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Quark counting rules for the production of cumulative pions with large transverse momenta

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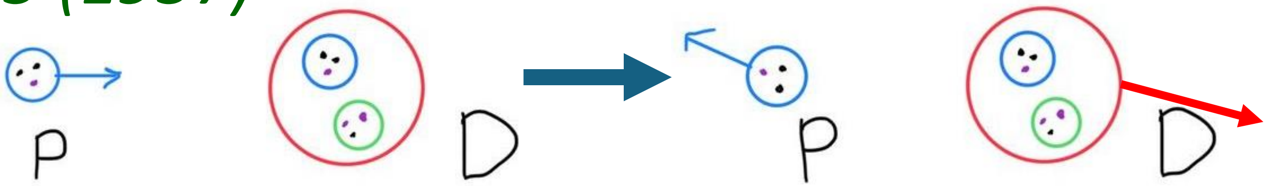
Historical note

- 1957 – The 1st experimental observations of the backward particle production in p+A collisions on a fixed target nucleus: *G.A. Leksin, ZhETF 32, 445 (1957)*



- 1957 – Flucton – intrinsic droplet of dense cold nuclear matter in a nucleus (2N flucton – 6 quark state) *Blokhintsev D.I., JETP 33 (1957) 1295*

Cumulative pion production

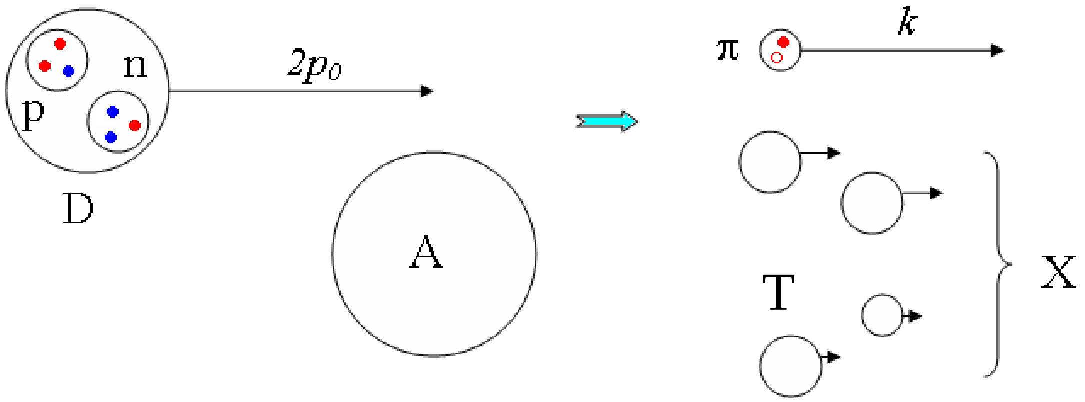
Production of particles from nuclei in a region, kinematically forbidden for reactions with free nucleons.

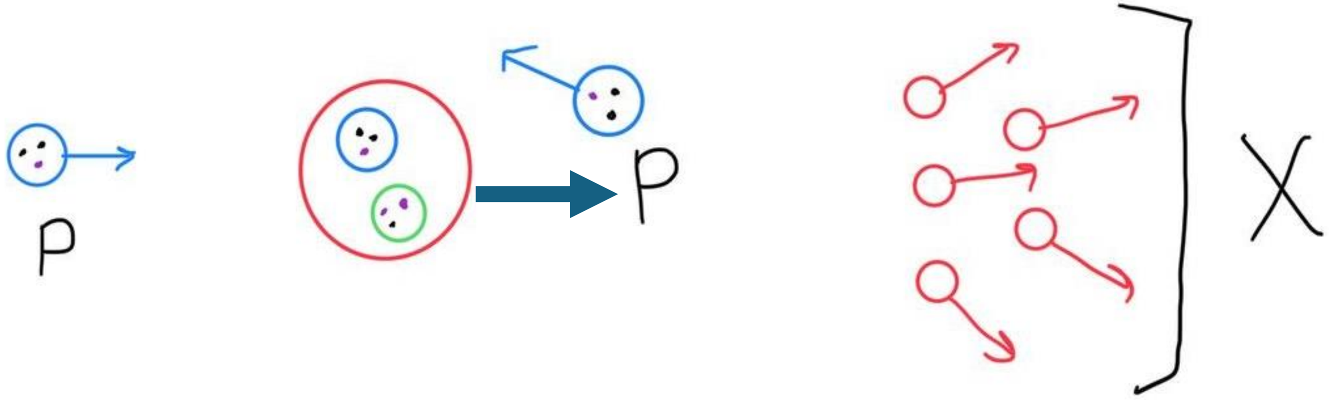
1970 - Nuclotron@Dubna – beams of relativistic deutrons (p_0=*5 GeV/c/nucleon*)
Stavinskiy V.S. → Fragmentation of projectile deuterons, D, on some target, T.
*Baldin A.M. et al., Yad.Fiz.***18** *(1973) 79*

