Workshop on Science with SpiRIT TPC

5-6 June 2015 *RIKEN*
Asia/Tokyo timezone

Relationship between nucleon and pion freeze out

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Outline

- Background
  - On the theoretical side:
    - Theory/Model richness
    - Model dependence
    - Observable systematicness and correlations
  - On the experimental side:
    - Existing flow data from FOPI/LAND at GSI
    - New ASY-EOS(S394) experiment at GSI
    - Ability of SπRIT interested by theoretical “coolies”
- Theoretical concerns (partially)
  - Multi-systems and multi-observables
  - Consistent dynamic process
  - Good after-burner
- Suggestions for upcoming SπRIT experiments

Background: on the theoretical side

- **Microscopic Many-Body Approaches**

  Non-relativistic Brueckner-Bethe-Goldstone (BBG) Theory

  Relativistic Dirac-Brueckner-Hartree-Fock (DBHF) approach

  Self-Consistent Green's Function (SCGF) Theory

  Variational Many-Body (VMB) approach

  Green's Function Monte Carlo Calculation

  V_{lowk} + Renormalization Group
- **Effective Field Theory**

  Density Functional Theory (DFT)

  Chiral Perturbation Theory (ChPT)

  QCD-based theory
- **Phenomenological Approaches**

  Relativistic mean-field (RMF) theory

  Quark Meson Coupling (QMC) Model

  Relativistic Hartree-Fock (RHF)

  Non-relativistic Hartree-Fock (Skyrme-Hartree-Fock)

  Thomas-Fermi (TF) approximations

  Self-consistent Relativistic Boltzmann Uehling-Uhlenbeck (SC-RBUU)

Go with:
Successes,
Uncertainties
Improvements

Need:
Successors
…

Background: on the theoretical side

- **Transport Models for HIC's at intermediate energies:**

- N-body approaches
  - QMD
  - AMD, BQMD, CMD
  - IDQMD, ImQMD, IQMD
  - FMD, LQMD, UrQMD

QMD-like

- One-body approaches
  - BUU
  - (I)BUU/VUU, GiBUU
  - BNV, LV, IBL

BUU-like

- Relativistic covariant approaches
  - RBUU/RVUU
  - RQMD

Background: on the theoretical side

Modelers	**Models**	**References**
A. Ono	AMD	PR**C66**(02)014603
C. Hartnack	IQMD	EPJ**A1**(98)151
P. Napolitani	BQMD	PR**202**(91)233
Y.X. Zhang	ImQMD	PL**B664**(08)145; PR**C71** (05)024604; PR**C74**(06)014602
P. Danielewicz	BUU	A lot! ☺
Q.-F. Li	UrQMD-m	PRC73(06)051601; 83(11)044617; 89(14)034606;89(14)044603;JPG32(06)151
P. Giordano	BNV (CT)	NP**A732**(04)202; PR**C72**(05)064609
M. Pfabe	BNV	NPA703 (2002) 603
T. Gaitanos	RBUU(Munich)	NP**A714**(03)643;NP**A741** (04) 209
GiBUU (SK)	BUU-Giessen	gibuu.physik.uni-giessen.de
GiBUU (RMF)	RBUU-Giessen	PL**B663**(08)197; arXiv:0904.2106v1; PR**C76**(07)044909
B.-A. Li	IBUU	PR**160**(88)189; PR**C44**(91)450 & 2095.
H. Schade	BUU	PLB 695 (2011)74

New Refs.

Puzzles related to SE at high-densities

(During 2009-2011)

