Heavy quark mass and potential in QGP

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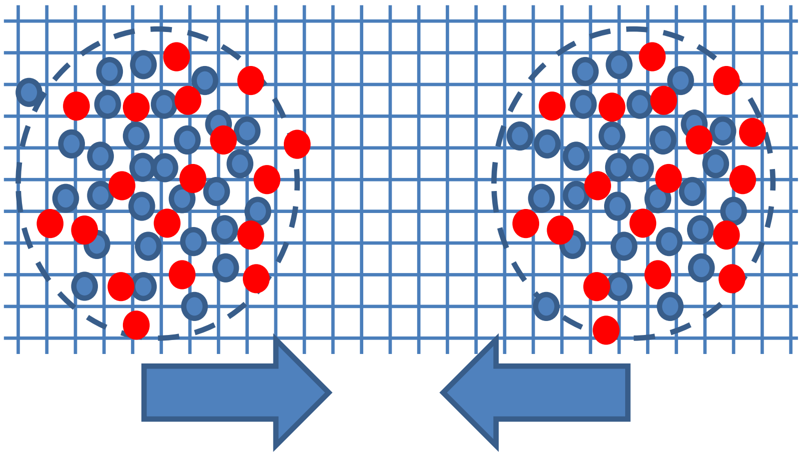
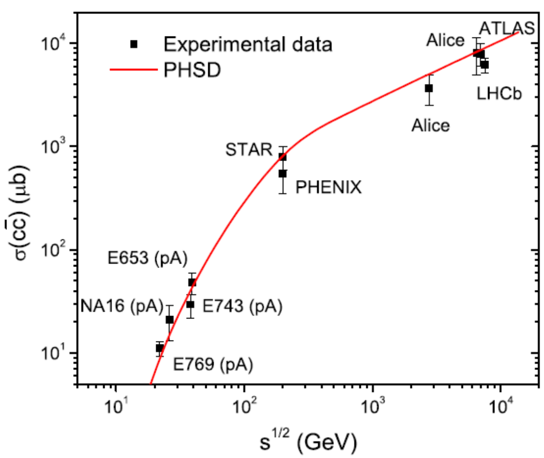
1. charm production in heavy-ion collisions

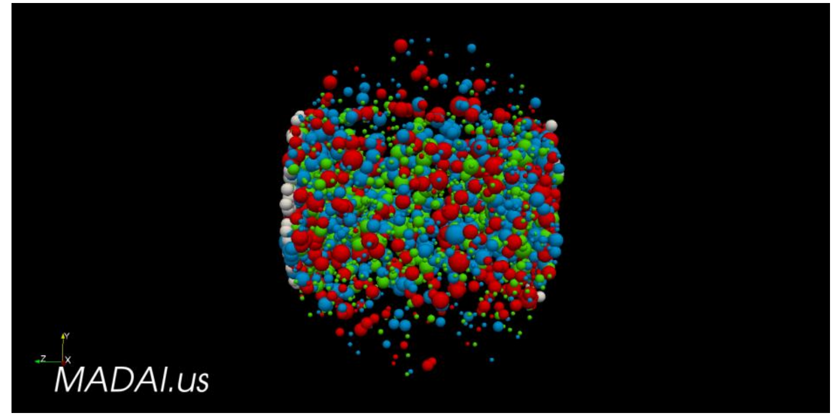
Heavy quark production through primary NN scattering



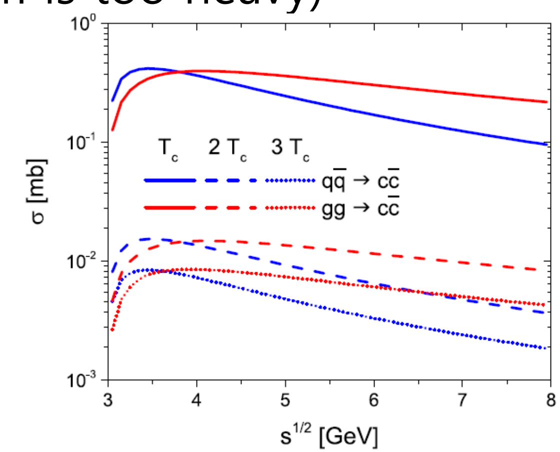
Produced heavy quark number is proportional to the number of nucleon-nucleon binary collisions



Heavy quark thermal production



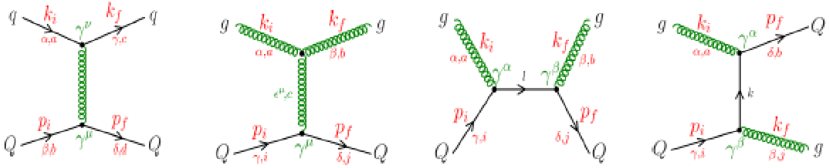
heavy quarks are produced in QGP through the scattering of thermal partons (it is not easy because charm is too heavy)

