Probing the properties of strongly interacting matter with heavy-ion collisions

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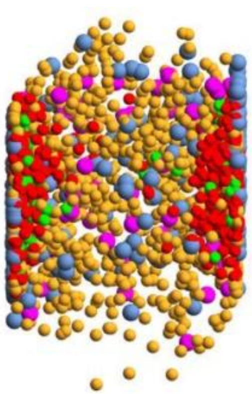
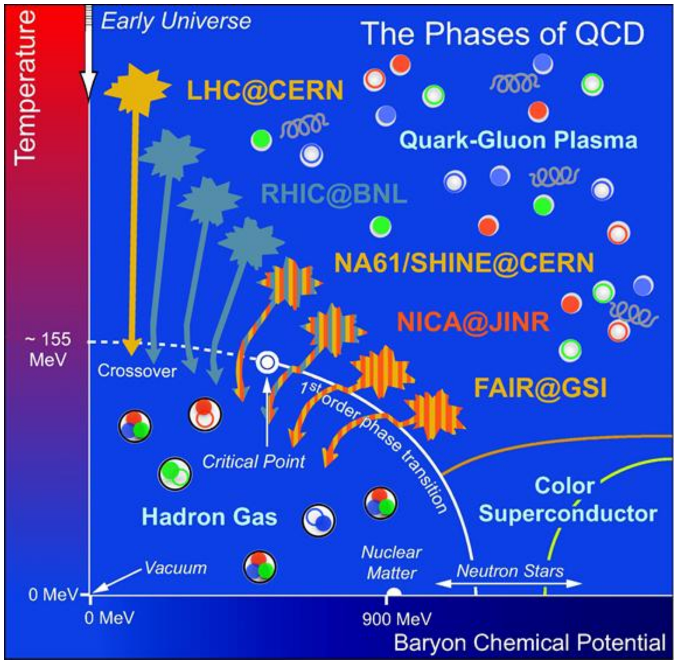
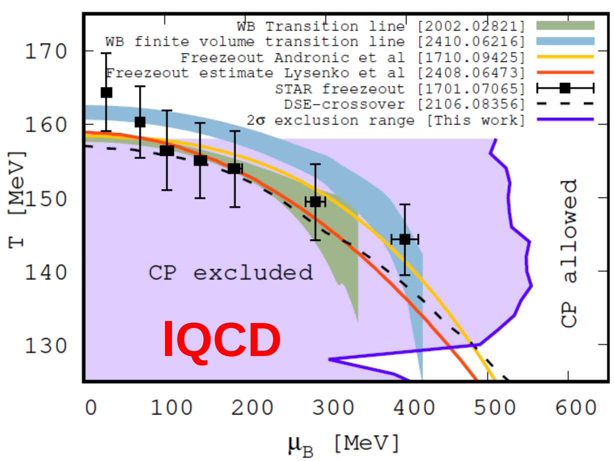
Workshop on recent developments from QCD to nuclear matter
17 – 20 December 2025
Institute of Physics, Academia Sinica, Taipei



Key questions of HICs :

The phase diagram of QCD





Jana N. Guenther, QM'2025, 2502.10267

- What are the **properties of the hot and dense matter** created in HICs?
- What are the **degrees-of-freedom**, their properties and interactions?

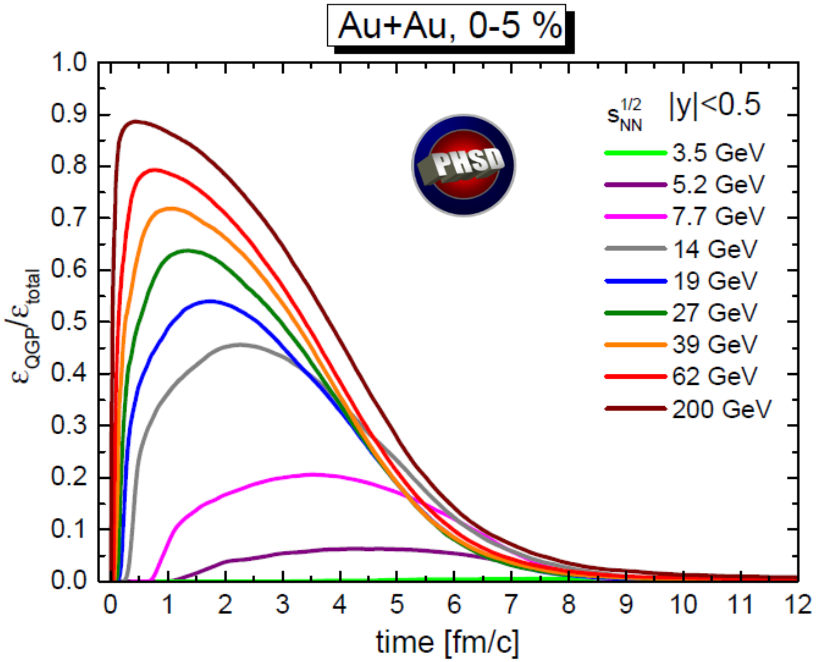
QGP: strongly interacting liquid
→ non-perturbative QCD

Hadronic matter: higly compressed and hot medium
→ chiral symmetry restoration effects

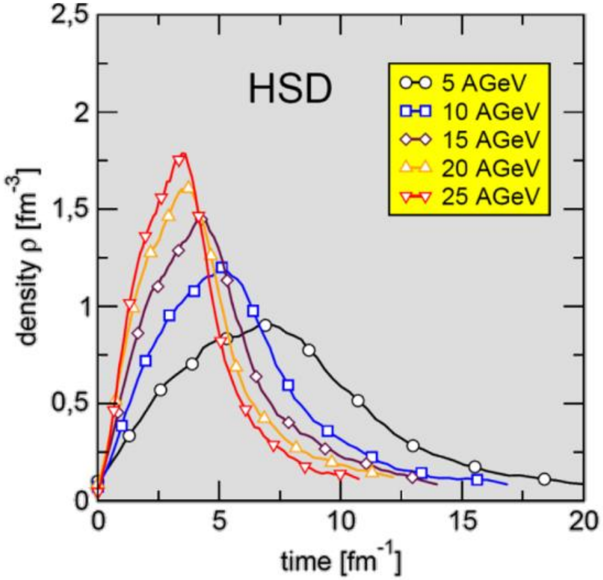
- Origin of the **phase transition**:
  crossover → ?... → 1st or 2nd order?!
- **Strong electromagnetic fields** are created during the HICs
  → polarization phenomena

Dense and hot matter created in HICs

Time evolution of the partonic energy fraction



Time evolution of the baryon density ρ

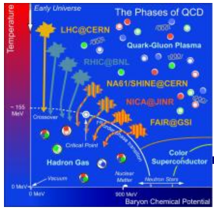


A. W. R. Jorge et al., 2503.05253

Large energy and baryon densities (above critical $\varepsilon > \varepsilon_{crit}$ ~ 0.4 GeV/fm^3) are reachable in central reactions at FAIR/BES STAR energies

➔ phase transition form hadronic matter to QGP

➔ strong in-medium modification of hadron properties (chiral symmetry restoration)



Dynamical description of strongly interacting matter

Goal: Microscopic modeling of heavy-ion collisions

PHSD & PHQMD

Parton-Hadron-String Dynamics & Parton-Hadron-Quantum-Molecular Dynamics

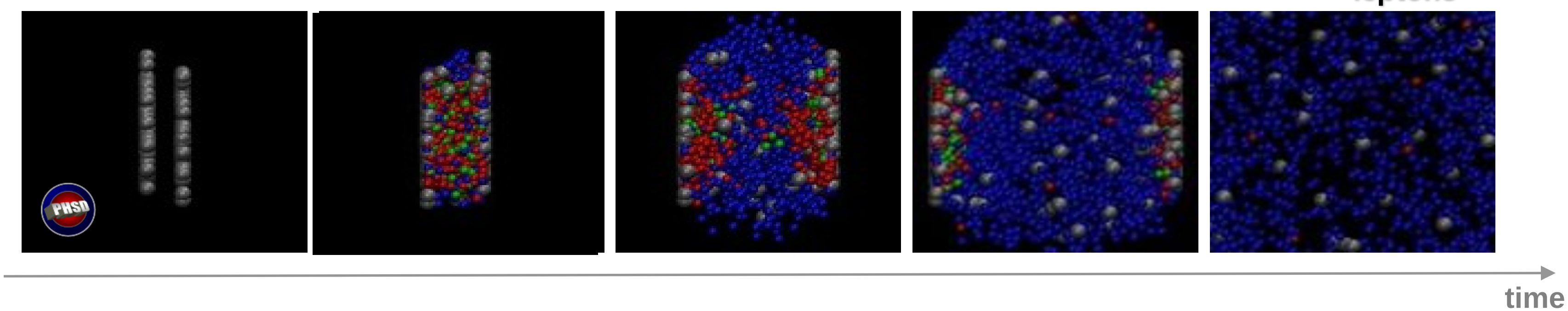
is a unified non-equilibrium microscopic transport approach for the description of the dynamics of strongly-interacting hadronic and partonic matter created in heavy-ion collisions and p+A, p+p, π+A reactions from SIS to LHC energies

