Heavy flavor dynamics in the parton-hadron-String dynamics (PHSD) transport approach

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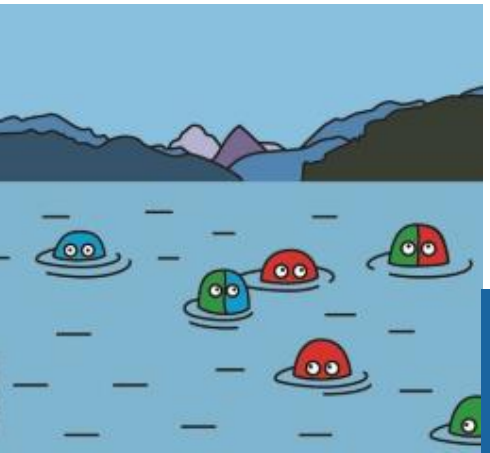
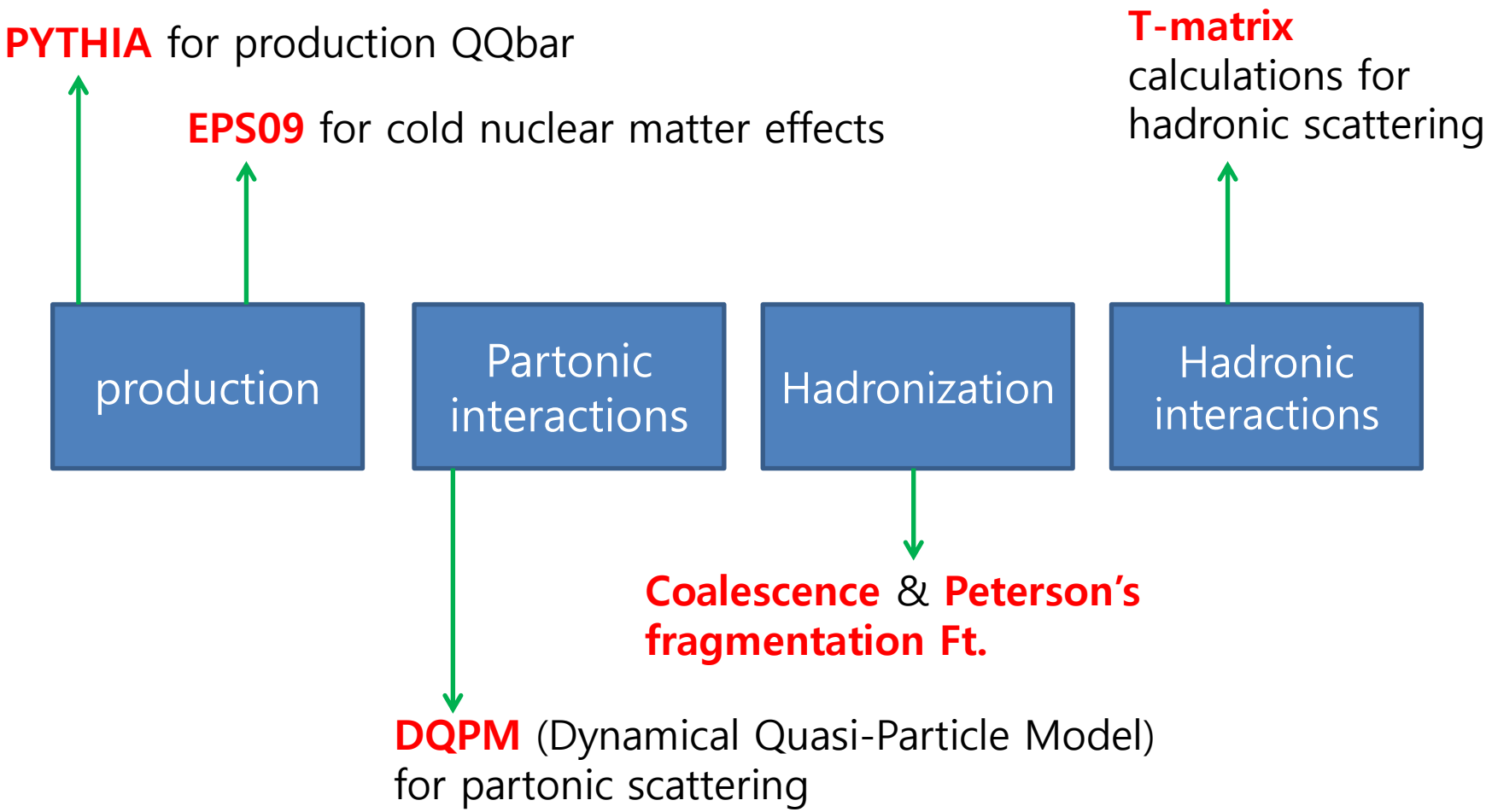


HF2022: Heavy Flavours from small to large systems

Schematic diagram of PHSD for heavy flavor



1. Partonic interactions of HF

- What we know about QGP is EoS as a function of T, μ_B from lQCD: (energy density, pressure, entropy density,…)
- Dynamical Quasi-Particle Model (DQPM) describes QGP by thermal partons which have T, μ_B-dependent pole mass and spectral width
- The form of pole mass and that of spectral width are inspired by the HTL calculations

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

$$\gamma_{q(\bar{q})}(T,\mu_B) = \frac{1}{3}\frac{N_c^2-1}{2N_c}\frac{g^2(T,\mu_B)T}{8\pi}\ln\left[\frac{2c}{g^2(T,\mu_B)}+1\right]$$

- But the strong coupling is fitted to lattice EoS

Dynamical Quasi-Particle Model (DQPM)

T-dependent running coupling

$$g^2(s/s_{SB}) = d((s/s_{SB})^e - 1)^f$$

s: entropy density
$s_{SB} = 19/9\pi^2 T^3$: Stefan-Boltzmann entropy density
d=169.934, e=-0.178434, f=1.14631

