OSAKA INSTITUTE OF TECHNOLOGY

科研費 KAKENHI JP24K07030

Probing momentum dependence of hydrodynamization in heavy-ion collisions

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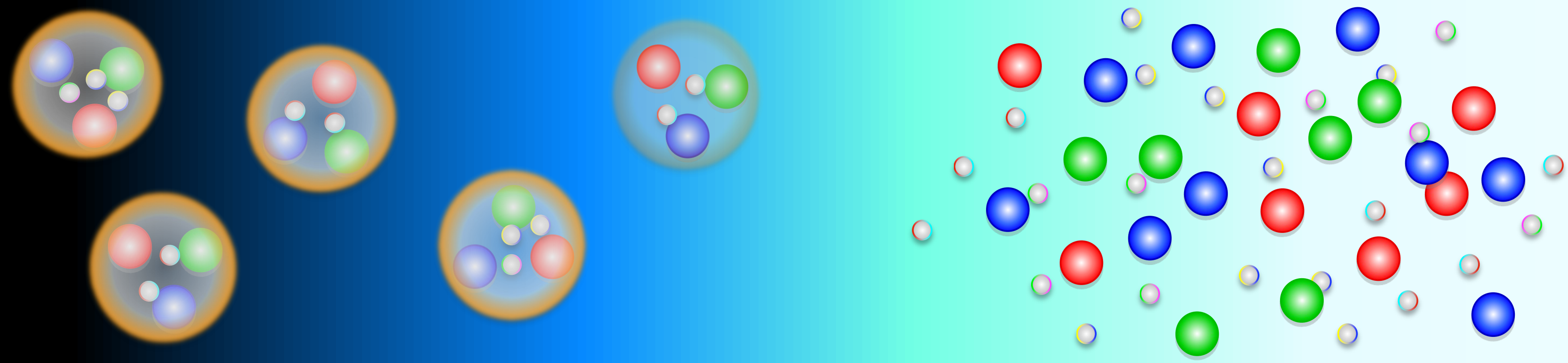
K. Kyan, AM, Phys. Rev. D **106**, 054004 (2022); AM, J. Phys. G **50**, 095103 (2023);
AM, in preparation

The 29th International Nuclear Physics Conference (INPC 2025)

29th May 2025, Daejeon, South Korea

Introduction

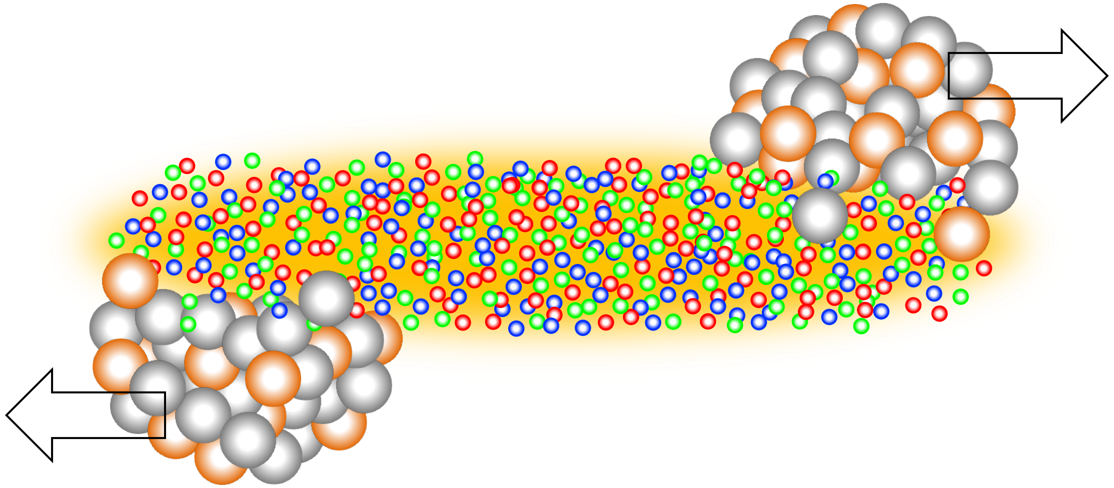
- QCD crossover transition



Hadrons are deconfined to quark-gluon plasma (QGP) above around $T \sim$ 155-160 MeV

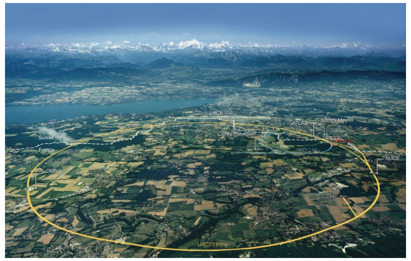
Introduction

- How to make the quark-gluon plasma on earth



Collide two nuclei (such as gold or lead) at nearly the speed of light

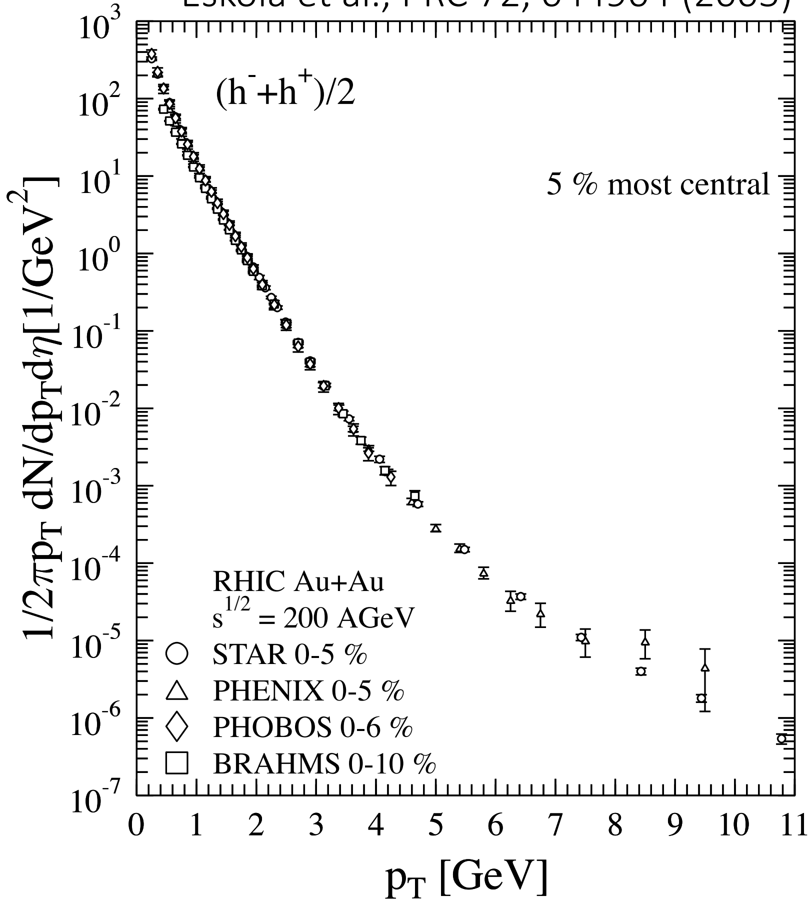
BNL Relativistic Heavy Ion Collider (2000-)
CERN Large Hadron Collider (2010-)



