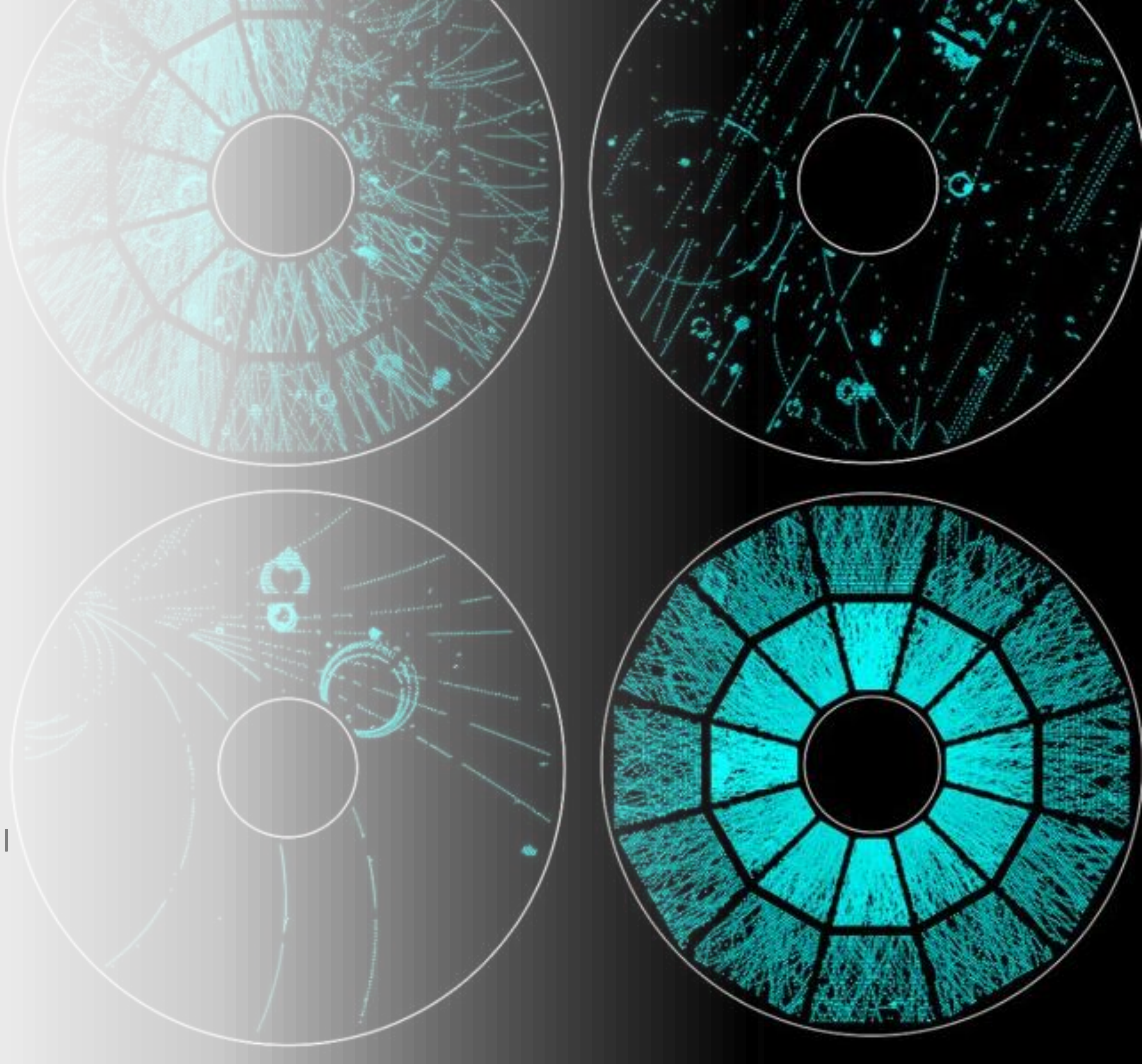
Measuring Global Observables in the STAR Experiment

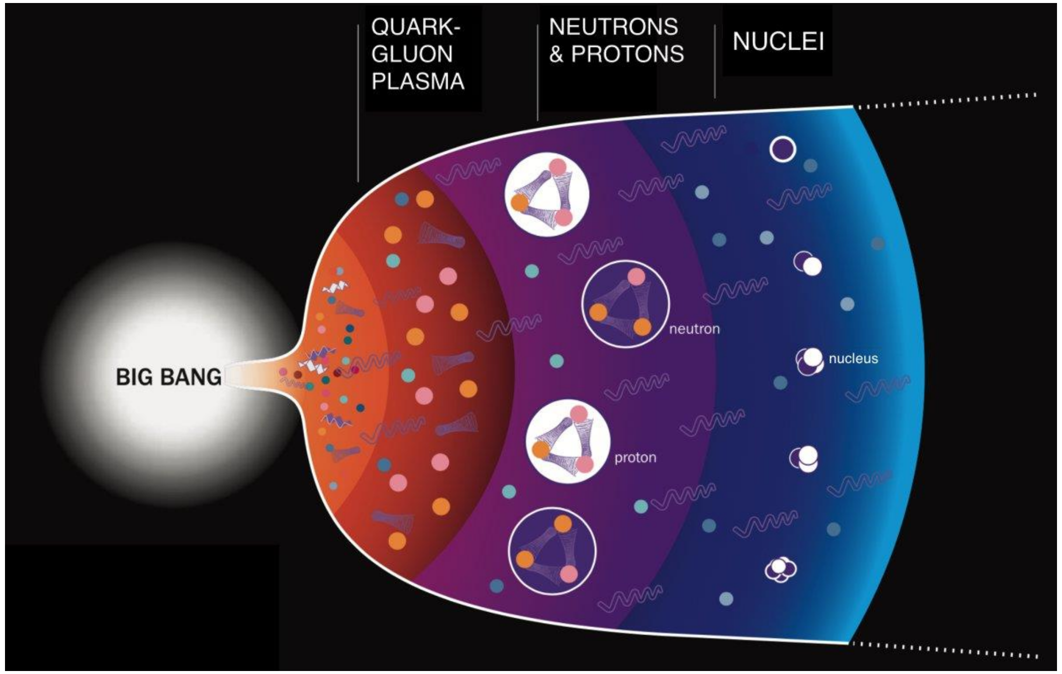
Grigory Nigmatkulov[1,2]

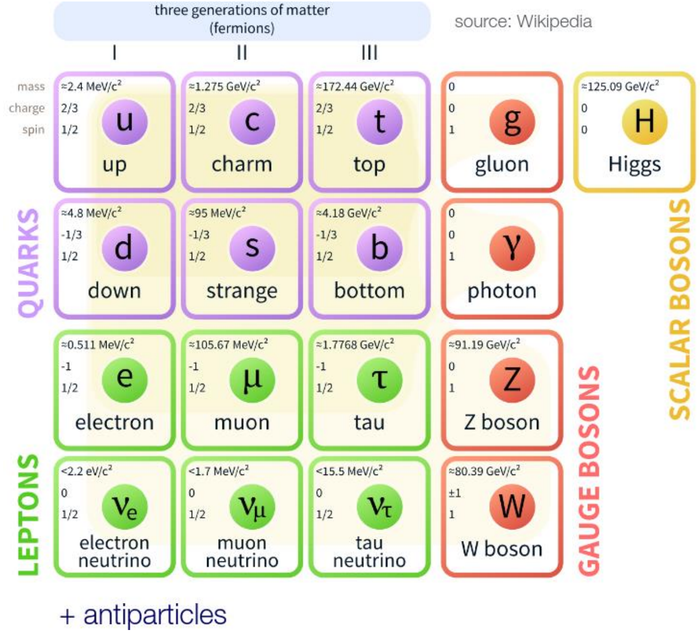
1. National Research Nuclear University MEPhI (Moscow Engineering Physics Insitute)

2. Joint Institute for Nuclear Research



Quark-Gluon Plasma

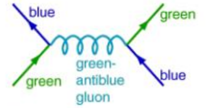




source: Wikipedia

Quarks come in three different colors: ●●●

Gluons: mediate interaction between quarks



Feynman diagram for an interaction between quarks generated by a gluon.

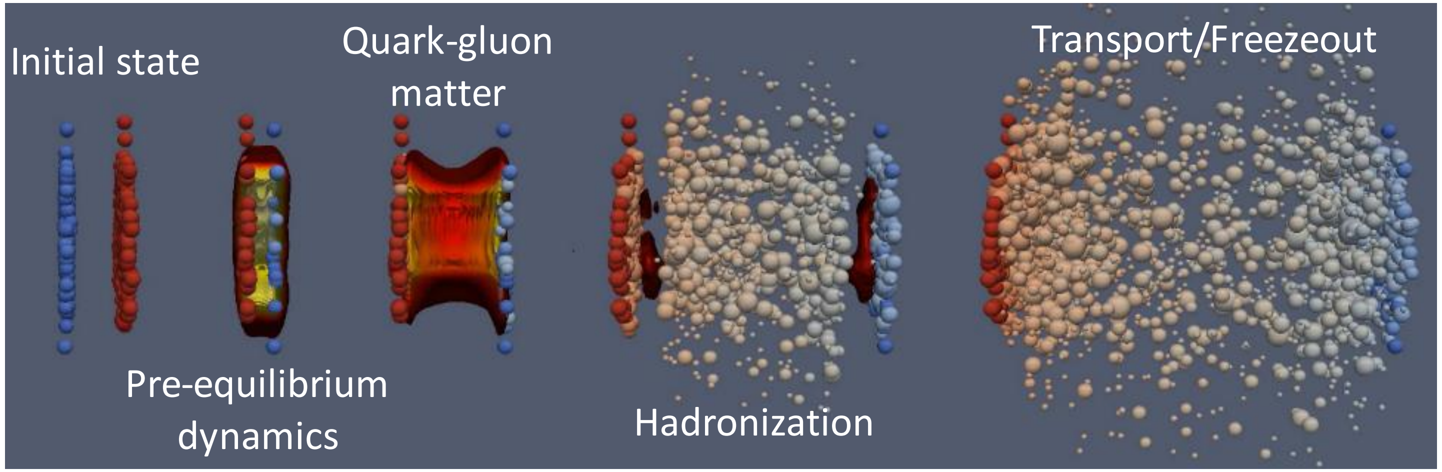
Quarks and gluons are the building blocks of protons and neutrons.

A strong nuclear force is the most powerful force involved with holding matter together. It is much stronger than the three other fundamental forces.

The strong nuclear force is so powerful, it makes it extremely difficult to separate quarks and gluons. Because of this, quarks and gluons are bound inside composite particles.

The only way to separate these particles is to create a state of matter known as quark-gluon plasma. In this plasma, the density and temperature are so high that protons and neutrons melt.

Collision Evolution



- Non-equilibrium evolution at early times
  - initial state at from QCD? Color Glass Condensate? ...
  - thermalization via strong interactions, plasma instabilities, particle production, ...
- Local thermal and chemical equilibrium
  - strong interactions lead to short thermalization times
  - evolution from relativistic fluid dynamics
  - expansion, dilution, cool-down
- Chemical freeze-out
  - for small temperatures one has mesons and baryons
  - inelastic collision rates become small
  - particle species do not change any more
- Thermal freeze-out
  - elastic collision rates become small
  - particles stop interacting
  - particle momenta do not change any more

System properties can be probed via:

- Transverse momentum particle spectra
- Momentum and angular correlations
- Azimuthal anisotropies
- Global and local polarization of particles
- Jet spectrum and shapes
- Fluctuation of conserved charges
- Etc...

Some definitions

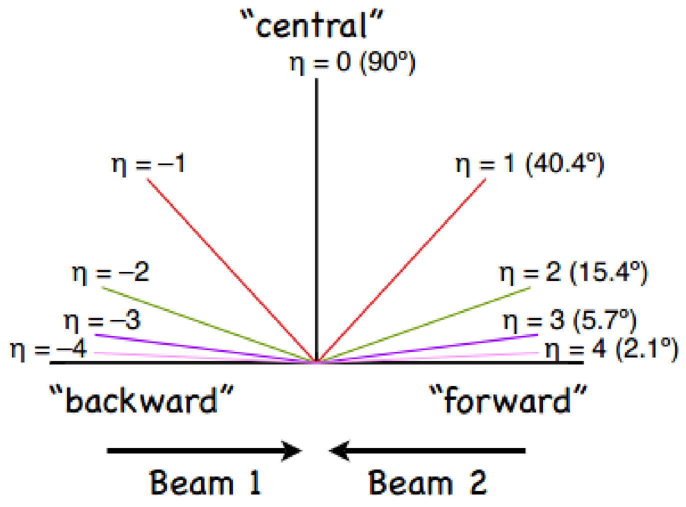
Kinematics

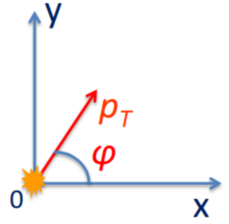
- *Pseudorapidity*, η, is used to describe polar angle (z-y plane): $\eta \equiv -\ln(\tan\frac{\theta}{2})$
- η is a good approximation of to the *rapidity*, y:

$$y \equiv \frac{1}{2}\ln(\frac{E+p_z}{E-p_z})$$

$$y \approx \eta,\ p \gg m,\ \theta \gg 1/\gamma$$

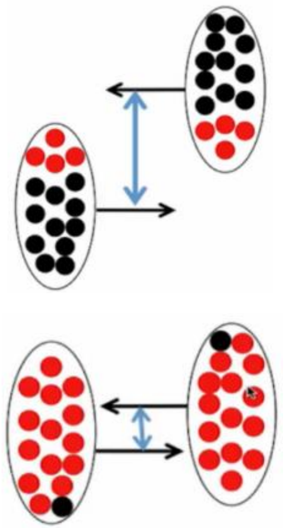
- Rapidity is invariant under Lorentz boosts in z
- *Azimuthal angle*, φ, is defined in x-y plane



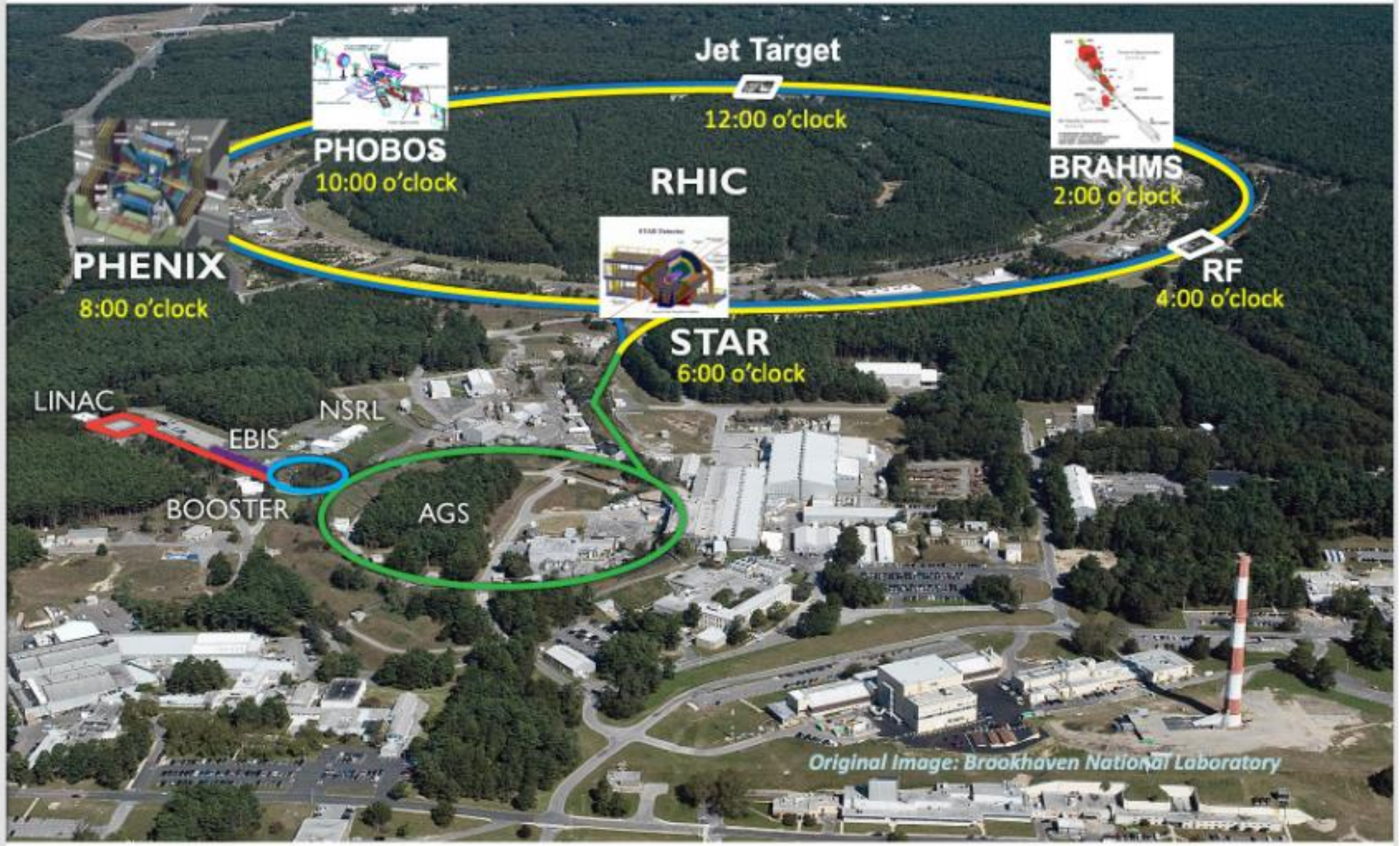


Collision centrality

- Peripheral collision
  - Large distance between centers of nuclei
  - Small number of nucleons-participants
  - Small multiplicity of created particles
- Central collision
  - Small distance between centers of nuclei
  - Large number of nucleons-participants
  - Large particle multiplicity

