(ANTI-)STRANGENESS PRODUCTION IN HEAVY ION COLLISIONS

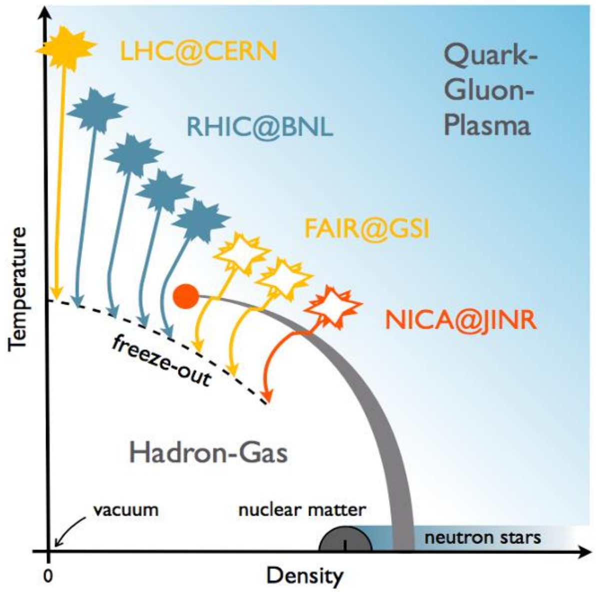
Pierre Moreau

for the PHSD group

Strangeness in Quark Matter 2015, Russia

DUBNA 2015

From NICA to LHC, passing by FAIR 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

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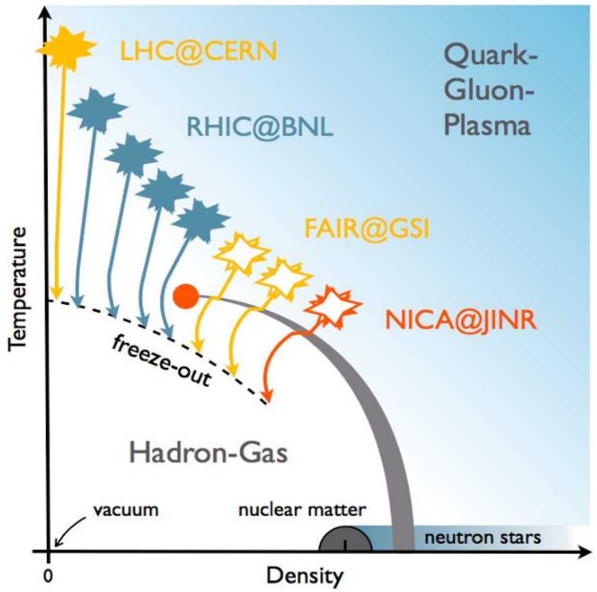
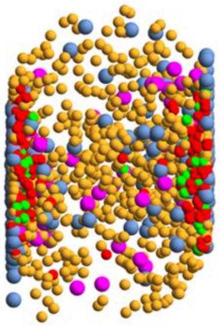


- Explore the QCD phase diagram and properties of hadrons at high temperature or high baryon density
- Phase transition from hadronic to partonic matter
- Goal: Study the properties of strongly interacting matter under extreme conditions from a microscopic point of view
- Realization: dynamical many-body transport approach



- 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

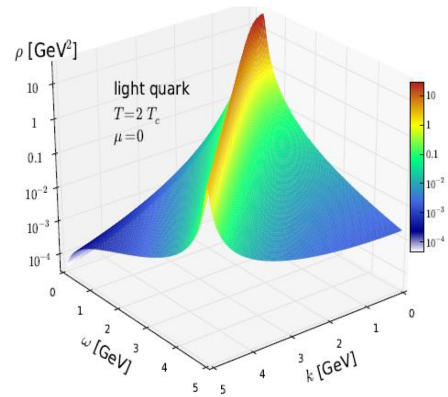
Parton-Hadron-String-Dynamics (PHSD)

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

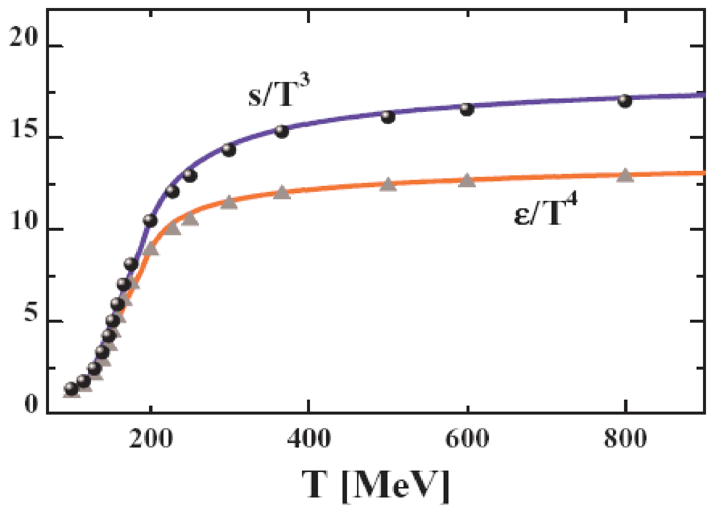
Dynamical Quasi-Particle Model (DQPM)

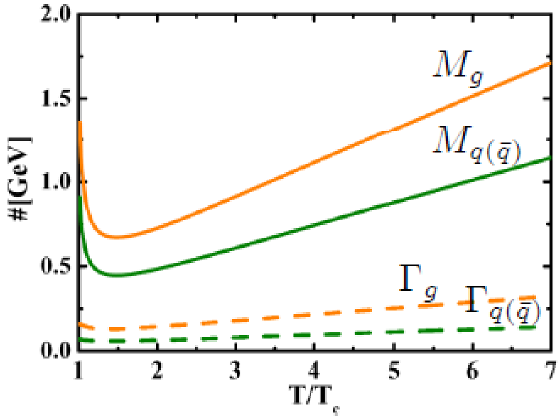
- The QGP phase is described in terms of interacting quasiparticles with Lorentzian spectral functions:

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



- Properties of quasiparticles are fitted to the lattice QCD results:



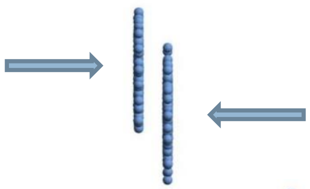


- Masses and widths of partons depend on the temperature of the medium

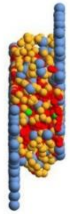
Peshier, Cassing, PRL 94 (2005) 172301; Cassing, NPA 791 (2007) 365: NPA 793 (2007)

Stages of a collision in PHSD

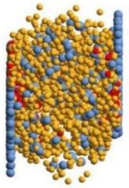
Initial A+A collision



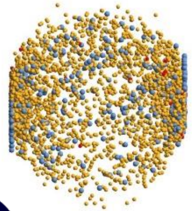
Partonic phase



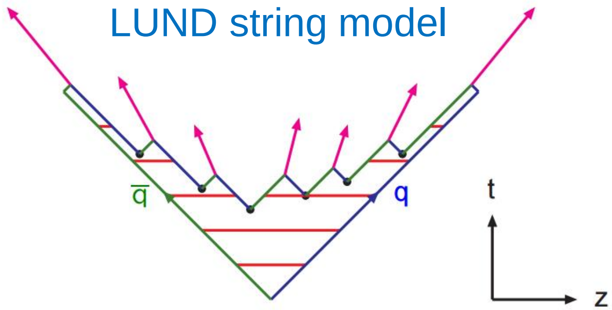
Hadronization



Hadronic phase



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



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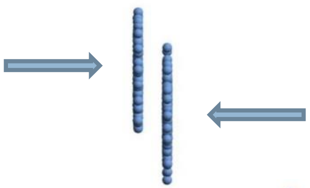

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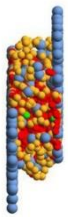

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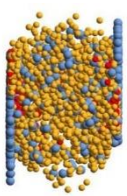

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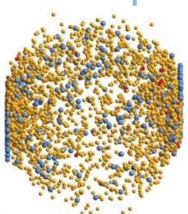

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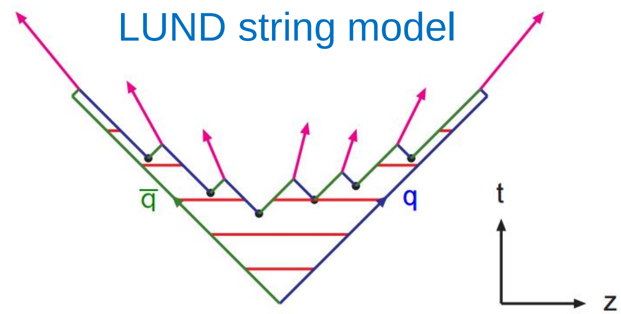

- Formation of a QGP state if $\epsilon > \epsilon_C = 0.5\ \mathrm{GeV.fm}^{-3}$
- Dissolution of new produced secondary hadrons into massive colored quarks and mean-field energy

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

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

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

$$m_q(\epsilon) \qquad \Gamma_q(\epsilon) \qquad U_q(\epsilon)$$

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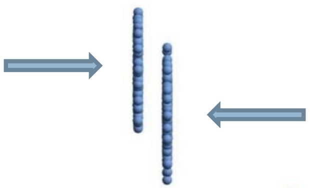

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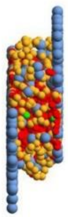

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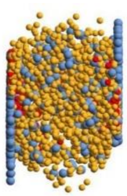

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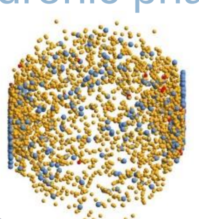
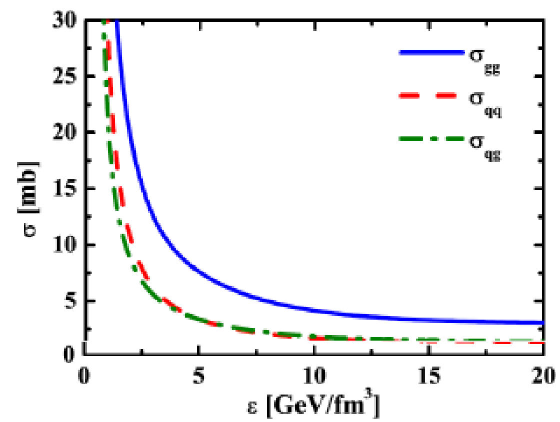


- Propagation of partons, considered as dynamical quasiparticles, in a self-generated mean-field potential from the DQPM
- EoS of partonic phase: ‚crossover' from Lattice QCD fitted by DQPM
- (quasi-)elastic collisions :

$$
\begin{array}{ll}
q+q \to q+q & g+q \to g+q \\
q+\bar{q} \to q+\bar{q} & g+\bar{q} \to g+\bar{q} \\
\bar{q}+\bar{q} \to \bar{q}+\bar{q} & g+g \to g+g
\end{array}
$$



- inelastic collisions :

$$
\begin{array}{ll}
q+\bar{q} \to g & \cancel{q+\bar{q} \to g+g} \\
g \to q+\bar{q} & \cancel{g \to g+g}
\end{array}
\Bigg\}
$$

Suppressed due to the large gluon mass

Stages of a collision in PHSD

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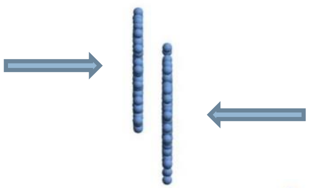

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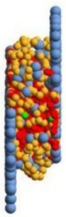

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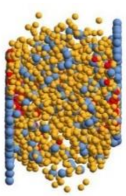

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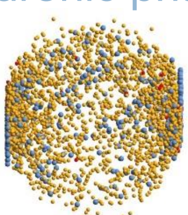
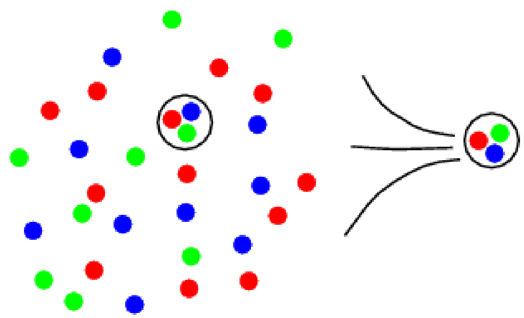


- Massive and off-shell (anti-)quarks hadronize to colorless off-shell mesons and baryons



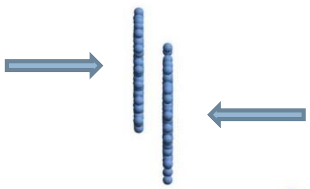
$$g \to q + \bar{q}, \qquad q + \bar{q} \leftrightarrow meson \ ('string') $$

