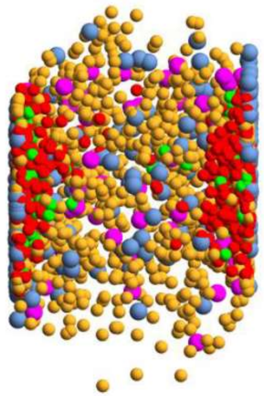
A review of the theoretical heavy-ion physics
(highlights)

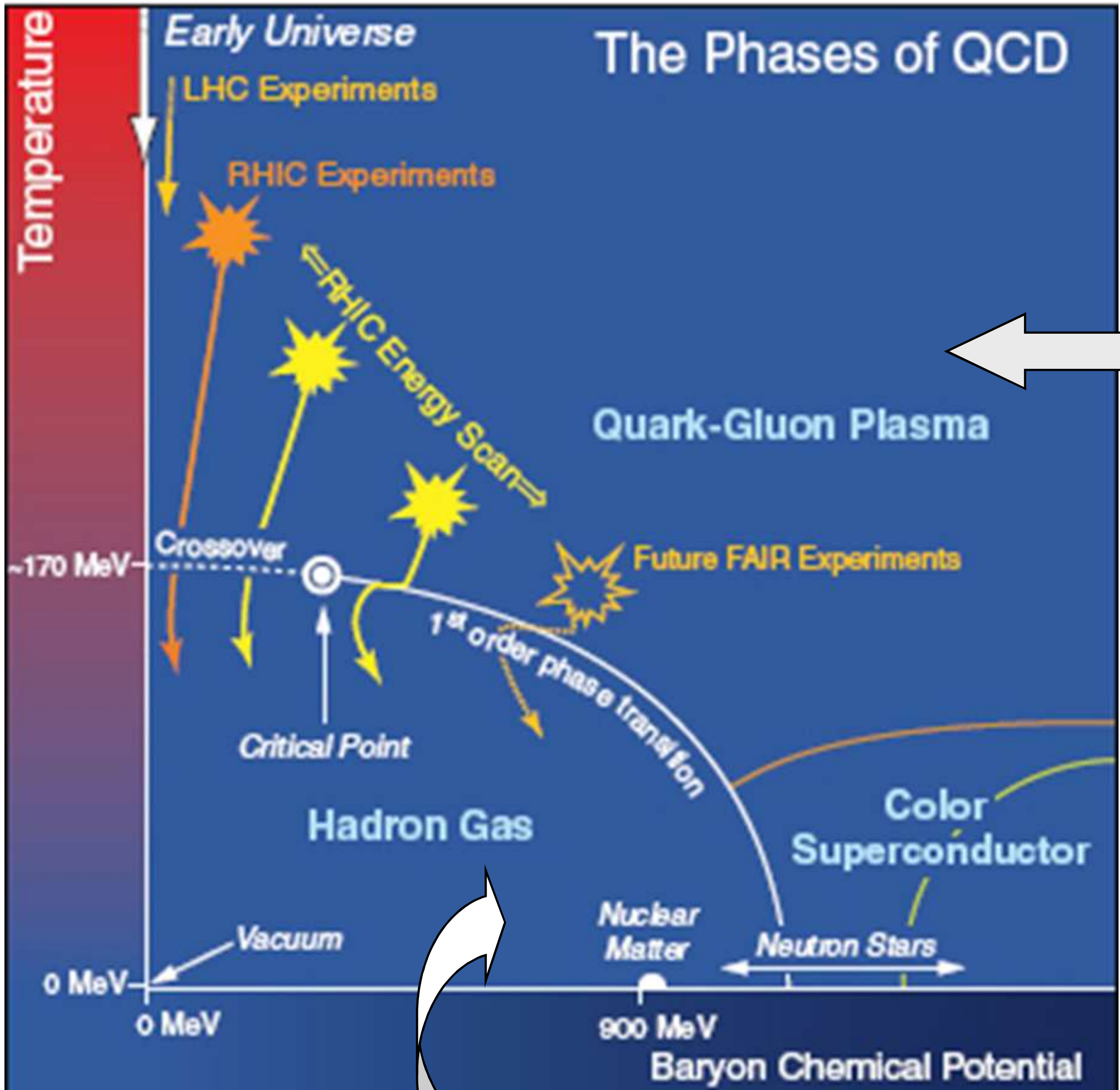
Elena Bratkovskaya

(GSI Darmstadt & Uni. Frankfurt)

The 3rd International Conference on Particle Physics and Astrophysics (ICPPA-2017)
MEPhI, Moscow, 2-6 October 2017

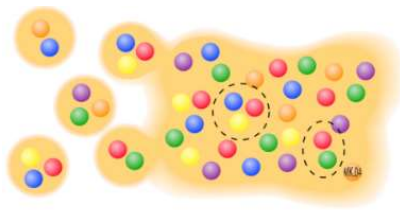


The ‚holy grail‘ of heavy-ion physics:



The phase diagram of QCD

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

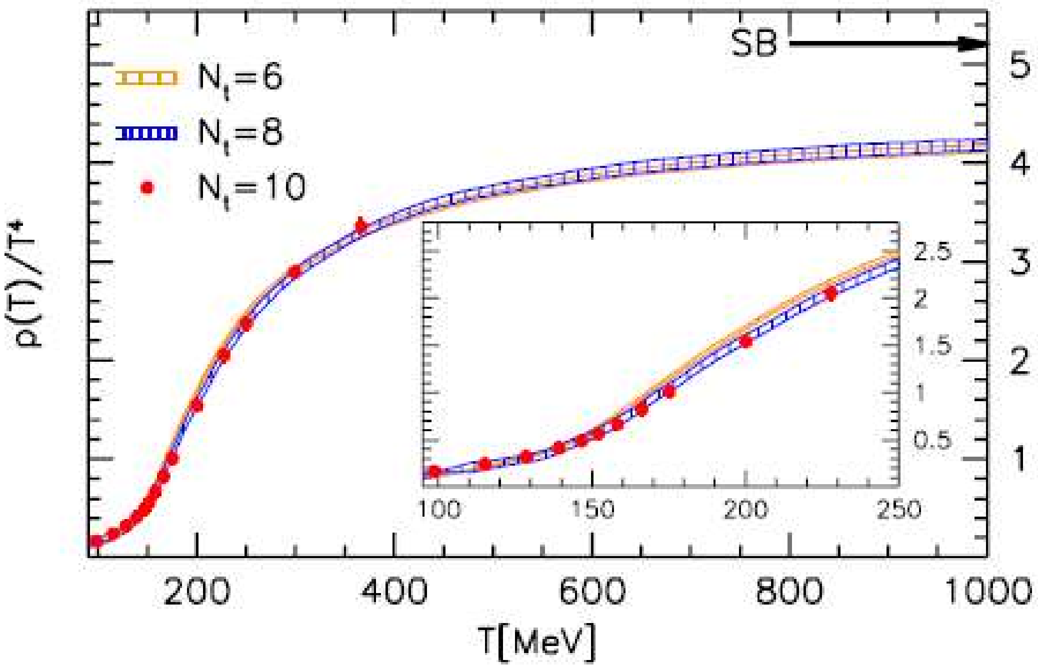


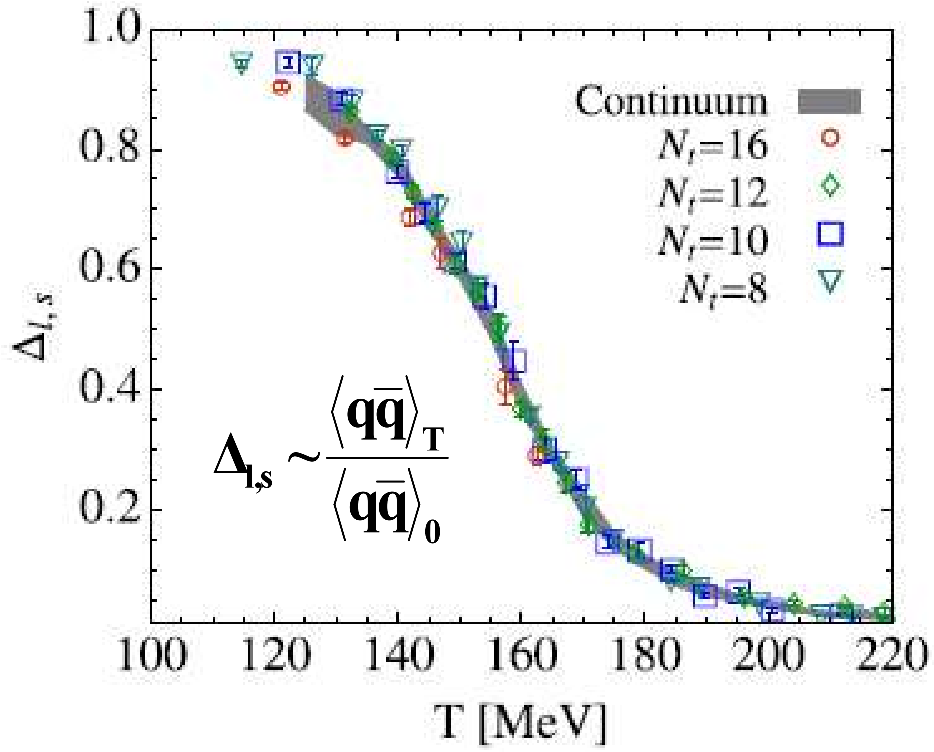
- Search for the critical point
- Search for signatures of chiral symmetry restoration
- Study of the in-medium properties of hadrons at high baryon density and temperature

Theory: Information from lattice QCD

I. deconfinement phase transition with increasing temperature + **II. chiral symmetry restoration with increasing temperature**

lQCD BMW collaboration: $\mu_q=0$



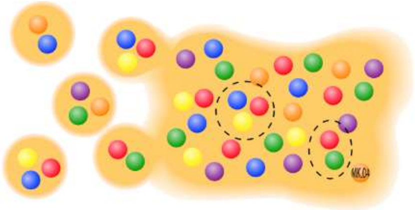


- **Crossover: hadron gas → QGP**

- **Scalar quark condensate $\langle q\bar{q}\rangle$ is viewed as an order parameter for the restoration of chiral symmetry:**

$$<\bar{q}q>= \begin{cases} \neq 0 & \text{chiral non-symmetric phase;} \\ = 0 & \text{chiral symmetric phase.} \end{cases}$$

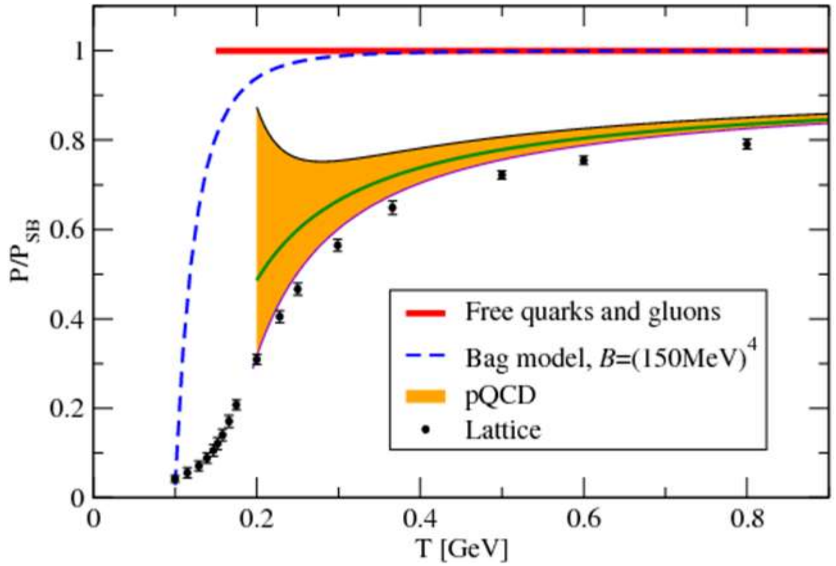
➔ **both transitions occur at about the same temperature T_C for low chemical potentials**



Degrees-of-freedom of QGP

❖ lQCD gives QGP EoS at finite μ_B

! need to be interpreted in terms of degrees-of-freedom



Non-perturbative QCD ← pQCD

Thermal QCD
= QCD at high parton densities:

pQCD:

- ❑ weakly interacting system
- ❑ massless quarks and gluons

Thermal QCD:

- ❑ strongly interacting system
- ❑ massive quarks and gluons

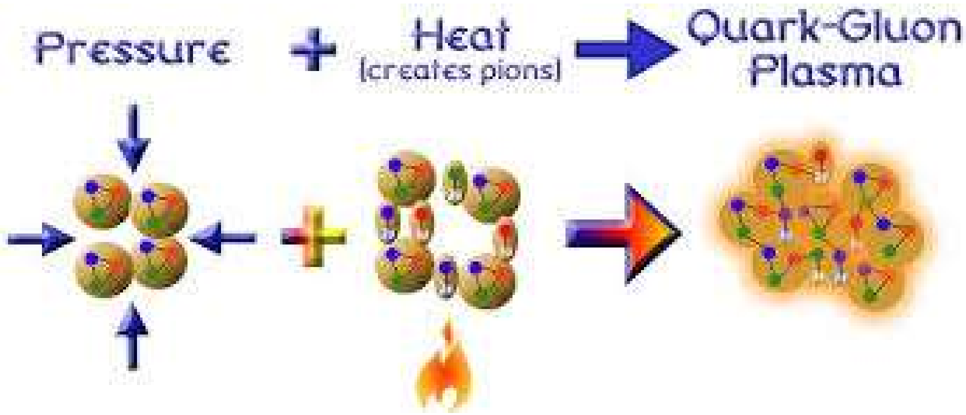
➔ quasiparticles
= effective degrees-of-freedom

