# Charm dynamics in heavy-ion collisions

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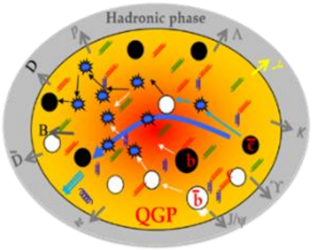
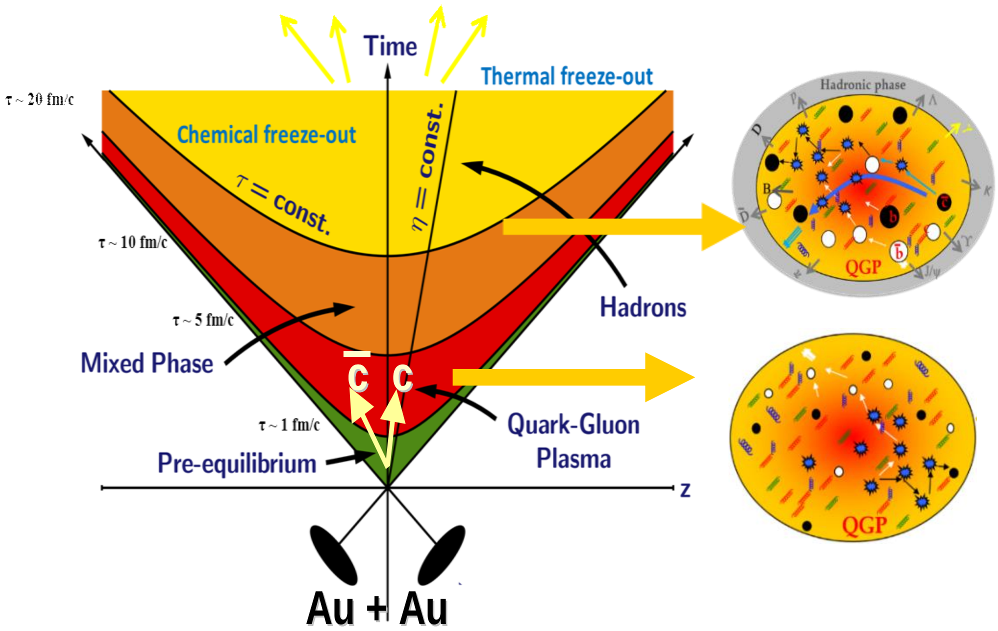
**SHINE Open Seminar,**
**30 July 2020**
**(Online)**



# Motivation

**The goal:** study of the properties of hot and dense nuclear and partonic matter by **‚charm probes‘ (or heavy quark probes)**




**The advantages of the 'charm probes':**

- ❑ **dominantly produced in the very early stages of the reactions in initial binary collisions with large energy-momentum transfer**

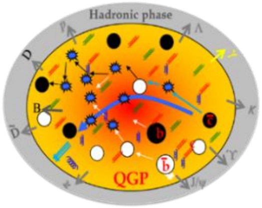
- ❑ **initial charm production is well described by pQCD – FONLL**

- ❑ **heavy quark scattering cross sections are small (compared to the light quarks) ➔ not in an equilibrium with the surrounding matter**

- ❑ **sensitive to the properties of the QGP during the expansion (and not only to its final state)**

**➔ Hope to use 'charm probes' for an early tomography of the QGP**

# Dynamical description of hard probes



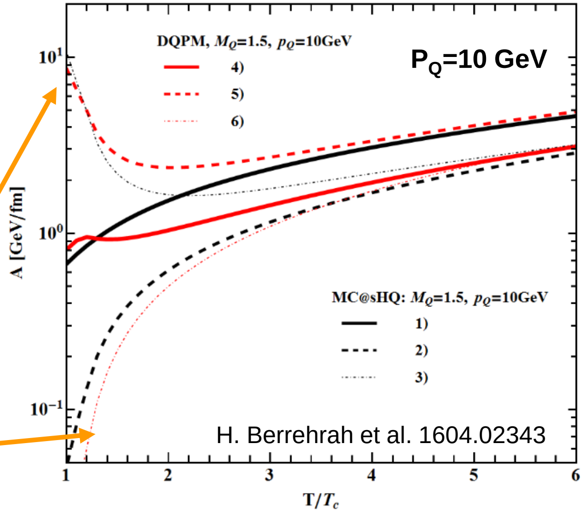

## I. Modeling of time evolution of the ‚medium' = system:

- expanding fireball models ← assumption of global equilibrium
- ideal or viscous hydrodynamical models ← assumption of local equilibrium
- microscopic transport models ← full non-equilibrium dynamics!

## II. Modeling of the interaction of the hard probes with the ‚medium':

- Fokker-Planck model, Langevin model ← transport coefficients $A = dp_L/dt, \quad \hat{q} = dp_T^2/dt$
- linear Boltzmann models ← cross sections
- microscopic collision integral ← cross sections

| | coupling | mass in gluon propagator | mass in external legs |
|---|---|---|---|
| 1) | $\alpha(Q^2)$ | $\kappa = 0.2, m_D$ | $m_{q,g} = 0$ |
| 2) | $\alpha(Q^2)$ | $\kappa = 0.2, m_D$ | $m_{q,g} = m_{q,g}^{DQPM}$ |
| 3) | $\alpha(T)$ | $\kappa = 0.2, m_D$ | $m_{q,g} = 0$ |
| 4) | $\alpha(T)$ | $m_g^{DQPM}$ | $m_{q,g} = m_{q,g}^{DQPM}$ |
| 5) | $\alpha(T)$ | $m_g^{DQPM}$ | $m_{q,g} = 0$ |
| 6) | $\alpha(Q^2)$ | $m_g^{DQPM}$ | $m_{q,g} = m_{q,g}^{DQPM}$ |

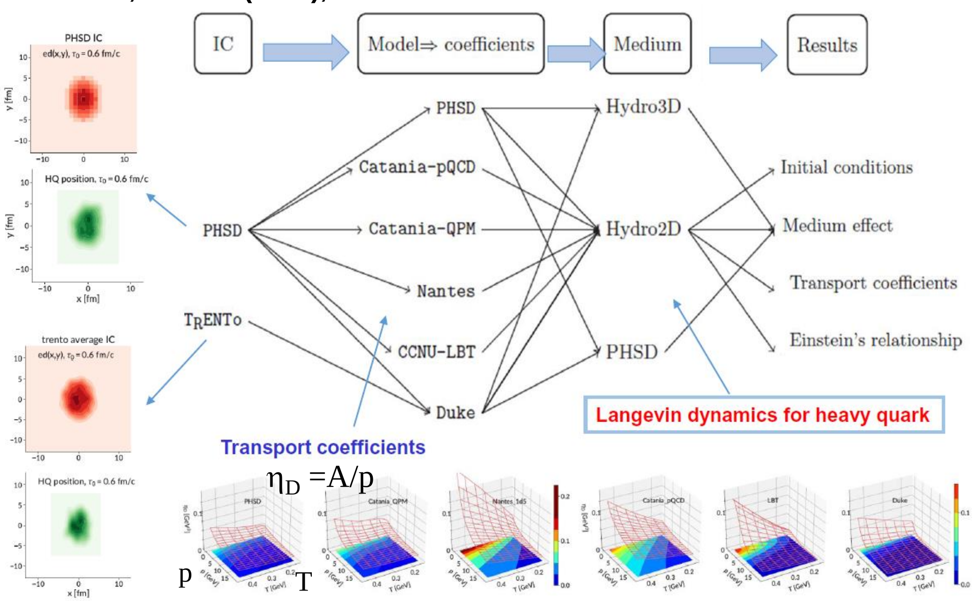


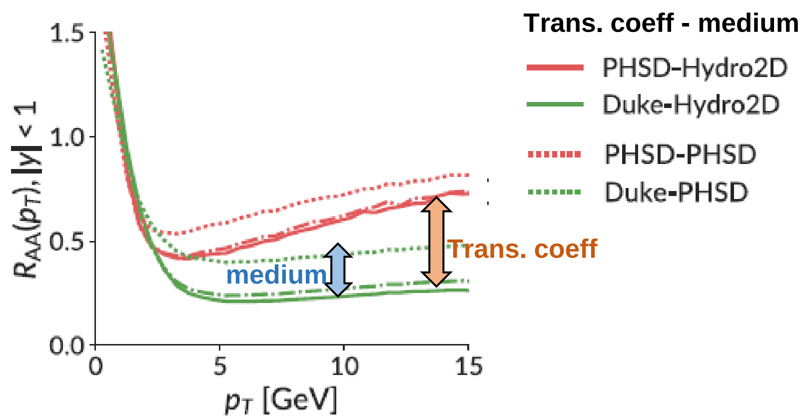
# Highlights of model comparisons

**EMMI-charm:** R. Rapp et al., NPA979 (2018) 21-86; **"Jet"-charm:** S. Cao et al., PRC 99, 054907 (2019)
**Frankfurt-Duke-Nantes-Catania:** Y. Xu et al., PRC 99 (2019), 014902; T. Song et al., PRC 101 (2020) 044901; ibid. 044903

- ❑ interaction of heavy quarks with medium; charm transport coefficients; initial conditions; comparison: Langevin vs. Boltzmann description;
- ❑ hydro vs. microscopic transport description of the medium; non-equilibrium effects etc.

Y. Xu et al., PRC 99 (2019), 014902



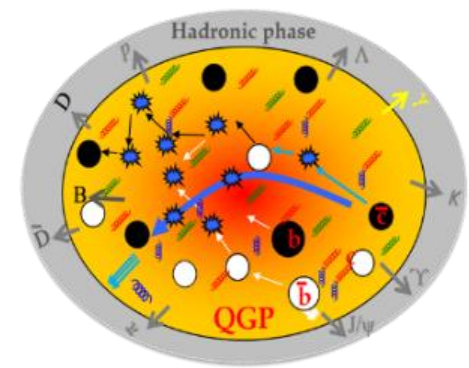

➔ Charm quarks are sensitive to the **history of the QGP evolution** and retain information on the entire time evolution from initial condition up to the late stage of the reaction

- ❑ **Initial conditions**: larger effect (up to 20%) on $v_2$ than on $R_{AA}$
- ❑ **Transport coefficients:** huge influence on $R_{AA}$ and $v_2$ within Langevin models
- ❑ **Medium evolution:** $R_{AA}$ and $v_2$ from nonequilibrium transport differ from hydro and Langevin results

➔ **Langevin models are not an appropriate tool to study the charm dynamics in HICs!**
➔ **Microscopic transport description** of HIC dynamics (medium) and charm interactions (based on Boltzmann collision terms) is required

# Dynamical Models → PHSD

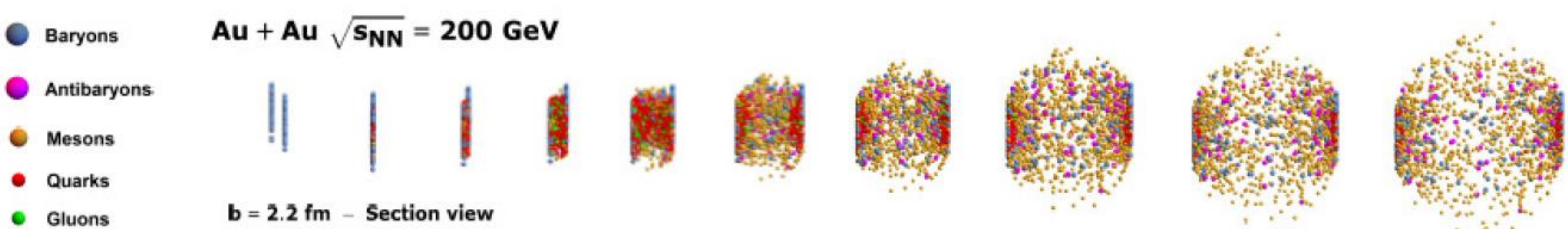
**The goal:**
**to describe the dynamics of charm quarks/mesons in all phases of HICs on a microscopic basis**

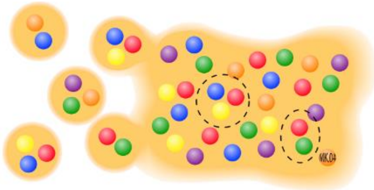



**Realization:**
**a dynamical non-equilibrium transport approach**

- **applicable for strongly interacting systems,**
- **which includes a phase transition from hadronic matter to QGP**

## The tool: PHSD approach



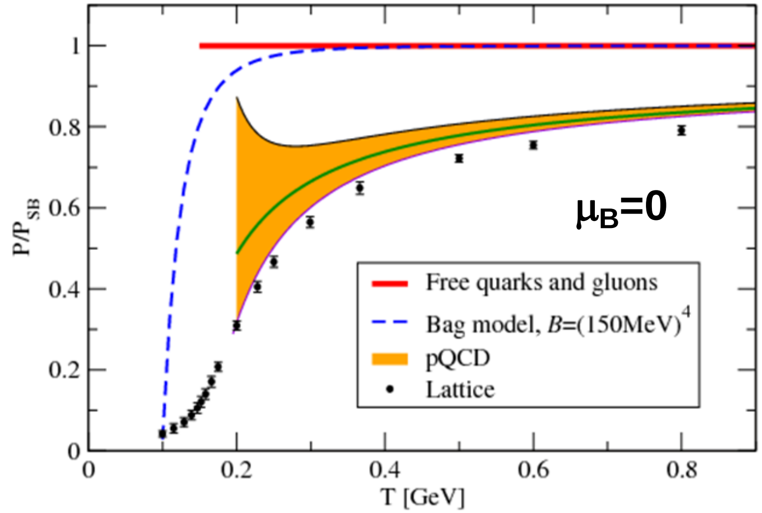


# Degrees-of-freedom of QGP

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 $\mu_B$

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




Non-perturbative QCD ← pQCD

**pQCD:**

- weakly interacting system
- massless quarks and gluons

**Thermal QCD**
**= QCD at high parton densities:**

- strongly interacting system
- massive quarks and gluons

➔ quasiparticles
= effective degrees-of-freedom

How to learn about the degrees-of-freedom of the QGP from HICs?
➔ microscopic transport approaches
➔ comparison to HIC experiments

# 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

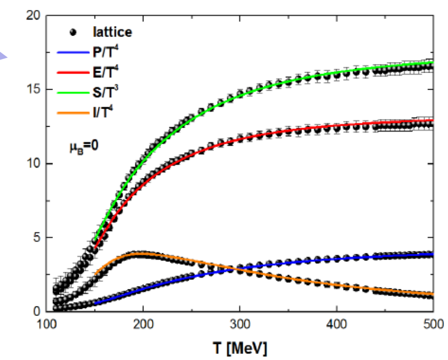
**Theoretical basis :**

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

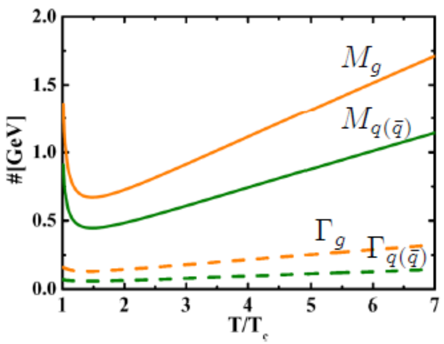
**Properties of the quasiparticles** are specified by scalar **complex self-energies:** $\Sigma_q = M_q^2 - i2\gamma_q\omega$

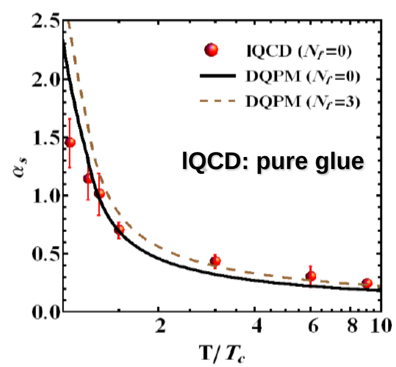
$Re\Sigma_q$ : **thermal masses** $(M_g, M_q)$; $Im\Sigma_q$ : **interaction widths** $(\gamma_g, \gamma_q)$ → spectral functions $\rho_q = -2ImG_q$