D + T → π + X

$p_0 >> m_N$: $p_0 < k < 2p_0$ - cumulative pions

The Rutherford-like experiments indicating the presence of droplets of dense nuclear matter in a target nucleus (fluctons).
Yu.D. Bayukov et al., Izv. AN SSSR 30, 521 (1966)

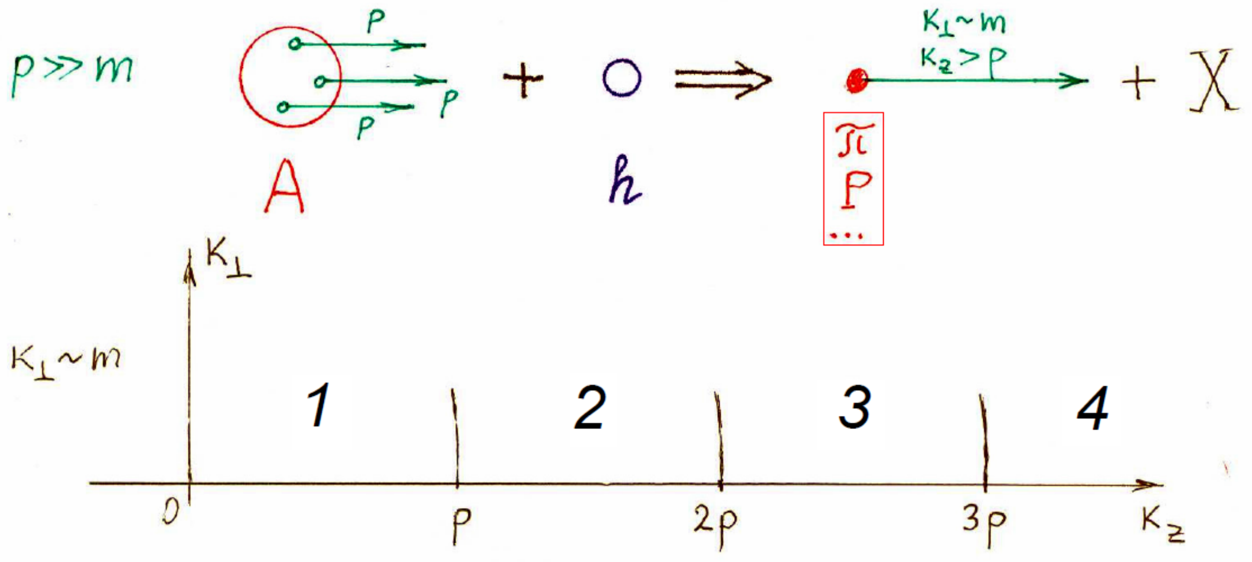




Fragmentation of projectile nucleus ↔ *Fragmentation of target nucleus*
(the same phenomenon in different frames of reference)

