Rapidity dependence study of charged pion production in relativistic nuclear collisions using Tsallis distribution

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Outline

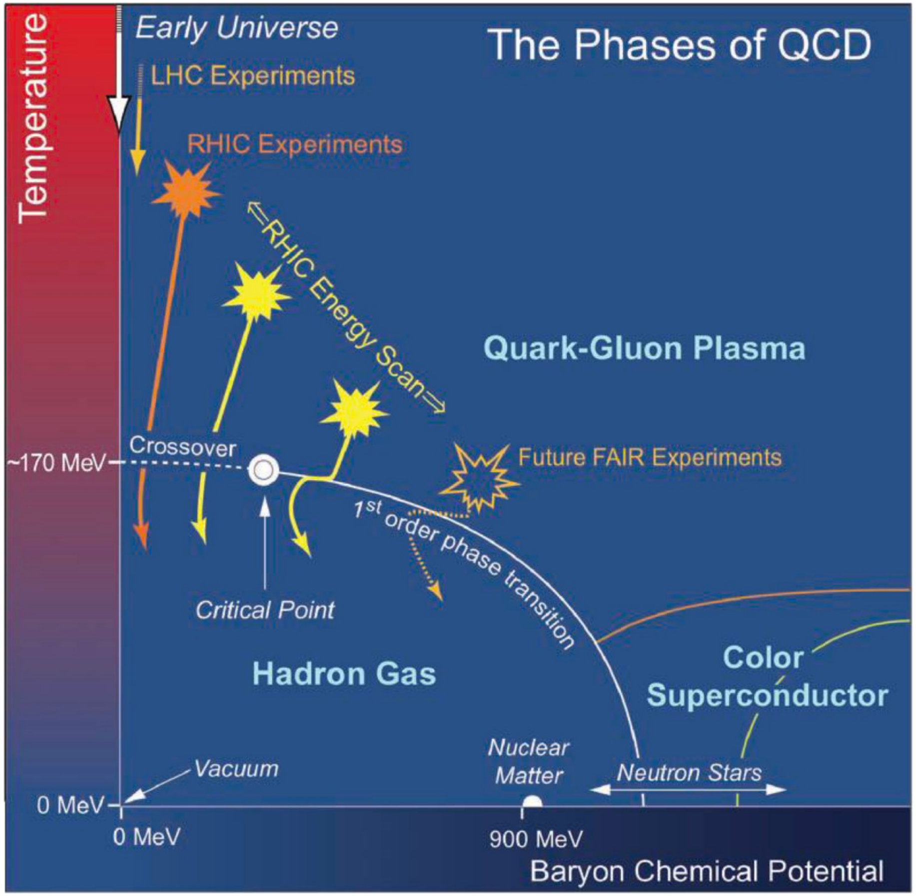
Motivation

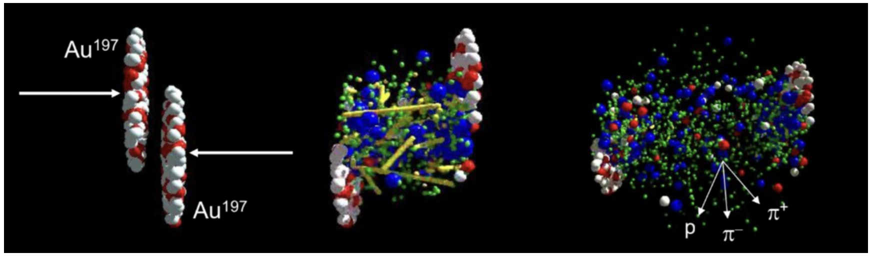
Tsallis distribution and data used

Results

Conclusions

Heavy-ion collision evolution





→ By changing the energy available in the collision and the projectile-target combinations, one can obtain systems characterized by various temperatures and baryon chemical potentials

