Probing Cold Dense Baryon Matter by Cumulative Processes

Victor Kim

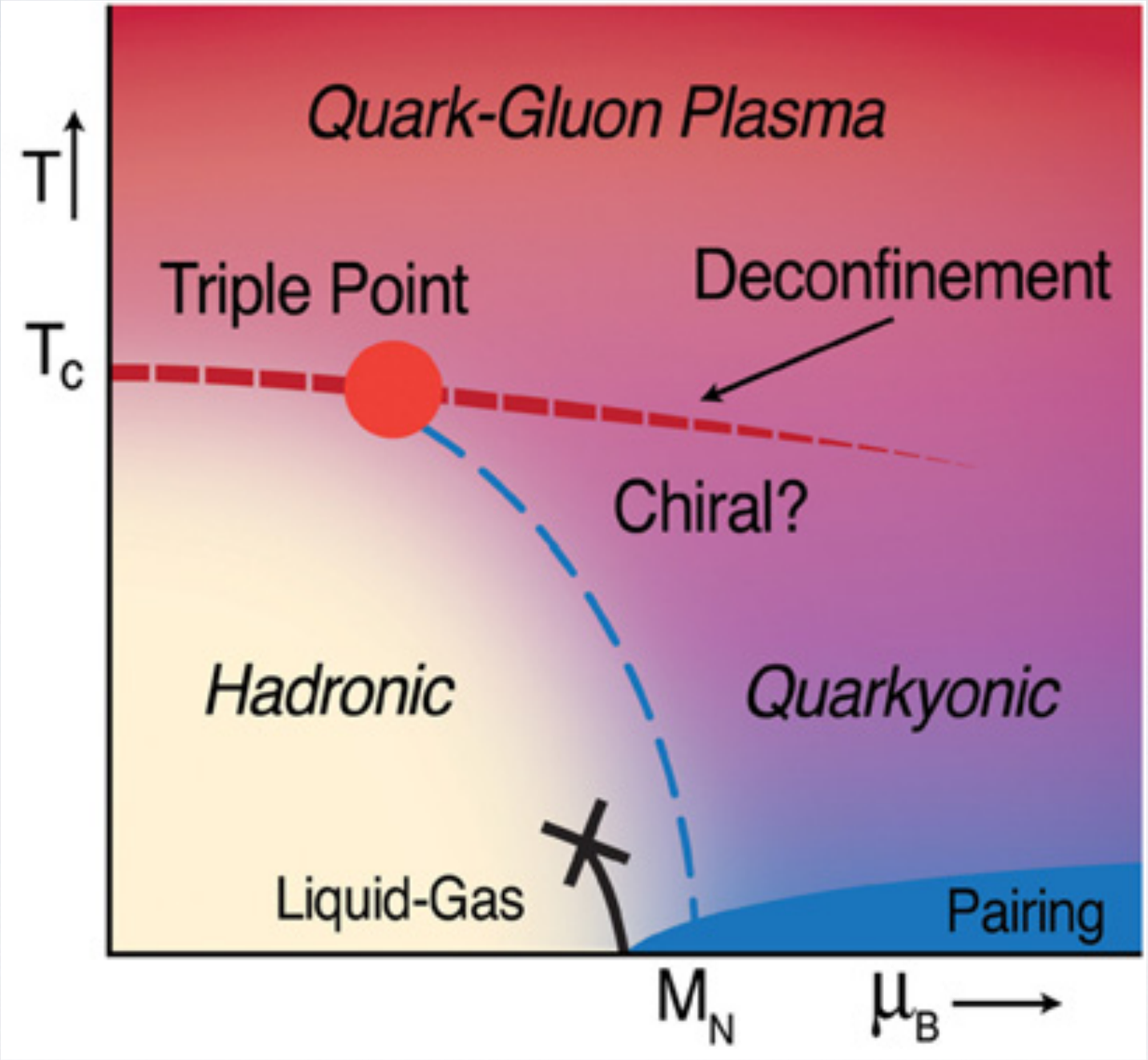
Petersburg Nuclear Physics Institute NRC KI, Gatchina

St. Petersburg Polytechnic University

Outline:

- QCD-evolution of nuclear structure functions
- EMC-effect: ratio of nuclear structure functions
- Cumulative processes in “cold” flucton models
- Flucton model EKKLS:
  hard nuclear quark sea at large X
- Summary

Cold Superdense Baryon Matter



Quarkyonic state?

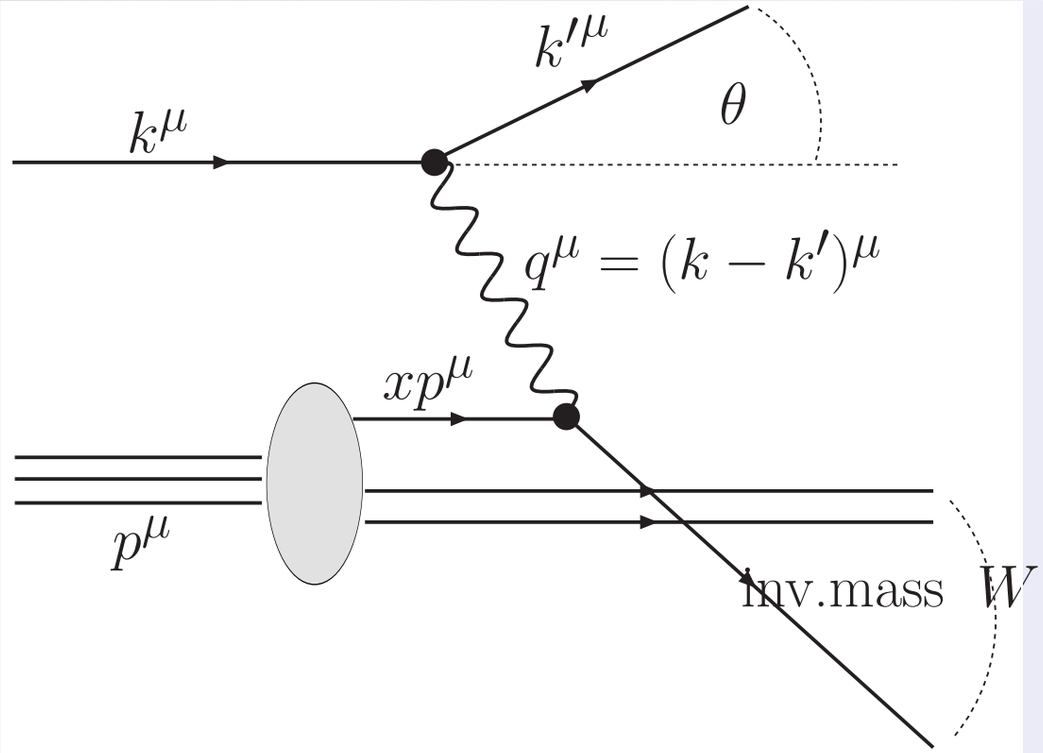
L.McLerran & L.McLerran & R. Pisarski (2007)
V. Braguta et al. (2016), ...

Two cornerstones of perturbative QCD for inclusve hard process description:

- factorization of hard processes
- GLAPD-evolution

Deep inelastic scattering (DIS)

- **Bjorken limit: s -> ∞ , Q^2/s = const**
- **Bjorken scaling violation due to GLAPD-evolution**



$$\nu = \frac{2pq}{m_p} \longrightarrow E - E'$$

(energy transfer)

$$x = \frac{Q^2}{2pq} \longrightarrow \frac{Q^2}{E - E'}$$

(momentum fraction of parton)

$$Q^2 = -q^2 = -2EE'(1 - \cos\theta)$$

(momentum transfer squared)

Deep inelastic scattering (DIS): structure functions

$$\frac{d\sigma_{\rm DIS}}{d^2\Omega} = \frac{\alpha^2 \cos^2\frac{\theta}{2}}{4E^2 \sin^4\frac{\theta}{2}} \left[W_2(\nu, Q^2) + 2W_1(\nu, Q^2)\right]$$

$$m_p W_1(\nu, Q^2) \longrightarrow F_1(x)$$

$$\frac{Q^2}{2m_p x} W_2(\nu, Q^2) \longrightarrow F_2(x)$$

$$2xF_1(x) = F_2(x)$$

$$F_1(x) = \sum_a q_a^2 f_a(x)\ , \quad q_a = \text{parton's charge}$$

- **Bjorken limit: s -> ∞ , Q^2 /s = const**
- **Bjorken scaling violation due to GLAPD-evolution**

Deep inelastic process (DIS): parton sum rules

Momentum sum rule:
all partons (quarks, antiquarks and gluons)
carry proton's momentum

$$\int_0^1 \mathrm{d}x\, x\, [f_u(x) + f_{\bar{u}}(x) + f_d(x) + f_{\bar{d}}(x) + f_s(x) + f_{\bar{s}}(x) + \ldots] = 1$$

Quarks in proton: baryon number conservation

$$\int_0^1 \mathrm{d}x\, [f_u(x) - f_{\bar{u}}(x)] = 2 \qquad \int_0^1 \mathrm{d}x\, [f_d(x) - f_{\bar{d}}(x)] = 1$$

$$\int_0^1 \mathrm{d}x\, [f_s(x) - f_{\bar{s}}(x)] = 0 \qquad \int_0^1 \mathrm{d}x\, [f_c(x) - f_{\bar{c}}(x)] = 0$$

Hard processes in QCD

Perturbative QCD for hard processes

$Q^2/s = x$ – fixed, $s \rightarrow \infty$ (Bjorken limit)

→

- Factorization of hard and soft contributions in leading twist

A.Efremov & A.Radyushkin (78-81)
A.Mueller, J.Collins, D.Soper, G. Sterman, …

$$\sigma_{HARD} = \sigma_{parton} \times F(x, Q^2) + (1/Q^2)$$

- GLAPD Q^2-evolution

V.Gribov & L.Lipatov (71-72), G.Altarelli & G.Parisi (77), Yu.Dokshitzer (77)

Structure functions of free nucleon and nucleus: deep inelastic scattering

Factorization of hard and soft contributions for DIS on free nucleon and nucleus:

$$\sigma_{HARD} = \sigma_{parton} \times F_N(x, Q^2) + (1/Q^2)$$

$$\sigma_{HARD} = \sigma_{parton} \times F_A(x, Q^2) + (1/Q^2)$$

factorization does not depend on type of target !

