Transport Workshop @ ECT*

Transport Studies in Korea

Young-Min Kim (UNIST)

on behalf of

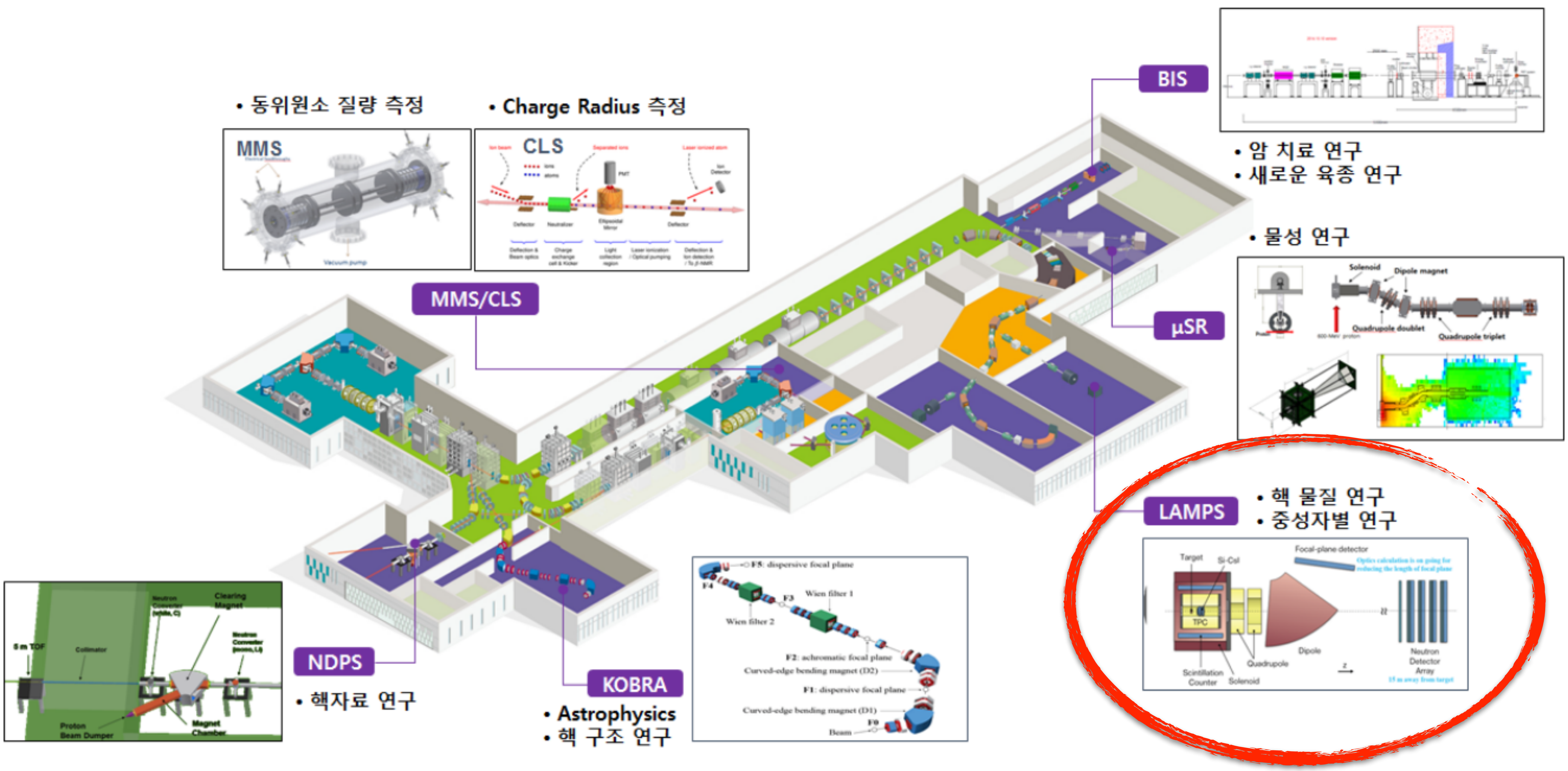
DJBUU collaboration: Sangyoung Jeon (McGill U.), Myungkuk Kim, Chang-Hwan Lee (PNU), Youngman Kim (IBS), Young-Min Kim (UNIST)

QMD collaboration: Kyungil Kim, Youngman Kim (IBS/RISP), Kang Seog Lee (CNU)

Contents

RAON : Korean Rare Isotope Accelerator

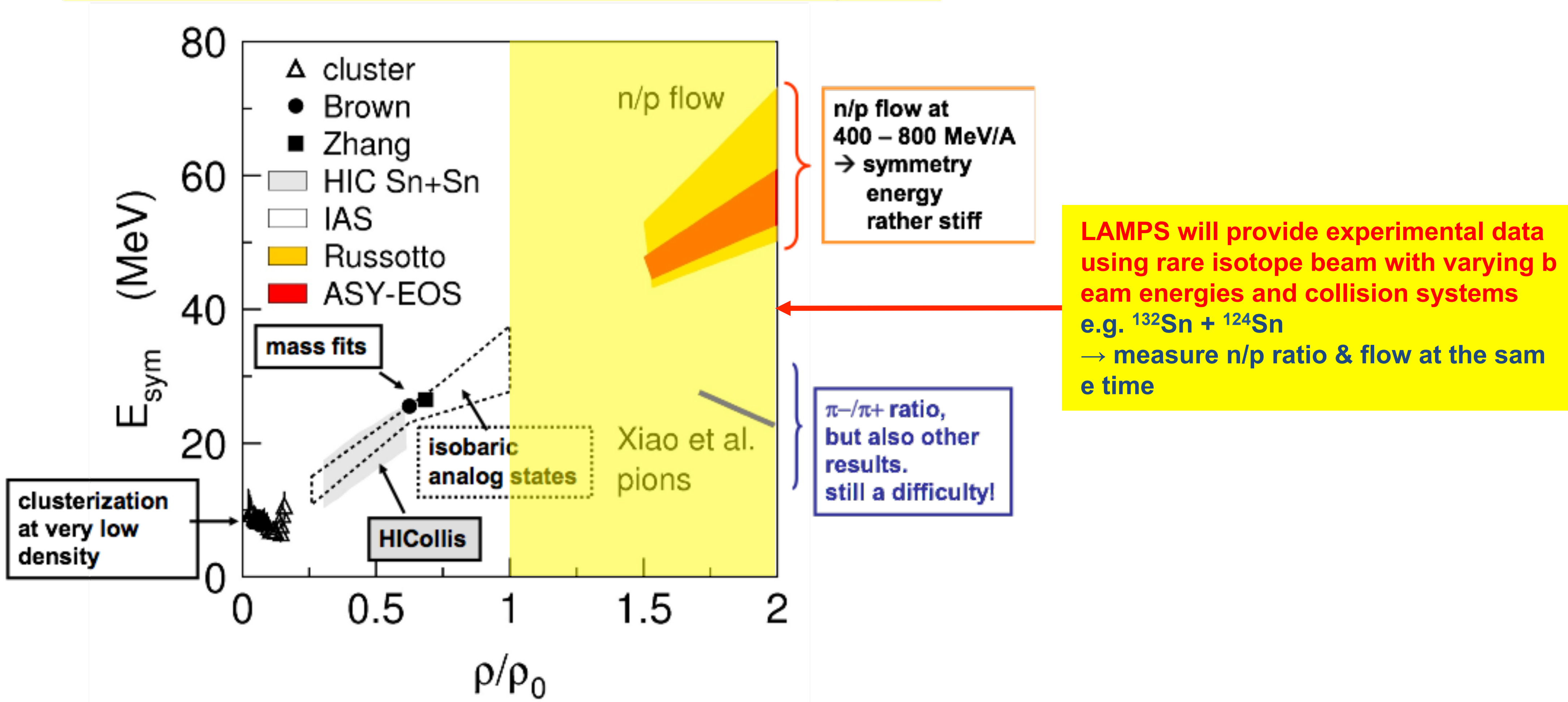
- **Experimental Systems**



LAMPS
(Large Acceptance Multi-Purpose Spectrometer)

- Possible experiment
  - Using 18.5 ~ 250 MeV/u RI beam through IF separtor, perform N/Z controlled heavy-ion collision experiment for studying density dependent symmetry energy of nuclear matter possible Day-1 experiment : $^{50,54}Ca+^{40}Ca$ to measure proton, neutron spectrum
  - Then, series of experiment for $^{50,54}Ca+^{40}Ca$, $^{68,70,72}Ni + ^{58}Ni$, $^{106,112,124,130,132}Sn + ^{112,118,124}Sn$ to measure particle spectrum, yield, ratio, collective flow etc. at the same time

Present Constraints on the Symmetry Energy (shown as $E_{sym}(\rho/\rho_0)$)



- Experimental data are measured with stable beams
- data of pion ratio and data of n/p flow are from different experiments
- Models in the market show different results even within same observable

Historical Progress on Transport studies

1. 2011, RAON project was launched.
   - Transport code for simulating heavy ion collision with RAON was needed.
2. 2012, School on Nuclear Transport at APCTP (Pohang, Korea)
   - Lecturers : H. Wolter, P. Danielewicz, A. Ono, T. Gaitanos, Q. Li, Z. Li
   - We started to study transport simulation with RBUU.
3. 2014, We joined the code comparison with RBUU @ 2014 transport workshop (Shanghai).
   - 2016, K.Kim, Y. Kim joined the transport code HW (J. Xu et al PRC 2016)
4. 2014, We (leader: Dr. K. Kim) started to develop a new QMD code.
5. 2015, Y. Lee (student@PNU) studied temperature estimation during collisions with RBUU.
6. 2015.10 ~ 2016.2, S. Jeon (McGill Univ.) developed prototype DJBUU during his sabbatical in IBS
   - M. Kim (student@PNU) joined DJBUU project
7. 2016, We started code comparison test with DJBUU.
8. 2016, DJBUU first paper was published in NPSM (domestic journal).
9. 2017, A new QMD first paper was published in JKPS.
10. 2017 ~ present, We continue to work with DJBUU and QMD for our researches.

