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Cumulative particle production and z-scaling

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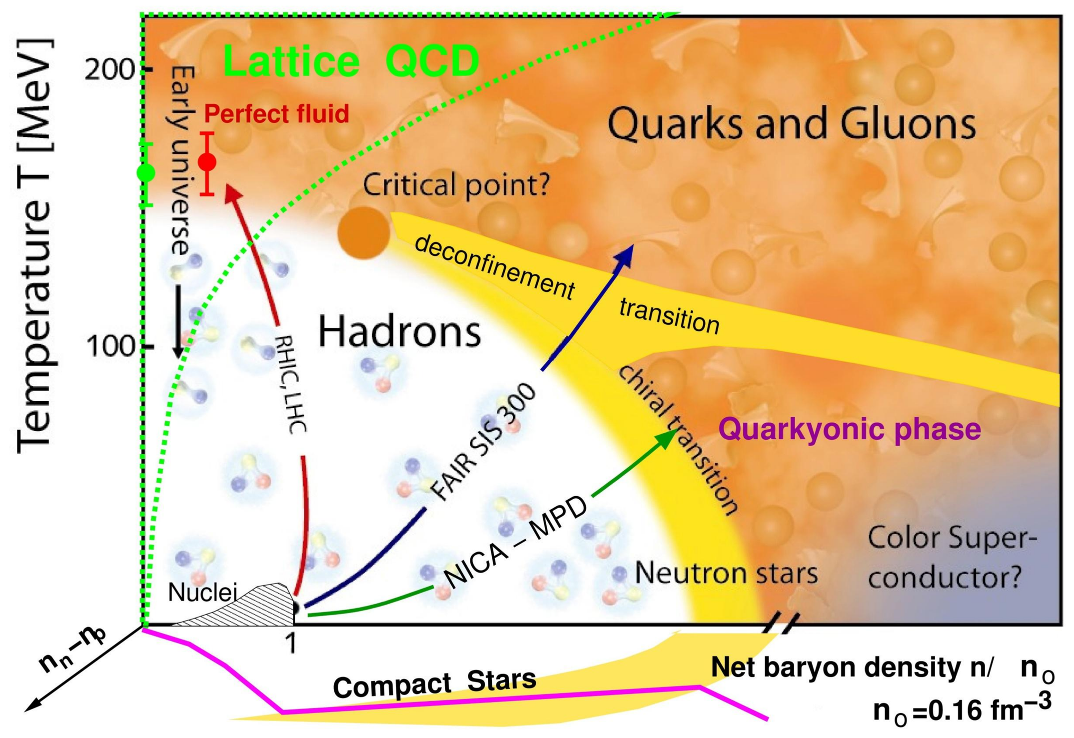
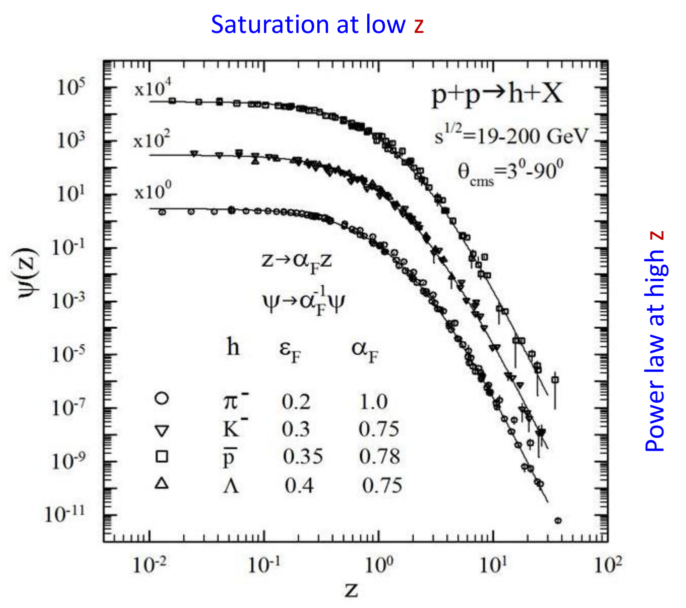
Abstract: Experimental data on inclusive charged particle spectra in p+A collisions are analyzed in the framework of z-scaling. The data on cross sections were taken by groups of G.Leksin at FNAL (Batavia), L.Zolin and V.Gapienko at IHEP (Protvino) with nuclear targets from beryllium up to tungsten. Spectra cover a special kinematics known as a cumulative region. Cumulative particles can be only produced in nuclear collisions. Their production is assumed to be sensitive to the state of the nuclear matter formed at the extreme conditions. Theory of z-scaling is developed for analysis of the cumulative processes and search for phase transition effects. The concept of z-scaling is based on principles of self-similarity, locality and fractality of constituent interactions at small scales. The momentum spectrum of the inclusive particle is recalculated to scaling function $\Psi(z)$ which depends on self-similarly parameter z. A microscopic scenario of p+A interactions in terms of momentum fractions x_1, x_2 is discussed. Results of the analysis are compared with the noncumulative data on high-p_T hadron production in p+A collisions obtained by J.Cronin, R.Sulyaev and D.Jaffe groups. Universality of the shape of function $\Psi(z)$ is used to predict inclusive cross sections of particles produced in the deep-cumulative region.

