Heavy quark dynamics in heavy-ion collisions

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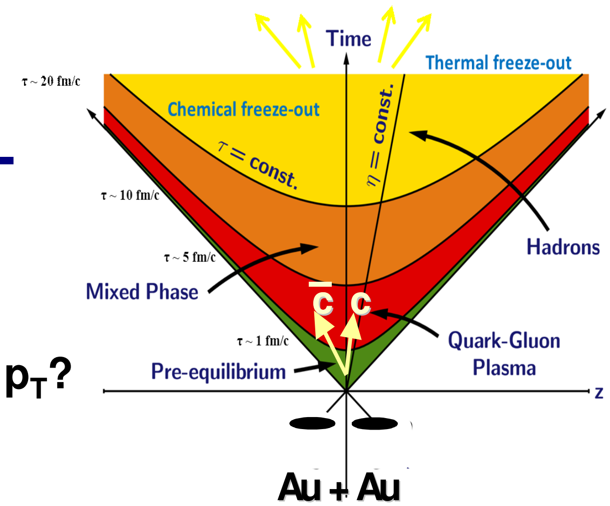
Strangeness in Quark Matter -2016,
UC Berkeley, USA
27 June – 1 July 2016

Motivation

- Hope to use **’heavy quark probes’** for a **tomography of the early stage of the QGP**
- What is **the origin for the “energy loss”** of charm at large p_T?



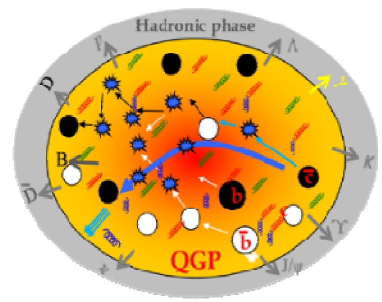
Dynamics of heavy quarks in A+A :

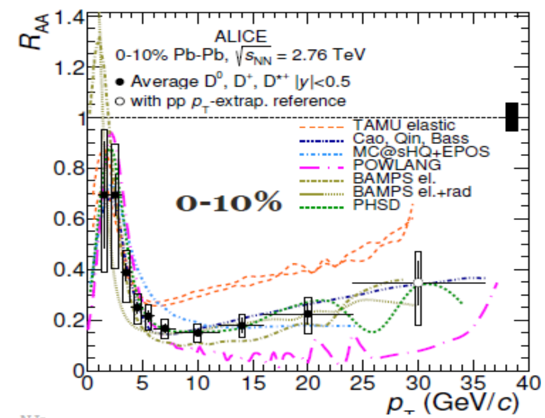
1. **Production** of heavy (charm and bottom) quarks in initial binary collisions + shadowing and Cronin effects

2. **Interactions in the QGP**:
   elastic scattering Q+q→Q+q → **collisional** energy loss
   gluon bremsstrahlung Q+q→Q+q+g → **radiative** energy loss

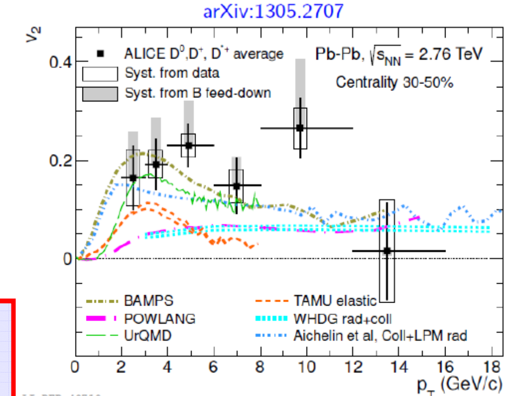
3. **Hadronization**: c/cbar quarks →D(D*)-mesons: coalescence vs fragmentation

4. **Hadronic interactions**: D+baryons; D+mesons



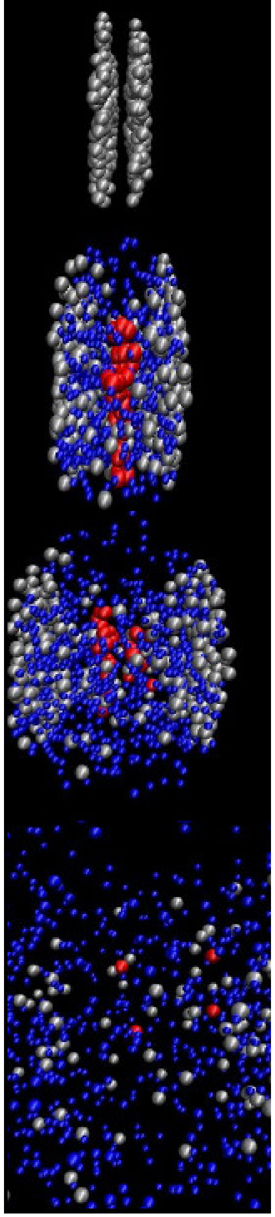


arXiv:1305.2707



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

Parton-Hadron-String-Dynamics (PHSD)



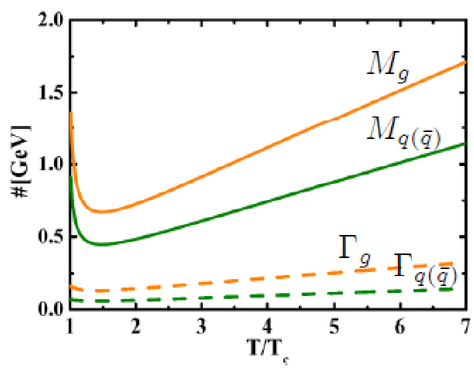
PHSD is a **non-equilibrium transport approach** with

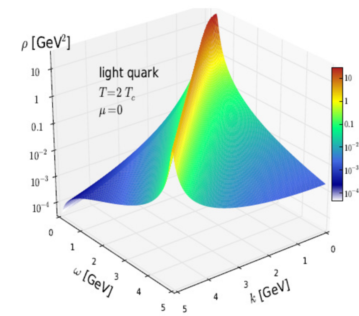
- explicit **phase transition** from hadronic to partonic degrees of freedom
- **lQCD EoS** for the partonic phase (‚crossover' at low μ_q)
- explicit **parton-parton interactions** - between quarks and gluons
- dynamical **hadronization**

❑ **QGP phase is described by the Dynamical QuasiParticle Model (DQPM) matched to reproduce lattice QCD**

A. Peshier, W. Cassing, PRL 94 (2005) 172301;
W. Cassing, NPA 791 (2007) 365: NPA 793 (2007)

- **strongly interacting quasi-particles:** massive quarks and gluons (g,q,q_{bar}) with sizeable collisional widths in a self-generated **mean-field potential**





- **Spectral functions:**

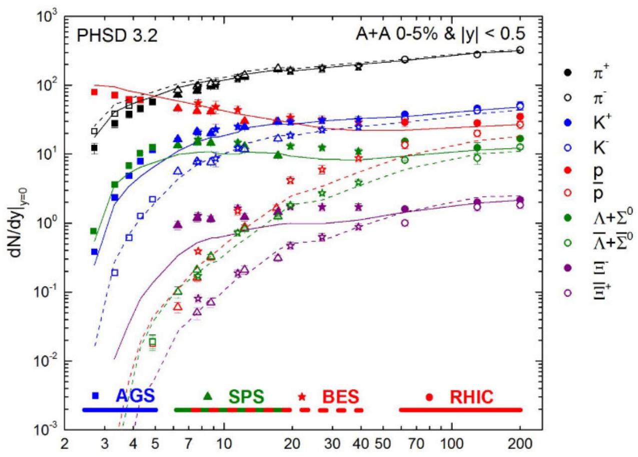
$$\rho_i(\omega,T) = \frac{4\omega\Gamma_i(T)}{\left(\omega^2 - \vec{p}^2 - M_i^2(T)\right)^2 + 4\omega^2\Gamma_i^2(T)} \quad (i = q,\bar{q},g)$$

❑ **Transport theory**: **generalized off-shell transport equations** based on the 1st order gradient expansion of Kadanoff-Baym equations (**applicable for strongly interacting systems**!)

