Status and Perspectives regarding hard probes from microscopic transport

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Precision Spectroscopy of QGP Properties with Jets and Heavy Quarks
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DAAD

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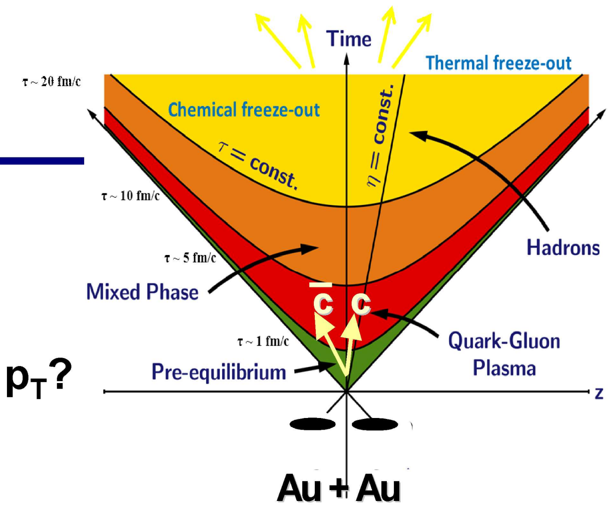
Heavy quarks –
open charm and beauty
(D/Dbar, B/Bbar)

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?



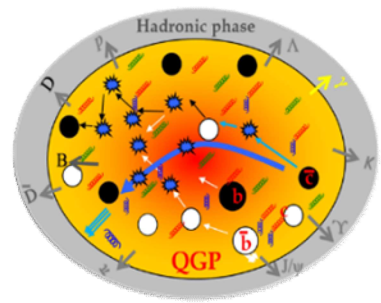
Dynamics of heavy quarks in A+A :

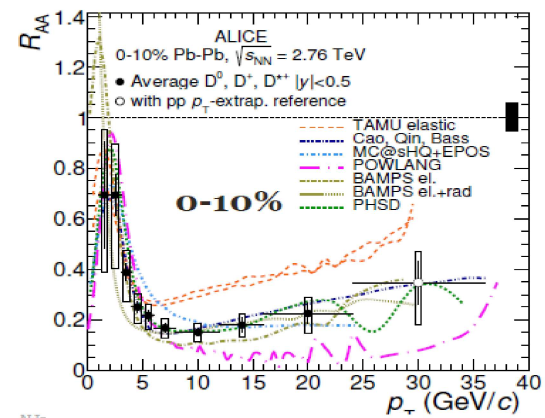
1. **Production** of heavy (charm and bottom) quarks in initial binary collisions + shadowing and Cronin effects

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

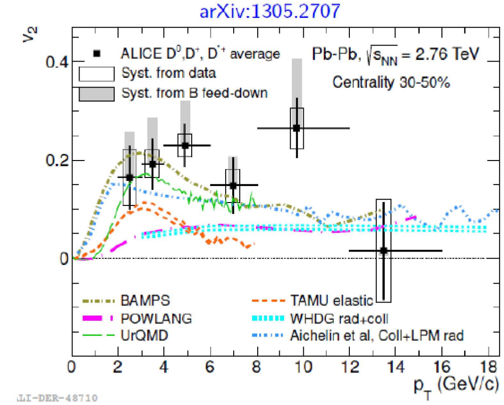
3. **Hadronization**: c/cbar quarks →D(D*)-mesons: coalescence vs fragmentation

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





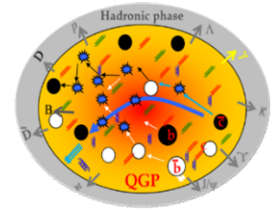
arXiv:1305.2707



Reliable dynamical models are needed!

Dynamical description of hard probes

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



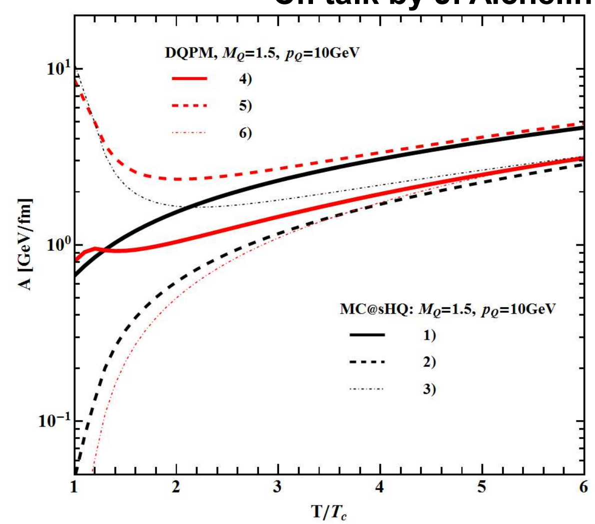
- ❑ expanding fireball models ← assumption of global equilibrium
- ❑ ideal or viscous hydrodynamical models ← assumption of local equilibrium
- ❑ microscopic transport models ← full non-equilibrium dynamics!

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

- ❑ Fokker-Planck model, Langevin model ← transport coefficients
- ❑ linear Boltzmann models ← cross sections
- ❑ microscopic collision integral ← cross sections

Cf. talk by J. Aichelin

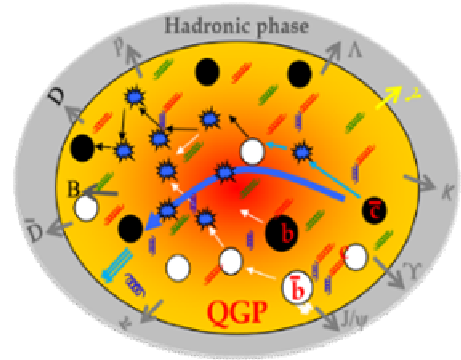
	coupling	mass in gluon propagator	mass in external legs
1)	$\alpha(Q^2)$	$\kappa = 0.2, m_D$	$m_{q,g} = 0$
2)	$\alpha(Q^2)$	$\kappa = 0.2, m_D$	$m_{q,g} = m_{q,g}^{DQPM}$
3)	$\alpha(T)$	$\kappa = 0.2, m_D$	$m_{q,g} = 0$
4)	$\alpha(T)$	m_g^{DQPM}	$m_{q,g} = m_{q,g}^{DQPM}$
5)	$\alpha(T)$	m_g^{DQPM}	$m_{q,g}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



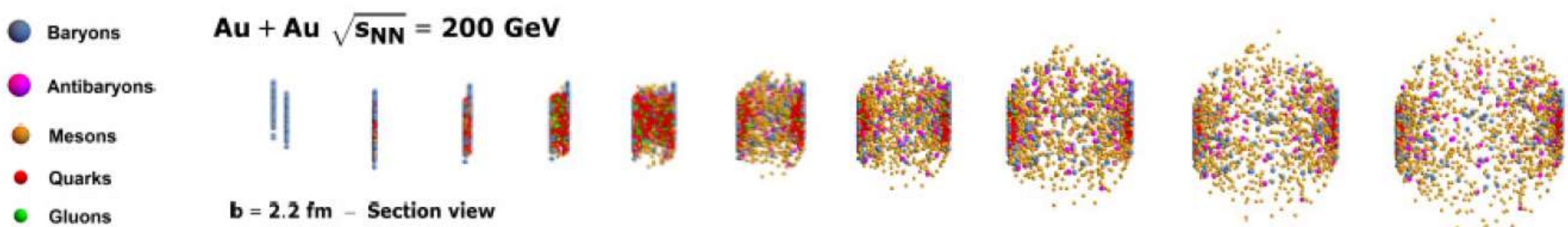
Dynamical Models → PHSD

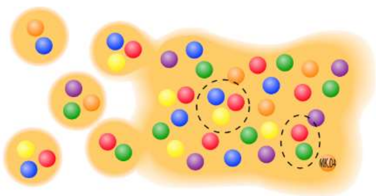
The goal:

to describe the dynamics of charm quarks/mesons in all phases of HIC on a microscopic basis



The tool: PHSD approach

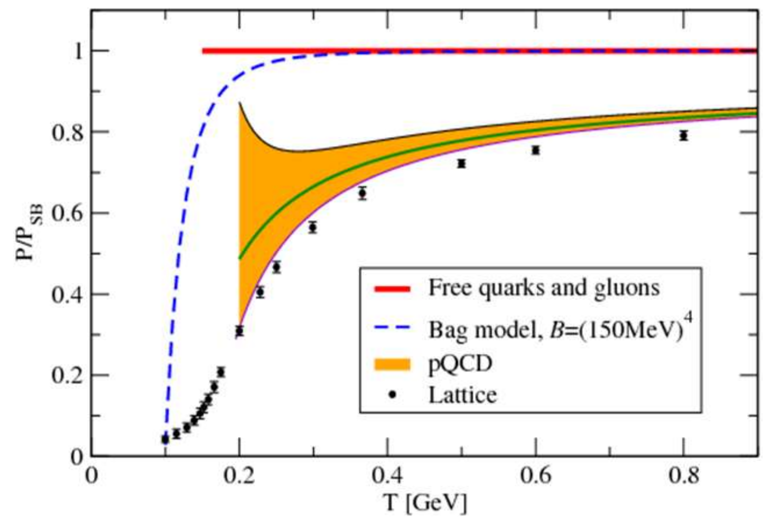




Degrees-of-freedom of QGP

❖ lQCD gives QGP EoS ➔

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



Non-perturbative QCD ← pQCD

pQCD:

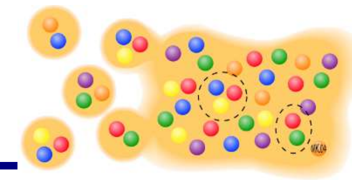
- ❑ weakly interacting system
- ❑ massless quarks and gluons

Thermal QCD = QCD at high parton densities:

- ❑ strongly interacting system
- ❑ massive quarks and gluons

❖ Effective degrees-of-freedom

From SIS to LHC: from hadrons to partons



The goal: to study of the phase transition from hadronic to partonic matter and properties of the Quark-Gluon-Plasma on a microscopic level

➔ need a consistent non-equilibrium transport approach

- with explicit parton-parton interactions (i.e. between quarks and gluons)
- explicit phase transition from hadronic to partonic degrees of freedom
- lQCD EoS for partonic phase (‚cross over' at μ_q=0)

- Transport theory for strongly interacting systems: off-shell Kadanoff-Baym equations for the Green-functions $S^<_h(x,p)$ in phase-space representation for the partonic and hadronic phase

⇨ **Parton-Hadron-String-Dynamics (PHSD)**

QGP phase is described by

Dynamical QuasiParticle Model (DQPM)

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

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

Dynamical QuasiParticle Model (DQPM) - Basic ideas:

DQPM describes QCD properties in terms of 'resummed' single-particle Green's functions (propagators) – in the sense of a two-particle irreducible (2PI) approach:

gluon propagator: $\Delta^{-1} = P^2 - \Pi$ & quark propagator $S_q^{-1} = P^2 - \Sigma_q$

gluon self-energy: $\Pi = M_g^2 - i2\Gamma_g\omega$ & quark self-energy: $\Sigma_q = M_q^2 - i2\Gamma_q\omega$

(scalar approximation)

- the resummed properties are specified by complex (retarded) self-energies which depend on temperature:
  - the real part of self-energies (Σ_q, Π) describes a dynamically generated mass (M_q,M_g);
  - the imaginary part describes the interaction width of partons (Γ_q, Γ_g)

- space-like part of energy-momentum tensor $T_{\mu\nu}$ defines the potential energy density and the mean-field potential (1PI) for quarks and gluons (U_q, U_g)

- 2PI framework guarantees a consistent description of the system in- and out-of equilibrium on the basis of Kadanoff-Baym equations with proper states in equilibrium

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

The Dynamical QuasiParticle Model (DQPM)

Properties of interacting quasi-particles:
massive quarks and gluons (g, q, q_{bar})
with Lorentzian spectral functions:

$$A_i(\omega, T) = \frac{4\omega\Gamma_i(T)}{\left(\omega^2 - \vec{p}^2 - M_i^2(T)\right)^2 + 4\omega^2\Gamma_i^2(T)}$$

$$(i = q, \bar{q}, g)$$

- **Modeling of the quark/gluon masses and widths → HTL limit at high T**
  - **quarks:**

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

    width: $\Gamma_{q(\bar{q})}(T) = \frac{1}{3}\frac{N_c^2 - 1}{2N_c}\frac{g^2 T}{8\pi}\ln\left(\frac{2c}{g^2} + 1\right)$

  - **gluons:**

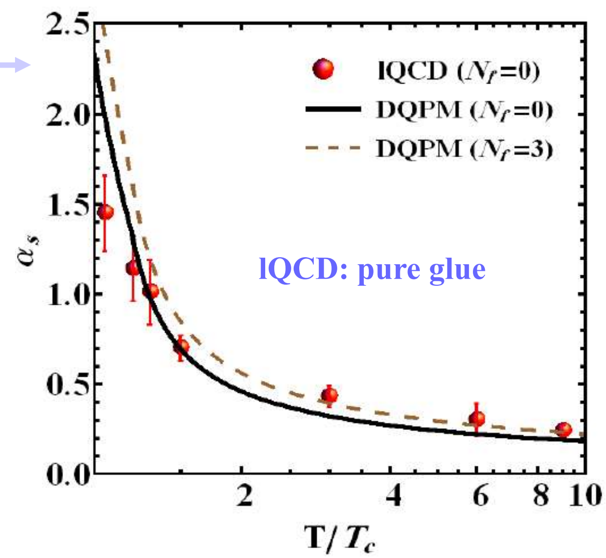
    $M_g^2(T) = \frac{g^2}{6}\left(\left(N_c + \frac{N_f}{2}\right)T^2 + \frac{N_c}{2}\sum_q \frac{\mu_q^2}{\pi^2}\right)$

    $\Gamma_g(T) = \frac{1}{3}N_c\frac{g^2 T}{8\pi}\ln\left(\frac{2c}{g^2} + 1\right)$

$N_c = 3$, $N_f = 3$

  - **running coupling: T-dependent $\alpha_S(T)$**

$$\alpha_s(T) = \frac{g^2(T)}{4\pi} = \frac{12\pi}{(11N_c - 2N_f)\ln[\lambda^2(T/T_c - T_s/T_c)^2]}$$



❑ **fit to lattice (lQCD) results (e.g. entropy density)**

with 3 parameters: T_s/T_c=0.46; c=28.8; λ=2.42
(for pure glue N_f=0)

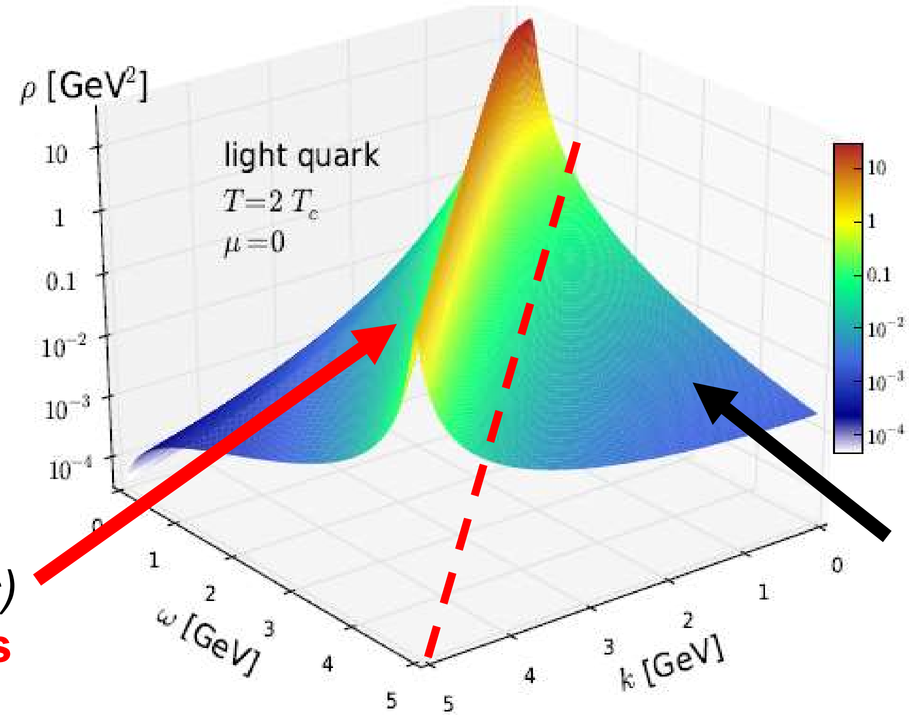
DQPM: Peshier, Cassing, PRL 94 (2005) 172301;
Cassing, NPA 791 (2007) 365: NPA 793 (2007)

The Dynamical QuasiParticle Model (DQPM)

$$A_i(\omega,T) = \frac{4\omega\Gamma_i(T)}{\left(\omega^2 - \vec{p}^2 - M_i^2(T)\right)^2 + 4\omega^2\Gamma_i^2(T)}$$

➔ **Broad spectral function of gluons and quarks**

time-like:
(real particles)
propagate as a particle



space-like:
(exchange quanta)
contribute to scalar-mean-field potential

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

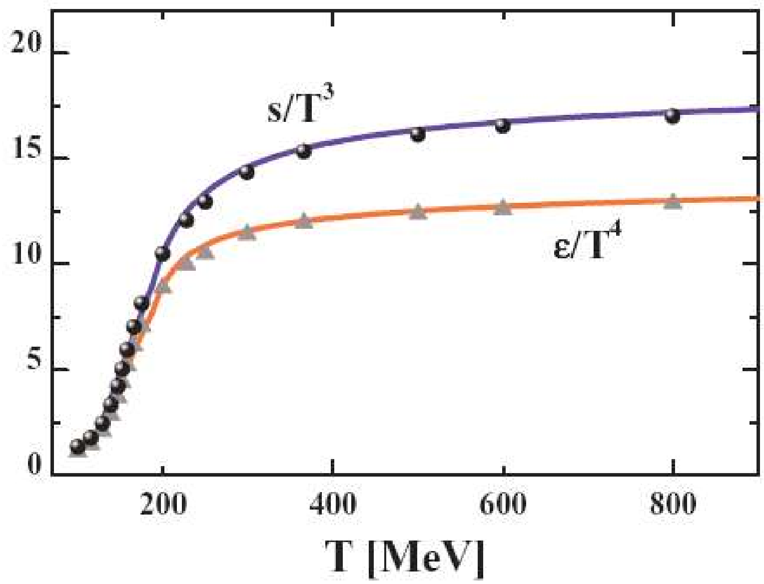
DQPM thermodynamics (N_f=3) and lQCD

- **Energy-momentum tensor $T_{\mu\nu}$ → thermodynamics of QGP**

→ **fit to lattice (lQCD) results with 3 parameters:**

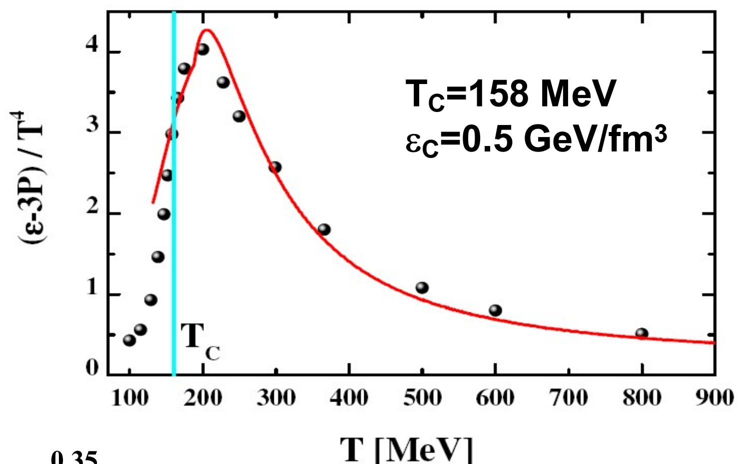
- **entropy** $s = \frac{\partial P}{dT}$ → **pressure P**
- **energy density:** $\epsilon = Ts - P$

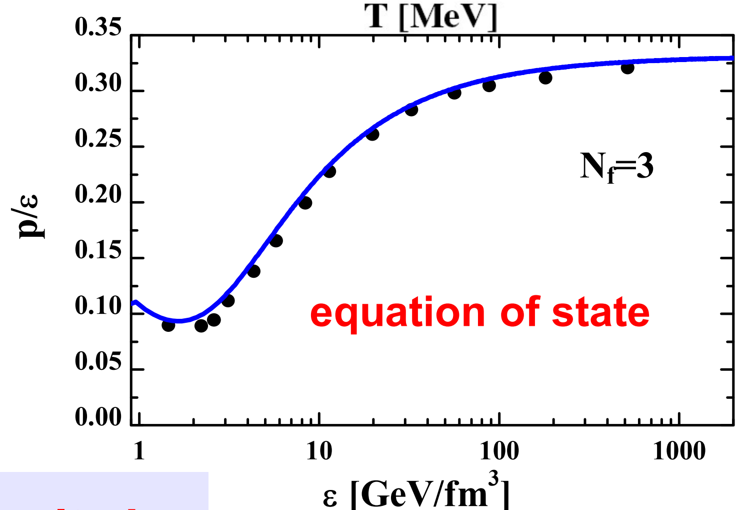
lQCD: Wuppertal-Budapest group
Y. Aoki et al., JHEP 0906 (2009) 088.



