FIAS Frankfurt Institute for Advanced Studies

HIC for FAIR Helmholtz International Center

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From hadrons to partons and back

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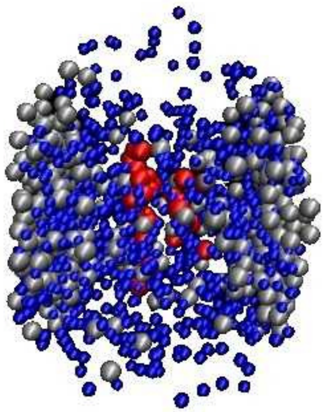
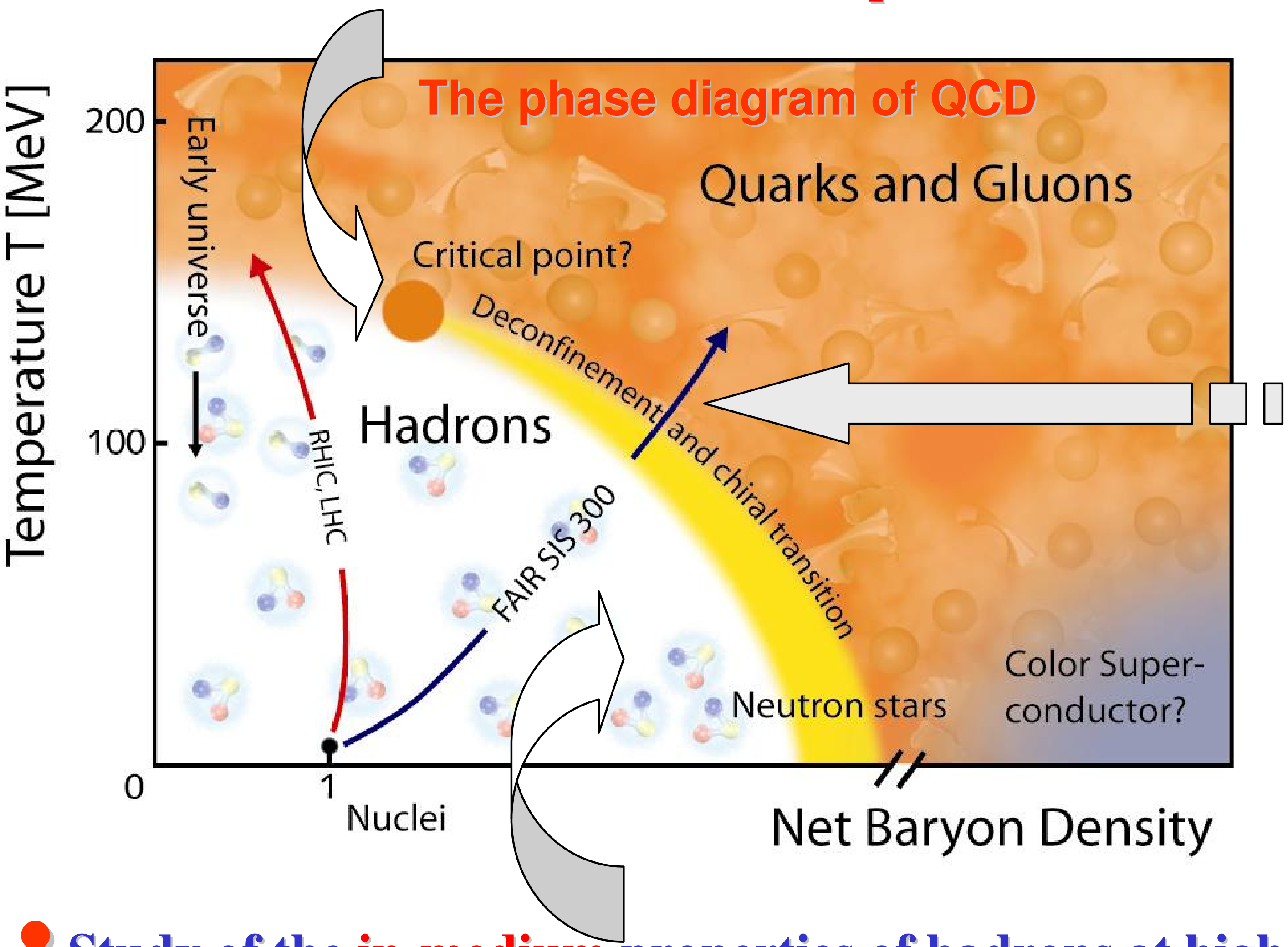


EMMI Nuclear and Quark Matter seminar, GSI, 9 July, 2014

PHSD

The holy grail of heavy-ion physics:

- Search for the critical point



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

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

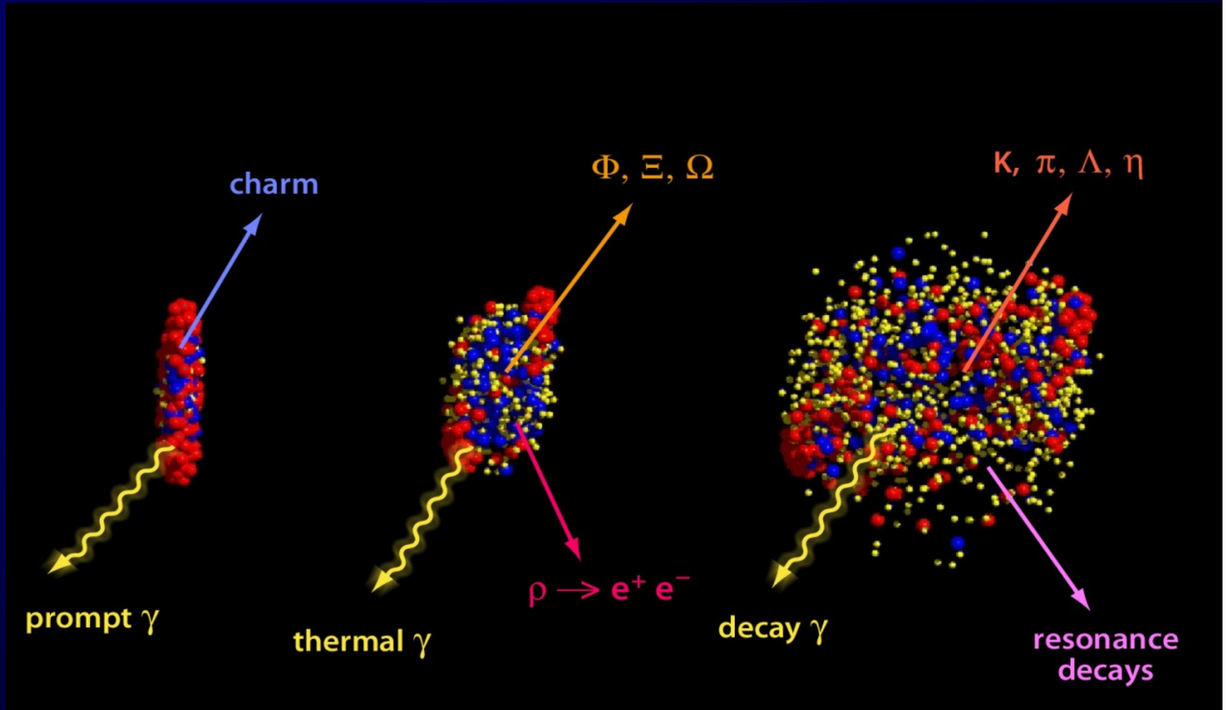
Signals of the phase transition:

- Multi-strange particle enhancement in A+A
- Charm suppression
- Collective flow (v_1, v_2, v_3, v_4)
- Thermal dileptons
- Jet quenching and angular correlations
- High p_T suppression of hadrons
- Nonstatistical event by event fluctuations and correlations
- Chiral Magnetic Effect

Experiment: measures final hadrons and leptons

How to learn about physics from data?

Compare with theory!



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

Semi-classical BUU equation

Ludwig Boltzmann

Boltzmann -Uehling-Uhlenbeck equation (non-relativistic formulation)
- propagation of particles in the **self-generated Hartree-Fock mean-field potential** $U(r,t)$ with an on-shell **collision term:**

$$\frac{\partial}{\partial t} f(\vec{r},\vec{p},t) + \frac{\vec{p}}{m}\vec{\nabla}_{\vec{r}}\, f(\vec{r},\vec{p},t) - \vec{\nabla}_{\vec{r}} U(\vec{r},t)\, \vec{\nabla}_{\vec{p}} f(\vec{r},\vec{p},t) = \left(\frac{\partial f}{\partial t}\right)_{coll}$$

collision term: elastic and inelastic reactions

$f(\vec{r},\vec{p},t)$ is the **single particle phase-space distribution function**
- probability to find the particle at position r with momentum p at time t

- self-generated **Hartree-Fock mean-field potential:**

$$U(\vec{r},t) = \frac{1}{(2\pi\hbar)^3} \sum_{\beta_{occ}} \int d^3r'\, d^3p\;\, V(\vec{r}-\vec{r}',t)\, f(\vec{r}',\vec{p},t) + (Fock\ term)$$

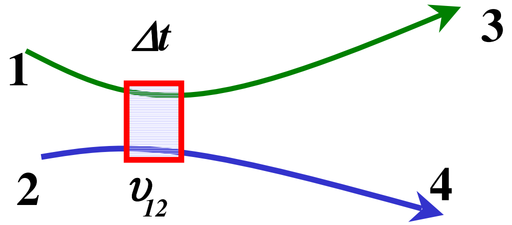
- **Collision term** for 1+2→3+4 (let's consider fermions) :

$$I_{coll} = \frac{4}{(2\pi)^3} \int d^3p_2\, d^3p_3 \int d\Omega\; |v_{12}|\, \delta^3(\vec{p}_1 + \vec{p}_2 - \vec{p}_3 - \vec{p}_4) \cdot \frac{d\sigma}{d\Omega}(1+2 \rightarrow 3+4) \cdot P$$

Probability including **Pauli blocking of fermions:**

$$P = f_3 f_4 (1-f_1)(1-f_2) - f_1 f_2 (1-f_3)(1-f_4)$$

Gain term: 3+4→1+2 — Loss term: 1+2→3+4



Dynamical description of strongly interacting systems

- **Semi-classical BUU** ➔ **solution for weakly interacting systems of particles**

How to describe strongly interacting systems?!

- **Quantum field theory ➔**

Kadanoff-Baym dynamics for resummed(!) single-particle Green functions $S^<$

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

(1962)

Integration over the intermediate spacetime

Green functions $S^<$/self-energies Σ:

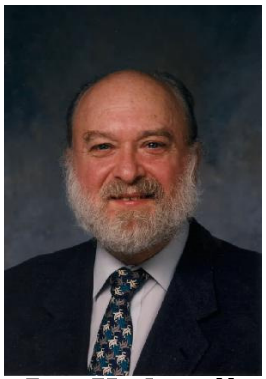
$$iS^<_{xy} = \eta \langle \{ \Phi^+(y) \Phi(x) \} \rangle$$
$$iS^>_{xy} = \langle \{ \Phi(y) \Phi^+(x) \} \rangle$$
$$iS^c_{xy} = \langle T^c \{ \Phi(x) \Phi^+(y) \} \rangle \quad - causal$$
$$iS^a_{xy} = \langle T^a \{ \Phi(x) \Phi^+(y) \} \rangle \quad - anticausal$$

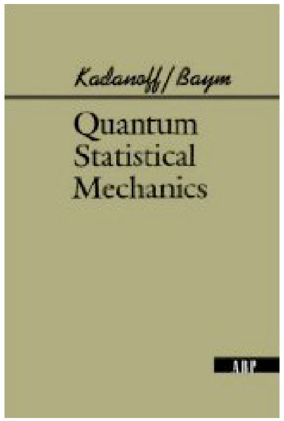
$$S^{ret}_{xy} = S^c_{xy} - S^<_{xy} = S^>_{xy} - S^a_{xy} \quad - retarded$$
$$S^{adv}_{xy} = S^c_{xy} - S^>_{xy} = S^<_{xy} - S^a_{xy} \quad - advanced$$

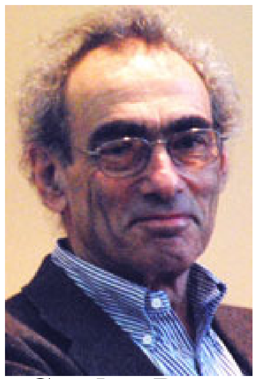
$$\hat{S}^{-1}_{0x} \equiv -(\partial^\mu_x \partial^x_\mu + M_0^2)$$

$$\eta = \pm 1 (bosons \,/\, fermions)$$

$$T^a (T^c) - (anti-) time - ordering \ operator$$


Leo Kadanoff




Gordon Baym

From Kadanoff-Baym equations to generalized 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 (GTE):

drift term — Vlasov term — backflow term — collision term = 'loss' term - 'gain' term

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

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

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

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

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

$\Gamma_{XP} = -Im\,\Sigma^{ret}_{XP}$ – 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

General testparticle off-shell equations of motion

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

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 for the time-like particles:

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

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

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

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

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

Collision term in off-shell transport models

Collision term for reaction 1+2->3+4:

$$I_{coll}(X,\vec{P},M^2) = Tr_2 Tr_3 Tr_4 A(X,\vec{P},M^2) A(X,\vec{P}_2,M_2^2) A(X,\vec{P}_3,M_3^2) A(X,\vec{P}_4,M_4^2)$$

$$|G((\vec{P},M^2)+(\vec{P}_2,M_2^2)\rightarrow(\vec{P}_3,M_3^2)+(\vec{P}_4,M_4^2))|^2_{\mathcal{A},\mathcal{S}}\ \delta^{(4)}(P+P_2-P_3-P_4)$$

$$[\,N_{X\vec{P}_3M_3^2}\,N_{X\vec{P}_4M_4^2}\,\bar{f}_{X\vec{P}M^2}\,\bar{f}_{X\vec{P}_2M_2^2} - N_{X\vec{P}M^2}\,N_{X\vec{P}_2M_2^2}\,\bar{f}_{X\vec{P}_3M_3^2}\,\bar{f}_{X\vec{P}_4M_4^2}\,]$$

with $\bar{f}_{X\vec{P}M^2} = 1 + \eta\, N_{X\vec{P}M^2}$ and $\eta = \pm 1$ for bosons/fermions, respectively.

The trace over particles 2,3,4 reads explicitly

for fermions

$$Tr_2 = \sum_{\sigma_2,\tau_2} \frac{1}{(2\pi)^4} \int d^3P_2 \frac{dM_2^2}{2\sqrt{\vec{P}_2^2+M_2^2}}$$

for bosons

$$Tr_2 = \sum_{\sigma_2,\tau_2} \frac{1}{(2\pi)^4} \int d^3P_2 \frac{dP_{0,2}^2}{2}$$

additional integration

The transport approach and the particle spectral functions are fully determined once the in-medium transition amplitudes G are known in their off-shell dependence!

Detailed balance on the level of 2<–>n: treatment of multi-particle collisions in transport approaches

W. Cassing, NPA 700 (2002) 618

Generalized collision integral for n <-> m reactions:

$$I_{coll} = \sum_n \sum_m \; I_{coll}[n \leftrightarrow m]$$

$$I^i_{coll}[n \leftrightarrow m] =$$

$$\frac{1}{2} N_n^m \sum_\nu \sum_\lambda \left(\frac{1}{(2\pi)^4}\right)^{n+m-1} \int \left(\prod_{j=2}^{n} d^4p_j \;\; A_j(x,p_j)\right) \left(\prod_{k=1}^{m} d^4p_k \; A_k(x,p_k)\right)$$

$$\times A_i(x,p) \; W_{n,m}(p,p_j;i,\nu \mid p_k;\lambda) \; (2\pi)^4 \; \delta^4(p^\mu + \sum_{j=2}^{n} p_j^\mu - \sum_{k=1}^{m} p_k^\mu)$$

$$\times [\tilde{f}_i(x,p) \prod_{k=1}^{m} f_k(x,p_k) \prod_{j=2}^{n} \tilde{f}_j(x,p_j) - f_i(x,p) \prod_{j=2}^{n} f_j(x,p_j) \prod_{k=1}^{m} \tilde{f}_k(x,p_k)].$$

$\tilde{f} = 1 + \eta f$ **is Pauli-blocking or Bose-enhancement factors; η=1 for bosons and η=–1 for fermions**

$W_{n,m}(p,p_j;i,\nu \mid p_k;\lambda)$ **is a transition probability**

Anti-barion production in heavy-ion reactions

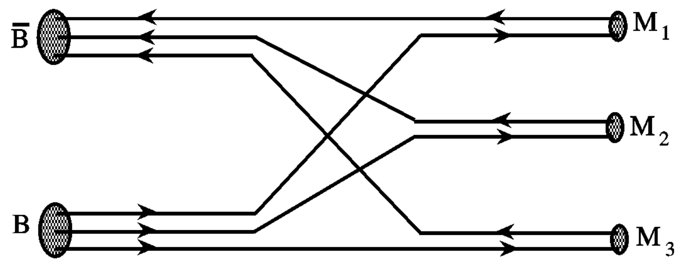
W. Cassing, NPA 700 (2002) 618

Multi-meson fusion reactions

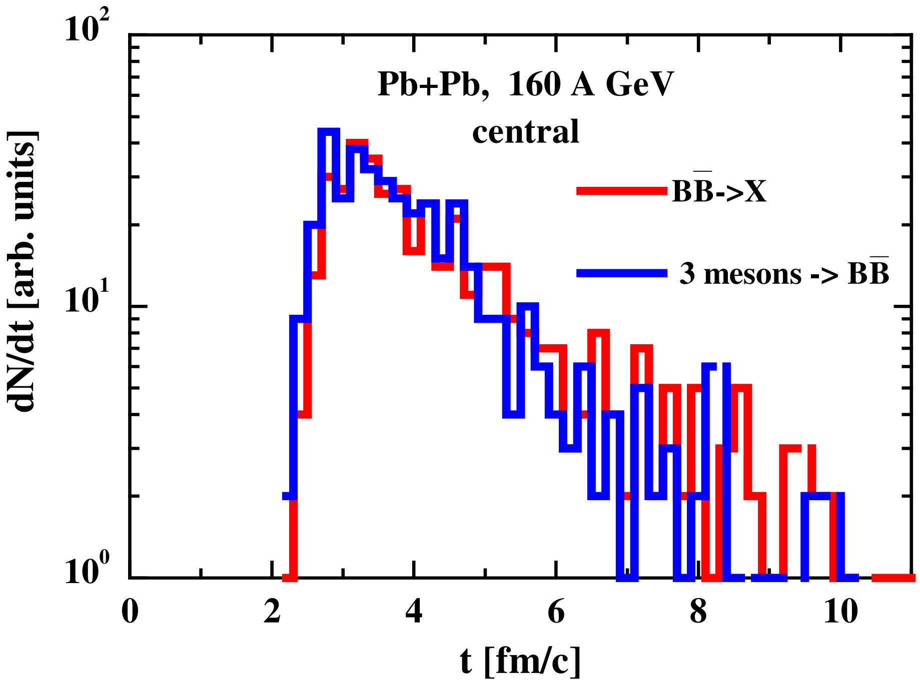
$m_1+m_2+...+m_n \leftrightarrow B+Bbar$

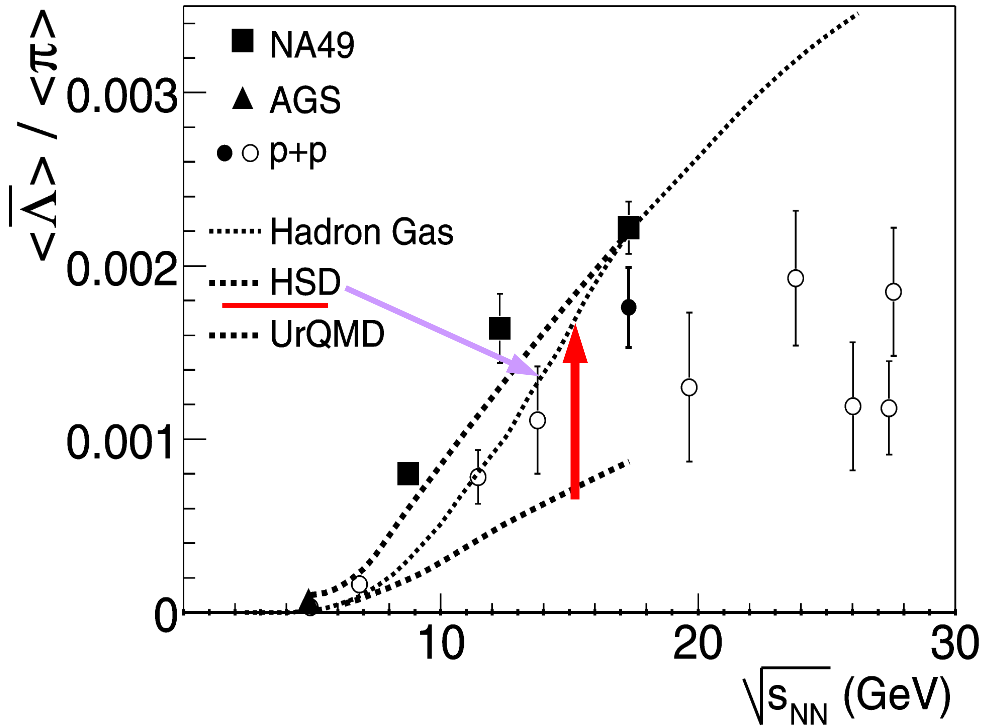
(m=π,ρ,ω,..)

important for antiproton, antilambda dynamics !