Phase diagram of strongly interacting matter



Main questions are: *if there is the critical point and where exactly, location of phase borders*

To try and answer that questions we suggest to use concept of z-scaling. It was designed at JINR by M. Tokarev, Yu. Panebratsev, I. Zborovsky and others. z-scaling reveals self-similar properties in hadron, jet and direct photon production in high energy pp & pp-bar collisions. Phys.Rev.D75,094008 (2007)

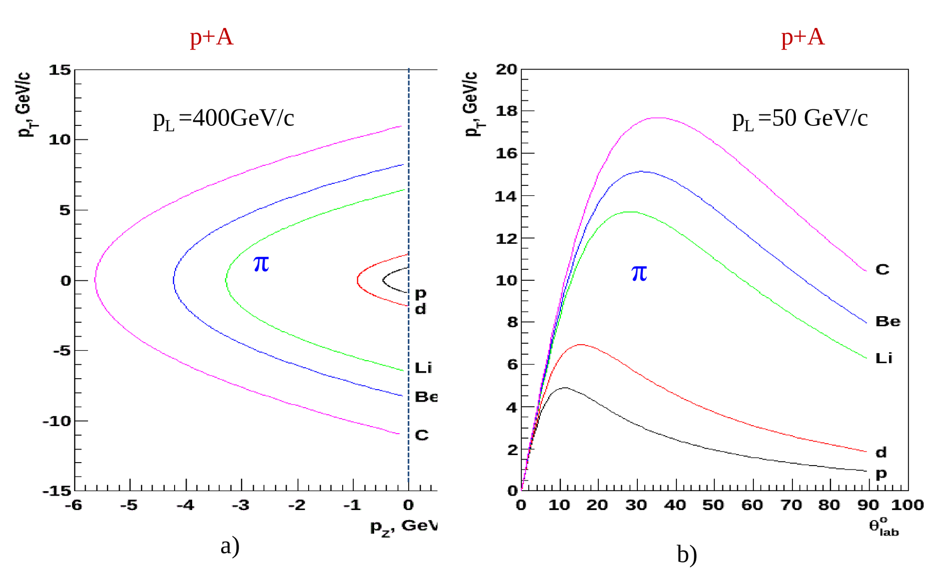


z-presentation of data taken at pp collisions represents scaling – "collapse" of data points onto a single curve.

