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ФИЗИКА ЧАСТИЦ ПРИ СРЕДНИХ  
И ВЫСОКИХ ЭНЕРГИЯХ



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«КУРЧАТОВСКИЙ ИНСТИТУТ»»

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# z-Scaling: Self-similarity from hundreds of MeV to TeV energies

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“Particle Physics at Intermediate and High Energies”,  
June 2 – 5, 2026, IHEP, Protvino, Russia



- Introduction
- $z$ -Scaling (ideas, definitions, hypothesis,...)
- Properties of data  $z$ -presentation
- $z$ -Scaling of hadron production in  $pp$  &  $\bar{p}p$  collisions  
(from  $U70$  to  $LHC$ :  $h, \pi, K, \dots \Omega, top, jets$ )
- Cumulative hadron production in  $pA$
- Scaling properties of hadron production in  $AuAu$  at  $RHIC$
- Microscopic scenario of hadron production
- Summary



## Search for new symmetries in Nature

Systematic analysis of inclusive cross sections of particle production in  $pp$ ,  $pA$  and  $AA$  collisions to search for general features of constituent structure, interaction and fragmentation over a wide scale range

## $z$ -Scaling as a tool in high energy physics

Development of  $z$ -scaling approach for description of production processes with various particles in inclusive reactions and verification of self-similarity principle

Some results of data analysis obtained in  $pp$  and  $AA$  collisions at  $U70$ ,  $ISR$ ,  $RHIC$ ,  $Tevatron$ ,  $LHC$

## The approach can be used to study

- Symmetry of constituent interactions at small scales
- Origin of flavor, spin,...
- Similarity and difference of  $u,d,s,c,b,t$  quark fragmentation
- Strangeness as a probe to search for new physics
- Phase transitions in  $pp$ ,  $pA$  and  $AA$  systems





"Fundamental symmetry principles dictate the basic laws of physics, control the structure of matter and define the fundamental forces in nature."

Leon M. Lederman

"...for every conservation law there must be a continuous symmetry..."

Emmy Nöether



The concepts of symmetry and invariance, play a large role and, it appears, an increasing role in physics.

Eugene P. Wigner



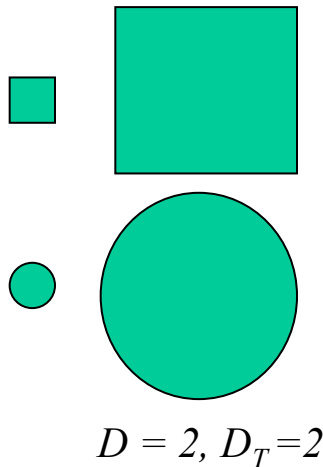
"Scaling" and "Universality" are concepts developed to understand critical phenomena.

Harry E. Stanley, Grigory I. Barenblatt,...

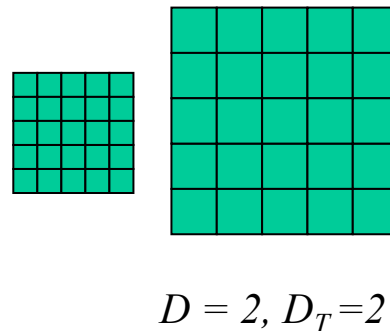


1. Two geometrical objects are similar if one is the result of a uniform scaling (enlarging or shrinking) of the other.
2. Object is self-similar if it is composed of parts similar to it as a whole.
3. Object is a (self) *similar fractal*, if it consists of parts like him as a whole on any scale.

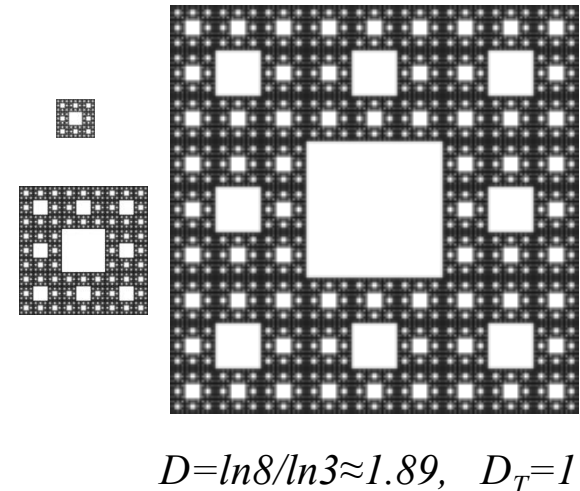
Similar objects



Self-similar object



Fractal

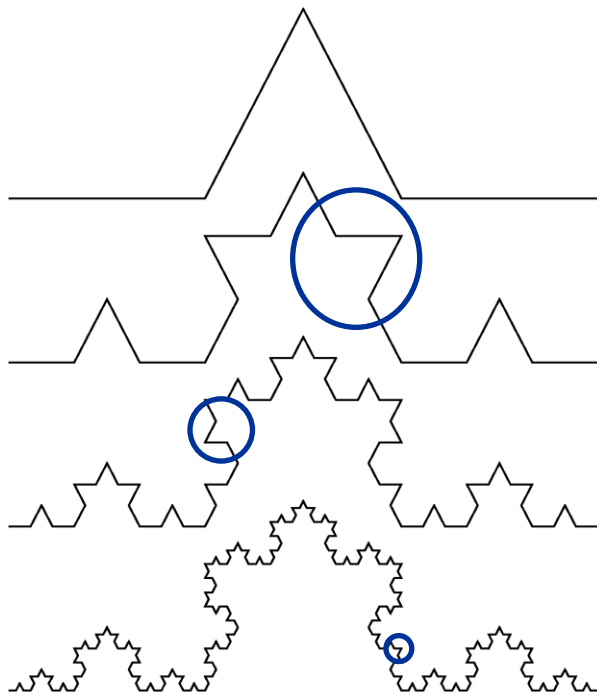


Topological dimension: point,  $D_T = 0$ ; line,  $D_T = 1$ ; surface,  $D_T = 2$ ; volume,  $D_T = 3$ .

$$p = 4, \quad q = 3$$



Swedish mathematician  
Nils Fabian Helge von Koch  
(1870-1924)



$$Z = Z_0 \cdot \varepsilon^{-\delta}$$



A curve length is a measure  
of fractal curve

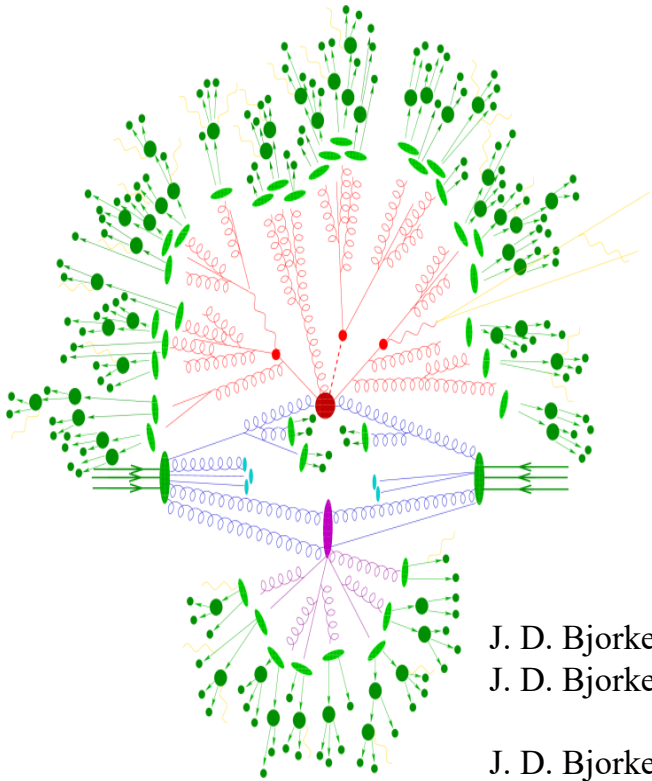


$$Z(\varepsilon) \Big|_{\varepsilon^{-1} \rightarrow \infty} \rightarrow \infty$$



- $\varepsilon^{-1} = q^n$  resolution
- $D = \text{Ln}(p)/\text{Ln}(q)$  fractal dimension
- $D_T = 1$  topological dimension
- $\delta = D - D_T$  anomalous fractal dimension





Set of hadrons produced in inelastic interaction are set of points of the phase-space  $\{p_T, \eta, \phi\}$

The distribution of points is determined by the interaction dynamics:

- hard scattering
- parton showers in the initial and final state
- multiparticle interactions
- fragmentation of partons into hadrons
- decay of unstable hadrons

J. D. Bjorken, Future Directions for QCD, SLAC-PUB-6477 (1994); arXiv:hep-ph/9610516

J. D. Bjorken, Fractal phase space as a diagnostic tool for high-energy multijet processes, Phys. Rev. D 45 (1992) 4077.

J. D. Bjorken, Energy Loss of Energetic Partons in Quark-Gluon Plasma: Possible Extinction of High  $p_T$  Jets in Hadron-Hadron Collisions. FERMILAB-Pub-82/59-THY, August, 1982

- A new direction for the study of QCD at high-energy colliders is the fractality of parton cascades, which leads to an anomalous dimension of the phase space.
- The clearly seeing this fractality is a big experimental task.
- Energy loss of energetic partons in Quark Gluon Plasma.



Fractal is the self-similar object whose  $D_F \neq D_T$

$N(l)$  - number of probes with size  $l$  covering the object

$$M = \lim_{l \rightarrow 0} \sum_1^N l^{D_T}$$

Euclidean:  $M = \text{const}$  independent of scale, determines size

Fractal:  $M \neq \text{const}$   $N(l)$  and  $l$  are changed in different ways

Hausdorff measure is introduced

to evaluate the dependence of  $N(l)$  on  $l$

$$M_H = \lim_{\delta \rightarrow 0} \sum_{i=1}^N l_i^d$$

$N$  - is number of probes with size  $l_i < d$

$$\begin{aligned} M_H &\rightarrow 0, & d > D_F \\ M_H &\rightarrow \text{const}, & d = D_F \\ M_H &\rightarrow \infty, & d < D_F \end{aligned}$$

Fractal dimension is the value  $D_F$  which provides the finite  $M_H$

Box fractal dimension

$$D_b = -\lim_{l \rightarrow 0} \frac{\ln N(l)}{\ln(l)}$$

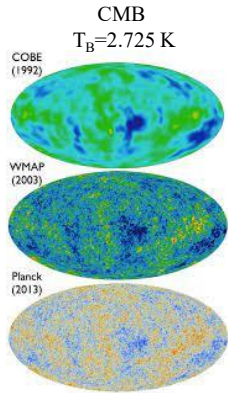
Triad Cantor Set



Fractal characteristics

- Base  $P=3$ , the original space is divided into 3 parts
- Structure  $S=101$ , the 1-st and 3-rd parts remains and 2-nd part is removed
- Independent partition
- Number of levels  $N_{lev}=5$
- Dimension  $D_F = \ln 2 / \ln 3$





Cosmic microwave background radiation



Milky Way galaxy



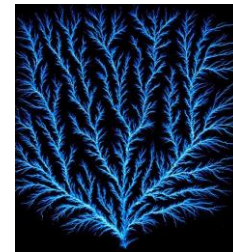
Russian doll



The shell of Epitoniid scalare



Romanesco Broccoli



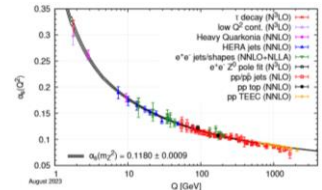
Electrical discharge Lichtenberg figure



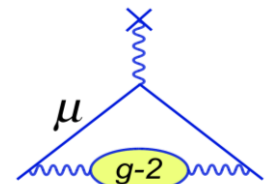
Frost pattern

**Self-similarity** is a property of physical phenomena and principle to construct theories

- Self-similarity is the **symmetry** of repeatability of structures and processes with change in a scale.
- The self-similarity **principle** states that structures and processes repeats with change of a scale.
- Self-similarity is the **unifying concept** for theories of fractals and chaos.
- **Phenomenon** that is self-similar looks the same or behaves the same when viewed at different magnifications.
- The **renormalization group** is related to scale invariance and conformal invariance, symmetries in which a system appears the same at all scales (**self-similarity**).



$\alpha_s$  - running coupling constant



Renormalization group





"Fundamental symmetry principles dictate the basic laws of physics, control the structure of matter, and define the fundamental forces in Nature."

Leon M. Lederman

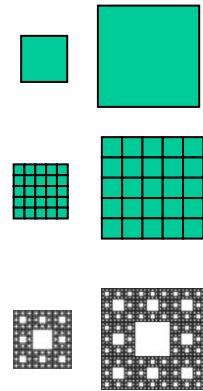
**Self-similarity** is a property of physical phenomena and principle to construct theories.

**Flavor, spin, mass** are fundamental properties of quarks. Their origin has relevance to structure of the momentum space at small scales.

**Phase transitions** and **critical phenomena**.  
Search for and study new states of nuclear matter.



- A self-similar object is exactly or approximately **similar** to a part of itself (i.e. the whole has the same shape as one or more of the parts).
- **Self-similarity** is a typical property of **fractals**.
- **Scale invariance** is an exact form of self-similarity where at any magnification there is a smaller piece of the object that **is similar** to the whole.



Description of a process in terms of a scaling function and similarity parameter

Reynolds number

$$Re = \rho V d / \eta$$

laminar & turbulent flow

Mach number

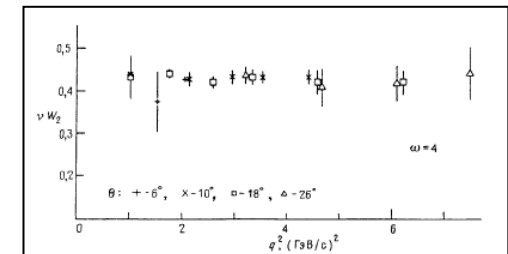
$$Ma = v / c$$

subsonic & supersonic wave

Bjorken variable

$$x = -q^2 / 2(pq)$$

low x & high x



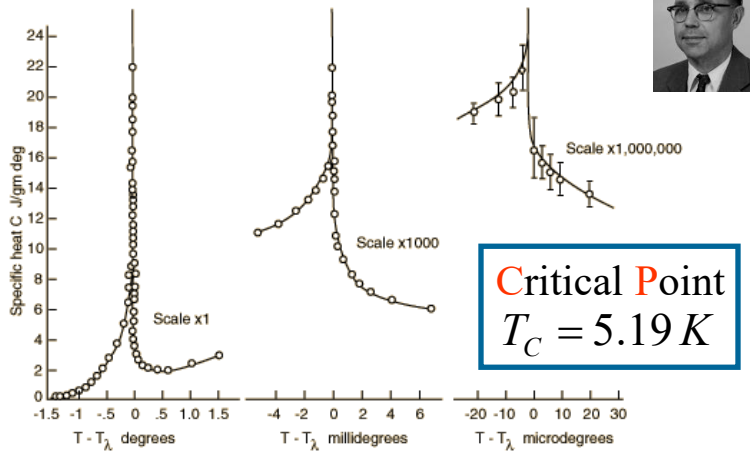
shock wave, explosion, confinement

Violation of a scaling is an indication of new phenomena.



