Parton-hadron dynamics in heavy-ion collisions

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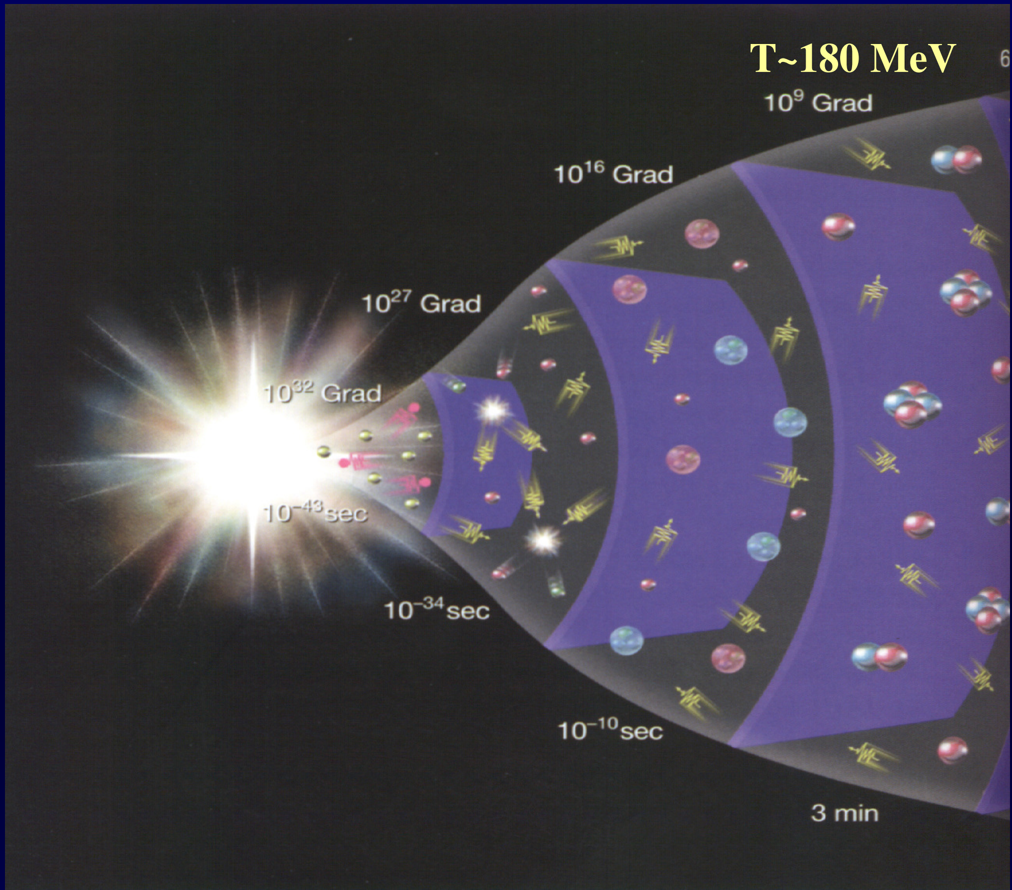
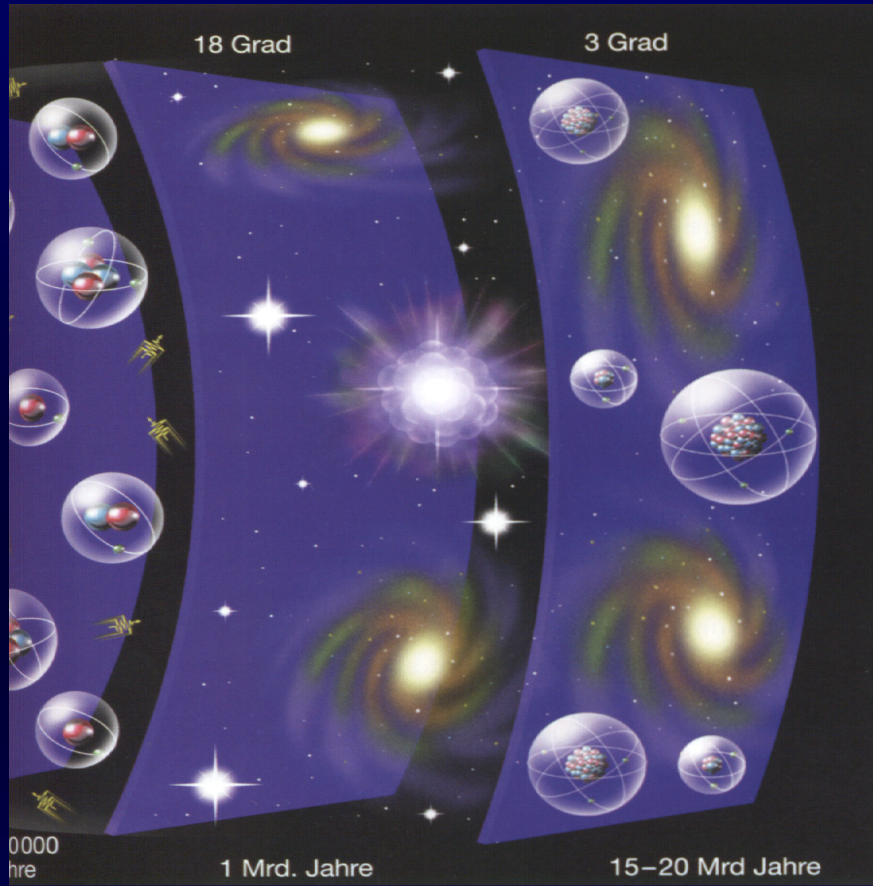
From Big Bang to Formation of the Universe





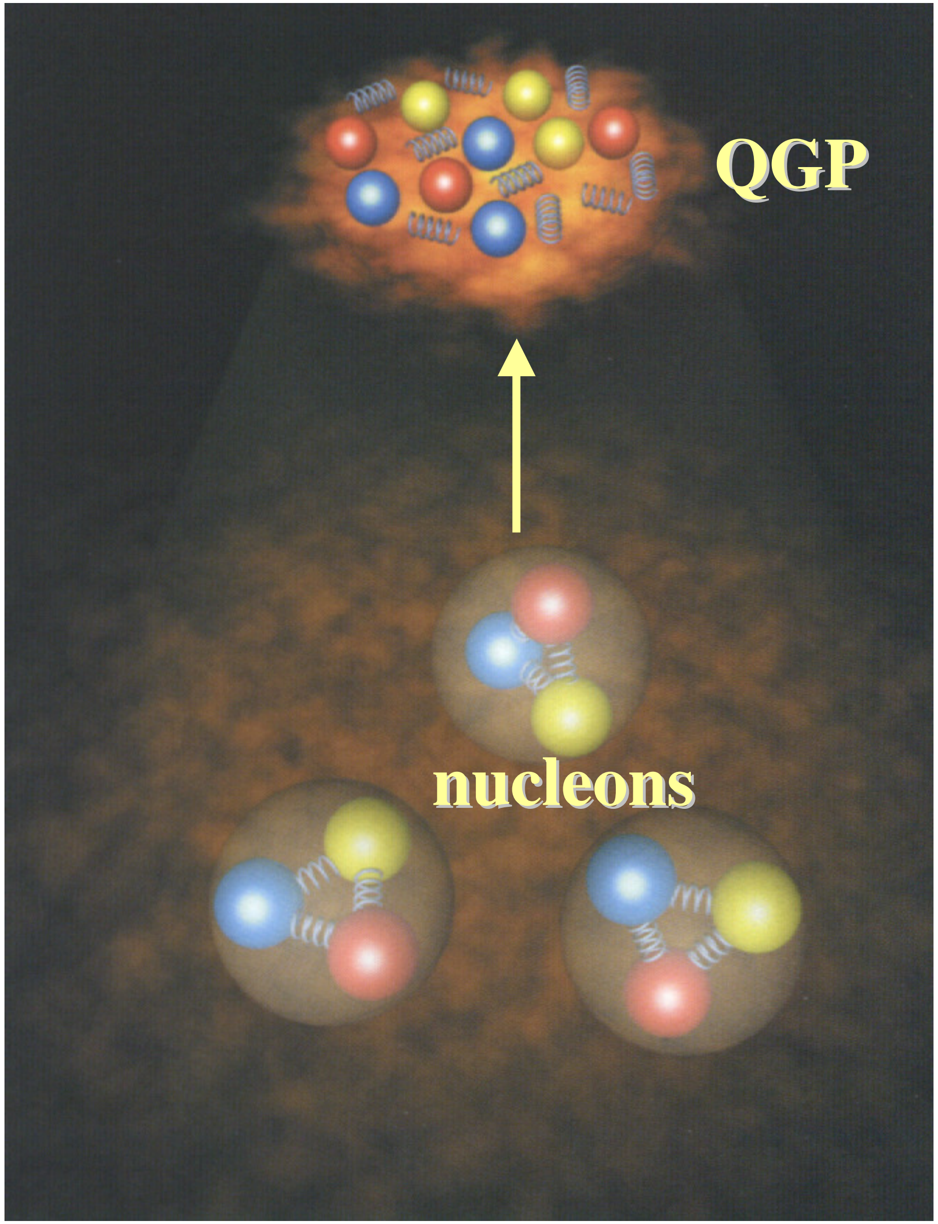
time	10^{-3}sec	3 min	300000 years	15 Mrd years
	quarks gluons photons	nucleons deuterons α–particles	atoms	our Universe

Can we go back in time ?

... back in time

‚Re-create' the Big Bang conditions:
matter at high temperature and pressure
such that
nucleons/mesons decouple to quarks and gluons --
Quark-Gluon-Plasma

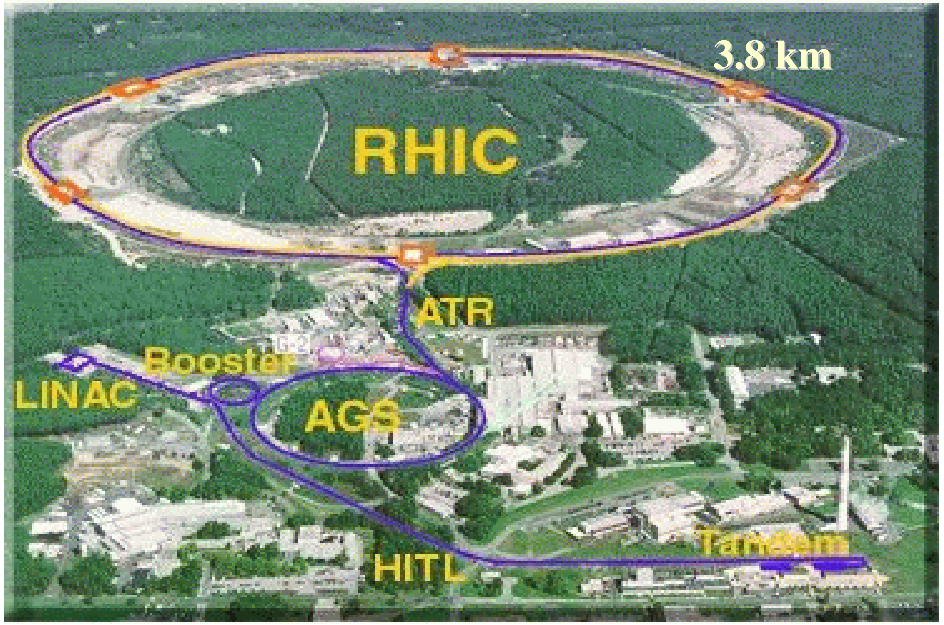
‚Little Bangs' in the Laboratory :
Heavy-ion collisions at ultrarelativistic energies



Heavy-ion accelerators

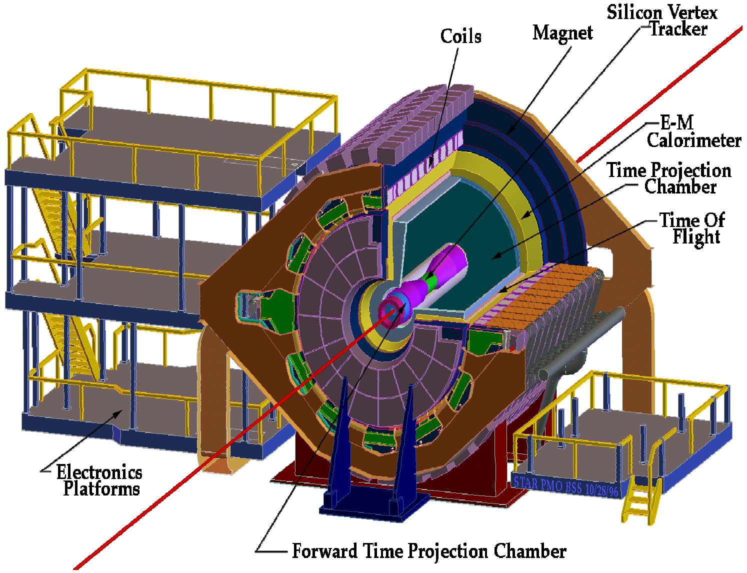
- **Super-Proton-Synchrotron – SPS - (CERN):** Pb+Pb at 160 A GeV

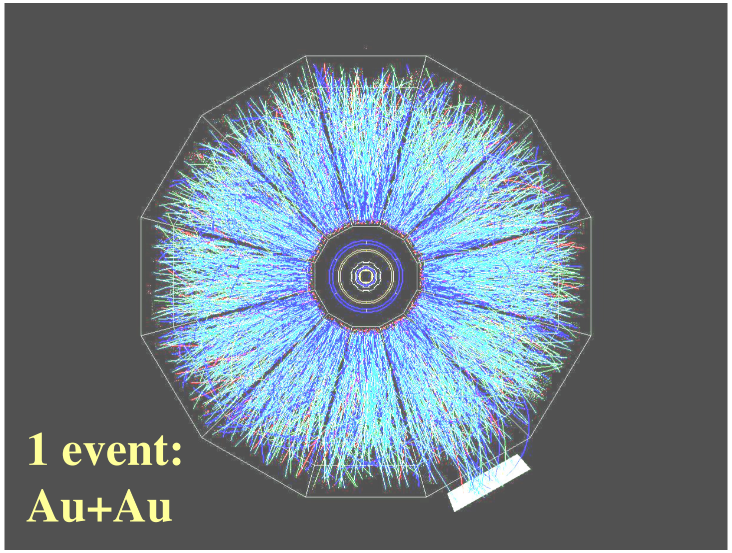
- **Relativistic-Heavy-Ion-Collider - RHIC - (Brookhaven):** Au+Au at 21.3 A TeV



- **Large Hadron Collider – LHC - (CERN):** Pb+Pb at 574 A TeV
- **Future facilities: FAIR (GSI), NICA (Dubna)**

STAR detector at RHIC



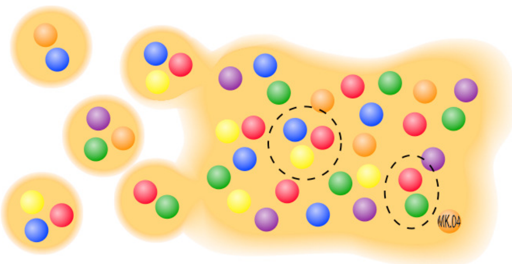


The QGP in Lattice QCD

Quantum Chromo Dynamics :

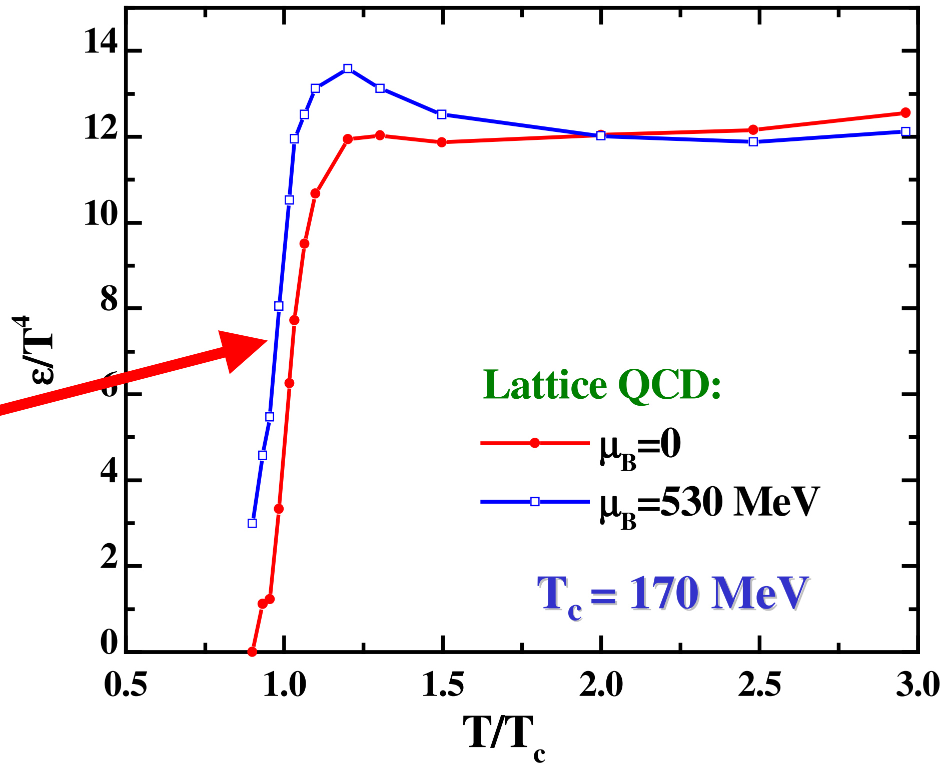
predicts strong increase of the energy density ε at critical temperature T_C ~170 MeV

