Self-similarity of high-p_T hadron production in pA collisions

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- z-Scaling (ideas, definitions, properties,…)
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- Conclusions

Motivation & Goals

Development of z-scaling approach for description of hadron production in inclusive reactions to search for signatures of new physics phenomena.

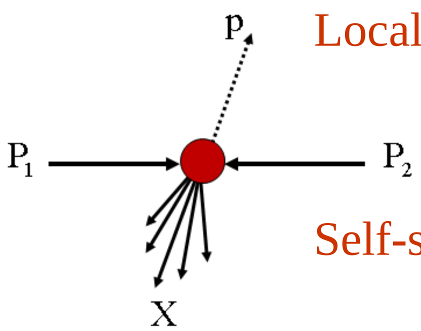
Analysis of new experimental data on inclusive spectra of hadron production in pA collisions obtained at U70 to verify properties of z-scaling in high-p_T cumulative region

- pA is a reference frame for pp & AA
- High-p_T process – hadron production at a constituent level
- Cumulative process:
  - – enhancement of nuclear matter compression
  - – particle formation is sensitive to state of matter
  - – search for indications of phase transition & CP

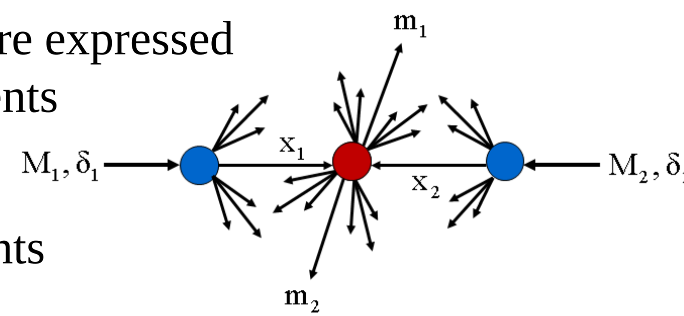
Verification of fundamental principles ,
(Lorenz invariance, self-similarity, scale relativity,…)
properties of particles and hadronization process.

z-Scaling

Principles: locality, self-similarity, fractality



Locality: collisions of hadrons and nuclei are expressed via interactions of their constituents (partons, quarks and gluons,...).



Self-similarity: interactions of the constituents are mutually similar.

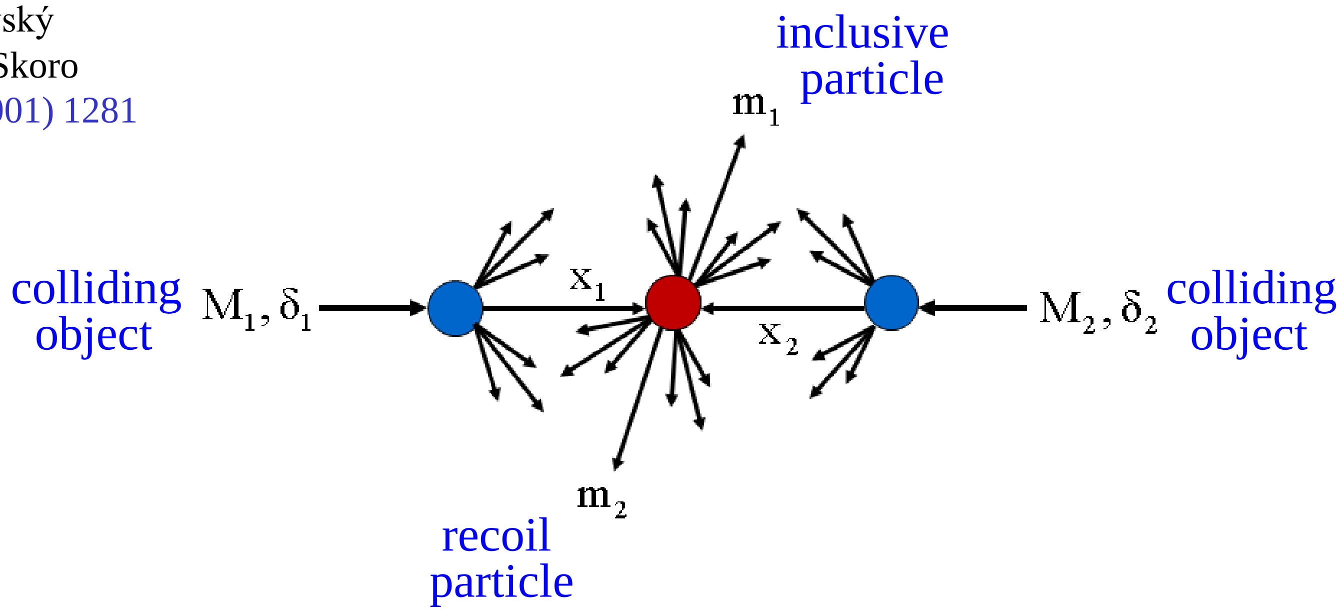
Fractality: the self-similarity over a wide scale range.

Hypothesis of z-scaling :

$s^{1/2}$, p_T, θ_{cms}	Inclusive particle distributions can be described in terms of constituent sub-processes and parameters characterizing bulk properties of the system.	x_1, x_2 δ_1, δ_2
$Ed^3\sigma/dp^3$	Scaled inclusive cross section of particles depends in a self-similar way on a single scaling variable z.	$\Psi(z)$

Locality of hadron interactions

M.T. & I.Zborovský
Yu.Panebratsev, G.Skoro
Int. J. Mod. Phys. A16 (2001) 1281
JINR E2-99-113



Constituent subprocess

$$(x_1 M_1) + (x_2 M_2) \Rightarrow (m_1) + (x_1 M_1 + x_2 M_2 + m_2)$$

Kinematical condition (4-momentum conservation law):

