# Electromagnetic probes of QGP

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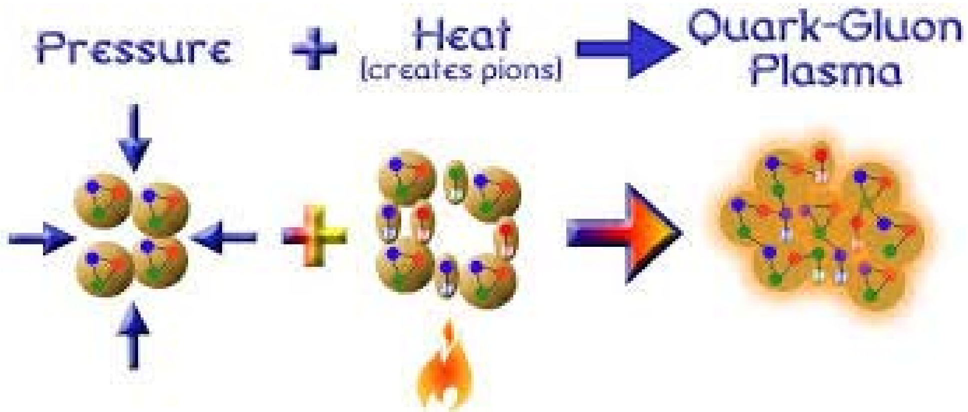
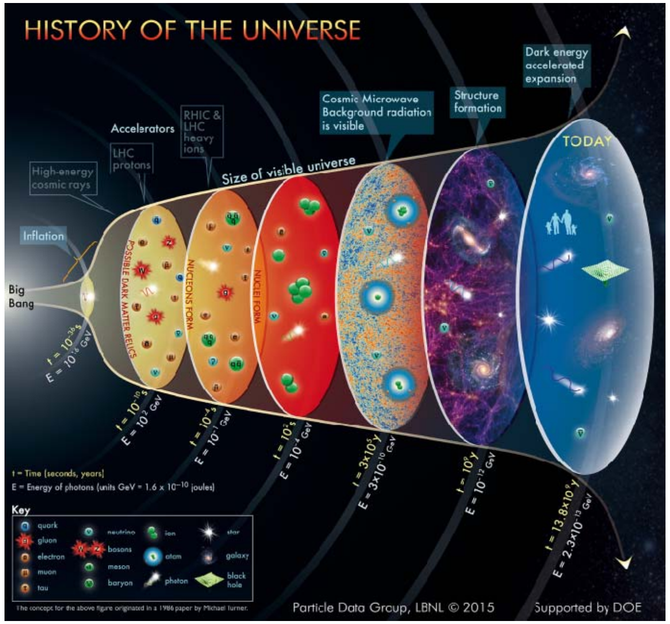
***8th International Workshop on Astronomy and Relativistic Astrophysics34th Winter Workshop on Nuclear Dynamics***
***IWARA2018***
***Ollantaytambo, Sacred Valley, Peru,***
***9 –15 September, 2018***

# Experiment: Heavy-ion collisions

## ❑ Heavy-ion collision experiment

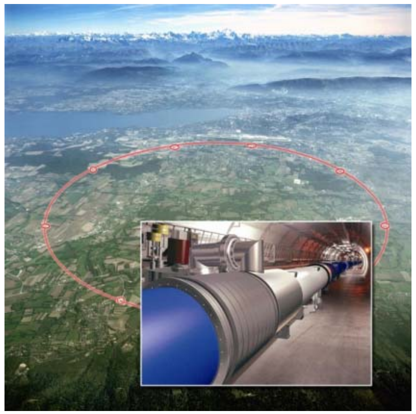
➔ ‚re-creation‘ of the Big Bang conditions in laboratory: matter at high pressure and temperature



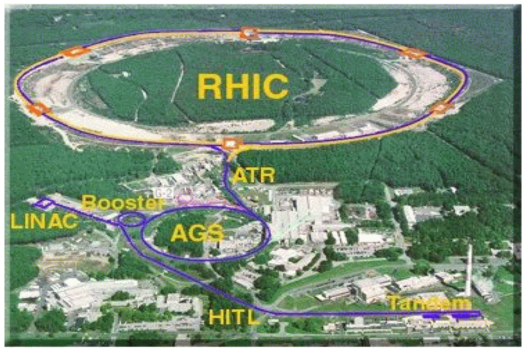




## ❑ Heavy-ion accelerators:

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

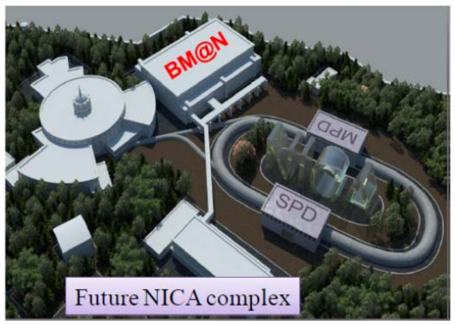


**Relativistic-Heavy-Ion-Collider - RHIC (Brookhaven):**
**Au+Au up to 21.3 A TeV**




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

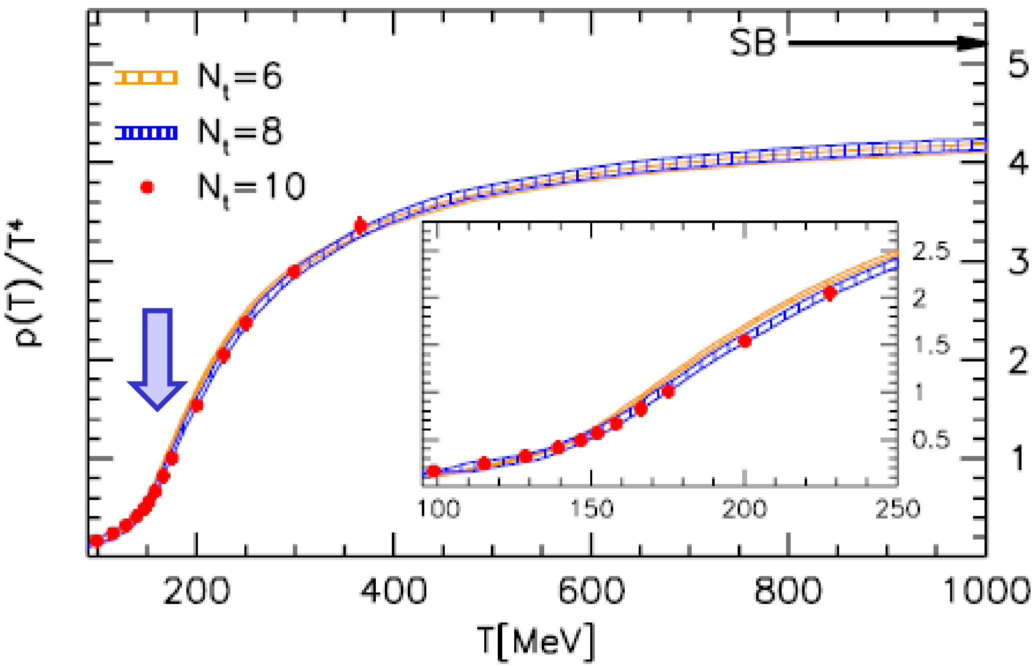
**Nuclotron-based Ion Collider fAcility – NICA (Dubna)**
**(Under construction)**
**Au+Au up to 60 A GeV**

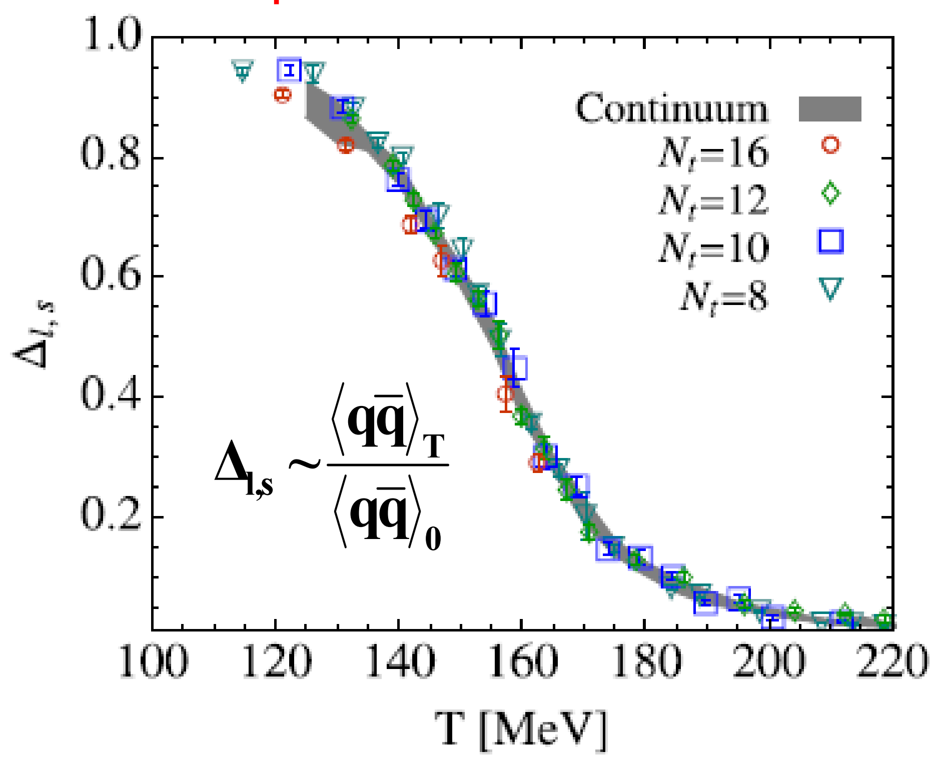


# Theory: Information from lattice QCD

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

**lQCD BMW collaboration:** $\mu_q=0$




- **Crossover: hadron gas → QGP, $T_C$ =156 MeV**

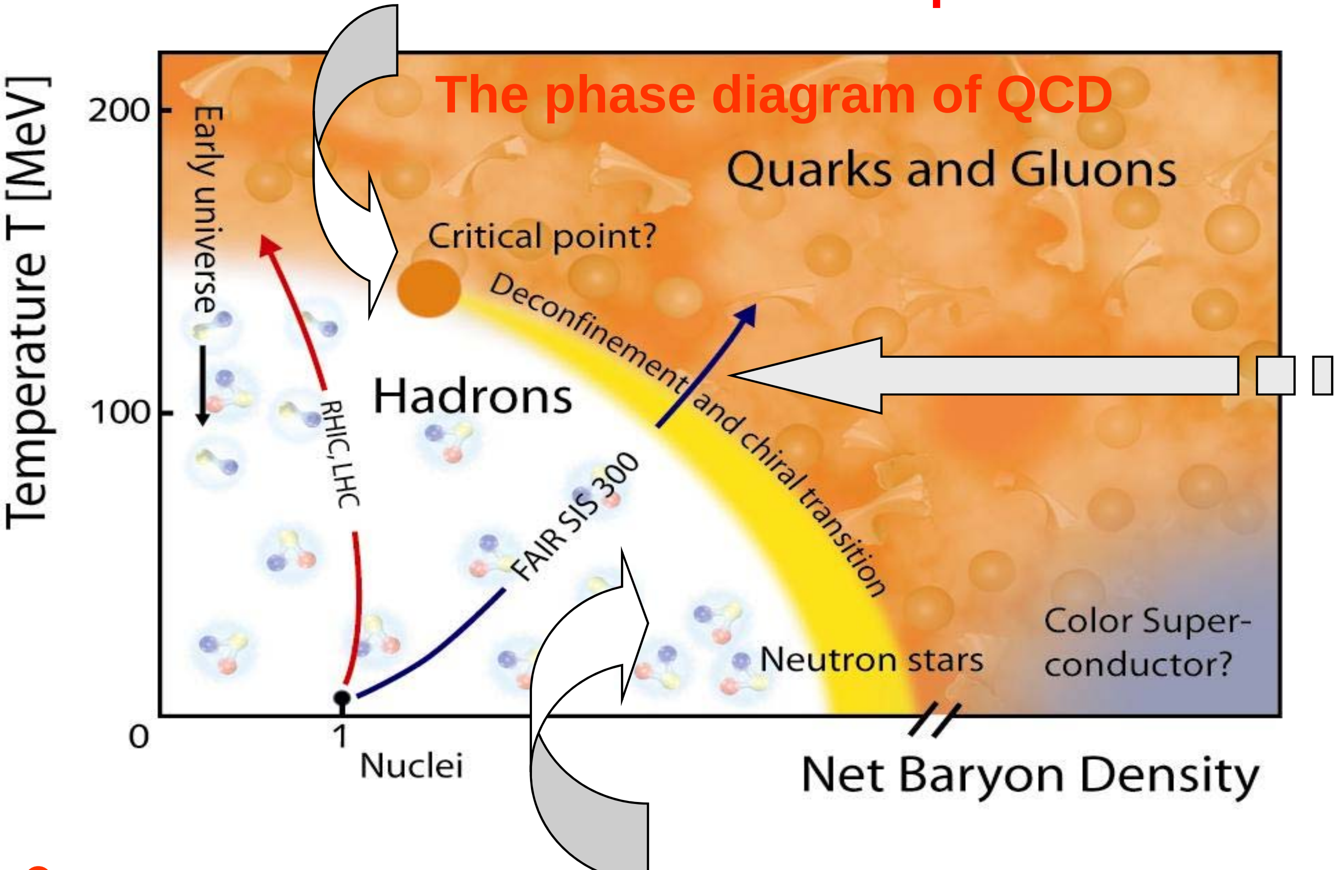
- **Scalar quark condensate $\langle q\bar{q}\rangle$ is viewed as an order parameter for the restoration of chiral symmetry:**

