Transport Model Evaluation Project (TMEP) for Intermediate-Energy Heavy-Ion Collisions

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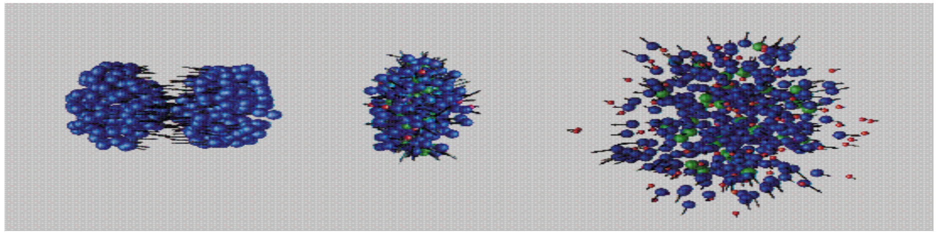
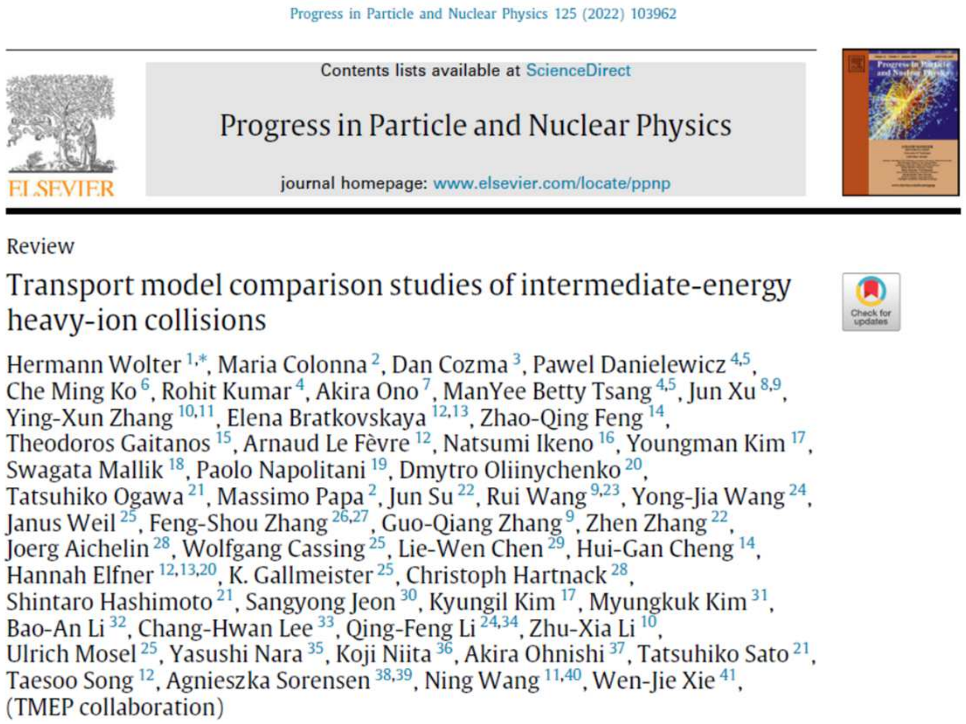


NUSYM2023, GSI, Darmstadt, Germany, Sep. 18-22, 2023

On behalf of the Transport Model Evaluation Project Collaboration



Progress in Particle and Nuclear Physics 125 (2022) 103962

Contents lists available at ScienceDirect

Progress in Particle and Nuclear Physics

journal homepage: www.elsevier.com/locate/ppnp

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Review

Transport model comparison studies of intermediate-energy heavy-ion collisions

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(TMEP collaboration)

Outline:

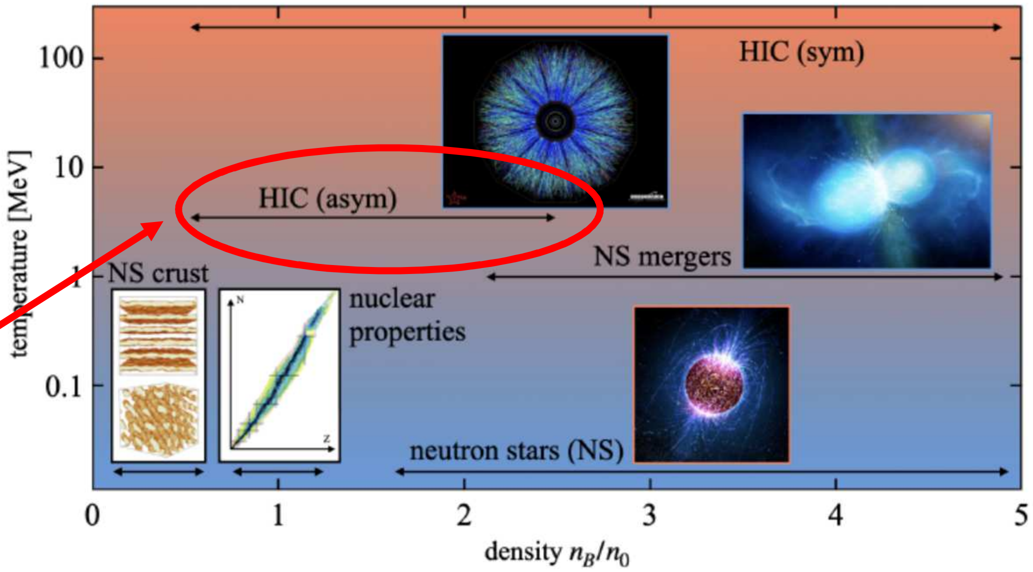
- Motivation: Importance of Heavy-Ion Collisions (HICs) for the exploration of the EOS, but model dependence of results of transport simulations

- Transport model comparisons under controlled conditions
  - box calculations,
  - HICs

- Conclusions, future projects, conclusions

Importance of intermediate-energy heavy-ion collisions for the exloration of equation-of-state (EOS)

→ filling the gap between information from nuclear structure ($\rho \leq \rho_0$) and neutron star observations ($\rho \geq 2.5\ \rho_0$)

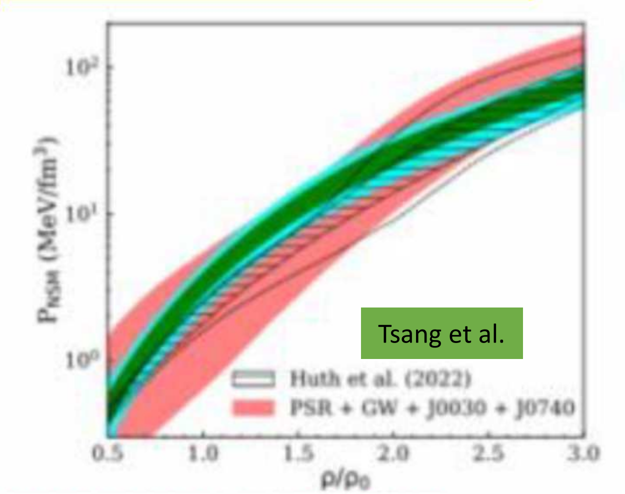


	density	asymm. β=N/Z	temp	equilibr	composition	accuracy
Nuclear structure	$\rho<\rho_0$	$\beta \leq 1.2$	≈ 0	yes	(yes)	high
HIC	$0 \leq \rho \leq 3\rho_0$	$\beta \leq 1.6$	(2–50)	no	yes	discussed here
astrophysics	$\rho>\rho_0$	$\beta \approx 10$	0	yes	(yes)	improving

inherent complexity of heavy-ion collisions

Constraints from HIC on the EOS: Contributions and Uncertainties
(Bayesian analysis from several sources)

Constraints on pressure of NS matter
-> only astrophysics
-> xEFT, Astro and HICs (Huth, et al., Nature 602
-> structure, HICs and Astro (C.Y.Tsang, in prep)

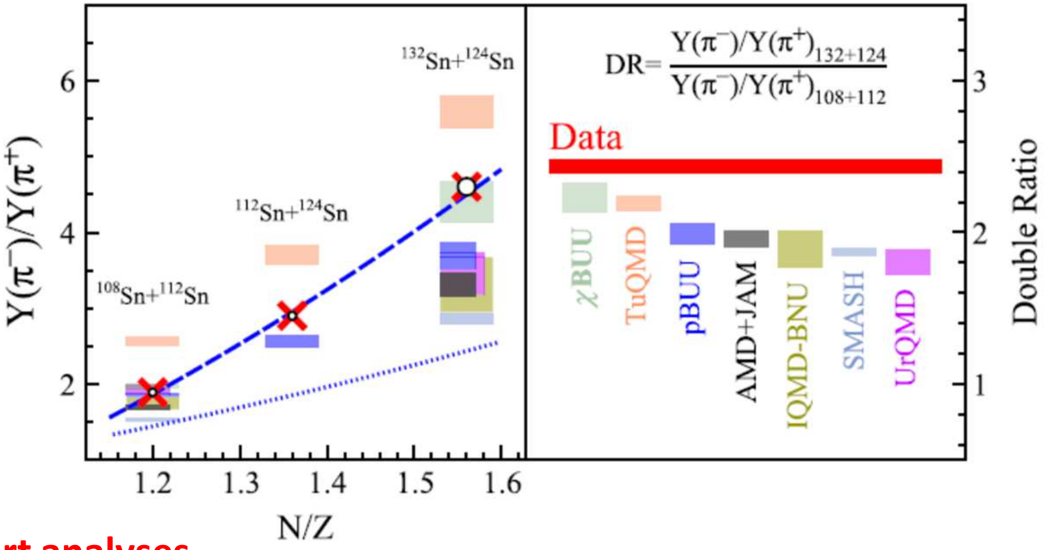


HIC make important contributions

model dependence of HIC results:

SπRIT data, Sn+Sn, 270 MeV/A,
Jhang, et al., PLB 813 (21)
predictions: best physics model of each code

large spread of results
sensitivity to symmetry energy (size of boxes)
relatively small

