

# Transverse momentum spectra of cumulative particles and the quark coherent coalescence

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# Outline

- Introduction. Definition of cumulative phenomenon.
- Cumulative kinematics: projectile and target fragmentation regions.
- Quark counting rules and the limiting fragmentation of nuclei.
- Deep Inelastic Scattering (DIS) in cumulative region.
- Description of flucton structure function asymptote near cumulative thresholds by the intrinsic diagrams of QCD in light-cone gauge.
- Explanation of the different slopes for DIS and for particle production in cumulative region.
- Direct and spectator contributions to the cumulative quark formation.
- Transverse momentum spectra of cumulative pions.
- Production of cumulative protons by Coherent Coalescence of three quarks (correspondence with the approach of Few Nucleon Short-Range Correlations in Nuclei).
- Suppression of contributions from non-diagonal quark coalescence diagrams.
- Transverse momentum spectra of cumulative protons.
- Comparison of transverse momentum spectra of cumulative pions and protons for various cumulative numbers.

# Cumulative Particle Production

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

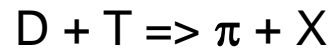
## Cumulative Pion Production

1970 - Nuclotron@Dubna – beams of relativistic deuterons ( $p_0=5 \text{ GeV}/c/\text{nucleon}$ )

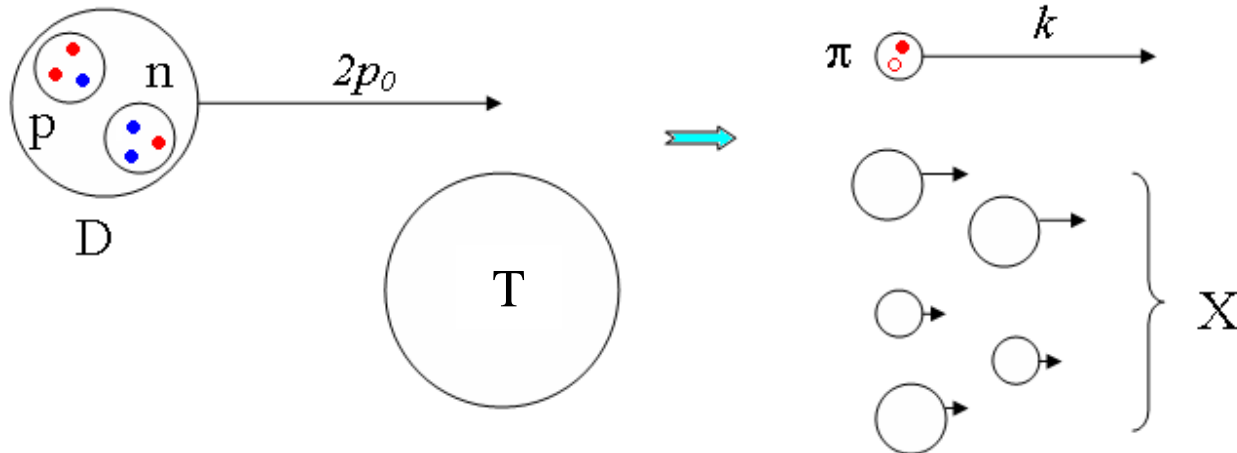
*Stavinskiy V.S.* =>

Fragmentation of projectile deuterons, D, on some target, T.

*Baldin A.M. et al., Yad.Fiz. 18 (1973) 79*



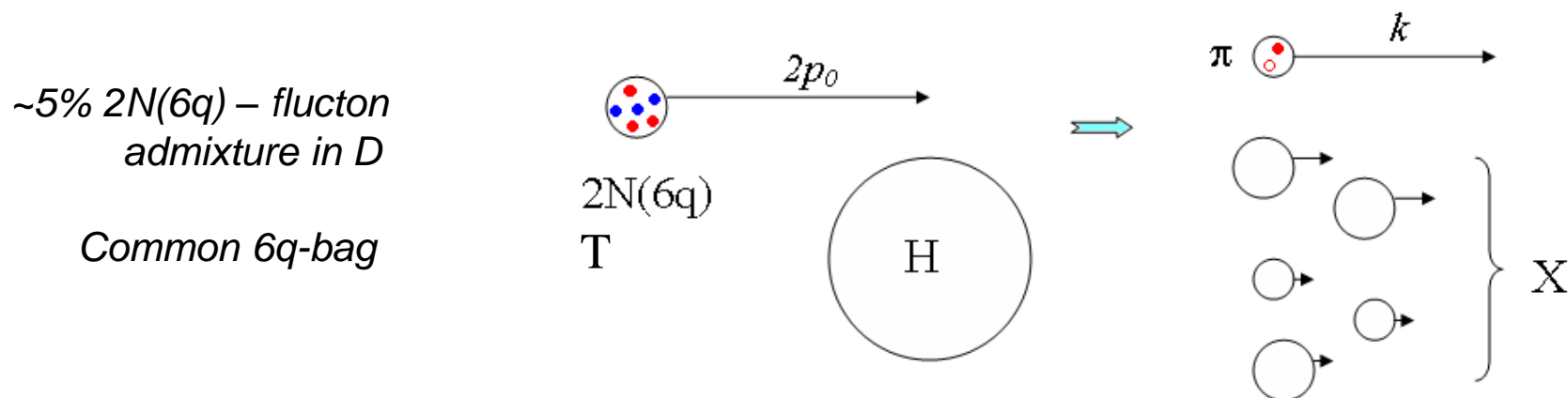
$p_0 \gg m_N$ :  $p_0 < k < 2p_0$  - cumulative pions



**Flucton** – intrinsic droplet of dense cold nuclear matter in a nucleus

*Blokhintsev D.I., JETP 33 (1957) 1295*

( $2N$  flucton – 6 quark state)



Fragmentation of **projectile** nucleus  $\Leftrightarrow$  Fragmentation of **target** nucleus  
(the same phenomenon in different frames of reference)

Cumulative fragmentation of **target** nucleus:

The 1st experimental observations of the **backward** particle production  
in  $p+A$  collisions on a **fixed target** nucleus:

*G.A. Leksin et al., ZhETF 32, 445 (1957)*

*L.S. Azhgirej et al., ZhETF 33, 1185 (1957)*

*Yu.D. Bayukov et al., Izv. AN SSSR 30, 521 (1966)*

The Reserford-like experiments indicating the presence of **droplets of dense nuclear matter in a target nucleus** (fluctons).

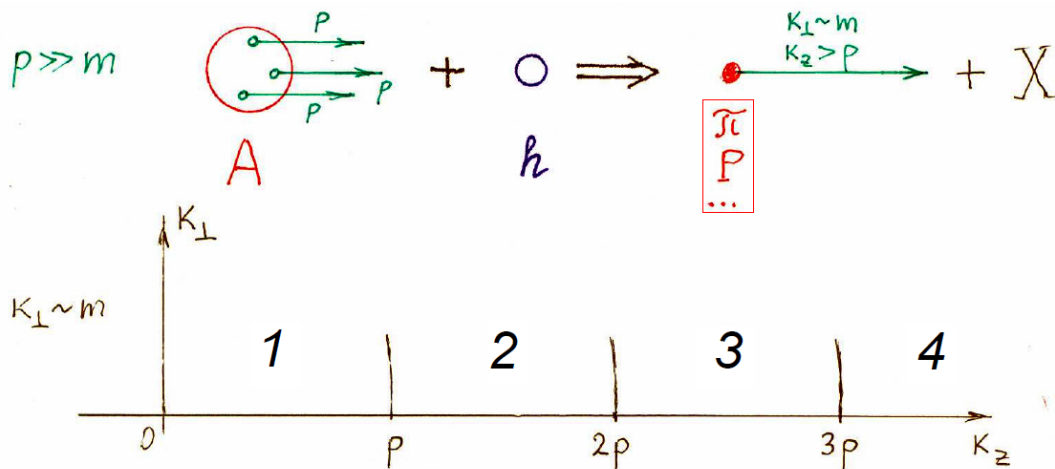
# Kinematics of cumulative production

Fragmentation of **projectile** nucleus

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

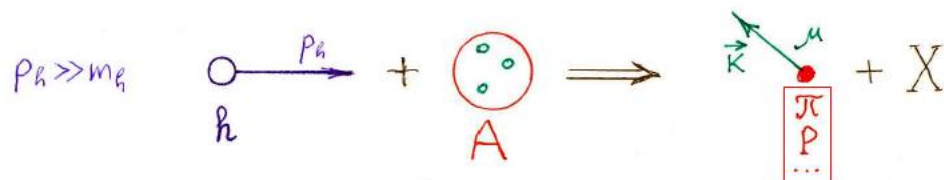
$k_z, p \gg m$ ,  $m$  – nucleon mass

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



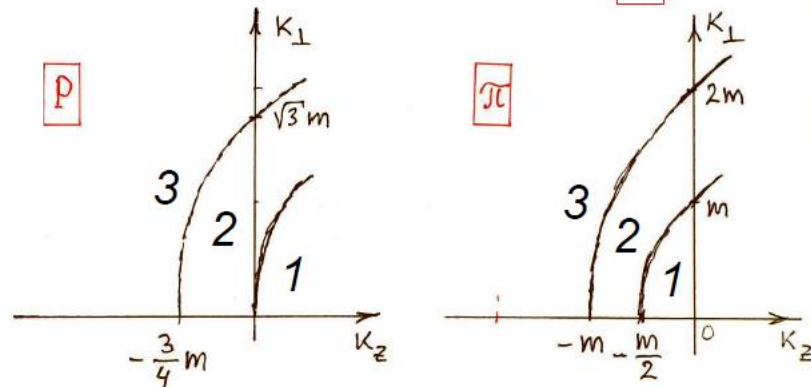
The borders increase with  $p$

Fragmentation of **target** nucleus



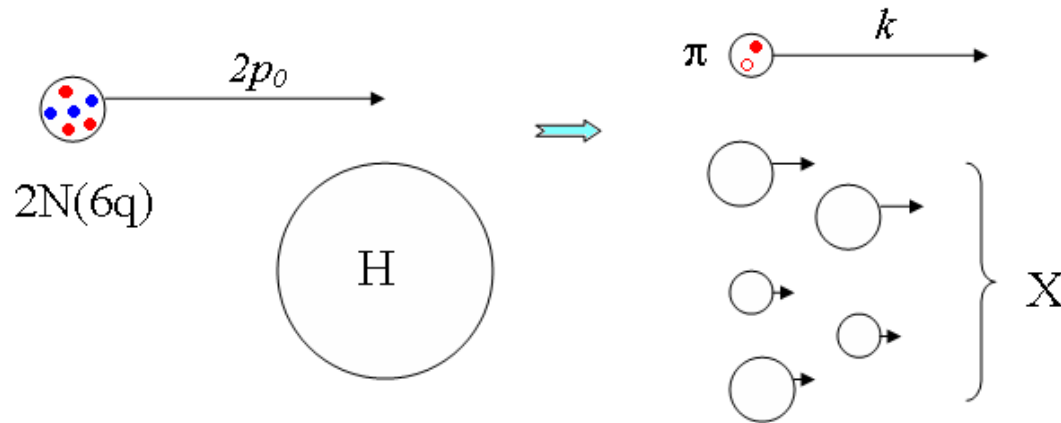
$$x \equiv \frac{k_-}{p_-} = \frac{\tilde{k}_0 - \tilde{k}_z}{m} = \frac{\sqrt{\tilde{k}_z^2 + k_{\perp}^2 + \mu^2} - \tilde{k}_z}{m}$$

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



The borders are fixed at  $p \gg m$

# Limiting fragmentation of light nuclei. Quark counting rules.



$1 < x < 2$  - the cumulative region (  $1 < x < f$  - for the  $fN$  flucton )

**Theoretical description near upper threshold:** for  $2N(6q)$  flucton  $k \rightarrow 2p_0$ ,  $x = k/p_0 \rightarrow 2$   
 (Limiting fragmentation of a nucleus)

**Quark counting rules:**  $I \sim \Delta^{2p-1}$

$\Delta$  – the deviation of  $x$  from its maximal value  $f$ ,  $\Delta = f - x$