⇒ Possible phase transition from hadronic to partonic matter (quarks, gluons) at critical energy density ε_C ~0.5 GeV/fm³



Lattice QCD:

energy density versus temperature

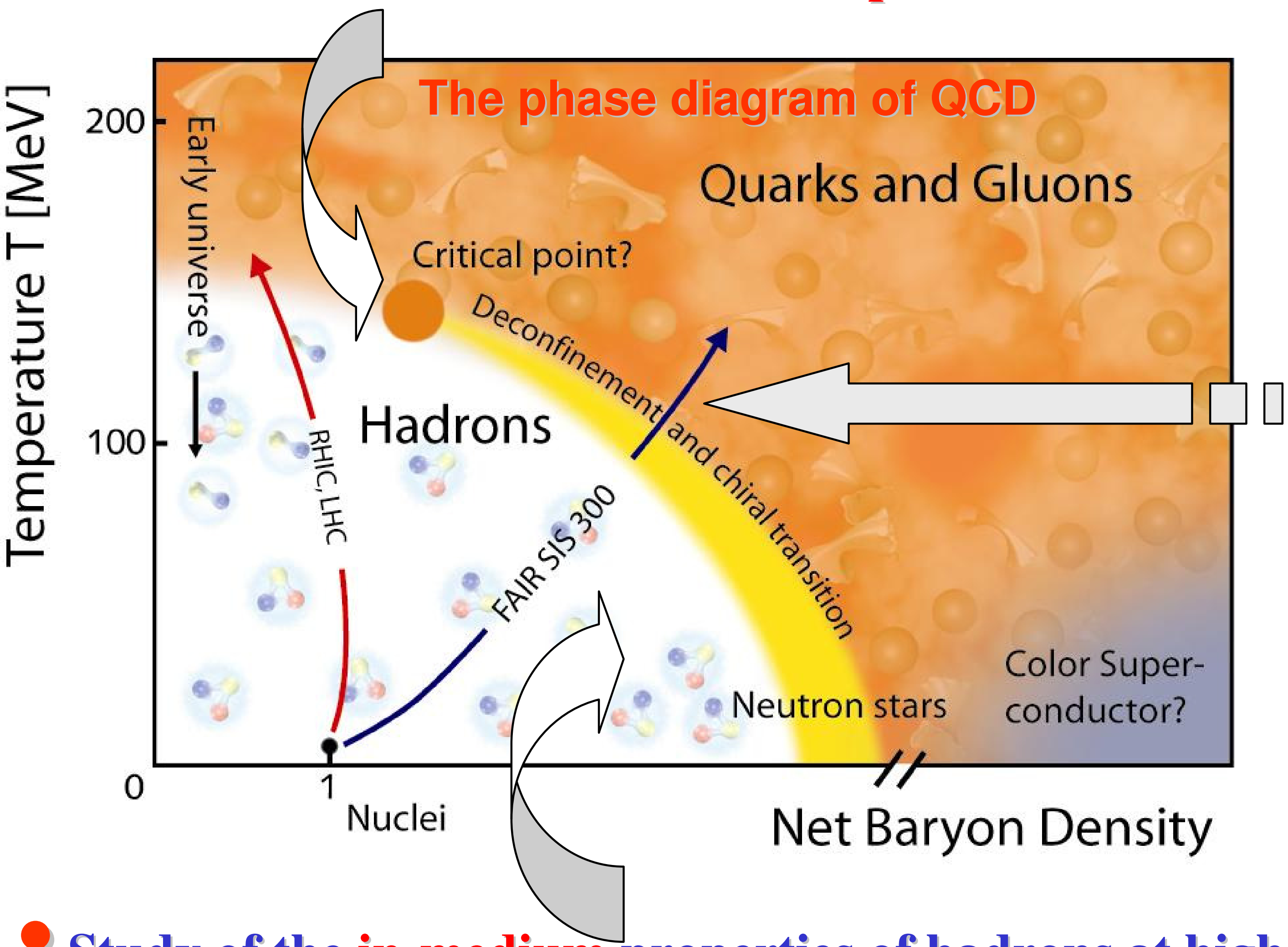


Z. Fodor et al., PLB 568 (2003) 73

Critical conditions - ε_C ~0.5 GeV/fm³ , T_C ~170 MeV - can be reached in heavy-ion experiments at bombarding energies > 5 GeV/A

The holy grail:

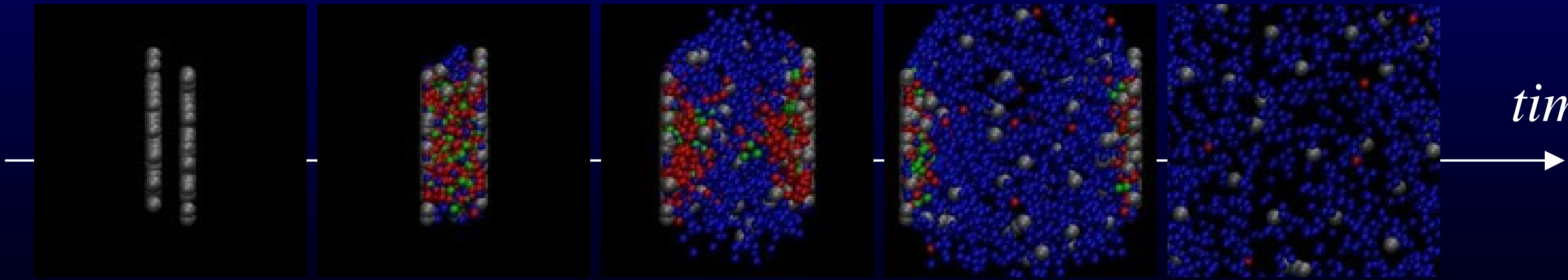
- Search for the critical point



- 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
- Study of the partonic medium beyond the phase boundary

‚Little Bangs‘ in the Laboratory



Quark-Gluon-Plasma ?

hadron degrees of freedom → quarks and gluons → hadron degrees of freedom

How can we prove that an equilibrium QGP has been created in central heavy-ion collisions ?!

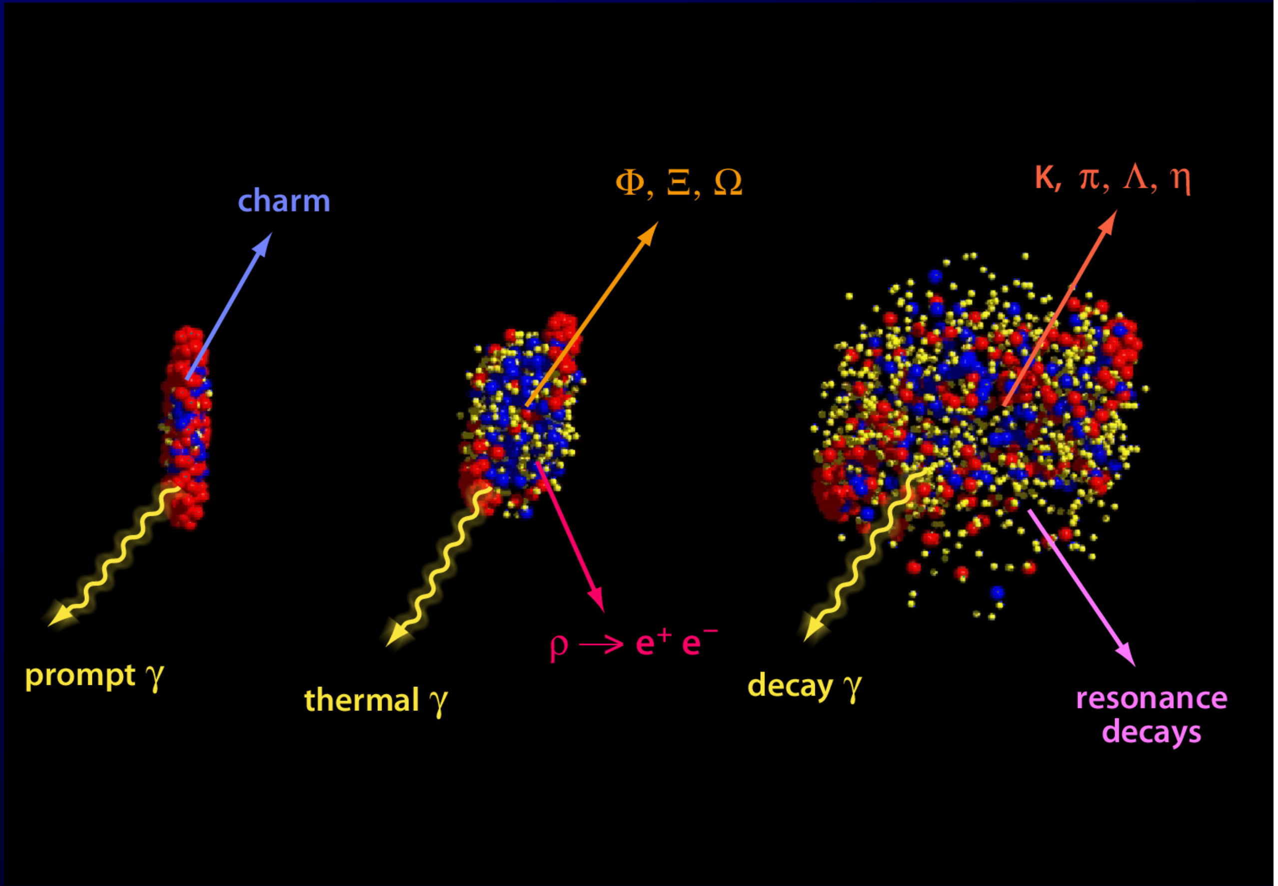
Signals of the phase transition:

- 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

[-: no dynamics]

- **Ideal hydrodynamical models:**

basic assumption: conservation laws + equation of state; assumption of local thermal and chemical equilibrium

[-: - simplified dynamics]

- **Transport models:**

based on transport theory of relativistic quantum many-body systems - off-shell Kadanoff-Baym equations for the Green-functions $S^{<}_{h}(x,p)$ in phase-space representation. Actual solutions: Monte Carlo simulations with a large number of test-particles

[+: full dynamics | -: very complicated]

→ Microscopic transport models provide a unique dynamical description of nonequilibrium effects in heavy-ion collisions

Dynamics of heavy-ion collisions –> complicated many-body problem!

Appropriate way to solve the many-body problem including all quantum mechanical features →

Kadanoff-Baym equations for Green functions S< **(from 1962)**

$$\boxed{\hat{S}_{0x}^{-1}\, S_{xy}^{<} \;=\; \Sigma_{xz}^{ret} \odot S_{zy}^{<} \;+\; \Sigma_{xz}^{<} \odot S_{zy}^{adv}}$$

$\hat{S}_{0x}^{-1}$ denotes the (negative) Klein-Gordon differential operator e.g. for bosons $\hat{S}_{0x}^{-1} = -(\partial_x^\mu \partial_\mu^x + M_0^2)$

"$\odot$" implies an integration over the intermediate spacetime coordinates from $-\infty$ to ∞.

Greens functions S / self-energies Σ :

retarded (ret), advanced (adv) (anti-)causal (a,c)

$$i\,S_{xy}^{c} = i\,S_{xy}^{++} = <T^c\{\Phi(x)\,\Phi^\dagger(y)\}>, \qquad i\,S_{xy}^{<} = i\,S_{xy}^{+-} = \eta<\{\Phi^\dagger(y)\,\Phi(x)\}>,$$

$$i\,S_{xy}^{>} = i\,S_{xy}^{-+} = <\{\Phi(x)\,\Phi^\dagger(y)\}>, \qquad i\,S_{xy}^{a} = i\,S_{xy}^{--} = <T^a\{\Phi(x)\,\Phi^\dagger(y)\}>.$$

$$S_{xy}^{ret} = S_{xy}^{c} - S_{xy}^{<} = S_{xy}^{>} - S_{xy}^{a}, \qquad S_{xy}^{adv} = S_{xy}^{c} - S_{xy}^{>} = S_{xy}^{<} - S_{xy}^{a}$$

$\eta = +1$ for bosons and $\eta =$ -1 for fermions.
T^c (T^a) represent the (anti-)time-ordering operators.

- **do Wigner transformation** $$F_{XP} = \int d^4(x-y)\; e^{iP_\mu(x^\mu - y^\mu)}\; F_{xy}$$
- **consider only contribution up to first order in the gradients**
  = a standard approximation of kinetic theory which is justified if the gradients in the mean spacial coordinate *X* are small

‚On-shell' transport models

Basic concept of the ‚on-shell' transport models (VUU, BUU, QMD etc.):

1) Transport equations = first order gradient expansion of the Wigner transformed Kadanoff-Baym equations
2) quasiparticle approximation: $A(x,p) = 2\pi\,\delta(p^2 - M^2)$

- for each particle species *i* (*i* = *N*, *R*, *Y*, π, ρ, K, …) the phase-space density f_i follows the transport equations

$$\left(\frac{\partial}{\partial t} + \left(\nabla_{\vec p} U\right)\nabla_{\vec r} - \left(\nabla_{\vec r} U\right)\nabla_{\vec p}\right) f_i(\vec r, \vec p, t) = I_{coll}(f_1, f_2, \ldots, f_M)$$

  - with collision terms I_{coll} describing elastic and inelastic hadronic reactions:

    baryon-baryon, meson-baryon, meson-meson, formation and decay of baryonic and mesonic resonances, string formation and decay (for inclusive particle production:

    BB –> X , mB –>X, X =many particles)

  - with propagation of particles in self-generated mean-field potential $U(p,\rho) \sim Re(\Sigma^{ret})/2p_0$

- Numerical realization – solution of classical equations of motion + Monte-Carlo simulations for test-particle interactions

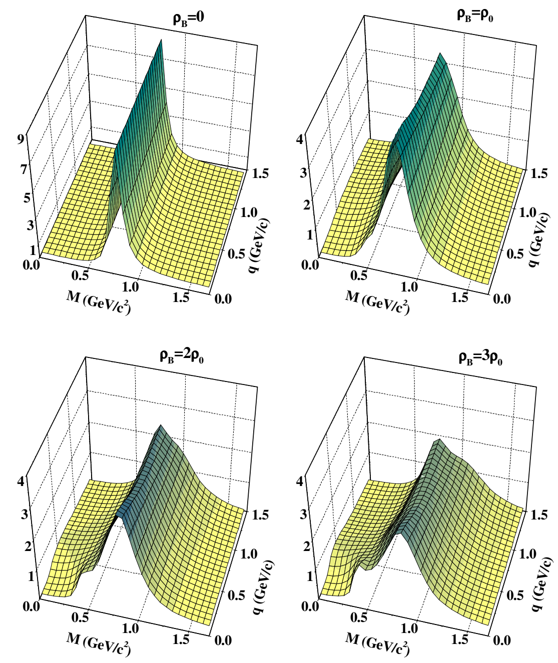
Study of in-medium effects within transport approaches

- **Semi-classical on-shell transport models** work very well in describing interactions of point-like particles and **narrow resonances** !