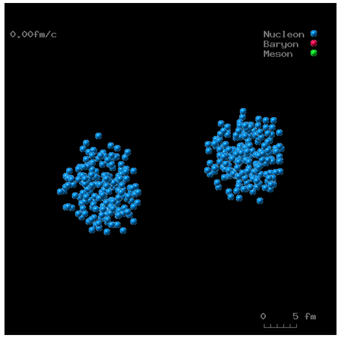


need to establish model uncertainty of transport analyses

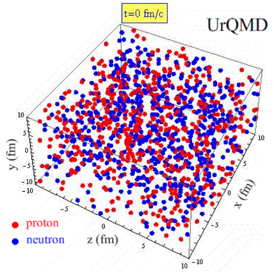
→ Transport Model Evaluation Project (TMEP): Compare transport codes with controlled conditions
Brief summary of efforts so far: review, H. Wolter, for TMEP, J. Progr. Part. Nucl. Phys. 125 (2022)

2004: HIC@about 1 GeV/A (E. Kolomeitsev, t al., J.Phys.G 31 (2005))
emphasis on π and K production, collision term dominates at this energy, not very sensitive to EOS

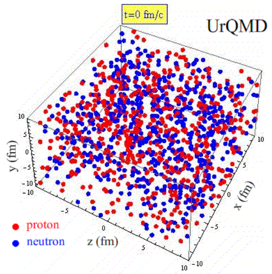
2009/2014: HIC@100, 400 MeV/A: (J. Xu, et al., PRC 93 (2016))
density evolution and nucleonic observables (stopp, flow)
considerable differences dep. on bombarding energy
→ difficult to identify exact reasons (e.g. blocking, initialization)



2018-2021 Box calculations: controlled calculations in a periodic box,
simple initialization, near equilibrium, exact limits
check separately ingredients of transport



2021/23 Back to HICs; Sn+Sn@270 MeV/A, system studied SPIRIT Collaboration, esp. pion observables
prediction before data: G. Jhang, et al., PLB 813 (2021) 136016
and controled comparison J. Xu, et al., arXiv:2308.05347 [nucl-th], JPPNP submitted



Box calculations with periodic BC:
study individual ingredients oftransport simulation

QMD codes, approx. for ρ^{γ}
weaker repulsion,

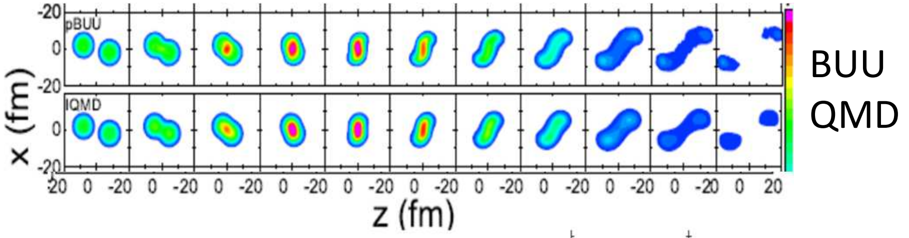
Non-Markovian memory effects in simulation of
collision term, esp. for inelastic processes

$$\frac{\partial f}{\partial t} + \frac{\vec{p}}{m}\nabla^{(r)} f(r,p:t) - \nabla^{(r)} U(r,p) \nabla^{(p)} f(r,p;t) = I_{el}(NN \leftrightarrow NN) + I_{inel}(NN \leftrightarrow N\Delta) + I_{decay}(\Delta \leftrightarrow N\pi) + \delta I_{fluc}$$

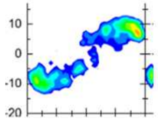
fluctuation of phase space: difference in BUU and QMD

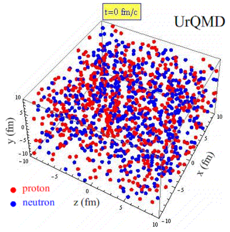
blocking factors (1-fi)
affected by fluctuations

explicit fluctuation term for BUU
Boltzmann-Langevin or
approximations



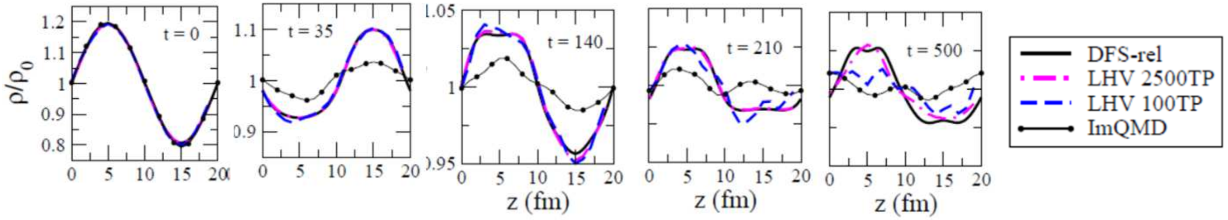
event in QMD





Mean field evolution (M. Colonna, et al., PRC104 (2021))

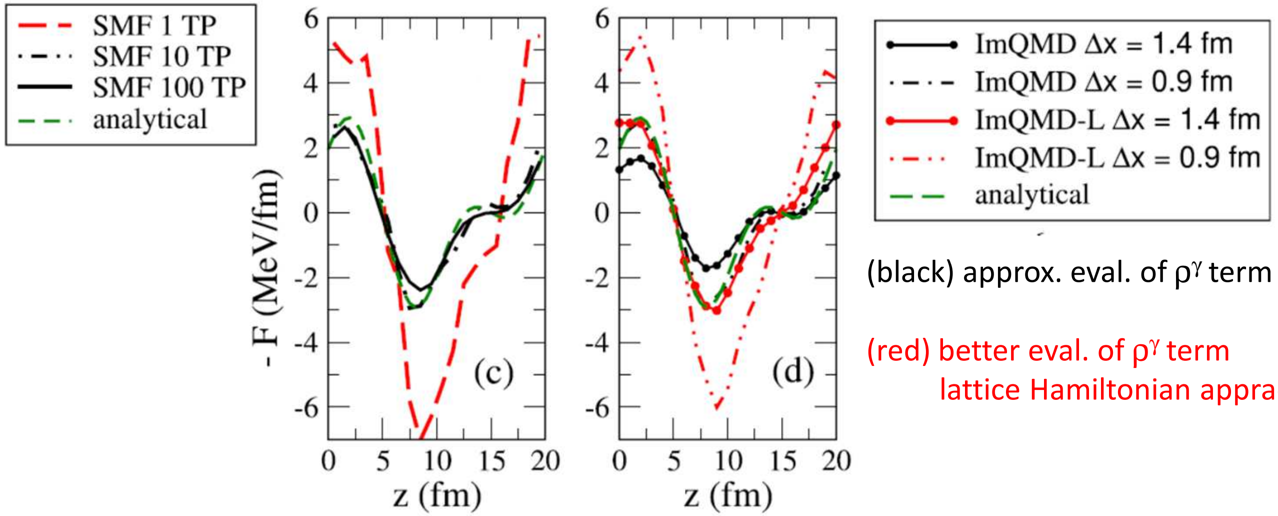
evolution of a standing wave



Force averaged in cells at initial time

SMF

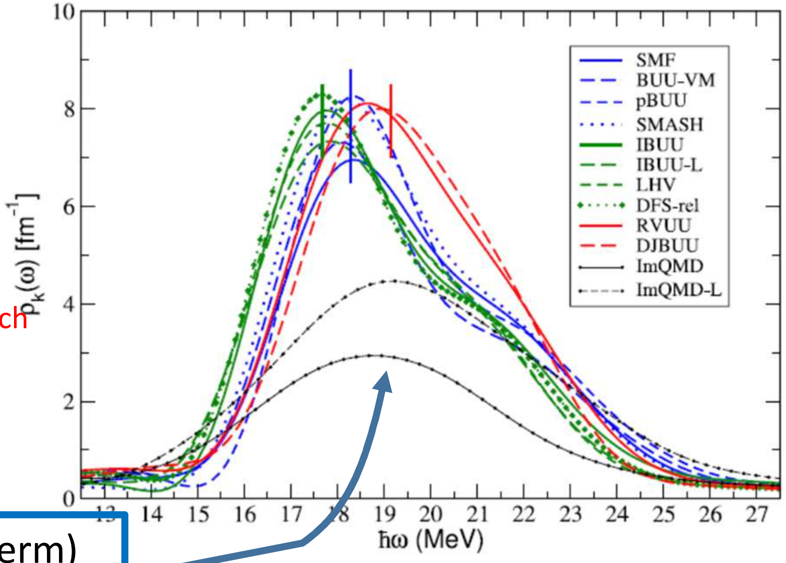
ImQMD



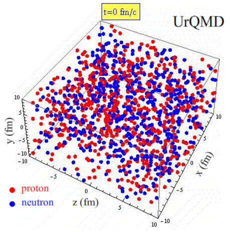
(black) approx. eval. of ρ^γ term

(red) better eval. of ρ^γ term
lattice Hamiltonian appraoch

strength function, power spectrum:
horizontal lines:exact results from Landau theory



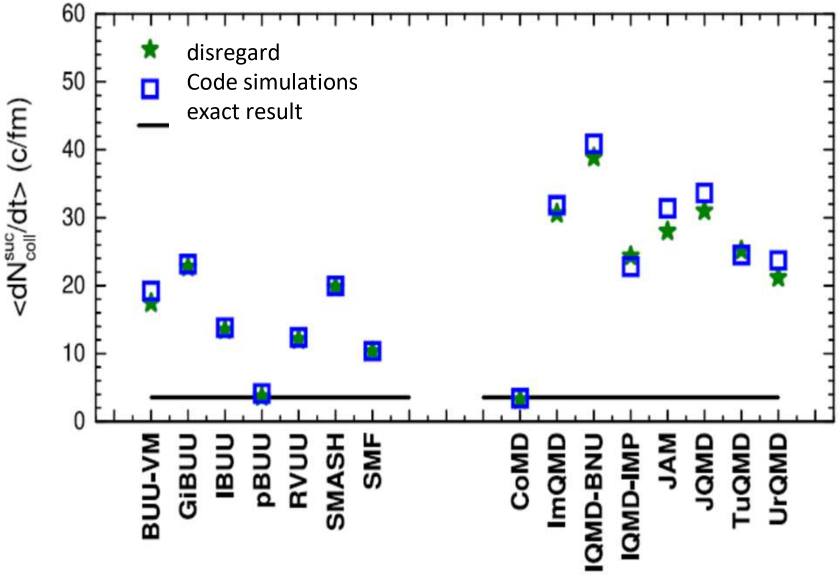
QMD codes: shift (for approximation to ρ^γ term)
broadening (larger fluctuations)