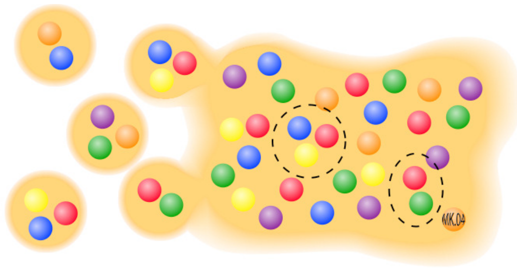


2<–>3





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)

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

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

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

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

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

  - **gluons:**

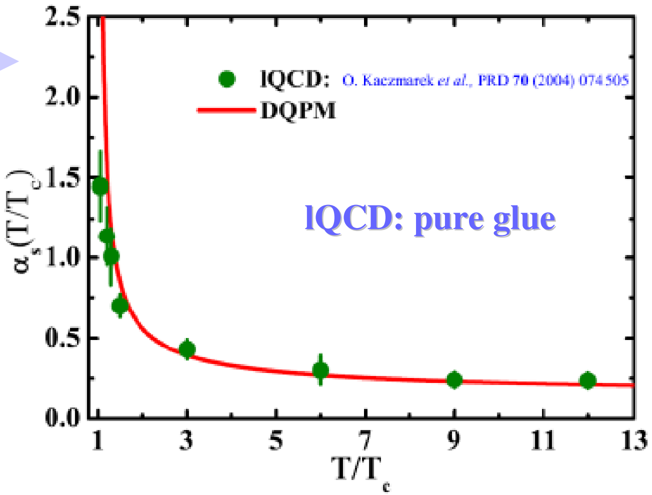
$$M_g^2(T) = \frac{g^2}{6}\left(\left(N_c + \frac{N_f}{2}\right)T^2 + \frac{N_c}{2}\sum_q \frac{\mu_q^2}{\pi^2}\right)$$

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

$N_c = 3$, $N_f=3$

- **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)**

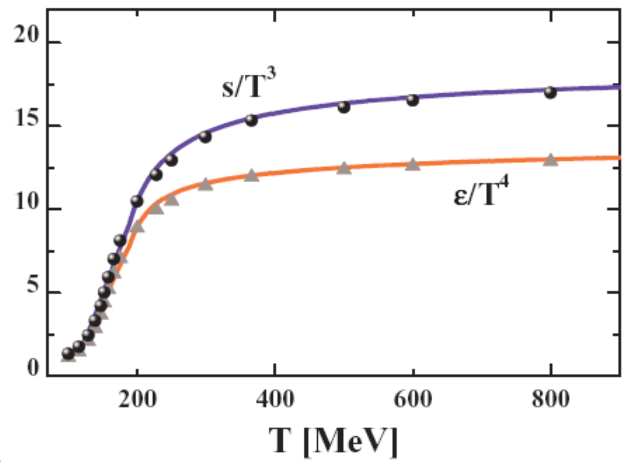
with 3 parameters: T_s/T_c=0.46; c=28.8; λ=2.42
(for pure glue N_f=0)

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

The Dynamical QuasiParticle Model (DQPM)

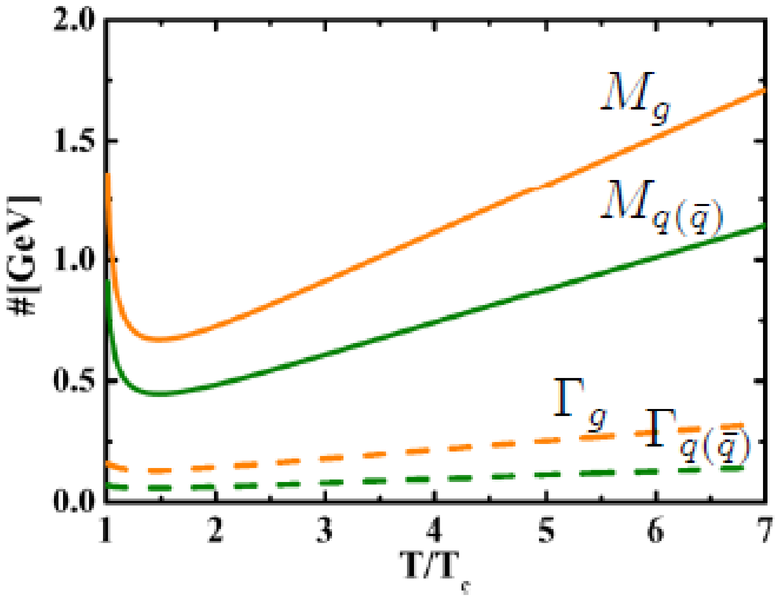
➢ **fit to lattice (lQCD) results** (e.g. entropy density)

* BMW lQCD data S. Borsanyi et al., JHEP 1009 (2010) 073

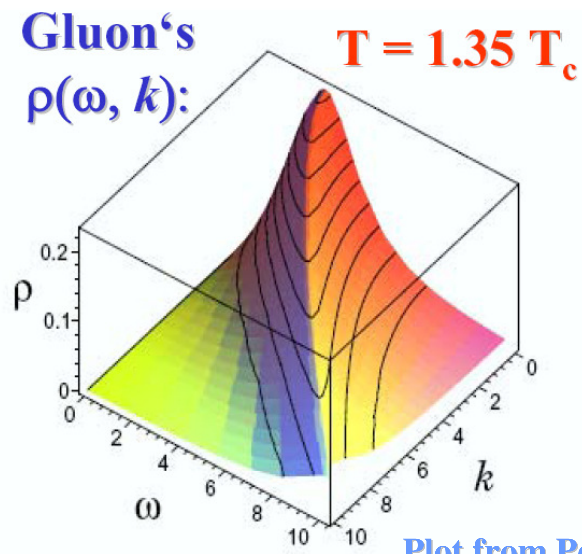


➔ **Quasiparticle properties:**

- large width and mass for gluons and quarks



T_C=158 MeV
ε_C=0.5 GeV/fm³

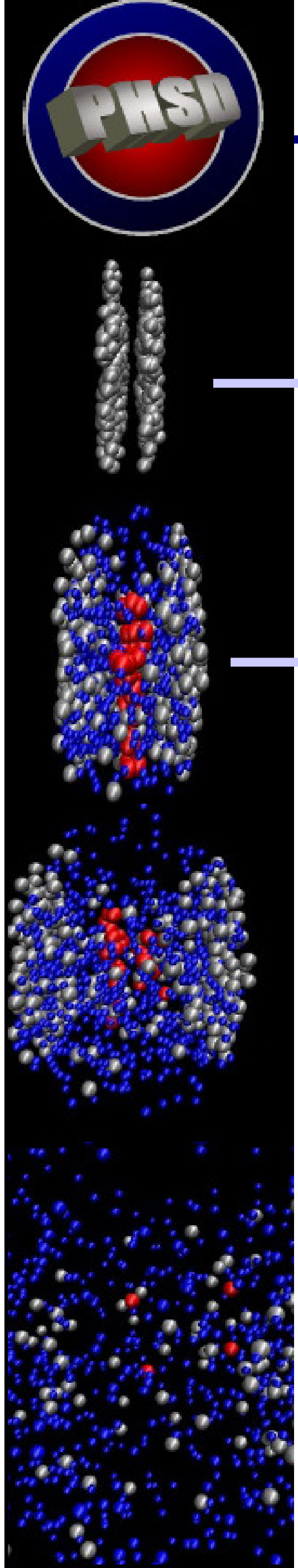


Plot from Peshier, PRD 70 (2004) 034016

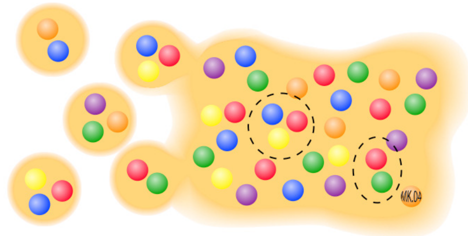
- **DQPM** matches well lattice QCD
- **DQPM** provides mean-fields (1PI) for gluons and quarks as well as effective 2-body interactions (2PI)
- **DQPM** gives transition rates for the formation of hadrons → PHSD

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

I. PHSD - basic concept



I. From hadrons to QGP:



- Initial A+A collisions – as in HSD:
  - string formation in primary NN collisions
  - string decay to pre-hadrons (B - baryons, m - mesons)

- Formation of QGP stage by dissolution of pre-hadrons (all new produced secondary hadrons) into massive colored quarks + mean-field energy

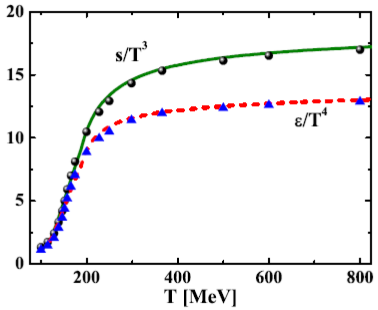
QGP phase: $\varepsilon > \varepsilon_{critical}$

$$B \rightarrow qqq,\ m \rightarrow q\bar{q} \quad \forall \quad U_q$$

based on the Dynamical Quasi-Particle Model (DQPM) which defines quark spectral functions, i.e. masses $M_q(\varepsilon)$ and widths $\Gamma_q(\varepsilon)$

+ mean-field potential U_q at given ε – local energy density

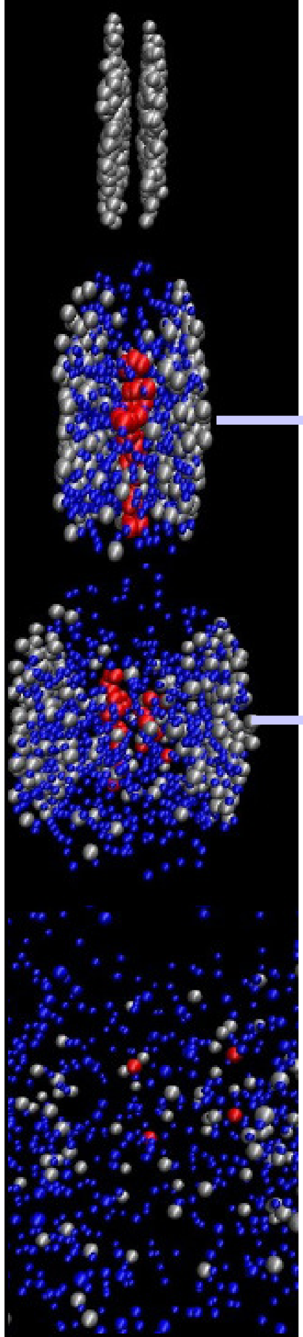
(ε related by lQCD EoS to T - temperature in the local cell)



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

II. PHSD - basic concept

II. Partonic phase - QGP:

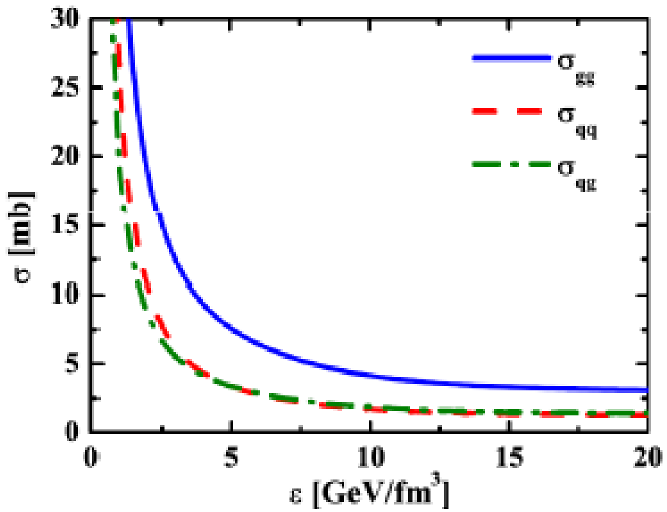


quarks and gluons (= ‚dynamical quasiparticles‘)
with off-shell spectral functions (width, mass) defined by the DQPM

- **in self-generated mean-field potential for quarks and gluons U_q, U_g from the DQPM**
- **EoS of partonic phase: ‚crossover‘ from lattice QCD (fitted by DQPM)**
- **(quasi-) elastic and inelastic parton-parton interactions:**
  using the effective cross sections from the DQPM

- **(quasi-) elastic collisions:**

$$q+q \to q+q \qquad g+q \to g+q$$
$$q+\bar{q} \to q+\bar{q} \qquad g+\bar{q} \to g+\bar{q}$$
$$\bar{q}+\bar{q} \to \bar{q}+\bar{q} \qquad g+g \to g+g$$



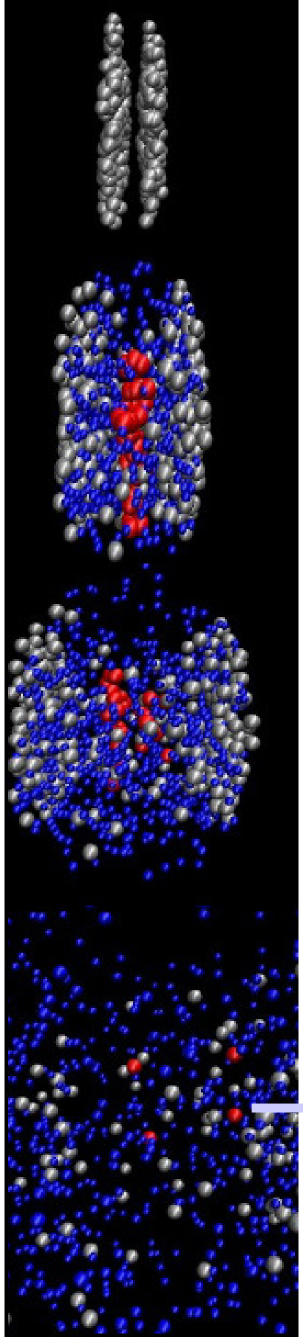
- **inelastic collisions:**
  (Breight-Wigner cross sections)

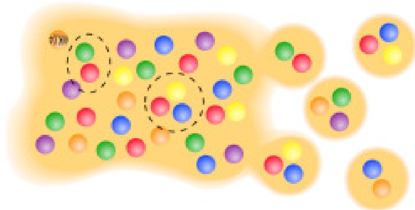
$$q+\bar{q} \to g$$
$$g \to q+\bar{q}$$

$$q+\bar{q} \to g+g$$
$$g \to g+g$$

suppressed (<1%) due to the large mass of gluons

III. PHSD - basic concept





III. Hadronization:

❑ **Hadronization: based on DQPM**

- massive, off-shell (anti-)quarks with broad spectral functions hadronize to off-shell mesons and baryons or color neutral excited states - ‚strings‘ (strings act as ‚doorway states‘ for hadrons)

$$g \rightarrow q + \bar{q}, \qquad q + \bar{q} \leftrightarrow meson\,('string')$$
$$q + q + q \leftrightarrow baryon\,('string')$$

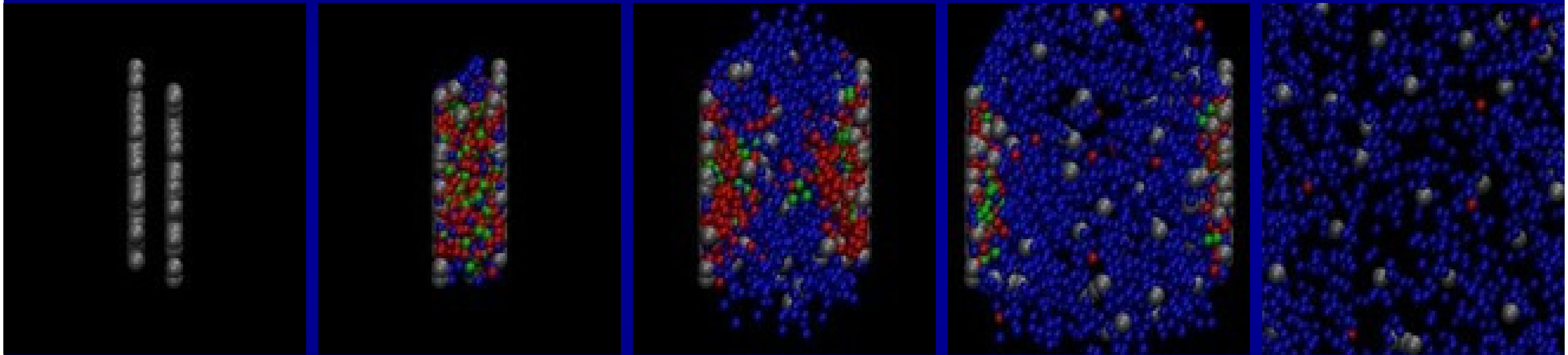
- **Local covariant off-shell transition rate for q+qbar fusion**
  ➔ **meson formation:**

$$\frac{dN^{q+\bar{q}\rightarrow m}}{d^4x\, d^4p} = Tr_q Tr_{\bar{q}}\, \delta^4(p - p_q - p_{\bar{q}})\, \delta^4\!\left(\frac{x_q + x_{\bar{q}}}{2} - x\right) \delta(flavor, color)$$
$$\cdot N_q(x_q, p_q) N_{\bar{q}}(x_{\bar{q}}, p_{\bar{q}}) \cdot \omega_q \rho_q(p_q) \cdot \omega_{\bar{q}} \rho_{\bar{q}}(p_{\bar{q}}) \cdot |M_{q\bar{q}}|^2\, W_m\!\left(x_q - x_{\bar{q}}, p_q - p_{\bar{q}}\right)$$

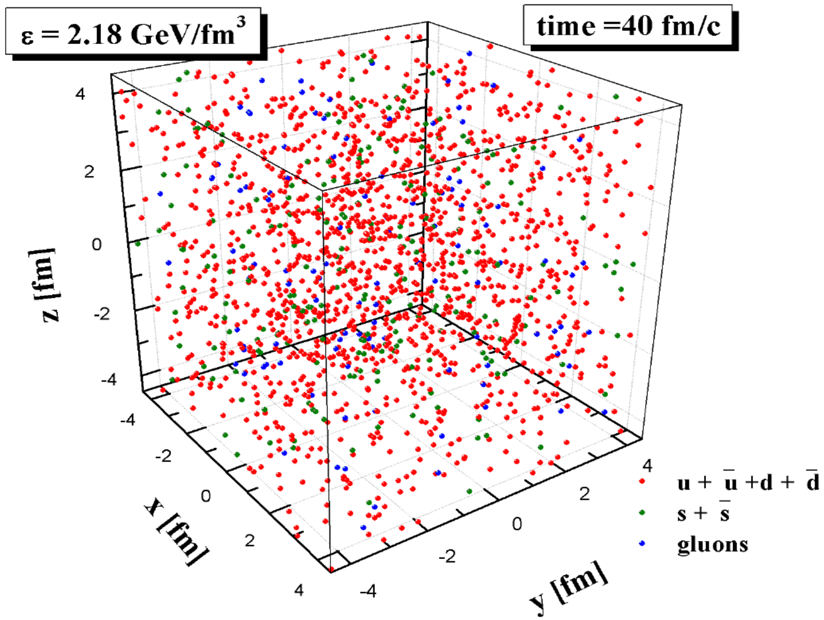
- ❑ $N_j(x,p)$ is the phase-space density of parton j at space-time position x and 4-momentum p
- ❑ W_m is the phase-space distribution of the formed ‚pre-hadrons‘ (Gaussian in phase space)
- ❑ $|M_{qq}|^2$ is the effective quark-antiquark interaction from the DQPM

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

Au+Au, 21.3 TeV, central



Properties of QGP in-equilibrium using PHSD



Properties of parton-hadron matter in-equilibrium

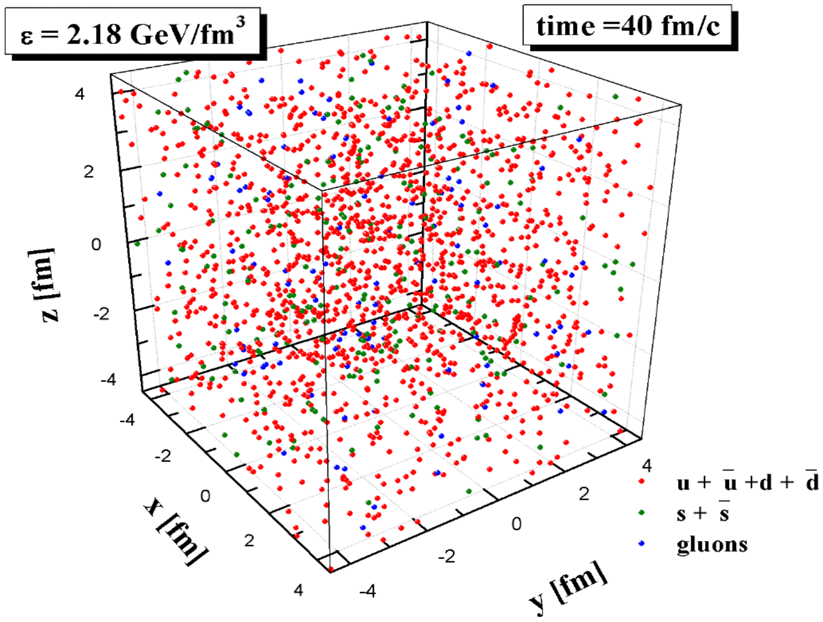
V. Ozvenchuk et al., PRC 87 (2013) 024901, arXiv:1203.4734
V. Ozvenchuk et al., PRC 87 (2013) 064903, arXiv:1212.5393

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



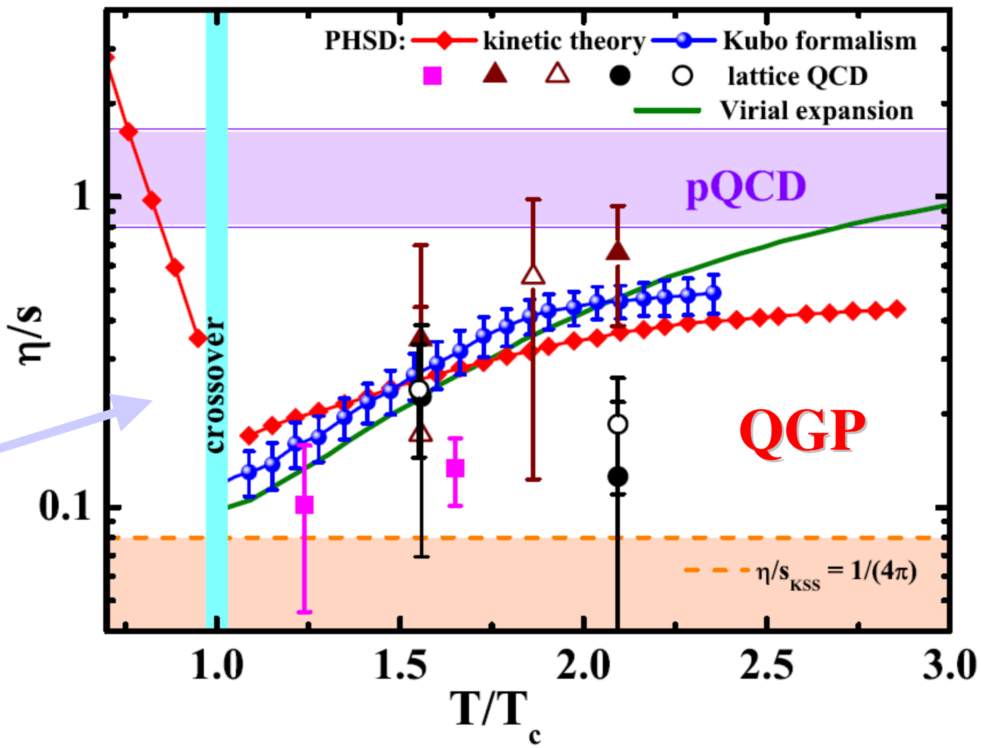
Properties of parton-hadron matter – shear viscosity

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., PRC 87 (2013) 064903

Bulk viscosity (mean-field effects)

- bulk viscosity in relaxation time approximation with mean-field effects:

Chakraborty, Kapusta, Phys. Rev.C 83, 014906 (2011).

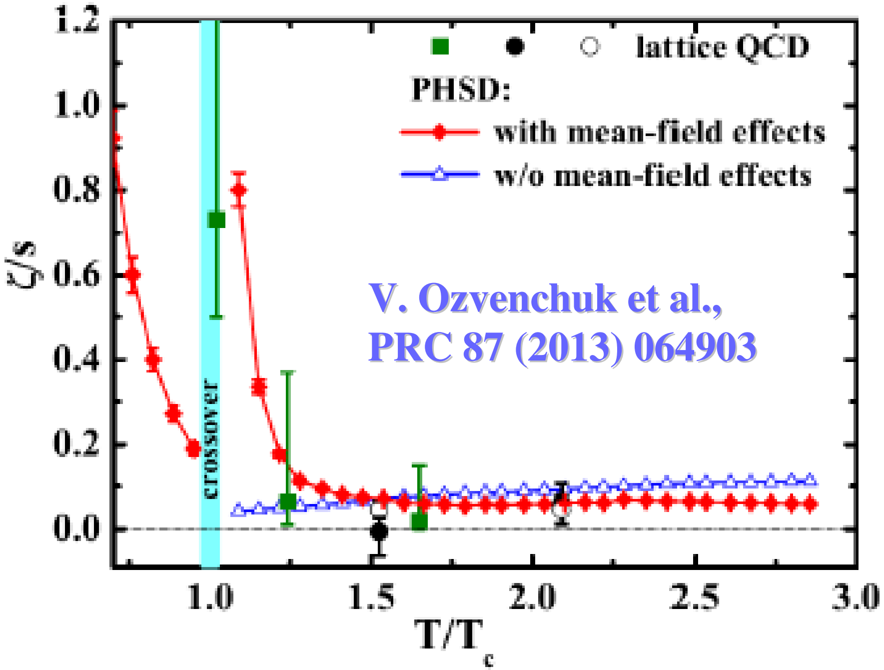
$$\zeta = \frac{1}{TV}\sum_{i=1}^{N}\frac{\Gamma_i^{-1}}{E_i^2}\left[\left(\frac{1}{3}-v_s^2\right)|\mathrm{p}|^2 - v_s^2\left(m_i^2 - T^2\frac{dm_i^2}{dT^2}\right)\right]^2$$

use DQPM results for masses for μ_q=0:

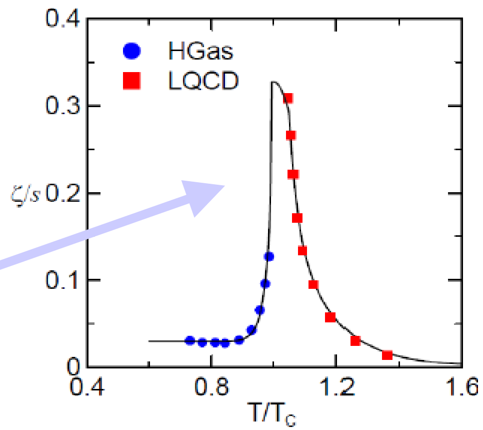
$$m_q^2 = \frac{1}{3}g^2T^2, \qquad m_g^2 = \frac{3}{4}g^2T^2$$

PHSD using the relaxation time approximation:

- significant rise in the vicinity of the critical temperature
- in line with the ratio from lQCD calculations



V. Ozvenchuk et al., PRC 87 (2013) 064903



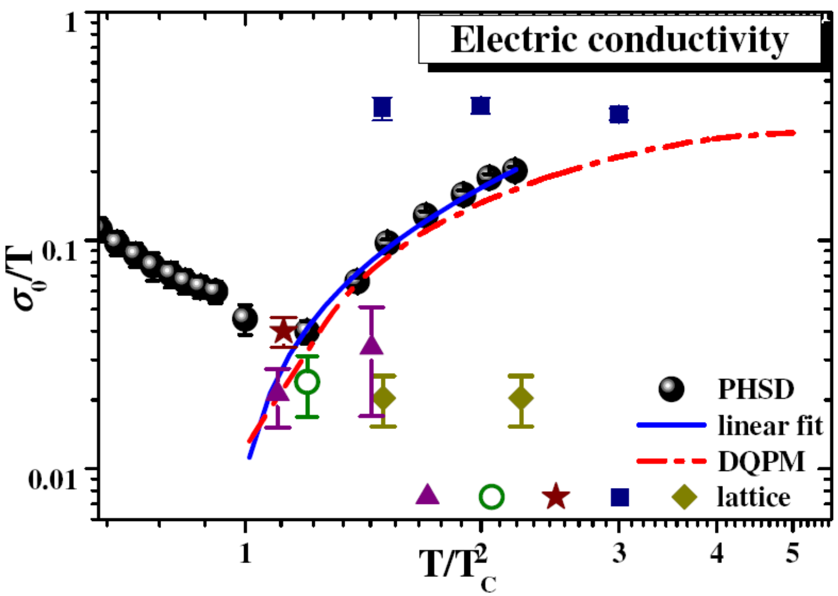
Plot from Gabriel Denicol

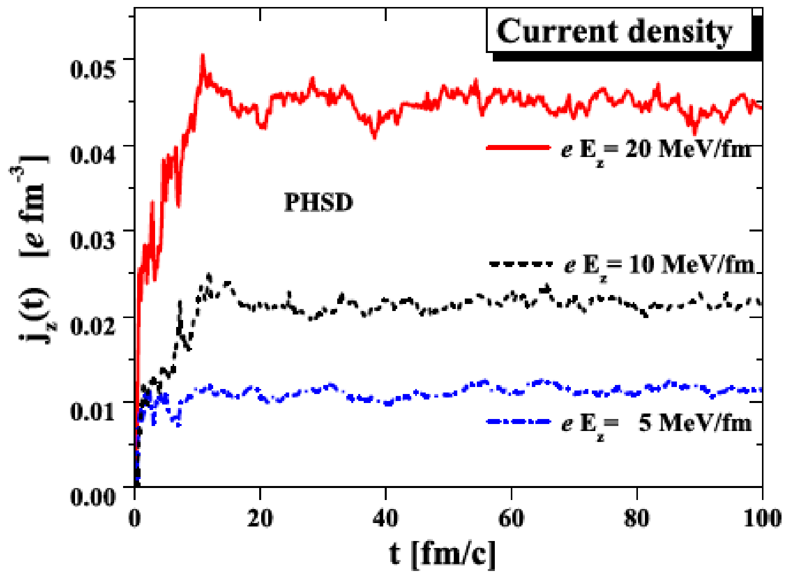
lQCD: Meyer, Phys. Rev. Lett. 100, 162001 (2008); Sakai,Nakamura, Pos LAT2007, 221 (2007).