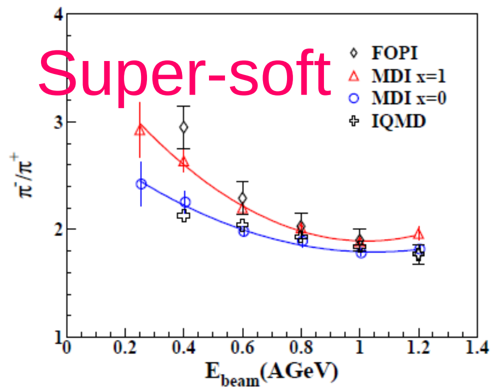
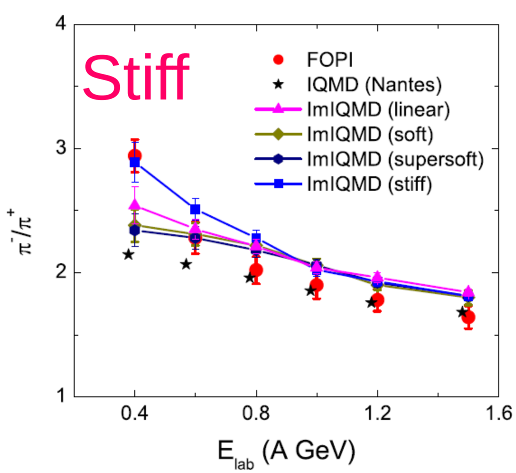
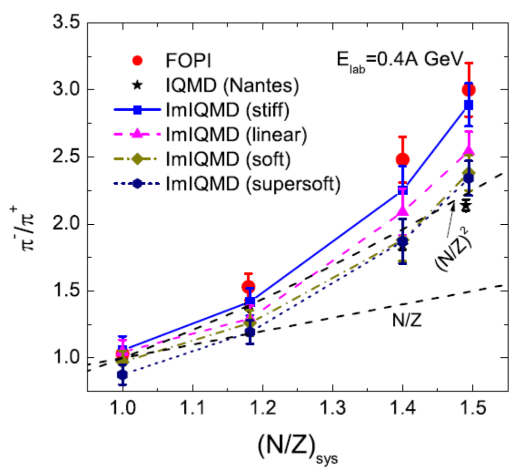


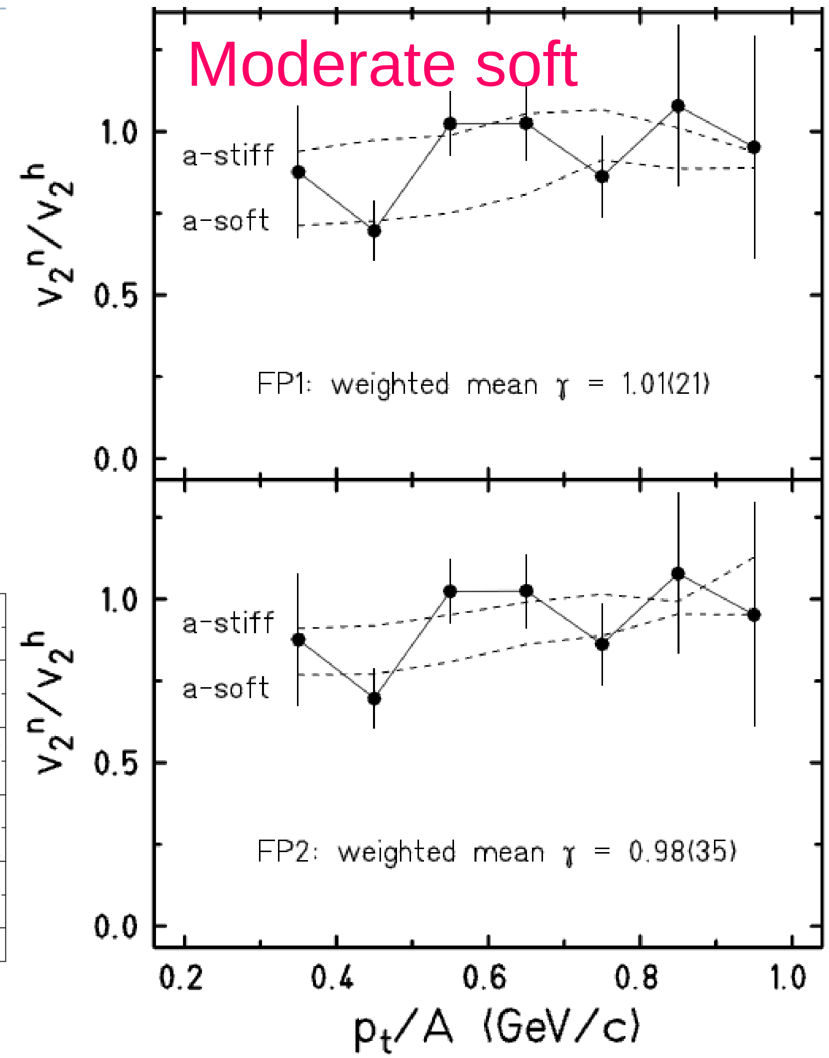
FIG. 4: (Color online)Excitation function of the π^-/π^+ ratio in central Au+Au collisions calculated with the IBUU04 in comparison with the FOPI data and the IQMD prediction.

