-Pb scattering at 5.02 TeV, for the 0-5% highest multiplicity (red dashed-dotted lines, circles) and 60-80% (green solid lines, triangles).

the range $|\eta| < 2.4$. In fig. 3, we compare experimental data [2] for pions (black symbols) with the simulations from QGSJETII (upper left figure), AMPT (upper right), EPOS LHC (lower left), and EPOS3 (lower right). The different curves in each figure refer to different centralities, with mean values (from bottom to top) of 8, 84, 160, and 235 charged tracks. They are shifted relative to each other by a constant amount. Concerning the models, QGSJETII is the easiest to discuss, since here there are no flow features at all, and the curves for the different multiplicities are identical. The data, however, show a slight centrality dependence: the spectra get somewhat harder with increasing multiplicity. The other models, AMPT, EPOS LHC, and EPOS3 are close to the data.

In figs. 4, 5, we compare experimental data [2] for kaons and protons (black symbols) with the simulations. The experimental shapes of the p_t spectra change considerably, getting much harder with increasing multiplicity. In QGSJETII, having no flow, the curves for the different multiplicities are identical. The AMPT model shows some (but too little) change with multiplicity. EPOS LHC goes into the right direction, whereas EPOS3 gives a reasonable description of the data. **It seems that hydrodynamical flow helps considerably to reproduce these data**.

Also ALICE [3] has measured identified particle production for different multiplicities in p-Pb scattering at 5.02 TeV. Here, multiplicity counts the number of charged particles in the range $2.8 < \eta_{\mathrm{lab}} < 5.1$. It is useful to study the multiplicity dependence, best done by looking at ratios. In fig. 6, we show the pion over kaon (K/π) ratio as a function of transverse momentum in p-Pb scattering at 5.02 TeV, for high multiplicity (red dashed-dotted lines, circles) and low multiplicity events (green solid lines, triangles), comparing data from ALICE [3] (symbols) and simulations from QGSJETII, AMPT, EPOS LHC, and EPOS3 (lines). In all models, as in the data, there is little multiplicity dependence. However, the QGSJETII model is considerably below the data, for both high and low multiplicity events. AMPT is slightly below, whereas EPOS LHC and EPOS3 do a reasonable job. Concerning the proton over pion (p/π) ratio, fig. 7,

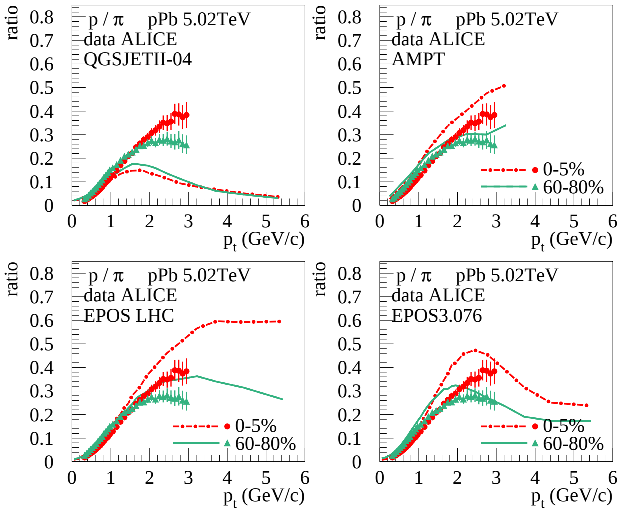

Figure 7. (Color online) Same as fig. 6, but proton over pion ratio.

