6th International Workshop on
Critical Point and Onset of Deconfinement
August 23-29, 2010 @ Joint Institute for Nuclear Research

Energy Scan in Heavy Ion Collisions and Search for a Critical Point

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Motivation

"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.Barenblat,…

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

z-Scaling can be used as a tool for searching for new physics in particle production at high energies.

Goals

- Search for and study of signatures of a phase transition and critical point in hadron production in heavy ion collisions at high transverse momenta and collision energies $\sqrt{s_{NN}} = 10-40$ GeV

- Exploiting the properties of z-scaling to study nuclear matter properties near a critical point (specific heat, A-dependence of fractal dimensions, fragmentation fractal dimensions, energy losses, ….)

- Study of the power law of the scaling function $\Psi(z)$ at high p_T (self-similarity at small scales, anisotropy of spacetime, …)

- Kinematical range preferable for searching for phase transition and CP (cumulative processes, high-p_T spectra,…)

Beam Energy Scan Program at SPS 1996-2011

CERN-SPSC-2006-034
SPSC-P-330
November 3, 2006

Study of Hadron Production in Hadron-Nucleus and Nucleus-Nucleus Collisions at the CERN SPS

NA61

The proposed physics program consists of

- measurements of hadron production in nucleus-nucleus collisions, in particular fluctuations and long range correlations, with the aim to identify the properties of the onset of deconfinement and find evidence for the critical point of strongly interacting matter,

- measurements of hadron production in proton-proton and proton-nucleus interactions needed as reference data for better understanding of nucleus-nucleus reactions; in particular correlations, fluctuations and high transverse momenta will be the focus of this study,

The two most important open questions are:

- what is the nature of the transition from the anomalous energy dependence measured in central Pb+Pb collisions at SPS energies to the smooth dependence measured in p+p interactions?
- is it possible to observe the predicted signals of the onset of deconfinement in fluctuations [69] and anisotropic flow [70]?

It is thus clear that only the new measurements at the CERN SPS can answer the important question:

- does the critical point of strongly interacting matter exist in nature and, if it does, where is it located?

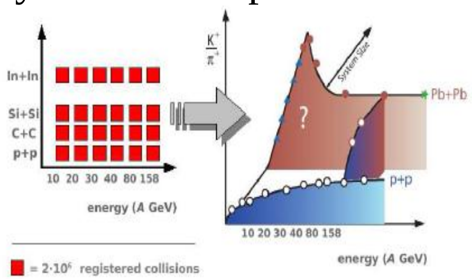
NA49

Energy, centrality, system-size scan

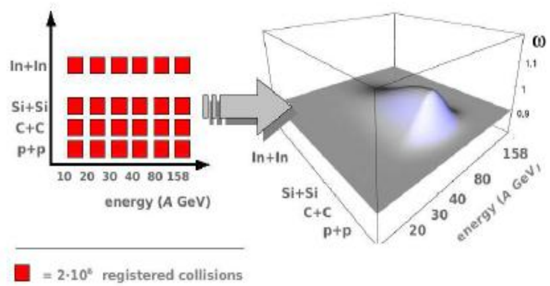
$\sqrt{s_{NN}}$ [GeV]	Centrality [%]	Statistics [K]	Taken [year]
17.3	10	800	1996
17.3	20	3000	2000
12.3	7	300	2000
8.8	7	700	1999
7.6	7	400	2002
6.3	7	300	2002

p+p, *Si+Si*, *Pb+Pb* at $\sqrt{s_{NN}}$ = 17.3 GeV

Energy, centrality, system-size dependence



Search for Critical Point



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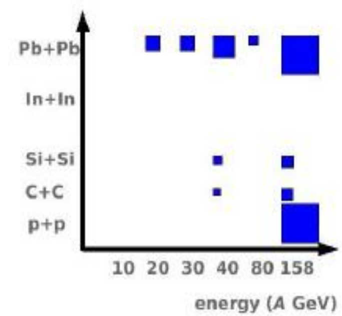
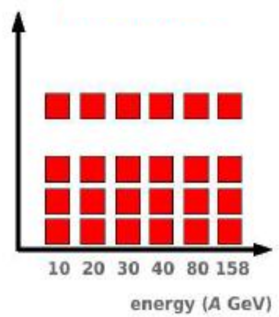


NA61



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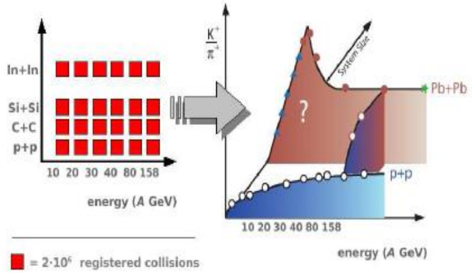
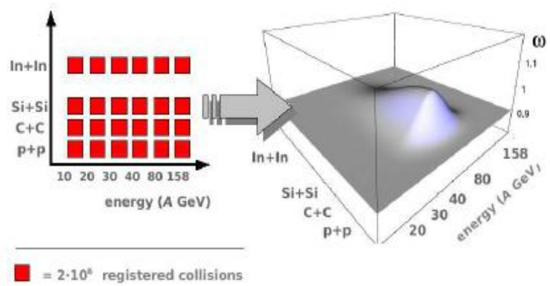
NA61
Energy, centrality, system-size scan

$\sqrt{s_{NN}}$ [GeV]	AA pp	Days	Statistics [M]	To be taken [year]
6.3-17.3	InIn pp	30 30	6 6	2009
6.3-17.3	SiSi pp	30 30	6 60	2010
6.3-17.3	CC pPb	30 30	6 6	2011

Energy, centrality, system-size dependence



Search for Critical Point



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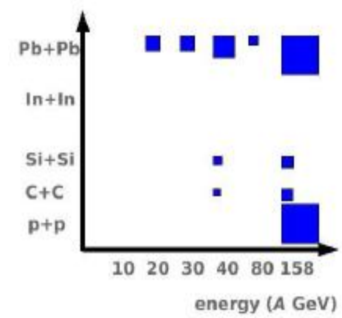
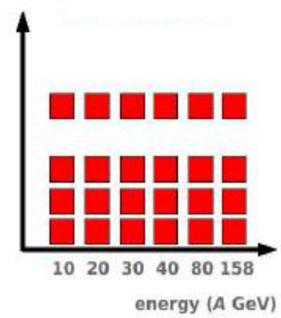
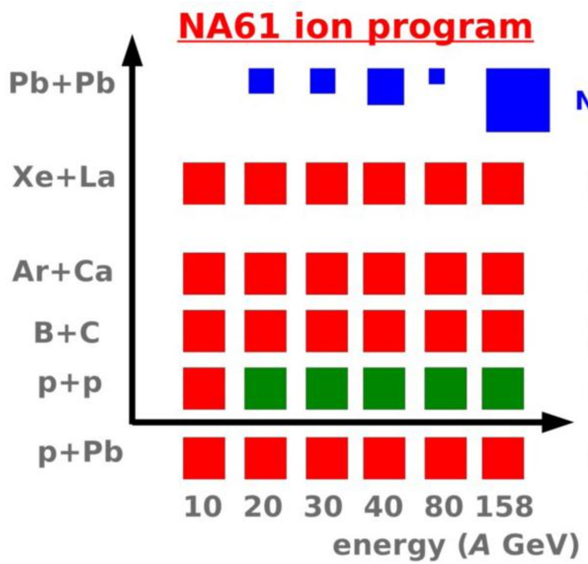


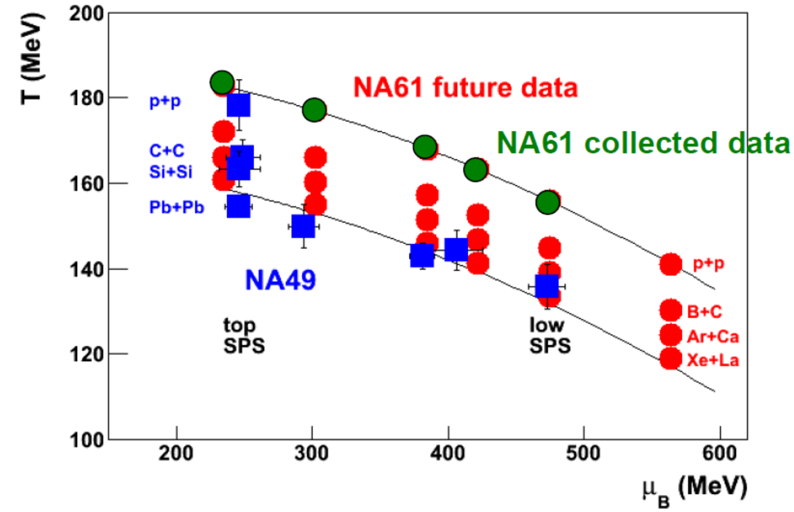
NA61



Energy Scan at SPS & NA61 Experiment

Physics of strongly interacting matter & pp, pA, AA

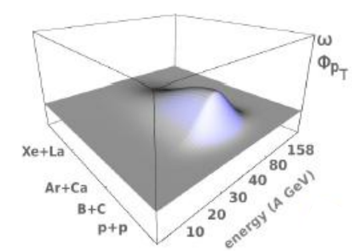




- System size and energy scan program is started.
- It is crucial for the study of the onset of decon-finement and search for the critical point.

