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How important are next-to-leading order models in predicting strange particle spectra in $p+p$ collisions at STAR?

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Abstract. STAR has measured a variety of strange particle species in $p+p$ collisions at $\sqrt{s}=200$ GeV. These high statistics data are ideal for comparing to existing leading- and next-to-leading order perturbative QCD (pQCD) models. Next-to-leading (NLO) models have been successful in describing inclusive hadron production using parameterized fragmentation functions (FF) for quarks and gluons. However, in order to describe identified strange particle spectra at NLO, knowledge of flavor separated FF is essential. Such FF have recently been parameterized using data by the OPAL experiment and allow for the first time to perform NLO calculation for strange baryons. In fact, comparing the STAR Λ data with these calculations allow to put a constraint on the gluon fragmentation function. We show that the leading-order (LO) event generator PYTHIA has to be tuned significantly to reproduce the STAR identified strange particle data. In particular, it fails to describe the observed enhancement of baryon-to-meson ratio at intermediate p_T (2–6 GeV/c). In heavy-ion (HI) collisions this observable has been extensively compared with models and shows a strong dependency on collision centrality or parton density. In the HI context the observed enhancement has been explained by recent approaches in terms of parton coalescense and recombination models.

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1 Introduction

Perturbative QCD has proven to be successful in describing inclusive hadron production in elementary collisions. Within the theory's range of applicability, calculations at next-to-leading order (NLO) have produced accurate predictions for transverse momentum spectra of inclusive hadrons at different energy scales [1, 2]. With the new high statistics proton-proton data at $\sqrt{s}=200$ GeV collected by STAR, we can now extend the study to identified strange hadrons as well as strange resonances.

The perturbative QCD calculation applies the factorization ansatz to calculate hadron production and relies on three ingredients. The non-perturbative parton distribution functions (PDF) are obtained by parameterizations of deep inelastic scattering data. They describe quantitatively how the partons share momentum within a nucleus. The second part, which is perturbatively calculable, consists of the parton cross-section amplitude evaluated to LO or NLO using Feynman diagrams. The third part consists of the non-perturbative fragmentation functions (FF) obtained from $e^+ + e^-$ collider data using quark-tagging algorithms. These parameterized functions are sufficiently well known for fragmenting light quarks, but less well known for fragmenting gluons and heavy quarks. Recently, Kniehl, Kramer and Pötter (KKP) have shown that FF are universal between $e^+ + e^-$ and $p+p$ collisions [3].

The theoretical mechanisms of baryon production have been difficult to understand and different attempts have been made [4]. In the string fragmentation approach the production of baryons is intimately related to di-quark production from strings. They then combine with a quark to produce a baryon. In NLO calculations, baryon production is based on the knowledge of baryon fragmentation functions (FF) from $e^+ + e^-$ collisions. So far the only baryon FF which has been accurately measured and parameterized is that of the proton [5]. Other groups have used a statistical approach to calculate FF [6].

In the following section, we compare our p+p data to PYTHIA, the most commonly used leading-order Monte Carlo event generator for elementary collisions. In particular, we study predictions for baryons and the ratios of baryons to mesons and see how parameter tunes affect the data. We then compare our data with more sophisticated NLO calculations.