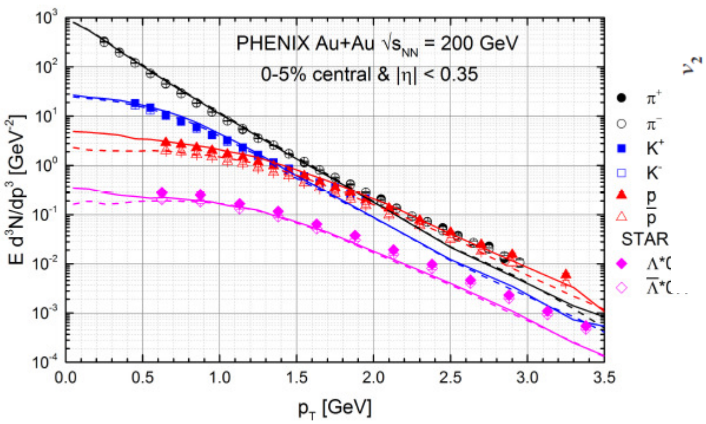
W. Cassing, E. Bratkovskaya, PRC 78 (2008) 034919; NPA831 (2009) 215; W. Cassing, EPJ ST 168 (2009) 3

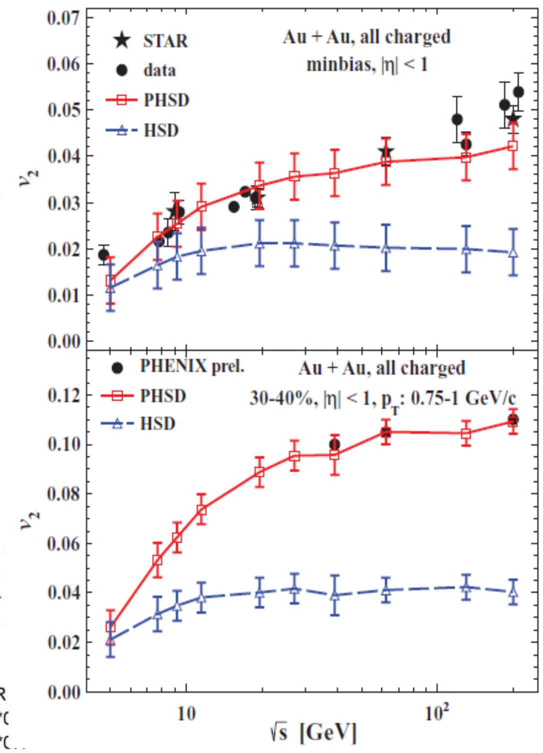
Non-equilibrium dynamics: description of A+A with PHSD

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

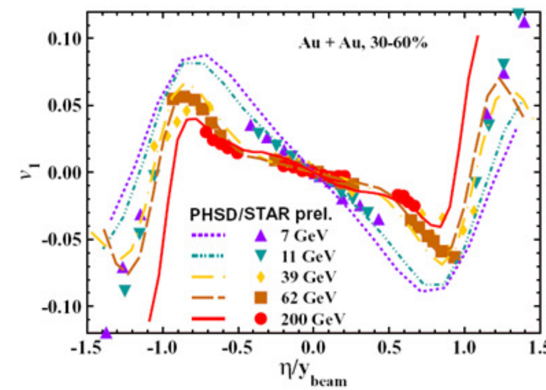


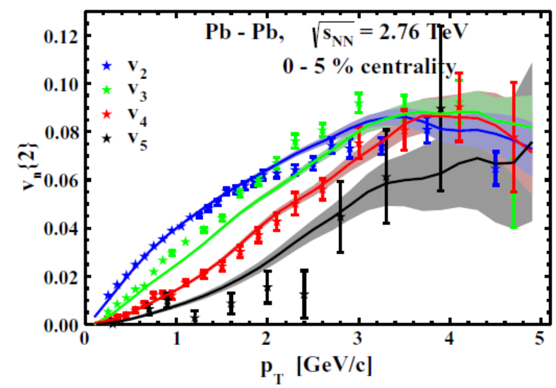
PHSD: P. Moreau





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



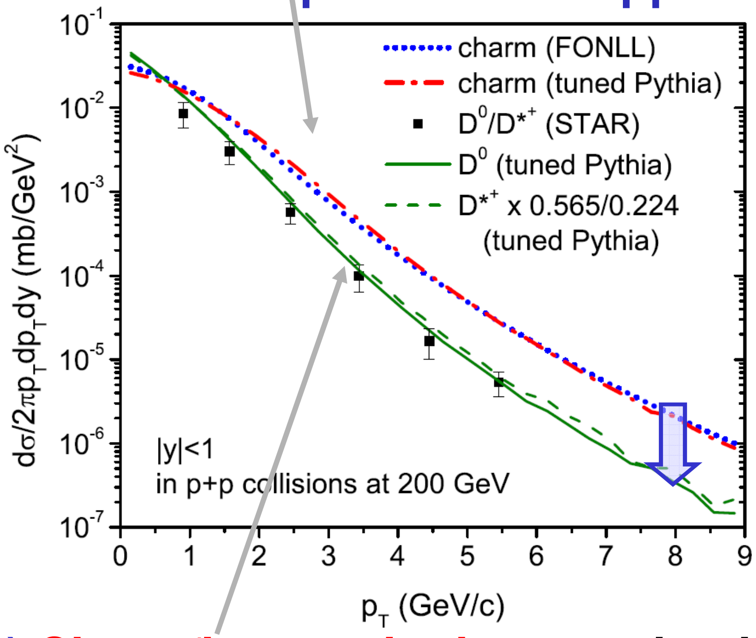


❑ **PHSD** provides a **good description of ‚bulk‘ observables** (y-, p_T-distributions, flow coefficients v_n, …) from SPS to LHC

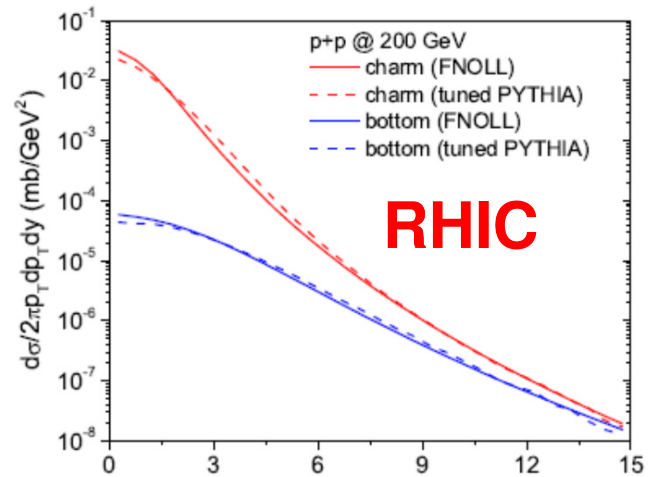
Heavy quark/hadron production in p+p collisions

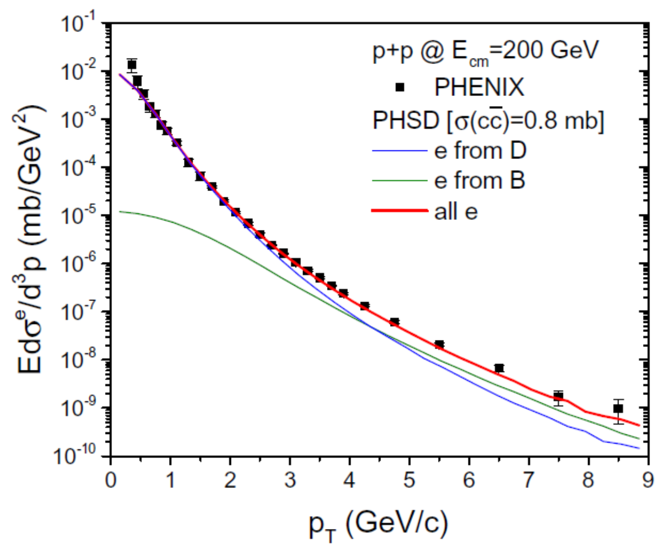
1) **Momentum distribution of heavy quarks:** use ‚tuned‘ PYTHIA event generator to reproduce FONLL (fixed-order next-to-leading log) results (R. Vogt et al.)

