HQ hadronization & hadronic phase in PHSD

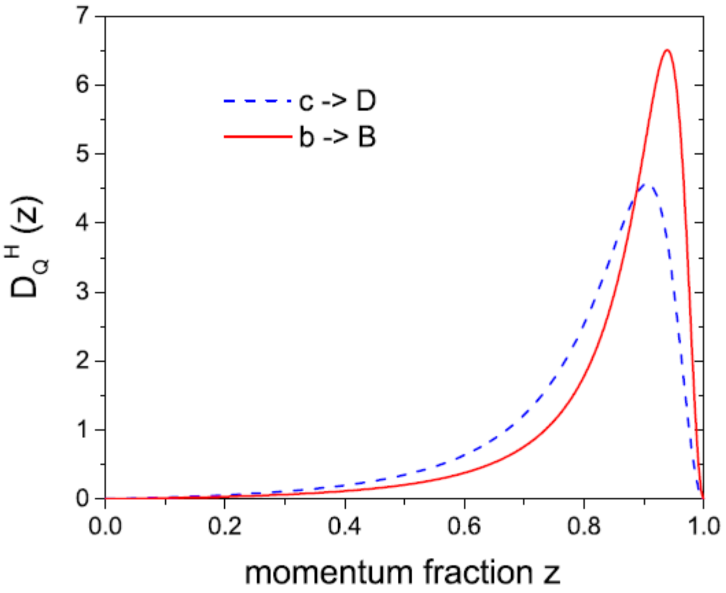
Taesoo Song, Elena Bratkovskaya

1. HQ fragmentation

- transverse momentum
- Peter's fragmentation function

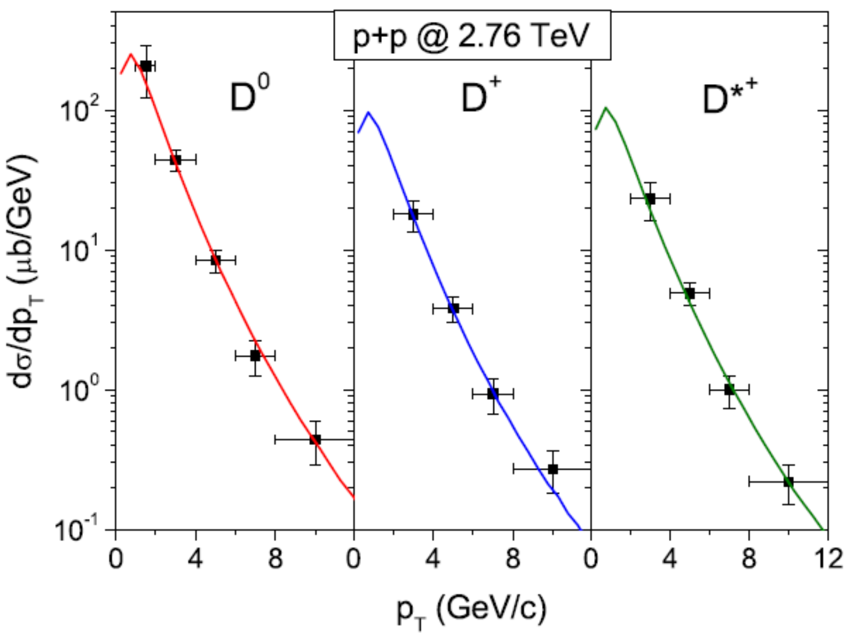
$$D_Q^H(z) \sim \frac{1}{z[1 - 1/z - \epsilon_Q/(1-z)]^2},$$

