Probing of parton transverse momentum dependent distributions in nuclei

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ISHEPP_2012

Outline

- Introduction
- Cumulative hadron production
- TMD distributions
- Mean transverse momentum distributions in cumulative reactions
- Conclusion and Outlook

Introduction

- The normal nuclear density of 0.16 – 0.17 nucleon/fm^3 corresponds to the average inter-nucleon (center-to-center) distance of d_{NN} =1.8 – 2 fm
- The electro-magnetic radius of a proton r_{em}≈0.85 fm

Nucleons are tightly packed inside nuclei and almost overlap

- Owing to the quantum fluctuations of nuclear density, two or even more nucleons can be even closer, forming dense and cold Compact Baryon Configurations (CBCs)

Current estimates of CBC size vary from 0.65 to 1 fm, which correspond to a density about four-to eightfold of the normal nuclear density.

Neutron stars

Introduction

- In conventional nucleon-meson physics CBCs are described as collection of tightly packed nucleons - SRCs of nucleons
- One can expect that the density of CBCs are high enough to modify the structure of underlying nucleonic constituents. At short inter-nuclear distances, nucleons can loose their identities and form multiquark configugtations

Studying of properties of CBCs provides

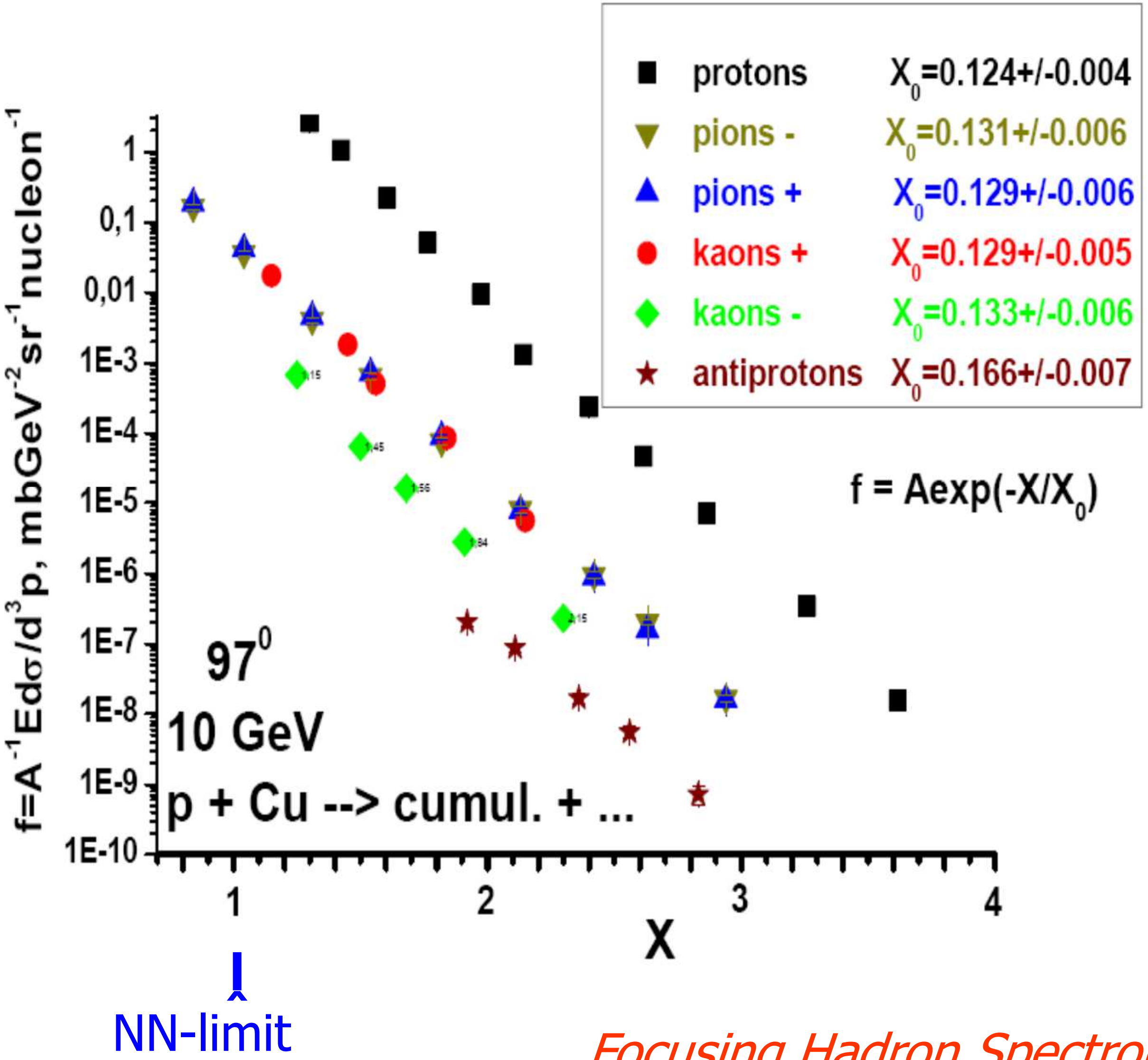
the possibility to distinguish between these two cases