Charm production in pp



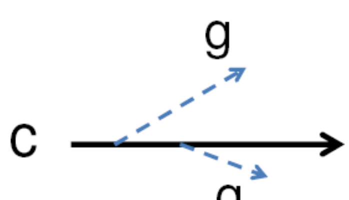
Beauty production in pp





2) **Charm/beauty hadron production in pp by heavy-quark fragmentation:**

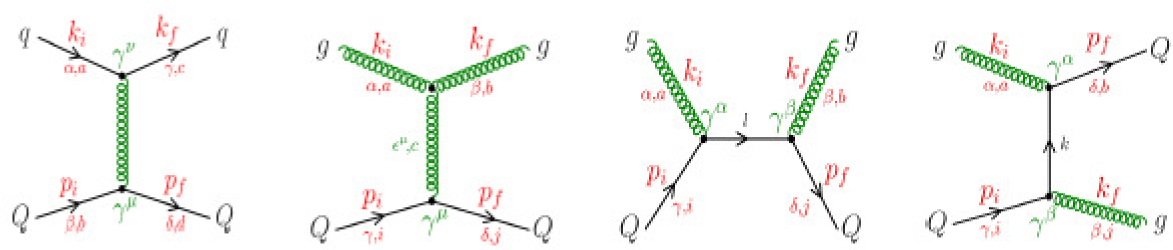
D^0 20 %
D^+ 17.4 %
D^{*0} 21.3 %
D^{*+} 22.4 %
Ds^+ 8 %
Λ_c 9.4 %



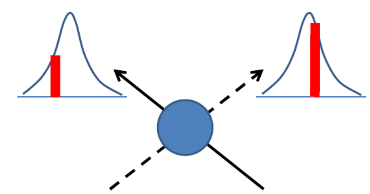
T. Song et al., PRC 92 (2015) 014910, arXiv:1503.03039

Heavy quark scattering in the QGP (DQPM)

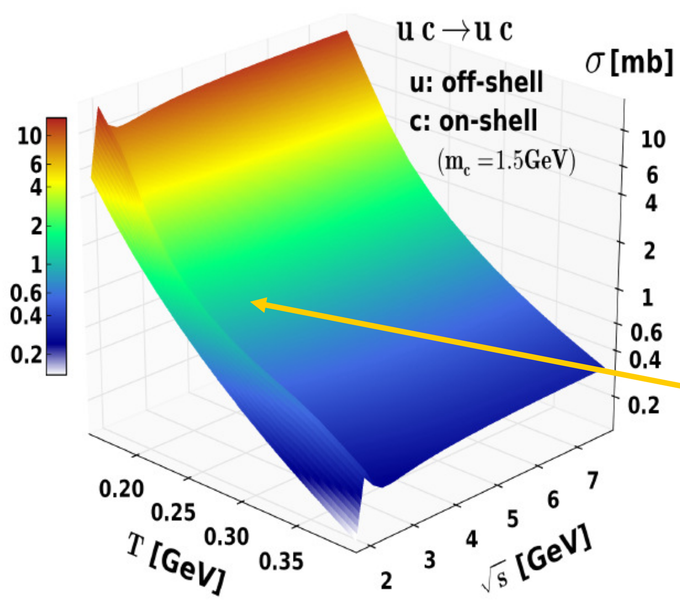
- Elastic scattering with **off-shell massive partons Q+q(g)→Q+q(g)**



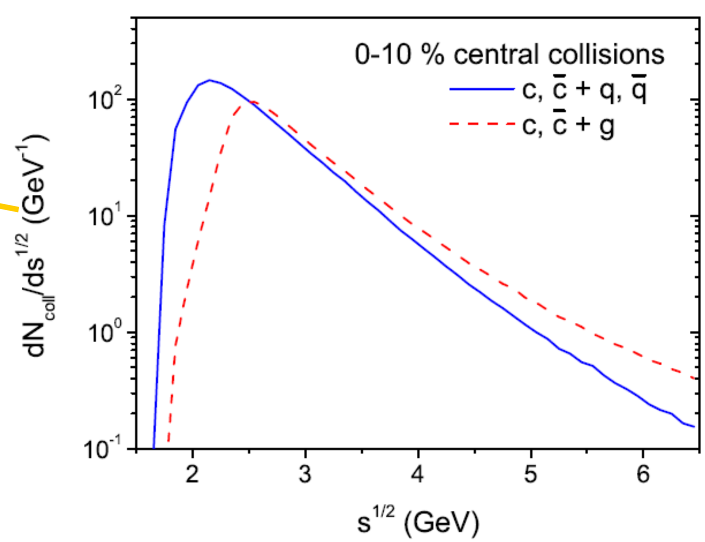
Non-perturbative QGP!



- **Elastic cross section uc→uc**



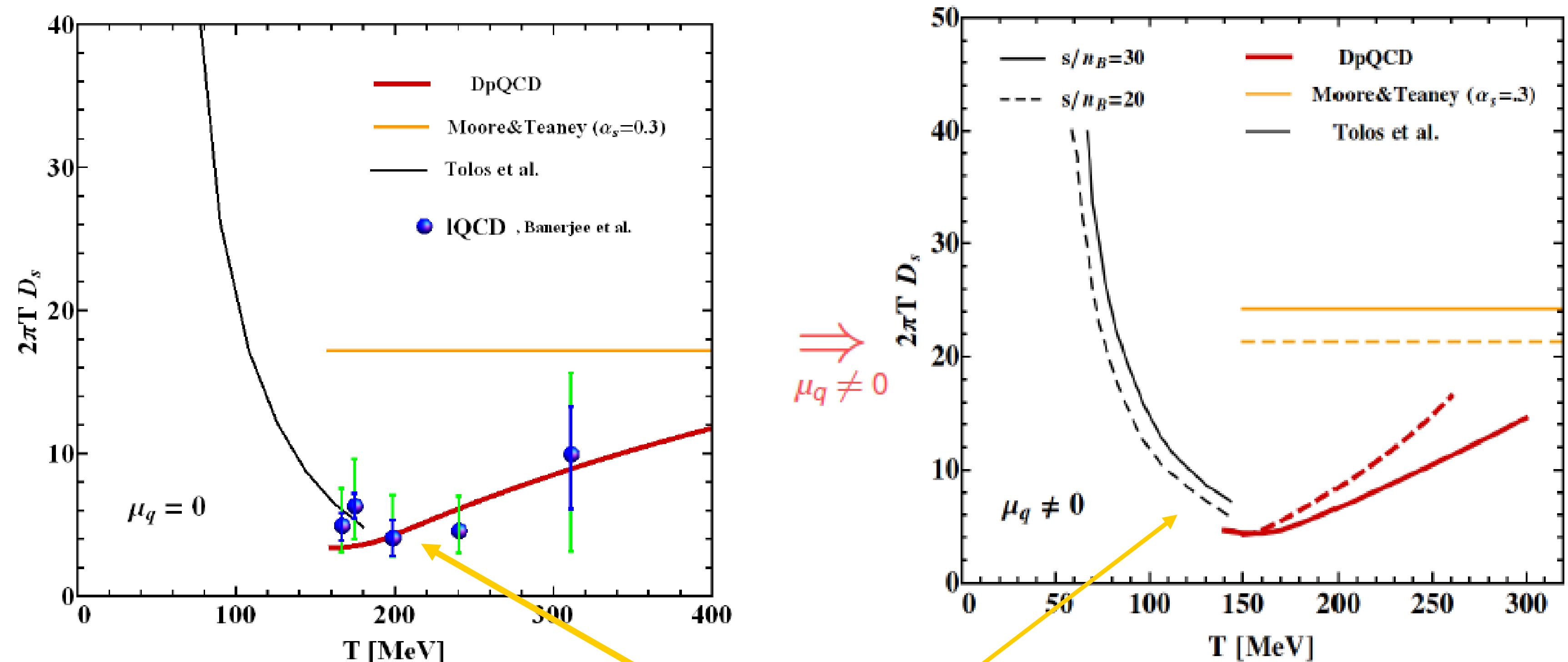
- **Distributions of Q+q, Q+g collisions vs $s^{1/2}$ in Au+Au, 10% central**



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

Charm spatial diffusion coefficient D_s in the hot medium

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



➔ Continuous transition at T_C!

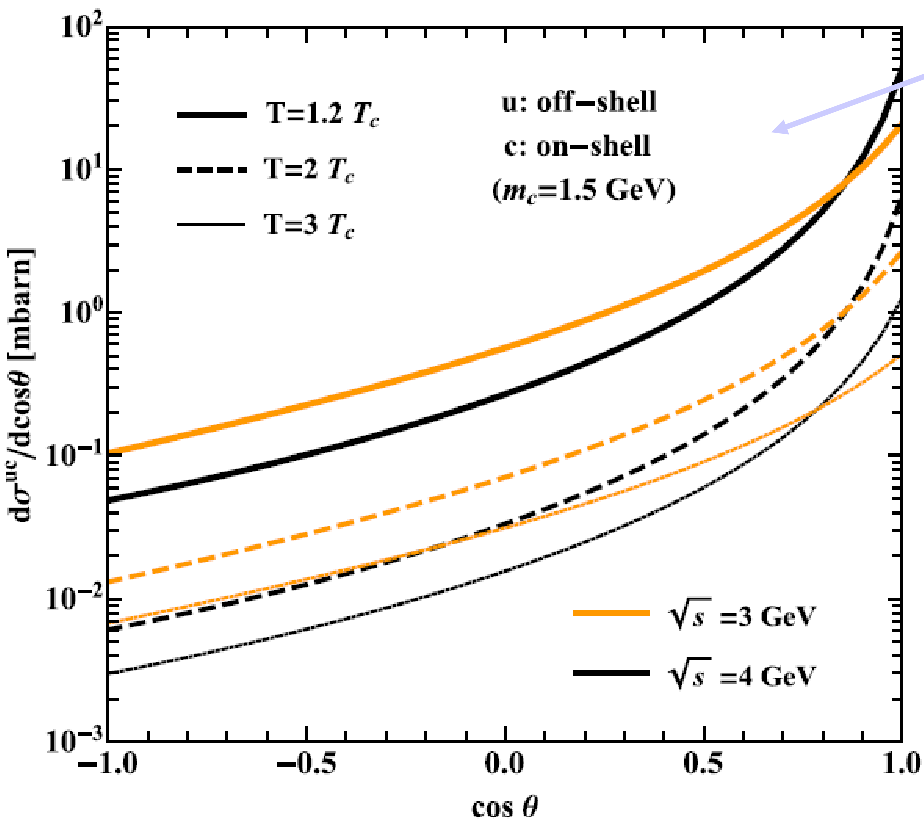
❑ T < T_c : hadronic D_s

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

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

Heavy quark scattering in the QGP

- **Differential elastic cross section** for uc→uc for $s^{1/2}$=3 and 4 GeV at 1.2T_C, 2T_C and 3T_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