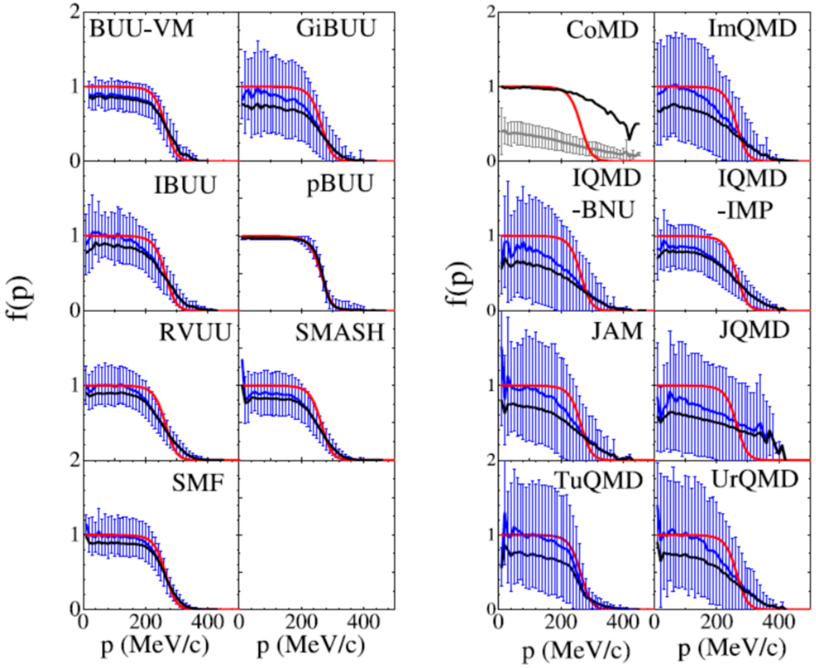


Collision intergral (only nucleons, with Pauli blocking, initialize at T=5 MeV)

(YX. Zhang, et al., PRC 97 (2018))

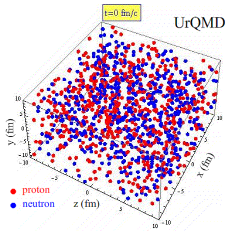
Collision rates, compared to exact result:
Systematic difference between BUU and QMD results





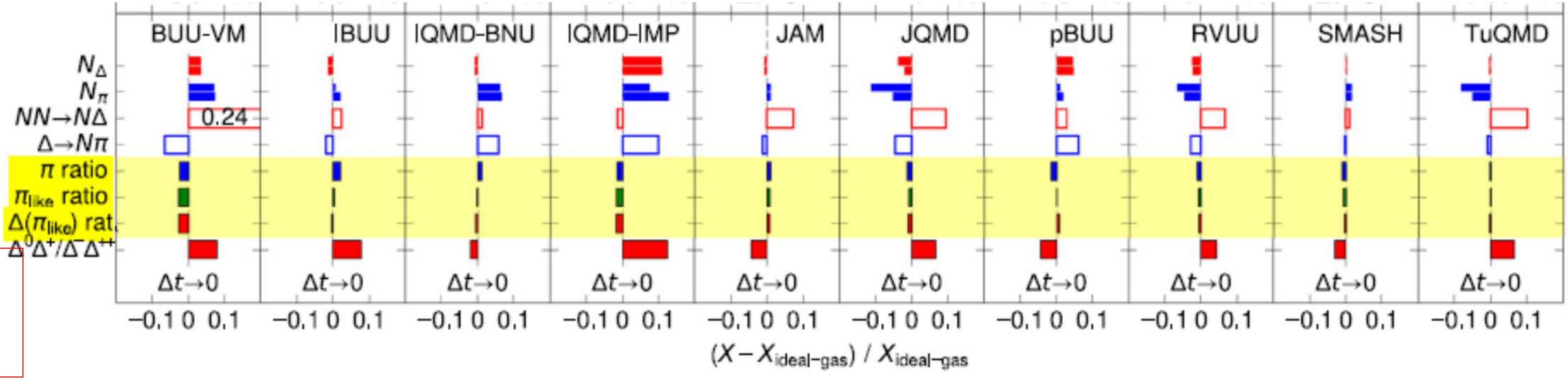
Reason: Fluctuations in Pauli blocking factor (1-f)
exact: red
average: blue
effective (enforce f≤1): black

generally underblocking (black ↔ red)



Pion production in a box (w/o Pauli blocking, (A. Ono, et al., PRC 100 (2019))

extrapolation to time step zero
multiplicities and multiplicity ratios (relative difference to exact result)

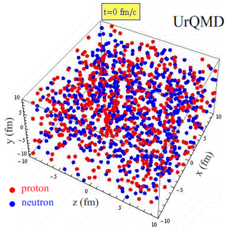


determines
π−/π+ ratio
in a HIC

Understanding differences
correlations between collisions (non-Markovian)

strategies in handling elastic and inelastic collisions

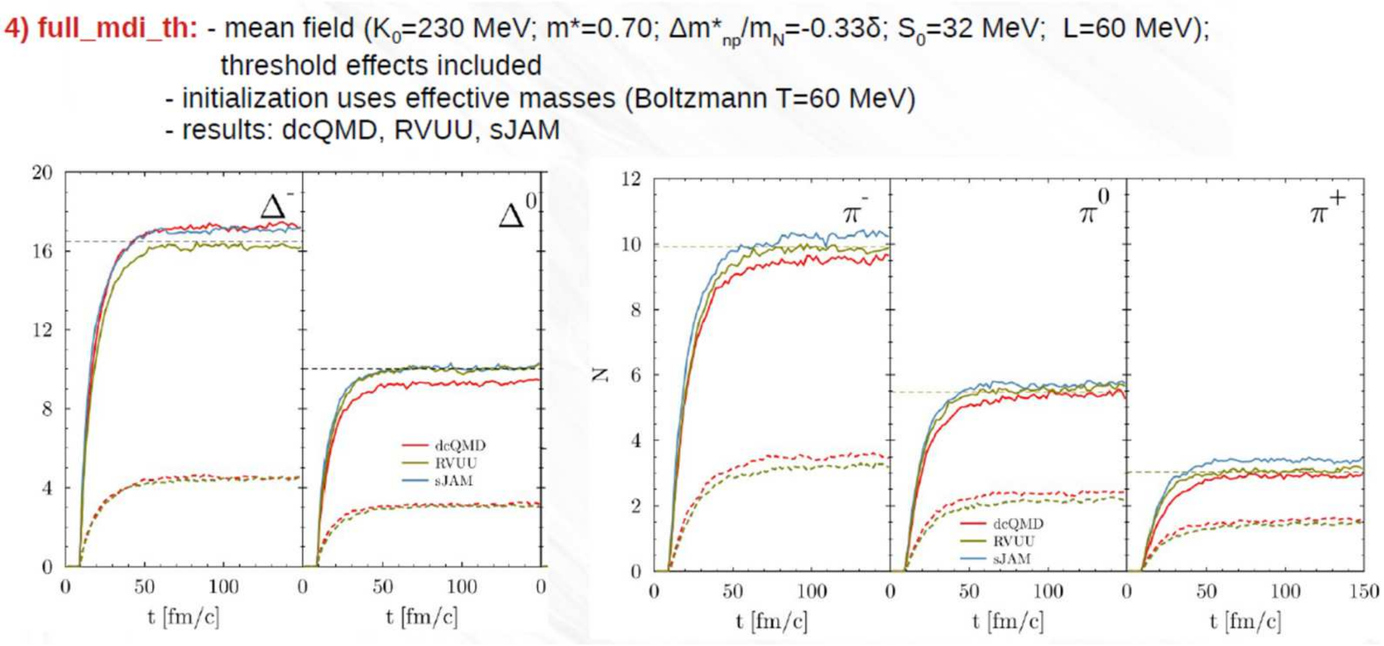
Cancel rather well in ratios



Collision integral with momentum-dependent interactions

(D. Cozma, et al., in preparation)

threshold shift in inelastic collisions with momentum dependent mean fields



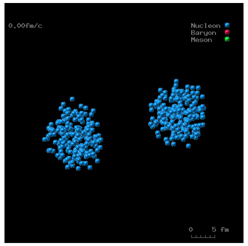
4) full_mdi_th: - mean field (K_0=230 MeV; m*=0.70; $\Delta m^*_{np}/m_N$=-0.33δ; S_0=32 MeV; L=60 MeV); threshold effects included

- initialization uses effective masses (Boltzmann T=60 MeV)
- results: dcQMD, RVUU, sJAM

solid lines: with threshold effect
dashed lines: without

thin dashed line: exact result
(thermal model)

rather good agreement between codes, but some deviations (being investigated)
demonstrates importance of considering threshold shift

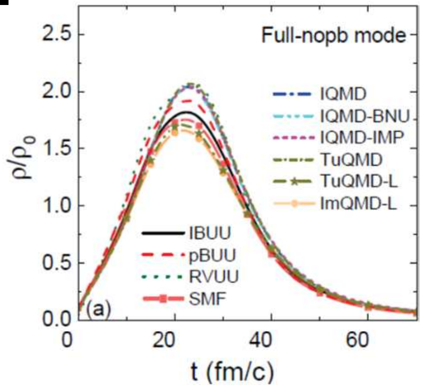


Back to HIC: Sn+Sn@270 MeV/A (J. Xu, et al., under review, PPNP))

similar to Au+Au@100,400 MeV/A (but with lessons from box calculations) + pion observables

