Dedicated to the memory of Alexei Sissakian

Energy Loss in Heavy Ion Collisions

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In Memoriam

Alexei Norairovich Sissakian
14.10.1944 – 01.05.2010

Contents

- Introduction (motivation & goals)
- Self-similarity in hadron production
  - z-Scaling - ideas, definitions, properties,…
- Energy scan of spectra at RHIC
- Energy loss in HIC vs. $s^{1/2}$, centrality, p_T
- Conclusions

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

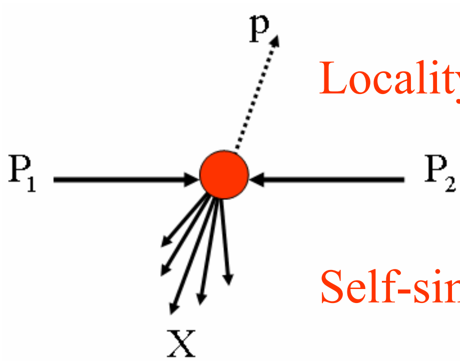
Development of z-scaling approach for description of hadron production in inclusive reactions to search for signatures of new state of nuclear matter (phase transitions, critical point, …)

Analysis of AA experimental data obtained at RHIC & SPS to verify properties of z-scaling observed in pp & $\bar{p}p$ collisions at U70, ISR, S$\bar{p}$pS, SPS and Tevatron.

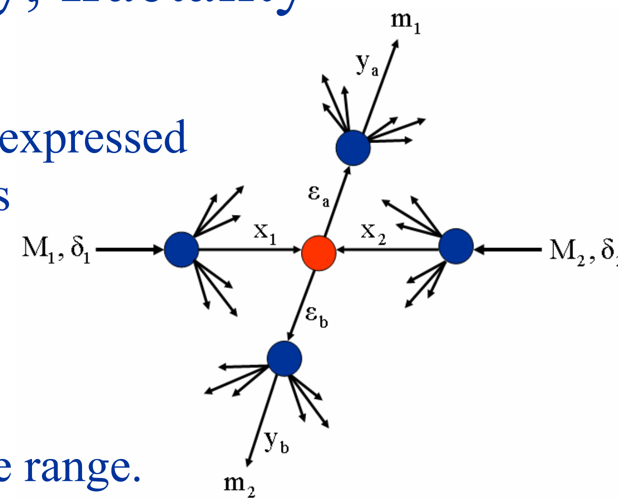
Estimation of constituent energy loss in central AA collisions vs. collision energy, centrality, transverse momentum over the range $s_{NN}^{1/2}$ = 9-200 GeV

z-Scaling

Principles: locality, self-similarity, fractality



Locality: collisions of hadrons and nuclei are expressed via interactions of their constituents (partons, quarks and gluons,...).



Self-similarity: interactions of the constituents are mutually similar.

Fractality: the self-similarity over a wide scale range.

Hypothesis of z-scaling :

$s^{1/2}$, p_T, θ_{cms}	Inclusive particle distributions can be described in terms of constituent sub-processes and parameters characterizing bulk properties of the system.	x_1, x_2, 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.	$\Psi(z)$

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Scaling & Universality

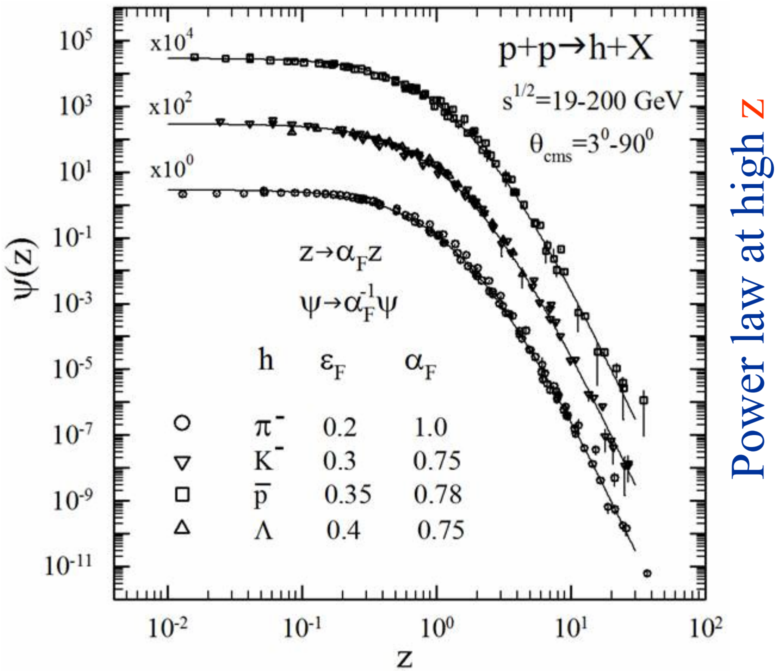
π^-, K^-, $\bar{p}$, Λ
in pp collisions

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



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

Energy scan of spectra
at U70, ISR, S$\bar{p}$pS, SPS, HERA, FNAL(fixed target), Tevatron, RHIC, LHC

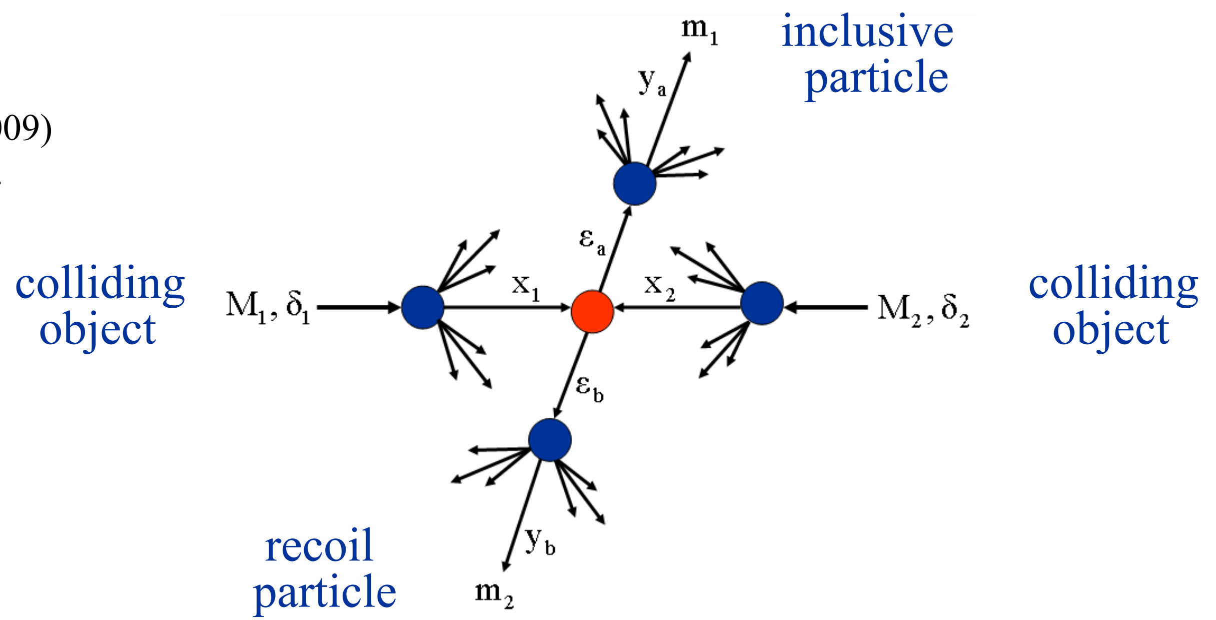
MT & I.Zborovsky
Phys.Rev.D75,094008(2007)
Int.J.Mod.Phys.A24,1417(2009)
J. Phys.G: Nucl.Part.Phys. 37,085008(2010)