BUU type Transport simulation

Boltzmann-Uehling-Uhlenbeck (BUU) eq.

$$p_a^\mu \partial_\mu f_a(x, \mathbf{p}_a) + F_a^j(x) \frac{\partial}{\partial p_a^j} f_a(x, \mathbf{p}_a) = \mathcal{C}_a[\{f_b(x, \mathbf{p}_b)\}]$$

$$\begin{aligned} C_{ab} &= \frac{1}{2} \int \frac{d^3p'}{(2\pi)^3 2E_{p'}} \int \frac{d^3k}{(2\pi)^3 2E_k} \int \frac{d^3k'}{(2\pi)^3 2E_{k'}} \left|\mathcal{M}_{ij}\right|^2 \, (2\pi)^4 \delta(p + k - p' - k') \\ &\times \left[f_a(x, \mathbf{p}') f_b(x, \mathbf{k}') \tilde{f}_a(x, \mathbf{p}) \tilde{f}_b(x, \mathbf{k}) - f_a(x, \mathbf{p}) f_b(x, \mathbf{k}) \tilde{f}_a(x, \mathbf{p}') \tilde{f}_b(x, \mathbf{k}') \right] \end{aligned}$$

RMF

$$\partial^2 \sigma + \frac{\partial U}{\partial \sigma} = -g_\sigma \rho_S$$

$$(\partial^2 + m_\omega^2)\omega^\nu = g_\omega j_b^\nu$$

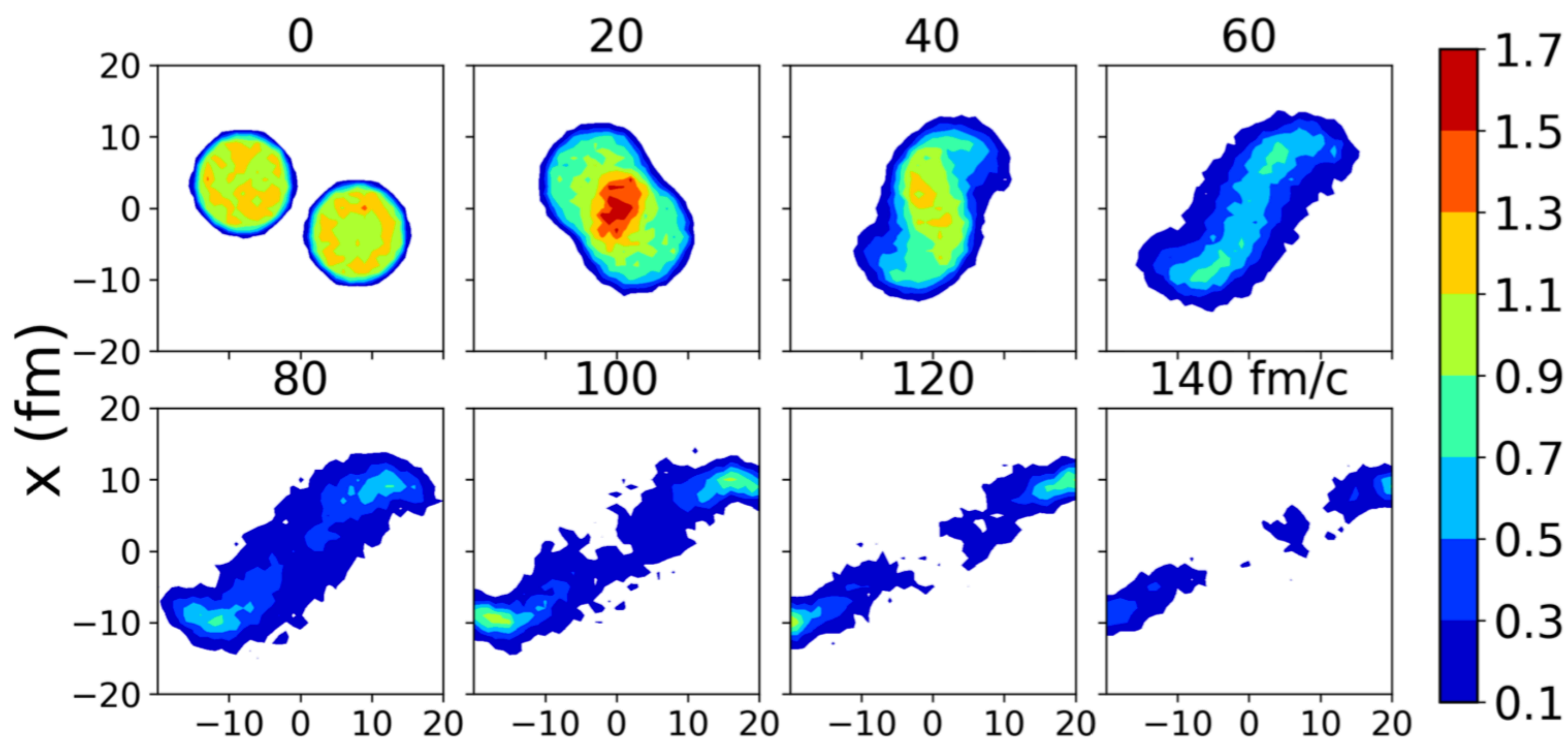
$$(\partial^2 + m_\rho^2)\boldsymbol{\rho}^\nu = g_\rho \boldsymbol{j}_I^\nu$$

Daejeon BUU (DJBUU)

- c / c++ language
- openMP implemented

$$\frac{d\mathbf{x}_a}{dt} = \frac{\mathbf{p}_a}{E_a}$$
$$\frac{d\mathbf{p}_a}{dt} = -\nabla V_a^0 - m_a^* \nabla S.$$

Kim, M. et al. in preparation



Test particle Method

^{197}Au+^{197}Au@ 100 AMeV, b=7fm

phase space density

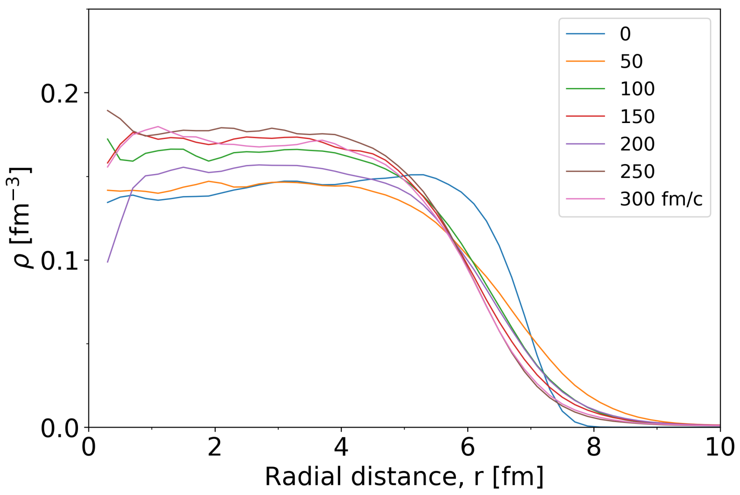
$$\hat{f}_a(x, \mathbf{p}) = \sum_{i=1}^{N_a N_{\text{test}}} (2\pi)^3 g_x(\mathbf{x} - \mathbf{x}_i(t)) g_p(\mathbf{p} - \mathbf{p}_i(t))$$

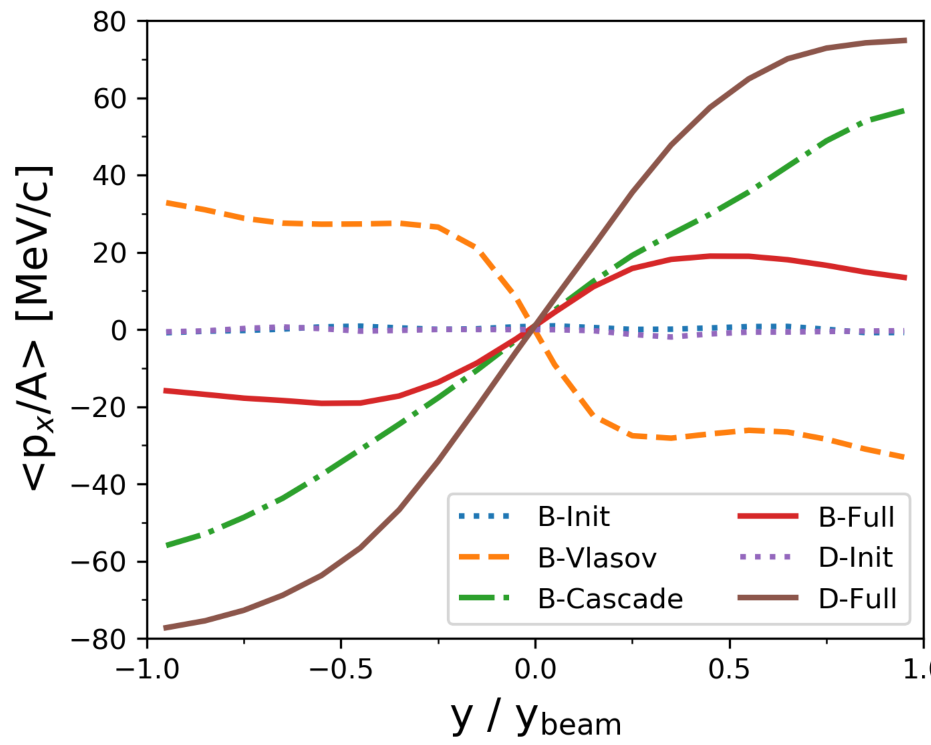
Au+Au collisions in DJBUU

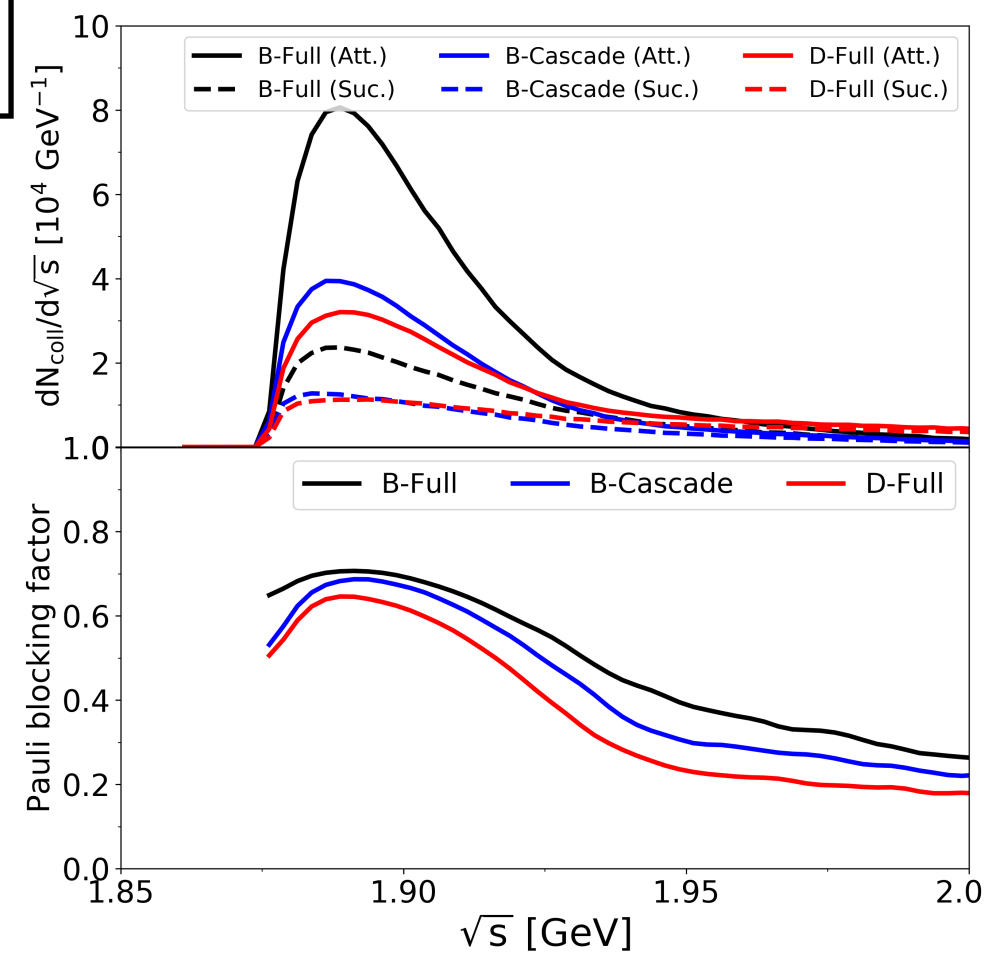
^{197}Au+^{197}Au collisions @ b=7 fm

B-mode: 100 AMeV
D-mode: 400 AMeV
Cascade: w/o mean fields
Vlasov: w/o collisions

