Quantifying Charged Kaon Excess Anomaly Within Hadronic Transport Approach

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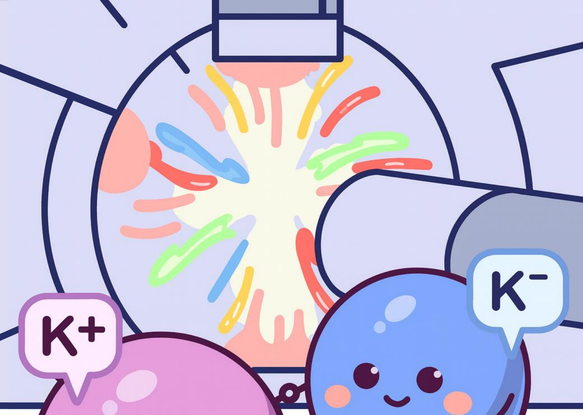


Introduction

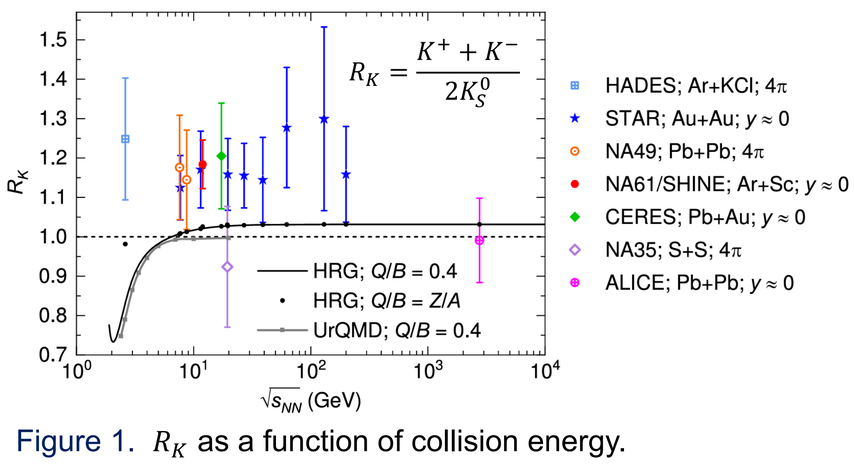


Figure 1. R_K as a function of collision energy.

Recent measurements by the NA61/SHINE Collaboration have revealed an unexpectedly large ratio of charged to neutral kaon yields in heavy-ion collisions at SPS energies [1]. This charged kaon excess anomaly challenges current descriptions of hadron production and suggests that additional physics mechanisms may be required. In hadronic transport approaches, kaon production is sensitive both to the isospin composition of the colliding nuclei and to the microscopic dynamics of $q\bar{q}$ pair creation. In this work, we employ the SMASH hadronic transport model [2] to investigate two effects of particular interest: nuclear neutron skin effect, and unequal $u\bar{u}$ and $d\bar{d}$ production rates. For the latter, we explore a multidimensional parameter space spanning light-quark pair-production asymmetry, strangeness and diquark suppression factors, and use Bayesian inference to identify the most probable parameter combinations consistent with the observed hadron yields.

Neutron Skin Effect

Heavy nuclei exhibit a neutron-rich periphery, modifying the effective isospin composition of nucleon-nucleon collisions. This may distort the expected value of R_K.

Here we perform a test with Pb+Pb collisions, because data on neutron skin are available [3-5]. Nuclei are generated using the Woods-Saxon distribution:

$$\rho_i \propto \frac{1}{e^{(r-R_i)/a_i}+1},$$

with parameters consistent with theoretical and experimental values:

$$R_p = 6.68 \text{ fm}, R_n = 6.69 \text{ fm}$$
$$a_p = 0.448 \text{ fm}, a_n = 0.607 \text{ fm}$$

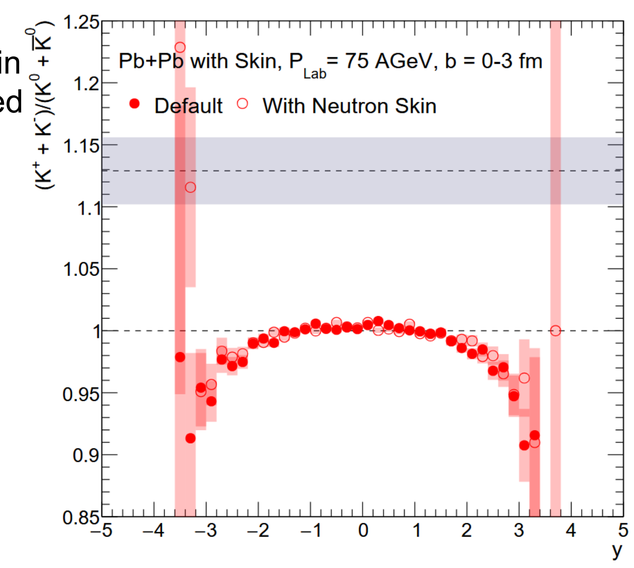


Figure 2. R_K in central Pb+Pb collisions with and without neutron skin effect.

