Self-similarity of negative particle production from the Beam Energy Scan Program at STAR

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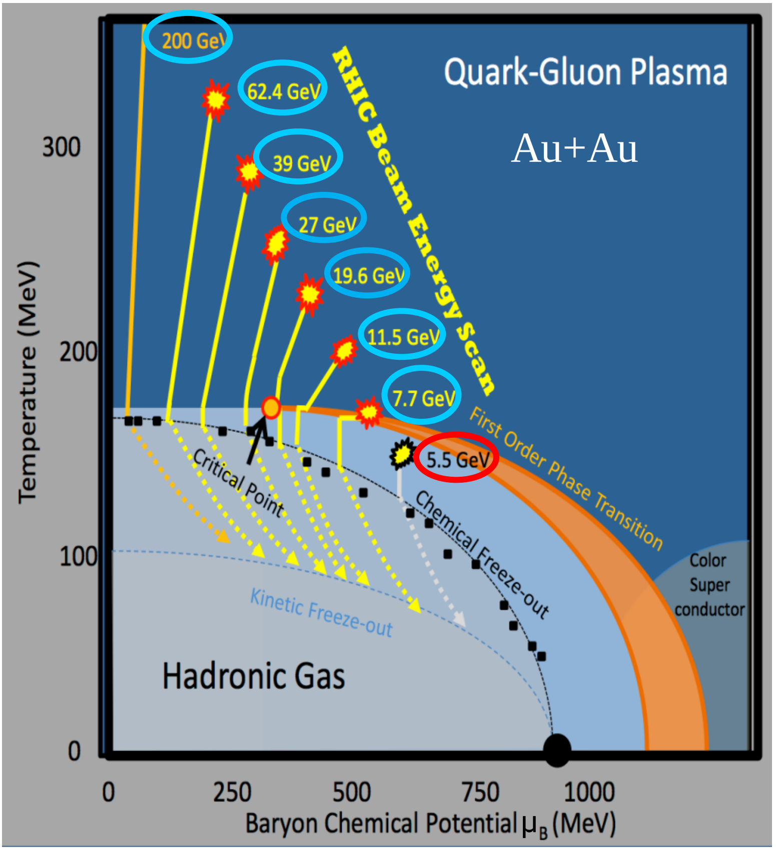
for the STAR Collaboration

Outline:

- Motivation (RHIC Beam Energy Scan)
- BES in Au+Au at $\sqrt{s_{NN}}$ = 7.7-39 GeV & 62.4,200 GeV
- p_T -Spectra vs. $\sqrt{s_{NN}}$, and centrality
- Self-similarity of negative particle production
- Energy loss vs. $\sqrt{s_{NN}}$, centrality and p_T
- Summary and Outlook

Beam Energy Scan at RHIC



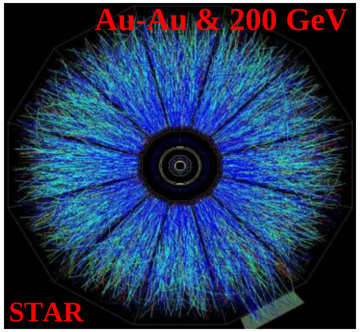
STAR Note SN0493.
Phys. Rev. C 81, 024911 (2010).
Phys.At. Nucl., 2011, V.74, №5, p.799.
STAR Note SN0598

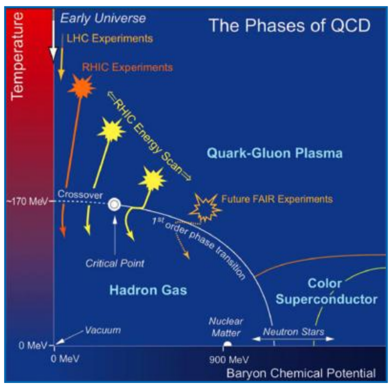
Motivation

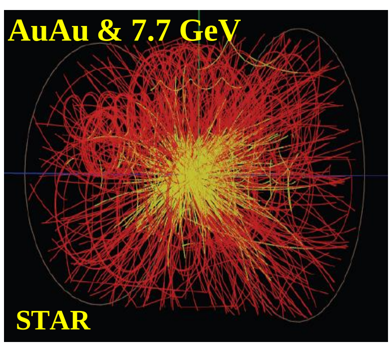
- Search for phase transition and critical point of strongly interacting matter
  - Elliptic & directed flows (v_2, v_1)
  - Azimuthally-sensitive femtoscopy
  - Fluctuation measures (<K/π>, <p/π>, <p_T>,..)
- Search for turn-off of new phenomena seen at higher RHIC energies
  - Constituent-quark-number scaling of v_2
  - Hadron suppression in central collisions R_{AA}
  - Ridge (Δφ-Δη 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]

