Chiral symmetry restoration versus deconfinement and open charm dynamics in relativistic heavy-ion collisions

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for the PHSD group

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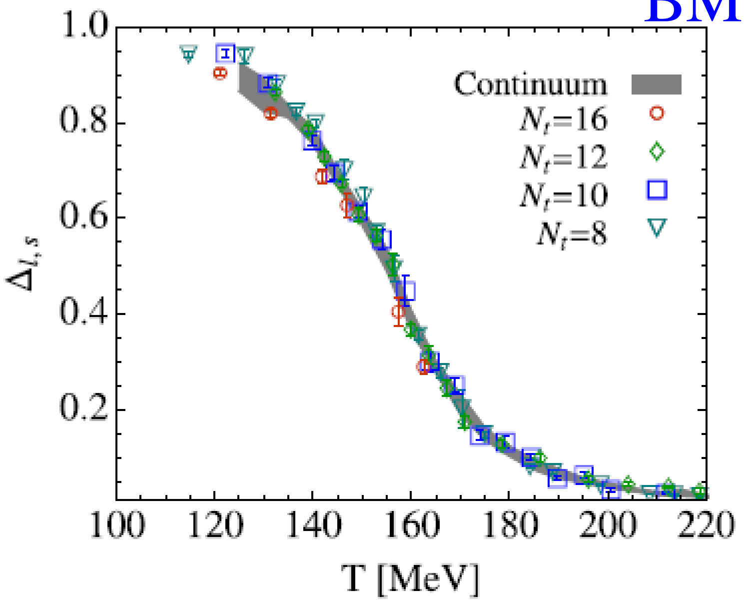
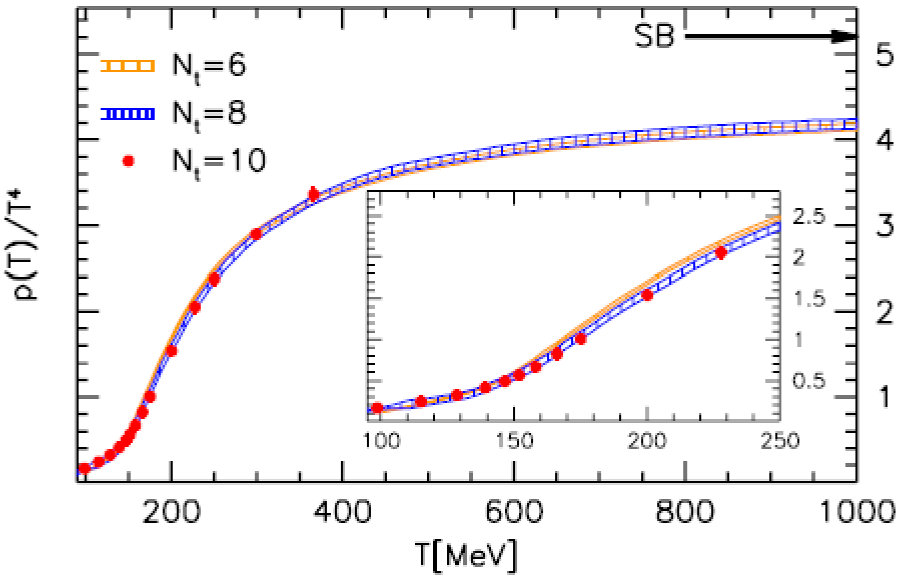
Information from lattice QCD

chiral symmetry restoration with increasing temperature + deconfinement phase transition with increasing temperature

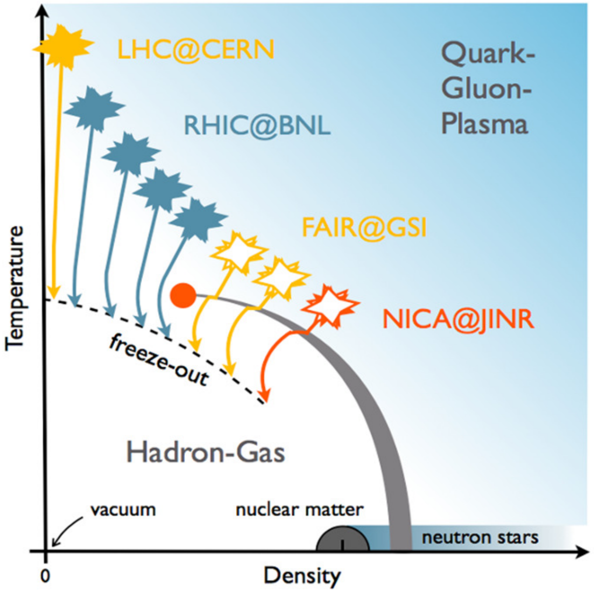
BMW collaboration





crossover: both transitions occur at about the same temperature T_c for low chemical potentials

From AGS to LHC, passing FAIR/NICA and RHIC…

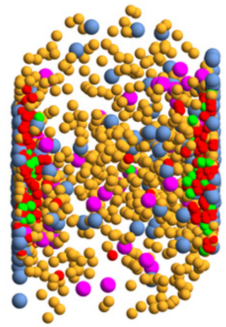


- Explore the QCD phase diagram and properties of hadrons at high temperature or high baryon density
- Phase transition from hadronic to partonic matter

- Goal: Study the properties of strongly interacting matter under extreme conditions from a microscopic point of view

- Realization: covariant off-shell transport approach

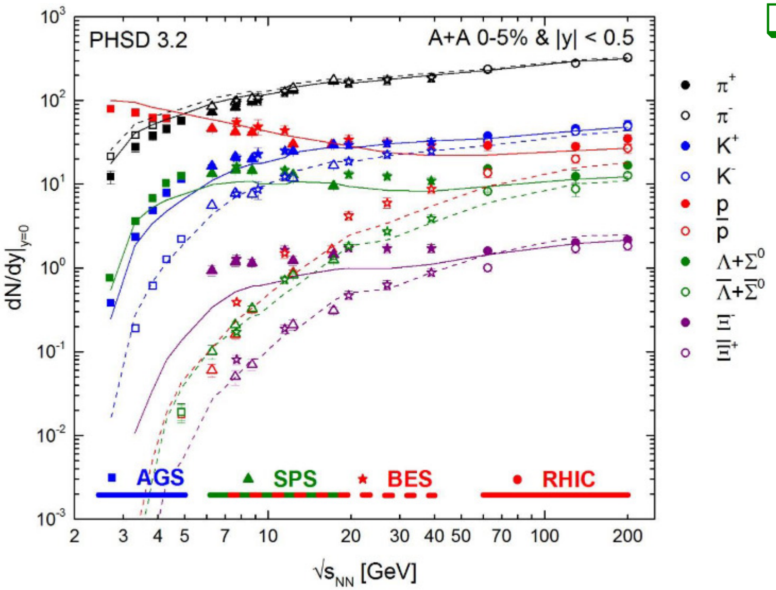
- Explicit parton-parton interactions, explicit phase transition from hadronic to partonic degrees of freedom
- Transport theory: off-shell transport equations in phase-space representation based on Kadanoff-Baym equations for the partonic and hadronic phase



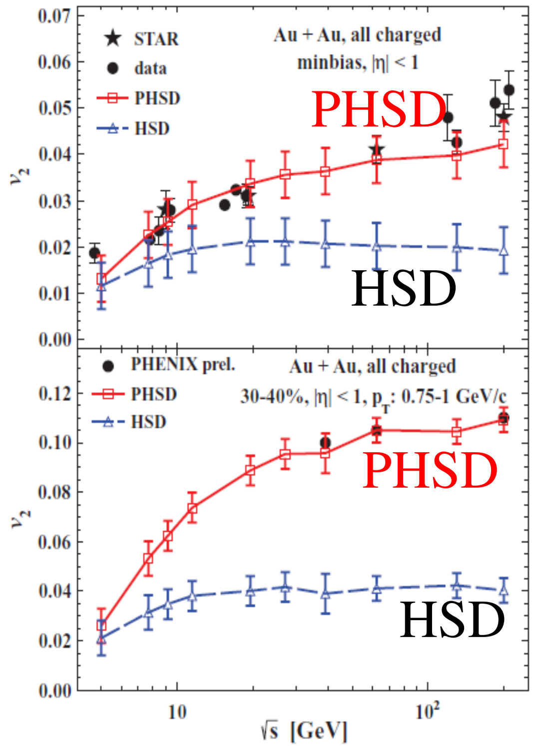
⇒ **Parton-Hadron-String-Dynamics (PHSD)**

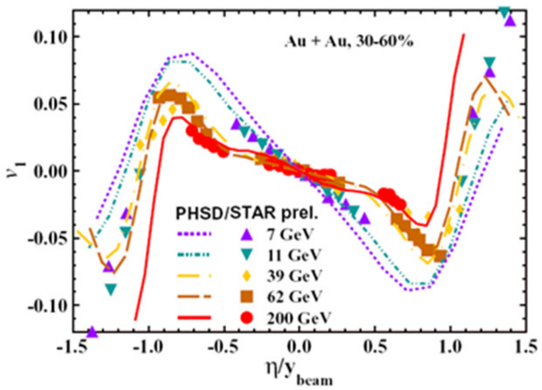
W.Cassing, E.Bratkovskaya, PRC 78 (2008) 034919; NPA831 (2009) 215; W.Cassing, EPJ ST 168 (2009) 3