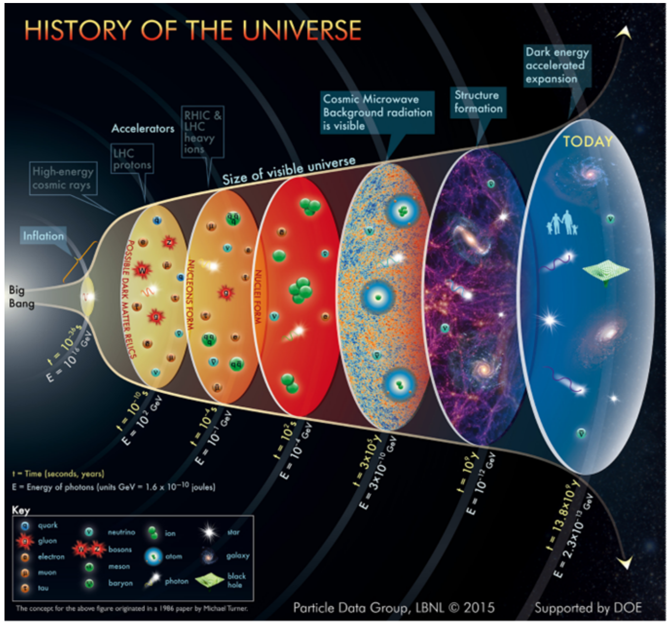
❖ How to learn about degrees-of-freedom of QGP ? ➔ HIC experiments

Experiment: Heavy-ion collisions

- **Heavy-ion collision experiment**

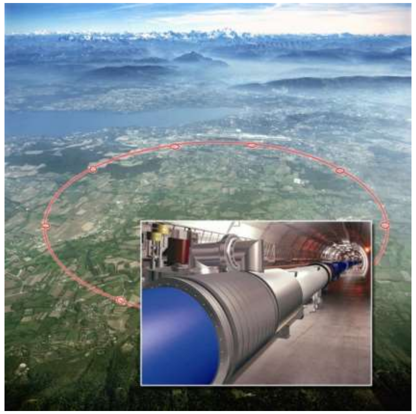
➔ ‚re-creation' of the Big Bang conditions in laboratory: matter at high pressure and temperature



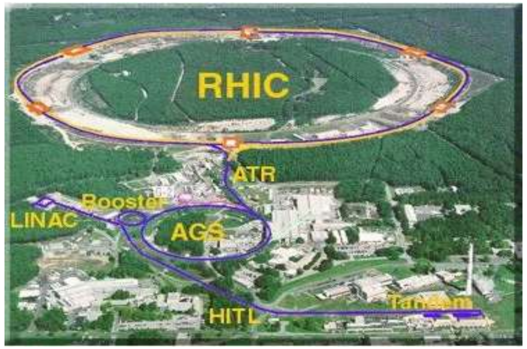


- **Heavy-ion accelerators:**

Large Hadron Collider - LHC (CERN):
Pb+Pb up to 574 A TeV

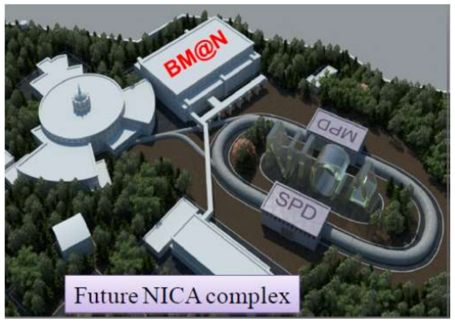


Relativistic-Heavy-Ion-Collider - RHIC (Brookhaven):
Au+Au up to 21.3 A TeV



Facility for Antiproton and Ion Research – FAIR (Darmstadt)
(Under construction)
Au+Au up to 10 (30) A GeV

Nuclotron-based Ion Collider fAcility – NICA (Dubna)
(Under construction)
Au+Au up to 60 A GeV



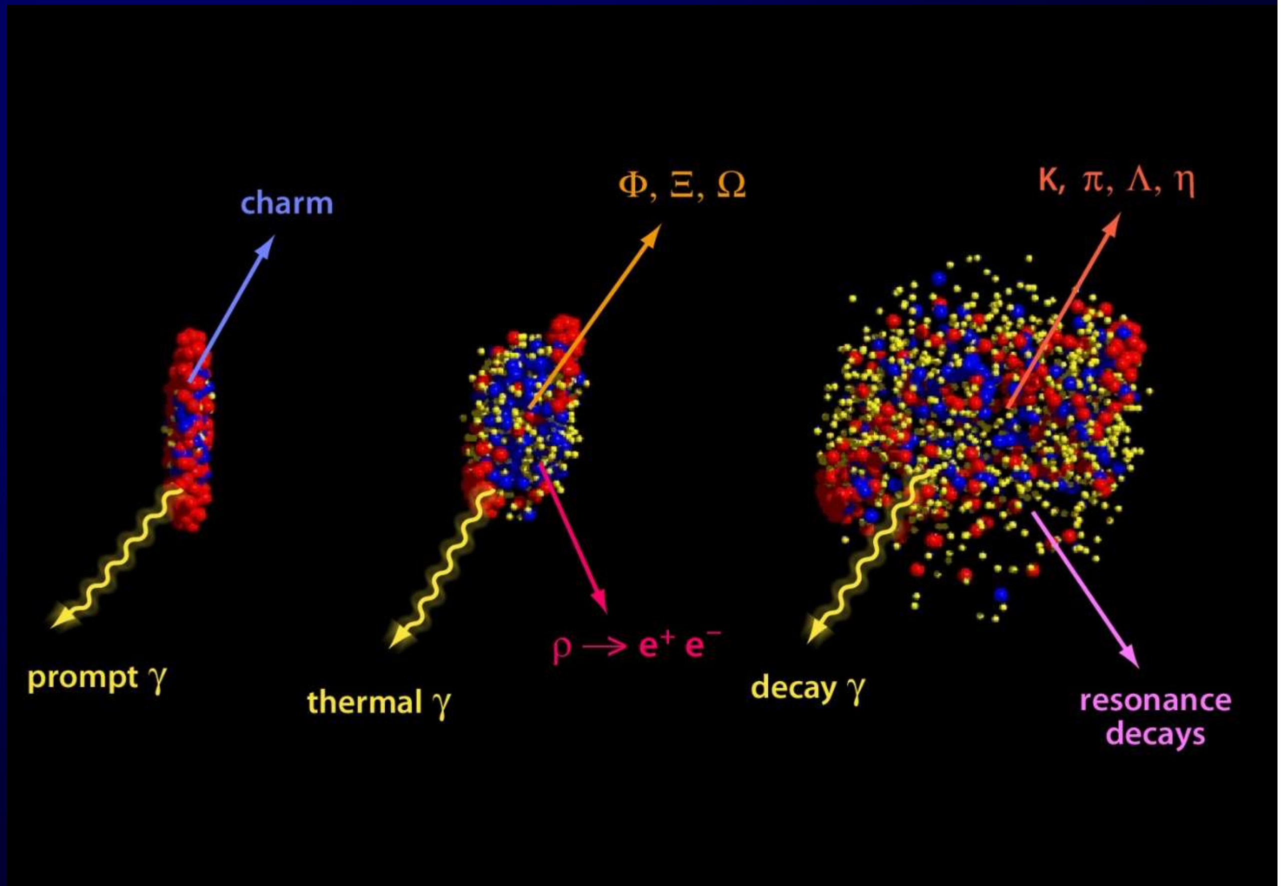
Signals of the phase transition:

- Multi-strange particle enhancement in A+A
- Charm suppression
- Collective flow (v_1, v_2)
- Thermal dileptons
- Jet quenching and angular correlations
- High p_T suppression of hadrons
- Nonstatistical event by event fluctuations and correlations
- ...

Experiment: measures final hadrons and leptons

How to learn about physics from data?

Compare with theory!



Basic models for heavy-ion collisions

- **Statistical models:**

basic assumption: system is described by a (grand) canonical ensemble of non-interacting fermions and bosons in thermal and chemical equilibrium
= thermal hadron gas at freeze-out with common T and μ_B

[- : no dynamical information]

- **Hydrodynamical models:**

basic assumption: conservation laws + equation of state (EoS);
assumption of local thermal and chemical equilibrium
- Interactions are ‚hidden' in properties of the fluid described by transport coefficients (shear and bulk viscosity η, ζ, ..), which is 'input' for the hydro models

[- : simplified dynamics]

- **Microscopic transport models:**

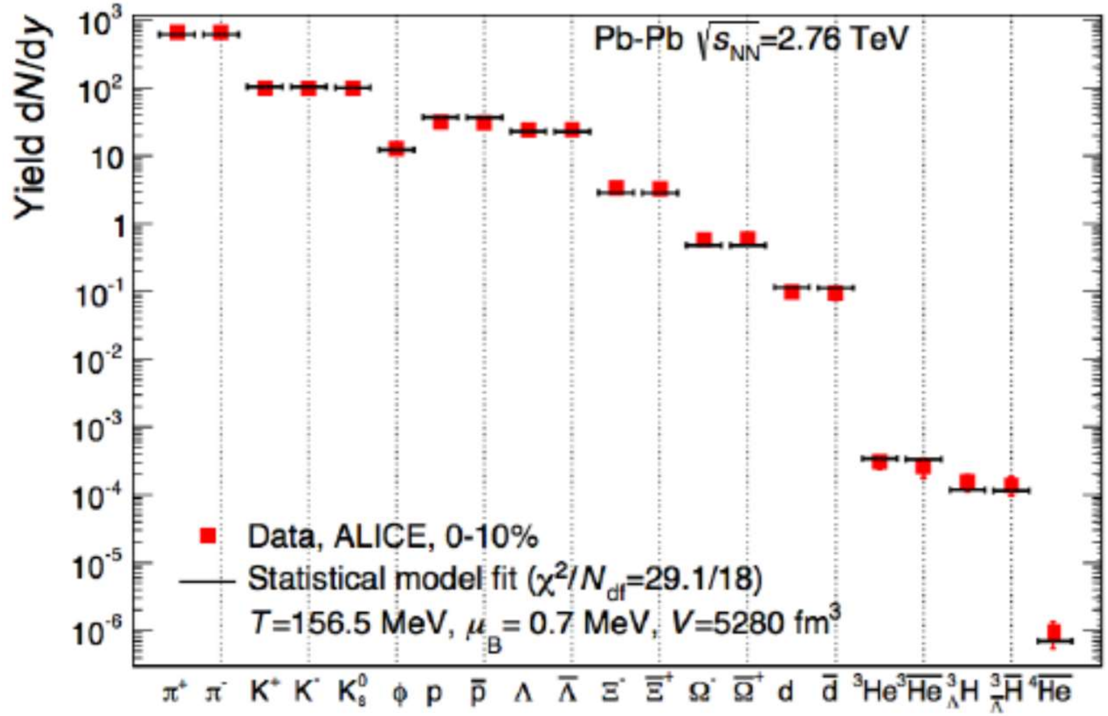
based on transport theory of relativistic quantum many-body systems
- Explicitly account for the interactions of all degrees of freedom (hadrons and partons) in terms of cross sections and potentials
- Provide a unique dynamical description of strongly interaction matter in- and out-off equilibrium:
- In-equilibrium: transport coefficients are calculated in a box – controled by lQCD
- Nonequilibrium dynamics – controled by HIC

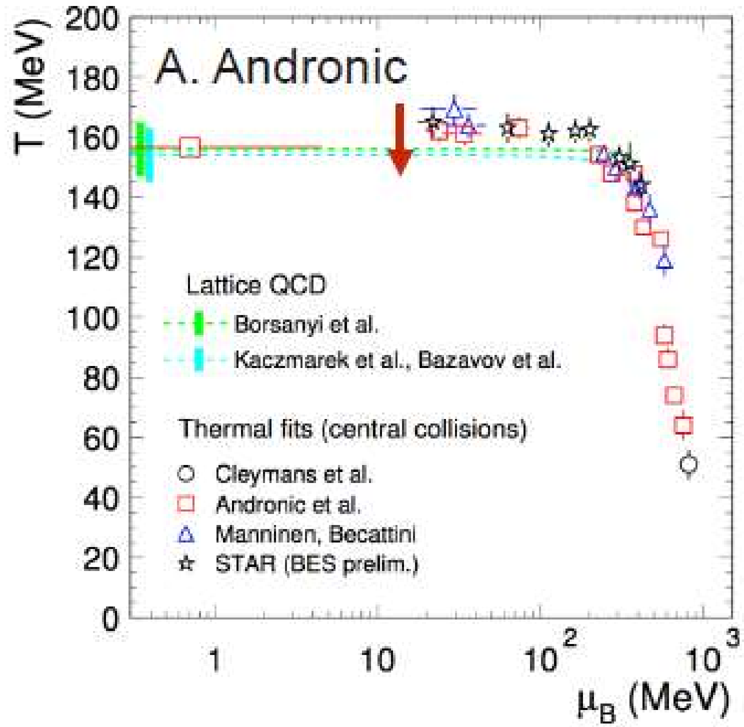
Actual solutions: Monte Carlo simulations

[+ : full dynamics | - : very complicated]

Results from statistical models for HIC

J. Stachel at al., J.Phys. Conf. Ser. 509 (2014) 012019





Good description of the hadron abundances by the thermal hadron gas model ➔
The hadron abundances are in rough agreement with a thermally equilibrated system !

➔ Partial thermal and chemical equilibration is approximately reached in central heavy-ion collisions at relativistic energies!

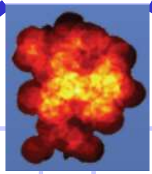
! Statistical models do not provide an answer to the origin of thermalization.
HIC dynamics and the approach to thermal equilibrium is driven by the interactions !

