NuSYM2018 @ Busan, Korea

Application of parity doublet model in HIC

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- Parity doublet model
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DJBUU project and RAON

- What is DJBUU
  DaeJeon Boltzmann-Uehling-Uhlenbeck

- **DaeJeon** is city name in Korea where **RAON** is under the construction

- Current collaboration members
  S. Jeon (McGill, chair), **Y. Kim** (RISP), **Myungkuk Kim, C.-H. Lee** (PNU) **Y.M. Kim** (UNIST)

New Physics: Sae Mulli, 66 (2016) 1563
http://dx.doi.org/10.3938/NPSM.66.1563

Rare Isotope Science Project (RISP)

RISP

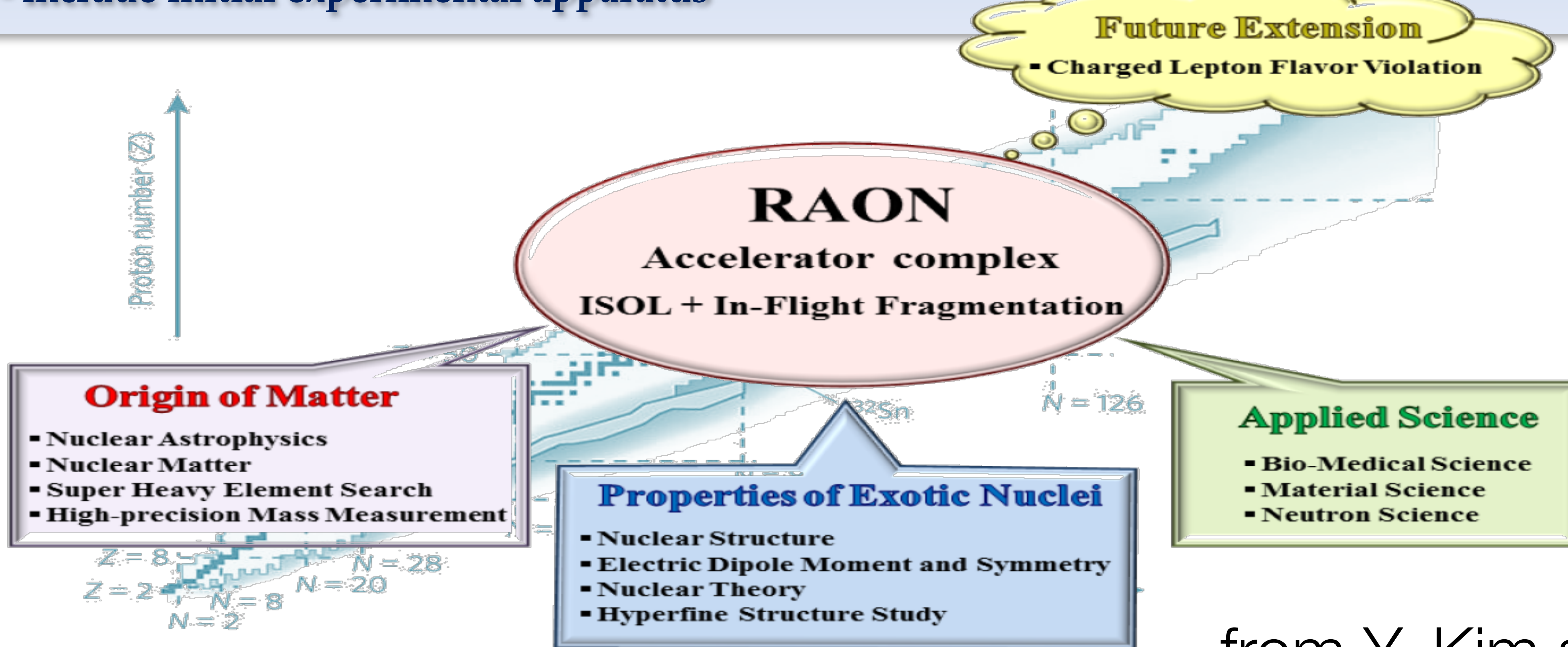
○ **Goal : To build a heavy ion accelerator complex RAON for rare isotope science researches in Korea**

○ **Project period : 2011.12 - 2021.12**

○ **Total Budget : ~$ 1.43 billion**

(Facilities ~ $ 0.46 bill., Bldgs & Utilities ~ $ 0.97 bill.)