- Central Au+Au, 200 A GeV:
  N(cc) ~19 pairs,
  N(Q+q)~130, N(Q+g) ~85 collisions
→ each charm quark makes
  ~ 6 elastic collisions in the QGP

→ 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 due to the large gluon mass in the DQPM

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

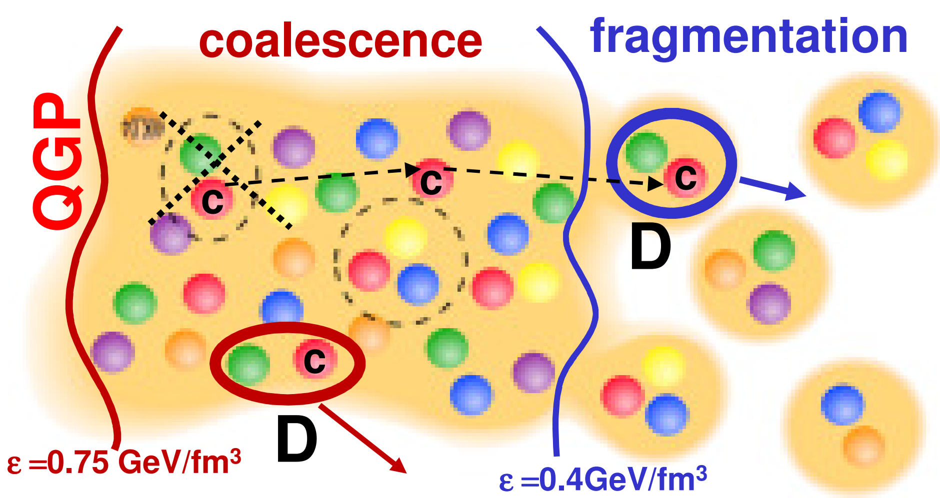
Hadronization of heavy quarks in A+A

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

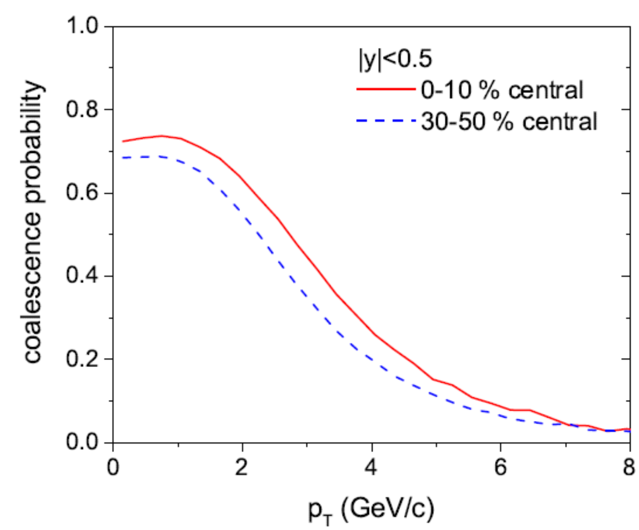
T. Song et al., PRC 93 (2016) 034906

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 $c+\bar{q} \rightarrow D$

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

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

Width δ ← 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 $D^* = D^*_0(2400)^0$, $D^*_1(2420)^0$, $D^*_2(2460)^{0\pm}$

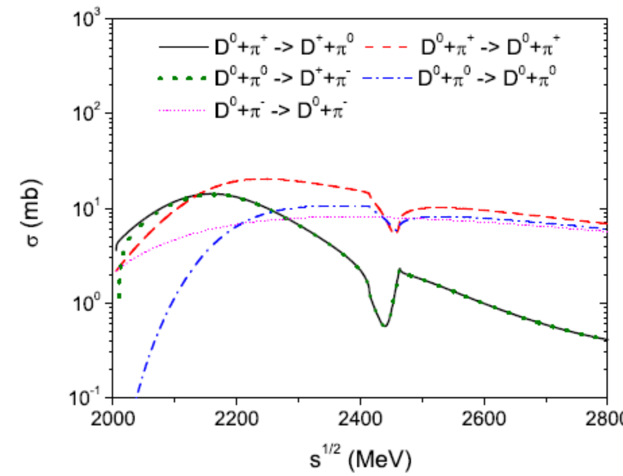
D-meson scattering in the hadronic phase

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 (π,K,Kbar,η)



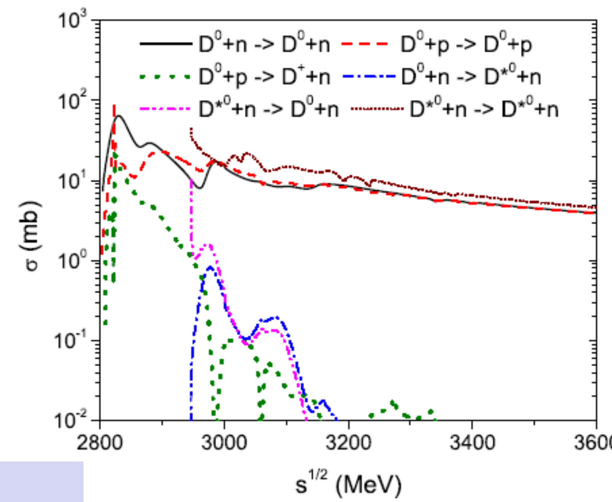
2. D-meson scattering with baryons

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 $J^P=3/2^+$**

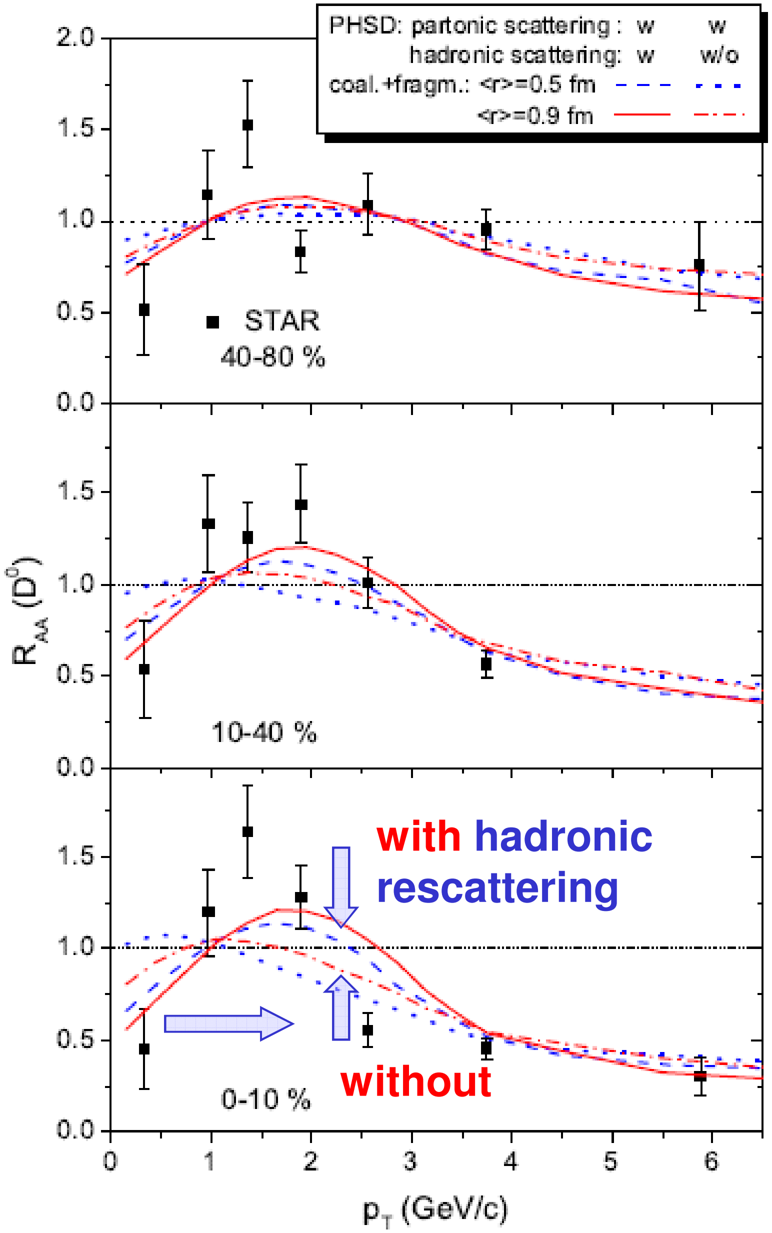
Unitarized scattering amplitude ➔ solution of coupled-channel Bethe-Salpeter equations:

$$T = T + VGT$$



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

R_{AA} at RHIC: hadronic rescattering

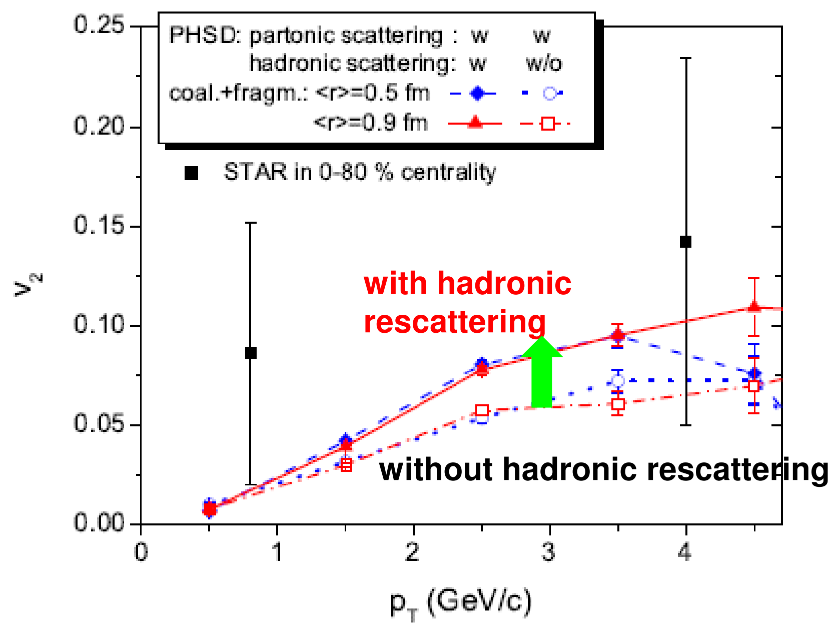


Influence of hadronic rescattering:

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**

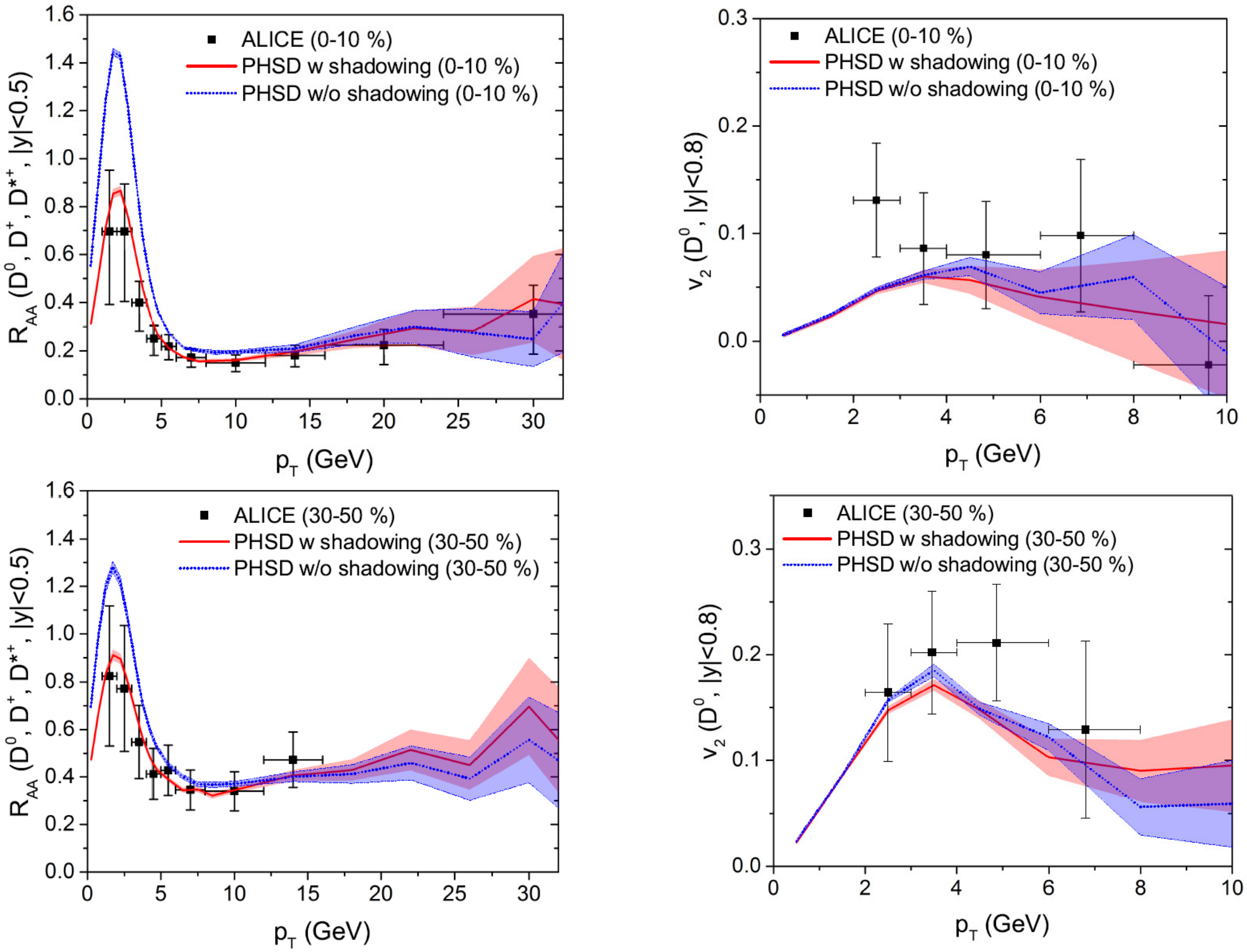
➔ **each D,D* makes ~ 2 scatterings with hadrons**