$$F_A(n, Q^2) = \int_C^1 x_A^{n-1} F_A(x, Q^2) dx_A = \sum C_\alpha \left(n, \frac{Q^2}{\mu^2}, \alpha(\mu^2)\right) f_{\alpha/A}(n, \mu^2) + O\left(\frac{1}{Q^2}\right)$$

$$f(n) = \int_0^1 dx\, dx^{n-1} f(x);$$

Nuclear structure function: deep inelastic scattering

$$F_A(n,Q^2) = \int\limits_C^1 x_A^{n-1}\, F_A(x,Q^2)dx_A = \sum C_\alpha\left(n,\frac{Q^2}{\mu^2},\alpha(\mu^2)\right) f_{\alpha/A}(n,\mu^2) + O\left(\frac{1}{Q^2}\right)$$

$$f(n) = \int_0^1 dx\, dx^{n-1} f(x);$$

$$\frac{d\, f_{a/A}(n,\mu^2)}{d\ln\mu^2} = \sum_b \gamma_{ab}\Big(n,\alpha(\mu^2)\Big) f_{b/A}(n,\mu^2)\,;$$

$$\mu^2 = Q^2;$$

$$V_a = q_a - \bar{q}_a\,, \quad f_1 = q^s(n,Q^2) = \sum_a (q_a + \bar{q}_a), \quad f_2 = G(n,Q^2);$$

$$\frac{dV_\alpha(n,Q^2)}{d\ln Q^2} = \gamma_{qq}^{NS}\Big(n,\alpha(Q^2)\Big) V_\alpha(n,Q^2);$$

$$\frac{df_i(n,Q^2)}{d\ln Q^2} = \gamma_{ik}^{S}\Big(n,\alpha(Q^2)\Big) f_k(n,G^2)\,, \quad i,k = 1.2$$

Nuclear structure functions: GLAPD-evolution (RG-evolution) for NonSinglet

$$\frac{\dot{V}_A}{V_A} = \frac{\dot{V}_N}{V_N} = \gamma_{qq}^{NS}\Big(n, \alpha(Q^2)\Big) \quad \Rightarrow \quad V_A(n, Q^2) = T_A^{NS}(n) \cdot V_N(n, Q^2)$$

$$V_A(x, Q^2) = \int\limits_x^A T_A^{NS}(y) V_N\Big(\frac{x}{y}, Q^2\Big)\frac{dy}{y} \equiv T_A^{NS} \otimes V_N$$

$$T = T(x)\,, \quad V_A, V_N \geq 0 \Rightarrow T \geq 0\,, \quad \int\limits_0^A T_A^{NS}(y)dy = 1\,.$$

Nuclear structure functions: GLAPD-evolution (RG-evolution) for Singlet

$$\begin{cases} f_A^{\pm} &= f_N^{\pm} \otimes T_A^{\pm} \\ f_N^{\pm} &= q_A^S + C^{\pm} g_N \end{cases}$$

$$S(n,Q^2) \;=\; K_{qq}(n)\, S(n,Q^2) + K_{qg}(n)\, G(n,Q^2)\,;$$

$$\frac{S_N(n,G^2)}{G_N(n,Q^2)} \;=\; \Big(1 - K_{qq}(n)\Big)^{-1} K_{qg}(n) \;=\; \frac{S_A(n,Q^2)}{G_A(n,Q^2)}$$

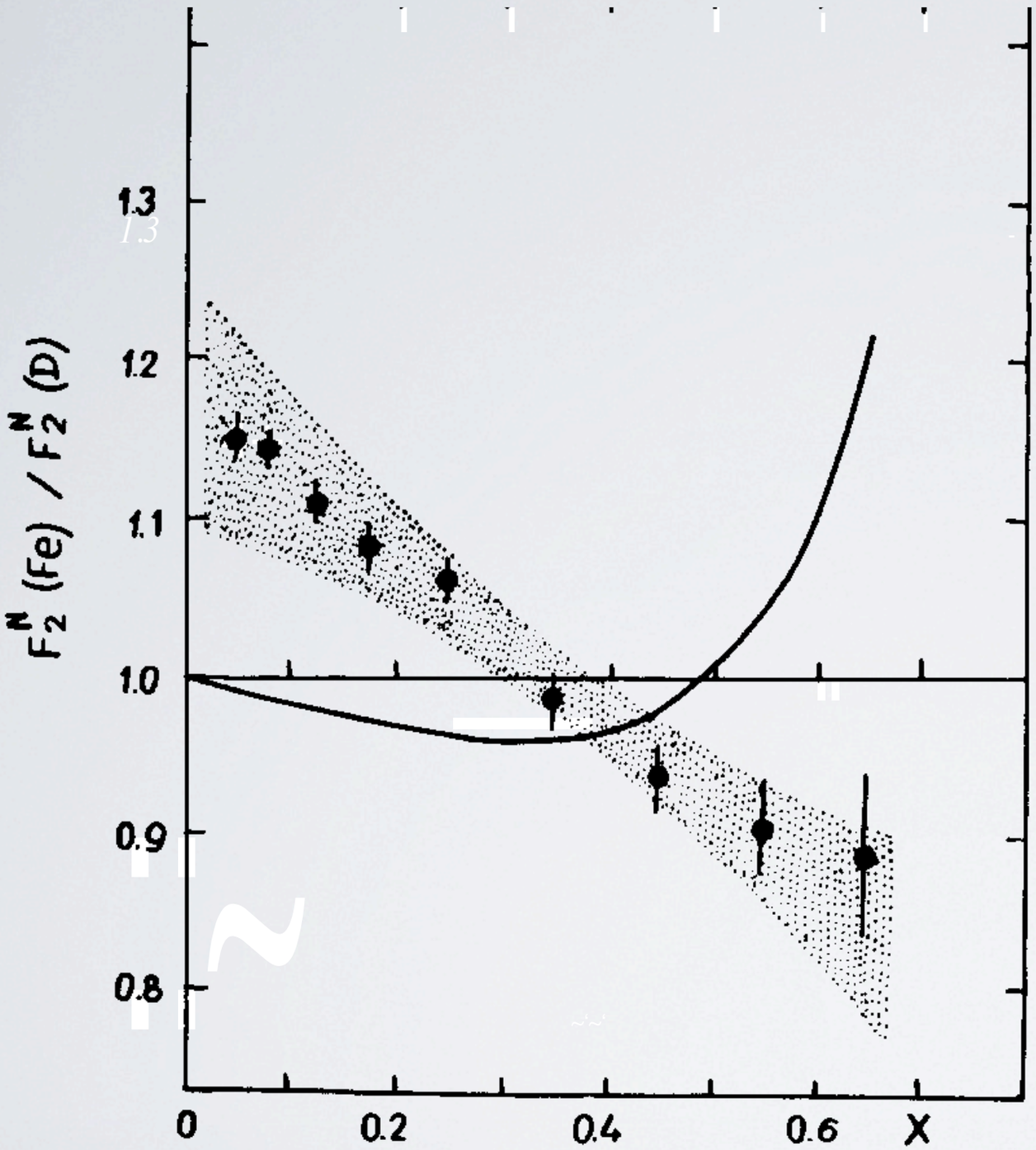
$$T^+ \;=\; T^- \;\equiv\; T_A^S\,;$$

Nuclear structure functions: GLAPD-evolution (RG-evolution) equations

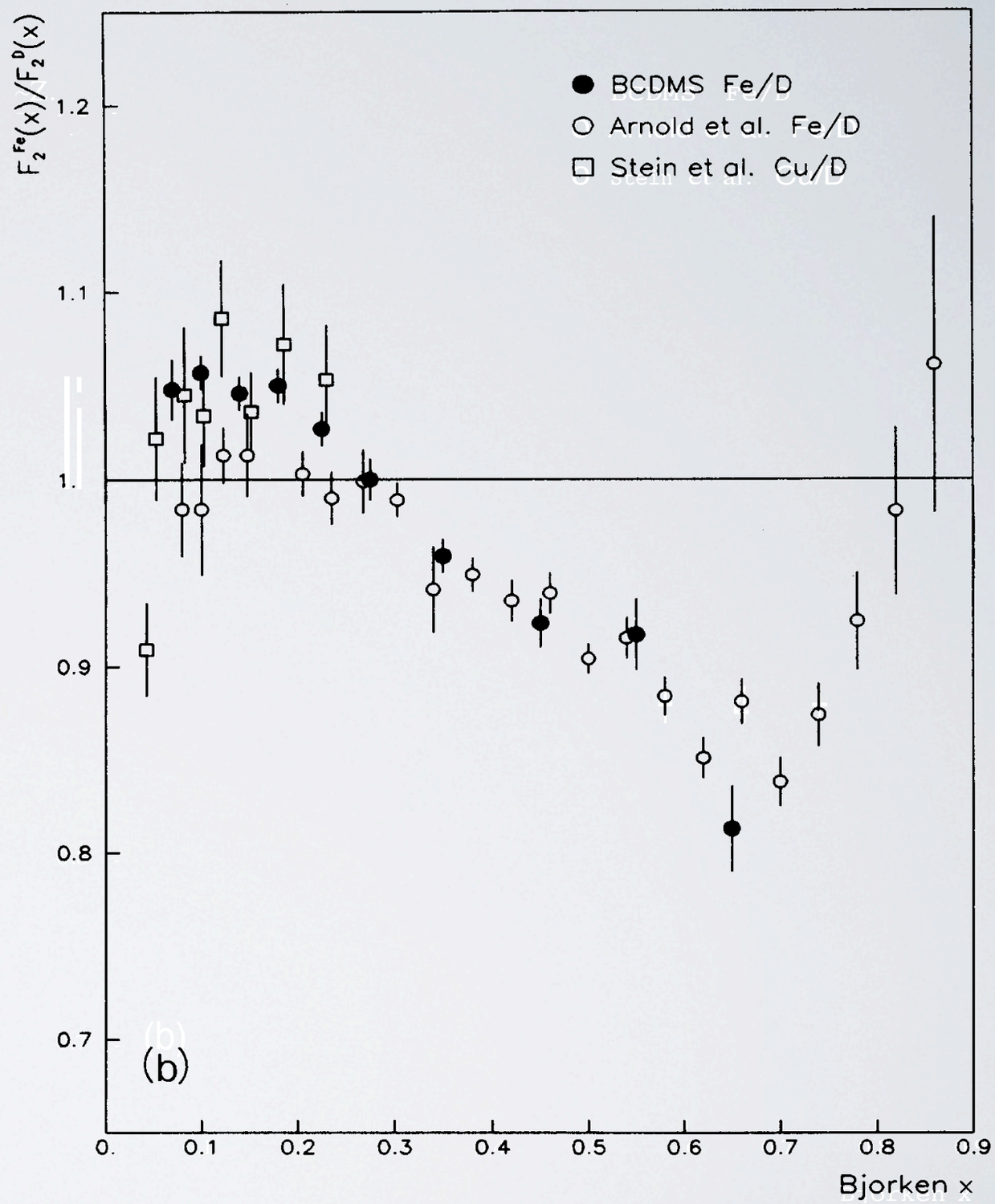
$$\begin{cases} V_A(n,Q^2) = T^{NS}(n)\cdot V_N(n,Q^2) \\ S_A(n,Q^2) = T^{S}(n)\cdot S_N(n,Q^2) \\ G_A(n,Q^2) = T^{S}(n)\cdot G_N(n,Q^2) \end{cases} = \begin{cases} V_A(x,Q^2) = \int\limits_0^A T^{NS}(y) V\left(\frac{x}{y},Q^2\right) dy \\ S_A(x,Q^2) = \int\limits_0^A T^{S}(y) S_N\left(\frac{x}{y},Q^2\right) dy \\ G(x,Q^2) = \int\limits_0^A T^{S}(y) S_N\left(\frac{x}{y},Q^2\right) dy \end{cases}$$