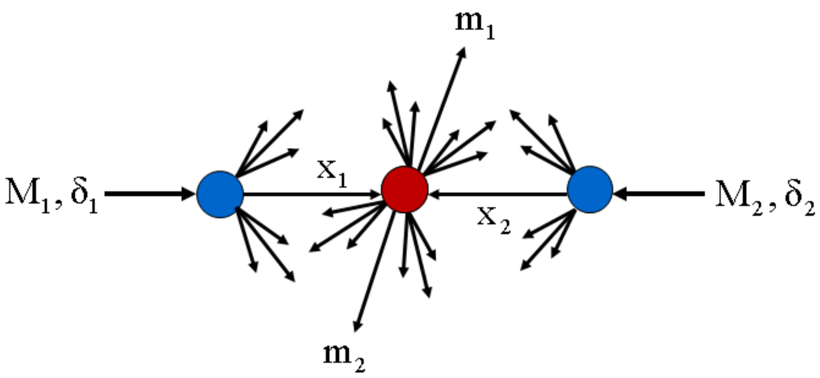
$$(x_1 P_1 + x_2 P_2 - p)^2 = M_X^2$$

Recoil mass: $M_X = x_1 M_1 + x_2 M_2 + m_2$

Self-similar parameter z

$$z = z_0 \Omega^{-1}$$

$$z_0 = \frac{s_\perp^{1/2}}{(dN_{ch}/d\eta|_0)\, m}$$



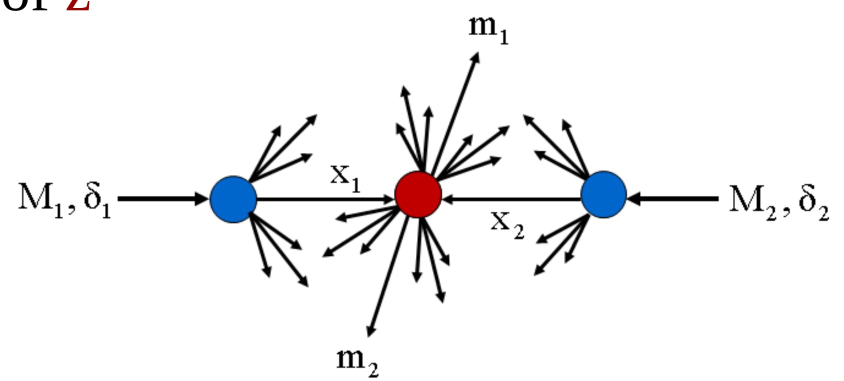
- Ω^{-1} is the minimal resolution at which a constituent subprocess can be singled out of the inclusive reaction
- $\sqrt{s_\perp}$ is the transverse kinetic energy of the subprocess consumed on production of m_1 & m_2
- $dN_{ch}/d\eta|_0$ is the multiplicity density of charged particles at $\eta = 0$
- m is an arbitrary constant (fixed at the value of nucleon mass)

Fractal measure z

The fractality is reflected in definition of z

$$z = z_0 \Omega^{-1}$$

$$\Omega = (1-x_1)^{\delta_1}(1-x_2)^{\delta_2}$$



Ω is relative number of configurations containing a sub-process with fractions x_1, x_2 of the corresponding 4-momenta

δ_1, δ_2 are parameters characterizing structure of the colliding objects

$\Omega^{-1}(x_1, x_2)$ characterizes resolution at which a constituent sub-process can be singled out of the inclusive reaction

$$z(\Omega)|_{\Omega^{-1} \to \infty} \to \infty$$

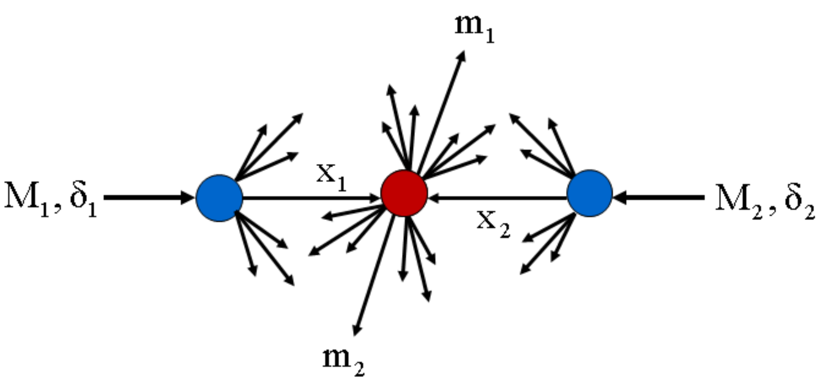
The fractal measure z diverges as the resolution Ω^{-1} increases.

Momentum fractions x_1, x_2

Principle of minimal resolution: The momentum fractions x_1, x_2 are determined in a way to minimize the resolution Ω^{-1} of the fractal measure z with respect to all constituent sub-processes taking into account 4-momentum conservation:

$$\Omega = (1 - x_1)^{\delta_1} (1 - x_2)^{\delta_2}$$

$$\partial\Omega / \partial x_1 \big|_{x_2 = x_2(x_1)} = 0$$



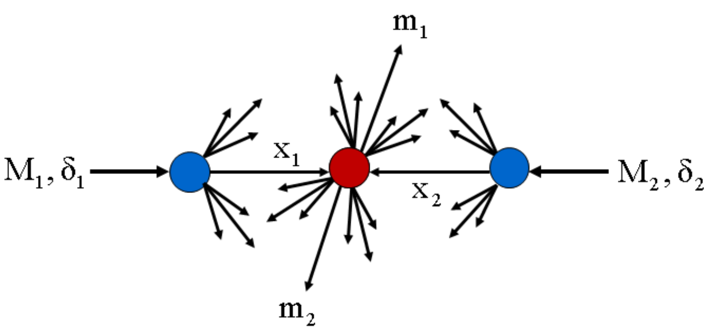
Momentum conservation law)

$$(x_1 P_1 + x_2 P_2 - p)^2 = M_X^2$$

Recoil mass

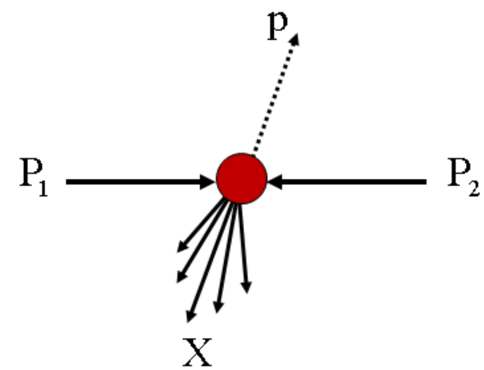
$$M_X = x_1 M_1 + x_2 M_2 + m_2$$

Scaling function $\Psi(z)$



$$\int_0^\infty \Psi(z)dz = 1$$

$$z \to \alpha_F z, \quad \Psi \to \alpha_F^{-1} \Psi$$



$$\Psi(z) = \frac{\pi}{(dN/d\eta)\cdot\sigma_{inel}} \cdot J^{-1} \cdot E\frac{d^3\sigma}{dp^3} \Longleftrightarrow \int E\frac{d^3\sigma}{dp^3} dyd^2p_\perp = \sigma_{inel}\cdot N$$

- σ_{in} - inelastic cross section
- N - average multiplicity of the corresponding hadron species
- $dN/d\eta$ - pseudorapidity multiplicity density at angle θ (η)
- $J(z,\eta;p_T^2,y)$ - Jacobian
- $Ed^3\sigma/dp^3$ - inclusive cross section

The scaling function $\Psi(z)$ is probability density to produce an inclusive particle with the corresponding z.

