Heavy-Ion Collision Simulation using Quark-Meson Coupling Model

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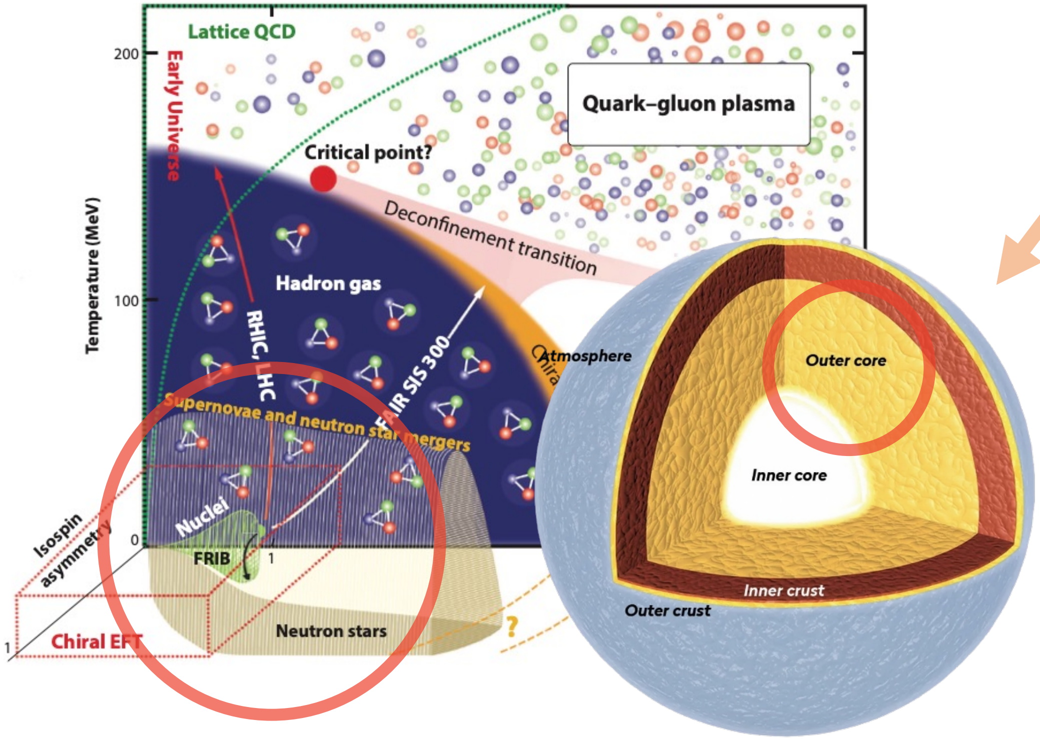
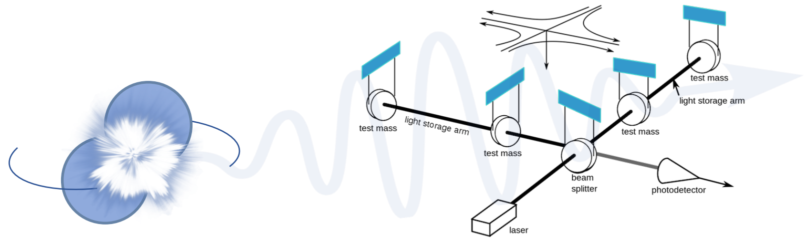
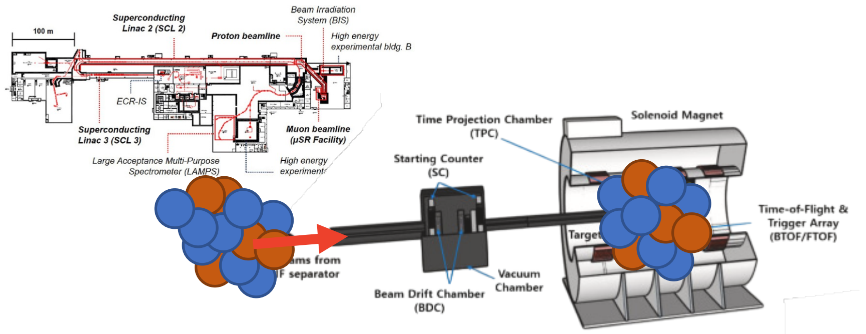
Nuclear matter : Why and How?