Kim, M. et al , in preparation







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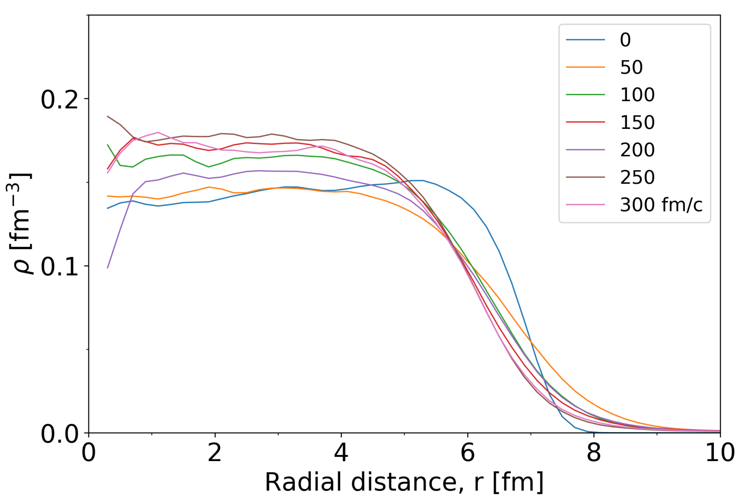
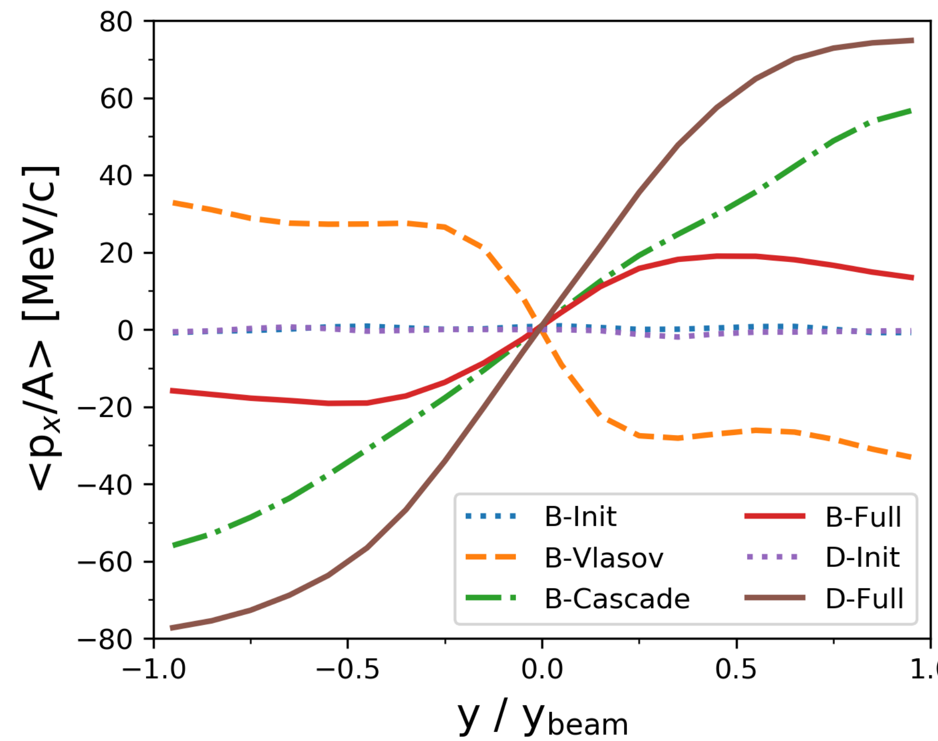
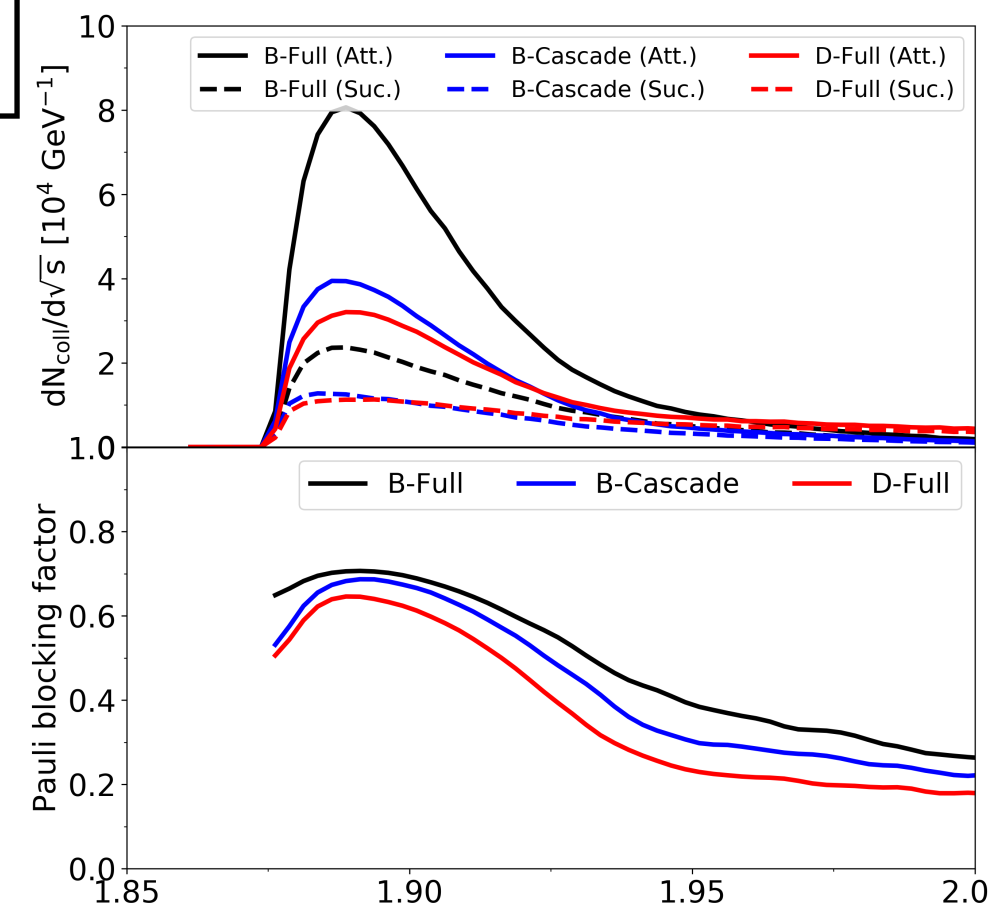




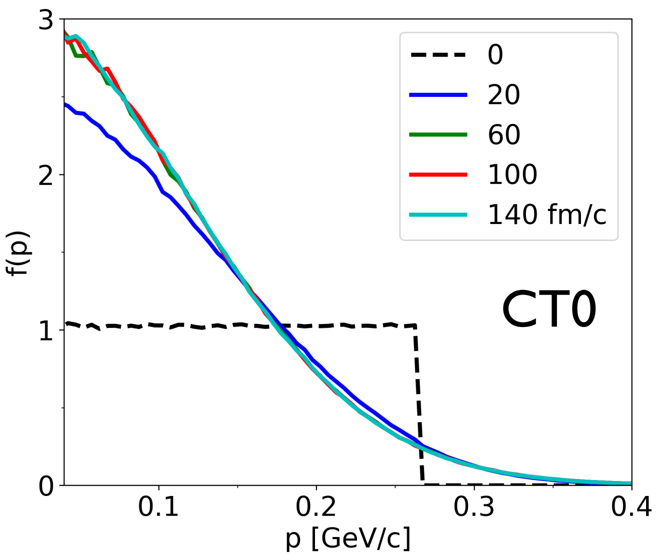


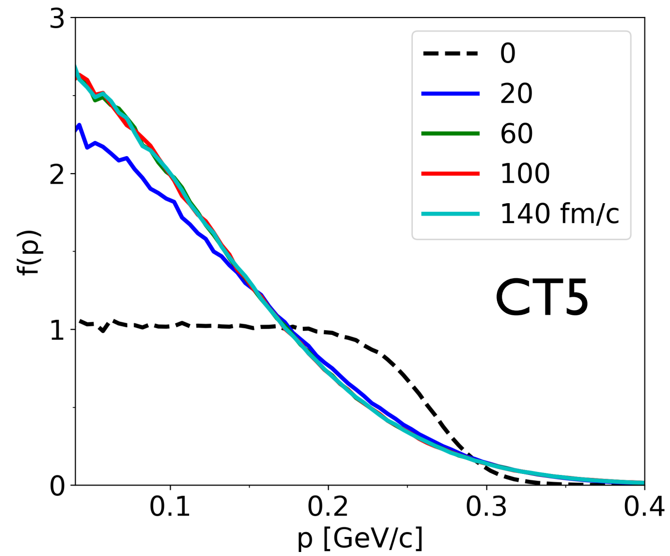
comparable to HIC comparison results (J. Xu et al., PRC.93.044609 (2016))