DIS (SIDIS), Cumulative processes

Cumulative hadron production

- -the process of hadron creation in the fragmentation region of a nucleus beyond the kinematical limits of the production of these hadrons in the collisions of elementary projectiles with isolated nucleons

Cumulative hadron production



Value of X determines the minimal target mass in units of nucleon mass (in lab frame) for which the production is kinematically possible

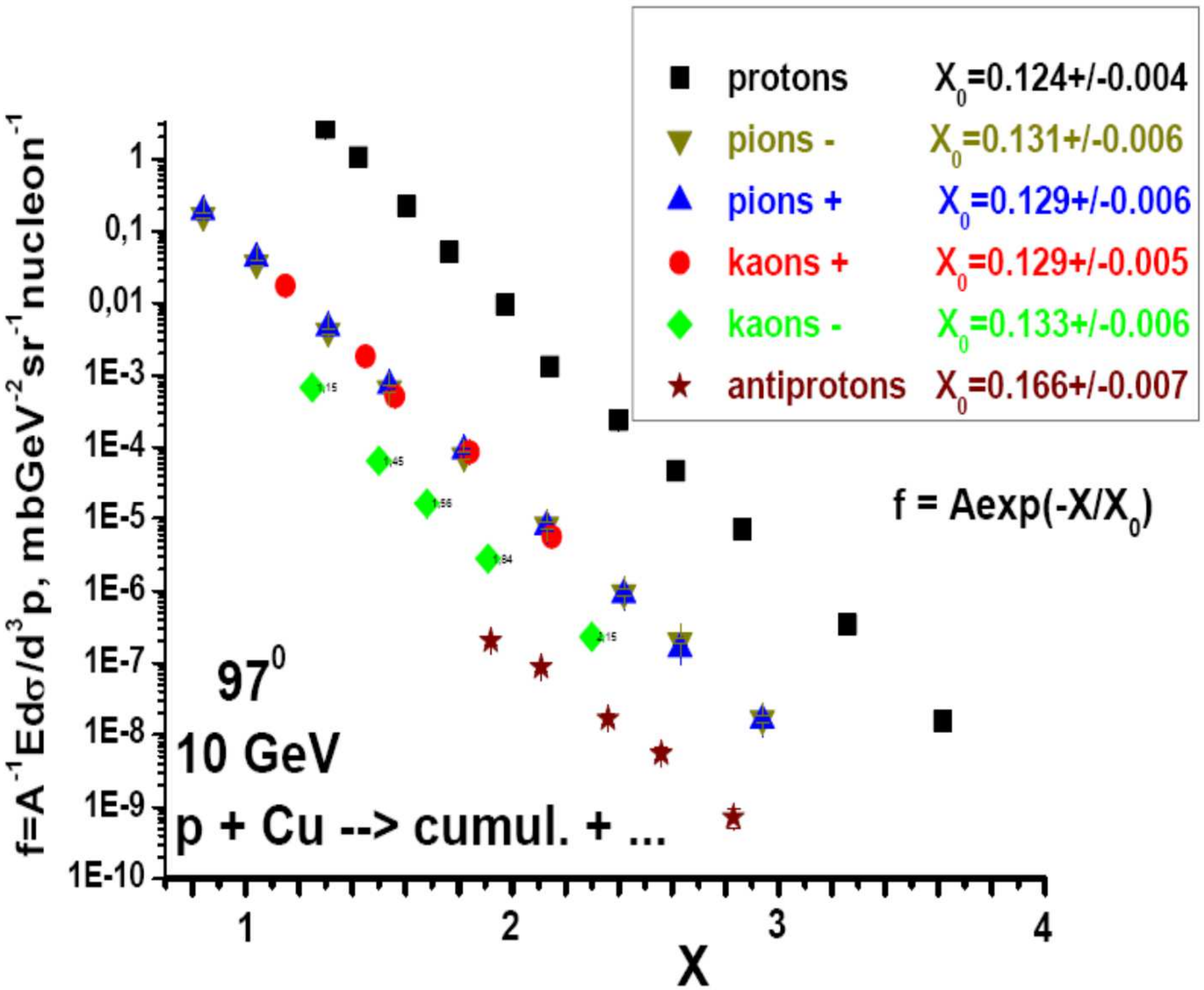
considerations are equivalent χ

Value of X determines a fraction of the quark momentum relative to the CBC momentum in IMF

Focusing Hadron Spectrometer (FAS) ITEP

Cumulative hadron production

Specific properties of spectra do not depend on the choice of variable (X, X_B, X_F, α)