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

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

Stages of a collision in PHSD

Initial A+A collision



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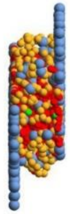

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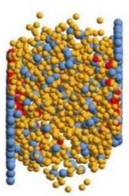

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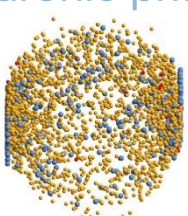

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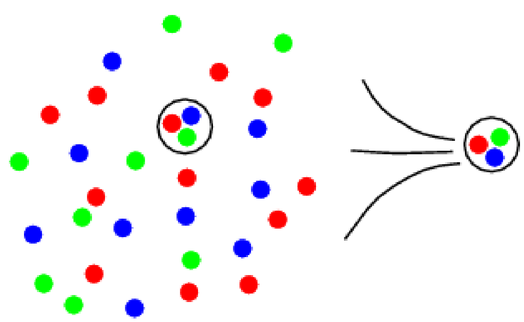

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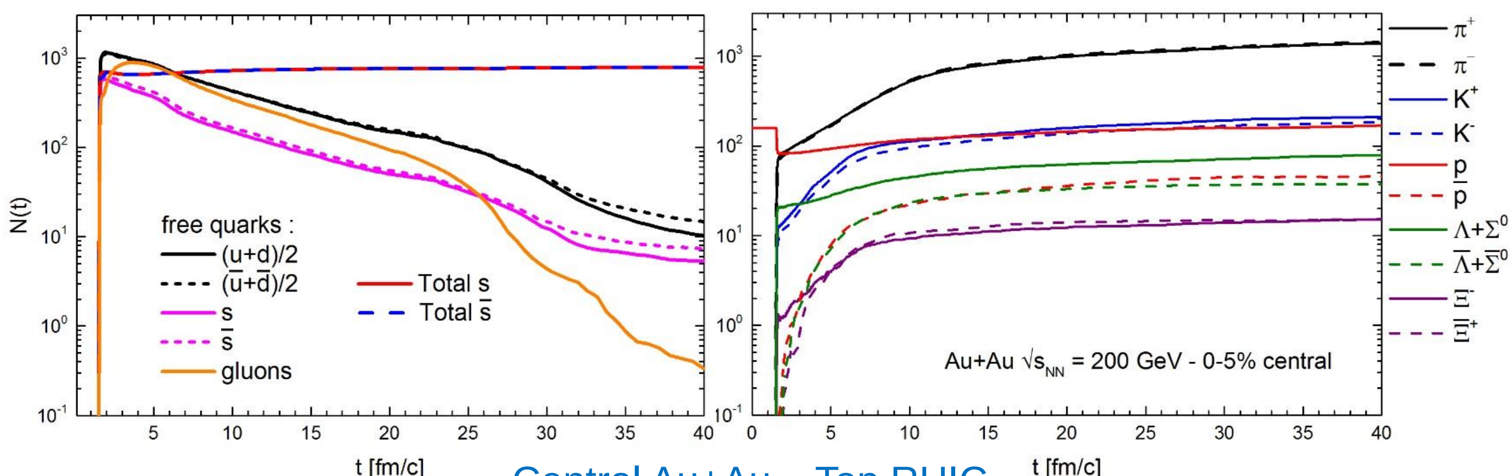
Number of partons and hadrons as a function of time:



Central Au+Au – Top RHIC

Stages of a collision in PHSD

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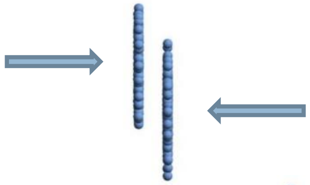

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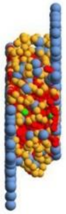

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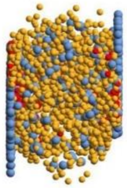

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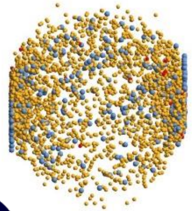
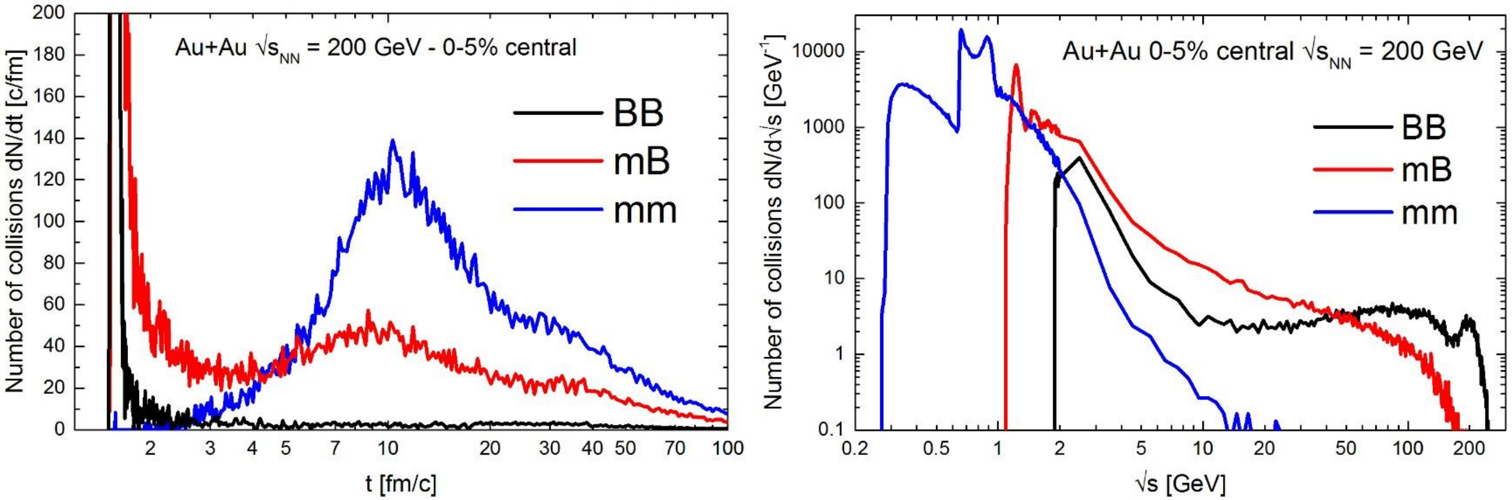


- Hadron-string interactions – off-shell HSD
  - Elastic and inelastic collisions between baryons (B), mesons (m) and resonances (R)

Distribution of hadron collisions as a function of time and collisional energy:



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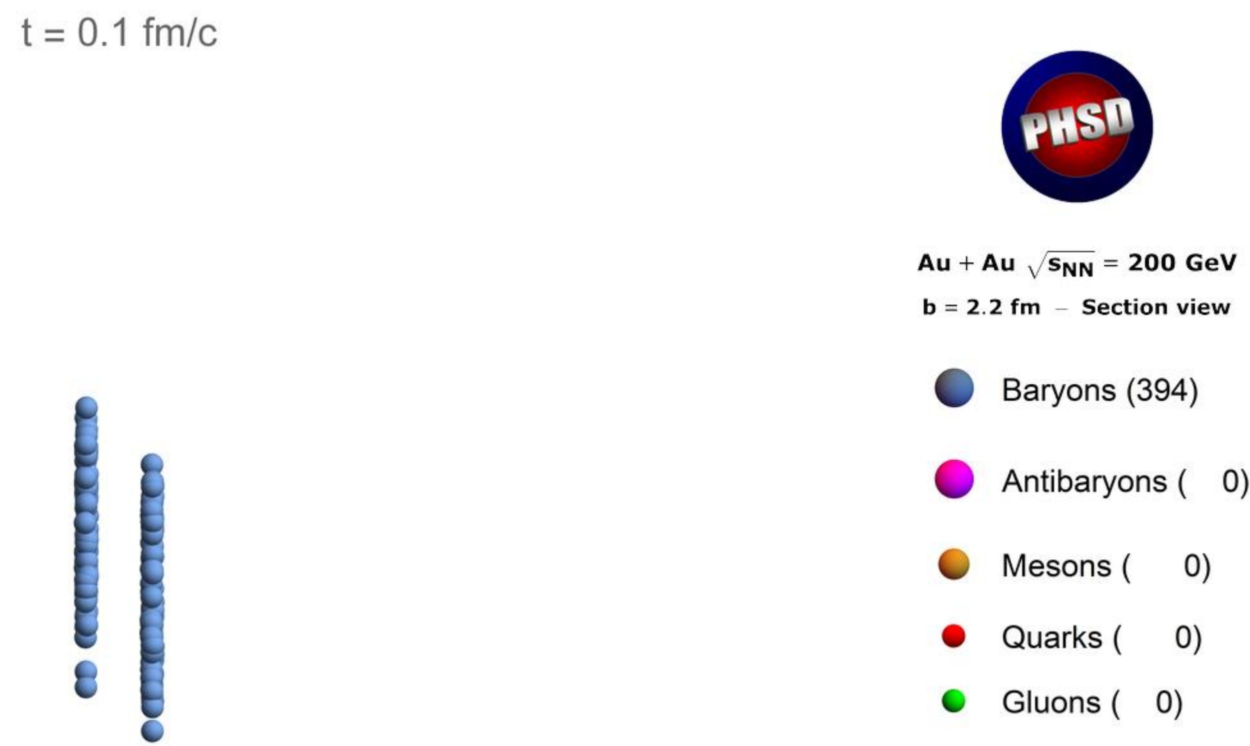
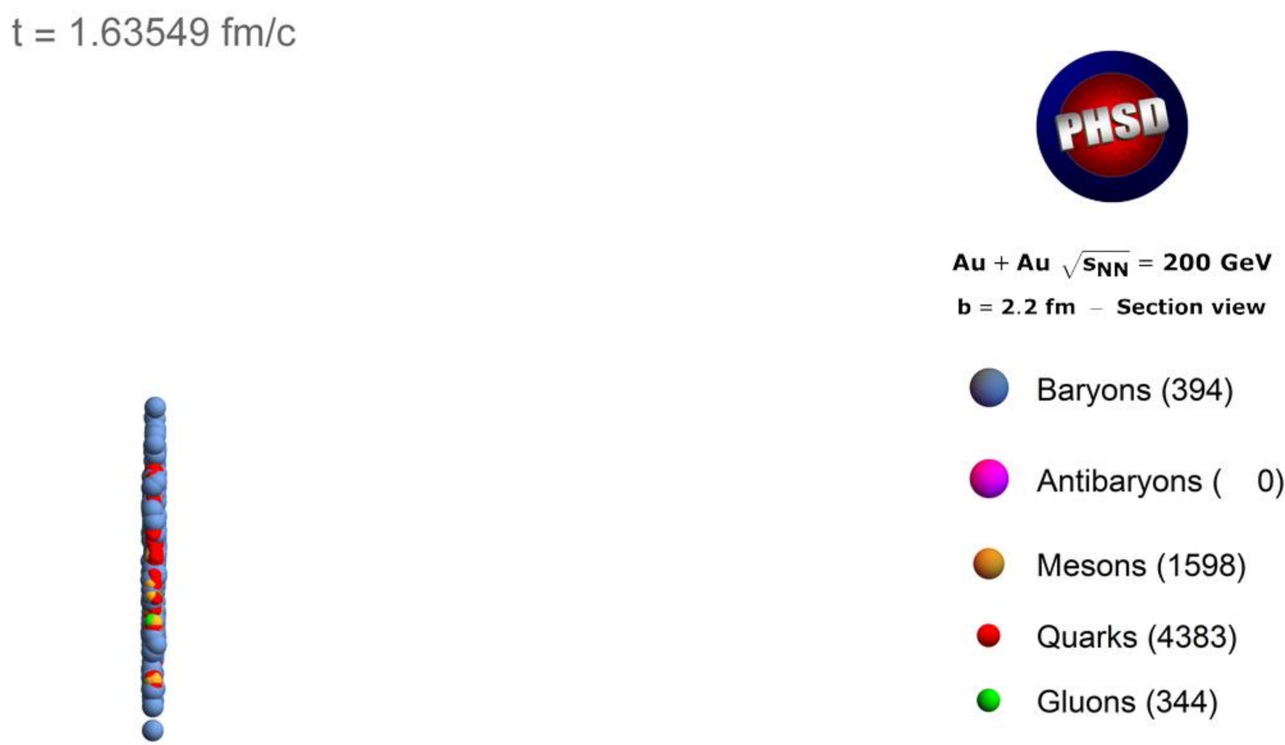