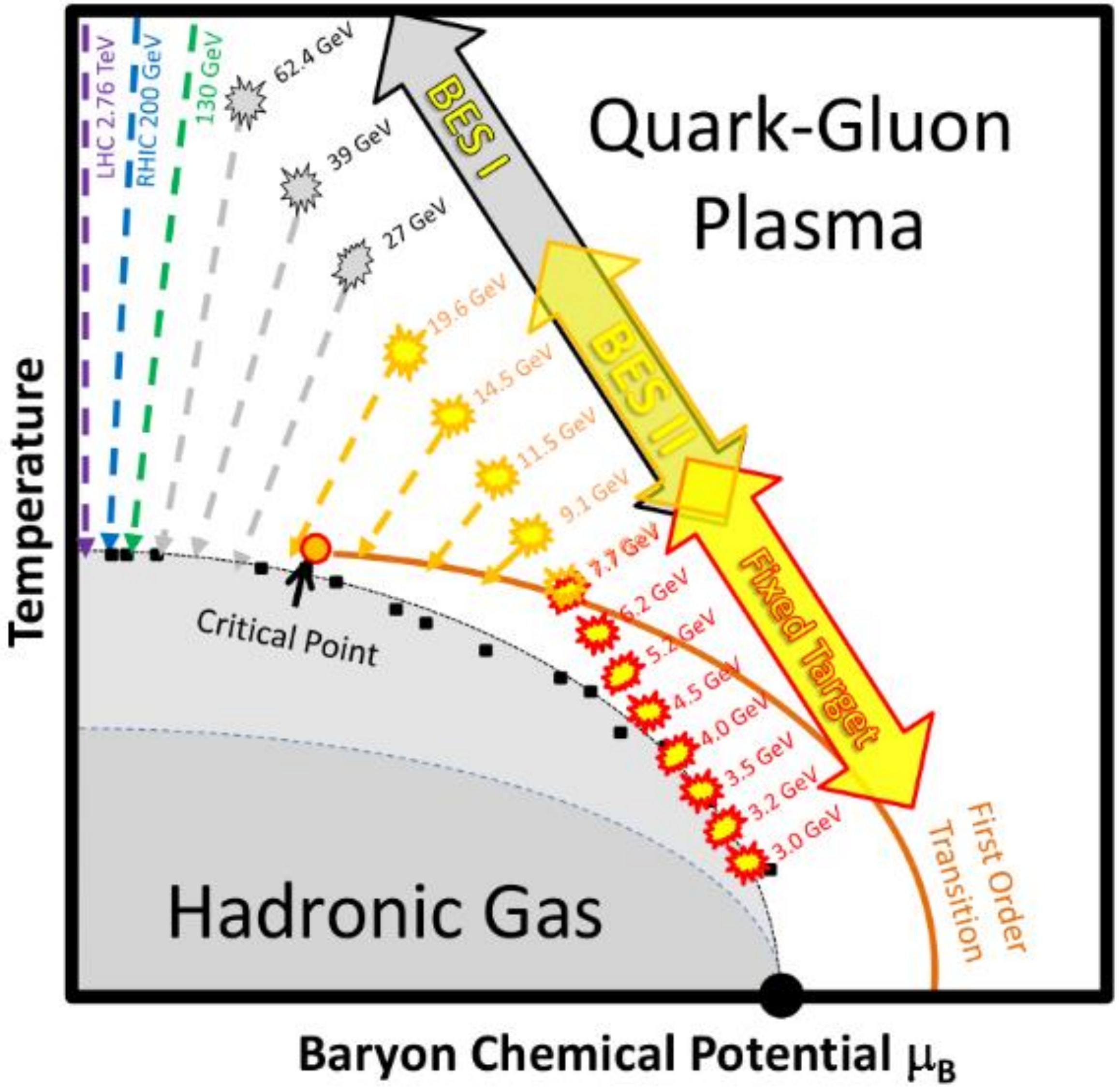


Relativistic Heavy Ion Collider (RHIC)



- **The most versatile particle collider**
  - ✓ The only polarized proton collider in the world
  - ✓ Type of collisions: p+p, p+Au, d+Au, Cu+Au, Cu+Cu, Ru+Ru, Zr+Zr, Au+Au, U+U,...
  - ✓ Center-of-mass energy for Au+Au collisions: $\underbrace{3.0 - 7.7}_{\text{Fixed-Target mode}} - \underbrace{7.7 - 200}_{\text{Collider mode}}$ GeV

BES-I -> BES-II and FXT

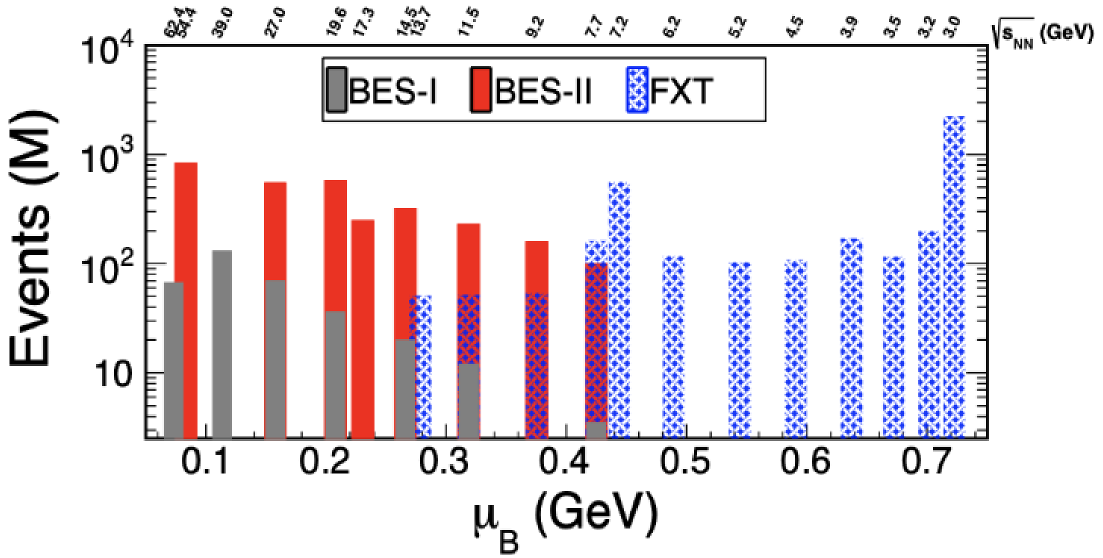


BES-I:

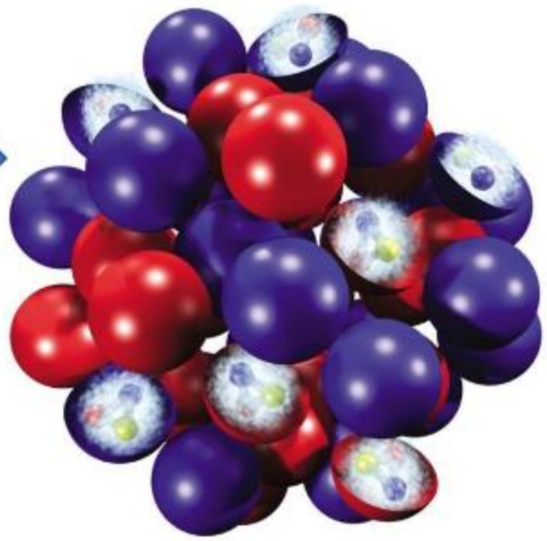
- Search for the QGP turn-off signatures
- Search for the first-order phase transition
- Search for the critical point

BES-II and fixed-target (FXT) program:

- Need higher statistics (≥10 times than in BES-I) for precise measurements
- Detector upgrades (increased acceptance and PID capabilities)
- Access to energies $\sqrt{s_{NN}}$<7.7 GeV via FXT



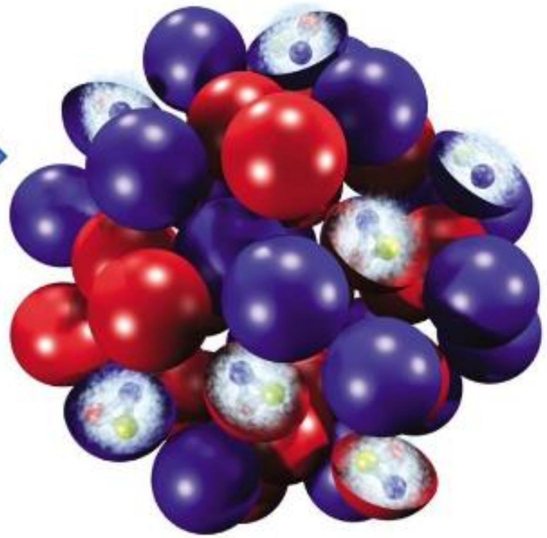
How Does the Nucleus Look Like?



- deBroglie wavelength of constituent partons is effected by the beam energy.

- Determines whether a parton images:
    A. The whole nucleus
    B. Individual nucleons
    C. Individual partons

How Does the Nucleus Look Like?



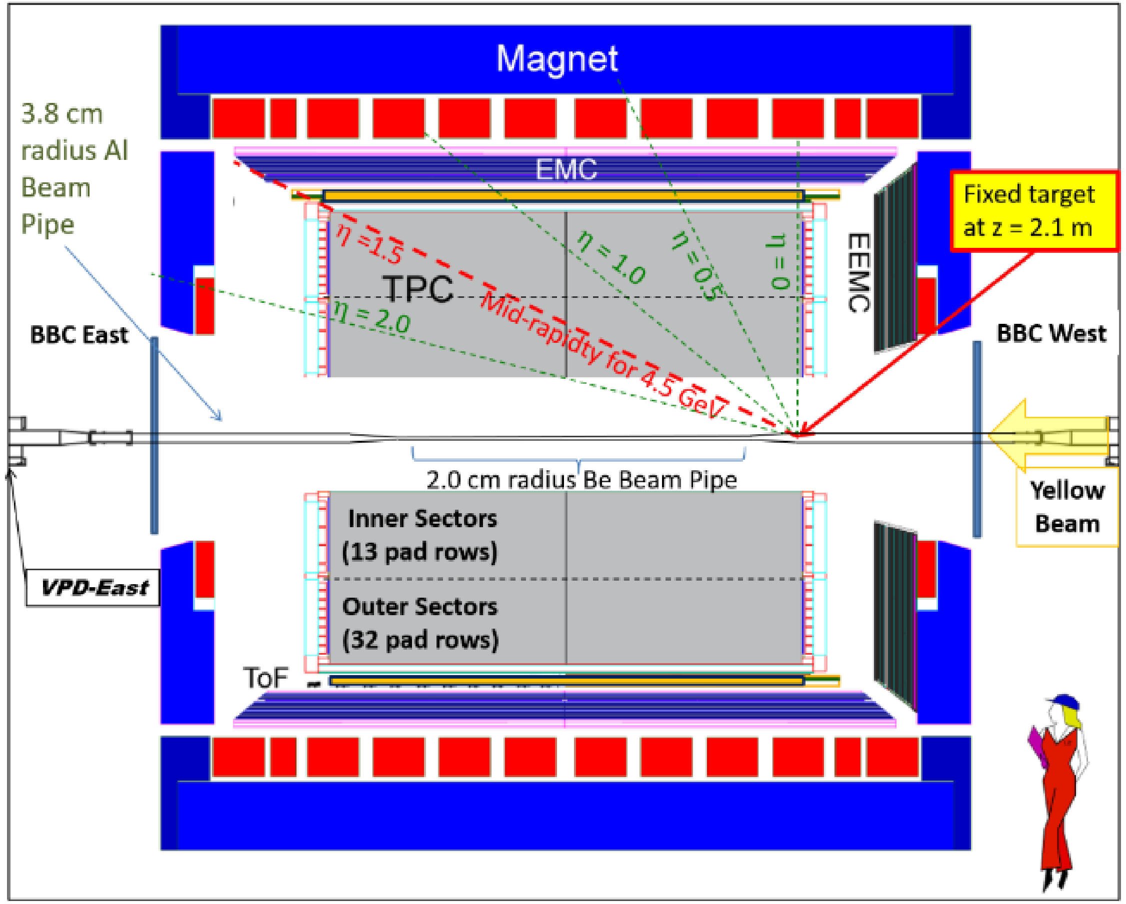
- deBroglie wavelength of constituent partons is effected by the beam energy.

- Determines whether a parton images:
  - A. The whole nucleus
  - B. Individual nucleons
  - C. Individual partons

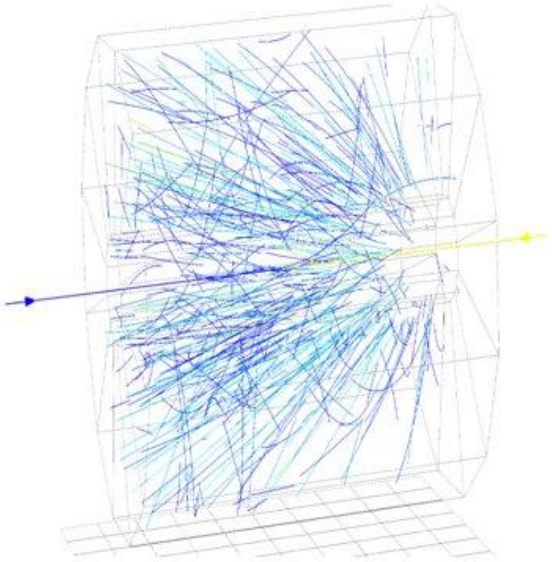
At lower energy, nucleons are opaque, and the valence quarks are stopped in the fireball.
Excess quarks ➔ higher μ_B

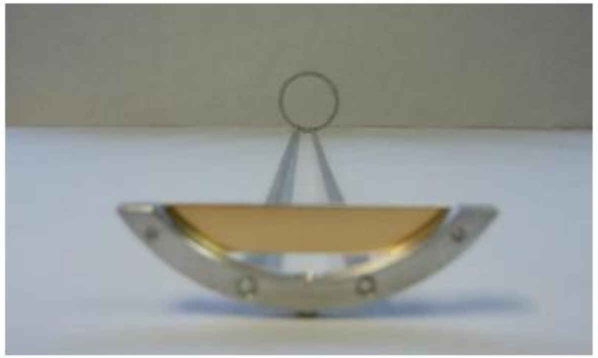
At higher energy, nucleons are transparent, and the valence quarks are pass through and exit the fireball.
Equal quarks and anti-quarks ➔ lower μ_B

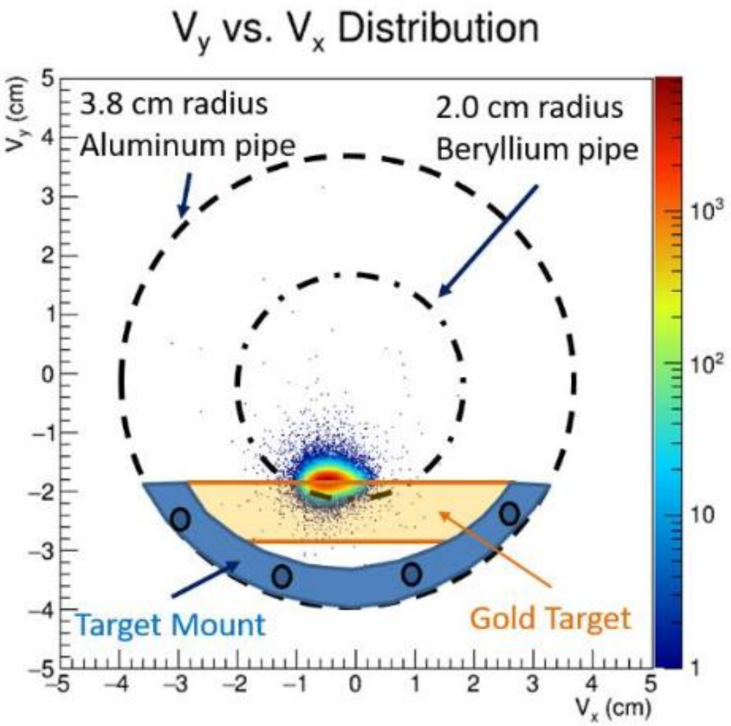
The STAR Experiment at RHIC



$$\eta = \frac{1}{2}\ln\left(\frac{|\mathbf{p}| + p_L}{|\mathbf{p}| - p_L}\right)$$