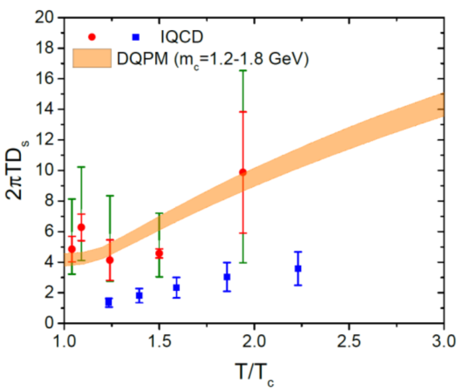


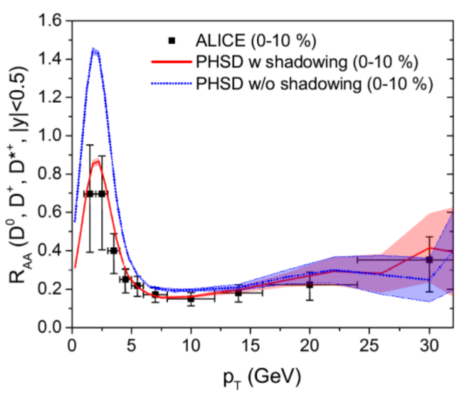
Heavy quark scattering in Dynamical Quasi-Particle Model

QGP is composed of massive off-shell quarks and gluons which reproduce lattice EoS

Heavy quark interacts with the massive off-shell quark/gluon





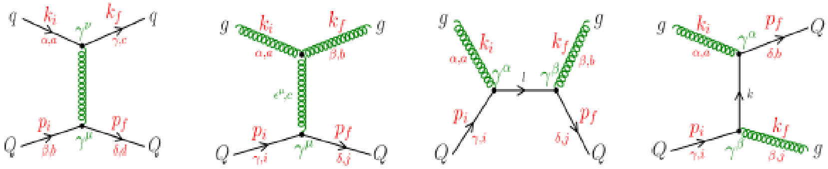


very successful results !

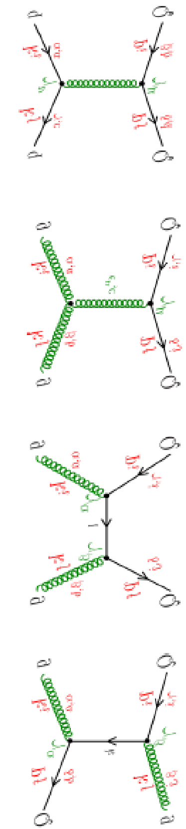
It reproduces the lattice data on Ds (spatial diffusion coefficients) and the experimental data on R_{AA} of D meson

H. Berrehrah et al., PRC **90**, 064906 (2014)
T. Song et al., PRC **93**, 034906 (2016)

Heavy quark scattering



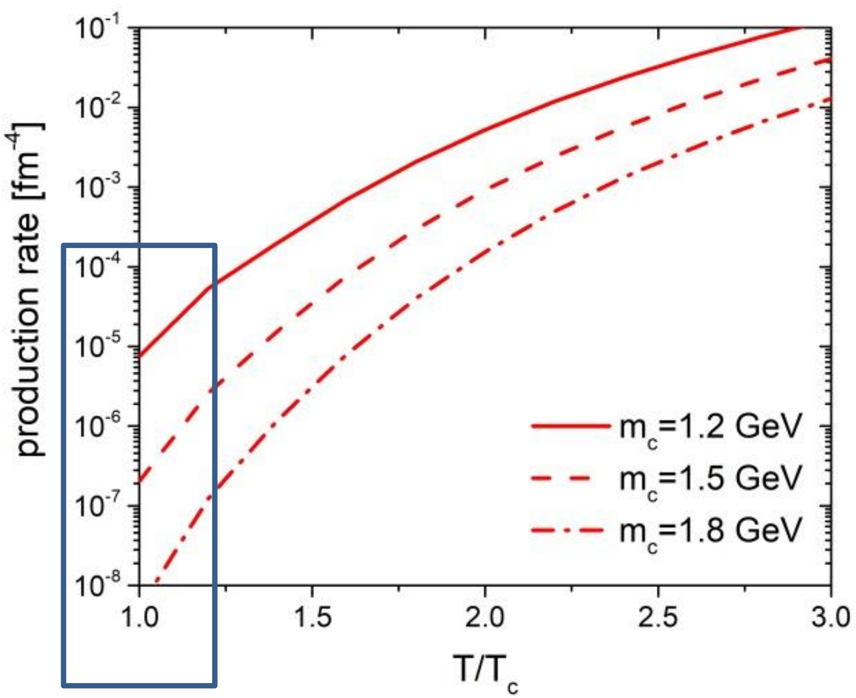
Heavy quark production



nothing but rotation of diagrams !!

Thermal production is very sensitive to charm quark mass

The number of produced charm per unit volume per unit time



Production rate is suppressed by 1000 times at Tc from 1.2 GeV to 1.8 GeV

T. Song et al., PRC **110**, 034906 (2024)

For the simulation of heavy ion collisions

Parton-Hadron-String Dynamics (PHSD) is a non-equilibrium microscopic transport approach for the description of dynamics of **strongly-interacting hadronic and partonic matter** produced in heavy-ion collisions