P.Moreau

Stages of a collision in PHSD



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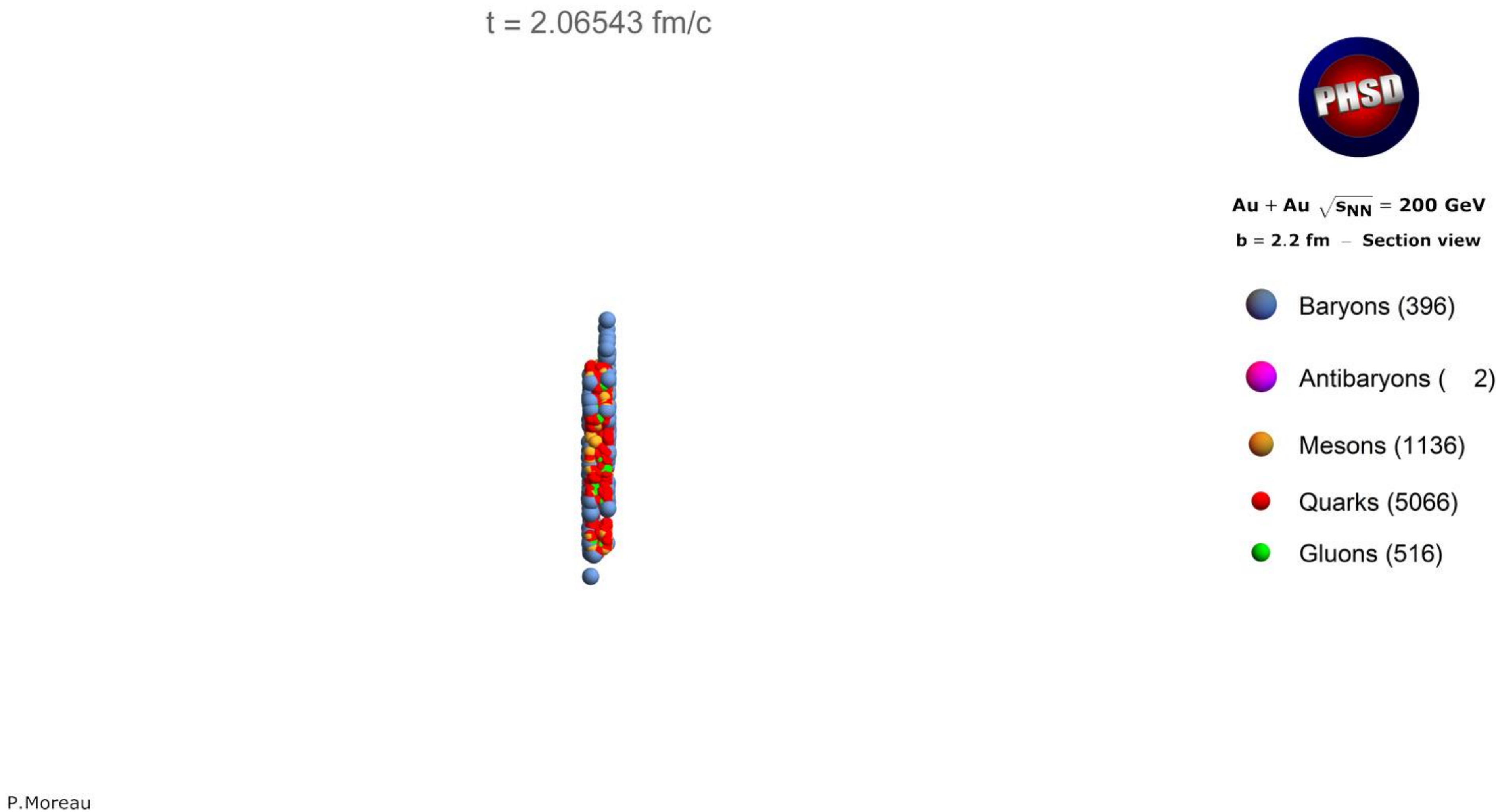

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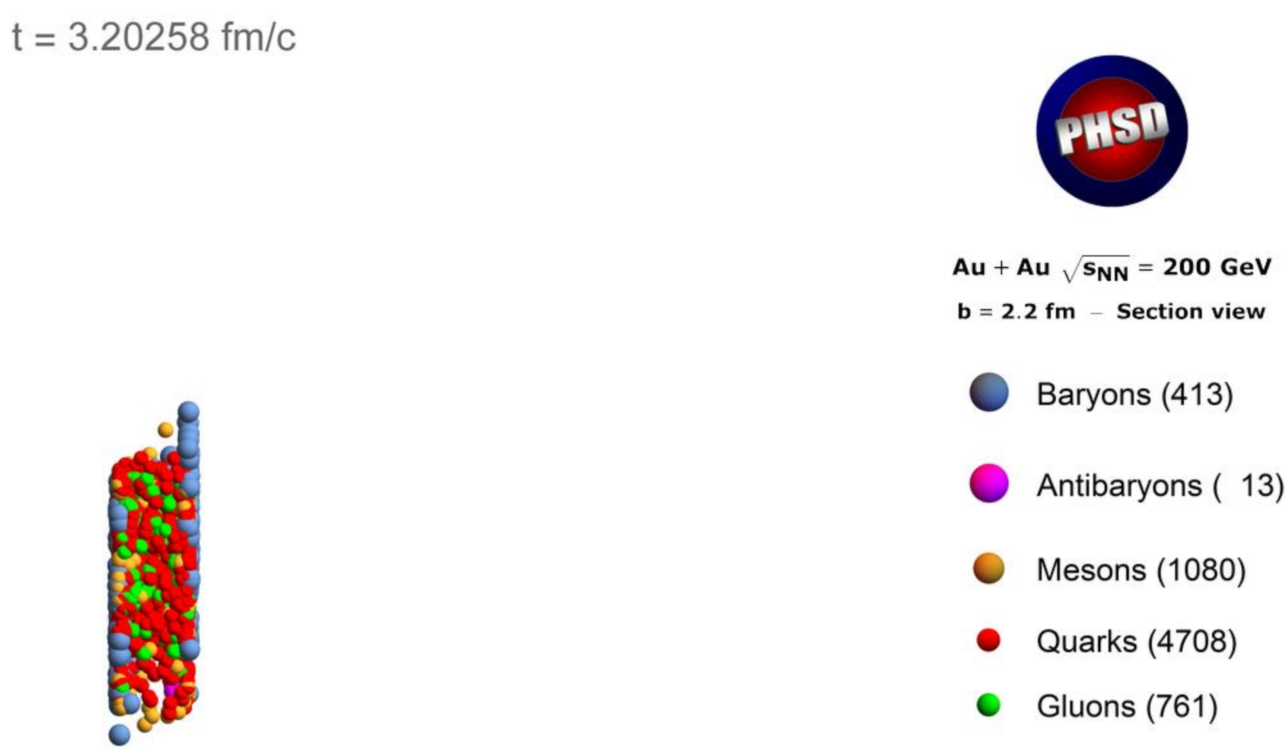

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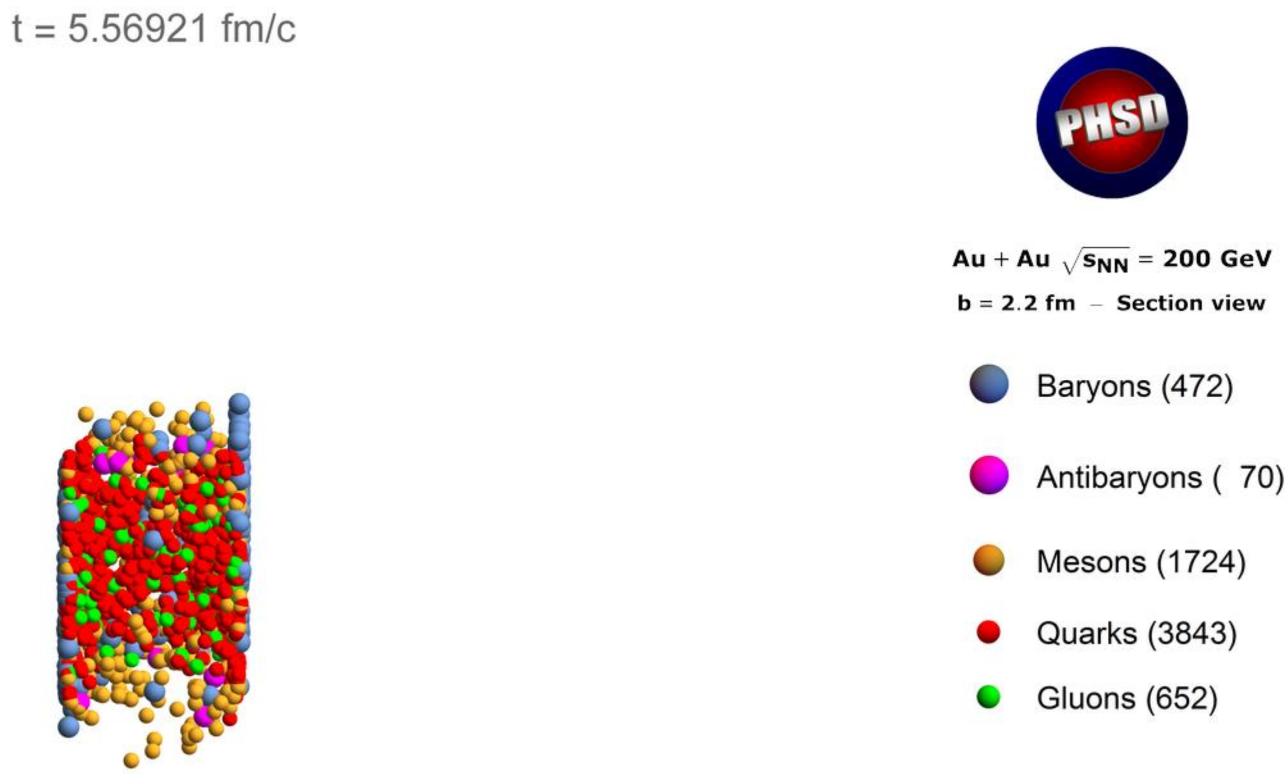

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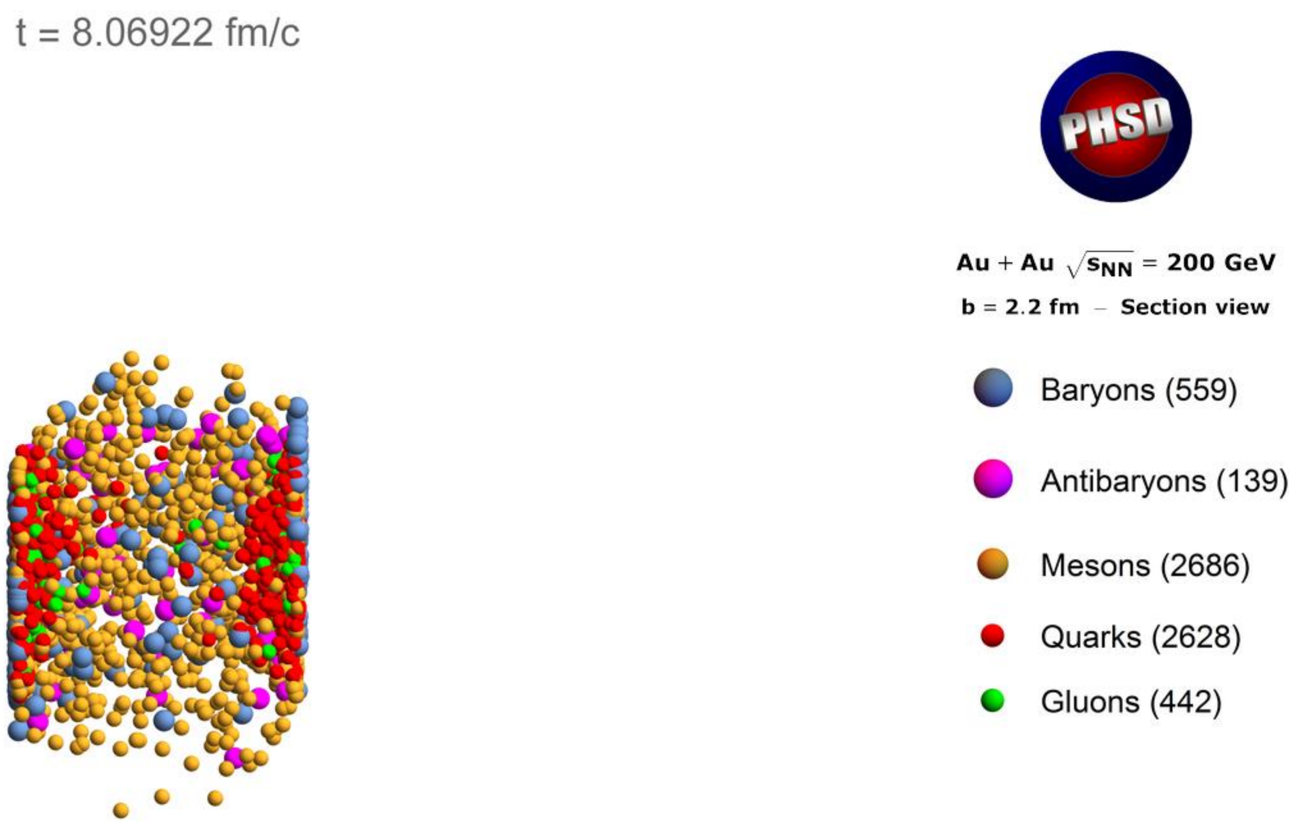