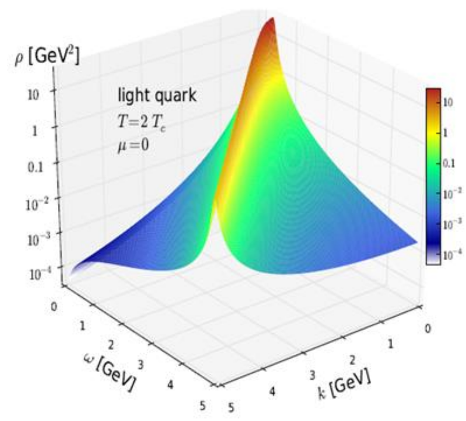
- introduce an **ansatz** (HTL; with few parameters) for the (T, $\mu_B$) dependence of masses/widths
- evaluate the **QGP thermodynamics** in equilibrium using the Kadanoff-Baym theory
- fix DQPM parameters by comparison to the entropy density s, pressure P, energy density ε from DQPM to **lQCD** at $\mu_B$ =0




## ➔ Quasi-particle properties at (T, $\mu_B$) :




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

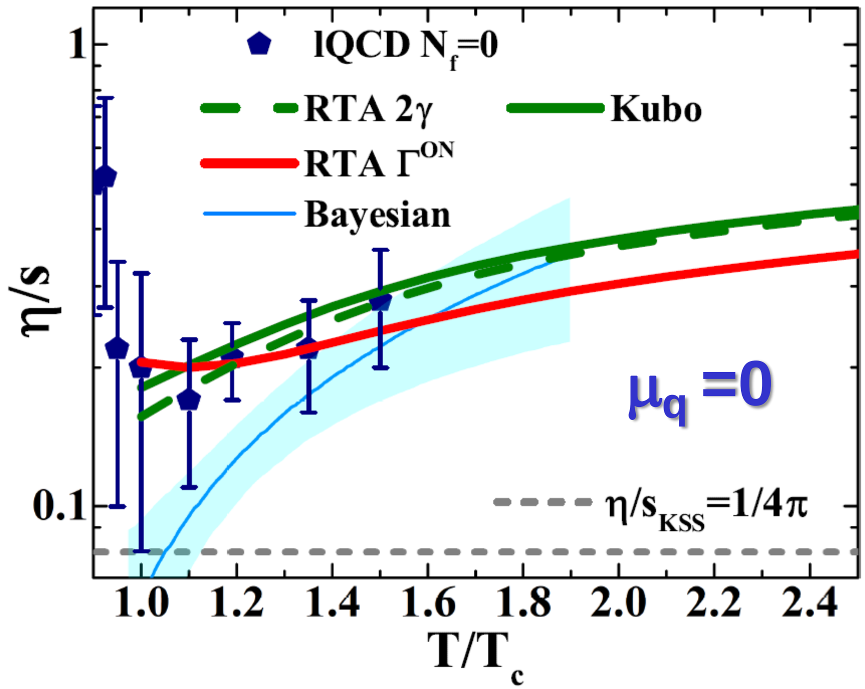
A. Peshier, W. Cassing, PRL 94 (2005) 172301; W. Cassing, NPA 791 (2007) 365: NPA 793 (2007), H. Berrehrah et al, Int.J.Mod.Phys. E25 (2016) 1642003; P. Moreau et al., PRC100 (2019) 014911; O. Soloveva et al., PRC101 (2020) 045203

# Transport coefficients: shear viscosity

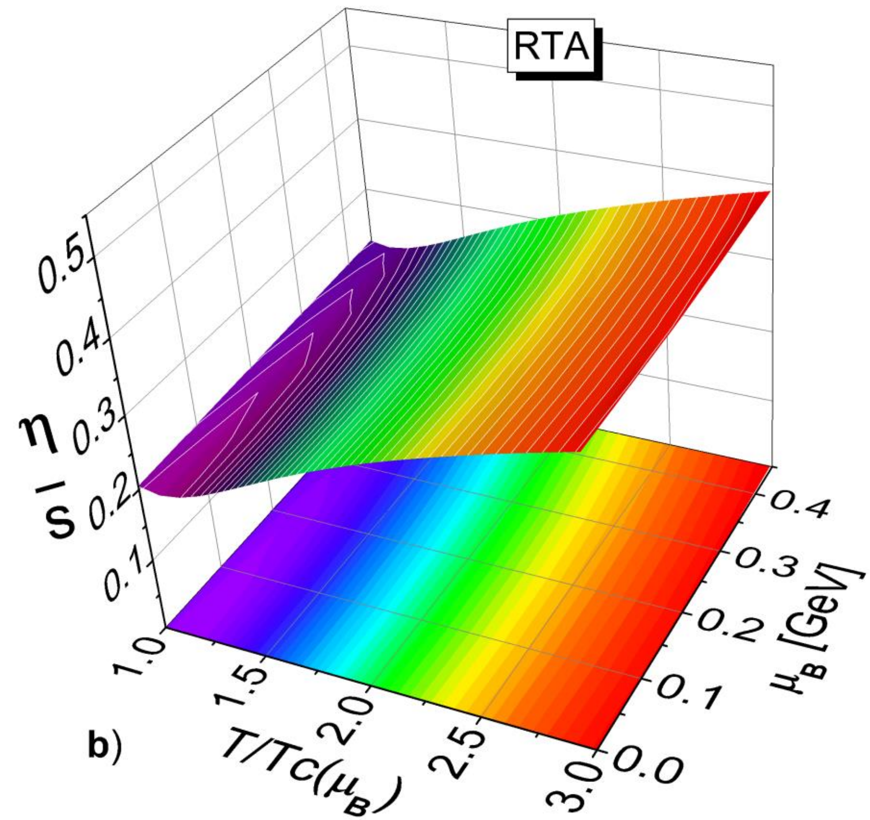
## Shear viscosity $\eta/s$ at finite T, $\mu_q$=0

- **DQPM:** Relaxation Time Approximation (RTA) and Kubo formalism

Hydro: Bayesian analysis, S. Bass et al. , NPA967 (2017) 67




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




- Very weak dependence of shear viscosity on $\mu_B$

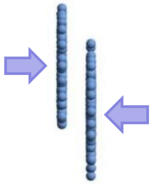
P. Moreau et al., PRC100 (2019) 014911; O. Soloveva et al., PRC 101 (2020) 045203

# Parton-Hadron-String-Dynamics (PHSD)

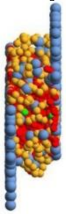
**PHSD** is a **non-equilibrium microscopic transport approach** for the description of **strongly-interacting hadronic and partonic matter** created in heavy-ion collisions

**Dynamics:** based on the solution of **generalized off-shell transport equations** derived from Kadanoff-Baym many-body theory

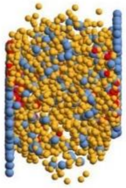
Initial A+A collision



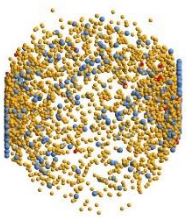
Partonic phase



Hadronization

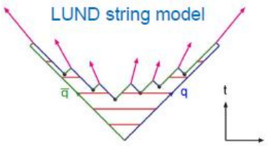


Hadronic phase

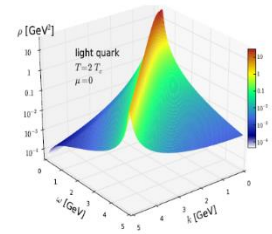


P.Moreau

- **Initial A+A collisions** :
  N+N → string formation → decay to pre-hadrons + leading hadrons

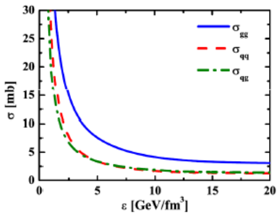



- **Formation of QGP stage** if local $\varepsilon > \varepsilon_{critical}$ =0.5 GeV/fm$^3$:
  dissolution of pre-hadrons → partons

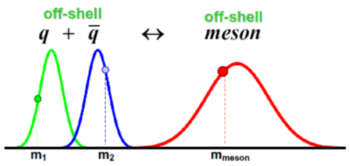



- **Partonic phase - QGP:**
  QGP is described by the Dynamical QuasiParticle Model (DQPM)
  matched to reproduce lattice QCD EoS for finite T and $\mu_B$ (crossover)

  - Degrees-of-freedom: strongly interacting quasiparticles:
    massive quarks and gluons (g,q,$q_{bar}$) with sizeable collisional widths in a self-generated mean-field potential
    propagated in self-generated mean-field potential Uq, Ug
  - Interactions: (quasi-)elastic and inelastic collisions of partons




- **Hadronization** to colorless off-shell mesons and baryons:
  Strict 4-momentum and quantum number conservation

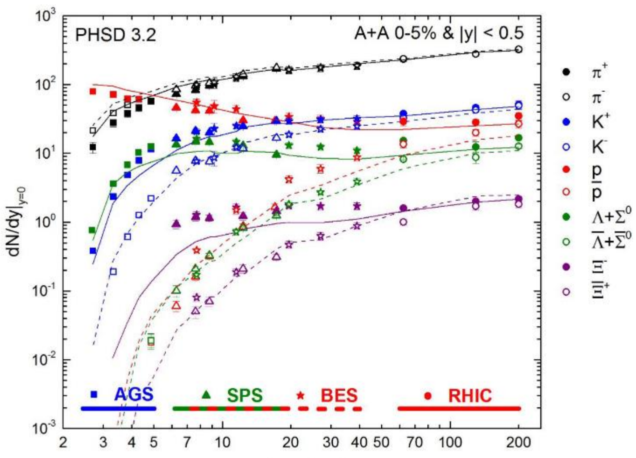



- **Hadronic phase: hadron-hadron interactions – off-shell HSD**

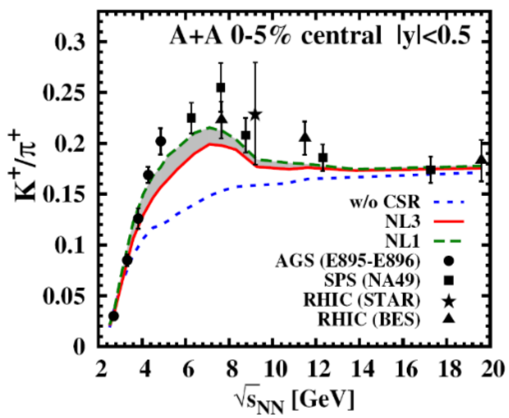
W. Cassing, E. Bratkovskaya, PRC 78 (2008) 034919; NPA831 (2009) 215; W. Cassing, EPJ ST 168 (2009) 3

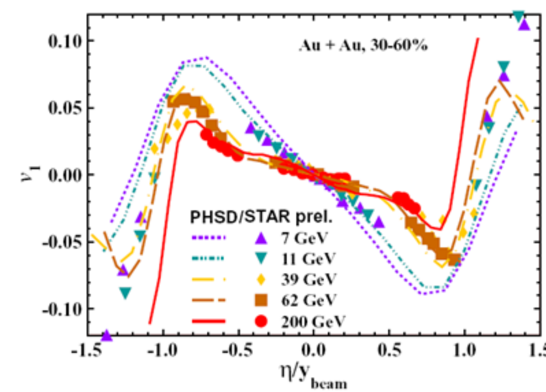
# Non-equilibrium dynamics: description of A+A with PHSD

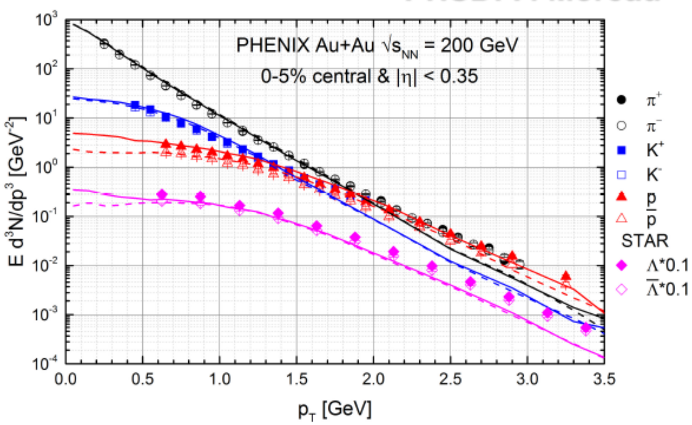
❑ **Important:** to be conclusive on charm observables, the **light quark dynamics** must be well under control!

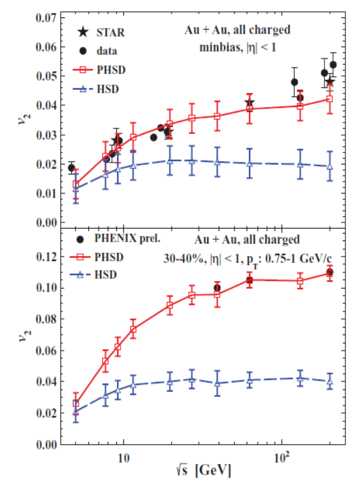


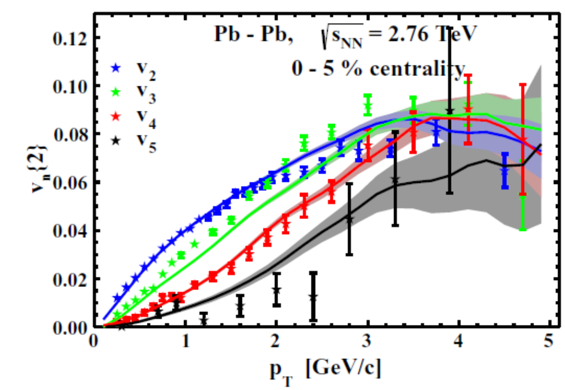

**PHSD: P. Moreau**



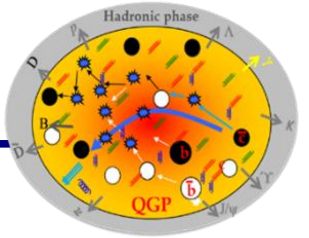



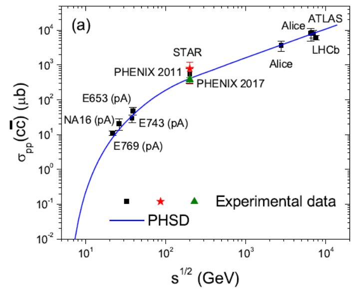

V. Konchakovski et al.,
PRC 85 (2012) 011902; JPG42 (2015) 055106

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

# Charm dynamics in PHSD

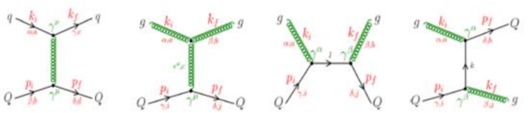



## Dynamics of heavy quarks in A+A :



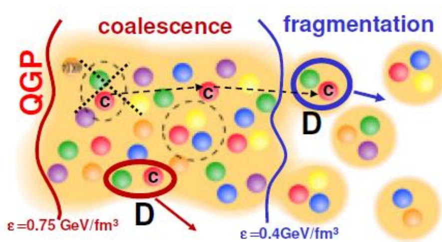

1. **Production** of heavy (charm and bottom) quarks in initial binary collisions + shadowing and Cronin effects

2. **Interactions in the non-perturbative QGP – according to the DQPM**: elastic scattering with off-shell massive partons Q+q→Q+q
   → **collisional** energy loss