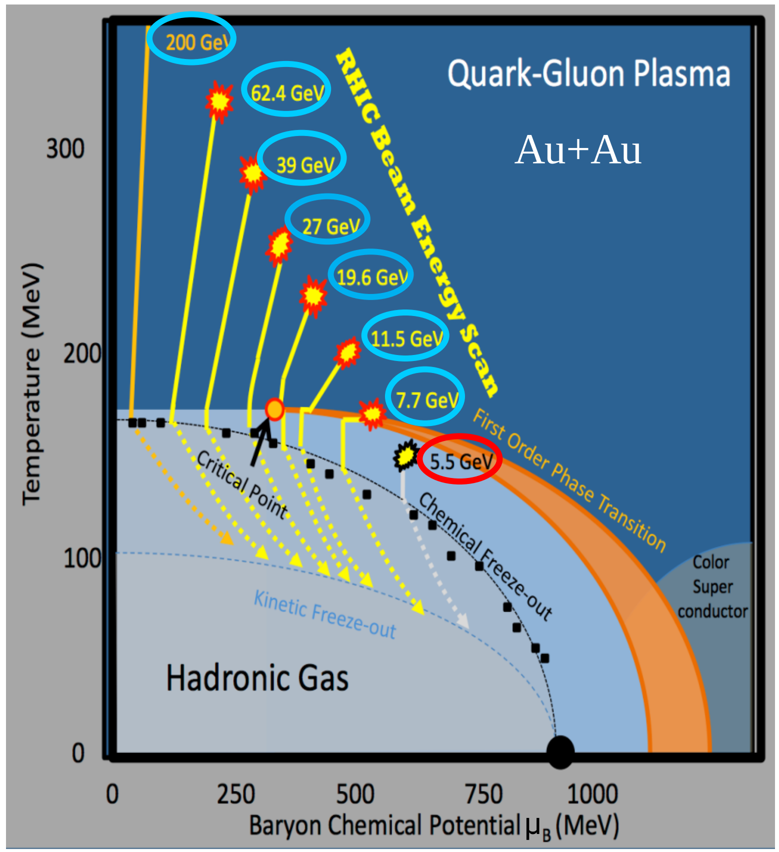
BES in Au+Au collisions at RHIC





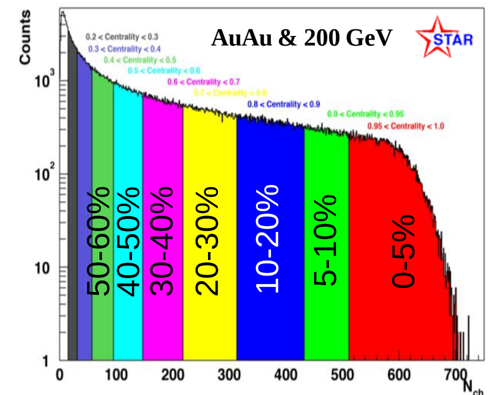


Phase diagram of nuclear matter



- Collision energy
- Event centrality
- Types of nuclei
- Kinds of probes
- ………

- Spectra
- Particle ratios
- Correlations
- Fluctuations
- Flow
- …….



- Phases
- Phase boundaries
- Phase transitions
- Critical Points
- …….

The study in detail the state of the nuclear matter produced in heavy ion collisions

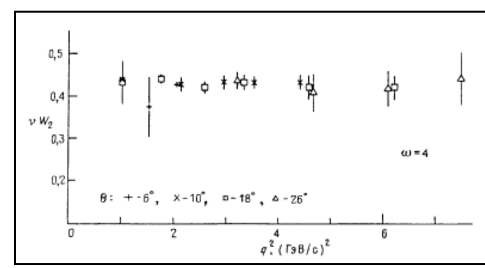
Self-similarity

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

Dimensionless dynamical function vs. self-similarity parameter

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

…………….



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Fundamental principles and symmetries

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

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

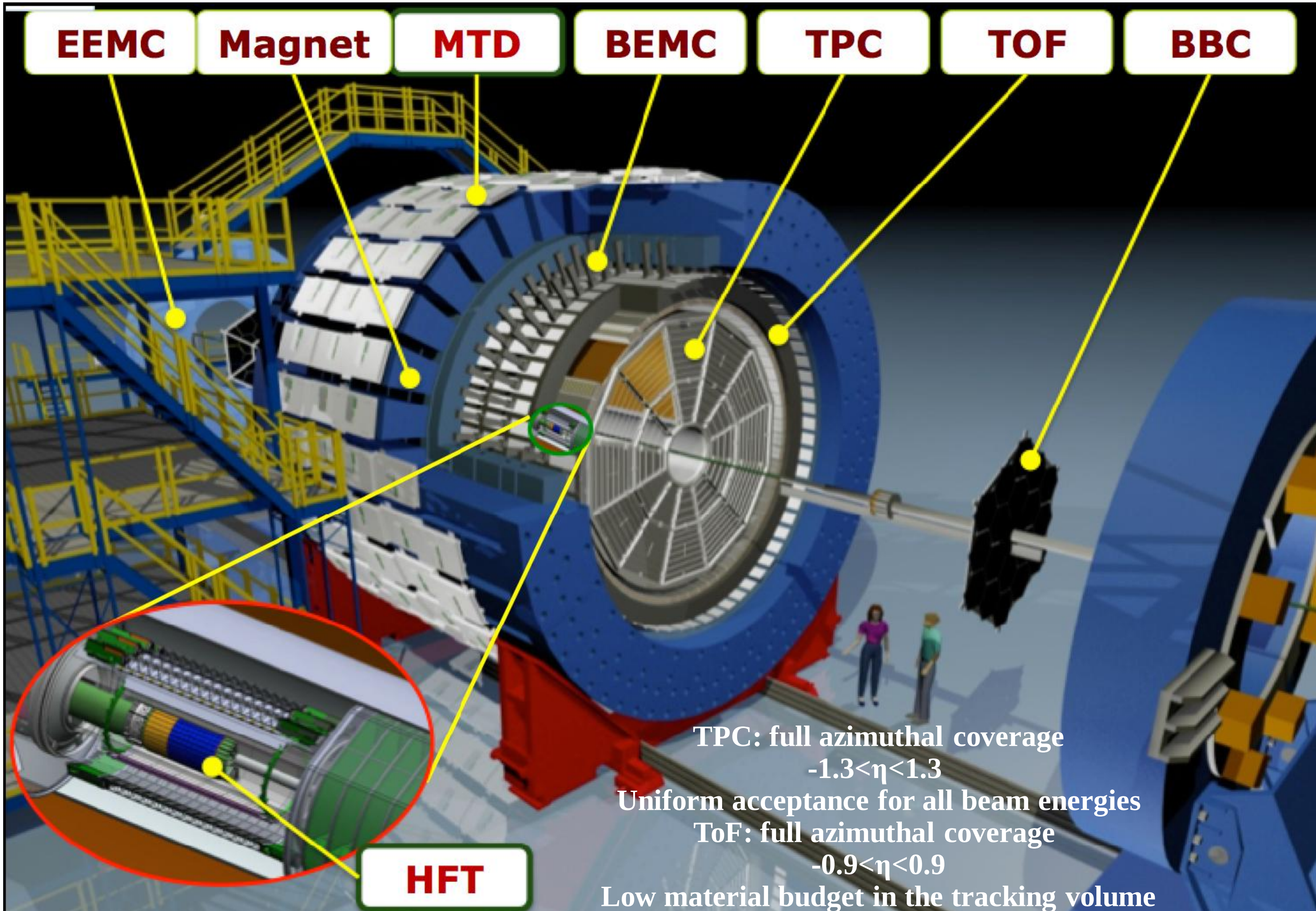
H.Stanley, G.Barenblatt,…

Phase transition and critical phenomena in nuclear matter

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

STAR collaboration

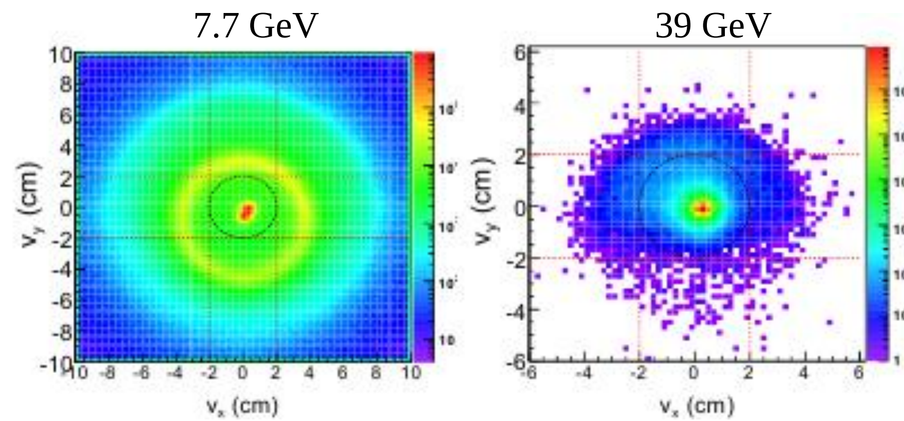
The Solenoid Ttracker At RHIC (STAR)



