Parton-Hadron-String Dynamics

Overview and recent developments

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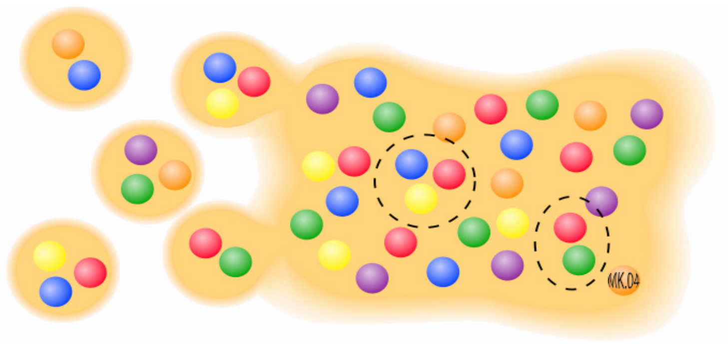
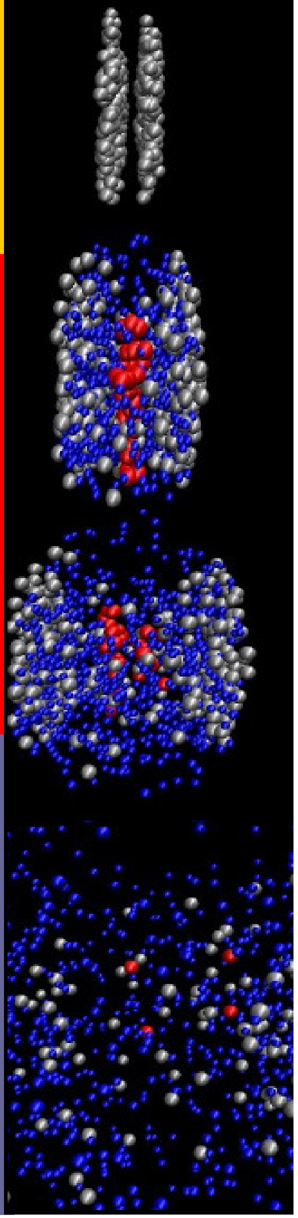
Transport description of the partonic and hadronic phases



Parton-Hadron-String-Dynamics (PHSD)

PHSD: heavy-ion collisions



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 Quasi-Particle Model (DQPM) – approximation to QCD

Partonic phase: quarks and gluons with constituent mass and broad spectral functions. Widths, masses defined by DQPM. Elastic and inelastic parton-parton interactions (effective cross sections adjusted to the DQPM in equilibrium):

- ✓ **q + qbar (flavor neutral) <=> gluon (colored)**
- ✓ **gluon + gluon <=> gluon (possible due to large spectral width)**
- ✓ **q + qbar (color neutral) <=> hadron resonances**

Hadronization: dynamical and off-shell transitions. Massive, off-shell quarks and gluons with broad spectral functions hadronize to off-shell hadrons:

- ✓ **gluons → q + qbar; q + qbar → off-shell meson or ‚string‘;**
- ✓ **q + q +q → baryon or ‚string‘; (‚strings‘ act as doorway states)**

Hadronic phase: hadron-string interactions and propagation by off-shell HSD

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

Parton-Hadron-String Dynamics

Main goal – description of heavy-ion collisions and properties of matter at high temperature and density as well as p+p and p(d)+A reactions at the same energy. Major features:

- ✓ **Unified description of collisions at all energies from AGS to LHC.**
- ✓ **Non-equilibrium approach: applicable to far from equilibrium configurations as explosion-like heavy-ion collisions as well as to equilibrated matter („in the box“).**
- ✓ **Dynamics: mean fields (hadronic and partonic), scattering (elastic, inelastic, 2<–>2, 2<–>n), resonance decays, retarded electro-magnetic fields.**
- ✓ **Phase transition (cross over) according to the lattice QCD equation of state, hadronic and partonic degrees of freedom, spacial co-existance, dynamical hadronisation.**
- ✓ **Off-shell transport: takes into account 2-particle correlations beyond the one-particle distributions.**

Boltzmann equation –> off-shell transport

$$\left(\frac{\partial}{\partial t} + \vec{v}_1 \cdot \nabla_{\vec{r}} + \frac{\vec{K}}{m} \cdot \nabla_{\vec{v}_1}\right) f_1 = \int d\Omega \int d\vec{v}_2\, \sigma(\Omega) |\vec{v}_1 - \vec{v}_2| \left(f_1' f_2' - f_1 f_2\right)$$

GENERALIZATION

(First order gradient expansion of the Wigner-transformed Kadanoff-Baym equations)

drift term **Vlasov term** **backflow term** **collision term = ‚loss' term - ‚gain' term**

$$\diamond\{P^2 - M_0^2 - Re\Sigma^{ret}_{XP}\}\{S^<_{XP}\} - \diamond\{\Sigma^<_{XP}\}\{ReS^{ret}_{XP}\} = \frac{i}{2}\left[\Sigma^>_{XP} S^<_{XP} - \Sigma^<_{XP} S^>_{XP}\right]$$

Backflow term incorporates the off-shell behavior in the particle propagation
! vanishes in the quasiparticle limit $A_{XP} = 2\pi\,\delta(p^2-M^2)$

Propagation of the Green's function $iS^<_{XP}=A_{XP}N_{XP}$, which carries information not only on the number of particles, but also on their properties, interactions and correlations

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

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

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

W. Cassing , S. Juchem, NPA 665 (2000) 377; 672 (2000) 417; 677 (2000) 4451

Off-shell equations of motion

Employ testparticle Ansatz for the real valued quantity $i\, S^{<}_{XP}$ -

$$F_{XP} = A_{XP} N_{XP} = i\, S^{<}_{XP} \sim \sum_{i=1}^{N} \delta^{(3)}(\vec{X} - \vec{X}_i(t))\ \delta^{(3)}(\vec{P} - \vec{P}_i(t))\ \delta(P_0 - \epsilon_i(t))$$

insert in generalized transport equations and determine equations of motion !

General testparticle off-shell equations of motion:

$$\frac{d\vec{X}_i}{dt} = \frac{1}{1 - C_{(i)}} \frac{1}{2\epsilon_i} \left[2\,\vec{P}_i + \vec{\nabla}_{P_i} Re\Sigma^{ret}_{(i)} + \frac{\epsilon_i^2 - \vec{P}_i^2 - M_0^2 - Re\Sigma^{ret}_{(i)}}{\Gamma_{(i)}} \vec{\nabla}_{P_i} \Gamma_{(i)} \right],$$

$$\frac{d\vec{P}_i}{dt} = -\frac{1}{1 - C_{(i)}} \frac{1}{2\epsilon_i} \left[\vec{\nabla}_{X_i} Re\Sigma^{ret}_i + \frac{\epsilon_i^2 - \vec{P}_i^2 - M_0^2 - Re\Sigma^{ret}_{(i)}}{\Gamma_{(i)}} \vec{\nabla}_{X_i} \Gamma_{(i)} \right],$$

$$\frac{d\epsilon_i}{dt} = \frac{1}{1 - C_{(i)}} \frac{1}{2\epsilon_i} \left[\frac{\partial Re\Sigma^{ret}_{(i)}}{\partial t} + \frac{\epsilon_i^2 - \vec{P}_i^2 - M_0^2 - Re\Sigma^{ret}_{(i)}}{\Gamma_{(i)}} \frac{\partial \Gamma_{(i)}}{\partial t} \right],$$

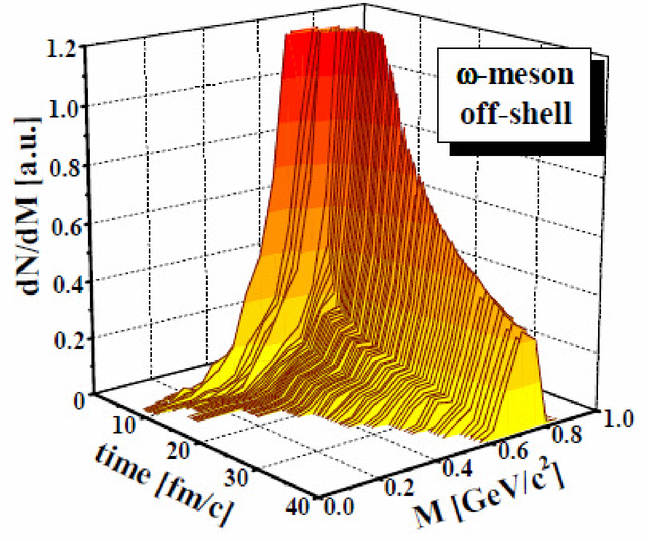
with $F_{(i)} \equiv F(t, \vec{X}_i(t), \vec{P}_i(t), \epsilon_i(t))$

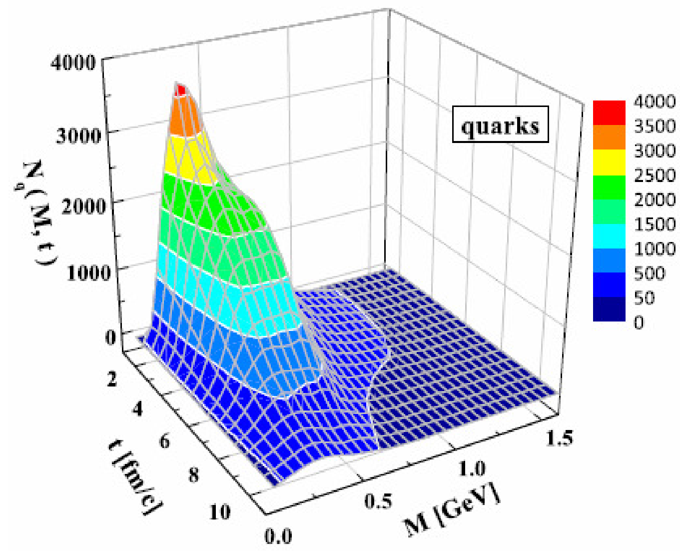
$$C_{(i)} = \frac{1}{2\epsilon_i} \left[\frac{\partial}{\partial \epsilon_i} Re\Sigma^{ret}_{(i)} + \frac{\epsilon_i^2 - \vec{P}_i^2 - M_0^2 - Re\Sigma^{ret}_{(i)}}{\Gamma_{(i)}} \frac{\partial}{\partial \epsilon_i} \Gamma_{(i)} \right]$$

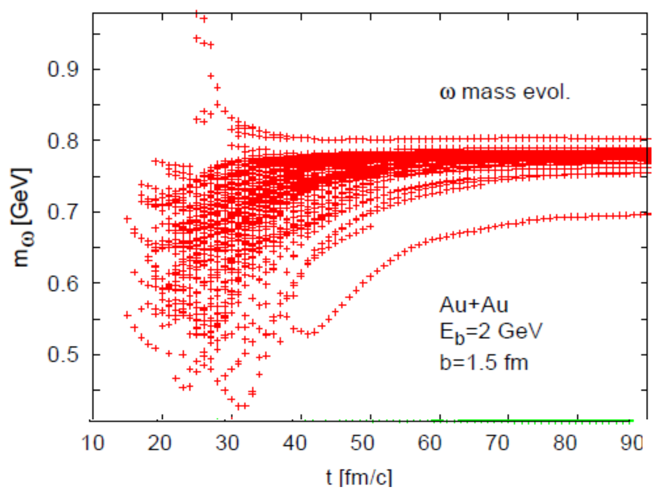
W. Cassing , S. Juchem, NPA 665 (2000) 377; 672 (2000) 417; 677 (2000) 445

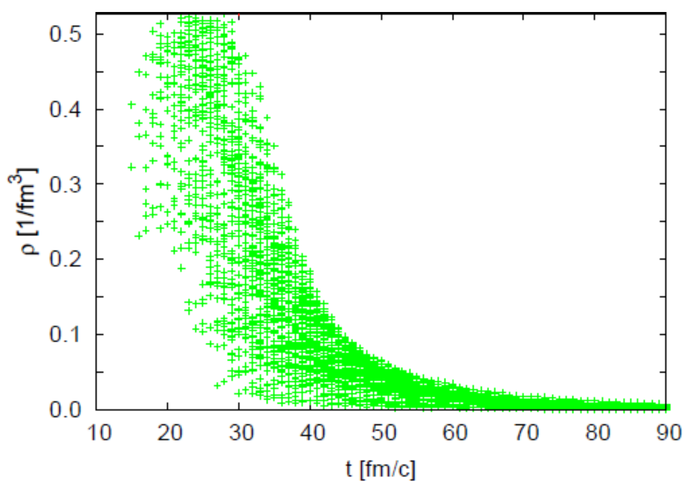
Results of off-shell transport simulations

The off-shell spectral function becomes on-shell in the vacuum dynamically!









E.L. Bratkovskaya, W. Cassing, V. P. Konchakovski, O. Linnyk, NPA856(2011) 162; E.L. Bratkovskaya, W. Cassing, NPA 807 (2008) 214; H.W. Barz, B. Kampfer, Gy. Wolf, M. Zetenyi, Open Nucl. Part. Phys. J. 3 (2010) 1

Dynamical Quasi-Particle Model (DQPM)

The Dynamical QuasiParticle Model (DQPM)

Basic idea: Interacting quasiparticles

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

$$\rho(\omega) = \frac{\gamma}{E}\left(\frac{1}{(\omega - E)^2 + \gamma^2} - \frac{1}{(\omega + E)^2 + \gamma^2}\right)$$

$E^2 = p^2+M^2-\gamma^2$

- **quarks**

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

width: $\gamma_q(T) = \frac{N_c^2 - 1}{2N_c} \frac{g^2 T}{4\pi} \ln\frac{c}{g^2}$

- **gluons:**

A. Peshier, PRD 70 (2004) 034016

$M^2(T) = \frac{g^2}{6}\left((N_c + \frac{1}{2}N_f)\, T^2 + \frac{N_c}{2}\sum_q \frac{\mu_q^2}{\pi^2}\right)$

$N_c = 3, N_f=3$

$\gamma_g(T) = N_c \frac{g^2 T}{4\pi} \ln\frac{c}{g^2}$

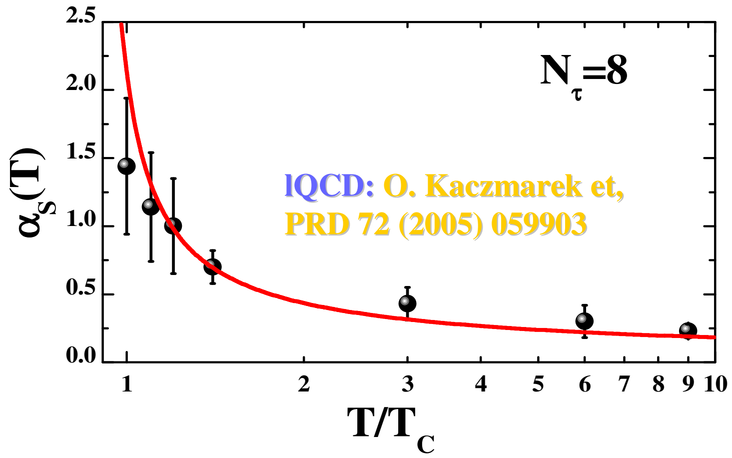
running coupling: $\alpha_S(T) = g^2(T)/(4\pi)$

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

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

with 3 parameters: T_s/T_c=0.46; c=28.8; λ=2.42

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



A. Peshier, PRD 70(2004)034016; A. Peshier, W. Cassing, PRL 94(2005)172301; Cassing, NPA 791(2007)365, NPA(2007)793

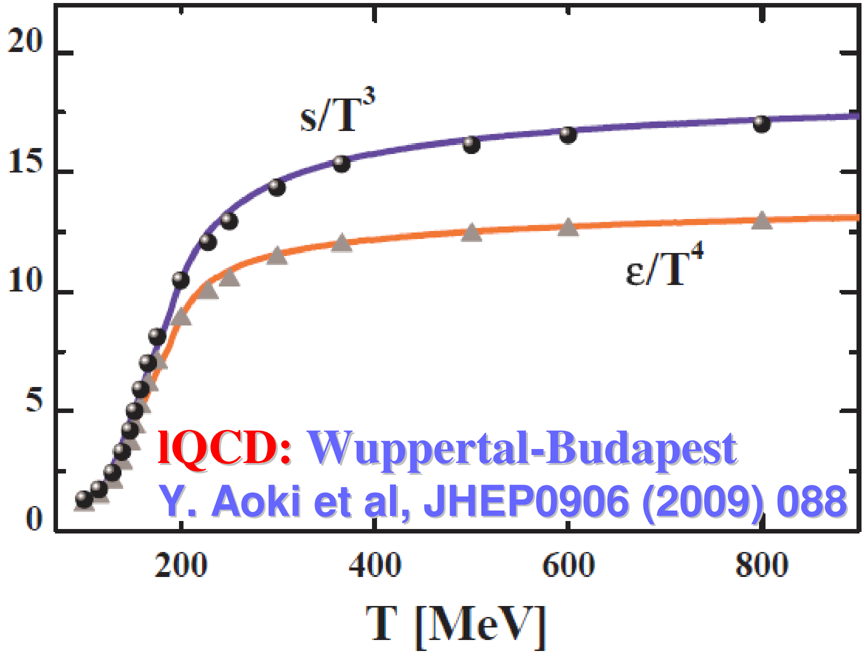
DQPM thermodynamics (N_f=3) and lQCD

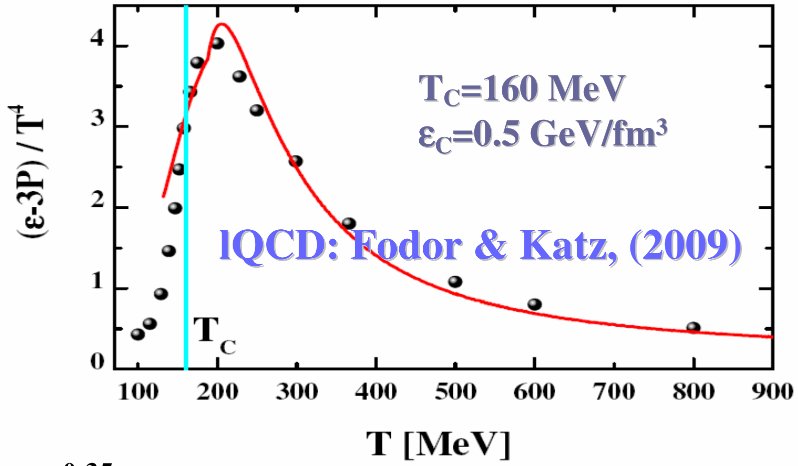
entropy $s = \frac{\partial P}{dT}$ → **pressure P**

