Exploring the partonic phase at finite chemical potential within heavy-ion collisions

Pierre Moreau, Olga Soloveva, Lucia Oliva, Taesoo Song, Wolfgang Cassing, Elena Bratkovskaya

25ème Congrès Général de la Société Française de Physique, Nantes, July 8, 2019

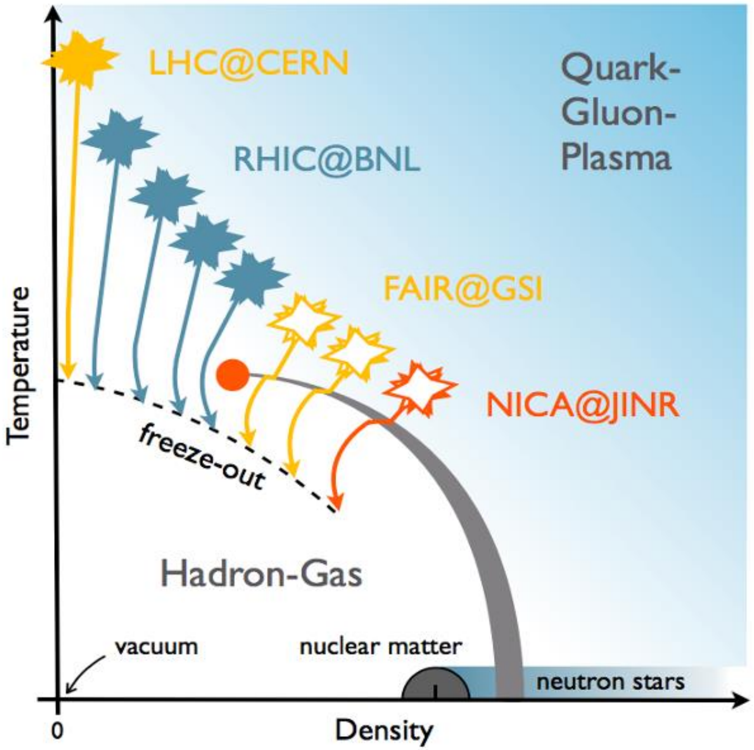
arXiv:1903.10257

Motivations

- Explore the **QCD phase diagram** at finite temperature and chemical potential through heavy-ion collisions

- **Available information:**
  - Experimental data at SPS, BES at RHIC
  - Lattice QCD calculation

Probes of the QGP at finite (T, μ_B)



Dynamical description of HIC

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

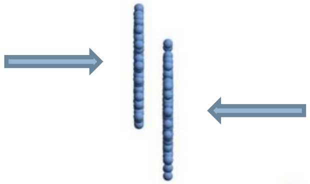
Parton-Hadron-String-Dynamics (PHSD)

- **Explicit parton-parton interactions, explicit 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**

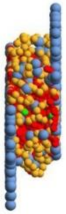
W.Cassing, E.Bratkovskaya, PRC 78 (2008) 034919; NPA831 (2009) 215; W.Cassing, EPJ ST 168 (2009) 3

Stages of a collision in PHSD

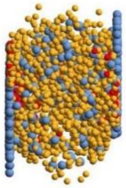
Initial A+A collision



Partonic phase



Hadronization



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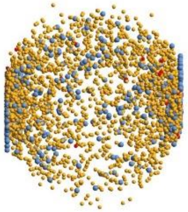
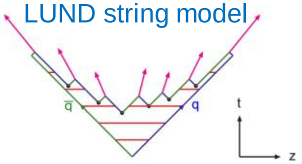


- **String formation in primary NN collisions**

→ decays to pre-hadrons (baryons and mesons)



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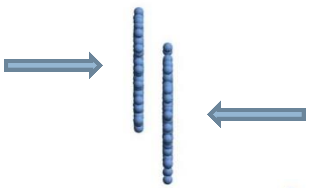

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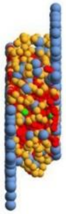

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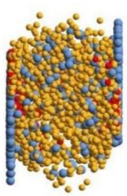

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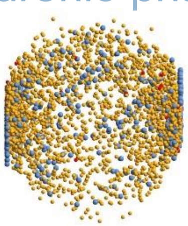

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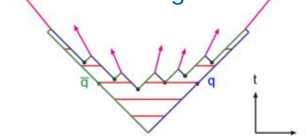
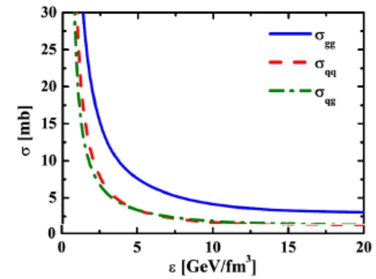
LUND string model



- **Formation of a QGP state if $\varepsilon > \varepsilon_{critical}$:**

Dissolution of pre-hadrons → DQPM

→ massive quarks/gluons and mean-field energy



(quasi-)elastic collisions :

$g + q \rightarrow g + q \qquad g + q \rightarrow g + q$

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

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inelastic collisions :

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

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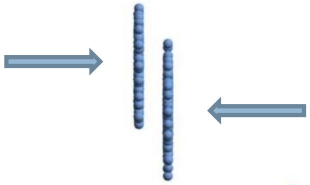

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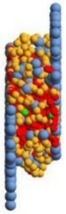

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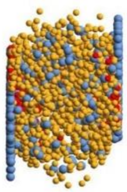

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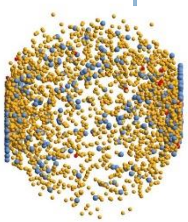

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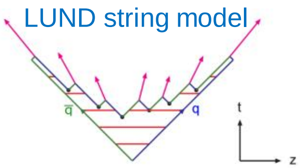

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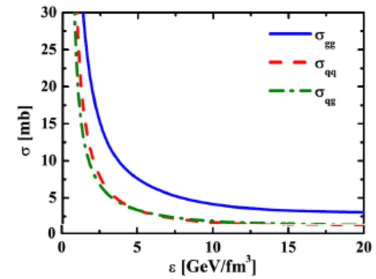

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- **Hadronization to colorless off-shell mesons and baryons**

$$g \to q+\bar{q}, \quad q+\bar{q} \leftrightarrow meson\ ('string')$$
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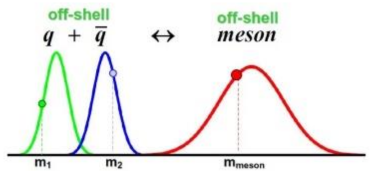
Strict 4-momentum and quantum number conservation



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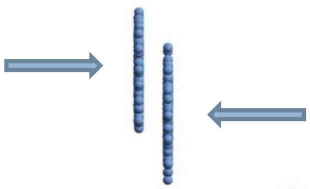

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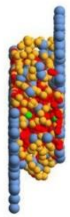

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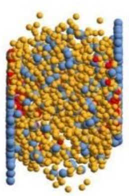

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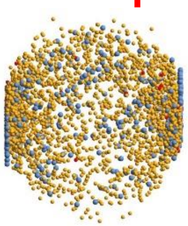

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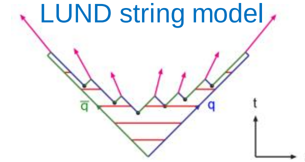

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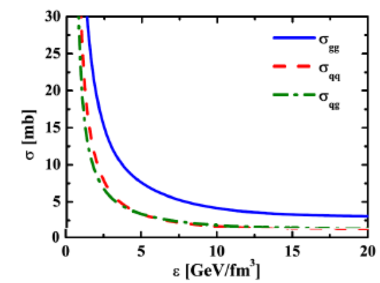

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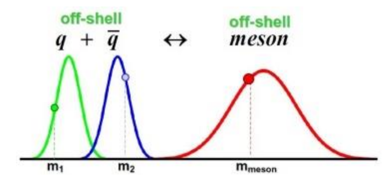

- **Hadron-string interactions – off-shell HSD**

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Stages of a collision in PHSD

P.Moreau

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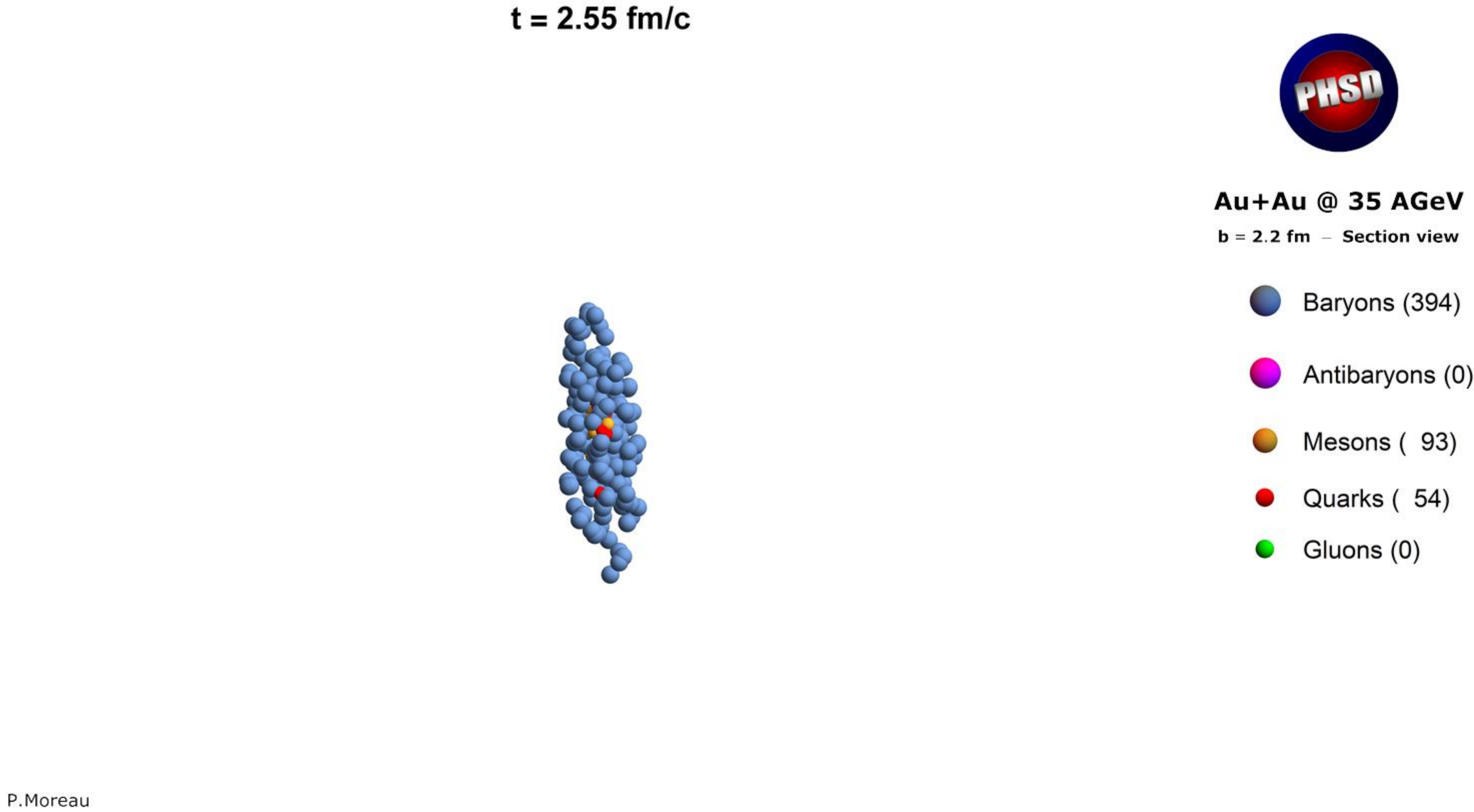

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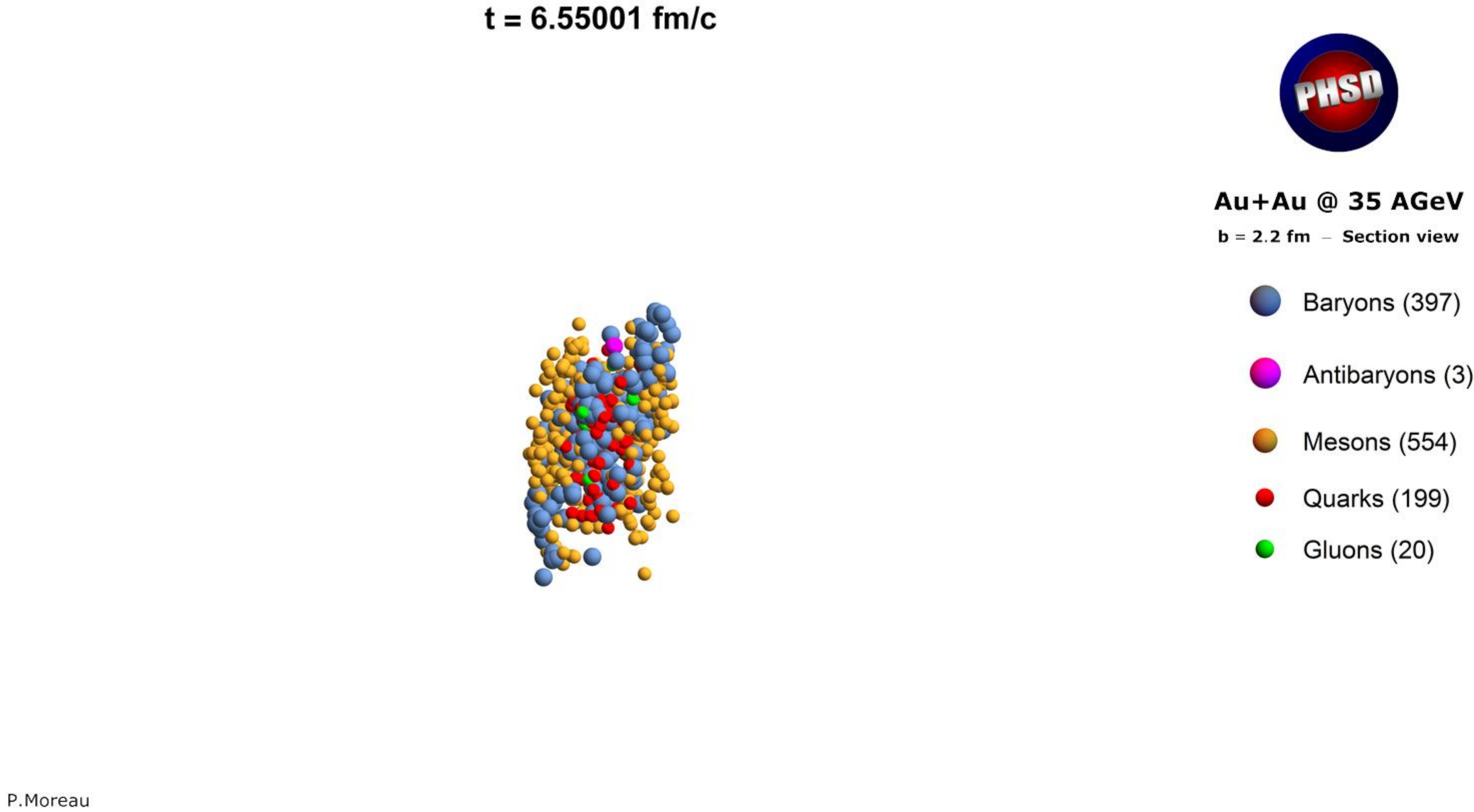

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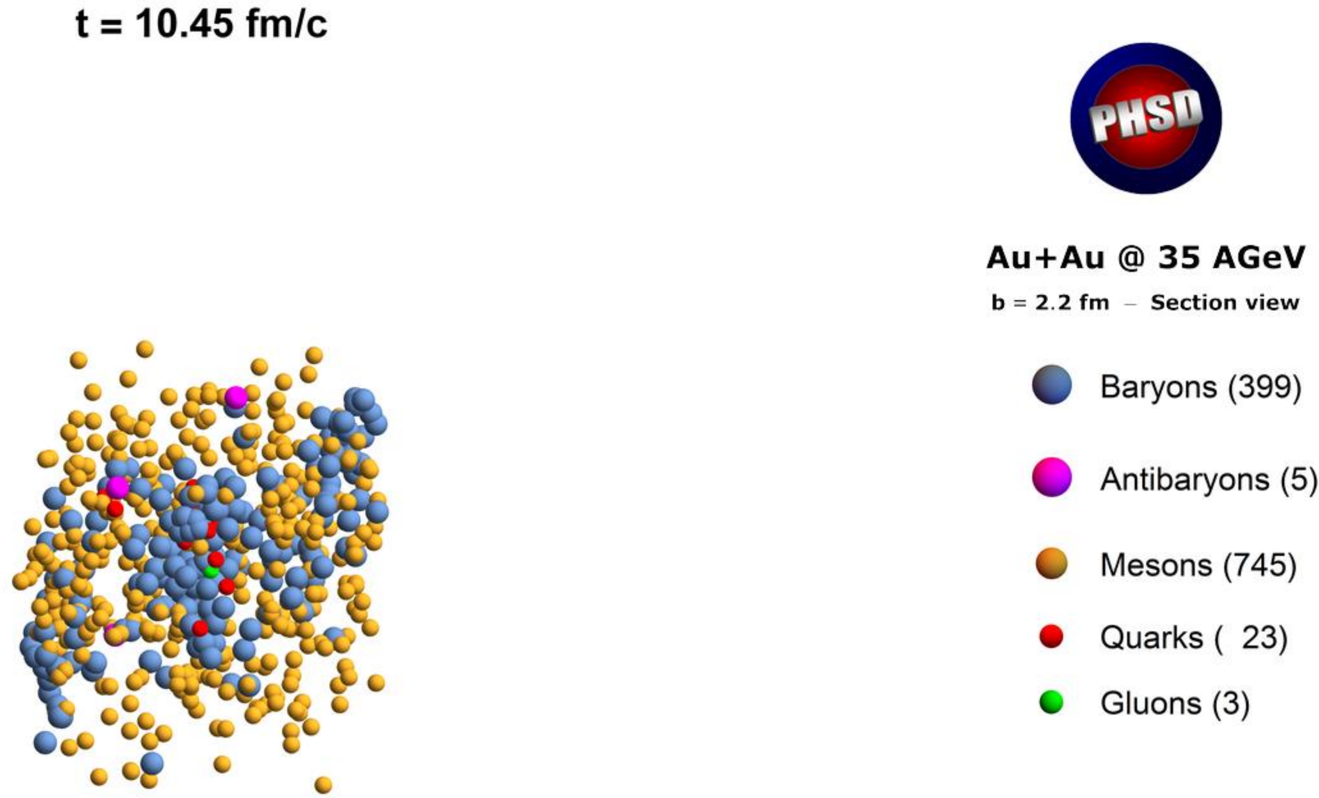

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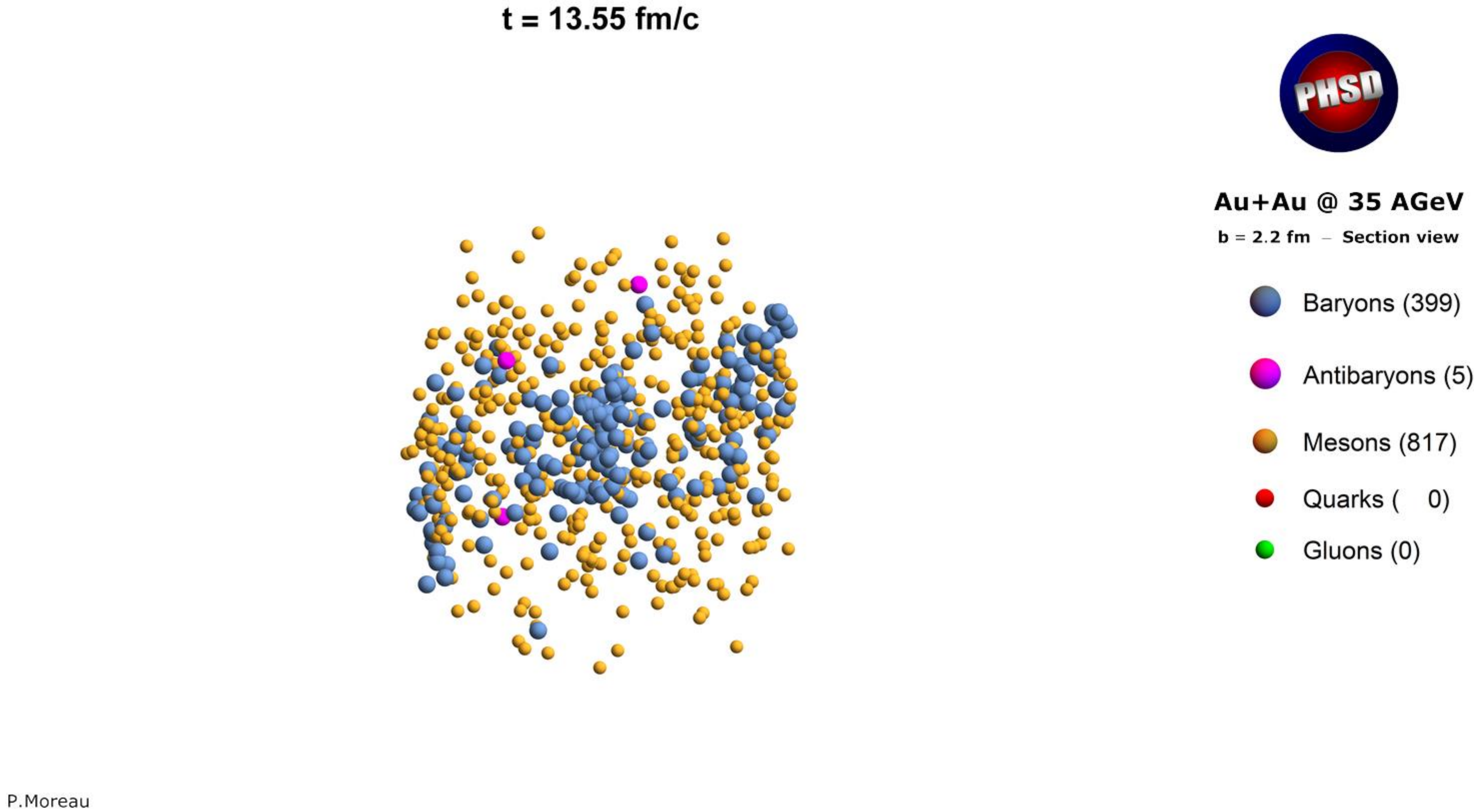