Data sample, event and track selections

Statistics

$\sqrt{s_{NN}}$ (GeV)	Year	Production	Events (M)
7.7	2010	P10ih	2.3
11.5	2010	P10ih	7.6
19.6	2011	P11id	17.2
27.0	2011	P11id	33.7
39.0	2010	P10ik	108.9
62.4	2010	P10ik	62.3
200	2010	P10ik	35.6



Event cuts

$\lvert V_z \rvert$ (cm)	$\lvert V_x - V_{x\ mean} \rvert$ (cm)	$\lvert V_y - V_{y\ mean} \rvert$ (cm)
<30	<2	<2

Track cuts at all energies

$\lvert \eta \rvert$	DCA	$N_{fit\ pts}$	$N_{fit\ pts}/N_{fit\ poss}$	$N_{dE/dX}$	p_{Tpr}/p_{Tgl}
<0.5	<1 cm	> 15	> 0.52	>10	7/10< & <10/7

STAR Collaboration,
B. Abelev et al.
Phys.Rev. C79, 034909 (2009)
Phys.Rev. C81, 024911 (2010)

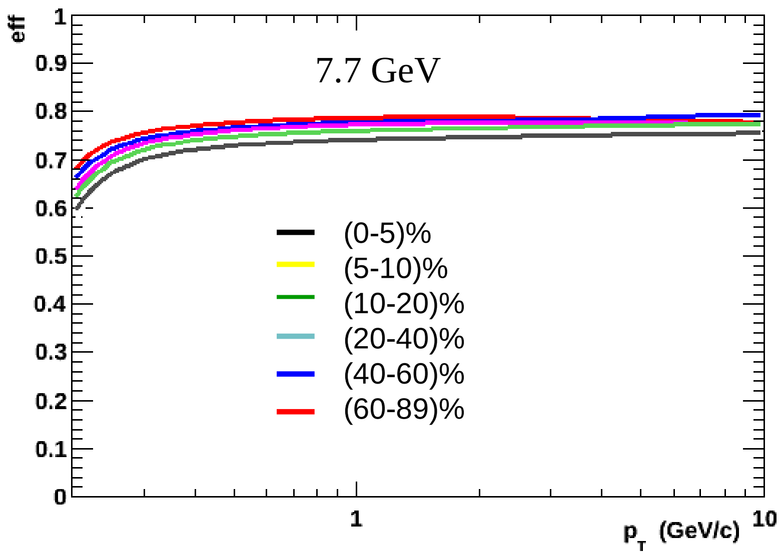
The events are divided into centrality classes:
0–5%, 5–10%, 10–20%, 20–40%, 40–60%, 60–80%.

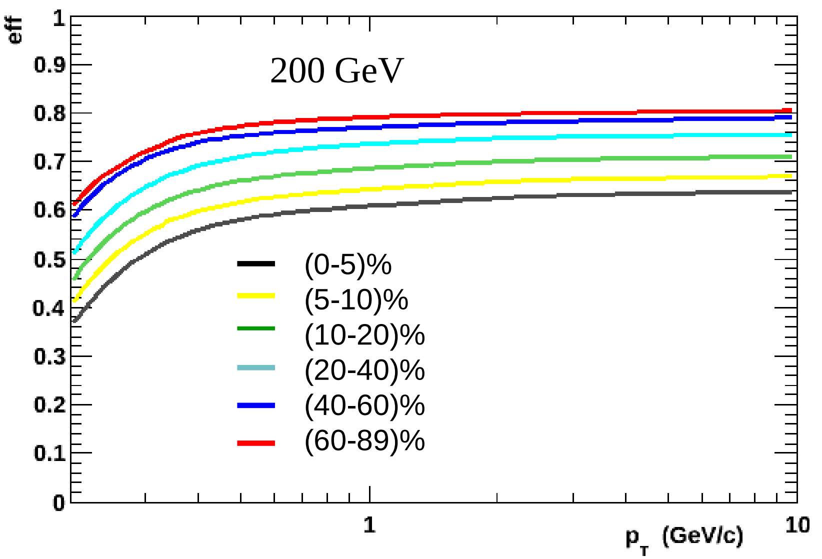
Efficiency of charged particles

- The efficiency is determined by measuring the reconstruction efficiency of Monte Carlo tracks embedded in real events and then run through the STAR reconstruction chain.
- For a given collision energy, centrality region, and particle species the efficiency is fit as a function of p_T using the functional form

$$\mathrm{eff} = A \cdot e^{-(B/p_T)^C}$$

- The parameters A, B, and C are determined for each centrality for unidentified particles using efficiencies for identified particles.





