Simulating heavy-ion collisions at BES energies

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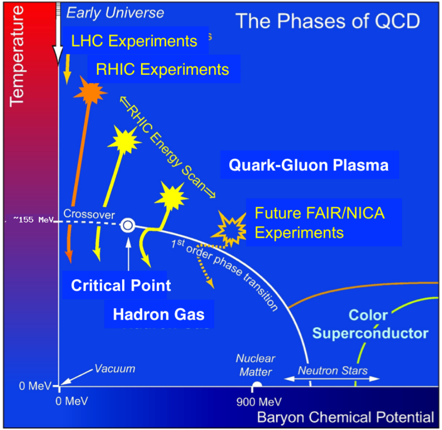
Beam Energy Scan



Standard model of HIC needs to be extended to finite baryon densities. In this work we

- Present a new LEXUS based initial state model
- Use a new crossover equation of state
- Calculate departure functions using a quasiparticle model at finite baryon densities
- Use these new developments to do a baseline calculation for observables at RHIC BES energies

LEXUS based initial conditions

- Original LEXUS (Linear EXtrapolation of Ultrarelativistic Scattering) had no free parameters S. Jeon and J. Kapusta, Phys. Rev. C. 56 (1997)
- LEXUS linearly extrapolated nucleon-nucleon scattering data to nucleus nucleus collisions. Goal was to provide a baseline which would work if there was no new physics beyond nucleon scattering
- Colliding nucleons are assumed to propagate in straight lines colliding with nuclei that cross its path
- Inelastic collisions produced mesons which were assumed to not further interact

LEXUS

- Probability of momentum loss in a collision is parametrized as

$$P(y_{loss}) = \lambda \frac{cosh(2y_0 - y_{loss})}{sinh(2y_0) - sinh(y_0)}$$

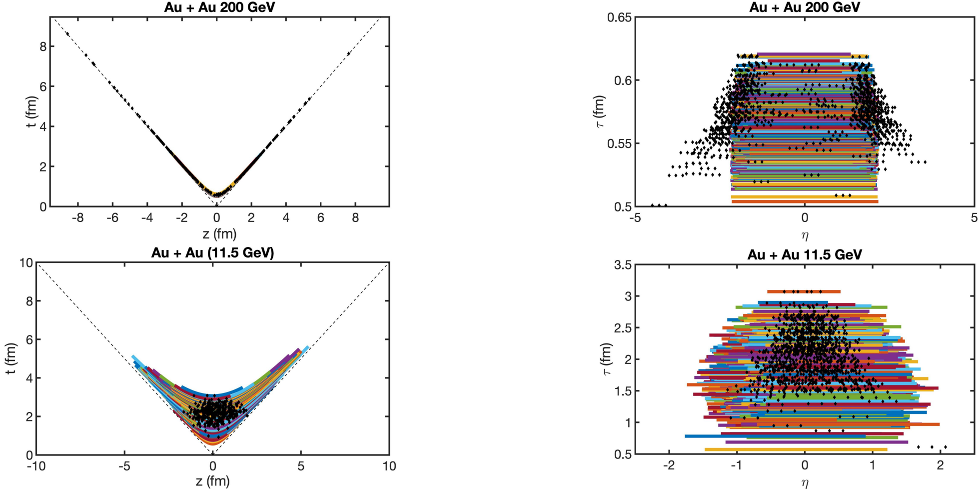
- Rapidity width of produced mesons is given by the Landau model

$$\sigma_L = \frac{8}{3} \frac{c_s^2}{1 - c_s^4} \log\left(\frac{\sqrt{s}}{2m_N}\right) \approx \log\left(\frac{\sqrt{s}}{2m_N}\right)$$

LEXUS inspired 3D initial state

- Nucleon sampling $\rightarrow$ Lorentz contraction $\rightarrow$ Binary collisions
- Nucleons are sampled from a Woods-Saxon distribution and Lorentz contracted in the beam direction
- Nucleons propagate in straight lines in beam direction
- Two nucleons from opposing nuclei collide with probability λ when their cylindrical trajectories overlap. Area of the cylinder is given by the total collision cross-section
- Hydrodynamic solver