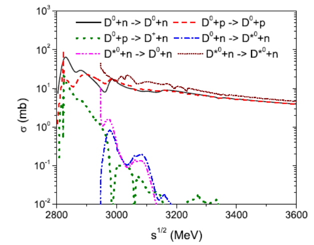


3. **Hadronization**: c/cbar quarks →D(D*)-mesons:

   Dynamical hadronization scenario for heavy quarks :
   **coalescence** with <r>=0.9 fm & **fragmentation**
   0.4< $\varepsilon$ < 0.75 GeV/fm³ $\varepsilon$ < 0.4 GeV/fm³




4. **Hadronic interactions**:
   D+baryons; D+mesons based on G-matrix and effective chiral Lagrangian approach with heavy-quark spin symmetry (>200 channels)
   (Juan Torres-Rincon, Laura Tolos)

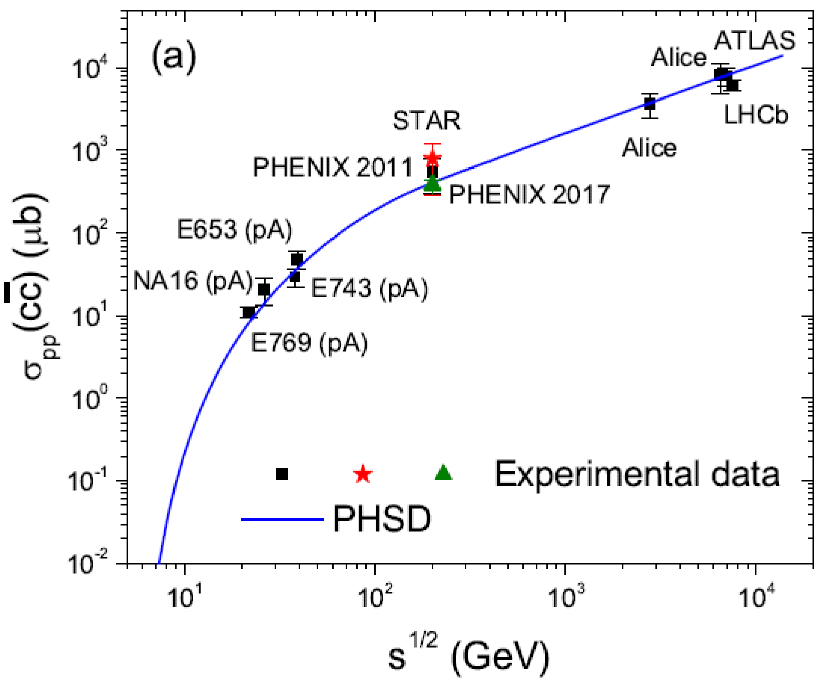



* PHSD references on charm dynamics:
Taesoo Song et al., PRC 92 (2015) 014910, PRC 93 (2016) 034906, PRC 96 (2017) 014905
PRC 97 (2018) 064907; PRC 101 (2020) 044901; PRC 101 (2020) 044903

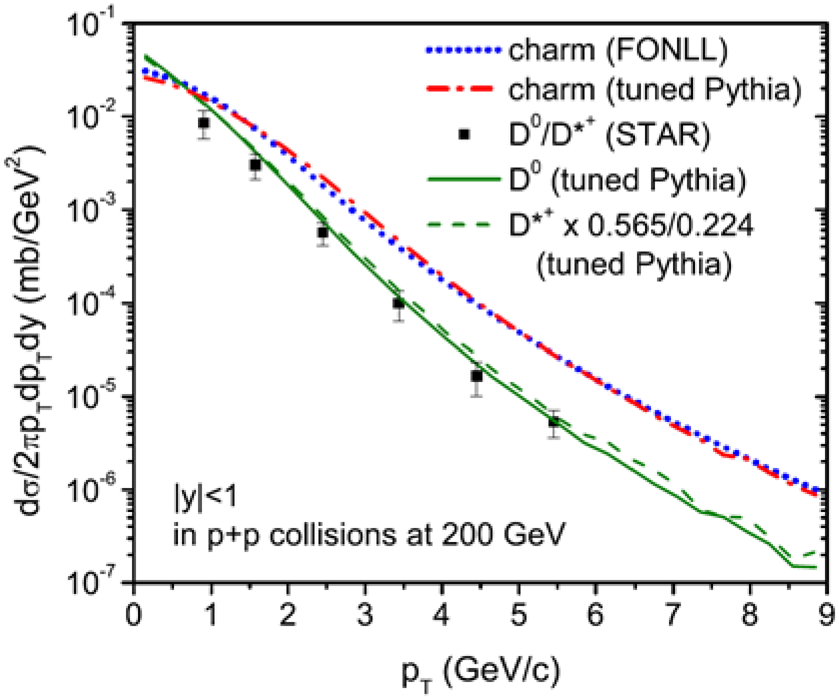
# Charm production in NN collisions

- A+A: charm production in initial NN binary collisions: probability $P = \frac{\sigma(c\bar{c})}{\sigma_{NN}^{inel}}$

The total cross section for charm production in p+p collisions $\sigma(c\bar{c})$




Momentum distribution of heavy quarks: use ‚tuned' PYTHIA event generator to reproduce FONLL (fixed-order next-to-leading log) results

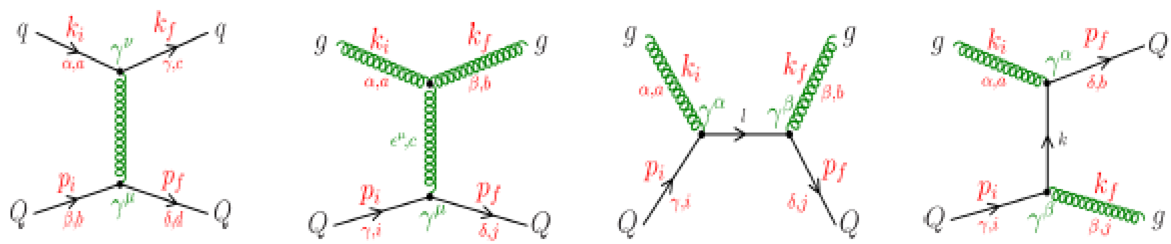



T. Song, W.Cassing, P.Moreau and E.Bratkovskaya, PRC 97 (2018) 064907

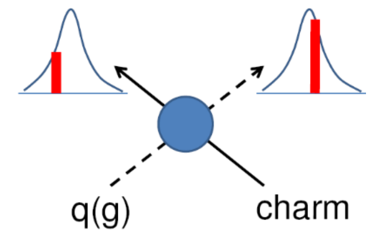
T. Song et al., PRC 92 (2015) 014910, PRC 93 (2016) 034906, PRC 96 (2017) 014905

# Heavy quark scattering in the QGP (DQPM)

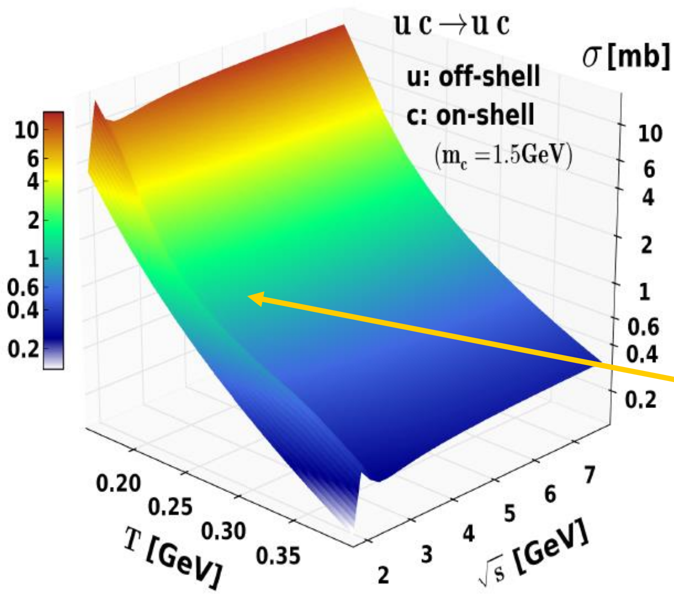
- Elastic scattering with **off-shell massive partons Q+q(g)→Q+q(g)**



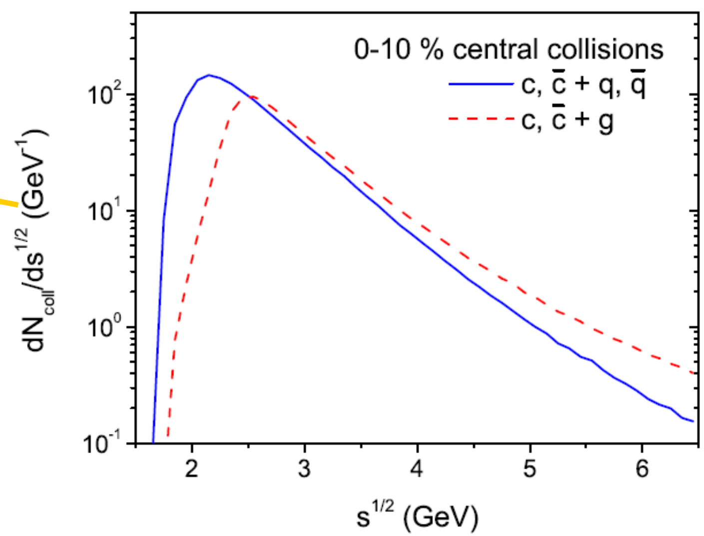
**Non-perturbative QGP!**




- **Elastic cross section uc→uc**



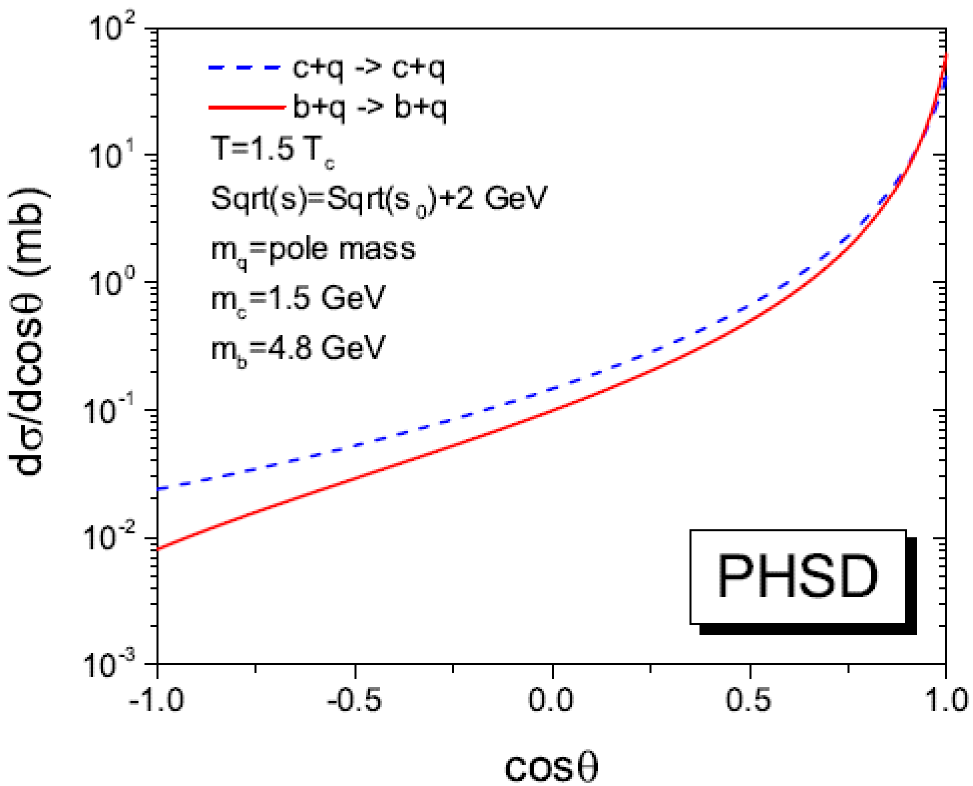

- **Distributions of Q+q, Q+g collisions vs $s^{1/2}$ in Au+Au, 10% central**




H. Berrehrah et al, PRC 89 (2014) 054901;
PRC 90 (2014) 051901; PRC90 (2014) 064906

# Heavy quark scattering in the QGP

- **Differential elastic cross section** for $cq \rightarrow cq$, $bq \rightarrow bq$ for $s^{1/2}=s_0^{1/2}$ +2GeV at $1.5T_C$




- **DQPM - anisotropic angular distribution**

**Note: pQCD - strongly forward peaked**
**→ Differences between DQPM and pQCD : less forward peaked angular distribution leads to more efficient momentum transfer**

**→ Smaller number (compared to pQCD) of elastic scatterings with massive partons leads to a larger energy loss**

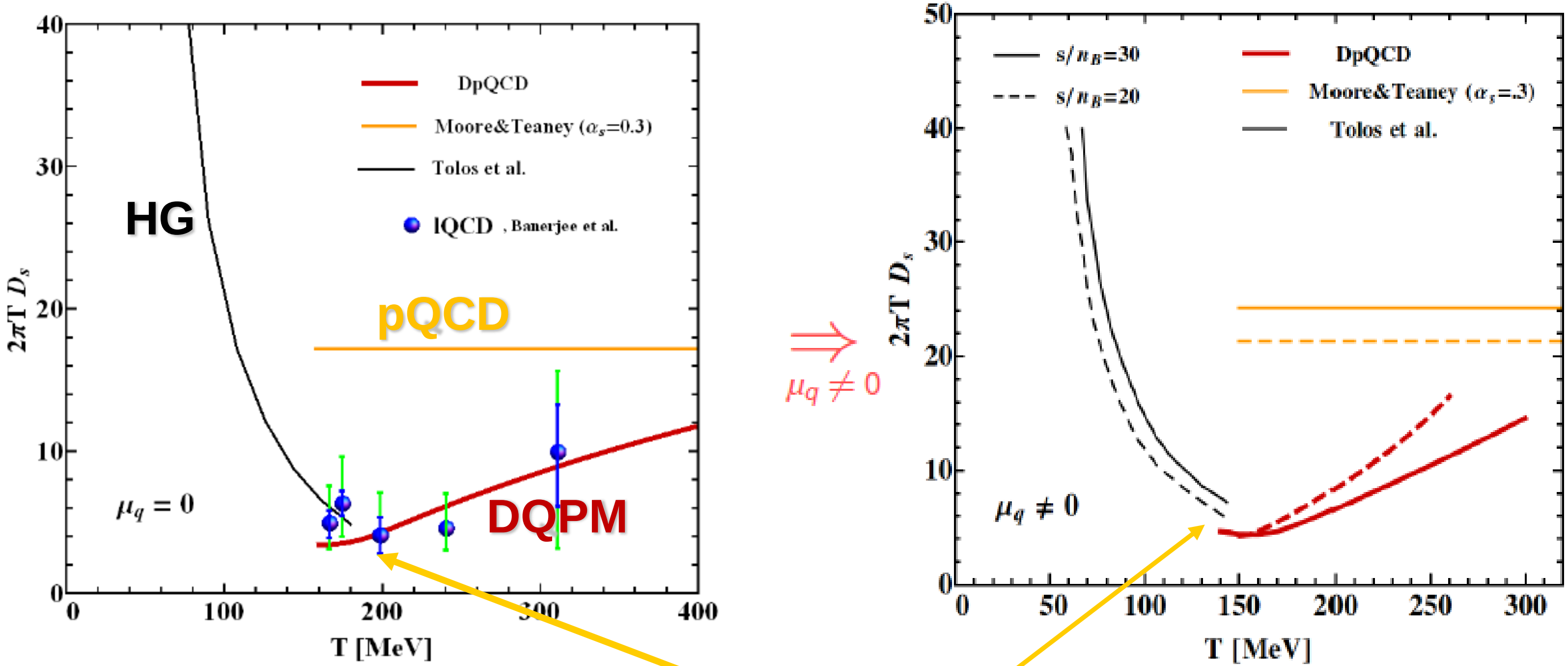
**! Note: radiative energy loss is NOT included yet in PHSD,**
**it is expected to be small (at low $p_T$) due to the large gluon mass in the DQPM**