Kinematics of cumulative production

Fragmentation of projectile nucleus



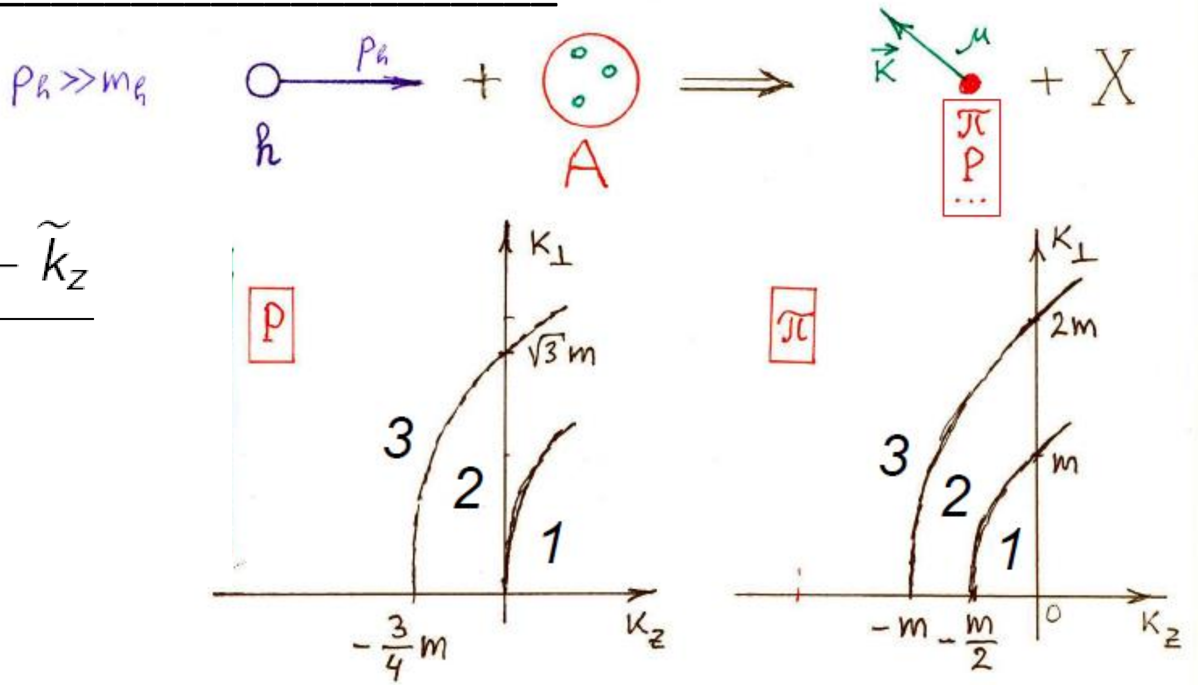
$$x \equiv \frac{k_+}{p_+} = \frac{k_0 + k_z}{p_0 + p_z} \approx \frac{k_z}{p}$$

$$k_z,\ p \gg m,\ \ m - \text{nucleon mass}$$

$$x = 1, 2, 3, \ldots, A$$

The borders increase with *p*

Fragmentation of target nucleus



$$x \equiv \frac{k_-}{p_-} = \frac{\tilde{k}_0 - \tilde{k}_z}{m} = \frac{\sqrt{\tilde{k}_z^2 + k_\perp^2 + \mu^2} - \tilde{k}_z}{m}$$

$$\tilde{k}_z = -\frac{xm}{2} + \frac{k_\perp^2 + \mu^2}{2xm}$$

The borders are fixed at *p>>m*

Flucton fragmentation region

Cumulative production at $|t| << s$

Description of the hadron asymptotics at x → 1

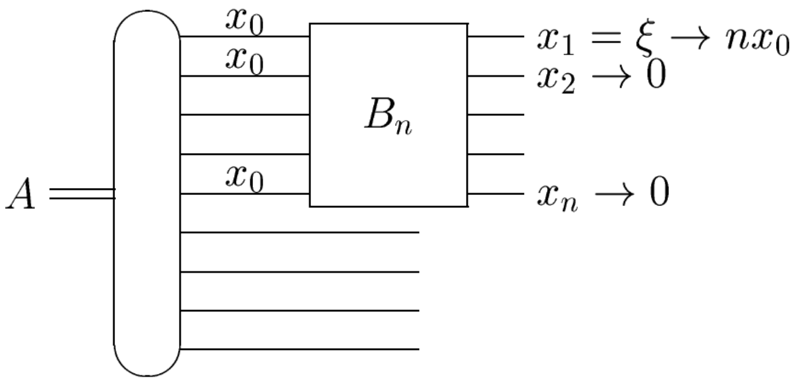
by the intrinsic diagrams of QCD in light-cone gauge with low-x spectator quarks interact with the target

