Study of multiquark fluctons in dd collisions

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SPD First Stage Physics Workshop 23 April 2025 Study of inclusive production cross-sections of pions and protons in a new cumulative region: central rapidities, large transverse momenta

$$d+d \rightarrow \pi+X$$

 $d+d \rightarrow p+X$

outside p+p kinematics:

$$p+p \rightarrow \pi+X$$

 $p+p \rightarrow p+X$

The mechanisms of pion and proton production are different!

Cumulative regions in dd and pd collisions



$$p_N \gg m_N \qquad p_N \approx \sqrt{s/2}$$

$$\frac{k_\perp}{p_N} = \frac{\sqrt{A_1 A_2}}{(A_1 + A_2)/2} \sqrt{\left(A_1 - \frac{k_z}{p_N}\right) \left(A_2 + \frac{k_z}{p_N}\right)}$$

We expect for the inclusive cross-section of the production of particles with large transverse momenta at midrapidities:

$$\frac{k_0 d^3 \sigma}{d^3 \mathbf{k}} = f(x, \eta) = C \, s^{-q_1} \, (f - x)^{q_2} \, F(\eta)$$

Quark Counting Rules with two asymptotic parameters: s>>m² and (f-x)

*q*₁, *q*₂ are different for production of pions and protons!

x - cumulative number $\eta = -\ln \operatorname{tg} \frac{\theta^*}{2}$ - pseudorapidity 2

Flucton-flucton interaction in dd collisions

- It can be studied only in new cumulative region of large transverse momenta in mid-rapidity region at NICA (not in the traditional cumulative region of fragmentation of one of the nuclei).
- There are no additional interactions in dd collision, compared with collisions of heavier nuclei, if both deuterons are in flucton configuration at the moment of collision.
- Higher frequency of dd collisions that can be recorded by the SPD, compared to the slower MPD (important for a registration of rare cumulative events).
- The studies in new cumulative region becomes possible due to the moderate energy of the NICA collider and is completely impossible at ultrahigh energies of the RHIC and LHC.

Comparison of Interaction Rates in AuAu (BiBi) collisions at MPD and in dd collisions at SPD

MPD:
$$L_{AuAu} = 10^{27} cm^{-2} c^{-1}$$



$$\sigma_{\rm AuAu}^{tot} \cong 7000 \ mb_{\odot}$$

$$I_{AuAu} = L_{AuAu} \, \sigma_{AuAu}^{tot} = 7 \, \mathrm{KHz}$$

V. Kekelidze, A. Kovalenko, R. Lednicky, V. Matveev, I. Meshkov, A. Sorin, G.Trubnikov, "Feasibility study of heavy-ion collision physics at NICA", Nuclear Physics A 967 (2017) 884–887.

Higher frequency of dd collisions that can be recorded by the SPD, compared to the slower MPD is important for a registration of rare cumulative events.

$$\sigma_{\rm dd}^{tot} \cong 120 \ mb$$

$$I_{dd} = L_{dd} \,\sigma_{dd}^{tot} = 120 \,\mathrm{KHz}$$

V.M. Abazov, et al. [The SPD collaboration], "Conceptual design of the Spin Physics Detector ArXiv:2102.00442v3 [hep-ex], 2022.

Pion and Proton Yields: Estimation of Production Rates at Different Initial Energies

Simulations using MC event generators:

Not done yet, as this **mechanism is missing in existing MC event generators**. It is necessary to introduce into MC generator some admixture of the 6-quark flucton into the deuteron wave function **with the theoretically assumed** functions of flucton fragmentation into observed particles (in progress with Semyon Yurchenko).

Estimates based on extrapolation from the region of fragmentation of a nucleus:

Vechernin V.V., Belokurova S.N., Yurchenko S.V. Phys Part Nucl, 2024, Vol. 55, pp. 889–894.

$$\langle n \rangle_{\rm dd} \cdot \sigma_{\rm dd}^{tot} = 4\pi \int_{0.5}^{1} dy \int_{k_{\perp}^{min}(y)}^{k_{\perp}^{max}(y)} dk_{\perp} k_{\perp} f(x(y,k_{\perp}),k_{\perp})$$

Table 1. The magnitude of the transverse momentum of cumulative pions and protons in dd scattering, corresponding to values of the variable x = 1 and 2 (k_{\perp}^{min}) and k_{\perp}^{max} and k_{\perp}^{max} at a given value of the rapidity y, for two values of the initial energy.