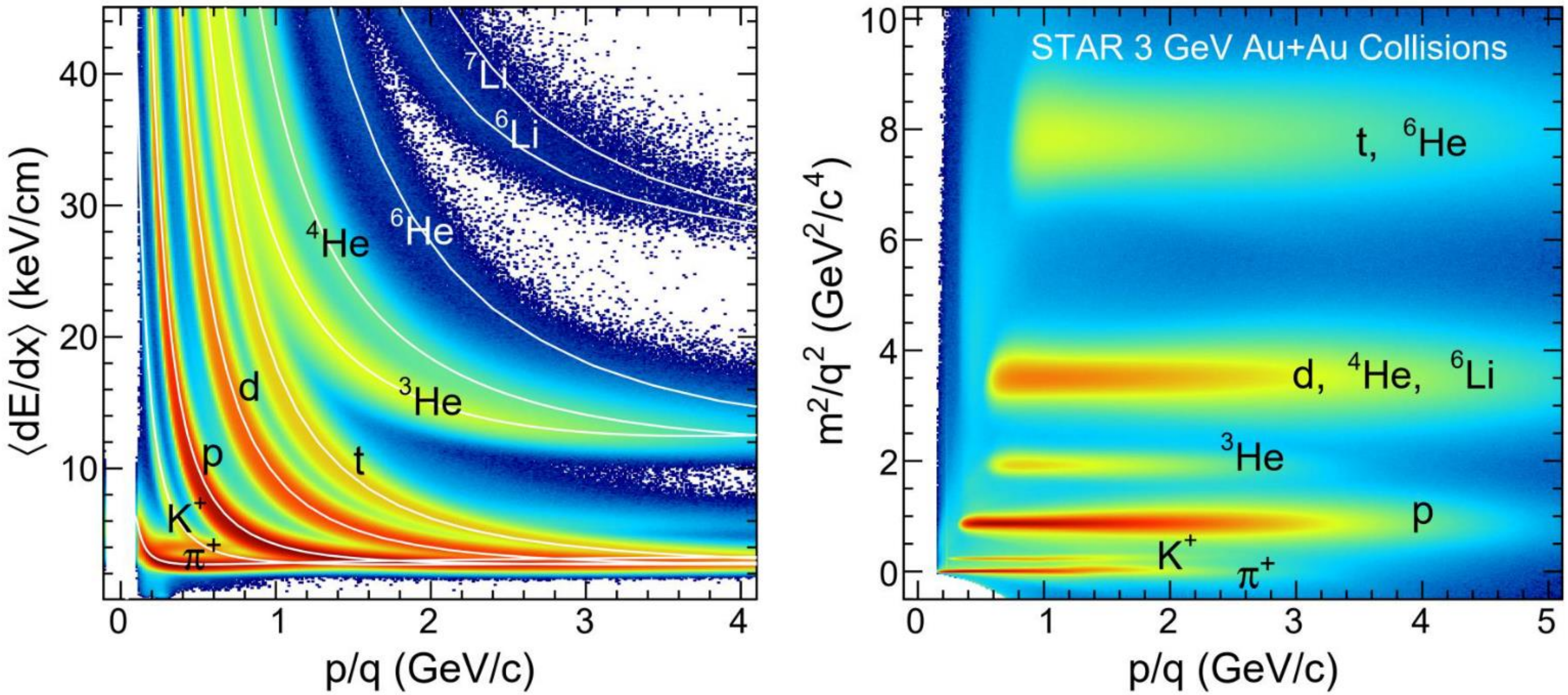




Gold target:

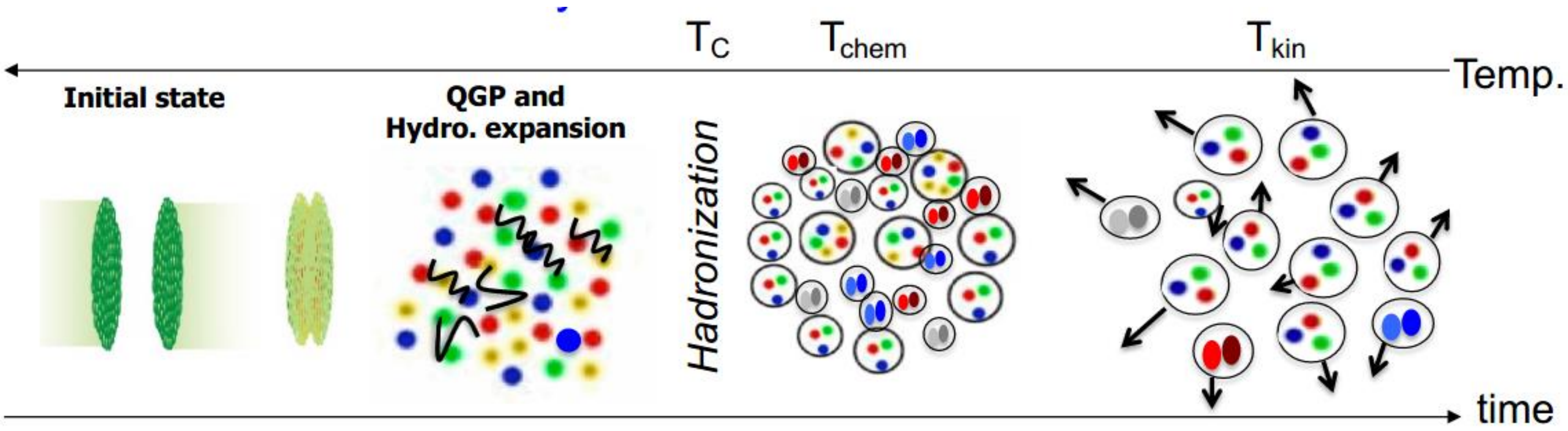
- 2 cm below nominal beam axis
- 2 m from center of STAR
- 250 μm foil

Particle Identification at STAR



Good particle identification in a broad momentum range using TPC and TOF

Evolution of the High-Energy Heavy-Ion Collision



Colliding ions	Deconfined state	Chemical freeze-out	Kinetic freeze-out
		✧ Inelastic collisions cease ✧ Particle yield fixed	✧ Elastic collisions cease ✧ Spectral shape fixed

Freeze-out (FO) parameters

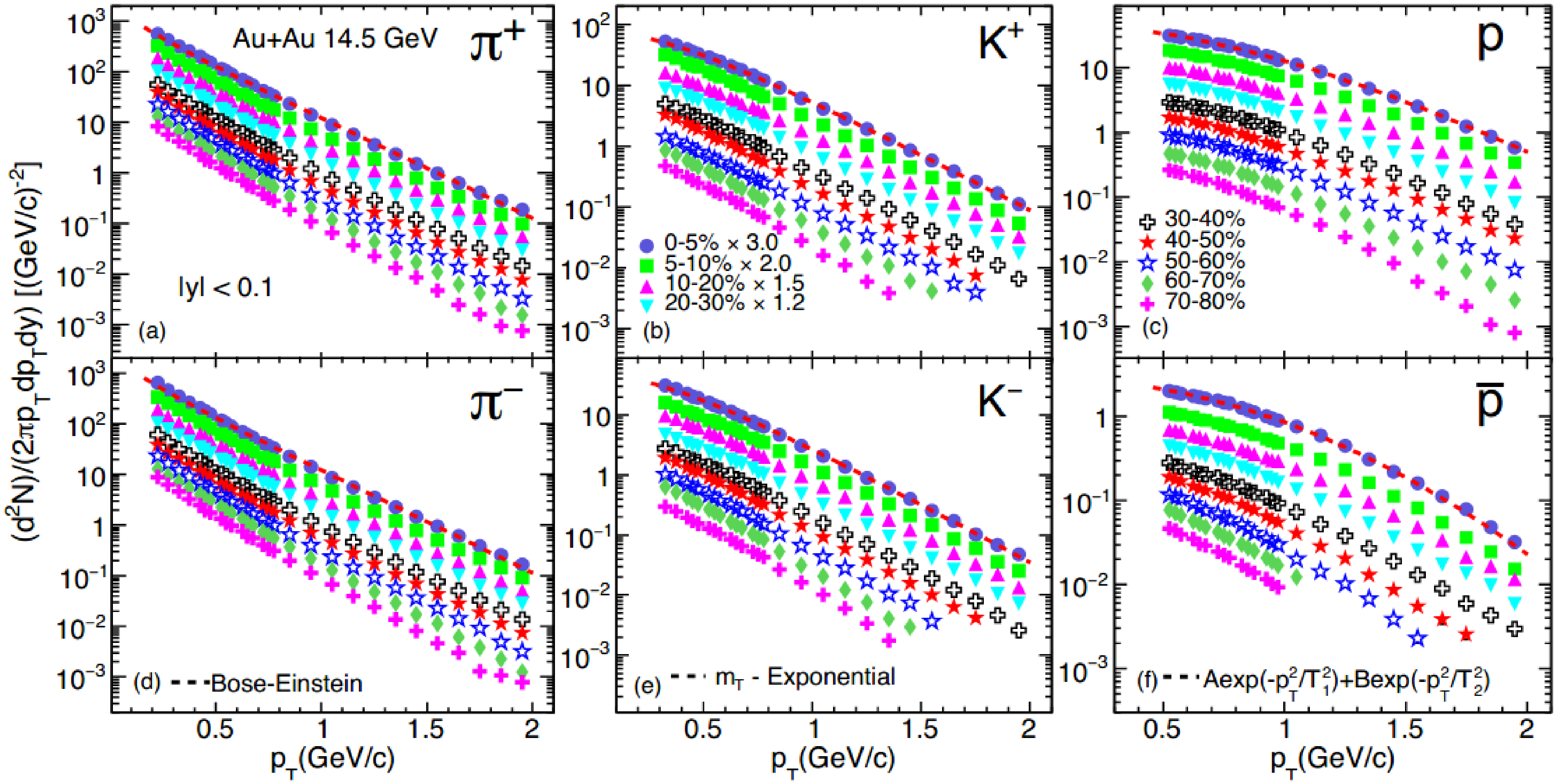
- Statistical thermal model: T_{ch} and μ_B
- Blast-wave model: T_{kin} and $\langle\beta\rangle$

Particle Yields and **Ratios:** provide Information about QCD phase diagram

Transverse Momentum Spectra

Au+Au @ 14.5 GeV

STAR. Phys. Rev. C 101, 024905 (2020)



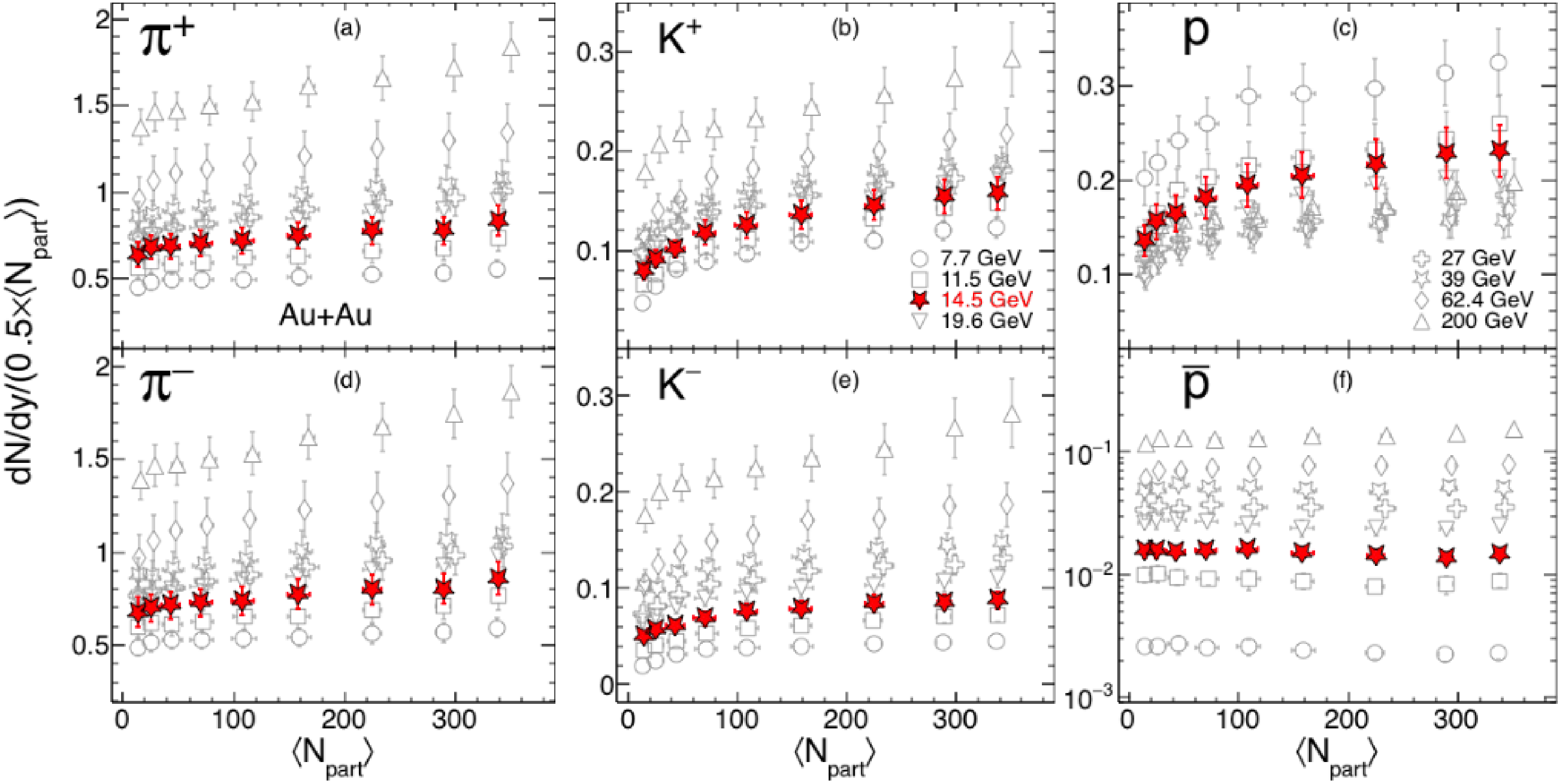
Integrating over full p_T range gives particle yield (dN/dy)

Particle Yields

STAR: PRC **96**, 044904 (2017)

Au+Au @ 14.5 GeV

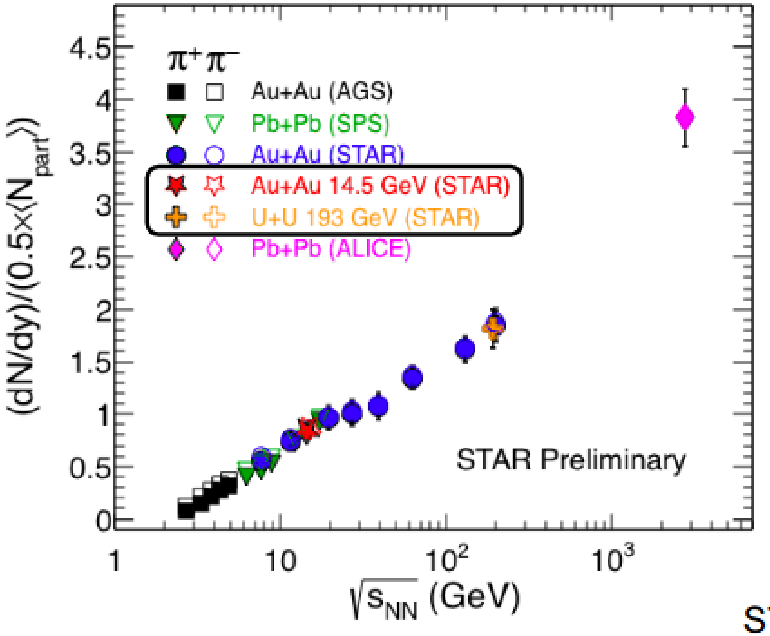
STAR. Phys. Rev. C 101, 024905 (2020)