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

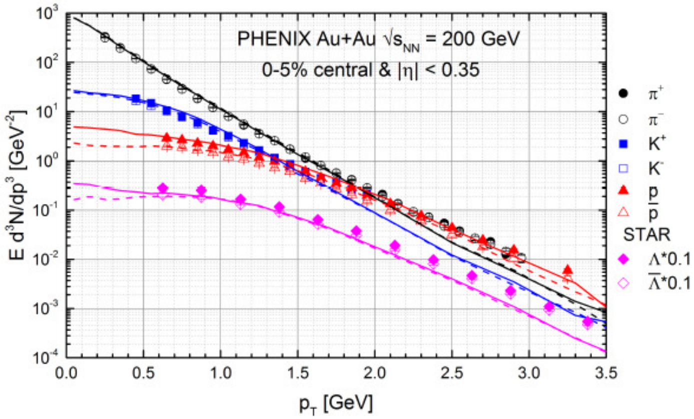


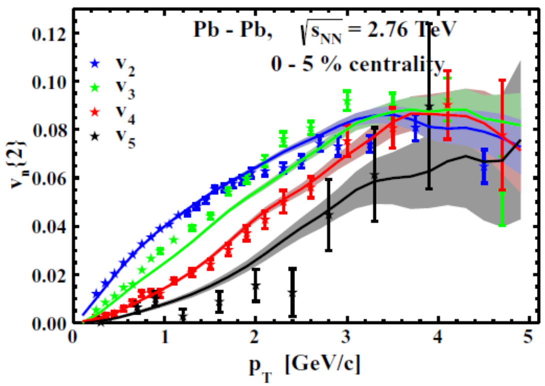
❑ PHSD: highlights





PHSD





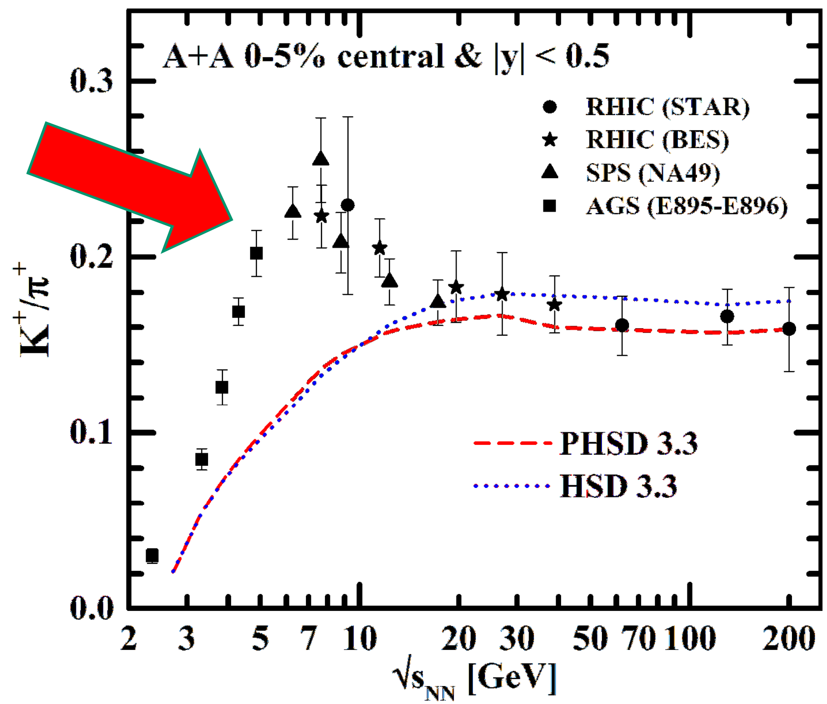
V. Konchakovski et al.,
PRC 85 (2012) 011902; JPG42 (2015) 055106

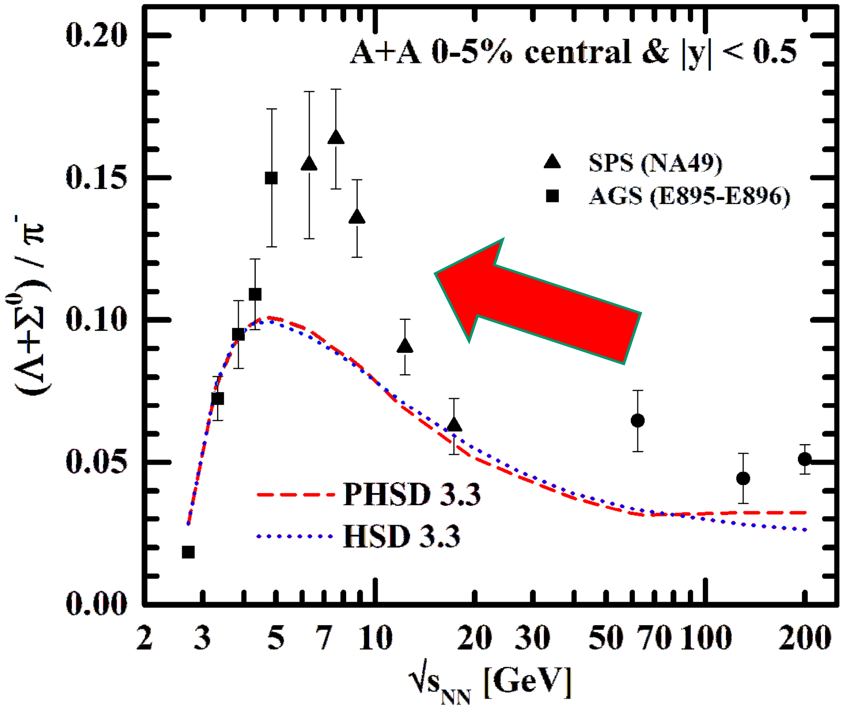
❑ **PHSD provides a good description of ‚bulk' observables (y-, p_T-distributions, flow coefficients v_n, …) from SIS to LHC**

Missing strangeness at FAIR/NICA energies !

- **Even when considering the creation of a QGP phase, the strangeness enhancement seen experimentally at FAIR/NICA energies remains unexplained**
  - **'Horn' not traced back to deconfinement**

Is there a problem for microscopic transport ?





strange quarks –
strangeness enhancement
and chiral symmetry restoration

strange quark-pair suppression in string decays

- According to the **Schwinger-formula**, the probability to form a massive $s\bar{s}$ in a string-decay is suppressed in comparison to light flavor $(u\bar{u}, d\bar{d})$

$$\frac{P(s\bar{s})}{P(u\bar{u})} = \frac{P(s\bar{s})}{P(d\bar{d})} = \gamma_s = \exp\left(-\pi\frac{m_s^2 - m_q^2}{2\kappa}\right)$$

string tension

- Considering a hot and dense medium, the above formula remains the same but **effective quark masses** should be employed. This dressing is due to a scalar coupling with the **in-medium quark condensate $\langle q\bar{q}\rangle$** according to:

$$m_s^* = m_s^0 + (m_s^v - m_s^0)\frac{\langle q\bar{q}\rangle}{\langle q\bar{q}\rangle_V} \qquad m_q^* = m_q^0 + (m_q^v - m_q^0)\frac{\langle q\bar{q}\rangle}{\langle q\bar{q}\rangle_V}$$

→ need to evaluate the scalar quark condensate in the medium !

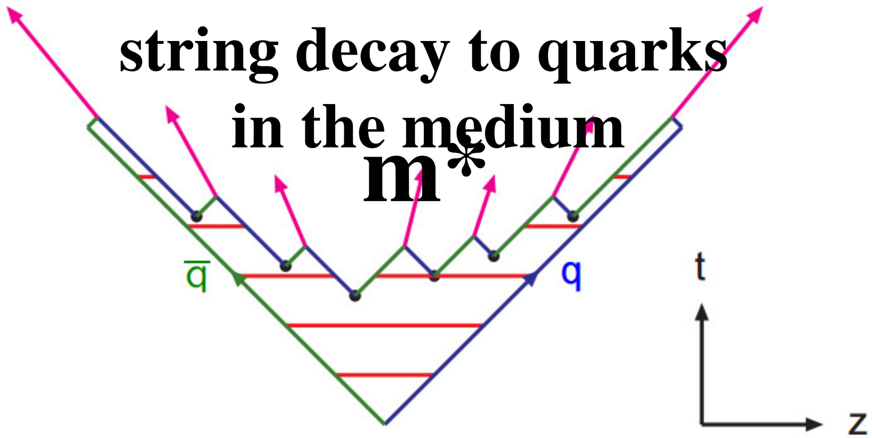
W. Cassing et al., PRC 93 (2016) 014902; A. Palmese et al., PRC94 (2016) 044912

Chiral symmetry restoration in the hadronic medium

- **The scalar quark condensate $\langle q\bar{q}\rangle$ is viewed as an order parameter for the restoration of chiral symmetry at high baryon density and temperature. It can be expressed in line with the Hellman-Feynman theorem by :**

$$\frac{\langle q\bar{q}\rangle}{\langle q\bar{q}\rangle_V} = 1 - \frac{\Sigma_\pi}{f_\pi^2 m_\pi^2}\rho_S - \sum_h \frac{\sigma_h \rho_S^h}{f_\pi^2 m_\pi^2}$$

where ρ_s is the scalar density obtained e.g. according to the non-linear $\sigma - \omega$ model, $\Sigma_\pi \approx 45$ MeV is the pion-nucleon Σ-term, and f_π and m_π are the pion decay constant and pion mass, given by the Gell-Mann-Oakes-Renner relation.

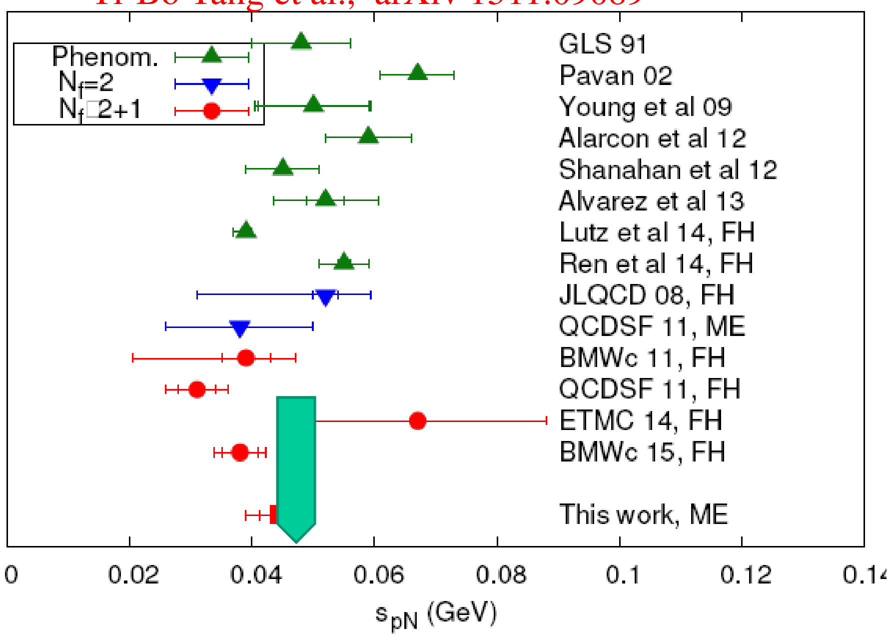


W. Cassing et al., PRC 93 (2016) 014902; A. Palmese et al., PRC94 (2016) 044912

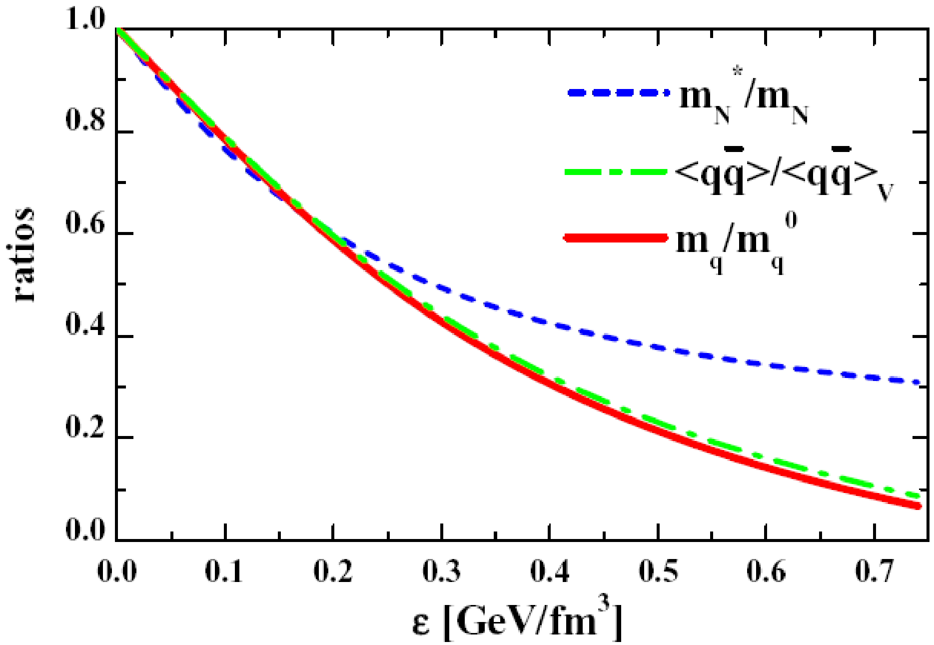
Chiral symmetry restoration in the hadronic medium

- pion-nucleon Σ-term : 45 MeV

Yi-Bo Yang et al., arXiv 1511.09089



scalar quark condensate $\langle q\bar{q}\rangle$ for NL3



→ in $$\frac{\langle q\bar{q}\rangle}{\langle q\bar{q}\rangle_V} = 1 - \frac{\Sigma_\pi}{f_\pi^2 m_\pi^2}\rho_S - \sum_h \frac{\sigma_h \rho_S^h}{f_\pi^2 m_\pi^2}$$

the leading terms are fixed within some uncertainty !