$p$  – the number of “donors”, stopped quarks,  $p = n - 1$

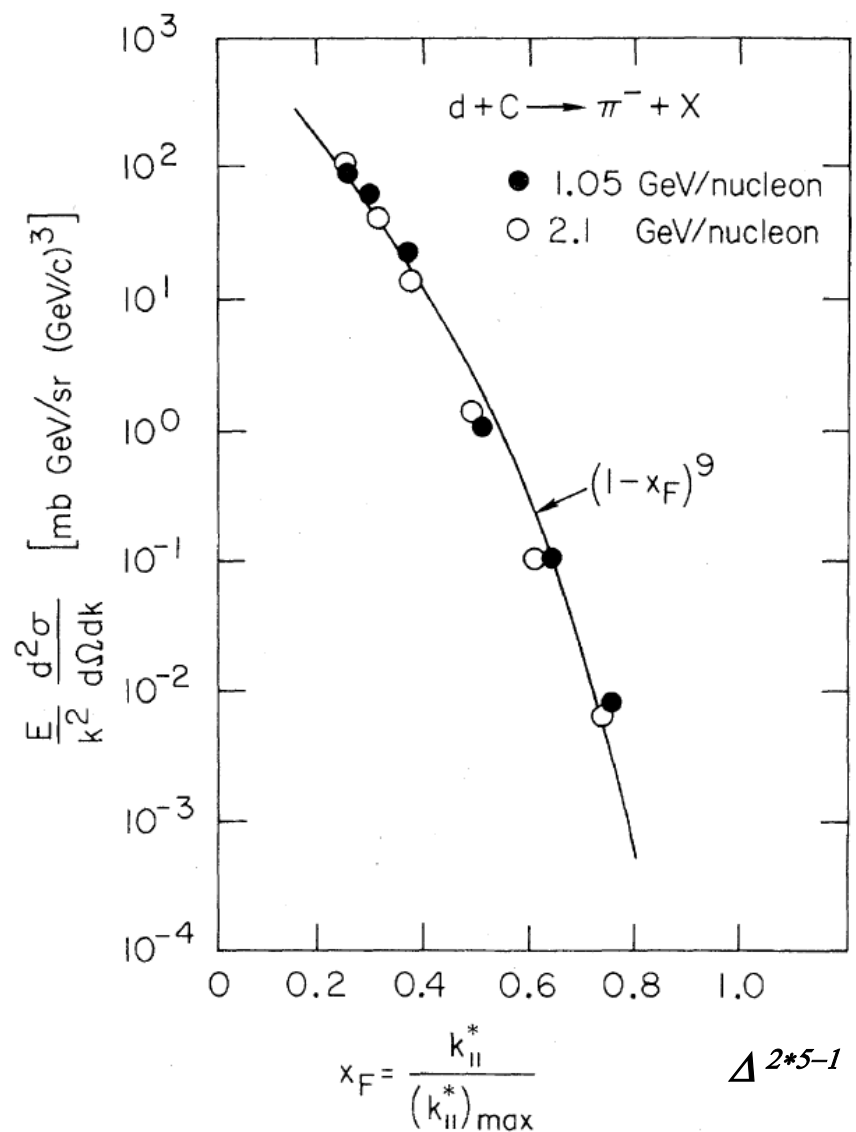
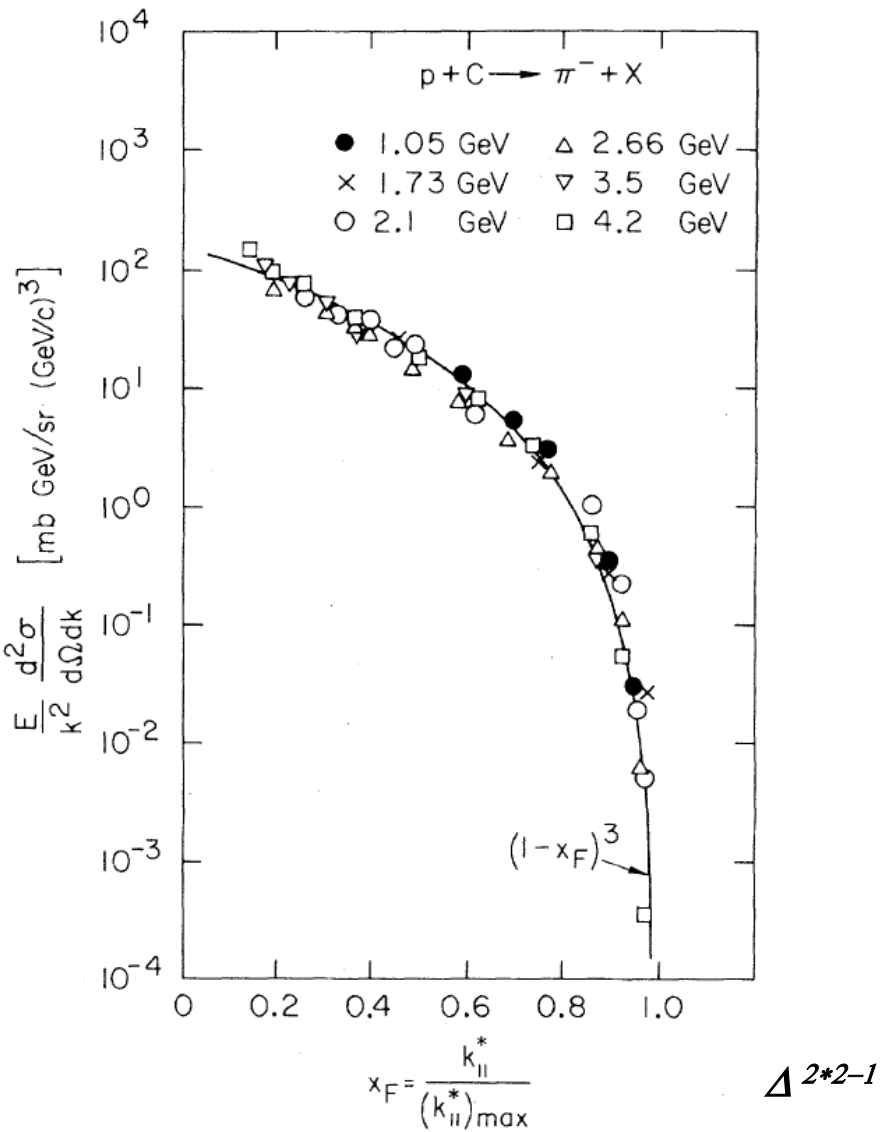
$n$  – the number of constituents.

For  $2N(6q)$  flucton  $f = 2$ ,  $n = 6$ ,  $p = 5$ , then  $I \sim (2-x)^{2 \cdot 5 - 1} = (2-x)^9 = \Delta^9$

*Brodsky S., Farrar G. Phys.Rev.Lett. 31 (1973) 1153*

*Matveev V.A., Muradyan R.M., Tavkhelidze A.N. Lett. Nuovo Cimento 7 (1973) 719*

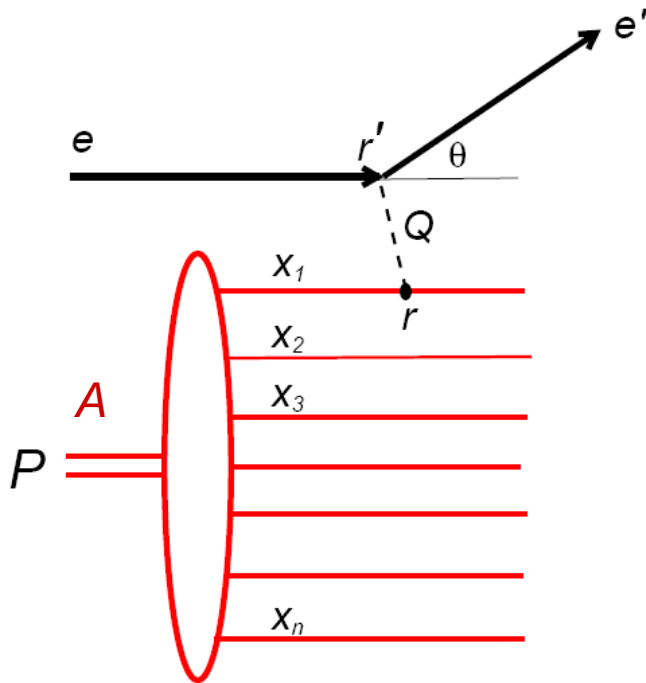
*Brodsky S.J., Chertok B.T. Phys.Rev. D14 (1976) 3003; Phys.Rev.Lett. 37 (1976) 269*



The experimental points from J. Papp et al., Phys.Rev.Lett. 34, 601 (1975).

# Deep Inelastic Scattering (DIS) in cumulative region

Lehman E., *Phys.Lett.62B (1976) 296* – connection of the limiting fragmentation of deuteron into pions with deuteron DIS structure function  $F_2$  (5%  $2N(6q)$ -flucton admixture in D)



$$|\mathbf{r} - \mathbf{r}'| \sim 1/|Q|, \quad |Q| \gg m$$

$$\xi \equiv \frac{-Q^2}{2(pQ)} = \frac{-Q^2}{2mQ_0}, \quad p = P/A$$

$$0 < \xi < A, \quad 1 < \xi < A - \text{cumulative region}$$

$$Q^2 = -4EE' \sin^2 \frac{\theta}{2}, \quad Q_0 = E - E'$$

$$x_1 \equiv \frac{k_{1+}}{p_+} \approx \frac{k_{1z}}{p} \geq \xi - \text{Bjorken scaling variable}$$

( $x_1 = \xi$  for elastic  $\gamma q$ )

Experimental observations of DIS in cumulative region:

Shuetz W.P. et al., *Phys.Rev.Lett.*, 38 (1977) 259 [D]

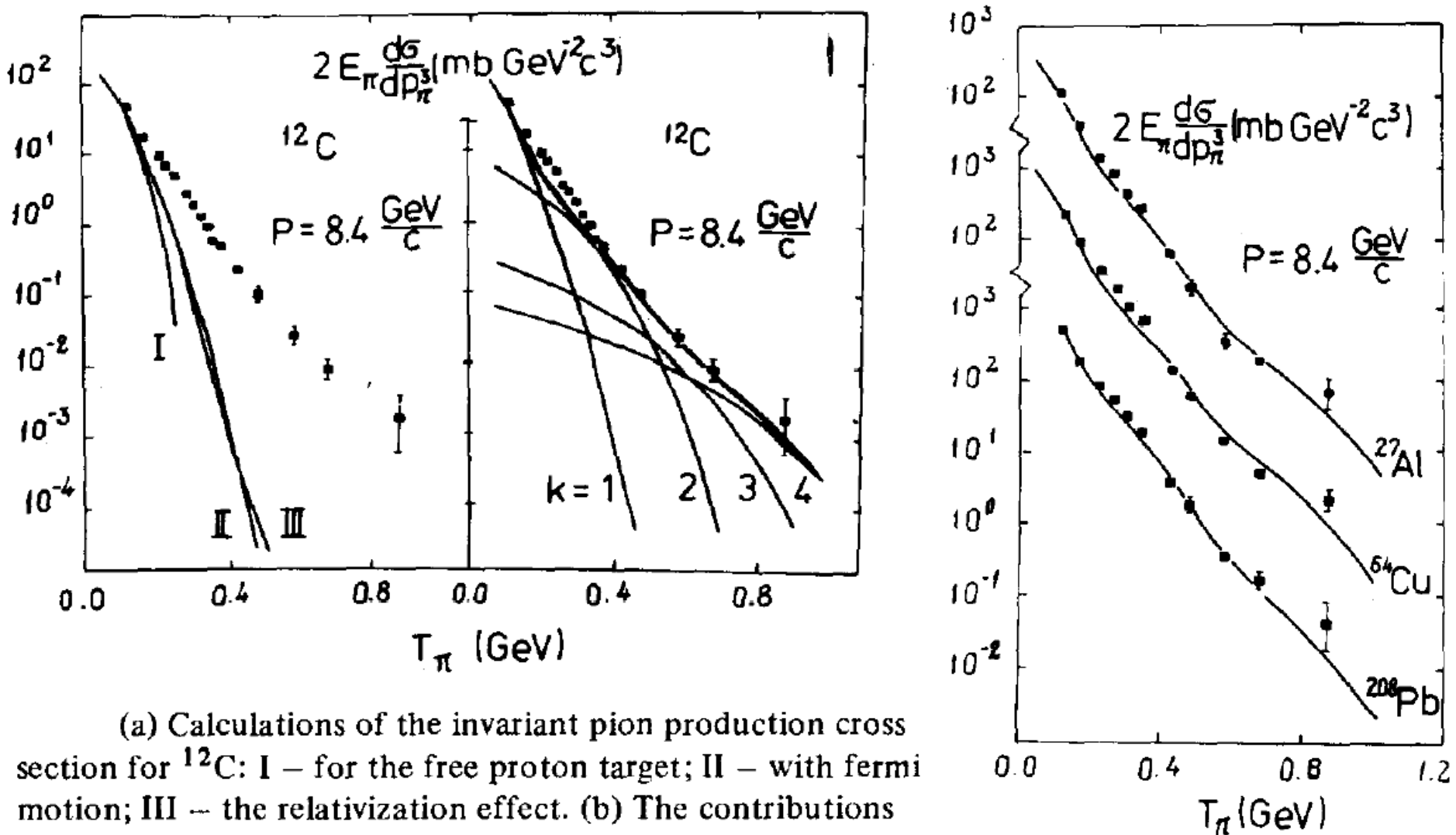
Filippone B.W. et al., *Phys.Rev.C*, 45 (1992) 1582 [Fe]

Benvenuti A.C. et al. (BCDMS collaboration) *Z. Phys.* C63 (1994) 29 [C]

Egiyan K.S., et al., *Phys.Rev.Lett.* 96 (2006) 082501 [ $^3\text{He}, ^4\text{He}, \text{C}, \text{Fe}$ ]



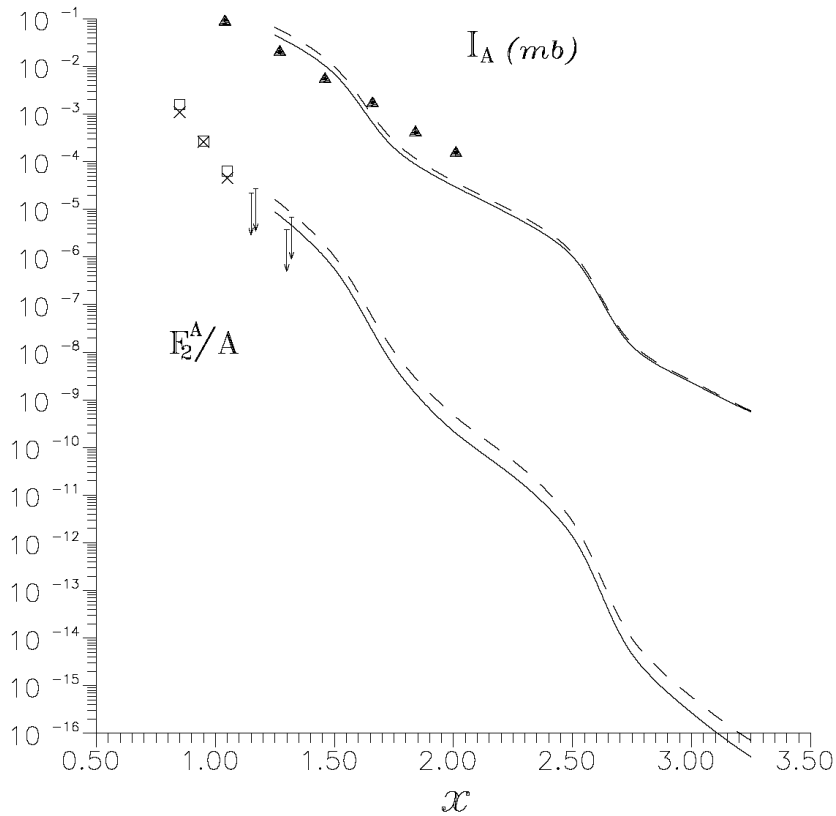




(a) Calculations of the invariant pion production cross section for  $^{12}\text{C}$ : I – for the free proton target; II – with fermi motion; III – the relativization effect. (b) The contributions of separate fluctuons with mass  $M_k = km_p$  where  $k$  is the order of cumulativity.