H. Berrehrah et al, PRC 89 (2014) 054901; PRC 90 (2014) 051901; PRC90 (2014) 064906

# Charm spatial diffusion coefficient $D_s$ in the hot medium

- **$D_s$ for heavy quarks as a function of T for $\mu_q$=0 and finite $\mu_q$ assuming adiabatic trajectories (constant entropy per net baryon $s/n_B$) for the expansion**

$$D_s = lim(\vec{p} \to 0) \frac{T}{M\eta_D}$$ where $\eta_D$ = A/p ; A(p,T) = drag coefficient




- **T < $T_c$ : hadronic $D_s$**

**L. Tolos , J. M. Torres-Rincon, PRD 88 (2013) 074019**
**V. Ozvenchuk et al., PRC90 (2014) 054909**

**➔ Continuous transition at $T_C$!**

**H. Berrehrah et al, PRC 90 (2014) 051901, arXiv:1406.5322**

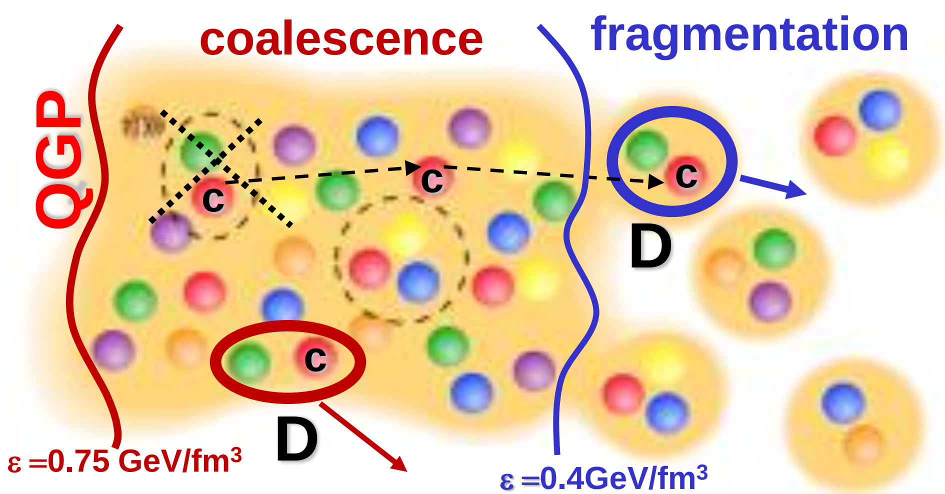
# Hadronization of heavy quarks in A+A

- PHSD: if the local energy density $\varepsilon \rightarrow \varepsilon_C$ ➔ hadronization of heavy quarks to hadrons

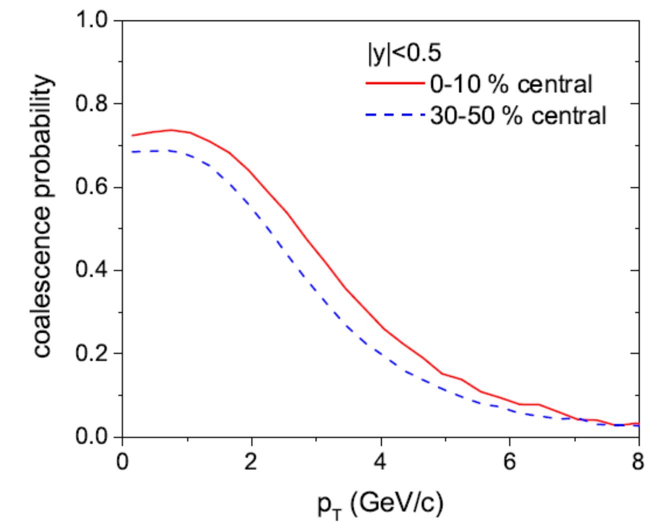
T. Song et al., PRC 93 (2016) 034906

**Dynamical hadronization scenario for heavy quarks :**

coalescence with <r>=0.9 fm & fragmentation
$0.4 < \varepsilon < 0.75$ GeV/fm$^3$ $\varepsilon < 0.4$ GeV/fm$^3$




**Coalescence probability in Au+Au at LHC**




Coalescence probability for $c+\bar{q}\rightarrow D$

$$f(\boldsymbol{\rho},\mathbf{k}_\rho)=\frac{8g_M}{6^2}\exp\left[-\frac{\boldsymbol{\rho}^2}{\delta^2}-\mathbf{k}_\rho^2\delta^2\right]$$

where $\boldsymbol{\rho}=\frac{1}{\sqrt{2}}(\mathbf{r}_1-\mathbf{r}_2),\quad \mathbf{k}_\rho=\sqrt{2}\,\frac{m_2\mathbf{k}_1-m_1\mathbf{k}_2}{m_1+m_2}$

Width $\delta$ ← from root-mean-square radius of meson <r>:

$$\langle r^2\rangle=\frac{3}{2}\frac{m_1^2+m_2^2}{(m_1+m_2)^2}\delta^2$$

Degeneracy factor : $g_M = 1$ for D, $= 3$ for $D^*=D^*_0(2400)^0$, $D^*_1(2420)^0$, $D^*_2(2460)^{0\pm}$

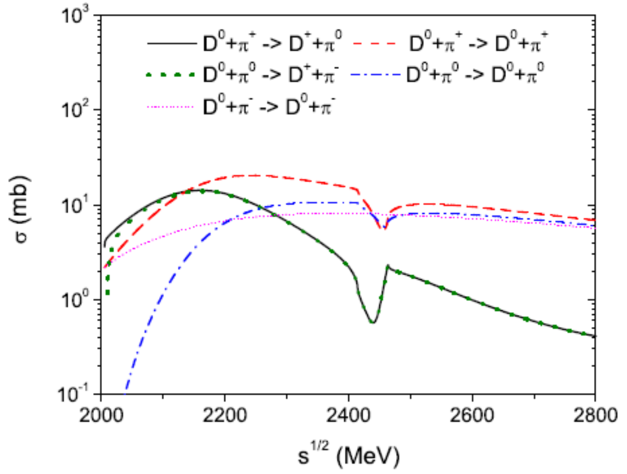
# D-meson scattering in the hadronic phase

## 1. D-meson scattering with mesons

L. M. Abreu, D. Cabrera, F. J. Llanes-Estrada, J. M. Torres-Rincon, Annals Phys. 326, 2737 (2011)

**Model:** effective chiral Lagrangian approach with heavy-quark spin symmetry

**Interaction of $D=(D^0,D^+,D^+_s)$ and $D^*=(D^{*0},D^{*+},D^{*+}_s)$ with octet $(\pi,K,\bar{K},\eta)$**



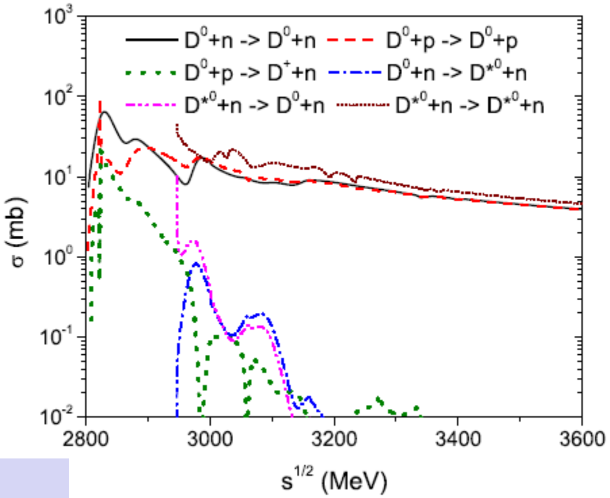

## 2. D-meson scattering with baryons

C. Garcia-Recio, J. Nieves, O. Romanets, L. L. Salcedo, L. Tolos, Phys. Rev. D 87, 074034 (2013)

**Model:** G-matrix approach: **interactions of $D=(D^0,D^+,D^+_s)$ and $D^*=(D^{*0},D^{*+},D^{*+}_s)$ with nucleon octet $J^P=1/2^+$ and Delta decuplet $J^P=3/2^+$**

**Unitarized scattering amplitude ➔ solution of coupled-channel Bethe-Salpeter equations:**

$$T = T + VGT$$

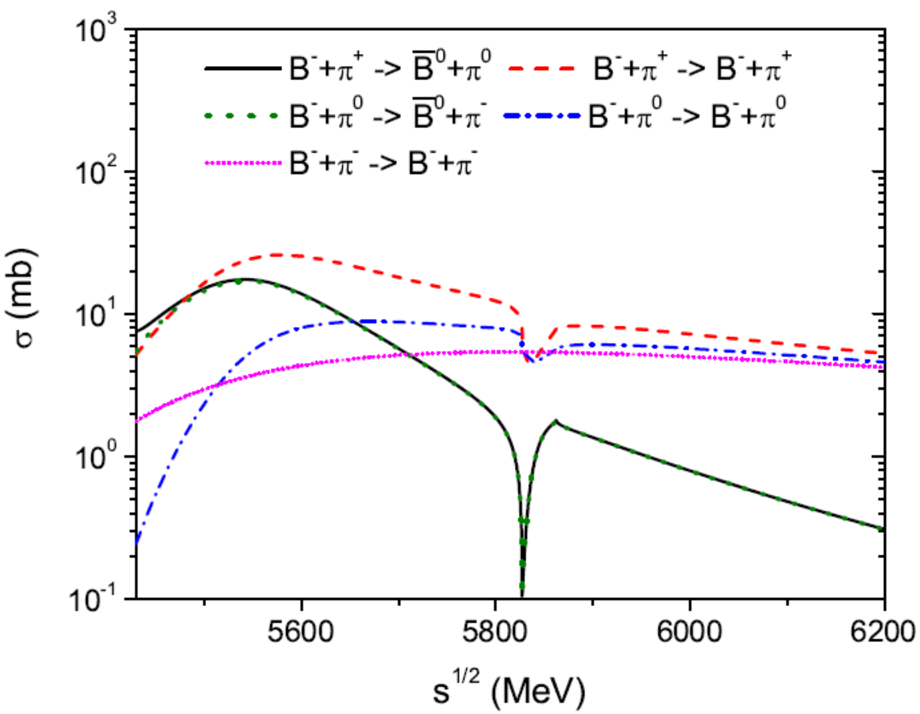



**➔ Strong isospin dependence and complicated structure (due to the resonance coupling) of D+m, D+B cross sections!**

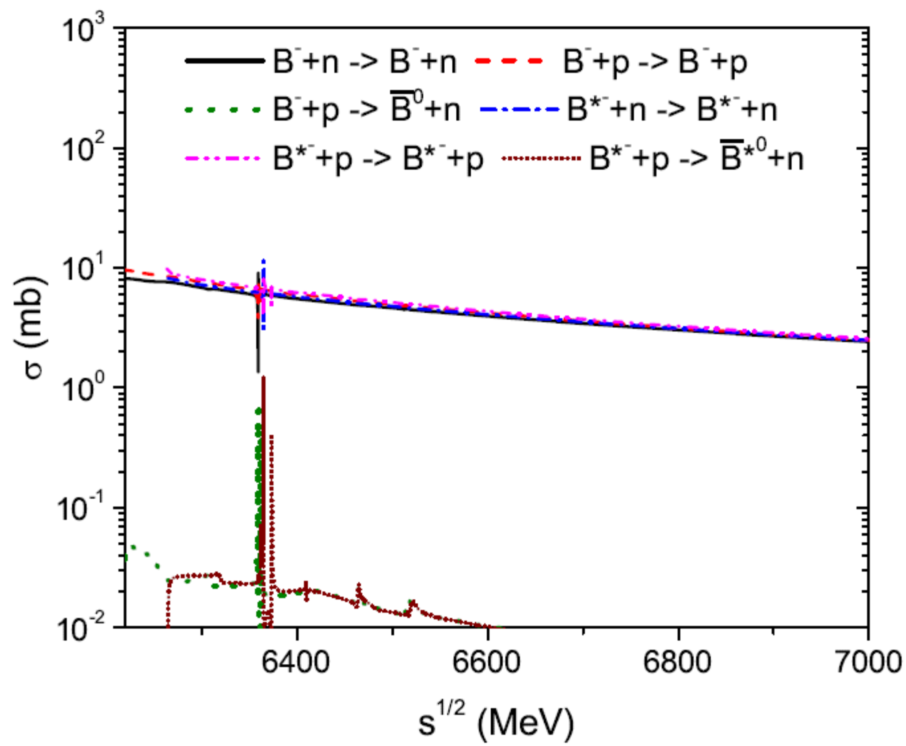
# B-meson scattering in the hadron gas

L. Tolos and J. M. Torres-Rincon, Phys. Rev. D 88, 074019 (2013)
J. M. Torres-Rincon, L. Tolos and O. Romanets, Phys. Rev. D 89, 074042 (2014)

**1. B-meson scattering with mesons**




**2. B-meson scattering with baryons**

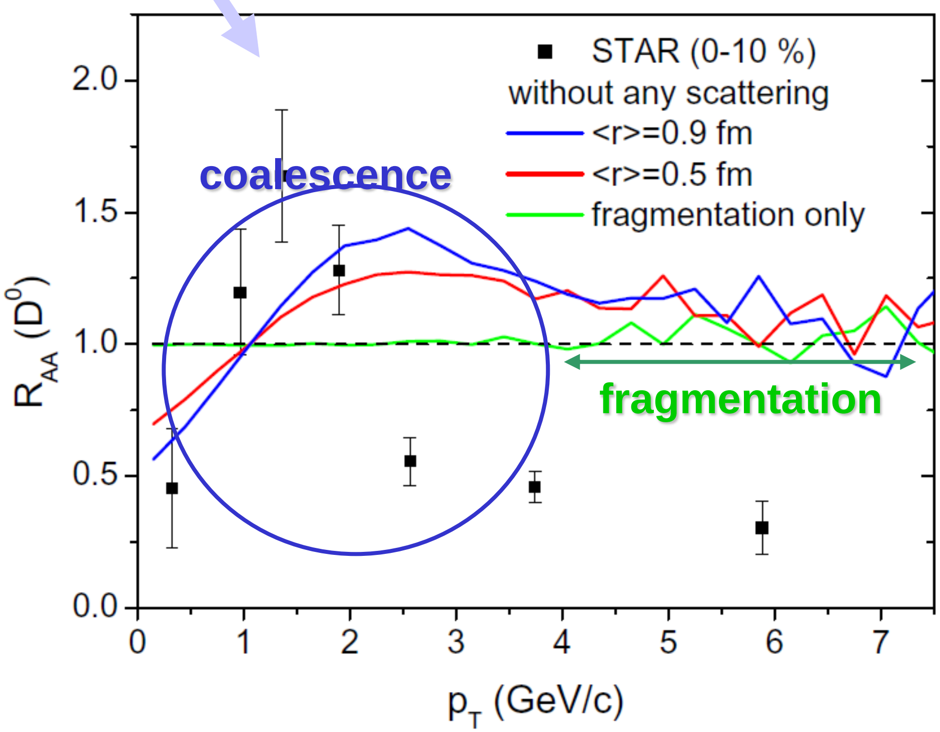



- **>200 hadronic channels** ➔ **implemented in the PHSD**

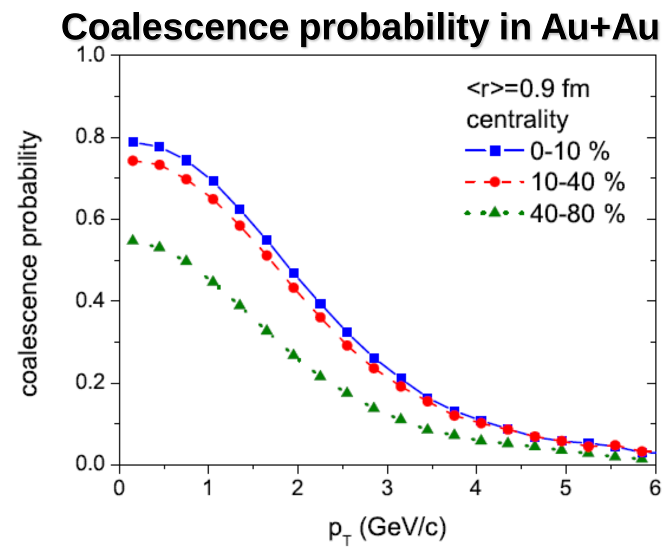
# $R_{AA}$ at RHIC - coalescence vs fragmentation