→ no new ‚parameters‘ !

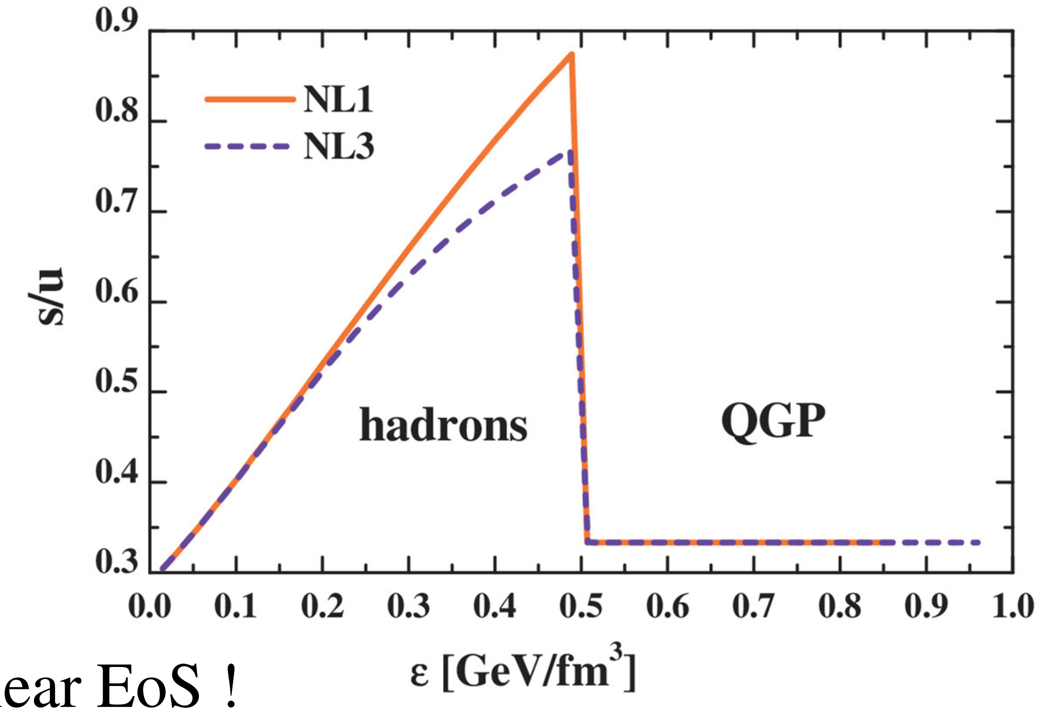
W. Cassing et al., PRC 93 (2016) 014902; A. Palmese et al., PRC94 (2016) 044912

Strangeness enhancement in the hadronic phase

Insert in: $$\frac{P(s\bar{s})}{P(u\bar{u})} = \frac{P(s\bar{s})}{P(d\bar{d})} = \gamma_s = \exp\left(-\pi\frac{m_s^2 - m_q^2}{2\kappa}\right)$$

- As a consequence of the **chiral symmetry restoration (CSR)**, the strangeness production probability increases with the energy density ε.

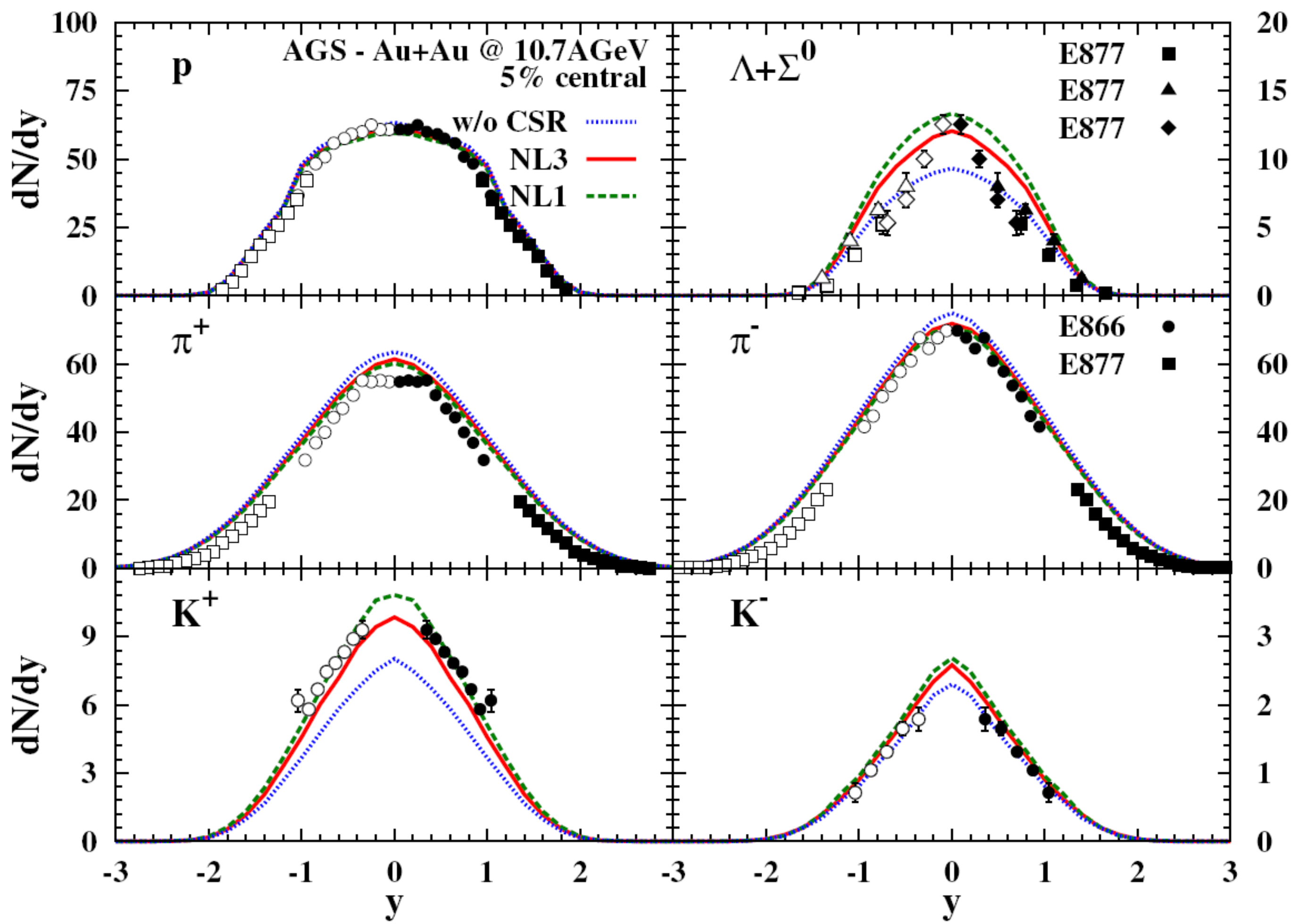
In the QGP phase, the string decay doesn't occur anymore and this effect is therefore suppressed.



Some dependence on the nuclear EoS !

W. Cassing et al., PRC 93 (2016) 014902; A. Palmese et al., PRC94 (2016) 044912

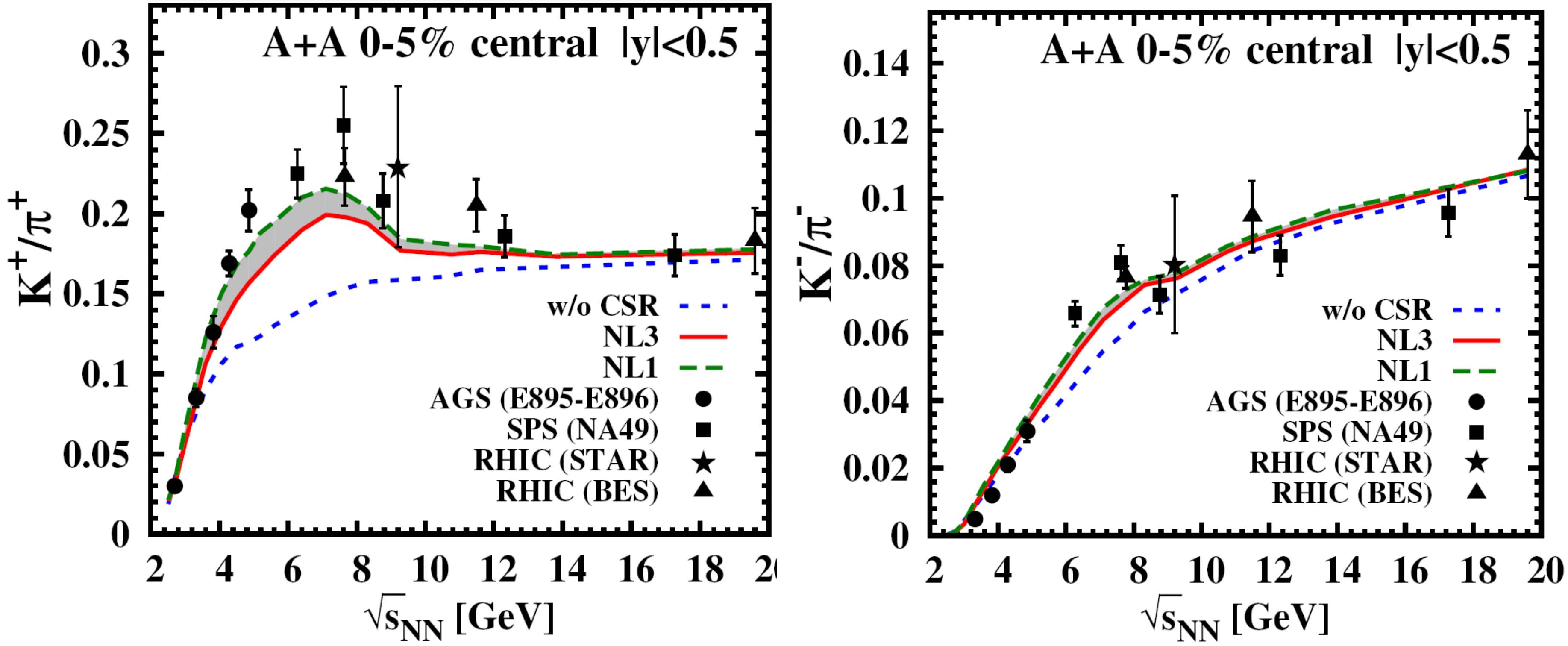
Comparison to data at AGS: 10.7 A GeV



looks quite good with CSR !

