NLO pQCD analysis of semi-inclusive pion and kaon production in proton-proton and heavy-ion collisions at the STAR and NICA kinematics. Tests of the parametrizations of Fragmentation Functions.

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Abstract

D.K., E. Christova and E. Leader, to be appeared in Int.J.Mod.Phys.A, e-Print: 2205.02516

Goals:

- to check compatibility of the published versions of the pion and kaon fragmentation functions with the STAR data on semi-inclusive pion and kaon production in proton-proton and heavy-ion collisions
- on the basis of these to make reliable predictions for the p_T spectra of the pions and kaons in inclusive pion and kaon production at the NICA collider
- NLO pQCD analysis using CTEQ6 PDFs and various FFs: DSEHS-14, DSEHS-17, LSS-15, AKK-08 and HKNS-07.

Abstract cont.

Conclusion:

- Within the experimental errors all tested sets of fragmentation functions provide a good fit to STAR data at the c.m. energy $\sqrt{S} = 200$ GeV, and the best ones are both LSS-15 and DSEHS-14 for pions and DSEHS-17 for kaons.
- The comparison of our predictions with BES STAR data on semi-inclusive hadron production in the most peripheral Au+Au collisions shows that for lower energy scales, like at NICA, a purely pQCD approach is inadequate and suggests the necessity to take into account also higher-order effects of initial-state soft-gluon radiation.

Abstract cont.

Nevertheless,

the BES STAR data at $\sqrt{S} = 11.5$ and 27 GeV on the p_T spectra of π^+, K^+ and also the ratios π^-/π^+ and K^-/K^+ seem favour LSS-15 and DSEHS-14 FFs for pions and DSEHS-17 for kaons, similarly as at the energy scale $\sqrt{S} = 200$ GeV.

- NICA - pQCD tests on the edge

Introduction

Based on pQCD and taking into account NLO partonic cross sections

R. K. Ellis, M. A. Furman, H. E. Haber, and I. Hinchliffe, Nucl. Phys. B 173, 397 (1980)
R. K. Ellis and J. C. Sexton, Nucl. Phys. B 269, 445 (1986)
F. Aversa, P. Chiappetta, M. Greco, and J. P. Guillet, Nucl. Phys. B 327, 105 (1989).

we have calculated the hadronic p_T-spectra of the final pions and kaons in single hadron production in pp collisions in the high p_T region, and compared it to the STAR data:

J. Adams et al. (STAR), Phys. Lett. B 616, 8 (2005), nucl-ex/0309012
J. Adams et al. (STAR), Phys. Lett. B 637, 161 (2006), nucl-ex/0601033
B. I. Abelev et al. (STAR), Phys. Rev. C 75, 064901 (2007), nucl-ex/0607033
G. Agakishiev et al. (STAR), Phys. Rev. Lett. 108, 072302 (2012), 1110.0579
L. Adamczyk et al. (STAR), Phys. Rev. C 96, 044904 (2017), 1701.07065

HKNS-07, AKK-08, DSEHS-14, LSS-15 and DEHSS-17 FFs:

M. Hirai, S. Kumano, T. H. Nagai, and K. Sudoh, Phys. Rev. D 75, 094009 (2007), hep-ph/0702250
S. Albino, B. A. Kniehl, and G. Kramer, Nucl. Phys. B 803, 42 (2008), 0803.2768
D. de Florian, R. Sassot, M. Epele, R. J. Hernandez-Pinto, and M. Stratmann, Phys. Rev. D 91, 014035 (2015), 1410.6027
E. Leader, A. V. Sidorov, and D. B. Stamenov, Phys. Rev. D 93, 074026 (2016), 1506.06381
D. de Florian, M. Epele, R. J. Hernandez-Pinto, R. Sassot, and M. Stratmann, Phys. Rev. D 95, 094019 (2017), 1702.06353

Formalism

We consider inclusive hadron production in proton-proton collisions:

$$p(P_A) + p(P_B) \to h(P^h) + X,$$

which proceeds through the hard-collision partonic subprocess:

$$a(p_a) + b(p_b) \to c(p_c) + X.$$

The basic concept underlying the theoretical analysis of most high energy interactions is **FACTORIZATION**.