The experimental points from A.M. Baldin et al., Yad. Fiz. 18 (1973) 79.

# The different slopes of spectra for DIS and for particle production in cumulative region



$$F_2^A(x) \sim \exp(-b_0 x) \quad b_0 \sim 16$$

$$I_A(x) \sim \exp(-b_s x) \quad b_s \sim 6 \div 8$$

*The experimental points from*

*Benvenuti A.C. et al. (BCDMS collaboration)*

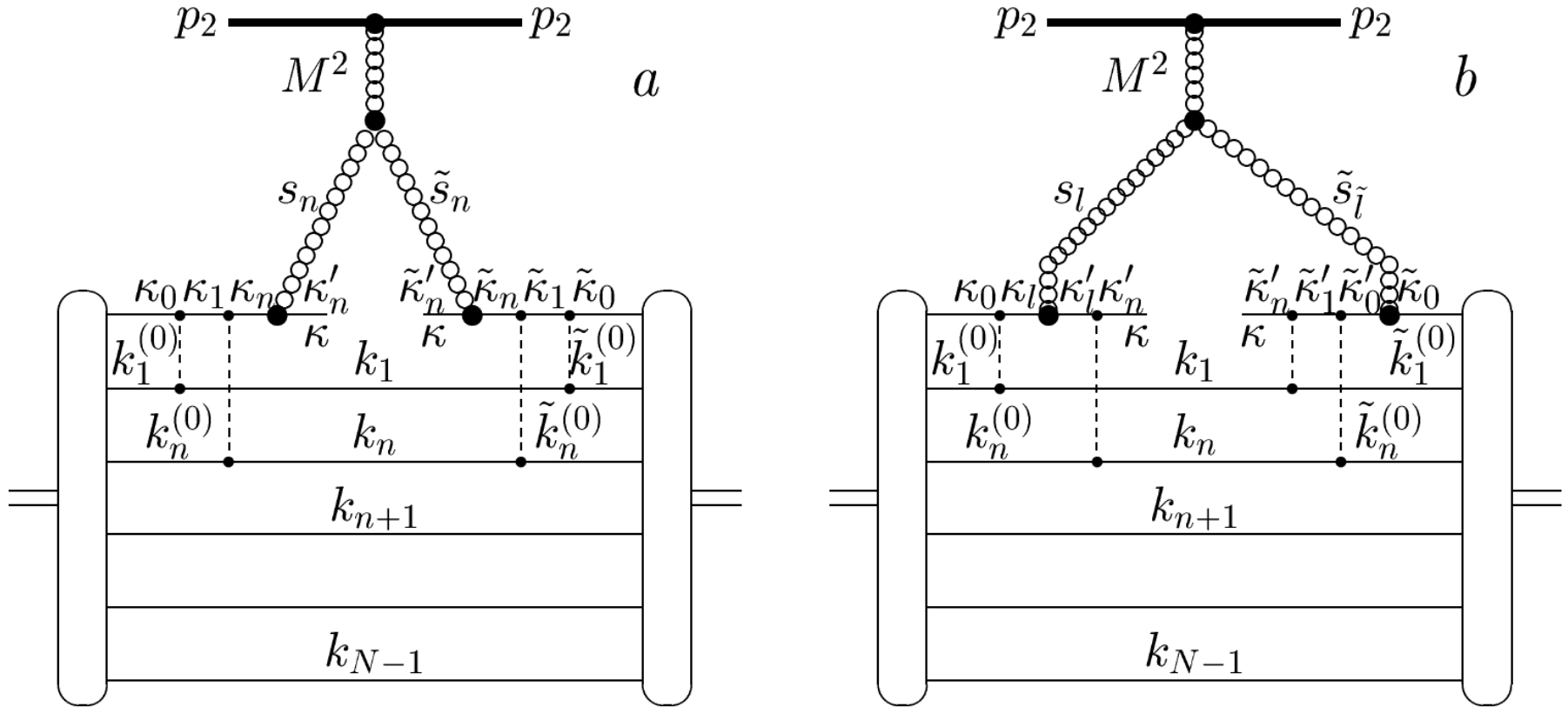
*Z. Phys. C63 (1994) 29*

*[ $^{12}\text{C}$ ,  $q^2 = 61 \text{ GeV}^2$ ,  $150 \text{ GeV}^2$ ].*

*Nikiforov N.A. et al. Phys. Rev. C22 (1980) 700*

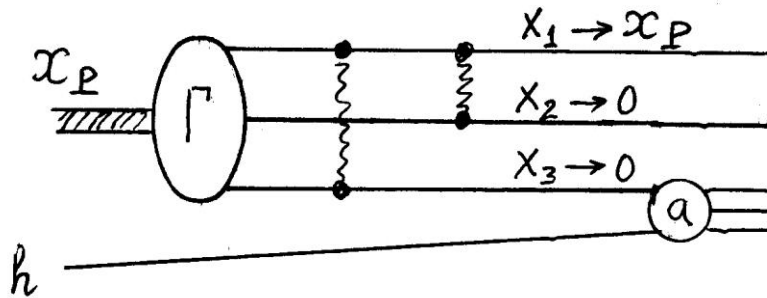
*[ $p+^{181}\text{Ta} \rightarrow p + X$ ,  $400 \text{ GeV}/c$ ]*

# Cancellation of the direct contributions to a cumulative quark formation



M.A. Braun, V.V. Vechernin, *Phys.Atom.Nucl.* **63** (1997) 432

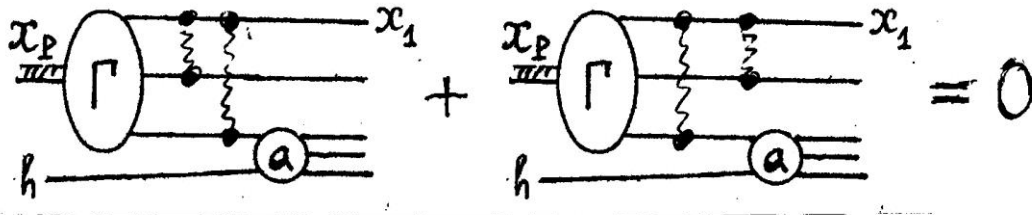
# Cancellations in spectator contributions to a cumulative quark formation



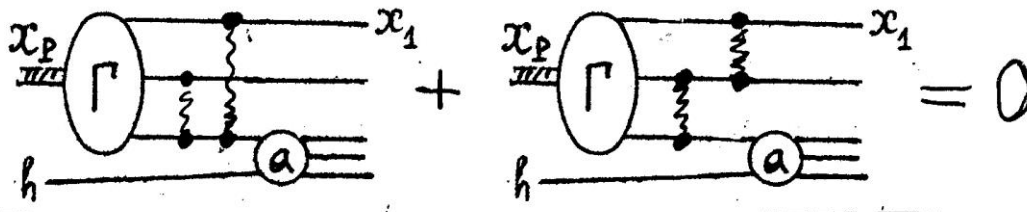
$$\sim (x_P - x_1)^{2p-1}$$

$$x_P = 1, 2, \dots$$

$$p=2 \Rightarrow \sim (1-x_1)^3$$

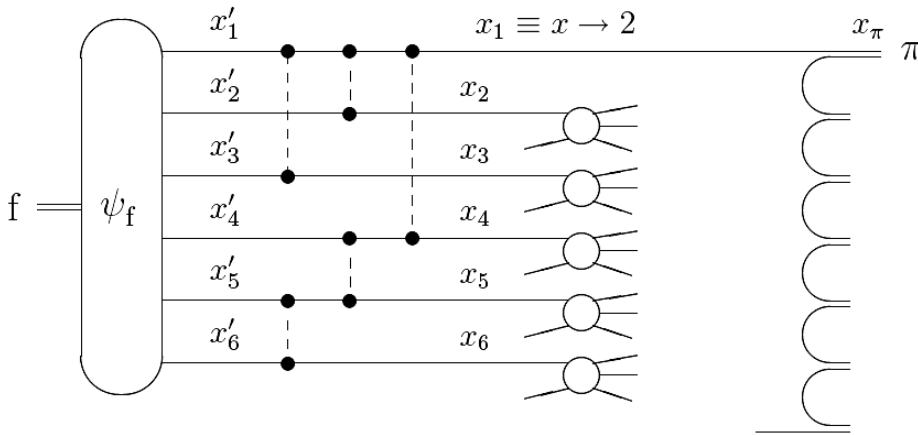


$$\sim (1-x_1)^q$$



$$q > 3$$

# Transverse momentum spectra of cumulative pions



- the cumulative pion production

$k_{\perp}$  – dependence:

*M.A. Braun, V.V. Vechernin,  
Phys.Atom.Nucl. **63**, 1831 (2000)*

$$\sigma_{pion}(x, k_{\perp}; p) = C(p) (x_{frag} - x)^{2p-1} f_p\left(\frac{k_{\perp}}{m}\right)$$

$$x < x_{frag}(p) = 1/3 + p/3$$

$p$  – the number of “donors”, stopped quarks

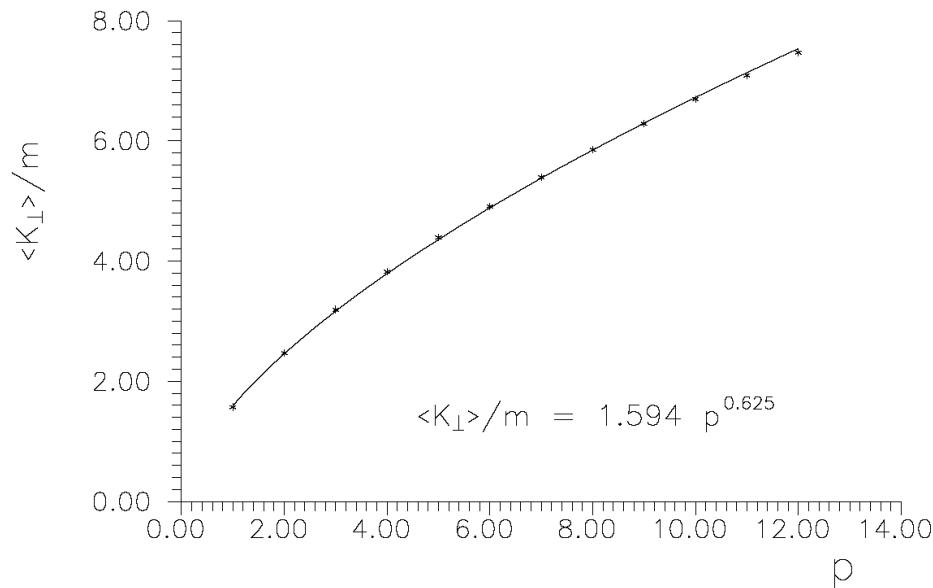
$m$  – the constituent quark mass

$$f_p(t) = \frac{1}{\pi^p} \int \prod_{i=1}^p \frac{d^2 t_i}{(t_i^2 + 1)^2} (2\pi)^2 \delta^{(2)}\left(\sum_{i=1}^p t_i + t\right)$$

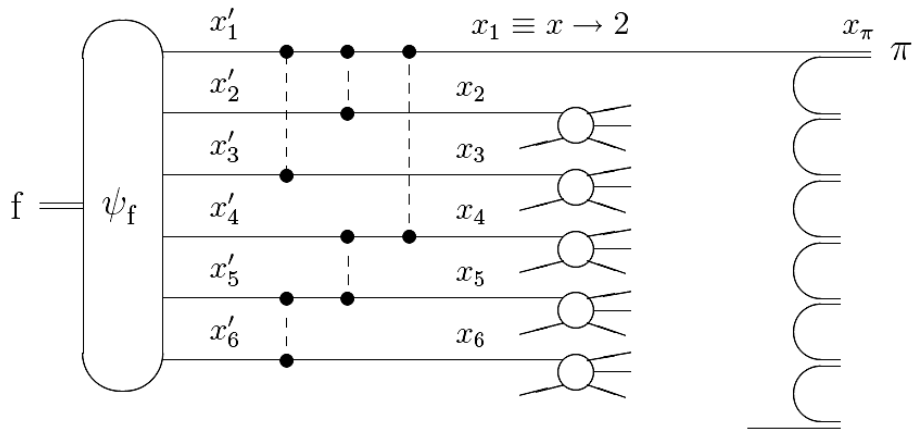
$$t = k_{\perp}/m, \quad t_i = k_{i\perp}/m$$

$$f_p(t) = 2\pi \int_0^{\infty} dz z J_0(tz) [z K_1(z)]^p$$

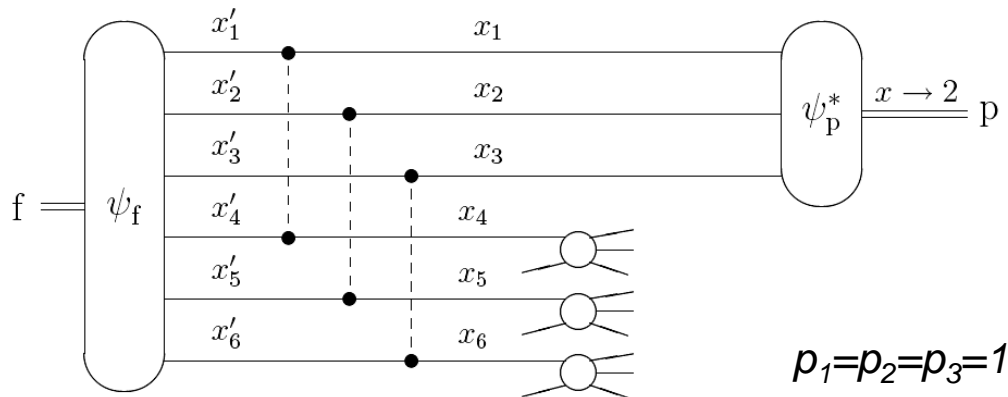
$$\langle |K_{\perp}| \rangle = pm \int_0^{\infty} dz K_0(z) (z K_1(z))^{p-1}$$