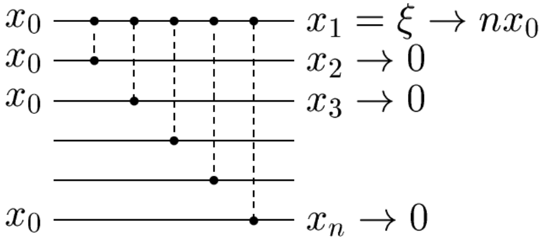
Brodsky S.J., Hoyer P., Mueller A., Tang W.-K., Nucl.Phys. ***B369*** *(1992) 519*

Description of the flucton asymptotic at $x \to f$,

f - the number of nucleons in flucton, n - the number of quarks in flucton, $x_0 = f / n$ (=1/3).

M.A. Braun, V.V. Vechernin, Nucl.Phys. ***B427*** *(1994) 614.*



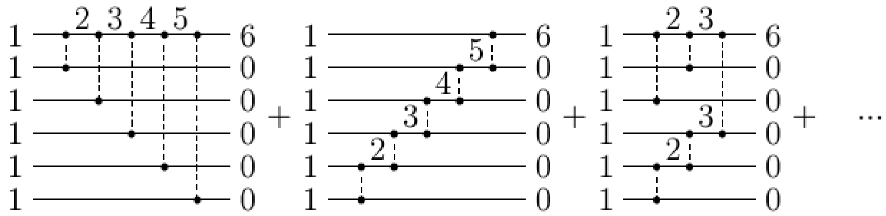


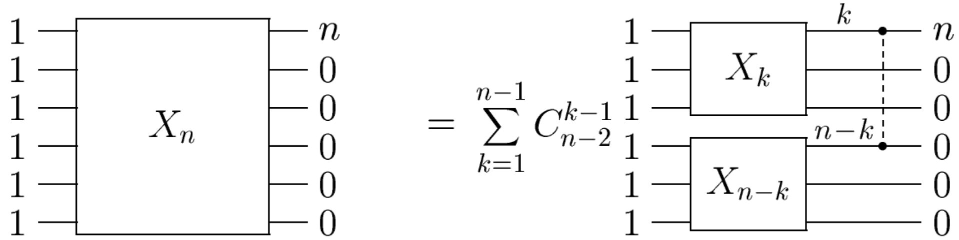
$\sim \Delta^{2p-1}$

$p = n-1$

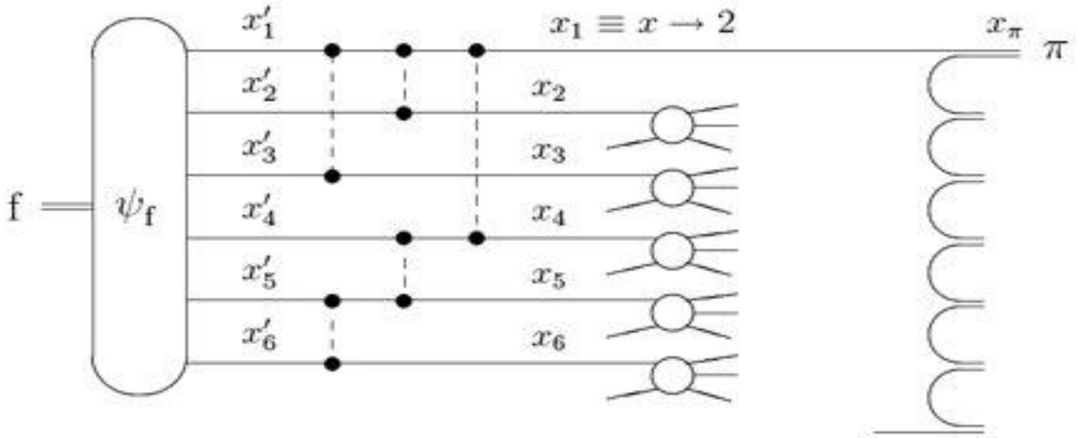
$\Delta = f - \mathbf{x} = nx_0 - \xi$

At $x_1 \to f$ => all $x_2,\ldots, x_n \to 0 \to$ all $|q_i| >> m \to$ pQCD works → min.number of hard exchanges. Simple instantaneous Coulomb part dominates in light-cone gauge.