- **interaction measure:**

$$W(T) := \epsilon(T) - 3P(T) = Ts - 4P$$





DQPM gives a good description of lQCD results !

Mean-field potential for quasiparticles

- Space-like part of energy-momentum tensor $T_{\mu\nu}$ defines the potential energy density:

$$V_p(T,\mu_q) = T^{00}_{g-}(T,\mu_q) + T^{00}_{q-}(T,\mu_q) + T^{00}_{\bar{q}-}(T,\mu_q)$$

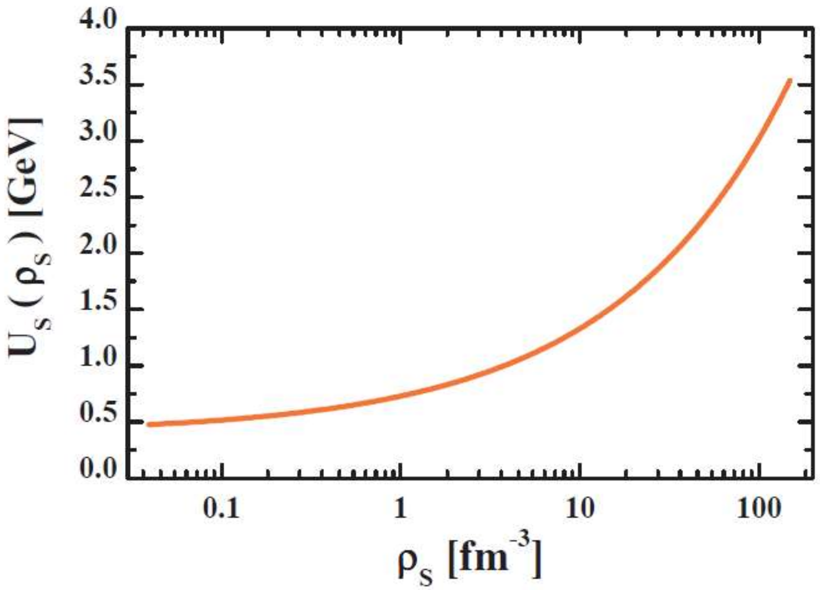
space-like gluons space-like quarks+antiquarks

- space-like energy density of quarks and gluons = ~1/3 of total energy density

➔ mean-field scalar potential (1PI) for quarks and gluons (U_q, U_g) vs scalar density ρ_S:

$$U_s(\rho_s) = \frac{dV_p(\rho_s)}{d\rho_s}$$

U_q=U_S, U_g~$2U_S$



Quasiparticle potentials (U_q, U_g) are repulsive !

➔ the force acting on a quasiparticle j:

$$F \sim M_j/E_j \nabla U_s(x) = M_j/E_j \; dU_s/d\rho_s \; \nabla\rho_s(x)$$

$j = g, q, \bar{q}$

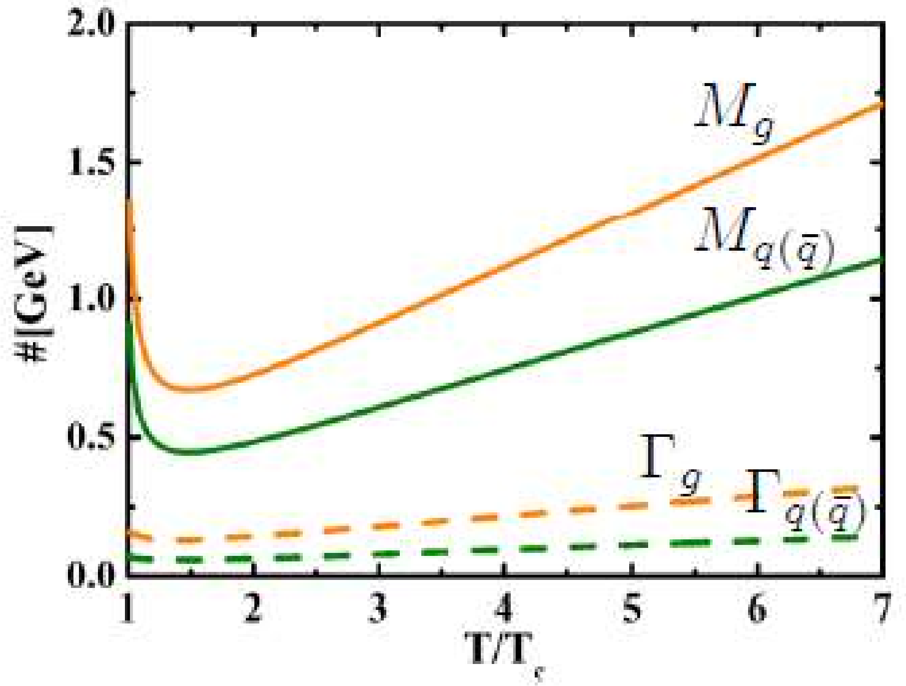
➔ accelerates particles

Cassing, NPA 791 (2007) 365: NPA 793 (2007)

The Dynamical QuasiParticle Model (DQPM)

➔ **Quasiparticle properties:**

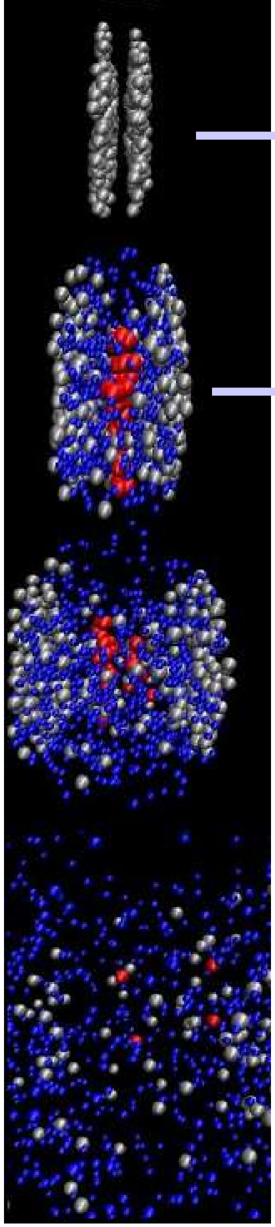
- **large width and mass for gluons and quarks**



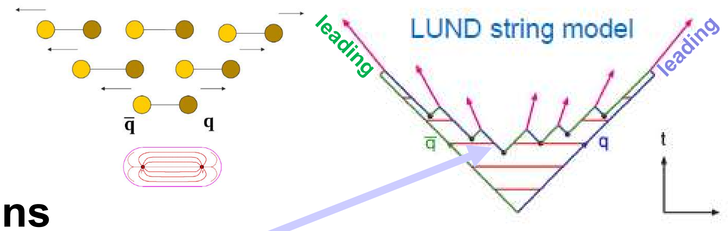
- **DQPM matches well lattice QCD**
- **DQPM provides mean-fields (1PI) for gluons and quarks as well as effective 2-body interactions (2PI)**
- **DQPM gives transition rates for the formation of hadrons → PHSD**

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

I. PHSD - basic concept



I. From hadrons to QGP:



- **Initial A+A collisions** – as in HSD:
  - string formation in primary NN collisions
  - string decay to pre-hadrons (= new produced secondary hadrons: *B* - baryons, *m* - mesons) ➔ 'flavor chemistry' from strings

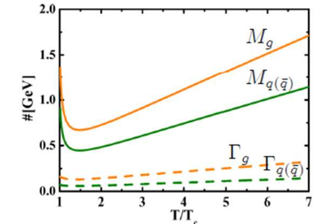
- **Formation of initial QGP stage** - if local energy density $\varepsilon > \varepsilon_c$ =0.5 GeV/fm^3:

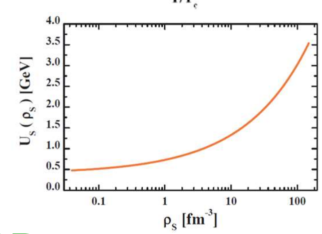
I. Dynamical Quasi-Particle Model (DQPM) defines:

1) properties of quasiparticles in equilibrium, i.e. masses $M_q(T)$ and widths $\Gamma_q(T)$ ($T \rightarrow \varepsilon$ by lQCD EoS)

2) 'chemistry' of 'initial state' of QGP: number of q, qbar, g

3) 'energy balance', i.e. the fraction of mean-field quark and gluon potentials U_q, U_g from the energy density ε





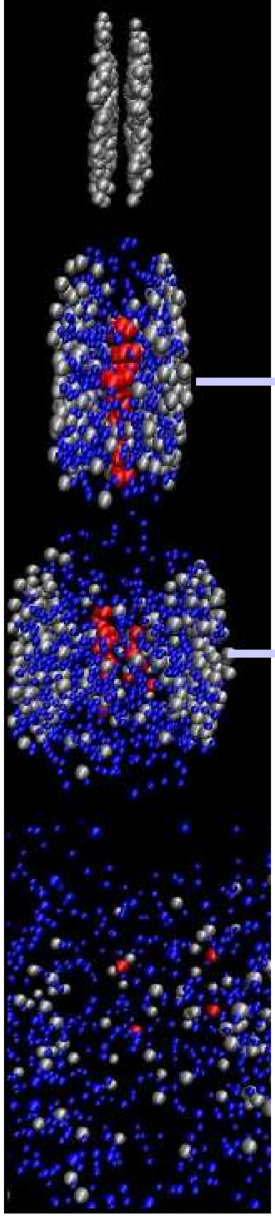
II. Realization of the initial QGP stage from DQPM in the PHSD:
by dissolution of pre-hadrons (keep 'leading' hadrons!) into massive colored quarks (and gluons) + mean-field energy

$$B \rightarrow qqq, \quad \tilde{m} \rightarrow q\bar{q}, \quad (q\bar{q}) \Rightarrow g \quad \forall \quad U_q, U_g$$

➔ allows to keep initial non-equilibrium momentum anisotropy !

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

II. PHSD - basic concept



II. Partonic phase - QGP:

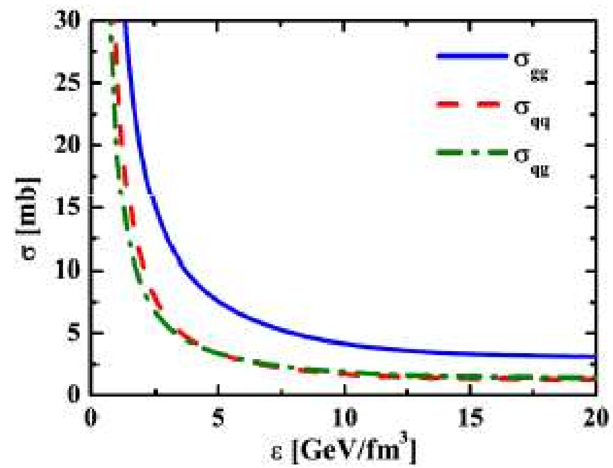
- Propagation of quarks and gluons (= ‚dynamical quasiparticles') with off-shell spectral functions (width, mass) defined by the DQPM in self-generated mean-field potential for quarks and gluons U_q, U_g

- EoS of partonic phase: ‚crossover' from lattice QCD (fitted by DQPM)

- (quasi-) elastic and inelastic parton-parton interactions: using the effective cross sections from the DQPM

  - (quasi-) elastic collisions:

$$q+q \to q+q \qquad g+q \to g+q$$
$$q+\bar{q} \to q+\bar{q} \qquad g+\bar{q} \to g+\bar{q}$$
$$\bar{q}+\bar{q} \to \bar{q}+\bar{q} \qquad g+g \to g+g$$

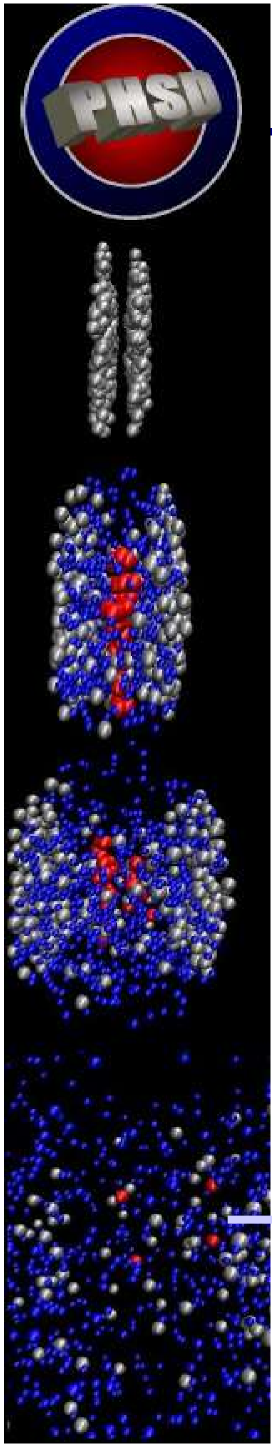


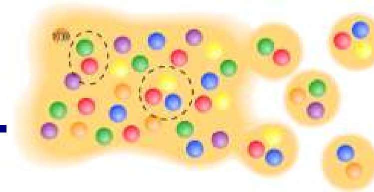
  - inelastic collisions: (Breit-Wigner cross sections)

$$\begin{cases} q+\bar{q} \to g \\ g \to q+\bar{q} \end{cases}$$

$$\left. \begin{array}{l} q+\bar{q} \to g+g \\ g \to g+g \end{array} \right\}$$ suppressed (<1%) due to the large mass of gluons

III. PHSD - basic concept

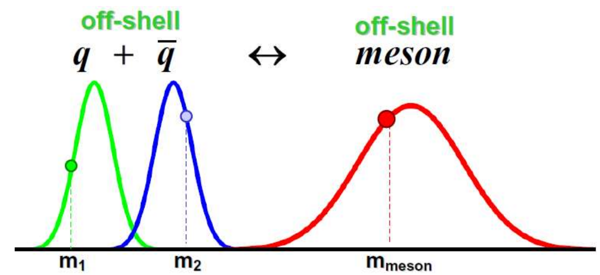




III. Hadronization (based on DQPM):

- massive, off-shell (anti-)quarks with broad spectral functions hadronize to off-shell mesons and baryons or color neutral excited states - ‚strings‘ (strings act as ‚doorway states‘ for hadrons)

$$g \to q + \bar{q}, \qquad q + \bar{q} \leftrightarrow meson \ ('string')$$
$$q + q + q \leftrightarrow baryon \ ('string')$$



- Local covariant off-shell transition rate for q+qbar fusion

➔ meson formation:

$$Tr_j = \sum_j \int d^4x_j d^4p_j/(2\pi)^4$$

$$\frac{dN^{q+\bar{q}\to m}}{d^4x\, d^4p} = Tr_q Tr_{\bar{q}}\ \delta^4(p - p_q - p_{\bar{q}})\ \delta^4\left(\frac{x_q + x_{\bar{q}}}{2} - x\right)\ \delta(flavor, color)$$
$$\cdot N_q(x_q, p_q)\ N_{\bar{q}}(x_{\bar{q}}, p_{\bar{q}}) \cdot \omega_q\ \rho_q(p_q) \cdot \omega_{\bar{q}}\ \rho_{\bar{q}}(p_{\bar{q}}) \cdot |M_{q\bar{q}}|^2\ W_m\left(x_q - x_{\bar{q}}, p_q - p_{\bar{q}}\right)$$

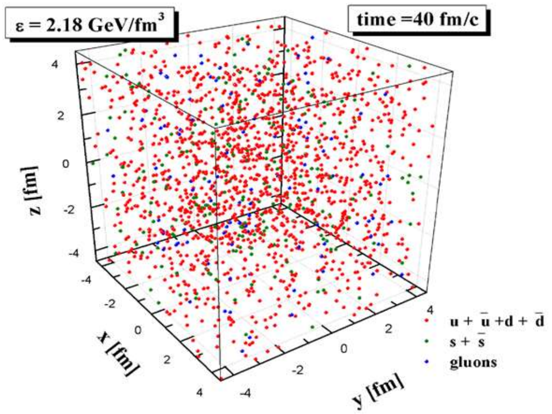
- $N_j(x,p)$ is the phase-space density of parton j at space-time position *x* and 4-momentum *p*
- W_m is the phase-space distribution of the formed ‚pre-hadrons‘ (Gaussian in phase space)
- $|M_{qq}|^2$ is the effective quark-antiquark interaction from the DQPM

➔ Strict 4-momentum and quantum number (flavour, color) conservation

IV. Hadronic phase: hadron-string interactions – off-shell HSD

QGP in equilibrium: Transport properties at finite (T, μ_q): η/s

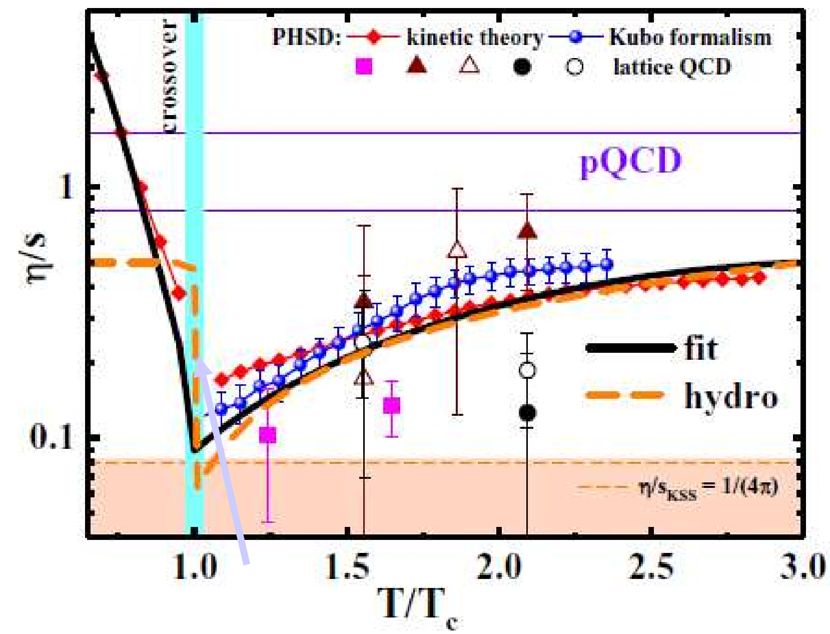
Infinite hot/dense matter =
PHSD in a box:



Shear viscosity η/s at finite T

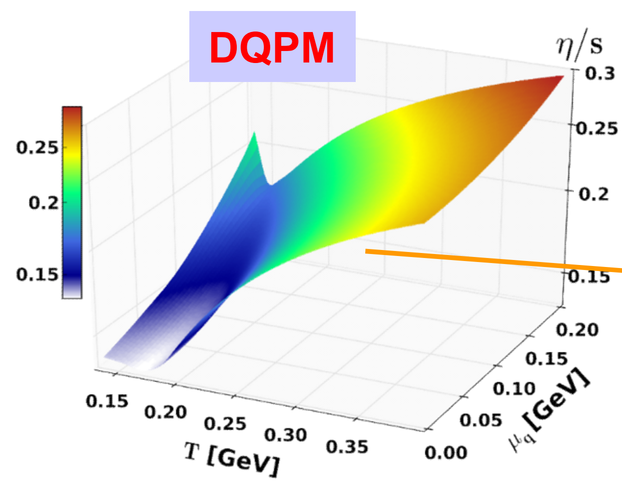
PHSD: V. Ozvenchuk et al., PRC 87 (2013) 064903

Hydro: Bayesian analysis, S. Bass et al.