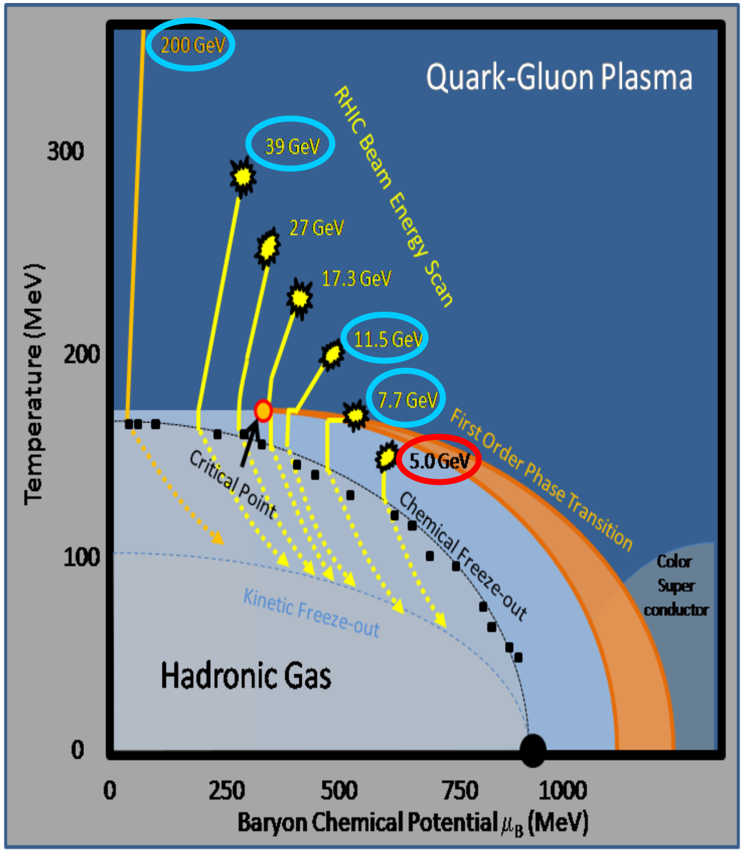
Expected signals

- E-by-E p_T-fluctuations
- Kink, horn, step vs. $F \approx s_{NN}^{1/4}$



A.Marcinek for NA61
Rencontres de Moriond "QCD and High Energy Interactions"
La Thuile, March 13-20, 2010, France

Energy Scan at RHIC & STAR experiment



- Search for phase transition and critical point
  - Elliptic & directed flow
  - Azimuthally-sensitive femtoscopy
  - Fluctuation measures
- Search for turn-off of new phenomena seen at higher RHIC energies
  - Constituent-quark-number scaling of v_2
  - Hadron suppression in central collisions
  - Ridge
  - Local parity violation
  - At higher RHIC energies T_{ch} is constant. Moving to sufficient low collision energy, expect T_{ch} to be smaller and vary with centrality. Study this variation in BES.

STAR Note SN0493

STAR: Phys. Rev. C 81, 024911 (2010)

AuAu Beam Energy Scan Program at RHIC

Experimental Study of the QCD Phase Diagram and Search for the Critical Point

STAR Run 10 Plan & Results (October 5 - June 8)

Beam Energy	μ_B (MeV)	Event Rate	8-hr Days/1M Events	Events proposed	8-hr days proposed
5	550	0.8	45	(100 k)	5
7.7	410	3	11	5M	56
11.5	300	10	3.7	5M	19
17.3	230	33	1.1	15M	16
27	150	92	0.4	33M	12
39	110	190	0.2	24M	5

Beam energy $\sqrt{s}$, GeV	Events proposed (Million)	Events taken (Million)
5.5	0.1	Not done
7.7	5	5
11.5	5	~7.8
17.3	15	Not done
27	33	Not done
39	24	~250
62.4	5	~170
200		~800

All goals significantly exceeded for some data points

Conservative estimate of rates and hours/day

Expected range of CP: μ_B = 150-600 MeV

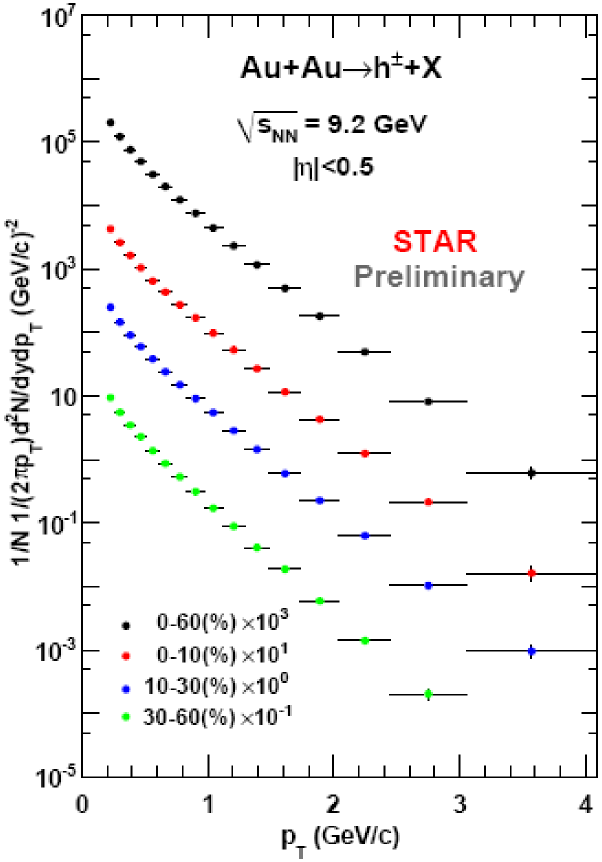
STAR Note SN0493

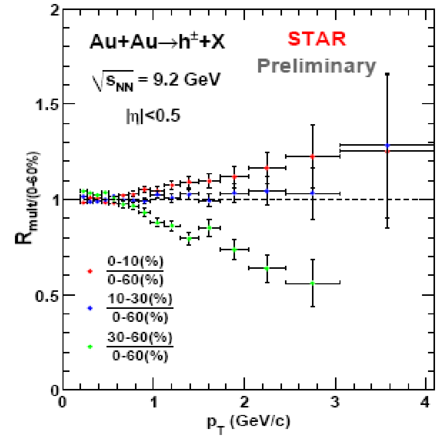
STAR: Phys. Rev. C 81, 024911 (2010)

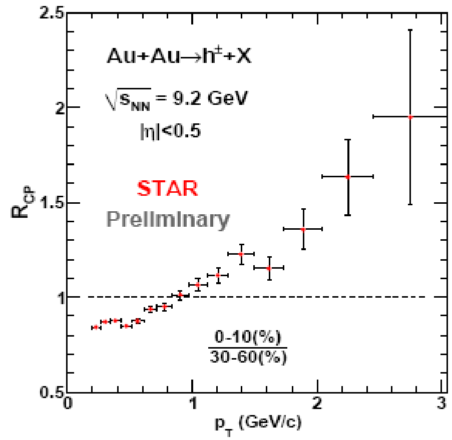
Yu.Gorbunov, STAR Collaboration
RHIC&AGS Annual User's Meeting
7-11 June, 2010, BNL, USA

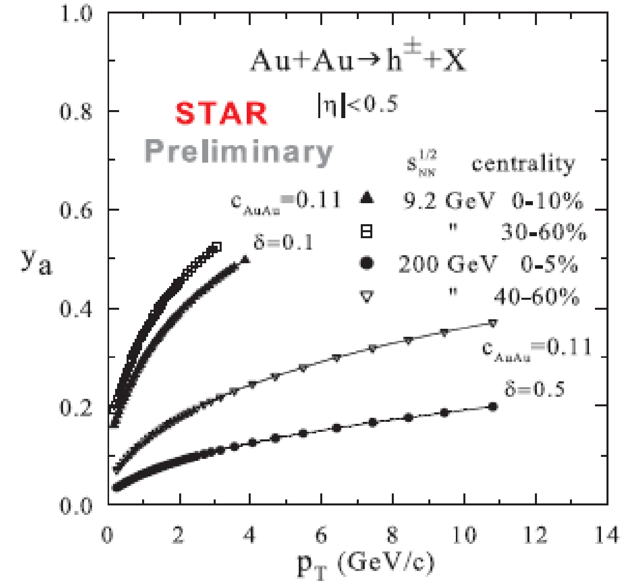
High-p_T Spectra of Charged Hadrons in Au+Au Collisions at $\sqrt{s_{NN}}$ = 9.2 GeV in STAR