$$\frac{\langle x_q \rangle_A}{\langle x_q \rangle_N} = \frac{\langle x_g \rangle_A}{\langle x_g \rangle_N} = 1$$

EMC-ratio for nuclear structure functions



EMC Coll. (1983)



BCDMS Coll. (1987)
SLAC (1987)

Nuclear structure functions: nucleon distribution

$$F_A(x,Q^2) \;=\; \int_0^A dy\, T_A(y)\cdot \underbrace{F\Big(\frac{x}{y},Q^2\Big)}_{\substack{expand\\ at\;\; y\simeq 1}}$$

C. Llewellyn Smith (1983)

$$F\left(\frac{x}{y},Q^2\right) \;\simeq\; F(x,Q^2)+(1-y)\,F'(x,Q^2)+(1/2)(1-y)^2\,F''(x,Q^2)+\ldots$$

$$R \;\simeq\; \langle T\rangle + \underbrace{\langle (1-y)T\rangle}_{\langle\delta\rangle}\, x\frac{F_N'(x)}{F_N(x)} + \frac{1}{2}\underbrace{\langle (1-y)^2T\rangle}_{\langle\delta^2\rangle}\, x\left[\frac{F_N''(x)}{F_N(x)}x + 2\frac{F_N'(x)}{F_N(x)}\right]$$

$$F_N \;\simeq\; C(1-x)^k, \quad k \;=\; 3 \qquad\qquad \langle\ldots\rangle \;\equiv\; \int_0^A \ldots\, dy$$

$$R \;=\; \frac{F_A}{F_N} \;=\; 1-\langle\delta\rangle\,\frac{kx}{1-x} + \frac{\langle\delta^2\rangle}{2}\,\frac{kx}{1-x}\left(\frac{(k-1)x}{(1-x)}-2\right)+\ldots$$

$$R(0.5) \;=\; 1-\langle\delta\rangle\,k \;=\; 1-\Delta_A$$

Nuclear structure functions: nucleon distributions

A.Efremov, A.Kaidalov, VK, G.Lykasov & N.Slavin – EKKLS (1988)

F_2-ratio (Singlet):

$$< T_A^S > -1 = \Delta_A > 0 \qquad \int_0^A d\alpha \left[T_A^S(\alpha) - T_A^{NS}(\alpha)\right] = \Delta_A > 0$$

xF_3-ratio (NonSinglet):

$$1 - < \alpha T_A^{NS} > = \delta_A > 0 \qquad \int_0^A d\alpha\, \alpha \left[T_A^S(\alpha) - T_A^{NS}(\alpha)\right] = \delta_A > 0$$

$$\delta_A \simeq \Delta_A \qquad (\text{more exactly } \tfrac{2}{3}\Delta_A)$$

$$R_2(x \simeq 0) = \int_0^A d\alpha\, T_A^S(\alpha) = 1 + \Delta_A > 1$$

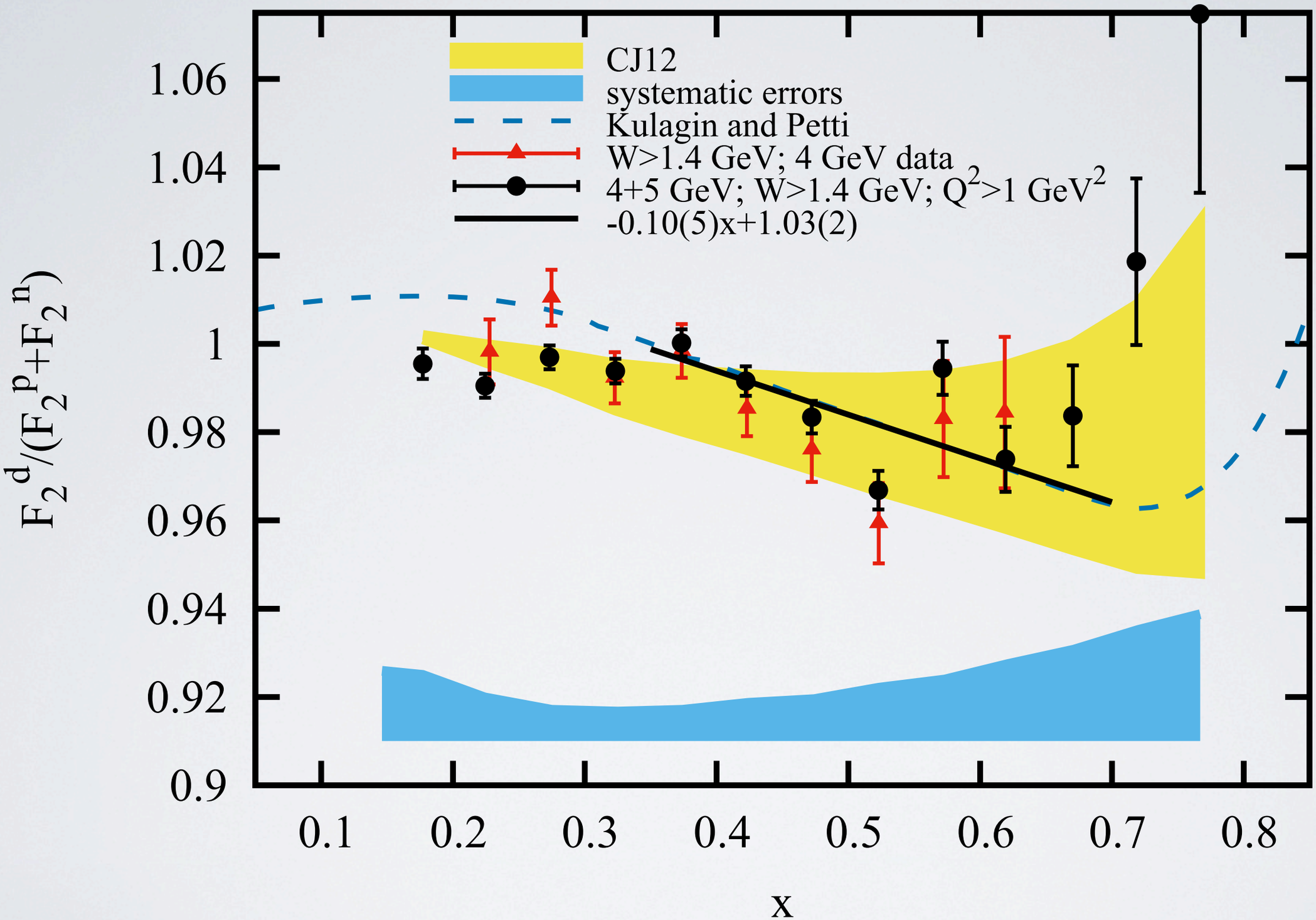
$$O_A(x, Q^2) \equiv \Sigma_A - V_A$$

$$= \int_x^A d\alpha\, T_A^{NS}(\alpha) O_N\left(\frac{x}{\alpha}, Q^2\right) + \int_x^A d\alpha \left[T_A^S(\alpha) - T_A^{NS}(\alpha)\right] \Sigma_N\left(\frac{x}{\alpha}, Q^2\right)$$