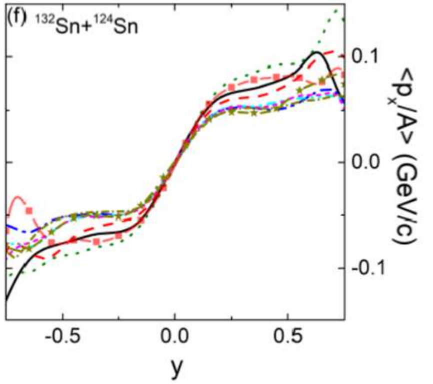
controlled input: common initializ., simple mom.-indep. EOS, σ_{el}=const, $\sigma_{NN\leftrightarrow N\Delta}$, $\sigma_{\Delta\leftrightarrow N\pi}$

density evolution



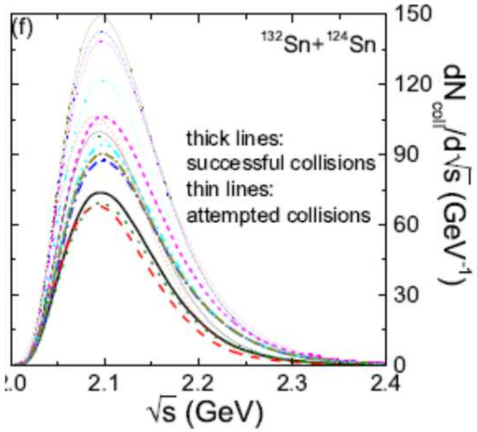
nucleon evolution not identical,
generally BUU codes have lower density
reasons can be understood:
fluctuations, aprox. in non-inear term in QMD,
weaker repulsion

side-ward flow

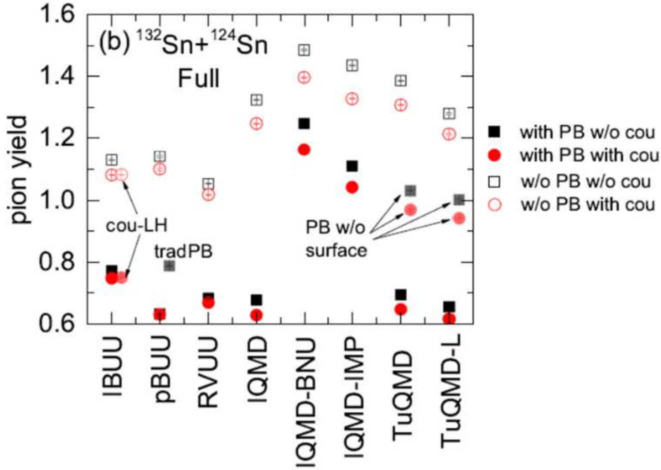


correspondingly different
stoppng and flow
BUU codes have stronger
flow

inelastic reaction rates NN→NΔ



weaker inelastic collision ates



pion multiplicities
(w and w/o Pauli and Coulomb
generalyy weaker for BUU

Conclusion: differences in the evolution of the system (caused here by approx. in averaging of force) leads to difference in pion observables

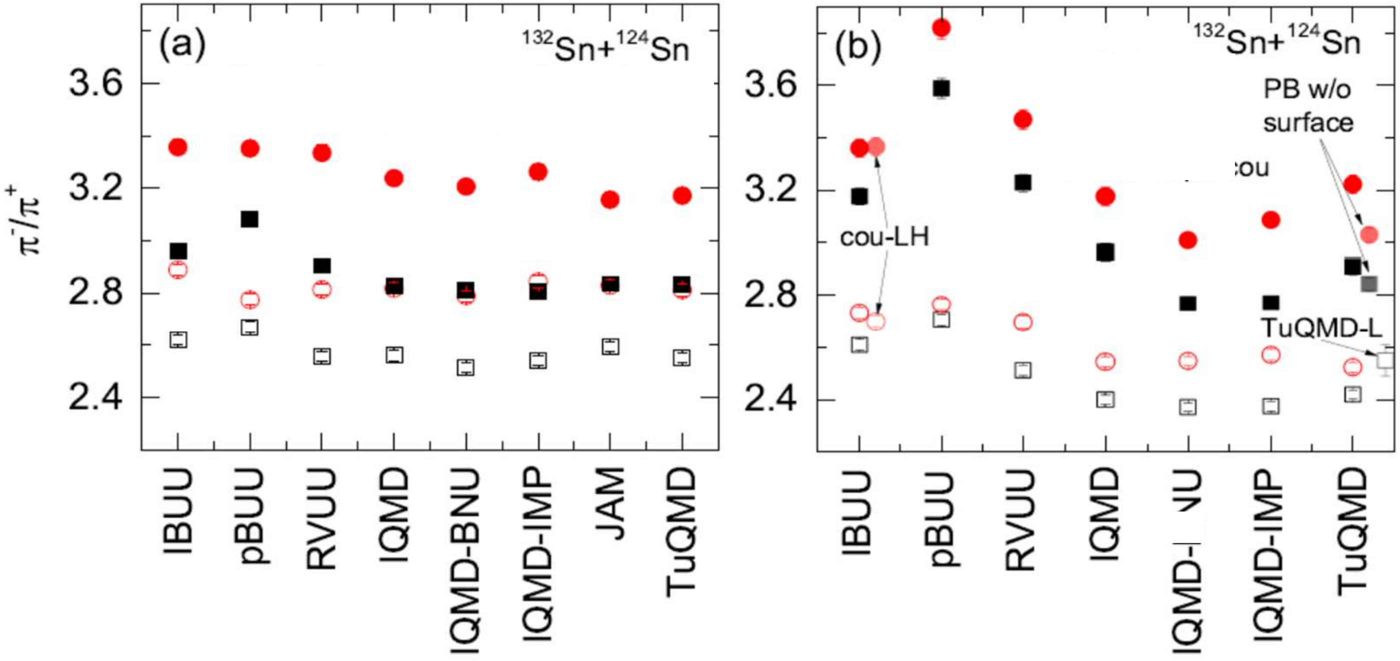
Sn+Sn@270 MeV/A (SπRIT setup)
Pion ratios

π-/π+ ratio

- ○ Open symbol w/o Pauli
- ● Full symbol with Pauli
- Black symbols w/o Coulomb (ok)

Only collisons (Cascade)

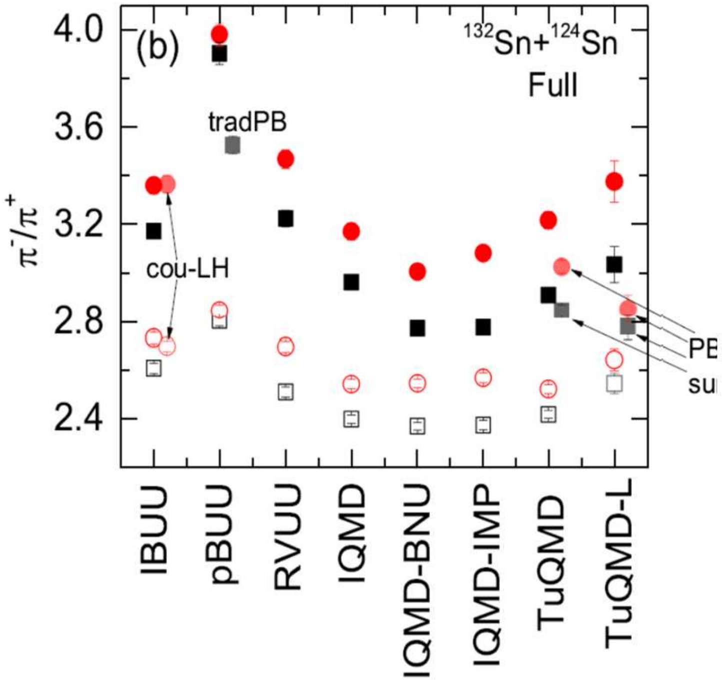
Full calc (mean field + collisions)



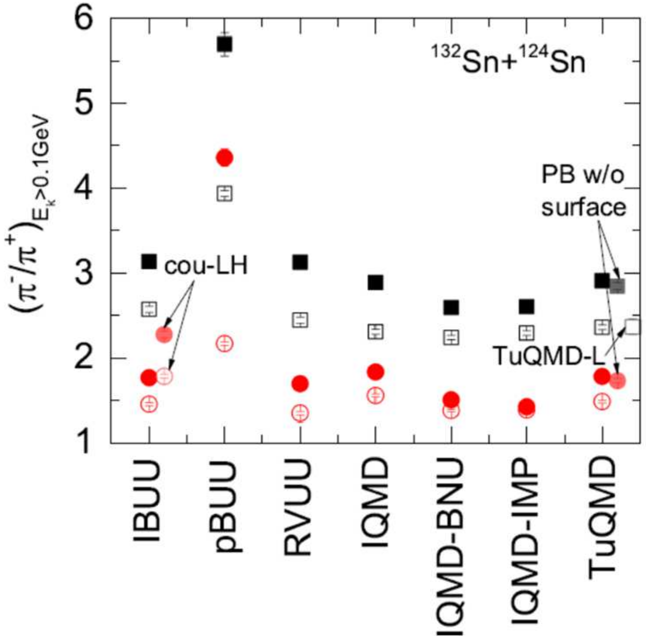
Rather good convergence w/o mean-field.
Not so good with mean-field.
Can be explained and related to nucleon observables (in most cases),

Selection effects on π–/π+ ratio

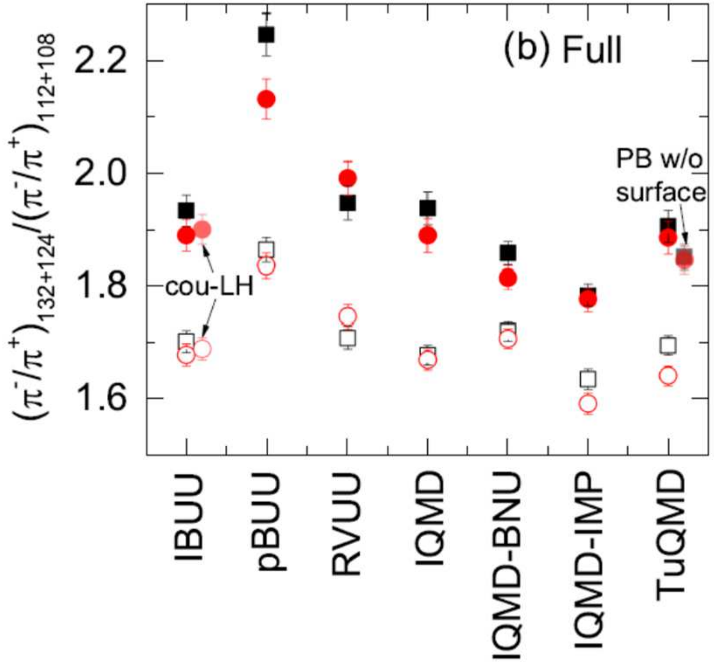
Single ratio π–/π+
(132Sn+124Sn)



Single ratio π–/π+
(132Sn+124Sn) (E_π>100 MeV)