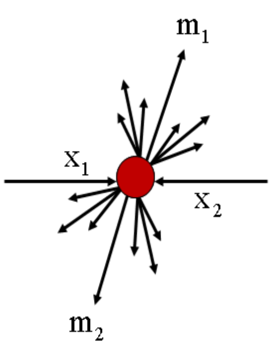
Transverse kinetic energy $\sqrt{s_\perp}$

$$s_\perp^{1/2} = (s_\lambda^{1/2} - M_1\lambda_1 - M_2\lambda_2) - m_1 + (s_\chi^{1/2} - M_1\chi_1 - M_2\chi_2) - m_2$$

energy consumed for the inclusive particle m_1

energy consumed for the recoil particle m_2

Fraction decomposition: $x_{1,2} = \lambda_{1,2} + \chi_{1,2}$



$$\lambda_{1,2} = \kappa_{1,2} + \nu_{1,2} \qquad \kappa_{1,2} = \frac{(P_{2,1}p)}{(P_2P_1) - M_1M_2}, \quad \nu_{1,2} = \frac{M_{2,1}m_2}{(P_2P_1) - M_1M_2}$$

$$\chi_{1,2} = (\mu_{1,2}^2 + \omega_{1,2}^2)^{1/2} \mp \omega_{1,2}$$

$$\mu_{1,2}^2 = \alpha^{\pm 1}(\lambda_1\lambda_2 + \lambda_0)\frac{1 - \lambda_{1,2}}{1 - \lambda_{2,1}}$$

$$\omega_{1,2} = \mu_{1,2}U, \quad U = \frac{\alpha - 1}{2\sqrt{\alpha}}\xi, \quad \alpha = \frac{\delta_2}{\delta_1}$$

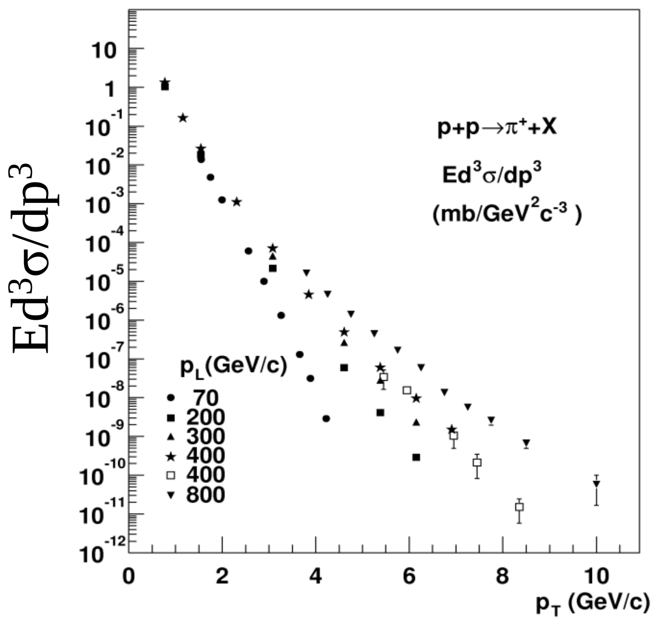
$$\lambda_0 = \bar{\nu}_0 - \nu_0$$

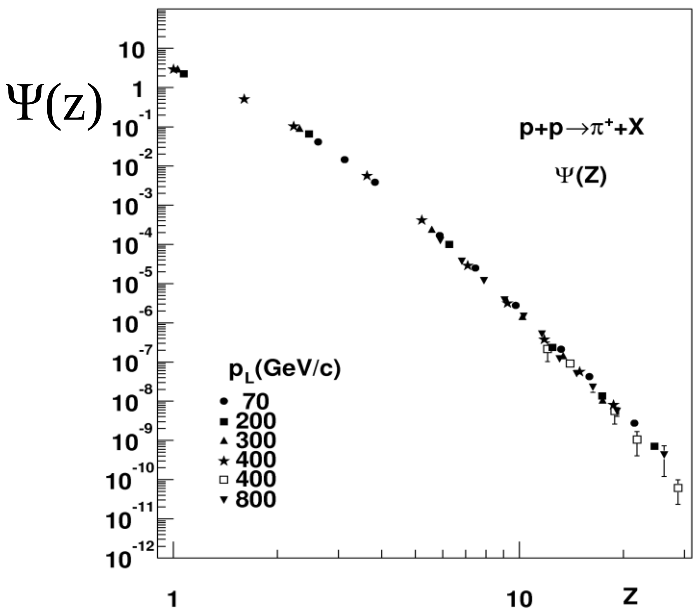
$$\xi^2 = (\lambda_1\lambda_2 + \lambda_0)/[(1-\lambda_1)(1-\lambda_2)] \qquad \bar{\nu}_0 = \frac{0.5m_2^2}{(P_1P_2) - M_1M_2}, \quad \nu_0 = \frac{0.5m_1^2}{(P_1P_2) - M_1M_2}$$

$$s_\lambda = (\lambda_1 P_1 + \lambda_2 P_2)^2 \qquad s_\chi = (\chi_1 P_1 + \chi_2 P_2)^2$$

The scaling variable z and scaling function $\Psi(z)$ are expressed via relativistic invariants.

Self-similarity of hadron production in pp





Spectra

- 10 orders of magnitude
- Sensitive to energy √s at high p_T
- Power law for high √s and p_T

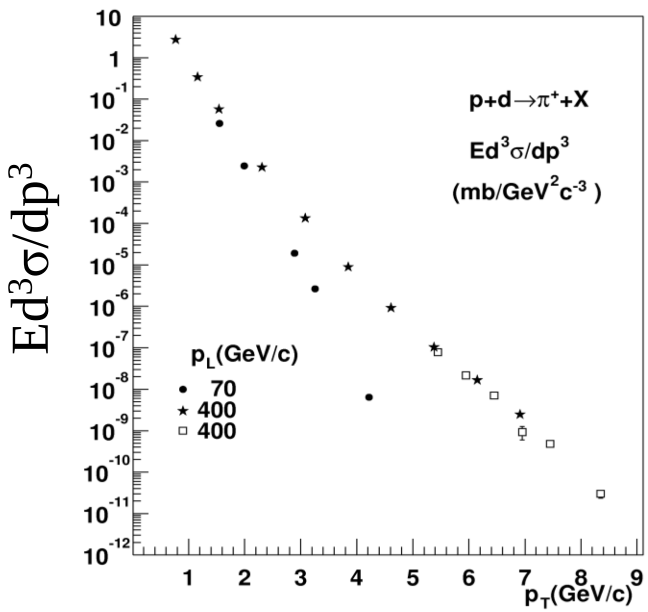
- Energy independence of Ψ(z)
- Power law of Ψ(z) at high z