Flavour Selection in PYTHIA

While the heavy-ion collisions are modelled using SMASH, the SMASH itself employs PYTHIA for particle production via string excitation and fragmentation at high energies. In PYTHIA a bunch of parameters is used to control the $q\bar{q}$ and $qq\overline{qq}$ pairs production. There is no difference between $u\bar{u}$ and $d\bar{d}$, while $s\bar{s}$ production is controlled by the strangeness suppression factor λ:

$$P(d\bar{d}) = P(u\bar{u}) = \frac{1}{2+\lambda}, \qquad P(s\bar{s}) = \frac{\lambda}{2+\lambda}$$

To enforce a difference in $u\bar{u}$ and $d\bar{d}$ pairs production rates, an additional parameter β was introduced ($-1 \le \beta \le 1$):

$$P(d\bar{d}) = \frac{1-\beta}{2+\lambda}, \qquad P(u\bar{u}) = \frac{1+\beta}{2+\lambda}, \qquad P(s\bar{s}) = \frac{\lambda}{2+\lambda}$$

In this work, we use the values of λ, β, and diquark suppression factor QQtoQ as free parameters.

Bayesian Inference

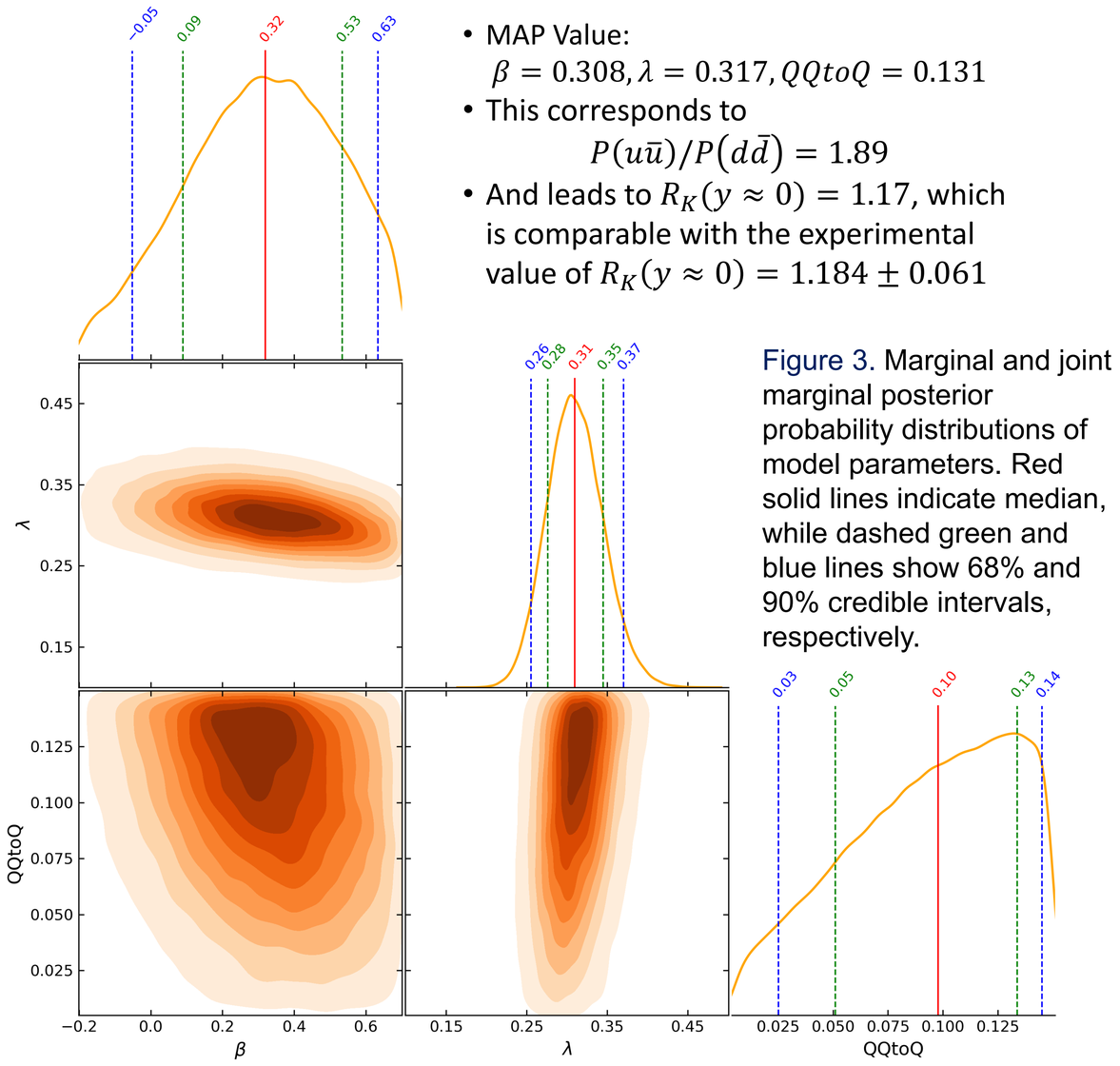
For a model, which for an input parameter vector $\vec{x} = (x_1, \dots, x_n)$ gives an output $\vec{y} = \vec{y}(\vec{x}) = (y_1, \dots, y_m)$, we want to find the "optimal" value of $\vec{x}$ to describe the experimental data $\vec{y}^{obs}$

$$\underbrace{\mathrm{P}(\vec{x}|\vec{y}^{obs})}_{\text{Posterior}} = \frac{\mathcal{L}(\vec{x};\vec{y}^{obs})P(\vec{x})}{P(\vec{y}^{obs})} \propto \underbrace{\mathcal{L}(\vec{x};\vec{y}^{obs})}_{\text{Likelihood}} \times \underbrace{P(\vec{x})}_{\text{Prior}}.$$