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

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

Locality of hadron interactions

M.T. & I.Zborovský
Part.Nucl.Lett.312(2006)
PRD75,094008(2007)
Int.J.Mod.Phys.A24,1417(2009)
J.Phys.G: Nucl.Part.Phys. 37,085008(2010)



Constituent subprocess

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

Kinematical condition (4-momentum conservation law):

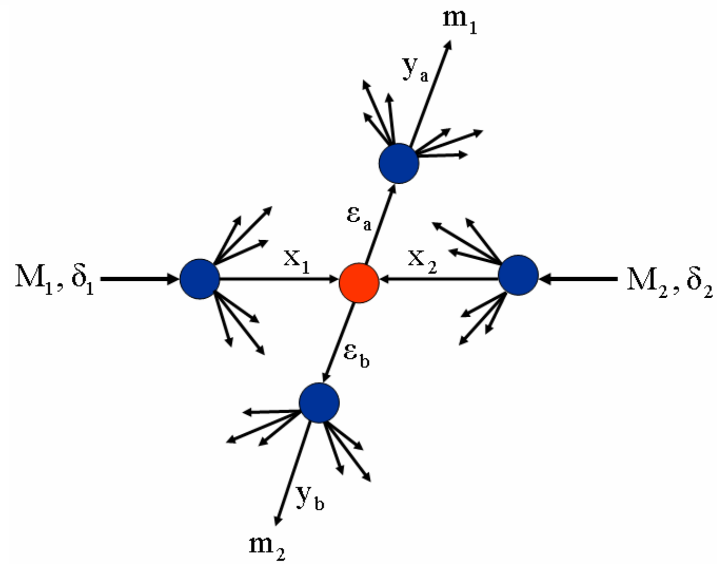
$$(x_1 P_1 + x_2 P_2 - p/y_a)^2 = M_X^2$$

Recoil mass: $M_X = x_1 M_1 + x_2 M_2 + m_2/y_b$

Self-similarity parameter z

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

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



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

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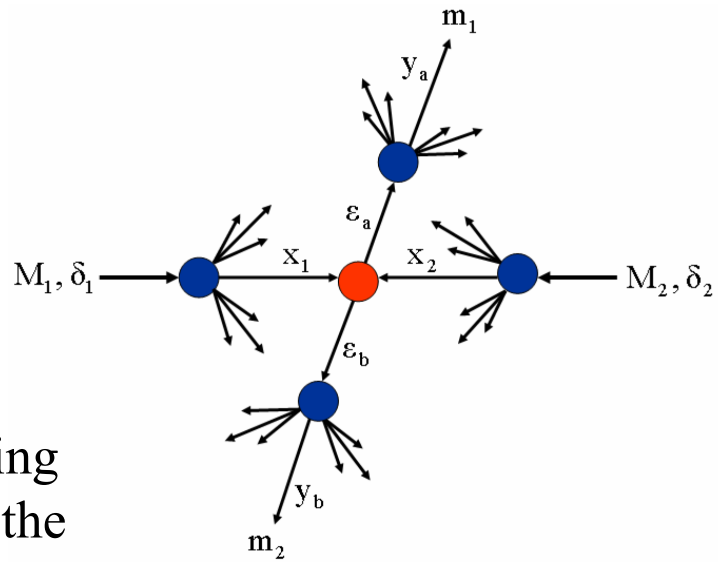
Fractal measure z

The fractality is reflected in definition of z

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

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



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

Ω^{-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

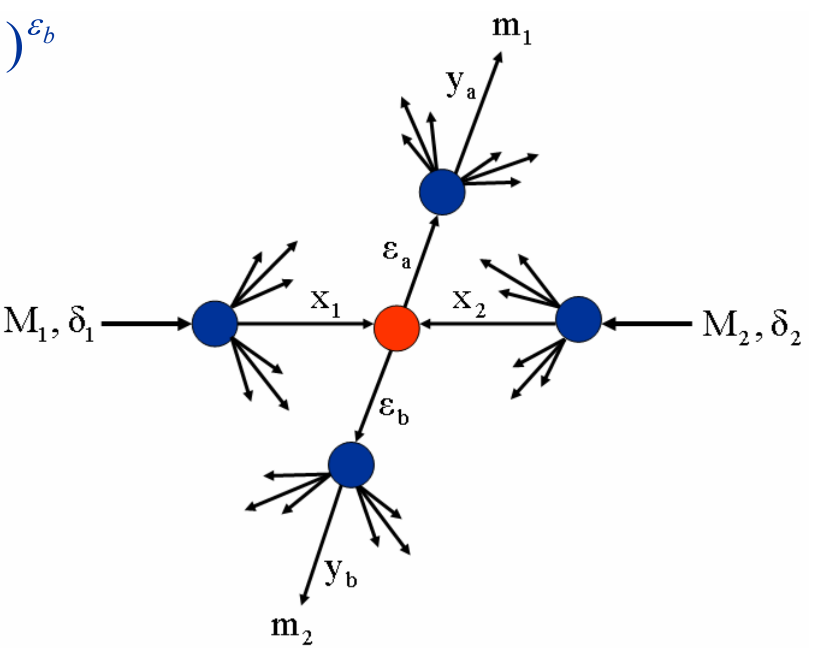
$$z(\Omega)|_{\Omega^{-1}\to\infty} \to \infty$$ The fractal measure z diverges as the resolution Ω^{-1} increases.

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:

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

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



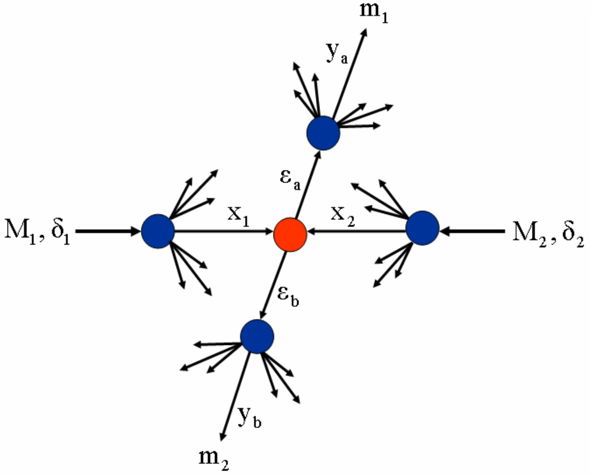
Momentum conservation law)

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

Recoil mass

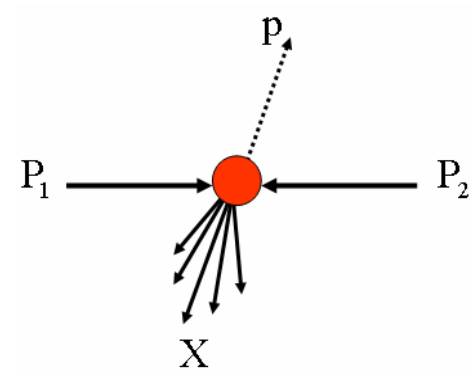
$$M_X = x_1M_1 + x_2M_2 + m_2/y_b$$

Scaling function $\Psi(z)$



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

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



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

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

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

Properties of $\Psi(z)$ in pp & $\bar{p}p$ collisions

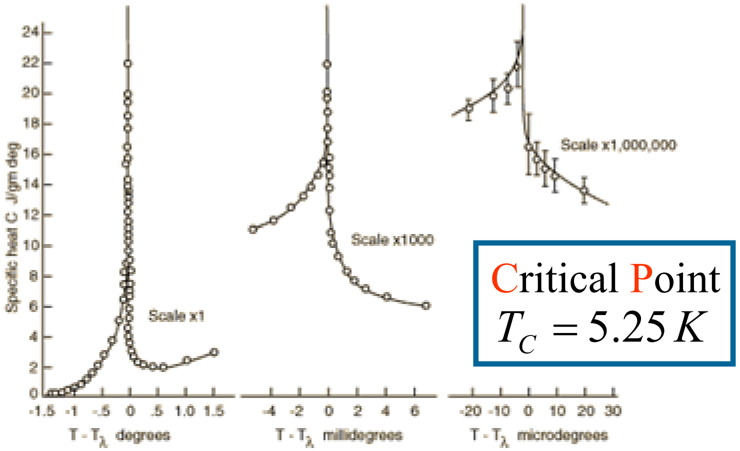
- Energy independence of $\Psi(z)$ ($s^{1/2} > 20$ GeV)
- Angular independence of $\Psi(z)$ ($\theta_{cms}=3^0$-90^0)
- Multiplicity independence of $\Psi(z)$ ($dN_{ch}/d\eta=1.5$-26)
- Power law, $\Psi(z) \sim z^{-\beta}$, at high z ($z > 4$)
- Flavor independence of $\Psi(z)$ ($\pi, K, \varphi, \Lambda, .., D, J/\psi, B, \Upsilon, \ldots$)
- 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)
J. Phys.G: Nucl.Part.Phys. 37,085008(2010)