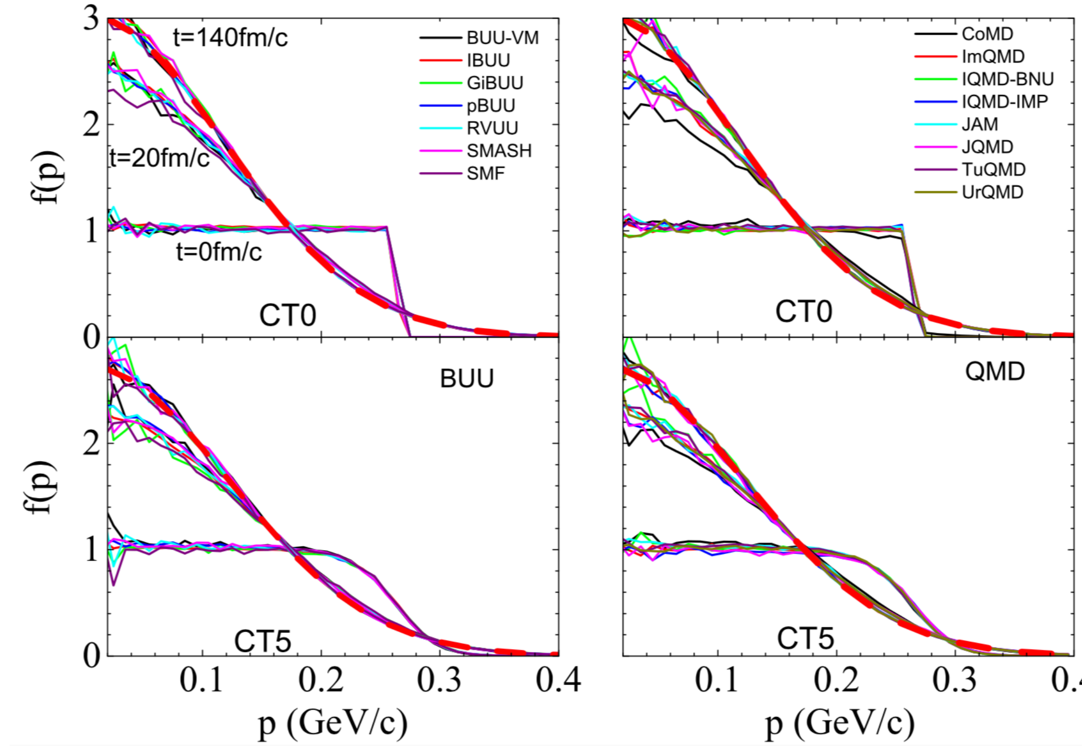
Box calculations in DJBUU (1)

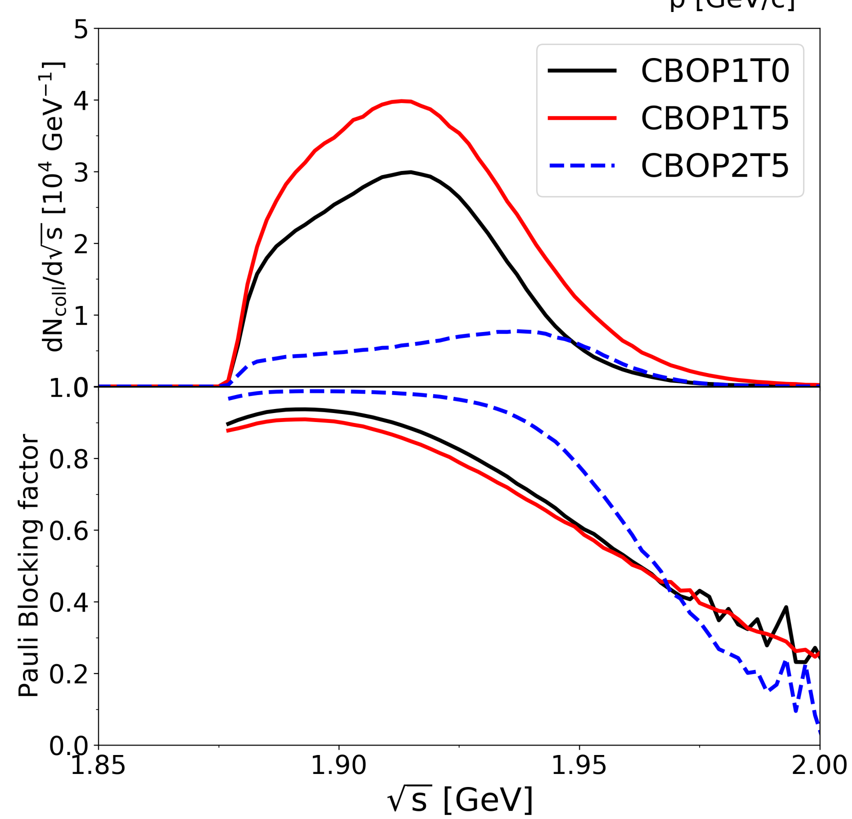
HW1: Collisions and Pauli blocking

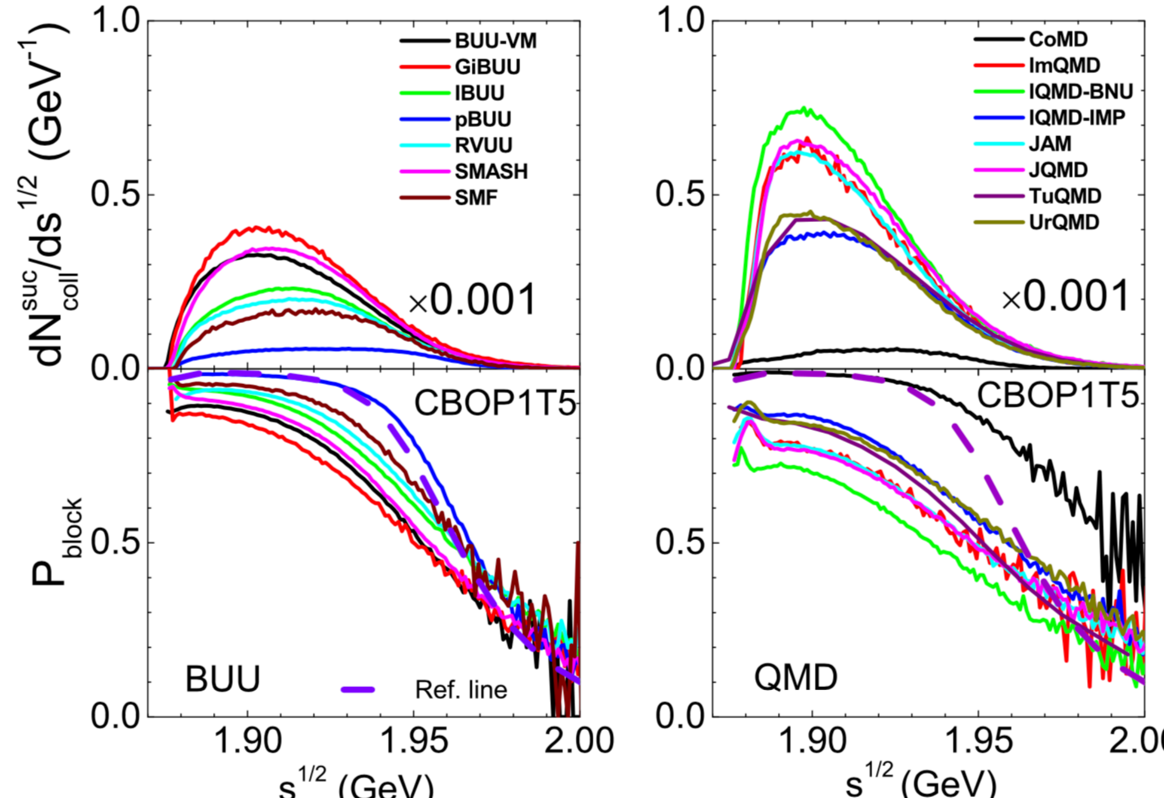
code comparison paper: HW1- PRC.97.034625







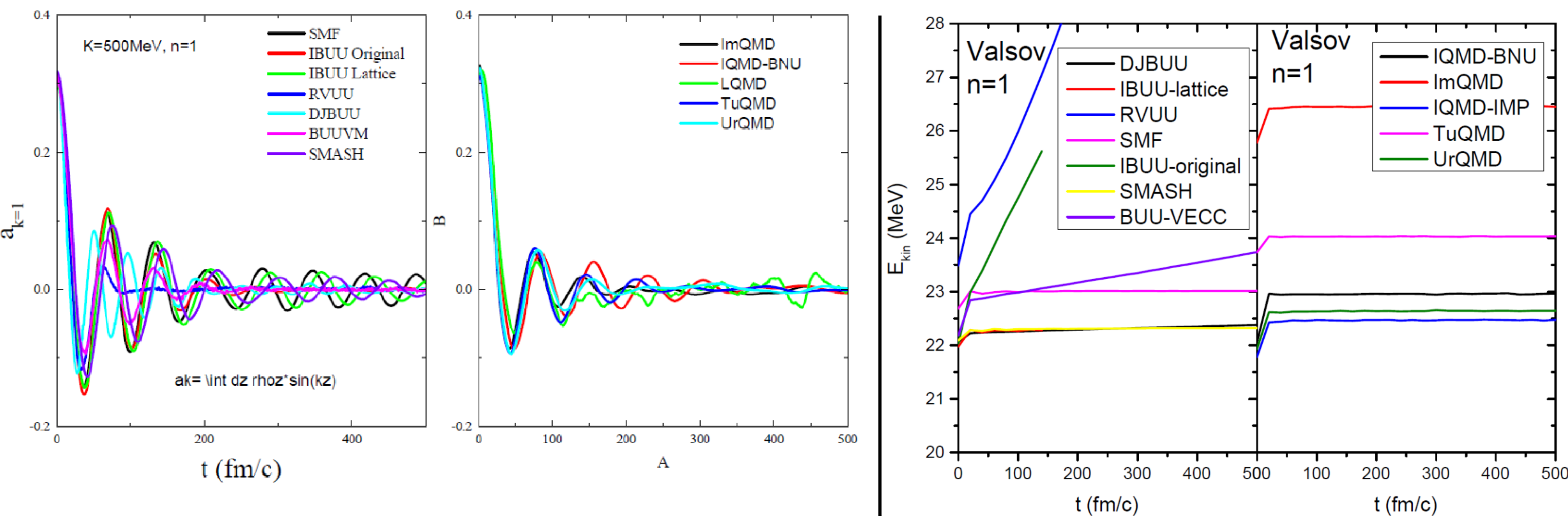




DJBUU (Kim, M. et al , in preparation)

Box calculations in DJBUU (2)