Initial state: Au+Au

Quark-Gluon Plasma: lQCD EoS
non-perturbative QCD - quasiaprticles

Dynamical Hadronization

Hadronic interactions
→final hadrons, clusters + leptons



→ provides a continuous description of the HIC dynamics:
– no artificial transition from micro- to macro-description as in hydro-type models, no jump in entropy and energy density

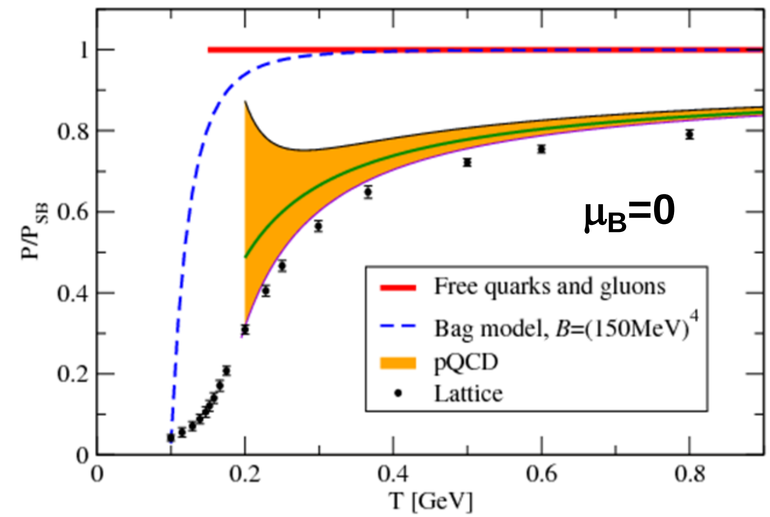
* PHSD,PHQMD are open source codes, available for experimental collaborations

Degrees-of-freedom of the QGP

For the microscopic transport description of the system one needs to know all degrees of freedom as well as their properties and interactions!

- lQCD gives QGP EoS at finite (T,μ_B)

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



Non-perturbative QCD ← pQCD

pQCD:

- weakly interacting system
- massless quarks and gluons

Thermal (non-perturbative) QCD:

- strongly interacting system
- massive quarks and gluons

→ Quasiparticles = effective degrees-of-freedom

QGP: Dynamical QuasiParticle Model (DQPM)

DQPM – effective model for the description of **non-perturbative** (strongly interacting) QCD based on **lQCD EoS**

Degrees-of-freedom: strongly interacting **dynamical quasiparticles** - quarks and gluons

Theoretical basis :

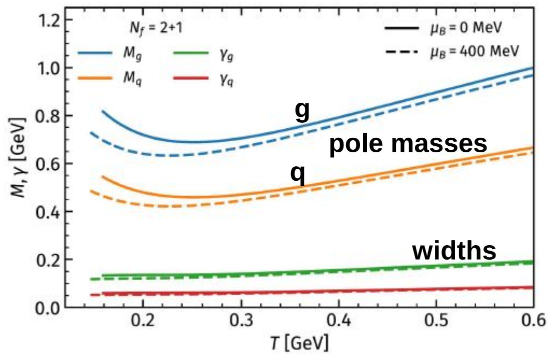
- ‚resummed' single-particle Green's functions → quark (gluon) propagator (2PI) : $G_q^{-1} = P^2 - \Sigma_q$

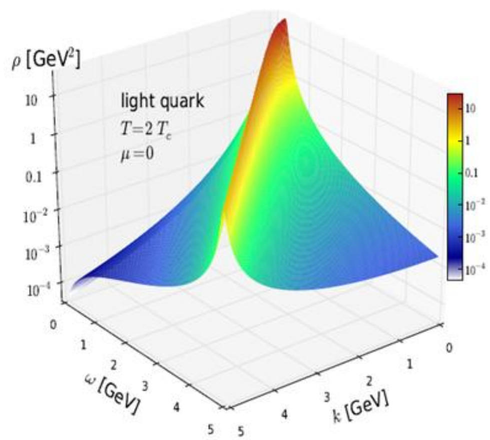
Properties of the quasiparticles are specified by scalar **complex self-energies:** $\Sigma_q = M_q^2 - i2\gamma_q\omega$

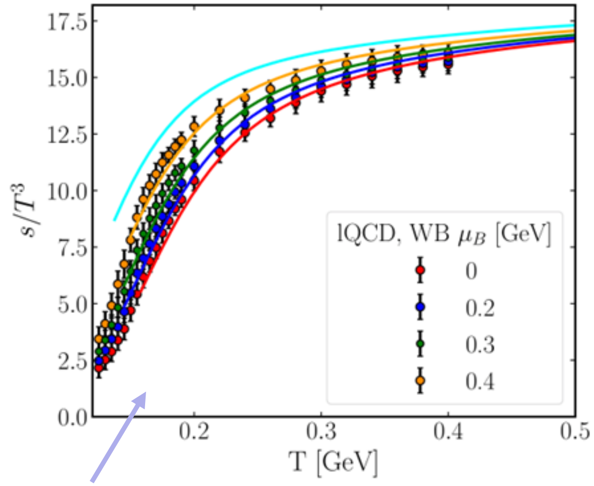
$Re\Sigma_q$: **thermal masses** (M_g, M_q); $Im\Sigma_q$: **interaction widths** (γ_g, γ_q) → spectral functions $\rho_q = -2ImG_q$

- introduce an ansatz (HTL; with few parameters) for the (T, μ_B) dependence of masses/widths
- evaluate the QGP thermodynamics in equilibrium using the Kadanoff-Baym theory
- fix DQPM parameters by comparison of the DQPM entropy density to lQCD at μ_B=0

→ **Quasi-particle properties at (T, μ_B) :**







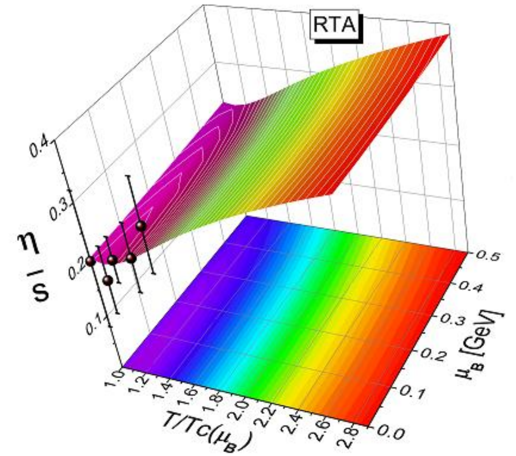
→ very good agreement with lQCD data for QGP thermodynamics **at finite (T, μ_B)**

- **DQPM** provides **mean-fields** (1PI) for q,g and **effective 2-body partonic interactions** (2PI); gives **transition rates** for the hadronization → **sQGP in PHSD**

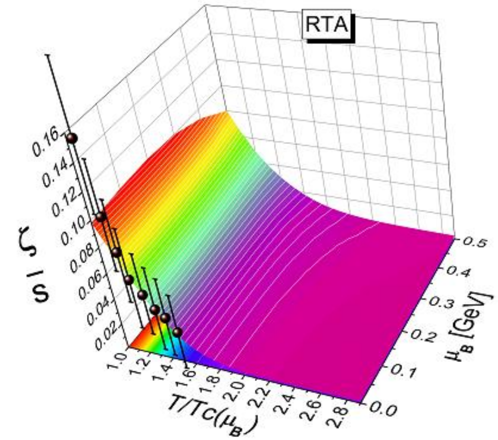
A. Peshier, W. Cassing, PRL 94 (2005) 172301; W. Cassing, NPA 791 (2007) 365: NPA 793 (2007), H. Berrehrah et al, Int.J.Mod.Phys. E25 (2016) 1642003; P. Moreau et al., PRC100 (2019) 014911; O. Soloveva et al., PRC101 (2020) 045203, I. Grishmanovskii et al., PRC 109 (2024) 024911

Transport coefficients: DQPM vs lQCD

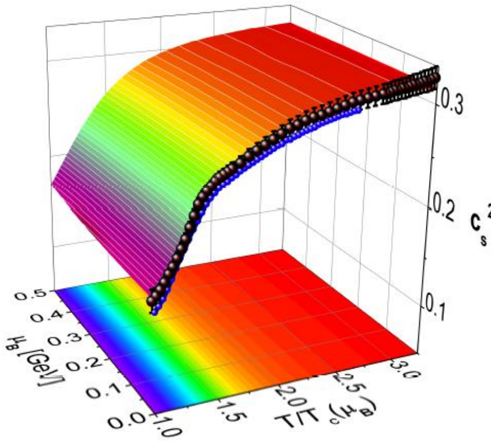
η/s versus (T,μ_B)