STAR nucl-ex/1004.5582v1









Data sample (2008)

~ 4000 events

- High-p_T spectra vs. centrality
- R_{CP} ratio vs. p_T
- Energy loss vs. p_T, $dN/d\eta$

Phase transition & z-Scaling

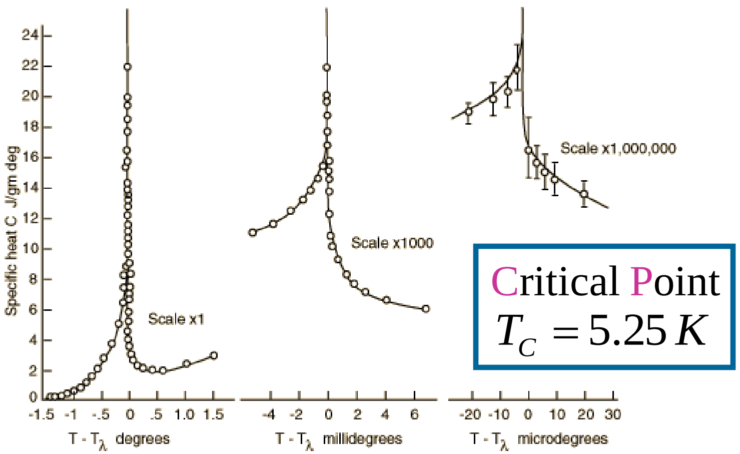
- Self-similarity is main feature of z-scaling revealed in hadron, jet and direct photon production in high energy hadron and nucleus collisions.
- Universality classes – hadrons, direct photons, jets, …, are characterized by different values of suitable parameters (critical exponents – fractal dimensions ε, δ).
- Generalized homogeneous functions describe the behavior of a thermodynamic system near a critical point (thermodynamic potentials - Gibbs potential G(T,p), Helmholtz potential F(T,V), Internal energy U(S,V), Enthalpy E(S,p)).
- Divergence of several properties of the system near the critical point:

$$c_V \propto (T - T_c)^{-\alpha} \quad \textit{heat capacity} \qquad k_T \propto (T - T_c)^{-\gamma} \quad \textit{compressibility}$$

Rate of the divergence is described by a set of critical exponents (α,γ). In the same universality class, the critical exponents are identical.

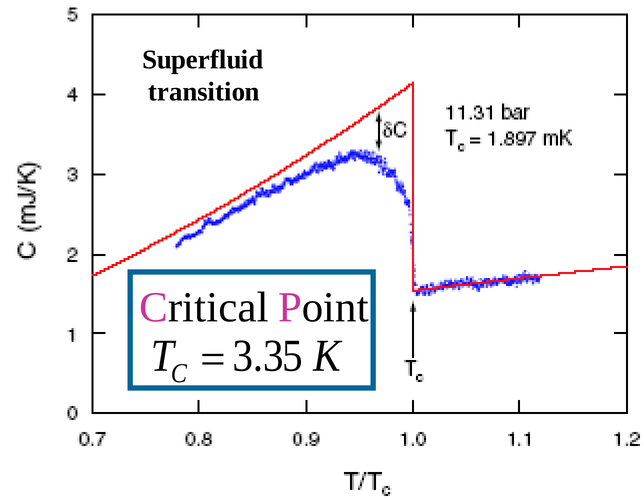
Self-similarity in condensed matter

Specific heat of liquid ^4He



H.E. Stanley, 1971

Heat capacity of liquid ^3He



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

- Close to a critical point, the singular part of thermodynamic potentials forms 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).

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

- Discontinuity of specific heat near a critical point.

z-Scaling & Universality in pp

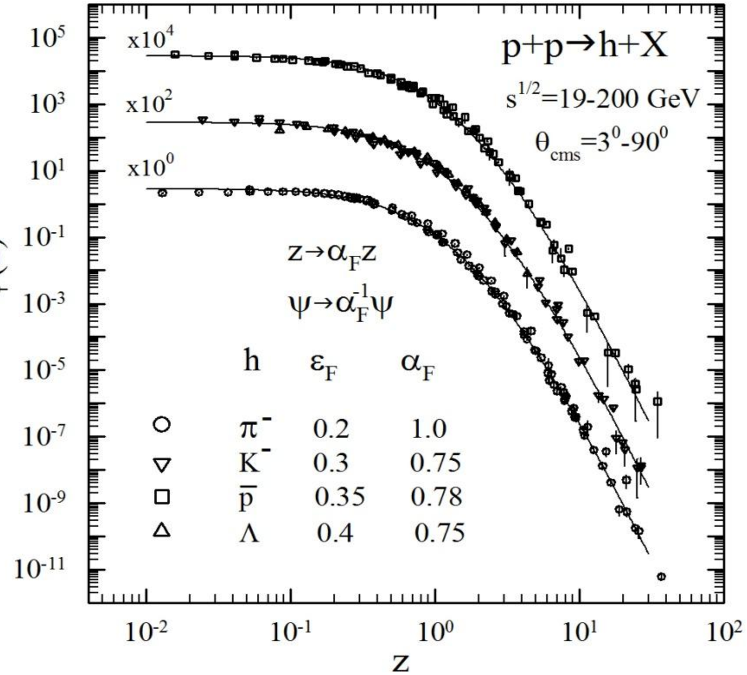
π^-, K^-, $\bar{p}$, Λ
in pp collisions

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



MT & I.Zborovsky
Phys.Rev.D75,094008(2007)
Int.J.Mod.Phys.A24,1417(2009)
J. Phys.G: Nucl.Part.Phys. 37,085008(2010)

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

- Energy & angular independence
- Flavor independence (π, K, p, Λ)
- Saturation for z<0.1
- Power law for high z>4

Scaling – "collapse" of data points onto a single curve.

z-Scaling & HIC

z-Scaling reflects self-similarity, locality and fractality
in particle production at a constituent level.
The variable z is a self-similar parameter.

Search for signatures of new state of nuclear matter in heavy ion collisions at high energy and multiplicity density
(phase transition, critical point,… QGP, GLASMA,…)

- Scaling in elementary processes as reference for nuclear collisions.
- Scaling features in HIC as sensitive characteristics of nuclear matter and signatures of new medium created in HIC.
- Parameters of theory sensitive to phase transition.

Analysis of experimental data on charged hadrons in AuAu collisions
at RHIC at $s^{1/2} = 9\text{-}200$ GeV
to search for CP & estimation of particle energy loss.

Scaling analysis in high energy interactions

Scaling variables

- $m_T = \sqrt{p_T^2 + m_0^2}$ — transverse mass
- $x_F = p_{||}^* / p_{||max}^*$ — Feynman variable
- $x_R = E^* / E_{max}^*$ — radial scaling variable
- $\alpha = k_+ / p_+$ — light-cone variable
- $x_{Bj} = -q^2 / 2(Pq)$ — Bjorken variable
- $n / < n >$ — P-KNO variable

➢ These scaling regularities have restricted range of validity

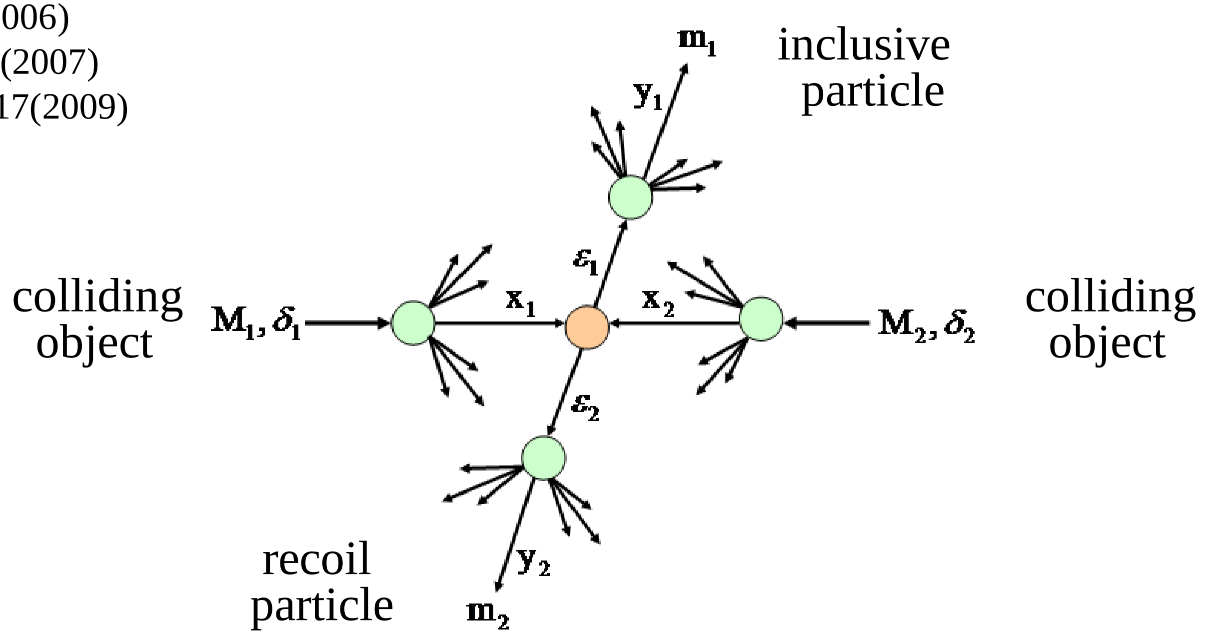
➢ Violation of the scaling laws can be indication of new physics

z-Scaling provides universal description of the inclusive particle cross sections over a wide kinematical region