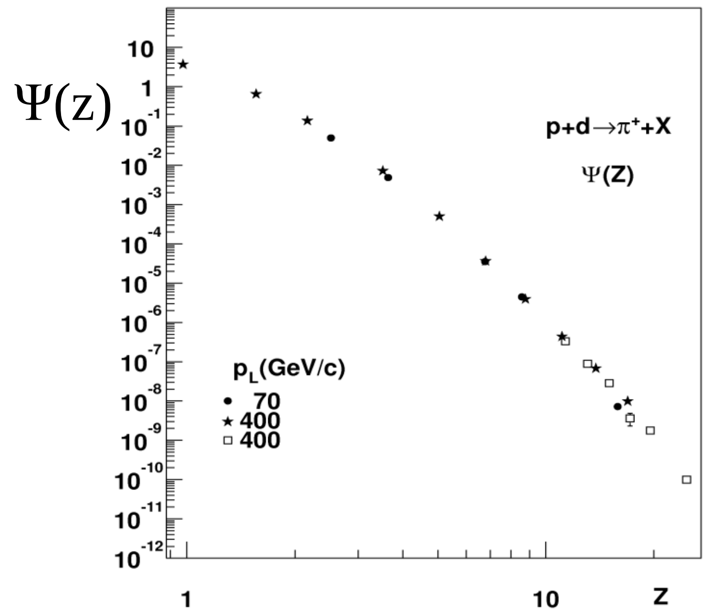
Scale invariance

Independence of the shape of the curve on {z,Ψ} plane on scale quantities √s, p_T, θ

J.W. Cronin et.al., Phys. Rev. D11 (1975) 3105.
D. Antreasyan et al., Phys. Rev. D19 (1979) 764.
V.V. Abramov et al., Sov. J. Nucl. Phys. 41 (1985) 357.
D.E. Jaffe et al., Phys. Rev. D40 (1989) 2777.

Self-similarity of hadron production in pD





Spectra

- 10 orders of magnitude
- Sensitive to energy $\sqrt{s}$ at high p_T
- Power law for high $\sqrt{s}$ and p_T

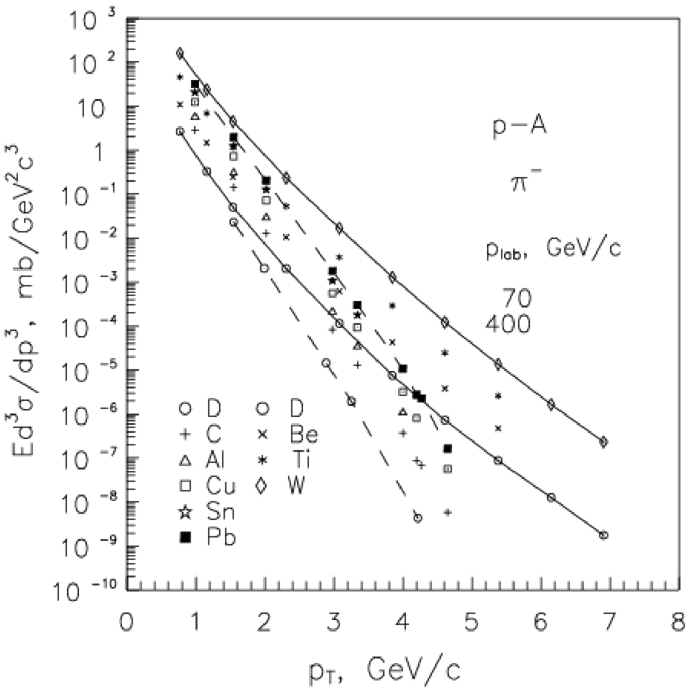
- Energy independence of $\Psi(z)$
- Power law of $\Psi(z)$ at high z

J.W. Cronin et.al., Phys. Rev. D11 (1975) 3105.
D. Antreasyan et al., Phys. Rev. D19 (1979) 764.
V.V. Abramov et al., Sov. J. Nucl. Phys. 41 (1985) 357.
D.E. Jaffe et al., Phys. Rev. D40 (1989) 2777.

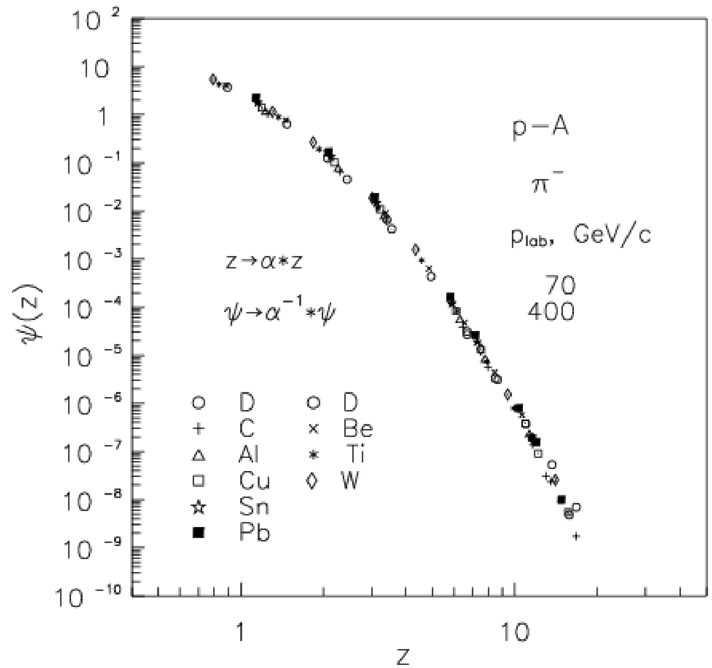
Fractal dimensions in pA & AA

$\delta_1 = A_1\delta$, $\delta_2 = A_2\delta$

Self-similarity of hadron production in pA



Strong dependence of spectra on √s at high p_T



- Energy independence of Ψ(z)
- Power law of Ψ(z) at high z
- A-dependence of Ψ(z)

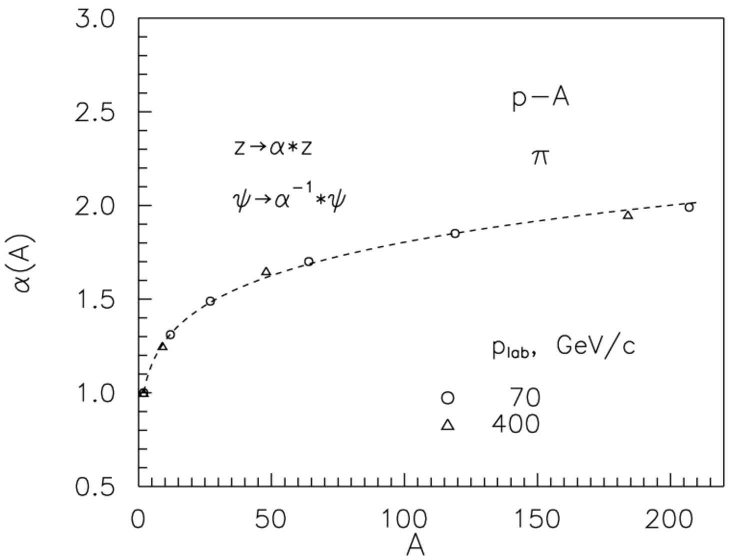
J.W. Cronin et al., Phys. Rev. D11 (1975) 3105.
D. Antreasyan et al., Phys. Rev. D19 (1979) 764.
V.V.Abramov et al., Sov. J. Nucl. Phys. 41 (1985) 357.
M.T., Yu.Panebratsev, I.Zborovsky, G.Skoro
JINR E2-99-113; Int. J. Mod. Phys. A16 (2001) 1281.