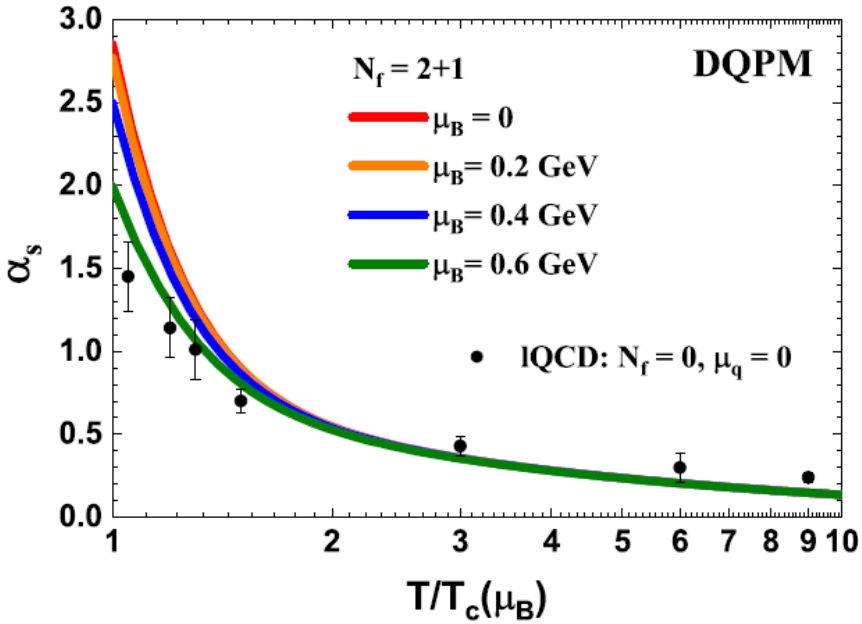
(T,μ)-dependent running coupling

$$g^2(T/T_c, \mu_B) = g^2(T^*/T_c(\mu_B), \mu_B = 0)$$

$$T^* = \sqrt{T^2 + \mu_q^2/\pi^2}\ ,\ T_c(\mu_B) = T_c\sqrt{1 - \alpha\mu_B^2}$$

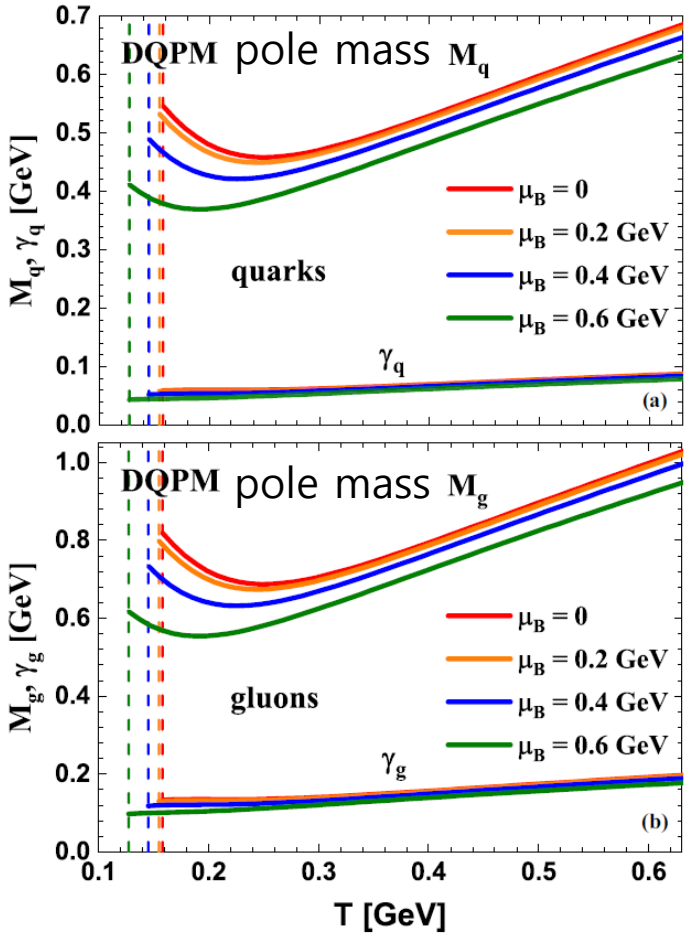
α=0.974 GeV^{-2} which is consistent with lattice data

Pierre Moreau, et al. PRC 100 (2018) 014911



Dynamical Quasi-Particle Model (DQPM)

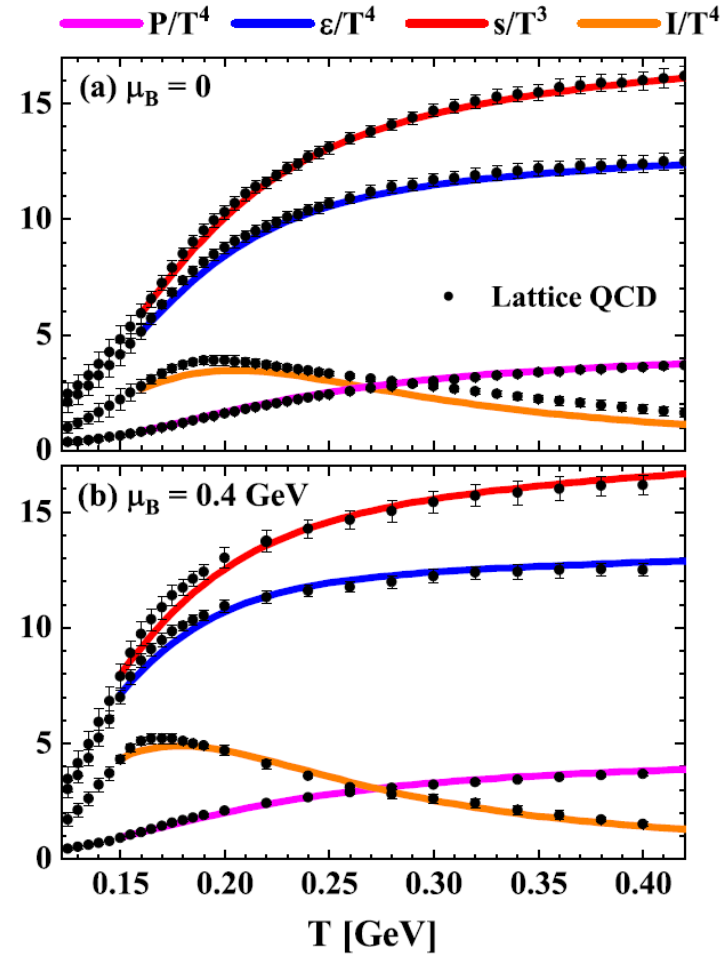
Lattice EOS is well reproduced both at $\mu_B = 0$ and $\mu_B \neq 0$