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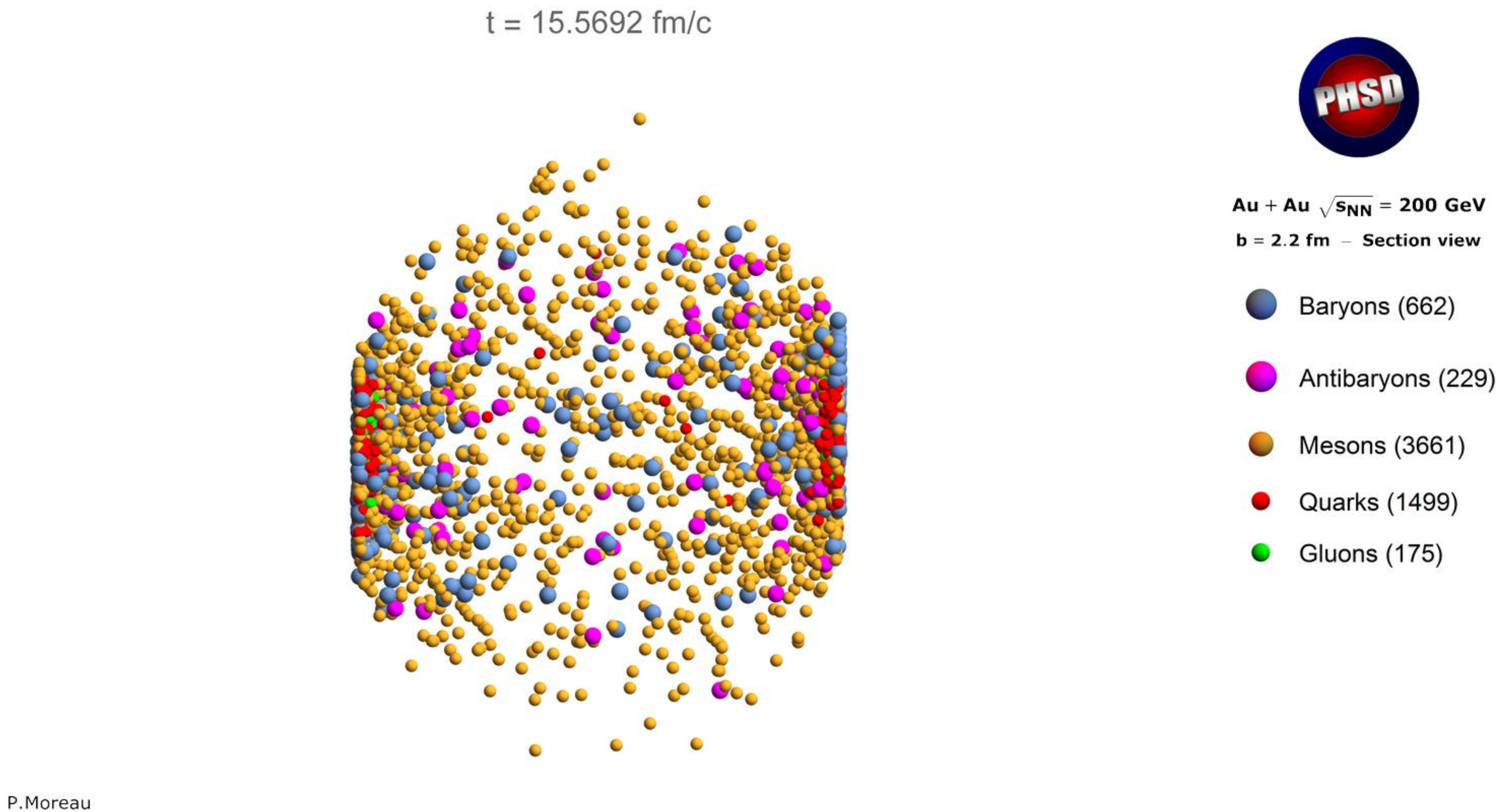

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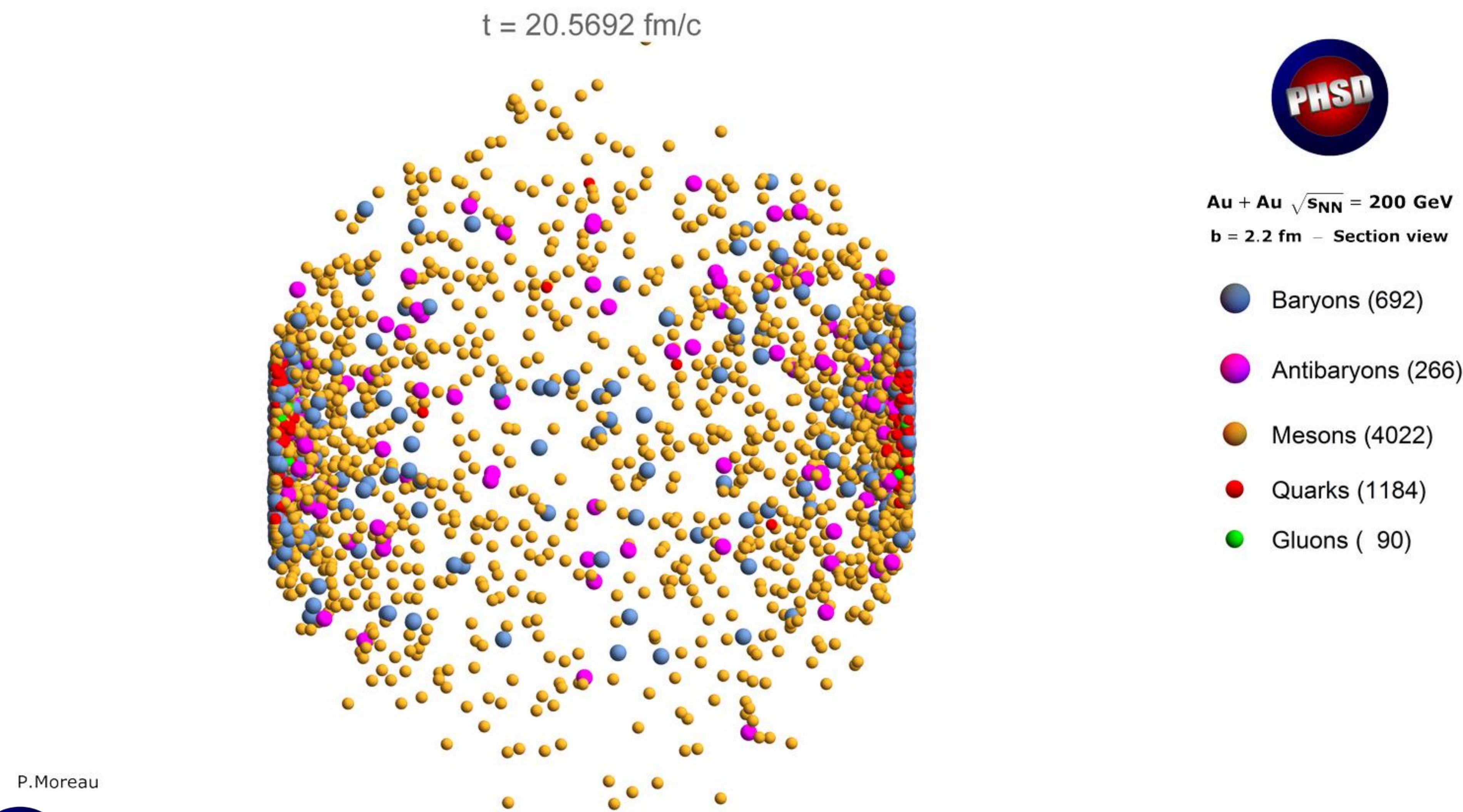
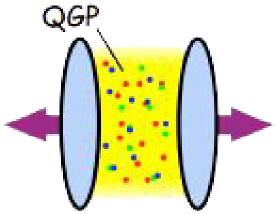
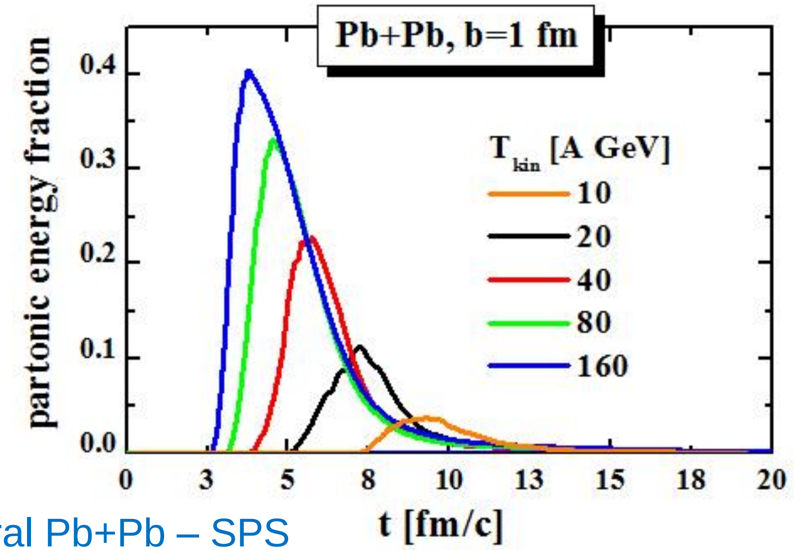


Partonic energy fraction in central A+A

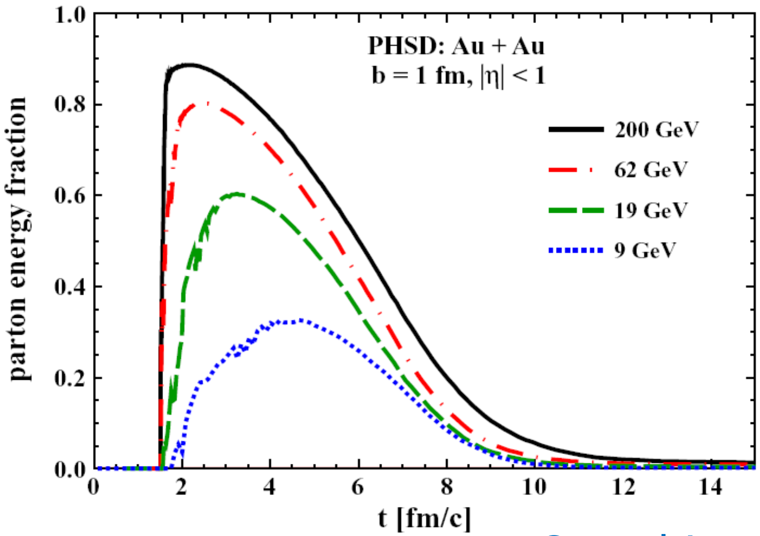
- At SPS, only a small part of the initial energy is converted into the QGP phase
- At top RHIC energies, the QGP phase at midrapidity contains roughly 90% of the energy



Time evolution of the partonic energy fraction for different energies:



Central Pb+Pb – SPS

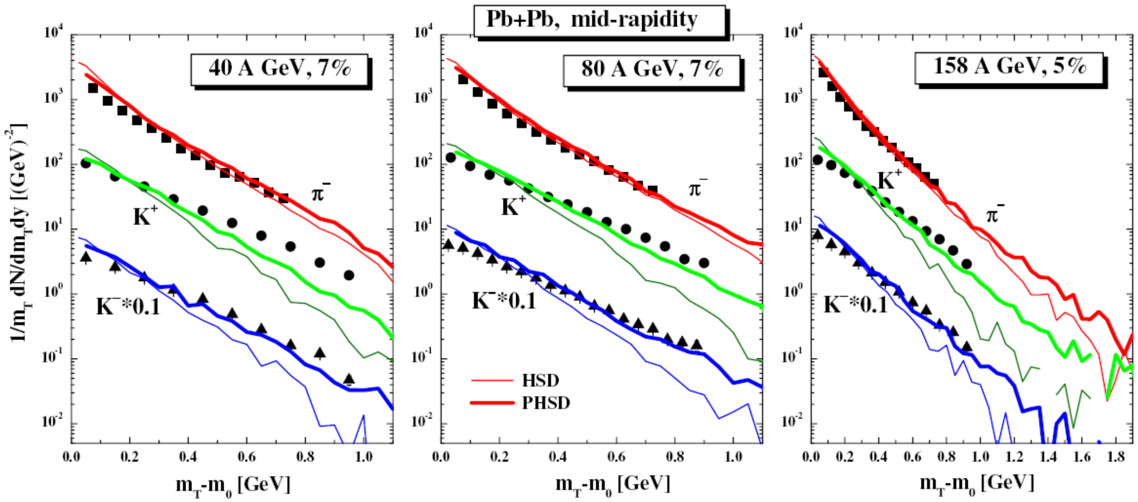


Central Au+Au

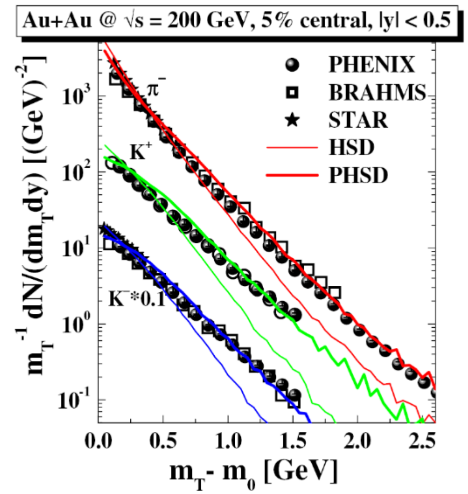
Transverse mass spectra (PHSD – HSD)

- 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



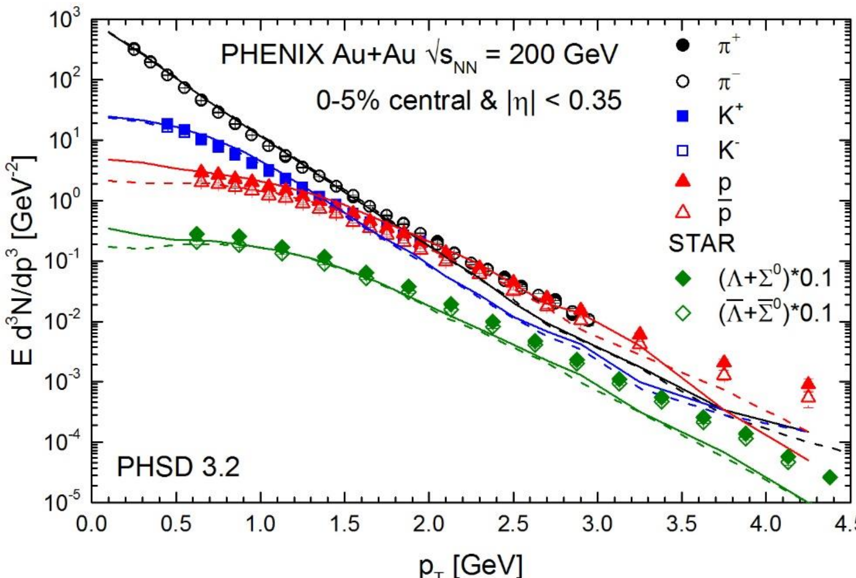
Central Au+Au – RHIC

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

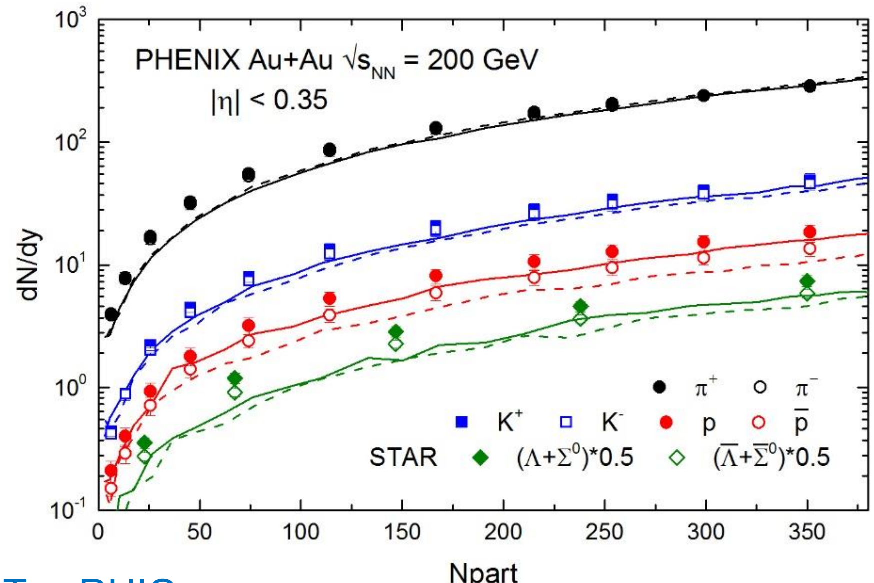
Au-Au at Top RHIC energies

- At high energies, particles and antiparticles are produced in quasi-equal quantities at midrapidity whatever the centrality of the collision
- Anti-baryon absorption at low pT is visible

pT spectra:



Production at midrapidity dN/dy:



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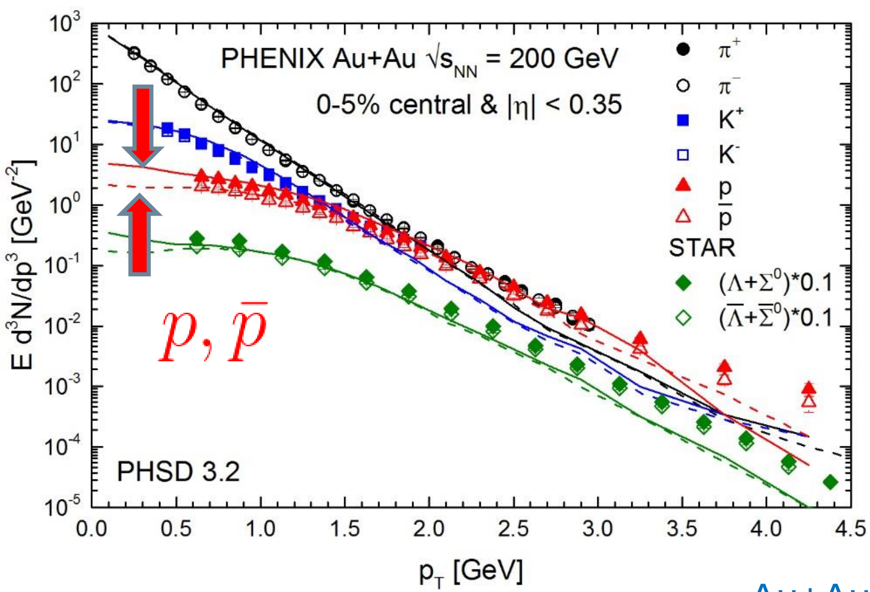

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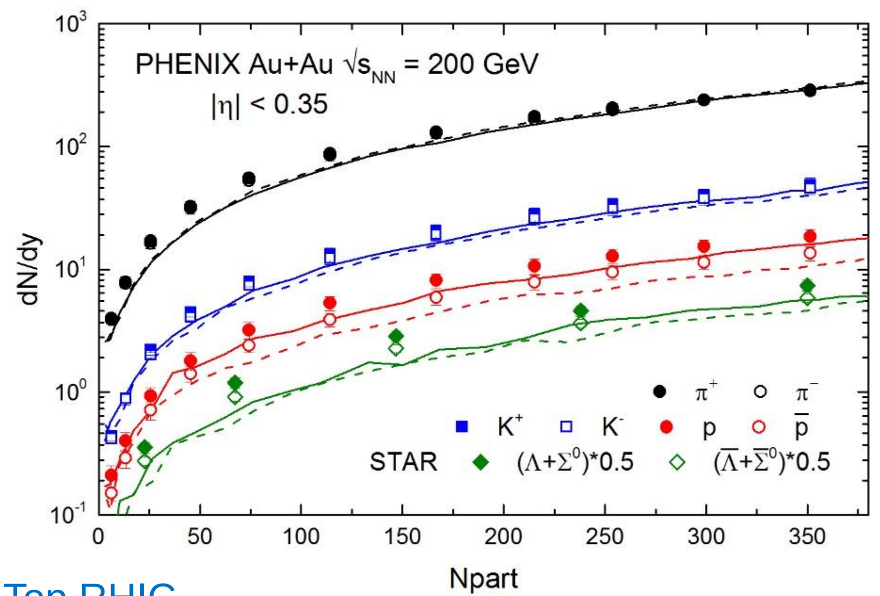
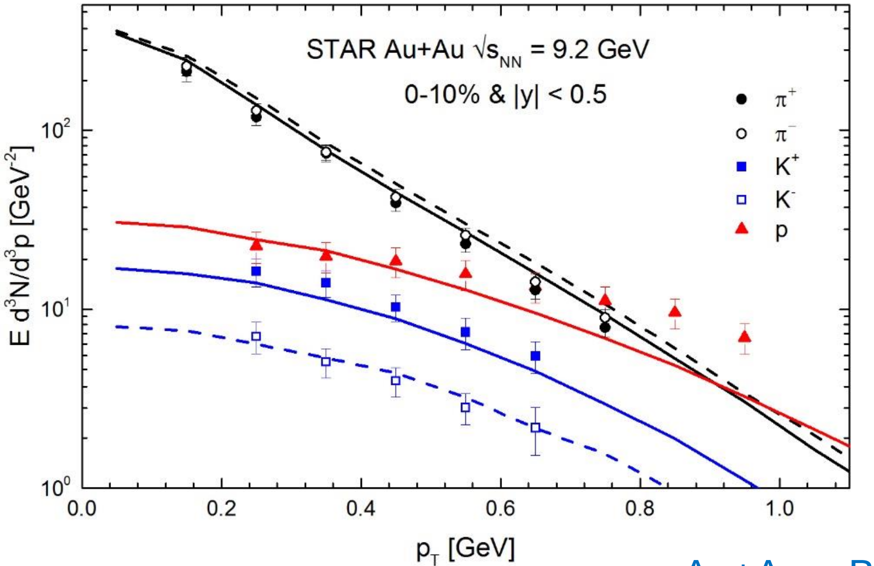


Au+Au – Top RHIC

Au-Au at BES @ RHIC energies

- At low energies, a clear difference appears between the production of particles and antiparticles, and also between positively and negatively charged mesons

pT spectra:



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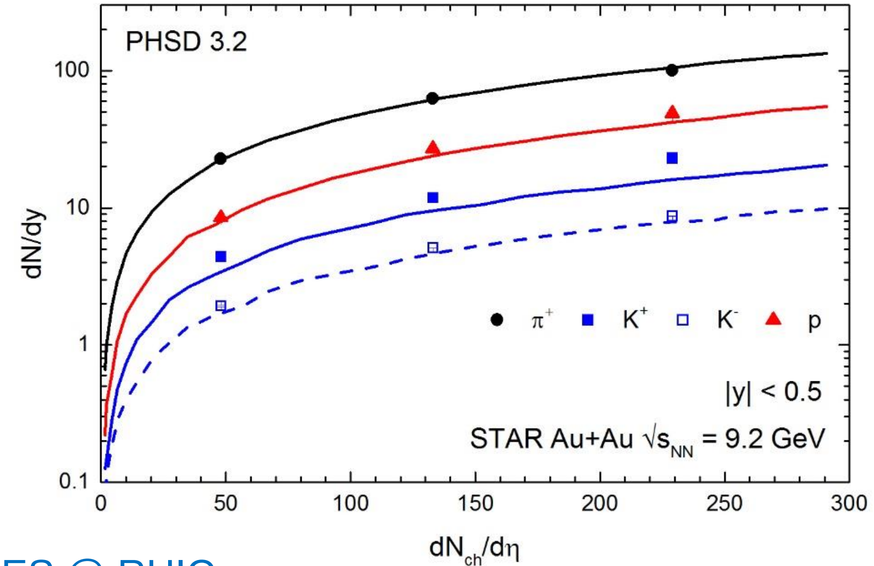
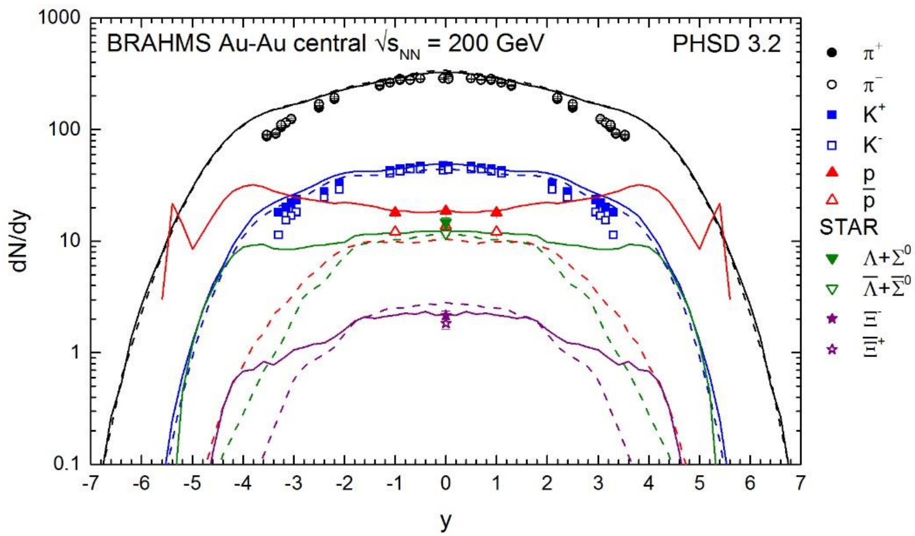