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

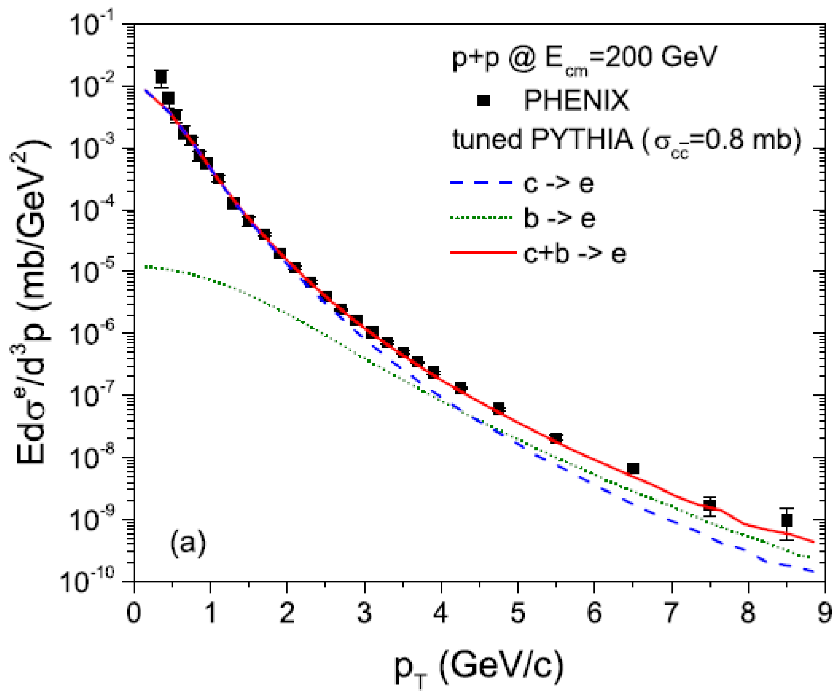


- rapidity
- is assumed to be same after the fragmentation

The chemical fractions of the charm quark decay into D^+, D^0, D^{*+}, D^{*0}, D_s, and Λ_c are taken to be 14.9, 15.3, 23.8, 24.3, 10.1, and 8.7% [30,43–45], respectively, and those of the bottom quark decay into B^-, $\bar{B}^0$, $\bar{B}^0{}_s$, and Λ_b are 39.9, 39.9, 11, and 9.2% [42].



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



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

2. HQ coalescence

- 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

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

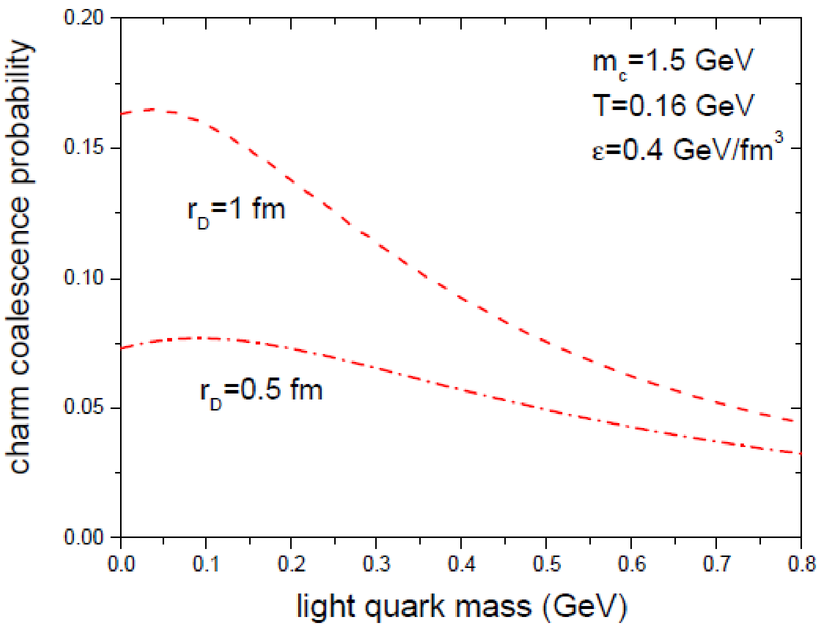
multiplied by 8 (=3+5)
to include $J^p=1^+, 2^+$
and divided by 36(=6*6)

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 (S-, P-, D-states …) with different coalescence radii → too complicated !!