- **In-medium models** - chiral perturbation theory, chiral SU(3) model, coupled-channel G-matrix approach, chiral coupled-channel effective field theory etc. predict **changes of the particle properties** in the hot and dense medium, e.g. strong **broadening of the spectral functions**

R. Rapp: ρ meson spectral function

$-\mathrm{Im}\, D_\rho\, (M,q,\rho_B,T)\ (\mathrm{GeV}^{-2})$
T=150 MeV



■ **Problem : How to treat short-lived (broad) resonances in semi-classical transport models?**

Semi-classical approaches: **on-shell transport models** based on quasi-particle approximation $A(X,P) = 2\pi\,\delta(P^2-M^2)$

● **Accounting for in-medium effects with medium-dependent spectral functions requires off-shell transport models bejong quasi-particle approximation !**

➔ back to Kadanoff-Baym equations

From Kadanoff-Baym equations to transport equations

After the first order gradient expansion of the Wigner transformed Kadanoff-Baym equations and separation into the real and imaginary parts one gets:

Generalized transport equations:

$$\Diamond\{\underbrace{P^2 - M_0^2}_{\text{drift term}} - \underbrace{Re\Sigma_{XP}^{ret}}_{\text{Vlasov term}}\}\{S_{XP}^<\} - \underbrace{\Diamond\{\Sigma_{XP}^<\}\{ReS_{XP}^{ret}\}}_{\text{backflow term}} = \frac{i}{2}[\underbrace{\Sigma_{XP}^> S_{XP}^<}_{\text{'loss' term}} - \underbrace{\Sigma_{XP}^< S_{XP}^>}_{\text{'gain' term}}]$$

collision term = 'loss' term - 'gain' term

Backflow term incorporates the off-shell behavior in the particle propagation

! vanishes in the quasiparticle limit $A_{XP} = 2\pi\,\delta(p^2-M^2)$

➔ 'on-shell' transport models (VUU, BUU, QMD, IQMD, UrQMD etc.)

Greens function $S^<$ characterizes the number of particles (N) and their properties (A – spectral function): $iS^<_{XP}=A_{XP}N_{XP}$

The imaginary part of the retarded propagator is given by normalized spectral function:

$$A_{XP} = i\left[S_{XP}^{ret} - S_{XP}^{adv}\right] = -2\,Im\,S_{XP}^{ret}\,, \qquad \int \frac{dP_0^2}{4\pi} A_{XP} = 1$$

For bosons in first order in gradient expansion:

$$A_{XP} = \frac{\Gamma_{XP}}{(P^2 - M_0^2 - Re\Sigma_{XP}^{ret})^2 + \Gamma_{XP}^2/4}$$

Γ_{XP} – width of spectral function = reaction rate of particle (at phase-space position XP)

4-dimentional generalizaton of the Poisson-bracket:

$$\Diamond\{F_1\}\{F_2\} := \frac{1}{2}\left(\frac{\partial F_1}{\partial X_\mu}\frac{\partial F_2}{\partial P^\mu} - \frac{\partial F_1}{\partial P_\mu}\frac{\partial F_2}{\partial X^\mu}\right)$$

W. Cassing , S. Juchem, NPA 665 (2000) 377; 672 (2000) 417; 677 (2000) 445

The baseline concepts of HSD

HSD – Hadron-String-Dynamics transport approach:

- for each particle species *i* (*i* = *N*, *R*, *Y*, π, ρ, K, …) the phase-space density f_i follows the generalized transport equations

  with collision terms I_{coll} describing:

  - elastic and inelastic hadronic reactions:

    baryon-baryon, meson-baryon, meson-meson

  - formation and decay of

    baryonic and mesonic resonances

  and strings - excited color singlet states *(qq - q)* or *(q – qbar)* -

  (for inclusive particle production: BB –> X , mB –>X, X =many particles)

BB <–> B´B´, BB <–> B´B´m

mB <–> m´B´, mB <–> B´

Baryons:

B=(p, n, Δ(1232),

N(1440), N(1535), ...)

Mesons:

m=(π, η, ρ, ω, ϕ, ...)

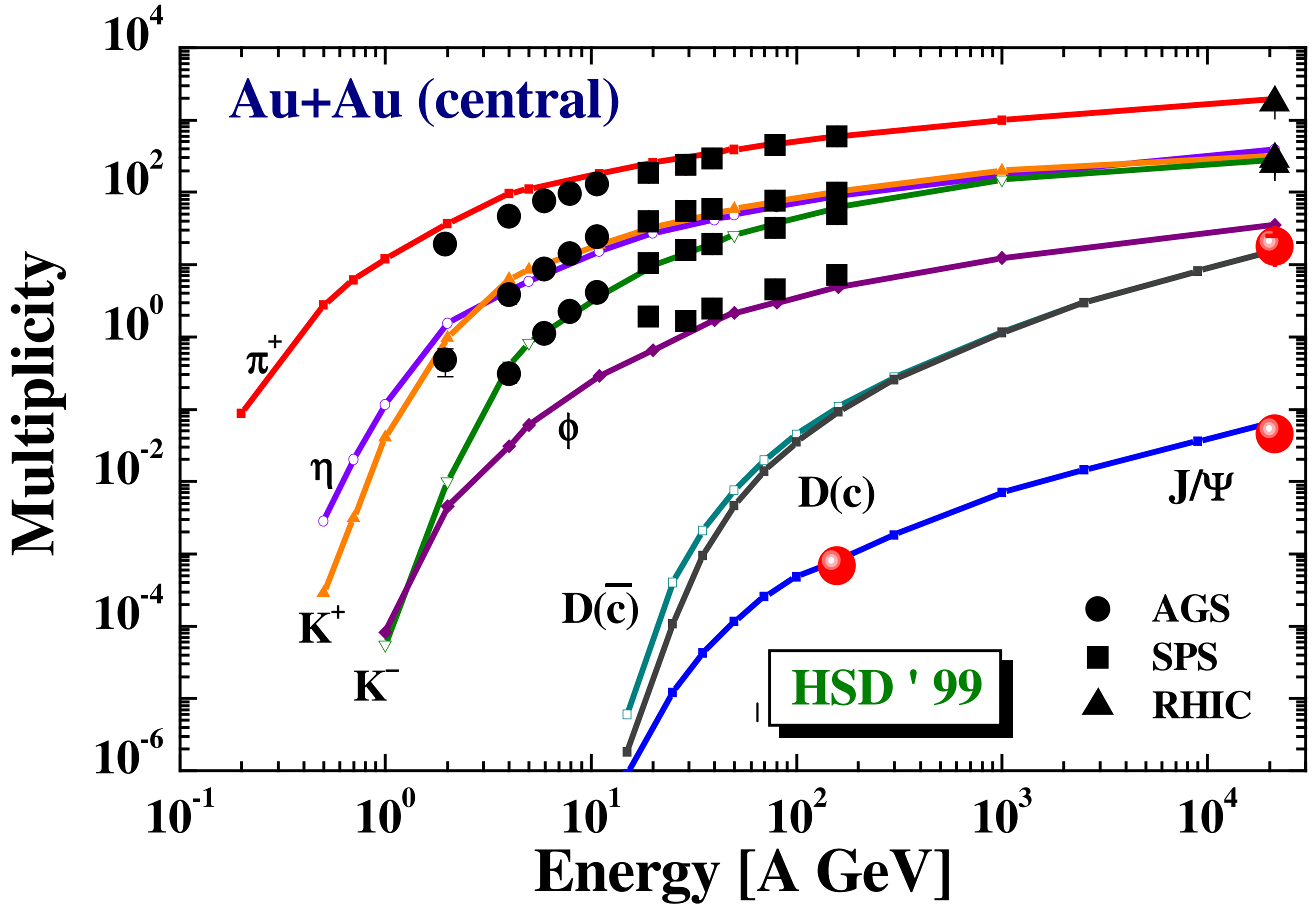
- implementation of detailed balance on the level of 1<–>2 and 2<–>2 reactions (+ 2<–>n multi-particle reactions in HSD !)

- off-shell dynamics for short-lived states

HSD is an open code: http://www.th.physik.uni-frankfurt.de/~brat/hsd.html

HSD – a microscopic model for heavy-ion reactions

- very good description of particle production in pp, pA, AA reactions
- unique description of nuclear dynamics from low (~100 MeV) to ultrarelativistic (>20 TeV) energies

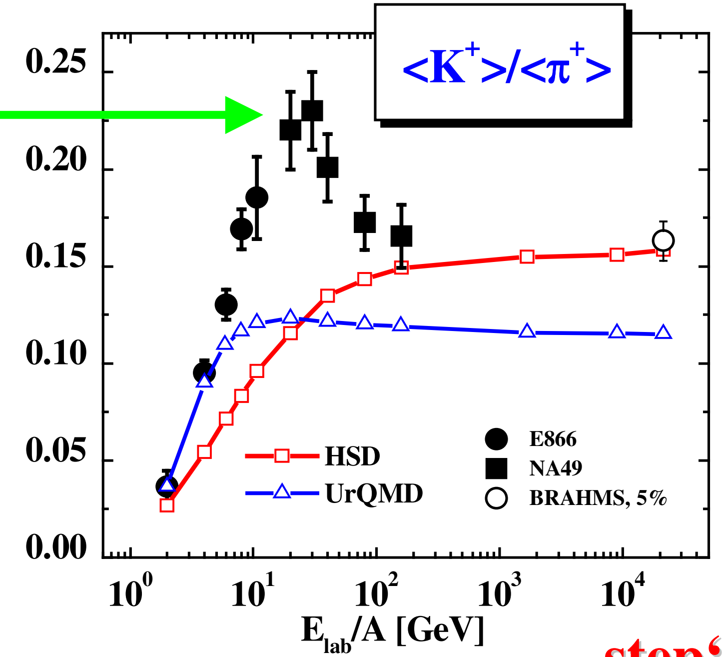


HSD predictions from 1999; data from the new millenium

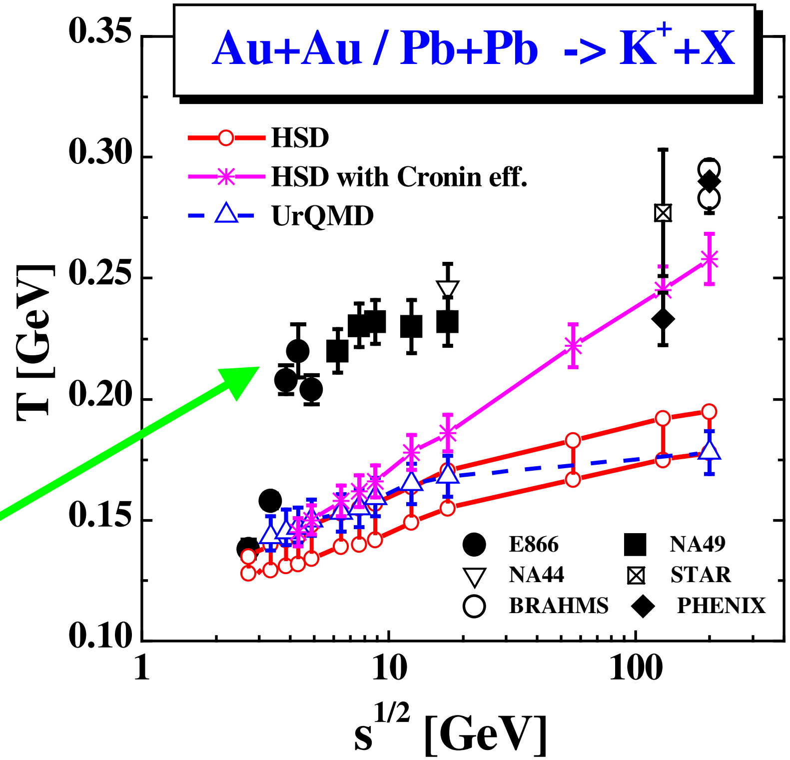
Hadron-string transport models (HSD, UrQMD) versus observables

- **Strangeness signals of QGP**

‚horn' in K^+/π^+



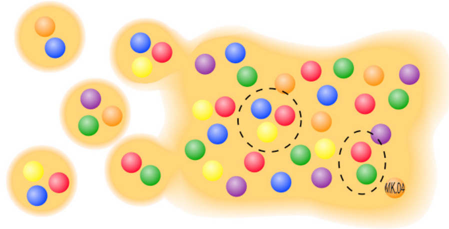
‚step' in slope T



Exp. data are not reproduced in terms of the hadron-string picture
=> evidence for nonhadronic degrees of freedom

PRC 69 (2004) 032302

Goal: microscopic transport description of the partonic and hadronic phase



Problems:

- How to model a QGP phase in line with lQCD data?
- How to solve the hadronization problem?

Ways to go:

pQCD based models:

- QGP phase: pQCD cascade
- hadronization: quark coalescence

→ AMPT, HIJING, BAMPS

‚Hybrid' models:

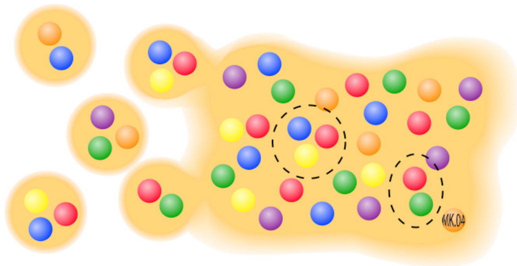
- QGP phase: hydro with QGP EoS
- hadronic freeze-out: after burner
- hadron-string transport model

→ Hybrid-UrQMD

- microscopic transport description of the partonic and hadronic phase in terms of strongly interacting dynamical quasi-particles and off-shell hadrons

→ PHSD

From hadrons to partons



In order to study the phase transition from hadronic to partonic matter – Quark-Gluon-Plasma – we need a consistent non-equilibrium (transport) model with

- explicit parton-parton interactions (i.e. between quarks and gluons) beyond strings!
- explicit phase transition from hadronic to partonic degrees of freedom
- lQCD EoS for partonic phase

Transport theory: off-shell Kadanoff-Baym equations for the Green-functions $S^{<}_{h}(x,p)$ in phase-space representation for the partonic and hadronic phase

⇒ **Parton-Hadron-String-Dynamics (PHSD)**

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

QGP phase described by

Dynamical QuasiParticle Model (DQPM)

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

The Dynamical QuasiParticle Model (DQPM)

Basic idea: **Interacting quasi-particles**

- **massive quarks and gluons** (g, q, q_{bar}) **with spectral functions :**

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

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

- **gluons:**

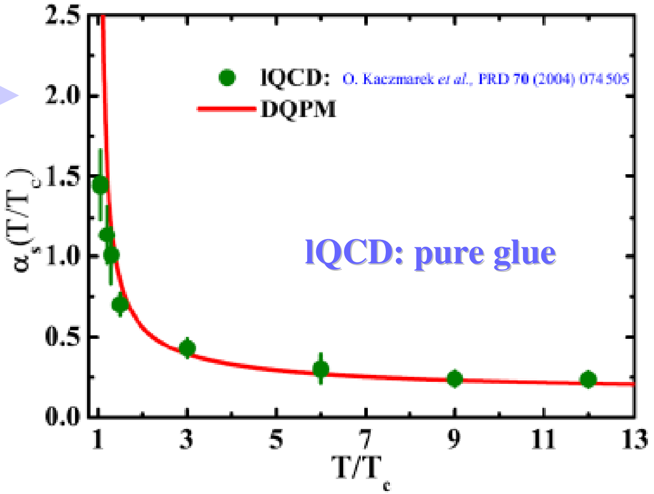
$$M_g^2(T) = \frac{g^2}{6}\left(\left(N_c + \frac{N_f}{2}\right)T^2 + \frac{N_c}{2}\sum_q \frac{\mu_q^2}{\pi^2}\right)$$

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

$N_c = 3$, $N_f=3$

- **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)

➔ **quasiparticle properties** (mass, width)

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

DQPM thermodynamics (N_f=3) and lQCD

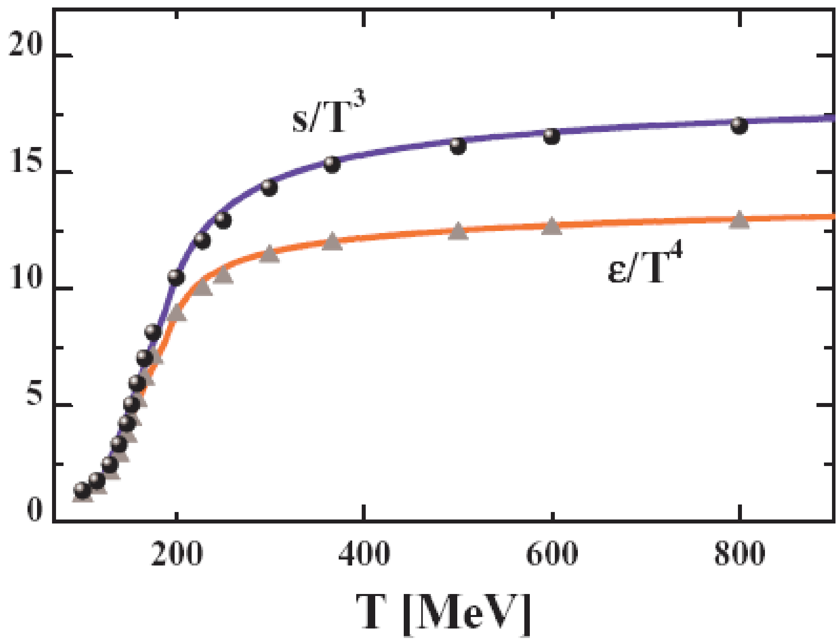
entropy $s = \frac{\partial P}{dT}$ → **pressure P**

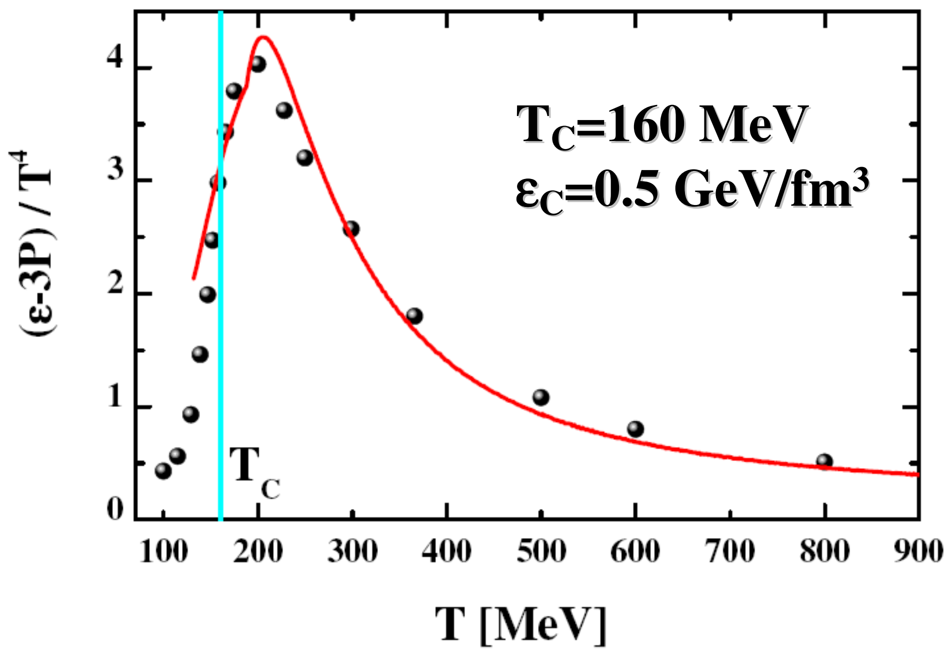
energy density: $\epsilon = Ts - P$

interaction measure:

$$W(T) := \epsilon(T) - 3P(T) = Ts - 4P$$

lQCD: Wuppertal-Budapest group
Y. Aoki et al., JHEP 0906 (2009) 088.



