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GOETHE UNIVERSITÄT FRANKFURT AM MAIN

Parton-Hadron Matter at Finite Temperature and Chemical Potential

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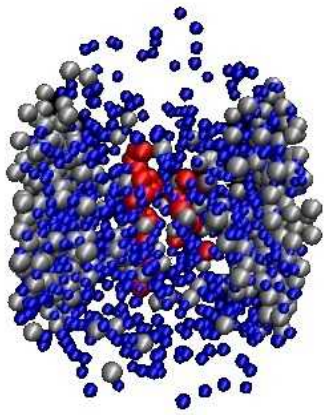
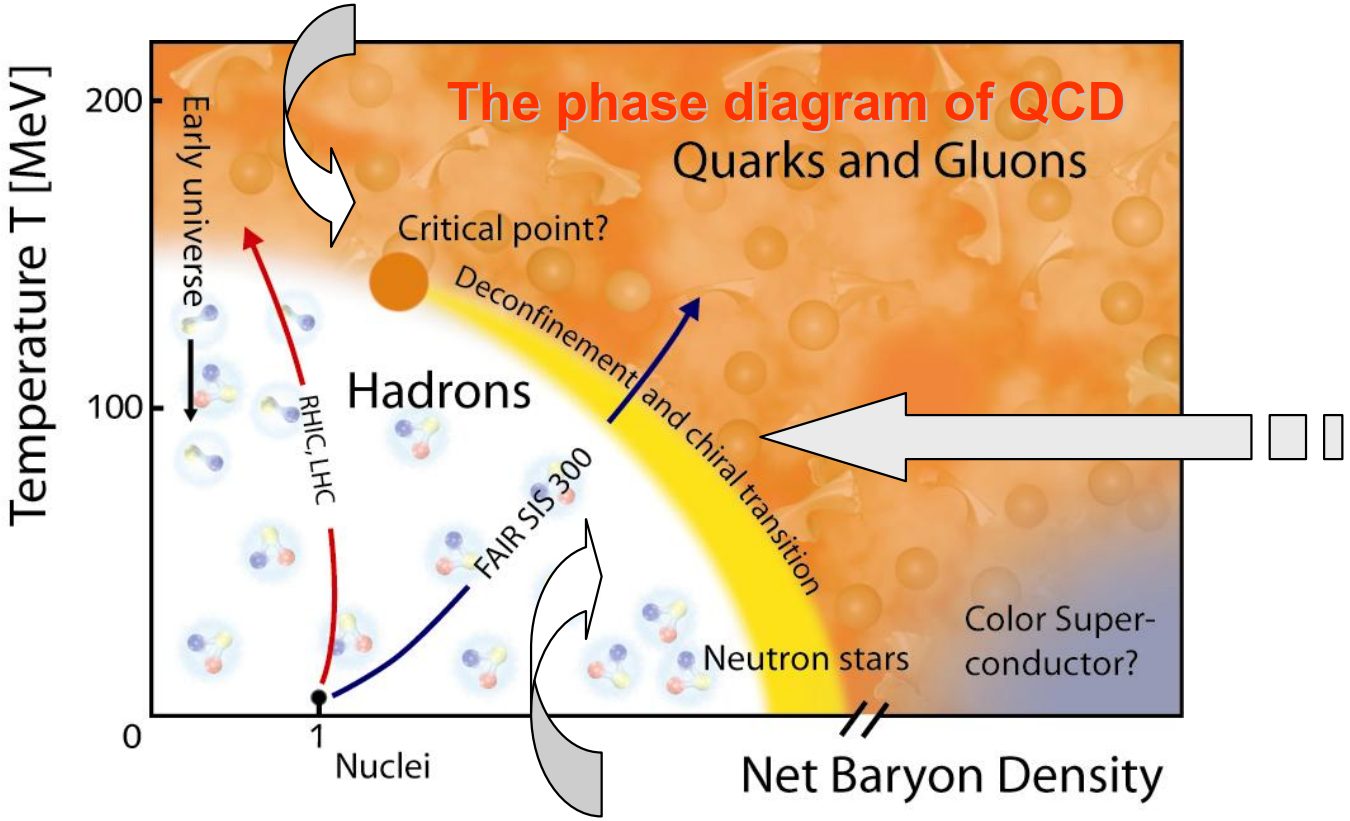


Keystone, Colorado, USA
25-31 January 2015

PHSD

The holy grail of heavy-ion physics:

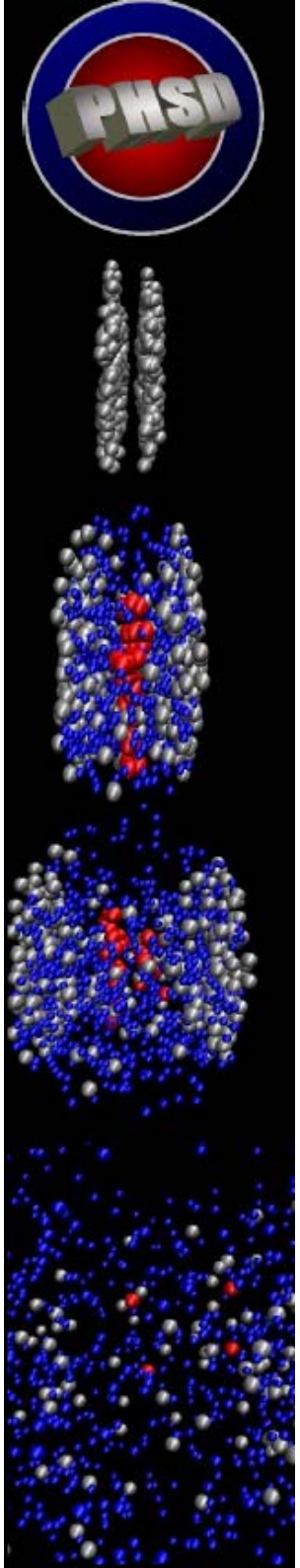
- Search for the critical point



- Study of the phase transition from hadronic to partonic matter – Quark-Gluon-Plasma

- Study of the in-medium properties of hadrons at high baryon density and temperature

The goal: to study of the phase transition from hadronic to partonic matter and properties of the Quark-Gluon-Plasma from microscopic origin



Parton-Hadron-String-Dynamics (PHSD)

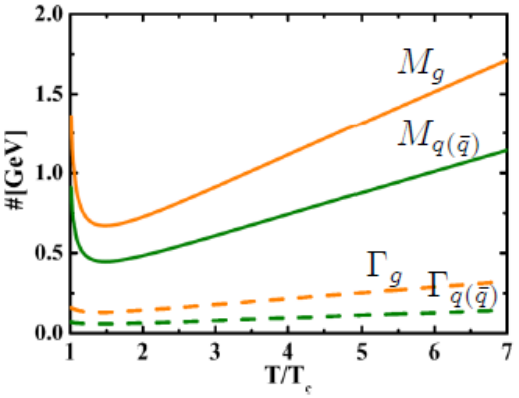
PHSD is a non-equilibrium transport model with

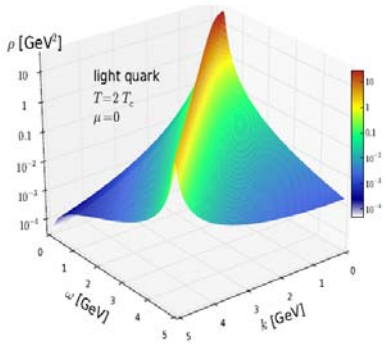
- **explicit phase transition from hadronic to partonic degrees of freedom**
- **IQCD EoS for the partonic phase (‚crossover' at μ_q=0)**
- **explicit parton-parton interactions - between quarks and gluons**
- **dynamical hadronization**

❑ **QGP phase is described by the Dynamical QuasiParticle Model (DQPM) matched to reproduce lattice QCD**

A. Peshier, W. Cassing, PRL 94 (2005) 172301;
W. Cassing, NPA 791 (2007) 365: NPA 793 (2007)

- **strongly interacting quasi-particles: massive quarks and gluons (g,q,q_{bar}) with sizeable collisional widths in self-generated mean-field potential**





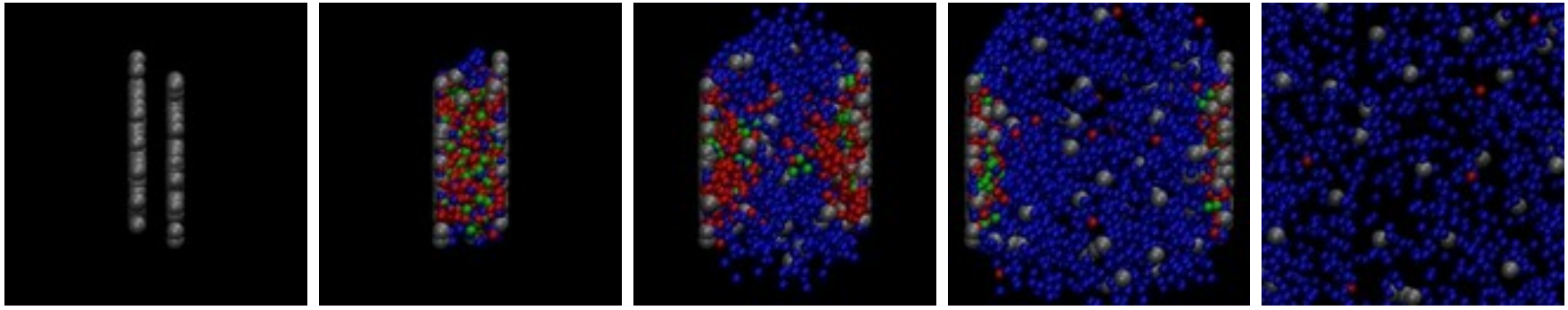
- **Spectral functions:**

$$\rho_i(\omega,T) = \frac{4\omega\Gamma_i(T)}{\left(\omega^2 - \vec{p}^{\,2} - M_i^{\,2}(T)\right)^2 + 4\omega^2\Gamma_i^{\,2}(T)} \qquad (i = q,\bar{q},g)$$

❑ **Transport theory: generalized off-shell transport equations based on the 1st order gradient expansion of Kadanoff-Baym equations (applicable for strongly interacting system!)**

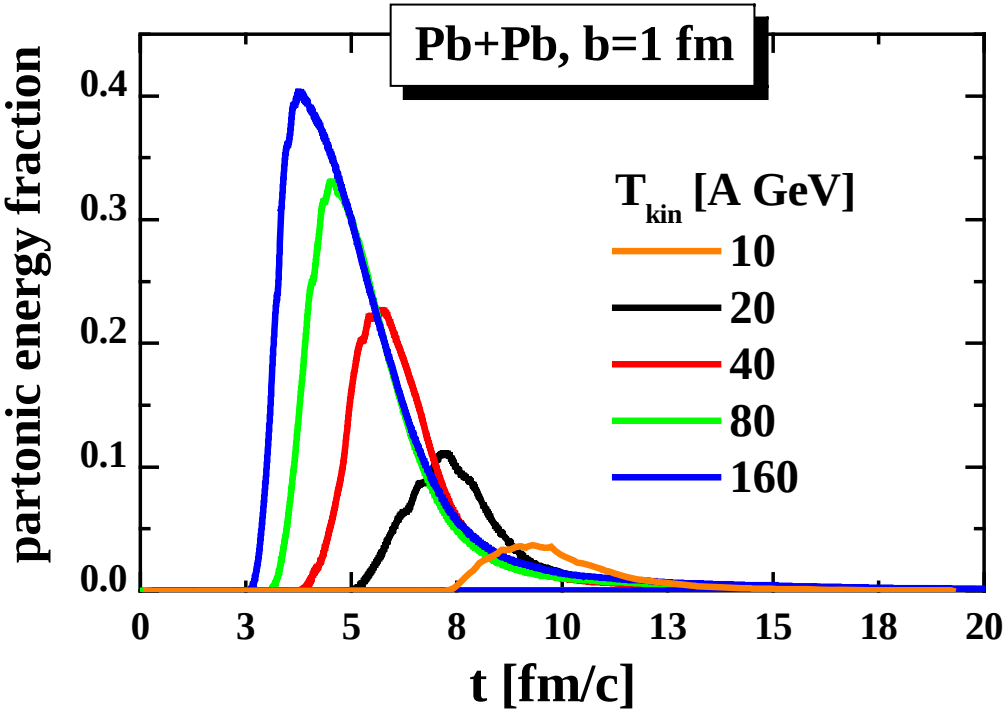
W. Cassing, E. Bratkovskaya, PRC 78 (2008) 034919; NPA831 (2009) 215; W. Cassing, EPJ ST 168 (2009) 3