- include initial experimental apparatus



from Y. Kim slide

Parity Doublet Model (Zschiesche et. al (2007))

- Nucleons and their parity (as well as chiral) partners belong to same multiplet.
- First realistic model by DeTar and Kunihiro (1989).
- Mass splitting between nucleon and chiral partner by the sigma field.
- Under $\mathrm{SU}(2)_L \times \mathrm{SU}(2)_R$ transformations, two nucleon fields transform as,

$$\psi_{1R} \to R\psi_{1R}, \quad \psi_{1L} \to L\psi_{1L},$$
$$\psi_{2R} \to L\psi_{2R}, \quad \psi_{2L} \to R\psi_{2L}.$$

- Chirally invariant mass, m_0

$$m_0(\bar{\psi}_2\gamma_5\psi_1 - \bar{\psi}_1\gamma_5\psi_2)$$
$$= m_0(\bar{\psi}_{2L}\psi_{1R} - \bar{\psi}_{2R}\psi_{1L} - \bar{\psi}_{1L}\psi_{2R} + \bar{\psi}_{1R}\psi_{2L}).$$

- The chiral Lagrangian in the mirror model

$$\mathcal{L} = \bar{\psi}_1 i\partial\!\!\!/ \psi_1 + \bar{\psi}_2 i\partial\!\!\!/ \psi_2 + m_0(\bar{\psi}_2\gamma_5\psi_1 - \bar{\psi}_1\gamma_5\psi_2)$$
$$+ a\bar{\psi}_1(\sigma + i\gamma_5\vec{\tau}\cdot\vec{\pi})\psi_1 + b\bar{\psi}_2(\sigma - i\gamma_5\vec{\tau}\cdot\vec{\pi})\psi_2$$
$$- g_\omega\bar{\psi}_1\gamma_\mu\omega^\mu\psi_1 - g_\omega\bar{\psi}_2\gamma_\mu\omega^\mu\psi_2 + \mathcal{L}_M,$$

- \sigma - \omega model of nuclear matter

$$\mathcal{L}_M = \frac{1}{2}\partial_\mu\sigma^\mu\partial^\mu\sigma_\mu + \frac{1}{2}\partial_\mu\vec{\pi}^\mu\partial^\mu\vec{\pi}_\mu - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$
$$+ \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu + g_4^4(\omega_\mu\omega^\mu)^2$$
$$+ \frac{1}{2}\bar{\mu}^2(\sigma^2 + \vec{\pi}^2) - \frac{\lambda}{4}(\sigma^2 + \vec{\pi}^2)^2 + \epsilon\sigma,$$

- $$m_i = m_{N\pm} = \frac{1}{2}\left(\sqrt{(a+b)^2\sigma^2 + 4m_0^2} \mp (a-b)\sigma\right).$$

Model detail will be in Prof. Harada talk on Wed.

- The chiral Lagrangian in the mirror model

$$\begin{aligned}\mathcal{L} = & \bar{\psi}_1 i\partial\!\!\!/ \psi_1 + \bar{\psi}_2 i\partial\!\!\!/ \psi_2 + m_0(\bar{\psi}_2\gamma_5\psi_1 - \bar{\psi}_1\gamma_5\psi_2) \\ & + a\bar{\psi}_1(\sigma + i\gamma_5\vec{\tau}\cdot\vec{\pi})\psi_1 + b\bar{\psi}_2(\sigma - i\gamma_5\vec{\tau}\cdot\vec{\pi})\psi_2 \\ & - g_\omega\bar{\psi}_1\gamma_\mu\omega^\mu\psi_1 - g_\omega\bar{\psi}_2\gamma_\mu\omega^\mu\psi_2 + \mathcal{L}_M,\end{aligned}$$

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Application to transport theory

WS initialization and parameter set of PDM

- Au nucleus initialization with Woods-Saxon form

$$\rho(r) = \frac{\rho_0}{1 + \exp[(r - R)/a]}$$

$$R = 1.12A^{1/3}, a = 0.6\text{fm}$$

- Parameter set of PDM from dense matter calculation

		m_{N-} [MeV]	m_0 [Mev]	m_σ [MeV]	$g_{N\omega}$	K [MeV]
Pisarski	set1	1500	790	370.63	6.79	510
Y. Kim	set2	1535	938	210.763	1.69342	240