- the recurrence relation



f – number of nucleons which formed flucton
n - number of quarks in flucton
p=n-1 - number of "donors", stopped quarks

$\Gamma = \Gamma(k'_{+i}, k'_{\perp i})$ **then after integration over all** k'_{-i} **we get:**

$\Gamma(k'_{+i}, k'_{\perp i}) \longrightarrow \Psi(k'_{+i}, k'_{\perp i})$ – light cone parton wave function of flucton

In all rest parts of the diagram, we can put: $k'_{+i} = \frac{f\,p_+}{n} = \frac{f}{n} p_+ = \frac{1}{3} p_+$

Then we get:

$$\int \Psi(k'_{-i}, k'_{\perp i})\ \delta(\sum_{i=1}^{n} k'_{+i} - f\,p_+)\ \delta^2(\sum_{i=1}^{n} k'_{\perp i}) \prod_{i=1}^{n} \frac{dk'_{+i}}{2k'_{+i}} d^2 k'_{\perp i} \sim \overline{\Psi}_{cms}(\{r_i - r_j = 0\})$$

Contribution of (n-1) "Gluon" exchanges and (n-2) internal quark propagators limits to constant, when at $x_1 \to f$ all $x_2, \ldots, x_n \to 0$

The main contribution comes from propagators of stopped quarks $k_{2,\ldots,}$ k_n , which defined the longitudinal and transverse momentum dependence.

Scaling of cumulative inclusive cross section in the flucton fragmentation region:

$$f_\pi(x, k_\perp) \equiv \frac{k_0\, d^3\sigma_\pi}{d^3\mathbf{k}} = C\, s^0\, (f - x)^{2p-1}\, \Phi_p\left(\frac{k_\perp}{m_q}\right)$$

Flucton-flucton interaction

Cumulative production at $|t| \sim s$

Flucton-flucton interaction in dd collisions

f+f in dd collisions - New and Clear!

- 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.
- The possibility to register, in addition to the cumulative particle, the particles formed from fragmentation of the flucton residue.
- 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.

Calculation of flucton-flucton cross-section

$$I(\mathbf{k}) \equiv (2\pi)^3\, 2k_0 \frac{d^3\sigma}{d^3\mathbf{k}} = \frac{1}{J}\int |T|^2\, d\tau_p\ ,$$

Inclusive cross section

$$d\tau_p \equiv (2\pi)^4 \delta^4(P_1 + P_2 - k - \sum_{i=1}^{p} l_i) \prod_{i=1}^{p} \frac{d^3\mathbf{l}_i}{2l_{i0}(2\pi)^3}\ ,$$

Phase-space element

$$J \equiv 4\sqrt{(P_1P_2)^2 - P_1^2P_2^2} = 4A_1A_2\sqrt{(p_1p_2)^2 - m_N^4} = 2A_1A_2\sqrt{s(s-4m_N^2)}\ .$$