T. Song, G. Coci, arXiv:2104.10987



- Ground state from the coalescence
- 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

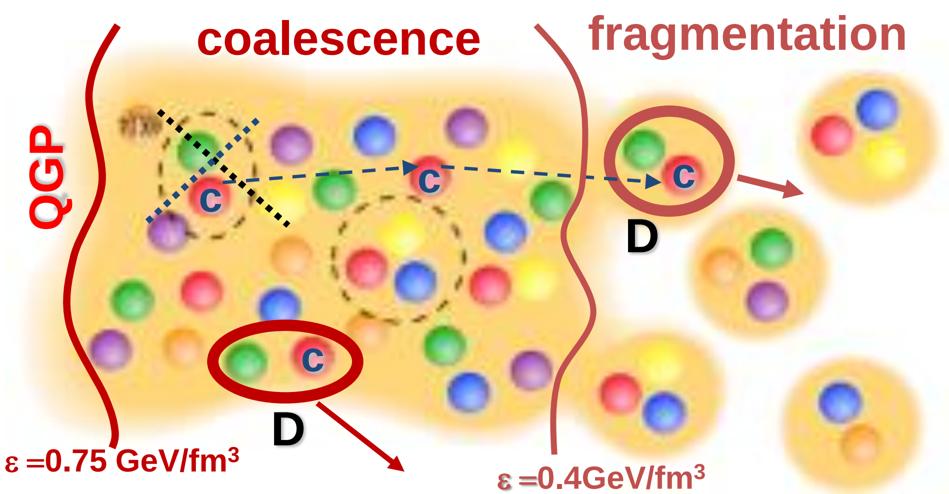
Hadronization of heavy quarks in A+A

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

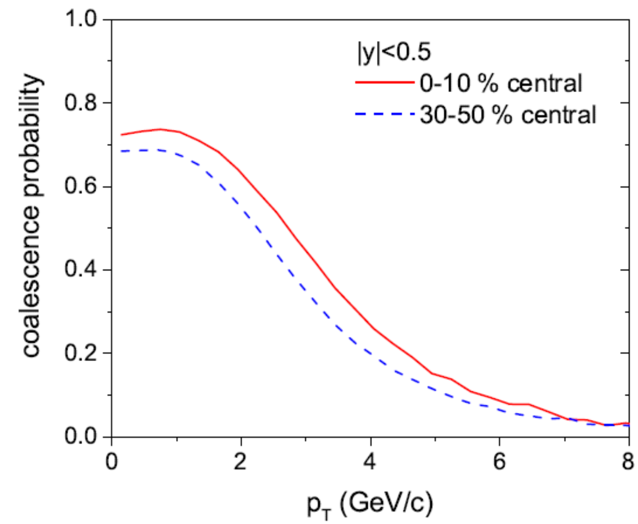
T. Song et al., PRC 93 (2016) 034906

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 Pb+Pb at LHC



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

3. Hadronic scattering

Modelling of D-meson scattering in the hadronic gas

1. D-meson scattering with mesons

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

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

Interaction of $D=(D^0,D^+,D^+_s)$ and $D^*=(D^{*0},D^{*+},D^{*+}_s)$ with octet (π,K,Kbar,η) :

$$\begin{aligned}\mathcal{L}_{LO} &= \langle \nabla^\mu D \nabla_\mu D^\dagger \rangle - m_D^2 \langle D D^\dagger \rangle - \langle \nabla^\mu D^{*\nu} \nabla_\mu D^{*\dagger}_\nu \rangle \\ &+ m_D^2 \langle D^{*\mu} D^{*\dagger}_\mu \rangle + ig \langle D^{*\mu} u_\mu D^\dagger - D u^\mu D^{*\dagger}_\mu \rangle \\ &+ \frac{g}{2m_D} \langle D^*_\mu u_\alpha \nabla_\beta D^{*\dagger}_\nu - \nabla_\beta D^*_\mu u_\alpha D^{*\dagger}_\nu \rangle \epsilon^{\mu\nu\alpha\beta}\end{aligned}$$

with

$$\begin{aligned}\nabla_\mu &= \partial_\mu - \tfrac{1}{2}(u^\dagger \partial_\mu u + u \partial_\mu u^\dagger), \\ u_\mu &= i\left(u^\dagger \partial_\mu u - u \partial_\mu u^\dagger\right)\end{aligned}$$