Au+Au – BES @ RHIC

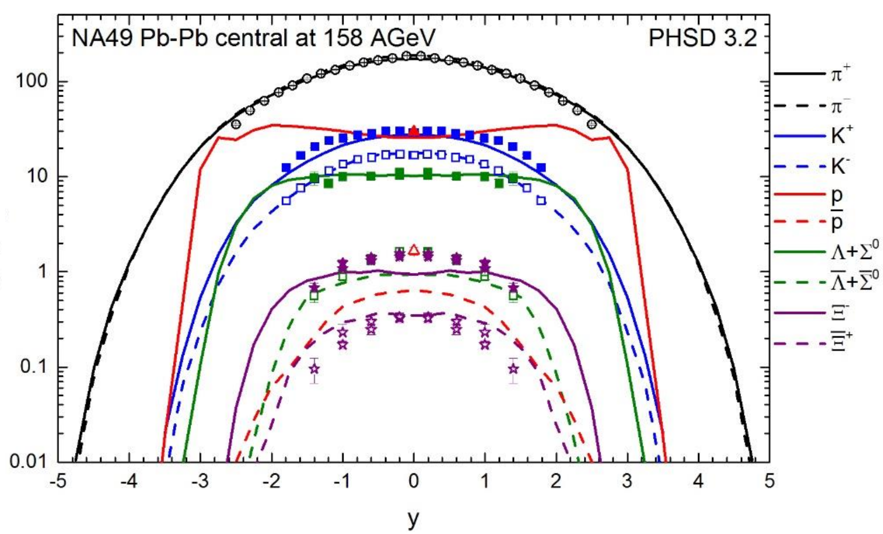
Rapidity spectra

- At high energies, the hadrons produced at midrapidity come mostly from the QGP phase
- At high rapidity, particles are more produced than antiparticles due to the high baryon density
- At low energies, the stopping of initial nucleons induces a high baryon density even at midrapidty which favors the production of baryons compared to antibaryons

Rapidity spectras:



Central Au+Au – Top RHIC



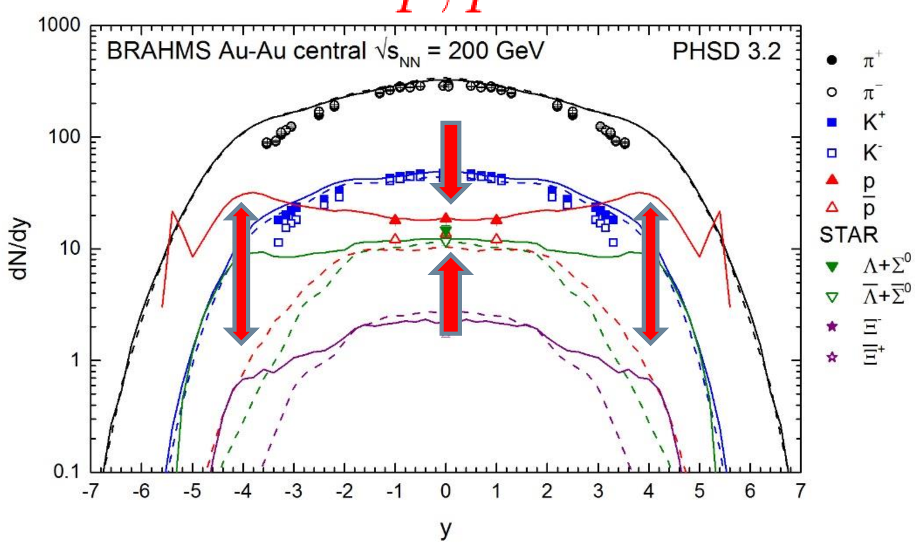
Central Pb+Pb – Top SPS

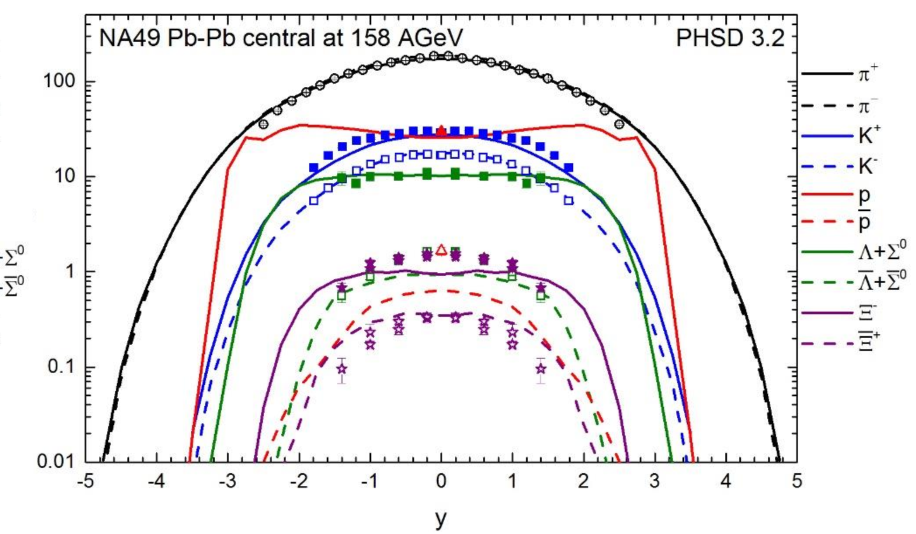
Rapidity spectra

- At high energies, the hadrons produced at midrapidity come mostly from the QGP phase
- At high rapidity, particles are more produced than antiparticles due to the high baryon density
- At low energies, the stopping of initial nucleons induces a high baryon density even at midrapidty which favors the production of baryons compared to antibaryons

Rapidity spectras:

$p, \bar{p}$





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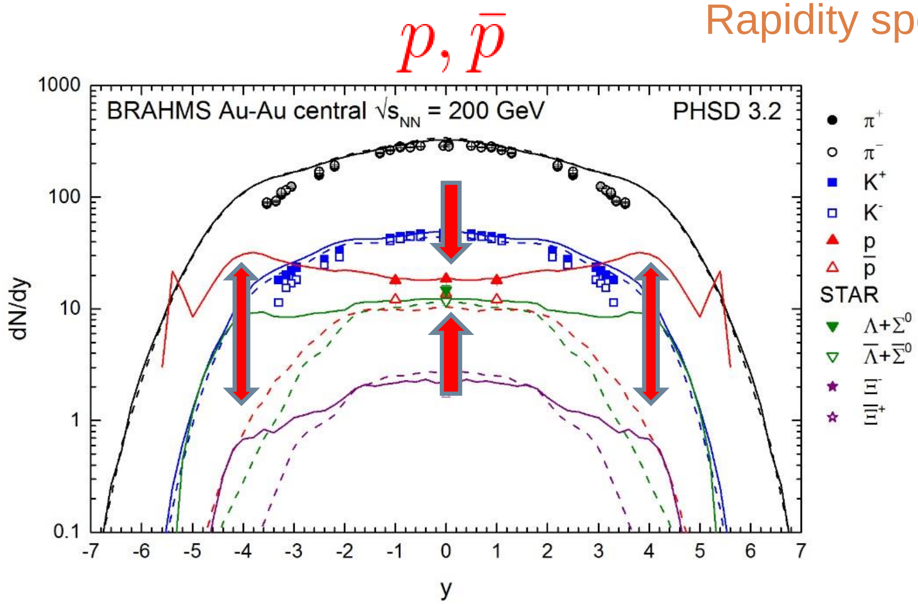

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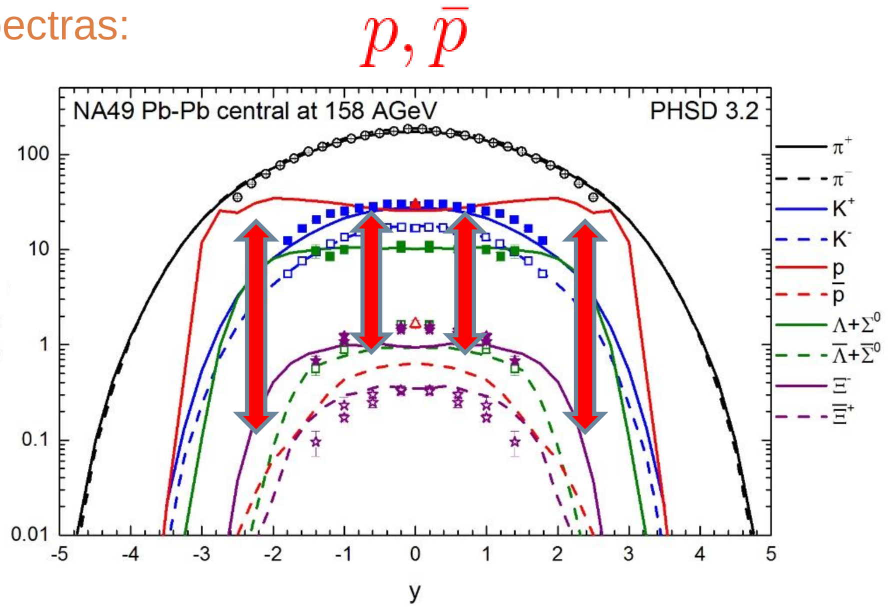

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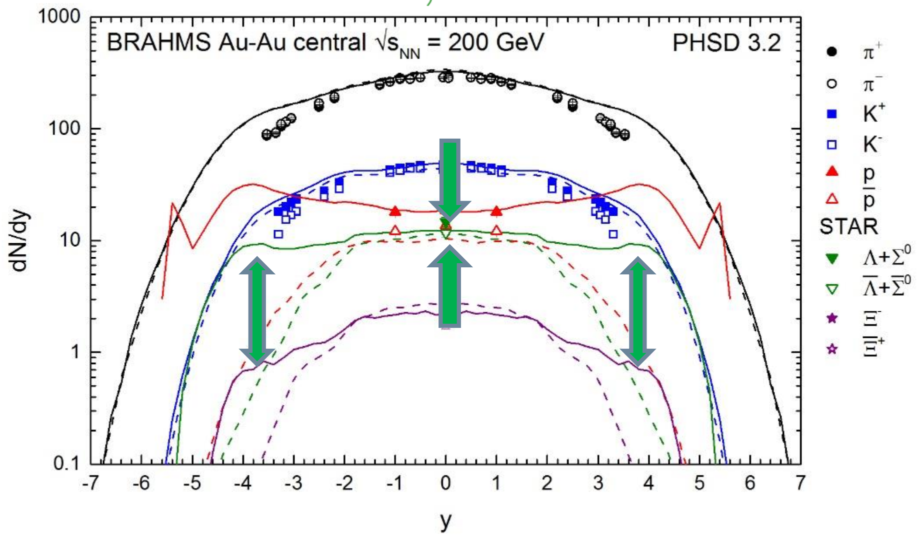

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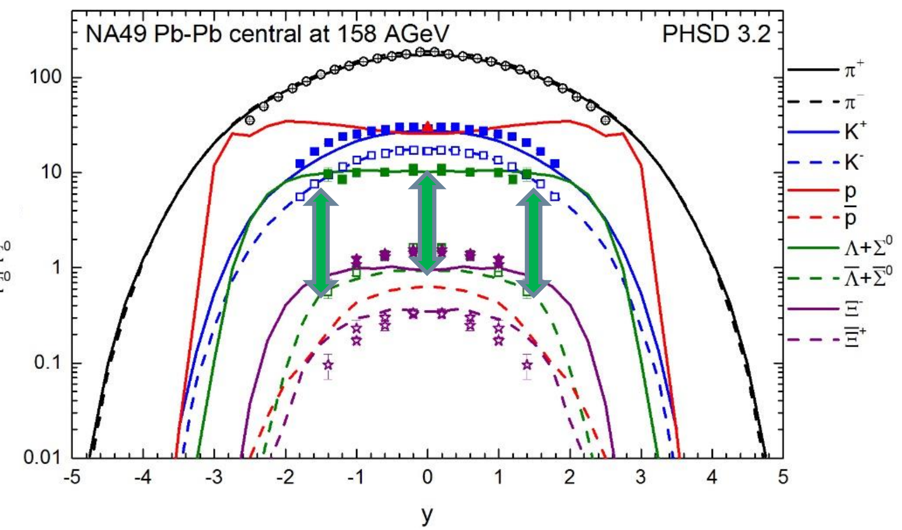