STAR, S.Horvat, QM2014
STAR, L.Kumar, QM2014

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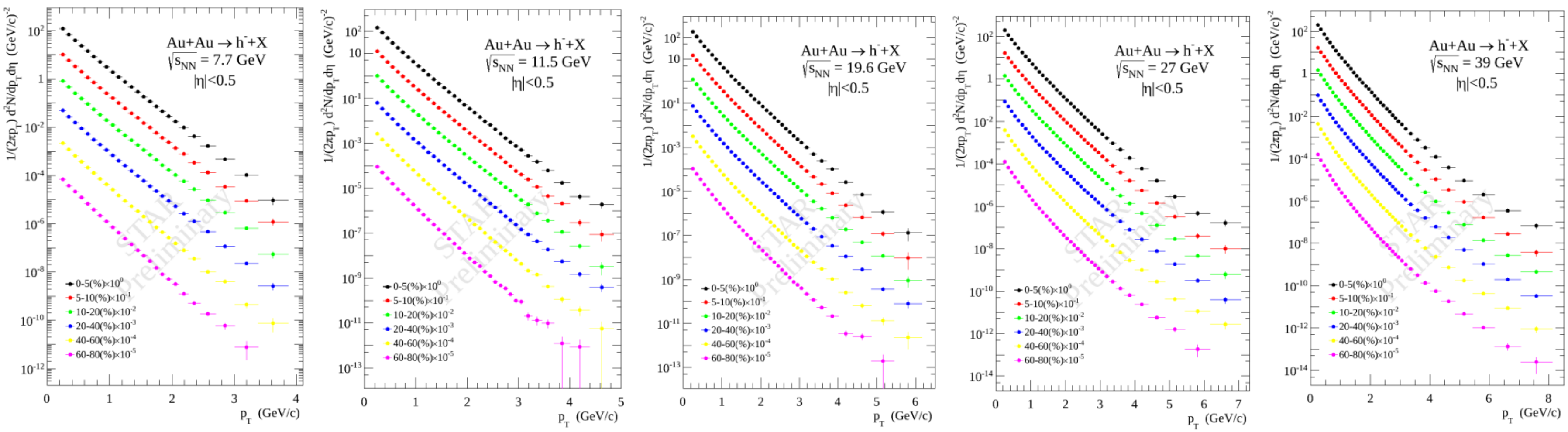
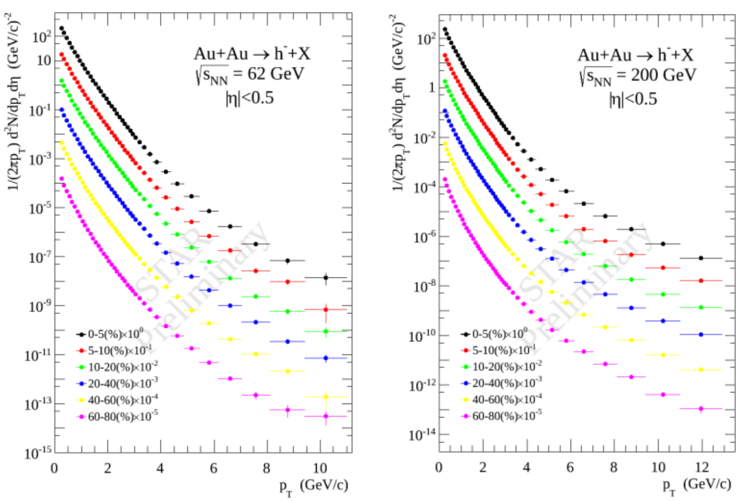
Transverse momentum spectra in Au+Au

BES-I energies



Top RHIC energies



Wide kinematic and dynamical range of particle production:

- Beam energy $\sqrt{s_{NN}}$ = 7-200 GeV
- Centrality 80% - 5% ($dN_{ch}/d\eta|_0 \approx$10-600)
- Transverse momentum p_T = 0.2-12 GeV/c

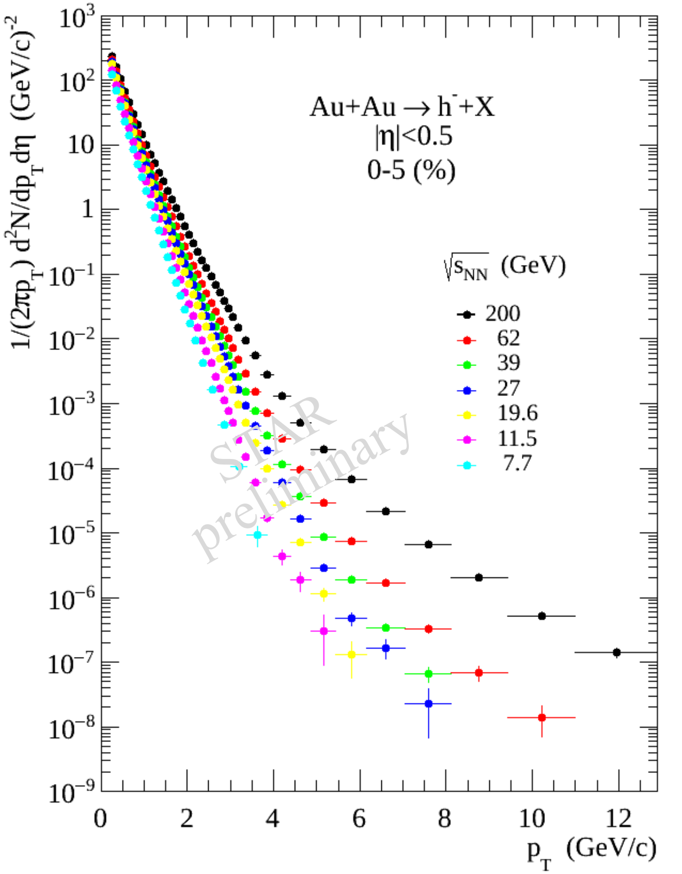
Unprecedented conditions to search for new phenomena in nuclear matter produced in heavy ion collisions.

Transverse momentum spectra in Au+Au

Dimensional dynamical function
versus
dimensional measurables

$$Ed^3N/dp^3 \quad \& \quad P_{1,2}, M_{1,2}, p, m, dN/d\eta$$

- Energy dependence of spectra
- Centrality dependence of spectra
- Exponential behavior of spectra at low p_T and energy $\sqrt{s_{NN}}$
- Power behavior of spectra at high p_T and energy $\sqrt{s_{NN}}$
- Difference of yields at various energies strongly increases with p_T



The study of critical phenomena in nuclear matter
in terms of dimensionless variables

Self-similarity in Au+Au collisions

Self-similarity parameter

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

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

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

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

Dimension of fragmentation

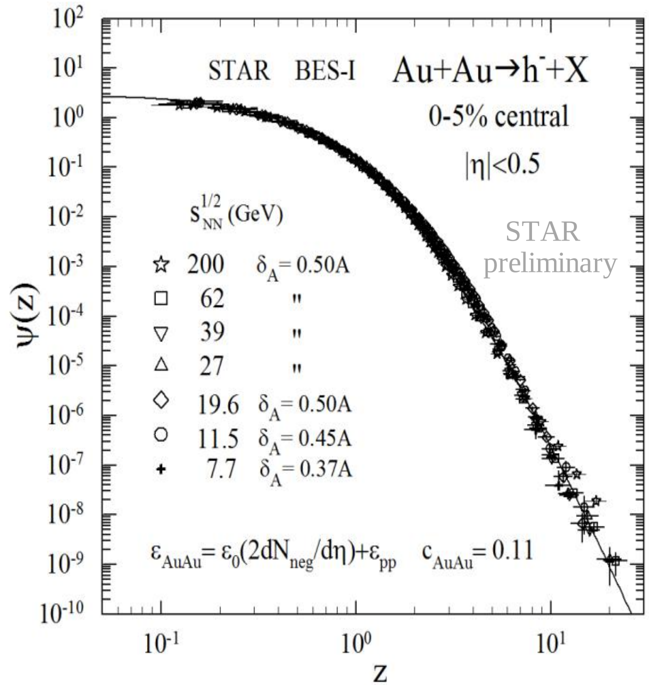
$$\varepsilon_{AA} = \varepsilon_0 (dN/d\eta) + \varepsilon_{pp}$$

Scaling function

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

M.T. & I.Zborovsky
PRD75,094008(2007)
IJMPA24,1417(2009)