- **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, arXiv:1503.03039

Charm R_{AA} at LHC: PHSD vs ALICE

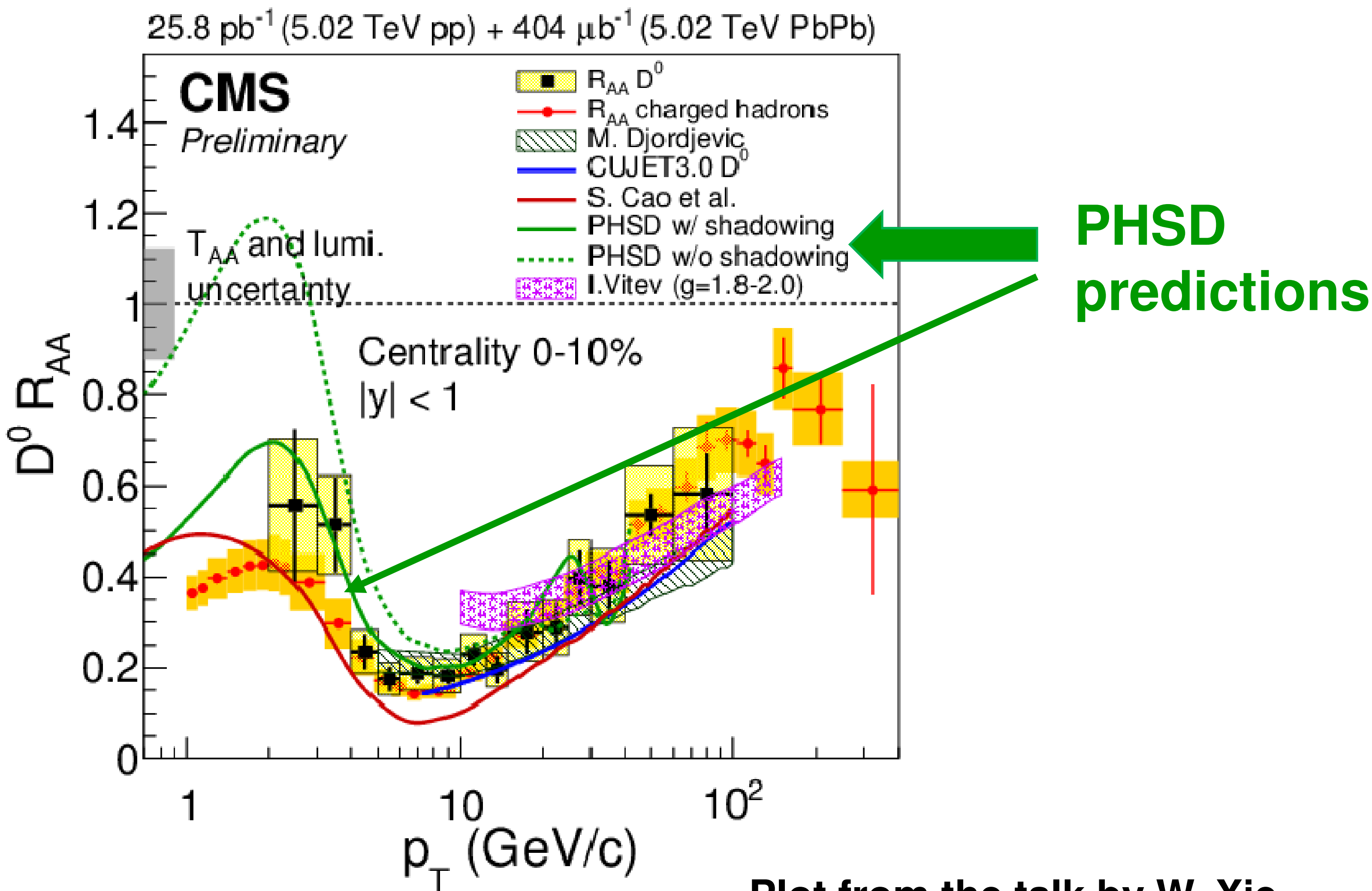


- in PHSD the energy loss of D-mesons at high p_T can be dominantly attributed to partonic scattering
- Shadowing effect suppresses the low p_T and slightly enhances the high p_T part of R_{AA}
- Hadronic rescattering moves R_{AA} peak to higher p_T; increases v_2

T. Song et al., PRC 93 (2016) 034906, arXiv:1512.0089

Charm R_{AA} at LHC: PHSD predictions for CMS

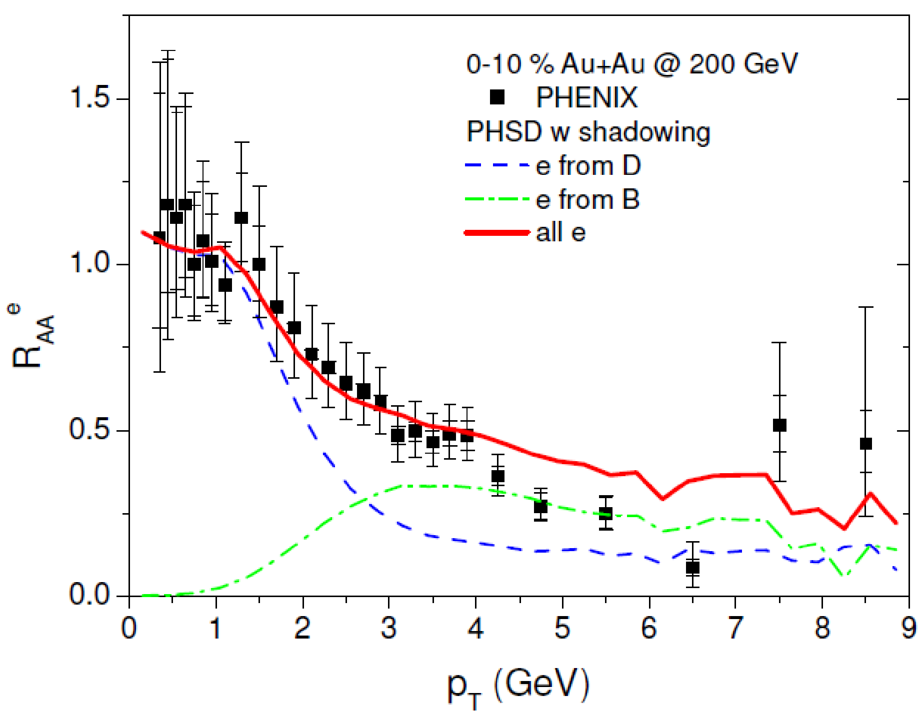
D meson production is suppressed in 5.02 TeV PbPb collisions