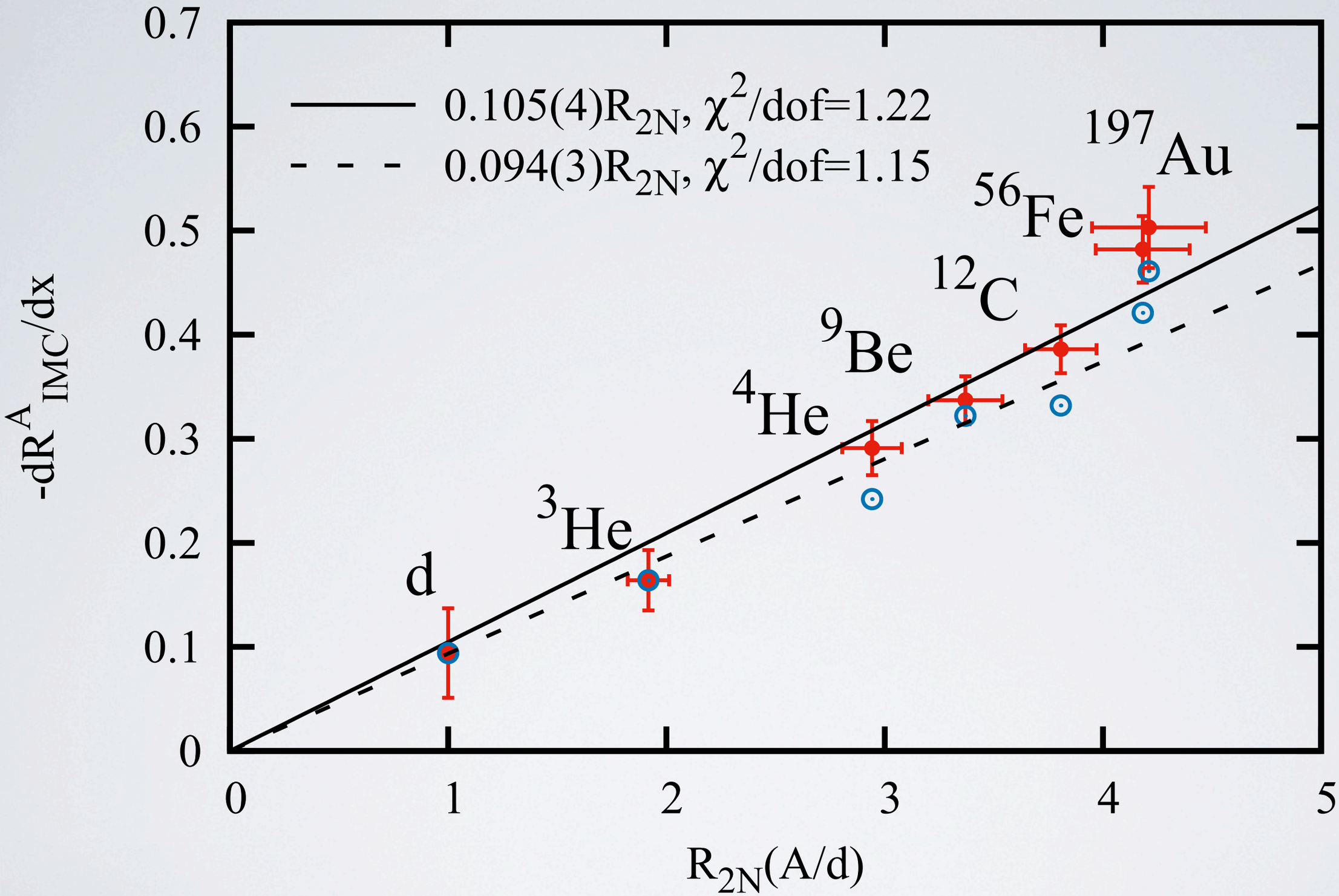
$$O'_A \simeq \Delta_A \cdot T_A^{NS} \otimes V_N$$

<- extra nuclear sea PDF is hard as nuclear valence PDF !

EMC-effect in Deutron: JLAB

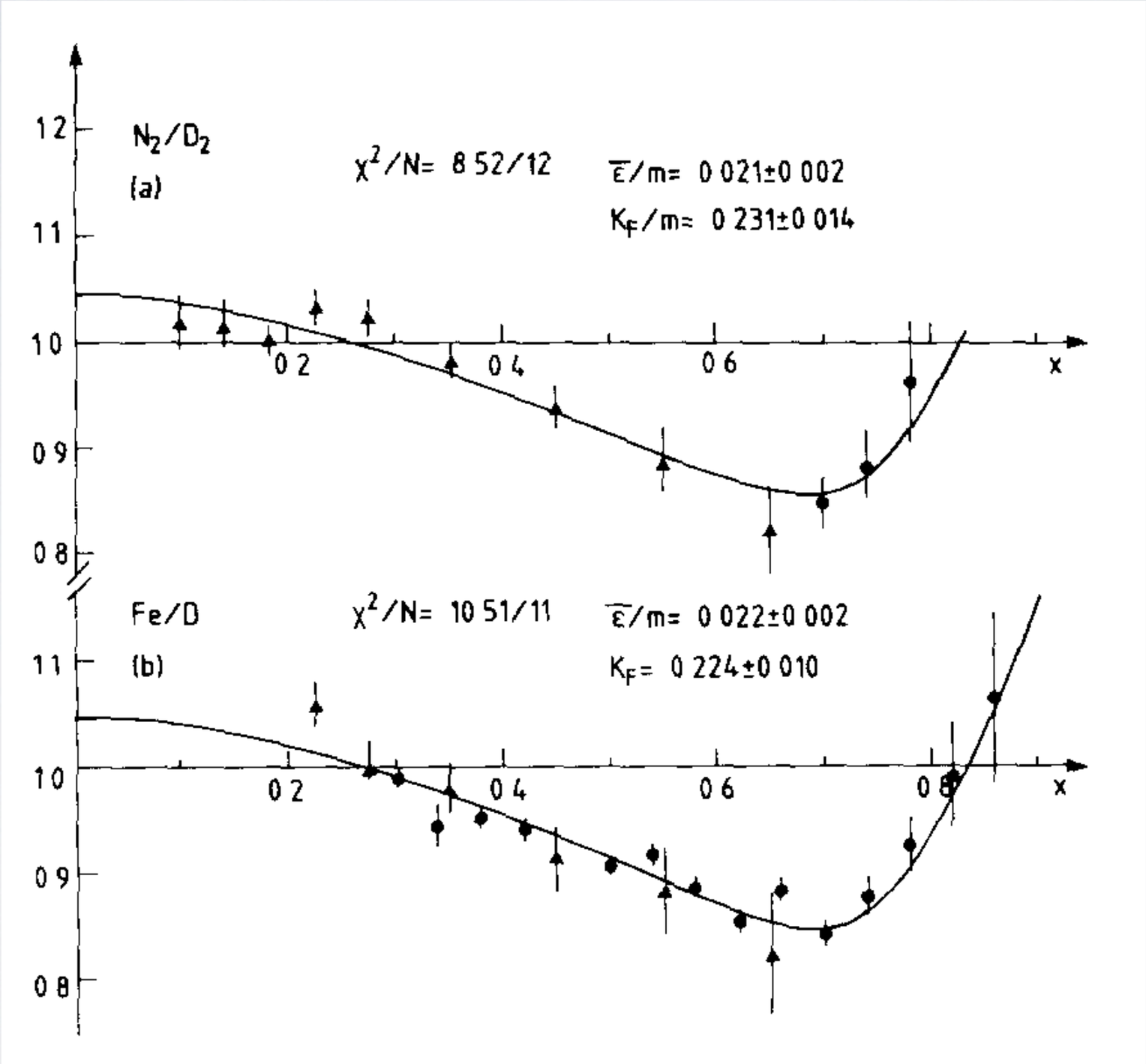


EMC x-slope: $R_{2N}(A/D)$-dependence



L. Weinstein et al (2011)
J. Arrington et al (2013)

EMC effect: momentum “re-pumping”: from valence to sea quarks Efremov (1986)



BCDMS (1987)

Nuclear structure functions at large X: multiquark fluctons

$$F_A(y) \;=\; \Sigma_{k=1}^{A}\, P_k F_k(y)$$

$$F_k(y) \;=\; C_k\, y^{A_k}\, (k-y)^{B_k}$$

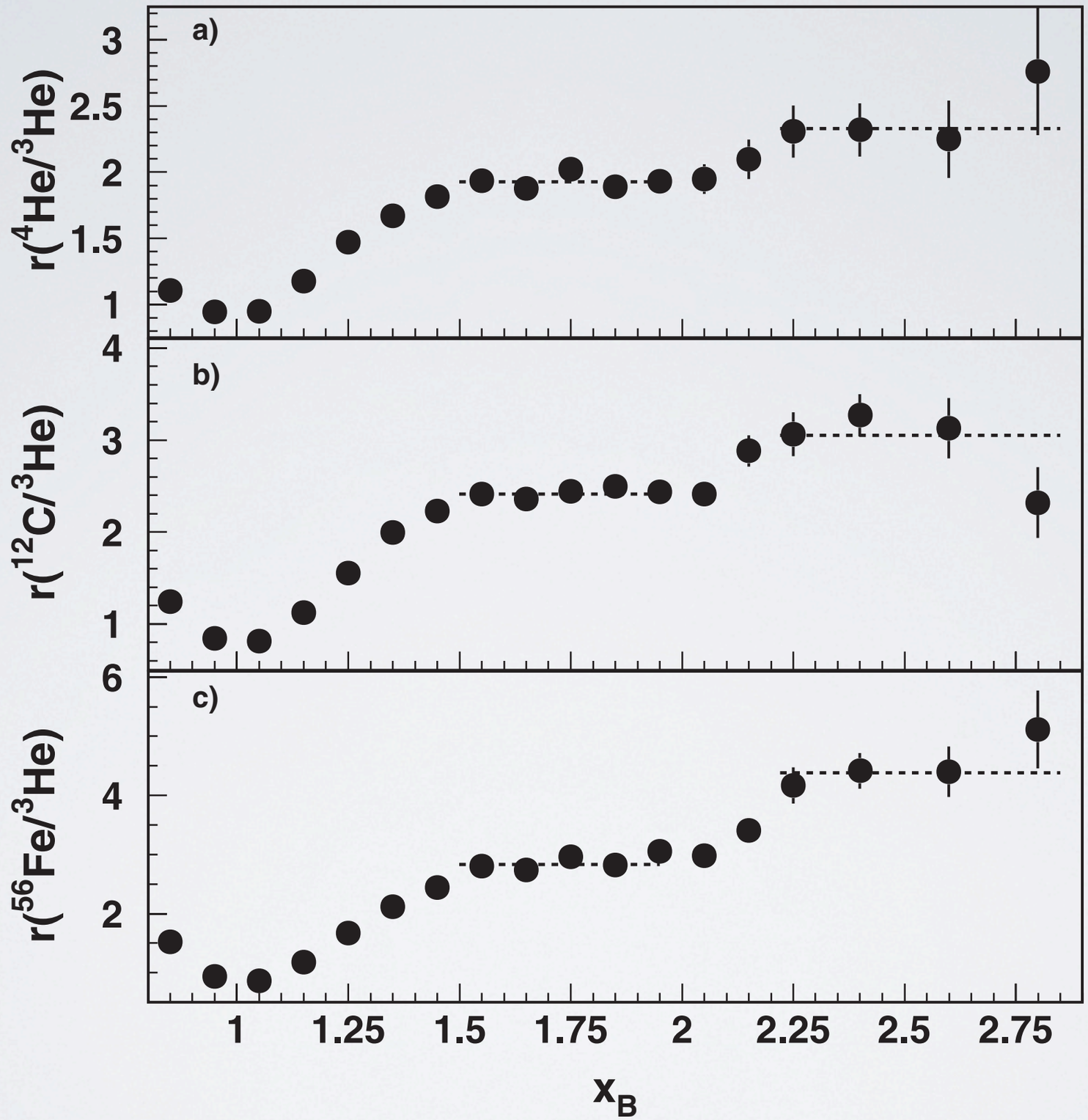
A.Efremov, A. Kaidalov, VK, G.Lykasov, N.Slavin - EKKLS (1988)