Introduction

- Interpretation of the momentum distribution

Eskola et al., PRC 72, 044904 (2005)



Introduction

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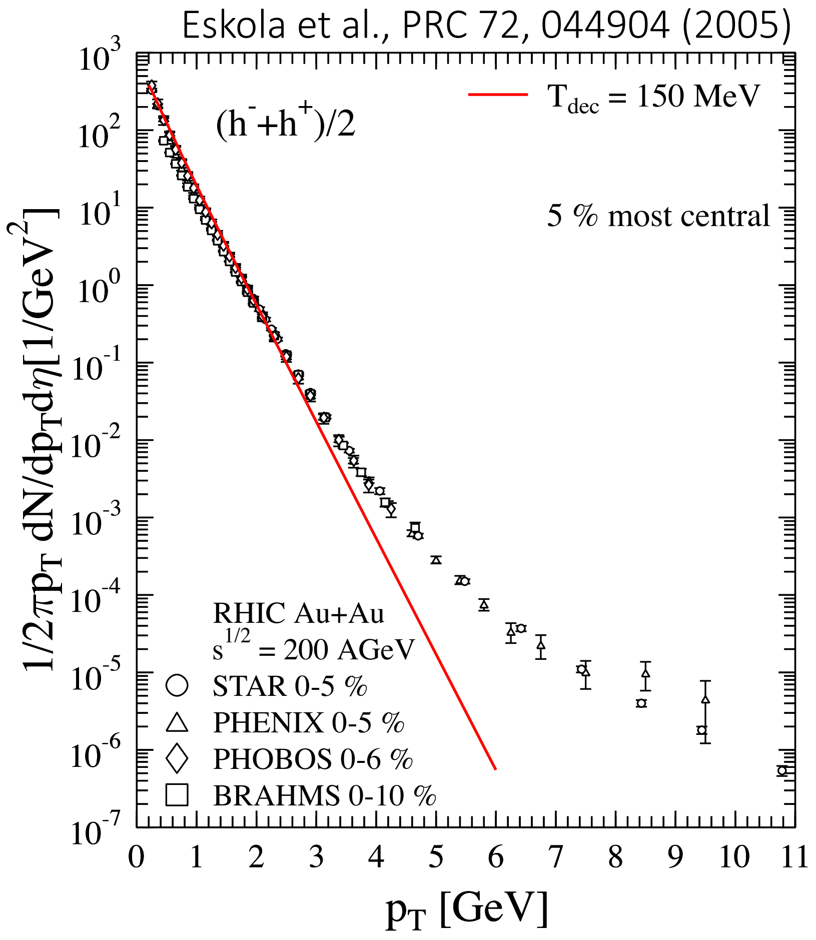


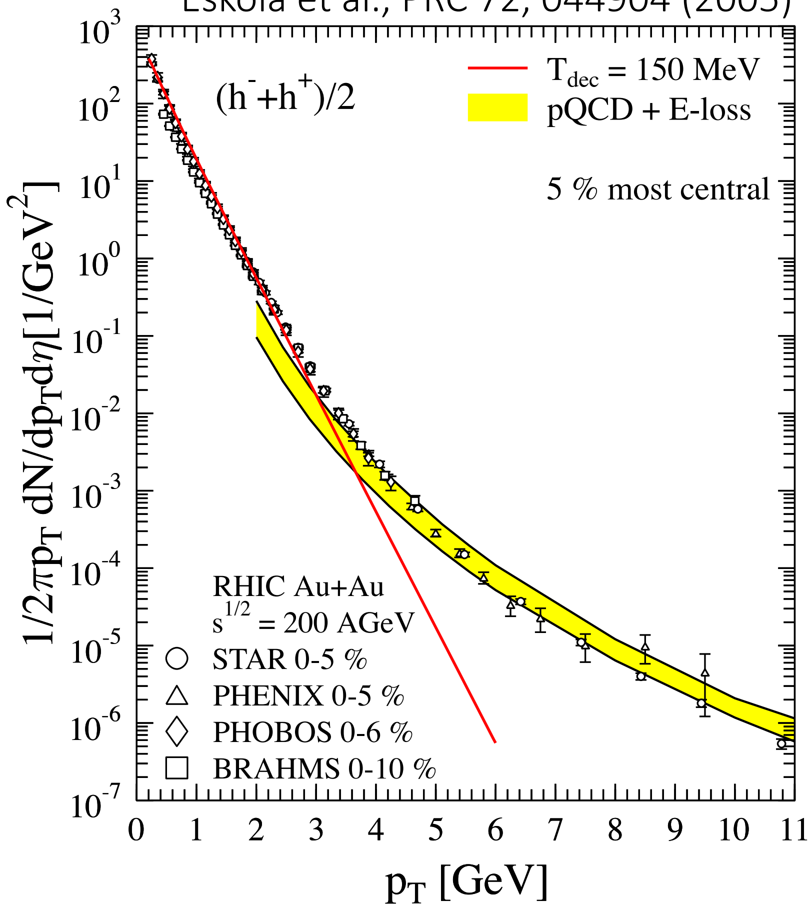
Low momentum region (< 2-4 GeV)