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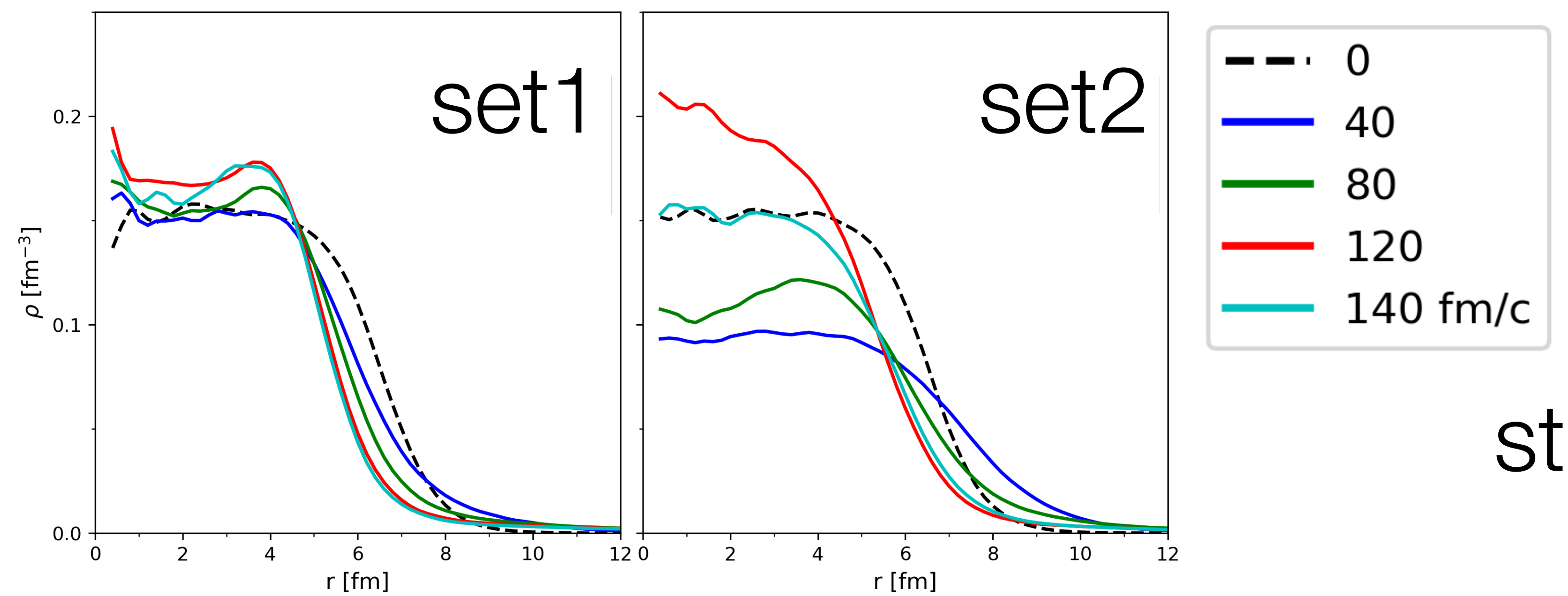
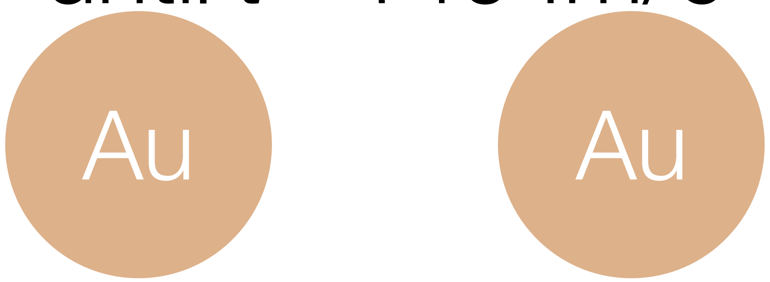
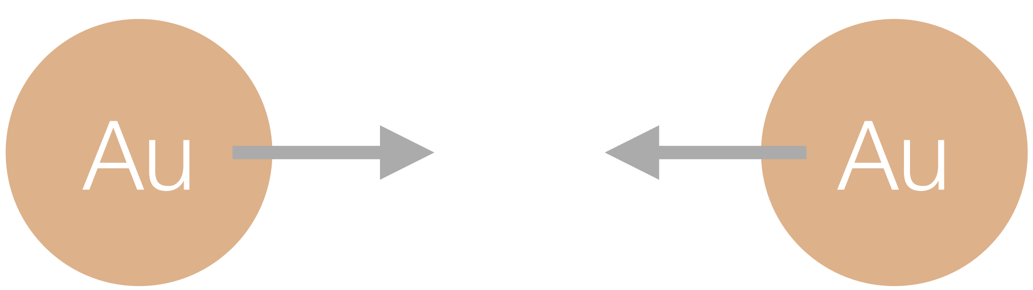
Static stability check and time evolution of central density