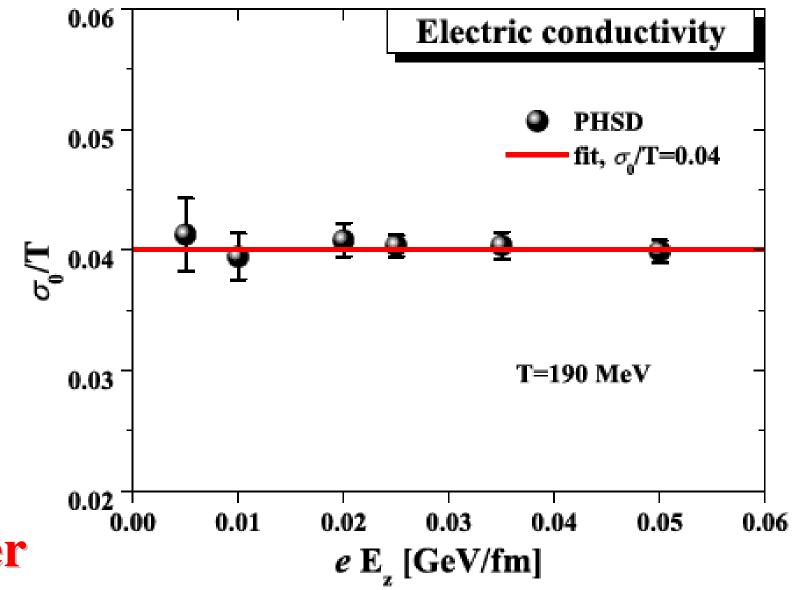
Properties of parton-hadron matter – electric conductivity

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

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



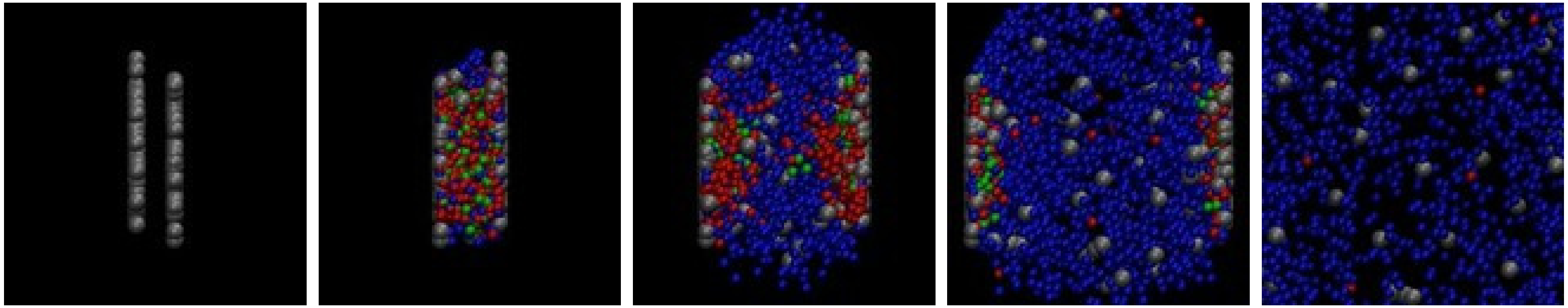




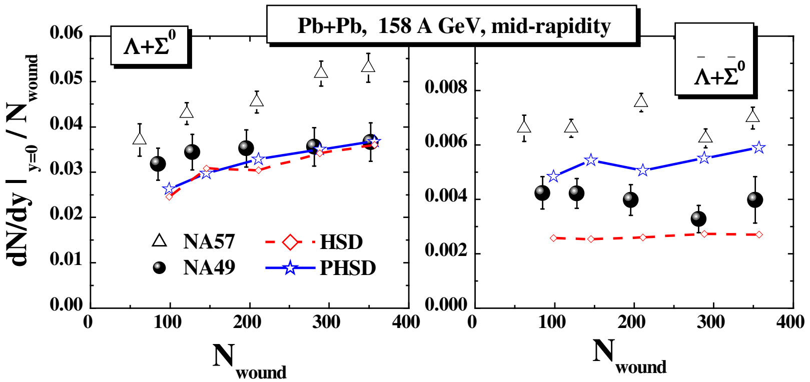
- the QCD matter even at T~ T_c is a much better electric conductor than Cu or Ag (at room temperature) by a factor of 500 !

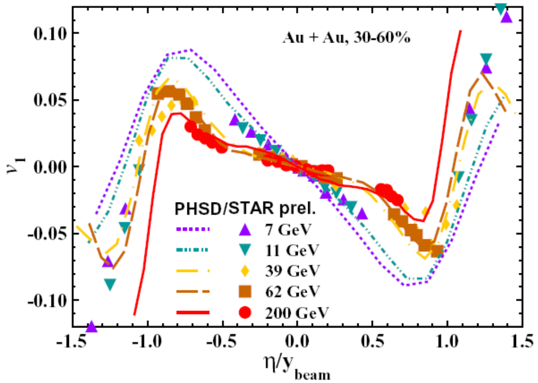
W. Cassing et al., PRL 110(2013)182301

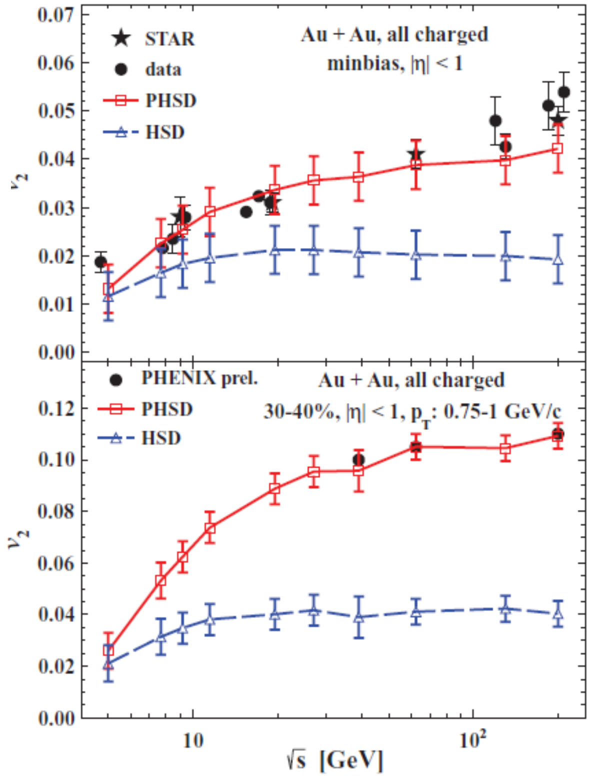
Bulk properties: rapidity, m_T-distributions, multi-strange particle enhancement in Au+Au

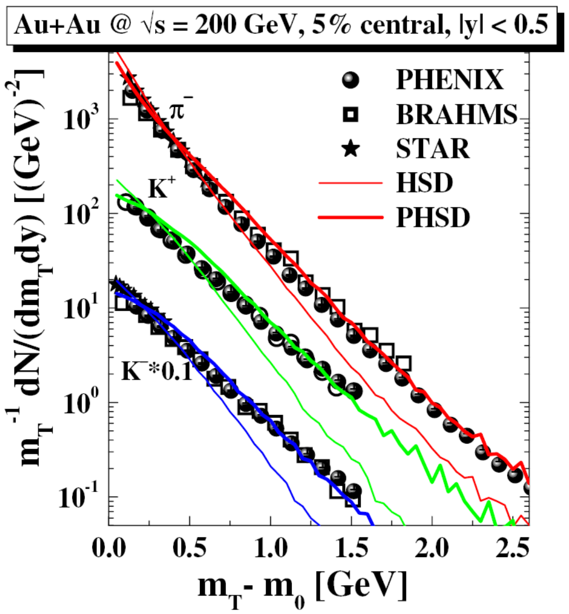


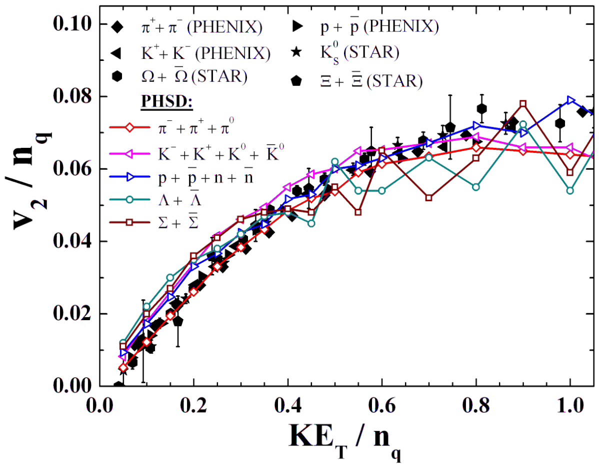
PHSD for HIC (highlights)

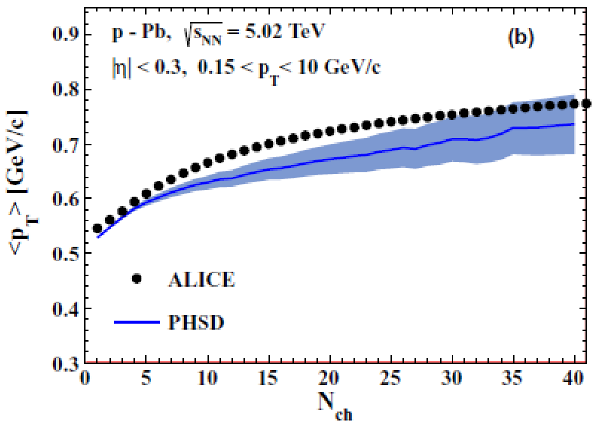


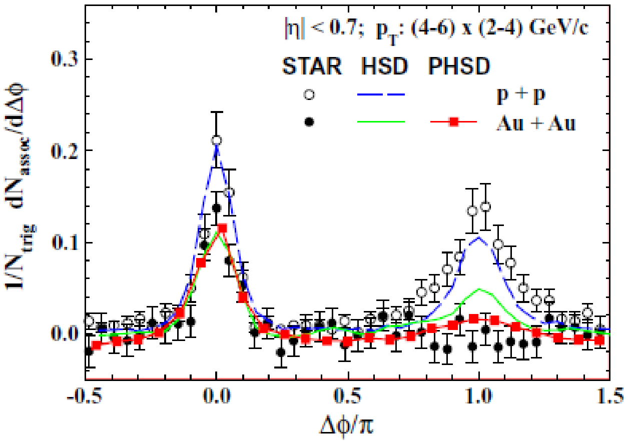






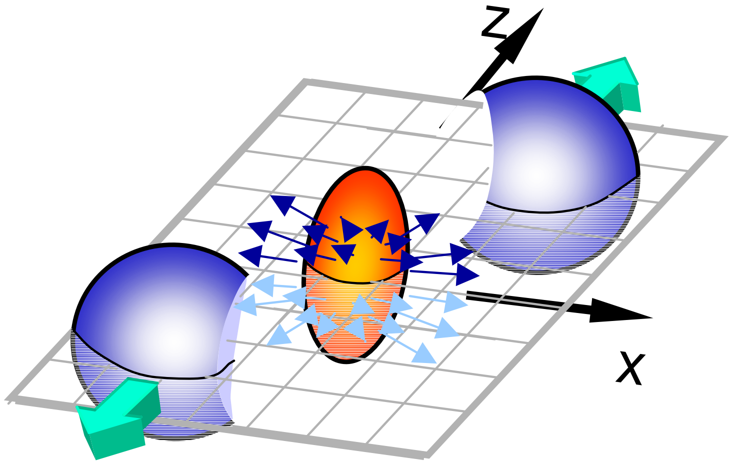






- **PHSD** provides a consistent description of HIC dynamics

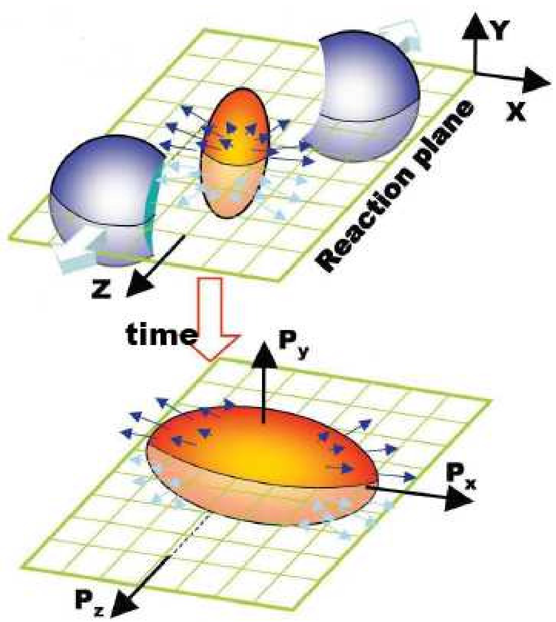
Collective flow: anisotropy coefficients (v_1, v_2, v_3, v_4) in A+A



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**



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

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

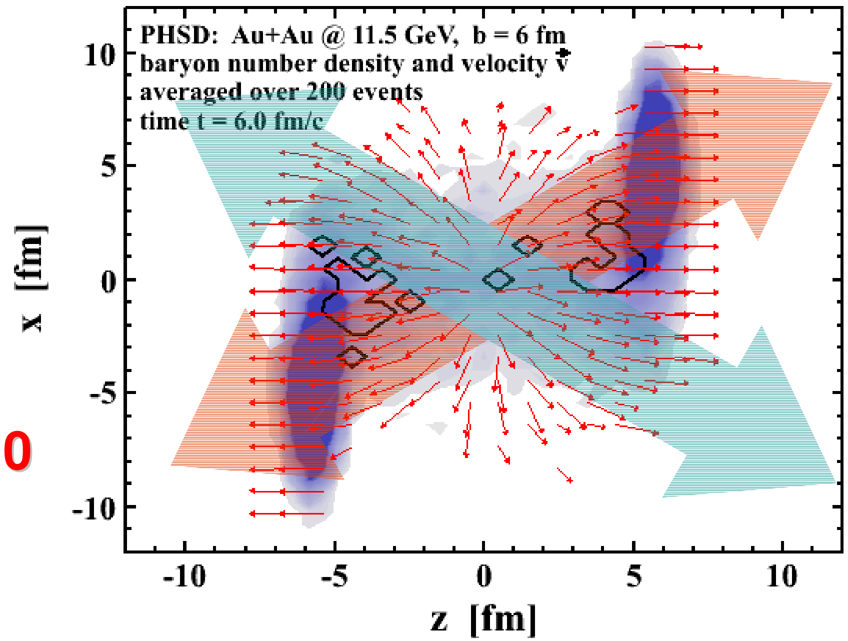
v_1: directed flow

v_2: elliptic flow

v_3: triangular flow…..

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

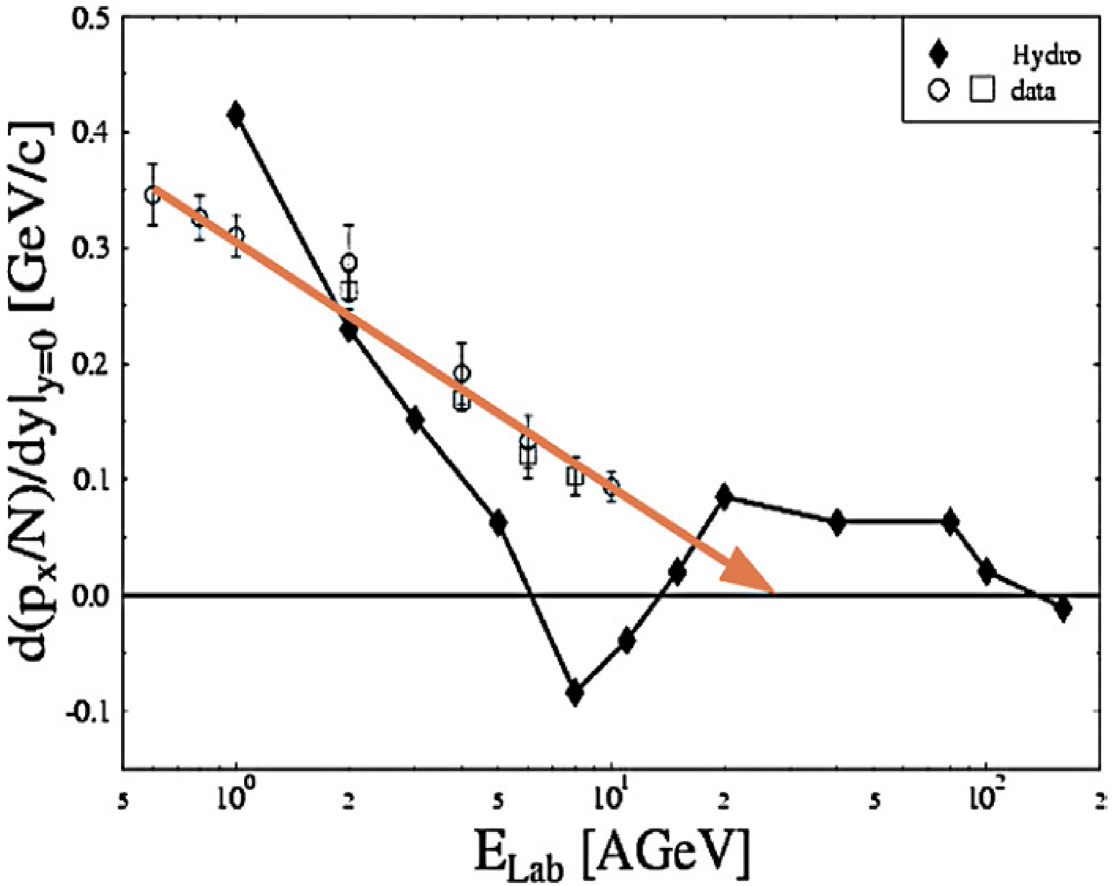
Directed flow $v_1 > 0$

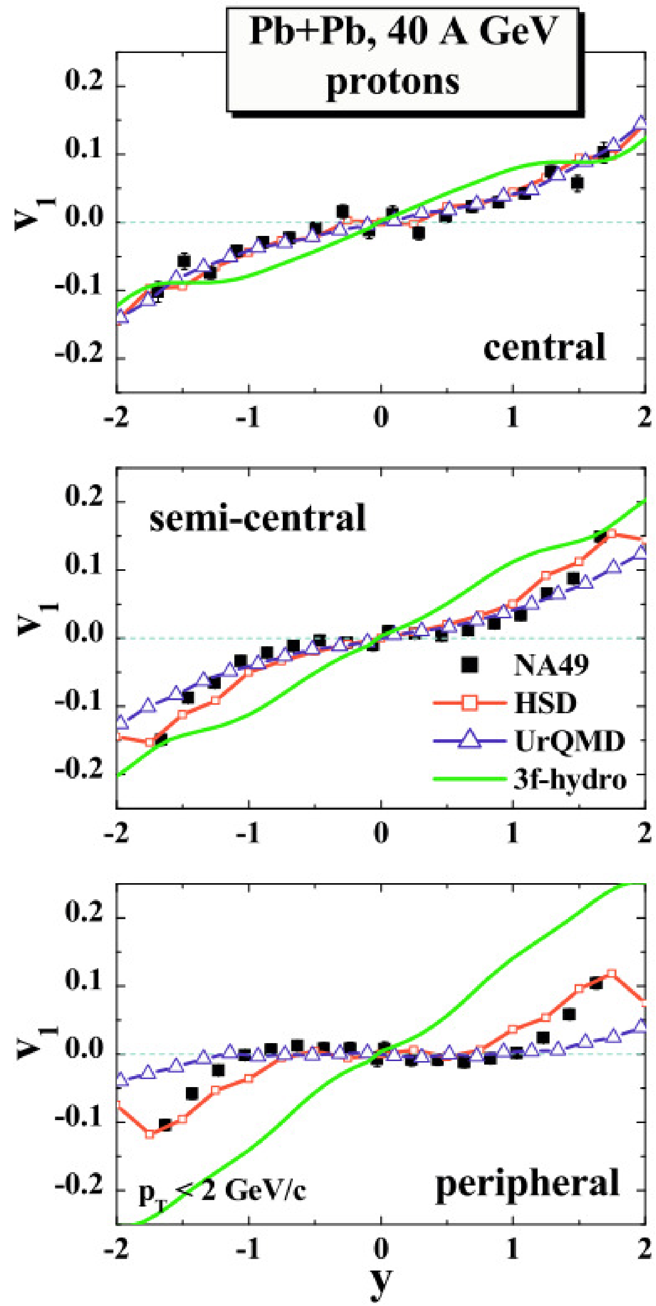


"Antiflow" $v_1 < 0$
"third flow component"

Collective flow signals of the Quark–Gluon Plasma

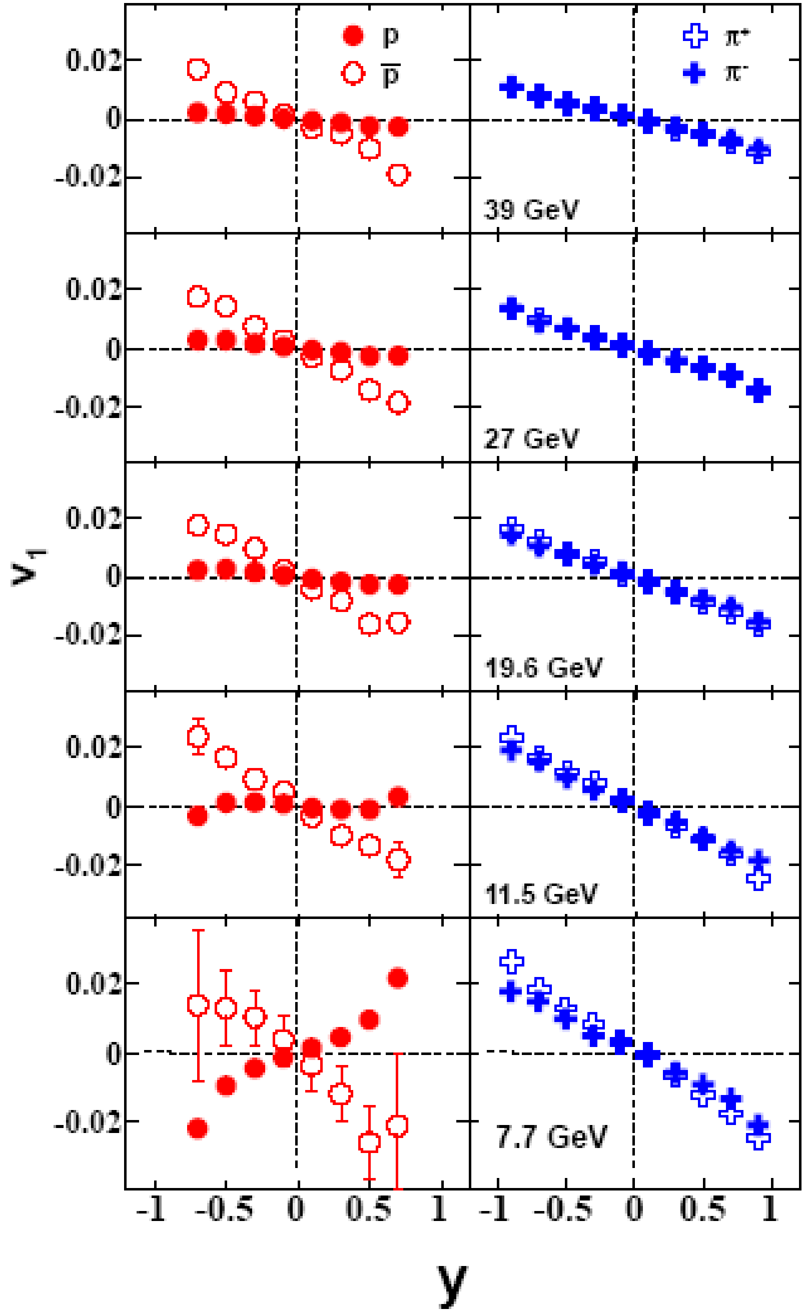
H. Stöcker, Nucl. Phys. A 750, 121 (2005)