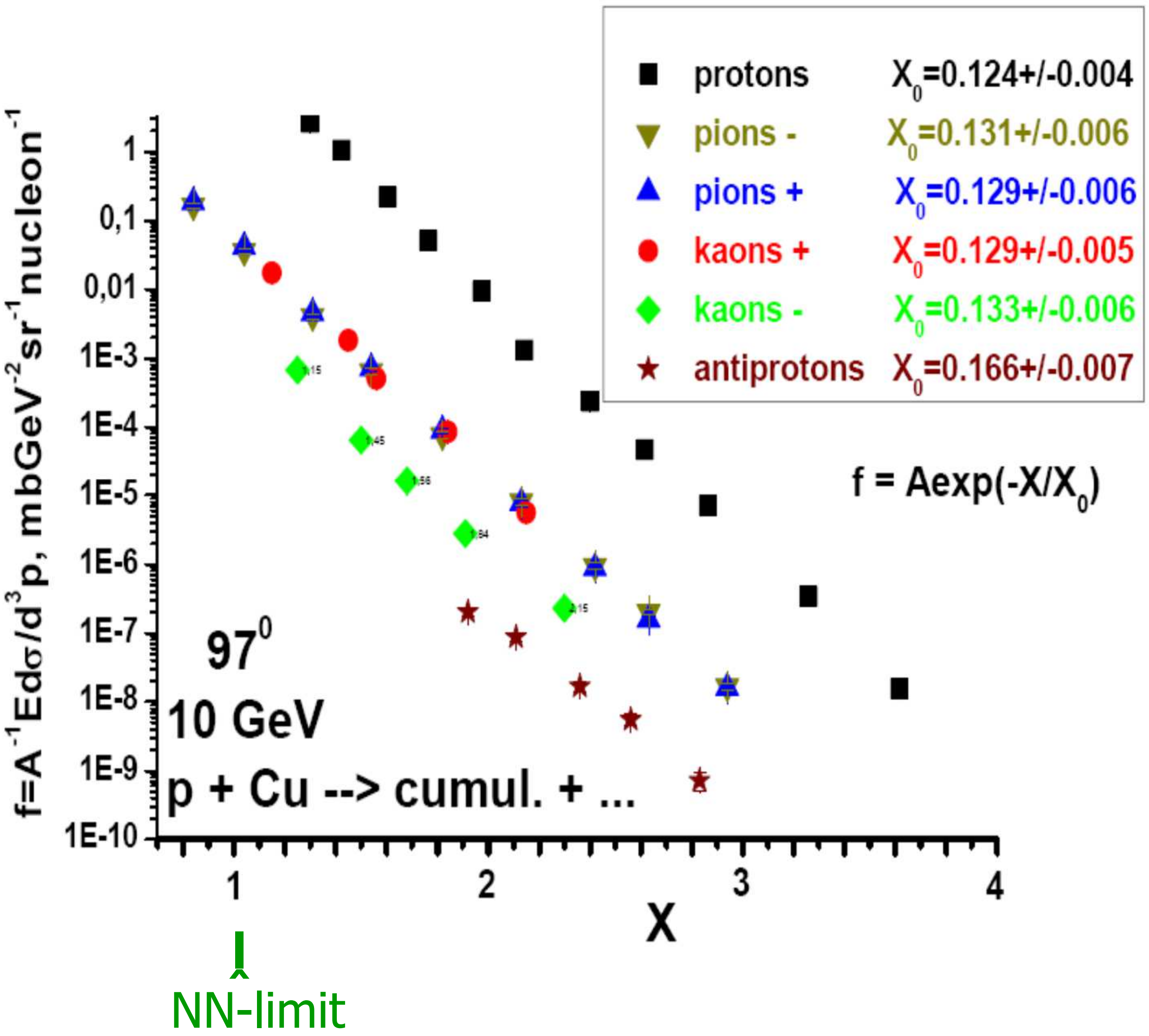


Cross sections vary by about 10 orders of magnitude.

Error bars are much less than the size of symbols.

Cumulative hadron production

Specific properties:



- Striking similarity of spectra $\Delta X_0 \leq 5\%$
- Enhanced strangeness production: the ratio $R(K^+/\pi^+) \approx 1$ $[K^+(u\bar{s}),\ \pi^+(u\bar{d})]$ c.f. $R_{pp} \approx 1/7$
- constant K^- /π^- ratio (strong decreasing in PP). "Collective" hard nuclear sea – A.Efremov $[K^-(s\bar{u}),\ \pi^-(d\bar{u})]$
- specific target mass dependence (A^α, α is discrete function of X). For details see Yu.T.K., V.A.Sheinkman et al., Phys.Rev.C85, 054904 (2012)

Cumulative hadron production

- The observed specific properties of high momentum cumulative hadron production evidence for the quark structure of CBCs.