➔ dynamical models of HIC

Dynamical models for HIC

Macroscopic

hydro-models:
- description of QGP and hadronic phase by hydrodanamical equations for fluid
- assumption of local equilibrium
- EoS with phase transition from QGP to HG
- initial conditions (e-b-e, fluctuating)



ideal
(Jyväskylä,SHASTA, TAMU, …)

viscous η, ζ,
(Romachkke,(2+1)D VISH2+1, VISHNU, (3+1)D MUSIC,…)

fireball models:
- no explicit dynamics: parametrized time evolution (TAMU)

‚Hybrid'
QGP phase: hydro with QGP EoS
- hadronic freeze-out: after burner - hadron-string transport model

(‚hybrid'-UrQMD, EPOS, …)

Microscopic

Non-equilibrium microscopic transport models – based on many-body theory

Hadron-string models
(UrQMD, IQMD, HSD, QGSM, SMASH …)

Partonic cascades
pQCD based
(Duke, BAMPS, …)

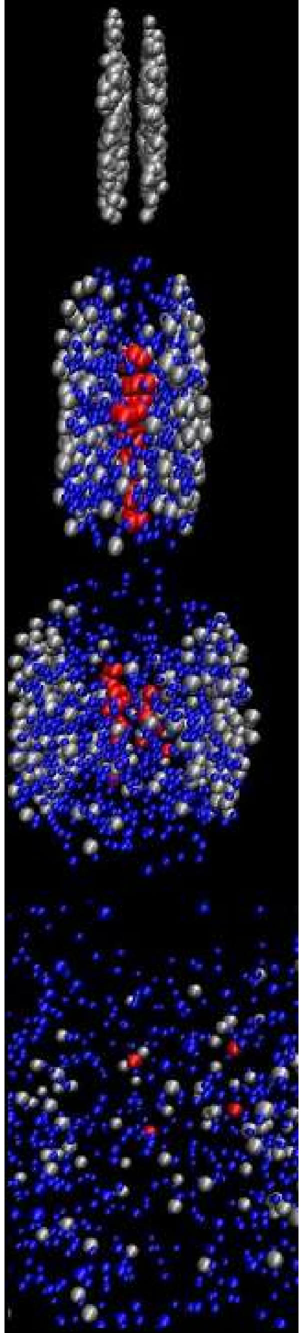
Parton-hadron models:
- QGP: pQCD based cascade
- massless q, g
- hadronization: coalescence

(AMPT, HIJING)

PHSD
- QGP: lQCD EoS
- massive quasi-particles (q and g with spectral functions) in self-generated mean-field
- dynamical hadronization
- HG: off-shell dynamics

(applicable for strongly interacting systems)

Parton-Hadron-String-Dynamics (PHSD)



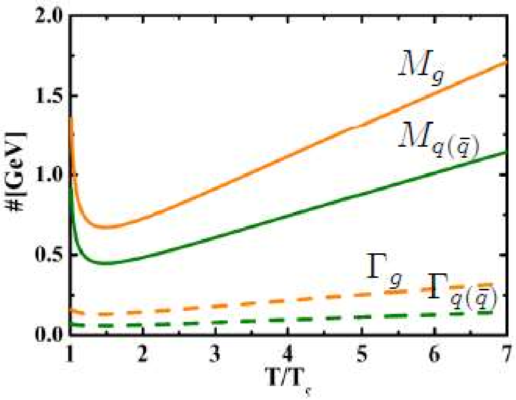
PHSD is a **non-equilibrium transport approach** with

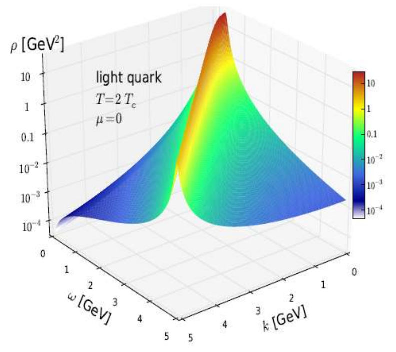
- explicit **phase transition** from hadronic to partonic degrees of freedom
- **lQCD EoS** for the partonic phase (‚crossover' at low μ_q)
- explicit **parton-parton interactions** - between quarks and gluons
- dynamical **hadronization**

❑ **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 a self-generated **mean-field potential**





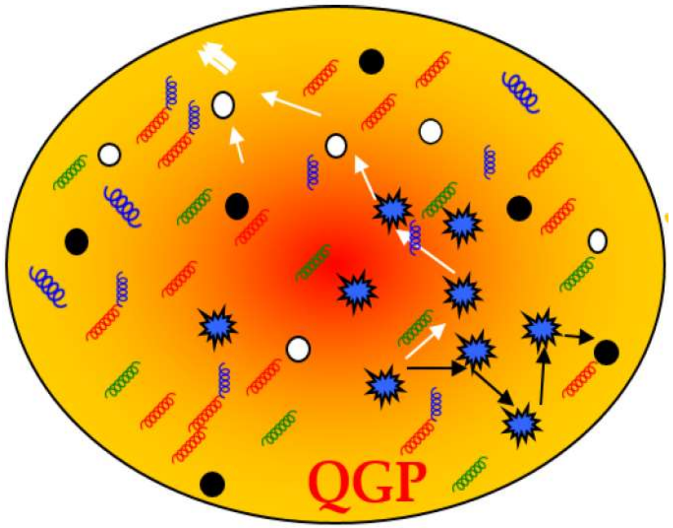
- **Spectral functions:**

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

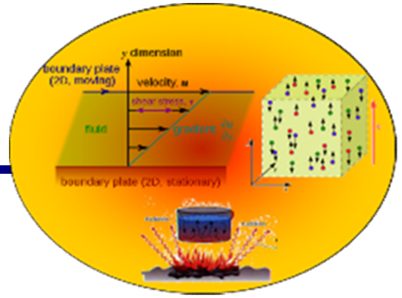
❑ **Transport theory**: **generalized off-shell transport equations** based on the 1st order gradient expansion of Kadanoff-Baym equations (**applicable for strongly interacting systems**!)

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

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

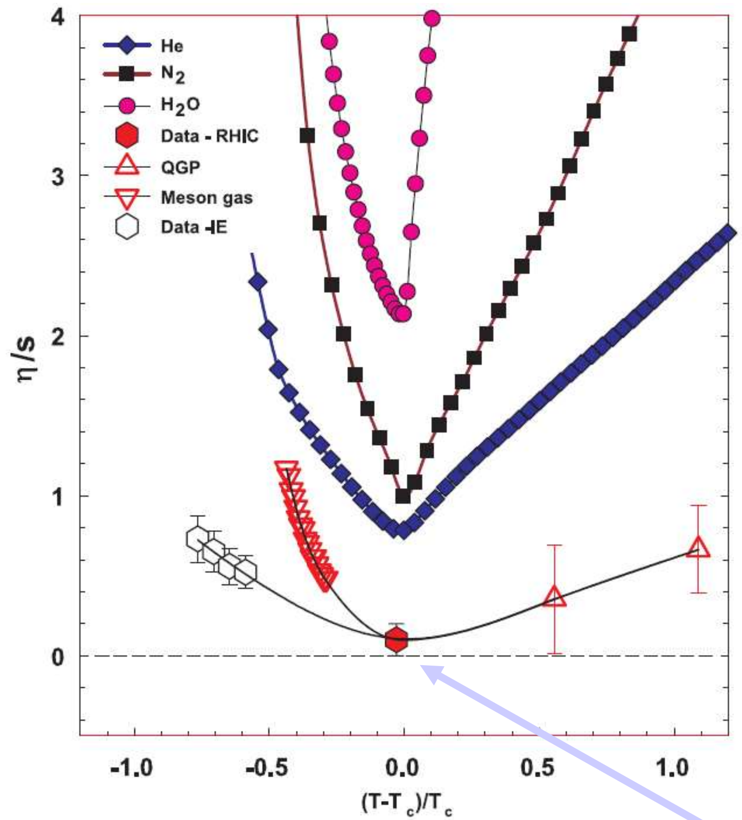


Transport properties at finite T, μ_q=0: shear viscosity η/s



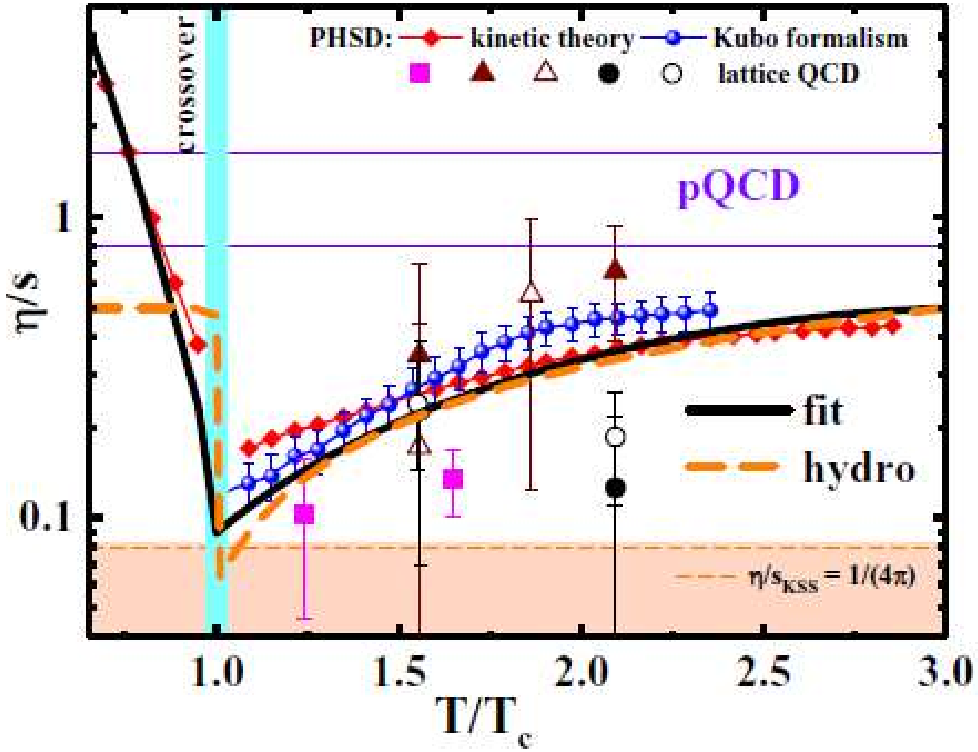
Compilation of the ratio of shear viscosity to entropy density for various substances

R. A. Lacey and A. Taranenko, PoS C FRNC2006, 021 (2006)



PHSD in a box: V. Ozvenchuk et al., PRC 87 (2013) 064903

Hydro: Bayesian analysis, S. Bass et al., 1704.07671



IQCD: η/s near T_C is very small !

➔ QGP : close to an ideal liquid, not a gas of weakly interacting quarks and gluons

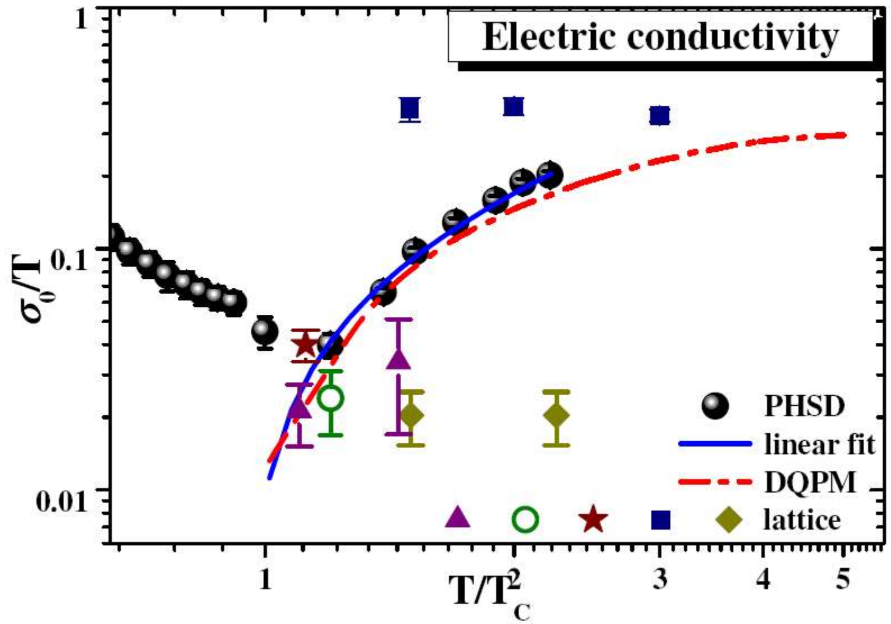
➔ QGP: strongly-interacting matter

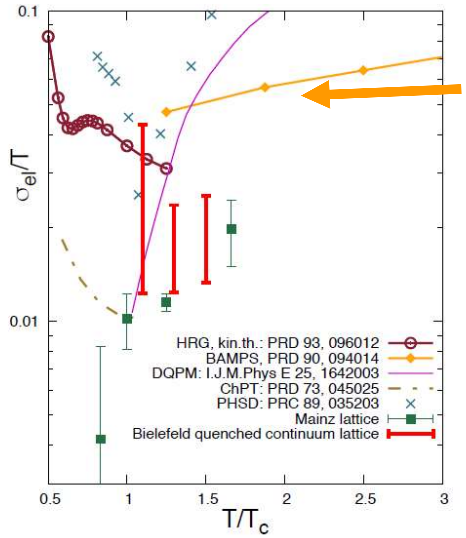
Transport properties at finite T, μ_q=0: Electric conductivity σ_e/T

PHSD in a box:

W. Cassing et al., PRL 110(2013)182301

σ_0 → Probe of electric properties of the QGP





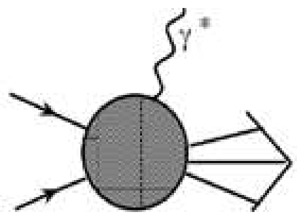
pQCD - BAMPS:
M.Greif, C.Greiner, G.Denicol, PRD93 (2016) 096012

- **the QCD matter even at T~ T_c is a much better electric conductor than Cu or Ag (at room temperature) by a factor of 500 !**

Exp. observables – photon and dilepton spectra

- **Photon emission:** rates at q_0→0 are related to electric conductivity σ_0

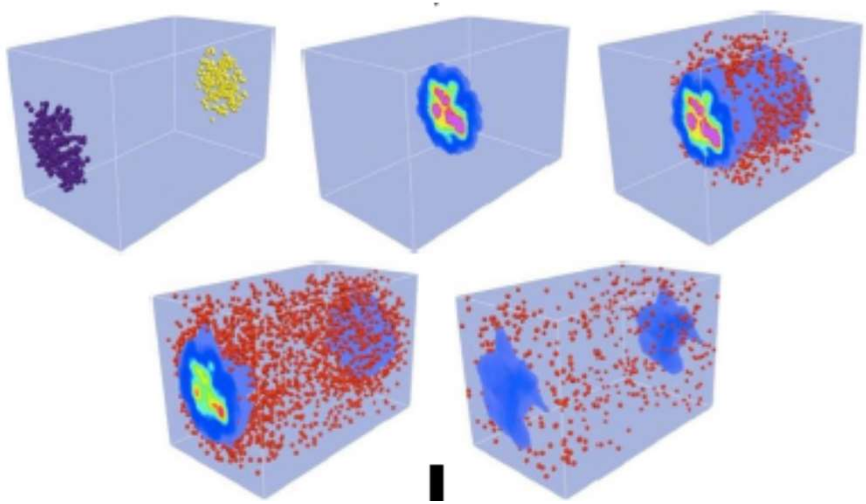
$$q_0 \frac{dR}{d^4x\, d^3q}\bigg|_{q_0\to 0} = \frac{T}{4\pi^3}\sigma_0$$



