Beam Energy Scan at RHIC & Search for Signatures of Phase Transition and Critical Point in z-scaling approach

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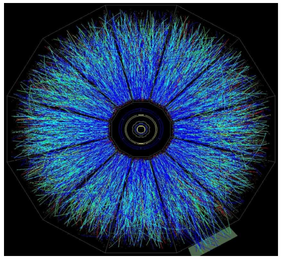
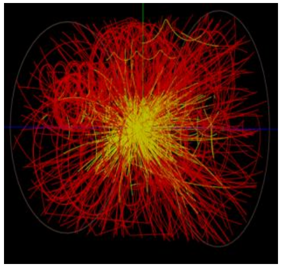




in collaboration
with Yu.Panebratsev, I.Zborovský, A.Kechechyan,
A.Alakhverdyants, A.Aparin

BLTP, Seminar, 11.04.12, Dubna

Contents

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.Barenblatt,…

Dense, strongly-coupled matter and an almost perfect liquid with partonic collectivity has been created in HIC at RHIC.

Experimental study of phase structure of QCD matter started ...

STAR, PHENIX, PHOBOS, BRAHMS - White papers - Nucl. Phys. A757 (2005)

USA-NSAC 2007 Long-range plan

Self-similarity principle

- The self-similarity of a pattern means that it is similar to a part of itself.
- Physical description in terms of self-similarity parameters constructed as suitable combinations of some physical quantities.

Self-similarity parameters (Re, Π, M,…):

Hydrodynamics

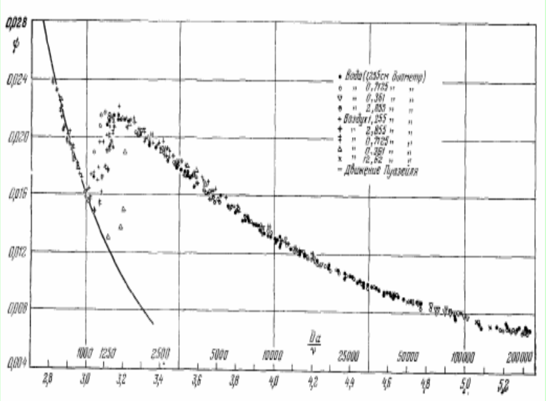
$Re=dU\rho/\mu$

d-diameter

U-velocity of the fluid

ρ-density of the fluid

μ-viscosity of the fluid



Point explosion

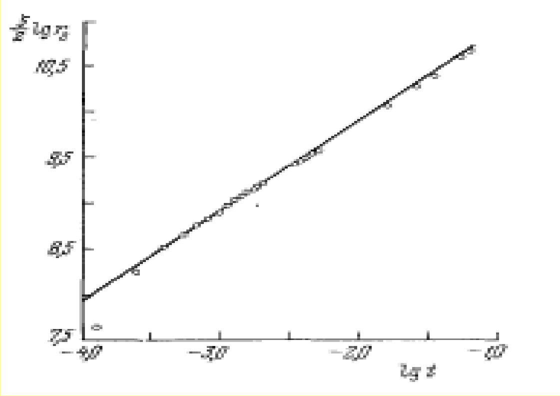
$\Pi=r(Et^2/\rho)^{-1/5}$

r-radius of the front wave

E-energy of the explosion

t-elapsed time

ρ-density of the environment

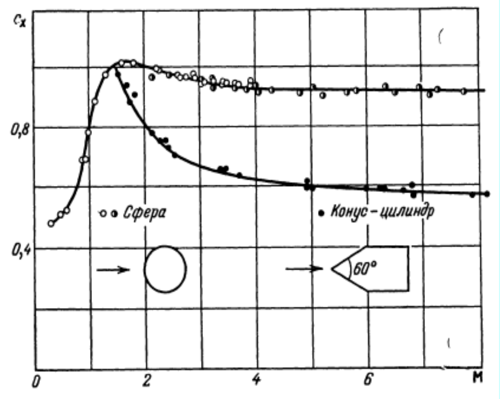


Aerodynamics

$M=v/c$

v - velocity of medium

c – velocity of sound



Thermodynamic potentials

Gibbs potential	G(T,p)	$G(\lambda^{a_\varepsilon}\varepsilon,\lambda^{a_p}p)=\lambda G(\varepsilon,p)$
Helmholtz potential	F(T,V)	$F(\lambda^{a_\varepsilon}\varepsilon,\lambda^{a_V}V)=\lambda F(\varepsilon,V)$
Internal energy	U(S,V)	$U(\lambda^{a_S}S,\lambda^{a_V}V)=\lambda U(S,V)$
Enthalpy	E(S,p)	$E(\lambda^{a_S}S,\lambda^{a_p}p)=\lambda E(S,p)$

Scaled temperature

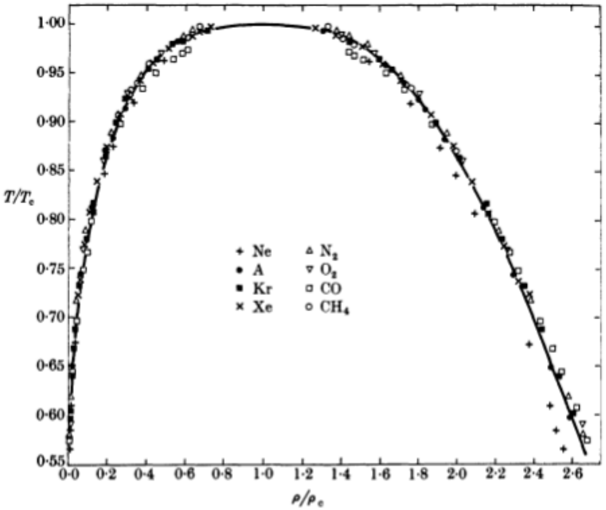
$$\varepsilon\equiv(T-T_c)/T_c$$

Ferromagnetics

$$p\to H$$
$$V\to M$$

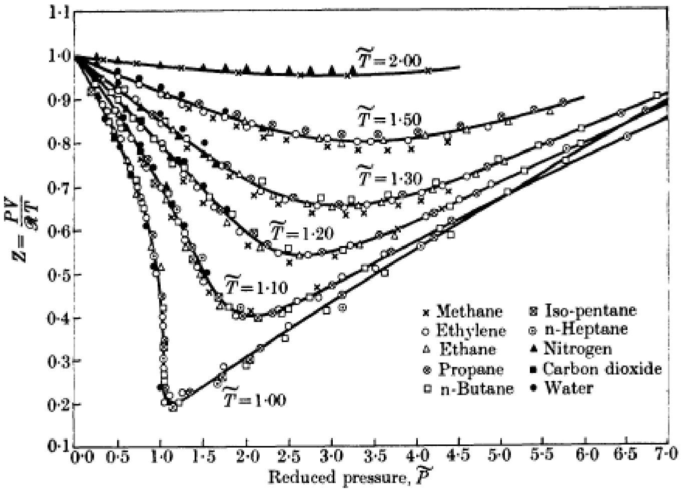
If one of the thermodynamic potentials is a generalized homogeneous function, then all thermodynamic potentials are GHPs.

Scaled density vs. scaled temperature



Data collapse

Compressibility vs. scaled pressure



All curves of this family can be “collapsed” onto a single curve.

Critical exponents

Fluid systems

$c_V \sim |\varepsilon|^{-\alpha}$

$\rho_L - \rho_G \sim |\varepsilon|^{\beta}$

$K_T \sim |\varepsilon|^{-\gamma}$ compressibility

Scaled temperature

$$\varepsilon \equiv (T - T_c)/T_c$$

Magnetic systems

$c_H \sim |\varepsilon|^{-\alpha'}$

$M_H \sim |\varepsilon|^{\beta'}$

$\chi_T \sim |\varepsilon|^{-\gamma'}$

$$K_T = -\frac{1}{V}\left(\frac{\partial^2 G}{\partial p^2}\right)_T$$

$$c_p = -T\left(\frac{\partial^2 G}{\partial T^2}\right)_p$$

$$\alpha_p = \frac{1}{V}\left(\frac{\partial^2 G}{\partial T \partial p}\right)$$

G

$$c_H = -T\left(\frac{\partial^2 G}{\partial T^2}\right)_H$$ specific heat

$$M_H = \left(\frac{\partial G}{\partial H}\right)_T$$ magnetization

$$\chi_T = -\frac{1}{V}\left(\frac{\partial^2 G}{\partial H^2}\right)_T$$ susceptibility

Dynamic properties

Transport of number of particles, energy, charge,…

Transport coefficients

$\Lambda(\text{thermal conductivity}) \sim \varepsilon^{-a}, \quad \varepsilon > 0$

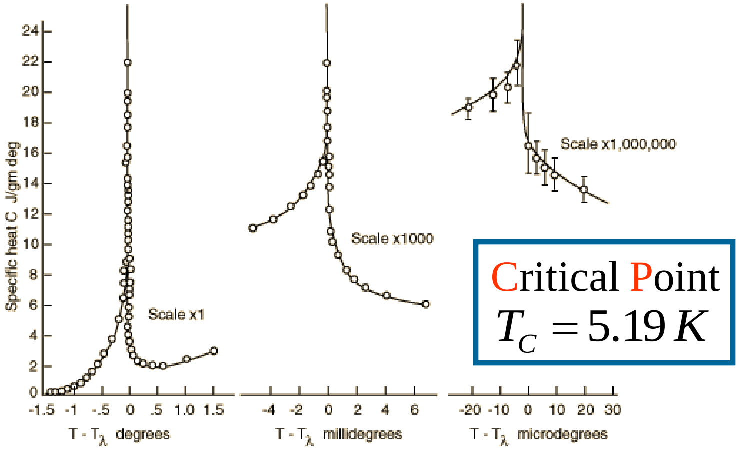
$\eta(\text{shear viscosity}) \sim \varepsilon^{-b}, \quad \varepsilon > 0$

$\zeta(\text{bulk viscosity}) \sim \varepsilon^{-c}, \quad \varepsilon > 0$

Critical exponents α,β,γ,δ,… define the behavior of physics quantities close to the Critical Point

Discontinuity of specific heat near a Critical Point

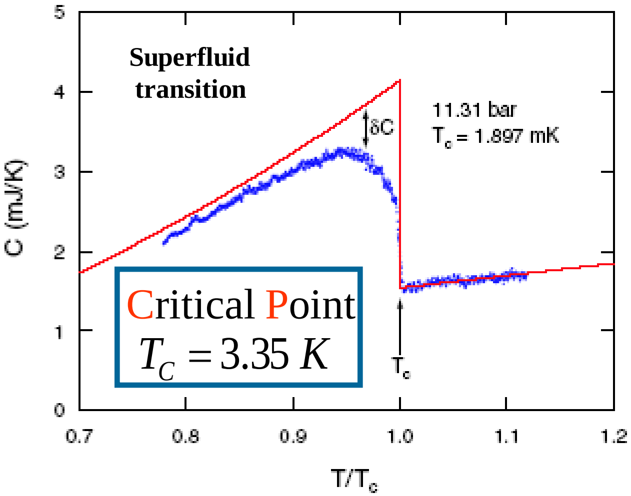
Specific heat of liquid ^{4}He



Critical Point
$T_C = 5.19\,K$

H.E. Stanley, 1971

Heat capacity of liquid ^{3}He



Critical Point
$T_C = 3.35\,K$

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

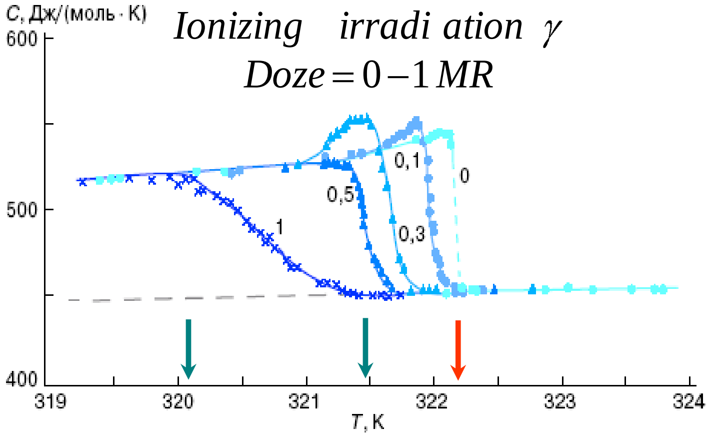
Ferroelectric crystal

$(CH_2NH_2COOH)_3 \cdot H_2SO_4$

Specific heat

Ionizing irradiation γ

$Doze = 0 - 1\,MR$



Critical Point

$T_C = 49.2^0 C$

Ferroelectric cristals

$BaTiO_3$

$KNaC_4H_4O_6 \cdot 4H_2O$

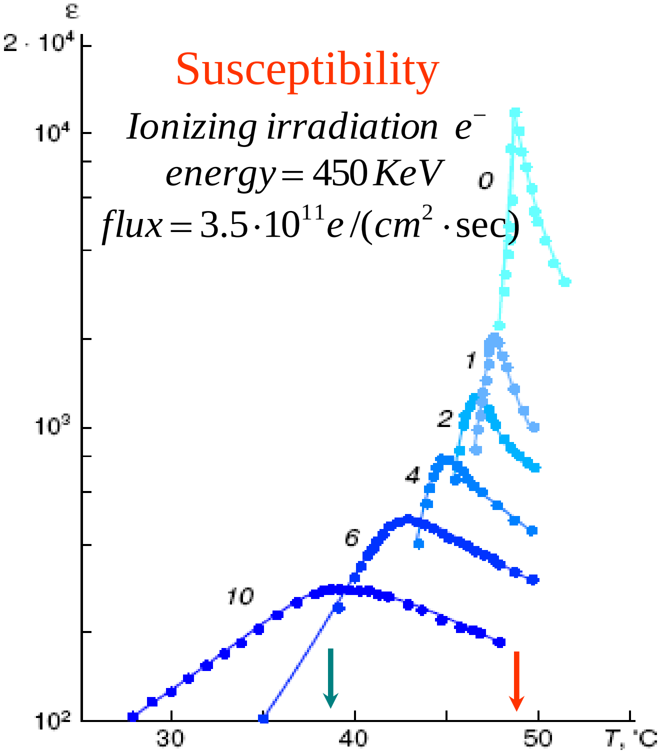
$(CH_2NH_2COOH)_3 \cdot H_2SO_4$

Susceptibility

Ionizing irradiation e^-

$energy = 450\,KeV$

$flux = 3.5 \cdot 10^{11} e/(cm^2 \cdot \sec)$

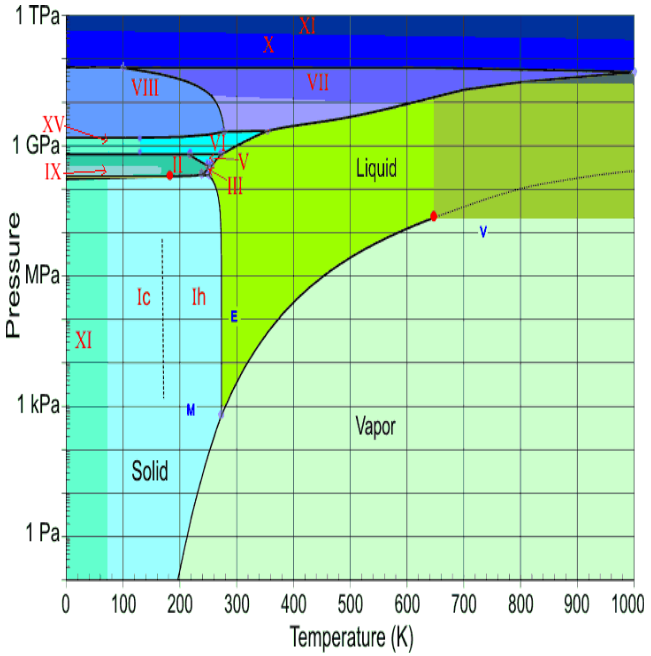


- ➢ Modification of crystal properties due to directed implantation of impurities or ionizing irradiation
- ➢ Anomalies of the properties in the region of the phase transitions

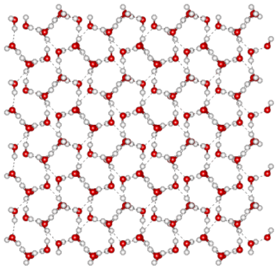
B.A.Strukov, Phase transitions,…(1996)

Phase Diagram of Strongly Interacting Matter

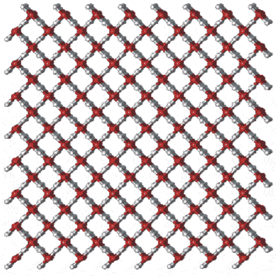
The phase diagram of water is established



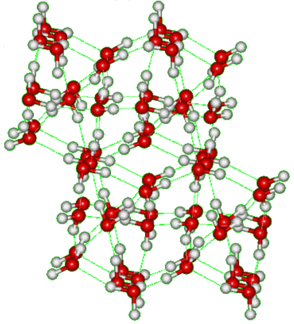
Ice III



Ice X

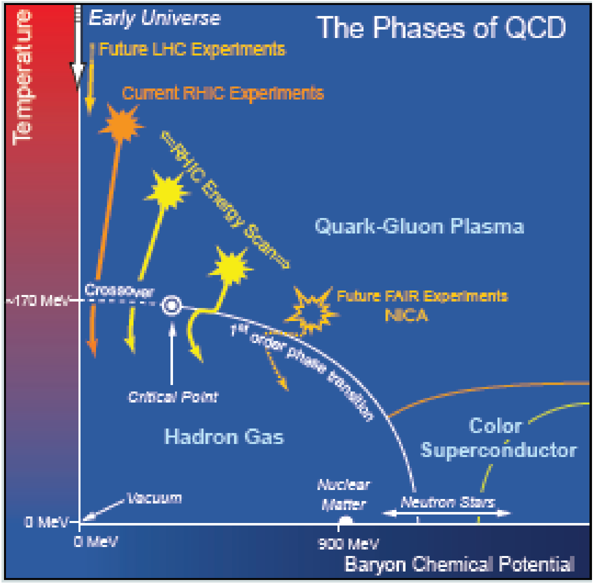


Ice XIII



- **Phases (ice I-XV, liquid, vapor)**
- **Phase boundaries**
- **Phase transitions**
- **Triple Point (16)**
- **Critical Point (2)**

The phase diagram of strongly interacting nuclear matter is under study



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

The Relativistic Heavy Ion Collider

3.83 km circumference

Two separated rings

120 bunches/ring

106 ns bunch crossing time

A+A, p+A, p+p

Maximum Beam Energy :

500 GeV for p+p

200A GeV for Au+Au

Luminosity

Au+Au: 2 x 10^{26} cm^{-2} s^{-1}

p+p : 2 x 10^{32} cm^{-2} s^{-1}

Beam polarizations

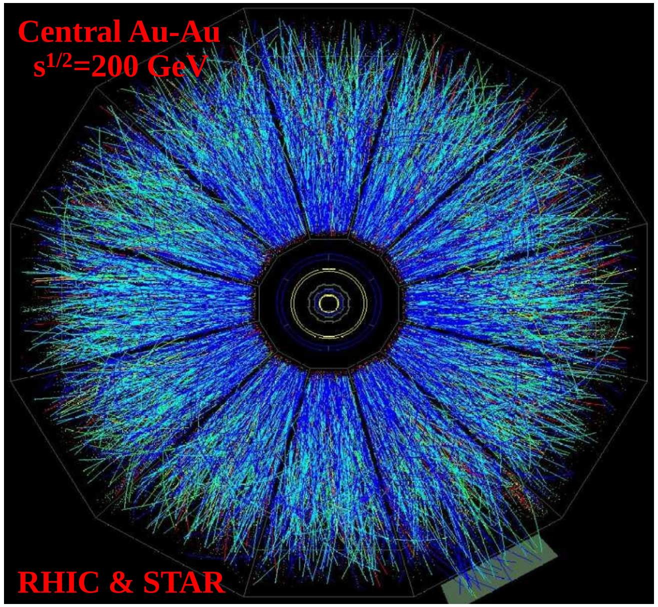
P=70%

Nucleus-nucleus collisions (AuAu, CuCu, dAu, CuAu, UU, … $\sqrt{s_{NN}}$ =7.7-200 GeV)

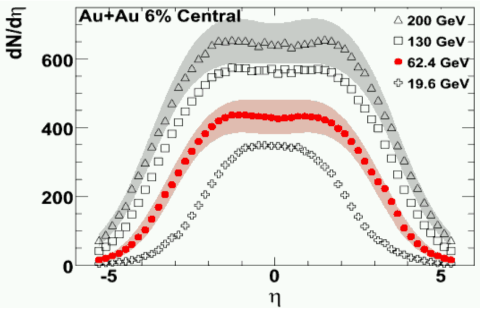
Polarized proton-proton collisions

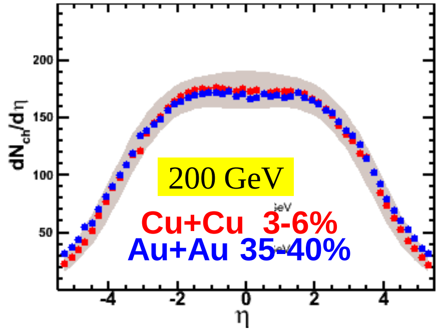
Main goal of investigations in relativistic AA collisions is search for and study new state of nuclear matter

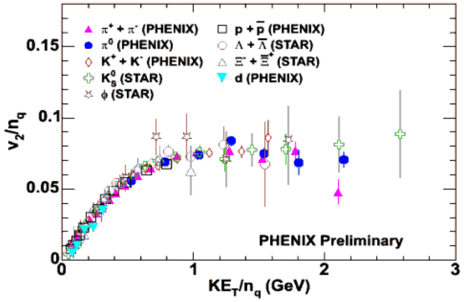
…, AGS, SPS, RHIC, LHC, …



…, NICA, FAIR, …





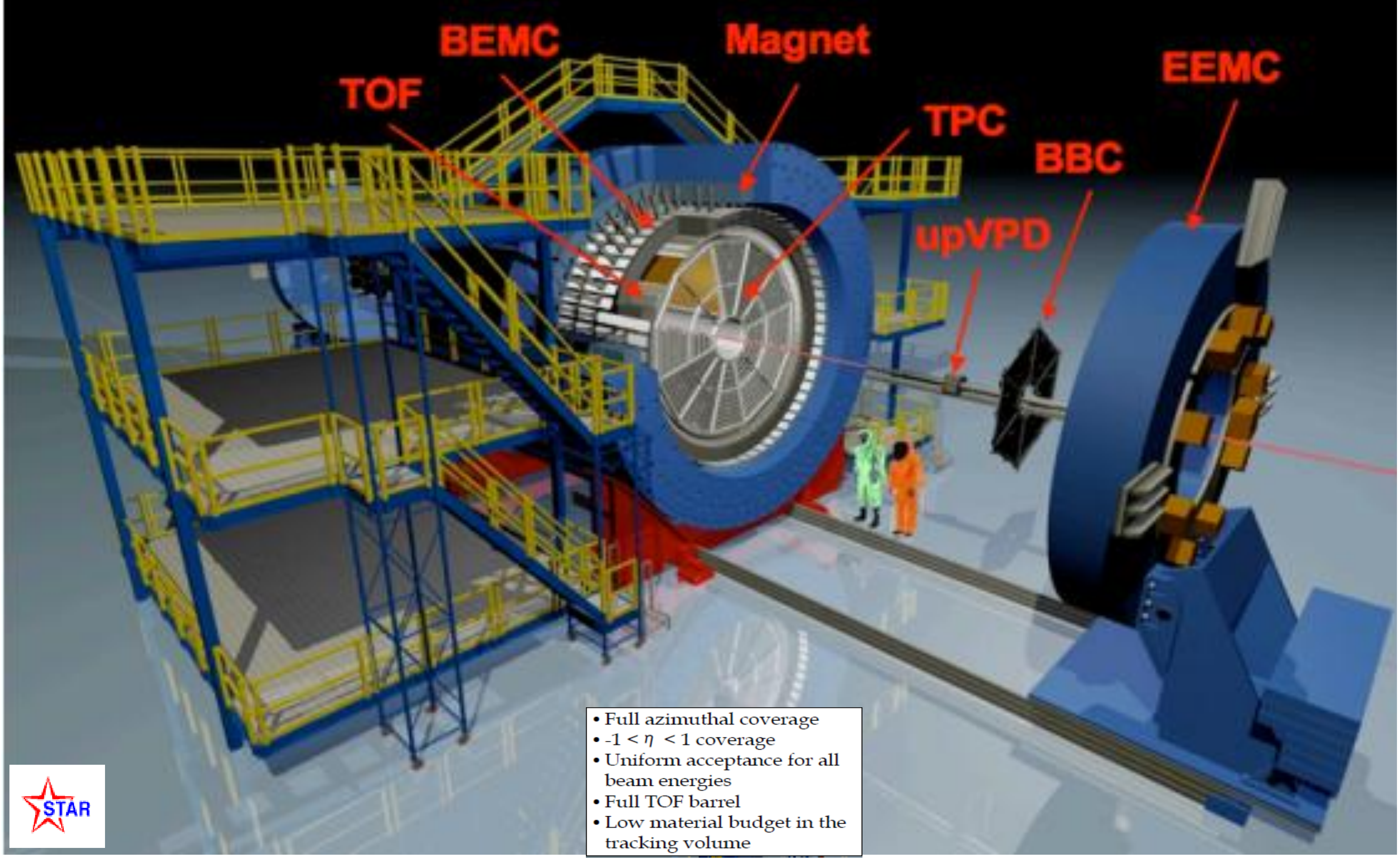


- ➢ High energy-density and very strong interacting matter was created at RHIC.
- ➢ RHIC data on $dN_{ch}/d\eta$, v_2 , R_{CP} ,… exhibit scaling laws.
- ➢ Transition to the new state of matter does not manifest abrupt changes in observables.