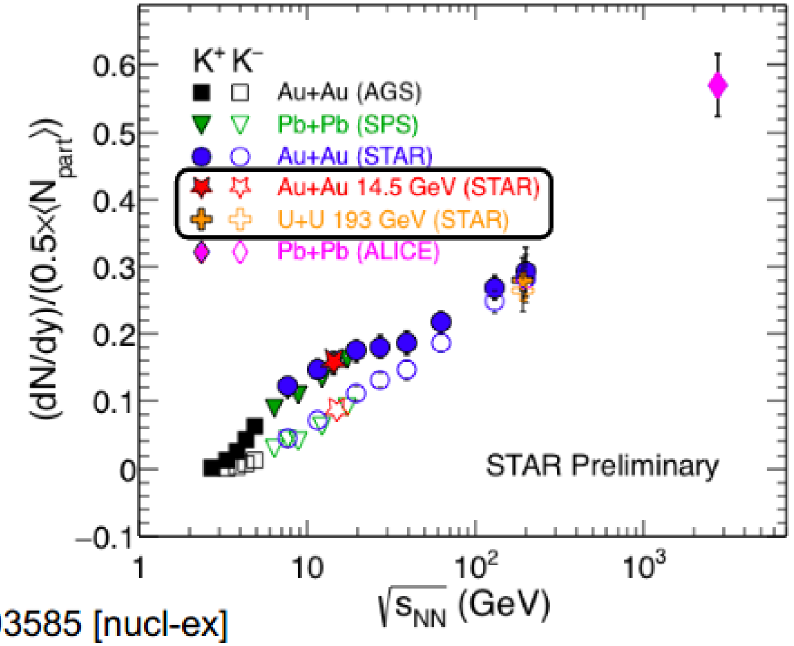
Yields @ 14.5 GeV:

-- Increase from peripheral to central collisions (except for $\bar{p}$)
-- Fall in the energy dependence trend

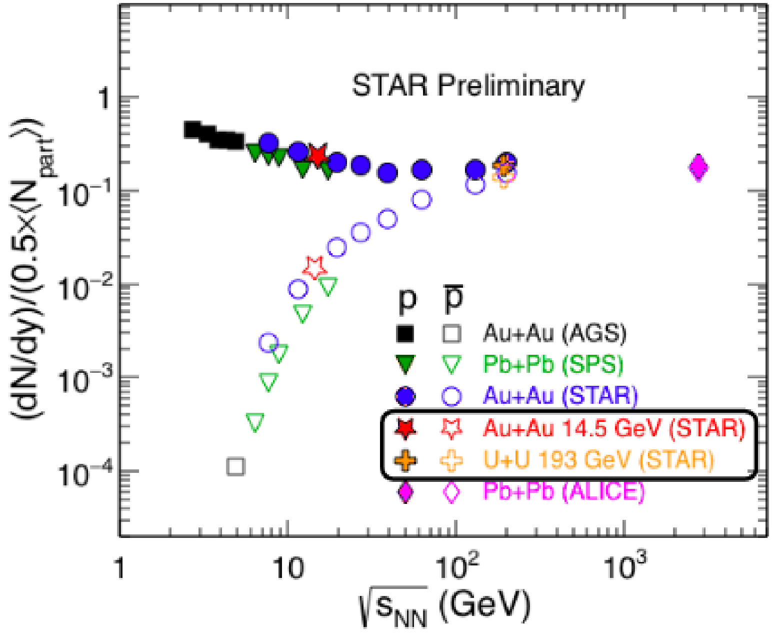
Energy Dependence of Particle Yields



STAR: PRC **96**, 044904 (2017)



STAR: arXiv:1908.03585 [nucl-ex]

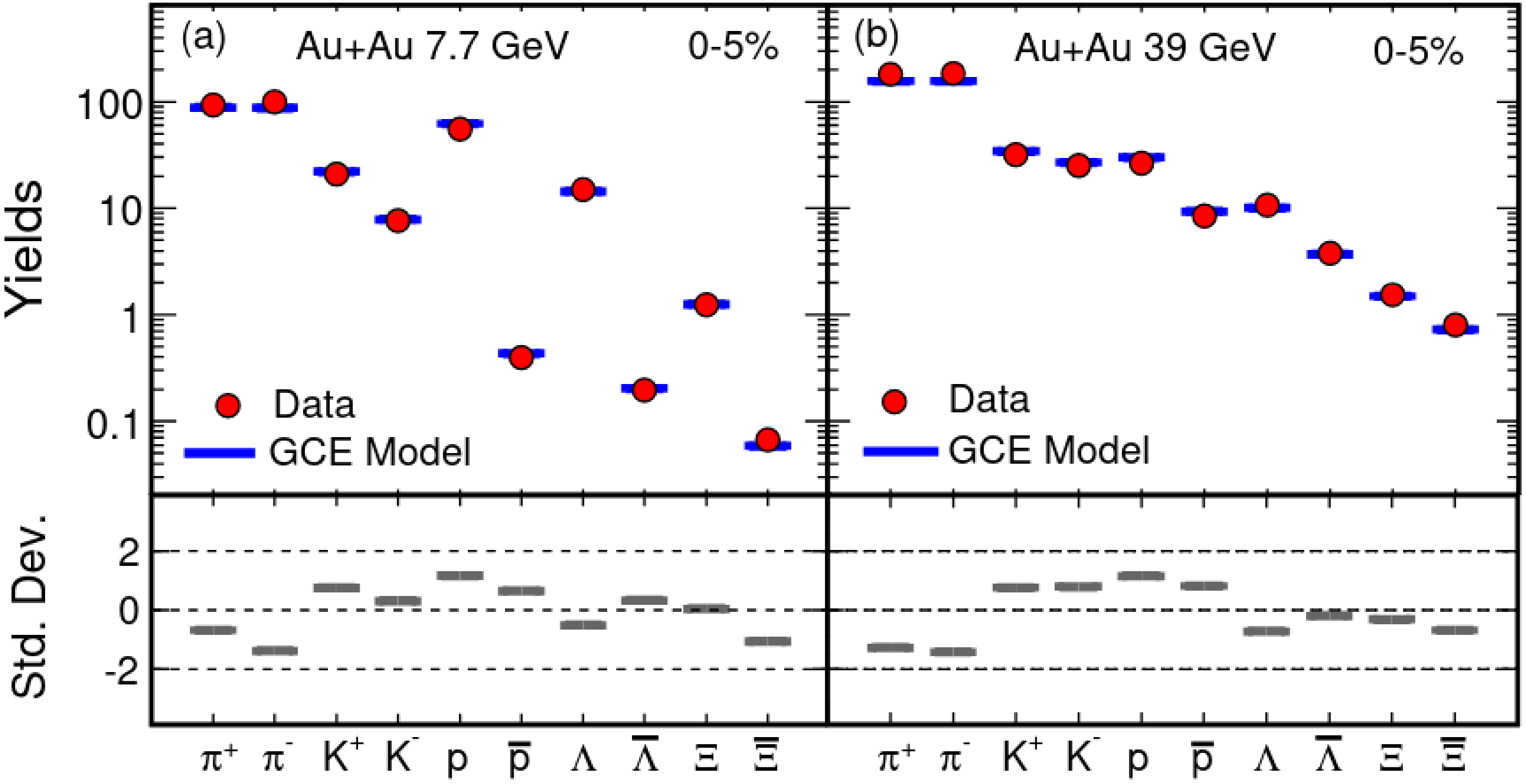


- Yields increase as a function of collision energy except for protons
- *Au+Au 14.5 GeV and U+U 193 GeV fit well in the trend*
- **Higher energies:** Similar (pair) production of particle and anti-particle

Lower energies: $\pi^- > \pi^+$, $K^+ > K^-$, $p > \bar{p}$

Extracting Baryon Chemical Potential and Temperature at Chemical Freeze-Out

STAR. Phys. Rev. C 96, 044904 (2017)



Considering the grand canonical case, for a hadron gas of volume V and temperature T, the logarithm of the total partition function is given by [50],

$$\ln Z^{GC}(T, V, \{\mu_i\}) = \sum_{\text{species i}} \frac{g_i V}{(2\pi)^3} \int d^3p \ln(1 \pm e^{-\beta(E_i-\mu_i)})^{\pm 1} \quad (7)$$

where, g_i and μ_i are degeneracy and chemical potential of hadron species i respectively, $\beta = 1/T$, and $E_i = \sqrt{p^2 + m_i^2}$, m_i being the mass of particle. The plus sign corresponds to fermions and minus sign to bosons. The chemical potential for particle species i in this case is given by

$$\mu_i = B_i\mu_B + Q_i\mu_Q + S_i\mu_S, \quad (8)$$

where B_i, S_i, and Q_i are the baryon number, strangeness, and charge number, respectively, of hadron species i, and μ_B, μ_Q, and μ_S are the respective chemical potentials.

Extracting Parameters of the Quark-Gluon Matter at Kinetic Freeze-Out

- The kinetic freeze-out parameters are obtained by fitting the spectra with a blast wave model. The model assumes that the particles are locally thermalized at a kinetic freeze-out temperature and are moving with a common transverse collective flow velocity. Assuming a radially boosted thermal source, with a kinetic freeze-out temperature T_{kin} and a transverse radial flow velocity β, the p_T distribution of the particles is given by

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

where m_T is the transverse mass of a hadron, $\rho(r) = \tanh^{-1}\beta$, and I_0 and K_1 are the modified Bessel functions.

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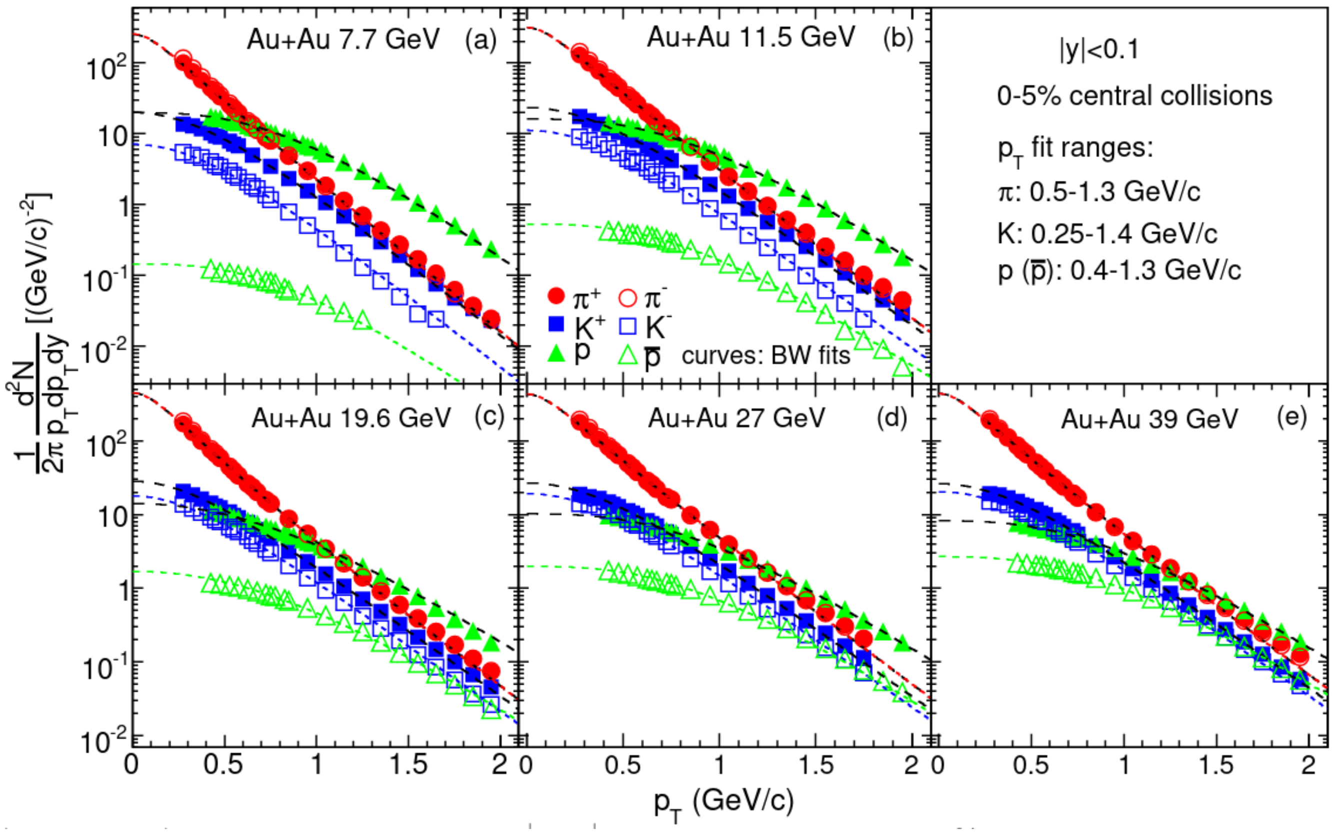

Mapping QCD Phase Diagram

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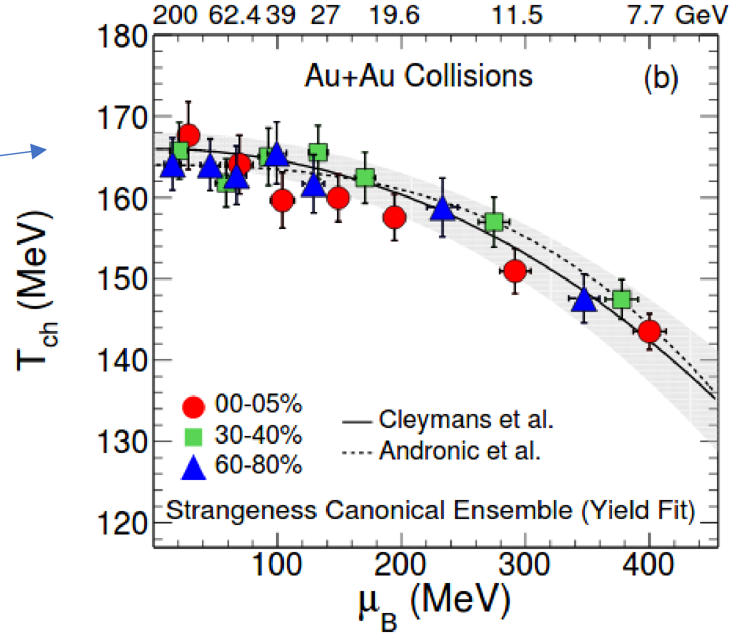
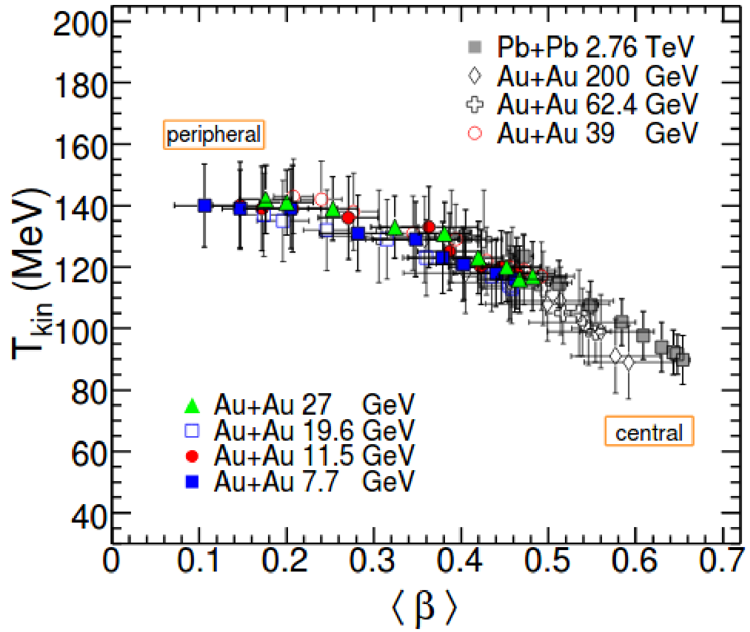
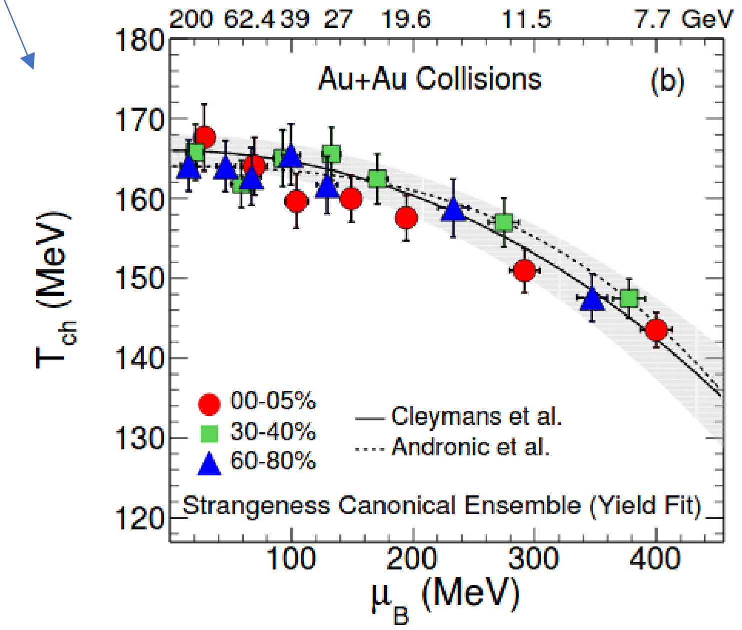
- Using a statistical equilibrium model and the measured particle yields, one can estimate the location of the phase diagram
- The 〈β〉 decreases from central to peripheral collisions indicating more rapid expansion in central collisions
- T_{kin} increases from central to peripheral collisions, consistent with the expectation of a shorter-lived fireball in peripheral collisions