$\sqrt{s_{NN}}$	$4 \mathrm{GeV}$			8 GeV		
	y	k_{\perp}^{min}	k_{\perp}^{max}	y	k_{\perp}^{min}	k_{\perp}^{max}
$\mathrm{dd} \to \pi$	0.5	1.728	2.752	0.5	4.197	6.672
$\mathrm{dd} \to \pi$	1.0	1.102	2.002	1.0	2.687	4.86
$\mathrm{dd} \to \mathrm{p}$	0.5	1.741	2.999	0.5	4.218	6.803
$\mathrm{dd} \to \mathrm{p}$	1.0	0.852	2.089	1.0	2.605	4.915

Pion and Proton Yields: Estimation of Production Rates in dd collisions at $\sqrt{s_{NN}}$ = 4 and 8 GeV

Table 2. The results of calculations of the multiplicity of pions and protons in the cumulative region by the formula (9), using the inclusive cross sections (1) and (2), for rapidities in the interval 0.5 < |y| < 1 formed in dd scattering due to the interaction of a nucleon with a 6-quark flucton.

	$\sqrt{s_{NN}}$	$4 \mathrm{GeV}$	$8 \mathrm{GeV}$
	x > 1.0	9.10^{-4}	$1.9 \cdot 10^{-4}$
$\langle n_{\pi^-} \rangle_{\rm dd}$	x > 1.2	$6.6 \cdot 10^{-5}$	$1.2 \cdot 10^{-5}$
	x > 1.5	$3.6 \cdot 10^{-7}$	$5.8 \cdot 10^{-8}$
	x > 1.0	$2.3 \cdot 10^{-2}$	9.10^{-6}
$\langle n_p \rangle_{\rm dd}$	x > 1.2	$1.2 \cdot 10^{-3}$	$4.6 \cdot 10^{-7}$
	x > 1.5	$1.04 \cdot 10^{-5}$	$4.2 \cdot 10^{-9}$



$$Y_{\rm dd} = 0.1 L_{\rm dd} \sigma_{\rm dd}^{\rm tot} \langle n \rangle_{\rm dd} t.$$

depends only on product $\langle n \rangle_{\rm dd} \sigma_{\rm dd}^{\rm tot}$ (see previous slide)

The SPD Collab. (V. Abazov et al.), Natural Science Review 1 1 (2024); arXiv:2404.08317 [hep-ex]

Pion and Proton Yields:

Estimation of Production Rates in dd collisions at $\sqrt{s_{NN}}$ = 4 and 8 GeV

Table 3. Estimates of the yields (Y_{dd}) of cumulative pions and protons in the rapidity interval 0.5 < |y| < 1 in dd collisions in one hour of data acquisition at the SPD facility of the NICA collider, calculated by the formulas (9) and (11) using the inclusive cross sections (1) and (2) and taking into account the luminosity reduction at energy 4 GeV [21] (see text).

	$\sqrt{s_{NN}}$	$4 \mathrm{GeV}$	8 GeV
	x > 1	400	8 000
$Y_{\rm dd} \to \pi^-$	x > 1.2	30	500
	x > 1.5	0.16	2.5
	x > 1	10 000	400
$Y_{\rm dd} \to p$	x > 1.2	500	20
	x > 1.5	4.5	0.18

The work was supported by the Russian Science Foundation, project 23-12-00042".

Inclusive cross sections for the production of pions and protons in dd-collisions, integrated over rapidity intervals 0.5 < |y| < 1



$$\frac{d\sigma}{dx} = \frac{\langle n \rangle_{\rm dd}^{\Delta x}}{\Delta x} \sigma_{\rm dd}^{tot} = \frac{2\pi}{\Delta x} \int_{0.5}^{1} dy \int_{k_{\perp}^{x}(y)}^{k_{\perp}^{x+\Delta x}(y)} dk_{\perp} k_{\perp} \times f(x(y,k_{\perp}),k_{\perp}), \qquad (9)$$

Vechernin V.V., Yurchenko S.V. Cumulative production at central rapidities and large transverse momenta in the quark model of flucton fragmentation, Moscow University Physics Bulletin, 2024, Vol. 79, Suppl. 1, pp. S174–S178.