Hydrodynamic model (strongly-coupled)

Introduction

■ Interpretation of the momentum distribution

Eskola et al., PRC 72, 044904 (2005)



Low momentum region (< 2-4 GeV)

Hydrodynamic model (strongly-coupled)

+

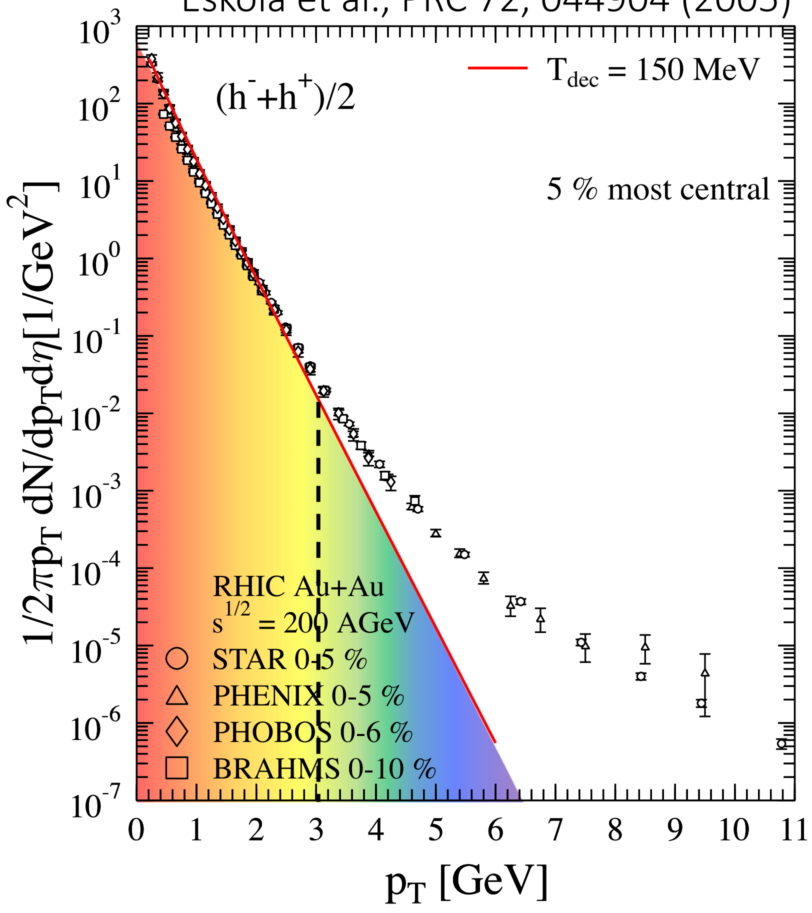
Medium-high momentum region (> 4-5 GeV)

perturbative QCD (weakly-coupled)

What participates in the fluid?

- Momentum dependence

Eskola et al., PRC 72, 044904 (2005)



Conventional approach

Assumes a thermal distribution
(= some high momentum components are hydrodynamized)

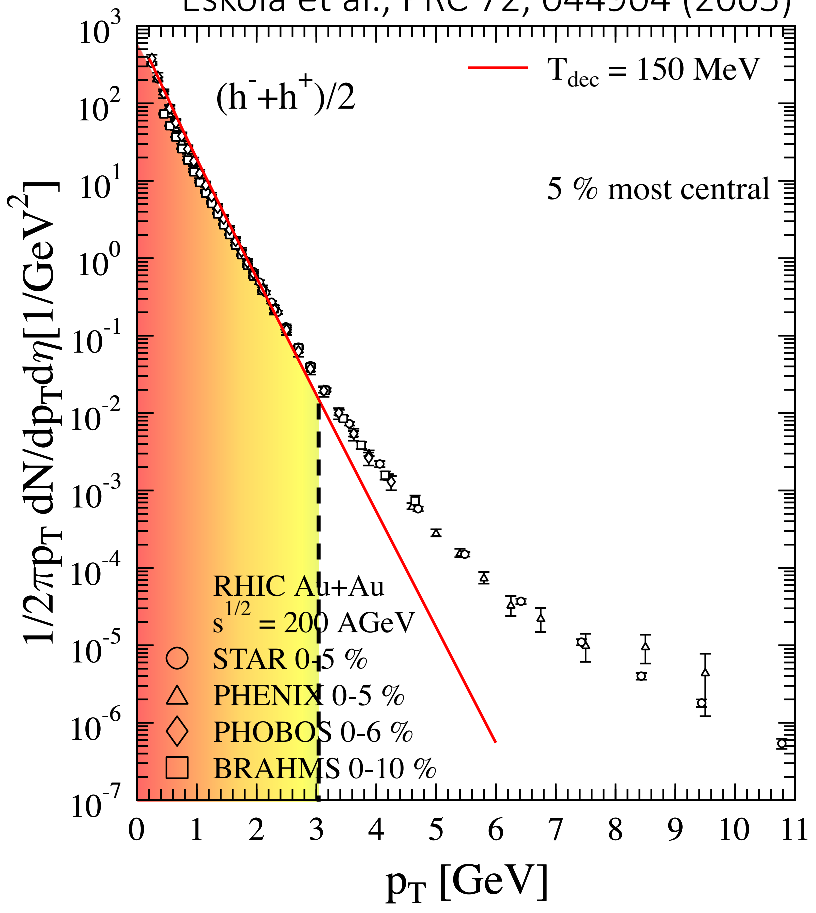
"Red" ⟷ "Violet"

Low momentum — High momentum

This work

- Two scenarios of correction to hydrodynamic model

Eskola et al., PRC 72, 044904 (2005)

