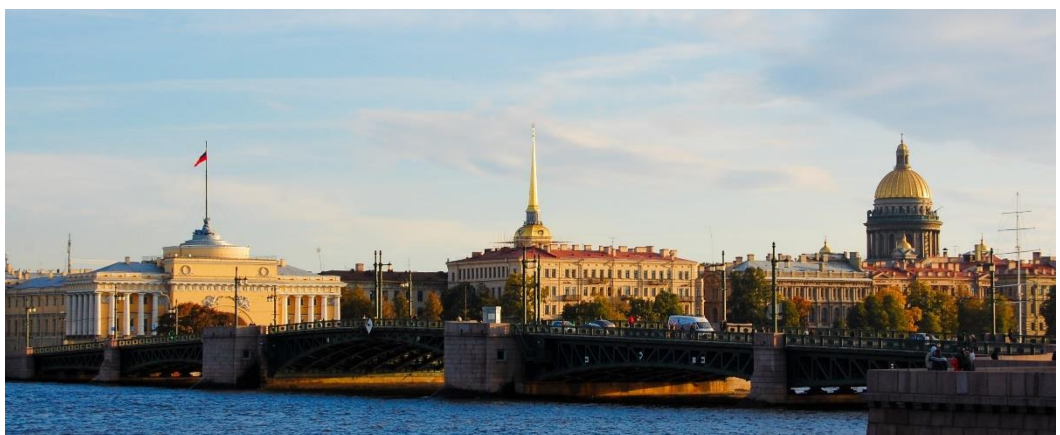
z-Scaling: Search for signatures of phase transition in nuclear matter

M. Tokarev* & I. Zborovsky**

*JINR, Dubna, Russia
**NPI, Řež, Czech Republic



Contents

- Introduction (phase transition signatures)
- z-Scaling (ideas, definitions)
- Properties of data z-presentation
- Self-similarity of strange particle production in $p+p$ collisions at RHIC
- Self-similarity of K^0_S meson production in Au+Au collisions at RHIC
- Constituent sub-process in Au+Au
  - momentum fractions, recoil mass and constituent energy loss vs. p_T, centrality, energy $\sqrt{s_{NN}}$
  - model parameters vs. collision energy
- Summary

Motivation & Goals

Search for new symmetries in Nature

Systematic analysis of inclusive cross sections of particle production in p+p, p+A and A+A collisions to search for general features of hadron and nucleus structure, constituent interaction and fragmentation process over a wide scale range

z-Scaling is a tool in high energy physics

Development of z-scaling approach for description of processes with strange particle production in inclusive reactions and verification of self-similarity principle

Analysis of STAR data on K_S^0 meson spectra in Au+Au collisions

The suggested approach can be used to study

- Origin of strangeness
- Symmetry of constituent interactions at small scales
- Similarity and difference of u,d,s,c,b,t quark fragmentation
- Strangeness as probe to search for new physics
- New phenomena in A+A in comparison with p+p

Fundamental principles and symmetries

"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 fundamental property of physical phenomena and one of general principles to construct theories.

Flavor is one of mystery properties of quarks.

Special topic:
Self-similarity of strangeness production in p+p and A+A.
Strange particles as dedicated probes of nuclear matter.

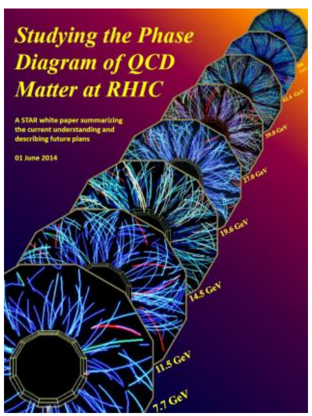
Fundamental principles and symmetries

Phase transition and critical phenomena in usual matter (gas, liquid, solid)

“Scaling” and “Universality” are concepts developed to understanding critical phenomena. Scaling means that systems near the critical points exhibiting self-similar properties are invariant under transformation of a scale. According to universality, quite different systems behave in a remarkably similar fashion near the respective critical points. Critical exponents are defined only by symmetry of interactions and dimension of the space.

H.Stanley, G.Barenblatt,…

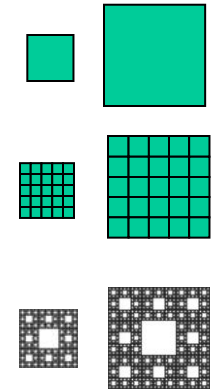
Phase transition and critical phenomena in nuclear matter



- The idea is to vary the collision energy and look for the signatures of QCD phase boundary and QCD critical point i.e. to span the phase diagram from the top RHIC energy (lower μ_B) to the lowest possible energy (higher μ_B).
- To look for the phase boundary, we would study the established signatures of QGP at 200 GeV as a function of beam energy. Turn-off of these signatures at particular energy would suggest the crossing of phase boundary.
- Similarly, near critical point, there would be enhanced fluctuations in multiplicity distributions of conserved quantities (net-charge, net-baryon).

STAR collaboration

Self-similarity



- 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.

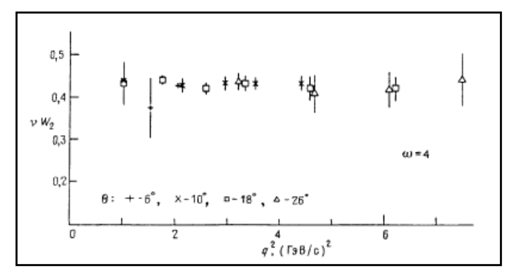
Dimensionless dynamical function vs. self-similarity parameter

- Drag force vs. Reynolds number $Re = \rho VD/\eta$ — hydrodynamics
- Drag force vs. Mach number $Ma = v/c$ — aerodynamics
- Structure function $F(x)$ vs. Bjorken variable $x = -q^2/2(pq)$ — deep-inelastic scattering

…………….

laminar & turbulent flow

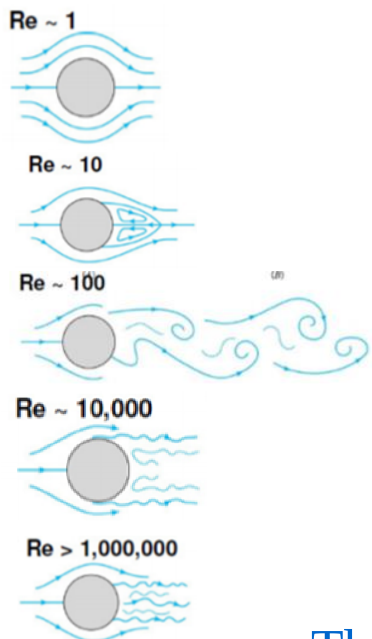
subsonic & supersonic wave

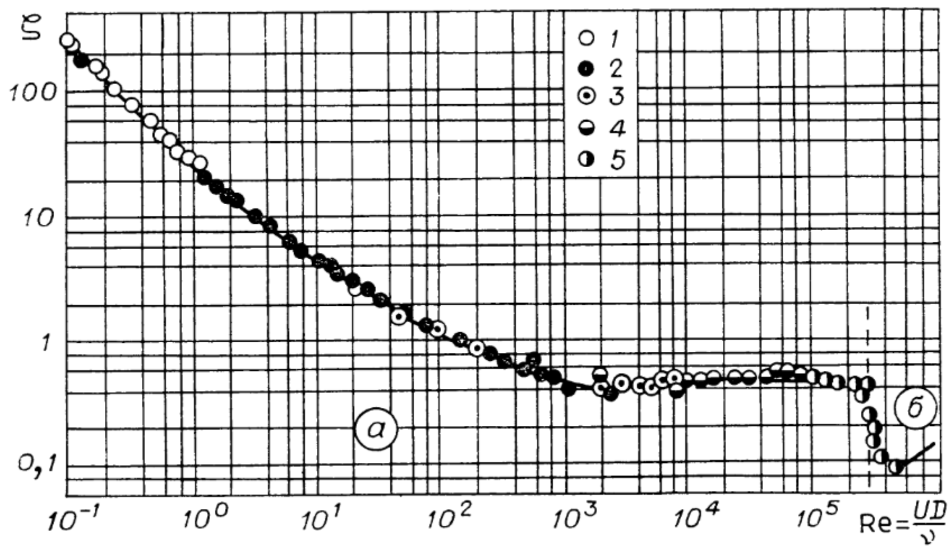


low x & high x

Drag coefficient c_D vs. Re for a circular sphere in flow

"Collapse" of data points onto a single curve





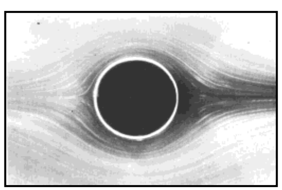
S.S.Kutateladze (1986)