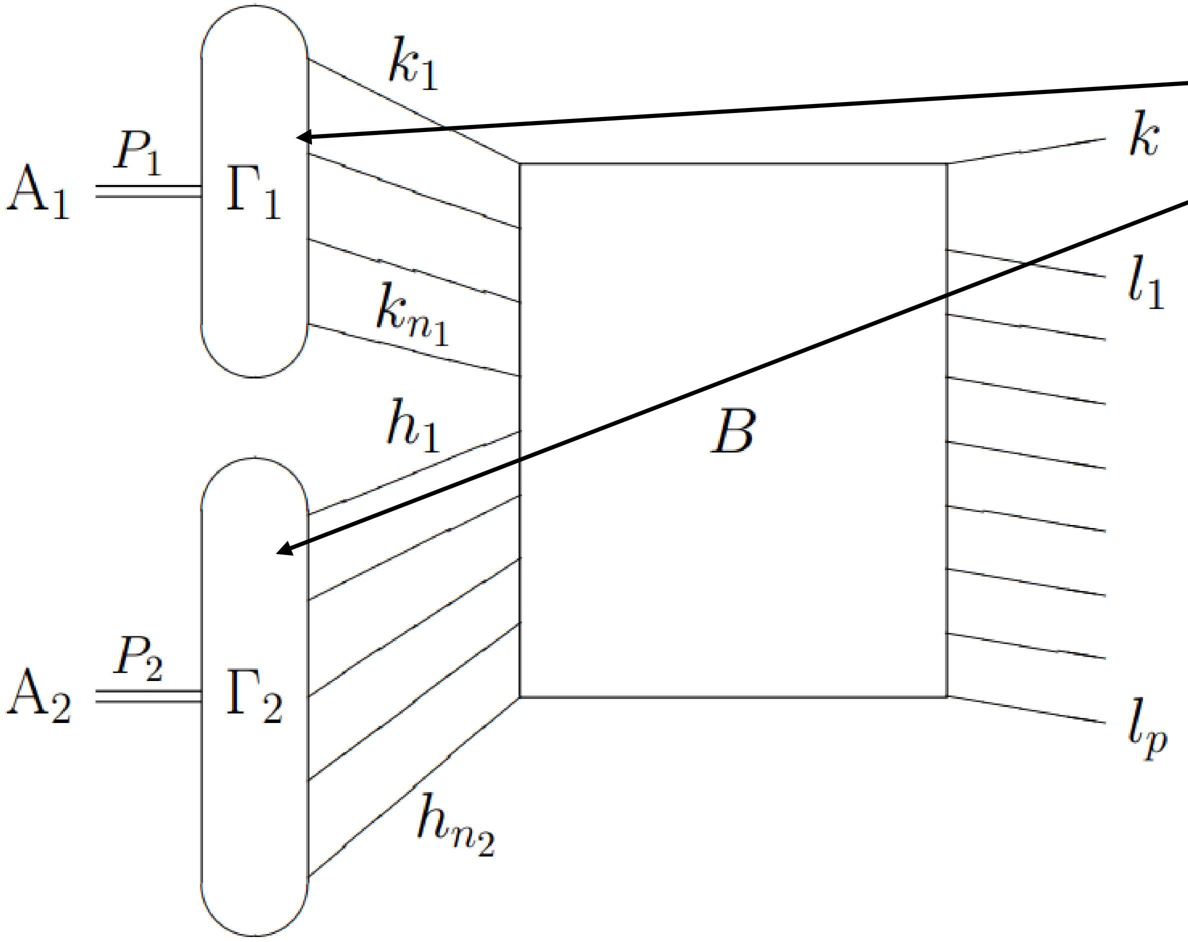
Invariant flux

$$I(\mathbf{k}) = \frac{1}{J}|T|^2\, \tau_p\ ,$$

$$\tau_p = (2\pi)^4 \int \delta^4(P_1 + P_2 - k - \sum_{i=1}^{p} l_i) \prod_{i=1}^{p} \frac{d^3\mathbf{l}_i}{2l_{i0}(2\pi)^3}\ ,$$