**Influence of hadronization scenarios: coalescence vs fragmentation**

**! Model study: without any rescattering (partonic and hadronic)**

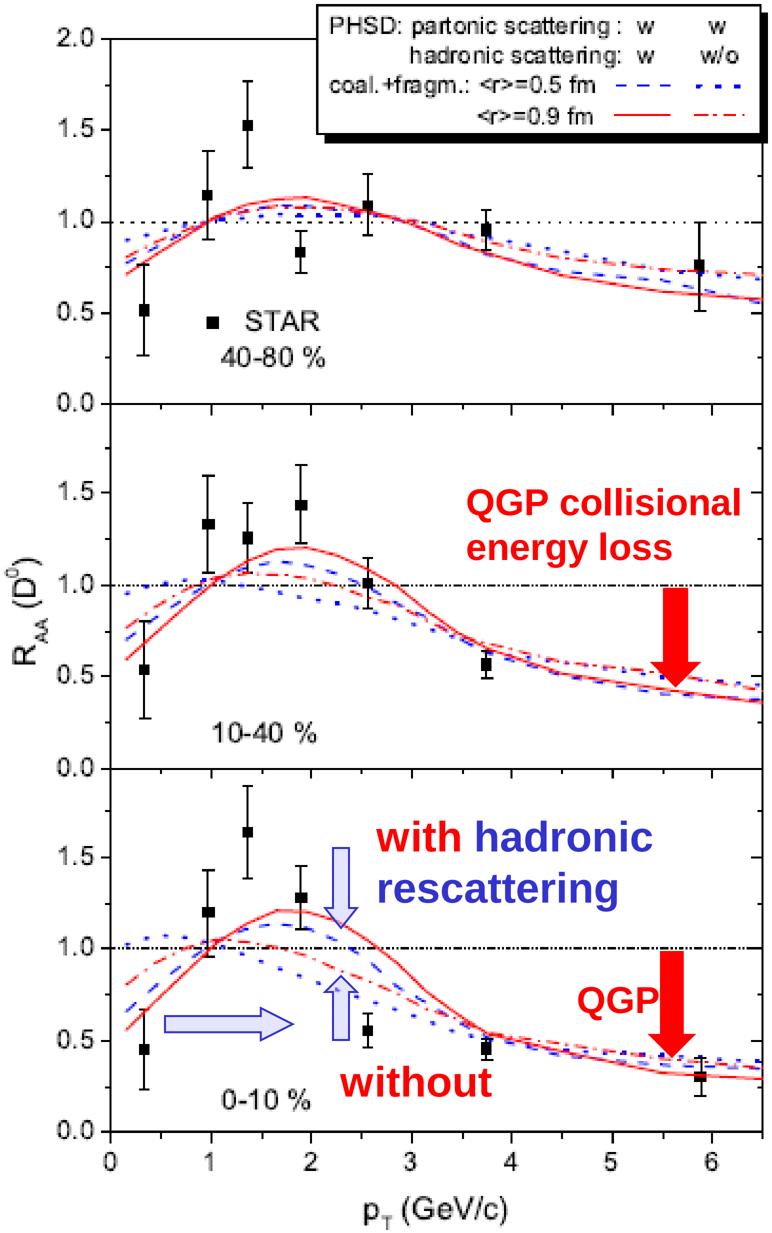



$$R_{AA}(p_T) \equiv \frac{dN_D^{\mathrm{Au+Au}}/dp_T}{N_{\mathrm{binary}}^{\mathrm{Au+Au}} \times dN_D^{\mathrm{p+p}}/dp_T}$$




- Expect: no scattering: $R_{AA}$=1
- Hadronization by fragmentation only (as in pp) ➔ $R_{AA}$=1
- Coalescence (not in pp!) shifts $R_{AA}$ to larger $p_T$ ➔ ‚nuclear matter' effect
- The hight of the $R_{AA}$ peak depends on the balance: coalescence vs. fragmentation

# $R_{AA}$ at RHIC: hadronic rescattering




## Influence of hadronic rescattering:

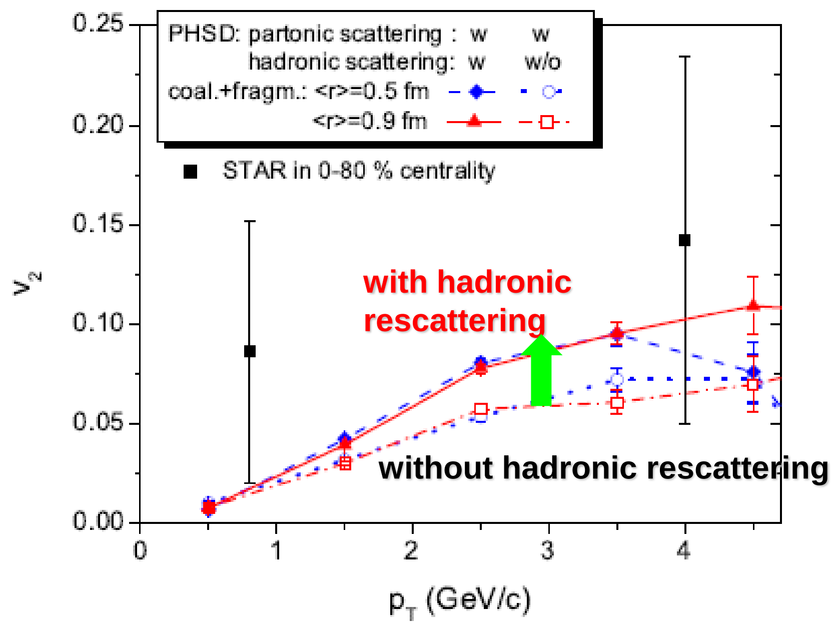
Central Au+Au at $s^{1/2}$ =200 GeV :

N(D,D*) ~30

N(D,D*+m) ~56 collisions

N(D,D*+B,Bbar) ~10 collisions

➔ each D,D* makes ~ 2 scatterings with hadrons




- Hadronic rescattering moves $R_{AA}$ peak to higher $p_T$ !
- substantially increases $v_2$ at larger $p_T$

T. Song et al., PRC 92 (2015) 014910

# Cold nuclear matter effect: shadowing +Cronin

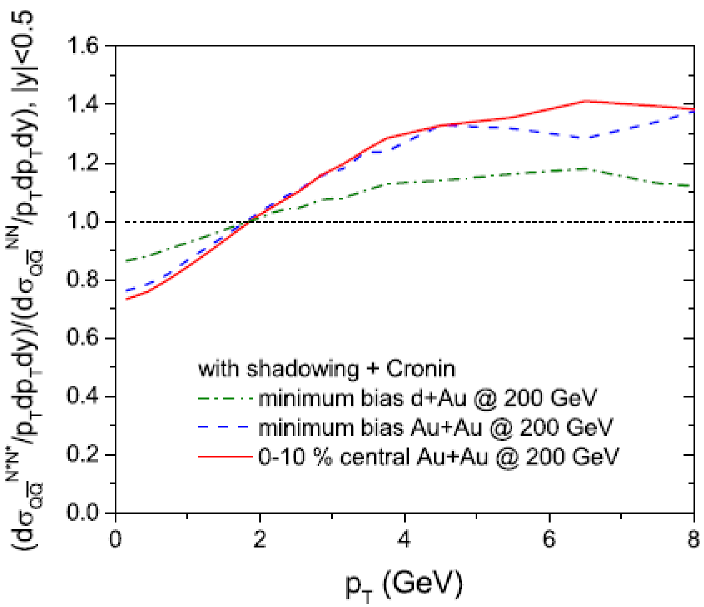
**Shadowing effect:** charm production is N*N* in HIC dominated by **gluon fusion**

$$\sigma_{c\bar{c}}^{N^*N^*}(s) = \langle R_g^{Pb}(x_1,Q) R_g^{Pb}(x_2,Q)\rangle \; \sigma_{c\bar{c}}^{NN}(s)$$

**$R_i^A(x_1,Q)$, $R_i^A(x_2,Q)$ for *i=j=gluon* are obtained from the EPS09 model**

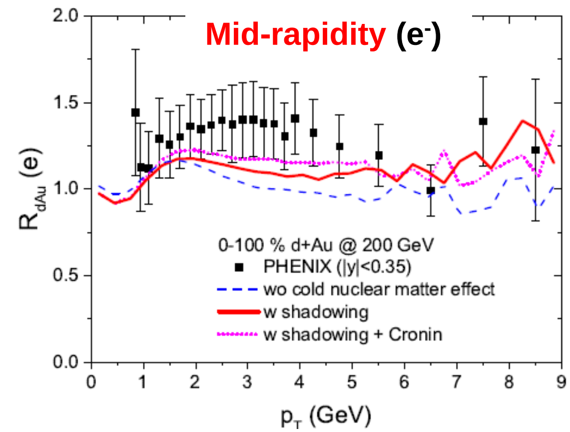
**K. J. Eskola, H. Paukkunen and C. A. Salgado, JHEP 0904, 065 (2009)**

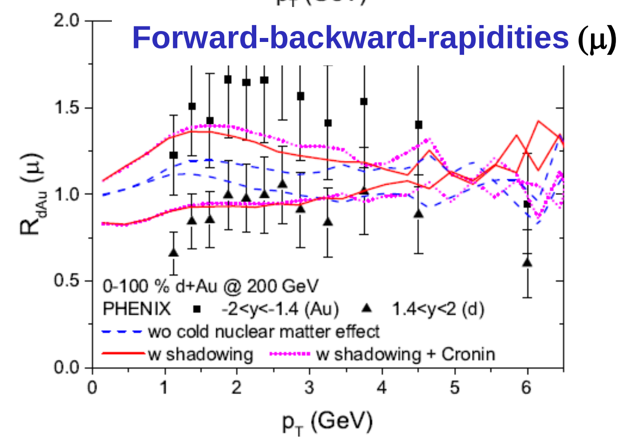
**The modifications of the charm transverse momentum in N*N* vs NN due to the shadowing and Cronin effects in d+A and Au+Au @ 200 GeV**




- **Shadowing effect increases $R_{AA}$ for low $p_T$**
- **Cronin effect increases $R_{AA}$ for $p_T$ >1 GeV**

**$R_{AA}$ from single $e^-$ ($\mu$) in d+Au @ 200 GeV**



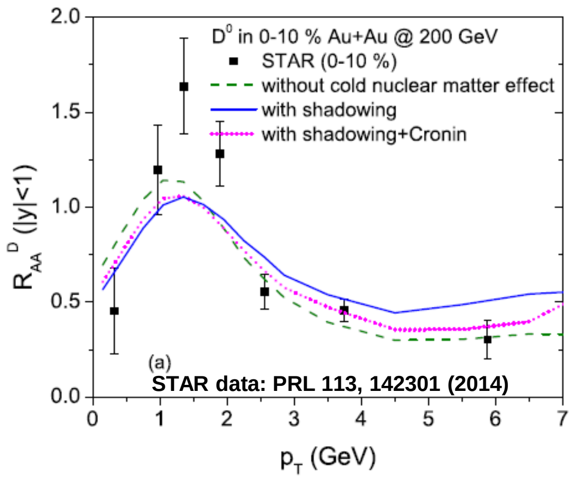



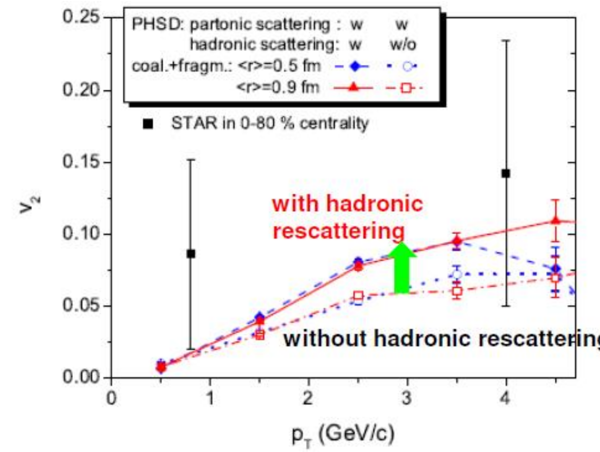

**T. Song et al., PRC 96, 014905 (2017)**

# PHSD vs charm observables at RHIC

## STAR

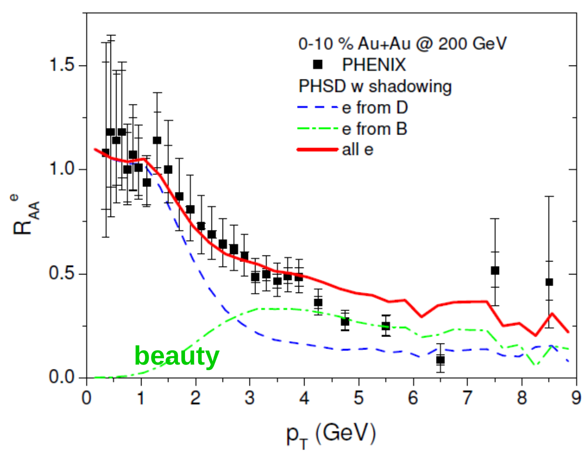
$R_{AA}$ and $v_2$ vs $p_T$ from $D^0$ -mesons in Au+Au @ 200 GeV ➔