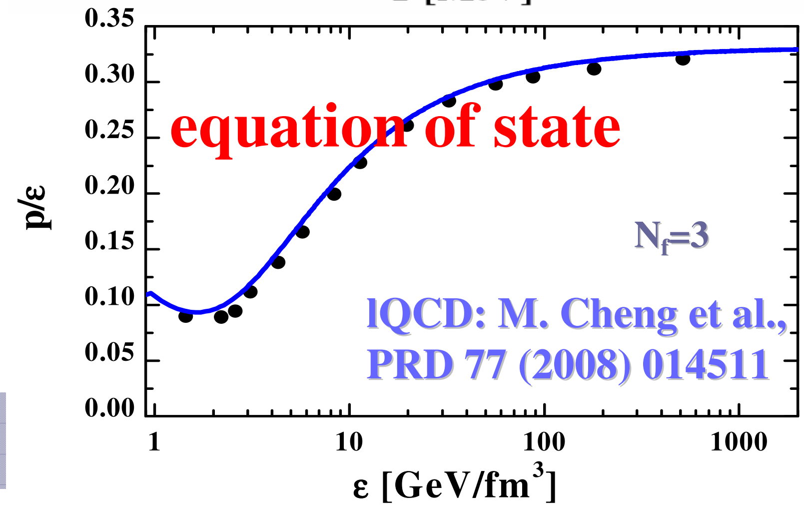
energy density: $\epsilon = Ts - P$

interaction measure:

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







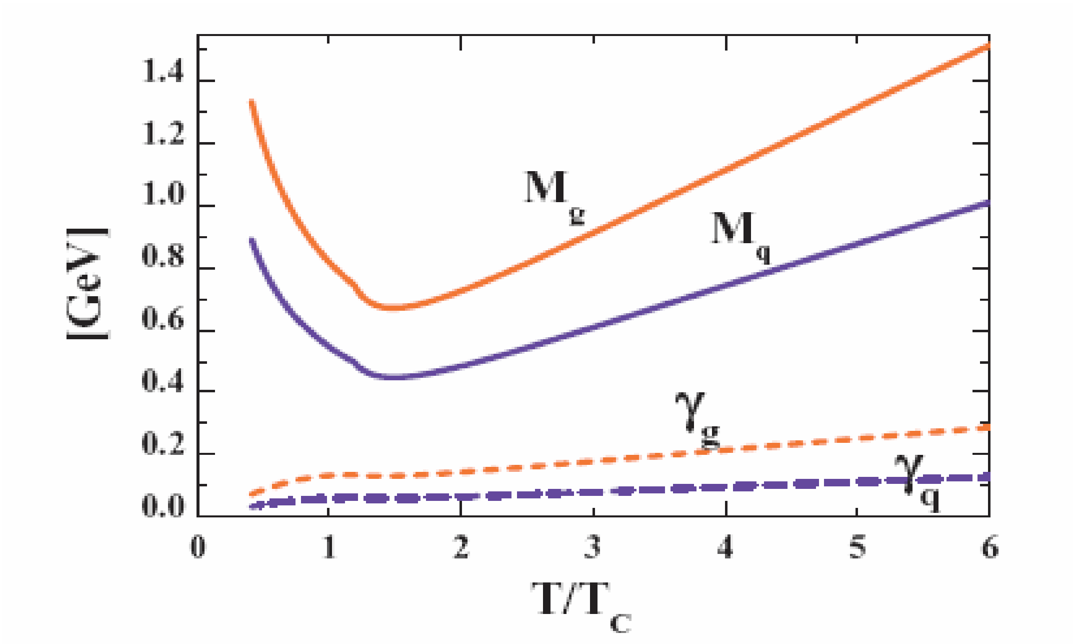
DQPM gives a good description of lQCD!

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

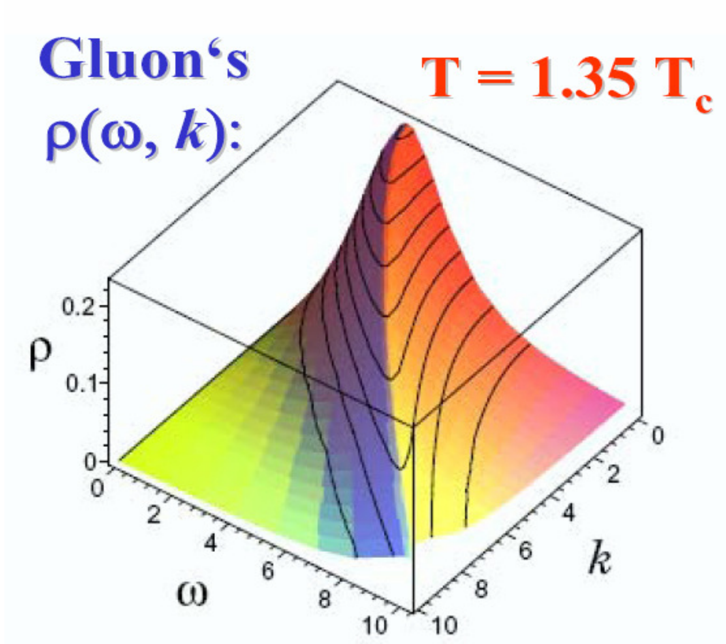
The Dynamical QuasiParticle Model (DQPM)

➔ **Quasiparticle properties:**

- **large width and mass for gluons and quarks**



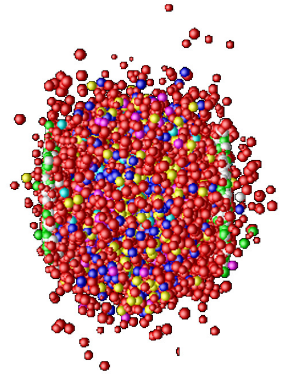
➔ **Broad spectral function :**



- **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**

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

Partonic phase summary



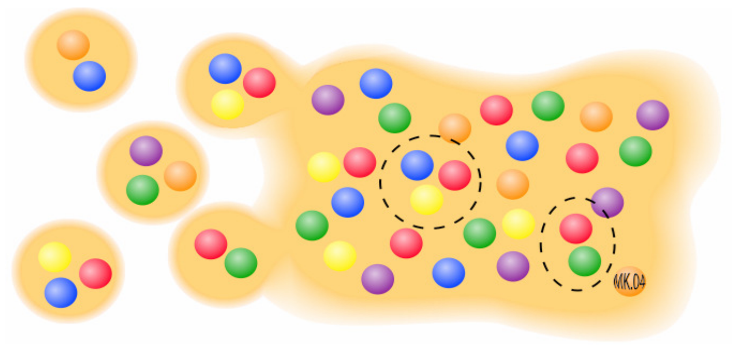
Partonic phase:

- **Degrees of freedom:**
  quarks and gluons (= ‚dynamical quasiparticles‘)
- **Properties of partons:**
  off-shell spectral functions (width, mass) defined by DQPM
- **EoS of partonic phase:**
  from lattice QCD (or DQPM)
- **Elastic parton-parton interactions:**
  using the effective cross sections from the DQPM
- **Inelastic parton-parton interactions:**
  - ✓ **quark+antiquark (flavor neutral) <=> gluon (colored)**
  - ✓ **gluon + gluon <=> gluon (possible due to large spectral width)**
  - ✓ **quark + antiquark (color neutral) <=> hadron resonances**

  Note: inelastic reactions are described by Breit-Wigner cross sections determined by the spectral properties of constituents (q, q_{bar}, g)
- **Parton propagation:**
  with self-generated potentials U_q, U_g

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

Hadronization



PHSD: 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
q + q +q → baryon

Parton-parton recombination rate =

$$\frac{dN_m(x,p)}{d^4x d^4p} = Tr_q Tr_{\bar{q}}\ \delta^4(p - p_q - p_{\bar{q}})\ \delta^4\left(\frac{x_q + x_{\bar{q}}}{2} - x\right)$$
$$\times \omega_q\ \rho_q(p_q)\ \omega_{\bar{q}}\ \rho_{\bar{q}}(p_{\bar{q}})\ |v_{q\bar{q}}|^2\ W_m(x_q - x_{\bar{q}}, p_q - p_{\bar{q}})$$
$$\times N_q(x_q, p_q)\ N_{\bar{q}}(x_{\bar{q}}, p_{\bar{q}})\ \delta(\text{flavor, color}). \quad (7)$$

W_m - Gaussian in phase space with $\sqrt{< r^2 >} = 0.66$ fm

Hadronization happens when the effective interactions |v| become attractive, approx. for parton densities $1 < \rho_P < 2.2$ fm^{-3} <= from DQPM

Note: nucleon: parton density $\rho_P^N = N_q / V_N = 3 / 2.5$ fm$^3 = 1.2$ fm^{-3}
meson: parton density $\rho_P^m = N_q / V_m = 2 / 1.2$ fm$^3 = 1.66$ fm^{-3}

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PHSD: hadronization

Conservation laws:

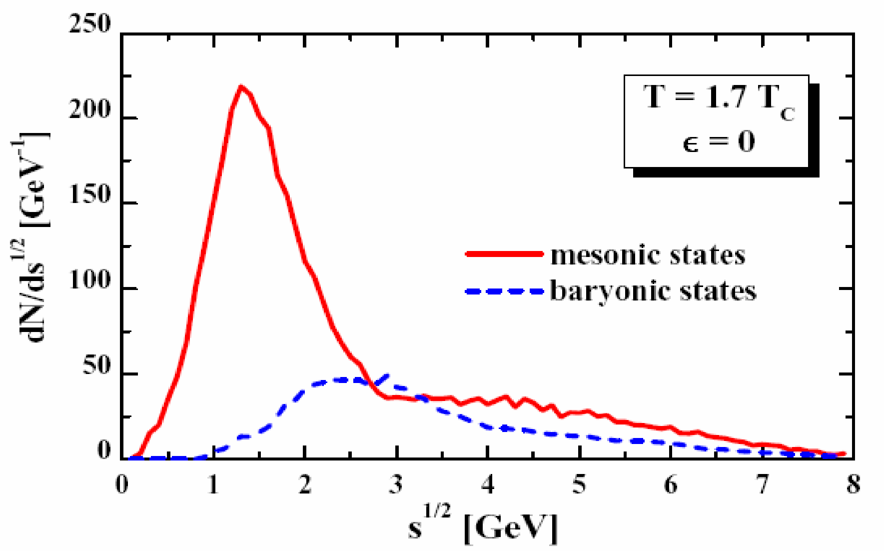
- ✓ 4-momentum conservation → invariant mass and momentum of hadron
- ✓ flavor current conservation → quark-antiquark content of hadron
- ✓ color + anticolor → color neutrality
- ✓ Since the partons are massive the formed states are very heavy (strings) →‘ entropy production in the hadronization!

- large parton masses → dominant production of vector mesons or baryon resonances (of finite/large width)

- hadronic resonances are propagated in HSD (and finally decay to the groundstates by emission of pions, kaons, etc.)

Hadronization details

Mass distributions for color neutral ‚mesons‘ and ‚baryons‘ after parton fusion:



These ‚prehadrons‘ decay according to JETSET to 0-, 1-,1+ mesons and the baryon octet/decouplet

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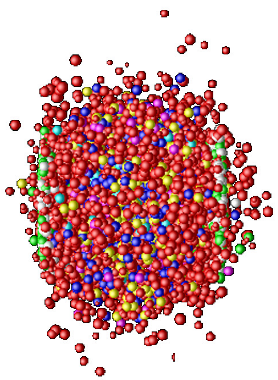
W. Cassing, EPJ ST 168 (2009) 3

Comparison of particle ratios with the statistical model (SM):

	p/π^+	Λ/K^+	K^+/π^+
PHSD	0.086	0.28	0.157
SM $T = 160$ MeV	0.073	0.22	0.179
SM $T = 170$ MeV	0.086	0.26	0.180

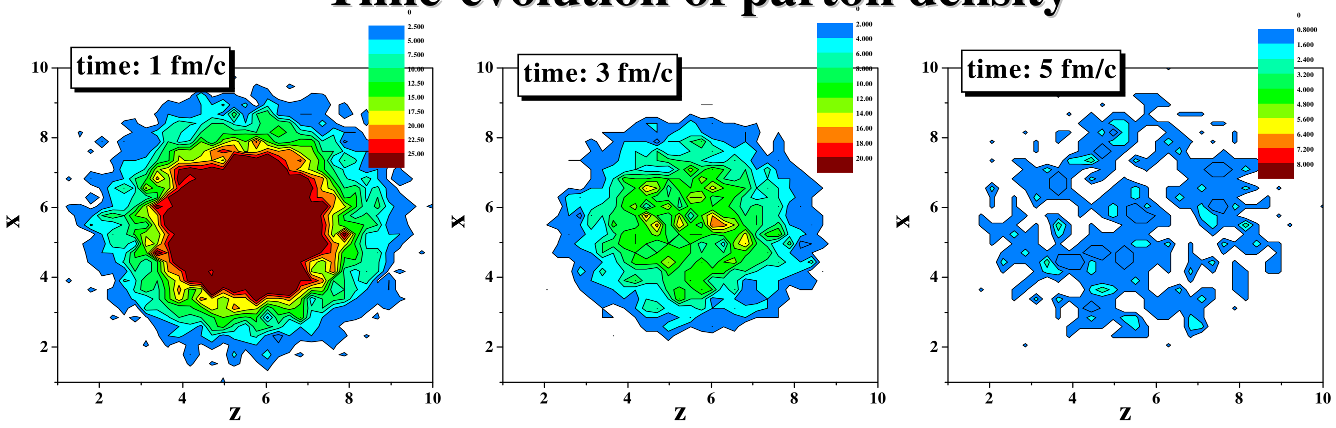
TABLE I: Comparison of particle ratios from PHSD with the statistical model (SM) [31] for T= 160 MeV and 170 MeV.

Observables 1: Corona and spectra

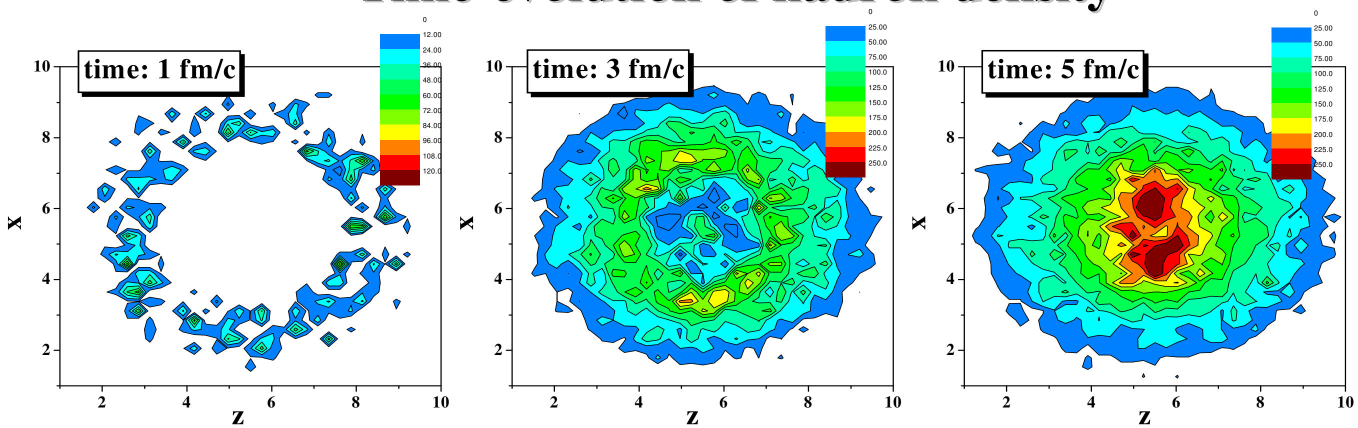


Expanding fireball

Time-evolution of parton density



Time-evolution of hadron density

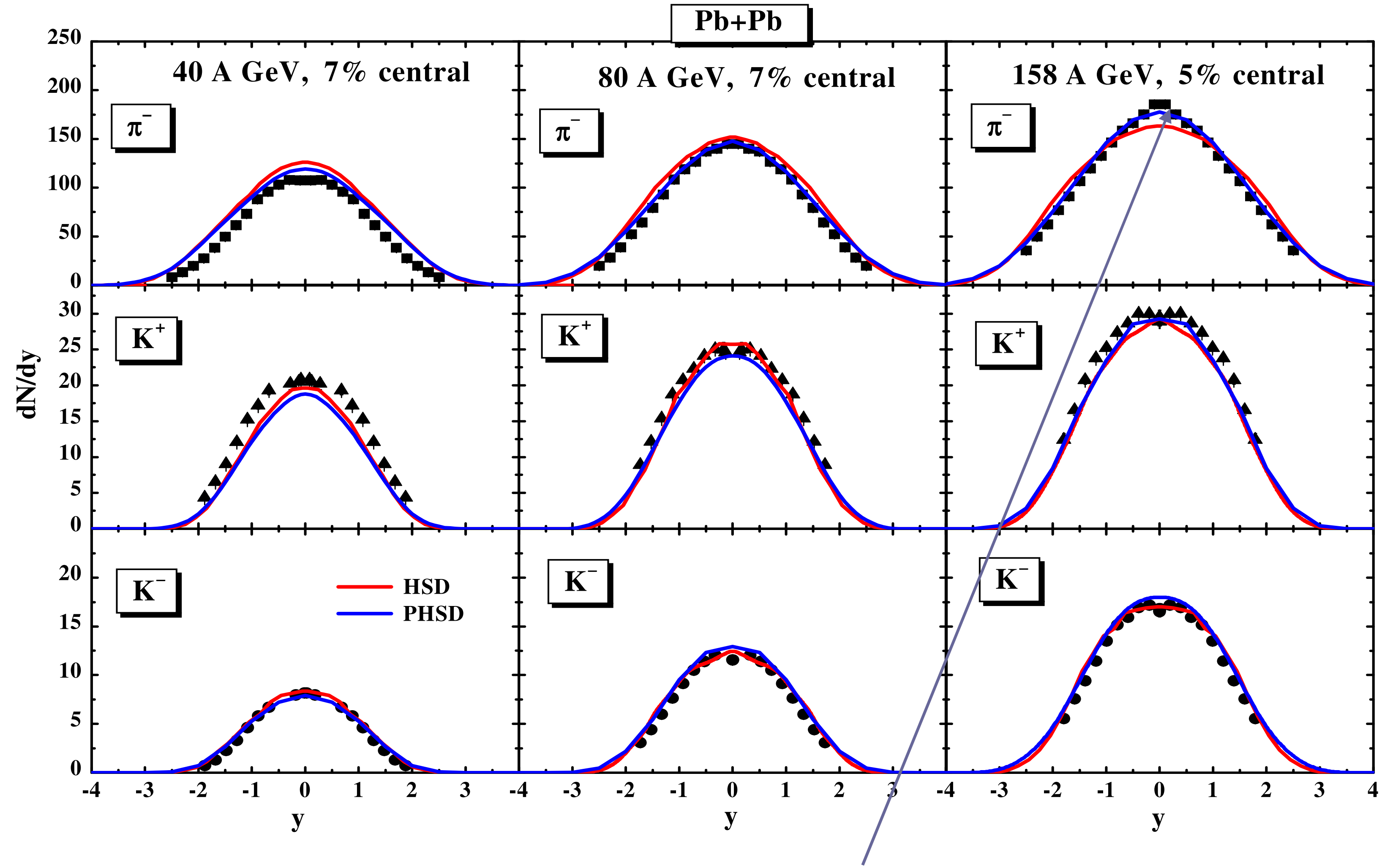


Expanding grid: $\Delta z(t) = \Delta z_0(1+a\ t)$!