Scale invariance

Independence of the shape of the curve on {z,Ψ} plane on scale quantities √s, p_T, θ

A-dependence of z-scaling

The scaling transformations of z and Ψ(z) allow us to compare scaling functions for different nuclei



$$z \rightarrow \alpha(A)\cdot z$$

$$\Psi(z) \rightarrow \alpha^{-1}(A)\cdot\Psi(z)$$

$$\alpha(A) \approx 0.9\, A^{0.15}$$

Self-similarity of nuclear modification of constituent interactions and hadron formation.

$$z = z_0\,\Omega^{-1}$$

$$\Omega = (1-x_1)^{\delta_1}(1-x_2)^{\delta_2}$$

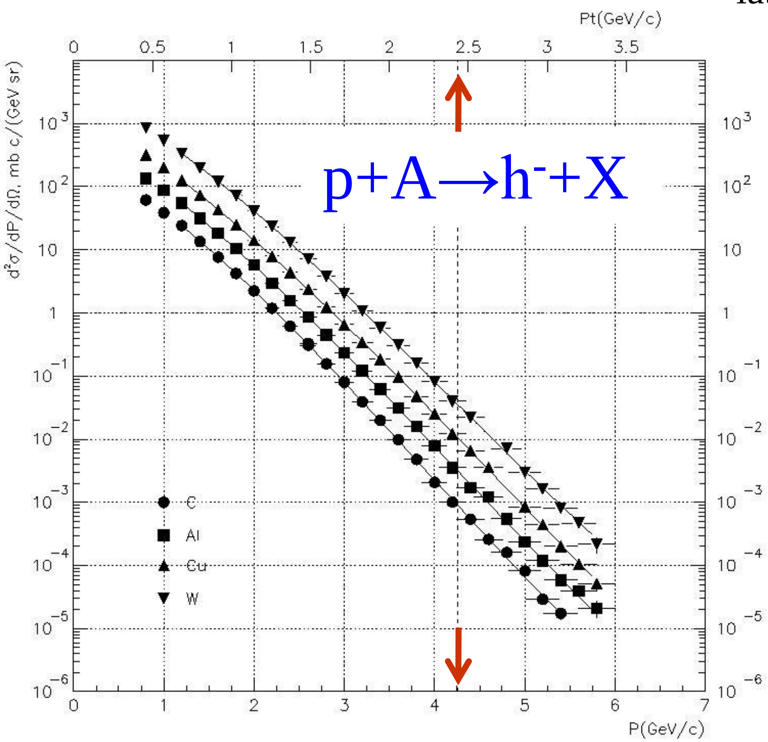
$$\delta_1 = A_1\delta,\ \ \delta_2 = A_2\delta$$

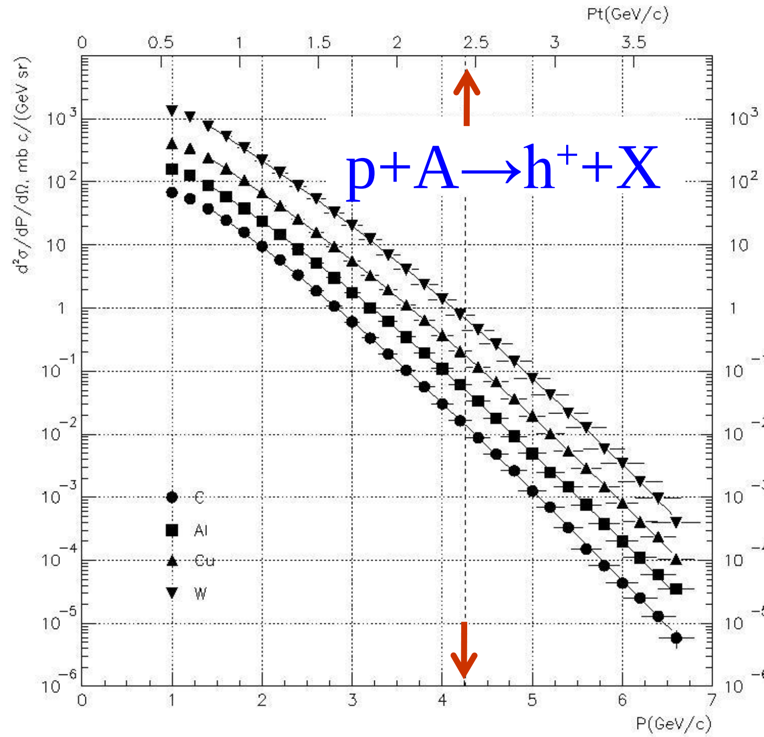
Self-similar parameter z
"Critical exponents" δ_1, δ_2
Preservation of self-similarity and discontinuity of δ_1, δ_2 is a signature of new physics

M.T., Yu.Panebratsev, I.Zborovsky, G.Skoro
JINR E2-99-113; Int. J. Mod. Phys. A16 (2001) 1281.

Charged hadron spectra in pA at U70

$d^2\sigma/dp/d\Omega$ $p_L = 50$ GeV/c $\theta_{lab} = 35^0$ A=C,Al,Cu,W





- Spectra in cumulative region: $p_T > 2.5$ GeV/c
- Smooth behavior of spectra vs. p_T

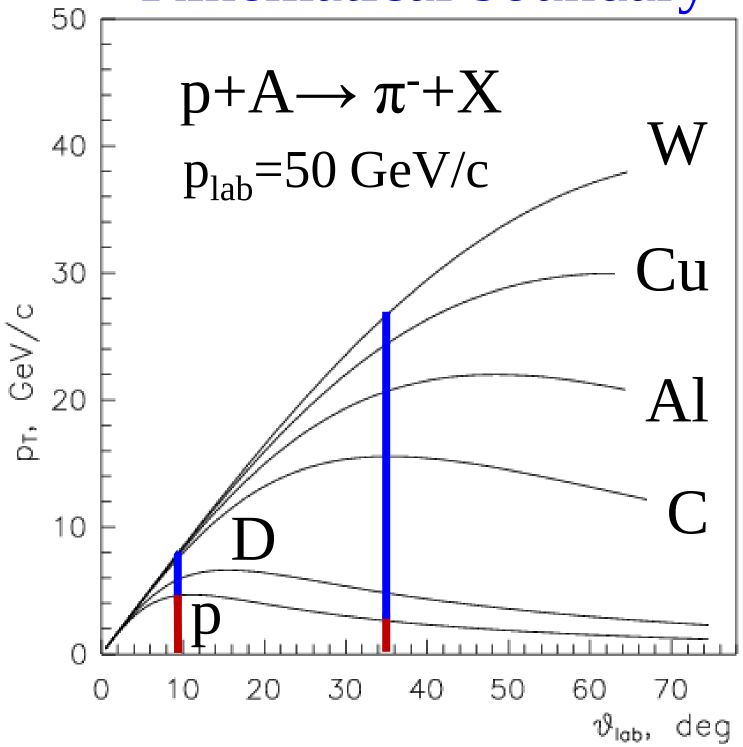
N.N. Antonov et al., "Physics of Fundamental Interactions"
RAS, ITEP, Moscow, Russia, November 21 - 25, 2011