Phys. Rev. Lett. 102, 062502, 2009





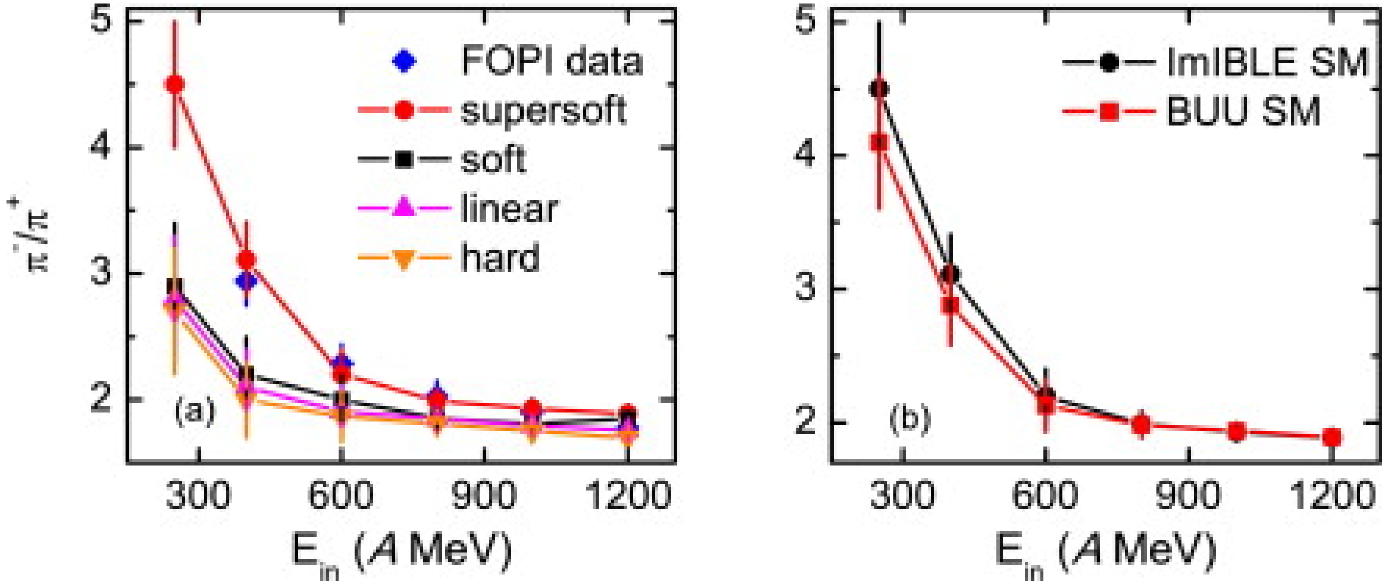
Z.Q. Feng, G.M. Jin, PL B683 (2010) 140



Physics Letters B 697 (2011) 471

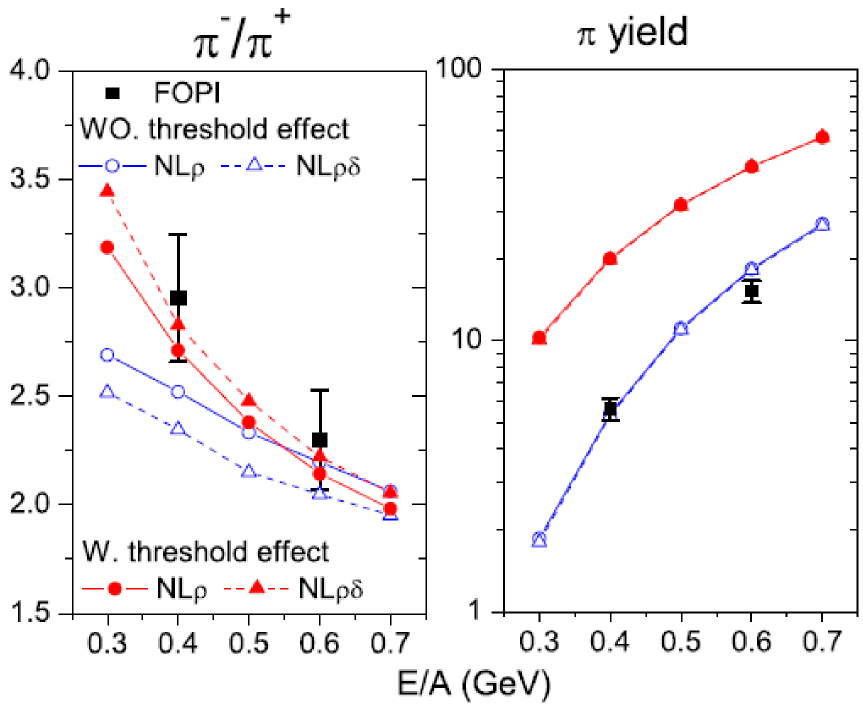
In the year 2013…

Super-soft, again



W. J. Xie, … F.S. Zhang, PLB 718 (2013) 1510

In the year 2014…



It does not matter? It DOES matter!

