PROCESSES IN COLLISIONS OF HEAVY IONS

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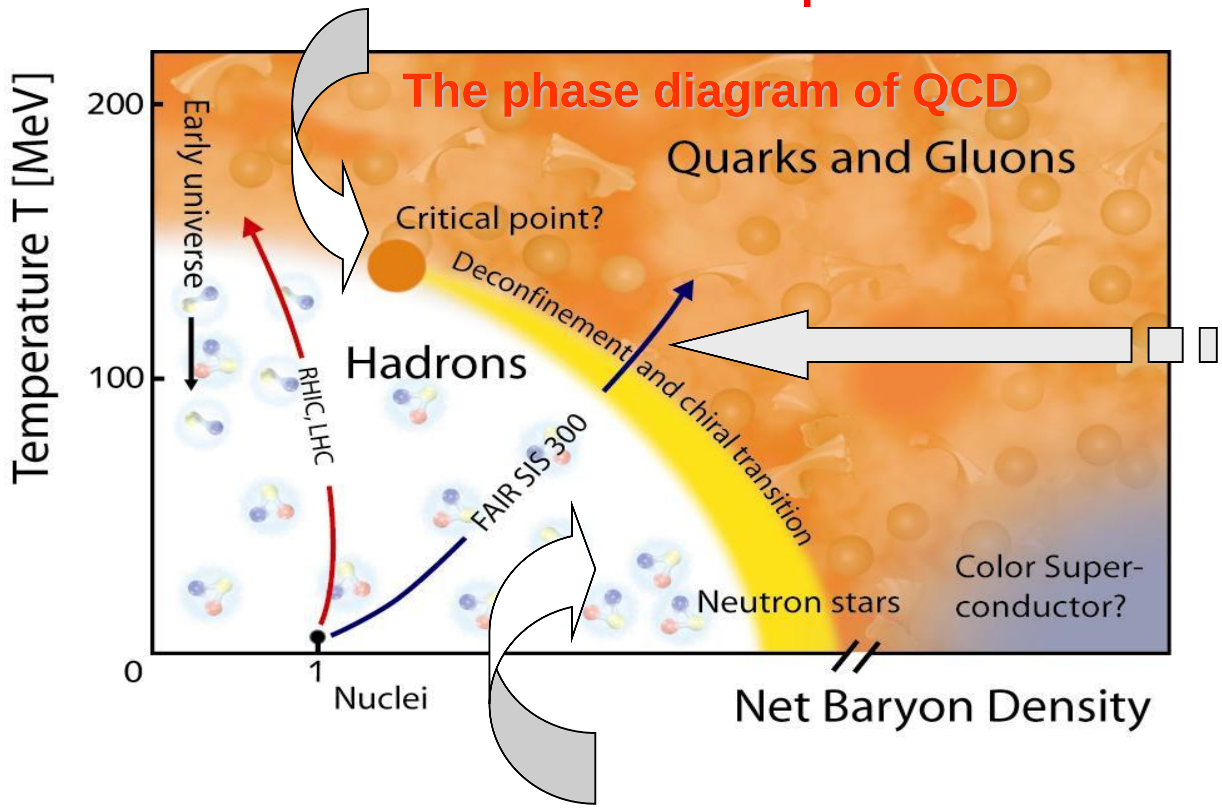
Main interests from heavy-ion collisions

Search for the **critical point**



Study of the **phase transition** from hadronic to partonic matter – **Quark-Gluon-Plasma**

Study of the **in-medium** properties of hadrons at high baryon density and temperature – chiral symmetry restoration

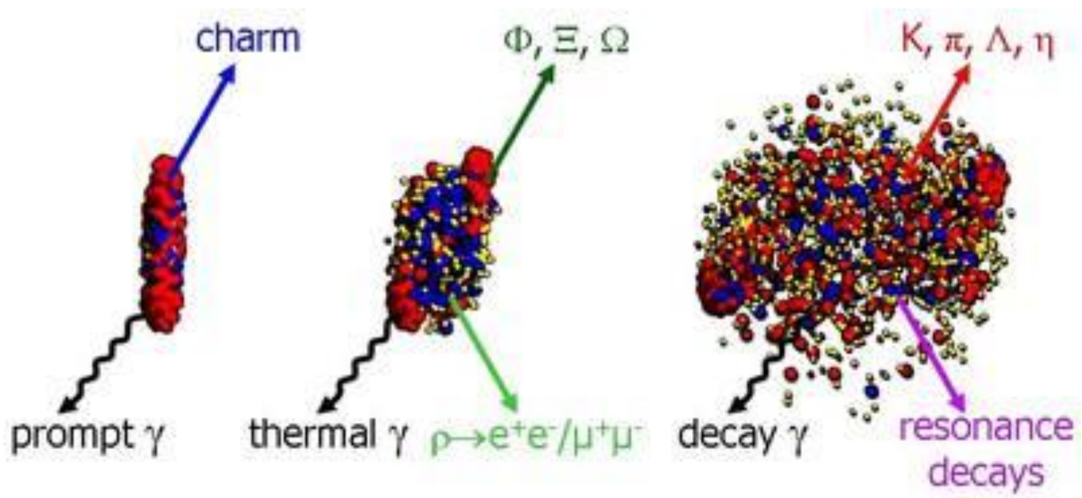
Signals of a phase transition

- **Multi-strange particle enhancement in A+A**
- **Charm suppression**
- **Collective flow (v_1, v_2)**
- **Thermal dileptons**
- **Jet quenching and angular correlations**
- **High p_T suppression of hadrons**
- **Nonstatistical event by event fluctuations and correlations**
- **...**

Experiment: measures final hadrons and leptons

How to learn about physics from data?

Compare with theory!



Models of heavy-ion collisions

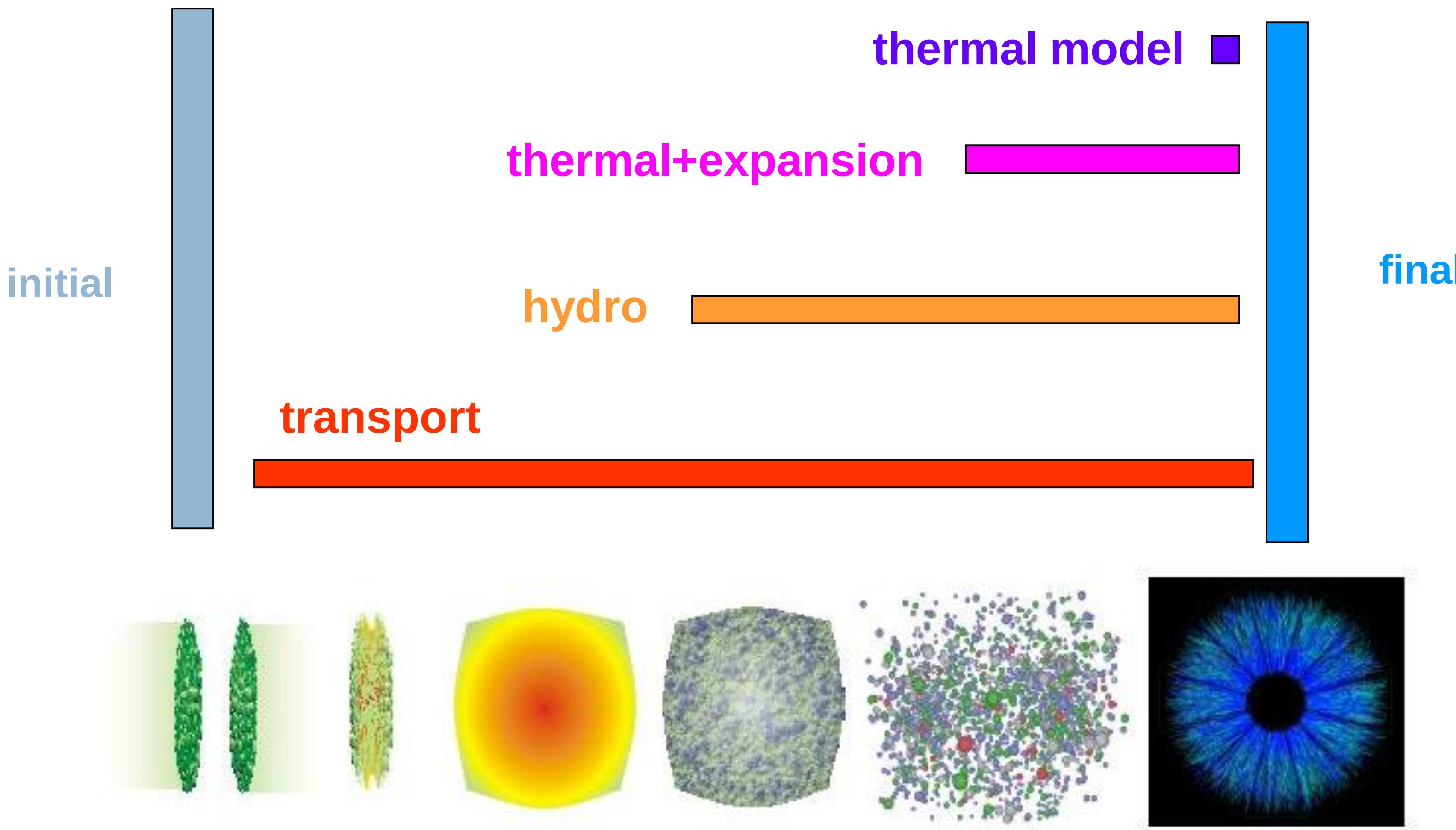
- **Statistical models:**
  basic assumption: system is described by a (grand) canonical ensemble of non-interacting fermions and bosons in thermal and chemical equilibrium
  [- : no dynamics]

- **Ideal hydrodynamical models:**
  basic assumption: conservation laws + equation of state; assumption of local thermal and chemical equilibrium
  [- : simplified dynamics]

- **Transport models:**
  based on transport theory of relativistic quantum many-body systems - nonequilibrium dynamics. Actual solutions: Monte Carlo simulations
  [+ : full dynamics | - : very complicated]

→ Microscopic transport models provide a unique dynamical description of nonequilibrium effects in heavy-ion collisions

Models of heavy-ion collisions



Basics of transport

- **Boltzmann-Uehling-Uhlenbeck equation (non-relativistic formulation)**

Evolution of the 1-body phase space distribution $f(\vec{r},\vec{p},t)$:

probability to find the particle at position r with momentum p at time t

$$\left(\frac{\partial}{\partial t} + \frac{\vec{p}}{m}.\vec{\nabla}_{\vec{r}} - \vec{\nabla}_{\vec{r}}\, U(\vec{r},t)\ .\vec{\nabla}_{\vec{p}} \right) f(\vec{r},\vec{p},t) = \left(\frac{\partial f}{\partial t} \right)_{coll}$$

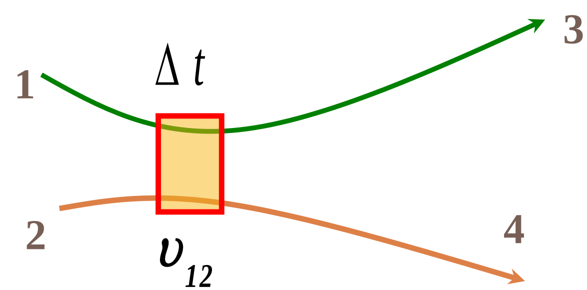
under the influence of a mean-field potential $U(\vec{r},t)$ and a 2-body on-shell collision term:

$$I_{coll} = \int \frac{d^3 p_2}{(2\pi)^3} \frac{d^3 p_3}{(2\pi)^3} \int d\Omega\, |v_{12}|\, (2\pi)^3 \delta^3(\vec{p}_1 + \vec{p}_2 - \vec{p}_3 - \vec{p}_4) \cdot \frac{d\sigma}{d\Omega}(1+2 \to 3+4) \cdot P$$

Probability including Pauli blocking of fermions:

$$P = f_3 f_4 (1-f_1)(1-f_2) - f_1 f_2 (1-f_3)(1-f_4)$$

Gain term: 3+4→1+2 **Loss term: 1+2→3+4**



Coupled channel equations

- **BUU eq. for different particles of type *i=1,…n***

Drift term=Vlasov eq. $$Df_i \equiv \frac{d}{dt} f_i = I_{coll}\left[f_1, f_2, ..., f_n\right]$$ collision term

$$i: \quad Baryons: \; p, n, \Delta(1232), N(1440), N(1535), ..., \Lambda, \Sigma, \Sigma^*, \Xi, \Omega; \; \Lambda_C$$

$$Mesons: \; \pi, \eta, K, \bar{K}, \rho, \omega, K^*, \eta', \phi, a_1, ..., D, \bar{D}, J/\Psi, \Psi', ...$$

➔ **coupled set of BUU equations for different particles of type *i=1,…n***

$$\begin{cases} Df_N = I_{coll}\left[f_N, f_\Delta, f_{N(1440)}, ..., f_\pi, f_\rho, ...\right] \\ Df_\Delta = I_{coll}\left[f_N, f_\Delta, f_{N(1440)}, ..., f_\pi, f_\rho, ...\right] \\ ... \\ Df_\pi = I_{coll}\left[f_N, f_\Delta, f_{N(1440)}, ..., f_\pi, f_\rho, ...\right] \\ ... \end{cases}$$

Coupled channel equations

Consider possible interactions for the sytem of *(N,R,m)*, where *N*-nucleons, *R*- resonances, *m*-mesons

- **elastic collisions:**

Baryon-baryon (BB):

$$NN \to NN$$
$$NR \to NR$$
$$RR' \to RR'$$

meson-Baryon (mB)

$$mN \to mN$$
$$mR \to mR$$

meson-meson (mm)

$$m\, m' \to m\, m'$$

Detailed balance:

$$a + b \leftrightarrow c$$
$$a + b \leftrightarrow c + d$$

- **inelastic collisions:**

Baryon-baryon (BB):

$$NN \leftrightarrow NR$$
$$NR \leftrightarrow NR'$$
$$NN \leftrightarrow RR'$$
...
$$BB \to X$$

meson-Baryon (mB)

$$mN \leftrightarrow R$$
$$mR \leftrightarrow R'$$
$$mB \leftrightarrow m'B'$$
...
$$mB \to X$$

meson-meson (mm)

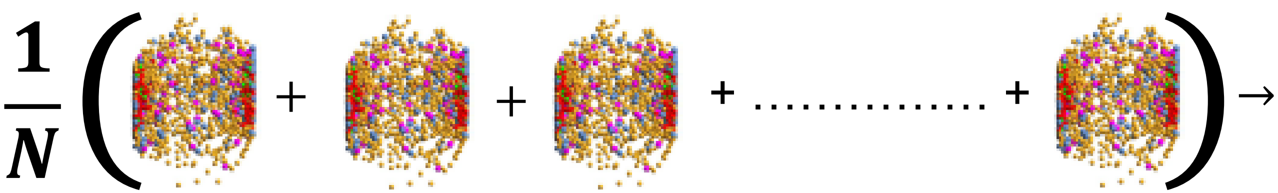
$$m\, m' \leftrightarrow \tilde{m}$$
$$m\, m' \leftrightarrow m'' m'''$$
...
$$m\, m' \to X$$

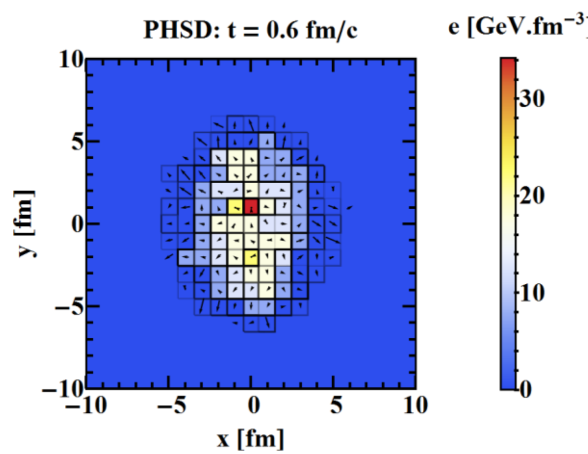
***X* - multi-particle state**

Test particle technique

- To solve this set of coupled channel equations, we asume that the distribution functions can be described as a sum of point-like particles (δ –functions)

- In order to have a smooth mean-field potential to propagate the particles, we need to average the profiles over N parallel ensembles :



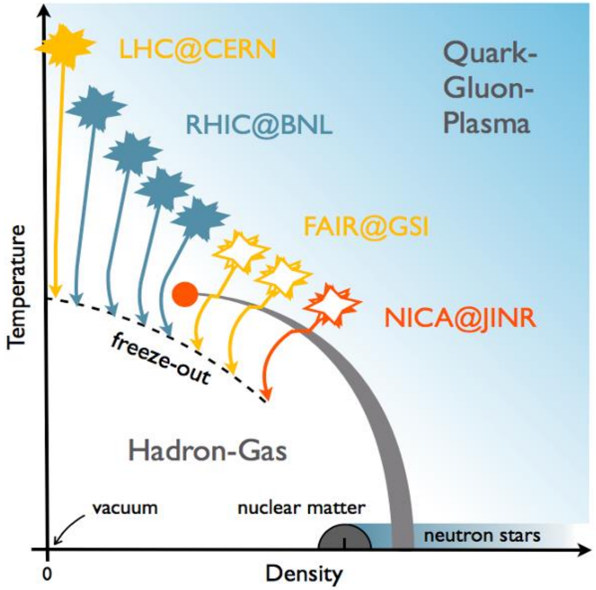


N = 30 here, Au+Au @ 200 GeV

- No exchange of particles between the parallel ensembles

- The particles are propagated according to averaged profiles in density which affects the mean-field potential or the Pauli-blocking factors by example

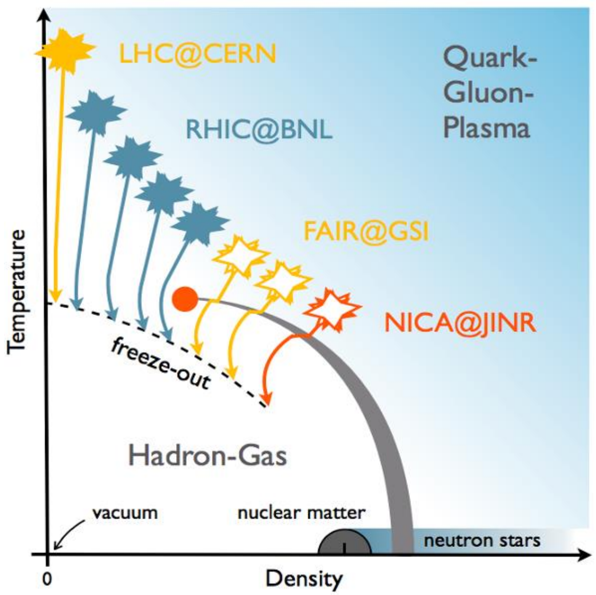
Dynamical description of heavy-ion collisions



- **Goal: Study the properties of strongly interacting matter under extreme conditions from a microscopic point of view**
- **Realization: dynamical many-body transport approach**

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

Dynamical description of heavy-ion collisions

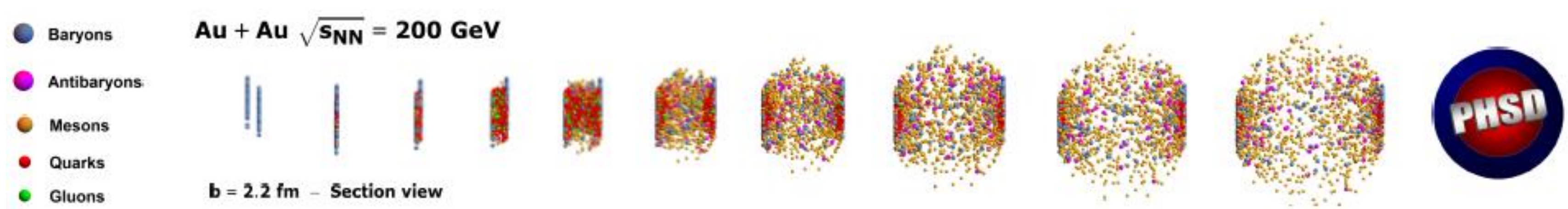


- **Goal:** **Study the properties of strongly interacting matter under extreme conditions from a microscopic point of view**
- **Realization: dynamical many-body transport approach**

Parton-Hadron-String-Dynamics (PHSD)

- **Explicit parton-parton interactions, explicit phase transiton 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**



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In medium effects

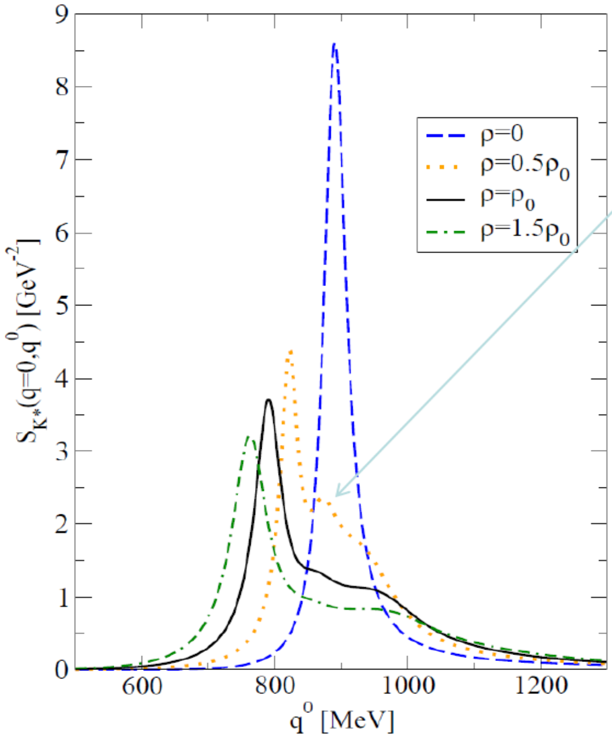
In-medium effects (on hadronic or partonic levels!): changes of particle properties in the hot and dense medium
Example: hadronic medium - vector mesons, strange mesons

Many-body theory:
Strong interaction

➔ large width = short life-time
➔ broad spectral function
➔ quantum object

- **How to describe the dynamics of broad strongly interacting quantum states in transport theory?**

$\bar{K}^*$ spectral function



Λ(1783)N^{-1} and Σ(1830)N^{-1} exitations

Barcelona / Valencia group

In medium effects

- The particle **gains an effective mass** through the interactions with the medium

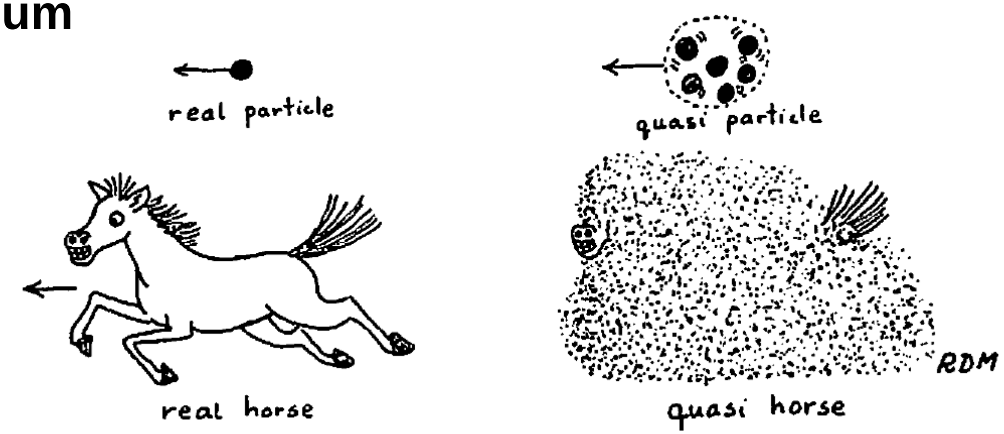


Fig. 0.4 *Quasi Particle Concept*

Drawing from:
A guide to Feynman Diagrams in the Many-Body Problem,
Richard D. Mattuck

Quasiparticle = real particle + interactions with the medium

- The quasiparticle has also a **finite lifetime τ** since collisions with other quasiparticles can change its properties :

$$\tau = \frac{1}{\Gamma}$$

Γ : interaction rate or collisional width of the particle

Resummed propagator

- **The propagator contains the important physical properties of the medium like the effective mass and width of the quasiparticles**

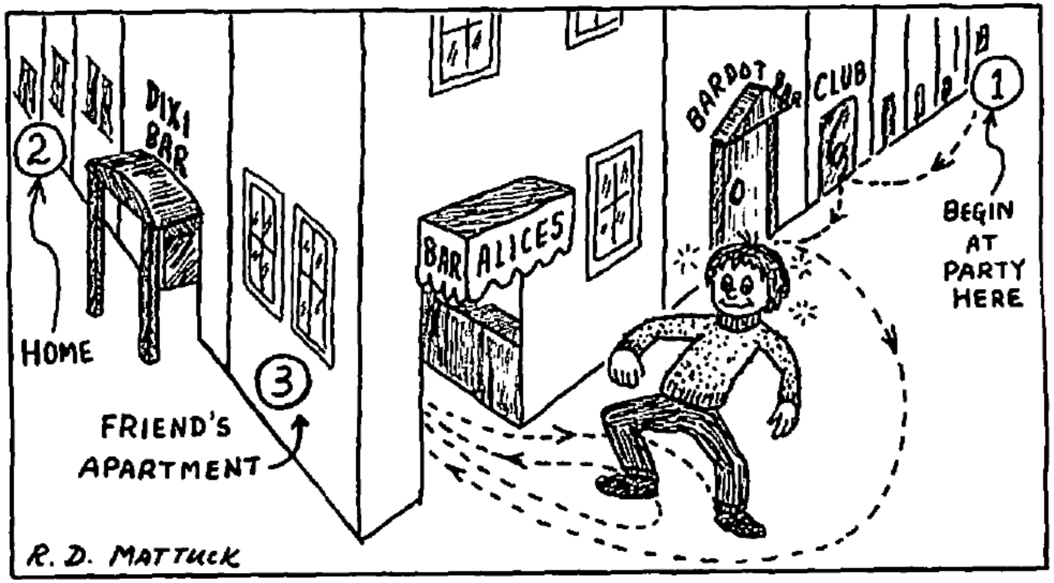


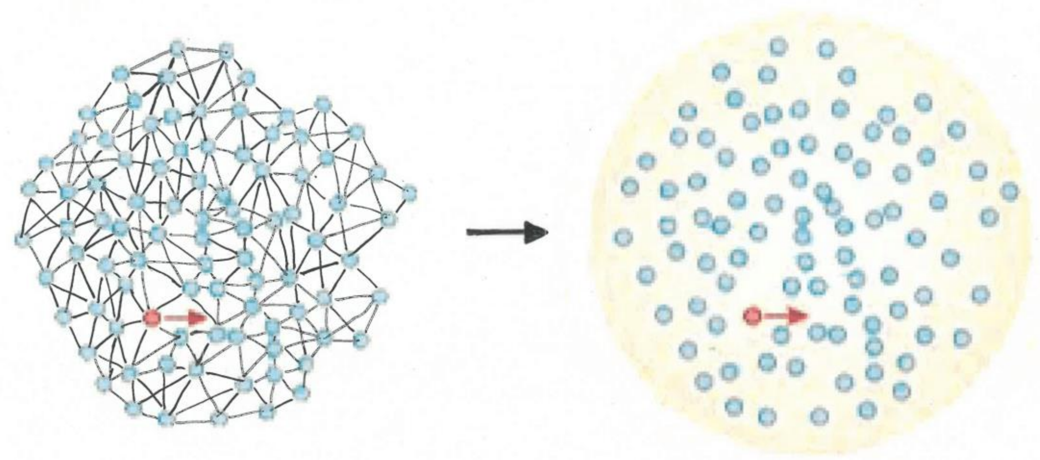
Fig. 1.1 ***Propagation of Drunken Man***

Drawing from:
A guide to Feynman Diagrams in the Many-Body Problem,
Richard D. Mattuck

- **For the propagation of quarks and gluons, all the probabilities of interaction with the QGP medium have to be taken into account to determine its properties**

Propagation of quasiparticles

- Instead of computing the evolution of the distribution function through coupled channel equations
  - Propagation of each single quasiparticle according to their propagator in a **mean-field potential** + **collisions with other quasiparticles**



- **Semi-classical on-shell BUU:** applies for small collisional width, i.e. for a weakly interacting systems of particles

How to describe strongly interacting systems?!

Description of strongly interaction system

- Quantum field theory ➔
  Kadanoff-Baym dynamics for resummed single-particle Green functions $S^<$

$$\hat{S}^{-1}_{0x}\, S^<_{xy} = \Sigma^{ret}_{xz} \odot S^<_{zy} + \Sigma^<_{xz} \odot S^{adv}_{zy}$$

Integration over the intermediate spacetime

Green functions $S^<$ / self-energies Σ:

$$iS^<_{xy} = \eta \langle \{\Phi^+(y)\Phi(x)\}\rangle$$

$$iS^>_{xy} = \langle \{\Phi(y)\Phi^+(x)\}\rangle$$

$$iS^c_{xy} = \langle T^c\{\Phi(x)\Phi^+(y)\}\rangle \quad - causal$$

$$iS^a_{xy} = \langle T^a\{\Phi(x)\Phi^+(y)\}\rangle \quad - anticausal$$

$$S^{ret}_{xy} = S^c_{xy} - S^<_{xy} = S^>_{xy} - S^a_{xy} \quad - retarded$$

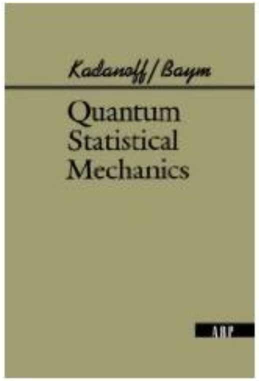
$$S^{adv}_{xy} = S^c_{xy} - S^>_{xy} = S^<_{xy} - S^a_{xy} \quad - advanced$$

$$\eta = \pm 1 (bosons\,/\,fermions)$$

$$T^a(T^c) - (anti-)time-ordering\ operator$$

$$\hat{S}^{-1}_{0x} \equiv -(\partial^{\mu}_x \partial^x_{\mu} + M^2_0)$$

(1962)



1st order gradient expansion of quantum Kadanoff-Baym equations

➔ **generalized transport equations**

Description of strongly interaction system

- **Employ testparticle Ansatz for the real valued quantity *i* $S^{<}_{XP}$ -**

$$F_{XP} = A_{XP} N_{XP} = i\, S^{<}_{XP} \sim \sum_{i=1}^{N} \delta^{(3)}(\vec{X} - \vec{X}_i(t))\ \delta^{(3)}(\vec{P} - \vec{P}_i(t))\ \delta(P_0 - \epsilon_i(t))$$

insert in generalized transport equations and determine equations of motion !

➔ **General testparticle Cassing's off-shell equations of motion for the time-like particles:**

$$\frac{d\vec{X}_i}{dt} = \frac{1}{1 - C_{(i)}} \frac{1}{2\epsilon_i} \left[2\,\vec{P}_i + \vec{\nabla}_{P_i} Re\Sigma^{ret}_{(i)} + \frac{\epsilon_i^2 - \vec{P}_i^2 - M_0^2 - Re\Sigma^{ret}_{(i)}}{\Gamma_{(i)}} \vec{\nabla}_{P_i} \Gamma_{(i)} \right],$$

$$\frac{d\vec{P}_i}{dt} = -\frac{1}{1 - C_{(i)}} \frac{1}{2\epsilon_i} \left[\vec{\nabla}_{X_i} Re\Sigma^{ret}_i + \frac{\epsilon_i^2 - \vec{P}_i^2 - M_0^2 - Re\Sigma^{ret}_{(i)}}{\Gamma_{(i)}} \vec{\nabla}_{X_i} \Gamma_{(i)} \right],$$

$$\frac{d\epsilon_i}{dt} = \frac{1}{1 - C_{(i)}} \frac{1}{2\epsilon_i} \left[\frac{\partial Re\Sigma^{ret}_{(i)}}{\partial t} + \frac{\epsilon_i^2 - \vec{P}_i^2 - M_0^2 - Re\Sigma^{ret}_{(i)}}{\Gamma_{(i)}} \frac{\partial \Gamma_{(i)}}{\partial t} \right],$$

with $F_{(i)} \equiv F(t, \vec{X}_i(t), \vec{P}_i(t), \epsilon_i(t))$

$$C_{(i)} = \frac{1}{2\epsilon_i} \left[\frac{\partial}{\partial \epsilon_i} Re\Sigma^{ret}_{(i)} + \frac{\epsilon_i^2 - \vec{P}_i^2 - M_0^2 - Re\Sigma^{ret}_{(i)}}{\Gamma_{(i)}} \frac{\partial}{\partial \epsilon_i} \Gamma_{(i)} \right]$$

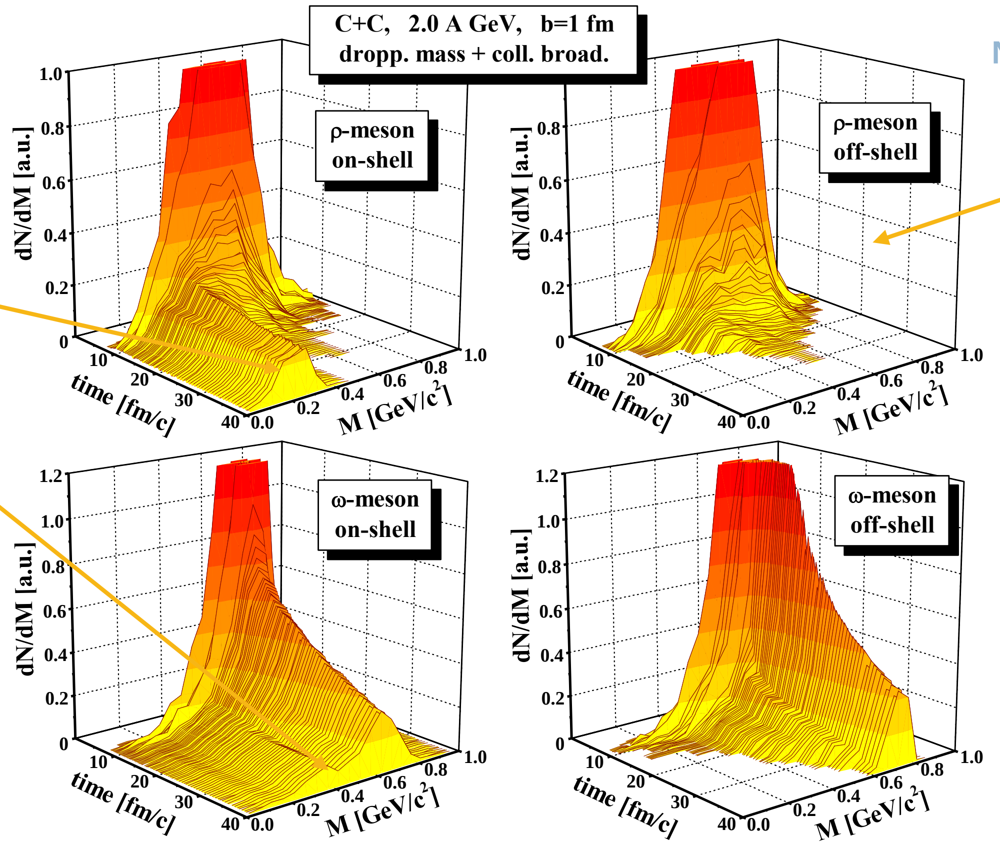
Description of strongly interaction system

Time evolution of the mass distribution of ρ and ω mesons for central C+C collisions (b=1 fm) at 2 A GeV for dropping mass + collisional broadening scenario

E.L.B. &W. Cassing, Nucl Phys A 807 (2008) 214

On-shell

On-shell model: low mass ρ and ω mesons live forever (and e.g. shine fake dileptons)!