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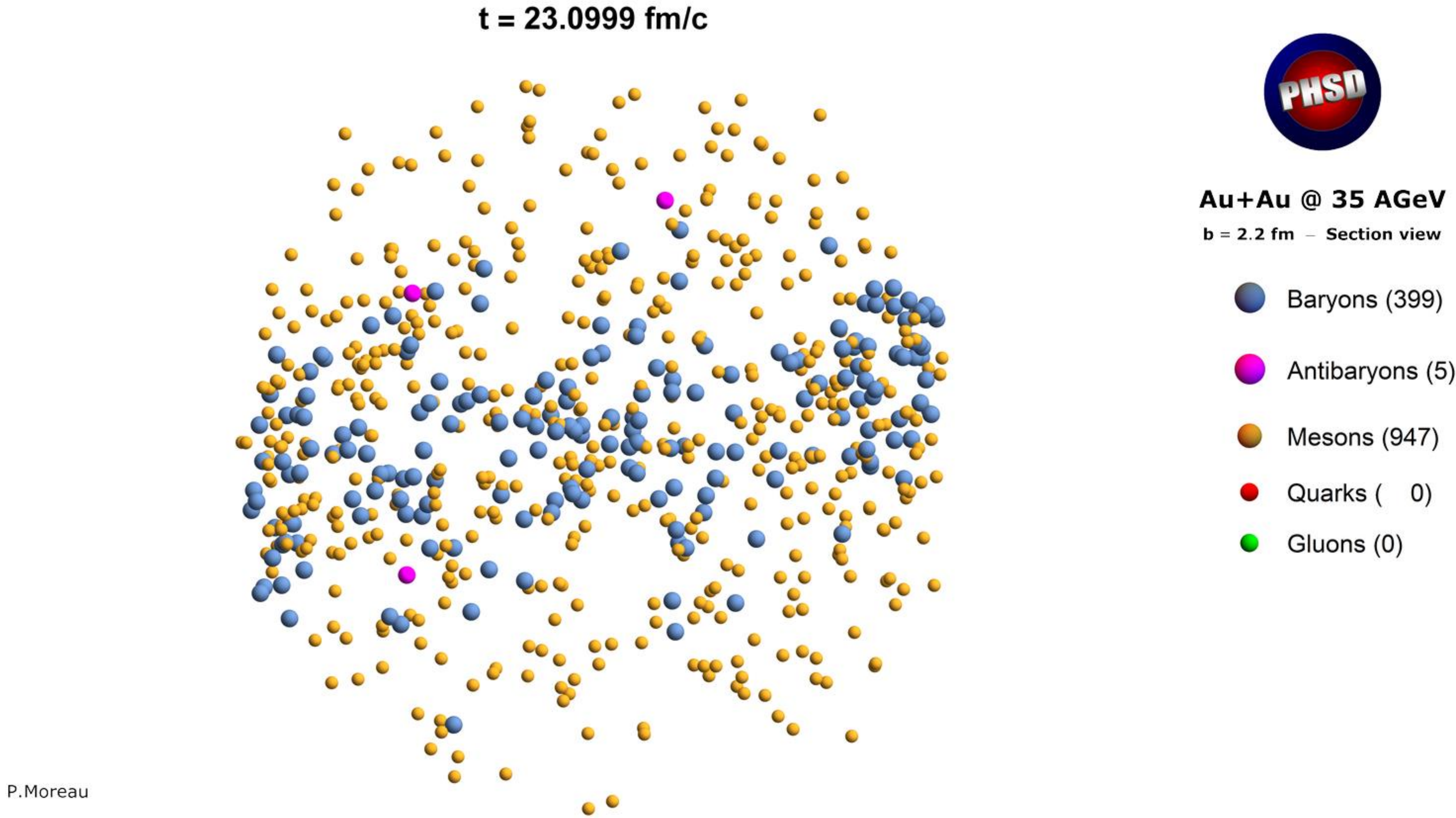

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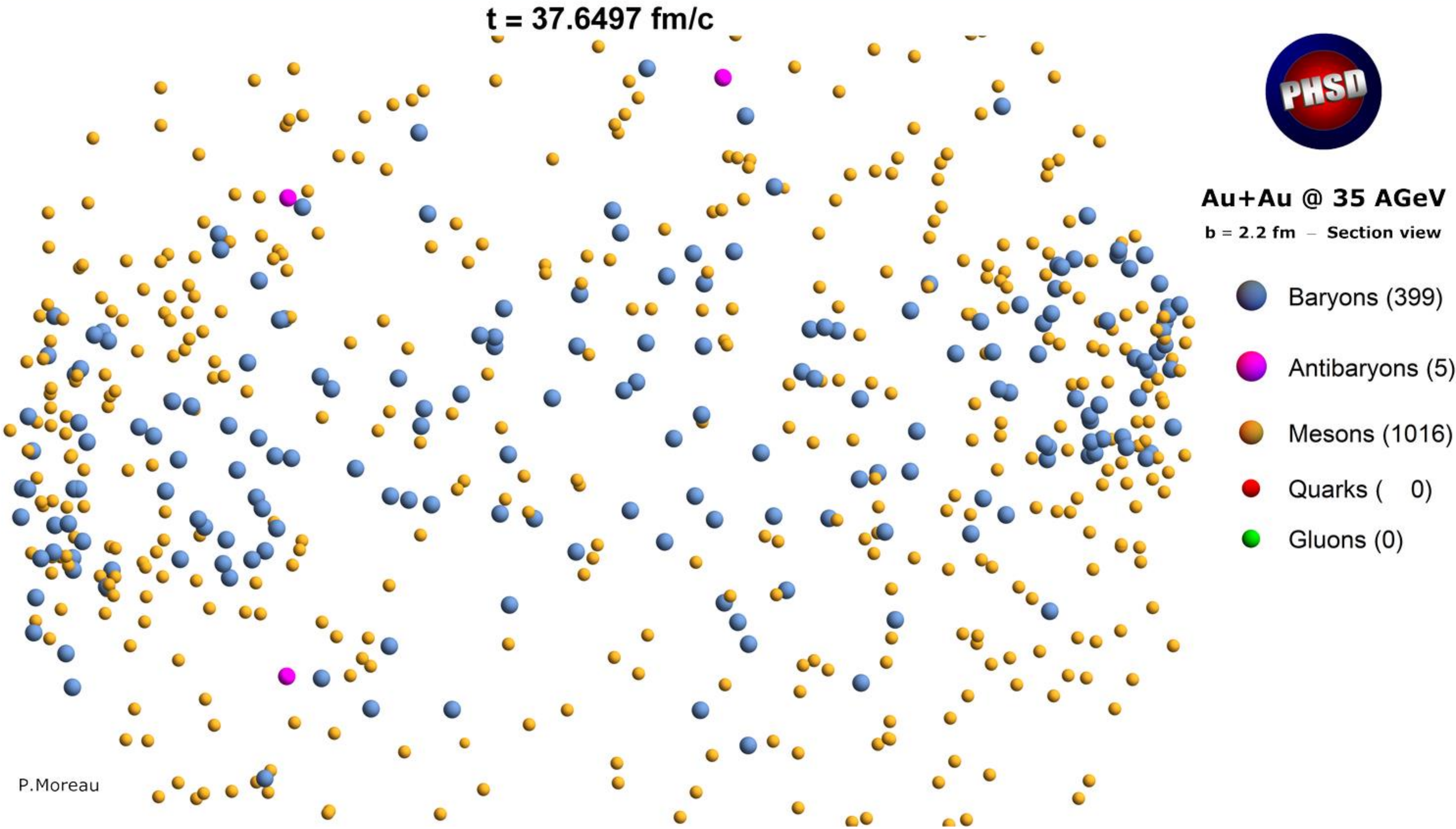

DQPM (T, μ_B)

QCD EoS, partonic interactions

Lattice data at finite (T, μ_B)

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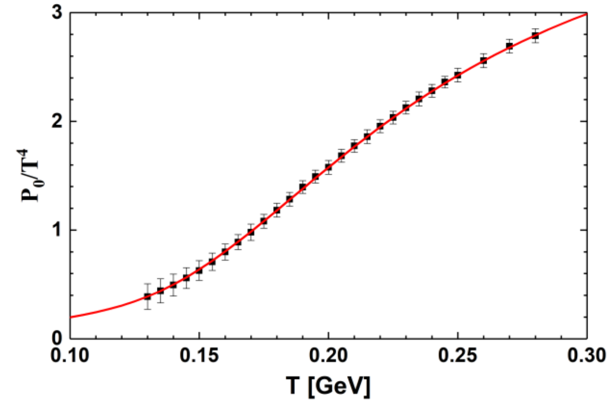
- Taylor series of thermodynamic quantities in terms of (μ_B/T)

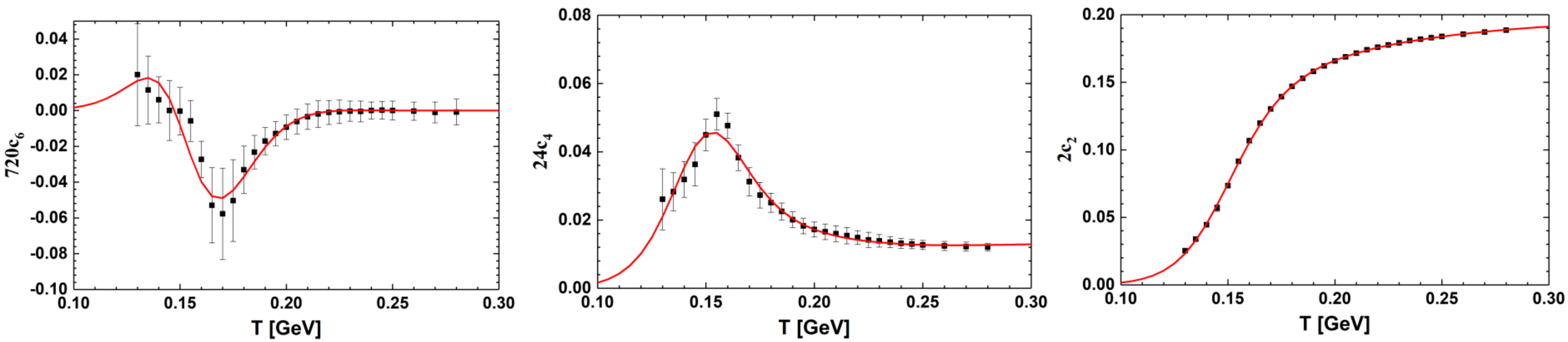
- For the pressure, we get:

$$\frac{P}{T^4} = c_0(T) + c_2(T)\left(\frac{\mu_B}{T}\right)^2 + c_4(T)\left(\frac{\mu_B}{T}\right)^4 + c_6(T)\left(\frac{\mu_B}{T}\right)^6 + \mathcal{O}\left(\mu_B^8\right)$$



- Conditions of heavy-ion collisions

$$\langle n_S \rangle = 0 \text{ and } \langle n_Q \rangle = 0.4 \, \langle n_B \rangle$$



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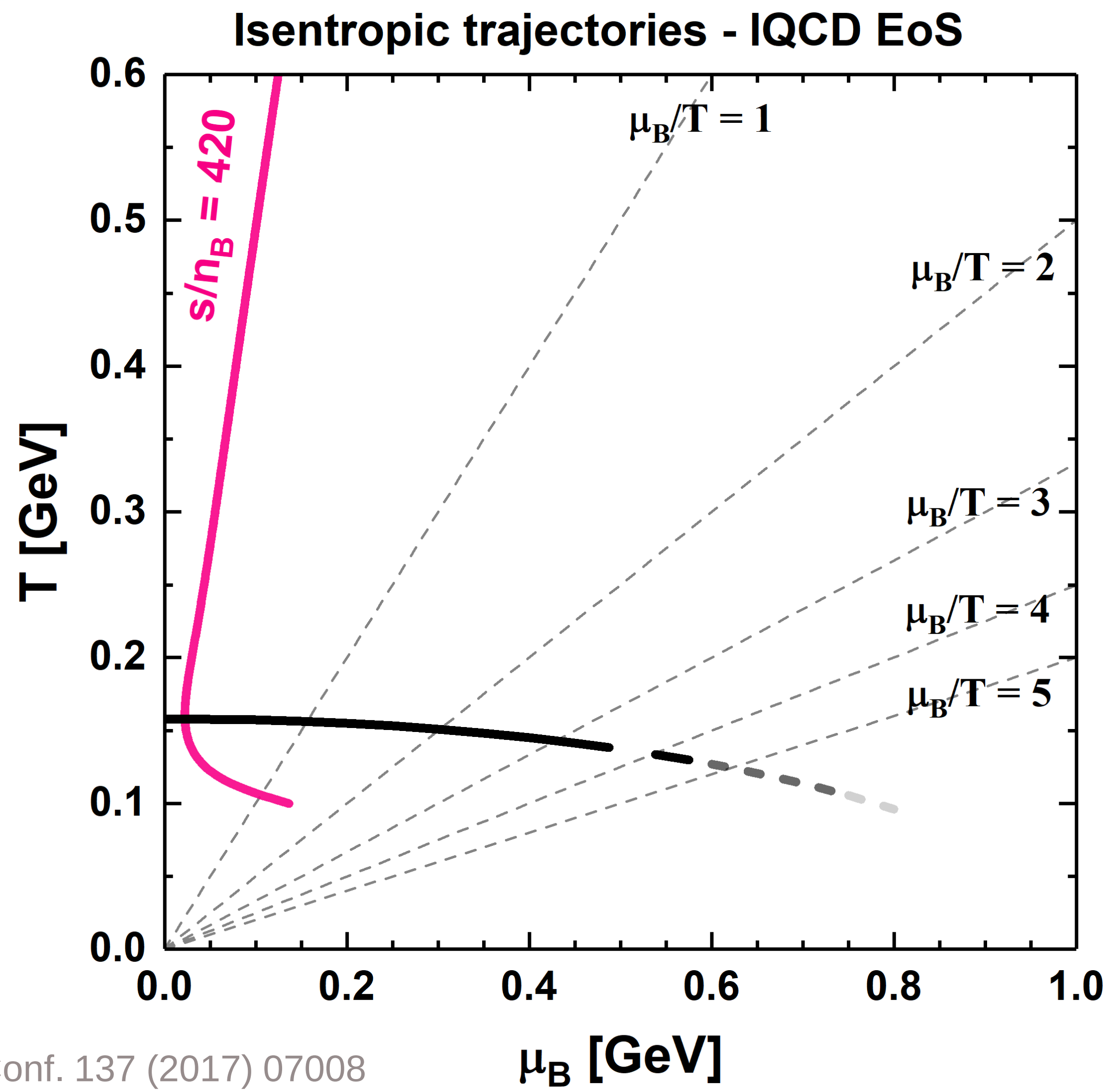
Isentropic trajectories for (T, μ_B)

- Correspondance $s/n_B \leftrightarrow$ collisional energy

s/n_B = 420 ↔ 200 GeV



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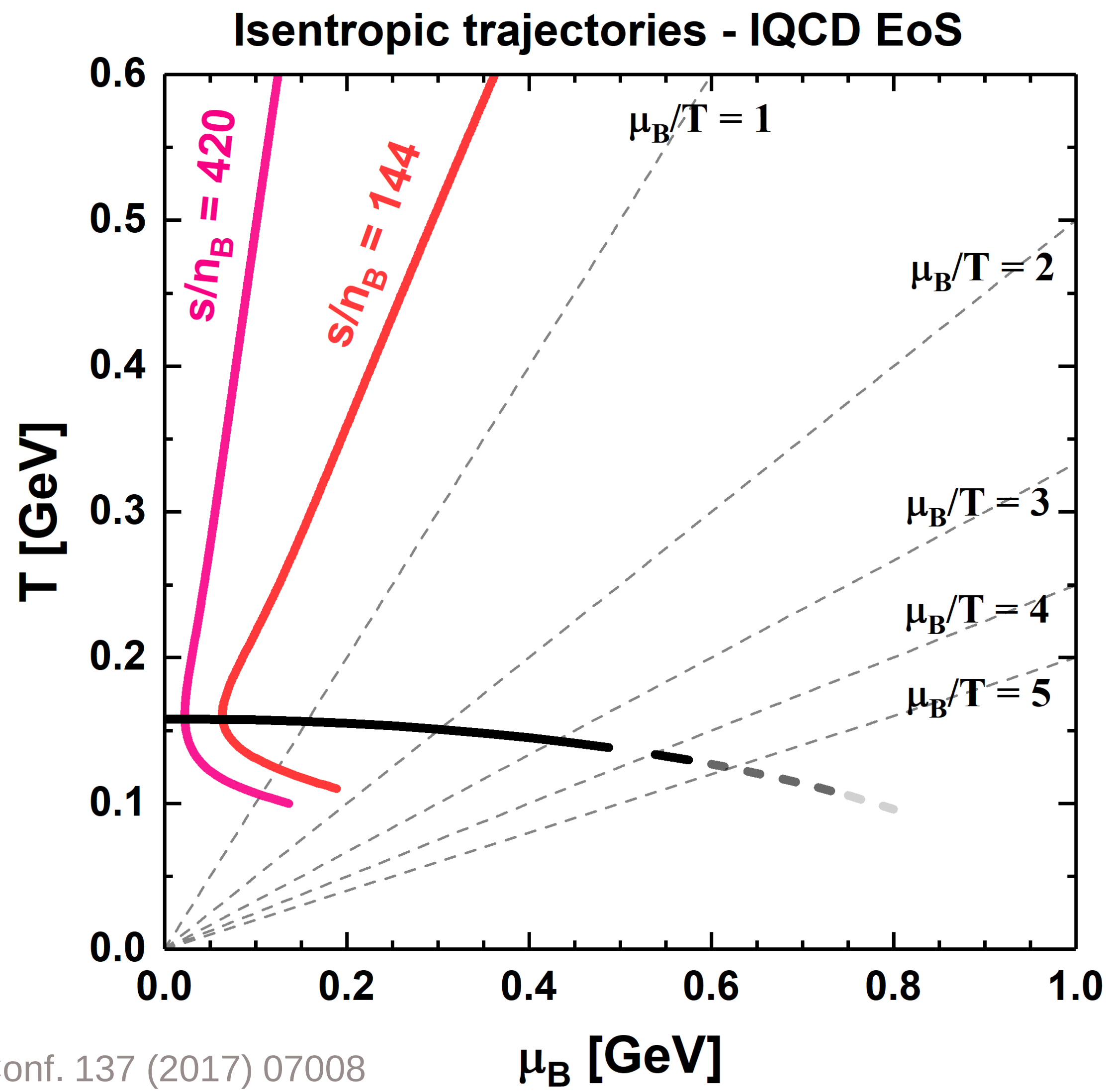

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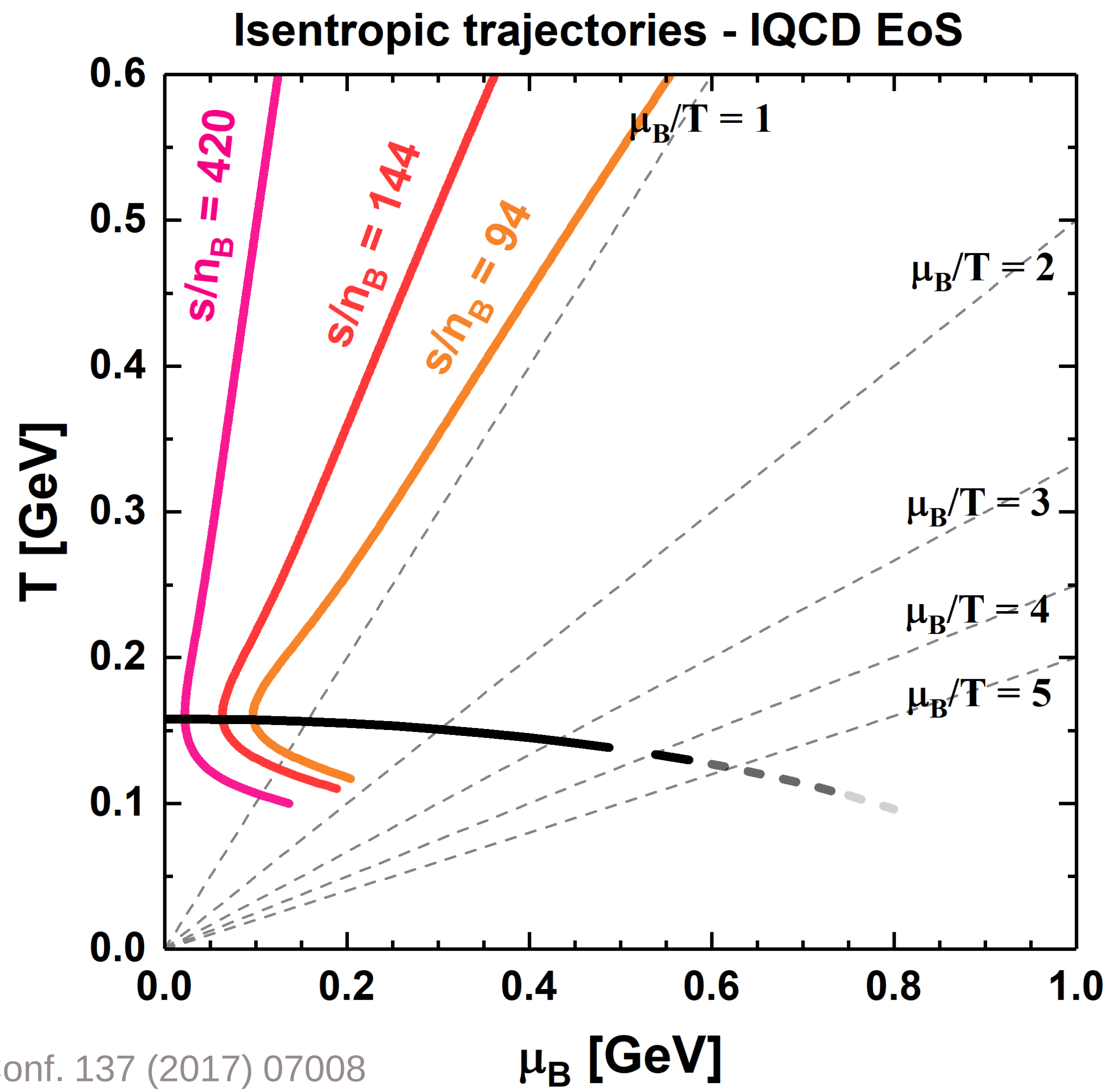
= 94 ↔ 39 GeV