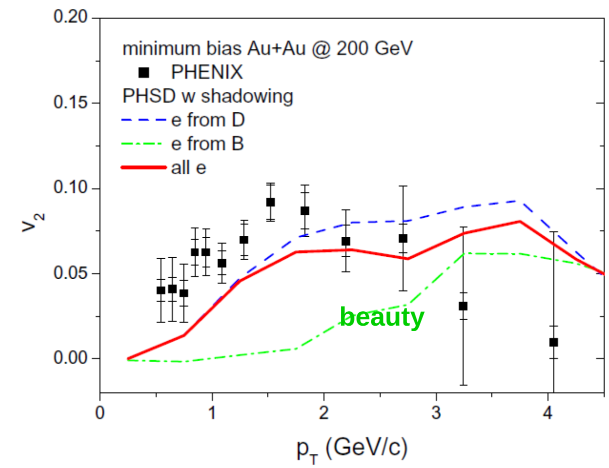



## PHENIX

$R_{AA}$ and $v_2$ vs $p_T$ from single electrons in Au+Au @ 200 GeV ➔

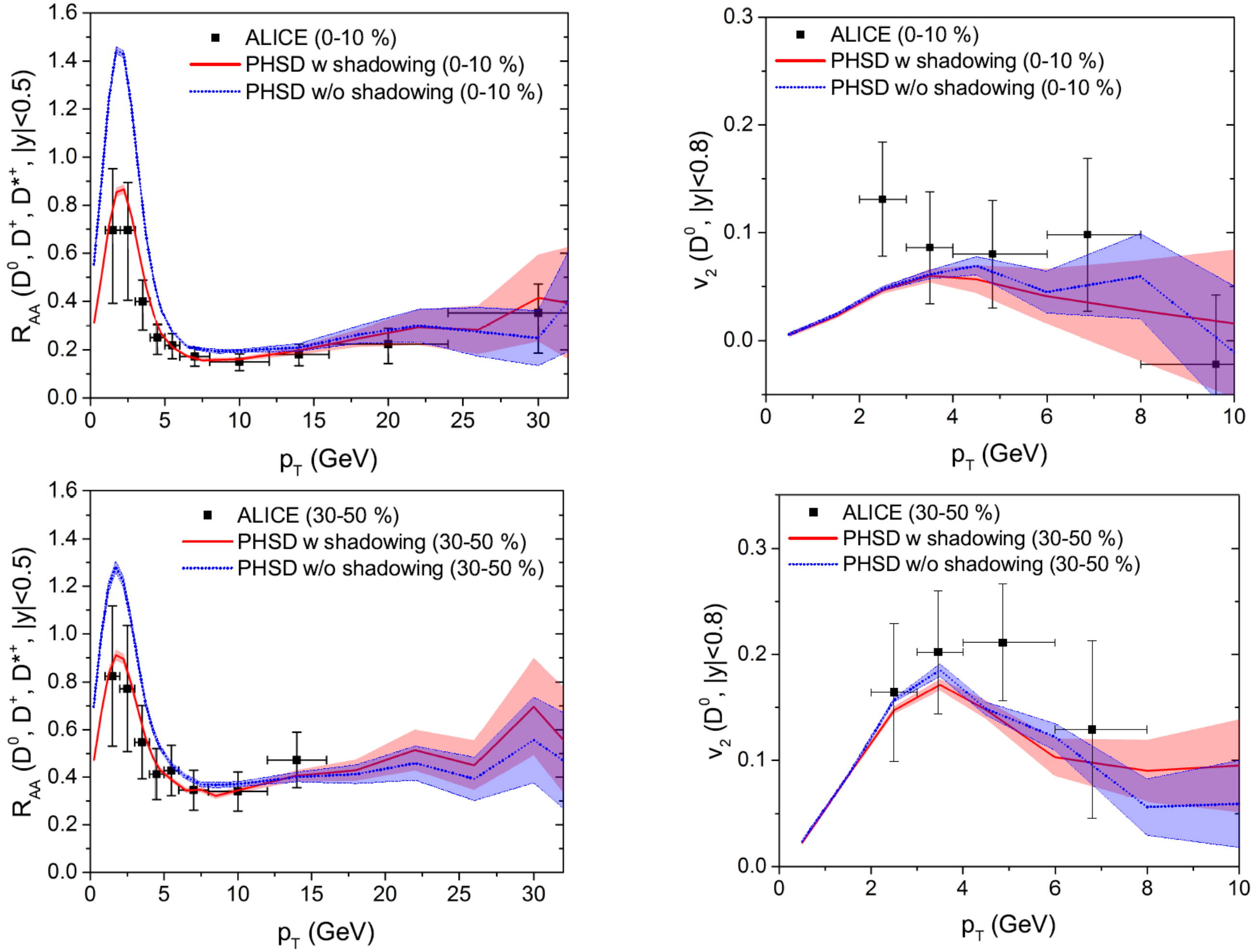



- ❑ The exp. data for the $R_{AA}$ and $v_2$ are described in the PHSD by QGP collisional energy loss due to elastic scattering of charm quarks with massive quarks and gluons in the QGP
+ by the dynamical hadronization scenario „coalescence & fragmentation“
+ by strong hadronic interactions due to resonant elastic scattering of D,D* with mesons and baryons
- ❑ Feed back from beauty contribution becomes dominant for single electrons $R_{AA}$ and $v_2$ at $p_T$ >3 GeV

T. Song et al., PRC 92 (2015) 014910, PRC 93 (2016) 034906, PRC 96 (2017) 014905

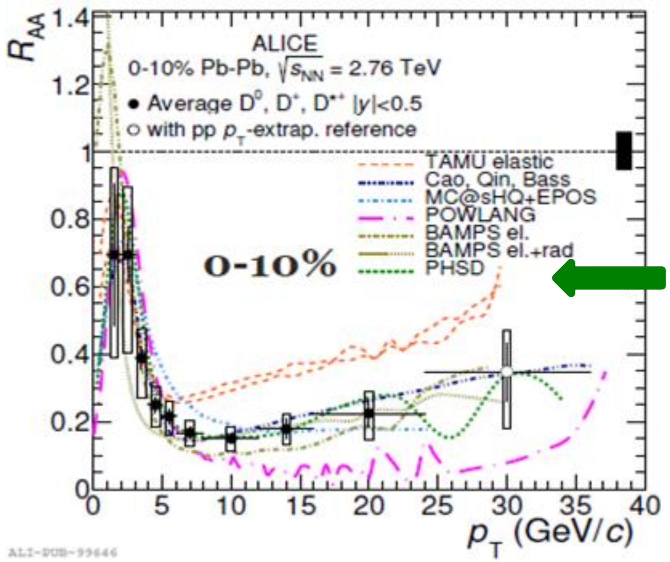
# Charm $R_{AA}$ at LHC: PHSD vs ALICE

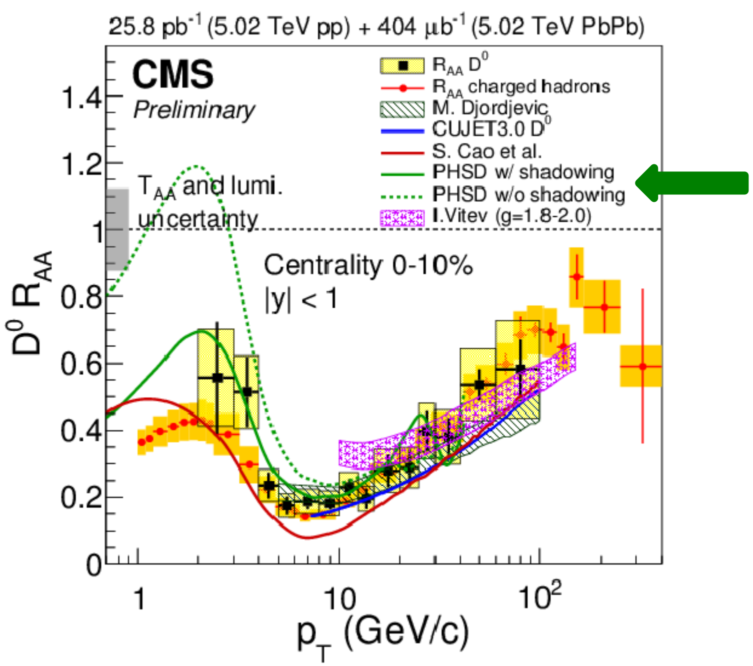



- **in PHSD the energy loss of D-mesons at high $p_T$ can be dominantly attributed to partonic scattering**
- **Shadowing effect suppresses the low $p_T$ and slightly enhances the high $p_T$ part of $R_{AA}$**
- **Hadronic rescattering moves $R_{AA}$ peak to higher $p_{T;}$ increases $v_2$**

**T. Song et al., PRC 93 (2016) 034906**

# PHSD vs charm observables at LHC (predictions)



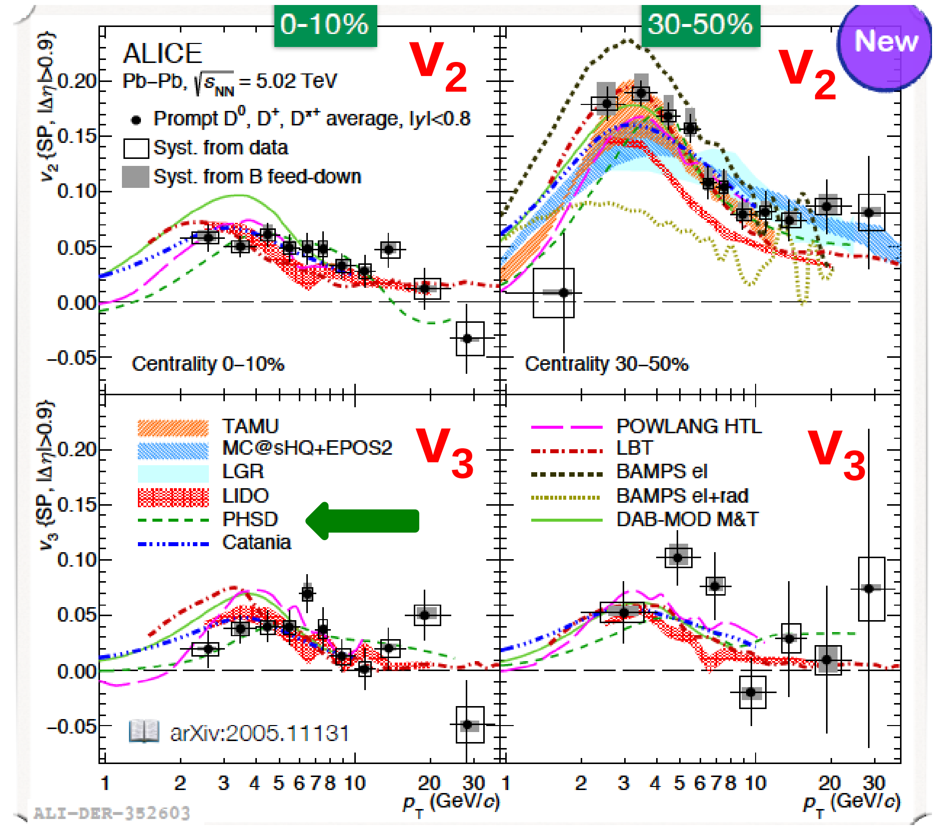
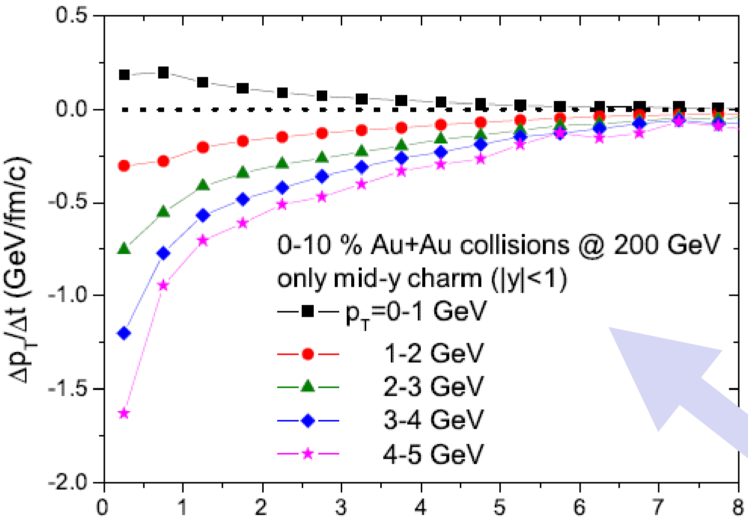



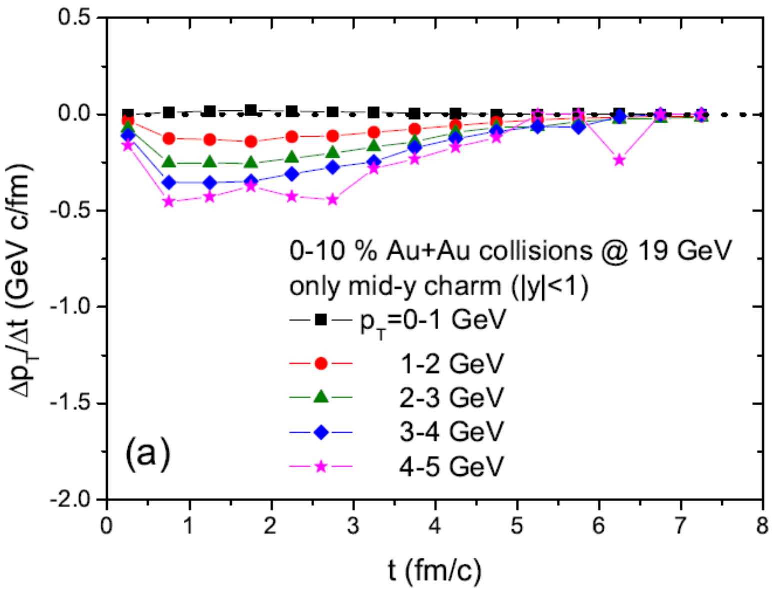

Fig. from the talk by Stefano Trogolo at HP-2020

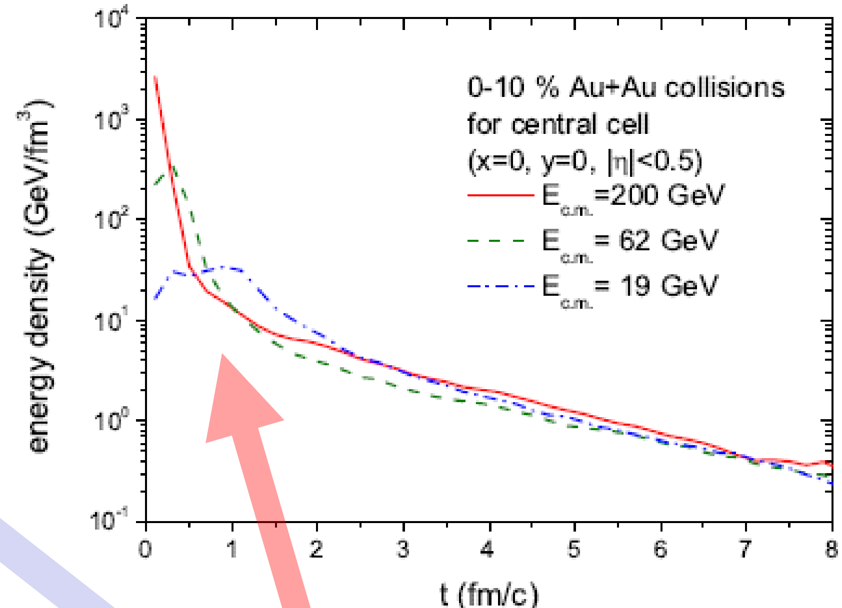
**T. Song et al., PRC 92 (2015) 014910,**
**PRC 93 (2016) 034906, PRC 96 (2017) 014905**

# Energy gain/loss at RHIC

- **Transverse momentum gain or loss of charm quarks per unit time at mid-rapidity in 0-10 % central Au+Au collisions at $s^{1/2}$= 200 and 19 GeV**