Off-shell

The off-shell spectral function becomes on-shell in the vacuum dynamically by propagation through the medium!

Dynamical Quasi-Particle Model (DQPM)

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 $S_q^{-1} = P^2 - \Sigma_q$

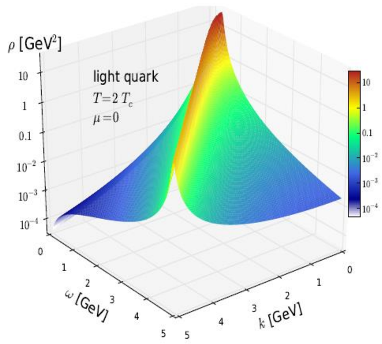
gluon self-energy: $\Pi = M_g^2 - i2\Gamma_g\omega$ & quark self-energy: $\Sigma_q = M_q^2 - i2\Gamma_q\omega$

(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)

- **The QGP phase is described in terms of interacting quasiparticles with Lorentzian spectral functions:**

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



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

Dynamical Quasi-Particle Model (DQPM)

Modeling of the quark/gluon masses and widths → HTL limit at high T

- **quarks:**

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

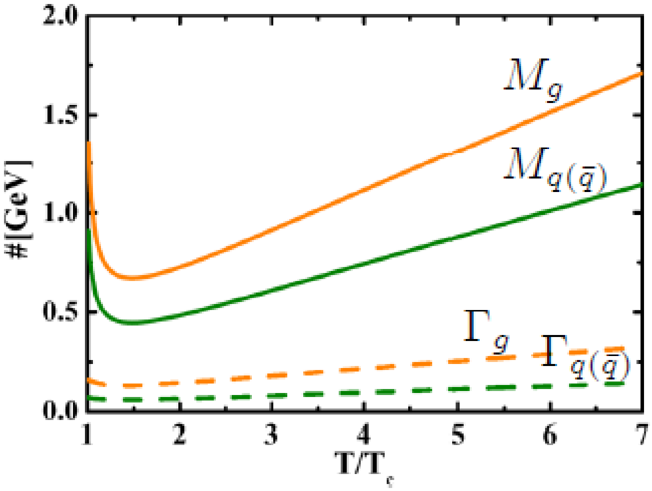
width: $\Gamma_{q(\bar q)}(T) = \frac{1}{3}\frac{N_c^2-1}{2N_c}\frac{g^2 T}{8\pi}\ln\left(\frac{2c}{g^2}+1\right)$

- **gluons:**

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

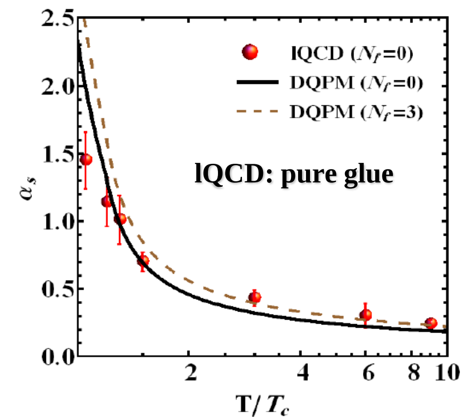
width: $\Gamma_g(T) = \frac{1}{3}N_c\frac{g^2 T}{8\pi}\ln\left(\frac{2c}{g^2}+1\right)$

$N_c = 3, N_f = 3$



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

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

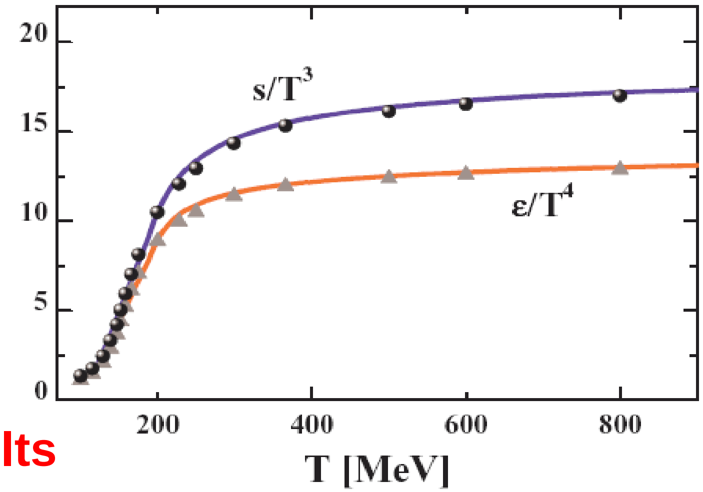


Peshier, Cassing, PRL 94 (2005) 172301; Cassing, NPA 791 (2007) 365: NPA 793 (2007)

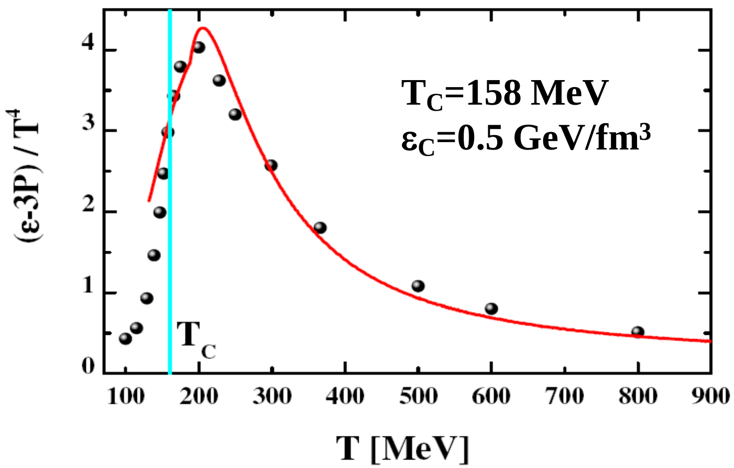
Dynamical Quasi-Particle Model (DQPM)

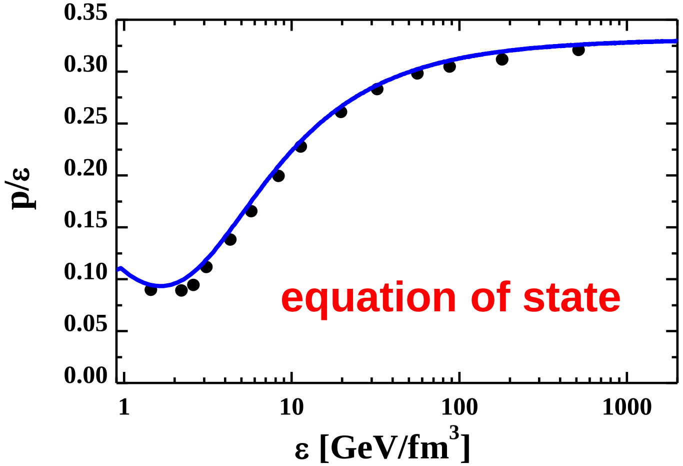
- Properties of quasiparticles are fitted to the lattice QCD results

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



DQPM gives a good description of lQCD results





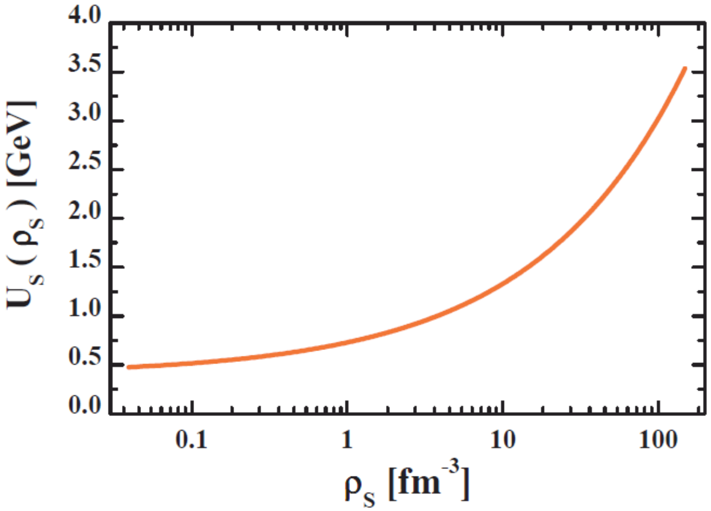
Peshier, Cassing, PRL 94 (2005) 172301; Cassing, NPA 791 (2007) 365: NPA 793 (2007)

Dynamical Quasi-Particle Model (DQPM)

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

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

where the potential energy density V_p is defined by the space-like part of energy-momentum tensor $T_{\mu\nu}$



Quasiparticle potentials (U_q, U_g) are repulsive!

$U_q = U_S$, $U_g \sim 2U_S$

- **Force acting on a quasiparticle j :**

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

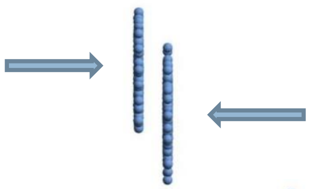
$$j = g, q, \bar{q}$$

Particles are accelerated!

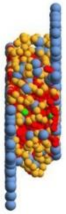
Peshier, Cassing, PRL 94 (2005) 172301; Cassing, NPA 791 (2007) 365: NPA 793 (2007)

Stages of a collision in PHSD

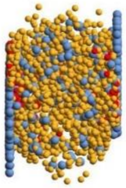
Initial A+A collision



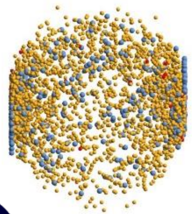
Partonic phase



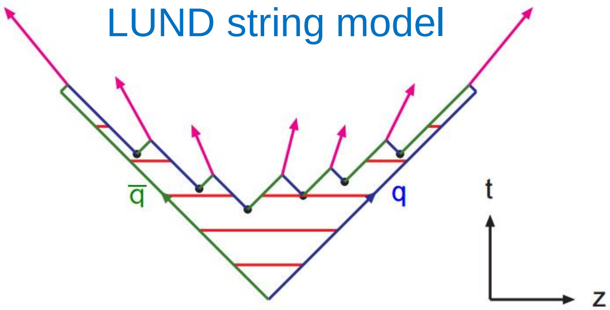
Hadronization



Hadronic phase



- **String formation in primary NN collisions**
- **String decays to pre-hadrons (baryons and mesons)**



String fragmentation

From http://www.physics.adelaide.edu.au/theory/staff/leinweber/VisualQCD/Nobel/

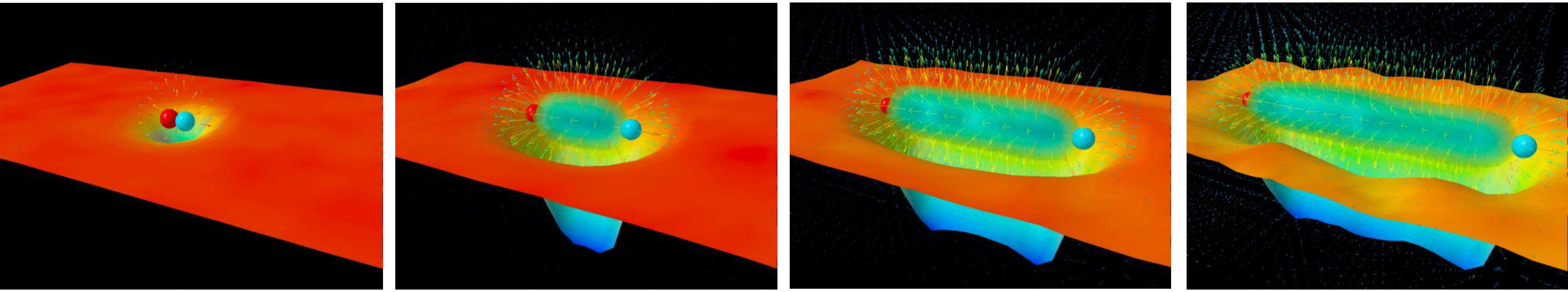
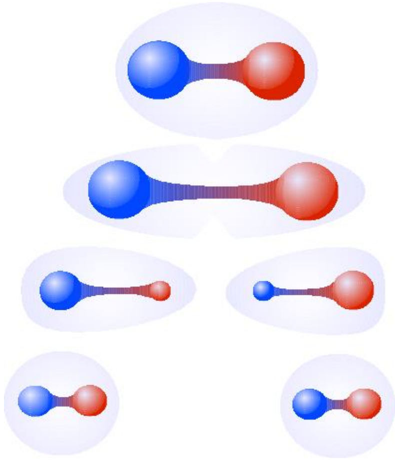


Illustration of a meson in lQCD with different separation distance between the quarks

- **Confinement: At large distances between quarks, the strong force increases greatly**
- **The hadrons are bound by a flux tube of gluons that behaves like a string**
  - **Production of particles result from the breaking of the string**



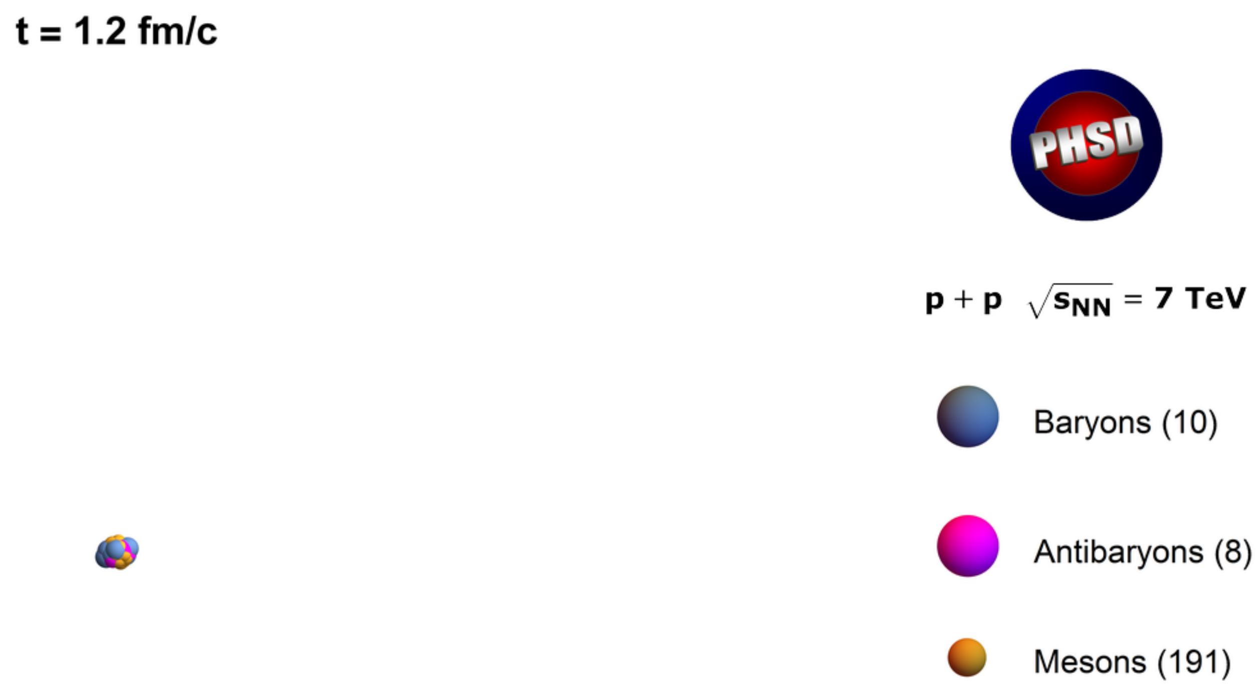
String breaking process

String fragmentation

P.Moreau

String fragmentation

String fragmentation

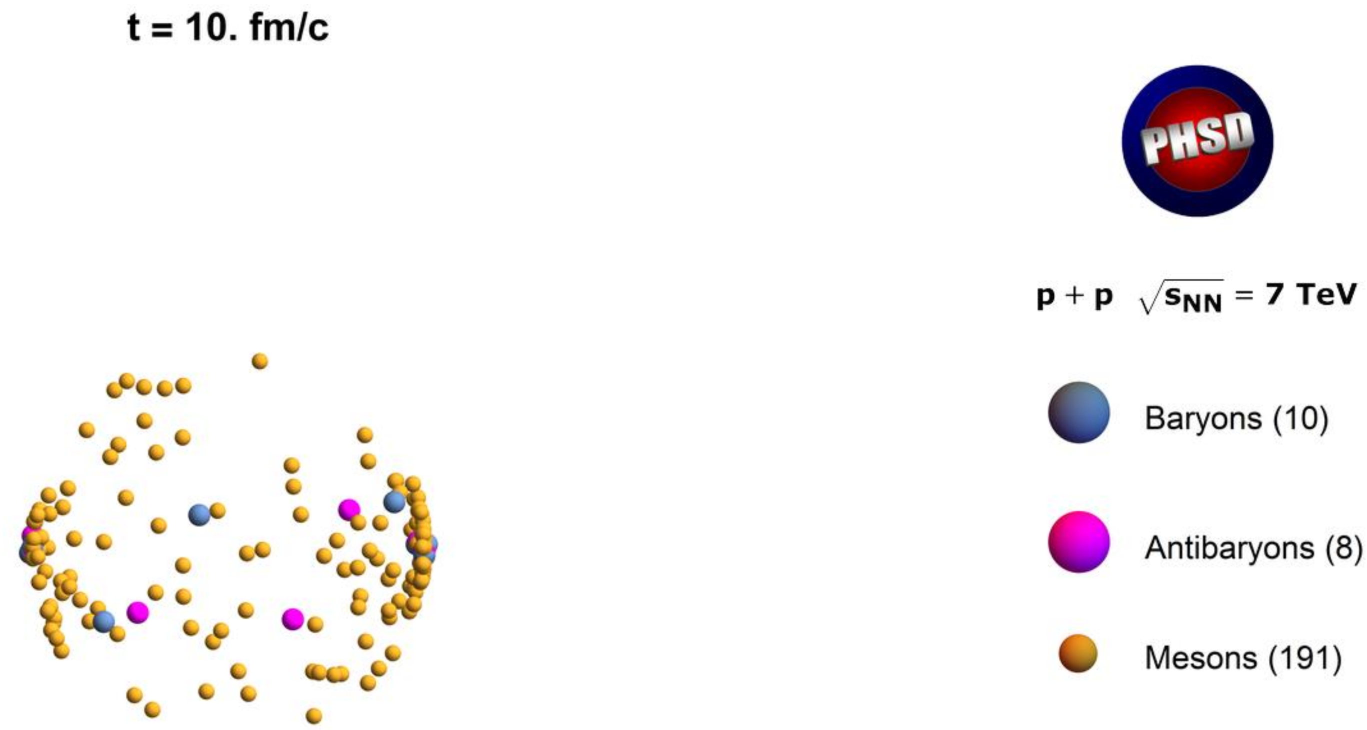


P.Moreau

String fragmentation

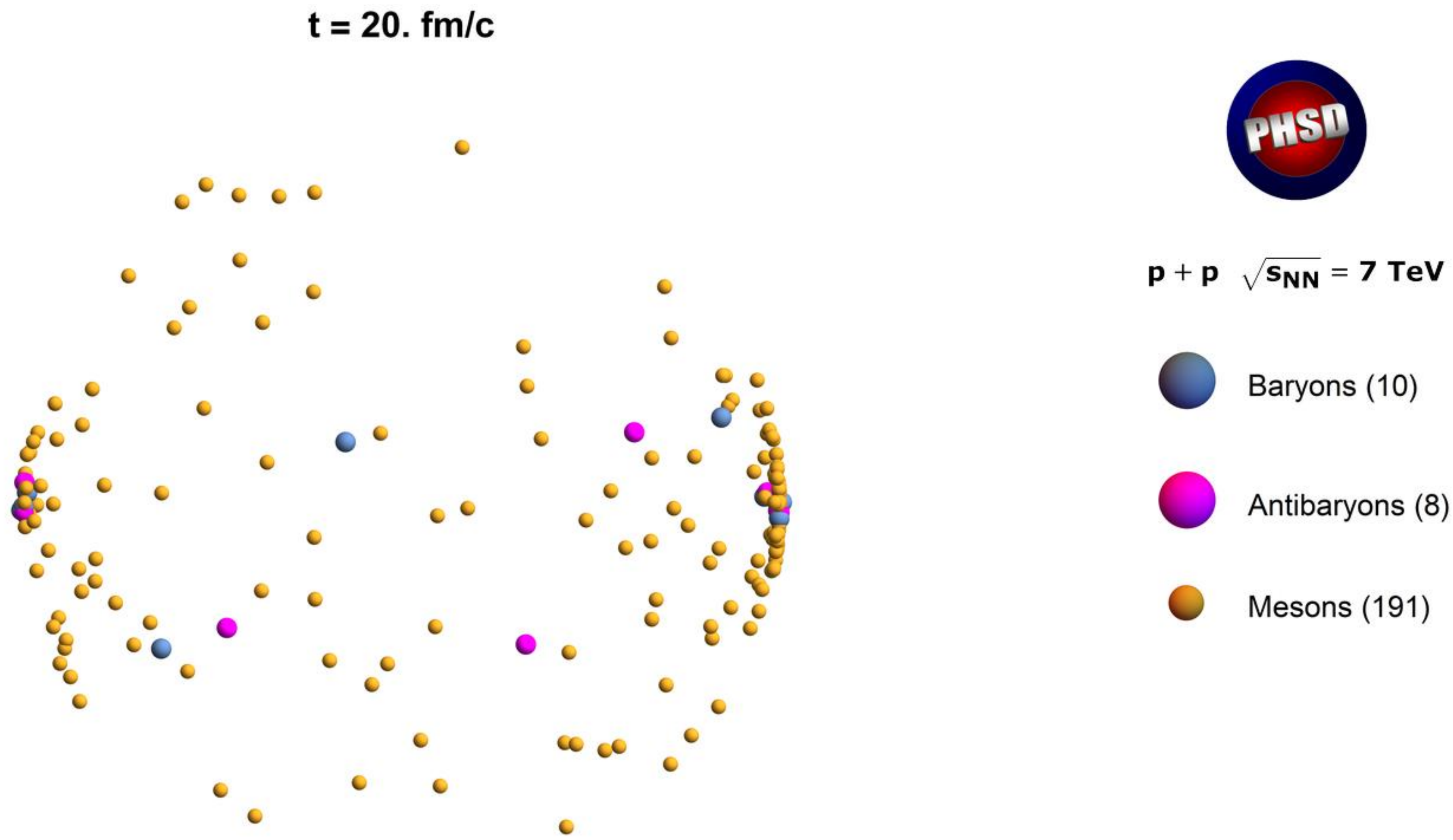
P.Moreau

String fragmentation



P.Moreau

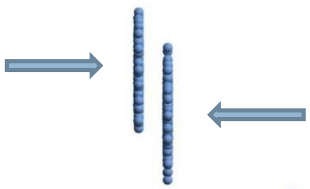
String fragmentation



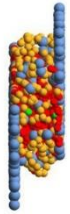
P.Moreau

Stages of a collision in PHSD

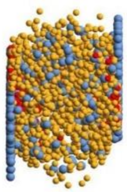
Initial A+A collision



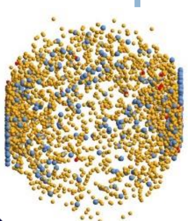
Partonic phase



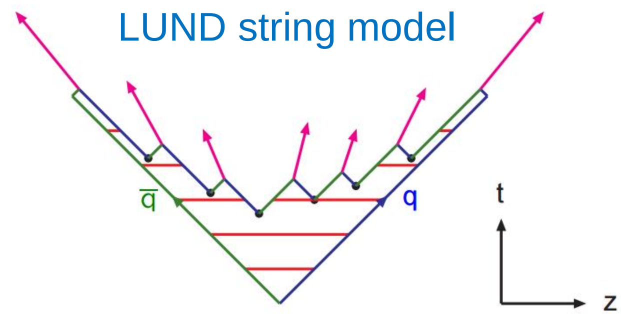
Hadronization



Hadronic phase



- **String formation in primary NN collisions**
- **String decays to pre-hadrons (baryons and mesons)**



- **Formation of a QGP state if** $\epsilon > \epsilon_C = 0.5\ \text{GeV.fm}^{-3}$
- **Dissolution of new produced secondary hadrons into massive colored quarks and mean-field energy**

$$B \to qqq\ (\bar{q}\bar{q}\bar{q}),\ m \to q\bar{q}\ +\ U_q$$

- **DQPM define the properties (masses and widths) of partons**

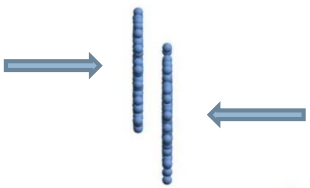
$$m_q(\epsilon) \quad \Gamma_q(\epsilon)$$

… and mean-field potential at a given local energy density ε

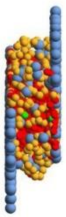
$$U_q(\epsilon)$$

Stages of a collision in PHSD

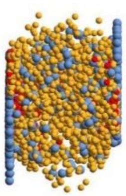
Initial A+A collision



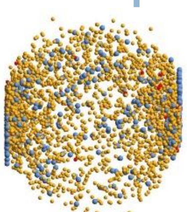
Partonic phase



Hadronization

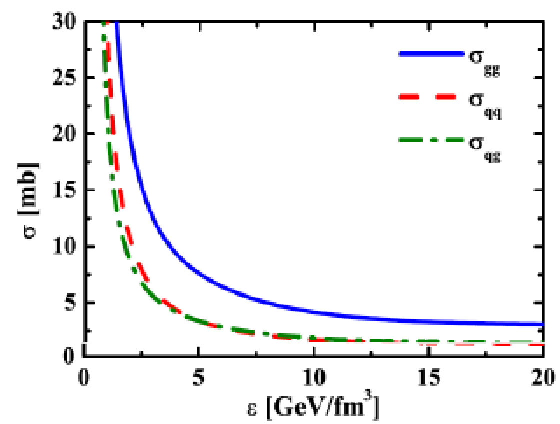


Hadronic phase



- **Propagation of partons, considered as dynamical quasiparticles, in a self-generated mean-field potential from the DQPM**
- **EoS of partonic phase: ‚crossover' from Lattice QCD fitted by DQPM**
- **(quasi-)elastic collisions :**

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



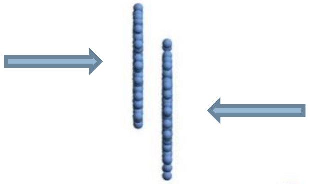
- **inelastic collisions :**

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

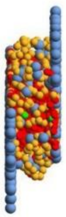
Suppressed due to the large gluon mass

Stages of a collision in PHSD

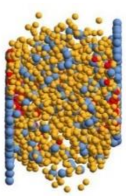
Initial A+A collision



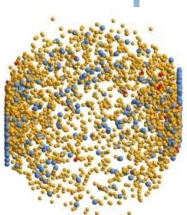
Partonic phase



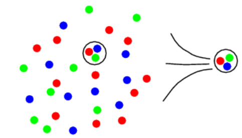
Hadronization



Hadronic phase

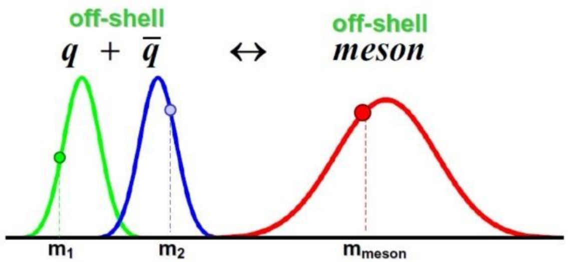


- Massive and off-shell (anti-)quarks hadronize to colorless off-shell mesons and baryons



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

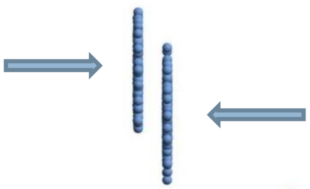
$$q + q + q \leftrightarrow baryon \;\; ('\,string\,')$$



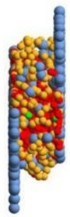
- Local covariant off-shell transition rate
- Strict 4-momentum and quantum number conservation

Stages of a collision in PHSD

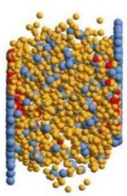
Initial A+A collision



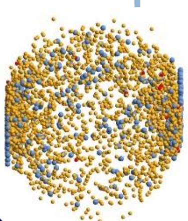
Partonic phase



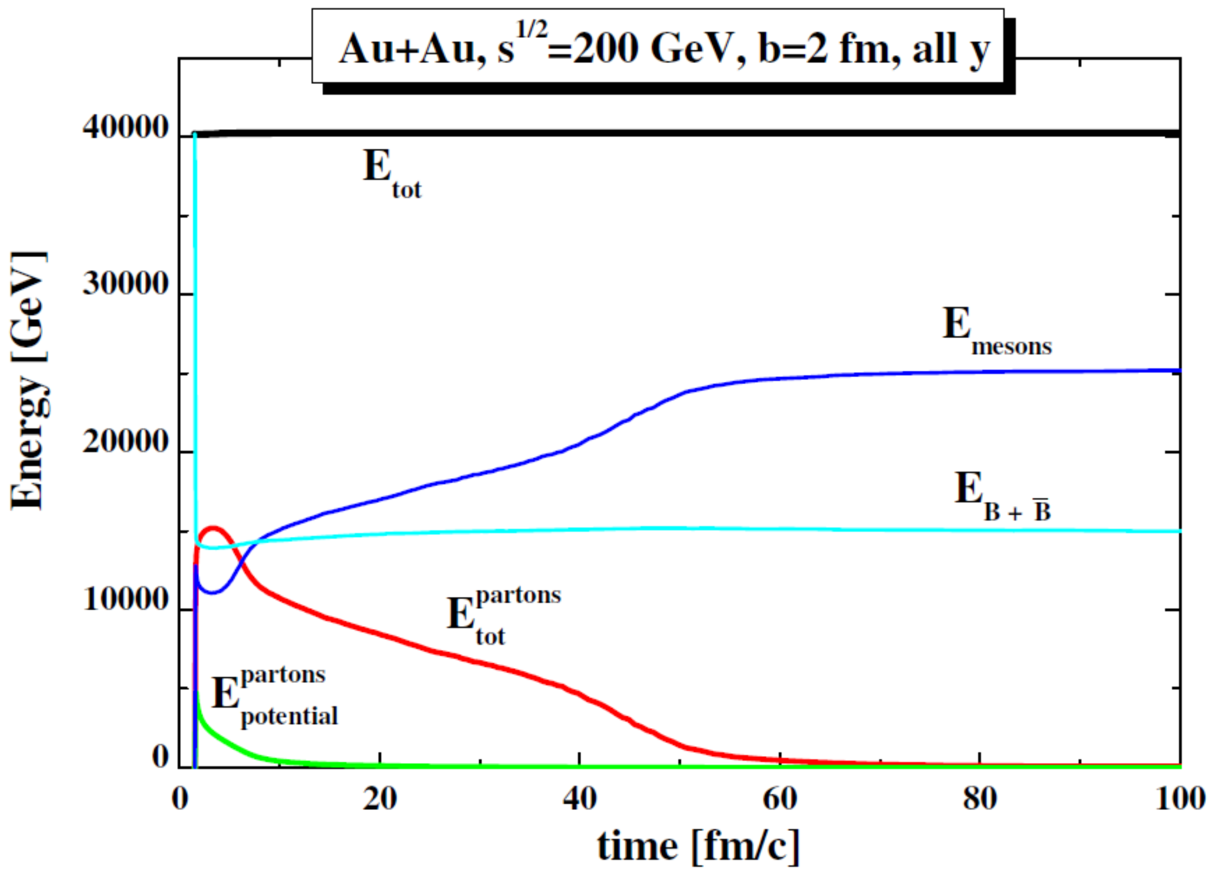
Hadronization



Hadronic phase

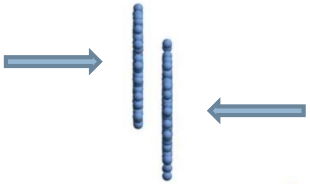


Energy distribution vs time:

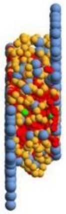


Stages of a collision in PHSD

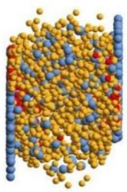
Initial A+A collision



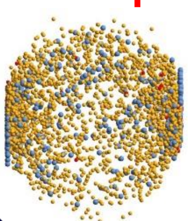
Partonic phase



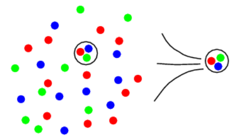
Hadronization

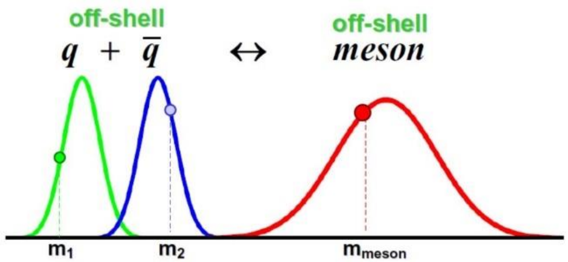


Hadronic phase



- **Massive and off-shell (anti-)quarks hadronize to colorless off-shell mesons and baryons**





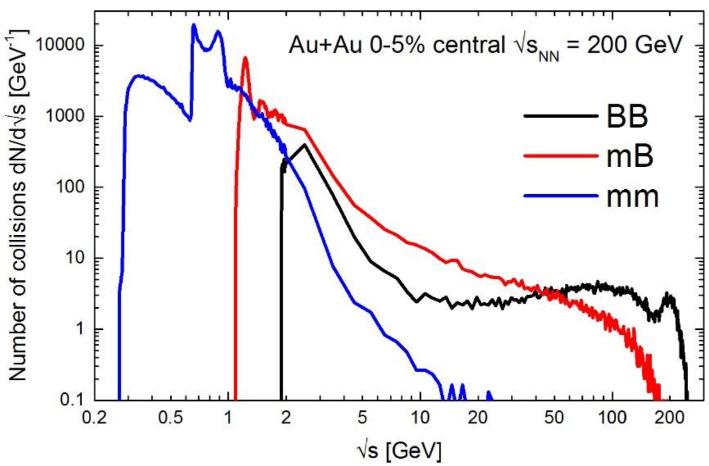
$$g \to q + \bar{q}, \qquad q + \bar{q} \leftrightarrow meson \ ('\,string\,')$$

$$q + q + q \leftrightarrow baryon \ ('\,string\,')$$

- **Local covariant off-shell transition rate**
- **Strict 4-momentum and quantum number conservation**

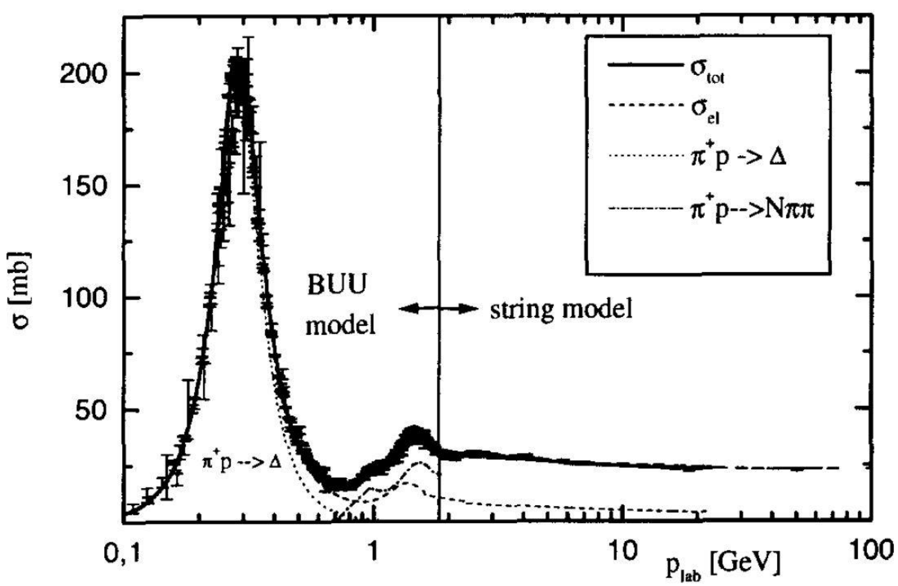
- **Hadron-string interactions – off-shell HSD**