Medium modifications on threshold energy is essential, which will be discussed later.

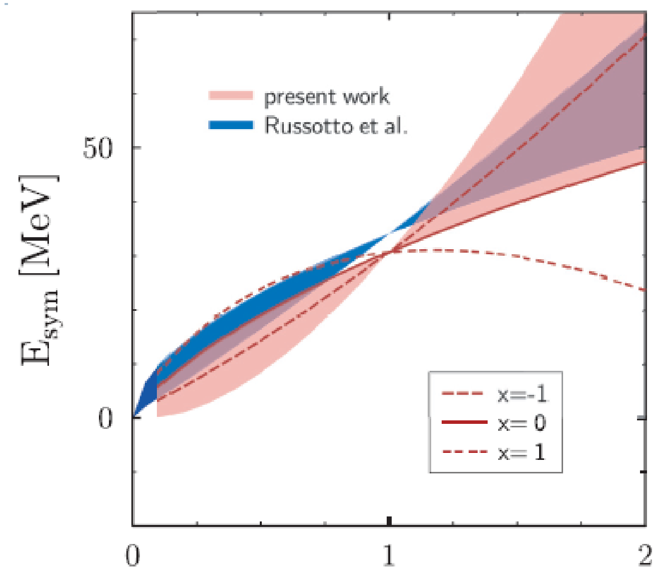
See, TS&CK, PRC91, 014901(2015) for more details

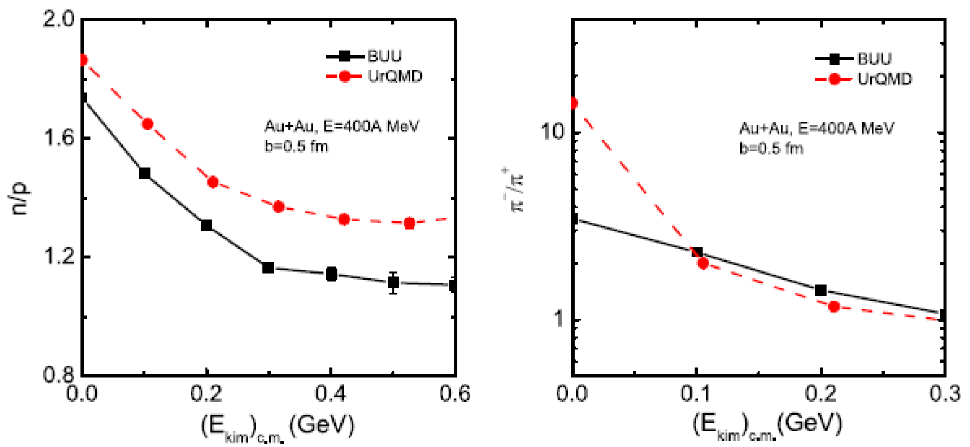
Model dependence in the comparsion work

- UrQMD & Tuebingen-QMD
- PRC **88, 044912 (2013)**

Good news!