# Coherent Quark Coalescence and Production of Cumulative Protons



- the cumulative pion production by hadronization of one fast quark



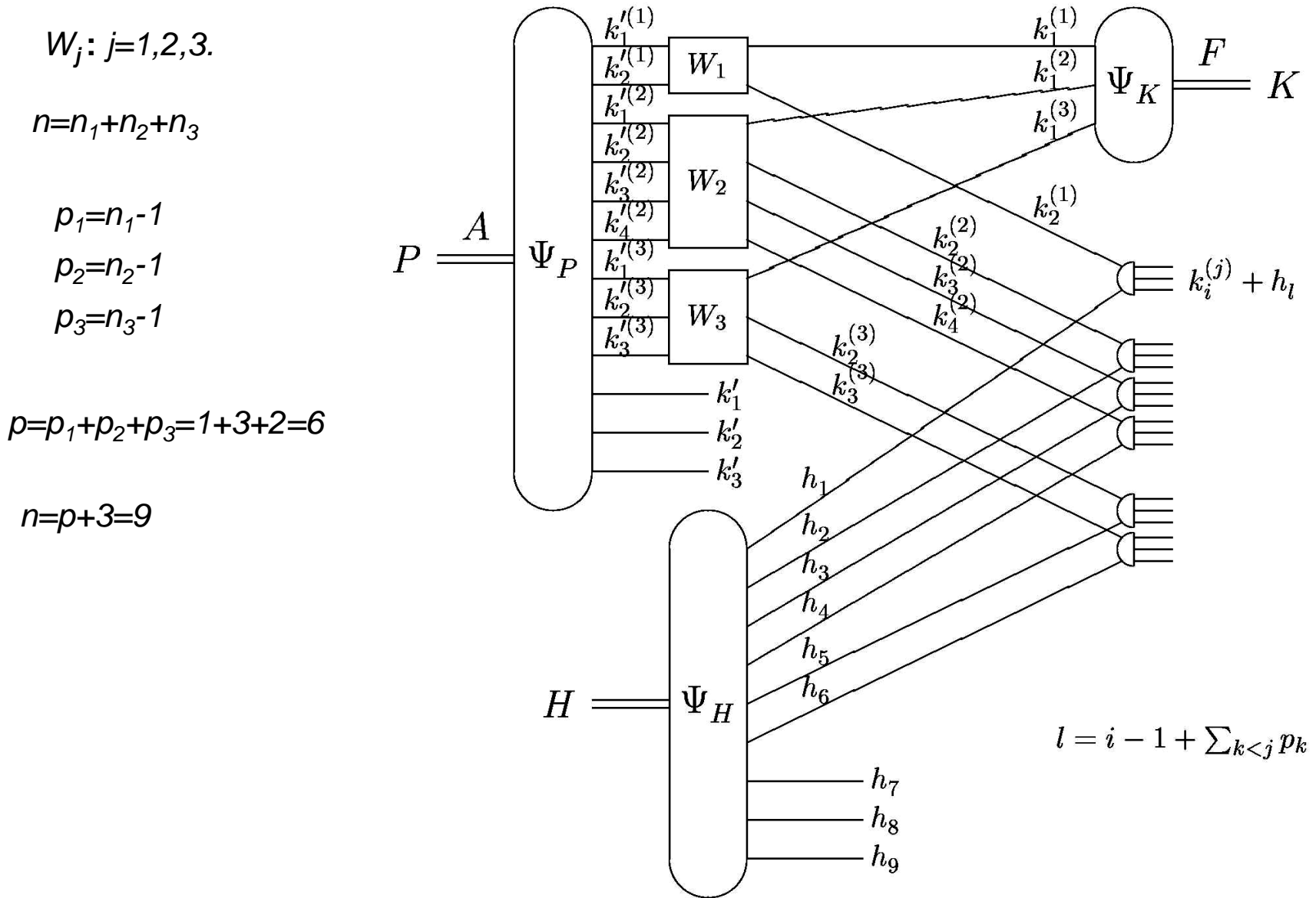
- the cumulative proton production

coherent quark coalescence mechanism:

*M.A. Braun, V.V. Vechnin, Nucl.Phys. **B92**, 156 (2001); Theor.Math.Phys **139**, 766 (2004)*

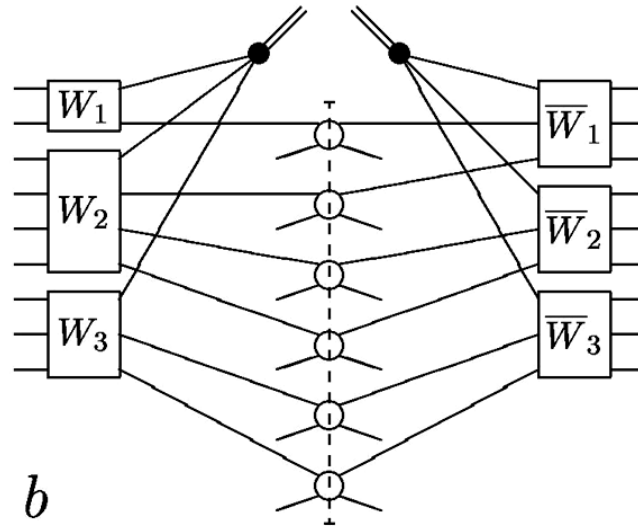
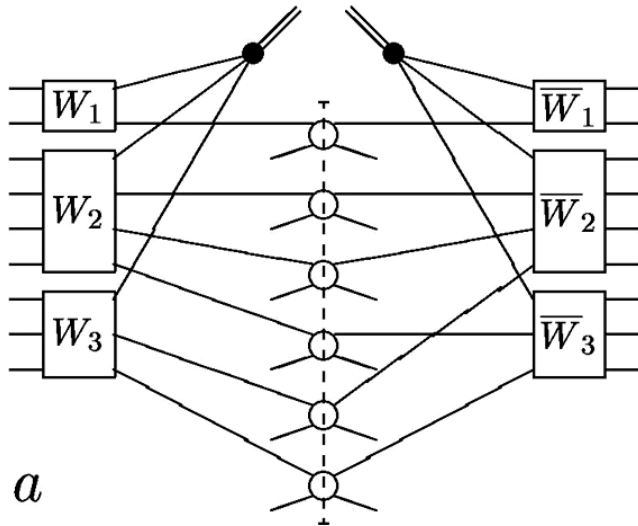
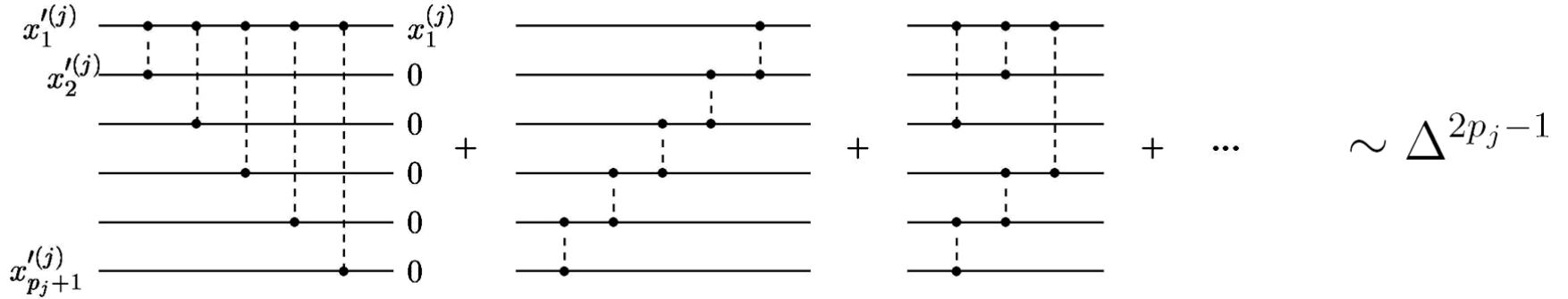
## Few nucleon short-range correlations in a nucleus

*L.L. Frankfurt, M.I. Strikmann, Phys. Rep. 76, 215 (1981); ibid 160, 235 (1988).*



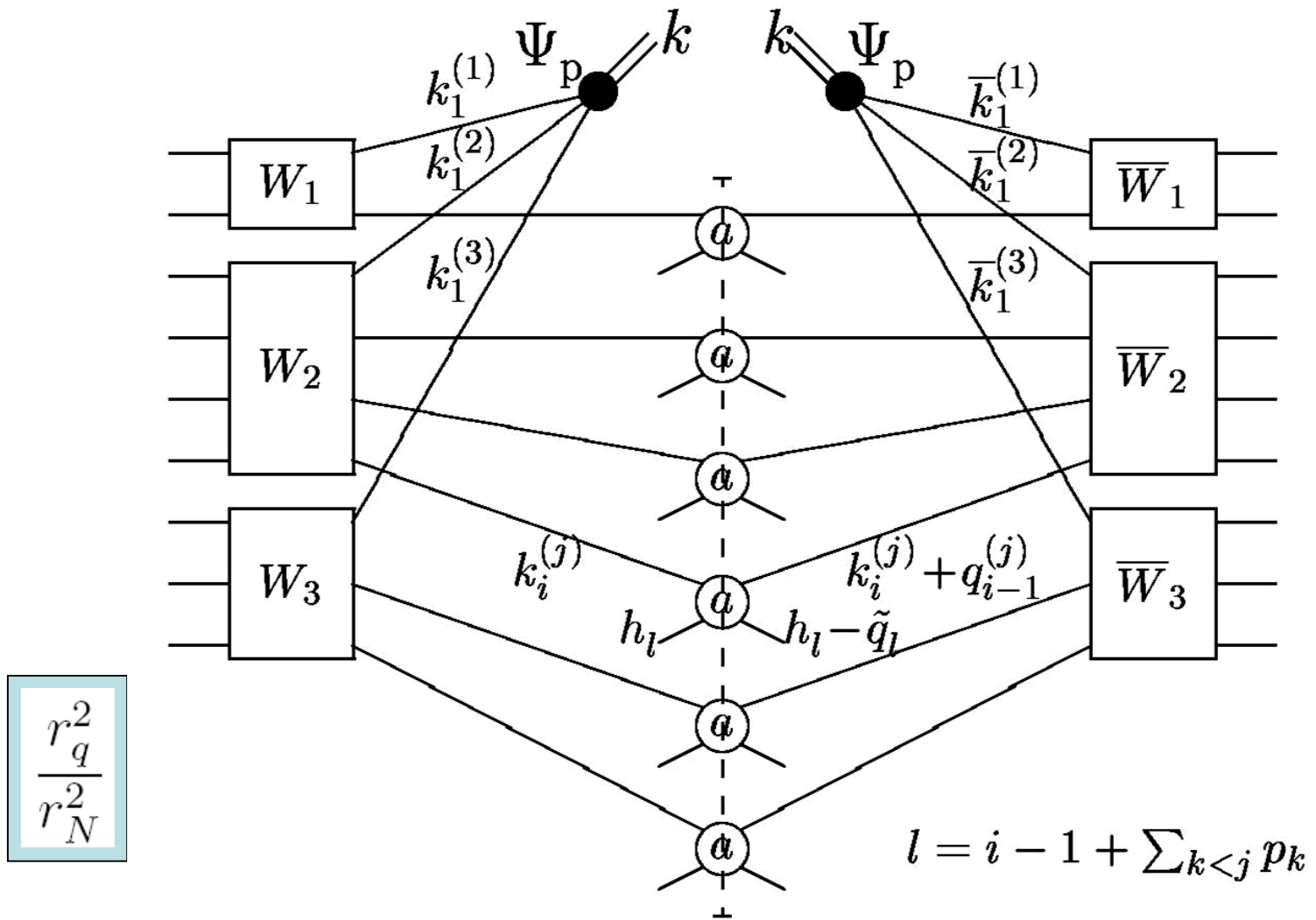


# Contributions to the blobs $W_j$ :



The examples of two types of non-diagonal contributions to the cross section of cumulative proton production:

*a* – all  $p_j = \bar{p}_j$ , *b* – some  $p_j \neq \bar{p}_j$



The diagonal contribution to the cross section of cumulative proton production.

