Enhanced Yield of Strange and Heavy-Flavour Particles from Few-Nucleon Clusters In High Energy pA Collisions

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Abstract

The possible correlation between the yield of strange and heavy-flavour particles and the emission of particles in the region outside pN-kinematics (the so-called cumulative region) in pA collisions is studied. The particle production in the cumulative area is considered as a trigger, confirming participation in the process of a dense few-nucleon cluster. From the modern point of view this cold dense nuclear matter clusters (fluctons), intrinsically presented in nuclei, could be regarded as multi-quark bags similar to the droplets of cold quark-gluon plasma.

For the description of particle production from such objects, the scheme based on the evaluation of the QCD diagram near thresholds [1-4] is applied. In this approach the production of pions in this area is explained by the hadronization of a fast cumulative quark [2,3], whereas in the production of protons is dominated by the coherent coalescence of three fast quarks from the cluster [3,4]. This approach, in particular, has already allowed to describe the transverse momentum dependence of the yields both the pions and the protons in the cumulative region, using the only parameter - the constituent quark mass, taken to be equal 300 MeV [5].

In present work, using the string fusion model, we analyze the fragmentation of the nuclear cluster residue after the emission of a particle in cumulative region. Previous studies [2,4] show that the diagrams are dominant, in which all rest quarks of the cluster (the donors, compensating the momentum of the fast quark(s)) must interact with the projectile. At the same time these donor quarks belong to a shrunk configuration in transverse plane of the reaction. As a consequence the strings formed in the interactions of the cluster remnant quarks with the projectile occur strongly overlapped in the impact parameter plane. Hence one can expect an enhanced yield of strange and charm particles due to sting fusion processes. As known, these processes lead to the additional production of heavy flavors (see e.g. [6] for the case of enhanced strangeness production). Along with the standard Schwinger-based version of a string fragmentation we consider also the modified version leading to the thermal-like spectra [7,8], what results in the increased production of the strange and heavy-flavour particles [9,10].

Basing on this picture we calculate the strength of the correlation between the yield of particles in the backward cumulative hemisphere and the magnitude of additional forward strange and charm particles production in relativistic pA collisions. The possibility of experimental observation of the given phenomenon is also discussed.

References:

1. M.A. Braun, V.V. Vechernin, Nucl. Phys. B 427, 614 (1994).
2. M.A. Braun, V.V. Vechernin, Phys. Atom. Nucl. 63, 1831 (2000).
3. M.A. Braun, V.V. Vechernin, Nucl. Phys. B (Proc. Suppl.) 92, 156 (2001).
4. M.A. Braun, V.V. Vechernin, Theor. Math. Phys. 139, 766 (2004).
5. V. Vechernin, AIP Conference Proceedings 1701, 060020 (2016).
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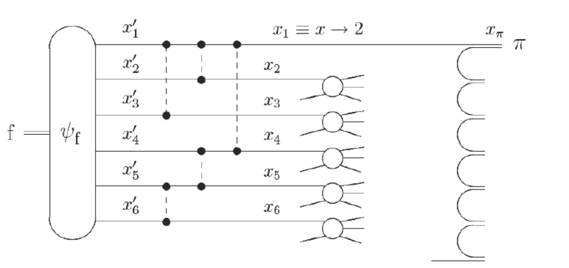
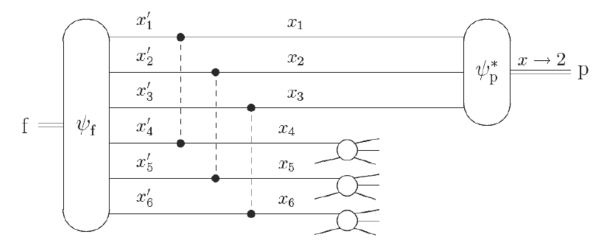
7. A. Bialas, Phys. Lett. B 466 (1999), 301.
8. N. Fischer, T. Sj?strand, JHEP 01 (2017) 140.
9. V. Vechernin, The correlation between yields of cumulative and heavy flavor particles in the model with string fusion, IV RUSSIAN-SPANISH CONGRESS: "Particle, Nuclear, Astroparticle Physics and Cosmology", 4-8 September 2017, JINR, Dubna (Russsia), 2017. https://indico.jinr.ru/getFile.py/access?resId=0&materialId=11&confId=132
10. H.J. Pirner, B.Z. Kopeliovich, K. Reygers, Strangeness Enhancement due to String Fluctuations, arXiv:1810.04736, 2018.