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

W. Cassing, E.L. Bratkovskaya, NPA 831 (2009) 215

Rapidity distributions of p, K+, K- at SPS



➔ **pion and kaon rapidity distributions become slightly narrower**

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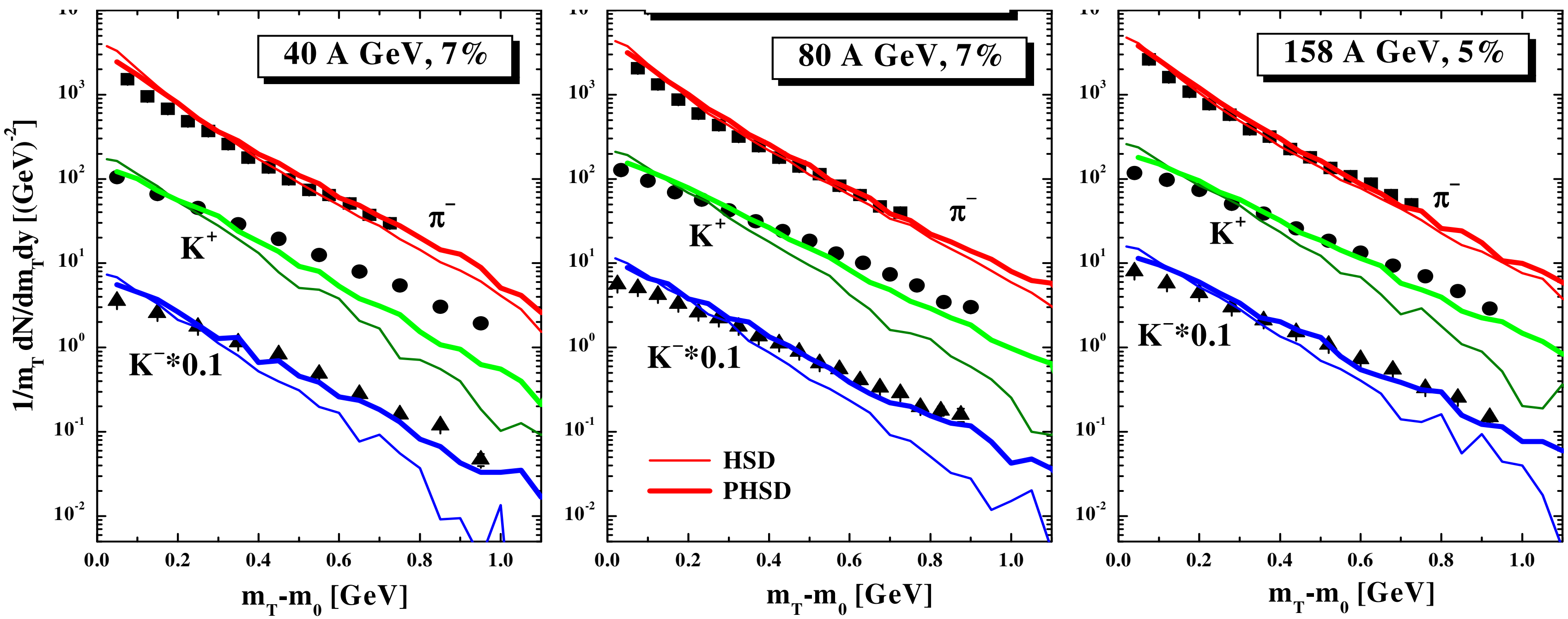
Transverse mass spectra at SPS

Central Pb + Pb at SPS energies



☺ PHSD gives harder spectra and works better than HSD at SPS (and top FAIR) energies

☹ However, at low SPS (and low FAIR) energies the effect of the partonic phase is NOT seen in rapidity distributions and m_T spectra

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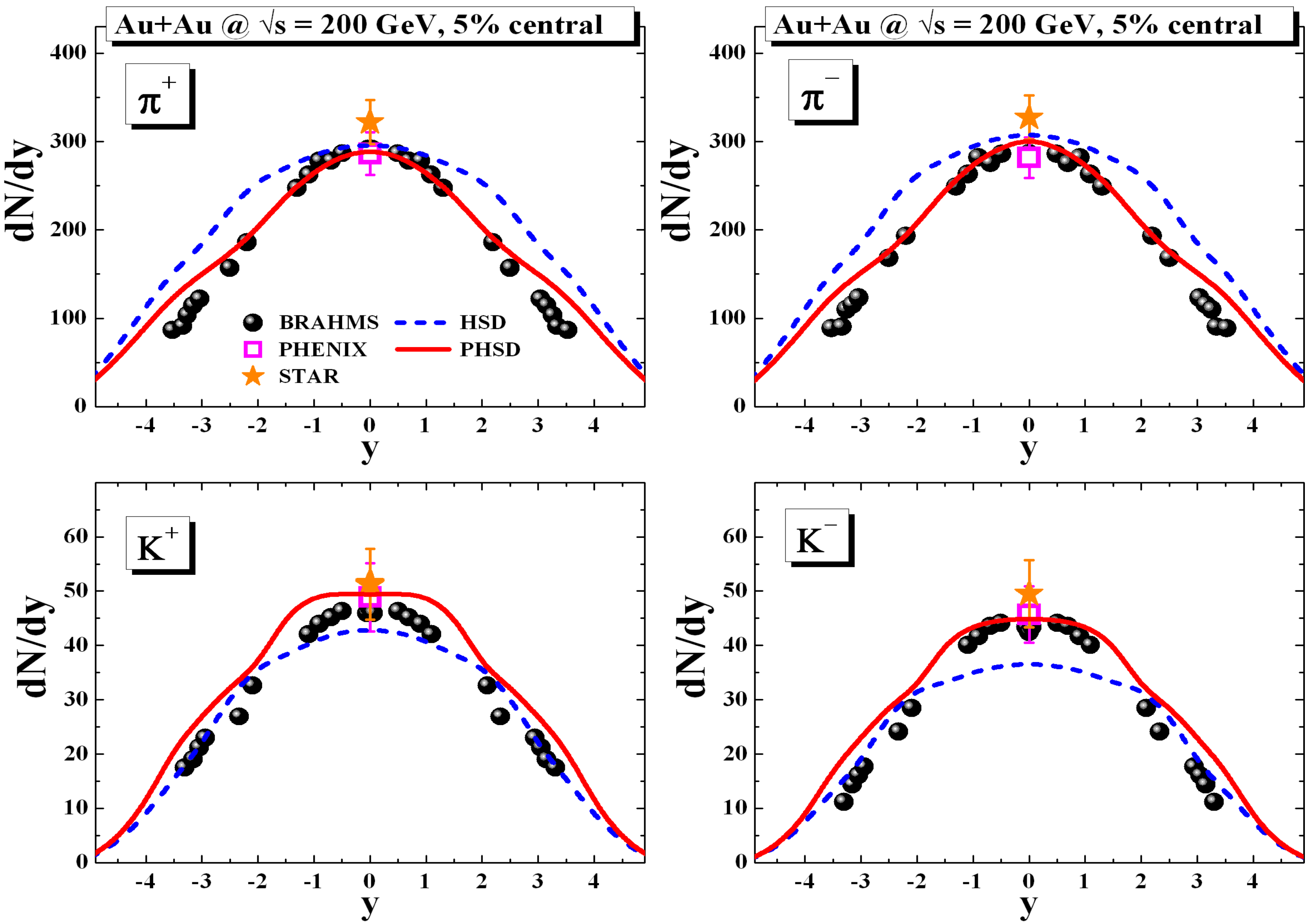
Rapidity distributions in central Au+Au at RHIC



➔ **reasonable description of the data from BRAHMS, STAR, PHENIX!**

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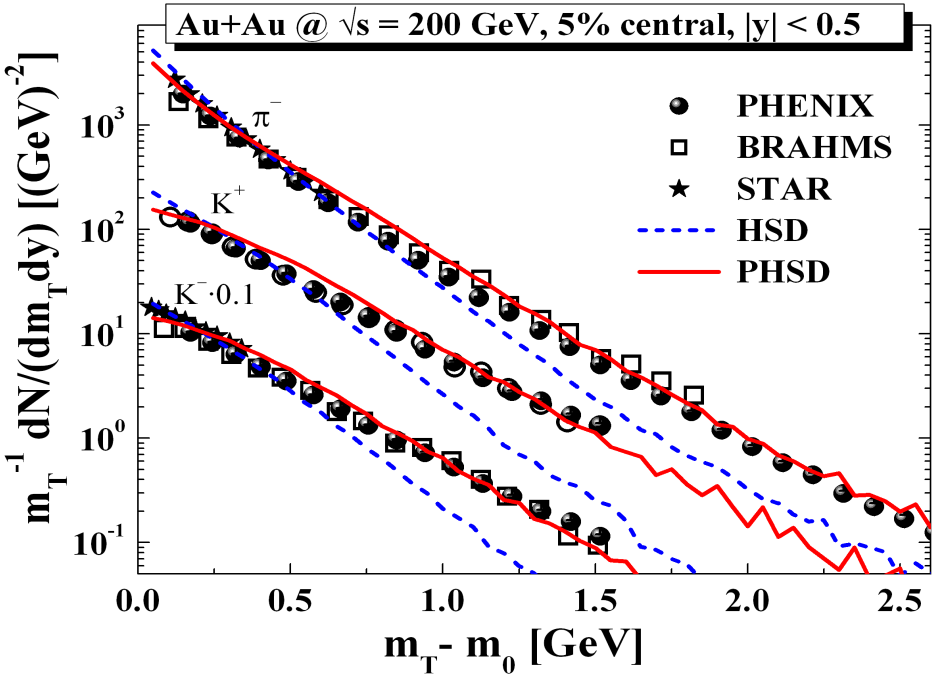
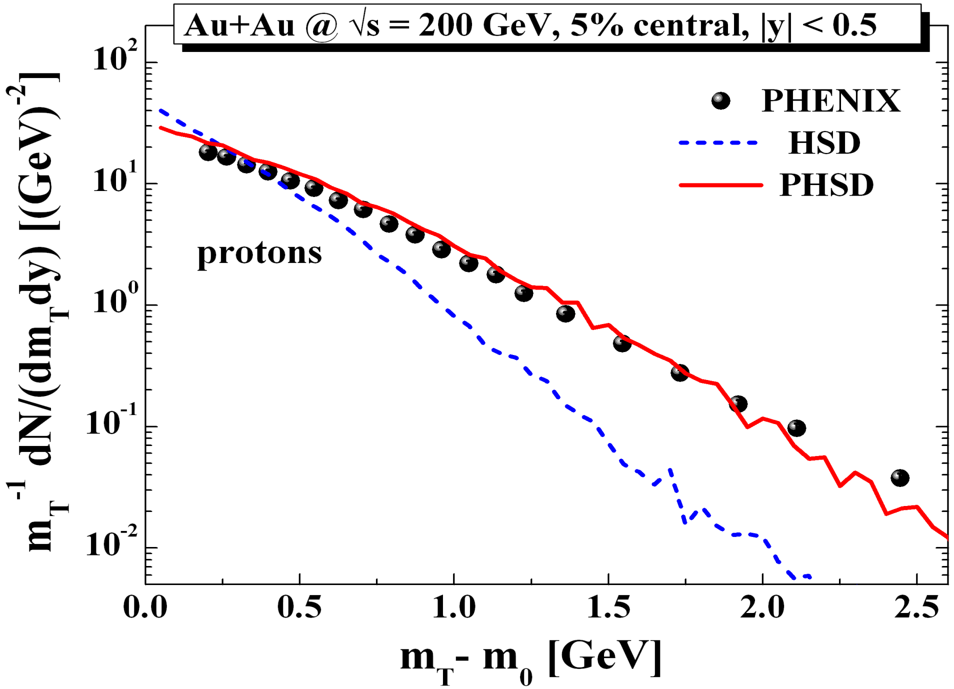
Transverse mass distributions at RHIC

Au+Au at midrapidity |y| < 0.5





➔ **PHSD gives harder spectra and works better than HSD at RHIC**

Note: In PHSD the protons at midrapidity stem from hadronization of quarks.

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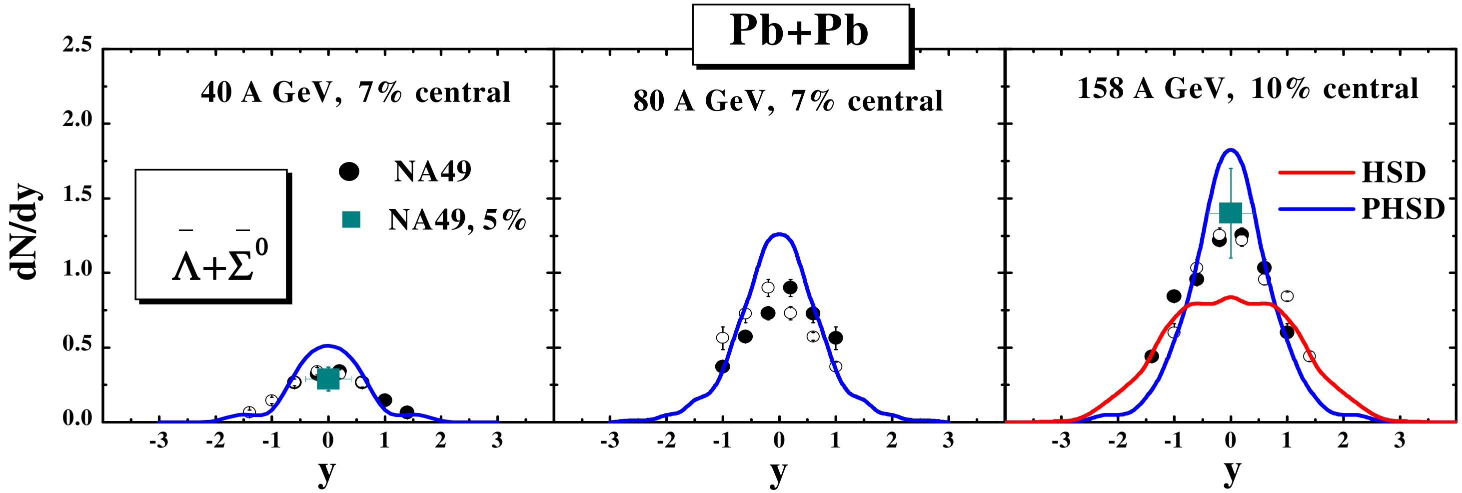
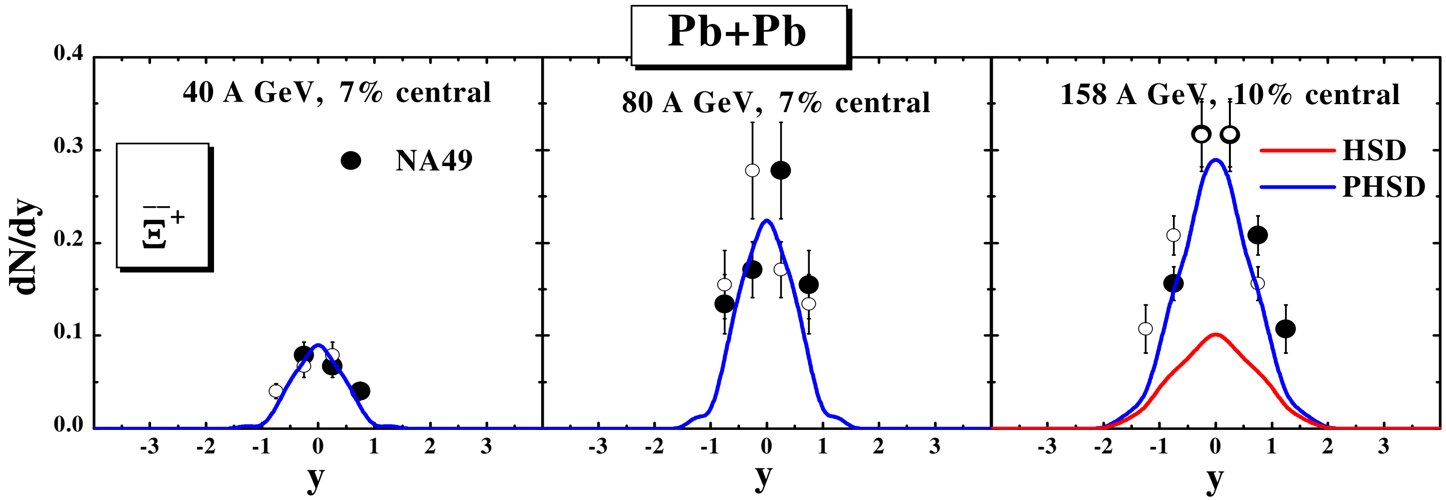
Rapidity distributions of (multi-)strange antibaryons



strange antibaryons

$\bar{\Lambda}+\bar{\Sigma}^0$



multi-strange antibaryon

$\bar{\Xi}^+$

➔ **enhanced production of (multi-) strange anti-baryons in PHSD**

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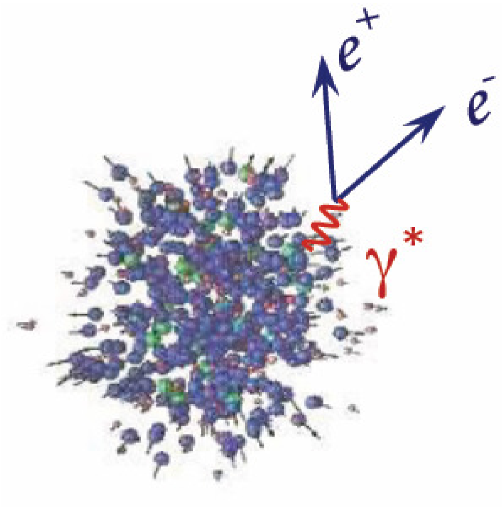
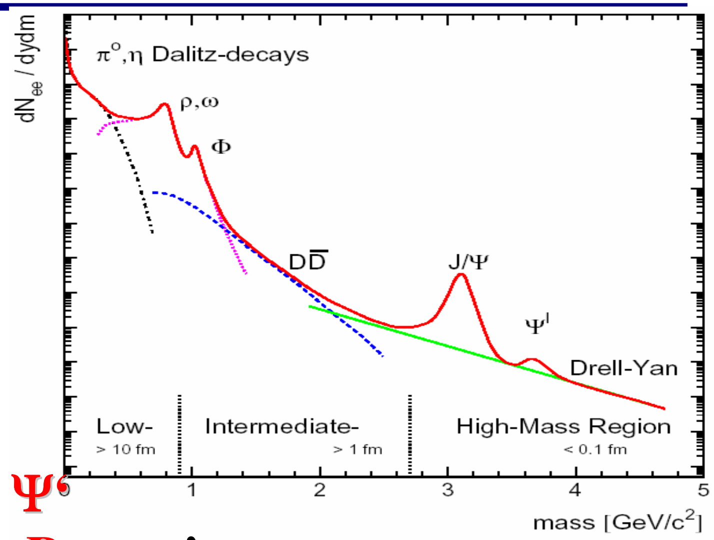
Observables 2: Dileptons