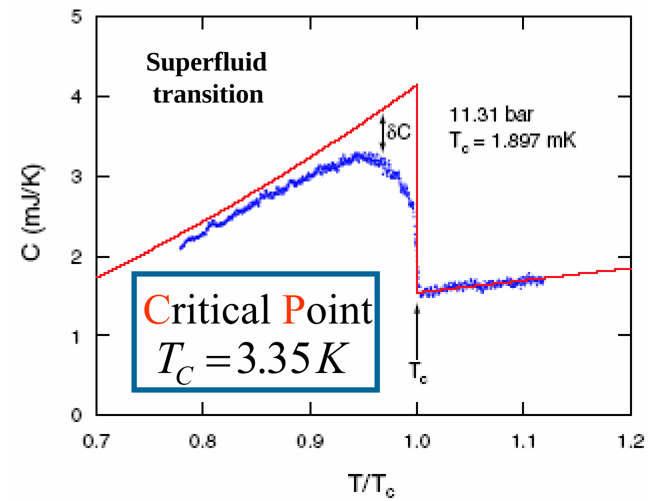
Discontinuity of specific heat near a critical point

Specific heat of liquid ^{4}He



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 thermo-dynamic 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).

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

Critical exponents define the behavior of thermodynamical quantities close to the Critical Point

Defects influence upon phase transition

Defects smear phase transitions

Ferroelectric crystal

$(CH_2NH_2COOH)_3 \cdot H_2SO_4$

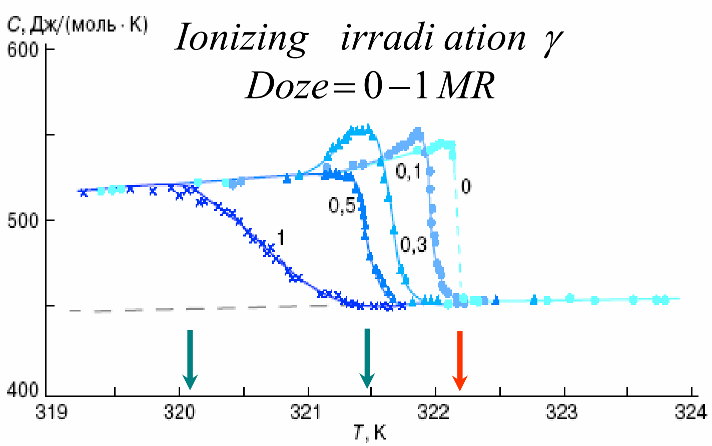
Ferroelectric cristals

$BaTiO_3$

$KNaC_4H_4O_6 \cdot 4H_2O$

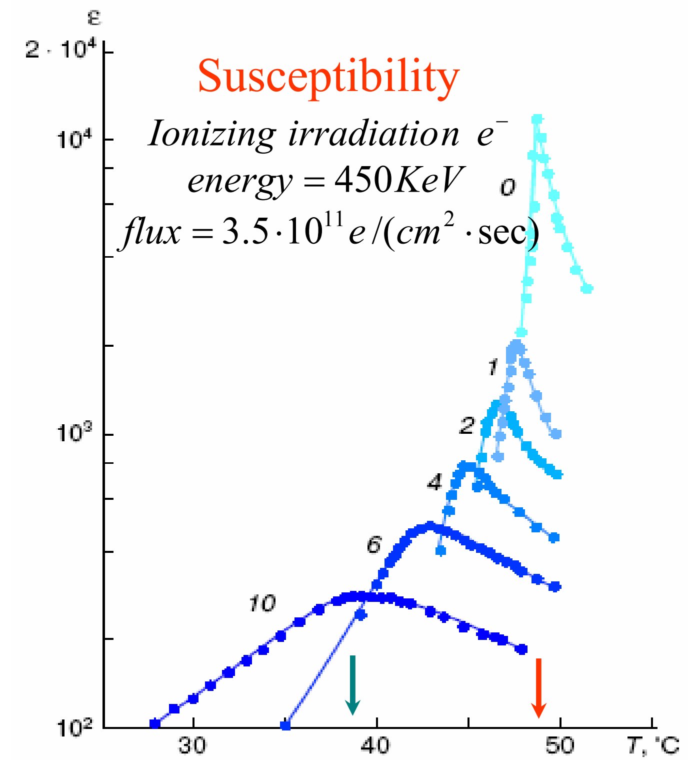
$(CH_2NH_2COOH)_3 \cdot H_2SO_4$

Specific heat



Critical Point

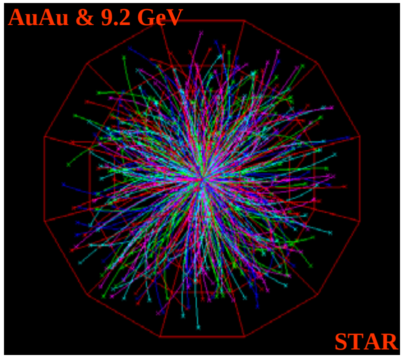
$T_C = 49.2^0 C$



- Modification of crystal properties due to directed implantation of impurities or ionizing irradiation
- Anomalies of the properties in the region of the phase transitions

B.A.Strukov, Phase transitions,…(1996)

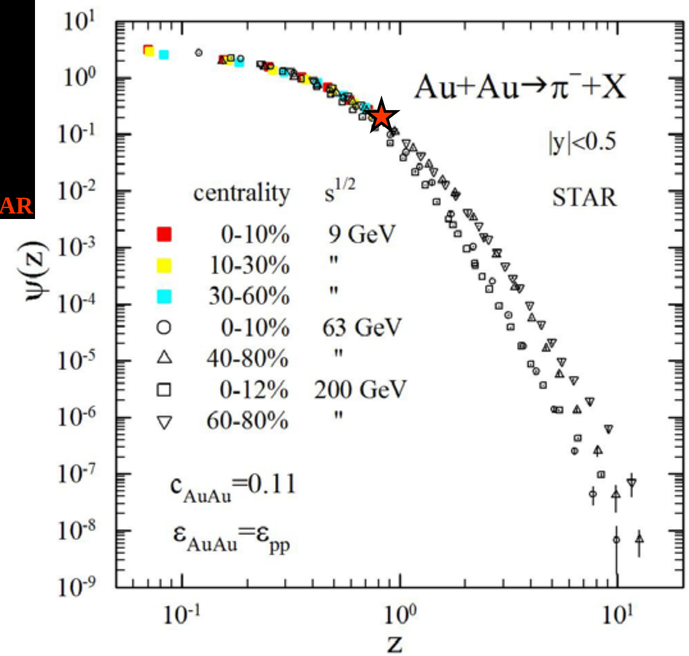
Energy scan of spectra in AuAu collisions