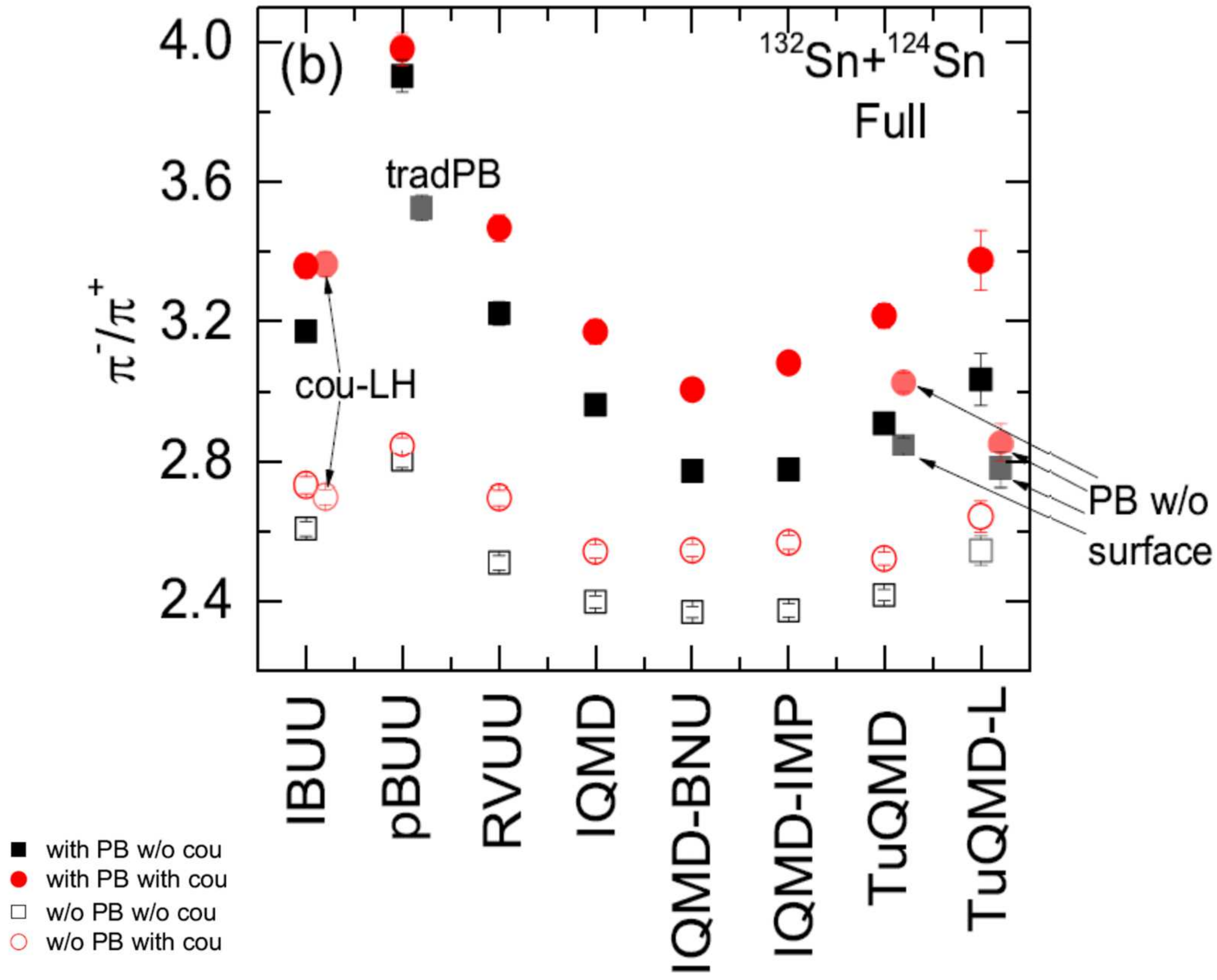


Double ratio π–/π+
(132+124)/(112+108)



Differences between models are not essentially different for

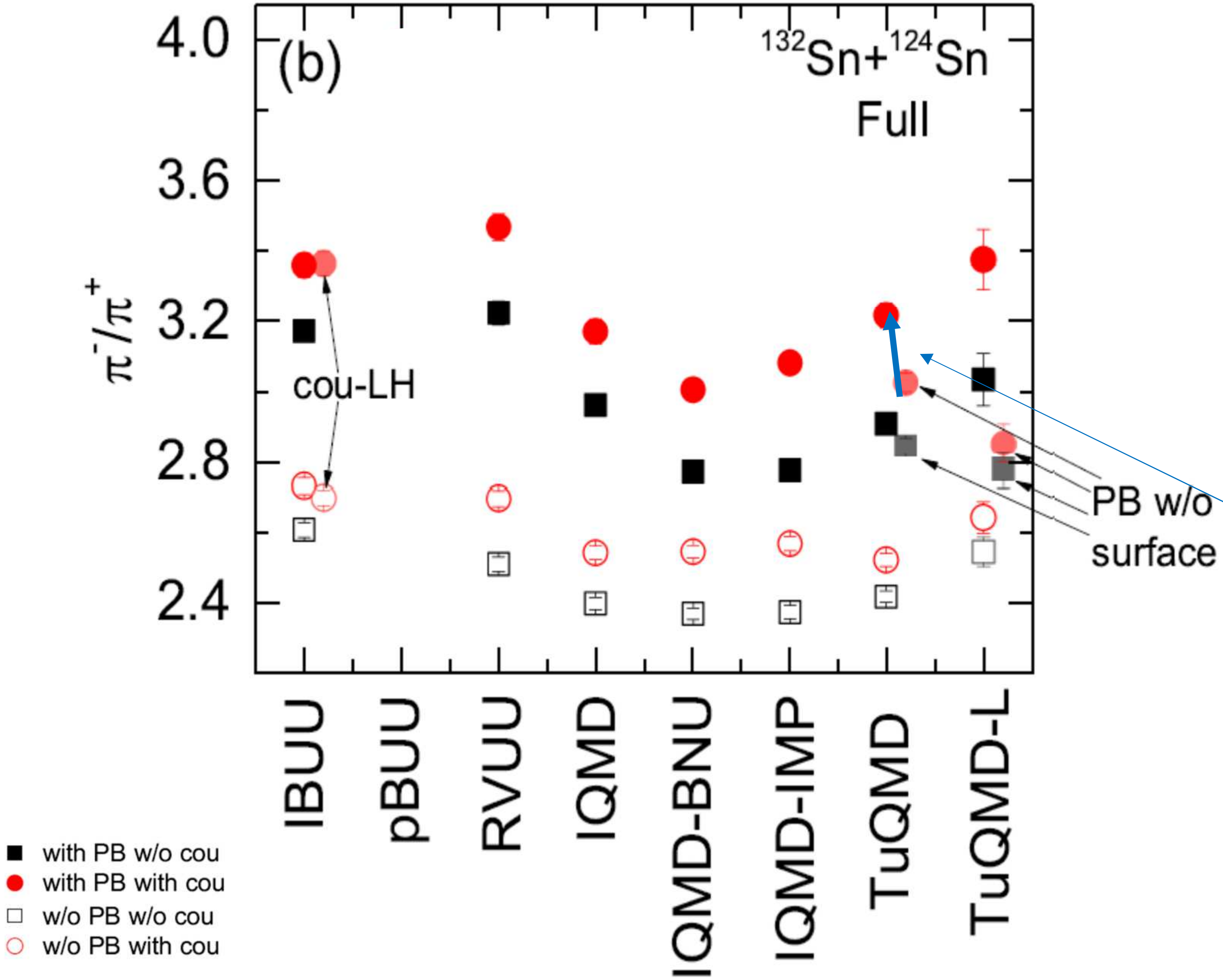
- selection of higher energy pions
- double ratio between neutron-rich and more symmetric Sn+Sn systems



Final result for charged pion ratios: Fig. 13b

looks not very convergent,
but worth a closer dicussion:

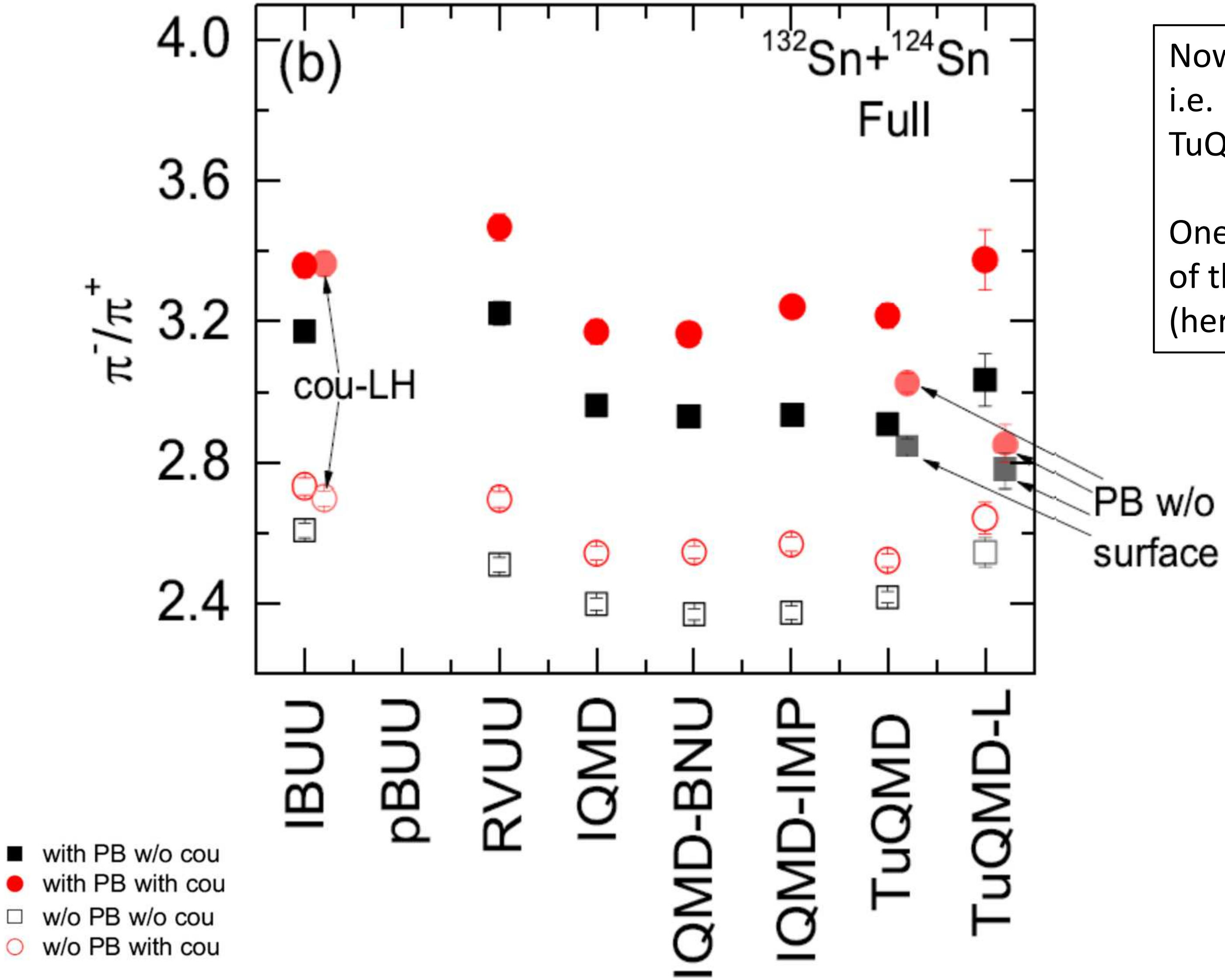
1. pBUU code sticks out in particular. But uses options not prescribed in the homework, π and Δ are not free particles (except for Coulomb) but feel symmetry potential. This will affect the charged pion ratios. Therefore take this code out of the comparison.