It is seen from data analysis that z-scaling has following main features:

- Energy independence of $\Psi(z)$ ($s^{1/2} > 20$ GeV)
- Angular independence of $\Psi(z)$ ($\theta_{cms}=3^0$-90^0)
- Multiplicity independence of $\Psi(z)$ ($dN_{ch}/d\eta=1.5$-26)
- Flavor independence of $\Psi(z)$ (π,K,φ,Λ,..,D,J/ψ,B,ϒ,…, top)
- Power law, $\Psi(z) \sim z^{-\beta}$, at high z ($z > 4$)
- Saturation of $\Psi(z)$ at low z ($z < 0.1$)

Concept of cumulation of nucleus was first proposed by A. Baldin and V. Stavinsky (JINR). Cumulative particles are particles produced in the kinematical region forbidden for free nucleon-nucleon interactions. Such particles can be produced only in the processes with participation of nuclei. The interest to the study of cumulative processes is motivated by searching for signatures of the phase transition in the high compressed nuclear matter.
Analysis of experimental data on inclusive spectra of cumulative hadron production in p+A collisions will allow to verify properties of z-scaling.



Kinematical borders in different presentation.
a) Borders of particle production in p_z – p_T presentation Backward hemisphere in laboratory system.
b) Borders of particle production in θ_{lab} - p_T presentation Forward hemisphere in laboratory system.

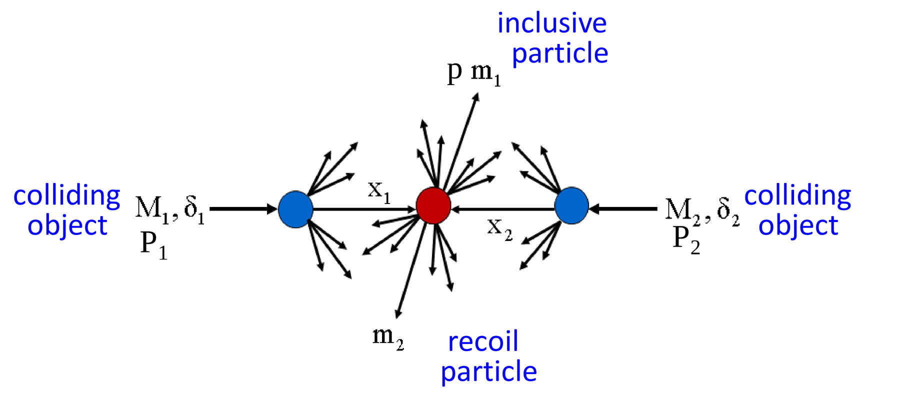
Basic ideas of z-scaling dealing with the investigation of the inclusive process. It is assumed that the main feature of the inclusive particle distribution of process

$$P_1 + P_2 \to p + X$$

at high energies can be described in terms of the corresponding kinematic characteristics of subprocess satisfying the 4-momentum conservation law written in the following form:

$$(x_1P_1 + x_2P_2 - p)^2 = M_X^2$$

The x_1 and x_2 are the fractions of incoming momentum P_1 and P_2 of the colliding objects with masses M_1 and M_2 respectively. The associate production of m_2 ensures conservation of additive quantum numbers.



The scaling variable z is defined as follows:

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

z_0 is the finite part of z

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

It is expressed via the ratio of the transverse energy $s_\perp$ released in the binary collision of constituents and the average multiplicity density $dN/d\eta$ at $\eta=0$ and nucleon mass m.

Ω is the divergent part of z

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

It describes a resolution at which the collision of the constituents can be singled out of this process. It represents a relative number of all initial configurations containing the constituents which carry fractions x_1 and x_2 of the incoming momenta.

δ_1, δ_2 are parameters of the theory characterizing structure of the colliding objects (so-called "fractal dimensions")
Discontinuity of δ_1, δ_2 is a signature of new physics
Value of δ-parameter for nucleus happened to be just simple multiplication of respective nucleon parameters

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

The symmetry transformation

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

of the scaling function and z parameter is used to compare functions Ψ for different nuclei. A-dependence of parameter α is described by the expression:

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

Scaling function $\Psi(z)$ depends in a self-similar manner on single dimensionless variable z. It is expressed via the measurable quantities and is written in the following form:

$$\Psi(z) = \frac{\pi}{(dN/d\eta)\cdot\sigma_{inel}}\cdot J^{-1}\cdot E\frac{d^3\sigma}{dp^3}$$

Here, $Ed^3\sigma/dp^3$ is the invariant cross section, $dN/d\eta$ (s,η)$ is the multiplicity density as a function of center-of-mass collision energy squared s and pseudorapidity η, σ_{in} is the inelastic cross section, J is the corresponding Jacobian. Factor J is known function of the kinematic variables, momenta and masses of the colliding and produced particles.