"Collapse" of data onto a single curve



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

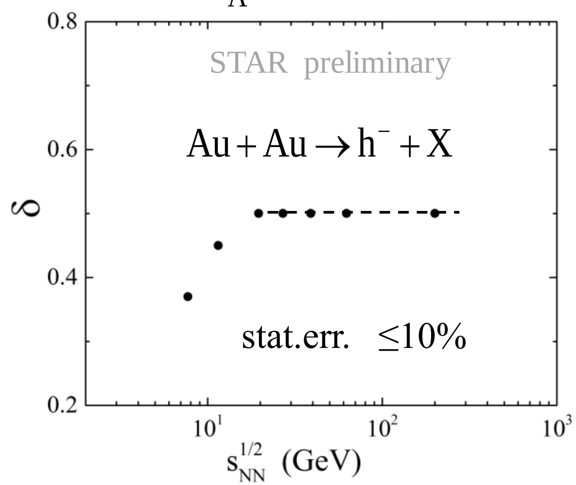
Indication on energy dependence of δ for $\sqrt{s_{NN}} < 19.6$ GeV

Model parameters: δ_A, ε_{AA}, c

Parameters δ_A, ε_{AA}, c are determined from the requirement of scaling behavior of Ψ as a function of self-similarity parameter z

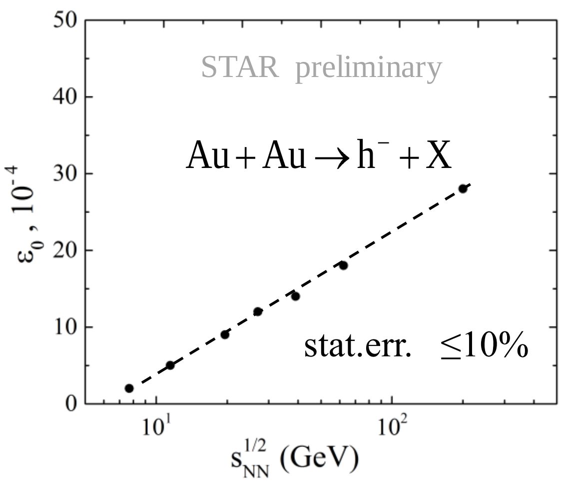
Nucleus fractal dimension

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



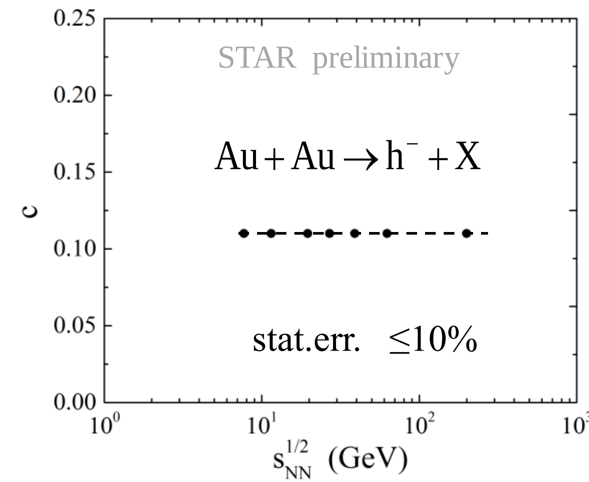
Fragmentation dimension

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



"Specific heat"

c



- δ decreases with energy for $\sqrt{s_{NN}} \leq 20$ GeV
- δ is independent of energy for $\sqrt{s_{NN}} \geq 20$ GeV
- ε_{AA} increases with energy
- c is independent of energy

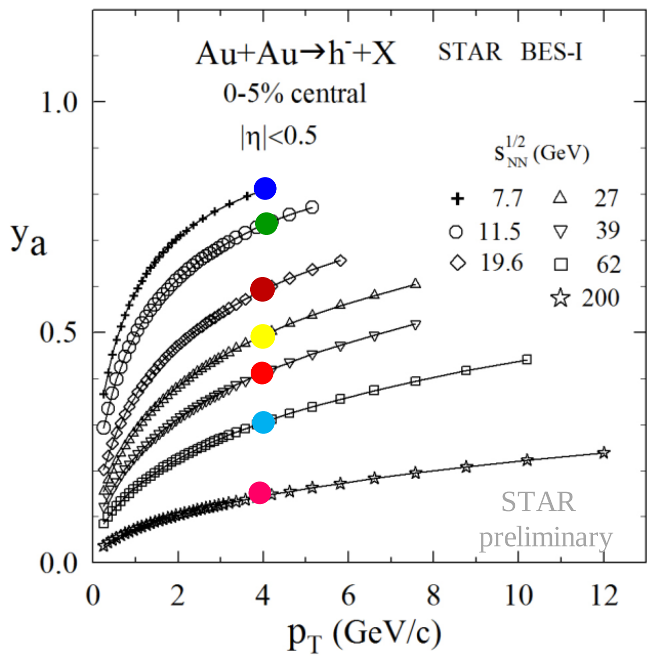
Search for discontinuity and correlations of the model parameters

Constituent energy loss & z-scaling

STAR
PRL 91 (2003) 172302

STAR
Phys. At. Nucl.
74 (2011) 799

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



Constituent energy loss

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

20% energy loss $q \approx 5$ GeV/c

25% energy loss $q \approx 5.3$ GeV/c

40% energy loss $q \approx 6.7$ GeV/c

50% energy loss $q \approx 8$ GeV/c

60% energy loss $q \approx 10$ GeV/c

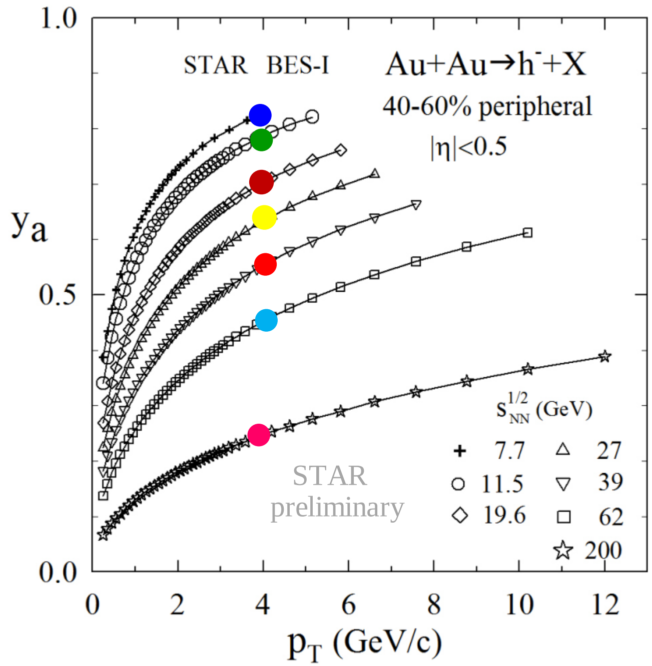
70% energy loss $q \approx 13.3$ GeV/c

85% energy loss $q \approx 26.6$ GeV/c

q - momentum of scattered constituent
p_T - transverse momentum of produced hadron