A. Palmese et al., PRC94 (2016) 044912

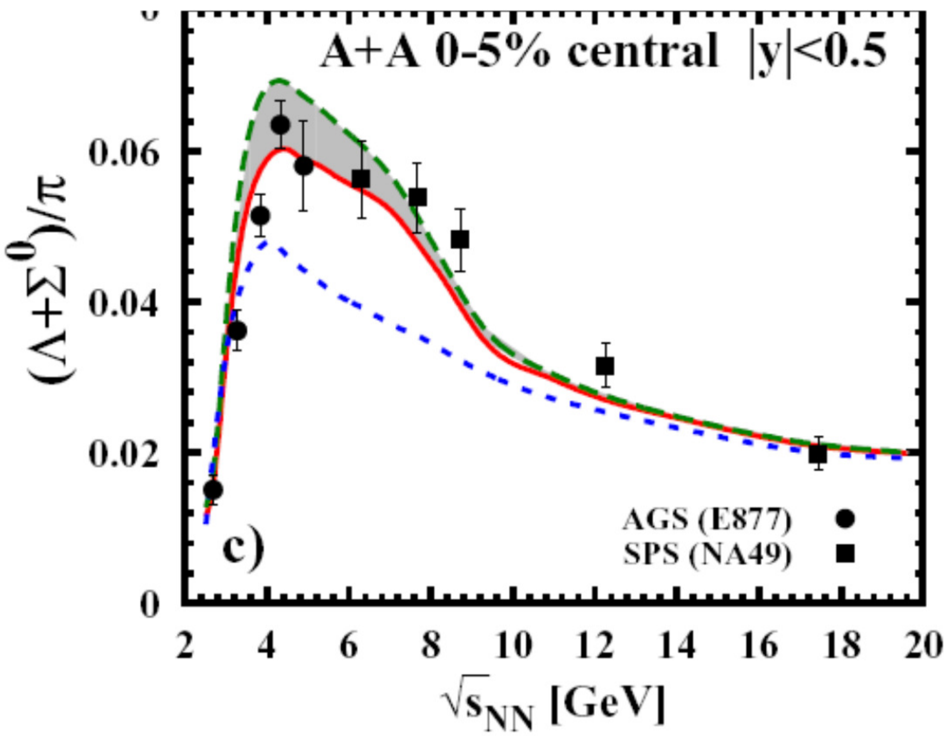
Excitation function of hadron ratios

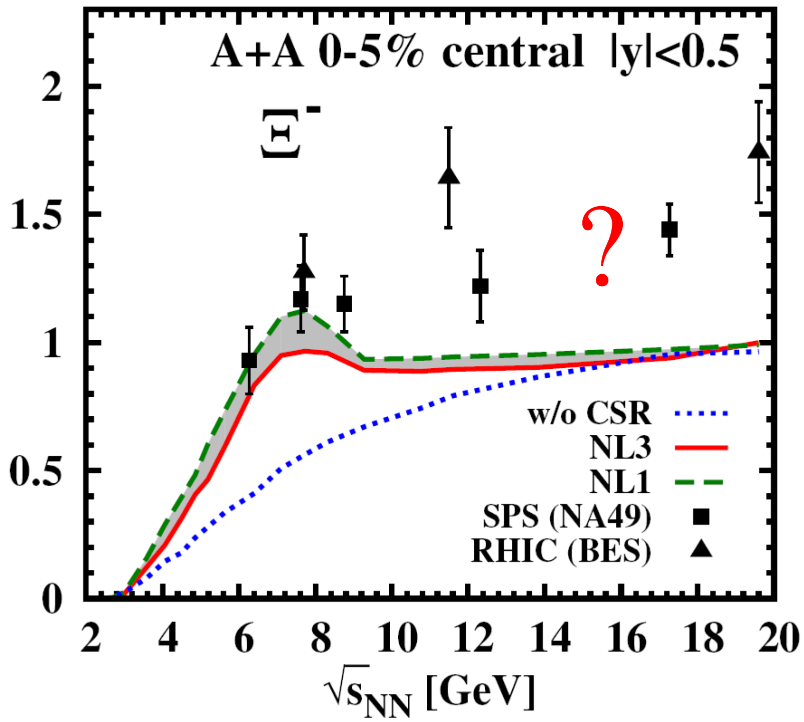


→ low sensitivity to the nuclear EoS

A. Palmese et al., PRC94 (2016) 044912

Excitation function of hadron ratios

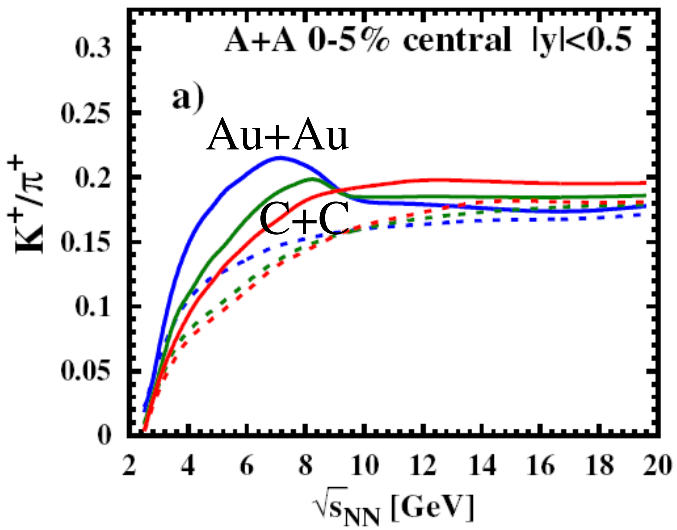


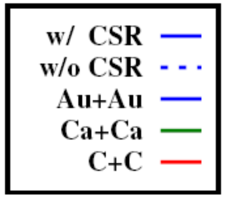


→ low sensitivity to the nuclear EoS

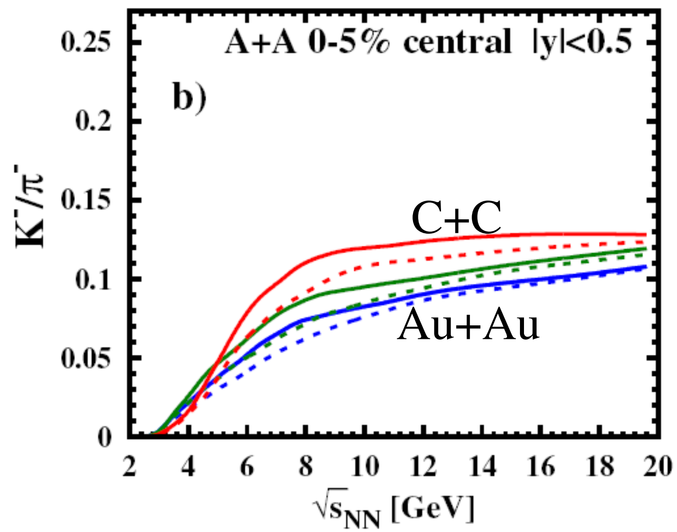
A. Palmese et al., PRC94 (2016) 044912

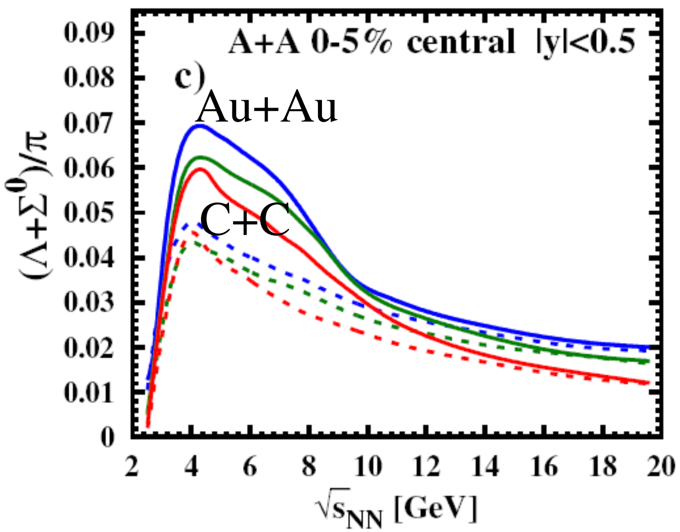
Predictions: Dependence on the system size