① Observations (ex. GW170817)



② Experiments (ex. HICs with RI)



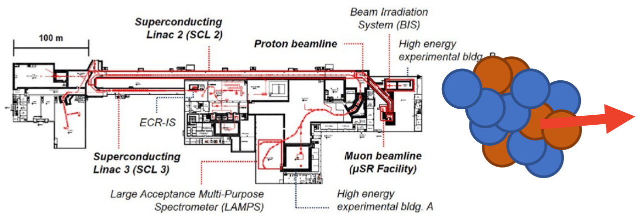
- Studying nuclear matter is important for both astro- and nuclear physics
- Astrophysics : Neutron star, CCSN…
- Nuclear physics : Binding energy, Symmetry energy, GMR, Neutron skin…

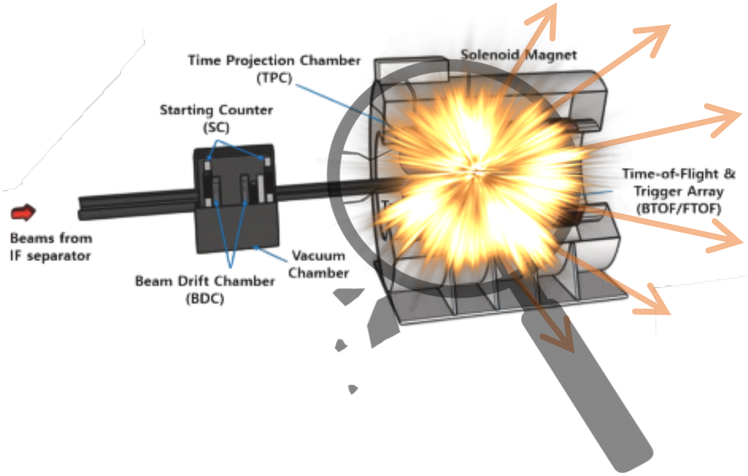
1

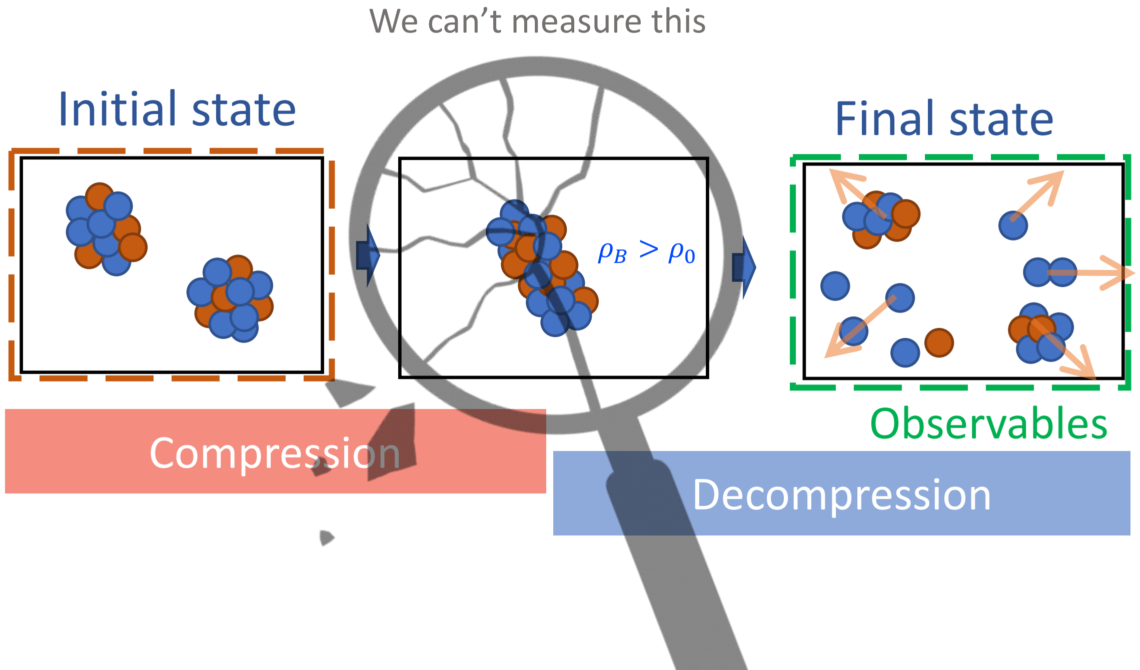
Heavy-ion Collisions (HICs)

- Can briefly generate dense nuclear matter
- Non-equilibrium process

RI beam facilities,
such as RAON







- To study nuclear matter from final states, we need a tool that bridges the EOS to observables

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Heavy-ion Collisions (HICs)

