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on High Energy Physics Problems

Relativistic Nuclear Physics &
Quantum Chromodynamics

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Self-similarity of cumulative hadron production in p-A collisions at low and high p_T

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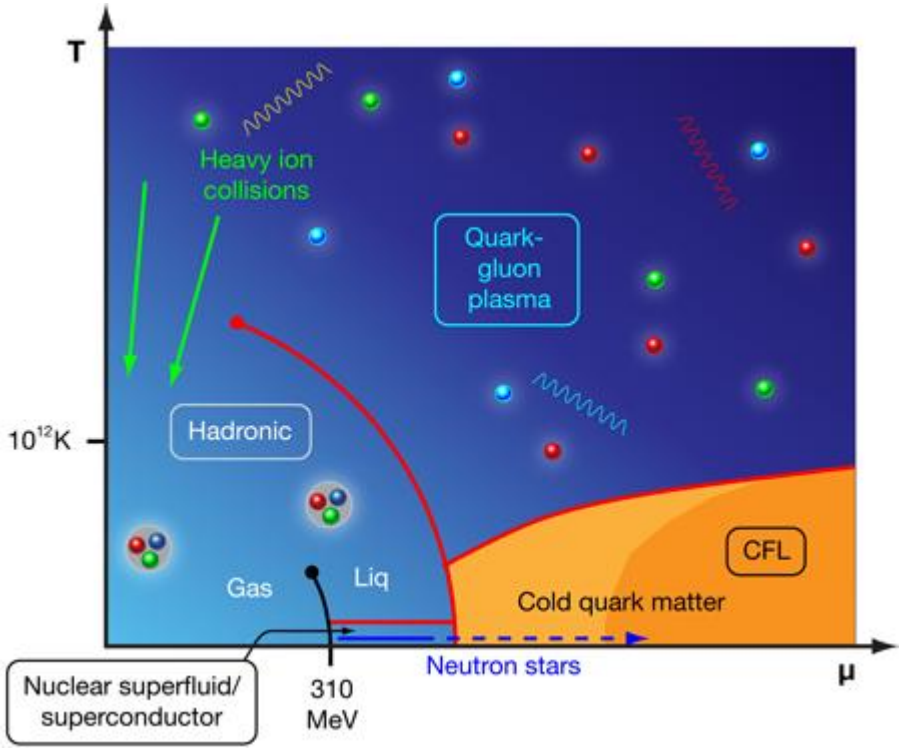
JINR, Dubna, Russia

Content

- ✓ Motivation and goals
- ✓ Theory description
- ✓ Cumulative particle production
- ✓ Conclusions



Motivation & Goals

Search for possible signatures of new physics phenomena in inclusive pp, pA , AA collisions.

z-Scaling reveals self-similar properties in hadron, jet and direct photon production in high energy p-p & p-p-bar collisions.

Analysis of experimental data on inclusive spectra of cumulative hadron production in pA collisions to verify properties of z-scaling.

- pA is a reference frame for pp & AA
- cumulative process:
  - enhancement of nuclear matter compression
  - particle formation is sensitive to state of matter
- search for indications of phase transition & CP

Self-similarity in physics

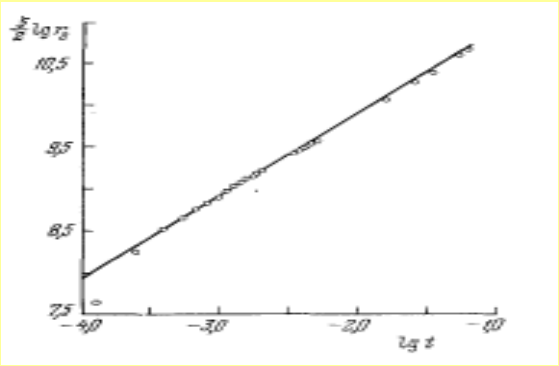
- Self-similarity means that a pattern is similar to a part of itself.
- Universal description using self-similarity variables constructed as suitable combinations of physical quantities.

Self-similarity variables Π (Re, π, M,…)

Point explosion

$\pi = r(Et^2/\rho)^{-1/5}$

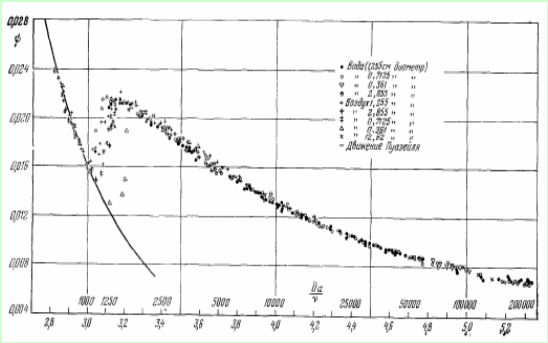
r-radius of the front wave
E-energy of the explosion
t-elapsed time
ρ-density of the environment



Hydrodynamics

$Re = dV\rho/\eta$

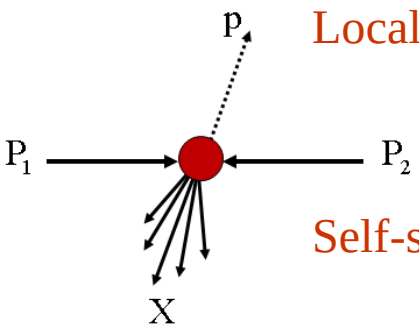
d-diameter
V-velocity of the fluid
ρ-density of the fluid
η-viscosity of the fluid



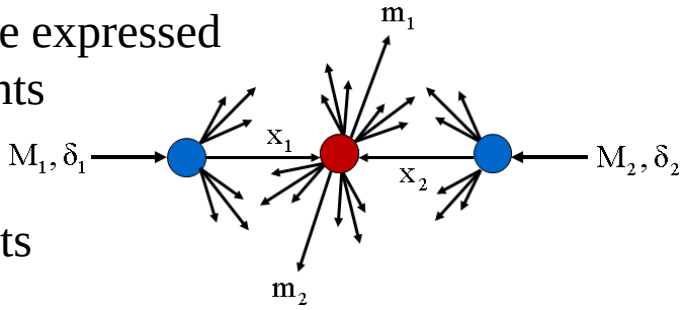
Dimensionless function & self-similarity variable

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.