Distribution of hadron collisions as a function collisional energy:

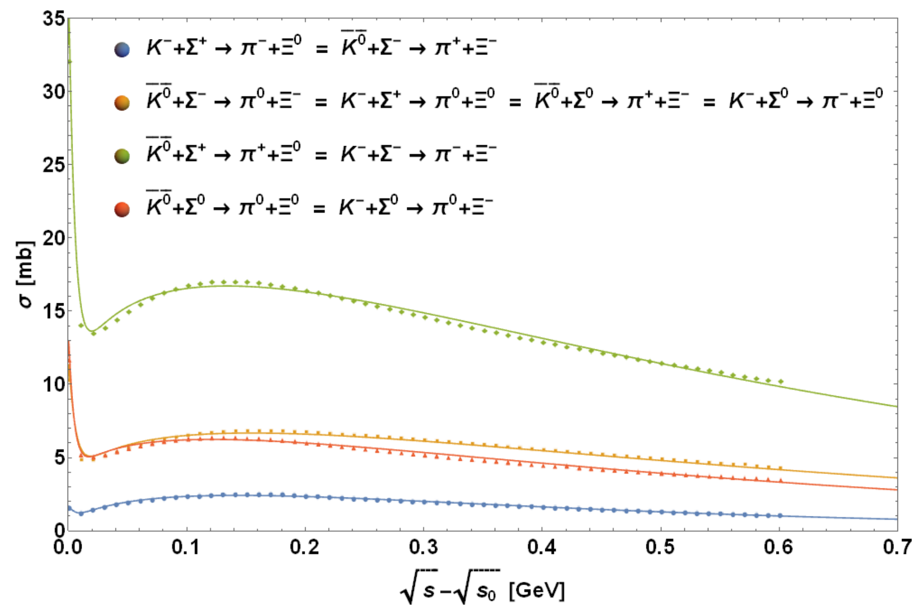


Hadronic interactions in HSD

- **Low energy hadron-hadron collisions are modelled on the basis of experimental cross sections (when available) or theoretical calculations whenever no data exist**



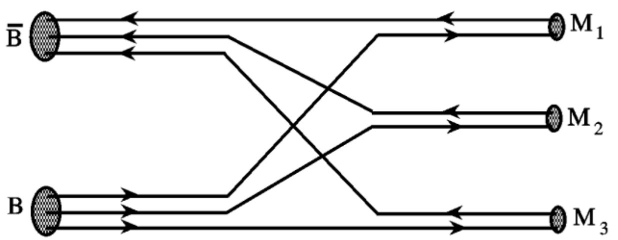
From J. Geiss, W. Cassing, C. Greiner, **Nucl.Phys. A644 (1998) 107-138**



Parametrizations from F.Li, L.W.Chen, C.M.Ko and S.H.Lee, **Phys.Rev. C85 (2012) 064902**

Antibaryon production in HSD

W. Cassing, NPA 700 (2002) 618



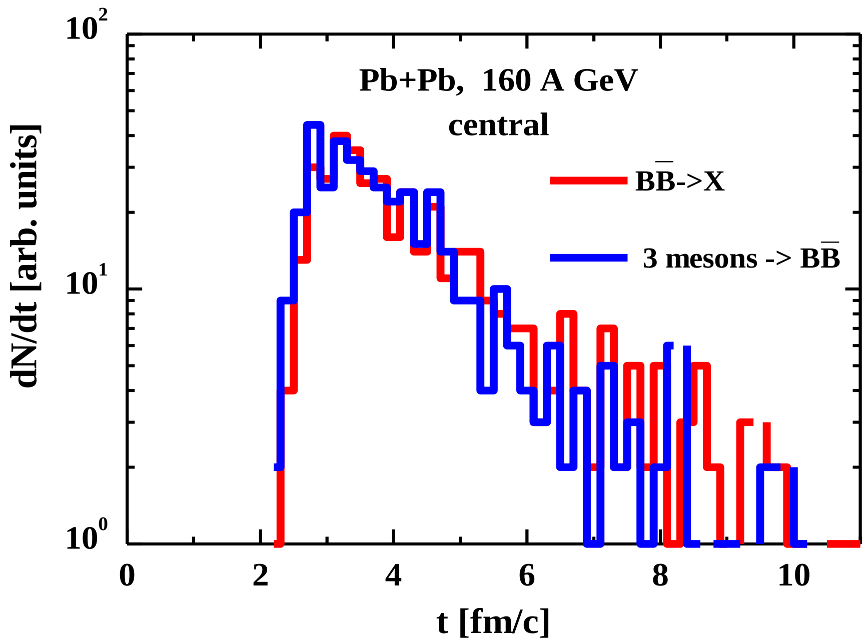
2 ↔ 3

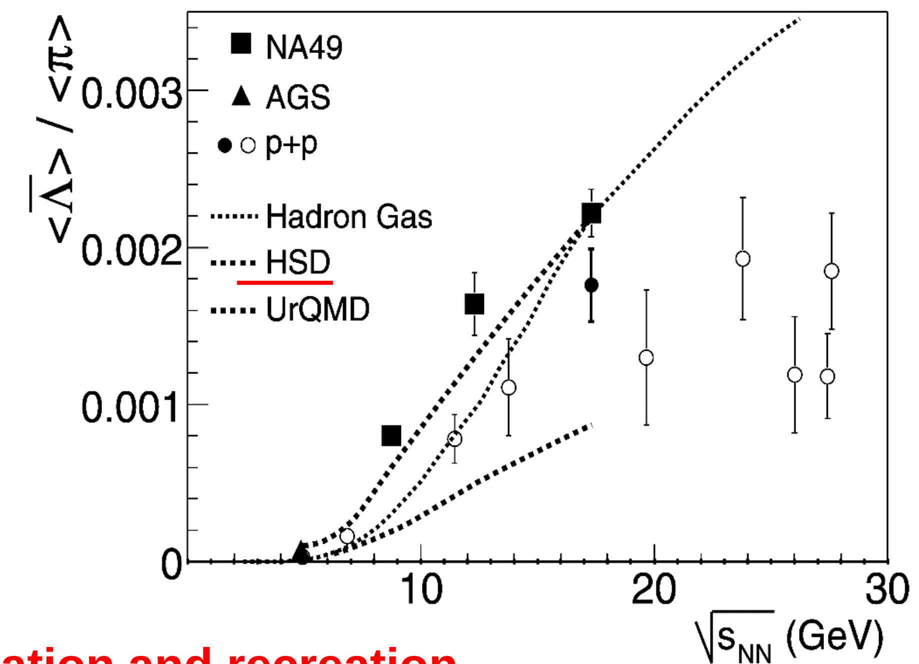
Multi-meson fusion reactions

$m_1 + m_2 + ... + m_n$ ←→ B+Bbar

(m = π, ρ, ω,..)

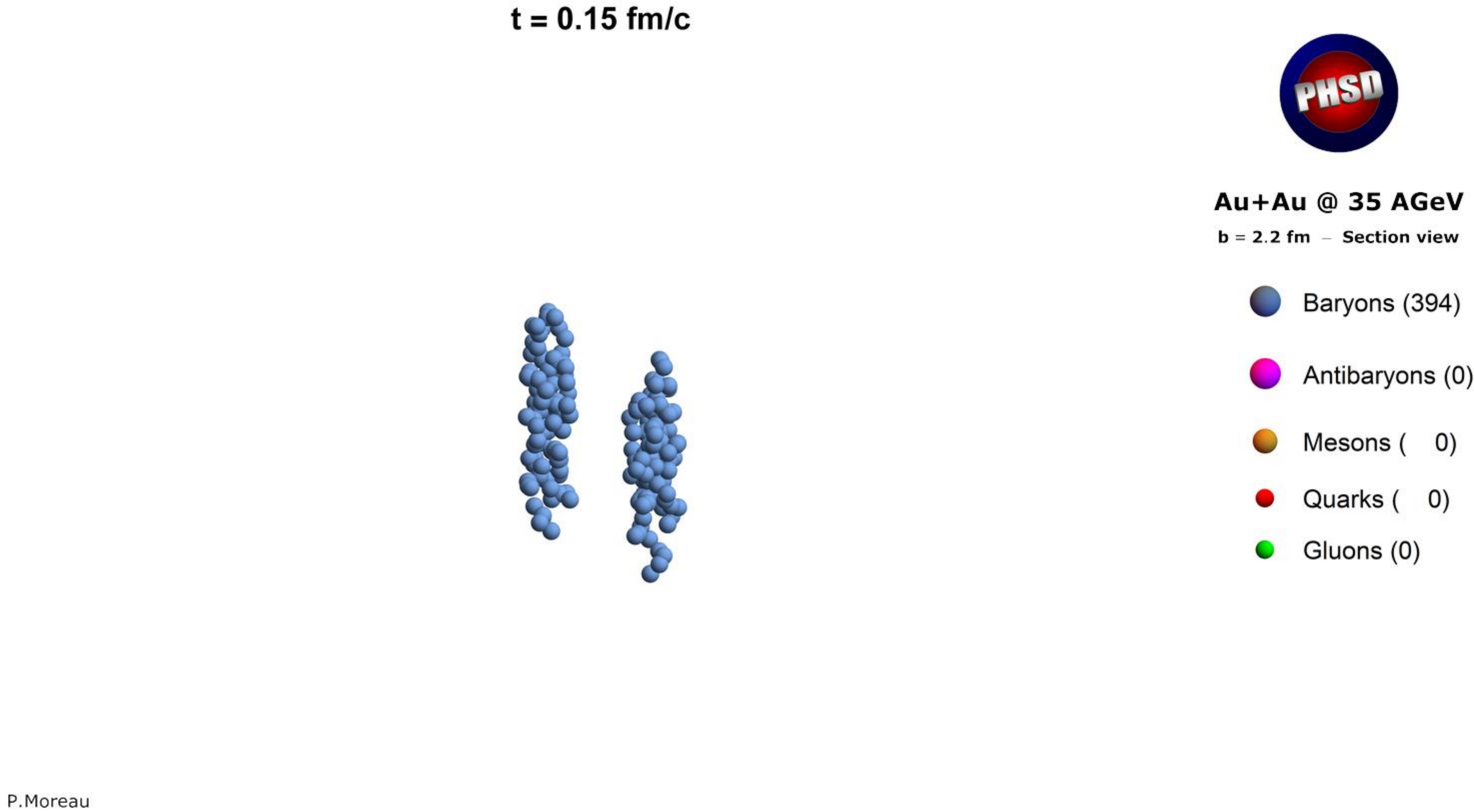
- **Important for $\bar{p}$, $\bar{\Lambda}$, $\bar{\Xi}$, $\bar{\Omega}$ dynamics !**



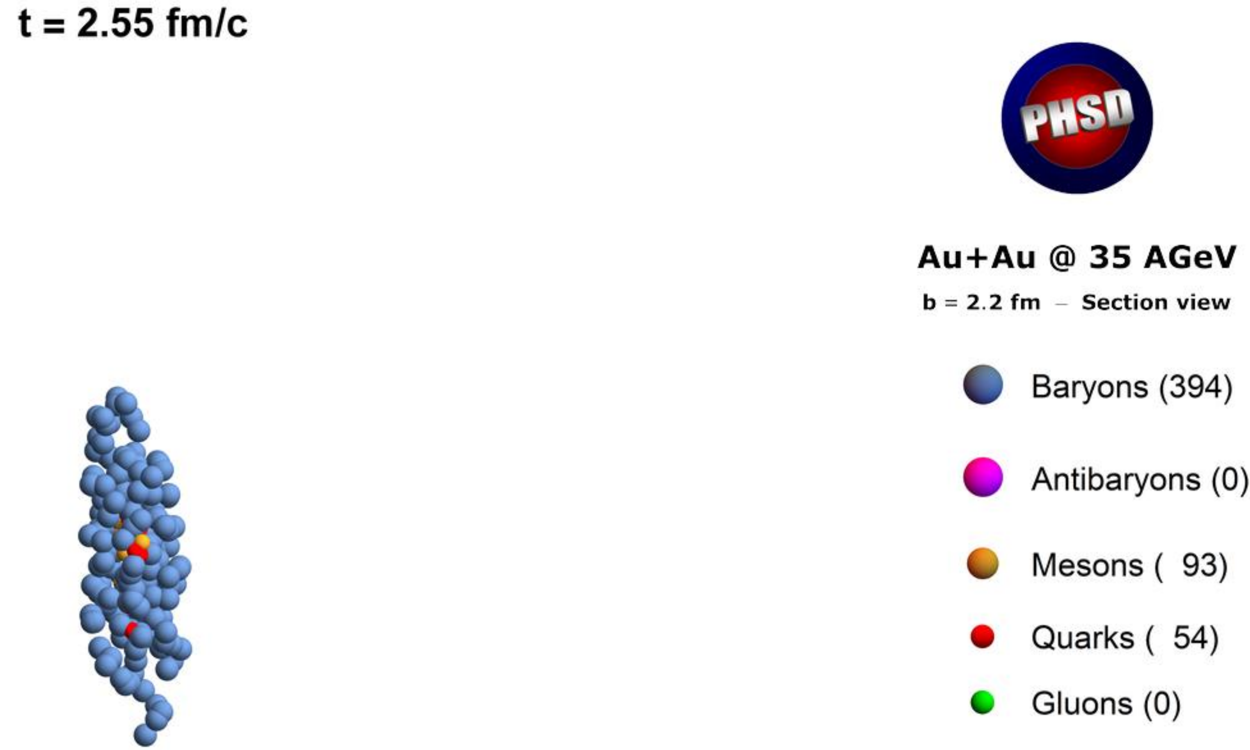


→ **approximate equilibrium of annihilation and recreation**

Stages of a collision in PHSD

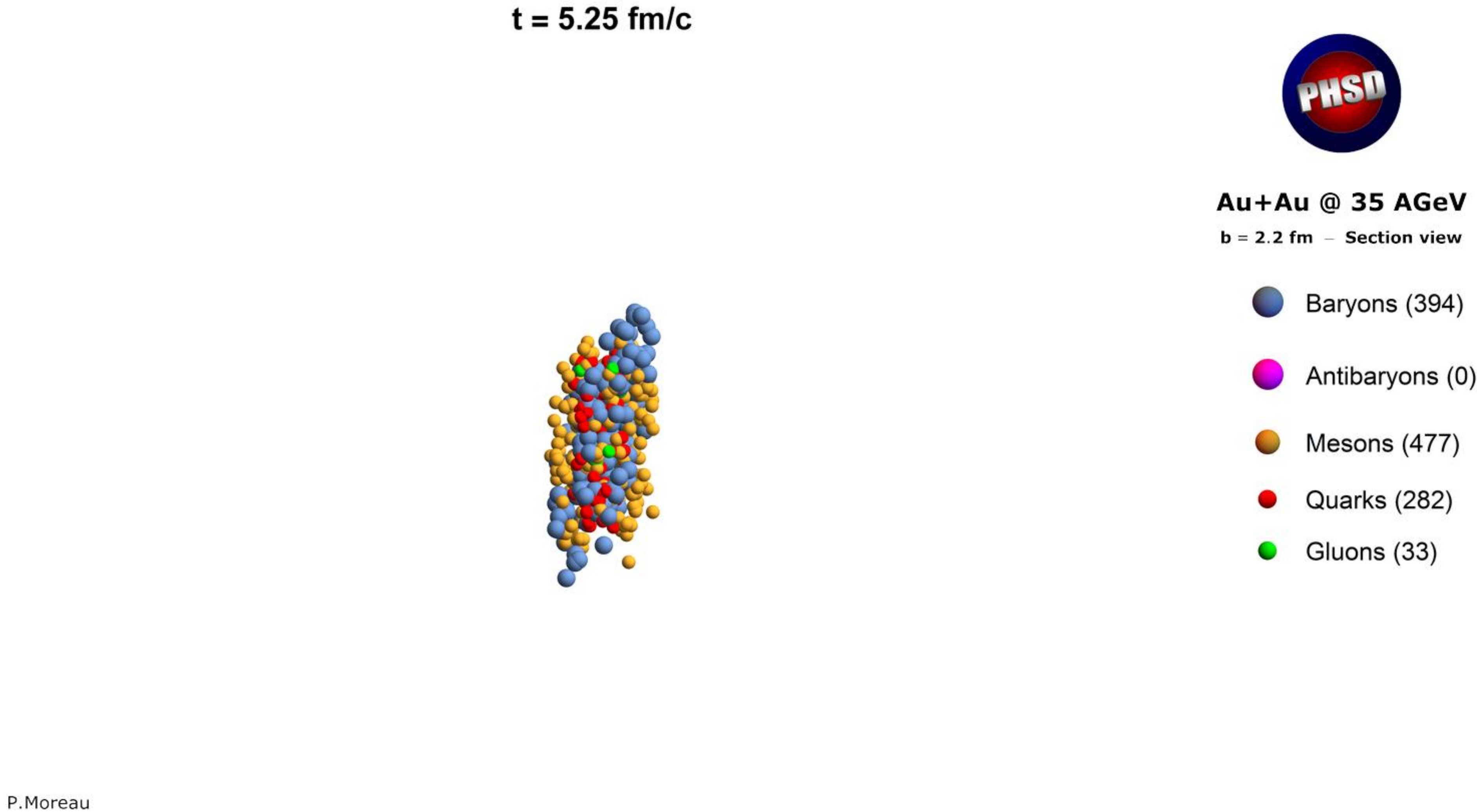


Stages of a collision in PHSD

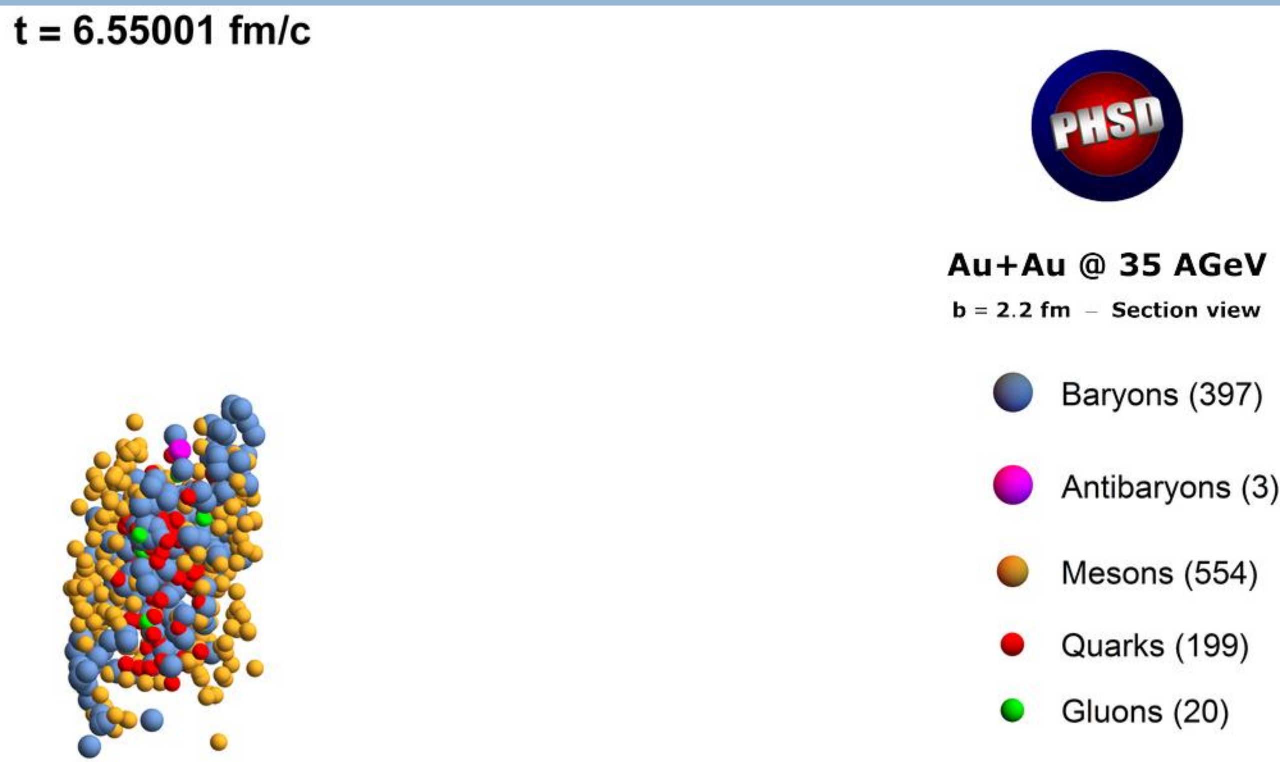


P.Moreau

Stages of a collision in PHSD

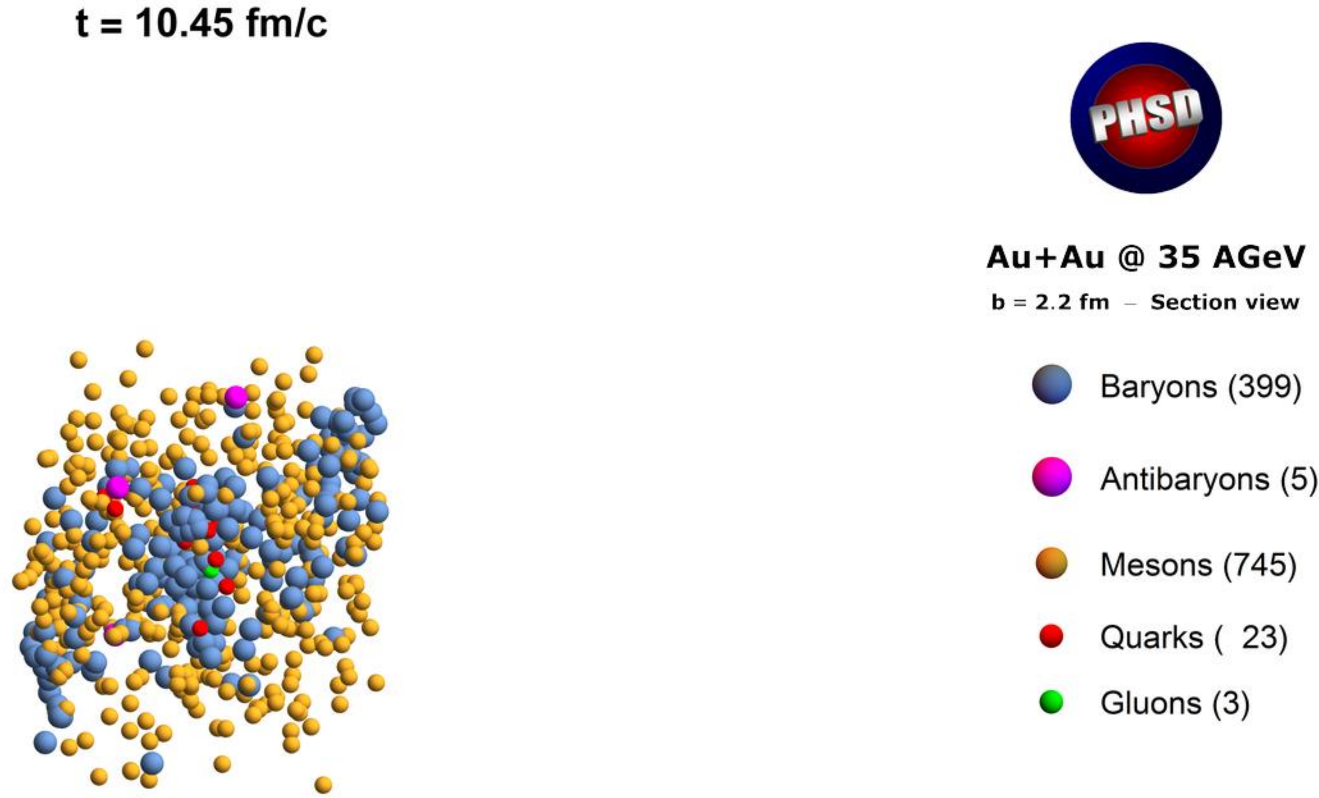


Stages of a collision in PHSD



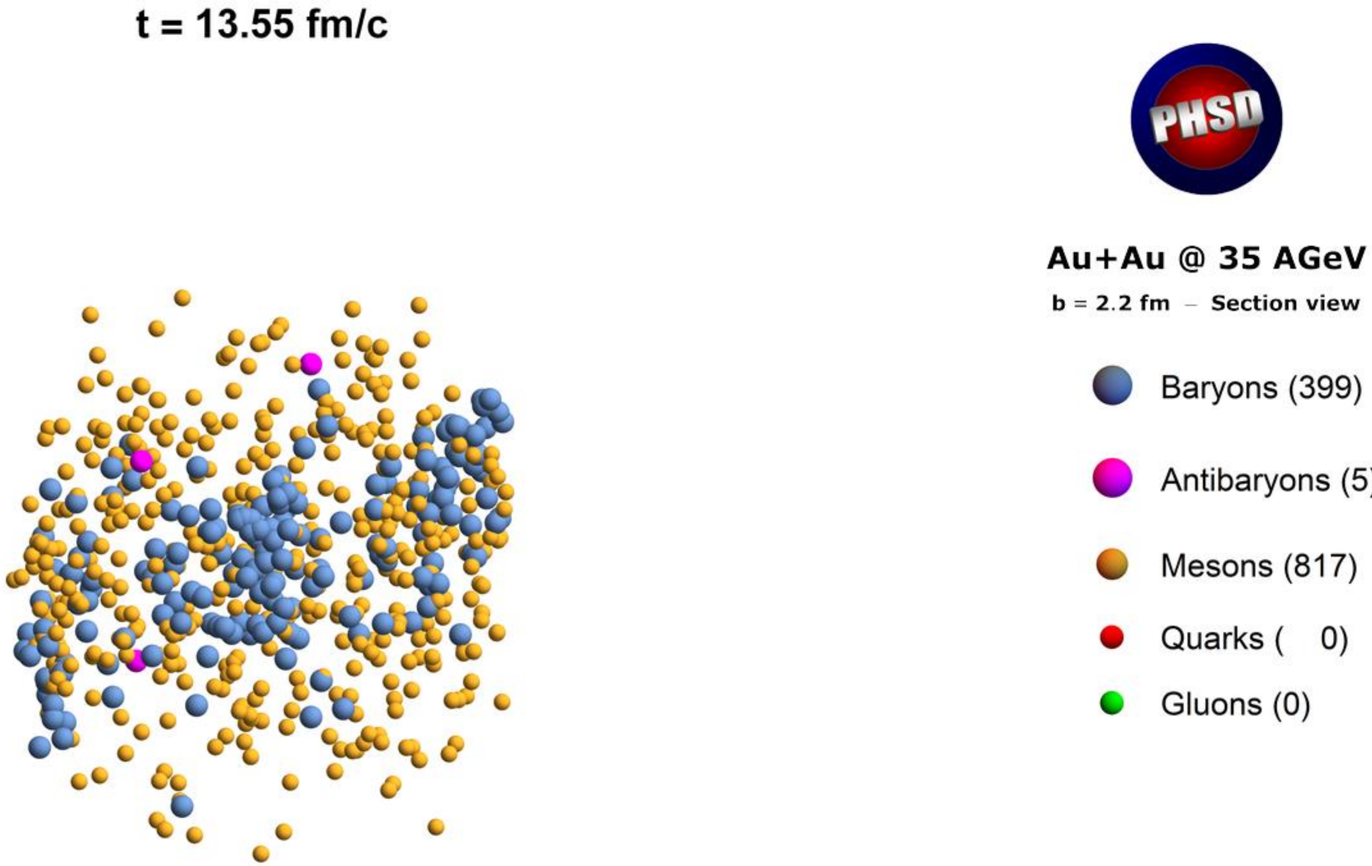
P.Moreau

Stages of a collision in PHSD



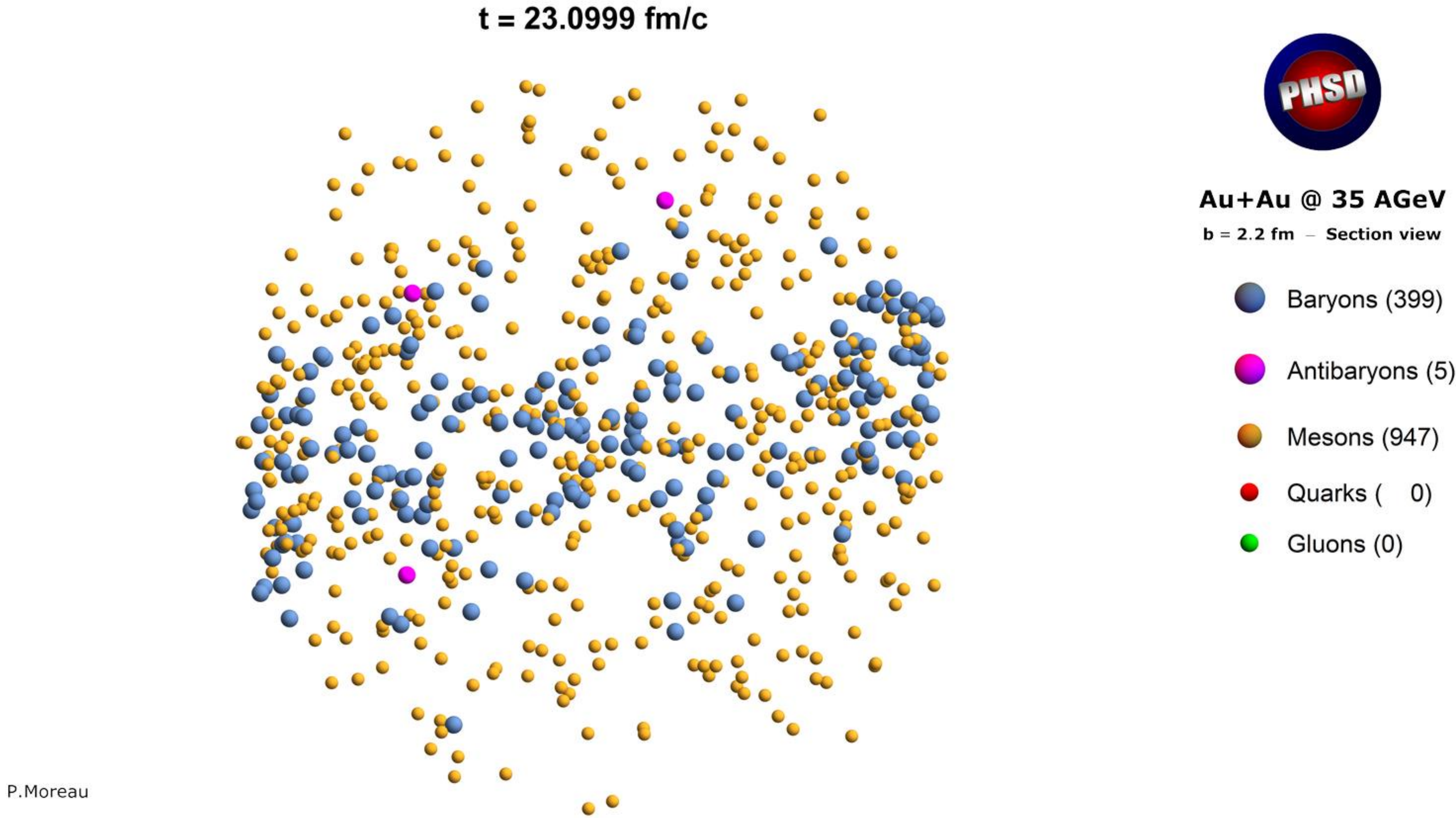
P.Moreau

Stages of a collision in PHSD

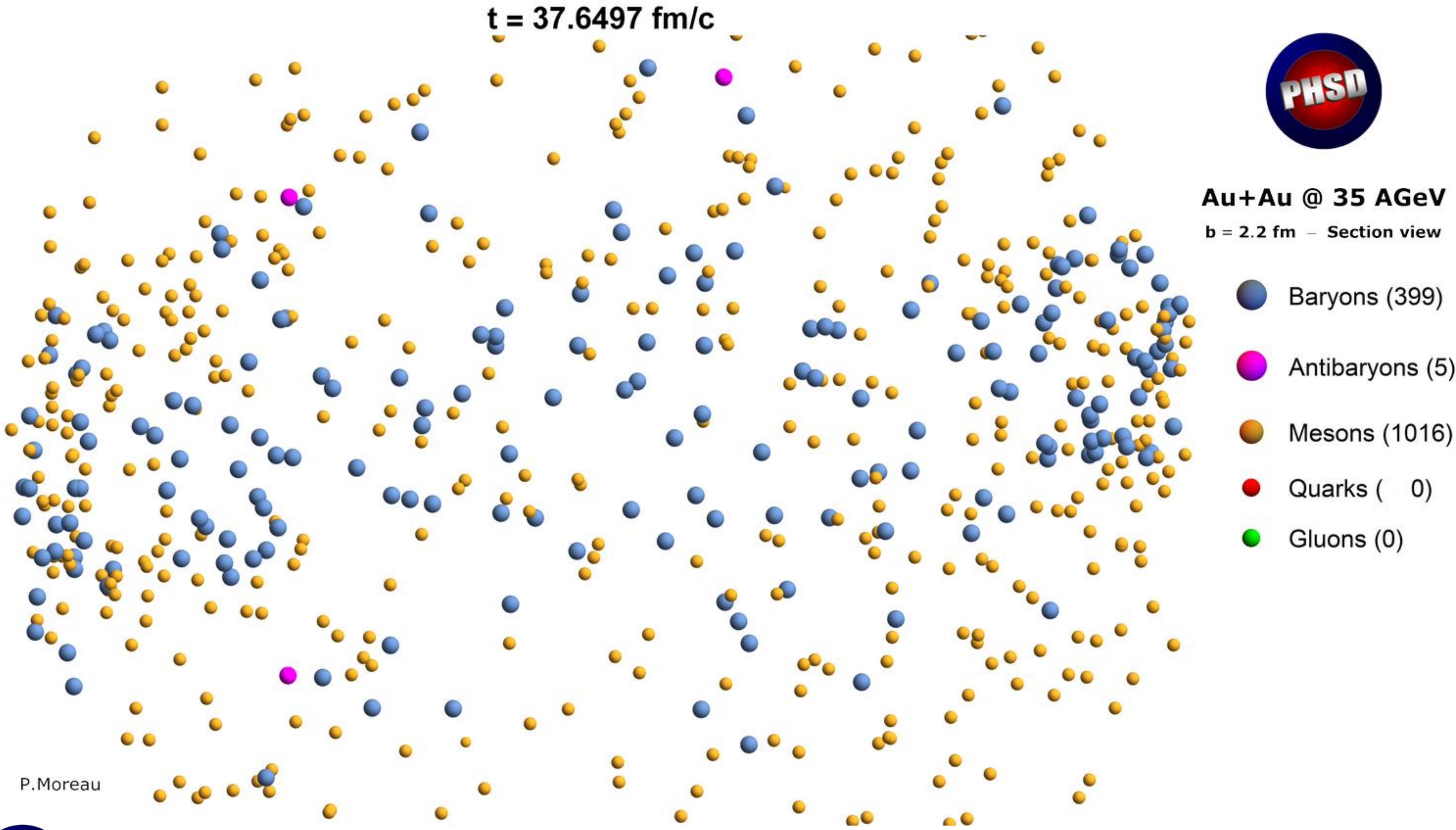


P.Moreau

Stages of a collision in PHSD

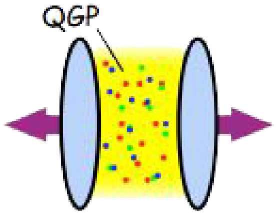


Stages of a collision in PHSD

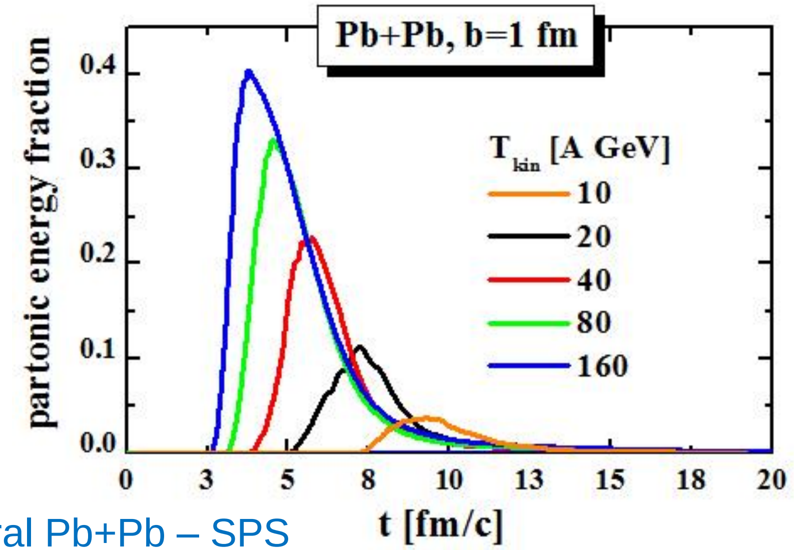


Partonic energy fraction in central A+A

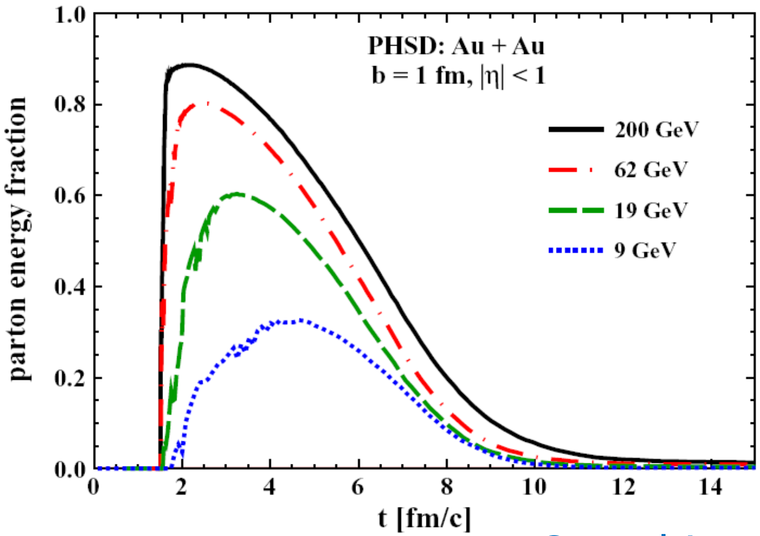
- At SPS, only a **small part of the initial energy** is converted into the **QGP** phase
- At top RHIC energies, the **QGP** phase at midrapidity contains roughly **90%** of the energy