- Can briefly generate dense nuclear matter
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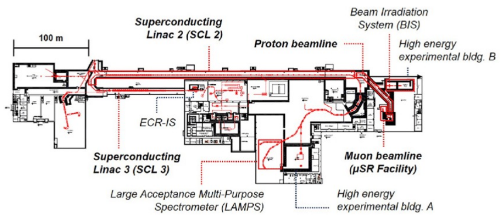
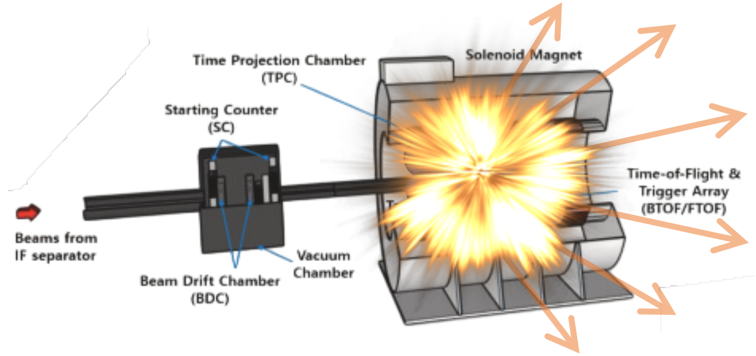
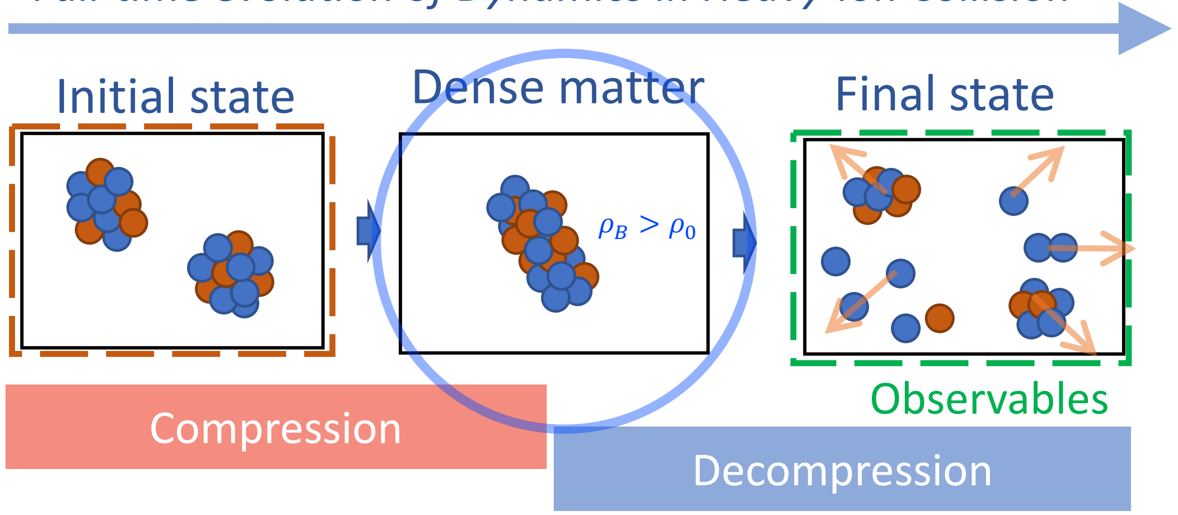
RI beam facilities, such as RAON

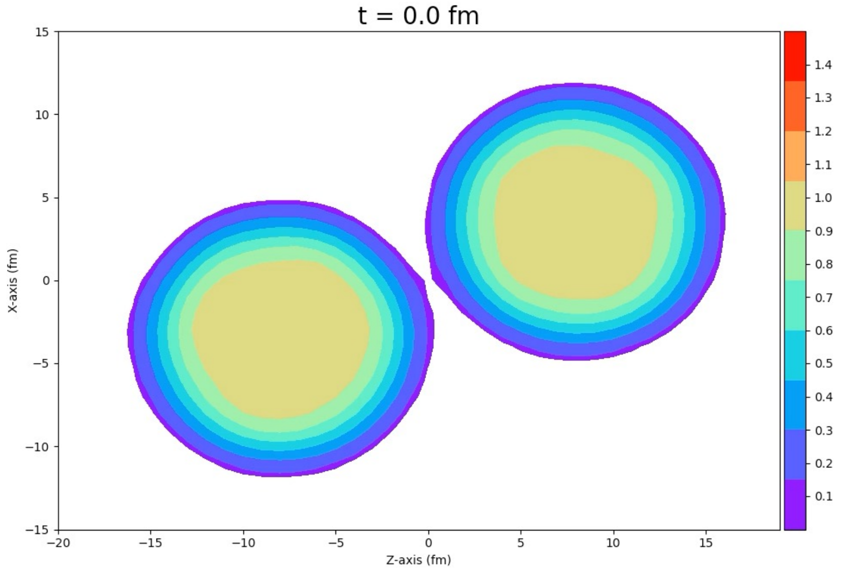




Full-time evolution of Dynamics in Heavy-Ion Collision



- Transport model



- Allow to study Nuclear EOS ~ HIC Observables

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DaeJeon Boltzmann-Uehling-Ulenbeck (DJBUU) model