(central+fragmentation region, $p_T > 0.5$ GeV/c, $s^{1/2} > 20$ GeV)

Hadron/nucleus collisions at a constituent level

M.T. & I.Zborovsky
Part.Nucl.Lett.312(2006)
Phys.Rev.D75,094008(2007)
Int.J.Mod.Phys.A24,1417(2009)



Constituent subprocess

$$(x_1M_1) + (x_2M_2) \Rightarrow (m_1/y_1) + (x_1M_1+x_2M_2+m_2/y_2)$$

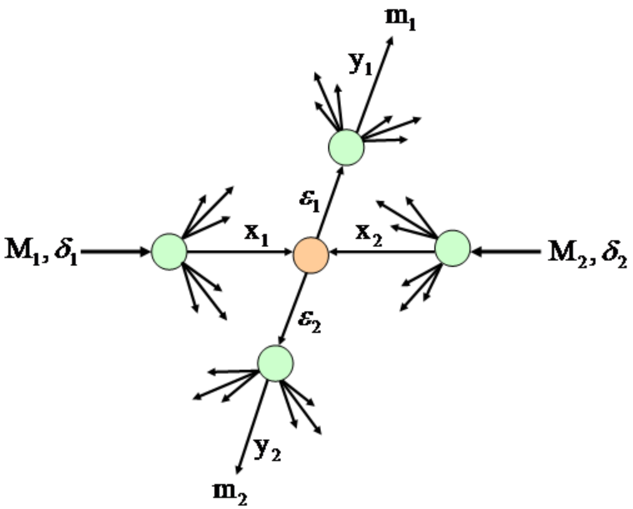
is subject to the kinematic condition:

$$(x_1P_1+x_2P_2-p/y_1)^2 = (x_1M_1+x_2M_2+m_2/y_2)^2$$

Scaling variable z

M.T. & I.Zborovsky
Part.Nucl.Lett.312(2006)
Phys.Rev.D75,094008(2007)
Int.J.Mod.Phys.A24,1417(2009)

$$z = \frac{s_{\perp}^{1/2}}{(dN_{ch}/d\eta|_0)^c \cdot m} \cdot \Omega^{-1}$$



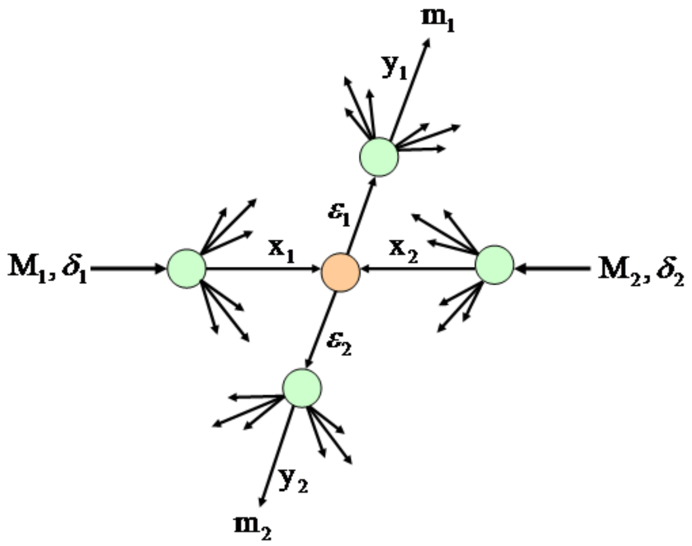
- $s_{\perp}^{1/2}$ is transverse kinetic energy of the constituent subprocess consumed on production of m_1 & m_2
- Ω^{-1} is minimal resolution at which the subprocess can be singled out of the inclusive reaction
- $dN_{ch}/d\eta|_0$ is the multiplicity density of charged particles at $\eta = 0$
- c is a parameter interpreted as "heat capacity" of the created medium
- m is arbitrary normalization (it is fixed at the value of nucleon mass)

$s_\perp^{1/2}$, Ω & momentum fractions x_1, x_2, y_1, y_2

Principle of minimal resolution: The momentum fractions x_1, x_2 and y_1, y_2 are determined in a way to minimize the resolution Ω^{-1} of the fractal measure z with respect to all constituent subprocesses taking into account momentum conservation:

$$\Omega = (1-x_1)^{\delta_1}(1-x_2)^{\delta_2}(1-y_1)^{\varepsilon_1}(1-y_2)^{\varepsilon_2}$$

$$\begin{cases} \partial\Omega/\partial x_1 \,|_{y_1=y_1(x_1,x_2,y_2)} = 0 \\ \partial\Omega/\partial x_2 \,|_{y_1=y_1(x_1,x_2,y_2)} = 0 \\ \partial\Omega/\partial y_2 \,|_{y_1=y_1(x_1,x_2,y_2)} = 0 \end{cases}$$



Kinematic condition:

$$(x_1P_1+x_2P_2-p/y_1)^2 = (x_1M_1+x_2M_2+m_2/y_2)^2$$

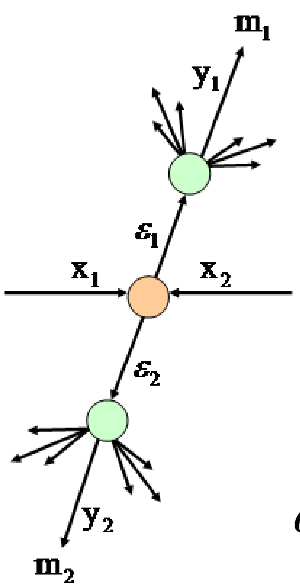
We set $\varepsilon_1 = \varepsilon_2 \equiv \varepsilon = \varepsilon_F$ which depends on the type (F) of the hadron (m_1)

Transverse kinetic energy $s_{\perp}^{1/2}$ consumed on production of m_1 & m_2

$$s_{\perp}^{1/2} = \underbrace{y_1(s_{\lambda}^{1/2} - M_1\lambda_1 - M_2\lambda_2) - m_1}_{\text{Kinetic energy consumed for the inclusive particle } m_1} + \underbrace{y_2(s_{\chi}^{1/2} - M_1\chi_1 - M_2\chi_2) - m_2}_{\text{Kinetic energy consumed for the recoil particle } m_2}$$

Kinetic energy consumed for the inclusive particle m_1

Kinetic energy consumed for the recoil particle m_2



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

$$\lambda_{1,2} = \kappa_{1,2}/y_1 + \nu_{1,2}/y_2$$

$$\kappa_{1,2} = \frac{(P_{2,1}p)}{(P_2P_1)}, \quad \nu_{1,2} = \frac{M_{2,1}m_2}{(P_2P_1)}$$

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

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

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

$$\lambda_0 = \bar{\nu}_0/y_2^2 - \nu_0/y_1^2$$

$$\xi^2 = (\lambda_1\lambda_2 + \lambda_0)/[(1-\lambda_1)(1-\lambda_2)]$$

$$\bar{\nu}_0 = \frac{0.5m_2^2}{(P_1P_2)}, \quad \nu_0 = \frac{0.5m_1^2}{(P_1P_2)}$$

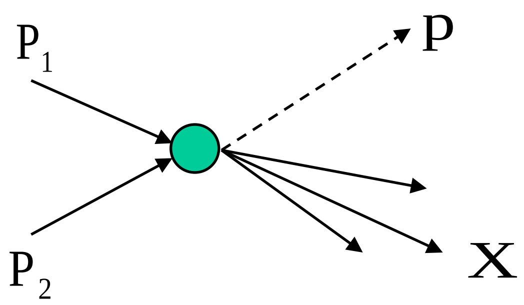
$$s_{\lambda} = (\lambda_1P_1 + \lambda_2P_2)^2$$

$$s_{\chi} = (\chi_1P_1 + \chi_2P_2)^2$$

Data analysis => $m_1 = m_2$

Scaling function $\Psi(z)$

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



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

Scaled particle yield vs. scaled transverse momentum

Normalization of $\Psi(z)$:

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

Scale transformation of z

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

preserves the normalization condition.