$$C_D = \frac{F_D}{\rho v^2 d^2}$$

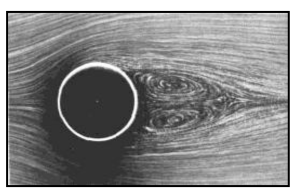
$$Re = \frac{\rho v d}{\eta}$$

The uniform flow passes over the circular cylinder

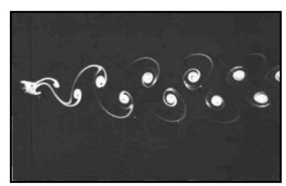
M.Van Dyke (1982)



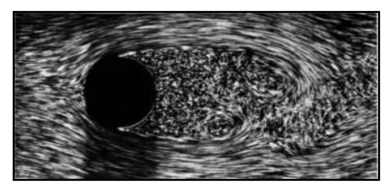
Re = 0,16



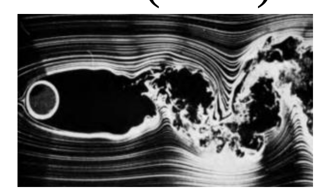
Re = 26



Re = 105



Re = 2000

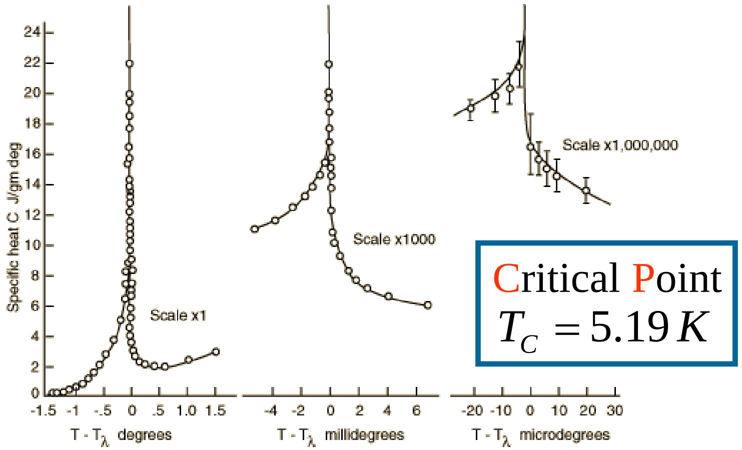


Re = 10000

- Self-similarity in laminar and turbulent flow
- Smooth behavior of transition from the laminar to turbulent flow

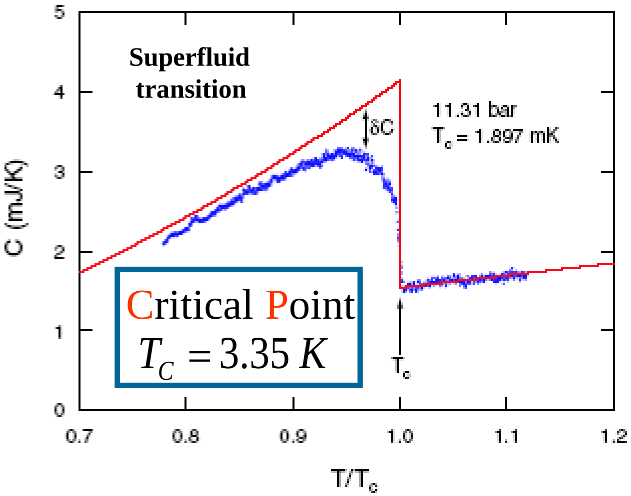
Discontinuity of specific heat near a Critical Point

Specific heat of liquid ^{4}He



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

Heat capacity of liquid ^{3}He



H. Choi et al., PRL 96, 125301 (2006)

- Near a critical point the singular part of thermodynamic potentials is a Generalized Homogeneous Function (GHF).
- The Gibbs potential $G(\lambda^{a_\varepsilon}\varepsilon, \lambda^{a_p} p) = \lambda G(\varepsilon, p)$ is GHF of (ε, p).

$$c_p \sim |\varepsilon|^{-\alpha} \qquad \varepsilon \equiv (T\text{-}T_c)/T_c \qquad c_p = -T(d^2G/dT^2)$$

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

Phase transitions & Critical phenomena

- Critical phenomena are phenomena that reveal unusual characteristic behavior of substances in the vicinity of phase transition points.
- They are observed due to an increase in the characteristic sizes of different fluctuations.
- In these phenomena, the self-similarity of the system arises spontaneously. This is a scale property that is characteristic for fractal structures.
- Second order transition is accompanied by a spontaneous symmetry breaking.

Signatures of critical phenomena:

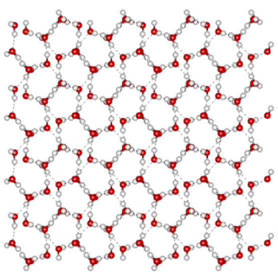
- increase in compressibility (liquid-vapor equilibrium)
- increase in magnetic and dielectric susceptibility in the vicinity of the Curie points of ferromagnets and ferroelectrics
- anomaly in heat capacity at the point of transition of helium to the superfluid state
- slowing of the mutual diffusion of substances near the critical points of mixtures of stratifying liquids
- anomaly in the propagation of ultrasound (absorption of sound and an increase in its dispersion)
- anomalies in viscosity, thermal conductivity, a slowdown in the establishment of thermal equilibrium, etc.

These anomalies are described by power laws with critical indices.
Strong fluctuations and an infinite correlation radius in such systems confirm self-similarity.

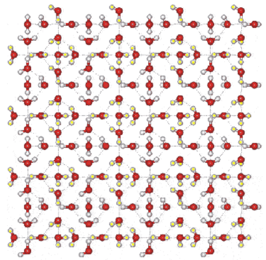
The phase diagram of water H_2O

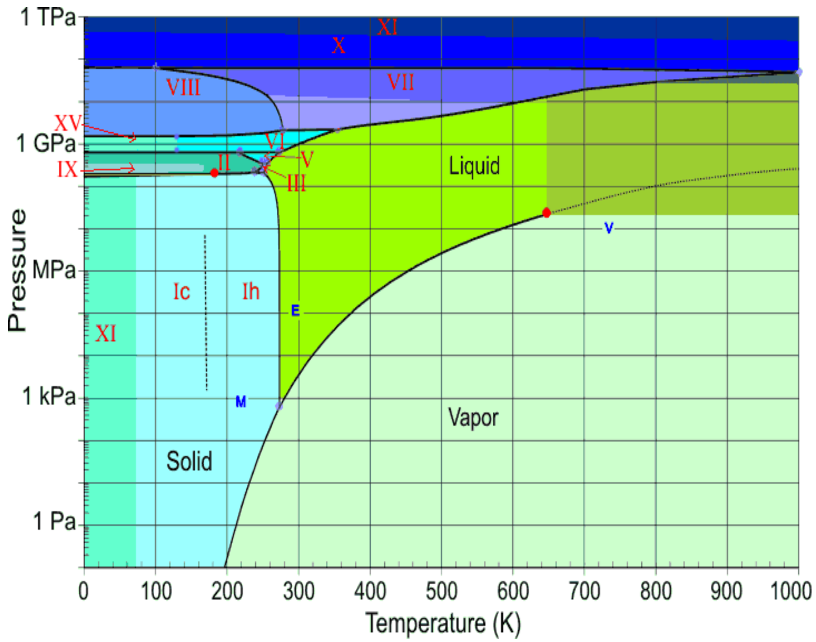
- Self-similarity as a symmetry principle is confirmed.
- The law of corresponding states, equation of state are found.
- Phase diagram – boundaries, triple and critical points,…, is established.
- Properties of phases are investigated.