# Singularity of specific heat near a **Critical Point**

## Specific heat of liquid $^4\text{He}$ Superfluid transition



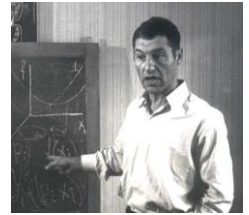
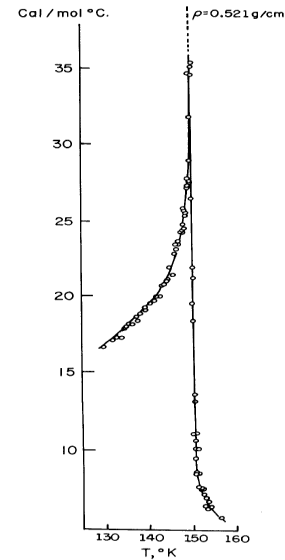
M. J. Buckingham and W. M. Fairbank, 1961  
H.E. Stanley, 1971

- Near a critical point the singular part of thermodynamic potentials is a Generalized Homogeneous Function (GHF).
- The Helmholtz potential  $F(\lambda^{\alpha_\varepsilon} \varepsilon, \lambda^{\alpha_V} V) = \lambda F(\varepsilon, V)$  is GHF of  $(\varepsilon, V)$ .

$$c_V \sim |\varepsilon|^{-\alpha} \quad \varepsilon \equiv (T - T_c)/T_c \quad c_V = -T(\partial^2 F / \partial T^2)|_V$$

Critical exponents define the behavior  
of thermodynamic quantities nearby the **Critical Point**.

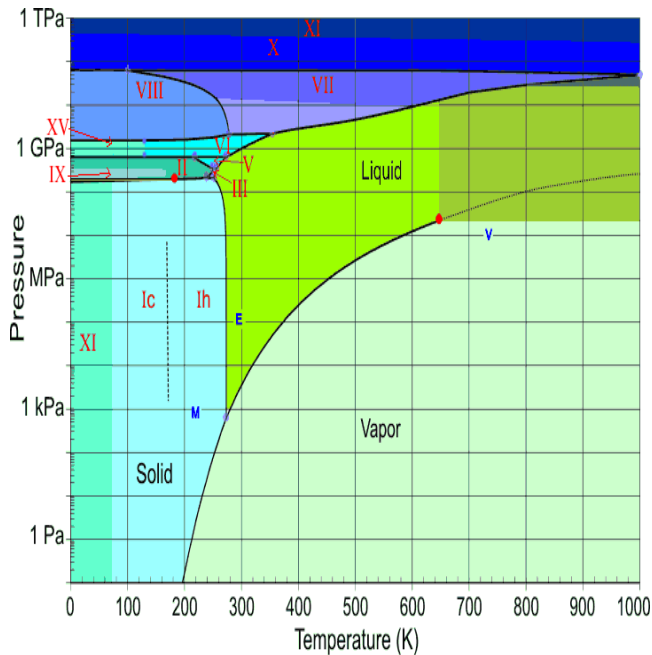
## Heat capacity of Ar



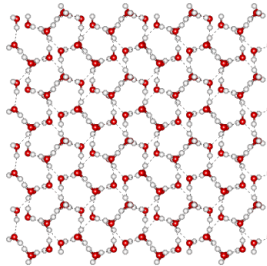
The isochoric heat capacity  $c_V$   
of argon becomes infinite  
at the vapor-liquid critical point.

A. V. Voronel' et al.  
Zh. Exp. Teor. Fiz. 43, 728 (1962).

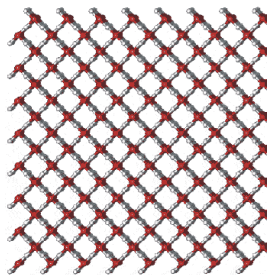
The phase diagram of water is established



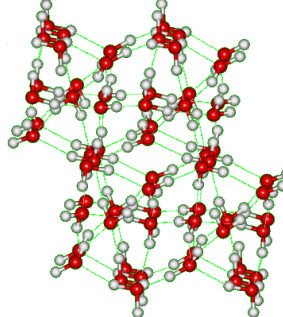
Ice III



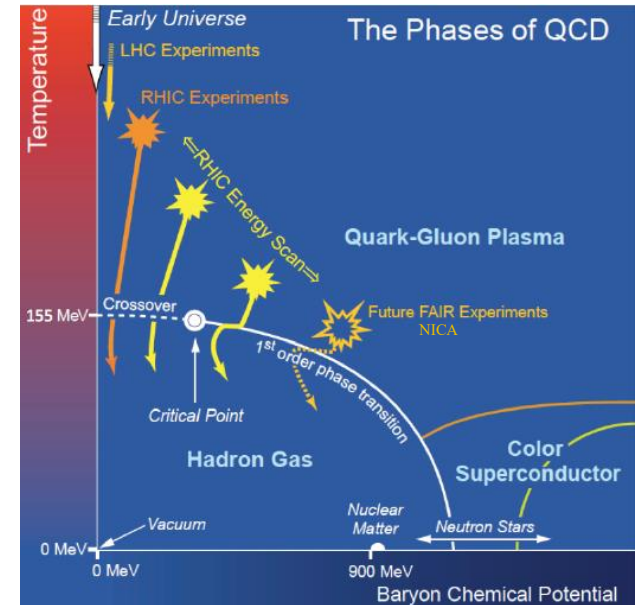
Ice X



Ice XIII



The phase diagram of strongly interacting nuclear matter is under study



- Phases (ice I-XV, liquid, vapor)
- Phase boundaries
- Phase transitions
- Triple Point (16)
- Critical Point (1)

- Phases - ?
- Phase boundaries - ?
- Phase transitions - ?
- Triple Point - ?
- Critical Point - ?



## Conclusions I

Symmetry principles are a fundamental tool in modern science, both to describe natural phenomena and to predict new ones and to construct consistent physical theories.



Symmetry is the idea by which man has tried throughout the ages to comprehend and create order, beauty and perfection.

Hermann Weyl

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## **z-Scaling:** ideas, definitions, hypothesis,...

- search for new symmetries in high energy physics
- search for new phenomena: particle substructure, phase transitions,...
- a tool for data analysis, verification and development of theory



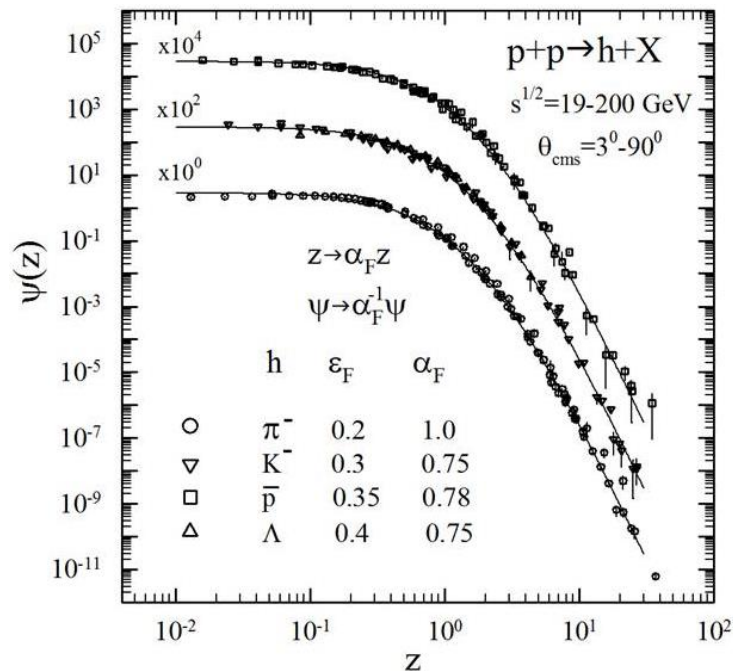
Inclusive cross sections of  $\pi^-$ ,  $K^-$ ,  $\bar{p}$ ,  $\Lambda$  in pp collisions

FNAL:  
PRD 75 (1979) 764

ISR:  
NPB 100 (1975) 237  
PLB 64 (1976) 111  
NPB 116 (1976) 77  
(low  $p_T$ )  
NPB 56 (1973) 333  
(small angles)

STAR:  
PLB 616 (2005) 8  
PLB 637 (2006) 161  
PRC 75 (2007) 064901

Saturation at low  $z$



Power law at high  $z$

Energy scan of spectra at U70, ISR, SppS, SPS, HERA, FNAL(fixed target), Tevatron, RHIC, LHC

MT & I.Zborovsky  
T.Dedovich

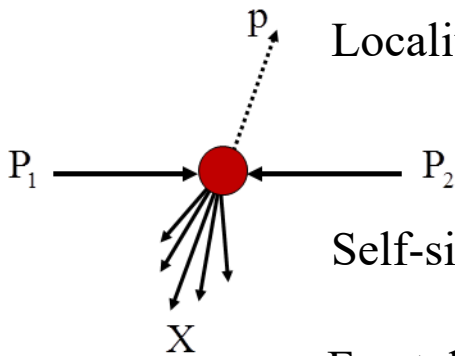
Phys.Rev.D75(2007)094008  
Int.J.Mod.Phys.A24(2009)1417  
J. Phys.G: Nucl.Part.Phys.  
37(2010)085008  
Int.J.Mod.Phys.A27(2012)1250115  
J.Mod.Phys.3(2012)815  
Int.J.Mod.Phys. A 32(2017)1750029

- Energy & angular independence
- Flavor independence ( $\pi$ ,  $K$ ,  $\bar{p}$ ,  $\Lambda$ )
- Saturation for  $z < 0.1$
- Power law  $\Psi(z) \sim z^{-\beta}$  for high  $z > 4$

Scaling – “collapse” of data points onto a single curve.  
Universality classes – hadron species ( $\epsilon_F$ ,  $\alpha_F$ ).



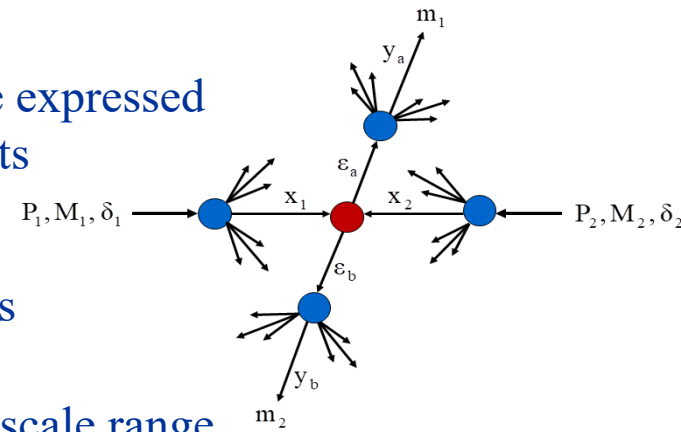
## Principles: locality, self-similarity, fractality



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: self-similarity is valid over a wide scale range.



## Hypothesis of z-scaling :

$$s^{1/2}, p_T, \theta_{\text{cms}}$$

Inclusive particle distributions can be described in terms of constituent sub-processes and parameters characterizing bulk properties of the system.

$$x_1, x_2, y_a, y_b$$

$$\delta_1, \delta_2, \epsilon_a, \epsilon_b, c$$

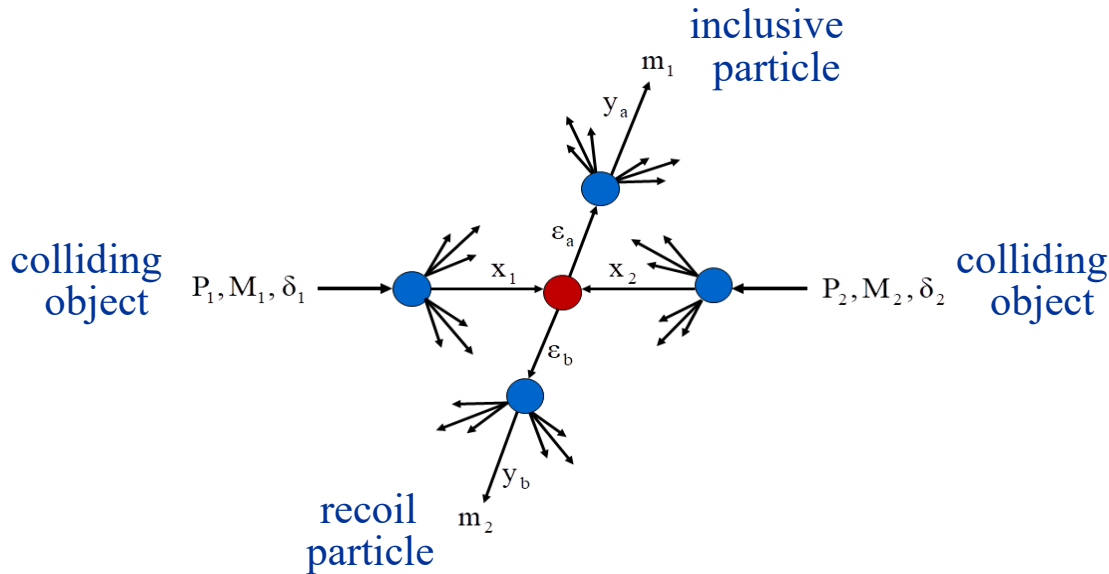
$$Ed^3\sigma/dp^3$$

Scaled inclusive cross section of particles depends in a self-similar way on a single scaling variable  $z$ .

$$\Psi(z)$$



## Collisions of colliding objects are expressed via interactions of their constituents



$P_1, P_2, p$  – momenta of colliding and produced particles

$M_1, M_2, m_1$  – masses of colliding and produced particles

$x_1, x_2$  – momentum fractions of colliding particles carried by constituents

$y_a, y_b$  – momentum fractions of scattered constituents carried by inclusive particle and its recoil

$\delta_1, \delta_2$  – fractal dimensions of colliding particles

$\epsilon_a, \epsilon_b$  – fractal dimensions of scattered constituents (fragmentation dimensions)

$m_2$  – mass of recoil particle

Elementary sub-process:

$$(x_1 M_1) + (x_2 M_2) \rightarrow (m_1 / y_a) + (x_1 M_1 + x_2 M_2 + m_2 / y_b)$$

Momentum conservation law for sub-process

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

Mass of recoil system

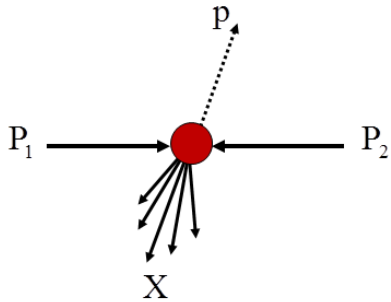
$$M_X = x_1 M_1 + x_2 M_2 + m_2 / y_b$$

M.Tokarev, I.Zborovský  
Yu.Panebratsev, G.Skoro  
Phys.Rev.D54 5548 (1996)  
Int.J.Mod.Phys.A16 1281 (2001)



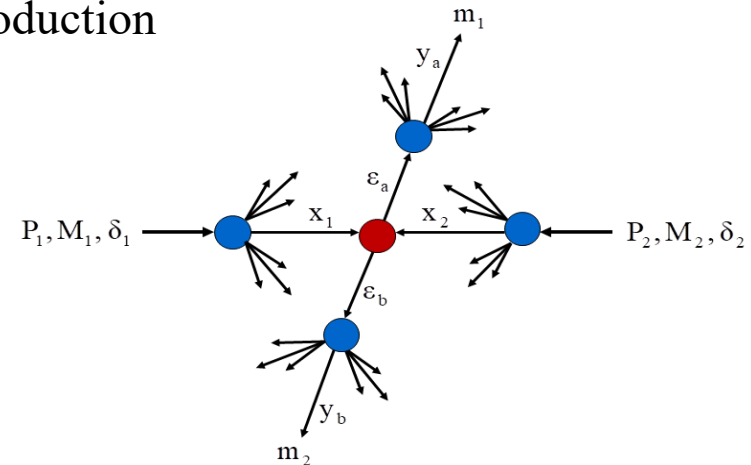
## Interactions of constituents are mutually similar