Time evolution of the partonic energy fraction for different energies:

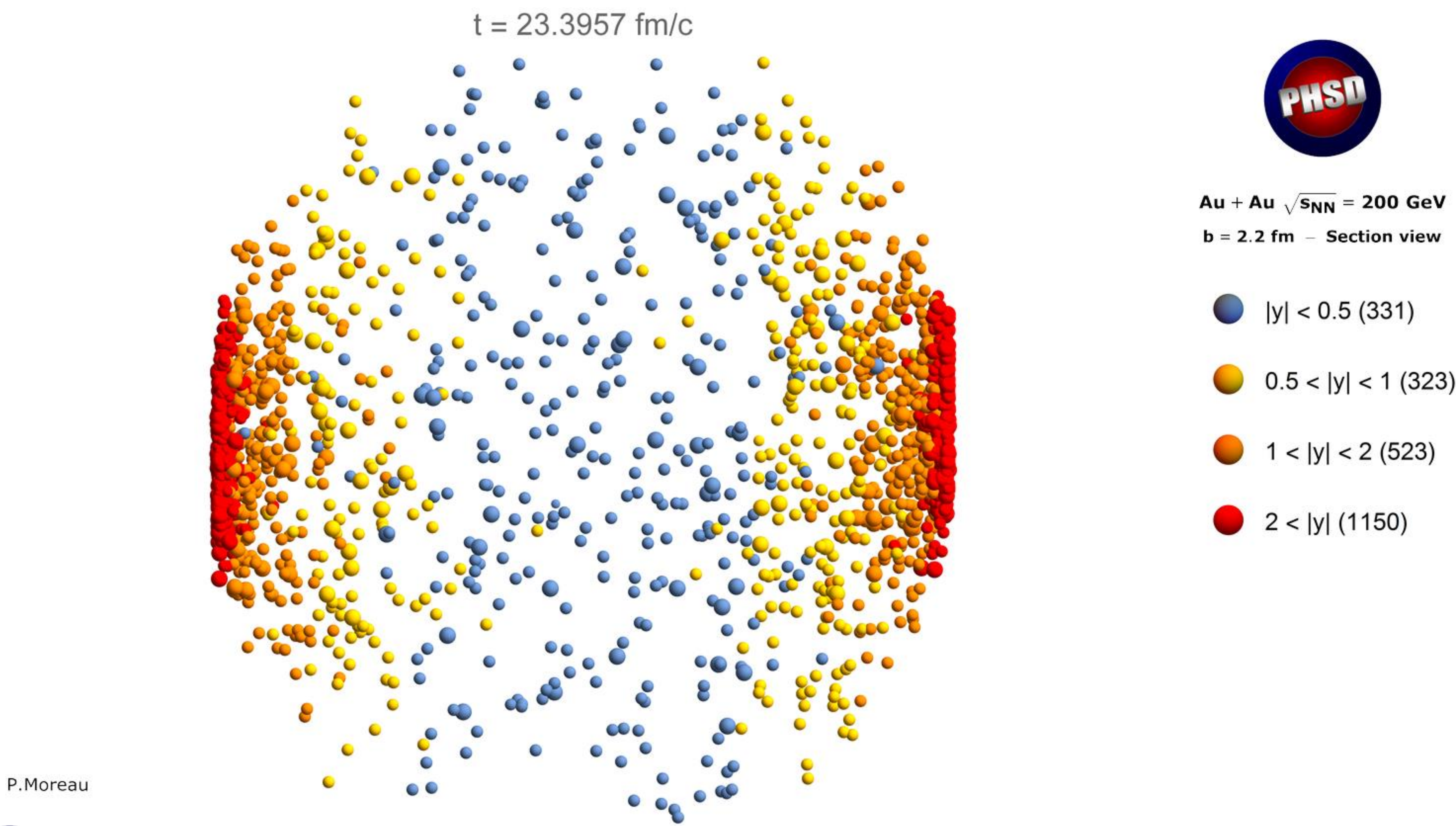


Central Pb+Pb – SPS

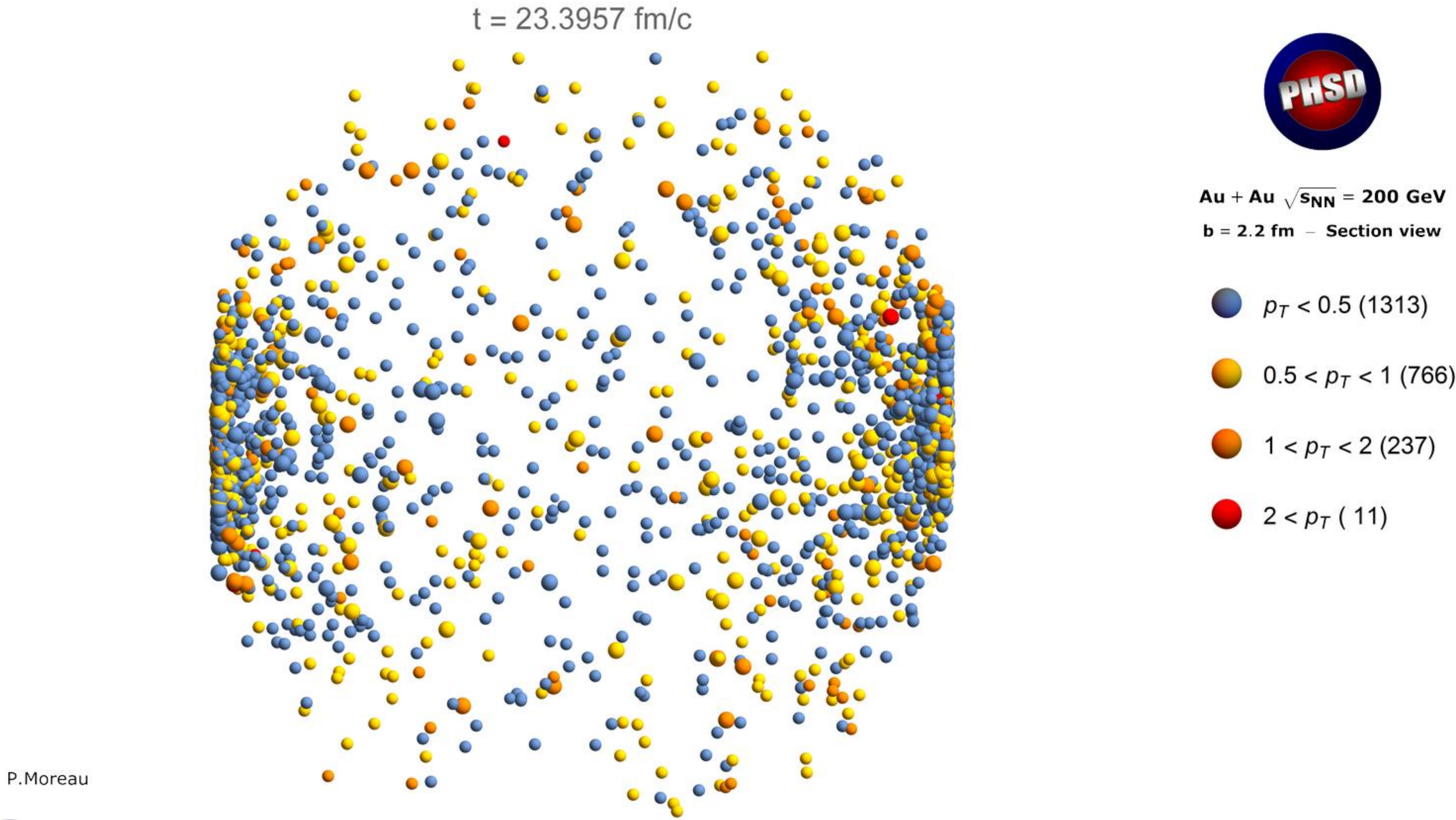


Central Au+Au

Distribution in rapidity



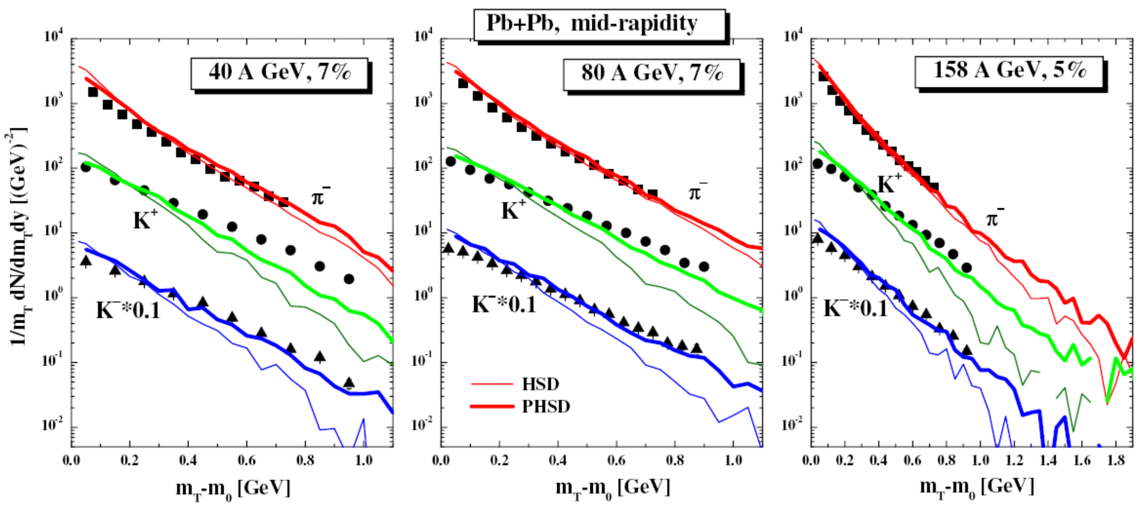
Distribution in p_T



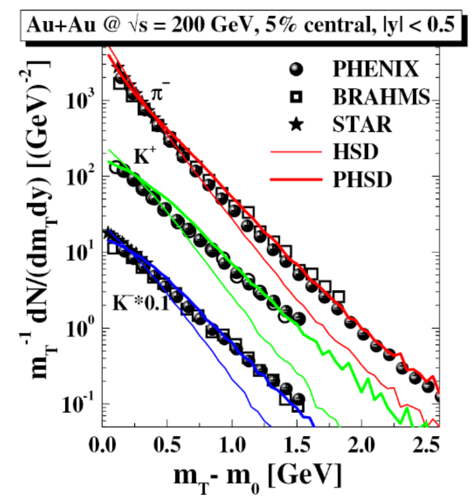
Transverse mass spectra (PHSD – HSD)

- With the HSD model, the high-pT spectra is not described properly especially at high energies where the parton energy fraction is major
- At low SPS energies, the difference is less visible since the partonic phase is not predominant

Transverse mass spectra for pions and kaons at different energies:



Central Pb+Pb – SPS energies



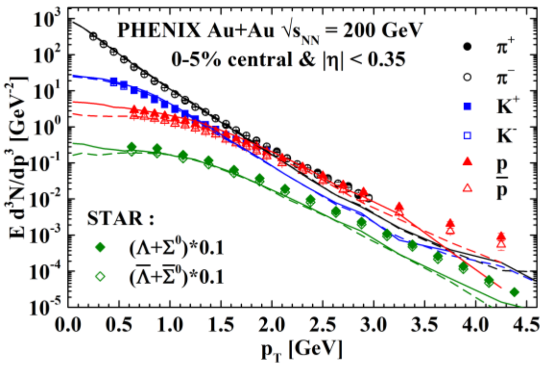
Central Au+Au – RHIC

W. Cassing & E. Bratkovskaya, NPA 831 (2009) 215; E. Bratkovskaya, W. Cassing, V. Konchakovski, O. Linnyk, NPA856 (2011) 162

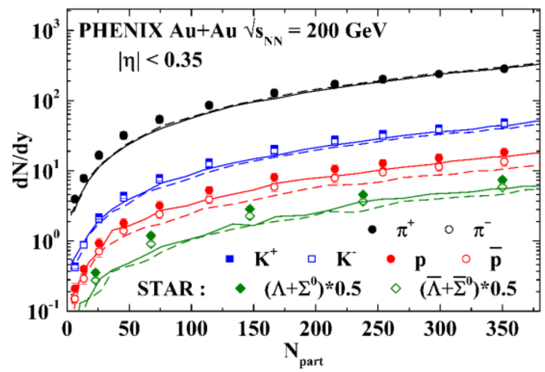
Bulk properties

Au+Au – Top RHIC

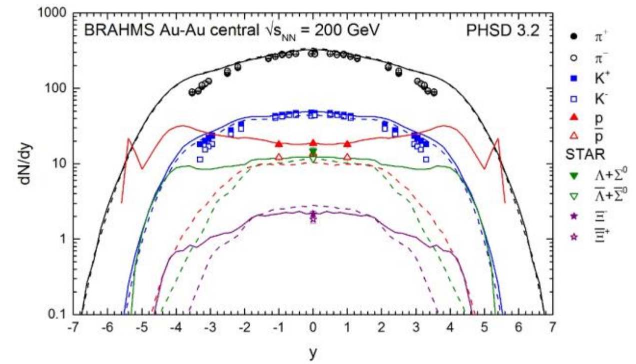
pT spectra:



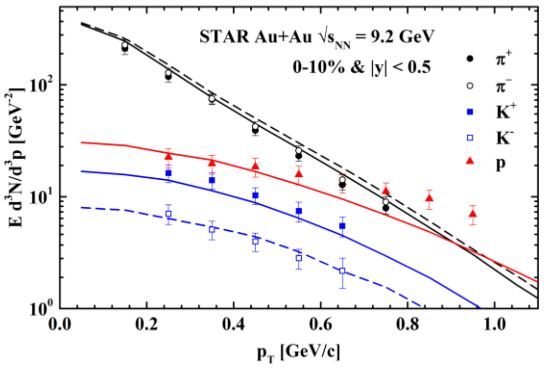
Production at midrapidity dN/dy:

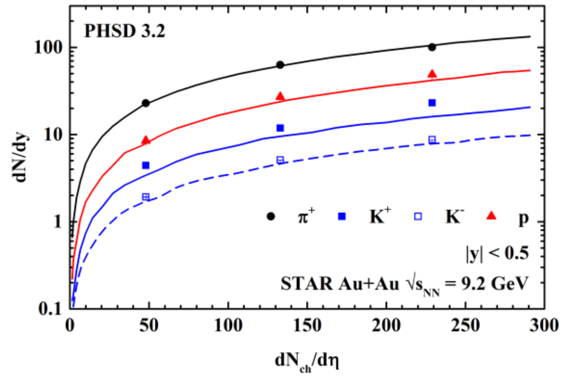


Rapidity spectras:

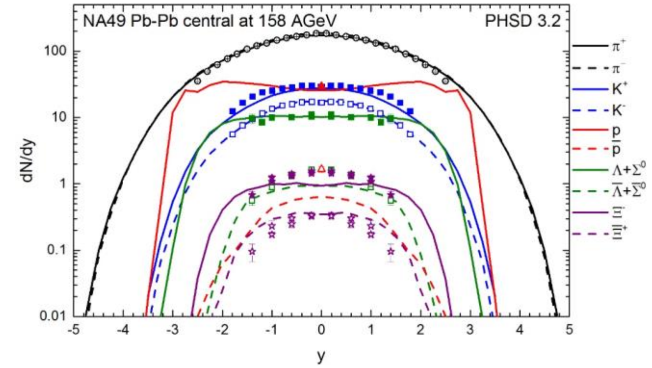


Au+Au – RHIC 9.2 GeV

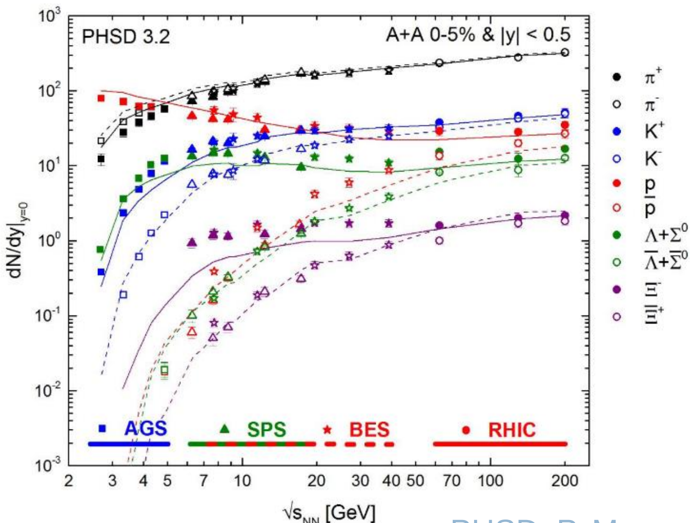




Pb+Pb – Top SPS

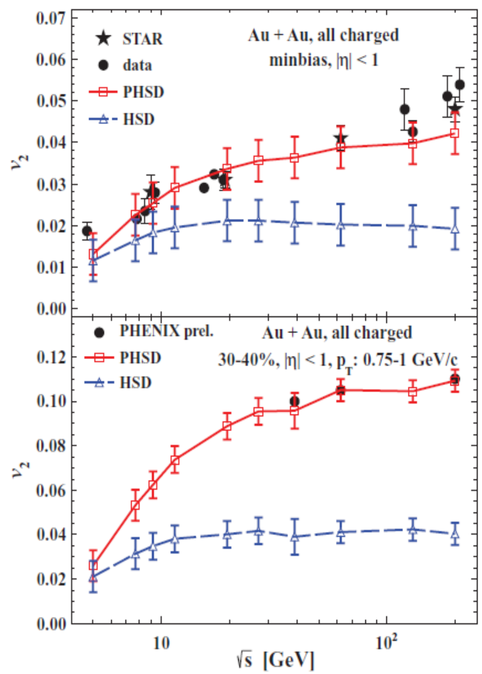


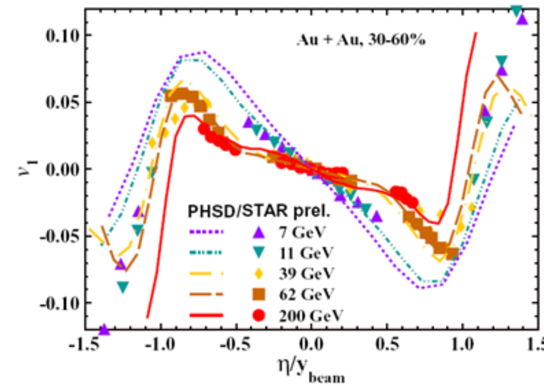
Description of A+A with PHSD

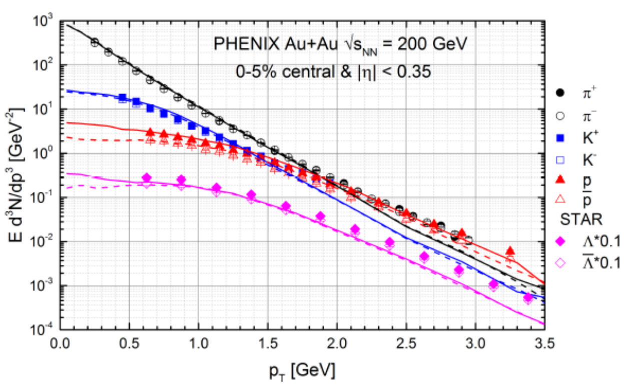


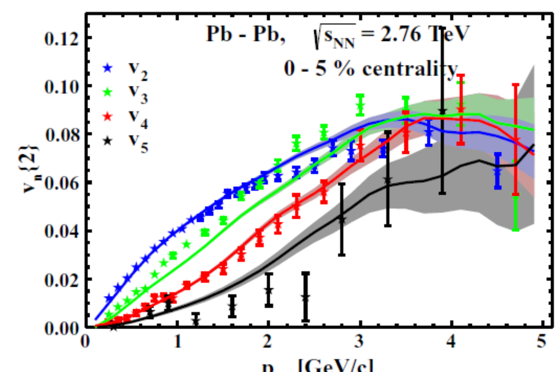
PHSD: P. Moreau

PHSD highlights









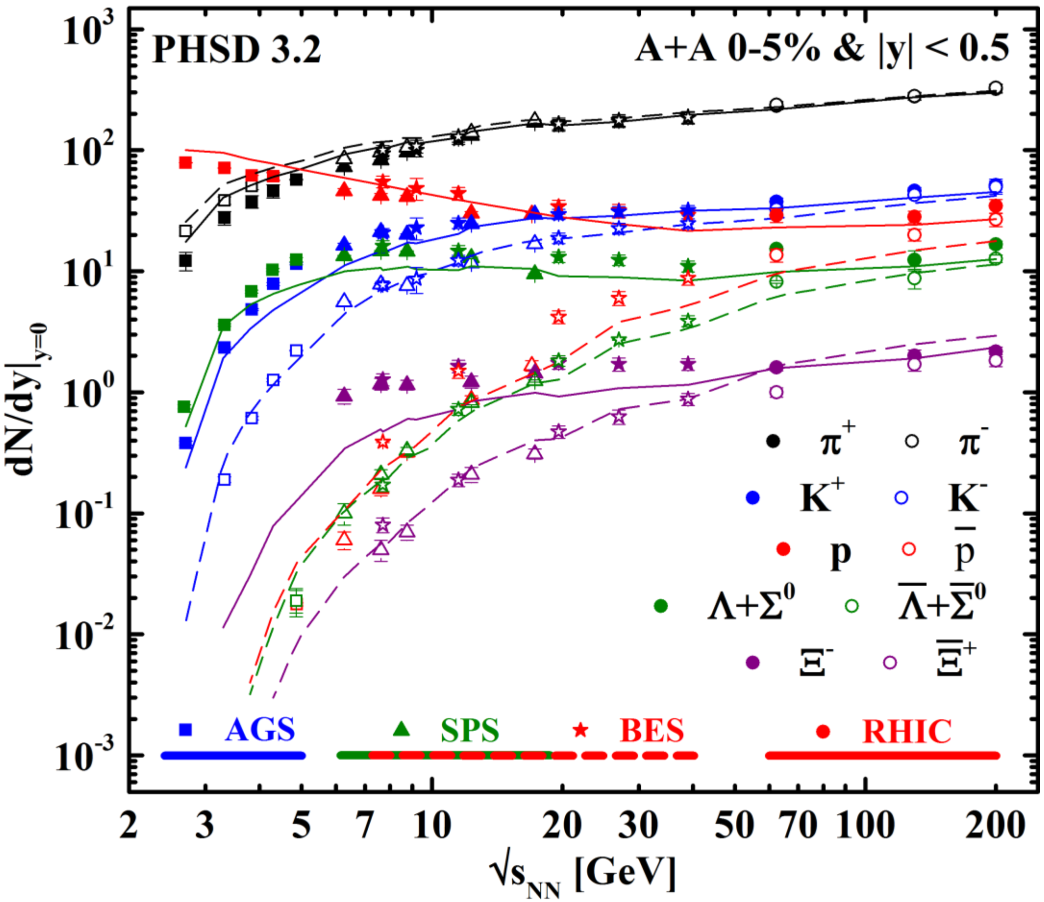
V. Konchakovski et al., **PRC 85 (2012) 011902; JPG42 (2015) 055106**

PHSD provides a good description of ‘bulk’ observables (y-, p_T-distributions, flow coefficients v_n) from SIS to LHC

Beam energy scan study

Production at midrapidity as a function of the collisional energy:

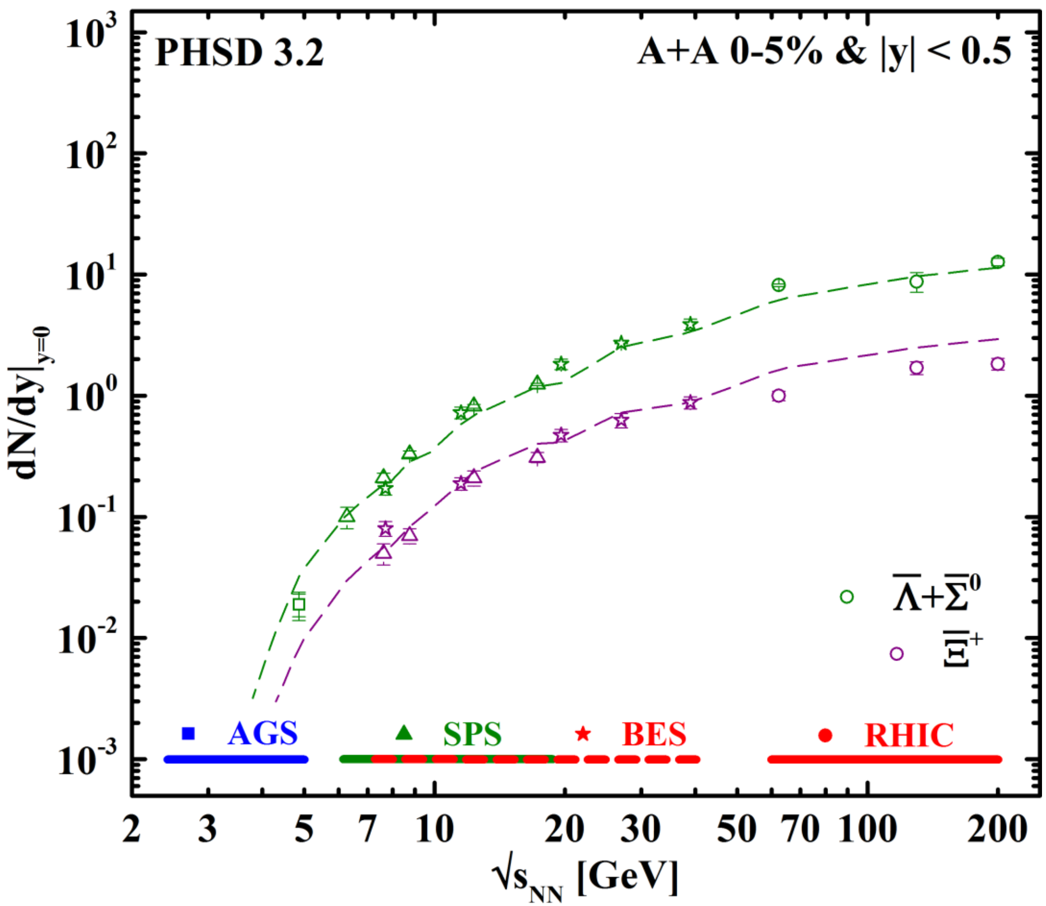
- By **decreasing the collisional energy**, the more the composition of produced particles is conditioned by the **composition of the initial state** (u and d quarks)
- At the **highest energies**, the composition of produced particles at midrapidity is conditionned by the **QGP content**



Beam energy scan study

Production at midrapidity as a function of the collisional energy:

- **Reasonable agreement for anti-strange baryons dominantly produced in the hadronization process from the QGP at midrapidity**



Beam energy scan study

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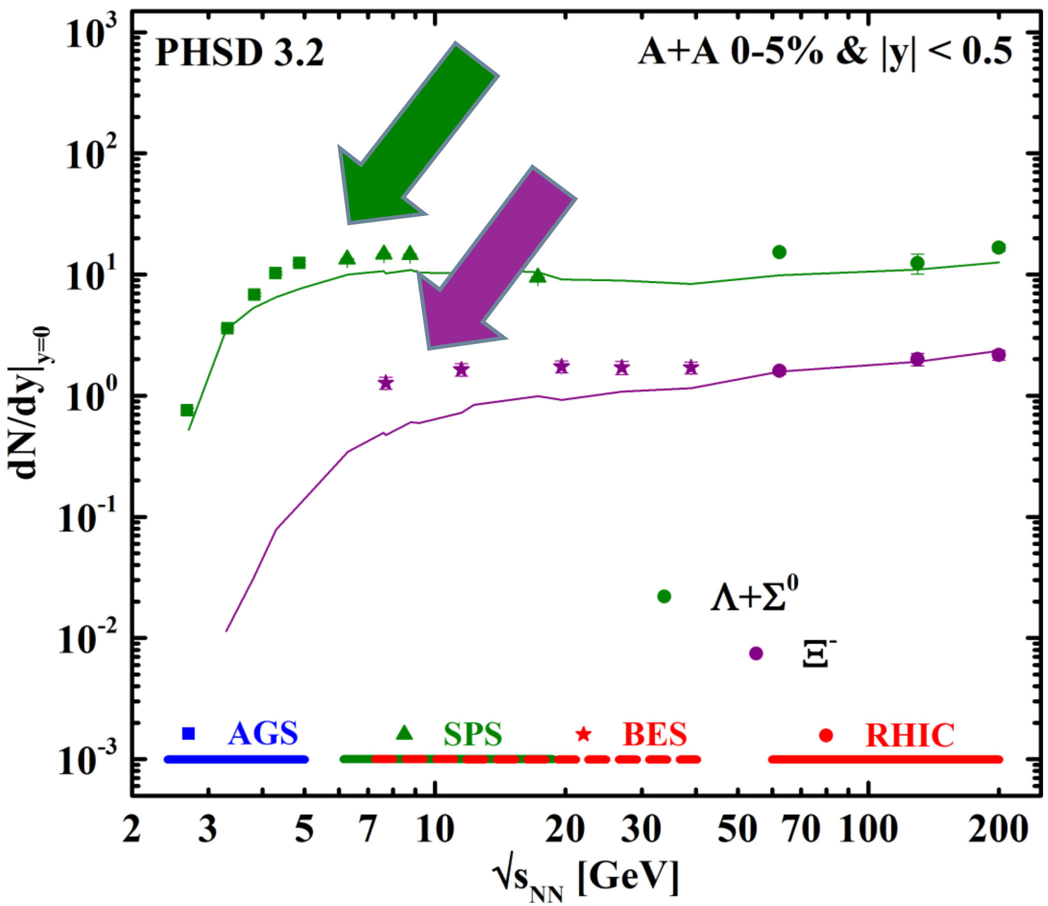

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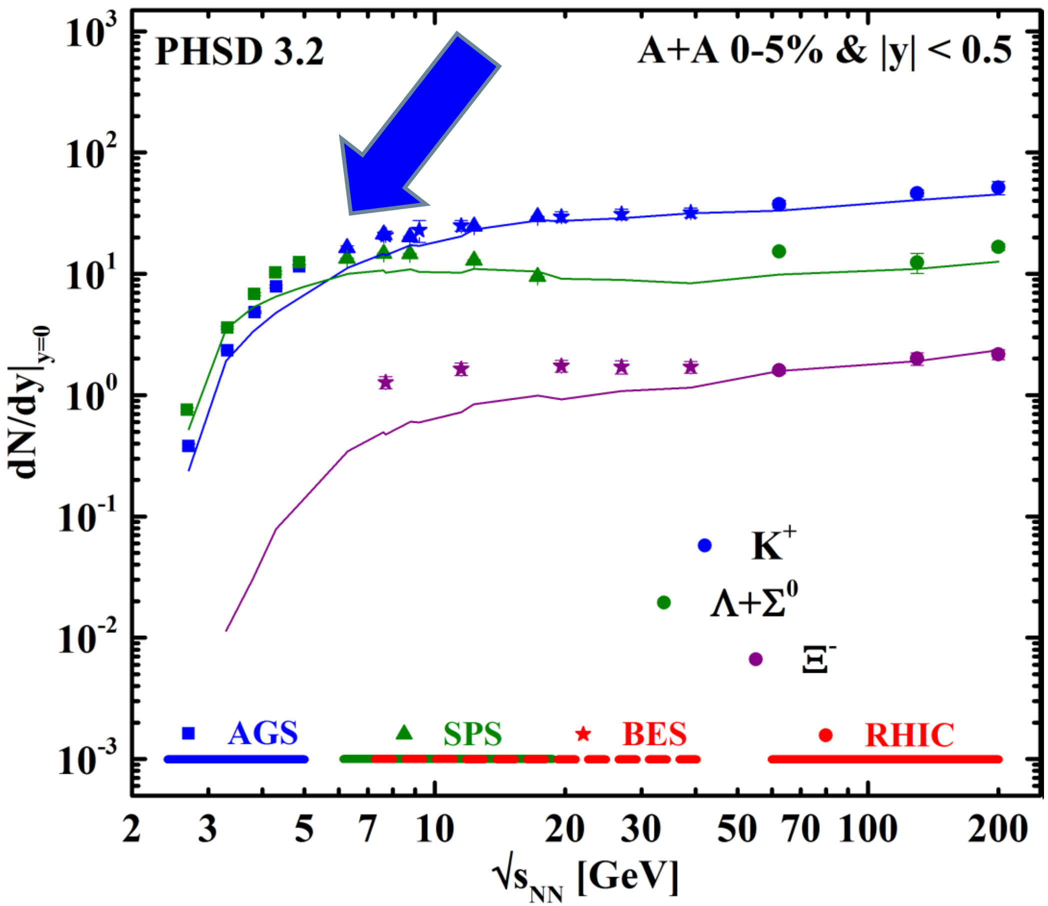
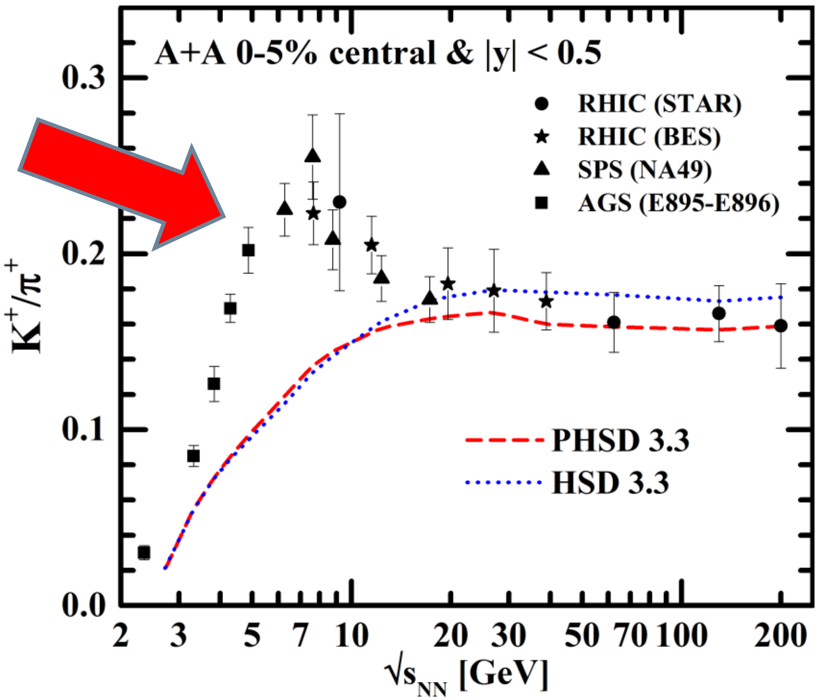
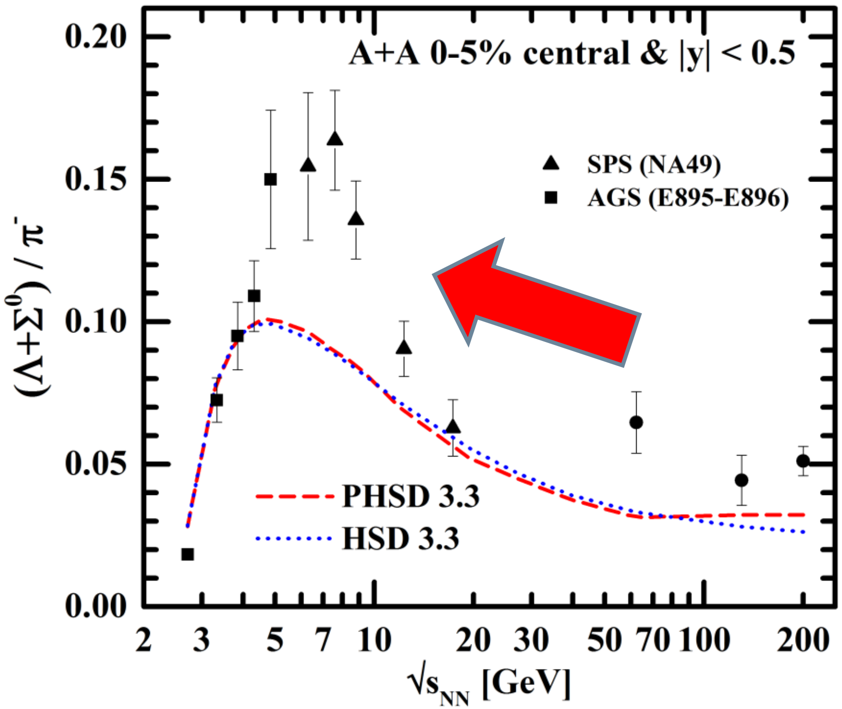


Missing strangeness ?