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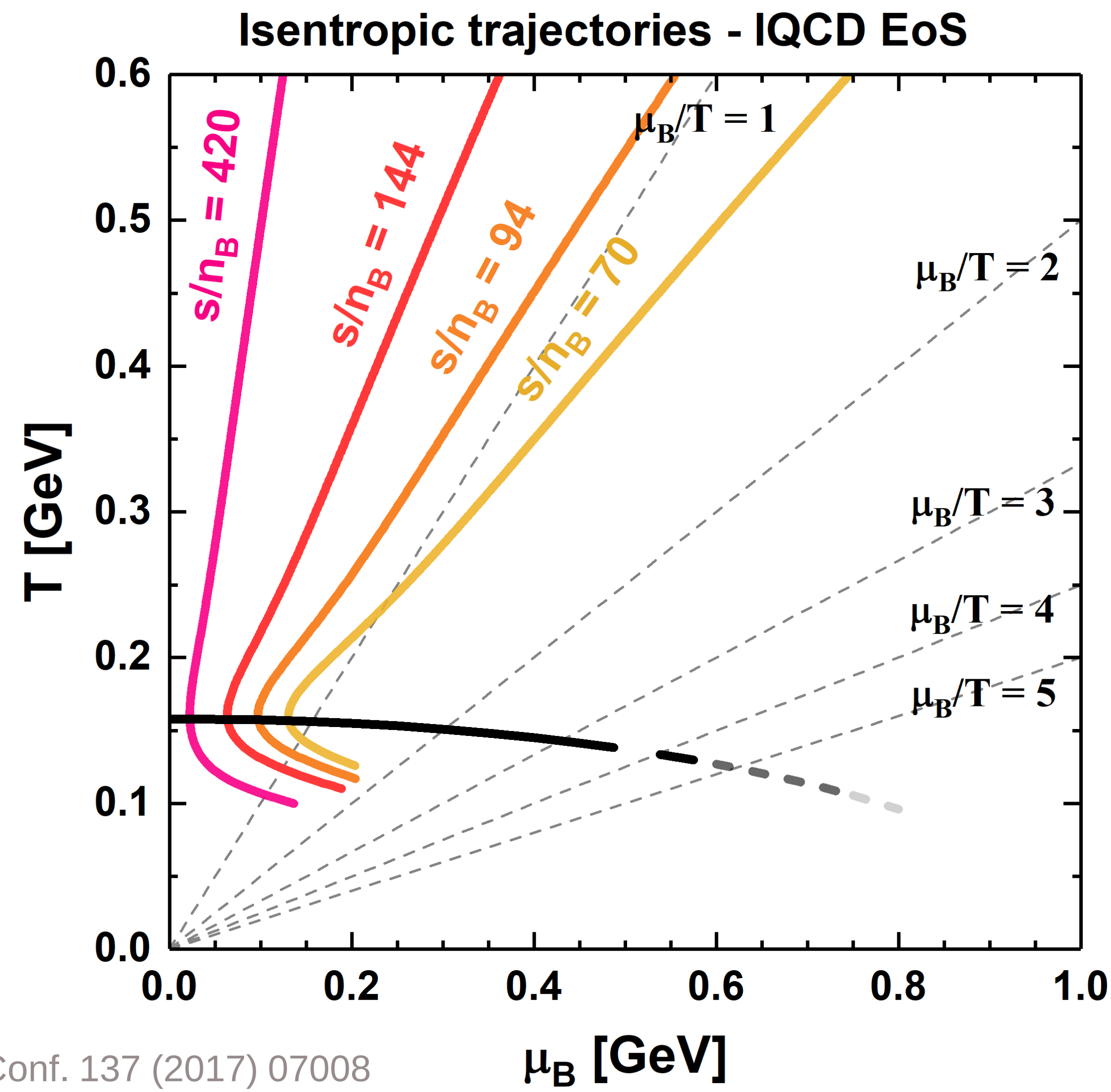
= 70 ↔ 27 GeV



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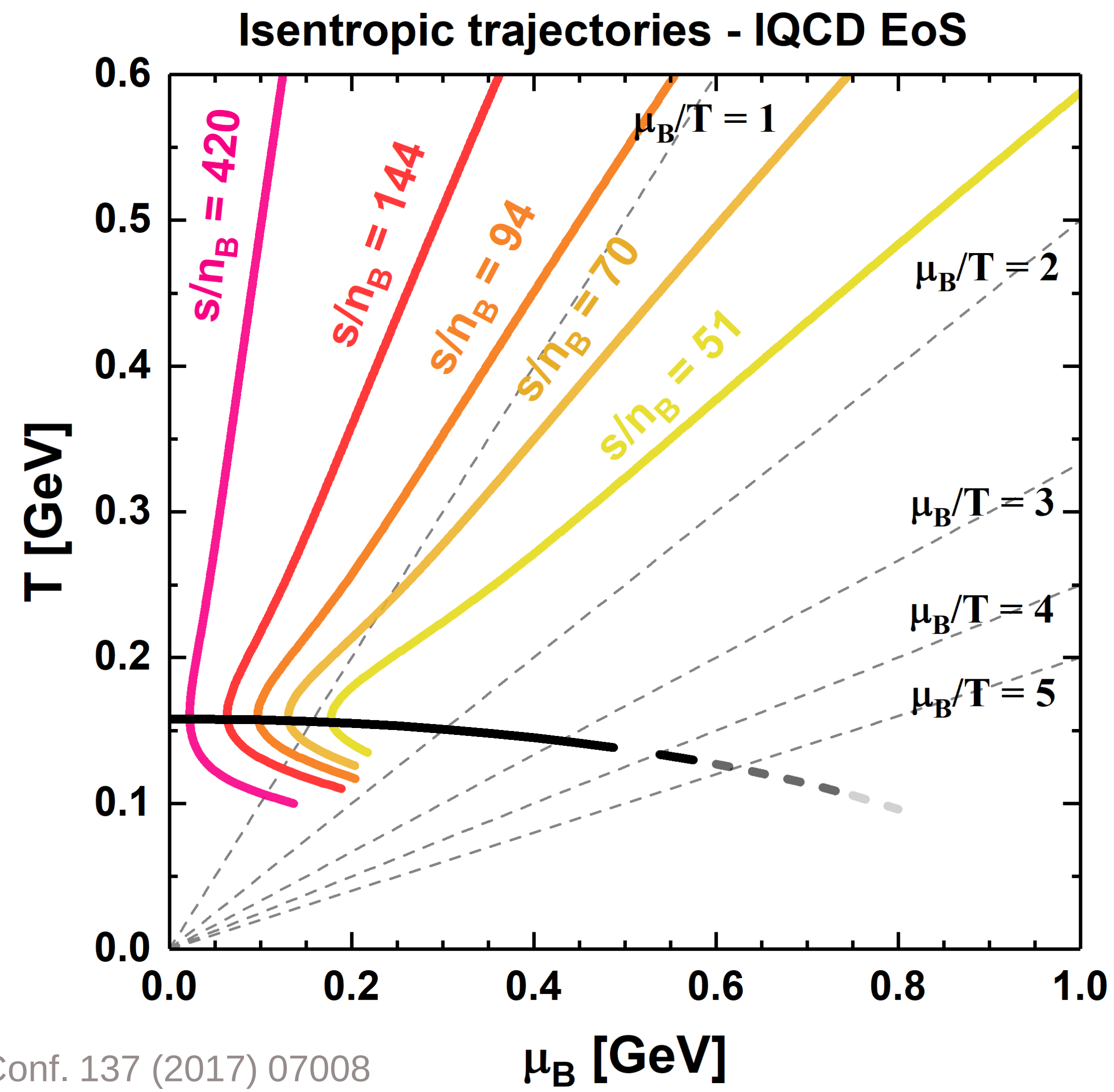
= 51 ↔ 19.6 GeV



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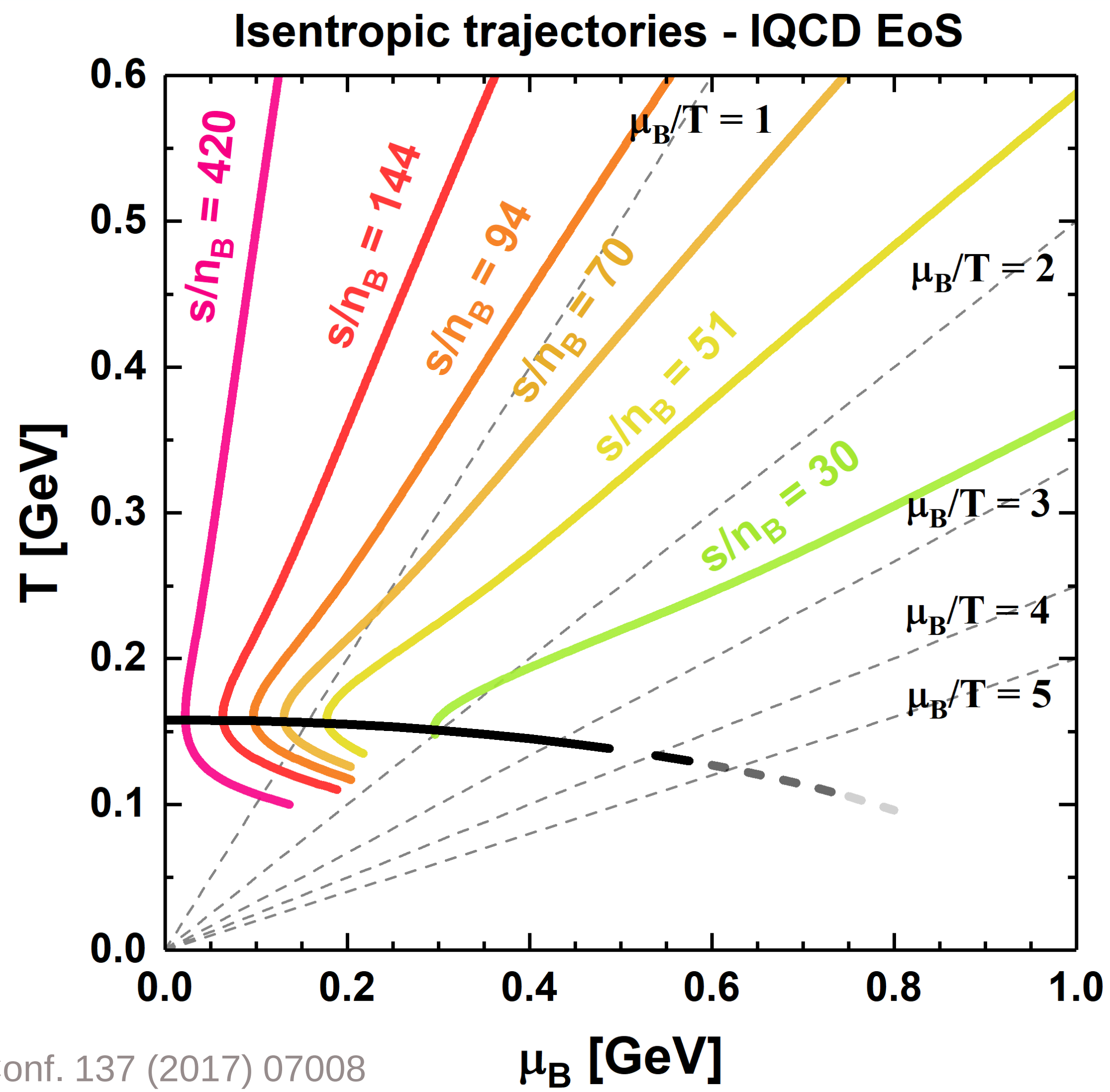
= 30 ↔ 14.5 GeV



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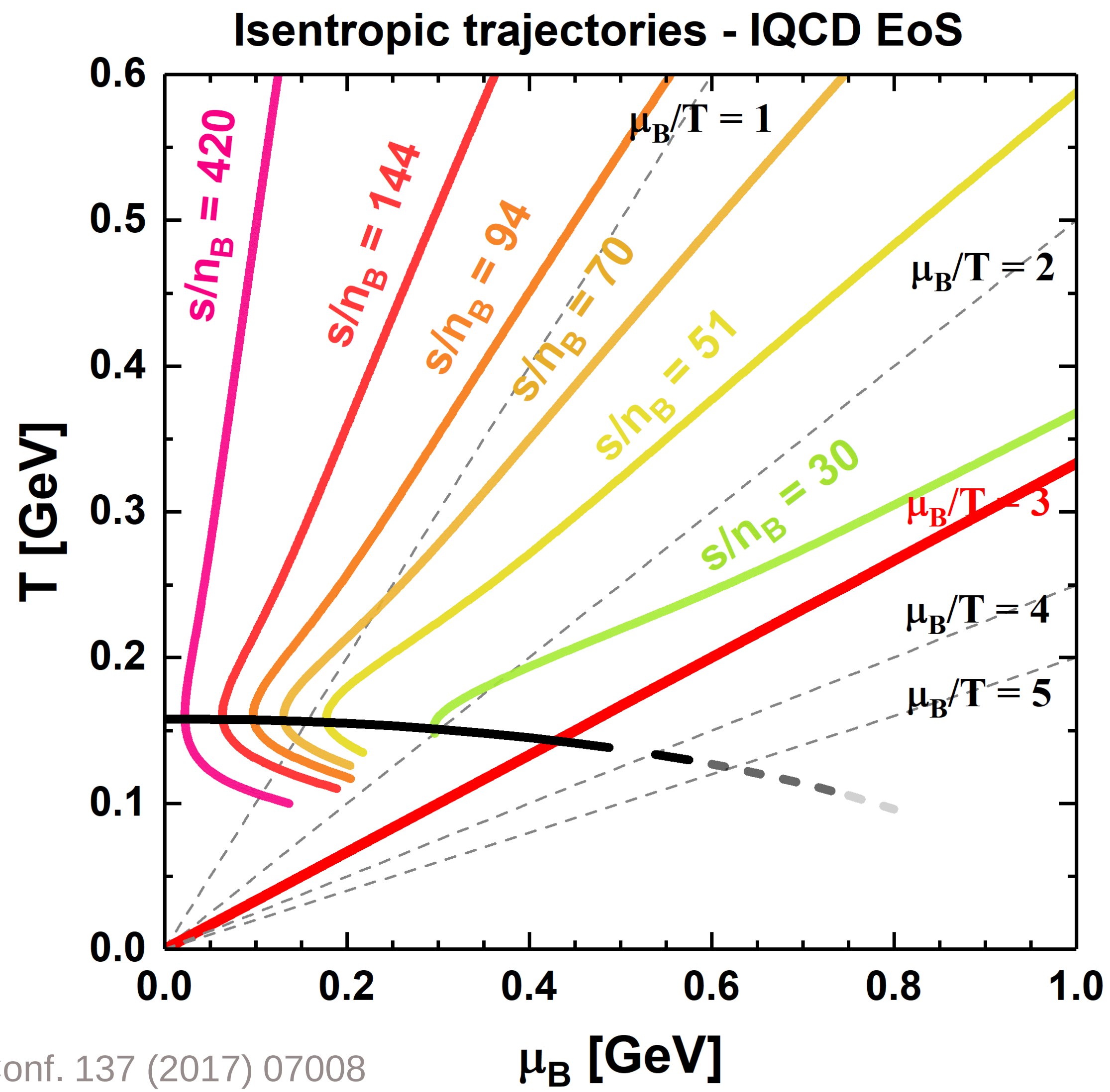
- **Safe for $(\mu_B/T) < 3$**



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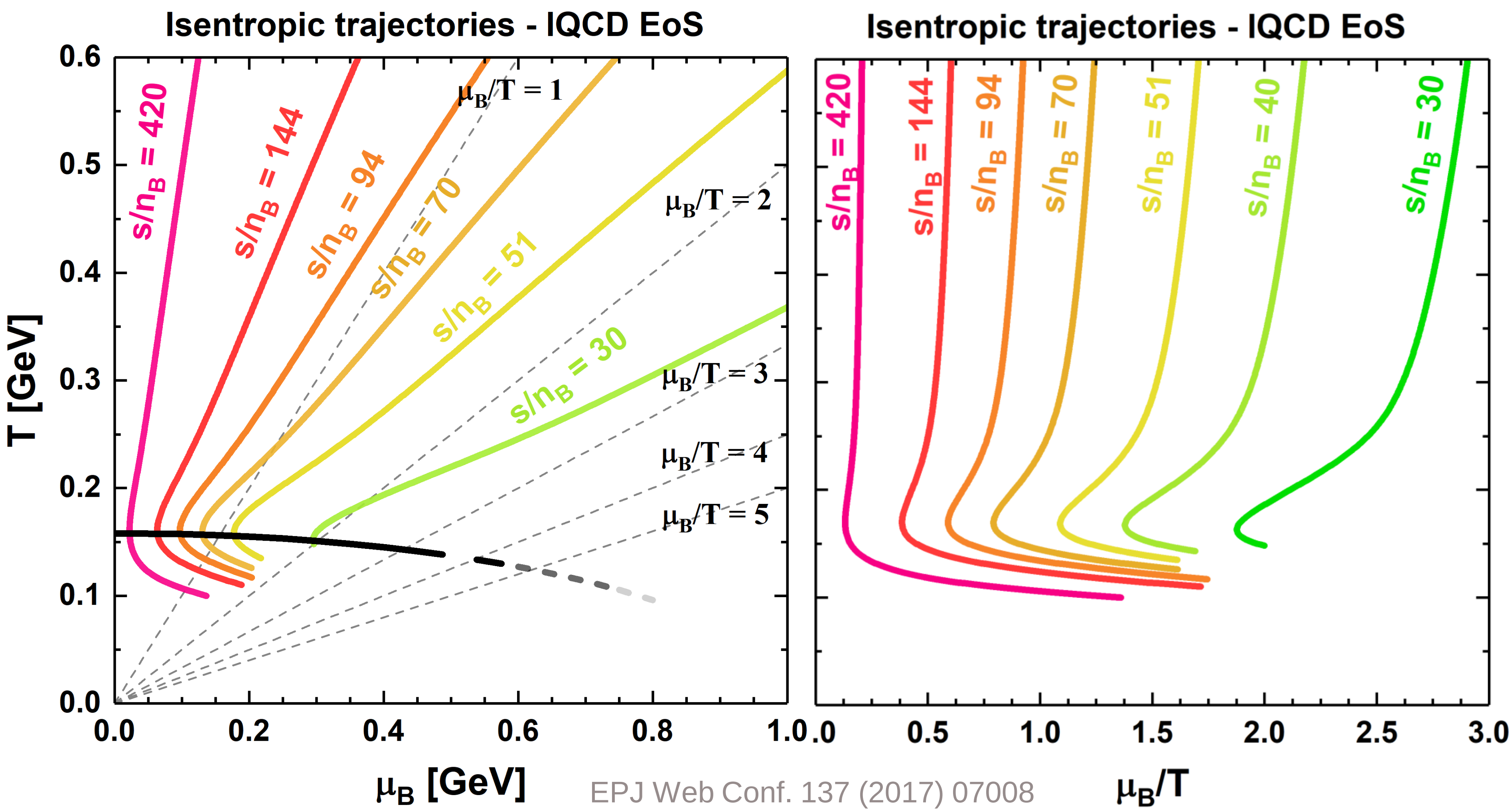

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Dynamical QuasiParticle Model (DQPM)

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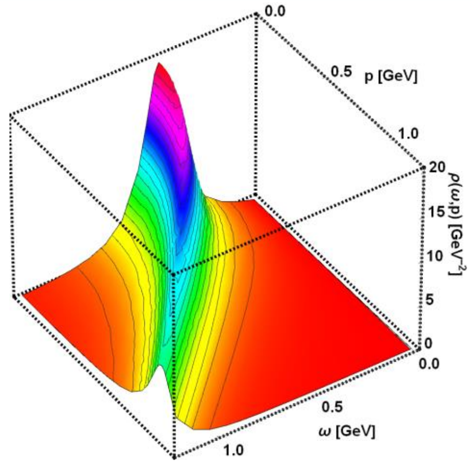
- The QGP phase is described in terms of interacting quasiparticles: quarks and gluons with Lorentzian spectral functions:

$$\rho_j(\omega,\mathbf{p}) = \frac{\gamma_j}{\tilde{E}_j}\left(\frac{1}{(\omega-\tilde{E}_j)^2+\gamma_j^2} - \frac{1}{(\omega+\tilde{E}_j)^2+\gamma_j^2}\right)$$
$$\equiv \frac{4\omega\gamma_j}{\left(\omega^2-\mathbf{p}^2-M_j^2\right)^2+4\gamma_j^2\omega^2}$$



- Resummed properties of the quasiparticles are specified by scalar complex self-energies:

gluon propagator: $\Delta^{-1} = P^2 - \Pi$	&	quark propagator $S_q^{-1} = P^2 - \Sigma_q$
gluon self-energy: $\Pi = M_g^2 - i2g_g\omega$	&	quark self-energy: $\Sigma_q = M_q^2 - i2g_q\omega$

- Real part of the self-energy: thermal mass (M_g, M_q)
- Imaginary part of the self-energy: interaction width of partons (γ_g, γ_q)

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

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Parton properties

- **Modeling of the quark/gluon masses and widths (inspired by HTL calculations)**

$$M_g^2(T,\mu_B) = \frac{g^2(T,\mu_B)}{6}\left(\left(N_c + \frac{1}{2}N_f\right)T^2 + \frac{N_c}{2}\sum_q \frac{\mu_q^2}{\pi^2}\right)$$

$$M_{q(\bar{q})}^2(T,\mu_B) = \frac{N_c^2-1}{8N_c} g^2(T,\mu_B)\left(T^2 + \frac{\mu_q^2}{\pi^2}\right)$$

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

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- **Only one parameter (c = 14.4) + (T,μ_B)- dependent coupling constant to determine from lattice results**

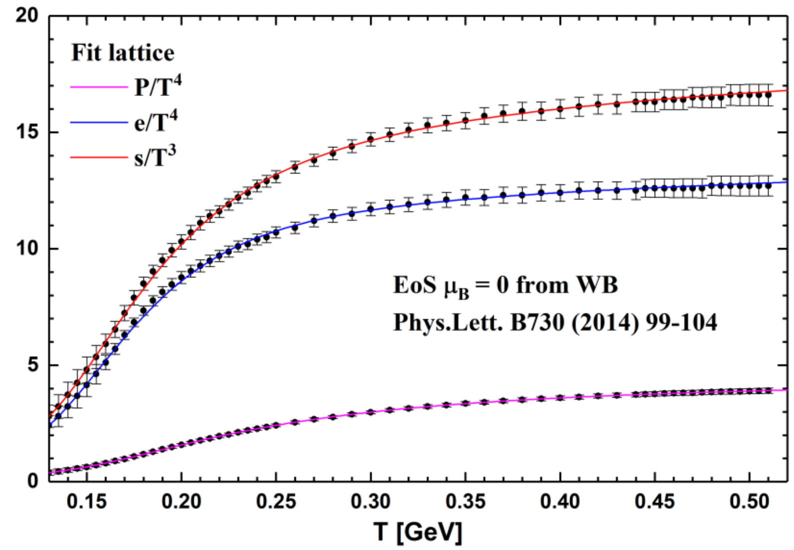
DQPM coupling constant

- **Input: entropy density as a function of temperature for $\mu_B = 0$**

$$g^2(s/s_{SB}) = d\left((s/s_{SB})^e - 1\right)^f$$

$$s_{SB}^{QCD} = 19/9\pi^2 T^3$$

Fit to lattice data:



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- **Scaling hypothesis at finite $\mu_B \approx 3\mu_q$**

$$g^2(T/T_c, \mu_B) = g^2\left(\frac{T^*}{T_c(\mu_B)}, \mu_B = 0\right)$$

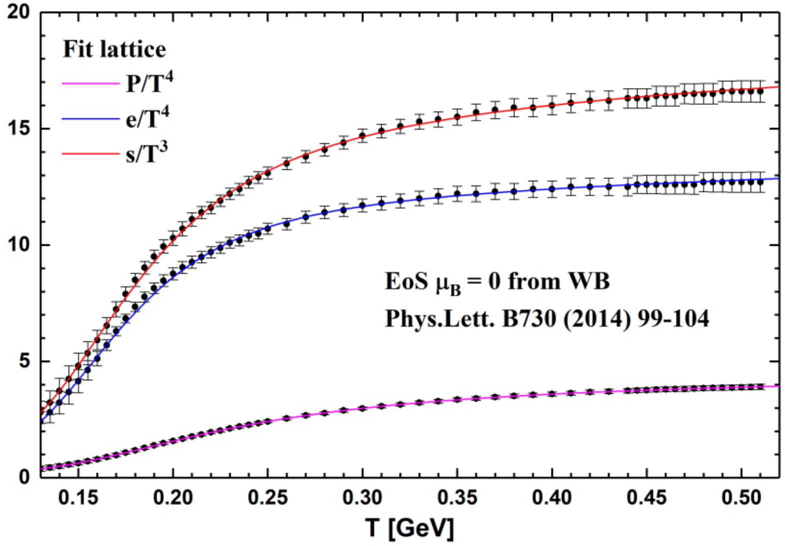
with the effective temperature

$$T^* = \sqrt{T^2 + \mu_q^2/\pi^2}$$

and the critical temperature at finite μ_B

$$T_c(\mu_B) = T_c\sqrt{1 - \alpha\mu_B^2}$$

Fit to lattice data:



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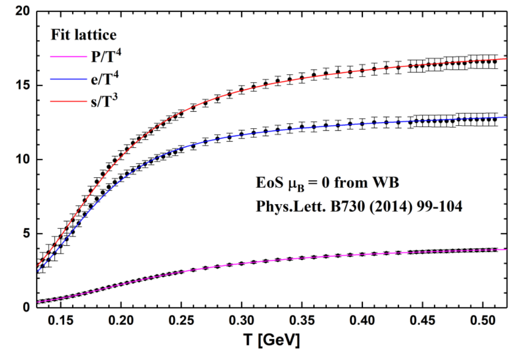
$$g^2(s/s_{SB}) = d\left((s/s_{SB})^e - 1\right)^f$$

$$s_{SB}^{QCD} = 19/9\pi^2 T^3$$

Fit to lattice data:



- **Scaling hypothesis at finite $\mu_B \approx 3\mu_q$**

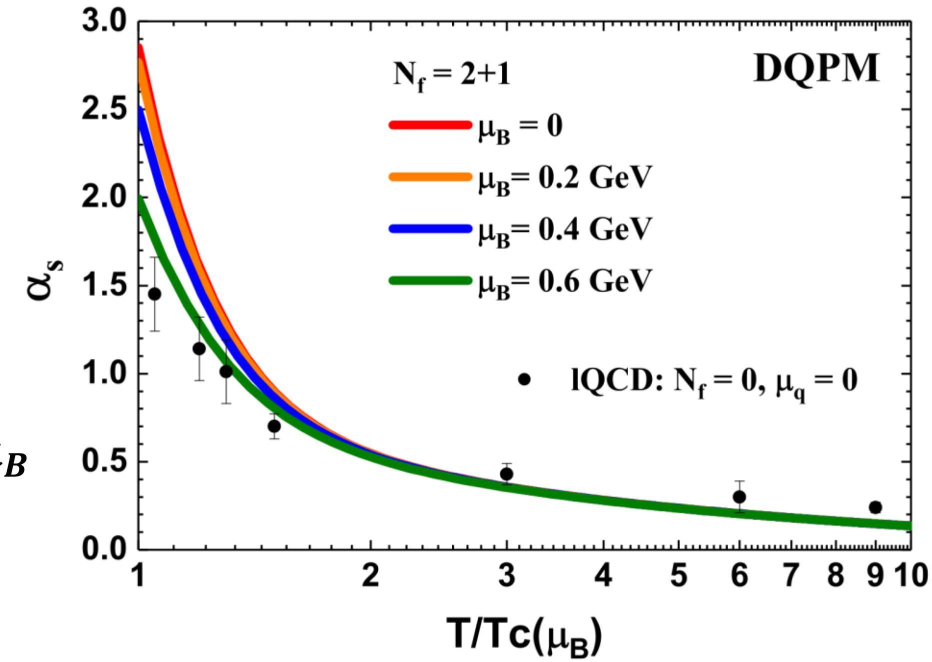
$$g^2(T/T_c, \mu_B) = g^2\left(\frac{T^*}{T_c(\mu_B)}, \mu_B = 0\right)$$

with the effective temperature

$$T^* = \sqrt{T^2 + \mu_q^2/\pi^2}$$

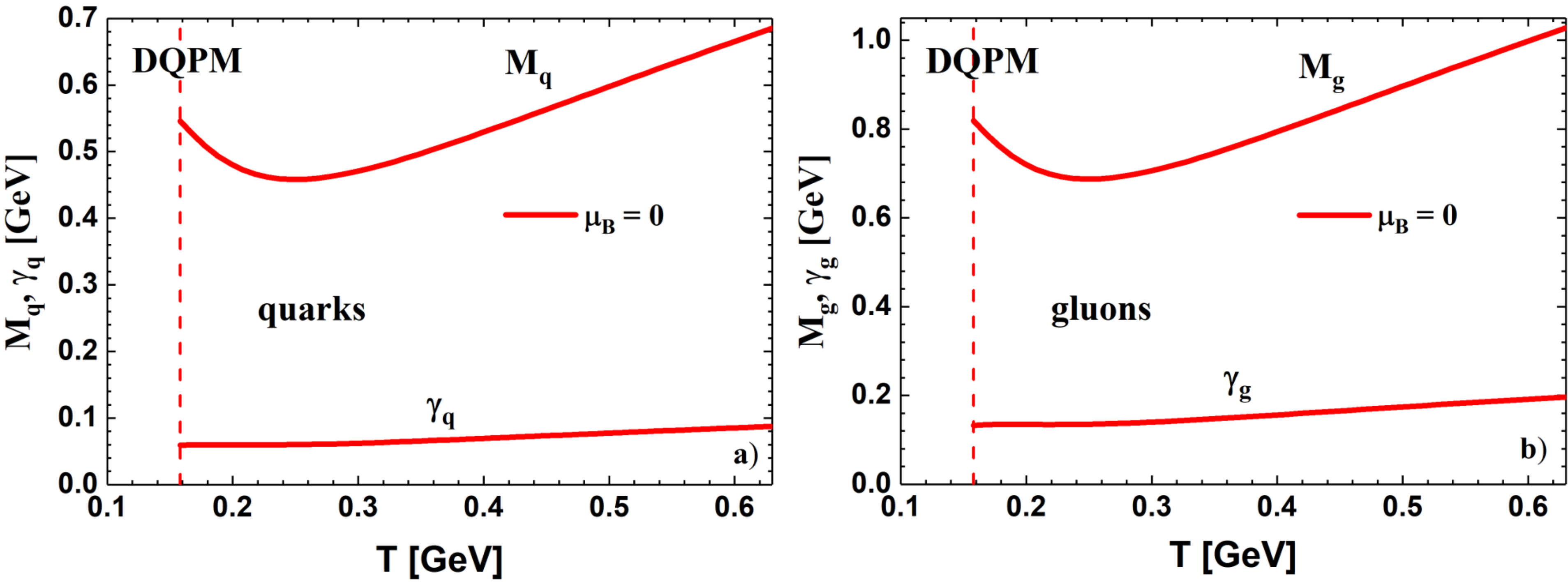
and the critical temperature at finite μ_B

$$T_c(\mu_B) = T_c\sqrt{1 - \alpha\mu_B^2}$$



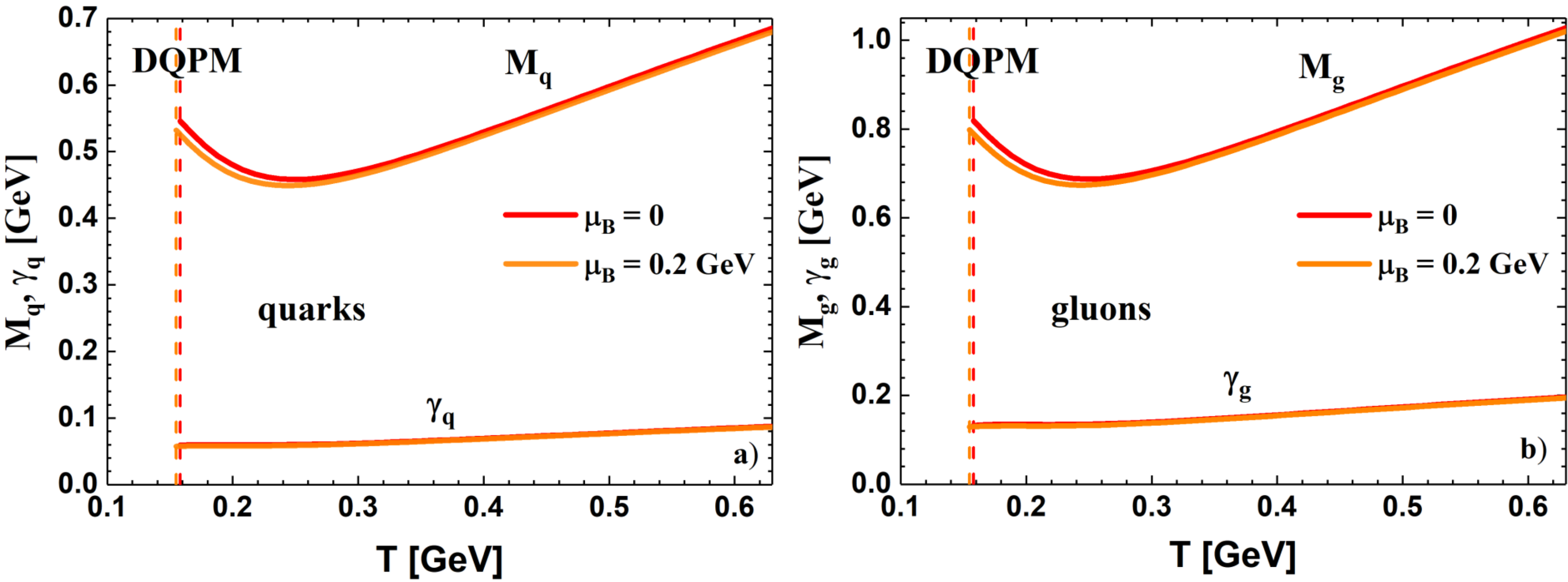
DQPM: parton properties

- **DQPM masses and widths as a function of (T, μ_B)**



DQPM: parton properties

- DQPM masses and widths as a function of (T, μ_B)



DQPM: parton properties

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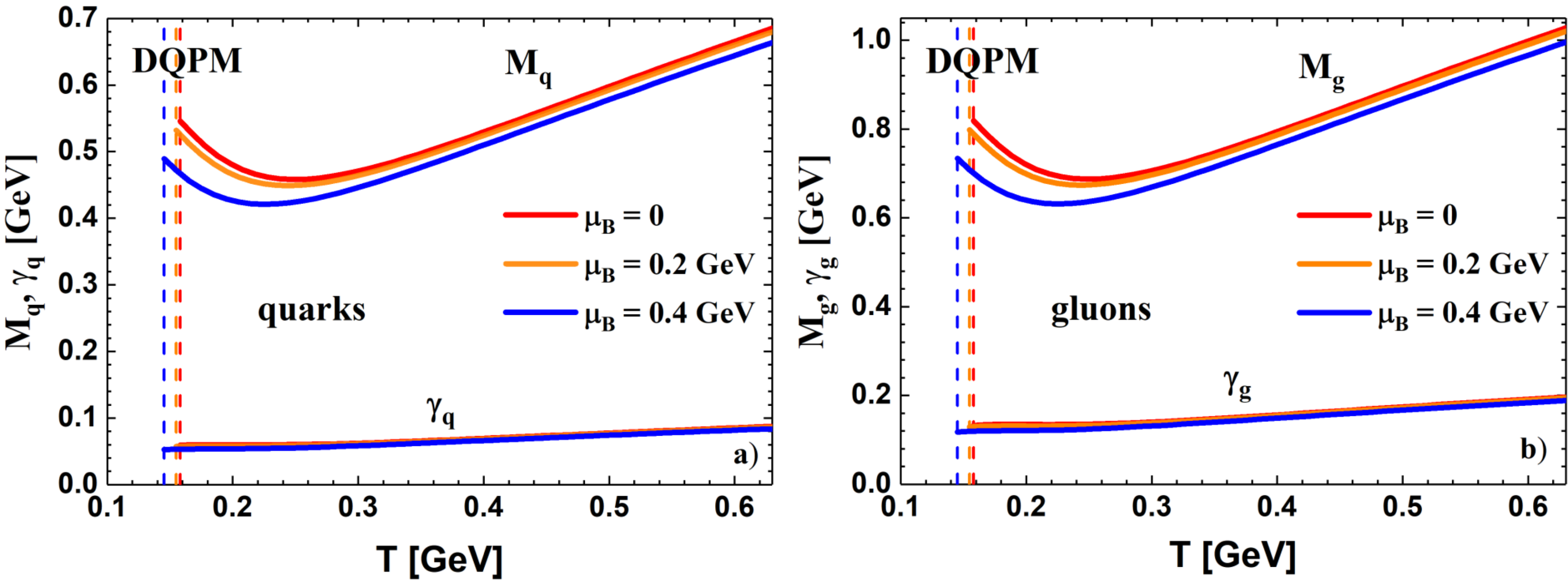

DQPM: parton properties

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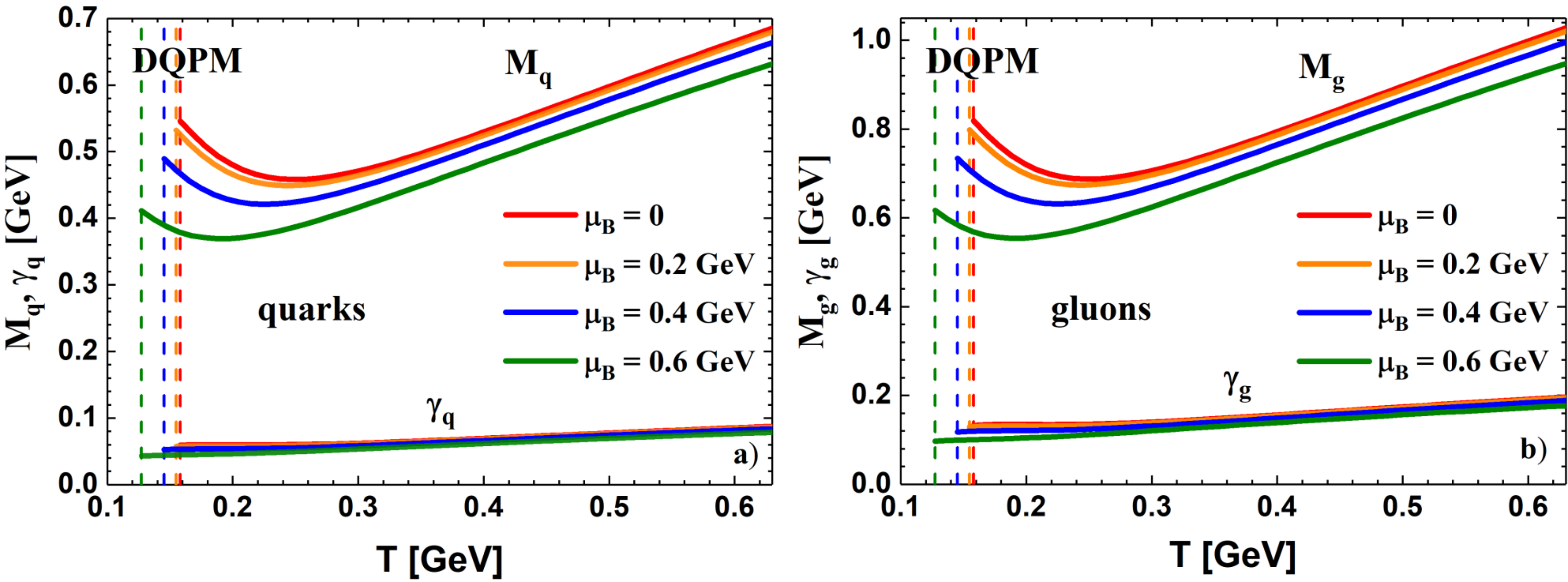

DQPM Thermodynamics

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- **Entropy and baryon density in the quasiparticle limit:**

$$s^{dqp} = -\int \frac{d\omega}{2\pi}\frac{d^3p}{(2\pi)^3}\Big[d_g \frac{\partial n_B}{\partial T}\left(\mathrm{Im}(\ln -\Delta^{-1}) + \mathrm{Im}\,\Pi\,\mathrm{Re}\,\Delta\right) + \sum_{q=u,d,s} d_q \frac{\partial n_F(\omega-\mu_q)}{\partial T}\left(\mathrm{Im}(\ln -S_q^{-1}) + \mathrm{Im}\,\Sigma_q\,\mathrm{Re}\,S_q\right) + \sum_{\bar{q}=\bar{u},\bar{d},\bar{s}} d_{\bar{q}} \frac{\partial n_F(\omega+\mu_q)}{\partial T}\left(\mathrm{Im}(\ln -S_{\bar{q}}^{-1}) + \mathrm{Im}\,\Sigma_{\bar{q}}\,\mathrm{Re}\,S_{\bar{q}}\right)\Big]$$

$$n^{dqp} = -\int \frac{d\omega}{2\pi}\frac{d^3p}{(2\pi)^3}\Big[\sum_{q=u,d,s} d_q \frac{\partial n_F(\omega-\mu_q)}{\partial \mu_q}\left(\mathrm{Im}(\ln -S_q^{-1}) + \mathrm{Im}\,\Sigma_q\,\mathrm{Re}\,S_q\right) + \sum_{\bar{q}=\bar{u},\bar{d},\bar{s}} d_{\bar{q}} \frac{\partial n_F(\omega+\mu_q)}{\partial \mu_q}\left(\mathrm{Im}(\ln -S_{\bar{q}}^{-1}) + \mathrm{Im}\,\Sigma_{\bar{q}}\,\mathrm{Re}\,S_{\bar{q}}\right)\Big]$$

Blaizot, Iancu, Rebhan, Phys. Rev. D 63 (2001) 065003

Note: The contribution of longitudinal gluons is neglected in the calculation of thermodynamic quantities

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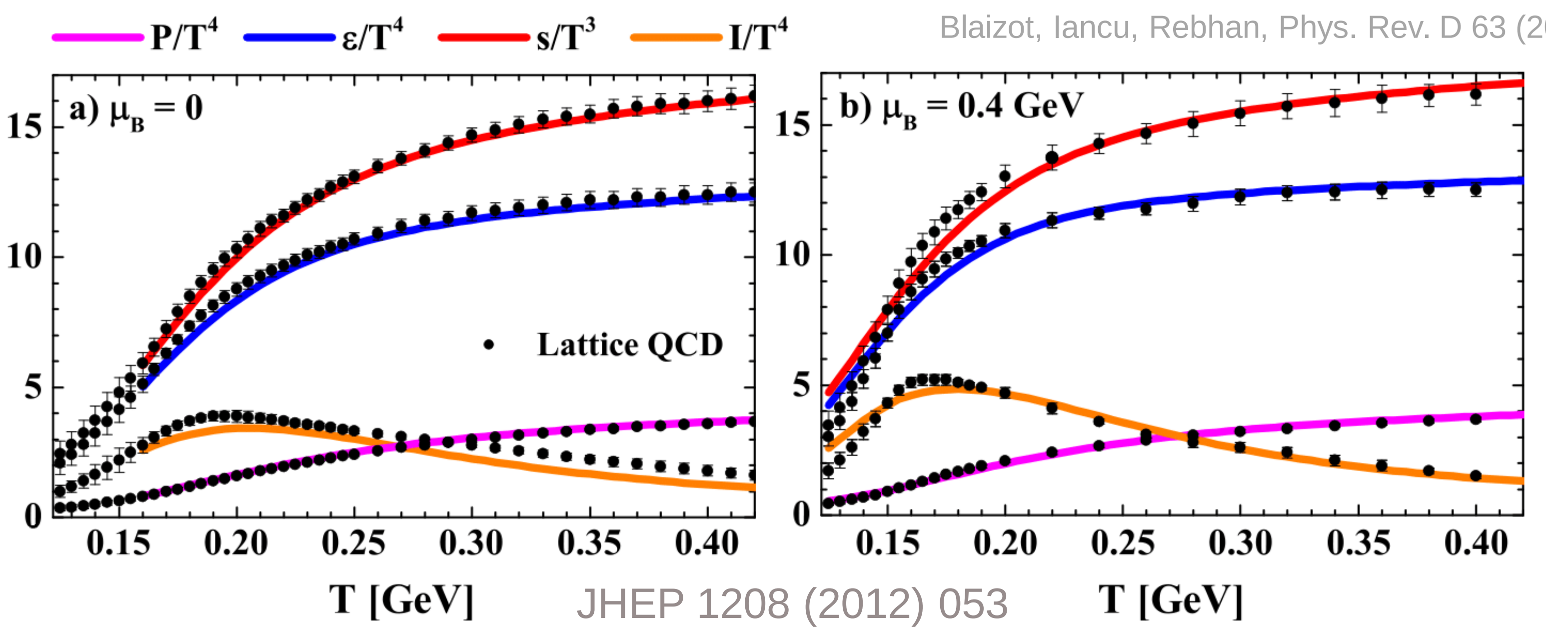
DQPM Thermodynamics

- **Entropy and baryon density in the quasiparticle limit:**

$$s^{dqp} = - \int \frac{d\omega}{2\pi} \frac{d^3p}{(2\pi)^3} \Big[d_g \frac{\partial n_B}{\partial T} \left(\mathrm{Im}(\ln - \Delta^{-1}) + \mathrm{Im}\,\Pi\, \mathrm{Re}\,\Delta \right) + \sum_{q=u,d,s} d_q \frac{\partial n_F(\omega - \mu_q)}{\partial T} \left(\mathrm{Im}(\ln - S_q^{-1}) + \mathrm{Im}\,\Sigma_q\, \mathrm{Re}\, S_q \right) + \sum_{\bar q=\bar u,\bar d,\bar s} d_{\bar q} \frac{\partial n_F(\omega + \mu_q)}{\partial T} \left(\mathrm{Im}(\ln - S_{\bar q}^{-1}) + \mathrm{Im}\,\Sigma_{\bar q}\, \mathrm{Re}\, S_{\bar q} \right) \Big]$$

$$n^{dqp} = - \int \frac{d\omega}{2\pi} \frac{d^3p}{(2\pi)^3} \Big[\sum_{q=u,d,s} d_q \frac{\partial n_F(\omega - \mu_q)}{\partial \mu_q} \left(\mathrm{Im}(\ln - S_q^{-1}) + \mathrm{Im}\,\Sigma_q\, \mathrm{Re}\, S_q \right) + \sum_{\bar q=\bar u,\bar d,\bar s} d_{\bar q} \frac{\partial n_F(\omega + \mu_q)}{\partial \mu_q} \left(\mathrm{Im}(\ln - S_{\bar q}^{-1}) + \mathrm{Im}\,\Sigma_{\bar q}\, \mathrm{Re}\, S_{\bar q} \right) \Big]$$

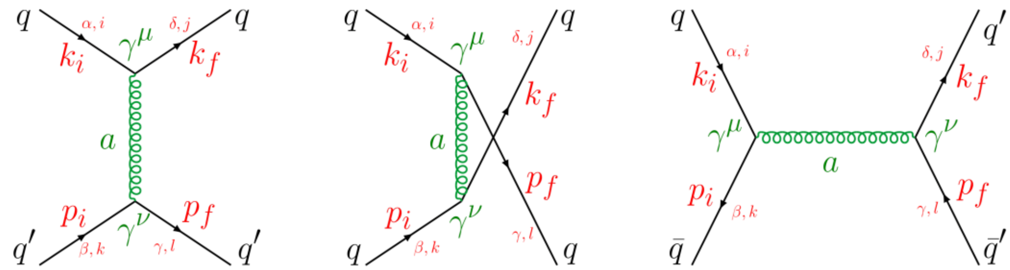
Blaizot, Iancu, Rebhan, Phys. Rev. D 63 (2001) 065003