- New evidence comes from studying of the transverse momentum dependence of the cross section

TMD parton distributions

- The behavior of fundamental constituents of nucleons is described by Parton Distribution Functions (PDFs)
- Historically, PDFs depended only on the longitudinal variable X. However, the parton transverse momentum is not negligible.
- “Spin puzzle”: unexpectedly small fraction (~1/4) of the proton’s spin that is due to the contribution from quarks and antiquarks
- New concept of Transverse Momentum Dependent (TMD) parton distribution can provides the information about the possible connection between orbital motion of partons and the spin of nucleons

TMD parton distributions and cumulative hadron production

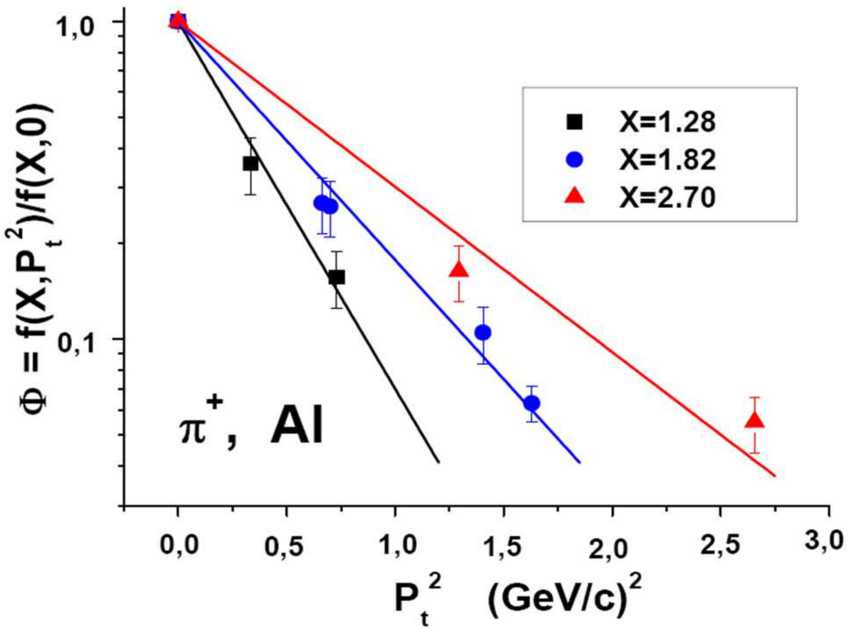
- Knowing invariant cross sections f(X) measured at different production angles allows to determine the function of the probability distribution

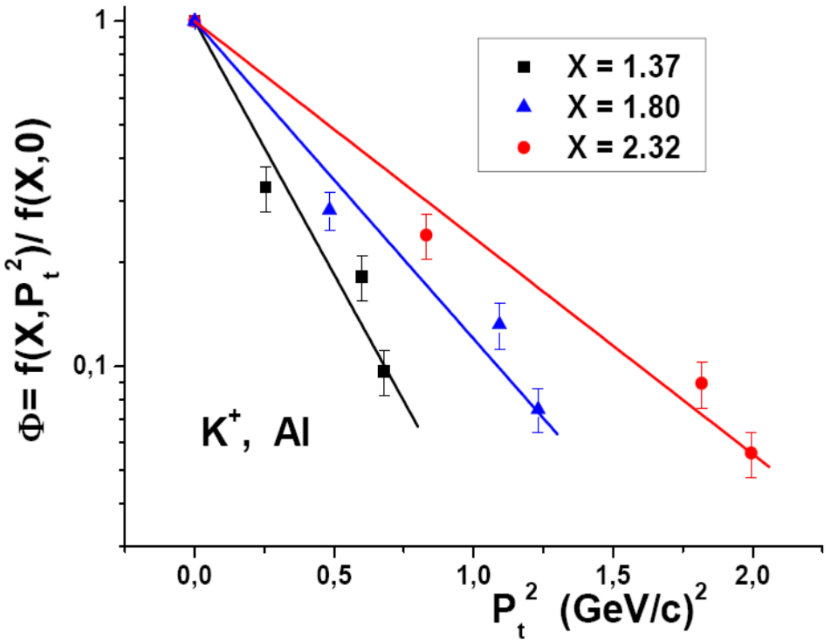
$$\Phi = \frac{f(X, P_t^2)}{f(X, P_t^2 = 0)}$$

The ratio determines the probability of hadron production with given P_t^2 relative to that with $P_t^2=0$

TMD parton distributions and cumulative hadron production

Broadening of the $\Phi(P_t^2)$ distribution with increasing of X for all types of hadrons





Along with the cross sections measured at the lab. angles of 97^0 and 119^0 in our experiment we also use the data on cumulative hadron production at 90^0, 120^0 and 180^0 at very similar kinematical conditions. ***A.M.Baldin et al., Preprint JINR E1-82-472 (1982); Preprint JINR E1-83-432 (1983)***