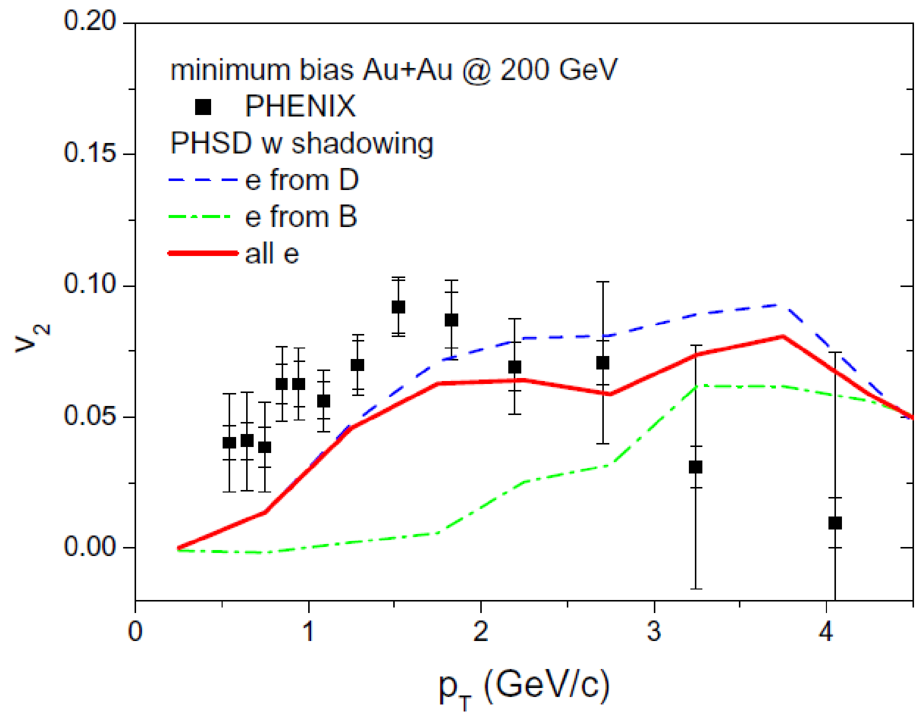


Plot from the talk by W. Xie

R_{AA}^e and v_2^e from single electrons: beauty contribution

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

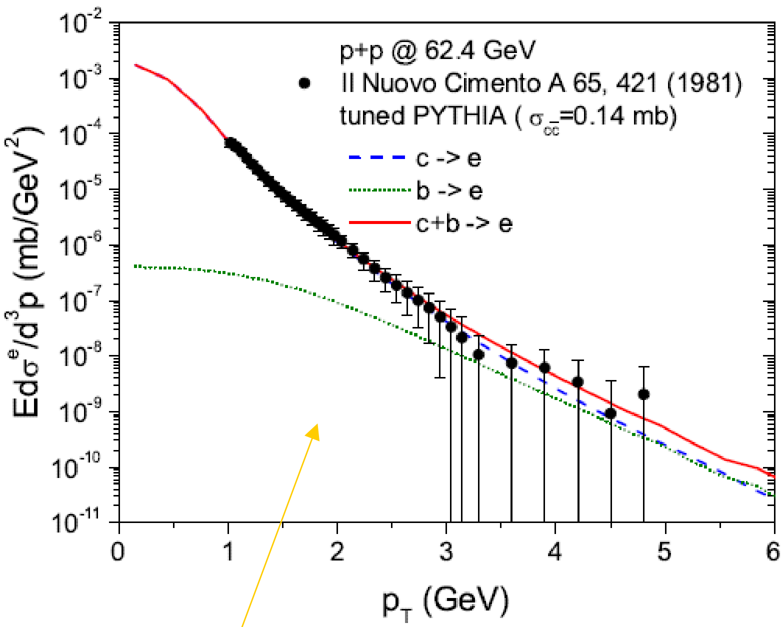


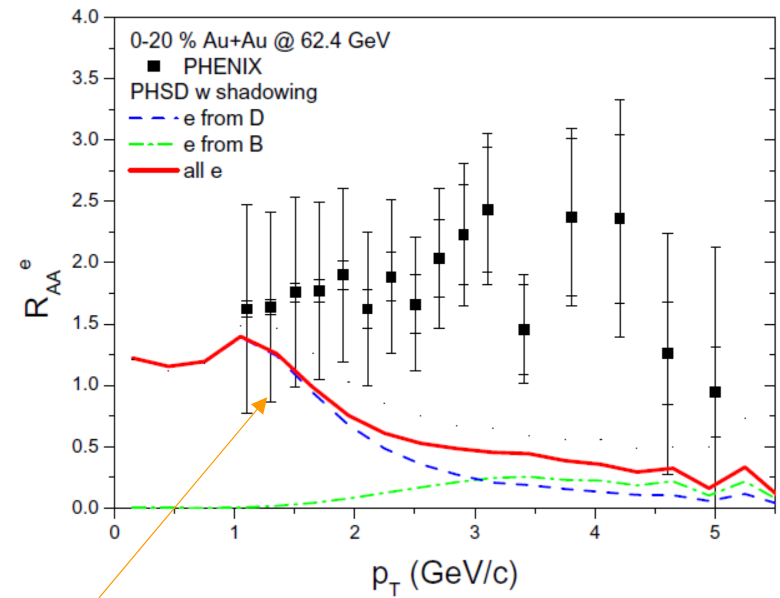


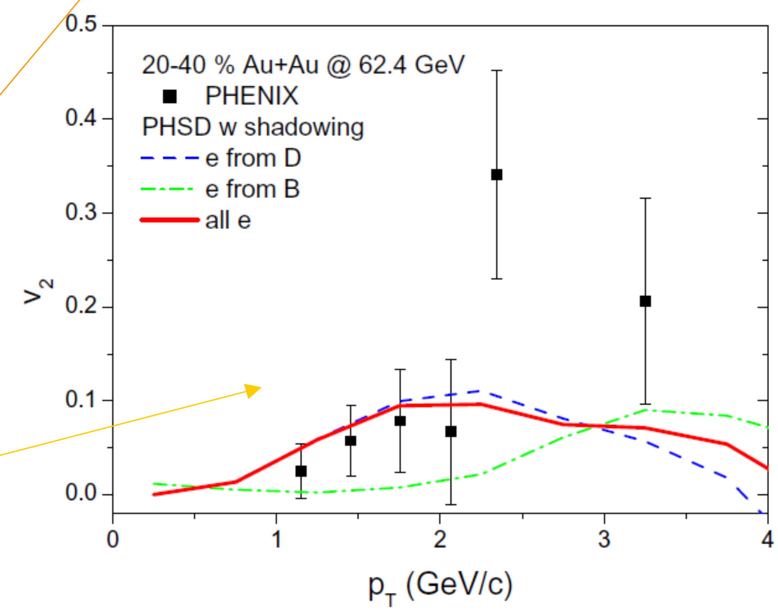
- Feed back from beauty contribution becoms dominant for p_T >3 GeV

T. Song et al., arXiv:1605.07887 [nucl-th]

R_{AA}^e and v_2^e of single electrons from Au+Au at 62.4 GeV



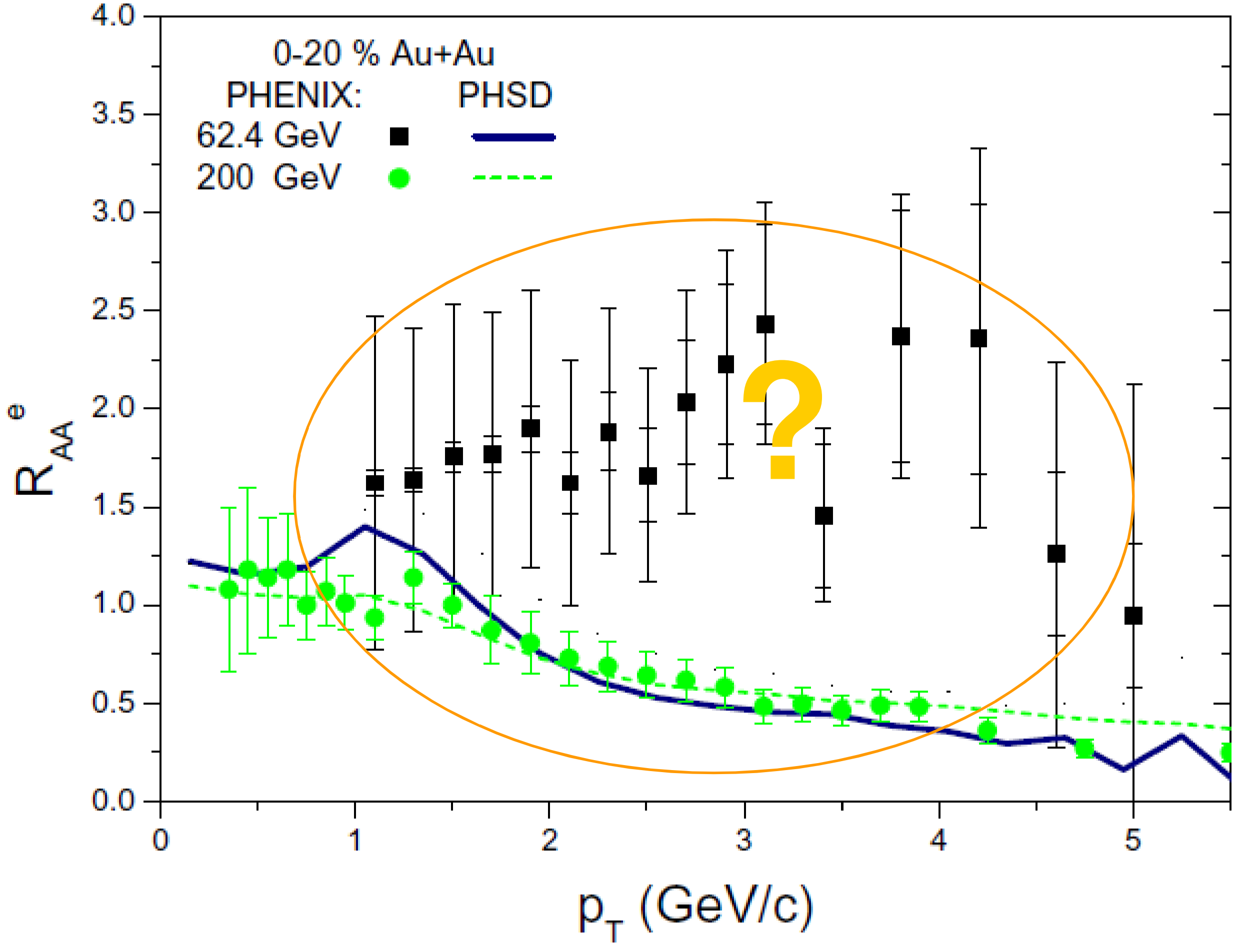




- **PHSD: pp data on electron p_T spectra are well reproduced**
- **PHENIX data on R_{AA}^e from single electrons from Au+Au at 62.4 GeV are not reproduced !**
- **v_2^e from single electrons from Au+Au at 62.4 GeV is in line with data**