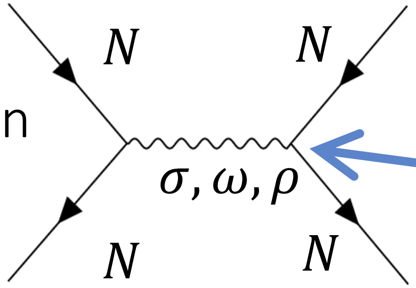
- Is a relativistic BUU model based on the Boltzmann equation.

$$\frac{1}{p^{*0}}\left[p^\mu \partial_\mu - \left(p_\mu \mathcal{F}^{\mu i} - m^* \partial^i m^*\right)\frac{\partial}{\partial p^i}\right] f(\vec{x},\vec{p}) = C(\vec{x},\vec{p})$$

Test particles method

① Propagation

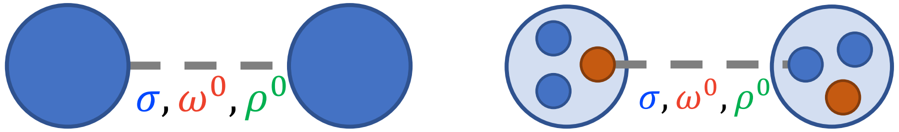
- Nuclear interaction from RMF theory (previous QHD)



- With QMC, can we do sth that we couldn't before?

- This work : Replacing

-QHD (Hadron) → -QMC (Quark)



- m^* for other baryons ($\Delta, \Lambda, \dots$) from g_σ^q
- Quark contribution in low-energy HICs…?

② Collision

$$C(\vec{x},\vec{p}) = C_{NN\leftrightarrow NN} + C_{NN\leftrightarrow N\Delta} + \cdots$$

- In-medium modification**: $\sigma_{NN\rightarrow N\Delta}(\rho_B) = \sigma_{NN\rightarrow N\Delta}(0) \times \exp\left(-C\frac{\rho_B}{\rho_0}\right)\left(\frac{N}{Z}\right)_{\text{sys}}^{x^{\pm,0}}$ * ***

(C, x^+, x^0, x^-) = (2.5, 0, 0.5, 2)

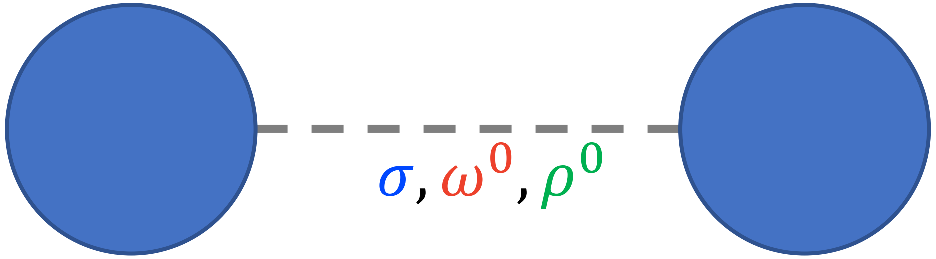
- Does this still work with QMC?

* Zhang and Ko, PRC, 2018, 98, 054614.
** MK Kim et al, Universe, 2022, 8, 564.

Relativistic Mean-Field (RMF) theory

① Quantum hadro-dynamics (QHD)

$$\mathcal{L}_{N,\mathrm{QHD}} = \bar{\psi}_N[i\gamma_\mu\partial^\mu - (m_N - g_\sigma\sigma) - g_\omega\gamma_0\omega^0 - g_\rho\gamma_0\,\tau_3\rho^0]\psi_N$$