until t= 140 fm/c

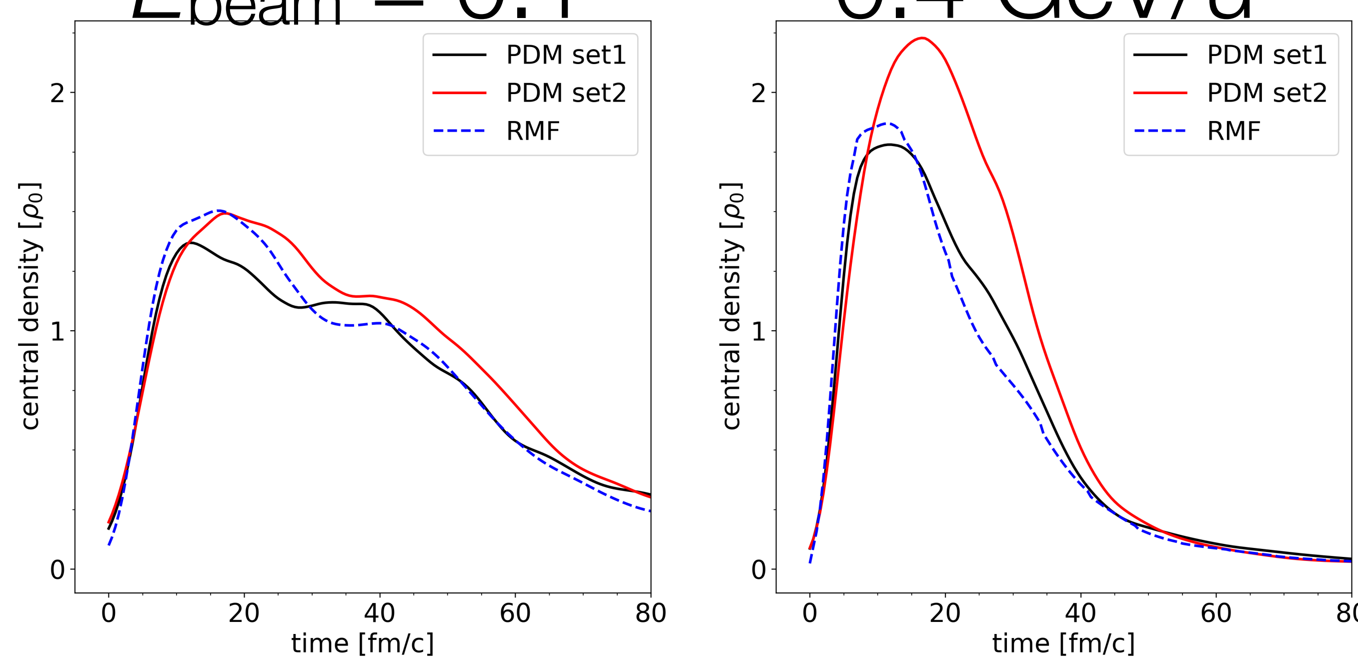


stability at same position



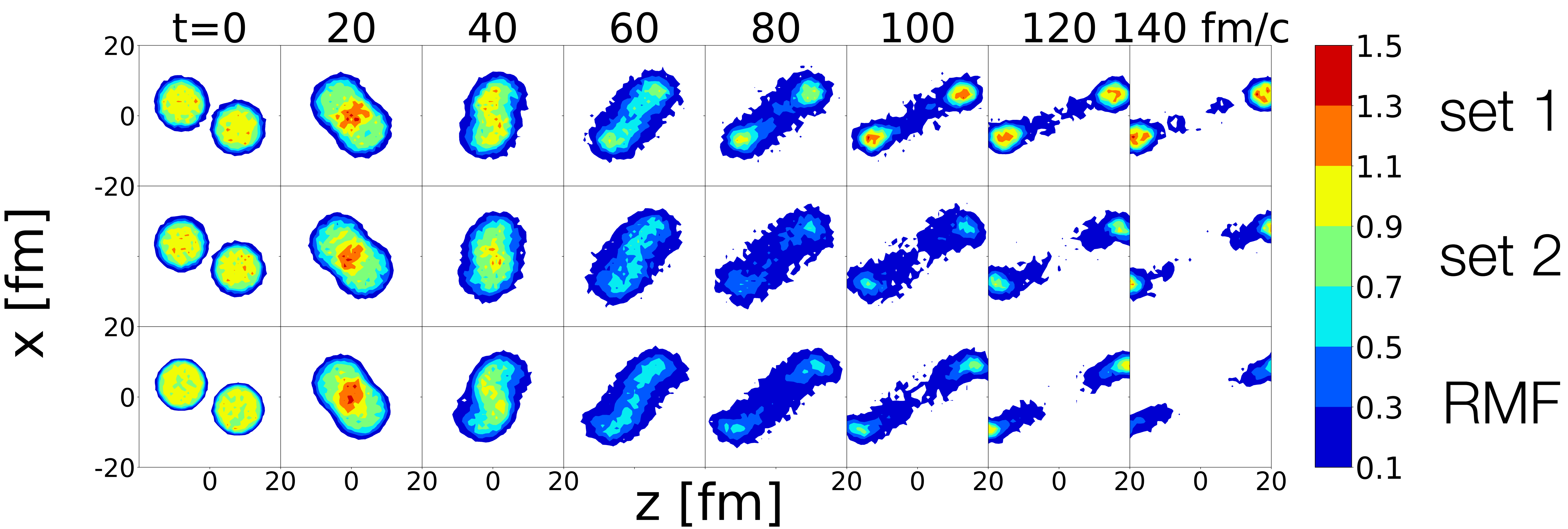
central collision