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

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

# 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

# Electromagnetic probes:  photons and dileptons

**Feinberg (76), Shuryak (78)**

## Advantages:

✓ **dileptons and real photons are emitted from different stages of the reaction and not effected by final-state interactions**

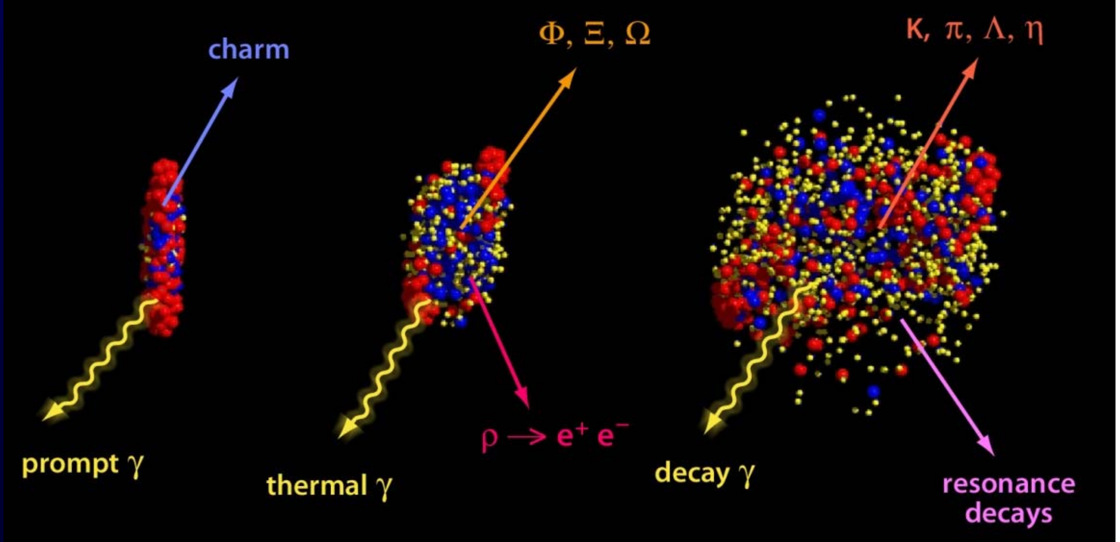
✓ **provide undistorted information about their production channels**

✓ **promising signal of QGP – ‚thermal' photons and dileptons**

➔ **Requires theoretical models which describe the dynamics of heavy-ion collisions during the whole time evolution!**

## Disadvantages:

- **low emission rate**
- **production from hadronic corona**
- **many production sources which cannot be individually disentangled by experimental data**



# Basic models for heavy-ion collisions

- **Statistical models:**

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

[ - : no dynamical information]

- **Hydrodynamical models:**

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

[ - : simplified dynamics]

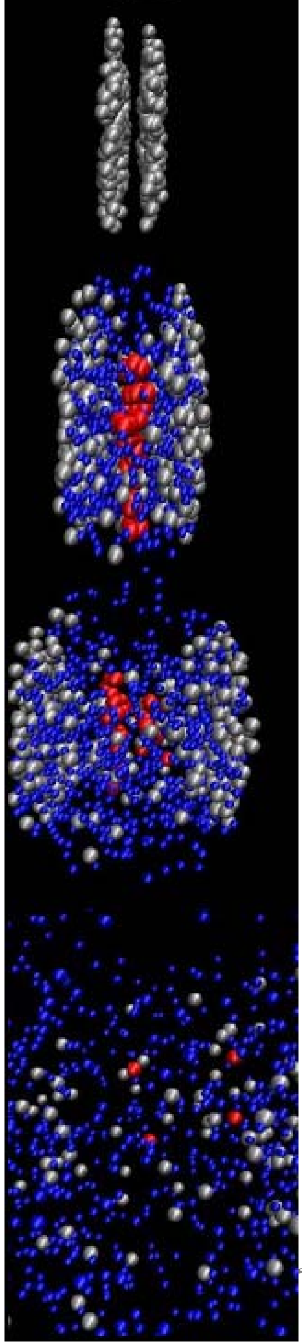
- **Microscopic transport models:**

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

Actual solutions: Monte Carlo simulations

[+ : full dynamics | - : very complicated]

# Parton-Hadron-String-Dynamics (PHSD)



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

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

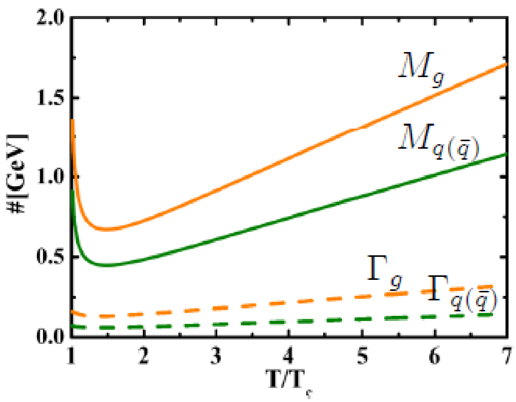
❑ **QGP phase is described by the Dynamical QuasiParticle Model (DQPM) matched to reproduce lattice QCD**

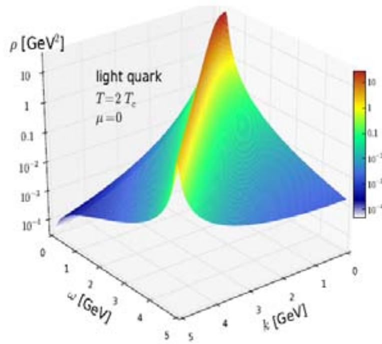
**A. Peshier, W. Cassing, PRL 94 (2005) 172301; W. Cassing, NPA 791 (2007) 365: NPA 793 (2007)**

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

- **Spectral functions:**

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



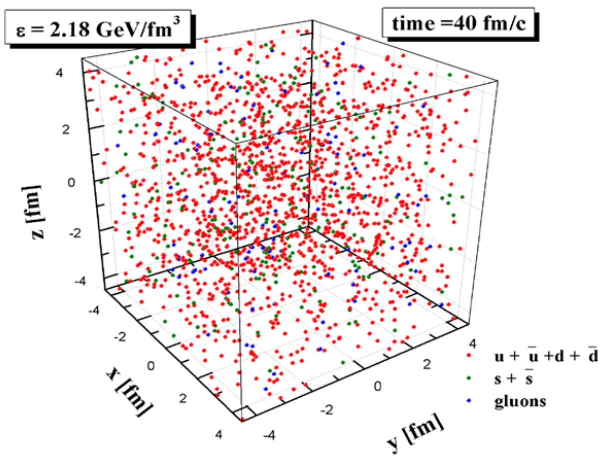




❑ **Transport theory: generalized off-shell transport equations based on the 1st order gradient expansion of Kadanoff-Baym equations (applicable for strongly interacting systems!)**

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

# QGP in equilibrium: Transport properties at finite (T, $\mu_q$): $\eta/s$

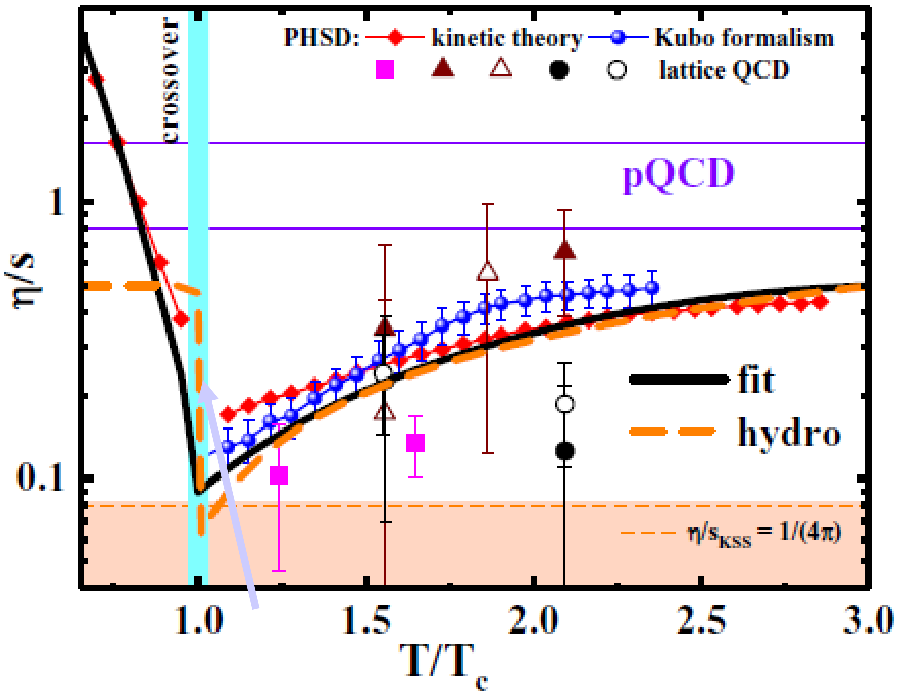
**Infinite hot/dense matter = PHSD in a box:**




**Shear viscosity $\eta/s$ at finite T**

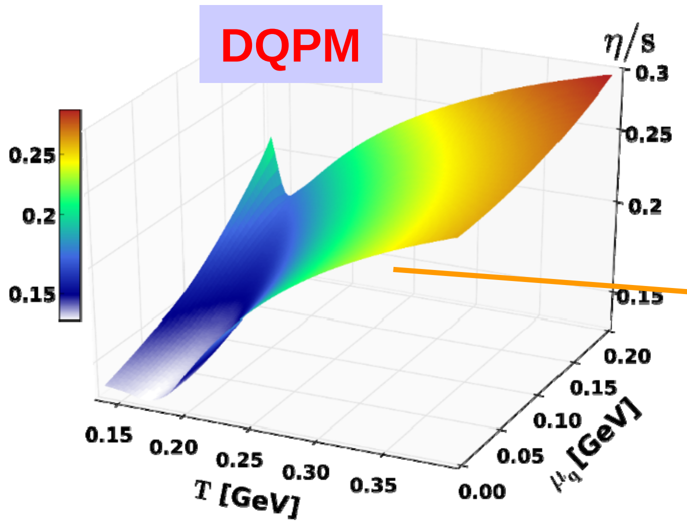
PHSD: V. Ozvenchuk et al., PRC 87 (2013) 064903

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




**Shear viscosity $\eta/s$ at finite (T, $\mu_q$)**

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




**QGP in PHSD = strongly-interacting liquid-like system**

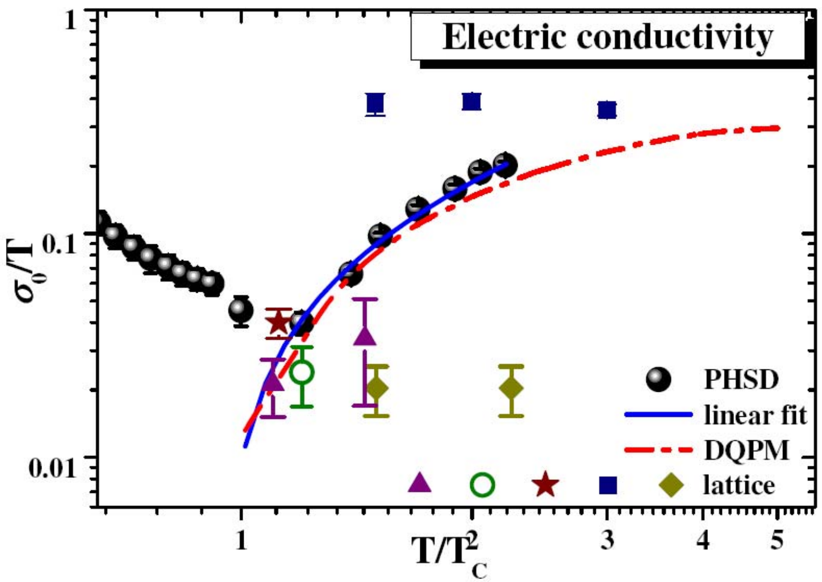
**$\eta/s$: $\mu_q$=0 ➔ finite $\mu_q$: smooth increase as a function of (T, $\mu_q$)**

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

# Transport properties at finite (T, $\mu_q$): $\sigma_e/T$

**PHSD in a box:**
**Electric conductivity $\sigma_e/T$ at finite T**

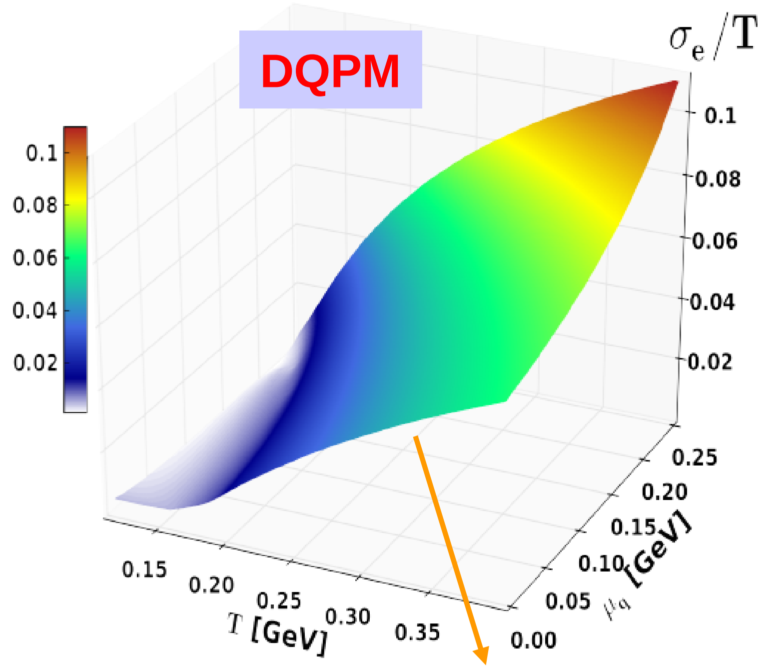
W. Cassing et al., PRL 110(2013)182301




- 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 !