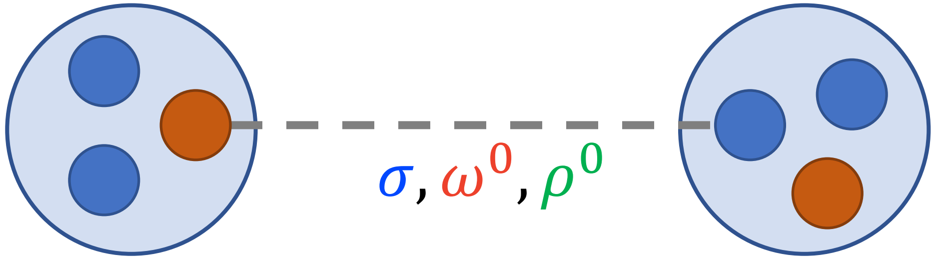


- Nucleon : Point particle

② Quark-meson coupling (QMC) *

- using the MIT bag model
- Nucleon : Bag containing quarks

$$\mathcal{L}_q = \bar{\psi}_q[i\gamma_\mu\partial^\mu - (m_q - g_\sigma^q\sigma) - g_\omega^q\gamma_0\omega^0 - g_\rho^q\gamma_0\,\tau_3\rho^0]\psi_q\Theta_{\mathrm{Bag}}$$



- Effective bag energy

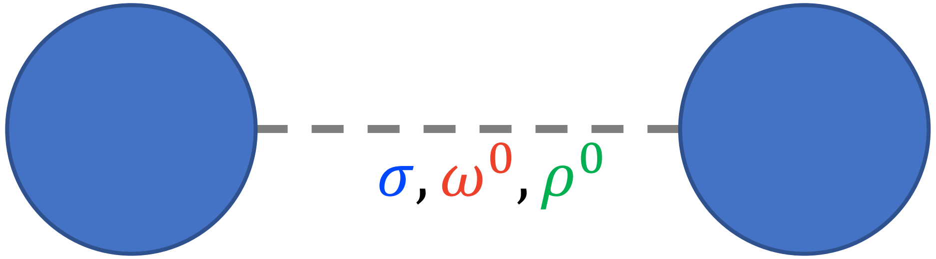
$$m_B^* = \sum_q \frac{n_q\Omega_q^* - z_0}{R_B^*} + \frac{4}{3}\pi(R_B^*)^3 B,$$

* Guichon, Physics Letters B, 200, 3

Relativistic Mean-Field (RMF) theory

① Quantum hadro-dynamics (QHD)

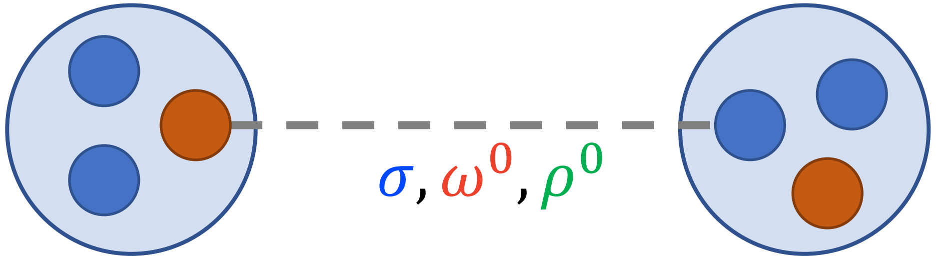
$$\mathcal{L}_{N,\mathrm{QHD}} = \bar{\psi}_N\left[i\gamma_\mu\partial^\mu - (m_N - g_\sigma\sigma) - g_\omega\gamma_0\omega^0 - g_\rho\gamma_0\,\tau_3\rho^0\right]\psi_N$$



② Quark-meson coupling (QMC) *

$$m_B^* = m_B - g_\sigma^N\sigma + \frac{a_B}{2}(g_\sigma^N\sigma)^2 + \cdots,$$

$$\mathcal{L}_{B,\mathrm{QMC}} = \bar{\psi}_B\left[i\gamma_\mu\partial^\mu - (m_B - g_\sigma(\sigma)\sigma) - g_\omega\gamma_0\omega^0 - g_\rho\gamma_0\,\tau_3\rho^0\right]\psi_B,$$



$$3q_\sigma^q S(0) = g_\sigma,\quad 3g_\omega^q = g_\omega,\quad g_\rho^q = g_\rho,$$

