# Thermodynamical properties of nuclear matter produced at high energy collisions

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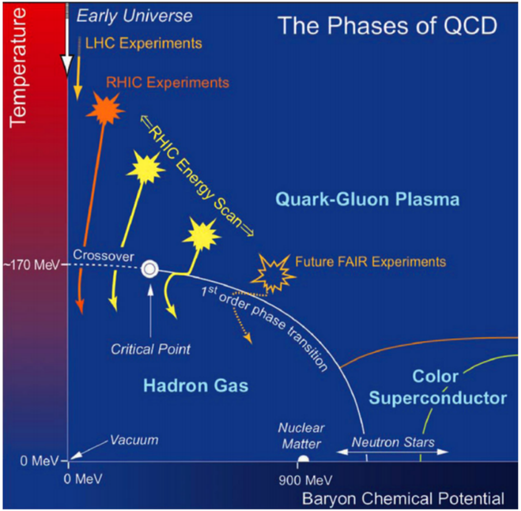
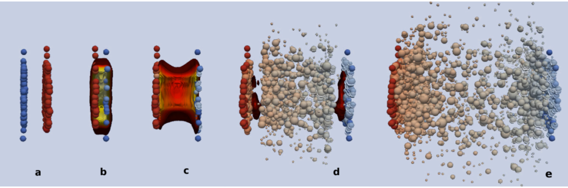
# QCD phase diagram

Parameters:

- Temperature $T$
- Baryon chemical potential $\mu$

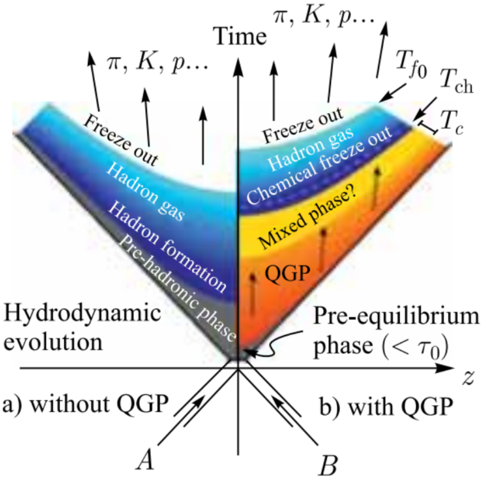


# Evolution of quark-gluon plasma




Stages of ultrarelativistic nuclear collision:

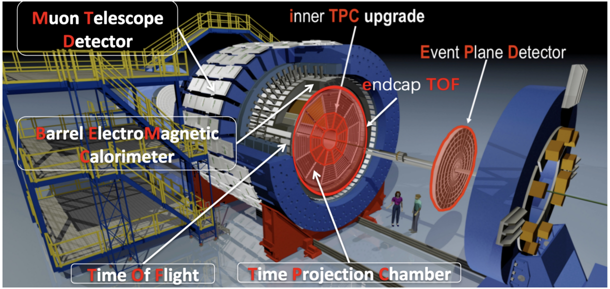
a) Nuclei go through each other
b) Expansion
c) Formation of hot matter
d) Hadron gas
e) Final patricles



# The STAR experiment

TPC (Time Projection Chamber)

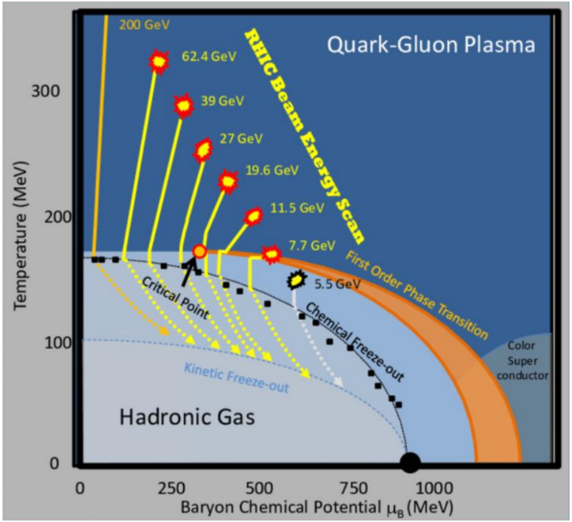
- used for tracking and identification
- length 4.2 m, diameter 4 m (1 m),
- azimuthal angle $2\pi$
- pseudorapidity range $|\eta| < 1$
- in a magnetic field 0.5 Tesla



# Beam Energy Scan program on RHIC

Used data:

- RHIC BES-I, 2010-2011
- $Au + Au\ \sqrt{S_{NN}} = 7.7 - 27$ GeV.
- transverse momentum spectra $p_T$
- Phys.Rev.C 96 (2017) 044904, 2017; Phys.Rev.C 102 (2020) 034909, 2020.