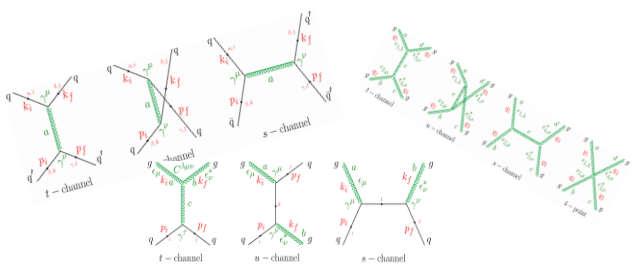
Bulk viscosity ζ/s



Speed of sound c_s^2



P. Moreau et al., PRC100 (2019) 014911;
O. Soloveva et al., PRC110 (2020) 045203

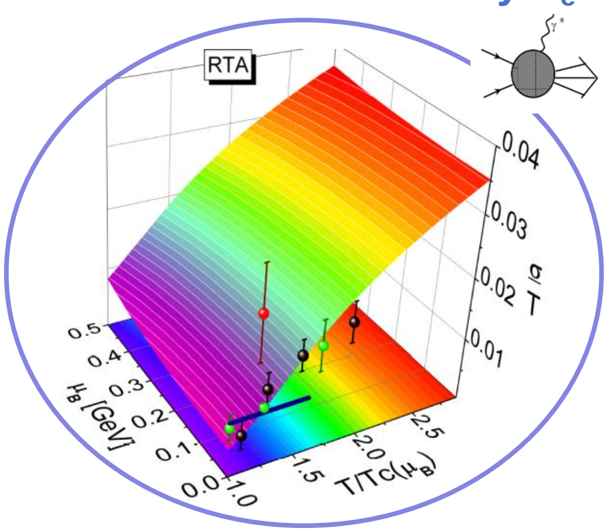


Full diffusion coefficient matrix:

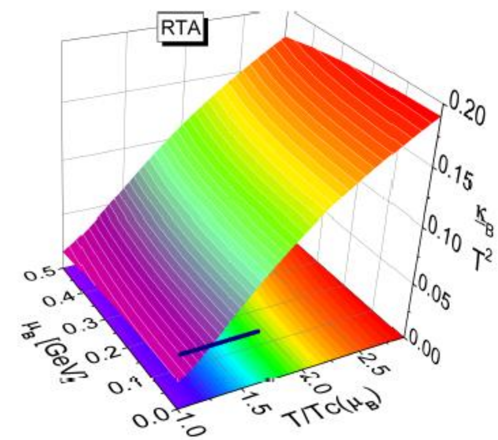
$$\begin{pmatrix} j_B^\mu \\ j_Q^\mu \\ j_S^\mu \end{pmatrix} = \begin{pmatrix} \kappa_{BB} & \kappa_{BQ} & \kappa_{BS} \\ \kappa_{QB} & \kappa_{QQ} & \kappa_{QS} \\ \kappa_{SB} & \kappa_{SQ} & \kappa_{SS} \end{pmatrix} \cdot \begin{pmatrix} \nabla^\mu \alpha_B \\ \nabla^\mu \alpha_Q \\ \nabla^\mu \alpha_S \end{pmatrix}$$

J. A. Fotakis et al., PRD 104 (2021) , 034014

Electric conductivity σ_e/T



Baryon diffusion coefficient κ_B/T^2



➔ Weak dependence of transport coefficients on μ_B

Dynamical description of strongly interacting hot and dense medium:

from BUU to Kadanoff-Baym

From weakly to strongly interacting systems

In-medium effects (on hadronic or partonic levels) = changes of particle properties in a hot and dense medium

Examples: hadronic medium - vector mesons, strange mesons, baryons

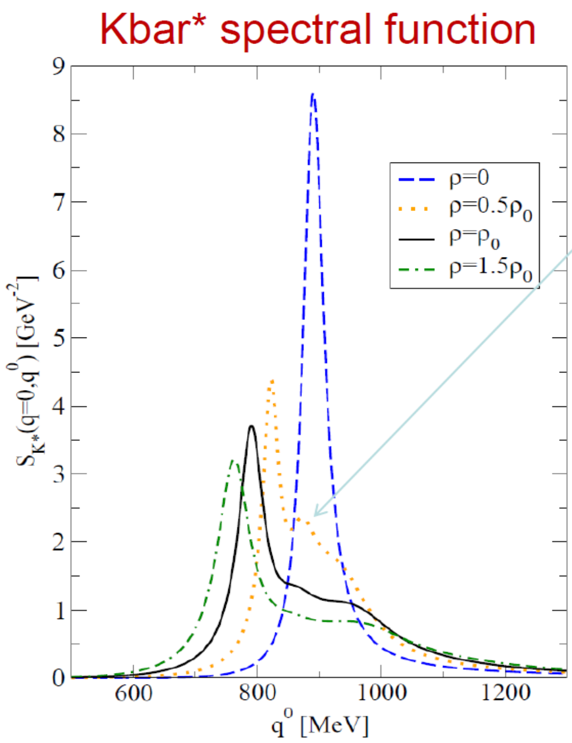
QGP – dressing of partons

Many-body theory:
Strong interaction ➔ large widths ➔ broad spectral functions ➔ quantum objects

- **How to describe the dynamics of broad strongly interacting quantum states in transport theory?**

Semi-classical on-shell BUU: applies for weakly interacting systems of particles

It is doable with quantum Kadanoff-Baym equations



Λ(1783)N^{-1} and Σ(1830)N^{-1} exitations

G-matrix:

Barcelona / Valencia group

Dynamical description of strongly interacting systems

- **Quantum field theory ➔**

Kadanoff-Baym dynamics for resummed single-particle **Green functions** $S^<$

(1962)

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

Integration over the intermediate spacetime

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

$$iS_{xy}^{<} = \eta \langle \{ \Phi^{+}(y) \Phi(x) \} \rangle$$

$$iS_{xy}^{>} = \langle \{ \Phi(y) \Phi^{+}(x) \} \rangle$$

$$iS_{xy}^{c} = \langle T^{c} \{ \Phi(x) \Phi^{+}(y) \} \rangle \quad - causal$$

$$iS_{xy}^{a} = \langle T^{a} \{ \Phi(x) \Phi^{+}(y) \} \rangle \quad - anticausal$$

$$S_{xy}^{ret} = S_{xy}^{c} - S_{xy}^{<} = S_{xy}^{>} - S_{xy}^{a} \quad - retarded$$

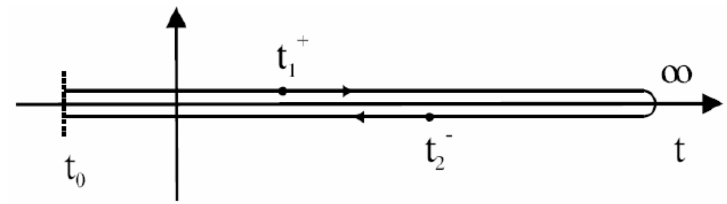
$$S_{xy}^{adv} = S_{xy}^{c} - S_{xy}^{>} = S_{xy}^{<} - S_{xy}^{a} \quad - advanced$$

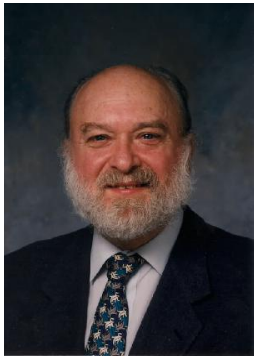
$$\hat{S}_{0x}^{-1} \equiv -(\partial_x^{\mu} \partial_{\mu}^{x} + M_0^2)$$

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

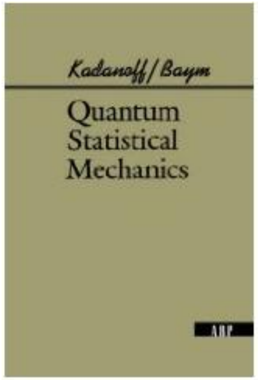
$$T^{a}(T^{c}) - (anti-)time-ordering\ operator$$

Real-time (Keldysh-) Contour





Leo Kadanoff



Gordon Baym

1st application for a spacially homodeneous system with deformed Fermi sphere:
P. Danielewicz, Ann. Phys. 152, 305 (1984); … H.S. Köhler, Phys. Rev. 51, 3232 (1995); …

Off-shell propagation: Kadanoff-Baym

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 = ‚gain' - ‚loss' term

$$\diamond\{P^2 - M_0^2 - Re\Sigma_{XP}^{ret}\}\{S_{XP}^{<}\} - \diamond\{\Sigma_{XP}^{<}\}\{ReS_{XP}^{ret}\} = \frac{i}{2}\left[\Sigma_{XP}^{>}S_{XP}^{<} - \Sigma_{XP}^{<}S_{XP}^{>}\right]$$

off-shell behavior

W. Botermans, R. Malfliet, Phys. Rep. 198 (1990) 115

- KB propagates 1-body 2-point Green functions $S^<(x,p) \rightarrow A(x,p)*N(x,p)$ in 8 dimensions
- $S^<$ carries information not only on the occupation number N_{XP} (as BUU), but also on the particle properties, interactions and correlations via the spectral function A_{XP}

Spectral function:

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

Reaction rate of particle:

$$\Gamma_{XP} = -\,Im\,\Sigma_{XP}^{ret} = 2\,p_0\Gamma$$

On-shell limit of KB:

- $A_{XP} \rightarrow \delta(p^2 - M^2)$ or A_{XP} has a constant shape in a medium, i.e. $\nabla_X\Gamma = 0, \quad \nabla_P\Gamma = 0$
- backflow term vanishes: KB → BUU

→ Generalized Cassing-Juchem off-shell equations of motion for testparticles → PHSD

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

Generalalized 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 !