2. There are two issues, where codes differ and one can try to estimate the effect on the results:

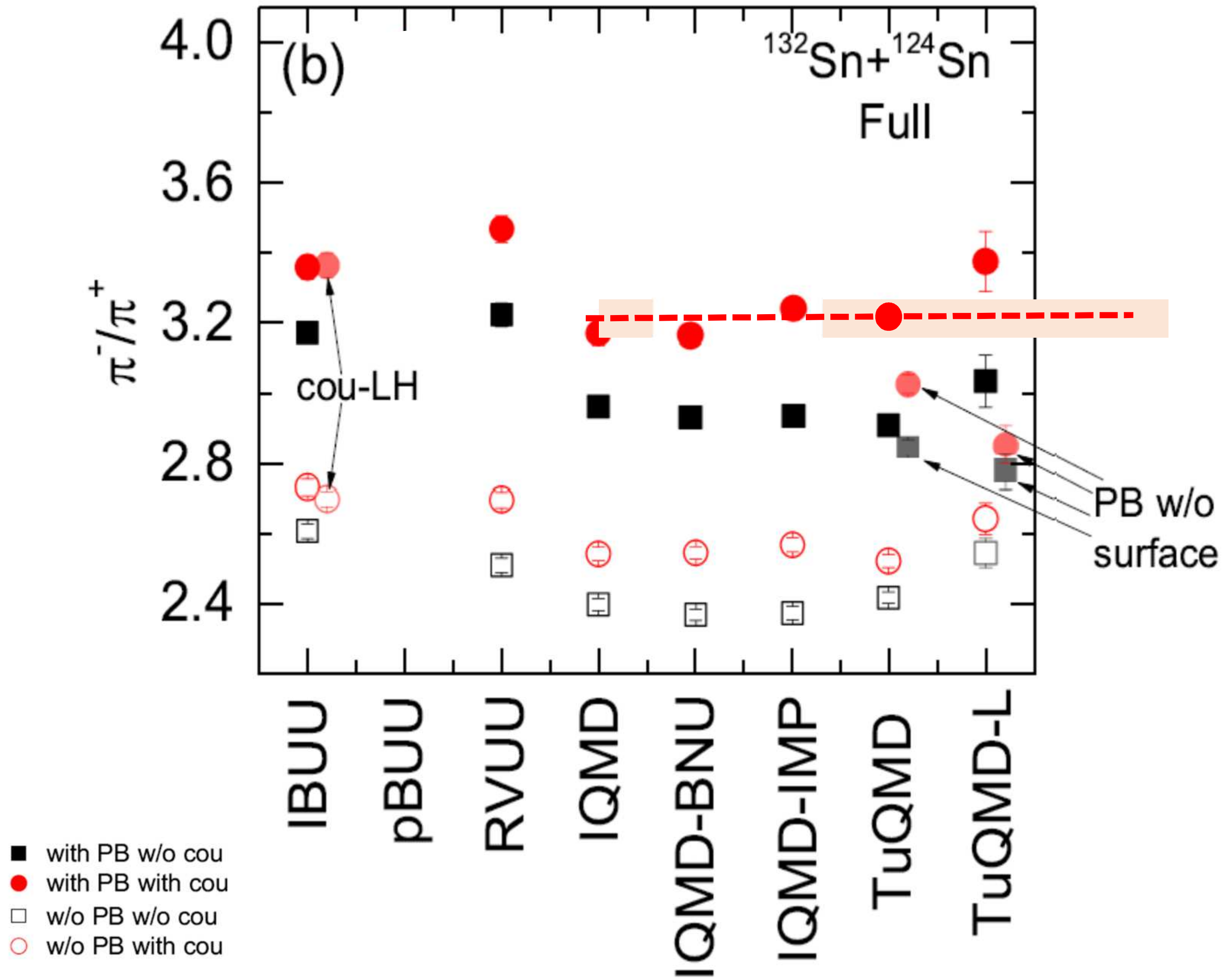
a) among QMD codes TuQMD and IQMD are using a surface correction of the PB. For BUU codes with a finer representation of the phase space this is not so important, but in QMD it is.
b) approximation in QMD of non-linear repulsive term

to a) The effect can be seen in the difference between standard TuQMD (with surface corr.) and TuQMD w/o surface (blue arrow). It increases the ratio.
To take this into account one can increase the results for IQMD-BNU and IQMD-IMP (with PB) by this amount. This is done in the next page.



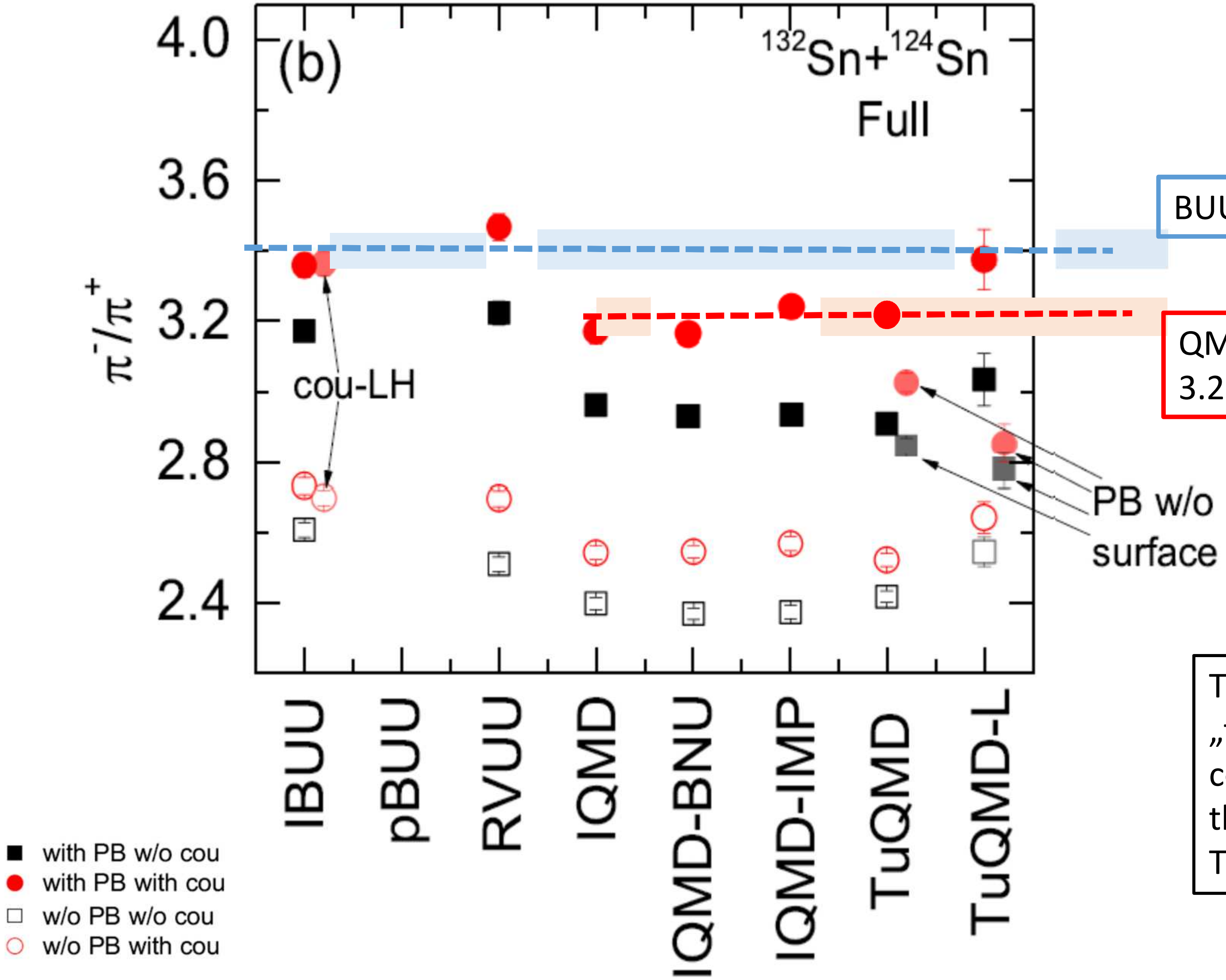
Now the four „traditional“ QMD codes i.e. IQMD, IQMD-BNU, IQMD-IMP, and TuQMD give similar results.