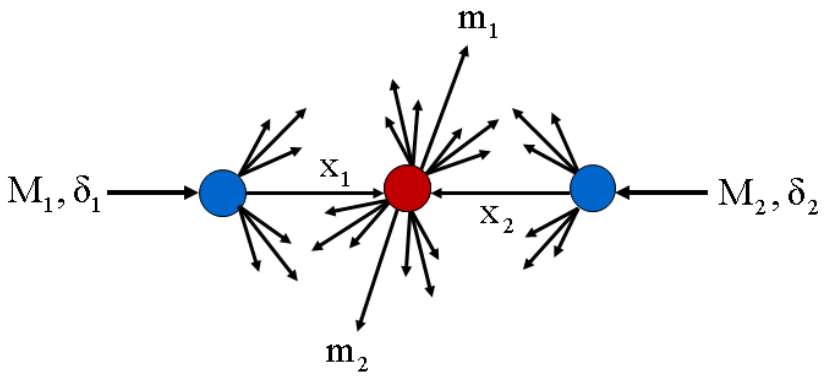
$\Psi(z)$

I.Zborovsky, M.Tokarev, Yu.Panebratsev, G.Skoro
Int.J.Mod.Phys. A16 (2001) 1281

Self-similar variable z

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

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



- $\sqrt{s_\perp}$ 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)
- Ω^{-1} is the minimal resolution at which a constituent subprocess can be singled out of the inclusive reaction

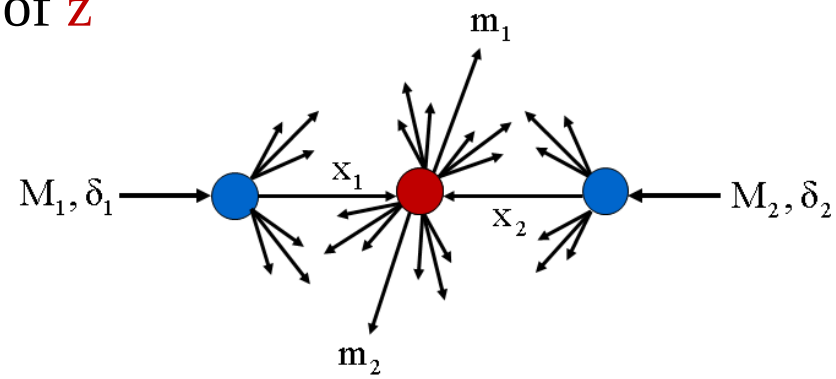
z is the dimensionless variable

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

Kinematic boundary

$$0 < x_1,\ x_2 < 1$$

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

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

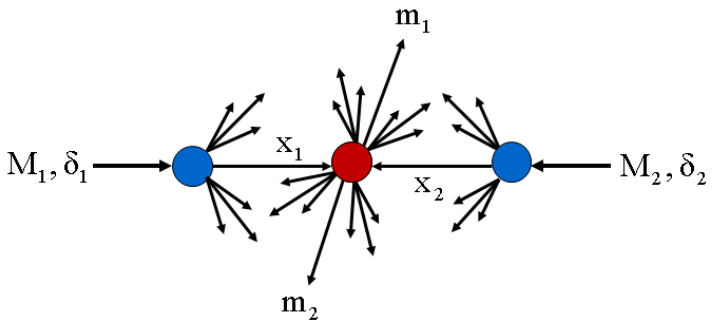
The fractal measure z diverges as the resolution Ω^{-1} increases.

Scaling function $\Psi(z)$

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

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

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



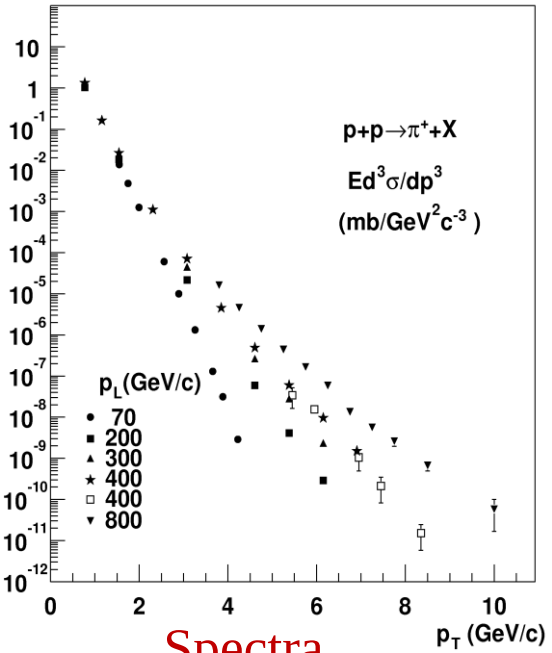
$$\Psi(z) = \frac{\pi}{(dN/d\eta)\cdot\sigma_{inel}} \cdot J^{-1} \cdot E\frac{d^3\sigma}{dp^3} \quad \Leftrightarrow \quad \int E\frac{d^3\sigma}{dp^3}dyd^2p_\perp = \sigma_{inel}\cdot N$$