- Even considering the creation of a QGP phase, the strangeness enhancement seen experimentally by NA49 and STAR at ~ 20-30 AGeV collisions remains puzzling
  - 'Horn' not traced back to deconfinement

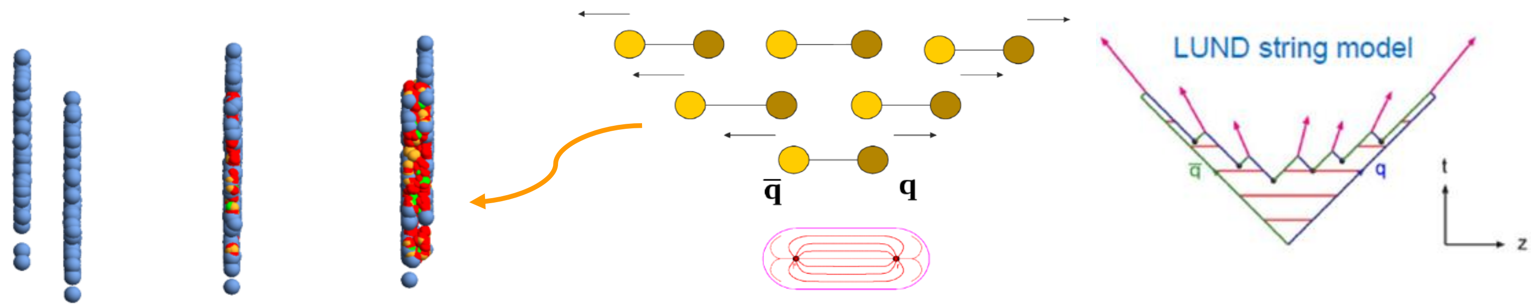




W. Cassing, A. Palmese, P. Moreau, E.L. Bratkovskaya - **Phys.Rev. C93 (2016), 014902**

Production of quarks by string decays

- **Initial state of heavy-ion collision:**



- **The 'flavor chemistry' of the final hadrons in the PHSD is mainly defined by the LUND string model**

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

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

m_s, m_q $(q = u, d)$: constituent quark masses

κ: string tension; in vaccum: $\kappa \sim 0.9$ GeV/fm $= 0.176$ GeV²

Dressing of quark masses

- m_s, m_q $(q = u, d)$ - **constituent ('dressed') quark masses**: **'dressing' of bare quark masses is due to the coupling to the scalar quark condensate** $\langle \bar{q}q \rangle$

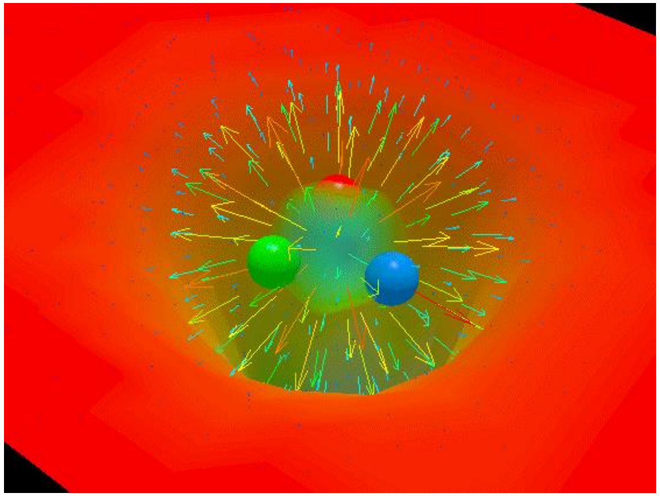
- **In vacuum (V) (e.g. p+p collisions):**

$\gamma_S \approx 0.3$ **with constituent quark masses :** m_q $(q = u, d) \approx 0.35$ **GeV and** $m_s \approx 0.5$ **GeV**

quark mass	constituent	bare
Up quark	336 MeV/c^2[1]	4.3–5.2 MeV/c^2
Down quark	340 MeV/c^2[1]	1.8–2.8 MeV/c^2
Strange quark	486 MeV/c^2[1]	92–104 MeV/c^2
Charm quark	1550 MeV/c^2[1]	1.3 GeV/c^2
Bottom quark	4730 MeV/c^2[1]	4.2–4.7 GeV/c^2
Top quark	177 000 MeV/c^2[1]	156–176 GeV/c^2

Wikipedia

View of a proton in lQCD



From http://www.physics.adelaide.edu.au/theory/staff/leinweber/VisualQCD/Nobel/

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- **In medium (e.g. A+A collisions):**

In the presence of a hot and dense medium, the constituent quark masses are modified

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

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

Gell-Mann-Oakes-Renner relation:

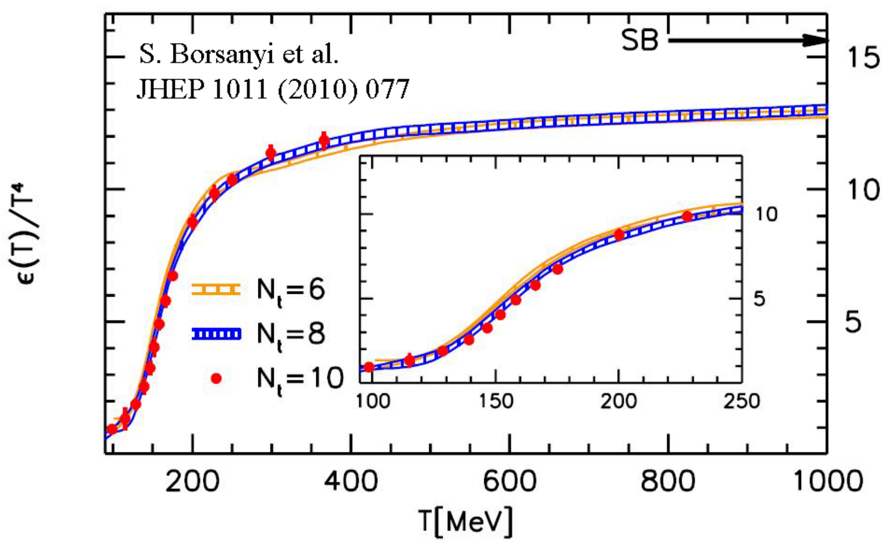
$$f_\pi^2 m_\pi^2 = -\frac{1}{2}(m_u^0 + m_d^0)\langle \bar{q}q \rangle_V$$

Bare quark masses:

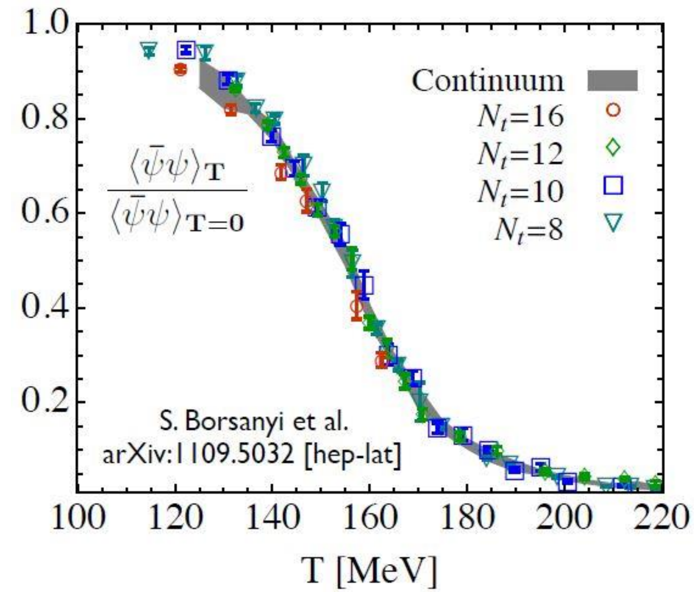
$$m_u^0 = m_d^0 \approx 7 \text{ MeV},\ m_s^0 \approx 100 \text{ MeV}$$

Information from lattice QCD

- **Deconfinement phase transition** **with increasing temperature**



- **Chiral symmetry restoration** **with increasing temperature**



- **Scalar quark condensate $\langle \bar{q}q \rangle$ is viewed as an order parameter for the restoration of chiral symmetry:**

$$< \bar{q}q >= \begin{cases} \neq 0 & \text{chiral non-symmetric phase;} \\ = 0 & \text{chiral symmetric phase.} \end{cases}$$

Chiral symmetry restoration in the hadronic phase

- The behavior of the scalar quark condensate $\langle \bar{q}q \rangle$ in the hadronic medium (baryons + mesons) can be obtained from:

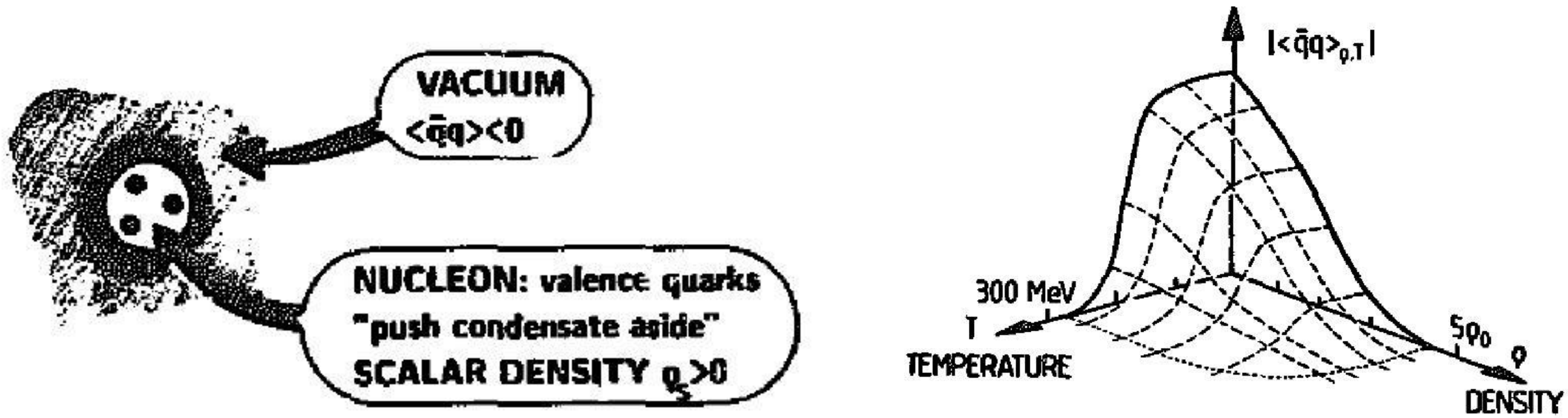
B.Friman et al.,
Eur, Phys, J, A 3, 165-170 (1998)

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

Baryonic medium

Mesonic medium

ρ_S : scalar density; $\Sigma_\pi \approx 45$ MeV : pion-nucleon Σ-term; f_π and m_π : pion decay constant and pion mass



Illustrations from W. Weise - **Nucl.Phys. A553 (1993) 59C-72C**

Chiral symmetry restoration in the hadronic phase

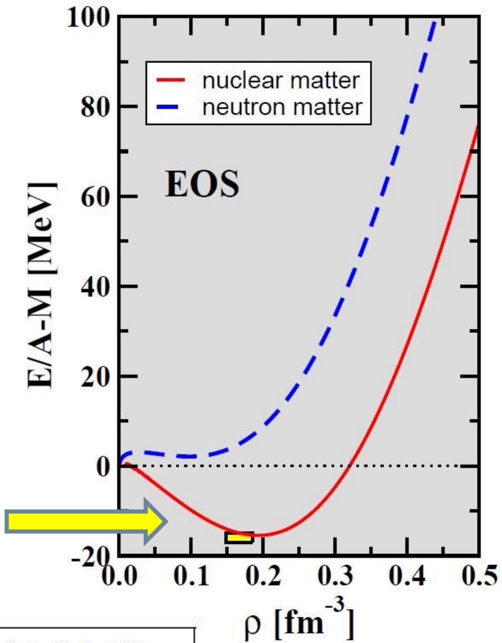
1) ρ_s is the **scalar density of baryonic matter** from the $\sigma - \omega$ **model**:

The scalar field $\sigma(x)$ mediates the scalar interaction of baryons with a g_s coupling.

$\sigma(x)$ is determined locally by the nonlinear gap equation :

$$\begin{cases} m_\sigma^2 \sigma(x) + B\sigma^2(x) + C\sigma^3(x) = g_s \rho_S = g_s d \int \frac{d^3p}{(2\pi)^3} \frac{m_N^*(x)}{\sqrt{p^2 + m_N^{*2}}} f_N(x, \mathbf{p}) \\ m_N^*(x) = m_N^V - g_s \sigma(x) \end{cases}$$

Example of parametrization for the binding energy per nucleon



Parameters m_σ, g_s, B, C are fixed to reproduce properties of nuclear matter at saturation density :

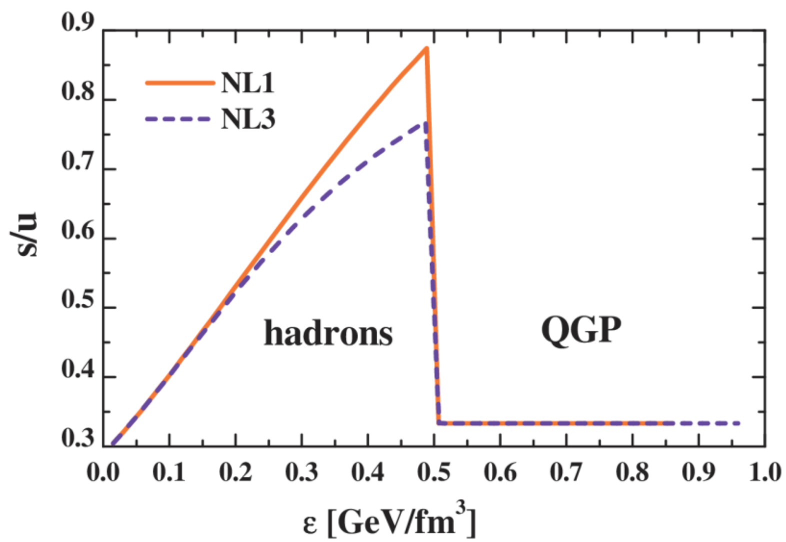
$$\rho_0 \simeq 0.16 \text{ fm}^{-3}; \quad k_{F_0} \simeq 1.36 \text{ fm}^{-1} = 260 \text{ MeV}; \quad \text{and} \quad E/A(\rho_0) \simeq -16 \text{ MeV} \quad .$$

2) ρ_S^h **is the scalar density of meson of type h (from PHSD)**

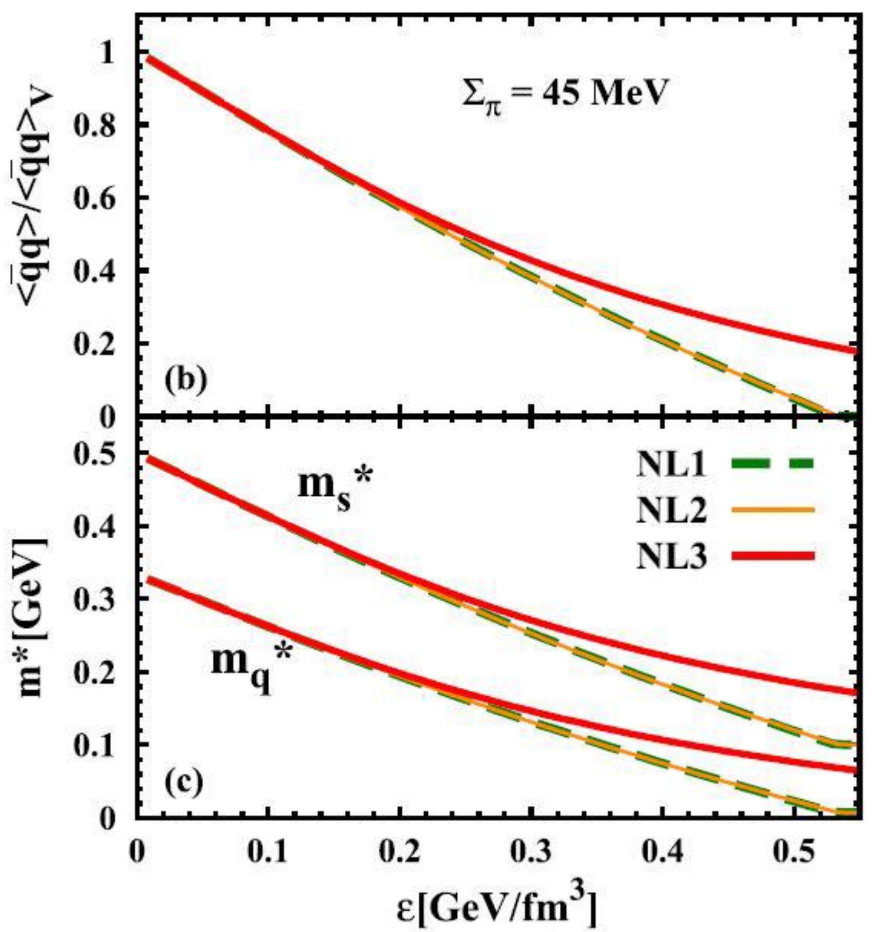
Chiral symmetry restoration vs deconfinement

- **Hadronic phase $\varepsilon < \varepsilon_c$: As a consequence of the chiral symmetry restoration (CSR), the strangeness production probability increases with the local energy density ε**

- **QGP phase $\varepsilon > \varepsilon_c$: the string decay doesn't occur anymore and this effect is therefore suppressed.**



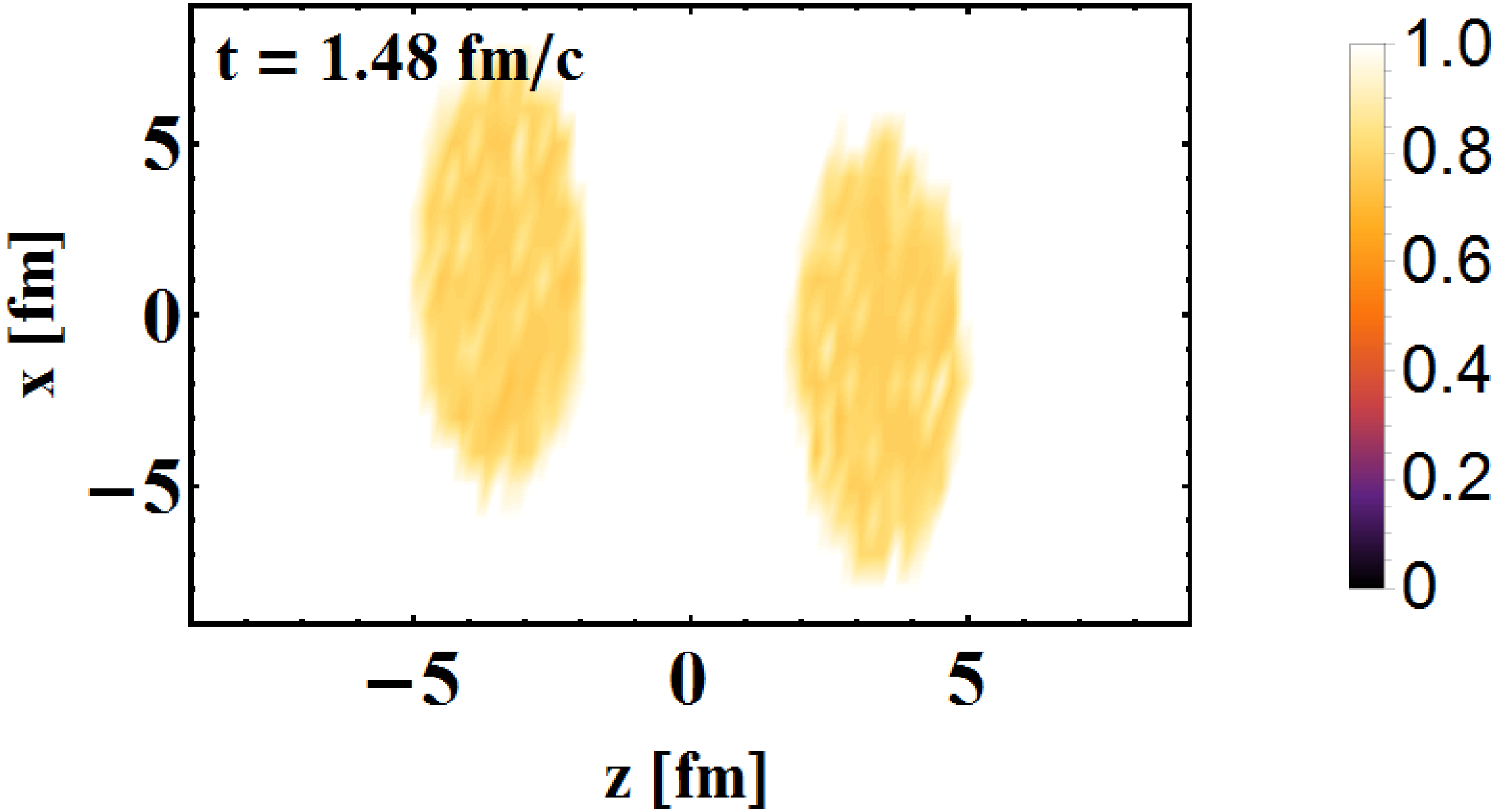
$T = 0$ in this illustration



Pb+Pb @ 30 AGeV – 0-5% central

Ratio of the quark scalar condensate compared to vacuum as a function of time ($y \approx 0$):

$$\frac{\langle \bar{q}q \rangle}{\langle \bar{q}q \rangle_V}$$



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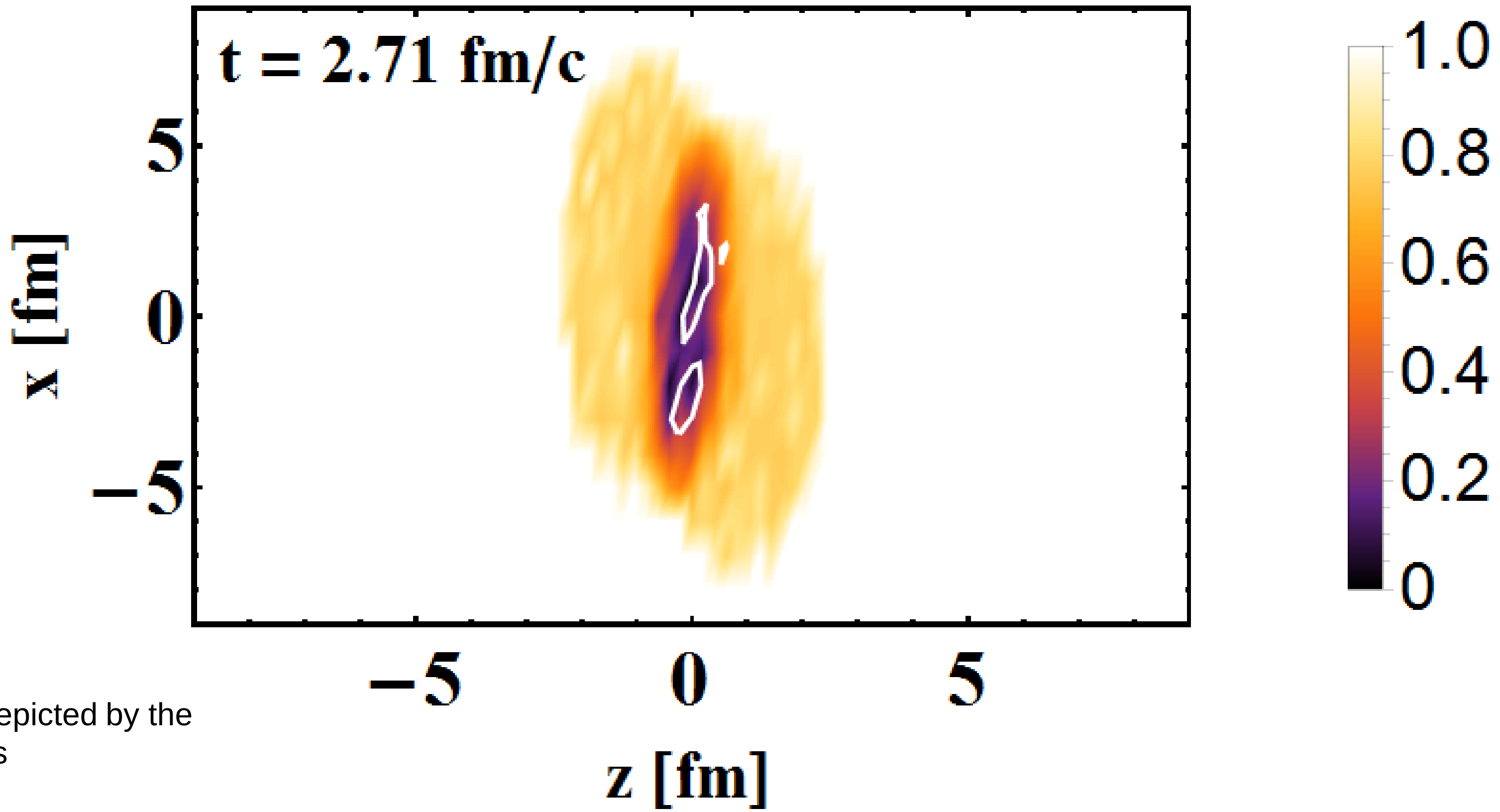

QGP phase depicted by the white contours

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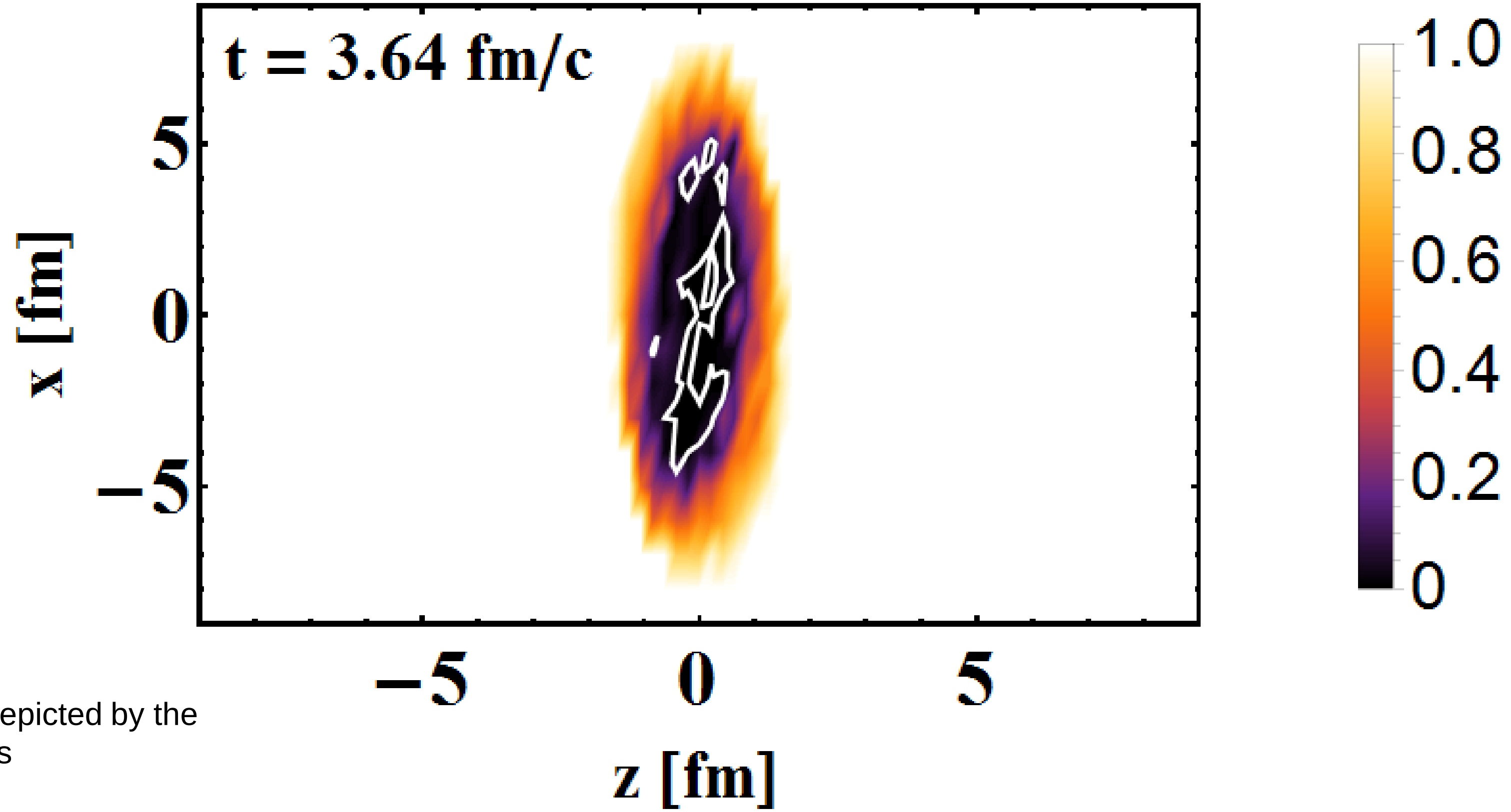

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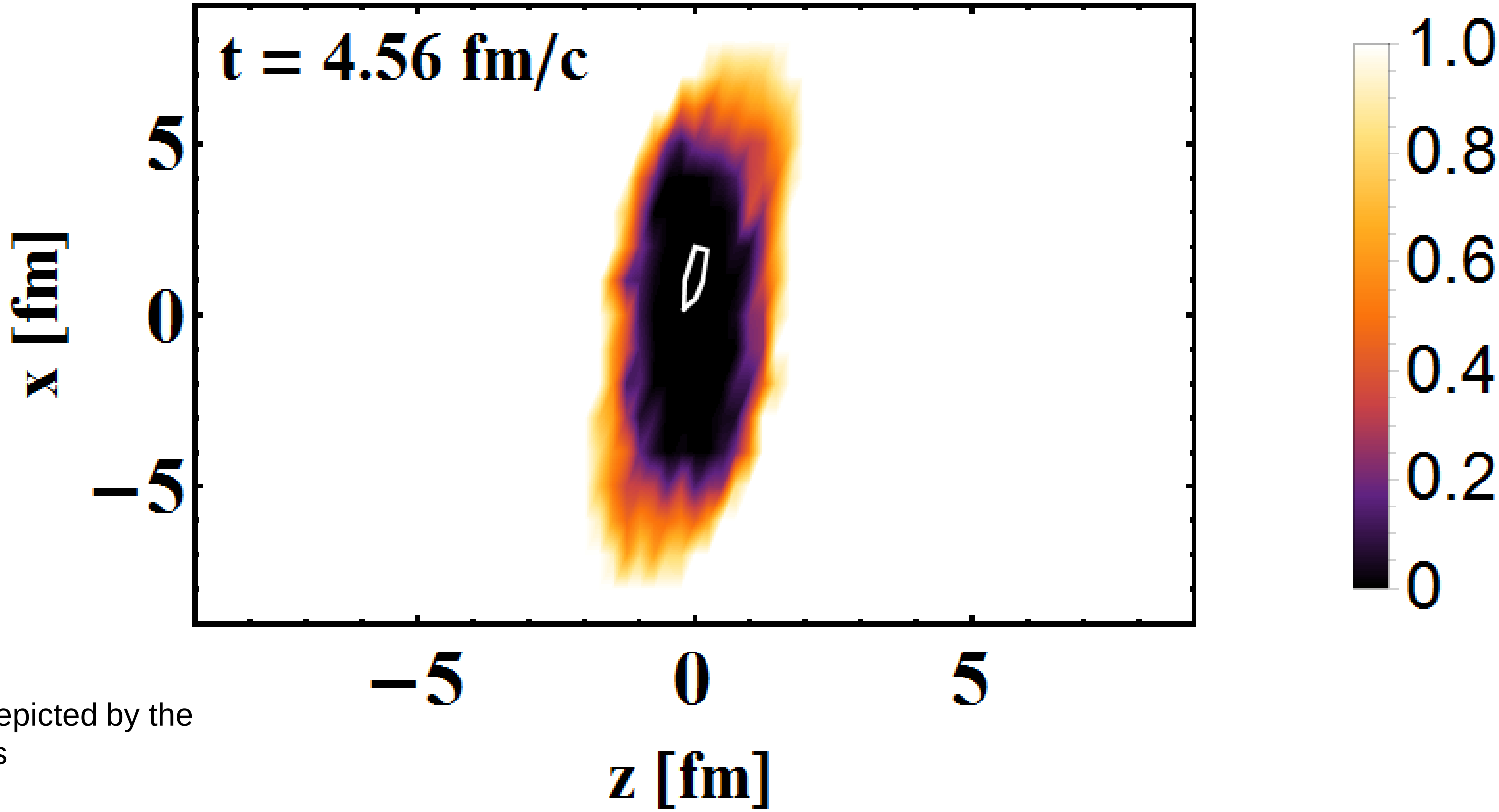