B. Vanderheyden, G. Baym, J. Stat. Phys. 93 (1998) 843

Blaizot, Iancu, Rebhan, Phys. Rev. D 63 (2001) 065 003

By using the extended g^2



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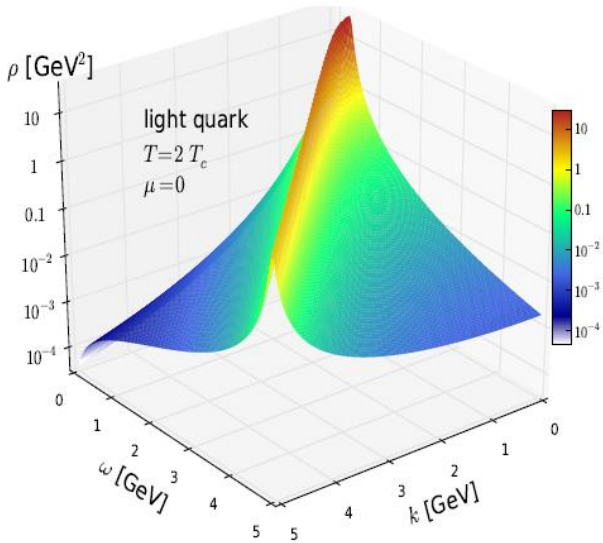
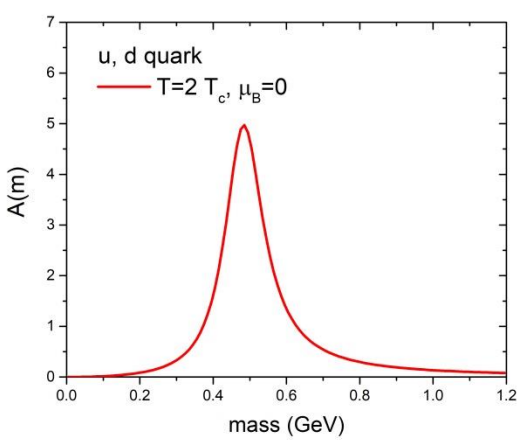
Parton spectral function



Lorentzian form

$$\rho_j(\omega, \mathbf{p}) = \frac{\gamma_j}{\tilde{E}_j}\left(\frac{1}{(\omega - \tilde{E}_j)^2 + \gamma_j^2} - \frac{1}{(\omega + \tilde{E}_j)^2 + \gamma_j^2}\right)$$

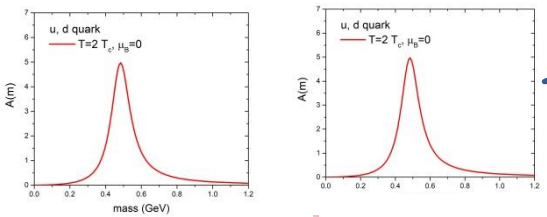
$$\equiv \frac{4\omega\gamma_j}{\left(\omega^2 - \mathbf{p}^2 - M_j^2\right)^2 + 4\gamma_j^2\omega^2}$$



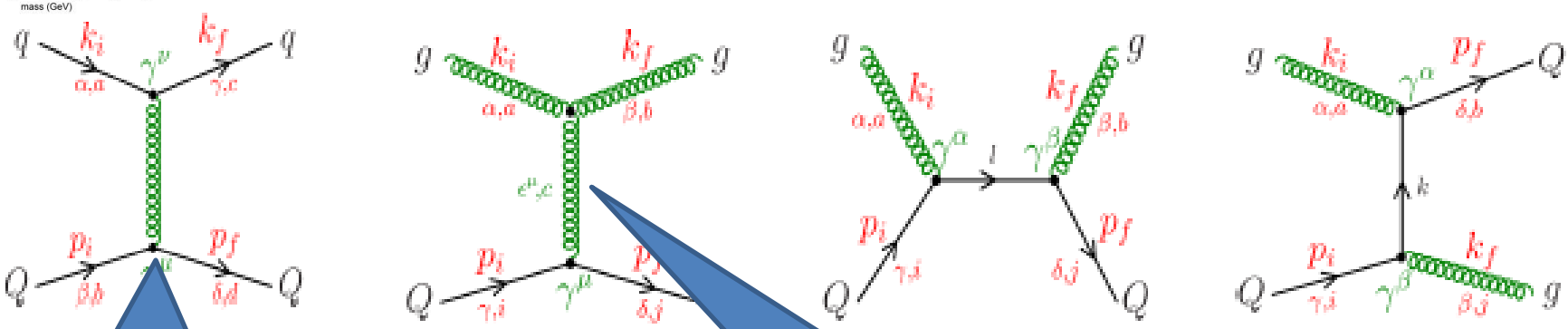
$$\rho_i^{\mathrm{BW}}(m) = \frac{2}{\pi}\frac{2m^2\gamma_i}{\left(m^2 - M_i^2\right)^2 + (2m\gamma_i)^2}.$$

For charm scattering, spectral function is simply approximated into Breit-Wigner form

HF interacts with the dynamical quasi-particles



HQ interacts with off-shell massive quark/gluon



Temperature-dependent strong coupling

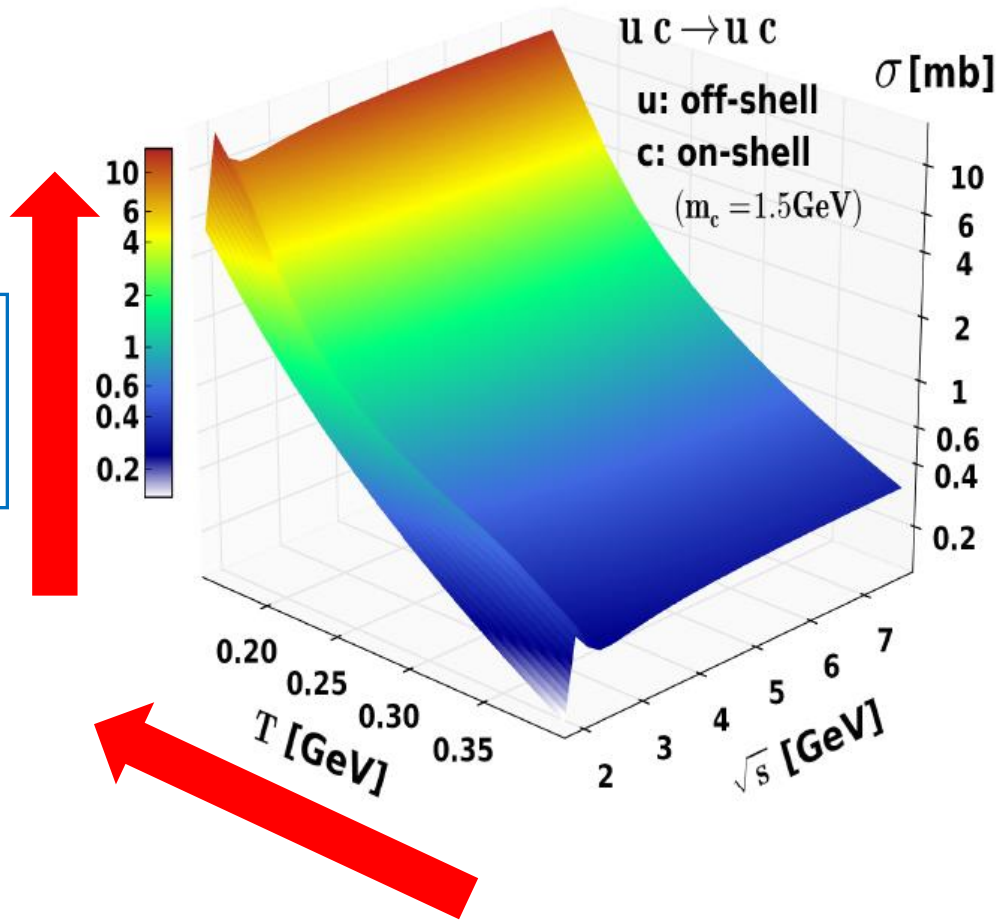
Off-shell massive gluon is exchanged: divergence-free without introducing a screening mass