- UrQMD & IBUU
- PLB 726 (2013) 211

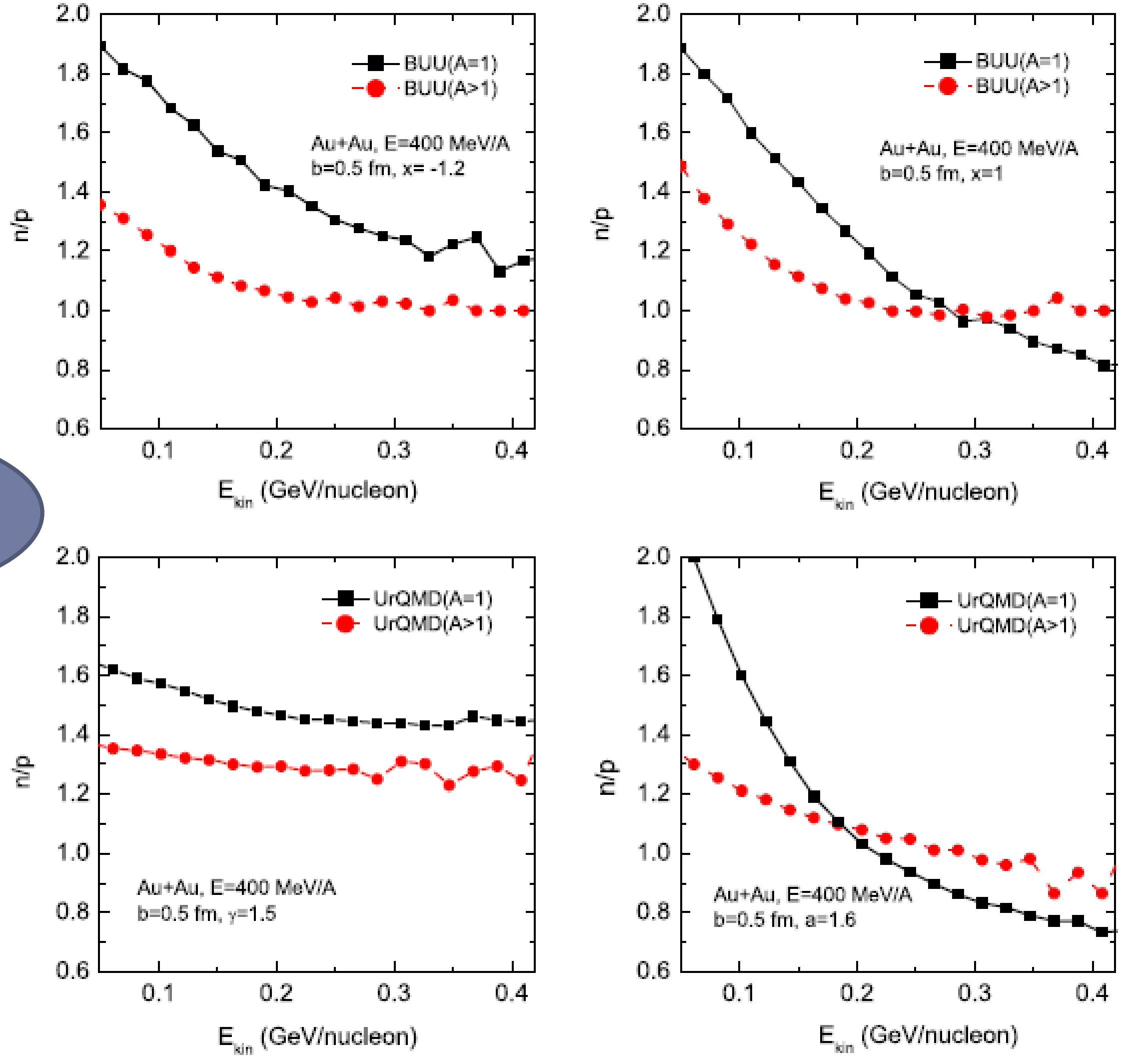




PLB738 (2014) 397

Further comparison between UrQMD&IBUU

Good news!