Shear viscosity η/s at finite (T, μ_q)

lQCD: $$\frac{T_c(\mu_q)}{T_c(\mu_q=0)} = \sqrt{1-\alpha\,\mu_q^2} \approx 1-\alpha/2\,\mu_q^2+\cdots$$



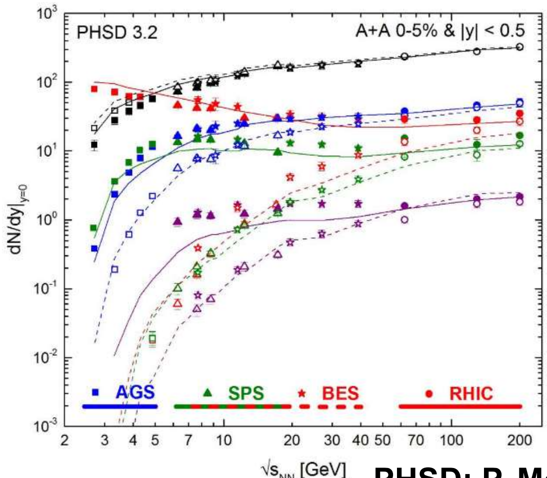
QGP in PHSD = strongly-interacting liquid-like system

η/s: $\mu_q=0$ ➔ finite μ_q: smooth increase as a function of (T, μ_q)

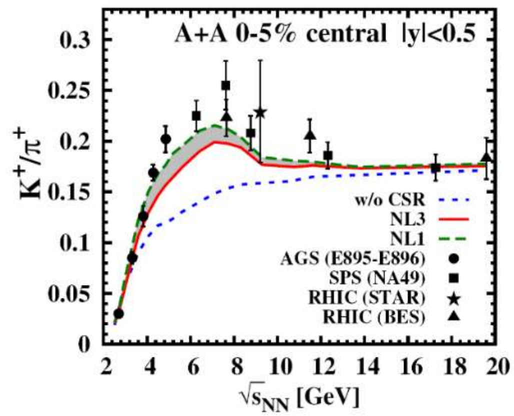
Review: H. Berrehrah et al. Int.J.Mod.Phys. E25 (2016) 1642003

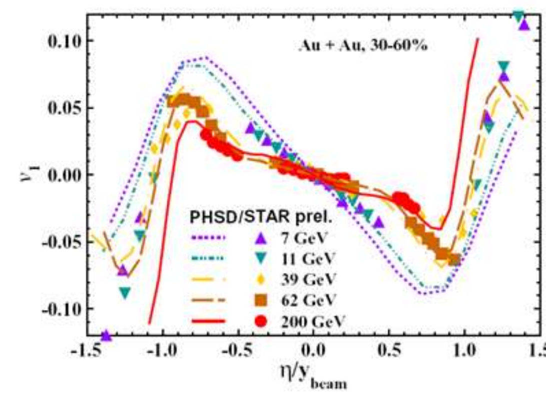
Non-equilibrium dynamics: description of A+A with PHSD

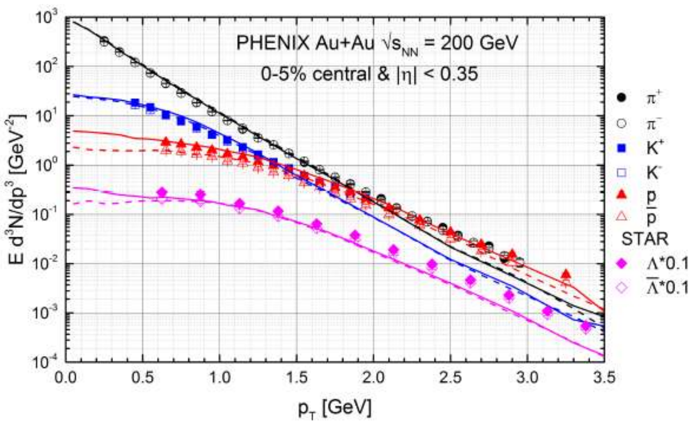
❑ **Important:** to be conclusive on charm observables, the **light quark dynamics** must be well under control!

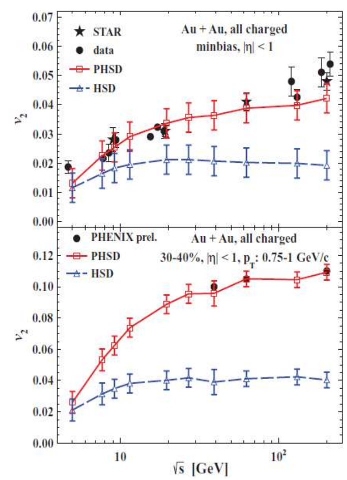


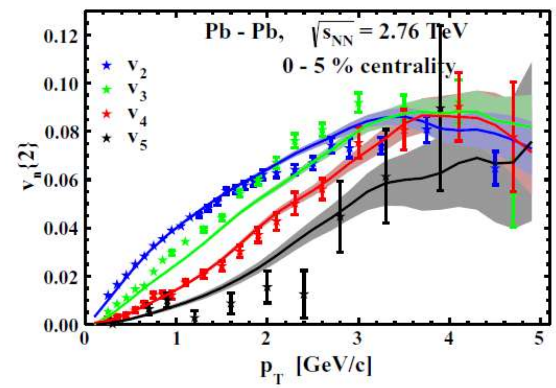
PHSD: P. Moreau











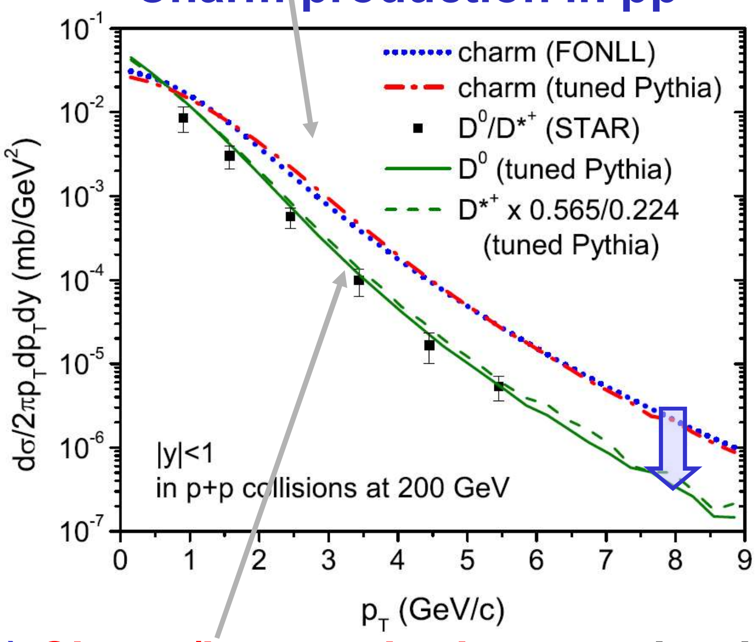
V. Konchakovski et al.,
PRC 85 (2012) 011902; JPG42 (2015) 055106

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

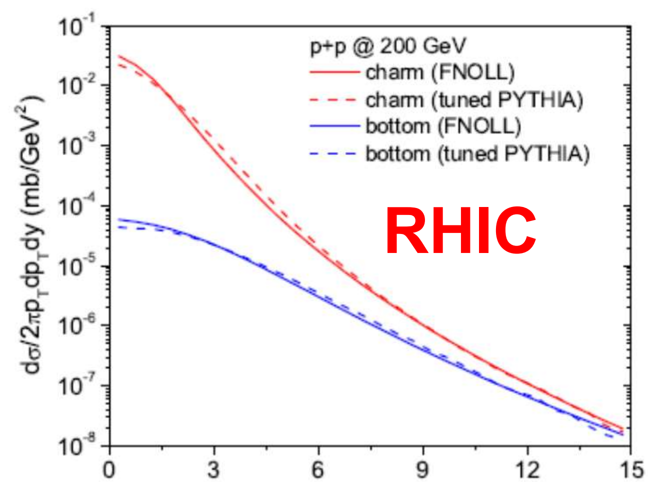
Heavy quark/hadron production in p+p collisions

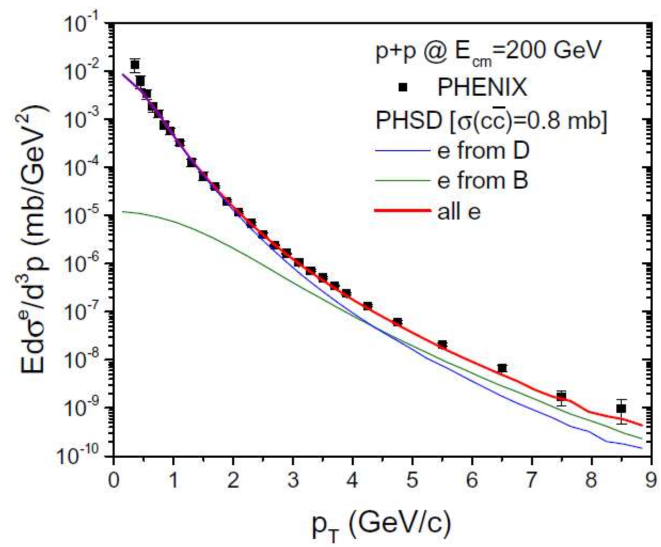
1) Momentum distribution of heavy quarks: use ‚tuned' PYTHIA event generator to reproduce FONLL (fixed-order next-to-leading log) results (R. Vogt et al.)

Charm production in pp



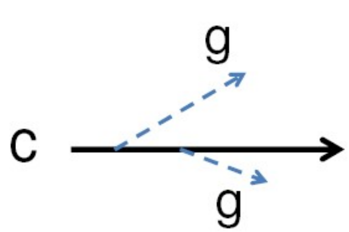
Beauty production in pp





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

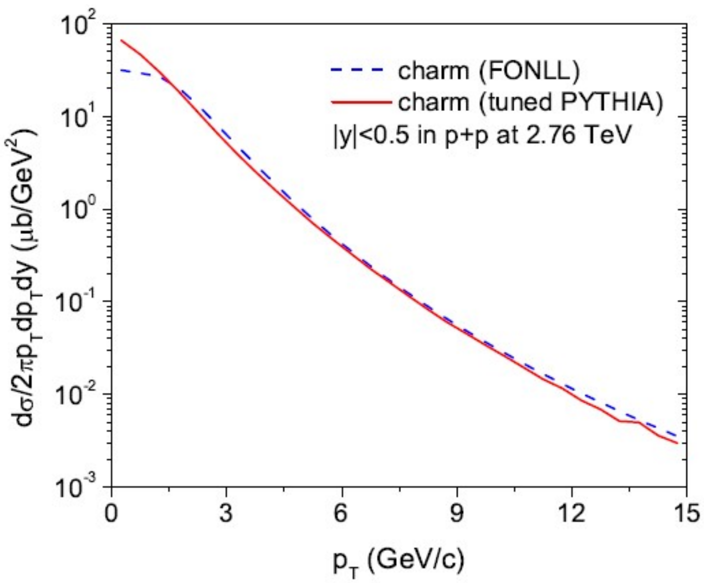
D^0 20 %
D^+ 17.4 %
D^{*0} 21.3 %
D^{*+} 22.4 %
Ds^+ 8 %
Λ_c 9.4 %

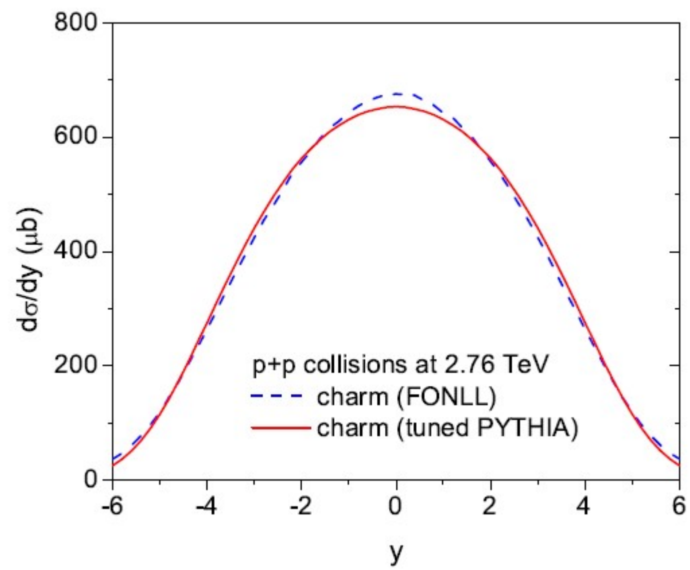


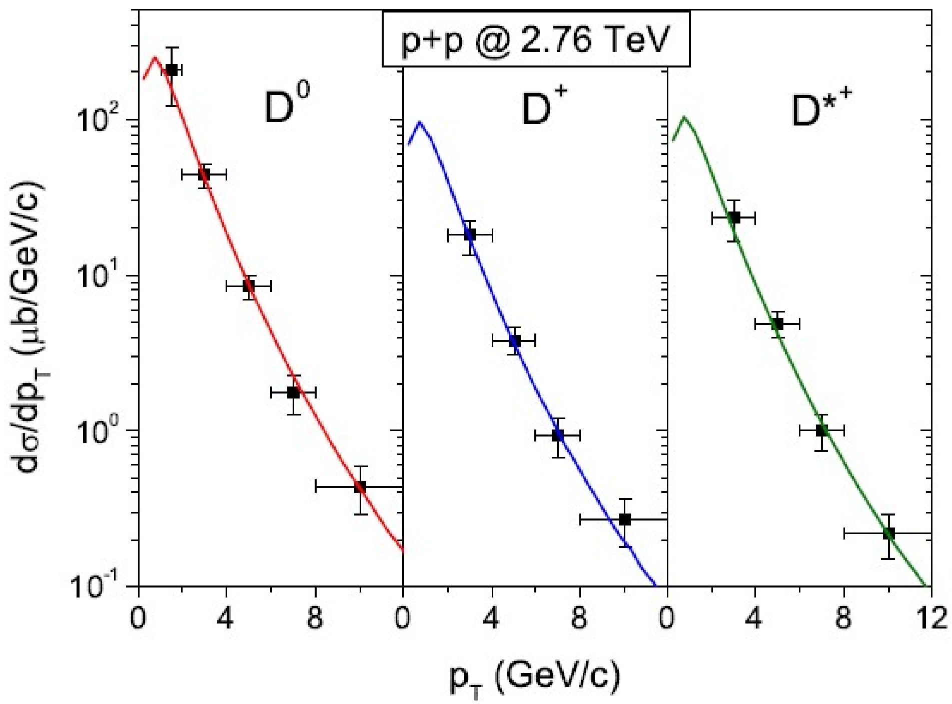
T. Song et al., PRC 92 (2015) 014910, arXiv:1503.03039

Charm quark/hadrons production in p+p collisions

LHC







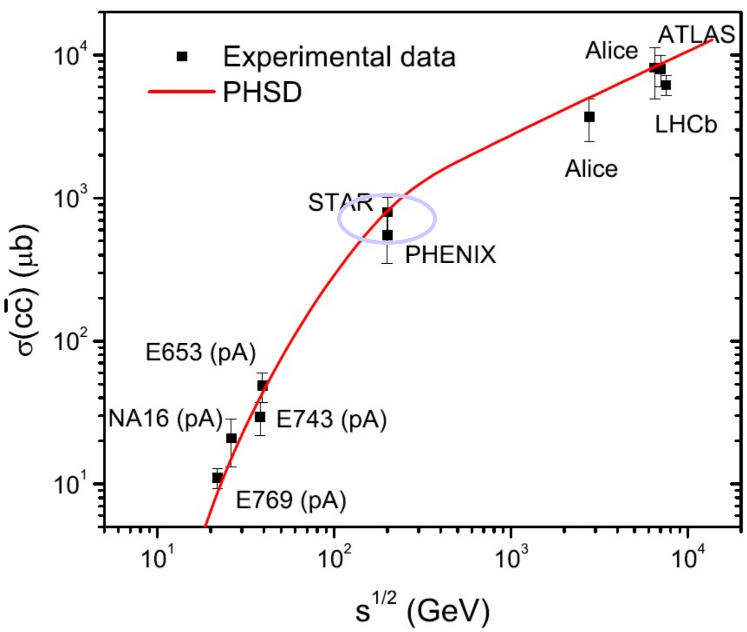
Momentum distribution of charm quark:
use ‚tuned' PYTHIA event generator to reproduce FONLL (fixed-order next-to-leading log) results (R. Vogt et al.)