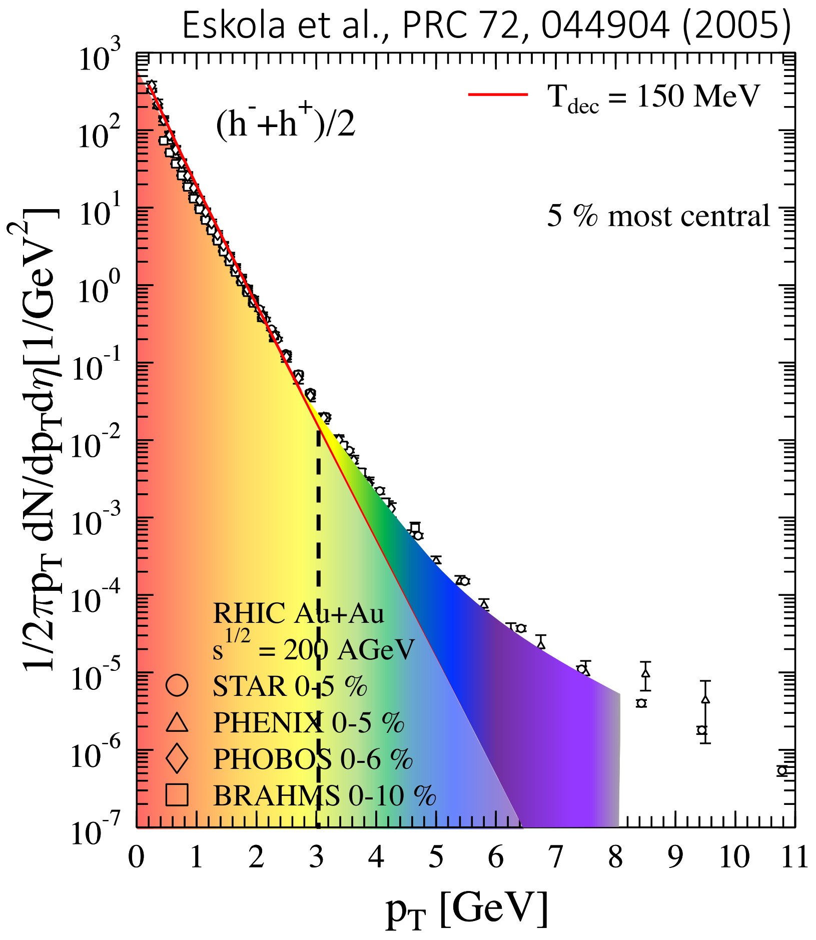


1. "Red" scenario

Only low momentum components are hydrodynamized

This work

- Two scenarios of correction to hydrodynamic model



1. "Red" scenario

Only low momentum components are hydrodynamized

2. "Violet" scenario

Medium-high momentum components are fully hydrodynamized

“Violet” scenario

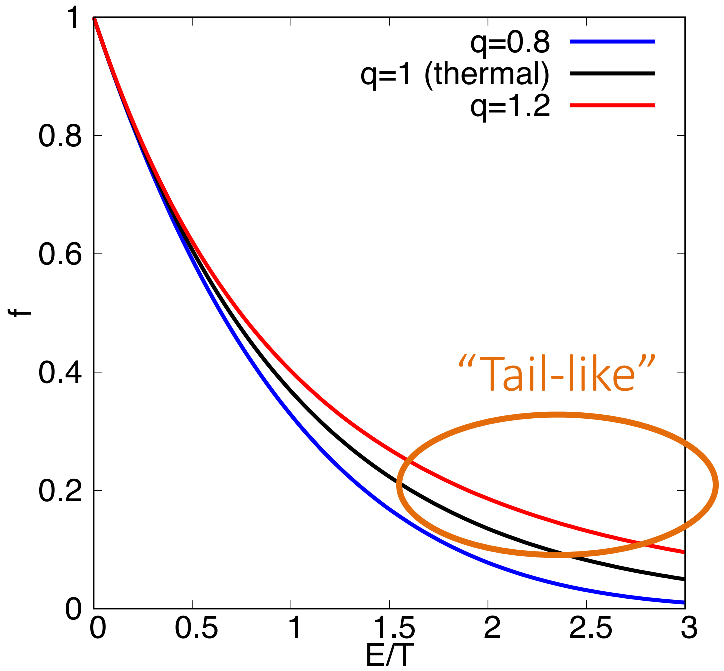
- Tsallis distribution

Tsallis, J. Statist. Phys. 52, 479 (1988); Braz. J. Phys. 29, 1 (1999)

$$\boxed{f = \left[1 - (1-q)\frac{E}{T}\right]^{\frac{1}{1-q}} \equiv \exp_q(-E/T)} \xrightarrow{q \to 1} f = \exp(-E/T)$$

Generalization of thermal distribution by q

With quantum statistics: $f = \dfrac{\exp_q(-E/T)}{1 \pm \exp_q(-E/T)}$



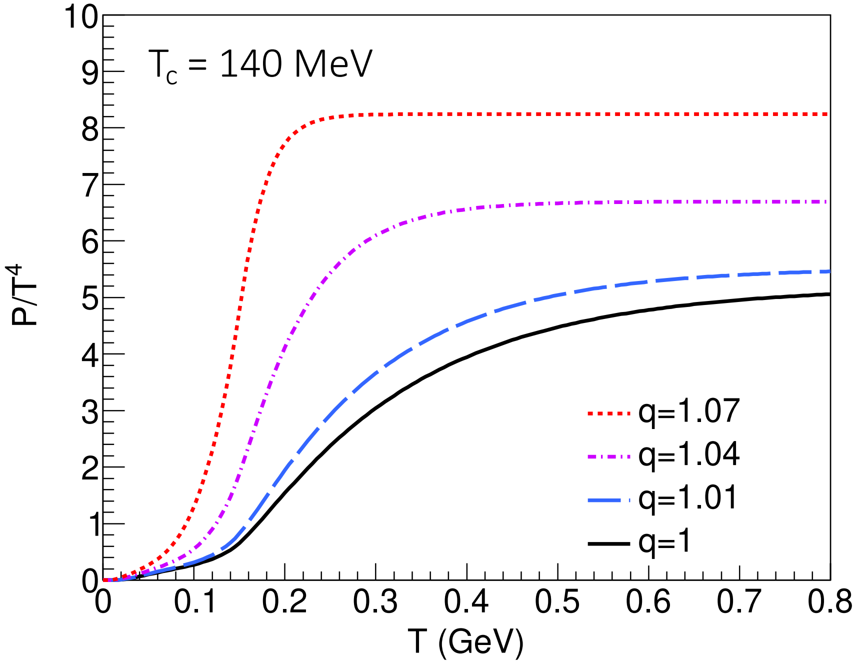
We use Tsallis statistics to treat medium-high momentum components as a fluid