# Blast-Wave model

- Let's assume that particles are radiated from a fireball expanding in the longitudinal and transverse directions with a certain distribution of radial velocities:

$$\beta(r) = \beta_S \left(\frac{r}{R}\right)^n, \ \langle\beta\rangle = \frac{2}{2+n}\beta_S,$$

where $n$ defines the shape of the flow profile.

- Then, the expressions for the spectrum of a thermal source with a Boltzmann distribution $e^{-(u^\nu p_\nu - \mu)/T}$ take the form:

$$\frac{\mathrm{d}N}{p_T\,\mathrm{d}p_T} \propto \int\limits_0^R r\,\mathrm{d}r\, m_T\, \mathrm{K}_1\left(\frac{m_T\cosh\rho}{T}\right)\mathrm{I}_0\left(\frac{p_T\sinh\rho}{T}\right), \ \rho = \tanh^{-1}\beta(r)$$

# Tsallis-3 statistics

- Tsallis entropy:

$$S = \sum_i \frac{p_i^q - p_i}{1-q}, \ \sum_i p_i = 1,$$

где $p_i$ - probability $i$th microscopic state of the system, $q \in [0, \infty]$.

- In the Gibbs limit $q \to 1$ the entropy recovers the Boltzmann-Gibbs entropy:

$$S = \sum_i p_i \ln p_i$$

- In Grand Canonical Ensemble thermodynamic potential $\Omega$ takes the form:

$$\Omega = \langle H \rangle - TS - \mu \langle N \rangle, \text{ where}$$

$$\langle H \rangle = \frac{1}{\theta} \sum_i p_i^q E_i, \ \langle N \rangle = \frac{1}{\theta} \sum_i p_i^q N_i, \ \theta = \sum_i p_i^q.$$

# Tsallis-3 statistics

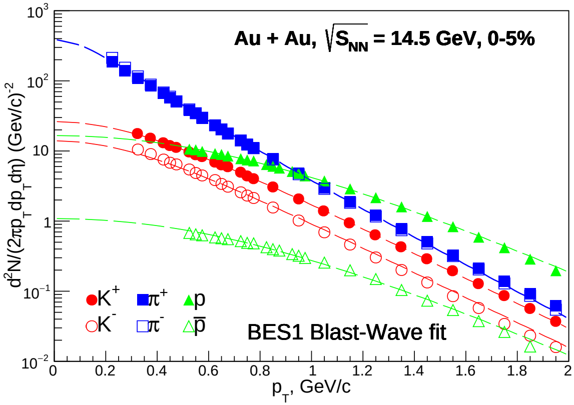
- The expression for transverse momentum distribution of particles of relativistic ideal gas in the grand canonical ensemble in rapidity range $y \in [y_{min}, y_{max}]$ takes the form:

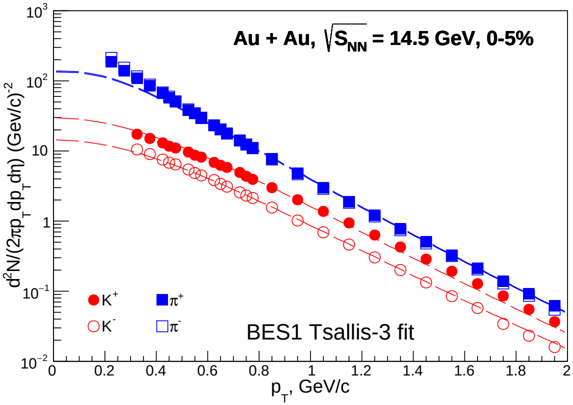
$$\left.\frac{\mathrm{d}^2 N}{p_T\, \mathrm{d}p_T\, \mathrm{d}y}\right|_{y_{min}}^{y_{max}} = \frac{gV}{(2\pi)^2} m_T \int\limits_{y_{min}}^{y_{max}} \mathrm{d}y \cosh y \times$$

$$\times \frac{1}{\theta} \sum_{n=0}^{n_0} \frac{\omega^n}{n!\, \Gamma\left(\frac{q}{q-1}\right)} \int\limits_0^{\infty} t^{\frac{1}{q-1}-n} e^{-t+\beta'(\Lambda - m_T \cosh y + \mu(n+1))} (\mathrm{K}_2(\beta' m))^n \, \mathrm{d}t$$

- In this work: $n_0 = 1$, $\mu = 0$.