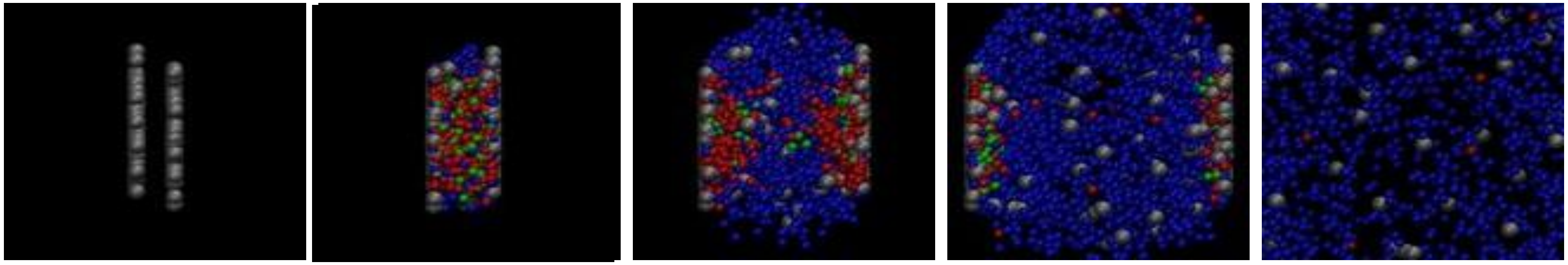
Dynamics: based on the solution of generalized off-shell transport equations derived from **Kadanoff-Baym many-body theory** (beyond semi-classical BUU)

Initial state: Au+Au

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

Dynamical
Hadronization

Hadronic interactions
→final hadrons + leptons



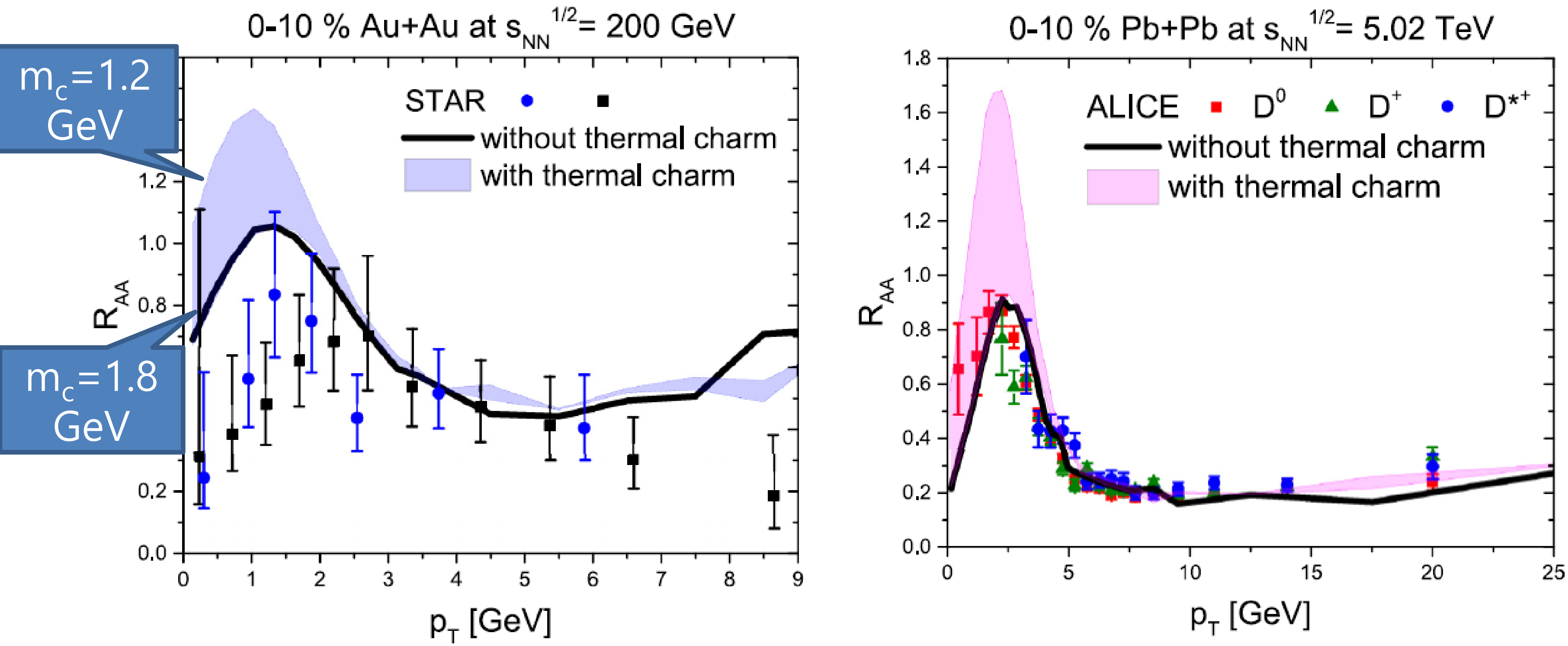
time

PHSD provides a good description of ‘bulk’ hadronic and electromagnetic observables from SIS to LHC energies

PHSD: W. Cassing, E. Bratkovskaya, PRC 78 (2008) 034919; NPA831 (2009) 215; P. Moreau et al., PRC100 (2019) 014911

Nuclear modification factor (R_{AA})

$$R_{AA}(p_T) \equiv \frac{dN_{AA}/dp_T}{N_{\rm binary}^{AA} \times dN_{pp}/dp_T}$$