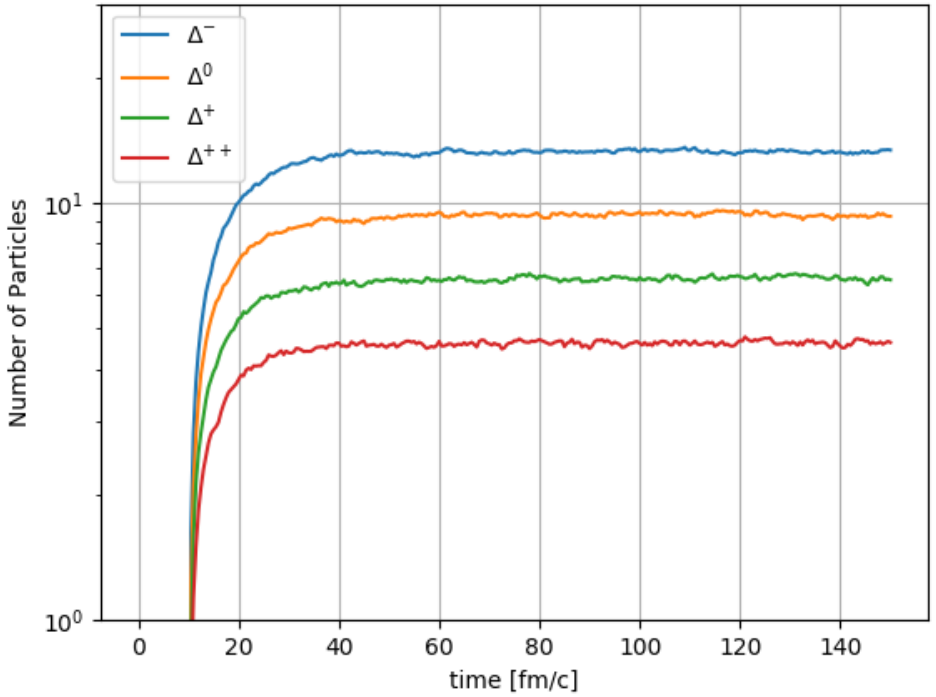
HW2: Vlasov mean field (DJBUU participated in)



taken from M. Colonna's presentation @ Transport 2018

Box calculations in DJBUU (3)

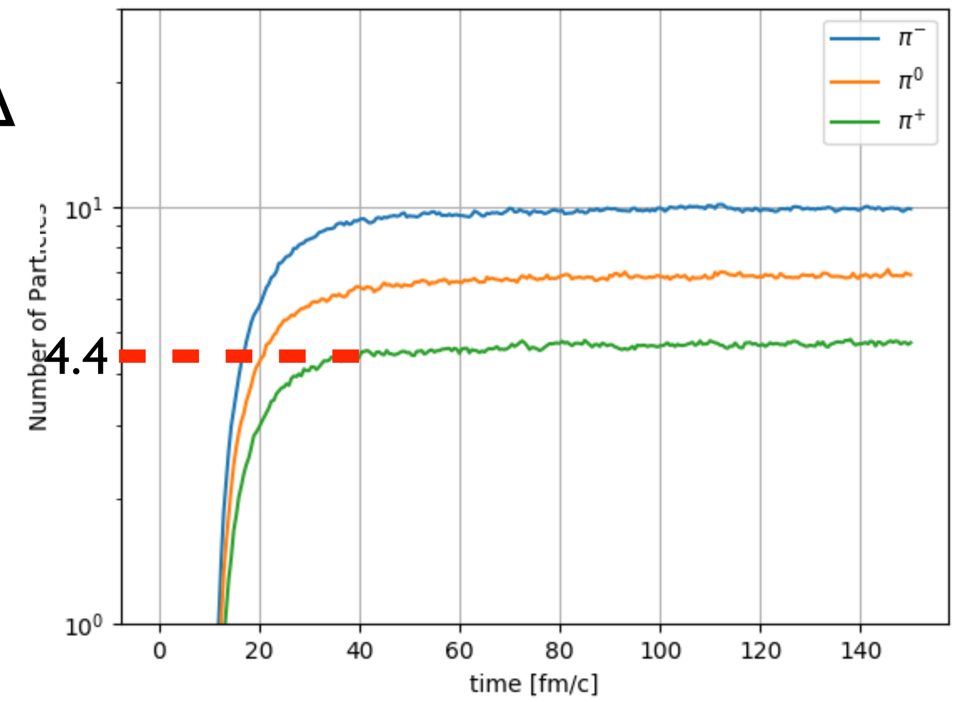
HW3: Pion production

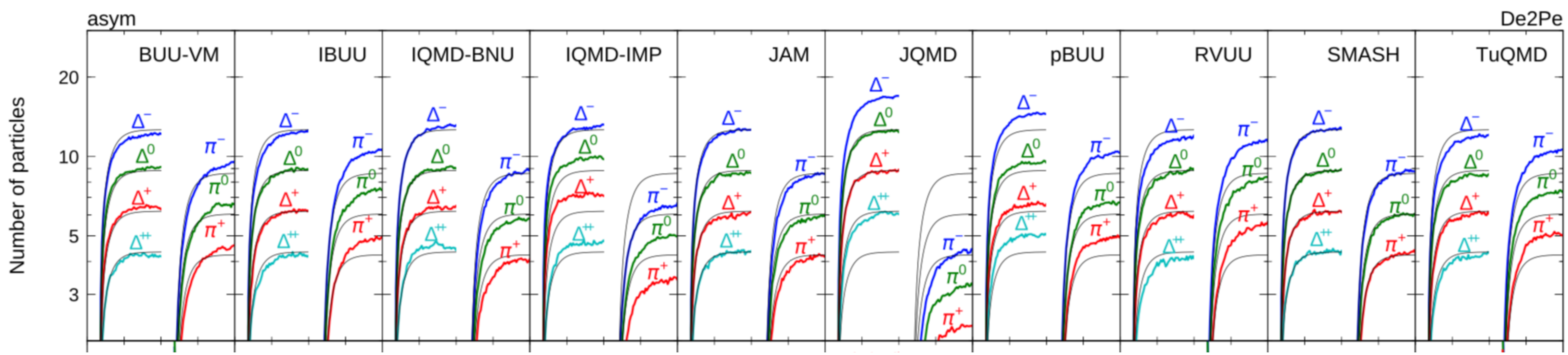


N + N <—> N + Δ

Δ <—> N + π

$$\pi^-/\pi^+ \approx (n/p)^2$$
$$= (1.5)^2 = 2.25$$



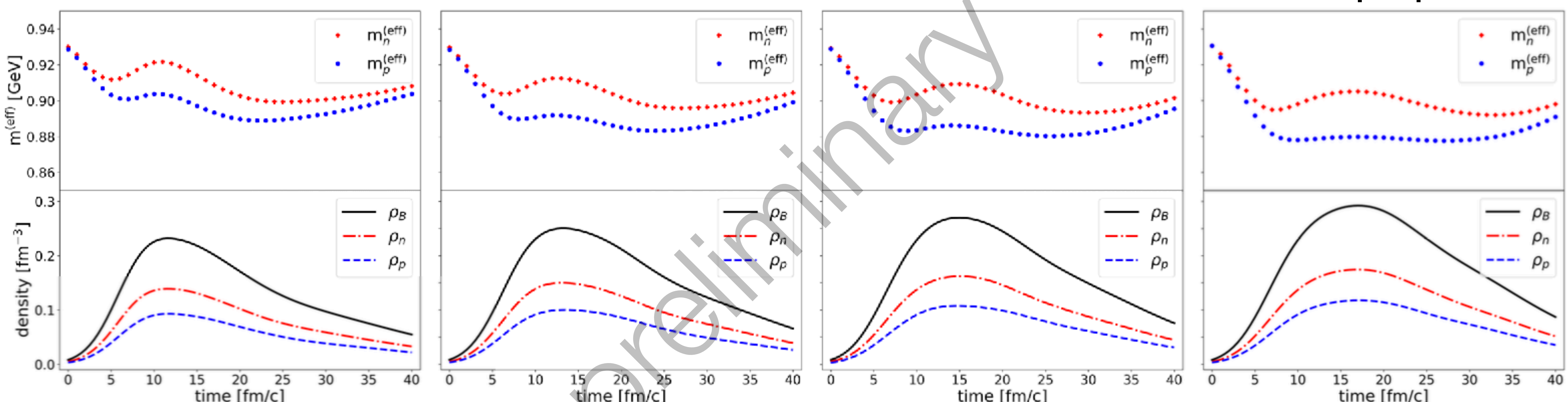


A. Ono, et al., arxiv:1904.02888

Test on extended Parity Doublet Model

Time evolution of neutron and proton effective masses and densities at the center in ^{197}Au+^{197}Au head-on collisions @ E_{beam}=400 A MeV, K=215 MeV

Kim, M. et al , in preparation



(a) $m_0 = 600$ MeV (b) $m_0 = 700$ MeV (c) $m_0 = 800$ MeV (d) $m_0 = 900$ MeV

More details are presented by M. Kim in the next presentation

QMD type transport simulation

$$H = \sum_i \frac{\vec{p}_i^2}{2m_i} + U_{tot},$$

$$\psi_i(\vec{r},t) = \frac{1}{(2\pi\sigma_r^2)^{3/4}} \exp\left(-\frac{(\vec{r}-\vec{r_i})^2}{4\sigma_r^2} + \frac{i}{\hbar}(\vec{p_i}\cdot\vec{r})\right)$$

$$U_{tot} = U_{Skyrme} + U_{surf} + U_{sym} + U_{coul}$$

phase space density $$f_i = \frac{1}{(2\pi\sigma_r\sigma_p)^3} \exp\left[-\frac{(\vec{r}-\vec{r_i})^2}{2\sigma_r^2} - \frac{(\vec{p}-\vec{p_i})^2}{2\sigma_p^2}\right]$$

$$\begin{aligned} U_{tot} = & \frac{\alpha}{2\rho_0}\sum_{i,j\neq i}\rho_{ij} + \frac{\beta}{\gamma+1}\sum_i\left(\sum_{j\neq i}\frac{\rho_{ij}}{\rho_0}\right) \\ & + \frac{g_{surf}}{2\rho_0}\sum_{i,j\neq i}\nabla^2_{r_i}(\rho_{ij}) \\ & + \frac{g_{sym}}{2\rho_0}\sum_{i,j\neq i}[2\delta_{\tau_i\tau_j}-1]\rho_{ij} \\ & + \frac{e^2}{2}\sum_{\substack{i,j\neq i,\\ (i,j \text{ for protons})}}\frac{1}{|\vec{r}_i-\vec{r}_j|}\operatorname{erf}\left(\frac{|\vec{r}_i-\vec{r}_j|}{2\sigma_r}\right) \end{aligned}$$