“White papers”
STAR, PHENIX, PHOBOS & BRAHMS

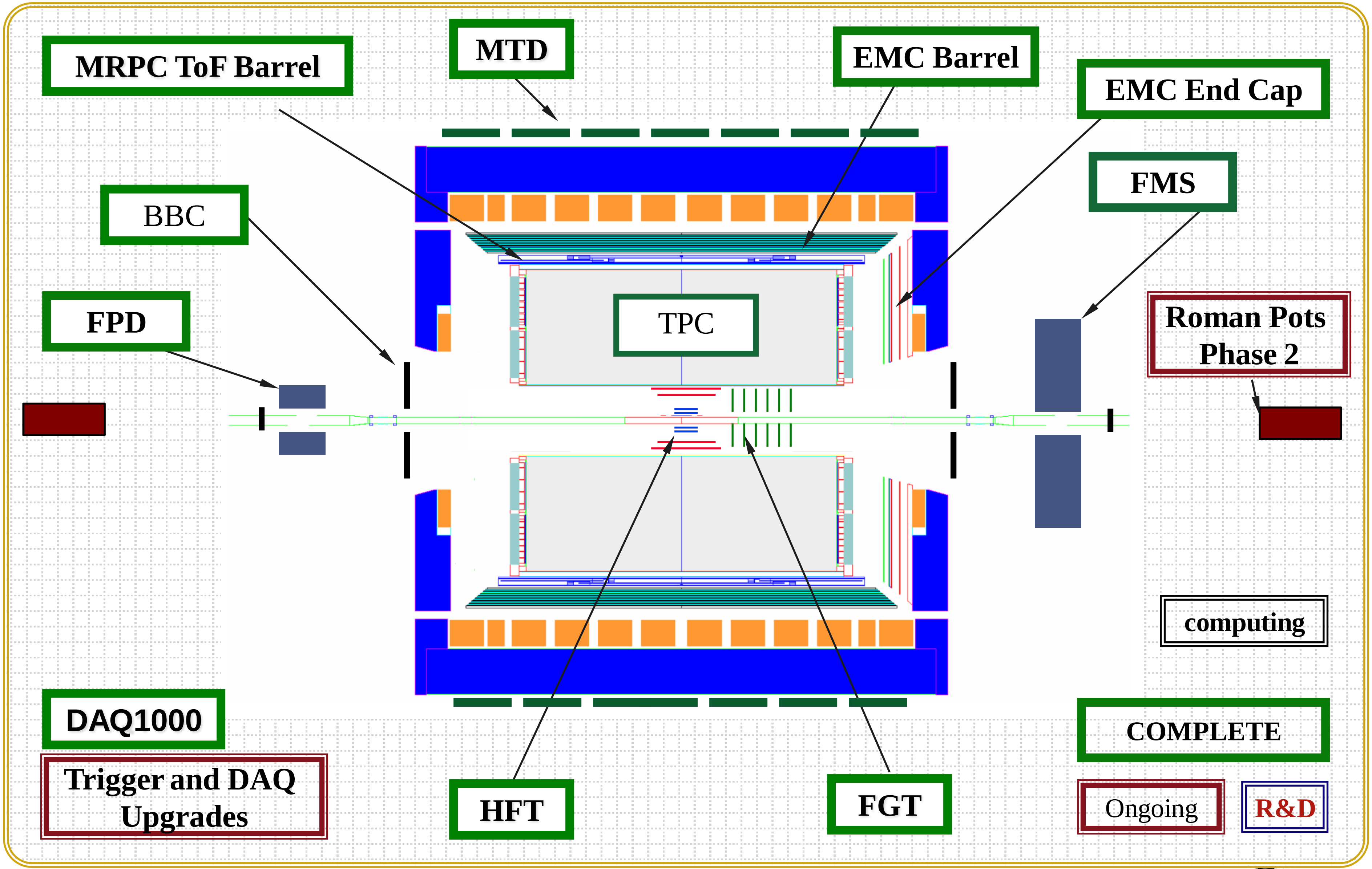
- ➢ What kind of interacting matter is created ?
- ➢ Thermodynamics, hydrodynamics, …
- ➢ Phase transition, critical point, …
- ➢ Self-similarty of created matter, …

The Solenoid Ttracker At RHIC (STAR)



- Full azimuthal coverage
- $-1 < \eta < 1$ coverage
- Uniform acceptance for all beam energies
- Full TOF barrel
- Low material budget in the tracking volume

STAR Detector



MRPC ToF Barrel

MTD

EMC Barrel

EMC End Cap

FMS

BBC

FPD

TPC

Roman Pots Phase 2

computing

DAQ1000

Trigger and DAQ Upgrades

HFT

FGT

COMPLETE

Ongoing

R&D

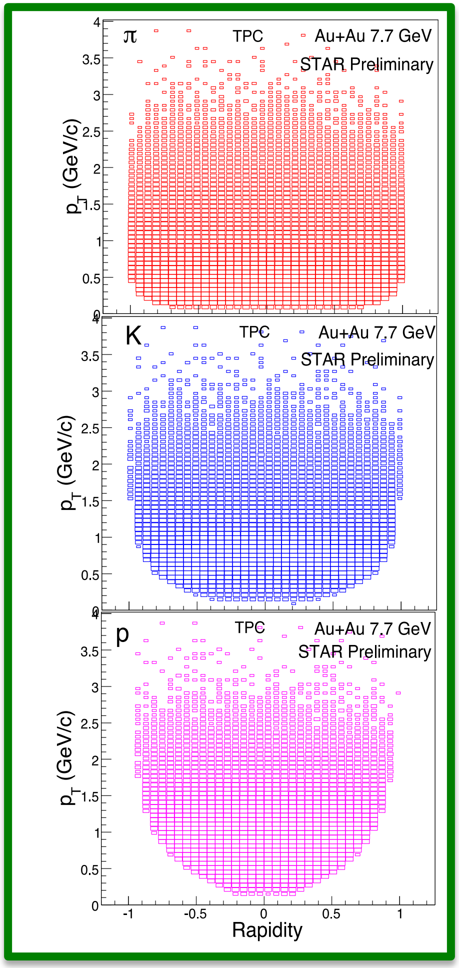
Identified Particle Acceptance at STAR

π

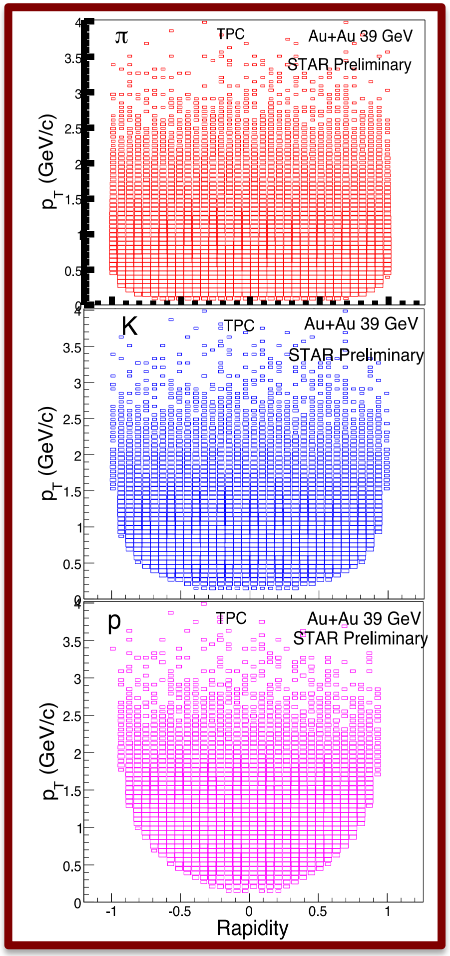
K

p

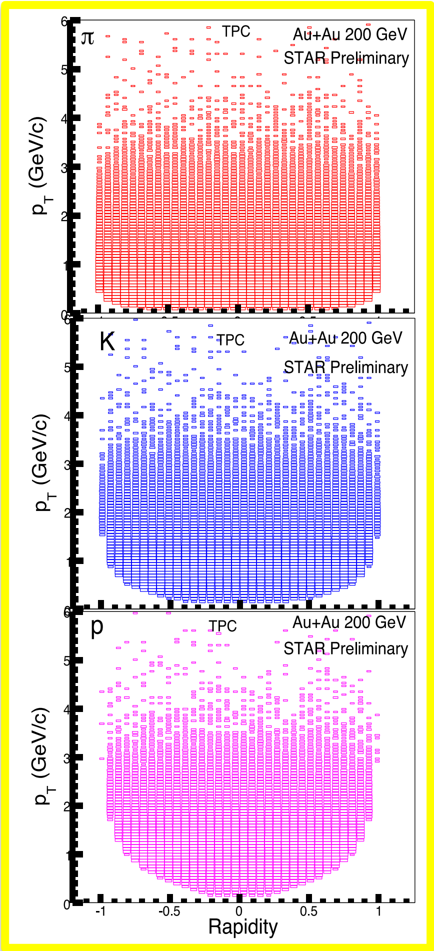
Au+Au 7.7 GeV



Au+Au 39 GeV



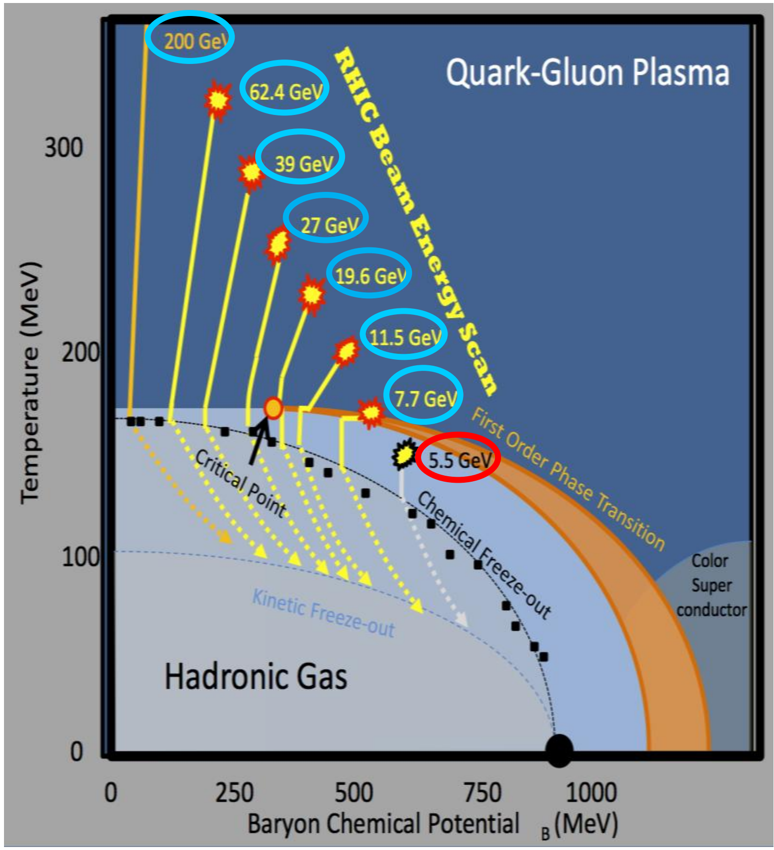
Au+Au 200 GeV



Homogeneous acceptance for all energies.

Beam Energy Scan at RHIC

Systematic study of AuAu collisions



STAR Note SN0493.

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

Phys.At.Nucl., 2011, V.74, №5, p.769.

Motivation

- **Search for phase transition and critical point of strongly interacting matter**
  - Elliptic & directed flow v_2, v_1
  - Azimuthally-sensitive femtoscopy
  - Fluctuation measures: $\langle K/\pi \rangle$, $\langle p/\pi \rangle$, $\langle p_T \rangle$, $\langle N_{ch} \rangle$…
- **Search for turn-off of new phenomena seen at higher RHIC energies**
  - Constituent-quark-number scaling of v_2
  - Hadron suppression in central collisions R_{AA}
  - Ridge ($\Delta\varphi$-$\Delta\eta$ correlations)
  - Local parity violation

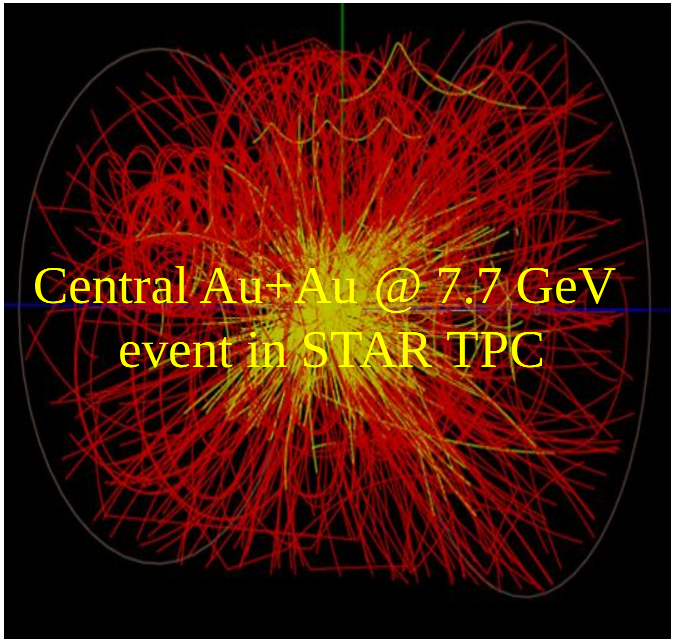
STAR Collaboration:

An Experimental Exploration of the QCD Phase Diagram: The Search for the Critcal Point and the Onset of Deconfinement

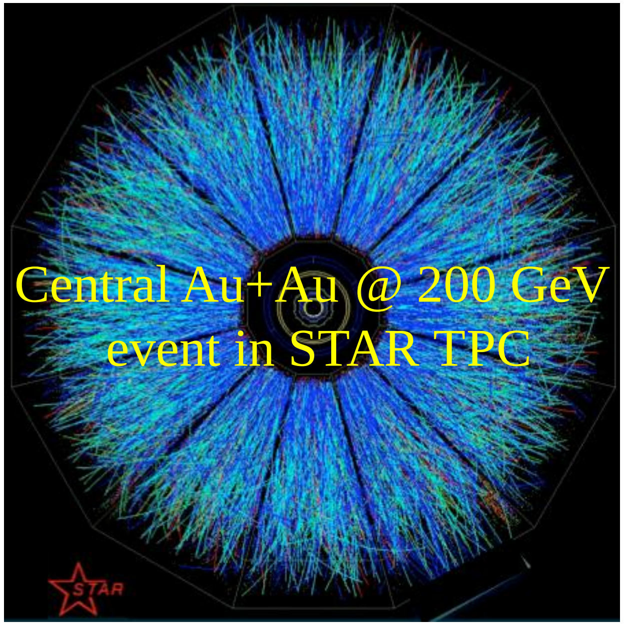
arXiv:1007.2613v1 [nucl-ex]

Beam Energy Scan Program
at STAR RHIC

- signatures for a phase transition
- signatures for a critical point
- boundary of phase diagram



Central Au+Au @ 7.7 GeV
event in STAR TPC

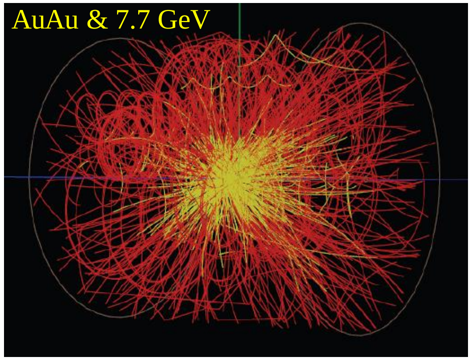


Central Au+Au @ 200 GeV
event in STAR TPC

RHIC beam energy scan with Au+Au:

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

AuAu Beam Energy Scan Program at RHIC



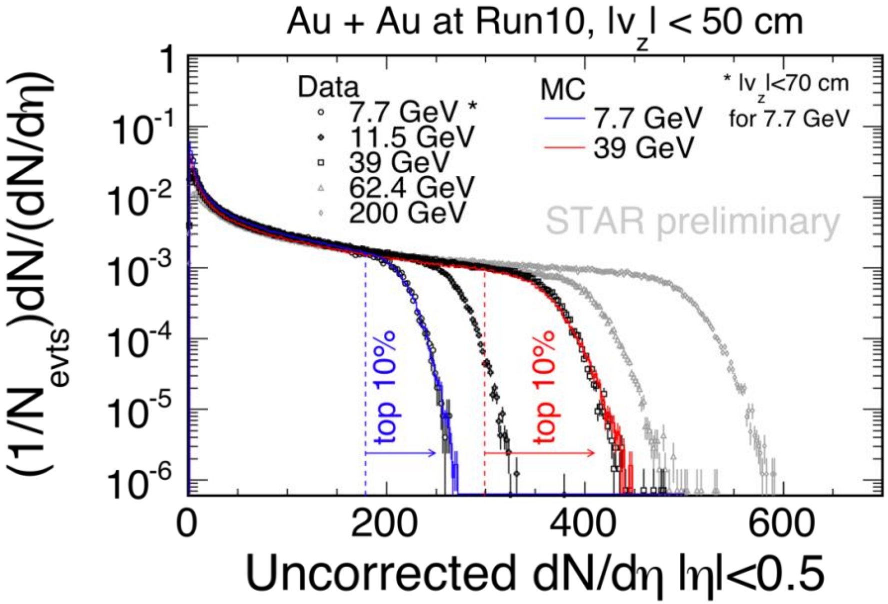
Experimental Study of the QCD Phase Diagram and Search for the Critical Point

STAR Note SN0493, Phys. Rev. C 81, 024911 (2010)

$\sqrt{s_{NN}}$ (GeV)	μ_B (MeV)	MB Events in Millions
5.0	550	
7.7	410	4.3
11.5	300	11.7
19.6	230	35.8
27	151	70 .4
39	112	130.4
62.4	73	67 .3
130	36	
200	24	

STAR Run 10,11

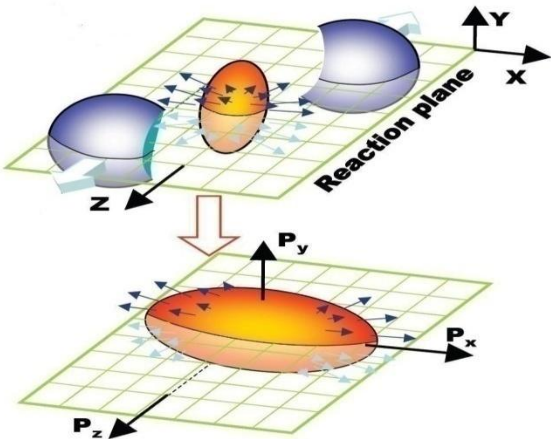
Multiplicity distribution



Flow of nuclear matter

collectivity of partonic degree of freedom

Directed (v_1) & Elliptic (v_2) flow in AuAu collisions



Coordinate-Space Anisotropy

↓

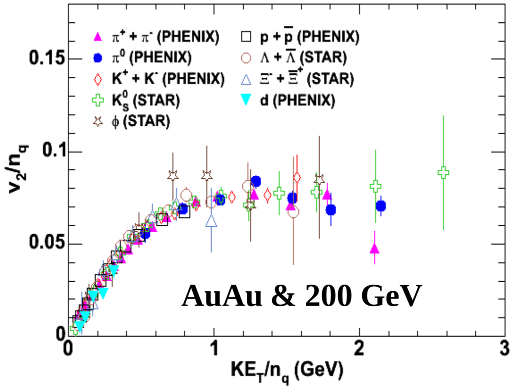
Momentum-Space Anisotropy

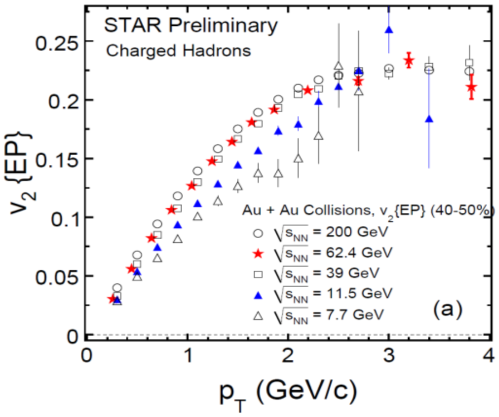
Fourier expansion of the momenta distribution

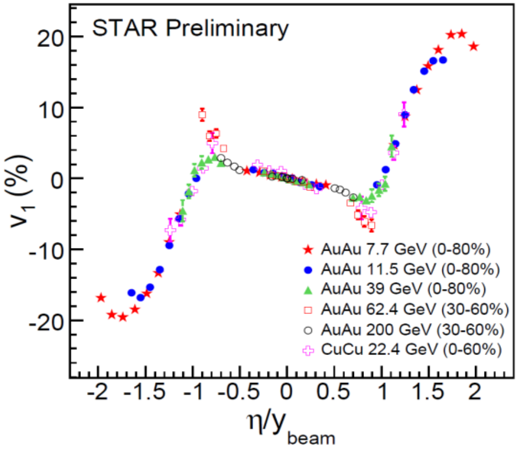
$$E\frac{d^3N}{d^3p} \propto \left(1+\sum_{n=1}^{\infty} 2v_n \cos n(\phi-\Psi_\mathrm{r})\right)$$

$$v_n = \langle \cos n(\phi-\Psi_r) \rangle$$

$$\phi = \tan^{-1}\left(\frac{p_y}{p_x}\right)$$

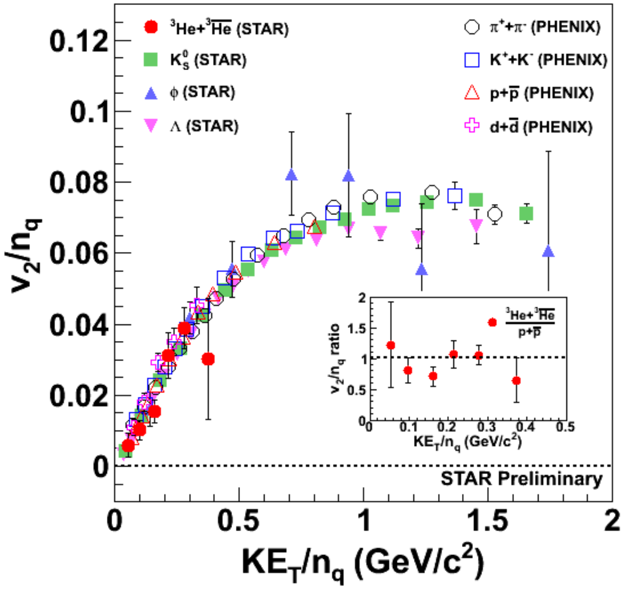


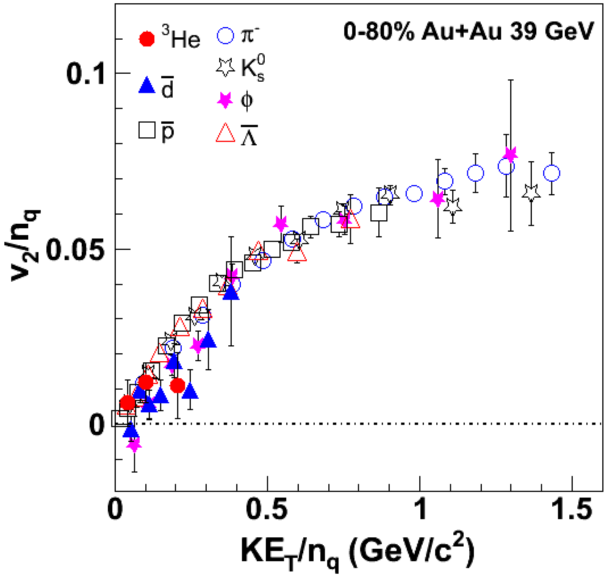




- v_1 (y) sensitive to baryon transport, space momentum correlations and QGP formation.
- v_2 provides the possibility to gain information about the degree of thermalization of the hot, dense medium.
- The breaking of v_2 number of quark scaling will indicate a transition from partonic to hadronic degrees of freedom.

NCQ scaling: Au+Au 200 & 39 GeV





Flow vs.
- energy
- centrality
- particle mass

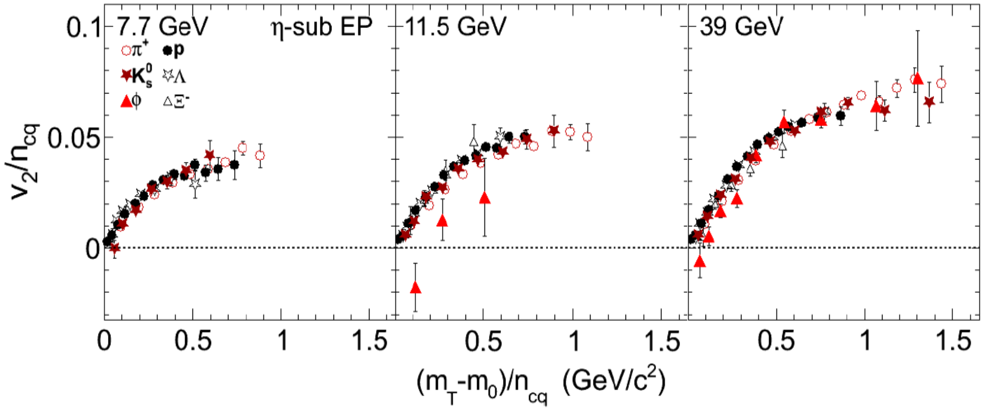
v2 of light nuclei scaled to the number of constituent quarks (NCQ) of their constituent nucleons, are consistent with NCQ scaled v2 of baryons and mesons

NCQ scaling holds good for v2 of light nuclei in Au+Au 39 GeV

C.Jena, CPOD 2011, November 7-11, Wuhan, China

BES @ NCQ scaling of v2

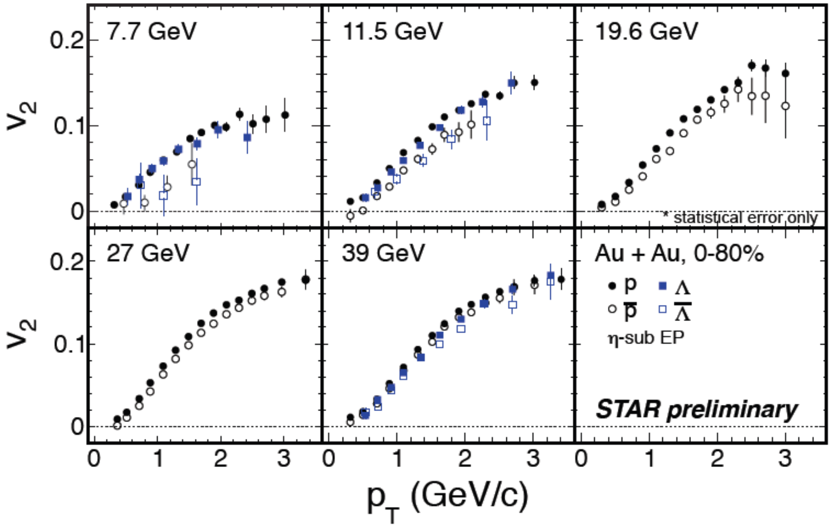
AuAu @ 7.7,11.5, 39



- Universal trend for most of particles
- φ meson v2 indicates strange quark collectivity becomes weaker with decreasing beam energy

S.Shi , CPOD, November 7-11, 2011, Wuhan, China

AuAu @ 7.7,11.5,19.6, 27, 39



- Difference of $v_2(p_T)$ between particles and antiparticles.