Phase-space

Calculation of amplitude T



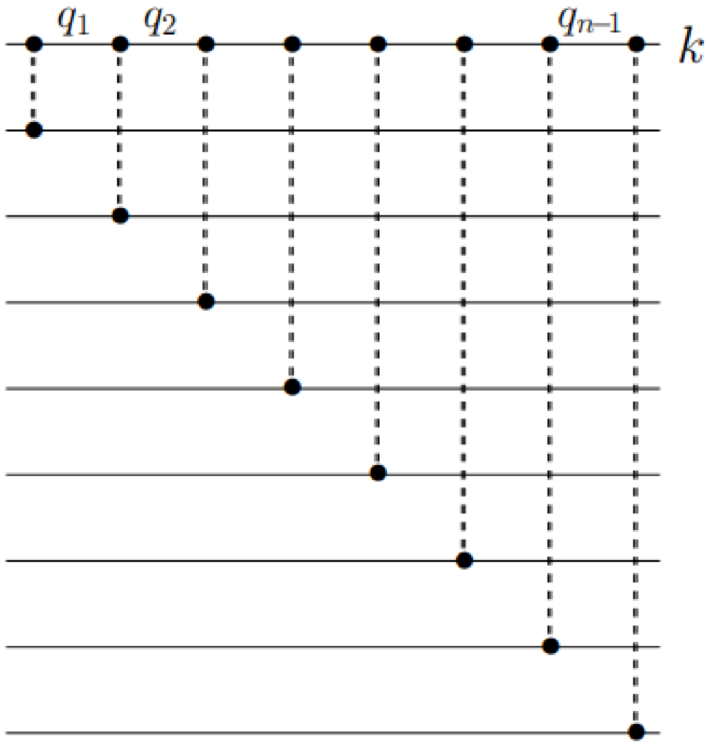
$$T = J_{n_1} J_{n_2} B \ .$$

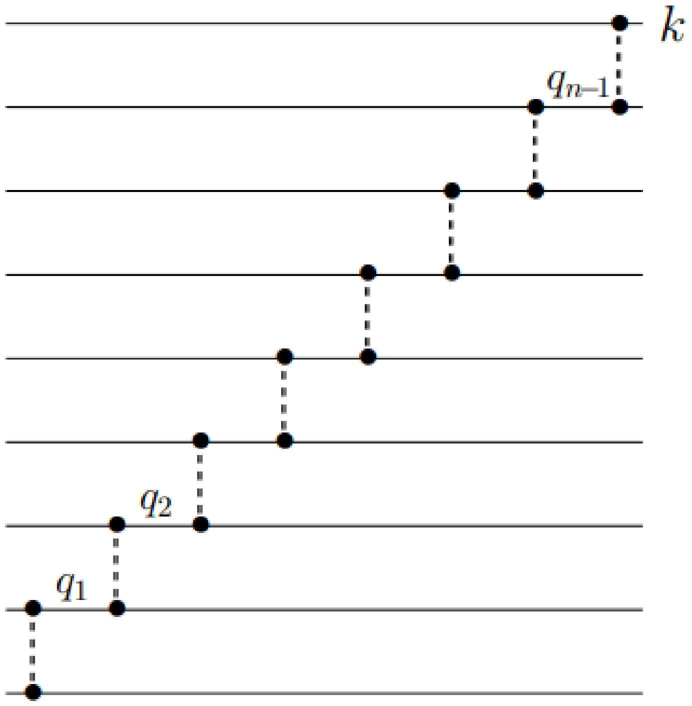
$$J_{n_1} \sim \psi_1(z_i - z_j = 0, \mathbf{r}_{i\perp} - \mathbf{r}_{j\perp} = 0) \ .$$

$$J_{n_1} = \frac{C_1}{m^{(n_1-1)/2} R_1^{3(n_1-1)/2}} \ ,$$

Same for J_{n_2}

Asymptote for hard block B





$$B = \frac{C_B}{s^{n-2}} = \frac{C_B}{s^{n_1+n_2-2}} \ ,$$

Final result

$$T = \frac{C_1\, C_2\, C_B}{m^{(n-2)/2} R_1^{3(n_1-1)/2} R_2^{3(n_2-1)/2} s^{n-2}} = \frac{C_1\, C_2\, C_B}{m^{(n-2)/2} R^{3(n-2)/2} s^{n-2}}.$$