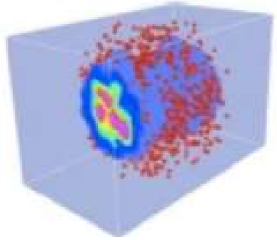
Review: H. Berrehrah et al. Int.J.Mod.Phys. E25 (2016) 1642003

Constraints on thermal properties of the QGP (transport coefficients) from exp. observables in high energy heavy-ion collisions

Hydro model: Bayesian analysis



Hydro model: Bayesian analysis



- ❑ **Extraction of QGP properties via a Model-to-Data Analysis**

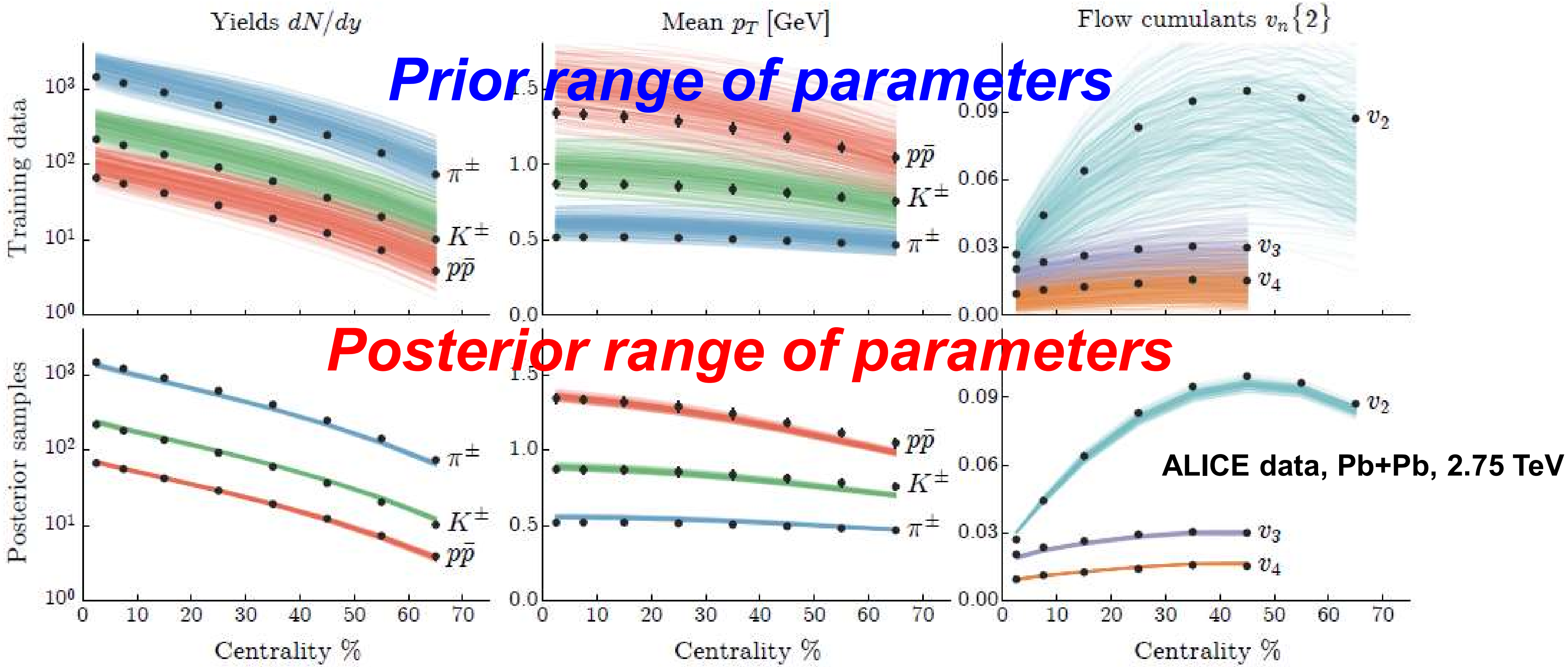
Model: VISHNU -
(2+1)D viscous hydro with
a microscopic hadronic afterburner
+ initial conditions, τ_0, η/s, ζ/s, ….

Bayesian analysis

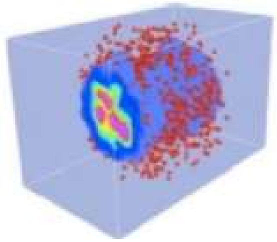
Exp. Data: observables

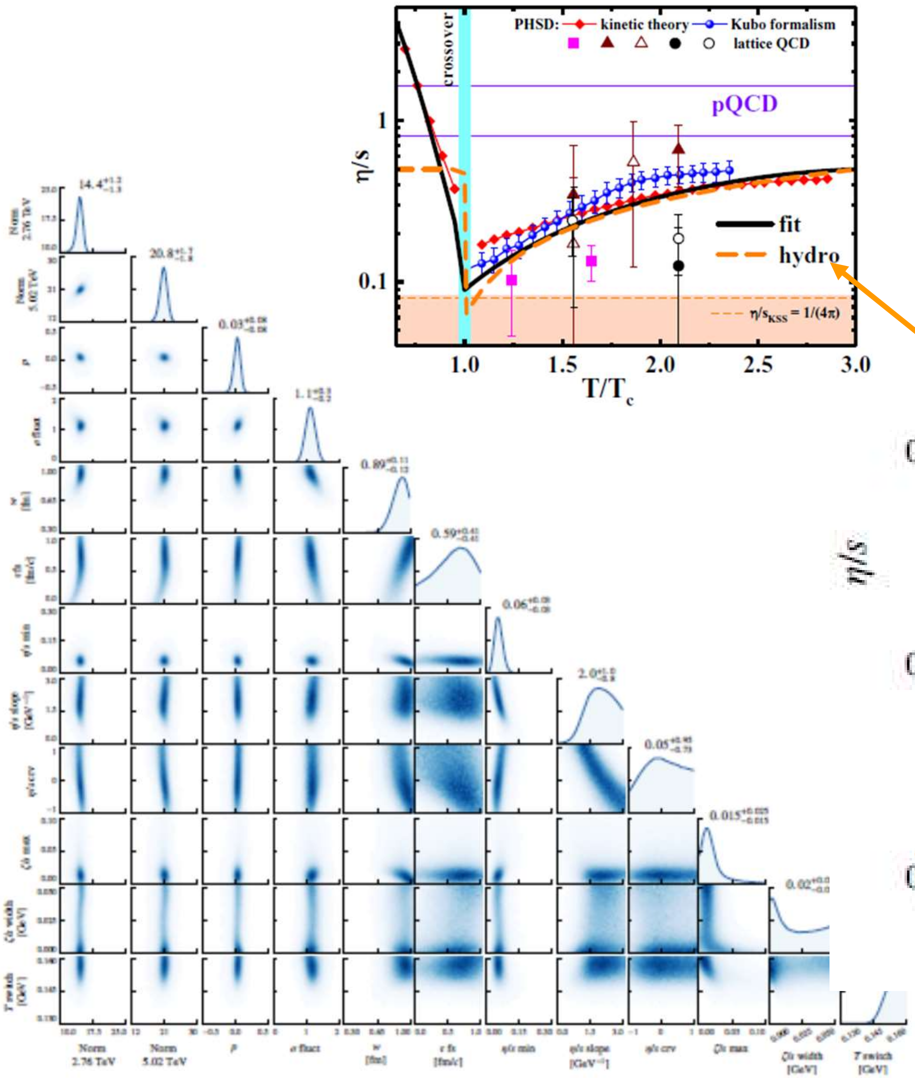
Probability distribution of all model parameters

S. Bass et al., 1605.03954; 1704.07671

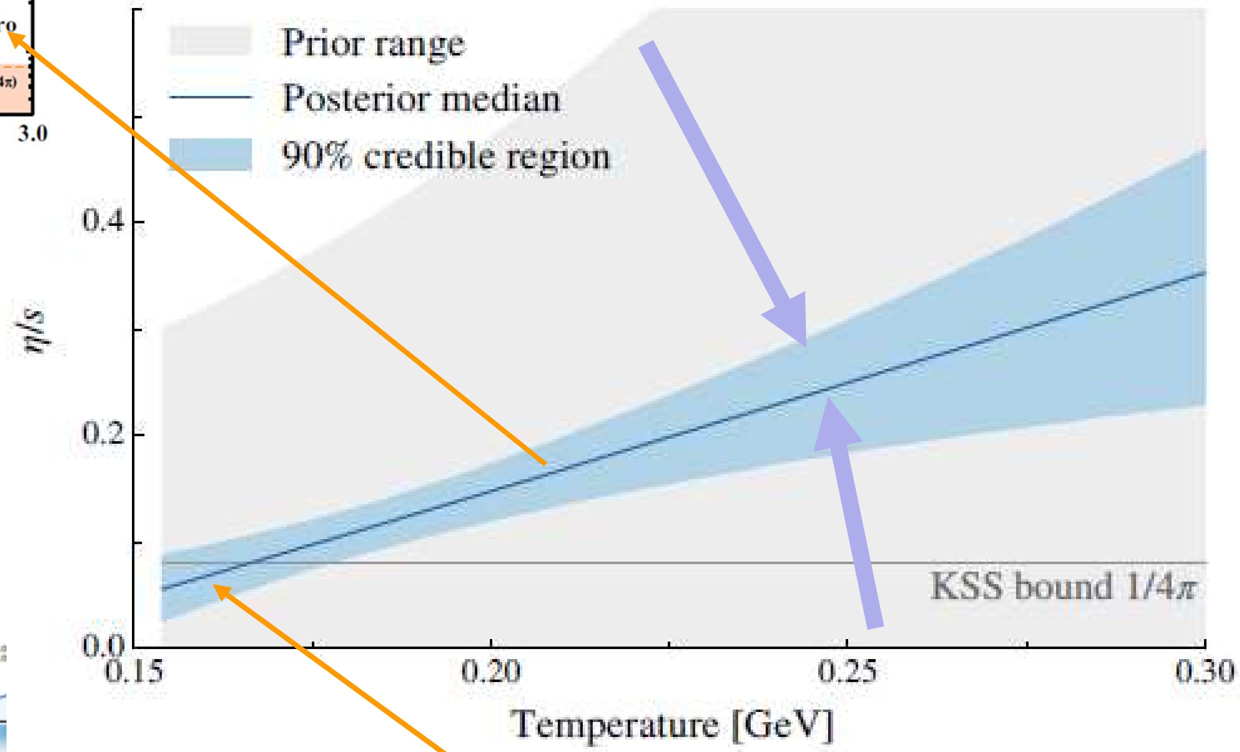


Hydro model: Bayesian analysis





Temperature Dependence of Shear Viscosities

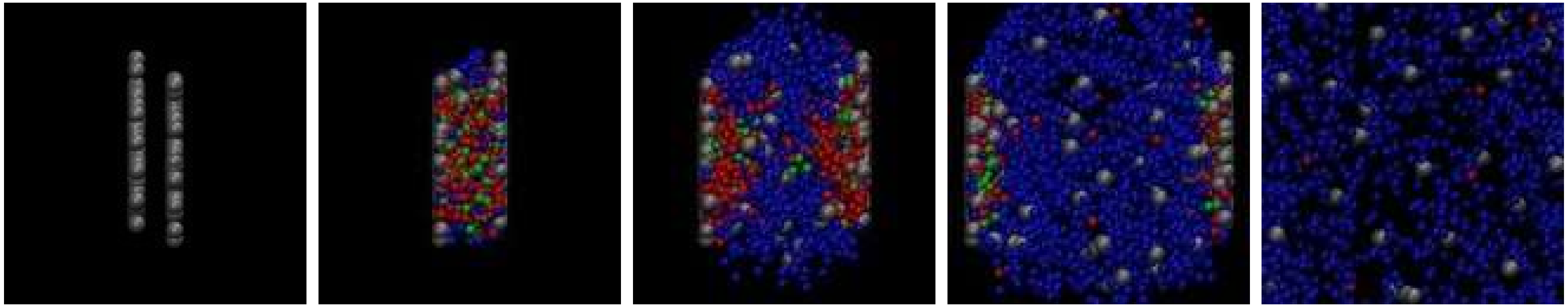


Calibrated Posterior Distribution of model parameters

Small η/s at T_C, growing in line with lQCD data!