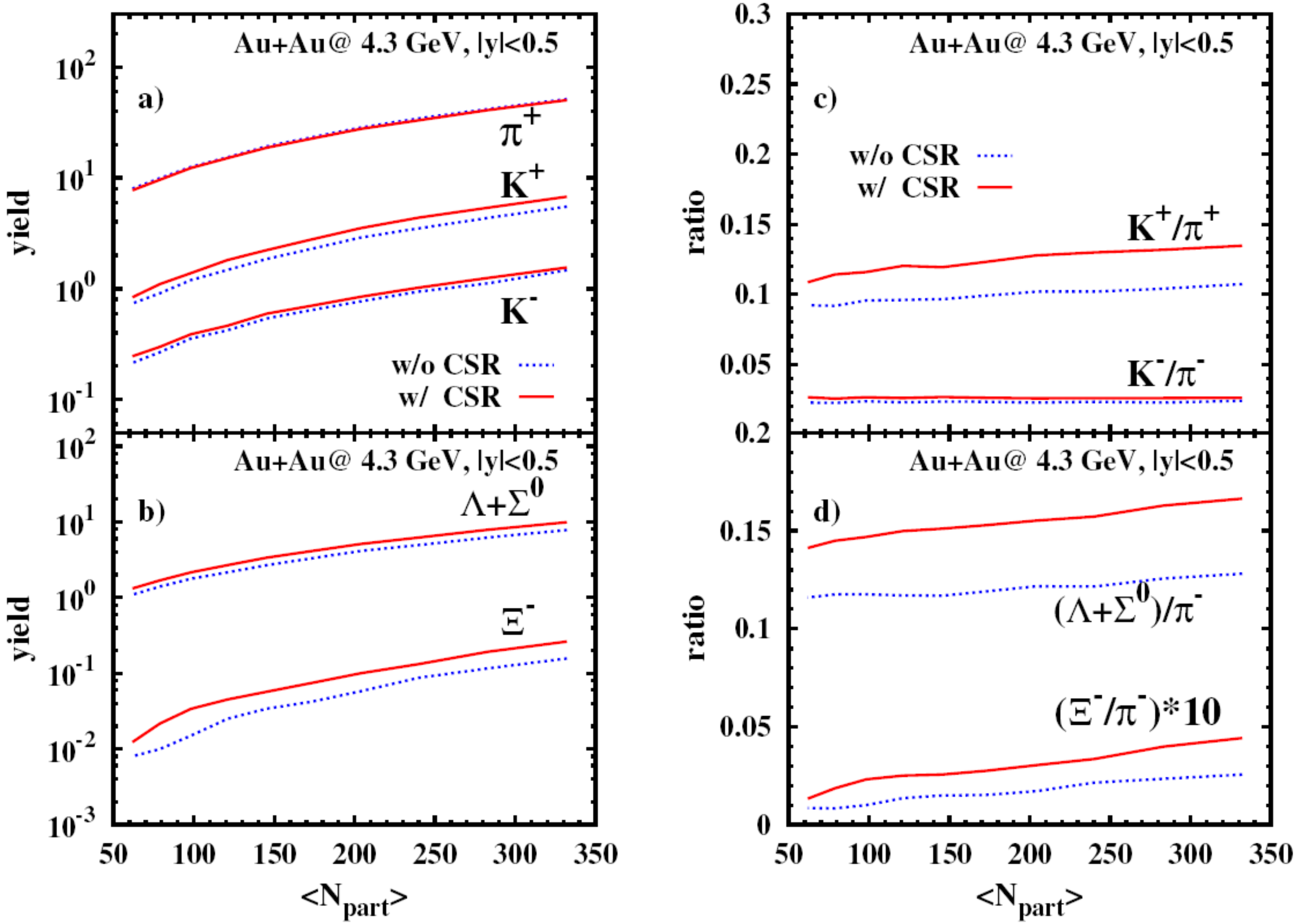
→ no ‚horn‘ for C+C





A. Palmese et al., PRC94 (2016) 044912

Predictions: Dependence on centrality



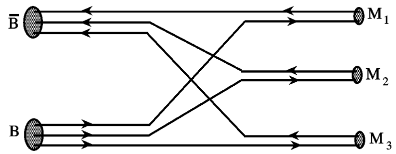
A. Palmese et al., PRC94 (2016) 044912

Detailed balance on the level of 2<->n:
treatment of multi-particle collisions in transport approaches

W. Cassing, NPA 700 (2002) 618

Generalized off-shell collision integral for *n <->m* reactions:

$$I_{coll} = \sum_n \sum_m \; I_{coll}[n \leftrightarrow m]$$



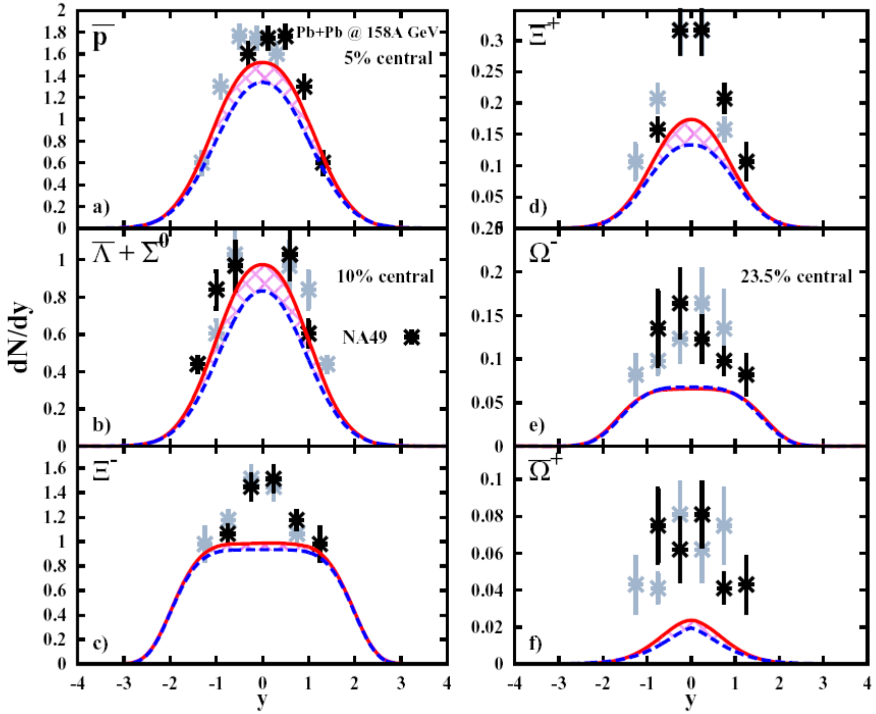
$$I^i_{coll}[n \leftrightarrow m] =$$
$$\frac{1}{2} N^m_n \sum_\nu \sum_\lambda \left(\frac{1}{(2\pi)^4}\right)^{n+m-1} \int \left(\prod_{j=2}^{n} d^4p_j \;\; A_j(x,p_j)\right) \left(\prod_{k=1}^{m} d^4p_k \; A_k(x,p_k)\right)$$
$$\times A_i(x,p) \; W_{n,m}(p,p_j;i,\nu \mid p_k;\lambda) \; (2\pi)^4 \; \delta^4(p^\mu + \sum_{j=2}^{n} p^\mu_j - \sum_{k=1}^{m} p^\mu_k)$$
$$\times [\tilde{f}_i(x,p) \prod_{k=1}^{m} f_k(x,p_k) \prod_{j=2}^{n} \tilde{f}_j(x,p_j) - f_i(x,p) \prod_{j=2}^{n} f_j(x,p_j) \prod_{k=1}^{m} \tilde{f}_k(x,p_k)].$$

$\tilde{f} = 1 + \eta f$ **is Pauli-blocking or Bose-enhancement factors;**
η=1 for bosons and η=-1 for fermions

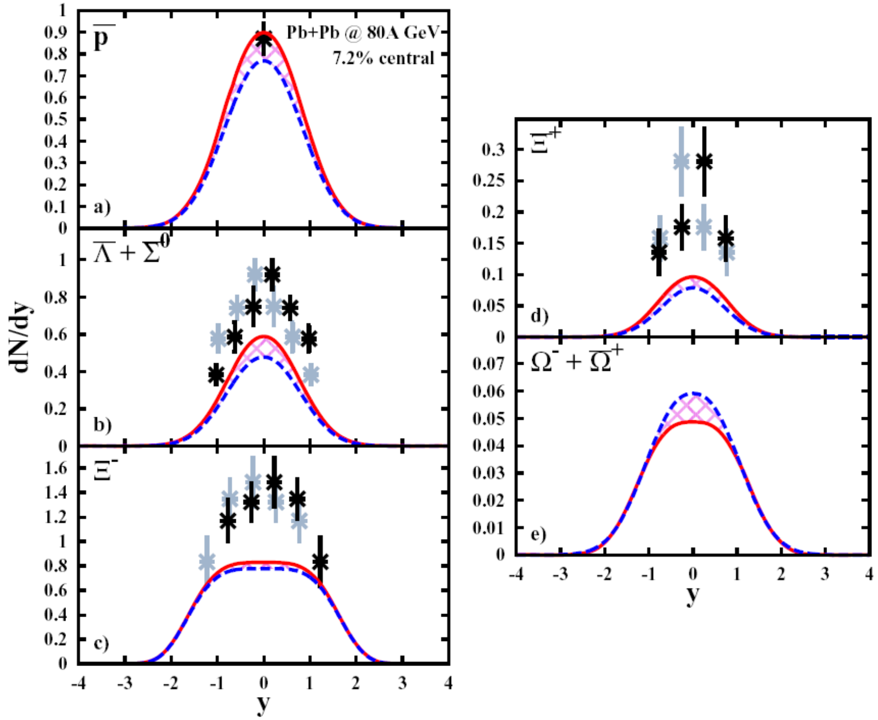
$W_{n,m}(p,p_j;i,\nu \mid p_k;\lambda)$ **is a transition probability**

Impact of 3-body reactions on baryon annihilation

158 AGeV



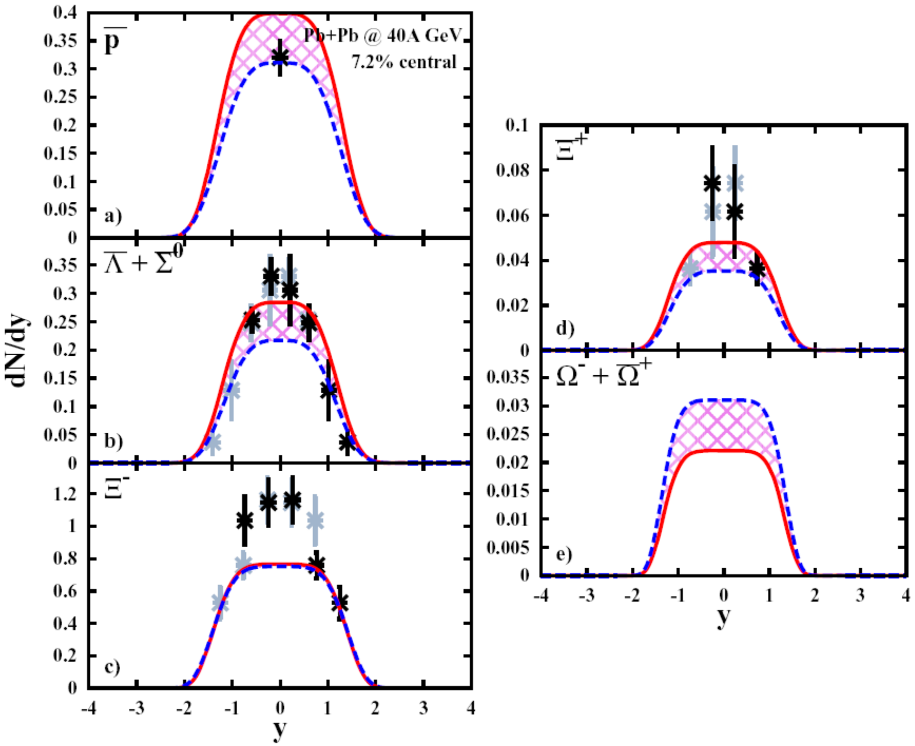
80 AGeV



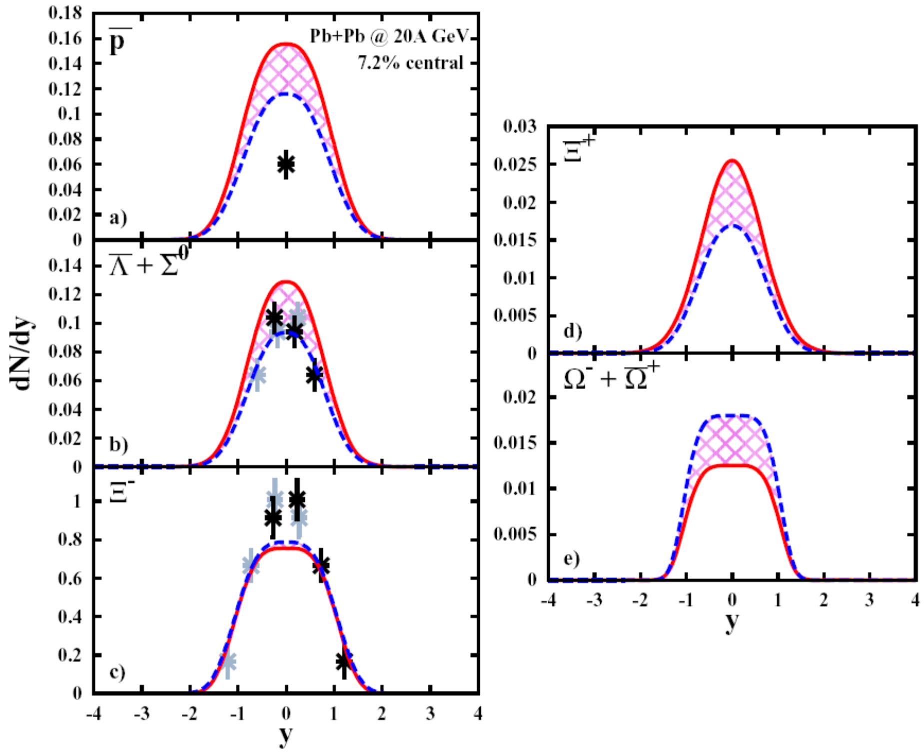
missing still some multistrange baryons and antibaryons !?