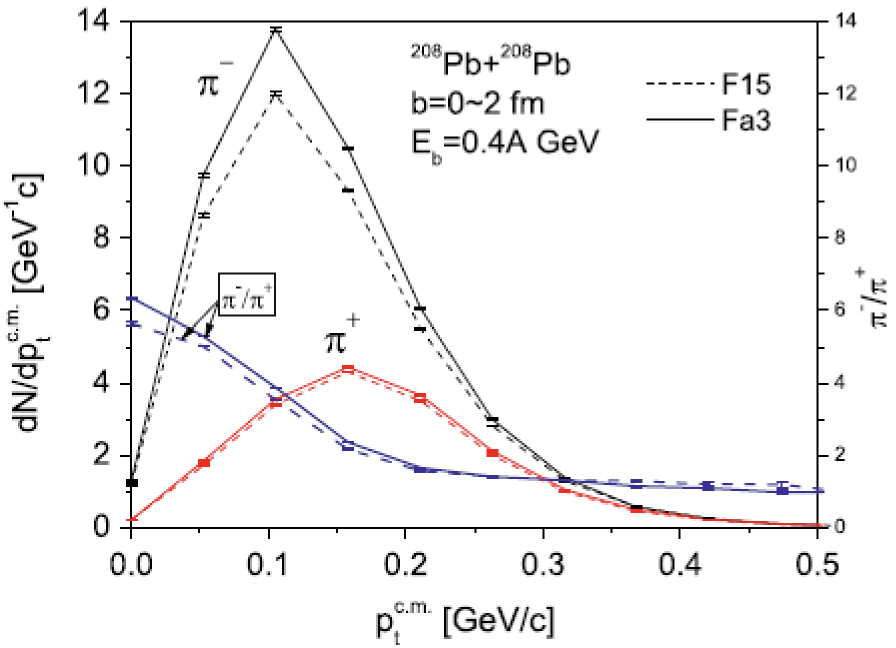
Probes of DDSE especially at high densities from the HICs

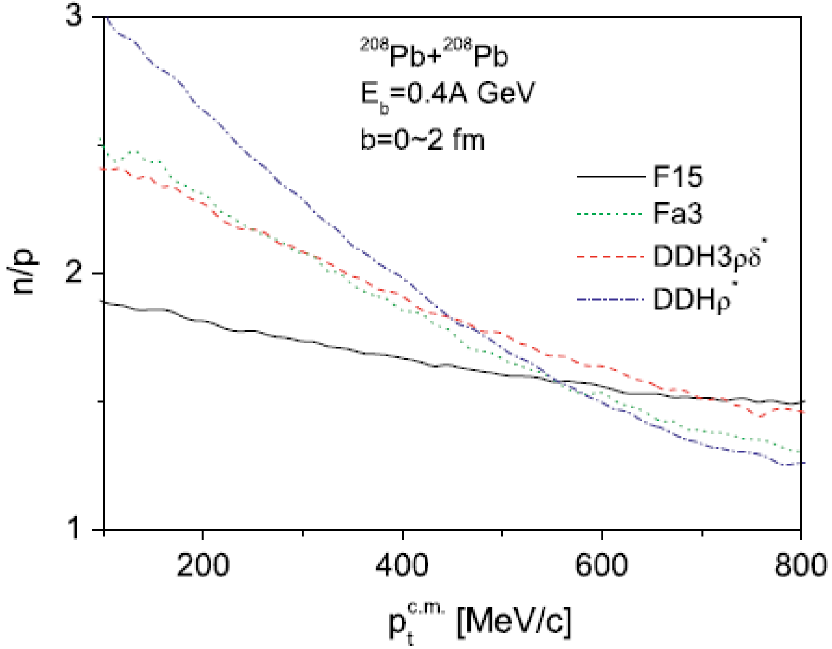
- The (double) ratio of multiplicities of nucleons, Δs, Σs, pions, kaons and hard photons as functions of Eb, b, N/Z; pt, y, Ekin, etc.
- The (double) flow, flow difference, differential flow of nucleons, pions as functions of Eb,b,N/Z,pt, y, Ekin, etc.