The cross-section for large momentum-transfer reactions may be factorized into long-distance (nonperturbative) pieces that contain the desired information on the structure of the nucleon in terms of its parton densities such as PDFs and FFs, and short-distance (perturbative) parts which describe the hard interactions of the partons e.g. partonic cross section.

Formalism cont.

Inclusive production of single hadrons is described in terms of **Parton Distribution Functions (PDFs), parton-parton interaction Cross Sections** calculated in the Standard Model (SM) and **Fragmentation Functions (FFs).**

While the PDFs are well known, the flavor-separated quark and gluon FFs are relatively new objects. Most directly the FFs have been extracted from one-hadron production in electron-positron collisions. However, this process in principle, cannot distinguish the quark and anti-quark FFs and information only about $D^h_{q+\bar{q}}$ is obtained.

In order to obtain separate quark and anti-quark FFs, one-hadron semi-inclusive lN and pp processes play an essential role.

Fragmentation Functions

Fragmentation: hadron production from a quark, antiquark, or gluon.

$D_i^h(z, Q^2)$ - fragmentation function of hadron h from a parton i.

It is probability to find the hadron h from a parton i with the energy fraction z.

Energy conservation:

$$\sum_h \int_0^1 dz\, z D_i^h(z, Q^2) = 1$$

$$h = \pi^+, \pi^0, \pi^-, K^+, K^0, \bar{K}^0, K^-, p, \bar{p}, \ldots$$

The strength of the hard interaction is controlled by the running α_s evaluated at a large Q^2 scale.

Cross Section

In the simple parton model the expression for the cross section for $pp \to hX$ in the c.m.s. of pp has the factorized form:

$$E^h \frac{d\sigma_{pp}^h}{d^3P^h} = \frac{1}{\pi} \sum_{ab\to cd} \int_{x_{a,min}}^1 dx_a \int_{x_{b,min}}^1 dx_b \frac{1}{z} \times$$
$$\times \left\{ q_a(x_a)q_b(x_b) \left[\frac{d\hat{\sigma}_{ab}^{cd}}{dt} D_c^h(z) + \frac{d\hat{\sigma}_{ab}^{cd}}{du} D_d^h(z) \right] \right.$$
$$\left. + q_a(x_b)q_b(x_a) \left[\frac{d\hat{\sigma}_{ab}^{cd}}{du} D_c^h(z) + \frac{d\hat{\sigma}_{ab}^{cd}}{dt} D_d^h(z) \right] \right\},$$

where $d\hat{\sigma}_{ab}^{cd}$ are the Born cross sections of order α_s^2.
PDFs $q(x)$ and FFs D_i^h are scale independent and $z = E^h/E_c$.

In the QCD improved parton model:

$$q(x) \to q(x, Q^2), \qquad D_q^h(z) \to D_q^h(z, Q^2).$$

LO Partonic Processes

There are 8 different $2 \to 2$ partonic processes that contribute to $d\sigma_{pp}^{h}$:

$$
\begin{aligned}
\hat{\sigma}_1 &: \quad q_i q_j \to q_i q_j, \quad \bar{q}_i \bar{q}_j \to \bar{q}_i \bar{q}_j, \quad q_i \bar{q}_j \to q_i \bar{q}_j, i \neq j \\
\hat{\sigma}_2 &: \quad q_i q_i \to q_i q_i, \quad \bar{q}_i \bar{q}_i \to \bar{q}_i \bar{q}_i, \\
\hat{\sigma}_3 &: \quad q_i \bar{q}_i \to q_j \bar{q}_j, \quad i \neq j \\
\hat{\sigma}_4 &: \quad q_i \bar{q}_i \to q_i \bar{q}_i \\
\hat{\sigma}_5 &: \quad q_i \bar{q}_i \to gg \\
\hat{\sigma}_6 &: \quad gg \to q_i \bar{q}_i \\
\hat{\sigma}_7 &: \quad q_i g \to q_i g \\
\hat{\sigma}_8 &: \quad gg \to gg
\end{aligned}
$$

LO cont.