Ice III

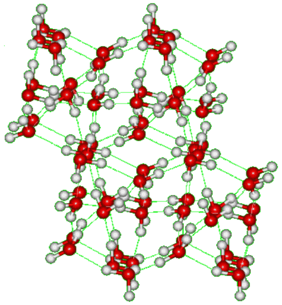


Ice VI





Ice XIII



- Phases (ice I-XVIII, liquid, vapor)
- Phase boundaries
- Phase transitions
- Triple Point (17)
- Critical Point (1)

What one can say about phase diagram of nuclear matter ?

Self-similarity in inclusive reactions.
Hadron production in p+p and A+A collisions
at high energies.

Self-similarity & z-scaling

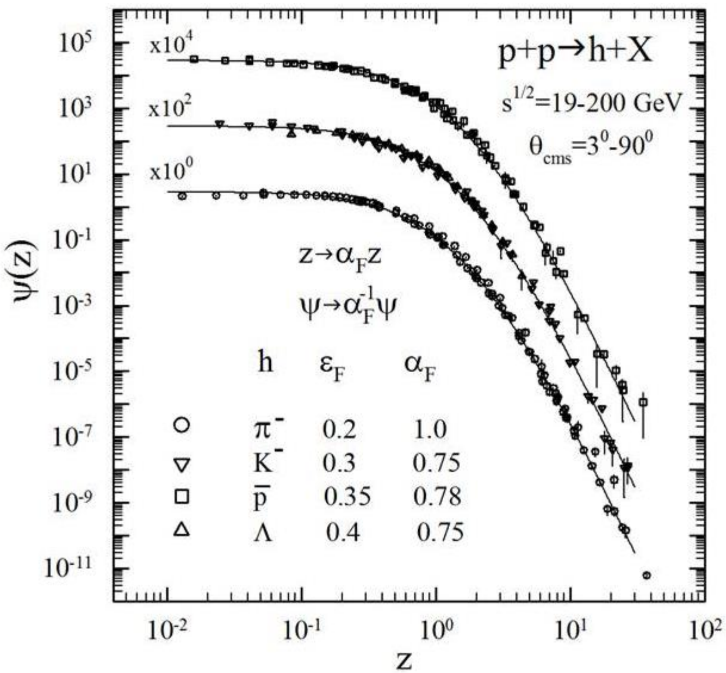
Inclusive cross sections of π^-, K^-, $\bar{p}$, Λ in pp collisions

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, S$\bar{p}$pS, SPS, HERA, FNAL(fixed target), Tevatron, RHIC, LHC

MT & I.Zborovsky
T.Dedovich
Phys.Rev.D75,094008(2007)
Int.J.Mod.Phys.A24,1417(2009)
J. Phys.G: Nucl.Part.Phys. 37,085008(2010)
Int.J.Mod.Phys.A27,1250115(2012)
J.Mod.Phys.3,815(2012)
Int.J.Mod.Phys. A32,1750029(2017)
Nucl. Phys. A993 (2020) 121646

- Energy & angular independence
- Flavor independence (π, K, $\bar{p}$, Λ)
- 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 (ε_F, α_F).

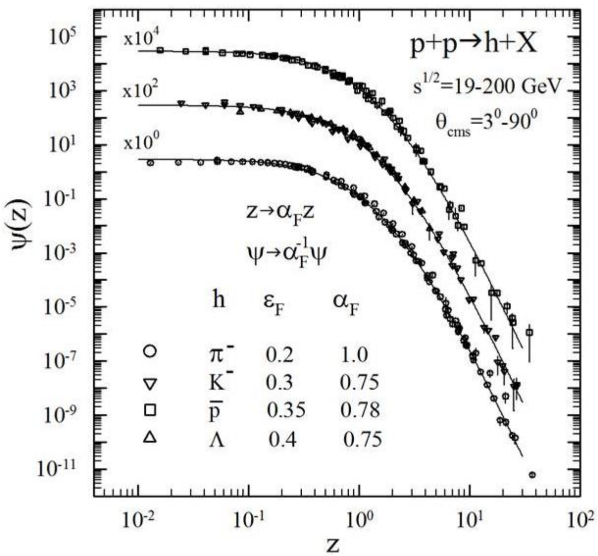
Self-similarity at RHIC

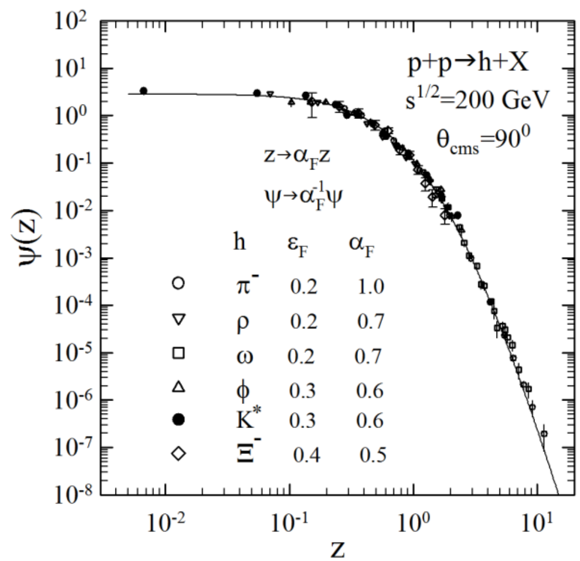
Flavor independence of scaling function

M.T. & I.Zborovský
Int.J.Mod.Phys. A24,1417(2009)

$\boxed{\pi^-, \rho, \omega, \phi, K^*, \Lambda, \Xi, J/\psi}$

"Collapse" of data points onto a single curve





STAR:
PRL 92 (2004) 092301
PLB 612 (2005) 181
PRC 71 (2005) 064902
PRC 75 (2007) 064901

PHENIX:
PRC 75 (2007) 051902

- Energy independence
- Angular independence
- Flavor independence
- Saturation for $z < 0.1$

- Power law $\Psi(z) \sim z^{-\beta}$ at large z
- ε_F, α_F independent of p_T, $s^{1/2}$

Self-similarity of particle production with various flavor content.

Properties of $\Psi(z)$ in p+p collisions

- 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)
- 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 $\Psi(z)$ (π,K,φ,Λ,..,D,J/ψ,B,Υ,…, 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.

z-Scaling:

ideas, definitions, hypothesis,…

Basic principles:

locality, self-similarity, fractality,…

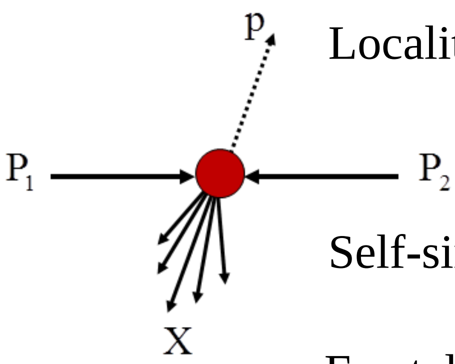
Signatures of Phase Transition & Critical Point:

irregularities of model parameters:

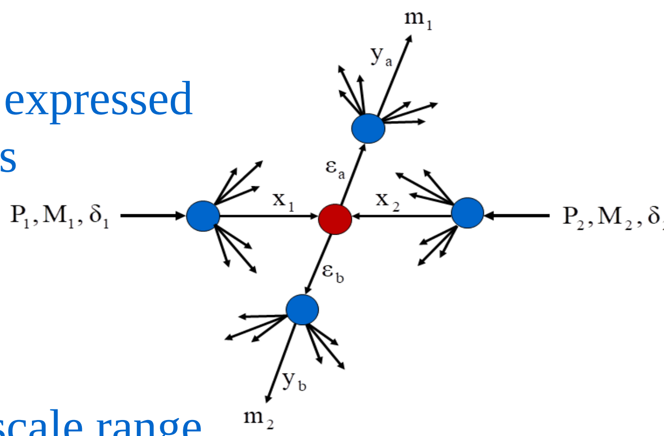
fractal dimensions & specific heat

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 constituents are mutually similar.