S. Bass et al., 1605.03954; 1704.07671

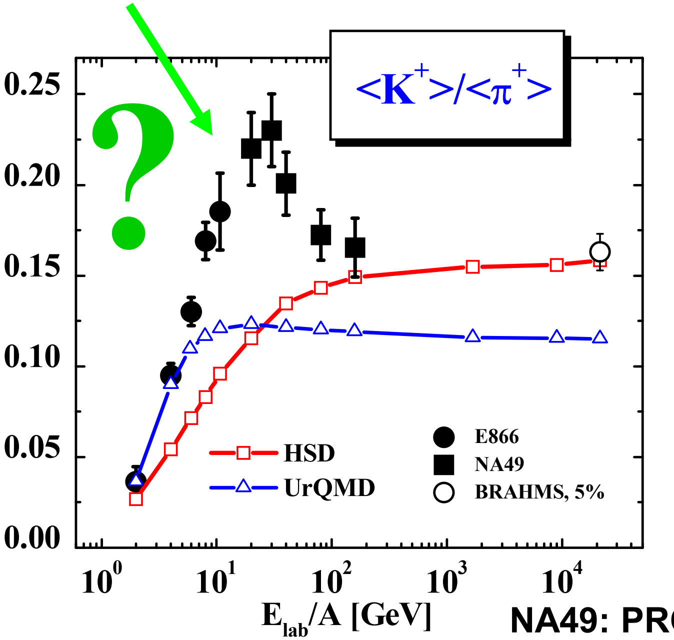
Traces of the QGP in observables in high energy heavy-ion collisions



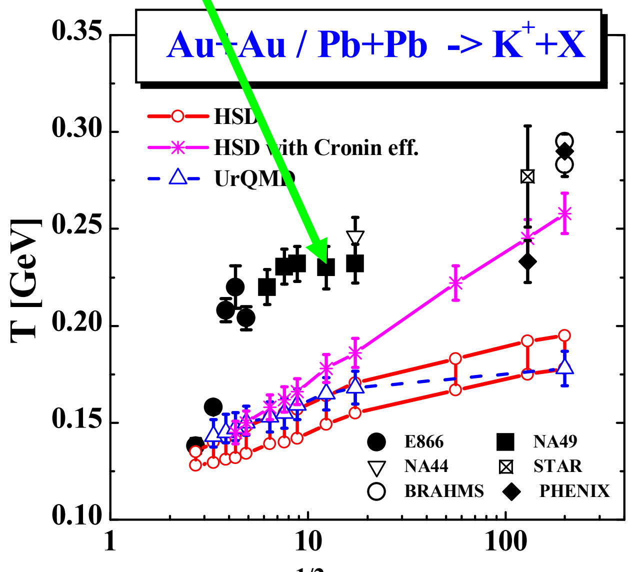
Signals for the phase transition (2000)

Hadron-string transport models (HSD, UrQMD) versus observables at ~ 2000

❑ ,horn' in K^+/π^+

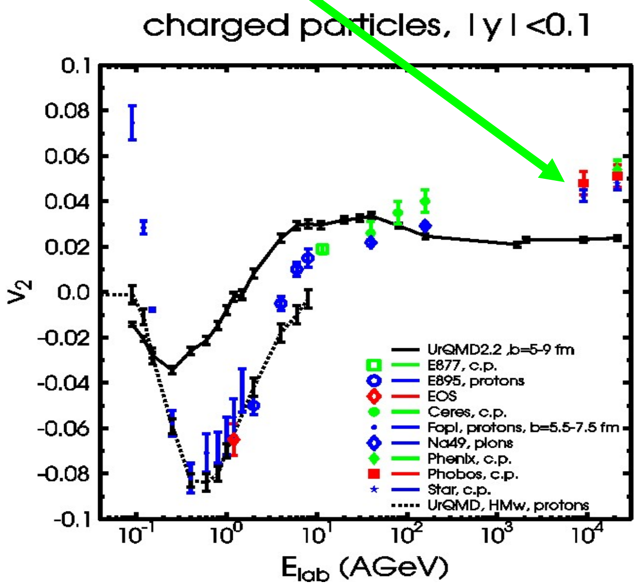


❑ ,step' in slope T



NA49: PRC66 (2002) 054902

❑ elliptic flow v_2



HSD, UrQMD: PRC 69 (2004) 032302

Status at 2000:

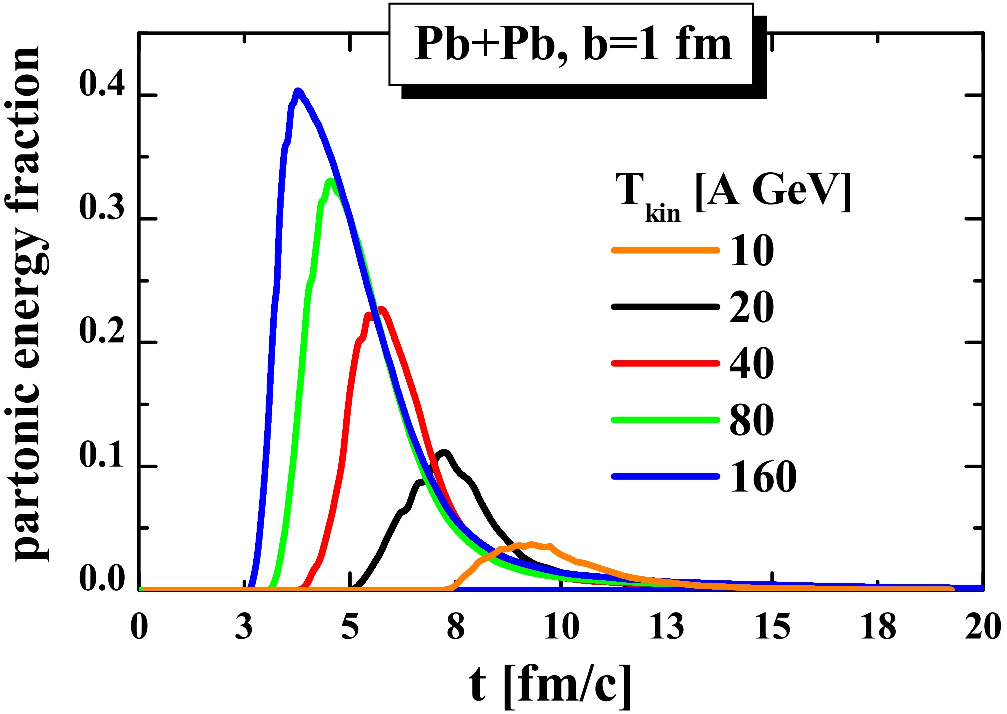
Exp. data are not reproduced in terms of the hadron-string picture

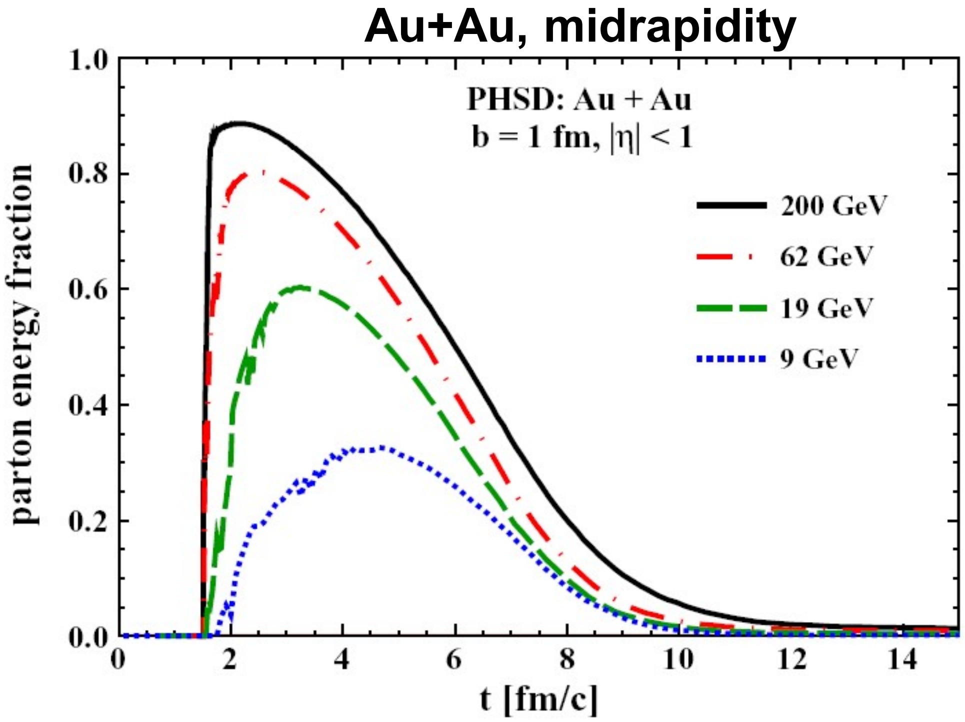
➔ evidence for partonic degrees of freedom + ... ?!

2000➔2017: development of microscopic transport models with phase transition from hadronic matter to QGP (PHSD, AMPT, HybridUrQMD,…)

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

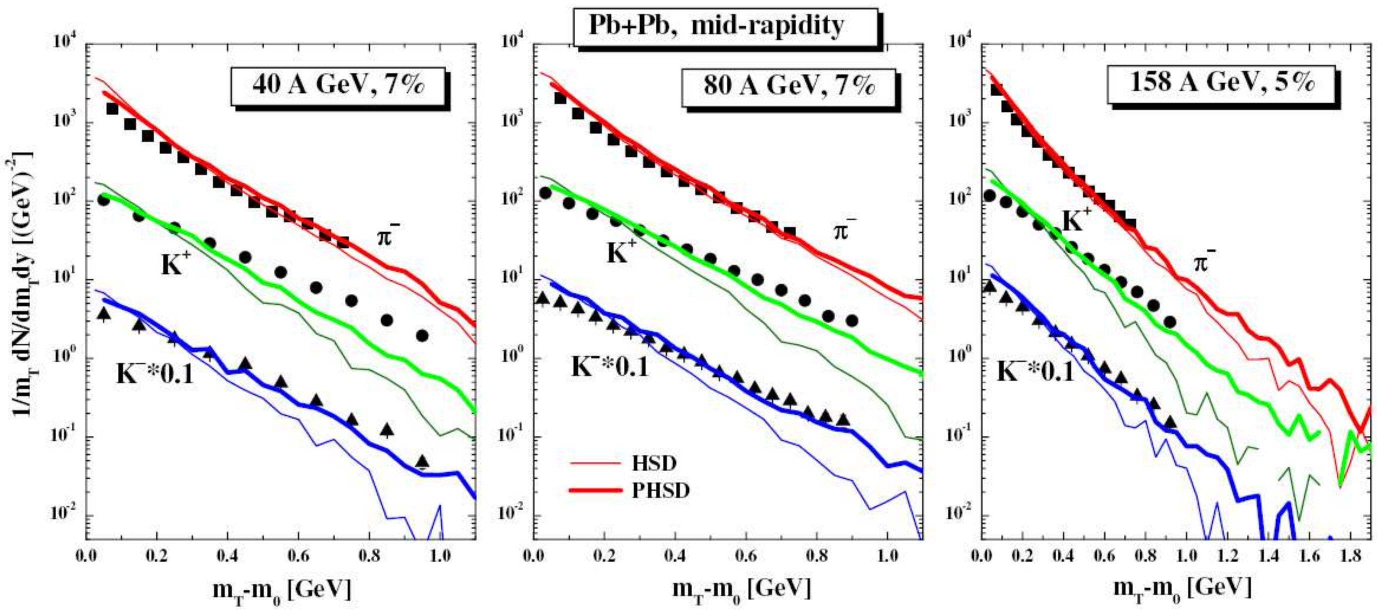
- SPS: Pb+Pb, 160 A GeV: only about 40% of the converted energy goes to partons; the rest is contained in the large hadronic corona and leading partons
- RHIC: Au+Au, 21.3 A TeV: up to 90% - QGP

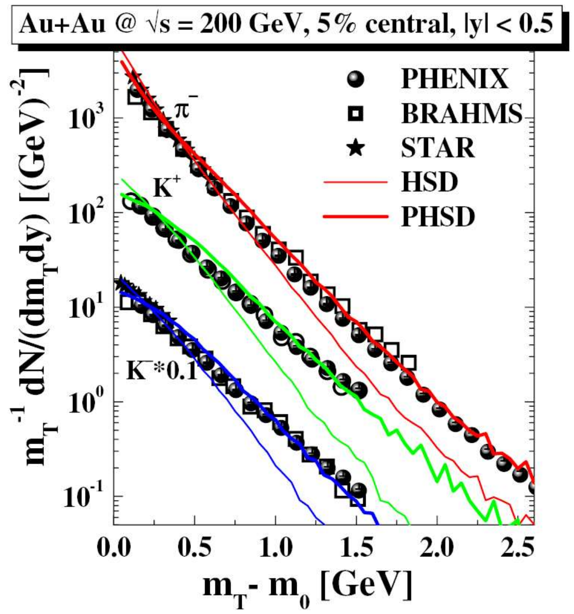
W. Cassing & E. Bratkovskaya, NPA 831 (2009) 215
V. Konchakovski et al., Phys. Rev. C 85 (2012) 011902

Transverse mass spectra from SPS to RHIC

Central Pb + Pb at SPS energies

Central Au+Au at RHIC





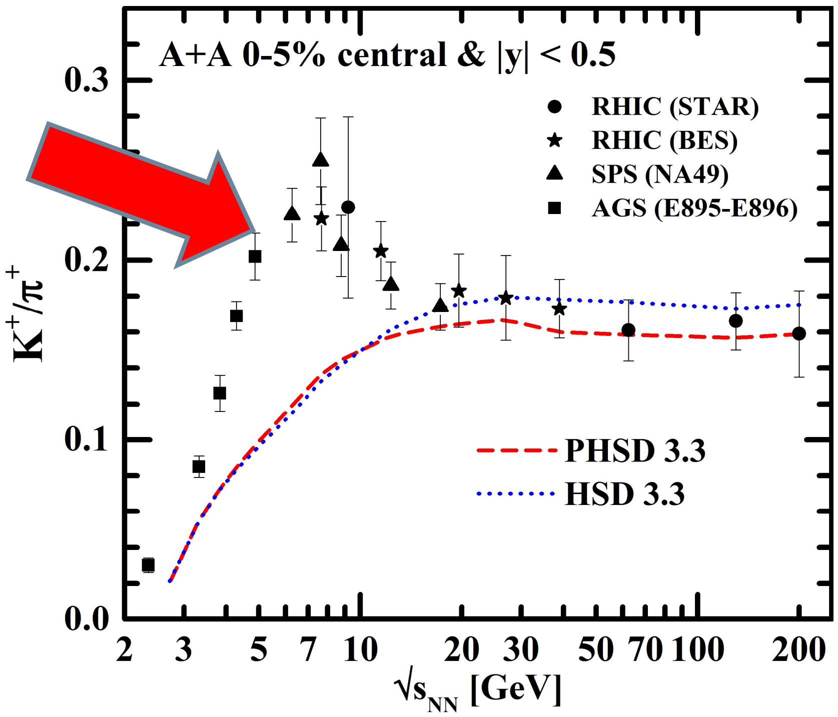
- PHSD gives harder m_T spectra and works better than HSD (wo QGP) at high energies – RHIC, SPS (and top FAIR, NICA)
- however, at low SPS (and low FAIR, NICA) energies the effect of the partonic phase decreases due to the decrease of the partonic fraction

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

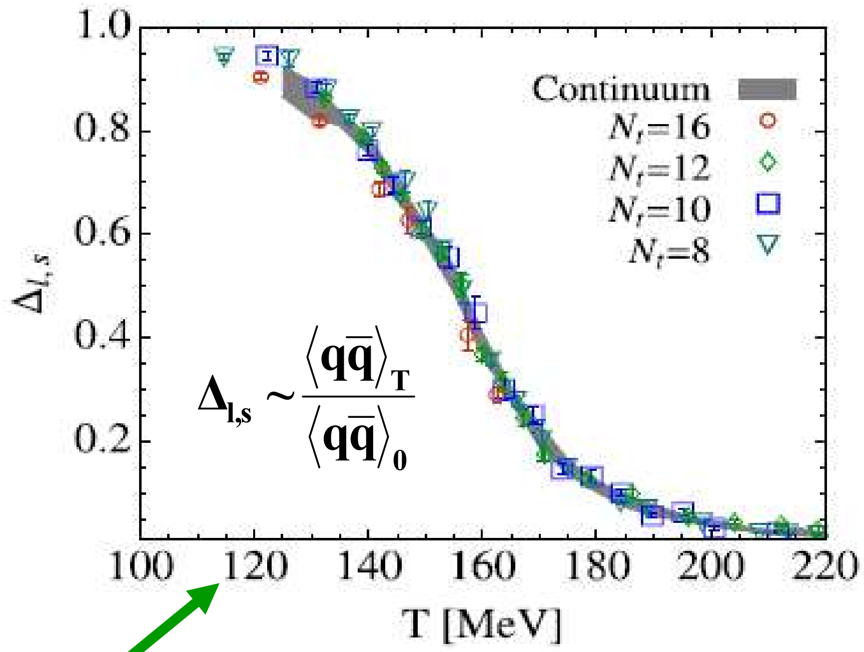
Problem: K^+/π^+ ‚horn' – 2015

PHSD: even when considering the creation of a QGP phase, the K^+/π^+ ‚horn' seen experimentally by NA49 and STAR at a bombarding energy ~30 A GeV (FAIR/NICA energies!) remains unexplained !