Energy Dependence of Freeze-out Parameters

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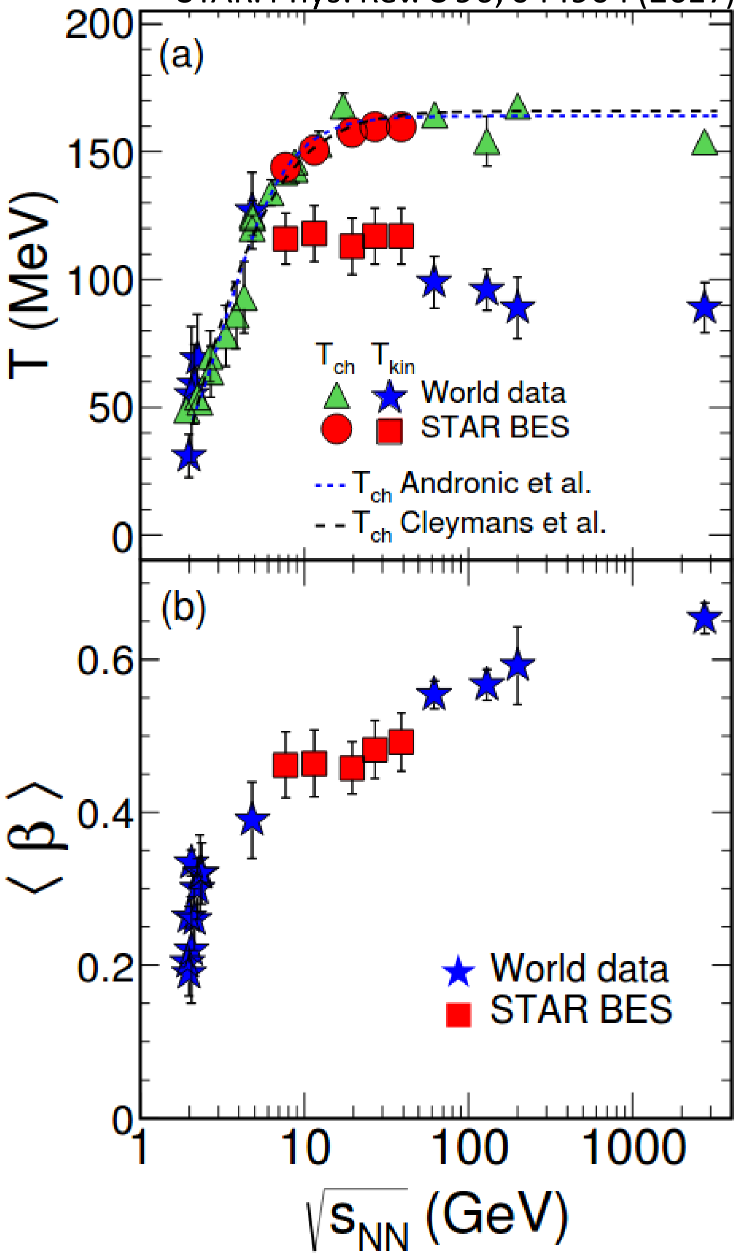
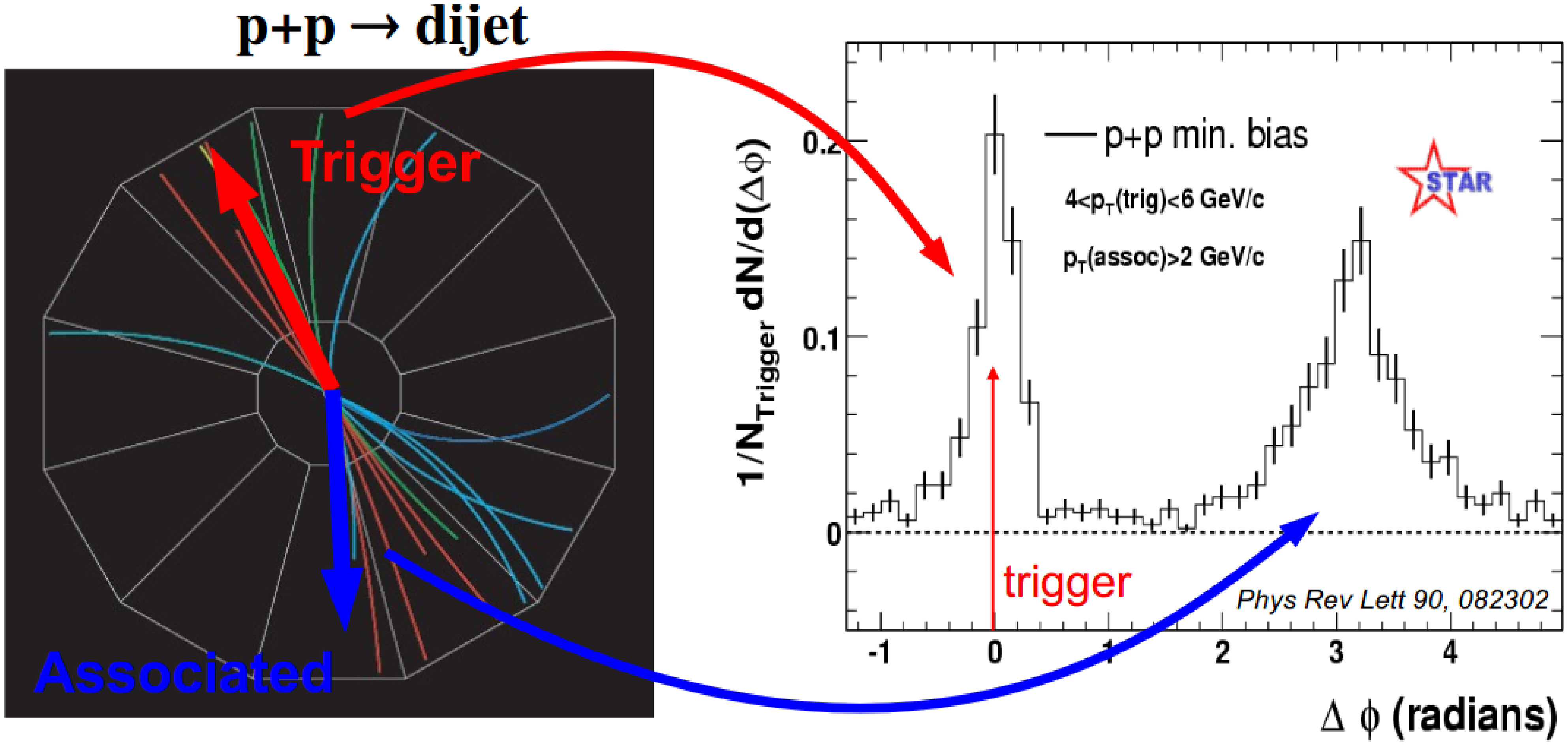


- Chemical freeze-out temperature increases and then saturates with beam energy
- Kinetic freeze-out temperature decreases while <β> (collectivity) increases with beam energy for central collisions
- Difference between chemical and kinetic freeze-out temperatures increases with beam energy
  - Suggests system interacts for longer duration at higher collisions energies

QGP at High Collision Energies



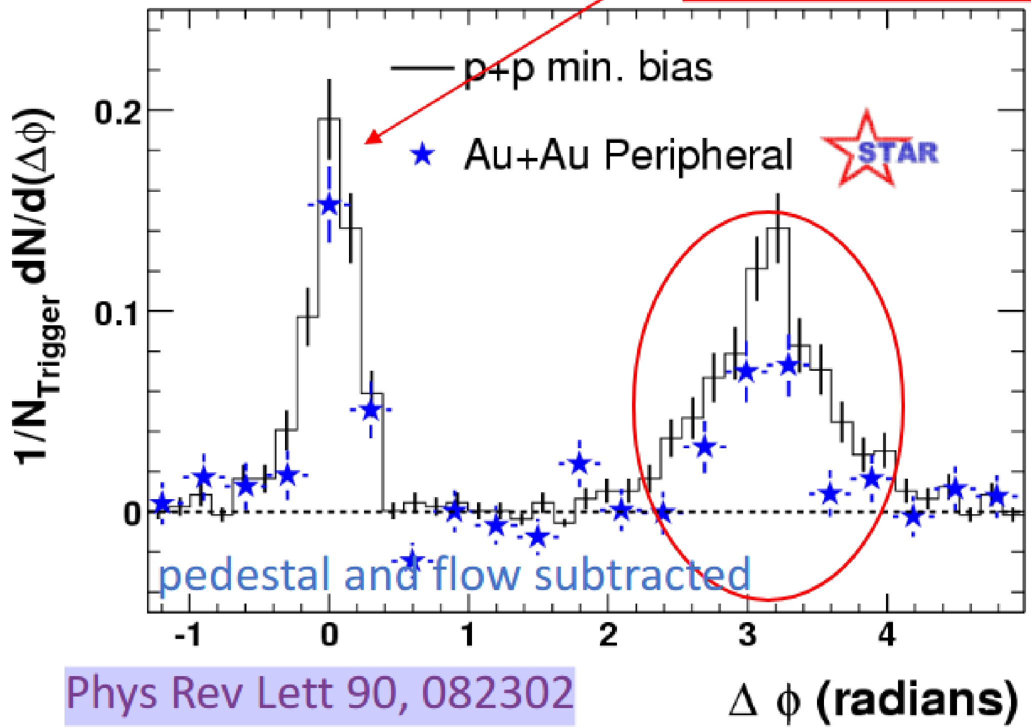
Select high momentum particles → biased towards jets

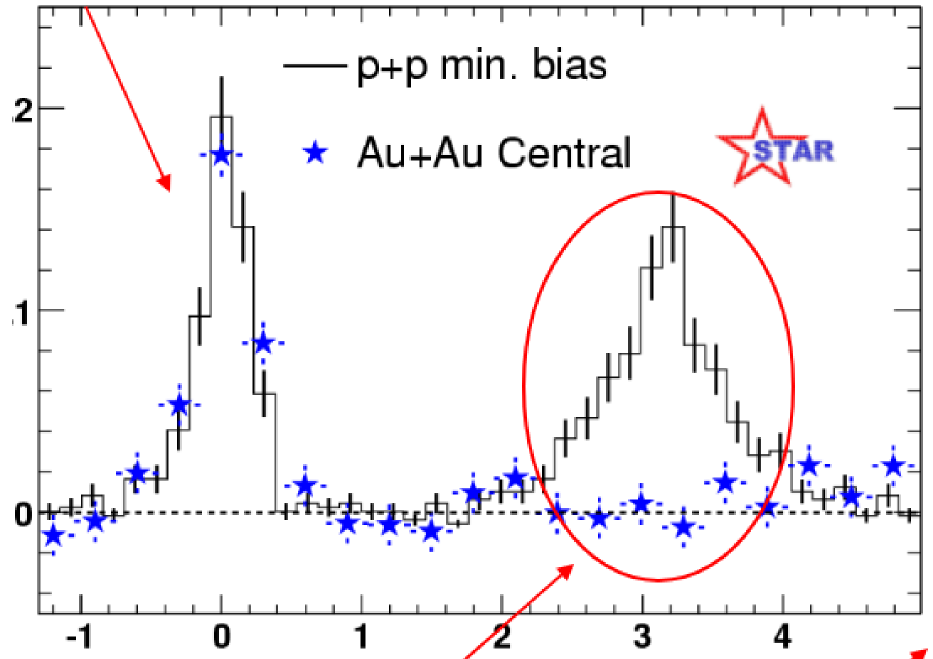
QGP at High Collision Energies

Au+Au peripheral

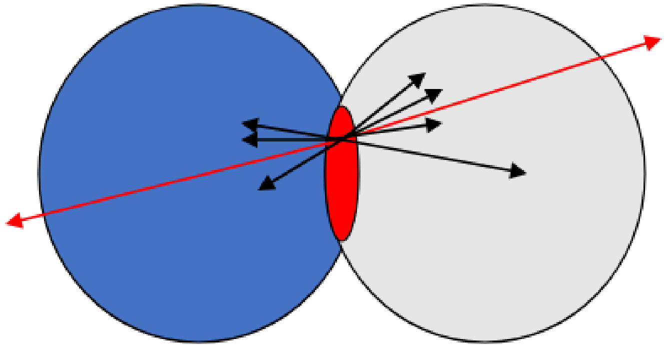
Near-side: peripheral and central Au+Au similar to p+p

Au+Au central

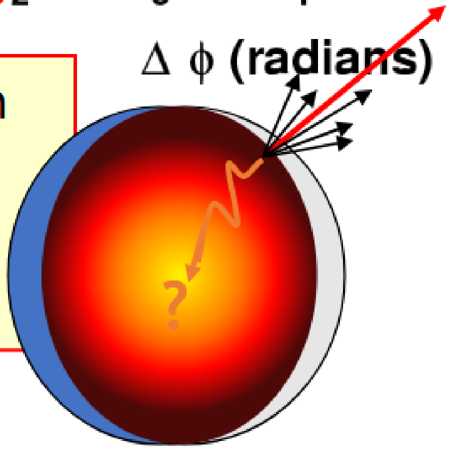




Phys Rev Lett 90, 082302



Strong suppression of back-to-back correlations in central Au+Au



Identifying QGP at High-Energy Collisions

$$R_{AA} = \frac{1}{N_{coll}} \times \frac{Y_{AA}}{Y_{pp}}$$

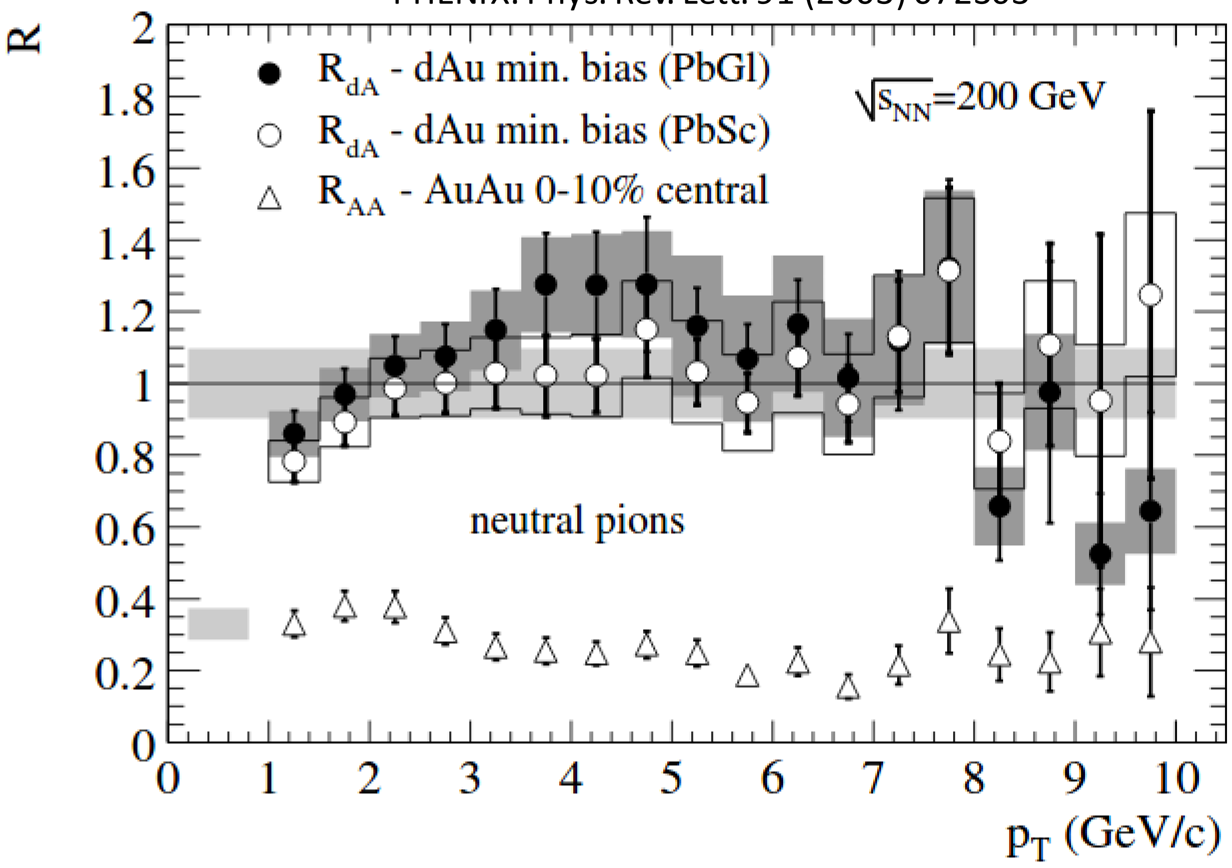
Superposition of NN collisions → $R_{AA}=1$