LEXUS inspired 3D initial state



Equation of State

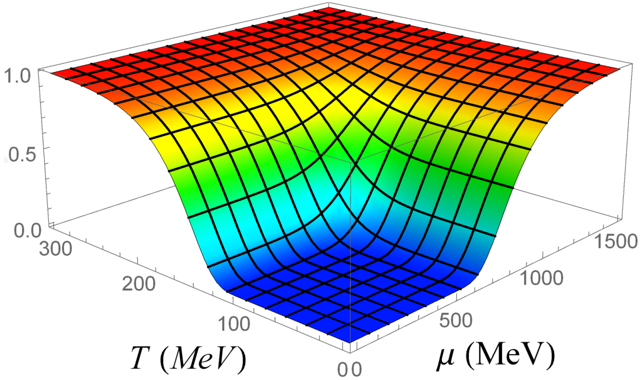
- Perturbative QCD EOS in QGP phase is matched to a hadron resonance gas EOS at low temperatures M. Albright, J. Kapusta and C. Young, Phys. Rev. C 90 (2014)

$$P(t,\mu) = S(T,\mu)P_{\text{QGP}}(T,\mu) + [1 - S(T,\mu)]P_{\text{HRG}}(T,\mu)$$

with

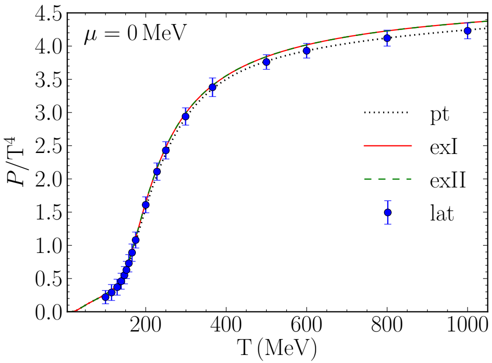
$$S(T,\mu) = \exp\left(-\frac{1}{\left(\frac{T}{T_0}\right)^r + \left(\frac{\mu}{\mu_0}\right)^r}\right)$$

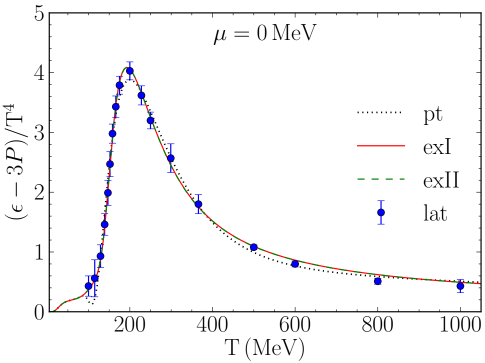
where r is an integer.



Equation of State

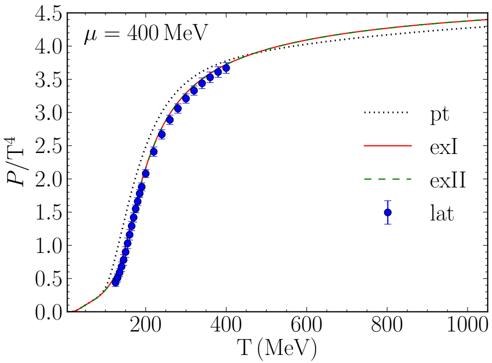
It shows good match with Lattice EOS at $\mu = 0$ ...