TMD parton distributions and cumulative hadron production

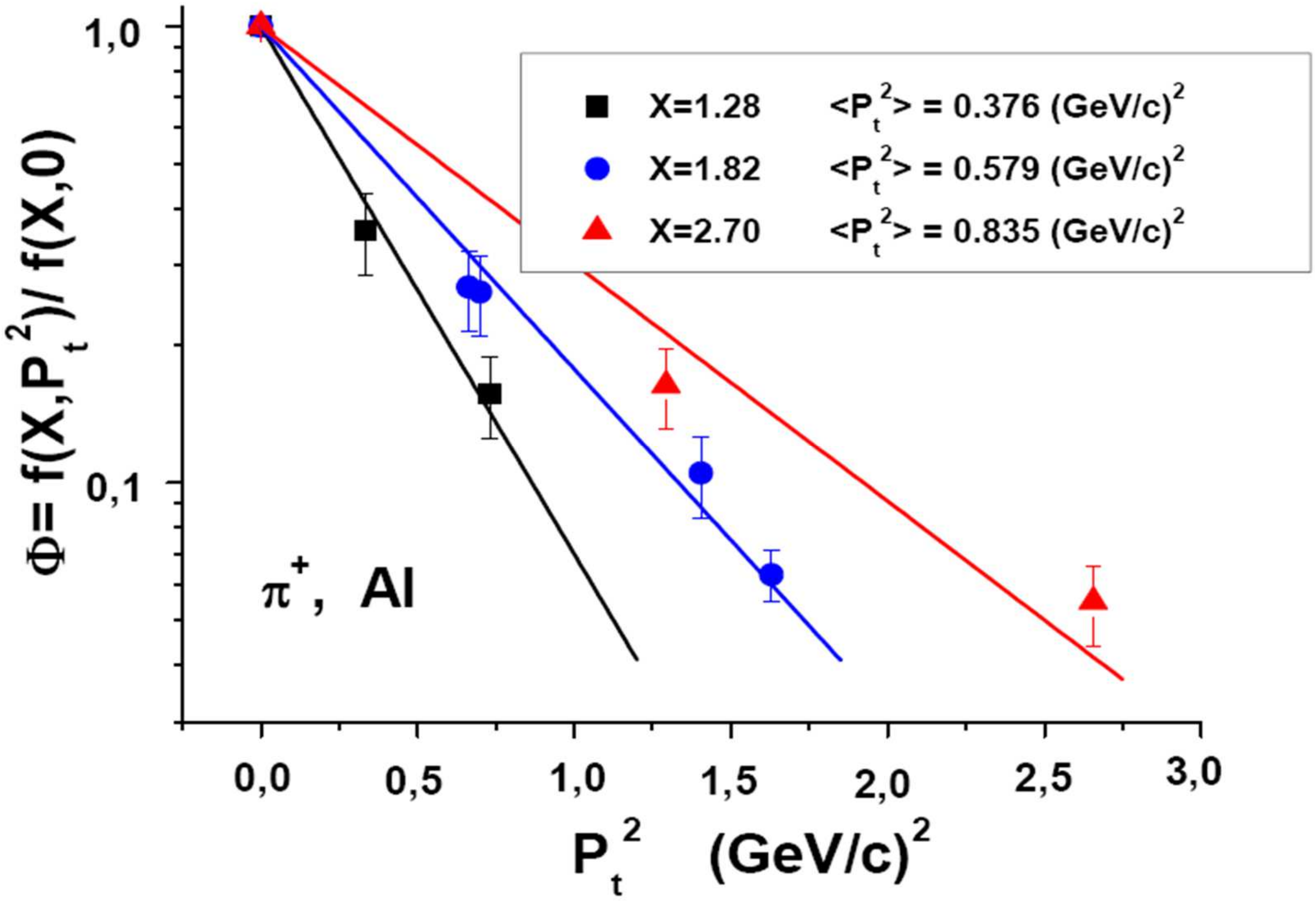
- Φ-function represents the probability distribution

$$\Phi(P_t^2) = \exp(-\gamma P_t^2); \qquad (1)$$

$$< P_t^2 > = \frac{\int_0^\infty P_t^2 \Phi(P_t^2) dP_t^2}{\int_0^\infty \Phi(P_t^2) dP_t^2}; \qquad (2)$$