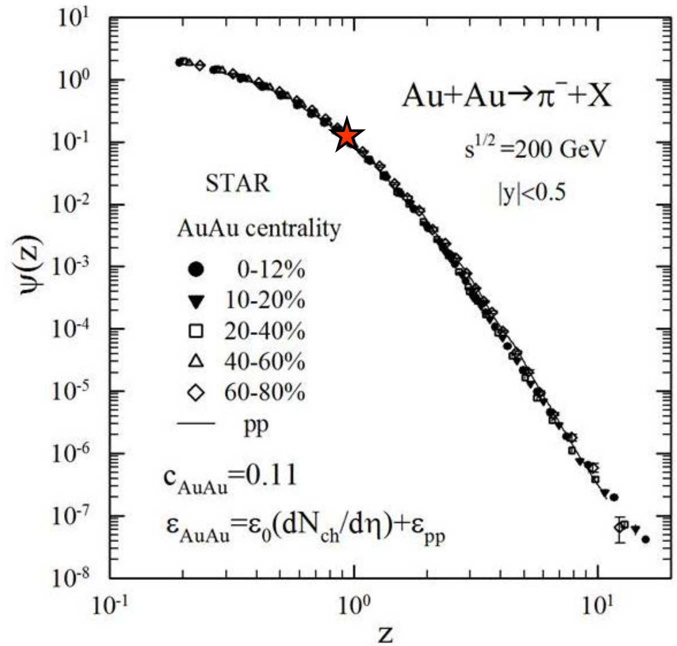


STAR
PLB 637 (2006) 161
PRL 97 (2006) 152301
PLB 655 (2007) 104

STAR
PRC 81 (2010) 024911

π^- in AuAu at 9.2 & 63, 200 GeV





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

- Saturation of $\Psi(z)$ for $z<0.1$
- Power law for $z > 4$
- Centrality dependence of $\Psi(z)$ at high z
- Fractal dimension ε_{AA} depends on centrality

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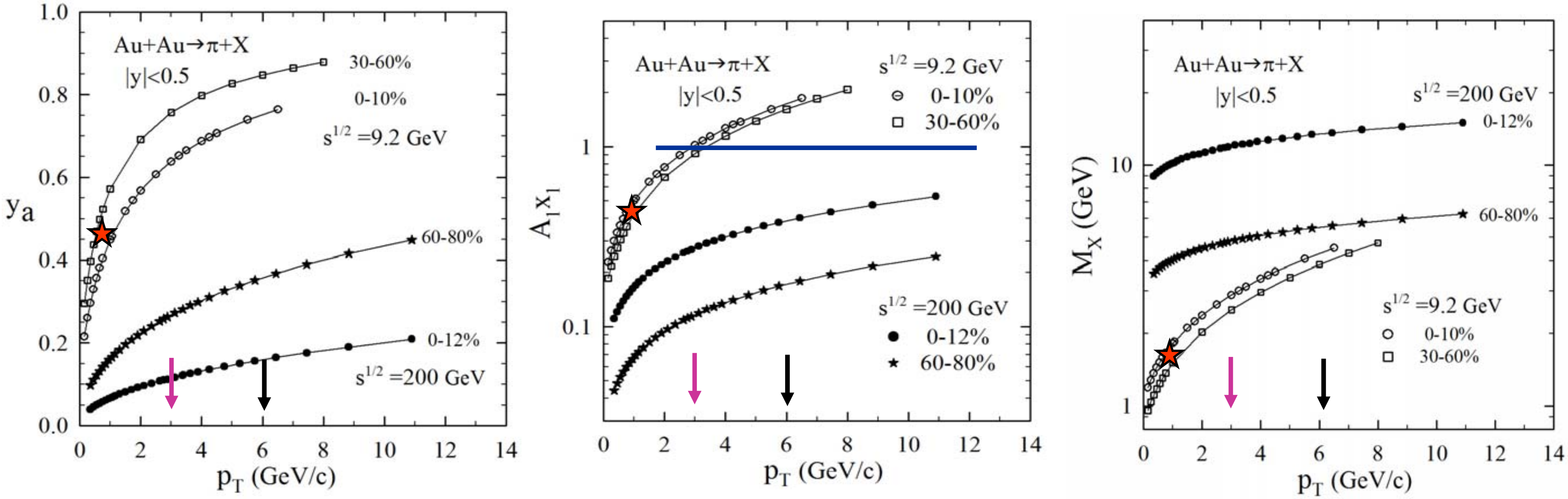
Energy loss vs. energy, centrality, p_T

π^- in AuAu at 9.2 & 200 GeV



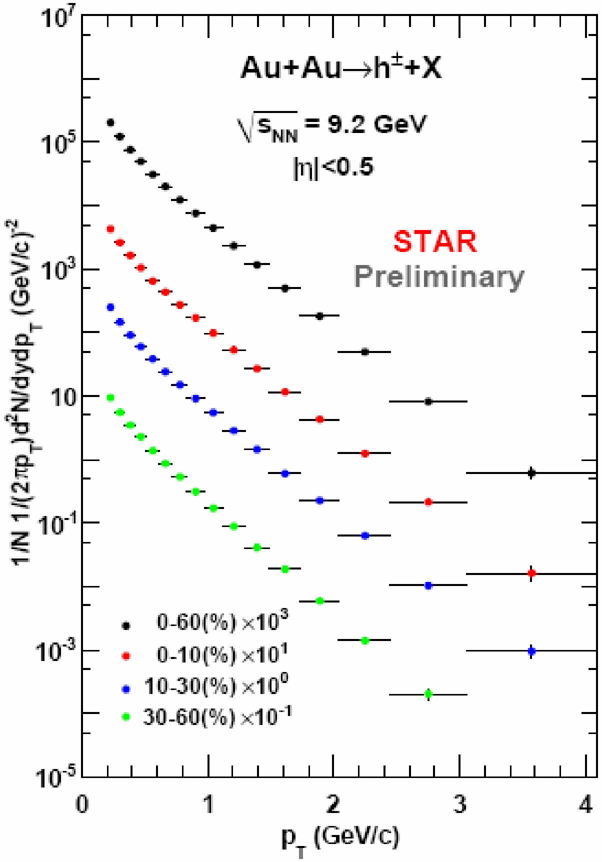
- y_a increases with p_T $\Rightarrow$ energy losses decreases with p_T
- y_a decreases with centrality $\Rightarrow$ energy losses increase with centrality
- x_1 is independent of centrality at 9.2 GeV
- M_X increases with p_T, $s^{1/2}$ and centrality

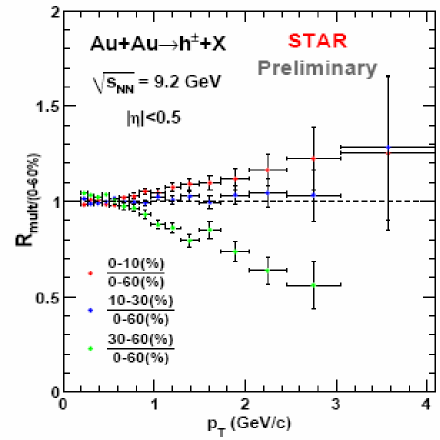
Smaller energy losses $\Rightarrow$ better localization of a Critical Point

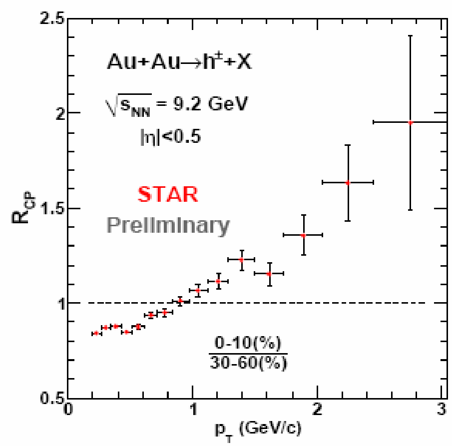
Cumulative region ($A_1x_1>1$) is most preferable to search for a Critical Point