The self-similarity parameter  $z$  is a dimensionless quantity, expressed through the dimensional values  $P_1, P_2, p, M_1, M_2, m_1, m_2$ , characterizing the process of inclusive particle production



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

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



- $\Omega^{-1}$  is the minimal resolution at which a constituent sub-process can be singled out of the inclusive reaction
- $s_{\perp}^{1/2}$  is the transverse kinetic energy of the sub-process consumed on production of  $m_1$  &  $m_2$
- $dN_{ch}/d\eta|_0$  is the multiplicity density of charged particles at  $\eta = 0$
- $c$  is a parameter interpreted as a “specific heat” of created medium
- $m_N$  is an arbitrary constant (fixed at the value of nucleon mass)

## Self-similarity over a wide scale range

Fractal measure

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

$$\Omega = (1 - x_1)^{\delta_1} (1 - x_2)^{\delta_2} (1 - y_a)^{\varepsilon_a} (1 - y_b)^{\varepsilon_b}$$

$$0 < x_1, x_2 < 1$$

$$0 < y_a, y_b < 1$$

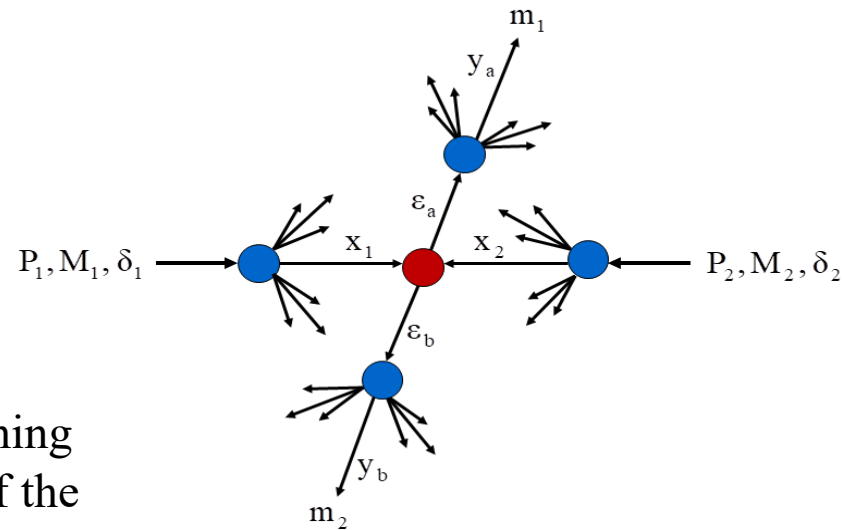
$\Omega$  is relative number of configurations containing a sub-process with fractions  $x_1, x_2, y_a, y_b$  of the corresponding 4-momenta

$\delta_1, \delta_2, \varepsilon_a, \varepsilon_b$  are parameters characterizing structure of the colliding objects and fragmentation process, respectively

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

The fractal measure  $z$  diverges as the resolution  $\Omega^{-1}$  increases.

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



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

## Momentum conservation law

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

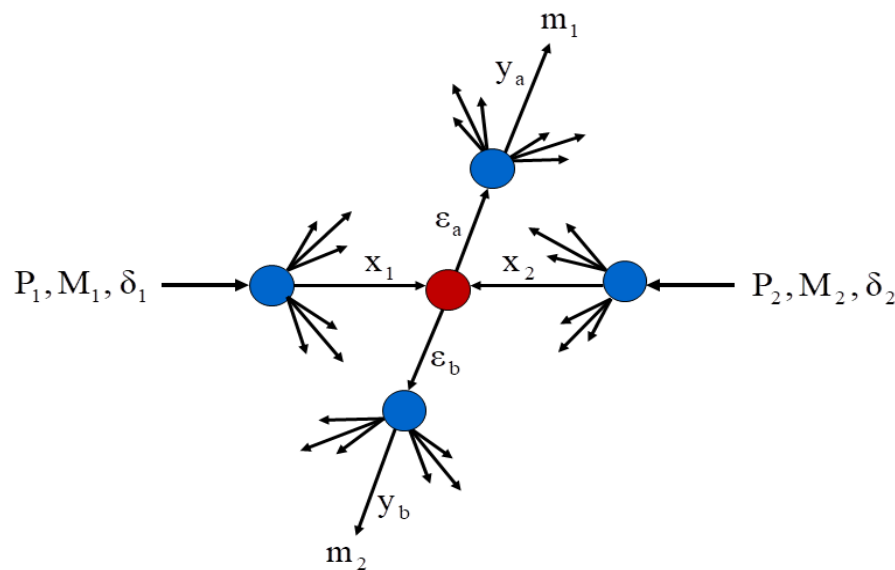
$$\begin{cases} \partial\Omega / \partial x_1 |_{y_a=y_a(x_1, x_2, y_b)} = 0 \\ \partial\Omega / \partial x_2 |_{y_a=y_a(x_1, x_2, y_b)} = 0 \\ \partial\Omega / \partial y_b |_{y_a=y_a(x_1, x_2, y_b)} = 0 \end{cases}$$

## Resolution of sub-process

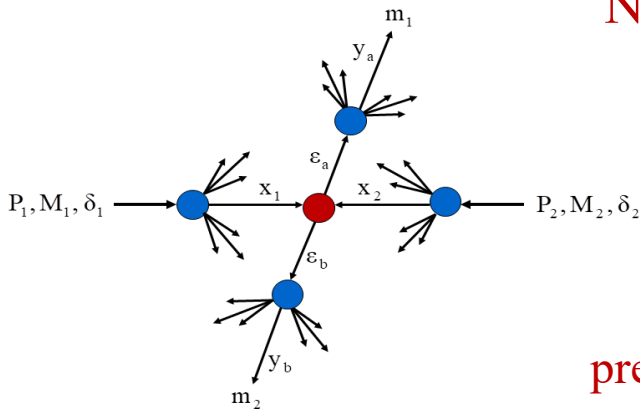
$$\Omega^{-1} = (1 - x_1)^{-\delta_1} (1 - x_2)^{-\delta_2} (1 - y_a)^{-\varepsilon_a} (1 - y_b)^{-\varepsilon_b}$$

## Mass of recoil system

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



Fractions  $x_1, x_2, y_a, y_b$  are expressed via Lorentz invariants – scalar products of 4-D momenta and particle masses.



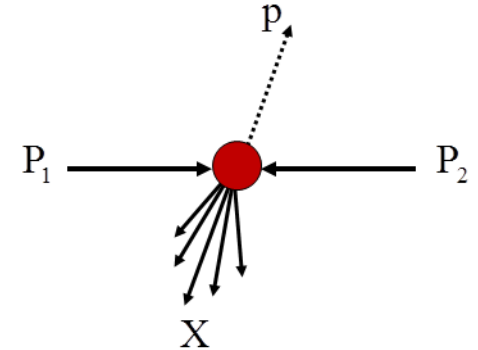
Normalization condition

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

Scale transformation

$$z \rightarrow \alpha_F z \quad \Psi(z) \rightarrow \alpha_F^{-1} \Psi(z)$$

preserves the normalization condition



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

- $\sigma_{inel}$  - the inelastic cross section
- $\langle N \rangle$  - the average multiplicity
- $dN/d\eta$  - the multiplicity density
- $J(z, \eta; p_T^2, y)$  - the Jacobian
- $E d^3\sigma/dp^3$  - the inclusive cross section

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

- Energy independence of  $\Psi(z)$  ( $s^{1/2} > 20$  GeV)
- Angular independence of  $\Psi(z)$  ( $\theta_{\text{cms}} = 3^\circ - 90^\circ$ )
- Multiplicity independence of  $\Psi(z)$  ( $dN_{\text{ch}}/d\eta = 1.5 - 26$ )
- Saturation of  $\Psi(z)$  at low  $z$  ( $z < 0.1$ )
- Power law,  $\Psi(z) \sim z^{-\beta}$ , at high  $z$  ( $z > 4$ )
- Flavor independence of  $\Psi(z)$  ( $\pi, K, \phi, \Lambda, \dots, D, J/\psi, B, Y, \dots, \text{top}$ )

These properties reflect **self-similarity**, **locality**, and **fractality** of hadron interactions at a constituent level.

It concerns the **structure** of the colliding objects, constituent interactions and fragmentation process.



## Conclusions II

- New method of analysis of inclusive particle spectra based on symmetry principles was proposed.
- The method is based on self-similarity of particle structure, constituent interactions and fragmentation process.
- The model parameters characterize the fractal structure of particles and medium.



## Self-similarity of hadron production in $p+p$ collisions

$p+p$  is of interest by itself:

- verification and search for new features
- search for a phase transition with different probes

$p+p$  interaction is a reference for  $p+A$  and  $A+A$  physics

PS, FNAL	J,W, Cronin et al., Phys.rev. D 11 (1975) 3105
PS, FNAL	D. Antreasyan et al., Phys. Rev. D 19 (1979) 764
U70	V.V. Abramov et al., Sov. J. Nucl. Phys. 31 (1980) 484
U70	V.V. Abramov et al., JETP Lett. 33 (1981) 289
Tevatron, FNAL	D. E. Jaffe et al., Phys. Rev. D 40 (1989) 2777
ISR, CERN	A. Breakstone et al., Z. Phys. C 69 (1995) 55
ISR, CERN	D. Drijard et al., Nucl. Phys. B 208 (1982) 1
RHIC, BNL	G. Agakishiev et al., Phys. Rev. Lett. 108 (2012) 072302

I.Zborovský, MT, Int. J. Mod. Phys. (2015) 1560103.

Int. J. Mod. Phys. A 32, 1750029 (2017)

Phys. Part. Nucl. 51, 141 (2020)



## Self-similarity parameter

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

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

$$\Omega = (1-x_1)^\delta (1-x_2)^\delta (1-y_a)^{\varepsilon_F} (1-y_b)^{\varepsilon_F}$$

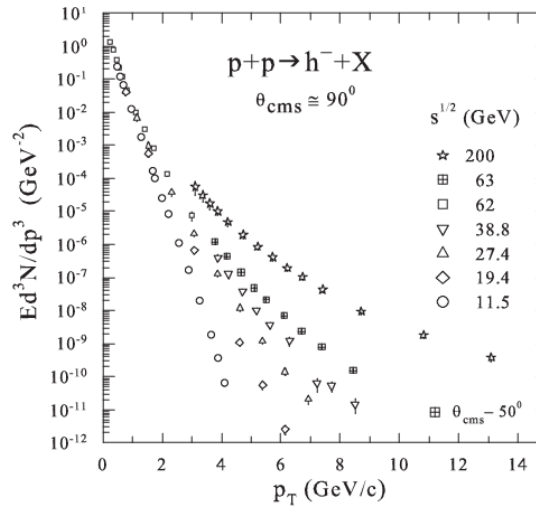
- $dN_{ch}/d\eta|_0$  - multiplicity density
- $c$  - “specific heat” of bulk matter
- $\delta$  - proton fractal dimension
- $\varepsilon_F$  - fragmentation fractal dimension

## Scaling function

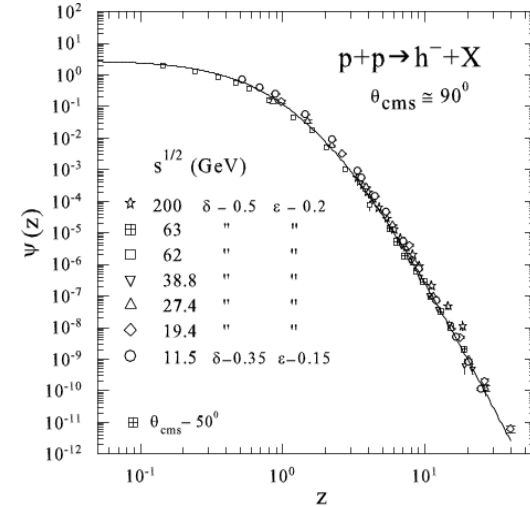
$$\Psi(z) = \frac{\pi}{(dN/d\eta) \cdot \sigma_{incl}} \cdot J^{-1} \cdot E \frac{d^3\sigma}{dp^3}$$

- **Universality:** the same shape of  $\Psi(z)$  vs.  $\sqrt{s}$ ,  $p_T$
- Asymptotic behavior of  $\Psi(z)$  at high  $z$  – power law.

## Strong sensitivity of data point to $\sqrt{s}$ at high $p_T$



## “Collapse” of data point onto a single curve



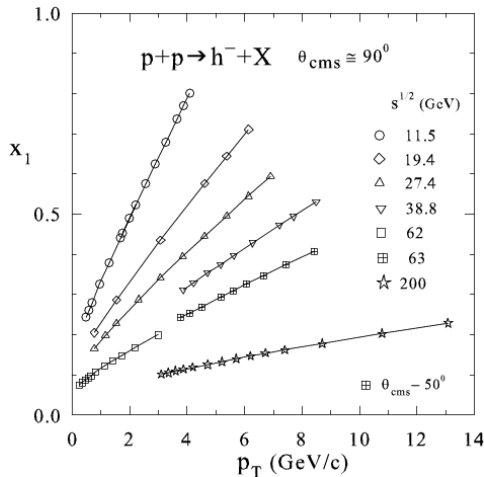
## $z$ -Scaling

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



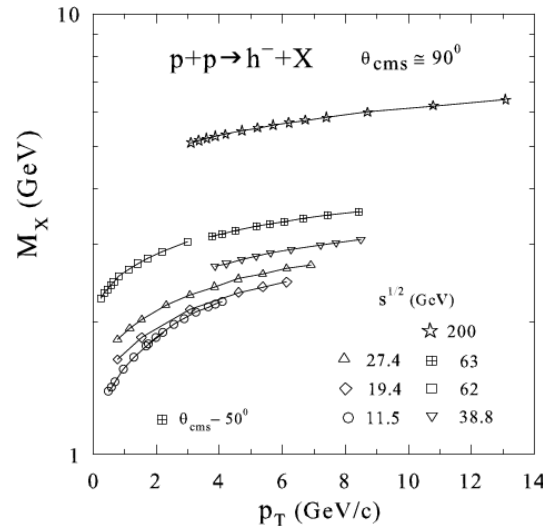
## Constituent level of particle production in terms of

### Momentum fraction $x_1$


 $x_1$ 

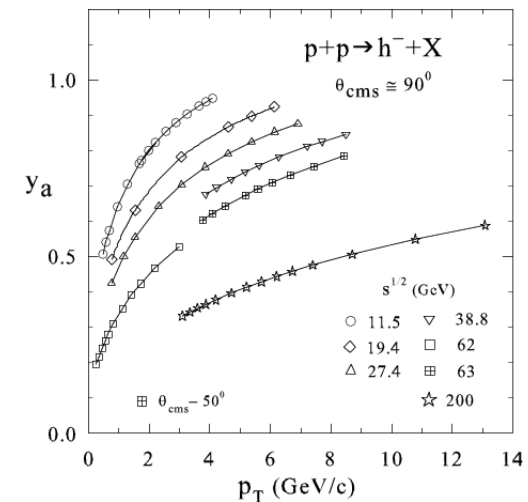
- increases with  $p_T$
- decreases with  $\sqrt{s}$

### Recoil mass $M_X$


 $M_X$ 

- increases with  $p_T$
- increases with  $\sqrt{s}$

### Energy loss $\Delta E/E = (1 - y_a)$


 $\Delta E/E$ 

- decreases with  $p_T$
- increases with  $\sqrt{s}$

- $p+p$  is a reference for  $p+A$  and  $A+A$
- high  $x_1$  and  $p_T$  – physics nearby a kinematic boundary

## Conclusions III

- Self-similarity of particle structure, constituent interactions and fragmentation process of hadron production in  $p+p$  collisions was found.
- Properties of the scaling function were described.
- Model parameters – **structural and fragmentation fractal dimensions** and specific heat, were determined from data analysis.