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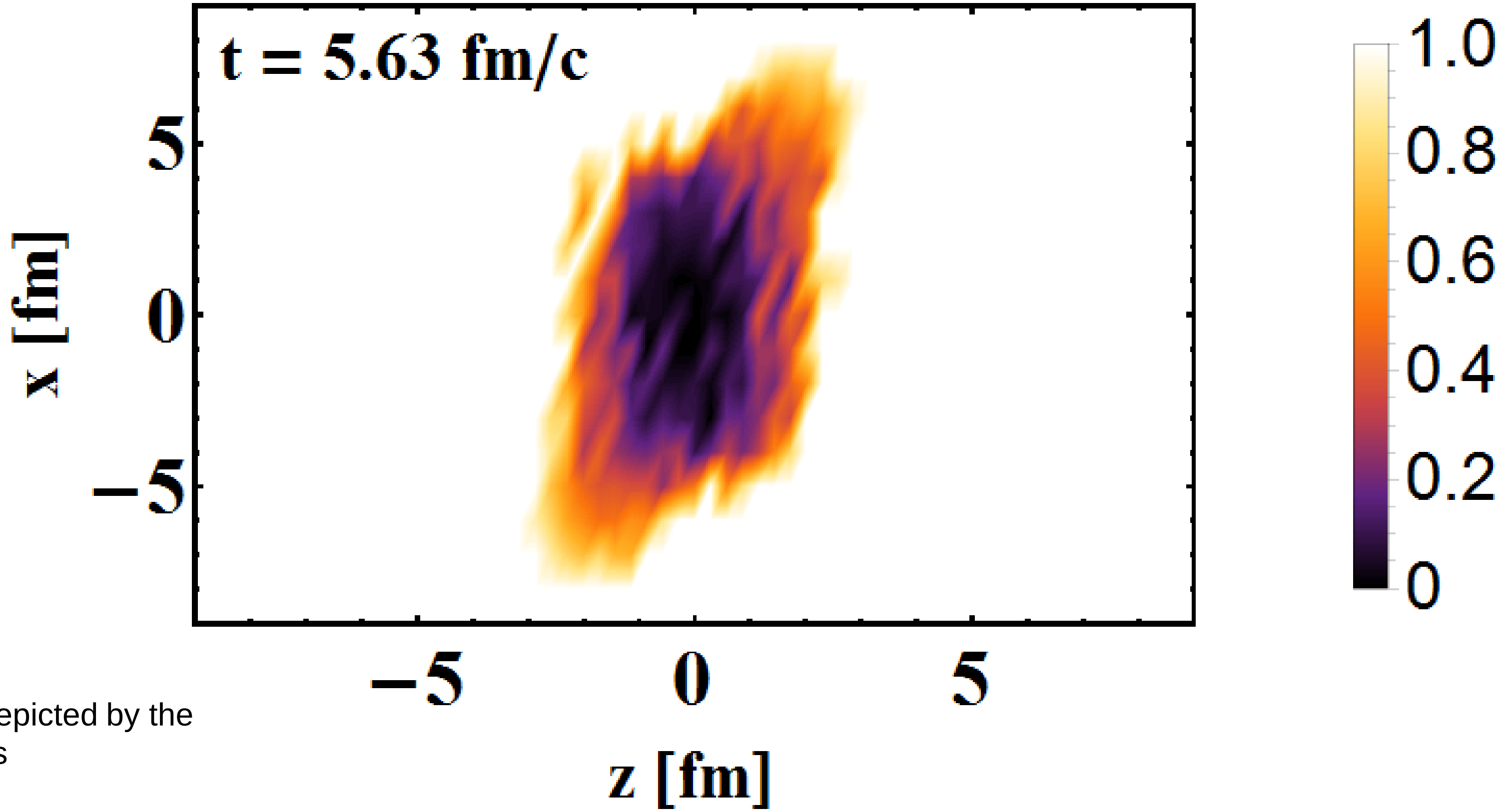

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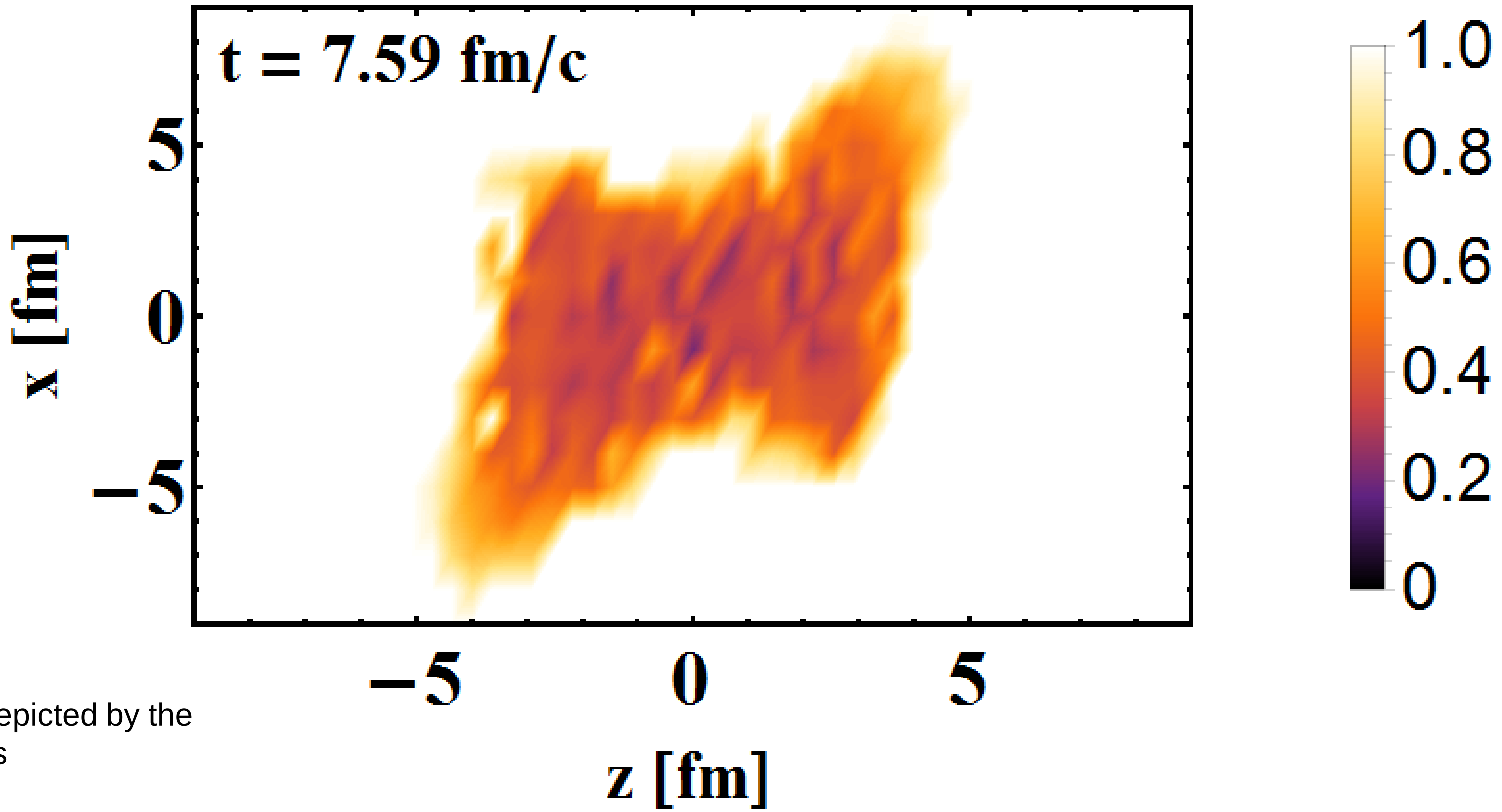

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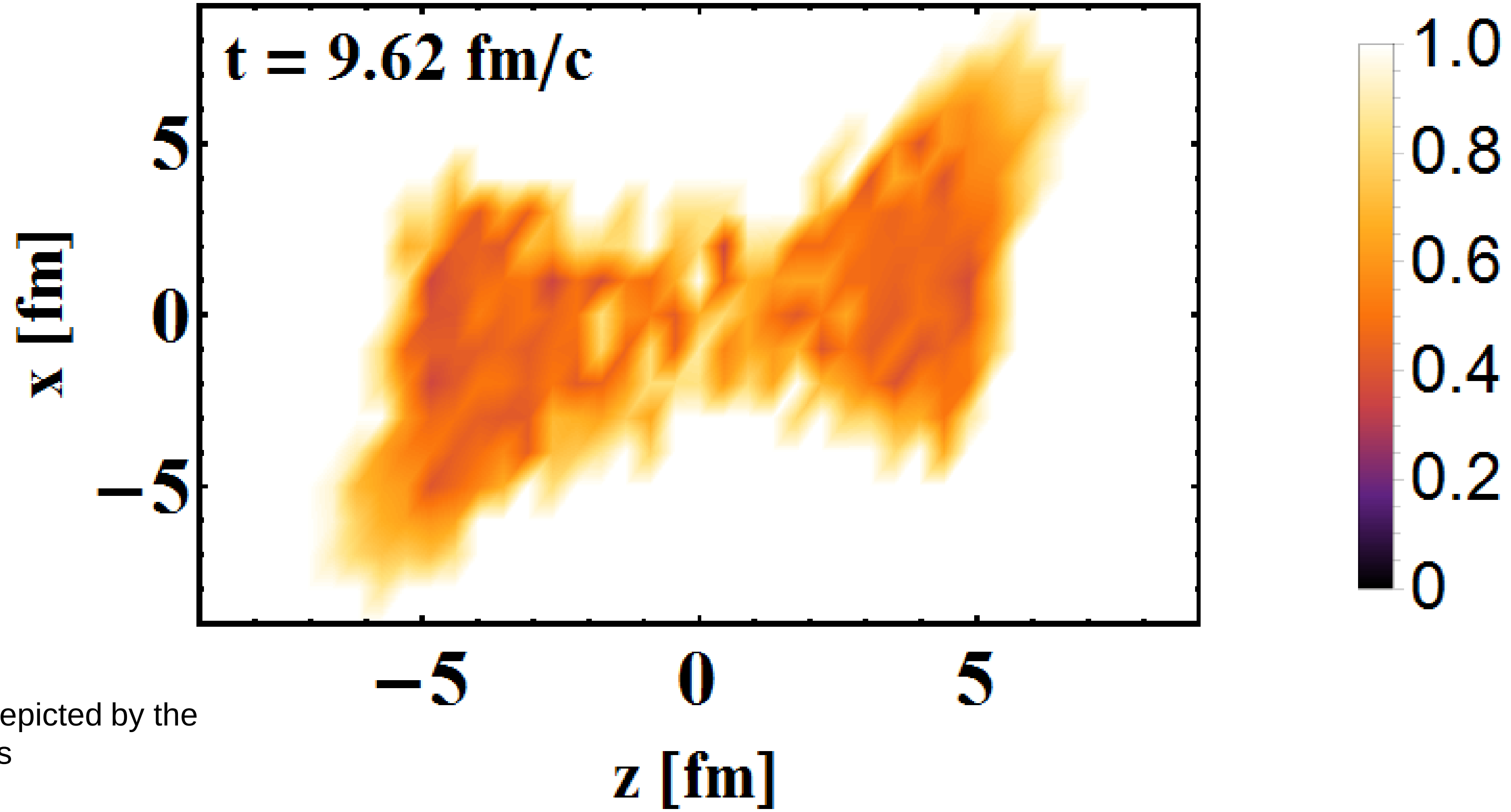

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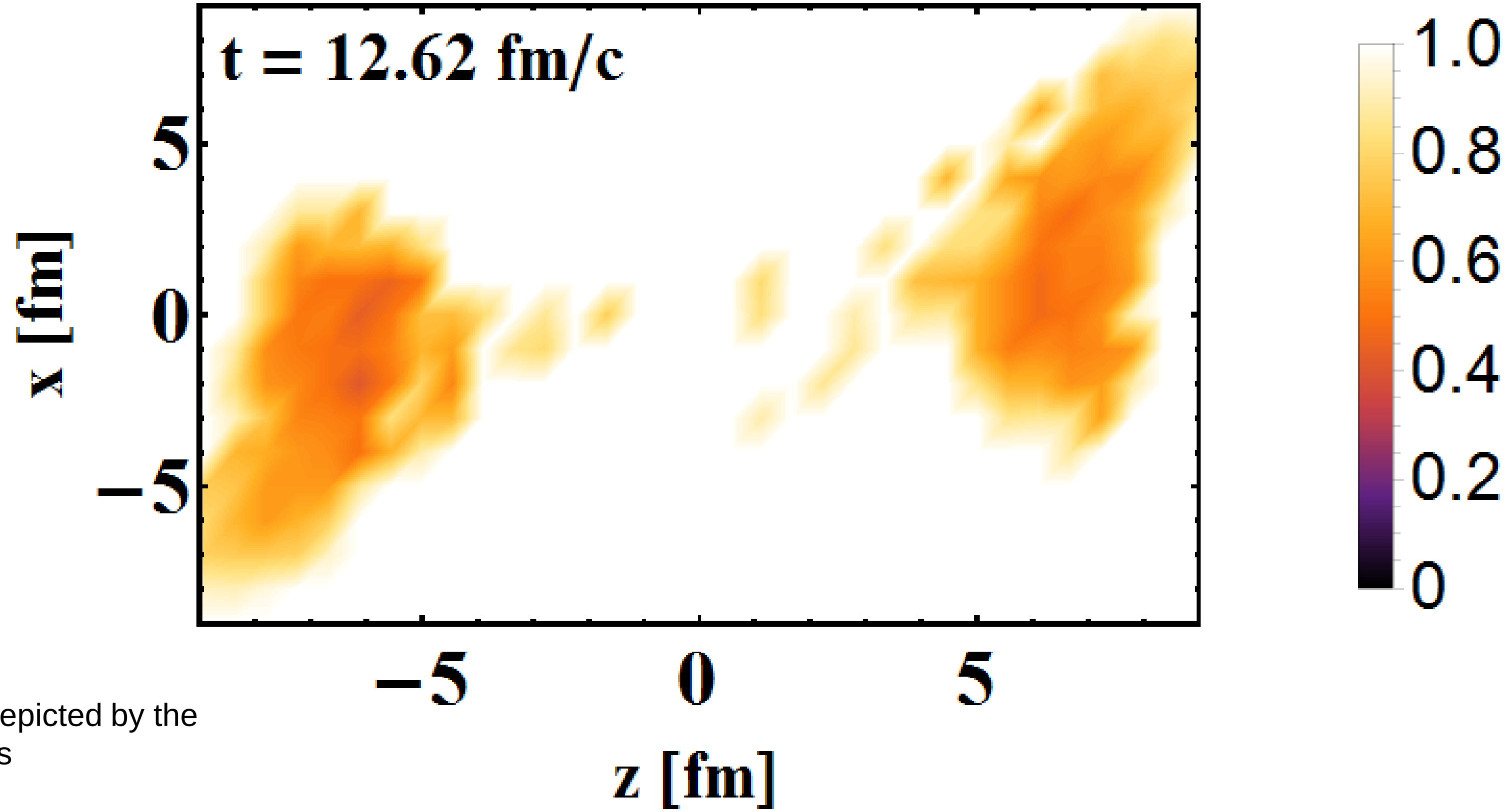
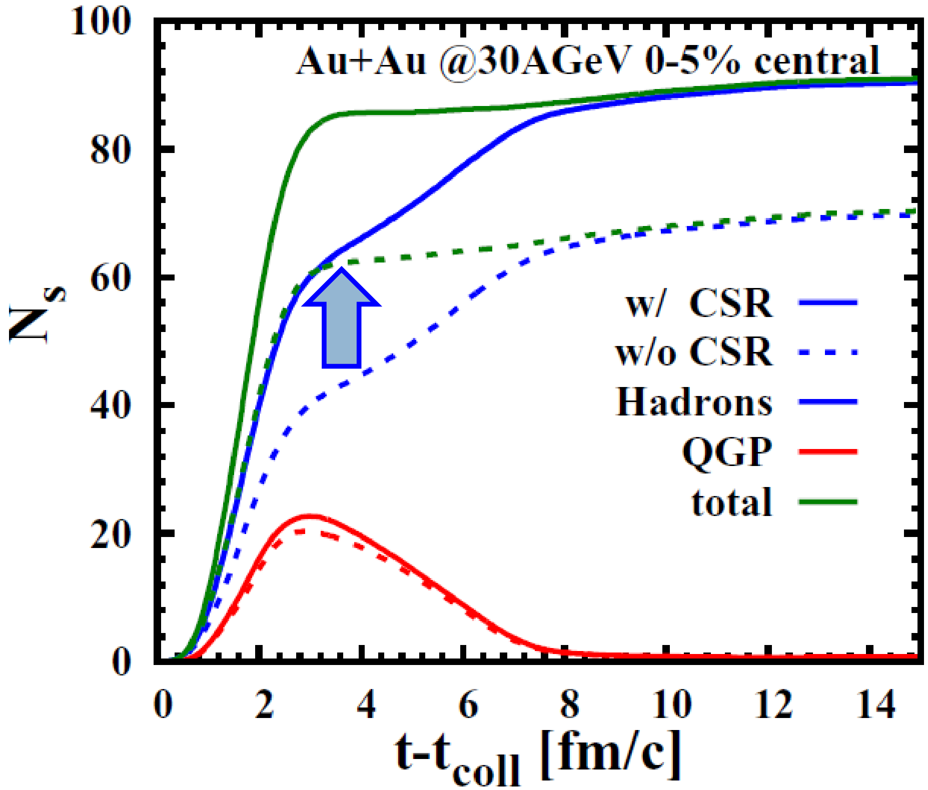


QGP phase depicted by the white contours

Au+Au @ 30 AGeV – 0-5% central

- Chiral symmetry restoration leads to the enhancement of strangeness production during the string fragmentation in the beginning of HIC



Palmese et al., **PRC94 (2016) 044912**, arXiv:1607.04073

Strange particle number Ns as a function of time

Chiral symmetry restoration in the hadronic phase

- The strangeness enhancement seen experimentally at FAIR/NICA energies probably involves the approximate restoration of chiral symmetry in the hadronic phase

W. Cassing, A. Palmese, P. Moreau, E.L. Bratkovskaya - **Phys.Rev. C93 (2016), 014902**

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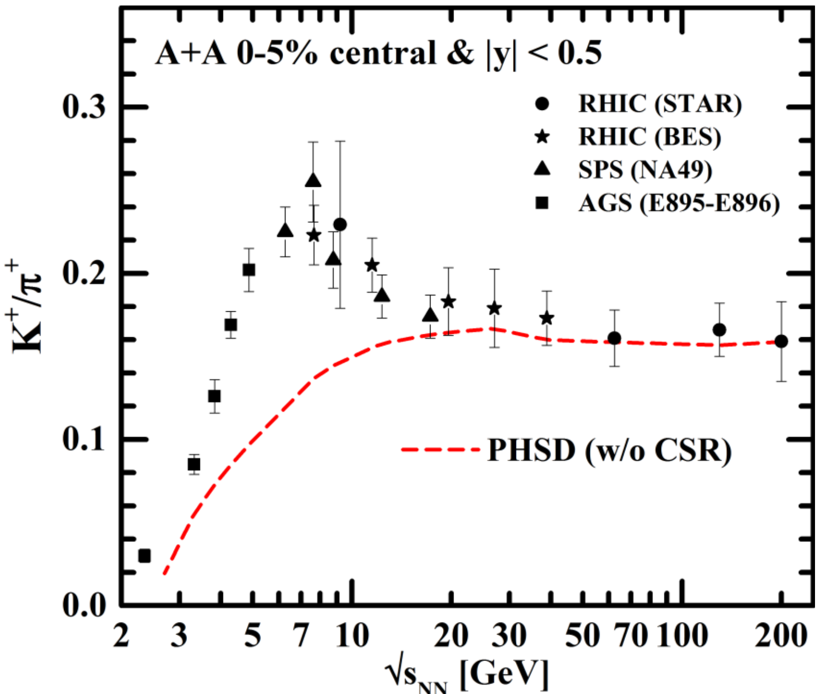

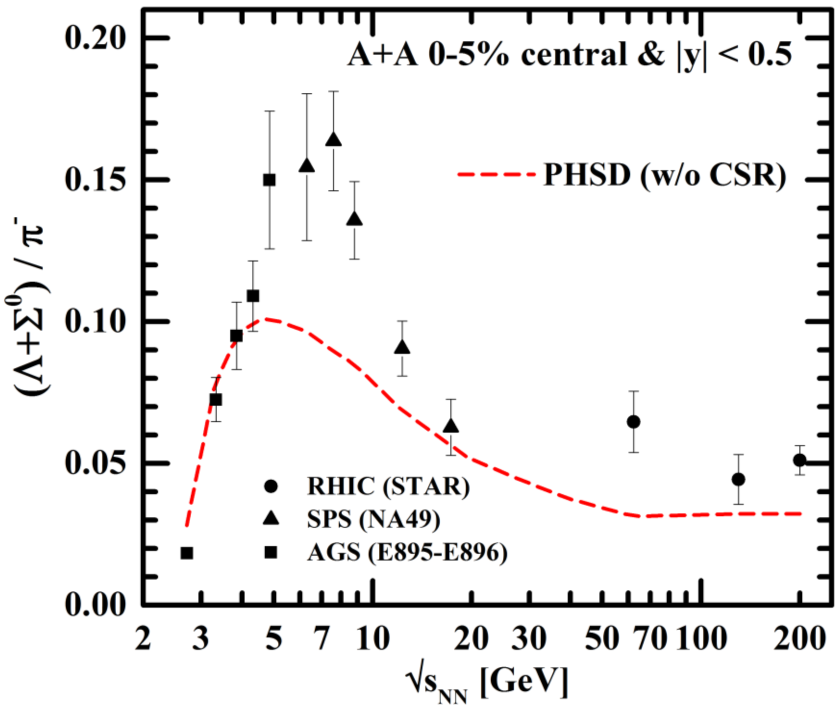

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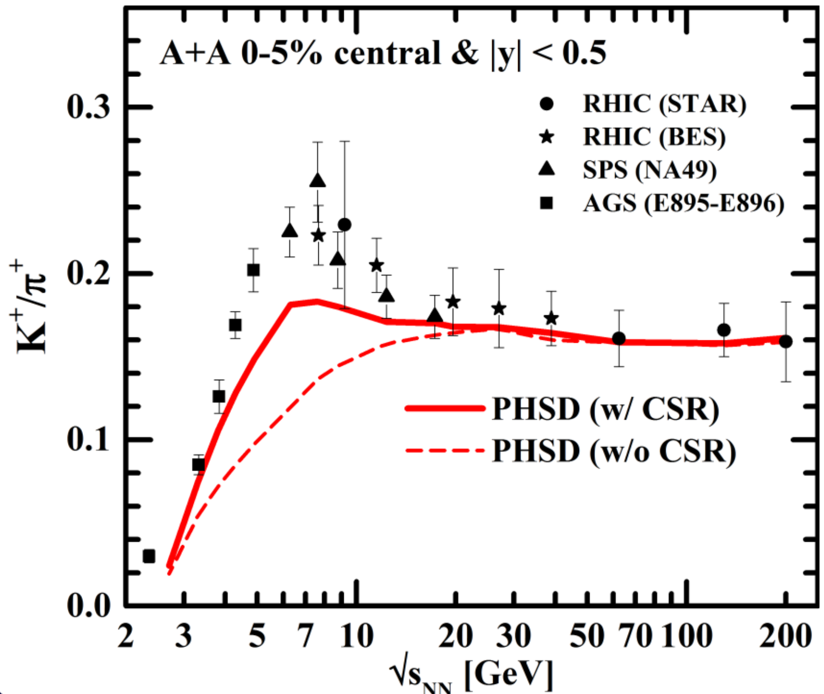

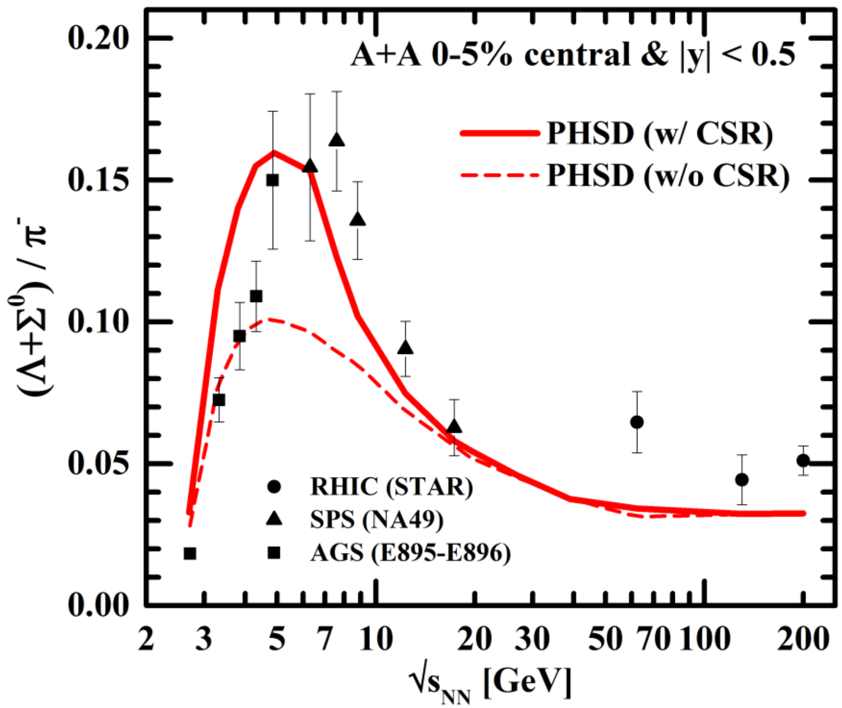

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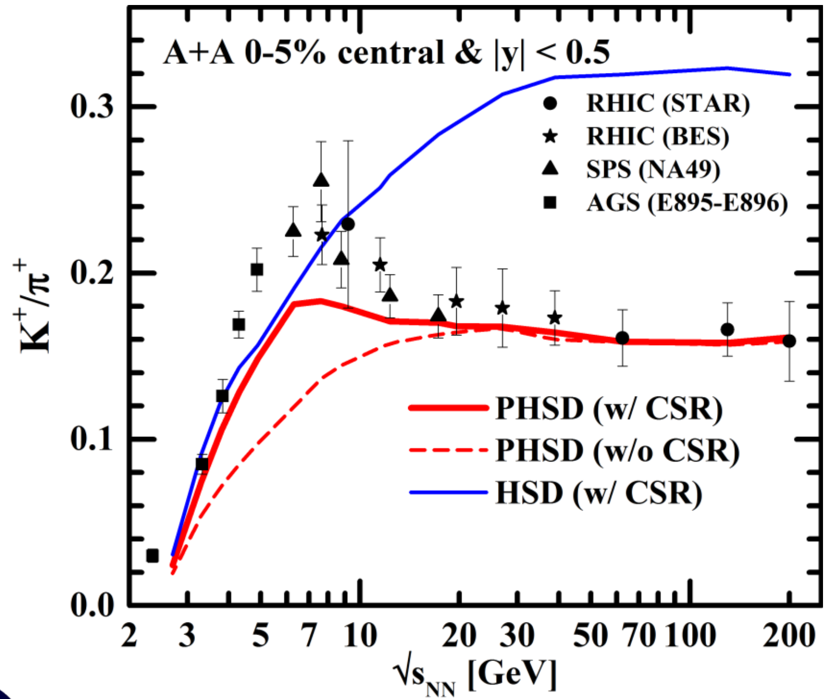
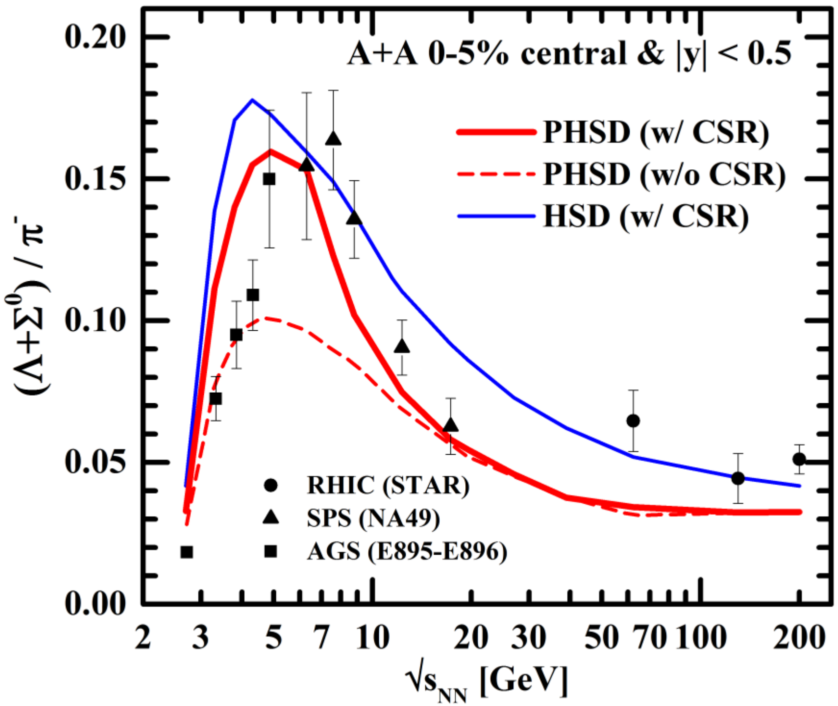
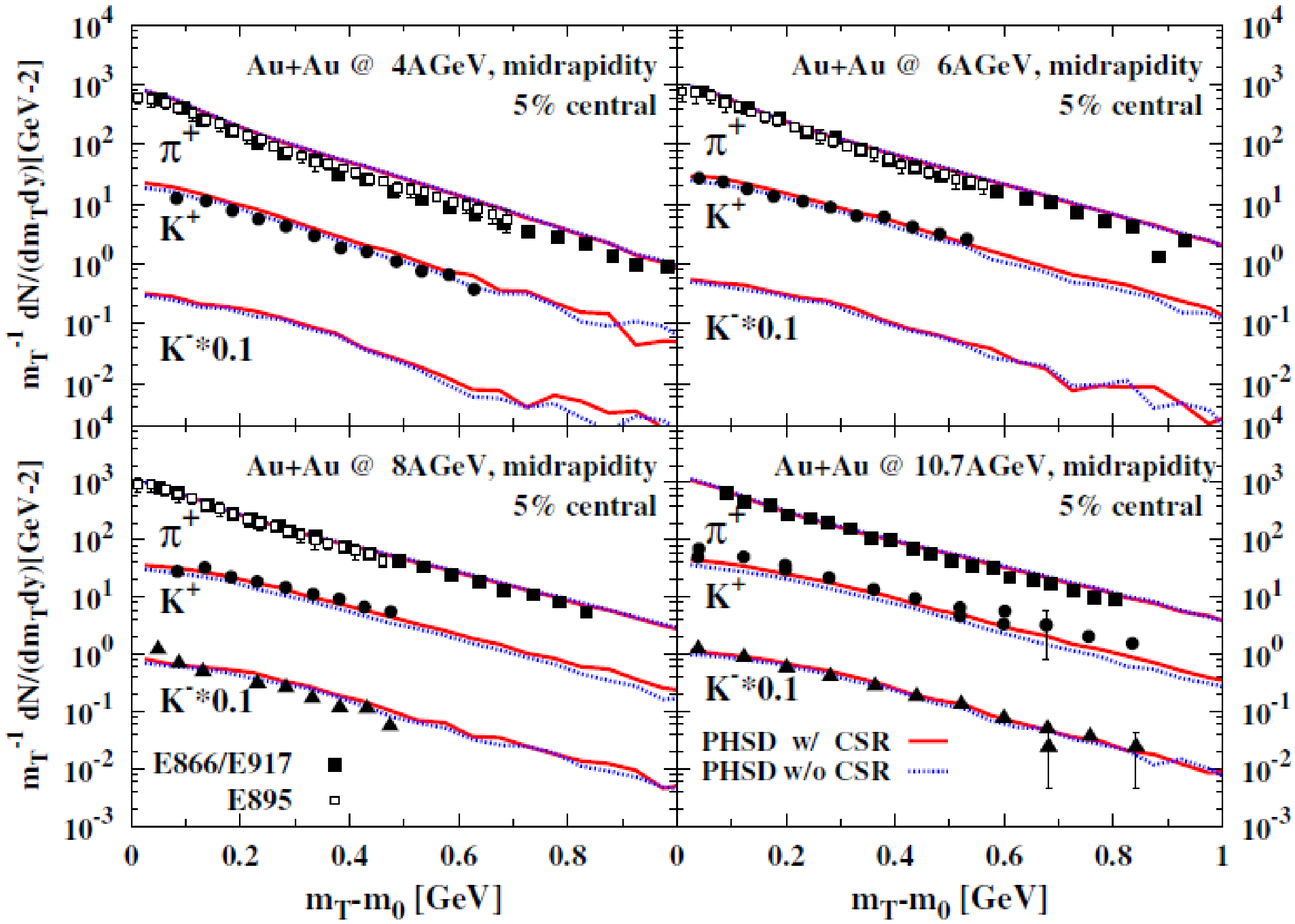