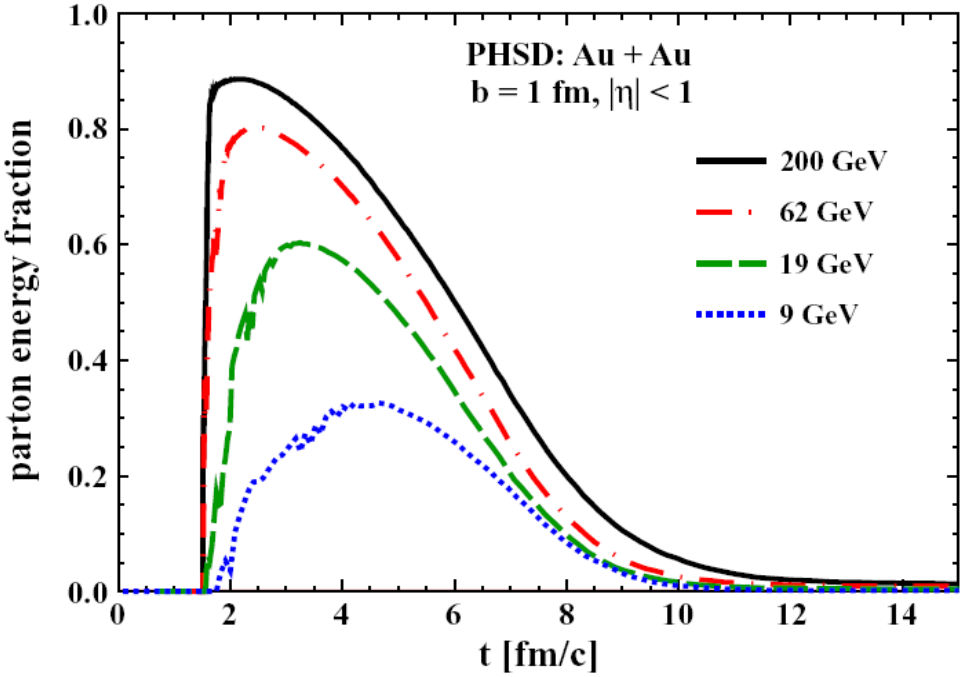
‚Bulk‘ properties in Au+Au collisions



Partonic energy fraction in central A+A

Time evolution of the partonic energy fraction vs energy



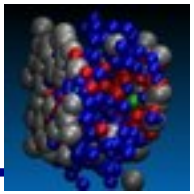


- Strong increase of partonic phase with energy from AGS to RHIC

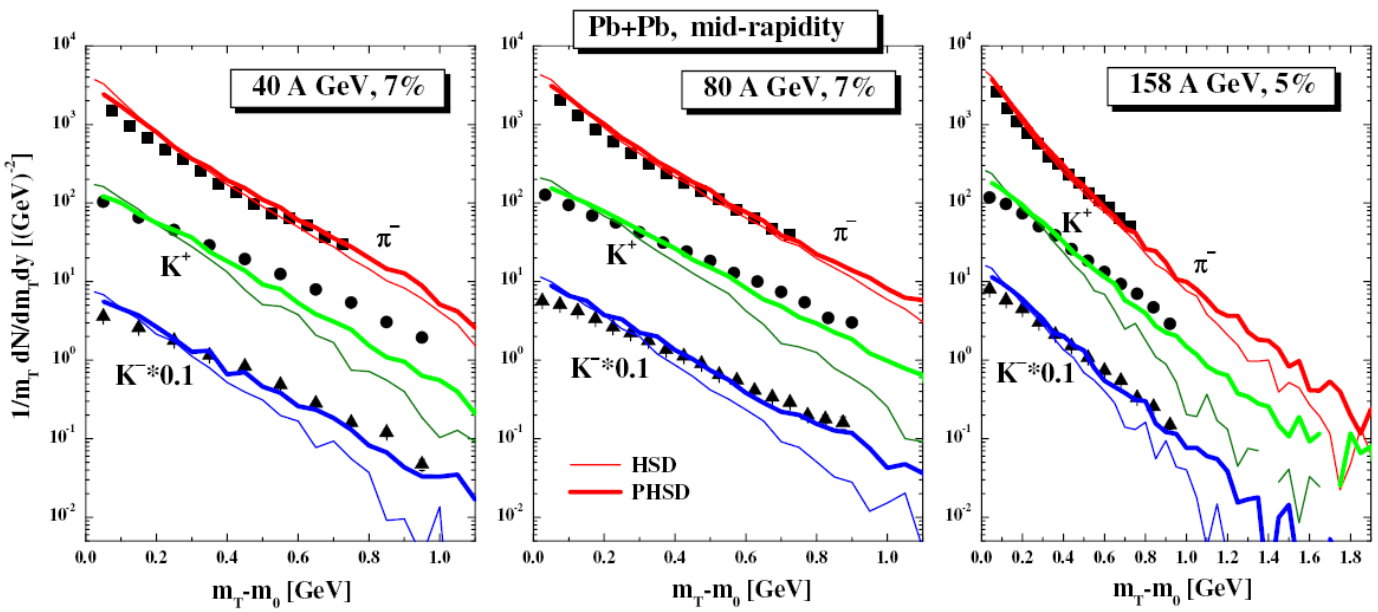
- SPS: Pb+Pb, 160 A GeV: only about 40% of the converted energy goes to partons; the rest is contained in the large hadronic corona and leading partons
- RHIC: Au+Au, 21.3 A TeV: up to 90% - QGP

W. Cassing & E. Bratkovskaya, NPA 831 (2009) 215
V. Konchakovski et al., Phys. Rev. C 85 (2012) 011902

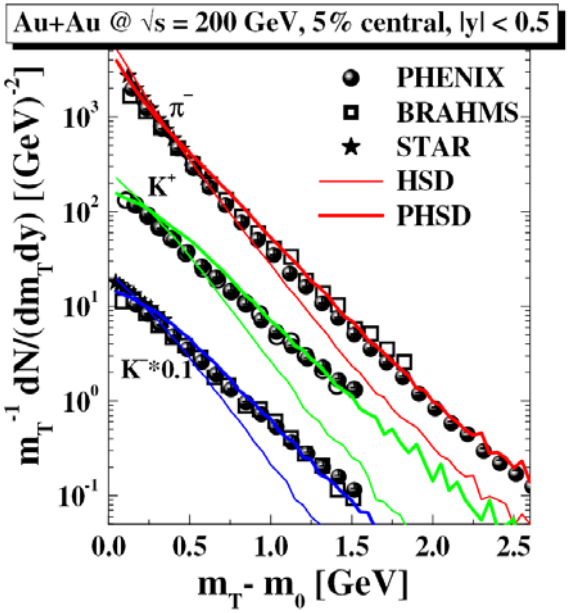
Transverse mass spectra from SPS to RHIC



Central Pb + Pb at SPS energies



Central Au+Au at RHIC

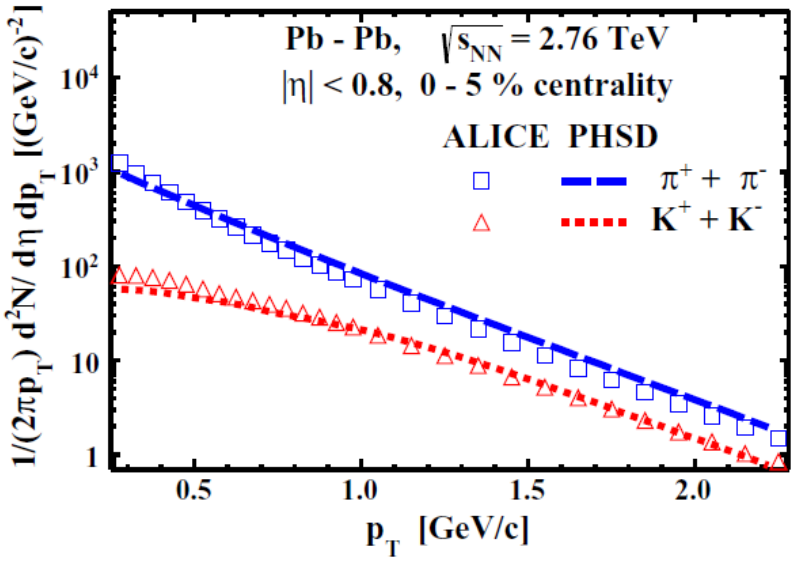


- **PHSD gives harder m_T spectra and works better than HSD (wo QGP) at high energies – RHIC, SPS (and top FAIR, NICA)**
- **however, at low SPS (and low FAIR, NICA) energies the effect of the partonic phase decreases due to the decrease of the partonic fraction**

W. Cassing & E. Bratkovskaya, NPA 831 (2009) 215
E. Bratkovskaya, W. Cassing, V. Konchakovski, O. Linnyk, NPA856 (2011) 162

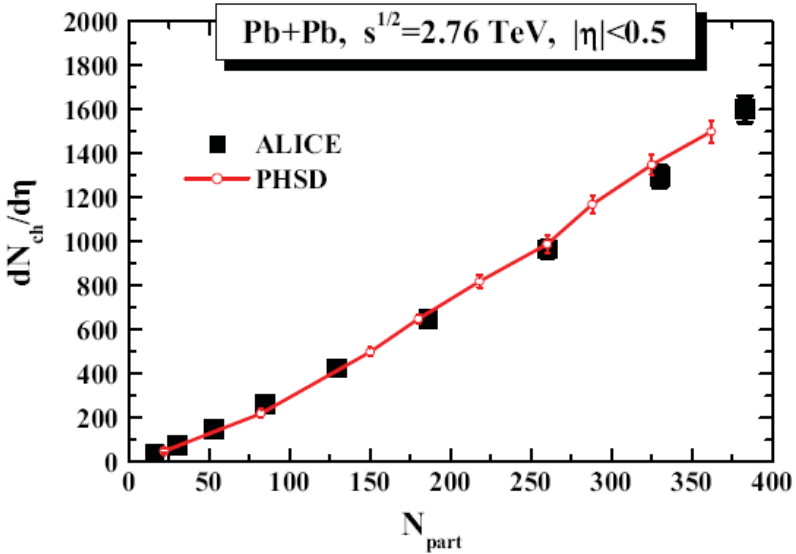
p_T spectra for Pb+Pb from PHSD at LHC

Low p_T spectra of pions and kaons



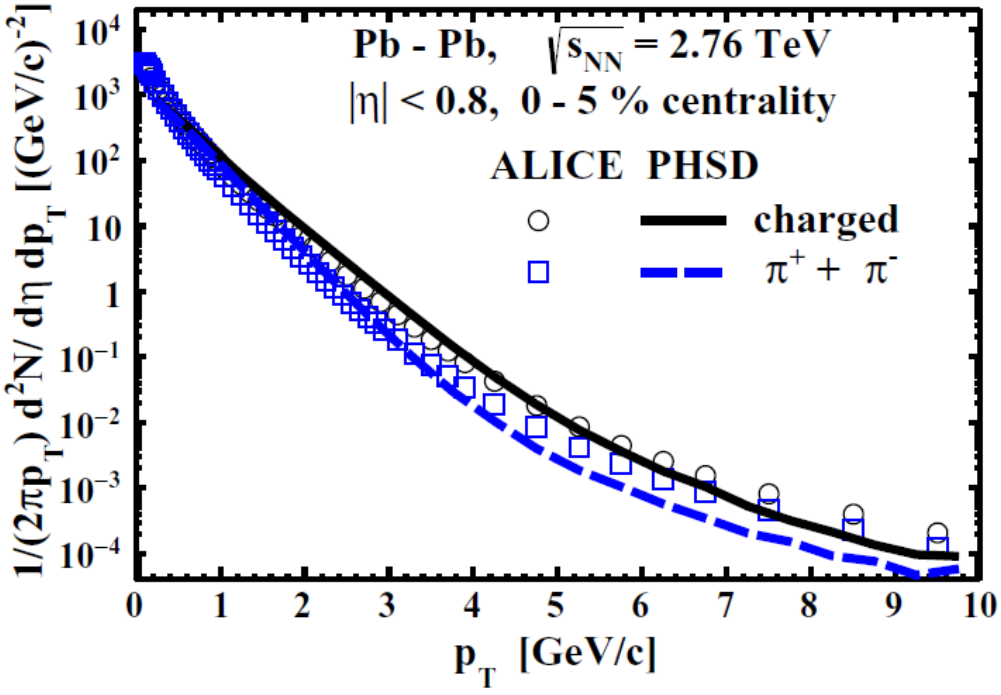
Charged particle multiplicity vs centrality