Impact of 3-body reactions on baryon annihilation

40 AGeV



20 AGeV



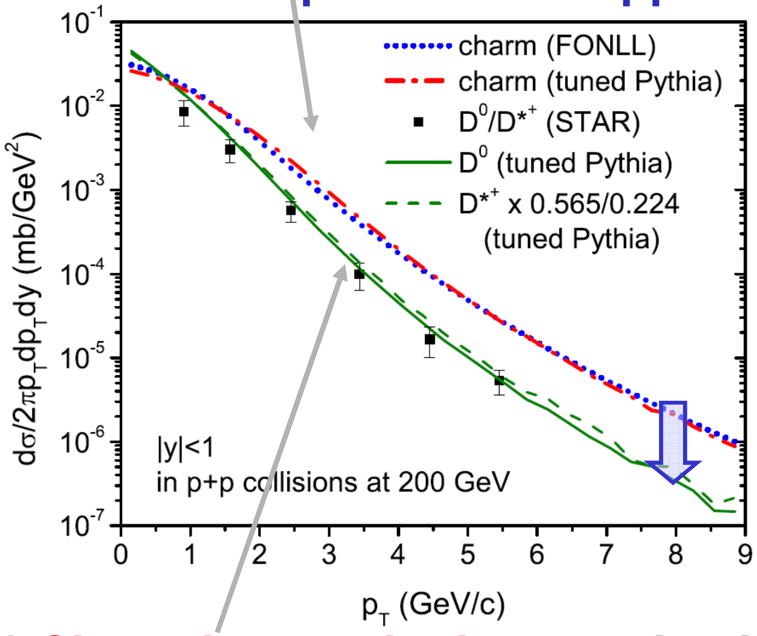
no exp. information on multistrange antibaryons

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

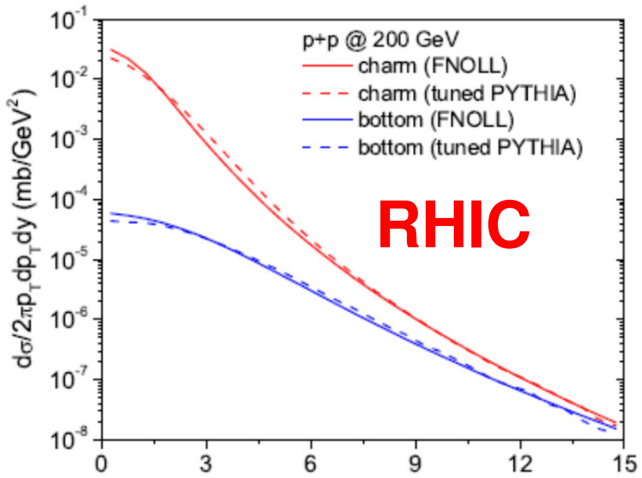
Heavy quark/hadron production in p+p collisions

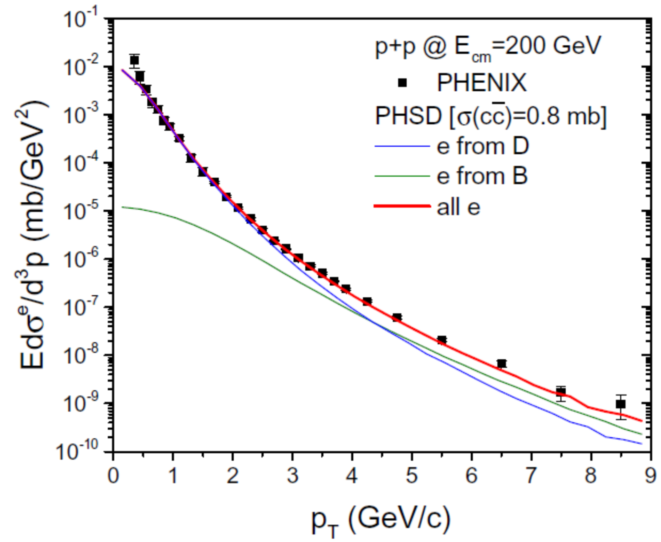
1) Momentum distribution of heavy quarks: use ‚tuned' PYTHIA event generator to reproduce FONLL (fixed-order next-to-leading log) results (R. Vogt et al.)

Charm production in pp



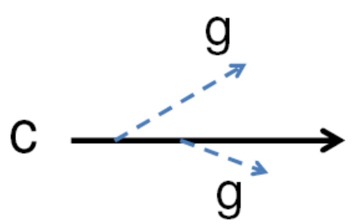
Beauty production in pp





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

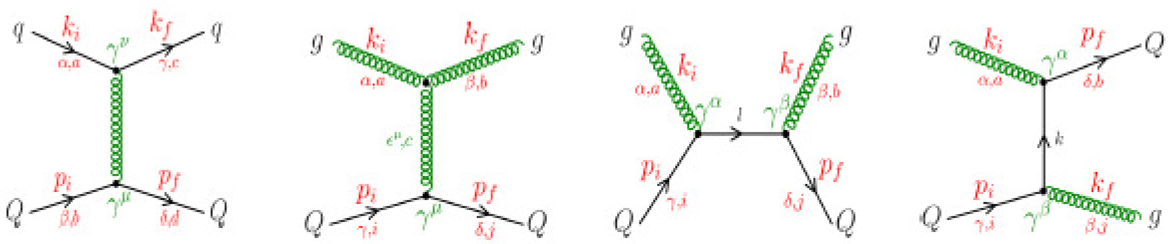
D^0 20 %
D^+ 17.4 %
D^{*0} 21.3 %
D^{*+} 22.4 %
Ds^+ 8 %
Λ_c 9.4 %



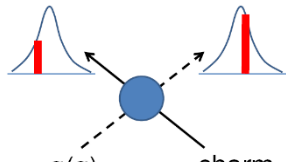
T. Song et al., PRC 92 (2015) 014910, arXiv:1503.03039

Heavy quark scattering in the QGP (DQPM)

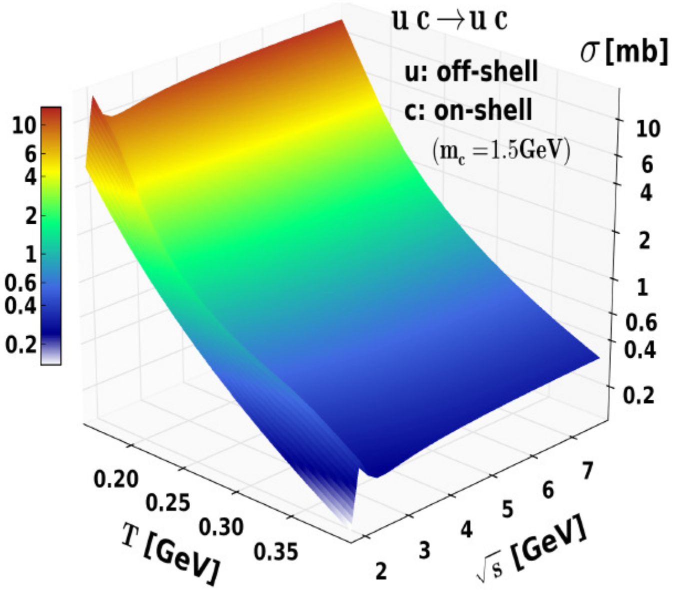
- **Elastic scattering with off-shell massive partons Q+q(g)→Q+q(g)**



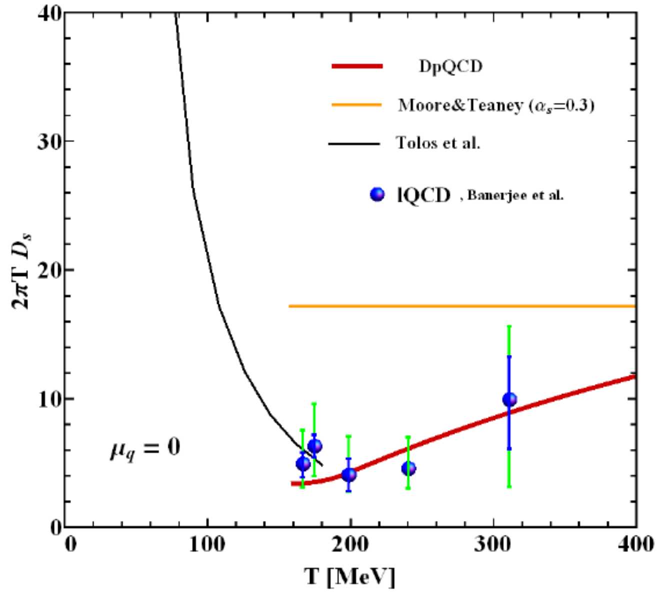
Non-perturbative QGP!



- **Elastic cross section uc→uc**



- **D_s for heavy quarks**



→ Continuous transition at T_C!