The goal is to find the Maximum a Posteriori (MAP) parameter values, i.e. the point in parameter space which maximizes the posterior distribution.

Model setup:

- Observables: $K^+, K^-, K_s^0, p, \bar{p}\ dN/dy$ at $y \approx 0$ in central Ar+Sc@75A GeV/c
- 80 training and 20 validation data sets with 100k full simulations per set
- Gaussian Processes with RBF kernel emulator to replace SMASH
- Markov Chain MC sampling to obtain the posterior distribution
- Uniform prior: $\beta \in [-0.2; 0.7],\ \lambda \in [0.1; 0.5],\ QQtoQ \in [0.05; 0.15]$



- MAP Value: $\beta = 0.308, \lambda = 0.317, QQtoQ = 0.131$
- This corresponds to $P(u\bar{u})/P(d\bar{d}) = 1.89$
- And leads to $R_K(y \approx 0) = 1.17$, which is comparable with the experimental value of $R_K(y \approx 0) = 1.184 \pm 0.061$

Figure 3. Marginal and joint marginal posterior probability distributions of model parameters. Red solid lines indicate median, while dashed green and blue lines show 68% and 90% credible intervals, respectively.

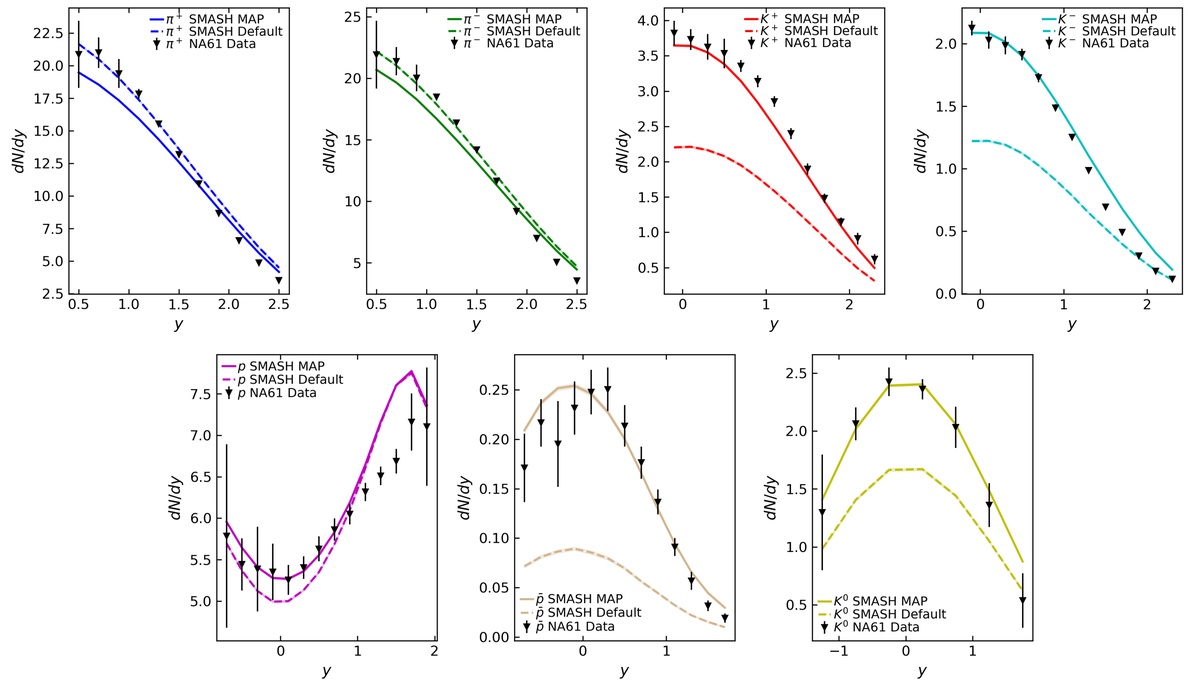


Figure 4. Rapidity spectra of identified hadrons (symbols) together with SMASH simulations in default configuration (dashed lines) and with MAP parameter values (solid lines).

Summary

- No visible effect from the neutron skin.
- It is not possible to reproduce the effect with the standard string fragmentation.
- Unequal $u\bar{u}$ and $d\bar{d}$ production rates are necessary.
- The best fit value of the light-quark pair-production asymmetry parameter is $\beta = 0.308$, which leads to $P(u\bar{u})/P(d\bar{d}) = 1.89$

References

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