**Electric conductivity $\sigma_e/T$ at finite (T, $\mu_q$)**

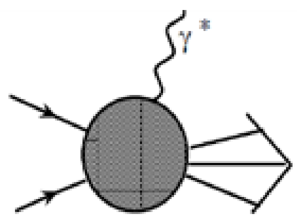
H. Berrehrah et al. , PRC93 (2016) 044914




$\sigma_e/T$ : $\mu_q$=0 ➔ finite $\mu_q$: smooth increase as a function of (T, $\mu_q$)

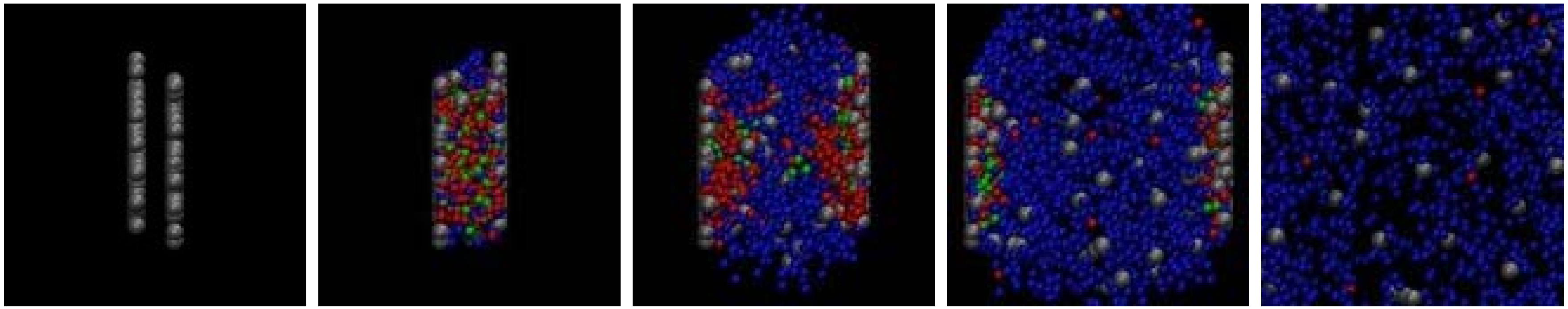
❑ **Photon emission:** rates at $q_0 \to 0$ are related to electric conductivity $\sigma_0$

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



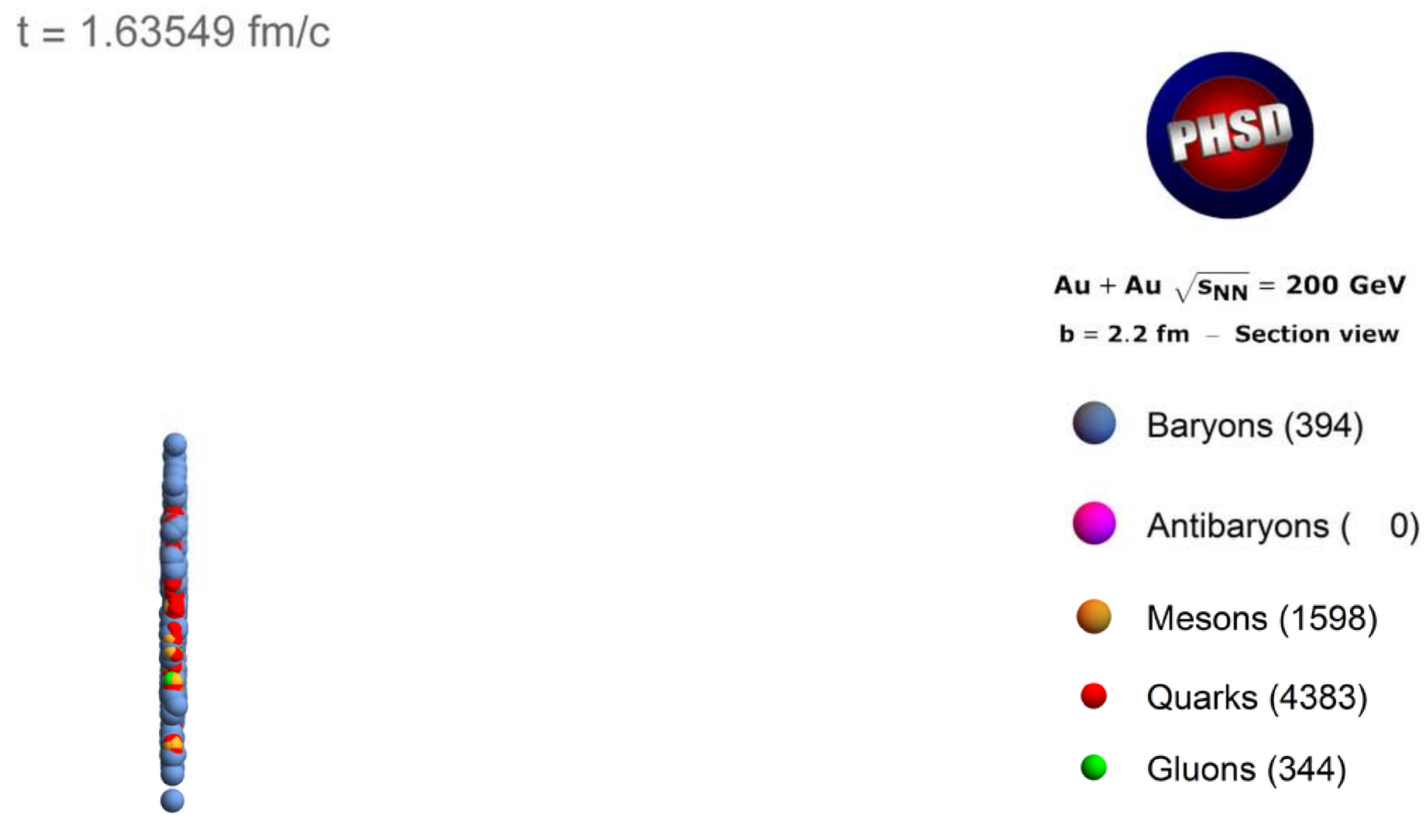

$\sigma_0$ ➔ Probe of electromagnetic properties of the QGP

# ‚Bulk‘ properties
# in Au+Au collisions



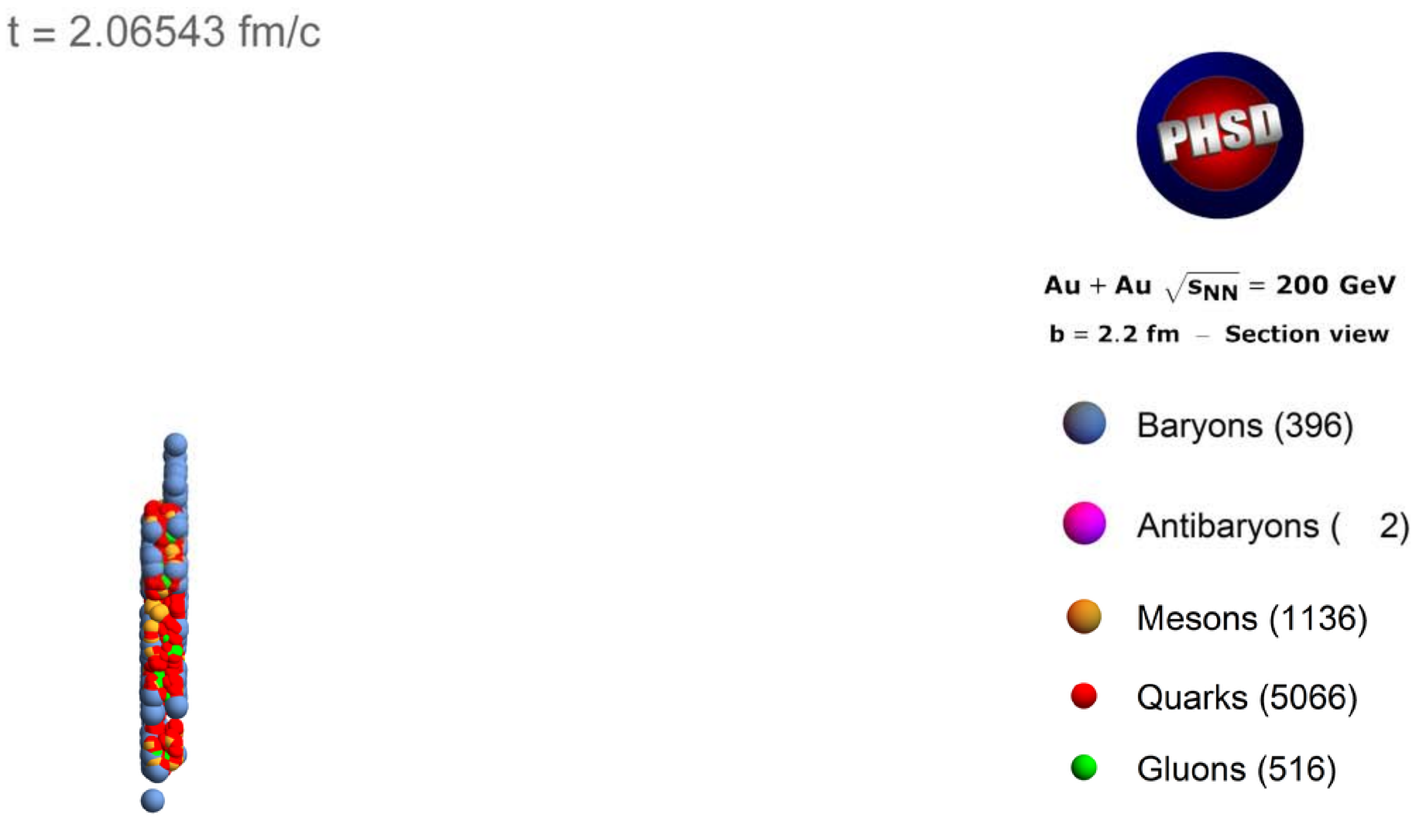
# Au+Au at 200 A GeV, b=2.2 fm

# Au+Au at 200 A GeV, b=2.2 fm




P.Moreau

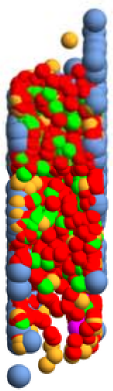
# Au+Au at 200 A GeV, b=2.2 fm




P.Moreau

# Au+Au at 200 A GeV, b=2.2 fm

t = 3.20258 fm/c




Au + Au $\sqrt{s_{NN}}$ = 200 GeV

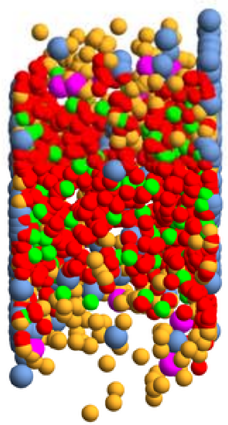
b = 2.2 fm – Section view

- Baryons (413)
- Antibaryons ( 13)
- Mesons (1080)
- Quarks (4708)
- Gluons (761)

P.Moreau

# Au+Au at 200 A GeV, b=2.2 fm

t = 5.56921 fm/c



Au + Au $\sqrt{s_{NN}}$ = 200 GeV

b = 2.2 fm – Section view

Baryons (472)

Antibaryons ( 70)