➔ **Generalized testparticle Cassing-Juchem 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 $F_{(i)} \equiv F(t, \vec{X}_i(t), \vec{P}_i(t), \epsilon_i(t))$

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

Realized in PHSD

Note: the common factor $1/(1-C_{(i)})$ can be absorbed in an ‚eigentime‘ of particle (i) !

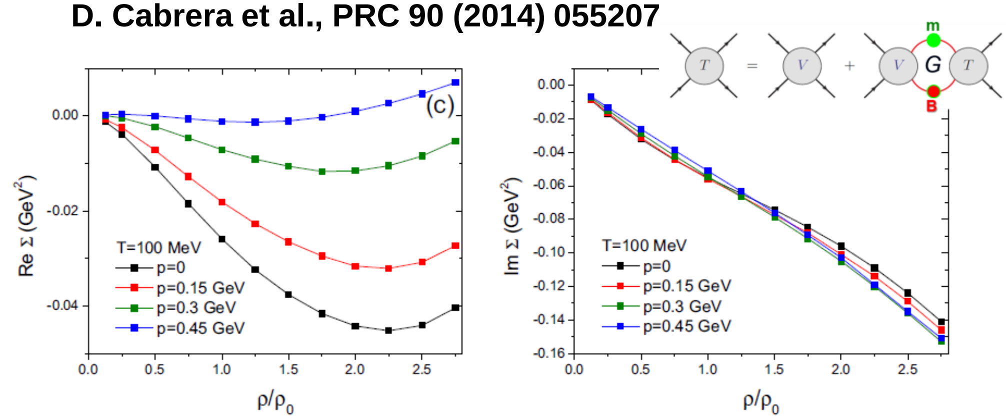
W. Cassing, *`Transport Theories for Strongly-Interacting Systems’,* Springer Nature: Lecture Notes in Physics 989, 2021
DOI: 10.1007/978-3-030-80295-0

Off-shell dynamics for antikaons at SIS energies

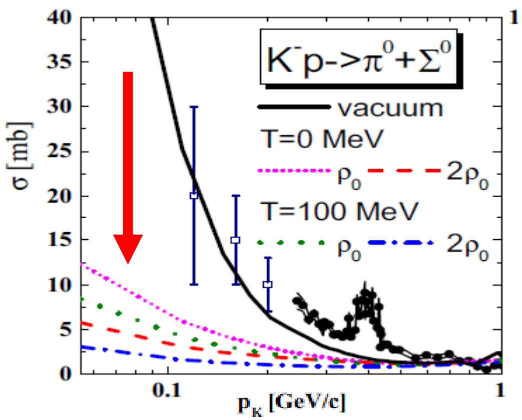
Spectral function of K^- within the G-matrix approach:

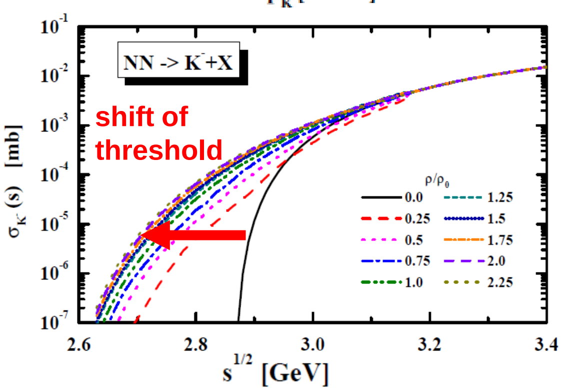
$$S_{\bar K}(k_0,\vec{k};T) = -\frac{1}{\pi}\frac{\mathrm{Im}\,\Sigma_{\bar K}(k_0,\vec{k};T)}{\left|k_0^2-\vec{k}^{\,2}-m_{\bar K}^2-\Sigma_{\bar K}(k_0,\vec{k};T)\right|^2}.$$

D. Cabrera et al., PRC 90 (2014) 055207

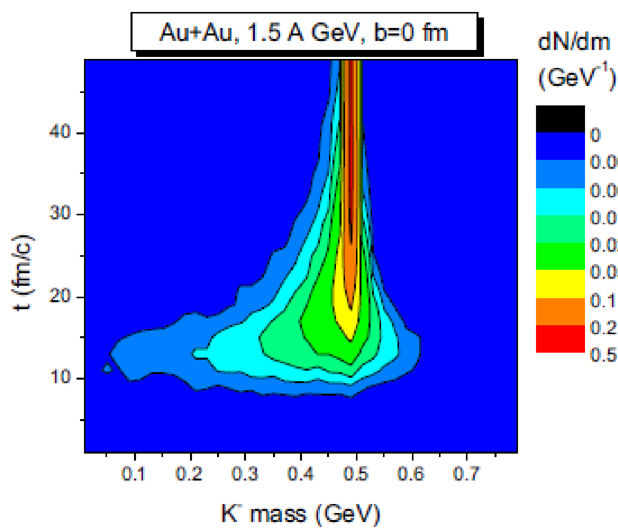


In-medium cross sections for K^- production and absorption are strongly modified in the medium:

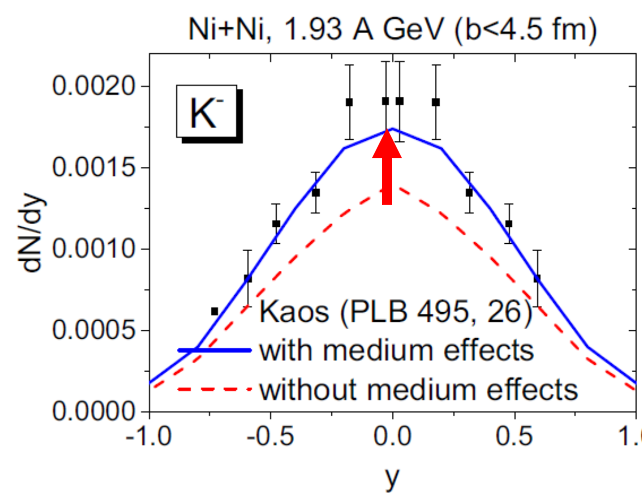




Time evolution of the K^- masses

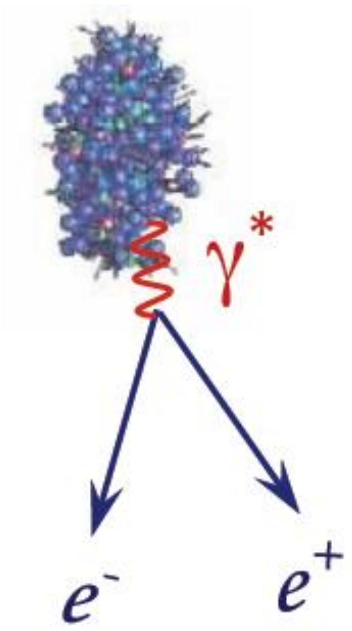


In-medium effects are mandatory for the description of experimental K^- spectra

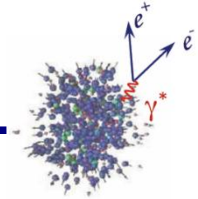


Taesoo Song et al., PRC 103, 044901 (2021)

Electromagnetic probes of the strongly interaction matter: dileptons



Physics with dileptons

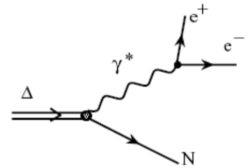


Low mass dileptons

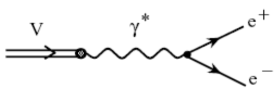
- probe of **hadronic in-medium effects – chiral symmetry restoration**

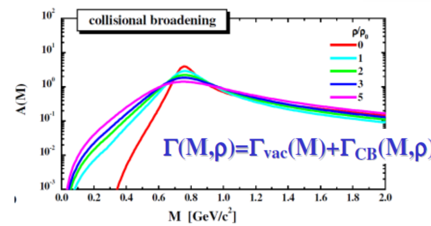
(late time emission)