Fractality: self-similarity is valid 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, y_a, y_b

$\delta_1, \delta_2, \varepsilon_a, \varepsilon_b, c$

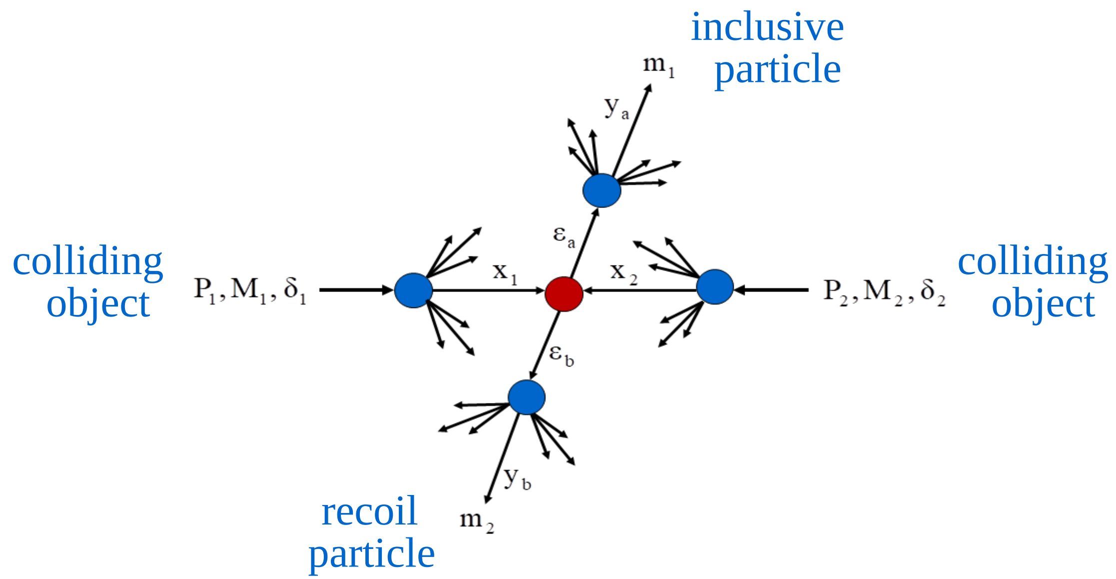
$Ed^3\sigma/dp^3$

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

$\Psi(z)$

Locality

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

δ_1, δ_2 – fractal dimensions of colliding particles

$\varepsilon_a, \varepsilon_b$ – fractal dimensions of scattered constituents (fragmentation dimensions)

m_2 – mass of recoil particle

Elementary sub-process:

$$(x_1M_1) + (x_2M_2) \rightarrow (m_1/y_a) + (x_1M_1+x_2M_2+m_2/y_b)$$

Momentum conservation law for sub-process

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

Mass of recoil system

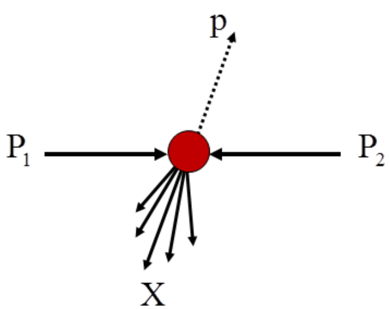
$$M_X = x_1M_1+x_2M_2+m_2/y_b$$

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

Self-similarity

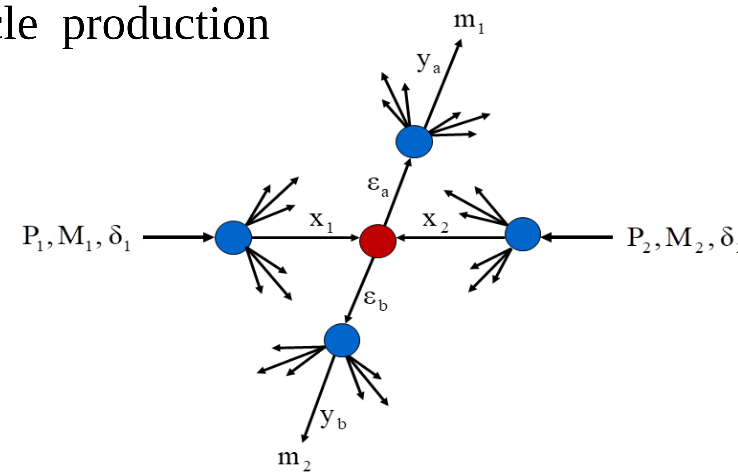
Interactions of constituents are mutually similar

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



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

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



- Ω^{-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)

Fractality

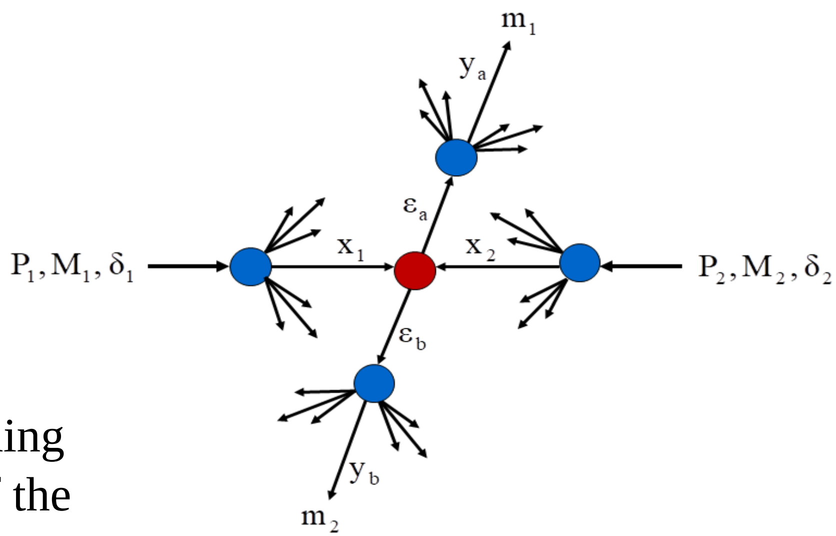
Self-similarity over a wide scale range

Fractal measure

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

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

$$0 < x_1, x_2 < 1 \qquad 0 < y_a, y_b < 1$$



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

δ_1, δ_2, ε_a, ε_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 Ω^{-1} increases.

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

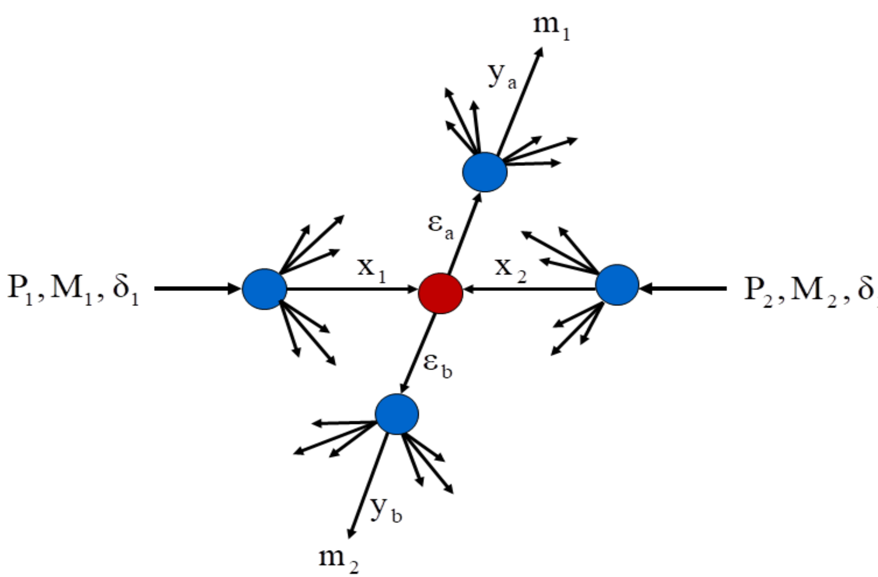
Momentum fractions: x_1, x_2, y_a, y_b

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 Ω^{-1} of the fractal measure z with respect to all constituent sub-processes taking into account 4-momentum conservation law:

Momentum conservation law

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

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



Resolution of sub-process

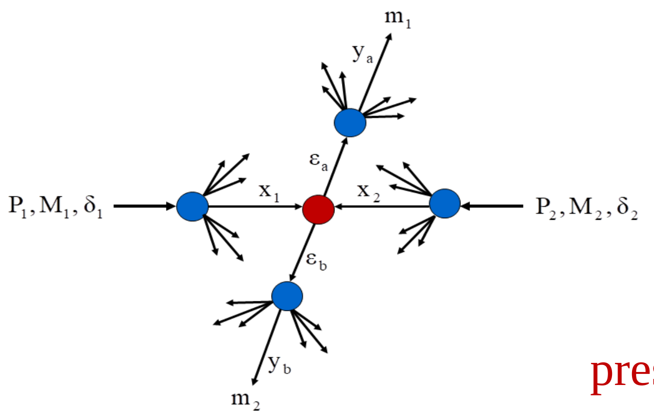
$$\Omega^{-1} = (1-x_1)^{-\delta_1}(1-x_2)^{-\delta_2}(1-y_a)^{-\varepsilon_a}(1-y_b)^{-\varepsilon_b}$$

Mass of recoil system

$$M_X = x_1M_1+x_2M_2+m_2/y_b$$

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

Scaling function $\Psi(z)$



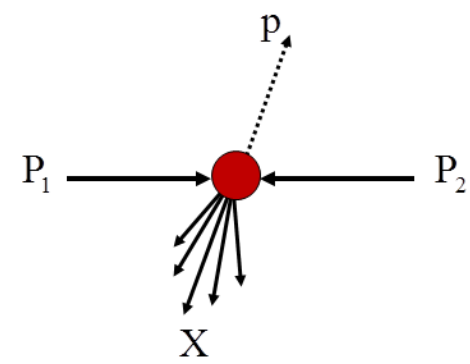
Normalization condition

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

Scale transformation

$$z \to \alpha_F \cdot z \qquad \Psi \to \alpha_F^{-1} \cdot \Psi$$

preserves the normalization condition



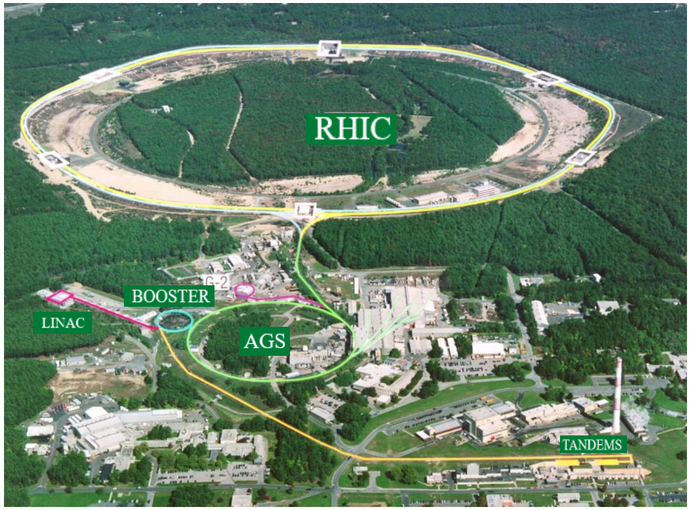
$$\Psi(z) = \frac{\pi}{(dN/d\eta)\cdot\sigma_{inel}} \cdot J^{-1} \cdot E\frac{d^3\sigma}{dp^3} \qquad \Longleftrightarrow \qquad \int E\frac{d^3\sigma}{dp^3} dy d^2p_\perp = \sigma_{inel} \cdot \langle N \rangle$$

- σ_{in} - 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
- $Ed^3\sigma/dp^3$ - the inclusive cross section

The scaling function $\Psi(z)$ is a probability density to produce the inclusive particle with the corresponding value of self-similarity variable z.

Strange particle production in p+p from RHIC

p+p @ RHIC



K^0_S, K^-, K^*, ϕ, Λ, Ξ, Ω, Σ^*, Λ^*

p+p is a benchmark for strangeness production in A+A collisions

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

Self-similarity of strangeness production in p+p

Universality: flavor independence of the scaling function

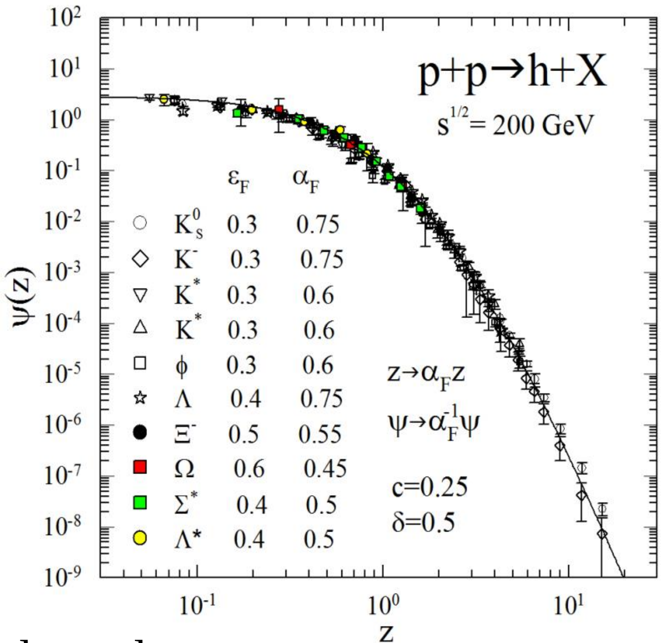
$\boxed{K^0_S, K^-, K^*, \phi, \Lambda, \Xi, \Omega, \Sigma^*, \Lambda^*}$

"Collapse" of data points onto a single curve

M.T.& I.Zborovský
Int.J.Mod.Phys.
A24,1417(2009)

Solid line for π^- meson is a reference frame

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



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

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

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- Angular independence
- Flavor independence
- Saturation for $z < 0.1$

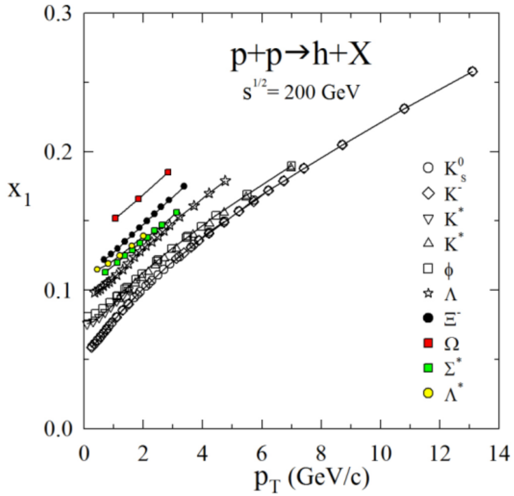
- Power law $\Psi(z) \sim z^{-\beta}$ at large z
- ε_F, α_F independent of p_T, $s^{1/2}$