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2 Data analysis

The present data were reconstructed using the STAR detector system which is described in more detail elsewhere [7]. The main detector used in this analysis is the time projection chamber (TPC) covering the full acceptance in azimuth and a large pseudo-rapidity coverage ($|\eta| < 1.8$). A total of 14 million non-singly diffractive (NSD) events were triggered with the STAR beam-beam counters (BBC) requiring two coincident charged tracks at forward rapidity. Due to the particulary low track multiplicity environment in $p+p$ collisions, only 76% of primary vertices are found correctly; from the remainder, 14% are lost and 10% are badly reconstructed as a MC-study showed. Of all triggered events, 7 million events passed the selection criteria requiring a valid primary vertex within 50 cm along the beam-line from the center of the TPC. The strange particles were identified from their weak decay to charged daughter particles. The following decay channels and the corresponding anti-particles were analyzed: $K^0_S \rightarrow \pi^+ + \pi^-$ (b.r. 68.6%), $\Lambda \rightarrow p + \pi^-$ (b.r. 63.9%), $\Xi^- \rightarrow \Lambda + \pi^-$ (b.r. 99.9%). Particle identification of the daughters was achieved by requiring the $\mathrm{d}E/\mathrm{d}x$ to fall within the 3σ-bands of the theoretical Bethe–Bloch parameterizations. Further background in the invariant mass was removed by applying topological cuts to the decay geometry. Corrections for acceptance and particle reconstruction efficiency were obtained, as a function of p_T, by a Monte Carlo based method of embedding simulated particle decays into real events and comparing the number of simulated and reconstructed.

3 Comparison to PYTHIA

3.1 Strange particle spectra

One of the most widely used models for simulating elementary collisions is PYTHIA [8]. It is a parton-shower based event generator that includes leading order parton processes and parton fragmentation based on the Lund model. The parton distributions of the initial state protons can be chosen from an array of PDFs (here we use CTEQ5M). The model is being actively used and the authors have recently released a version with completely overhauled multiple scattering and shower algorithms (version 6.3) [9]. The PYTHIA version used in this paper is 6.317.

The string fragmentation based on the Lund model requires only two parameters to define the shape of the