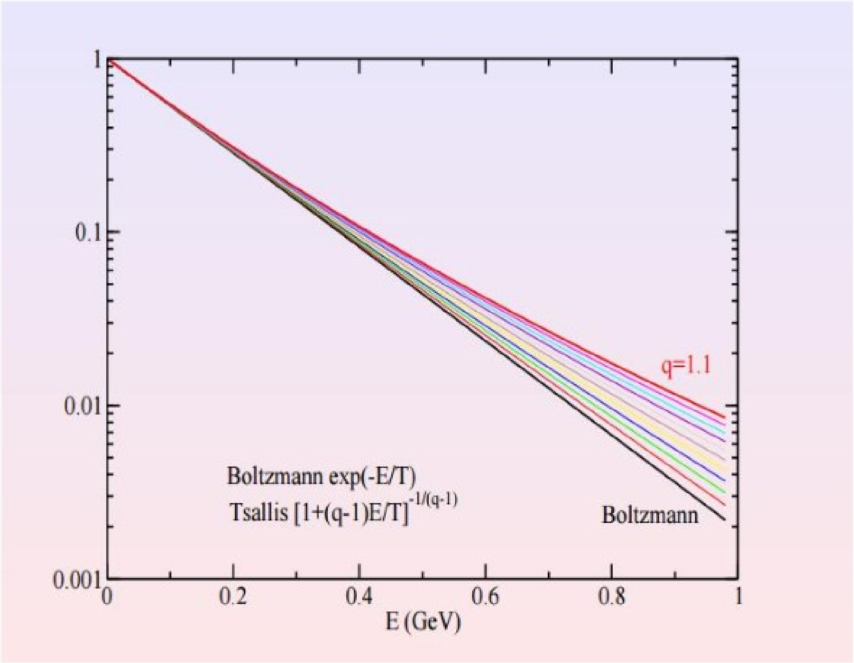
→ different regions on the phase diagram can be investigated

Tsallis distribution

$$\frac{d^2N}{p_T\,dp_T\,dy} = gV\frac{m_T\cosh(y)}{(2\pi)^2}\times \left[1+(q-1)\frac{m_T\cosh(y)-\mu}{T}\right]^{\frac{q}{1-q}}.$$

where g is the degeneracy factor, V is the volume, y is the rapidity, m is the particle rest mass and m_T is the transverse mass.

→ The T parameter can be interpreted as an effective temperature at kinetic freeze-out



→ The non-extensivity parameter, q → the deviation from the standard Boltzmann distribution. This parameter can be related to the non-equilibrium degree of the system and intrinsic fluctuations in the hadronic medium

→ q = 1 → thermal equilibrium

→ q > 1 → non-equilibrium dynamics, temperature fluctuations

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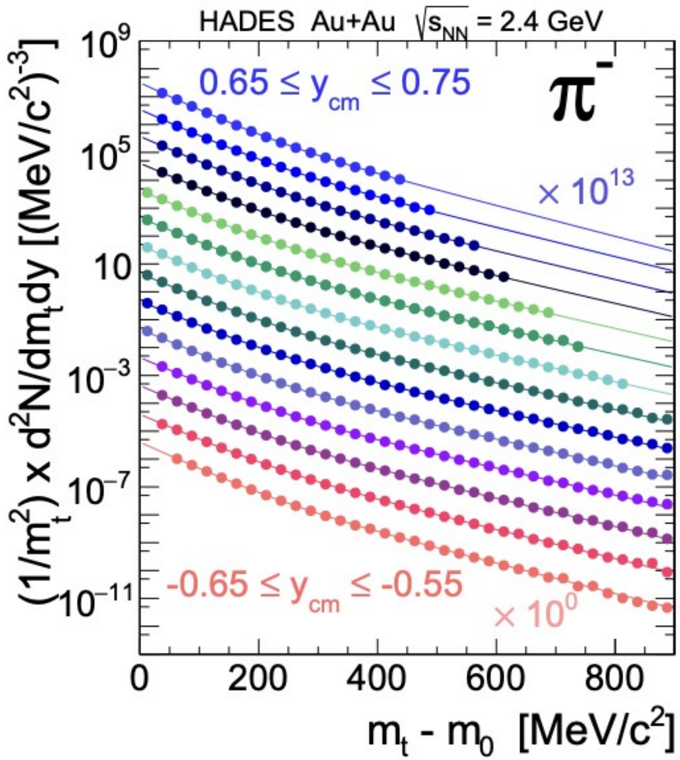