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

$$= -i\delta_{ab}\frac{g^{\mu\nu} - q^{\mu}q^{\nu}/M_g^2}{q^2 - M_g^2 + 2i\gamma_g q_0}$$

❑ Elastic cross section uc→uc

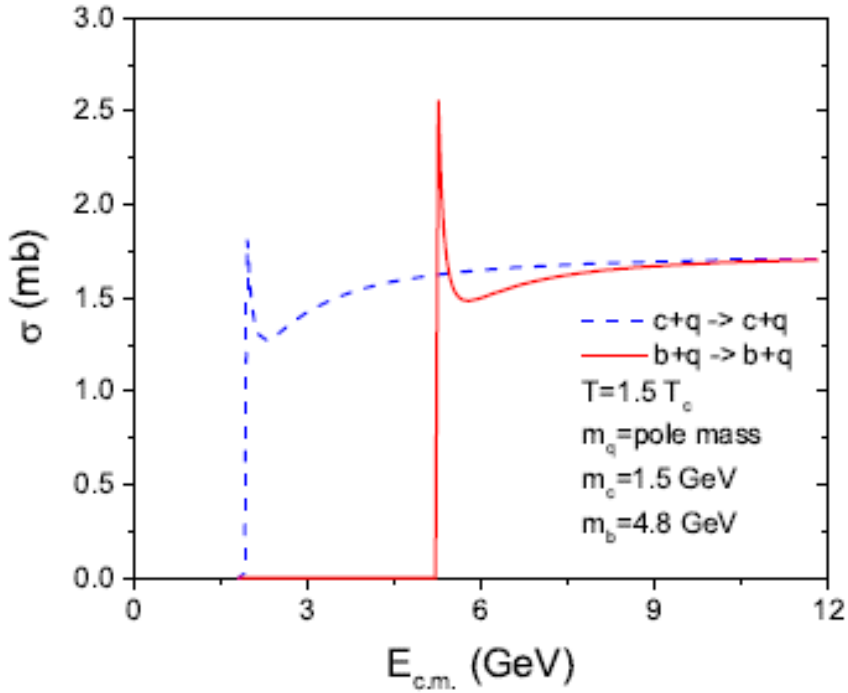
❑ cross section rapidly increases near T_c due to g(T)



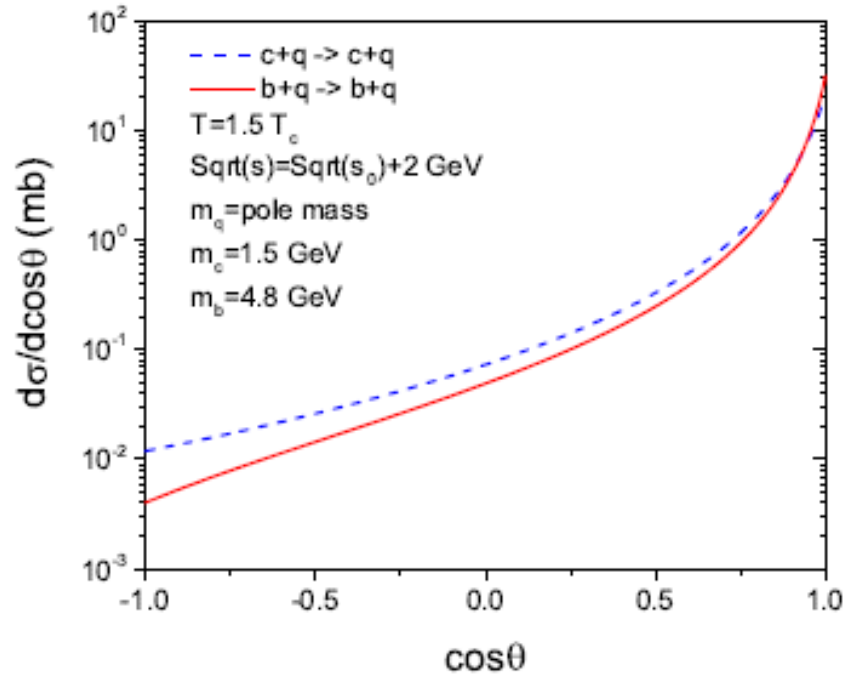
H. Berrehrah et al, PRC 89 (2014) 054901; PRC 90 (2014) 051901; PRC90 (2014) 064906

Charm & bottom quark cross section

Total cross sections



differential cross sections



Total cross sections are similar, but bottom cross section is more highly forward peaked, because it is heavier.