➔ The origin of 'horn' is not traced back to deconfinement ?!



IQCD BMW collaboration:



?

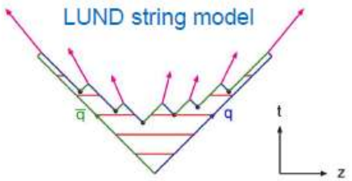
Can it be related to chiral symmetry restoration in the hadronic phase?!

W. Cassing, A. Palmese, P. Moreau, E.L. Bratkovskaya, PRC 93, 014902 (2016)

Chiral symmetry restoration vs. deconfinement

I. Initial stage of HIC collisions:

Hadronic matter ➔ string formation



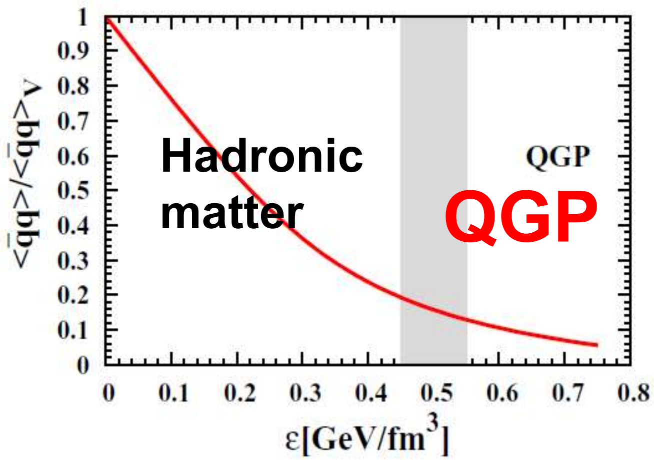
$$\frac{P(s\bar{s})}{P(u\bar{u})}=\frac{P(s\bar{s})}{P(d\bar{d})}=\gamma_S=\exp\left(-\pi\frac{m_S^{*2}-m_q^{*2}}{2\kappa}\right)$$

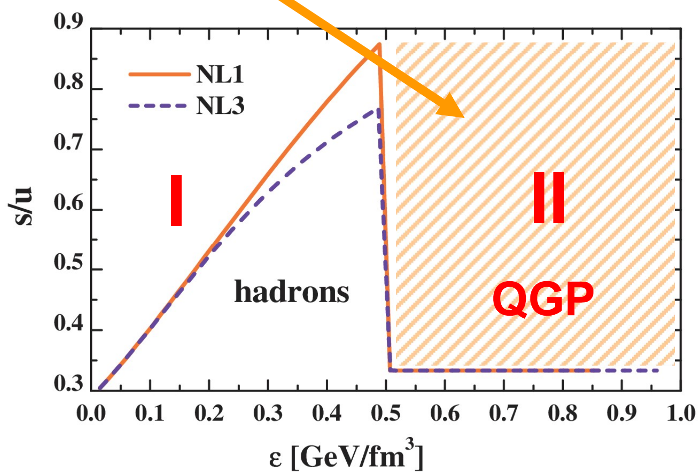
$$\mathbf{m}_q^*=\mathbf{m}_q^0+(m_q^V-m_q^0)\frac{<\mathbf{q\bar{q}}>}{<\mathbf{q\bar{q}}>_V}$$

II. QGP

(time-like partons, explicit partonic interactions)

III. Hadronic phase





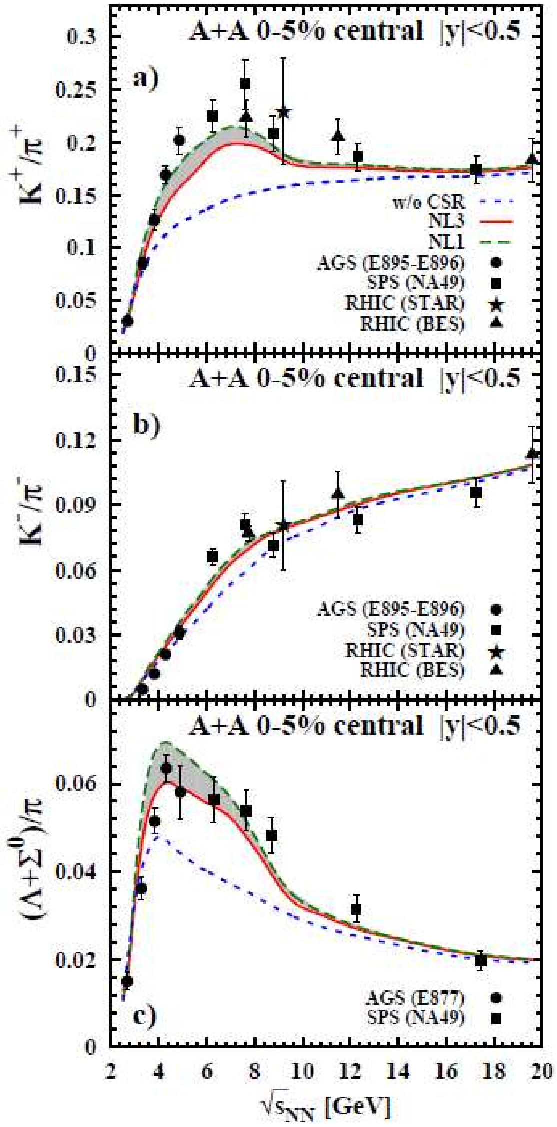
- **Chiral symmetry restoration** via **Schwinger mechanism** (and non-linear $\sigma-\omega$ model) changes the „flavour chemistry" in string fragmentation (1PI):

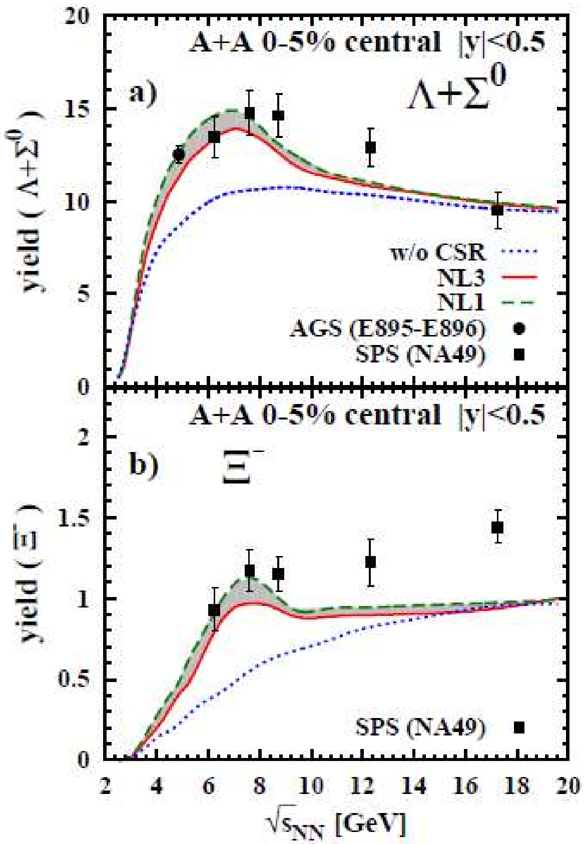
  $\langle q\bar{q}\rangle/\langle q\bar{q}\rangle_V \rightarrow 0$ ➔ $m_s^* \rightarrow m_s^0$ ➔ **s/u grows**

➔ **the strangeness production probability increases with the local energy density ε (up to ε_C) due to the partial chiral symmetry restoration!**

Excitation function of hadron ratios and yields

A. Palmese et al., PRC94 (2016) 044912 , arXiv:1607.04073





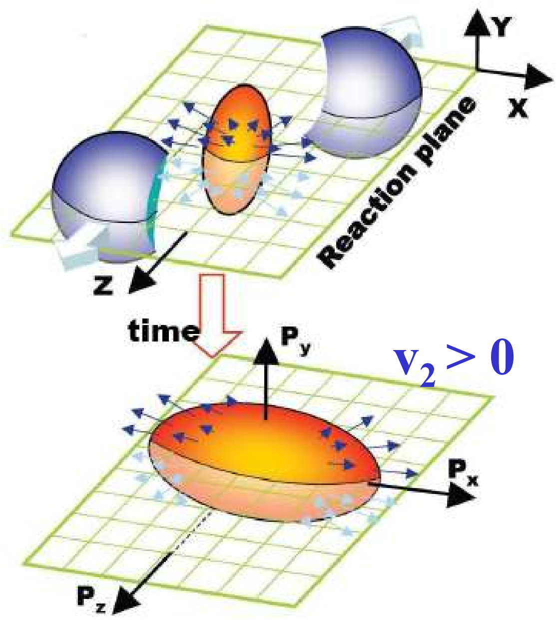
- Influence of EoS: NL1 vs NL3 ➔ low sensitivity to the nuclear EoS
- Excitation function of the hyperons $\Lambda+\Sigma^0$ and Ξ^- show analogous peaks as K^+/π^+, $(\Lambda+\Sigma^0)/\pi$ ratios due to CSR

Chiral symmetry restoration leads to the enhancement of strangeness production in string fragmentation in the beginning of HIC in the hadronic phase

Anisotropy coefficients v_n

Non central Au+Au collisions :

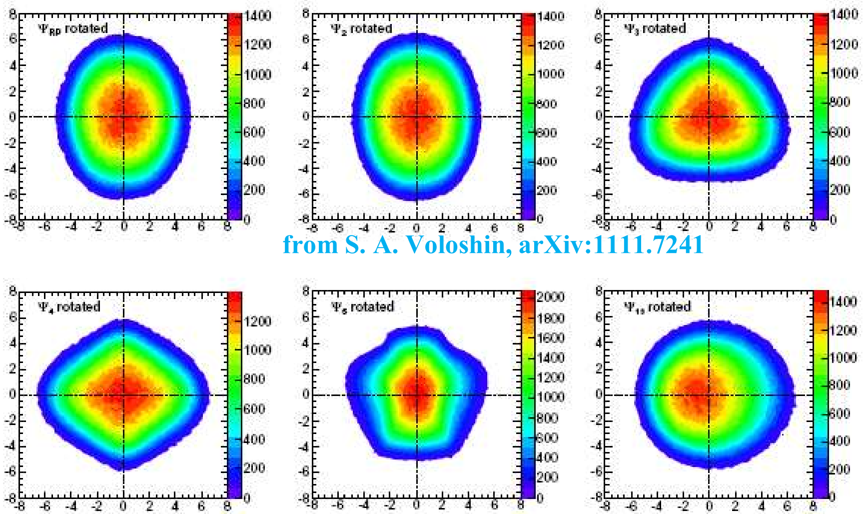
- **interaction between constituents leads to a pressure gradient → spatial asymmetry is converted to an asymmetry in momentum space → collective flow**



$$\frac{dN}{d\varphi} \propto \left(1 + 2\sum_{n=1}^{+\infty} v_n \cos\left[n(\varphi - \psi_n)\right]\right)$$

$$v_n = \left\langle \cos n\left(\varphi - \psi_n\right)\right\rangle, \quad n = 1,2,3..,$$

$$v_1 = \left\langle \frac{p_x}{p_T} \right\rangle, \quad v_2 = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle$$