Function Ψ is normalized as follows:

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

The relation allows us to interpret the function as a probability density to produce a particle with the corresponding value of variable z.

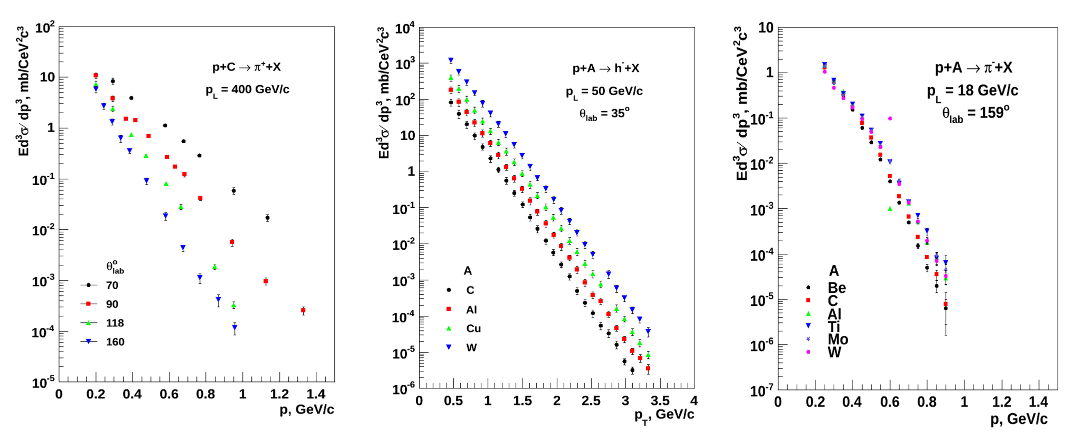
Data sets used for analysis

Experiment performed by G.Leksin group: N.A. Nikiforov et al., Phys.Rev.C22 (1980)700.
The data have been taken with fixed target of the Tevatron (FNAL, Batavia). The data on inclusive invariant cross sections $Ed^3\sigma/dp^3$ for π^-, π^+, K^+, K^-, p, p-bar hadrons produced in a backward hemisphere in p+A collisions at p_L = 400 GeV/c and at angle θ_{lab} of 70°, 90°, 118° and 160° were measured.
The measurements were performed over momentum range of $0.2 < p < 1.25$ GeV/c using Li, Be, C, Al, Cu, Ta nuclear targets.

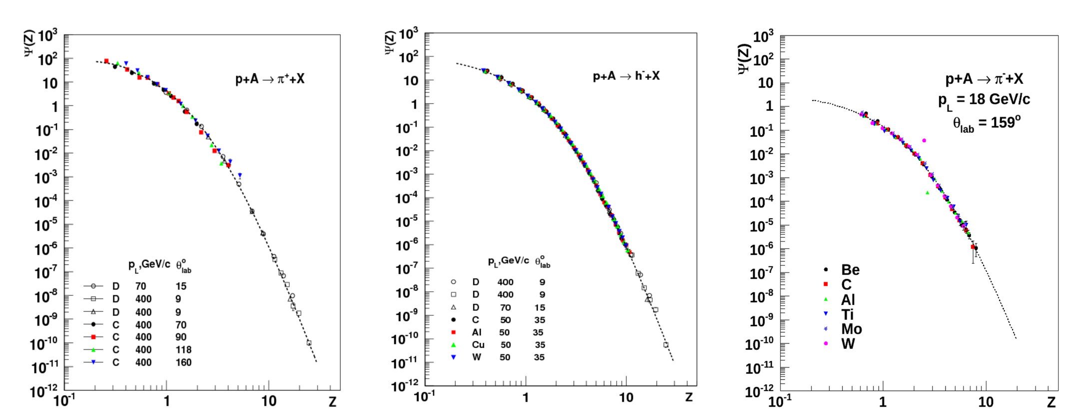
Experiment performed by V.Gapienko group: V.V.Ammosov et al., Phys. At. Nucl. 76 (2013) 1213.
The data on inclusive momentum spectra for unidentified hadrons produced in p+A collisions at p_L = 50 GeV/c and θ_{lab} =35° were obtained at U70 .
The measurements were performed over the range of $0.5 < p_T < 3.8$ GeV/c using C, Al, Cu and W nuclear targets. The cumulative region corresponds to the range $p_T > 2.5$ GeV/c.