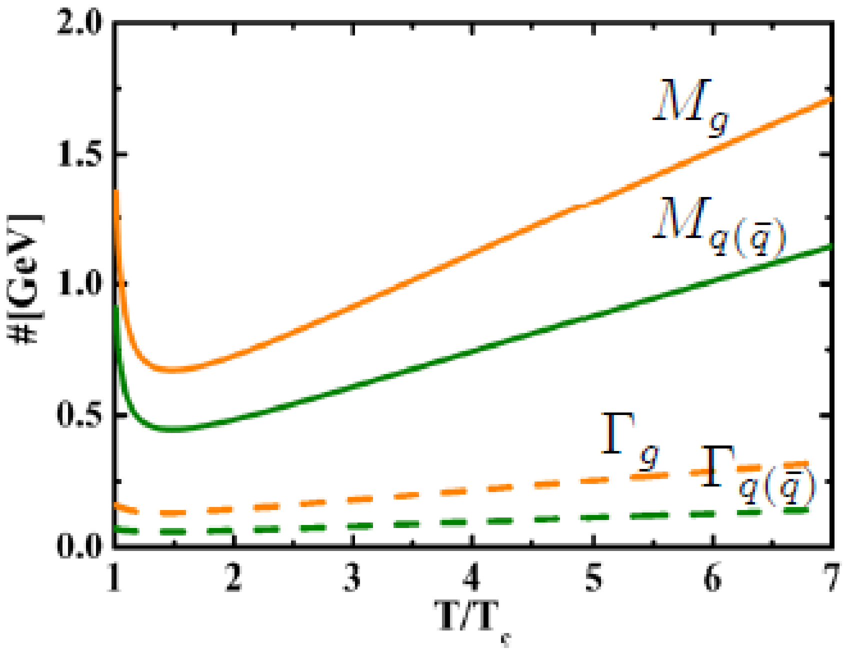


DQPM gives a good description of lQCD results !

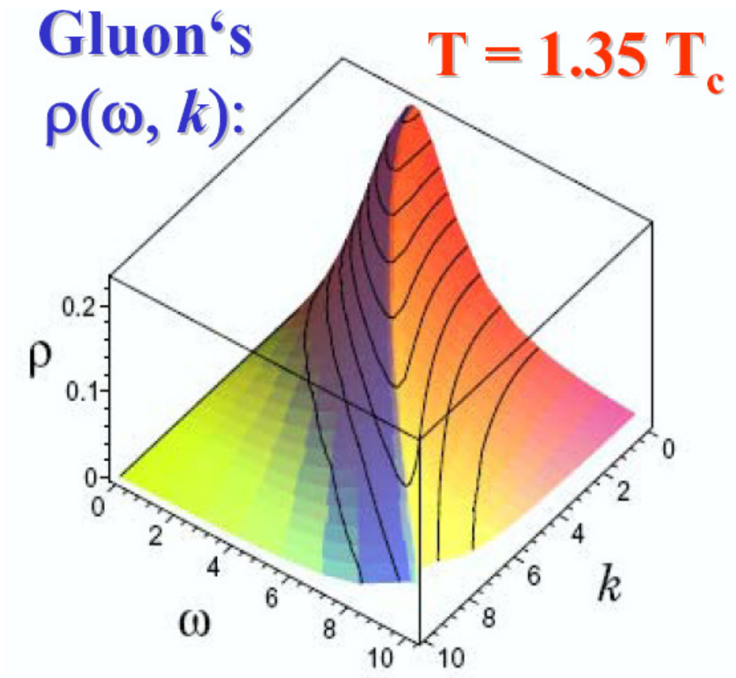
The Dynamical QuasiParticle Model (DQPM)

➔ Quasiparticle properties:

- large width and mass for gluons and quarks



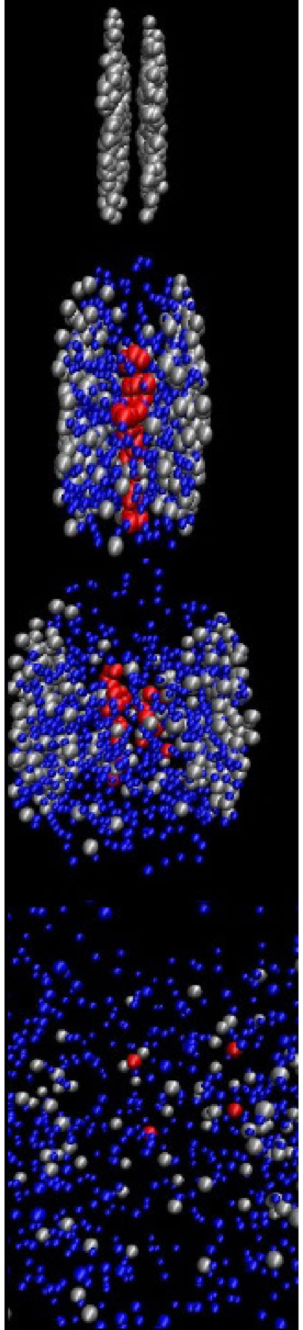
➔ Broad spectral function :



- **DQPM** matches well lattice QCD
- **DQPM** provides mean-fields (1PI) for gluons and quarks
  as well as effective 2-body interactions (2PI)
- **DQPM** gives transition rates for the formation of hadrons → PHSD

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

PHSD - basic concept



Initial A+A collisions – HSD: string formation and decay to pre-hadrons

Fragmentation of pre-hadrons into quarks: using the quark spectral functions from the Dynamical QuasiParticle Model (DQPM) - approximation to QCD

Partonic phase: quarks and gluons (= ‚dynamical quasiparticles‘) with off-shell spectral functions (width, mass) defined by the DQPM

QGP phase:
$\varepsilon > \varepsilon_{critical}$

- ❑ **elastic and inelastic parton-parton interactions:**
  using the effective cross sections from the DQPM
  - ✓ **q + qbar (flavor neutral) <=> gluon (colored)**
  - ✓ **gluon + gluon <=> gluon (possible due to large spectral width)**
  - ✓ **q + qbar (color neutral) <=> hadron resonances**
- ❑ **self-generated mean-field potential for quarks and gluons**

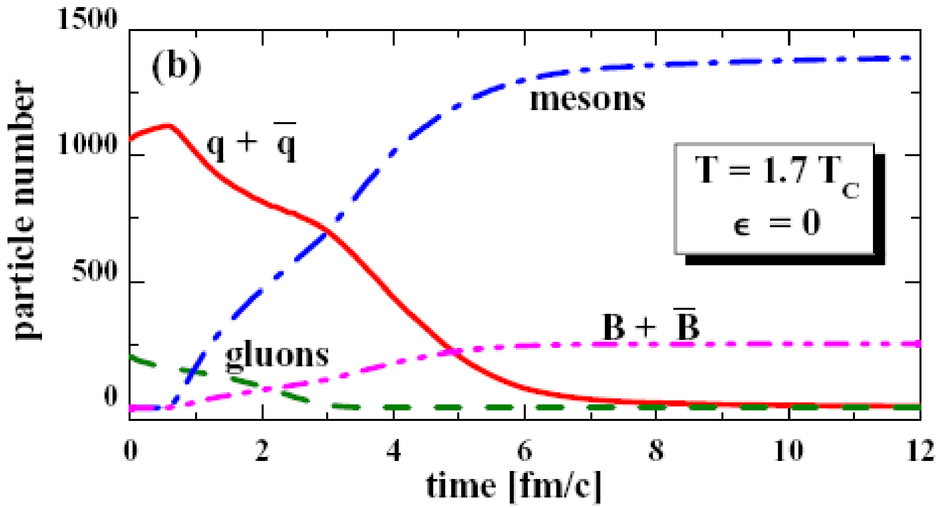
Hadronization: based on DQPM - massive, off-shell quarks and gluons with broad spectral functions hadronize to off-shell mesons and baryons:
gluons → q + qbar; q + qbar → meson (or string);
q + q +q → baryon (or string) (strings act as ‚doorway states‘ for hadrons)

Hadronic phase: hadron-string interactions – off-shell HSD

W. Cassing, E. Bratkovskaya, PRC 78 (2008) 034919;
NPA831 (2009) 215; EPJ ST 168 (2009) 3; NPA856 (2011) 162.

PHSD: hadronization of a partonic fireball

E.g. time evolution of the partonic fireball at initial temperature 1.7 T_c at $\mu_q=0$



Consequences:

➢ Hadronization: $q+q_{bar}$ or 3q or $3q_{bar}$ fuse to color neutral hadrons (or strings) which subsequently decay into hadrons in a microcanonical fashion, i.e. obeying all conservation laws (i.e. 4-momentum conservation, flavor current conservation) in each event!

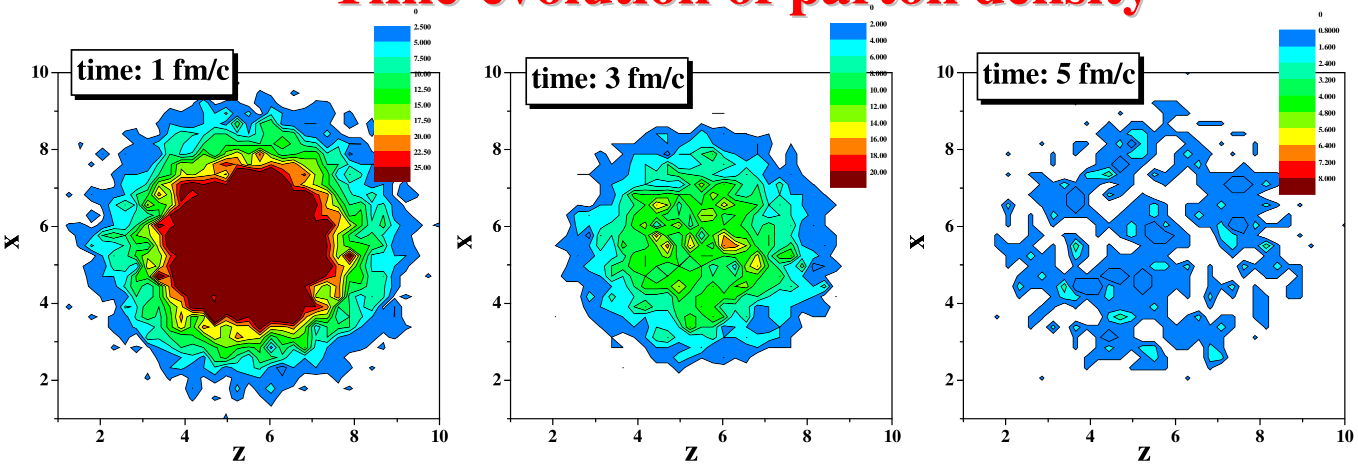
➢ Hadronization yields an increase in total entropy S (i.e. more hadrons in the final state than initial partons) and not a decrease as in the simple recombination models!

➢ Off-shell parton transport roughly leads a hydrodynamic evolution of the partonic system

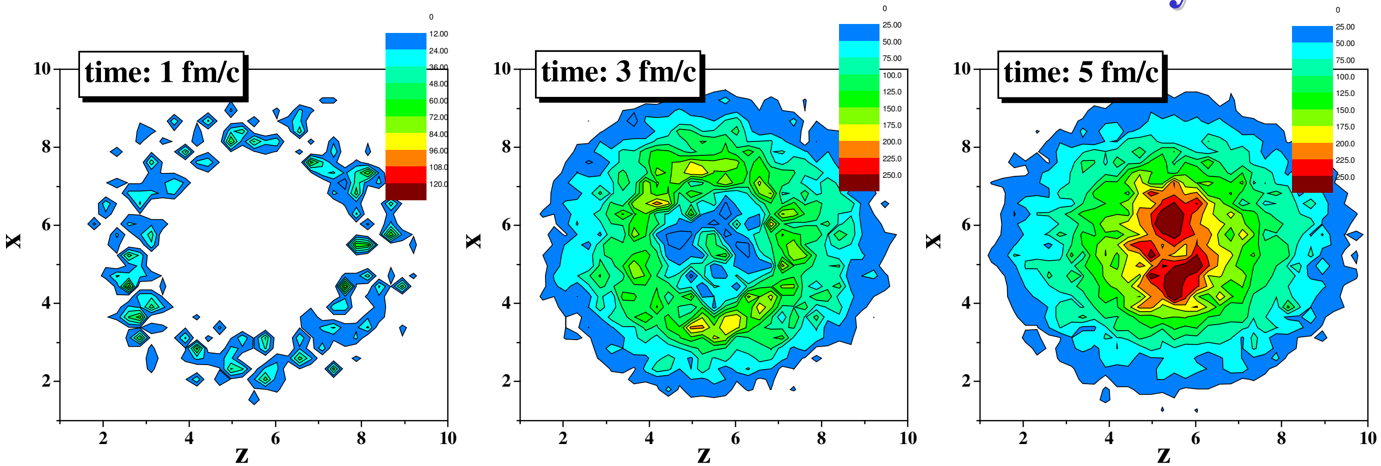
W. Cassing, E. Bratkovskaya, PRC 78 (2008) 034919;
NPA831 (2009) 215;
W. Cassing, EPJ ST 168 (2009) 3

PHSD: Expanding fireball

Time-evolution of parton density



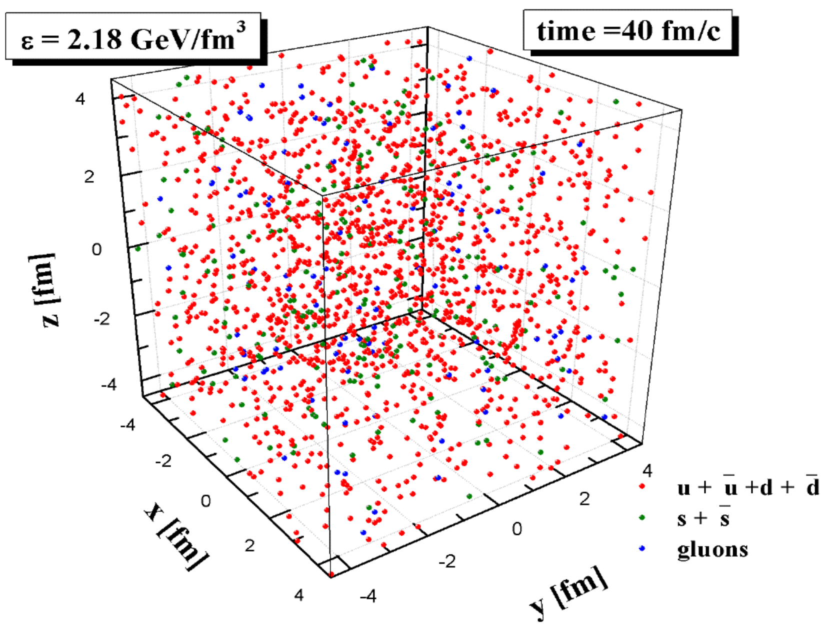
Time-evolution of hadron density



Expanding grid: $\Delta z(t) = \Delta z_0(1+a\ t)$!