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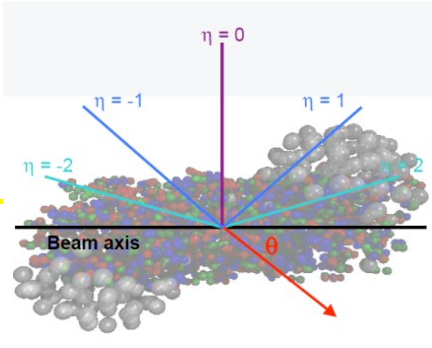
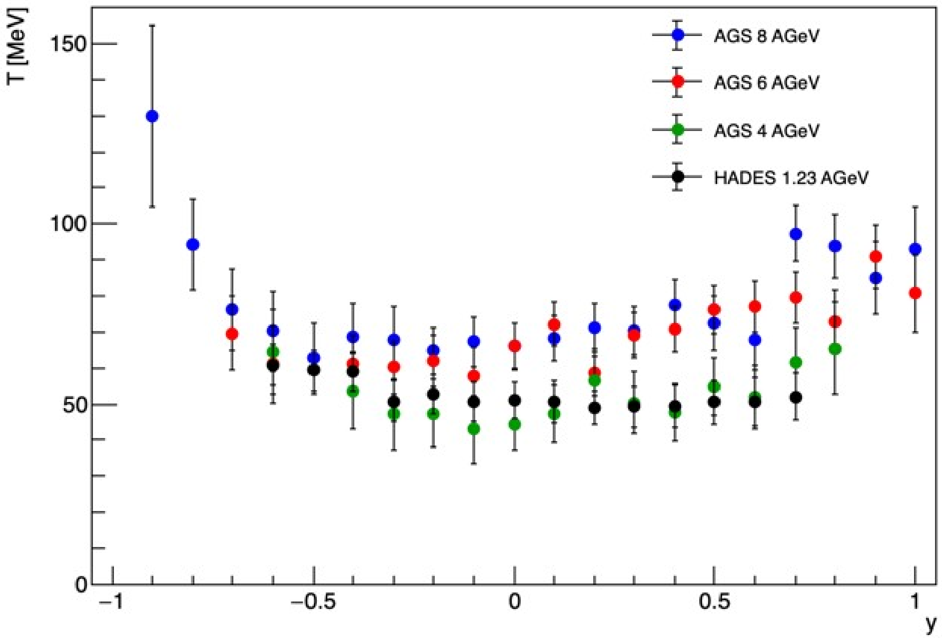
Tsallis temperature vs rapidity





→ AGS data: Au+Au at E_{beam} = 4, 6 and 8 AGeV ($\sqrt{s_{NN}}$ = 3, 3.6 and 4.1 GeV);

→ HADES data: Au+Au at E_{beam} = 1.23 GeV ($\sqrt{s_{NN}}$ = 2.4 GeV);

→ Tsallis temperature increases from midrapidity to forward rapidities for all studied energies

→ the shape of m_T spectra is changing with rapidity → spectra are becoming harder in the forward region compared to the central region

→ at forward rapidities, particle emission is increasingly influenced by projectile fragmentation and other non-equilibrium processes

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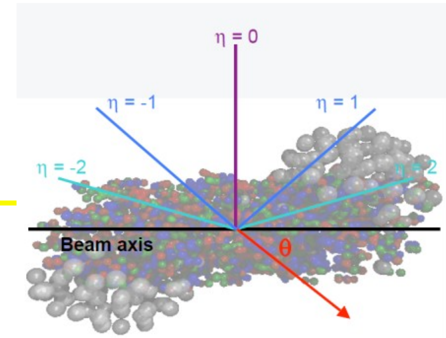
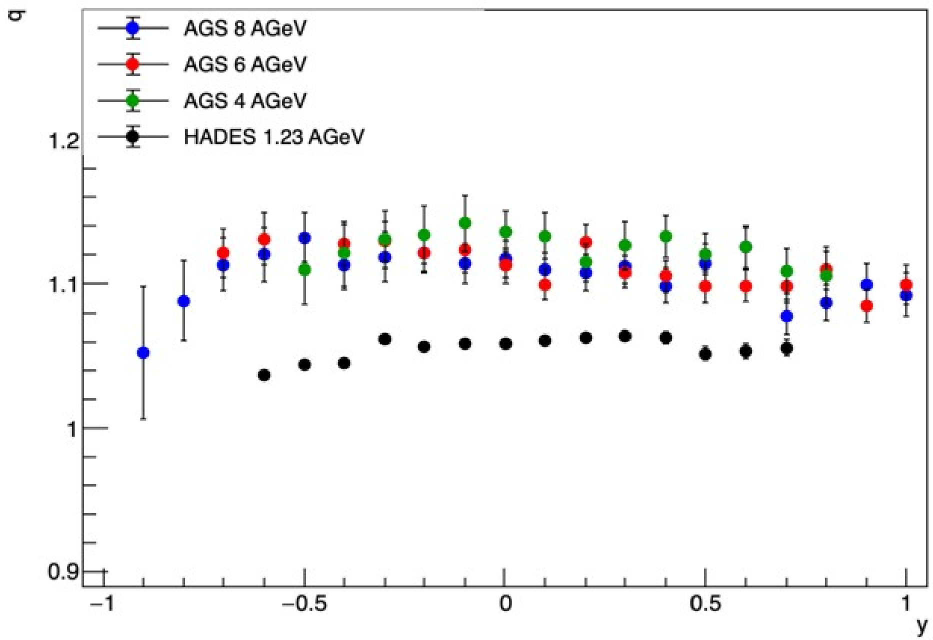
Non-extensivity parameter vs rapidity