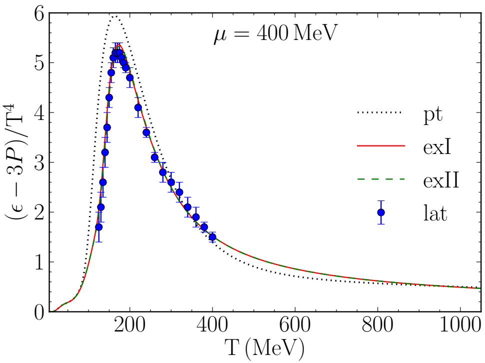




Equation of State

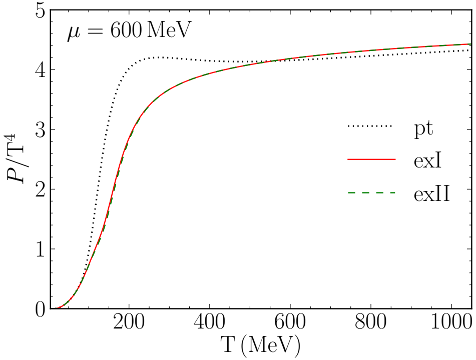
... and with Lattice EOS calculated at non-zero μ using Taylor expansion...

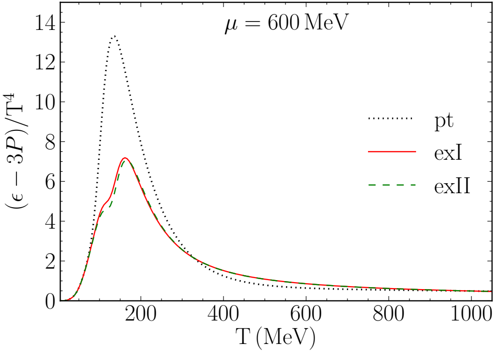




Equation of State

... and could be extended beyond.





Departure Functions

- Departure functions account for non-equilibrium corrections at freezeout

$$\begin{aligned} f_a &= f_a^{\rm eq}\left(1+\phi_a\right) \\ \phi_a &= -A_a\partial_\rho u^\rho - B_a p_a^\nu D_\nu\left(\frac{\mu_B}{T}\right) + C_a p_a^\mu p_a^\nu\left(D_\mu u_\nu + D_\nu u_\mu + \frac{2}{3}\Delta_{\mu\nu}\partial_\rho u^\rho\right) \end{aligned}$$

- Numerical studies using linear sigma model suggests that the relaxation time $\tau(E_a) \propto E_a \equiv \tau' E_a$ P. Chakraborty and J. Kapusta, Phys. Rev. C 95 (2017)
- For shear correction, we get $C_a = \frac{\tau'}{2T}$ with $\tau' = \frac{\eta}{2Tw}$

Thermal conductivity

- Unlike shear viscosity, the expression for thermal conductivity associated with baryon current is not so simple

$$B_a = \tau' \left(b_a - \frac{n_B}{w} E_a \right) - b(T, \mu_B)$$

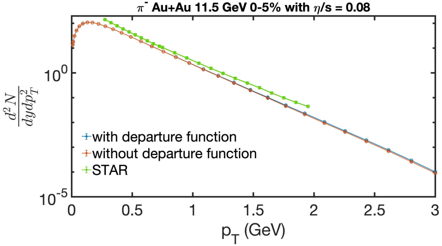
where

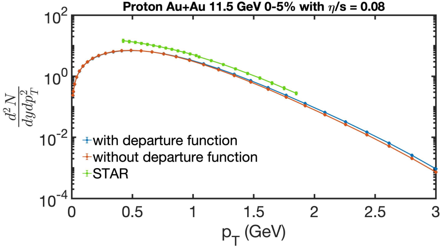
$$b = \frac{\tau' T}{w^2} \left[Ts(T\chi_{T\mu} + \mu_B \chi_{\mu\mu}) - Tn_B(T\chi_{TT} + \mu_B \chi_{T\mu}) - n_B w \right]$$