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

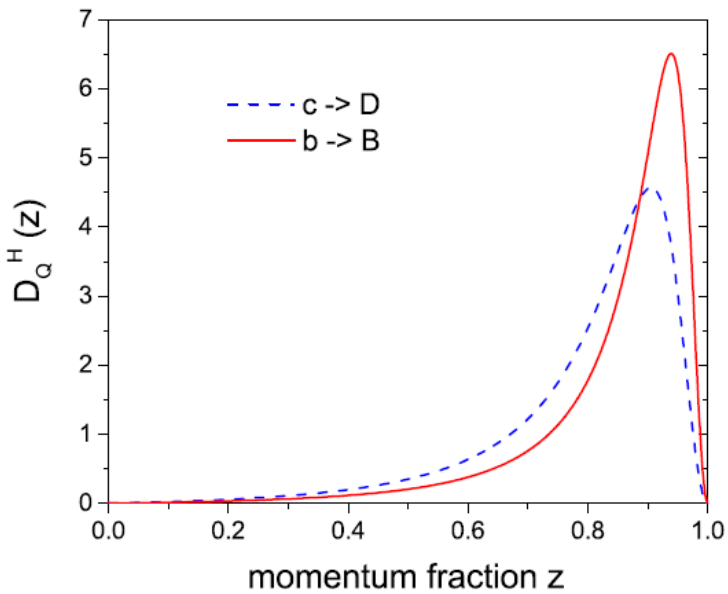
2. Hadronization of HF

- Peterson's fragmentation function

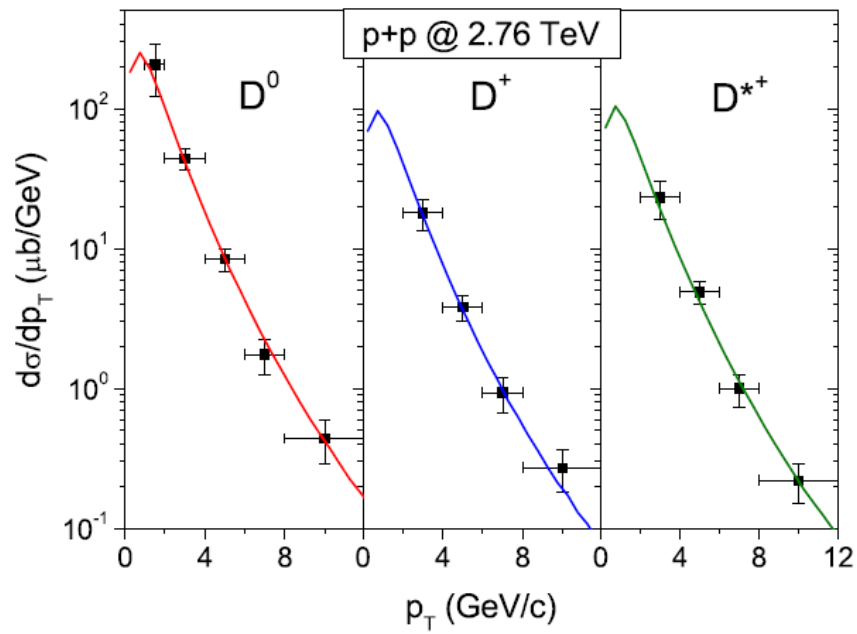
for transverse momentum

$$D_Q^H(z) \sim \frac{1}{z[1 - 1/z - \epsilon_Q/(1-z)]^2},$$

$\epsilon_Q = 0.01$ for charm and 0.004 for bottom



Chemical fractions:
D^+, D^0, D^{*+}, D^{*0}, D_s, Λ_c
15, 15, 24, 24, 10, 9 %



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

- Wigner function for S state coalescence probability

$$\Phi(\mathbf{r},\mathbf{p}) = 8\exp\left[-\frac{r^2}{\sigma^2} - \sigma^2 p^2\right],$$

$$\mathbf{r} = \mathbf{r_1} - \mathbf{r_2},$$

$$\mathbf{p} = (m_2\mathbf{p_1} - m_1\mathbf{p_2})/(m_1 + m_2).$$

in center-of-mass frame

0.9 fm

$$\langle r_M^2 \rangle = \frac{1}{2}\langle(\mathbf{R} - \mathbf{r_1})^2 + (\mathbf{R} - \mathbf{r_2})^2\rangle$$

$$= \frac{1}{2}\frac{m_1^2 + m_2^2}{(m_1 + m_2)^2}\langle r^2\rangle = \frac{3}{4}\frac{m_1^2 + m_2^2}{(m_1 + m_2)^2}\sigma^2,$$

multiplied by 4 (=1+3) to include D* and divided by 36(=6*6)

- Wigner function for P state coalescence probability

$$\left(\frac{16}{3}\frac{y_i^2}{\sigma_i^2} - 8 + \frac{16}{3}\sigma_i^2 k_i^2\right)\exp\left(-\frac{y_i^2}{\sigma_i^2} - k_i^2\sigma_i^2\right)$$

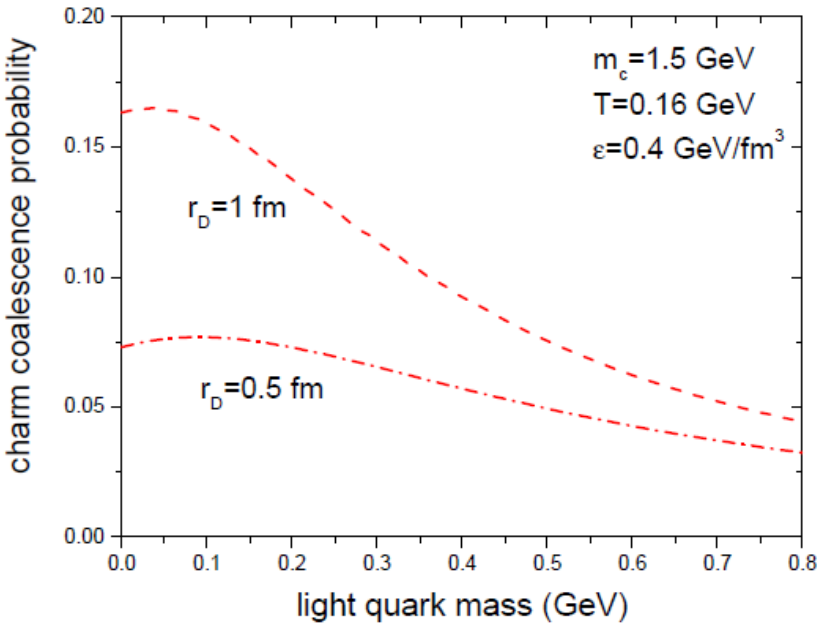
multiplied by 8 (=3+5) to include $J^p=1^+$, 2^+ and divided by 36(=6*6)

1. We assume P states decay to D(D*) + π as soon as hadronized
2. D_s is similarly treated

Model Study: total coalescence probability of thermal charm

Charm can be projected into all possible states with different coalescence radii → too complicated !!