Dilepton emission probes 2-particle correlations in contrast to 1-particle distributions

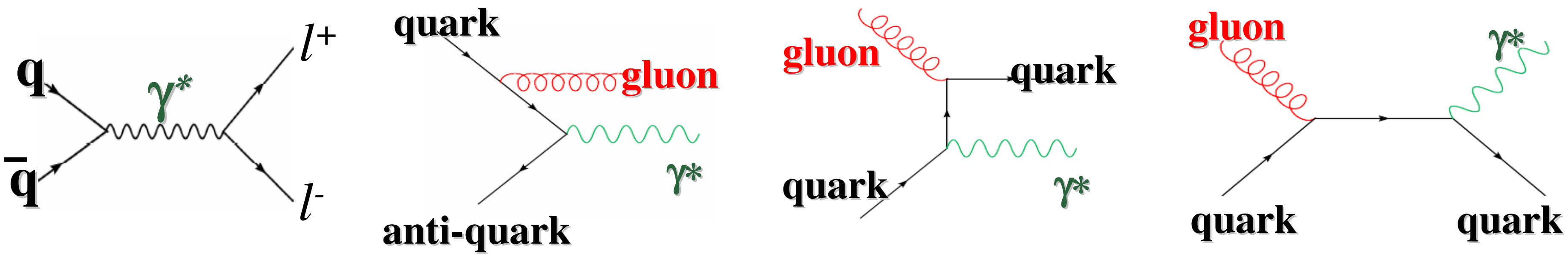


Example: dilepton measurements access spectral functions of the particles, i.e. their interaction rates and decay properties

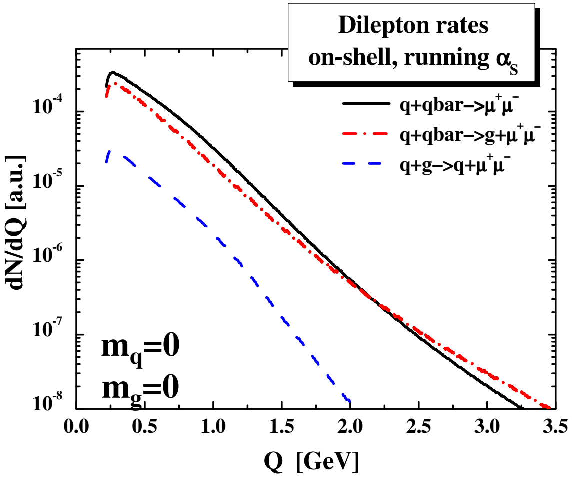
Hadronic channels included:

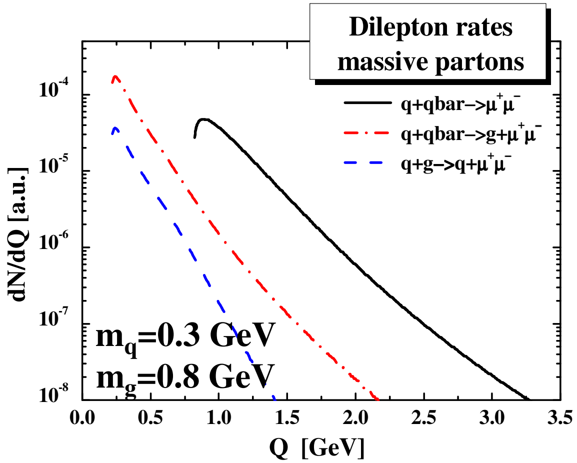
- direct and Dalitz decays of π_0, η, η', ρ, ω, ϕ, J/Ψ, Ψ'
- semi-leptonic decays of (un-)correlated $D+D_{bar}$, $B+B_{bar}$ pairs
- radiation from secondary mesons: π + π, π + ρ, π + ω, ρ + ρ, $\pi + a_1$

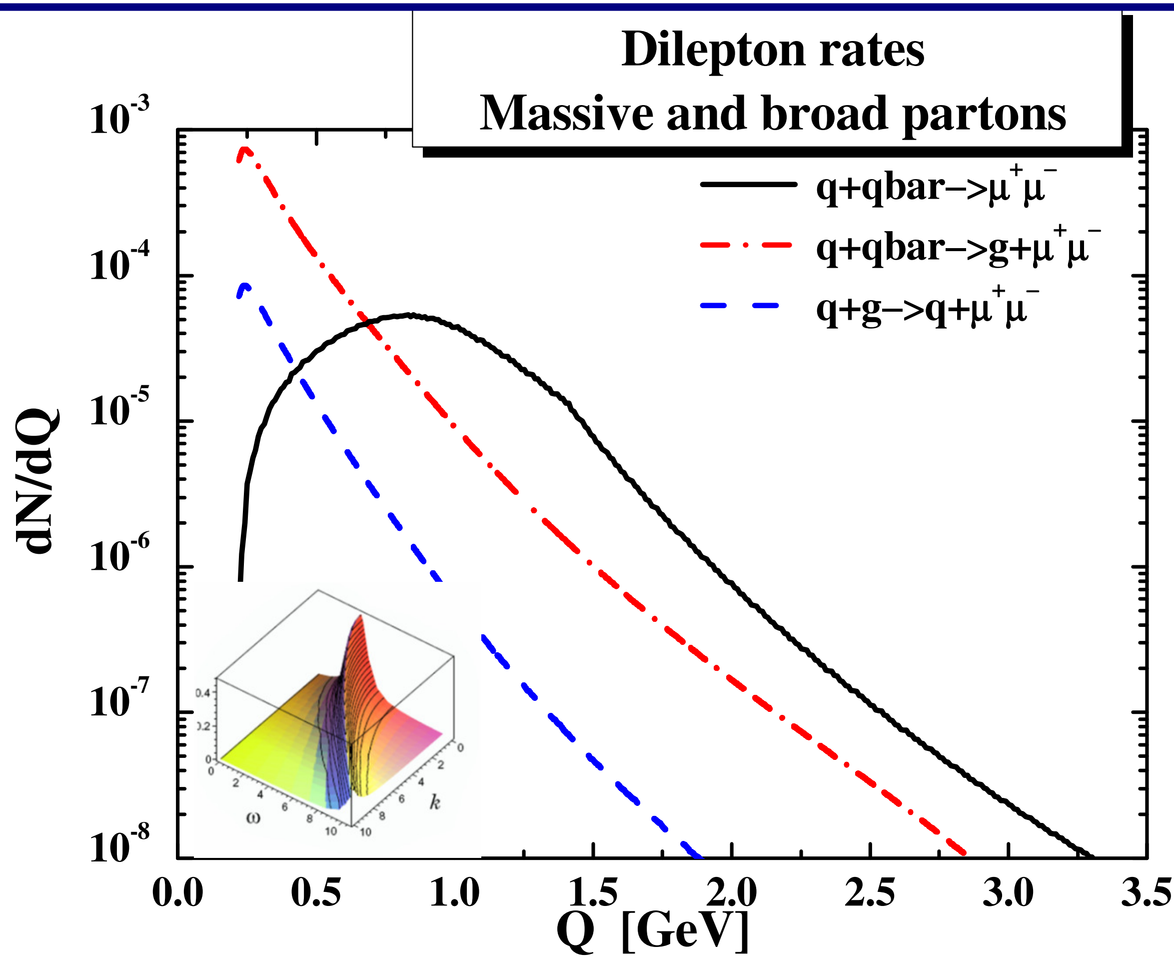
Partonic channels:



Massive and broad quarks and gluons





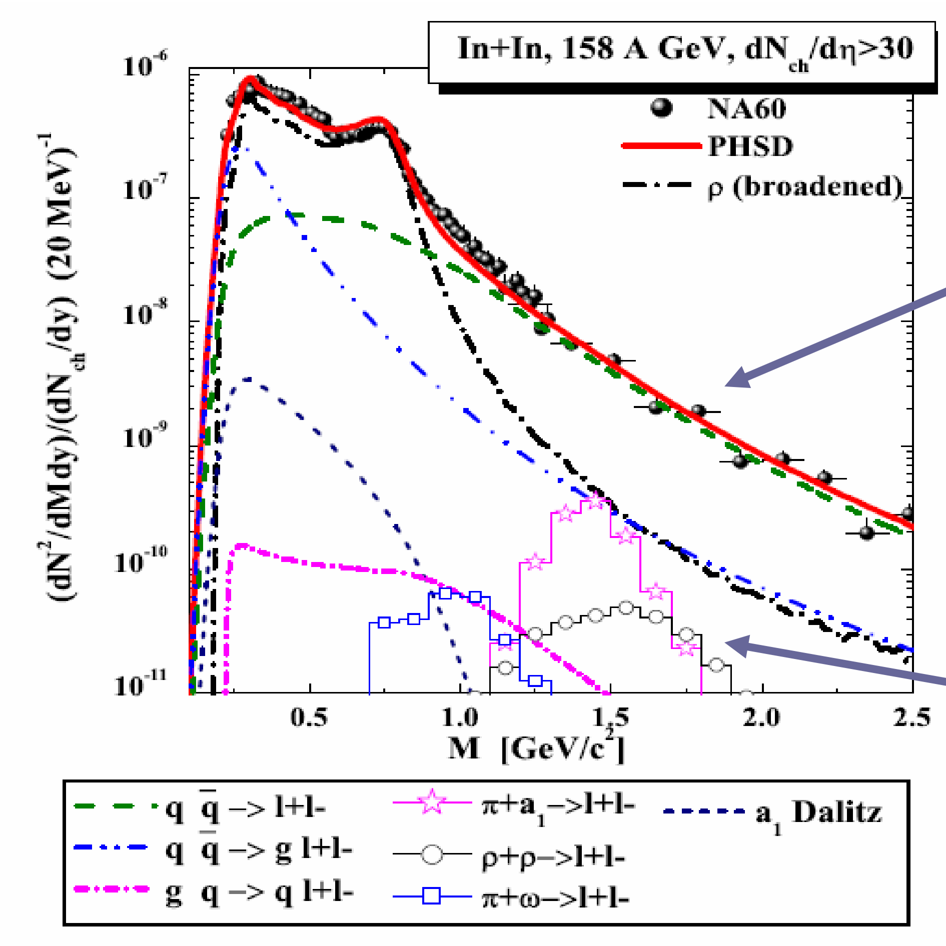


Due to broad spectral functions of partons, the threshold of the Born term is smeared, the contributions of the 2–>2 processes increased.

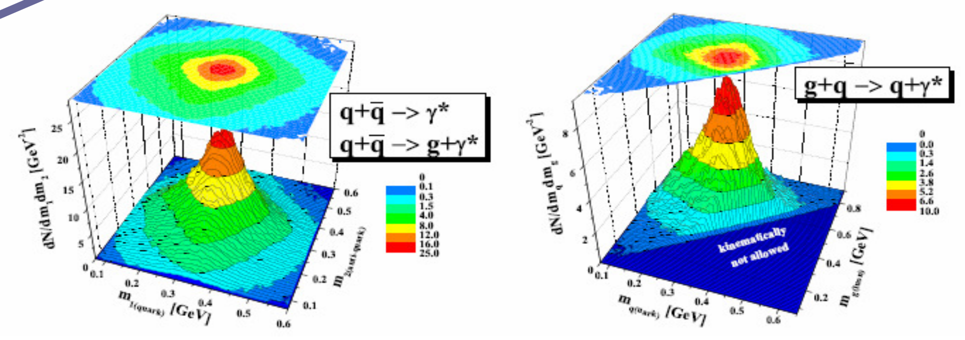
O. Linnyk, J.Phys.G38 (2011) 025105

Dileptons at SPS: NA60

Acceptance corrected NA60 data



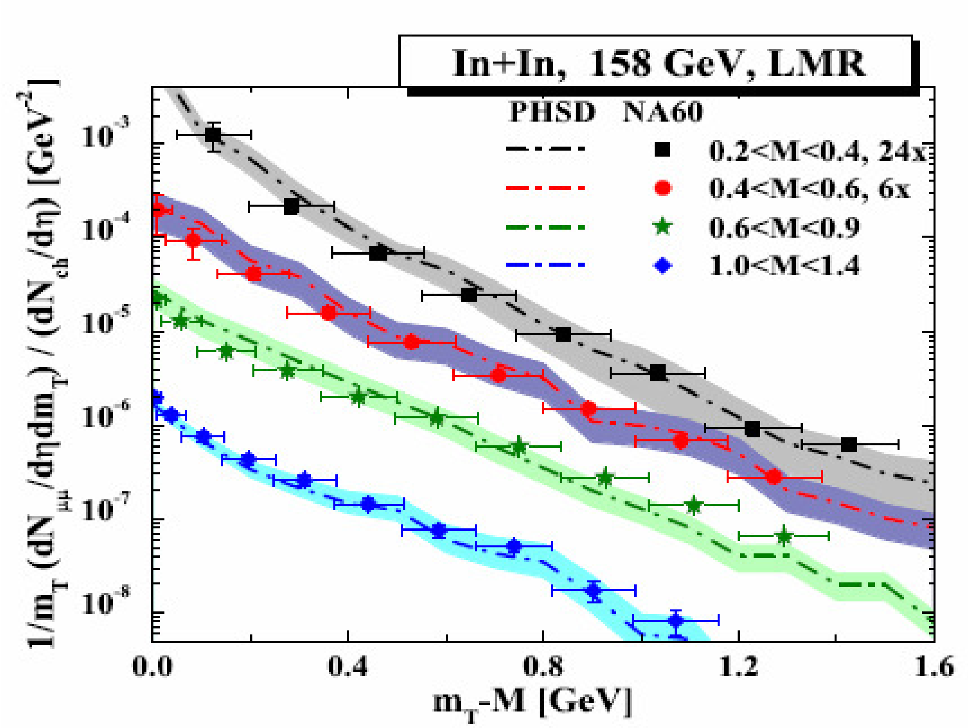
- Mass region above 1 GeV is dominated by partonic radiation



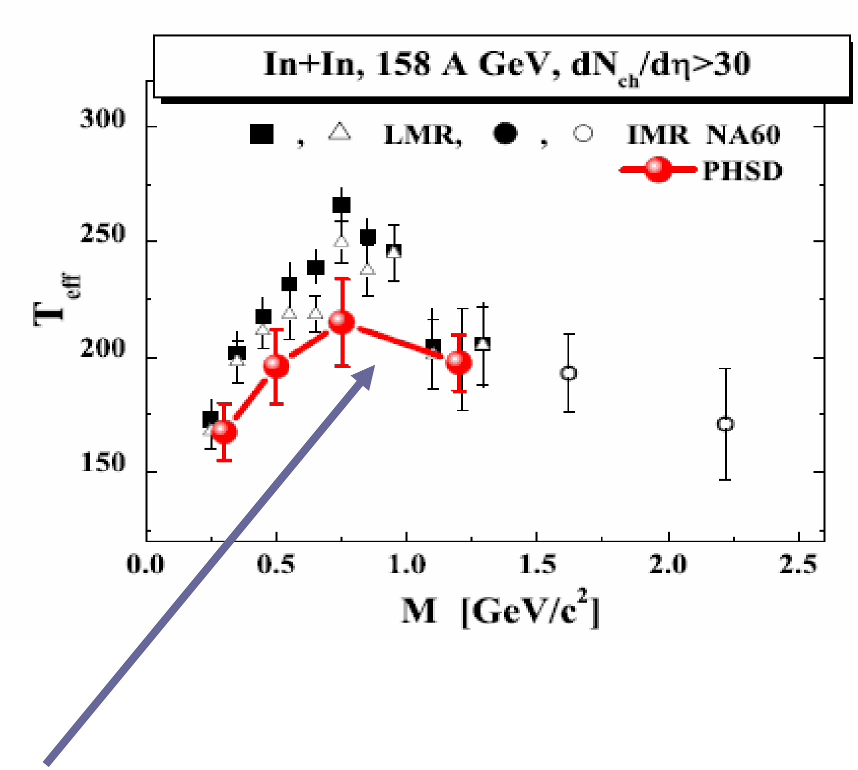
- Contributions of "4π" channels (radiation from multi-meson reactions) are small

O. Linnyk, E. Bratkovskaya, 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

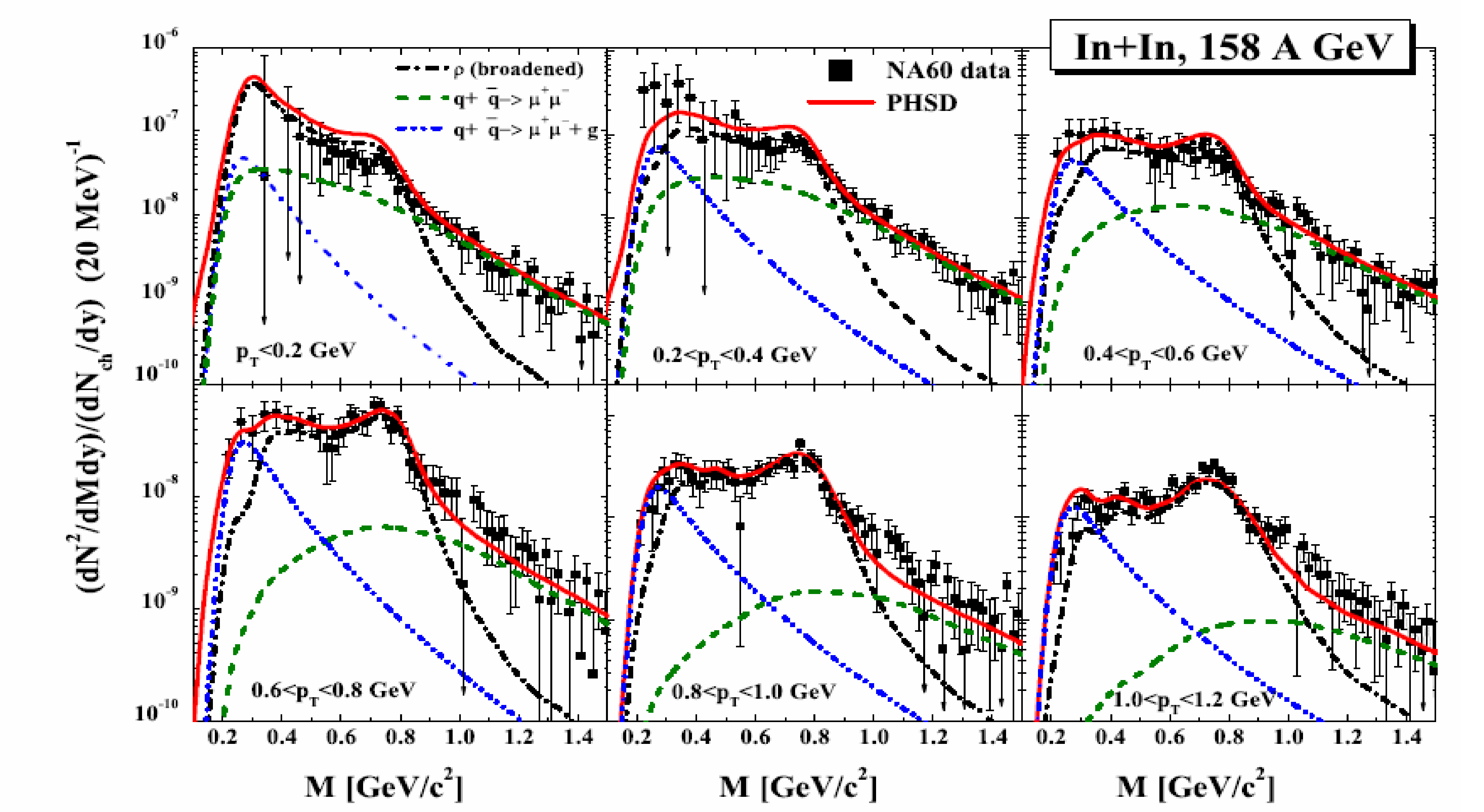


Conjecture:

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

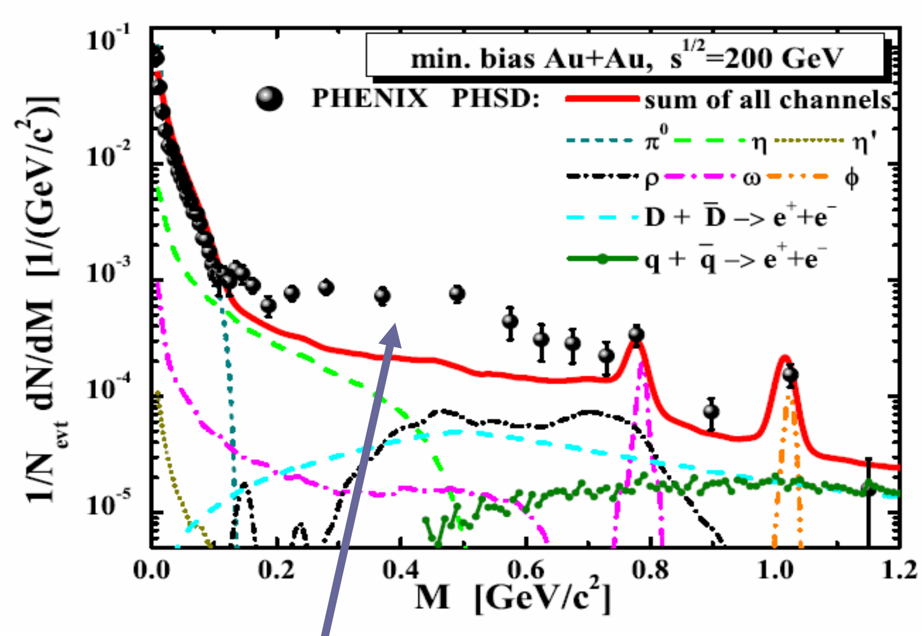
O. Linnyk, E. Bratkovskaya, V. Ozvenchuk, W. Cassing and C.M. Ko, PRC 84 (2011) 054917

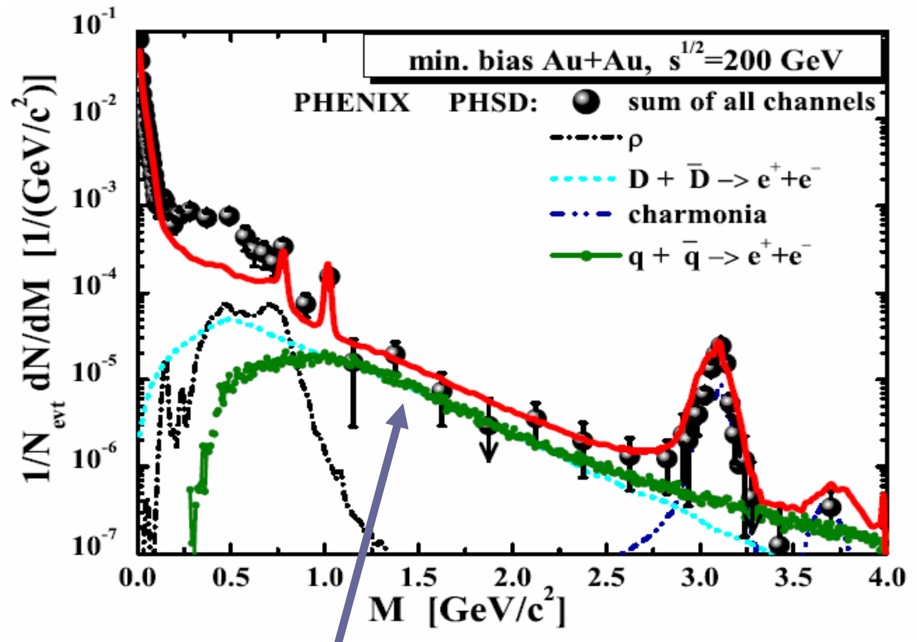
Dileptons at SPS: NA60



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

PHENIX: dileptons from partonic channels





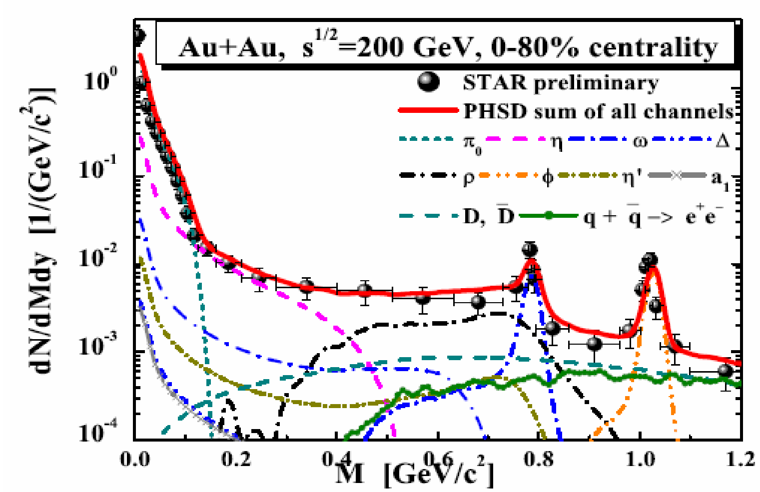
- **The excess over the considered mesonic sources for M=0.15-0.6 GeV is not explained by the QGP radiation as incorporated presently in PHSD**

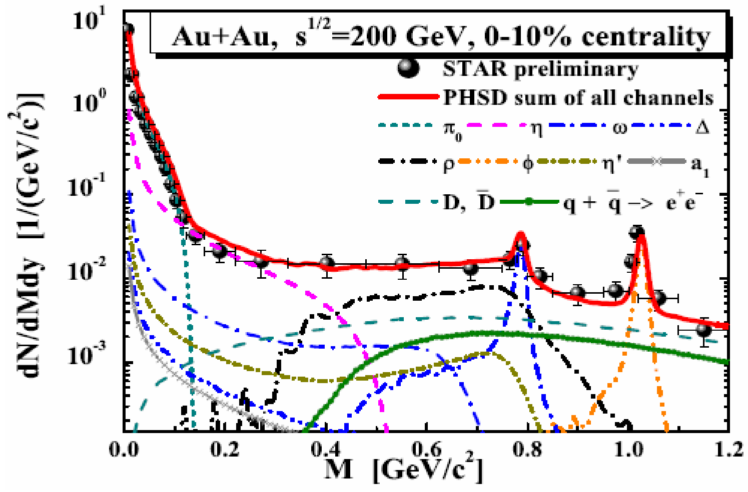
- **The partonic channels fill up the discrepancy between the hadronic contributions and the data for M>1 GeV**

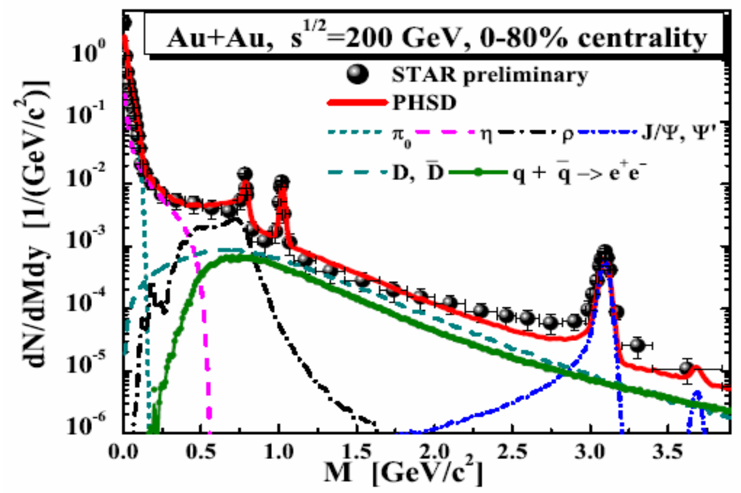
–> Talk by Jaakko Manninen!

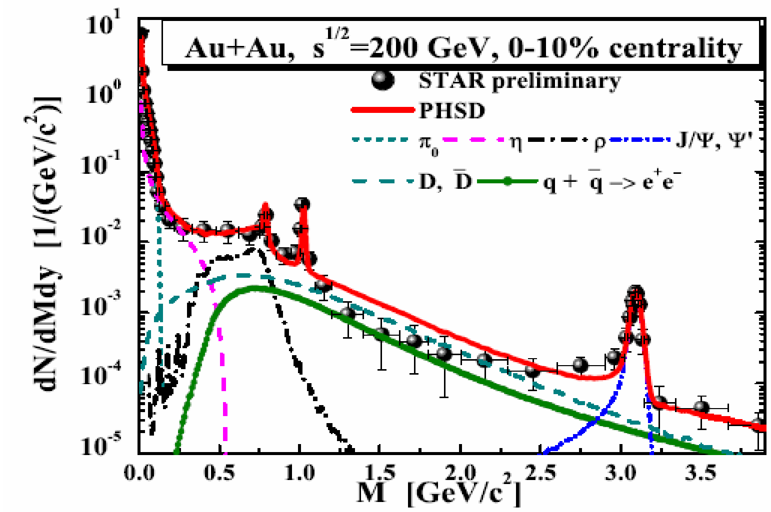
O. Linnyk, W. Cassing, J. Manninen, E.Bratkovskaya and C.M. Ko, PRC 85 (2012) 024910

STAR: dilepton mass spectra







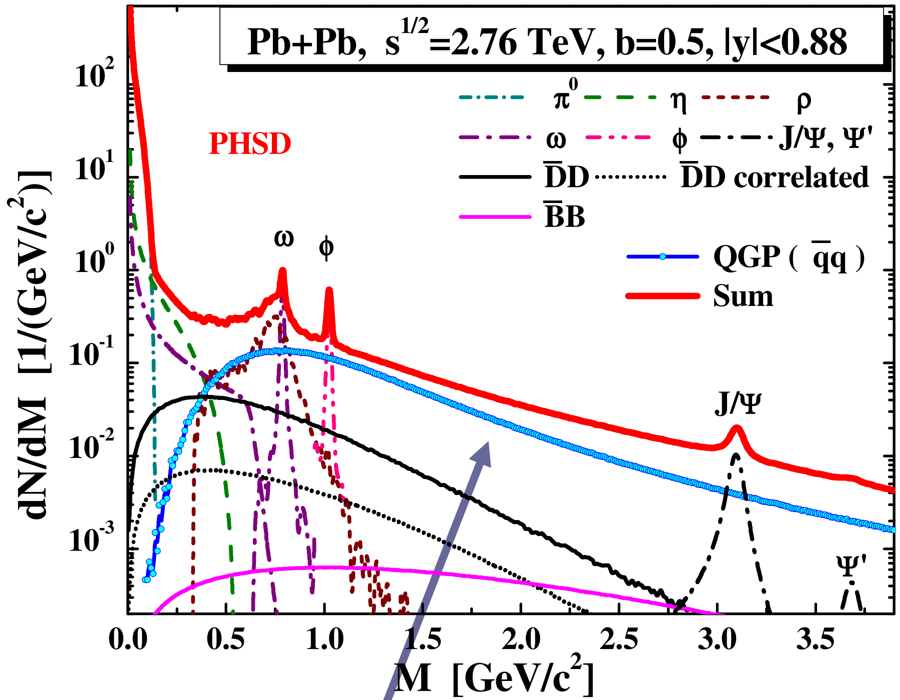


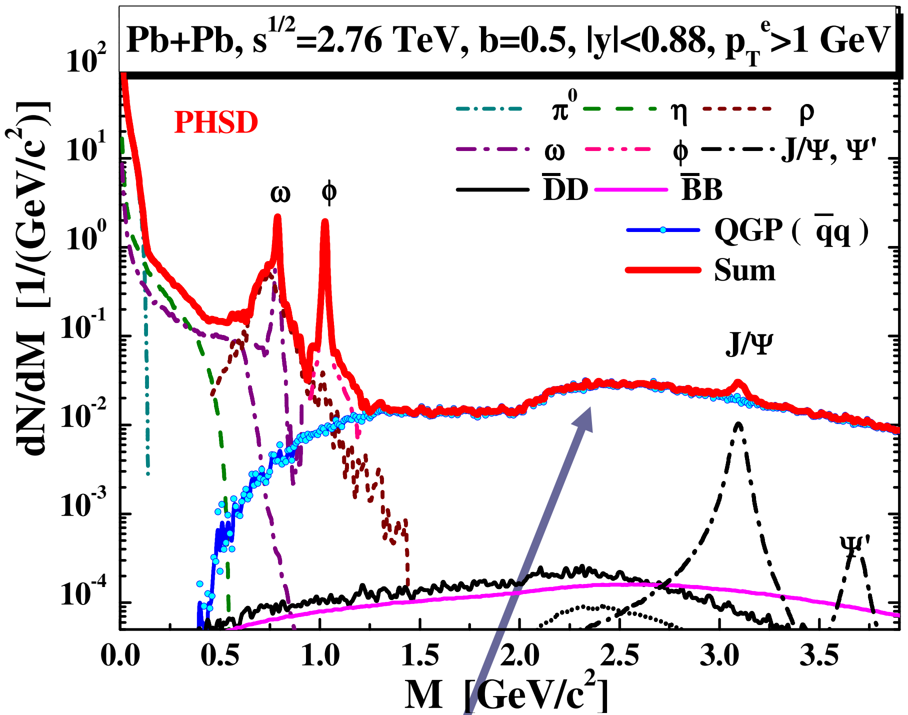
- **STAR data are well described**

–> Talk by Jaakko Manninen!

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

LHC: dilepton mass spectra





QGP(qbar-q) dominates at M>1.2 GeV

p_T cut enhances the signal of QGP(qbar-q)

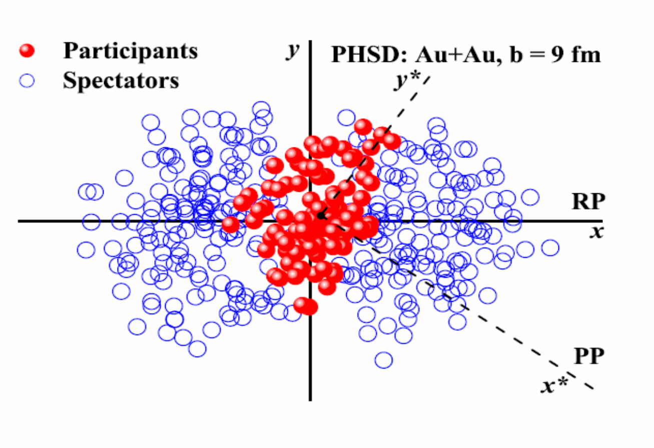
D-, B-mesons energy loss from Pol-Bernard Gossiaux and Jörg Aichelin

JPsi and Psi' nuclear modification from Che-Ming Ko and Taesoo Song

–> Talk by Jaakko Manninen!

O. Linnyk, J. Manninen et al. (2012)

Observables 3:
Flow harmonics (v_1, v_2, v_3, v_4)



Expanding fireball v_2

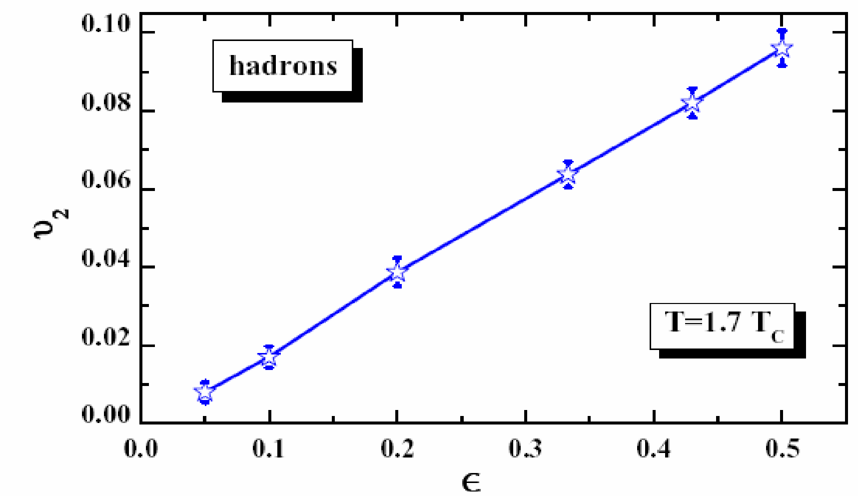
Elliptic flow v_2 is defined by an anisotropy in momentum space:

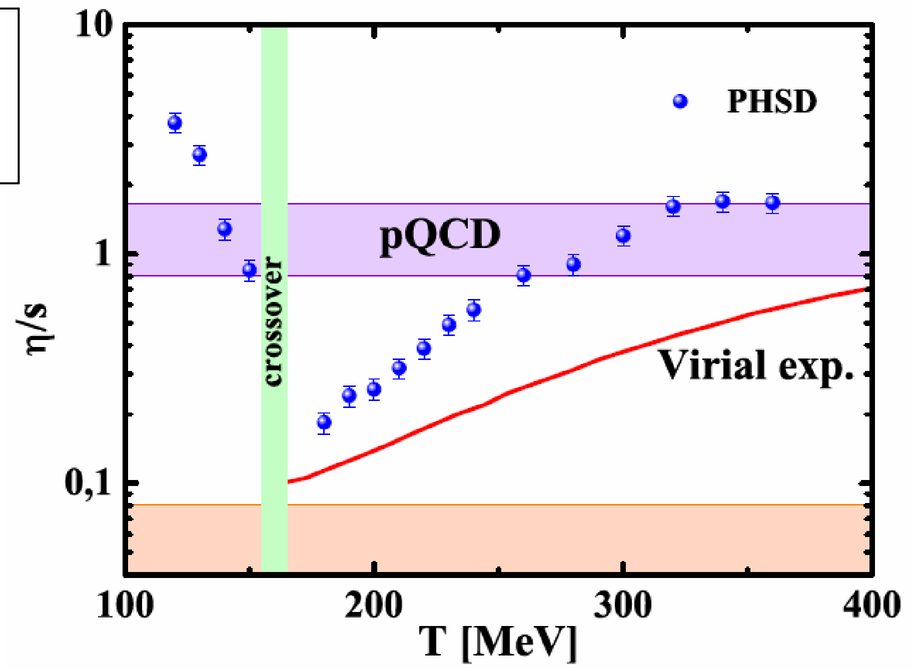
$$v_2 = (p_x^2 - p_y^2)/(p_x^2 + p_y^2)$$

Initially: $v_2 = 0$ → study final v_2 versus initial eccentricity ε !

$$\varepsilon = (\sigma_y^2 - \sigma_x^2)/(\sigma_y^2 + \sigma_x^2)$$

v_2/ε = const.
indicates ideal hydrodynamic flow !