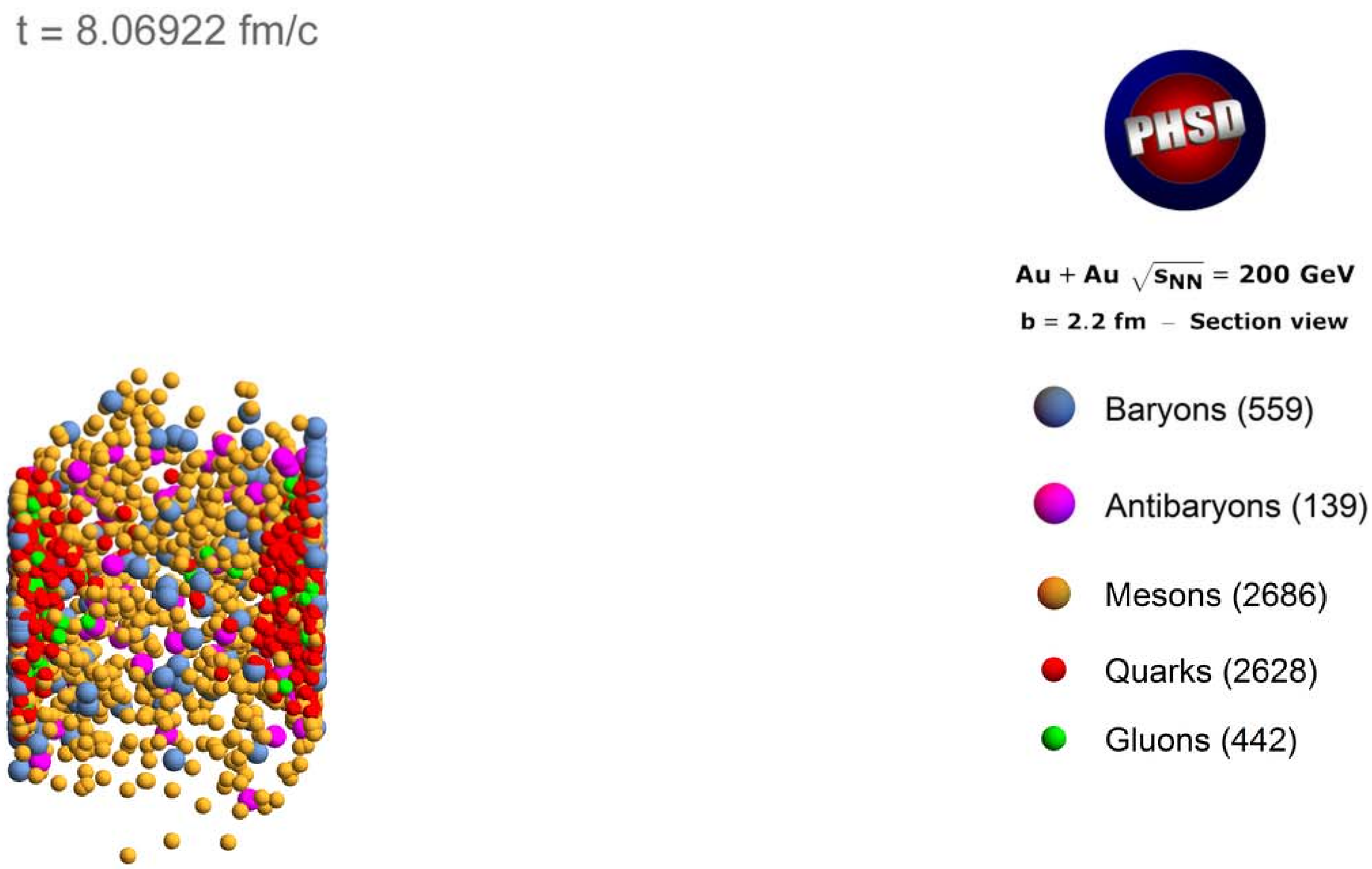
Mesons (1724)

Quarks (3843)

Gluons (652)