- 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

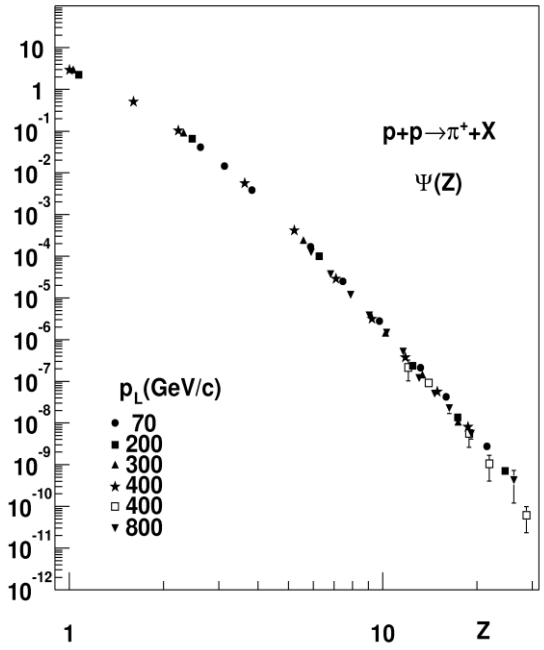
The scaling function $\Psi(z)$ is probability density to produce the inclusive particle with the corresponding z.

Self-similarity of hadron production in pp

FNAL (Batavia) & IHEP (Protvino)



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

Scale invariance

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

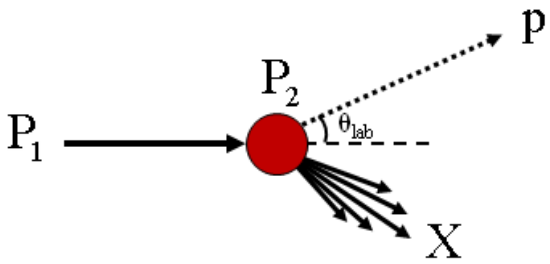
Cumulative processes

A.M.Baldin & V.S.Stavinsky (1971)

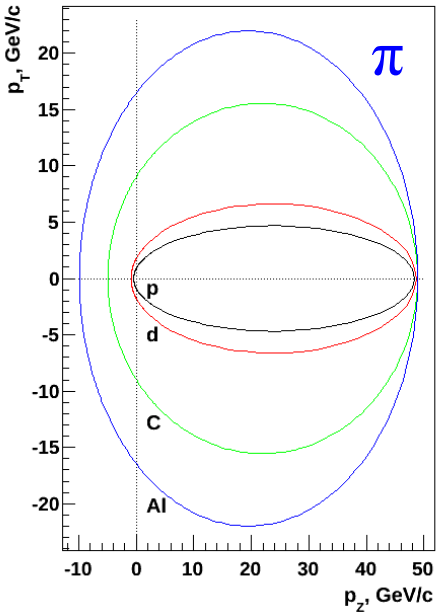
The cumulative particle is a particle produced
in the region forbidden for free nucleon kinematics:

$$P_1 + P_2 \rightarrow p + X$$

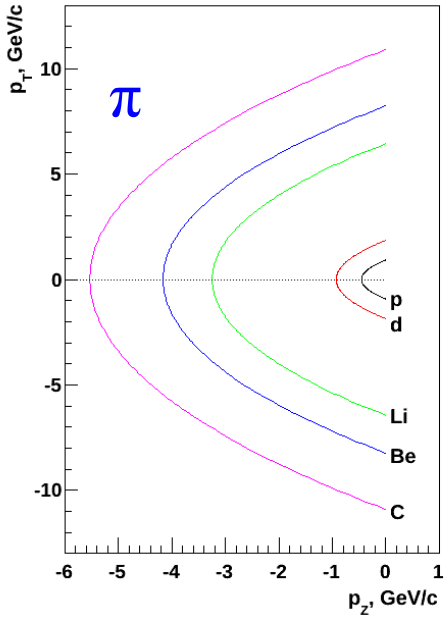
$$(P_1 + P_2 - p)^2 = M_X^2 \quad \Rightarrow \quad p^A_{max} > p^p_{max}$$



pA p_L =50 GeV/c



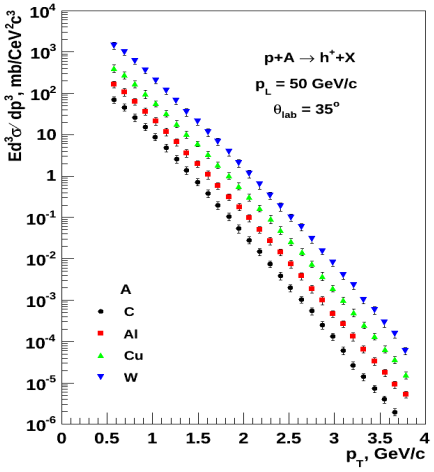
pA p_L =400GeV/c

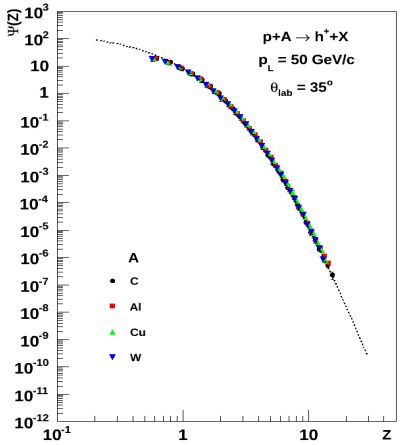


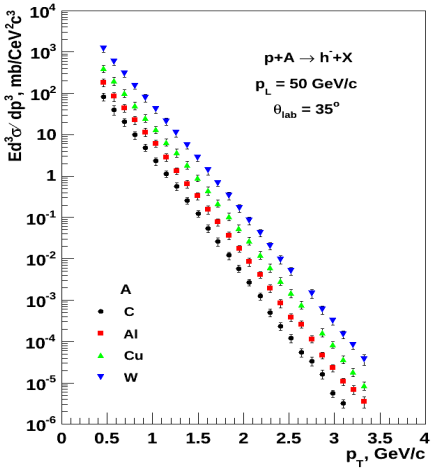
Conservation laws:

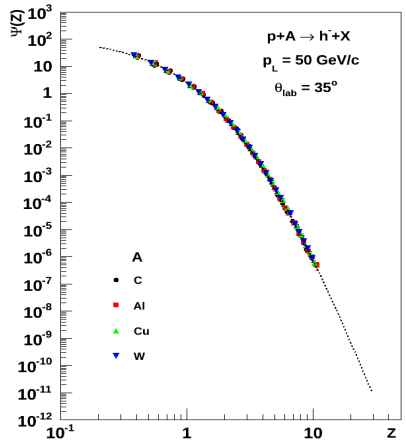
- 4-momentum
- electric charge
- baryon number
- flavors (u,d,s,c,b)

High-p_T cumulative hadron spectra in pA at U70









U70 (V.Gapienko et al.)

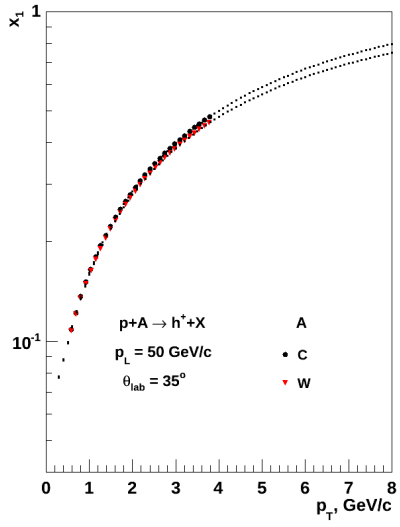
p_L = 50 GeV/c, A = C,Al,Cu,W
θ_{lab} = 35 deg.

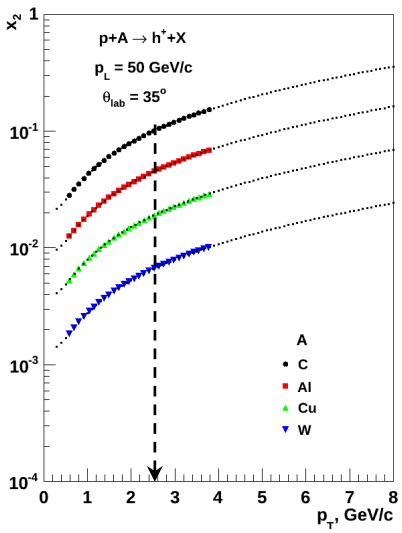
- Universal shape of $\Psi(z)$
- Power law for $z > 4$
- No discontinuity of δ_A

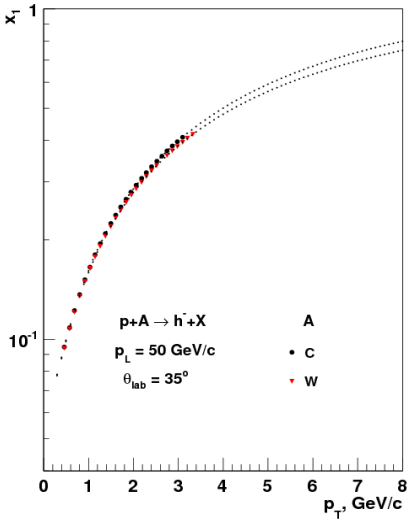
A.Aparin & M.Tokarev
Phys. Part. and Nucl. Let.
V. 11, 4, (2014) 381

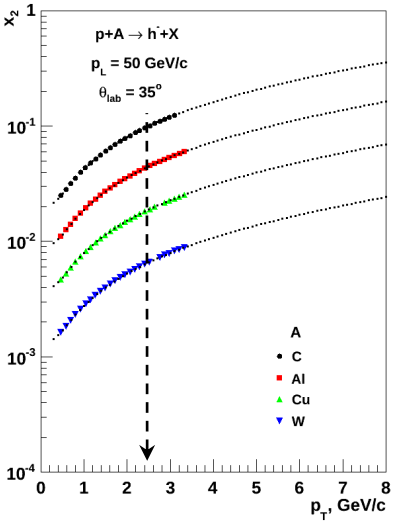
N.N.Antonov et al. (IHEP, Protvino) "Physics of Fundamental Interactions", Russian Academy of Science, ITEP,Moscow, Russia, 21-25 November, 2011.
V.V.Ammosov et al., Phys. At. Nucl. 76 (2013) 1213.