two-body density

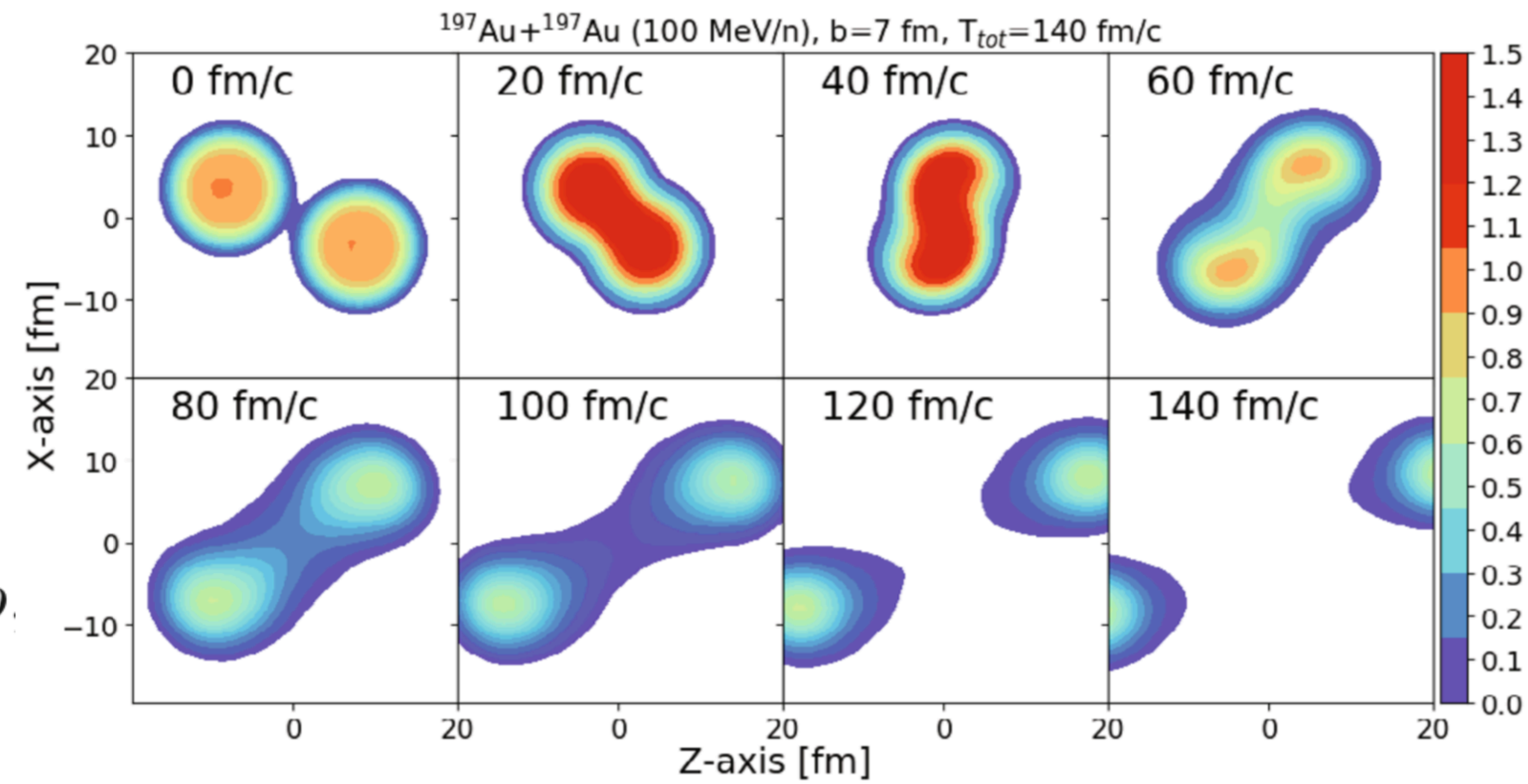
$$\rho_{ij} = \frac{1}{(4\pi\sigma_r^2)^{3/2}} \exp\left[-\frac{1}{4\sigma_r^2}(\vec{r}_i-\vec{r}_j)^2\right]$$

Kim, K. et al. , JKPS, 71, 628 (2017)

QMD type transport simulation

$$\frac{d\vec{r_i}}{dt} = \nabla_{\vec{p_i}} H; \qquad \frac{d\vec{p_i}}{dt} = -\nabla_{\vec{r_i}} H$$

Kim, K. et al. , JKPS, 71, 628 (2017)



the integrated phase density of the final state of scattered particle i,

$$\tilde{f}_i = \frac{1}{2}\sum_j \delta_{\tau_i,\tau_j} \int_{h^3} f_j(\vec{r},\vec{p})\, d^3r d^3p$$

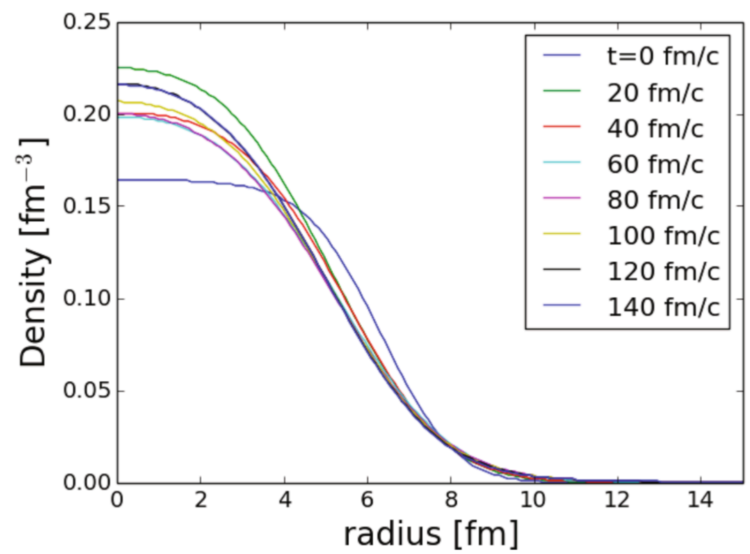
$^{197}Au+^{197}Au$@ 100 A MeV, b=7fm

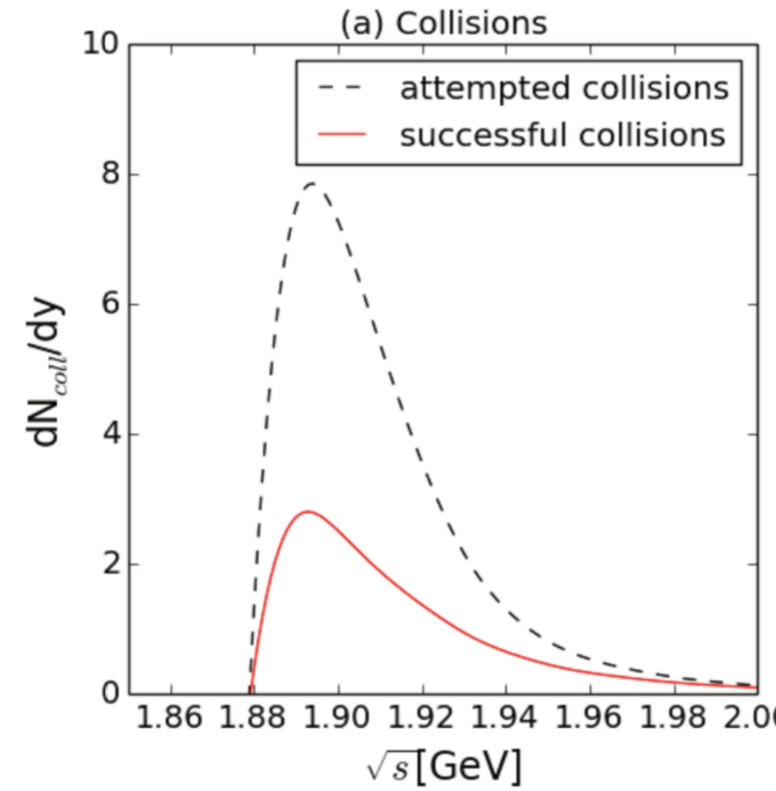
QMD can provide the event-by-event analysis