Kinematics

$p^{\pi}_{T\max}$ (GeV/c)

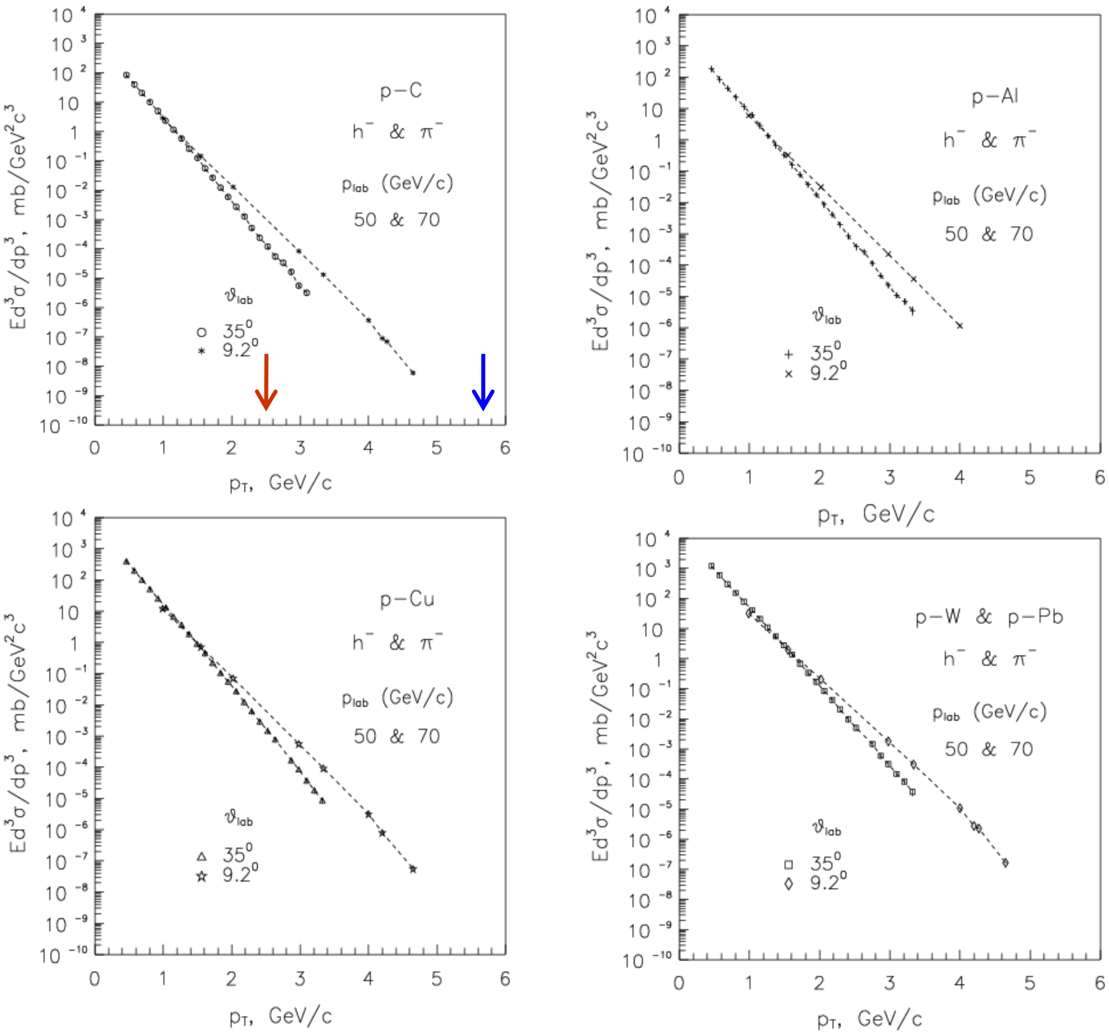
P	2.6	5.6
D	4.8	7.4
C	15.6	10.0
Al	20.7	10.4
Cu	24.4	10.6
W	26.7	10.7
p (GeV/c)	50	70
ϑ_{lab}	35^0	9^0

Kinematical boundary



Cumulative region: $p^{pA}_{max} > p^{pp}_{max}$

High-p_T hadron spectra in pA at U70



U70
SPIN & FODS

SPIN, N.N. Antonov et al.,
"Physics of Fundamental Interactions"
RAS, ITEP, Moscow, Russia,
November 21 - 25, 2011

FODS, V.V.Abramov et al.,

Sov. J. Nucl. Phys. 41 (1985) 357.

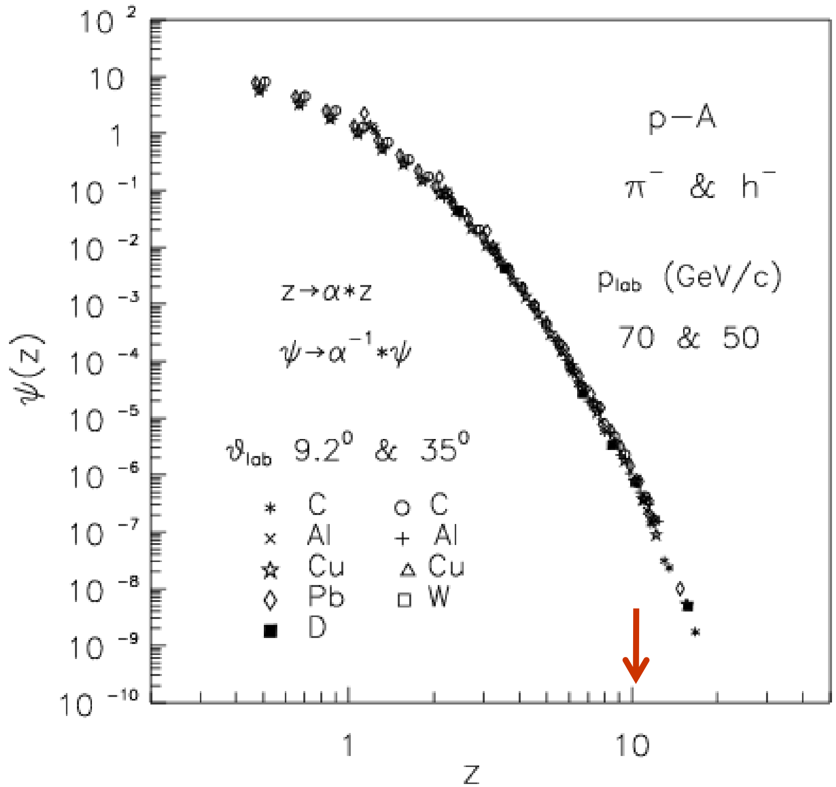
Self-similarity
High-p_T and cumulative hadron production in pA