PHSD: Phys.Rev. C87 (2013) 014905; arXiv:1208.1279



p_T spectra of charged hadrons and pions

central Pb+Pb at $s^{1/2}$=2.76 TeV

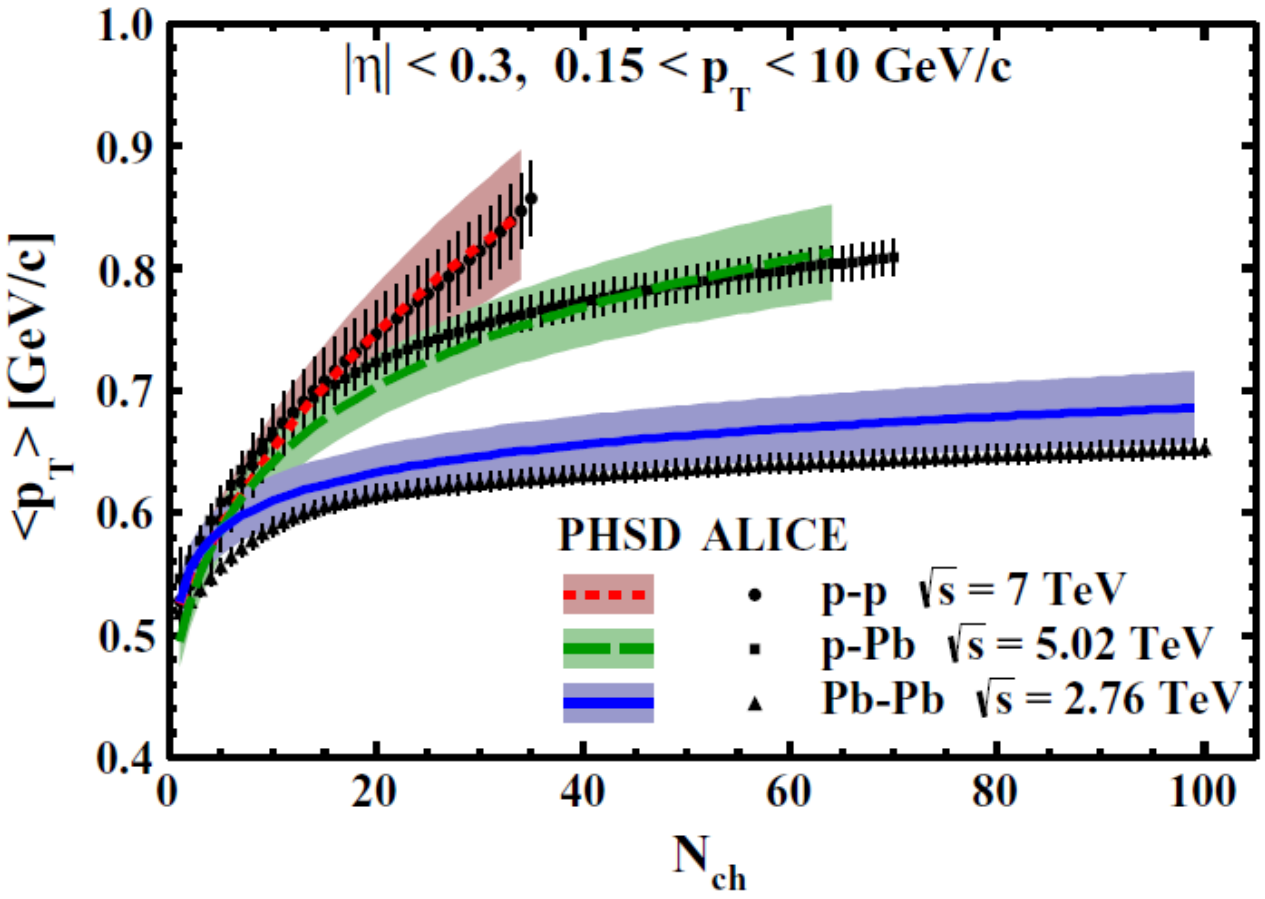


➔ PHSD reproduces ALICE data on Pb+Pb

V. Konchakovski, W. Cassing, V. Toneev, arXiv:1411.5534

Correlations of mean p_T vs N_{ch} at LHC

Mean p_T of charged hadrons at midrapidity vs N_{ch} for



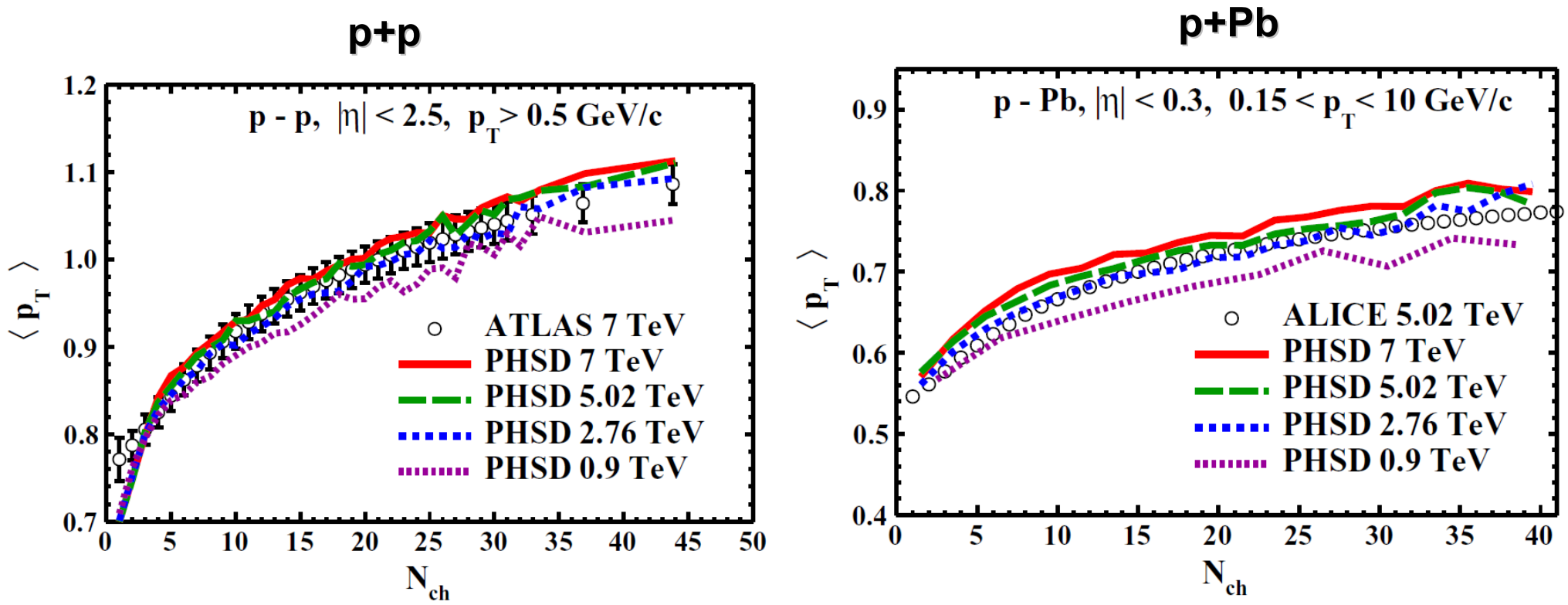
p+p at $s^{1/2}$=7 TeV
p+Pb at $s^{1/2}$=5.02 TeV,
Pb+Pb at $s^{1/2}$=2.76 TeV

➔ PHSD reproduces ALICE data on mean p_T

- Why the mean p_T spectra of p+p and p+Pb are identical at low N_{ch} ?
- What is the origin for the ‚hierarchy' of mean p_T at larger N_{ch} ?

V. Konchakovski, W. Cassing, V. Toneev, arXiv:1411.5534

Energy dependence of mean p_T vs N_{ch} at LHC



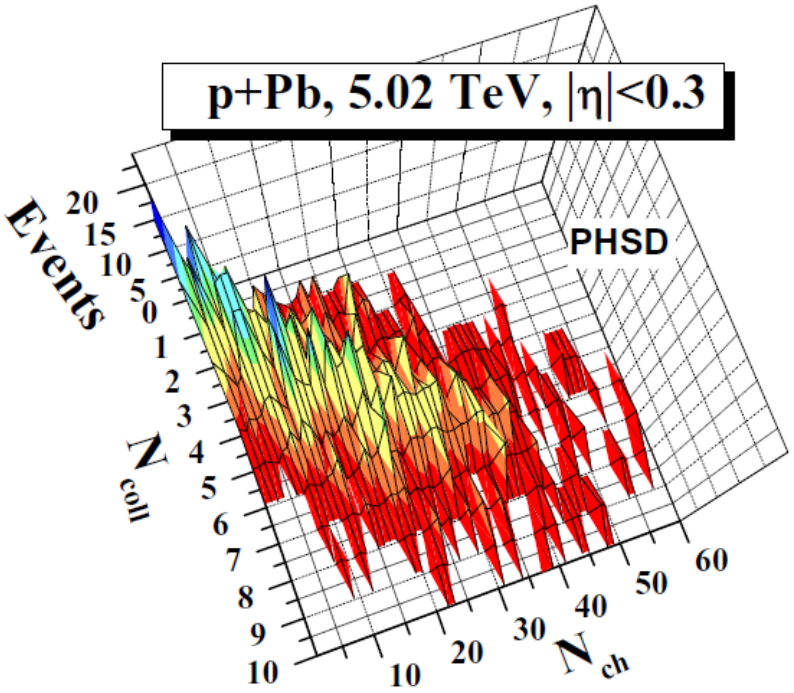
❑ The correlations of $\langle p_T \rangle$ of charged hadrons at midrapidity vs N_{ch} do not change much at LHC energies from 2.76 to 7 TeV for pp and p+Pb

➔ Relatively weak energy dependence of $\langle p_T \rangle$ vs N_{ch}

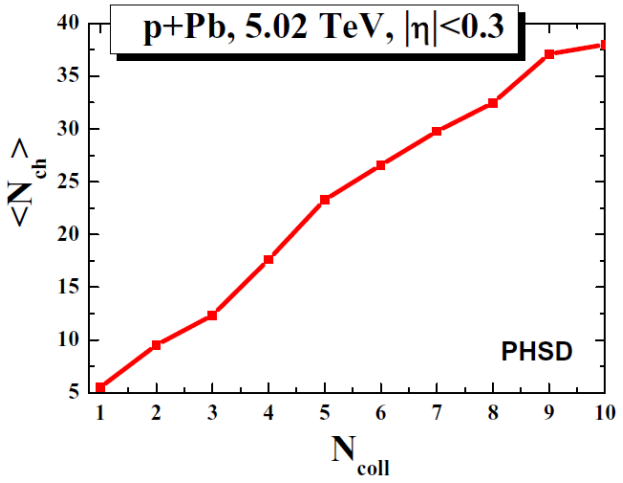
V. Konchakovski, W. Cassing, V. Toneev, arXiv:1411.5534

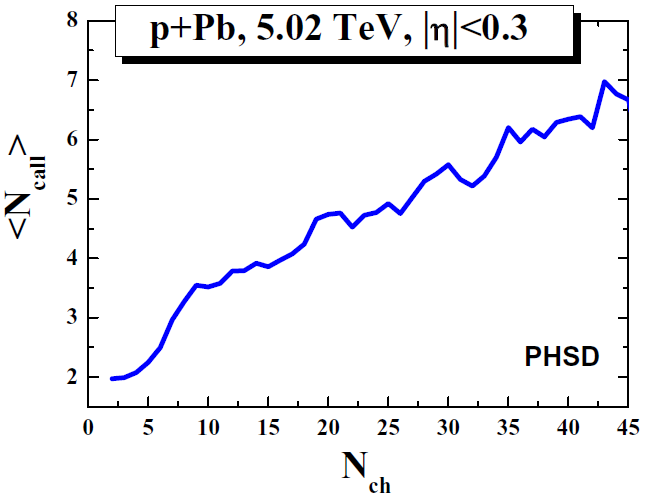
N_{coll} and N_{ch} correlations in p+Pb at LHC from PHSD

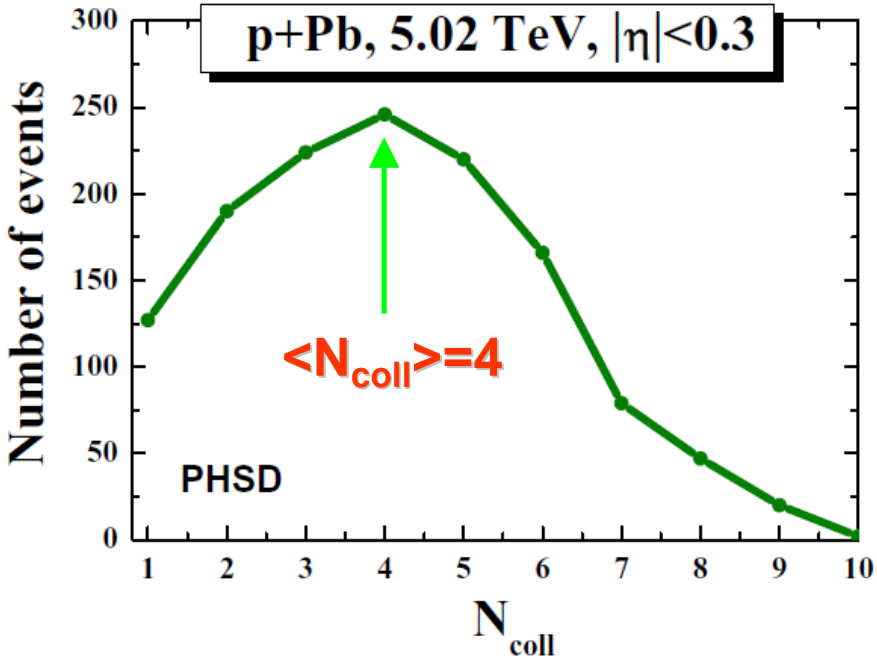
Number of events in p+Pb, $|\eta|<0.3$ vs N_{ch} and N_{coll}