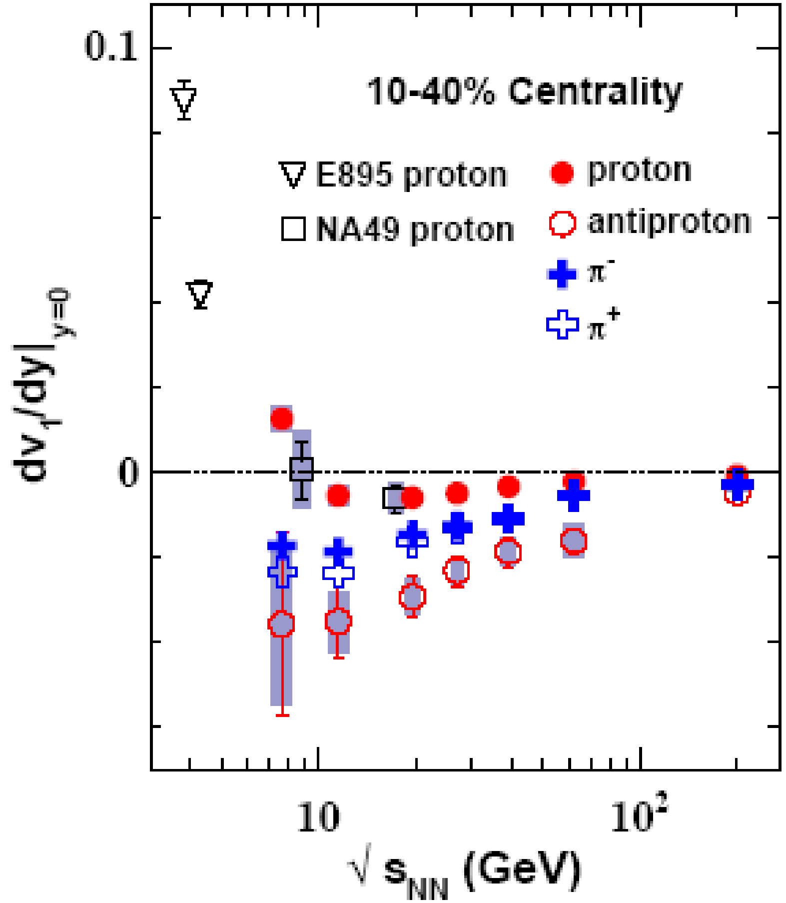




- Early hydro calculation predicted the "softest point" at E_{lab}= 8 AGeV
- A linear extrapolation of the data (arrow) suggests a collapse of flow at E_{lab}= 30 AGeV

Recent measurements of v_1 of identified hadrons

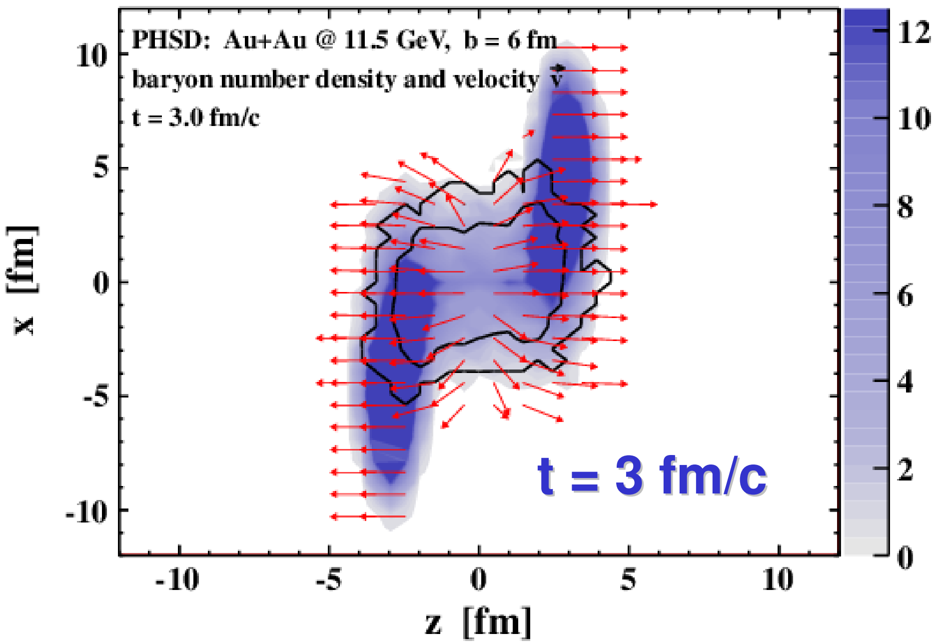


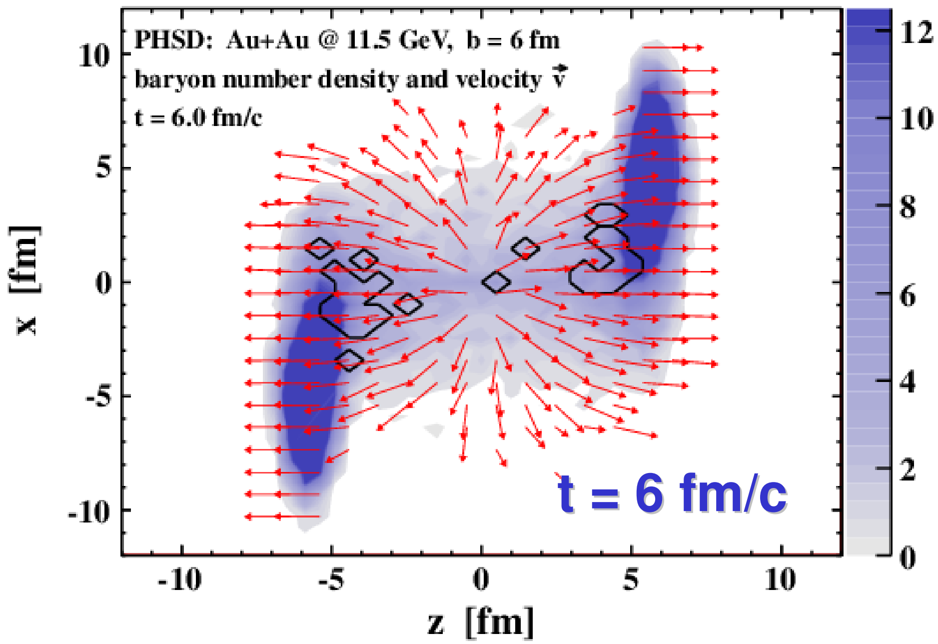


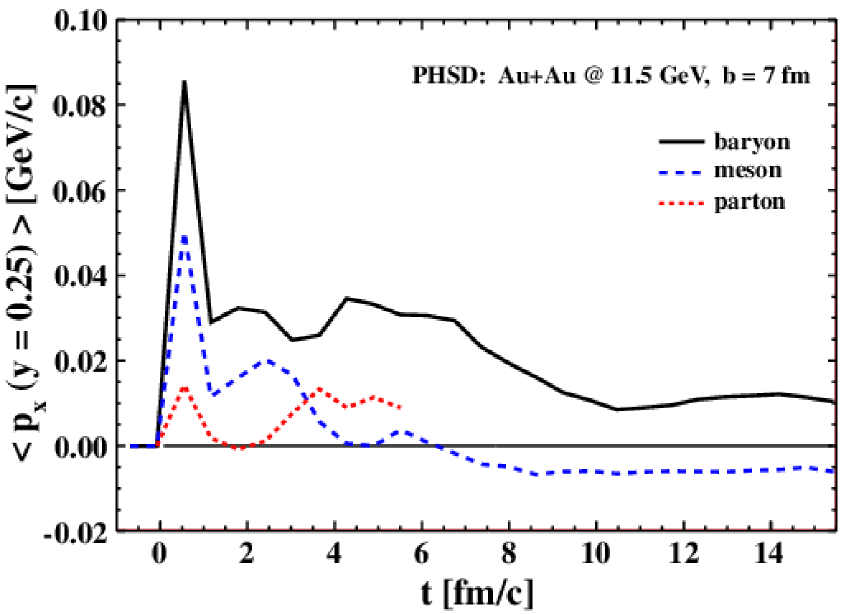
➔ measured distributions are smooth !

STAR collaboration, arXiv:1401.3043

PHSD: snapshot of the reaction plane







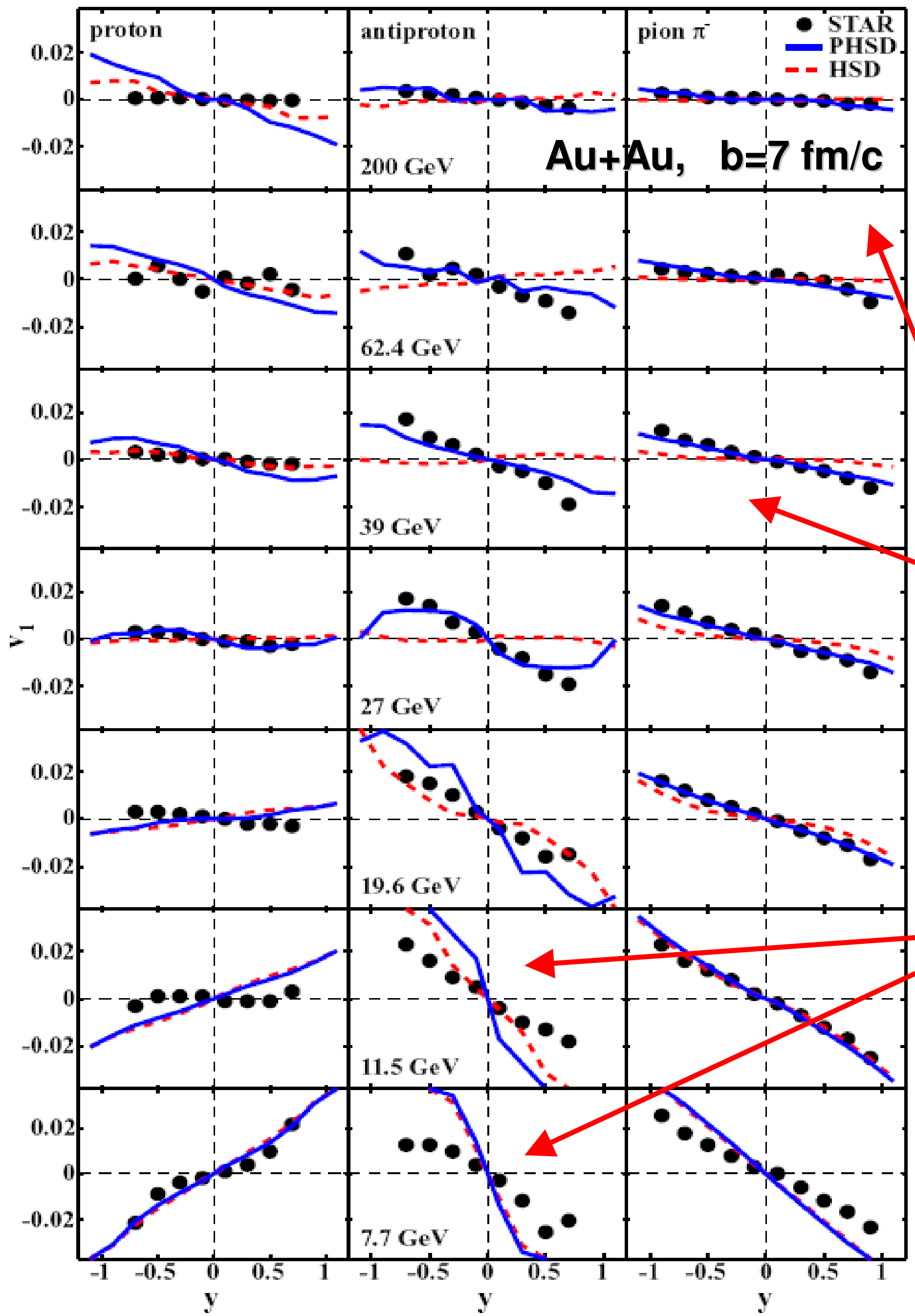
- **Color scale:** baryon number density
  Black levels: QGP- parton density 0.6 and 0.01 fm^{-3}
  Red arrows: local velocity of baryon matter

- **Directed flow v_1 is formed at an early stage of the nuclear interaction**

- **Baryons are reaching positive and mesons – negative value of v_1**

V. Konchakovski, W. Cassing, Yu. Ivanov, V. Toneev, PRC(2014), arXiv:1404.2765

Directed flow from PHSD and HSD



- **Models:**
  *** HSD (red) – warning: NO hadronic potentials, cascade mode!**
  *** PHSD (blue) – repulsive parton potential**

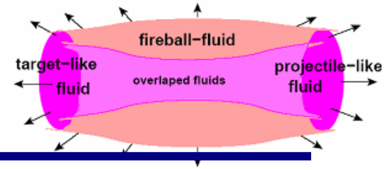
- **Antiprotons in PHSD are produced dominantly from hadronization at highest energies; multi-meson fusion reactions are important for the v_1 at low energies!**

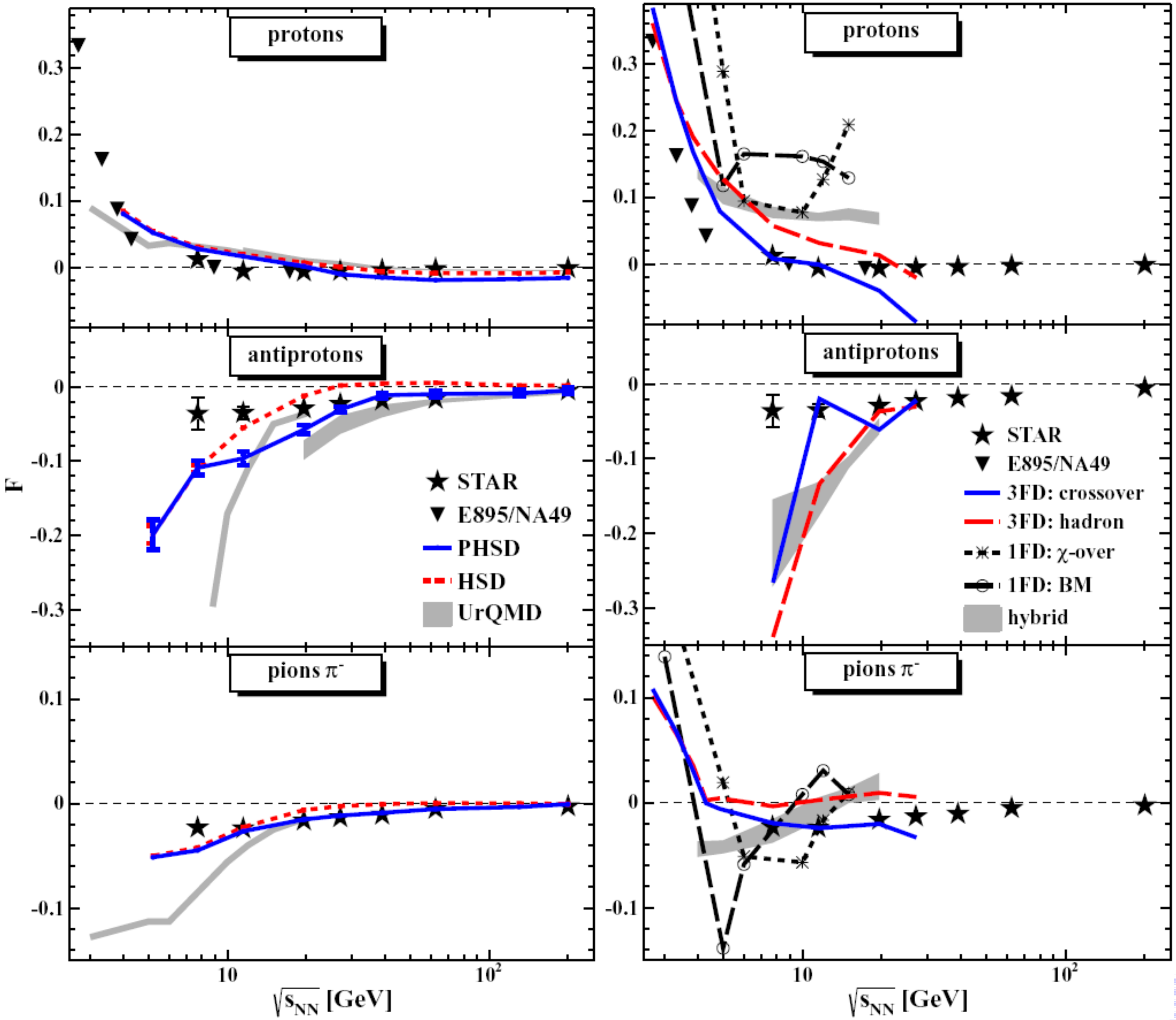
- **higher energies ➔ influence of QGP**
  lower energies ➔ dominance of hadronic matter and hadronic reaction channels (absorption and recreation)

- **Discrepancies at low energy – indication on the influence of hadronic potential (cf. AMPT results)**

V. Konchakovski, W. Cassing, Yu. Ivanov, V. Toneev, PRC(2014), arXiv:1404.2765
STAR Collaboration, arXiv:1401.3043

Excitation function of v_1 slopes





- **The slope of $v_1(y)$ at midrapidity:**

$$F = \frac{d v_1}{dy}\Big|_{y=0}$$

Models:

- HSD, PHSD
- 3D-Fluid Dynamic approach (3FD)
- UrQMD
- Hybrid-UrQMD
- 1FD-hydro with chiral cross-over and Bag Model (BM) EoS

➔ smooth crossover?!

STAR Collaboration, arXiv:1401.3043

PHSD/HSD and 3D-fluid hydro: V. Konchakovski, W. Cassing, Yu. Ivanov, V. Toneev, PRC(2014), arXiv:1404.2765

Hybrid/UrQMD/Hydro: J. Steinheimer, J. Auvinen, H. Petersen, M. Bleicher, H. Stöcker, PRC 89 (2014) 054913

Messages from directed flow

- The PHSD reproduces the general trends in the $v_1(y)$ excitation functions in the energy range $\sqrt{s}$ =7.7-200 GeV.
  We don't see any "wiggle-like" structures as expected by early hydro calculations but see a softening of the EoS in the BES range.

- The PHSD results differ from those of HSD where no explicit partonic degrees of freedom are incorporated. A comparison of both microscopic models has provided detailed information on the effect of parton dynamics on the directed flow (especially for pions).

- Inclusion of antiproton annihilation into several mesons as well as the inverse multi-meson fusion processes in HSD/PHSD help to reproduce antiproton directed flow at lower energies.

- 3-Fluid Dynamic approach (3FD) gives reasonable results for proton and pion slopes of v_1 but fails at 7.7 GeV for antiprotons

- Crossover transition agrees better with the experiment than the pure hadronic EoS

Direct photon flow puzzle

?

EMMI Rapid Reaction Task Force

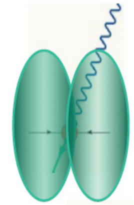
Direct-Photon Flow Puzzle

February 24-28, 2014, GSI, Darmstadt, Germany

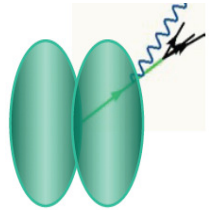
Production sources of photons in p+p and A+A

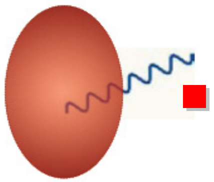
- **Decay photons (in pp and AA):**

$$m \rightarrow \gamma + X, \quad m = \pi^0, \eta, \omega, \eta', a_1, \ldots$$

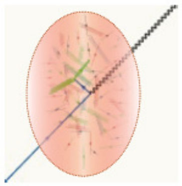


- **Direct photons: (inclusive(=total) – decay) – measured experimentally**
  - **hard photons:** (large p_T, in pp and AA)
    - **prompt** (pQCD; initial hard N+N scattering)
    - **jet fragmentation** (pQCD; qq, gq bremsstrahlung) (in AA can be modified by parton energy loss in medium)

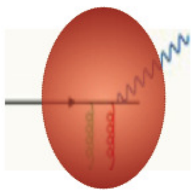




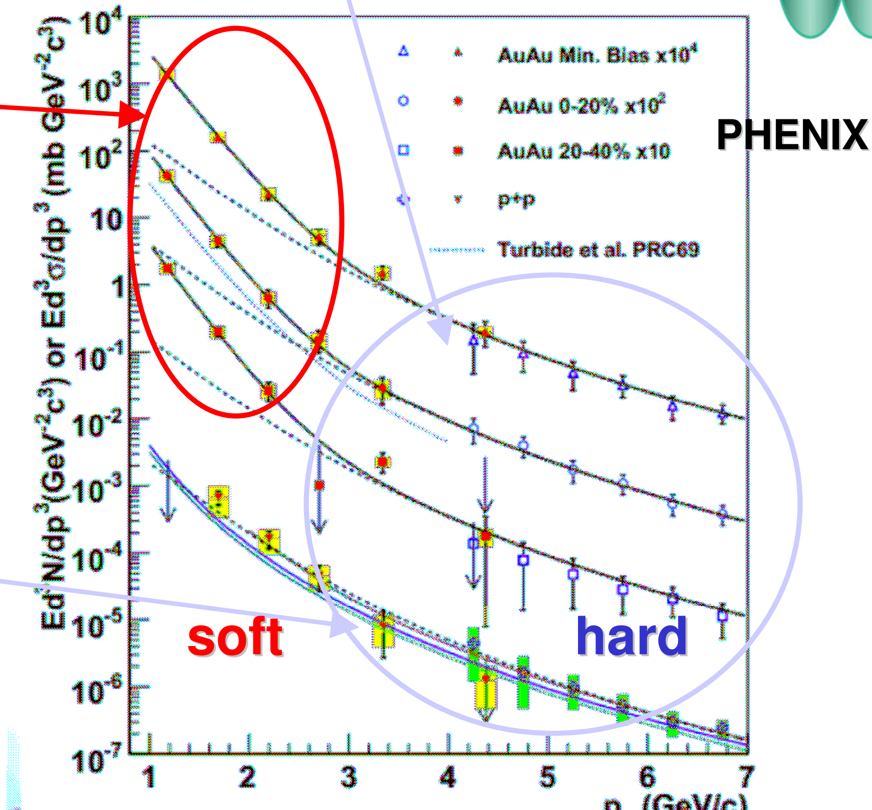
  - **thermal photons:** (low p_T, in AA)
    - QGP
    - Hadron gas



  - **jet-γ-conversion in plasma** (large p_T, in AA)



  - **jet-medium photons** (large p_T, in AA) - scattering of hard partons with thermalized partons $q_{hard}+g_{QGP}\rightarrow\gamma+q$, $q_{hard}+qbar_{QGP}\rightarrow\gamma+q$



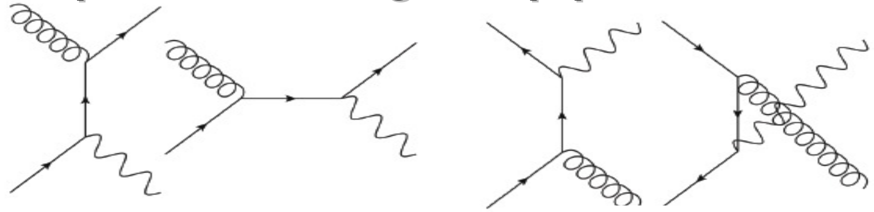
Phys. Rev. C 81, 034911 (2010)

Production sources of thermal photons

Thermal QGP:

HTL program (Klimov (1981), Weldon (1982), Braaten & Pisarski (1990); Frenkel & Taylor (1990), ...)