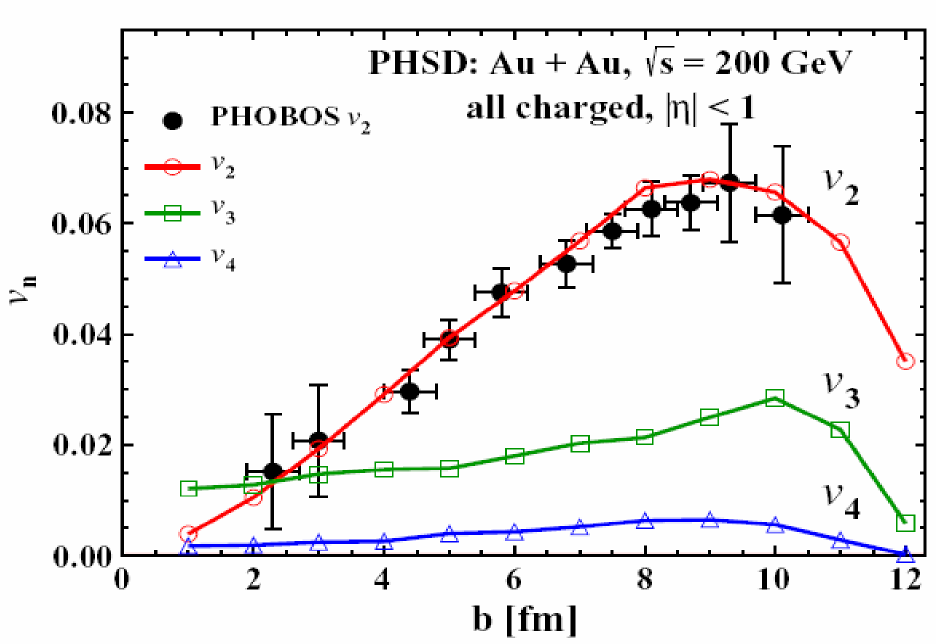


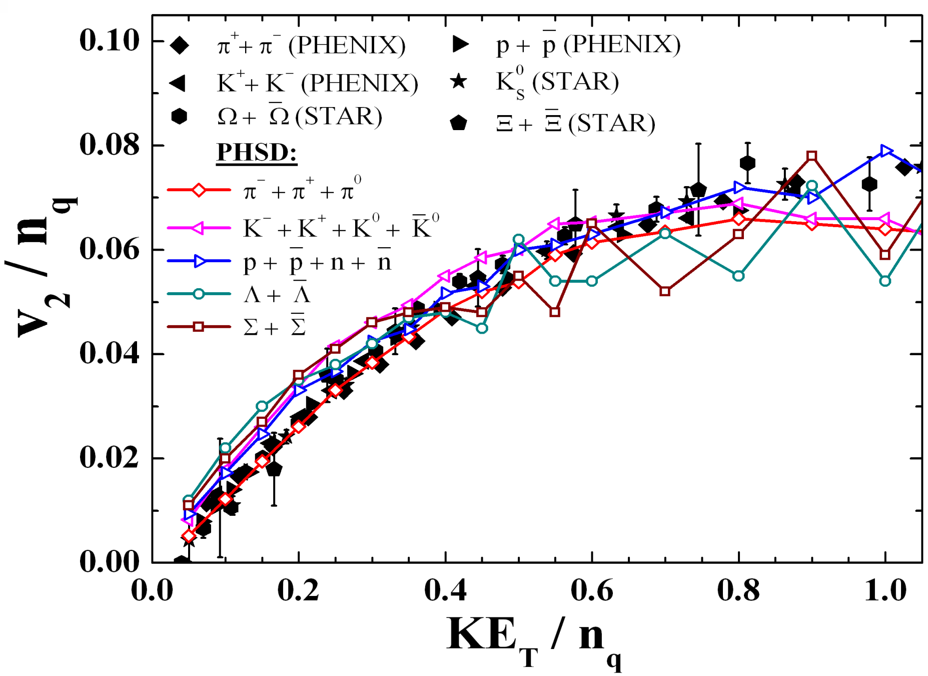


Expected since η/s is very small in the DQPM and PHSD. –> Talk by Vitalii Ozvenchuk!

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

Flow harmonics at RHIC





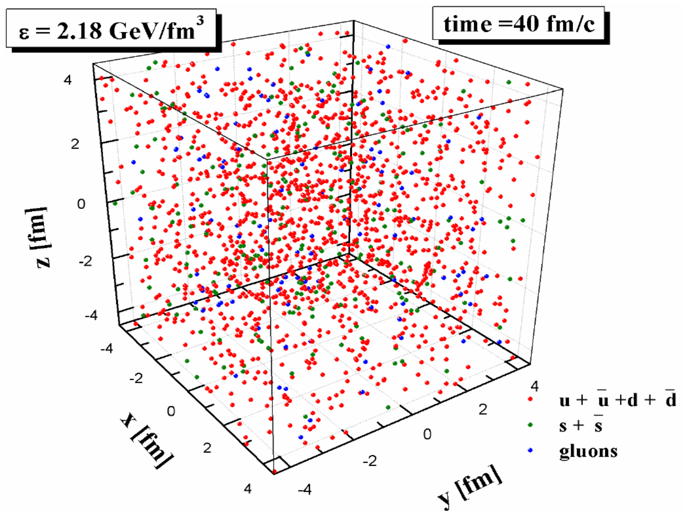
Increase of v_2 with impact parameter but flat v_3 and v_4

The scaling of v_2 with the number of constituent quarks n_q in line with data .

–> Talk by Volodya Konchakovski!

E. Bratkovskaya, W. Casssing, V. Konchakovski, O. Linnyk, NPA856 (2011) 162;
V. P. Konchakovski et al., PRC 85 (2012) 044922

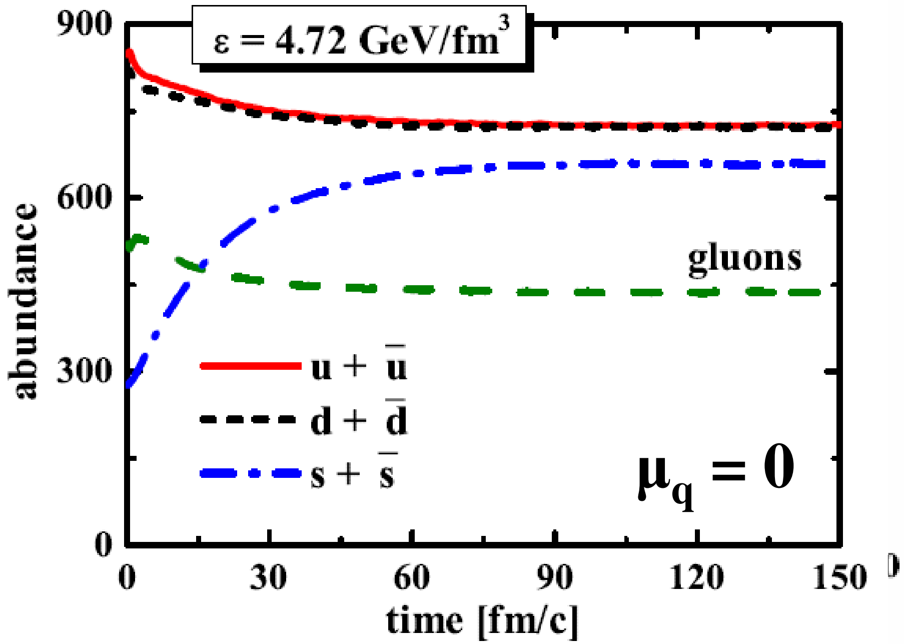
Equilibration

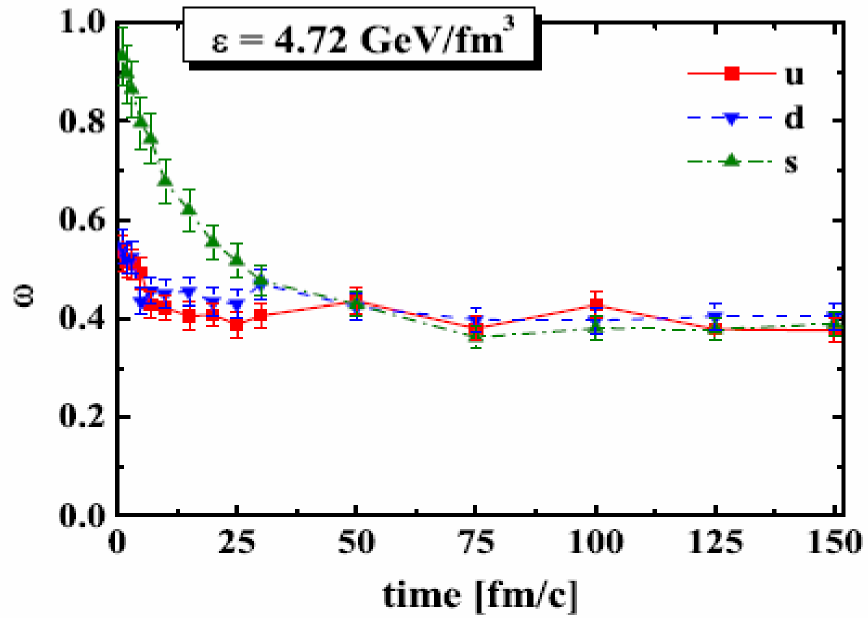


'Infinite' parton matter. Equilibration.

Initialize the system in a finite box with periodic boundary conditions with some number of partons and 4-momentum distributions in line with the DQPM → energy density $\varepsilon = E/V$ and chemical potential μ_q

Evolve the system in time until equilibrium is achieved





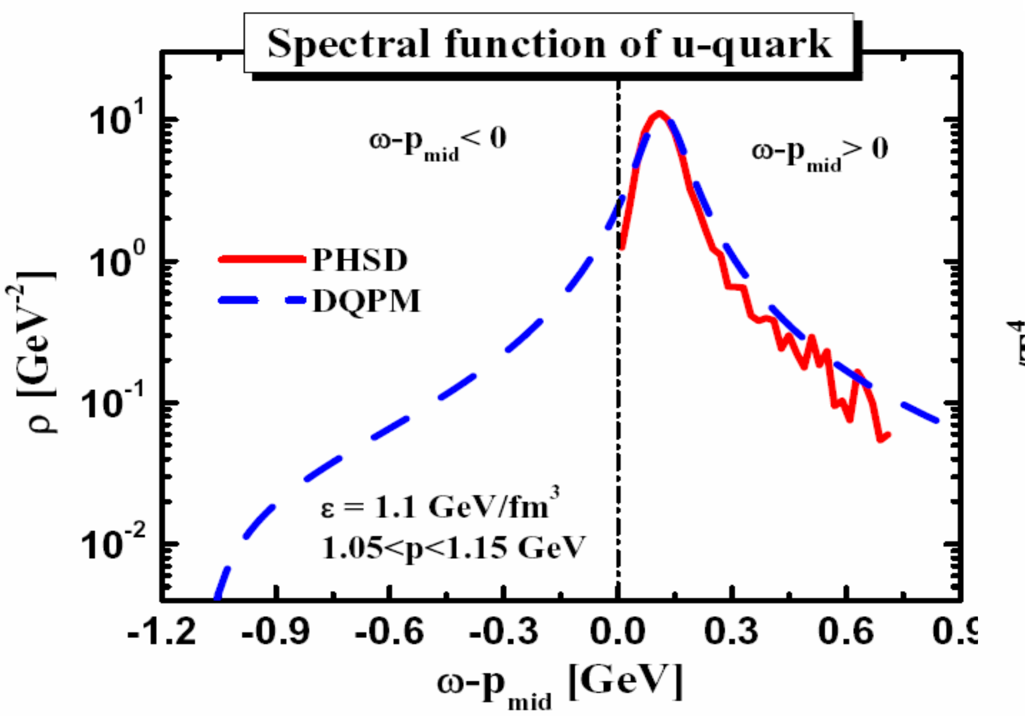
Fluctuations in parton number

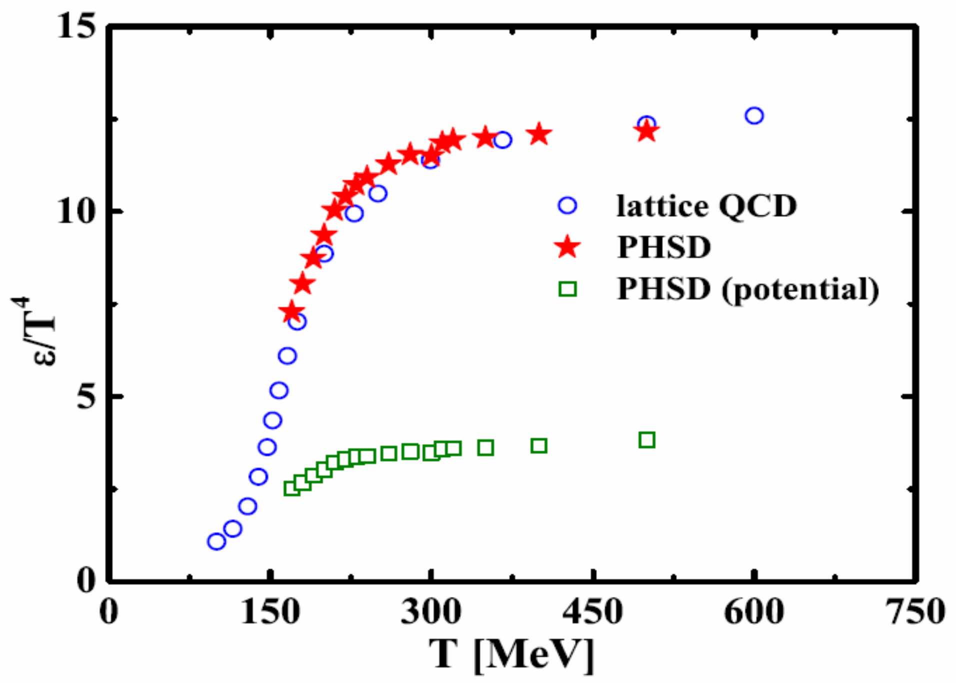
–> Talk by Vitalii Ozvenchuk!

V. Ozvenchuk, O. Linnyk, M. I. Gorenstein, E. L. Bratkovskaya, W. Cassing., arXiv:1203.4734

Equilibrium properties.

Equilibrium spectral function of u-quark | **Equation of state**



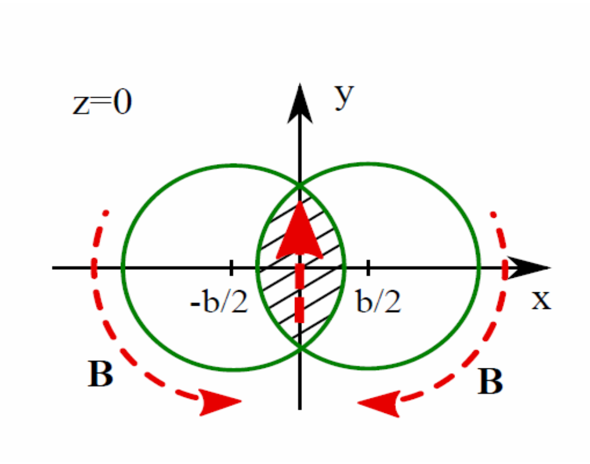


Good match between PHSD and the DQPM
Note: PHSD propagates only time-like partons

–> Talk by Vitalii Ozvenchuk!

V. Ozvenchuk, O. Linnyk, M. I. Gorenstein, E. L. Bratkovskaya, W. Cassing., arXiv:1203.4734

Electro-magnetic fields, Chiral magnetic effect



PHSD - transport model with electromagnetic fields

Generalized transport equations in the presence of electromagnetic fields :

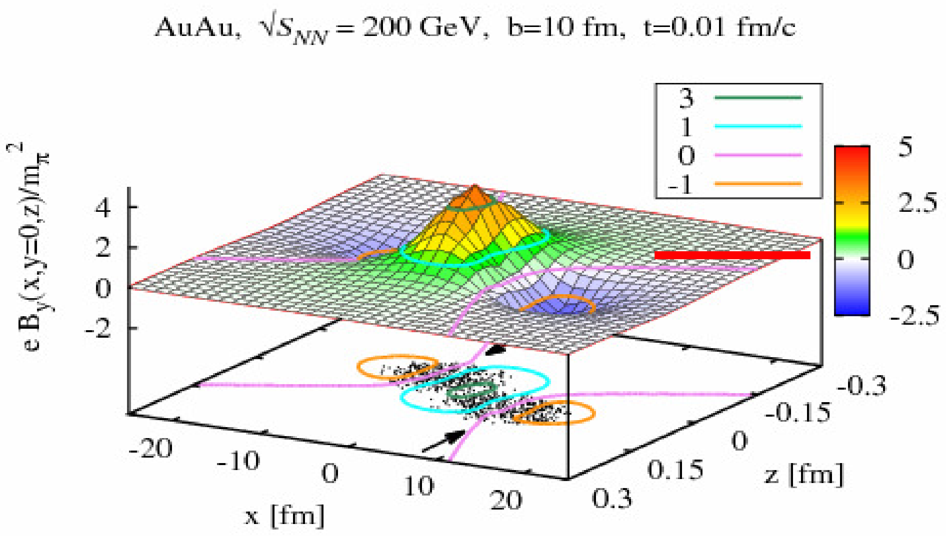
$$\dot{\vec{r}} \rightarrow \frac{\vec{p}}{p_0} + \vec{\nabla}_p U \;, \quad U \sim Re(\Sigma^{ret})/2p_0$$

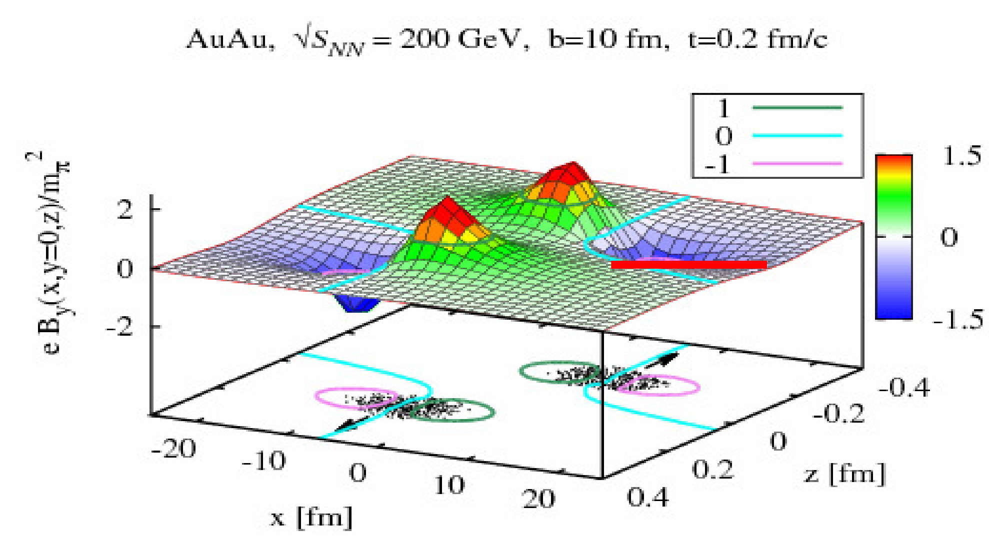
$$\dot{\vec{p}} \rightarrow -\vec{\nabla}_r U + e\vec{E} + e\vec{v} \times \vec{B}$$

$$\vec{A}(\vec{r},t) = \frac{1}{4\pi} \int \frac{\vec{j}(\vec{r'},t')\, \delta(t - t' - |\vec{r} - \vec{r'}|/c)}{|\vec{r} - \vec{r'}|}\, d^3r'dt'$$

$$\Phi(\vec{r},t) = \frac{1}{4\pi} \int \frac{\rho(\vec{r'},t')\, \delta(t - t' - |\vec{r} - \vec{r'}|/c)}{|\vec{r} - \vec{r'}|}\, d^3r'dt'$$

Magnetic field evolution in HSD/PHSD :





–> Talk by Volodya Konchakovski!