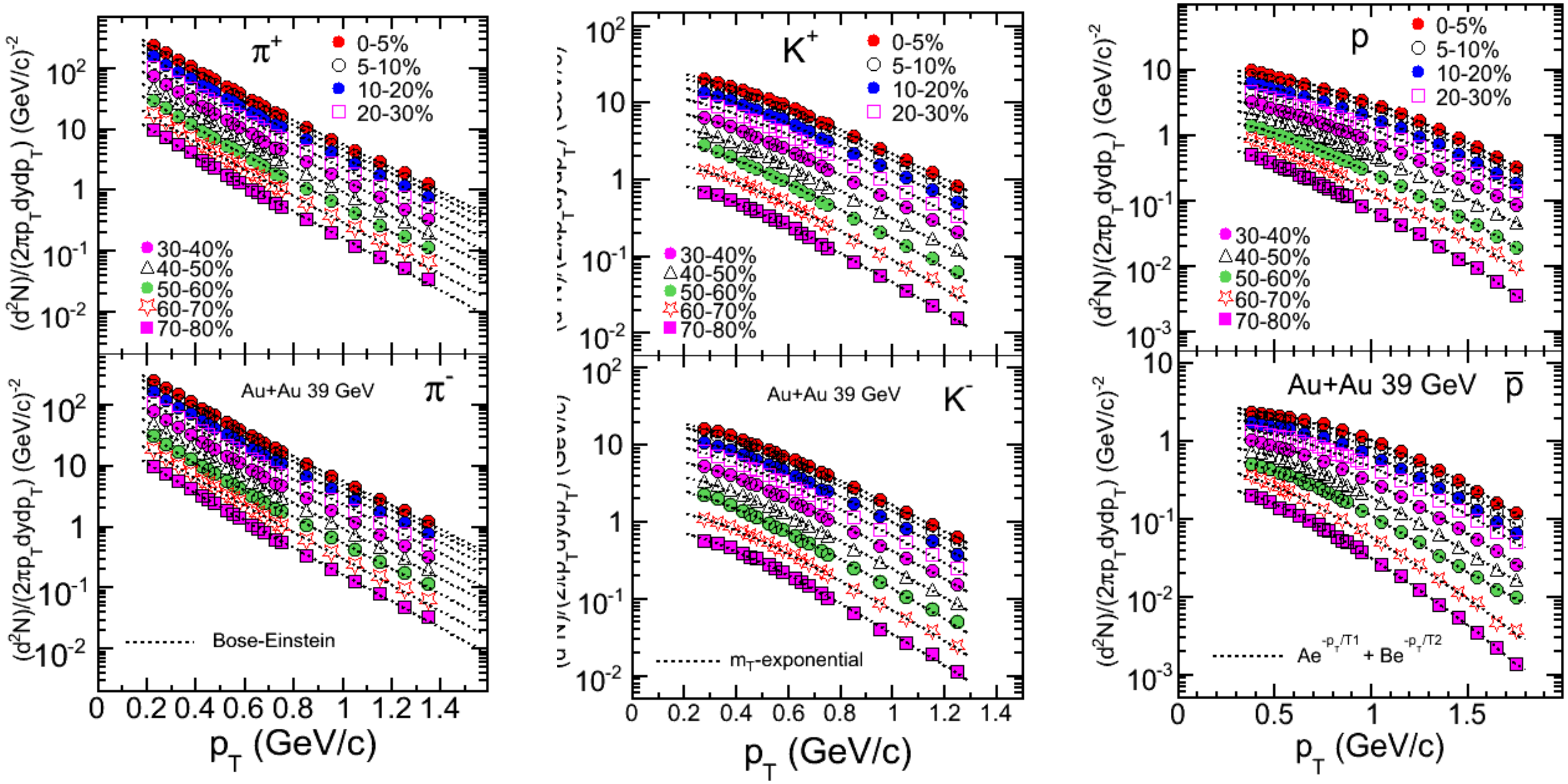
H.Masui,
Moriond QCD and High Energy Interactions,
March 10-17, 2012

Spectra

probing QCD phase diagram
with identified particles: $\pi^{+/-}$, $K^{+/-}$ and $\overline{p}/p$
in STAR BES program

$\pi^{+/-}$, $K^{+/-}$ and $\bar{p}/p$ spectra in AuAu

Au+Au @ 39 GeV

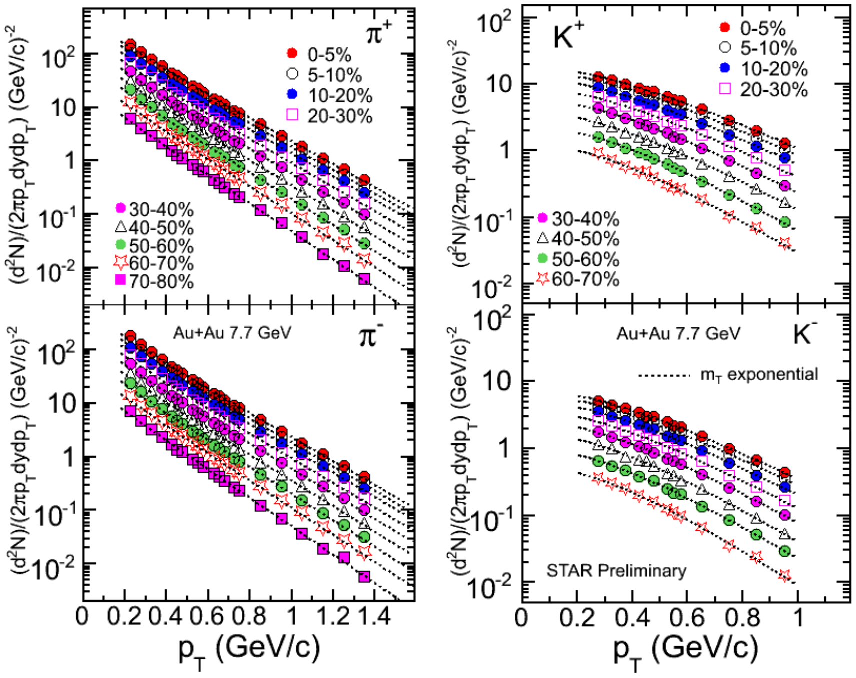


- BES spectra obtained with TPC and TOF:
  - ✓ Consistent with dE/dx in overlapping range

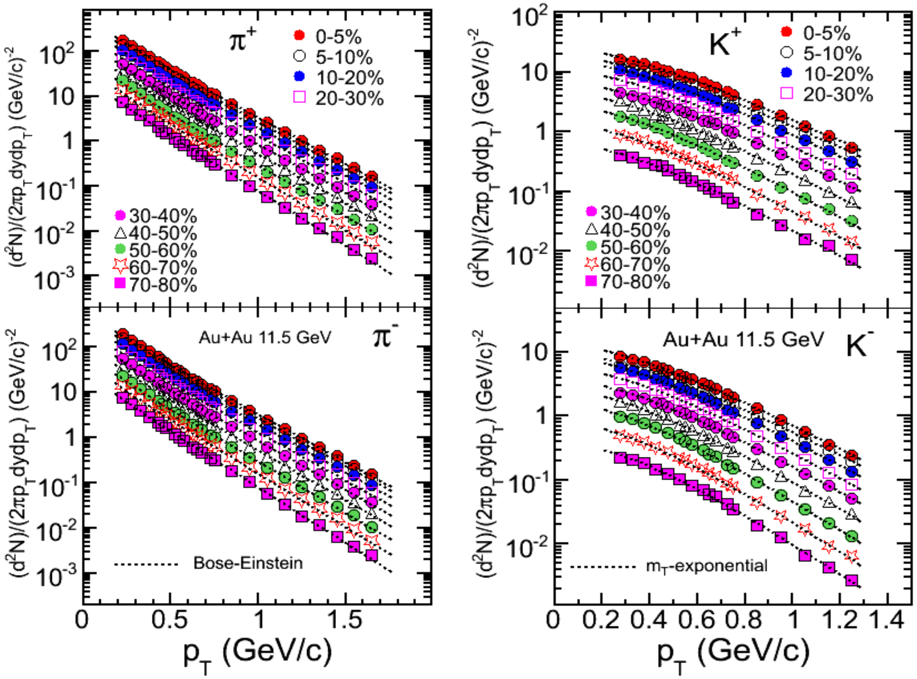
L. Kumar, CPOD 2011, November, China

$\pi^{+/-}$, $K^{+/-}$ spectra in AuAu

Au+Au @ 7.7 GeV



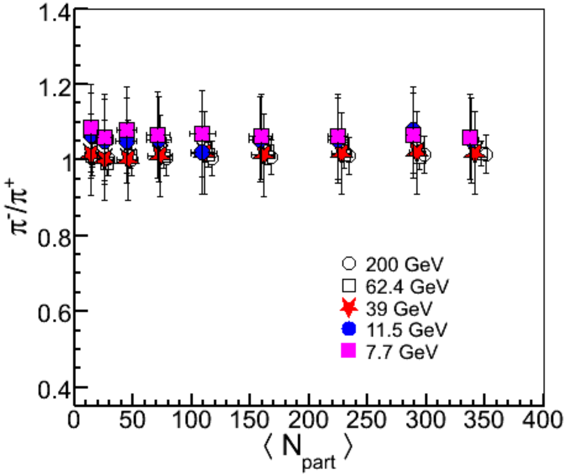
Au+Au @11.5 GeV



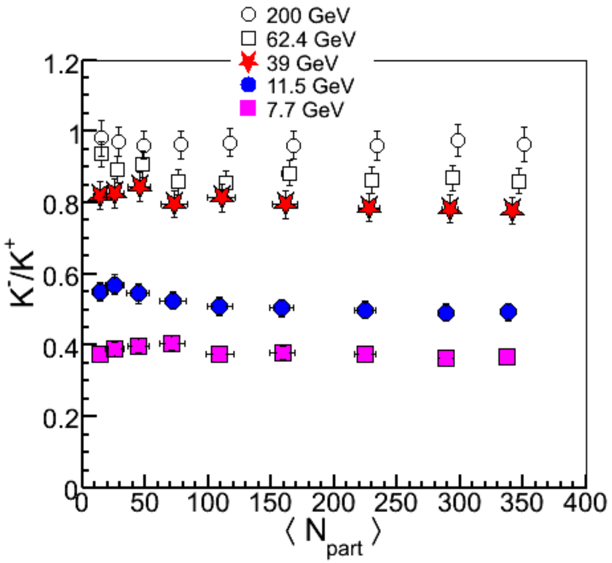
- Spectra of identified particle up to 1.5 GeV/c.

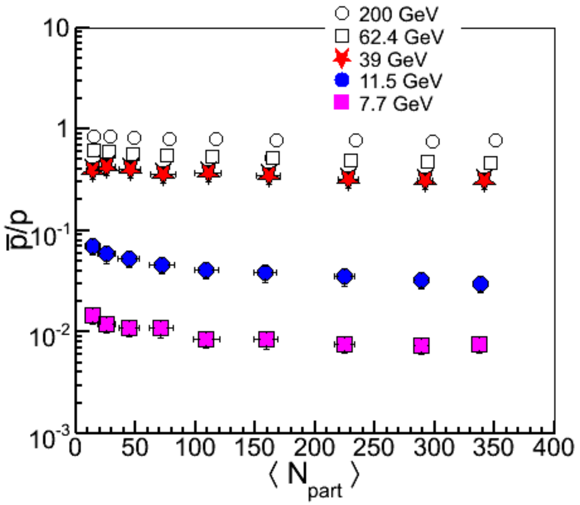
L. Kumar ICPAQGP, 2010

AntiParticle to Particle ratio vs. Centrality



AuAu @ 7.7,11.5, 39, 62.4, 200 GeV



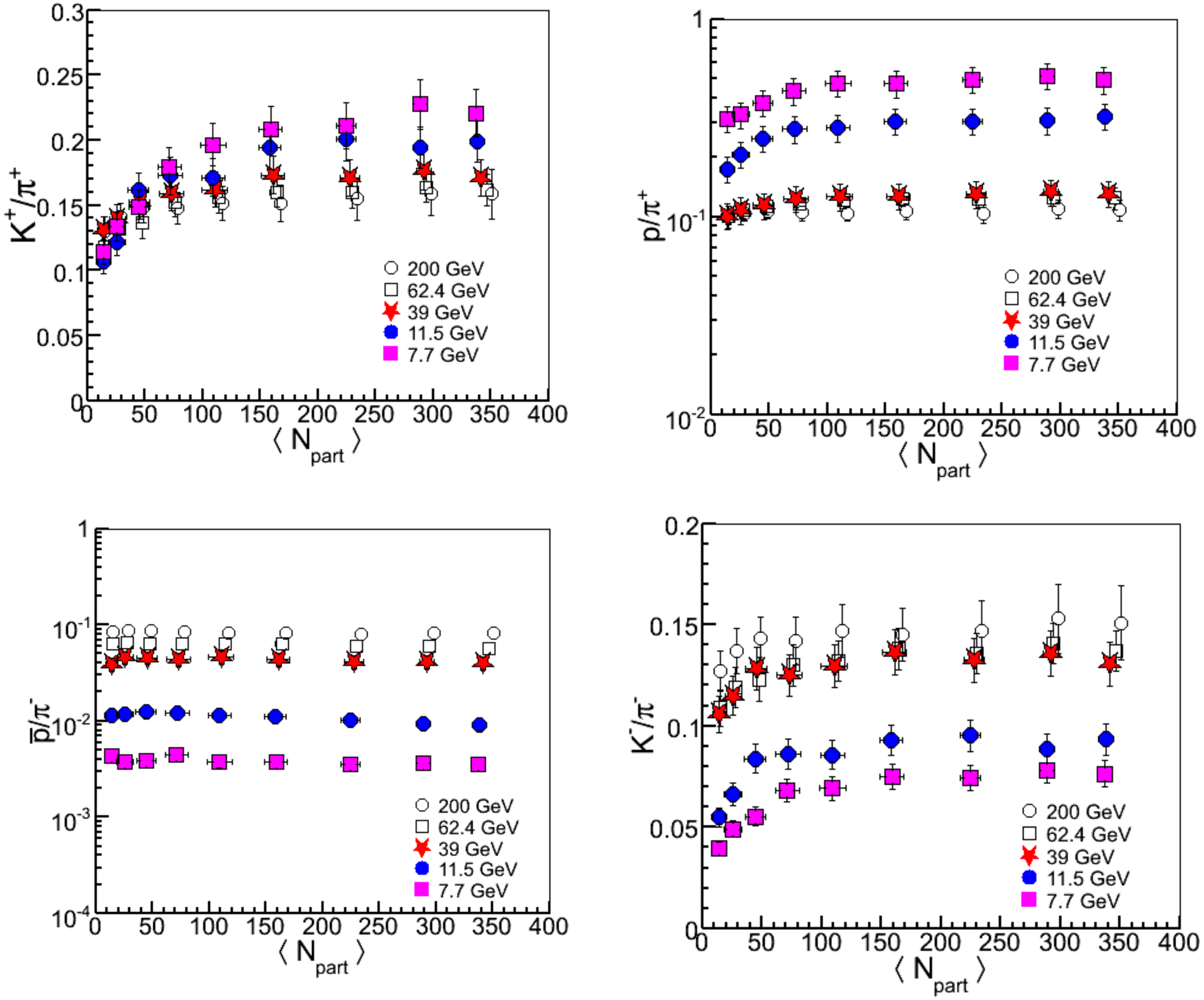


- Ratios are flat vs. centrality
- Ratios increase vs.energy $\sqrt{s_{NN}}$

L. Kumar, CPOD 2011, November, China

Particle ratio vs. Centrality

AuAu @ 7.7,11.5, 39, 62.4, 200 GeV



- K^+/π^+ and p/π^+ ratios increases with decrease in energy

- K^-/π^- and p^-/π^- ratios increases with energy

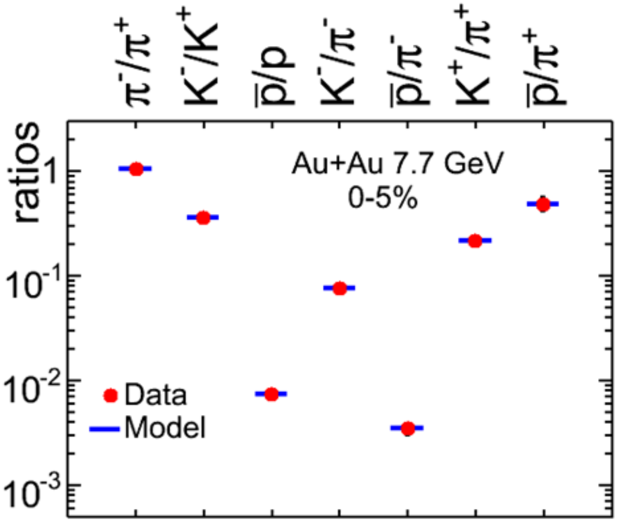
Chemical Freeze-out

Statistical-Thermal Model (THERMUS):

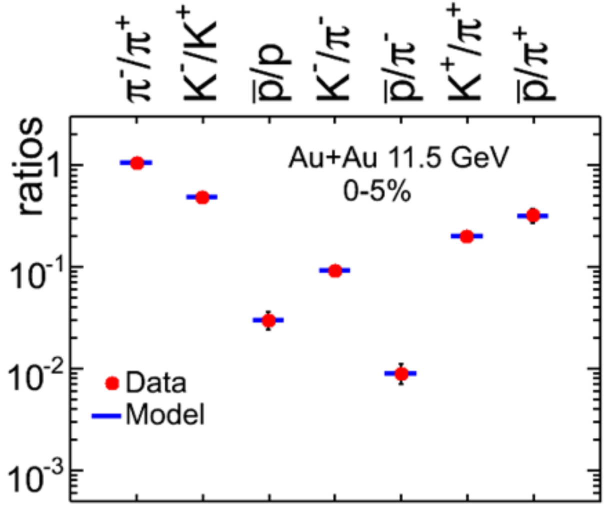
$$n = \frac{1}{V}\frac{\partial(T\ln Z)}{\partial\mu} = \frac{VTm_i^2 g_i}{2\pi^2}\sum_{k=1}^{\infty}\frac{(\pm1)^{k+1}}{k}\left(e^{\beta k\mu_i}\right)K_2\left(\frac{km_i}{T}\right)$$

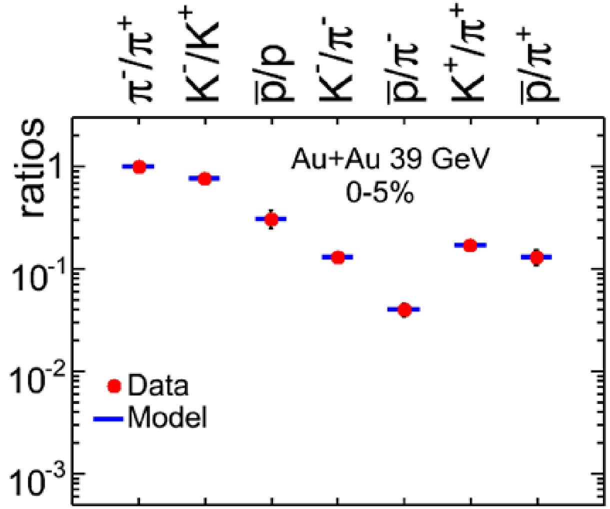
$\beta=1/T$; -1(+1) for fermions (bosons), Z=partition function; m_i = mass of hadron species i; V = volume; T = Temperature; K_2= 2nd order Bessel function; g_i = degeneracy; μ_i = chemical potential

- ✧Fitted particle ratios with THERMUS
- ✧Used grand-canonical approach
- ✧Two main parameters: T_{ch} and μ_B



S. Wheaton & J. Cleymans, hep-ph/ 0407174;
S. Wheaton, J. Cleymans & M. Hauer, comp. phys. Comm. 180 (2009) 84.

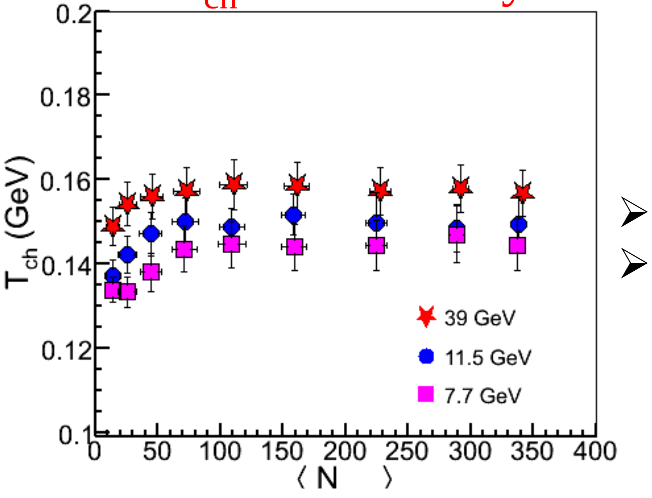




$$\langle n_i\rangle = \frac{(2J_i+1)\,V}{(2\pi)^3}\int d^3p\,\frac{1}{\gamma_s^{-S_i}\,exp[(E_i-(\mu_B+\mu_S+\mu_Q))/T]\pm1}$$

BES @ Chemical Freeze-out

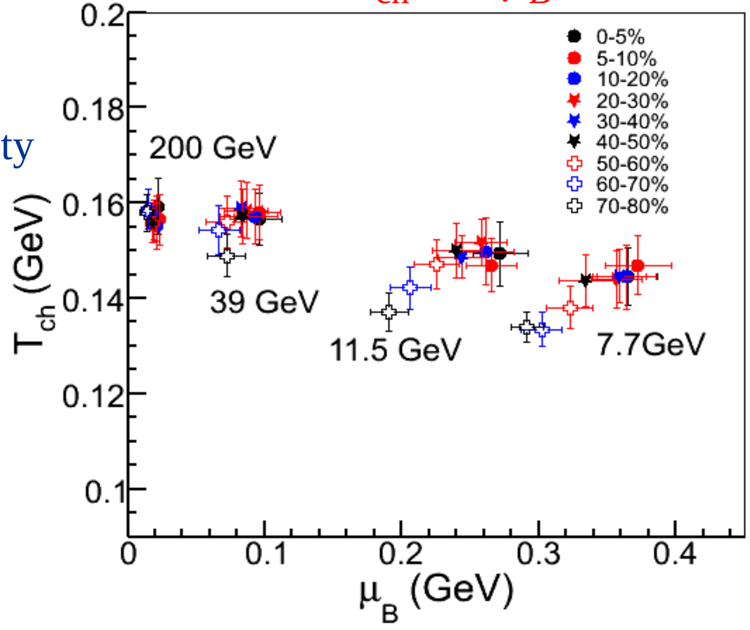
T_{ch} vs. centrality



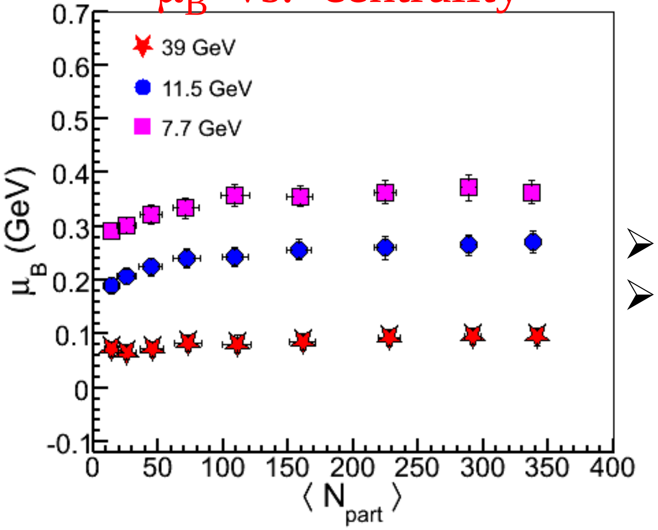
T_{ch}

- ➢ increases with energy
- ➢ saturates with centrality

T_{ch} vs. μ_B



μ_B vs. centrality



μ_B

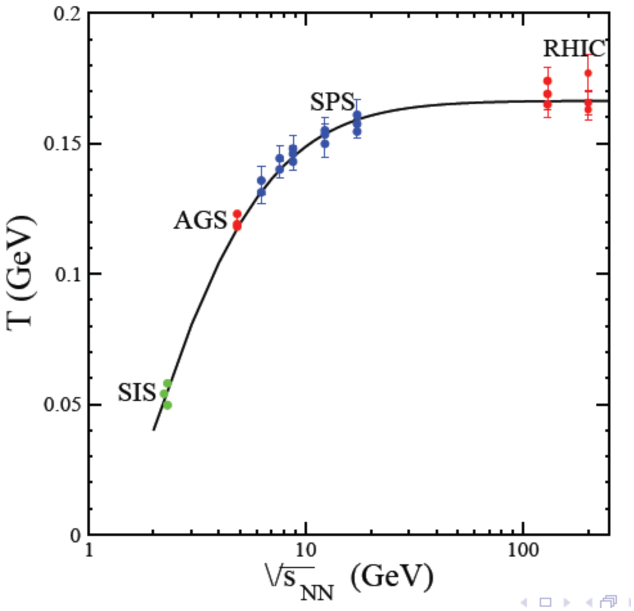
- ➢ decreases as energy increases
- ➢ saturates with centrality

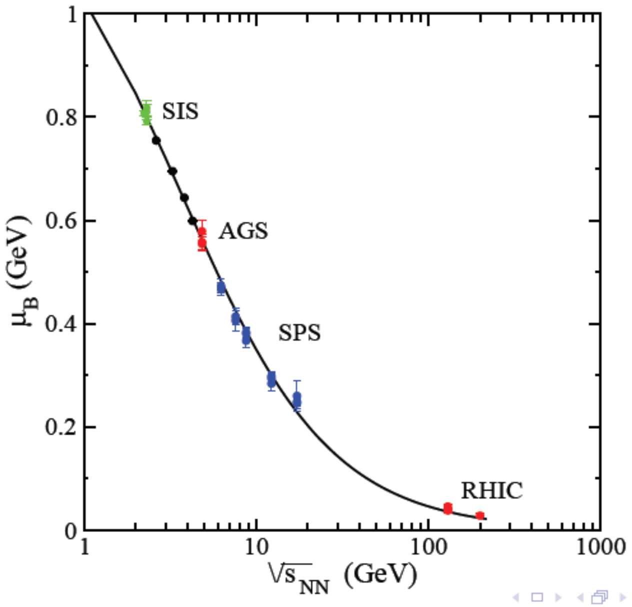
Phase boundary depends
on centrality

Statistical termodynamical model

Particle ratio fitted by thermal model to extract Chemical freeze-out temperature (T) and baryon chemical potential (μ_B).