Self-similarity of strangeness production in p+p

K^0_S, K^-, K^*, ϕ, Λ, Ξ, Ω, Σ^*, Λ^*

Constituent sub-process in terms of

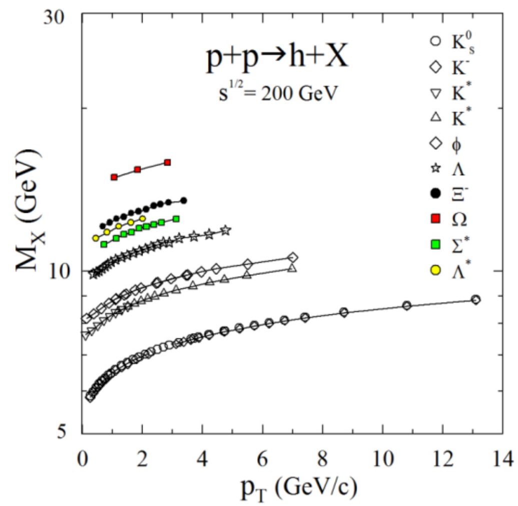
Momentum fraction



The more strangeness,
the larger momentum fraction

$$x_1^{\Omega} > x_1^{\Xi} > x_1^{\Sigma} > x_1^{K}$$

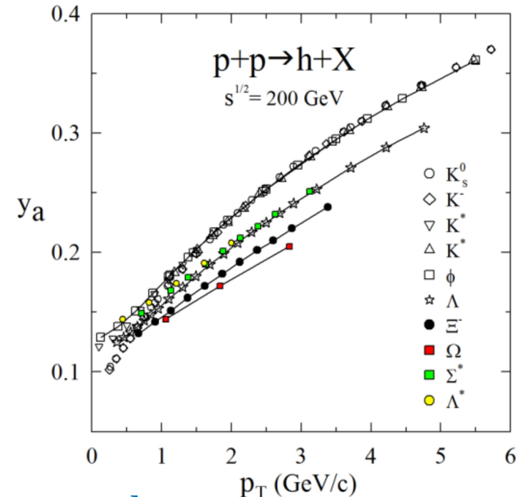
Recoil mass



The more strangeness,
the larger recoil mass

$$M_X^{\Omega} > M_X^{\Xi} > M_X^{\Sigma} > M_X^{K}$$

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



The more strangeness,
the larger energy loss

$$\varepsilon_{\Omega} > \varepsilon_{\Xi} > \varepsilon_{\Sigma} > \varepsilon_{K}$$

Smooth behavior of x_1, y_a, M_X vs. p_T.

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

Self-similarity of K_S^0 meson production in p+p

Self-similarity parameter

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

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

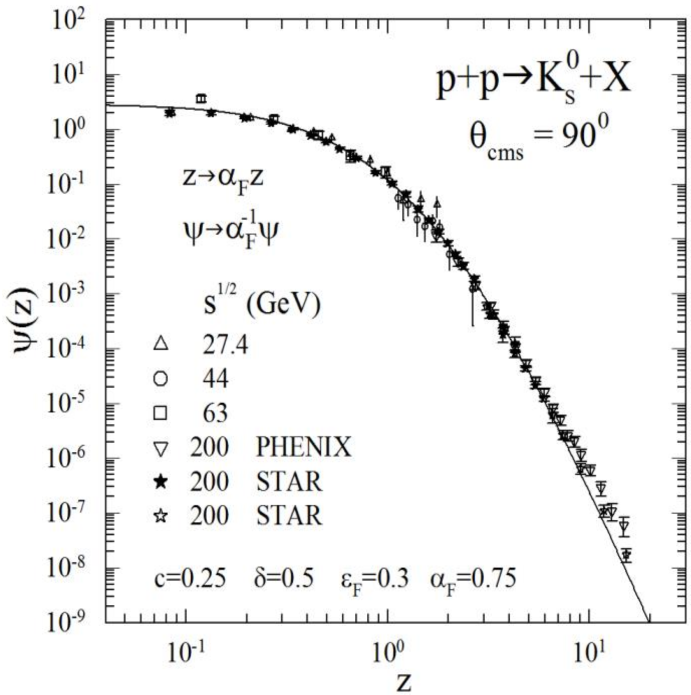
$$\Omega = (1-x_1)^\delta (1-x_2)^\delta (1-y_a)^{\varepsilon_F} (1-y_b)^{\varepsilon_F}$$

- $dN_{ch}/d\eta|_0$ - multiplicity density
- c - "specific heat" of bulk matter
- δ - proton fractal dimension
- ε_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 onto a single curve



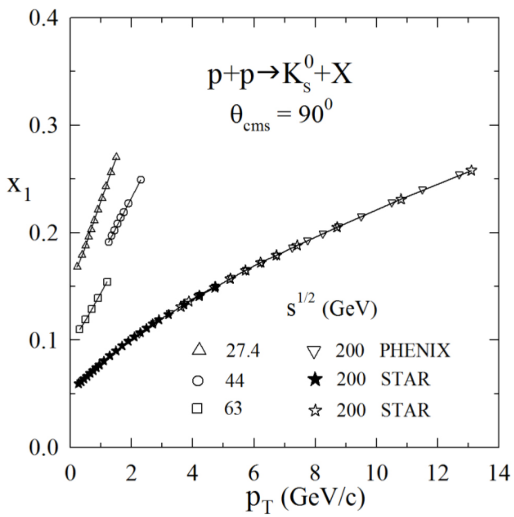
- Energy independence of $\Psi(z)$
- Centrality independence of $\Psi(z)$
- Power law at high z
- Saturation at low z

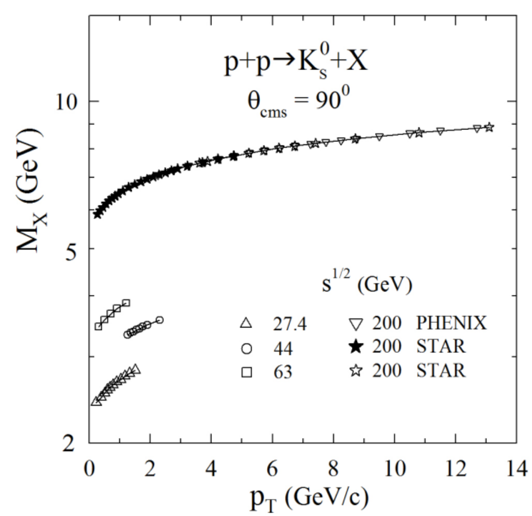
Universality: the same shape of Ψ both for K_S^0 and π^- (solid line)

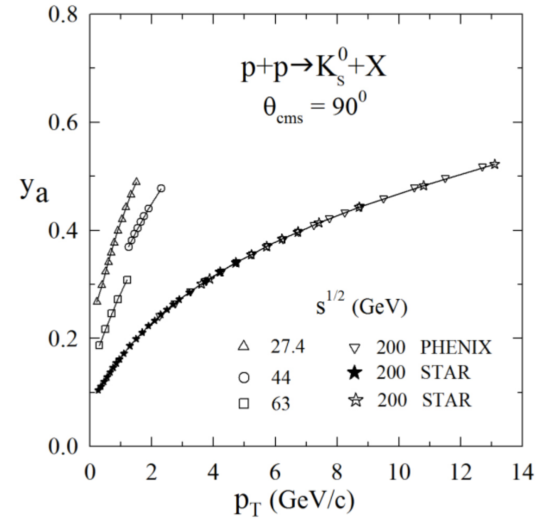
Self-similarity of K_S^0 meson production in p+p

Constituent sub-process in terms of

Momentum fraction | Recoil mass | Energy loss $\Delta E/E \sim (1-y_a)$







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

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

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

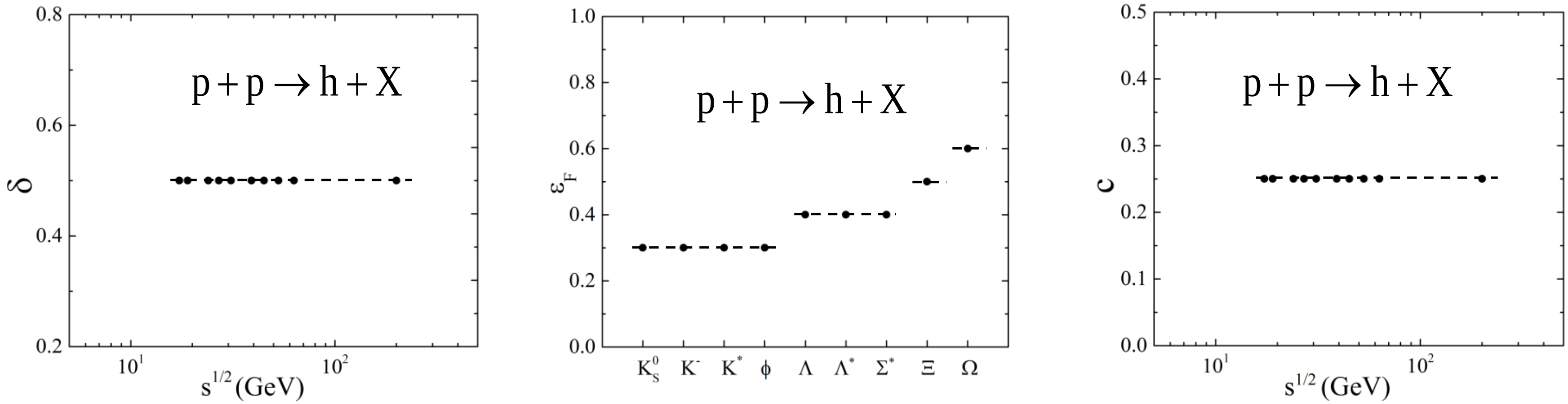
Smooth behavior of x_1, y_a, M_X vs. p_T, collision energy