Figure 2. Inclusive cross sections for the production of pions (\circ, \Box) and protons (\triangle, ∇) in dd collisions, integrated over rapidity intervals 0.5 < |y| < 1 and available for study with NICA SPD, respectively, for two initial energies $\sqrt{s_{NN}} = 4$ and 8 GeV, as a function of the light-cone cumulative variable $x = 2x_+$ (open simbols) and the cumulative number $x = x_M$ (solid symbols). Model calculations by (9) using (1) and (2). (Curves serve to guide the eye.)

$$f + 2N$$
$$x_1 = x = x_M$$
$$x_2 = 2$$

Backup slides

Kinematics



 $d+d \rightarrow \pi+X$ at quark level (A₁=A₂=A=2, n = 6)

$$p_N = P_A/A \qquad p_N \gg m_N$$

Initial state:

$$k_i \sim P_A/n = p_N/3 \qquad n = 3A$$

$$h_i \sim -P_A/n = -p_N/3 \qquad n = 3A$$

Final state:

$$k \sim P_A = A p_N = n p_N/3$$

 $l_i \sim -P_A/(2n-1) = -\frac{n}{3(2n-1)} p_N$

V. Vechernin, S. Yurchenko Int.J.Mod.Phys. E, 2441022, DOI: 10.1142/S0218301324410222

$$s = s_{NN}$$
 10

Schmidt I.A., Blankenbecler R. Phys.Rev. D15 (1977) 3321



Threshold behaviour of *inclusive cross sections* (quark counting rules) at |t|<<s. *The experimental points from J. Papp et al., Phys.Rev.Lett.* 34, 601 (1975).

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Quark counting rules for *elastic and quasi elastic* reactions with nuclei

Matveev V.A., Muradyan R.M., Tavkhelidze A.N. Lett. Nuovo Cimento 7 (1973) 719 Brodsky S., Farrar G. Phys.Rev.Lett. 31 (1973) 1153; Phys.Rev. D11 (1975) 1309 Brodsky S., Chertok B.T., Phys.Rev. D14 (1976) 3003; Phys.Rev.Lett. 37 (1976) 269 $s \rightarrow \infty$, t/s fixed

$$(d\sigma/dt)_{\pi p \to \pi p} \sim s^{-8}, \ (d\sigma/dt)_{pp \to pp} \sim s^{-10}, \ (d\sigma/dt)_{\gamma p \to \pi p} \sim s^{-7}, \ (d\sigma/dt)_{\gamma p \to \gamma p} \sim s^{-6}$$

 $\sim s^{-n}$ A+B->C+D $n=n_A+n_B+n_C+n_D-2$ $n_p=3$ $n_{\pi}=2$ $n_{\gamma}=1$

$$\frac{d\sigma}{dt}(A + B \rightarrow C + D) \rightarrow \frac{1}{t^{N-2}}f(t/s) \qquad N = n_A + n_B + n_C + n_D$$

Yu.L. Dokshitzer, QCD Phenomenology, Lectures at the CERN–Dubna School, Pylos, August 2002

the deuteron break-up by a photon, $\gamma + D \rightarrow p + n$

$$\frac{d\sigma}{dt} = \frac{f(\Theta)}{s^{K-2}}; \qquad \frac{t}{s} = \text{const}, \qquad \text{K-2=1+6+3+3-2=11}$$

For light nuclei:

Yu.N. Uzikov, Indication of Asymptotic Scaling in the Reactions dd->p³H, dd->n³He and pd->pd, JETP Letters 81 (2005) 303.