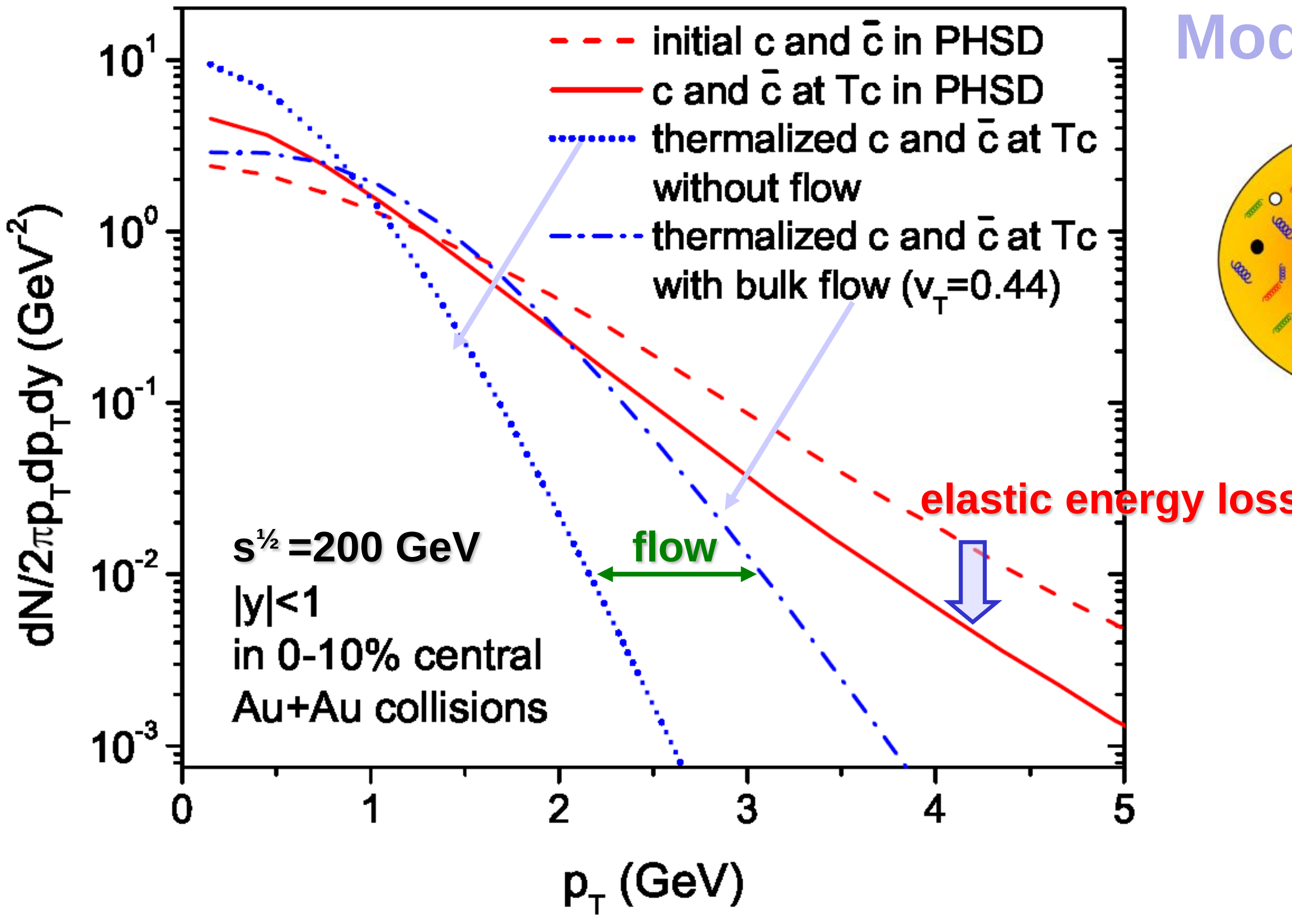


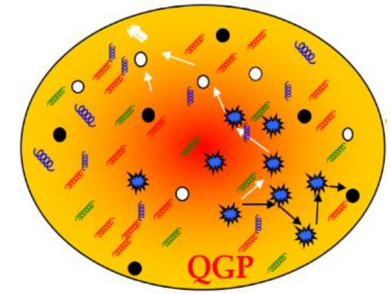




**A considerable energy and transverse momentum loss happens in the initial stage of heavy-ion collisions during the QGP phase, because the energy density is extremely large**

# Thermalization of charm quarks in A+A ?




**Model study**

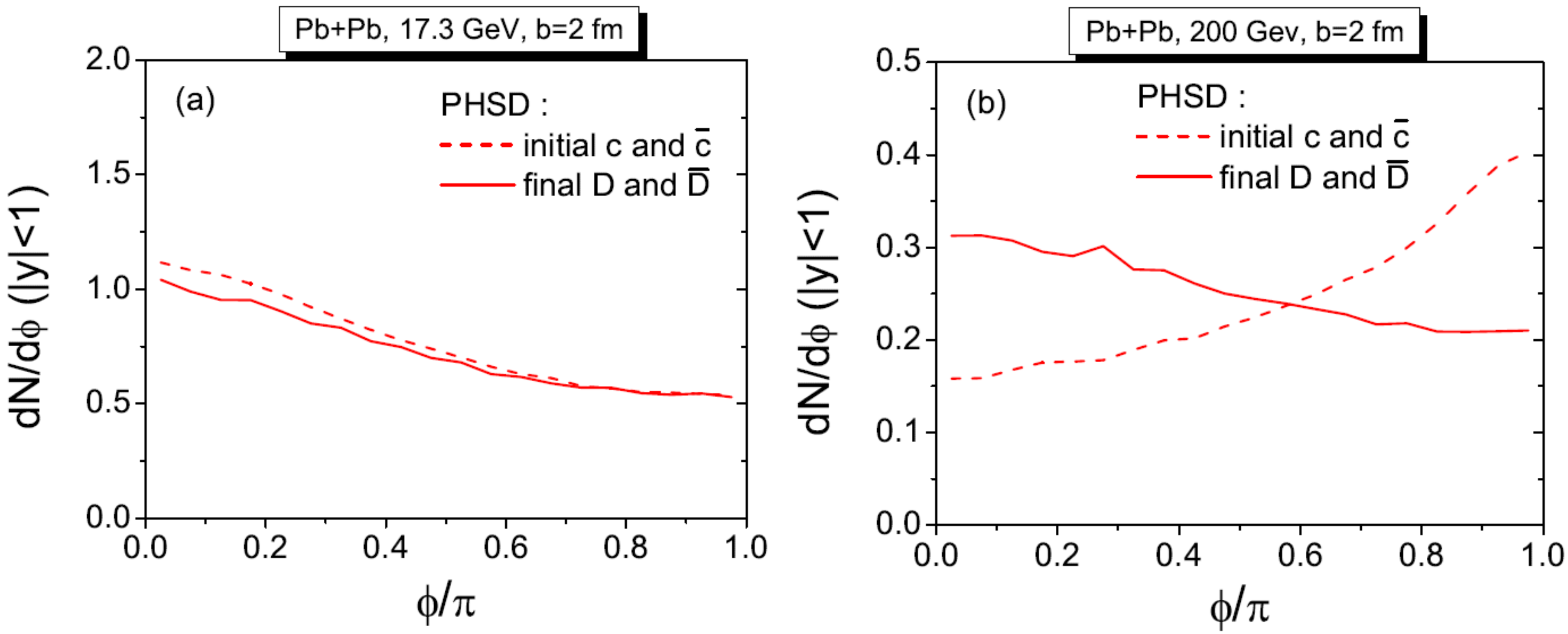



- **Scattering of charm quarks with massive partons softens the $p_T$ spectra**
  **➔ elastic energy loss**
- **Charm quarks are close to thermal equilibrium at low $p_T$ < 2 GeV/c**

**T. Song et al., PRC 92 (2015) 014910**

# Angular correlation between D-Dbar

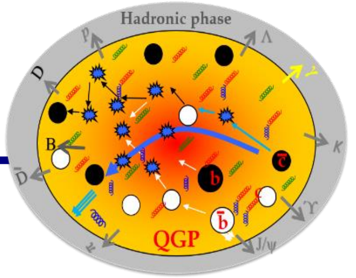
**Azimuthal angular distribution between the transverse momentum of D-Dbar at midrapidity (|y| < 1) before (dashed lines) and after the interactions with the medium (solid lines) in central Pb+Pb collisions at $s^{1/2}$ = 17.3 and 200 GeV**




- **Initial correlations - from PYTHIA : peaks around $\phi = 0$ for $\sqrt{s}$ = 17.3 GeV, while around $\phi = \pi$ for $\sqrt{s}$= 200 GeV**
- **Final correlations: smeared at $\sqrt{s}$= 200 GeV due to the interaction of charm quarks in QGP**

**T. Song, W.Cassing, P.Moreau and E.Bratkovskaya, PRC 97 (2018) 064907**

# Summary - I




- **PHSD provides a microscopic description of non-equilibrium charm dynamics in the partonic and hadronic phases**

- **Partonic rescattering suppresses the high $p_T$ part of $R_{AA}$, generates $v_2$**

- **Hadronic rescattering moves $R_{AA}$ peak to higher $p_T$, increases $v_2$**

- **The structure of $R_{AA}$ at low $p_T$ is sensitive to the hadronization scenario, i.e. to the balance between coalescence and fragmentation**

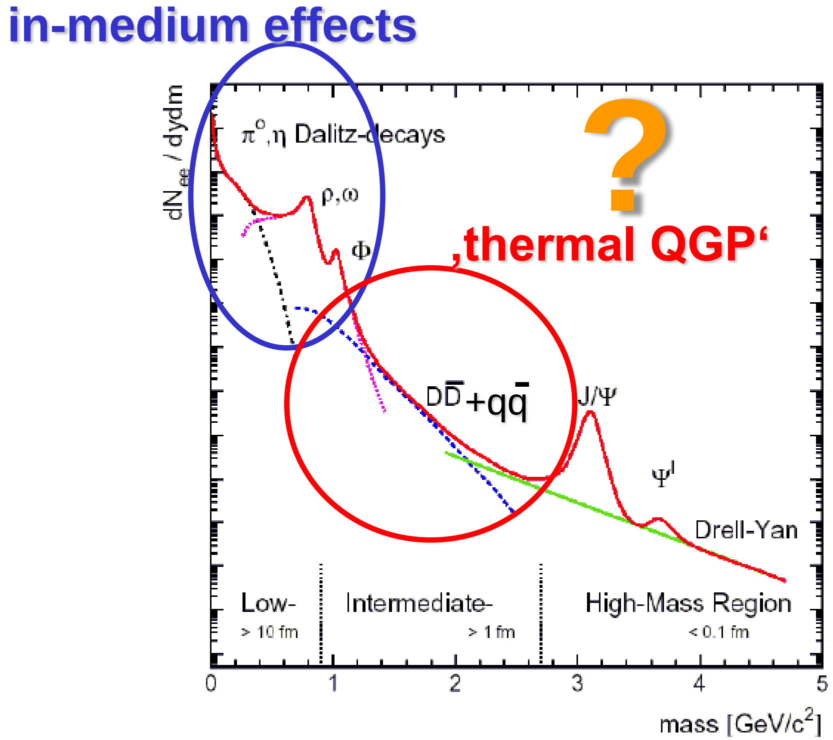
- **Shadowing effects suppress $R_{AA}$ at LHC at low transverse momenta, Cronin effect slightly increases $R_{AA}$ above $p_T$ >1 GeV**

- **The exp. data for the $R_{AA}$ and $v_2$ at RHIC and LHC are described in the PHSD by QGP collisional energy loss due to the elastic scattering of charm quarks with massive quarks and gluons in the QGP phase**
  **+ by the dynamical hadronization scenario „coalescence & fragmentation“**
  **+ by strong hadronic interactions due to resonant elastic scattering of D,D* with mesons and baryons**

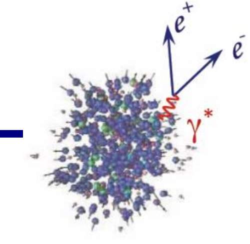
- **Feed back from beauty contribution for $R_{AA}^e$ and $v_2^e$ from single electrons for Au+Au at 200 GeV becomes dominant for $p_T$ >3 GeV**

- **Initial azimuthal angular correlation of QQbar pairs is washed out during the evolution dominantly due to the transverse flow**

# Thermal dileptons from QGP vs. dileptons from correlated charm



# Dilepton sources



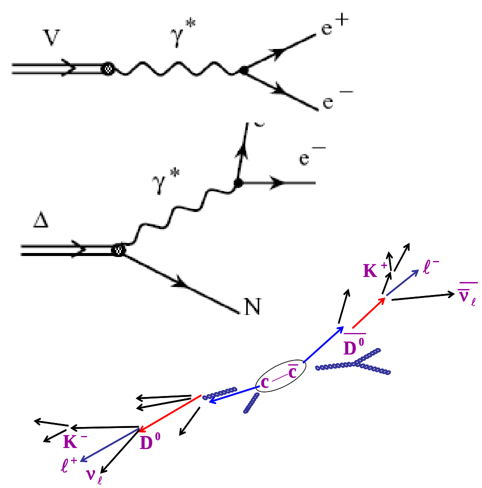

- **from the QGP via partonic (q,qbar, g) interactions:**

**PHSD: non-perturbative QGP → DQPM**

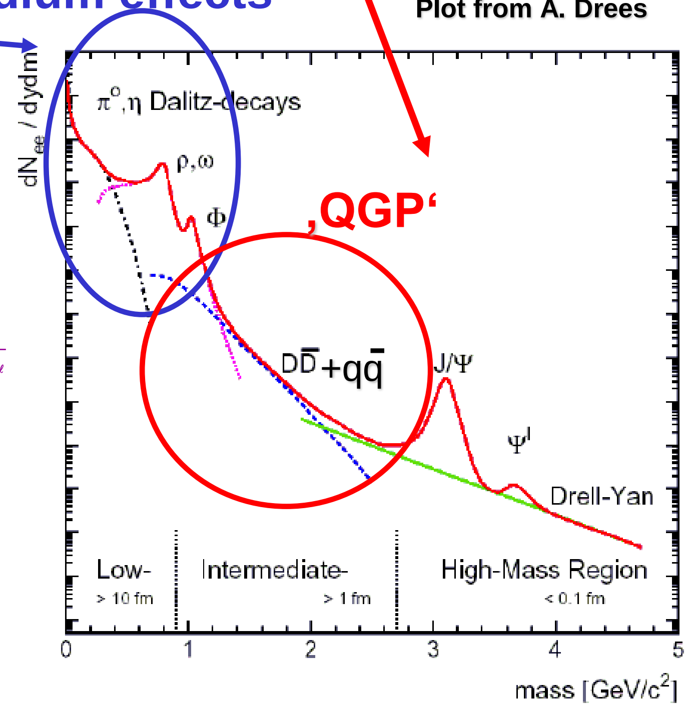

- **from hadronic sources:**

**in-medium effects**

- **direct decay of vector mesons ($\rho,\omega,\phi,J/\Psi,\Psi'$)**
- **Dalitz decay of mesons and baryons ($\pi^0,\eta,\Delta,\ldots$)**
- **correlated D+Dbar pairs**
- **radiation from multi-meson reactions ($\pi+\pi$, $\pi+\rho$, $\pi+\omega$, $\rho+\rho$ , $\pi+a_1$) - ‚4π‘**