JHEP 1208 (2012) 053

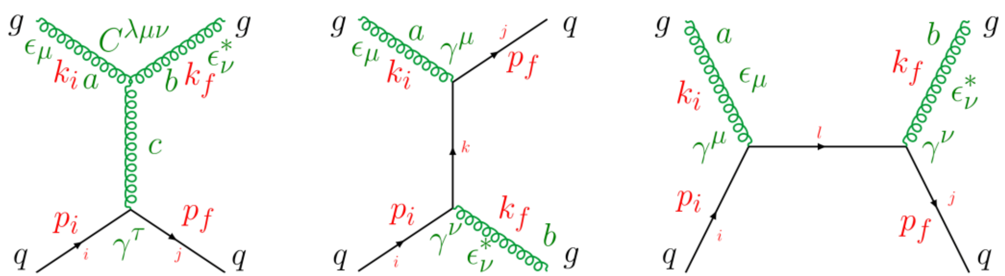
Partonic interactions: matrix elements

qq', $q\bar{q}$



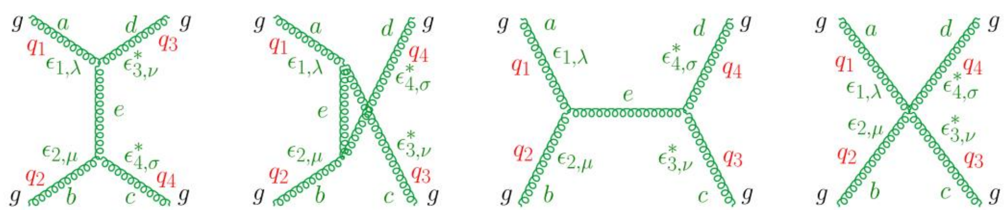
$t-$channel $u-$channel $s-$channel

gq



$t-$channel $u-$channel $s-$channel

gg

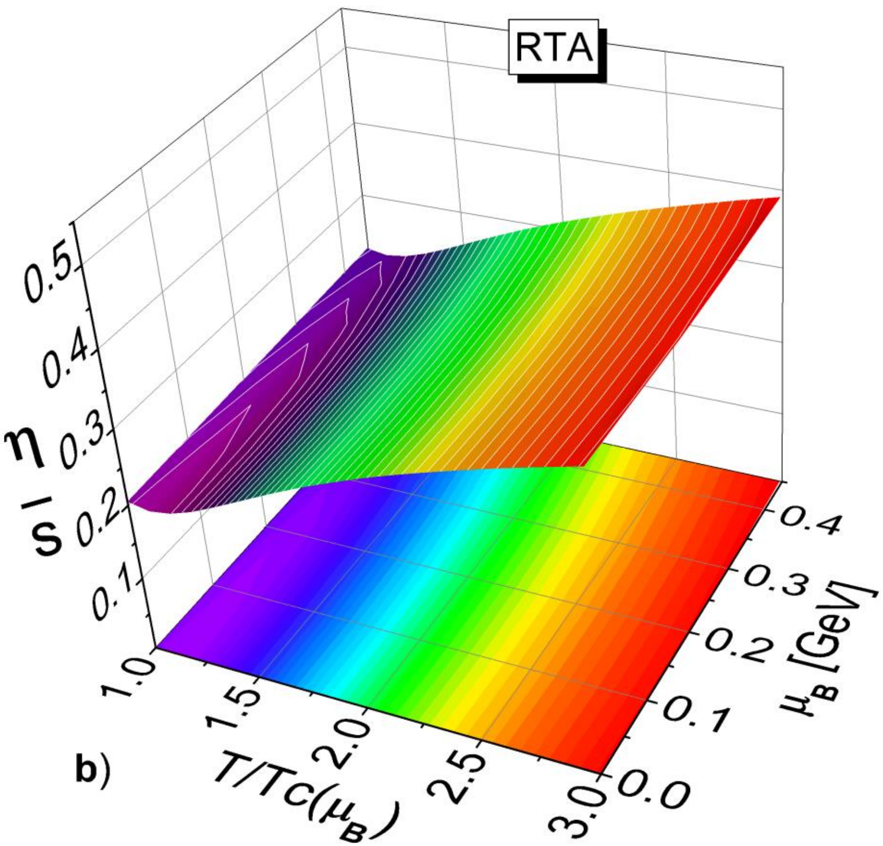


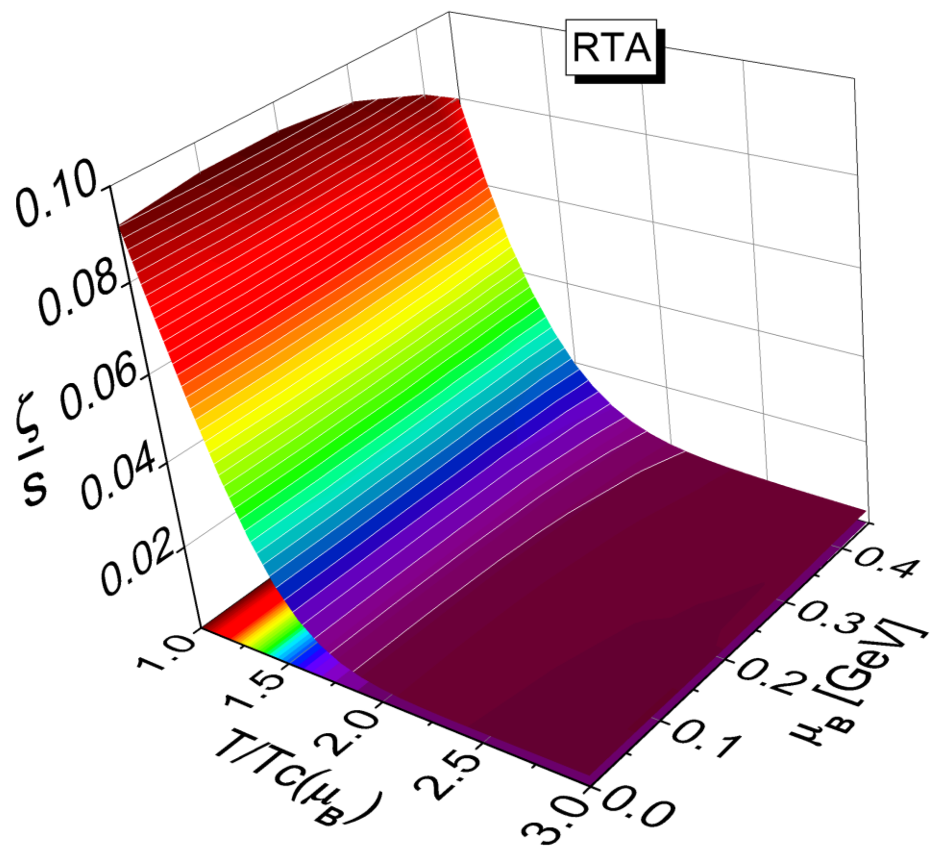
$t-$channel $u-$channel $s-$channel $4-$point

Shear and bulk viscosities (T, μ_B)

$$\eta^{\rm RTA}(T,\mu_q) = \frac{1}{15T}\int \frac{d^3p}{(2\pi)^3} \sum_{i=q,\bar{q},g} \left(\frac{\mathbf{p}^4}{E_i^2\ \Gamma_i(\mathbf{p}_i,T,\mu_q)}\ d_i\left((1\pm f_i(E_i))f_i(E_i)\right)\right) + \mathcal{O}(\Gamma_i)$$

$$\zeta^{\rm RTA}(T,\mu_q) = \frac{1}{9T}\int \frac{d^3p}{(2\pi)^3} \sum_{i=q,\bar{q}} [\mathbf{p}^2 - 3c_s^2(E_i^2 - T^2\frac{dm_q^2}{dT^2})]^2 \left(\frac{\mathbf{p}^4}{E_i^2\ \Gamma_i(\mathbf{p}_i,T,\mu_q)}\ d_i\left((1\pm f_i(E_i))f_i(E_i)\right)\right) + \mathcal{O}(\Gamma_i)$$





QGP:

in equilibrium → off equilibrium

DQPM → PHSD

Energy-momentum tensor in PHSD

CRC–TR 211
Strong-interaction matter under extreme conditions

- **In each space-time cell of the PHSD, the energy-momentum tensor is calculated by the formula:**

$$T^{\mu\nu} = \sum_i \frac{p_i^\mu p_i^\nu}{E_i}$$

- **Diagonalization of the energy-momentum tensor to get the energy density and pressure components expressed in the local rest frame (LRF)**

$$T^{\mu\nu} = \begin{pmatrix} T^{00} & T^{01} & T^{02} & T^{03} \\ T^{10} & T^{11} & T^{12} & T^{13} \\ T^{20} & T^{21} & T^{22} & T^{23} \\ T^{30} & T^{31} & T^{32} & T^{33} \end{pmatrix} \Rightarrow \begin{pmatrix} \epsilon^{LRF} & 0 & 0 & 0 \\ 0 & P_x^{LRF} & 0 & 0 \\ 0 & 0 & P_y^{LRF} & 0 \\ 0 & 0 & 0 & P_z^{LRF} \end{pmatrix}$$

- **Landau-matching condition:**

Xu et al., Phys.Rev. C96 (2017), 024902

$$T^{\mu\nu} u_\nu = \epsilon u^\mu = (\epsilon g^{\mu\nu}) u_\nu$$

Baryon density in PHSD

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- **Calculation of the baryon current in each cells of the PHSD**

$$J_B^\mu = \sum_i \frac{p_i^\mu}{E_i} \frac{(q_i - \bar{q}_i)}{3}$$

- **Lorentz transformation to obtain the local baryon density:**

$$n_B = \gamma_E \left(J_B^0 - \vec{\beta}_E \cdot \vec{J}_B \right) = \frac{J_B^0}{\gamma_E}$$

with $\vec{\beta}_E = \vec{J}_B / J_B^0$ **being the Eckart velocity.**

Illustration for HIC $\left(\sqrt{s_{NN}} = 17 \text{ GeV}\right)$

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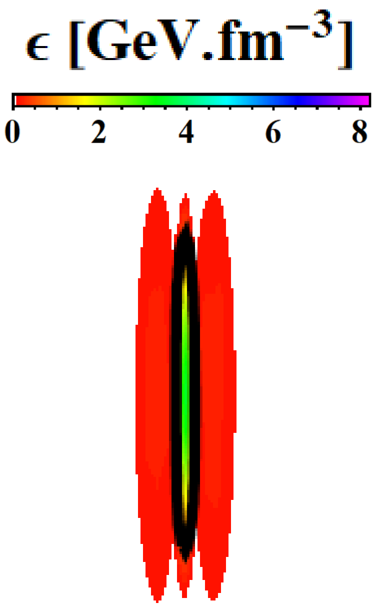
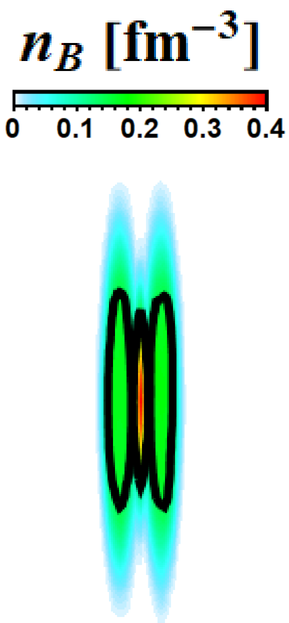




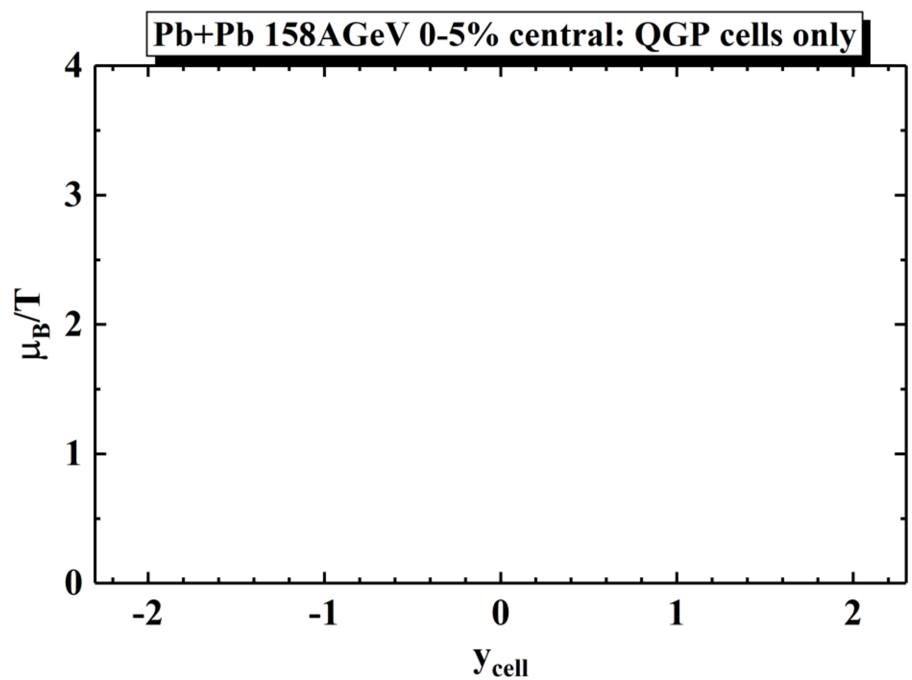
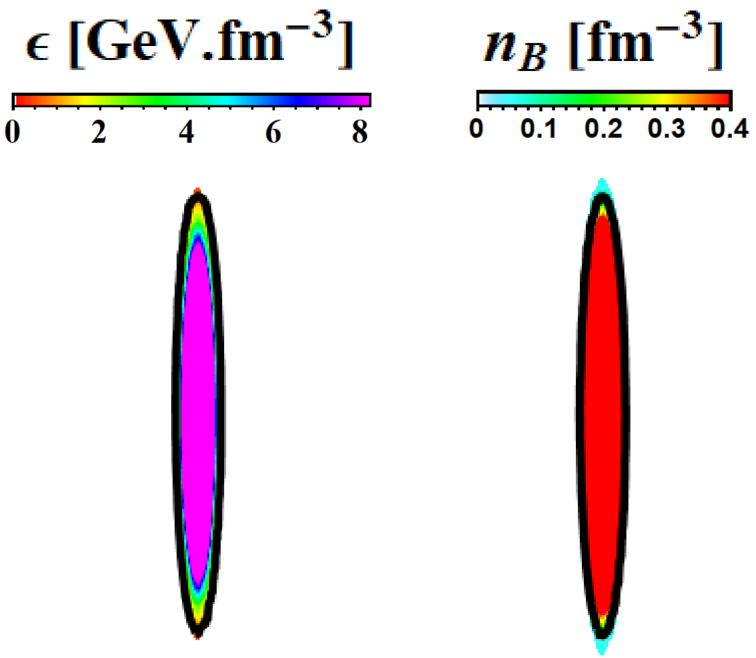


Illustration for HIC $(\sqrt{s_{NN}} = 17\ \text{GeV})$



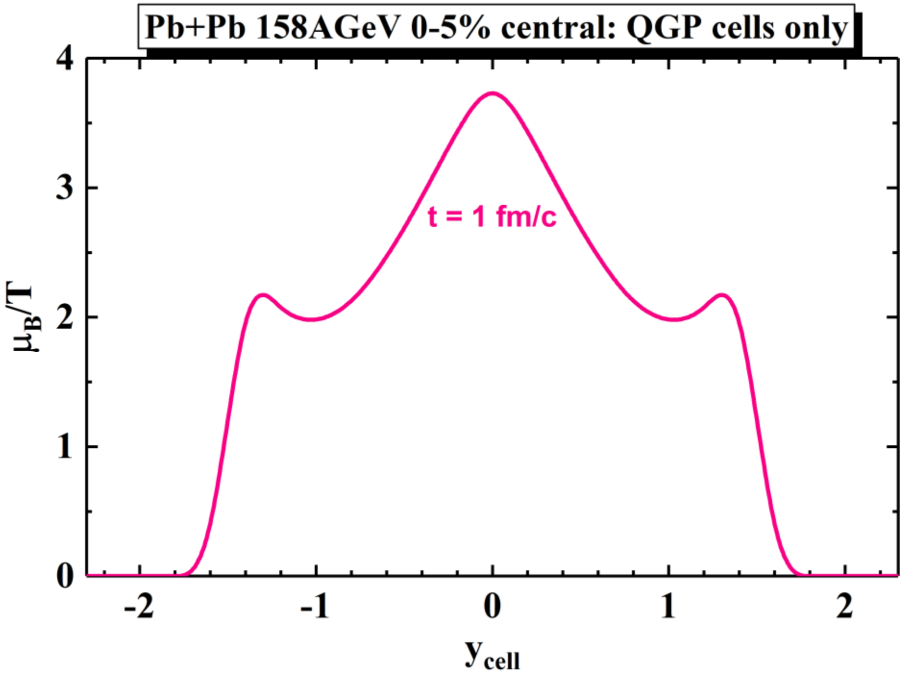
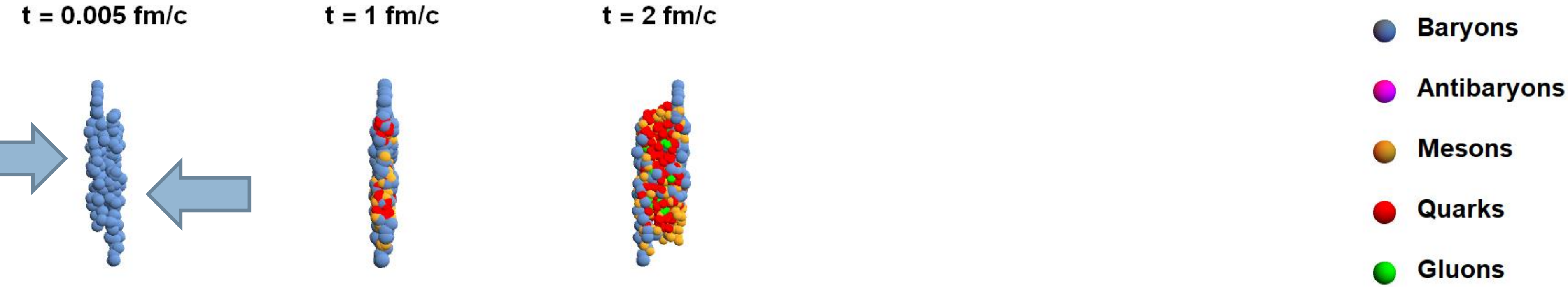
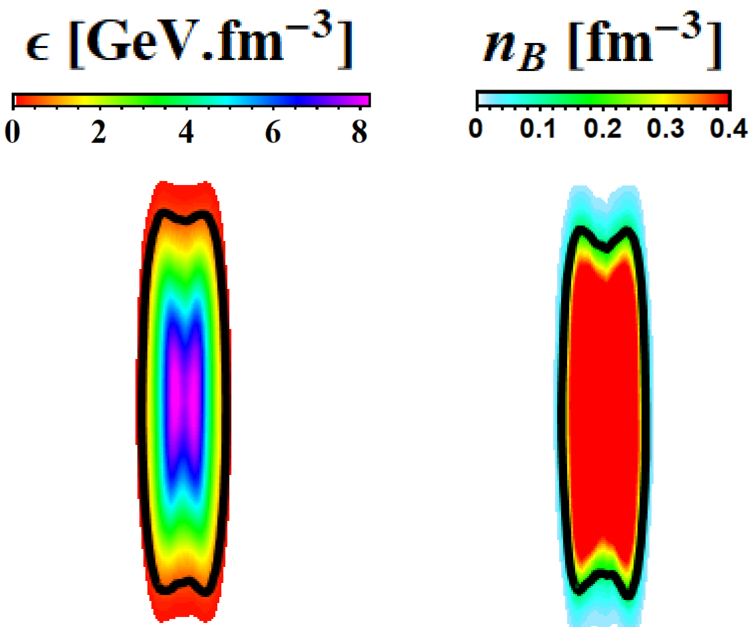


Illustration for HIC $(\sqrt{s_{NN}} = 17\text{ GeV})$





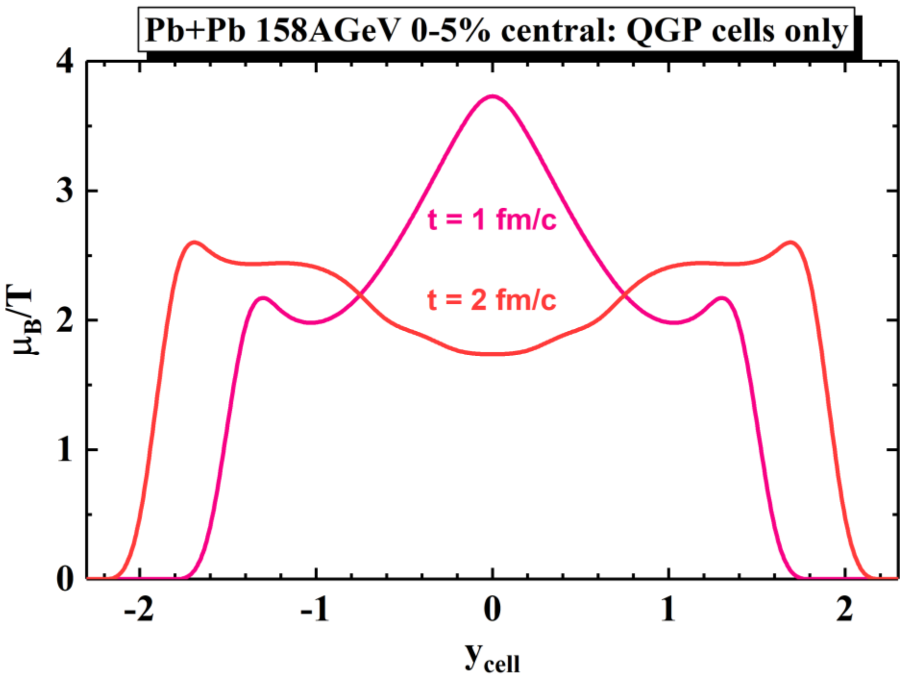
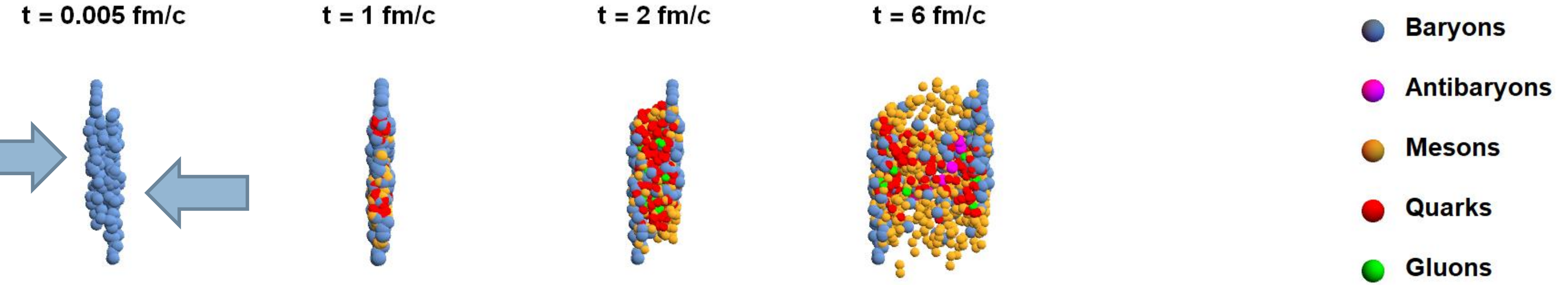
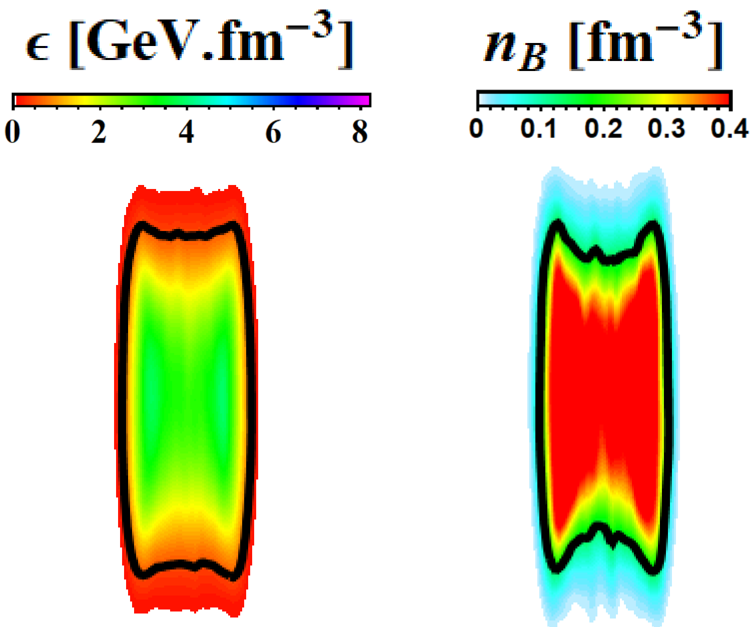