Correlations of ‚mean values' N_{ch} and N_{coll}





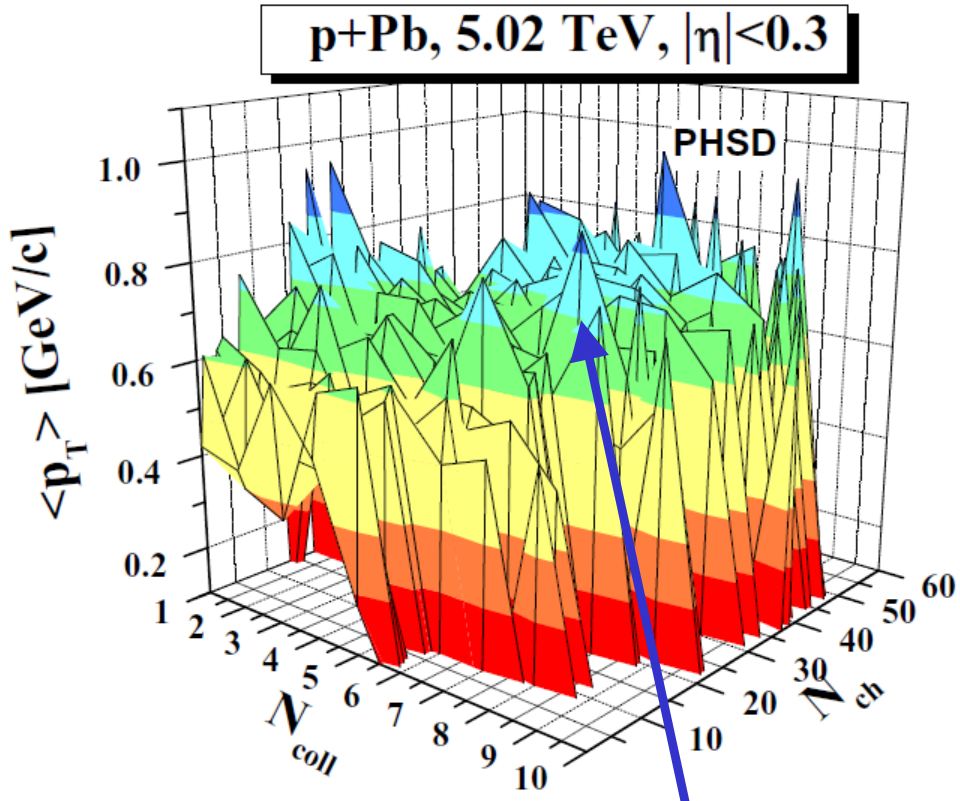


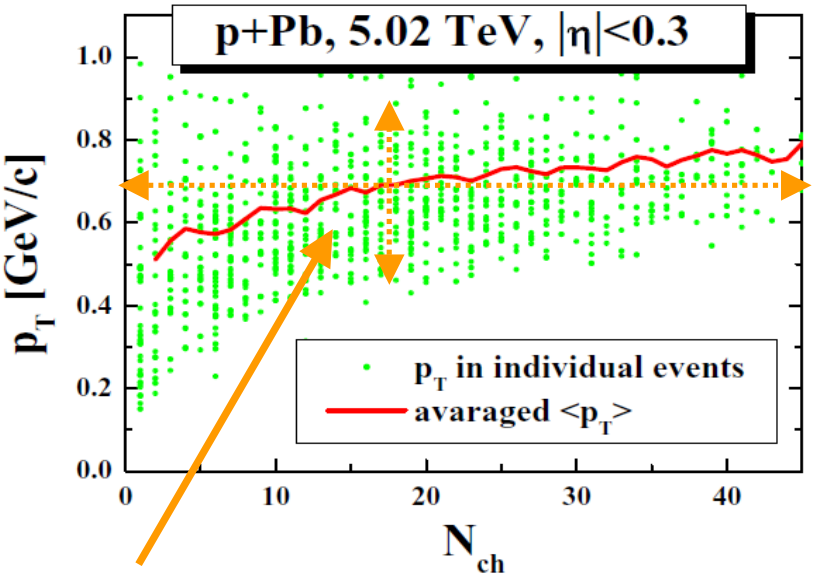
PHSD for p+Pb, $|\eta|<0.3$:

- ➔ **wide distribution** in (N_{coll}, N_{ch}); no strong correlations between N_{ch} and N_{coll} except for low N_{coll}
- ➔ linear dependence of mean values N_{ch} and N_{coll}
- ➔ $\langle N_{coll} \rangle = 4$

Correlations of p_T vs N_{coll} and N_{ch} in p+Pb from PHSD

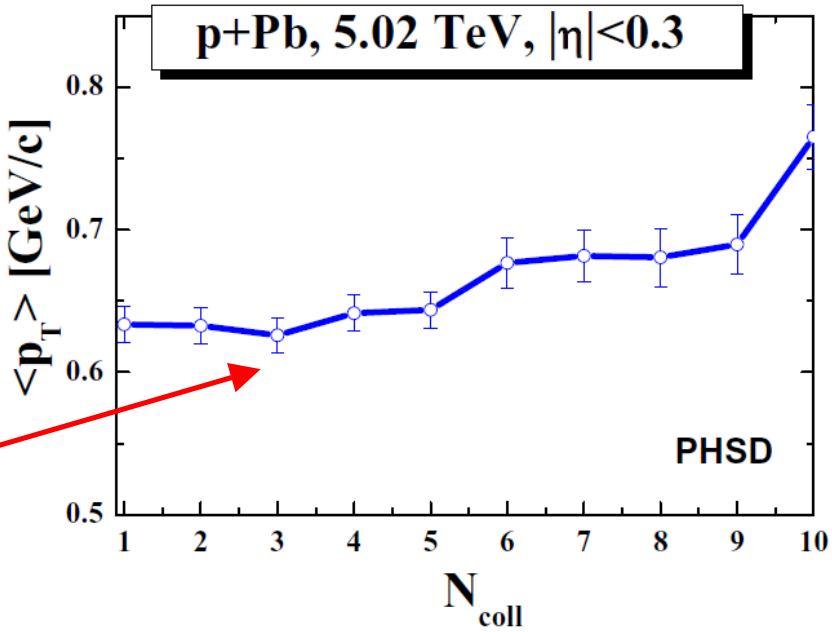
$\langle p_T \rangle$ in p+Pb, $|\eta|<0.3$ vs. N_{ch} and N_{coll}





➔ Huge e-by-e p_T fluctuations vs N_{ch}

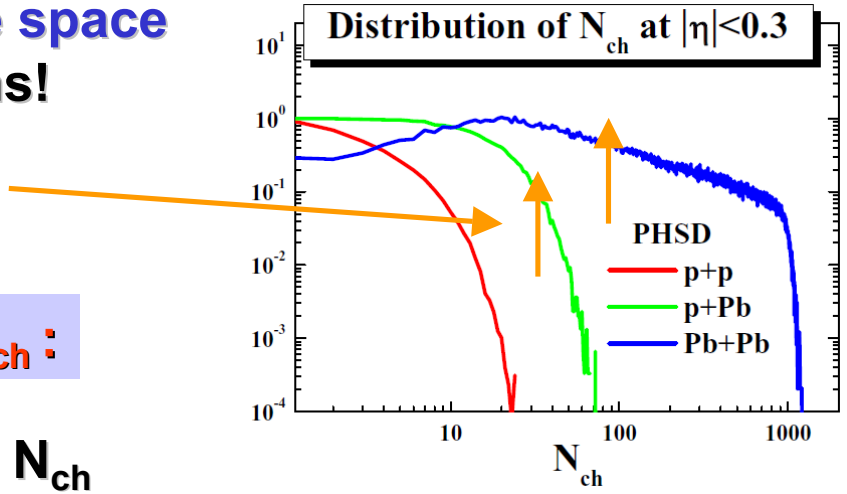
➔ $\langle p_T \rangle$ is flat vs.(N_{coll}, N_{ch})



Correlations of $<p_T>$ vs N_{ch} at LHC

Note!

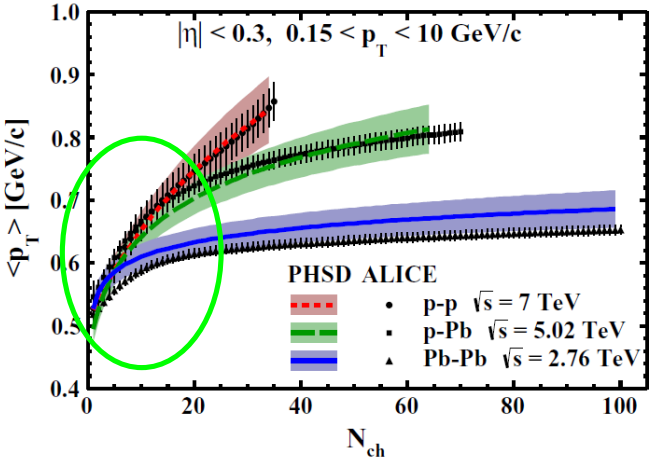
* probe only narrow part of the total phase space for $|\eta|<0.3$ ➔ large influence of correlations!
* probe only peripheral Pb+Pb and up to semi-central p+Pb



The origin for the ‚hierarchy' of $<p_T>$ vs N_{ch} :

- p+p: $N_{coll}=1$; $<p_T>$ grows ~linearly with vs. N_{ch}
- p+Pb: at low N_{ch} → N_{coll}~1-2 ➔ similar to pp
  at larger N_{ch} → N_{coll} >>1
  = summation of multiple (soft) collisions !

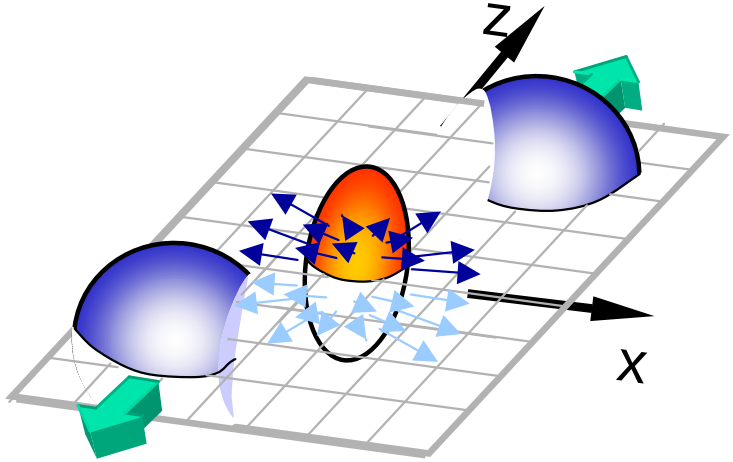
e.g. $<N_{coll}>=4$ corresponds to total N_{ch}~20
➔ in each individual j-collision $N_{ch}(j)$ is small
and $p_T(j)$ is small to end up with total N_{ch}~20
and $<p_T>$ ~0.65 GeV/c



- Pb+Pb: (similar to p+Pb) – multiple collisions!
  ! secondary collisions lowering $<p_T>$

➔ correlations between averages!

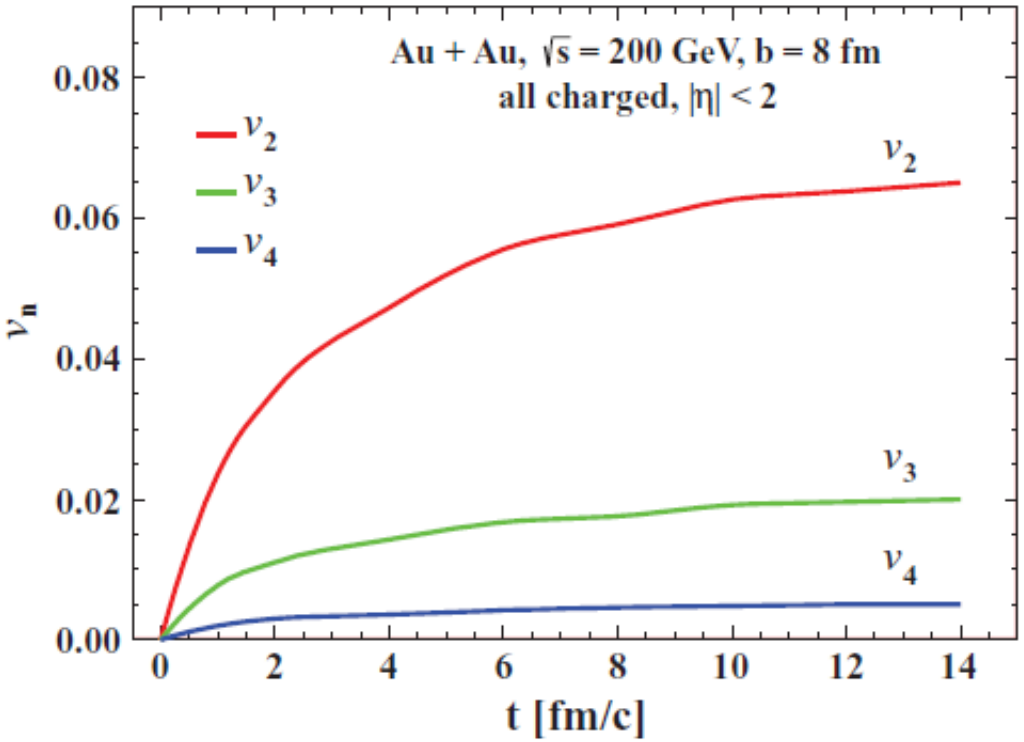
Collective flow, anisotropy coefficients (v_1, v_2, ...) in A+A



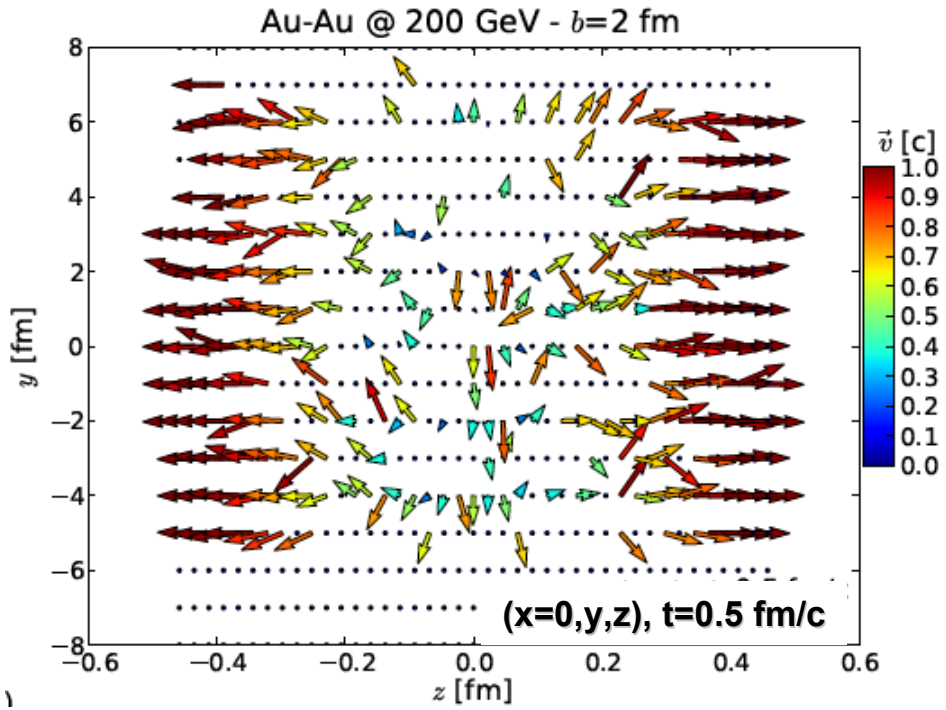
Development of azimuthal anisotropies in time