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

Hadronization of heavy quarks in A+A

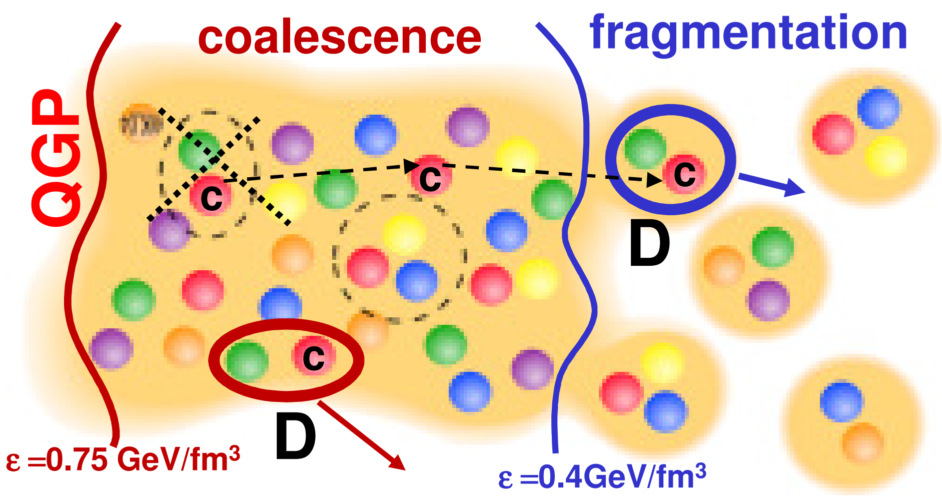
- PHSD: if the local energy density $\varepsilon \rightarrow \varepsilon_C$ ➔ hadronization of heavy quarks to hadrons

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

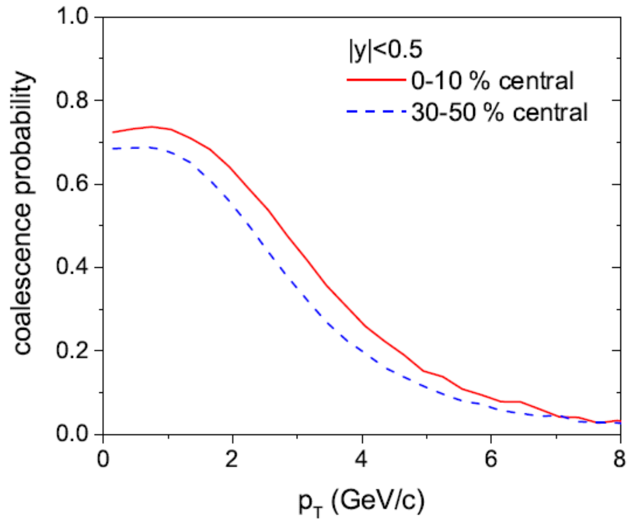
Dynamical hadronization scenario for heavy quarks :

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

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

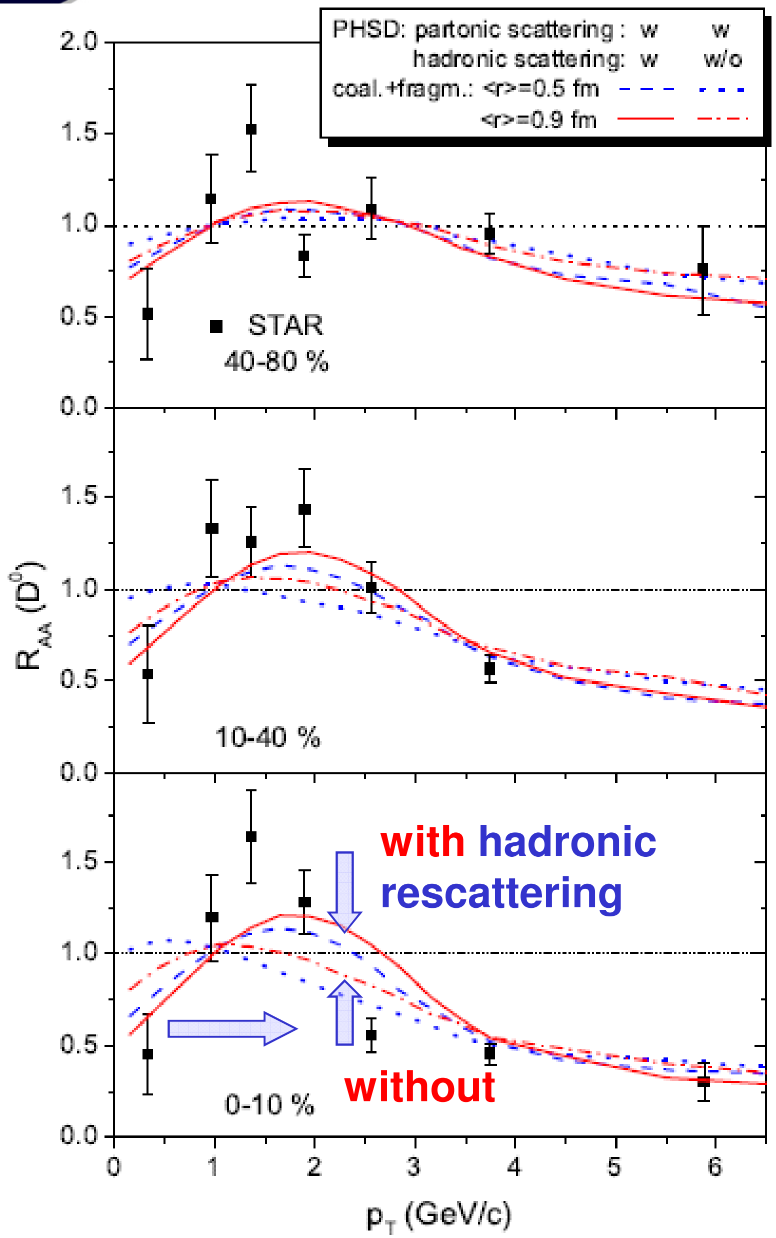
where $\boldsymbol{\rho}=\frac{1}{\sqrt{2}}(\mathbf{r}_1-\mathbf{r}_2),\quad \mathbf{k}_\rho=\sqrt{2}\,\frac{m_2\mathbf{k}_1-m_1\mathbf{k}_2}{m_1+m_2}$

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

R_{AA} at RHIC: hadronic rescattering



Influence of hadronic rescattering:

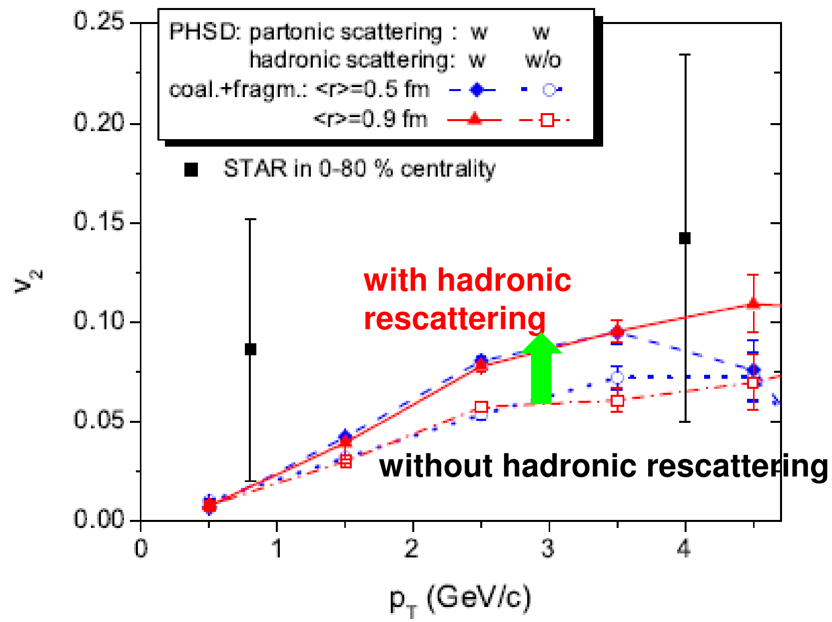
Central Au+Au at $s^{1/2}$ =200 GeV :

N(D,D*) ~30

N(D,D*+m) ~56 collisions

N(D,D*+B,Bbar) ~10 collisions

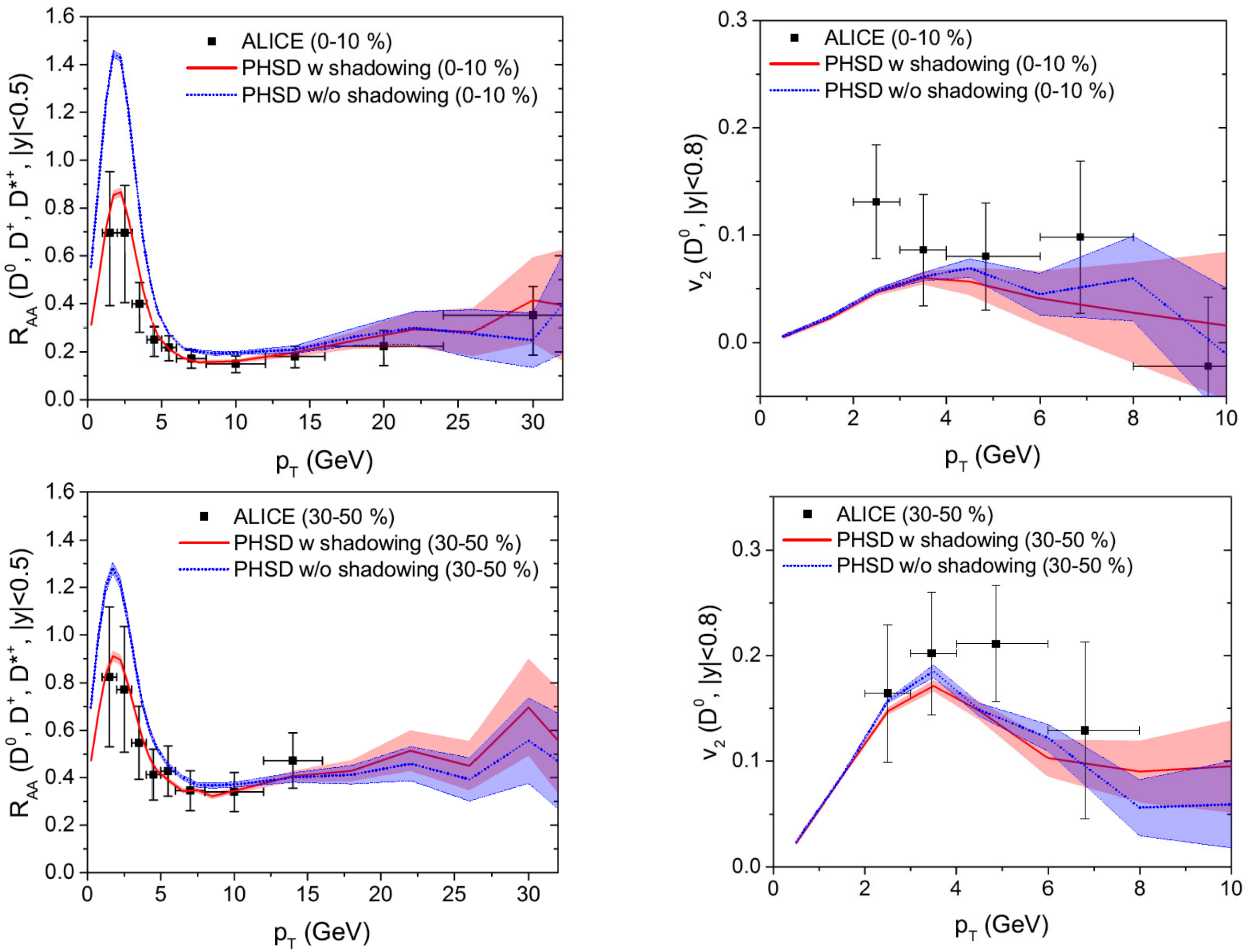
➔ **each D,D* makes ~ 2 scatterings with hadrons**