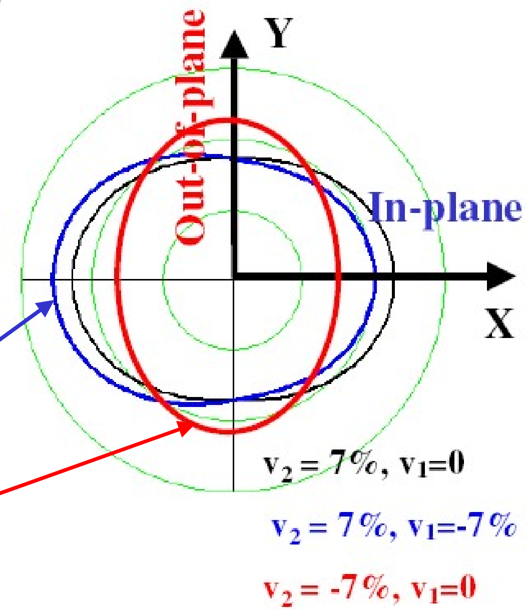


from S. A. Voloshin, arXiv:1111.7241

v_1: directed flow

v_2: elliptic flow

v_3: triangular flow



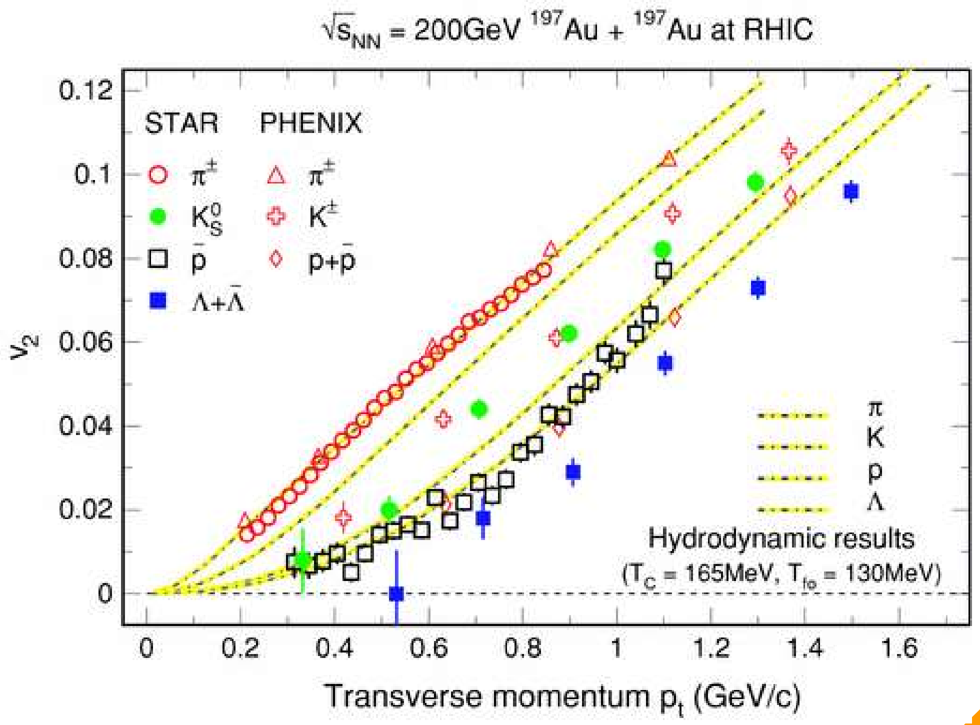
$v_2 > 0$ indicates in-plane emission of particles

$v_2 < 0$ corresponds to a squeeze-out perpendicular to the reaction plane (out-of-plane emission)

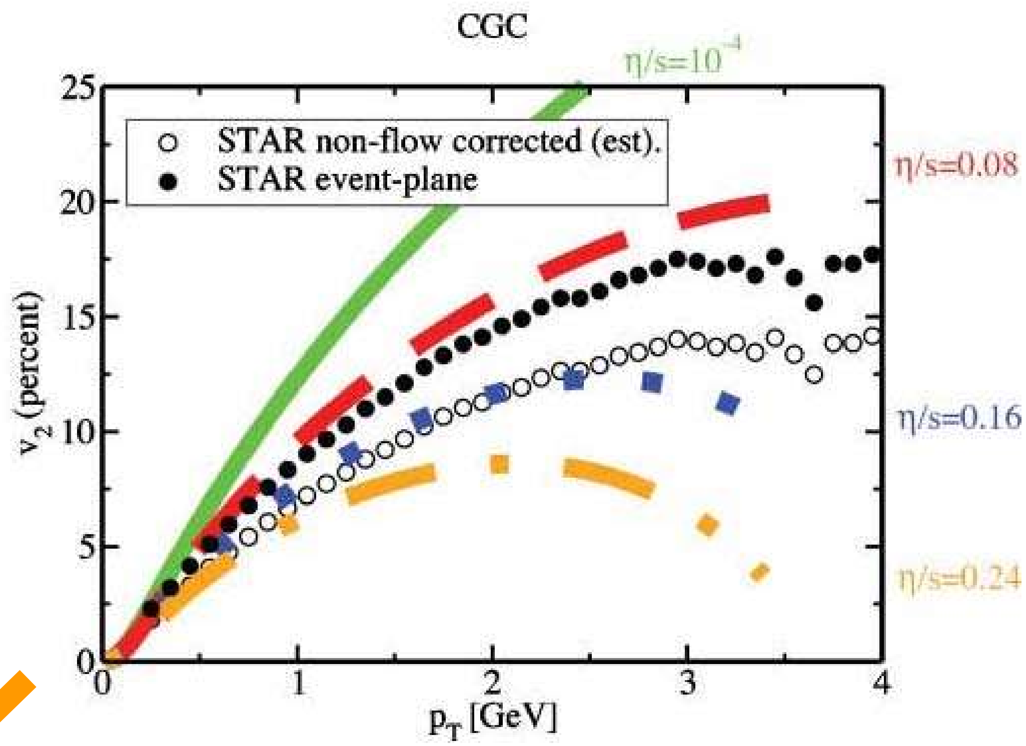
Hydrodynamic models: elliptic flow v_2

Comparison between hydro simulations and experimental data for the elliptic flow

Ideal hydrodynamic → **Viscous hydrodynamics**



Heinz:2001



Luzum,Romatschke:2008

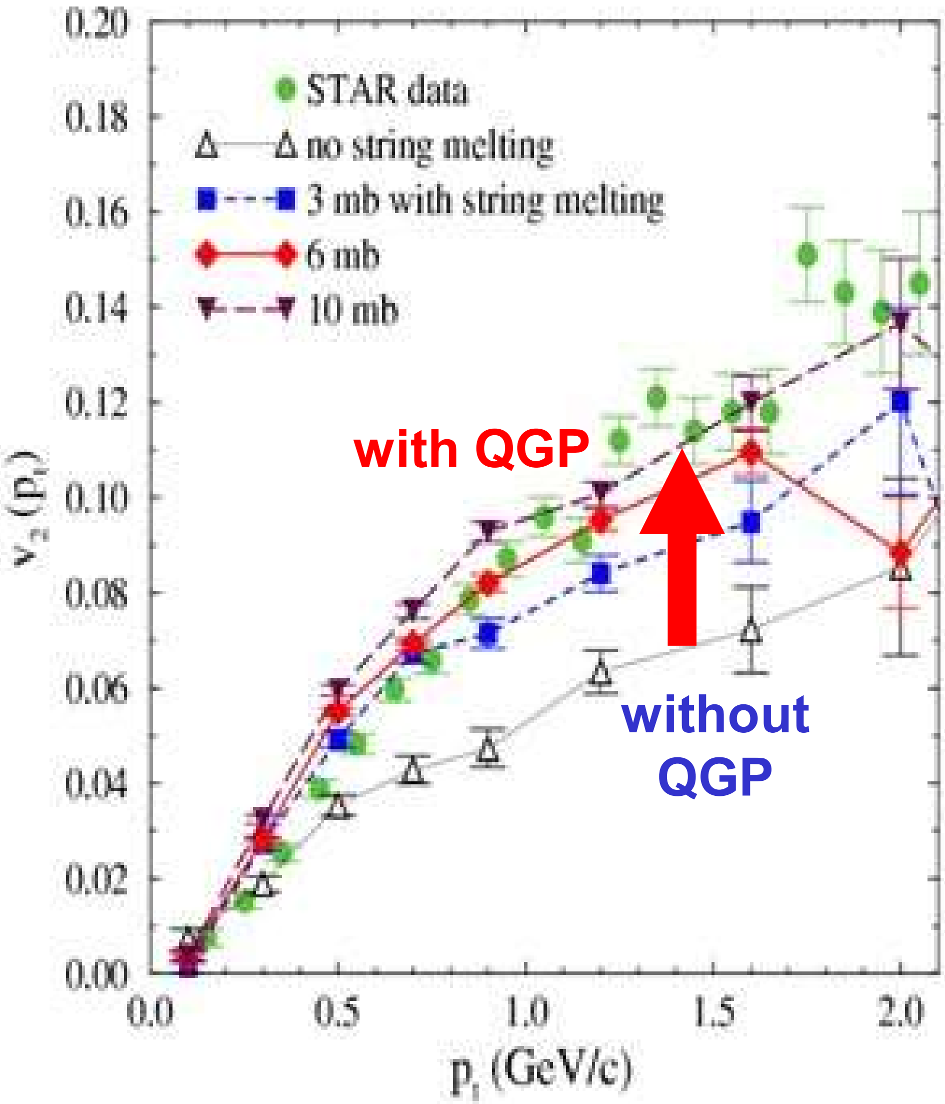
Ideal hydro: reproduces exp. data at low p_T , overestimates v_2 at p_T > 1.2 GeV/c

➔ Viscosity of QGP has to be accounted for ➔ viscous hydro

Elliptic flow v_2 is sensitive to η/s

Transport model AMPT: elliptic flow v_2

AMPT: Lin, Pal, Zhang, Li, Ko, PRC 61 (2000) 067901; PRC72 (2005) 064901



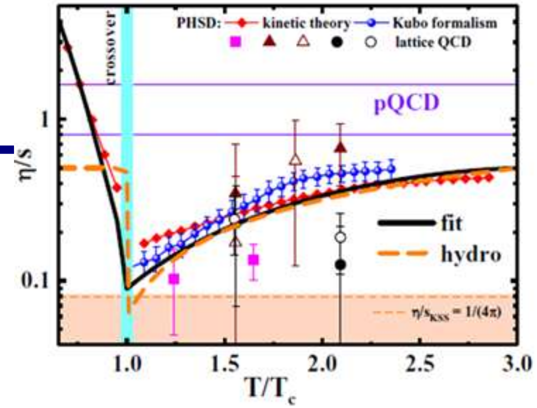
AMPT model:

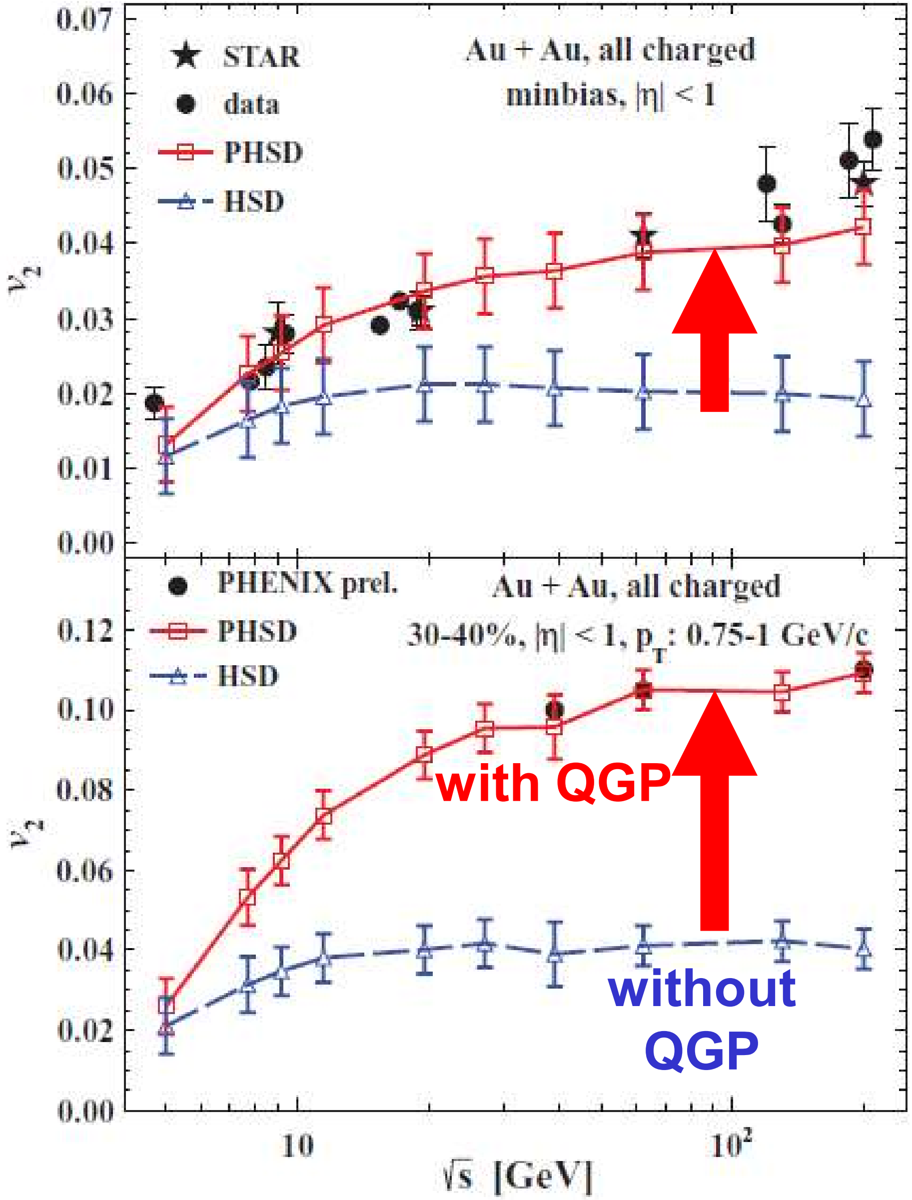
- **Initial conditions: HIJING (soft strings and hard minijets)**
- **QGP creation via string melting**
- **QGP interaction pQCD based cascade ZPC with massless q, g with constant cross sections σ =3,6,10 mb**
- **hadronization: coalescence**
- **hadronic scattering: ART**

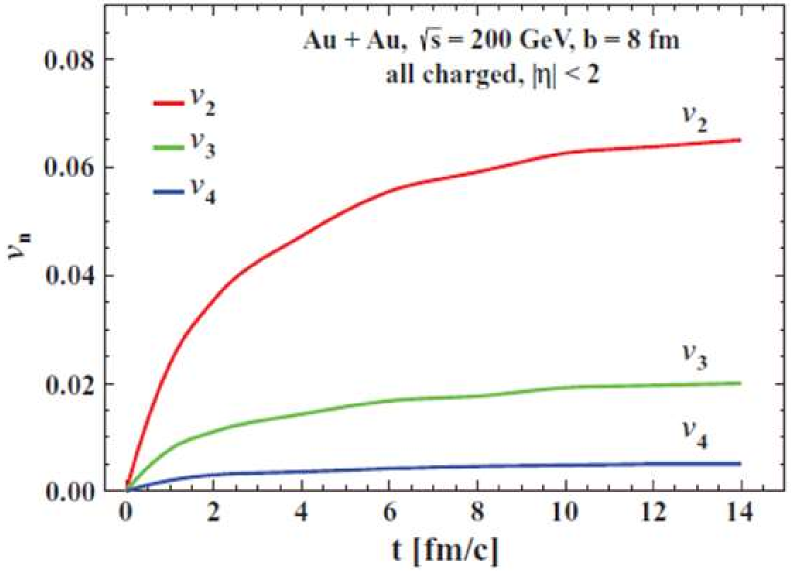
■ **v_2 data can be reproduced only within the string melting scenario and strong partonic interactions σ ~10 mb!**

➔ interactions in the QGP phase are mandatory !