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

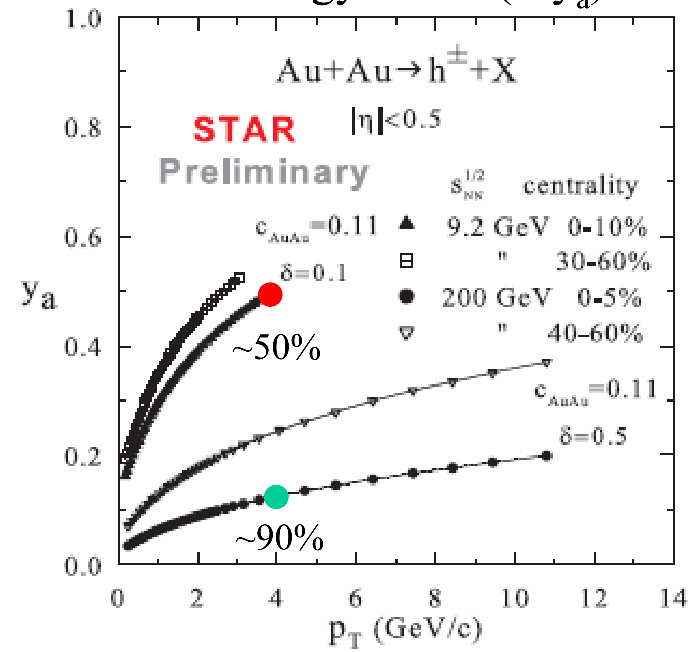
STAR nucl-ex/1004.5582







Energy loss ~ $(1-y_a)$



Data sample (2008)

~ 4000 events

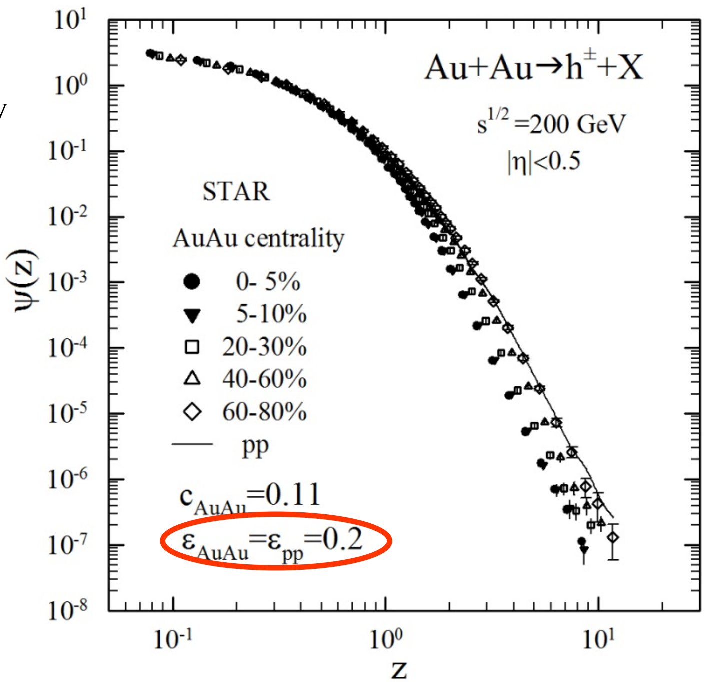
- High-p_T spectra vs. centrality
- R_{CP} ratio vs. p_T
- Energy loss vs. p_T, $dN/d\eta$

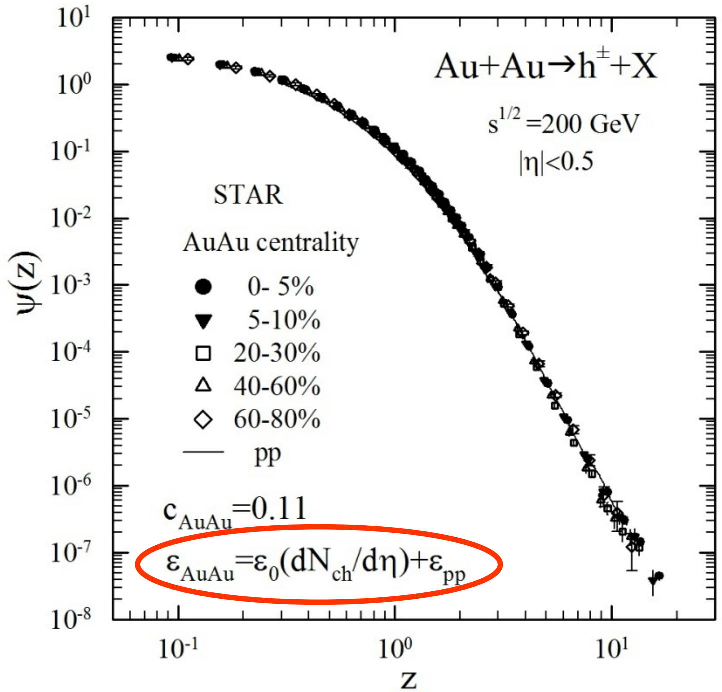
Multiplicity dependence of fragmentation dimension ε_{AA}

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 $\Psi(z)$
in central AuAu collisions
for $\varepsilon_{AuAu} = \varepsilon_{pp}$

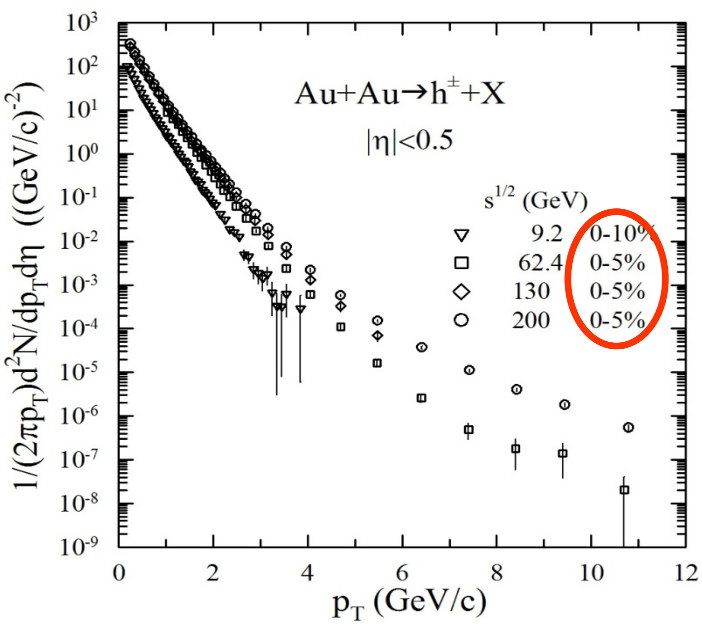
- The same $\Psi(z)$ in pp & AuAu for all centralities
- Dimension ε_{AuAu} depends on multiplicity
- "Specific heat" c_{AuAu}=0.11 for all centralities

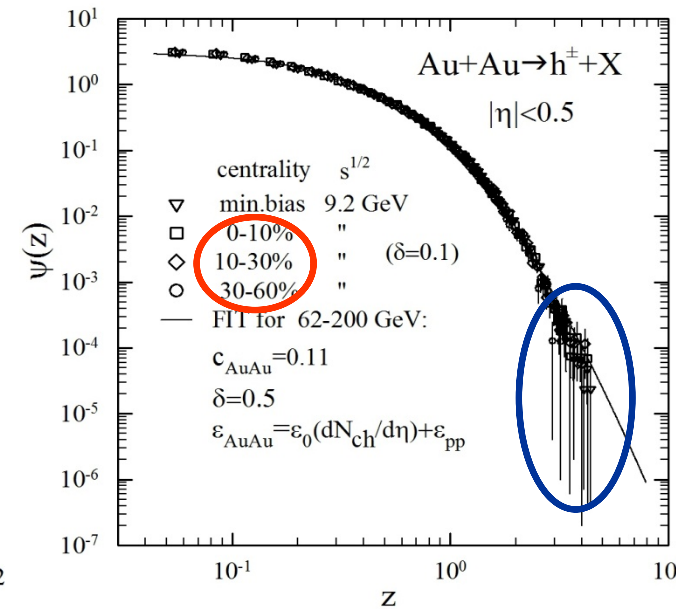
Multiplicity dependence of fragmentation process in HIC