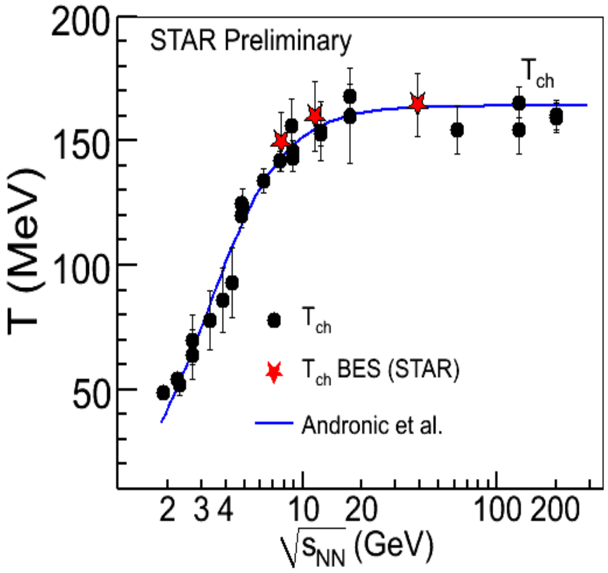
J. Cleymans et al, Phys. Rev. C73 (2006) 034905

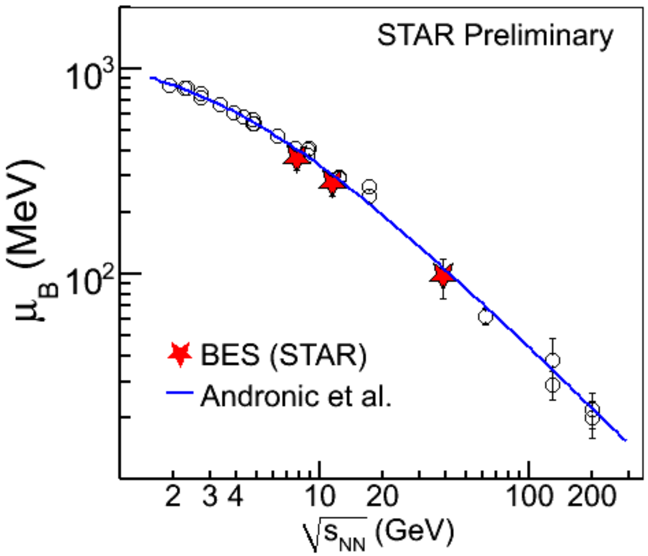


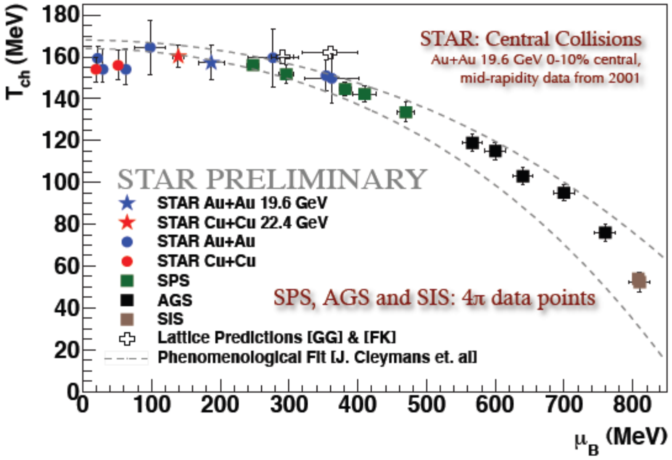


- Smooth dependence of T_{ch} and μ_B on energy
- T_{ch} is flat for $\sqrt{s_{NN}}$ >20 GeV
- μ_B is tending to zero if $\sqrt{s_{NN}} \to \infty$
- RHIC: $\mu_B \approx 24$ MeV at $\sqrt{s_{NN}}$ =200 GeV
- LHC: $\mu_B \approx 0.87$ MeV at $\sqrt{s_{NN}}$ =5500 GeV

Data @ Stat-Thermo Model







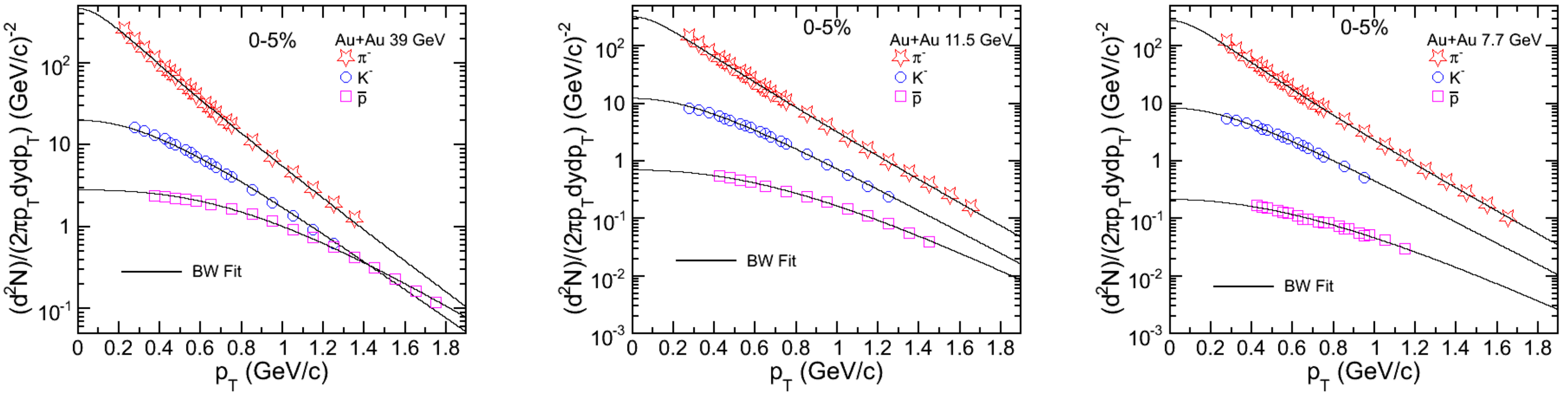
Smooth dependence everywhere.

L.Kumar, QM2011

BES @ Kinetic Freeze-out

Blast-Wave (BW) Model:

$$\frac{dN}{p_T dp_T} \propto \int_0^R r dr m_T I_0\left(\frac{p_T \sinh\rho(r)}{T_{kin}}\right) \times K_1\left(\frac{m_T \cosh\rho(r)}{T_{kin}}\right)$$

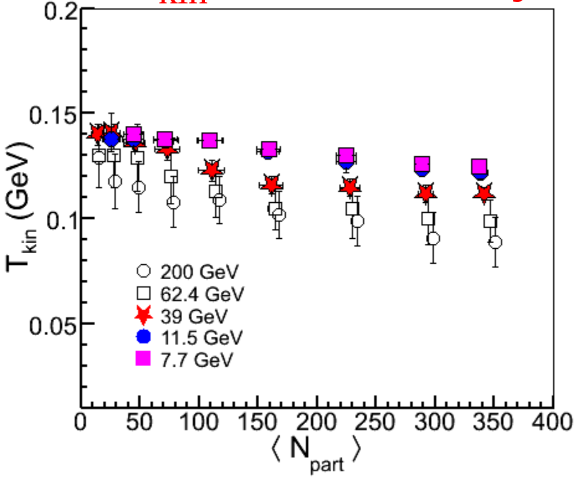


- ✧ Spectra are fitted simultaneously with BW
- ✧ Two main parameters: T_{kin} and $<\beta>$

F.Retiere , M.Lisa, Phys.Rev. **C70** (2004) 044907
http://www.star.bnl.gov/public/hbt/BlastWave/

BES @ Kinetic Freeze-out

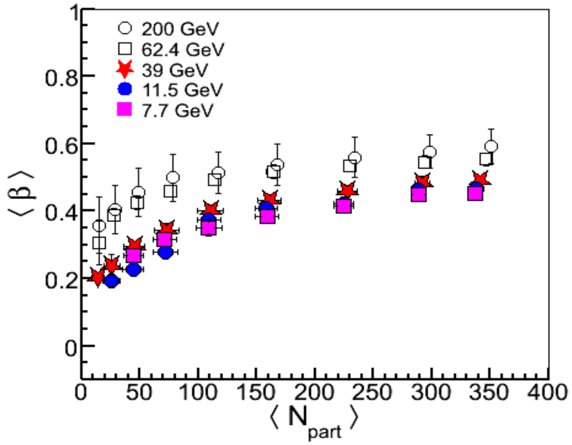
T_{kin} vs. centrality



T_{kin}

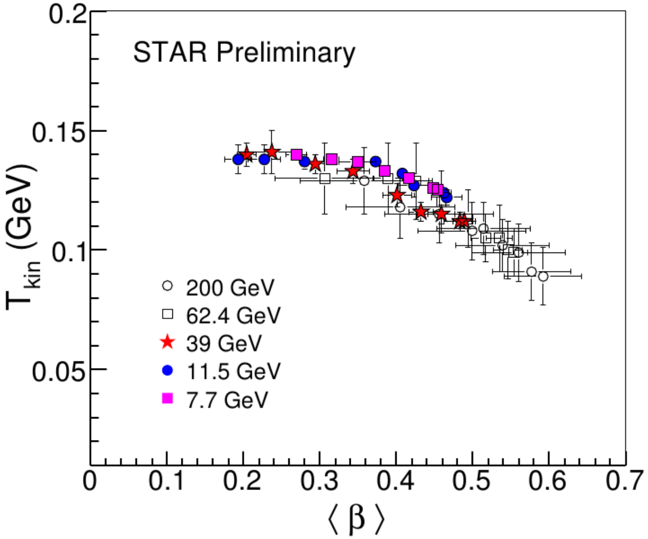
- ➢ decreases as energy increases
- ➢ saturates with centrality

<β> vs. centrality



<β>

- ➢ increases with energy
- ➢ saturates with centrality



Smooth behavior

T_{kin} vs. centrality

<β> vs. centrality

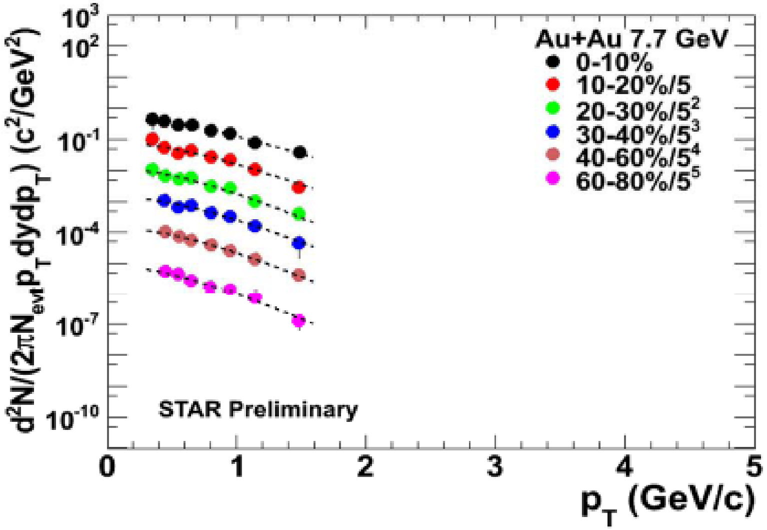
T_{kin} vs. <β>

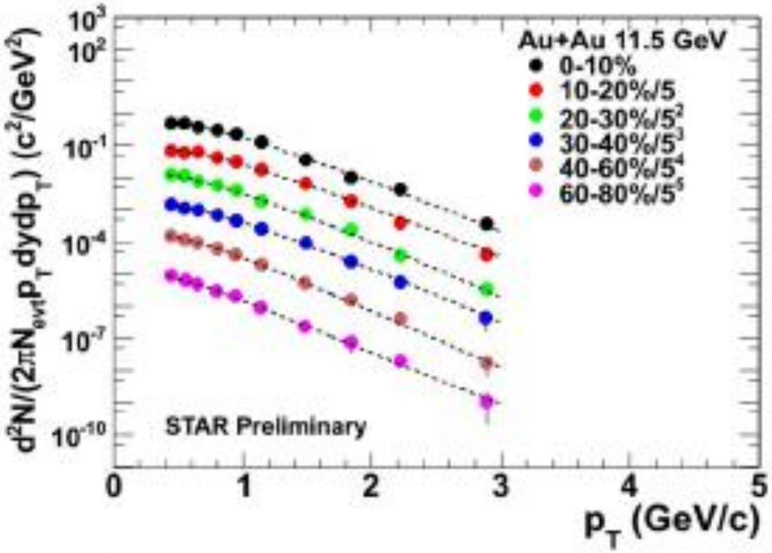
R.Witt @ STAR
LLWI, February 7, 2012, Alberta, Canada

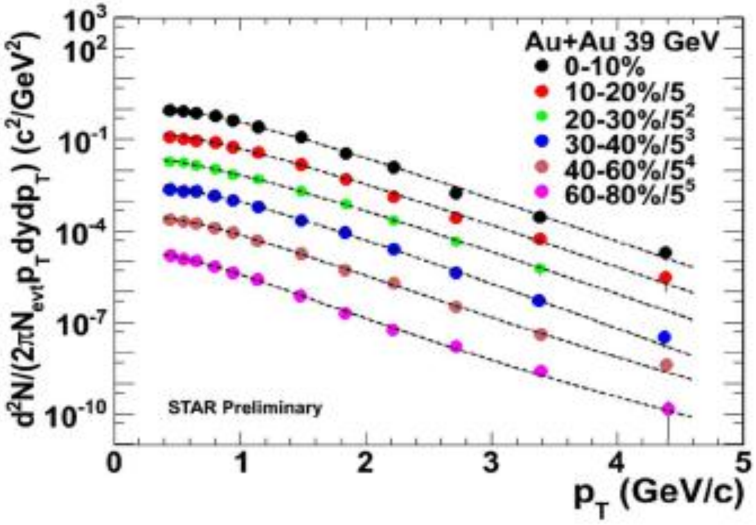
Spectra

probing QCD phase diagram with identified particles: φ, K_S^0, Λ, Ξ , Ω,… in STAR BES program

Spectra from $\varphi \rightarrow K^+K^-$ decay channel





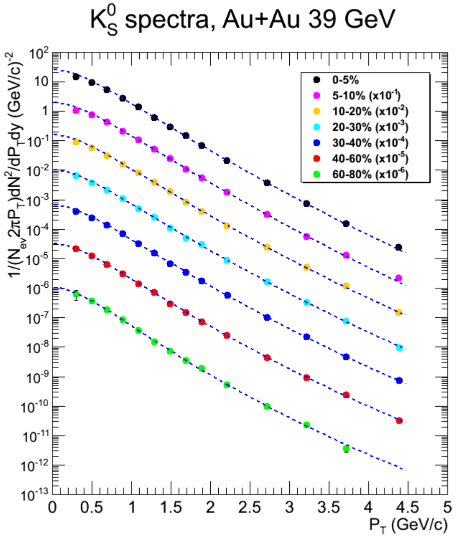


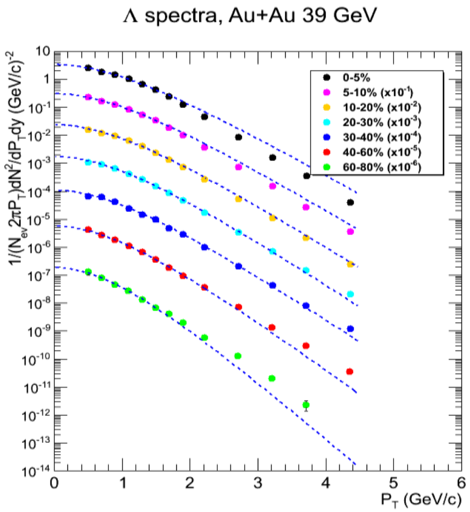
Transverse momentum spectra
are well described by the Levy function
with parameters T & n

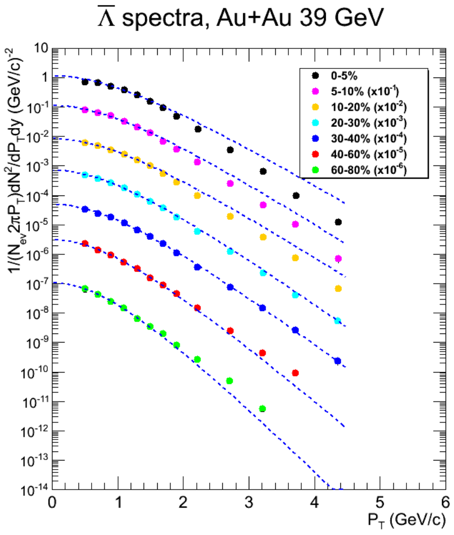
$$\frac{1}{2\pi p_T}\frac{d^2N}{dp_T dy} = dN/dy\frac{(n-1)(n-2)}{2\pi nT(nT+m(n-2))}(1+\frac{\sqrt{p_T^2+m^2}-m}{nT})^{-n}$$

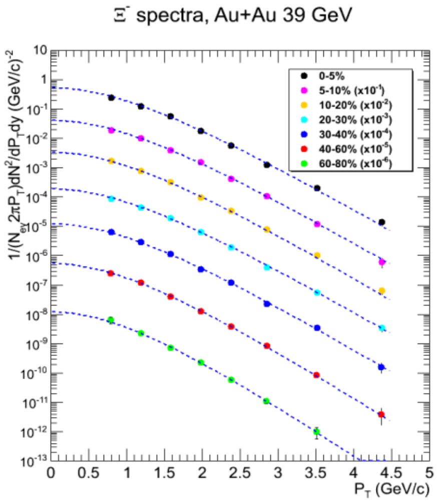
X. Zhang, CPOD 2011, November 7-11, Wuhan, China

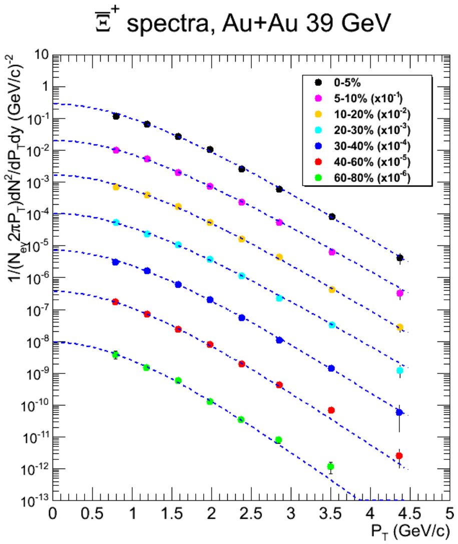
Spectra of strange particles K_S^0, Λ, Ξ


K_S^0 spectra, Au+Au 39 GeV


Λ spectra, Au+Au 39 GeV


$\bar{\Lambda}$ spectra, Au+Au 39 GeV


Ξ^- spectra, Au+Au 39 GeV


$\bar{\Xi}^+$ spectra, Au+Au 39 GeV

$\sqrt{s}$=39 GeV

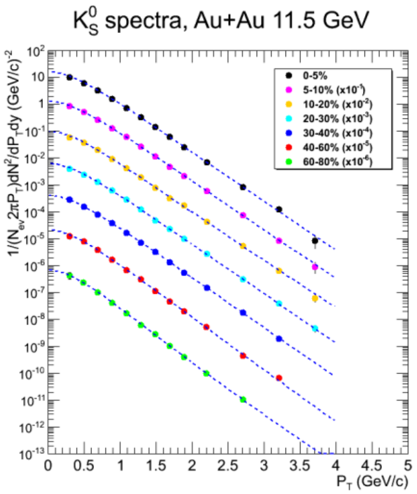
Λ spectra are weak decay feed-down corrected:

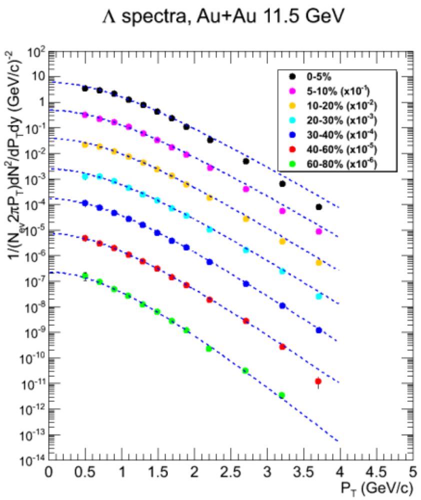
~ 20% for Λ

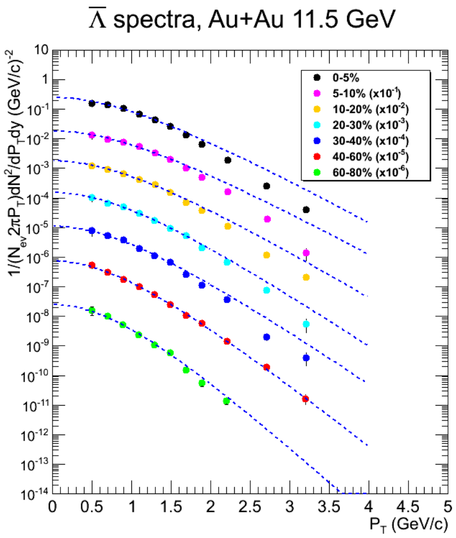
~ 25% for anti-Λ

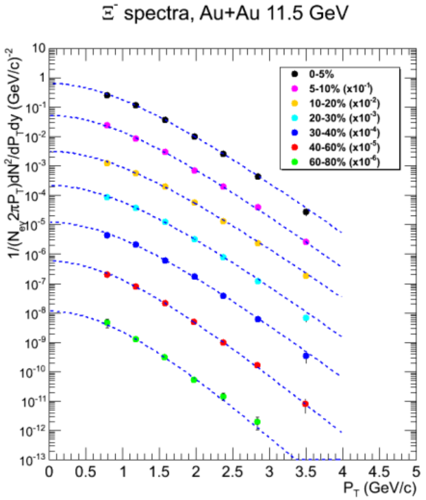
X.Zhu, CPOD 2011, November 7-11, 2011, China

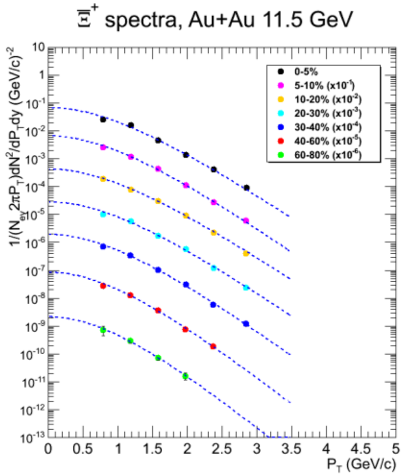
Spectra of strange particles K_S^0, Λ, Ξ


K_S^0 spectra, Au+Au 11.5 GeV


Λ spectra, Au+Au 11.5 GeV


$\overline{\Lambda}$ spectra, Au+Au 11.5 GeV


Ξ^- spectra, Au+Au 11.5 GeV

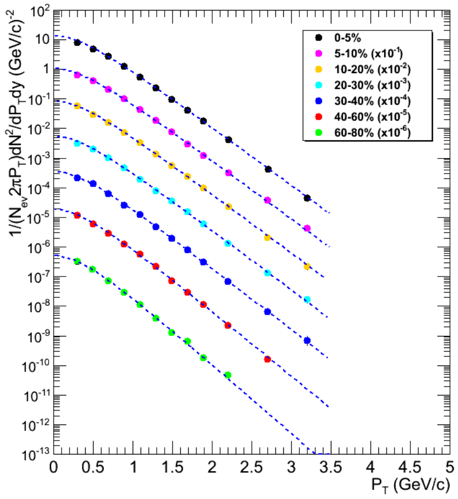

$\overline{\Xi}^+$ spectra, Au+Au 11.5 GeV

$\sqrt{s}$=11.5 GeV

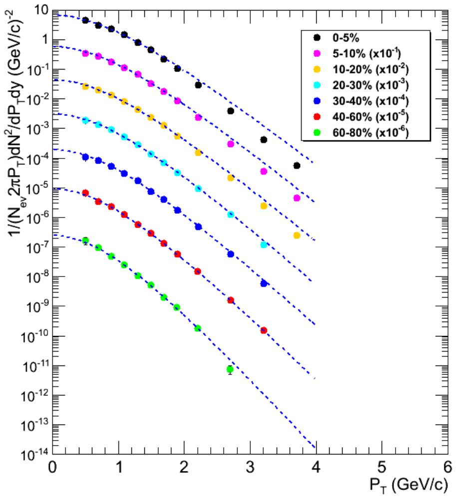
Λ spectra are weak decay
feed-down corrected:
~ 15% for Λ
~ 27% for anti-Λ

X.Zhu, CPOD 2011, November 7-11, 2011, China

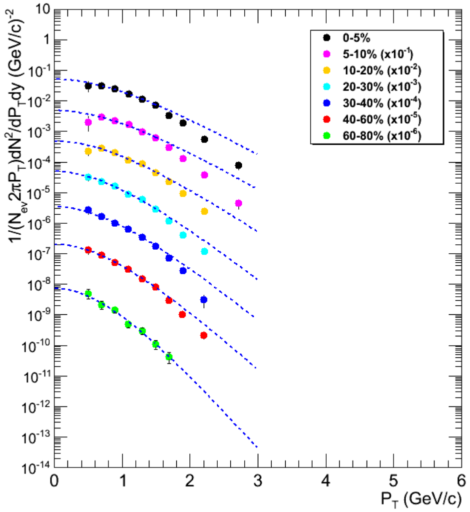
Spectra of strange particles K_S^0, Λ, Ξ



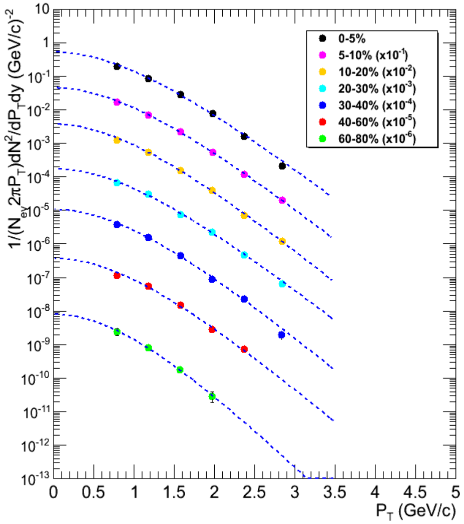
K_S^0 spectra, Au+Au 7.7 GeV



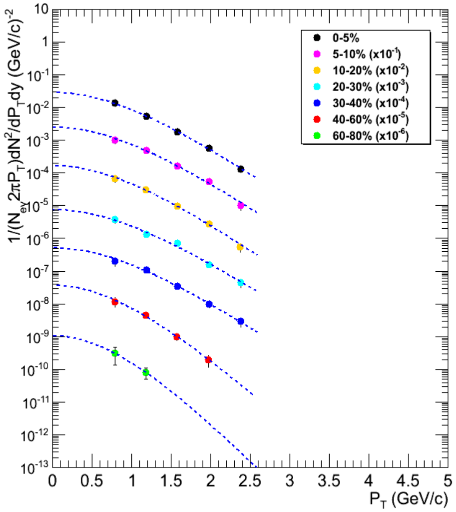
Λ spectra, Au+Au 7.7 GeV



$\overline{\Lambda}$ spectra, Au+Au 7.7 GeV



Ξ^- spectra, Au+Au 7.7 GeV



$\overline{\Xi}^+$ spectra, Au+Au 7.7 GeV

$\sqrt{s}$=7.7 GeV

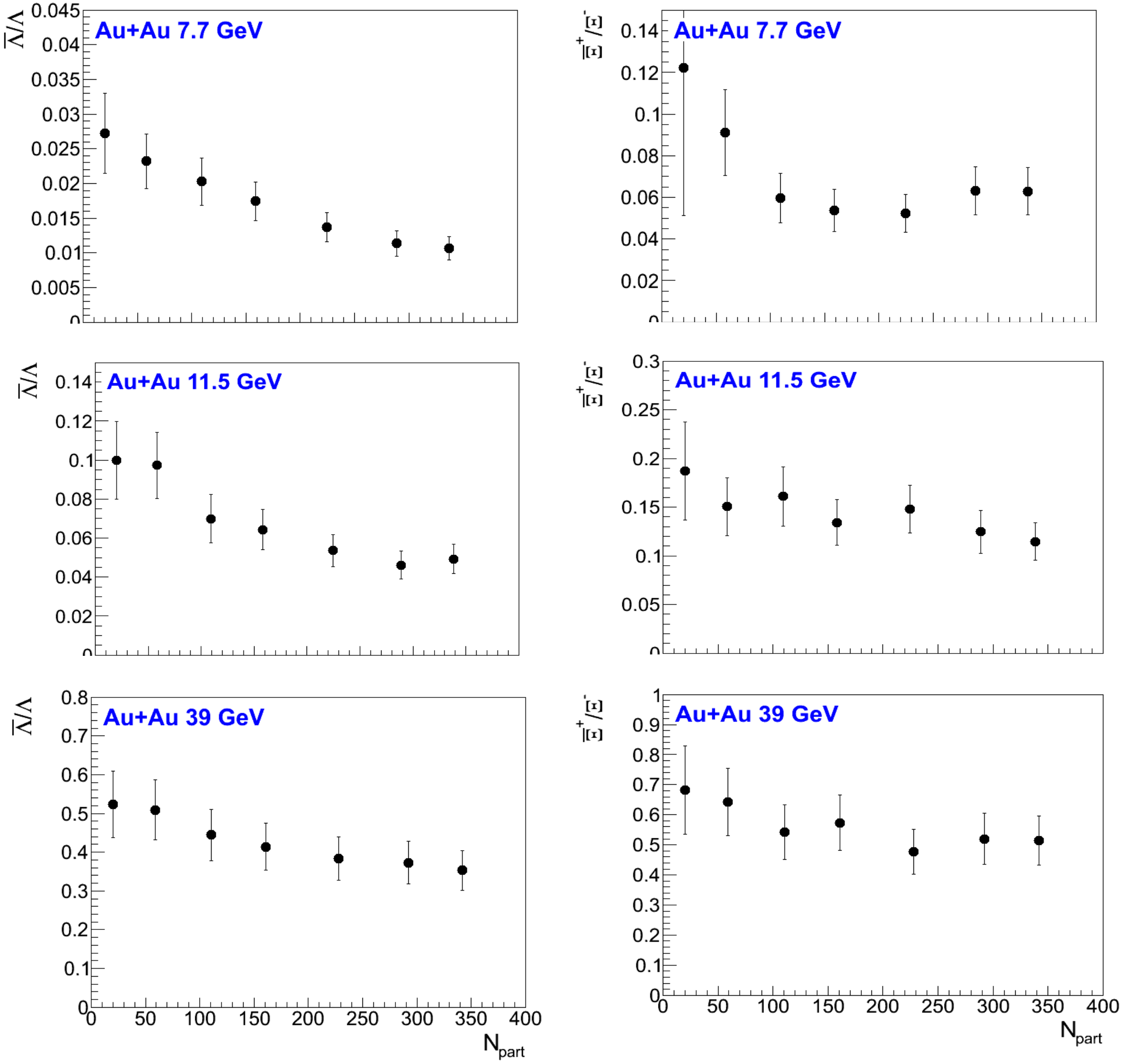
Λ spectra are weak decay feed-down corrected:

~ 11% for Λ

~ 35% for anti-Λ

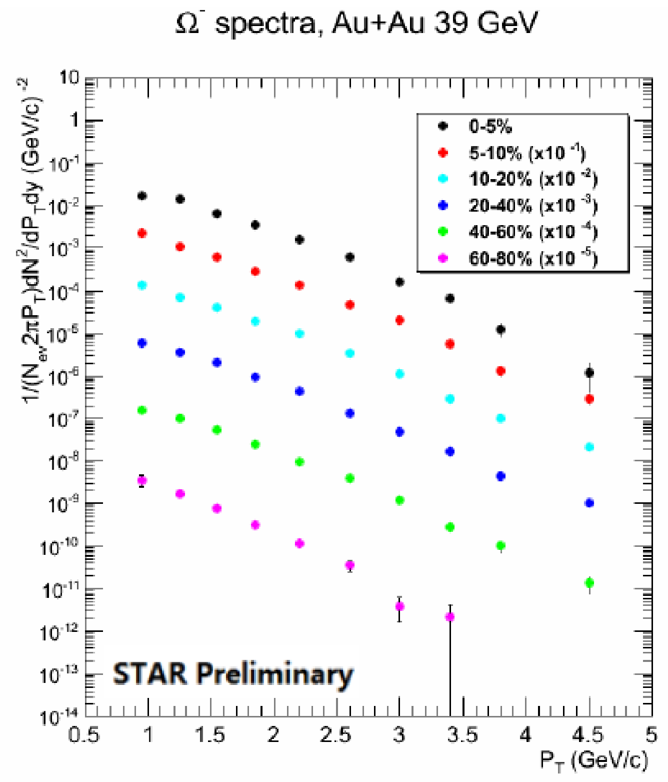
X.Zhu, CPOD 2011, November 7-11, 2011, China

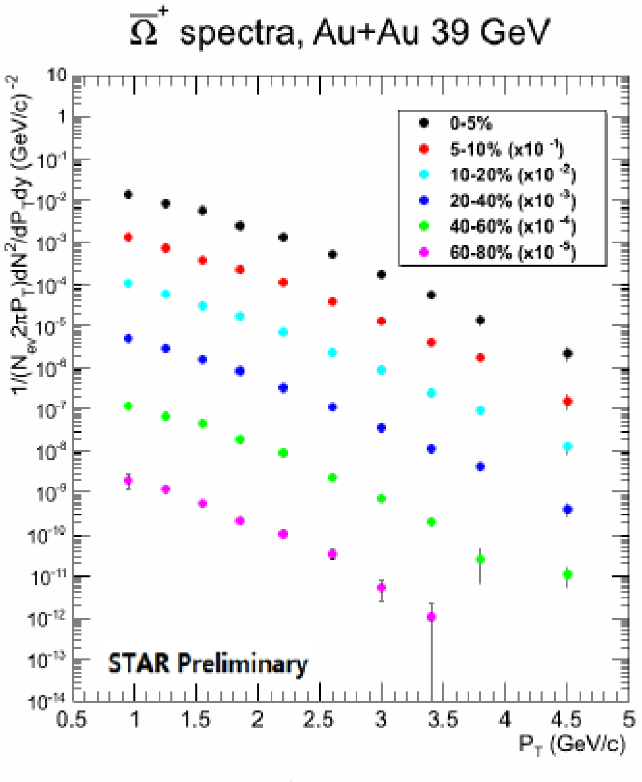
Anti-baryon to baryon ratio: $\bar{\Lambda}/\Lambda$, $\bar{\Xi}/\Xi$



- ➢ Ratio decreases with the increase of centrality.
- ➢ Ratio decreases with energy.
- ➢ Ratio increases with mass.

Spectra of strange baryons Ω, $\bar{\Omega}$





Strangeness vs. energy, centrality,…

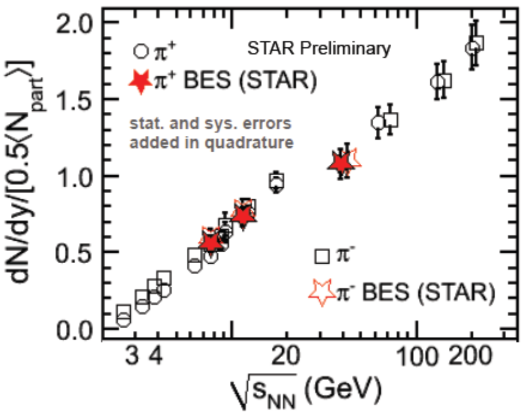
Dependence of signature of phase transition
near a Critical Point over a range $\sqrt{s_{NN}}$ = 7.7-39 GeV on flavor.

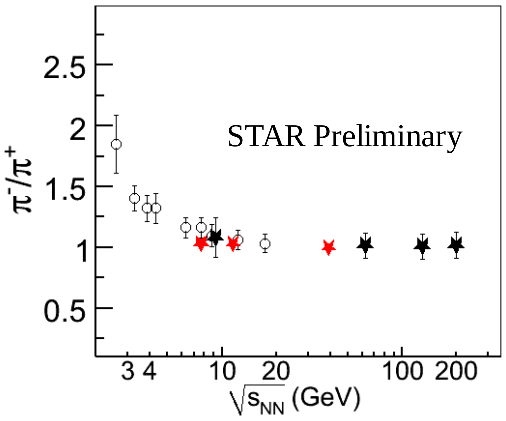
F.Zhao, APS, DNP, 2011, October 26-29, East Lansing, USA

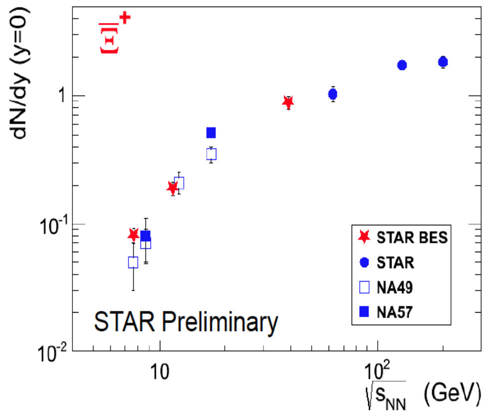
Comparison with other data

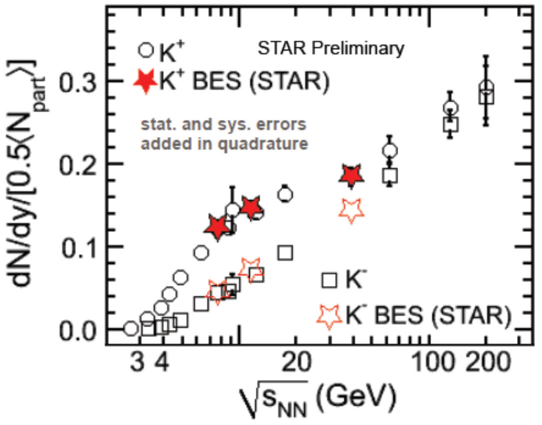
probing QCD phase diagram
with identified particles: π, φ, $K^{\pm}$, K_S^0, Λ, Ξ , Ω,…
in STAR BES program

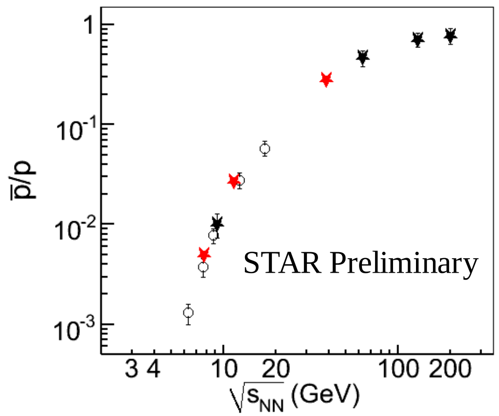
Spectra, particle ratios,... vs. energy, centrality

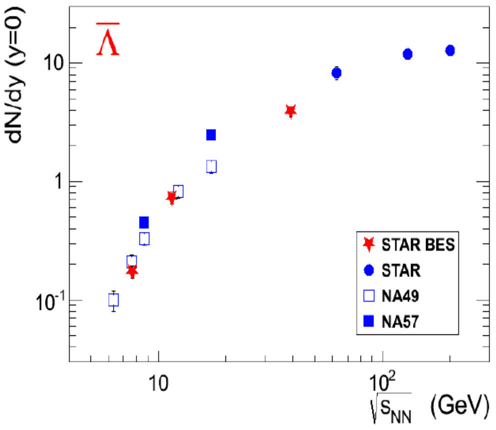








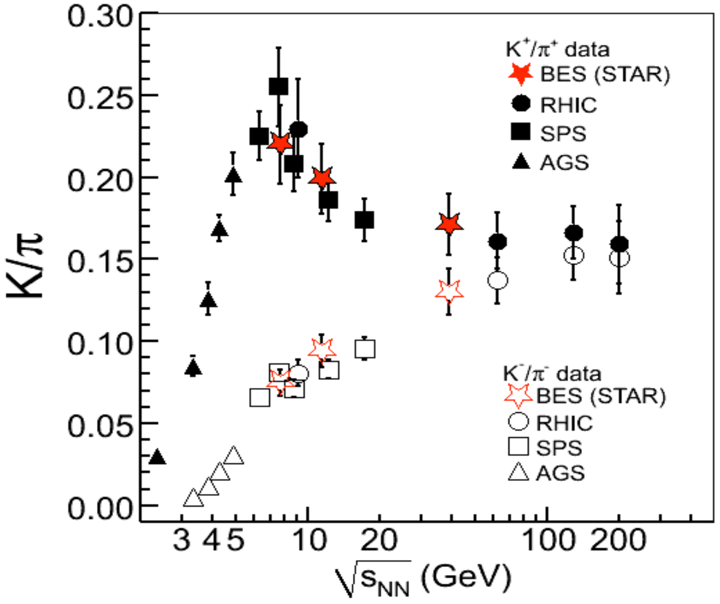


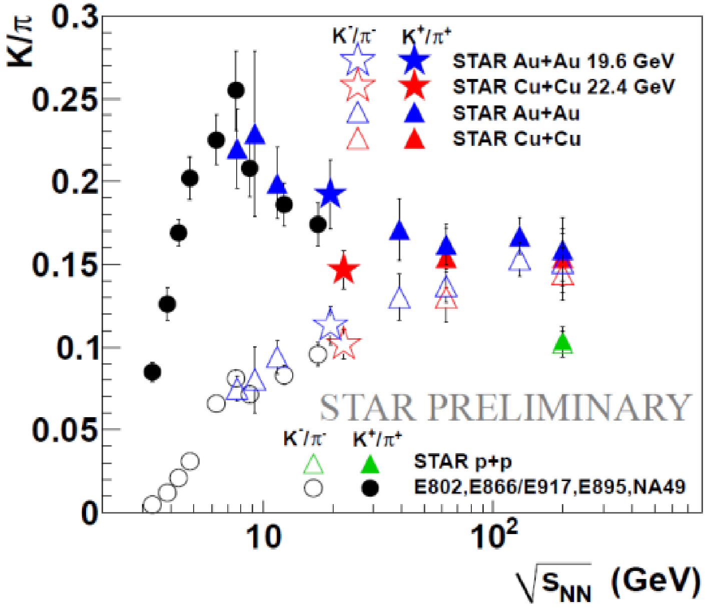


- General tendencies of new data are preserved
- Smooth dependencies are observed

A.Schmah, CPOD,Wuhan,China, Nov.2011
M.Mitrovski, EPIC@LHC, Bari, July, 2011
L. Kumar, ICPAQGP 2010

Ratio K/π vs. energy

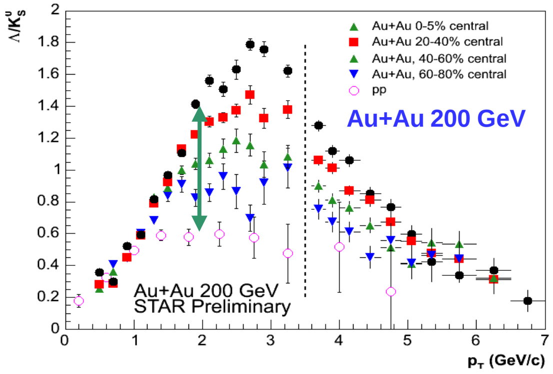


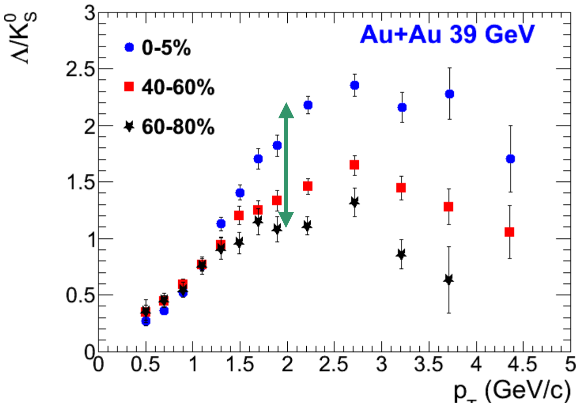


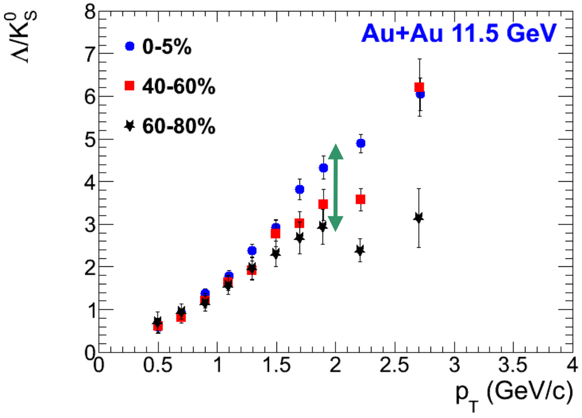
- ➢ Agreement with AGS, SPS data
- ➢ Enhanced K^+/π^+ in comparison with K^-/π^-

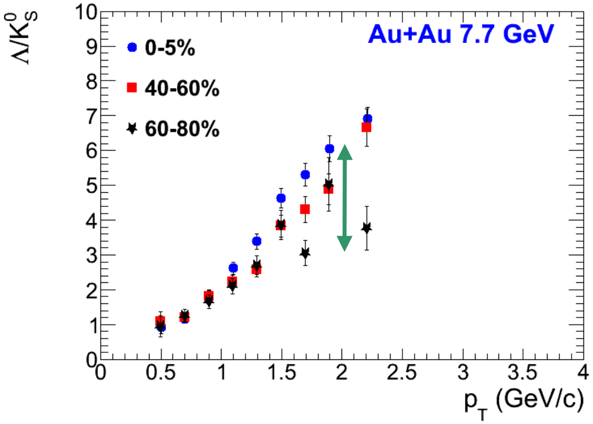
S.Kabana , SQM, September, 2011, Krakow, Poland

Λ/K^0_S ratio vs. energy and centrality





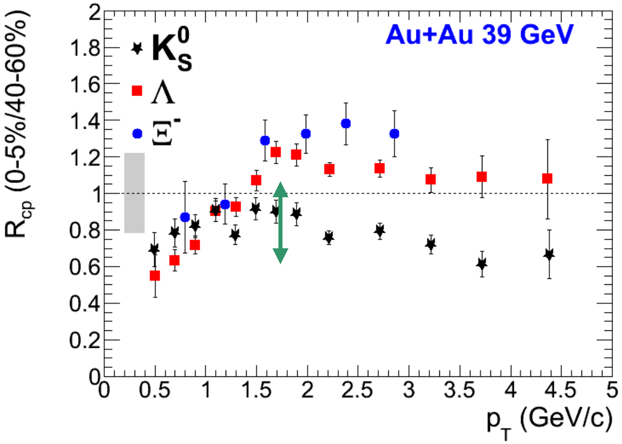


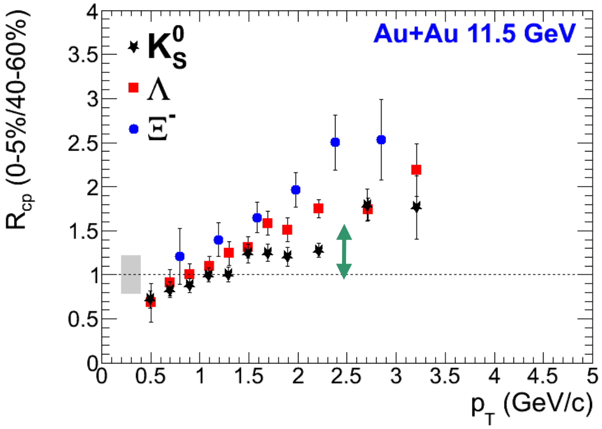


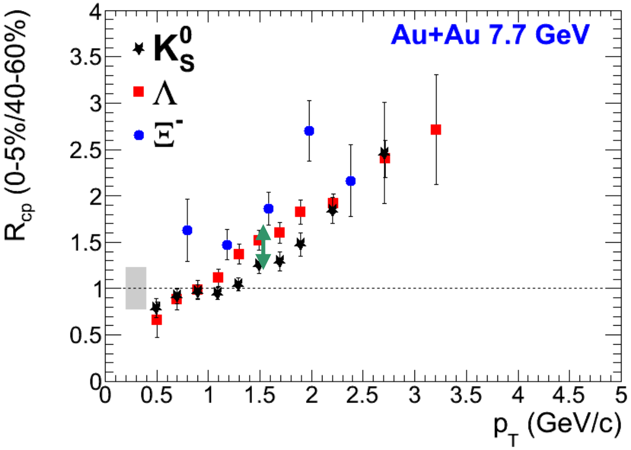
Ratio increases as the beam energy decreases.

X. Zhu, CPOD, November 7–11, 2011, China

R_{CP} ratio vs. energy and centrality





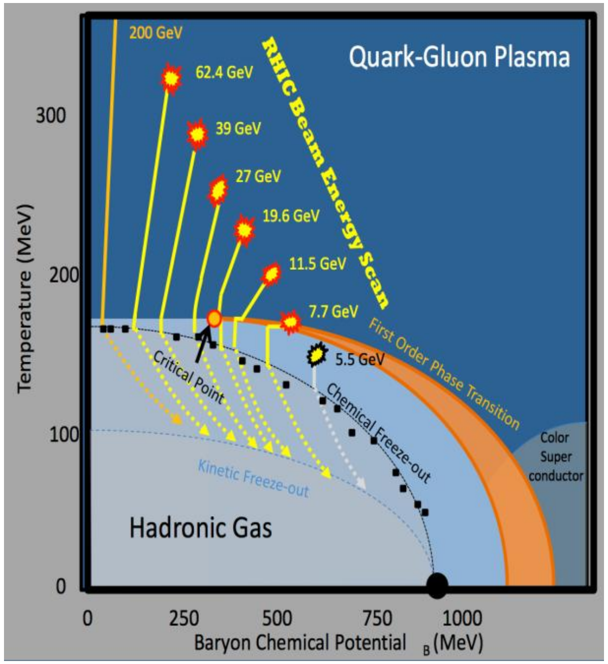


Baryon-meson splitting increases with energy.

Beam Energy Scan in AuAu collisions at RHIC

PHASE I – completed with huge success !

(7.7, 11.5, 19.6, 27, 39 and 39 GeV runs) + 62 & 200 GeV



$\sqrt{s_{NN}}$ (GeV)	Good events in Million MB
5.0	
7.7	4.3
11.5	11.7
19.6	35.8
27	70.4
39	130.4

+ ~ 67.3 M @ 62.4 GeV

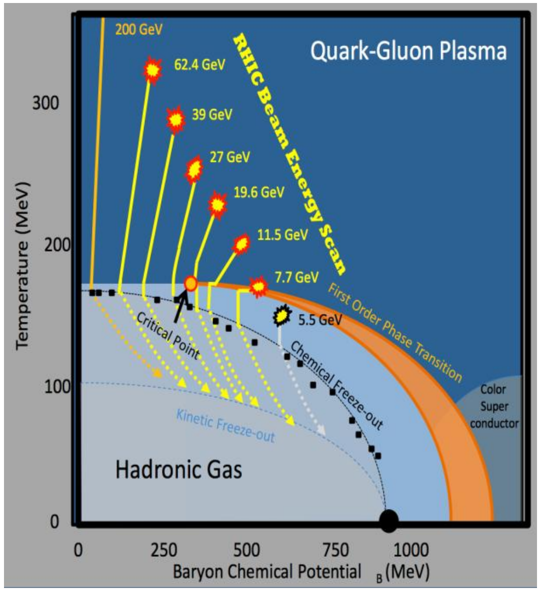
Extended μ_B range covered by RHIC :
20 ~ 400 MeV ($\sqrt{s_{NN}}$ = 200 - 7.7 GeV)

Conclusions

- Beam Energy Scan program in AuAu collisions at RHIC was reviewed.
- Experimental data and comparison with some models were presented.
- BES (I) data demonstrate a smooth behavior vs. energy and centrality.

No indications on discontinuity ⟶ more sophisticated analysis is required.

- High-p_T spectra of charged hadrons at $\sqrt{s_{NN}}$ =7.7, 11.5, 19.6, 27, 39 GeV are soon expected from BES (I) at RHIC.

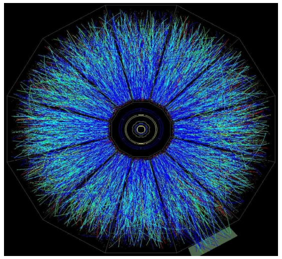


The obtained results may be of interest
in searching for a Critical Point
and signatures of phase transition
in hadron matter produced
at SPS, RHIC and LHC in present,
and FAIR & NICA in future.

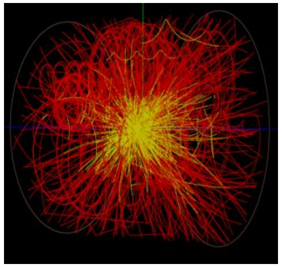
z-Scaling
&
Search for Signatures of Phase Transition and Critical Point

M. Tokarev

JINR, Dubna, Russia



Письма в ЭЧАЯ, 7 (2010) 271.
Phys.Part.Nucl.Lett., 8 (2011) 533.
Phys.At.Nucl., 75 (2012) 700.



in collaboration
with Yu.Panebratsev, I.Zborovský, A.Kechechyan,
A.Alakhverdyants, A.Aparin

BLTP, Seminar, 02.05.12, Dubna

Contents

Regularities in high energy interactions

Scaling variables

- $x_{Bj} = -q^2/2(Pq)$ Bjorken scaling
- $x_F = p^*_{||}/p^*_{||max}$ Feynman scaling
- $n/<n>$ Polyakov-Koba-Nielsen-Olesen scaling
- t,s,u Matveev-Muradyan-Tavkhelidze Brodsky-Farrar Quark Counting Rules

…..

- ➢ These scaling regularities have restricted range of validity.
- ➢ Violation of the scaling laws can be indication of new physics.

New regularity - z-Scaling
Universal description of inclusive particle cross sections over a wide kinematical region
(central+fragmentation region, $p_T > 0.5$ GeV/c, $s^{1/2} > 20$ GeV)

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

Scaling & Universality & Saturation

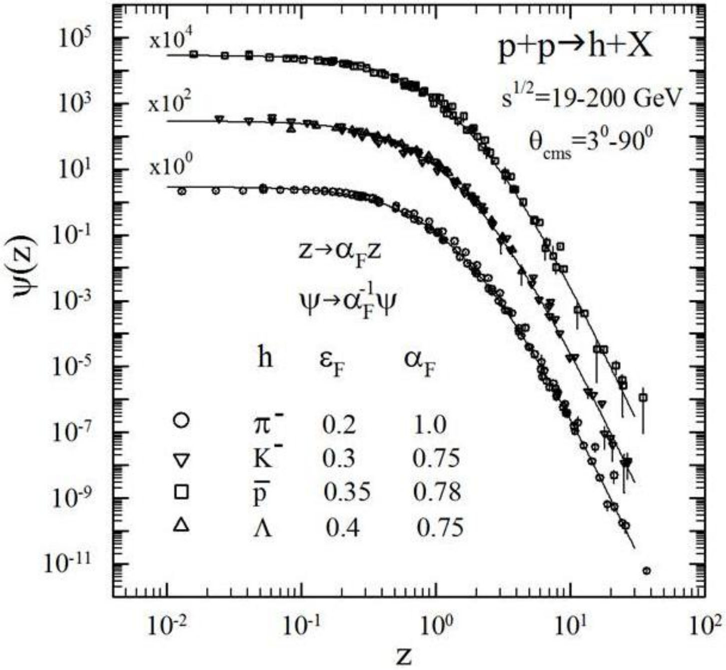
Inclusive cross sections of
π^-, K^-, $\bar{p}$, Λ
in pp collisions

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, Sp̄pS, SPS, HERA,
FNAL(fixed target),
Tevatron, RHIC, LHC

MT & I.Zborovsky
Phys.Rev.D75,094008(2007)
Int.J.Mod.Phys.A24,1417(2009)

- 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.
Scaled particle yield (Ψ) vs. scaled variable (z).
Universality classes – hadron species (ε_F, α_F).