Momentum fractions x_1,x_2 vs. p_T









$p+A \rightarrow \pi+X$

$p_{T\,max}^{\pi}$ (GeV/c)	p	C	Al	Cu	W
	2.62	15.6	20.7	24.4	26.7

Kinematic boundary

$0 < x_1,\ x_2 < 1$

Non-cumulative region

$x_2 < 1/A$

Cumulative region

$x_2 > 1/A$

Deep-cumulative region

$x_2 >> 1/A$

Deep-cumulative hadron spectra in pA

predictions based on z-scaling

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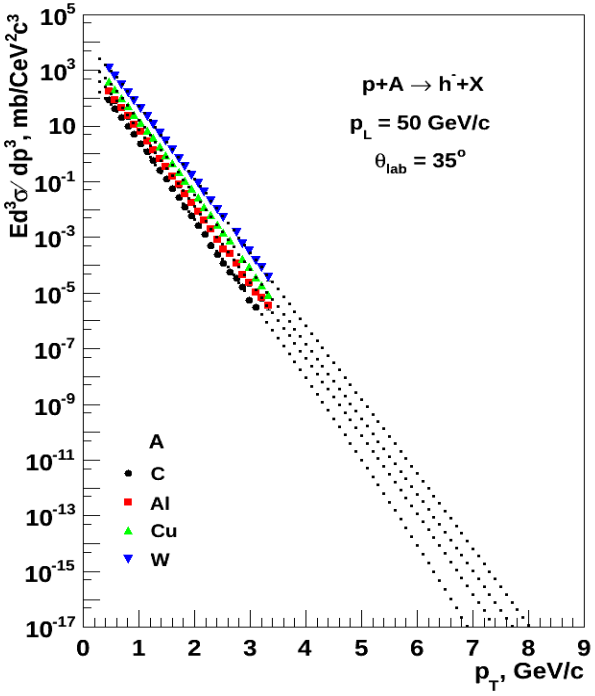
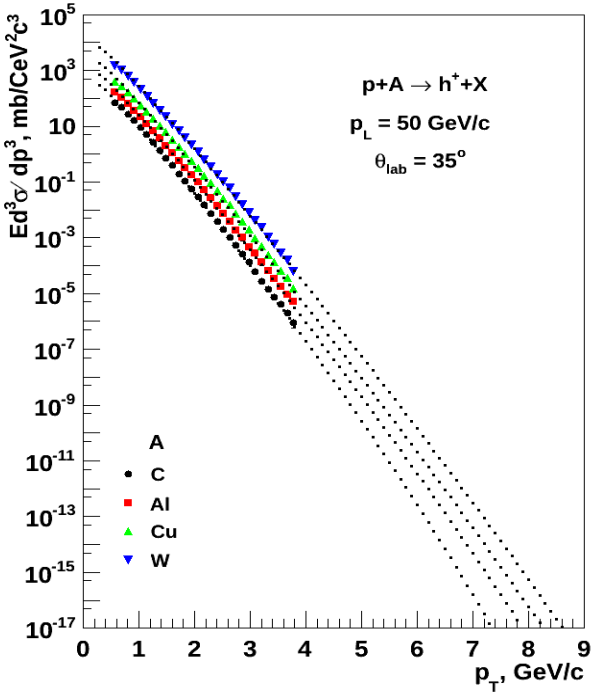


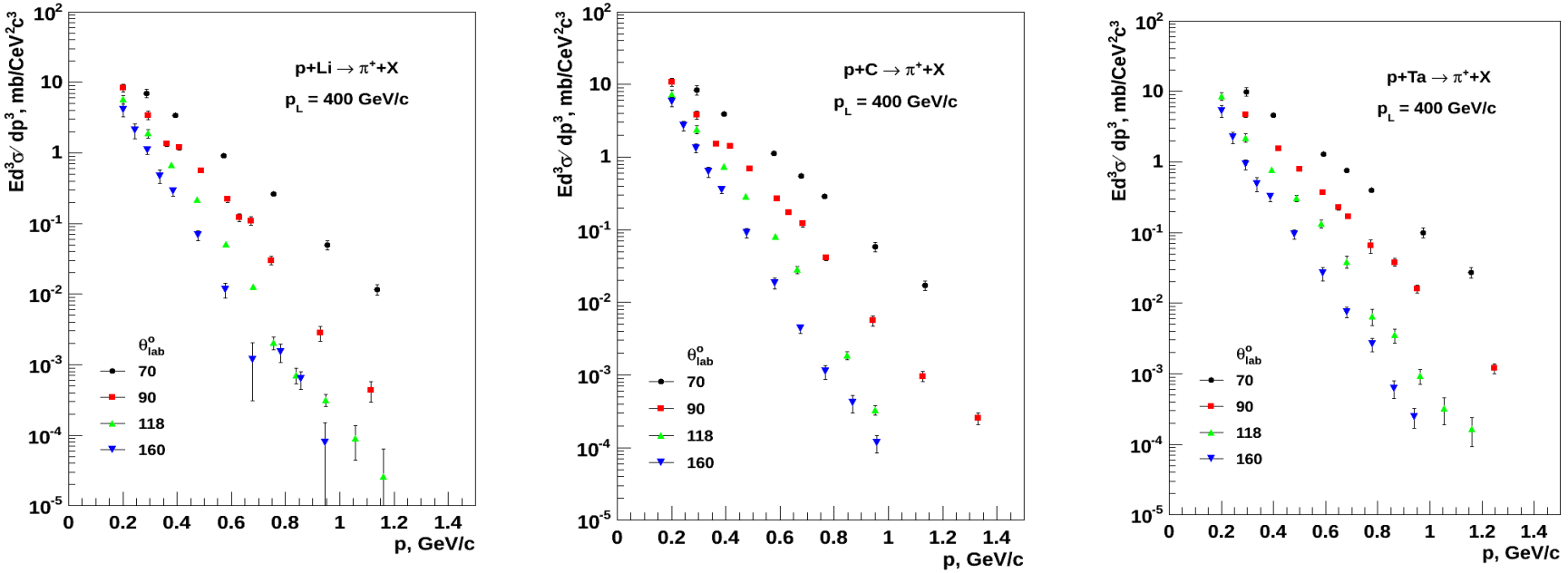


- Spectra in deep-cumulative & high-p_T region: $p_T > 2.5$ GeV/c
- Exponential behavior of spectra vs. p_T
- Verification of the additive law $\delta_A = A\delta_N$

Cumulative pion spectra in pA at FNAL

G.Leksin et al.

p_L = 400 GeV/c, A = Li,Be,C,Al,Cu,Ta θ_{lab} = 70,90,118,160 deg.