Energy scan of spectra in AuAu collisions

Charged hadrons in central AuAu collisions at 200, 130, 62.4, 9.2 GeV

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

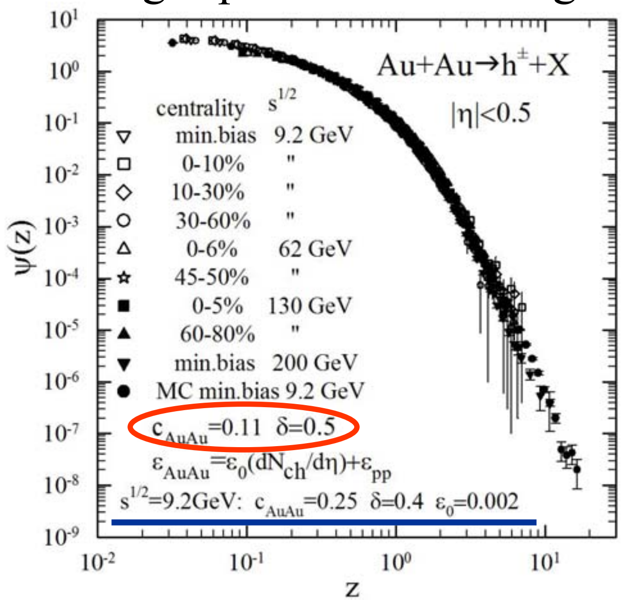
- Energy scan of the spectra: $s^{1/2} = 9 - 200$ GeV
- Centrality dependence of the spectra at high p_T
- Power law for all centralities for $p_T > 2$ GeV/c
- Fragmentation (ε_{AA}) depends on centrality

Change of the parameters c, δ, ε ⇒ indication on new properties of matter
Discontinuity of the parameters c, δ, ε ⇒ indication of existence of CP

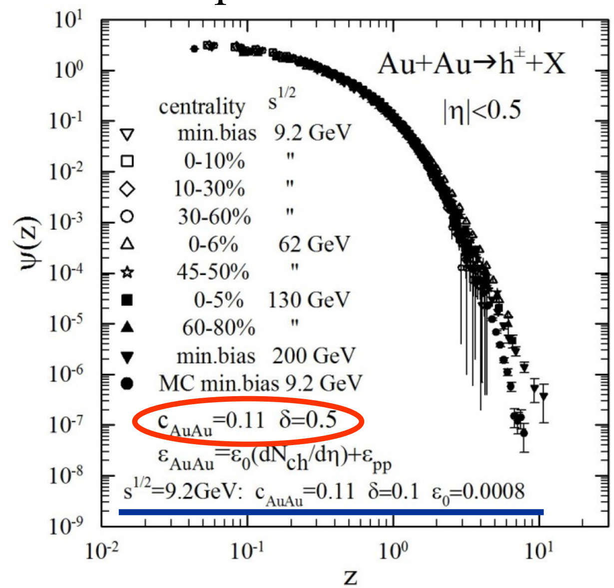
Charged hadrons in central AuAu collisions

Spectra in z presentation - Different Scenarios

Large specific heat & large δ



Small specific heat & small δ



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

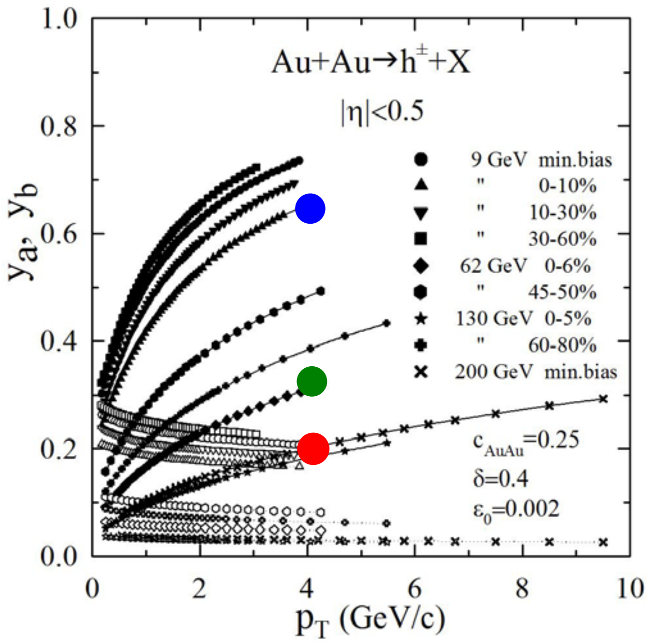
$$\Omega = (1-x_1)^{\delta_1}(1-x_2)^{\delta_2}(1-y_a)^{\varepsilon_a}(1-y_b)^{\varepsilon_b}$$

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

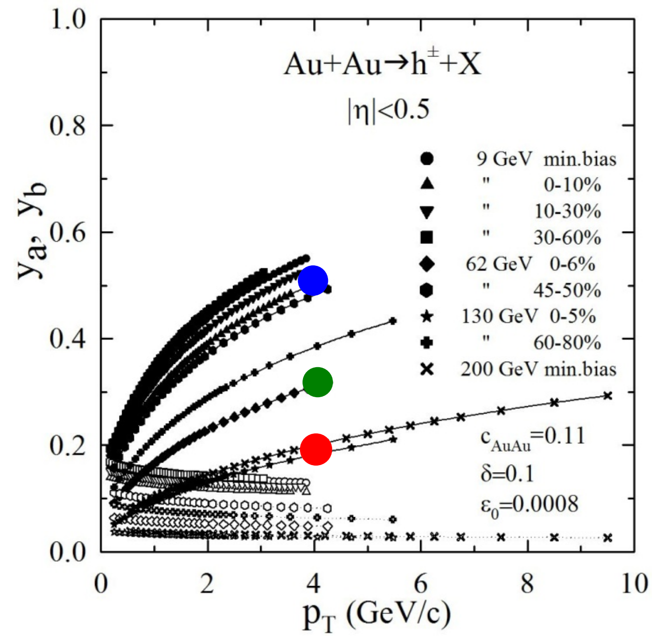
Energy loss in AuAu collisions

Momentum fractions y_a, y_b in different scenarios

Large specific heat & large δ



Small specific heat & small δ



Large specific heat & large δ:
- 35% energy loss, $q \approx 6$ GeV
- 70% energy loss, $q \approx 13$ GeV
- 82% energy loss, $q \approx 22$ GeV

Small specific heat & small δ:
- 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 as centrality increases $\Rightarrow$ energy losses increase with centrality
- y_b is flat with $p_T \Rightarrow$ weak 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,δ=0.4) < energy losses (c=0.11,δ=0.1)

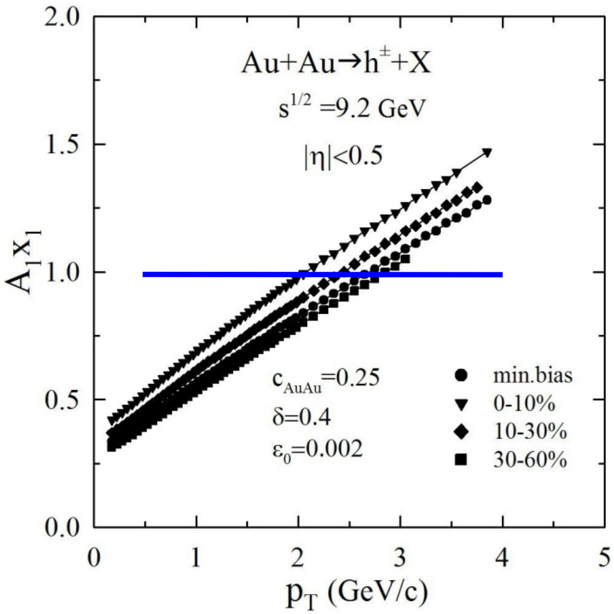
Smaller energy losses ⇒ better localization of a Critical Point…..