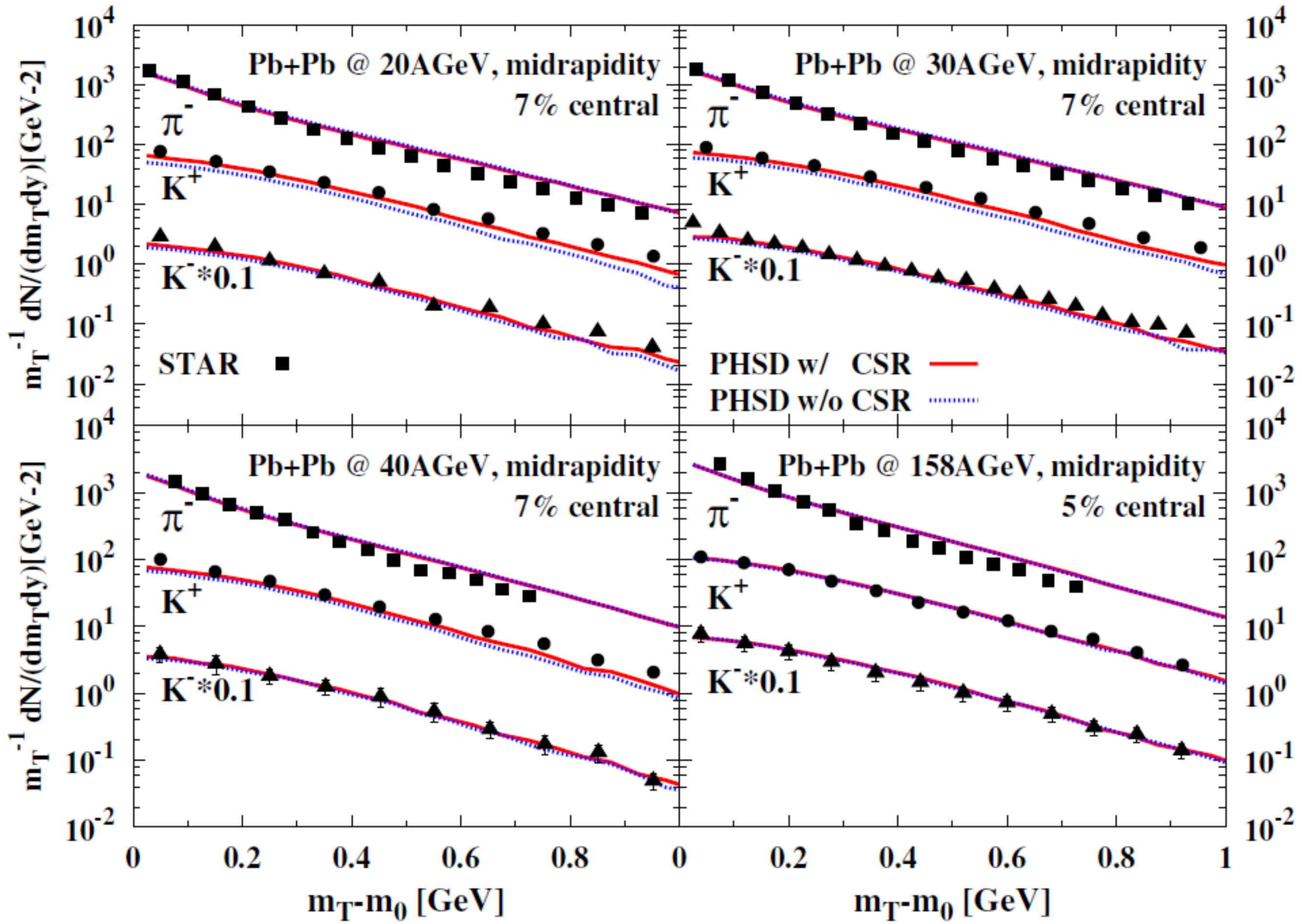


m_T spectra of pions and kaons at AGS energies



Palmese et al., **PRC94 (2016) 044912**, arXiv:1607.04073

m_T spectra of pions and kaons at SPS energies

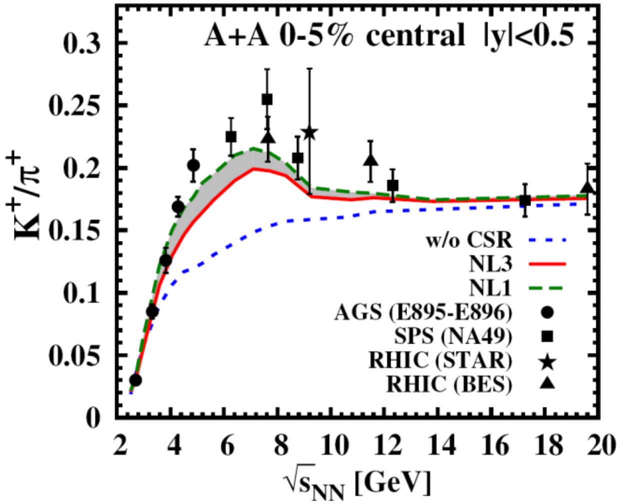


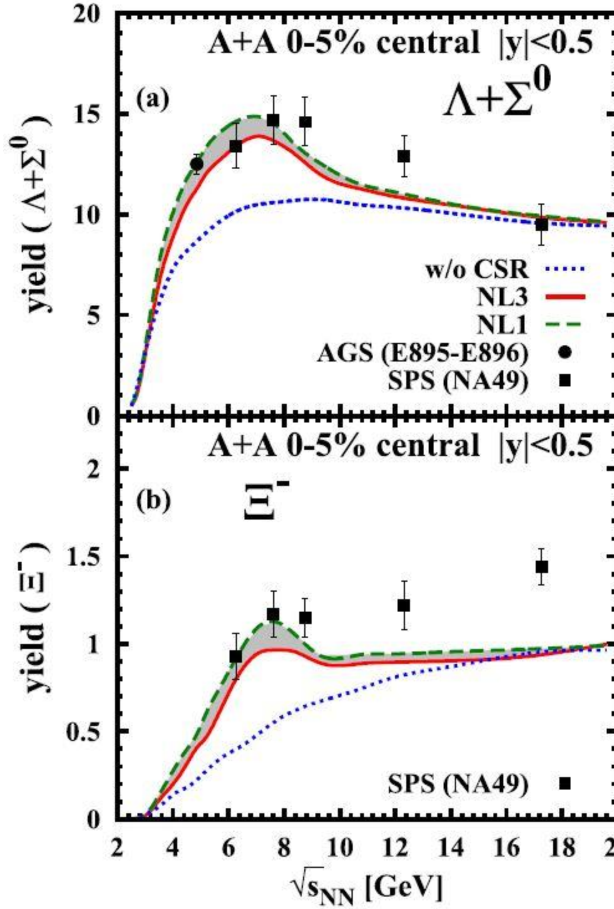
Palmese et al., **PRC94 (2016) 044912**, arXiv:1607.04073

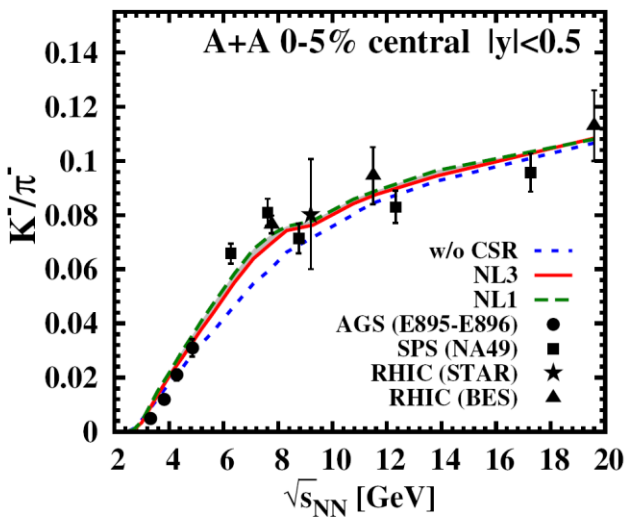
Sensitivity to the nuclear equation of state

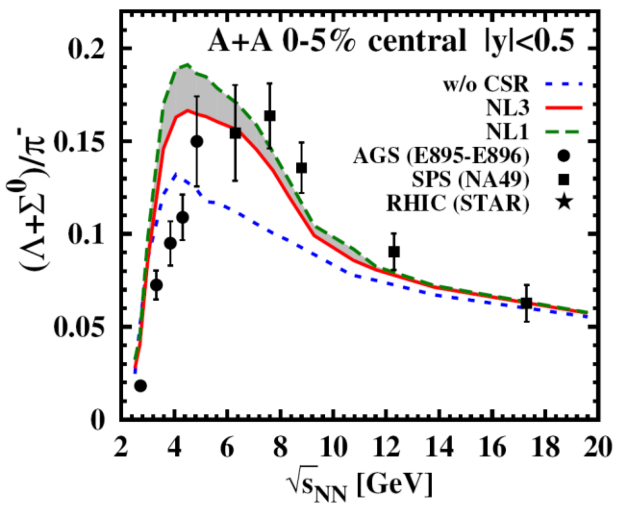
Palmese et al.,
PRC94 (2016) 044912,
arXiv:1607.04073

Low sensitivity to the nuclear equation of state!

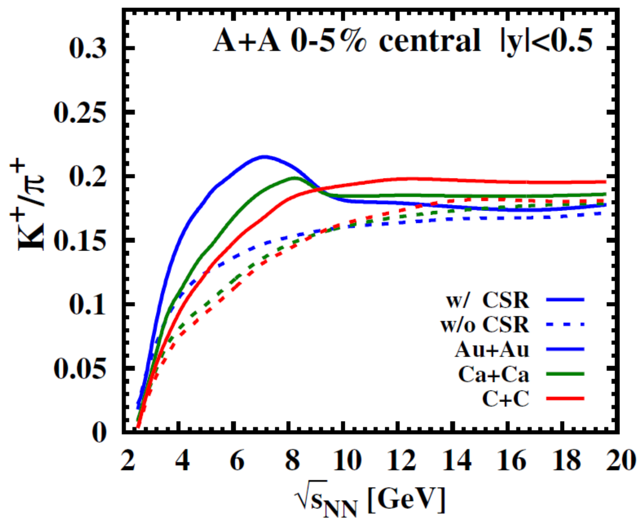


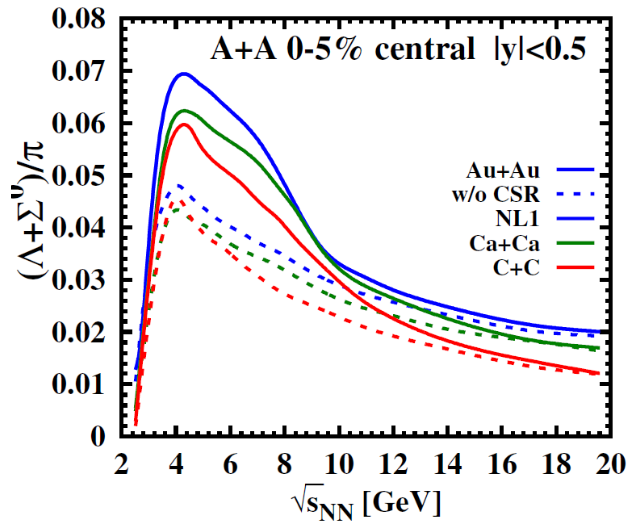


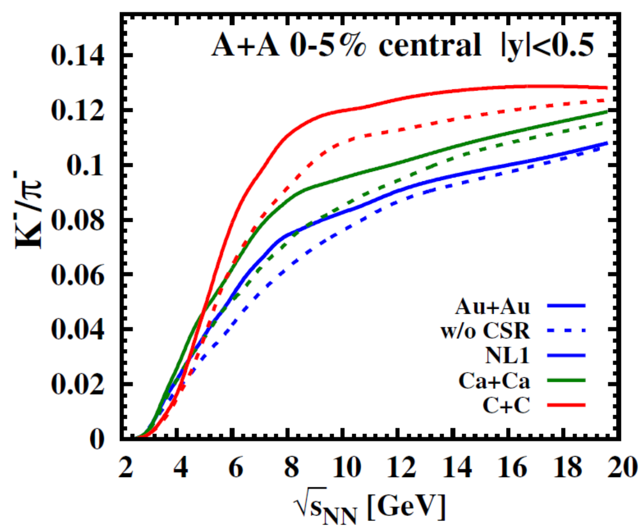




Sensitivity to the system size: A+A collisions



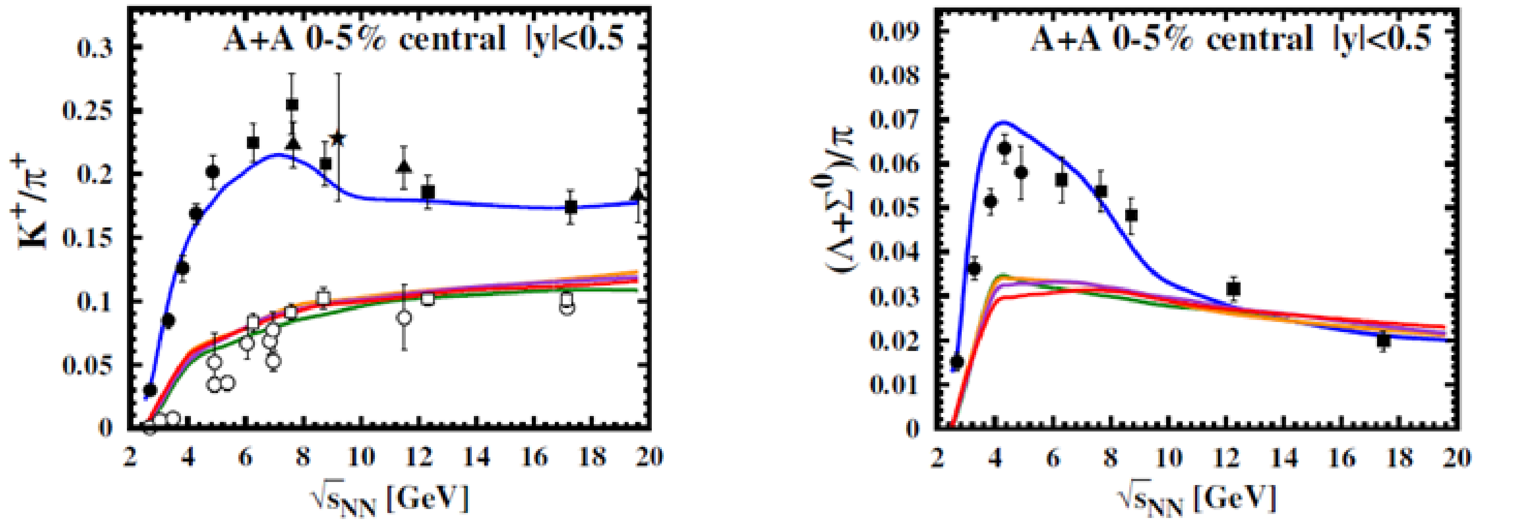


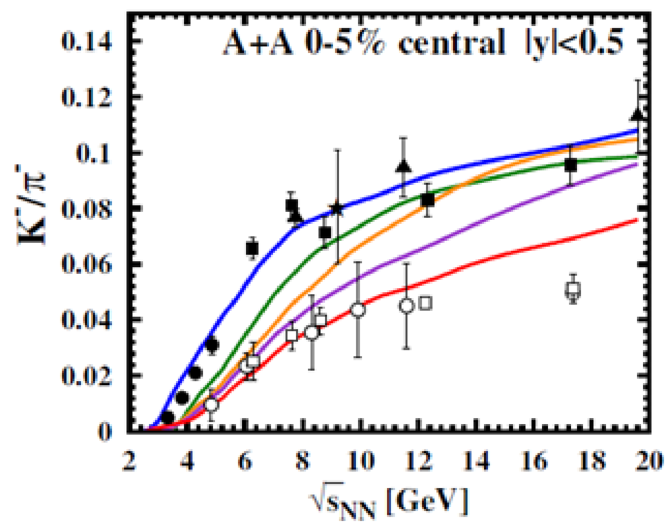


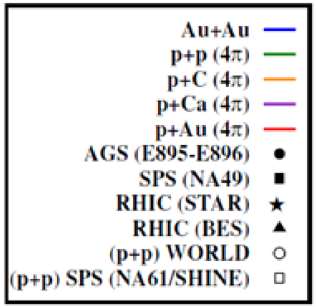
- If the **system size is smaller**:
  - the peak of K^+/π^+ **disappears**
  - the peak of $(\Lambda + \Sigma^0)/\pi$ **remains** in the same position in energy, but getting smaller

Palmese et al., **PRC94 (2016) 044912**, arXiv:1607.04073

Sensitivity to the system size: p+A collisions





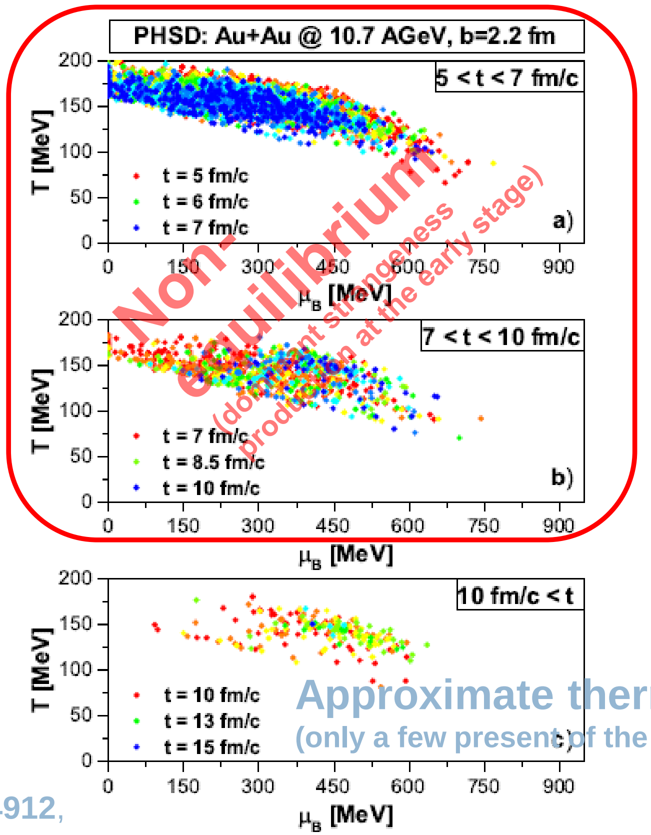


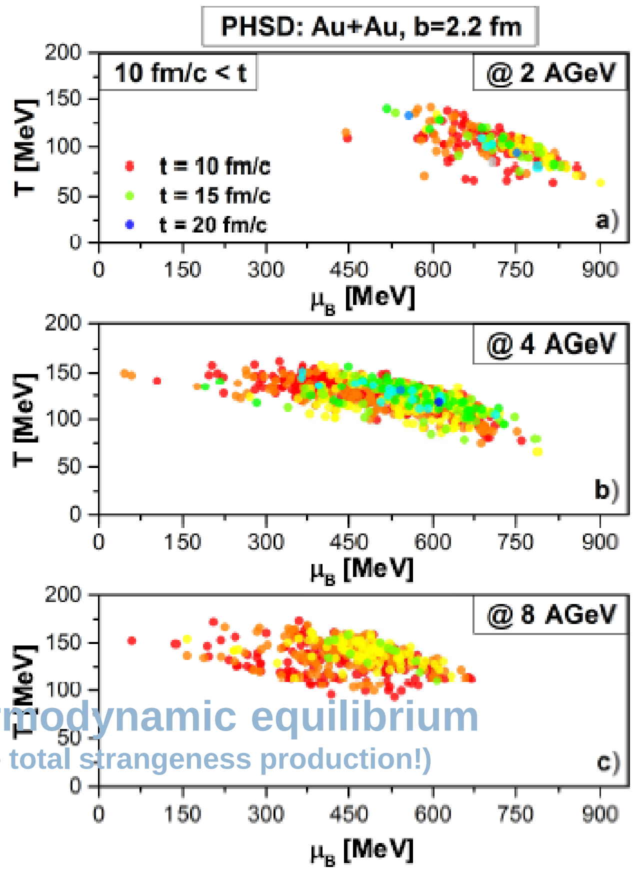
- **In p+A collisions strange to non-strange particle ratios show no peaks**

Palmese et al., **PRC94 (2016) 044912**, arXiv:1607.04073

Thermodynamics of strangeness in HIC

- **Which parts of the phase diagram in the (T, μ_B)-plane are probed by heavy-ion collisions via the strangeness production?**





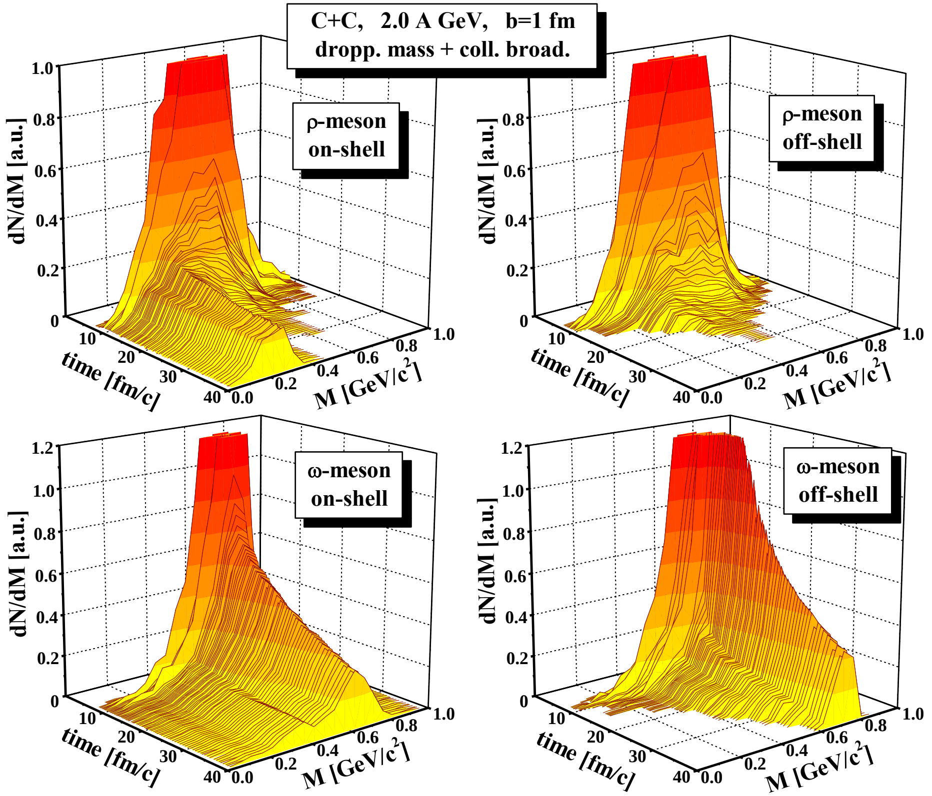
Approximate thermodynamic equilibrium
(only a few percent of the total strangeness production!)

Palmese et al.,
PRC94 (2016) 044912,
arXiv:1607.04073

the spread in T and μ_B is very large !

Summary

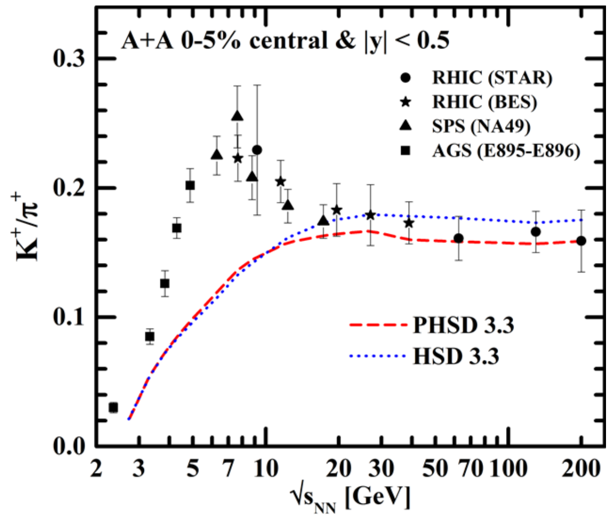
- The PHSD approach includes off-shell dynamics: it is designed to study the properties of hadronic or partonic degrees of freedom in a high-density medium

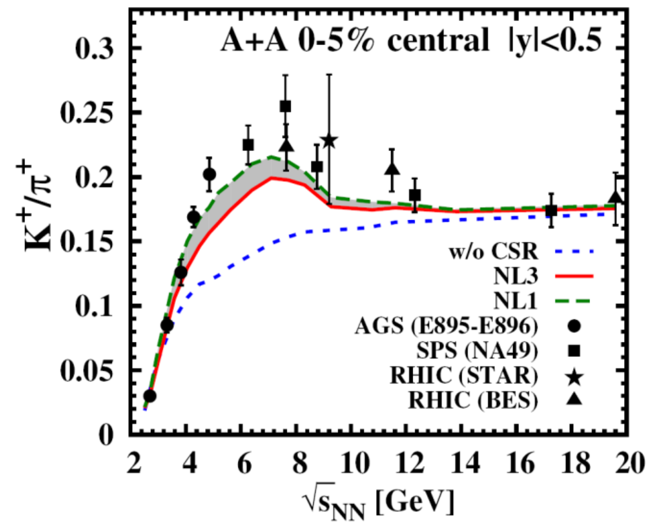


- PHSD provides a good agreement with experimental data for bulk particles from RHIC to AGS energies

- Probes like multi-strange baryons or charm mesons can be used to understand the behavior of strongly interacting matter at low collisional energy

Summary





- **The strangeness enhancement ('horn') seen experimentally by NA49 and STAR at a bombarding energy ~ 20-30 AGeV (FAIR/NICA energies) cannot be attributed to a 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 partonic medium → a 'horn' emerges**

Thank you for your attention!

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GOETHE UNIVERSITÄT FRANKFURT AM MAIN
FIAS Frankfurt Institute for Advanced Studies
HIC for FAIR Helmholtz International Center
HGS-HIRe for FAIR Helmholtz Graduate School for Hadron and Ion Research
Bundesministerium für Bildung und Forschung
DAAD
DFG Deutsche Forschungsgemeinschaft
JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN
Subatech
TEXAS A&M UNIVERSITY
JINR Joint Institute for Nuclear Research
UAB Universitat Autònoma de Barcelona
Duke UNIVERSITY

Initial conditions in heavy-ion collisions

To study the influence of the initial degrees of freedom, we consider two extreme scenarios:

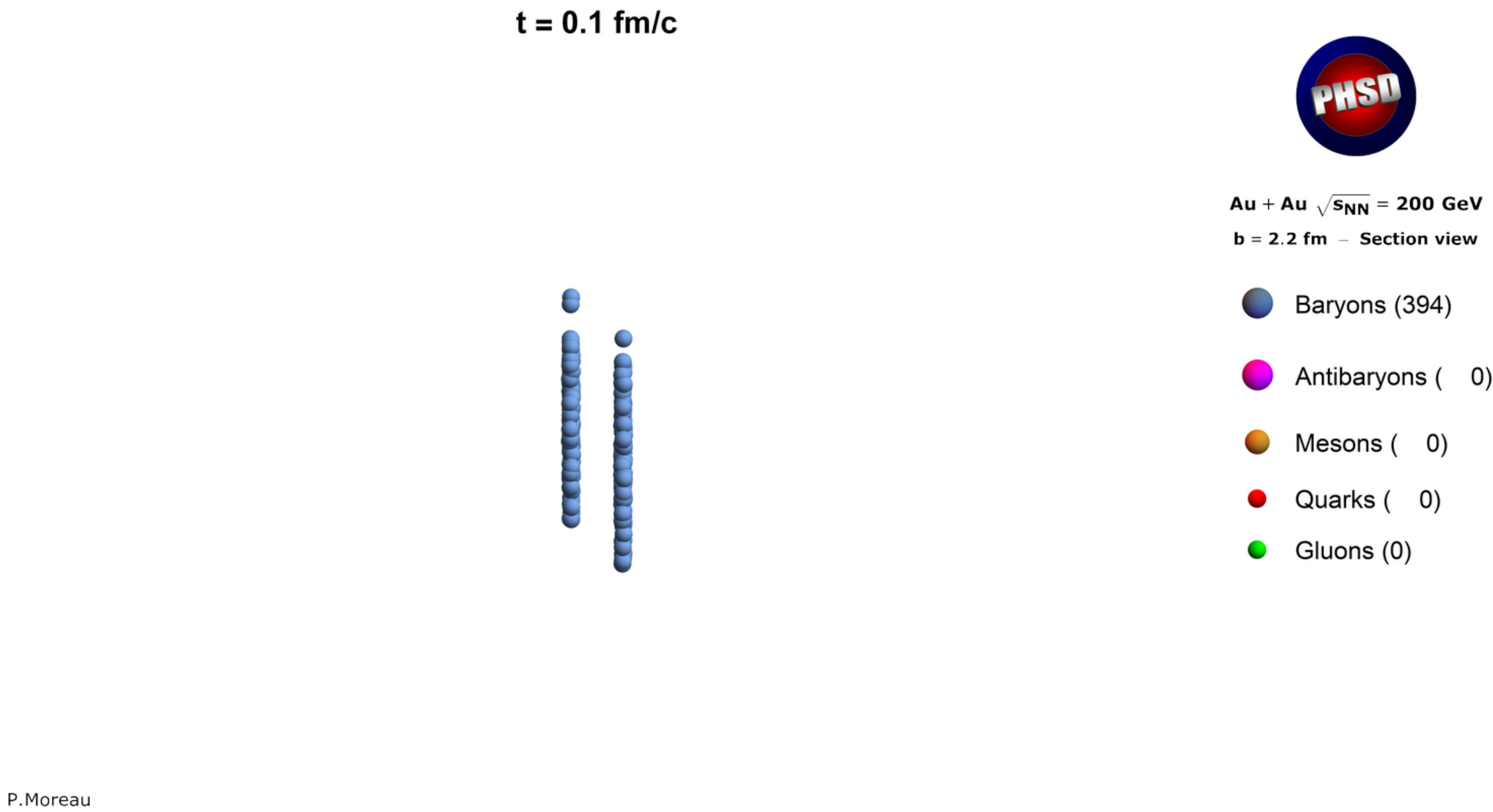
- **Scenario I : gluon initial condition (gluon IC)**
  - **In the PHSD dissolution routine, we exchange the massive quark and antiquark pairs by massive gluons alone, which preserves the energy-momentum tensor $T_{\mu\nu}(x)$**

- **Scenario II : quark initial condition (quark IC)**
  - **Dissolution of produced hadrons by string fragmentation into quarks and antiquark**

In the default PHSD

- **The newly produced hadrons are dissolved (as in Scenario II), and some gluons are created by quark – antiquark fusion (as in Scenario I). But the ratio $q\bar{q}/gluon$ is fixed by DQPM at the same local energy density ϵ.**

Gluon initial condition



Gluon initial condition

P.Moreau

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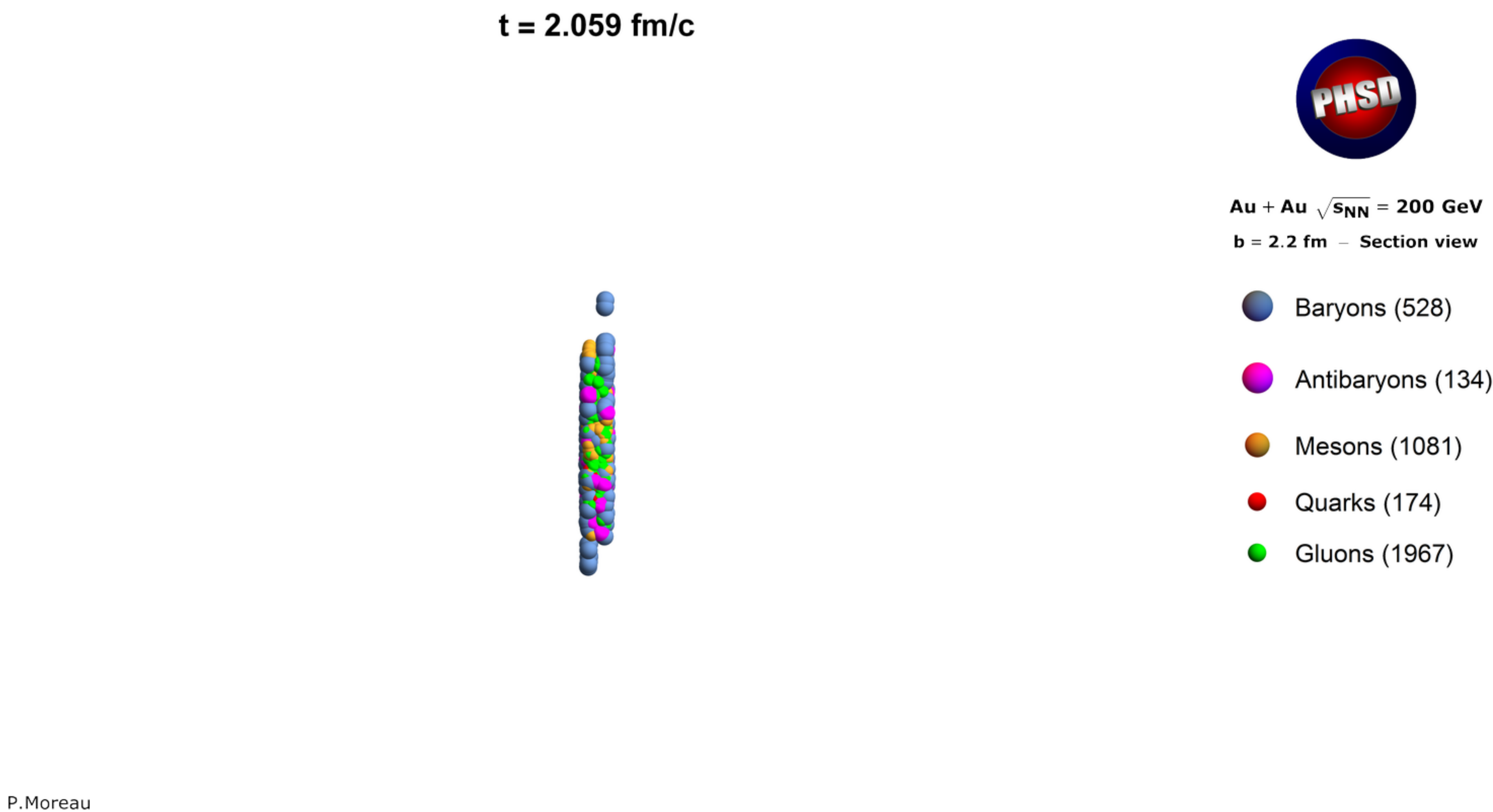

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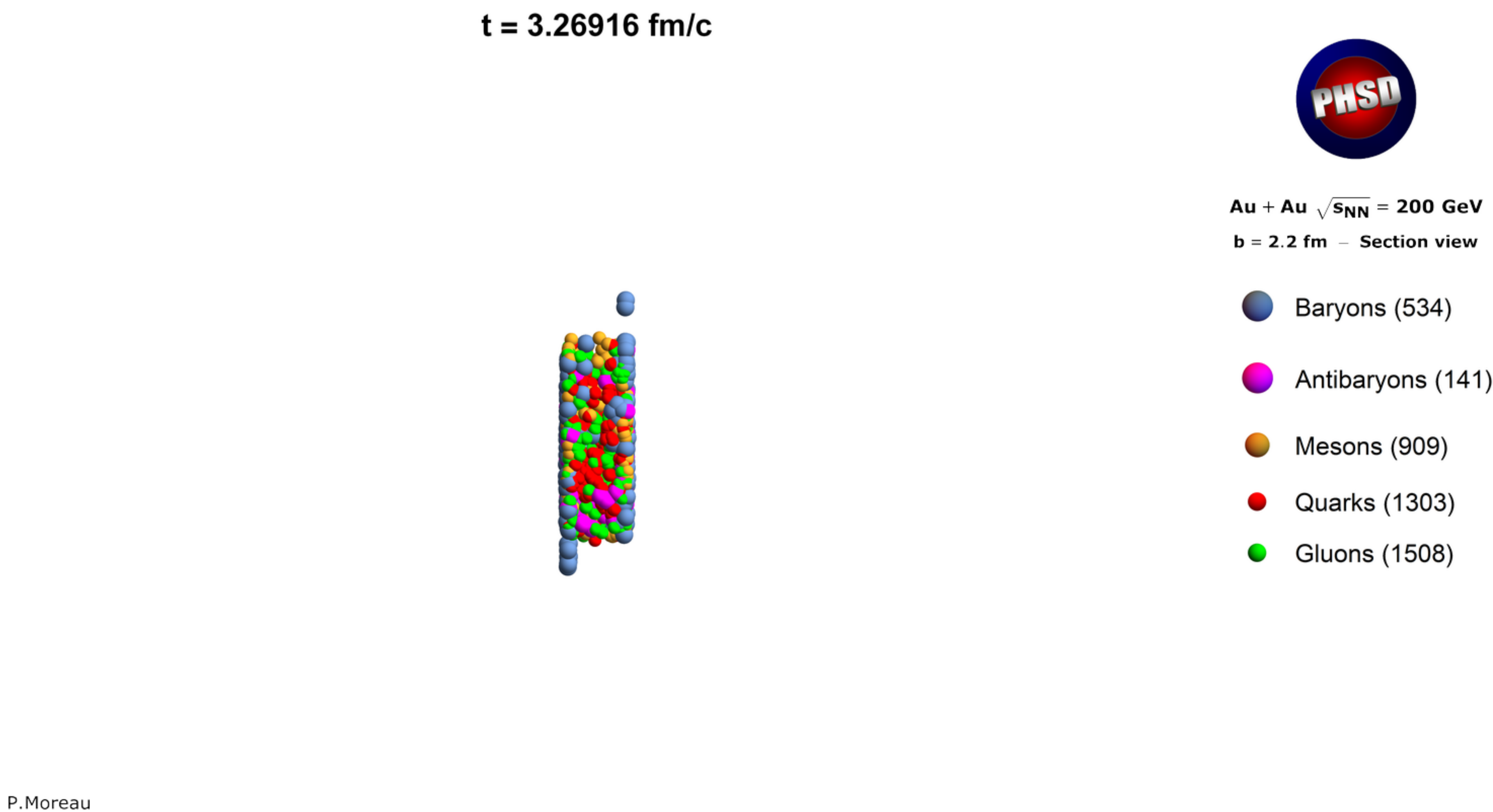