Note the presence of the interference effects also in this case!

$$\sigma_{pion}(x, k_{\perp}; p) = C(p) (x_{frag} - x)^{2p-1} f_p \left( \frac{k_{\perp}}{m} \right)$$

$$x < x_{frag}(p) = 1/3 + p/3$$

$p=n-1$

*M.A. Braun, V.V. Vechernin, Phys.Atom.Nucl. 63, 1831 (2000)*

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$$\sigma_{prot}(x, k_{\perp}; p_1, p_2, p_3) = C(p_1, p_2, p_3) (x_{coal} - x)^{2p-1} f_{p_1} \left( \frac{k_{\perp}}{3m} \right) f_{p_2} \left( \frac{k_{\perp}}{3m} \right) f_{p_3} \left( \frac{k_{\perp}}{3m} \right)$$

$$x < x_{coal}(p) = 1 + p/3, \quad p = p_1 + p_2 + p_3$$

$p=n-3$

*M.A. Braun, V.V. Vechernin, Theor.Math.Phys. 139, 766 (2004)*

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$$f_p(t) = 2\pi \int_0^{\infty} dz z J_0(tz) [z K_1(z)]^p$$

$J_0(z)$  - the Bessel function,  $K_1(z)$  - the modified Bessel function.

$$(2\pi)^{-2} \int f_p(|\mathbf{b}|) d^2\mathbf{b} = (2\pi)^{-1} \int_0^{\infty} f_p(t) t dt = 1$$

Note that for  $p=1$  it can be simplified to  $f_1(t) = 4\pi/(t^2 + 1)^2$

$$e^{-b_s x} = 10^2,$$

$$b_s \approx 7, \quad x = -2/3$$

$$\varphi_{pion}(k_{\perp}, p) \equiv \sigma_{pion}(x, k_{\perp}; p) / \sigma_{pion}(x, 0; p) = f_p \left( \frac{k_{\perp}}{m} \right) / f_p(0)$$


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$$\varphi_{prot}(k_{\perp}, p) \equiv \sigma_{prot}(x, k_{\perp}; p) / \sigma_{prot}(x, 0; p)$$

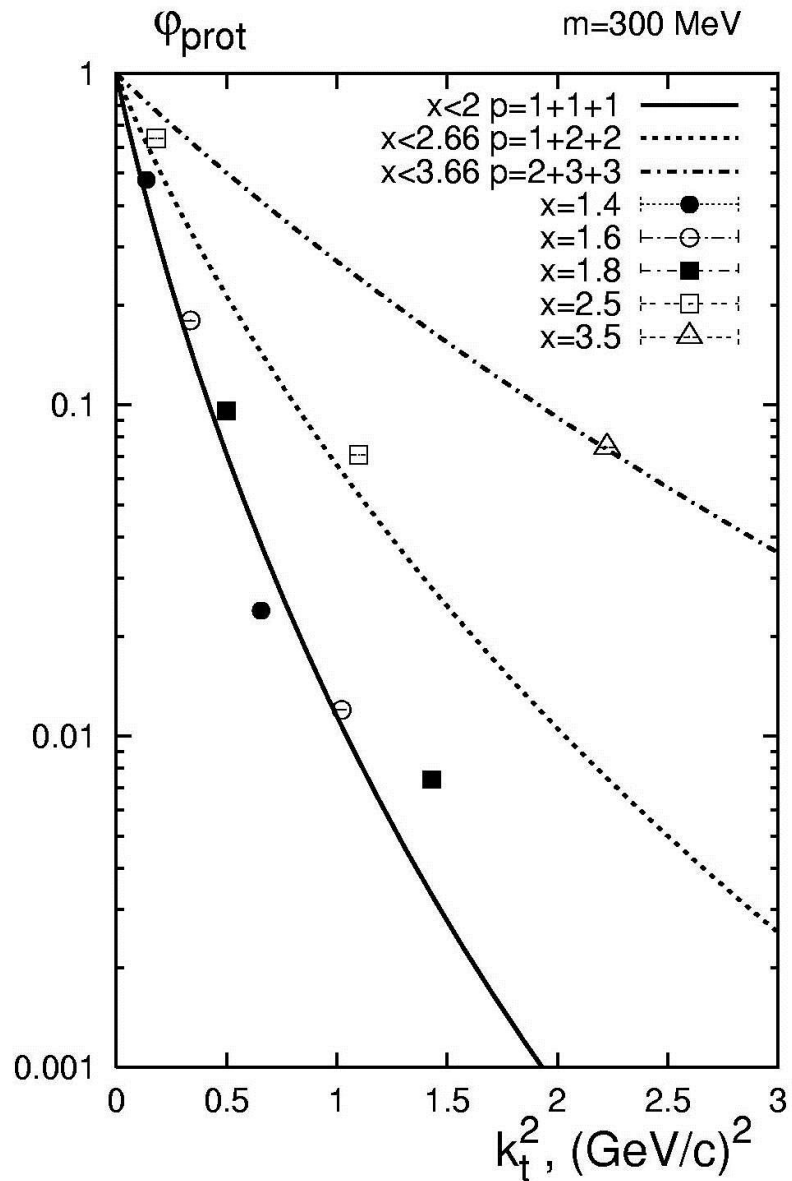
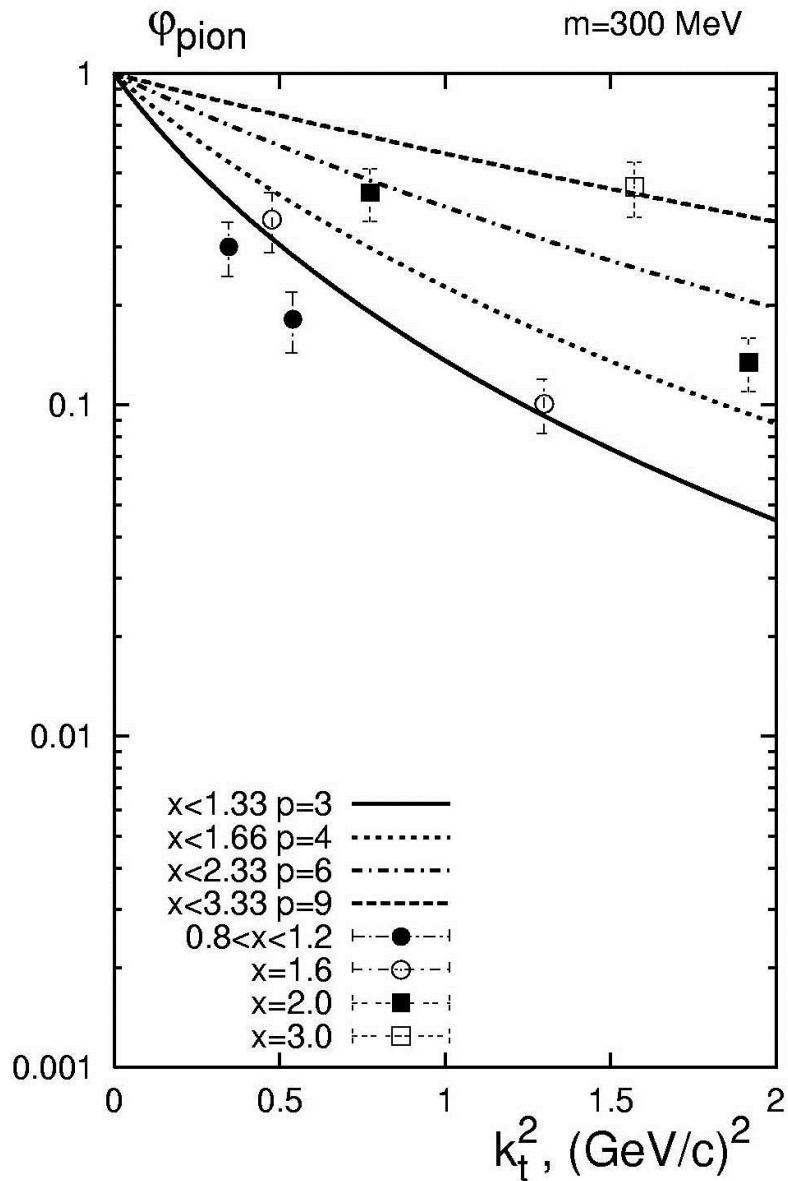
$$\varphi_{prot}(k_{\perp}, p) = \frac{\sum_{p_1, p_2, p_3} \delta_{p, p_1+p_2+p_3} C(p_1, p_2, p_3) f_{p_1} \left( \frac{k_{\perp}}{3m} \right) f_{p_2} \left( \frac{k_{\perp}}{3m} \right) f_{p_3} \left( \frac{k_{\perp}}{3m} \right)}{\sum_{p_1, p_2, p_3} \delta_{p, p_1+p_2+p_3} C(p_1, p_2, p_3) f_{p_1}(0) f_{p_2}(0) f_{p_3}(0) \dots}$$

$$\varphi_{prot}(k_{\perp}, p_1, p_2, p_3) \equiv \frac{\sigma_{prot}(x, k_{\perp}; p_1, p_2, p_3)}{\sigma_{prot}(x, 0; p_1, p_2, p_3)} = \frac{f_{p_1} \left( \frac{k_{\perp}}{3m} \right) f_{p_2} \left( \frac{k_{\perp}}{3m} \right) f_{p_3} \left( \frac{k_{\perp}}{3m} \right)}{f_{p_1}(0) f_{p_2}(0) f_{p_3}(0)}$$

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

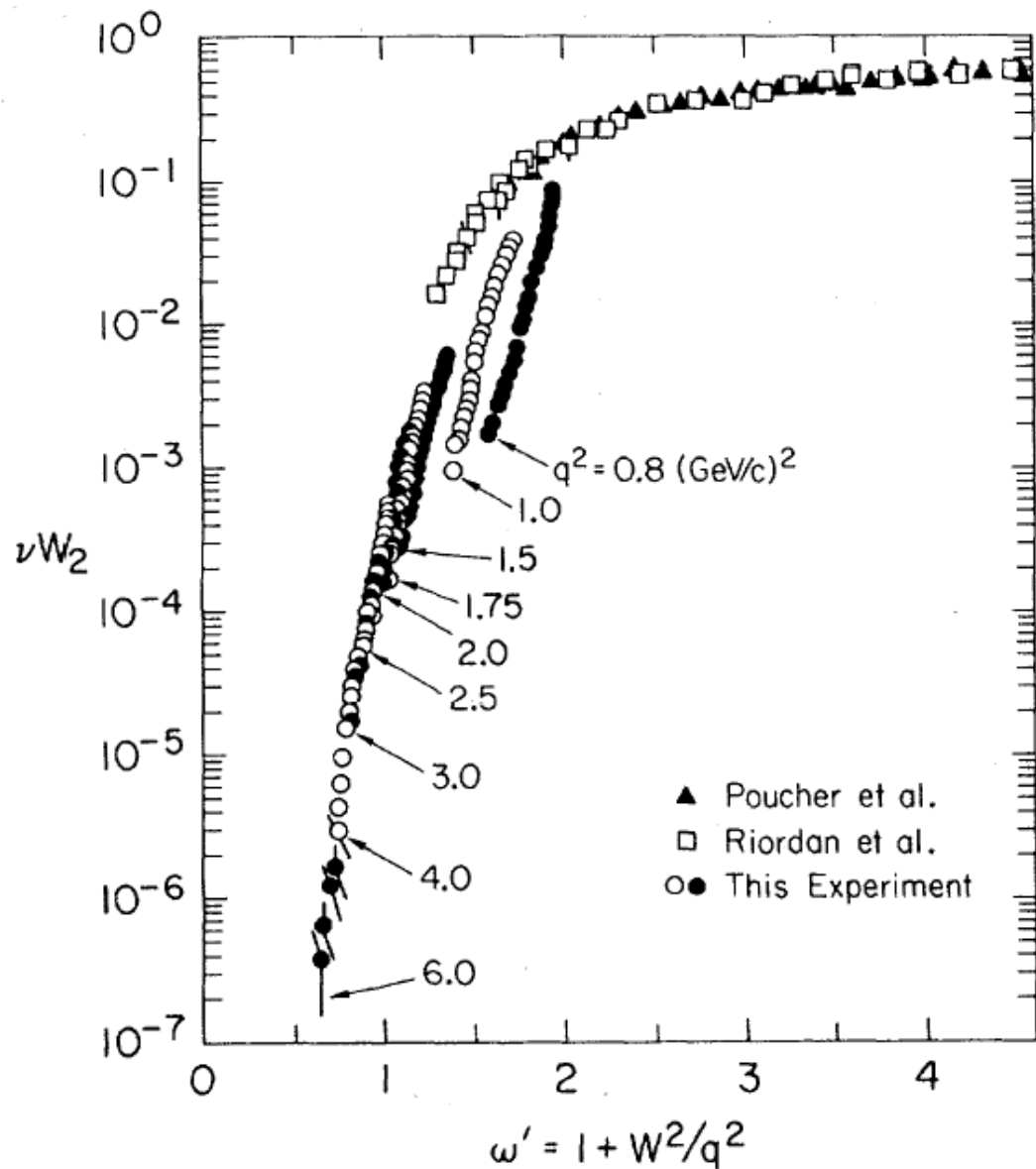
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V. Vechernin, AIP  
 Conference Proceedings  
 1701 (2016) 060020.