Illustration for HIC ($\sqrt{s_{NN}} = 17$ GeV)





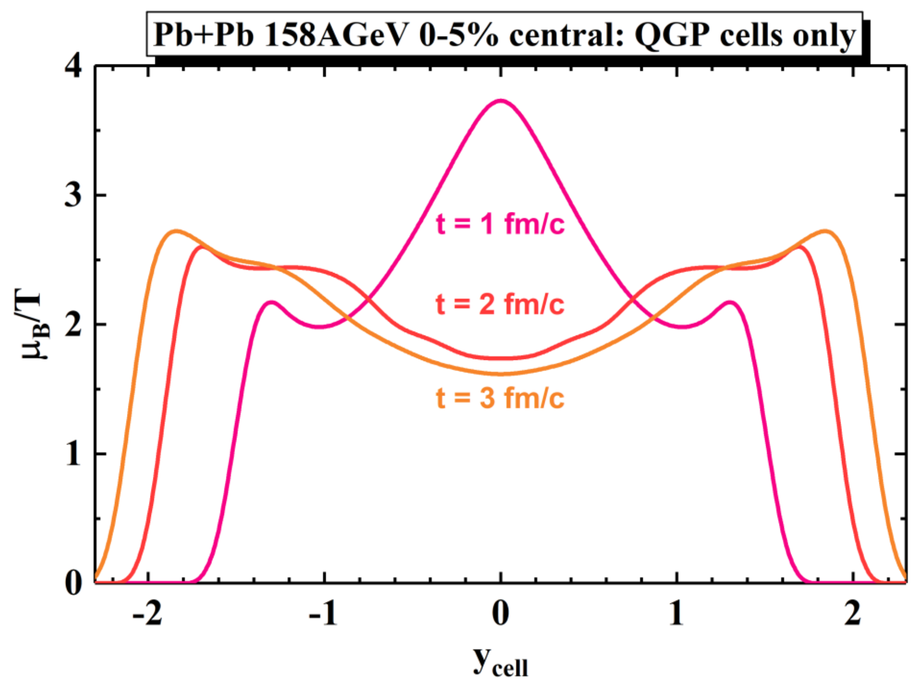
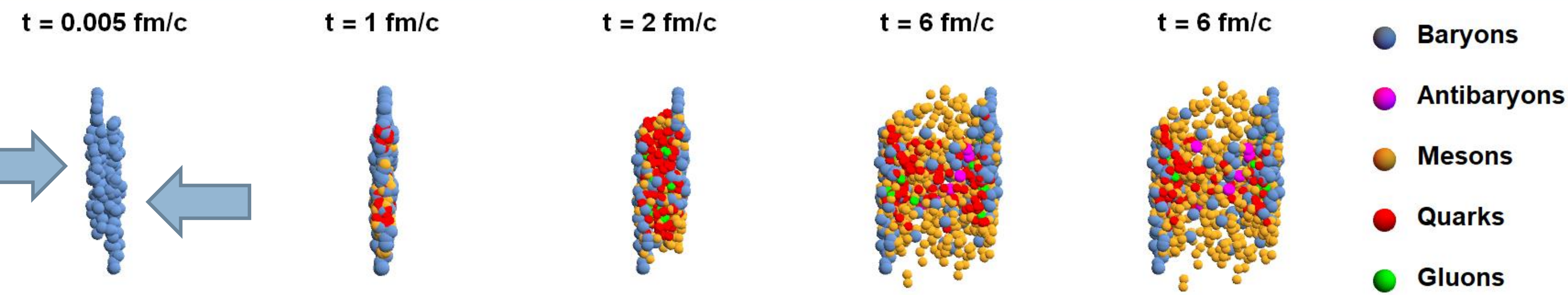
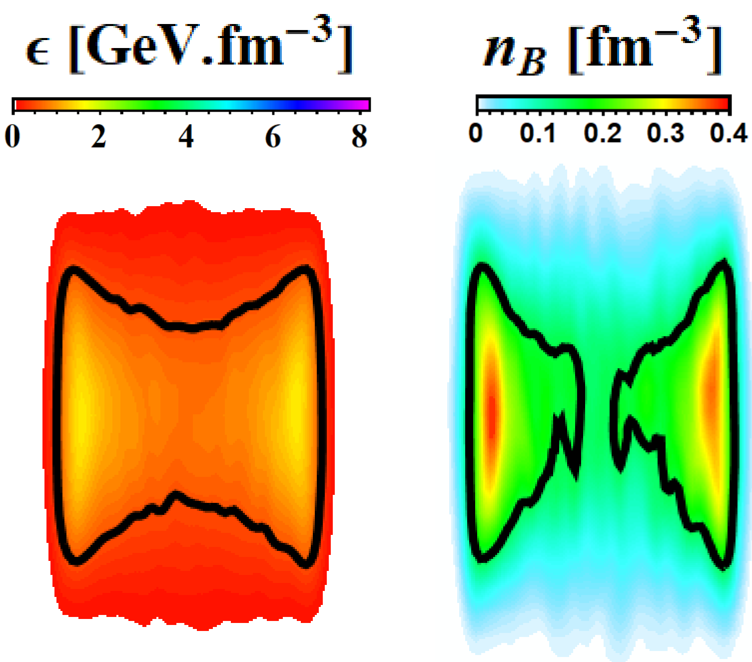
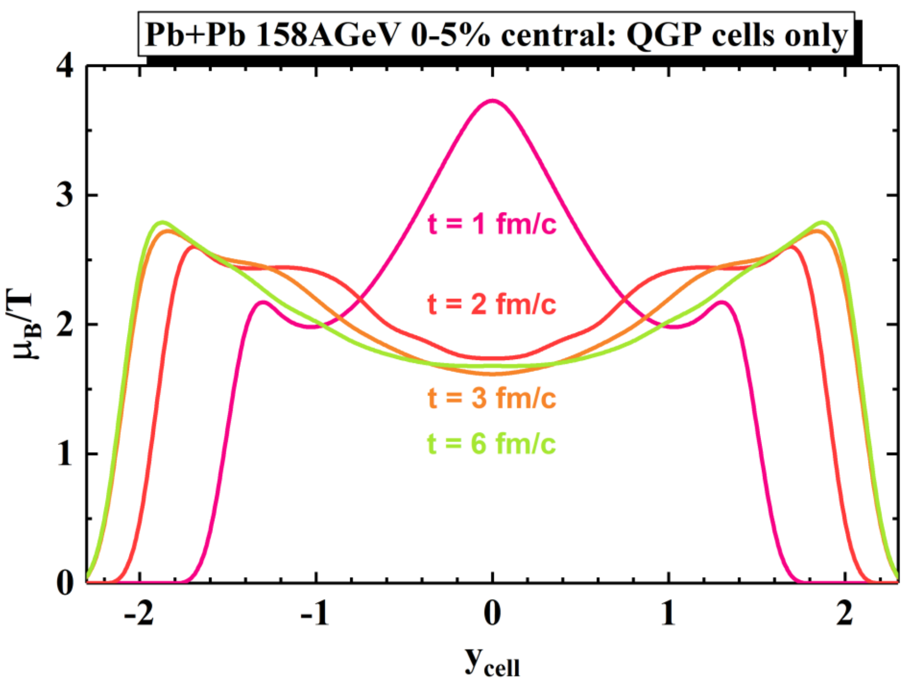


Illustration for HIC $(\sqrt{s_{NN}} = 17$ GeV$)$







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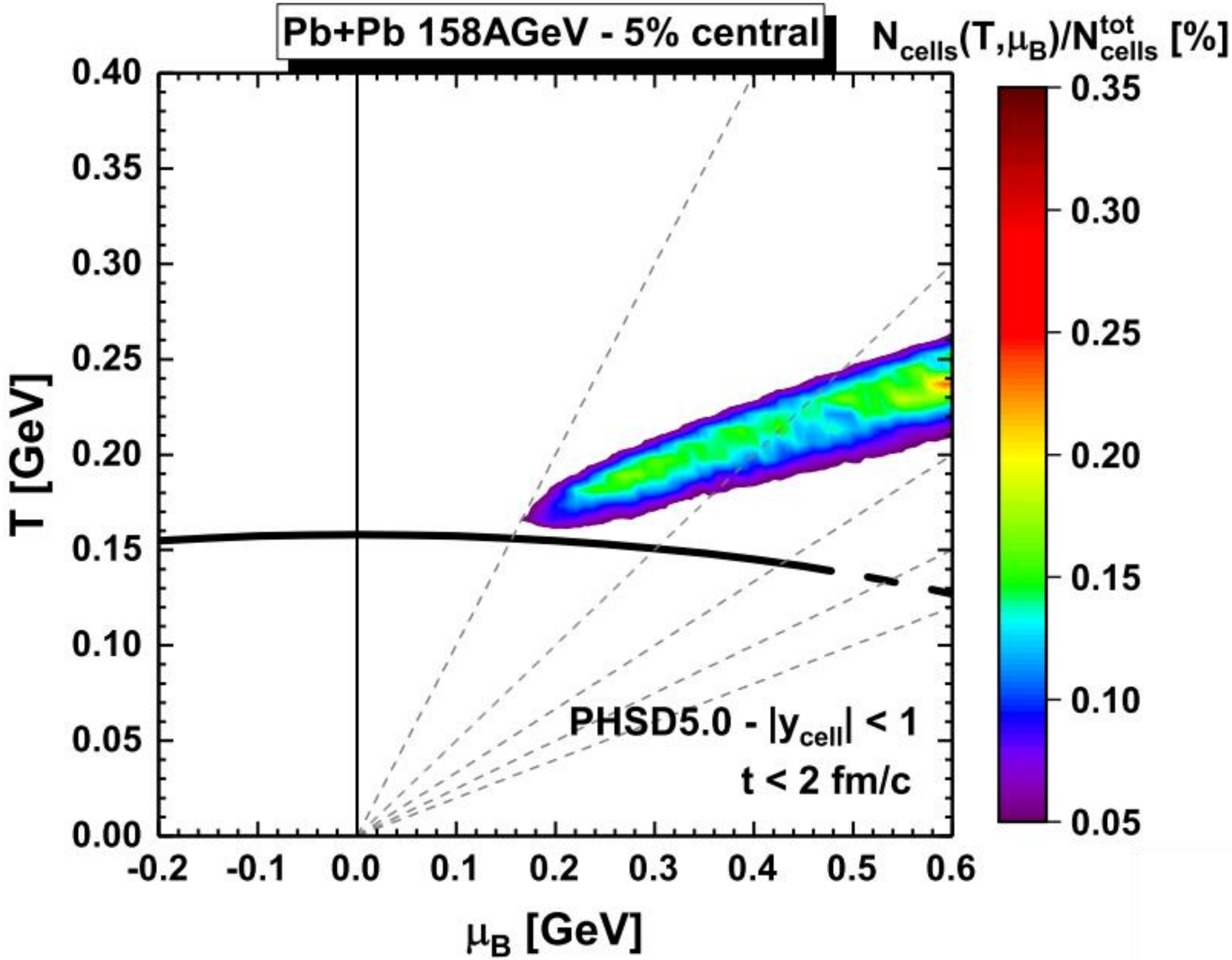

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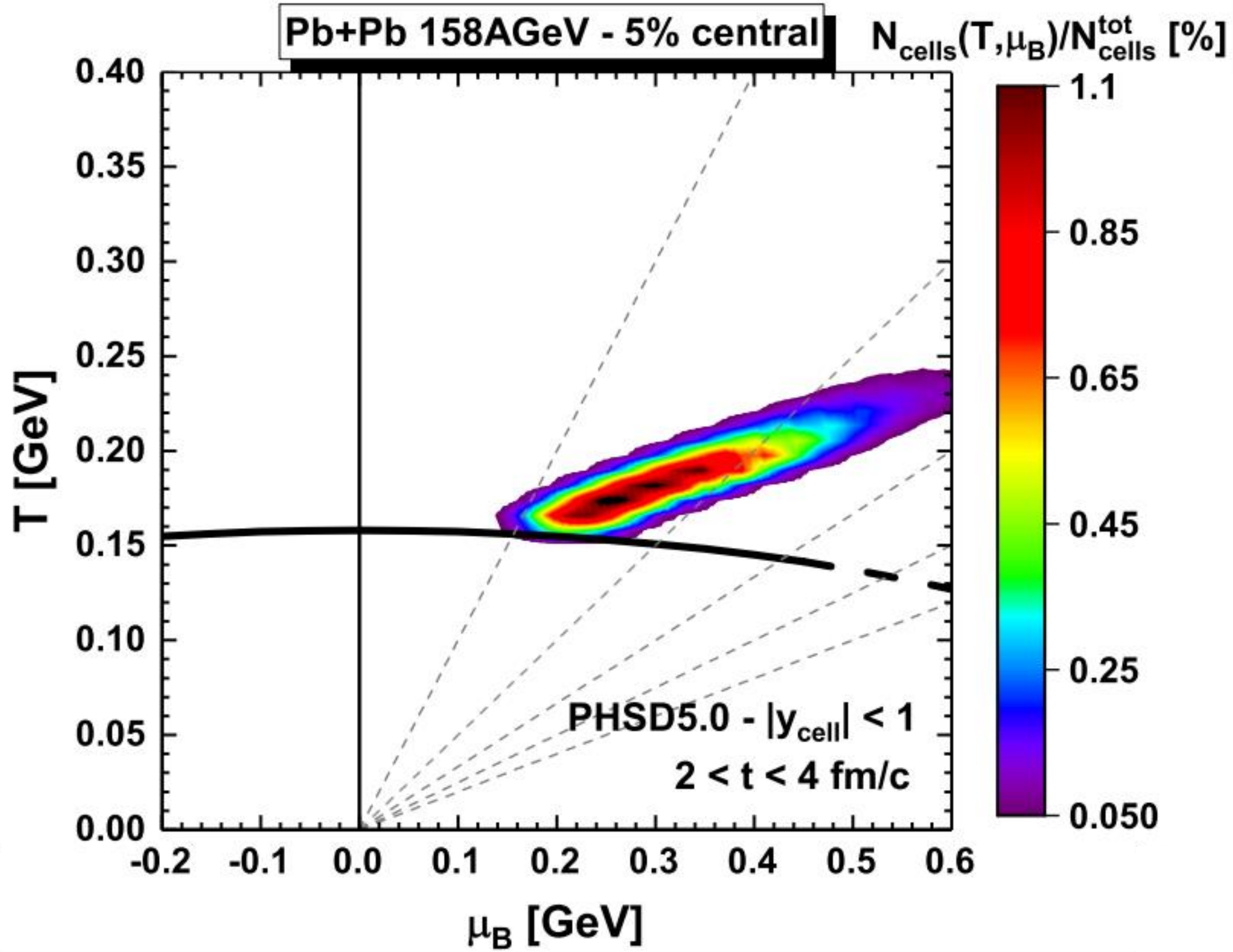

Illustration for HIC ($\sqrt{s_{NN}} = 17$ GeV)

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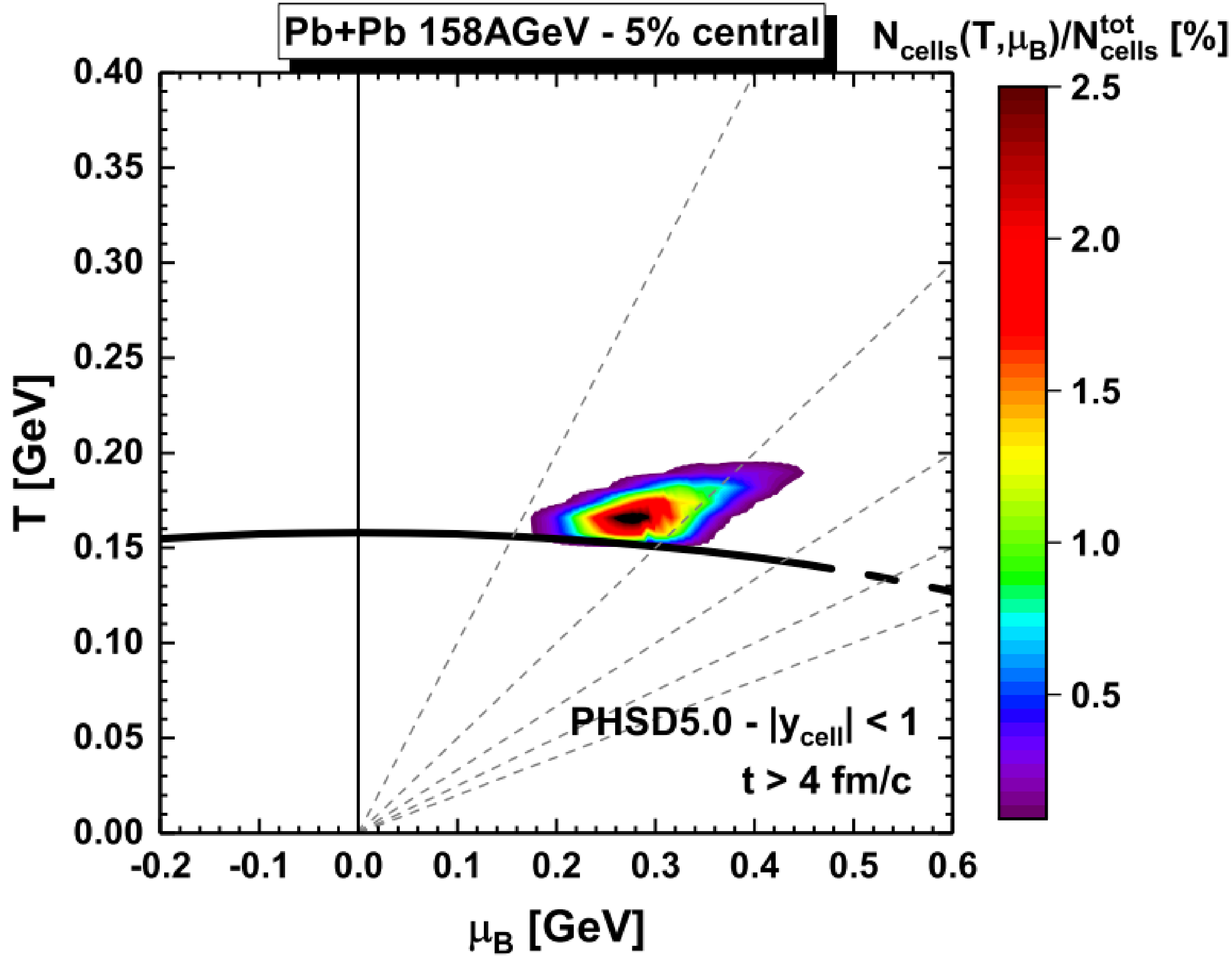
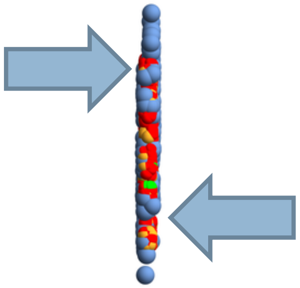
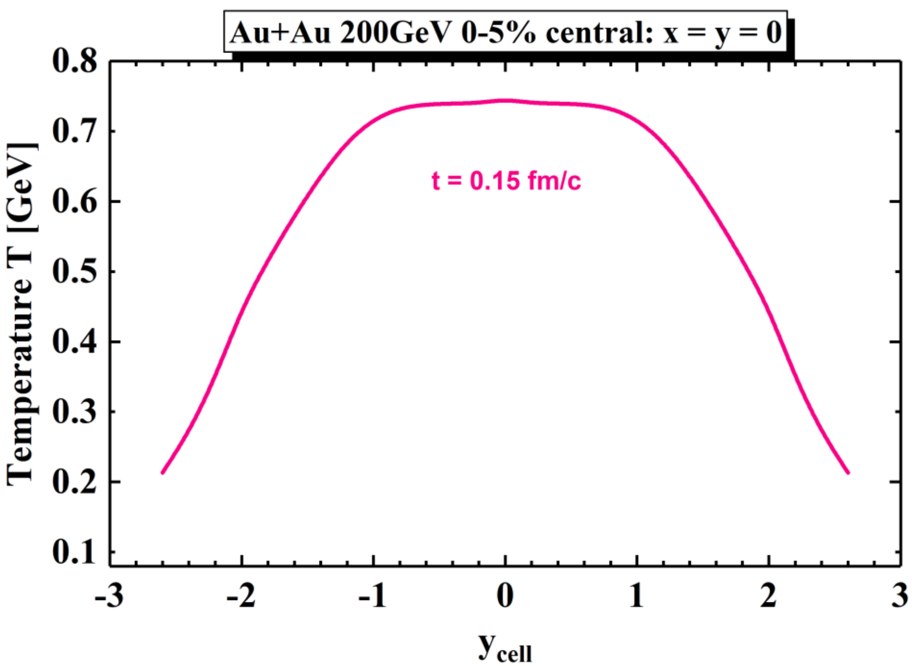


Illustration for HIC ($\sqrt{s_{NN}} = 200$ GeV)