at center position

E_{beam} = 0.1   0.4 GeV/u



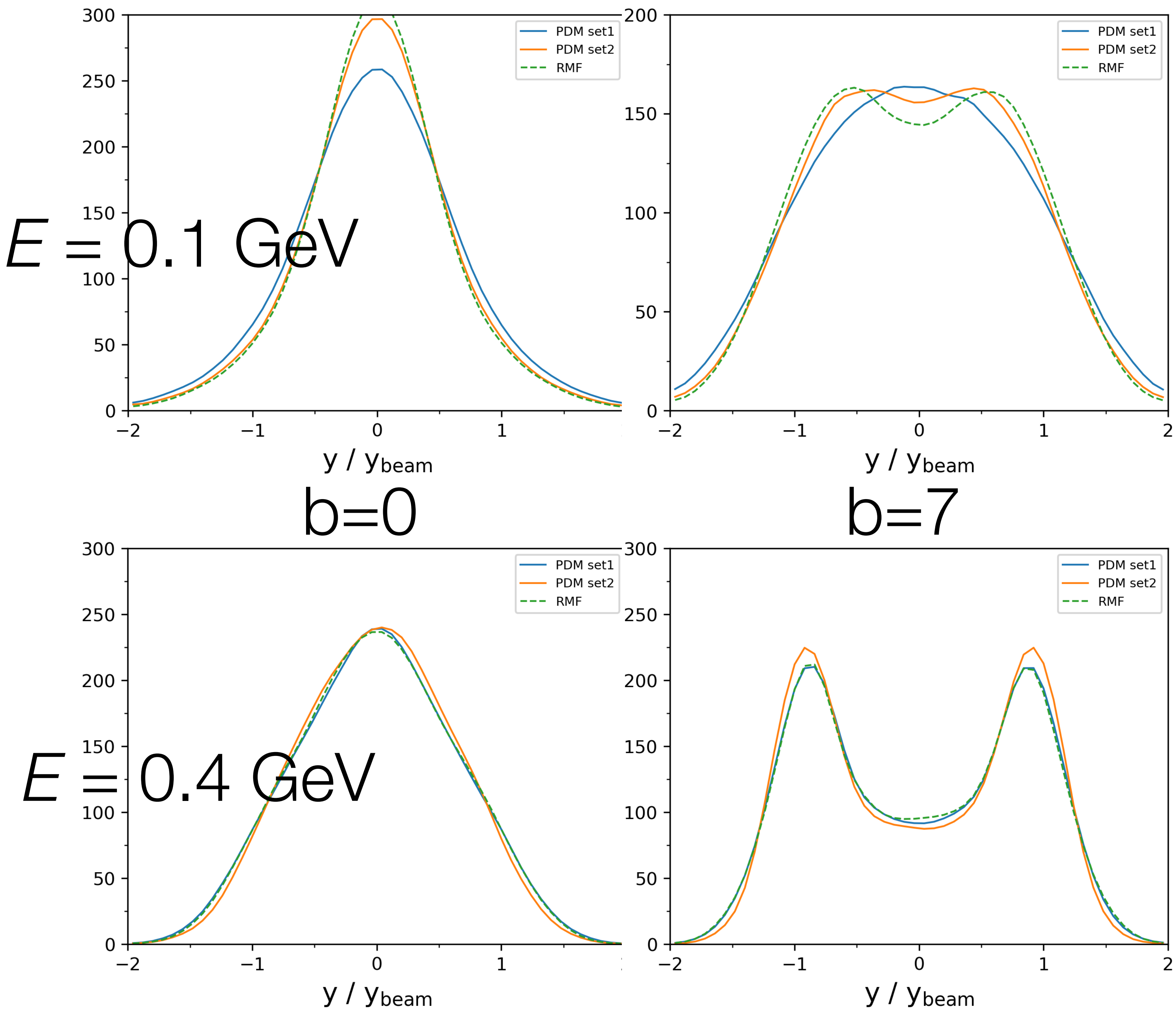
Density evolution at b=7 fm Au + Au collision