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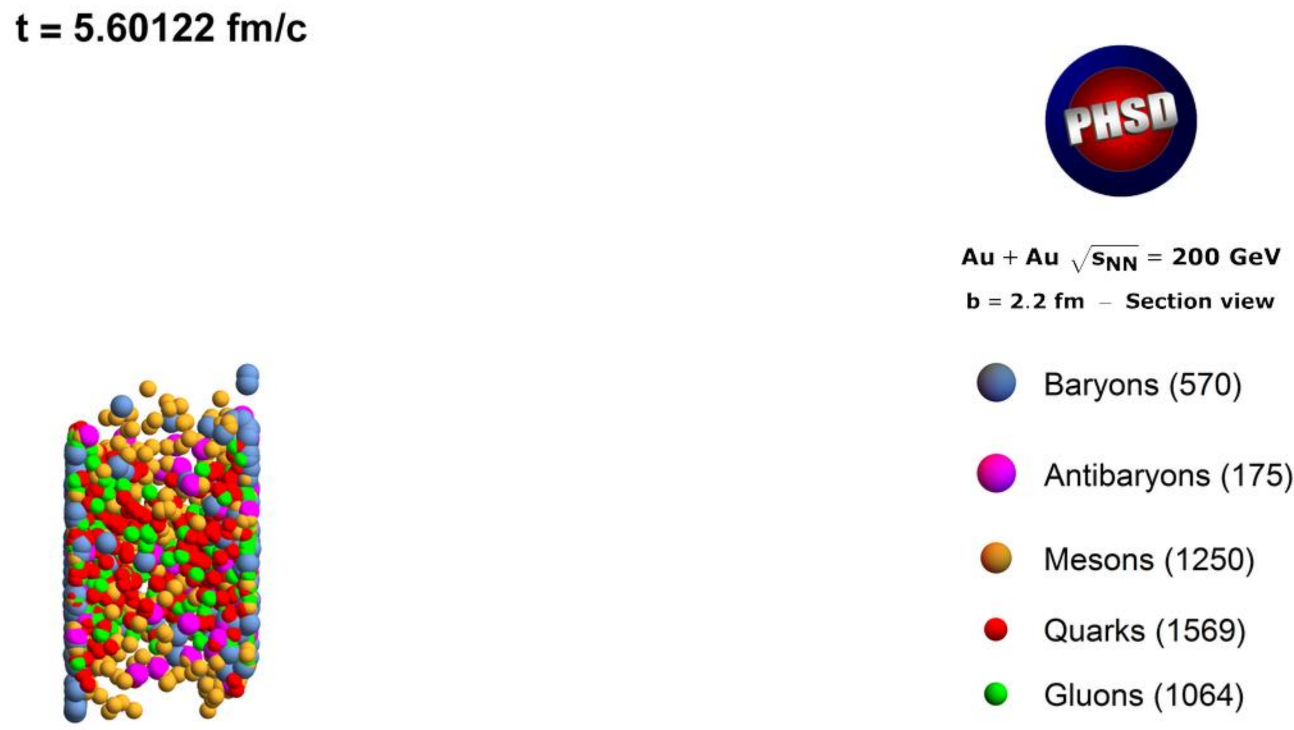

P.Moreau

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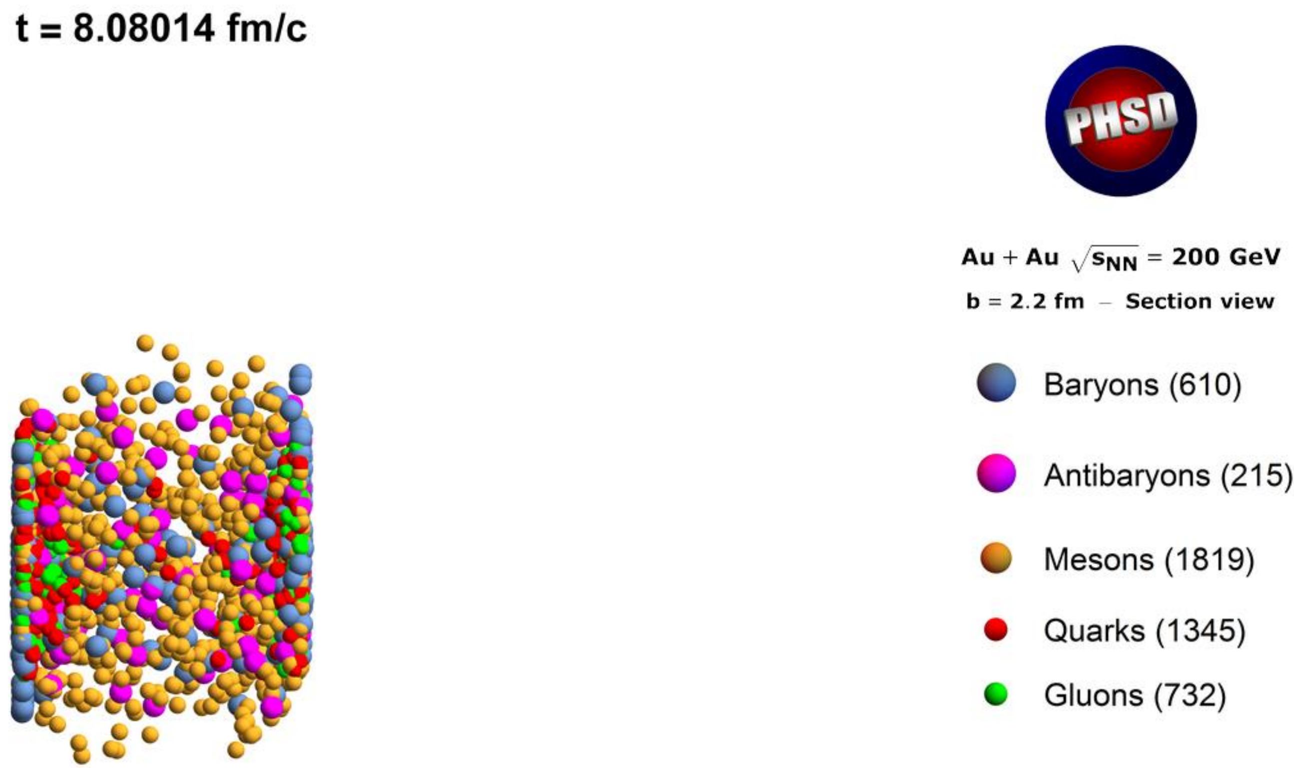

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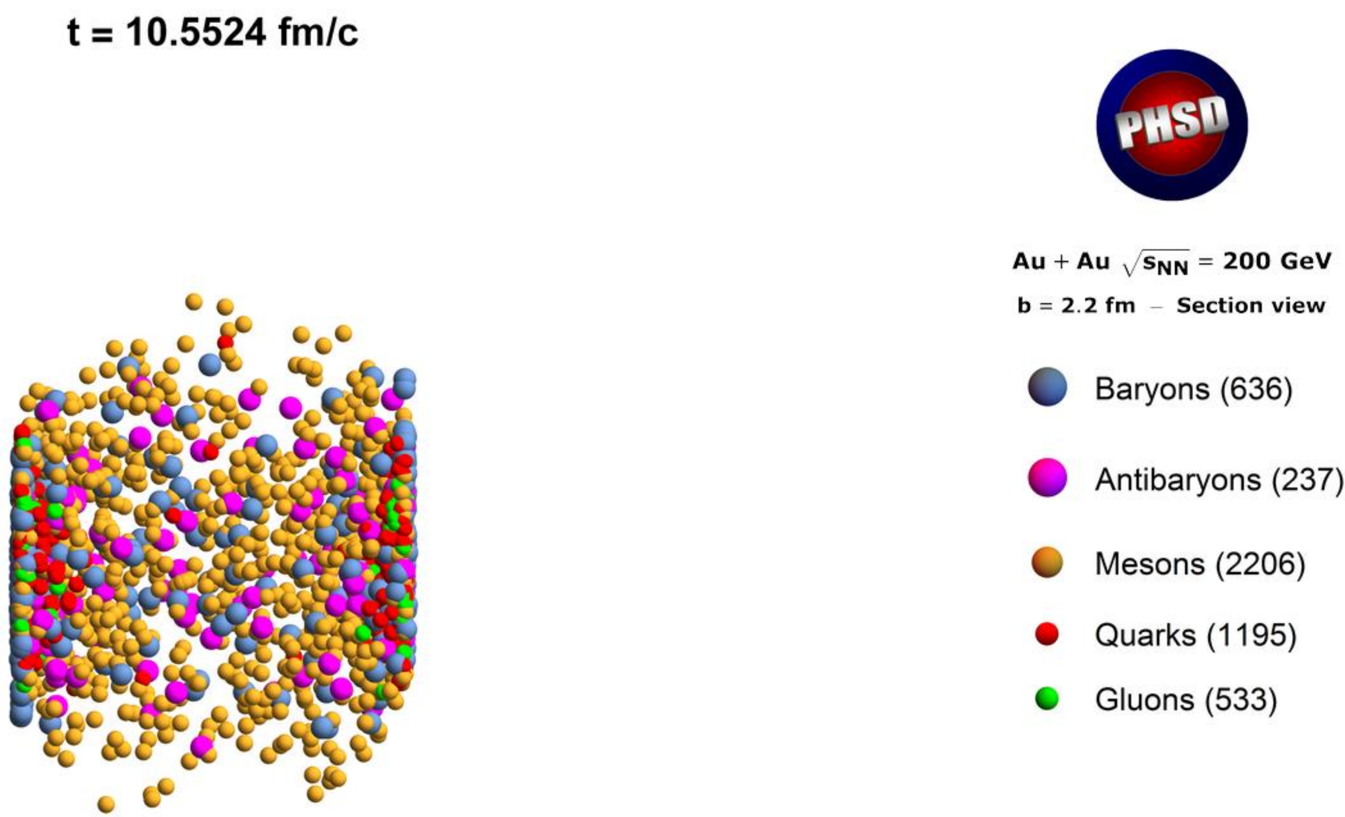

P.Moreau

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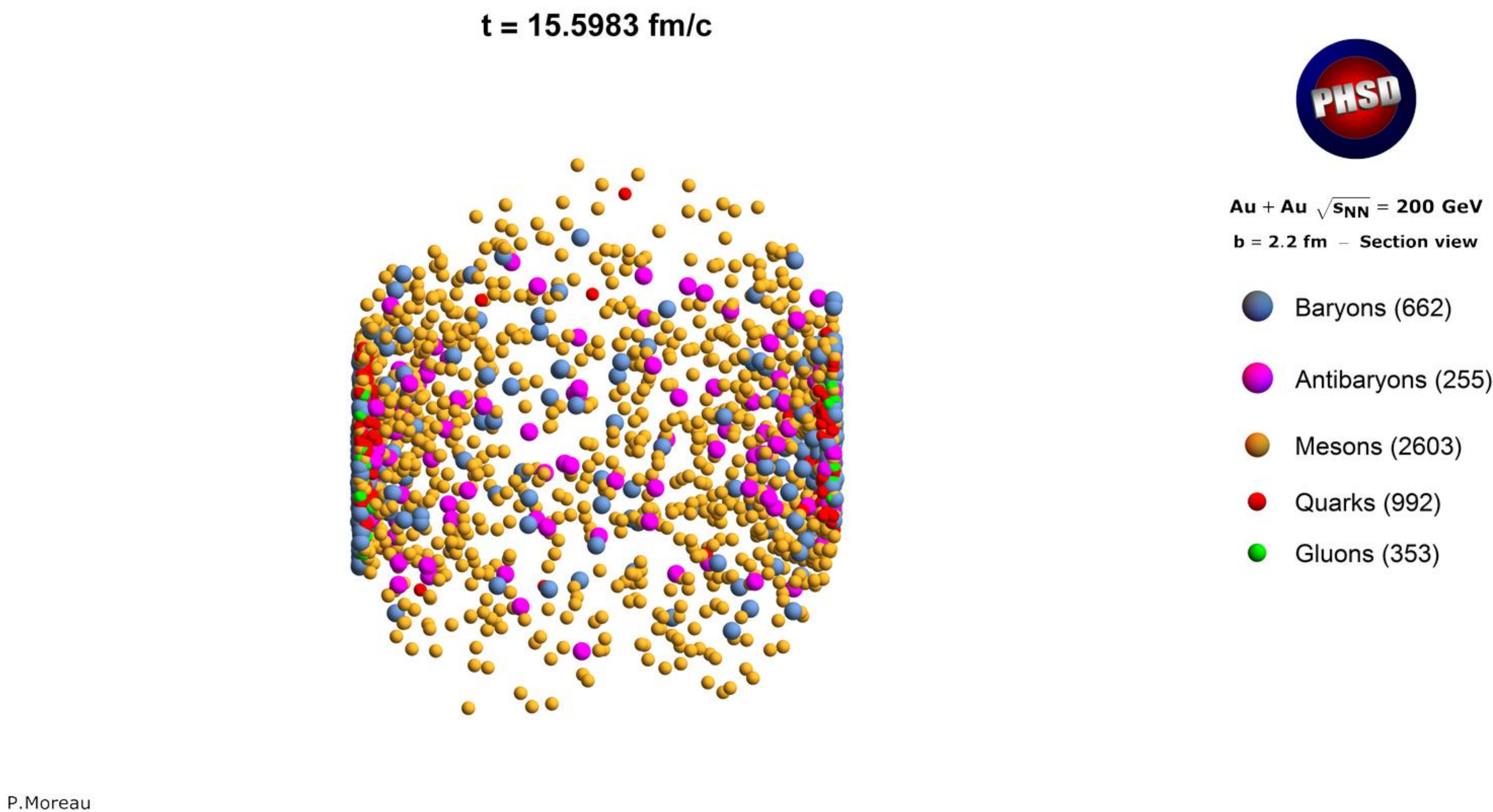

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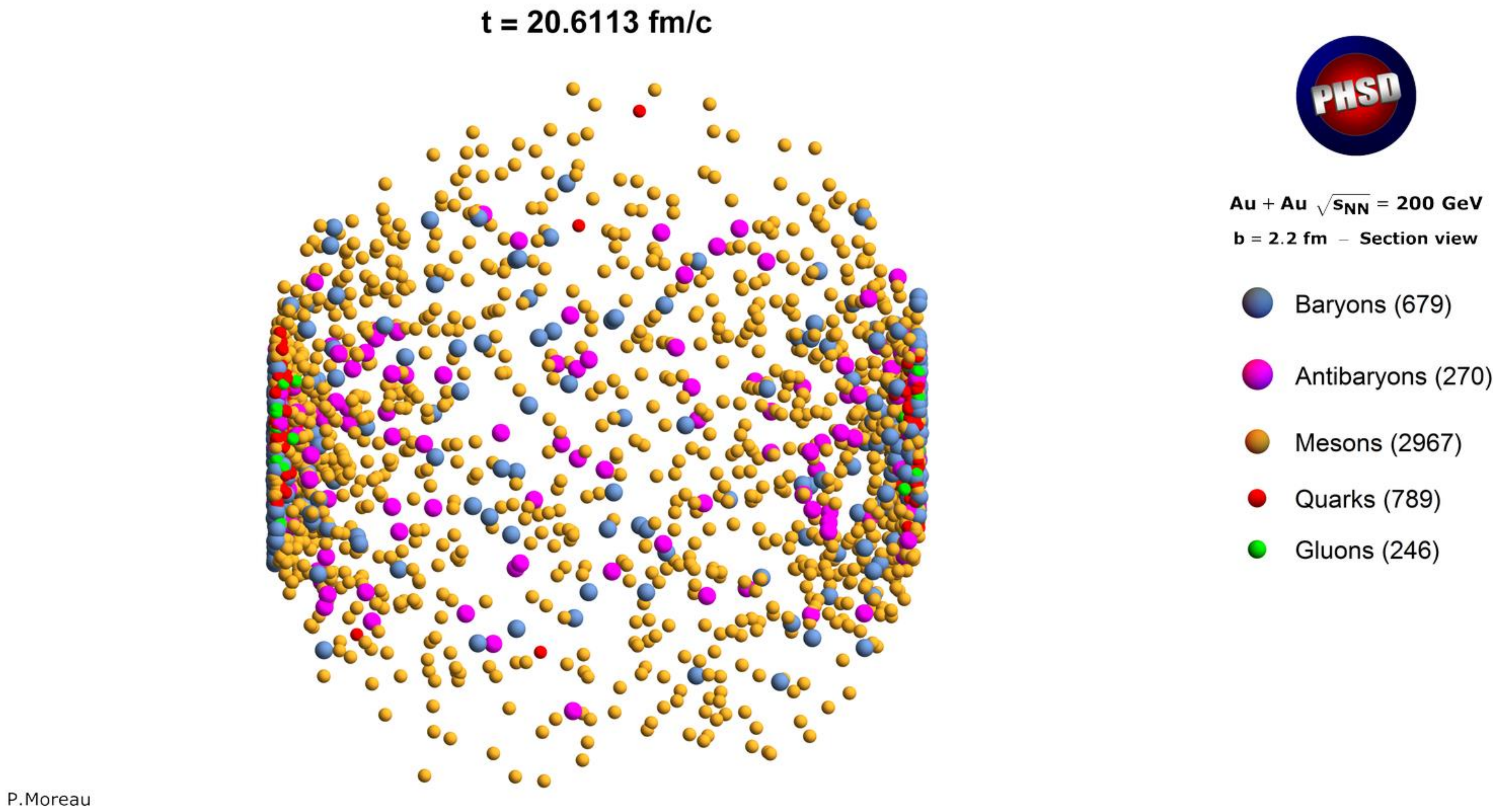


Number of partons as a function of time

- Scenario II (quark IC) is much closer to the standard PHSD because of the large gluon mass:

$$M_g \approx 3/2\, M_q$$

- Scenario I (gluon IC):

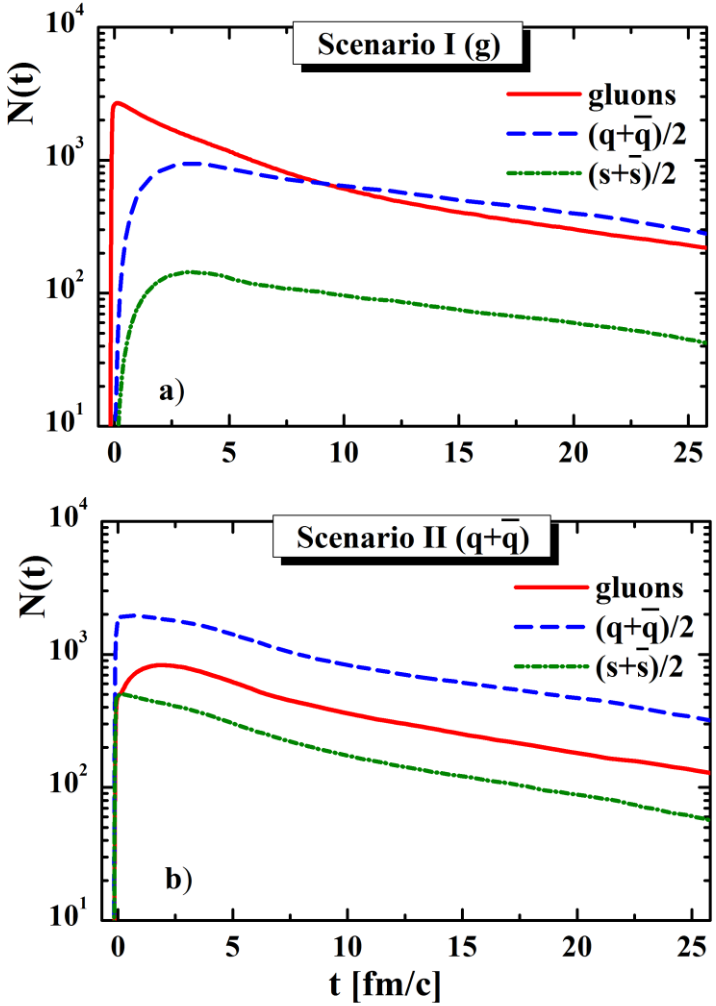
Quarks are produced by the decay of heavy gluons through time

- Scenario II (quark IC):

Quarks are generated by the dissolution of formed hadrons via string decays

Gluons appears by $q+\bar{q}$ annihilation

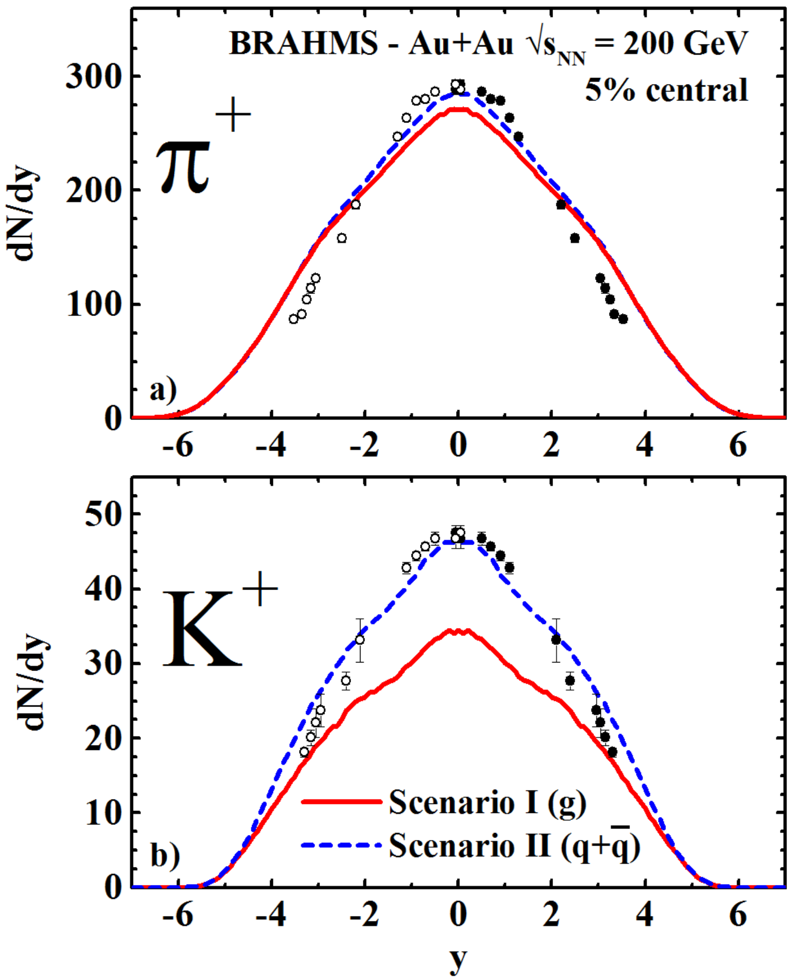
Central Au+Au – Top RHIC



Impact on hadronic observables

- **Strangeness production is clearly underestimated in Scenario II (gluon IC) where the strange quarks are not present in the beginning**

  Equilibration time for strangeness in PHSD is in of the order of 20-30 fm/c



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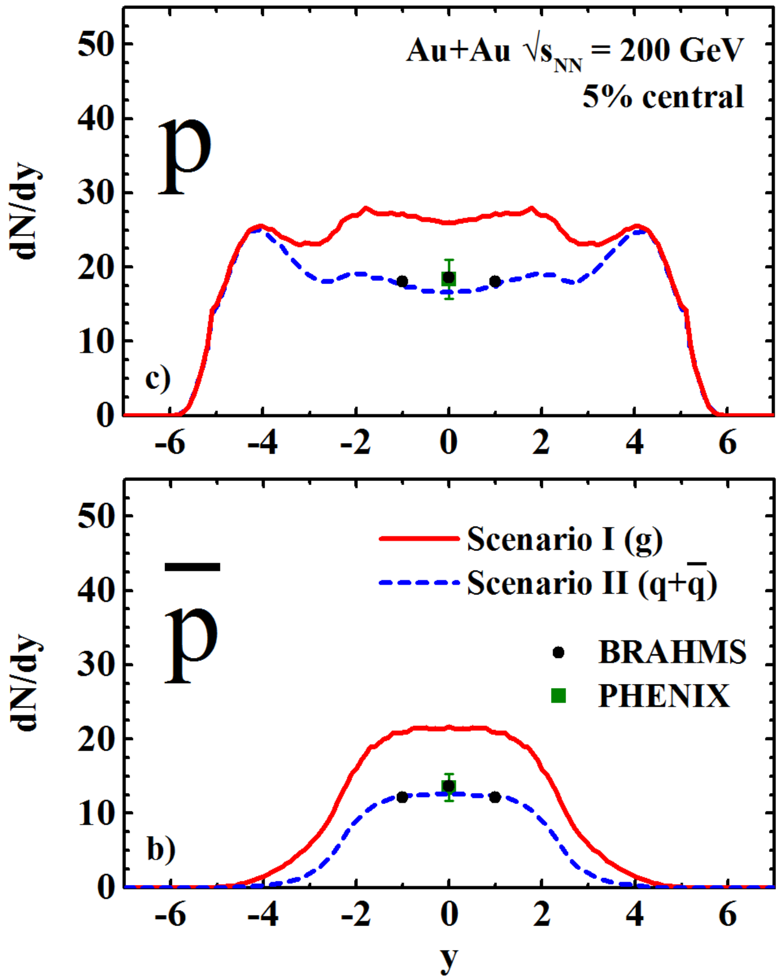

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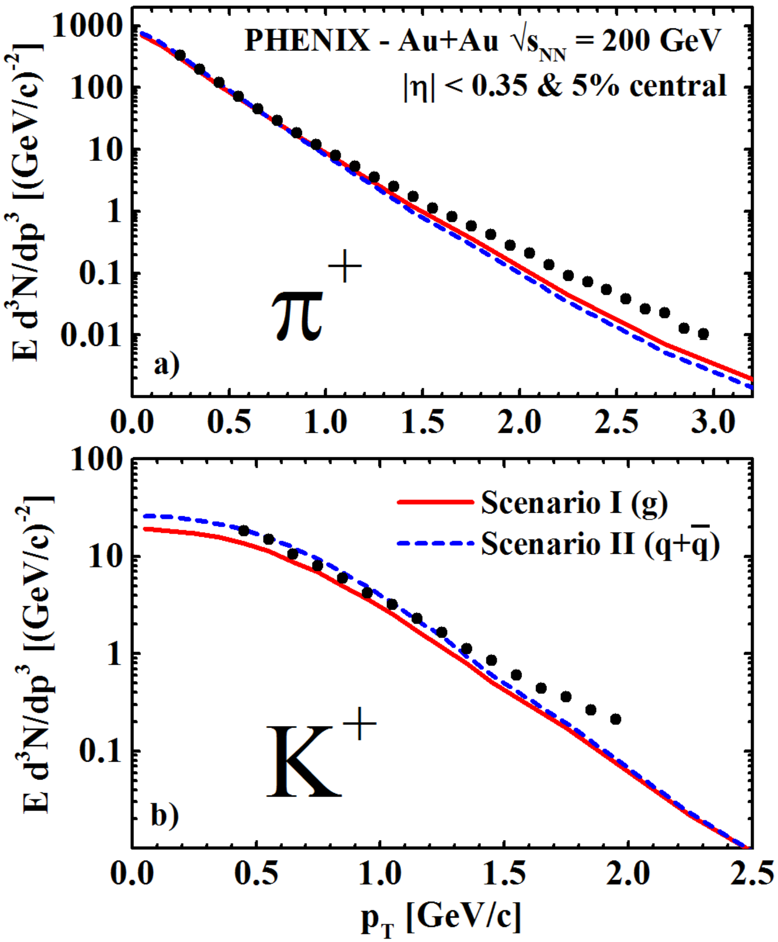

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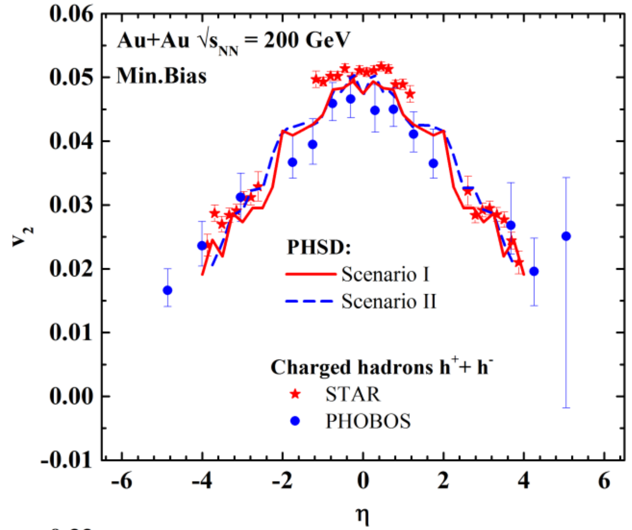
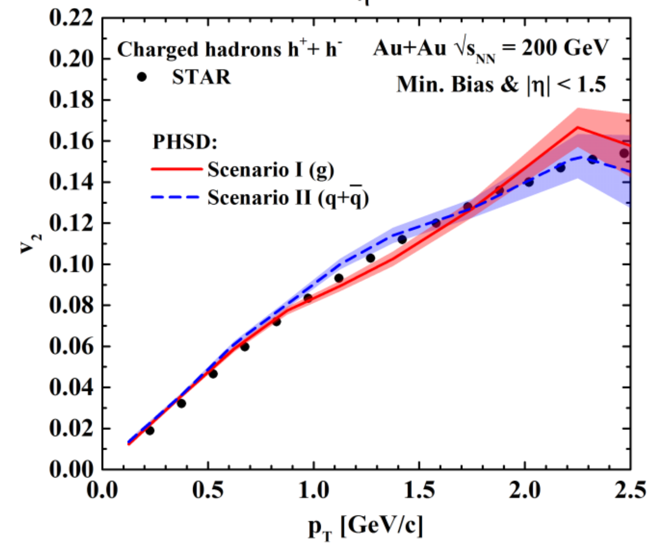
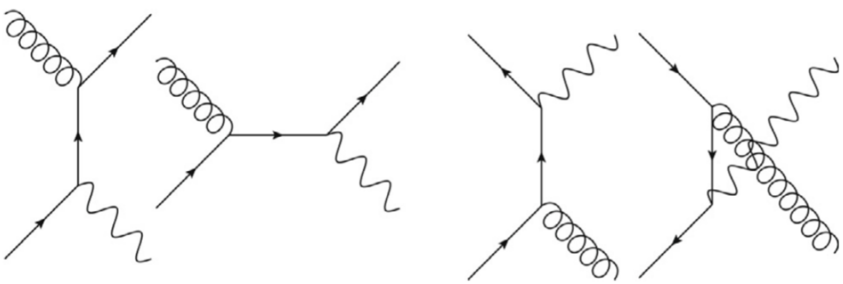




Impact on electromagnetic observables

- **Suppression of energetic photons in scenario I (gluon IC) produced by $q + \overline{q}$ annihilation**



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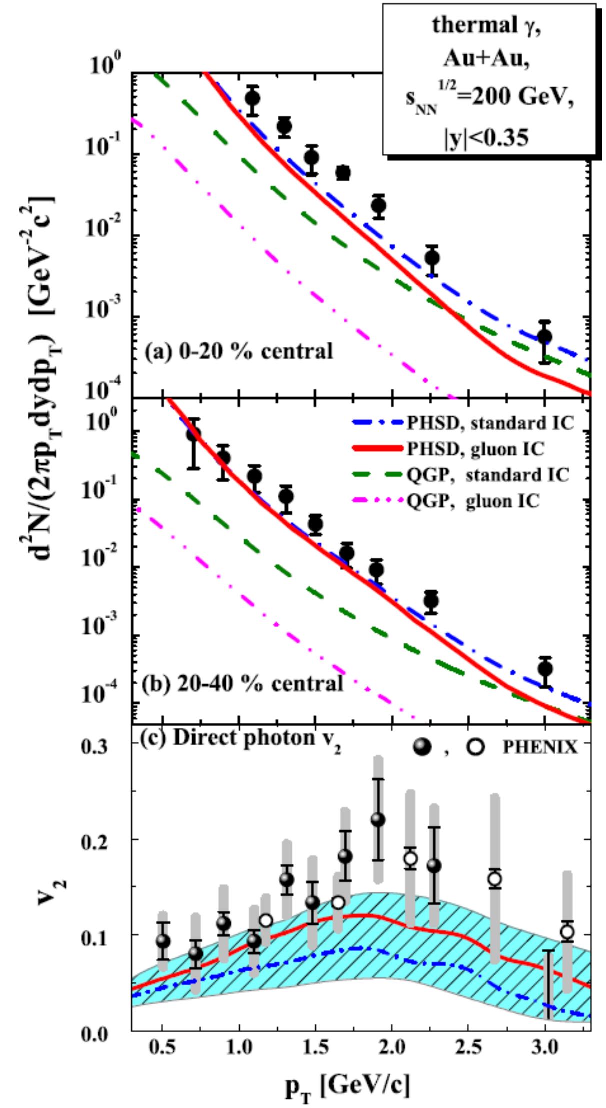
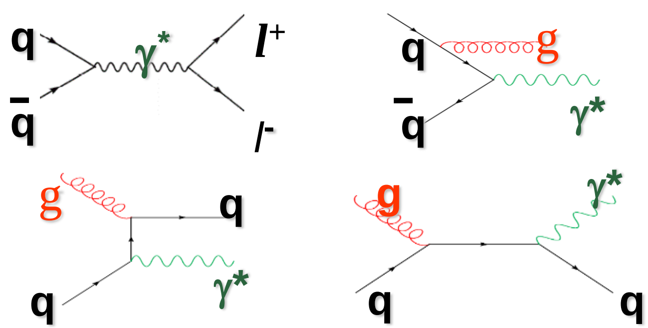


- **Hadronic channels are predominant (mm and mB bremsstrahlung majoritarely)**

- **v_2 in Scenario I (gluon IC) is larger since the photon production is reduced and delayed in QGP**

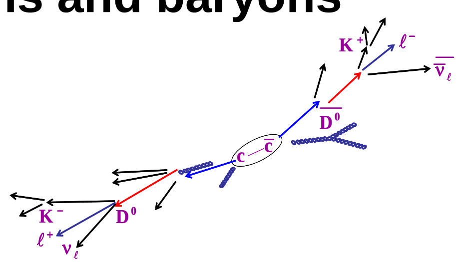
Impact on electromagnetic observables

- **Suppression of dileptons in scenario I (gluon IC) produced by $q + \overline{q}$ annihilation**



Hadronic sources:

- **Direct decay of vector mesons (ρ,ω,ϕ,J/Ψ,Ψ')**
- **Dalitz decay of mesons and baryons (π^0,η, Δ,…)**
- **Correlated $D\overline{D}$ pairs**
- **Drell-Yan process**



Dileption mass spectra