Suppression → $R_{AA}<1$

Enhancement → $R_{AA}>1$

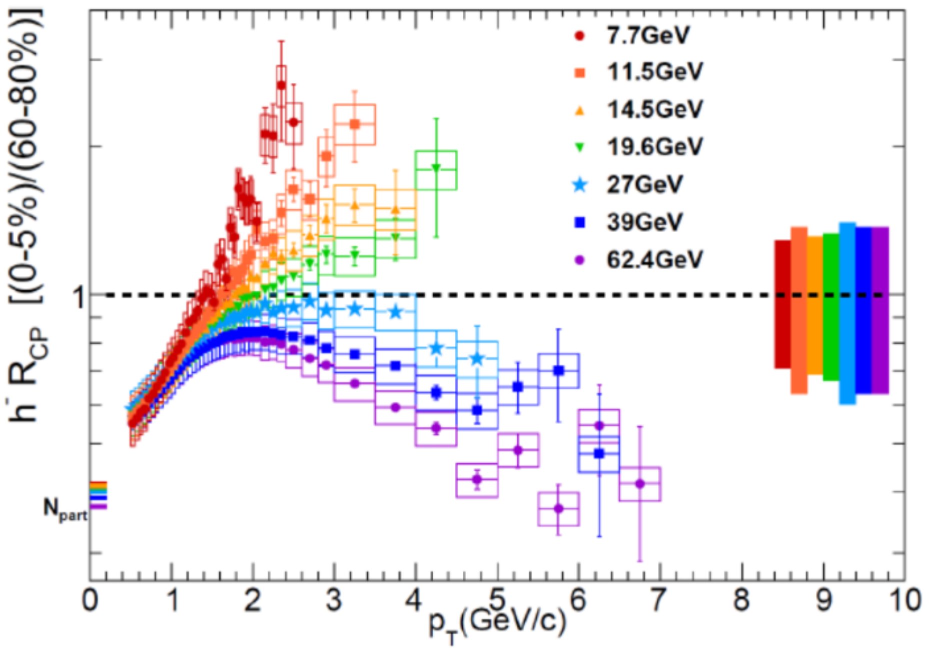
- The data clearly indicate that there is no suppression of high-pT particles in d+Au collisions.
- The data suggest, instead, that the suppression of high-pT hadrons in Au+Au is more likely a final state effect of the produced dense medium

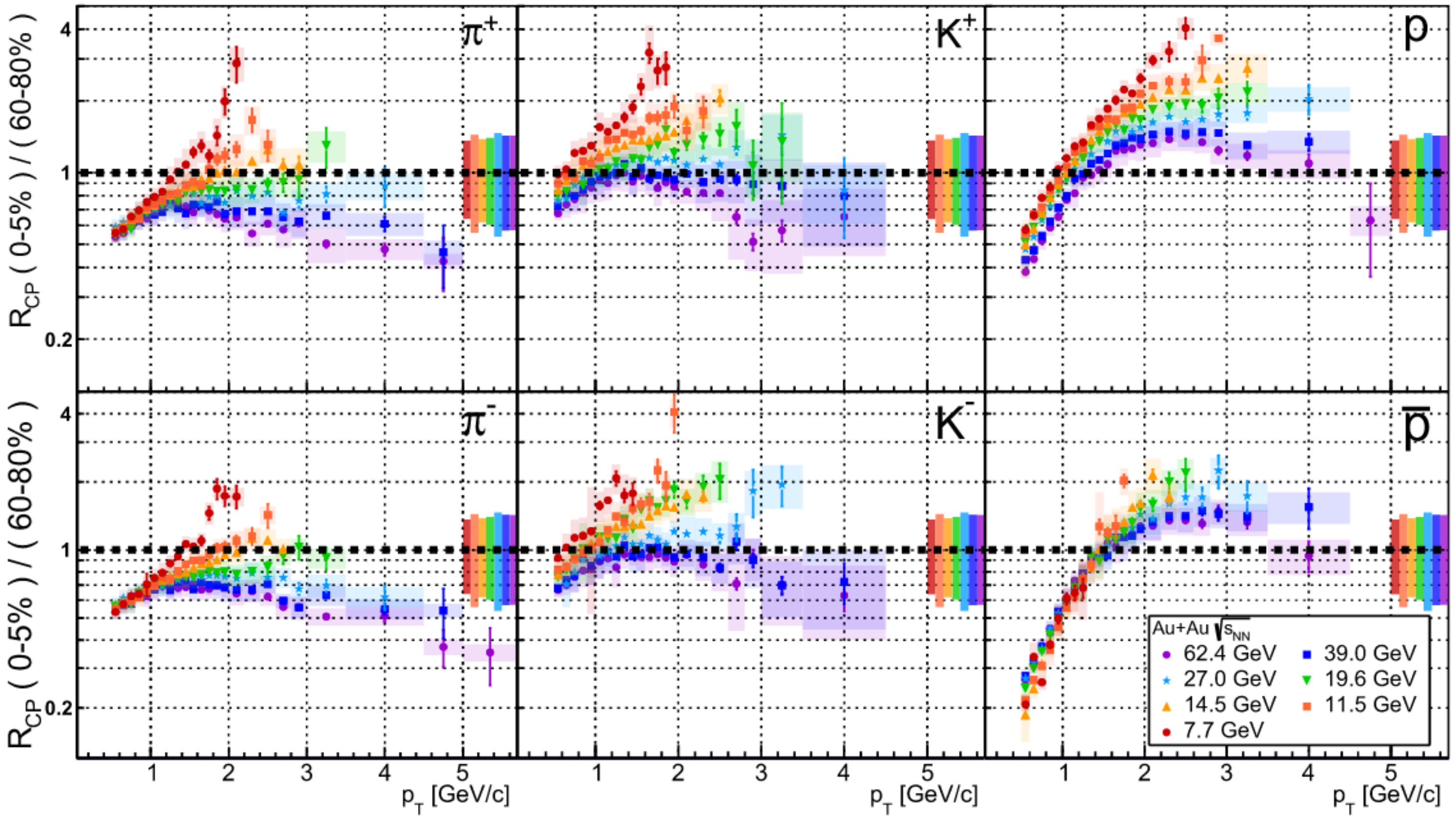
PHENIX. Phys. Rev. Lett. 91 (2003) 072303



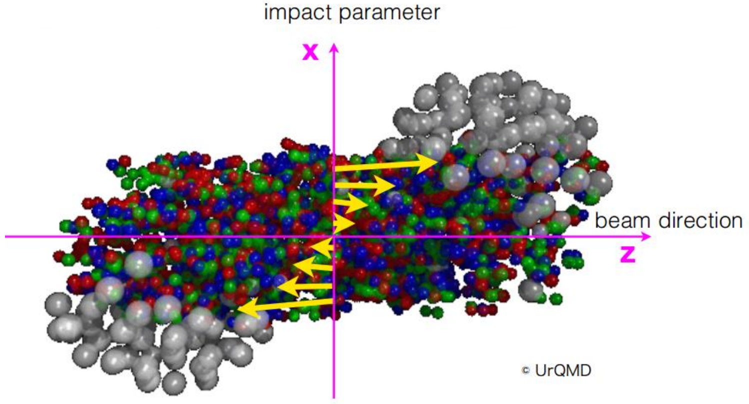
Searching for Turn-Off Signatures of QGP

$$R_{cp} = \frac{d^2Ndp_t d\eta / < N_{coll} > (central)}{d^2Ndp_t d\eta / < N_{coll} > (peripheral)}$$

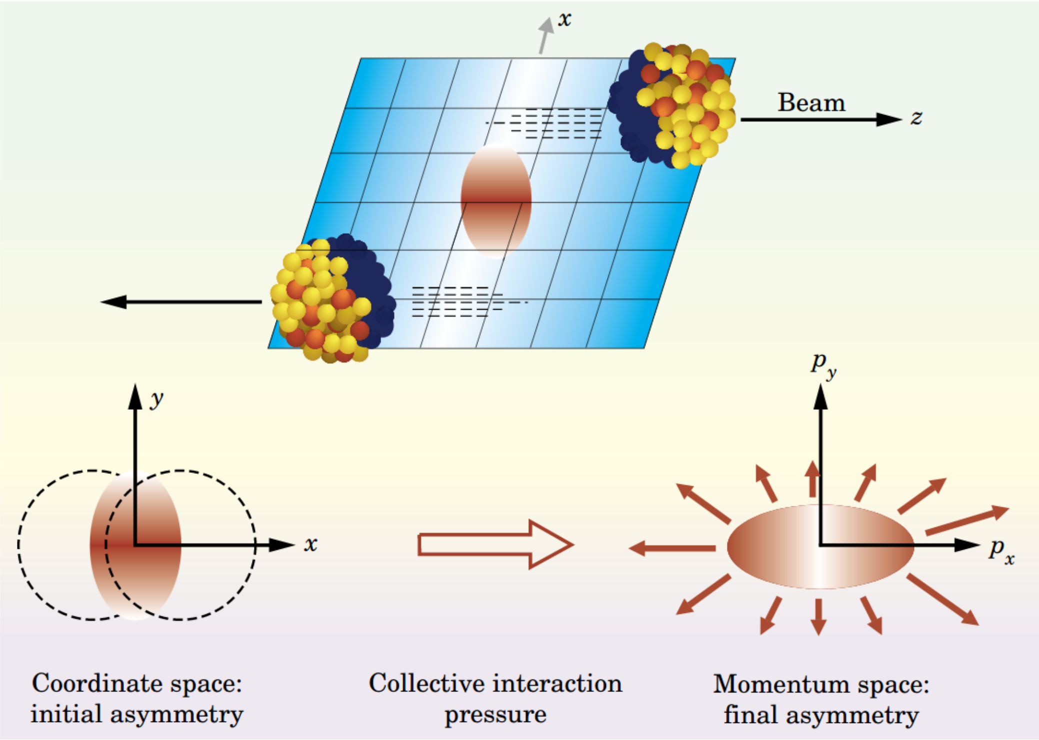




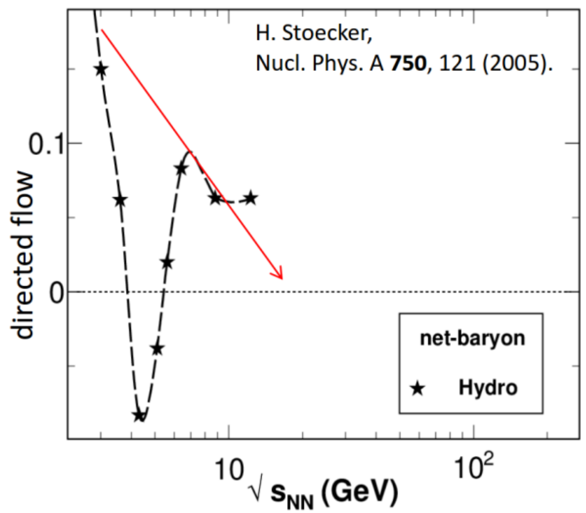
Azimuthal Anisotropy in Heavy-Ion Collisions



$$E\frac{d^3N}{d^3p}=\frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}\left(1+\sum_{n=1}^{\infty}2v_n\cos[n(\phi-\Psi_r)]\right)$$

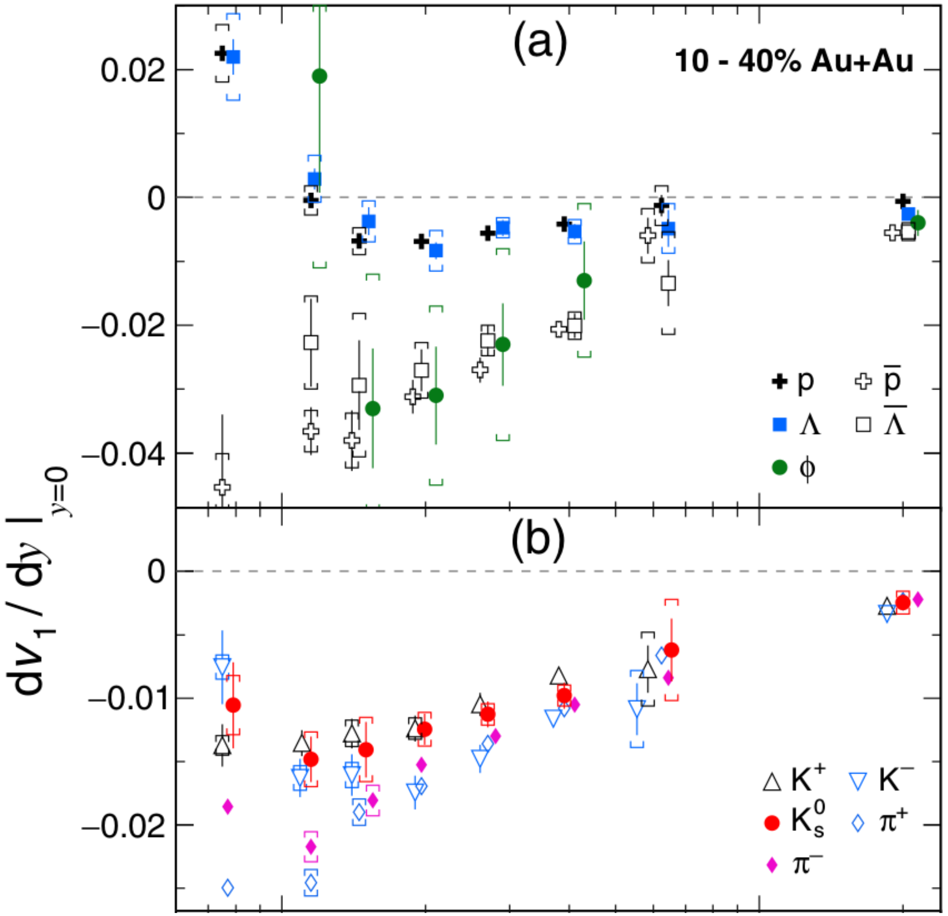


- v_1=<p_x/p_T> – directed flow
  - Describes the sideward collective motion of particles within the reaction plane (x-z)
  - Probe of the softening of the EoS:
    - Strong softening: consistent with the 1st-order phase transition
    - Weaker softening: more likely due to crossover
- v_2 – elliptic flow
  - Sensitive to the properties of the medium



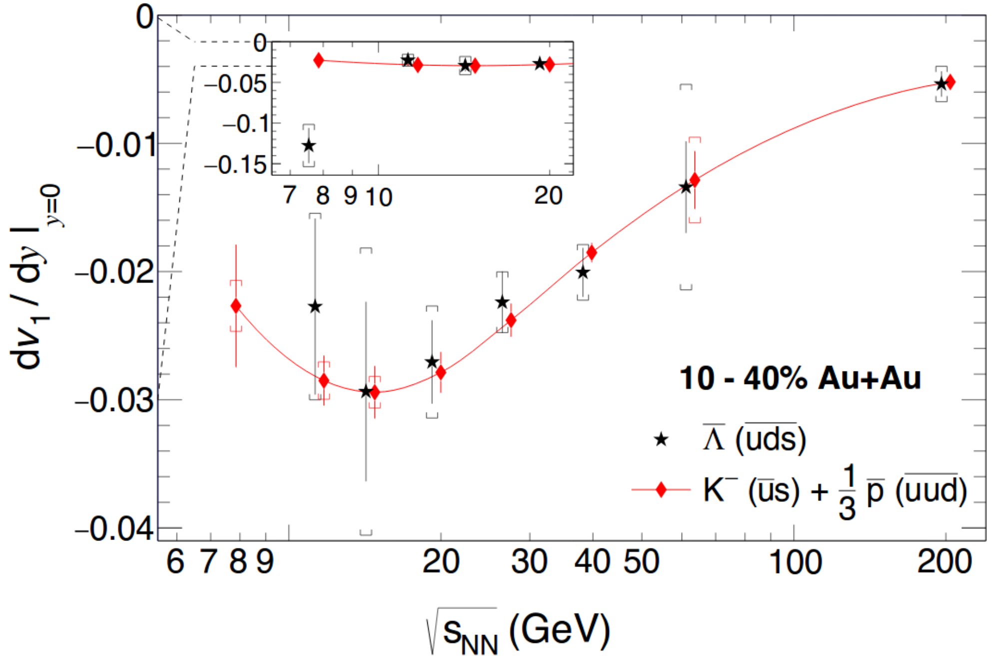
Nara, Niemi, Steinheimer, Stöker. Phys. Lett. B 769 (2017) 543
Ivanov, Soldatov. Phys. Rev. C 91 (2015) 024915

Beam-Energy Dependence of Directed Flow



- dv_1/dy for Λ and p agree within uncertainties
- dv_1/dy slope for baryons changes sign in the region $\sqrt{s_{NN}}$<14.5 GeV
- Particles (anti-p, anti-Λ, and φ) with produced quarks show similar behavior for $\sqrt{s_{NN}}$>14.5 GeV
- Mesons show negative dv_1/dy