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)

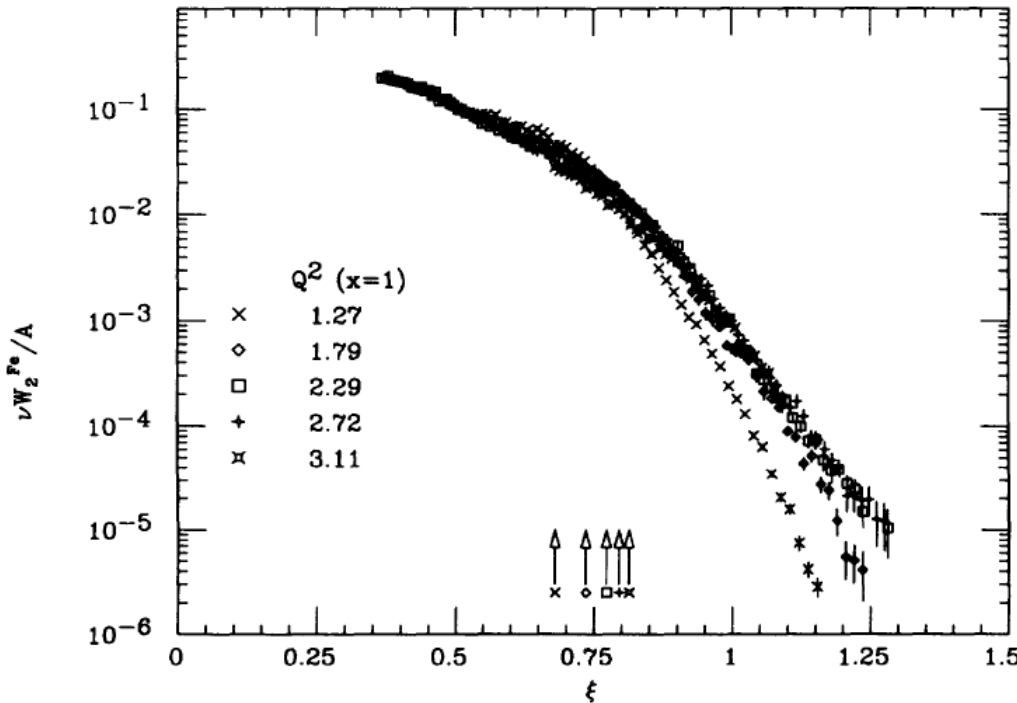
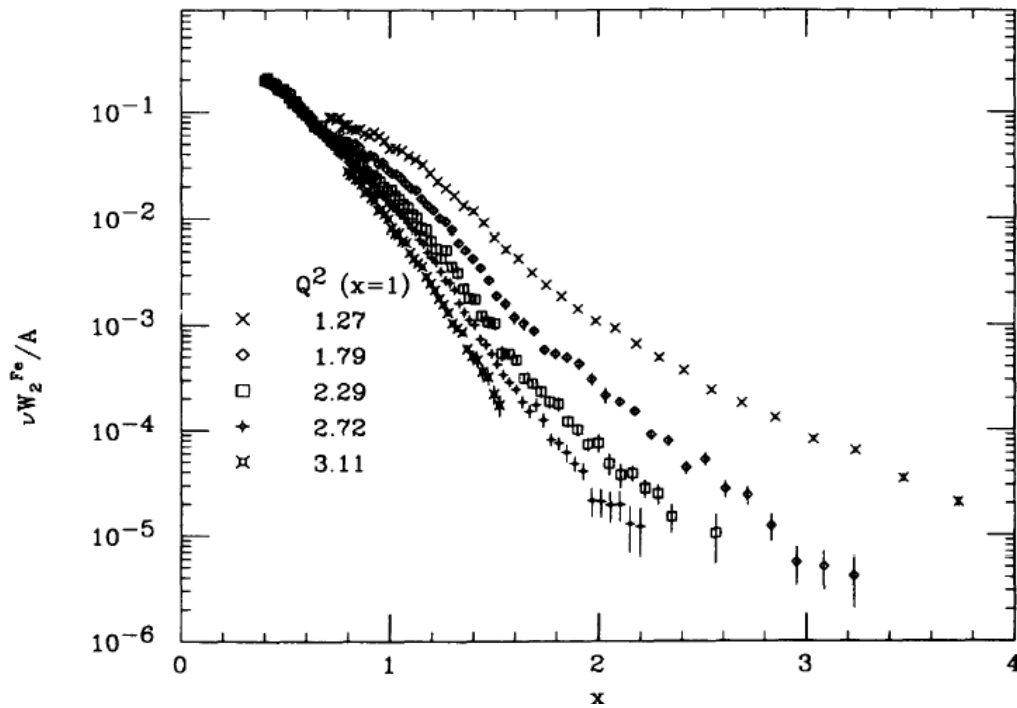
# Backup slides



$$W^2 = M^2 + 2M\nu - q^2$$

$$\omega' = \frac{1}{\xi} + \frac{M^2}{q^2} = \frac{1}{\xi} + \frac{m^2}{|Q^2|}$$

Filippone B.W. et al.,  
*Phys.Rev.C, 45 (1992) 1582*



*Freedom at moderate energies:  
 Masses in color dynamics*

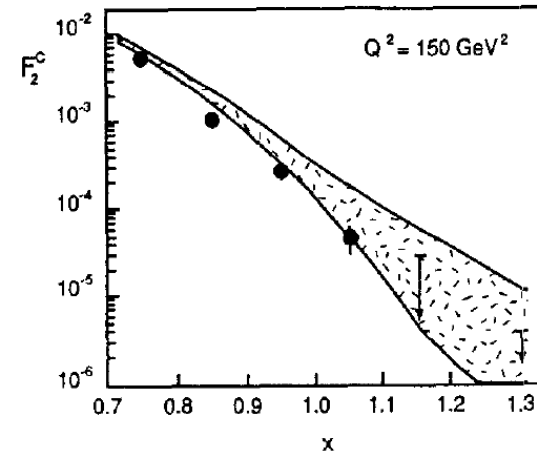
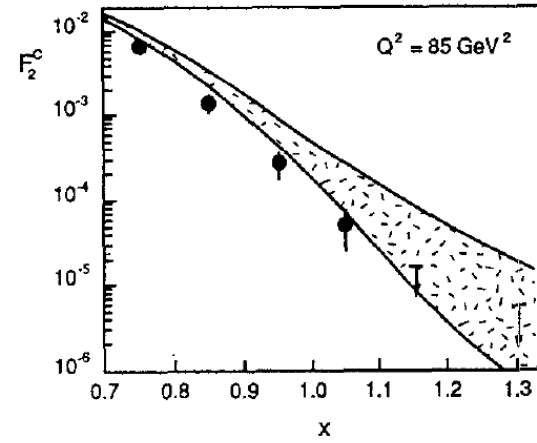
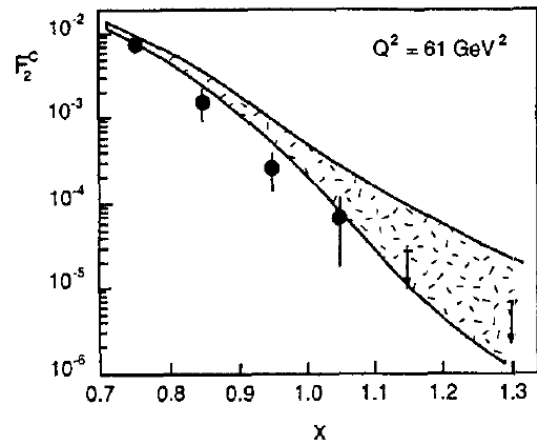
Georgi H., Politzer H.D.

*Phys. Rev. D 14, 1829 (1976)*

$$\xi = 2x / [1 + (1 + 4M^2x^2/Q^2)^{1/2}]$$

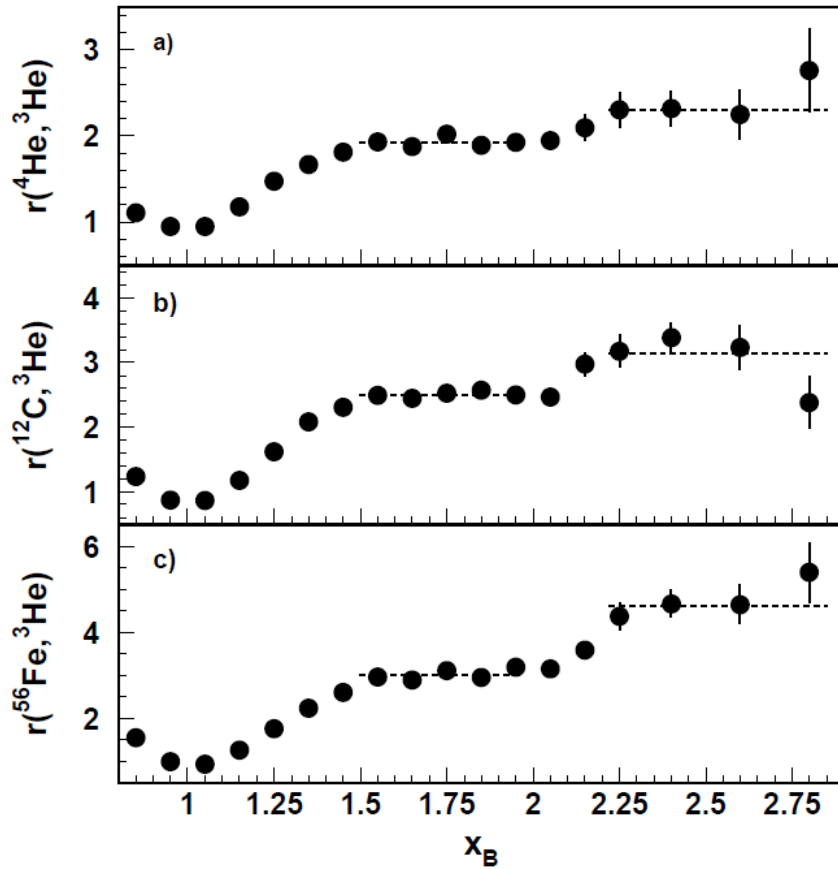


*Benvenuti A.C. et al. (BCDMS collaboration) Z. Phys. C63 (1994) 29*



*L. Frankfurt, M. Strikman, Phys. Rep. 160 (1988) 325*

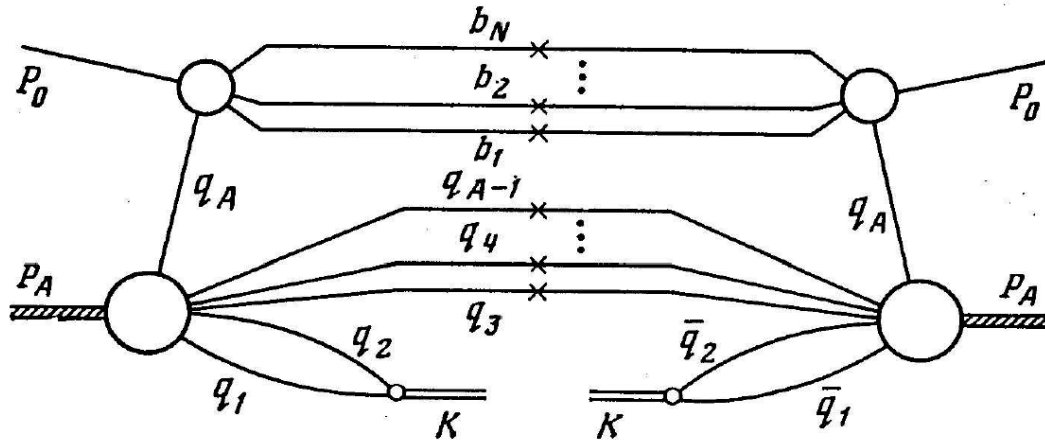
*K.S. Egiyan, et al.,  
Phys.Rev.Lett. 96 (2006) 082501*



$$r(A, {}^3\text{He}) = \frac{A(2\sigma_{ep} + \sigma_{en})}{3(Z\sigma_{ep} + N\sigma_{en})} \frac{3\mathcal{Y}(A)}{A\mathcal{Y}({}^3\text{He})} C_{\text{rad}}^A$$

	$a_2(A/{}^3\text{He})$	$a_{2N}(A)(\%)$	$a_3(A/{}^3\text{He})$	$a_{3N}(A)(\%)$
${}^3\text{He}$	1	$8.0 \pm 1.6$	1	$0.18 \pm 0.06$
${}^4\text{He}$	$1.93 \pm 0.01 \pm 0.03$	$15.4 \pm 3.2$	$2.33 \pm 0.12 \pm 0.04$	$0.42 \pm 0.14$
${}^{12}\text{C}$	$2.49 \pm 0.01 \pm 0.15$	$19.8 \pm 4.4$	$3.18 \pm 0.14 \pm 0.19$	$0.56 \pm 0.21$
${}^{56}\text{Fe}$	$2.98 \pm 0.01 \pm 0.18$	$23.9 \pm 5.3$	$4.63 \pm 0.19 \pm 0.27$	$0.83 \pm 0.27$

Coherent Coalescence at nucleon level, formation of light cumulative fragments (criticism of the Butler-Pearson coalescence model).



$$X(\mathbf{k}) = \frac{I_A^{(d)}(2\mathbf{k})/A}{(I_A(\mathbf{k})/A)^2},$$

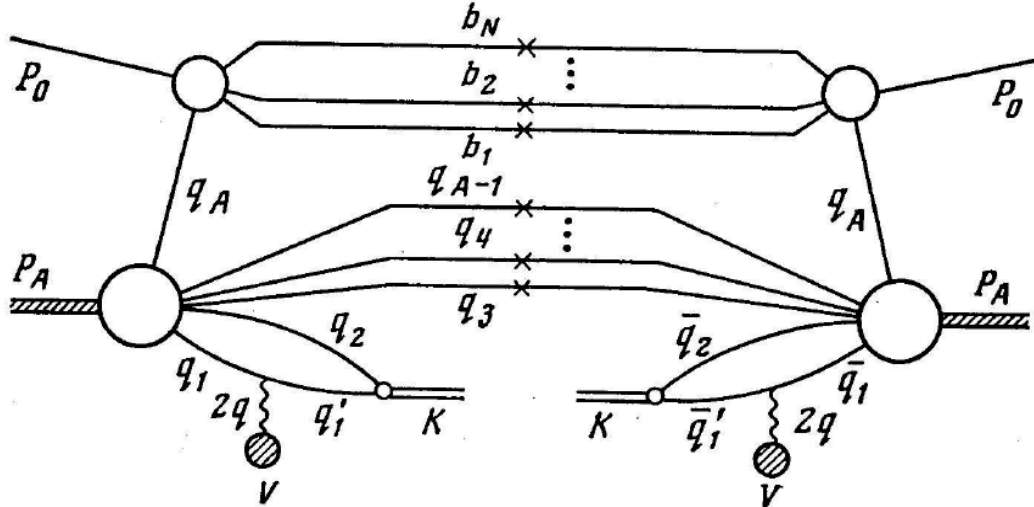
$$(m\varepsilon_A)^{\frac{1}{2}} \ll k \ll m \leq P_0$$