Properties of $\Psi(z)$ in pp/$\bar{p}$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)
- 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,…)
- Saturation of $\Psi(z)$ at low z ($z < 0.1$)

These properties reflect self-similarity, locality,
and fractality of the hadron interaction at constituent level.
It concerns the structure of the colliding objects, interactions
of their constituents, and fragmentation process.

M.T. & I.Zborovsky
Phys.At.Nucl. 70,1294(2007)
Phys.Rev. D75,094008(2007)
Int.J.Mod.Phys.A24,1417(2009)

Universality classes & F-independence of $\Psi(z)$

Saturation at low z

π^-, K^-, $\bar{p}$, Λ
in pp collisions

FNAL:
PRD 75 (1979) 764

ISR:
NPB 100 (1975) 237
PLB 64 (1976) 111
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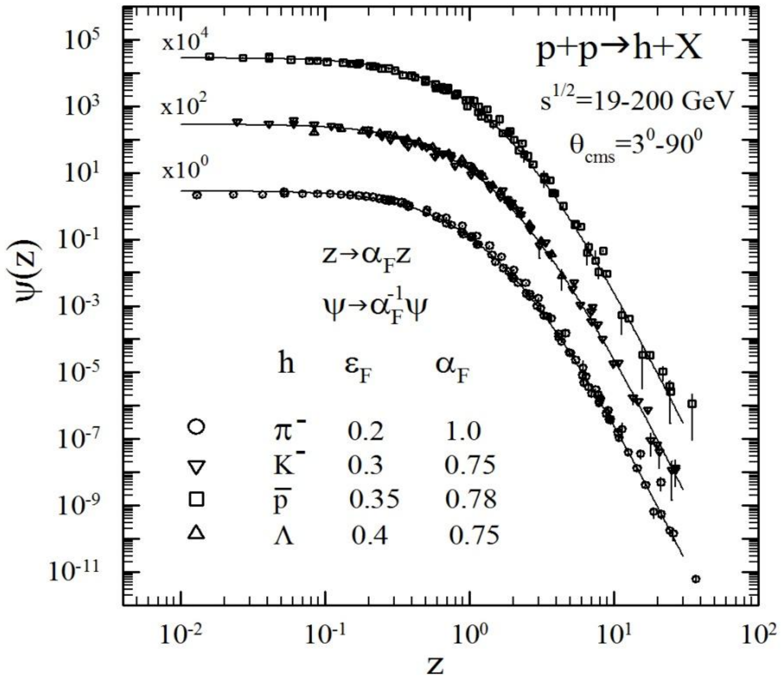
PLB 637 (2006) 161
PRC 75 (2007) 064901



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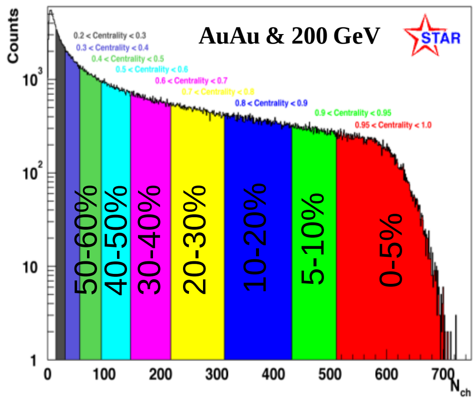
- $\psi(z) \sim z^{-\beta}$ at large z
- ε_F, α_F independent of p_T, $s^{1/2}$, θ_{cms}

- Energy & angular independence
- Flavor independence (π, K, p, Λ)
- Saturation for z<0.1
- Power law for high z>4

Scaling – "collapse" of data points onto a single curve.
Scaled particle yield vs. scaled transverse momentum.
Universality classes – hadron species (ε_F, α_F).

Self-similarity parameter z in AA collisions

$z = z_0 \Omega^{-1}$ $\quad z_0 = \frac{s_\perp^{1/2}}{(dN_{ch}/d\eta|_0)^c m_N}$ $\quad \Omega = (1-x_1)^{\delta_{A1}}(1-x_2)^{\delta_{A2}}(1-y_1)^{\varepsilon}(1-y_2)^{\varepsilon}$



Ingredients of z characterizing AA collisions:

- $dN_{ch}/d\eta|_0$ - multiplicity density in AA collisions
- c - "specific heat" in AA collisions
- δ_A - nucleus fractal dimension
- ε - fragmentation dimension in AA collisions

These quantities characterize properties of medium created in AA collisions.

Additivity of fractal dimensions in pA collisions: $\delta_A = A\delta$

consistent with z-scaling in pD, pBe, pTi, pW collisions

This property is connected with factorization of $\Omega = (1-x_1)(1-x_2)^{A\delta}\ldots$
for small values of $x_2 \equiv x_A \equiv x_N/A$.

$\delta_1 = A_1\delta$ & $\delta_2 = A_2\delta$ for AA collisions

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I.Zborovsky
Yu.Panebratsev
G.Skoro
PRC 59 (1999) 2227

Variable z & Entropy *S*

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

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

$$\Omega = (1-x_1)^{\delta_1}(1-x_2)^{\delta_2}(1-y_1)^{\varepsilon}(1-y_2)^{\varepsilon}$$

$$z \cong \frac{s_\perp^{1/2}}{W}$$

$$W = (dN_{ch}/d\eta|_0)^c \cdot \Omega$$

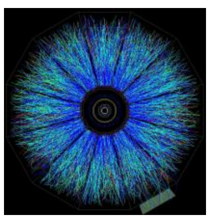
- relative number of such constituent configurations which contain the configuration $\{x_1, x_2, y_1, y_2\}$

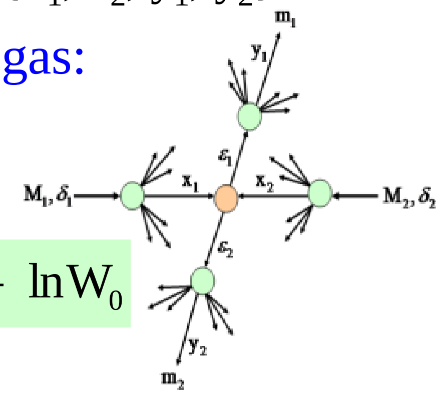
Statistical entropy:

$$S = \ln W$$

Thermodynamical entropy for ideal gas:

$$S = c_V \ln T + R \ln V + S_0$$





$$S = c \cdot \ln(dN_{ch}/d\eta|_0) + \ln[(1-x_1)^{\delta_1}(1-x_2)^{\delta_2}(1-y_1)^{\varepsilon}(1-y_2)^{\varepsilon}] + \ln W_0$$

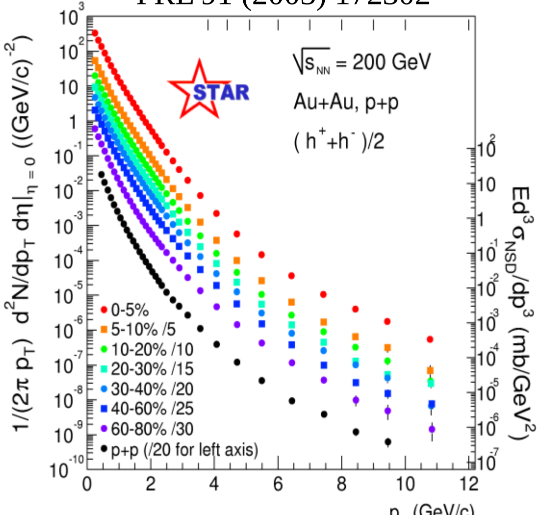
- $dN_{ch}/d\eta|_0$ characterizes "temperature" of the colliding system.
- Provided local equilibrium, $dN_{ch}/d\eta|_0 \sim T^3$ for high temperatures and small μ.
- c has meaning of a "specific heat" of the produced medium.
- Fractional exponents $\delta_1, \delta_2, \varepsilon$ are fractal dimensions in the space of $\{x_1, x_2, y_1, y_2\}$.
- Entropy increases with $dN_{ch}/d\eta|_0$ and decreases with increasing resolution Ω^{-1}.