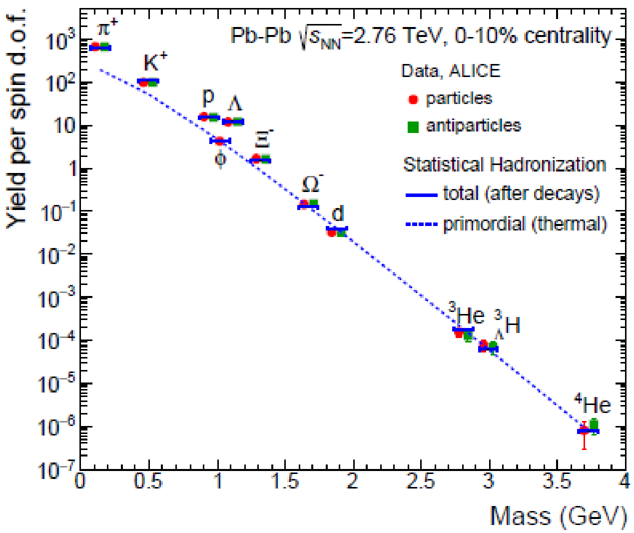
Experimental data on R_{AA} favor a large charm quark mass (1.8 GeV) rather than the bare mass (~1.2 GeV) in QCD Lagrangian

T. Song et al., PRC **110**, 034906 (2024)

3. Heavy quark mass near T_c

(supplementary & supporting study)

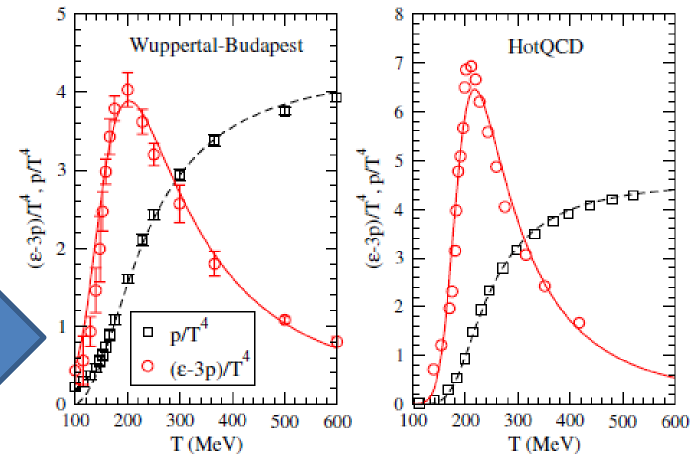
Hadron resonance gas model below Tc



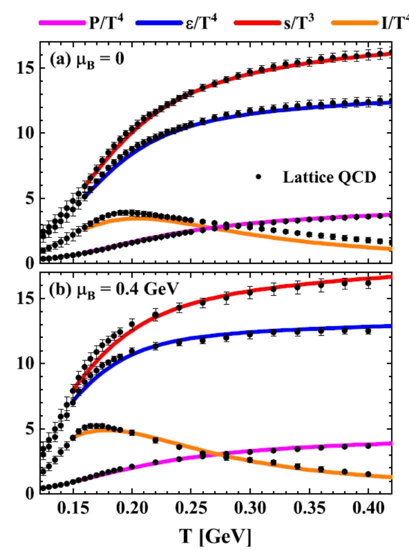
The hadron gas phase is composed of all resonances existing in nature

Both must meet each other at Tc

Quasi-particle model above Tc



S. Plumari et al., PRD84, 094004 (2011)



P. Moreau et al., PRC100, 041911 (2019)

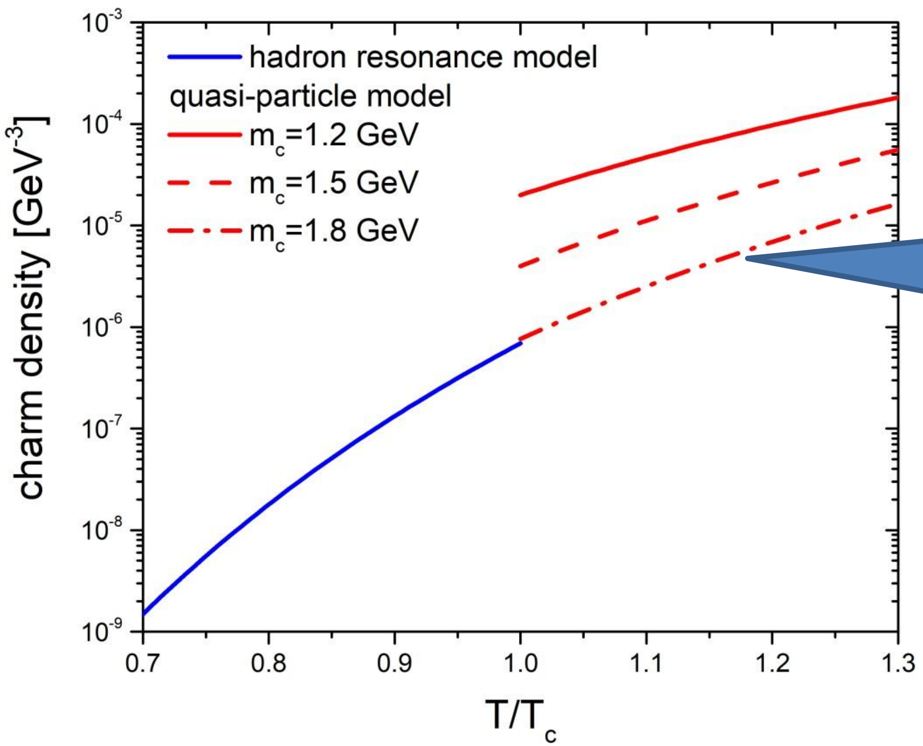
QGP is composed of massive quarks and gluons