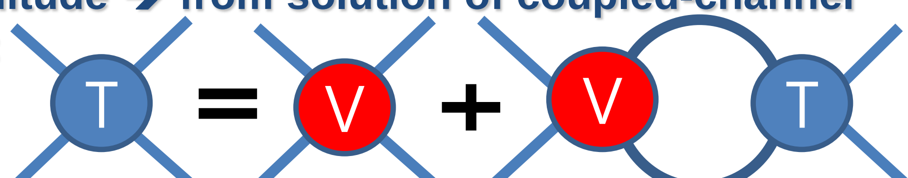
$$U = u^2 = \exp\left(\frac{\sqrt{2} i \Phi}{f}\right) \qquad \Phi = \begin{pmatrix} \frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta & \pi^+ & K^+ \\ \pi^- & -\frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta & K^0 \\ K^- & \bar{K}^0 & -\frac{2}{\sqrt{6}}\eta \end{pmatrix}$$

2. D-meson scattering with baryons

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 $J^P=3/2^+$

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

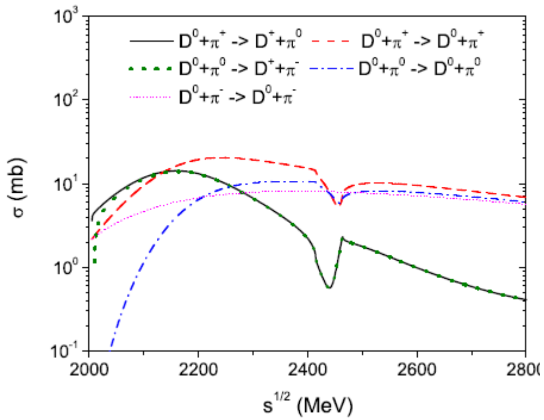
Unitarized scattering amplitude ➔ from solution of coupled-channel Bethe-Salpeter equations:

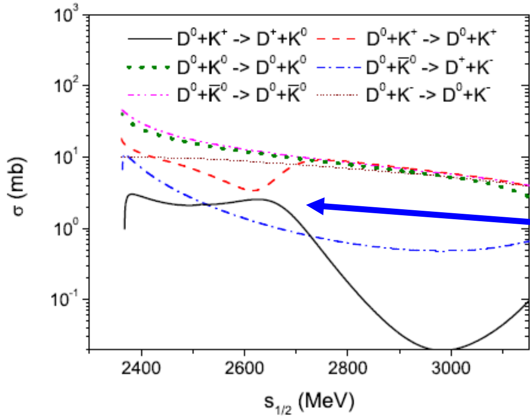


T. Song et al., PRC 92 (2015) 014910, arXiv:1503.03039

D-meson scattering in the hadron gas

1. D-meson scattering with mesons



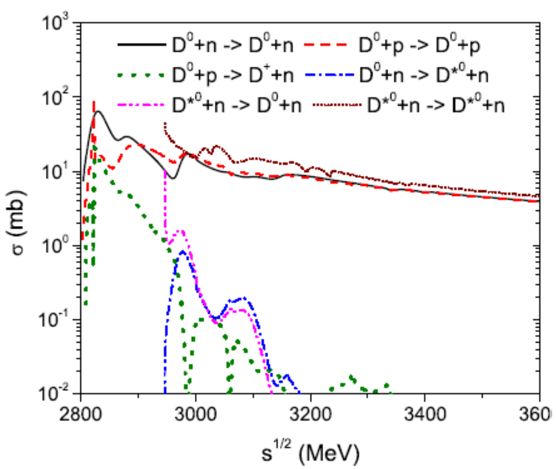


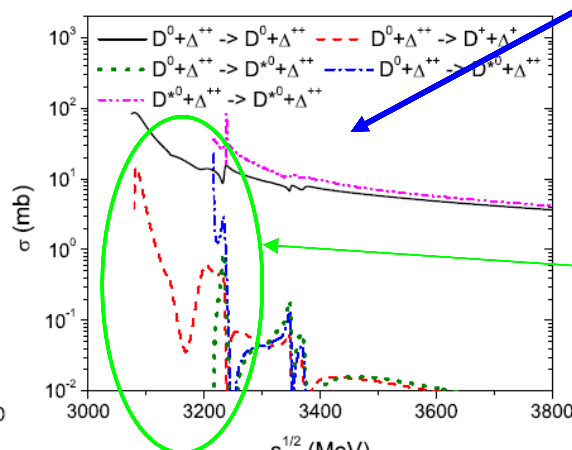
1a) cross sections with $m=\rho, \omega, \phi, K^*, \ldots$ taken as