$$S(\sigma) = \int_{Bag}\bar{\psi}_q(y)\psi_q(y)d^3y$$

* Guichon, Physics Letters B, 200, 3

DJBUU+QMC project : implementing QMC in DJBUU

① Benchmarking DJBUU+QMC against DJBUU+QHD

② Benchmarking DJBUU+QMC comparing experimental data

③ Investigating pion production using DJBUU+QMC : Ongoing

Present stage

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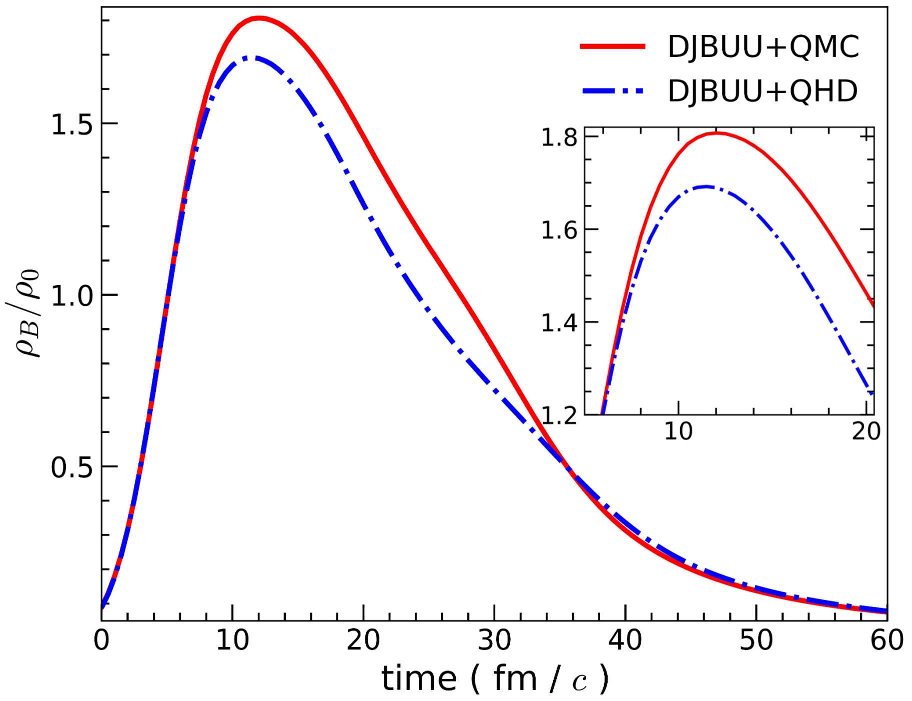
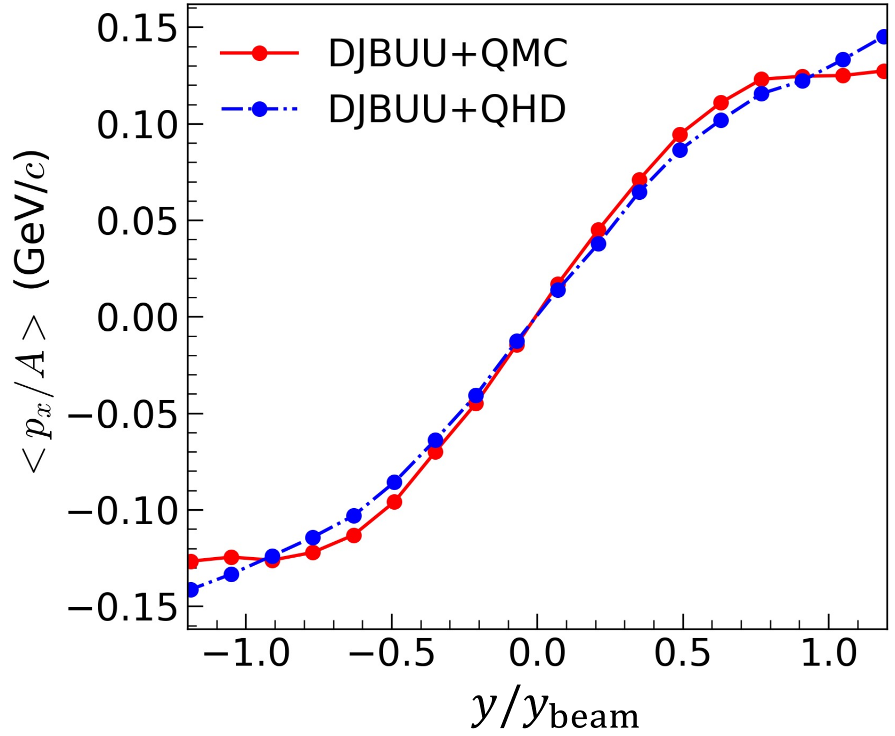
Future plans

④ Upgrading DJBUU for further application of QMC in HICs
(e.g. adding hyperon and their channals
to study hyperons in medium produced by HICs using QMC)

Central density and Transverse flow

- ^{197}Au+^{197}Au, E_{beam} = 400 A MeV, 0.25 < b_0 < 0.45 (FOPI)