Hadron resonance gas model below Tc

Charm density is calculated with all charm hadron masses from the particle data group (PDG)
→ no free parameter

Quasi-particle model above Tc

Charm density is calculated with charm quark mass in medium (QGP) which is the only parameter

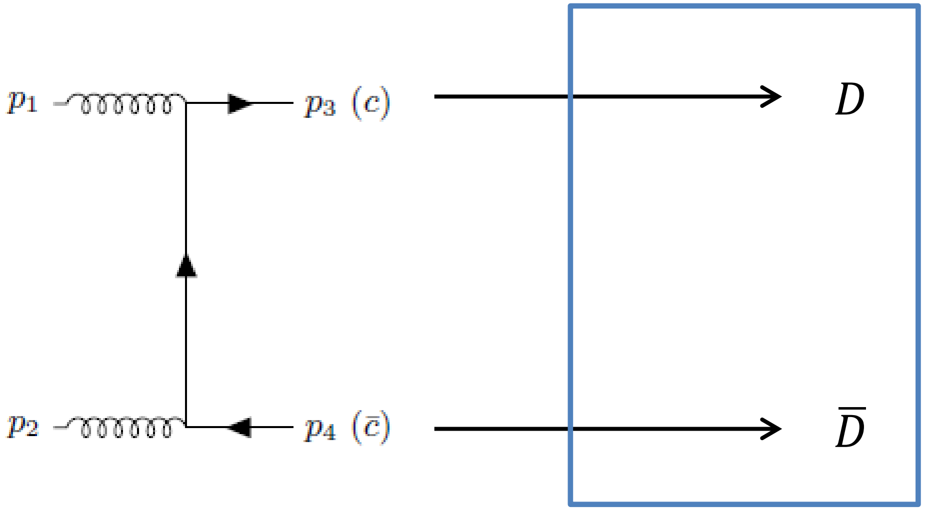


The massive charm quark (1.8 GeV) is favored

T. Song et al., Phys. Scr. 99 (2024) 125304

4. Heavy quark potential in QGP

in vacuum

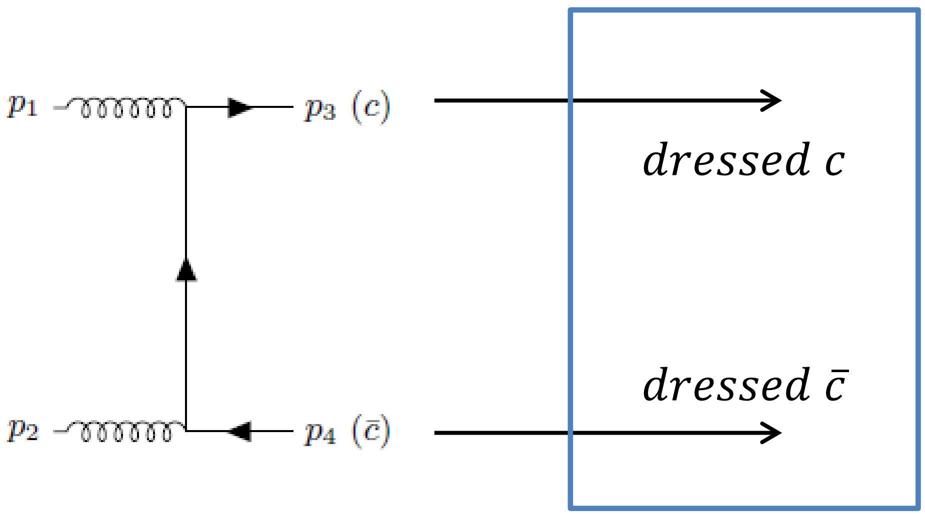


$$m_D = m_0 + \frac{1}{2}V\left(r = \infty\right)$$

m_0: bare mass (1.26 GeV for charm)