Maximal entropy *S* ⇔ minimal resolution Ω^{-1} of the fractal measure z

Suppression of spectra in AuAu

Nuclear modification factor R_{AA} , R_{CP}

PRL 91 (2003) 172302



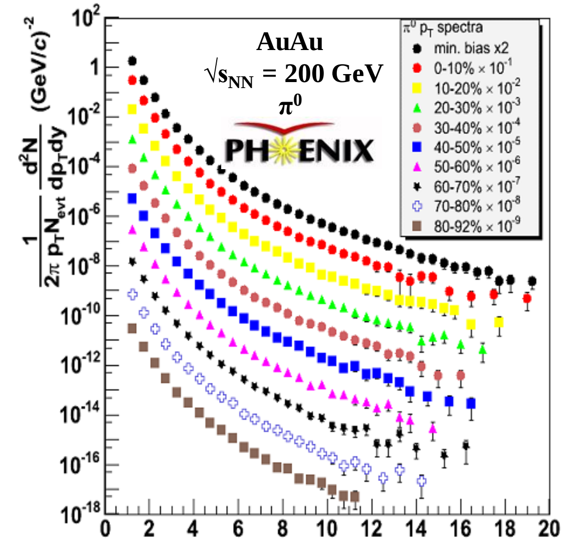
$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{T_{AA} d^2\sigma^{NN}/dp_T d\eta}$$

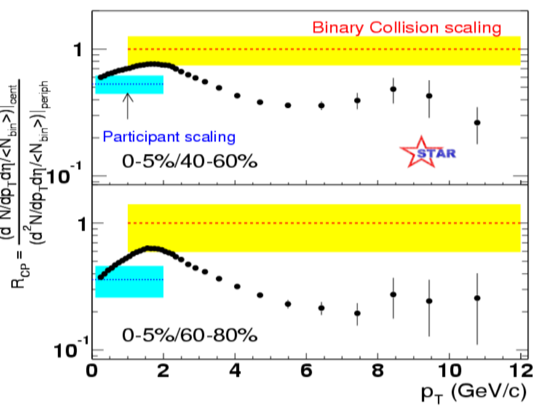
$$R_{CP} = \frac{d^2N/dp_t d\eta / \langle N_{bin} \rangle_{central}}{d^2N/dp_t d\eta / \langle N_{bin} \rangle_{peripheral}}$$

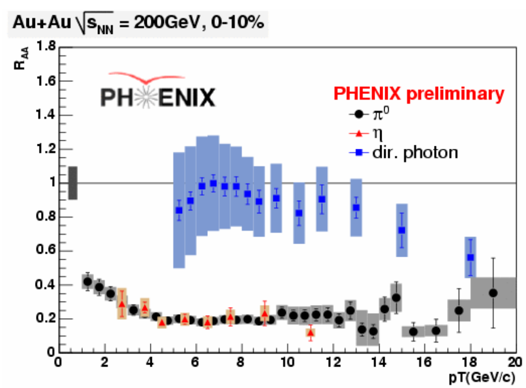
Suppression of hadron yields

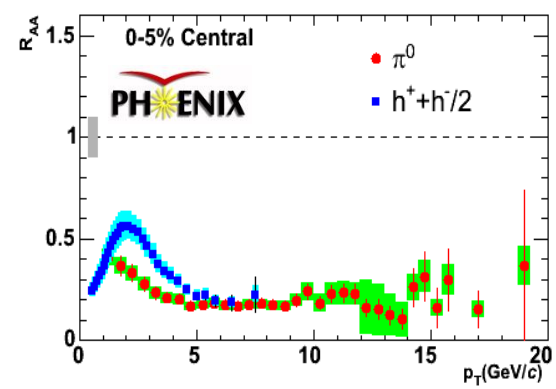
Dissipative medium

Energy loss









To understand partonic interactions within a dense colored medium

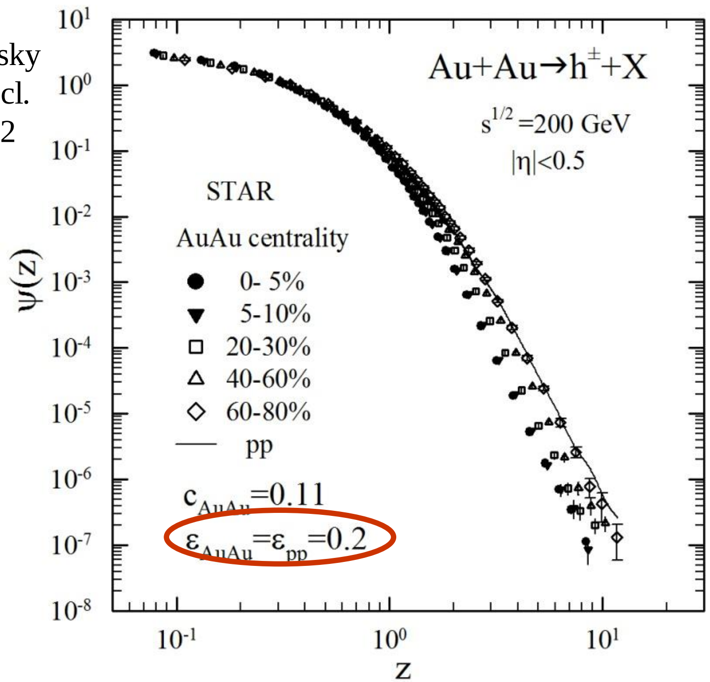
Binary-scaled suppression factor ~ 4-5

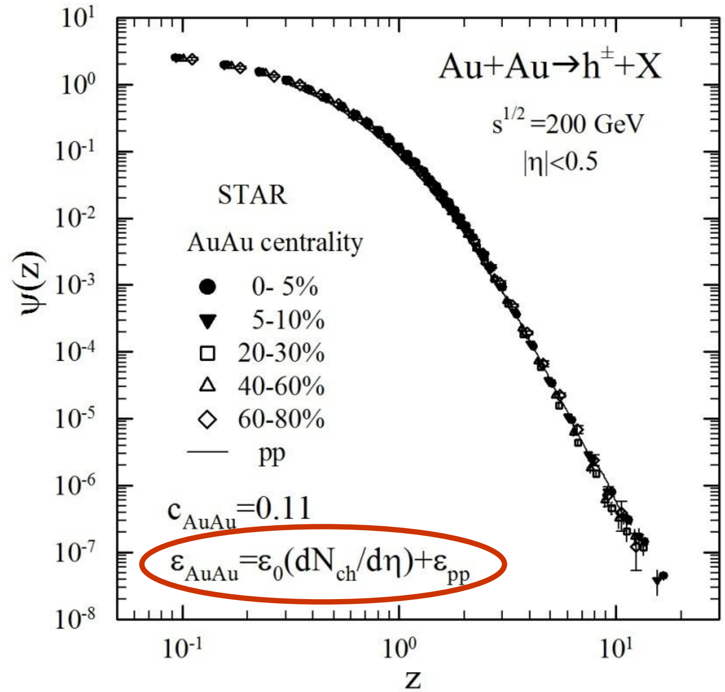
Multiplicity dependence of fragmentation dimension ε_{AA}

Charged hadrons in central AuAu collisions at 200 GeV

STAR: PRL 91 (2003) 172302

MT & I.Zborovsky
Phys.Atom. Nucl.
72 (2009) 552





Suppression of Ψ(z)
in central AuAu
for $\varepsilon_{AuAu} = \varepsilon_{pp}$

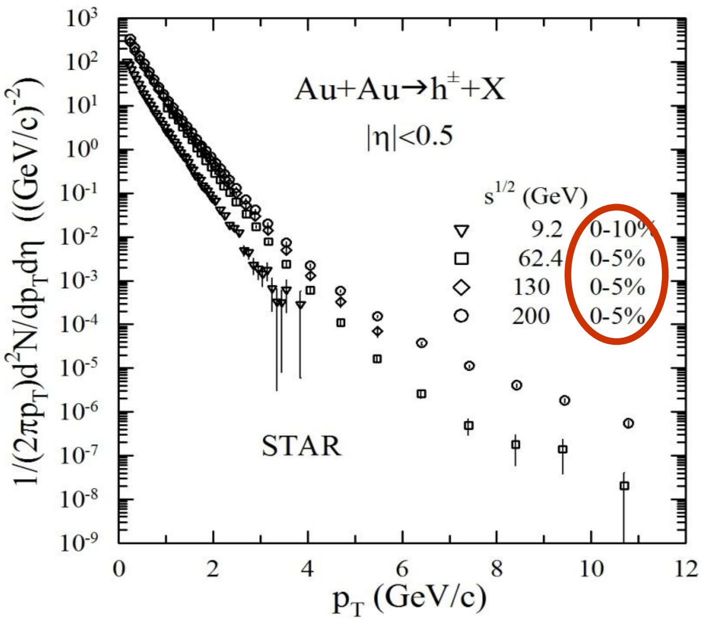
- The same Ψ(z) in pp & AuAu for all centralities
- Dimension ε_{AuAu} depends on AuAu multiplicity
- "Specific heat" c_{AuAu}=0.11 for all centralities