Coherent Quark Coalescence and Production of Cumulative Protons

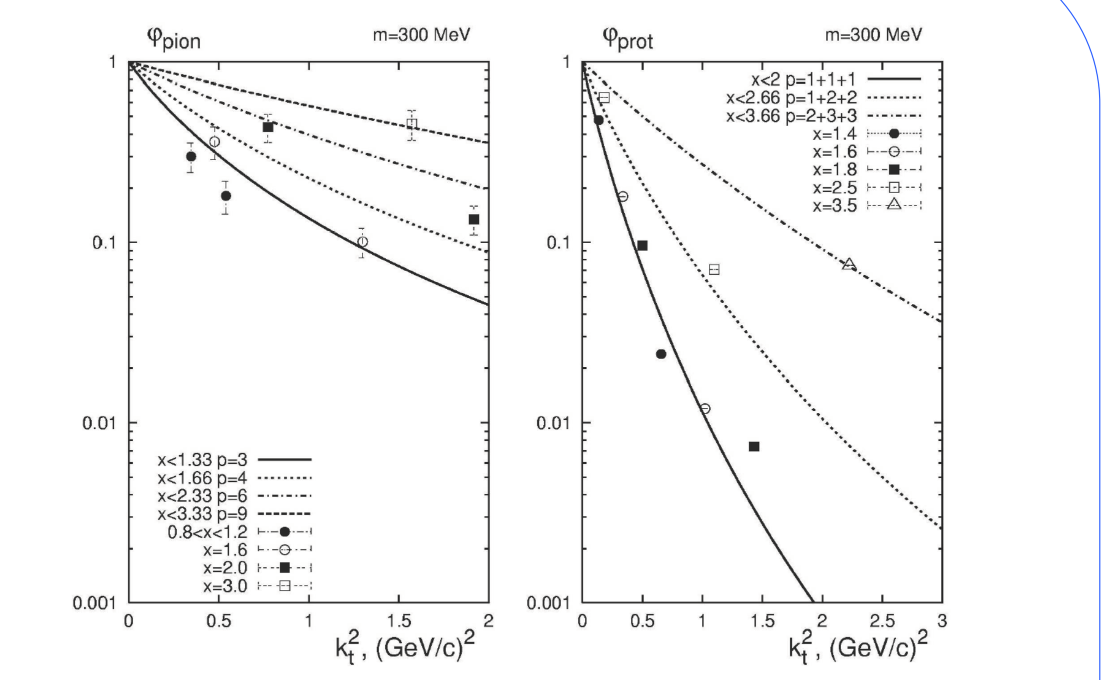


- the cumulative pion production
by hadronization of one fast quark
*M.A. Braun, V.V. V ,
Nucl.Phys.**B 427**, 614 (1994);
Phys.Atom.Nucl. **60**, 432 (1997);
63, 1831 (2000)*



- the cumulative proton production
by coherent quark coalescence mechanism:
*M.A. Braun, V.V. V ,
Nucl.Phys.**B 92**, 156 (2001);
Theor.Math.Phys **139**, 766 (2004)*

The last recalls the few nucleon short-range correlations in a nucleus
*L.L. Frankfurt, M.I. Strikmann, Phys. Rep. 76, 215 (1981);
ibid 160, 235 (1988).*

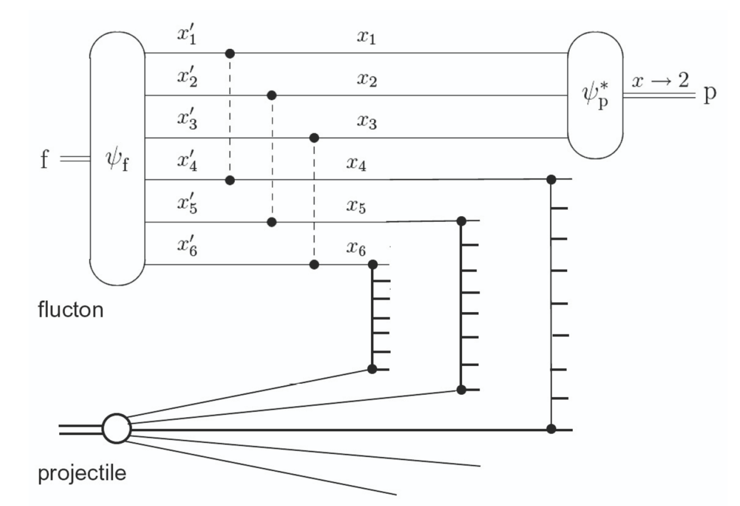


*V. V ,
AIP Conference Proceedings
1701 (2016) 060020.*

*S.V. Boyarinov et al., Sov.J.Nucl.Phys. **46**, 871 (1987)
S.V. Boyarinov et al., Physics of Atomic Nuclei **57**, 1379 (1994)
S.V. Boyarinov et al., Sov.J.Nucl.Phys. **55**, 917 (1992)*

No free parameters (!) only m – the constituent quark mass: $m = 300$ MeV.