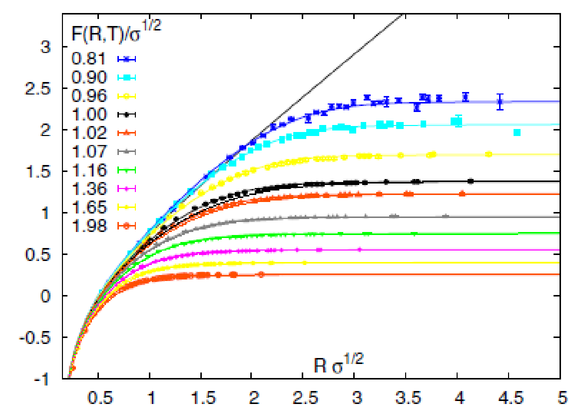
(anti)charm must be hadronized

in QGP



$$m_c(\mathrm{T}) = m_0 + \frac{1}{2}V\left(r = \infty, T\right)$$

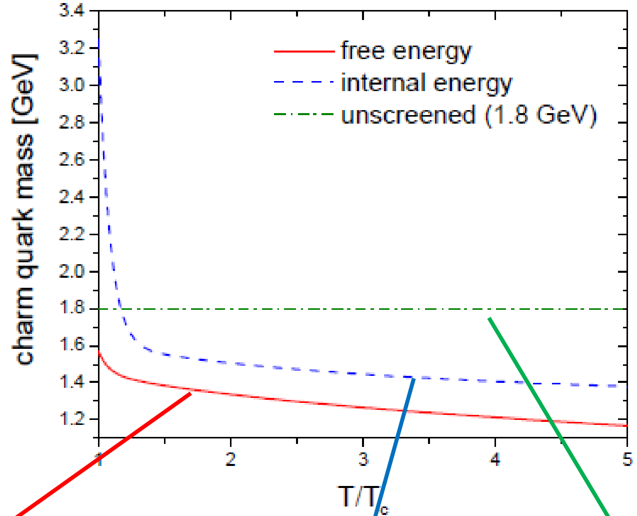
m_0: bare mass (1.26 GeV for charm)



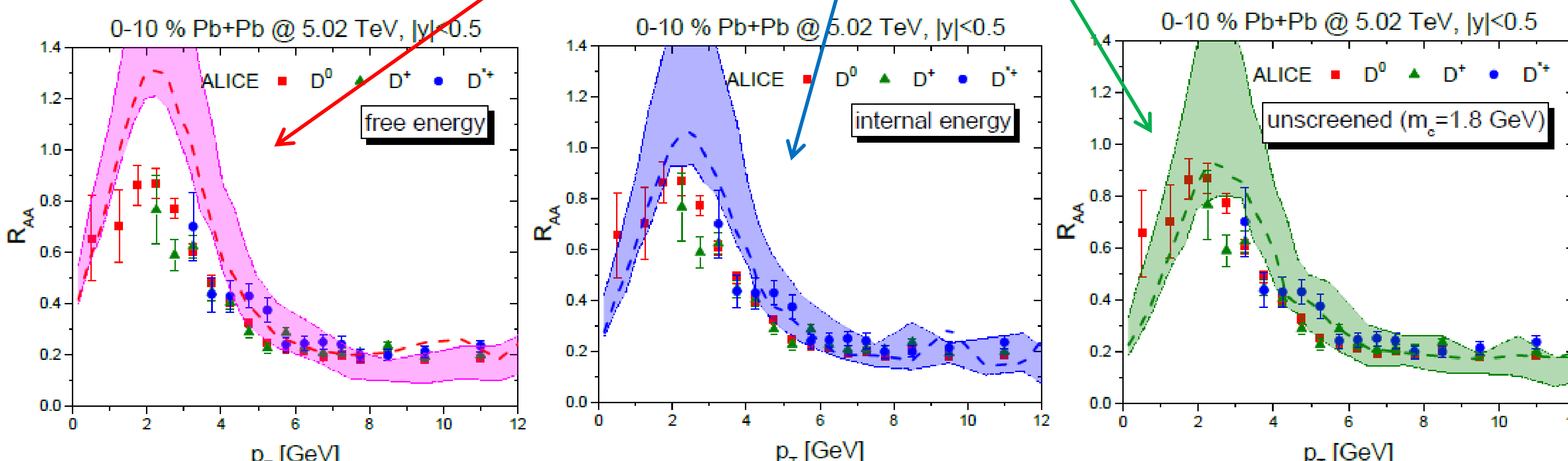
1. (anti)charm need not be hadronized

2. But (anti)charm is different from free quark, and dressed in QGP

Test of three potentials



Color bands indicate un certainties from the sha dowing effects (EPS09)



Free energy potential overestimates

T. Song et al., 2411.07383

4. Summary

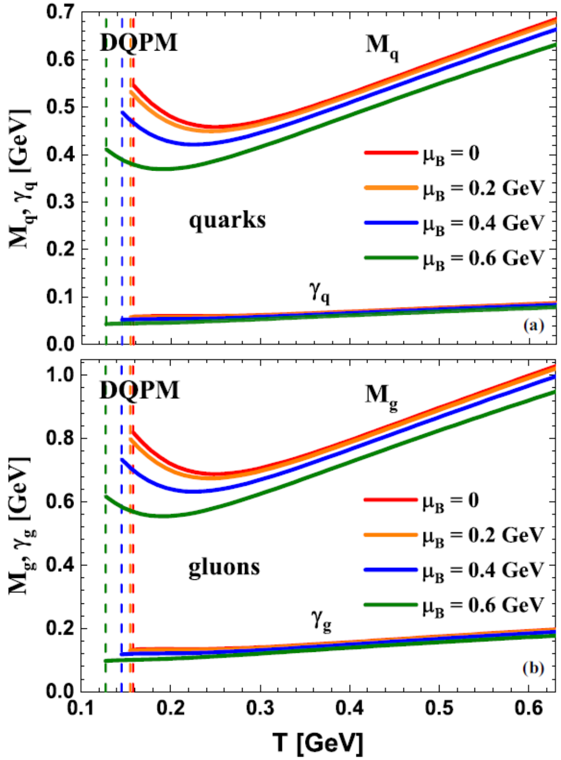
- Charm quark in QGP is not a free quark but strongly interacting with partonic matter, through which it gains a not small effective mass