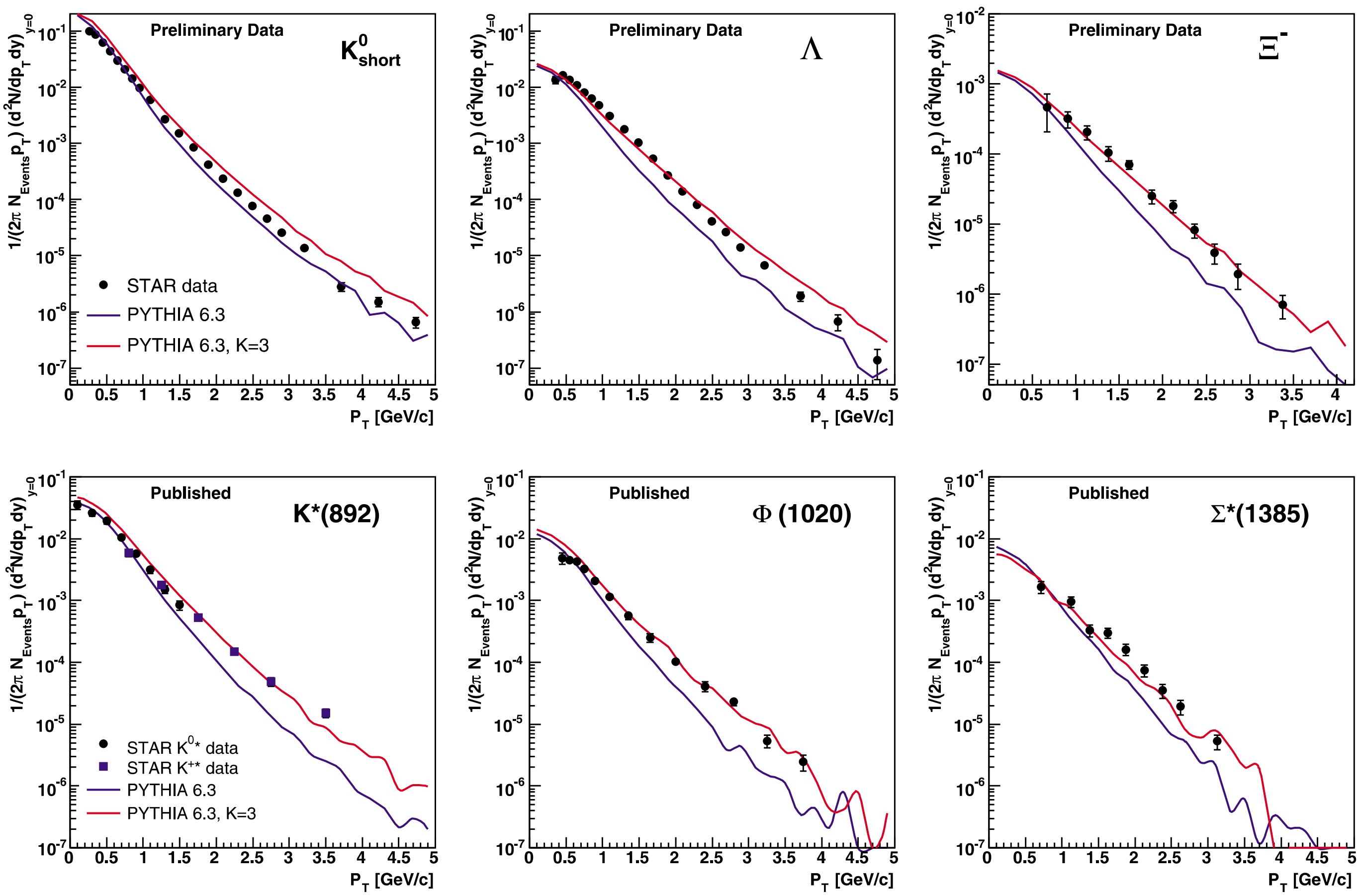

Fig. 1. *Top*: Minimum-bias p_T spectra for K^0_S, Λ and Ξ at ($|y| < 0.5$) from $p+p$ at $\sqrt{s} = 200$ GeV. *Bottom*: K^* and φ, and Σ^* p_T spectra at mid-rapidity. In the *left panel*, *black symbols* are K^{0*} and *blue symbols* are K^{+*} [11–13]

fragmentation function and is universal for all light quark flavors. Baryons are produced from di-quarks and their probability is suppressed with respect to $\bar{q}q$ pair production. Next-to-leading order processes can be "simulated" in PYTHIA by tuning the K-factor (MSTP(33)) or by increasing the parton shower activity. This will enhance the relative probability of hard processes of type quark–gluon and thus mock-up the contributions from higher order processes.

In Fig. 1 (upper row), we compare PYTHIA calculations for strange mesons and baryons to the measured STAR data. Whereas the default parameters (blue line) agree quite well for the K^0_S, they clearly underestimate the yields at intermediate p_T for the Λ and Ξ^-. By increasing the K-factor to 3 (red line) we achieve a reasonable agreement with the data. In Fig. 1 (lower row), we compare PYTHIA to the strange resonances K^*, φ and Σ^*. Again, only when applying a higher K-factor does the calculation agree with our data.

In summary, PYTHIA is capable of describing p_T spectra for a variety of particles from $p+p$ collisions at RHIC energies. However, we have presented evidence that a tune of the LO K-factor is necessary in particular for strange baryons and resonances. Of course, we have not explored all possibilities of parameter "tunes" and there may be other, equivalent ways of reproducing the data.

What are the possible reasons for this discrepancy? The "naive" reason, supported by the K-factor tune, is that higher order contributions may be significant. However it is troubling that the pions do not seem to require this tune as shown previously [14], even though a similar study of K-factors for non-identified hadrons found that at $\sqrt{s} = 200$ GeV a value of 3 was needed [15].

Another, perhaps more natural explanation, may be related to fragmentation functions for baryons in PYTHIA. In the next section we will discuss possible changes to the baryon production parameters, ie. the di-quark suppression factors, which may help solve this discrepancy.

3.2 Baryon production

In string models, baryon production in its simplest form is understood via the production of di-quark pairs from string-breaking and their recombination with other quarks. This process is suppressed with respect to $\bar{q}$–q pairs from string-breaking resulting in systematically lower baryon yields than mesons. The default value for the suppression factor is $P(qq) = 0.1P(q)$. We have increased this value to 0.125 (PYTHIA parameter PARJ(1)). Similarly the strange di-quarks are suppressed with a default factor $P(sq) = 0.4P(q)$, which we have increased to 0.5 (PYTHIA parameter PARJ(3)).