**Fractal dimension** is a fundamental property of each particle, just like mass, charge, spin, flavor,...

I.Zborovsky & MT  
Int. J. Mod. Phys. A 33, 1850057 (2018)  
ICHEP 2020, Prague, July 28 –August 6  
MU Physics Bulletin 79 (2024) S120  
Phys. Part. Nucl. Lett. 22 (2025) 151



# Strange hadron production in $pp$ collisions

$pp$  is of interest by itself:

- verification and search for new features
- search for a phase transition with different probes

$pp$  interaction is a reference frame for  $pA$  and  $AA$  physics

## Origin of flavor ?



## Self-similarity parameter

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

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

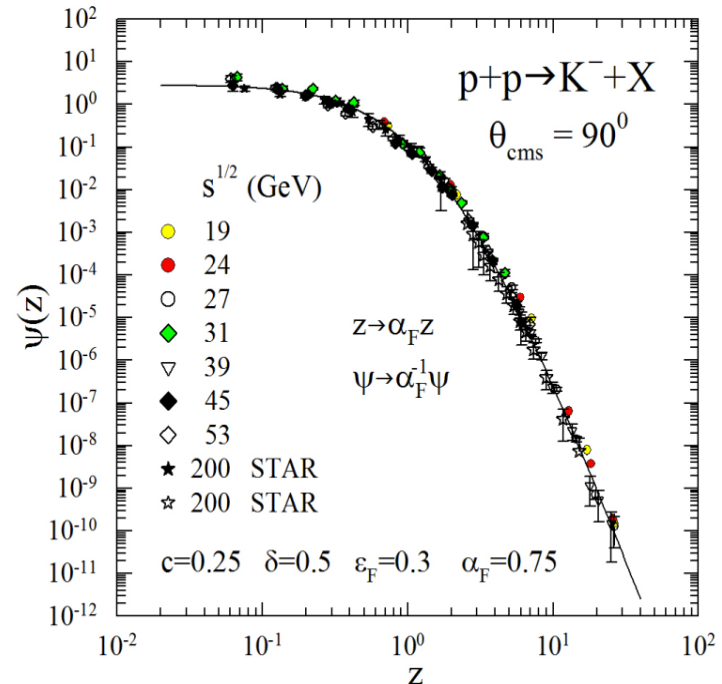
$$\Omega = (1-x_1)^\delta (1-x_2)^\delta (1-y_a)^{\varepsilon_F} (1-y_b)^{\varepsilon_F}$$

- $dN_{ch}/d\eta|_0$  - multiplicity density
- $c$  - “specific heat” of bulk matter
- $\delta$  - proton fractal dimension
- $\varepsilon_F$  - fragmentation fractal dimension

## Scaling function

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

“Collapse” of data points onto a single curve



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

Universality: the same shape of  $\Psi(z)$  both for  $K^-$  and  $\pi^-$  (solid line)



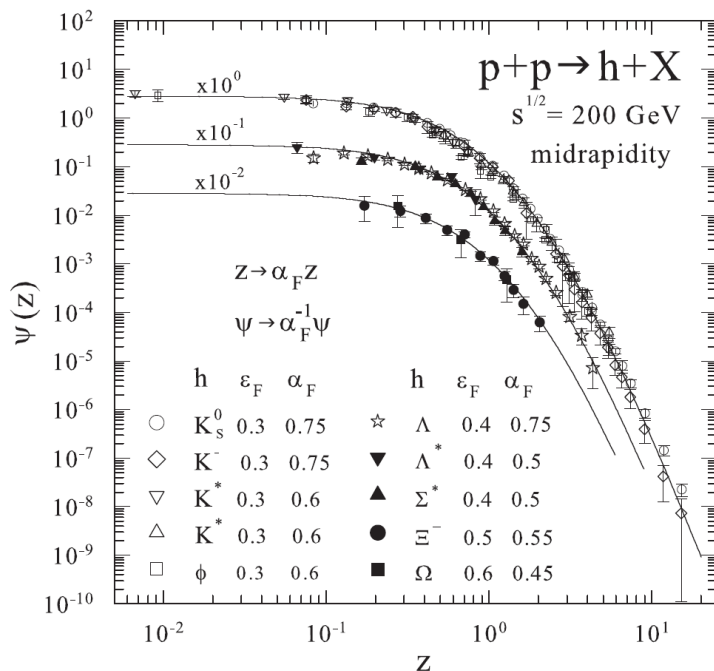
## Universality: flavor independence of the scaling function

$K_S^0, K^-, K^*, \phi, \Lambda, \Xi, \Omega, \Sigma^*, \Lambda^*$

M.T.& I.Zborovský  
Int.J.Mod.Phys.  
A32,1750029(2017)

Solid line for  $\pi^-$  meson  
is a reference frame

$$\varepsilon_\pi = 0.2, \quad \alpha_\pi = 1$$



PRL 92 (2004) 092301  
PRL 97 (2006) 132301  
PLB 612 (2005) 181  
PRC 71 (2005) 064902  
PRC 75 (2007) 064901  
PRL 108 (2012) 072302



PRC 75 (2007) 051902  
PRD 83 (2011) 052004  
PRC 90 (2014) 054905

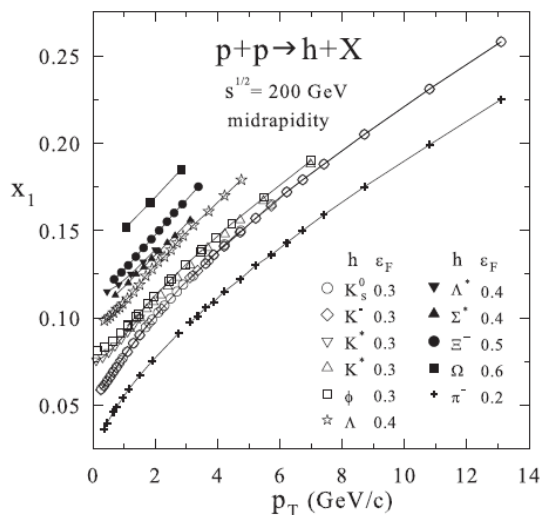
- Flavor independence
- Saturation for  $z < 0.01$
- Power law  $\Psi(z) \sim z^{-\beta}$  at large  $z$
- $\varepsilon_F, \alpha_F$  independent of  $p_T, s^{1/2}$



$$K_S^0, K^-, K^*, \phi, \Lambda, \Xi, \Omega, \Sigma^*, \Lambda^*$$

Constituent level of particle production in terms of

Momentum fraction

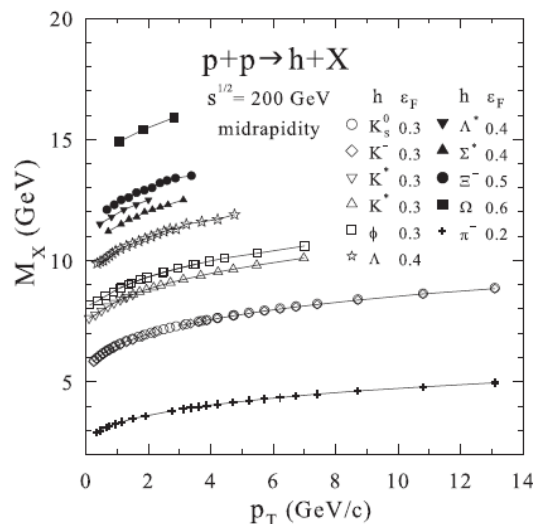


$$X_1^{\text{Baryon}} > X_1^{\text{Meson}}$$

The more strangeness, the larger momentum fraction

$$X_1^\Omega > X_1^\Xi > X_1^\Sigma$$

Recoil mass

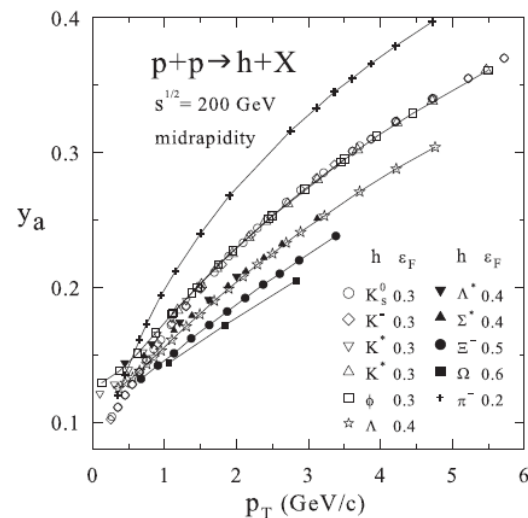


$$M_X^{\text{Baryon}} > M_X^{\text{Meson}}$$

The more strangeness, the larger recoil mass

$$M_X^\Omega > M_X^\Xi > M_X^\Sigma$$

Energy loss  $\Delta E/E \sim (1-y_a)$



$$\varepsilon^{\text{Baryon}} > \varepsilon^{\text{Meson}}$$

The more strangeness, the larger energy loss

$$\varepsilon_\Omega > \varepsilon_\Xi > \varepsilon_\Sigma$$

Self-similarity dictates the properties of constituent sub-process.

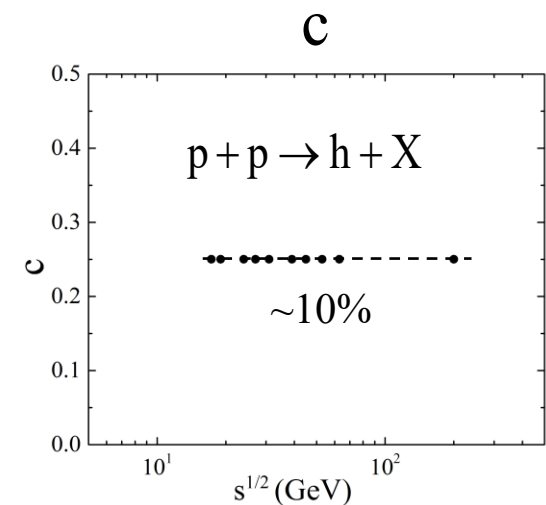
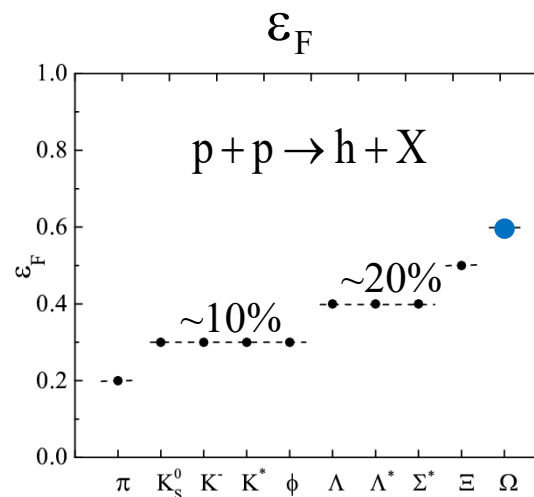
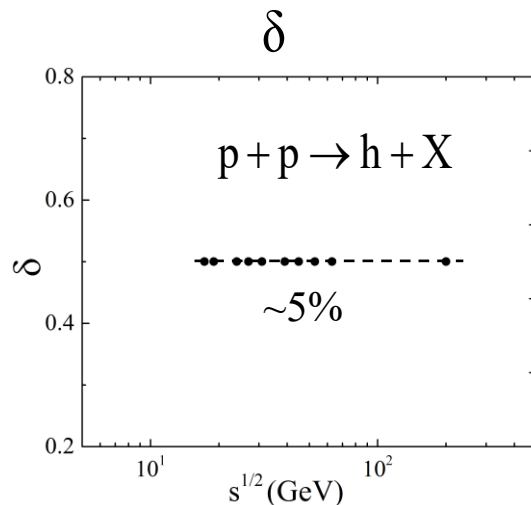


Parameters  $\delta$ ,  $\epsilon_F$ ,  $c$  are found from the scaling behavior of  $\Psi$  as a function of self-similarity variable  $z$

Proton fractal dimension

Fragmentation dimension

“Specific heat”



- $\delta$ ,  $\epsilon_F$ ,  $c$  are independent of  $\sqrt{s}$ ,  $p_T$
- $\epsilon_F$  depends on flavor

A discontinuity and strong correlation of the model parameters could give indication on new physics in pp collisions:  
Search for phase transition, critical point .... with strange probes.

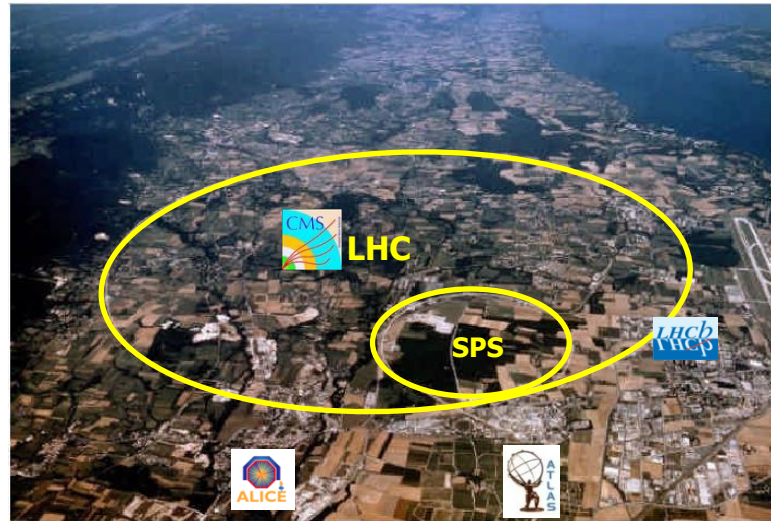
## Conclusions IV

- Strange particles are probes of the matter produced in **pp** collisions.
- Self-similarity of strange particle structure, constituent interactions and fragmentation process was confirmed.
- The fractal structure of strange particles was justified.



# Top quark production in $pp$ collisions at the LHC

What about self-similarity and flavor independence of  $\Psi(z)$  for top quark production in  $pp$  collisions at the LHC ?



J.Mod.Phys.3(2012)815

ISMD2016

Phys.Part.Nucl.Lett.14(2017)681





"Fundamental symmetry principles dictate the basic laws of physics, control the structure of matter, and define the fundamental forces in Nature."

Leon M. Lederman

**Self-similarity** is a property of physical phenomena and principle to construct theories.

**Flavor** is a fundamental property of **top** quark. The flavor has relevance to the structure of the momentum space at small scales.