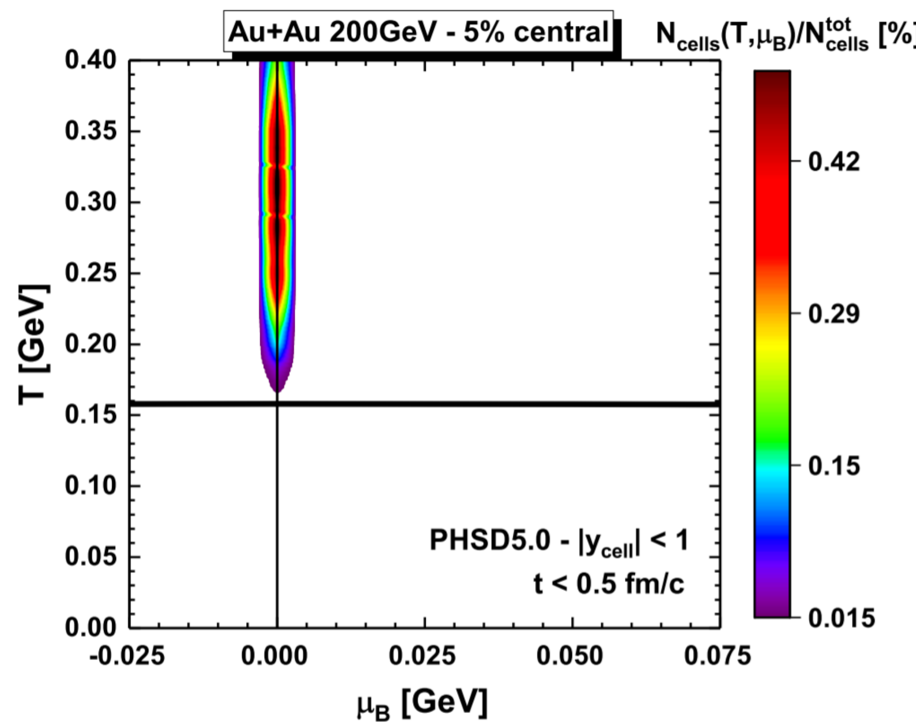
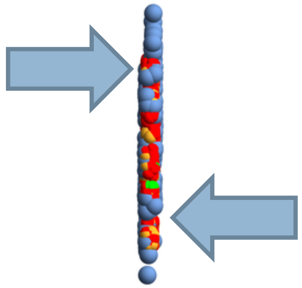
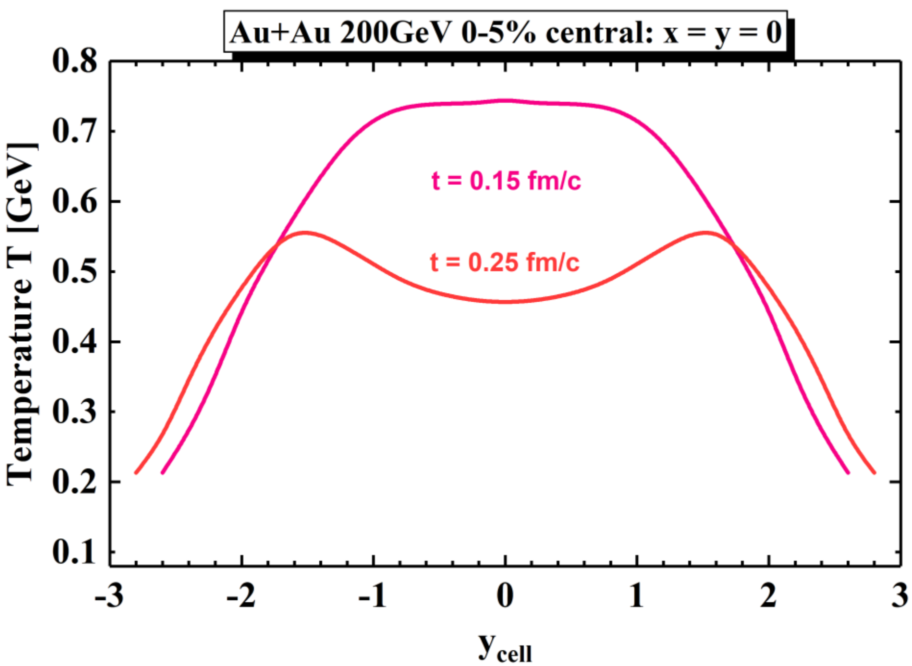
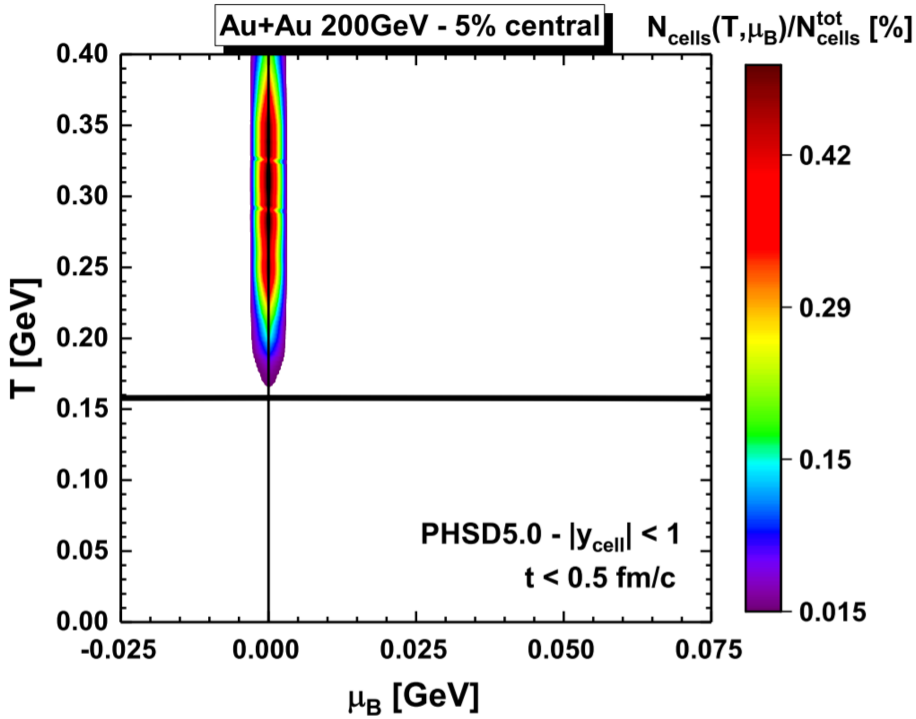


Illustration for HIC ($\sqrt{s_{NN}} = 200$ GeV)







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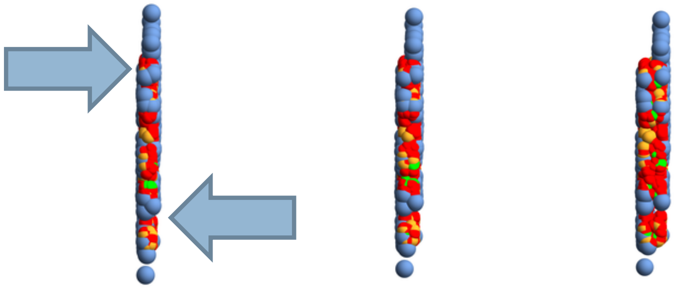
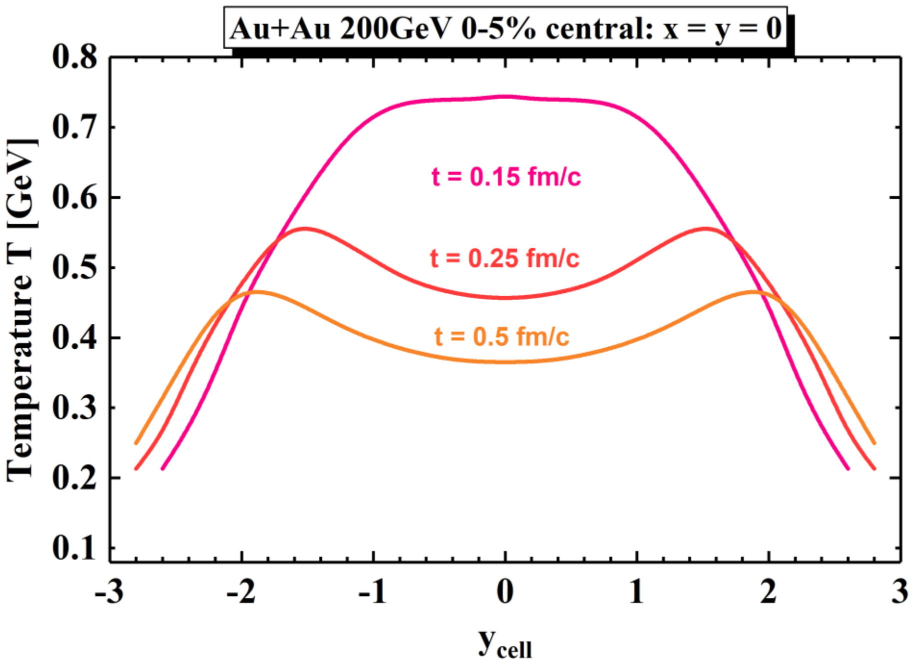




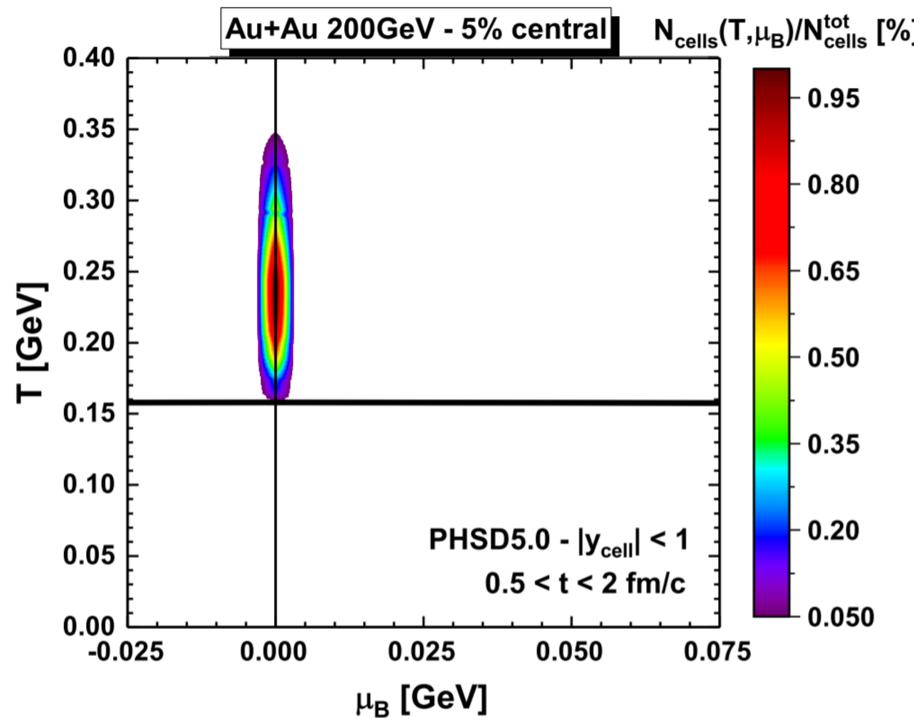
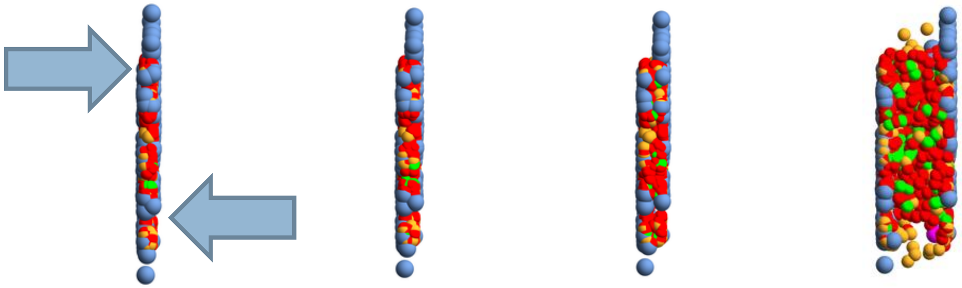
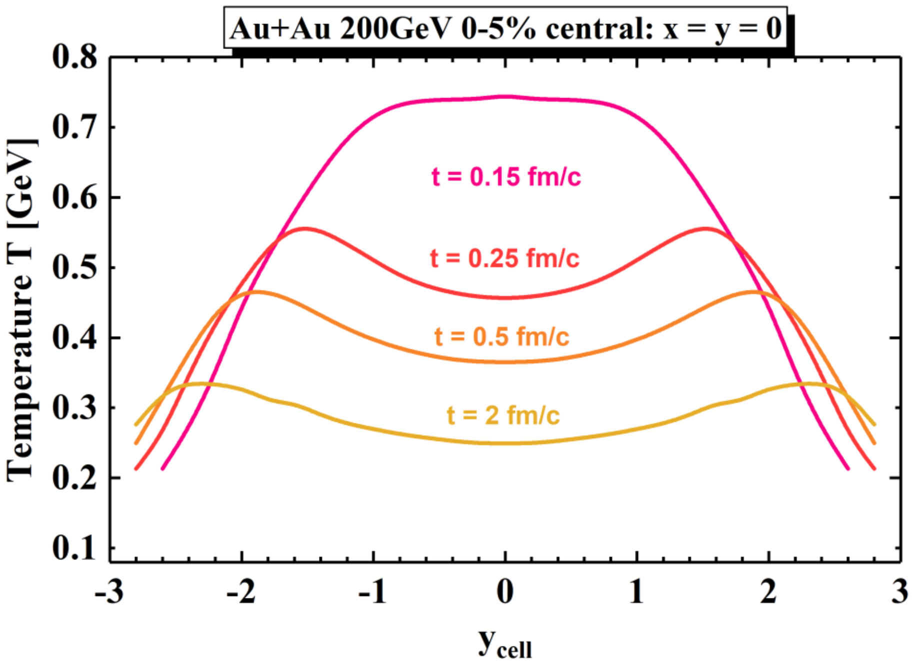


Illustration for HIC ($\sqrt{s_{NN}} = 200$ GeV)





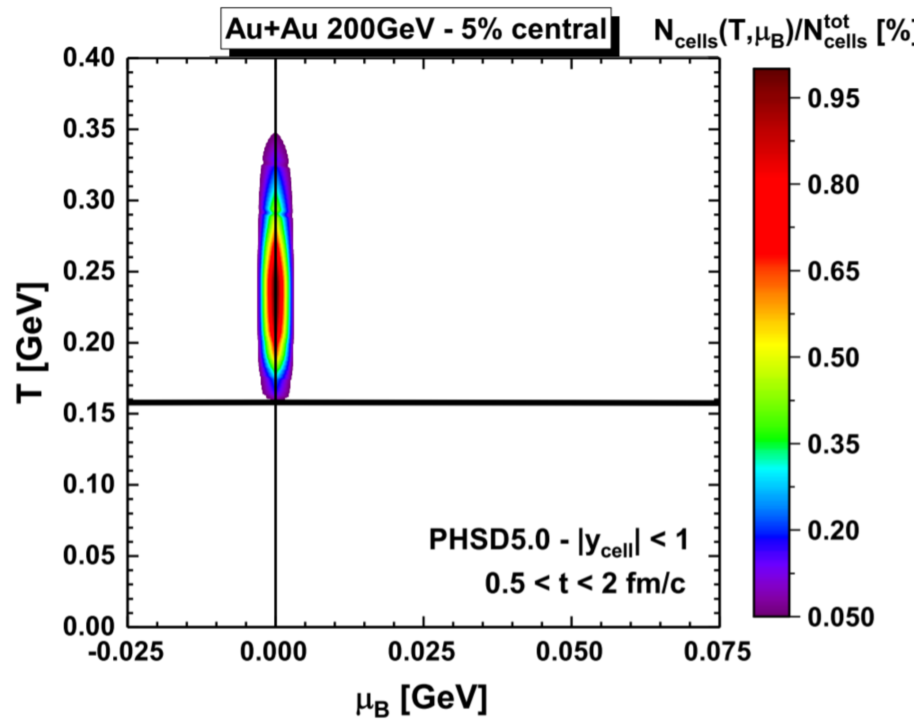
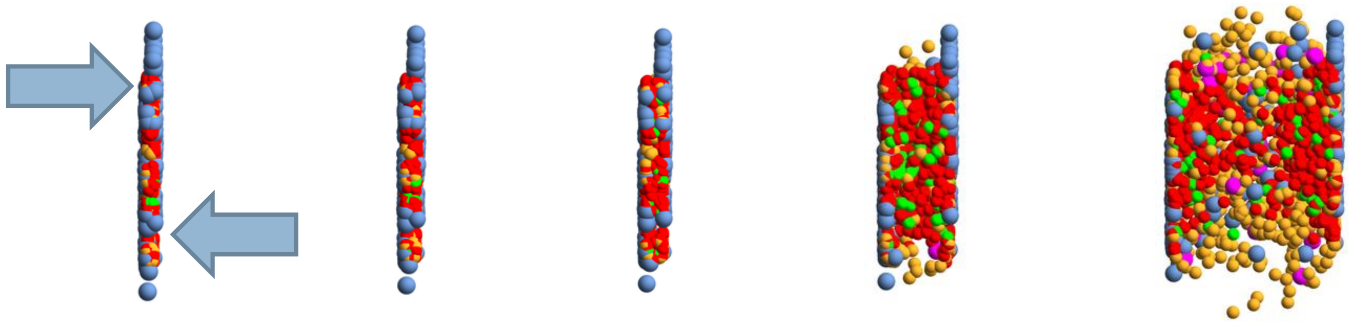
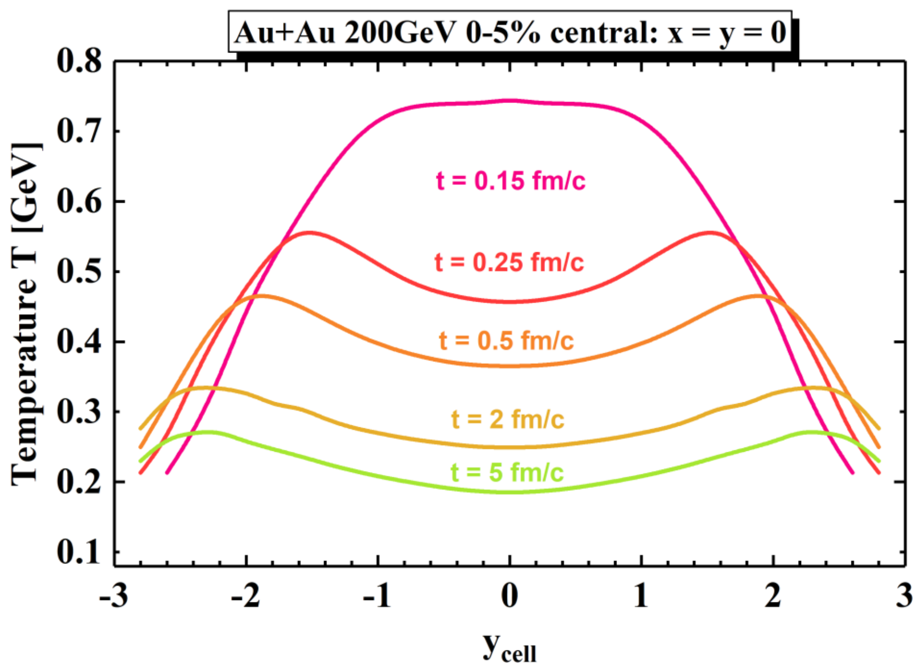


Illustration for HIC ($\sqrt{s_{NN}} = 200$ GeV)





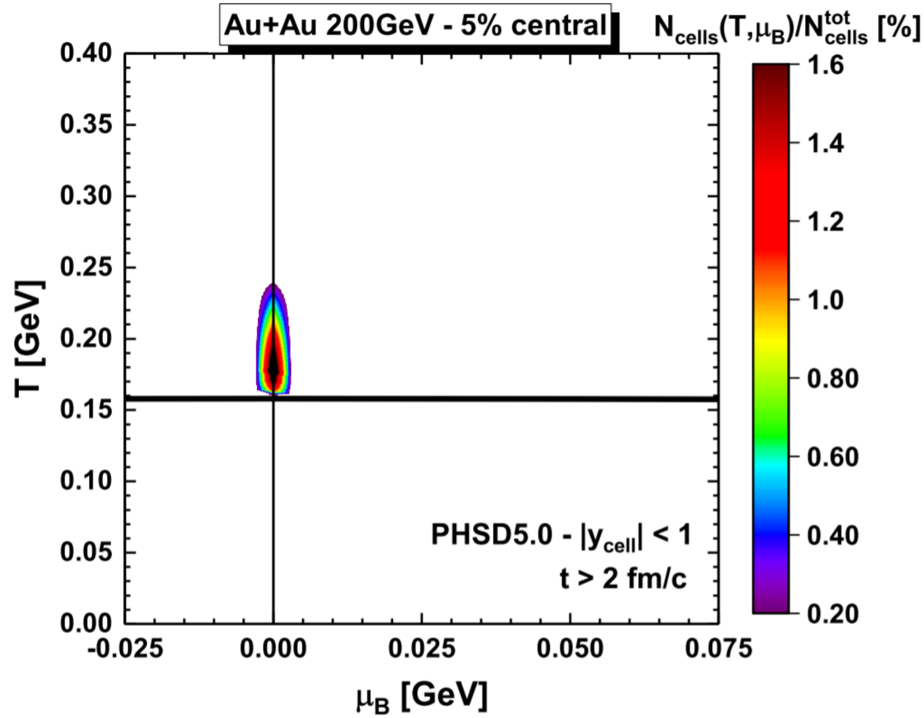
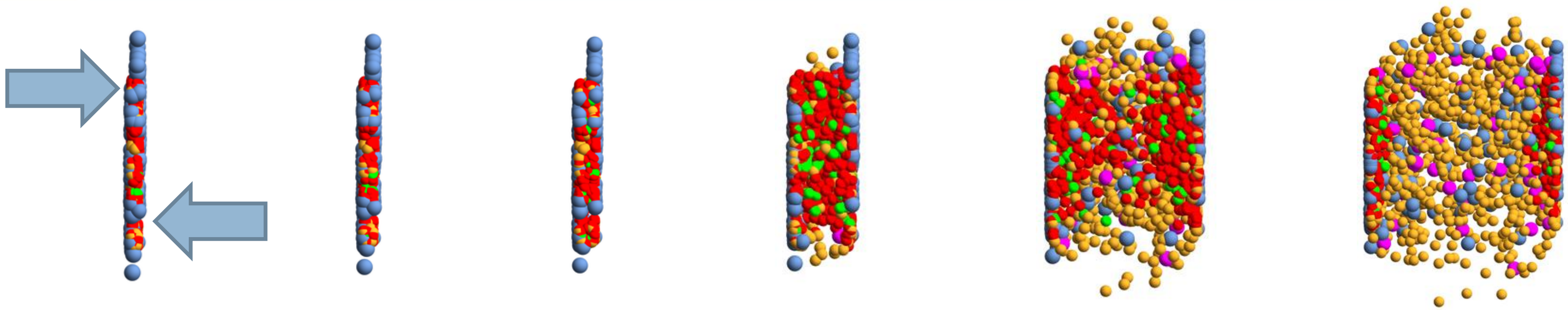
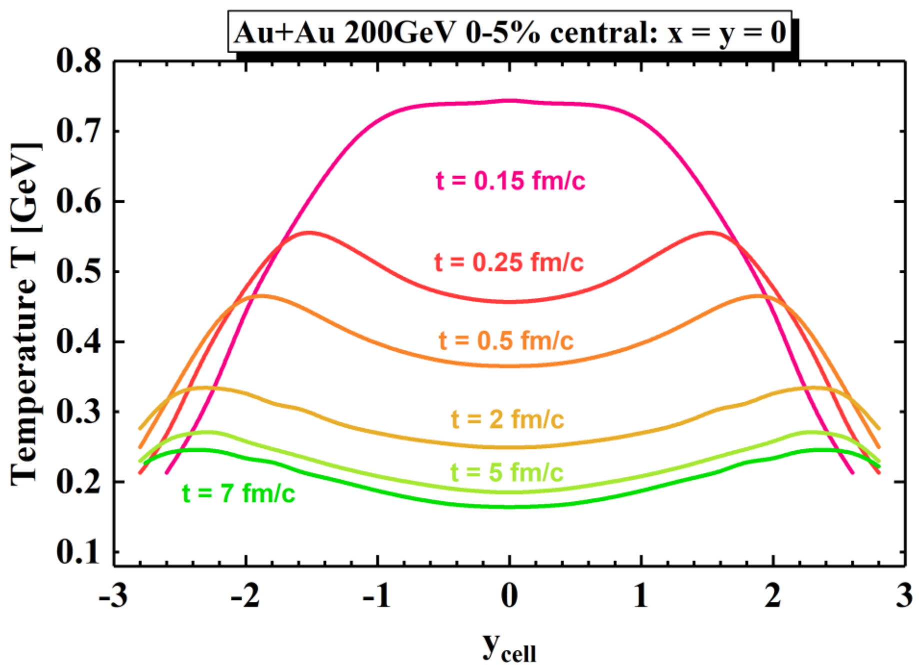
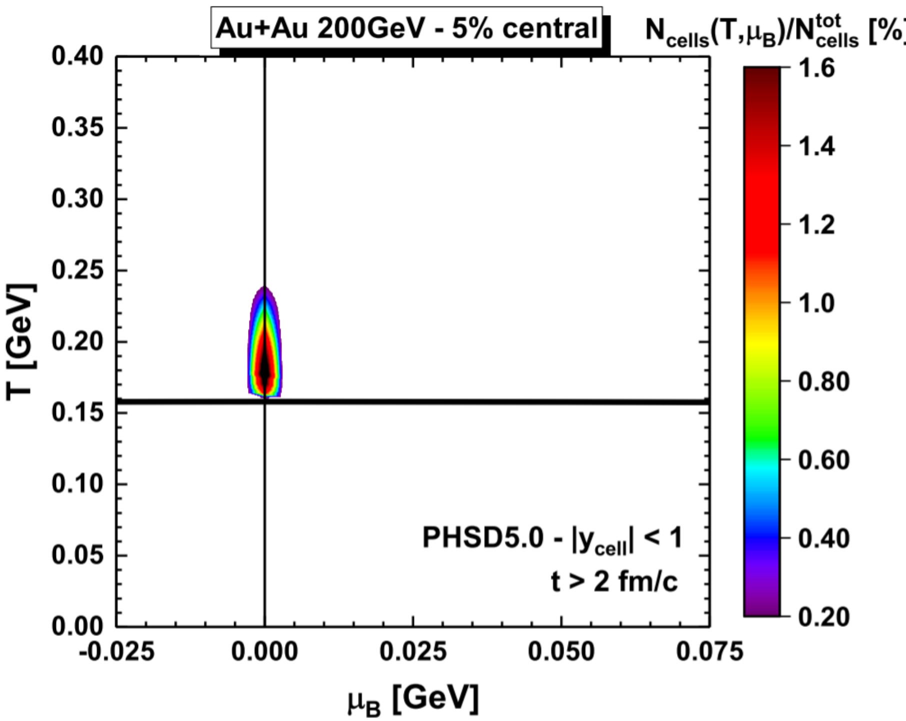