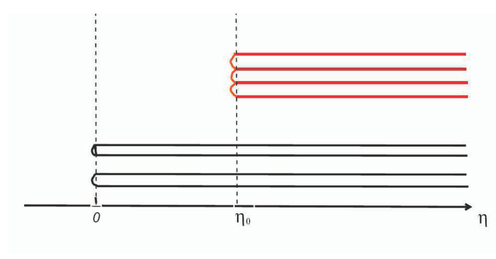
Flucton cumulative fragmentation



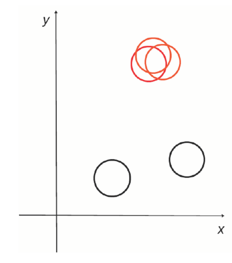
Formation of the donor strings
due to interaction of the flucton recoil with the projectile
(all donors have to interact with the projectile)
[M.A. Braun, V.V. V , Phys.Atom.Nucl. 60, 432 (1997))]

Flucton cumulative fragmentation

1) **Cumulative particle momentum needs to be compensated by longitudinal momenta of the donors => Donor strings are shifted to positive rapidities**
2) **Cumulative fragmentation of flucton needs *shrunk* flucton configuration in transverse plane *[M.A. Braun, V.V. V , Theor.Math.Phys. 139, 766 (2004)]***
=> Overlapping of donor strings



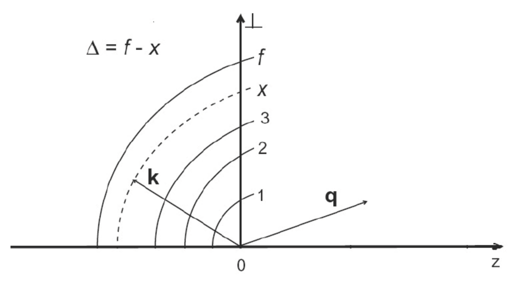
Rapidity distribution of the donor strings (in laboratory frame)



Transverse plane distribution of the donor strings

- the donor strings
- general valence quark strings

Kinematics of simultaneous cumulative and heavy flavor particles production



In the rest frame of fragmentating nucleus at large initial energy:

$$-x_F \approx x \equiv \frac{k_-}{p_-} = \frac{\sqrt{k_z^2+\mu_\perp^2}-k_z}{m_N} > 0$$

$$x_q \equiv \frac{q_-}{p_-} = \frac{\sqrt{q_z^2+M_\perp^2}-q_z}{m_N} > 0$$

The kinematical border is given by the condition: $x + x_q = f$

For the given deviation Δ of the x from its maximal value for flucton with f nucleons, we have:

$$q_-^{max} = m_N\,(f-x) = m_N\,\Delta$$

Then by $q_z = \frac{1}{2}\left(\frac{M_\perp^2}{q_-} - q_-\right)$ we find $q_z^{min} = \frac{1}{2}\left(\frac{M_\perp^2}{m_N\,\Delta} - m_N\,\Delta\right)$

- min q_z depends only on Δ (not on f and **k** components)
- no dependence on initial energy (at large energies)
- dependence only on particle masses, not on their quantum numbers (that is not true at small initial energies)

That gives for the minimal rapidity of the heavy flavor particle:

$$y_{min} = -\ln\frac{m_N\,\Delta}{M_\perp}$$

where the rapidity is defined in a standard way: $y \equiv \frac{1}{2}\ln\frac{q_+}{q_-} = \ln\frac{M_\perp}{q_-}$

	M = 0.5 GeV		M = 1.87 GeV	
Δ	min q_z, GeV	y_{min}	min q_z, GeV	y_{min}
0.9	-0.275	-0.526	1.644	0.793
0.8	-0.210	-0.408	1.949	0.911
0.7	-0.139	-0.275	2.328	1.044
0.6	-0.060	-0.120	2.818	1.199
0.5	0.031	0.062	3.485	1.381
0.4	0.144	0.285	4.462	1.604
0.3	0.302	0.573	6.059	1.892
0.2	0.571	0.978	9.206	2.297
0.1	1.283	1.671	18.554	2.990