T. Song, G. Coci, arXiv:2104.10987



- Ground state from the coalescence model
- Heavier states from the statistical model

$$\frac{\text{number density of all charm hardons}}{\text{number density of } D^0} = 7.47,$$

at T_c

The total coalescence probability is much lower than 1

There must be correlations in color, momentum, coordinate spaces

Hadronization of heavy quarks in A+A

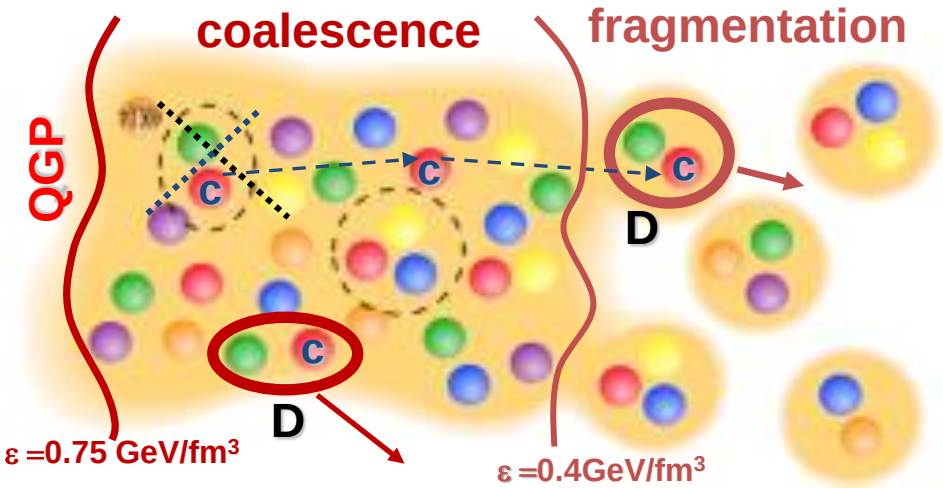
- **PHSD: if the local energy density $\varepsilon \rightarrow \varepsilon_C$ ➔ hadronization of heavy quarks to hadrons**

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

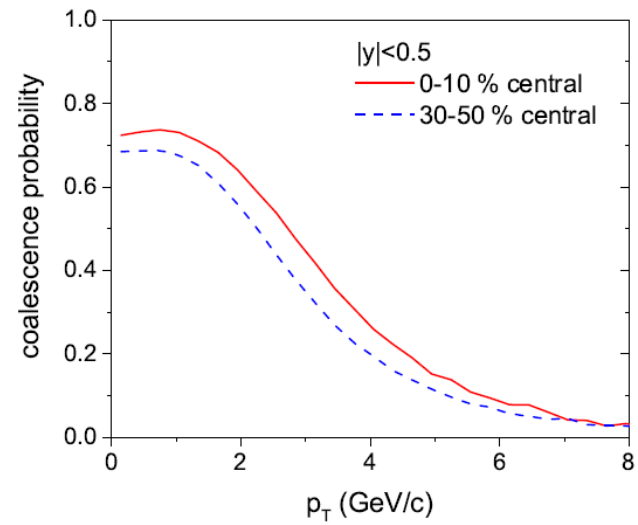
Dynamical hadronization scenario for heavy quarks :

coalescence with <r>=0.9 fm & fragmentation

$0.4 < \varepsilon < 0.75$ GeV/fm^3 $\quad$ $\varepsilon < 0.4$ GeV/fm^3



Coalescence probability in Pb+Pb at LHC

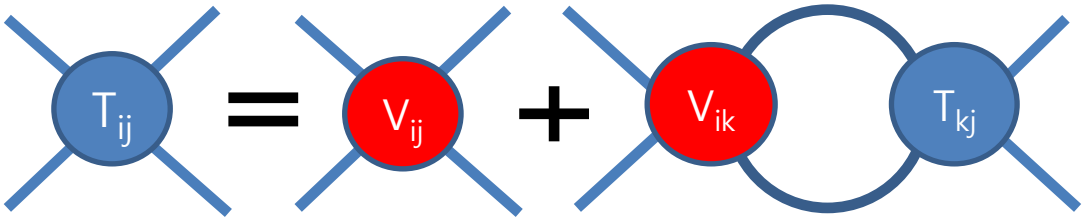


T. Song et al. PRC 93 (2016) 034906

3. Hadronic interactions of HF

- Basic transition amplitude **V** is obtained from the effective chiral Lagrangian with heavy quark spin symmetry
- **$D=(D^0,D^+,D^+_s)$ or $D^*=(D^{*0},D^{*+},D^{*+}_s)$ interacts with**
- **flavor octet meson (π,K,Kbar,η) or**
- **nucleon octet $J^P=1/2^+$ and Delta decuplet $J^P=3/2^+$**

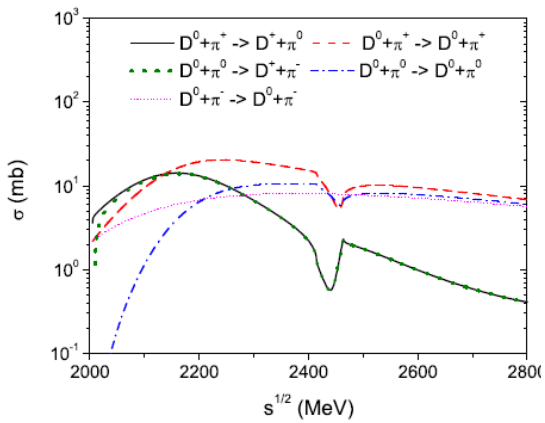
- **V** is unitarized through $T=V+VGT$,
- where **G** is propagators of heavy meson and light meson(baryon)