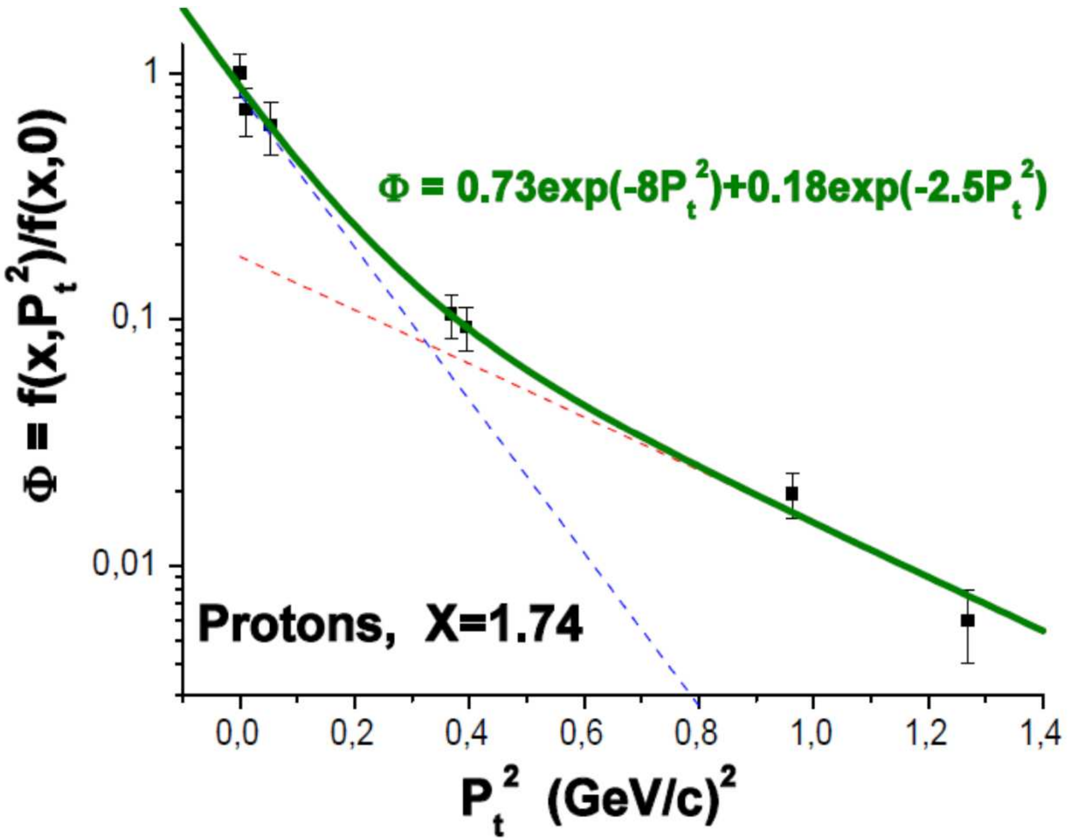
$$< P_t^2 > = \frac{\int_0^\infty P_t^2 \exp(-\gamma P_t^2) dP_t^2}{\int_0^\infty \exp(-\gamma P_t^2) dP_t^2} = \frac{1}{\gamma}; \qquad (3)$$

TMD parton distributions and cumulative hadron production



TMD parton distributions and cumulative hadron production

Simple approximation $\Phi(P_t^2)=\exp(-\gamma P_t^2)$ yields $\chi^2/ndf \sim 2$.
$\Phi(P_t^2)$ dependence is more complex.



Two component structure is clearly seen

The function becomes less steep at the region of high transverse momenta

Study of high momentum component of the P_t^2 - distribution

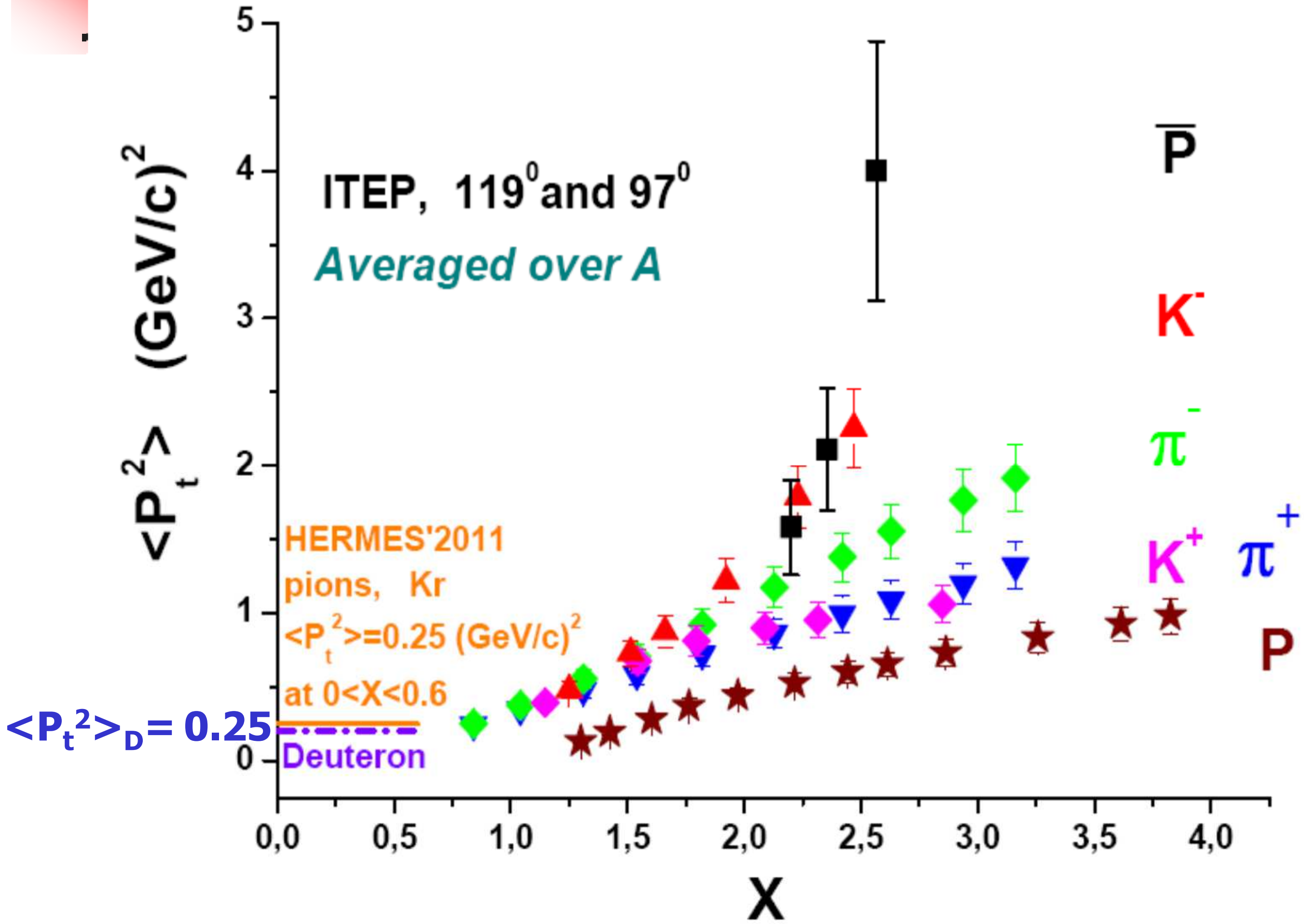
- In the subsequent analysis we use only ITEP data obtained at 97^0 and 119^0 in lab.