- Hard quark sea at X > 1: $S_A(x) \sim S_N(x) + \Delta_A V_A(x)$

- Flucton fragmentation based on quark-gluon strings model

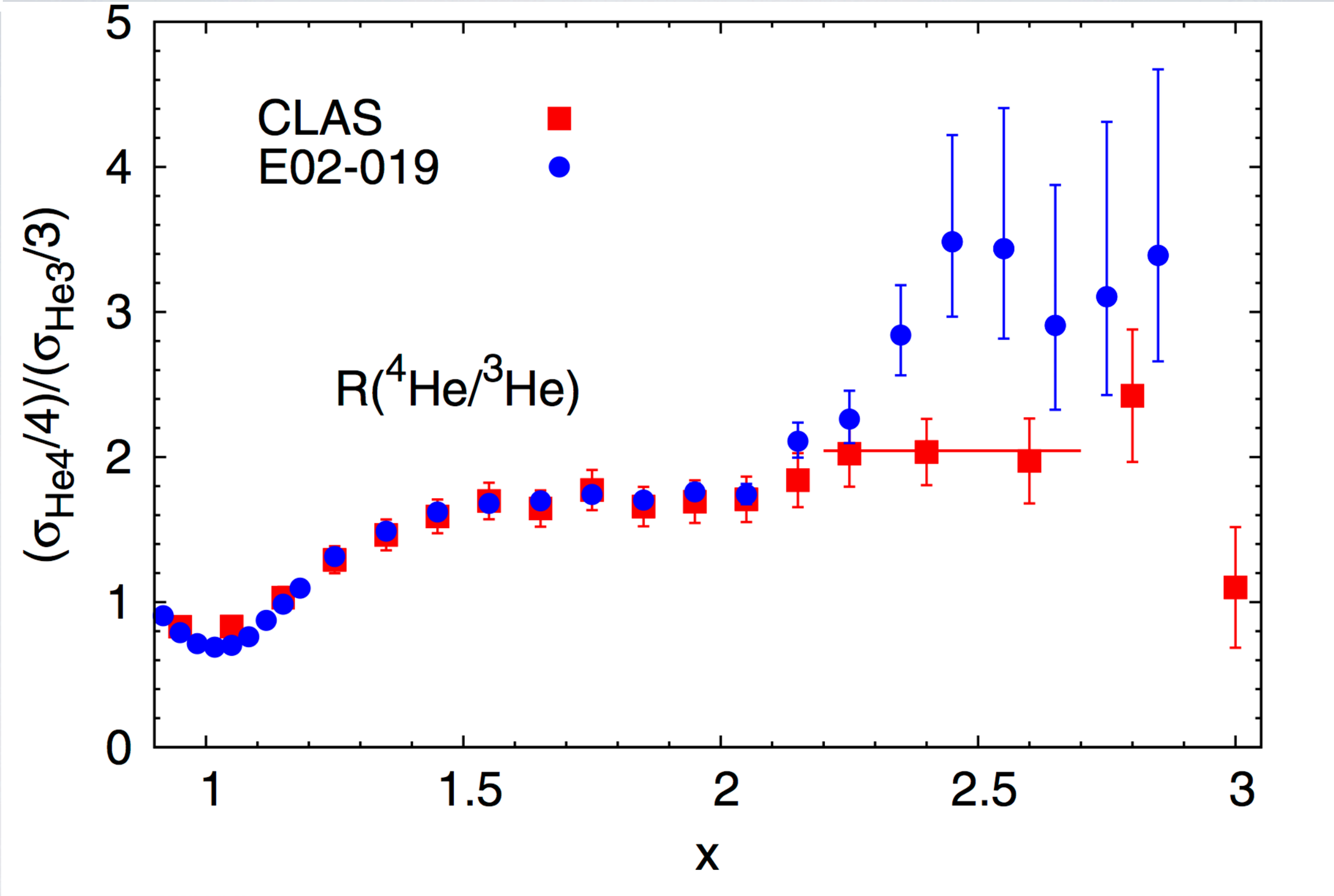
Nuclear structure functions at large X
in LO and NLO with TMC and higher twists
VK (1991)

Nuclear structure function at X > 1



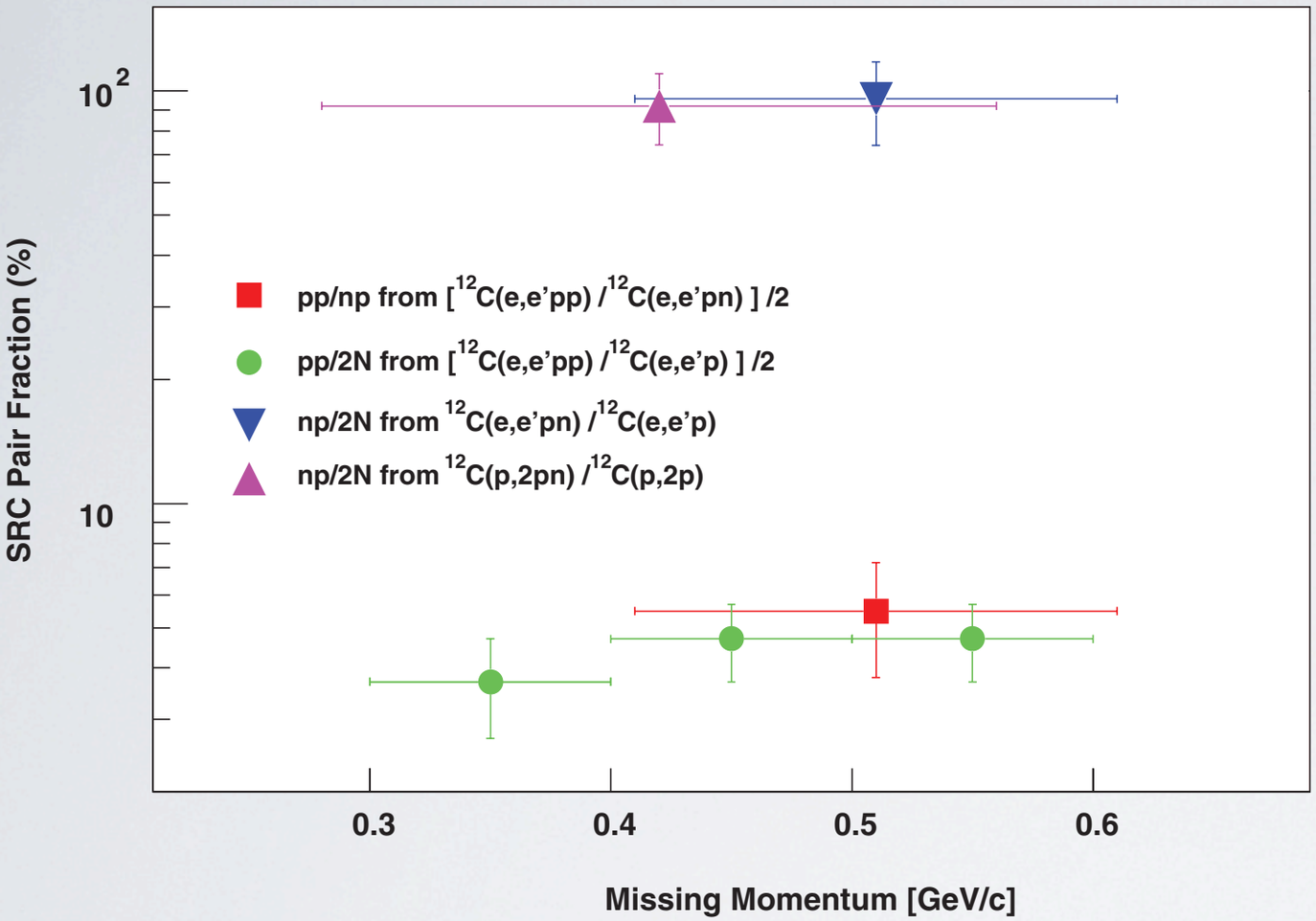
JLAB CLAS Coll., K. Egiyan (06)

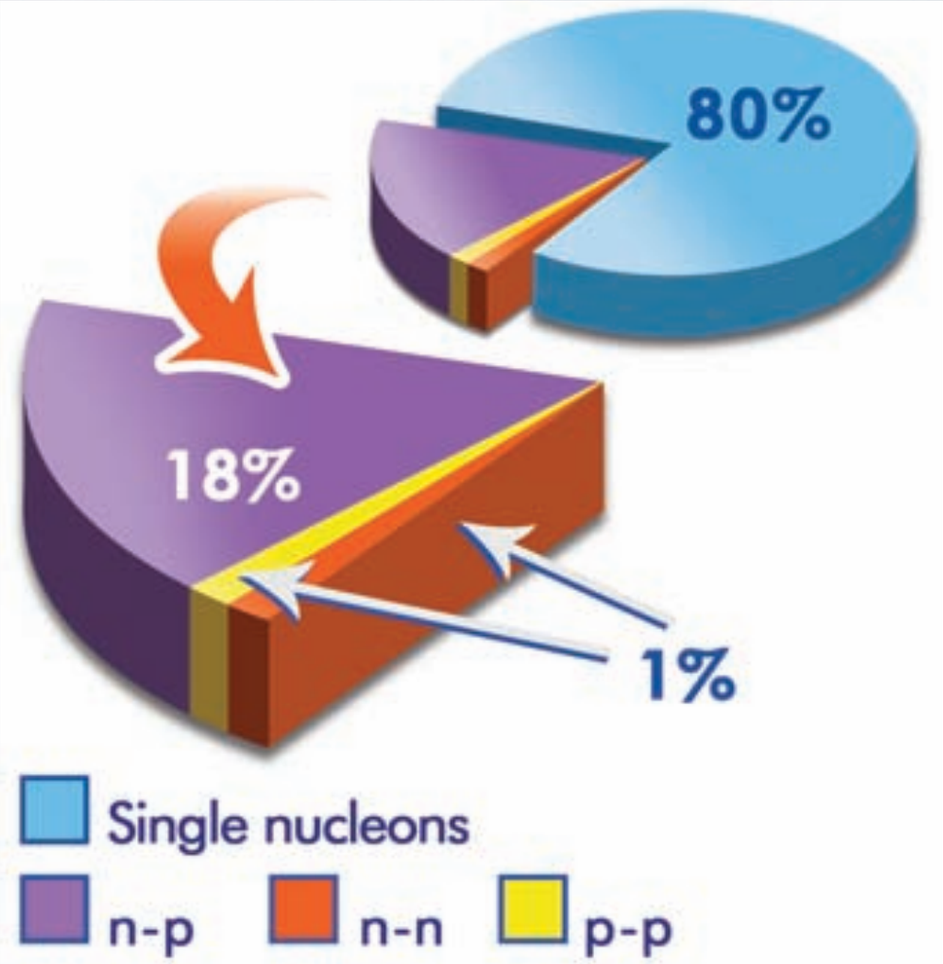
Nuclear structure function at X > 1



JLAB E02-019 (2012), <Q2> = 2.9 GeV²
JLAB CLAS (2006) – no IS corrections, <Q2> = 1.6 GeV²