- ❑ **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

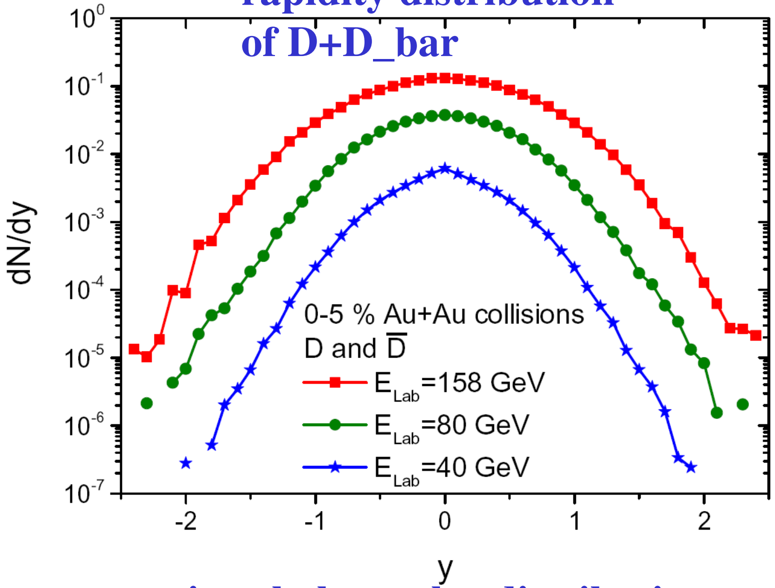


- in PHSD the energy loss of D-mesons at high p_T can be dominantly attributed to partonic scattering
- Shadowing effect suppresses the low p_T and slightly enhances the high p_T part of R_{AA}
- Hadronic rescattering moves R_{AA} peak to higher p_T; increases v_2

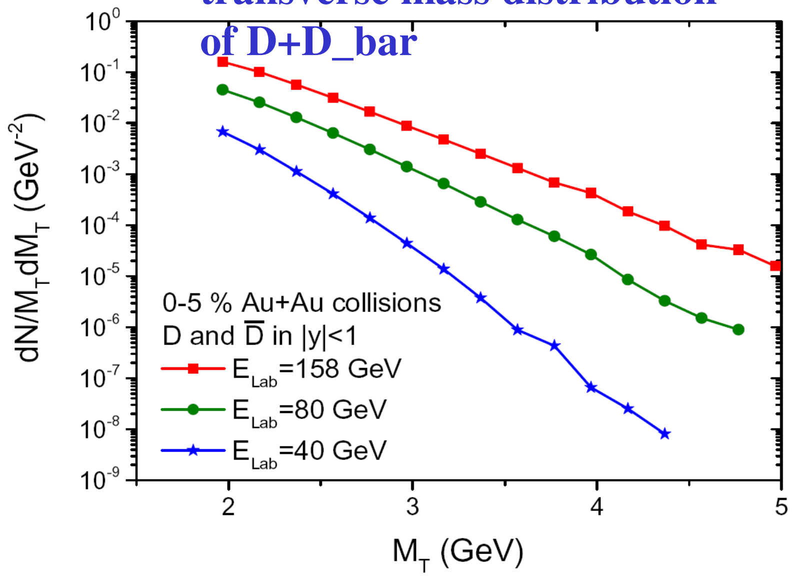
T. Song et al., PRC 93 (2016) 034906, arXiv:1512.0089

Charm dynamics at SPS energies in central Au+Au

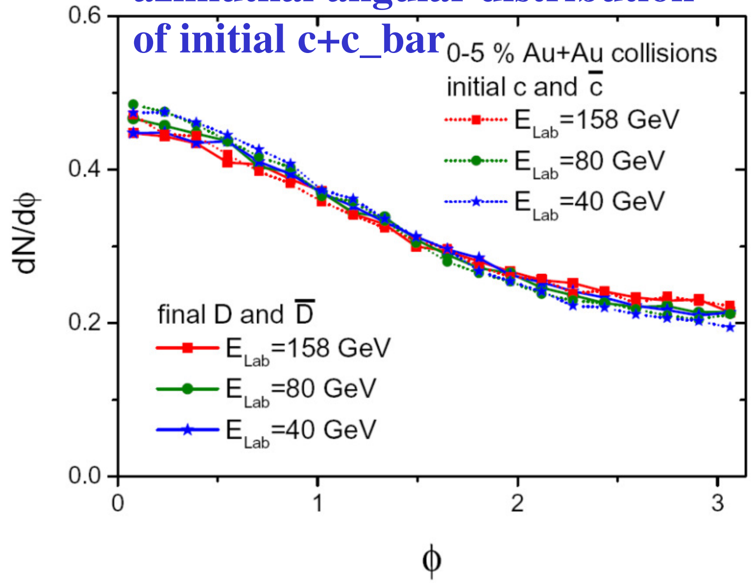
rapidity distribution of D+D_bar



transverse mass distribution of D+D_bar

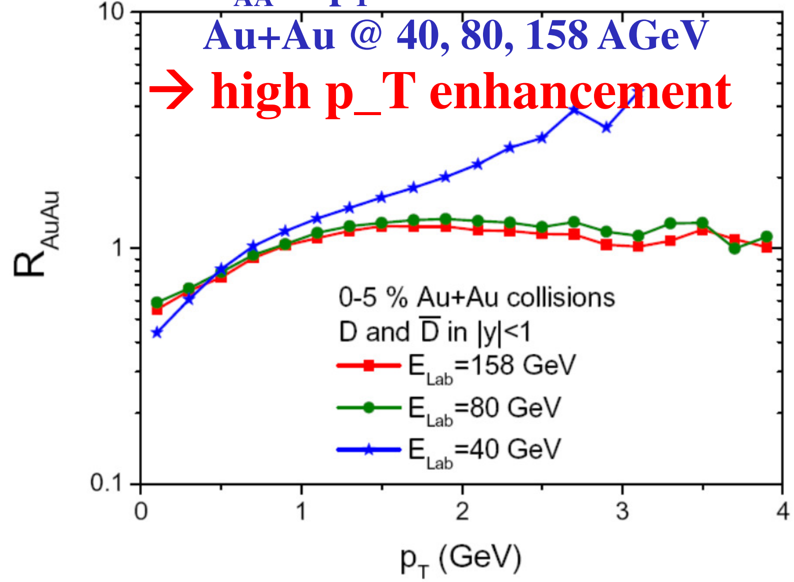


azimuthal angular distribution of initial c+c_bar

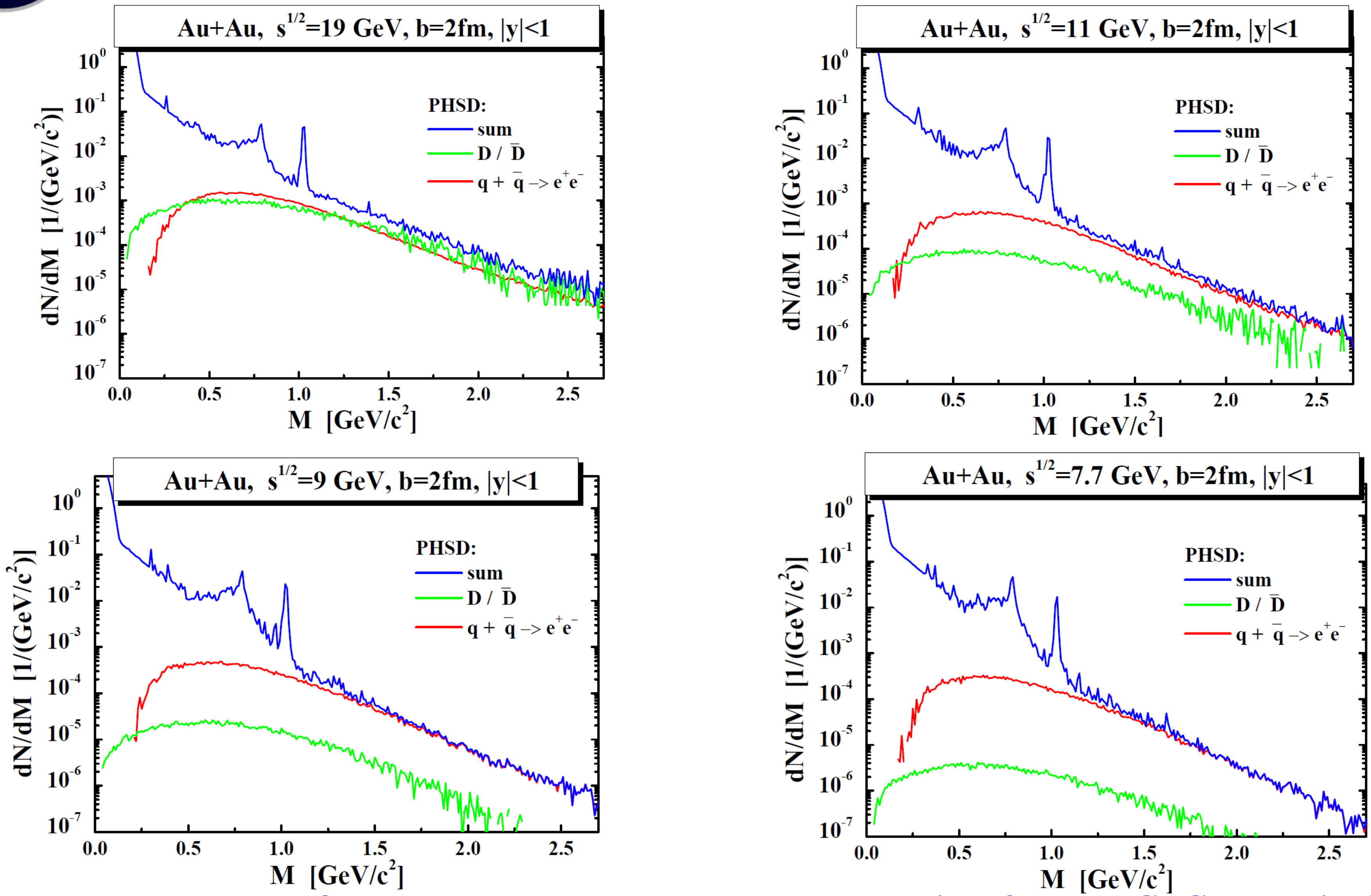


R_{AA} vs p_T from central Au+Au @ 40, 80, 158 AGeV

→ high p_T enhancement

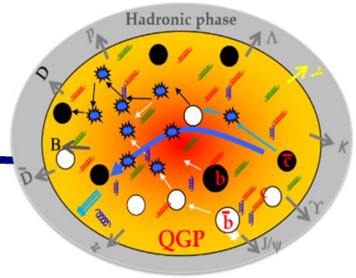


Dileptons at FAIR/NICA energies: predictions



The background from open charm becomes subleading for low SPS energies!
QGP annihilation clearly dominant for m > 1.2 GeV !

Summary



- PHSD provides a microscopic description of non-equilibrium dynamics in the partonic and hadronic phases

- The strangeness enhancement at AGS/FAIR/NICA energies cannot be attributed to deconfinement

- Including essential aspects of chiral symmetry restoration in the hadronic phase, we observe a rise in the K^+/π^+ ratio at low $\sqrt{s_{NN}}$ and then a drop due to the appearance of a deconfined partonic medium → a 'horn' emerges
PHSD: detailed predictions for the mass and centrality dependence of the K^+/π^+ ratio as well as for multistrange baryons and antibaryons

- Charm dynamics reasonably well under control at RHIC and LHC energies
→ detailed predictions for FAIR/NICA/SPS + dileptons

- 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; high p_T enhancement of charm at low SPS energies !

Thank you!

Reviews on PHSD and DQPM:

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