Compton scattering **q-qbar annihilation**



+ soft ...

$q(\bar{q}) + g \rightarrow q(\bar{q}) + \gamma$ $q + \bar{q} \rightarrow g + \gamma$

- **Rates beyond pQCD:**
  off-shell massive q, g
  (used in PHSD)
  O. Linnyk, JPG 38 (2011) 025105;
  Poster by O. Linnyk & QM'2014

- **pQCD LO: 'AMY'** Arnold, Moore, Yaffe, JHEP 12, 009 (2001) ← QGP rates used in hydro !
- **pQCD NLO:** talk by Jacopo Ghiglieri

Hadronic sources:

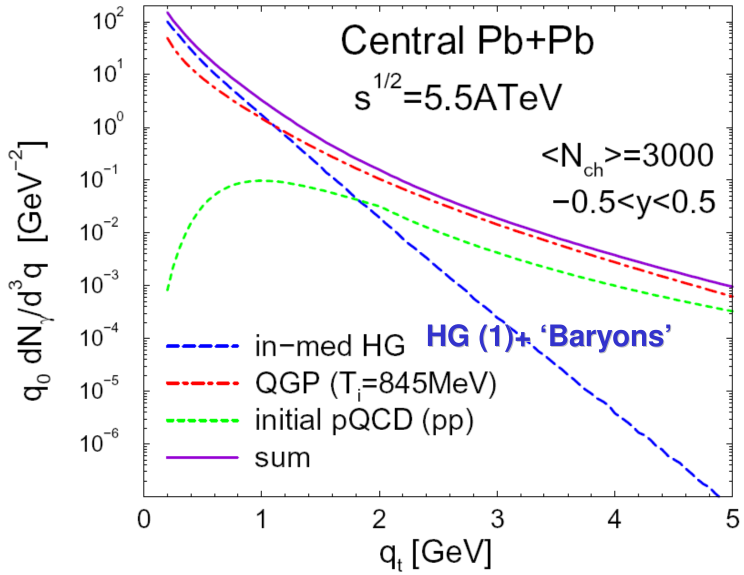
(1) secondary mesonic interactions:

$\pi+\pi \rightarrow \rho+\gamma,\ \rho+\pi \rightarrow \pi+\gamma,\ \pi+K \rightarrow \rho+\gamma, \ldots$

(2) meson-meson and meson-baryon bremsstrahlung:

$m+m \rightarrow m+m+\gamma, \quad m+B \rightarrow m+B+\gamma,$

$m=\pi,\eta,\rho,\omega,K,K^*,\ldots, \quad B=p,\Delta,\ldots$

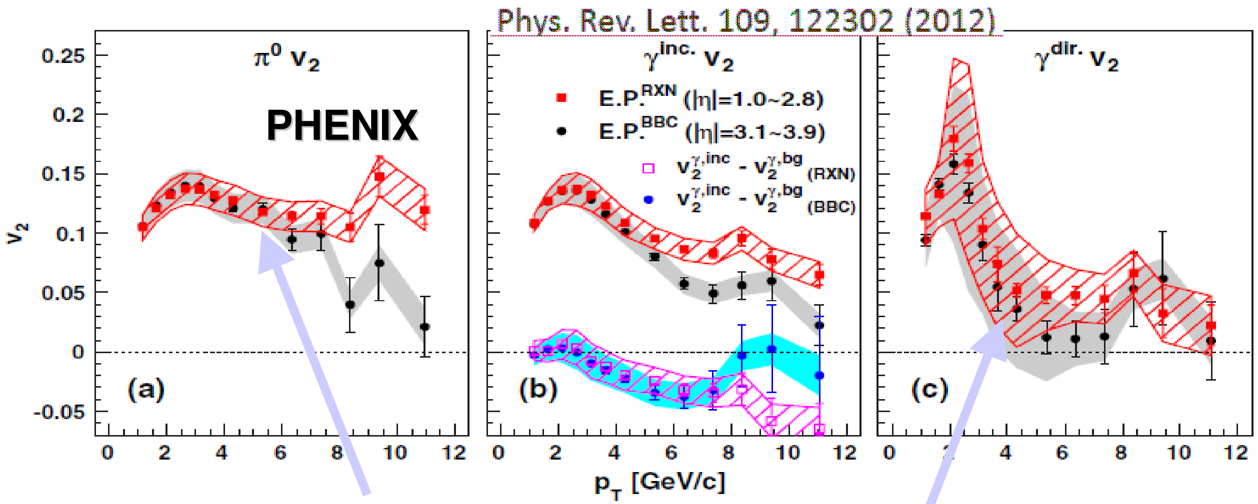


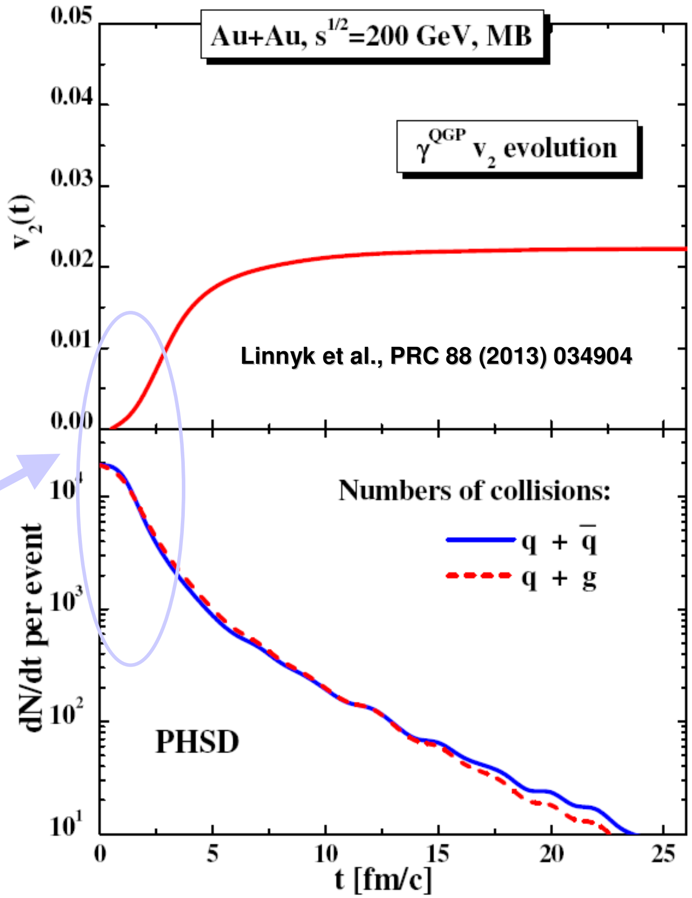
Models: chiral models, OBE, SPA ...
Kapusta, Gale, Haglin (91), Rapp (07), ...

→ HG rates (1) used in hydro ('TRG' model) - massive Yang-Mills approach:
Turbide, Rapp, Gale, PRC 69, 014903 (2004)

PHENIX: Photon v_2 puzzle

$$\frac{dN}{d\phi} = \frac{1}{2\pi}\left(1 + 2\sum_{n\geq 1} v_n \cos\left(n(\phi - \Psi_n^{RP})\right)\right)$$





!

- **PHENIX (also now ALICE):**
  strong elliptic flow of photons $v_2(\gamma^{dir}) \sim v_2(\pi)$
- **Result from a variety of models:** $v_2(\gamma^{dir}) \ll v_2(\pi)$
- **Problem:** QGP radiation occurs at **early times** when elliptic flow is not yet developed ➔ expected $v_2(\gamma^{QGP}) \rightarrow 0$
- v_2 = weighted average $v_2 = \frac{\sum_i N^i \cdot v_2^i}{\sum_i N^i}$ ➔ **a large QGP contribution gives small $v_2(\gamma^{QGP})$**

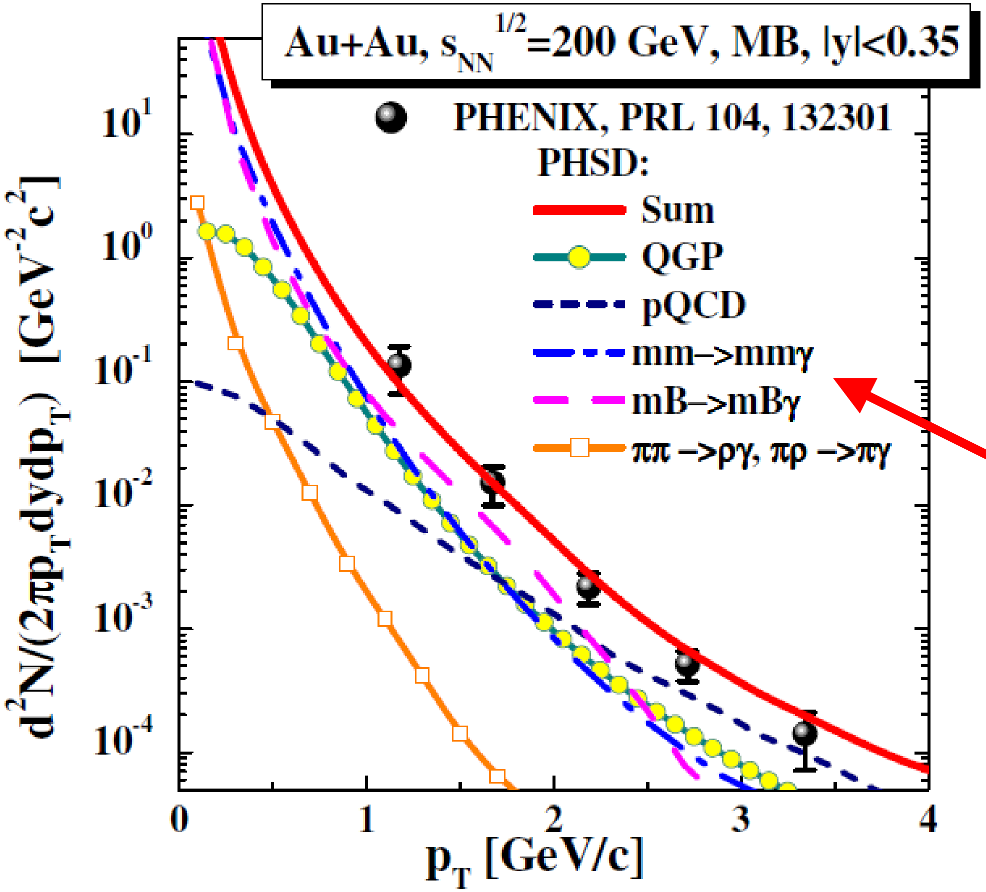
- **NEW** (QM'2014): **PHENIX, ALICE experiments** - **large photon v_3 !**

➔ **Challenge for theory – to describe spectra, v_2, v_3 simultaneously !**

PHSD: photon spectra at RHIC: QGP vs. HG ?

- Direct photon spectrum (min. bias)

Linnyk et al., PRC88 (2013) 034904; PRC 89 (2014) 034908



PHSD:

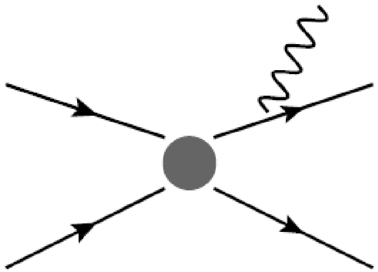
- **QGP gives up to ~50% of direct photon yield below 2 GeV/c**

! sizeable contribution from hadronic sources
– meson-meson (mm) and meson-Baryon (mB) bremsstrahlung

$$m+m \to m+m+\gamma,$$

$$m+B \to m+B+\gamma,$$

$$m=\pi,\eta,\rho,\omega,K,K^*,\ldots$$
$$B=p$$



The slope parameter T_{eff} (in MeV)			
PHSD			PHENIX
QGP	hadrons	Total	[38]
260 ± 20	200 ± 20	220 ± 20	233 ± 14 ± 19

!!! mm and mB bremsstrahlung channels can not be subtracted experimentally !

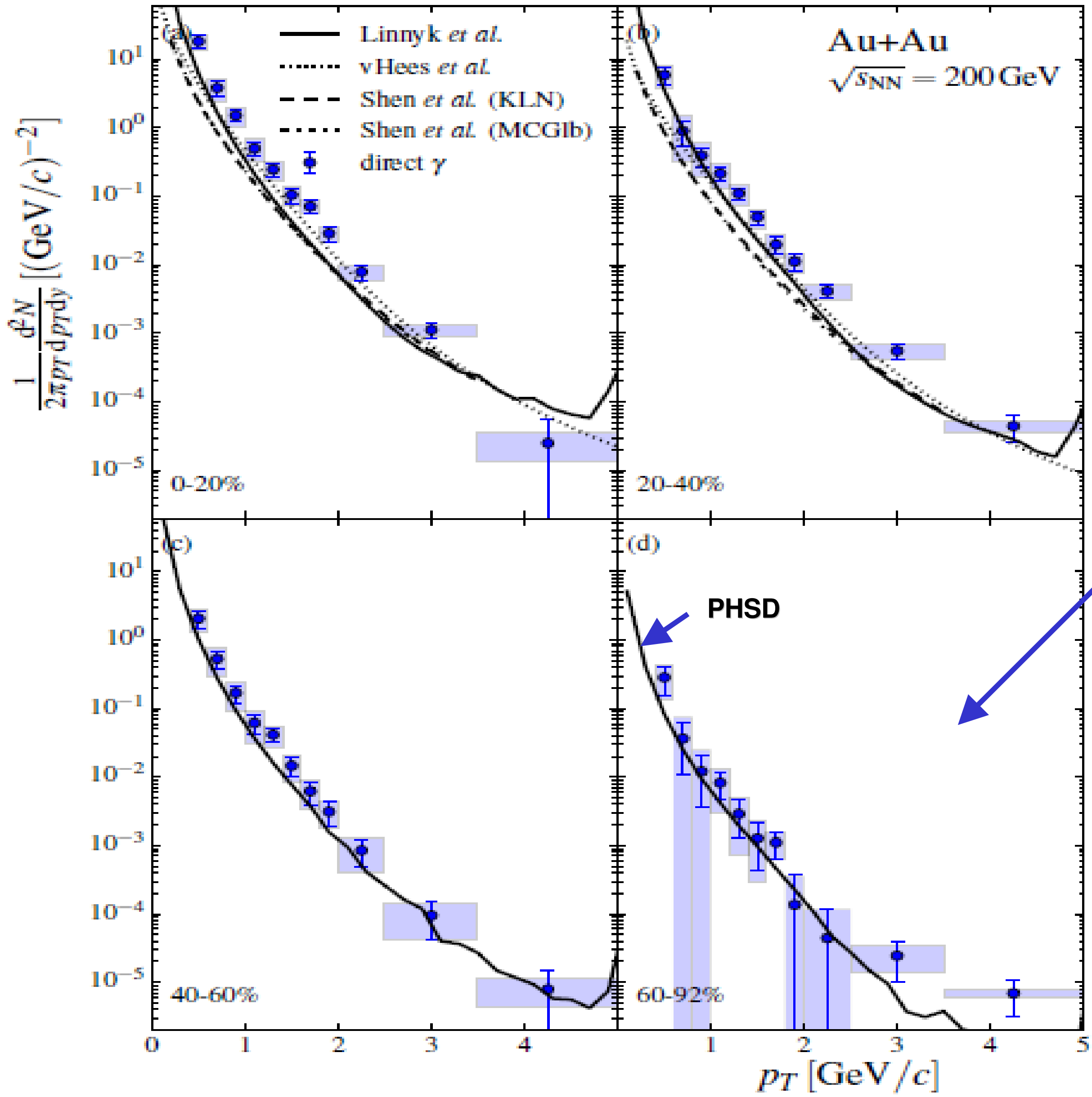
Measured Teff > ‚true' T → ‚blue shift' due to the radial flow!

Photon p_T spectra at RHIC for different centralities

PHENIX data - arXiv:1405.3940

from talk by S. Mizuno at QM'2014

PHSD predictions:
O. Linnyk et al, Phys. Rev. C 89 (2014) 034908



❑ PHSD approximately reproduces the centrality dependence

❑ mm and mB bremsstrahlung is dominant at peripheral collisions

!!! Warning:
large uncertainties in the Bremsstrahlung channels in the present PHSD results !

Bremsstrahlung – trivial ‚background‘?

- **Uncertainties in the Bremsstrahlung channels in the present PHSD results :**

1) based on the Soft-Photon-Approximation (SPA) (factorization = strong x EM)

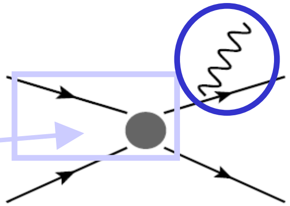
- **Soft Photon Approximation (SPA):**

  $m_1+m_2 \rightarrow m_1+m_2+\gamma$

  C. Gale, J. Kapusta, Phys. Rev. C 35 (1987) 2107

$$q_0 \frac{d^3\sigma^\gamma}{d^3q} = \frac{\alpha}{4\pi}\frac{\bar{\sigma}(s)}{q_0^2}$$

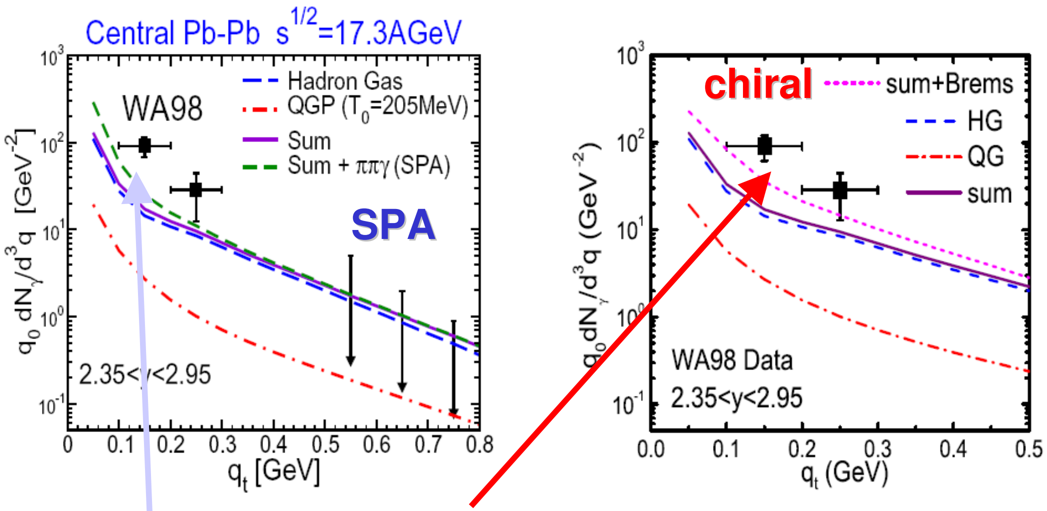
$$\bar{\sigma}(s) = \frac{s-(M_1+M_2)^2}{2M_1^2}\sigma(s),$$



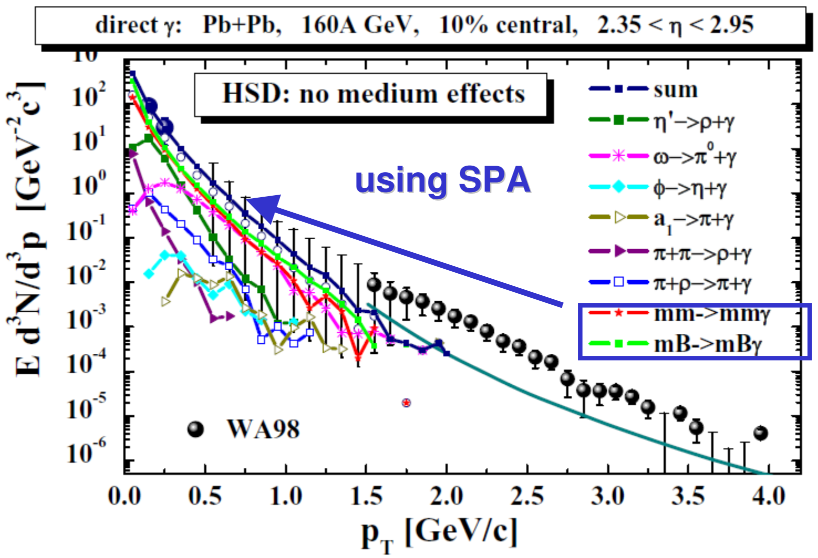
2) little experimental constraint on many m+m and m+B elastic cross sections

- **Bremsstrahlung: seen at SPS - WA98**

Firebal model: Liu, Rapp, Nucl. Phys. A 96 (2007) 101



HSD: E. B., Kiselev, Sharkov, PR C78 (2008) 034905



- **effective chiral model for $\pi\pi \rightarrow \pi\pi\gamma$, $\pi K \rightarrow \pi K\gamma$ bremsstrahlung gives larger contribution than SPA**

➔ Bremsstrahlung has been an important source of soft photons at SPS!

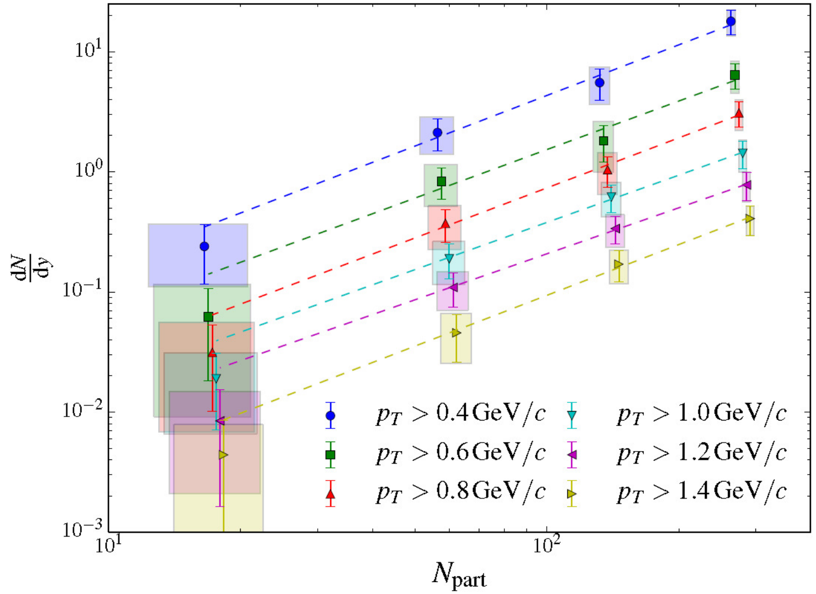
Centrality dependence of the ‚thermal' photon yield

O. Linnyk et al, Phys. Rev. C 89 (2014) 034908

PHENIX (arXiv:1405.3940):

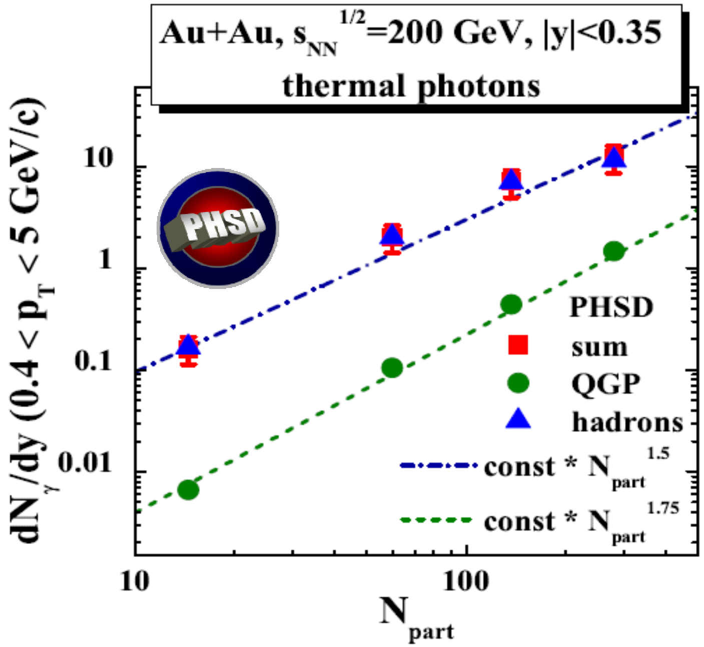
scaling of thermal photon yield vs centrality:
$dN/dy \sim N_{part}^{\alpha}$ with $\alpha \sim 1.48 \pm 0.08$

('Thermal' photon yield = direct photons - pQCD)



PHSD predictions:

- Hadronic channels scale as $\sim N_{part}^{1.5}$
- Partonic channels scale as $\sim N_{part}^{1.75}$



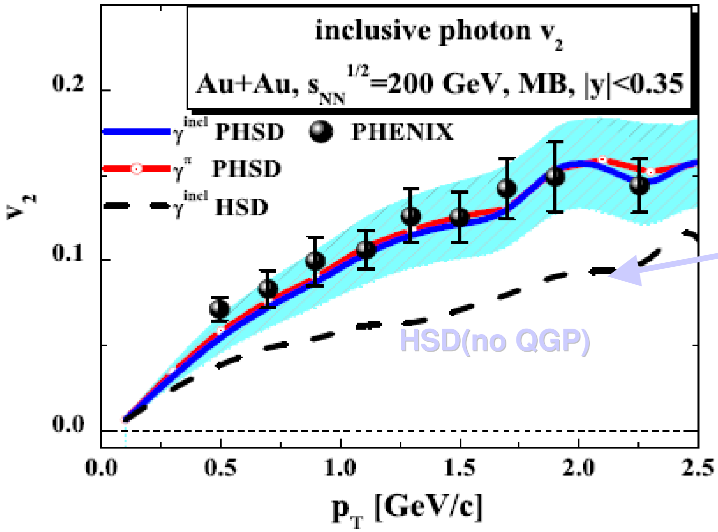
- **PHSD:** scaling of the thermal photon yield with N_{part}^{α} with $\alpha \sim 1.5$
- similar results from viscous hydro:
  (2+1)d VISH2+1: α(HG) ~1.46, α(QGP) ~2, α(total) ~1.7

➔ **What do we learn?**
Indications for a dominant **hadronic origin of thermal photon production?!**

Are the direct photons a barometer of the QGP?