In Table 1 we show recently measured baryon yields in $p+p$ collisions at mid-rapidity. Values for Λ have been corrected for feed-down (FD) from Ξ^--decays. From the values in the table, it is clear that the tuned values for PYTHIA are in better agreement with the experimental measurements of STAR than the default values. However, it must be said that the agreement is confined to low

Table 1. STAR $\mathrm{d}N/\mathrm{d}y$ for various baryons from $p+p$ collisions at $\sqrt{s} = 200$ GeV ($|y| < 0.5$) compared to PYTHIA 6.317. Pythia baryon tune is defined as PARJ(1) = 0.125 ($D = 0.1$) and PARJ(3) = 0.5 ($D = 0.4$)

Particle	STAR $\mathrm{d}N/\mathrm{d}y$	PYTHIA	PYTHIA tuned
proton	0.11 ± 0.01	0.096	0.11
Λ (FD)	0.0385 ± 0.0035	0.0297	0.0371
Ξ^-	0.0026 ± 0.0009	0.0020	0.0029

p_T and that this tune does not change the shape of the PYTHIA spectra to improve the high p_T part.

3.3 Baryon to meson ratios

Recent heavy-ion data from STAR show a large enhancement of the baryon to meson ratios at intermediate p_T, which is associated with parton coalescence and recombination models [16]. Λ and K^0_S are ideal candidates for comparing baryon to meson production at these momenta since they can be cleanly identified via the topological reconstruction method described at the beginning.

In Fig. 2 we show the measured Λ/K^0_S ratio vs. p_T measured by STAR, together with 3 different calculations by PYTHIA. Open symbols depict Ξ^- feed-down corrected Λ yields. Clearly, the default PYTHIA calculation lies well below the data. Increasing the LO K-factor does not improve the ratio much at low p_T, although it does

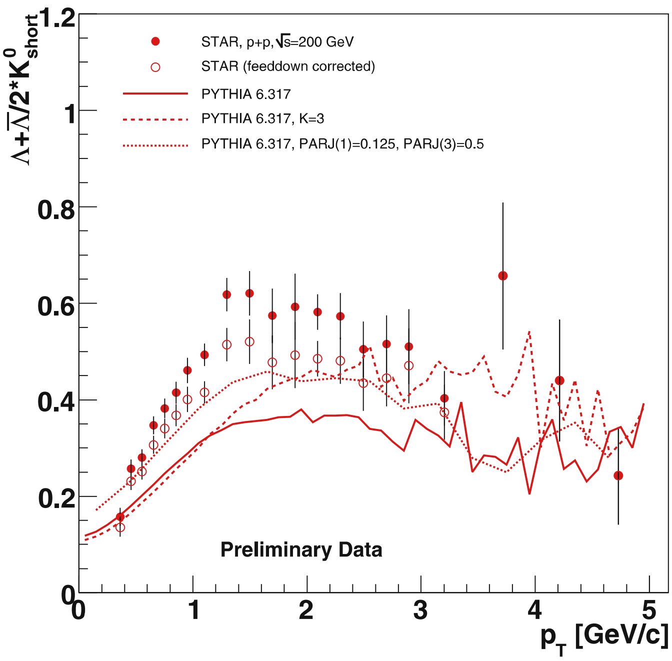

Fig. 2. Ratio of $\Lambda + \bar{\Lambda}/2 \times K^0_S$ vs. p_T from STAR data compared to three different tunes of PYTHIA 6.317. Data are shown with and without feed-down correction, whereas PYTHIA calculations are corrected for feed-down