Cold Dense Baryon Matter: 2-nucleon correlations





JLAB: np-pair dominance in NN-correlations in C^{12} - Pb^{207}

R.Subedi et al. (2008,2014)

Cumulative Processes:

generic definition:

processes beyond one free-nucleon kinematics

- **fixed nucleus target: backward particle production**
  data: G.Leksin et al. (57), M.Mescheryakov et al. (57), …

- **nucleus projectile fragmentation:**
  particles with momentum > momentum per nucleon
  scaling: A.Baldin (1971), data: V.Stavinsky et al. (1971)

Efremov's classification: hot and cold models

Hot models:

rescattering, resonances, fireballs, final state interaction, …

V. Kopeliovich, M.Braun & V. Vechernin, …

Cold models:

fluctons, short-range nucleon correlations, multiquark bags, …

D. Blokhintsev, V. Lukyanov, A. Efremov, V. Burov, A. Titov, L. Kaptari, L. Frankfurt, M. Strikman, A. Kaidalov, VK, G. Lykasov, …

Cumulative Processes: definition

“Cold” models ->

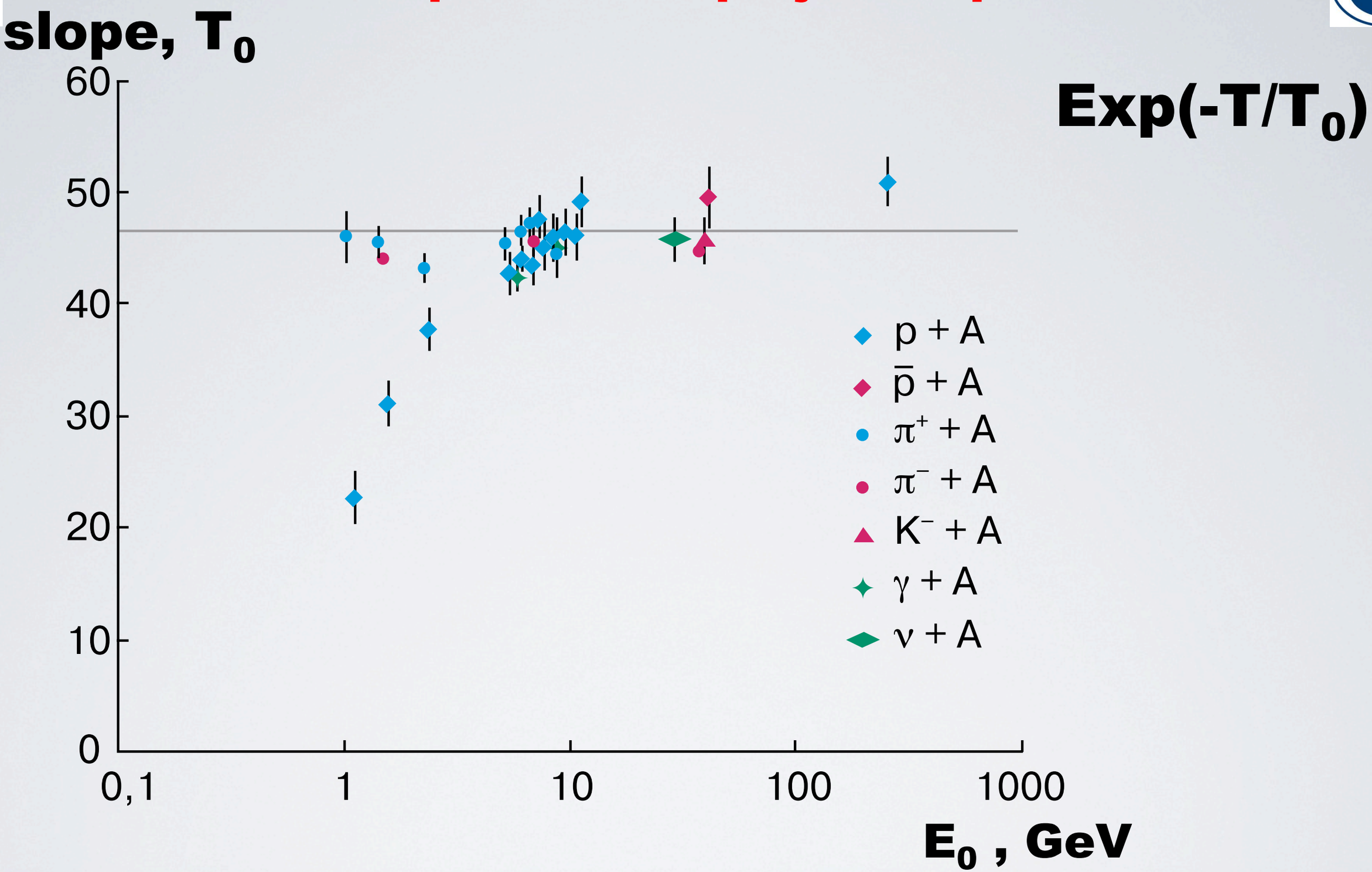
- Nuclear processes beyond one free-nucleon kinematics
- scaling property

->

Cumulative processes (definition):

scaling nuclear processes with X > 1

Cumulative processes: projectile particles



Energy of projectile E_0

Cumulative Processes: scaling properties

How to distinguish "hot" and "cold" models?

"Hot" models:

rescattering, resonances, fireballs, final state interaction, …
may "ignite" hot medium, etc. ->
dependence on projectile hadron/nucleus

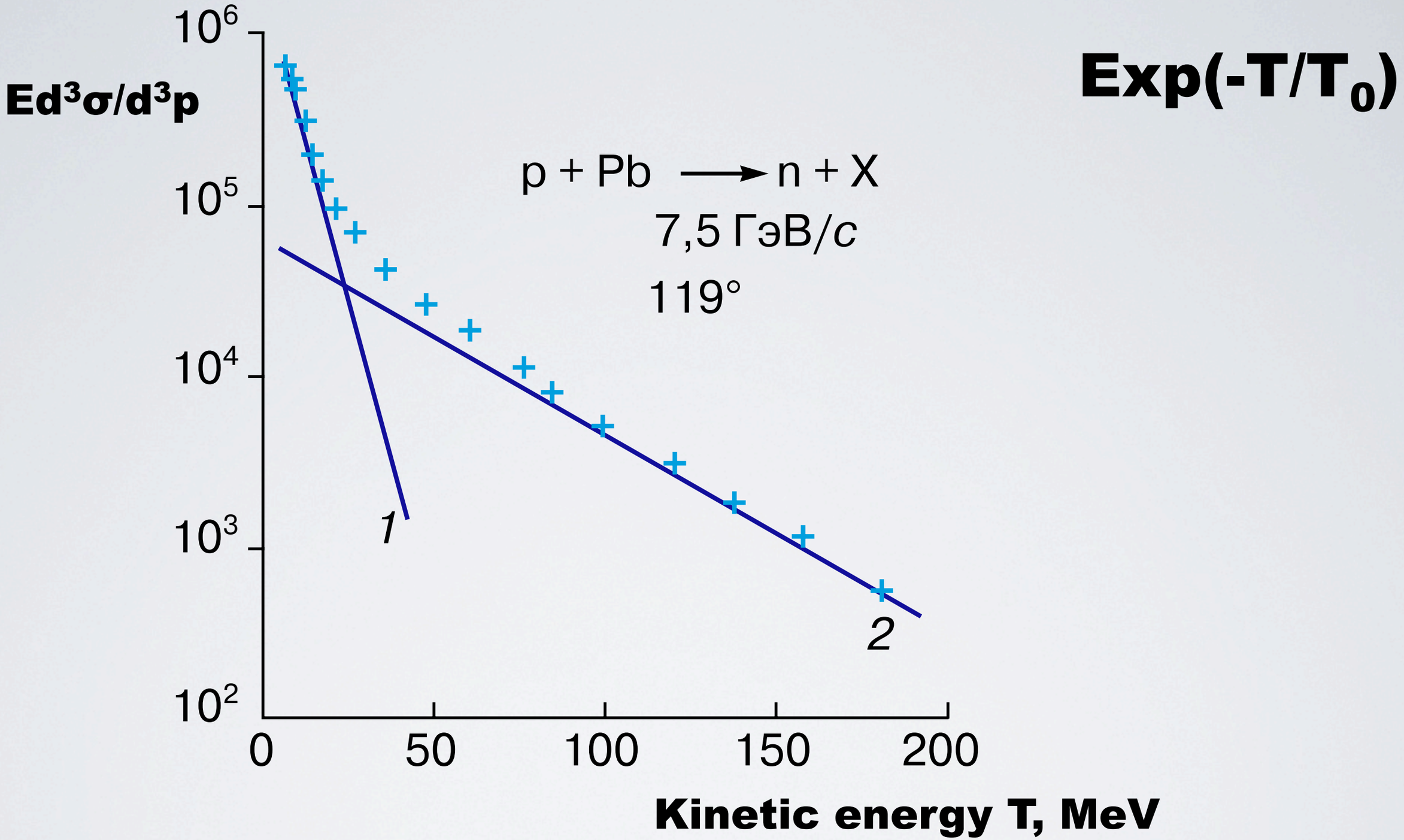
nonlocal interactions ->
no scaling properties !