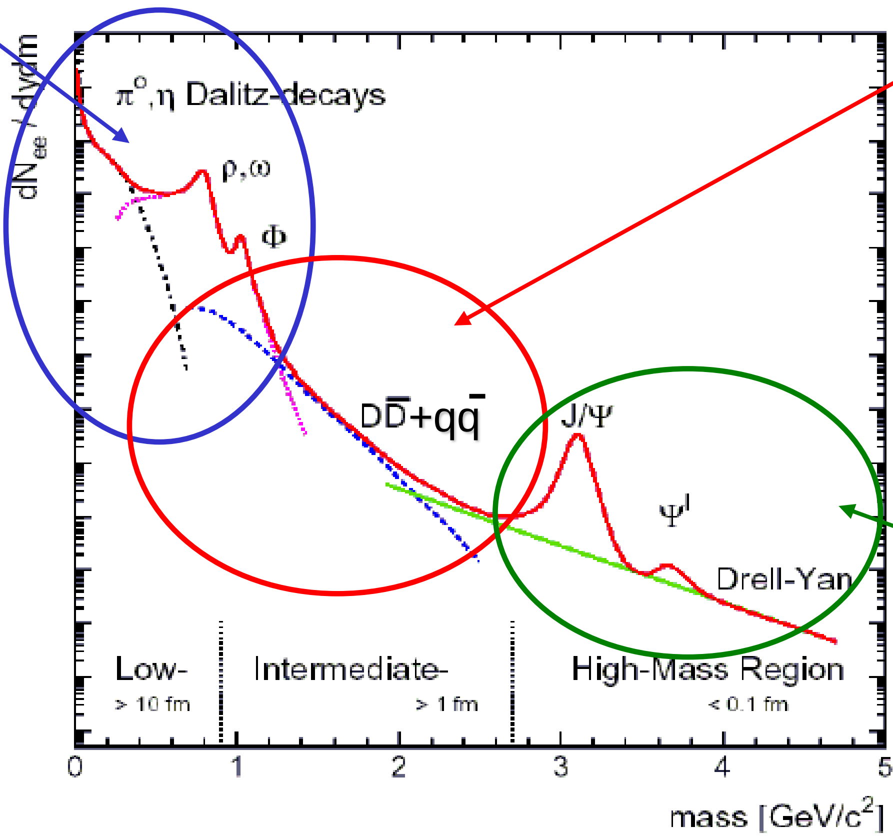
- Bremsstrahlung
- Dalitz decay of mesons and baryons ($\pi^0, \eta, \Delta, \ldots$)



- direct decay of vector mesons

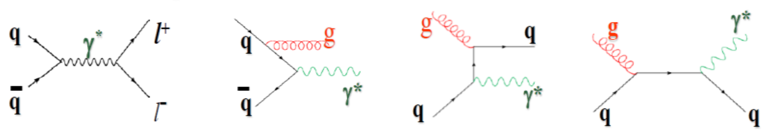




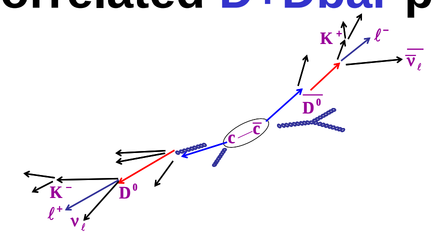


Intermediate mass dileptons

– probe of **‚thermal QGP'**



– correlated **D+Dbar** pairs



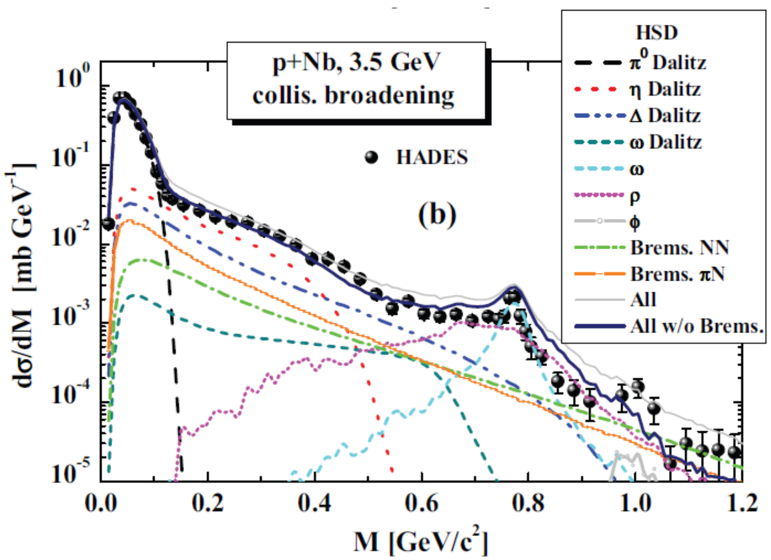
High-mass dileptons

– probe of **pQGP (DY)** and **hard probes**

(early time emission)

Dileptons from pA ans πA reactions

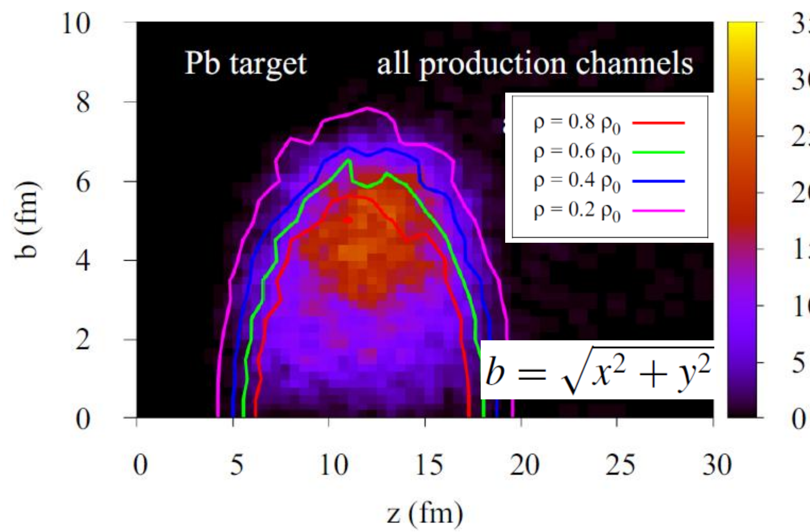
- p+A and π+A reactions probe the nuclear matter at normal nuclear density ρ_0
- vector mesons (ρ, ω, ϕ) are produced dominantly at the surface and travel through the nuclei
  ➔ medium effects:
  - dropping mass
  - collisional broadening
  - coll. broad. + dropping mass

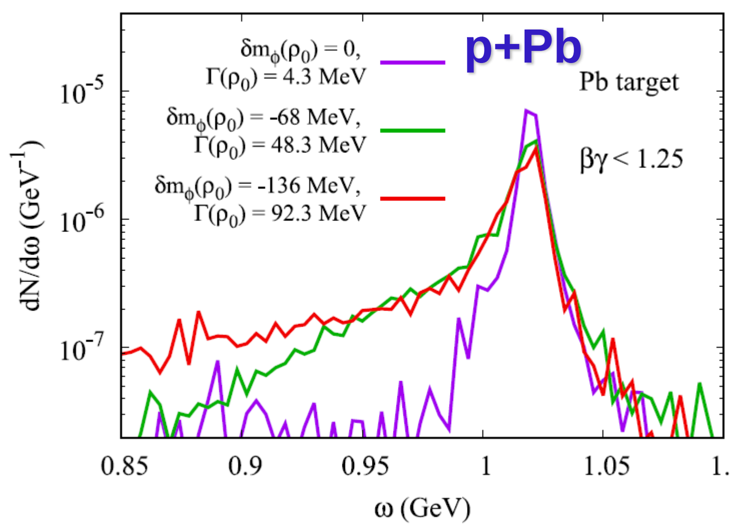


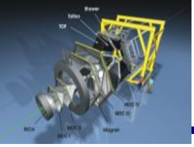
W. Cassing et al, PL B 396 (1997) 26;
E.B, PLB 29 (2002) 26; PRC 87, 064907 (2013)