M.A. Braun, V.V. Vechernin,  
Yad.Fiz. 36 (1982) 614

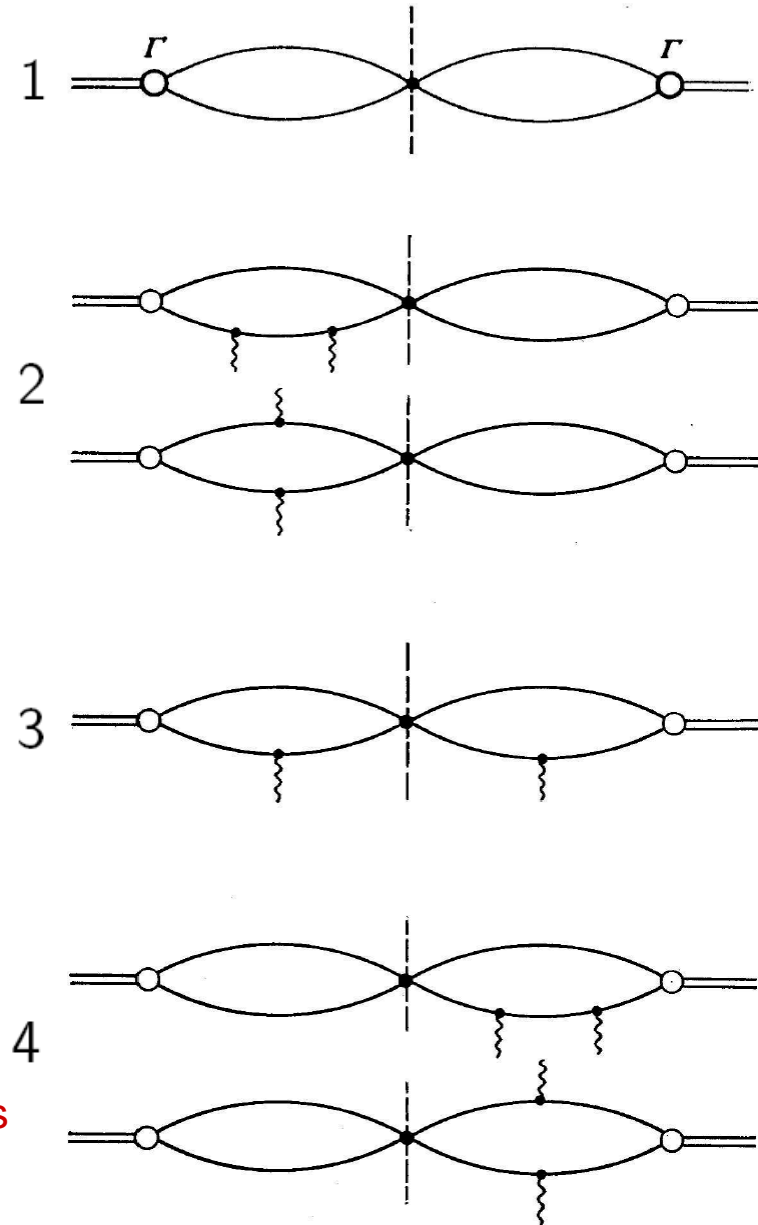
$$\rho_d(\mathbf{K}) = \int d\mathbf{q}_1 d\bar{\mathbf{q}}_1 \varphi\left(\frac{\mathbf{q}_1 - \mathbf{q}_2}{2}\right) \varphi^*\left(\frac{\bar{\mathbf{q}}_1 - \bar{\mathbf{q}}_2}{2}\right) \times$$

$$\times \int \prod_{j=3}^{A-1} d\mathbf{q}_j \varphi_A(\mathbf{q}_1, \mathbf{q}_2, \dots, \mathbf{q}_j, \dots) \varphi_A^*(\bar{\mathbf{q}}_1, \bar{\mathbf{q}}_2, \dots, \mathbf{q}_j, \dots) .$$

- nucleons are **off mass shell** => **direct** coalescence is possible
- **coherence** of the coalescence process



M.A. Braun, V.V. Vechnin,  
Yad.Fiz. 44 (1986) 784



Butler S.T., Pearson C.A., Phys.Rev. 129 (1963) 863

$$X^{\text{BP}} = \frac{A\sigma_N}{\sigma_A} 48^2 \pi I(R) \gamma m^2 \frac{W_0^2}{K^2}$$

$$q_{1,2} = K/2 \pm k, \quad \bar{q}_{1,2} = K/2 \pm \bar{k}$$

$$\int |A_1(\mathbf{k}) + A_2(\mathbf{k})|^2 d\mathbf{k} =$$

$$= \int \{ |A_1(\mathbf{k})|^2 + |A_2(\mathbf{k})|^2 + A_1(\mathbf{k})A_2^*(\mathbf{k}) + A_1^*(\mathbf{k})A_2(\mathbf{k}) \} d\mathbf{k}$$

$$\left| \int \{ A_1(\mathbf{k}) + A_2(\mathbf{k}) \} d\mathbf{k} \right|^2 =$$

$$= \iint \{ A_1(\mathbf{k})A_1^*(\bar{\mathbf{k}}) + A_2(\mathbf{k})A_2^*(\bar{\mathbf{k}}) + A_1(\mathbf{k})A_2^*(\bar{\mathbf{k}}) + A_1^*(\mathbf{k})A_2(\bar{\mathbf{k}}) \} d\mathbf{k}d\bar{\mathbf{k}}$$

For a real potential  $V$  the contributions  
2 and 4 cancel the BP contribution 3

Braun M.A., Vechernin V.V.

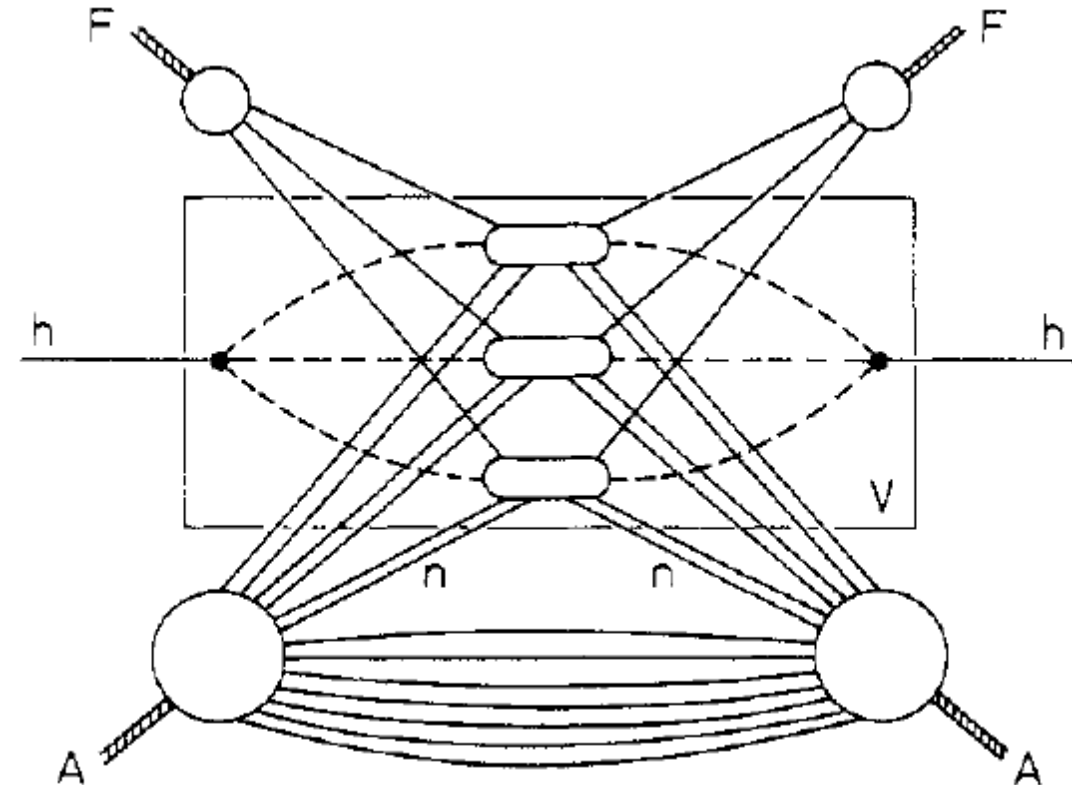
Production of fast fragments in high-energy hadron collisions with nuclei

J. Phys. G 16 (1990) 1615-1626

$$D_F = 2sF I_F, \quad I_F = (2\pi)^3 2f_F, \quad f_F = p_{F0} d^3\sigma_F/d^3\mathbf{p}_F$$

$$\frac{D_F^{(n)}}{2s} = \frac{(nF)!}{(n!)^F} C_A^{nF} (2m)^{1-nF} \left(\frac{d_n}{2s}\right)^F J_F^{(n)}$$

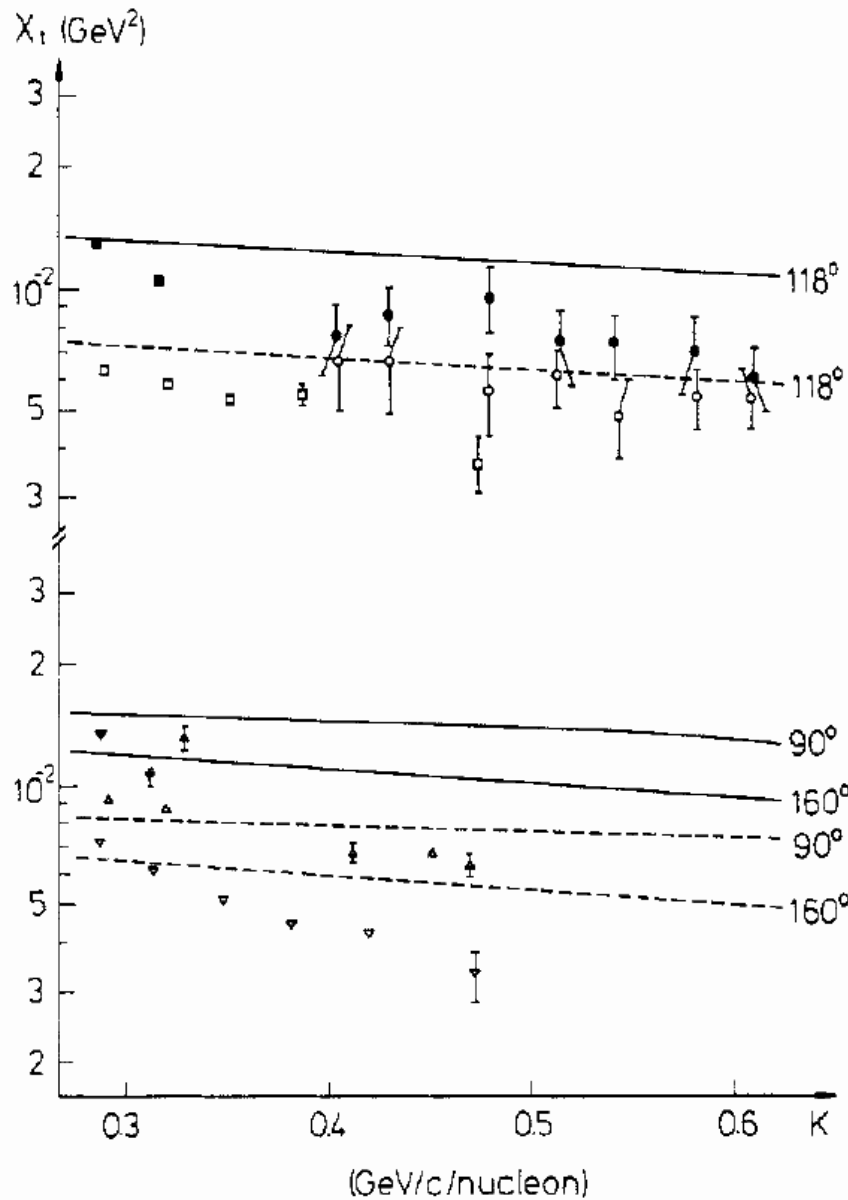
$$J_F^{(n)} = \int d^2\mathbf{b} dz_1 \dots dz_F |\psi_F(\mathbf{y}_i)|^2 \rho_A(\mathbf{b}, z_1; \dots \leftarrow n \rightarrow \dots \mathbf{b}, z_1; \dots, \mathbf{b}, z_F; \dots \leftarrow n \rightarrow \dots \mathbf{b}, z_F)$$