T. Osada and G. Wilk, Phys. Rev. C 77, 044903 (2008)
K. Kyan, AM, Phys. Rev. D 106, 054004 (2022)

Equation of state

- Hadron resonance gas (HRG) + parton gas

Particle Data Group: PRD 98, 030001 (2018)



The pressure increases with q, reflecting the contribution of long-tail in f

P_{had} increases faster than P_{QGP}

$\frac{dP}{dT} > 0$ is satisfied only if $q \lesssim 1.07$-1.09

Those equations of states are available for downloading:
https://sites.google.com/site/akihikomonnai/downloads

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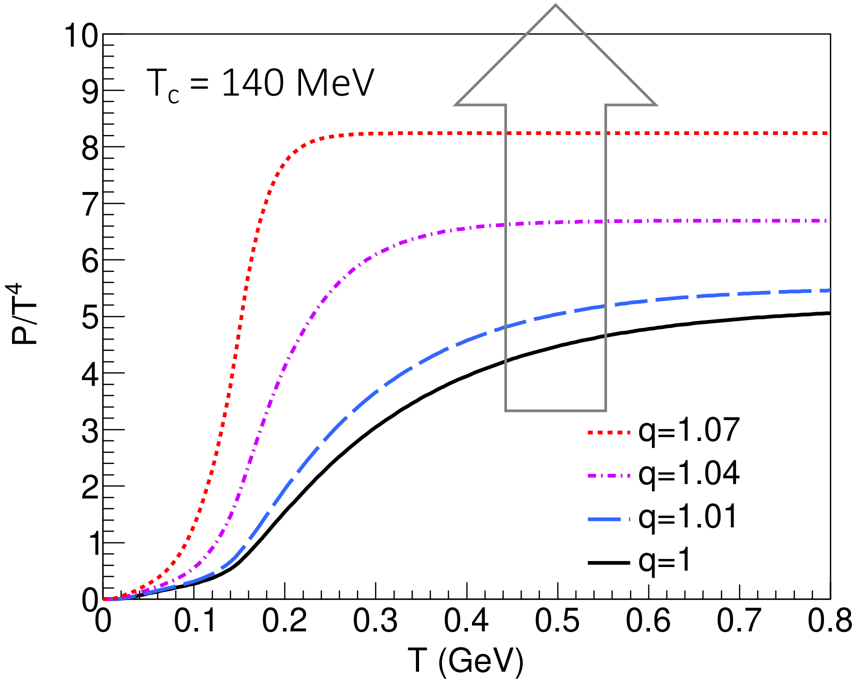

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Hydrodynamic model

- (2+1)-dimensional inviscid hydrodynamic model

AM, PRC 90, 021901(R) (2014)

Initial condition: Monte-Carlo Glauber model (event-averaged)
2.76 TeV Pb+Pb collisions (0-5%, 20-30%)

Initial time: $\tau_{\mathrm{ini}} = 0.4$ fm/c

Hadronic decay: Sollfrank, Koch, and Heinz, Phys. Lett. B 252, 256 (1990)

- Hadron production

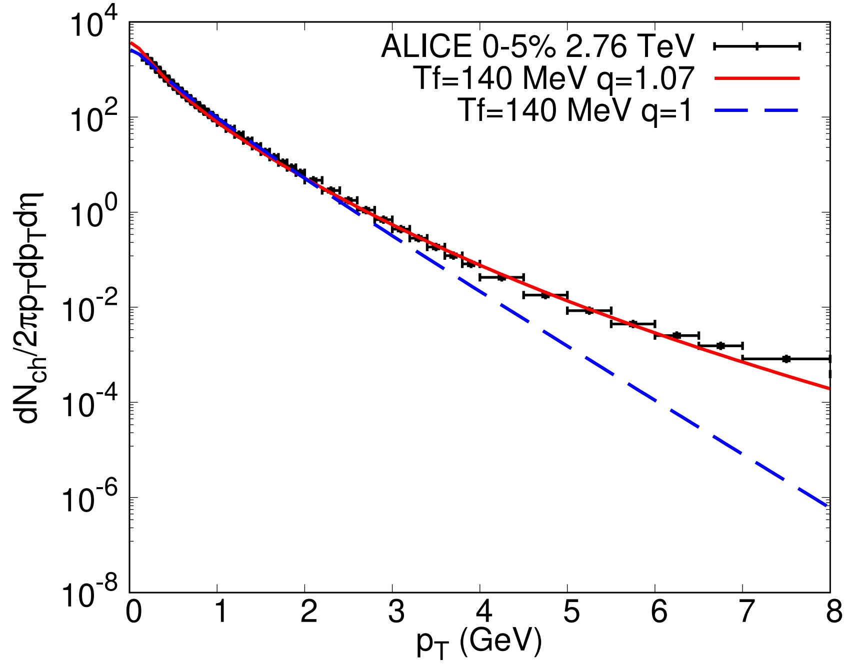
Cooper and Frye, Phys. Rev. D 10, 186 (1974)

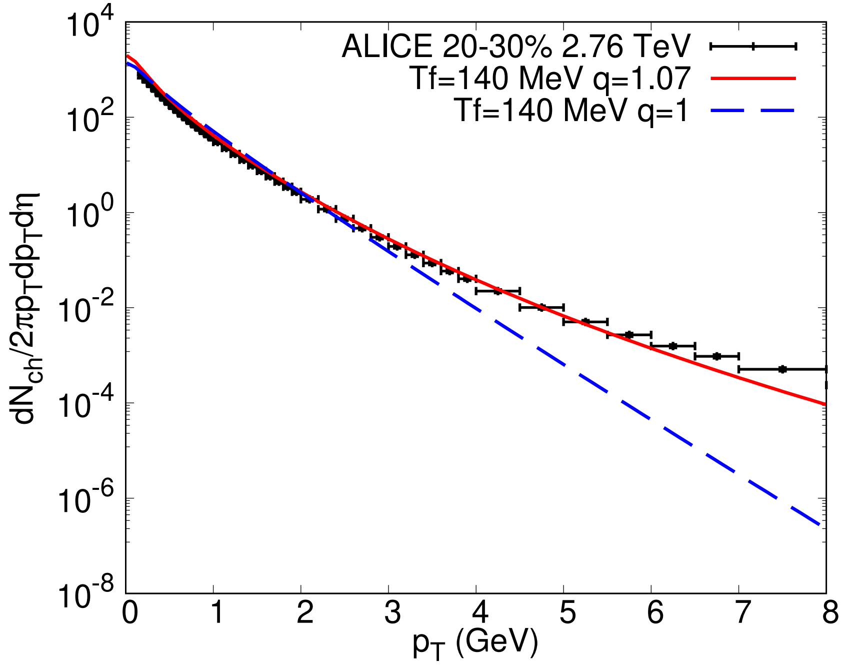
$$E \frac{dN_i}{d^3p} = \frac{g_i}{(2\pi)^3} \int_\Sigma f_i^q p^\mu d\sigma_\mu$$