ϕ-meson: in-medium effects in p+A, 13 GeV/c

P. Gubler et al, PRC111 (2025) 034908; 2507.00420

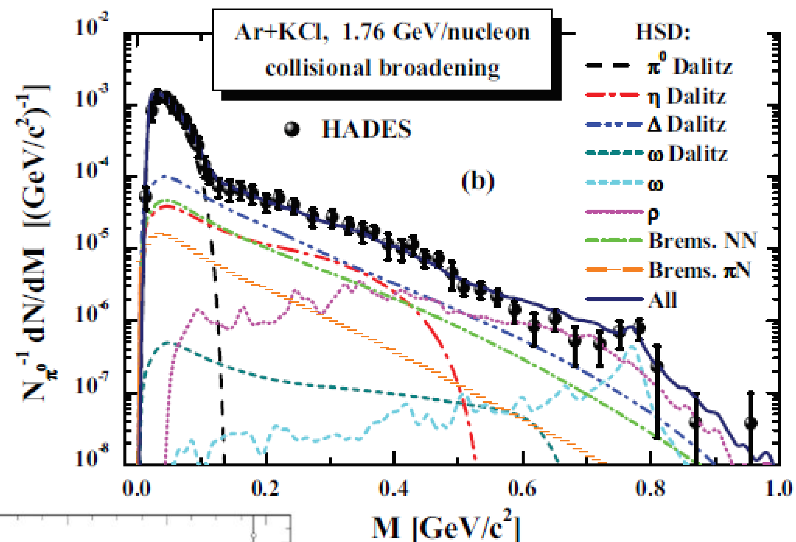




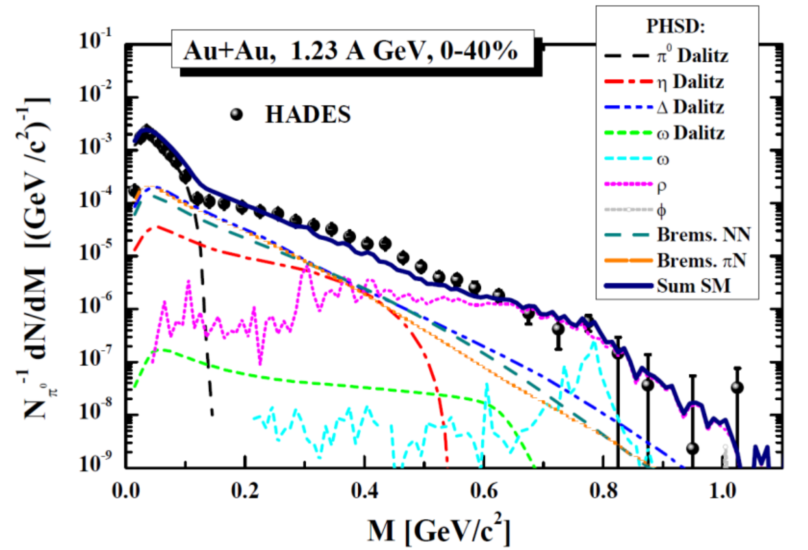


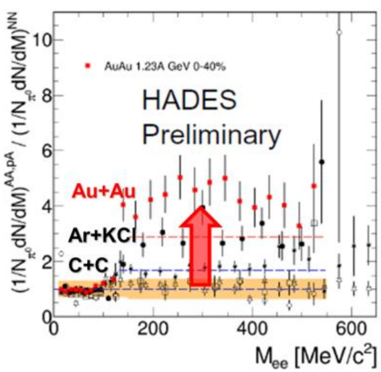
Dileptons at SIS energies - HADES

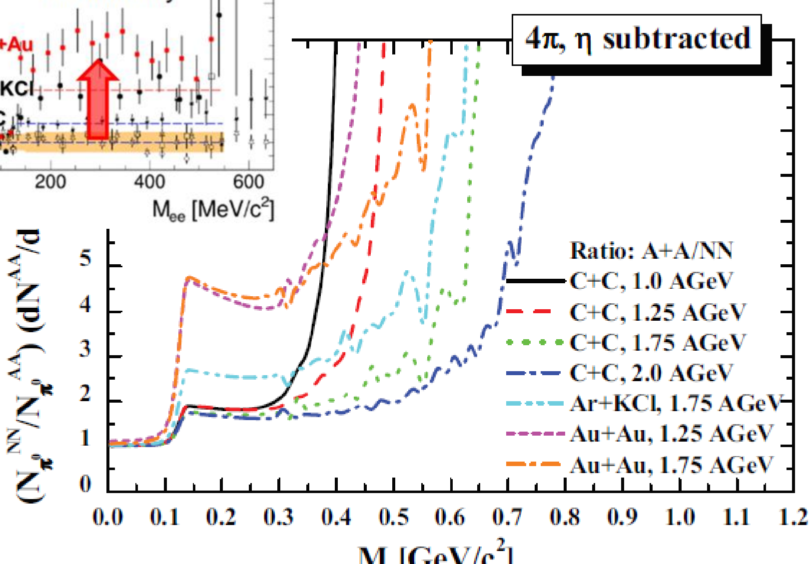
E. B., J. Aichelin, M. Thomere, S. Vogel, M. Bleicher, PRC 87 (2013) 064907



I. Schmidt, E.B., M. Gumberidze, R. Holzmann, PRD 104 (2021), 015008







❑ **Strong in-medium enhancement** of dilepton yield in Au+Au vs. NN

❑ **Increases with the system size:**

1) **multiple Δ regeneration** – dilepton emission from intermediate Δ's which are part of the reaction cycles $\Delta \rightarrow \pi N$; $\pi N \rightarrow \Delta$ and $NN \rightarrow N\Delta$; $N\Delta \rightarrow NN$

2) **pN bremsstrahlung** which scales with N_{bin} and not with N_{part} , i.e. pions

3) **Collisional broadening** of ρ,ω,ϕ mesons

Dilepton spectra

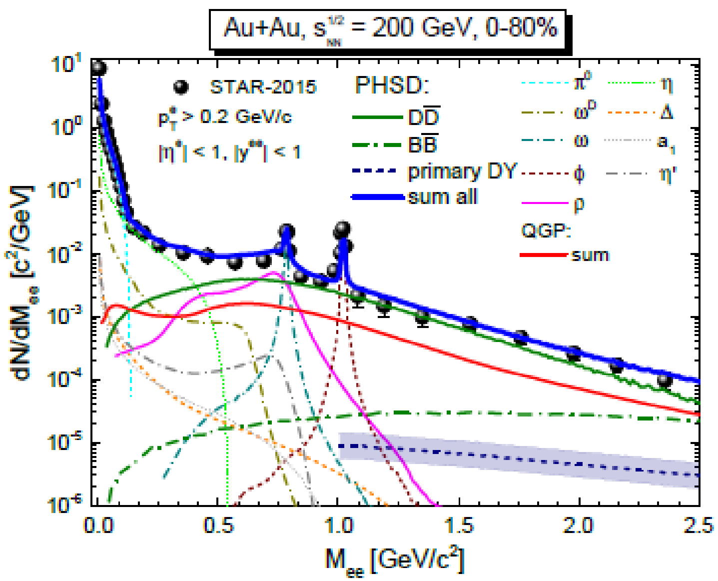
PHSD dilepton spectra including:

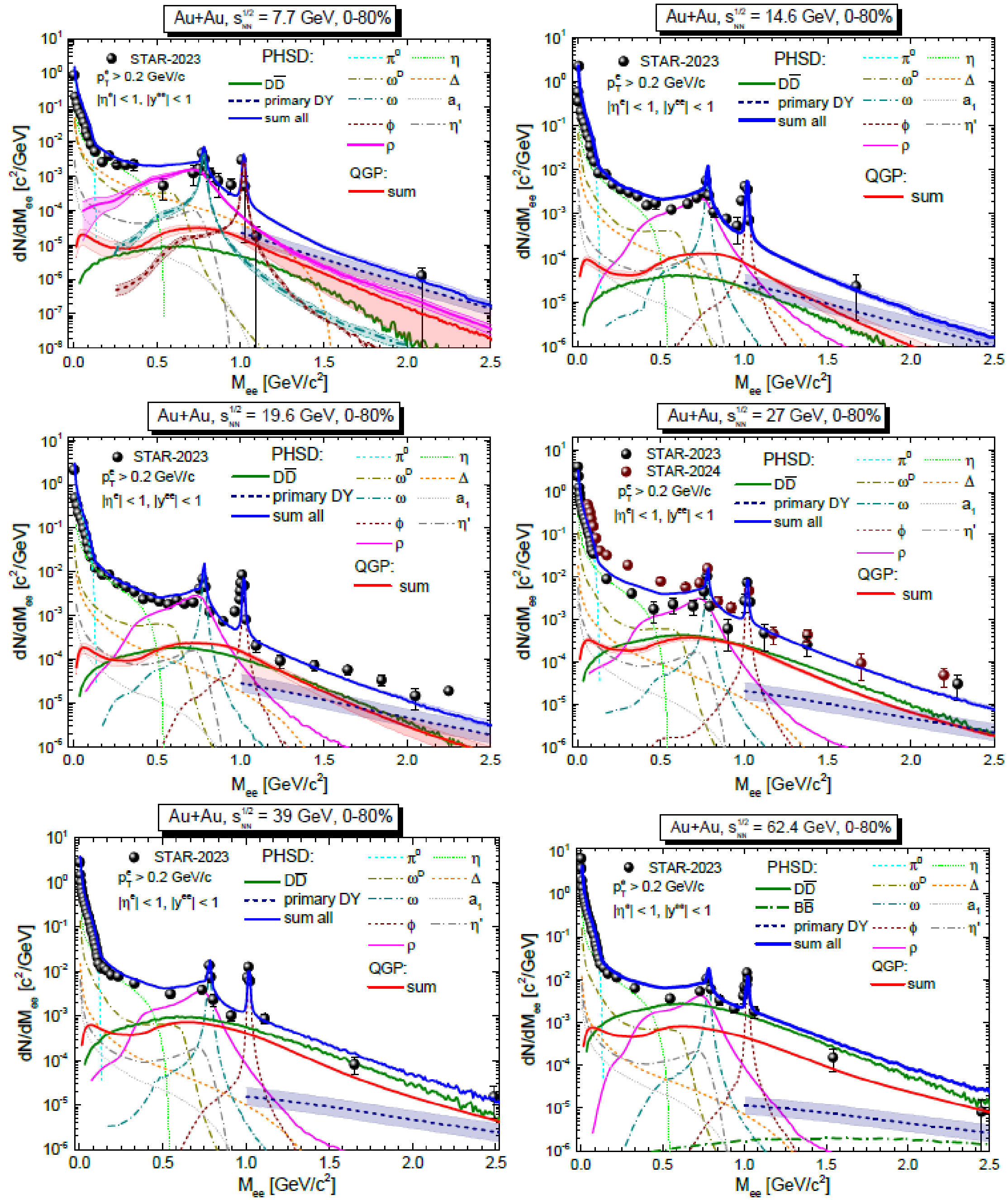
a collisional broadening of the vector meson spectral functions

+ primary DY

+ correlated charm + beauty

+ QGP
$$\left\{ \begin{array}{l} q\bar{q} \to e^+e^- \\ q\bar{q} \to g e^+e^- \\ gq(\bar{q}) \to q(\bar{q})e^+e^- \end{array} \right.$$