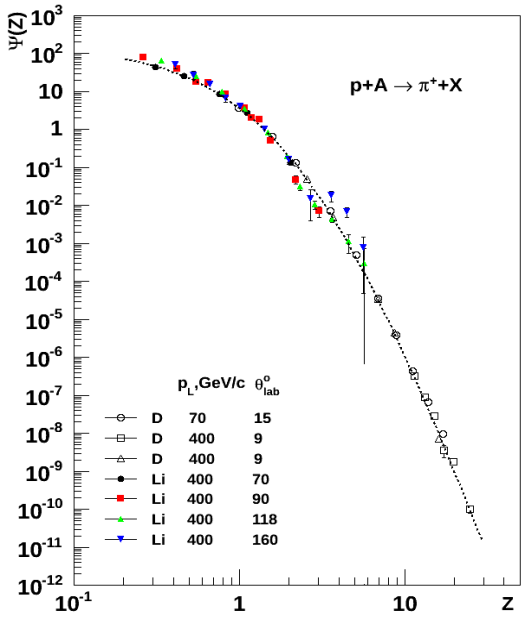


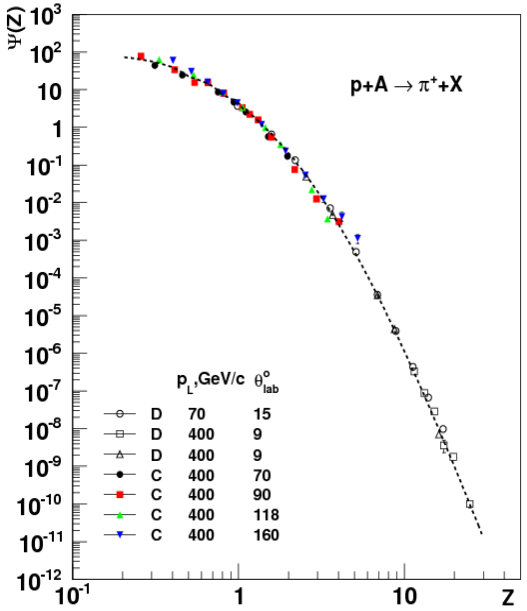
- Spectra in cumulative region: p > 0.5 GeV/c.
- Smooth behavior of spectra vs. p.
- Strong angular dependence with p.
- A-dependence of spectra (A=7-181).

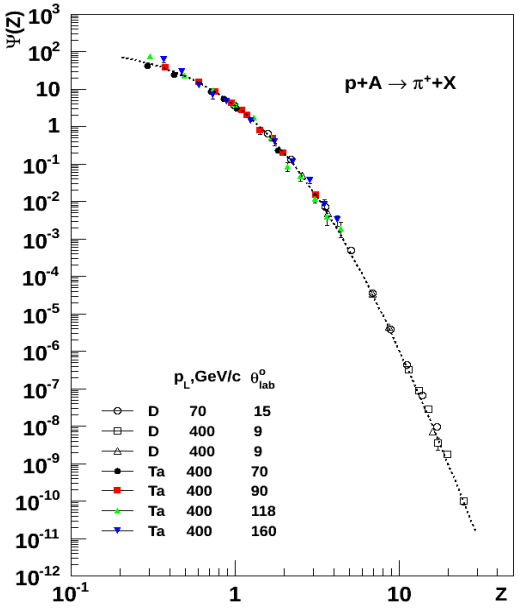
N.A. Nikiforov et al., Phys.Rev.C22 (1980)700.

Low-p_T cumulative pion production in pA at FNAL

FNAL (G.Leksin et al.)







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

Scale invariance

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

$z \to \alpha(A)z$ $\quad$ $\Psi \to \alpha^{-1}(A)\Psi$

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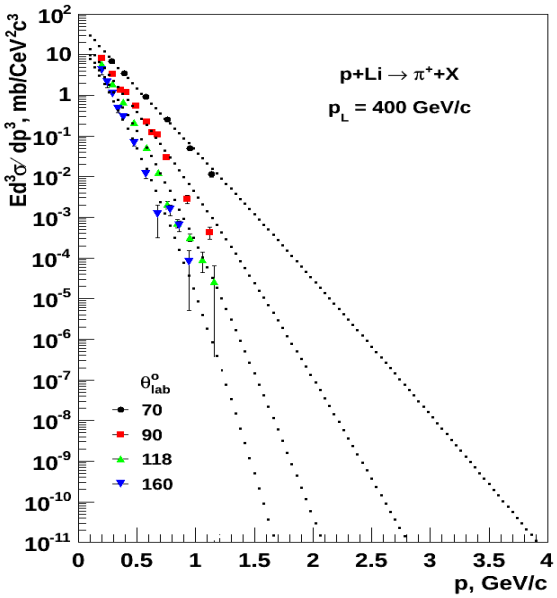
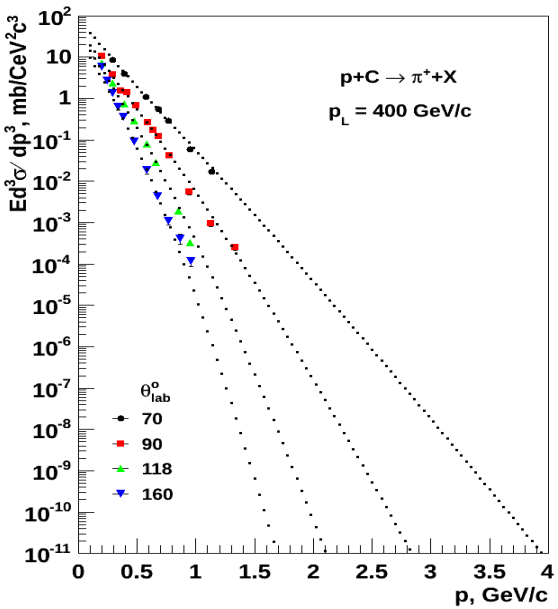
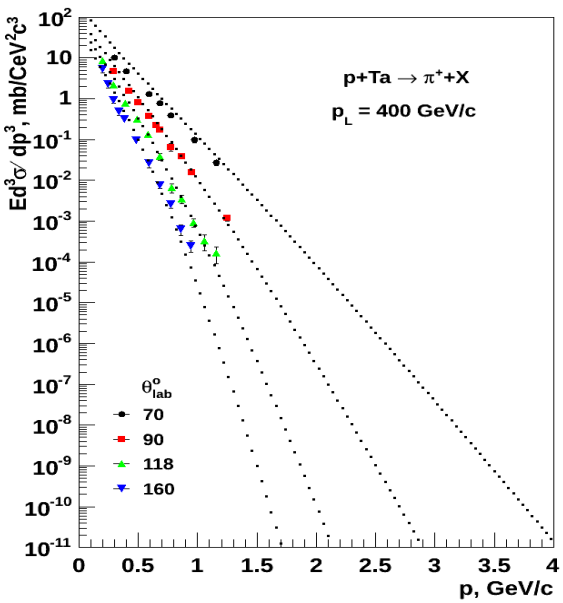
Deep-cumulative pion spectra in pA