JINR

Momentum fraction x_1A_1 in AuAu collisions

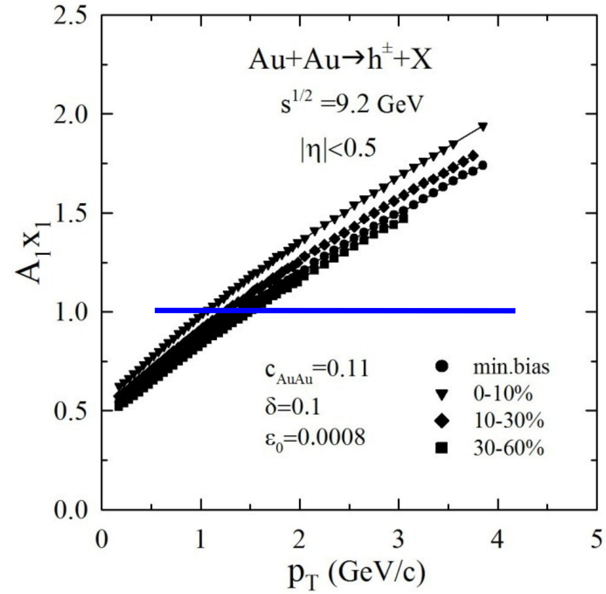
Momentum fraction x_1A_1 in different scenarios

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 $\Rightarrow$ better localization of a Critical Point

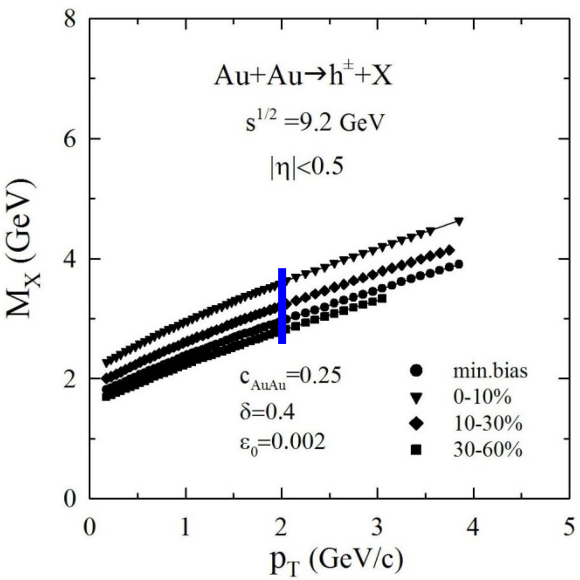
Cumulative region ($x_1A_1 > 1$) is most preferable to search for a Critical Point

Recoil mass M_X

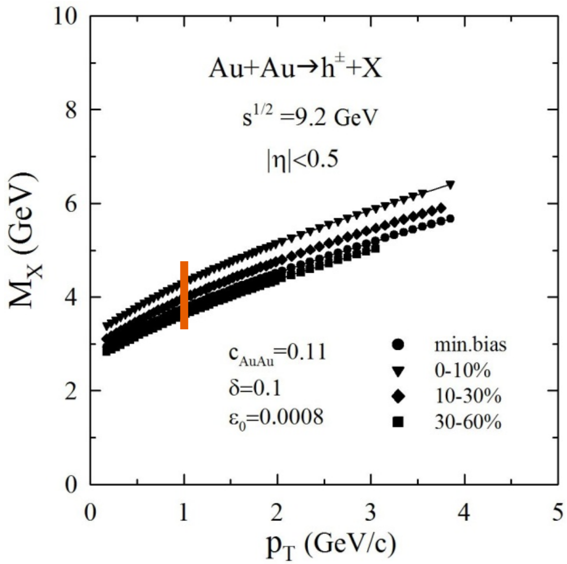
Recoil mass in different scenarios

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

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 way-side

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

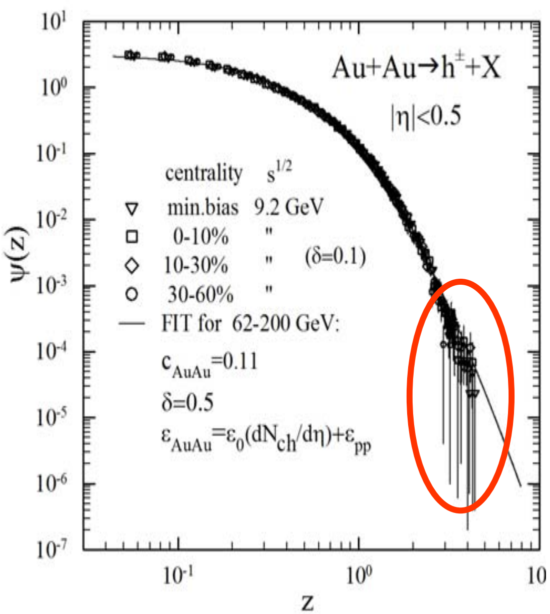
M_X increases with p_T, $s^{1/2}$, centrality due to decrease of the fraction y_b

Self-similarity restoration & Search for location of CP

Self-similarity parameter z

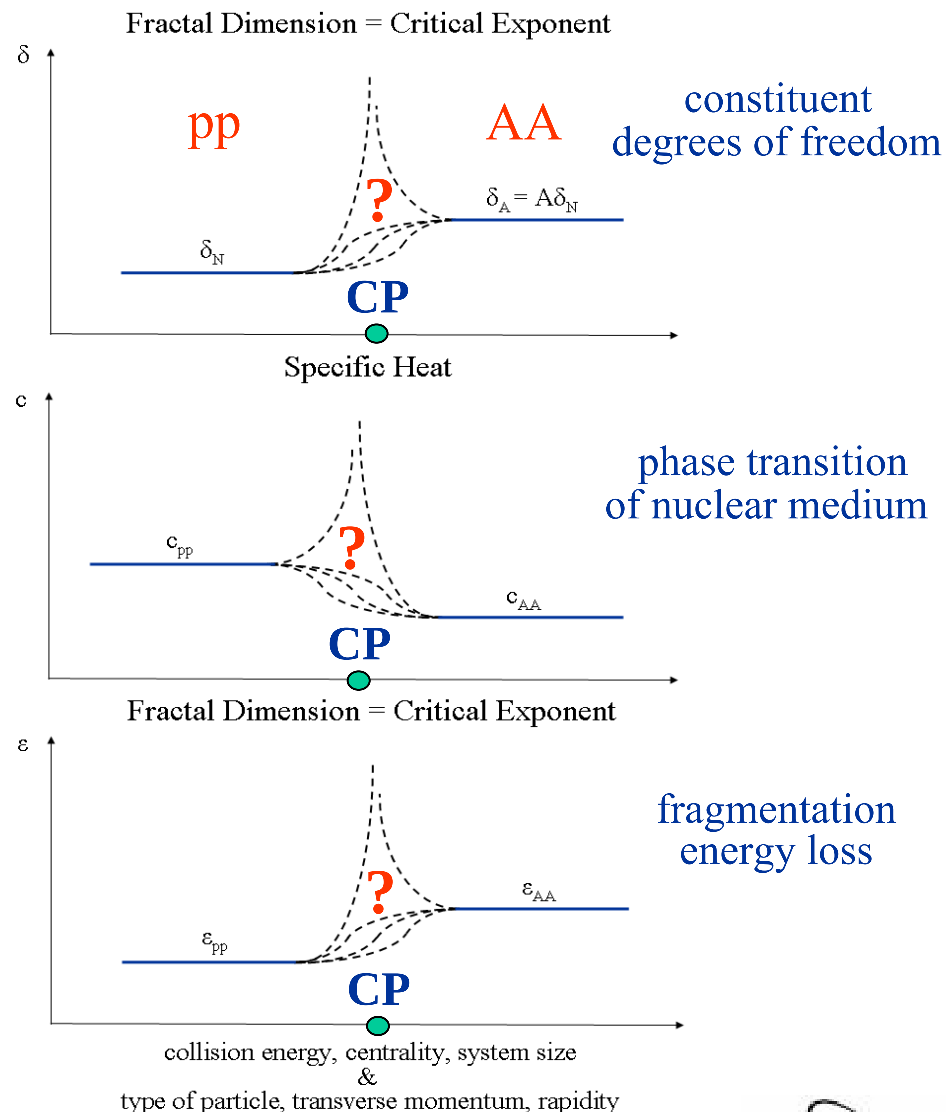
$$z = \frac{s_{\perp}^{1/2}}{(dN_{ch}/d\eta|_0)^c m_N} \cdot \Omega^{-1}$$