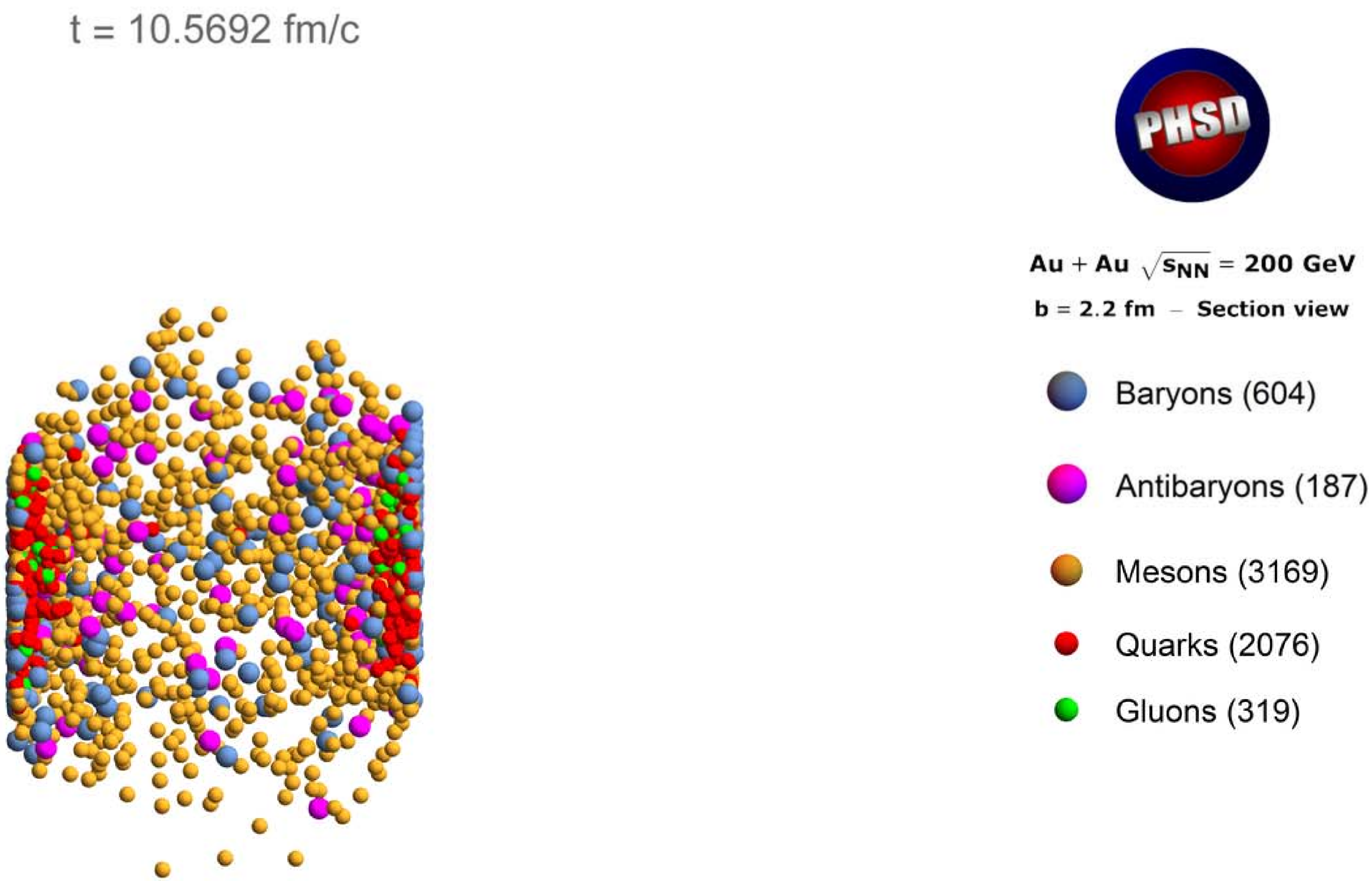
P.Moreau

# Au+Au at 200 A GeV, b=2.2 fm



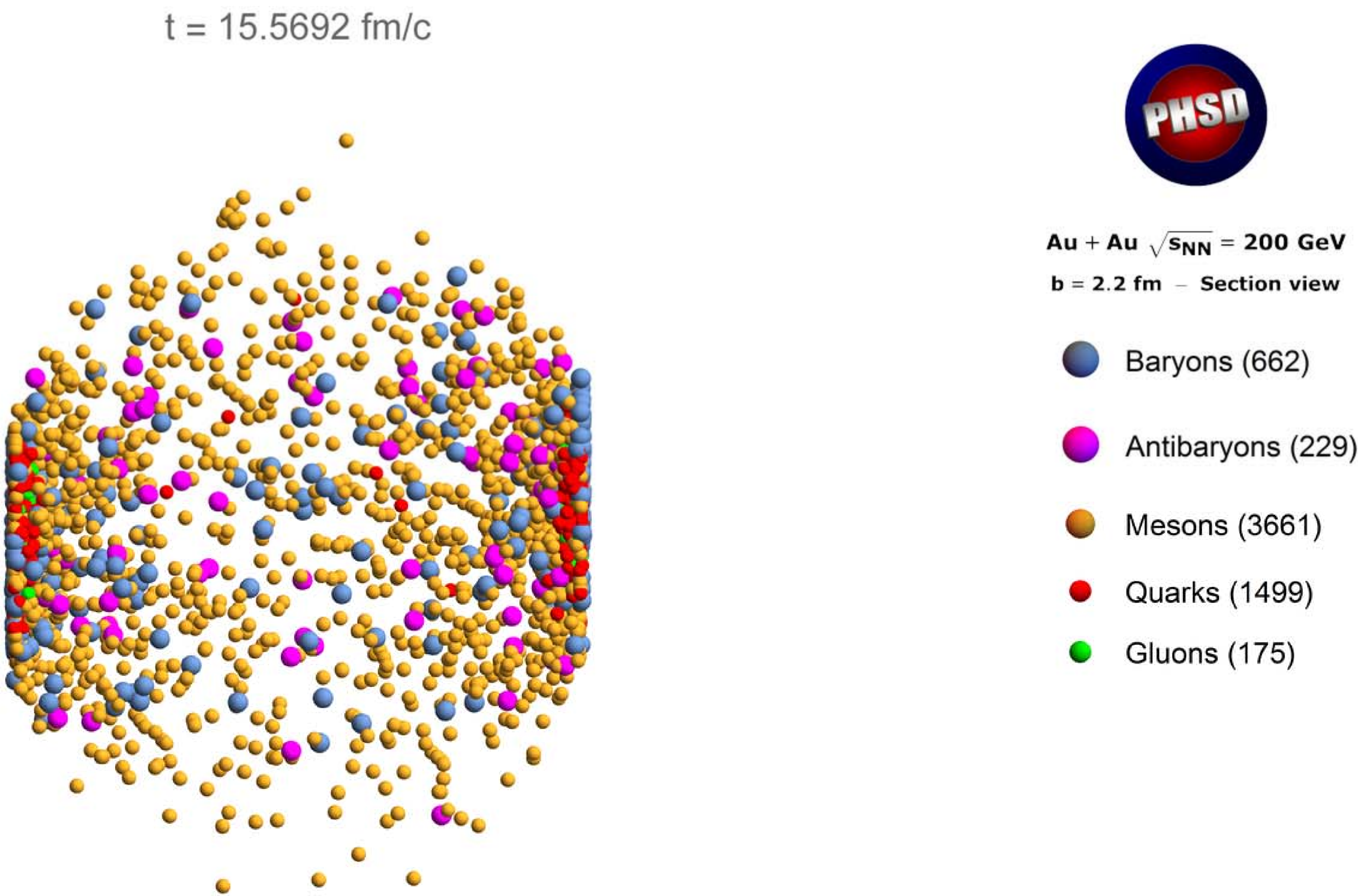

P.Moreau

# Au+Au at 200 A GeV, b=2.2 fm



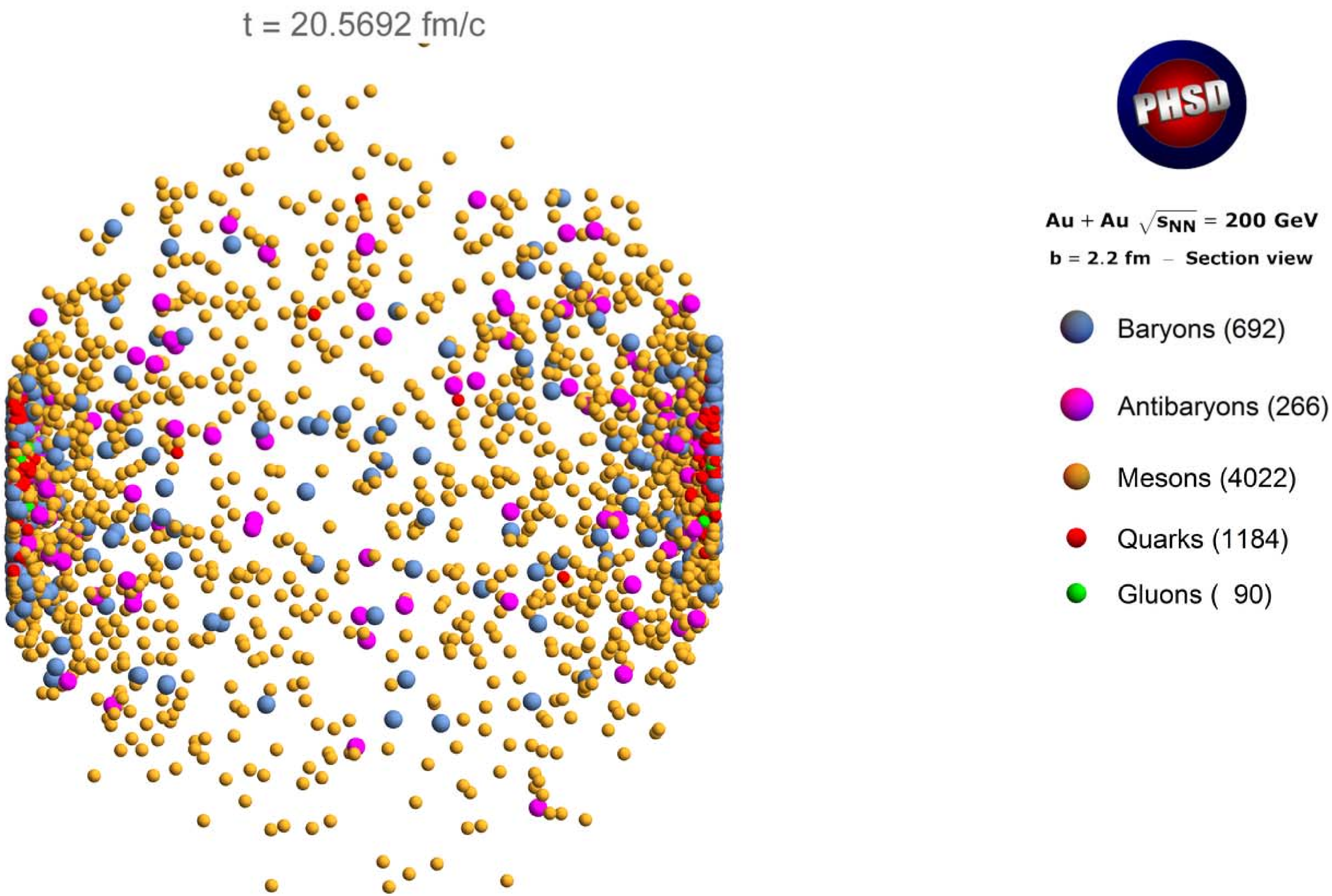

P.Moreau

# Au+Au at 200 A GeV, b=2.2 fm




P.Moreau

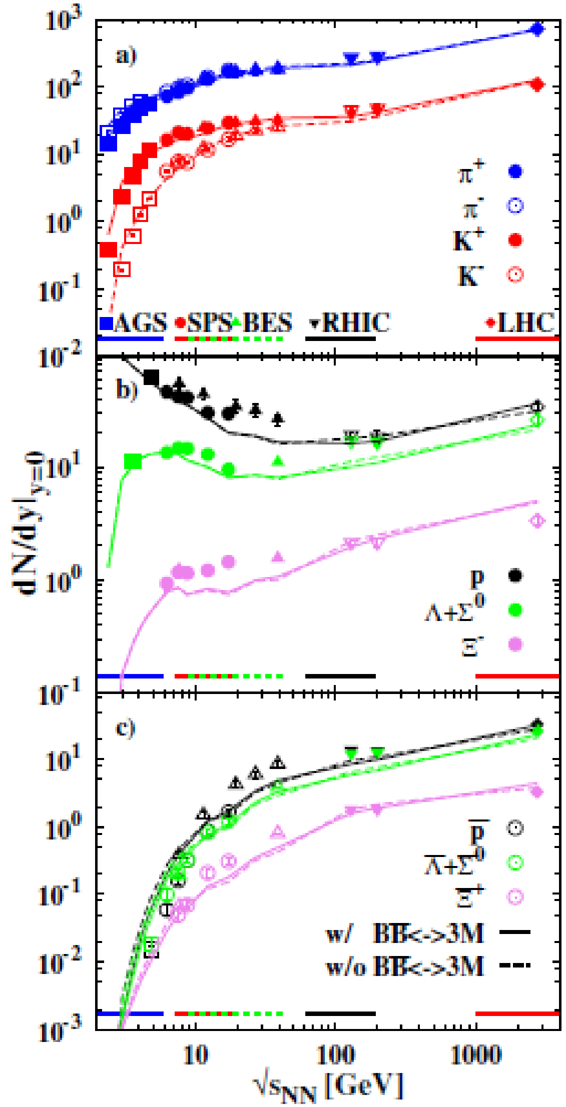
# Au+Au at 200 A GeV, b=2.2 fm

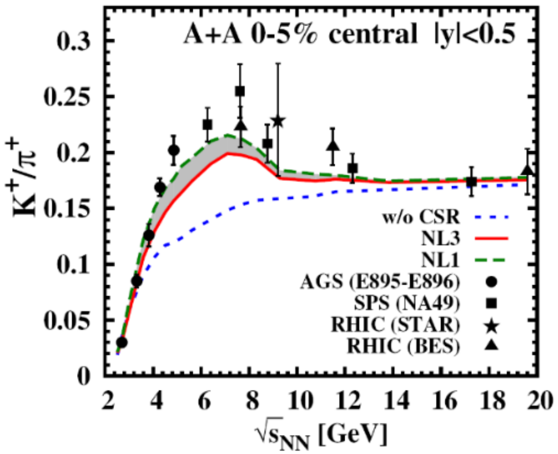


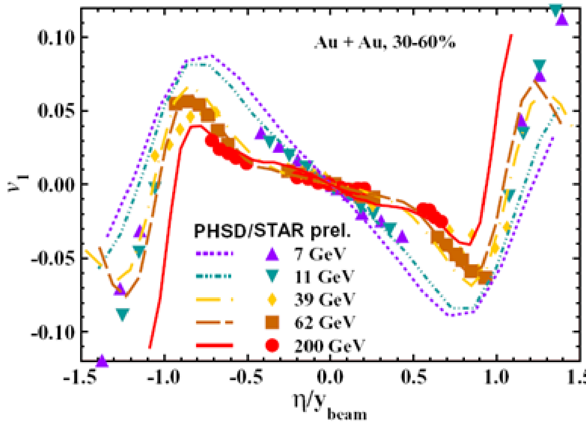

P.Moreau

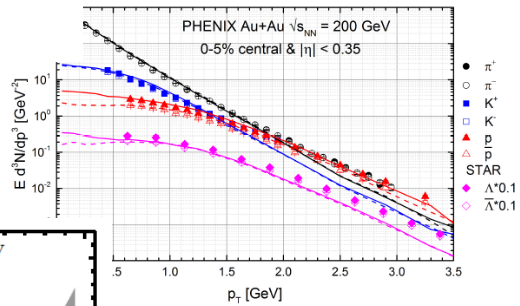
# Non-equilibrium dynamics: description of A+A with PHSD

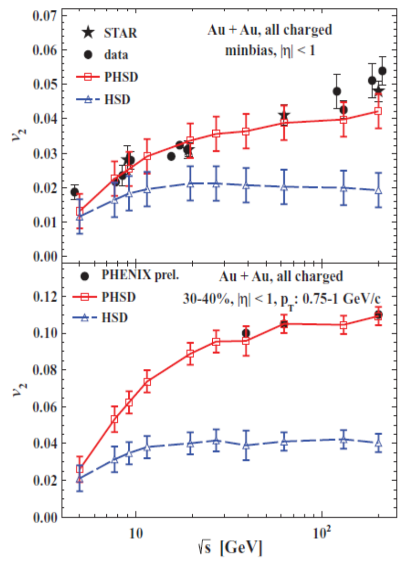
## ❑ PHSD: highlights

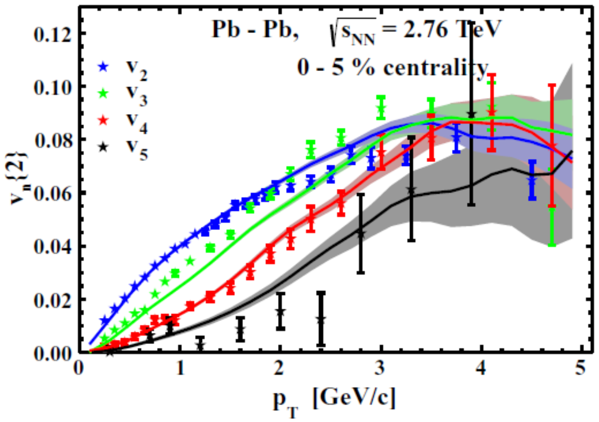


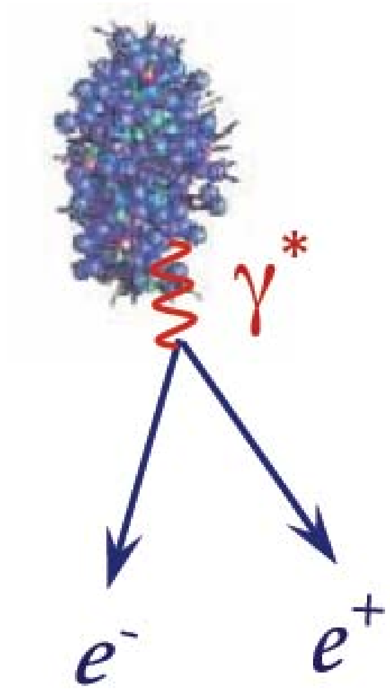




PRC 85 (2012) 011902; JPG42 (2015) 055106

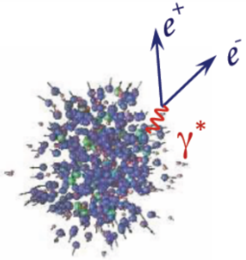
arXiv:1801.07557

❑ **PHSD provides a good description of ‚bulk' observables (y-, $p_T$-distributions, flow coefficients $v_n$, …) from SIS to LHC**

# Dileptons as a probe of the QGP and in-medium effects

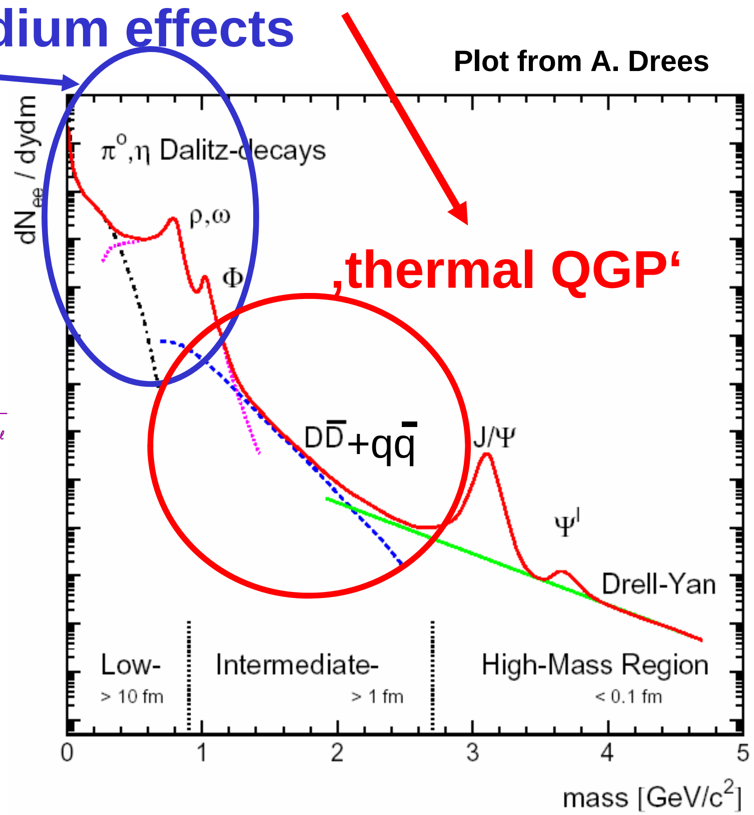


# Dilepton sources

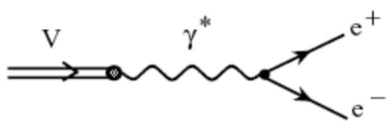



- **from the QGP via partonic (q,qbar, g) interactions:**

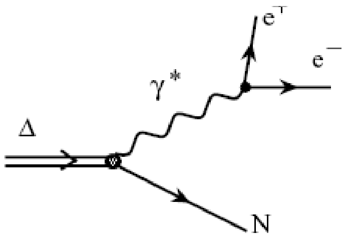

- **from hadronic sources:**



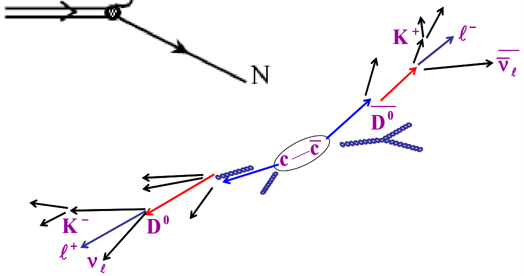

- **direct decay of vector mesons** (ρ,ω,φ,J/Ψ,Ψ')