Dynamics of string decay

J. Schwinger, Phys. Rev. 82, 664 (1951).
A.I. Nikshov, Nucl. Phys. B21, 346 (1970).
T.D. Cohen and D.A. McGady, Phys.Rev.D 78, 036008 (2008).
Only $n=1$ contribution.

$$W = \frac{\rho^2}{4\pi^3}\sum_q\sum_{n=1}^{\infty}\frac{1}{n^2}\exp(-n\pi m_q^2/\rho) \equiv \sum_q w_q \qquad m_q\ (q = u, d, s, c, \ldots)$$

$$W = \int d^2k_T\,\widetilde{W}(k_T^2) \qquad \widetilde{W} = \frac{\rho}{4\pi^3}\sum_q\sum_{n=1}^{\infty}\frac{1}{n}\exp[-n\pi(m_q^2+k_T^2)/\rho]$$

E.G. Gurvich, Phys.Lett. 87B (1979) 386.
A. Casher, H. Neunberg and S. Nussinov, Phys. Rev. D20 (1979) 179.
M. Gyulassy and A. Iwazaki, Phys. Lett. B165 (1985) 157.

A. Bialas, Phys.Lett.B 466 (1999) 301. $\frac{dn_\kappa}{d^2p_\perp} \sim e^{-\pi m_\perp^2/\kappa^2}$ => $\frac{dn}{d^2p_\perp} \sim e^{-m_\perp/T}$

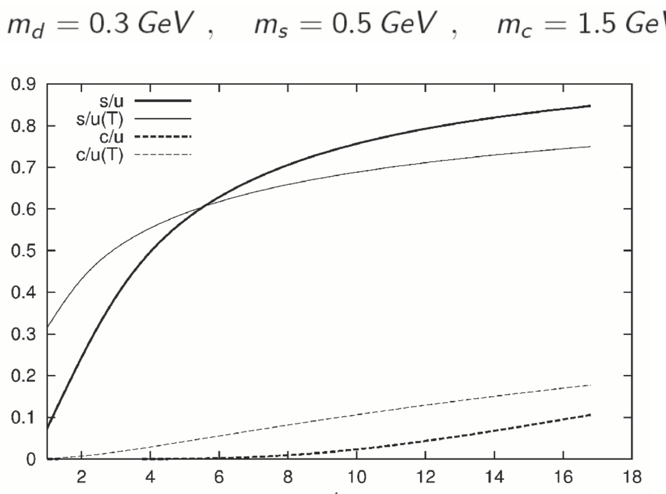
$$\langle\kappa^2\rangle = \rho = \frac{1}{2\pi\alpha'}\ , \quad \alpha' = 0.9 GeV^{-2}\ , \quad \rho = 0.18 GeV^2$$

(From the parameters of the potential connecting heavy quarks in nonrelativistic models one obtains the close value $\rho = 0.19$ GeV^2.)

$$T = \sqrt{\frac{\langle\kappa^2\rangle}{2\pi}} \approx 170 MeV$$

Increase of the relative strangeness and charm production with string fusion

$$m_u = m_d = 0.3\,GeV\ ,\quad m_s = 0.5\,GeV\ ,\quad m_c = 1.5\,GeV$$



$$\langle K^-\rangle/\langle\pi^-\rangle \quad = 0,12\ (\sqrt{s} = 0.9\ TeV) \quad = 0,1\ (\sqrt{s} = 0.2\ TeV)$$

ALICE Collaboration, Eur. Phys. J. C71,1594(2011) "Strange particle production in proton-proton collisions at 0.9 TeV with ALICE at the LHC"
*STAR Collaboration, Phys. Rev. C**75**, (2007) 064901.*