❑ Do we see the **QGP pressure** in $v_2(\gamma)$ if the photon productions is **dominated by hadronic sources?**

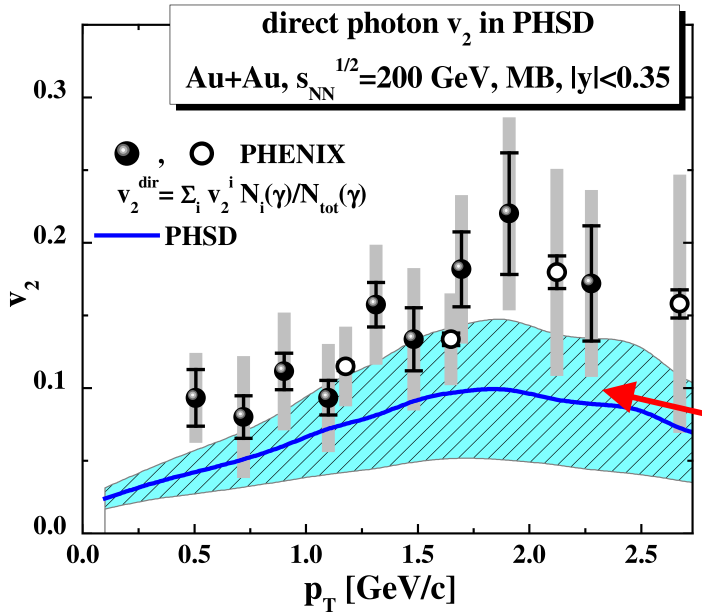
PHSD: Linnyk et al., PRC88 (2013) 034904; PRC 89 (2014) 034908



1) $v_2(\gamma^{incl}) = v_2(\pi^0)$ - inclusive photons mainly come from π^0 decays

▪ HSD (without QGP) underestimates v_2 of hadrons and inclusive photons by a factor of 2, wheras the PHSD model with QGP is consistent with exp. data

➔ The **QGP causes the strong elliptic flow of photons indirectly**, by enhancing the v_2 of final hadrons due to the partonic interactions



Direct photons (inclusive(=total) – decay):

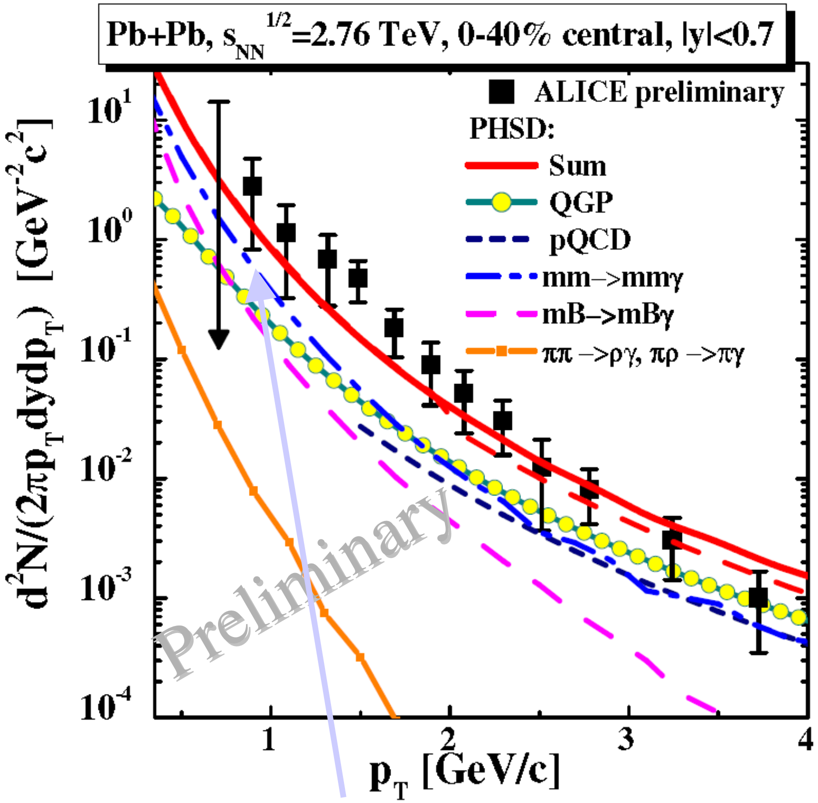
2) $v_2(\gamma^{dir})$ of direct photons in PHSD underestimates the PHENIX data :

$v_2(\gamma^{QGP})$ is very small, but QGP contribution is up to 50% of total yield ➔ lowering flow

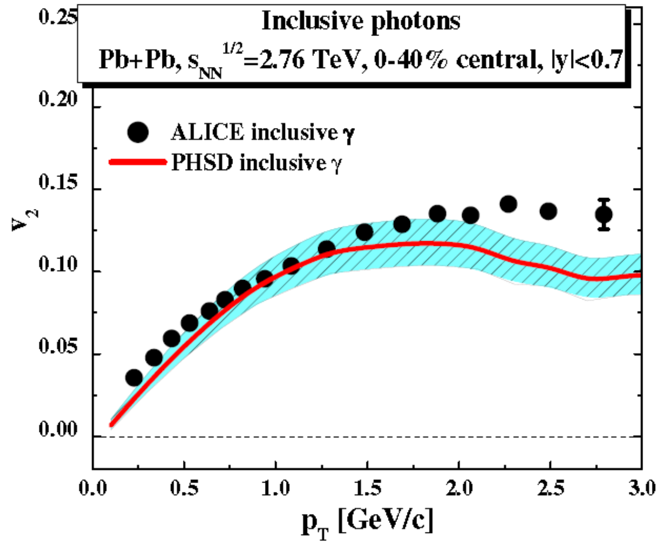
➔PHSD: $v_2(\gamma^{dir})$ comes from **mm and mB bremsstrahlung !**

Photons from PHSD at LHC

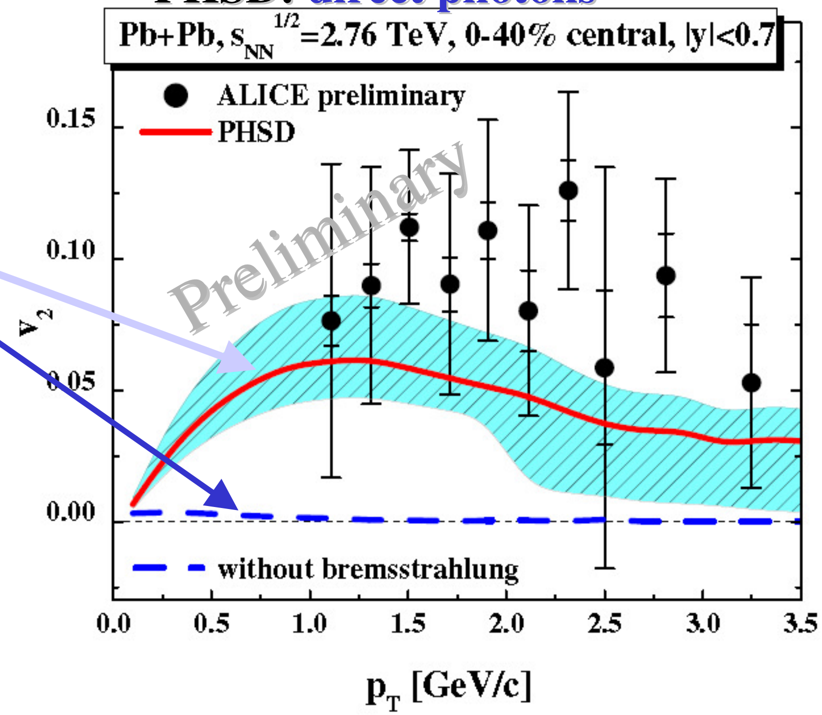
PHSD- preliminary: Olena Linnyk



PHSD: v_2 of inclusive photons



PHSD: direct photons



- ❑ Is the considerable elliptic flow of direct photons at the LHC also of hadronic origin as for RHIC?!

- ❑ The photon elliptic flow at LHC is lower than at RHIC due to a larger relative QGP contribution / longer QGP phase.

➔ LHC (similar to RHIC):
hadronic photons dominate spectra and v_2

Towards the solution of the v_2 puzzle

- Is hadronic bremsstrahlung a ‚solution‘?

Other scenarios:

- **Early-time magnetic field effects ?**

(Basar, Kharzeev, Skokov, PRL109 (2012) 202303; Basar, Kharzeev, Shuryak, arXiv:1402.2286)

„ … a novel photon production mechanism stemming from the conformal anomaly of QCD-QED and the existence of strong (electro)magnetic fields in heavy ion collisions.“
Exp. checks: v_3 , centrality dependence of photon yield (PHENIX: arXiv:1405.3940)

- **Glasma effects ?**

(L. McLerran, B. Schenke, arXiv: 1403.7462)

„ … Photon distributions from the Glasma are steeper than those computed in the Thermalized Quark Gluon Plasma (TQGP). Both the delayed equilibration of the Glasma and a possible anisotropy in the pressure lead to a slower expansion and mean times of photon emission of fixed energy are increased.“

- **Pseudo-Critical Enhancement of thermal photons near T_C ?**

(H. van Hees, M. He, R. Rapp, arXiv:1404.2846)
cf. talk by R. Rapp at QM*2014

- **non-perturbative effects?**

semi-QGP - cf. talk by S. Lin at QM‘2014

- **???**

… shining in the darkness

Some messages from the ‘photon adventure’:

- The photons provide a critical test for the theoretical models: models constructed to reproduce the ‚hadronic world‘ fail to explain the photon experimental data!

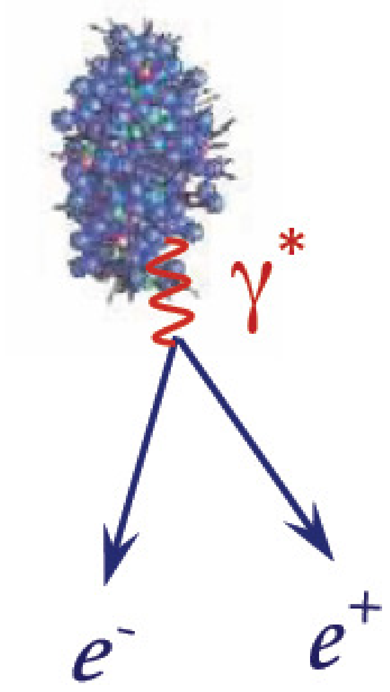
- The details of the hydro models (fluctuating initial conditions, viscousity, pre-equilibrium flow) have small impact on the photon observables

- The role of mm and mB bremsstrahlung has been underestimated ?!

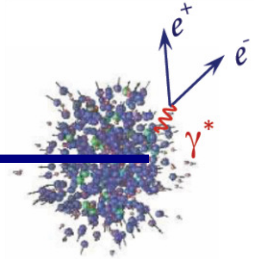
- The importance of initial phases of the reaction: large photon v_2 requires the development of pre-equilibrium / initial flow ?!

Photons – one of the most sensitive probes for the dynamics of HIC!

Dileptons

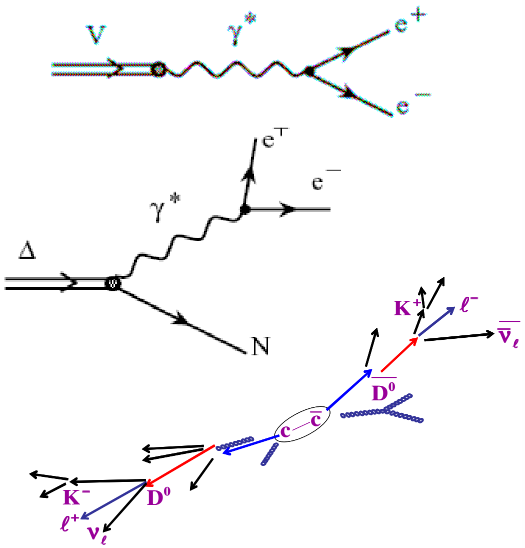


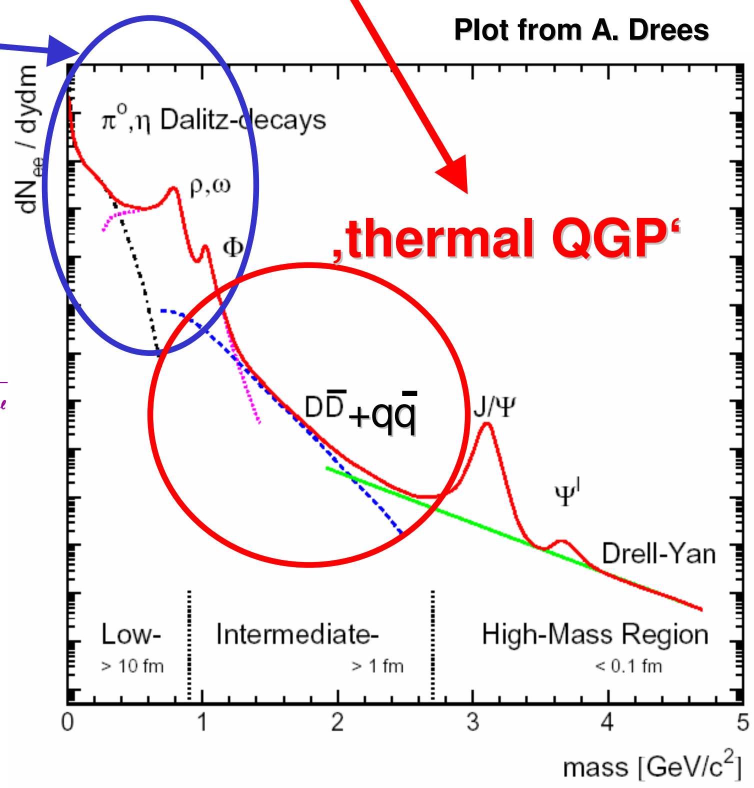
Dilepton sources



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

- **from hadronic sources:**





- **direct decay of vector mesons (ρ,ω,φ,J/Ψ,Ψ')**

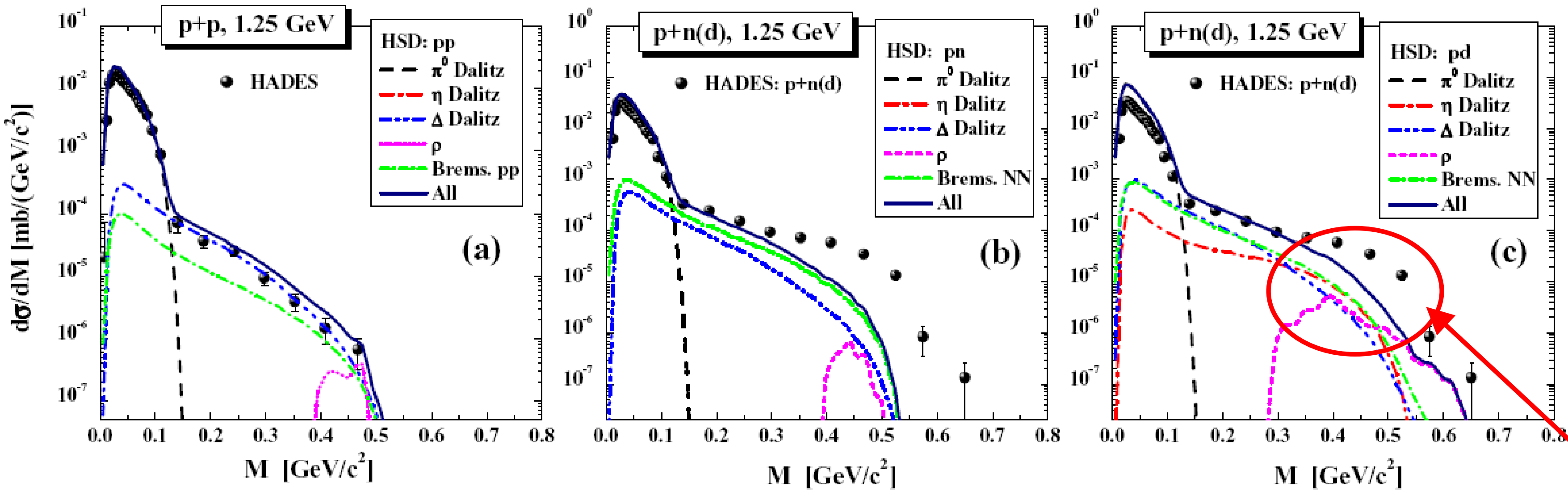
- **Dalitz decay of mesons and baryons (π^0,η, Δ,…)**

- **correlated D+Dbar pairs**

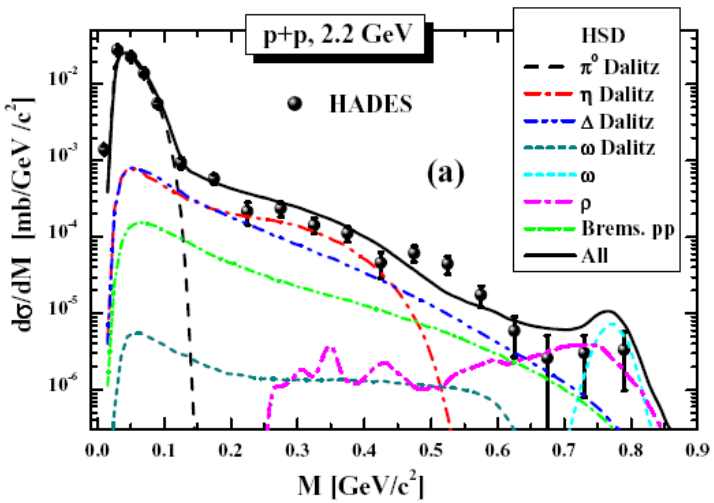
- **radiation from multi-meson reactions**
  ($\pi+\pi$, $\pi+\rho$, $\pi+\omega$, $\rho+\rho$, $\pi+a_1$) - **,4π'**

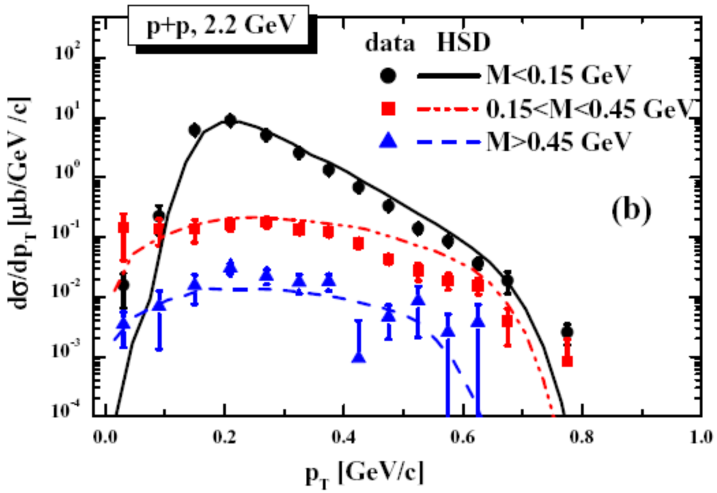
! Advantage of dileptons:
additional „degree of freedom" (*M*) allows to disentangle various sources

Dileptons at SIS (HADES): p+p, p+n(d)



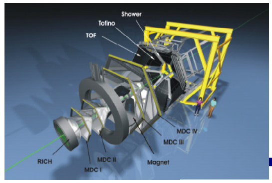
- **pn(d)@1.25 GeV**- missing yield at M>0.35 GeV!



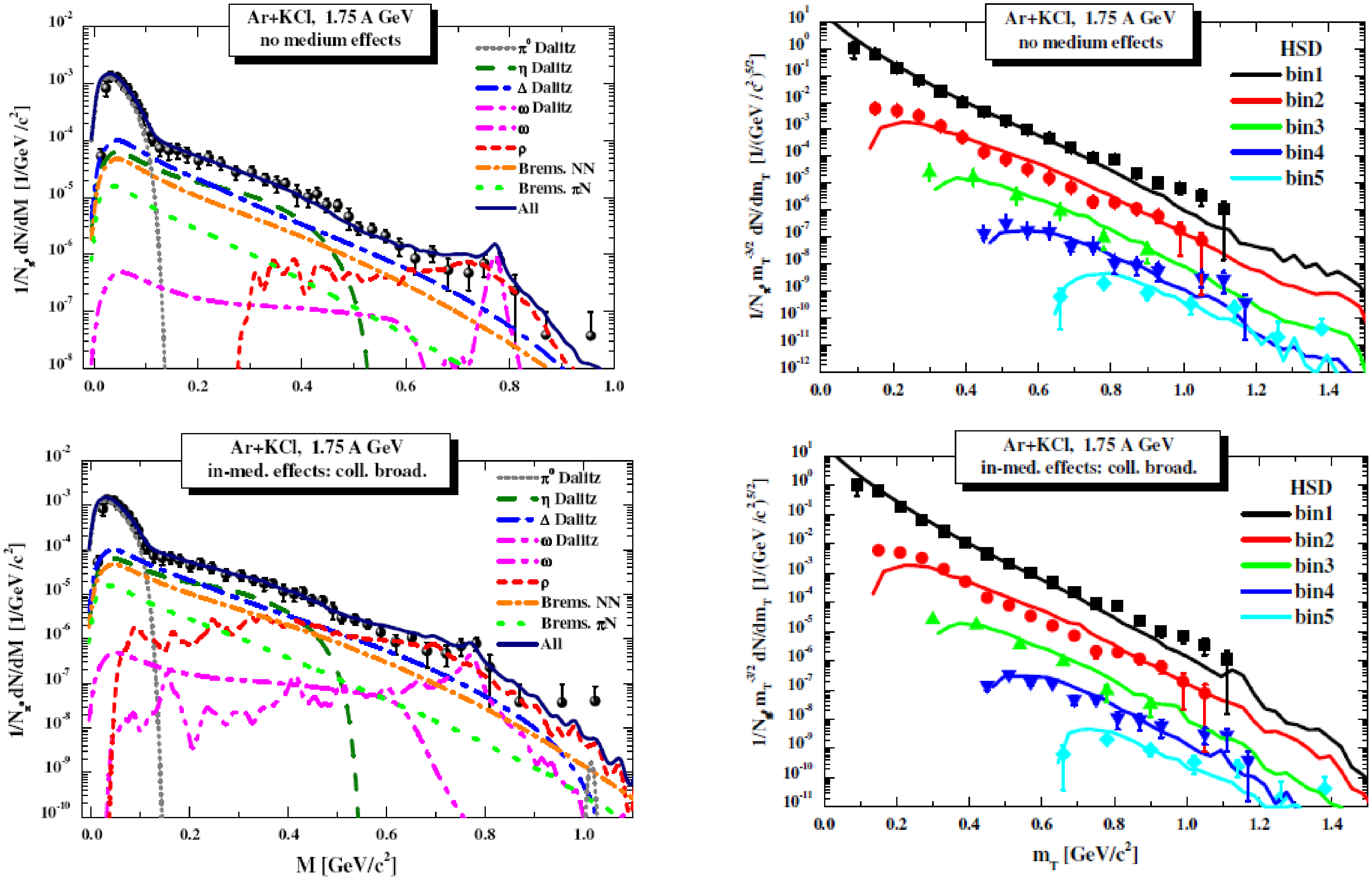


➔ **Measurements of elementary reactions pp, pn and πN are very important for the interpretation of heavy-ion data!**