**Top physics** is a pillar of the current research program in **HEP** and provides stringent tests of **SM**.



## Top-quark discovery 1995

CDF Collab. F.Abe et al.  
Phys. Rev. Lett. 74 (1995)2626.  
DØ Collab. S.Abachi et al.  
Phys. Rev. Lett. 74(1995)2632.

$$m_t \approx 170 \text{ GeV}$$

### Gluon fusion

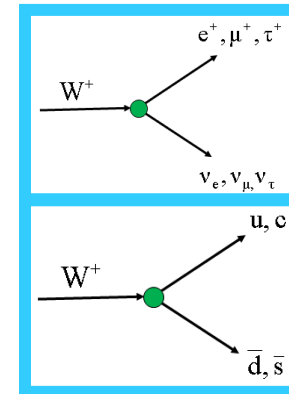
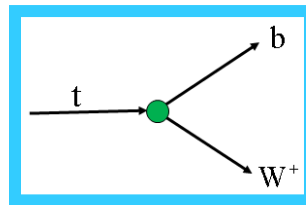
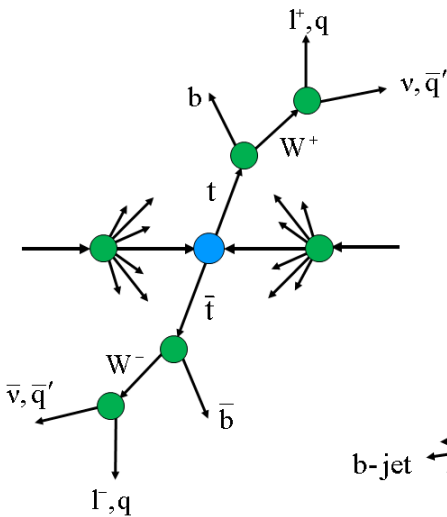


LHC	13 TeV	~ 90%
LHC	7,8 TeV	~ 85%
Tevatron	1.96 TeV	~ 15%

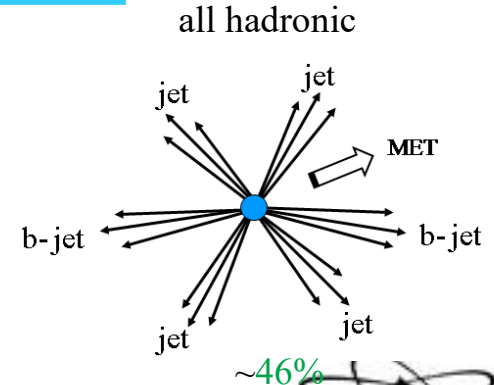
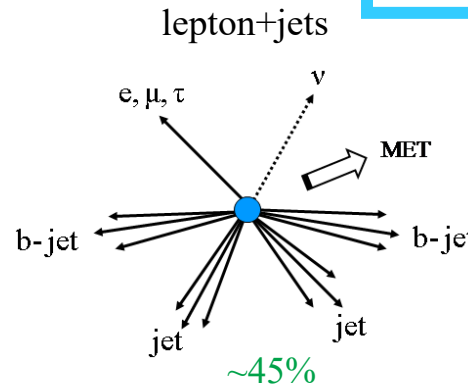
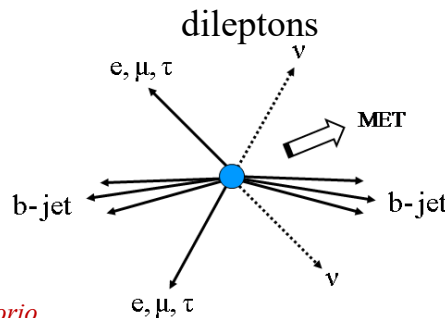
### Quark-antiquark annihilation



~10%
~15%
~85%



W decay modes  
leptons  
jets



Alberto Orso Maria Iorio  
(for the ATLAS, CMS, and LHCb collaborations ~9%)  
DIS2016, Hamburg, Germany



## Self-similarity parameter

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

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

Solid line for  $\pi^-$  meson  
is a reference curve

$$\varepsilon_{\pi} = 0.2, \quad \alpha_{\pi} = 1$$

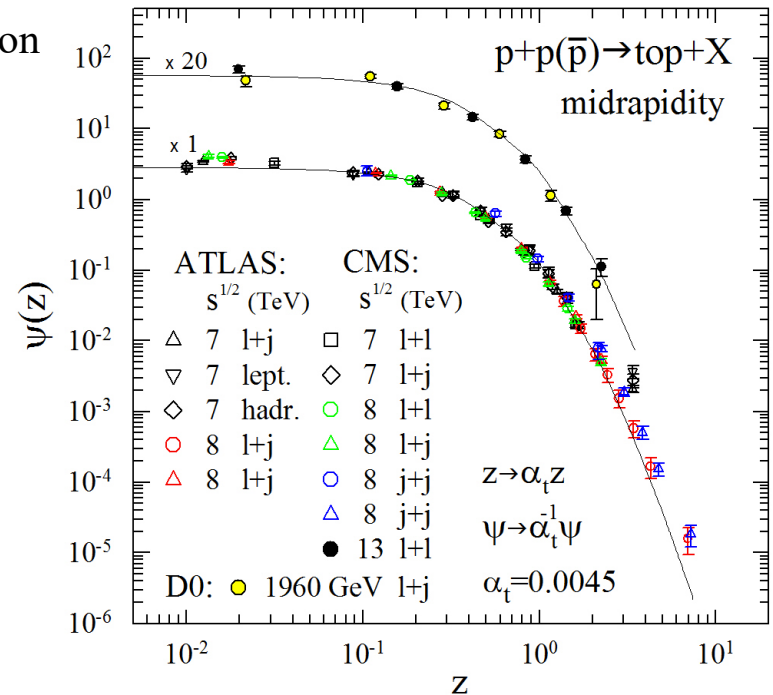
$$\Omega = (1-x_1)^{\delta} (1-x_2)^{\delta} (1-y_a)^{\varepsilon_F} (1-y_b)^{\varepsilon_F}$$

- $dN_{ch}/d\eta|_0$  - multiplicity density
- $c$  - “specific heat” of bulk matter
- $\delta$  - proton fractal dimension
- $\varepsilon_F$  - fragmentation fractal dimension

## Scaling function

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

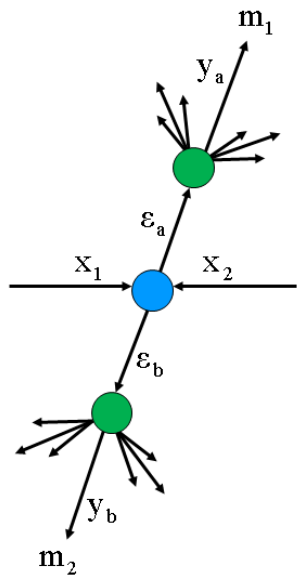
“Collapse” of data points onto a single curve



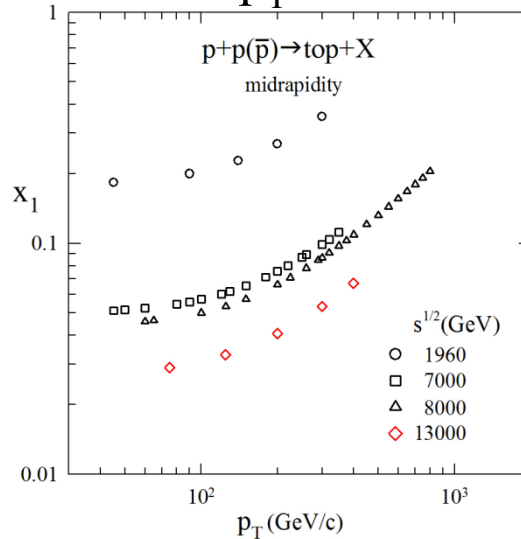
- Energy independence of  $\Psi(z)$
- Centrality independence of  $\Psi(z)$
- Power law at high  $z$
- Saturation at low  $z$

Universality: the same shape of  $\Psi(z)$  both for top and  $\pi^-$  (solid line)





## Momentum fractions vs. $p_T$ & $\sqrt{s}$



Top quark:

$$y_{\text{top}} \approx 1,$$

$$\varepsilon_{\text{top}} \approx 0,$$

$$M_X \approx m_{\text{top}}$$

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

$$\Omega = (1-x_1)^\delta (1-x_2)^\delta (1-y_a)^{\varepsilon_F} (1-y_b)^{\varepsilon_F}$$

$$M_X = x_1 M_1 + x_2 M_2 + m_{\text{top}} / y_{\text{top}}$$

Negligible energy loss  $\rightarrow$  high sensitivity at high  $x_1$  to

- structure of colliding objects (dimensions  $\delta_1, \delta_2$ )
- constituent interactions (“specific heat”  $c$ )
- transition of point-like massless top to massive top ( $m_{\text{top}} \approx m_{\text{Au}}$ ) !!!

Verification of universality of  $\Psi(z)$  shape over a wide  $z$ -range.

Extraction of  $\varepsilon_{\text{top}}$   $\rightarrow$  estimation of energy loss.

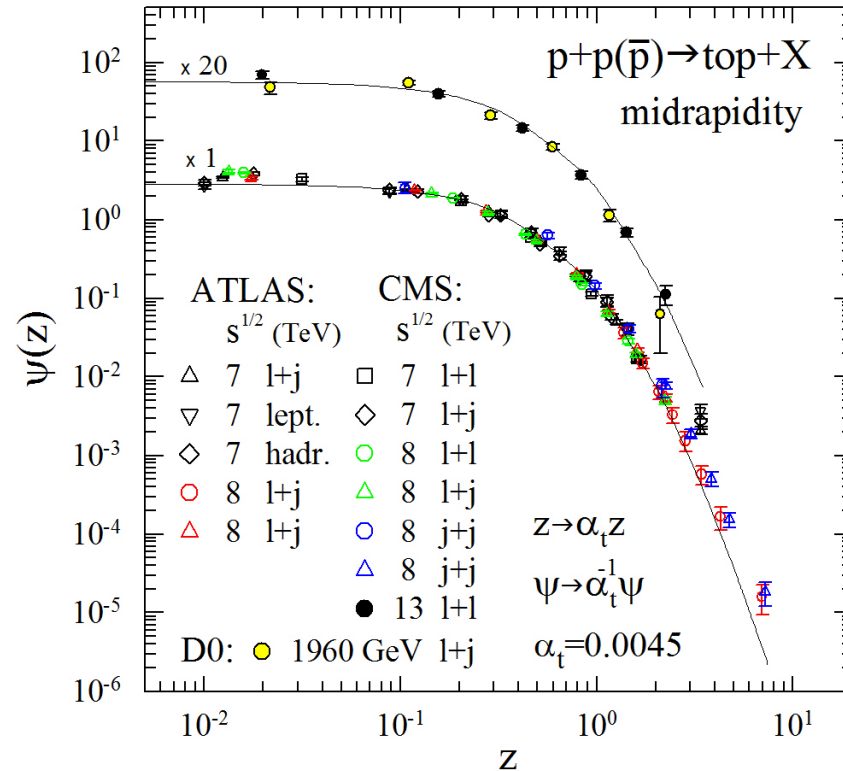
# Self-similarity of top quark production at LHC @ Tevatron



$s^{1/2}$  (GeV)

- 1960 PRD90(2014)092006
- △ 7000 PRD90(2014)072004
- ▽ 7000 JHEP06(2015)100
- ◇ 7000 JHEP06(2015)100
- 7000 EPJC73(2013)2339
- ◇ 7000 EPJC73(2013)2339
- 8000 PRD93(2016)032009
- △ 8000 arXiv:1511.04716
- 8000 EPJC75(2015)542
- △ 8000 EPJC75(2015)542
- 8000 EPJC76(2016)128
- △ 8000 arXiv:1605.00116
- ◆ 13000 CMS TOP 16-011

“Collapse” of data points onto a single curve



- Energy independence of  $\Psi(z)$
- Flavor independence of  $\Psi(z)$
- Saturation of  $\Psi(z)$  for or  $z < 0.1$
- Fractal dimensions  $\delta = 0.5$ ,  $\varepsilon_{\text{top}} = 0$
- “Specific heat”  $c = 0.25$

LHC & Tevatron data  
confirm self-similarity  
of top quark production in  $pp$  &  $p\bar{p}$



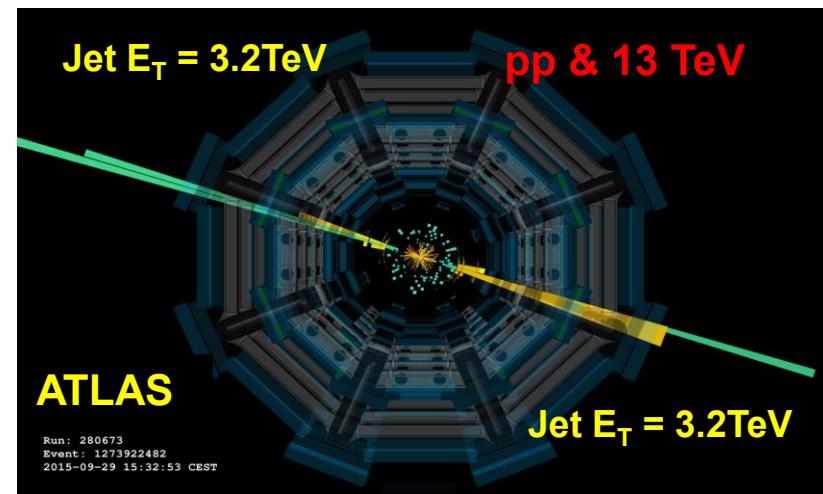
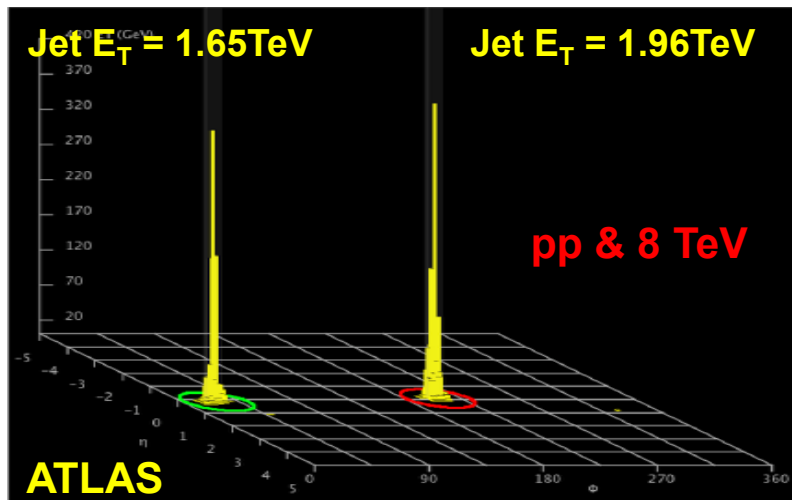
## Conclusions V

- Understanding flavor origin based on top quark production.
- Self-similarity of top quark structure, its interactions and fragmentation process was confirmed.
- The fractal structure of top quark was justified.
- Negligible energy loss was found.