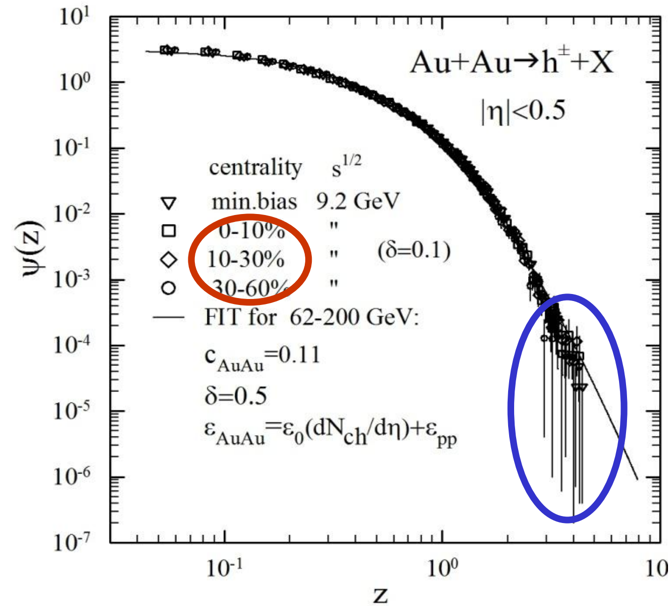
Multiplicity dependence of fragmentation process in HIC

Energy dependence of spectra in central AuAu

Spectra in p_T & z presentations

STAR:
PRL 89 (2002) 202301
PRL 91 (2003) 172302
arXiv:1004.5582





π at SPS & RHIC

⇓

MT & I.Zborovsky
Phys.Part.Nucl.Lett.
7(2010)171

- Energy scan of the spectra: $s^{1/2}$ = 9 - 200 GeV
- Centrality dependence of the spectra at high p_T
- Power law for all centralities for $p_T > 2$ GeV/c
- Theoretical models to extract information on mechanisms of constituent interactions, particle formation, properties of medium.

Change of the parameters $c, \delta, \varepsilon \Rightarrow$ indication on new properties of matter

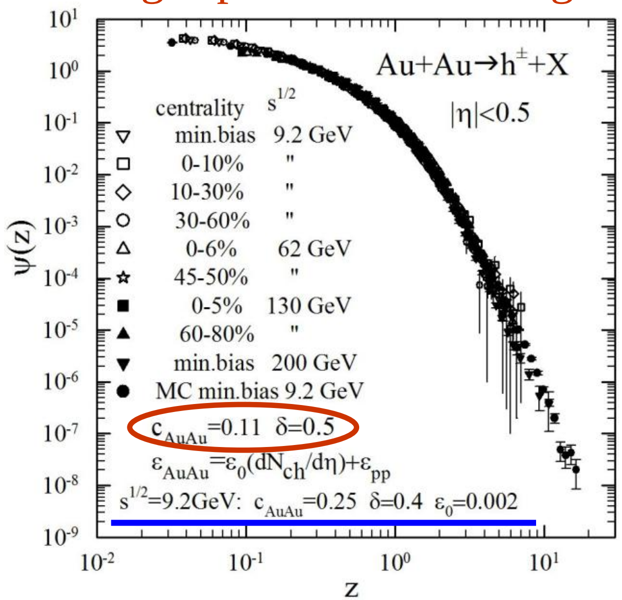
Discontinuity of the parameters $c, \delta, \varepsilon \Rightarrow$ indication of existence of CP

JINR

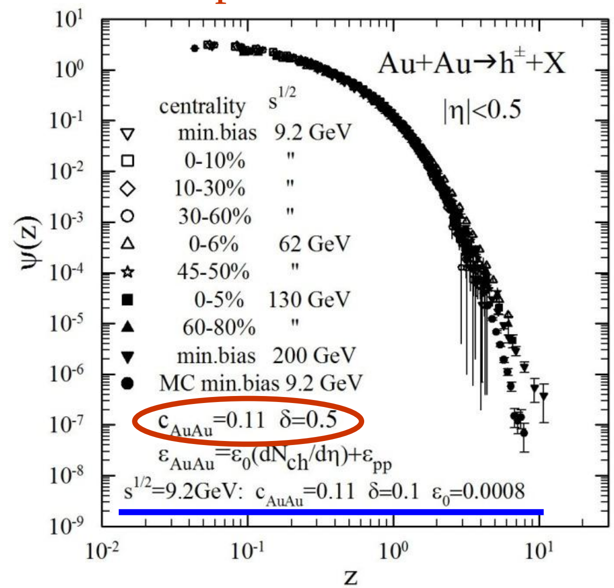
Charged hadrons in central AuAu collisions

Spectra in z presentation - Different scenarios

Large specific heat & large δ



Small specific heat & small δ



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

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

- The same $\Psi(z)$ for different centralities & energies
  ε_{AuAu} depends on AuAu multiplicity density
- Scenarios of interaction: large vs. small “specific heat”
- Correlation of c_{AuAu} , ε, δ
- Centrality dependence of the spectra constraints c_{AuAu}
- Different scenarios in high-z range (p_T > 6 GeV/c)

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

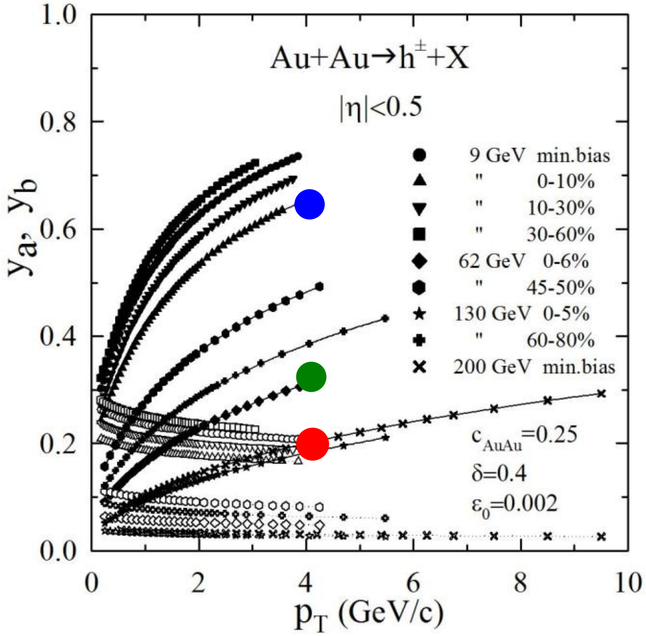
Momentum fractions y_a, y_b in different scenarios

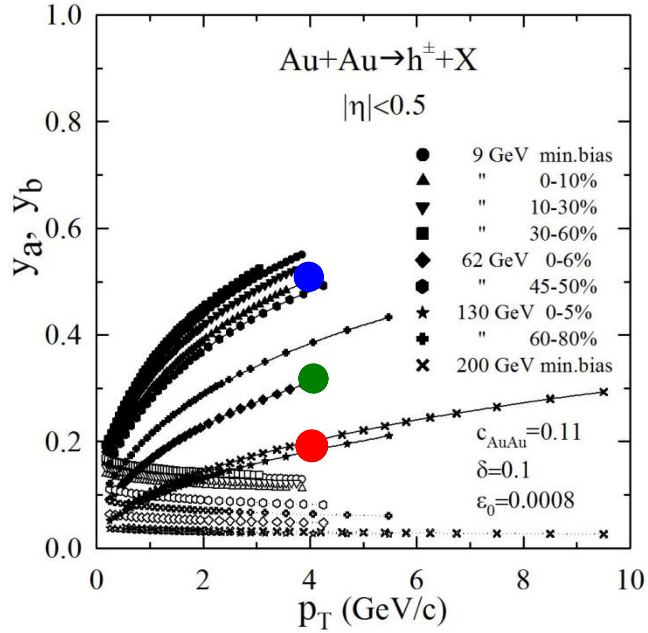
Large specific heat & large δ | Small specific heat & small δ

35% energy loss $q \approx 6$ GeV

70% energy loss $q \approx 13$ GeV

82% energy loss $q \approx 22$ GeV





50% energy loss $q = 8.$ GeV

70% energy loss $q \approx 13.$ GeV

82% energy loss $q \approx 22$ GeV

- y_a increases with $p_T \Rightarrow$ energy losses decrease with p_T
- y_a decreases with $s^{1/2} \Rightarrow$ energy losses increase with $s^{1/2}$
- y_a decreases with centrality $\Rightarrow$ energy losses increase with centrality
- y_b is flat with $p_T \Rightarrow$ week dependence of M_X on p_T
- $y_b \ll y_a$ for $p_T > 1$ GeV/c $\Rightarrow$ soft (high multiplicity) recoil M_X

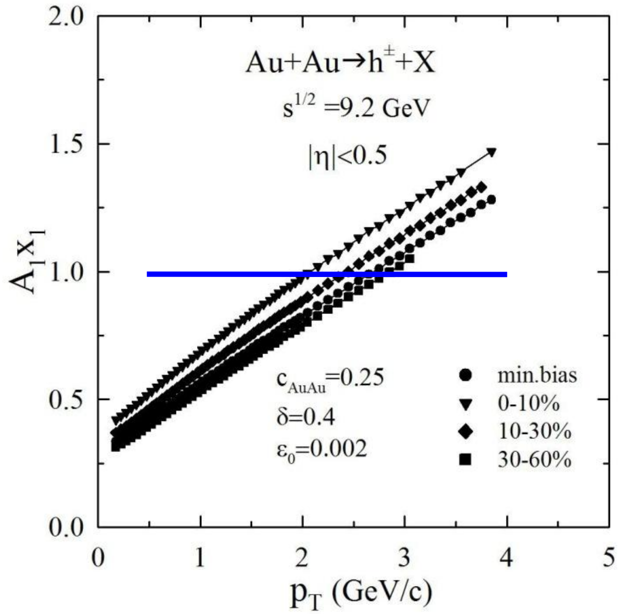
Energy losses ($c=0.25, \delta=0.4$) < Energy losses ($c=0.11, \delta=0.1$)

Smaller energy losses $\Rightarrow$ better localization of a Critical Point…..