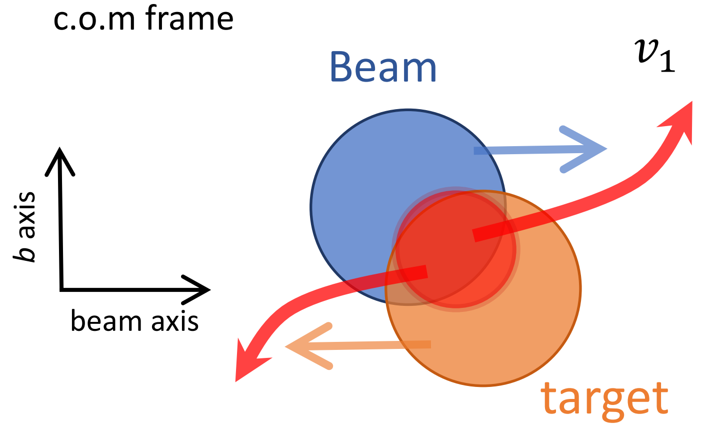




- QMC shows higher central density than QHD.
- Transverse flows are similar, but QMC result is slightly stiffer

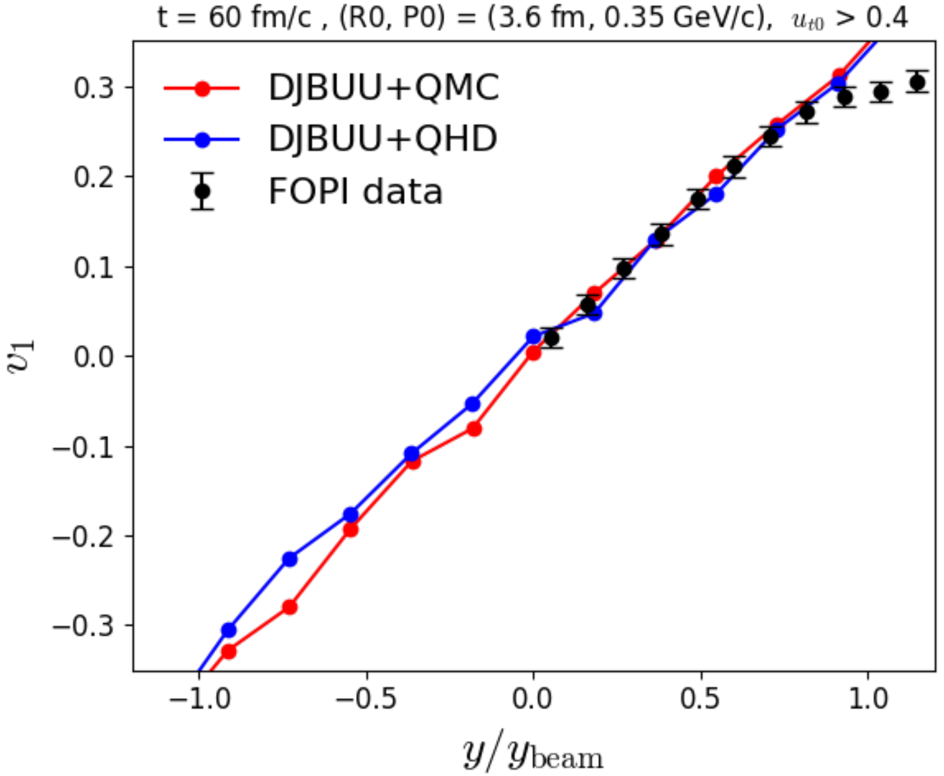
Directed flow

- ^{197}Au+^{197}Au, E_{beam} = 400 A MeV, 0.25 < b_0 < 0.45 (FOPI)



$$\frac{dN}{d\phi} = v_0[1 + 2v_1\cos(\phi) + \cdots],$$

$$v_1 = \left\langle \frac{p_x}{p_t} \right\rangle = \langle \cos(\phi) \rangle$$



- Directed flows show similar trend to transverse flows.
- Both match experimental data.