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




- **correlated D+Dbar pairs**

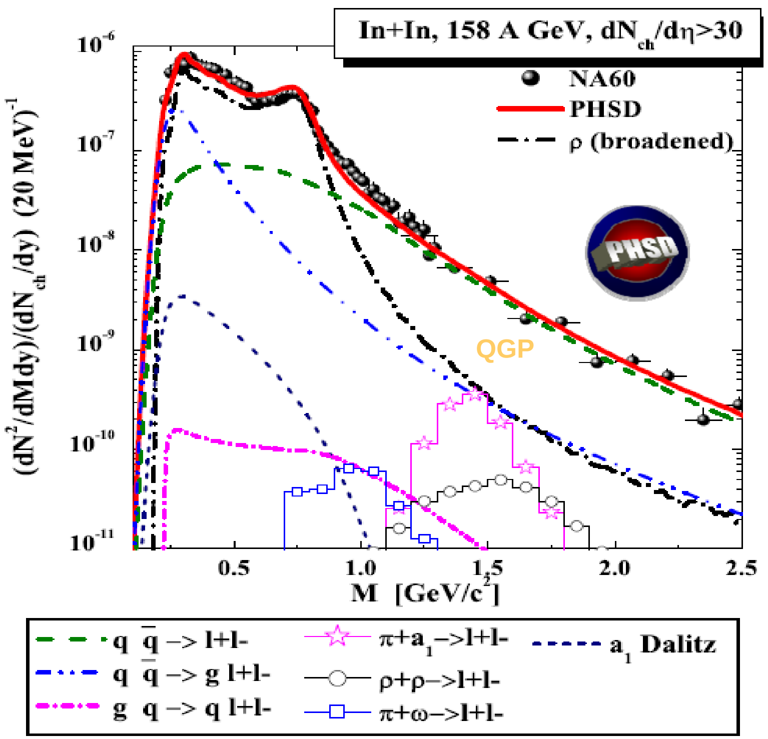



- **radiation from multi-meson reactions** (π+π, π+ρ, π+ω, ρ+ρ , π+$a_1$) - ,4π'

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

# Lessons from SPS: NA60

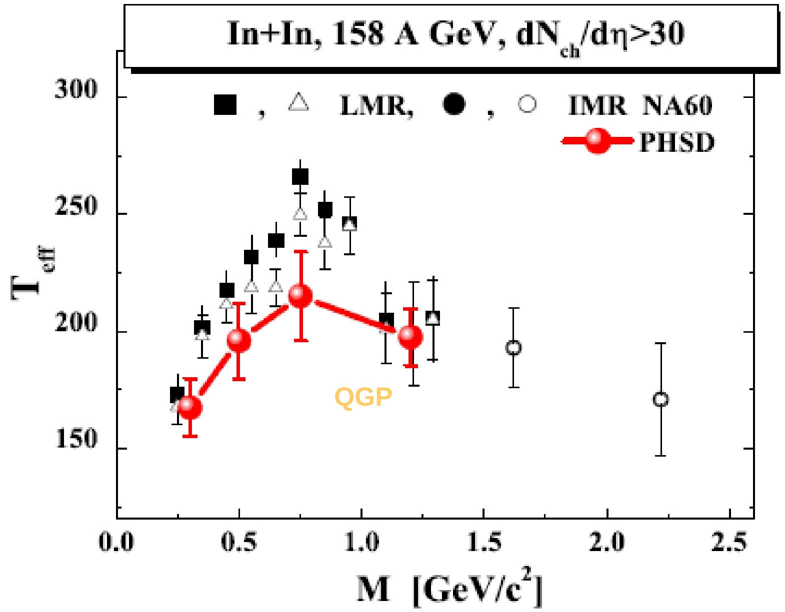
## ❑ Dilepton invariant mass spectra:




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

## ❑ Inverse slope parameter $T_{eff}$:

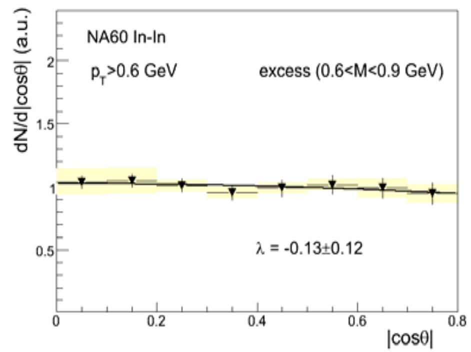
**spectrum from QGP is softer than from hadronic phase since the QGP emission occurs dominantly before the collective radial flow has developed**




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

**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**

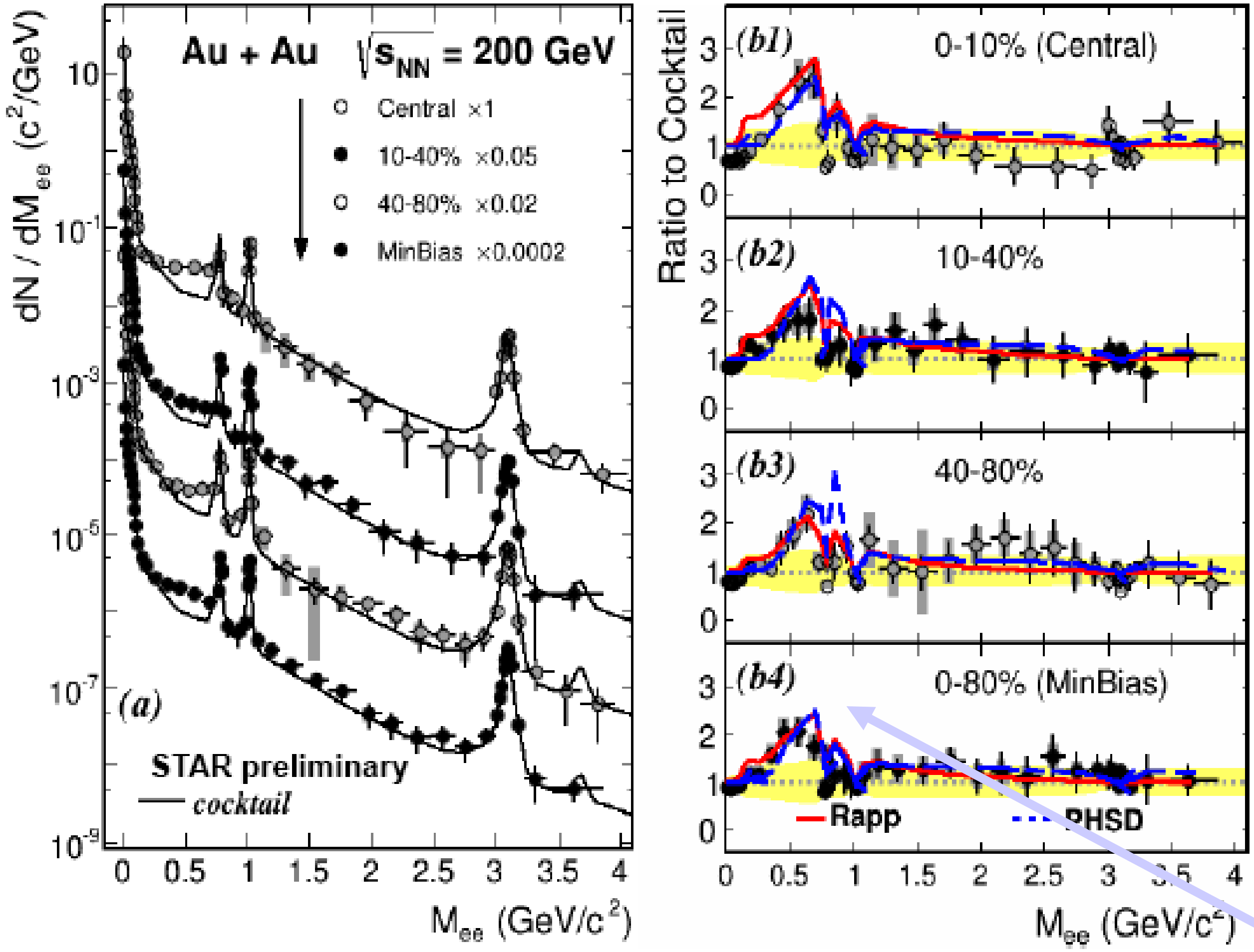



PRL 102 (2009) 222301

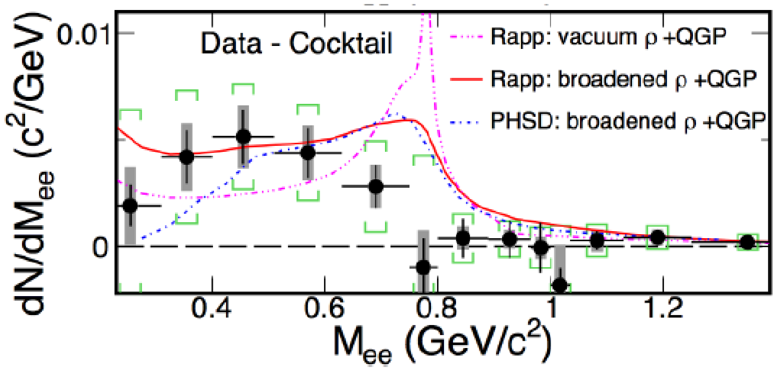
# Dileptons at RHIC: STAR data vs model predictions

**PRC 92 (2015) 024912**

**Centrality dependence of dilepton yield**




**Excess in low mass region, min. bias**




**Models:**

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

**Low masses:**

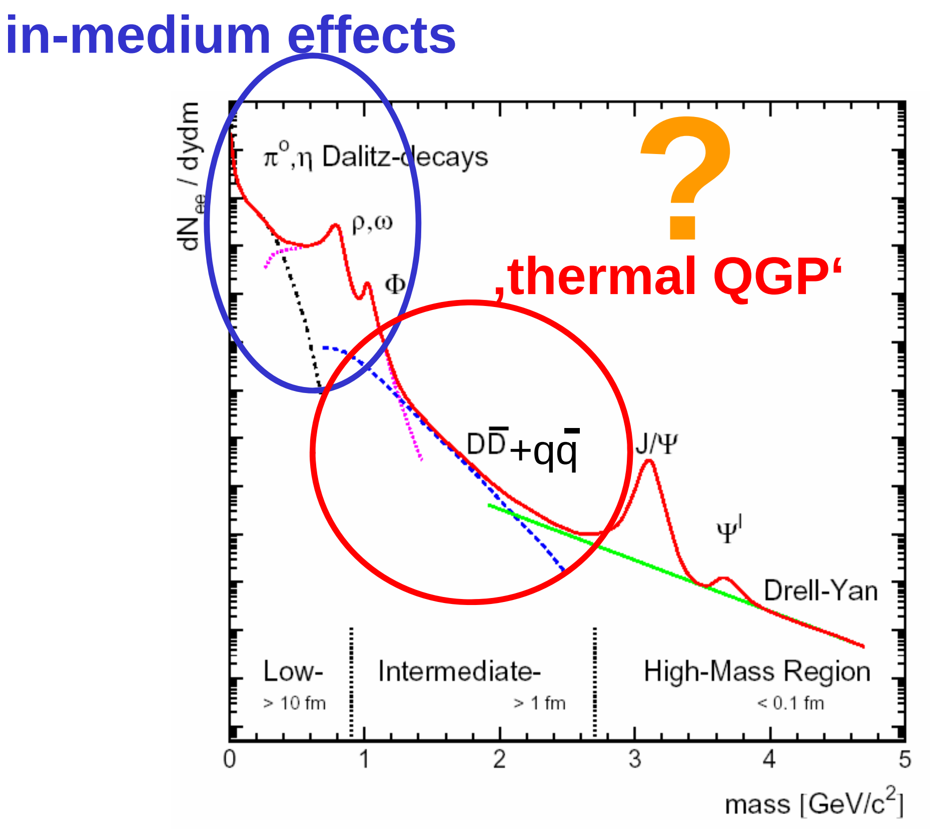
**collisional broadening of ρ**

**Intermediate masses:**

**QGP dominant**

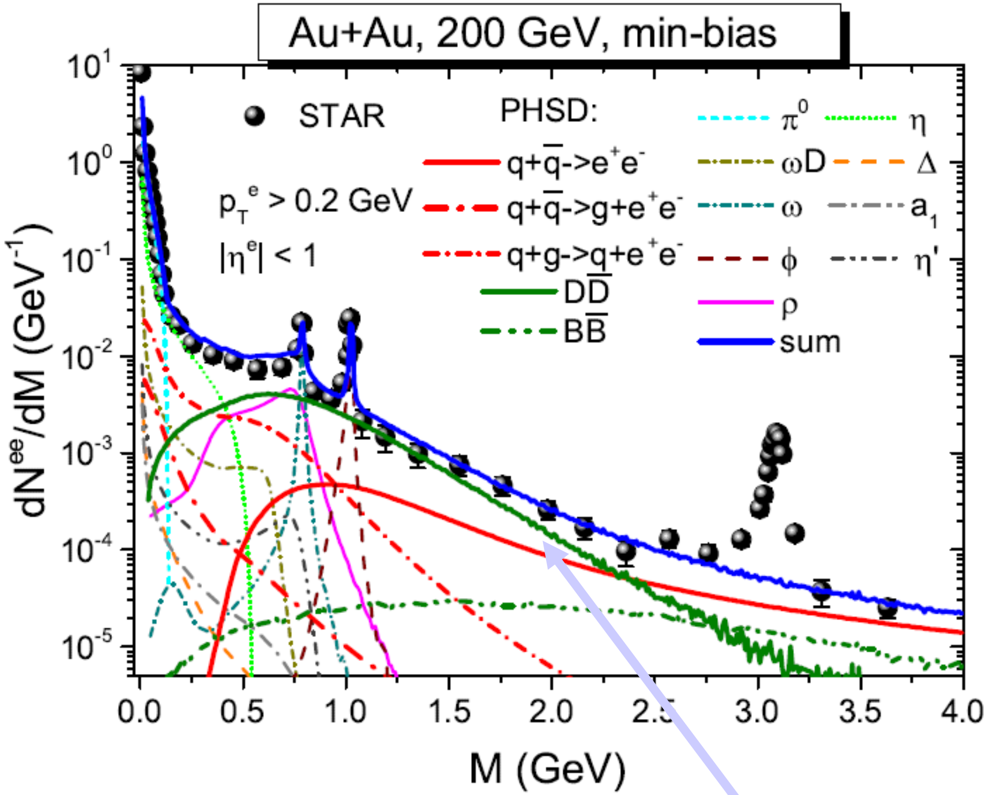
**Message: STAR data are described by models within a collisional broadening scenario for the vector meson spectral function + QGP**