PHSD: spacial phase ‚co-existence‘ of partons and hadrons, but NO interactions between hadrons and partons (since it is a cross-over)

Properties of QGP in-equilibrium using PHSD



Properties of parton-hadron matter in-equlibrium

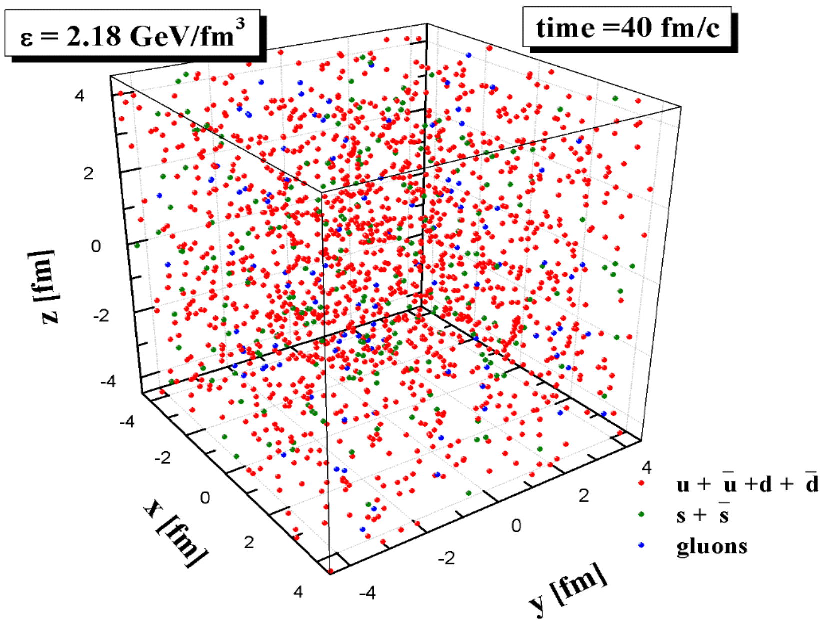
V. Ozvenchuk et al., PRC 87 (2013) 024901, arXiv:1203.4734
V. Ozvenchuk et al., arXiv:1212.5393

The goal:

- study of the dynamical equilibration of QGP within the non-equilibrium off-shell PHSD transport approach
- transport coefficients (shear and bulk viscosities) of strongly interacting partonic matter
- particle number fluctuations (scaled variance, skewness, kurtosis)

Realization:

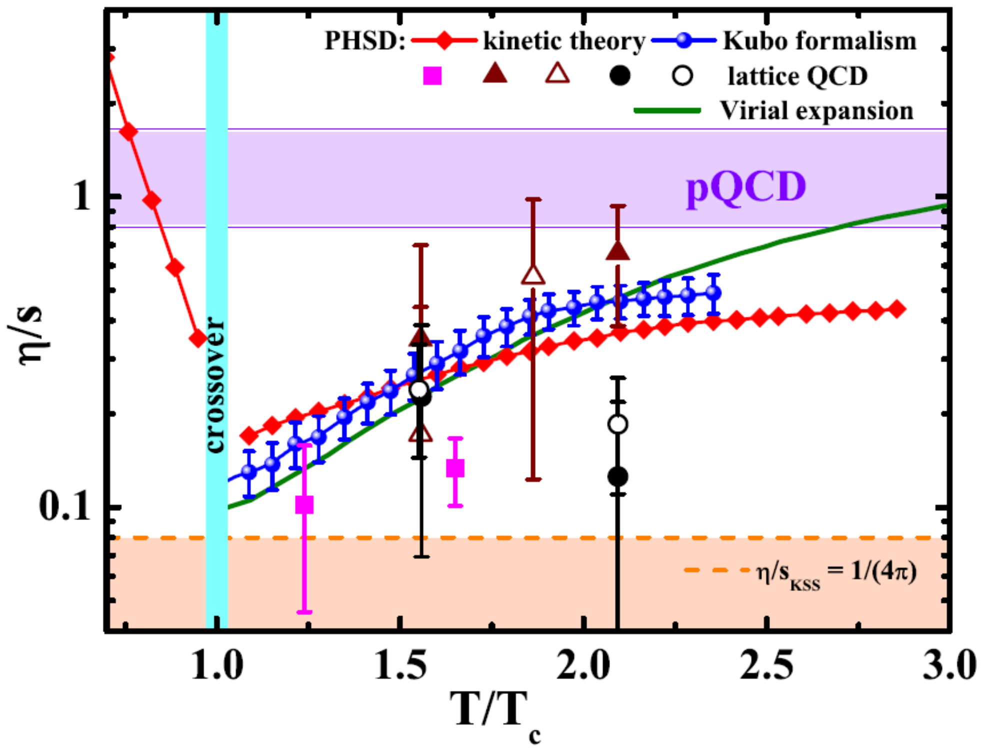
- Initialize the system in a finite box with periodic boundary conditions with some energy density ε and chemical potential μ_q
- Evolve the system in time until equilibrium is achieved



Properties of parton-hadron matter – shear viscosity

η/s using **Kubo formalism** and the **relaxation time approximation** (‚kinetic theory')

- **$T=T_C$:** η/s shows a minimum (~0.1) close to the critical temperature
- **$T>T_C$:** QGP - pQCD limit at higher temperatures
- **$T<T_C$:** fast increase of the ratio η/s for hadronic matter →
  - lower interaction rate of hadronic system
  - smaller number of degrees of freedom (or entropy density) for hadronic matter compared to the QGP



Virial expansion: S. Mattiello, W. Cassing, Eur. Phys. J. C 70, 243 (2010).

QGP in PHSD = strongly-interacting liquid

V. Ozvenchuk et al., arXiv:1212.5393

Properties of parton-hadron matter – electric conductivity

- The response of the strongly-interacting system in equilibrium to an external electric field eE_z defines the electric conductivity σ_0:

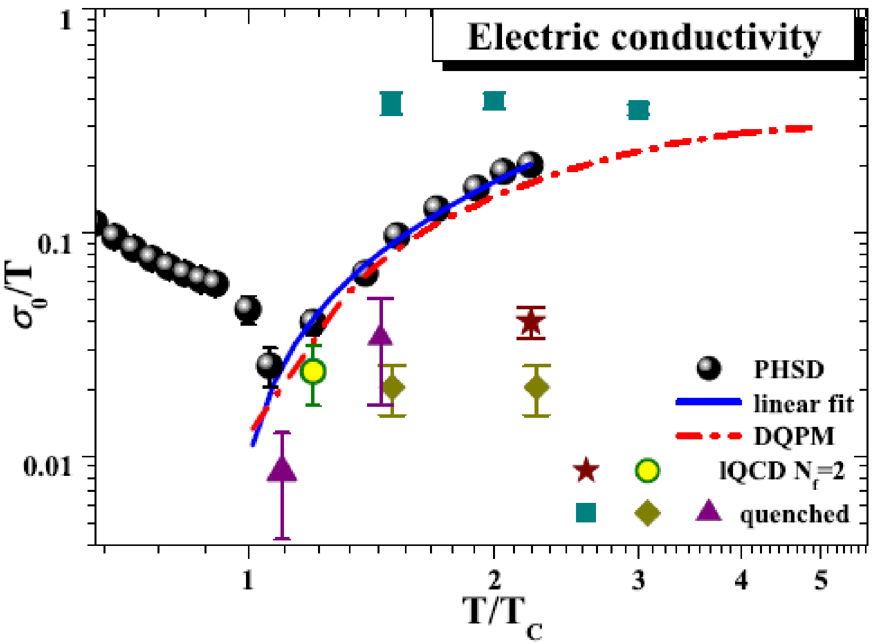
$$\frac{\sigma_0}{T} = \frac{j_{eq}}{E_z T}, \qquad j_z(t) = \frac{1}{V} \sum_j eq_j \frac{p_z^j(t)}{M_j(t)}$$

- additional force from external electric field eE_z:

$$\frac{d}{dt} p_z^j = q_j e E_z$$

- Note: pQCD result at leading order :

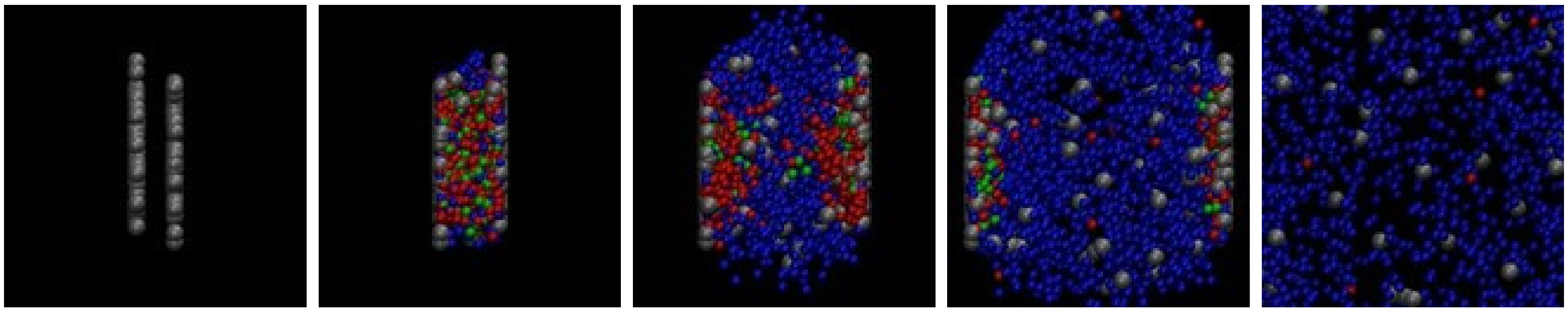
$$\sigma_0/T \approx 5.97/e^2 \approx 65$$



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

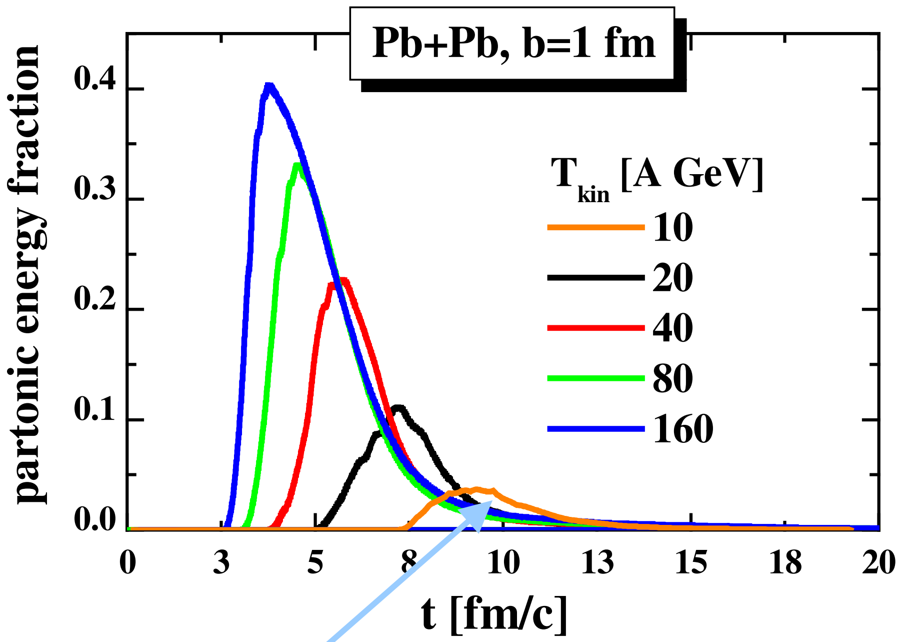
W. Cassing et al., PRL (2013), arXiv:1302.0906 [hep-ph]

Bulk properties:
rapidity, m_T-distributions,
multi-strange particle enhancement in Au+Au

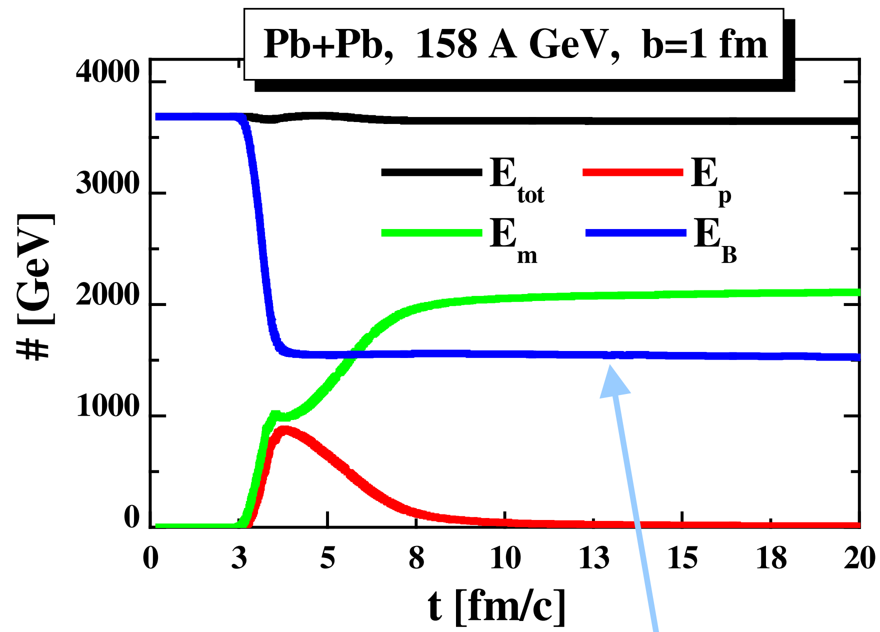


Application to nucleus-nucleus collisions

partonic energy fraction vs energy



energy balance



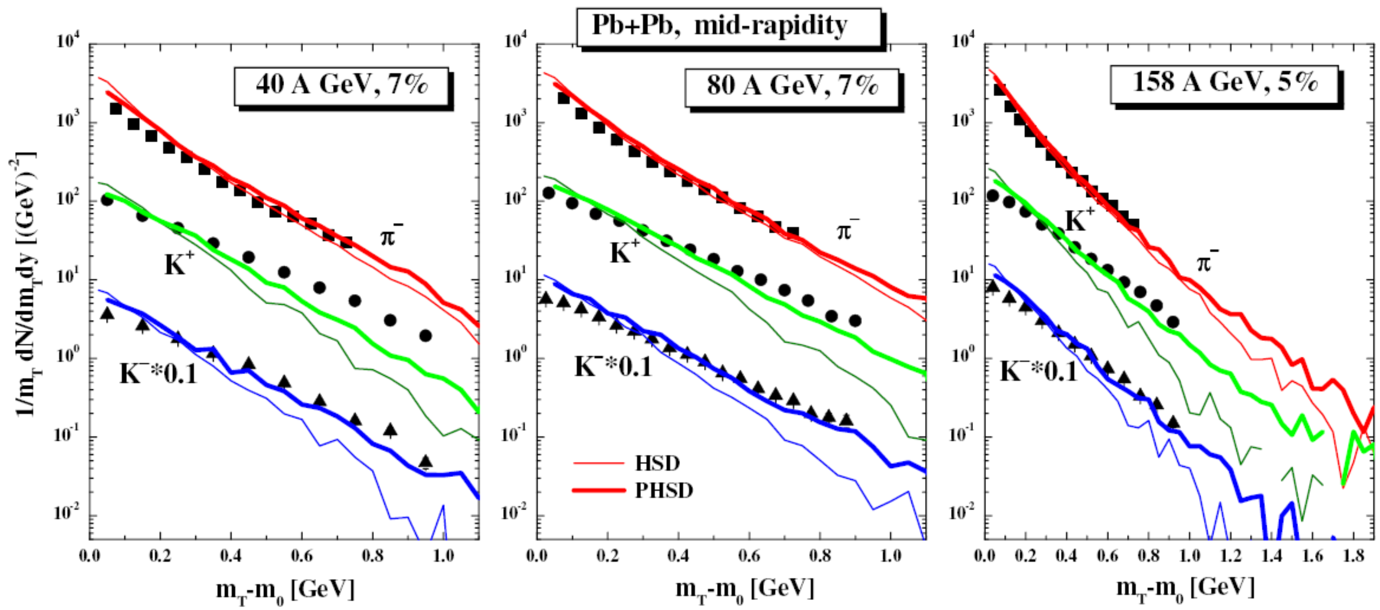
- Dramatic decrease of partonic phase with decreasing energy