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, …)

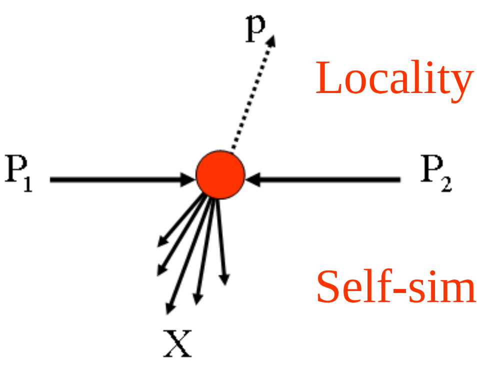
Analysis of AA experimental data obtained at RHIC & SPS to verify properties of z-scaling observed in pp & $\bar{p}p$ collisions at U70, ISR, S$\bar{p}p$S, SPS and Tevatron.

Estimation of constituent energy loss in central AA collisions vs. collision energy, centrality, transverse momentum over the range $\sqrt{s_{NN}} = 7.7\text{-}200$ GeV

Problem: Impurities and defects smear phase transition.
Low energy loss region is preferable for search for CP.

z-Scaling

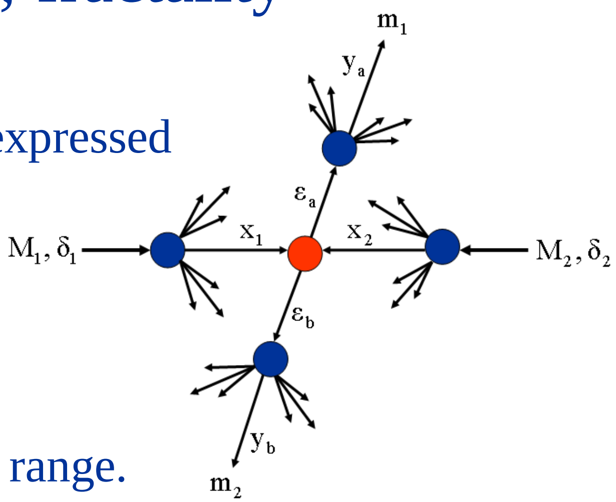
Principles: locality, self-similarity, fractality



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

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

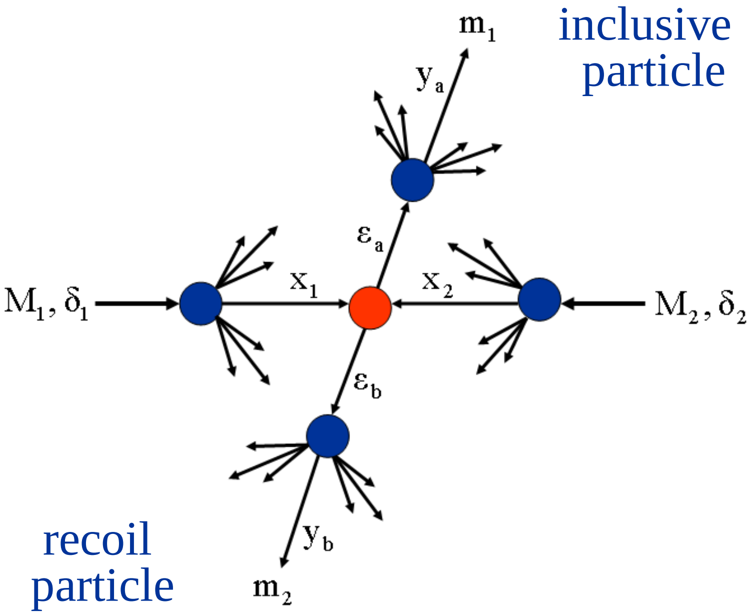
$Ed^3\sigma/dp^3$

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

$\Psi(z)$

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)



inclusive particle

colliding object

colliding object

recoil particle

Constituent subprocess

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

Kinematical condition (4-momentum conservation law):

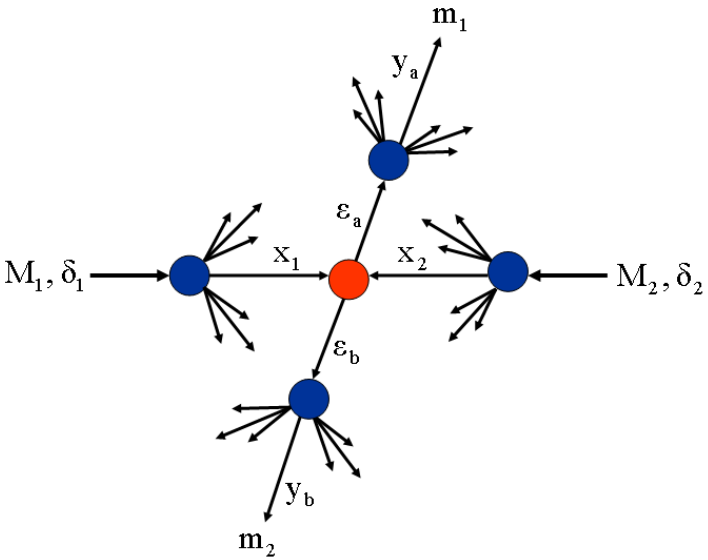
$$(x_1P_1+x_2P_2-p/y_a)^2 = M_X^2$$

Recoil mass: $M_X= x_1M_1+x_2M_2+m_2/y_b$

Self-similarity parameter z

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

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



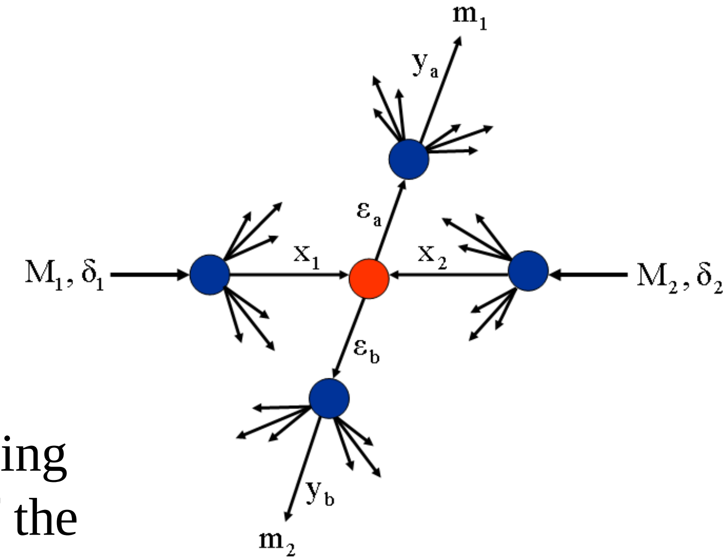
- Ω^{-1} is the minimal resolution at which a constituent subprocess can be singled out of the inclusive reaction
- $s_{\perp}^{1/2}$ is the transverse kinetic energy of the subprocess consumed on production of m_1 & m_2
- $dN_{ch}/d\eta|_0$ is the multiplicity density of charged particles at $\eta =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

Fractal measure z

The fractality is reflected in definition of z

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

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



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

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

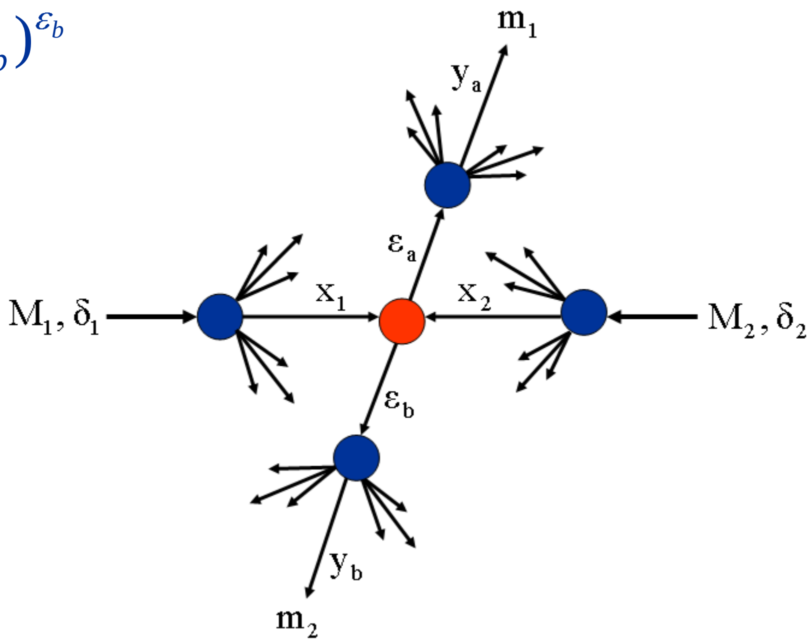
The fractal measure z diverges as the resolution Ω^{-1} increases.

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:

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

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



Momentum conservation law)

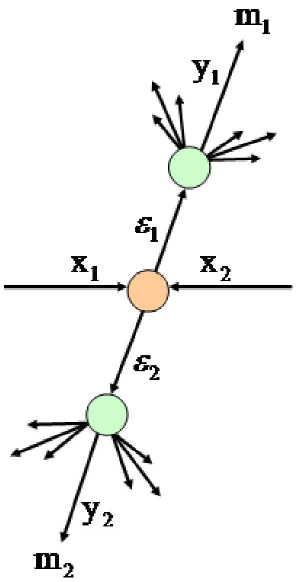
$$(x_1P_1+x_2P_2-p/y_a)^2 = M_X^2$$

Recoil mass

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

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

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



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

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

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

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

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

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

$$\mu_{1,2}^2 = \alpha^{\pm1}(\lambda_1\lambda_2 + \lambda_0)\frac{1-\lambda_{1,2}}{1-\lambda_{2,1}}$$

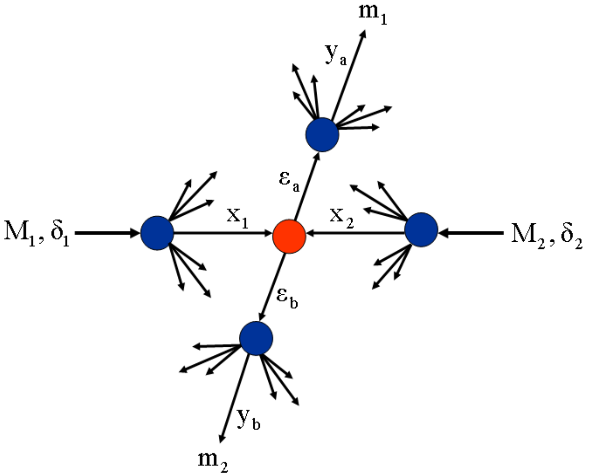
$$\lambda_0 = \bar{\nu}_0/y_2^2 - \nu_0/y_1^2$$

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

$$\boxed{s_\lambda = (\lambda_1P_1 + \lambda_2P_2)^2} \qquad \boxed{s_\chi = (\chi_1P_1 + \chi_2P_2)^2}$$

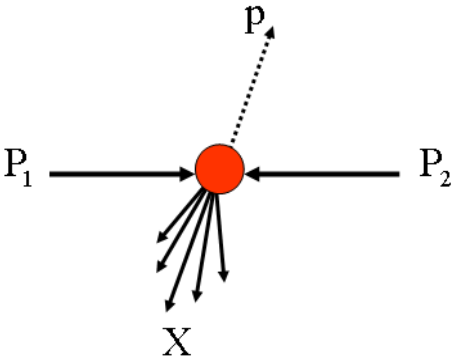
All dimensionless quantities are expressed via relativistic invariants.

Scaling function $\Psi(z)$



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

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



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

- ➢ 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)

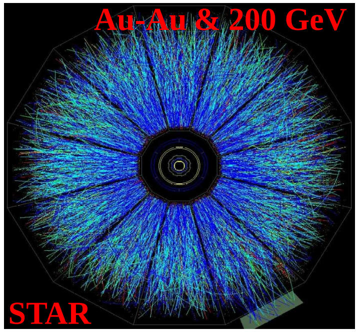
z-Scaling & Heavy Ion Collisions

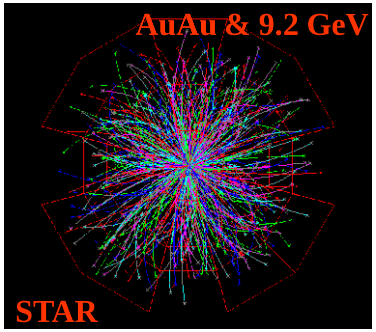
z-Scaling reflects self-similarity, locality and fractality
of particle production at a constituent level.
The variable z is a self-similarity parameter.

New tool in searching for signatures of new state of nuclear matter
created in HIC at high energy and high multiplicity density
(phase transition, critical point, QGP…)

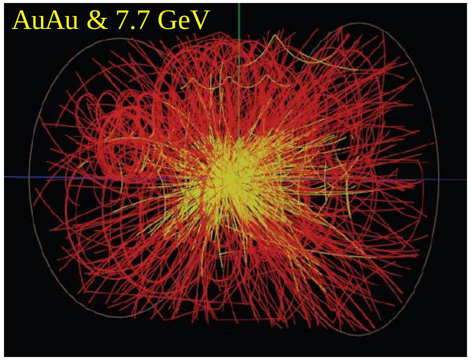
- Scaling in pp / $\bar{p}p$ collisions is a reference frame for AA collisions.
- Observed scaling features in AA are sensitive characteristics of nuclear matter and signatures of new medium created in HIC.
- Change of parameters of z-scaling can indicate a phase transition.

Analysis of experimental data on charged hadrons
produced in AuAu collisions at $\sqrt{s_{NN}} = 7.7\text{-}200$ GeV at RHIC
to search for CP & estimation of particle energy loss.





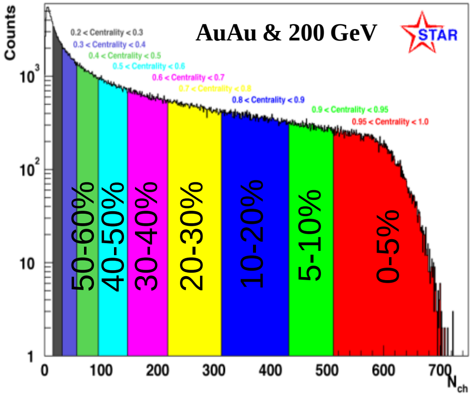
Self-similarity of hadron production in pp &AA collisions



M.Tokarev

Self-similarity parameter z in AA collisions

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



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 δ_A in pA collisions:

$\delta_A = A\delta$

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

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

$\delta_{A1}=A_1\delta$ & $\delta_{A2}=A_2\delta$ for AA collisions

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

JINR

Variable z & Entropy S

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

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

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

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

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

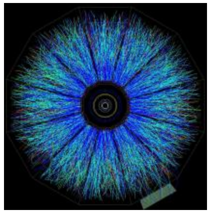
- relative number of such constituent configurations which contain the configuration $\{x_1, x_2, y_a, y_b\}$

Statistical entropy:

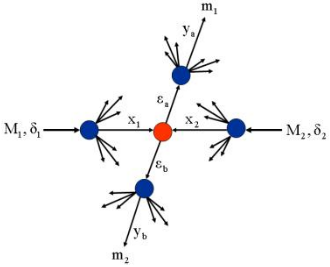
$$S = \ln W$$

Thermodynamical entropy for ideal gas:

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



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

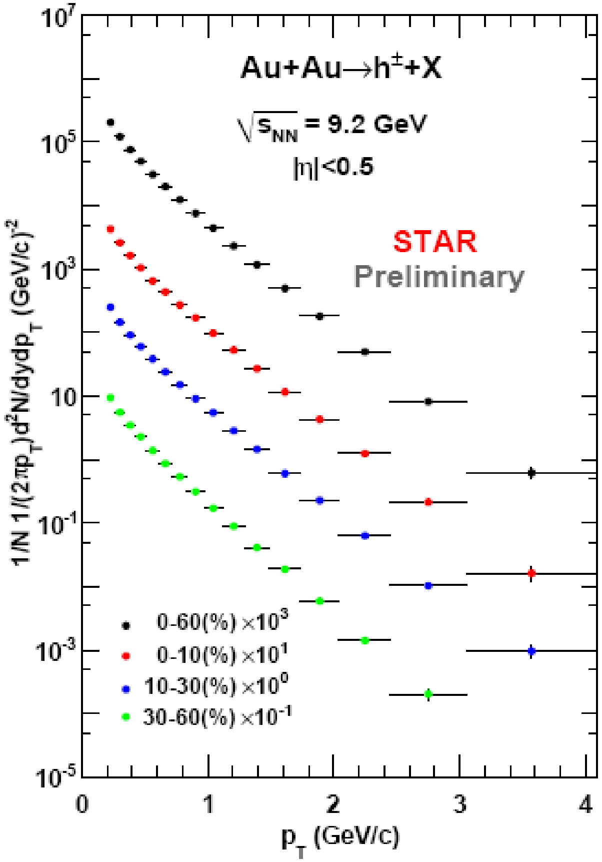


- $dN_{ch}/d\eta|_0$ characterizes "temperature" of the colliding system.
- Provided local equilibrium, $dN_{ch}/d\eta|_0 \sim T^3$ for high temperatures and small μ.
- c has meaning of a "specific heat" of the produced medium.
- Fractional exponents $\delta_1, \delta_2, \varepsilon$ are fractal dimensions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

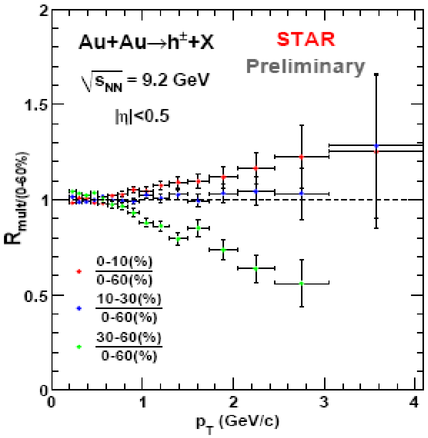
High-p_T Spectra of Charged Hadrons in Au+Au Collisions at $\sqrt{s_{NN}}$ = 9.2 GeV in STAR

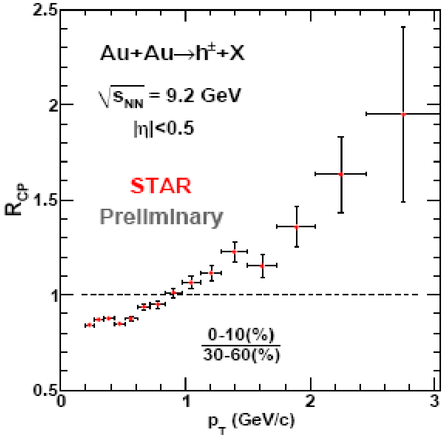
STAR test Run 2008



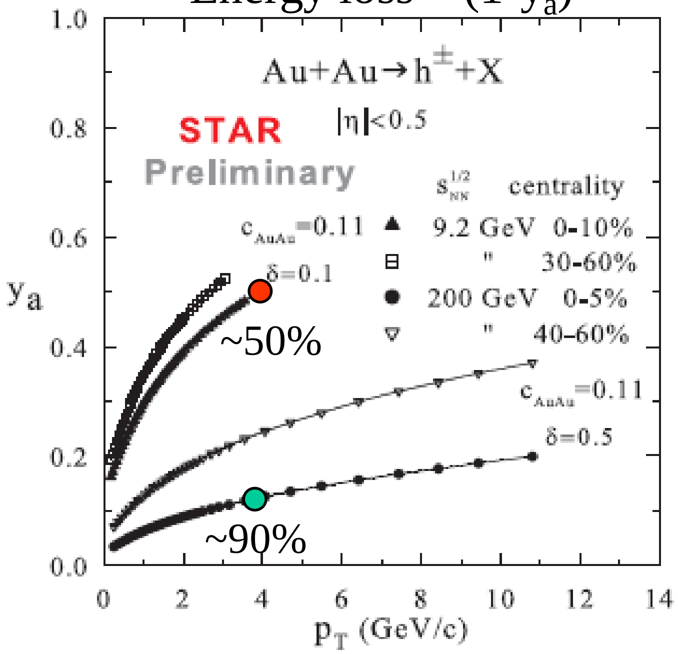
STAR: Phys. At. Nucl., 2011,
V.74, №5, p.769

STAR, PRC 81 (2010) 024911





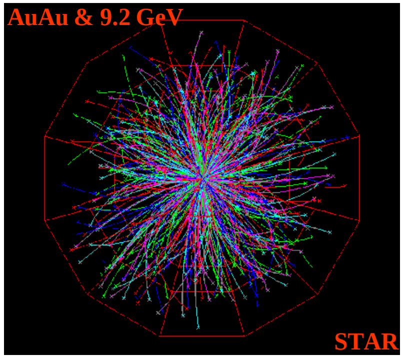
Energy loss ~ (1-y_a)



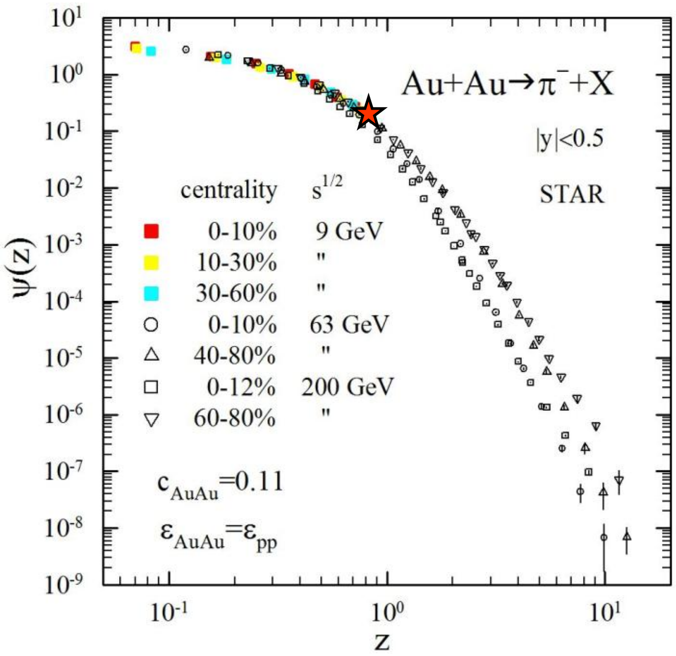
Data sample (2008)
~ 4000 events (!!!)

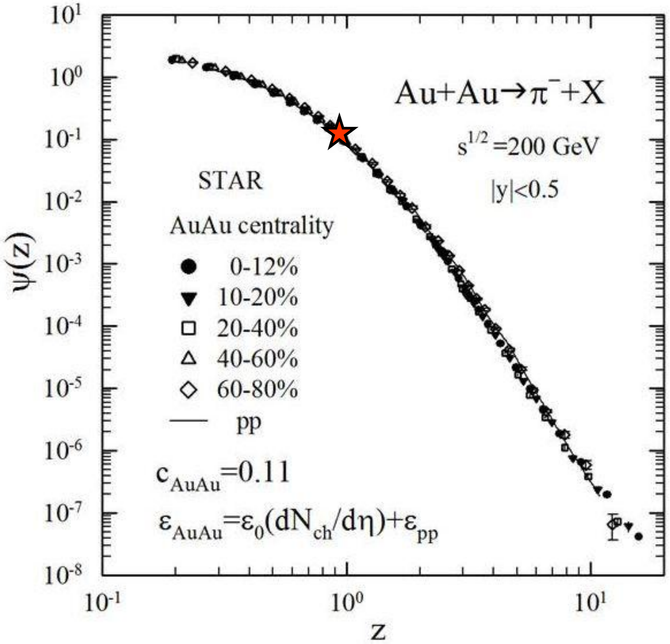
- High-p_T spectra vs. centrality
- R_{CP} ratio vs. p_T
- Energy loss vs. p_T, dN/dη

Energy scan of spectra in AuAu collisions



π^- in AuAu at 9.2 & 63, 200 GeV





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

STAR
PRC 81 (2010) 024911

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

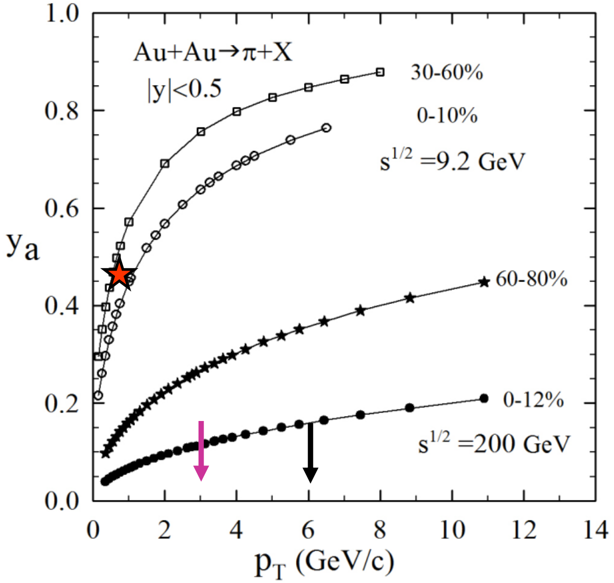
$$\Omega = (1-x_1)^{\delta_A}(1-x_2)^{\delta_A}(1-y_a)^{\varepsilon}(1-y_b)^{\varepsilon}$$

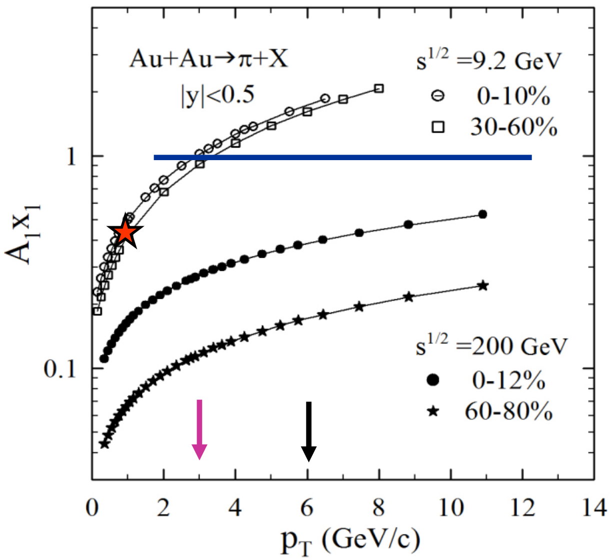
$$\delta_A = A\delta$$

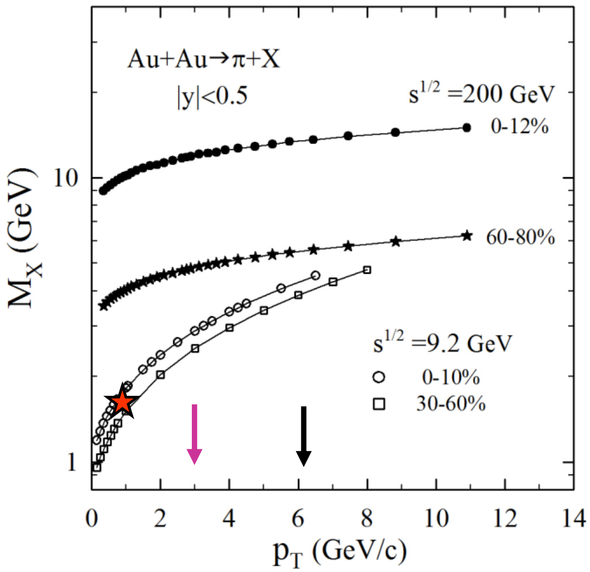
- Saturation of $\Psi(z)$ for $z<0.1$
- Power law for $z > 4$
- Centrality dependence of $\Psi(z)$ at high z
- Fractal dimension ε depends on centrality
- Spectra at high p_T are sensitive to c-δ correlation