predictions based on z-scaling







- Spectra in cumulative region: $p > 0.5$ GeV/c
- Smooth behavior of spectra vs. p_T
- Verification of the additive law $\delta_A = A\delta$

N.A. Nikiforov et al., Phys. Rev. C22 (1980) 700
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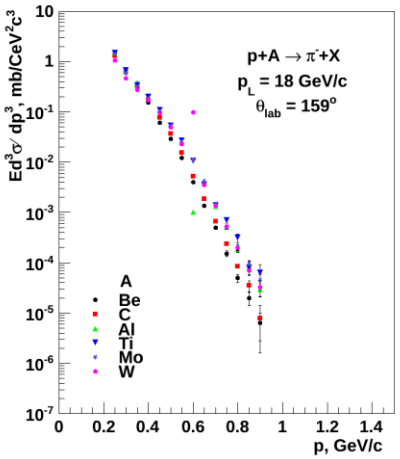
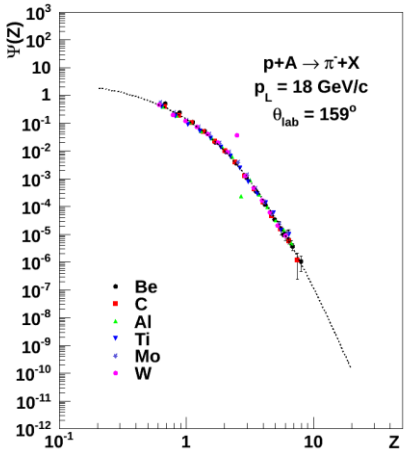
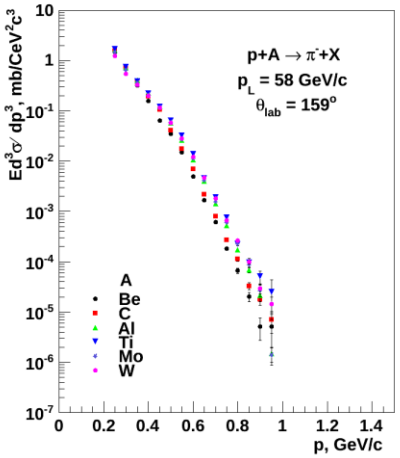
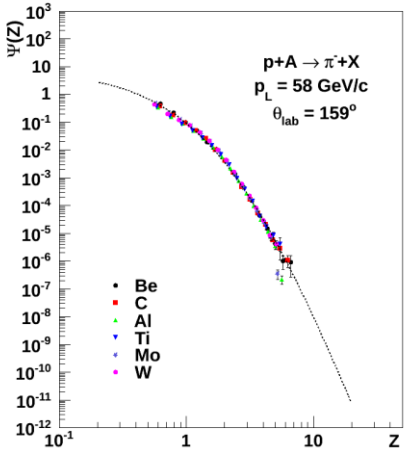
Low-p_T cumulative pion spectra in pA at U70









U70 (L.Zolin et al.)

p_L = 18, 58 GeV/c,
A = Be, C, Al, Ti, Mo, W,
θ_{lab} = 159 deg.

- Universal shape of $\Psi(z)$
- Power law for $z > 4$
- No discontinuity of δ_A

A.Aparin & M.Tokarev
Phys. Part. and Nucl. Let.
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O.P.Gavrishchuk et al., Nucl. Phys. A523 (1991) 589.

Deep-cumulative pion spectra in pA

predictions based on z-scaling

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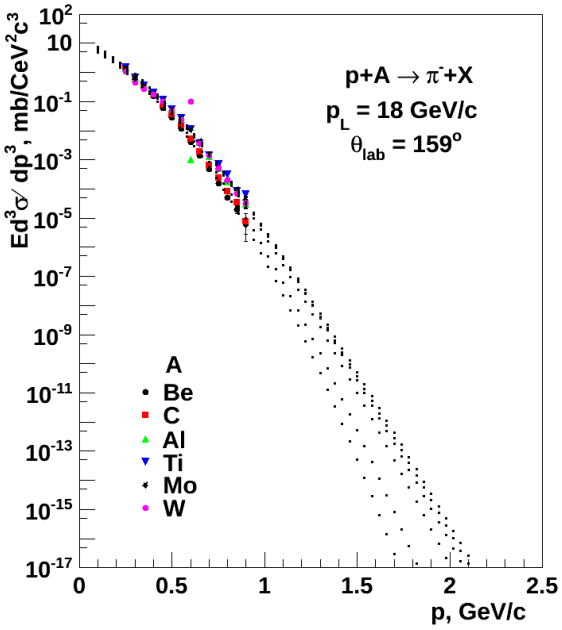
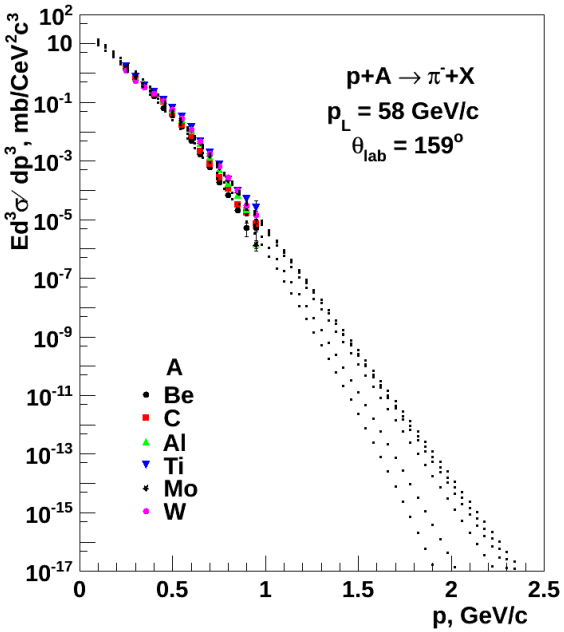