$\hat{\sigma}_1$: $q_i q_j \to q_i q_j$, $\quad \bar{q}_i \bar{q}_j \to \bar{q}_i \bar{q}_j$, $\quad q_i \bar{q}_j \to q_i \bar{q}_j$, $\quad \bar{q}_i q_j \to \bar{q}_i q_j$, $\quad i \neq j$

$$
\begin{aligned}
\hat{\sigma}_1 : \quad \sum_{i \neq j} \quad & q_i(x_a) q_j(x_b) \left[D^h_{q_i} \frac{d\hat{\sigma}_1}{dt} + D^h_{q_j} \frac{d\hat{\sigma}_1}{du} \right] \\
+ \quad & \bar{q}_i(x_a) \bar{q}_j(x_b) \left[D^h_{\bar{q}_i} \frac{d\hat{\sigma}_1}{dt} + D^h_{\bar{q}_j} \frac{d\hat{\sigma}_1}{du} \right] \\
+ \quad & q_i(x_a) \bar{q}_j(x_b) \left[D^h_{q_i} \frac{d\hat{\sigma}_1}{dt} + D^h_{\bar{q}_j} \frac{d\hat{\sigma}_1}{du} \right] \\
+ \quad & \bar{q}_i(x_a) q_j(x_b) \left[D^h_{\bar{q}_i} \frac{d\hat{\sigma}_1}{dt} + D^h_{q_j} \frac{d\hat{\sigma}_1}{du} \right]
\end{aligned}
$$

$i \neq j : \ i = u, j = d, s; \ i = d, j = u, s, \quad i = s, j = u, d.$

$$
\frac{d\hat{\sigma}_i(ab \to cd)}{dt} = \frac{\pi \alpha_s^2(Q^2)}{s^2} |M_i(s,t,u)|^2
$$

NLO

A complete $O(\alpha_s^3)$ calculation of the parton-parton scattering contributing to inclusive production of a hadron at large transverse momenta was presented by

F. Aversa, P. Chiappetta, M. Greco, and J. P. Guillet,
Nucl. Phys. B 327, 105 (1989).

The result includes the radiative corrections for all parton subprocesses involving quarks and gluons.

Numerical support:

- INCNLO: P. Aurenche, T. Binoth, M. Fontannaz, J.-P. Guillet, G. Heinrich, E. Pilon and M. Werlen,
  `https://lapth.cnrs.fr/PHOX_FAMILY/readme_inc.html`
- Kumano et. al.'s code for calculating the FFs:
  `http://research.kek.jp/people/kumanos/ffs.html`

The choice $AL = 1$ is mandated by the equivalent choice made in the two loop anomalous dimensions. This ambiguity does not affect the leading terms c_i in eq. (22) and is numerically irrelevant. We have used $AL = 0$ in our numerical results.

This concludes our discussion about the basic formulas for the one hadron and jet inclusive cross sections. We present in the next section our detailed analytical results for the various processes.

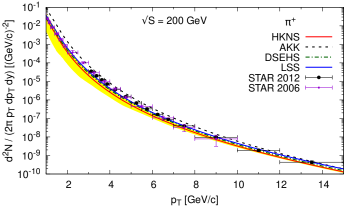
3. $O(\alpha_s^3)$ cross sections for parton–parton scattering processes

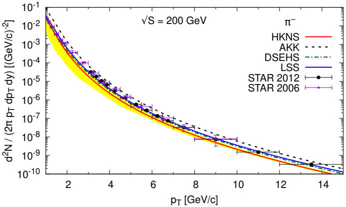
We consider the following inclusive processes:

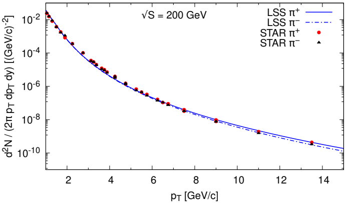
(A01)	$q_j q_k \to q_j + X,$	
(A02)	$\to q_k + X,$	
(A03)	$\to g + X,$	(24a)
(A11)	$q_j \bar{q}_k \to q_j + X,$	
(A12)	$\to \bar{q}_k + X,$	
(A13)	$\to g + X,$	(24b)
(A21)	$q_j \bar{q}_j \to \bar{q}_k + X,$	
(A22)	$\to q_k + X,$	(24c)
(B01)	$q_j q_j \to q_j + X,$	
(B02)	$\to g + X,$	(24d)
(C01)	$q_j g \to q_k + X,$	
(C02)	$\to \bar{q}_k + X,$	
(C03)	$\to \bar{q}_j + X,$	(24e)
(D01)	$q_j \bar{q}_j \to q_j + X,$	
(D02)	$\to \bar{q}_j + X,$	
(D03)	$\to g + X,$	(24f)
(E01)	$q_j g \to q_j + X,$	
(E02)	$\to g + X,$	(24g)
(F01)	$gg \to g + X,$	
(F02)	$\to q_j + X,$	(24h)