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

Charm quark production in A+A

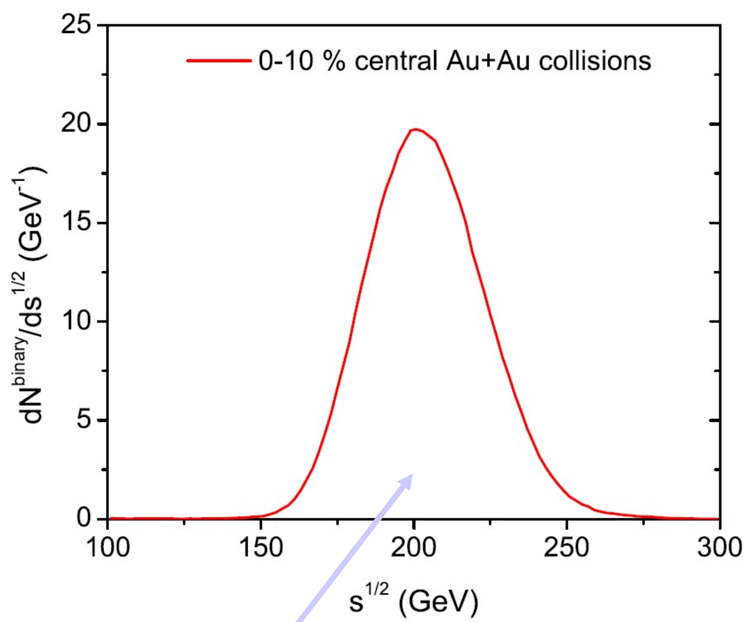
- A+A: charm production in **initial NN binary collisions:** probability $P = \frac{\sigma(c\bar{c})}{\sigma_{NN}^{inel}}$

- **The total cross section for charm production in p+p collisions σ(cc)**



- **The energy distribution of binary NN collision including Fermi smearing**

Au+Au, 0-10%, 200 GeV

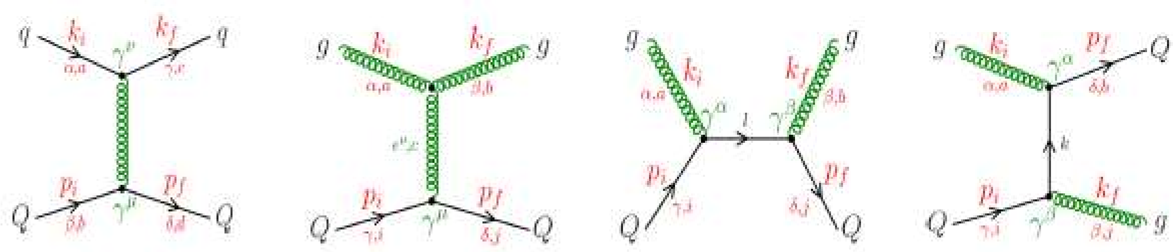


Collision energy smearing due to the Fermi motion

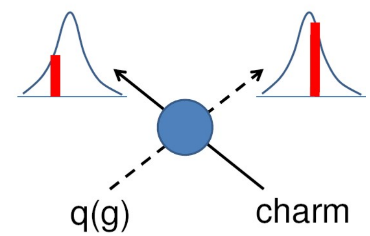
T. Song et al., PRC 92 (2015) 014910, arXiv:1503.03039

Heavy quark scattering in the QGP (DQPM)

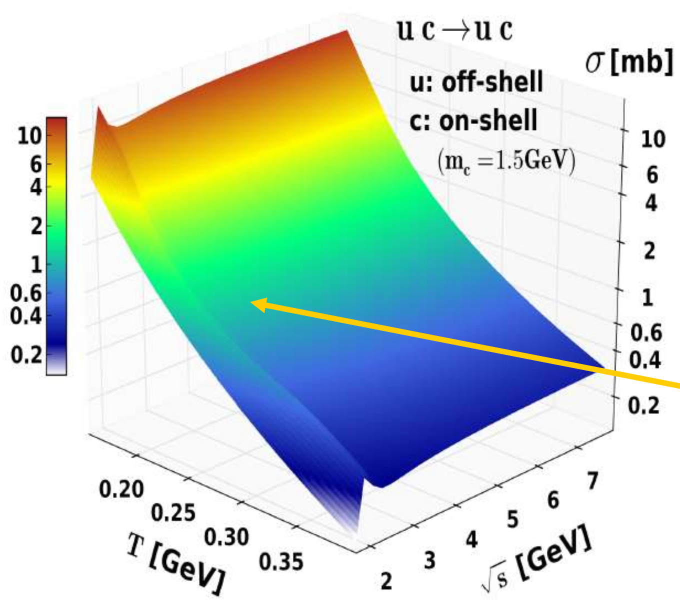
- Elastic scattering with **off-shell massive partons Q+q(g)→Q+q(g)**



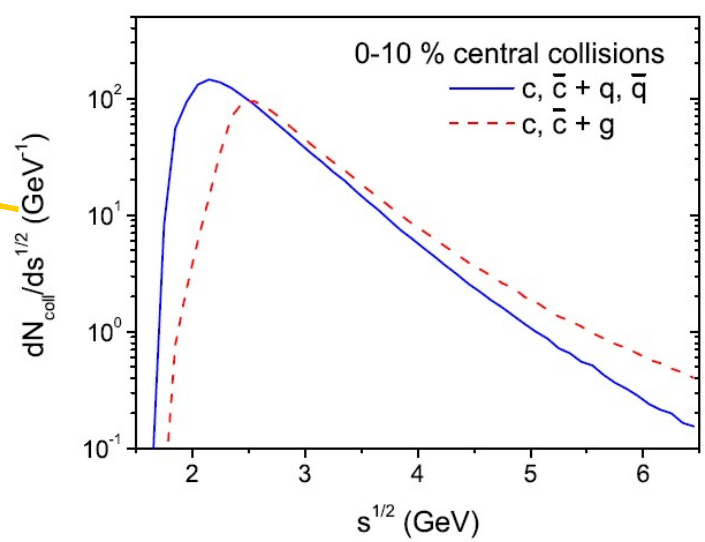
Non-perturbative QGP!



- **Elastic cross section uc→uc**



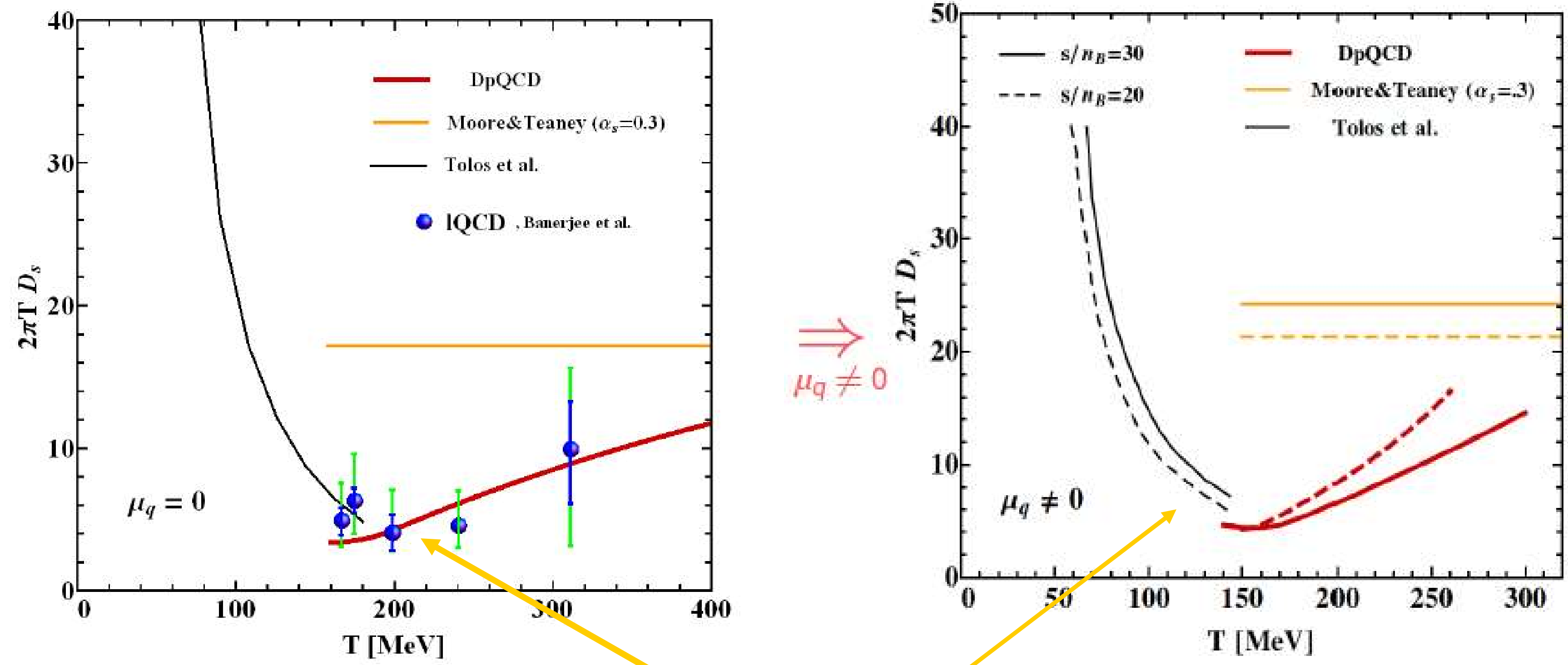
- **Distributions of Q+q, Q+g collisions vs $s^{1/2}$ in Au+Au, 10% central**



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



❑ T < T_c : hadronic D_s

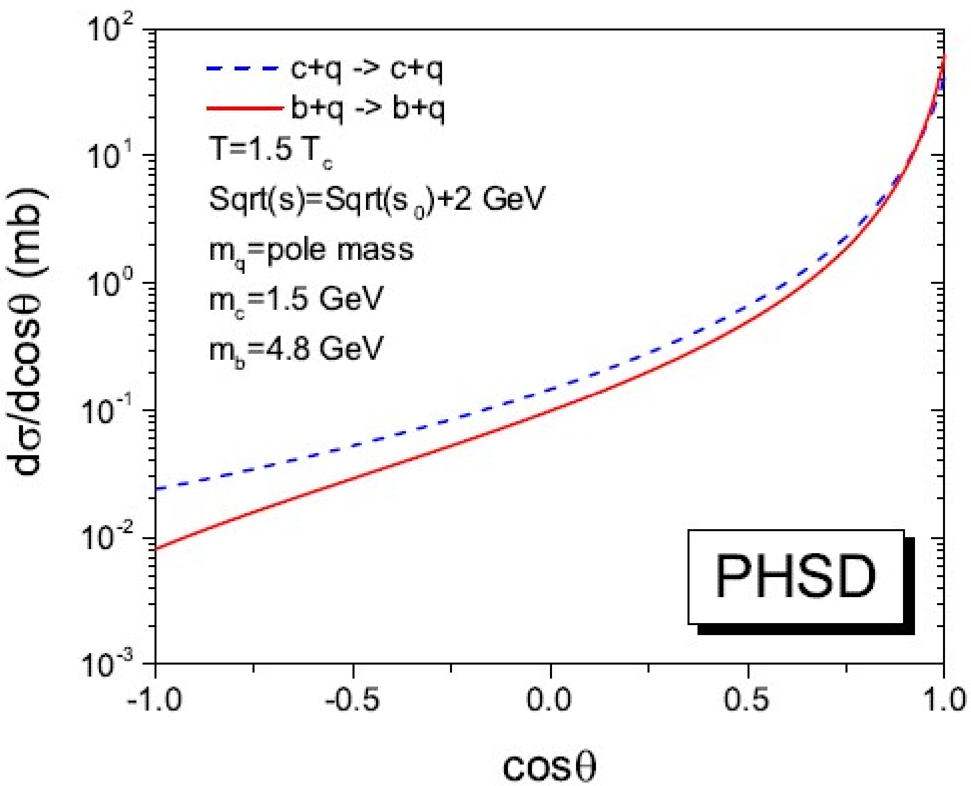
L. Tolos , J. M. Torres-Rincon, PRD 88 (2013) 074019
V. Ozvenchuk et al., PRC90 (2014) 054909

➔ Continuous transition at T_C!

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

Heavy quark scattering in the QGP

- **Differential elastic cross section for cq→cq, bq→bq for $s^{½}=s_0^{½}$ +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

Hadronization of heavy quarks in A+A

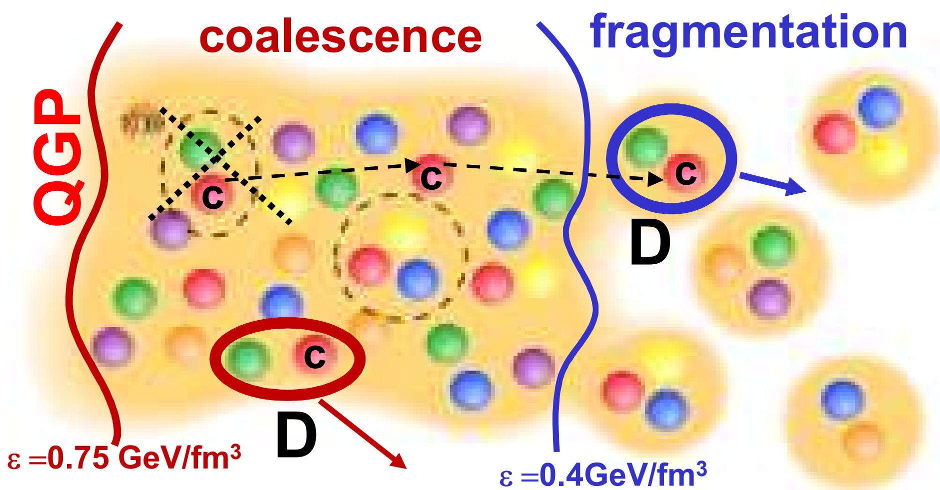
❑ **PHSD:** if the local energy density $\varepsilon \rightarrow \varepsilon_C$ ➔ hadronization of heavy quarks to hadrons

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

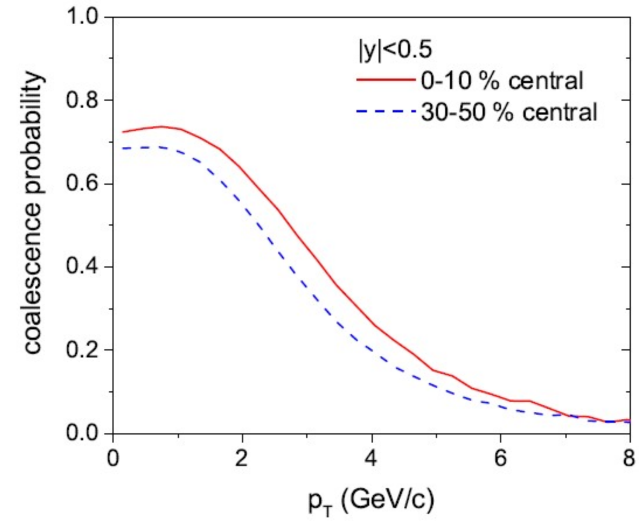
Dynamical hadronization scenario for heavy quarks :

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

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

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)$^{0\pm}$

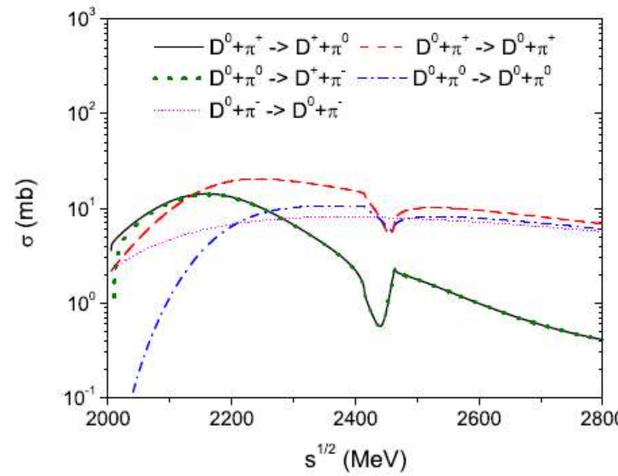
D-meson scattering in the hadronic phase

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)



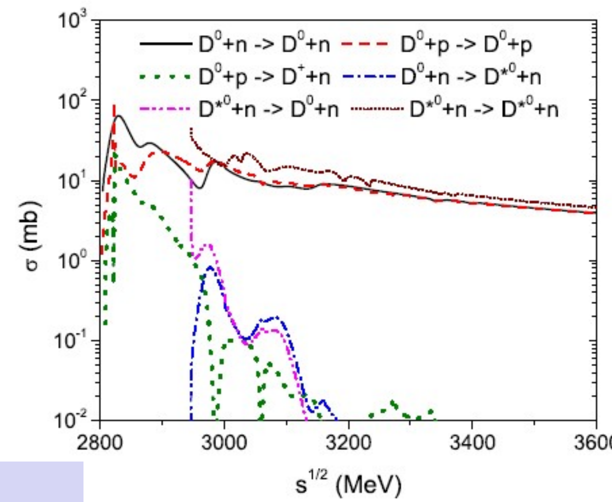
2. D-meson scattering with baryons

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:

$$T = T + VGT$$

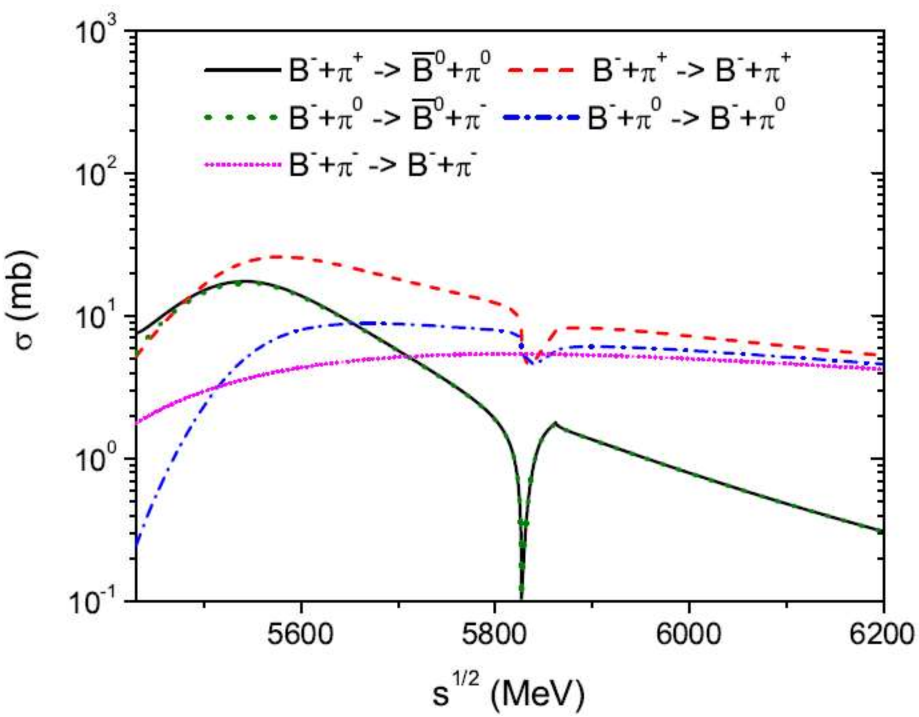


➔Strong isospin dependence and complicated structure (due to the resonance coupling) of D+m, D+B cross sections!

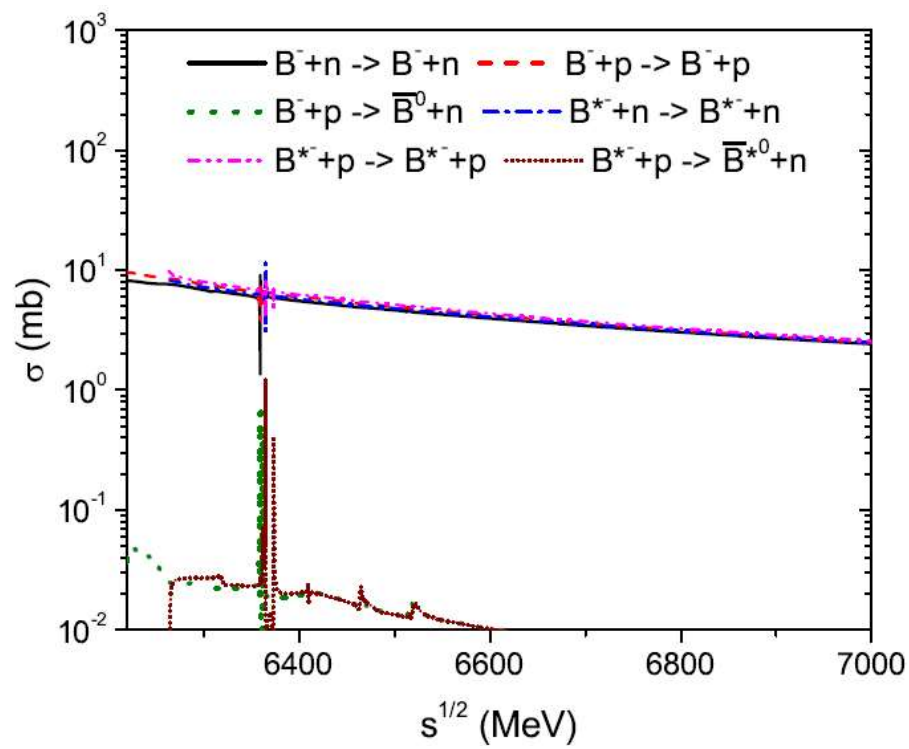
B-meson scattering in the hadron gas

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

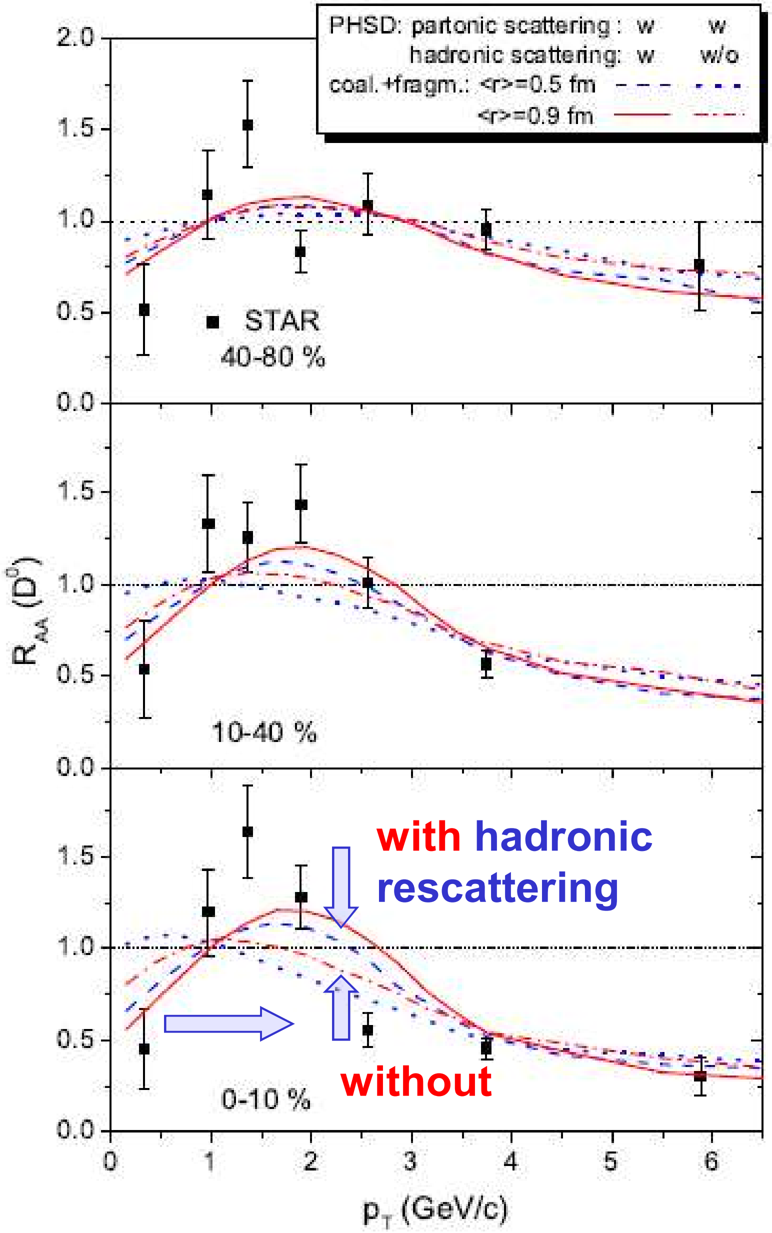


2. B-meson scattering with baryons



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

R_{AA} at RHIC: hadronic rescattering



Influence of hadronic rescattering:

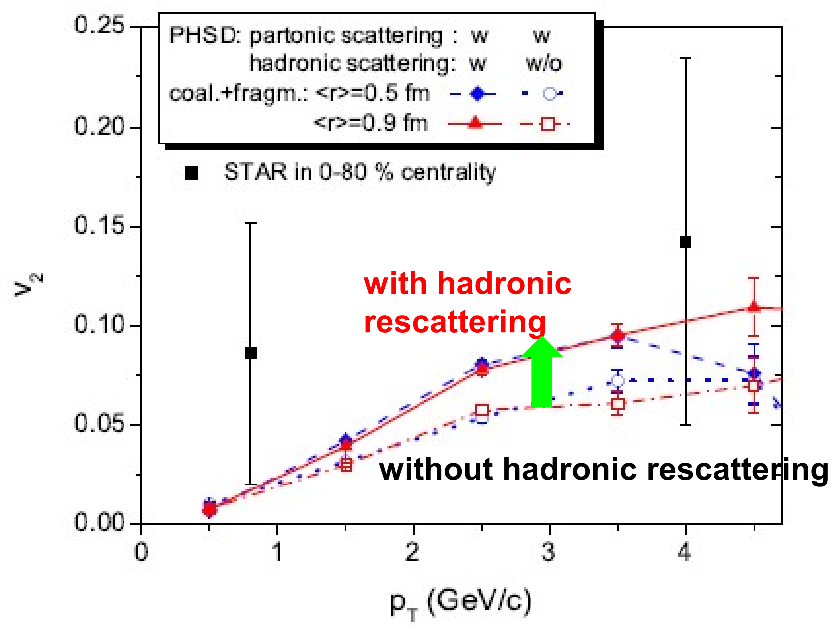
Central Au+Au at $s^{1/2}$ =200 GeV :

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**

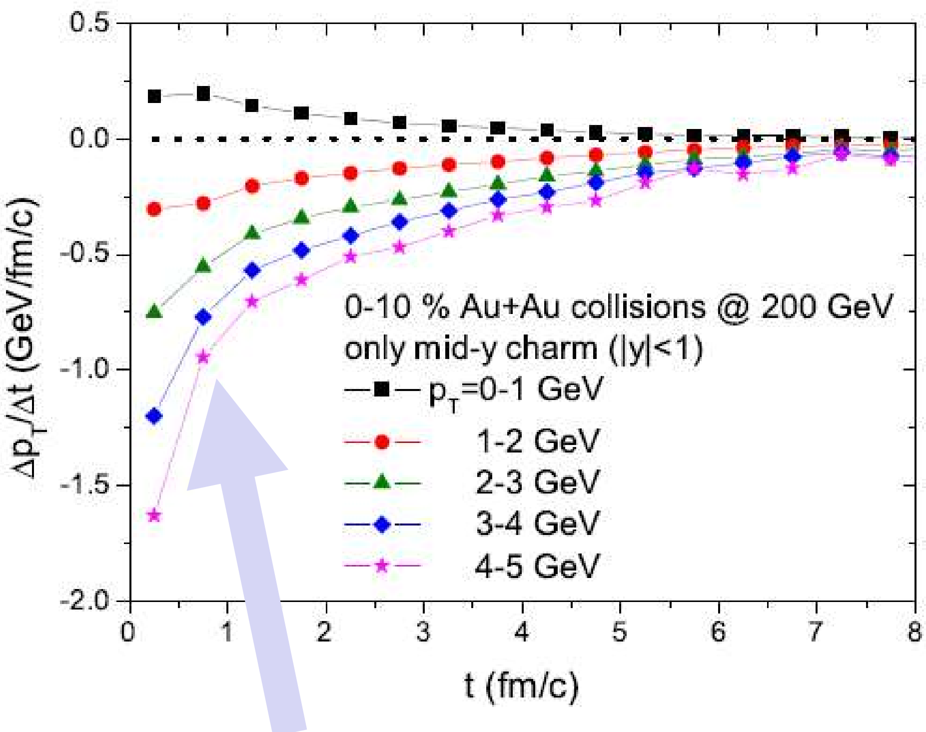


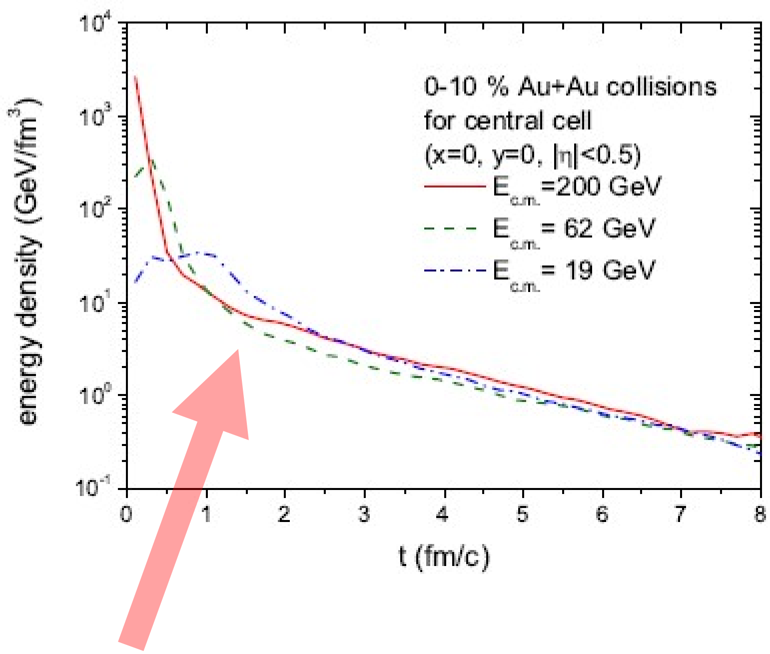
- **Hadronic rescattering moves R_{AA} peak to higher p_T !**
- **substantially increases v_2 at larger p_T**

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

Energy gain/loss at RHIC

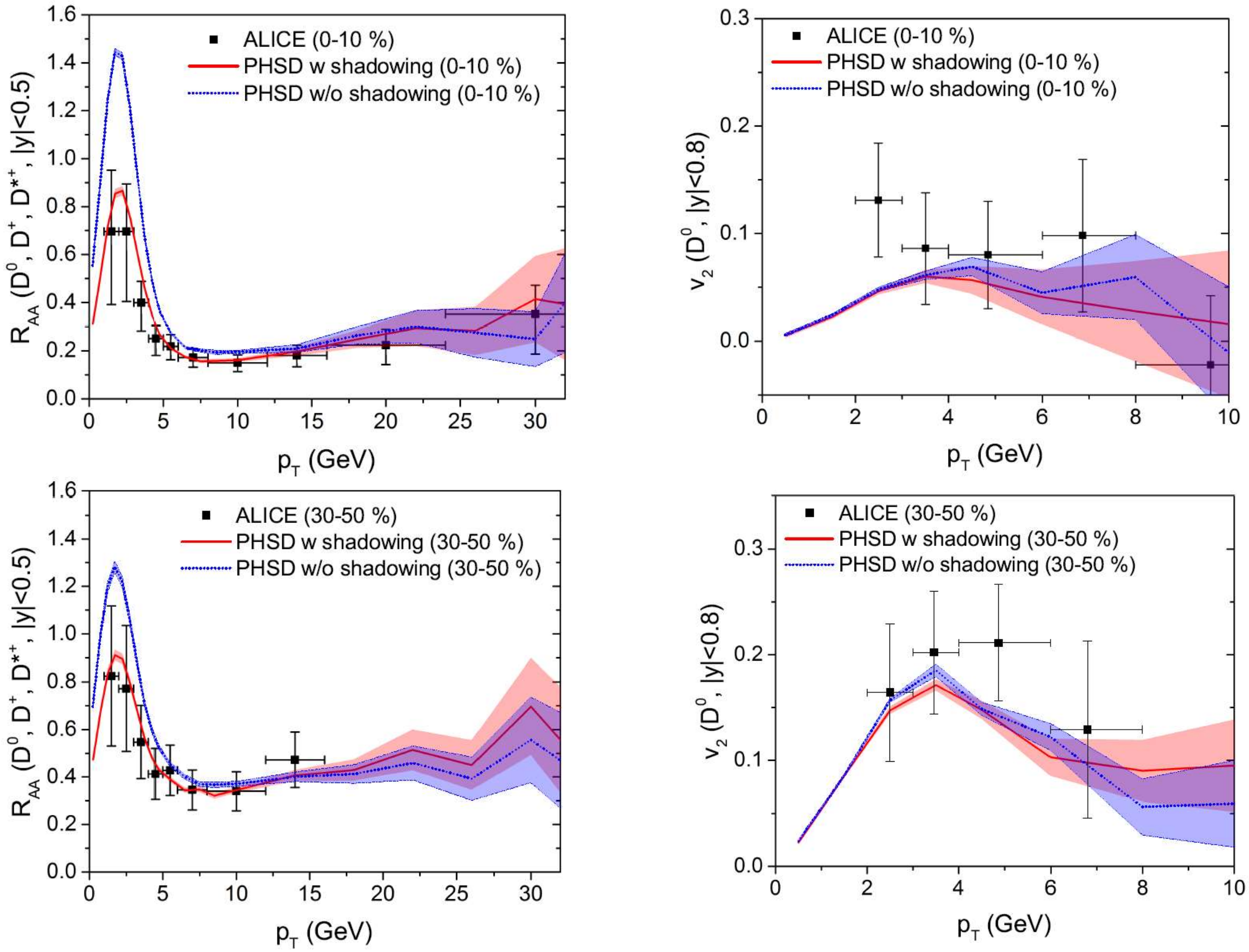
- **Transverse momentum gain or loss of charm quarks per unit time at mid-rapidity in 0-10 % central Au+Au collisions at 200 GeV**





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

Charm R_{AA} at LHC: PHSD vs ALICE

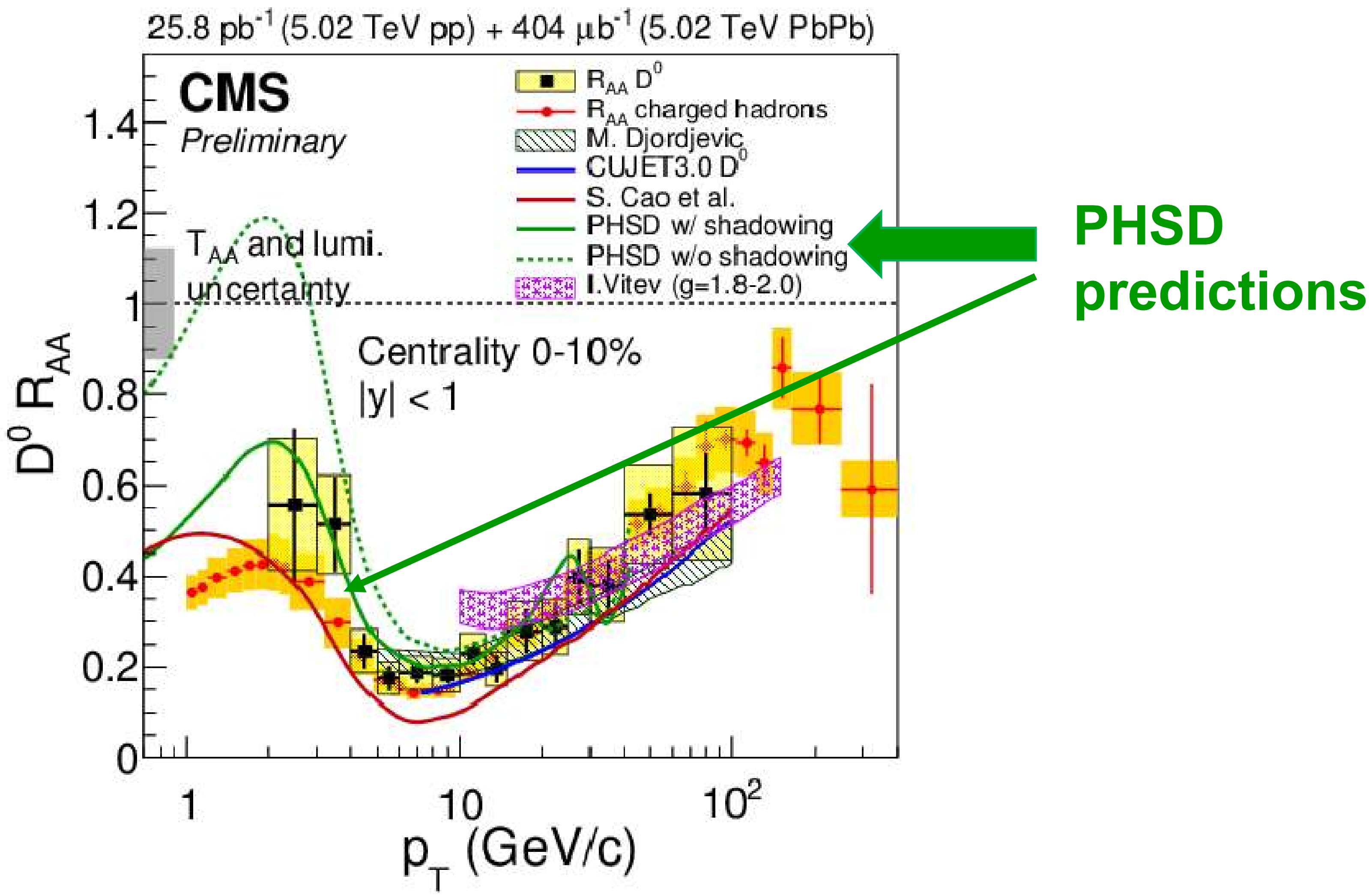


- in PHSD the energy loss of D-mesons at high p_T can be dominantly attributed to partonic scattering
- Shadowing effect suppresses the low p_T and slightly enhances the high p_T part of R_{AA}
- Hadronic rescattering moves R_{AA} peak to higher $p_{T;}$ increases v_2

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

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

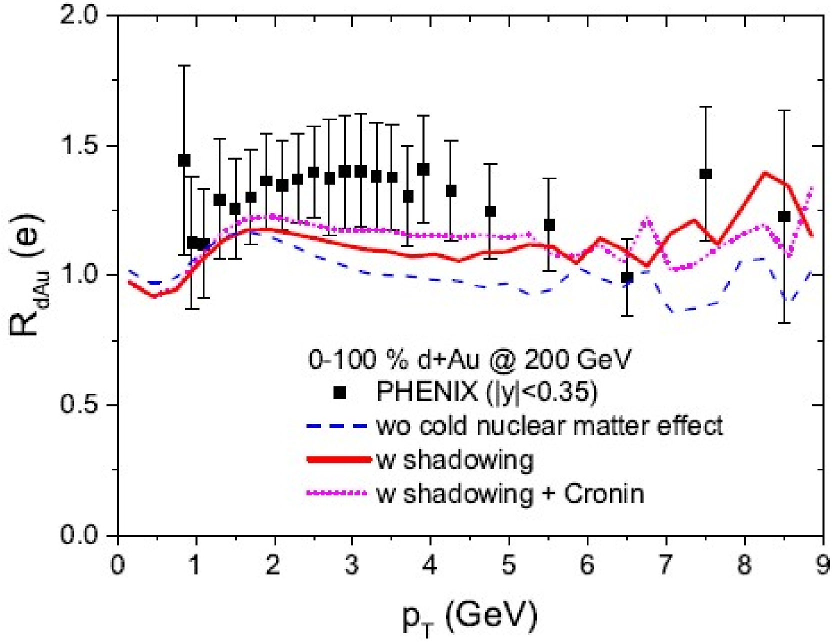
D meson production is suppressed in 5.02 TeV PbPb collisions



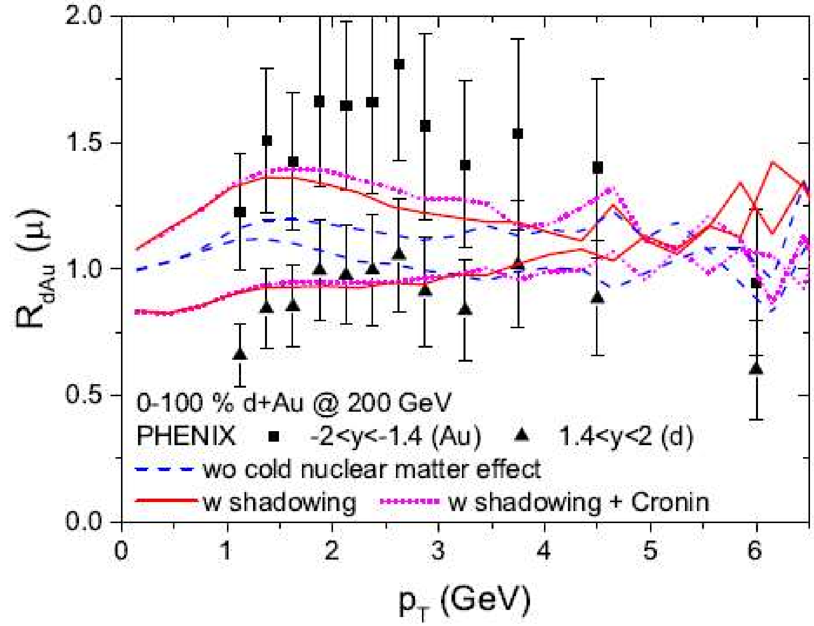
Cold nuclear matter effect: shadowing +Cronin

R_{AA} from single electrons in d+Au @ 200 GeV

Mid-rapidity (e)