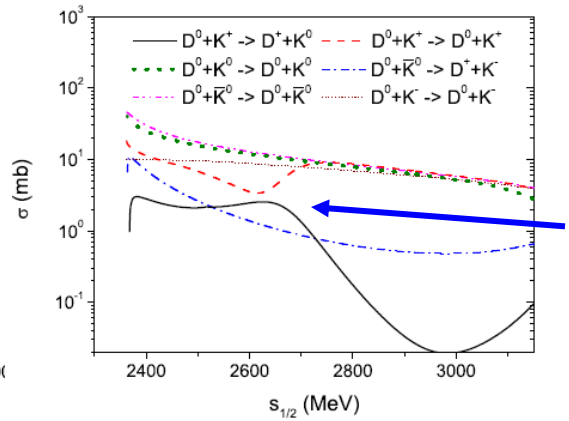


- **T** is unitarized transition amplitude

D-meson scattering in the hadron gas

1. D-meson scattering with mesons



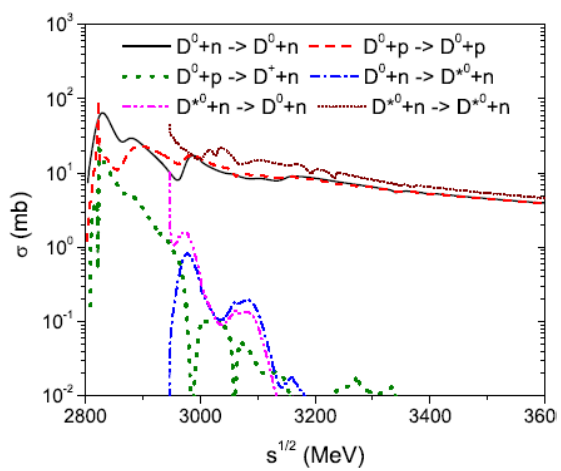


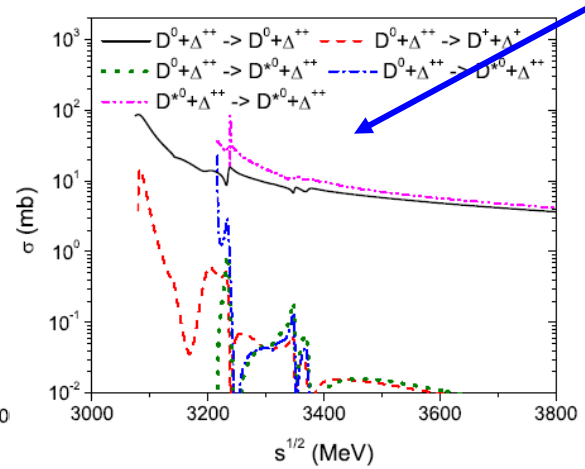
1a) cross sections with *m*=ρ, ω,ϕ,$K*$,... taken as

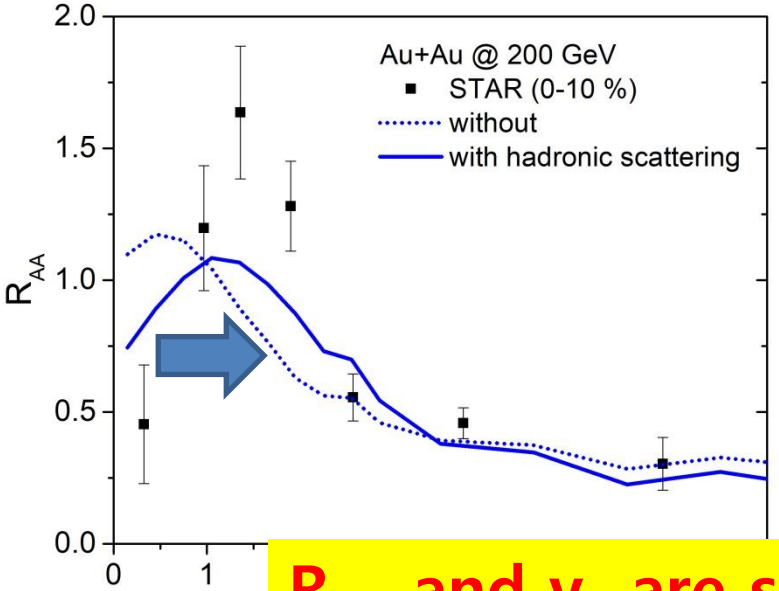
$$\sigma(D, D^* + m) = 10\,mb$$

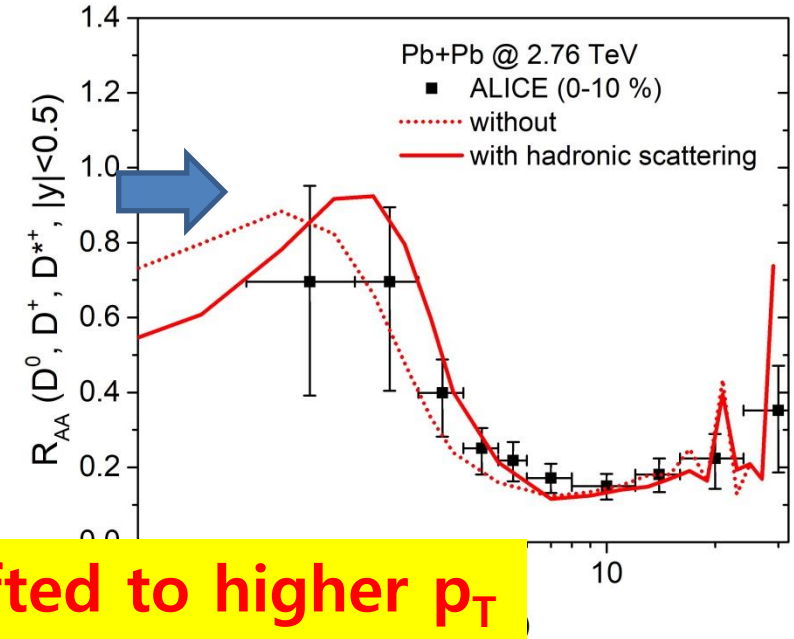
➔Strong isospin dependence and complicated structure due to the resonance coupling of D+m, D+B cross sections!