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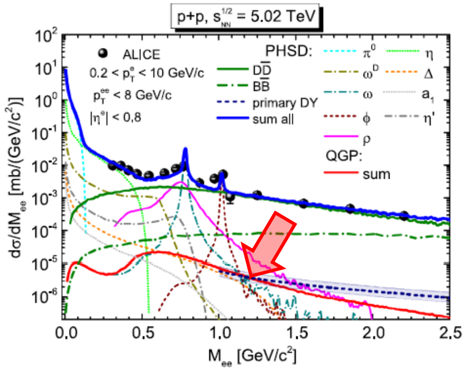
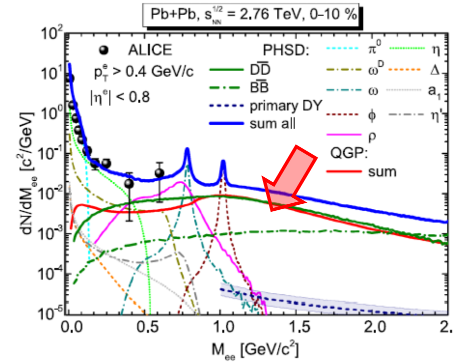
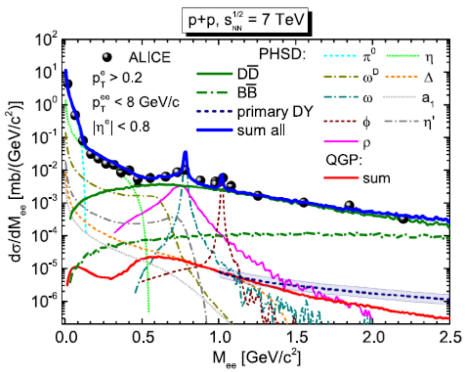
Dileptons at LHC

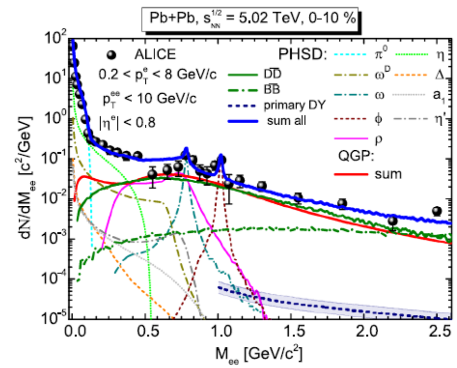
p+p

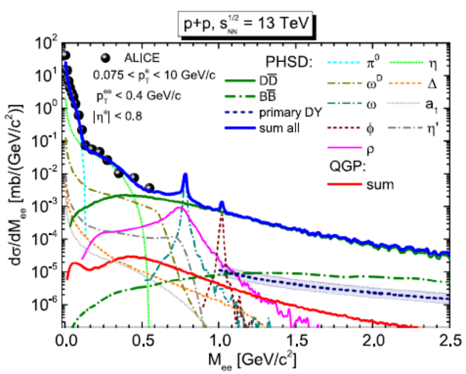
Pb+Pb

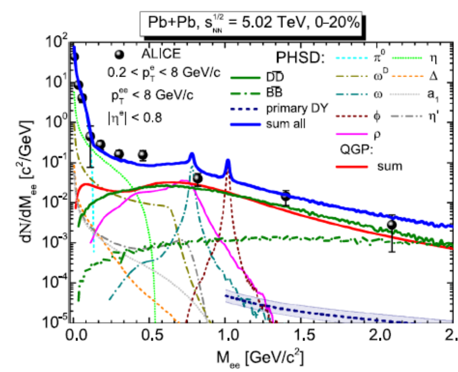












- **p+p:** (M>1.2GeV) correlated charm (dominant) + dileptons from **QGP droplets**
  A+A: dilepton yield from **QGP** = dilepton yield from correlated **charm**

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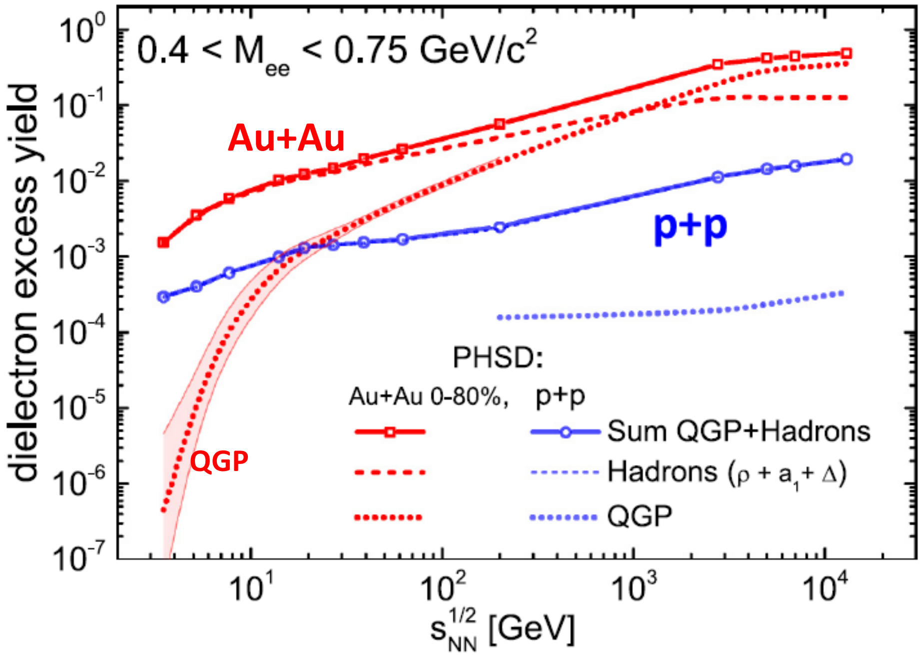
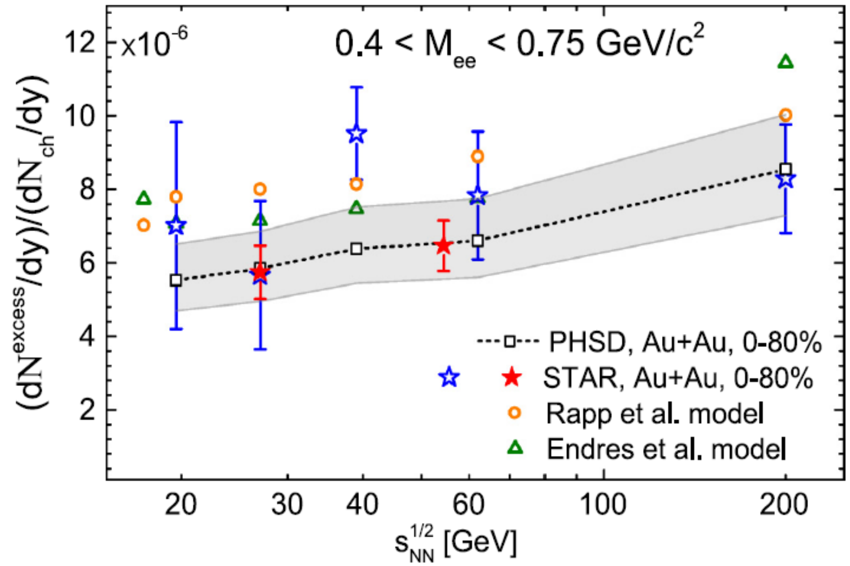
Dileptons: excitation functions for 0.4<M<0.75GeV

Excitation function of dilepton excess yield integrated for 0.4 < M < 0.75 GeV

Dilepton excess yield = total – 'cocktail' (expected contributions from hadronic decays at freezeout)





For 0.4 < M < 0.75 GeV:

- ❑ **Dominant contribution – vector meson decays**
  ➔ favours in-medium modifications of vector meson spectral function – collisional broadening
- ❑ **QGP contribution increases with energy**
- ❑ **p+p: dileptons are dominated by hadronic channels (vector mesons)**