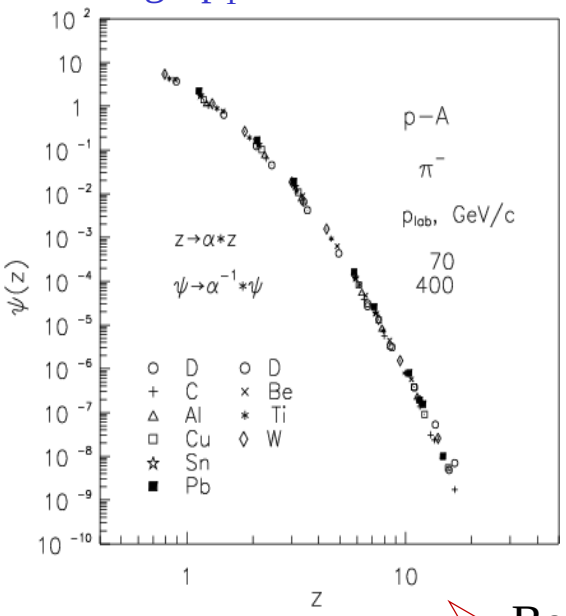
- Spectra in deep-cumulative & low-p_T region: $p > 0.6$ GeV/c
- Exponential behavior of spectra vs. p.

Discontinuity of δ_A is a signatures of phase transition of compressed nuclear matter

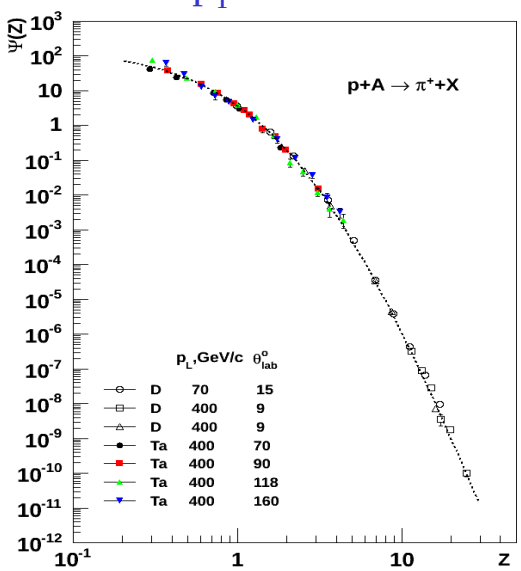
Self-similarity of hadron production in pA

FNAL (J.Cronin, G.Leksin, D.Jaffe) & U70 (R.Sulyaev, V.Gapienko)

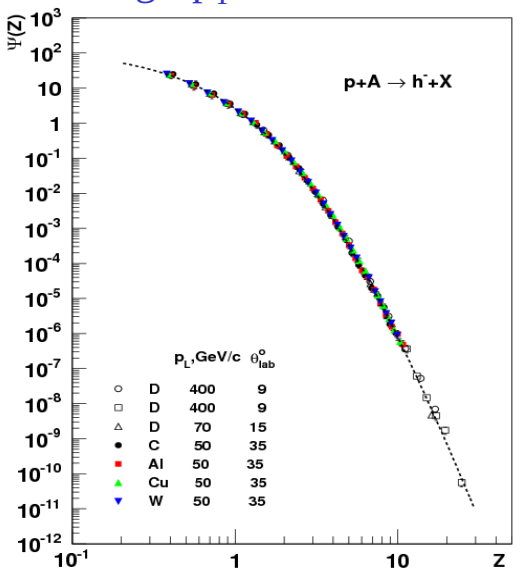
high-p_T & noncumulative



low-p_T & cumulative



high-p_T & cumulative



- Beam Energy Scan in pA
- Spectra of cumulative identified particles
- Multiplicity density $dN_{ch}/d\eta$ vs. $\sqrt{s}$ and η
- Centrality dependence of spectra

Search for phase transition & CP ⟺ Search for violation of z-scaling

Conclusions

- Data on cumulative hadron spectra obtained by G.Leksin, L.Zolin and V.Gapienko groups in pA collisions at $\sqrt{s}$ = 11 – 27.4 GeV were analyzed in the framework of z-scaling.
- Results of this analysis were compared with previous ones from the data obtained by J. Cronin, R. Sulyaev and D. Jaffe groups.
- Indication on self-similarity of hadron production in pA collisions at high energies in the cumulative region were obtained.
- Universality of the shape of $\Psi(z)$ was used to predict particles spectra in pA collisions in the deep-cumulative range ($1/A << x_2 < 1$).

The results can be used to develop the program to search for new physics phenomena in pA collisions at U70, RHIC, LHC & NICA, FAIR

Thank you for your attention!