Modified with Tsallis statistics (for energy-momentum conservation)

Numerical results

- Charged particle p_T spectra for LHC 2.76 TeV Pb+Pb collisons



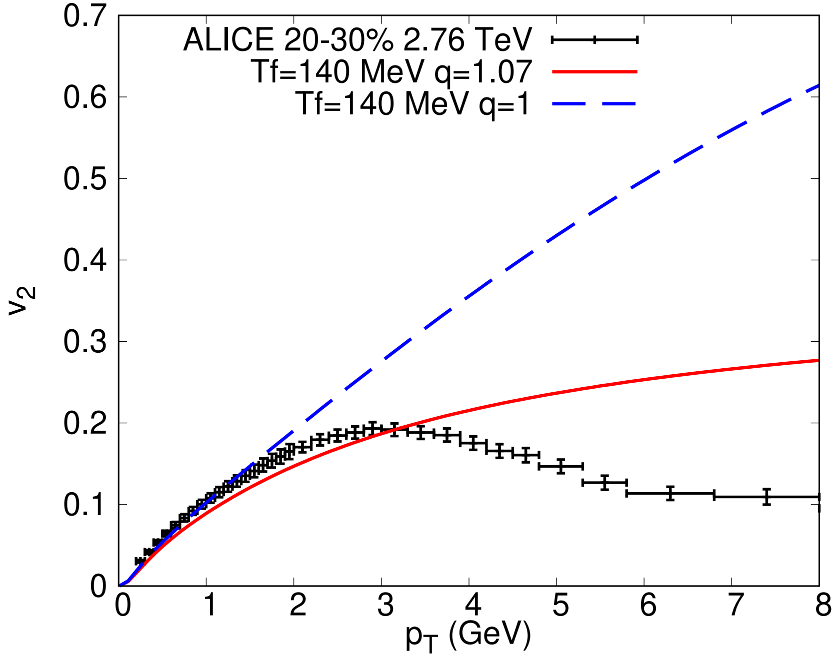


p_T spectra is described up to 3-4 GeV by thermal distribution (q = 1) and 7-8 GeV by Tsallis distribution (q = 1.07)

Numerical results

Ollitrault, PRD 46, 229 (1992)
Poskanzer and Voloshin, PRC 58, 1671 (1998)

- Charged particle elliptic flow v_2 for LHC 2.76 TeV Pb+Pb collisons



Elliptic flow: azimuthal anisotropy of momentum distributions

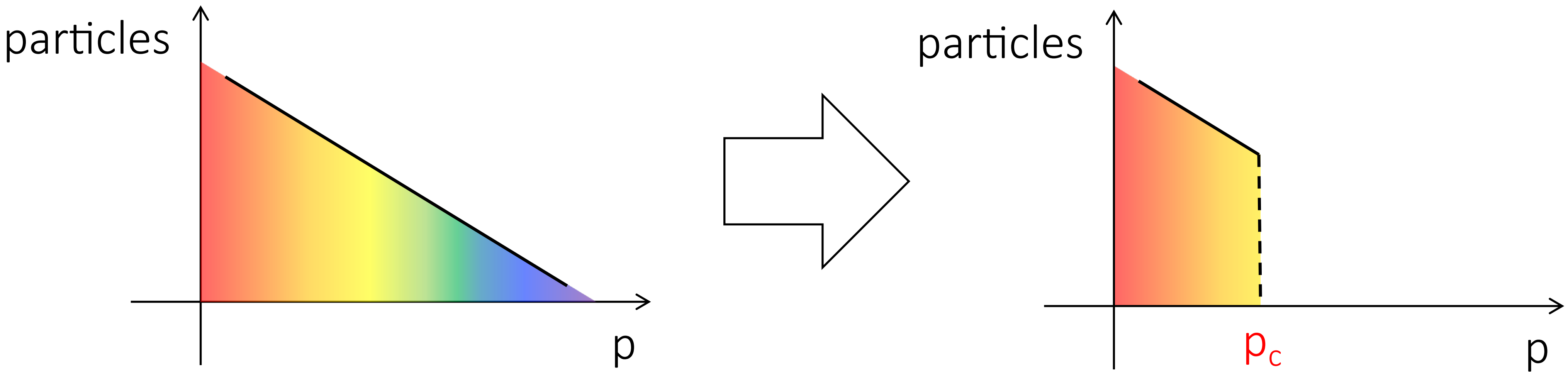
$$\frac{dN}{d\phi} = \frac{N}{2\pi}[1 + 2v_1 \cos(\phi - \Psi_1) + 2v_2 \cos(2\phi - 2\Psi_2) + \cdots]$$