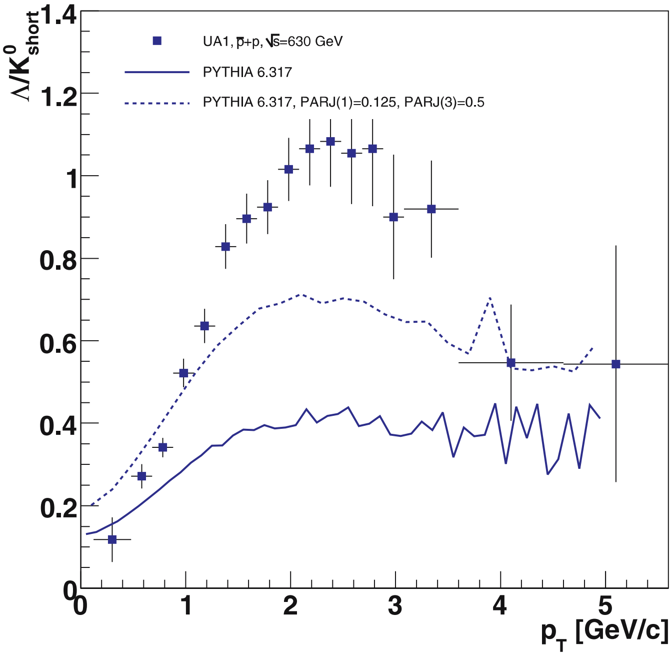

Fig. 3. Ratio of Λ/K^0_S vs. p_T from UA1 data compared to two different tunes of PYTHIA 6.317

describe the ratio at high p_T. However, using the tuned baryon parameters discussed in the previous section improves the agreement at low p_T considerably. Thus, we need to us a combination of both K-factor and baryon parameter tune to simultaneously describe the spectra and the ratios.

This result triggers the interesting question as to the possible energy dependence of this baryon production parameter. To investigate this further, we have used data for strange mesons and baryons from the UA1 collaboration, which measured $p+\bar{p}$ collisions at $\sqrt{s}=630$ GeV and produced the particle ratio presented in Fig. 3 [18].

The figure clearly shows that the disagreement with default PYTHIA for the baryon to meson ratio is not specific to our energy scale but also exists at higher energies. At $\sqrt{s}=630$ GeV, the difference between PYTHIA and data is about a factor of 3 and the enhancement of Λ/K^0_S is twice as large as in STAR. Even when tuning PYTHIA to the same values as for STAR the discrepancy between data and model remains large. This may be an indication that the effects observed in this ratio in heavy-ion data are present in some form in $p+p$ data. It remains to be understood whether the enhancement of the ratio is due to parton density (multiplicity) or to collision energy.

4 Comparison to next-to-leading order pQCD

In this final section we discuss the improvements which have recently been made by next-to-leading order calculations using more precisely parameterized fragmentation functions. Fragmentation functions for separated quark flavors have been notoriously difficult to obtain due to the lack of sufficiently precise collider data. However, OPAL has recently published flavor tagged data from $e^+ + e^-$ collisions which allowed theorists to compute better fragmentation functions [17].

In Figs. 4 and 5 we compare two different NLO calculations to our K^0_S and Λ data. The first one (black lines) uses older FF by Kniehl *et al.* (KKP) and Vogelsang *et al.* (WV) [19]. The second one (red lines) was done by Albino *et al.* (AKK) using more recent FF based on the light flavor tagged OPAL data [20].

Clearly, these newer parameterizations improve the description of our Λ data greatly. However, in order to achieve this agreement, they fix the initial gluon to Λ fragmenta-