V. Voronyuk et al., Phys.Rev. C83 (2011) 054911

Conclusions

- **Parton-Hadron-String-Dynamics (PHSD) theory provides a consistent description of the phase transition to the QGP in heavy-ion collisions. The dynamical quasiparticle model (DQPM) defines the input for the partonic phase in the PHSD transport in line with lattice QCD.**

- **Phase transition to the deconfined phase leads to narrower rapidity distributions of produced mesons, harder p_T spectra, constituent quark number scaling of v_2, enhancement of antihyperon yield. Partonic repulsive mean fields generate flow which scales with the initial space eccentricity as in an ideal hydro.**

- **The dilepton data provide evidence for off-shell dynamics of vector mesons and partons. QGP radiation seen in the data.**

- **In the 'box', the PHSD shows a low viscosity in the partonic phase, slow equilibration of strangeness; spectral functions in line with DQPM.**

Thank you!

Wolfgang Cassing
Elena Bratkovskaya

Volodya Konchakovski
Jaakko Manninen
Vitalii Ozvenchuk
Rudy Marty

PHSD Team

Che-Ming Ko
Taesoo Song
Jörg Aichelin
Pol Bernard Gossiaux
Mark I. Gorenstein
Viatcheslav D. Toneev
Vadym Voronyuk

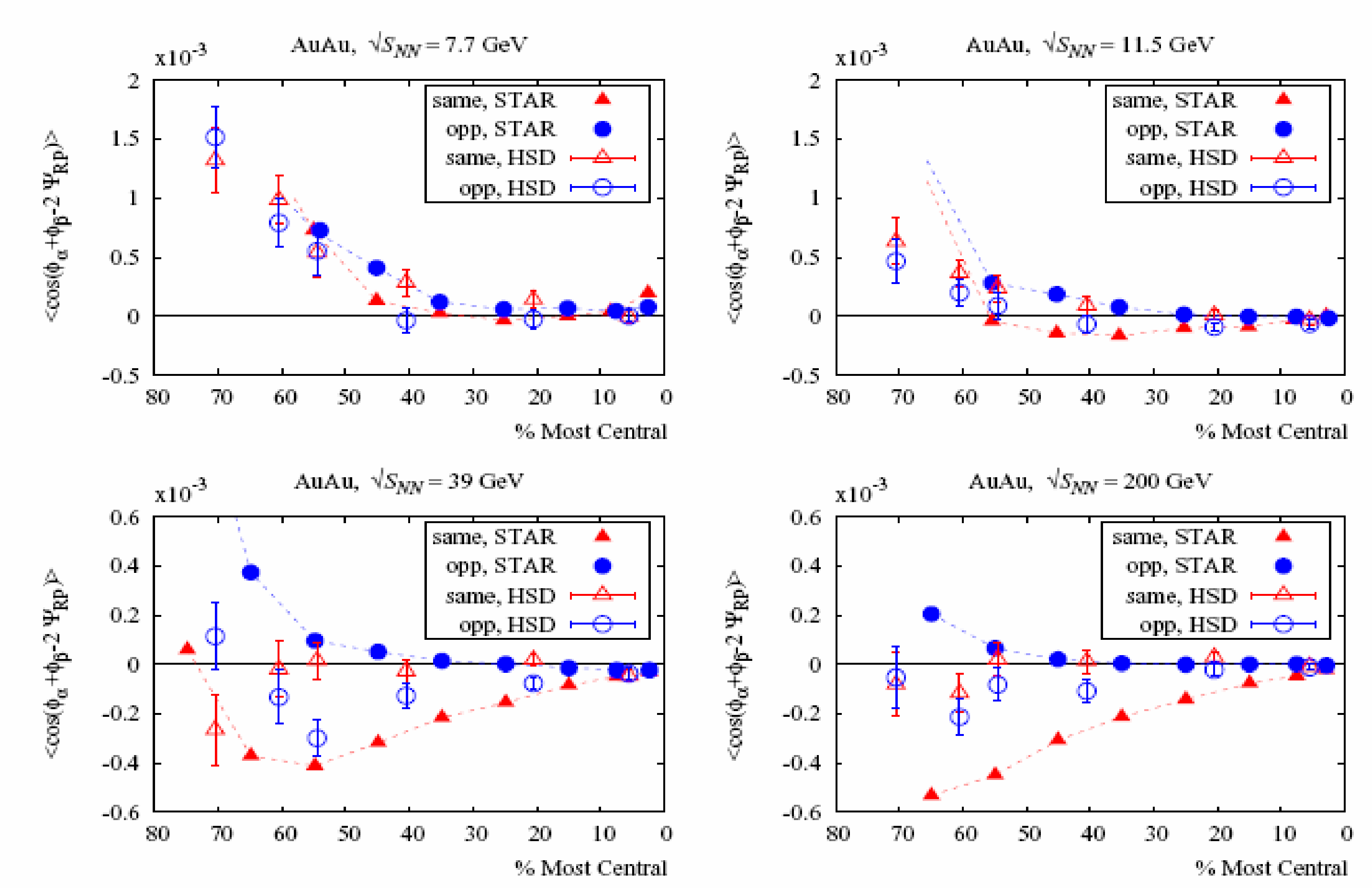
Collaboration

HIC for FAIR
Helmholtz International Center

Back up slides

Angular correlation wrt. reaction plane

$$\langle \cos(\psi_\alpha + \psi_\beta - 2\Psi_{RP}) \rangle$$



Angular correlation is of hadronic origin up to sqrt(s) = 11 GeV !

V. D. Toneev et al., PRC 85 (2012) 034910

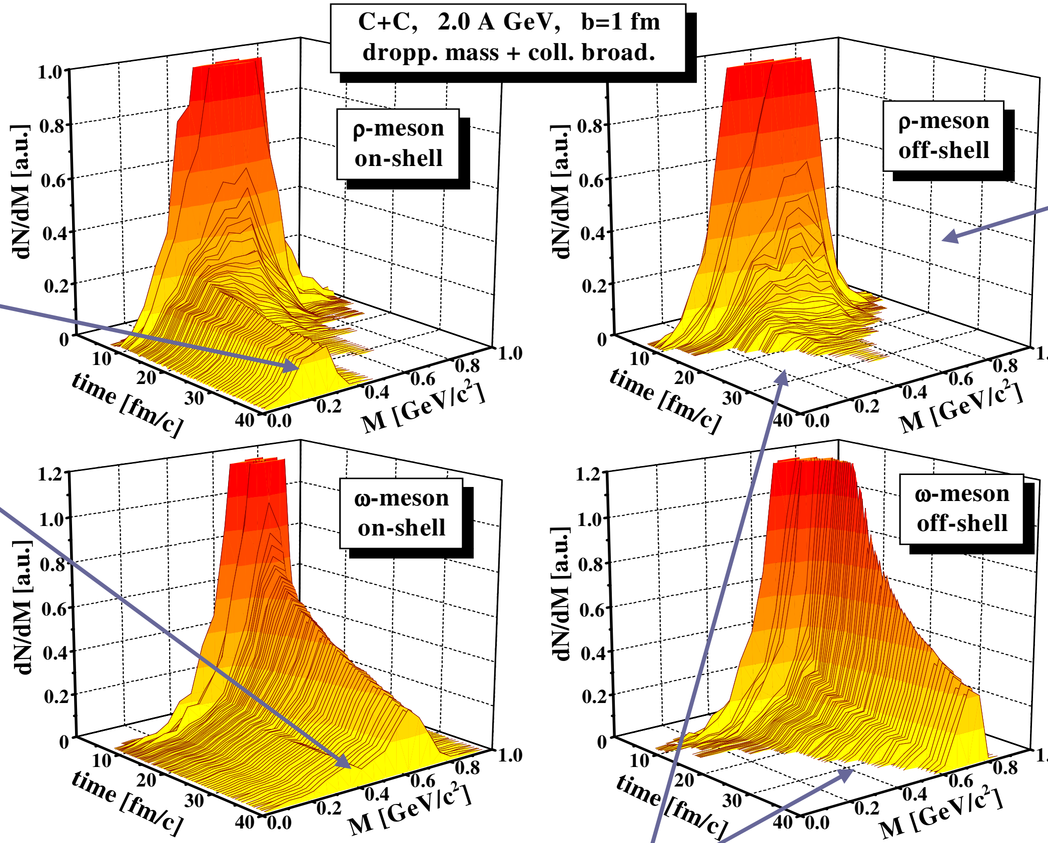
Off-shell vs. on-shell transport dynamics

Time evolution of the mass distribution of ρ and ω mesons for central C+C collisions (b=1 fm) at 2 A GeV for dropping mass + collisional broadening scenario

E.L.B. &W. Cassing, NPA 807 (2008) 214

On-shell

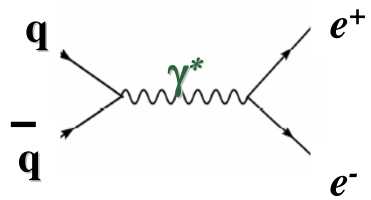
On-shell model: low mass ρ and ω mesons live forever and shine dileptons!



Off-shell

The off-shell spectral function becomes on-shell in the vacuum dynamically by propagation through the medium!

Off-shell LO q+qbar



$$\left(\frac{d^3\hat{\sigma}(q\bar{q}\to l^+l^-)}{dQ^2 dx_F dq_T^2}\right)^{\text{DY}}_{\text{on-shell}} = \frac{4\pi\alpha^2 e_q^2}{9Q^4}\frac{x_1x_2}{x_1+x_2}(1-x_1x_2)$$
$$\times\delta(q_T^2)\delta\left(Q^2-x_1x_2S_{NN}\right)\delta\left(x_F-\frac{x_2-x_1}{1-x_1x_2}\right)$$

$$Q^2 = s = x_1x_2S_{NN};$$
$$x_F = (x_2-x_1)/(1-x_1x_2)$$

$$\left(\frac{d^3\hat{\sigma}(m_1,m_2,\vec{p}_1,\vec{p}_2)}{dQ^2 dx_F dq_T^2}\right)^{DY}_{off-shell} =$$
$$\kappa'\left[2Q^4 - Q^2\left(m_1^2-6m_1m_2+m_2^2\right)-\left(m_1^2-m_2^2\right)^2\right]$$
$$\times\delta\left(Q^2-m_1^2-m_2^2-2(p_1\cdot p_2)\right)$$
$$\times\delta\left(x_F-\frac{\sqrt{s}}{s-Q^2}(p_{2z}-p_{1z})\right)$$
$$\times\delta\left(q_T^2-(\vec{p}_{1\perp}+\vec{p}_{2\perp})^2\right),$$

with

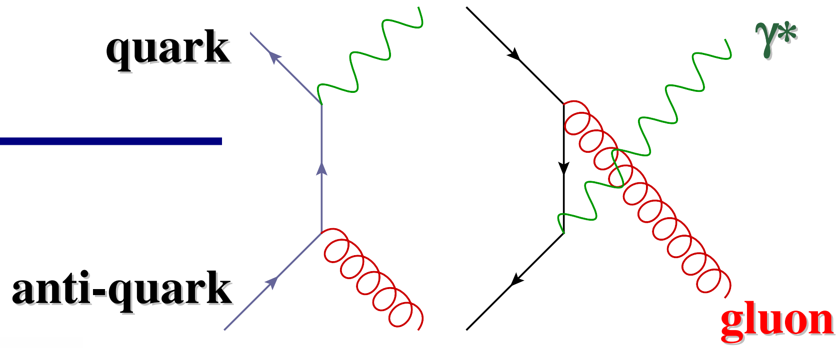
$$\kappa' = \frac{\pi\alpha^2 e_q^2}{3Q^4N_c\sqrt{(p_1\cdot p_2)^2-m_1^2m_2^2}}.$$

Note: In the limit of parton masses→0, the perturbative QCD result is recovered

O. L., S. Leupold, U. Mosel, PRD 75 (2007) 014016

Off-shell NLO q+qbar

$$\frac{d\sigma(l^+l^-)}{dQ^2dt} = \frac{\alpha}{3\pi Q^2}\frac{d\sigma(\gamma^*)}{dt}\sqrt{1-\frac{Q_0^2}{Q^2}}\left(1+\frac{Q_0^2}{2Q^2}\right)$$



$$d\sigma = \frac{\Sigma|\bar{M}_{i\to f}|^2\varepsilon_1\varepsilon_2\Pi\frac{d^3p_f}{(2\pi)^3}}{\sqrt{(p_1p_2)^2-m_1^2m_2^2}}(2\pi)^4\delta(p_1+p_2-\Sigma p_f)$$

$$M = M_a + M_b$$

$$\begin{aligned} M_a &= -e_qeg_sT^l_{ij}\frac{\epsilon_\nu(q)\epsilon_{\sigma l}(k)}{p_3^2-m_3^2} \\ &\times u_i(p_1,m_1)\left[\gamma^\nu(\hat{p}_3+m_3)\gamma^\sigma\right]v_j(p_2,m_2) \end{aligned}$$

$$\begin{aligned} M_b &= -e_qeg_sT^l_{ij}\frac{\epsilon_{\sigma l}(k)\epsilon_\nu(q)}{\bar{p_3}^2-m_3^2} \\ &\times u_i(p_1,m_1)\left[\gamma^\eta(\hat{\bar{p}}_3+m_3)\gamma^\nu\right]v_j(p_2,m_2) \end{aligned}$$

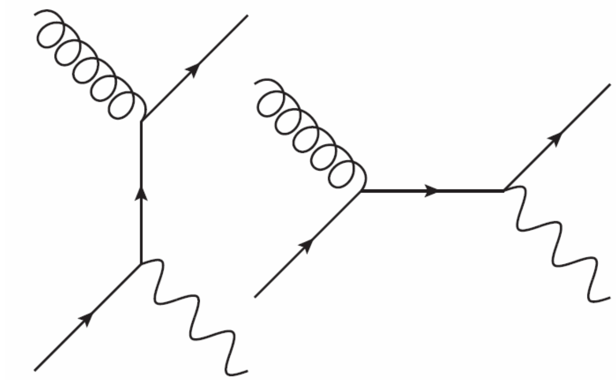
$$\sum|M|^2 = \sum M_a^*M_a + \sum M_b^*M_b + \sum M_a^*M_b + \sum M_b^*M_b.$$

$$\begin{aligned} \sum|M_a|^2 = -\frac{e_q^2e^2g_s^2\mathrm{Tr}\{T^2\}}{(p_3^2-m_3^2)^2}\Big[&\mathrm{Tr}\left\{\gamma_\sigma(\hat{p_3}+m_3)\gamma_\nu(\hat{p_1}+m_1)\gamma^\nu(\hat{p_3}+m_3)\gamma^\sigma(\hat{p_2}-m_2)\right\} \\ &-\frac{1}{Q^2}\mathrm{Tr}\left\{\gamma_\sigma(\hat{p_3}+m_3)\hat{q}(\hat{p_1}+m_1)\hat{q}(\hat{p_3}+m_3)\gamma^\sigma(\hat{p_2}-m_2)\right\} \\ &-\frac{A}{k^2}\mathrm{Tr}\left\{\hat{k}(\hat{p_3}+m_3)\gamma_\nu(\hat{p_1}+m_1)\gamma^\nu(\hat{p_3}+m_3)\hat{k}(\hat{p_2}-m_2)\right\} \\ &+\frac{A}{k^2Q^2}\mathrm{Tr}\left\{\hat{k}(\hat{p_3}+m_3)\hat{q}(\hat{p_1}+m_1)\hat{q}(\hat{p_3}+m_3)\hat{k}(\hat{p_2}-m_2)\right\}\Big] \end{aligned}$$