Au + Au collisions at $s^{1/2}$ = 200 GeV

- Time evolution of v_n for b = 8 fm



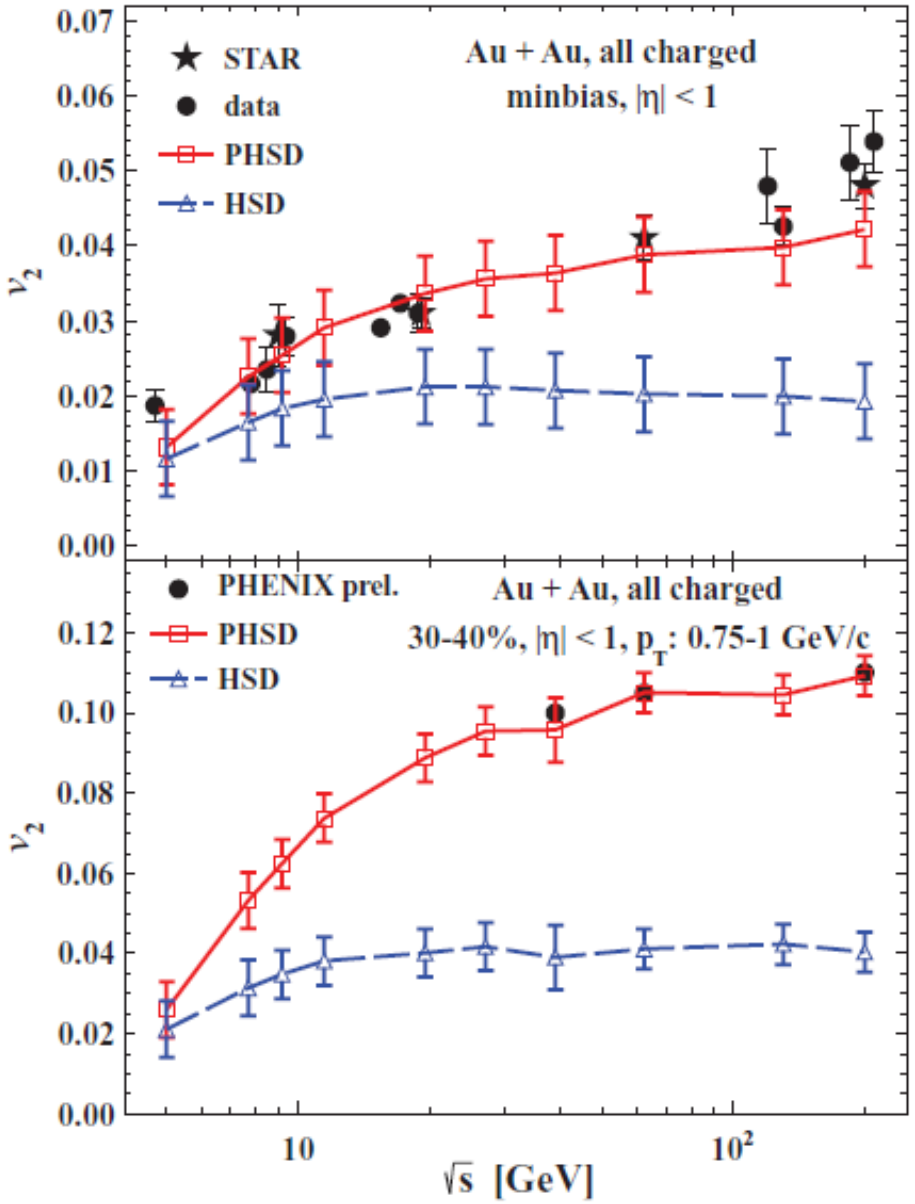
- Flow velocity for b = 2 fm (x=0,y,z), t=0.5 fm/c

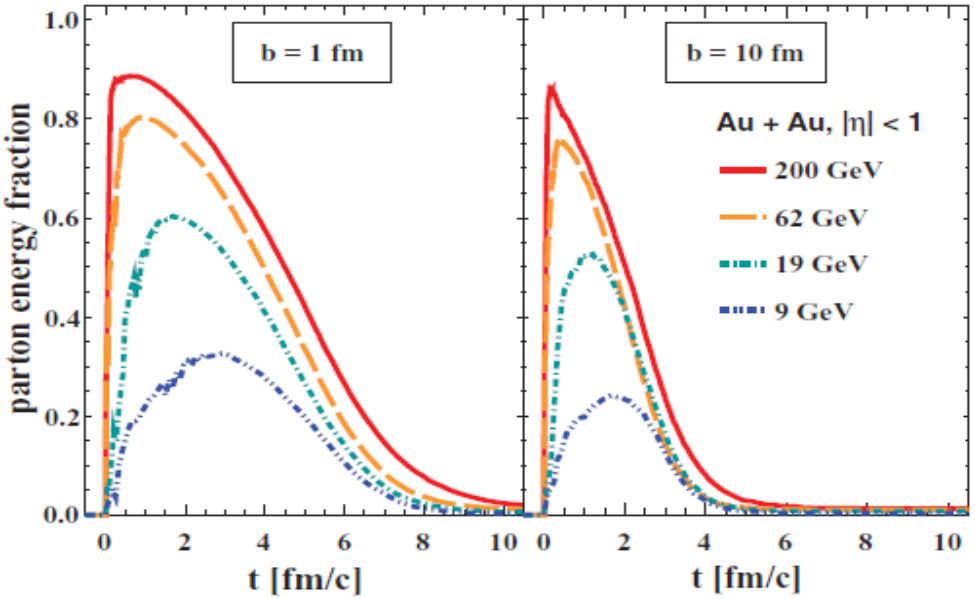


- Flow coefficients reach their asymptotic values by the time of 6–8 fm/c after the beginning of the collision

V. Konchakovski, E. Bratkovskaya, W. Cassing, V. Toneev, V. Voronyuk, Phys. Rev. C 85 (2012) 011902

Elliptic flow v_2 vs. collision energy for Au+Au

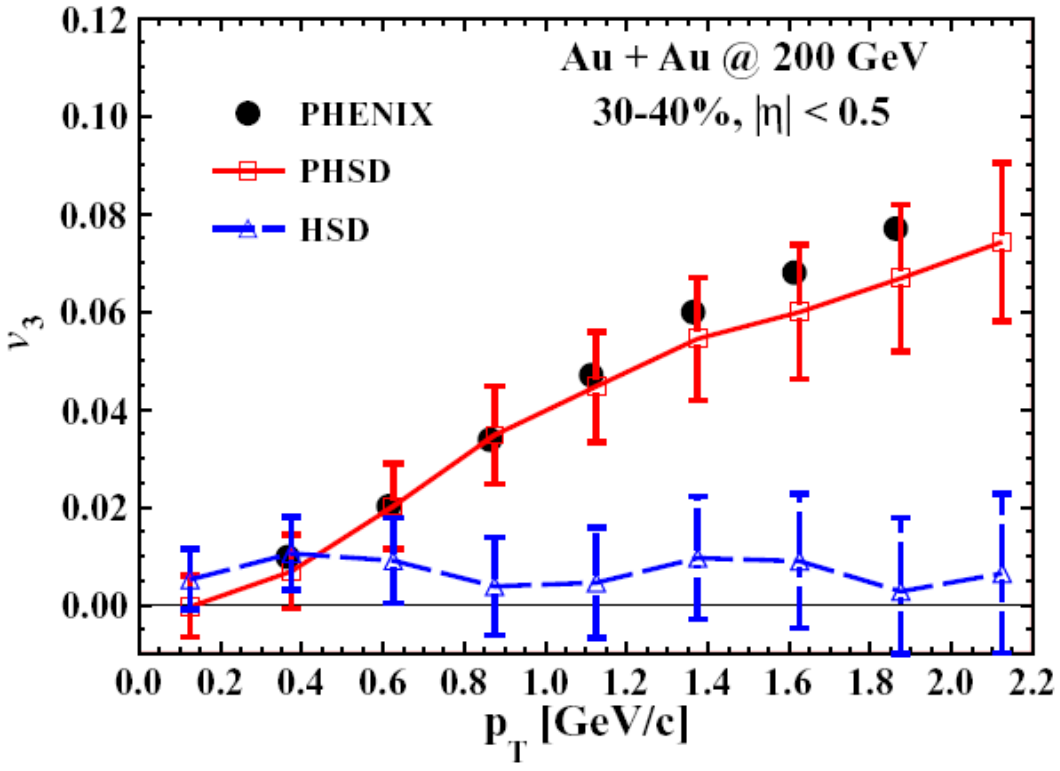




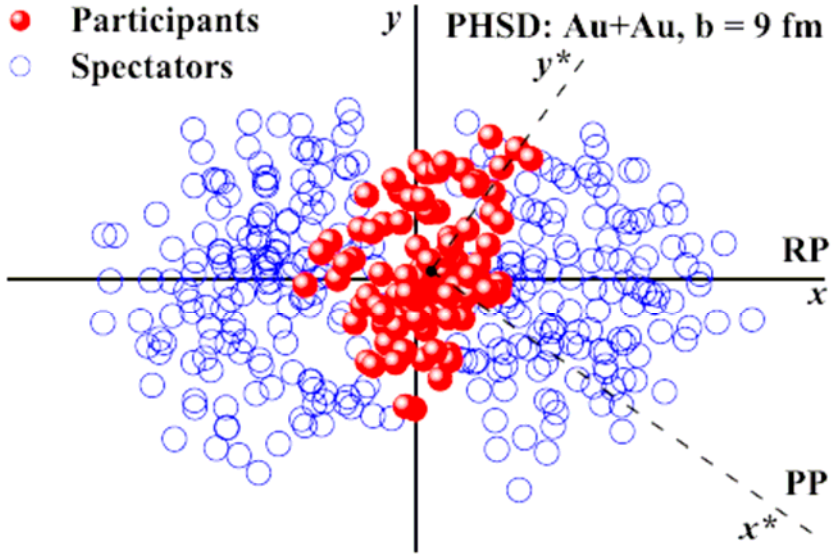
- v_2 in PHSD is larger than in HSD due to the repulsive scalar mean-field potential $U_s(\rho)$ for partons
- v_2 grows with bombarding energy due to the increase of the parton fraction

V. Konchakovski, E. Bratkovskaya, W. Cassing, V. Toneev, V. Voronyuk, Phys. Rev. C 85 (2012) 011902

Transverse momentum dependence of triangular flow at RHIC



triangular flow

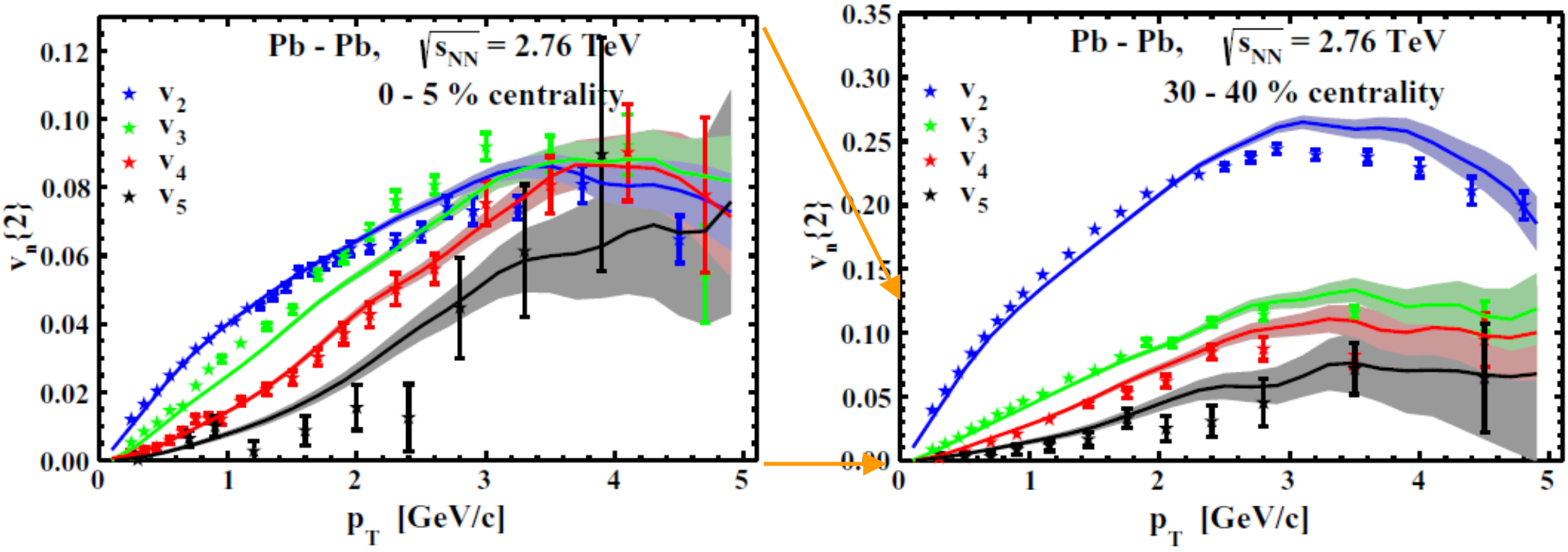


- HSD (without QGP) shows a flat p_T distribution
- PHSD shows an increase of v_3 with p_T

➔ v_3 : needs partonic degrees of freedom !