STAR. Phys. Rev. Lett. 120 (2018) 062301

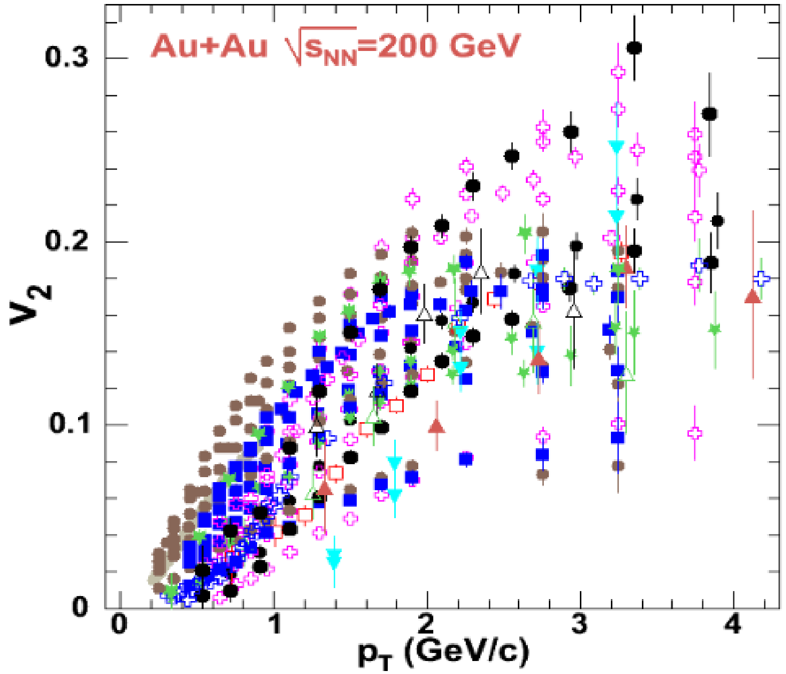


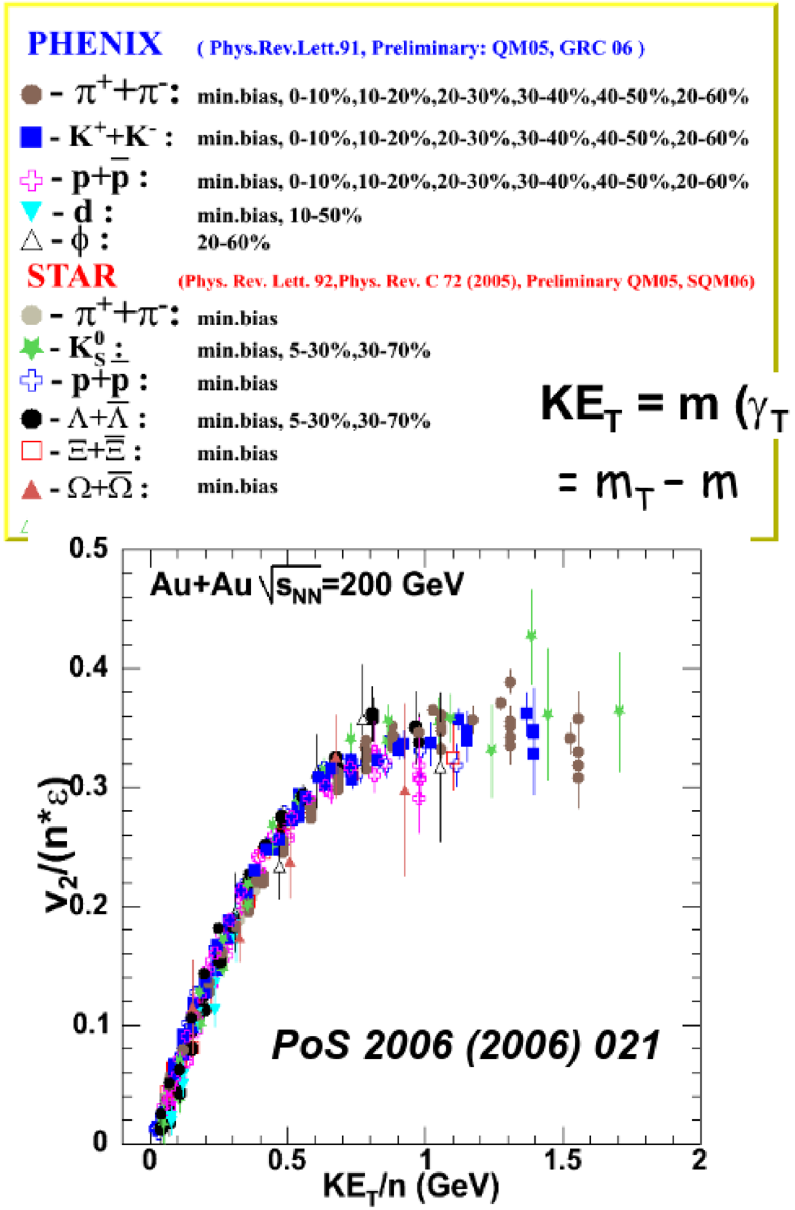
For anti-Λ, prediction using coalescence sum rule agrees with measured v_1 above $\sqrt{s_{NN}}$=11.5 GeV

<u>Assumptions for coalescence sum rule</u>:

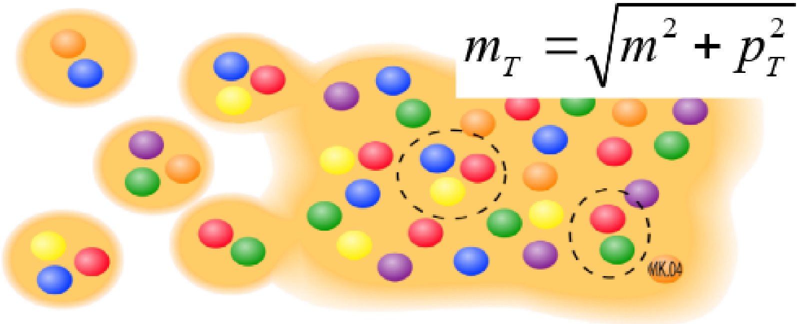
1. v_1 is developed at prehadronic stage
2. Specific types of quarks have the same v_1
3. Hadrons are formed via coalescence

Anisotropic Flow at RHIC – scaling relations





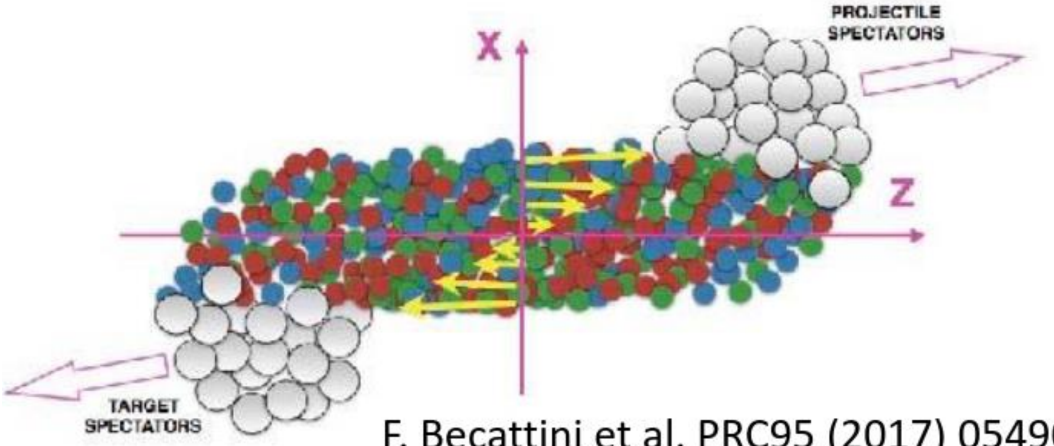
$$KE_T = m(\gamma_T - 1)$$
$$= m_T - m$$



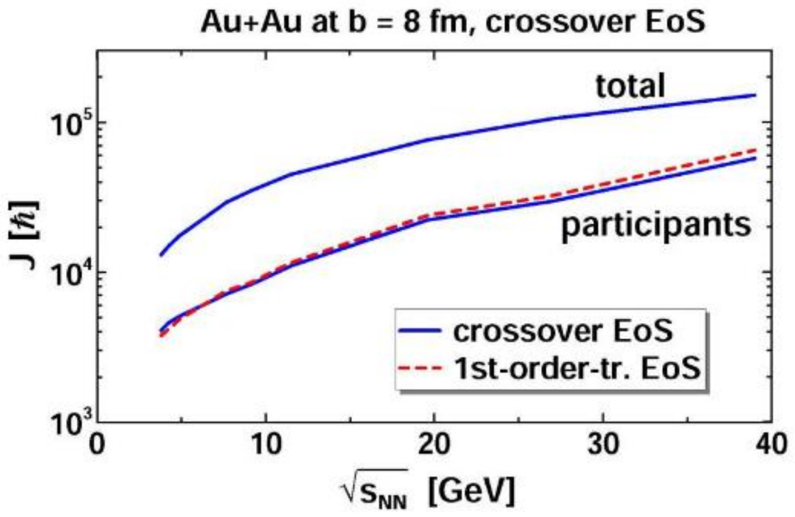
$$m_T = \sqrt{m^2 + p_T^2}$$

n=2 for mesons and n=3 for baryons

Vortical motion of nuclear matter

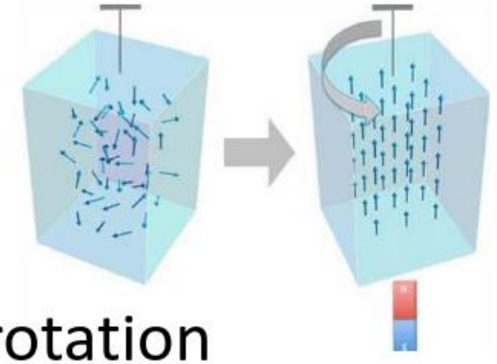


F. Becattini et al. PRC95 (2017) 054902



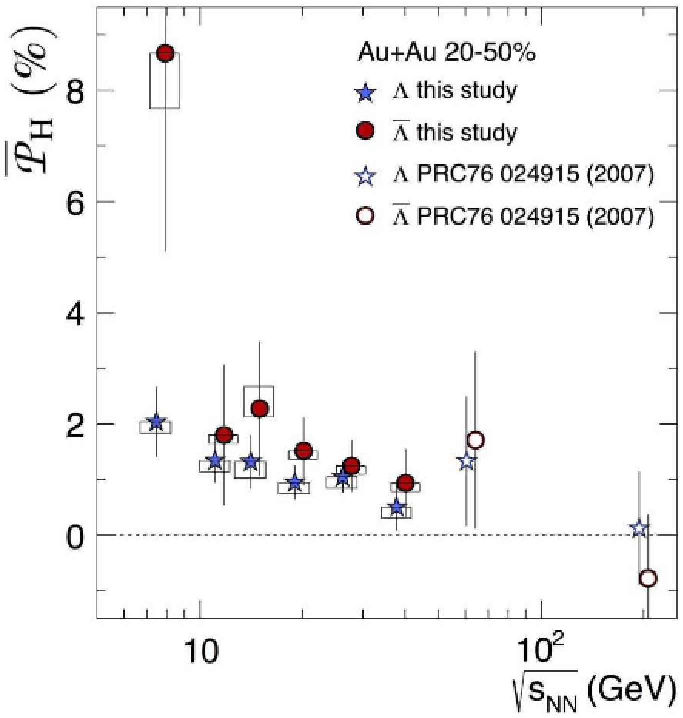
Vortical motion: $\boldsymbol{\omega} = (1/2)\ \boldsymbol{\nabla} \times \mathbf{v}$ = **Vorticity**

Relativistic Vorticity = $\omega_{\mu\nu} = \frac{1}{2}(\partial_\nu u_\mu - \partial_\mu u_\nu)$



- Angular momentum → spin polarization
- Similarly to Barnett effect (1915): magnetization by rotation

Polarization Measurements



STAR

- ✓ Global Λ and anti-Λ polarization [Nature 548, 62 (2017)]
- ✓ Local polarization of hyperons along the beam direction [PRL 123, 132301 (2019)]
- ✓ Measurement of global spin alignment of vector Mesons [NPA 1005 (2021) 121733]
- ✓ Global polarization of Ξ and Ω hyperons at 200 GeV
- ✓ [PRL 126 (2021) 16, 162301]

Global polarization is measured from the angular distributions of hyperon decay product:

$$P_H = \frac{8}{\pi \alpha_H} \frac{\langle \sin(\Psi_1 - \phi_d^*) \rangle}{\text{Res}(\Psi_1)}$$

Thermal vorticity:

$$\omega = k_B T (P_\Lambda + P_{\bar{\Lambda}})/\hbar \qquad \omega \sim (9 \pm 1) \times 10^{21} s^{-1}$$

F. Becattini et al., PRC95, 054902(2017)

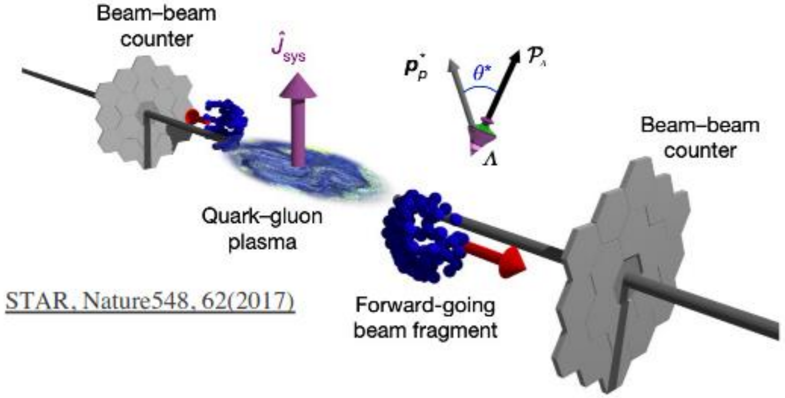
At NICA and FAIR energies, data are still very scarce

- ➢ HADES: Λ Polarization at 2.4 GeV [PLB 835 (2022) 137506]
- ➢ STAR-FXT: Λ Polarization at 3 and 7.2.GeV

PRC 104 (2021) L061901; EPJ Web Conf. 259, 06003 (2022).

Global Polarization in BES and FXT

The average vorticity points along the direction of the angular momentum of the $\hat{J}_{sys}$



STAR, Nature548, 62(2017)

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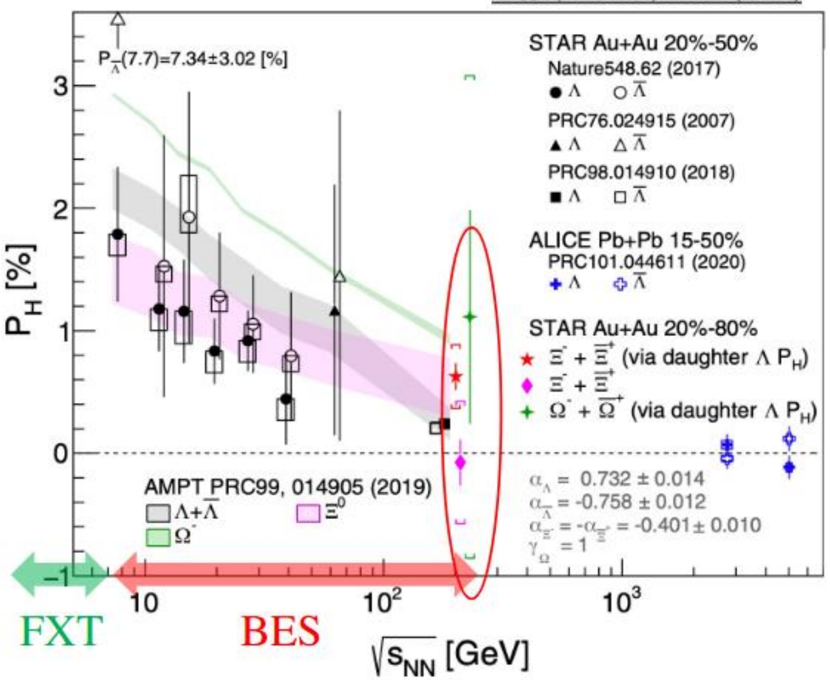
F. Becattini et al., PRC95, 054902(2017)

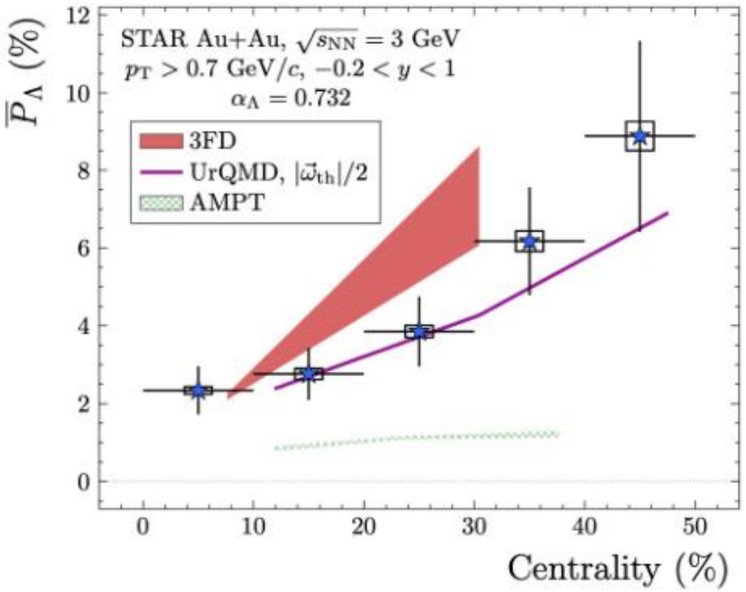
STAR, PRL126, 162301(2021)



Large angular momentum transferred by the two colliding nuclei

Stronger polarization at lower collision energies.