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

Model parameters: δ, ε_F , c

Parameters δ, ε_F , c are found from
the scaling behavior of Ψ as a function of self-similarity variable z

Proton fractal dimension δ | Fragmentation dimension ε_F | "Specific heat" c



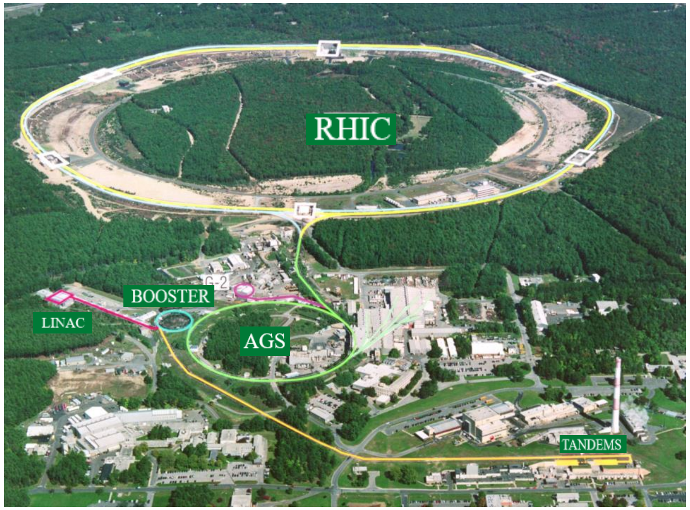
- δ, ε_F , c are independent of $\sqrt{s}$, p_T
- ε_F depends on flavor

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

Strange particle production in Au+Au from RHIC

Au+Au @ BES-I

STAR



PHENIX

K^0_S, K^-, K^*, ϕ, Λ, Ξ, Ω, Σ^*, Λ^*

J. Adam et al. (STAR Collaboration)
Phys. Rev. C 102 (2020) 034909

Self-similarity of K_S^0 meson production in Au+Au

Self-similarity parameter

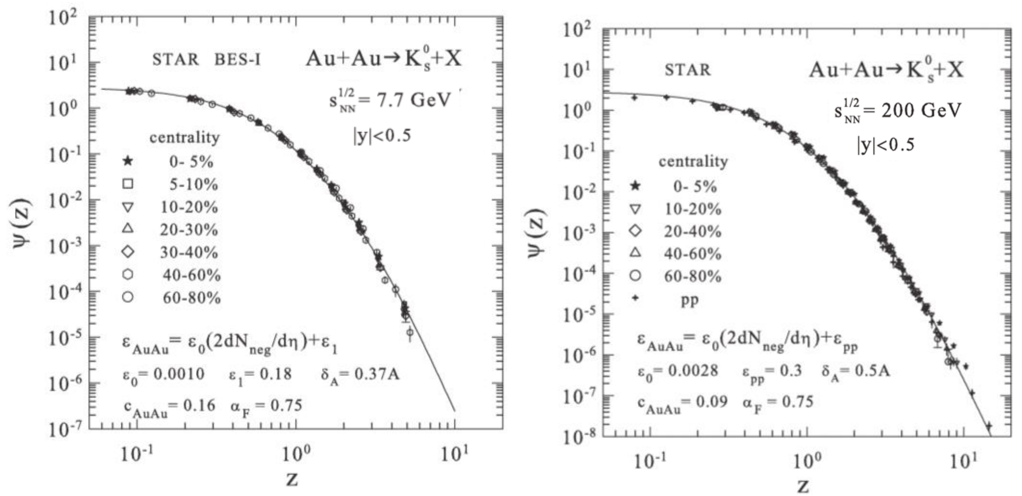
$$z = z_0 \Omega^{-1}$$

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

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

- $dN_{ch}/d\eta|_0$ - multiplicity density
- c_{AA} - "specific heat" of bulk matter
- δ_A - nucleus fractal dimension
- ε_{AA} - fragmentation dimension

"Collapse" of data points onto a single curve



AA collisions:

$$\delta_A = A\delta$$

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

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

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

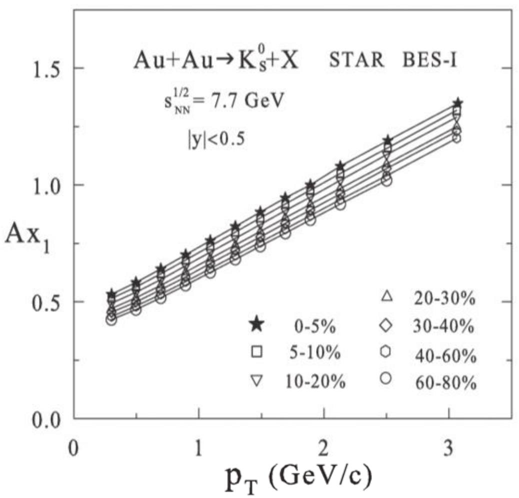
Indication of a decrease of δ for $\sqrt{s_{NN}} < 19.6$ GeV

M.T. & I.Zborovsky, Nucl. Phys. A993 (2020) 121646

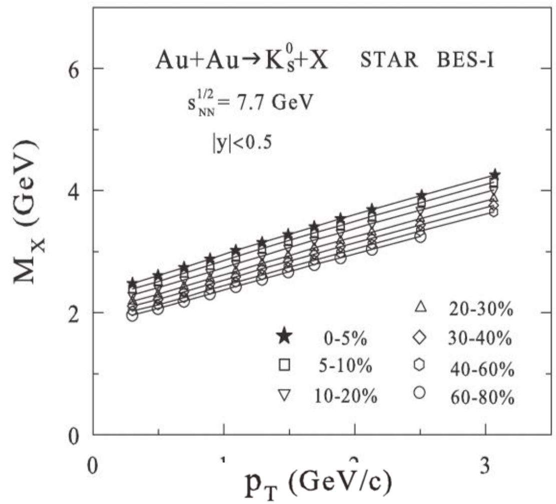
K_S^0 production in Au+Au @ 7.7 GeV

Constituent sub-process in terms of

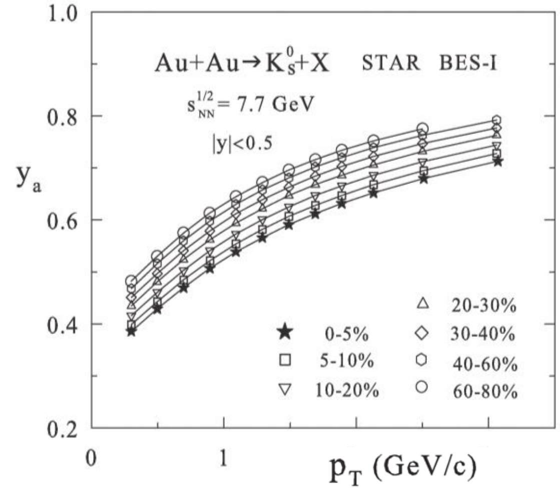
Momentum fraction Ax_1



Recoil mass M_X



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



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

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

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

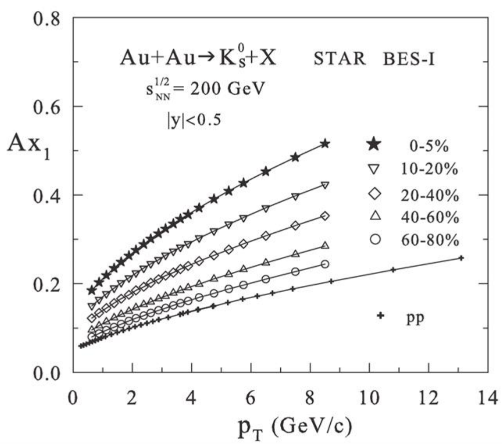
Smooth behavior of x_1, y_a, M_X vs. p_T, centrality