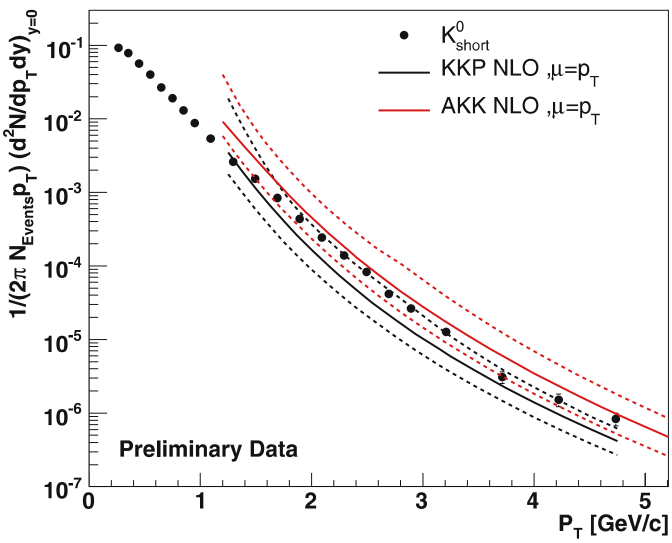

Fig. 4. p_T spectra for K^0_S at midrapidity ($|y|<0.5$) from $p+p$ at $\sqrt{s}=200$ GeV compared to two different NLO calculations. *Dashed lines* indicate the scale uncertainty of the NLO calculation, i.e. $\mu=0.5p_T$ (*lower*), $\mu=2p_T$ (*upper*)

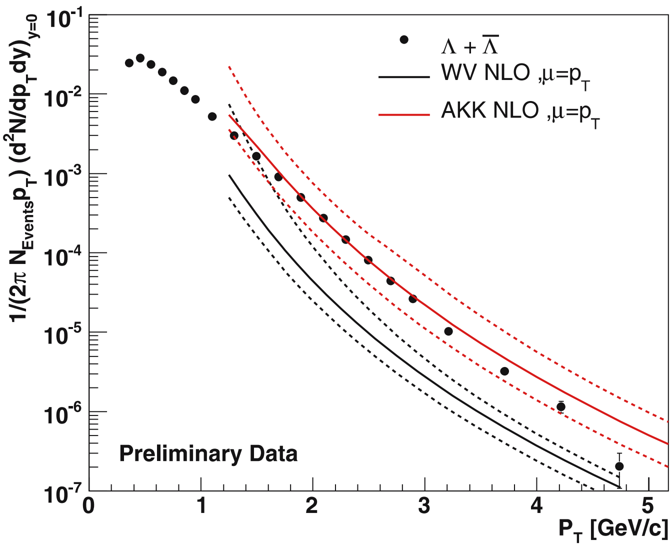

Fig. 5. p_T spectra for Λ at midrapidity ($|y|<0.5$) from $p+p$ at $\sqrt{s}=200$ GeV compared to two different NLO calculations

tion function (D_g^Λ) to that of the proton, then estimate that an additional scaling factor of 3 is necessary to achieve agreement with STAR data. However, this modified FF for D_g^Λ also works well in describing the $p+\bar{p}$ SPS data at $\sqrt{s}=630$ GeV. It therefore appears that the STAR data is a better constraint for the high z part of the gluon fragmentation function than the OPAL $e^+ + e^-$ data. Similar conclusions with respect to the important role of $p+p$ collisions have been drawn elsewhere [21].

5 Summary

We have shown that the theoretical description of identified strange particles in $p+p$ and $p+\bar{p}$ collisions is still not fully understood. This is especially important since these models are now extensively used to predict observables for the LHC-era, and therefore one should be aware of their limitations. Phenomenological LO models can be tuned to describe the data but still struggle to describe baryon production at intermediate p_{T}.

Baryon production, and in particular the baryon to meson yield ratios at intermediate p_{T}, are one of the "hot" topics in current heavy-ion research at RHIC. The $p+p$ data presented here allows us to look at the ratio in elementary collisions and check how well it is understood in a simple system. The fact that PYTHIA baryon production parameters need to be tuned quite considerably to achieve an agreement is interesting. We also showed that at the higher energies, i.e. $\sqrt{s}=630$ GeV, this difference is even larger. This is an indication that the baryon to meson effects previously observed in heavy-ion collisions are present in some form in $p+p$ data, and that the associated physics phenomena therefore need to be explained without requiring the presence of a quark–gluon plasma.

Next-to-leading order calculations have greatly improved with light flavor tagged fragmentation functions. However the high-z range of the gluon FF previously extracted from $e^+ + e^-$ data seems inconsistent with $p+p$ and $p+\bar{p}$ data, indicating that RHIC data could be valuable in constraining the gluon FF.

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