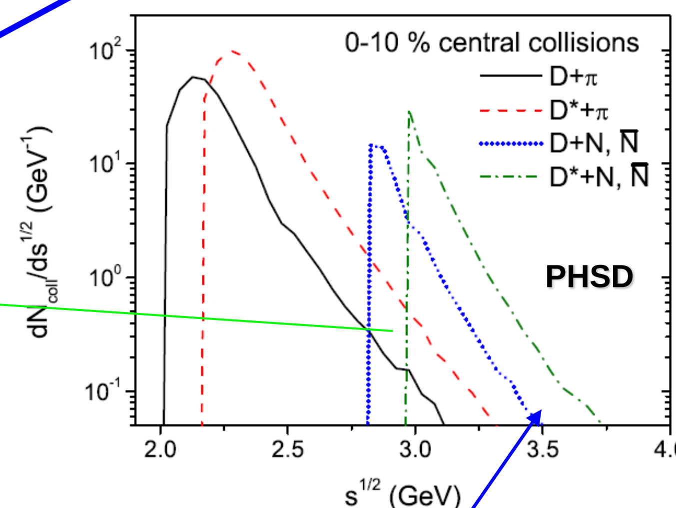
$$\sigma(D, D^* + m) = 10\,mb$$

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

2. D-meson scattering with baryons





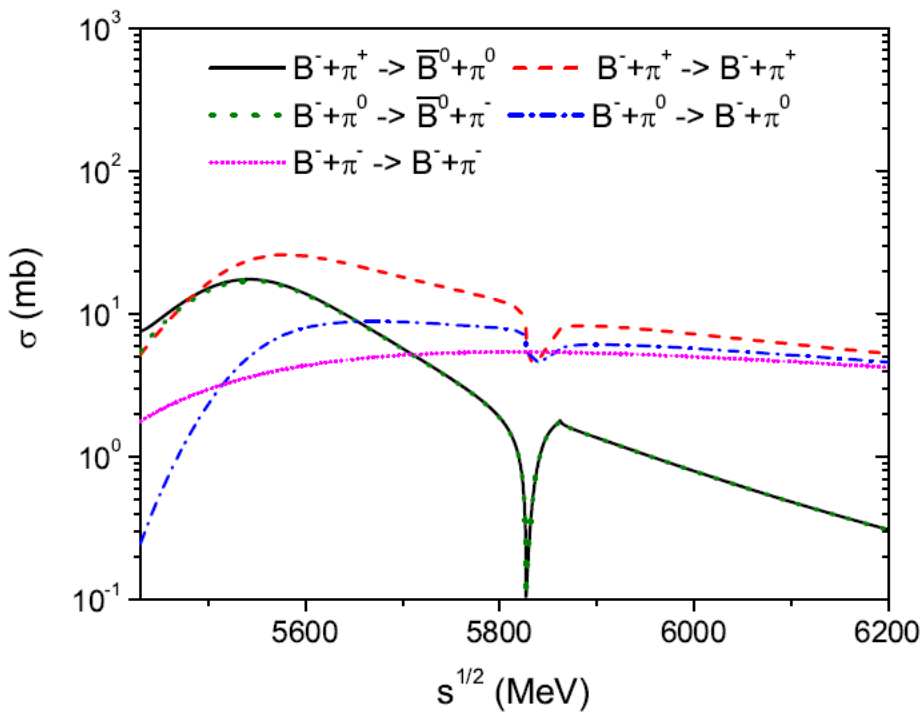


➔ **Hadronic interactions become ineffective for the energy loss of D,D* mesons at high transverse momentum (i.e. large $s^{1/2}$)**

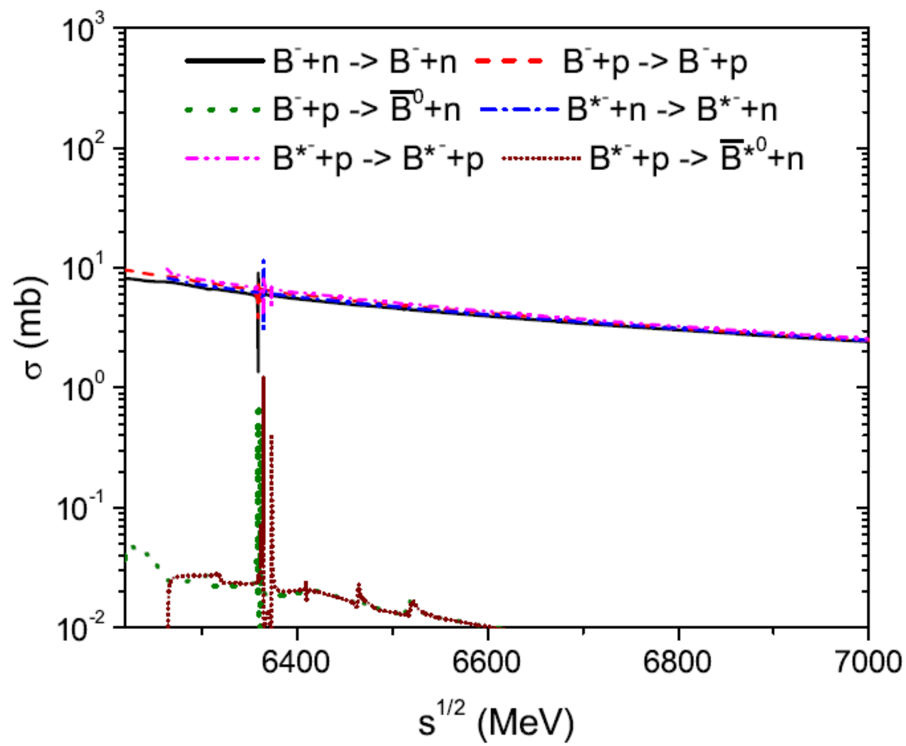
B-meson scattering in the hadron gas

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)