## Jet production in $pp$ collisions at LHC

- Jet as a probe of constituent interactions at small scale
- Self-similarity of constituent substructure

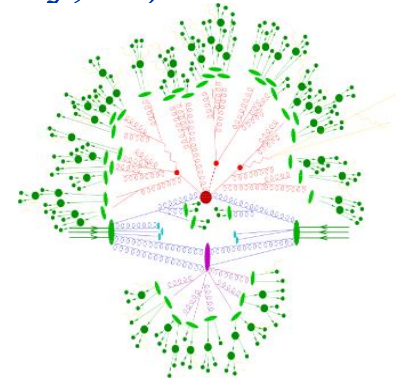


Int.J.Mod.Phys.A15 (2000) 3495  
 Int.J.Mod.Phys.A27 (2012) 1250115  
 Phys. Part. Nucl. 51 (2020) 141



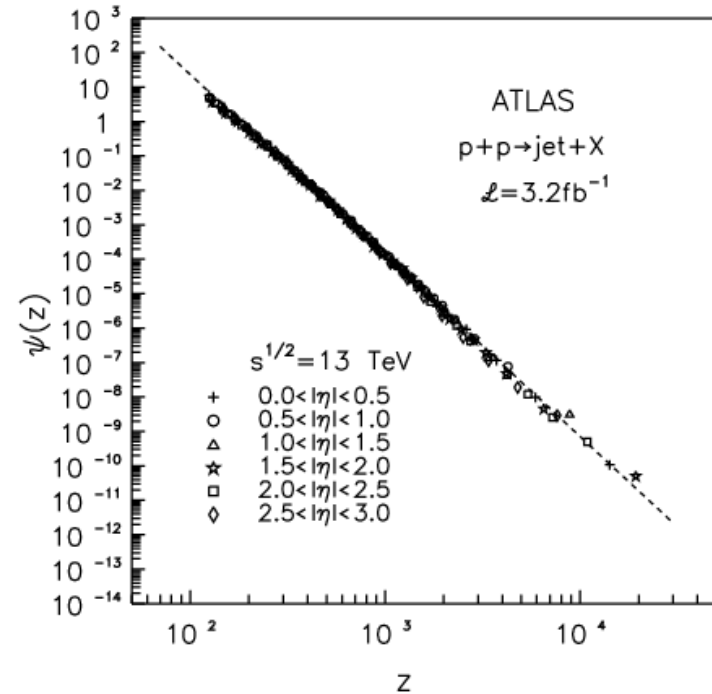
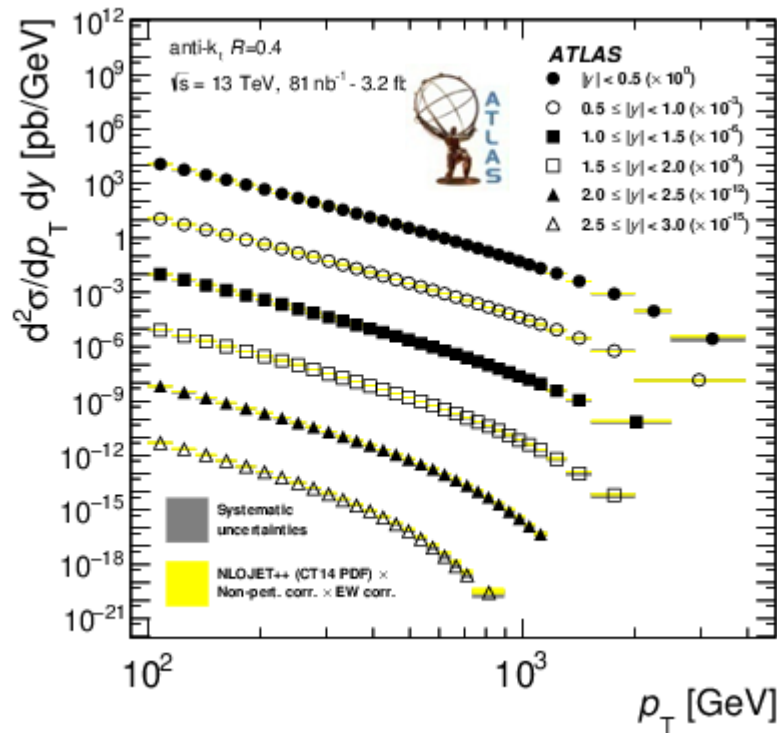
Development of **z**-scaling approach for description of **jet** production in inclusive reactions to search for signatures of new physics (phase transitions, quark compositeness, extra dimensions, black holes, fractality of space-time, **complementary restrictions for theory**,...)

Analysis of experimental data on jet production in **pp** obtained at the **LHC** to verify properties of **z**-scaling observed in **p $\bar{p}$**  collisions at the **S $\bar{p}$ pS**, Tevatron.



- Jet is a direct manifestation of hadron structure at a constituent level
- Non-perturbative mechanism of quark, gluon fragmentation into hadrons
- Properties of sub-structure of the colliding objects, interactions of their constituents, and fragmentation process at small scales.
- Jets as objects for identification of particles (**t**, **b** production,...)
- Fundamental principles (self-similarity, fractality)





Measurements of inclusive jet cross section:

- Highest collision energy  $\sqrt{s}=13 \text{ TeV}$
- Probing large momentum  $100 < p_T < 3500 \text{ GeV}$
- Rapidity region  $|y| < 3.0$
- Agreement with NLO pQCD

- Angular independence of  $\Psi(z)$
- Power law,  $\Psi(z) \sim z^{-\beta}$ , up to  $z \approx 10^4$
- Self-similarity of jet production

**ATLAS** confirms

z-scaling of jet production in pp

ATLAS Collaboration

JHEP 05 (2018) 195

M.Tokarev

PPIHE2026, IHEP, Protvino, Russia



## DØ Collaboration

- B.Abbott et al., Phys.Rev.Lett. 82, 2451 (1999)
- B.Abbott et al., Phys.Rev. D64, 032003 (2001)
- D.Elvira, Ph.D Thesis Univsodad de Buenos Aires, Argentina (19)
- V.M.Abazov et al., Phys.Lett. B525, 211 (2002)
- V.M.Abazov et al., Phys.Rev.Lett. 101, 062001 (2008)

## CMS Collaboration,

- Phys.Rev.Lett.107 (2011) 132001
- CMS PAS QCD-11-004
- Phys. Rev. D 87 (2013) 112002
- CMS-SMP-14-017, 2015.
- CMS PAS SMP-15-007

## M.T. & T. Dedovich

- Int. J. Mod. Phys.
- A15 (2000) 3495

## M.T. & T.Dedovich

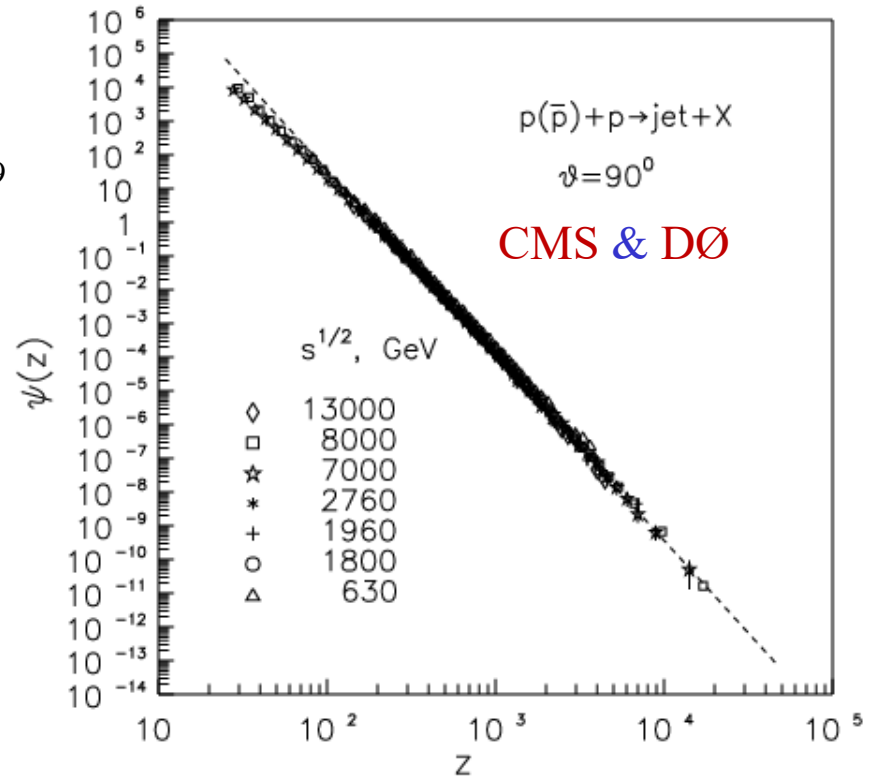
- Phys.At. Nucl. 68, 404 (2005)

## M.T. & I.Zborovsky

- Phys.Part.Nucl.Lett. 3, 312 (2006)

## M.T. & I.Zborovsky

- High-pT Physics at LHC 09
- February 4-7, 2009
- Prague, Czech Republic
- PoS (High-p<sub>T</sub> physics09) 046



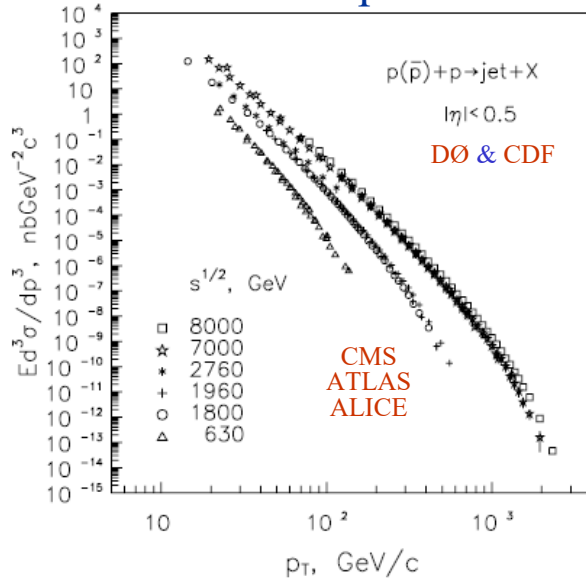
- Energy independence of  $\Psi(z)$
- **Universality of  $\Psi(z)$  in pp & p $\bar{p}$**
- Power law of  $\Psi(z)$  for  $z > 10^2$

**CMS & DØ confirm z-scaling of jet production**

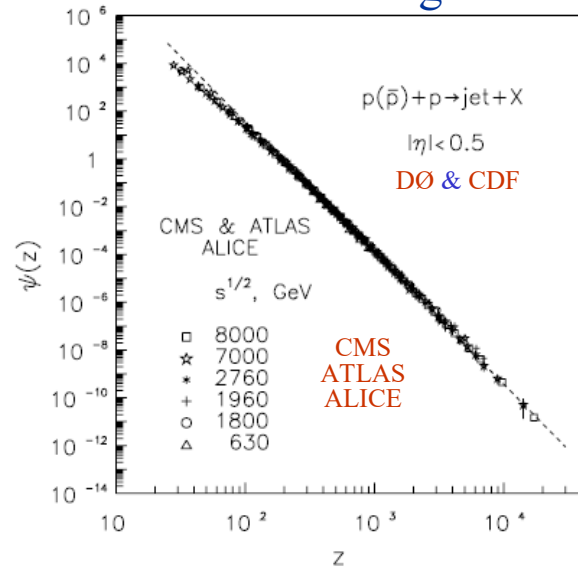


At the energy -  $\sqrt{s} = 8 \text{ TeV}$ , highest momentum -  $p_T \approx 2.4 \text{ TeV}/c$ ,  
 smallest scale  $\sim 8 \cdot 10^{-5} \text{ fm}$

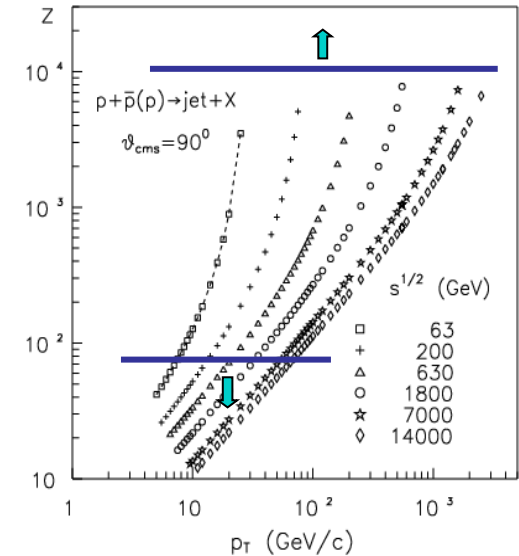
Jet spectra



z-scaling



z- $p_T$  plot



## Test of z-scaling at LHC

M.T. & T.Dedovich, I.Zborovsky  
 Int.J.Mod.Phys.A15 (2000) 3495  
 Int.J.Mod.Phys.A27 (2012)1250115

Structural phenomena  $\iff$  constituent substructure,...

Collective phenomena  $\iff$  multiple interactions, phase transitions,...

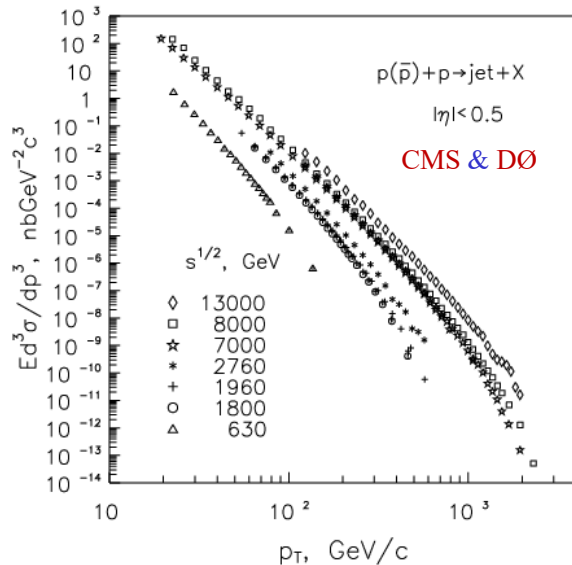
Self-similarity at small scales  $\iff$  fractal topology of momentum space,...

## Search for new phenomena at LHC

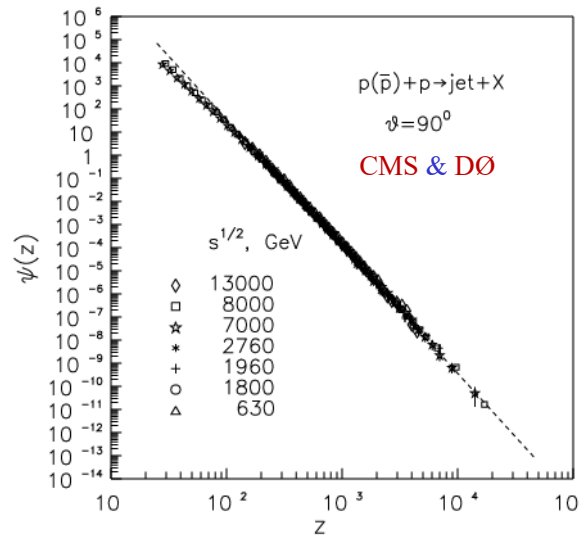


At the energy -  $\sqrt{s} = 13$  TeV, highest momentum -  $p_T \approx 3.5$  TeV/c ,  
 smallest scale  $\sim 5.6 \cdot 10^{-5}$  fm

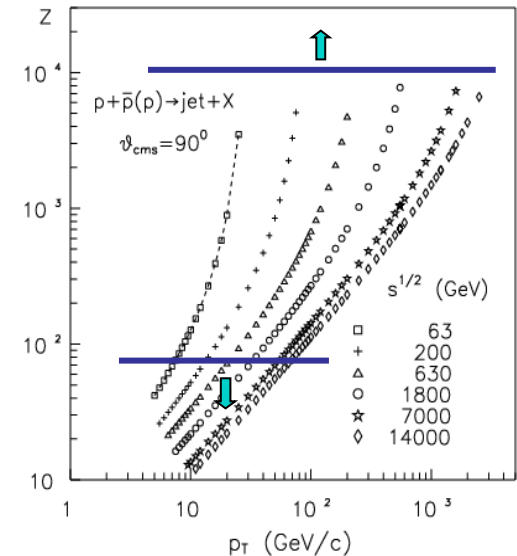
Jet spectra



z-scaling



z- $p_T$  plot



## New test of z-scaling at LHC

M.T. & T.Dedovich, I.Zborovsky  
 Int.J.Mod.Phys.A15 (2000) 3495  
 Int.J.Mod.Phys.A27 (2012)1250115

Structural phenomena  $\iff$  constituent substructure,...