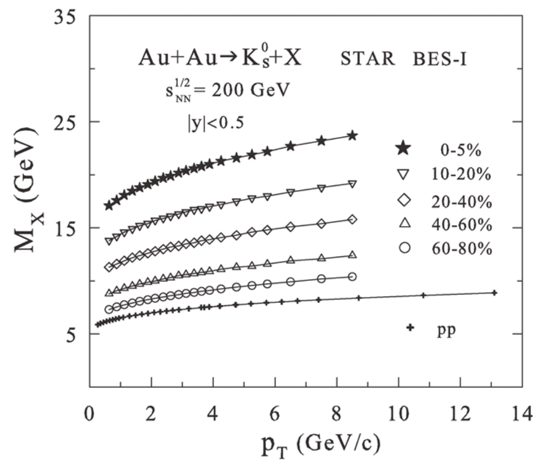
- High x_1 and p_T → compressed matter
- Large M_X → high density recoil system
- High y_a → small energy loss

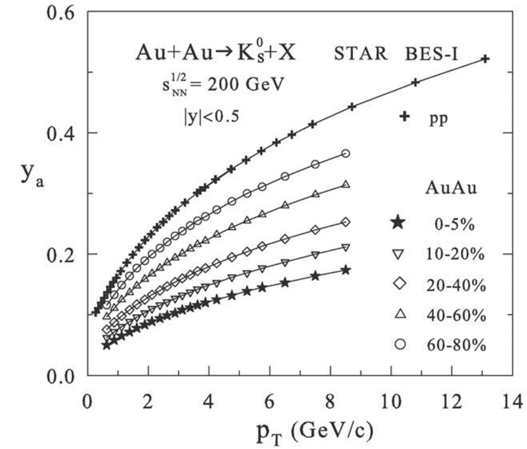
K_S^0 production in Au+Au @ 200 GeV

Constituent sub-process in terms of

Momentum fraction Ax_1 | Recoil mass M_X | Energy loss $\Delta E/E \sim (1-y_a)$







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

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

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

Smooth behavior of x_1, y_a, M_X vs. p_T, centrality

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

Self-similarity of K_S^0 production in Au+Au

Self-similarity parameter

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

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

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

- $dN_{ch}/d\eta|_0$ - multiplicity density
- c_{AA} - "specific heat" of bulk matter
- δ_A - nucleus fractal dimension
- ε_{AA} - fragmentation dimension

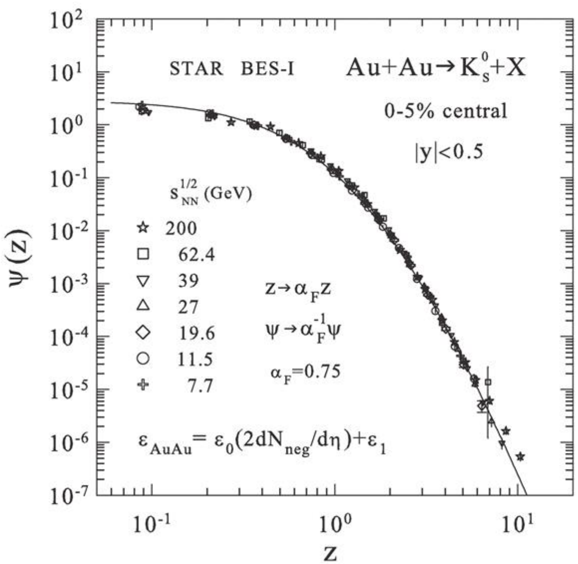
AA collisions:

$$\delta_A = A\delta$$

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

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

"Collapse" of data points onto a single curve



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

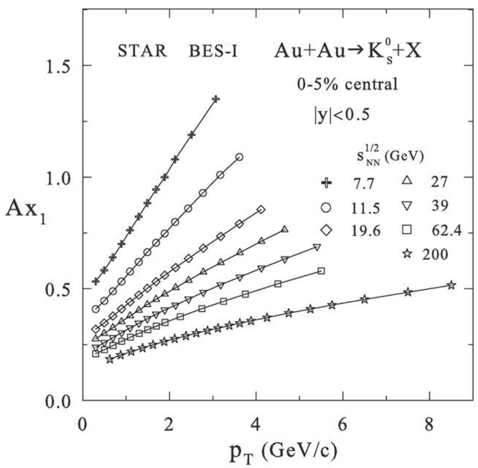
Indication of a decrease of δ for $\sqrt{s_{NN}} < 19.6$ GeV

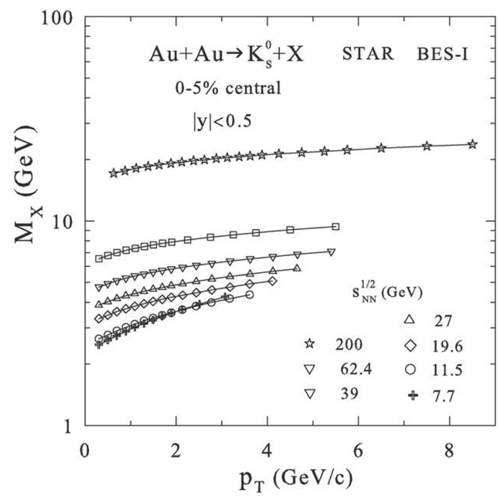
M.T. & I.Zborovsky, Nucl. Phys. A993 (2020) 121646

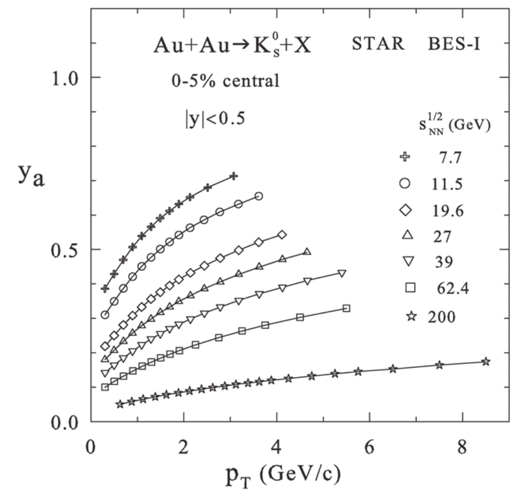
K_S^0 production in central Au+Au @ 7.7-200 GeV

Constituent sub-process in terms of

Momentum fraction Ax_1 | Recoil mass M_X | Energy loss $\Delta E/E \sim (1-y_a)$







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

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

Energy loss
- 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 → compressed nuclear matter
- Large M_X → high density recoil system
- High y_a → small energy loss

Signatures of Phase Transition and Critical Point

- **Discontinuity** of the model parameters: "specific heat"- c, fractal dimension – δ
- **Enhancement** of c-δ correlation
- **Energy loss** is a contamination factor leading to smearing of the phase transition signatures

Summary

- STAR BES-I data on transverse momentum spectra of K_S^0 mesons produced in Au+Au collisions at RHIC in mid-rapidity region were analyzed in the z-scaling approach.
- Self-similarity of strange K_S^0 meson production in Au+Au collisions over a wide kinematical and centrality range was found.
- Constituent energy loss as a function of collision energy and centrality, and transverse momentum of K_S^0 meson was estimated.
- Model parameters - fractal dimensions and "specific heat", were found.
- Universality of Ψ vs. z and smooth behavior x_1, y_a, M_X vs. p_T, centrality, collision energy were observed.
- The method of data analysis is extended for systematic description of A+A collisions with production of identified hadrons.

Specific features of constituent sub-process with strange particles found in the z-scaling approach can be sensitive to critical phenomena in Quark Matter created in A+A collisions.

Thank You for Your Attention !