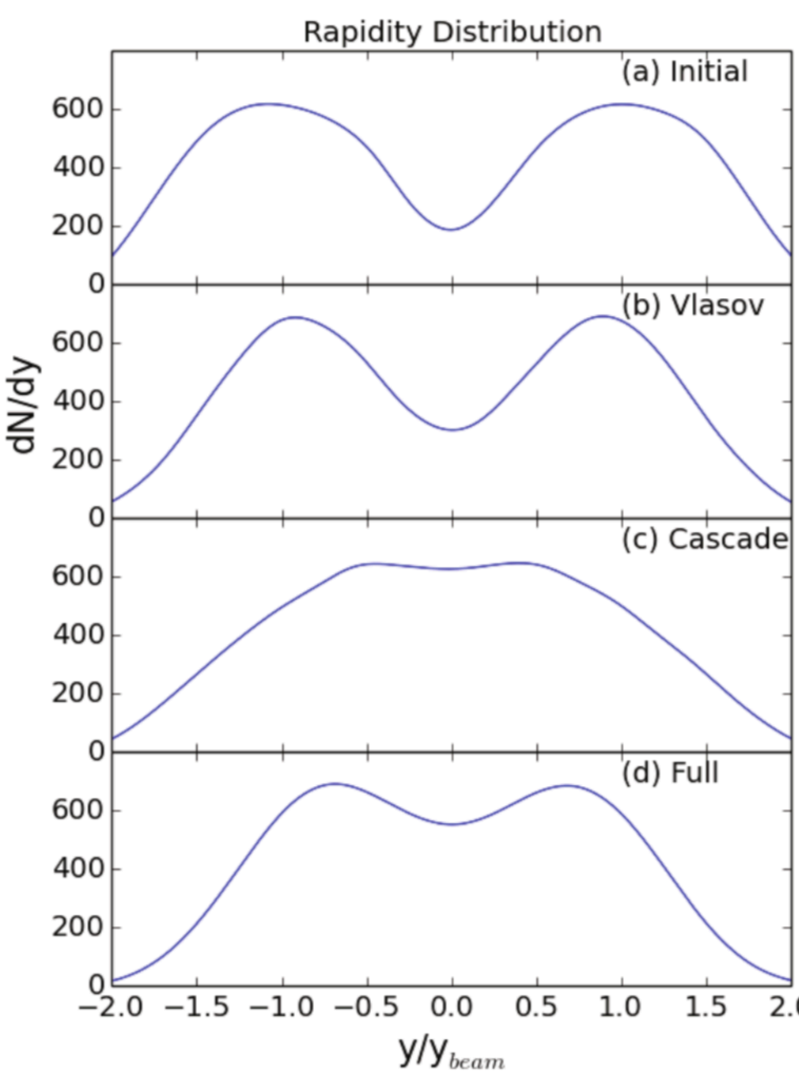
Au+Au collisions in QMD

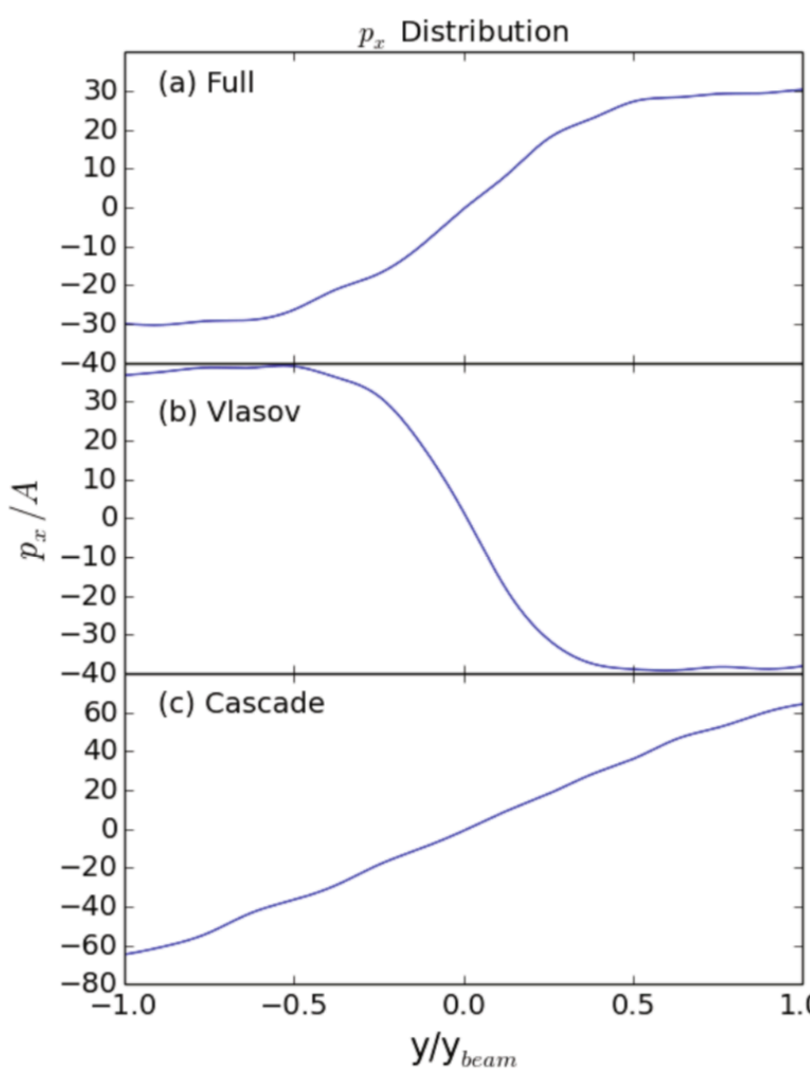
Kim, K. et al. , JKPS, 71, 628 (2017)

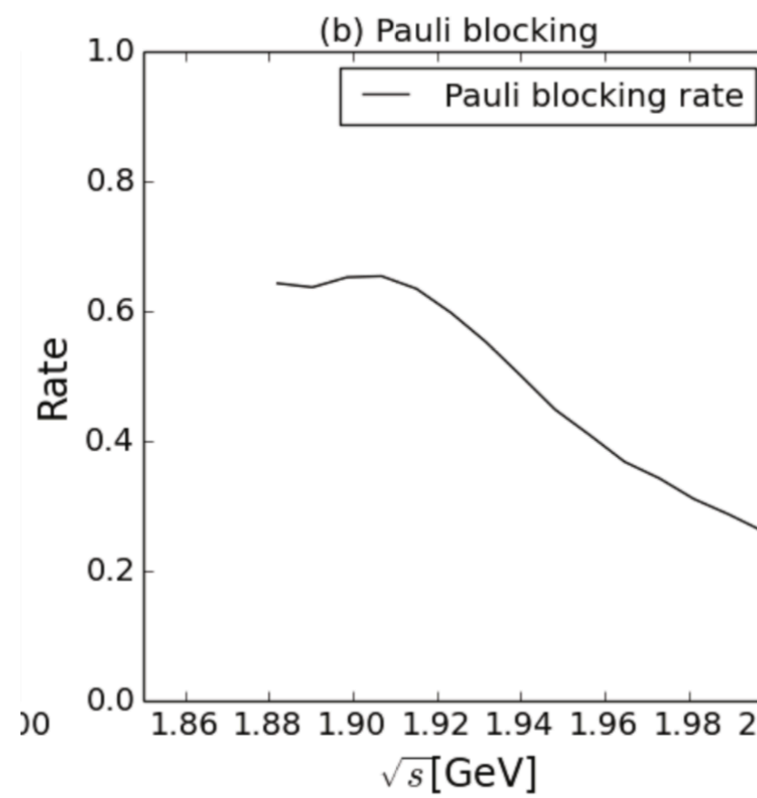
^{197}Au+^{197}Au collisions
@ 100 AMeV, b=7 fm











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^{197}Au+^{197}Au collisions
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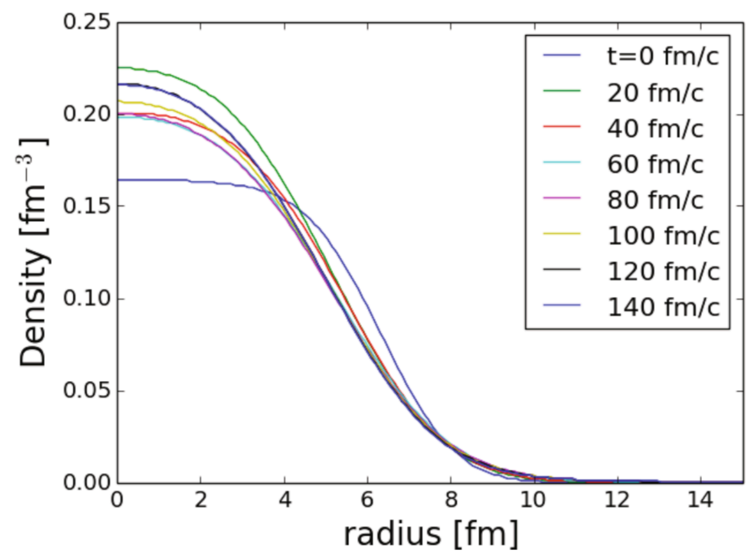
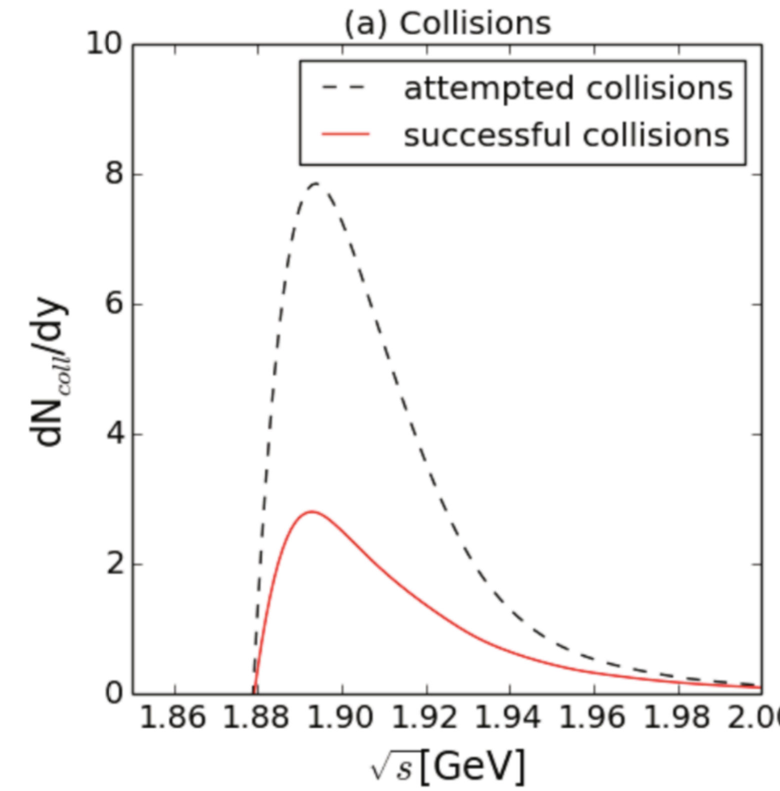
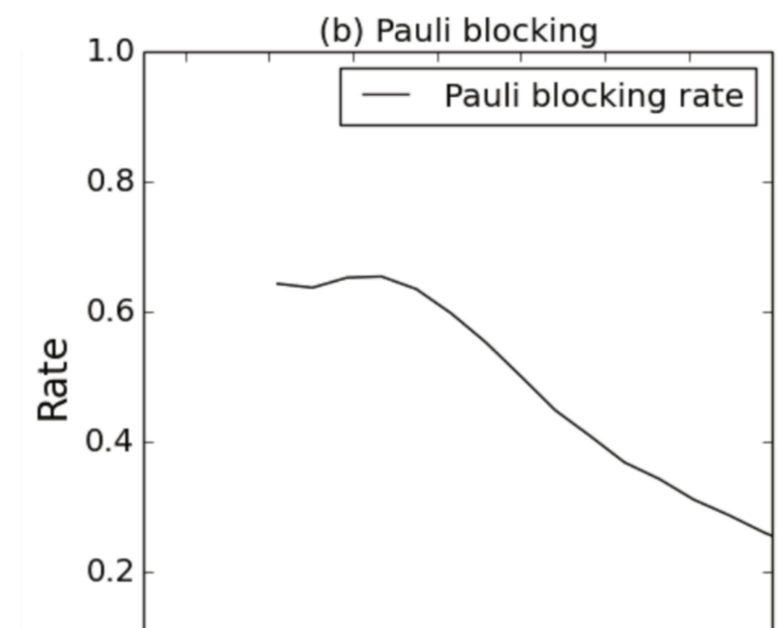
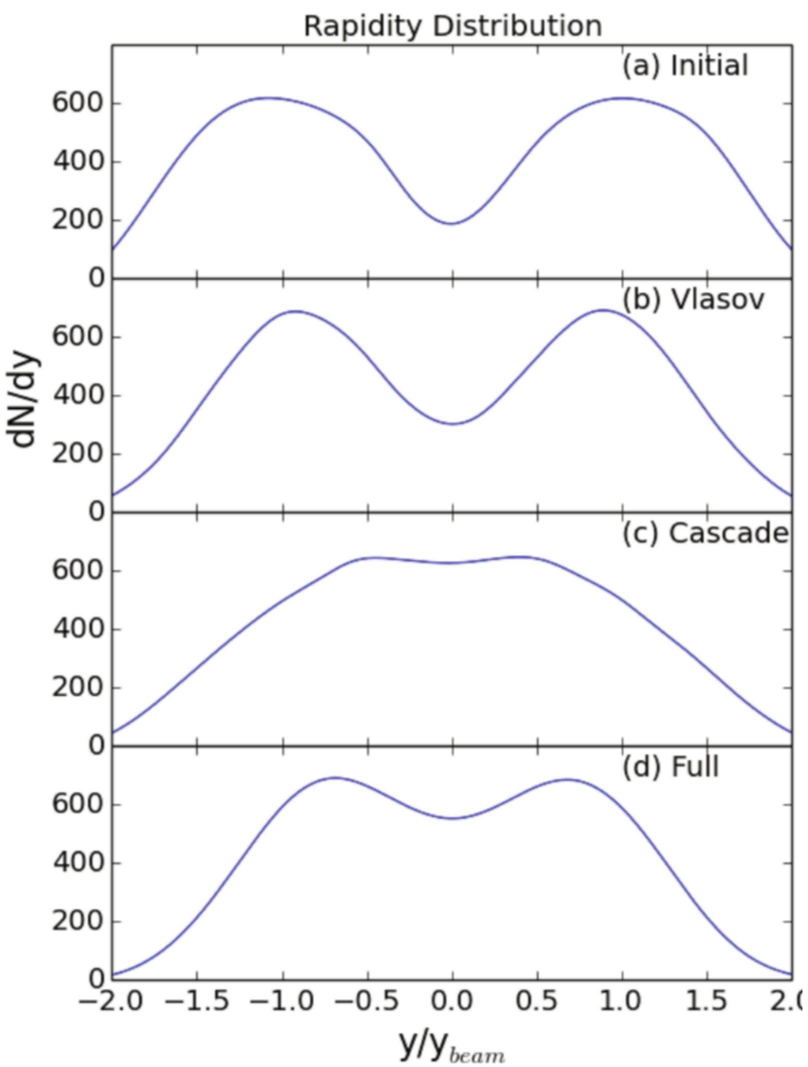
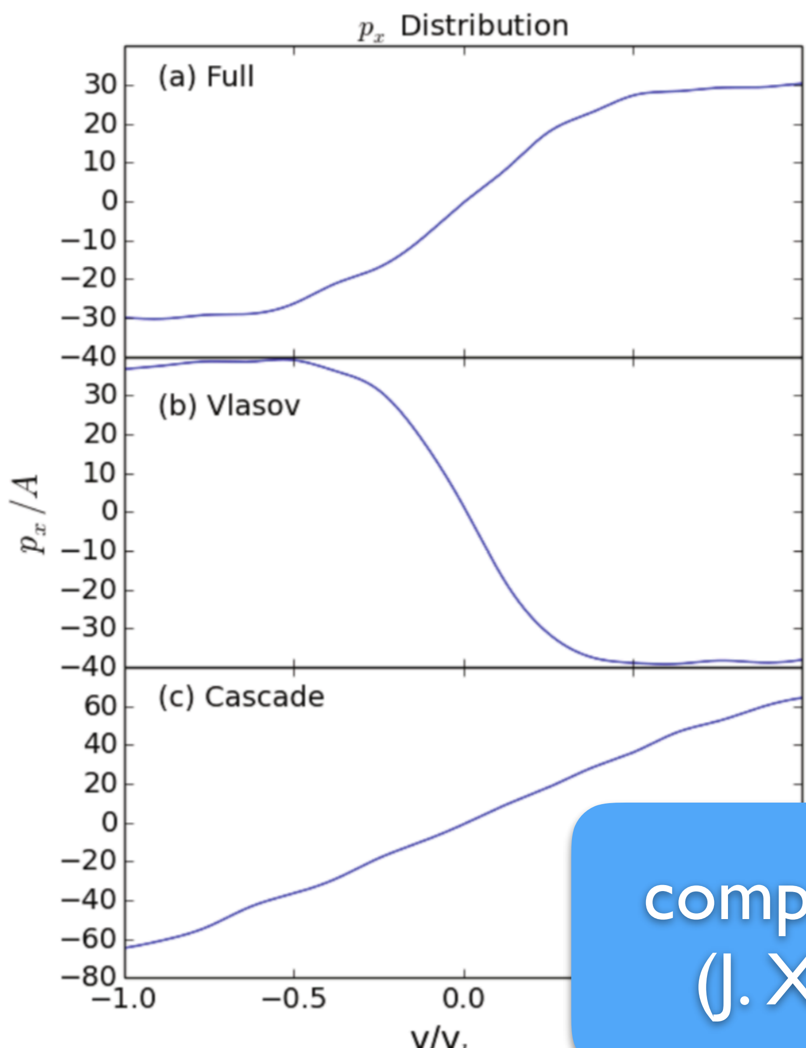