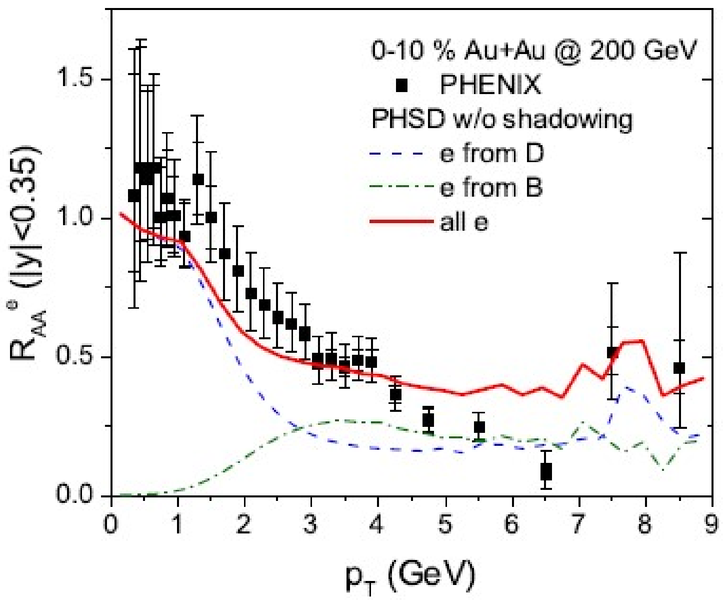
Forward-backward-rapidities (μ)

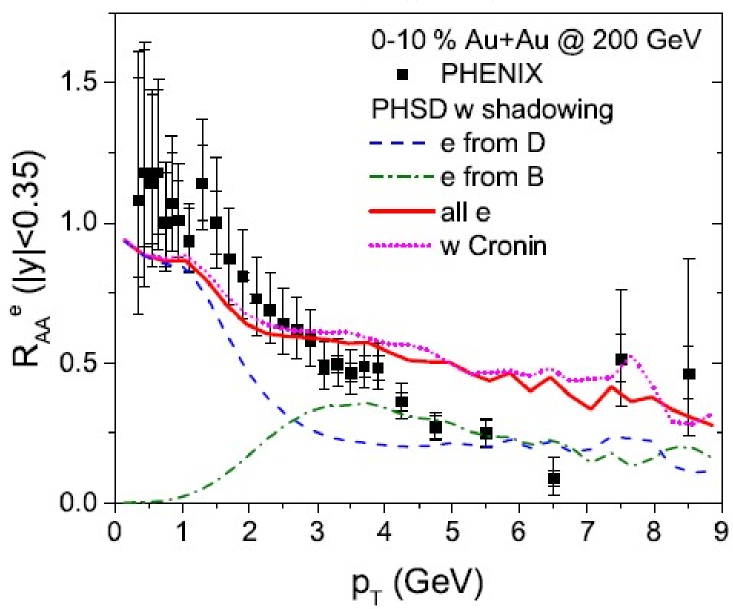


- ❑ **Cronin effect increases R_{AA} for p_T >1 GeV**

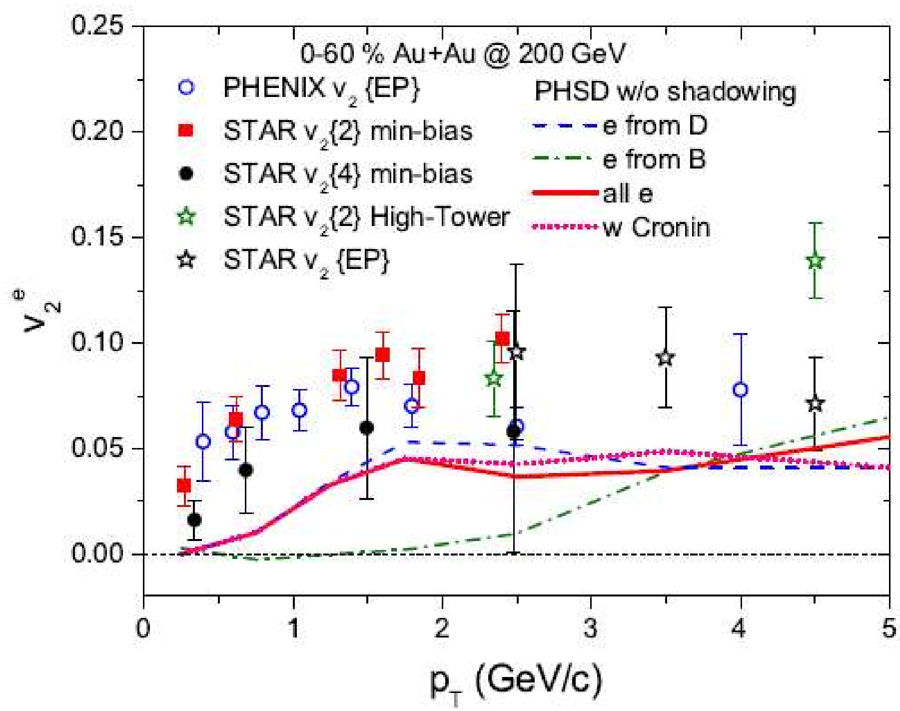
T. Song et al., arXiv:1605.07887 [nucl-th]

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





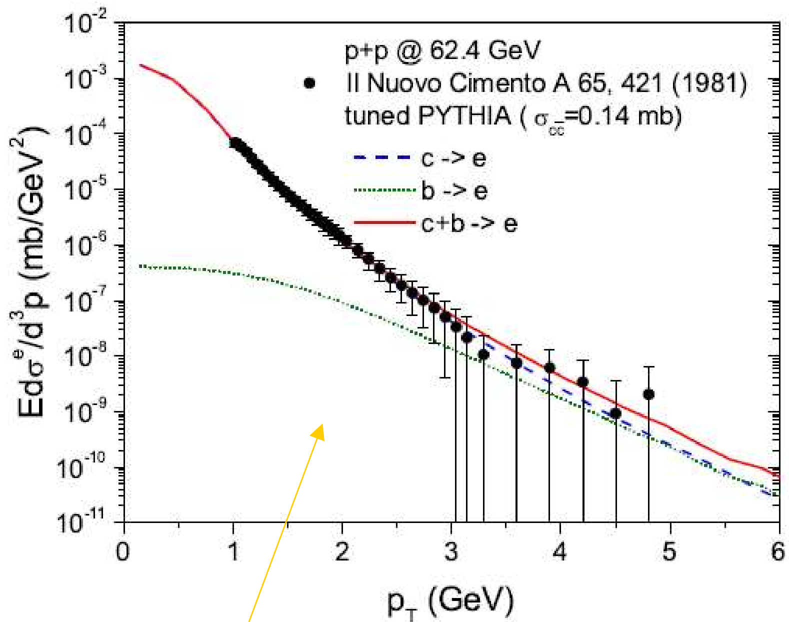
R_{AA} and v_2 vs p_T from single electrons in Au+Au @ 200 GeV

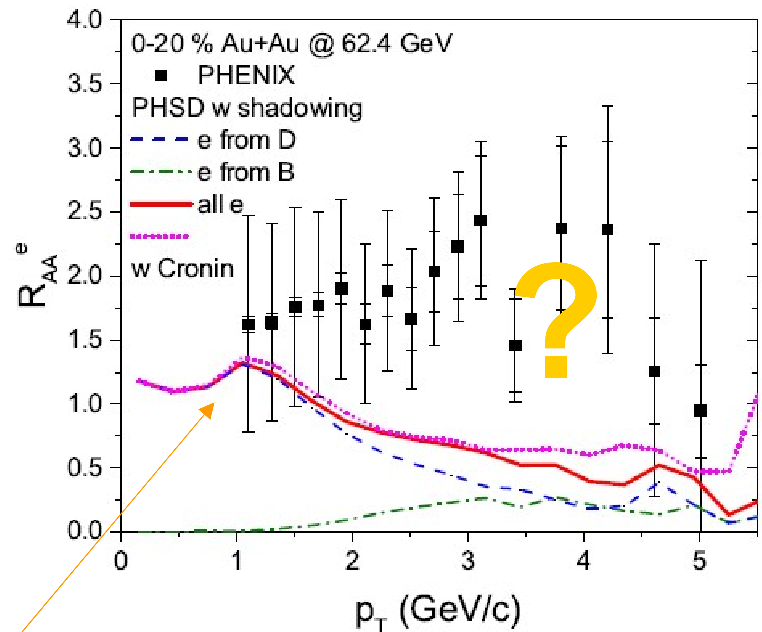


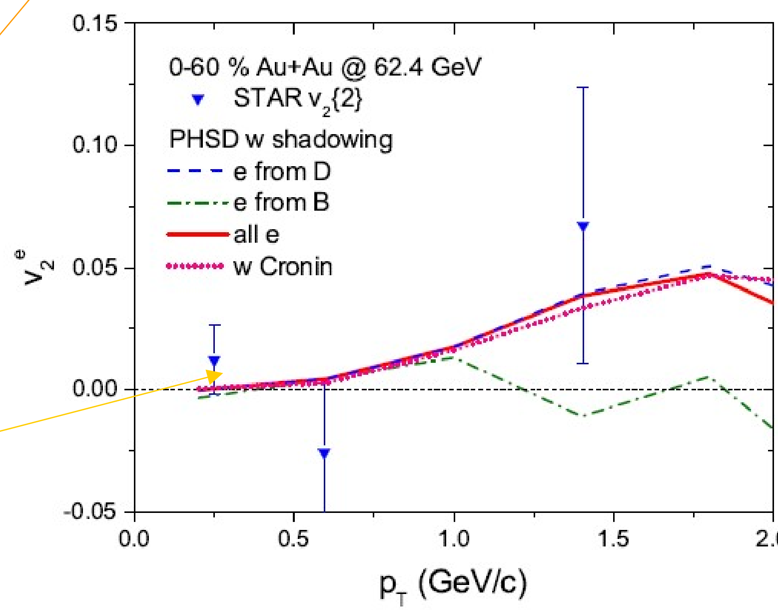
- ❑ **Feed back from beauty contribution becomes dominant for p_T >3 GeV**
- ❑ **Anti-shadowing enhancement of beauty**

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



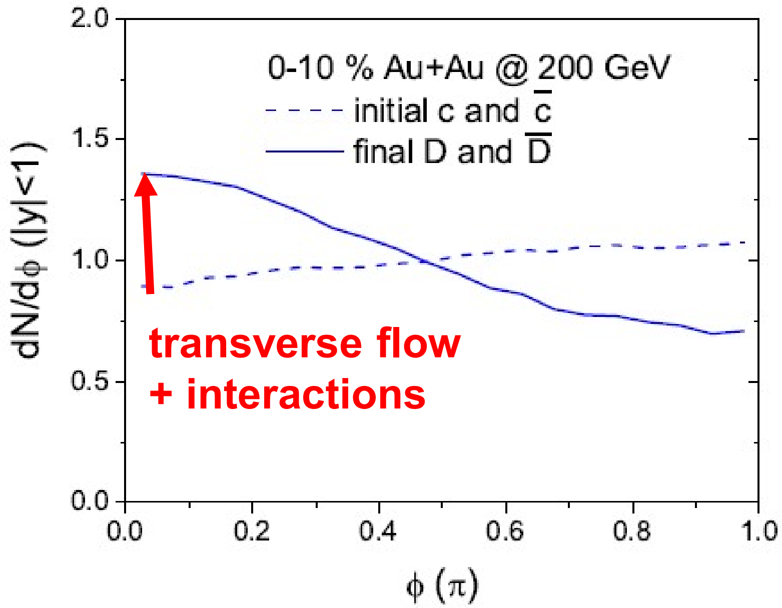


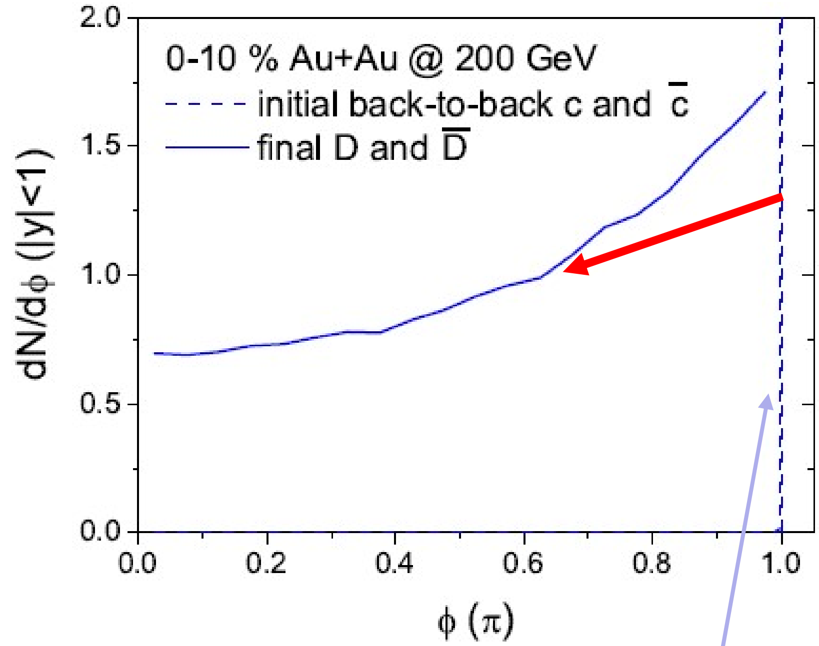


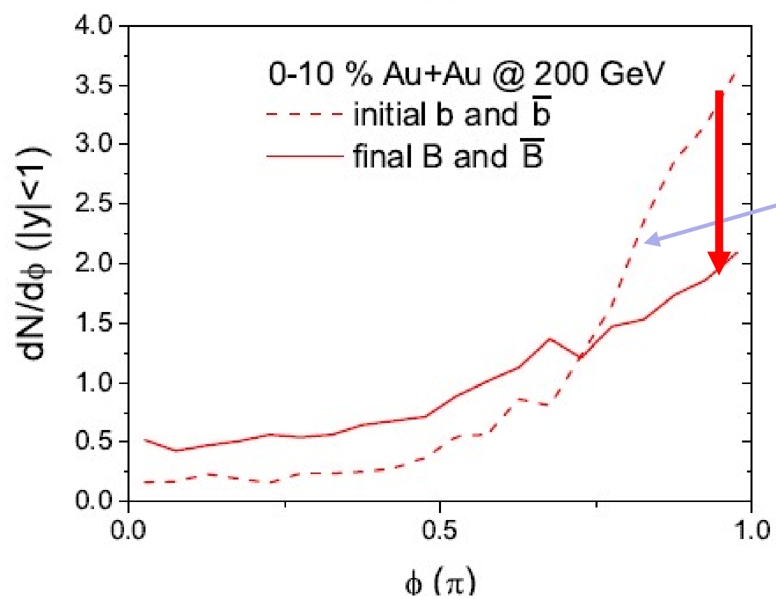
- **PHSD: pp data on electron p_T spectra are well reproduced**
- **PHENIX data on R_{AA}^e from single electrons from Au+Au at 62.4 GeV are not reproduced !**
- **v_2^e from single electrons from Au+Au at 62.4 GeV is in line with data**

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

Azimuthal angular correlations: Q-Qbar



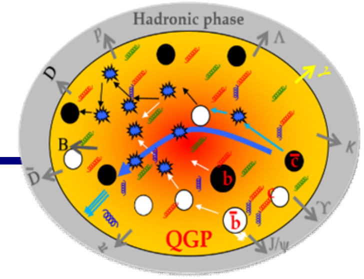




➔ **Initial azimuthal angular correlation of QQbar pairs is completely washed out during the evolution of the heavy-ion collision, even in case they are assumed to be initially produced back-to-back (model study) mainly due to the transverse flow + interactions**

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, **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

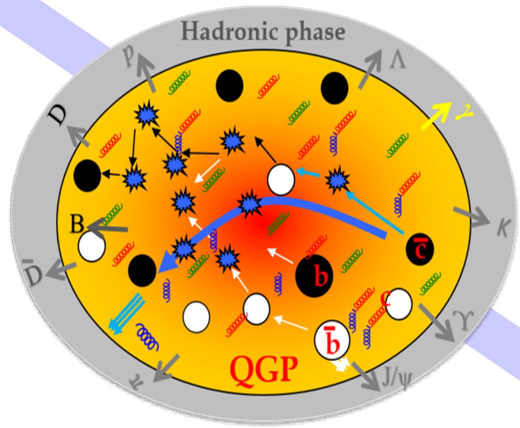
- **Initial azimuthal angular correlation** of QQbar pairs is **washed out** during the evolution dominantly due to the transverse flow

Heavy quarks –
hidden charm (J/Ψ, χ, Ψ‘)

1995-2008

HSD review on charm: O. Linnyk, E.B., W. Cassing, Int. J. Mod. Phys. E17 (2008) 1367-1439

Historical reminder



2015

T. Song et al., arXiv:1503.03039
PRC 93 (2016) 034906, etc.

I.-II. Scenarios for charmonium suppression in A+A

- **I. QGP threshold melting**

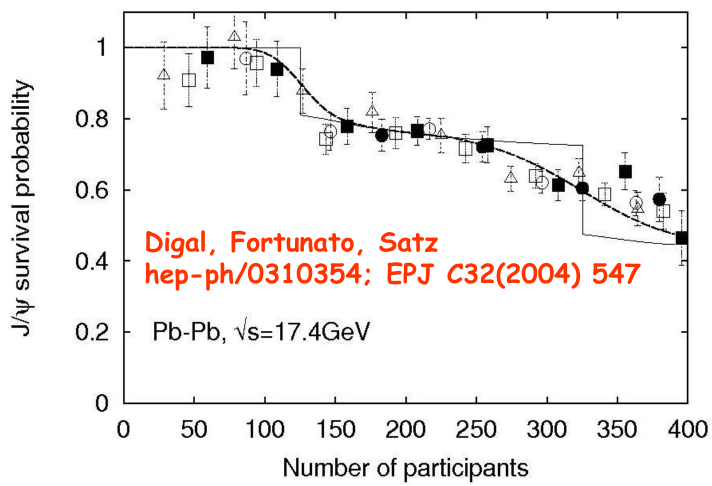
[Satz et al'03]

Quarkonium dissociation temperatures:

state	$J/\psi(1S)$	$\chi_c(1P)$	$\psi'(2S)$
T_d/T_c	2.10	1.16	1.12

Dissociation energy density

$\varepsilon_d \sim 2(T_d/T_c)^4$



- **II. Comover absorption**

+ recombination by D-Dbar annihilation

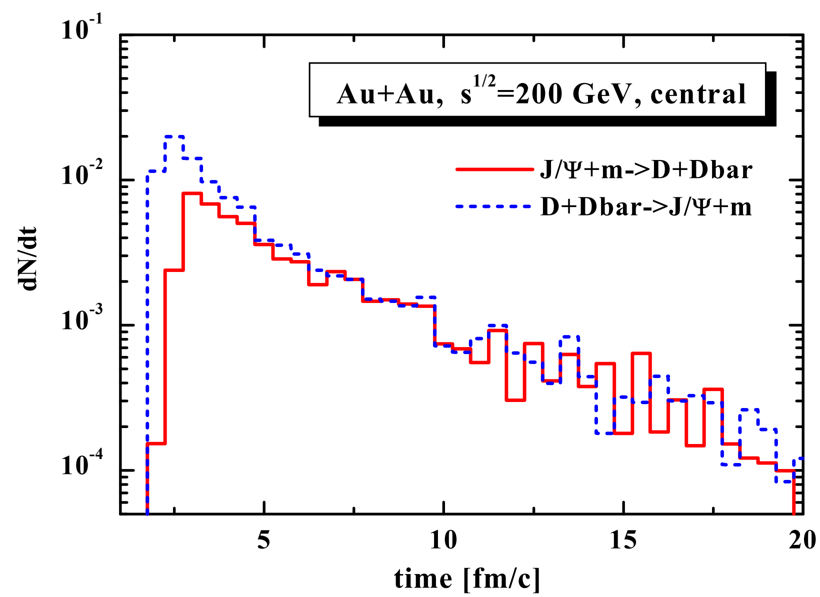
[Gavin & Vogt, Capella et al.`97]:

charmonium absorption by low energy inelastic scattering with ‚comoving' mesons (m= π,η,ρ,...):