- Keep ongoing …

Experimental windows are useful

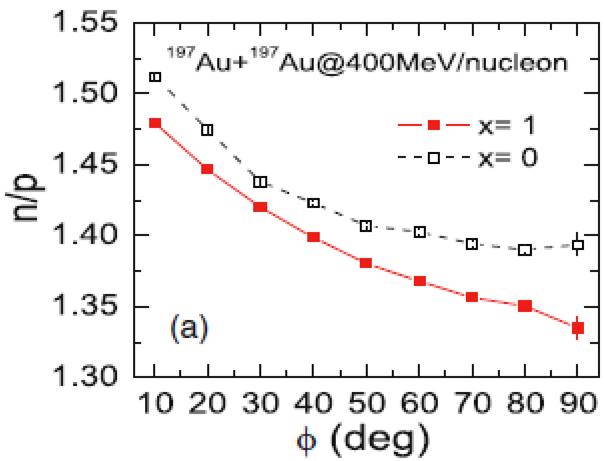
A previous example from PRC **72**, 034613 (2005)

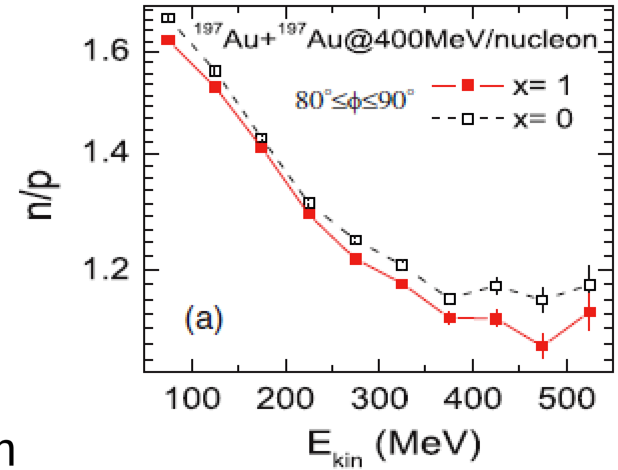




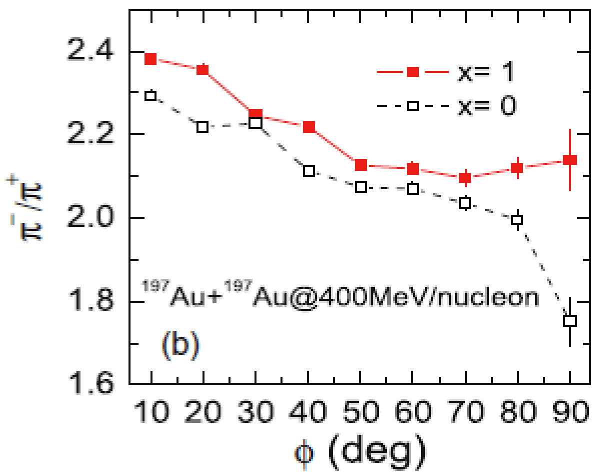
Experimental windows are useful

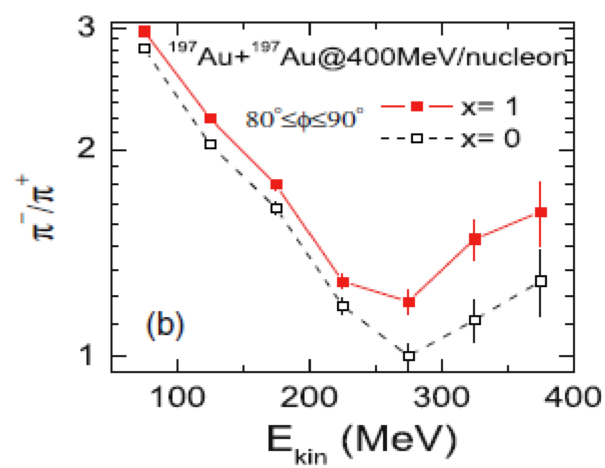
A recent example from PRC 88, 057601 (2013)