One can calculate the mean and the variance of the results for these codes, see next page. (here for PB_cou (red solid circles))



QMD-codes with surface corr
3.22±0.05 (1.8%)

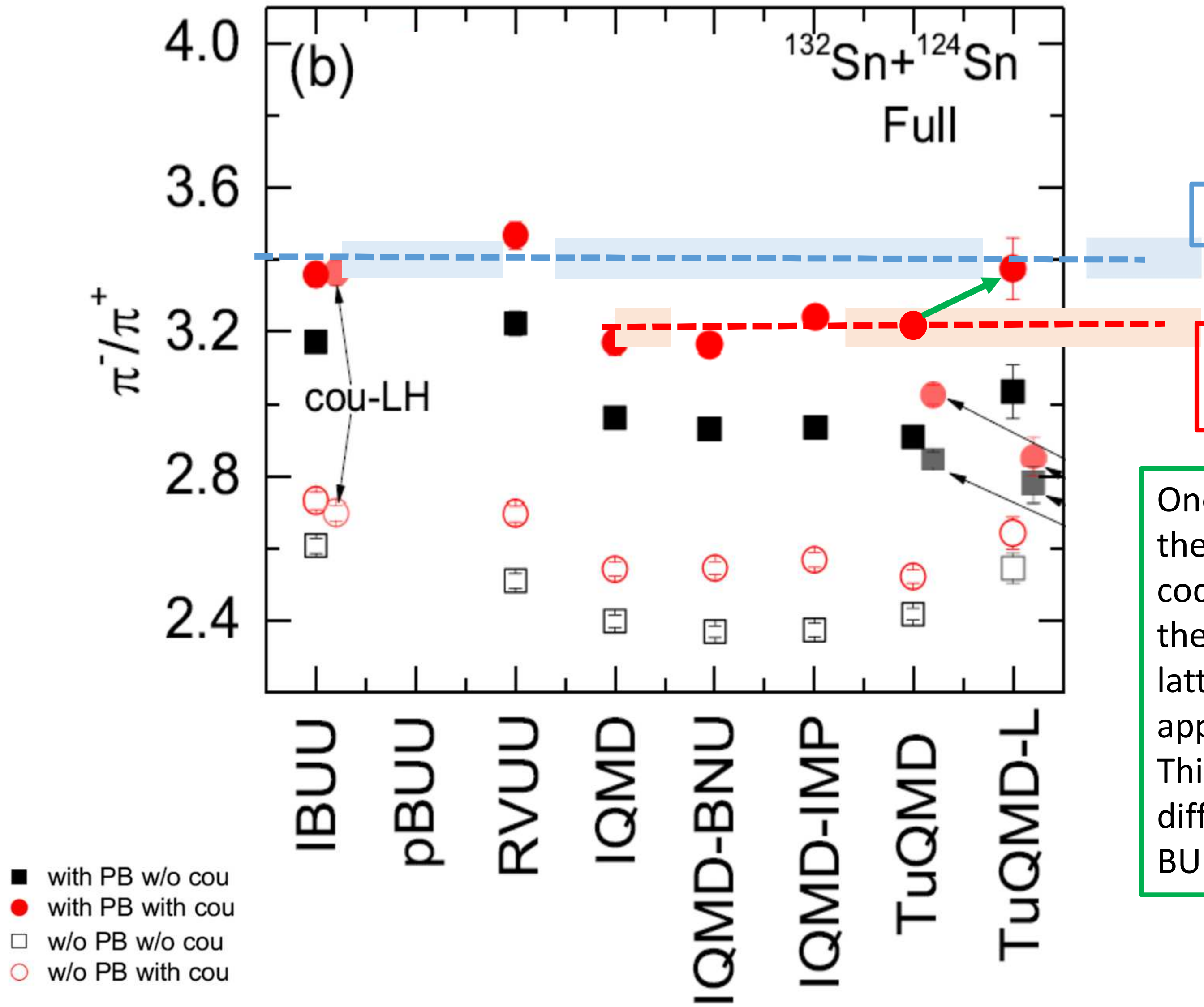
One can now similarly determine the mean and variance for the BUU codes IBUU and RVUU. Here we can as a first estimate also include the TuQMD-L code, because it was shown that with the lattice version QMD codes are comparable to BUU codes.
(The TuQMD-L result has larger statistical error because it was calculated with fewer events. We disregard this in this first estimate.)



BUU-type codes, 3.40±0.05

QMD-codes with surface corr
3.22±0.05 (1.8%)

There remains a difference between „traditional“ QMD codes and BUU-like codes, which is considerably larger thn the variances for each class.
This is discussed in the next page.

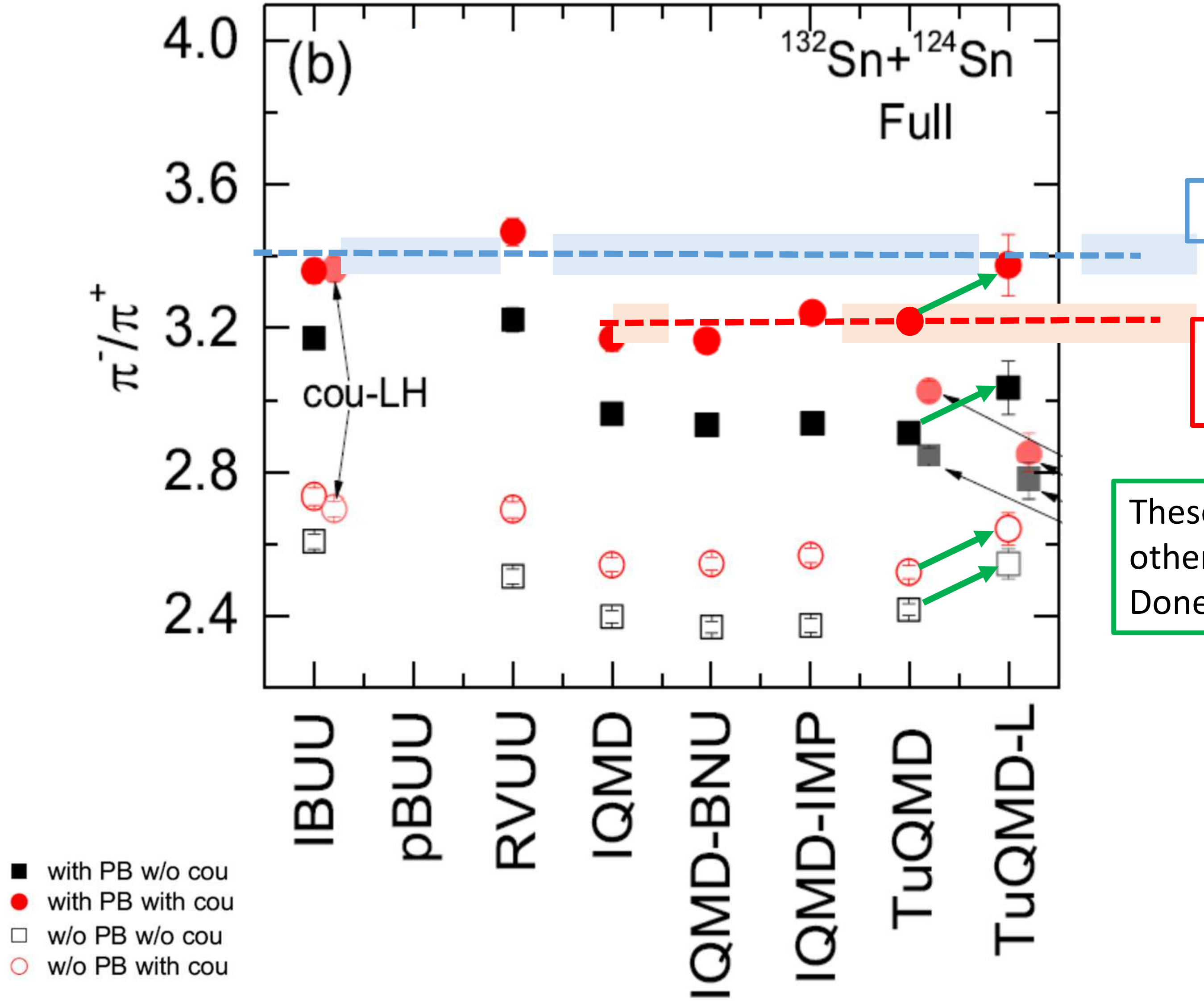


BUU-type codes, 3.40±0.05

difference
0.18

QMD-codes with surface corr
3.22±0.05 (1.8%)

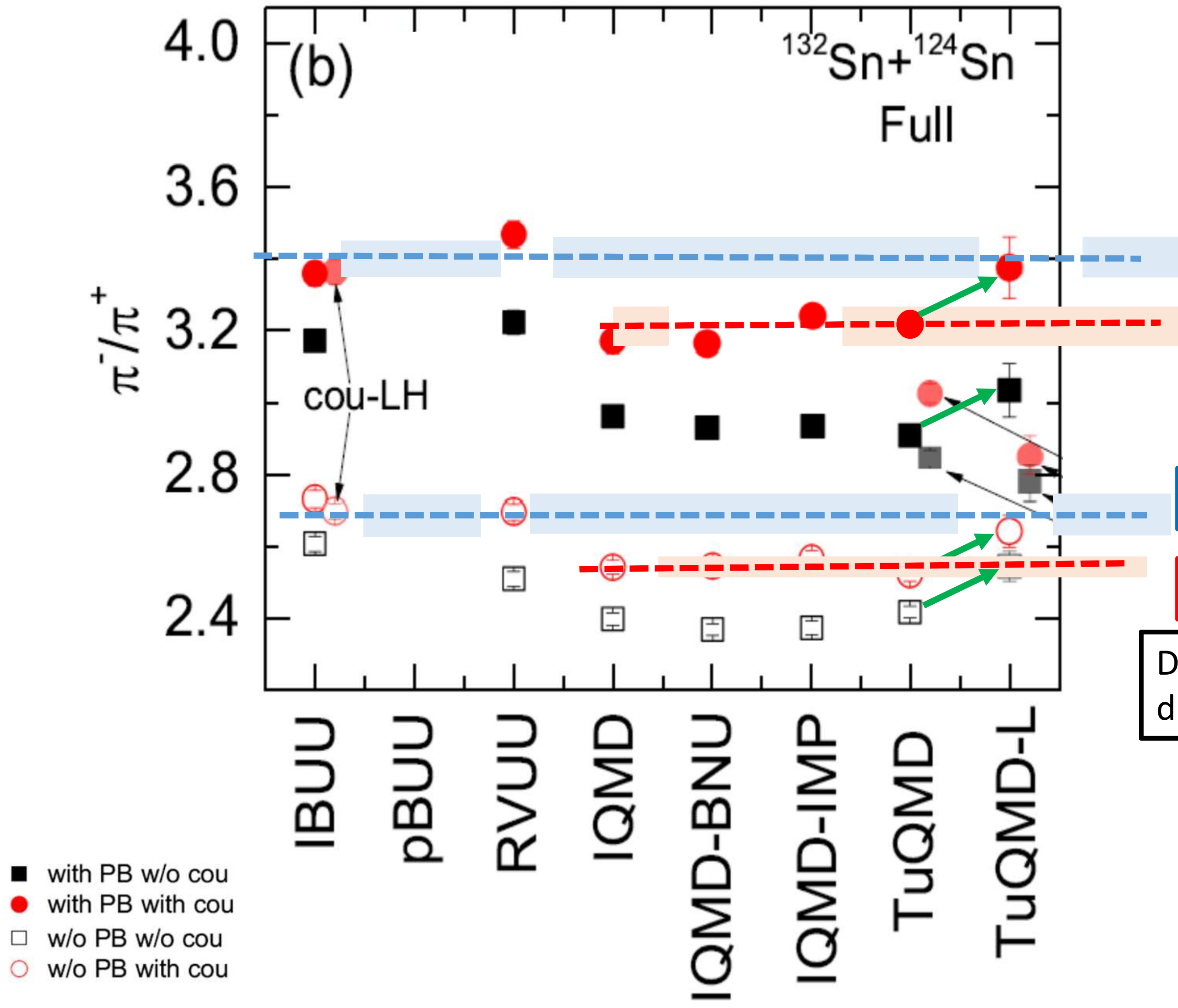
One can invoke point 2b), the approximation of the non-linear term in the „traditional“ QMD codes. Its effect is seen in the difference between the TuQMD and TuQMD-L codes, because the lattice QMD method largely avoids this approximation (green arrow).
This difference (0.18) very closely agrees with the difference between the traditional QMD and the BUU-like codes (0.16).