- E = 100 MeV/u



RMF : NLρ in σωρ RMF model from B. Liu et. al (2002) set 1

Momentum distribution
(rapidity distribution and transverse flow)



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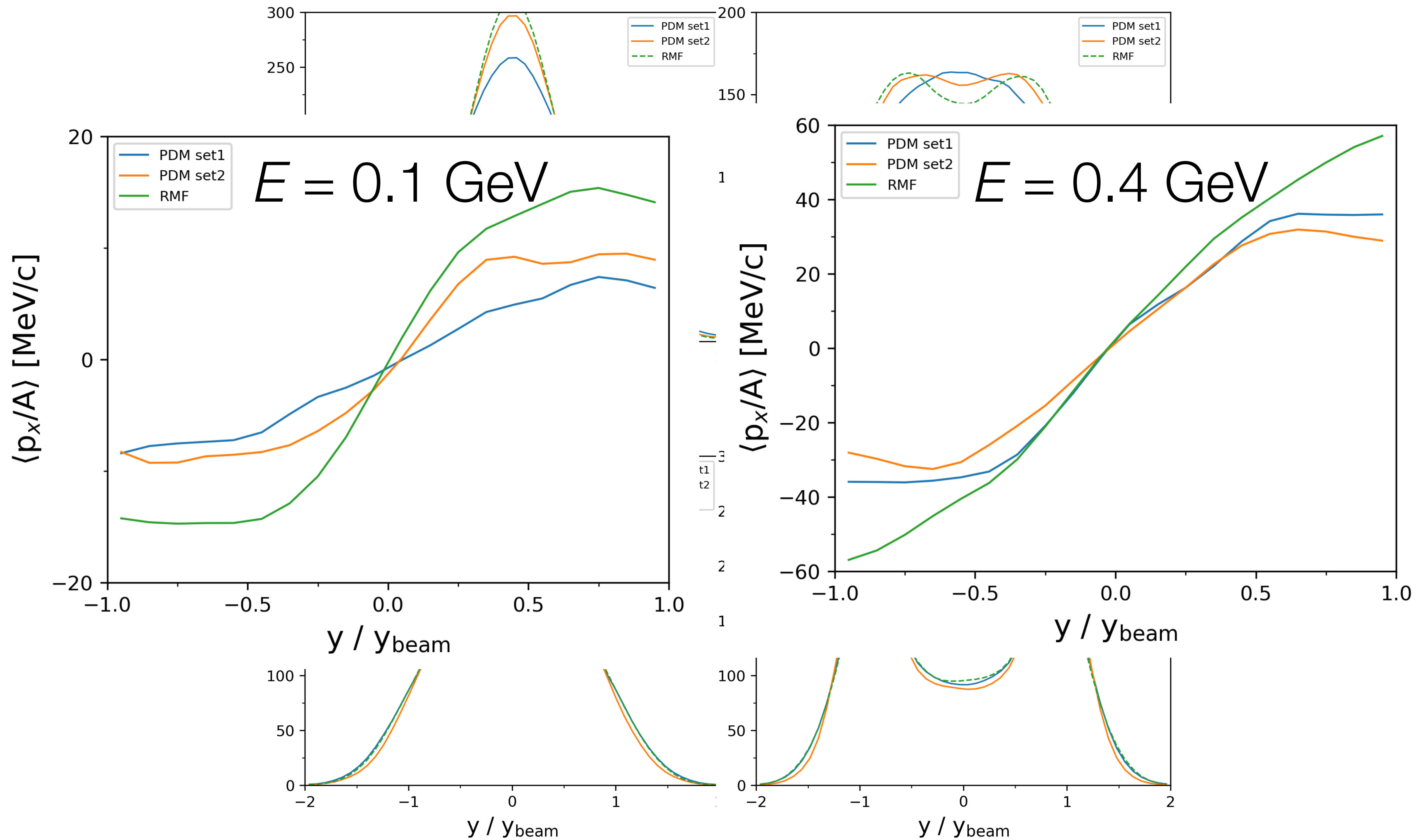
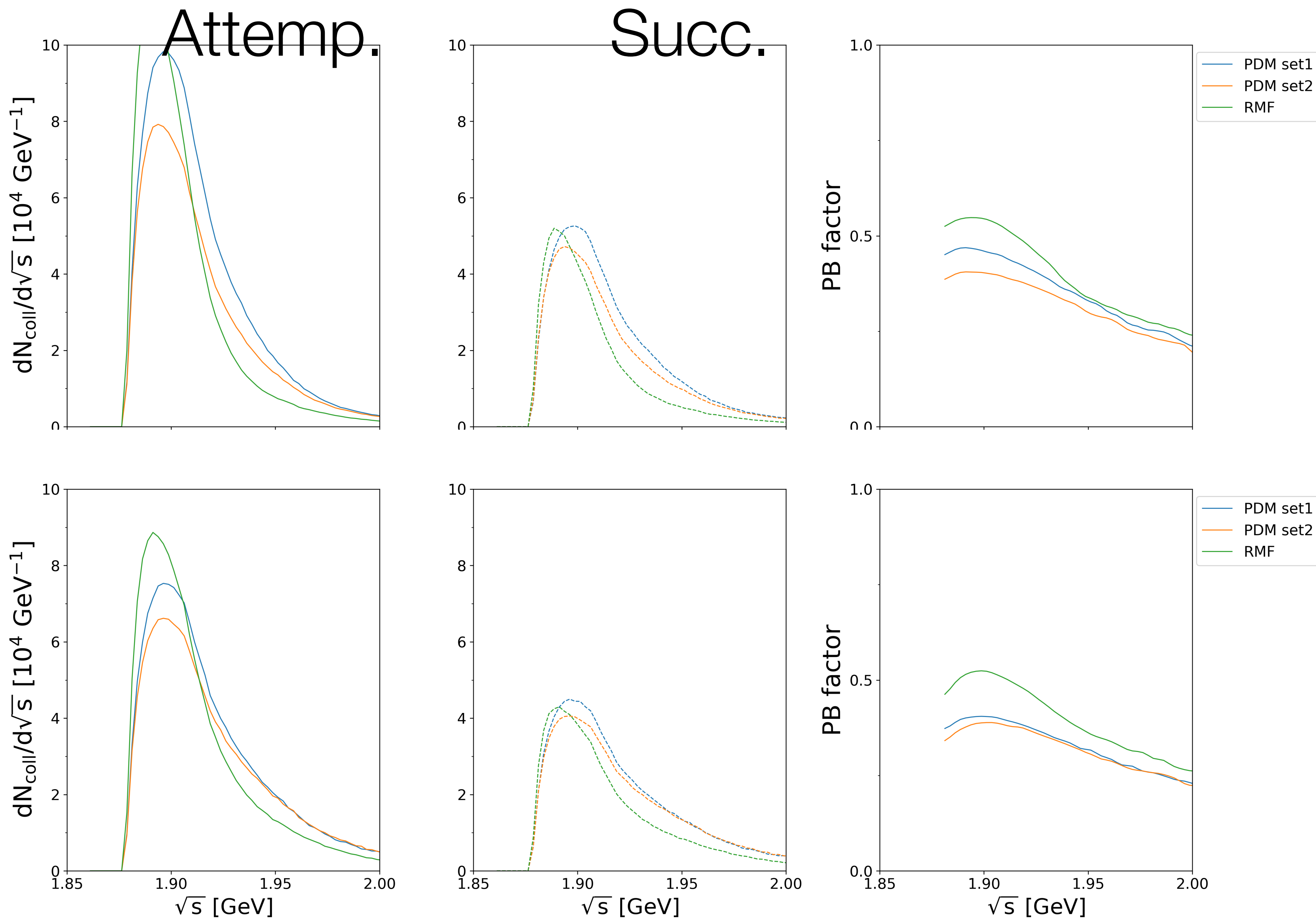