Tsallis description may work up to p_T around 4 GeV without viscosity

⚠ Quantitative comparison is not possible with event-averaged simulations

“Red” scenario

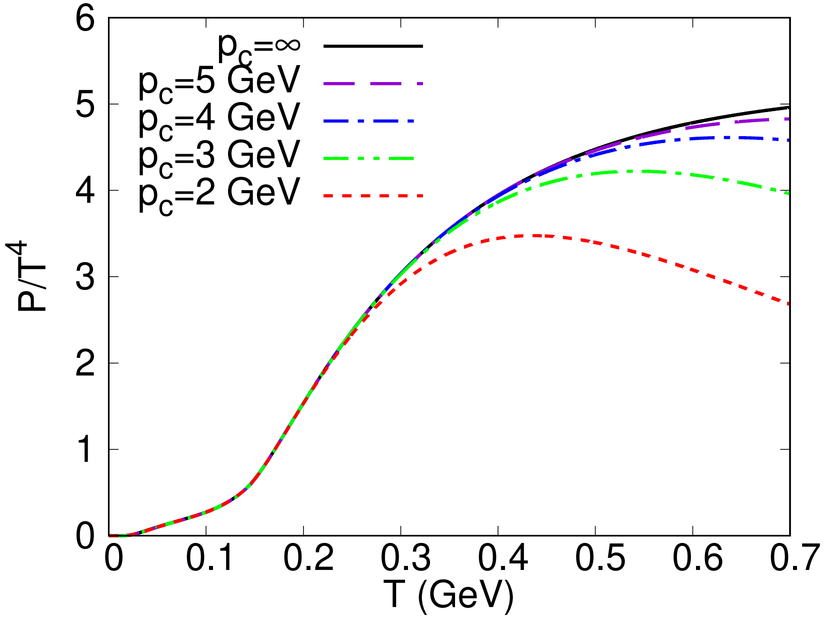
- Momentum cutoff method



We introduce an upper limit (p_c) for the momenta of strongly-coupled components

Equation of state

- Results



Pressure: $P = \pm T \sum_i \int_0^{p_c} \frac{g_i d^3p}{(2\pi)^3} \ln\left[1 \pm \exp\left(-\frac{E_i}{T}\right)\right]$

i: index for particle species

Hadron resonance gas 

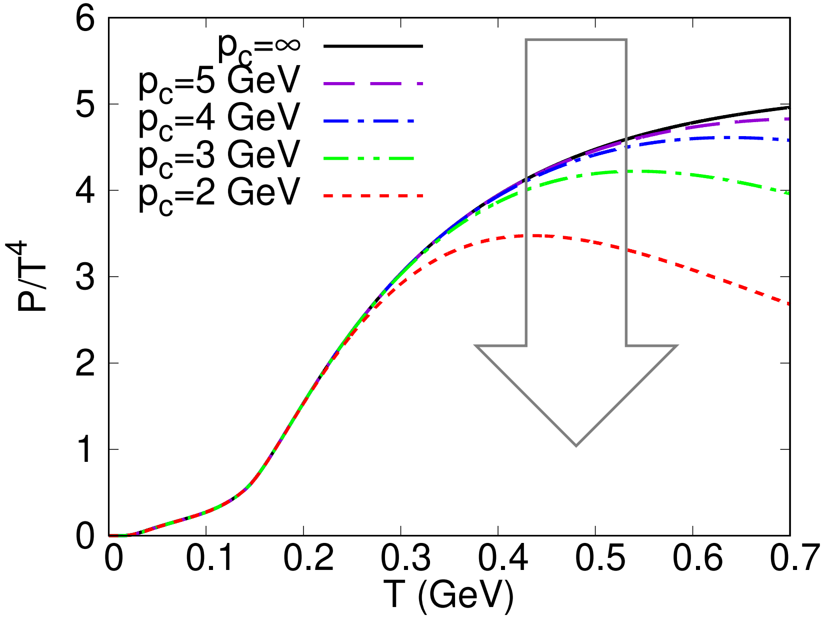
(2+1)-flavor parton gas 

Connect the pressures similarly to the "violet" case

The effect of p_c is larger at higher temperatures; negligible in the hadronic phase (≈ minimal effects on hadron production)

Equation of state

- Results



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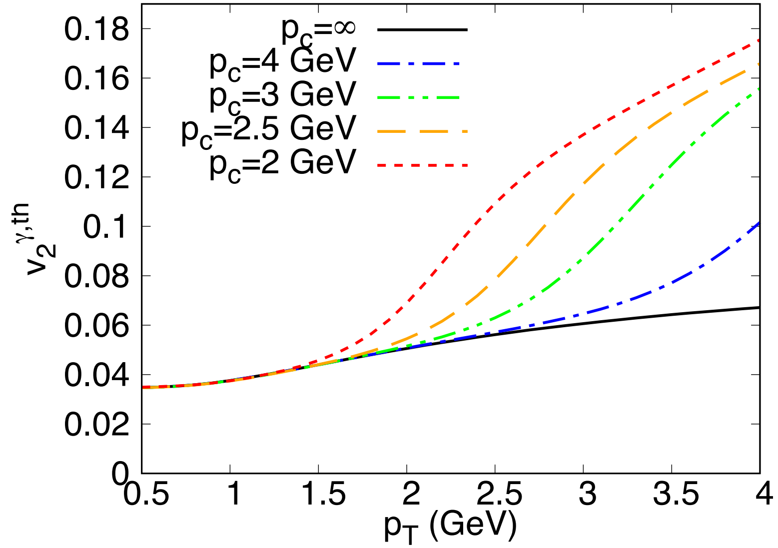
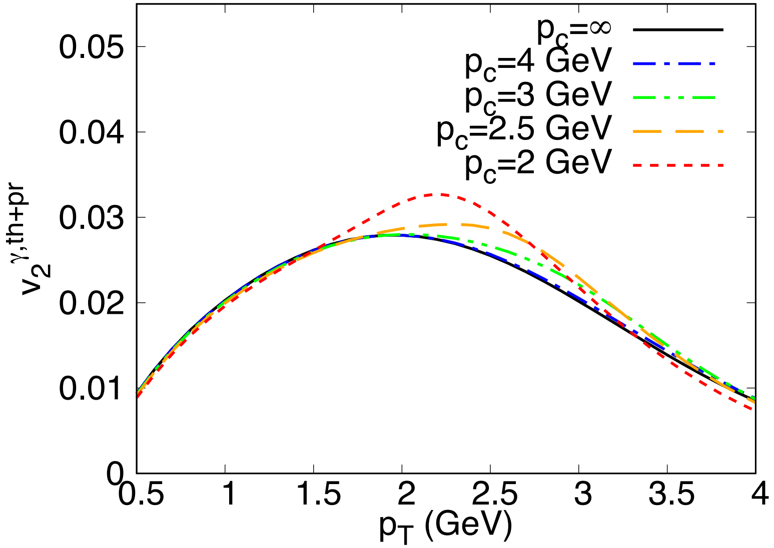
Numerical results