Transport model PHSD: elliptic flow v_2



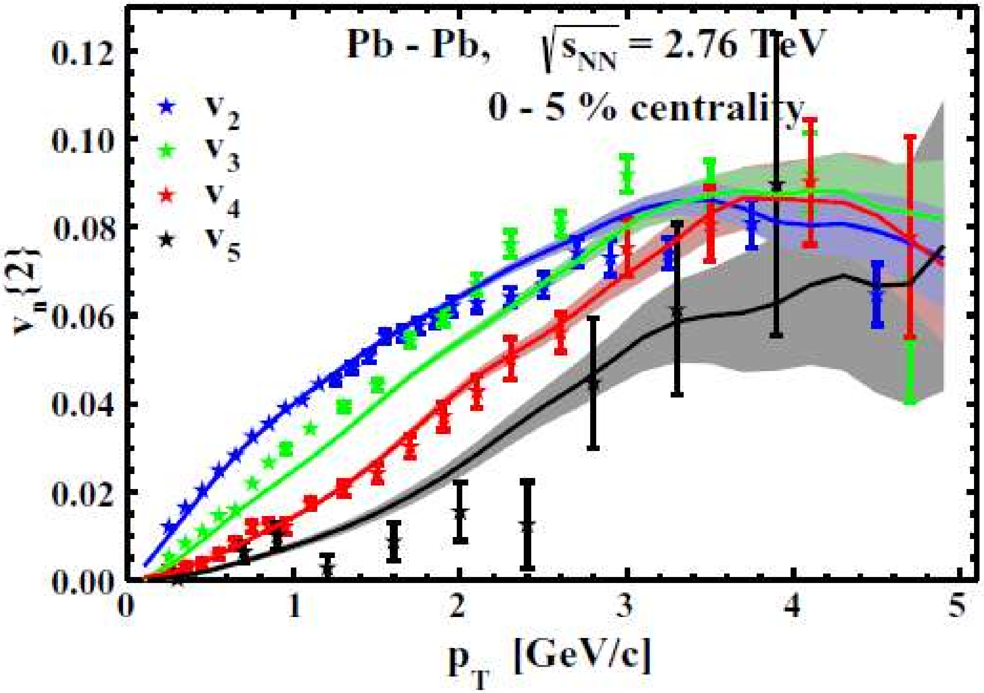


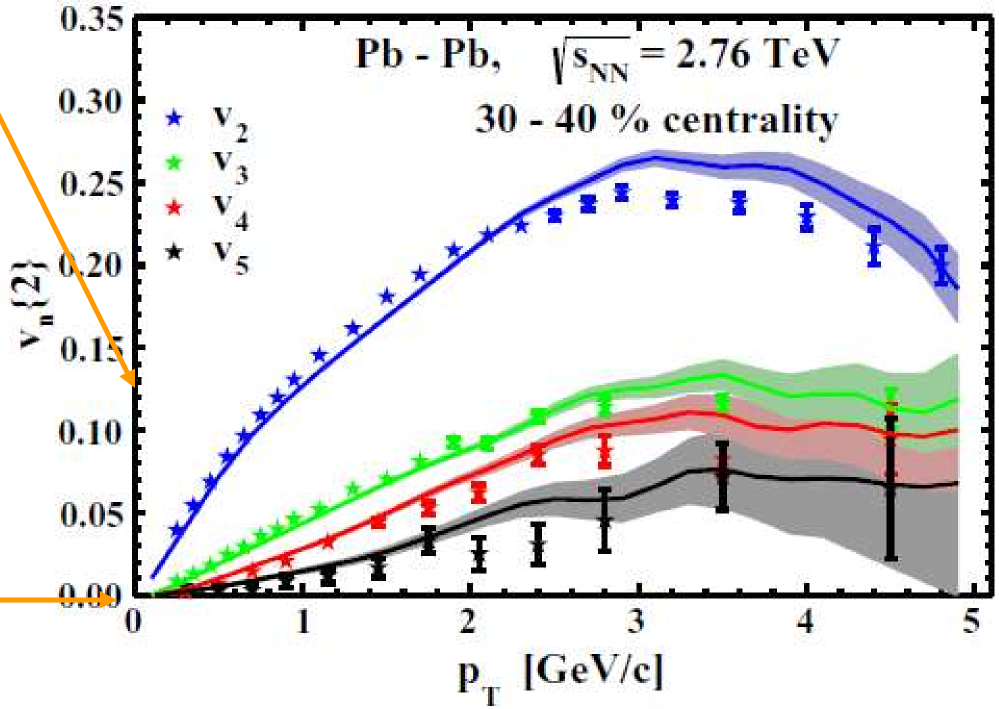


- v_2 in PHSD is larger than in HSD due to the repulsive scalar mean-field potential $U_s(\rho)$ for partons
- v_2 grows with bombarding energy due to the increase of the parton fraction

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

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

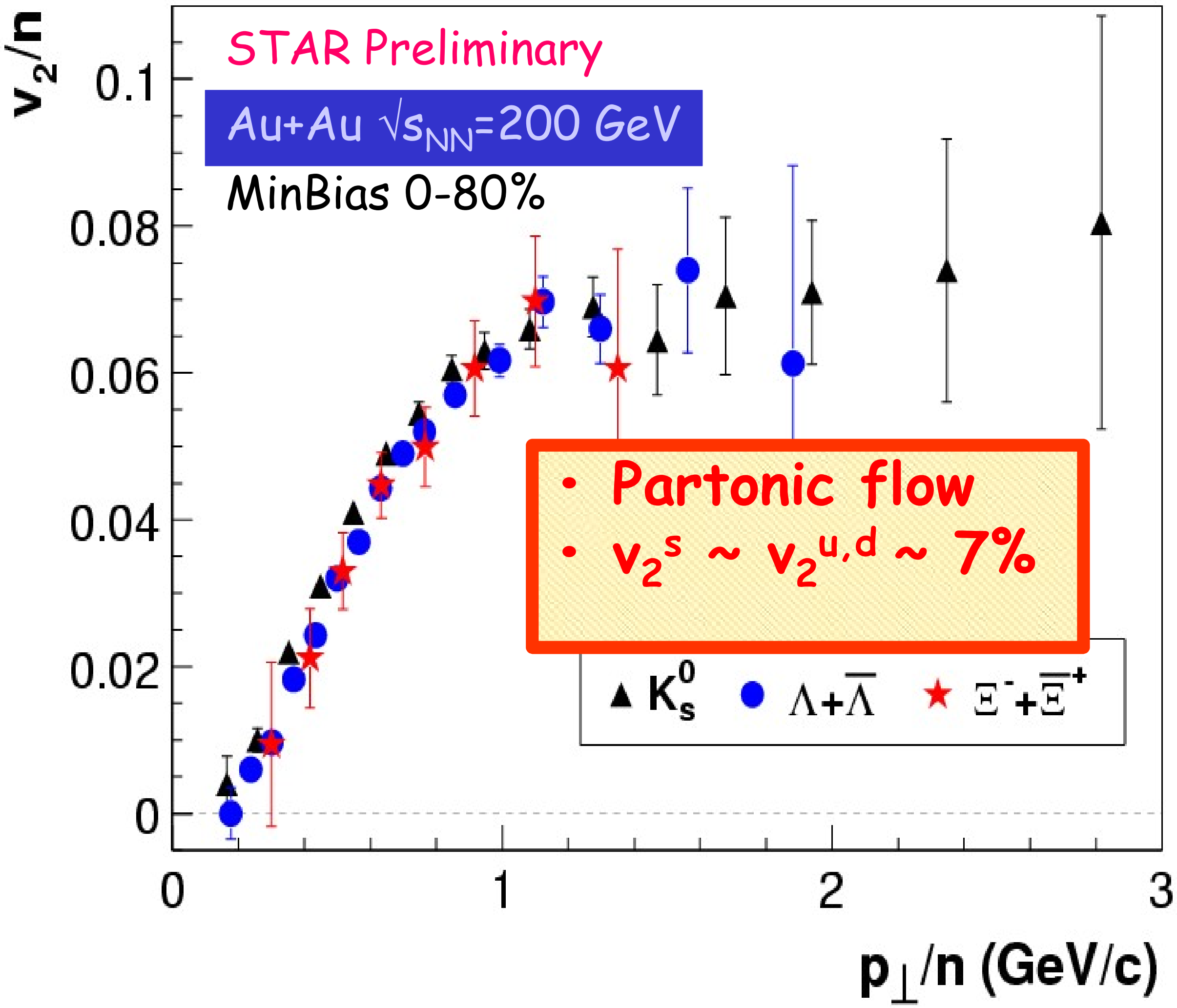
PRL 107 (2011) 032301

lines – PHSD (e-by-e)

v_n (n=3,4,5) develops by interaction in the QGP and in the final hadronic phase

V. Konchakovski, W. Cassing, V. Toneev, J. Phys. G: Nucl. Part. Phys 42 (2015) 055106

Flow at partonic level



- Partonic flow
- $v_2^s \sim v_2^{u,d} \sim 7\%$

- The complex behaviour of v_2 can be « simply » explained at partonic level

$$v_2^p(p_t) = \frac{v_2^B(3p_t)}{3}$$

$$v_2^p(p_t) = \frac{v_2^M(2p_t)}{2}$$

$$v_2^p(p_t) = \frac{v_2^h(np_t)}{n}$$

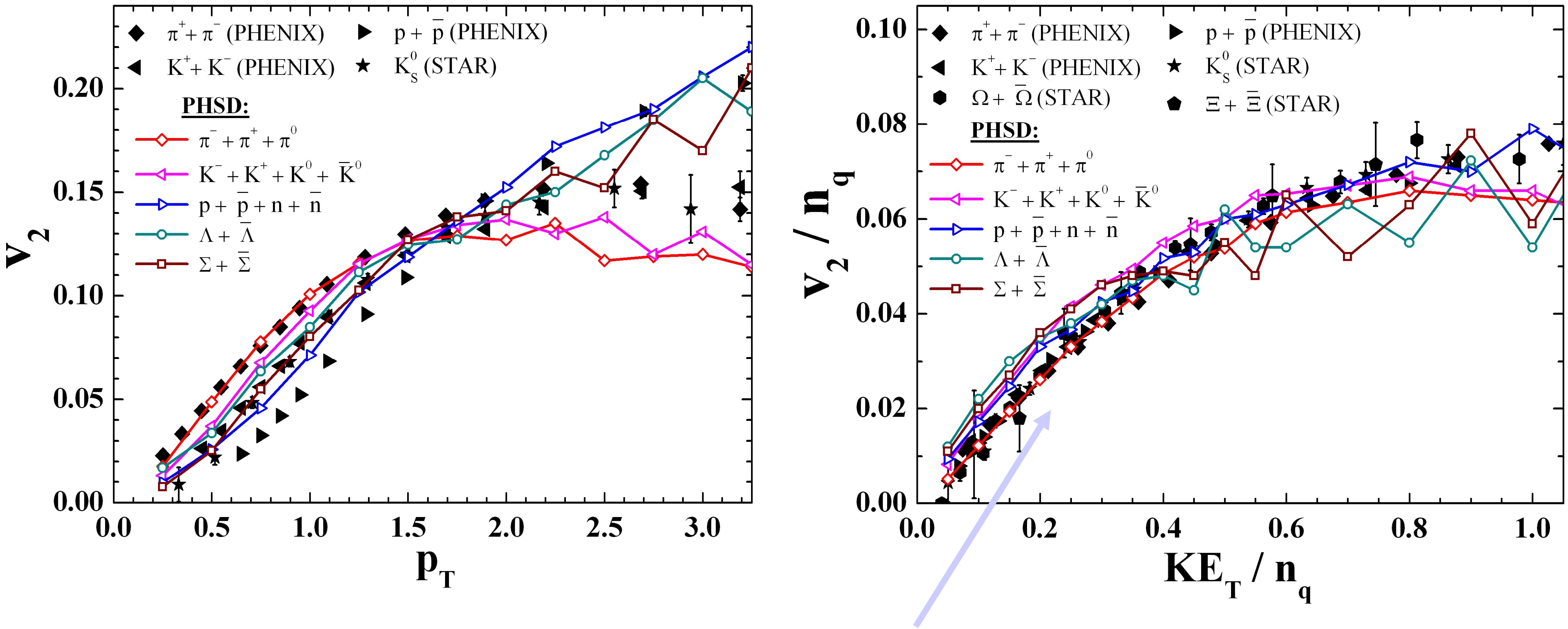
… at intermediate p_T !

Idea of flow per constituent – Coalescence/Recombination
Elliptic flow developed at partonic level

STAR

Cf. R. A. Lacey and A. Taranenko, PoS C FRNC2006, 021 (2006)

Transport results - PHSD: Elliptic flow scaling at RHIC



- **PHSD: The scaling of v_2 with the number of constituent quarks n_q is roughly in line with the data**
- **Collectivity in QGP: ➔ all hadrons flow with about the same velocity!**

E. Bratkovskaya, W. Cassing, V. Konchakovski, O. Linnyk, NPA856 (2011) 162

Messages from the study of spectra and collective flow

- m_T spectra are harder with QGP interaction than without 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

Summary

Theory versus experimental observables:

- **indication for a partial chiral symmetry restoration**
- **evidence for strong partonic interactions in the early phase of relativistic heavy-ion reactions**

⇒ **formation of the sQGP in HIC!**