The non perturbative and pQCD contributions to charm production

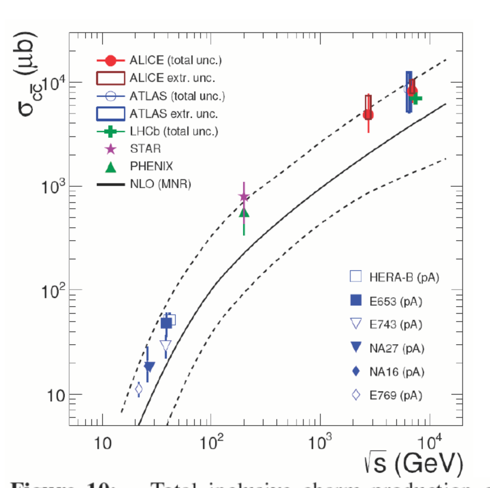


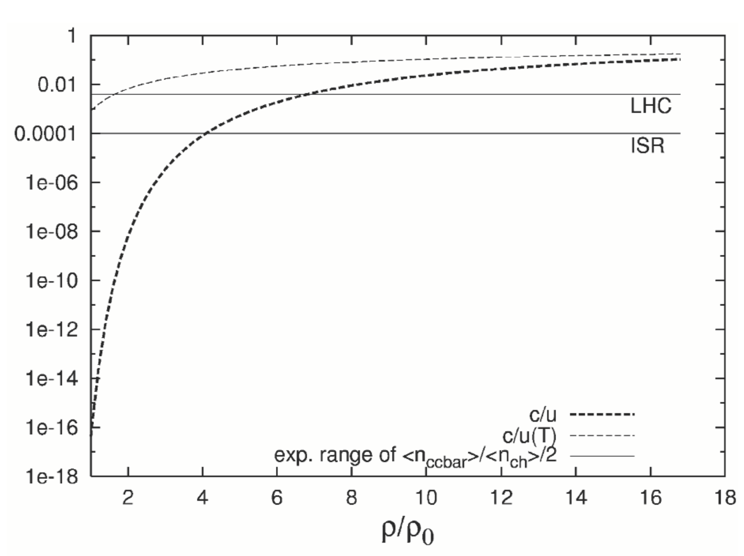
Figure 10: Total inclusive charm production cross section in nucleon–nucleon collisions as a function of $\sqrt{s}$ [51,68,73,80–82]. Data are from pA collisions for $\sqrt{s} < 100$ GeV and from pp collisions for $\sqrt{s} > 100$ GeV. Data from pA collisions were scaled by $1/A$. Results from NLO pQCD calculations (MNR [76]) and their uncertainties are shown as solid and dashed lines.

ALICE Collaboration, Phys. Rev. C 94, 054908 (2016)
"D-meson production in p-Pb collisions at 5.02 TeV and in pp collisions at 7 TeV".

*C. Lourenco and H. K. Wohri,
Phys. Rept. 433 (2006) 127–180.*
"Heavy flavour hadro-production from fixed-target to collider energies,"

M.L.Mangano, P.Nason,G. Ridolfi, Nucl. Phys. B373 (1992) 295 "Heavy quark correlations in hadron collisions at next-to-leading order"

So in principle the experimental data lives room for the non perturbative contribution to charm production, e.g. due to the string fusion effects.



Increase of the relative charm production with string fusion

The non perturbative contribution, we are interested in (due to the additional string fusion effects in flucton recoil), can be more noticeable at small initial energies in fix-target pA experiments as in discussed future experiments with modified NA61 at SPS.

We also expect that this contribution will manifest itself more clear in p collisions with light nuclei (pD, pHe), because of the absence of other string fusion effects.

The observables

We define the two class of events with and without the particle (proton or pion) with $x > x_0$ in cumulative region and introduce the ratio:

$$\gamma = \frac{\sigma_{h.f.}^{with\ cum.part.}(y > y_{min}(\Delta))}{\sigma_{h.f.}^{without\ cum.part.}(y > y_{min}(\Delta))}$$

In described approach we expect that $\gamma > 1$

The restriction to the rapidity region $y > y_{min}(\Delta)$
is necessary to suppress the increase of the phase volume
of the heavy flavor particle production in the case without cumulative particle.

$y_{min}(\Delta)$ was calculated above for the case of large initial energies,

$$\Delta = [x_0] + 1 - x_0$$

Summary:

1) So in this approach based on the combination of two complementary models (flucton cumulative fragmentation + string fusion)
we can expect the positive correlation between production of particle in the backward cumulative region and relative yield of heavy flavors in forward direction.
2) The non perturbative contribution to the production of heavy flavor particles, due to the additional string fusion effects in flucton recoil,
can be more noticeable at small initial energies in fix-target pA experiments, as in discussed future experiments with modified NA61 at SPS.
3) We also expect that this contribution will manifest itself more clear in p collisions with light nuclei (pD, pHe), because of the absence of other string fusion effects.

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