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



Correlation of δ,ε,c
in cumulative region

Location of CP



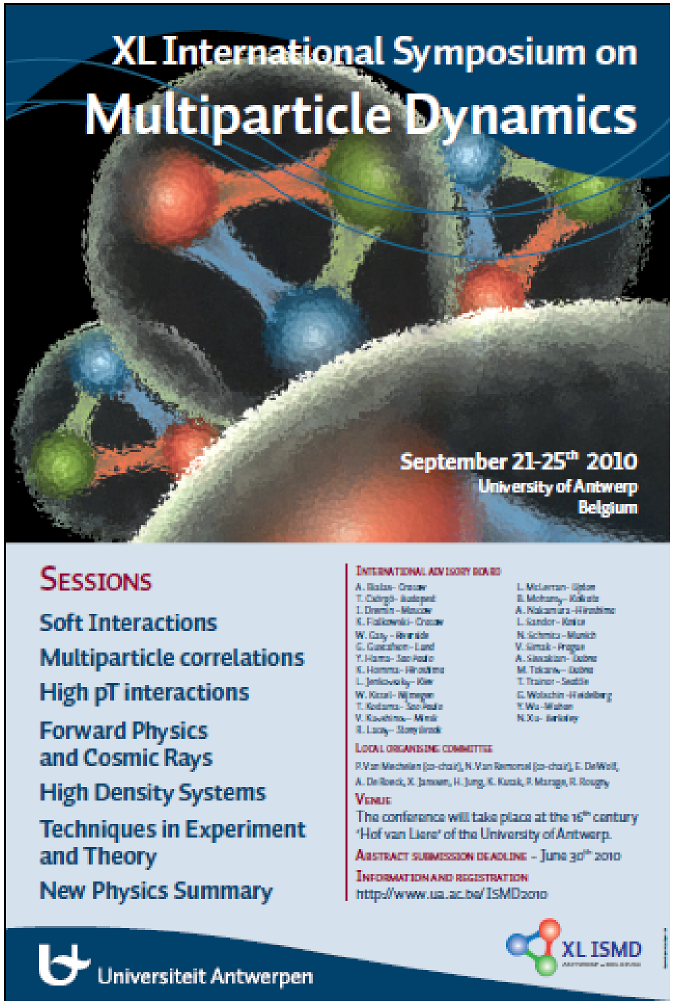
Conclusions

- Results of analysis of energy scanned 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 the self-similarity, locality, and fractality of hadron interactions at a constituent level.
- Microscopic scenarios of hadron production were suggested.
- The constituent energy loss in AuAu collisions in terms of the momentum fractions were estimated. Its dependence on collision energy, centrality, and momentum of produced hadron was studied.
- Discontinuity of c, δ, ε as a signature of phase transition was suggested.

The obtained results may be of interest in searching for a Critical Point and signatures of phase transition in hadron matter at SPS, RHIC, Tevatron, and LHC in present, and at FAIR (GSI) & NICA (JINR) in future.

International Symposium on Multiparticle Dynamics

Antwerp University, Belgium, 21-25 September, 2010



Thank You For Attention !

First LHC data on charged hadron production

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Charged hadrons in pp collisions at low p_T

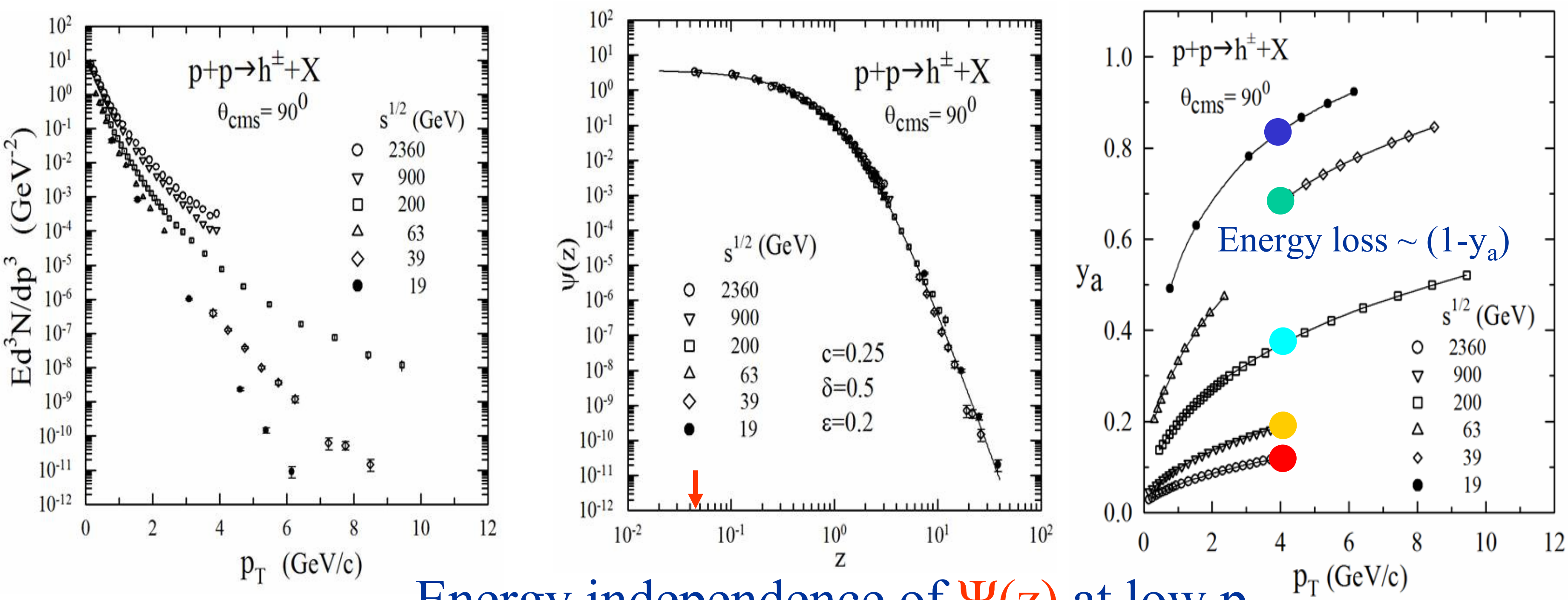
LHC: CMS Coll.
JHEP 02 (2010) 041

RHIC: STAR Coll.
PRL 91 (2003) 172302

ISR: BS Coll.
NPB 100 (2007) 237

FNAL (fixed target)
PRD 19 (1979) 764
PRD 40 (1989) 2777

M.T. & I.Zborovský
J.Phys.G: Nucl.Part.Phys. 37,085008(2010)



Energy independence of $\Psi(z)$ at low p_T

Saturation of $\Psi(z)$ at low z is confirmed at LHC