T. Song et al., arXiv:1605.07887 [nucl-th]

R_{AA}^{e} from of electrons: 62.4 vs. 200 GeV

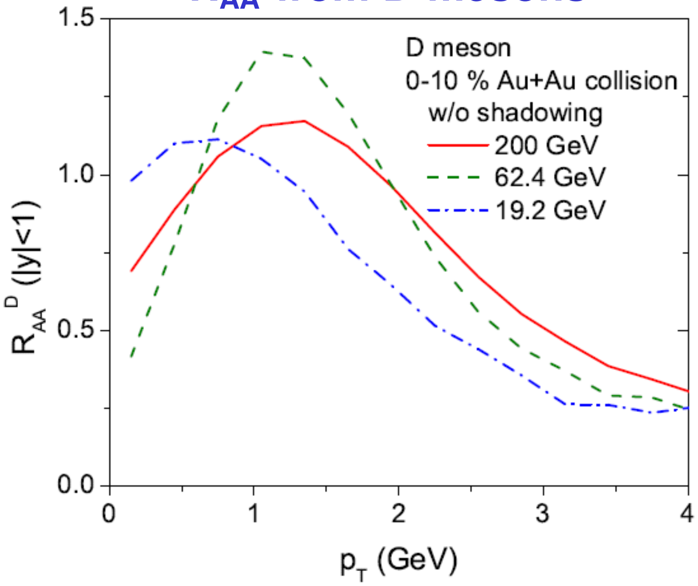


- **PHENIX:**

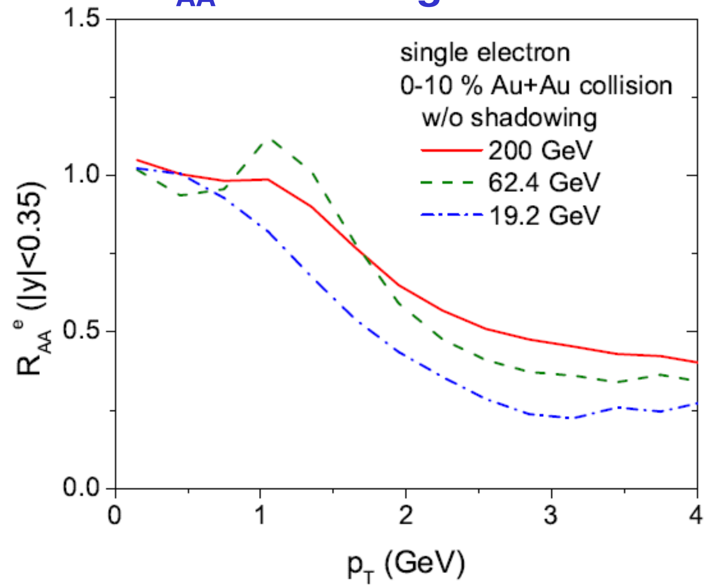
R_{AA}^{e} of single electrons from Au+Au at 62.4 GeV is much larger than at 200 GeV !

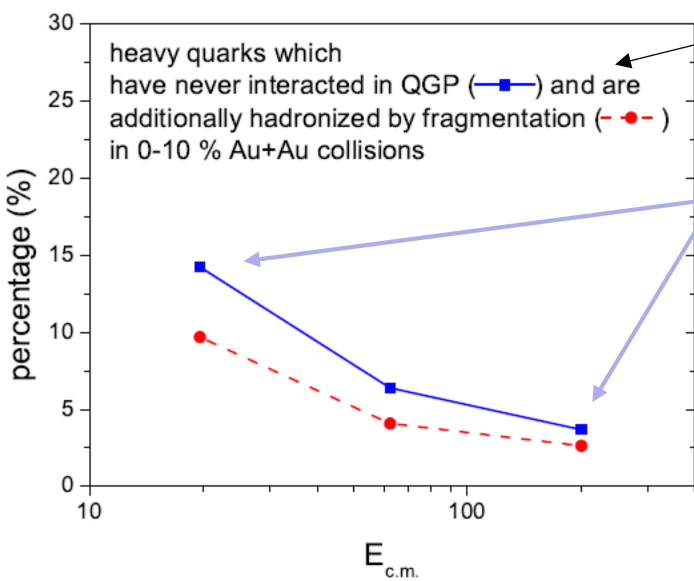
R_{AA} vs. beam energy

R_{AA} from D-mesons



R_{AA}^{e} from single electrons





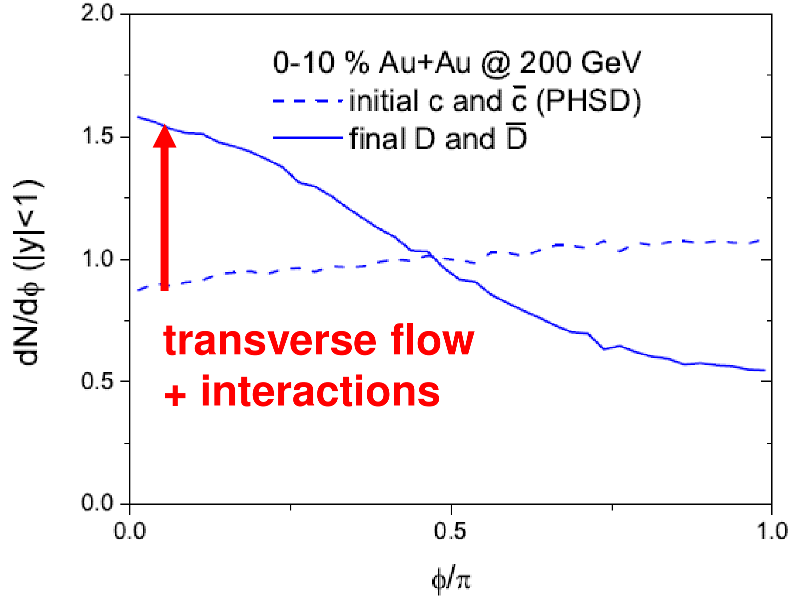
Fraction of HQ not interacting in QGP

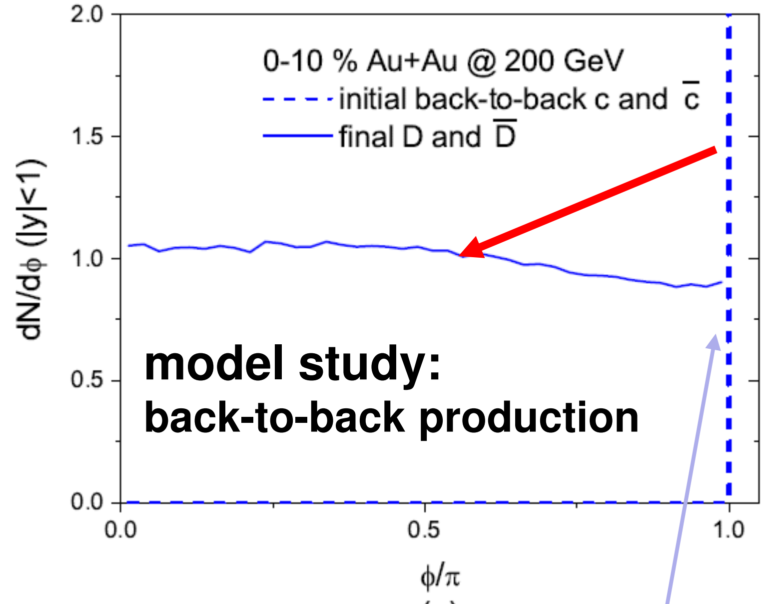
- ❑ **QGP fraction increases with energy**
- ❑ **Sizable Hadronic Corona at low energies**

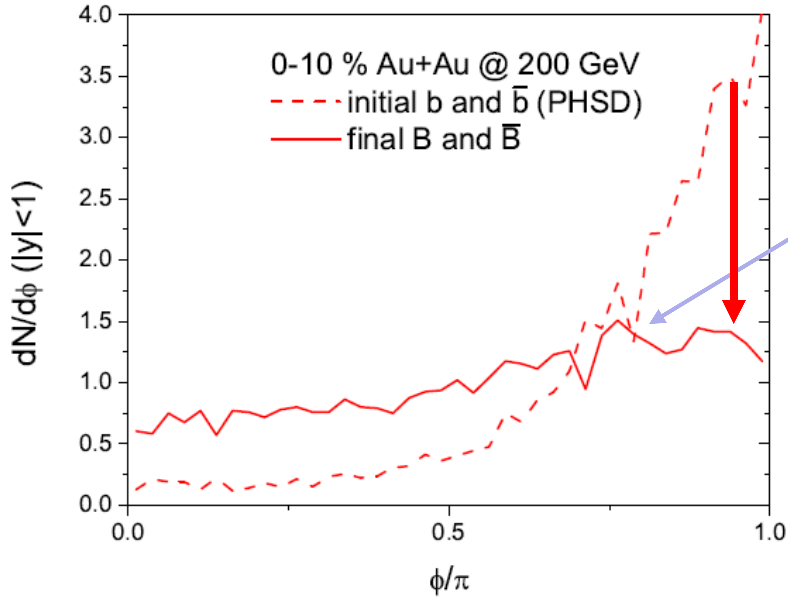
Au+Au, 200 GeV, central: each charm quark makes ~ 6 elastic collisions in QGP;
each D,D* makes ~ 2 scatterings with hadrons

T. Song et al., arXiv:1605.07887 [nucl-th]

Azimuthal angular correlations: Q-Qbar



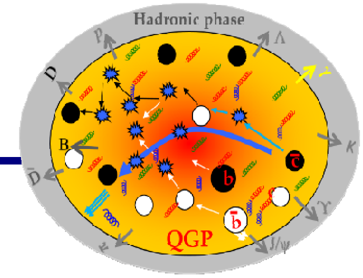




➔ **Initial azimuthal angular correlation of QQbar pairs is completely washed out during the evolution of the heavy-ion collision, even in case they are assumed to be initially produced back-to-back (model study) mainly due to the transverse flow + interactions**

T. Song et al., arXiv:1605.07887 [nucl-th]

Summary



- **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

- 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

Thank you!