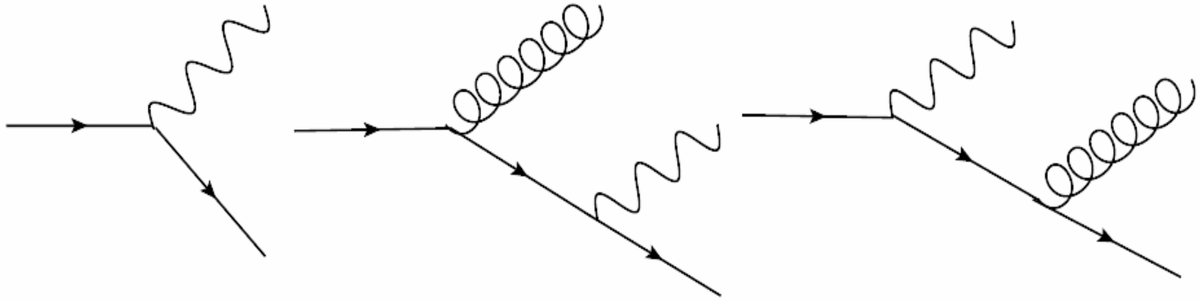
…etc. See details in

O. L., J.Phys.G38 (2011) 025105

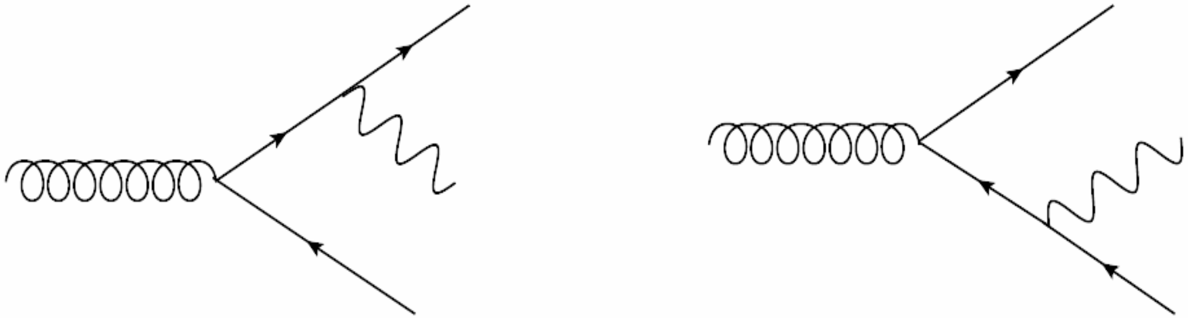
Sub-leading diagrams



Gluon Compton Scattering



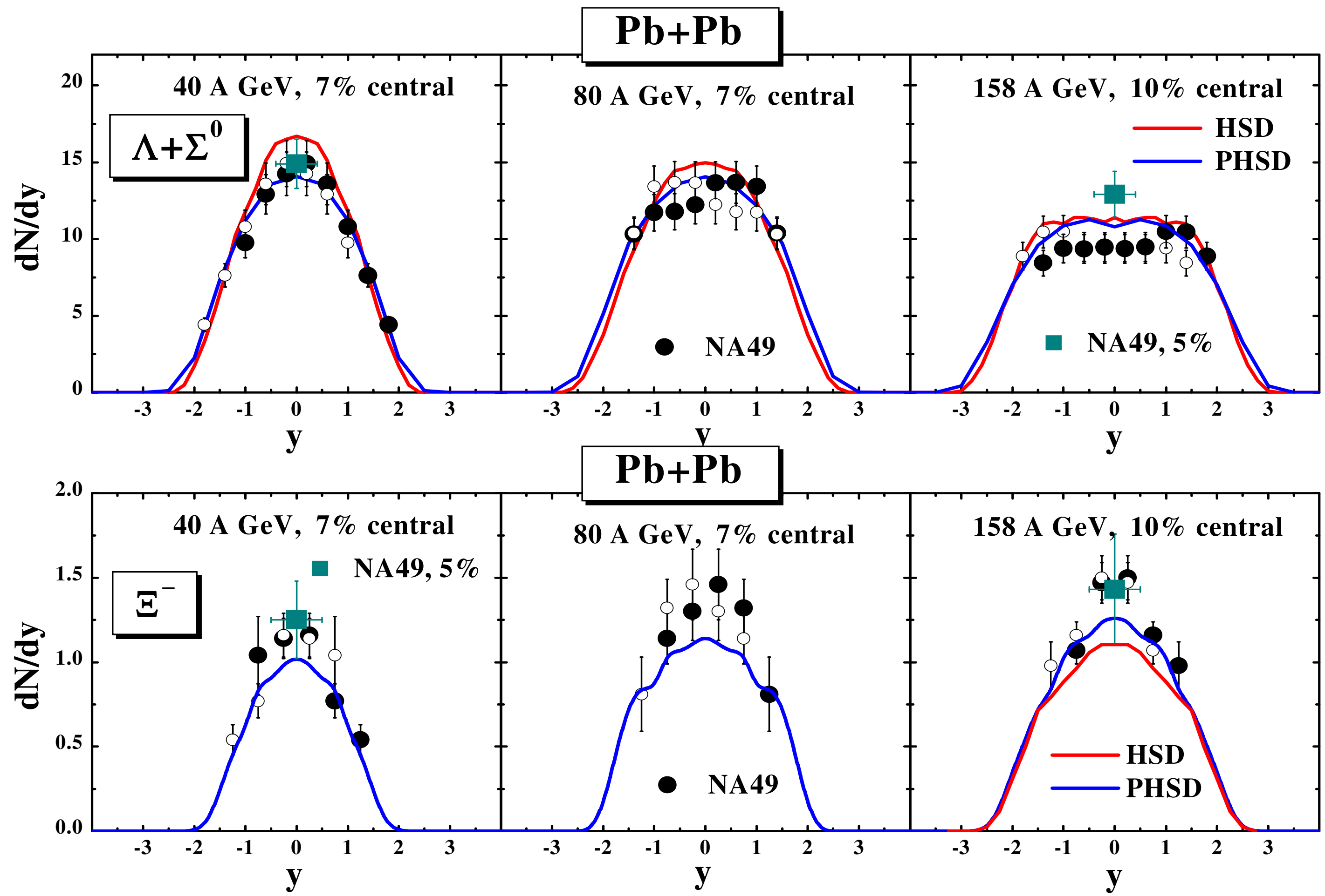
Virtual quark decay



Virtual gluon decay

O. L., J.Phys.G38 (2011) 025105

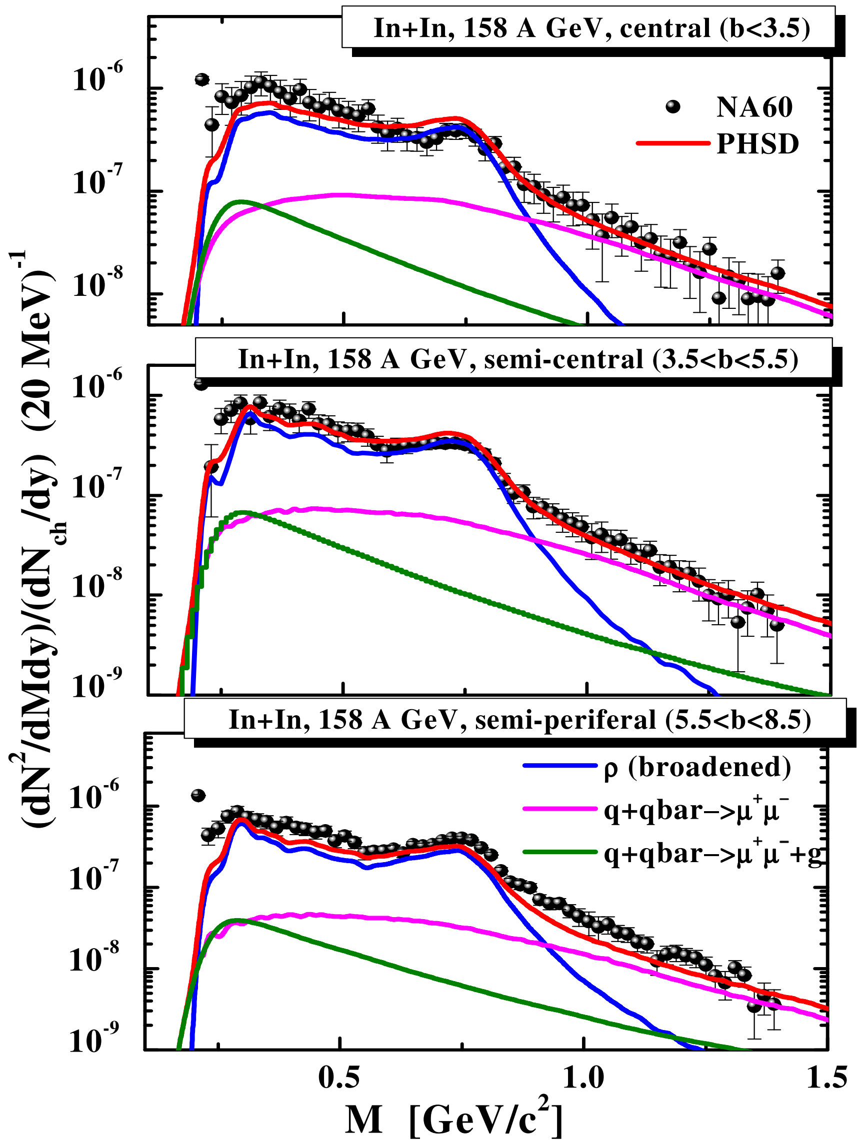
Rapidity distributions of strange baryons



➔ PHSD similar to HSD, reasonable agreement with data

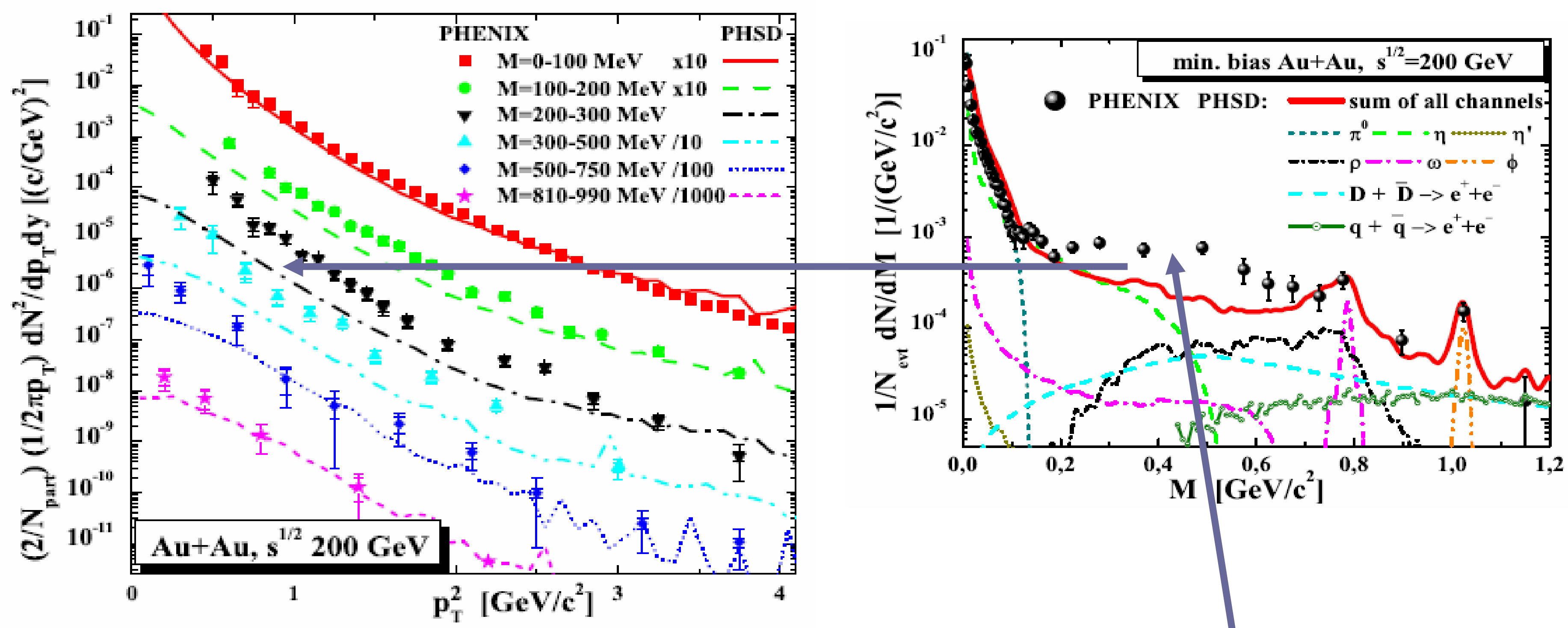
Cassing & Bratkovskaya, NPA 831 (2009) 215

Centrality dependent NA60 data



Dominant rho-channel at low and quark annihilation at intermediate masses !

PHENIX: p_T spectra



- The lowest and highest mass bins are described very well
- Underestimation of p_T data for 100<M<750 MeV bins consistent with dN/dM
- The ‘missing source’(?) is located at low p_T !

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

Dileptons from (in-medium) hadrons

Included channels:

- direct meson (Dalitz) decays of π_0, η, η`, $\rho$, $\omega$, $\phi$, J/$\Psi$, $\Psi$`
- correlated D+Dbar pairs
- radiation from seconday mesons ($\pi+\pi$, $\pi+\rho$, $\pi+\omega$, $\rho + \rho$, $\pi+a_1$)

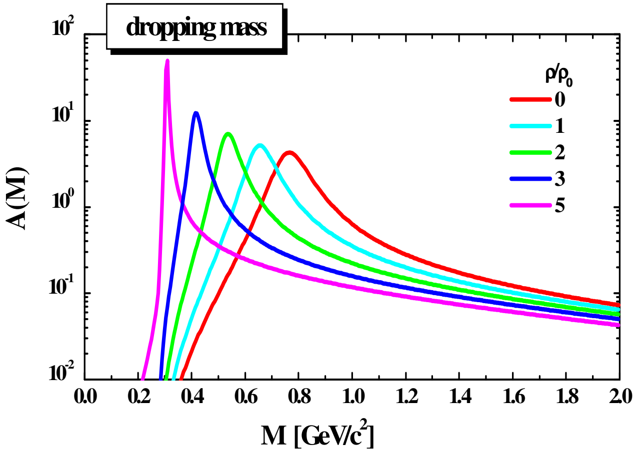
Full off-shell propagation of in-medium spectral functions through the hadronic medium

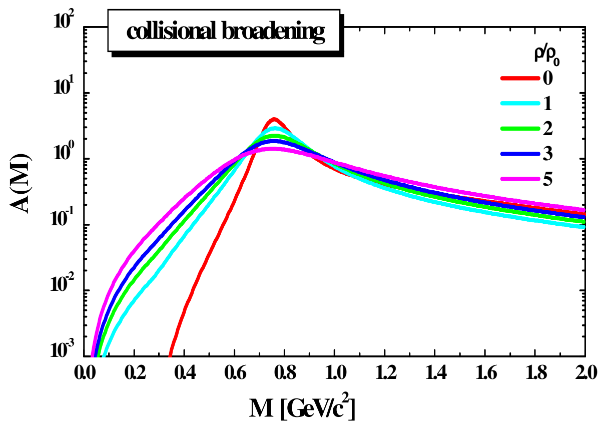
In-medium scenarios for ρ, ω, a_1:

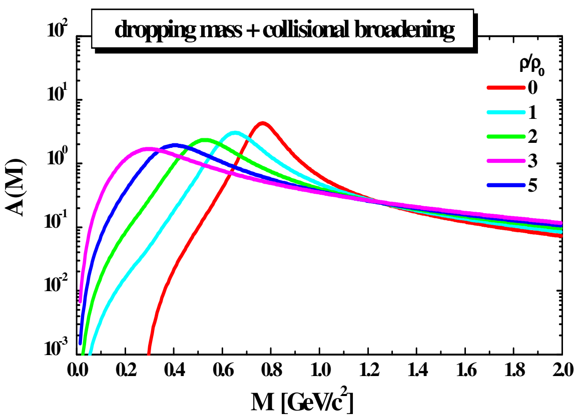
dropping mass — $m^*=m_0(1-\alpha\rho/\rho_0)$

collisional broadening — $\Gamma(M,\rho)=\Gamma_{vac}(M)+\Gamma_{CB}(M,\rho)$

dropping mass + coll. broad.



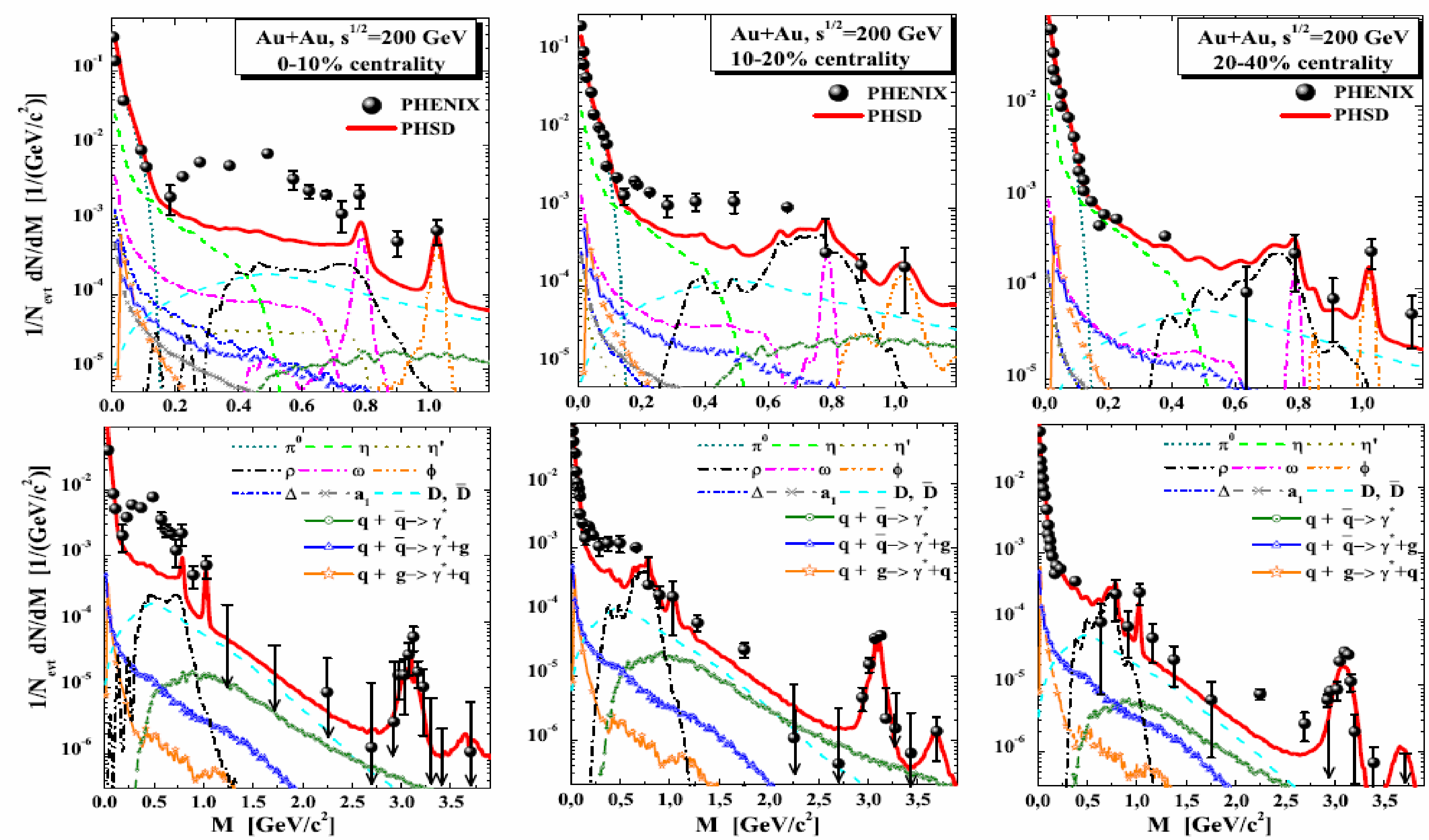




(Examples for ρ spectral functions.)

E. Bratkovskaya, W. Cassing, O. L., PLB 670 (2009) 428

PHENIX: mass spectra



(a)0-10% centrality (b)10-20% centrality (c)20-40% centrality

- Peripheral collisions (and pp) are well described, however, central fail!

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