V. Konchakovski, E. Bratkovskaya, W. Cassing, V. Toneev, V. Voronyuk, Phys. Rev. C 85 (2012) 044922

V_n (n=2,3,4,5) of charged particles from PHSD at LHC



- PHSD: increase of v_n (n=2,3,4,5) with p_T
- v_2 increases with decreasing centrality
- v_n (n=3,4,5) show weak centrality dependence

symbols – ALICE
PRL 107 (2011) 032301
lines – PHSD (e-by-e)

V. Konchakovski, W. Cassing, V. Toneev, arXiv:1411.5534

Messages from the study of spectra and collective flow

- PHSD gives harder m_T spectra than HSD (without QGP) at high energies – LHC, RHIC, SPS

- at RHIC and LHC the QGP dominates the early stage dynamics

- at low SPS (and low FAIR, NICA) energies the effect of the partonic phase decreases

➔ influence of the finite quark chemical potential μ_q ?!

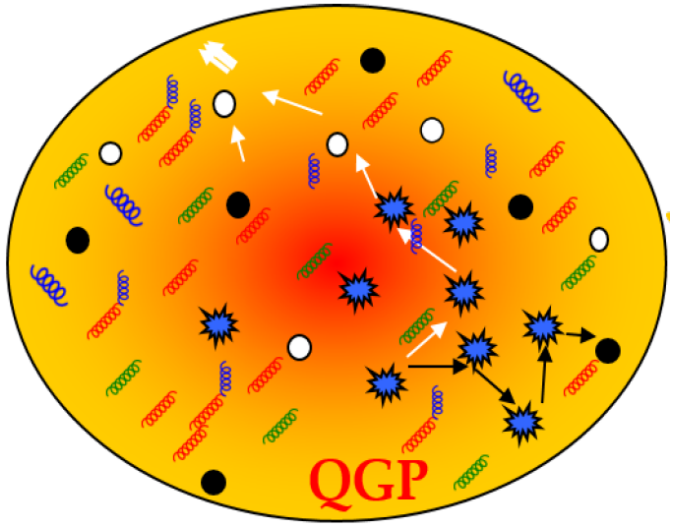
- Anisotropy coefficients v_n as a signal of the QGP:

  - quark number scaling of v_2 at ultrarelativistic energies – signal of deconfinement

  - growing of v_2 with energy – partonic interactions generate a larger pressure than the hadronic interactions

  - v_n, n=3,.. – sensitive to QGP

Thermodynamic and transport properties of sQGP in equilibrium at finite temperature and chemical potential



Hamza Berrehrah et al.

The Dynamical QuasiParticle Model (DQPM) at finite T

Properties of interacting quasi-particles: massive quarks and gluons (g, q, q_{bar}) with Lorentzian spectral functions :

$$A_i(\omega,T)=\frac{4\omega\Gamma_i(T)}{\left(\omega^2-\vec{p}^{\,2}-M_i^{\,2}(T)\right)^2+4\omega^2\Gamma_i^{\,2}(T)} \qquad (i=q,\bar{q},g)$$

- Modeling of the quark/gluon masses and widths → HTL limit at high T

- **quarks:**

mass: $M^2_{q(\bar{q})}(T)=\frac{N_c^2-1}{8N_c}g^2\left(T^2+\frac{\mu_q^2}{\pi^2}\right)$

width: $\Gamma_{q(\bar{q})}(T)=\frac{1}{3}\frac{N_c^2-1}{2N_c}\frac{g^2T}{8\pi}\ln\left(\frac{2c}{g^2}+1\right)$

- **gluons:**

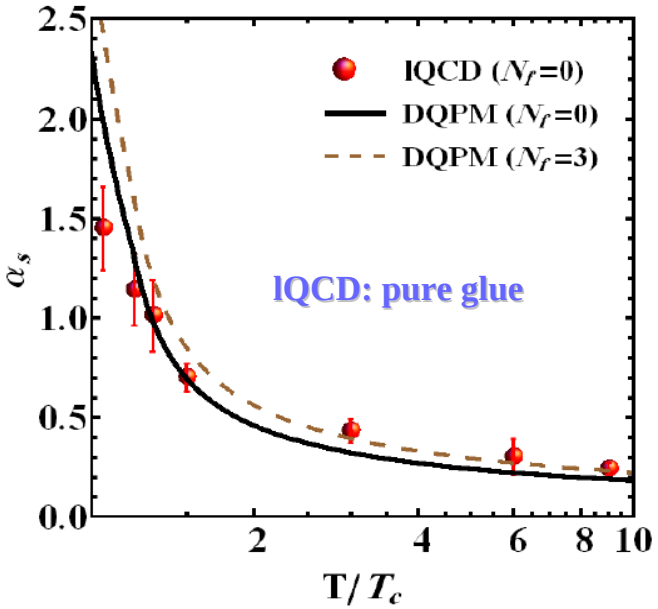
$$M_g^2(T)=\frac{g^2}{6}\left(\left(N_c+\frac{N_f}{2}\right)T^2+\frac{N_c}{2}\sum_q\frac{\mu_q^2}{\pi^2}\right)$$

$$\Gamma_g(T)=\frac{1}{3}N_c\frac{g^2T}{8\pi}\ln\left(\frac{2c}{g^2}+1\right)$$

$N_c = 3$, $N_f=3$

- **running coupling** (pure glue):

$$\alpha_s(T)=\frac{g^2(T)}{4\pi}=\frac{12\pi}{(11N_c-2N_f)\ln[\lambda^2(T/T_c-T_s/T_c)^2]}$$



❑ fit to lattice (lQCD) results (e.g. entropy density)

with 3 parameters: T_s/T_c=0.46; c=28.8; λ=2.42
(for pure glue N_f=0)

DQPM: Peshier, Cassing, PRL 94 (2005) 172301;
Cassing, NPA 791 (2007) 365: NPA 793 (2007)

DQPM at finite (T, μ_q): scaling hypothesis

❑ **Scaling hypothesis for the effective temperature T* for $N_f = N_c = 3$**

$$T^{*2} = T^2 + \frac{\mu_q^2}{\pi^2}$$

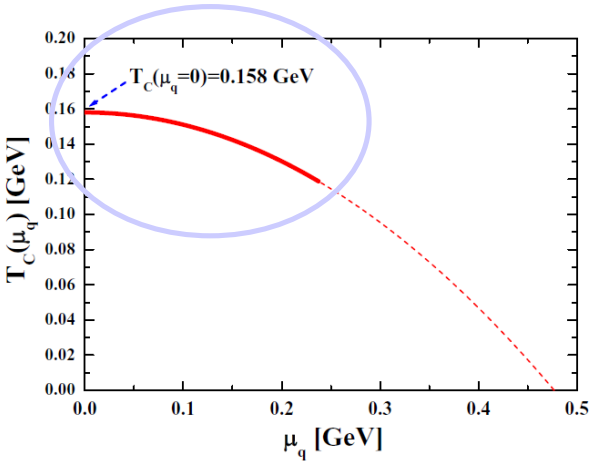
$$\mu_u = \mu_d = \mu_s = \mu_q$$

❑ **Coupling constant:**

$$g(T/T_c(\mu=0)) \longrightarrow g(T^*/T_c(\mu))$$

❑ **Critical temperature $T_c(\mu_q)$:**

obtained by requiring a constant energy density ε for the system at $T=T_c(\mu_q)$ where ε at $T_c(\mu_q=0)=158$ GeV is fixed by IQCD at $\mu_q=0$



$$\frac{T_c(\mu_q)}{T_c(\mu_q=0)} = \sqrt{1-\alpha\,\mu_q^2} \approx 1 - \alpha/2\,\mu_q^2 + \cdots$$

$$\alpha \approx 8.79\ \mathrm{GeV}^{-2}$$

! Consistent with lattice QCD:

IQCD: C. Bonati et al., PRC90 (2014) 114025

$$\frac{T_c(\mu_B)}{T_c} = 1 - \kappa \left(\frac{\mu_B}{T_c}\right)^2 + \cdots$$

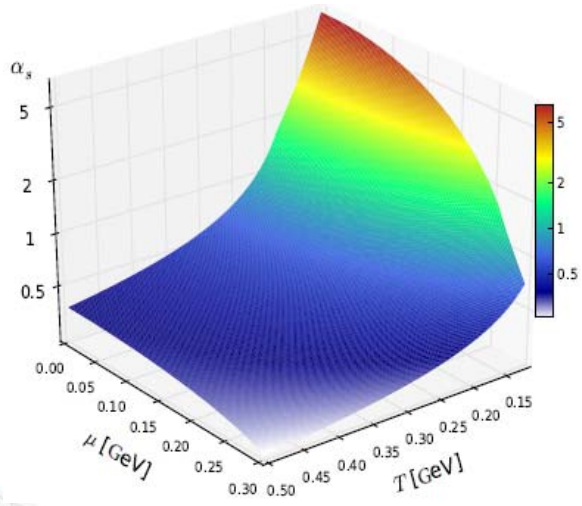
IQCD $\kappa = 0.013(2)$ ⟷ $\kappa_{DQPM} \approx 0.0122$

H. Berrehrah et al. arXiv:1412.1017

DQPM at finite (T, μ_q): quasiparticle masses and widths

❑ Coupling constant:

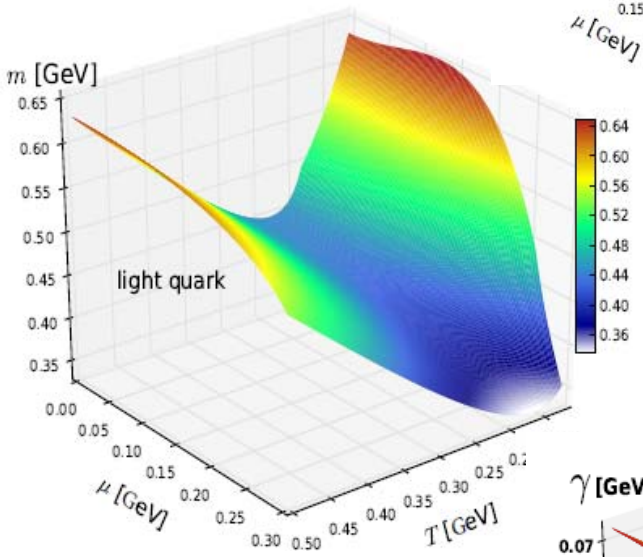
$$g^2(T^\star/T_c(\mu_q)) = \frac{48\pi^2}{(11N_c - 2N_f)\ln\left(\lambda^2(\frac{T^\star}{T_c(\mu_q)} - \frac{T_s}{T_c(\mu_q)})^2\right)}$$



❑ Quark and gluon masses:

$$M_g^2(T^\star,\mu_q) = \frac{g^2(T^\star/T_c(\mu_q))}{6}(N_c + \frac{1}{2}N_f)\ T^{\star 2},$$

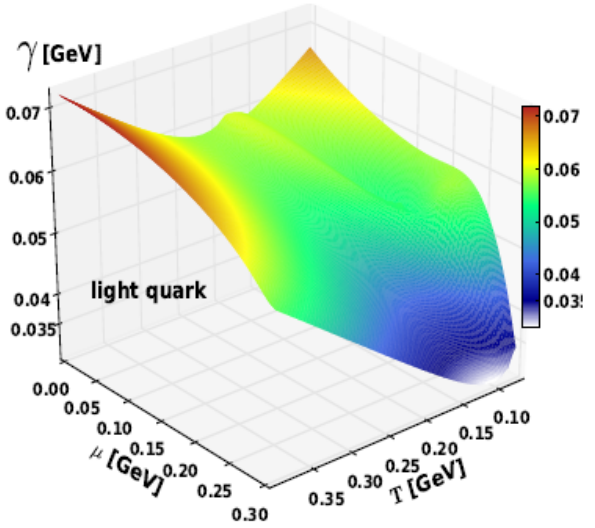
$$M_q^2(T^\star,\mu_q) = \frac{N_c^2-1}{8N_c} g^2(T^\star/T_c(\mu_q))\ T^{\star 2},$$



❑ Quark and gluon widths:

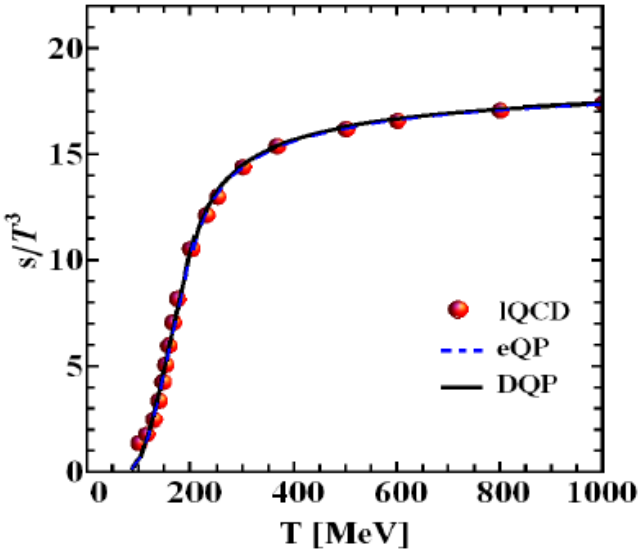
$$\gamma_g(T,\mu_q) = \frac{1}{3}N_c\frac{g^2(T^*/T_c(\mu_q))}{8\pi}\ T\ \ln\left(\frac{2c}{g^2(T^*/T_c(\mu_q))}+1\right),$$

$$\gamma_q(T,\mu_q) = \frac{1}{3}\frac{N_c^2-1}{2N_c}\frac{g^2(T^*/T_c(\mu_q))}{8\pi}\ T\ \ln\left(\frac{2c}{g^2(T^*/T_c(\mu_q))}+1\right).$$

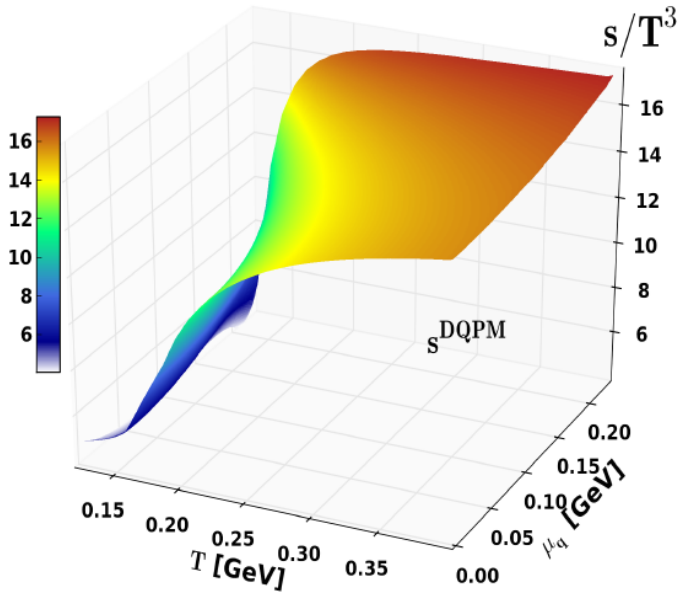


DQPM: thermodynamics at finite (T, μ_q)

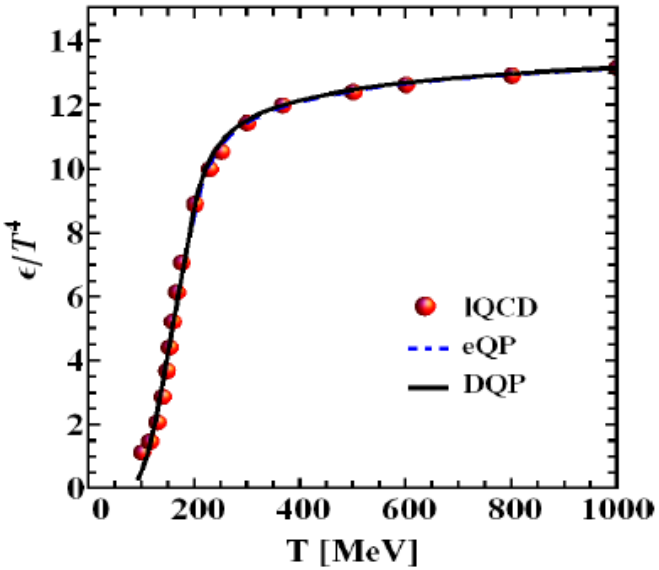
- Entropy density at finite T



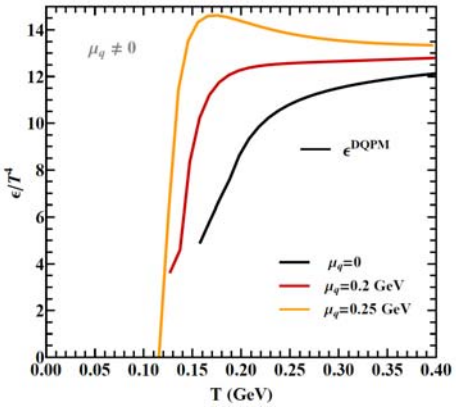
Entropy density at finite (T, μ_q)

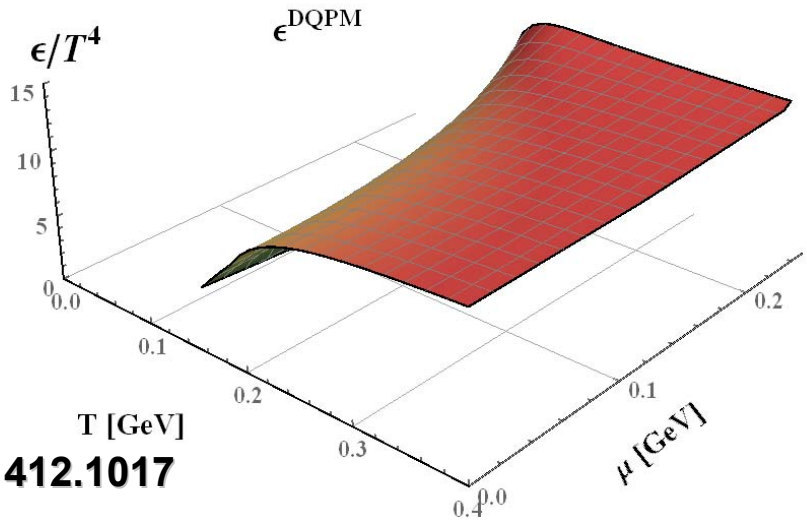


- Energy density at finite T



Energy density at finite (T, μ_q)

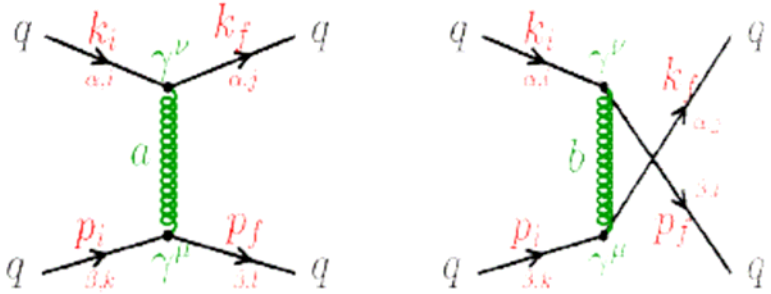




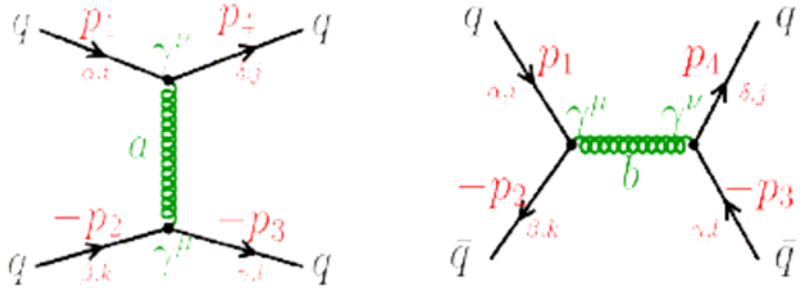
H. Berrehrah et al. arXiv:1412.1017

DQPM: q, qbar, g elastic scattering at finite (T, μ_q)