"Cold" models:

fluctons, short-range nucleon correlations, multiquark bags, …

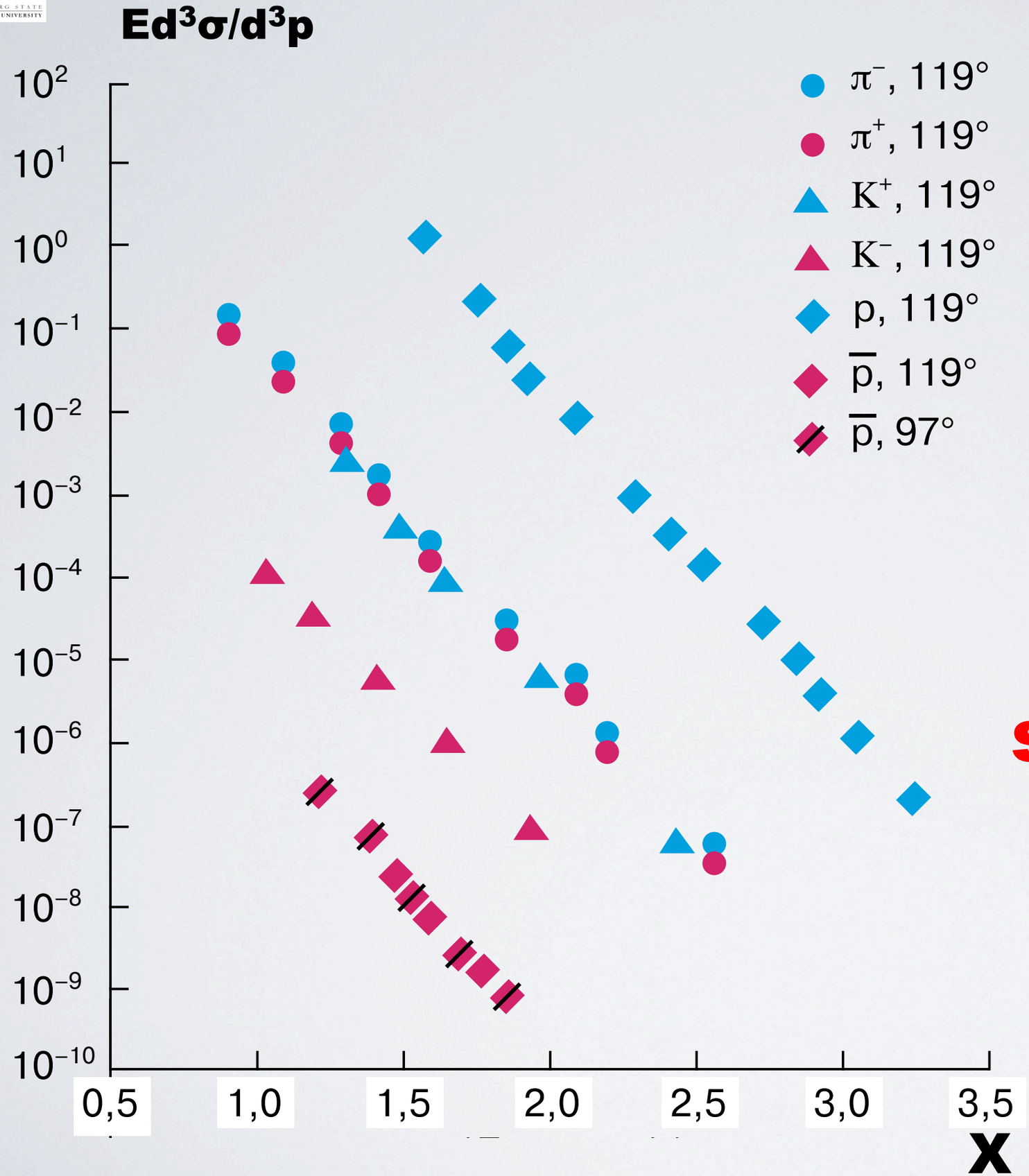
local interactions ->
scaling properties !
nuclear parton struction function

Cumulative processes: backward particles



1 – evaporation
2 – cumulative

Cumulative proceess: superscaling !



A.Efremov, A.Kaidalov, VK, G.Lykasov, N.Slavin (1988)

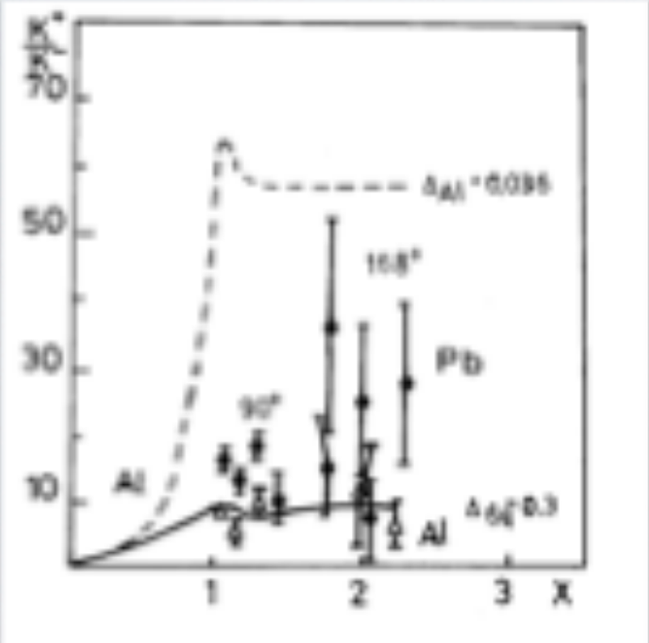
prediction for pure "sea" particles: K^- antiproton

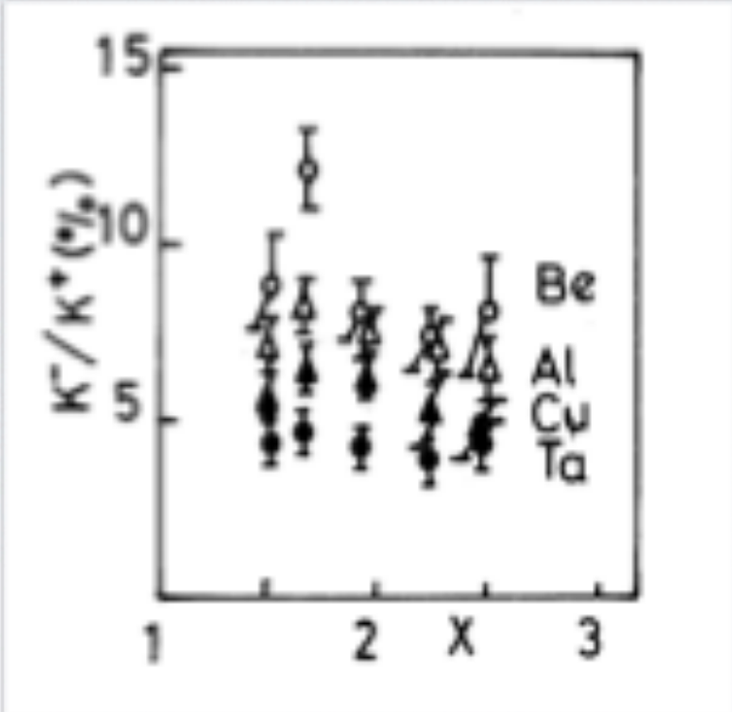
equal slopes: superscaling !

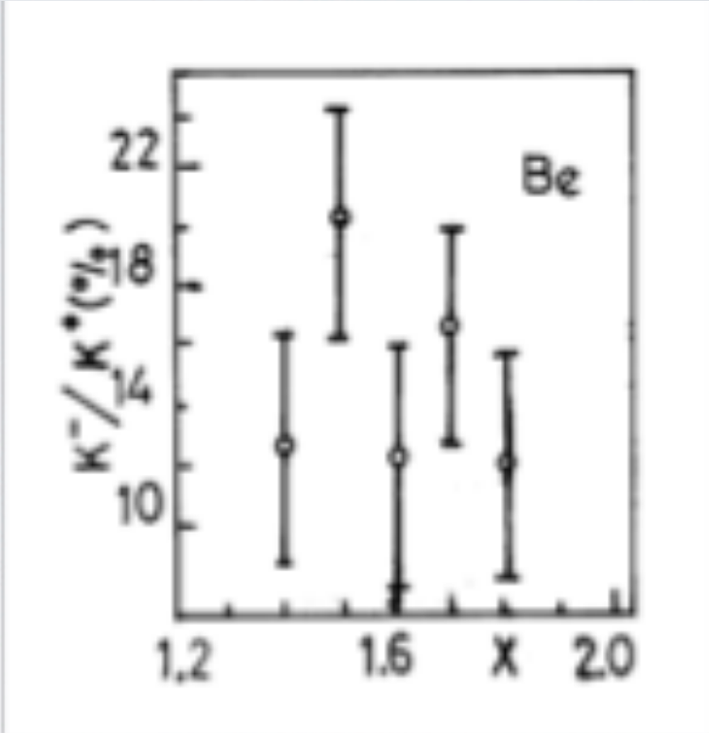
ITEP data: Leksin et al. (1989)

Cumulative processes: hard “collective” nuclear sea at X > 1

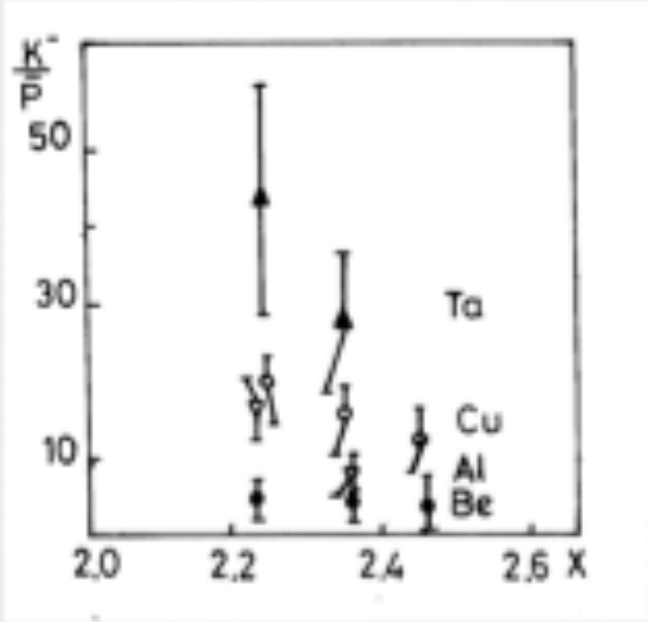
hard “collective” quark sea in nuclei confirmed by data