Momentum fraction x_1A_1 in AuAu

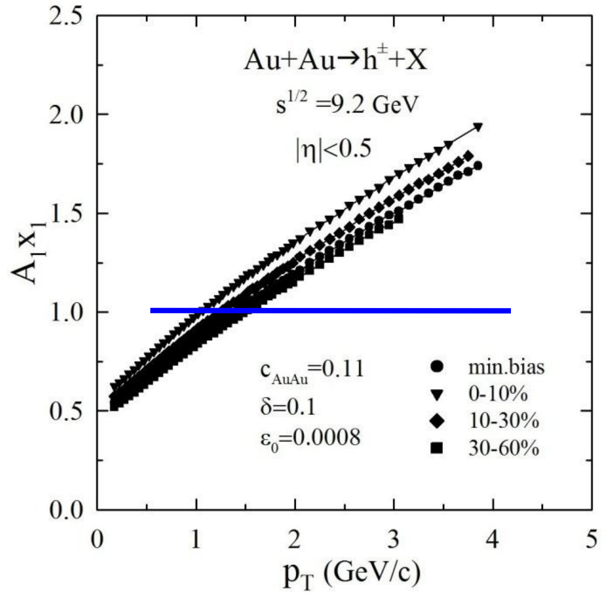
Momentum fractions x_1A_1 in different scenarios

Large specific heat & large δ



- Cumulative region at $p_T > 2$ GeV/c
- Smaller energy loss
- Not smeared sub-structure

Small specific heat & small δ



- Cumulative region at $p_T > 1$ GeV/c
- Larger energy loss
- Smeared sub-structure

Smaller energy losses ⇒ better localization of a Critical Point

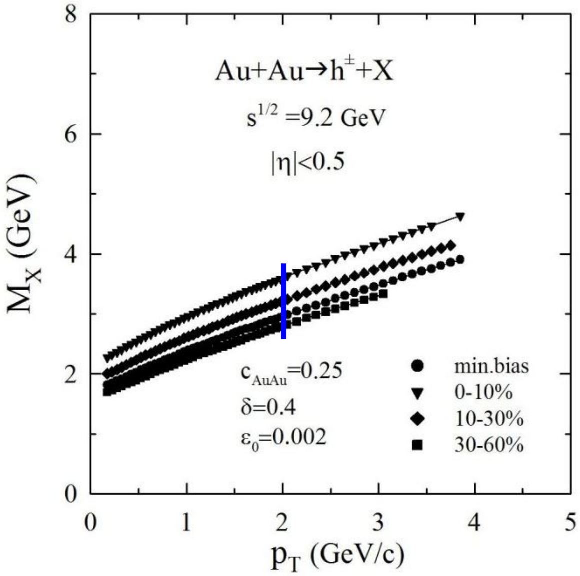
Cumulative region ($x_1A_1 > 1$) is most preferable to search for a Critical Point

Recoil mass M_X

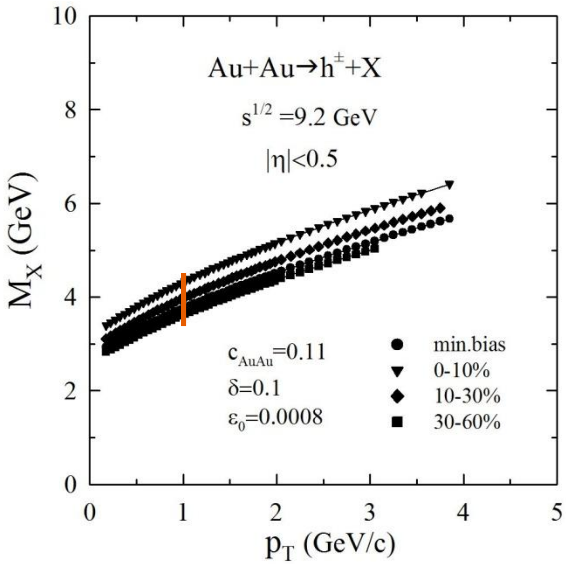
Recoil mass in different scenarios

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

Large specific heat & large δ



Small specific heat & small δ

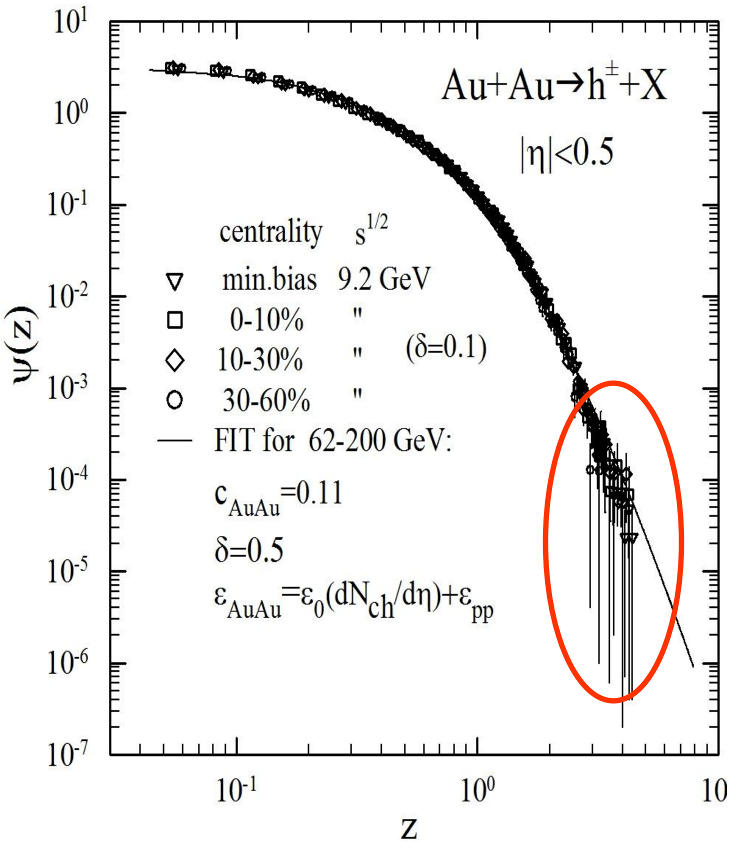


- Cumulative region at $p_T > 2$ GeV/c
- Smaller energy loss
- Not smeared sub-structure
- Smaller multiplicity in the away-side

- Cumulative region at $p_T > 1$ GeV/c
- Larger energy loss
- Smeared sub-structure
- Larger multiplicity in the away-side

M_X increases with p_T, $s^{1/2}$, centrality due to a decrease of the fraction y_b

Charged hadron spectra in AuAu & 9.2 GeV



- The same $\Psi(z)$ for all centralities & energies
  ε_{AuAu} depends on AuAu multiplicity density
- Scenario #2: small "specific heat" & small δ_{Au}
- Correlation of c_{AuAu}, ε, δ at high p_T
- Centrality dependence of the spectra constrains c_{AuAu}
- Discrimination of the scenarios at high-z (p_T > 6 GeV/c)

Beam Energy Scan Program at RHIC & SPS

could help to discriminate different scenarios of constituent interactions and localize a CP.

Conclusions

- Results of analysis of the spectra of charged hadrons produced in AuAu collisions at $s^{1/2}$ = 200, 130, 62.4, 9.2 GeV in the z-scaling approach were presented.
- We argue that z-scaling reflects self-similarity, locality, and fractality of hadron interactions at a constituent level.
- Different microscopic scenarios of the interactions were suggested.
- Properties of the kinematic characteristics ($x_{1,2}$, $y_{a,b}$, M_X) of constituent sub-processes were discussed.
- The constituent energy loss in AuAu collisions in terms of the momentum fractions were estimated. Its dependence on centrality, collision energy, and momentum of the produced hadron was studied.
- Possible change or discontinuity of the parameters c, δ, ε was suggested as signature of phase transition or Critical Point.

The obtained results may be of interest in searching for critical point and signatures of phase transition at SPS, RHIC, Tevatron, and LHC in present, and at FAIR & NICA in the future.

Thanks for your attention !