J/Ψ+m <-> D+Dbar

Ψ'+m <-> D+Dbar

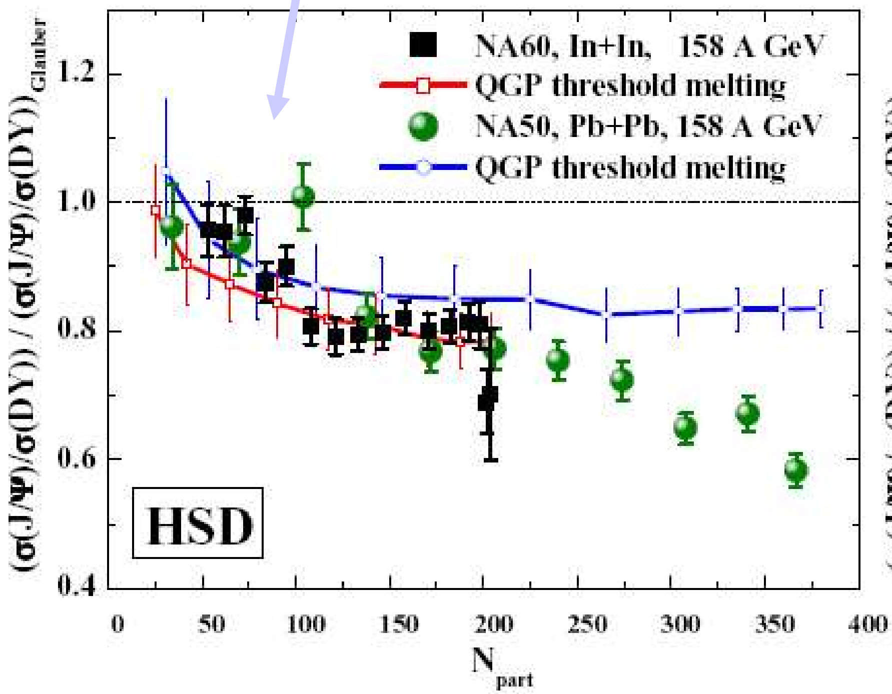
χ_c+m <-> D+Dbar

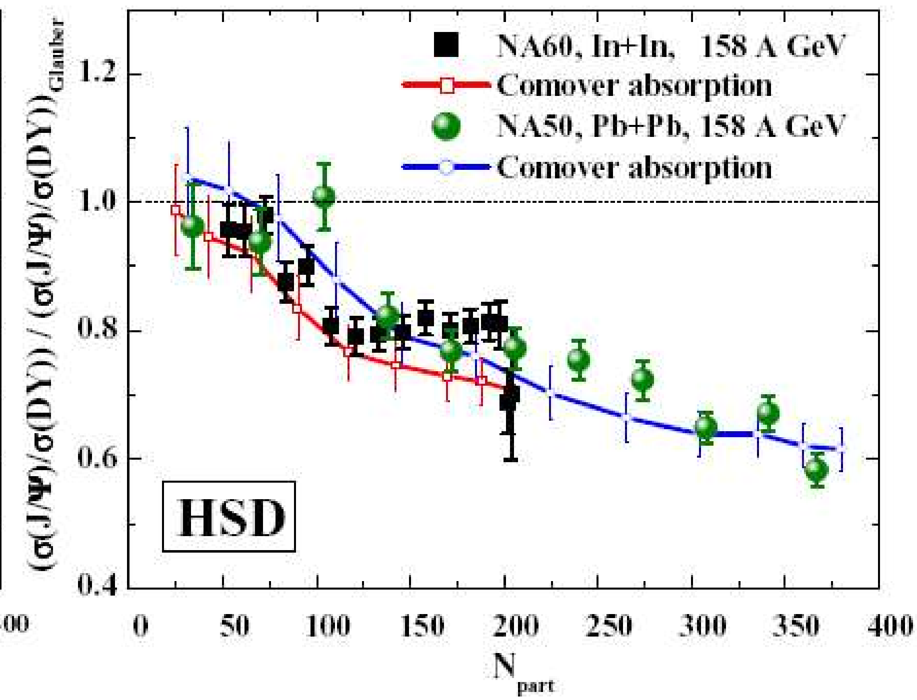


Scenarios for charmonium suppression in A+A

- The comover absorption scenario is qualitatively consistent with exp. data (for In+In and Pb+Pb) at SPS energies

- QGP threshold melting is not supported by data

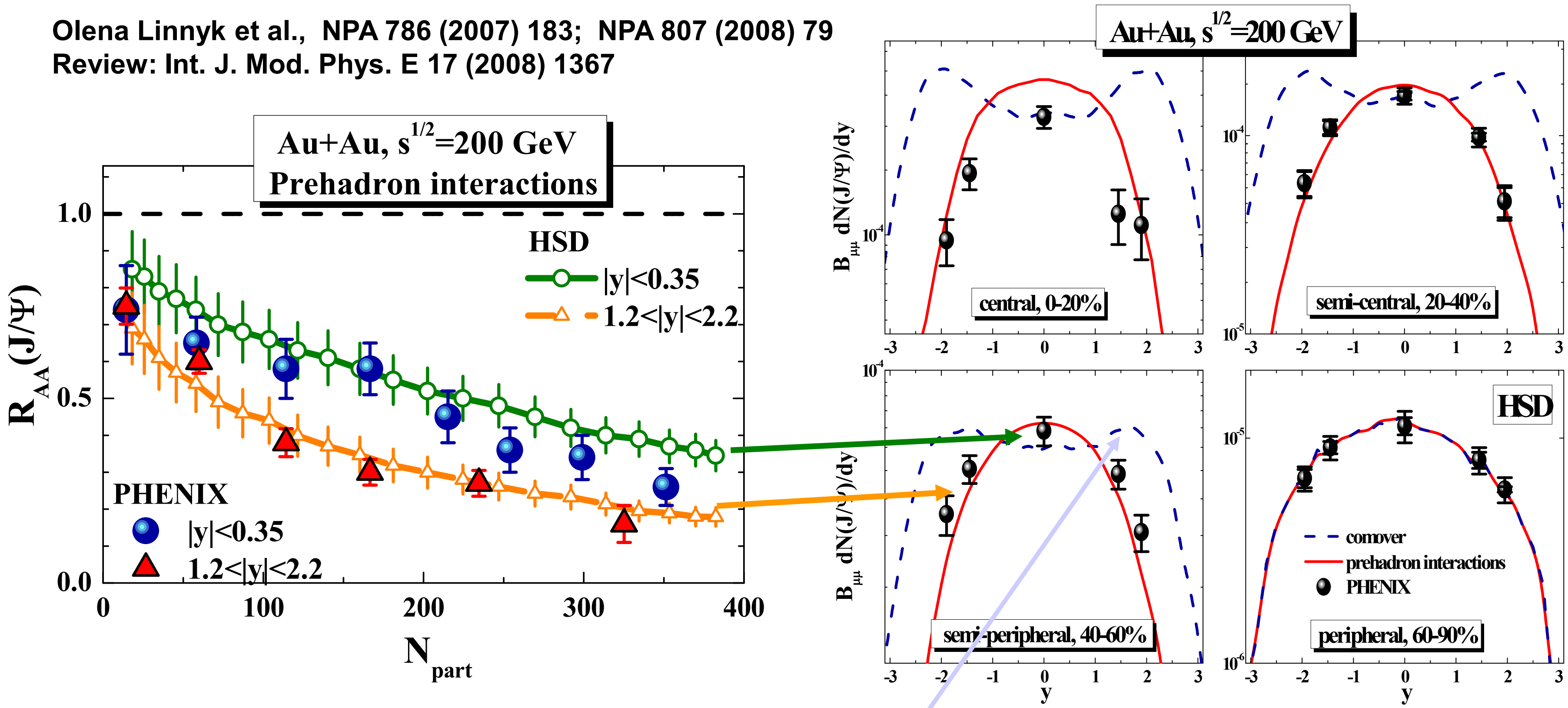




[Olena Linnyk et al.,
nucl-th/0612049, NPA 786 (2007) 183]

J/Ψ suppression in Au+Au at RHIC: Pre-hadronic interaction scenario

Olena Linnyk et al., NPA 786 (2007) 183; NPA 807 (2008) 79
Review: Int. J. Mod. Phys. E 17 (2008) 1367



❑ In the comover scenario the J/Ψ suppression at mid-rapidity is stronger than at forward rapidity, unlike the PHENIX data

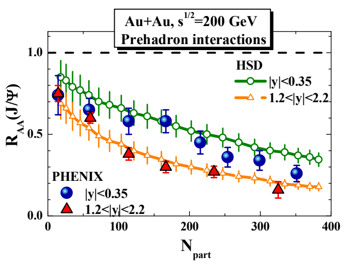
❑ In the prehadronic interaction scenario the J/Ψ rapidity distribution has the right shape like the PHENIX data => can describe the RHIC data at $s^{1/2}$=200 GeV for Au+Au at mid- and forward-rapidities simultaneously

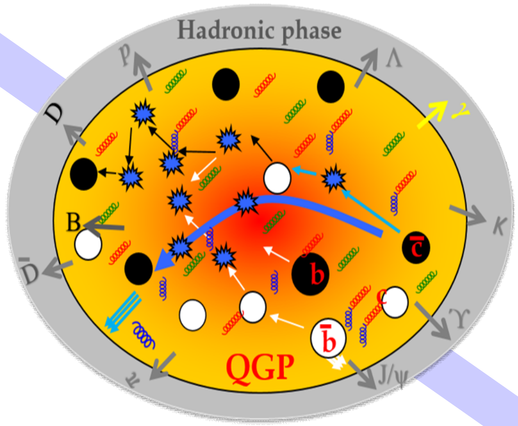
➔ evidence for non-hadronic nature of the interactions ➔ sQGP

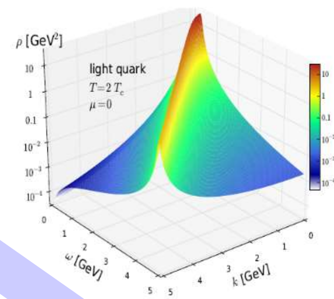
Charmonium suppression in A+A

→ QGP interaction is needed!

1995-2008







2017

Perspectives:

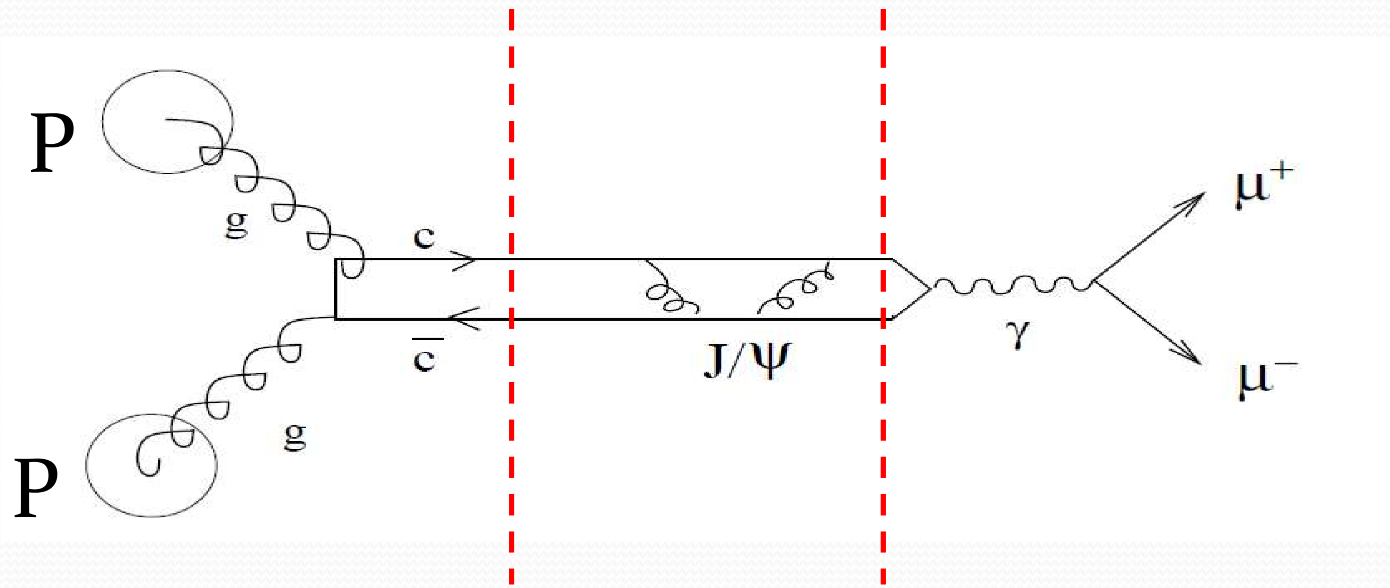
Microscopic description of charmonia interaction in QGP

5. J/ψ production in HIC (in progress)

Talk by Taesoo Song (INT Workshop, 1st week)

based on Taesoo Song, Joerg Aichelin, E.B., arXiv:1705.00046

J/ψ production in p+p collisions



PYTHIA event generator

Wigner projection

Sudden approximation

- $\Phi = J/\psi(1S),\ \ \chi_c(1P),\ \psi'(2S)$
- $\lim_{t\to\infty}\langle\Phi(t)|c\bar{c}(-t)\rangle \approx \langle\Phi|c\bar{c}\rangle$: sudden approximation
- $|\langle\Phi|c\bar{c}\rangle|^2 \sim$ Wigner function, Phys.Rev. C94 (2016) 034901

$$\Phi_S^W(\mathbf{r},\mathbf{p}) = 8\frac{D}{d_1 d_2}\exp\left[-\frac{r^2}{\sigma^2}-\sigma^2p^2\right],$$

$$\Phi_P^W(\mathbf{r},\mathbf{p}) = \frac{16}{3}\frac{D}{d_1 d_2}\left(\frac{r^2}{\sigma^2}-\frac{3}{2}+\sigma^2p^2\right)\times\exp\left[-\frac{r^2}{\sigma^2}-\sigma^2p^2\right],$$

$$r = r_c - r_{\bar{c}}$$

$$p = \frac{p_c - p_{\bar{c}}}{2}$$

D : degeneracy of Φ

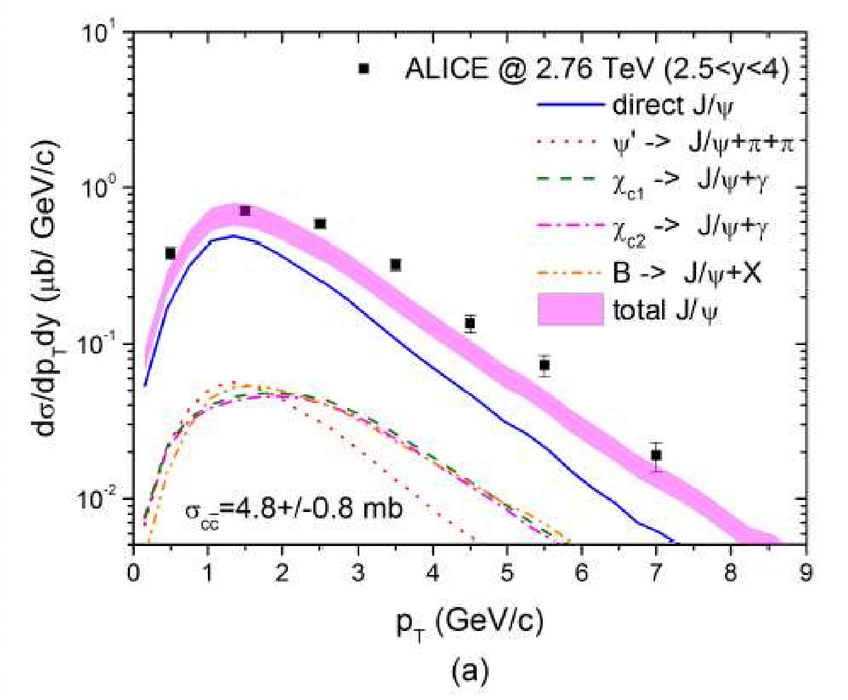
d_1 : degeneracy of c

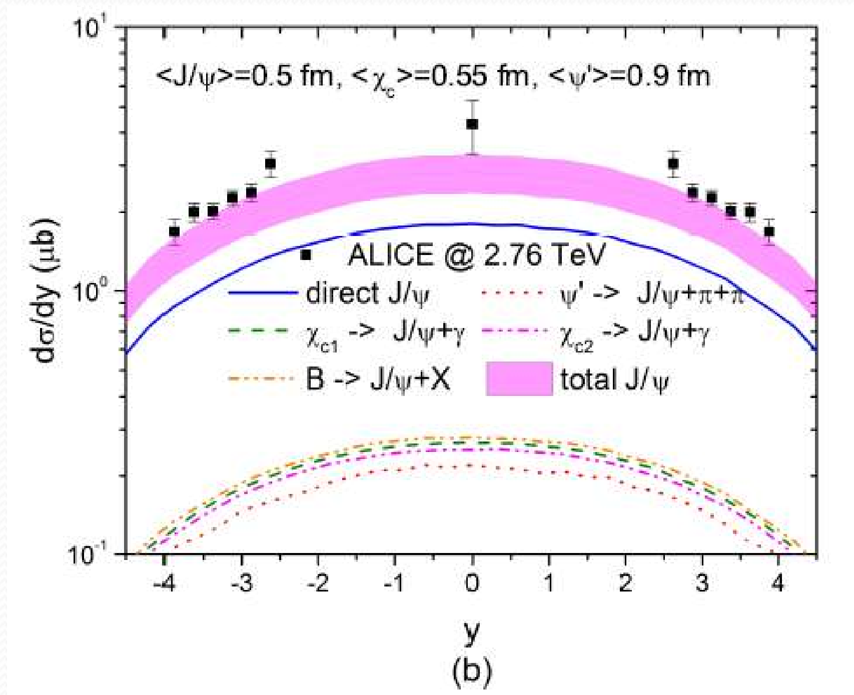
d_2 : degeneracy of anti-c

$\sigma \sim$ radius of Φ

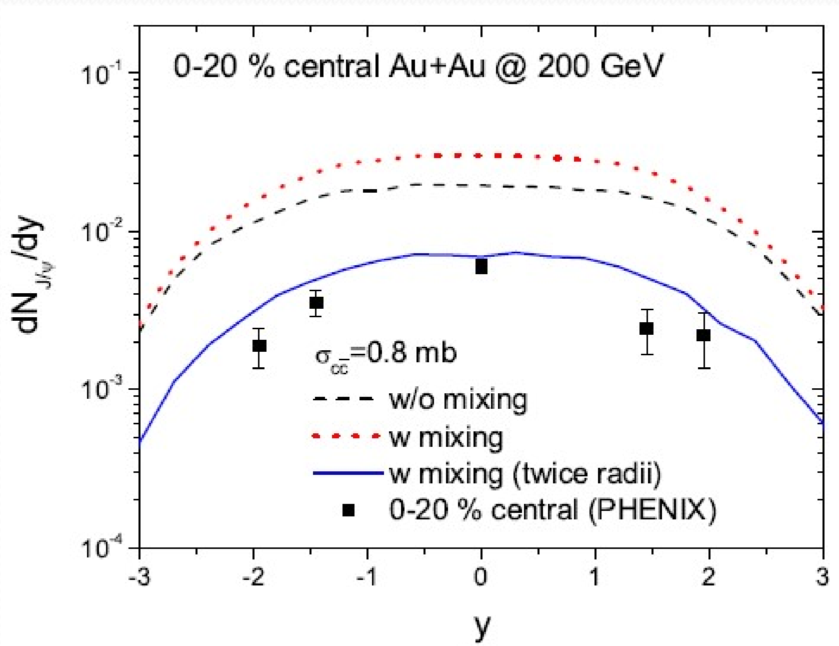
pp: comparison with ALICE data

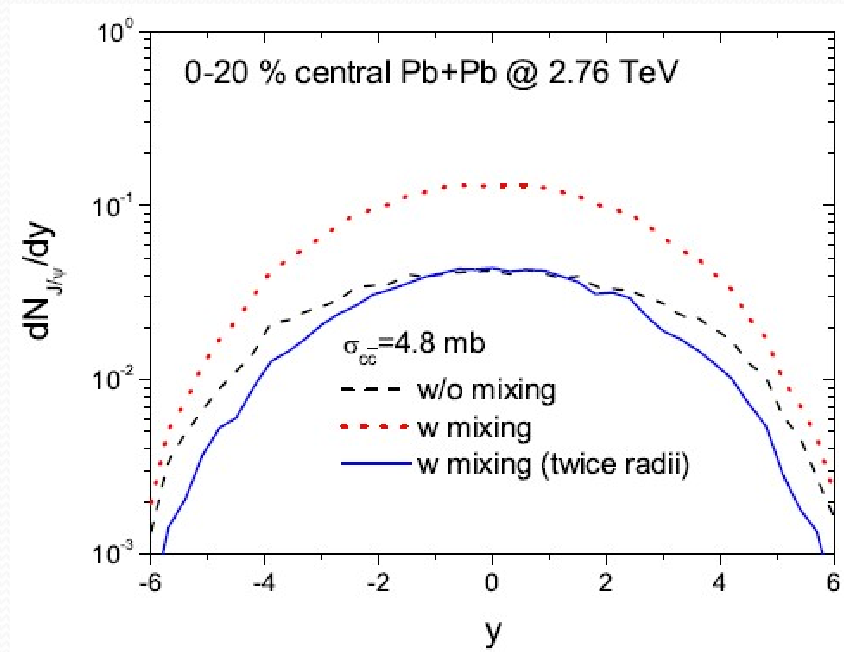
we use the same charmonia radii as at RHIC