E.B., J. Aichelin, M. Thomere, S. Vogel, and M. Bleicher, PRC 87 (2013) 064907



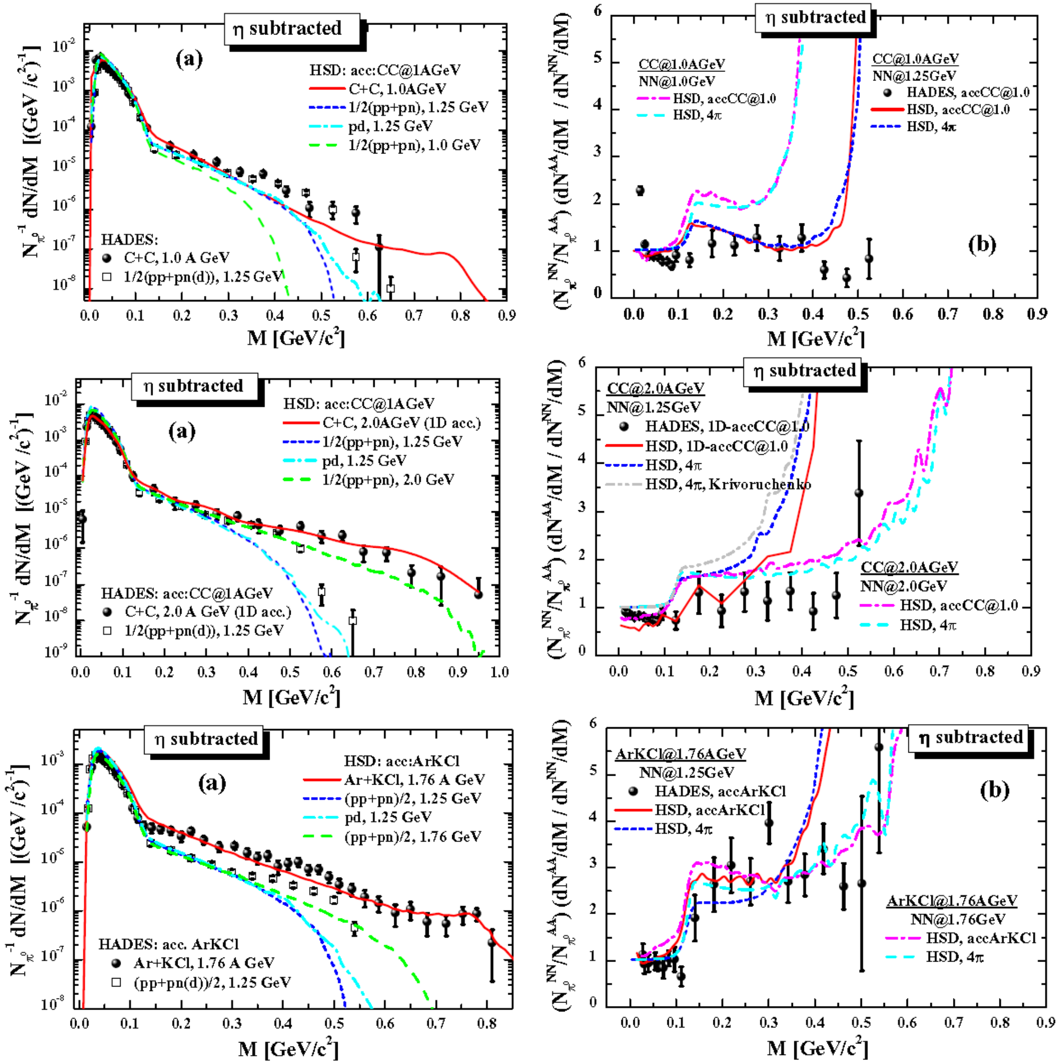
HSD: Dileptons from Ar+KCl at 1.75 A GeV - HADES



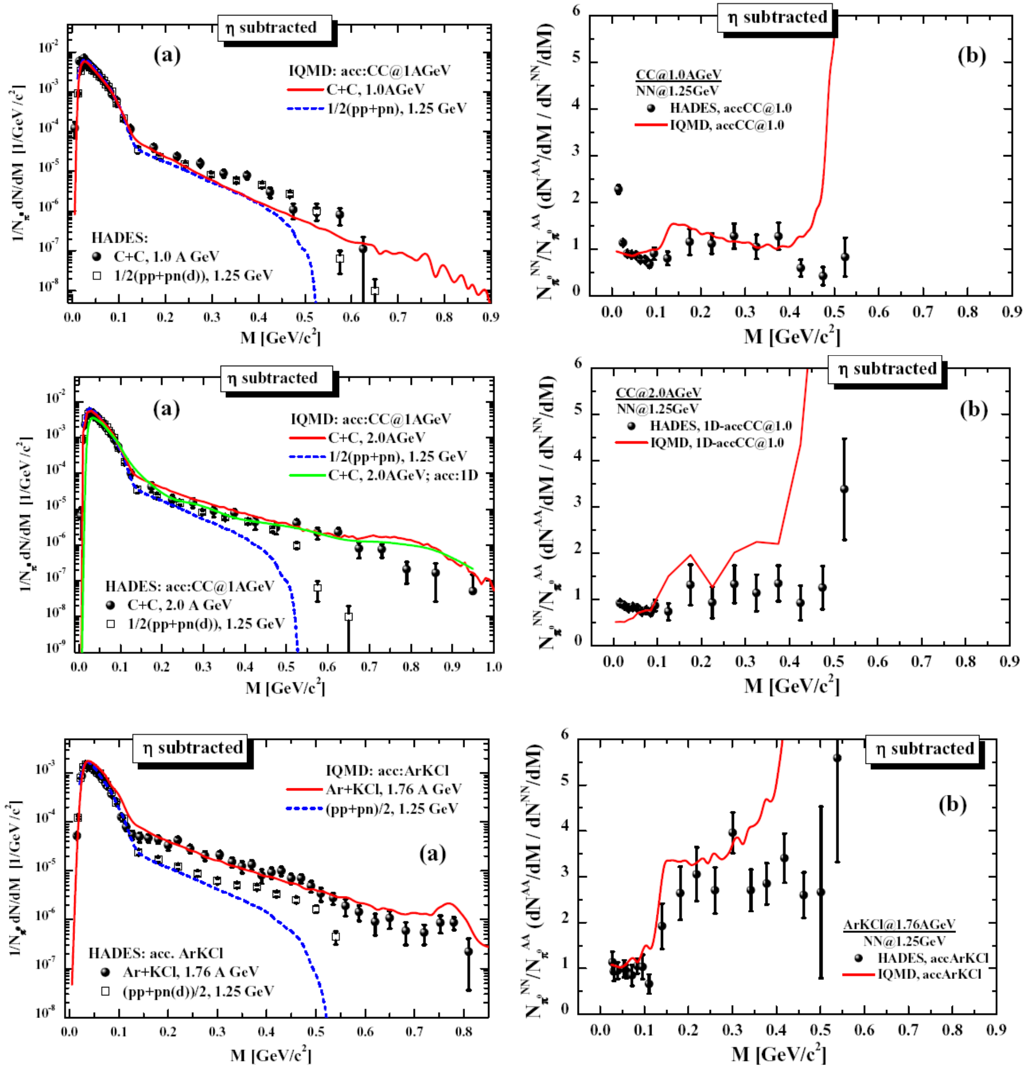
- **In-medium effects are more pronounced for heavy systems such as Ar+KCl**
- **The peak at M~0.78 GeV relates to ω/ρ mesons decaying in vacuum**

Dileptons at SIS (HADES): A+A vs N+N

- **HSD**



- **IQMD**



➔ Strong enhancement of dilepton yield in A+A vs. NN is reproduced by HSD and IQMD!

E.B., J. Aichelin, M. Thomere, S. Vogel, and M. Bleicher, PRC 87 (2013) 064907

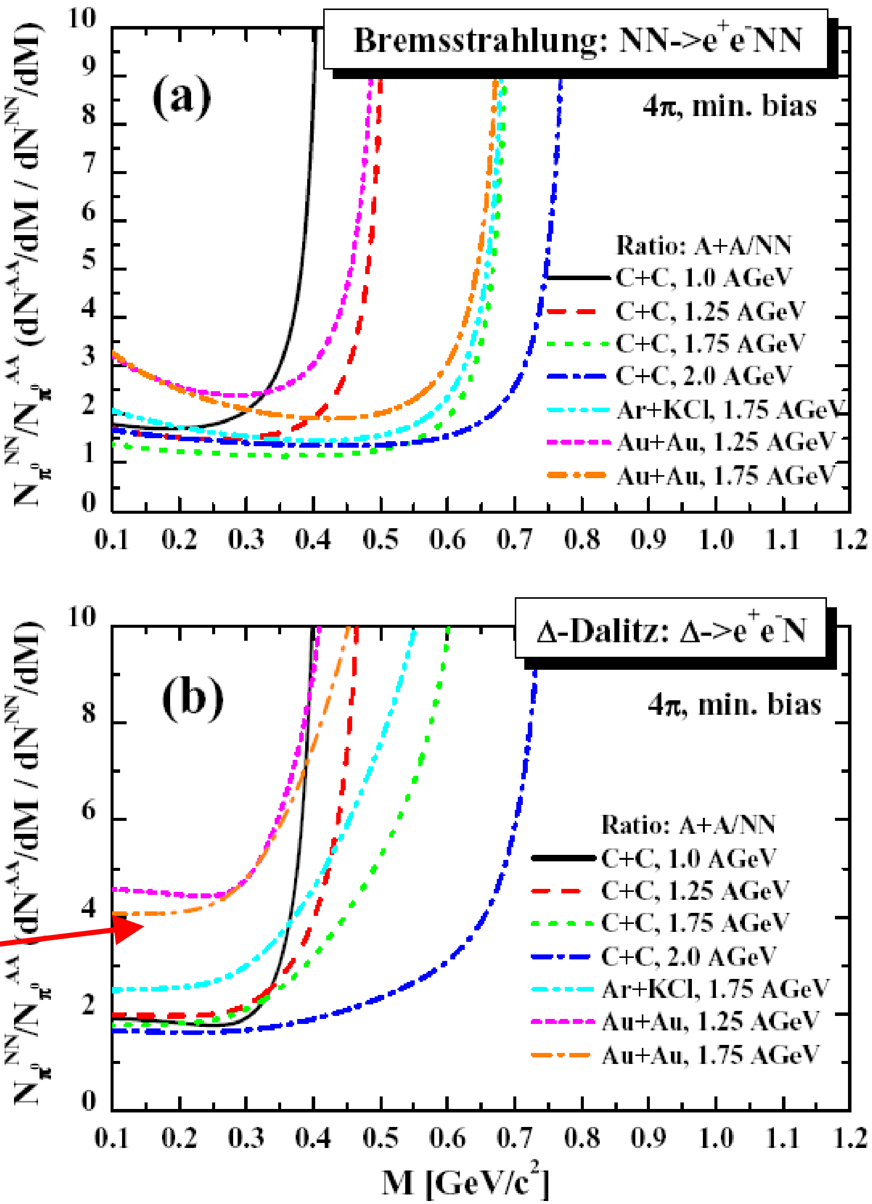
Dileptons at SIS (HADES): A+A vs NN

- Two contributions to the enhancement of dilepton yield in A+A vs. NN

1) the pN bremsstrahlung which scales with the number of collisions and not with the number of participants, i.e. pions;

2) the multiple Δ regeneration – dilepton emission from intermediate Δ's which are part of the reaction cycles Δ→πN; πN →Δ and NN→NΔ; NΔ→NN

- Enhancement of dilepton yield in A+A vs. NN increases with the system size!

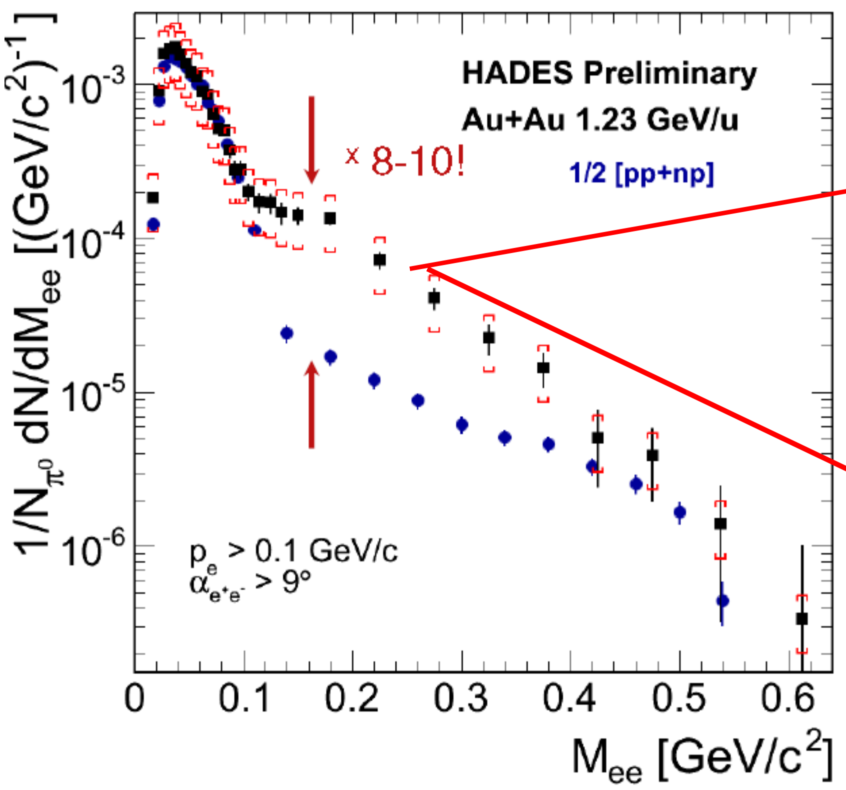


E.B., J. Aichelin, M. Thomere, S. Vogel, and M. Bleicher, PRC 87 (2013) 064907

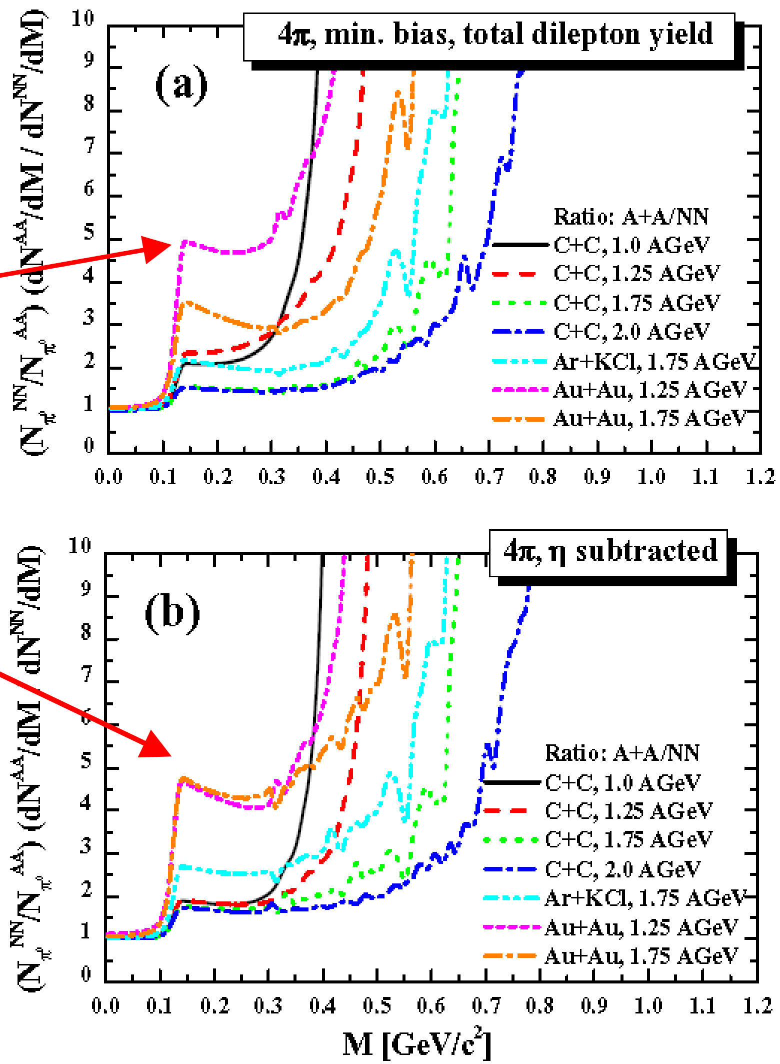
Dileptons at SIS (HADES): Au+Au

HADES preliminary: Au+Au, 1.23 A GeV

T. Galatyuk, QM'2014



▪ **HSD predictions (2013)**



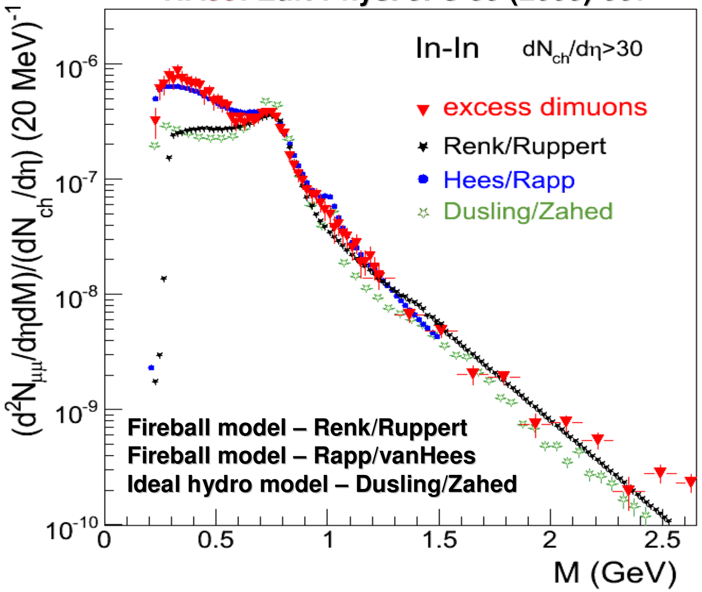
➔ **Strong in-medium enhancement of dilepton yield in Au+Au vs. NN – measurement of Δ regeneration by HADES!**

E.B., J. Aichelin, M. Thomere, S. Vogel, M. Bleicher, PRC 87 (2013) 064907

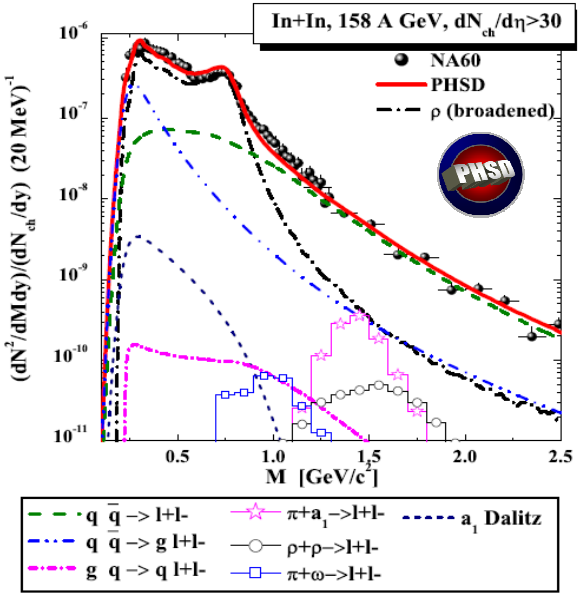
Lessons from SPS: NA60

❑ Dilepton invariant mass spectra:

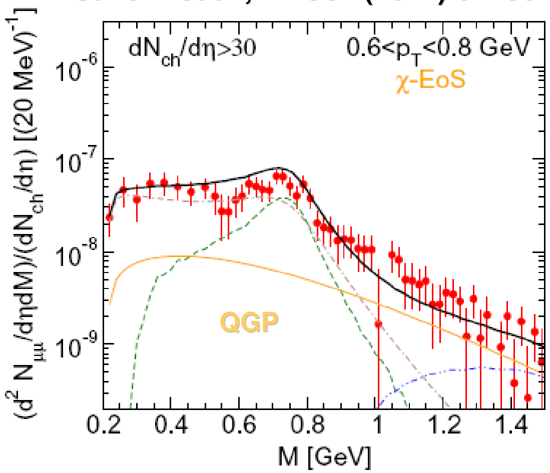
NA60: Eur. Phys. J. C 59 (2009) 607



PHSD:
Linnyk et al, PRC 84 (2011) 054917

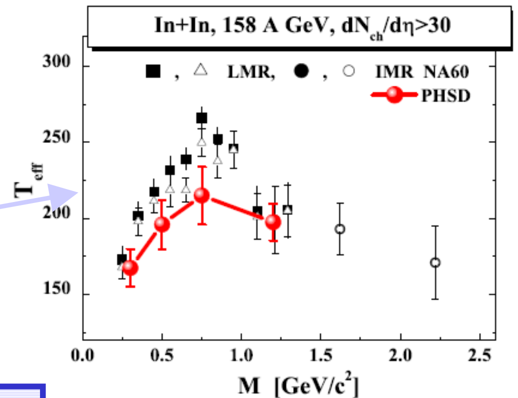


Hybrid-UrQMD:
Santini et al., PRC84 (2011) 014901



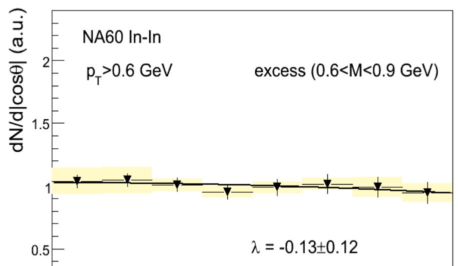
❑ Inverse slope parameter T_{eff}:

spectrum from QGP is softer than from hadronic phase since the QGP emission occurs dominantly before the collective radial flow has developed



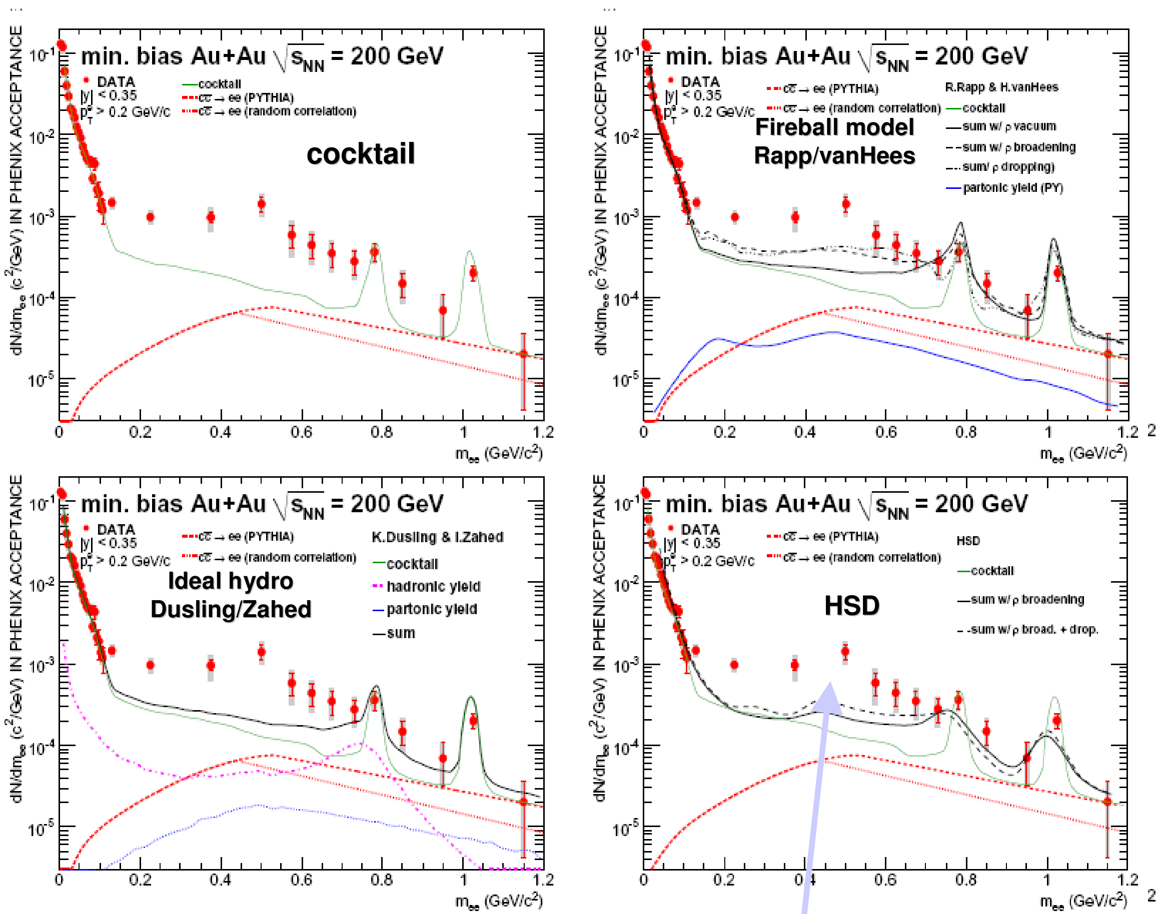
Message from SPS: (based on NA60 and CERES data)