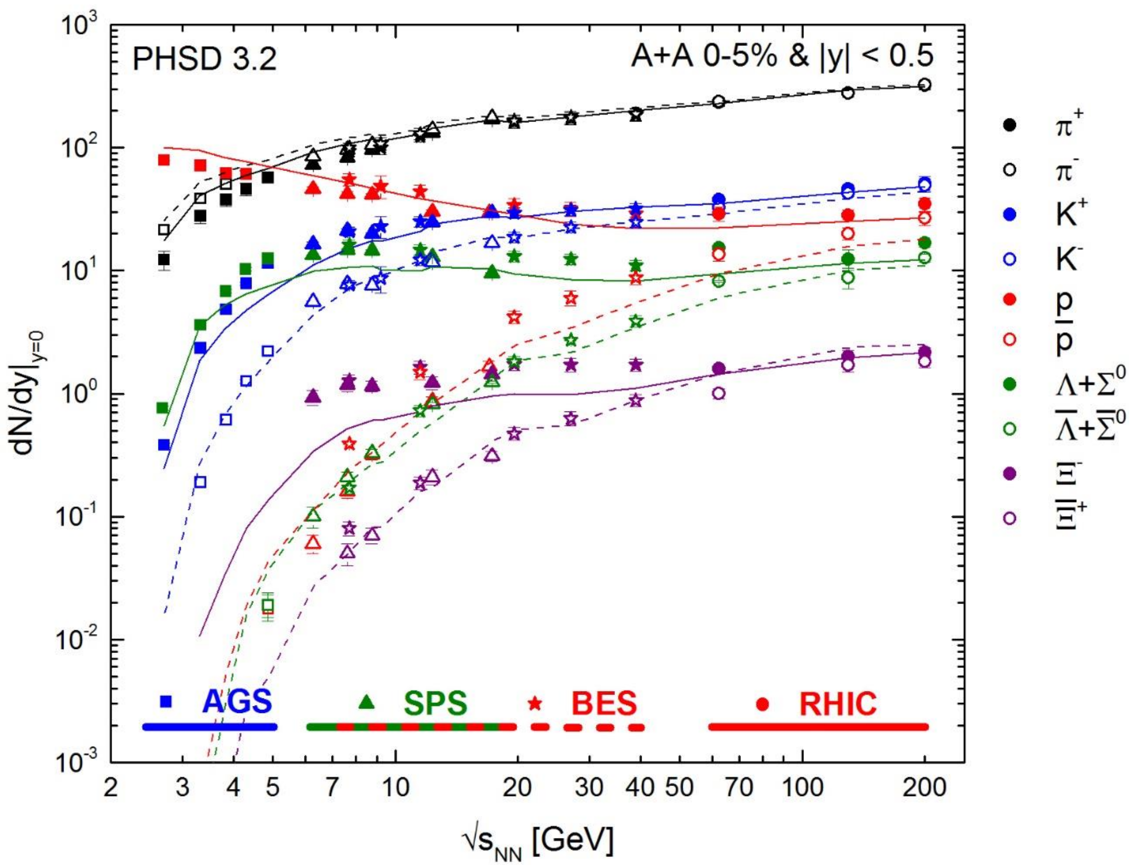
Central Pb+Pb – Top SPS

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

- At the highest energies, the composition of produced particles at midrapidity is conditionned by the plasma composition



Strange baryon production

- Multi-step production of multi-strange baryons Ξ and Ω:

Hyperon (Y = Λ, Σ) production

$$\boxed{\begin{gathered} \pi + N \leftrightarrow K + Y \\ N + N \leftrightarrow N + Y + K \\ N + \bar{K} \leftrightarrow Y + \pi \end{gathered}}$$

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⇨

Cascade (Ξ) production

$$\boxed{\begin{gathered}Y + \bar{K} \leftrightarrow \Xi + \pi \\ Y + Y \leftrightarrow \Xi + N\end{gathered}}$$

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$$\pi + N \leftrightarrow K + Y$$
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⇒

Cascade (Ξ) production

$$Y + \bar{K} \leftrightarrow \Xi + \pi$$
$$Y + Y \leftrightarrow \Xi + N$$

⇒

Ω production

$$\Xi + \bar{K} \leftrightarrow \Omega + \pi$$
$$\Xi + \Xi \leftrightarrow \Omega + Y$$

Strange baryon production

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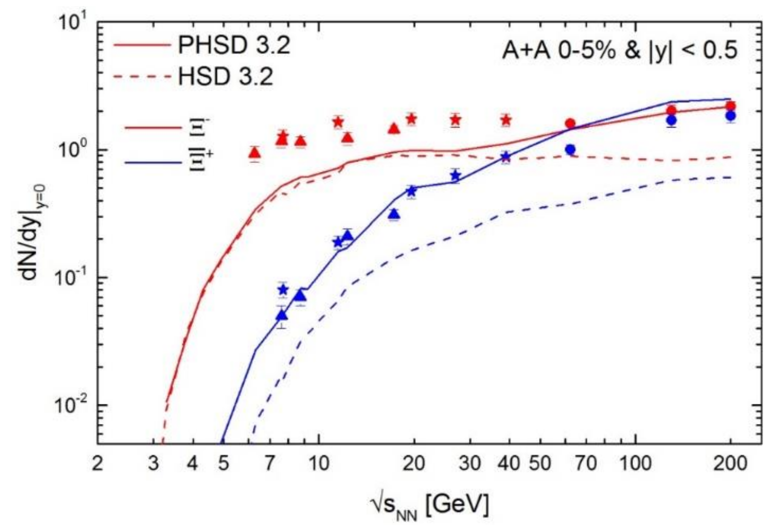
Ω production

$$\Xi + \bar{K} \leftrightarrow \Omega + \pi$$
$$\Xi + \Xi \leftrightarrow \Omega + Y$$

- At low energies, the production of multi-strange baryons comes mostly from the hadronic processes

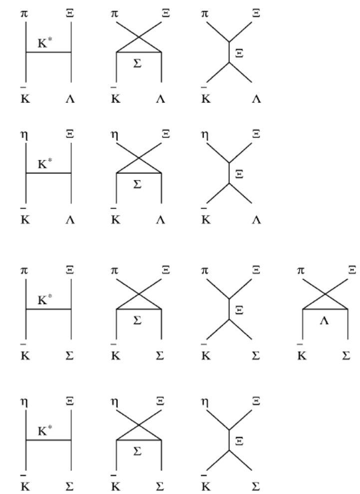
- QGP phase plays an important role in the production of anti-multi-strange baryons



Ingredients for multi-strange baryon production

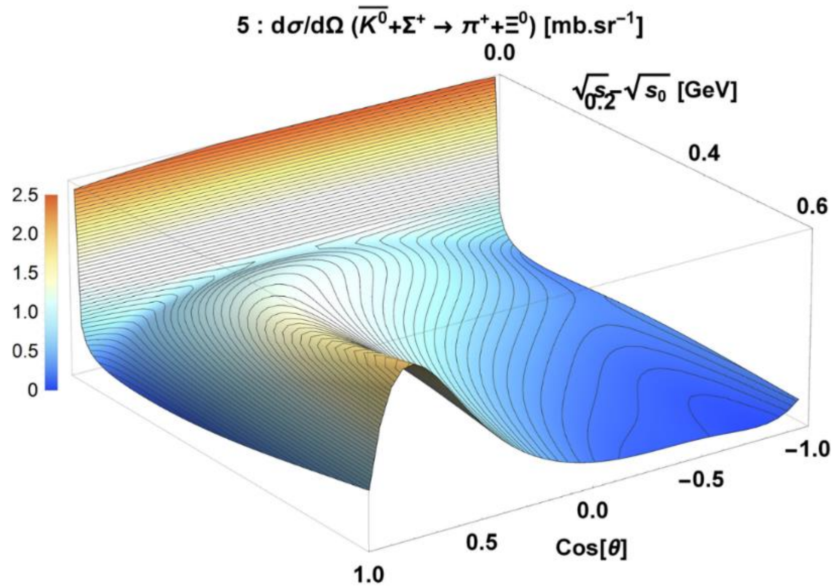
- Implementation of charge-channel decomposition of strangeness exchange reactions
- Taken from the coupled channel approach based on a SU(3)-invariant hadronic Lagrangian from

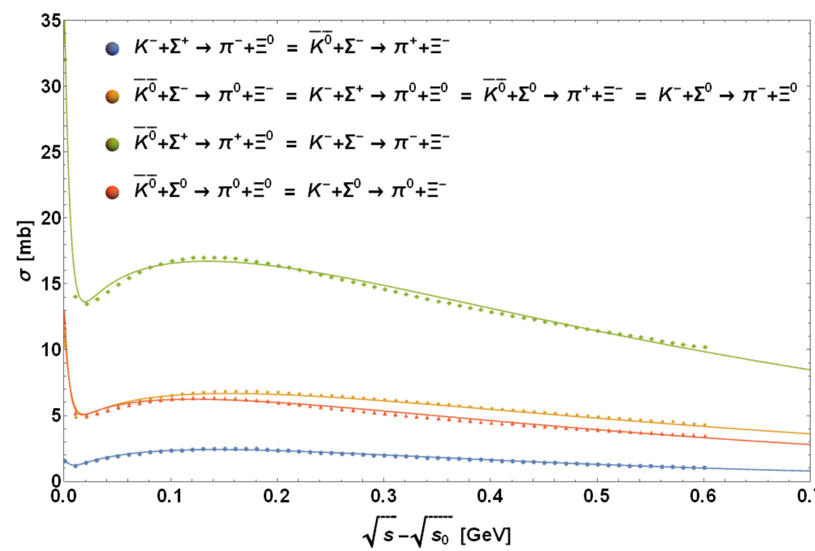
C.H. Li & C.M. Ko, Nucl.Phys. A712 (2002) 110-130



Born diagrams for Ξ production from strangeness exchange reactions

$$\bar{K} + \Lambda/\Sigma \leftrightarrow \Xi + \pi$$

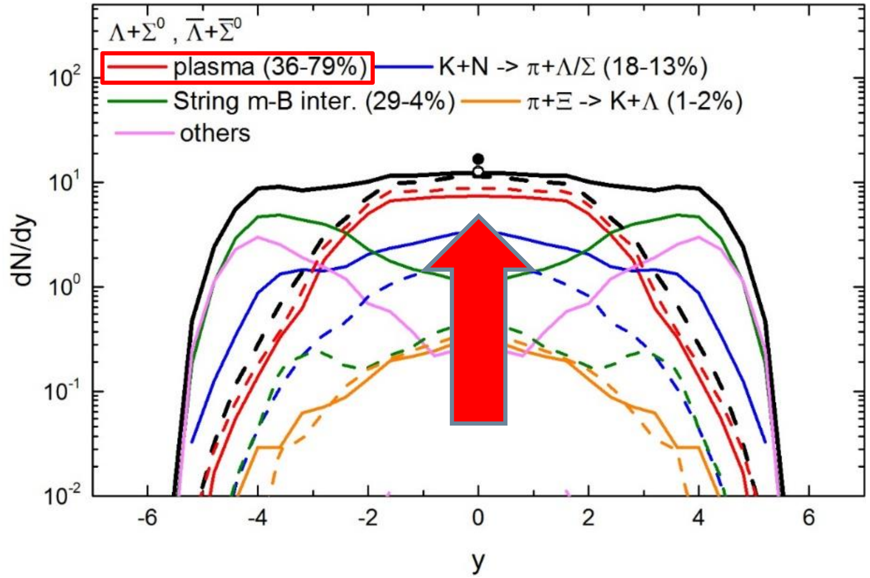




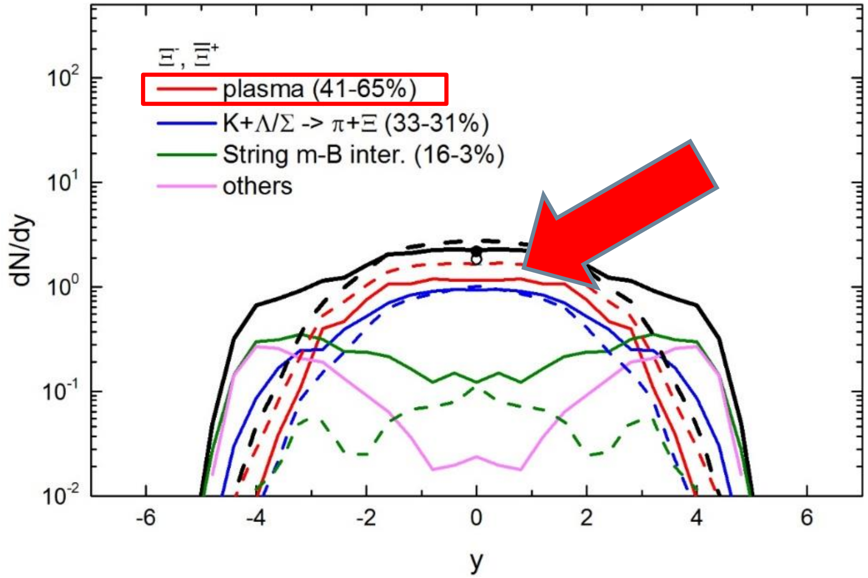
Rapidity spectra - Channel decomposition