Energy losses ~(1-y_a) vs. energy, centrality, p_T

π^- in AuAu at 9.2 & 200 GeV







- y_a increases with p_T ⇒ energy losses decreases with p_T
- y_a decreases with centrality ⇒ energy losses increase with centrality
- x_1 is independent of centrality at 9.2 GeV
- M_X increases with p_T, $\sqrt{s_{NN}}$ and centrality

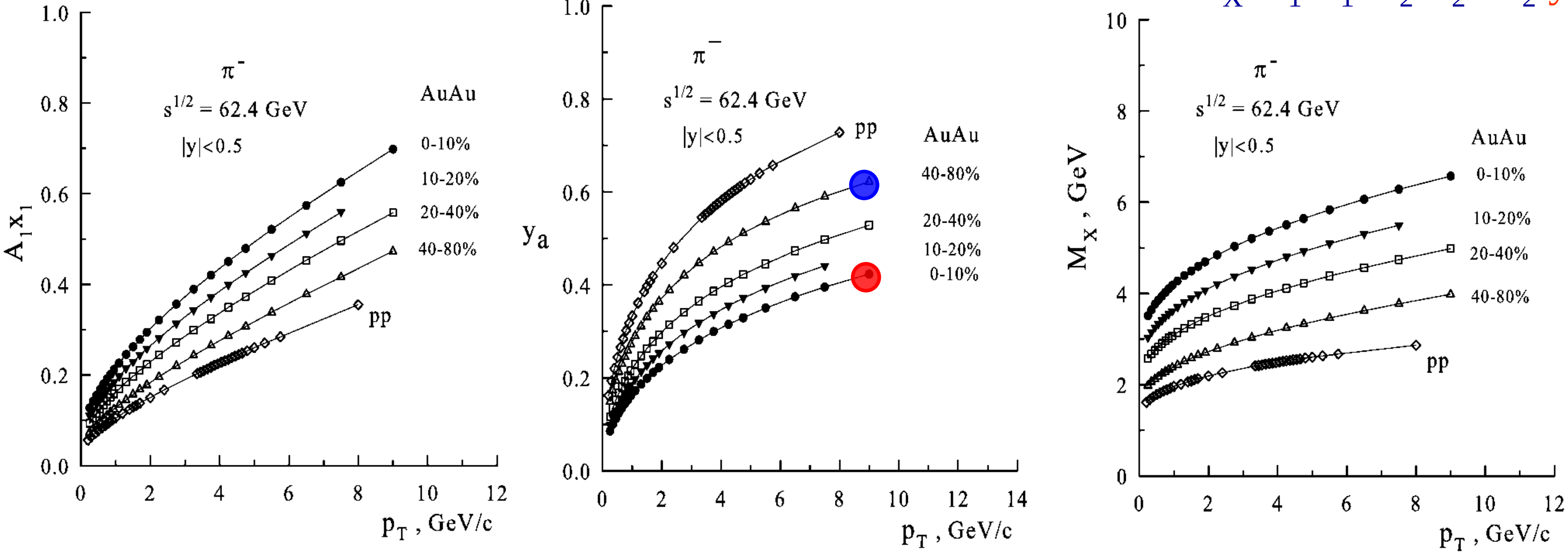
Smaller energy losses ⇒ better localization of a Critical Point

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

Momentum fractions x_1 , y_a & recoil mass M_X

STAR π^- in AuAu at 62.4 GeV

$M_X=x_1M_1+x_2M_2+m_2/y_b$



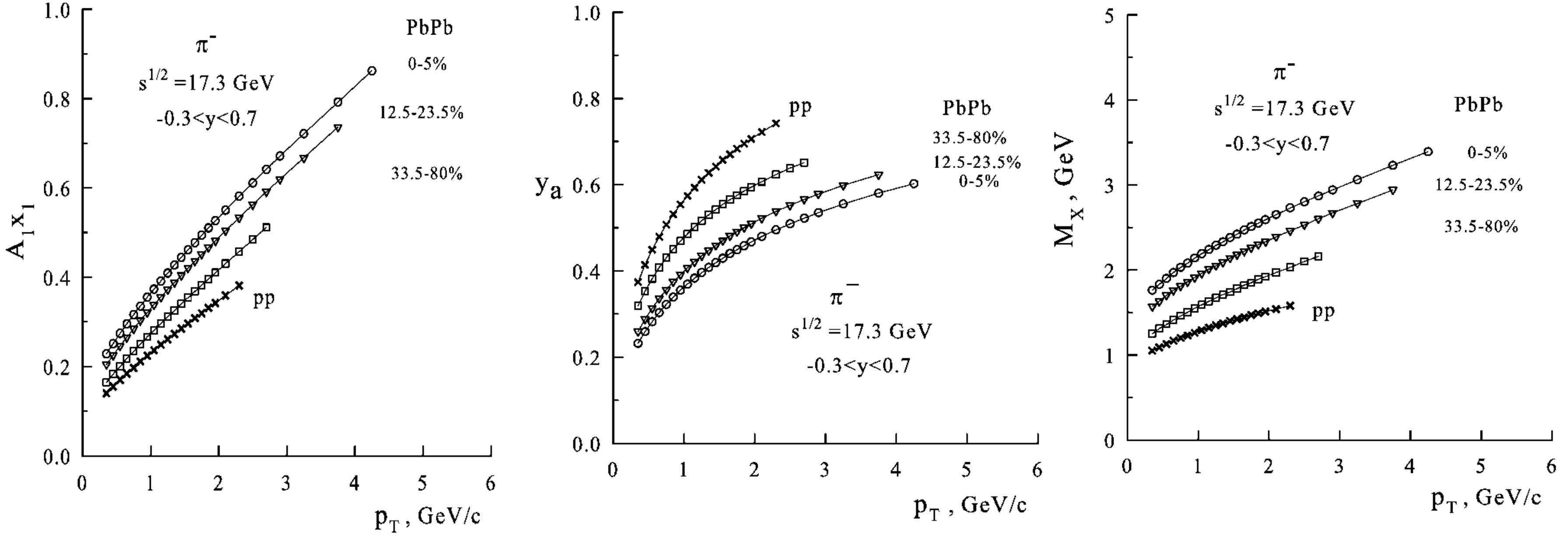
- p_T dependence of x_1 is dependent of centrality
- y_a increases with p_T ⇒ energy losses decrease with p_T
- y_a decreases with centrality ⇒ energy losses increase with centrality
- M_X increases with p_T, $s^{1/2}$ and centrality

Momentum fractions x_1, y_a & recoil mass M_X

NA49

π^- in PbPb at 17.3 GeV

$M_X=x_1M_1+x_2M_2+m_2/y_b$



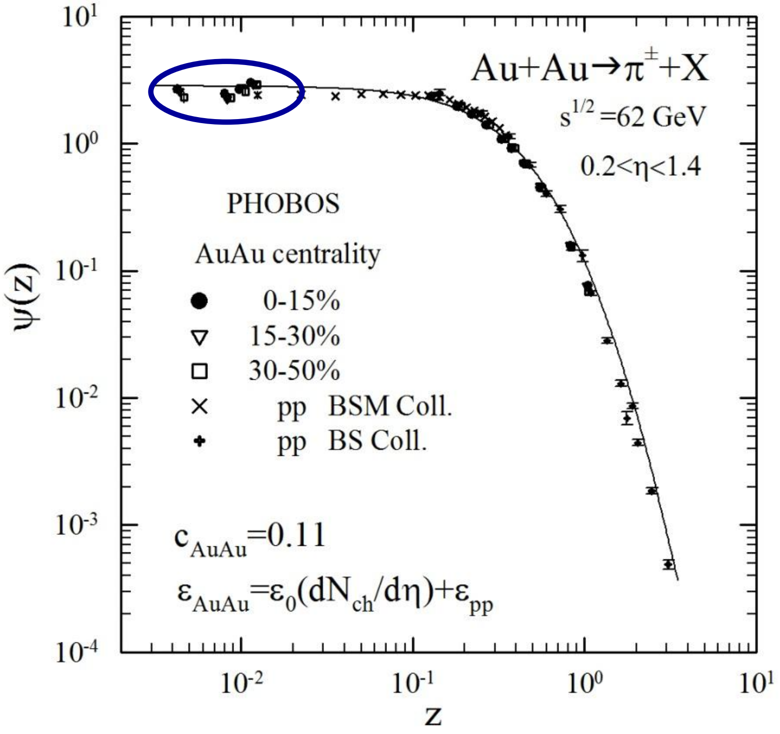
- p_T dependence of x_1 is dependent of centrality
- y_a increases with p_T ⇒ energy losses decrease with p_T
- y_a decreases with centrality ⇒ energy losses increase with centrality
- M_X increases with p_T, $s^{1/2}$ and centrality

Saturation of $\Psi(z)$ at low z in AuAu collisions

PHOBOS:
PRC 75 (2007) 024910

ISR:
NPB 100 (1975) 237
PLB 64 (1976) 111 (low p_T)

π in pp & AuAu collisions



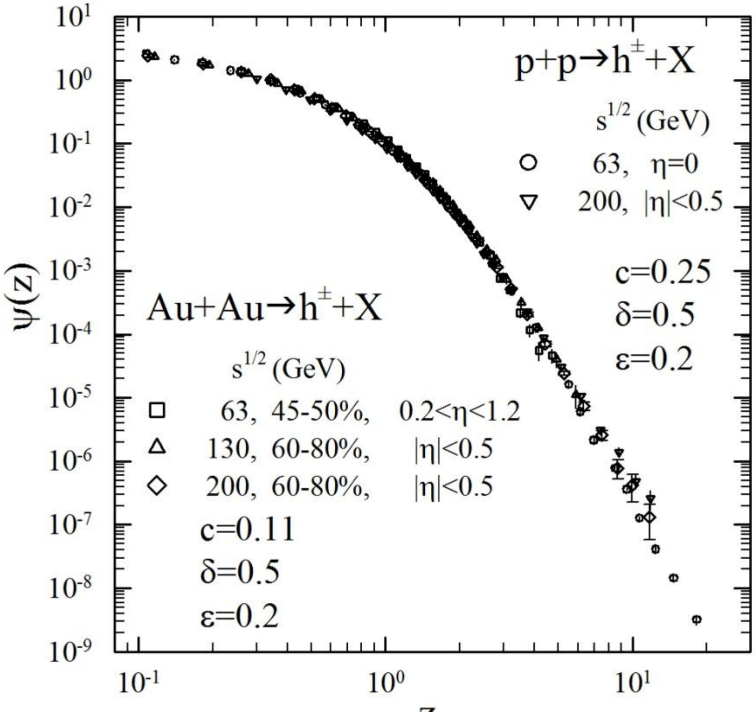
$$z \cong \frac{s_{\perp}^{1/2}}{(dN_{ch}/d\eta|_0)^c}$$

at low z (low p_T)

- The saturation of $\Psi(z)$ in AuAu for z<0.1
- The centrality (multiplicity) independence of $\Psi(z)$ in AuAu
- Restoration of the shape of $\Psi(z)$ over a wide z-range

Self-similarity in peripheral AuAu collisions

Charged hadrons in pp & AA @ 63, 130, 200 GeV



ISR: NPB 208 (1982)1

STAR: PRL 89 (2002) 202301;
PRL 91 (2003) 172302

PHOBOS: PRL 94 (2005) 082304

pp collisions:

$dN_{ch}/d\eta|_0$ for non-single-diffractive events

AA collisions:

$dN_{ch}/d\eta|_0$ for corresponding AA centrality

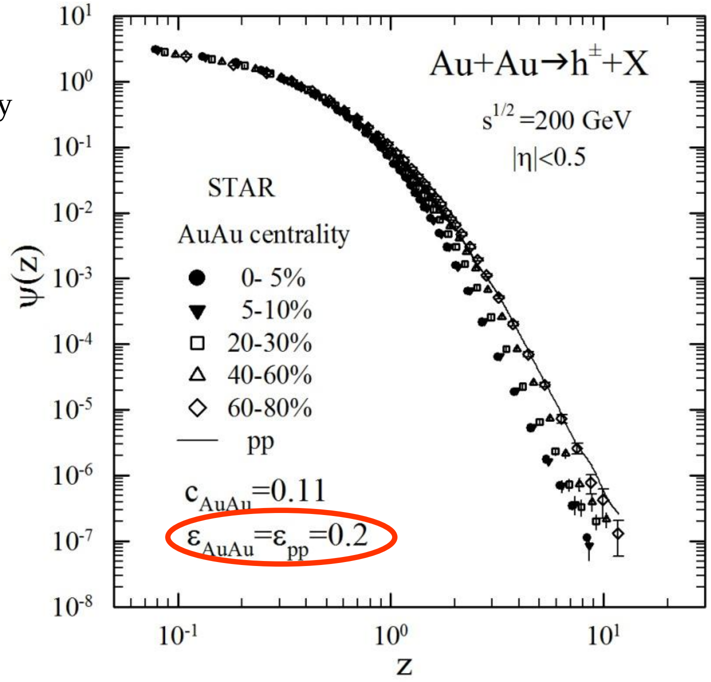
- The energy independence of Ψ(z) in peripheral AuAu
- The same shape of Ψ(z) for pp & peripheral AuAu
- “Specific heat” $c_{AuAu}= 0.11 < c_{pp}= 0.25$
- The same ε in pp & peripheral AuAu

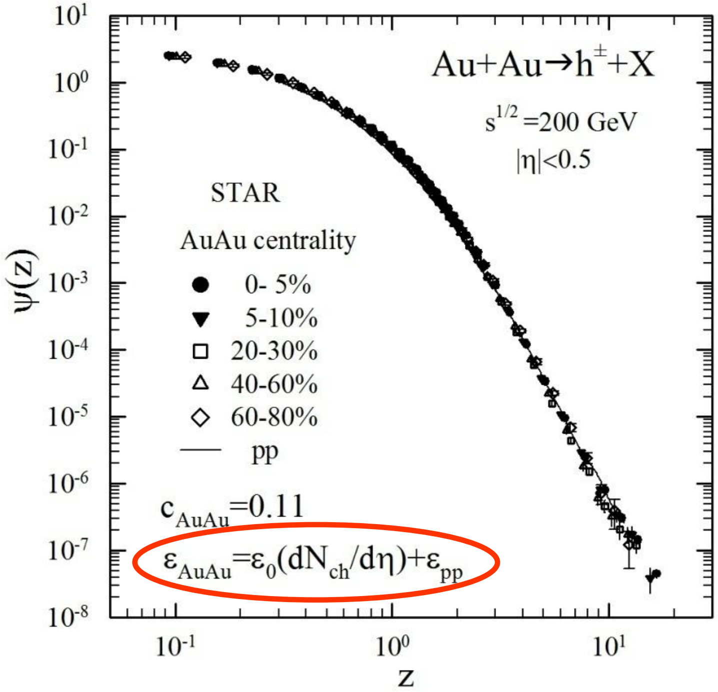
Multiplicity dependence of fragmentation dimension ε_{AA}

Charged hadrons in central AuAu collisions at 200 GeV

STAR: PRL 91 (2003) 172302

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





Centrality dependence (decrease)
of Ψ(z) in central AuAu collisions
for $\varepsilon_{AuAu} = \varepsilon_{pp}$

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

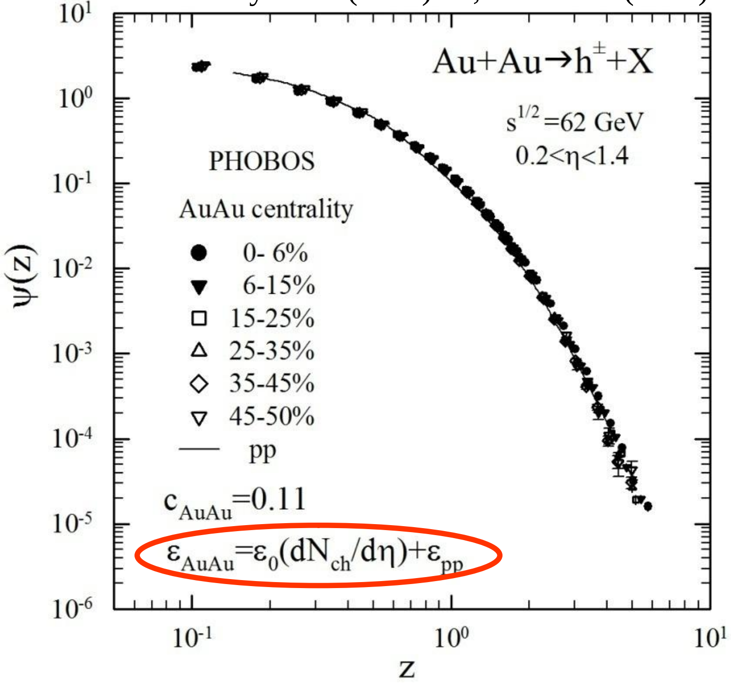
Multiplicity dependence of fragmentation process in HIC

Self-similarity in AuAu collisions

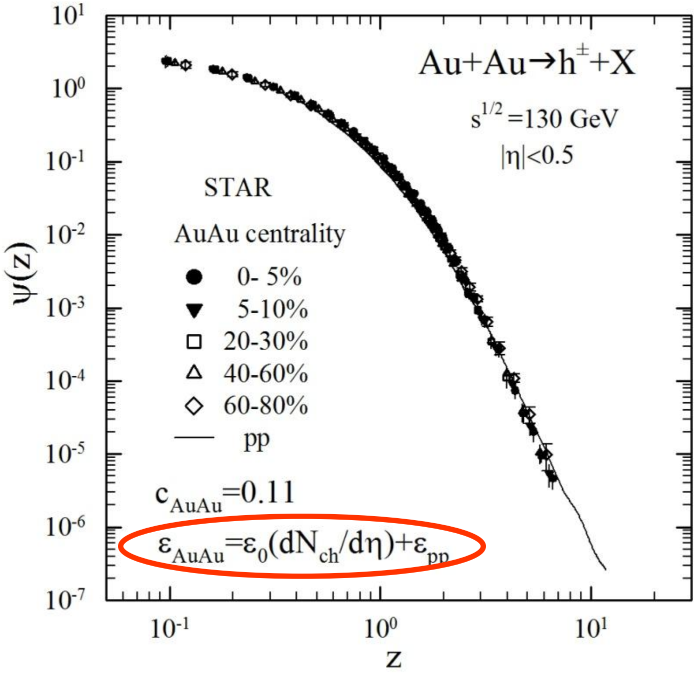
Charged hadrons in pp & AuAu @ 62, 130 GeV

PHOBOS: PRL 94 (2005) 082304

ISR: Z.Phys.C69 (1995) 55; NPB 208 (1982)1



STAR: PRL 89 (2002) 202301; PRL 91 (2003) 172302



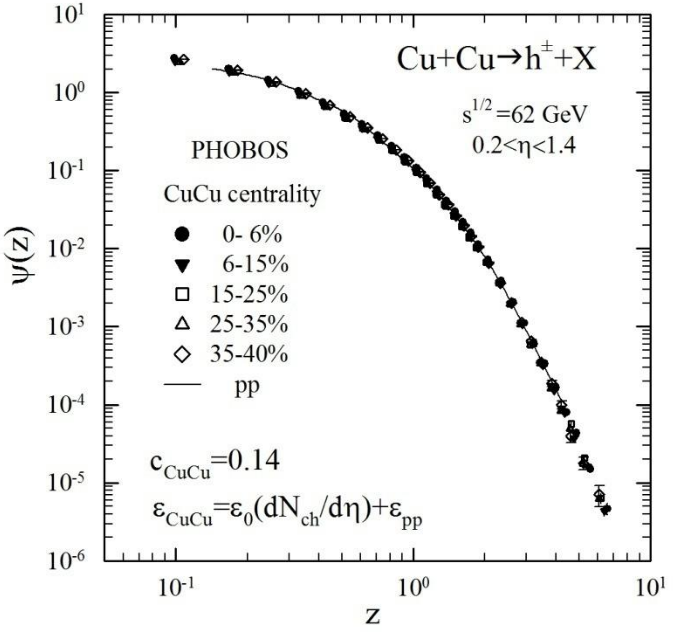
- The same Ψ(z) in AuAu & pp for ε_{AuAu} is dependent of AuAu multiplicity
- "Specific heat" c_{AuAu}=0.11 (constant with $s^{1/2}$)
- ε_0 increases with $s^{1/2}$: ε_0(62GeV)=0.0018 < ε_0(130GeV)=0.0022< ε_0(200GeV)=0.0028

Restoration of self-similarity in central AuAu collisions

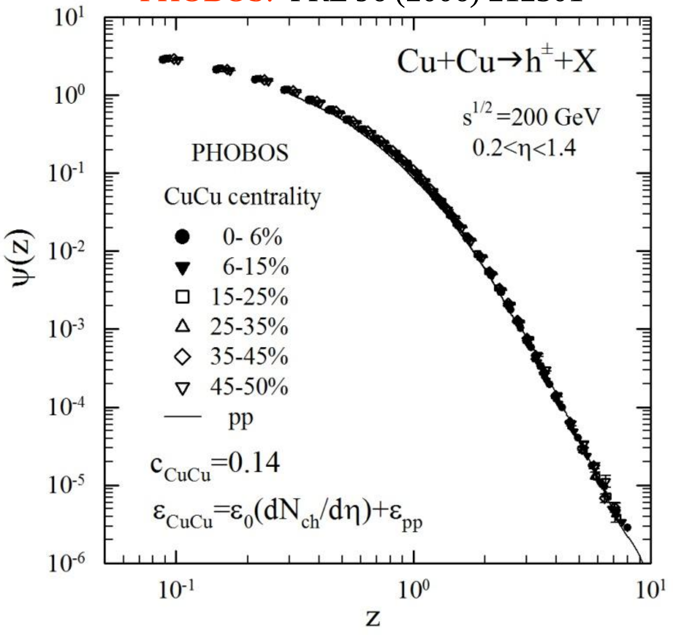
Self-similarity in CuCu collisions

Charged hadrons in pp & CuCu @ 62, 200 GeV

ISR: Z.Phys.C69 (1995) 55; NPB 208 (1982) 1



PHOBOS: PRL 96 (2006) 212301



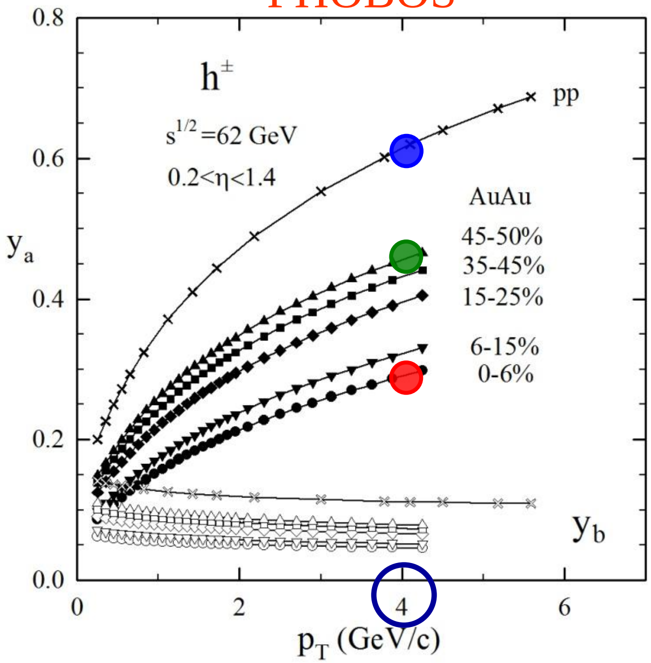
- The same Ψ(z) in CuCu & pp for ε_{CuCu} is dependent of CuCu multiplicity
- "Specific heat" c_{CuCu}=0.14 is independent of $s^{1/2}$
- ε_0 increases with $s^{1/2}$: ε_0(62GeV) =0.005< ε_0(200GeV) =0.008 (CuCu)

Restoration of self-similarity in central CuCu collisions

Energy losses in pp & AuAu

Energy loss ~ $(1-y_a)$

PHOBOS

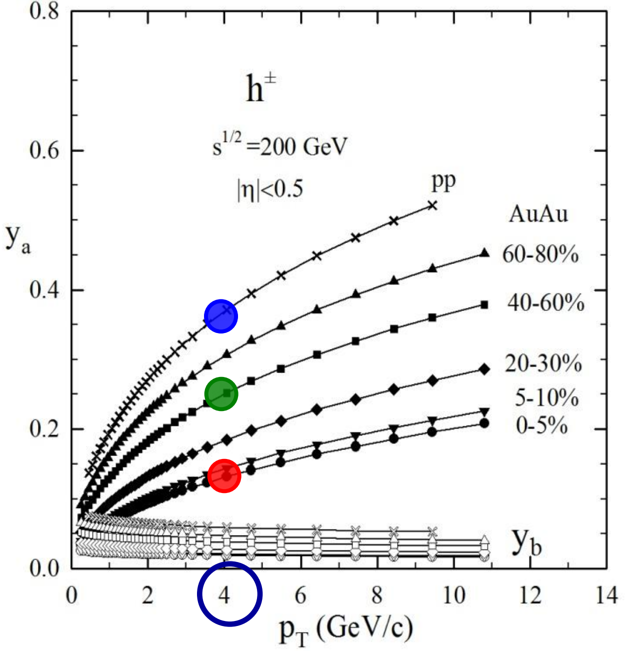


40%
energy loss
$q = 6.6$ GeV

55%
energy loss
$q = 8.8$ GeV

75%
energy loss
$q = 16$ GeV

STAR



65%
energy loss
$q=11.4$GeV

75%
energy loss
$q = 16$ GeV

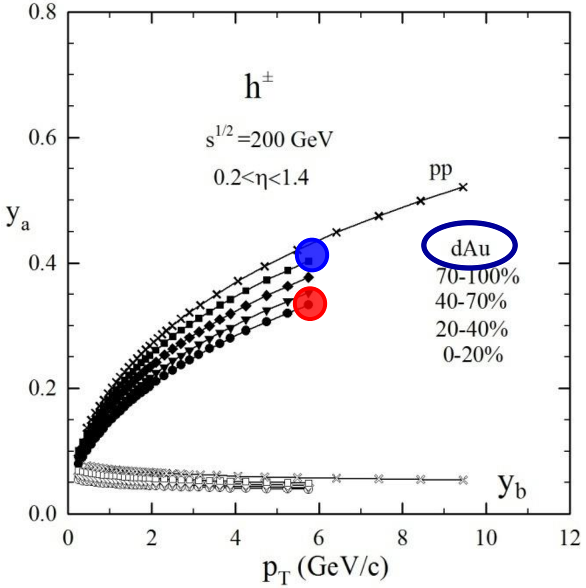
90%
energy loss
$q = 40$ GeV

- 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 $p_T \Rightarrow$ 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