→ q values are larger in the midrapidity region → a decreasing q with increasing y suggests that temperature fluctuations become weaker away from midrapidity

→ at AGS, the central rapidity region experiences the largest deviations from thermal equilibrium, associated with the highest particle density, intense rescattering, resonance production, and fluctuations.

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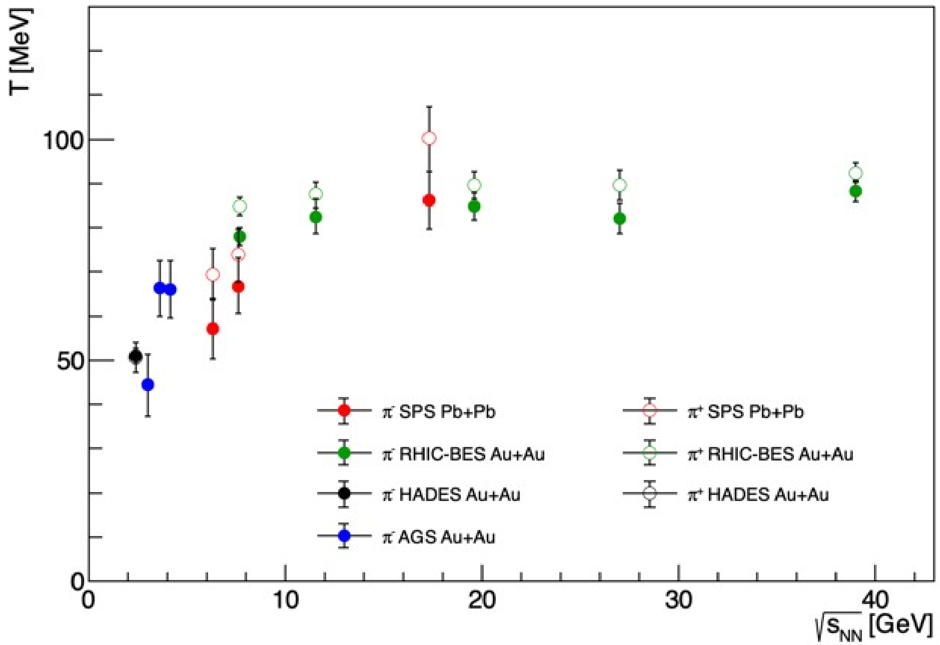
Tsallis temperature vs energy



→ T increases from HADES and AGS energies and saturates above $\sqrt{s_{NN}}$ ~ 11 GeV

→ this behaviour could be related to the transition between the baryon-rich regime explored at AGS and HADES energies and the higher-energy regime explored at the RHIC Beam Energy Scan energies

AGS data: Au+Au at E_{beam} = 4, 6 and 8 AGeV ($\sqrt{s_{NN}}$ = 3, 3.6 and 4.1 GeV); HADES data: Au+Au at E_{beam} = 1.23 GeV ($\sqrt{s_{NN}}$ = 2.4 GeV); SPS data: Pb+Pb data at E_{beam} = 20, 30 and 158 AGeV ($\sqrt{s_{NN}}$ = 6.3, 7.6 and 17 GeV) and STAR-BES data: Au+Au at $\sqrt{s_{NN}}$ = 7.7, 11.5, 19.6, 27 and 39 GeV