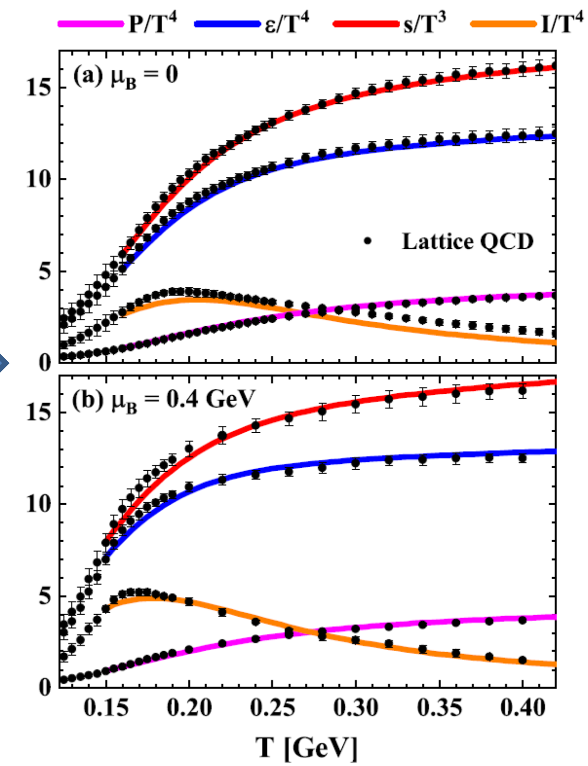
- From the comparison of the hadron resonance gas model and quasi-particle model charm quark mass is around 1.8 GeV near Tc which is close to D meson mass.

- Long range heavy quark potential is related to the dressed charm quark mass in QGP. LHC date on R_{AA} of D meson disfavors the free energy heavy quark potential at large distance.

Thank you for your attention!

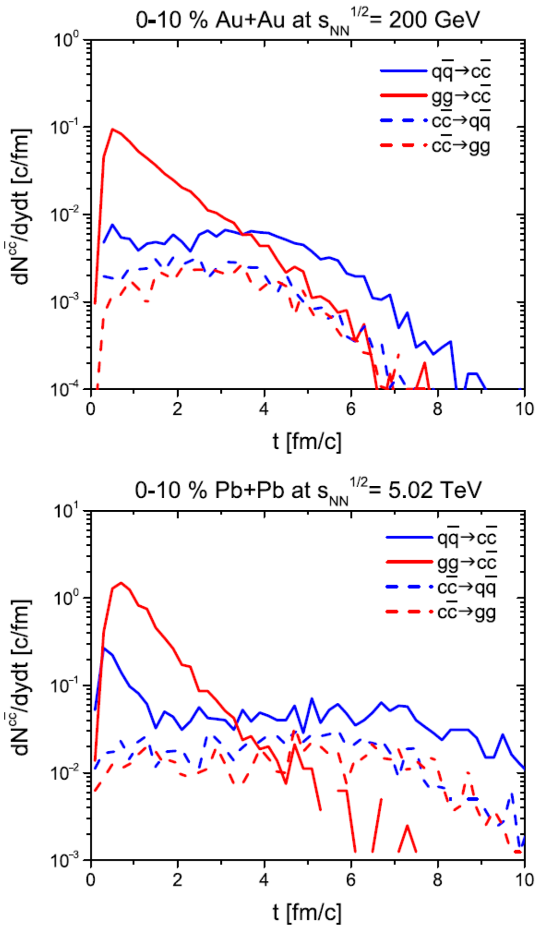
Dynamical Quasi-Particle Model (DQPM)





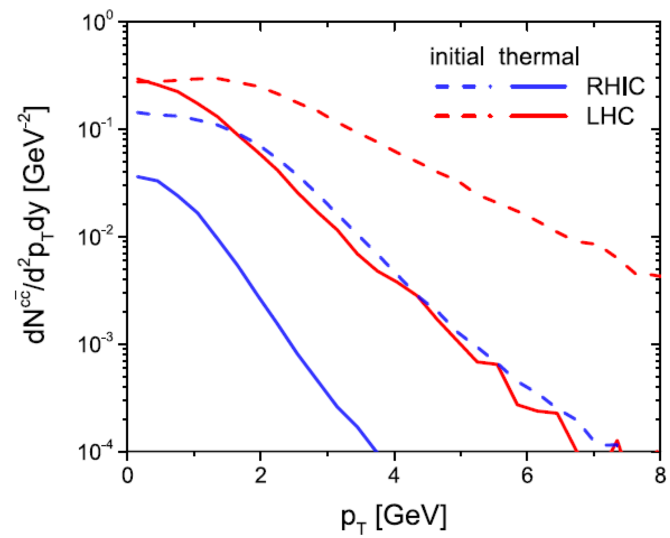
(anti)quark and gluon mass and width depend on temperature and μ_B.
They can describe the EoS of QGP from the lattice QCD calculations