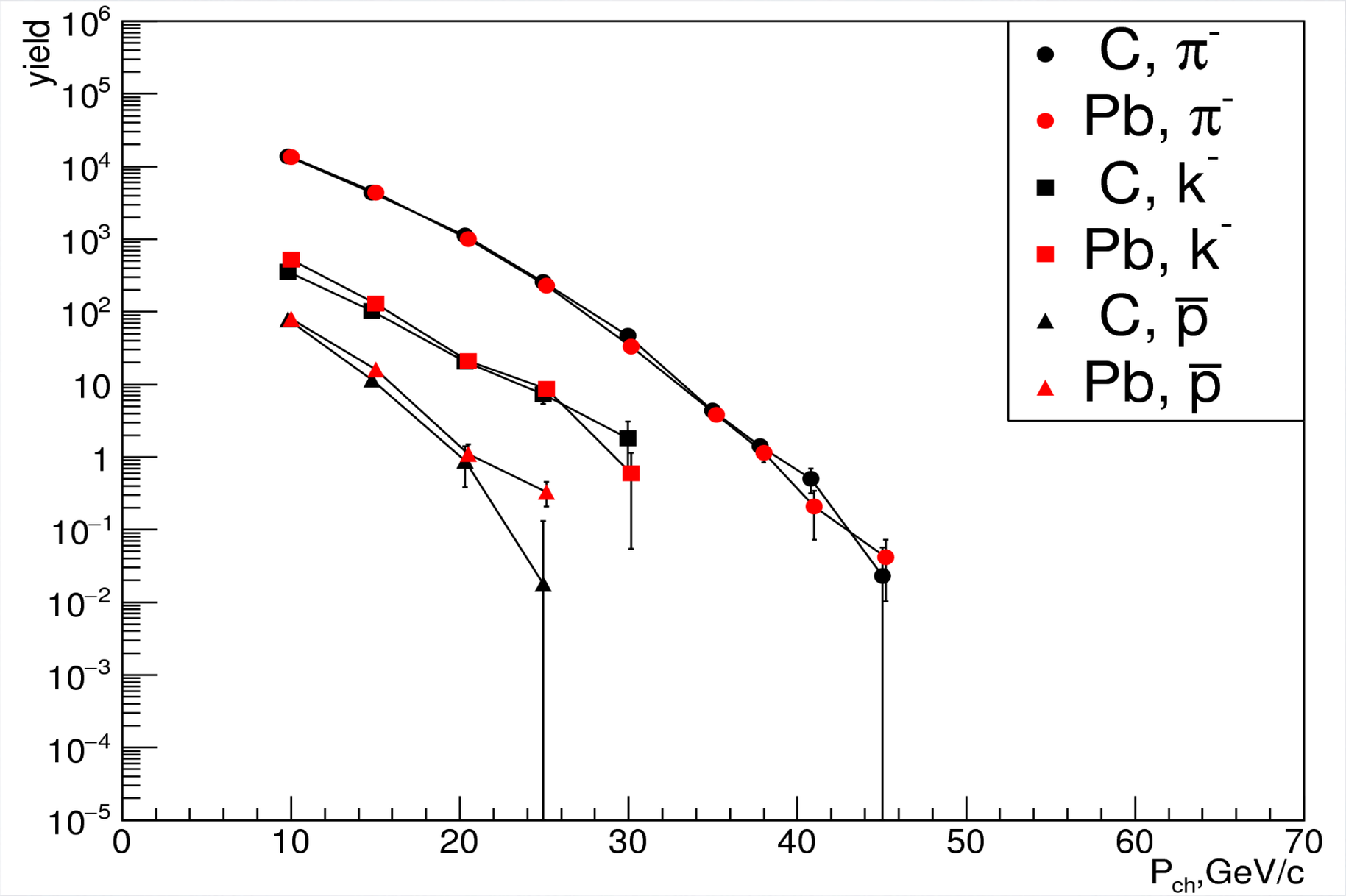
V. Stavinsky et al. (82) **Yu. Kiselev et al. (89)** **L. Zolin et al. (92)**



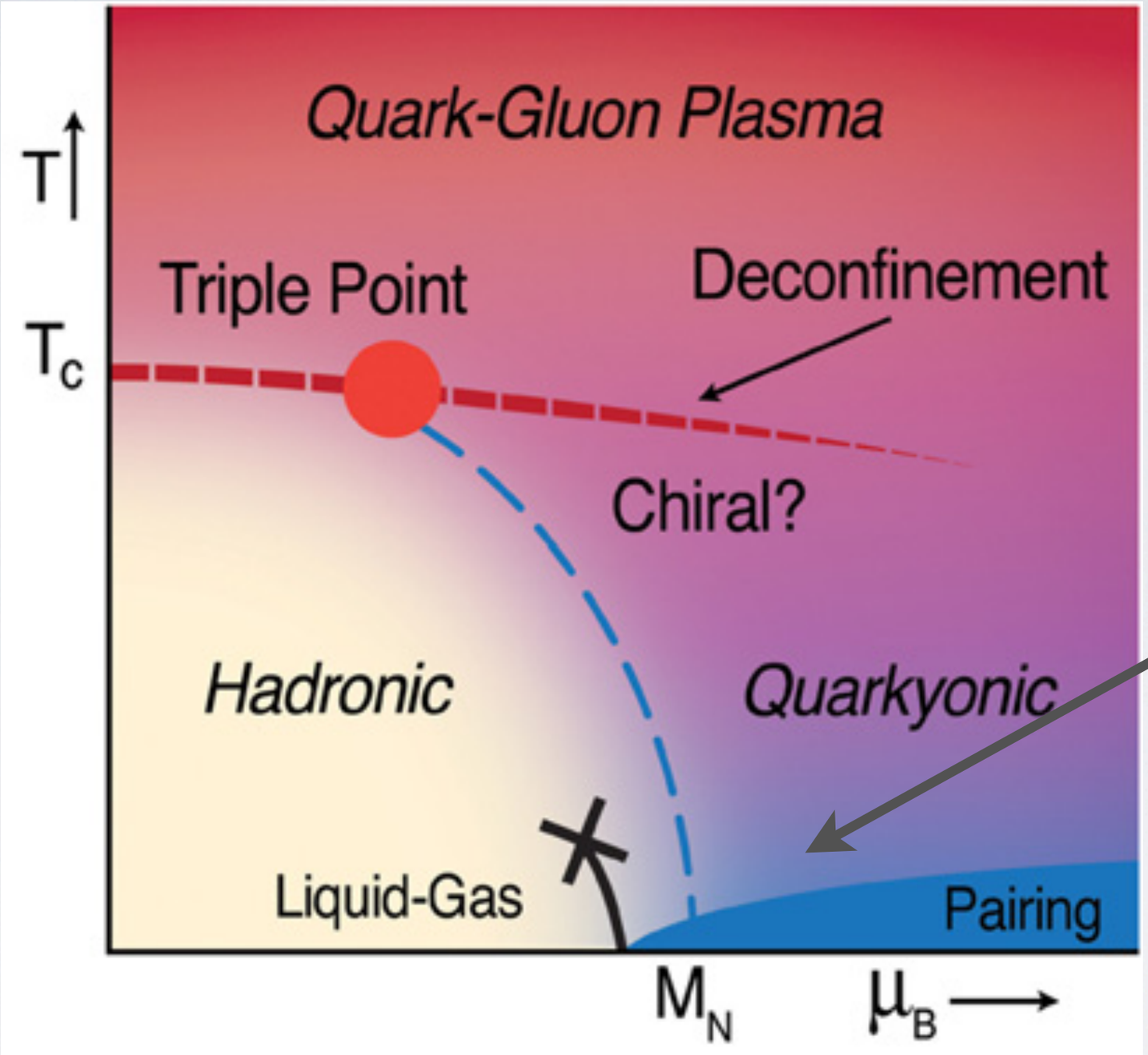
Cumulative processes: Carbon beam @ IHEP NRC KI (Protvino)

beam: C^{12} 20 GeV/N forward fragmentation
fixed targets: C^{12}, Pb^{207}

FODS-2, Bogolyubsky et al. (Baldin Conf, 2016)



Cumulative processes at NICA: Cold Superdense Baryon Matter



Cumulative
X > 5 ?

L.McLerran & R. Pisarski (07)

Lattice: quarkyonic at $\rho > 5\rho_0$ V. Braguta et al. (16)

Nuclear structure functions at large X vs cumulative processes

Low Q^2 :

Flucton fragmentation based on quark-gluon strings model

A.Efremov, A. Kaidalov, VK, G.Lykasov, N.Slavin - EKKLS (1988)

Cumulative process JINR, ITEP, IHEP

High and moderate Q^2:

Nuclear structure functions at large X
in LO and NLO with TMC and higher twists

VK (1991)

Cumulative DIS process BCDMS, JLAB

Unified description at low, moderate and high Q^2 : ?

in progress

Cumulative processes at NICA: Cold Superdense Baryon Matter

How cumulative particle production will shed light on Cold Superdensed Baryon Matter?

Cumulative process at NICA:

BM@N experiment: X > 3 - 5?

Working group
Cumulative particle production and observables

A. Andrianov, M. Braun, VK, V. Vechernin et al.
A.Stavinsky, S.Shimansky et. al.
(PNPI, ITEP, SPbU, SPbPU & JINR)
in progress

MC event generator HARDPING with nuclei
Ya.Berdnikov, VK et al.

Summary

- **Evolution of nuclear structure functions at large X**

- **Multiquark fluctons:**
  EMC effect
  Cumulative processes
  Cronin effect

- **Flucton model and Cold Superdense Baryon Matter:**
  phase transition?
  chemical potential?
  isoscalar dominance?
  quarkyonic phase?