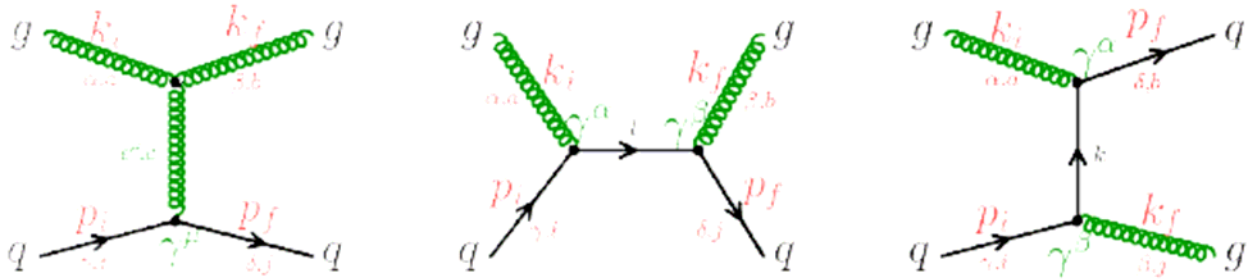
q q



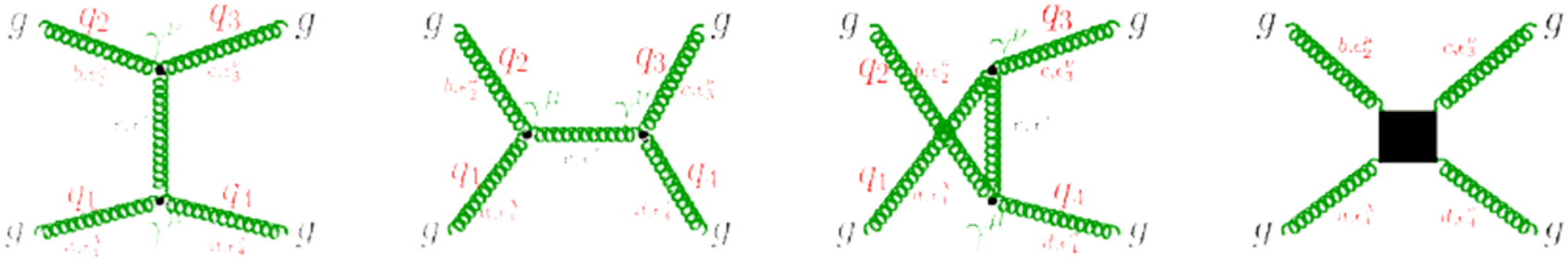
q $\bar{q}$



q g



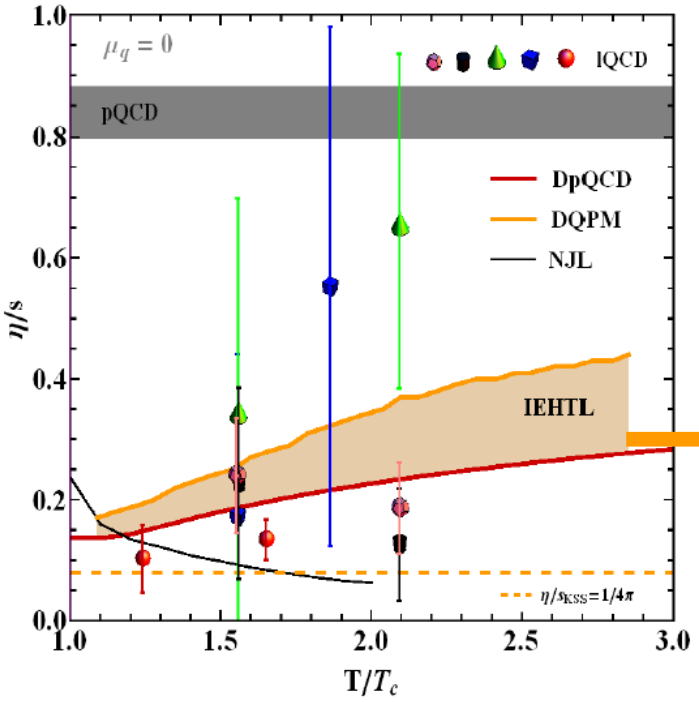
g g

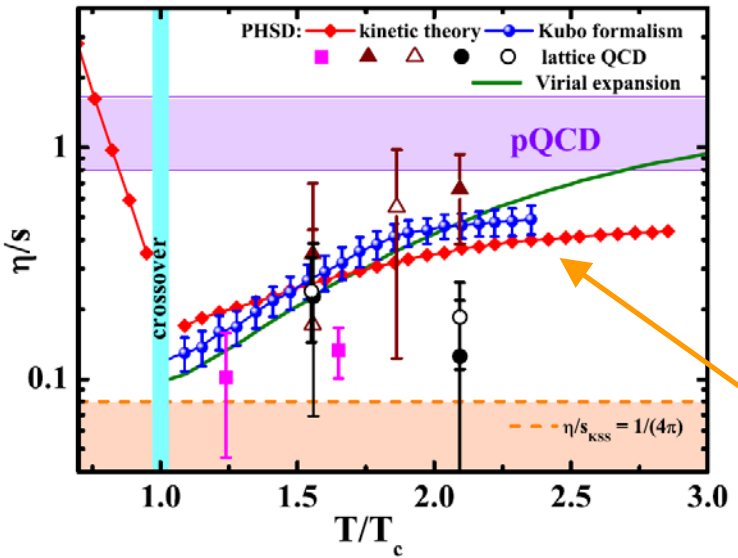


Hamza Berrehrah et al. arXiv:1412.1017

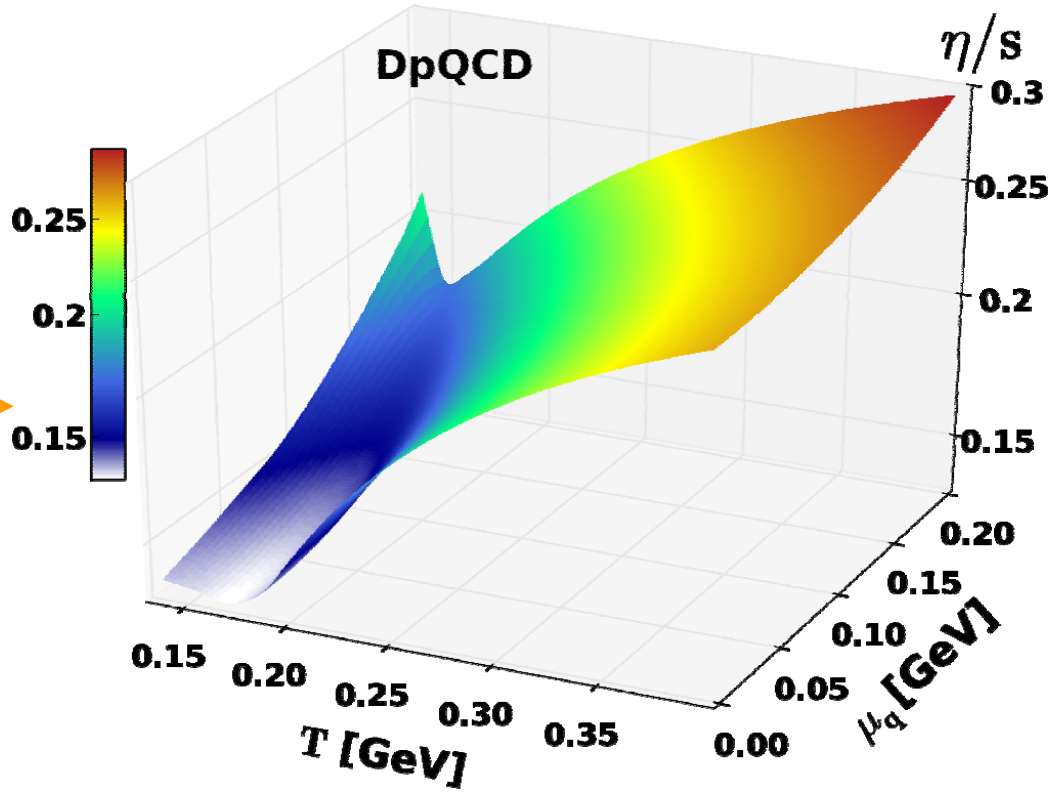
I. DQPM: transport properties at finite (T, μ_q) : η/s

Shear viscosity η/s at finite T





Shear viscosity η/s at finite (T, μ_q)



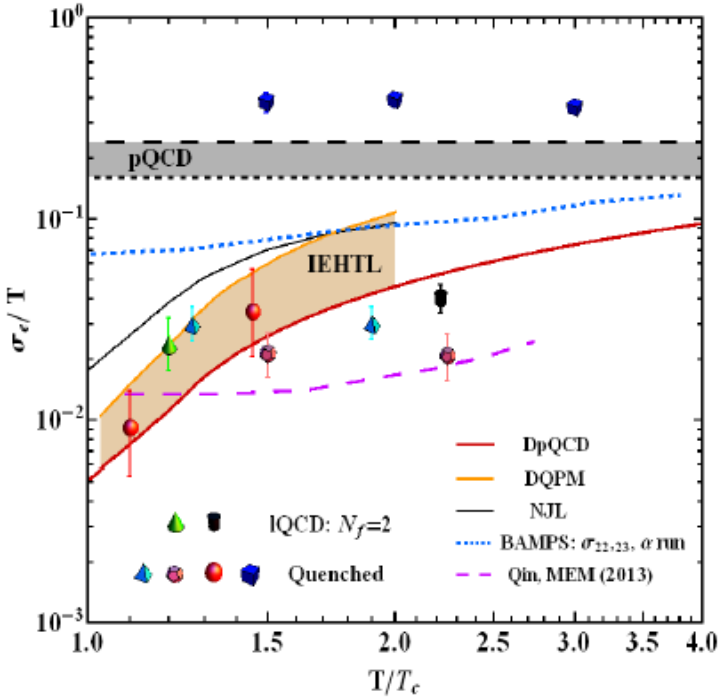
η/s: μ_q=0 ➔ finite μ_q:
smooth increase as a function of (T, μ_q)

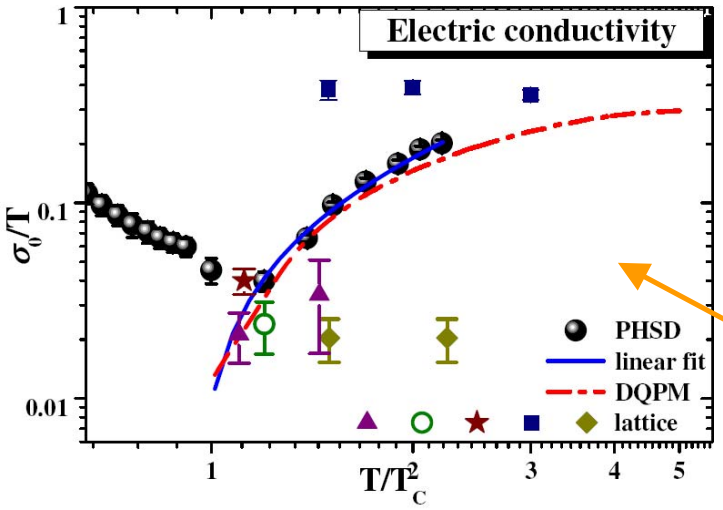
H. Berrehrah et al. arXiv:1412.1017

PHSD in a box: V. Ozvenchuk et al., PRC 87 (2013) 064903
Virial expansion: S. Mattiello, W. Cassing, EPJ C70 (2010) 243
NJL: R. Marty et al., PRC 88 (2013) 045204

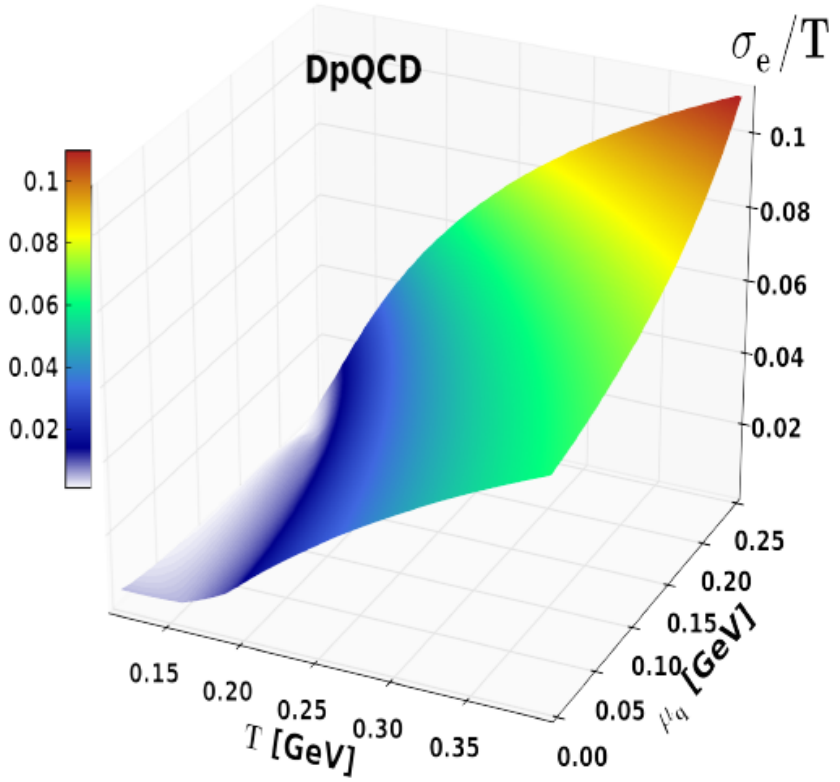
II. DQPM: transport properties at finite (T, μ_q): σ_e/T

Electric conductivity σ_e/T at finite T





Electric conductivity σ_e/T at finite (T, μ_q)



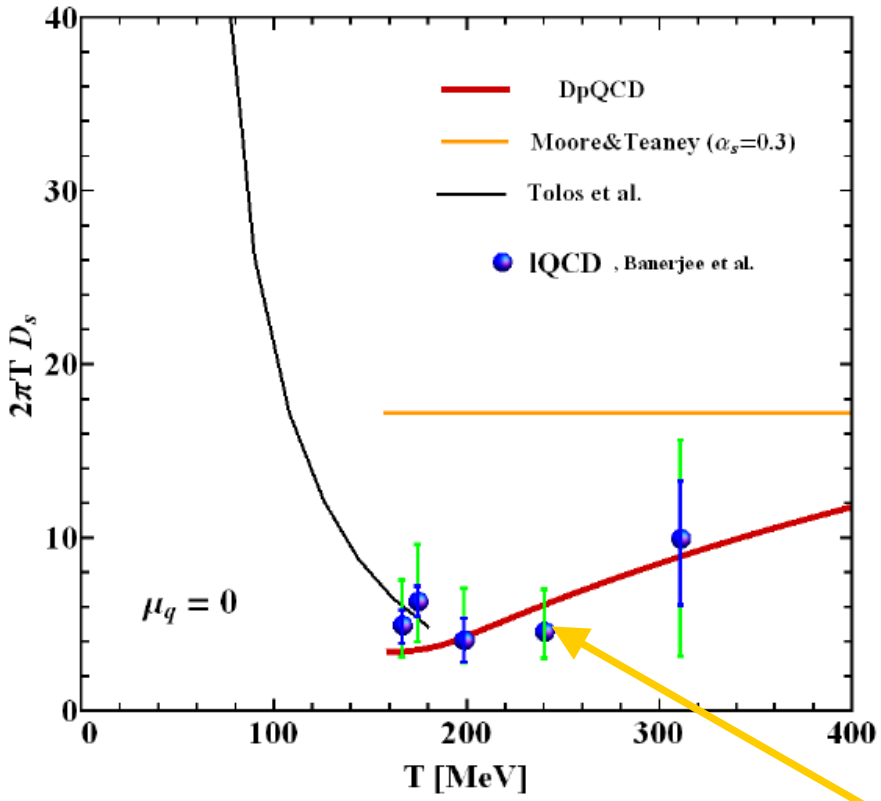
σ_e/T : μ_q=0 ➔ finite μ_q:
smooth increase as a function of (T, μ_q)

H. Berrehrah et al. arXiv:1412.1017

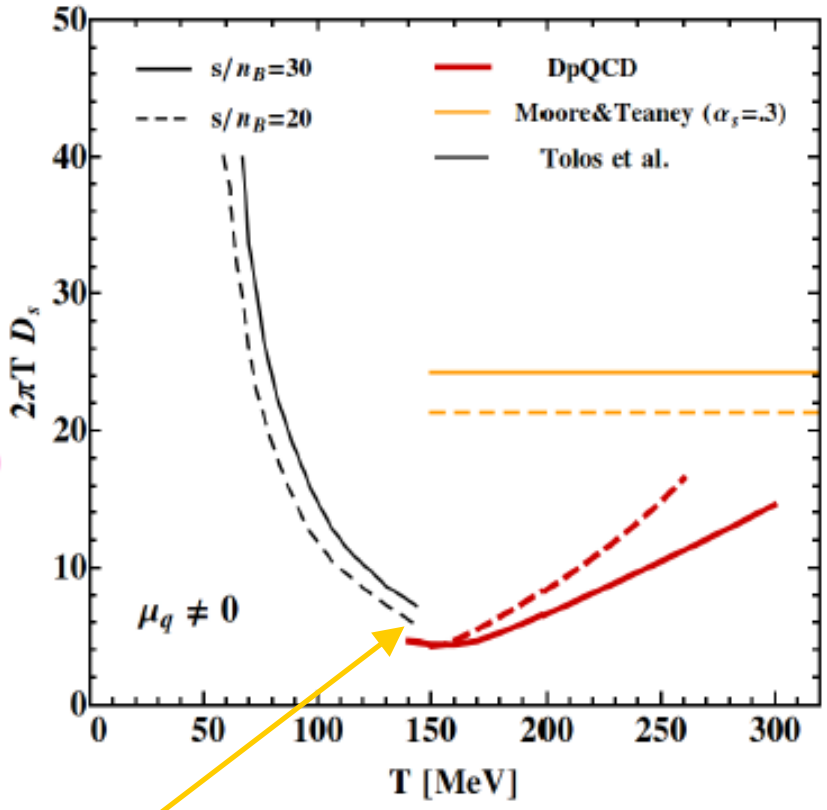
PHSD in a box: W. Cassing et al., PRL 110(2013)182301
NJL: R. Marty et al., PRC 88 (2013) 045204

Charm spatial diffusion coefficient D_s in the hot medium

- D_s for heavy quarks as a function of T for μ_q=0 and finite μ_q



$\Rightarrow$ $\mu_q \neq 0$



➔ **Continuous transition at T_c!**

❑ **$T < T_c$: hadronic D_s**

L. Tolos , J. M. Torres-Rincon,
Phys. Rev. D 88, 074019 (2013)

H. Berrehrah et al, PRC 90 (2014) 051901, arXiv:1406.5322

Summary: DQPM at finite (T, μ_q)

❑ Extension of the DQPM to finite μ_q using scaling hypothesis for the effective temperature T*

❑ μ_q=0 ➔ finite μ_q:

- variations in the QGP transport coefficients
- smooth dependence on (T, μ_q)
- η/s, ζ/s, σ_e/T, D_s show minima around T_C at μ_q=0 and finite μ_q

❑ Outlook

Implementation into PHSD: from T,μ_q=0 ➔ finite T,μ_q

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Thank you!