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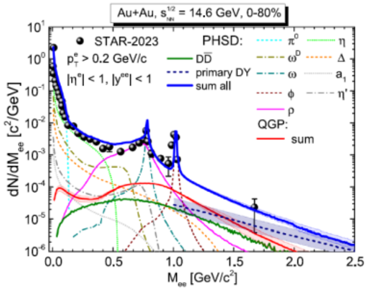
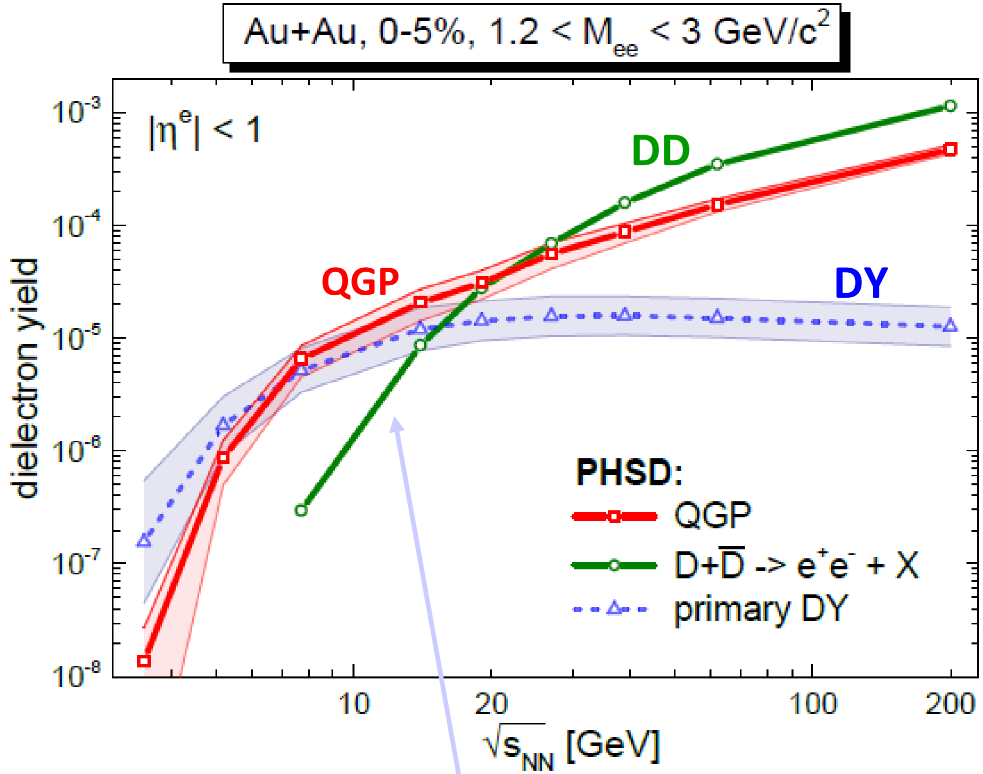
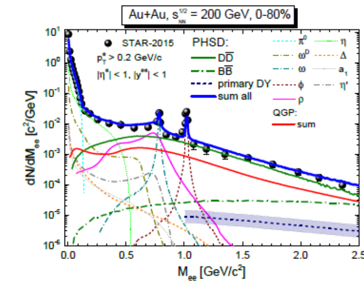
Cf. T. Song et al., Phys. Rev. C97 (2018), 064907

Dileptons: excitation functions for 1.2<M<3GeV

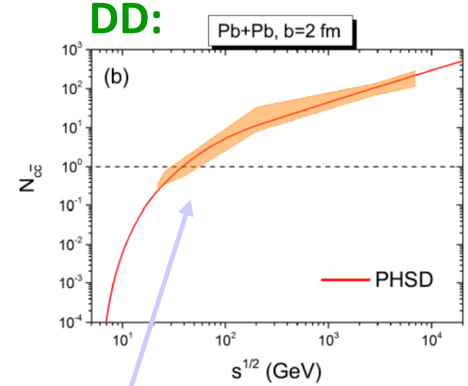
Excitation function of dilepton yield integrated for 1.2 < M < 3GeV







DD:



For 1.2 < M < 3GeV:

- **Dileptons from QGP overshine charm dileptons (D-Dbar) with decreasing beam energy**
- **Primary DY could be “subtracted” from AA dilepton spectra using pp data**

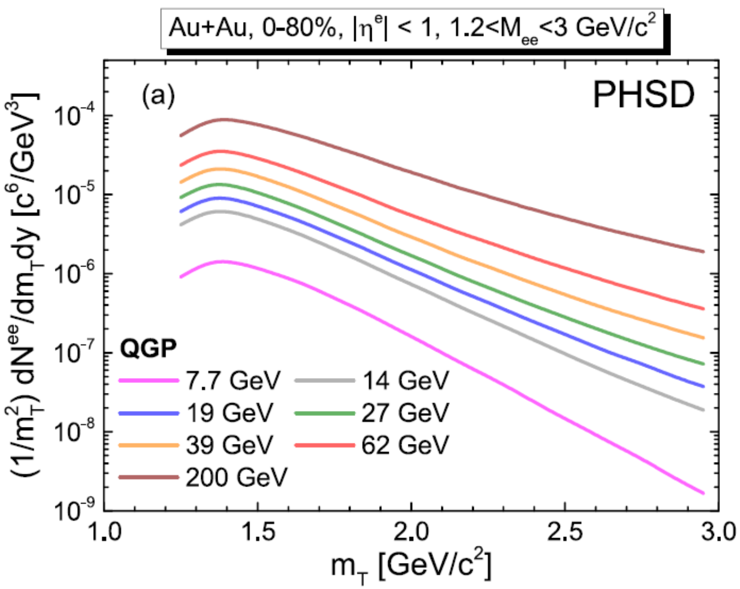
A. W. R. Jorge et al., 2503.05253, PRC111 (2025) 064904

Cf. T. Song et al., Phys. Rev. C97 (2018), 064907

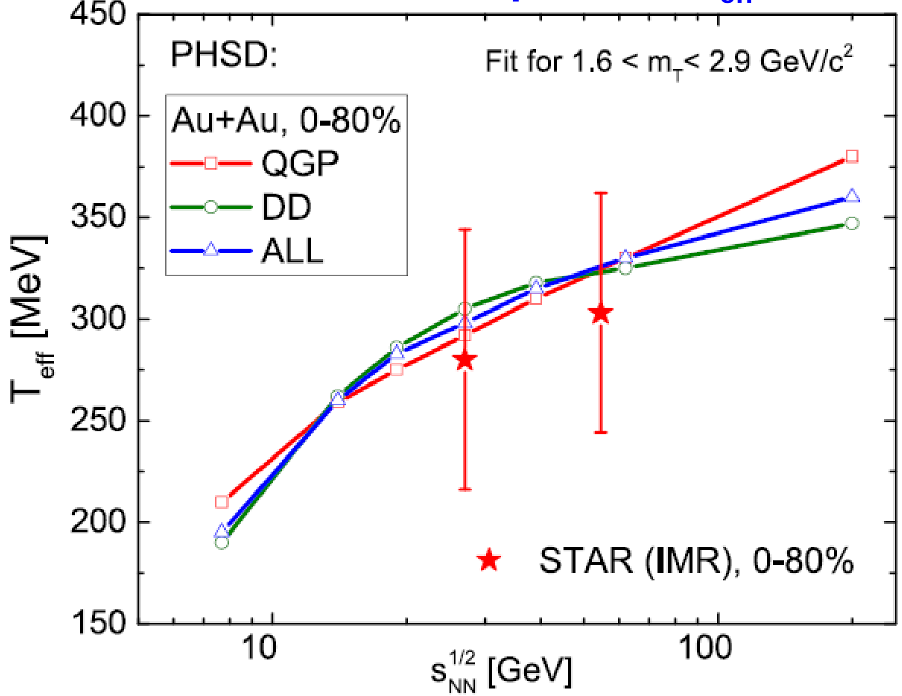
Effective T_{eff}

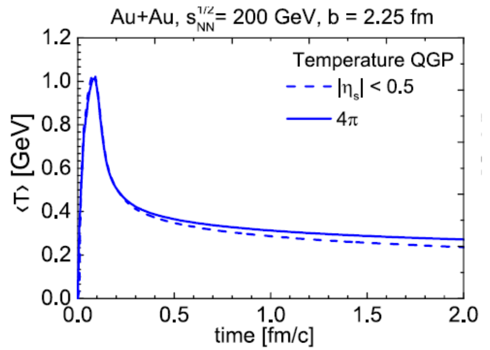
Transverse mass spectra
➔ Effective temperature
$1.6 < m_T < 2.9$ GeV/c²

$$\frac{1}{m_T^2}\frac{d\sigma}{dm_T dy} \sim e^{\beta m_T}$$



Excitation function of effective temperature T_{eff}





- measurement of T_{eff} allows to penetrated inside the hot and dense matter and to probe its thermal properties

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Summary

- Transport theory is the general basis for an understanding of nuclear dynamics on a microscopic level

Dynamical description of strongly interacting matter:

- **Degrees-of-freedom:**
  QGP: strongly interacting quasiparticles (quarks and gluons) ➔ DQPM
  HG: off-shell hadrons (+ physics beyond the standard model – dark matter)
- **Dynamics:**
  PHSD: microscopic transport approach based on the solution of generalized off-shell transport equations derived from Kadanoff-Baym many-body theory
- PHQMD: QMD dynamics + dynamical cluster formation

Theory versus experimental observables:

- evidence for strong partonic interactions in the early phase of relativistic heavy-ion reactions
  ➔ formation of the sQGP in HIC!

PHSD-PHQMD code

Realization: parallel ensemble method

Computer language: Fortran

PHSD mode

Initialization A+A
+ propagation of baryons:
Mean Field dynamics
(BUU)

PHQMD mode

Initialization A+A
+ propagation of baryons:
Quantum Molecular dynamics
(QMD) – n-body model

Propagation of partons (quarks, gluons) and mesons:
Mean Field dynamics (Kadanoff-Baym, BUU)

Collision integral = interactions of hadrons and partons (QGP)

Optionally

Cluster recognition: MST (Minimum Spanning Tree)
or SACA (Simulated Annealing Clusterization Algorithm)
or coalescence mechanism + kinetic deuterons

Final output – “events” : OSCAR, ROOT, Rivet formats