# What is the best energy range to observe thermal dileptons from QGP ?

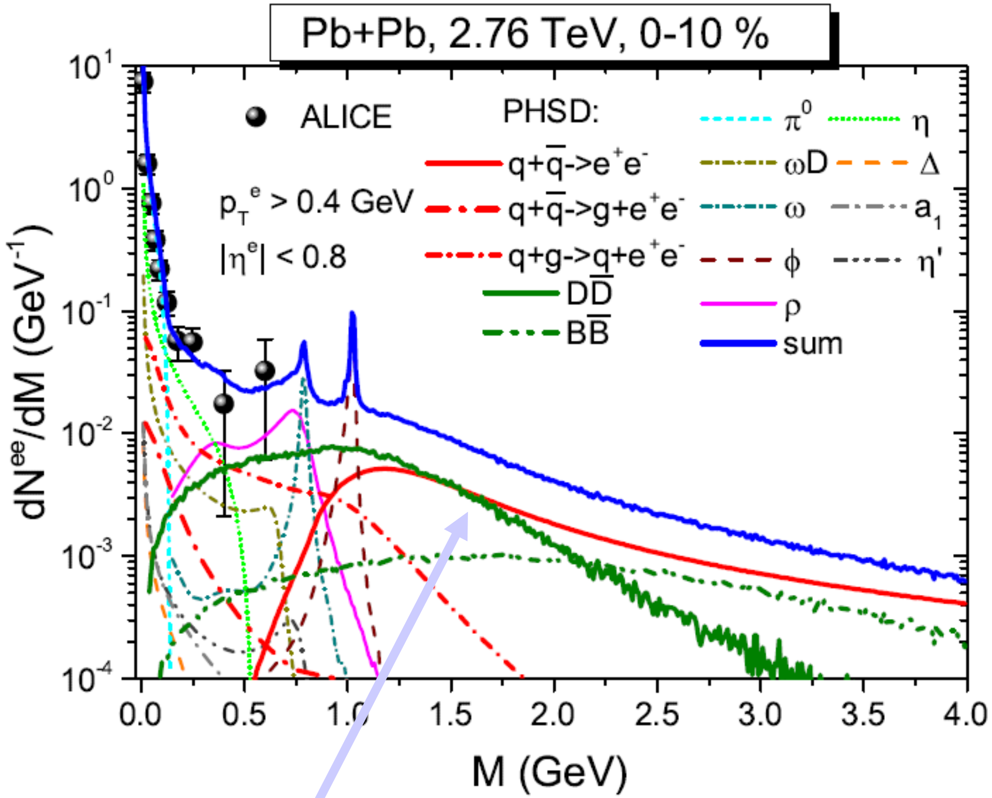


# Dileptons at RHIC and LHC

## RHIC




## LHC




**Message:**

**STAR data at 200 GeV and the ALICE data at 2.76 TeV are described by PHSD within**

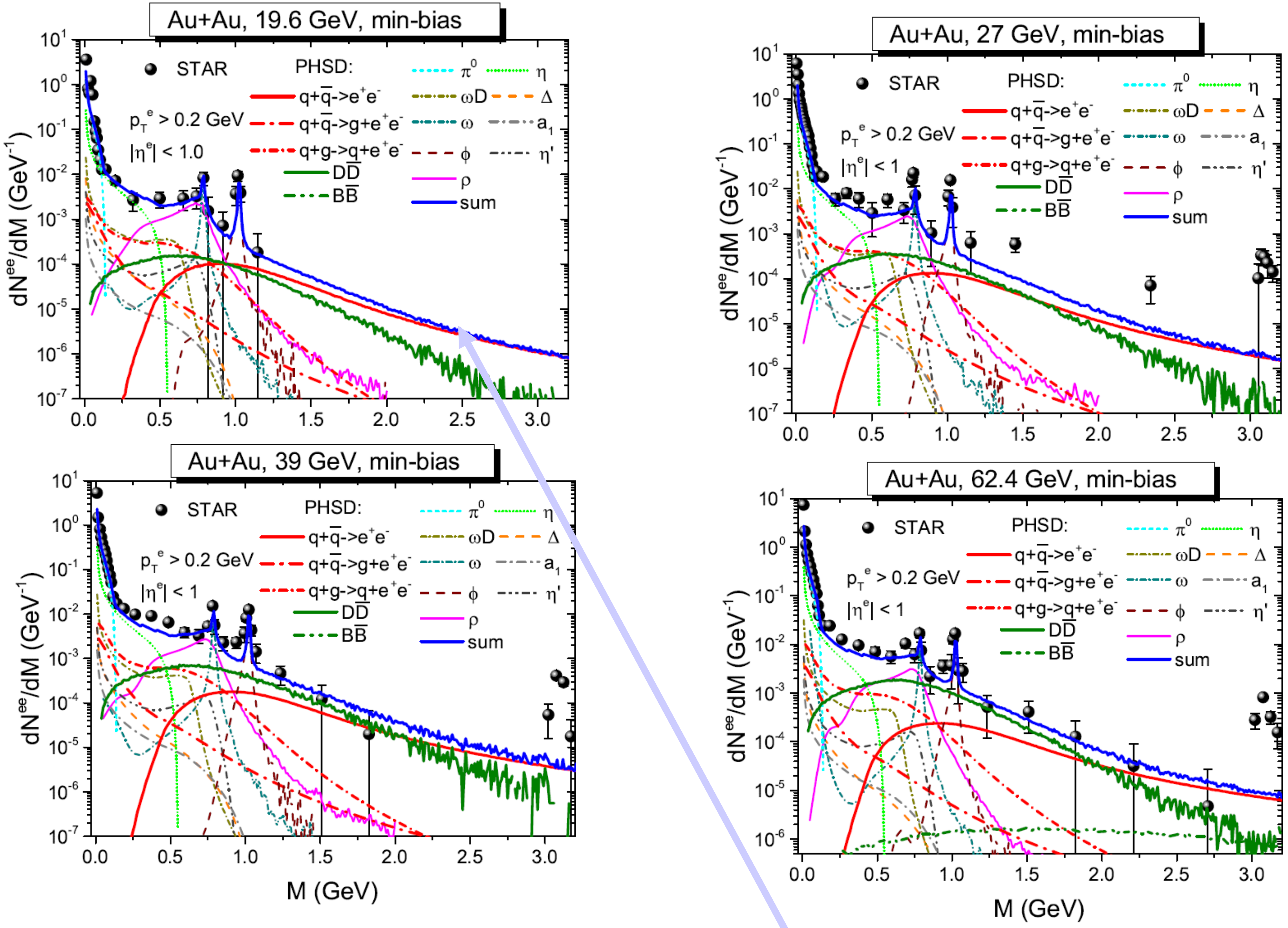
**1) a collisional broadening scenario for the vector meson spectral functions**
**+ QGP + correlated charm**

**2) Charm contribution is dominant for 1.2 < M < 2.5 GeV**

T. Song, W.Cassing, P.Moreau and E.Bratkovskaya, Phys. Rev. C 97 (2018) 064907

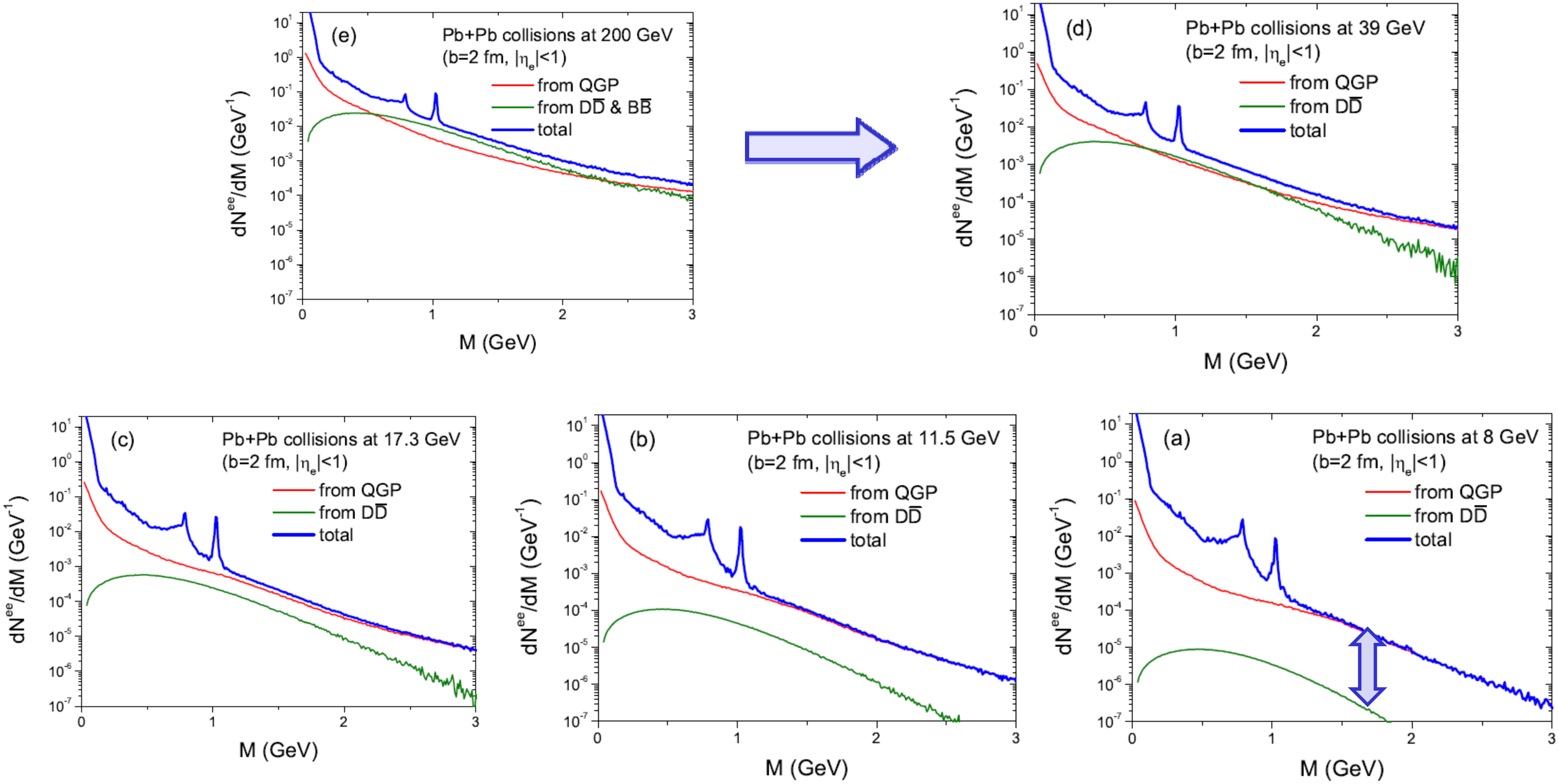
# Dileptons from RHIC BES: STAR

T. Song, W.Cassing, P.Moreau and E.Bratkovskaya, Phys. Rev. C 97 (2018) 064907




**QGP and charm are dominant contributions for intermediate masses at BES RHIC**
**→ measurements of charm at BES RHIC are needed to control charm production !**