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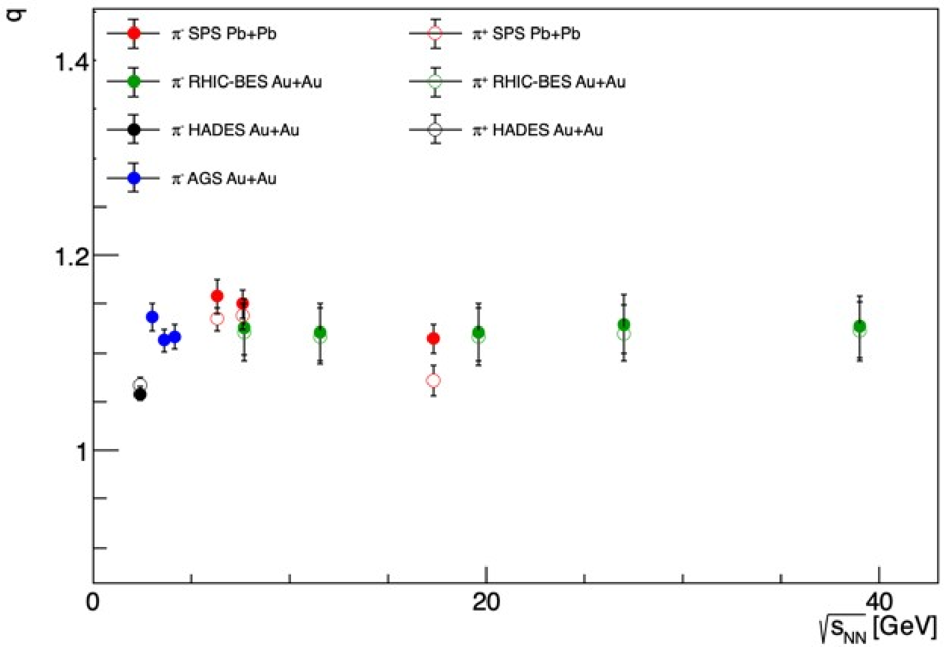
q parameter vs energy



→ q quantifies deviations from thermal equilibrium, reflecting fluctuations, correlations, and non-equilibrium dynamics.

→ at RHIC-BES energies the degree of non-equilibrium no longer increases despite the higher collision energy.

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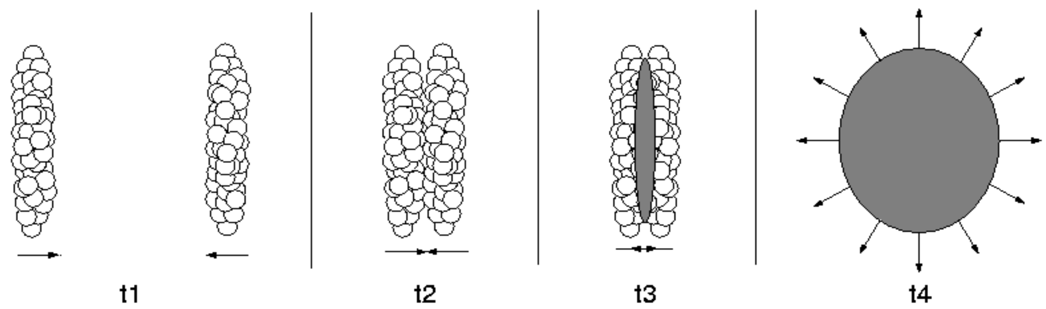
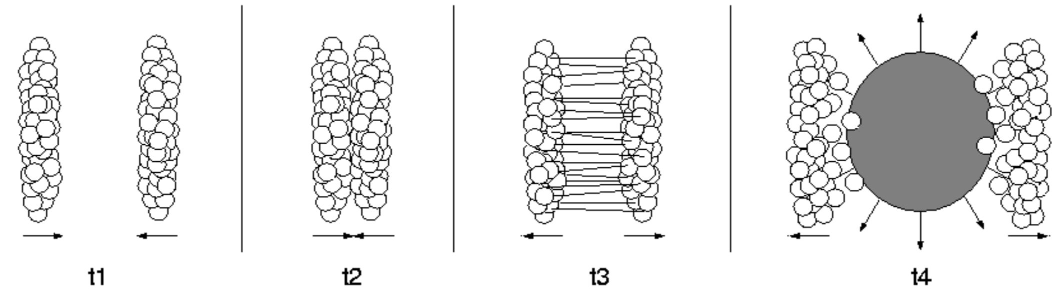
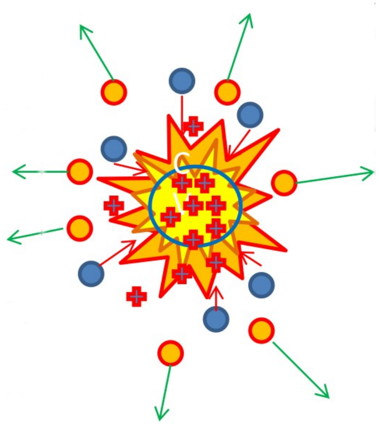
From full stopping to transparency...