PIONS

The cross sections $\sigma_{pp}^{\pi^+}$ and $\sigma_{pp}^{\pi^-}$ calculated for different sets of FFs, compared to STAR data.



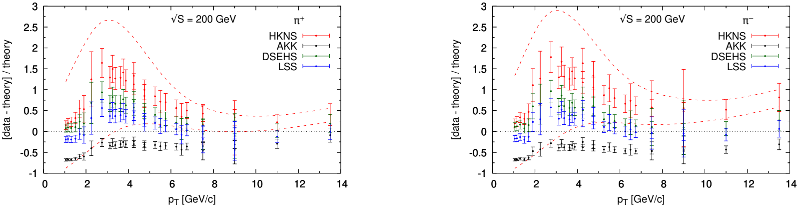




LSS: NLO QCD analysis of the HERMES data on pion multiplicities.

PIONS cont.

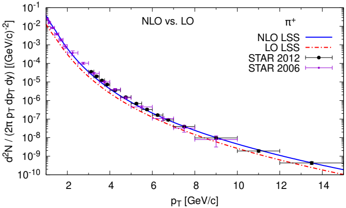
The ratio (data-theory)/theory for the cross sections: $\sigma_{pp}^{\pi^+}$ (left) and $\sigma_{pp}^{\pi^-}$ (right) for different FFs. The experimental error bars and theoretical uncertainties (dashed) for HKNS are shown.

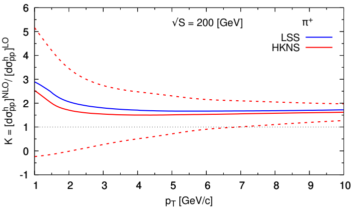


PIONS cont.

Left: a comparison of the NLO and LO results for the cross section $\sigma_{pp}^{\pi^+}$ with the use of LSS FFs together with the STAR data. Right: the K factor vs p_T. The HKNS error band is shown.

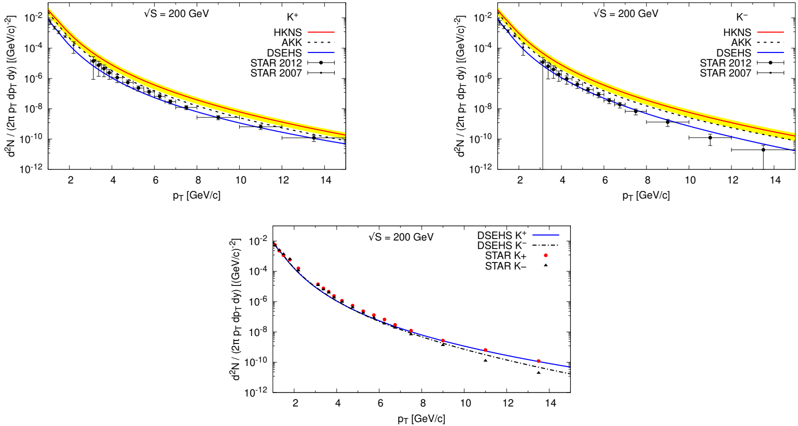
$$K = \frac{\left[d\sigma_{pp}^{h}\right]^{\mathfrak{NLO}}}{\left[d\sigma_{pp}^{h}\right]^{\mathfrak{LO}}}$$





KAONS

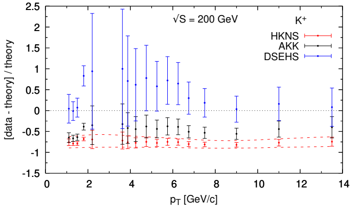
The cross sections $\sigma_{pp}^{K^+}$ and $\sigma_{pp}^{K^-}$ calculated for different sets of FFs, compared to STAR data.