2. D-meson scattering with baryons

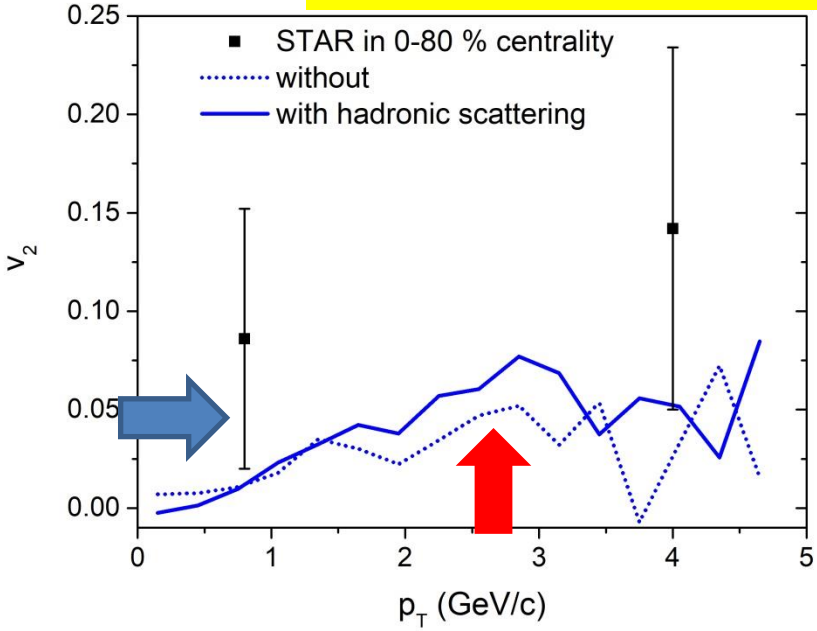


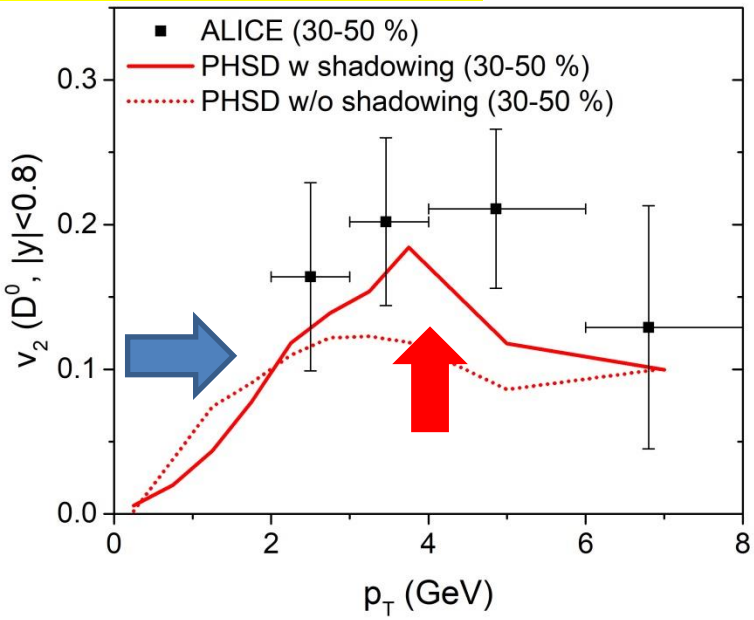






R_{AA} and v_2 are shifted to higher p_T and v_2 is enhanced





4. What is distinguished in PHSD

- Partonic matter (QGP) is described with massive-offshell (anti)quarks and gluons which reproduce lattice EoS
- Coalescence is repeatedly tried from 0.75 GeV/fm^3 to 0.4 GeV/fm^3 of energy density such that coalescence probability is large enough at low p_T
- Hadronic scattering has nonnegligible effects on HF based on the calculations in the effective Lagrangian with unitarization

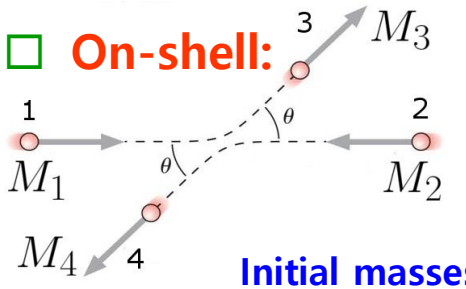
Thank you for your attention

contents

- 1. partonic interactions of HF in PHSD
- 2. hadronization of HF in PHSD
- 3. hadronic interactions of HF in PHSD
- 4. summary

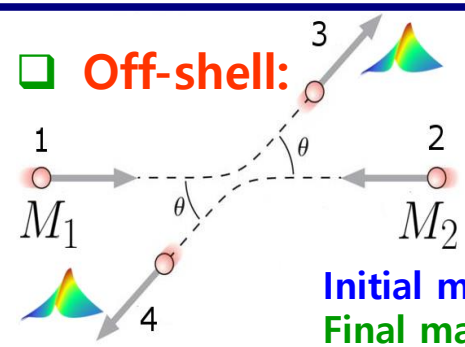
Differential cross sections

- **On-shell:**

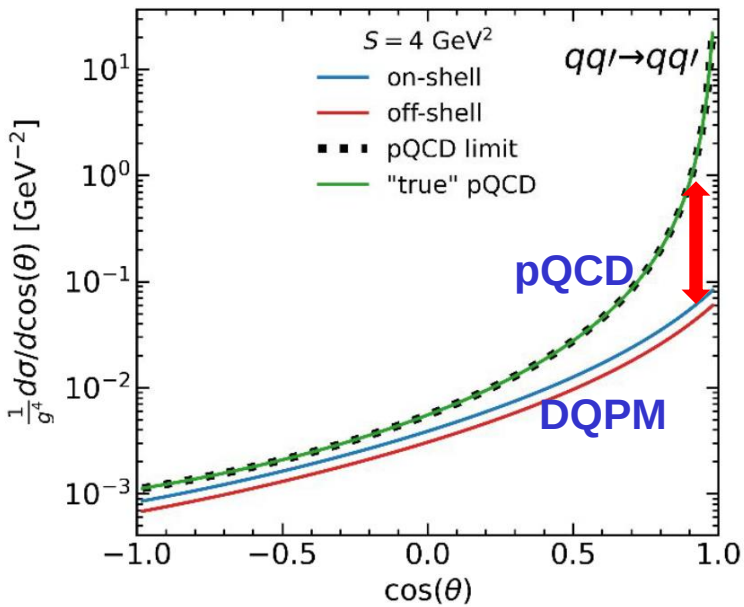


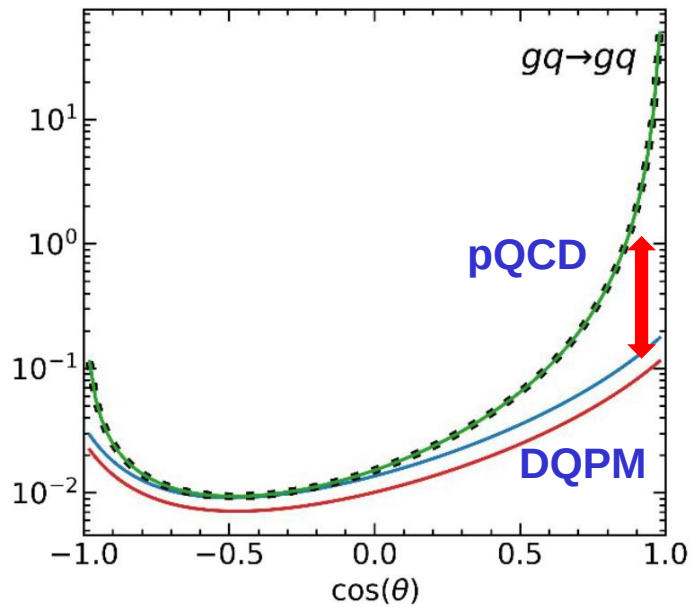
Initial masses: pole masses
Final masses: pole masses

- **Off-shell:**



Initial masses: pole masses
Final masses: integration over spectral functions





- **DQPM: M→0, γ→0 ➔ reproduces pQCD limits**
- **Differences between DQPM and pQCD : less forward peaked angular distribution le ads to more efficient momentum transfer**

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