Two advantage over combined analysis:

- cross section ratio Φ can be determined more precisely
- inclusion of 'sea' particles (antikaons and antiprotons)

- Values of $<P_t^2>$ were averaged over A (A=Be, Al, Cu, Ta) since they do not reveal a significant target mass dependence

Study of high momentum component of the P_t^2 - distribution



- $<P_t^2>$ increases with X and reach the magnitude of 1-2 (GeV/c)^2
- at X≈1 the results agree well with those at X<1 presented by HERMES collaboration
- comparison the effect in the regions X<1 and X>1
- $<P_t^2>$ depends on flavors: the most strong effect is observed for 'sea' K^- and antiprotons

TMD parton distributions contain direct information about quark orbital motion

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Study of high momentum component of the P_t^2 - distribution

In terms of the quark models and QCD, there are several contributions to the transverse momentum distribution of produced hadrons:

- primordial transverse momentum,
- gluon radiation of the struck quark,
- the formation and soft multiple interactions of the ‘pre-hadron’, and
- the interaction of the formed hadrons with the surrounding nuclear matter.

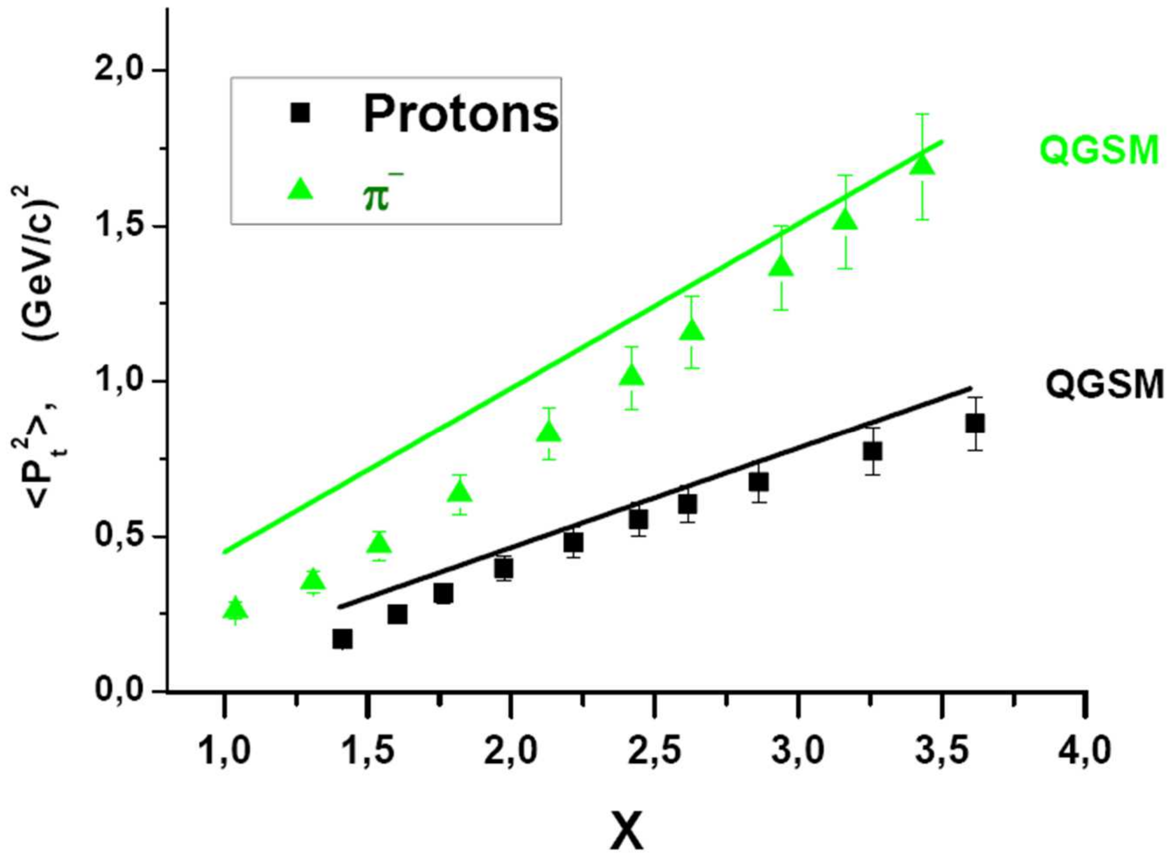
To disentangle these contributions one needs a model