- 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!
(hadronic corona effect, cf. talk by J. Aichelin)

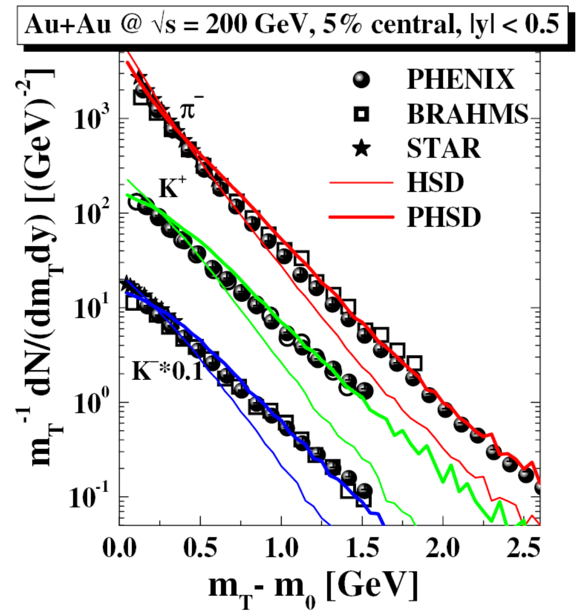
Cassing & Bratkovskaya, NPA 831 (2009) 215

PHSD: Transverse mass spectra

Central Pb + Pb at SPS energies



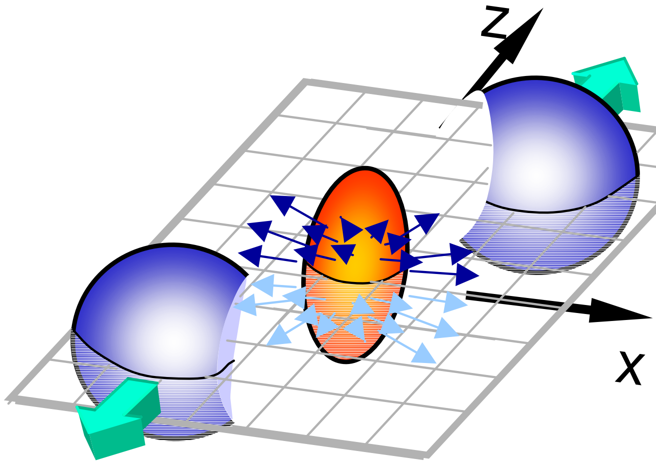
Central Au+Au at RHIC



- PHSD gives harder m_T spectra and works better than HSD 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

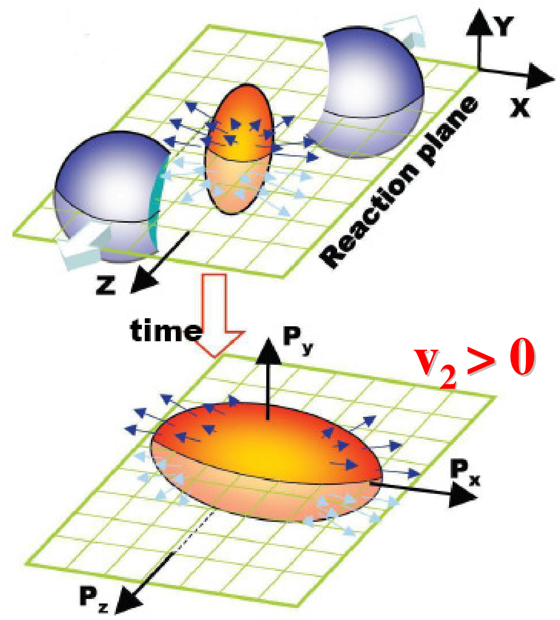
Collective flow: anisotropy coefficients (v_1, v_2, v_3, v_4) in A+A



Anisotropy coefficients

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**



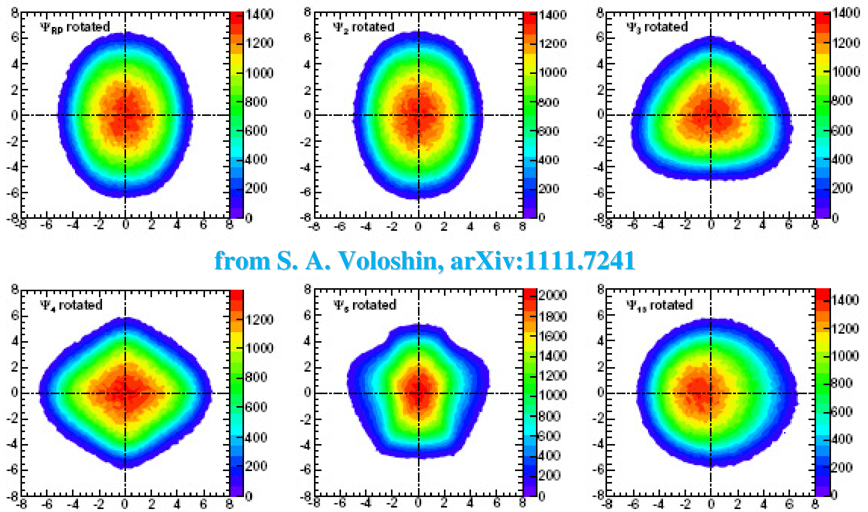
$$\frac{dN}{d\varphi} \propto \left(1 + 2\sum_{n=1}^{+\infty} v_n \cos\left[n(\varphi - \psi_n)\right]\right)$$

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

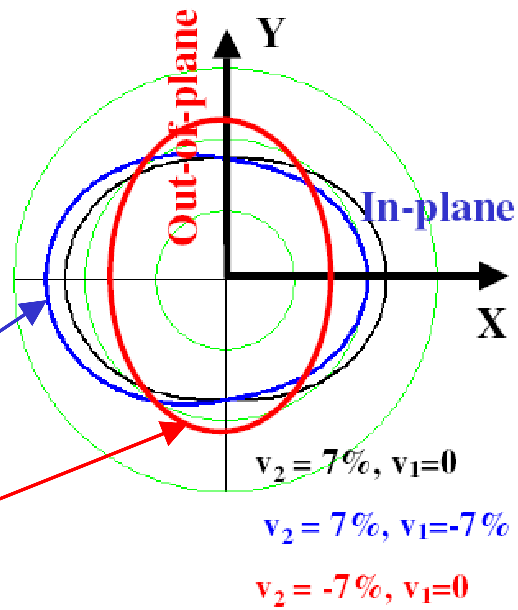
v_1: directed flow

v_2: elliptic flow

v_3: triangular flow…..



from S. A. Voloshin, arXiv:1111.7241

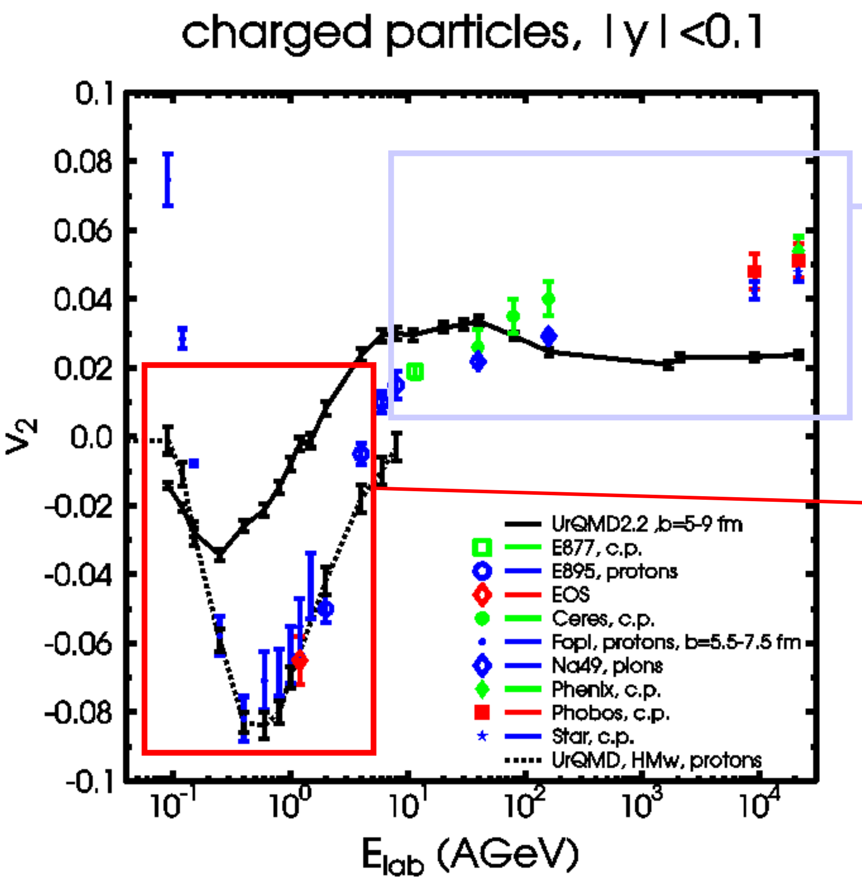


$v_2 > 0$ indicates in-plane emission of particles

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

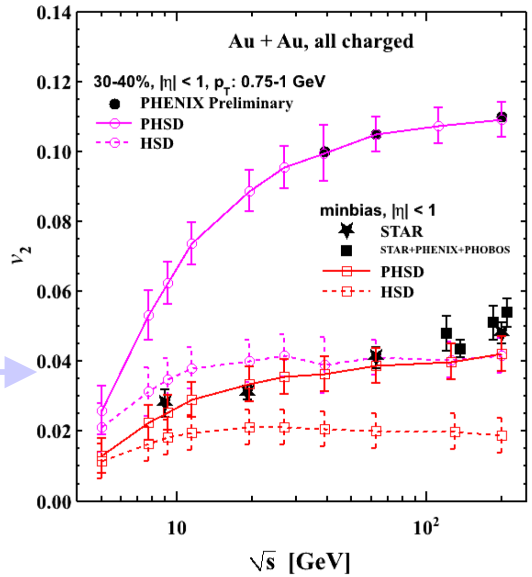
Collective flow: v_2 excitation functions

The excitation function for v_2 of charged particles from string-hadron transport models – UrQMD:

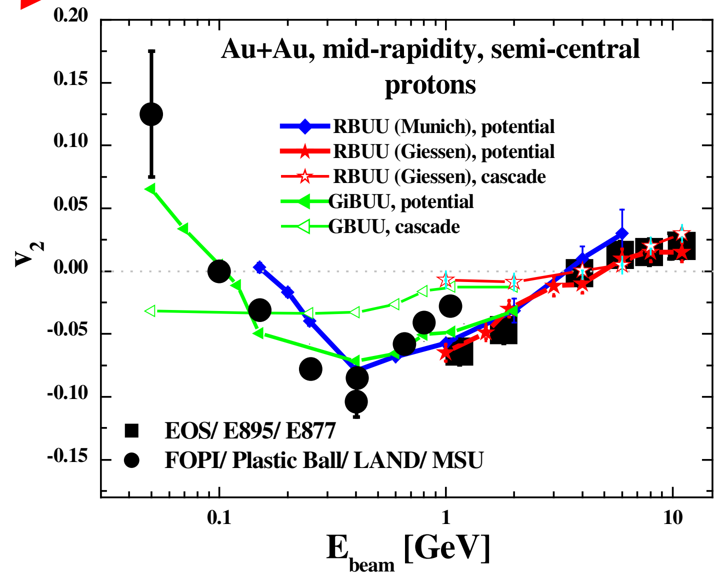


QGP

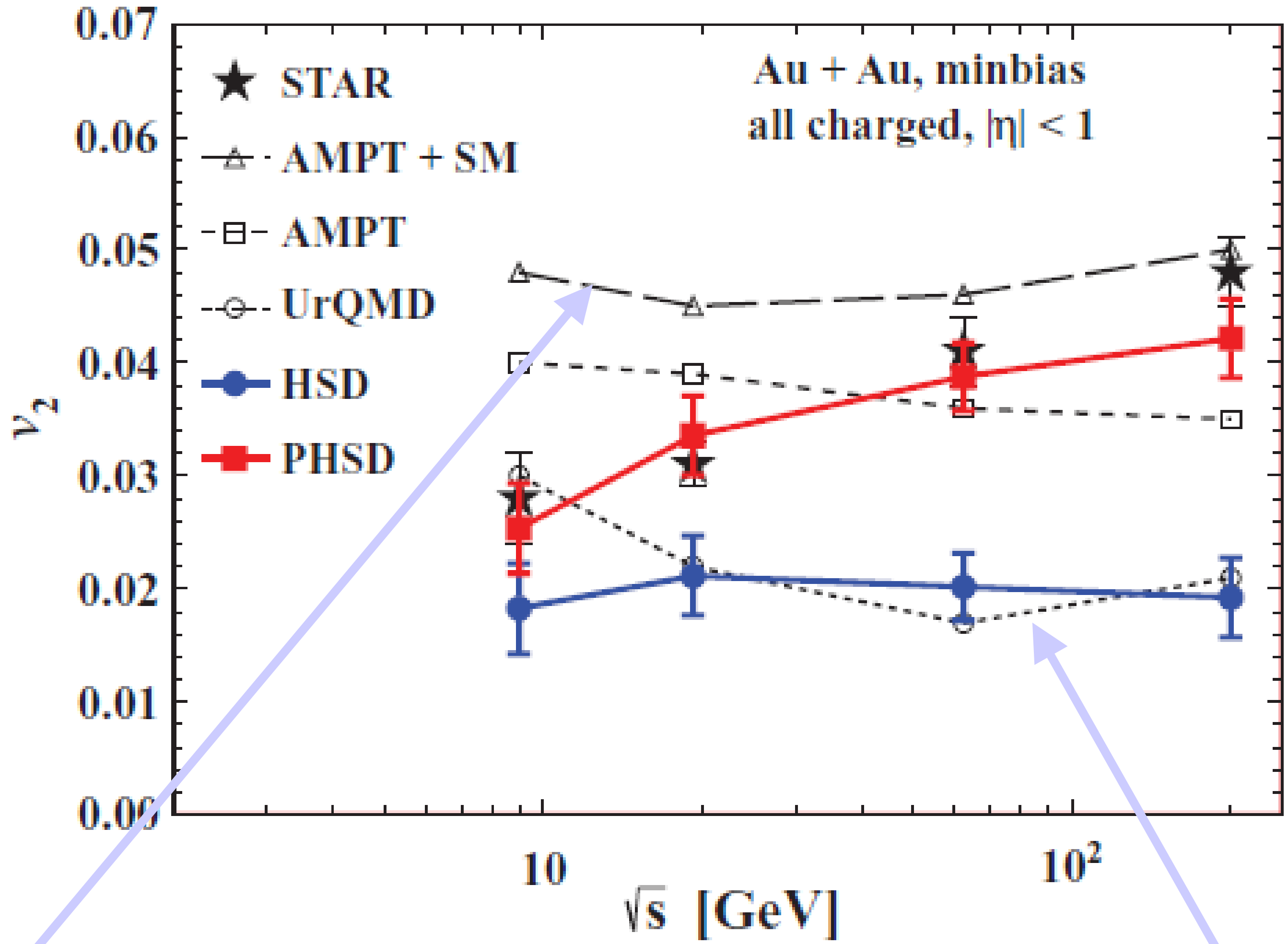
PHSD



Influence of hadron potentials ➔ EoS

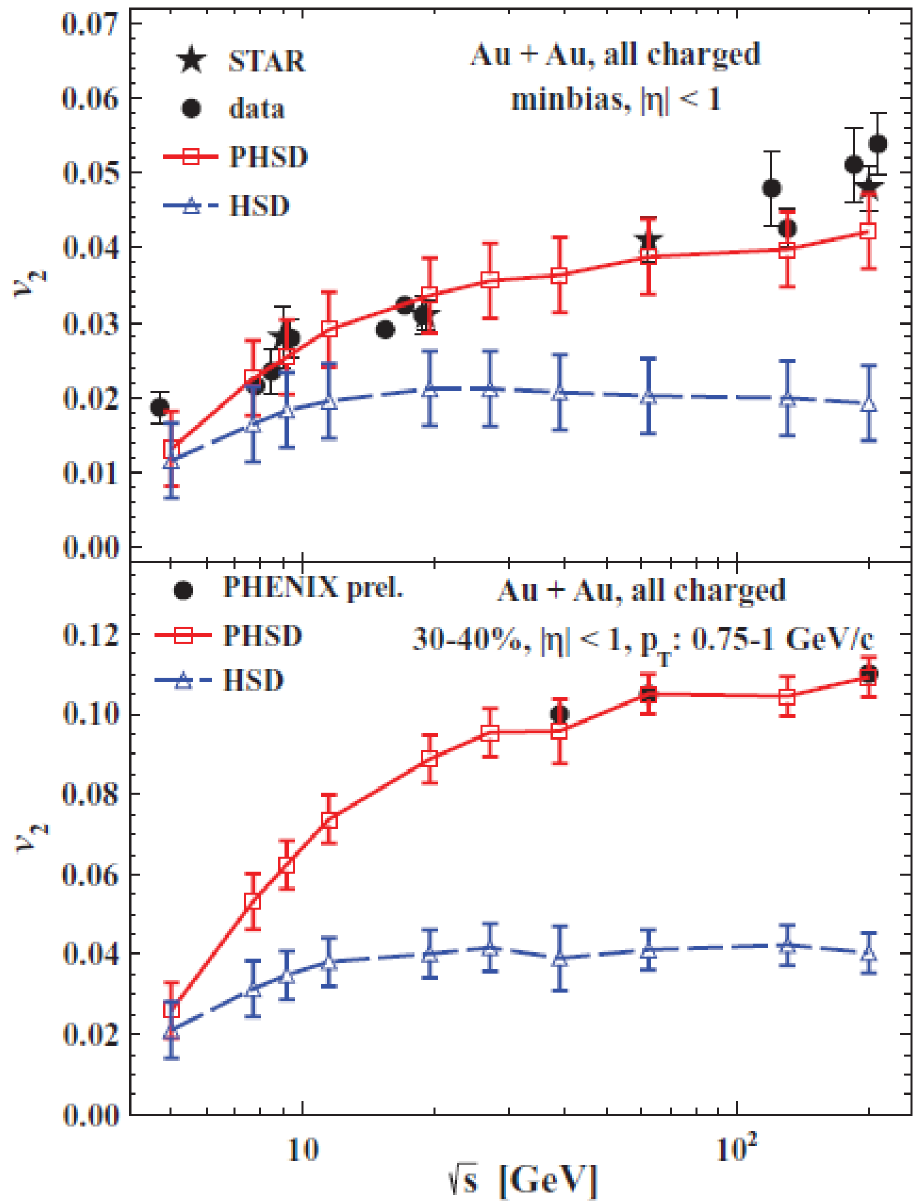


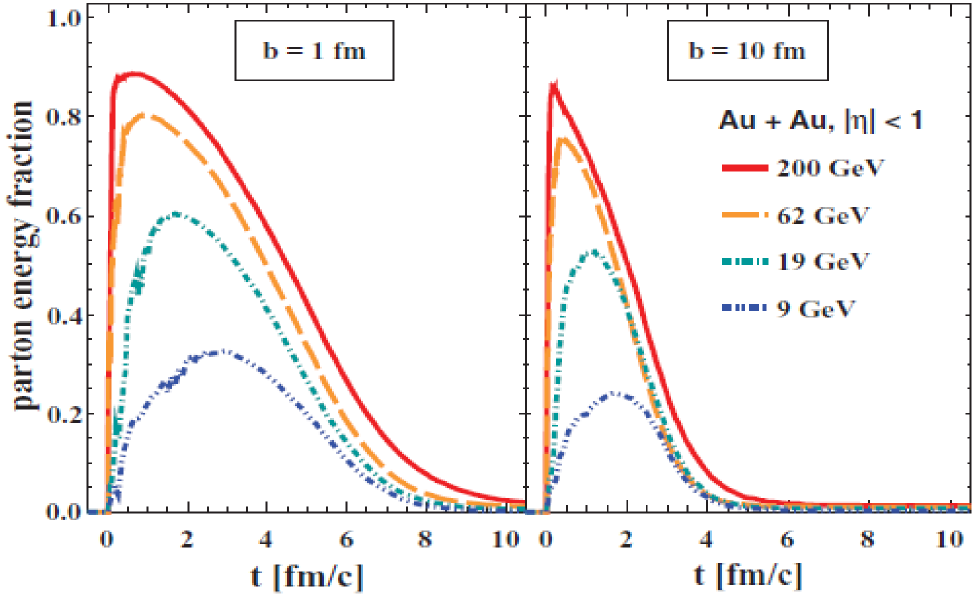
Excitation function of elliptic flow



Excitation function of elliptic flow is not described by hadron-string or purely partonic models (hadronic corona effect, cf. talk by J. Aichelin) !

Elliptic flow v_2 vs. collision energy for Au+Au



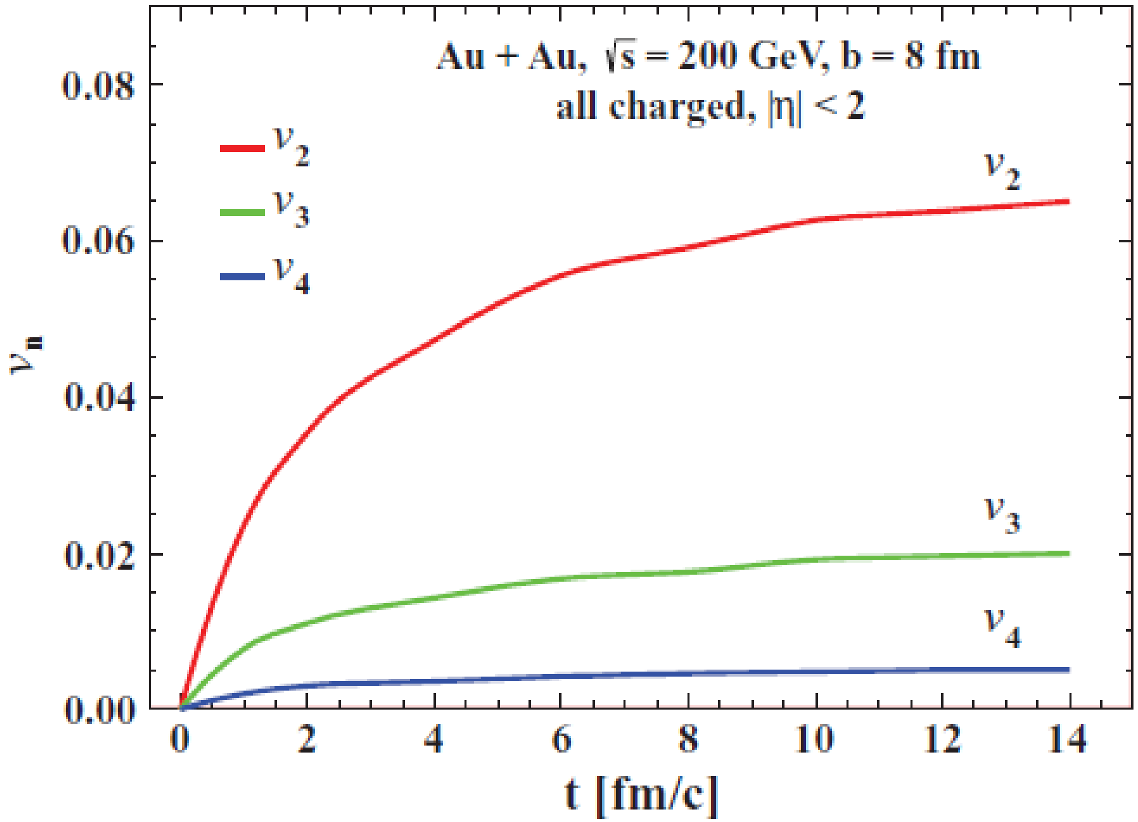


- v_2 in PHSD is larger than in HSD due to the repulsive scalar mean-field potential $U_s(\rho)$ for partons
- v_2 grows with bombarding energy due to the increase of the parton fraction

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

Development of azimuthal anisotropies in time

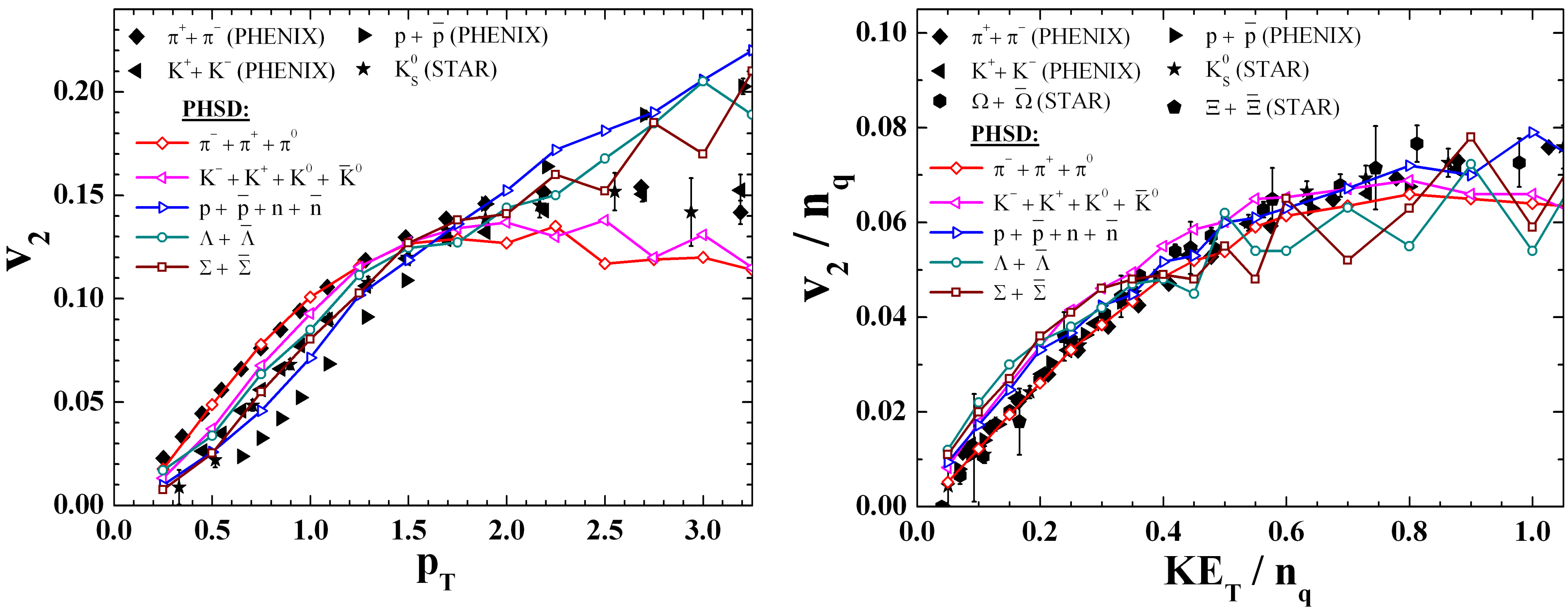
Time evolution of v_n for Au + Au collisions at $s^{1/2}$ = 200 GeV with impact parameter b = 8 fm.



- 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

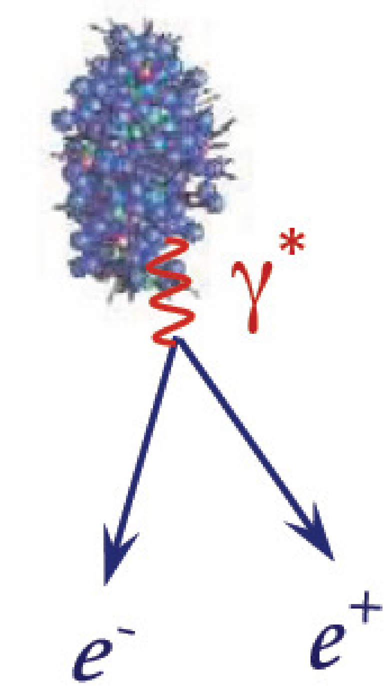
Scaling properties: quark number scaling

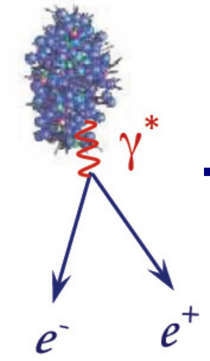


- The mass splitting at low p_T is approximately reproduced as well as the meson-baryon splitting for $p_T > 2$ GeV/c !
- The scaling of v_2 with the number of constituent quarks n_q is roughly in line with the data at RHIC.

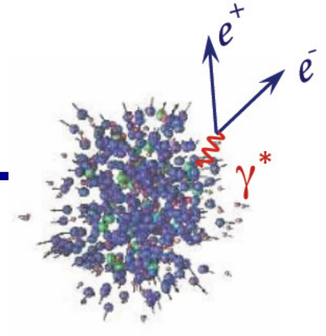
E. Bratkovskaya, W. Cassing, V. Konchakovski, O. Linnyk, NPA856 (2011) 162

Dileptons





Electromagnetic probes: dileptons and photons



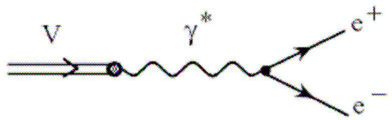
➢ **Dileptons are emitted from different stages of the reaction and not much effected by final-state interactions**

Dilepton sources:

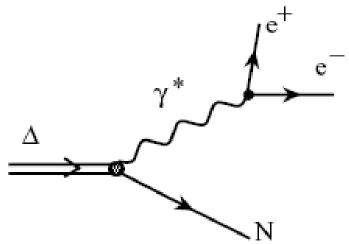
- **from the QGP via partonic (q,qbar, g) interactions:**

- **from hadronic sources:**

•**direct decay of vector mesons (ρ,ω,ϕ,J/Ψ,Ψ‘)**

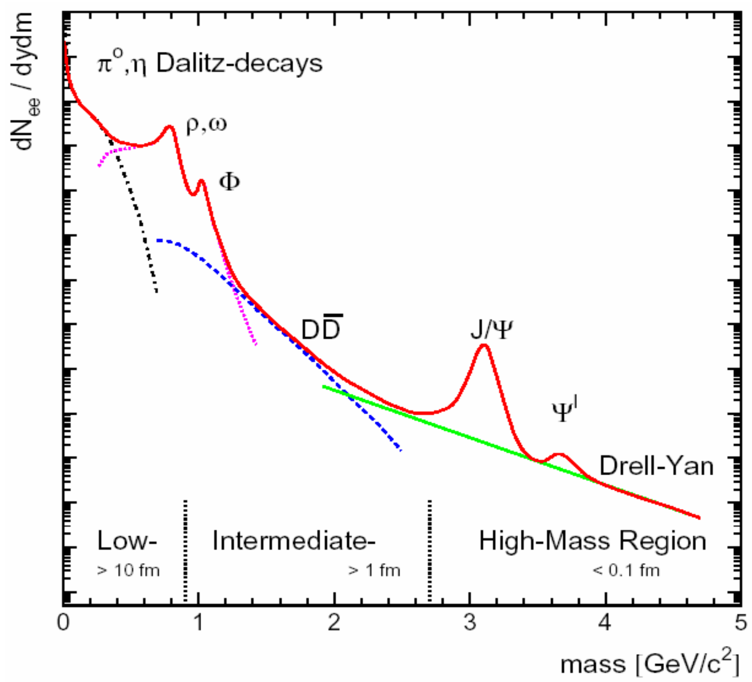


•**Dalitz decay of mesons and baryons (π^0,η, Δ,…)**



•**correlated D+Dbar pairs**

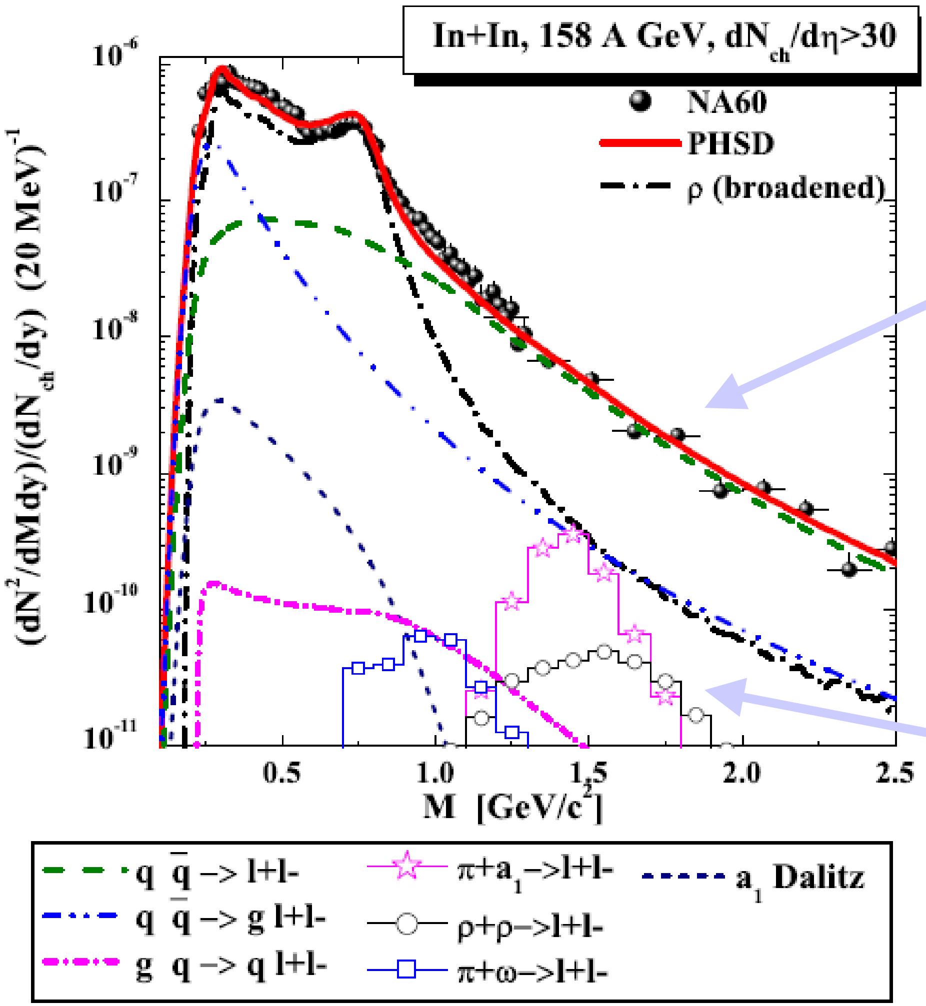
•**radiation from multi-meson reactions (π+π, π+ρ, π+ω, ρ+ρ , π+a_1) - ‚4π‘**