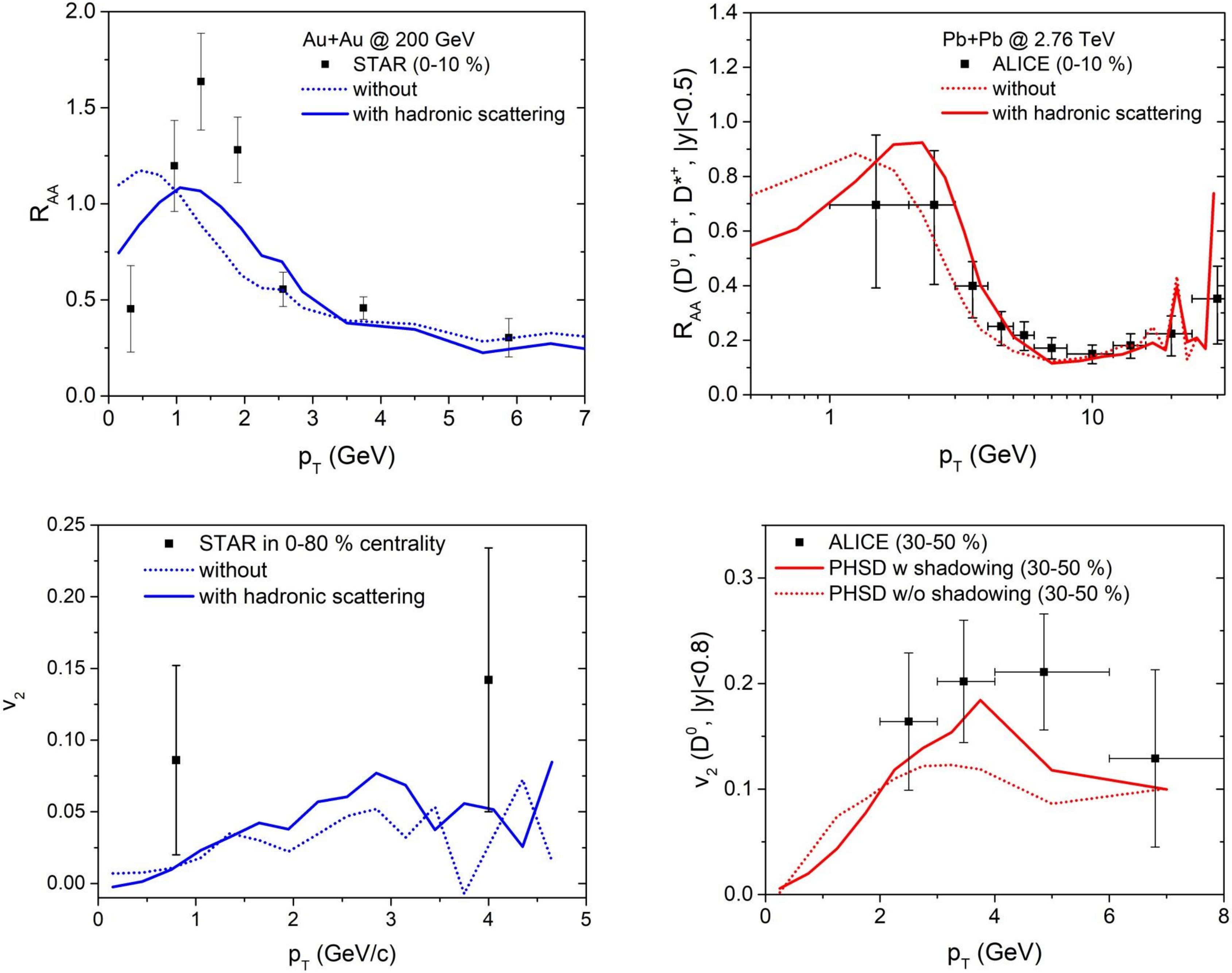
1. B-meson scattering with mesons



2. B-meson scattering with baryons

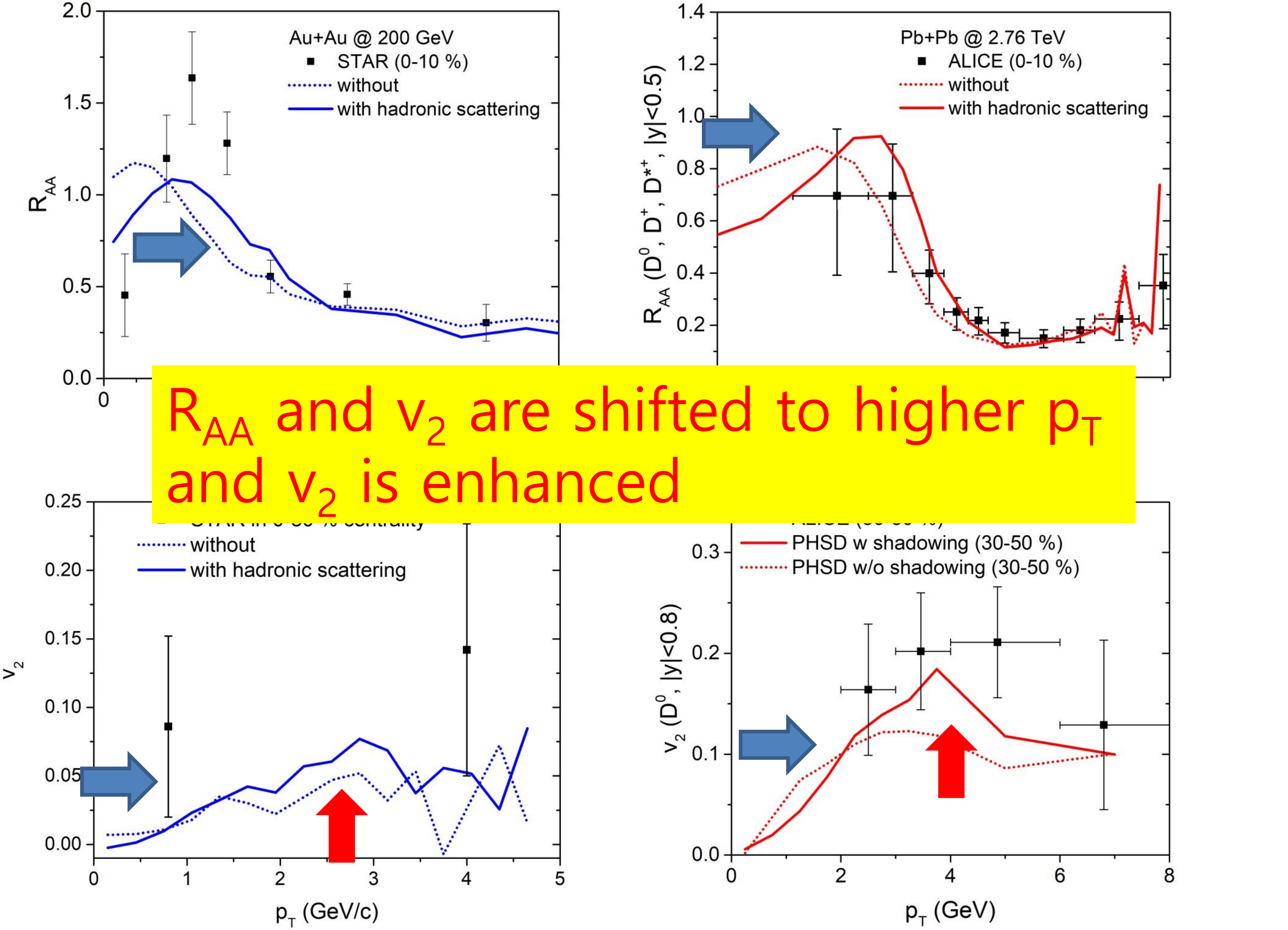


- **More than 200 hadronic channels** ➔ **implemented in the PHSD**
- thanks to Juan M. Toress-Rincon!



Au+Au @ 200 GeV
STAR (0-10 %)
without
with hadronic scattering
R_{AA}
p_T (GeV)
Pb+Pb @ 2.76 TeV
ALICE (0-10 %)
without
with hadronic scattering
R_{AA} (D^0, D^+, D^{*+}, |y|<0.5)
p_T (GeV)
STAR in 0-80 % centrality
without
with hadronic scattering
v_2
p_T (GeV/c)
ALICE (30-50 %)
PHSD w shadowing (30-50 %)
PHSD w/o shadowing (30-50 %)
v_2 (D^0, |y|<0.8)
p_T (GeV)

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



Thank you for your attention!