Full stopping:

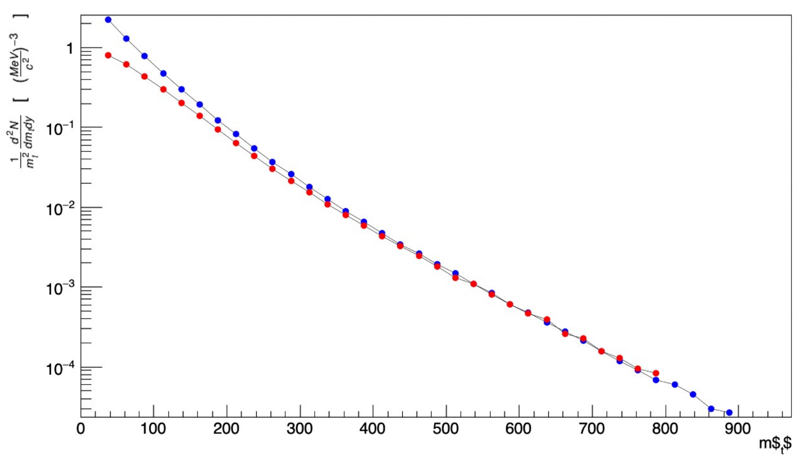


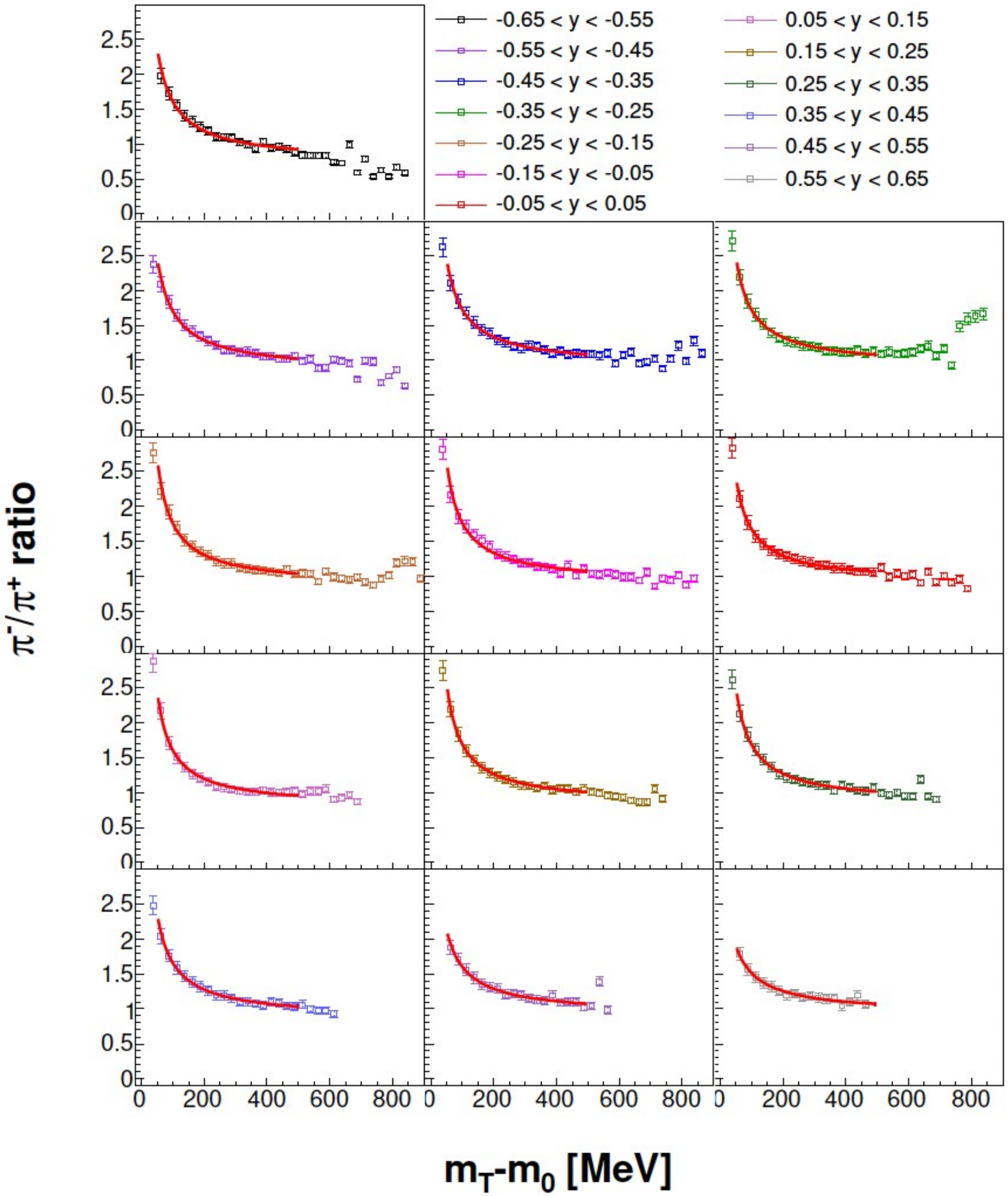
Transparency





Coulomb interaction between the pions and positive net-charge → π+ (π-) are accelerated (decelerated) by the Coulomb field generated by the positive charge





Model*:

- considers that during the fireball expansion, a charged pion will receive a momentum change due to the Coulomb interaction or "Coulomb kick", p_c

$$p_c \equiv \left| p_T - p_{T,0} \right| \cong 2e^2 \frac{dN^{\mathrm{ch}}}{dy} \frac{1}{R_f}$$