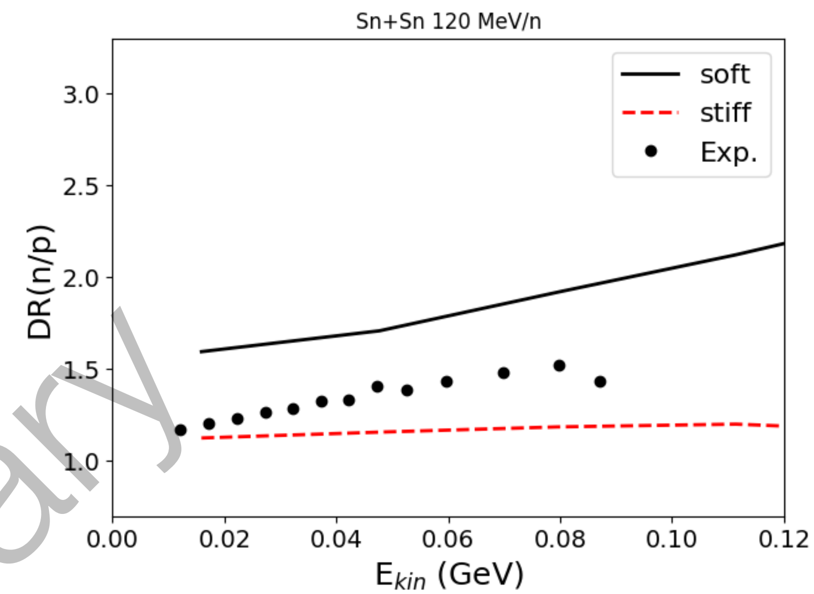
comparable to HIC comparison results
(J. Xu, et al., PRC.93.044609 (2016))

Recent results from QMD

Dr. K. Kim is working on the feasibility study of the possible research subject with RAON.

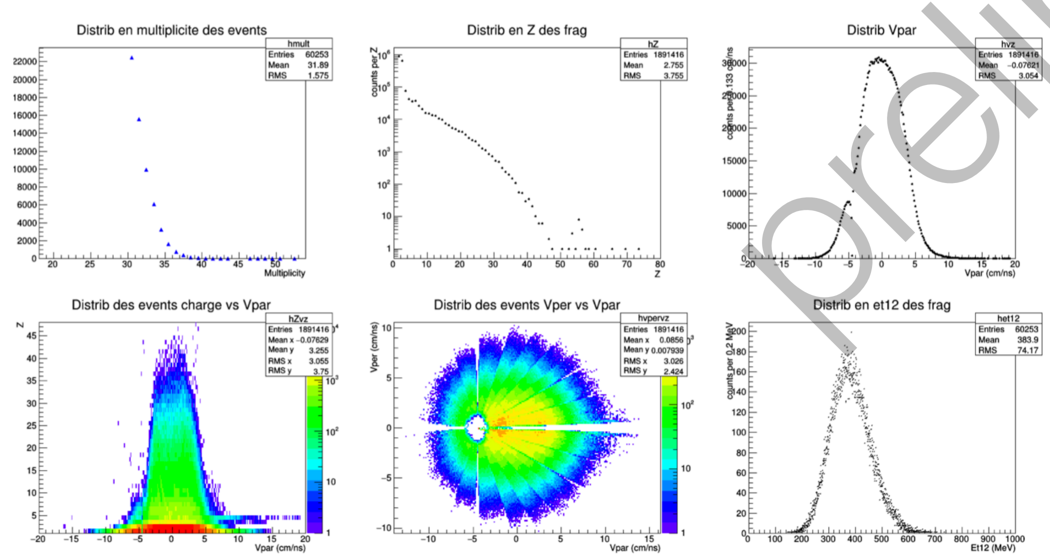
<Double n/p ratio from NSCL>

$$\mathrm{DR(n/p)} = \frac{\mathrm{n/p}(^{124}\mathrm{Sn} + ^{124}\mathrm{Sn})}{\mathrm{n/p}(^{112}\mathrm{Sn} + ^{112}\mathrm{Sn})}$$



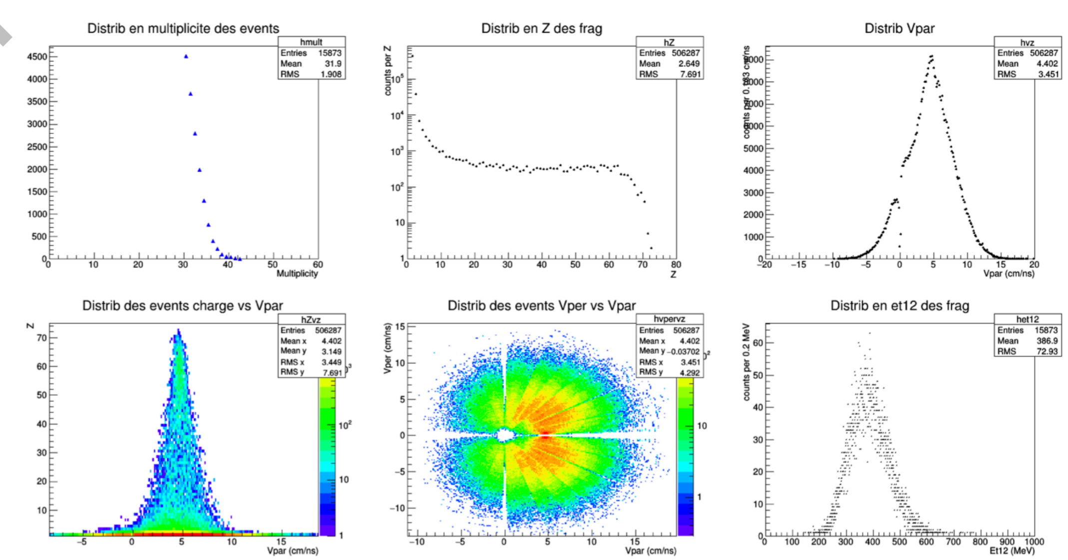
<Comparison with GANIL experimental data>

129Xe+119Sn@39MeV/A experimatal data [mult>=30]



<GANIL exp.>

129Xe+124Sn@39MeV/A QMD+GeminiDecay [mult>=30]
(p1 parameter)



< QMD >

provided by Kyungil Kim (IBS/RISP)

Summary and Future Plans

1. The main purpose of our transport studies is to use for explaining results which will be obtained from RAON.

   - We developed two new transport codes (DJBUU, QMD)
   - Code comparison tests were conducted. DJBUU participated in HW2.
   - We are conducting more realistic HIC simulation.
   - The code comparison test on Sn+Sn collisions is on-going.

2. DJBUU adopt extended Parity Doublet Model (ePDM) to see how the observables from HIC depend on chiral invariant mass.

   - More models will be adopted.
   - We plan to implement Skyrme-type potential (KIDS EoS) into DJBUU.

3. QMD is currently used for the feasibility study of the possible research in RAON

   - comparison with GANIL experiments.

4. More observables will be compared with experimental results.

Thank you for your attention.