$$\mathbf{y}_i = \left( \mathbf{0}_\perp, \frac{k_-}{m} z_i \right)$$

$$k_- = k_0 - k_z = (k^2 + m^2)^{1/2} - k \cos \theta.$$

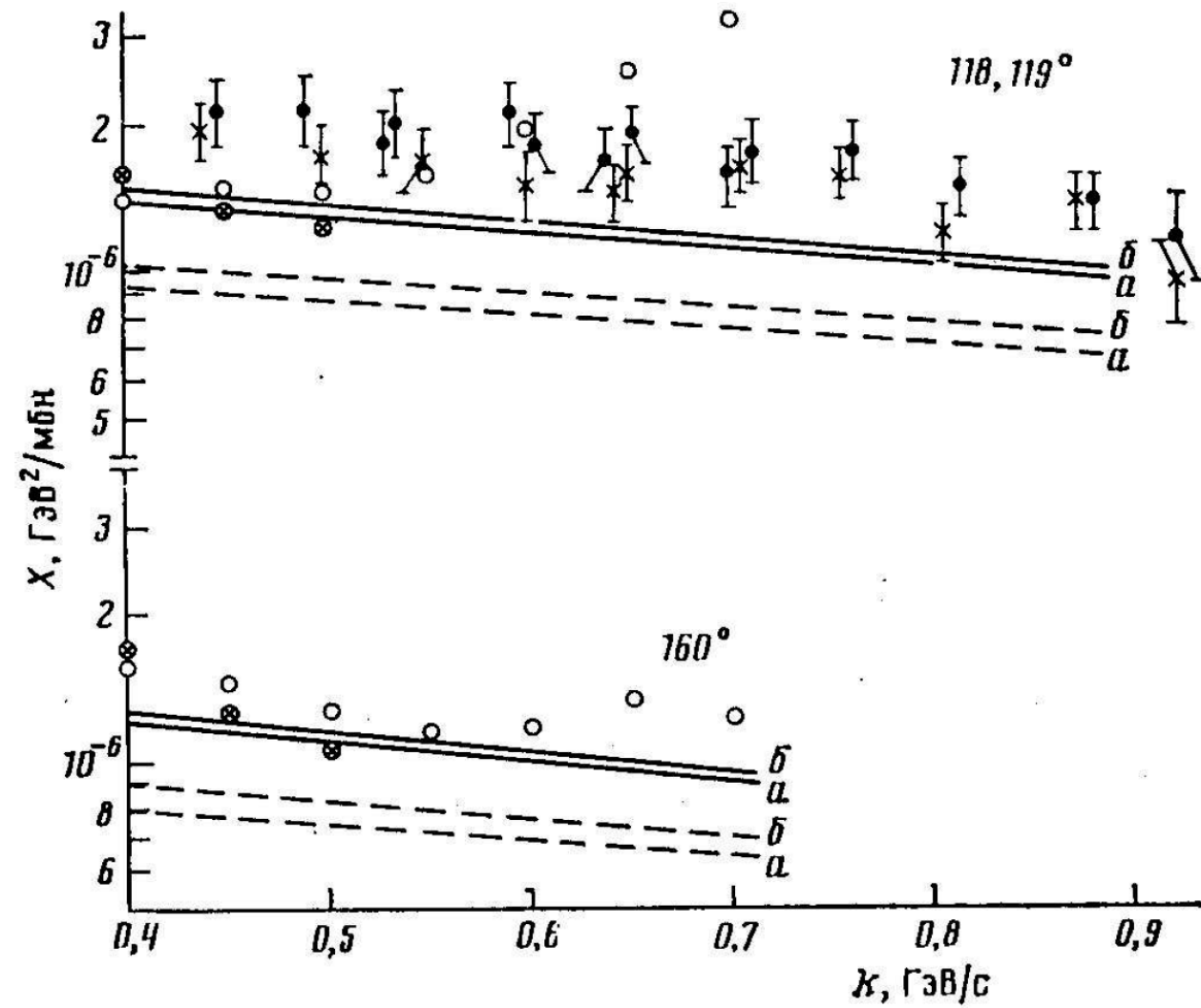
$k_-$  - scaling  
of the coalescence coefficient



$$[\chi_F(\mathbf{k})]^{F-1} = \frac{f_F(F\mathbf{k})/\sigma_A^{in}}{[f_1(\mathbf{k})/\sigma_A^{in}]^F} = [2(2\pi)^3 \sigma_A^{in}]^{F-1} \frac{I_F}{(I_1)^F}$$

The coalescence coefficient for the emission of tritium in the backward hemisphere in the lab. system, (i.e. in the cumulative area of the target nucleus fragmentation region of the process (1)). The full and broken curves are the results of our calculations with a formula, which is similar to (29) but with  $n = 2$ , for the target nuclei Cu and Ta, respectively. The experimental data points correspond to the production of tritium in the following reactions: ▲, ■ and ▼, on Cu for the angles  $90^\circ$ ,  $118^\circ$  and  $160^\circ$ , △, □ and ▽, on Ta for the same angles at the initial energy 400 GeV [10]; ● and ○, on Cu and Ta for the angle  $119^\circ$  at the initial energy 10 GeV [2].

M.A. Braun, V.V. Vechernin,  
Yad.Fiz. 47 (1988) 1452



$$X = (I_A^{(d)} / A) / (I_A / A)^2$$

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

Brodsky S., Farrar G. *Phys.Rev.Lett.* 31 (1973) 1153

Brodsky S., Chertok B.T., *Phys.Rev.* **D14** (1976) 3003

Matveev V.A., Muradyan R.M., Tavkhelidze A.N. *Lett. Nuovo Cimento* 7 (1973) 719

$s \rightarrow \infty$ ,  $t/s$  fixed

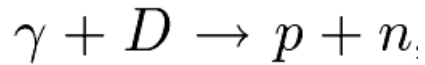
$$(d\sigma/dt)_{\pi p \rightarrow \pi p} \sim s^{-8}, (d\sigma/dt)_{pp \rightarrow pp} \sim s^{-10}, (d\sigma/dt)_{\gamma p \rightarrow \pi p} \sim s^{-7}, (d\sigma/dt)_{\gamma p \rightarrow \gamma p} \sim s^{-6}$$

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

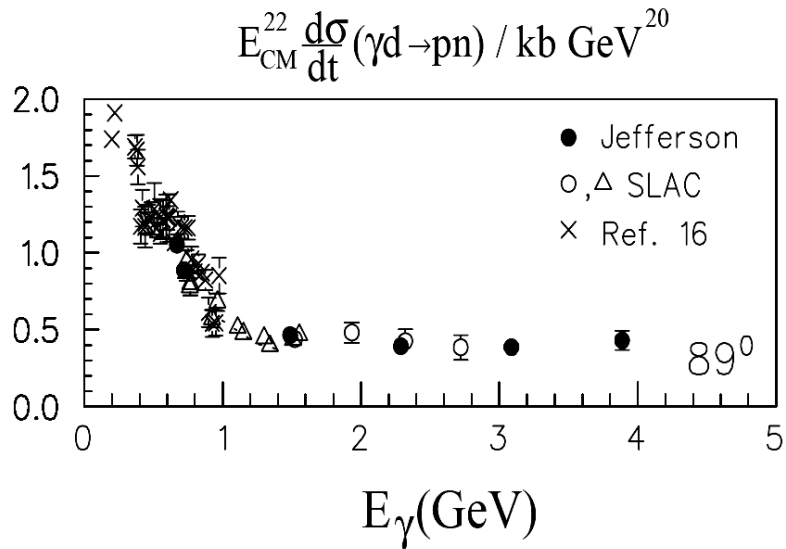
$$\frac{d\sigma}{dt}(A+B \rightarrow C+D) \rightarrow \frac{1}{t^{N-2}} f(t/s)$$

$$N=n_A+n_B+n_C+n_D$$





$$1+6+3+3=13 \Rightarrow \sim s^{-11} = E^{-22}$$



C. Bochna et al., Phys. Rev. Lett. **81** (1998) 4576.

Too early ?

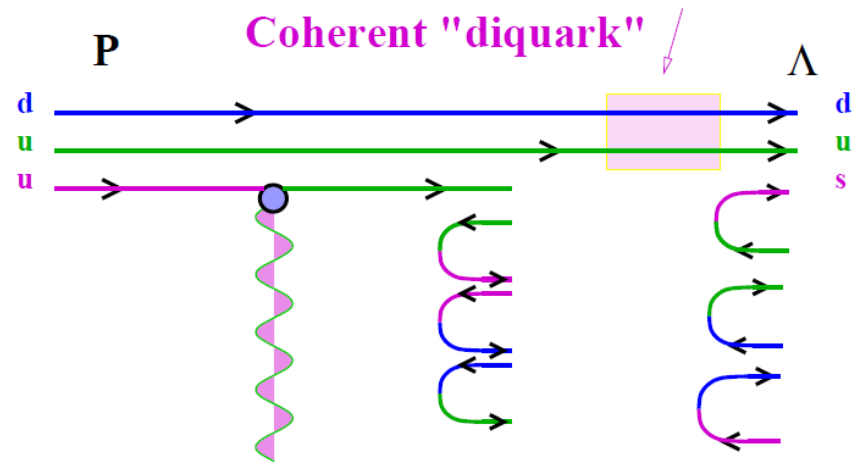


Fig. 4a: Gluon exchange produces a leading baryon.

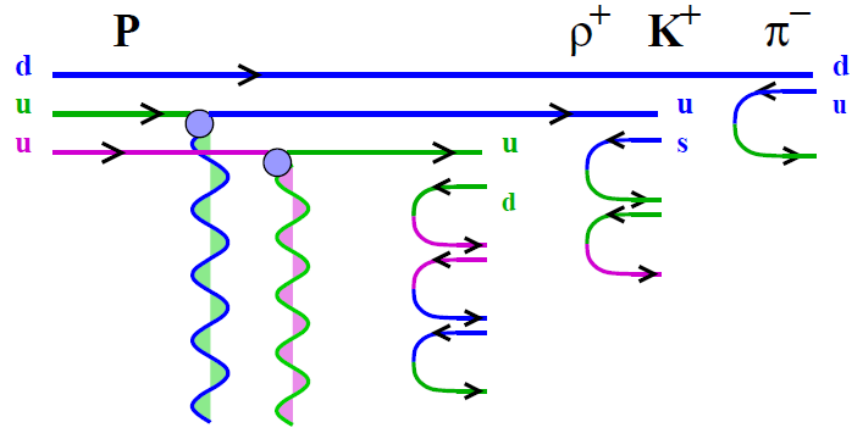


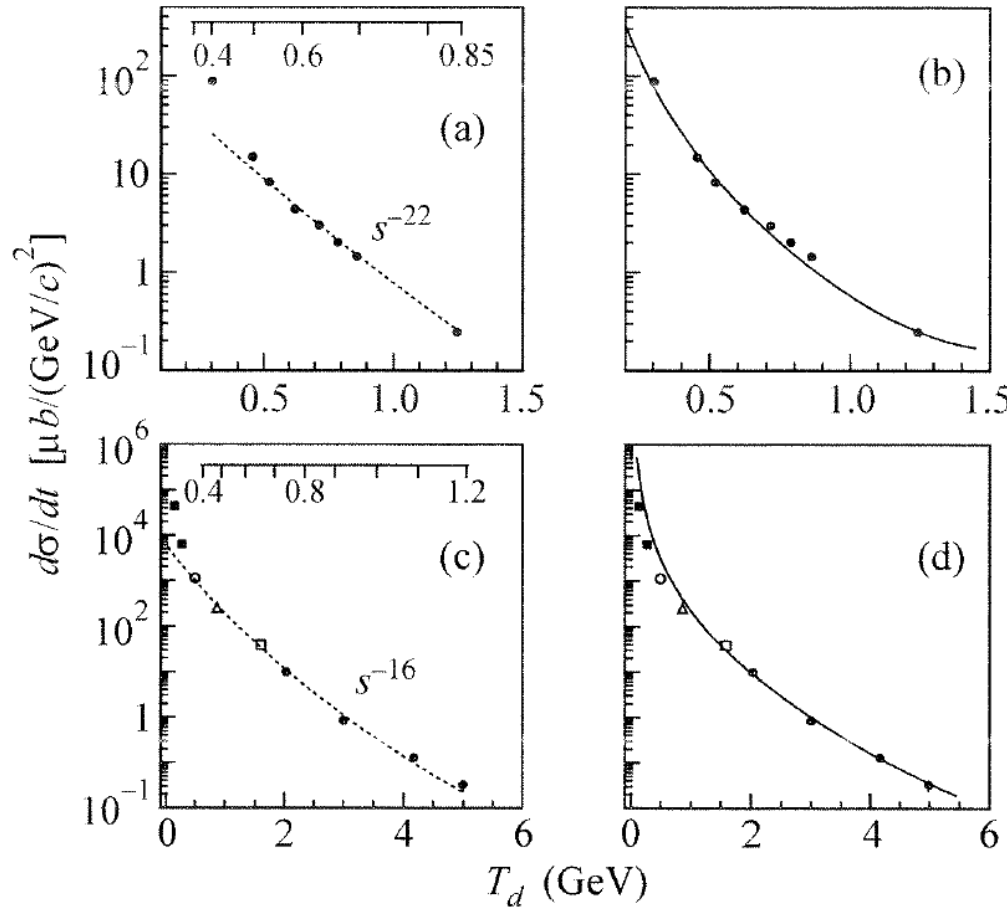
Fig. 4b: Double exchange “breaks up” the proton.



$$6+6+3+9-2=22$$



$$3+6+3+6-2=16$$



**Fig. 2.** The differential cross section of the  $dd \rightarrow n^3\text{He}$  and  $dd \rightarrow p^3\text{H}$  reactions at  $\theta_{\text{cm}} = 60^\circ$  (a), (b) and  $dp \rightarrow dp$  at  $\theta_{\text{cm}} = 127^\circ$  (c), (d) versus the deuteron beam kinetic energy. Experimental data in (a), (b) are taken from [20]. In (c), (d), the experimental data (closed squares), (○), (△), (open square), and (●) are taken from [22–26], respectively. The dashed curves give the  $s^{-22}$  (a) and  $s^{-16}$  (c) behavior. The full curves show the result of calculations using the Regge formalism given by Eqs. (2)–(4) with the following parameters: (b)  $C_1 = 1.9 \text{ GeV}^2$ ,  $R_1^2 = 0.2 \text{ GeV}^{-2}$ ,  $C_2 = 3.5$ ,  $R_2^2 = -0.1 \text{ GeV}^{-2}$ ; (d)  $C_1 = 7.2 \text{ GeV}^2$ ,  $R_1^2 = 0.5 \text{ GeV}^{-2}$ ,  $C_2 = 1.8$ ,  $R_2^2 = -0.1 \text{ GeV}^{-2}$ . The upper scales in (a) and (c) show the relative momentum  $q_{pn}$  (GeV/c) in the deuteron for the ONE mechanism.