~ s⁻²² (6+6+3+9-2=22) and ~ s⁻¹⁶ (3+6+3+6-2=16)

Future studies

\Box From pion to proton production ($AA \rightarrow \pi X => AA \rightarrow pX$)

- <u>leading</u> cumulative <u>diquark</u> (including diquarks into scheme),
 V.T. Kim, Modern Phys. Lett. A 3 (1988) 909
- <u>coalescence</u> (recombination) of three cumulative quarks
 M.A. Braun, V.V. Vechernin, Nucl.Phys.B92 (2001) 156;
 Theor.Math.Phys 139, 766 (2004);

V.Vechernin, AIP Conf.Proc.1701 (2016) 060020

(three point B, can't to neglect all small initial momemta in B)

□ From partonic to hadronic final states

 $M_X \sim (A - x)\sqrt{s}$, so at rather small NICA energies => dd $\rightarrow \pi NNNN$ and dd $\rightarrow pNNN$

Coherent Quark Coalescence and Production of Cumulative Protons



 the cumulative pion production by hadronization of one fast quark *M.A. Braun, V.V. Vechernin, 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. Vechernin, Nucl.Phys.***B 92**, 156 (2001); *Theor.Math.Phys* **139**, 766 (2004); *V.Vechernin, AIP Conf.Proc.*1701 (2016) 060020.

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).* But instead of using the relativistic generalization of non-relativistic NN wave function **the microscopic analysis of the flucton fragmentation process near cumulative thresholds on the base of the intrinsic diagrams of QCD in light-cone gauge** *Brodsky S.J., Hoyer P., Mueller A., Tang W.-K., Nucl. Phys.* **B369** (1992) 519. **14 Was developed and applied.**



V.Vechernin, 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)



N. Antonov, V. Gapienko, G. Gapienko, M. Ilushin, A. Prudkoglyad, V. Romanovskiy, <u>A. Semak</u>, I. Solodovnikov, M. Ukhanov, V. Viktorov "High pt anti-proton and meson production in cumulative pA reaction <u>at 50 GeV/c</u>" (National Research Center Kurchatov Institute - Institute for High Energy Physics, Protvino) LXX International Conference "NUCLEUS – 2020. Nuclear physics and elementary particle physics. Nuclear physics technologies", St Petersburg, October 11-17, 2020.

Incorporating diquarks

V.T. Kim, Diquarks and Dynamics of Large P(T) Baryon Production, Mod.Phys.Lett.A 3 (1988) 909.

 p/\square^\square ratio explanation, using that the diquark distribution function is harder: $(1-x)^1$ vs $(1-x)^3$ for quarks [$(1-x)^{2p-1}$].

Yu.L. Dokshitzer, QCD Phenomenology, Lectures at the CERN–Dubna School, Pylos, August 2002



Fig. 4a: Gluon exchange produces a leading baryon.

M.A. Braun, V.V. Vechernin, Nuclear Structure Functions and Particle Production in the Cumulative Region in the Parton Model, Nucl.Phys. B427 (1994) 614

Can string junction carries the baryon number?

L. Montanet, G. C. Rossi, and G. Veneziano, "Baryonium Physics," Phys. Rept. 63, 149–222 (1980).

D. Kharzeev, "Can gluons trace baryon number?" Phys.Lett. B 378, 238–246 (1996), arXiv:nucl-th/9602027. Can be verified experimentally by studing of baryon stopping in central pp and AA collisions.

Yu.M. Shabelski,
String Junction and Diffusion of Baryon Charge in Multiparticle Production Processes, arXiv: 0705.0947 [hep-ph], (2007).
F. Bopp, Yu.M. Shabelski,
String junction effects for forward and central baryon production in hadron-nucleus collisions Eur.Phys.J.A 28 (2006) 237-243

G.Pihan, A.Monnai, B.Schenke, Chun Shen, Unveiling baryon charge carriers through charge stopping in isobar collisions arXiv:2405.19439v1 [nucl-th] (2024).

Connection with diquarks: Now B=1 corresponds to diquark



Variation of the number of participant and NN collisions in AA (dd) interactions

Vechernin, V.V. and Nguyen, H.S. Phys. Rev. C 84 (2011) 054909

So for variation of the number of participant and NN collisions in AA (dd) interactions the general analytical formulas from textbooks ("the optical approximation"): C.-Y. Wong, Introduction to High-Energy Heavy-Ion Collisions (World Scientific, Singapore, 1994).

R. Vogt, Ultrarelativistic Heavy-Ion Collisions (Elsevier, Amsterdam, 2007). are not correct and are not supported by MC simulations.