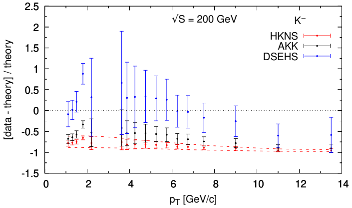


DSEHS: electron-positron annihilation, lepton-nucleon deep-inelastic scattering, and proton-proton collisions including STAR 2012.

KAONS cont.

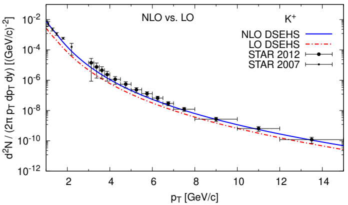
The ratio (data-theory)/theory for the cross sections: $\sigma_{pp}^{K^+}$ (left) and $\sigma_{pp}^{K^-}$ (right) for different FFs. The experimental error bars and theoretical uncertainties (dashed) for HKNS are shown.

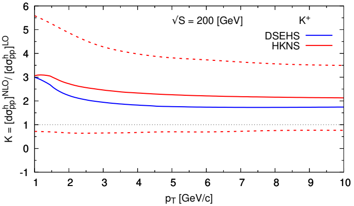




KAONS cont.

Left: a comparison of the NLO and LO results for the cross section $\sigma_{pp}^{K^+}$ with the use of DSEHS FFs together with the STAR data. Right: the K factor vs p_T. The HKNS error band is shown.





The Best Fit

$$\chi^2 = \frac{1}{N}\sum_i^N \frac{(\sigma_i^{exp} - \sigma_i^{th})^2}{\Delta_i^2}$$

FFs	π^+	π^-	K^+	K^-	$\pi^+ - \pi^-$	$K^+ - K^-$
HKNS	10.2	11.7	124	222	0.136	0.335
AKK	77.2	83.3	16.0	34.1	-	-
DSEHS	4.55	4.39	1.18	1.31	0.148	0.329
LSS	2.83	2.46	-	-	0.143	-

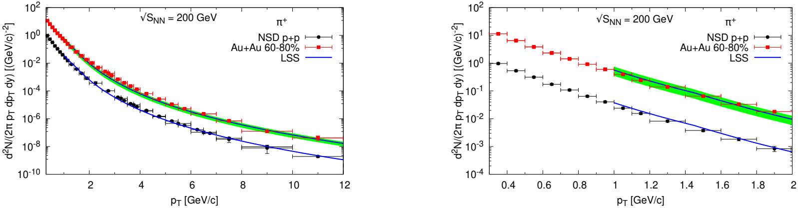
We take into account the combined STAR data for $p_T > 1$ Gev$/c$ with $N = 30$ experimental points for pions (STAR 2006 and STAR 2012), and $N = 17$ for kaons (STAR 2007 and STAR 2012), respectively.

Beam Energy Scan: heavy-ion collisions

We use the phenomenological result of scaling that spectral shapes and relative particle yields are similar in $p+p$ and peripheral $A+A$ collisions where the nuclear effects are negligible:

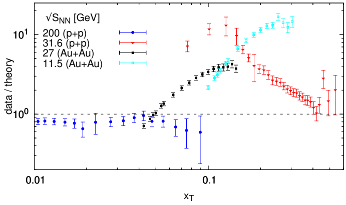
$$\frac{d^2N^{AA}}{dp_T\,dy} = N_{\rm coll}\,\frac{d^2N^{pp}}{dp_T\,dy}; \qquad \frac{d^2N^{pp}}{2\pi\,p_T\,dp_T\,dy} = \frac{1}{\sigma^{pp}_{inel}}\,E_h\,\frac{d\sigma^h_{pp}}{d^3P_h}$$

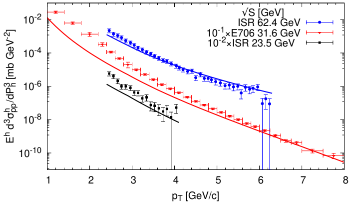
The cross sections $\sigma^{\pi^+}_{pp}$ and $\sigma^{\pi^+}_{AuAu}$ compared to STAR data at $\sqrt{S} = 200$ GeV. $N_{\rm coll} = 21.2^{+6.6}_{-7.9}$ and $\sigma^{pp}_{inel} = 42$ mb. The error bands correspond to the systematic uncertainties of $N_{\rm coll}$.