BUU-type codes, 3.40±0.05

QMD-codes with surface corr
3.22±0.05 (1.8%)

These arguments would work similarly for the other modes of calculation
Done in the next page for noPB_cou



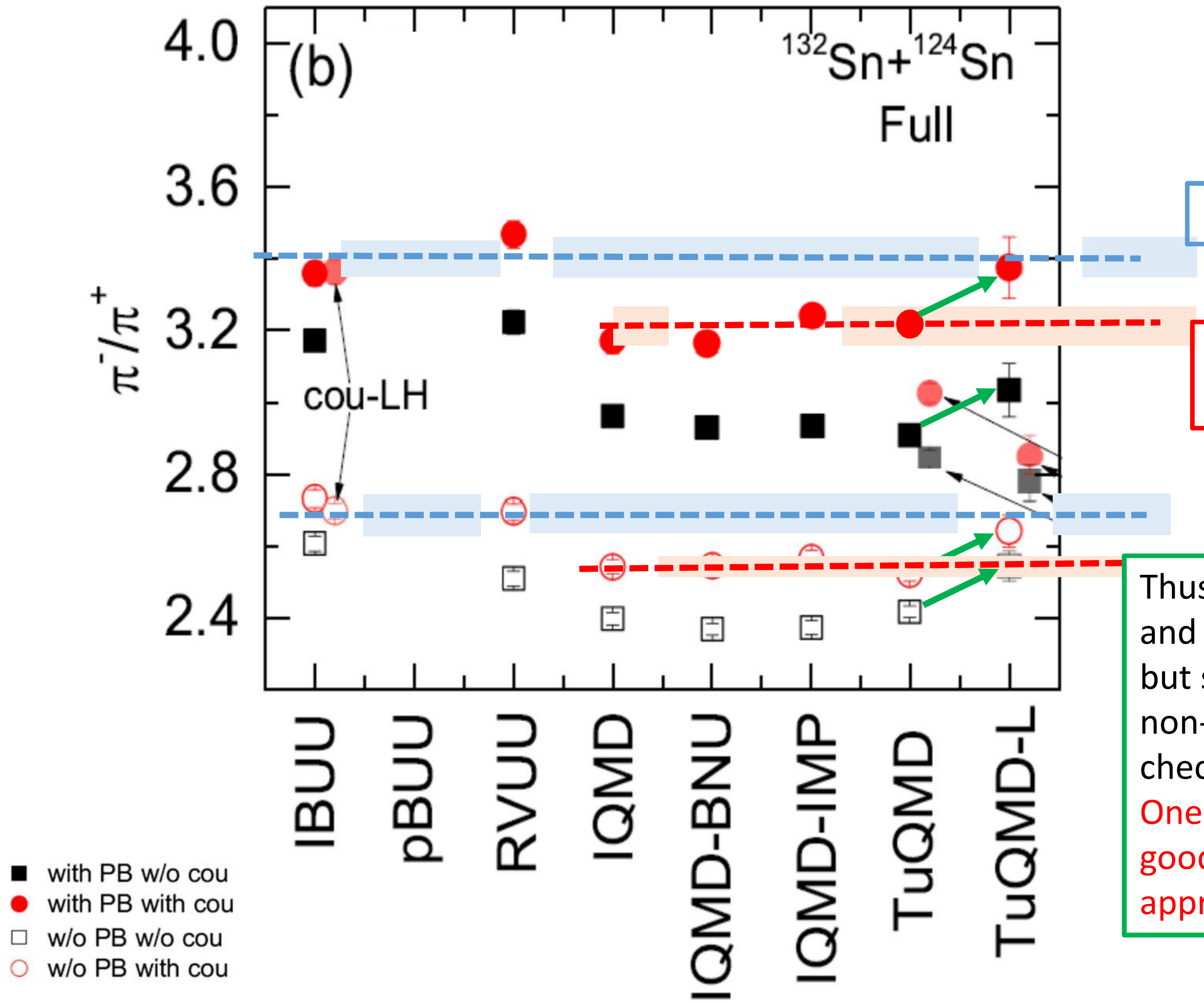
BUU-type codes, 3.40±0.05

QMD-codes with surface corr
3.22±0.05 (1.8%)

BUU-like codes (w/o PB) 2.69±0.04

QMD codes (w/o PB) 2.54±0.02

Difference between BUU and QMD-T 0.15
difference TuQMD-T and TuQMD-L 0.12



BUU-type codes, 3.40±0.05

QMD-codes with surface corr
3.22±0.05 (1.8%)

Thus the systematic difference between BUU and QMD does not depend on PB or Coulomb, but seems to depend on the evaluation of the non-linear force term. (Could and should be checked more directly.)
One could now argue that actually we have a good convergence between the codes, if this approx. had not been done.

(Intermediate) Conclusion on Results of TMEP:

Code comparison under controlled conditions:

w.r.t. physical model, degrees of freedom, mean fields and cross sections,
w.r.t. set-up of collision (Impact parameter, intialization(?), time-step(?), etc.)

→ **we observe differences!**

- able to explain most of them, depending on specific features or strategies of the model
- some can be eliminated (e.g. evaluation of non-linear potential, Coulomb effects)
- one of the main reasons is the **amount of fluctuations**, in particular the QMD-BUU difference.
- other are due to strategies, which are not described by the theory, and are equally plausible (e.g. calculation of blocking factors, surface corrections,...)

HIC are open systems (contrary to box calculations)

- small differences can lead to large final differences, i.e. observables
- the bulk evolution of a HIC should be under control, before secondary observables can be compared
- difficult to disentangle sources of differences in HICs

Box calculations are very important to understand transport simulations:

- compare partly to **exact results** and thus judge the apropriateness of strategies
- learn about **sensitive aspects** of transport, disentagle effects of different ingredients
- importance of **fluctuations,** main difference BUU-QMD, different philosophies, (affect many aspects, e.g. force calculation, blocking factors)
- importance of strategies of **coarse graining** (averaging over fluctuations)
- non-Markovian (**memory effects**) effects. Memory loss is an idealization!

What a code comparison **cannot** do:

- the physical models are simple, and in many respects insufficient
  (simple, mom-independent mean fields, neglect of eff. mass and threshold effects, constant cross sections, neglect of clusterization, neglect of spectral functions, tc.)

→ we do not attempt to solve physical problems, e.g. of the pion production,
but hope that this activity will help to clarify physical problems

What a code comparison **can do**:

investigate the **sensitivity to the physical model** (within its limitations), e.g. to assumptions about the SE
investigate the **sensitivity towards different strategies**
recommend robust observables or identify large uncertanties

New goal of code evaluations:

simple comparisons fo codes comes to an end.
It will not be possible to reach sufficient agreement between codes, i.e. a model independence
next best thing: **uncertainty quantification of transport analyses**.
not: average and variance of model predictions
but: **Bayesian analysis of model dependence:** multi-observable, multi-code analysis
basic assumption: a model which describes many observables well has a bigger weight

List of future projects and/or open problems in transport
(to be discussed on Friday in round-table and TMEP sessions)

List of future projects and/or open problems in transport (compact)

a) **test of HIC with realistic ingredients (**mom-dep potentials (effecive masses, n-p mass splitting), threshold effects)
combination of pion HIC and box study;
sensitivity study of typical observables (n/p ratio, pi-/pi+ ratio) to stiffnesss of SE, sensitivity to collision energy

b) uncertainty quantification of transport model results
uncertainty of one code from Bayesian analysis, but
model dependence? Multi-observable/Multi-code Bayesian

c) role of fluctuations in transport analysis
main difference between QMD and BUU approaches
QMD classical correlations smeared by wp width vs. BUU deterministic -> include fluctuations explicitely (BL)

Come on Friday to TMEP meeting!

d) description of cluster production (esp.light clusters LC) in transport:
diff. forms of coalescence (a-posteriori) vs. dynamical cluster production, influences other observables (e.g. pion prod.)

e) production of strange particle producton.
e.g. K0/K+ which should be more sensitive to high-density region and less sensitive to final state effects

f) a) implementation of microscopic input for density functional and in-medium cross sections into transport codes,
e.g. from Dirac-Brueckner calculations or from chiral EFT
b) implementation of EoSs from meta-modelling into transport codes

g) Short-Range-Correlations (SRC) in transport (established in structure, lead to a high-moment
should be important in transport studies, but how to include?
(initialization with HMT, change of the density functional, 3-particle scattering terms, off-shell dynamics?)

Thank you for your attention