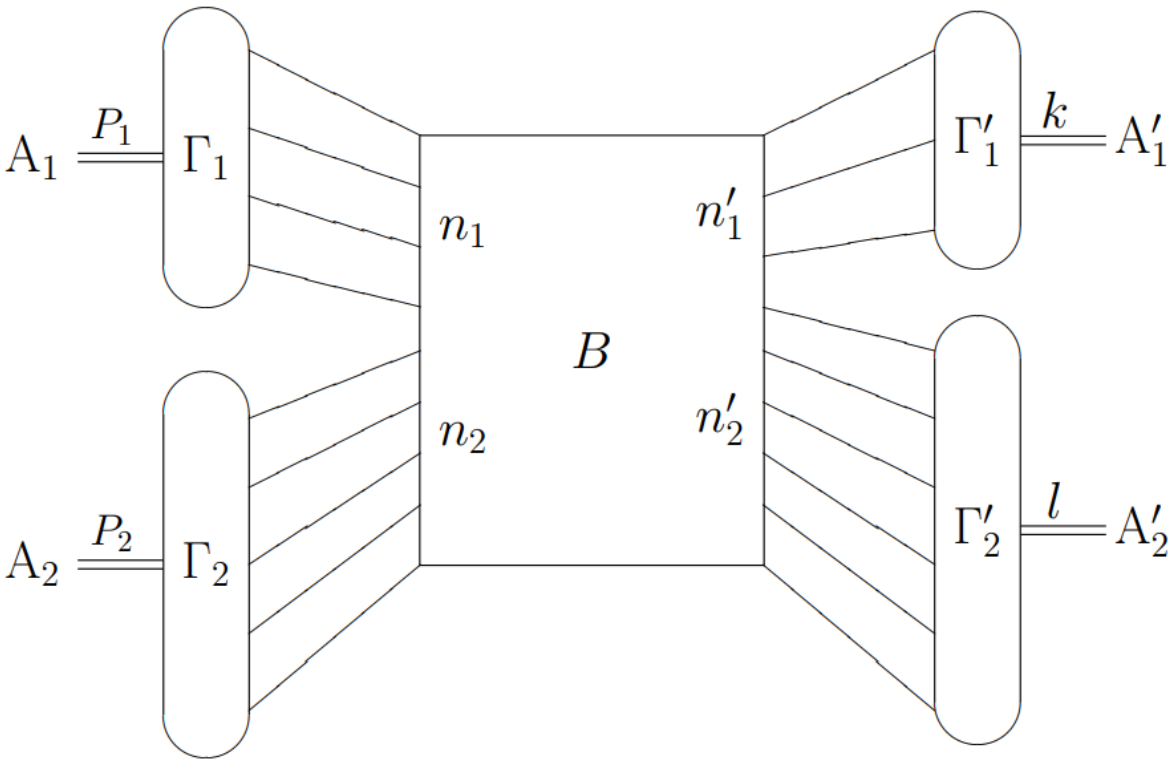
$$\tau_p = \frac{1}{2^{4p-5} p^{3p/2-1} m^{p-1}} \frac{\left[\frac{A}{\pi} s(A-x)\right]^{\frac{3}{2}p-\frac{5}{2}}}{\left(\frac{3}{2}p-\frac{5}{2}\right)!} \,,$$

$$I(x) \equiv (2\pi)^3\, 2k_0 \frac{d^3\sigma}{d^3\mathbf{k}} = \frac{C(A-x)^{\frac{3}{2}p-\frac{5}{2}}}{(m^2 R^3)^{p-1} s^{(p+3)/2}}$$

Quark counting rules for inclusive cross section (two small parameters)

Quark counting rules for quasi-elastic cross section

$$\frac{d\sigma}{dt} = \frac{\bar{C}}{s^{2n-2}\, m^{2n-4} R_1^{3(n_1-1)} R_2^{3(n_2-1)} R_1'^{3(n_1'-1)} R_2'^{3(n_2'-1)}} \,,$$



$$n = n_1 + n_2 = n_1' + n_2',$$

$$\frac{d\sigma}{dt} \sim \frac{1}{s^{n_1+n_2+n_1'+n_2'-2}} \,,$$

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

(correspondence with old results, one small parameter)

ToDo

- Include diquarks as constituents [V.T. Kim, Diquarks and Dynamics of Large P(T) Baryon Production, Mod.Phys.Lett.A 3 (1988) 909].
- Investigate effect of hadronization of constituents in final state on quark counting rules.
- Study cumulative baryon production.

Summary

- Asymptotes for the inclusive cross sections for particle production in the new cumulative region of large transverse momenta at mid-rapidities is obtained.
- The found dependences of the inclusive cross section on the initial energy and cumulative number can be usedto describe the production of pions with high transverse momentum in dd collisions in the SPD experiment at the NICA collider.

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Thank you for attention!