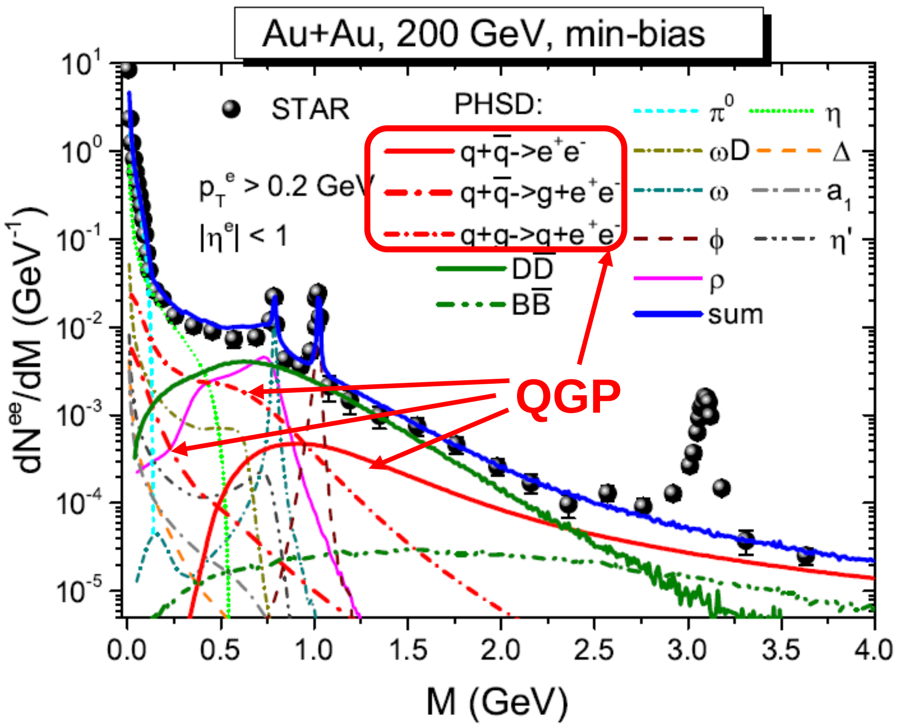

Plot from A. Drees



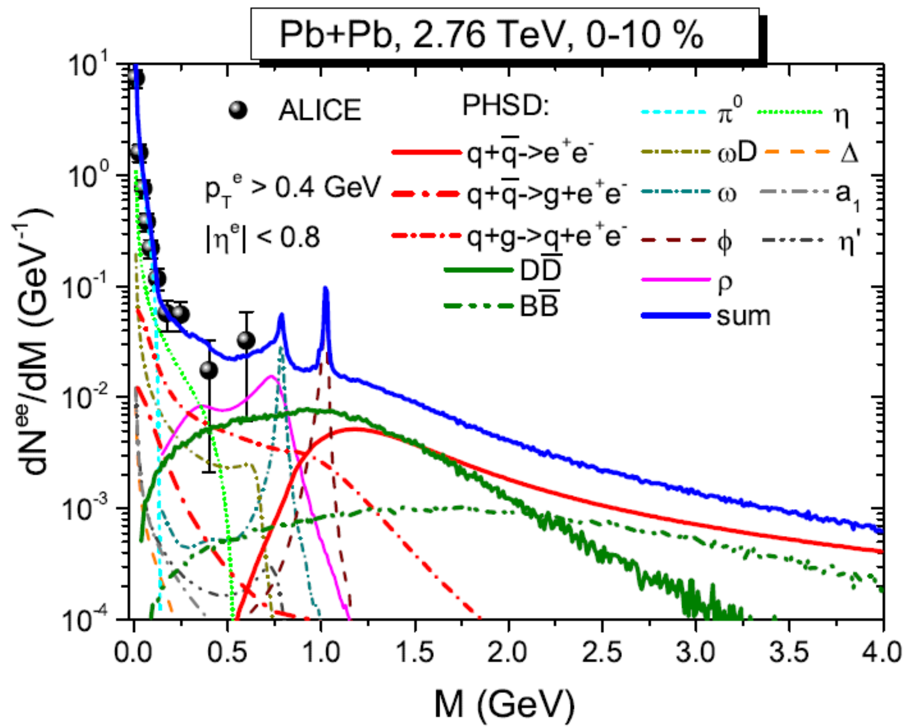

**What is the best energy range to observe dileptons from QGP?**

# Dileptons at RHIC and LHC

## RHIC




## LHC




**Message:**

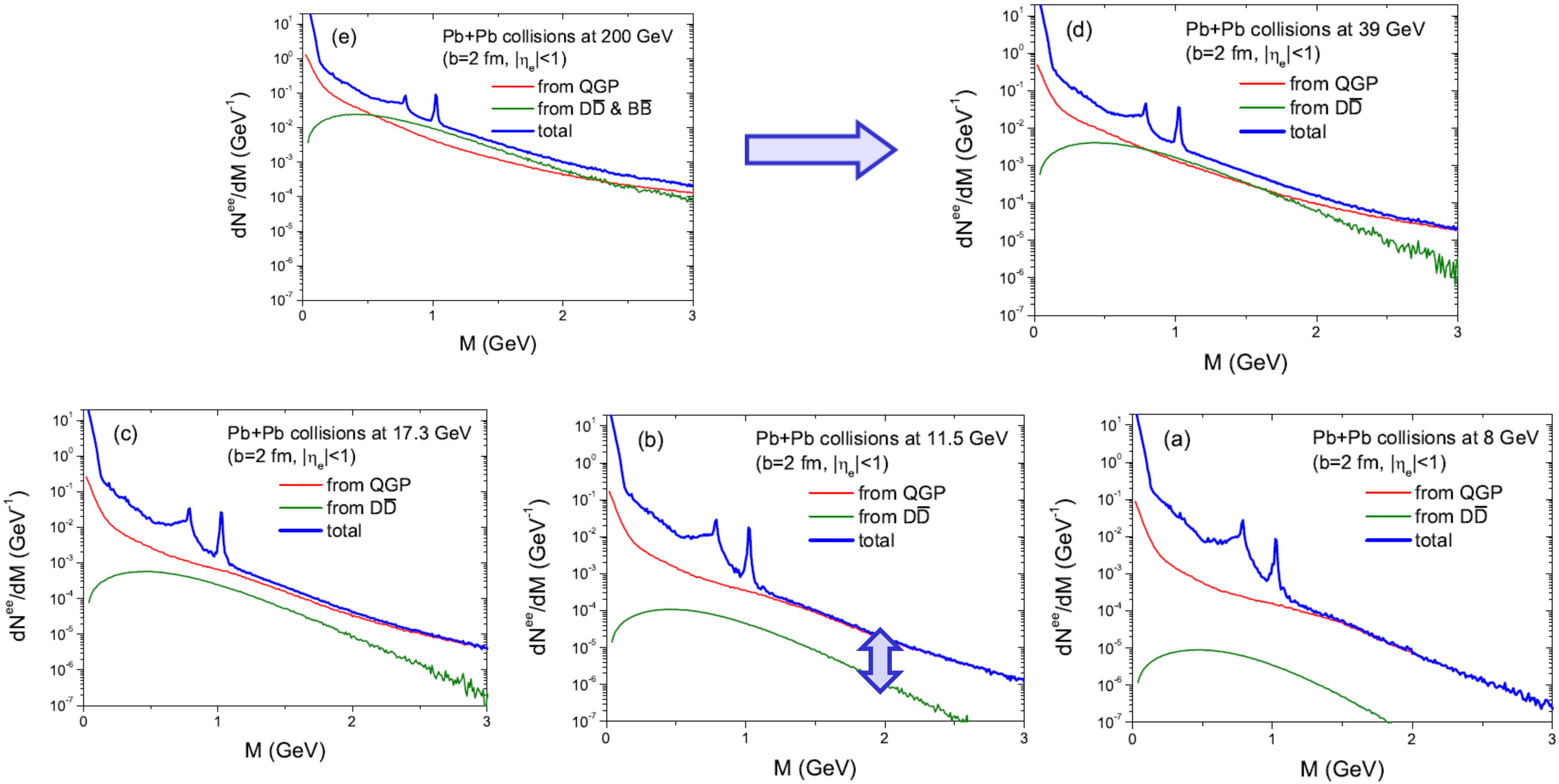
**STAR data at 200 GeV and the ALICE data at 2.76 TeV are described by PHSD within**

**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, PRC 97 (2018) 064907

# Dileptons at FAIR/NICA energies: predictions




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

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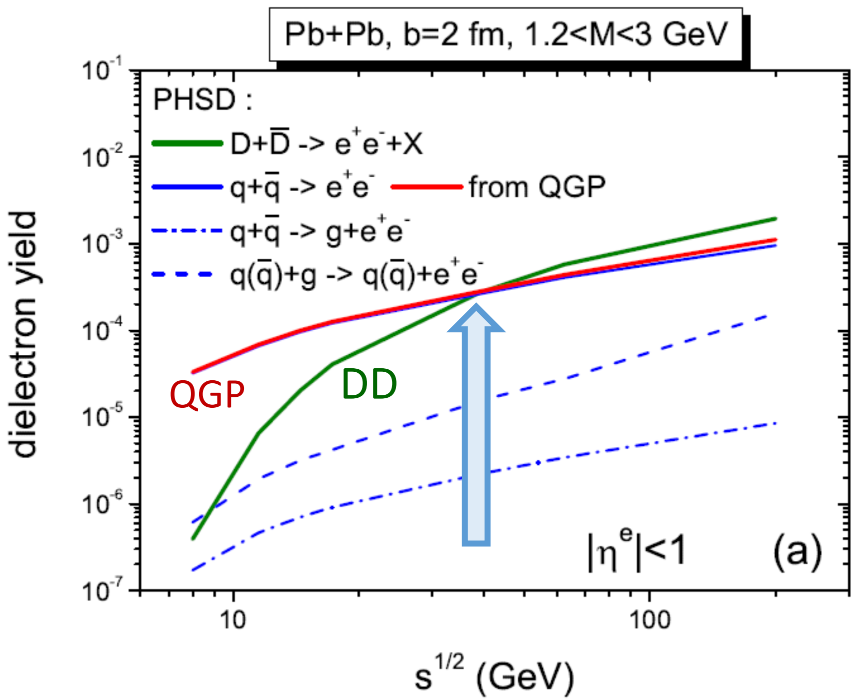
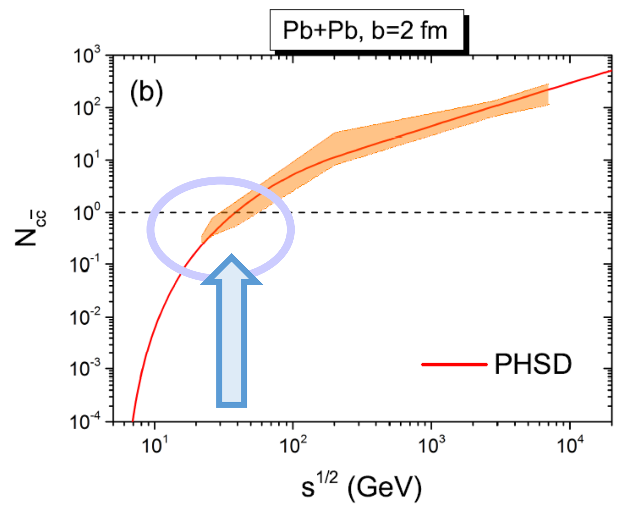
# Dileptons: QGP vs charm

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

**mid-rapidity**




**The number of primary cc pairs in Pb+Pb collisions at b=2 fm as a function of $s^{1/2}$**




*** The shaded area shows the uncertainty in the number of ccbar pairs in Pb+Pb due to the uncertainty in the charm production cross section in p+p collisions**

**QGP contribution overshines charm with decreasing energy: $\sqrt{s} \leq 30\ GeV$**

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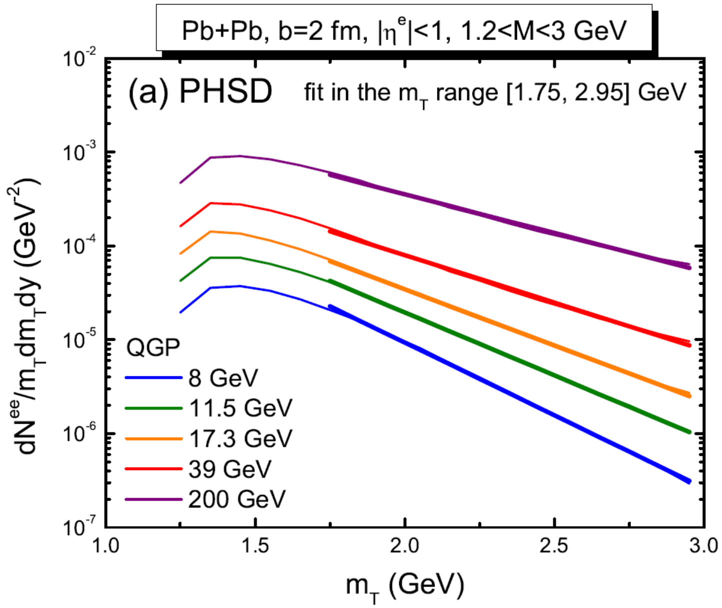
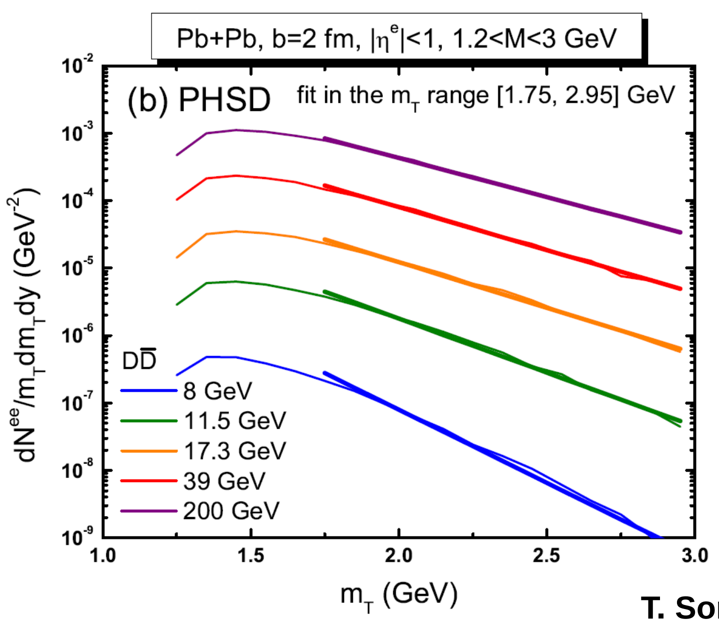
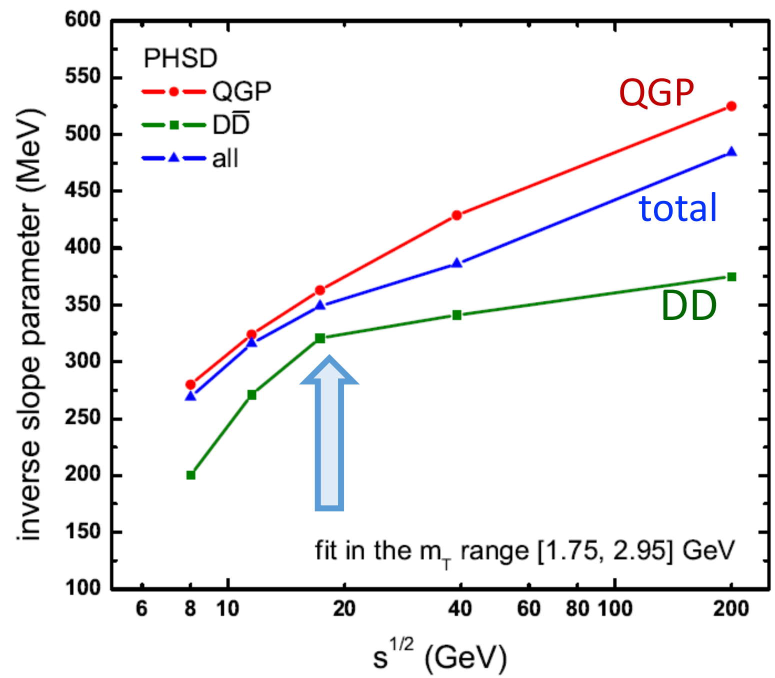
# Dilepton transverse mass spectra




**The inverse slope parameter in the mass range M=[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, PRC 97 (2018) 064907

# Summary - II

- Charm quarks are sensitive to the history of the QGP evolution and retain information on the entire time evolution from initial stage up to the late stage of the HIC

➔ heavy quarks are a very suitable probe to study the QGP properties

- Intermediate dilepton masses M>1.2 GeV :
  - Dominant sources : QGP (qbar-q) and correlated charm D/Dbar
  - Fraction of QGP grows with increasing energy; however, the relative contribution of QGP dileptons to dileptons from charm pairs increases with decreasing energy

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

# Thanks to: PHSD group - 2020

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**Duke University:**
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**Catania University:**
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*PHSD home page:*
*http://theory.gsi.de/~ebratkov/phsd-project/PHSD/index1.html*