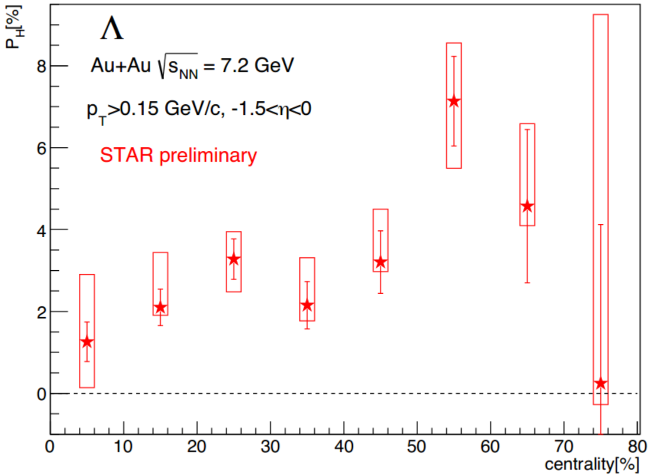
STAR, arXiv:2108.00044



Much larger $\bar{P}_\Lambda$ in FXT 3 GeV at 20-50%

4.91 ± 0.81 (stat.) ± 0.15 (syst.)%

Larger hyperon polarization for more peripheral collisions



Opens up new directions in the study of the hottest, least viscous and most vortical fluid matter.

Correlation Femtoscopy

- Two-particle correlation function (CF):

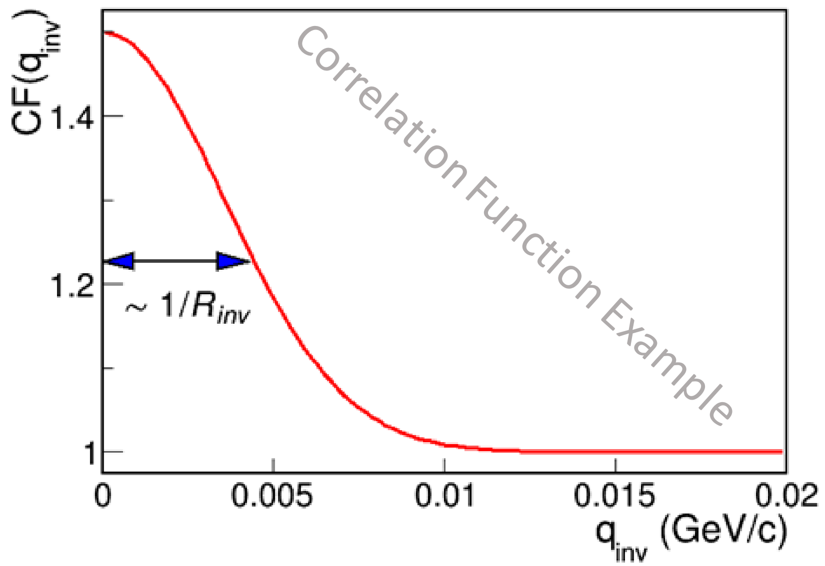
$$CF(p_1, p_2)=\int d^4r\, S(r, k)\, |\Psi_{1,2}(r, k)|^2$$

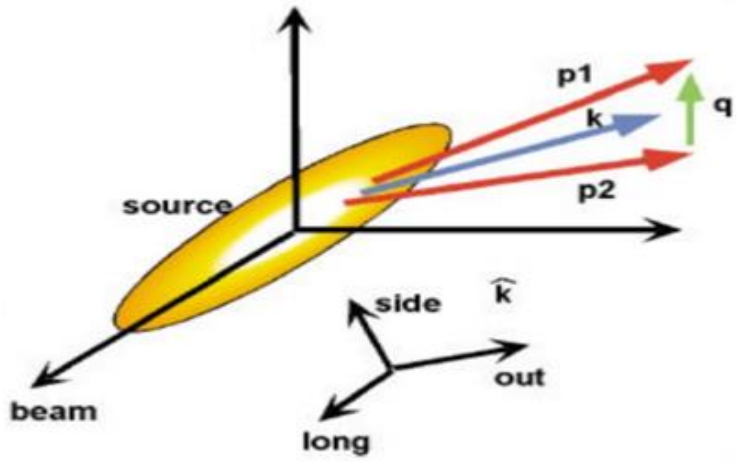
$$r=x_1-x_2 \text{ and } q\equiv q_{inv}= p_1 - p_2$$

- Experimentally:

$$CF(q) = A(q)/B(q)$$

  - A(q) – contain quantum statistical (QS) correlations and final state interactions (FSI)
  - B(q) – obtained via mixing technique (does not contain QS and FSI)





S. Pratt. PRD 33 (1986) 1314
G. Bertsch. PRC 37 (1988) 1896

The relative pair momentum can be projected onto the Bertsch-Pratt, out-side-long system:

q_{long} – along the beam direction

q_{out} – along the transverse momentum of the pair

q_{side} – perpendicular to longitudinal and outward directions

Correlation functions are constructed in Longitudinally Co-Moving System (LCMS), where $p_{1z}+p_{2z}=0$

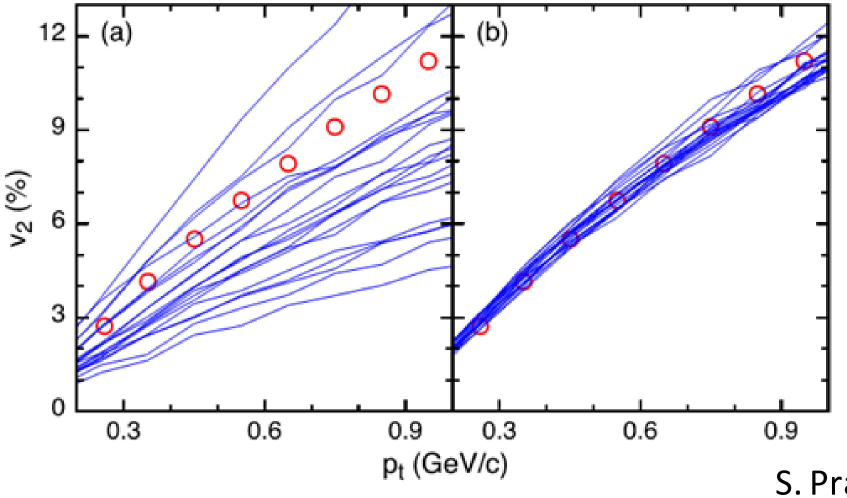
Why Correlation Femtoscopy?

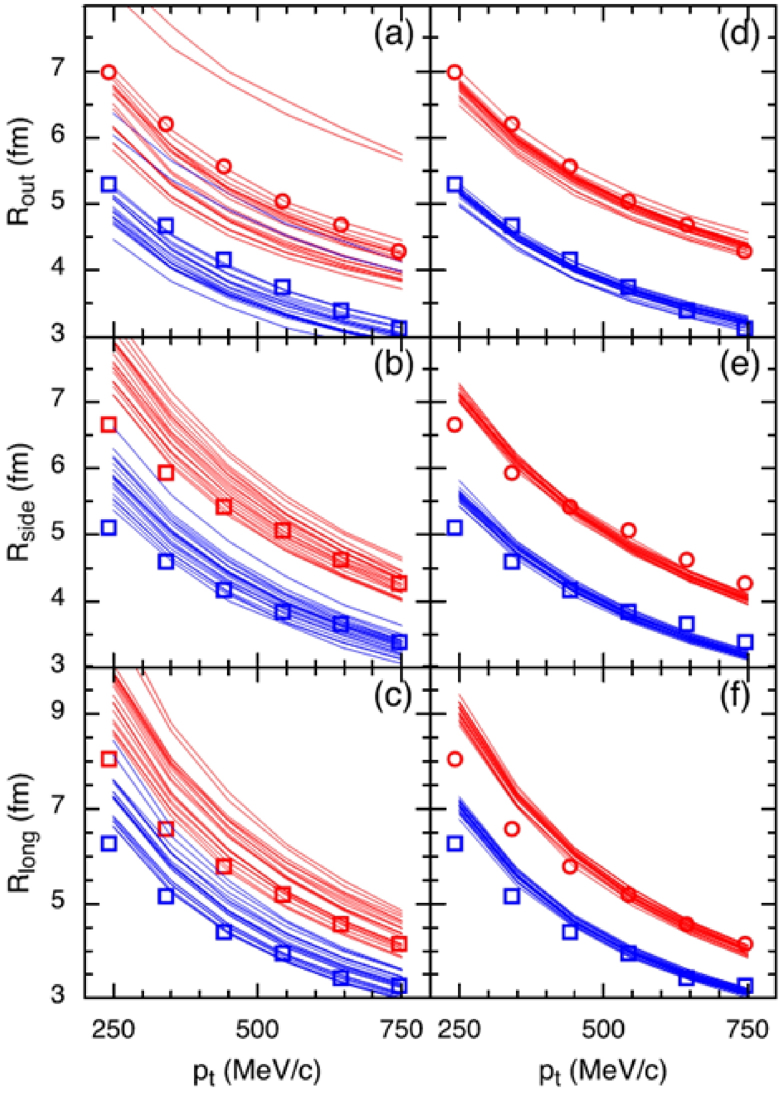
- Access to the spatial and temporal information about a particle-emitting source at kinetic freeze-out

- Different particle species are sensitive to various effects (Final State Interactions (FSI), transport properties, asymmetries, etc...)

V.M. Shapoval et al. NPA 968 (2017) 391
M.A. Lisa et al. Ann. Rev. Nucl. Part. Sci. 55 (2005) 357
D.H. Rischke, M. Gyulassy. NPA 608 (1996) 479
R. Lednicky et al. Phys. Lett. B 373 (1996) 30

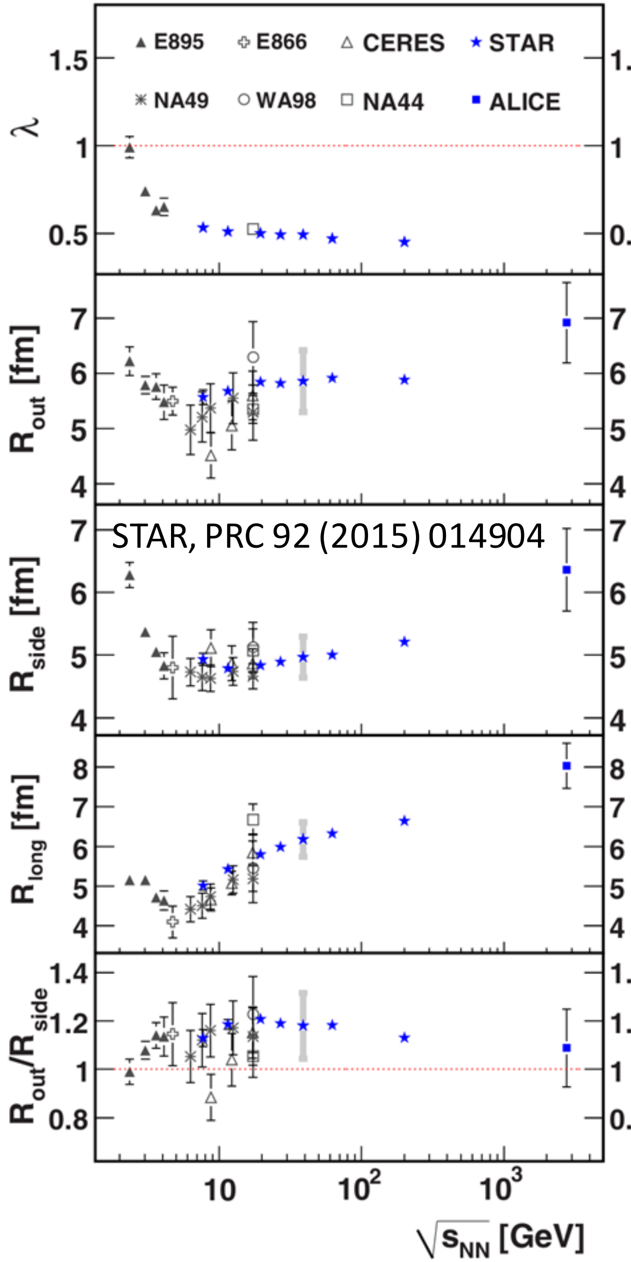
- Strong model constraints





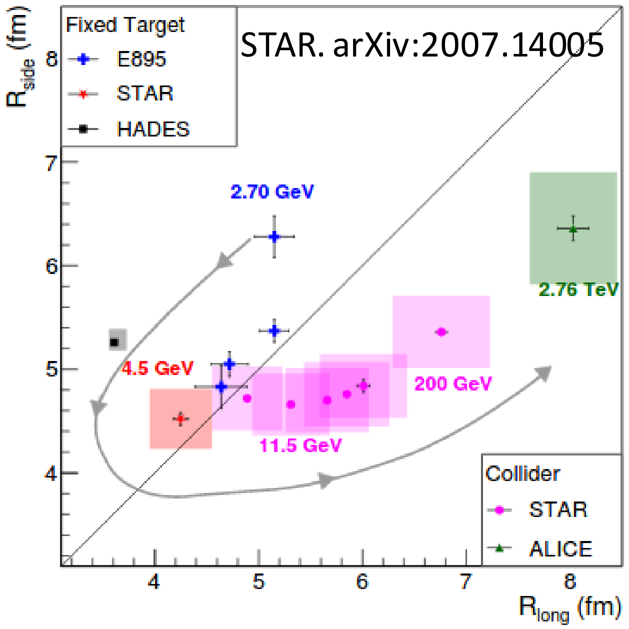
S. Pratt et al. PRL 114 (2015) 202301

Femtoscopy: World Systematics



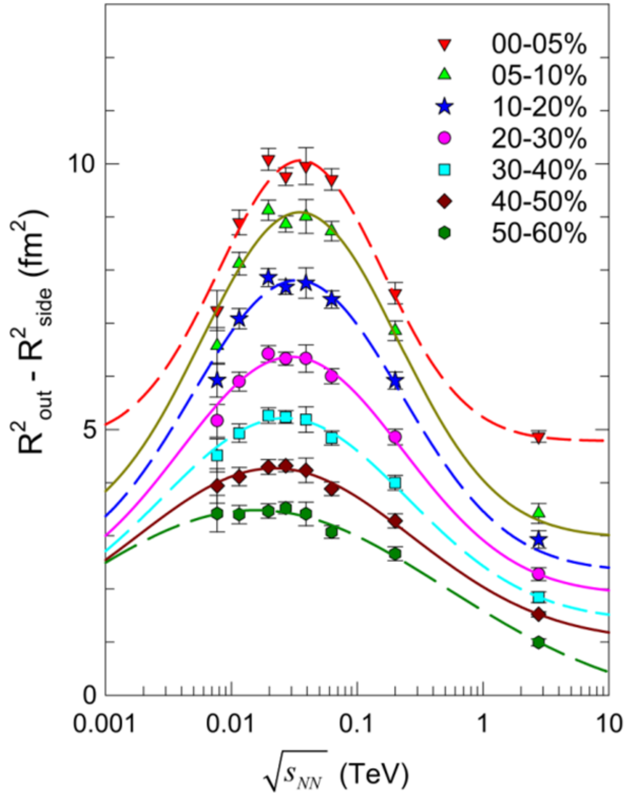
STAR, PRC 92 (2015) 014904

- Precise measurements in a broad energy range (from 7.7 GeV to 2.76 TeV)
- Need more high-statistics measurements at low energies
- Precise measurements exist only with pions
  - Need heavier particles



STAR. arXiv:2007.14005

Lacey. PRL 114 (2015) 142301



Summary

- Many exciting results from STAR
- Most of the physics measurements rely on the precise measurement of:
  - Collision centrality
  - Event plane
  - Particle momentum
  - Particle identification
- More results will appear soon for the data from the Beam Energy Scan II program

Thank you for your attention
ध्यान देने के लिए आपका धन्यवाद