AA: without any nuclear matter effect



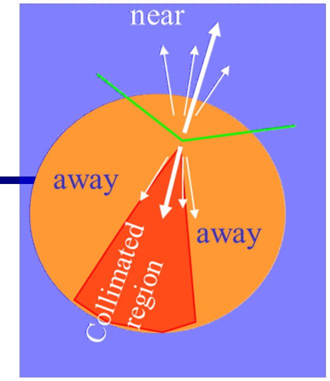


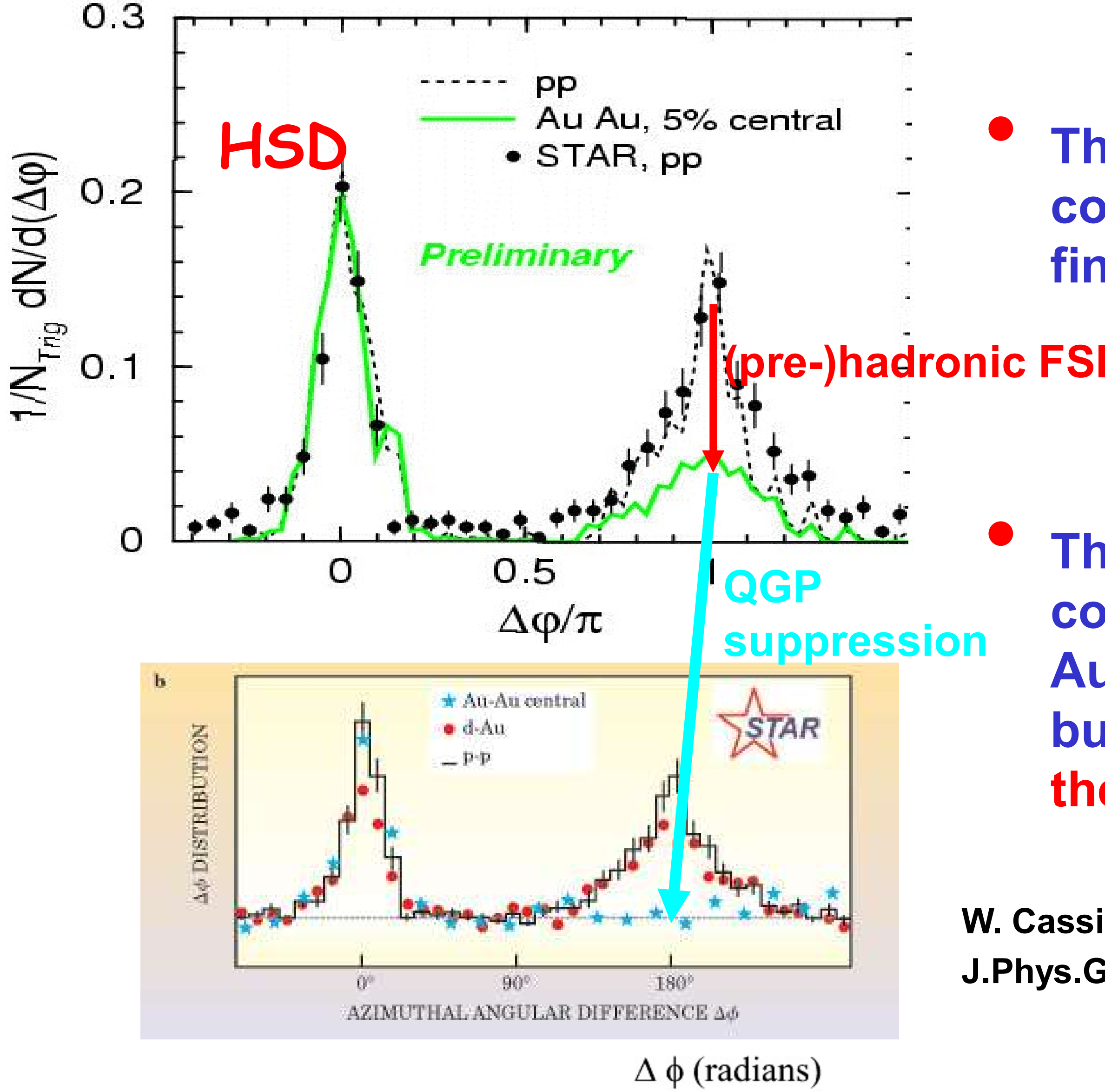
1. Charmonium production from two different charm quark pairs (mixing) enhances total J/ψ
2. According to lattice QCD, the radii of charmonia increase (weakly binding) at high T. It suppresses total J/ψ

Jet quenching and angular correlations in A+A

Historical reminder

Jet suppression: dN/dφ (HSD)

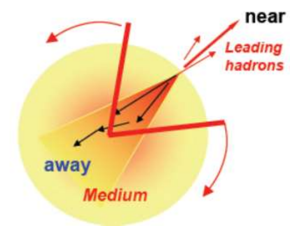




- The jet angular correlations for **pp** are fine !
- The near-side jet angular correlation for central Au+Au is well described, but **the suppression of the far-side jet is too low !**

W. Cassing, K. Gallmeister, C. Greiner,
J.Phys.G30 (2004) S801; NPA 748 (2005) 41

New exp. data: ϕ-η angular correlations



STAR
Eur.Phys.J.C61 (2009) 569-574

PHOBOS
Phys.Rev.Lett.104 (2010) 062301

Intermediate p_T: near-side ridge

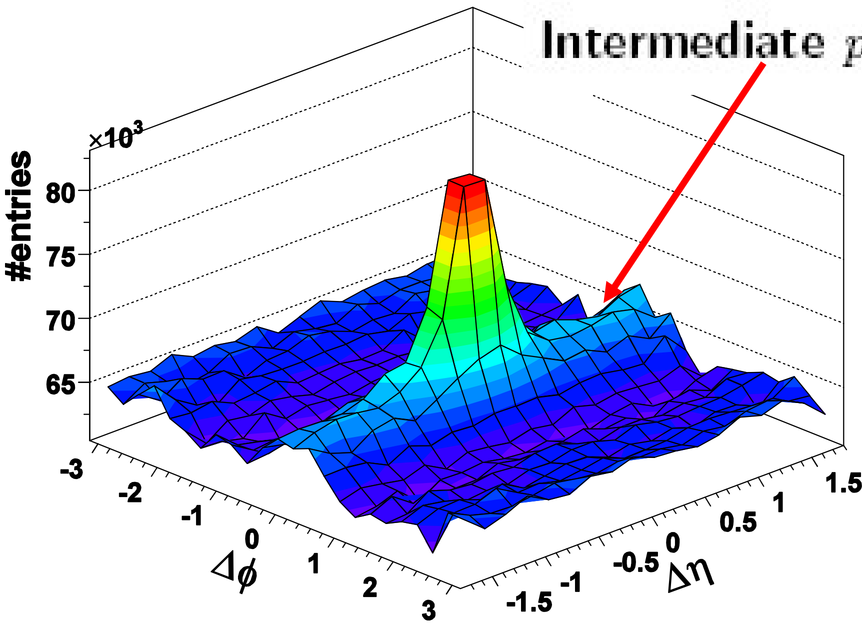


Fig. 1. (Color on-line) Preliminary associated particle distributions in $\Delta\eta$ and $\Delta\phi$ with respect to the trigger hadron for associated particles with 2 GeV/$c < p_T^{assoc} < p_T^{trig}$ in 0-12% central Au+Au collisions. Two different trigger p_T selections are shown: $3 < p_T^{trig} < 4$ GeV/c (upper panel) and $4 < p_T^{trig} < 6$ GeV/c (lower panel). No background was subtracted.

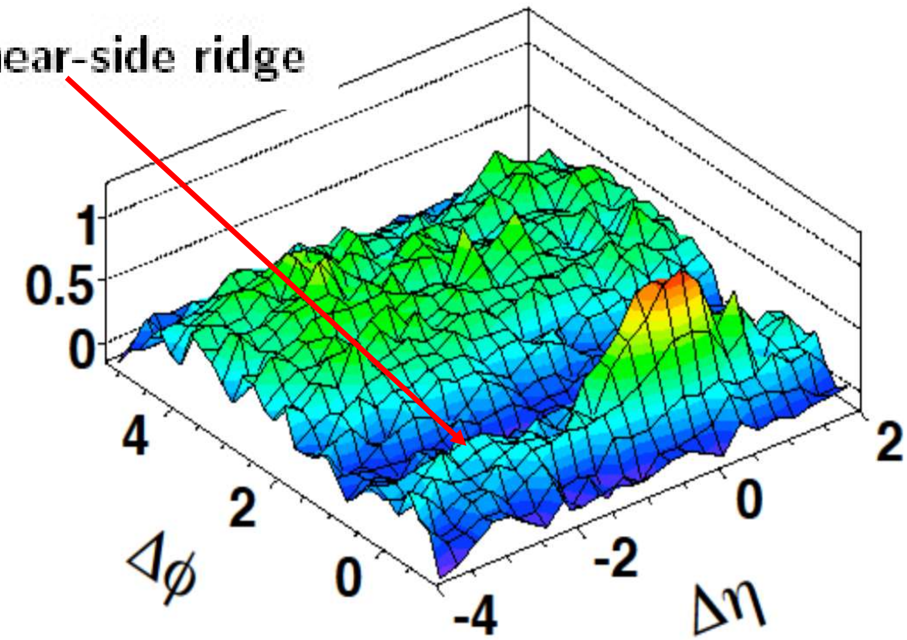
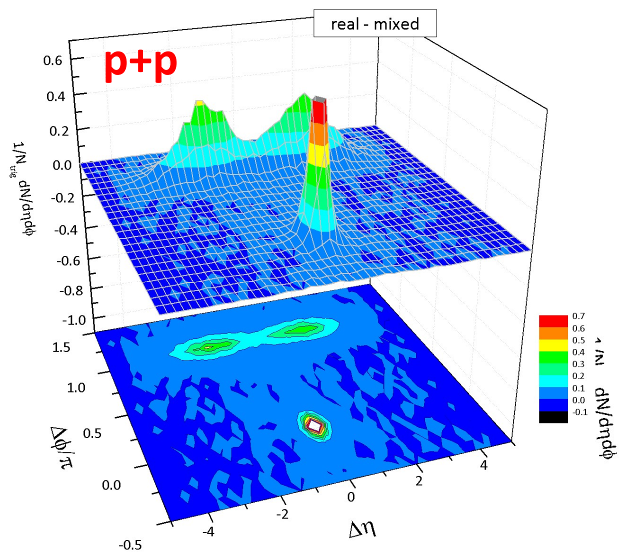
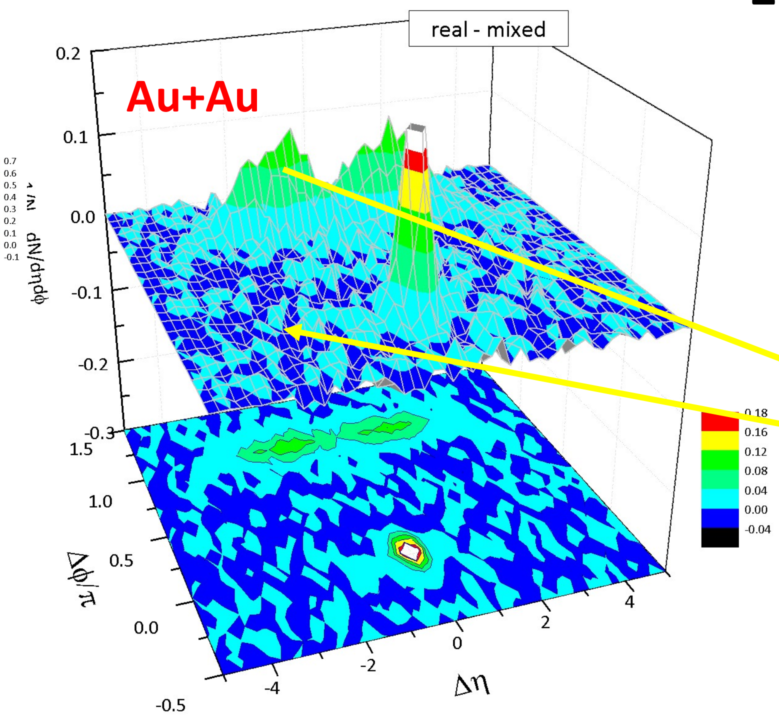


FIG. 2: (color online) Per-trigger correlated yield with $p_T^{trig} > 2.5$ GeV/c as a function of $\Delta\eta$ and $\Delta\phi$ for $\sqrt{s}$ and $\sqrt{s_{NN}}$=200 GeV (a) PYTHIA p+p and (b) PHOBOS 0-30% central Au+Au collisions. (c) Near-side yield integrated

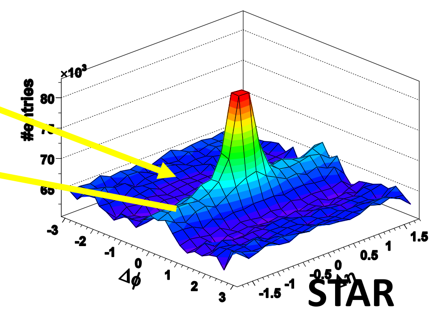
I: High p_T particle correlations in HSD vs. STAR data



Real-Mixed distribution



STAR: High p_T:
p_T(trig) > 4 GeV/c
2 < p_T(assoc) < 4 GeV

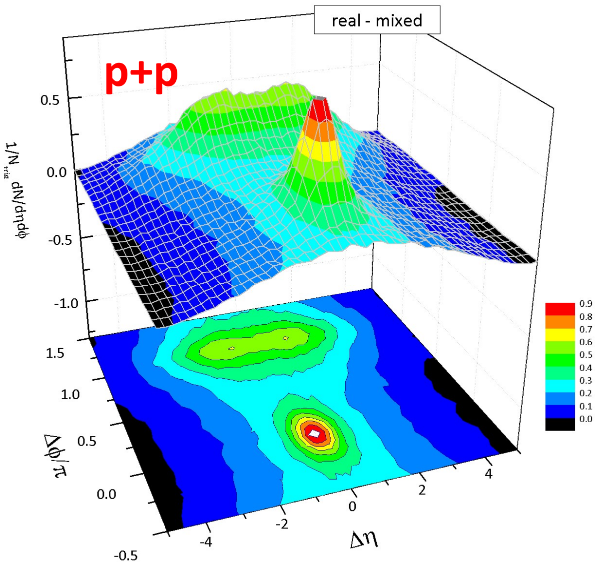


HSD vs. STAR:

- away side structure is suppressed in Au+Au collisions in comparison to p+p, however, HSD doesn‘t provide enough high p_T suppression to reproduce the STAR Au+Au data
- near-side ridge structure is NOT seen in HSD!

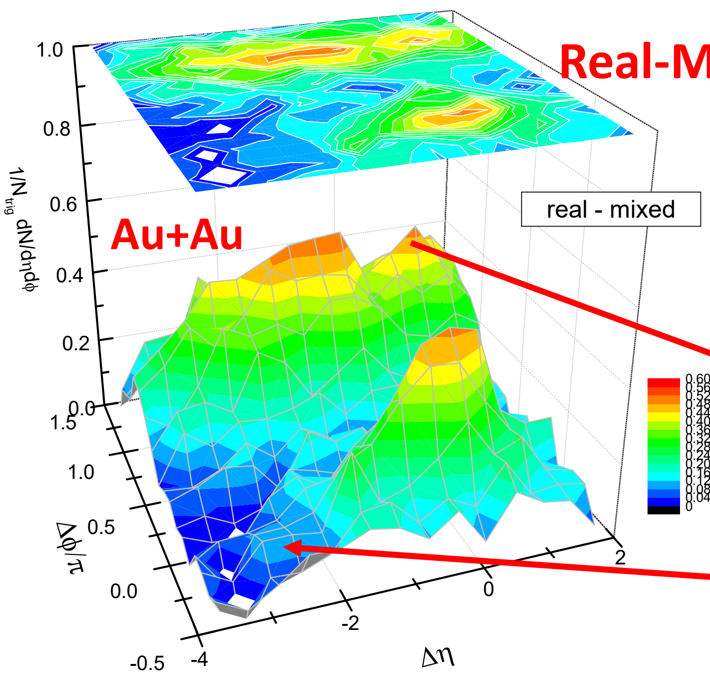
V. Konchakovski et al., Phys. Rev. C82 (2010) 037902

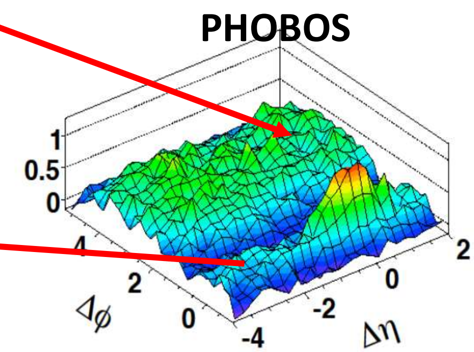
II: Intermediate p_T particle correlations in HSD vs. PHOBOS data



PHOBOS: Intermediate p_T:
p_T(trig) > 2.5 GeV/c; 0.02 < p_T(assoc) < 2.5 GeV

Real-Mixed distribution





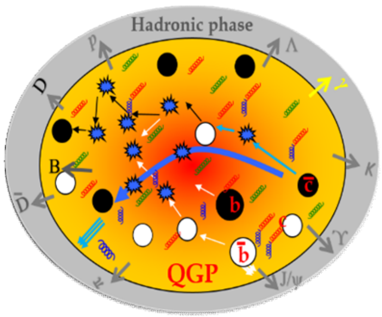
HSD vs. PHOBOS:

- **away side structure is suppressed in Au+Au collision in comparison to p+p, however, HSD doesn‘t provide enough high p_T suppression to reproduce the PHOBOS Au+Au data**
- **near-side ridge structure is NOT seen in HSD!**

V. Konchakovski et al., Phys. Rev. C82 (2010) 037902

Jet suppression: Perspectives within PHSD

2004



2017

Findings:

- **Hadronic interactions give ½ of suppression of the far-side jets!**
- **QGP interaction is needed !**

Perspectives:

- **Microscopic description of jet suppression by propagation via partonic and hadronic medium**
- **Study of the medium responds**

Thank you!