U70

SPIN & FODS

$$z = z_0\,\Omega^{-1}$$

$$\Omega = (1-x_1)^{\delta_1}(1-x_2)^{\delta_2}$$

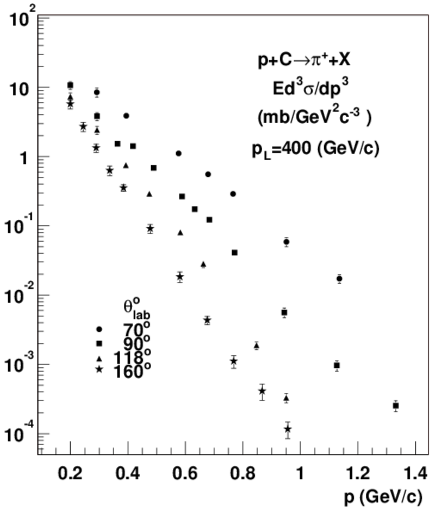


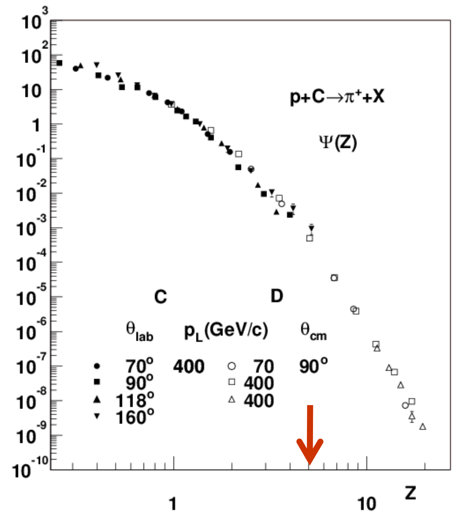
- Universal shape of $\Psi(z)$
- Power law for $z > 4$
- No discontinuty of $\delta_2 = A_2\delta$

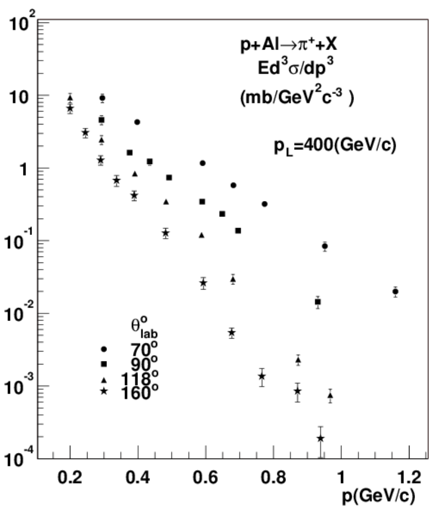
Scale invariance

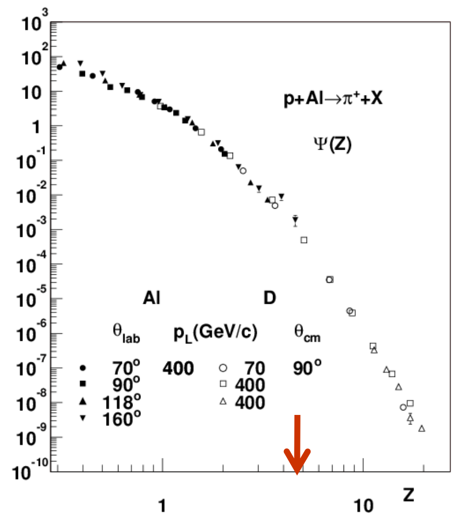
Independence of the shape of the curve on $\{z,\Psi\}$ plane on scale quantities $\sqrt{s}$, p_T, θ

High-p_T and cumulative hardron production in pA









C, Al & D

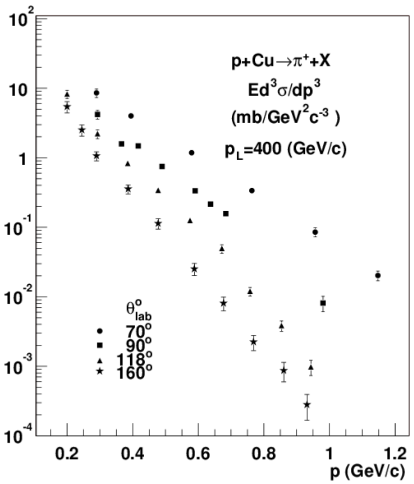
N.A. Nikiforov et al., Phys. Rev. C22 (1980) 700.
J.W. Cronin et.al., Phys. Rev. D11 (1975) 3105.
D. Antreasyan et al., Phys. Rev. D19 (1979) 764.
V.V. Abramov et al., Sov. J. Nucl. Phys. 41 (1985) 357.
D.E. Jaffe et al., Phys. Rev. D40 (1989) 2777.

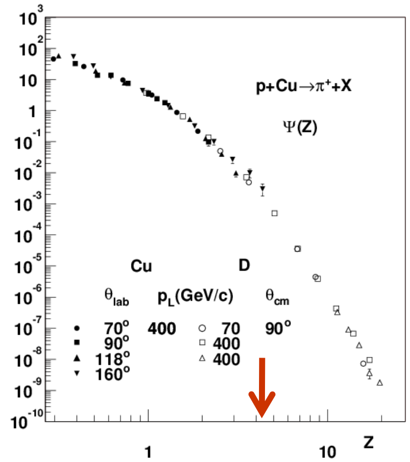
$$\theta^{\pi}_{lab} = 180^0$$

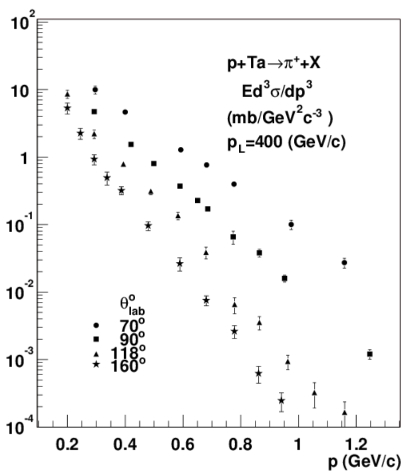
p^{π}_{max} (GeV/c)	p	D	C	Al	p_L (GeV/c)
	0.447	0.905	5.13	10.6	70
	0.456	0.928	5.53	12.2	400
	0.459	0.933	5.63	12.7	∞

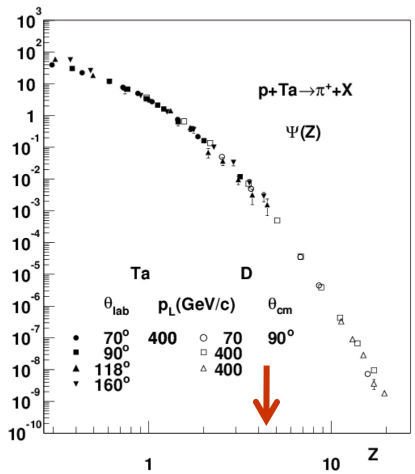
D.Toivonen & MT (2003)