Collective phenomena  $\iff$  multiple interactions, phase transitions,...

Self-similarity at small scales  $\iff$  fractal topology of momentum space,...

## Search for new phenomena at LHC



## Conclusions VI

- Jets are direct indications on substructure of hadrons.
- Jets are probes of hadron and nuclear medium.
- Self-similarity of jet production was confirmed.
- Fractal structure of jets was justified.
- Universality of tagged jet structure was suggested.



A.M.Baldin & V.S.Stavinsky (1971,1973)

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



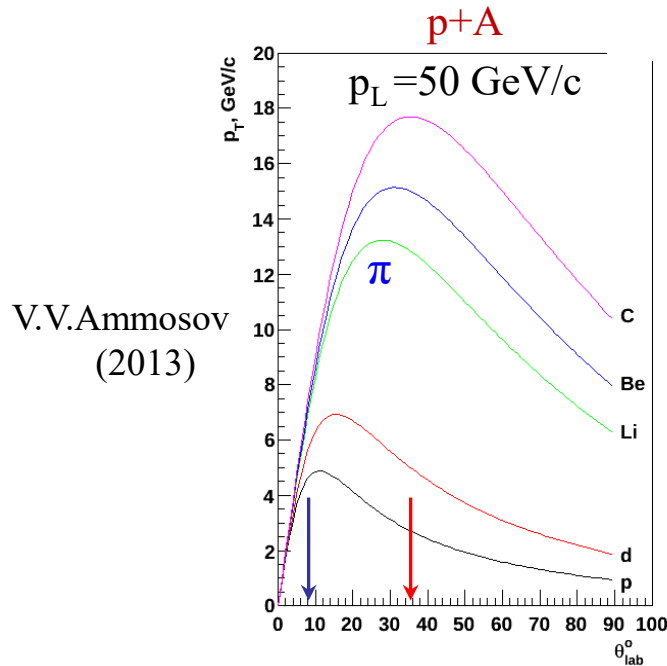
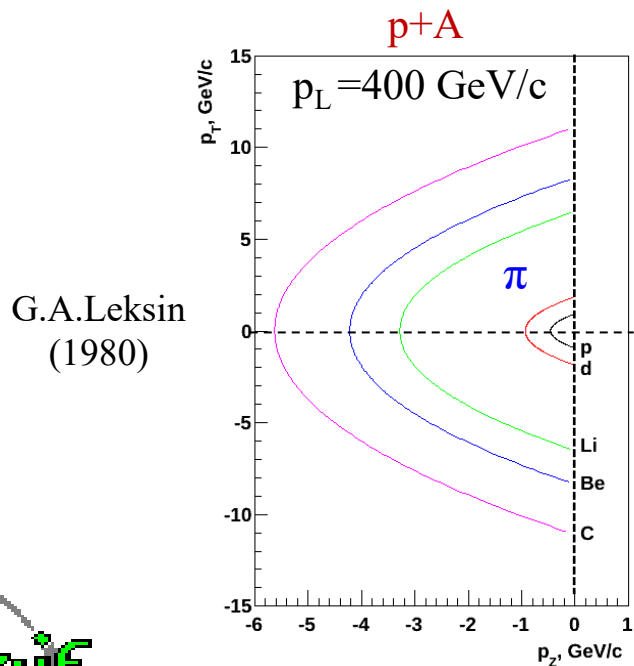
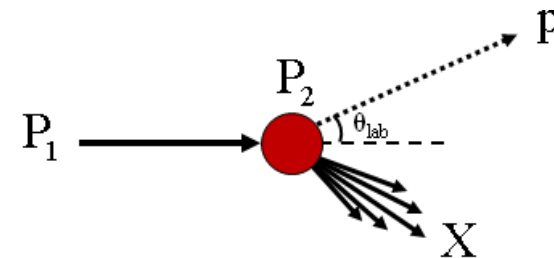
A.M.Baldin



V.S.Stavinsky

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

$$(P_1 + P_2 - p)^2 = M_X^2 \quad \min M_X \rightarrow p_{\max}^A > p_{\max}^p$$



**Conservation laws:**

- 4-momentum
- electric charge
- baryon number
- flavor



---

# Hadron production

## in $pp$ & $pA$ at high- $p_T$ in non-cumulative region as a reference frame for cumulative processes

PS, FNAL	J.W. Cronin et al., Phys.rev. D 11 (1975) 3105
PS, FNAL	D. Antreasyan et al., Phys. Rev. D 19 (1979) 764
U70	V.V. Abramov et al., Sov. J. Nucl. Phys. 31 (1980) 484
U70	V.V. Abramov et al., JETP Lett. 33 (1981) 289
Tevatron, FNAL	D. E. Jaffe et al., Phys. Rev. D 40 (1989) 2777
ISR, CERN	A. Breakstone et al., Z. Phys. C 69 (1995) 55
ISR, CERN	D. Drijard et al., Nucl. Phys. B 208 (1982) 1
RHIC, BNL	G. Agakishiev et al., Phys. Rev. Lett. 108 (2012) 072302

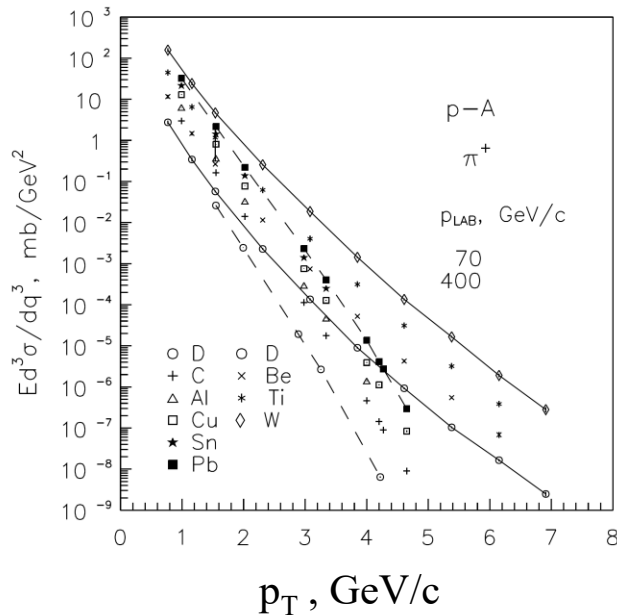
I.Zborovský, MT, Int. J. Mod. Phys. (2015) 1560103.  
Int. J. Mod. Phys. A 32, 1750029 (2017)  
Phys. Part. Nucl. 51, 141 (2020)



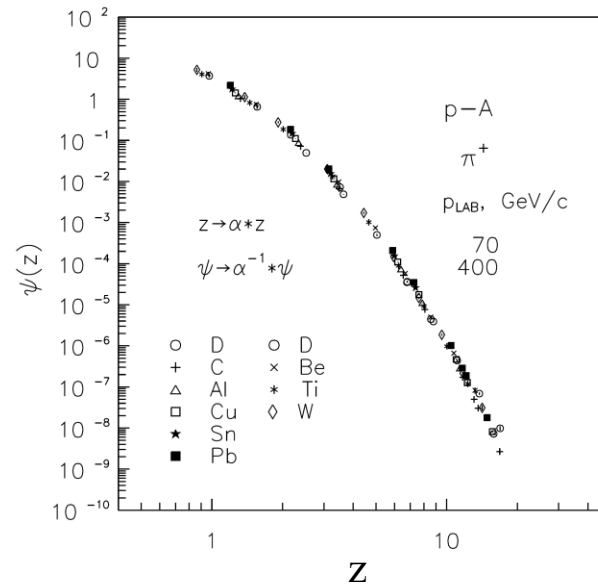
# Self-similarity of hadron production in $p+A$

A quarter of a century ago:  $p+A$  at FNAL & U70

Spectra in  $p_T$  and  $z$ -presentation



Strong dependence of spectra  
on  $\sqrt{s}$  at high  $p_T$

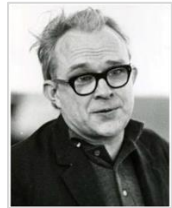


- Energy independence of  $\Psi(z)$
- Power law of  $\Psi(z)$  at high  $z$
- A-dependence of  $\Psi(z)$

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.

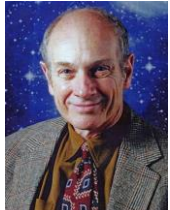
JINR preprint E2-2001-246, Dubna, 2001  
 hep-ph/0111202v1, 16 Nov. 2001  
 IJMP A16 (2001) 1281





G. Leksin

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



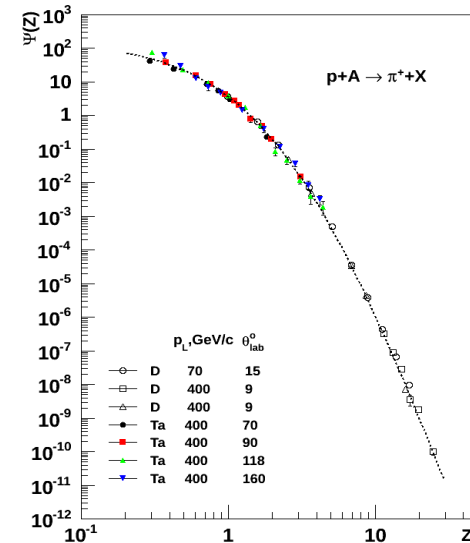
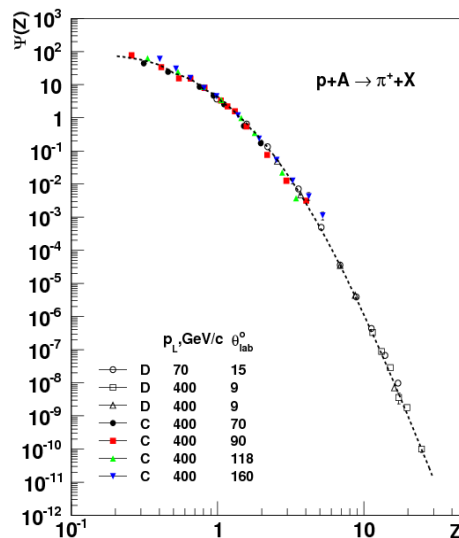
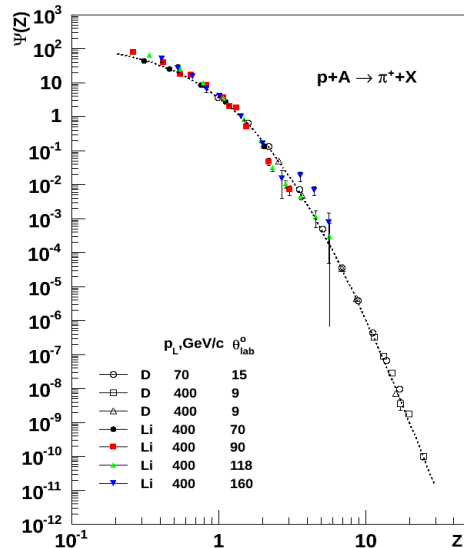
J. Cronin



R. Sulyaev



D. Jaffe



## Scale invariance

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

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

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

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

N.A. Nikiforov et al., Phys. Rev. C22 (1980) 700.  
A. Aparin, MT, Phys. Part. Nucl., Lett. 11 (2014) 91

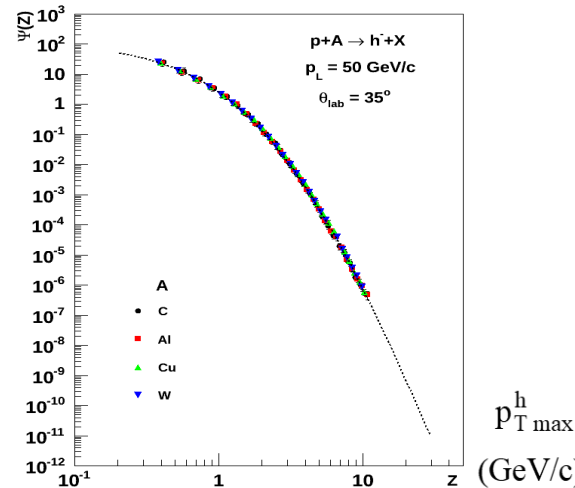
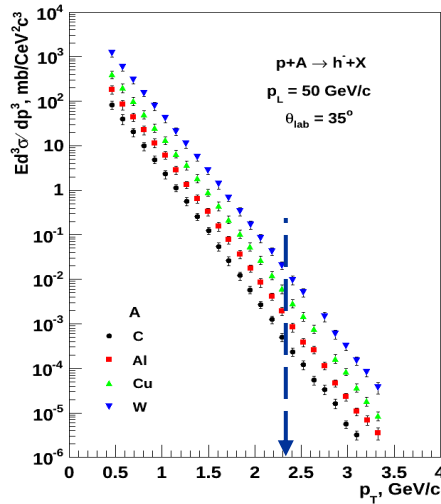


U70 (V.Ammosov, V.Gapienko, R.Sulyaev) & FNAL (J.Cronin, D.Jaffe)

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



V. Ammosov



C, Al, Cu, W & D

- Collapse of data points
- Universal shape of  $\Psi(z)$
- Self-similarity over a wide kinematic range

$p_L = 50$  (GeV/c)  $\theta_{lab} = 35^\circ$

$p$	C	Al	Cu	W
2.62	15.6	20.7	24.4	26.7

- Spectra in cumulative region:  $p_T > 2.5$  GeV/c.
- Smooth behavior of spectra vs.  $p_T$ .
- A-dependence of spectra ( $A=12-184$ ).

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

Cumulation  
under nucleus compression

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., Yad.Fiz. 76 (2013) 1276.

A.Aparin, MT

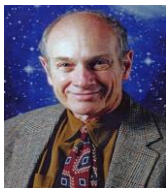
Phys. Part. Nucl. Lett., 11 (2014) 381.