Scaling at different energies

Left: ratios of data to theory for the inclusive π^+ (STAR), and also π^0 (E706), production in $p+p$ and the most peripheral Au+Au collisions as a function of $x_T = 2p_T/\sqrt{S}$ at different $\sqrt{S_{NN}}$: 200, 27 and 11.5 GeV at STAR, and 31.6 GeV at E706. Right: the NLO pQCD results for the p_T spectra of π^0 at different $\sqrt{S}$ compared to the measurements in $p+p$ collisions at ISR and E706.



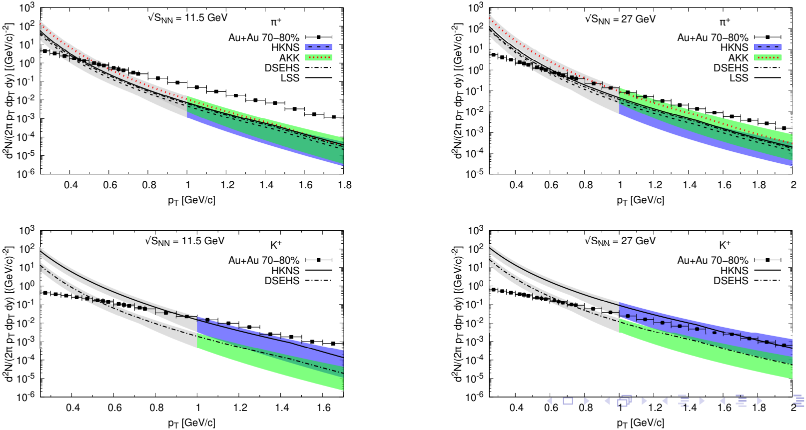


Scaling works well at high energies, significantly above the energy scales specific for NICA.

BES STAR Au+Au at $\sqrt{S} = 11.5$ and 27 GeV

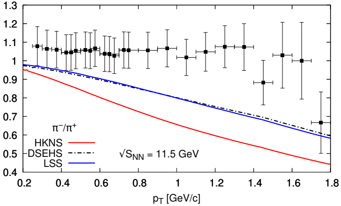
Transverse momentum spectra for h^+ in Au+Au the most peripheral collisions. $N_{coll} = 14 \pm 7$. The error bands correspond to the systematic uncertainties of N_{coll} and theoretical uncertainties due to Q scale variation,

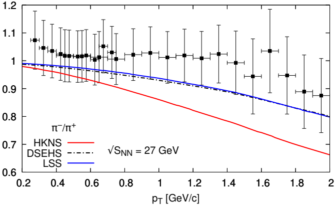
$$p_T/2 \leqslant Q \leqslant 2p_T.$$

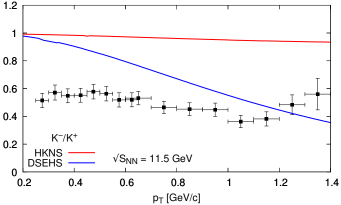


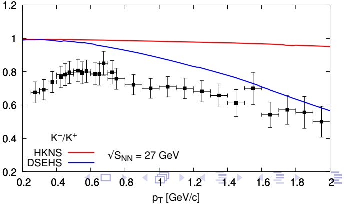
Au+Au $\sqrt{S} = 11.5$ and 27 GeV cont.

Ratios of the transverse momentum spectra h^-/h^+ in Au+Au the most peripheral collisions. It is reasonable to assume that at a given energy the additional initial state soft-gluon emission corrections are the same for particles and antiparticles produced in $p+p$ collisions.









Conclusions

- Using NLO approach, we have compared the predictions for the semi-inclusive cross-sections for hadron production in $p + p$ and Au+Au collisions based on various FFs with the STAR data.
- LSS for pions and DSEHS for kaons are significantly better parametrizations than the others at the energy scale $\sqrt{S} = 200$ GeV and for lower energy scales, like at NICA, as well.
- At NICA energy scales, a purely pQCD approach is inadequate and suggests the necessity to take into account also higher-order effects of initial-state soft-gluon radiation.