- Photon elliptic flow

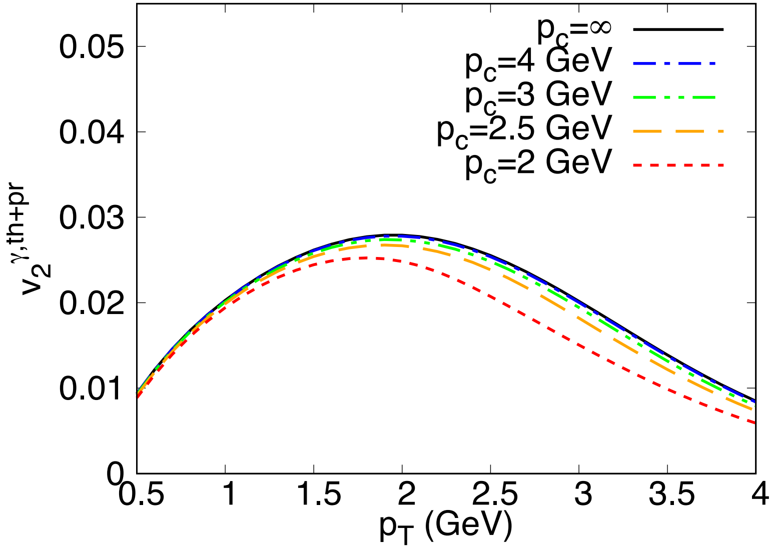
thermal



thermal + prompt



thermal + prompt + *high p_T

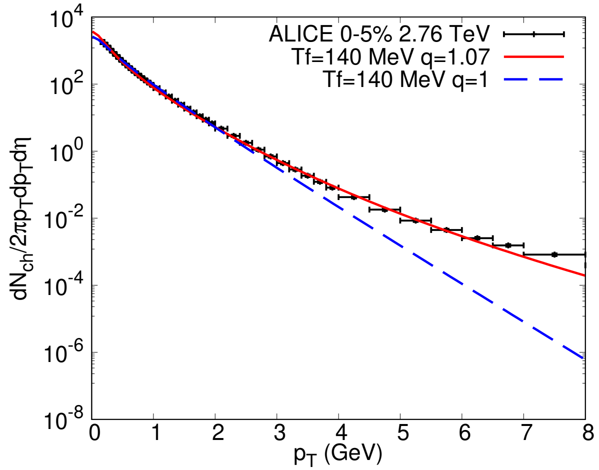


Photon v_2 is sensitive to the choice of p_c; whether it is enhanced or not depends on the high p_T contributions

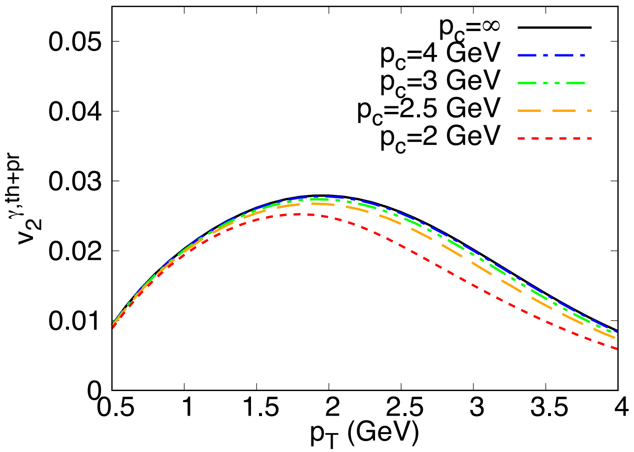
*conjectured here as thermal photons with no anisotropy

Summary

- "Violet" scenario (high momentum fluid)
  - Charged particle spectra can be described up to 7-8 GeV by Tsallis statistics with q=1.07
  - Elliptic flow v_2 suggests a narrower range of applicability

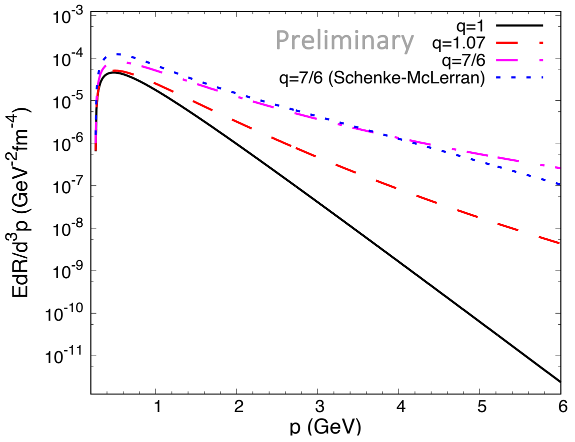


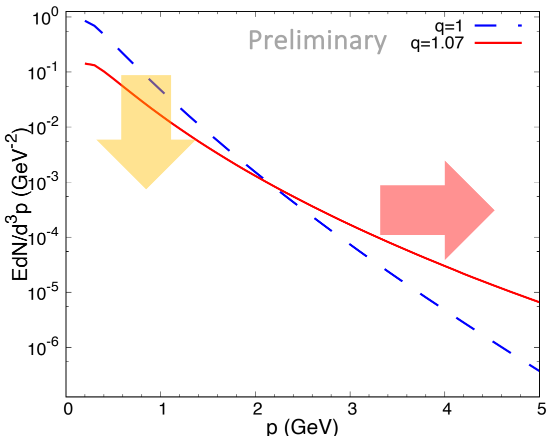
- "Red" scenario (low momentum fluid)
  - Equation of state is affected in the QGP phase
  - Elliptic flow v_2 can be sensitive to the momentum cutoff p_c



Outlook

- Future directions
  - Introduction of viscous corrections and event-by-event estimations for comparison with the experimental data
  - Estimation of energy-momentum exchange of hard and soft sectors
  - Calculation of direct photons in the Tsallis hydrodynamic model





Thank you for listening!

들어주셔서 감사합니다!