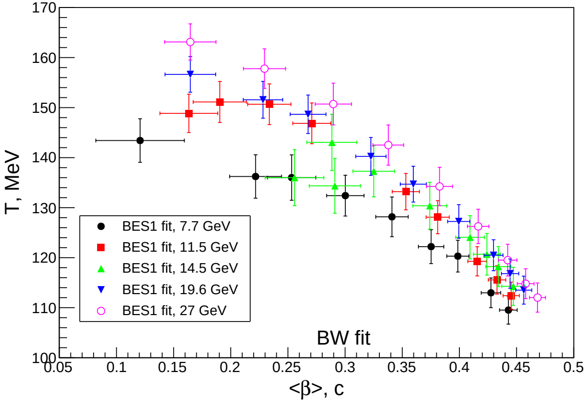
# Fit comparision



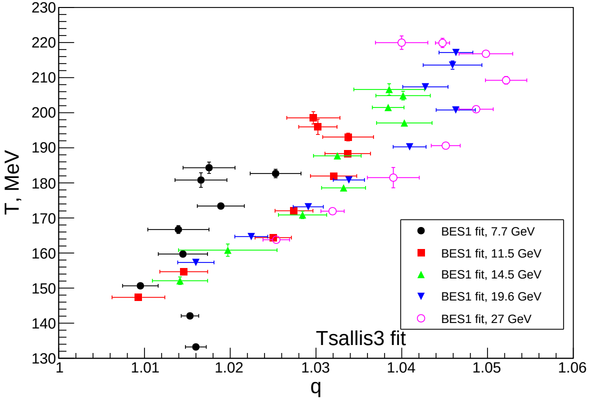



# Parameters variation

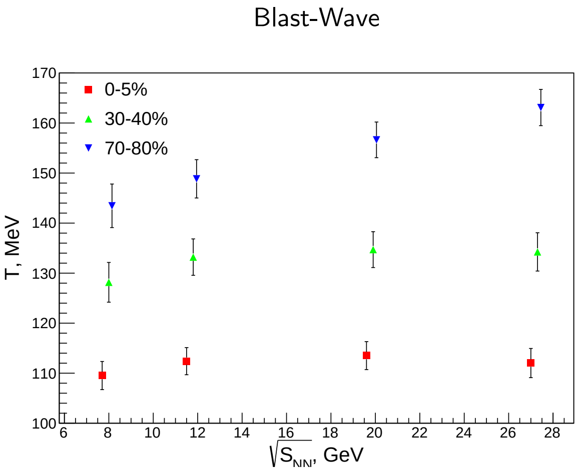
Blast-Wave

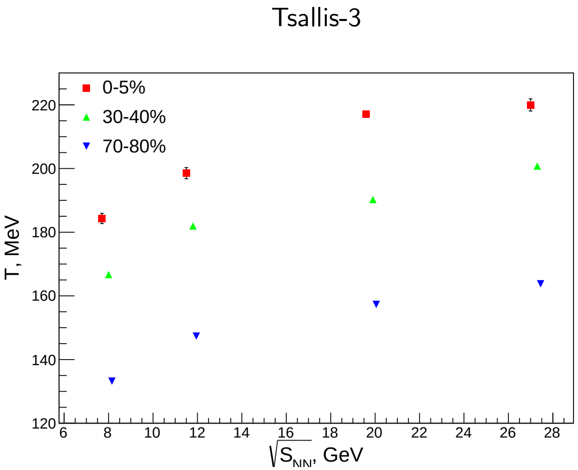



Tsallis-3



# Energy dependence



# Conclusion

- Two approaches: Blast-Wave and q-dual statistics.
- Blast-Wave can give us information about the radial flow and the kinetic freeze-out temperature.
- q-dual statistics can give us information about the degree of deviation of the system from the classical equilibrium.
- Obtained results:
  - Blast-Wave:
    Almost no energy dependence, kinetic freeze-out temperature monotonically decreases with increasing centrality, while the expansion velocity increases.
  - q-dual: Weak energy dependence, Tsallis effective temperature monotonically increases with increasing centrality.

Thank you for your attention!