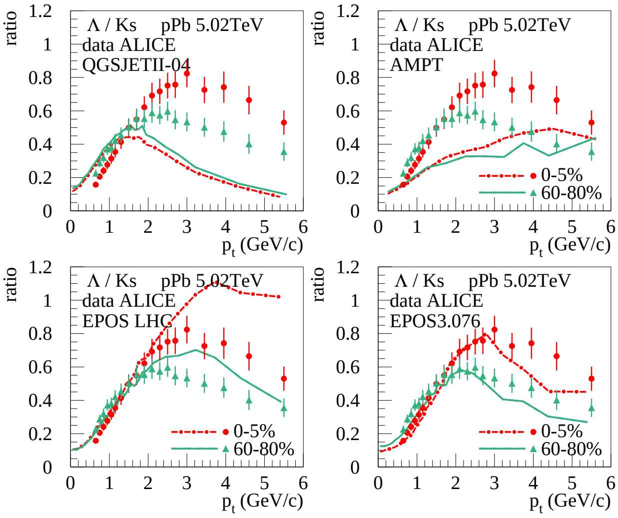

Figure 8. (Color online) Same as fig. 6, but Λ over K_s ratio.

again QGSJETII is way below the data, for both high and low multiplicity events, whereas the three other models show the trend correctly, but being slightly above the data. Most interesting are the lambdas over kaon (Λ/K_s) ratios, as shown in fig. 8, because here a wider transverse momentum range is considered, showing a clear peak structure with a maximum around 2-3 GeV/c and a slightly more pronounced peak for the higher multiplicities. QGSJETII and AMPT cannot (even qualitatively) reproduce this structure. EPOS LHC shows the right trend, but the peak is much too high for the high multiplicities. EPOS3 is close to the data.

To summarize these ratio plots (keeping in mind that the QGSJETII model has no flow, AMPT “some” flow, EPOS LHC a parametrized flow, and EPOS3 hydrodynamic flow): Flow seems to help considerably. However, from the Λ/K_s ratios, we conclude that EPOS LHC uses a too strong radial flow for high multiplicity events. The hydrodynamic flow employed in EPOS3 seems to get the experimental features reasonably well. Crucial is the core-corona procedure discussed earlier: there is more core (compared to corona) in more central collisions, but the centrality (or multiplicity) dependence is not so strong, and there is already an important core (=flow) contribution in peripheral events.

Finally, we sketch very briefly results on elliptical flow v_2 obtained from dihadron correlations, showing ALICE results [25, 26] and EPOS3 simulation, see ref. [27] for details. In fig. 9. we plot v_2 as a function of p_t. Clearly visible in data and in the simulations: a separation of the results for the three hadron species: in the p_t range of 1-1.5 GeV/c, the kaon v_2 is somewhat below the pion one, whereas the proton result is clearly below the two others. Within our fluid dynamical approach, the above results are nothing but a “mass splitting”. The effect is based on an asymmetric (mainly elliptical) flow, which translates into the corresponding azimuthal asymmetry for particle spectra. Since a given velocity translates into momentum as $m_A\gamma v$, with m_A being the mass of hadron type A, flow effects show up at higher values of p_t for higher mass particles.

To summarize : Comparing experimental data on identified particle production to various Monte Carlo generators, we conclude that hydrodynamical flow seems to play an important role in p-Pb and even in p-p scattering.

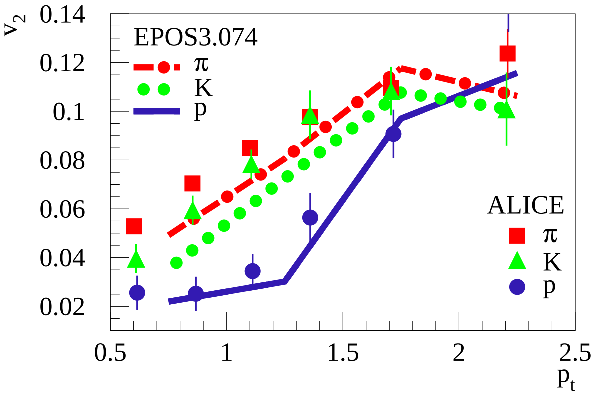

Figure 9. (Color online) Elliptical flow coefficients v_2 for pions, kaons, and protons. We show ALICE results (squares) and EPOS3 simulations (lines). Pions appear red, kaons green, protons blue.

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