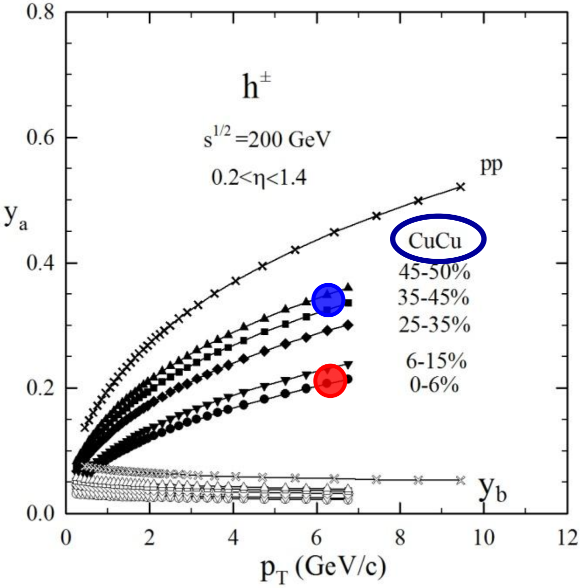
Energy losses in dAu, CuCu, AuAu @ 200 GeV

Energy loss ~ (1-y_a)

PHOBOS



PHOBOS



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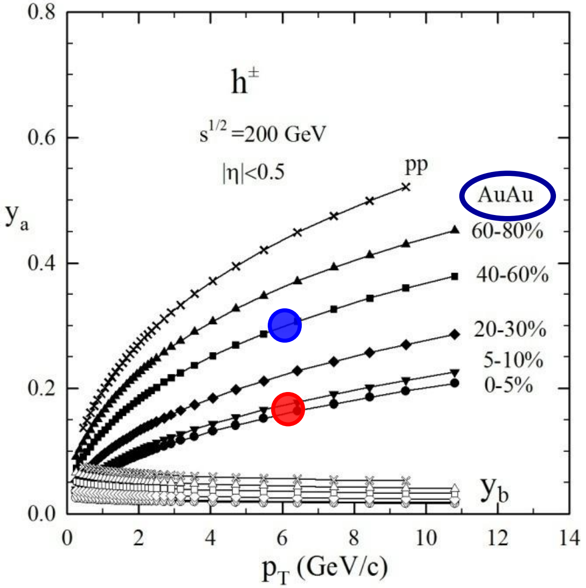
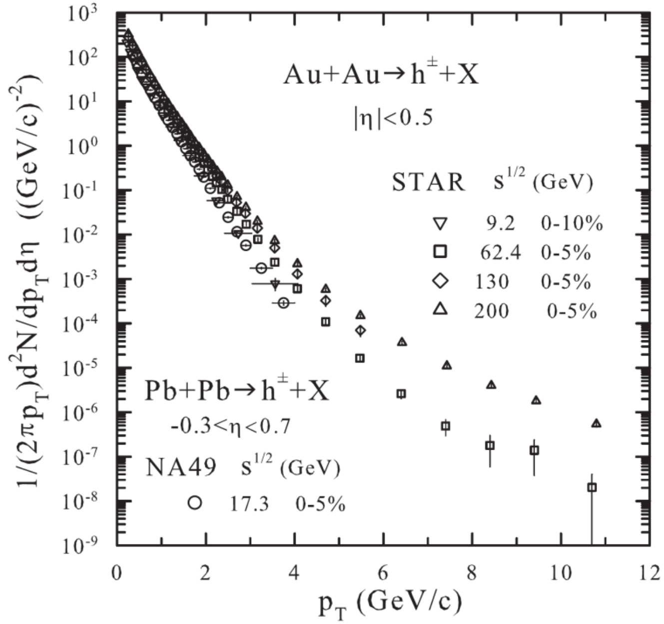


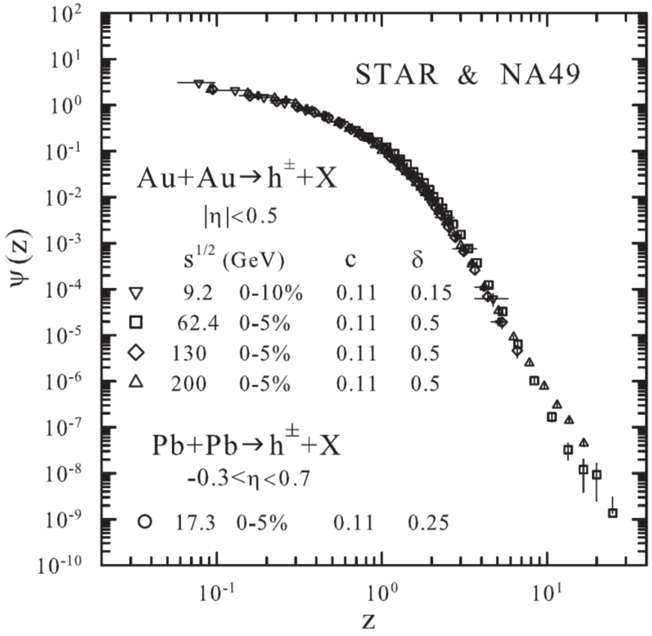
- y_a increases with $p_T \Rightarrow$ energy losses decrease with p_T
- y_a decreases with $s^{1/2} \Rightarrow$ energy losses increase with $s^{1/2}$
- y_a decreases as centrality increases $\Rightarrow$ energy losses increase with centrality
- y_b is flat with $p_T \Rightarrow$ week dependence of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

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: $\sqrt{s_{NN}}$ = 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) depends on centrality

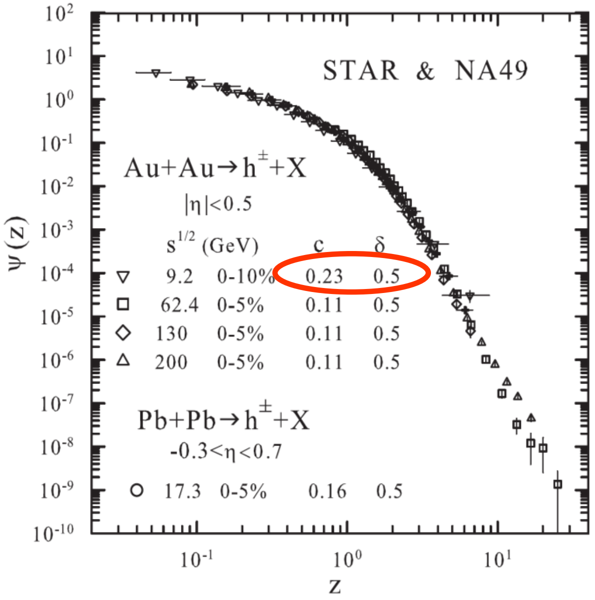
Change of the parameters c, δ, ε ⇒ indication on new properties of matter

Discontinuity of the parameters c, δ, ε ⇒ indication of existence of CP

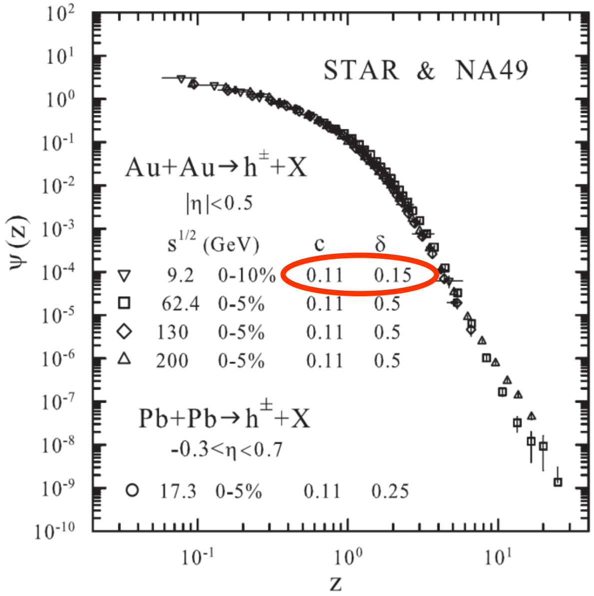
Charged hadrons in central AuAu collisions

Spectra in z presentation - two scenarios

I Large specific heat c & large δ



II Small specific heat c & small δ



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

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

$$\delta_A = A\delta$$

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

Energy losses in AuAu collisions ~ (1-y_a)

Momentum fractions y_a, y_b in different scenarios

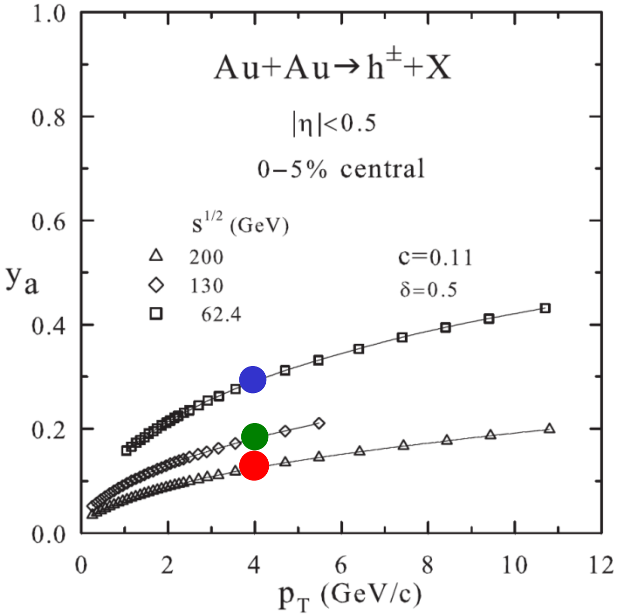
I Large specific heat c & large δ : c=0.23, δ=0.5

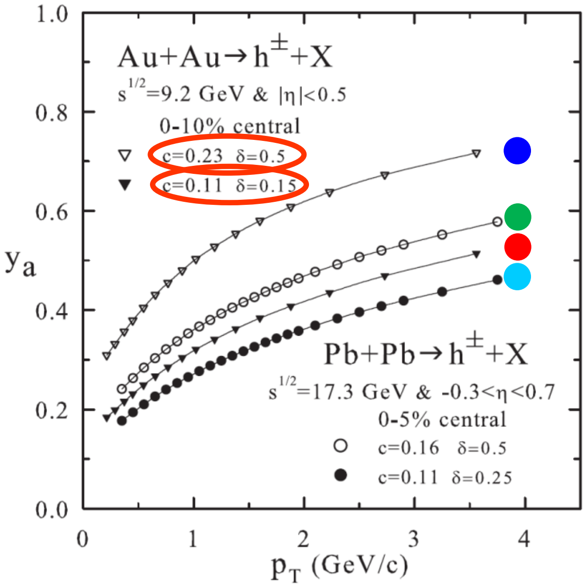
II Small specific heat c & small δ : c=0.11, δ=0.11

70%
energy loss
q ≈ 5.7 GeV

82%
energy loss
q ≈ 22 GeV

89%
energy loss
q ≈ 36 GeV





28%
energy loss
q ≈ 5.6 GeV

40%
energy loss
q ≈ 6.7 GeV

45%
energy loss
q ≈ 7.3 GeV

55%
energy loss
q ≈ 8.9 GeV

- y_a increases with $p_T \Rightarrow$ energy losses decrease with p_T
- y_a decreases with $\sqrt{s_{NN}} \Rightarrow$ energy losses increase with $\sqrt{s_{NN}}$
- 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

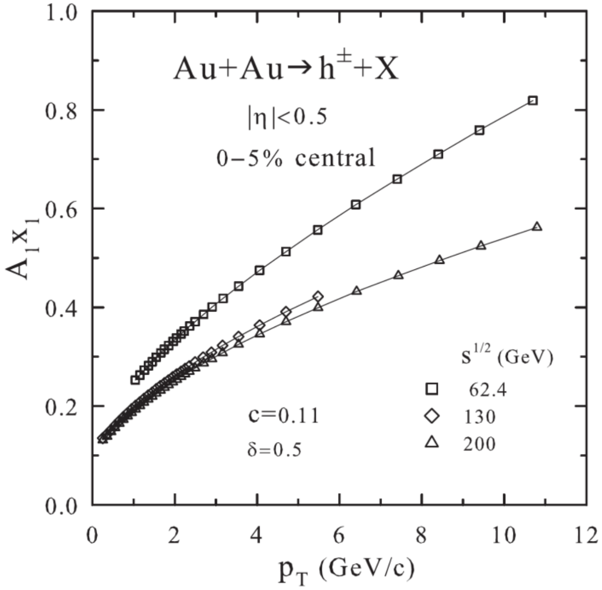
Energy losses (c=0.23,δ=0.5) < Energy losses (c=0.11,δ=0.15)

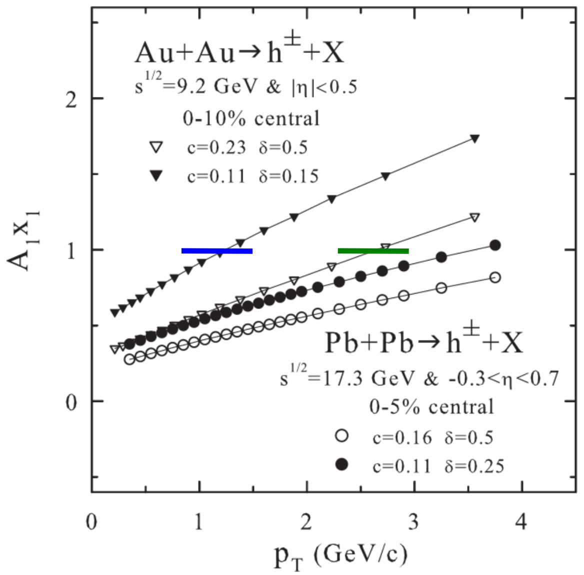
Smaller energy losses ⇒ better localization of a Critical Point…..

Momentum fraction x_1A_1 in AuAu collisions

Different scenarios

I Large specific heat c & large δ : c=0.23, δ=0.5
II Small specific heat c & small δ : c=0.11, δ=0.11





I

- Cumulative region at $p_T > 2.5$ GeV/c
- Smaller energy losses
- Not smeared sub-structure

II

- Cumulative region at $p_T > 1.5$ GeV/c
- Larger energy losses
- 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

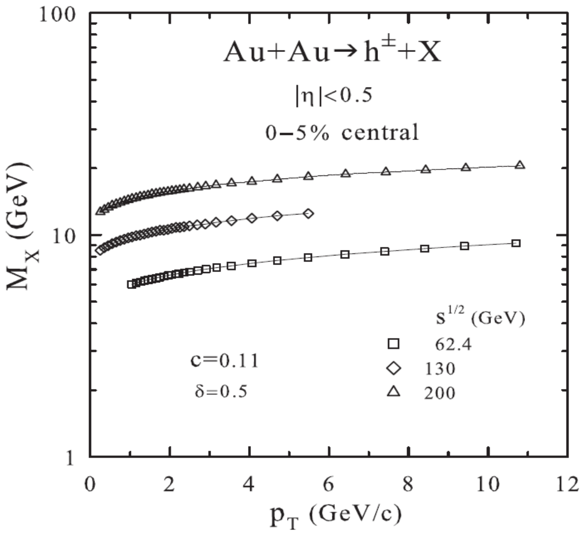
Recoil mass M_X

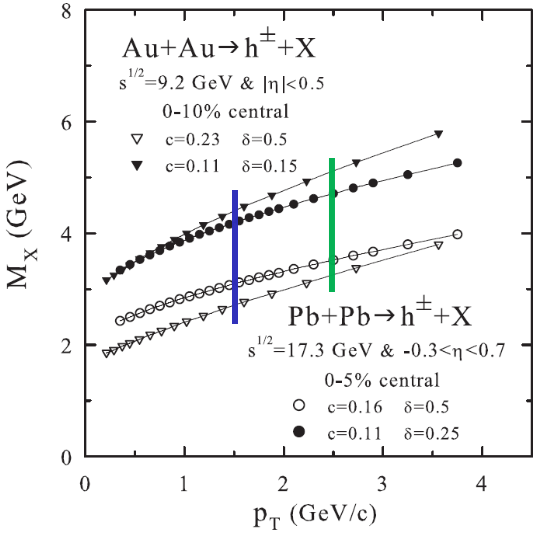
Recoil mass in different scenarios

$M_X=x_1M_1+x_2M_2+m/y_b$

I Large specific heat c & large δ : $c=0.23$, $\delta=0.5$

II Small specific heat c & small δ : $c=0.11$, $\delta=0.11$





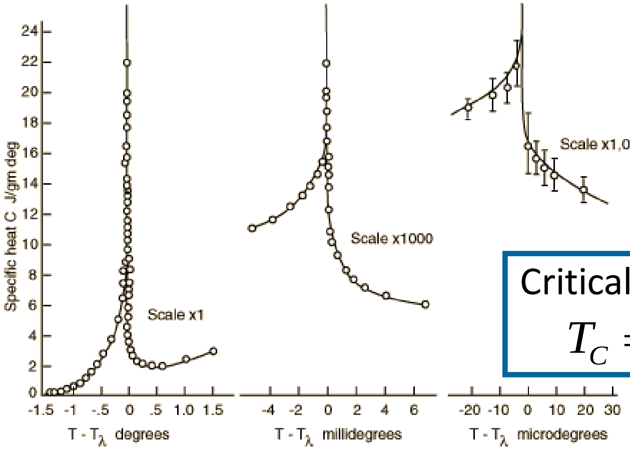
I
- Cumulative region at $p_T > 2.5$ GeV/c
- Smaller energy losses
- Not smeared sub-structure
- Smaller multiplicity in the way-side

II
- Cumulative region at $p_T > 1.5$ GeV/c
- Larger energy losses
- Smeared sub-structure
- Larger multiplicity in the way-side

M_X increases with p_T, $\sqrt{s_{NN}}$, centrality due to decrease of the fraction y_b

Discontinuity and Smearing near a Critical Point

Heat capacity ^4He

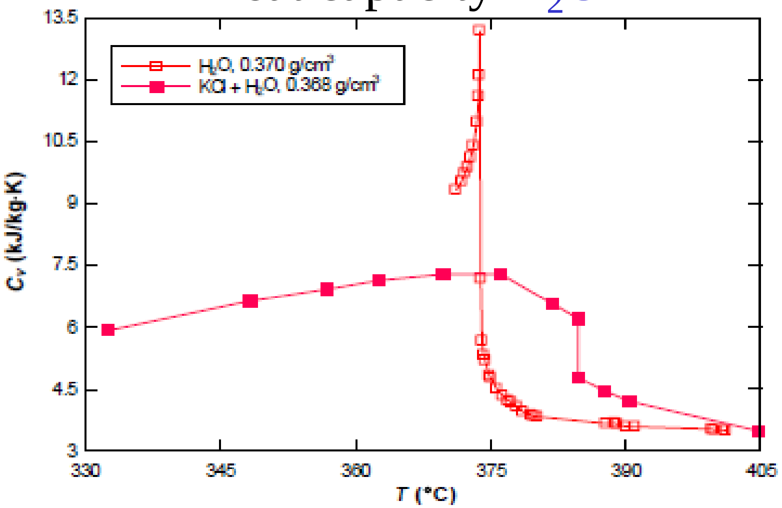


Critical Point

$$T_C = 5.19\,K$$

H.E. Stanley, 1971

Heat capacity H_2O



N.G. Polikhronidi et al. *Int.J.Thermophysics* 2001, 22, (1), 189-200.

$$c_v = -T(\partial^2 G/\partial T^2)_V$$

G - Gibbs potential

$$\varepsilon \equiv (T - T_c)/T_c$$

ε - scaled temperature

$$c_v \sim |\varepsilon|^{-\alpha}$$

α - critical exponent

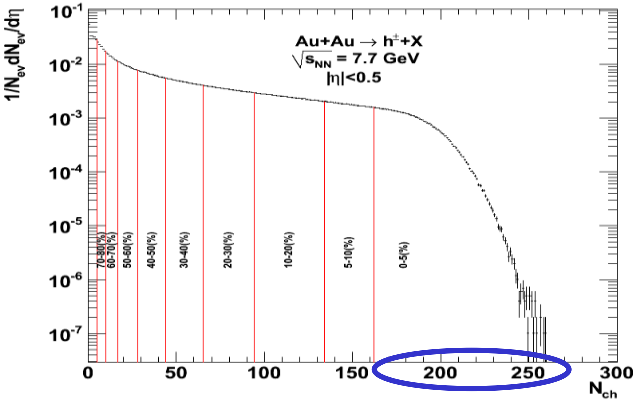
- Discontinuity of heat capacity near a Critical Point
- Impurities smear the region of localization of a Critical Point
- Region with small energy loss is of most preferable for search for localization of a Critical Point

Signatures of phase transition and Critical Point:

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

MC UrQMD study of hadron spectra in AuAu at high p_T

Multiplicity distribution

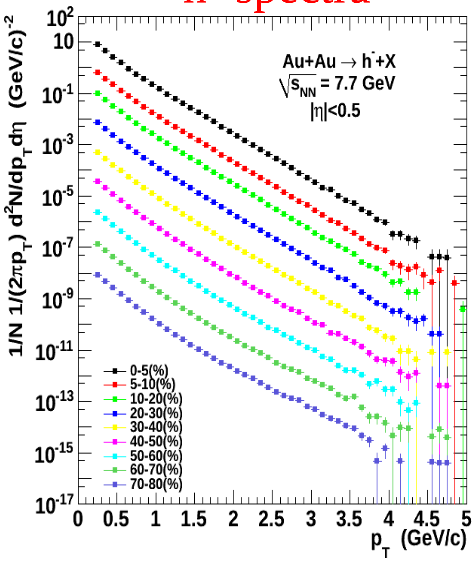


AuAu @ 7.7 GeV

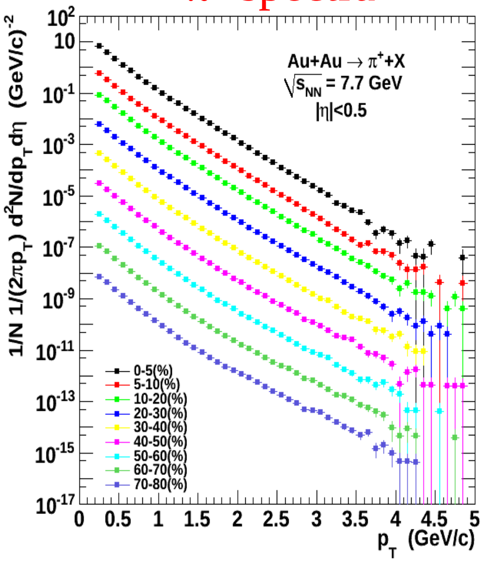
Centrality, %	0-5	5-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80
<N ch>	182	148	113	79	54	36	23	14	8

10 Mevts

h^- spectra



π^+ spectra



Centrality dependence of spectra

- ➢ High energy density
- ➢ Sensitivity of particle formation to state of nuclear medium at high p_T
- ➢ Small energy loss

$$\varepsilon = \frac{E_T}{\pi R^2 \tau A^{2/3}} \frac{dN_{ch}}{d\eta}$$

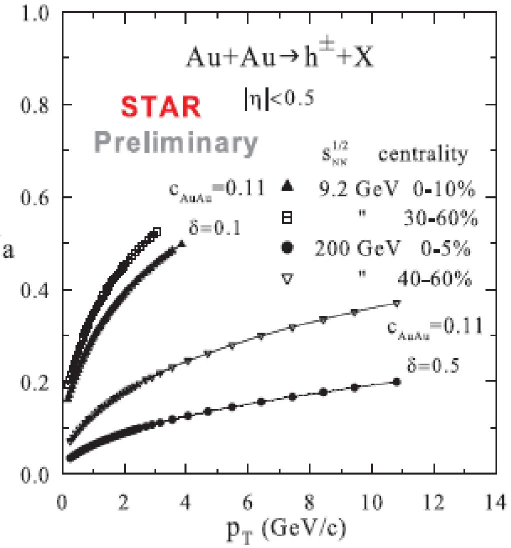
M.Tokarev

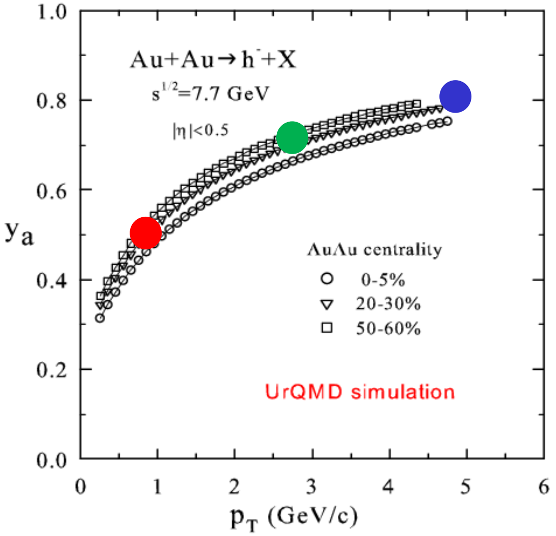
Energy loss in AuAu collisions at $\sqrt{s_{NN}}$=7.7 GeV

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

STAR
PRL 91 (2003) 172302
ЯФ 74 (2011) 1

z-Scaling
M.T.
I.Zborovsky
PRD 75(2007) 094008
IJMPA 24 (2009) 1417
……………





Energy loss 20%
p_T=5 GeV/c
$q_T \approx 6.3$ GeV/c

Energy loss 30%
p_T=3 GeV/c
$q_T \approx 4.3$ GeV/c

Energy loss 50%
p_T=1 GeV/c
$q_T \approx 2$ GeV/c

ΔE – constituent energy loss, E (q) – constituent energy (momentum)

y_a – constituent energy fraction carried away by inclusive particle.

Less energy loss better localization of a Critical Point.

- Energy loss increases with energy and centrality and decreases as transverse momentum p_T increases.
- High-p_T region (>4 GeV/c) at $\sqrt{s_{NN}}$ =5-40 GeV is of more preferable for search for phase transition and a Critical Point.

Conclusions

- Results of analysis of experimental data on charged hadrons produced in Heavy Ion collisions at $\sqrt{s_{NN}}$ =7.7-200 GeV at RHIC in the framework of z-scaling were presented.
- Search for signatures of phase transition of nuclear matter and Critical Point in the approach was discussed.

- The constituent energy loss in AuAu collisions vs. energy and centrality collisions was estimated.
- Discontinuity & correlation of c,δ as a signatures of phase transition and Critical Point in nucleus-nucleus collisions was discussed.
- High-p_T spectra of charged hadrons at $\sqrt{s_{NN}}$ =7.7,11.5,19.6,27, 39 GeV are soon expected from BES at RHIC.

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

Thank You for Attention !!!