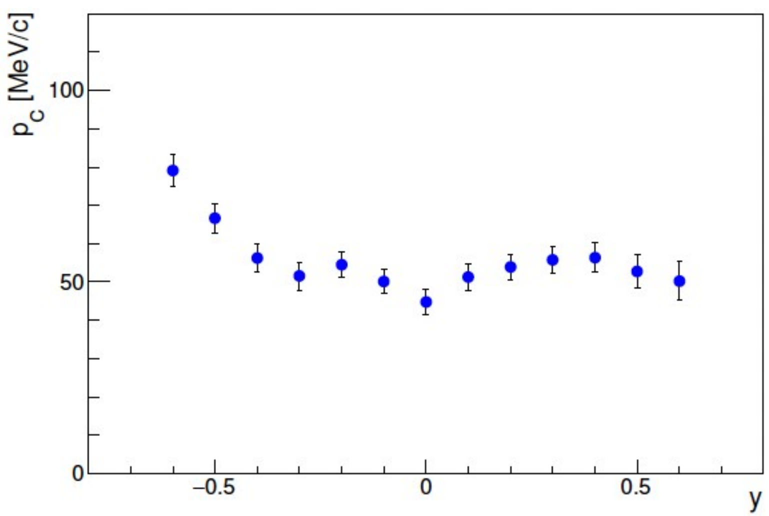
where $p_{T,0}$ is the transverse momentum at freeze-out, p_T is the final transverse momentum, dN_{ch}/dy is the net-charge distribution and R_f is the kinetic freeze-out radius. The charged pion ratio is:

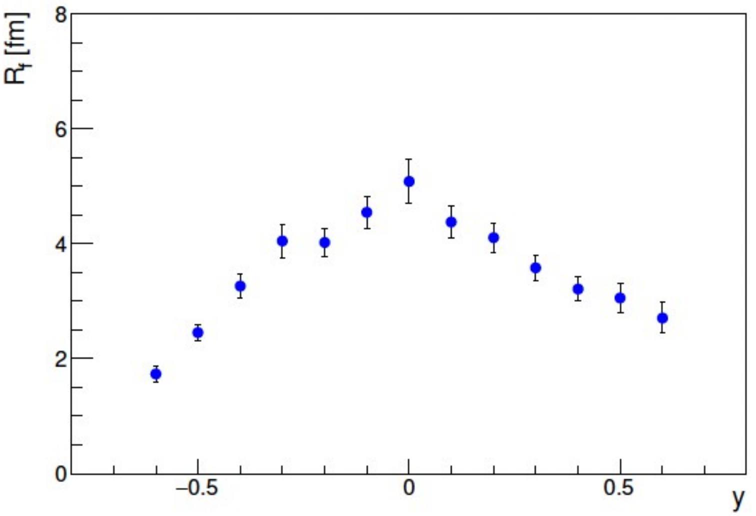
$$\frac{\pi^-}{\pi^+} = \left\langle \frac{\pi^-}{\pi^+} \right\rangle \frac{p_T + p_c}{p_T - p_c} \exp\left(\frac{m_T^- - m_T^+}{T} \right)$$

where T thermal freeze-out temperature, $\langle \pi^-/\pi^+ \rangle$ initial pion ratio and $m_T^{\pm} = \sqrt{m^2 + (p_T \pm p_c)^2}$