High-p_T and cumulative hadron production in pA









Cu, Ta & D

- Collapse of data point
- Universal shape of $\Psi(z)$
- Self-similarity of hadron production over a wide range of energy $\sqrt{s}$, angle θ and atomic number A

$$\theta^{\pi}_{lab} = 180^0$$

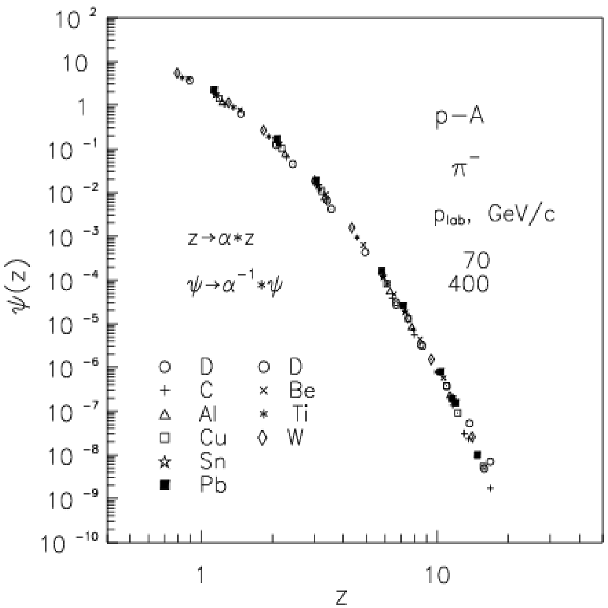
p^{π}_{max} (GeV/c)	p	D	Cu	Ta	p_L (GeV/c)
	0.447	0.905	20.7	37.8	70
	0.456	0.928	27.9	69.8	400
	0.459	0.933	30.0	84.7	∞

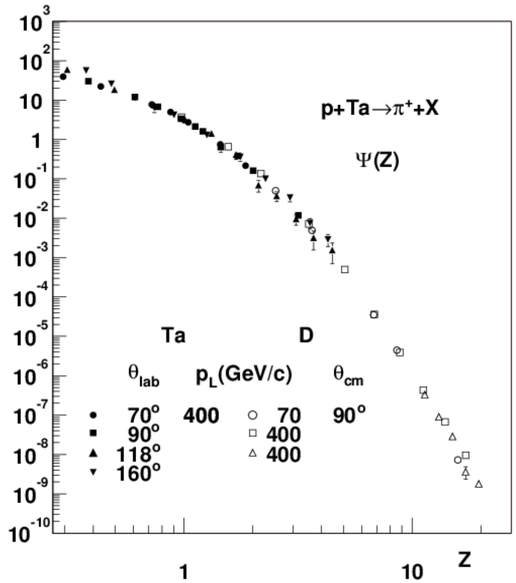
D.Toivonen & MT (2003)

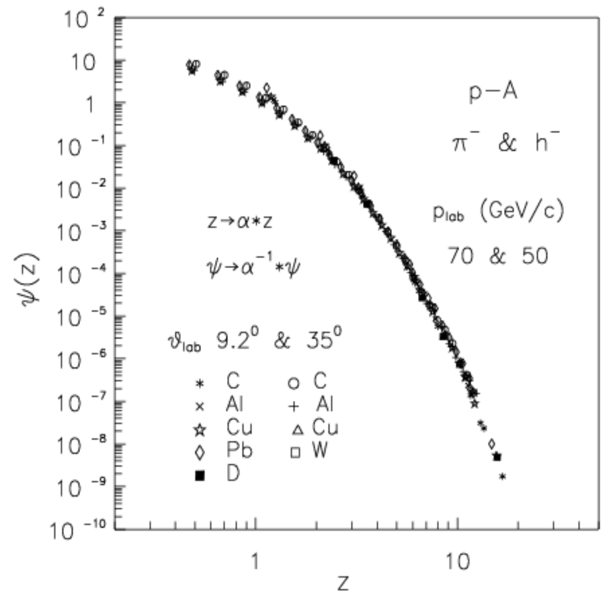
Self-similarity
High-p_T and cumulative hadron production in pA

FNAL
J.Cronin & D.Jaffe

U70
SPIN & FODS







Open questions:

- Spectra of cumulative identified particles
- Multiplicity density $dN_{ch}/d\eta$ vs. $\sqrt{s}$ and η
- Centrality dependence of the spectra
- Power law of $\Psi(z)$ in cumulative region

Goal: Search for violation of z-scaling → search for phase transition & CP

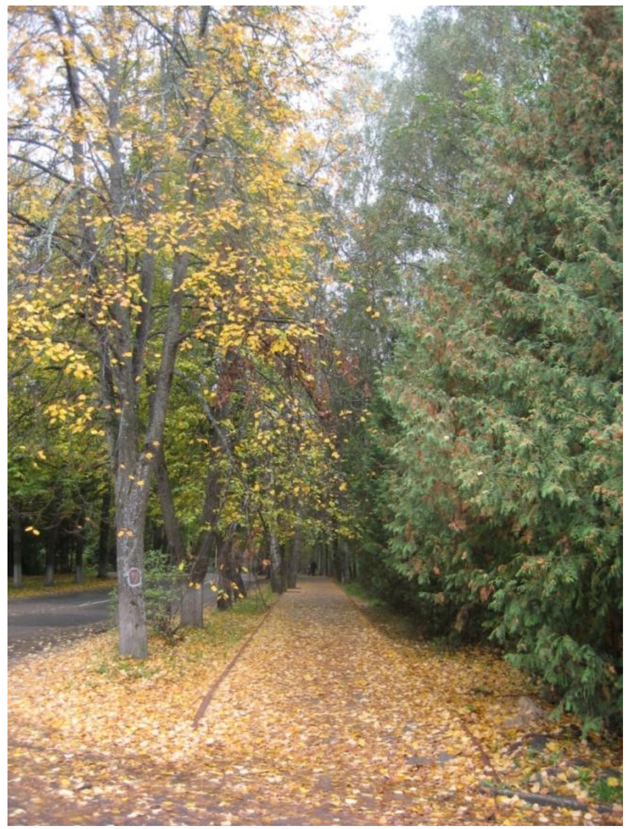
Conclusions

- New U70 data on charged hadron production in pA collisions were analyzed in the z-scaling approach.
- Results of new analysis were compared with previous one from data taken by J. Cronin, R. Sulyaev, G. Leksin and D. Jaffe groups.
- Confirmation of self-similarity of hadron production in pA collisions in high-p_T cumulative region were obtained.
- z-Scaling of charged hadron production in pA collisions at high energies manifests self-similarity, locality and fractality of hadron interactions at a constituent level.

New kinematical region is available for search of new physics phenomena in hadron production at U70.

JINR

Thank you for your attention !



Back-up slides

Angular Dependence of Multilicity Density