1) Low mass spectra - evidence for the in-medium broadening of ρ-mesons
2) Intermediate mass spectra above 1 GeV - dominated by partonic radiation
3) The rise and fall of T_{eff} – evidence for the thermal QGP radiation
4) Isotropic angular distribution – indication for a thermal origin of dimuons

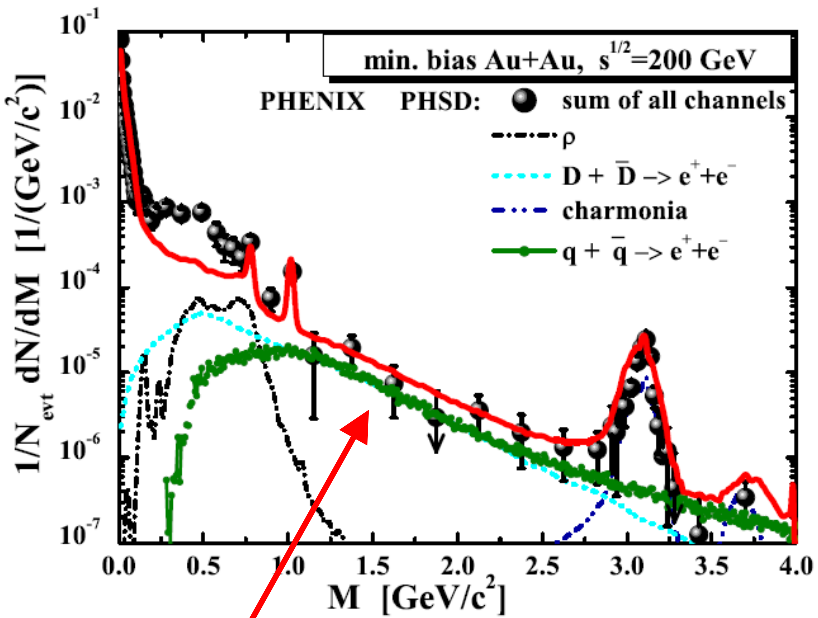


PRL 102 (2009) 222301

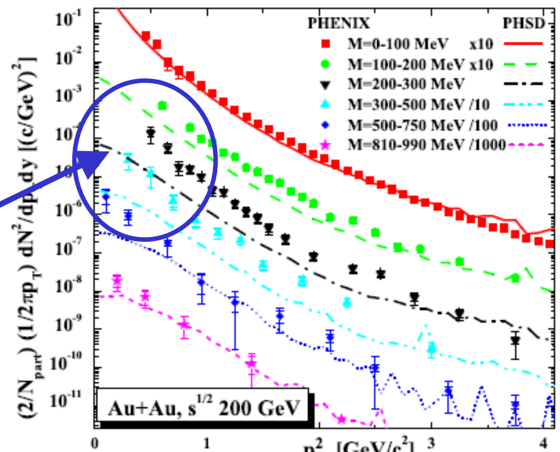
Dileptons at RHIC: PHENIX



PHENIX: PRC81 (2010) 034911



Linnyk et al., PRC 85 (2012) 024910



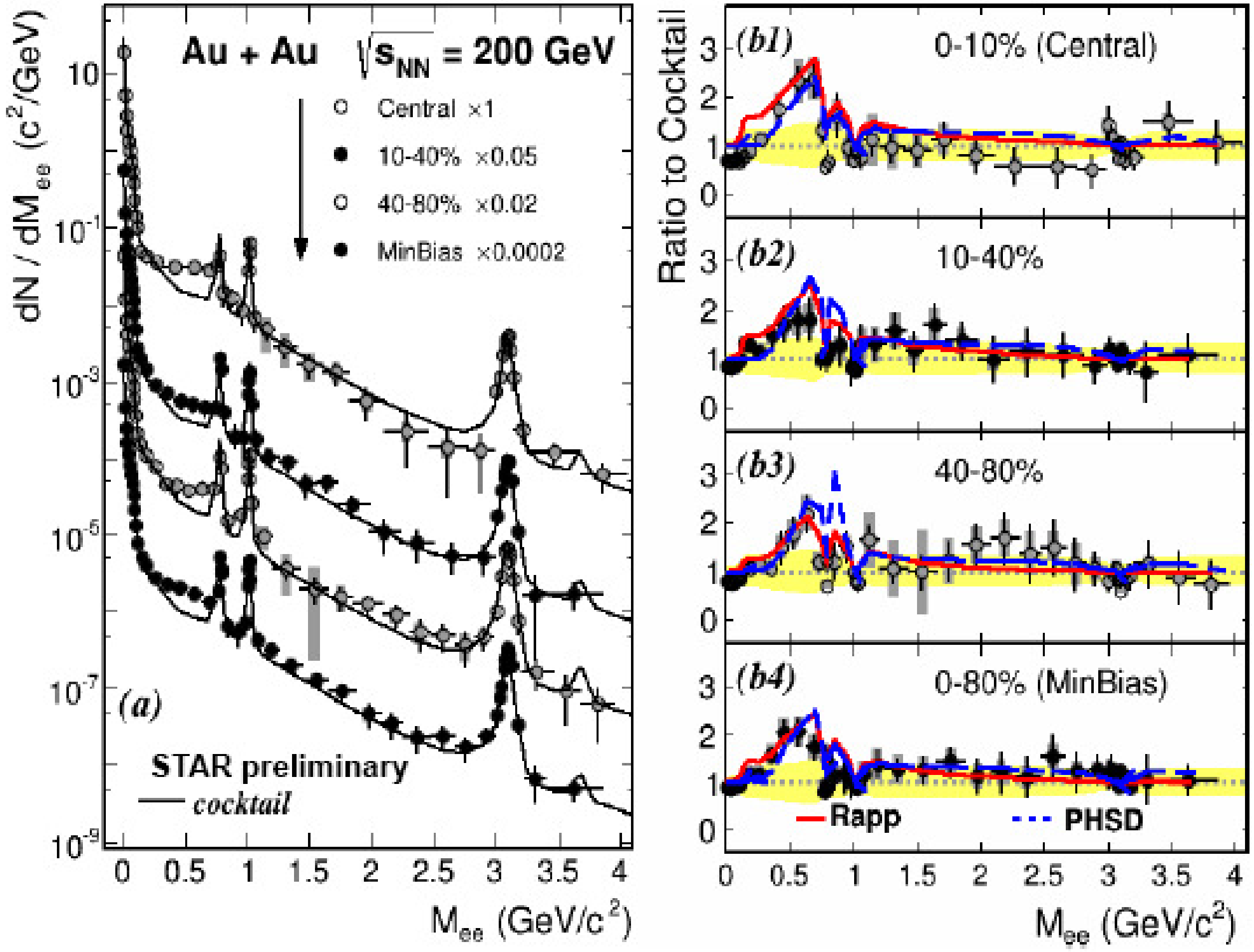
Message:

- **Models** provide a **good description of pp data** and **peripheral Au+Au** data, however, **fail in describing the excess for central collisions** even with **in-medium scenarios** for the vector meson spectral function
- The '**missing source**'(?) is located at **low p_T**
- **Intermediate mass spectra – dominant QGP contribution**

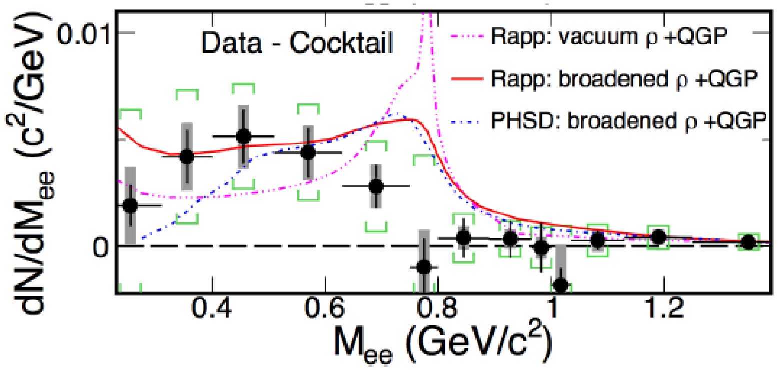
Dileptons at RHIC: STAR data vs model predictions

(Talk by P. Huck at QM'2014)

Centrality dependence of dilepton yield



Excess in low mass region, min. bias



Models:

- **Fireball model – R. Rapp**
- **PHSD**

Low masses:

collisional broadening of ρ

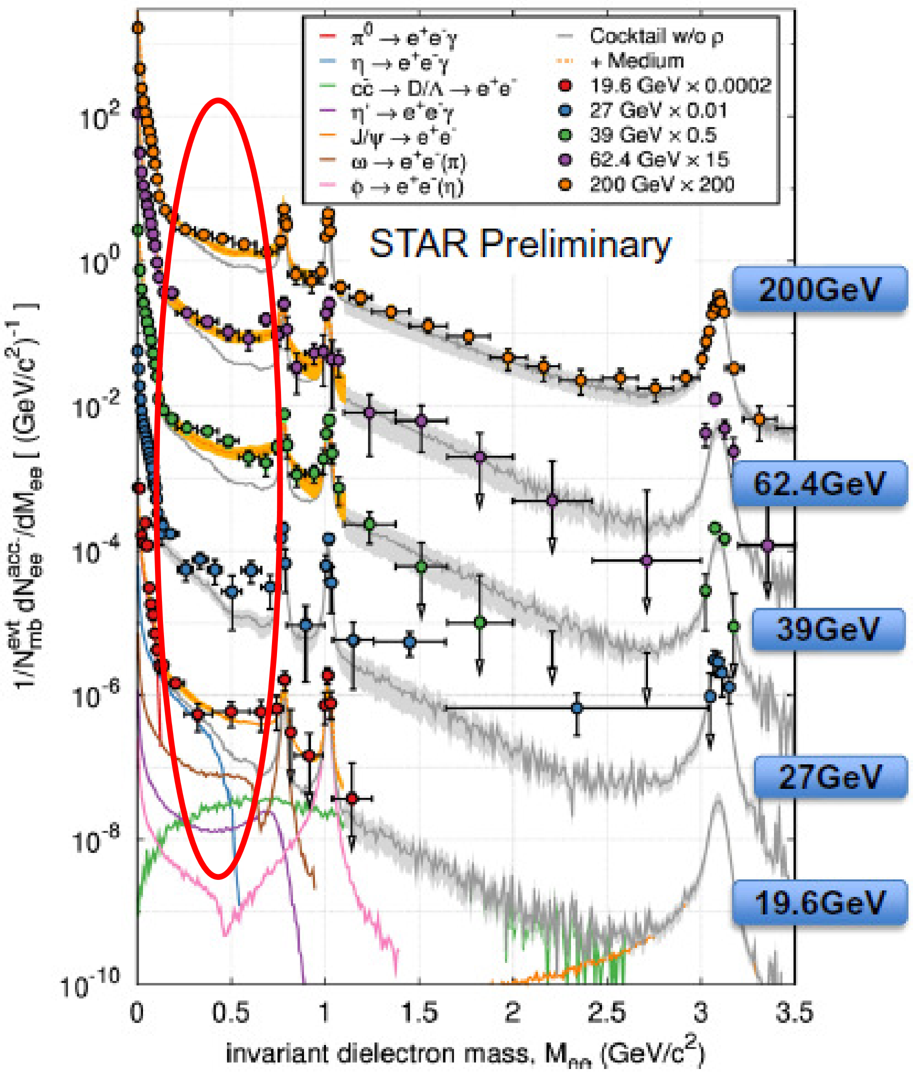
Intermediate masses:

QGP dominant

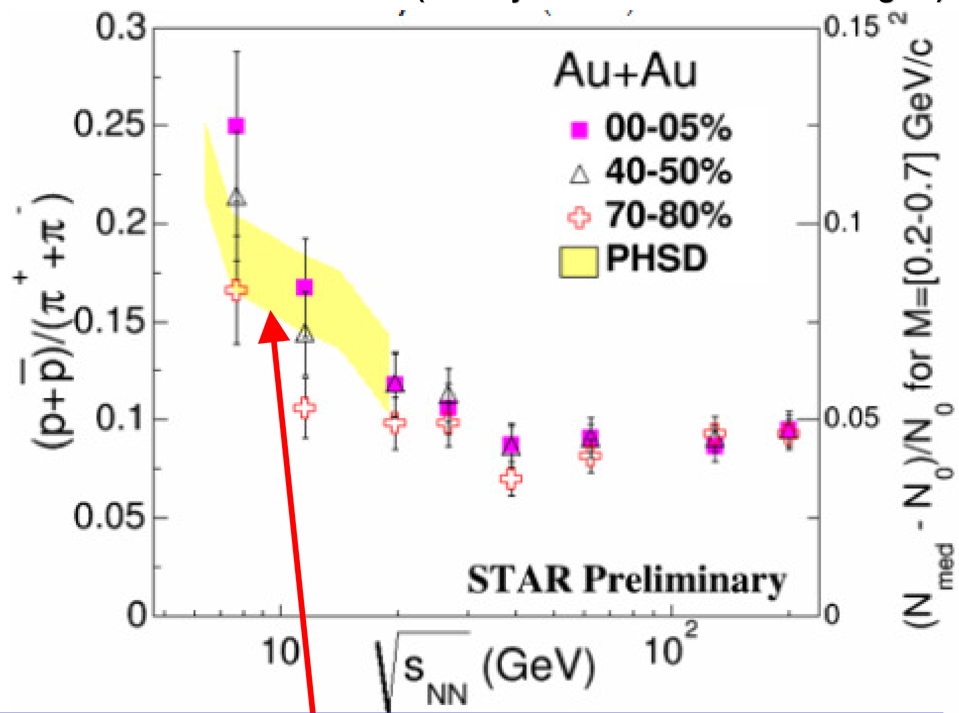
Message: **STAR data** are described by models within a **collisional broadening** scenario for the vector meson spectral function + **QGP**

Dileptons from RHIC BES: STAR

(Talk by Nu Xu at QM'2014)



(Talk by Nu Xi at 23d CBM Meeting'14)

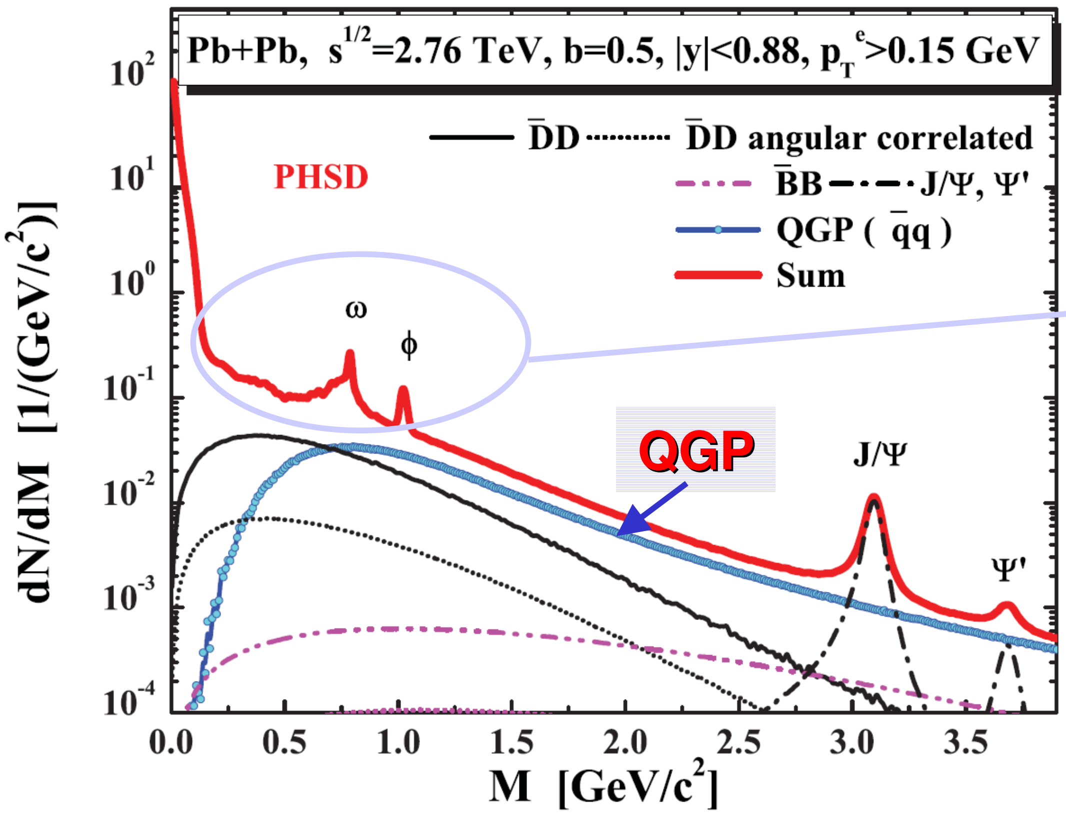


Message:

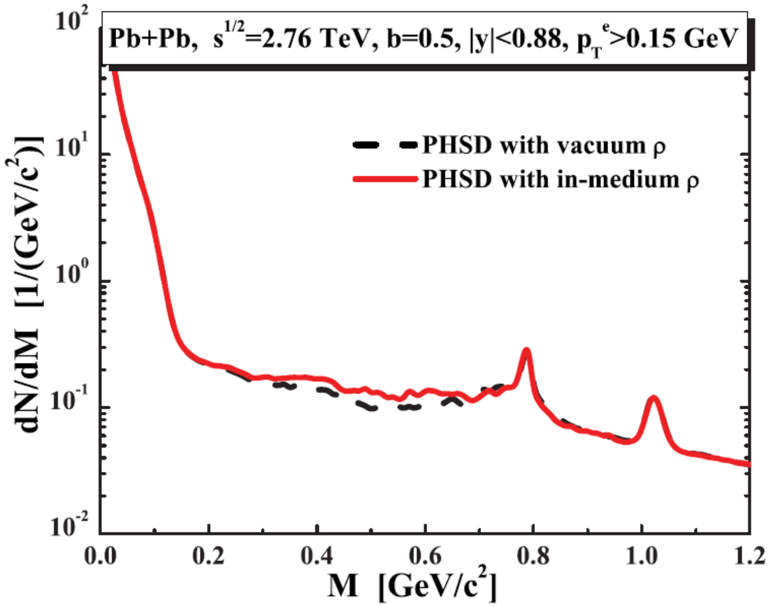
- **BES-STAR data** show a **constant low mass excess** (scaled with N(π^0)) within the measured energy range
- PHSD model: **excess increasing with decreasing energy** due to a longer ρ-propagation in the high baryon density phase

➔ Good perspectives for future experiments – **CBM(FAIR) / MPD(NICA)**

Dileptons at LHC



O. Linnyk, W. Cassing, J. Manninen, E.B., P.B. Gossiaux, J. Aichelin, T. Song, C.-M. Ko, Phys.Rev. C87 (2013) 014905; arXiv:1208.1279



Message:

- low masses - hadronic sources: in-medium effects for ρ mesons are small
- intermediate masses: QGP + D/Dbar
  - charm 'background' is smaller than thermal QGP yield
  - QGP(qbar-q) dominates at M>1.2 GeV → clean signal of QGP at LHC!

Messages from dilepton data

❑ **Low dilepton masses:**

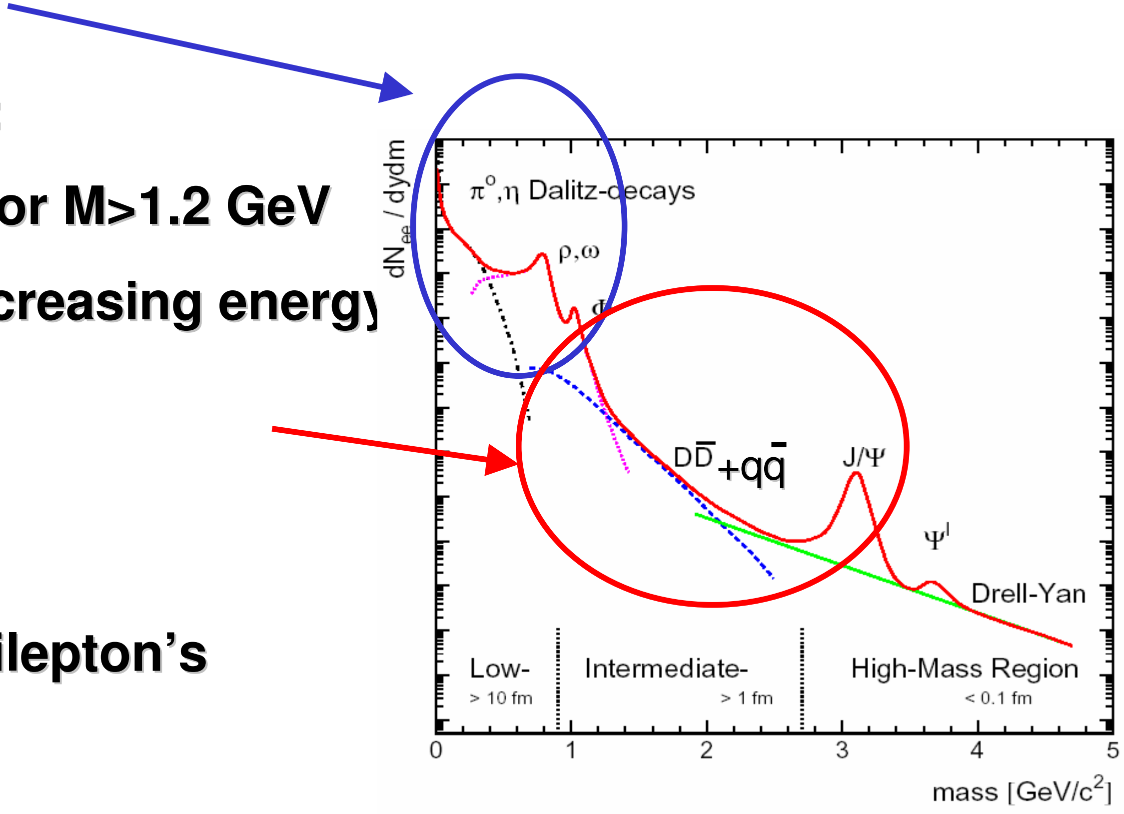
- **Dilepton spectra show sizeable changes due to the in-medium effects – modification of the properties of vector mesons (as collisional broadening) - which are observed experimentally**

- **In-medium effects can be observed at all energies from SIS to LHC**

❑ **Intermediate dilepton masses:**

- **The QGP (qbar-q) dominates for M>1.2 GeV**

- **Fraction of QGP grows with increasing energy at the LHC it is dominant**



Outlook:

*** experimental energy scan**

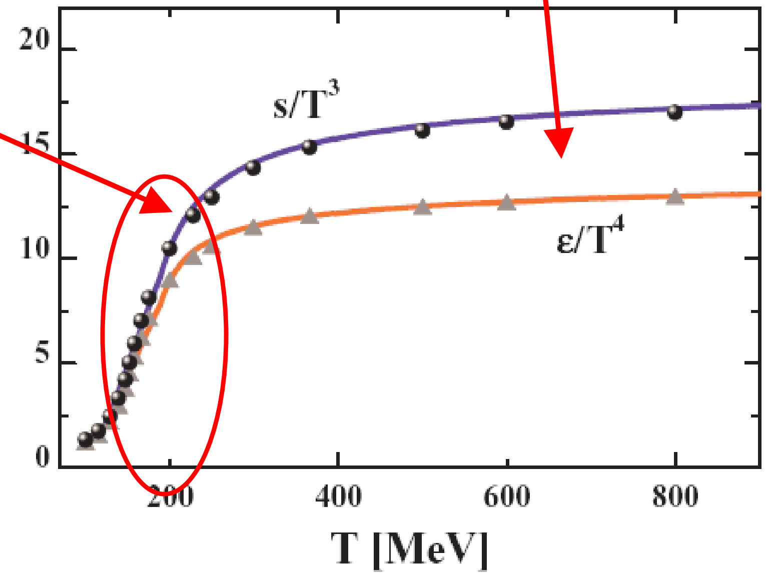
*** experimental measurements of dilepton's higher flow harmonics v_n**

Outlook - Perspectives

What is the stage of matter close to T_c and large μ:

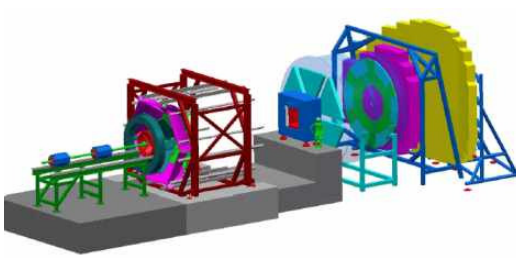
- ❑ 1st order phase transition?
- ❑ ‚Mixed' phase = interaction of partonic and hadronic degrees of freedom?

Lattice EQS for m=0
➔ ‚crossover' , $T > T_c$



Open problems:

- How to describe a first-order phase transition in transport models?
- How to describe parton-hadron interactions in a ‚mixed' phase?



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