Experiment performed by L. Zolin group: O.P.Gavrishchuk et al., Nucl. Phys. A523 (1991) 589.
The data have been taken with an internal target of the U-70 proton synchrotron (IHEP, Serpukhov). Low-p_T invariant inclusive spectra of π^-, π^+ meson production in pA collisions at a laboratory angle of θ_{lab} = 159° using Be, C, Al, Ti, Mo, W nuclear targets. The momentum of projectile protons was 18 GeV/c. The momentum range p > 0.5 GeV/c corresponds to the cumulative pion production.

Momentum presentation of particle spectra



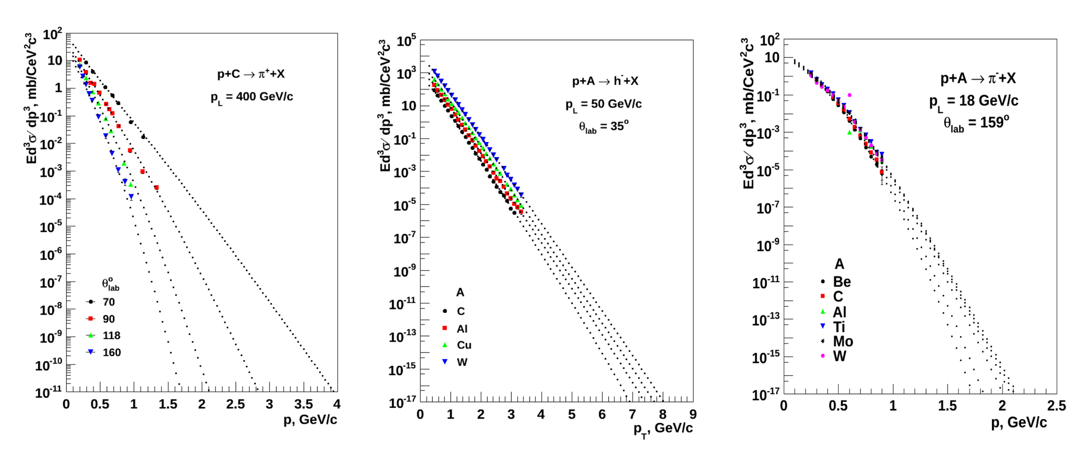
Z presentation of particle spectra fitted by Levy function



JINR preprints: A.Aparin & M.Tokarev, E2-2013-54,.E2-2013-104, E2-2013-139

Conclusions:

- **Data on cumulative hadron spectra obtained by G.Leksin, L.Zolin and V.Gapienko groups in p+A collisions at $\sqrt{s}$ = 11 – 27.4 GeV were analyzed in the framework of z-scaling.**
- **No evidences of new physics were found in the data.**
- **Indication on self-similarity of hadron production in p+A collisions at high energies in the cumulative region were obtained.**
- **Universality of the shape of Ψ(z) was used to predict particles spectra in p+A collisions in deep-cumulative region.**
- **Method of z-scaling could be useful tool for data analysis at future heavy ion experiments FAIR (GSI) & NICA (JINR).**



Momentum presentation of particle spectra with predictions recalculated from Ψ function