P. Moreau et al., PRC100, 014911 (2019)



Charm production & annihilation with time for m_c=1.5 GeV

Charm p_T spectra for m_c=1.5 GeV



1. Both heavy quark production & annihilation are considered using the detailed balance
2. Thermal production dominates in the early stage at high T

3. p_T spectrum of thermal charm is softer than that of initial charm

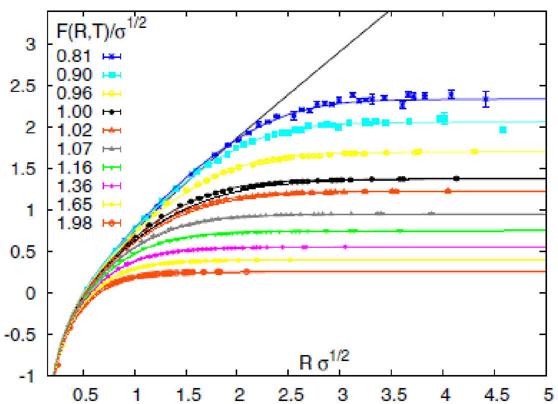
T. Song et al., PRC **110**, 034906 (2024)

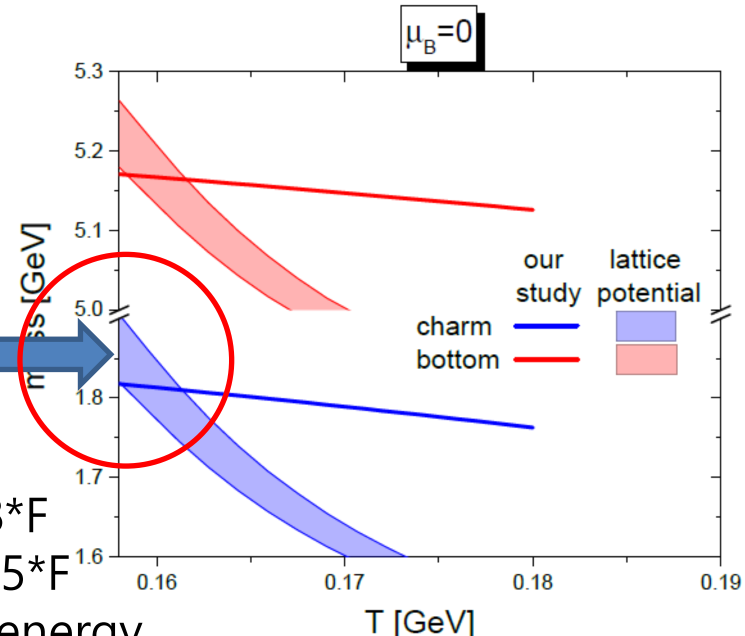
also supported by heavy quark potential from lattice

$$m(T) = m_0 + \frac{1}{2}V\left(r = \infty, T\right)$$

m_0: bare mass (1.26 GeV for charm, 4.62 GeV for bottom)

S. Digal et al., EPJC 43 (2005) 71





upper limit: 0.2*U+0.8*F

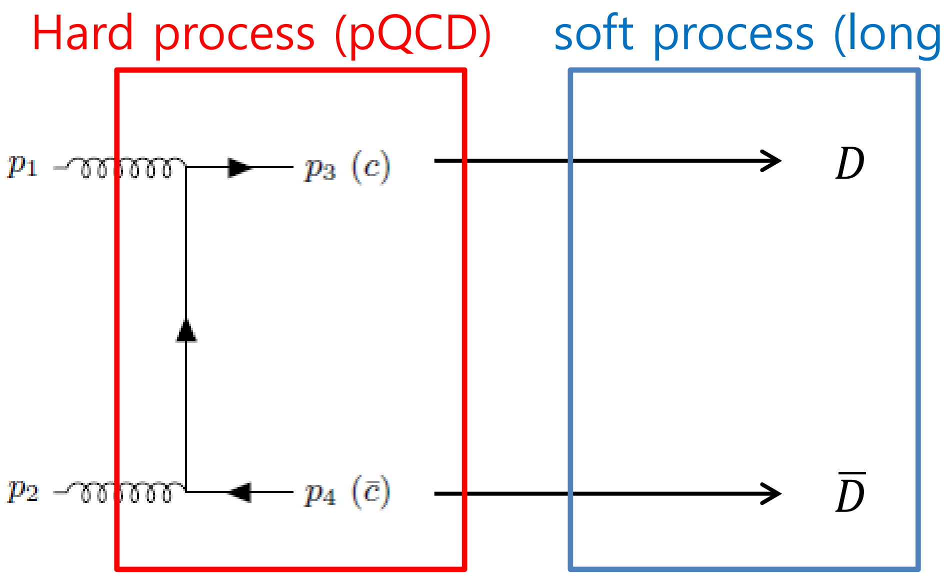
lower limit: 0.15*U+0.85*F

U: internal energy, F: free energy

P. Gubler et al. PRD101,114029 (2020)

One can see the good agreement near Tc

in vacuum



$$m_D = m_0 + \frac{1}{2} V\left(r = \infty\right)$$

m_0: bare mass (1.26 GeV for charm)

1. (anti)charm must be hadronized

2. If $\sqrt{s} < 2m_D$, (anti)charm must be annihilated or form a quarkonium