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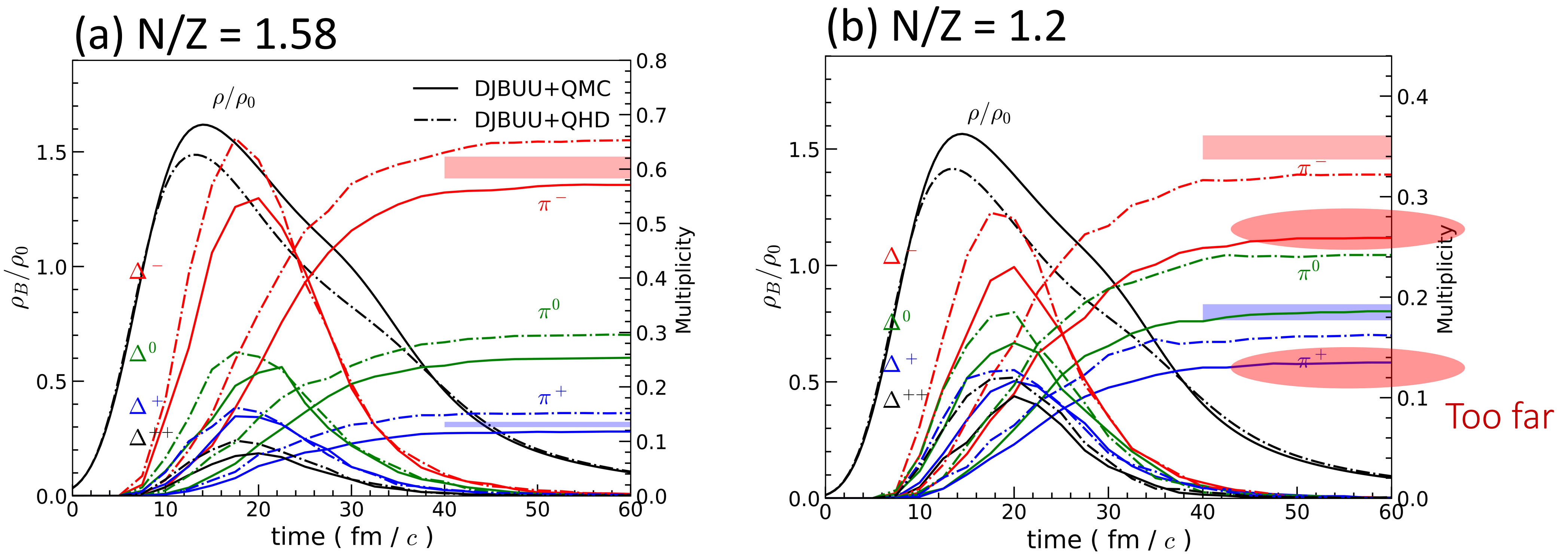
Central densities and π production

- Sn+Sn , E_{beam} = 270 A MeV, b = 3 fm (SπRIT)



EOS dependence was washed out?

- QMC shows higher central densities
- but lower yields (due to modification; C= 2.5)

$$\sigma_{NN\to N\Delta}(\rho_B) = \sigma_{NN\to N\Delta}(0)\times \exp\left(-C\frac{\rho_B}{\rho_0}\right)\left(\frac{N}{Z}\right)_{\text{sys}}^{x^{\pm,0}}$$

We can't use same parameter set of in-medium cross-section

π production

$$\mathrm{DR} = \frac{[Y(\pi^-)/Y(\pi^+)]_{132+124}}{[Y(\pi^-)/Y(\pi^+)]_{108+112}}.$$

	(a) ^{132}Sn + ^{124}Sn ($N/Z = 1.56$)			(b) ^{108}Sn + ^{112}Sn ($N/Z = 1.2$)			DR
	$Y(\pi^-)$	$Y(\pi^+)$	SR	$Y(\pi^-)$	$Y(\pi^+)$	SR	
w/ QHD	0.655(18)	0.153(10)	4.78(45)	0.322(8)	0.163(7)	2.04(9)	2.34(10)
w/ QMC	0.573(15)	0.118(6)	5.14(31)	0.259(11)	0.136(10)	2.11(18)	2.44(10)
w/ QMC (C=2.2)	0.686(14)	0.152(10)	4.99(40)	0.328(13)	0.156(9)	2.23(15)	2.23(11)
Exp.	0.603(20)	0.131(5)	4.60(11)	0.349(12)	0.186(8)	1.89(4)	2.44(10)

- By reducing C from 2.5 to 2.2, yields are better matched, keeping consistency with the Double pion ratio (DR)

- Assignment : Can we get a universal in-medium modification that independently work for various EOSs(or other parameter sets)?
- Ongoing: Studying EOS dependence without any in-medium modification.

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5. Summary

- The DJBUU model describes Heavy-Ion Collisions (HICs) using Relativistic BUU model, acting as a bridge between nuclear matter properties and HIC observables.
- The Quark-Meson Coupling model, quark-based RMF approach, incorporates nucleon-nucleon (NN) interactions through quark and meson coupling mechanisms.
- With DJBUU+QMC and the original DJBUU, we performed simulations of:
  - Au+Au systems, focusing on central density, transverse and directed flow, to verify the applicability of QMC to HIC simulation.
  - Sn+Sn systems, focusing on central density, π yields and their ratios.
    → Matching yields and ratios with different parameter set of in-medium modification.
    → Ongoing : studying pion production without in-medium effects on *NN* collision.

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