Collision and Pauli blocking

E = 0.1

E = 0.4



Summary and future plan

- Model testing of simple PDM can give difference in observable physical quantities in HIC.

- Chirally invariant mass, m0, through the transport code can be tested and through the results one can figure out the strongly correlated observable parameter.

- Considering mesonic Lagrangian including ρ meson, isospin asymmetry can be studied.

- We will study on Δ production of PDM in transport theory.

Set1 and Set2

	m_σ	$g_{\omega N}$	m_0	g_4	a	b
$N^-(1535)$	210.763 MeV	1.69342	938 MeV	0	11.875	5.46407
$N^-(1200)$	180.457 MeV	1.913	890 MeV	0	7.77939	4.97066

Table 4: The best parameter sets for $N^-(1535)$ and $N^-(1200)$.

TABLE I. Fit parameter and nuclear matter properties for the four fits mainly used. For all parameter sets: $E/A(\rho_0) - m_N = -16$ MeV, $\rho_0 = 0.16$ fm^{-3} and the vacuum nucleon mass $m_N = 939$ MeV.

	$P1$	$P2$	$P3$	$P4$
m_{N^-} [MeV]	1200	1200	1500	1500
g_4	0	3.8	0	3.8
m_0 [MeV]	790	790	790	790
m_σ [MeV]	318.56	302.01	370.63	346.59
$g_{N\omega}$	6.08	6.77	6.79	7.75
a	9.16	9.16	13.00	13.00
b	6.35	6.35	6.97	6.97
$\bar{\mu}$ [MeV]	147.50	128.93	199.26	176.29
λ	4.75	4.16	6.82	5.82
$m_{N^+}(\rho_0)/m_{N^+}$	0.86	0.86	0.84	0.83
$m_{N^-}(\rho_0)/m_{N^-}$	0.79	0.78	0.73	0.72
K [MeV]	436.41	374.75	510.57	440.51

$$\frac{E_0}{A} - m_N = -16.5\,\text{MeV} \quad \text{at} \quad n_0 = 0.153\,\text{fm}^{-3}\,.$$

$$\lambda = \frac{m_\sigma^2 - m_\pi^2}{2\sigma_0^2}, \qquad \left.\frac{\partial(\Omega/V)}{\partial\sigma}\right|_{\bar\sigma,\bar\omega} = -\bar\mu^{\,2}\bar\sigma + \lambda\bar\sigma^3 - \epsilon$$

$$\bar\mu^{\,2} = \frac{m_\sigma^2 - m_\pi^3}{2}, \qquad + \sum_i \rho_i^*(\bar\sigma, \bar\omega) \left.\frac{\partial m_i}{\partial\sigma}\right|_{\bar\sigma} = 0,$$

$$\epsilon = m_\pi^2 f_\pi, \qquad \left.\frac{\partial(\Omega/V)}{\partial\omega_0}\right|_{\bar\sigma,\bar\omega} = -m_\omega^2\bar\omega - 4g_4^4\bar\omega^3$$

$$+ g_\omega \sum_i \rho_i(\bar\sigma, \bar\omega) = 0.$$