- (Anti-)strange baryons are dominantly produced by the QGP phase at mid-rapidity
- Production of strange baryons through hadronic processes are favoured at high rapidity regions where the fragments of initial nuclei are situated
- Even at high energies, the production of Ξ through strange exchange reactions is about 30% of the total production

$\Lambda+\Sigma^0, \bar{\Lambda}+\bar{\Sigma}^0$



$\Xi^-, \bar{\Xi}^+$



Central Au+Au @ 200 GeV – Top RHIC

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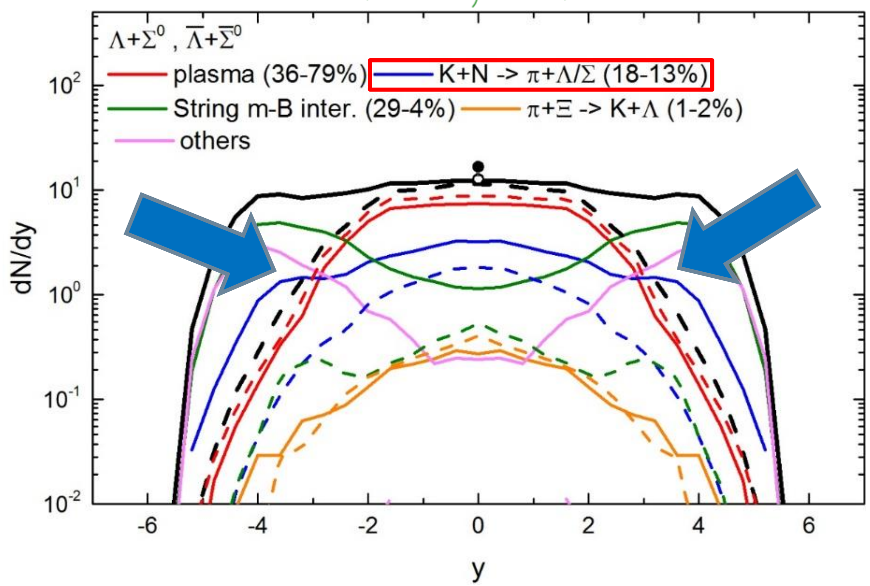
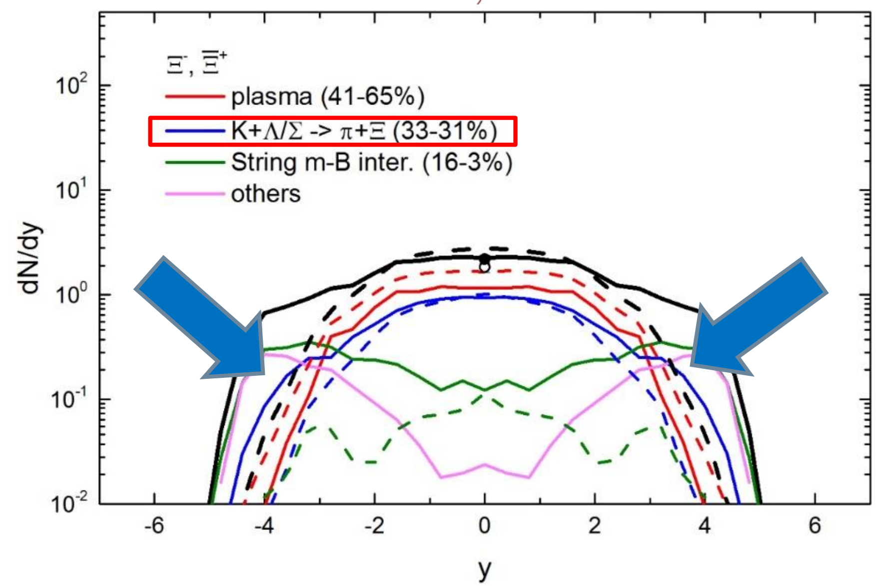


$\Xi^-, \bar{\Xi}^+$



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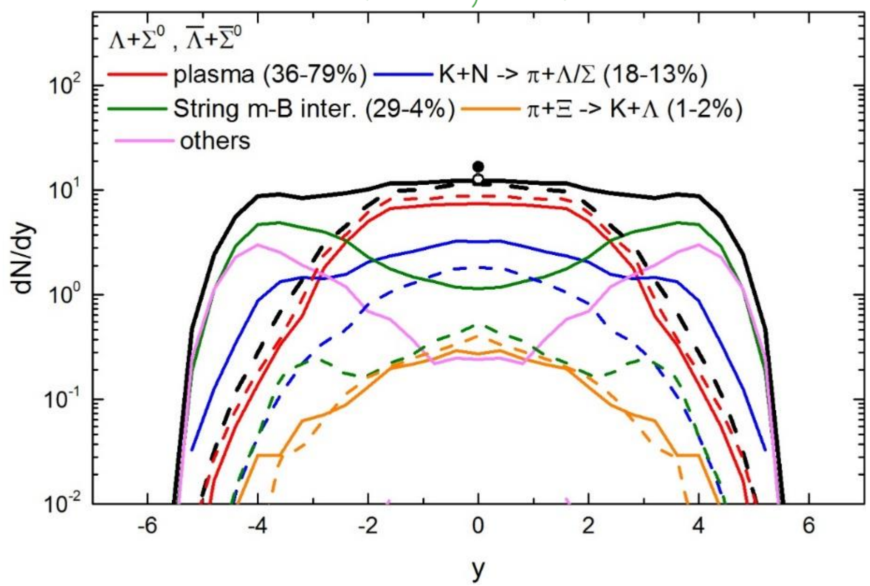

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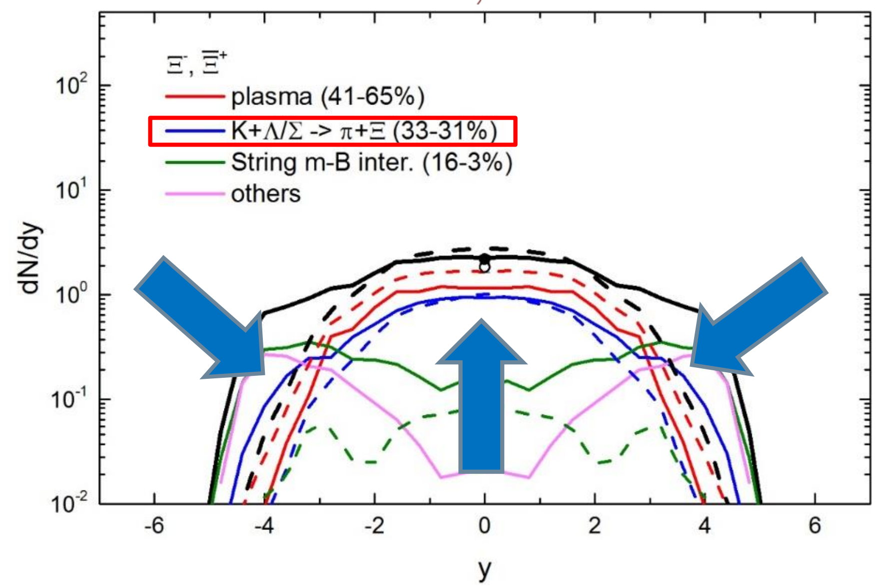

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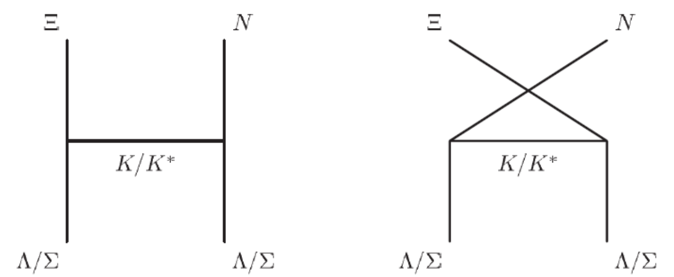
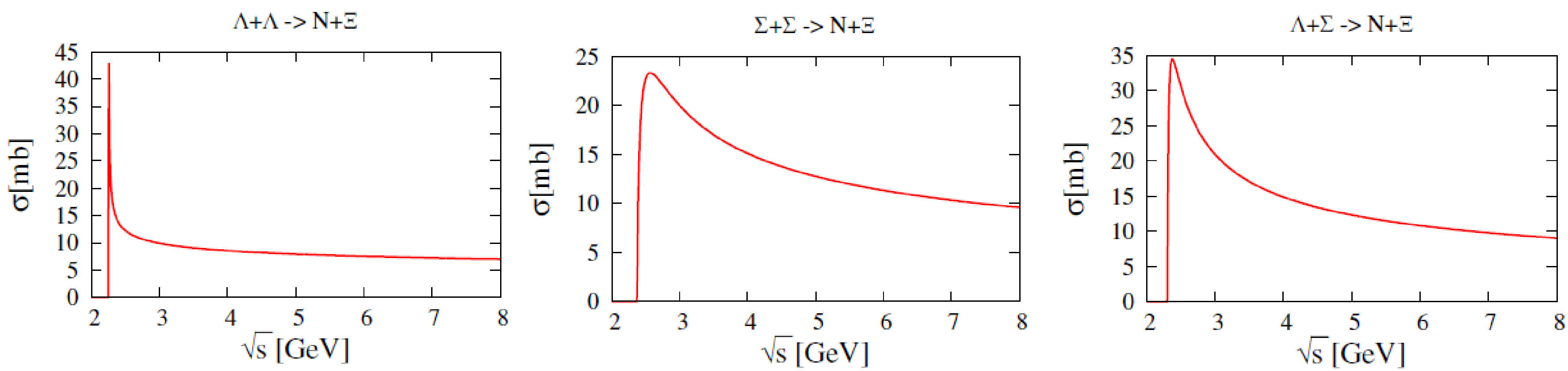
F. Li, L. Chen, C.M. Ko, and S.H. Lee,

Phys. Rev. C 85, 064902



Born diagrams for the reactions $\Lambda\Lambda \to N\Xi$, $\Lambda\Sigma \to N\Xi$, and $\Sigma\Sigma \to N\Xi$

$$Y + Y \leftrightarrow \Xi + N$$



Note: this cross-section is not considered in the results presented here

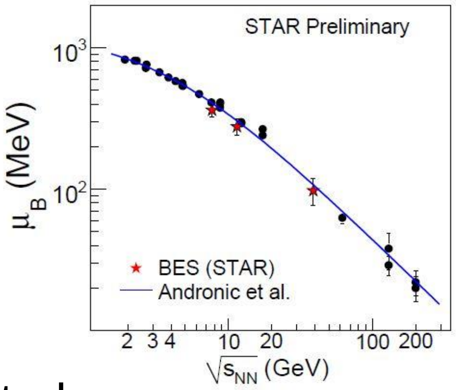
By Alessia Palmese

Conclusion

- By decreasing the collisionnal energy, more differences appear between the production of particle and antiparticle, even at midrapidity regions

- Partonic and hadronic processes are both necessary to approach the yield of multi-strange baryons (work in progress)

- Cross sections from the DQPM at finite chemical potential may also play a significant role at low collisional energy



- Signatures from a chiral phase transition are under study

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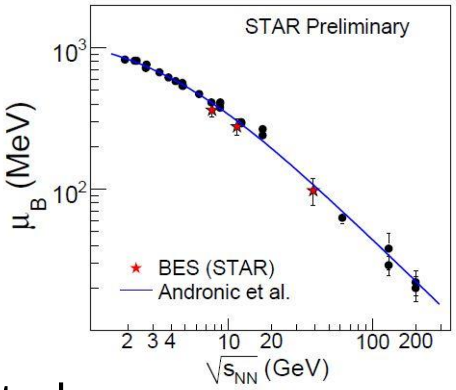

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THANK YOU FOR YOUR ATTENTION