Constituent energy loss & z-scaling

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



STAR
PRL 91 (2003) 172302

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Phys. At. Nucl. 74 (2011) 799

20% energy loss $q \approx 5$ GeV/c

25% energy loss $q \approx 5.3$ GeV/c

30% energy loss $q \approx 5.7$ GeV/c

35% energy loss $q \approx 6.2$ GeV/c

45% energy loss $q \approx 7.3$ GeV/c

55% energy loss $q \approx 8.9$ GeV/c

75% energy loss $q \approx 16$ GeV/c

Constituent energy loss

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

q - momentum of scattered constituent
p_T - transverse momentum of produced hadron

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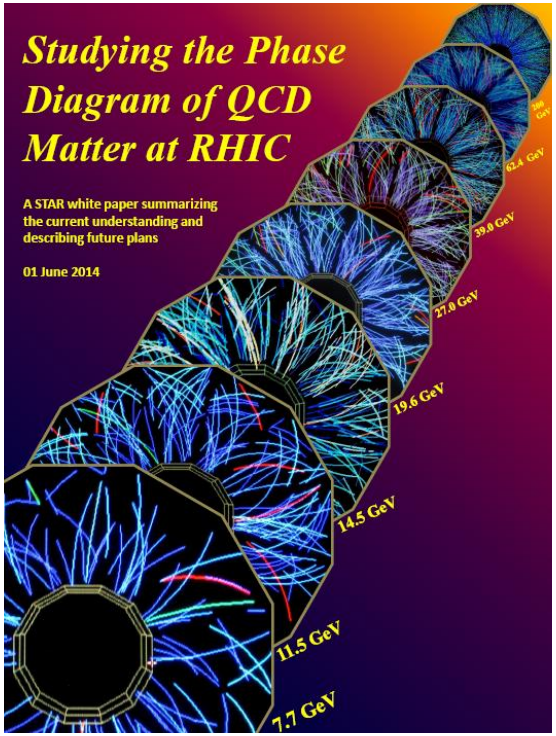
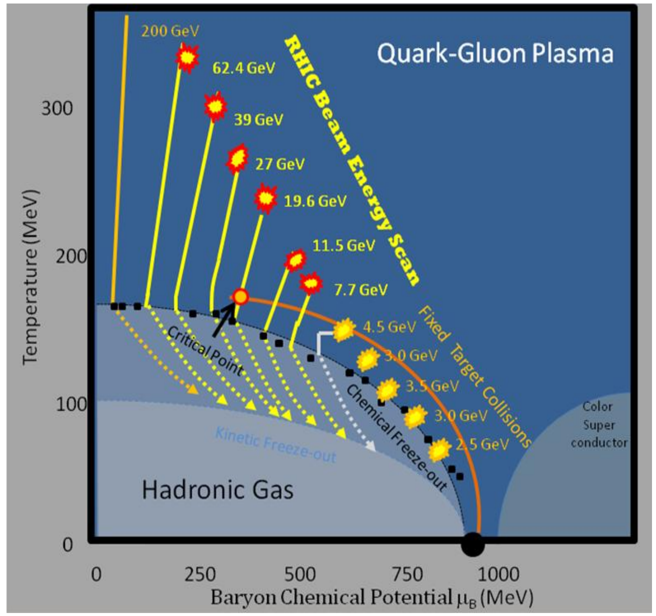
Future: Beam Energy Scan-II at RHIC

BES phase II will start 2019-2020

$\sqrt{s_{NN}} = 2.5 - 19.6$ GeV



STAR Note SN0598



Collider mode $\sqrt{S_{NN}}$ (GeV)	Collider mode μ_B (MeV)	Fixed target mode $\sqrt{S_{NN}}$ (GeV)	Fixed target mode μ_B (MeV)
19.6	205	4.5	585
14.5	250	3.9	633
11.5	315	3.5	670
7.7	420	3.0	720
5.0	550	2.5	775

Daniel Cebra
"Long-range Plan for Nuclear Science"
Joint Town Meeting , 2014
Temple University, Philadelphia, PA

Phase diagram of nuclear matter
The existence and study of

- Phases
- Phase boundaries
- Phase transitions
- Critical Points

High-statistics measurements

$\sqrt{S_{NN}}$ (GeV)	7.7	9.1	11.5	14.5	19.6
BES I (Mevts)	4.3	---	11.7	24	36
BES II (Mevts)	100	160	230	300	400

Quark and gluon degrees of freedom

- Partonic energy loss and fragmentation in the medium
- Constituent quark scaling
- Non-monotonic behavior of fluctuations and correlations
- Critical phenomena

Summary & Outlook

- Transverse momentum spectra of negative hadrons produced in Au+Au collisions at $\sqrt{s_{NN}}$ = 7.7-200 GeV in the pseudorapidity region $|\eta|<0.5$ as a function of collision centrality were obtained.

- Self-similarity of negative particle production in heavy ion collisions over a wide kinematic range was found.

- Constituent energy loss as a function of energy and centrality of collisions and transverse momentum of inclusive particle was estimated in the z-scaling approach.

- The energy dependence of fractal and fragmentation dimensions and "specific heat" was studied.

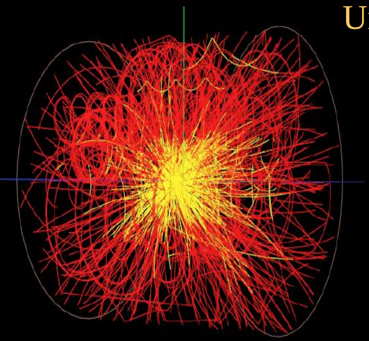
- Higher statistics in Au+Au is expected in BES-II. More precise and sophisticated data analysis is ahead.