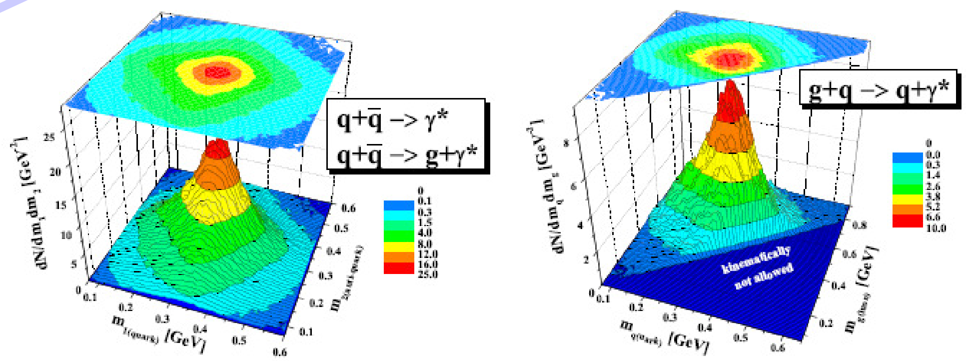
➔ **Dileptons are an ideal probe to study the properties of the hot and dense medium**

Dileptons at SPS: NA60

Acceptance corrected NA60 data



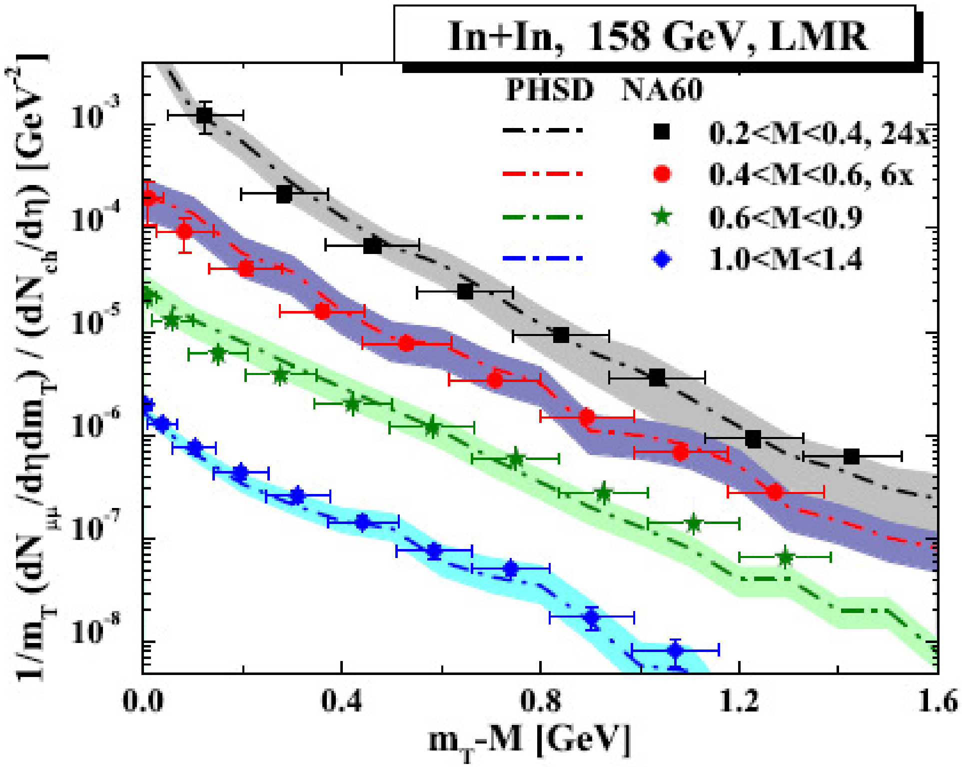
- Mass region above 1 GeV is dominated by partonic radiation !



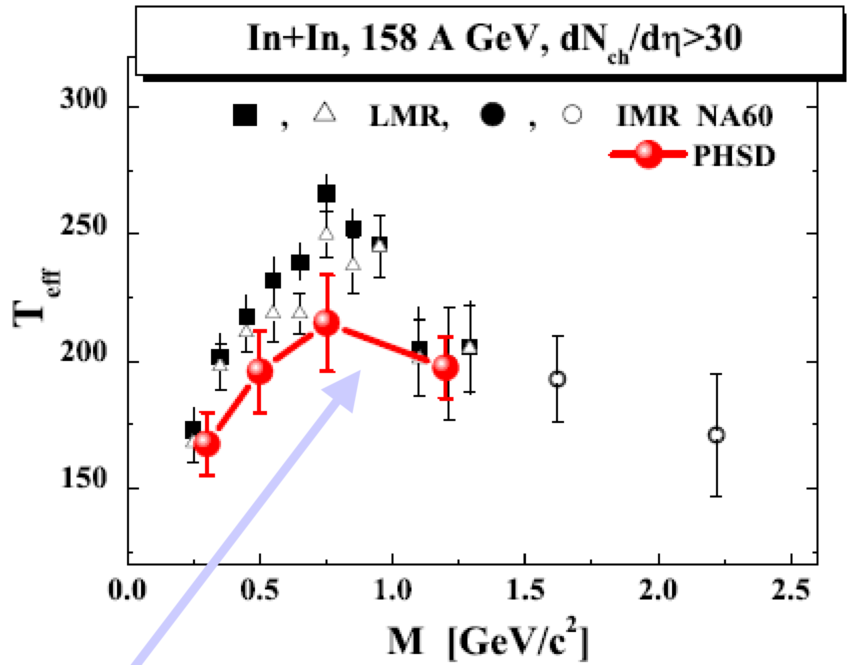
- Contributions of "4π" channels (radiation from multi-meson reactions) are small

O. Linnyk, E.B., V. Ozvenchuk, W. Cassing and C.-M. Ko, PRC 84 (2011) 054917

NA60: m_T spectra



- Inverse slope parameter T_{eff} for dilepton spectra vs NA60 data

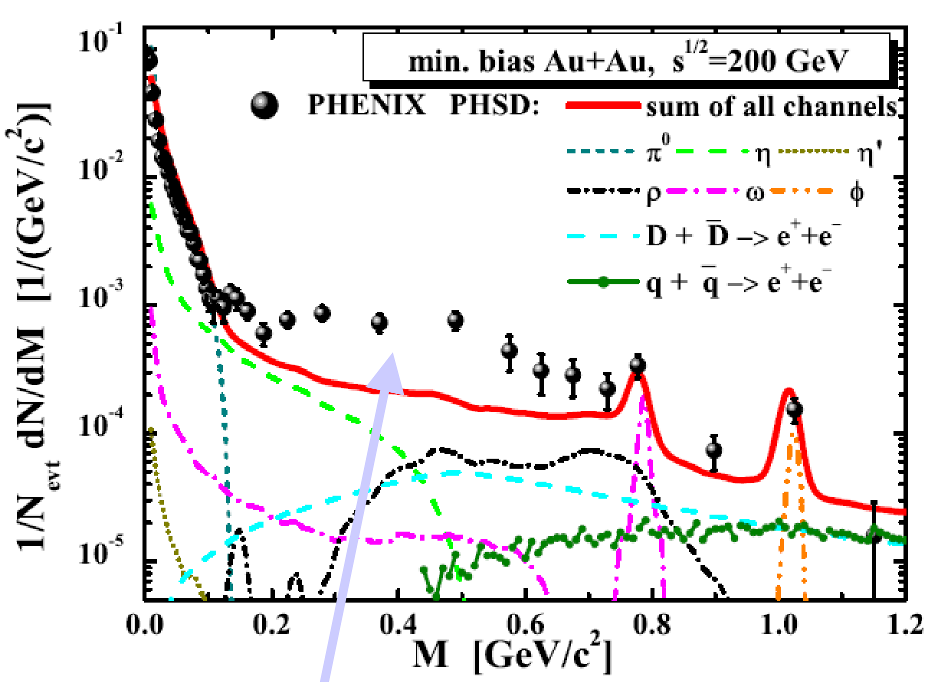


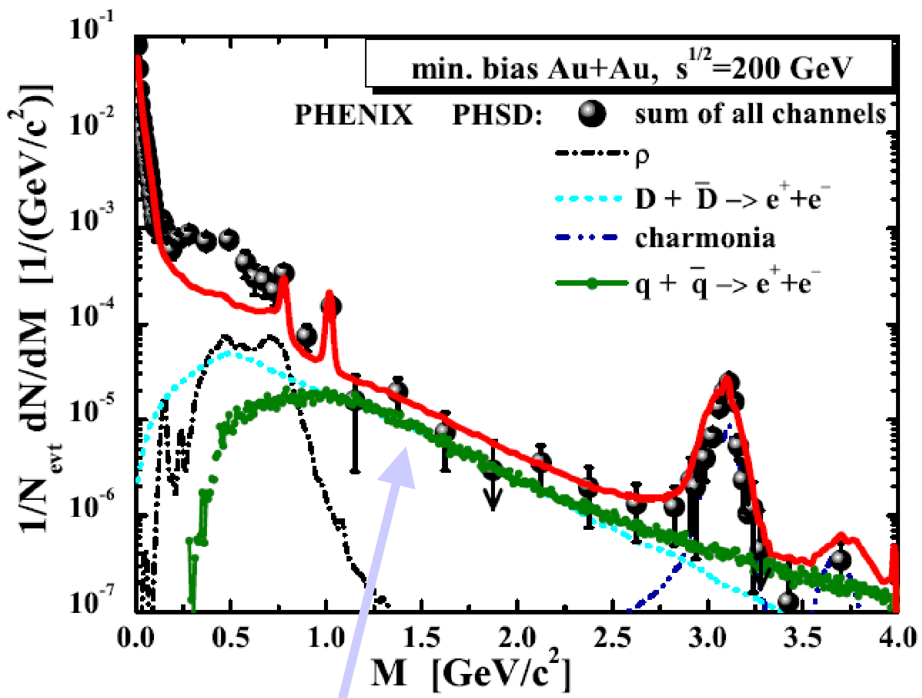
Conjecture:

- spectrum from sQGP is softer than from hadronic phase since quark-antiquark annihilation occurs dominantly before the collective radial flow has developed (cf. NA60)

O. Linnyk, E.B., V. Ozvenchuk, W. Cassing and C.-M. Ko, PRC 84 (2011) 054917

PHENIX: dileptons from partonic channels



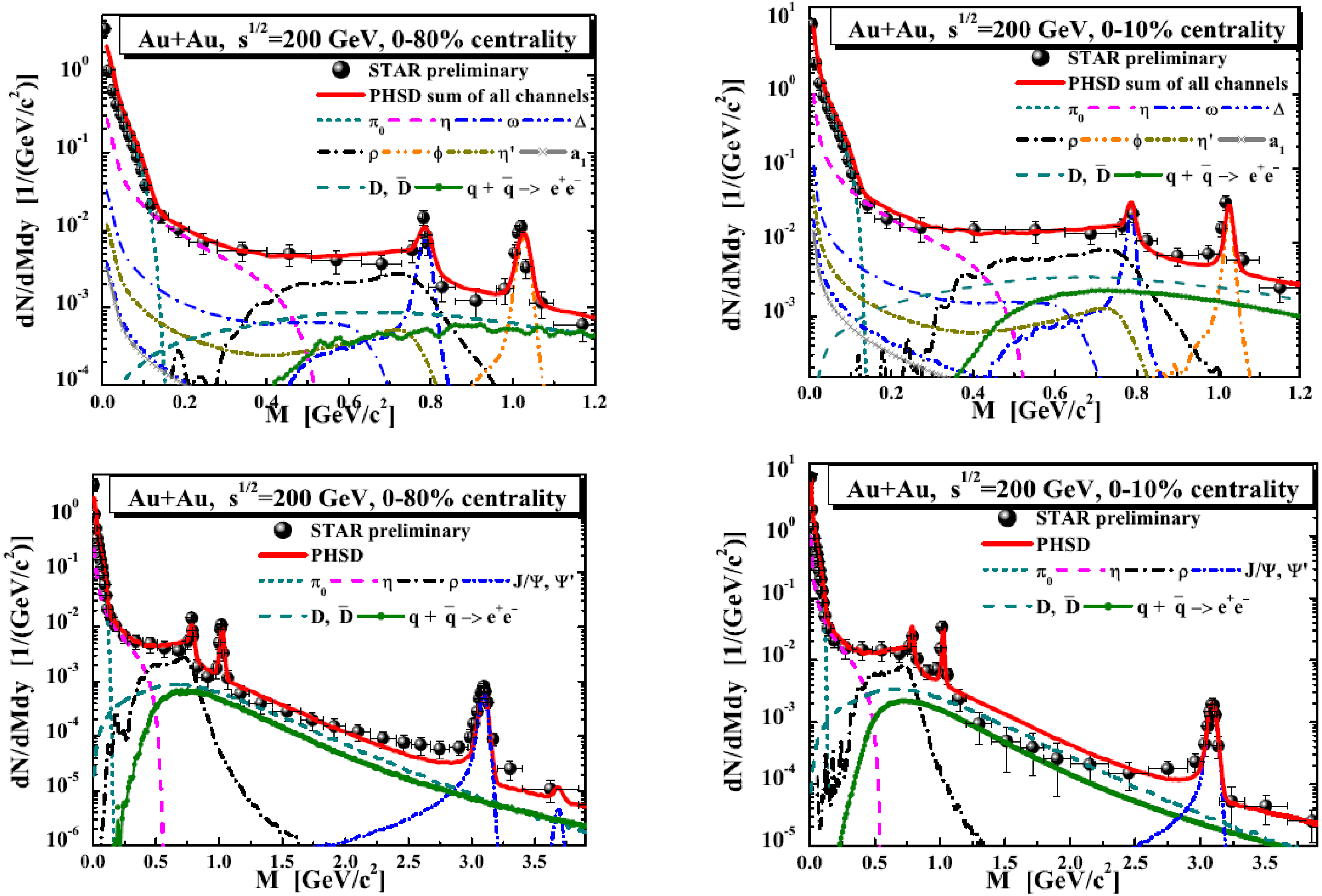


- The **excess** over the considered mesonic sources for M=0.15-0.6 GeV is not explained by the QGP radiation as incorporated presently in PHSD

- The **partonic channels** fill up the discrepancy between the hadronic contributions and the data for M>1 GeV

O. Linnyk, W. Cassing, J. Manninen, E.B. and C.-M. Ko, PRC 85 (2012) 024910

STAR: mass spectra



- **STAR data are well described!**

O. Linnyk, W. Cassing, J. Manninen, E.B. and C.-M. Ko, PRC 85 (2012) 024910

Summary

- PHSD provides a consistent description of off-shell parton dynamics in line with the lattice QCD equation of state (from the BMW collaboration)

- PHSD versus experimental observables:
  - enhancement of meson m_T slopes (at top SPS and RHIC)
  - strange antibaryon enhancement (at SPS)
  - partonic emission of high mass dileptons at SPS and RHIC
  - enhancement of collective flow v_2 with increasing energy
  - quark number scaling of v_2 (at RHIC)
  - jet suppression
  - …

$\Rightarrow$ evidence for strong nonhadronic interactions in the early phase of relativistic heavy-ion reactions

$\Rightarrow$ formation of the sQGP established!

PHSD group

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Thank you!