Theoretical description-1 (QGSM)

Quark Gluon String Model (QGSM) based on 1/N expansion in QCD (*A.Efremov, A.Kaidaov, V.Kim, G.Lykasov, and N.Slavin)*

- QGSM presumes the existence of CBCs (multiquark configurations) as an inherent property of nuclear structure and considers the process of cumulative hadron production in the reference frame where the nucleus moves with high momentum
- According to the model, each CBC initially contains a quark configuration of the X and P_t distribution
- Value of X determines the quark momentum relative to CBC momentum in the frame of moving nucleus
- Cumulative hadrons with X>1 originate from the fragmentation of **superfast quarks** of a multiquark configuration **carrying a light cone momentum fraction greater than that of a single nucleon**

Theoretical description-1 (QGSM)



- Reasonable quantitative description of our old pion and proton data in QGSM

More information now !

Extension of QGSM to the description of strange mesons and antiprotons is highly desirable

A.Kaidalov, G.Lykasov, and N.Slavin Proc.of IX ISHEPP, v.1 p.271,Dubna 1988

Theoretical description-2 (BHPS model)

- S.J.Brodsky
  P.Hoyer
  C.Peterson
  N.Sakai

- **The intrinsic** quarks and gluons exist over a time scale independent of any probe momentum, they are associated with the bound state hadron dynamics.

- In proton $|uudQ\bar{Q}>$ see talk G.Lykasov (Wednesday, Sept.12)
- $Q\bar{Q}$ is $u\bar{u}$, $d\bar{d}$, $s\bar{s}$

- The intrinsic component **is expected to be enhanced in nuclei** due to the overlapping of the nucleon wave functions

Theoretical description -2 (BHPS model)

Fock expansion of the w.f.

ΔtΔE≈ħ

"life time" Δt of a state is maximal when ΔE is minimal

The general form of a Fock-state wave function is

$$\psi(k_{ti}, x_i) = \frac{\Gamma(k_{ti}, x_i)}{M^2 - \sum_{i=1}^{n}\left(\frac{m^2 + k_t^2}{x}\right)_i},$$

$$\sum_{i=1}^{n} x_i = 1; \quad \sum_{i=1}^{n} k_{ti} = 0;$$

by momentum conservation

For light quarks (u, d, s)

$$m^2 << k_t^2$$

Energy denominator is minimal and the longitudinal momentum distributions are maximal when the constituents with the largest transverse momentum have the largest light-cone fraction x_i

In agreement with experiment !

Theoretical description -3

- Color String Fusion model

(QCD motivated approach)

See talks *V. Vechernin*

$$\mathbf{pp} \rightarrow \mathbf{pA}$$

Theoretical assistance is needed to describe the observed strong increasing of mean transverse momentum squared at large X for different flavors

Conclusions

- A common goal of both particle and nuclear physics is to understand the structure of the nucleon and nucleus in terms of their fundamental constituents

- Study of Compact Baryon Configurations (CBCs) - objects of the nuclear structure at small-distance scales – offers the possibility to investigate the quark and gluon degrees of freedom in nuclei

- Observation of large values of $\langle P_t^2 \rangle$ at X>1 which significantly exceed those for nucleons provides new evidence for the quark structure of CBCs

- Large values of $\langle P_t^2 \rangle$ at X>1 indicate the strong orbital motion of quarks inside CBCs

Outlook

- High luminosity of the upgraded JLab12 accelerator and first-class detectors offer the excellent opportunity to investigate the quark-gluon structure of nuclei in more details

  (new variables in SIDIS kinematics : Q^2, ν, $z=E_h/E_\gamma$)

- High density of CBC provides an unique possibility to study QCD diagram at low T and high μ_B

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- **Thank you**