The STAR Collaboration

BES-I at RHIC

AuAu & 7.7, 11.5, 14.5, 19.6, 27, 39 & 62.4, 200 GeV

AGH University of Science and Technology-Argonne National Laboratory-Brookhaven National Laboratory-University of California-Berkeley,Davis,Los Angeles-Central China Normal University-University of Illinois at Chicago-Creighton University-Czech Technical University in Prague-Nuclear Physics Institute AS CR-Frankfurt Institute for Advanced Studies-Institute of Physics, Bhubaneswar-Indian Institute of Technology-Indiana University-Alikhanov Institute for Theoretical and Experimental Physics-University of Jammu-Joint Institute for Nuclear Research, Dubna-Kent State University-University of Kentucky-Korea Institute of Science and Technology Information-Institute of Modern Physics-Lawrence Berkeley National Laboratory-Max-Planck-Institut fur Physik-Michigan State University-Moscow Engineering Physics Institute-National Institute of Science Education and Research-Ohio State University-Institute of Nuclear Physics PAN-Panjab University-Pennsylvania State University-Institute of High Energy Physics, Protvino-Purdue University-Pusan National University-University of Rajasthan-Rice University-University of Science and Technology of China-Shandong University-Shanghai Institute of Applied Physics-Temple University-Texas A&M University-University of Texas-University of Houston-Tsinghua University-United States Naval Academy-Valparaiso University-Variable Energy Cyclotron Centre-Warsaw University of Technology-Wayne State University-World Laboratory for Cosmology and Particle Physics,Cairo-Yale University-University of Zagreb



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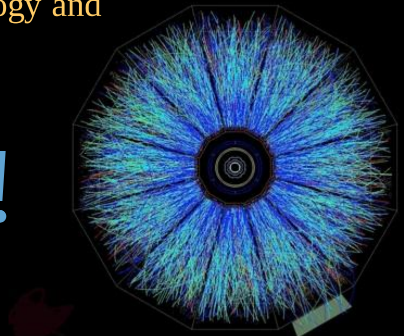


Backup Slides

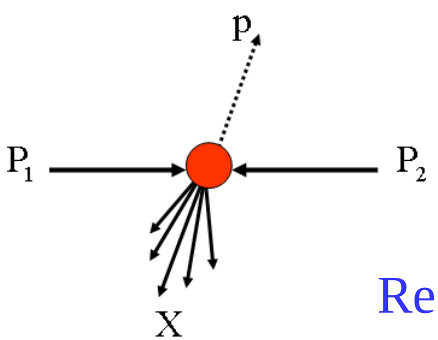
Self-similarity of hadron production in AA collisions: z-Scaling

z-Scaling

Hypothesis :

$s^{1/2}$, 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; $\delta_1, \delta_2, \varepsilon_a, \varepsilon_b, c$

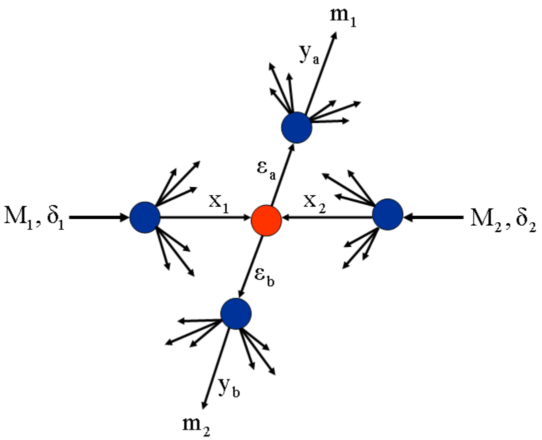
$Ed^3\sigma/dp^3$, $dN/d\eta$ — Scaled inclusive cross section of particles depends in a self-similar way on a single scaling variable z. — $\Psi(z)$



Momentum conservation law for constituent binary collision:

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

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

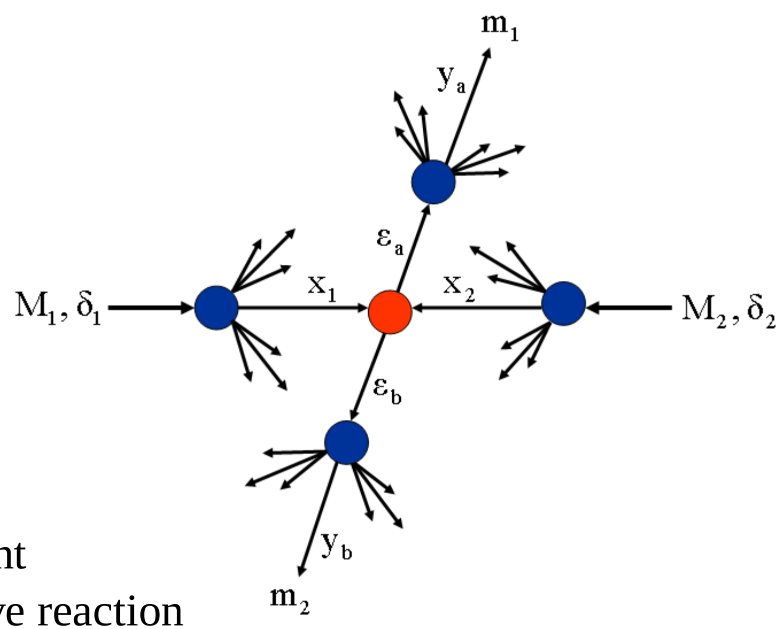


Self-similarity parameter z

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

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

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



- Ω^{-1} is the minimal resolution at which a constituent subprocess can be singled out of the inclusive reaction
- $\delta_1, \delta_2, \varepsilon_a, \varepsilon_b$ characterize fractal structure of the colliding objects and fragmentation process, respectively
- x_1, x_2, y_a, y_b momentum fractions of colliding objects and scattered constituents carried by initial constituents and inclusive and recoil particles
- $s_\perp^{1/2}$ is the transverse kinetic energy of the sub-process consumed on particle production with masses 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)

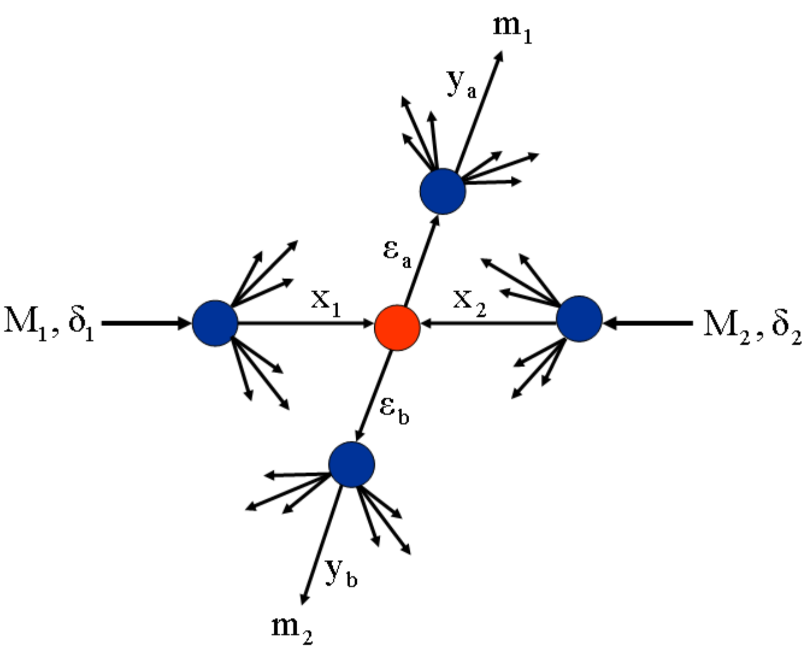
STAR

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 self-similarity parameter z with respect to all constituent sub-processes taking into account 4-momentum conservation:

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

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



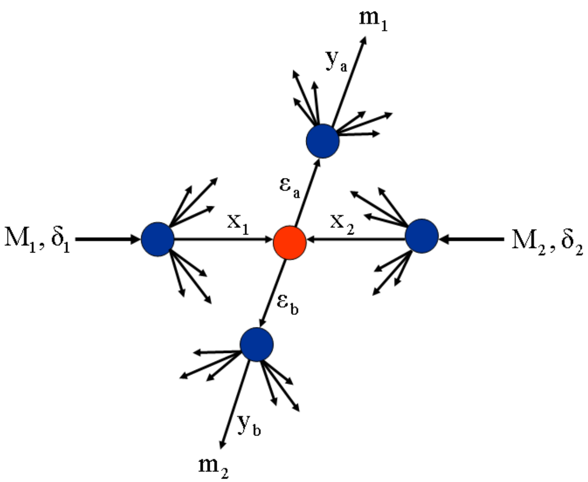
Momentum conservation law

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

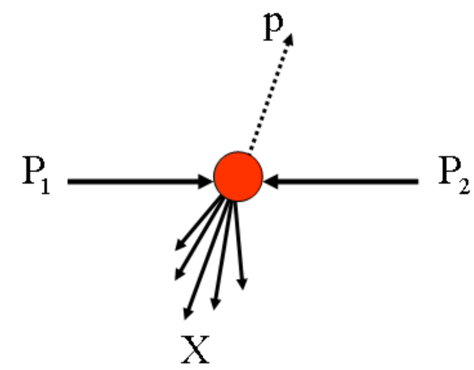
Recoil mass

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

Scaling function Ψ(z)



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



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

- σ_{in} - inelastic cross section
- N - average multiplicity
- $dN/d\eta$ - multiplicity density
- $J(z,\eta;p_T^2,y)$ - Jacobian
- $Ed^3\sigma/dp^3$ - inclusive cross section

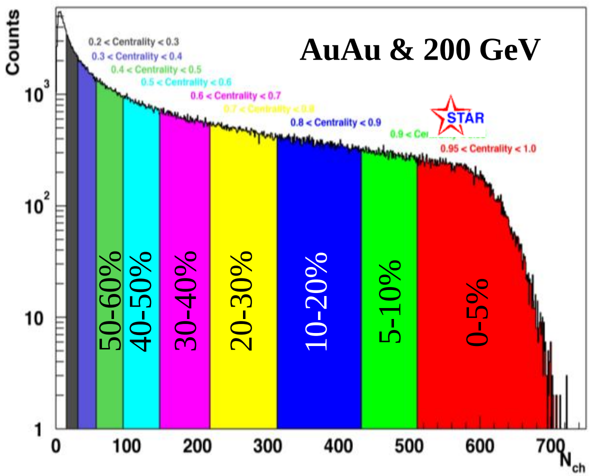
The scaling function Ψ(z) is a probability density
to produce the inclusive particle with the corresponding z.

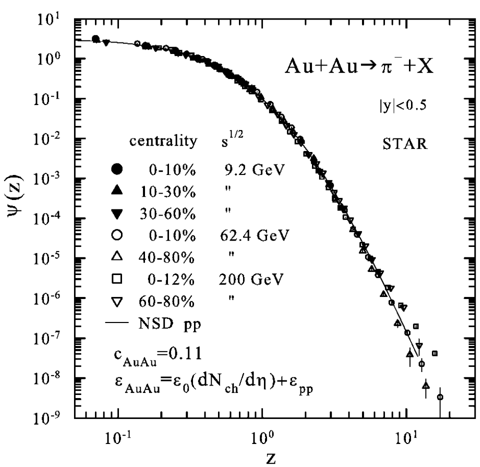
Self-similarity parameter z in AA collisions

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

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

$$\Omega = (1-x_1)^{\delta_{A_1}} (1-x_2)^{\delta_{A_2}} (1-y_a)^{\varepsilon} (1-y_b)^{\varepsilon}$$





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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 δ_A in AA collisions:

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

Self-similarity in Au+Au collisions

Self-similarity parameter

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

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

$$\Omega = (1-x_1)^{\delta_{A_1}} (1-x_2)^{\delta_{A_2}} (1-y_a)^{\varepsilon} (1-y_b)^{\varepsilon}$$

- $dN_{ch}/d\eta|_0$ - multiplicity density
- c - "specific heat" of bulk matter
- δ - nucleus fractal dimension
- ε - fragmentation fractal dimension

Dimension of fragmentation

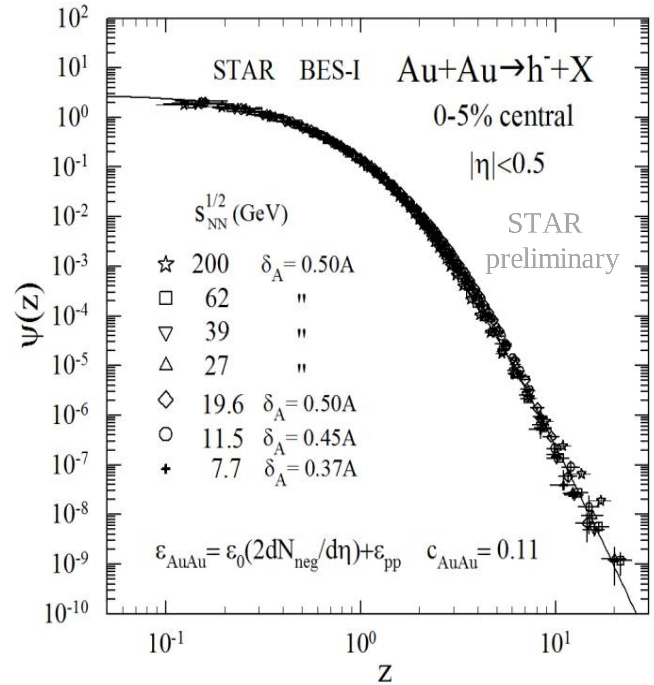
$$\varepsilon_{AA} = \varepsilon_0 (dN/d\eta) + \varepsilon_{pp}$$

Scaling function

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

M.T. & I.Zborovsky
PRD75,094008(2007)
IJMPA24,1417(2009)

"Collapse" of data onto a single curve



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

Indication on energy dependence of δ for $\sqrt{s_{NN}} < 19.6$ GeV

Thank you for your patience !