*H. W. Barz, J. P. Bondorf, J. J. Gaardhøje, and H. Heiselberg, Phys. Rev. C 57 (1998)2536–2546; H. Heiselberg, Nuclear Physics A 638 (1998) 479C

Rapidity dependence

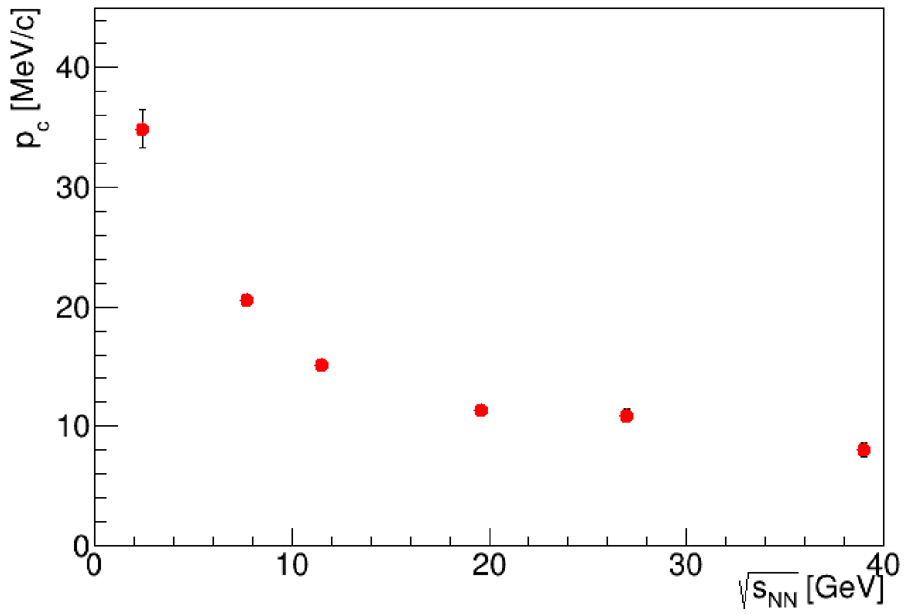




→ HADES m_T spectra of charged pions produced in Au+Au collisions at 2.4 GeV → Coulomb momentum has the smallest values near the mid-rapidity and increases towards large rapidities → the Coulomb effects on the charged pion spectra increase at larger rapidities, probably due to the possible influence of the target and beam spectator charges

→ The kinetic freeze-out radius decreases from the mid-rapidity region towards high rapidities, indicating that at forward and backward rapidities the system volume is smaller

Energy dependence



→ data from HADES and RHIC-BES Au+Au collisions

→ Coulomb momentum decreases with the increase of beam energy, showing that the Coulomb interaction is stronger at lower energies.

If the colliding nuclei are fully stopped, due to a larger stopped charge in the overlap volume a stronger Coulomb field is generated, and this Coulomb field has a stronger influence on the charged pions.

Conclusions

- Tsallis fits suggest that the dense baryonic matter created at HADES and AGS energies is well described by a nearly thermal source with only moderate non-equilibrium effects → the weak rapidity dependence indicates that the degree of non-equilibrium is relatively uniform throughout the system at freeze-out

- Tsallis temperature increases from HADES to AGS energies due to strong baryon stopping → at SPS and RHIC-BES energies, T saturates, reflecting the transition to a transparency-dominated regime where additional beam energy mainly drives expansion and particle production rather than further heating

- The parameter q is close to unity across all energies, indicating a system close to thermal equilibrium. Its weak energy dependence and saturation at higher energies suggest that the degree of non-equilibrium changes only slightly despite the transition from stopping to transparency

- The Coulomb effect decreases with the energy → consistent with the transition from strong baryon stopping to increasing nuclear transparency, resulting in a progressively weaker Coulomb influence on the charged pion spectra

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