and we have susceptibilities

$$\chi_{xy} = \frac{\partial^2 P(T, \mu)}{\partial x \partial y}$$

pT Spectra

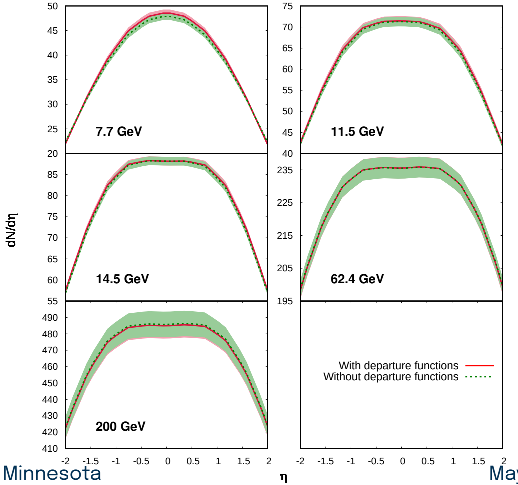




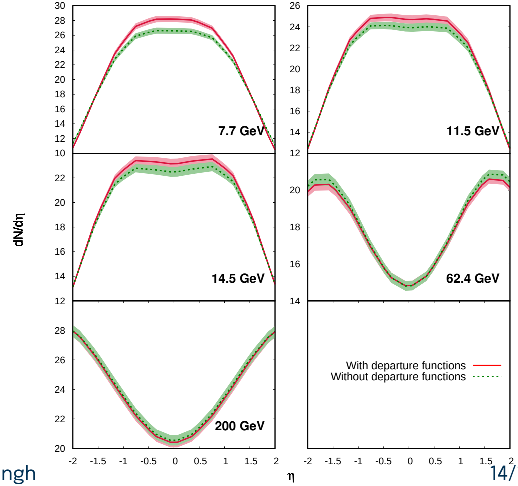
- No overall normalization used
- No initial flow. Initial flow will necessitate use of higher η/s which will lead to more entropy production
- No bulk used here. That will also contribute to multiplicity
- No hadronic cascade. Pion winds shift proton spectra to higher p_T

Rapidity spectra

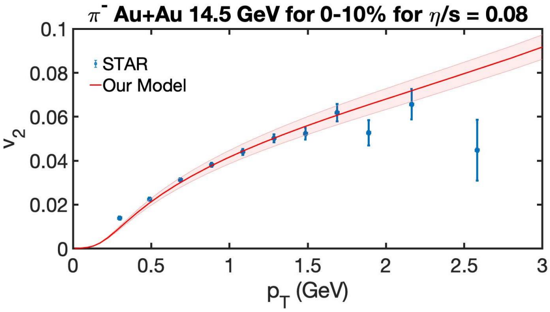
Pions



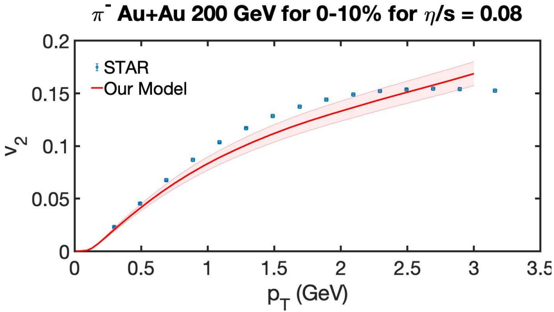
Protons



v_2



π⁻ Au+Au 14.5 GeV for 0-10% for η/s = 0.08
STAR
Our Model
v2
pT (GeV)
0.1
0.08
0.06
0.04
0.02
0
0.5
1
1.5
2
2.5
3



π⁻ Au+Au 200 GeV for 0-10% for η/s = 0.08
STAR
Our Model
v2
pT (GeV)
0.2
0.15
0.1
0.05
0
0.5
1
1.5
2
2.5
3
3.5

Summary

- We present our results for simulations of HICs at non-zero baryon densities. A new baseline calculation for RHIC-BES energies using a LEXUS based initial state, a crossover EOS without critical point and departure functions at finite baryon densities
- A LEXUS inspired 3D initial state model was used
- A crossover EOS from matching HRG and pQCD results was used at finite baryon densities
- Departure functions are calculated at finite baryon densities
- Get reasonable matching to data without an overall normalization

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