Illustration for HIC ($\sqrt{s_{NN}} = 200$ GeV)

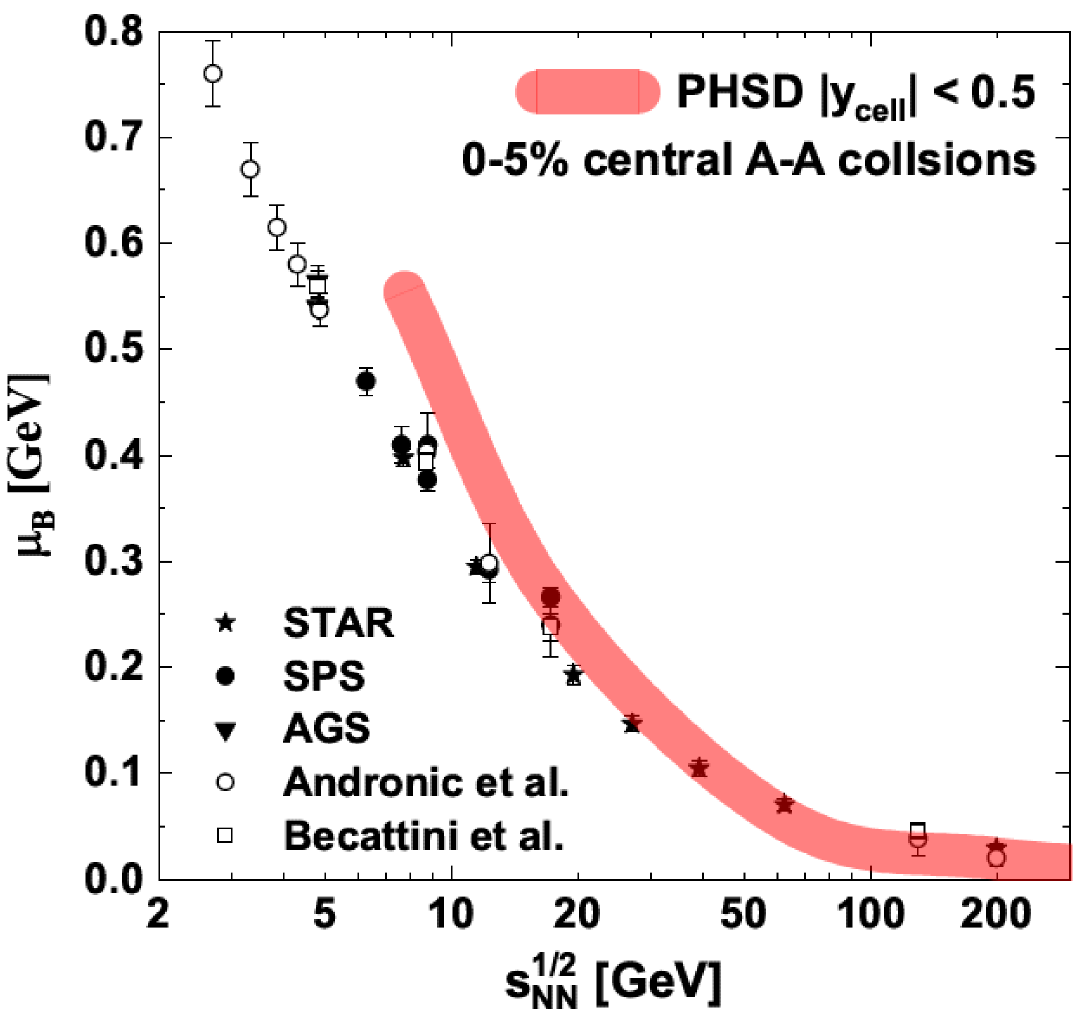






μ_B-dependence as a function of $\sqrt{s_{NN}}$

- Comparison between:
  - μ_B obtained from a statistical analysis of exp. data
  - μ_B probed in PHSD simulations around the chemical freeze out temperature T_{ch}
- Two completely different quantities!!!



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Strong-interaction matter under extreme conditions

Traces of the QGP at finite μ_B in observables of heavy-ion collsions

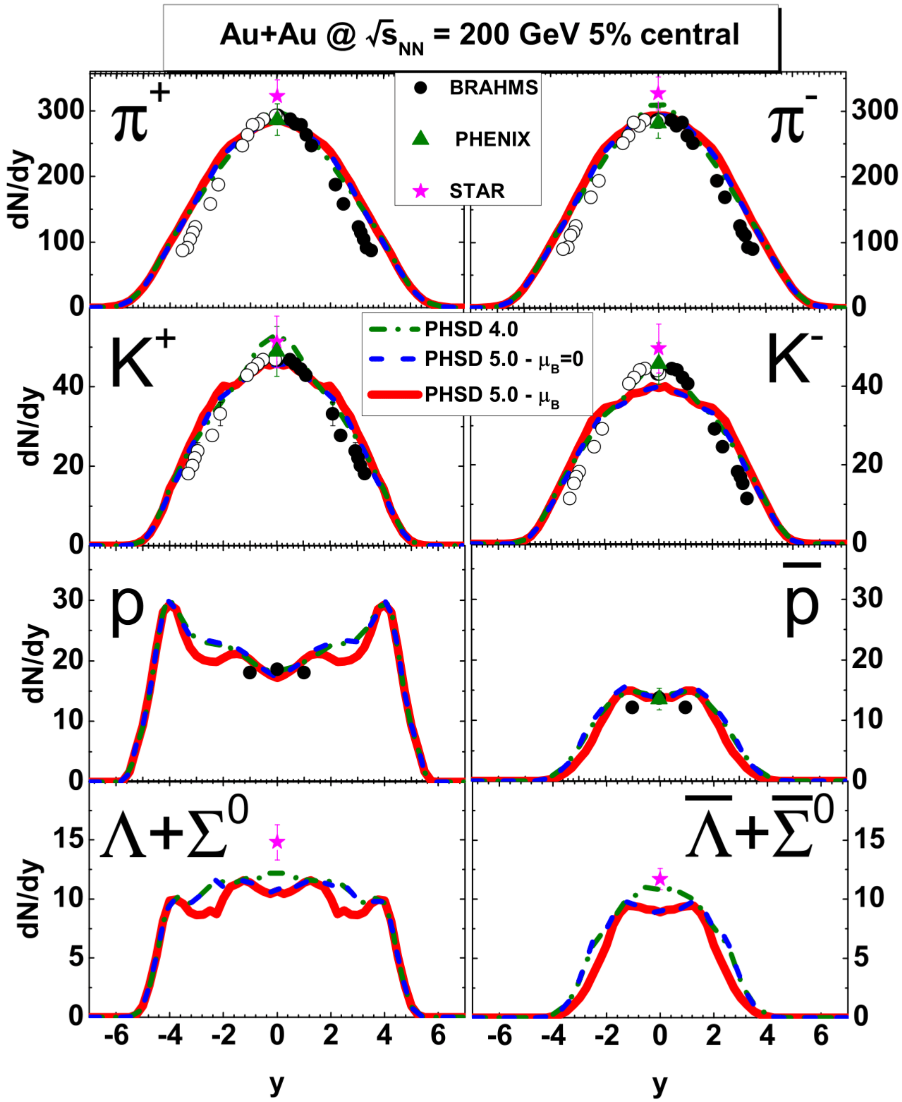
PHSD

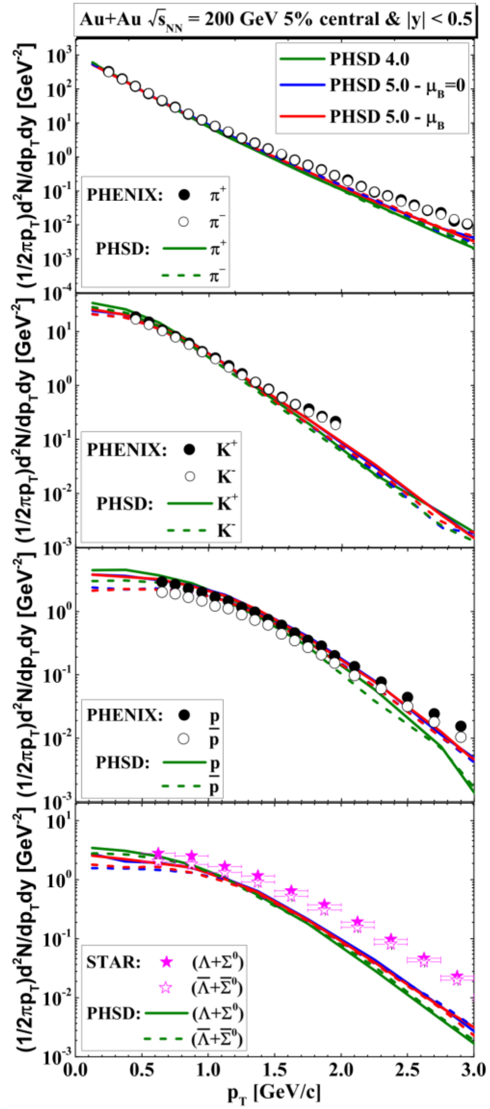
Results for HIC

- **Comparison between three different results:**

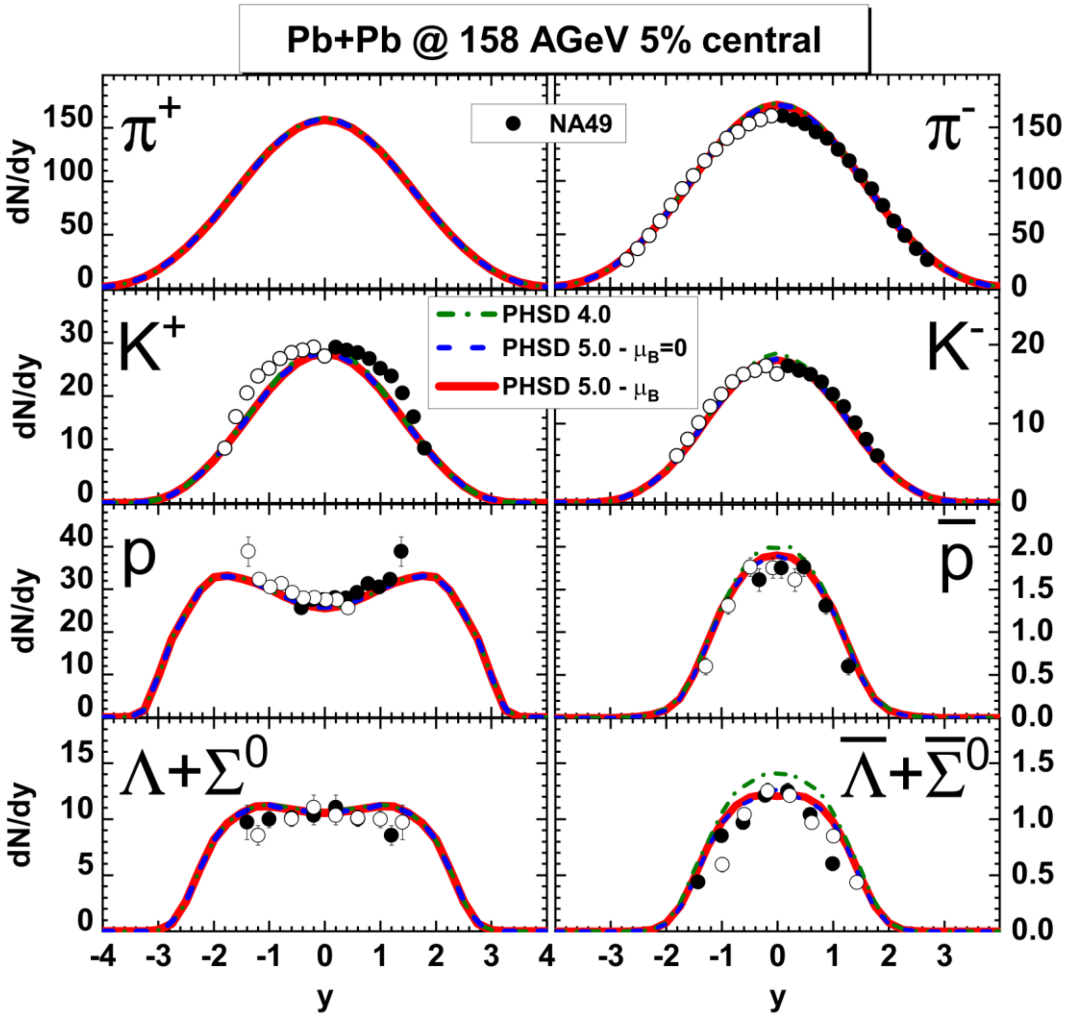
1) **PHSD 4.0 : only $\sigma(T)$ and $M(T)$**
2) **PHSD 5.0 : with $\sigma\left(\sqrt{s}, T, \mu_B = 0\right)$ and $M(T, \mu_B = 0)$**
3) **PHSD 5.0 : with $\sigma\left(\sqrt{s}, T, \mu_B\right)$ and $M(T, \mu_B)$**

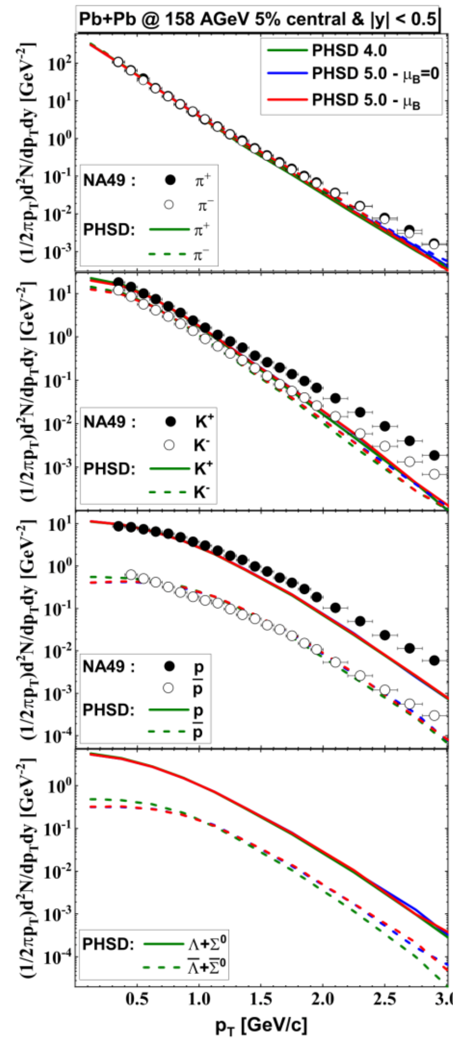
Results for HIC ($\sqrt{s_{NN}} = 200$ GeV)





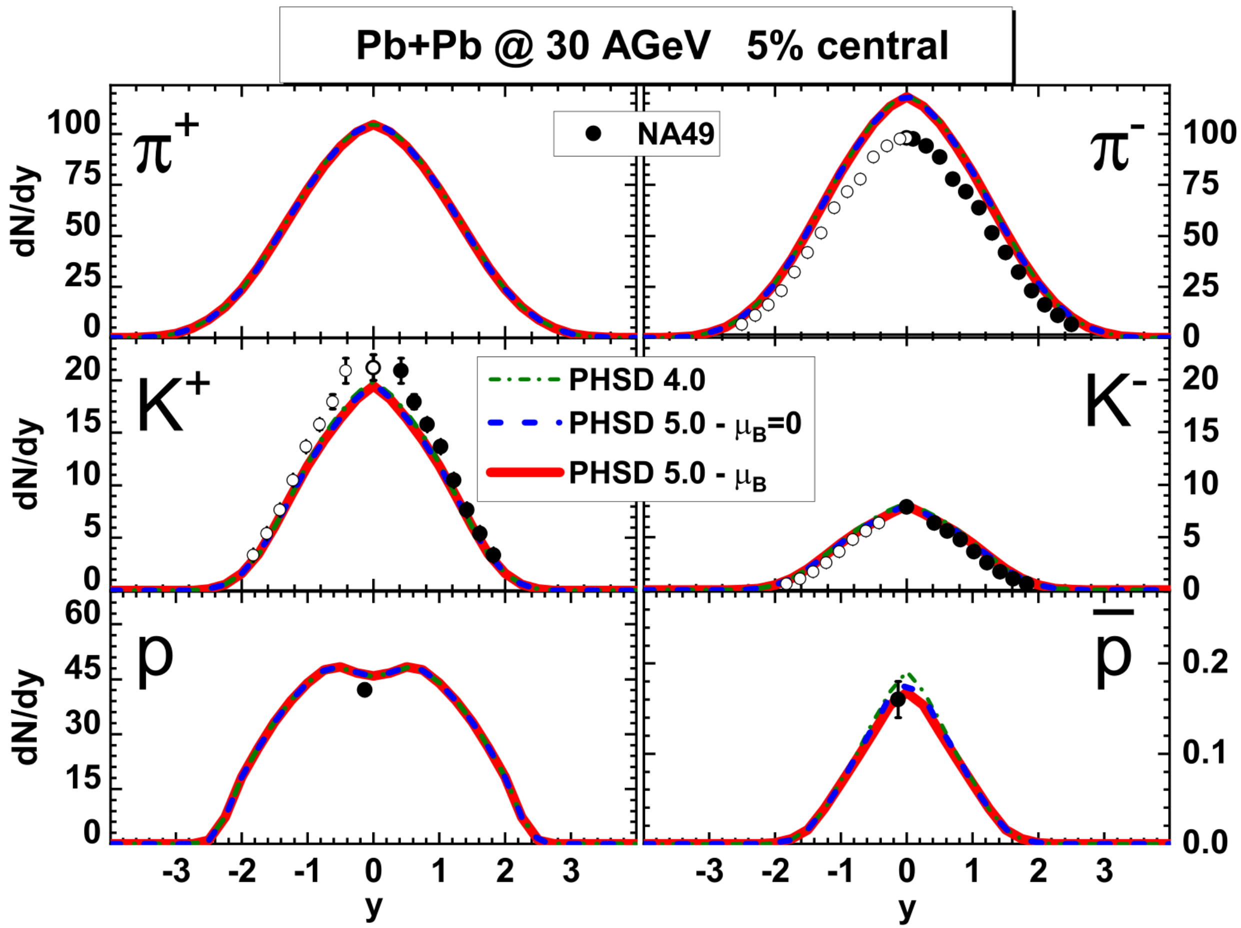
Results for HIC ($\sqrt{s_{NN}} = 17$ GeV)

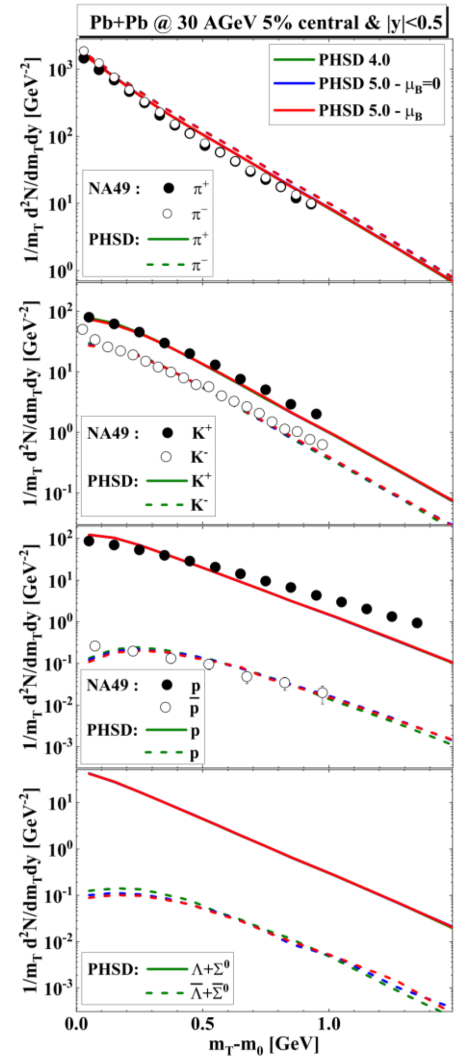




Results for HIC ($\sqrt{s_{NN}} = 7.6$ GeV)

CRC-TR 211 Strong-interaction matter under extreme conditions





Summary / Outlook

CRC–TR 211 Strong-interaction matter under extreme conditions

- **(T, μ_B)-dependent cross sections and masses have been implemented in PHSD**
- **High-μ_B regions are probed at low $\sqrt{s_{NN}}$ or high rapidity regions**
- **But, QGP fraction is small at low $\sqrt{s_{NN}}$: no effects seen in bulk observables**

- **Outlook:**
  - **Study more sensitive probes to finite-μ_B dynamics**
  - **Use of a more sophisticated QuasiParticle Model with momentum dependent masses and widths**
  - **Possible 1st order phase transition at larger μ_B ?**

Thank you for your attention!

Energy density and baryon density

- Illustration of the **energy density** and **baryon density**