Self-similar properties  
of nuclear matter

A=12-184



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



J. Cronin

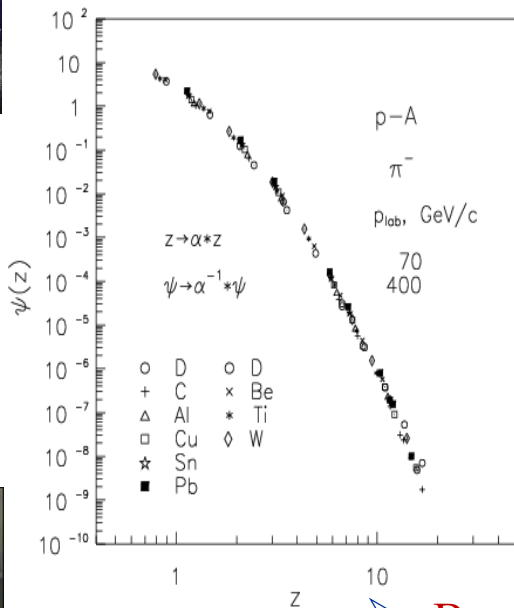


R. Sulyaev

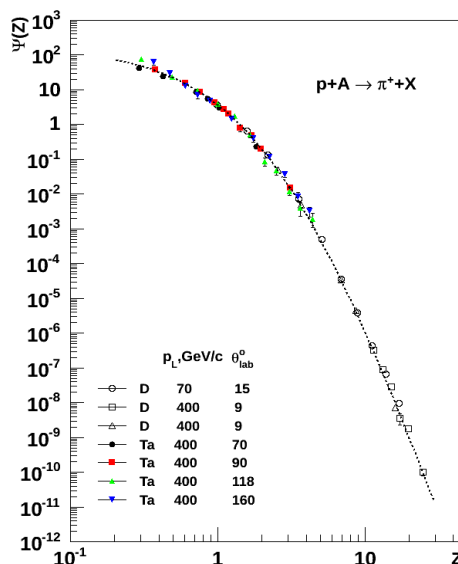


D. Jaffe

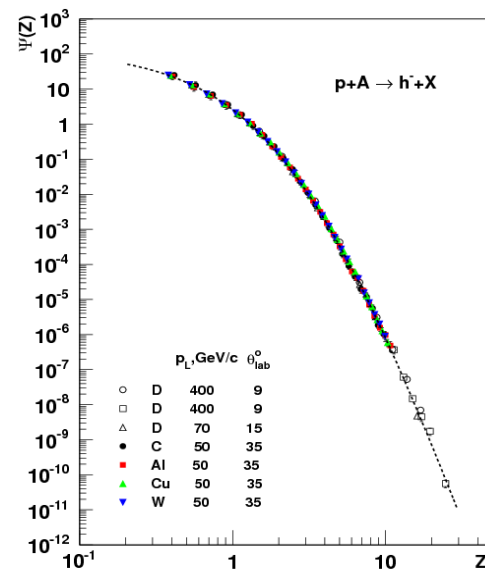
high- $p_T$  & non-cumulative



low- $p_T$  & cumulative



high- $p_T$  & cumulative



G. Leksin



V. Ammosov

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

- Verification of  $z$ -scaling in cumulative range
- Smooth transition from high- $p_T$  to cumulative range



## Conclusions VII

- Self-similarity of particle structure, constituent interactions and fragmentation process of hadron production in non-cumulative and cumulative regions in  $p+A$  collisions were verified.
- Smooth behavior of  $\Psi(z)$  in the overlapping range was found.
- There is no observed discontinuity of fractal dimensions -  $\delta$ ,  $\varepsilon$  and “specific heat”-  $c$ .



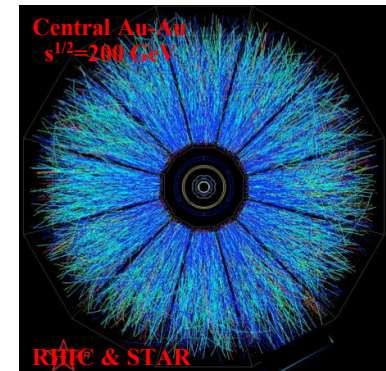
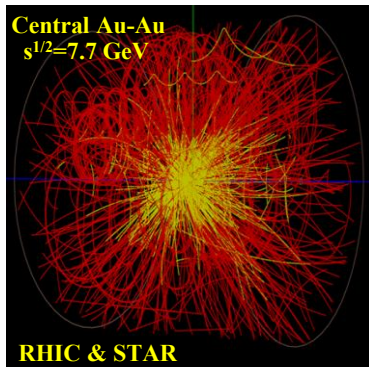
# Scaling features of hadron production in Au+Au at RHIC

Probing microscopic structure of the hot- and high-  
density nuclear matter at multiple length scales

Self-similarity of hadron production

**RHIC Beam Energy Scan with Au+Au:**

$$\sqrt{s_{NN}} = 7.7, 11.5, 14.5, 19.6, 27, 39, 62, 130, 200 \text{ GeV}$$



Int. J. Mod. Phys. (2015) 1560103

Nucl. Phys. A993 (2020) 121646

Nucl. Phys. A1025 (2022) 122492

## Self-similarity parameter

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

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

$$\Omega = (1-x_1)^{\delta_{A1}} (1-x_2)^{\delta_{A2}} (1-y_a)^{\varepsilon_{AA}} (1-y_b)^{\varepsilon_{AA}}$$

- $dN_{ch}/d\eta|_0$  - multiplicity density
- $c_{AA}$  - “specific heat” of bulk matter
- $\delta_A$  - nucleus fractal dimension
- $\varepsilon_{AA}$  - fragmentation dimension

## A+A collisions:

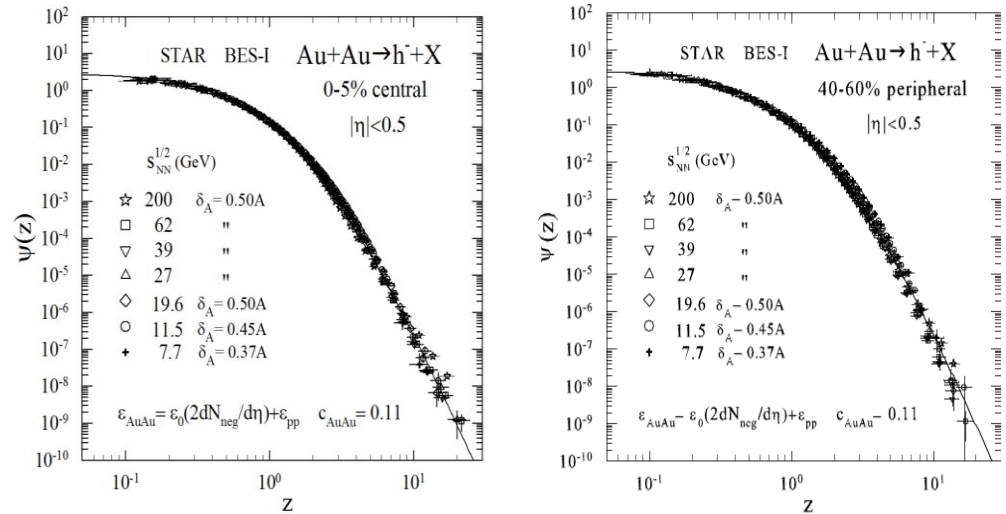
$$\delta_A = A\delta$$

$$\varepsilon_{AA} = \varepsilon_0 (dN_{AA}/d\eta) + \varepsilon_{pp}$$

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

MT, A.Kechechyan, I.Zborovsky  
Nucl. Phys. A993 (2020) 121646

## “Collapse” of data points onto a single curve



## z-Scaling

- Energy independence of  $\Psi(z)$
- Centrality independence of  $\Psi(z)$
- Dependence of  $\varepsilon_{AA}$  on multiplicity
- Power law at low- and high- $z$  regions

Indication of a decrease  
of  $\delta$  for  $\sqrt{s_{NN}} < 19.6$  GeV

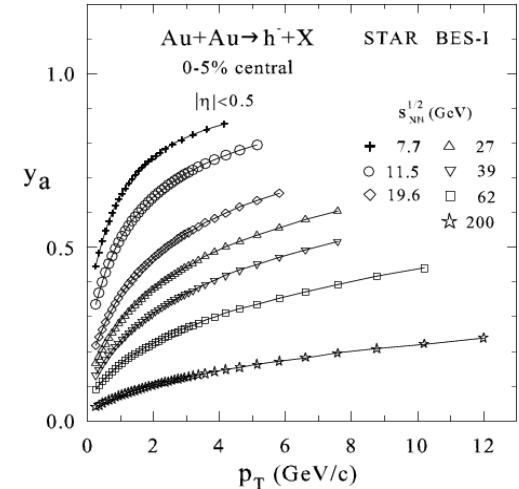
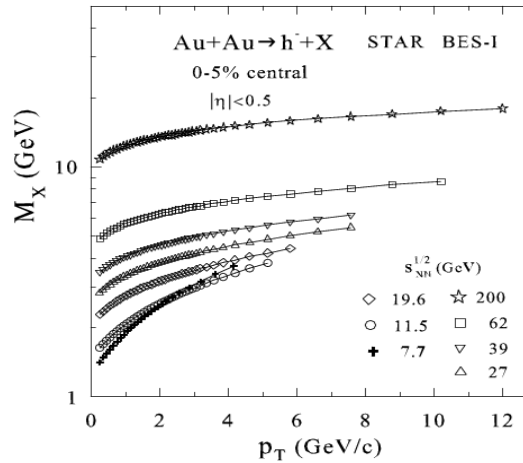
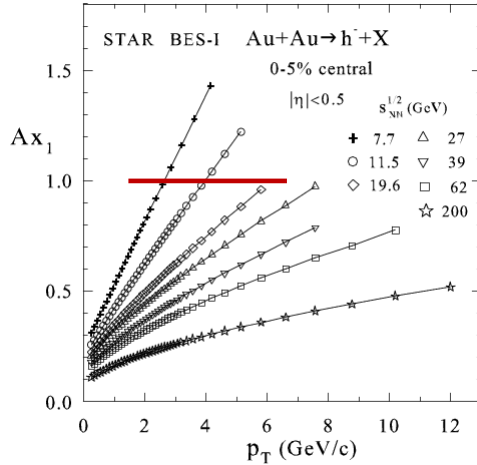


## Constituent sub-process in terms of

Momentum fraction  $Ax_1$

Recoil mass  $M_X$

Energy loss  $\Delta E/E=(1-y_a)$



$Ax_1$

$M_X$

$\Delta E/E$

- increases with  $p_T$
- decreases with  $\sqrt{s_{NN}}$

- increases with  $p_T$
- increases with  $\sqrt{s_{NN}}$

- decreases with  $p_T$
- increases with  $\sqrt{s_{NN}}$

Smooth behavior of  $x_1, y_a, M_X$  vs.  $p_T$ , centrality, collision energy

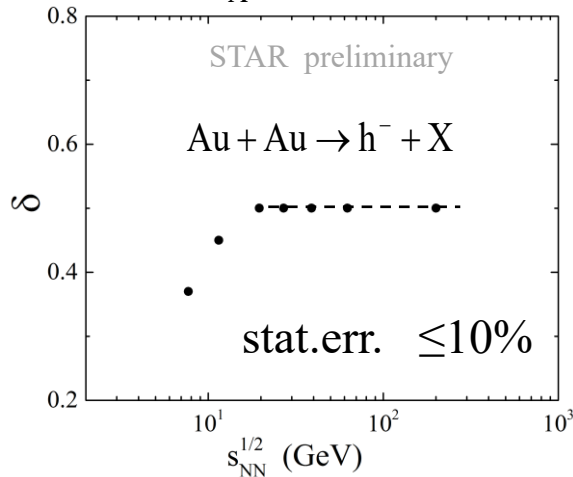
- High  $x_1$  and  $p_T \rightarrow$  compressed matter
- Large  $M_X \rightarrow$  high density recoil system
- High  $y_a \rightarrow$  small energy loss



Parameters  $\delta_A, \varepsilon_{AA}, c_{AA}$  are determined from the requirement of scaling behavior of  $\Psi$  as a function of self-similarity parameter  $z$

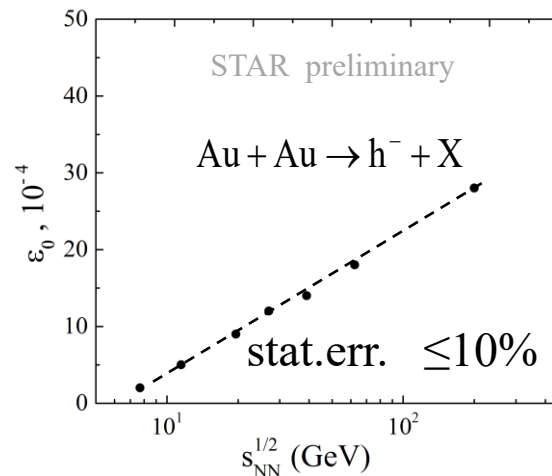
Nucleus fractal dimension

$$\delta_A = A \cdot \delta$$



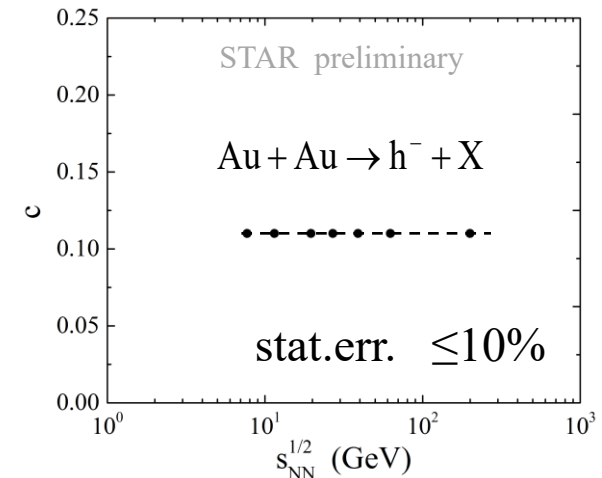
Fragmentation dimension

$$\varepsilon_{AA} = \varepsilon_0 (dN_{AA}/d\eta) + \varepsilon_{pp}$$



“Specific heat”

$$c_{AA}$$



- $\delta_A$  decreases with energy for  $\sqrt{s_{NN}} \leq 20$  GeV
- $\delta_A$  is independent of energy for  $\sqrt{s_{NN}} \geq 20$  GeV
- $\varepsilon_{AA}$  increases with energy
- $c_{AA}$  is independent of energy

Search for discontinuity and correlations of the model parameters.



- Some results of data analysis on **charged hadrons, strange mesons and baryons, jet and top quark** production in **pp** collisions obtained at the **U70, ISR, RHIC, Tevatron, LHC** using the **z-scaling** approach were presented and discussed.
- **z-Scaling** of particle production manifests **self-similarity, locality and fractality** of hadron interactions at a constituent level.
- Results of analysis of the **STAR BES-I** data on negative hadrons produced in **Au+Au** collisions demonstrate smooth behavior in **z-presentation** vs. collision energy, centrality over a wide range of **p<sub>T</sub>** and support the concept.
- Parameter correlations as signatures of phase transition and **Critical Point** were suggested.
- **z-Scaling** gives restriction on the asymptotic behavior of particle spectra in high-**p<sub>T</sub>** region.

Verification of **z-scaling** concept can be of interest in searching for new phenomena in particle and nuclear physics over a wide range of transverse momentum and collision energy.



**КОНФЕРЕНЦИЯ  
ФИЗИКА ЧАСТИЦ ПРИ СРЕДНИХ  
И ВЫСОКИХ ЭНЕРГИЯХ**

«ИНСТИТУТ ФИЗИКИ ВЫСОКИХ ЭНЕРГИЙ  
ИМЕНИ А.А. ЛОГУНОВА НАЦИОНАЛЬНОГО ИССЛЕДОВАТЕЛЬНОГО ЦЕНТРА  
«КУРЧАТОВСКИЙ ИНСТИТУТ»

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МОСКОВСКАЯ ОБЛАСТЬ

**НАУЧНАЯ ПРОГРАММА КОНФЕРЕНЦИИ:**  
РЕДКИЕ РАСПАДЫ ЛЕГКИХ МЕЗОНОВ  
СПЕКТРОСКОПИЯ АДРОНОВ  
СИЛЬНЫЕ ВЗАИМОДЕЙСТВИЯ  
СПИНОВЫЕ ЭФФЕКТЫ ВО ВЗАИМОДЕЙСТВИИ АДРОНОВ  
РЕЛЯТИВИСТСКАЯ ЯДЕРНАЯ ФИЗИКА  
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