# Dileptons at FAIR/NICA energies: predictions




**Relative contribution of QGP versus charm increases with decreasing energy!**

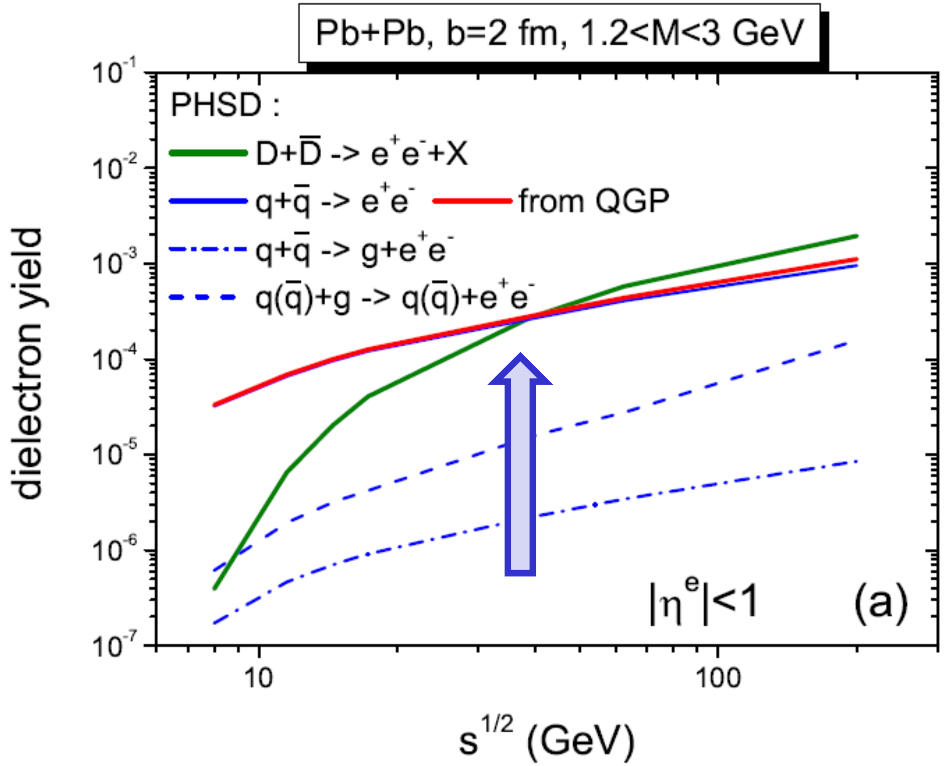
T. Song, W.Cassing, P.Moreau and E.Bratkovskaya, Phys. Rev. C 97 (2018) 064907

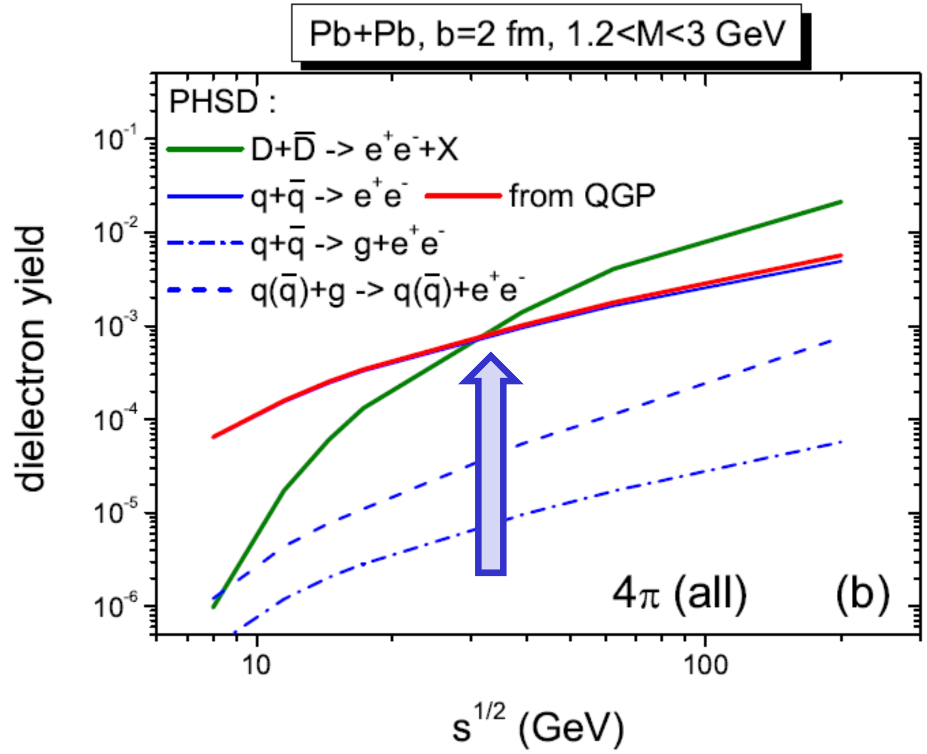
# Dileptons: QGP vs charm

## Excitation function of dilepton multiplicity integrated for 1.2<M<3GeV

mid-rapidity

all rapidities (4π)

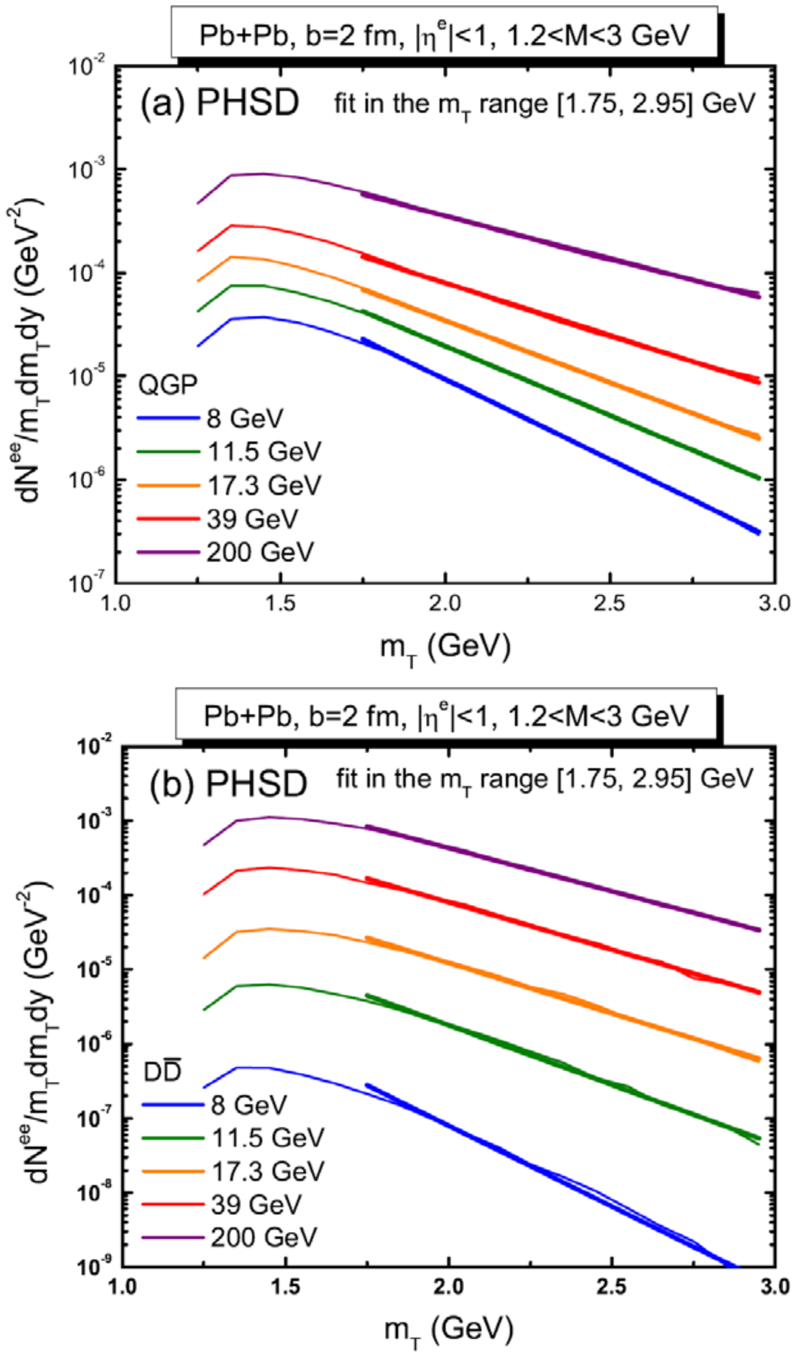


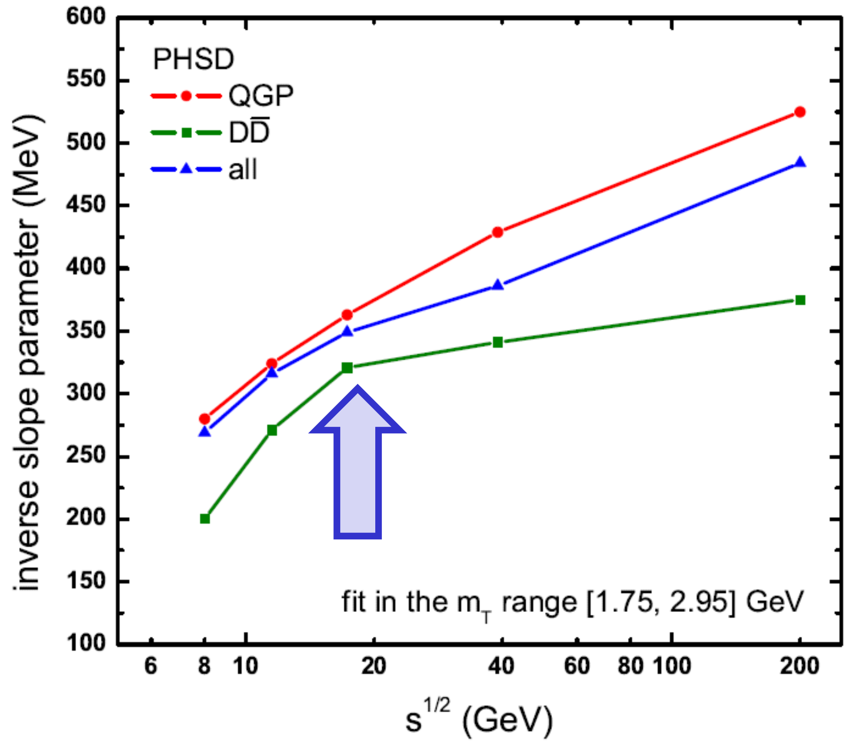

**QGP contribution overshines charm with decreasing energy!**
**➔ Good perspectives for FAIR/NICA and BES RHIC!**

T. Song, W.Cassing, P.Moreau and E.Bratkovskaya, Phys. Rev. C 97 (2018) 064907

# Dilepton transverse mass spectra




The **inverse slope parameter** in the mass range [1.75,2.95]




- **Inverse slope parameter: QGP contribution is harder than that from D-Dbar**
- **The excitation function of the total inverse slope parameter shows characteristic changes at $s^{1/2}$>20 GeV**

T. Song, W.Cassing, P.Moreau and E.Bratkovskaya, Phys. Rev. C 97 (2018) 064907

# Messages from the dilepton study

## ❑ 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

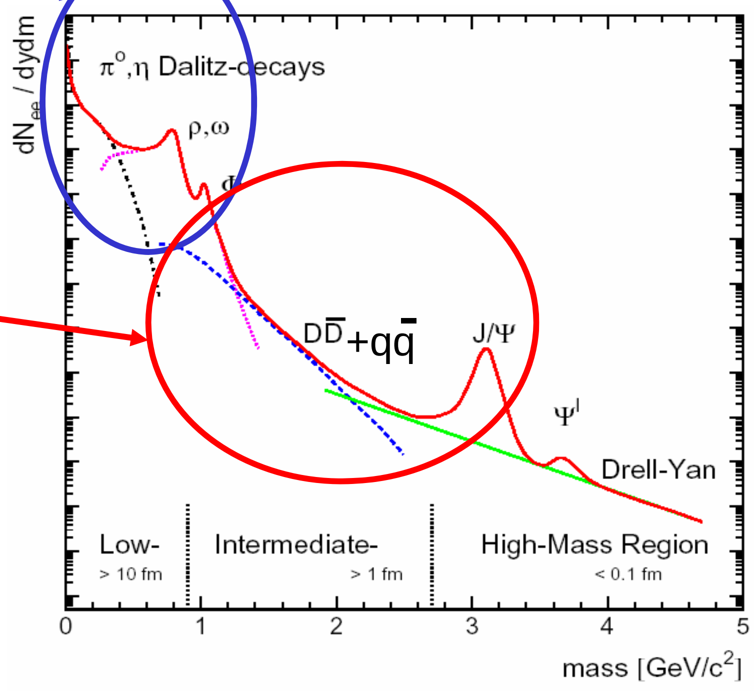
- **In-medium effects** can be observed at **all energies from SIS to LHC; excess increasing with decreasing energy** due to a longer ρ-propagation in the high baryon-density phase

## ❑ Intermediate dilepton masses M>1.2 GeV :

- Dominant sources : **QGP** (qbar-q) , correlated charm D/Dbar

- Fraction of QGP **grows** with increasing energy; however, the relative contribution of QGP to dileptons from charm pairs increases with decreasing energy

➔ Good perspectives for **FAIR/NICA**




Review: O. Linnyk et al., Prog. Part. Nucl. Phys. 89 (2016) 50

T. Song, W.Cassing, P.Moreau and E.Bratkovskaya, Phys. Rev. C 97 (2018) 064907

# Thank you for your attention !


# Thanks to the Organizers !