b=7 fm

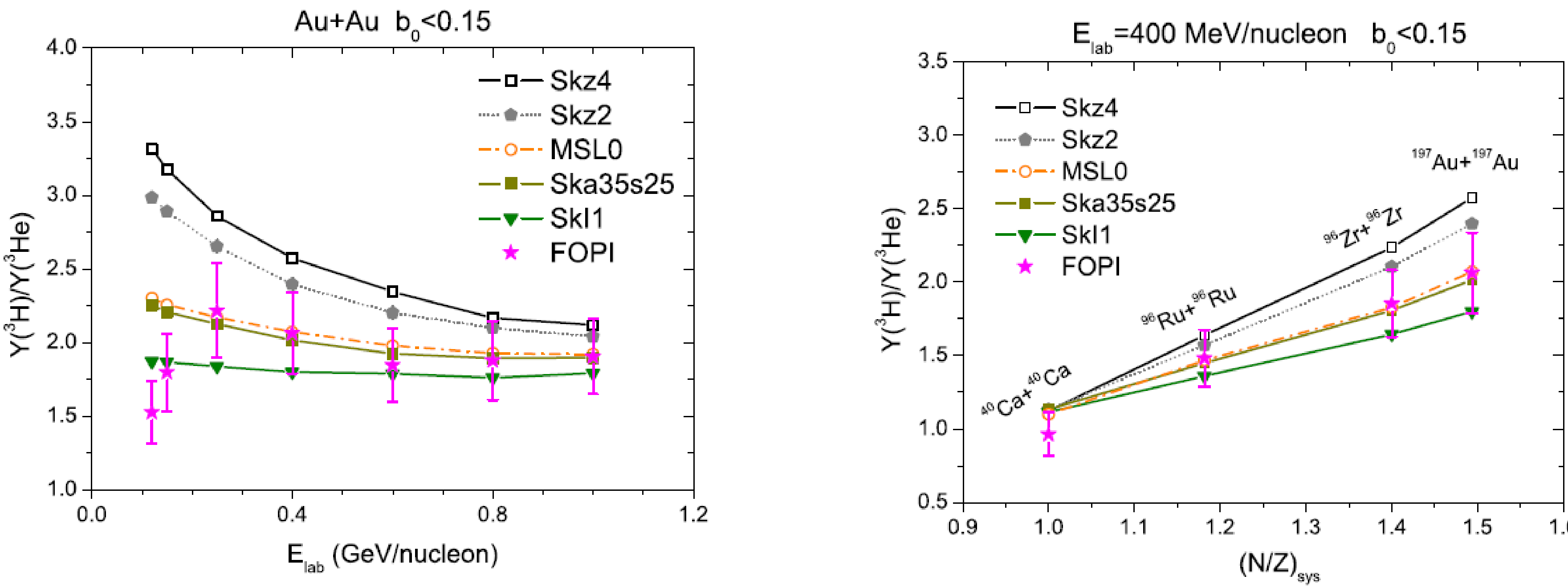




SE at $\rho<\rho_0$ should be also noticed…

A recent example from: Eur. Phys. J. A (2015) **51**: 37

is found that the $^3H/^3He$ ratio is sensitive to the nuclear symmetry energy at sub-saturation densities. Model calculations with moderately soft to linear symmetry energies are in qualitatively agreement with the $^3H/^3He$ ratio data of the FOPI Collaboration. This result is in line with both the recent constraints on the low-density symmetry energy available in the literature and our previous results for the high-density symmetry energy obtained with the elliptic flow of free nucleons and hydrogen isotopes as a sensitive probe.

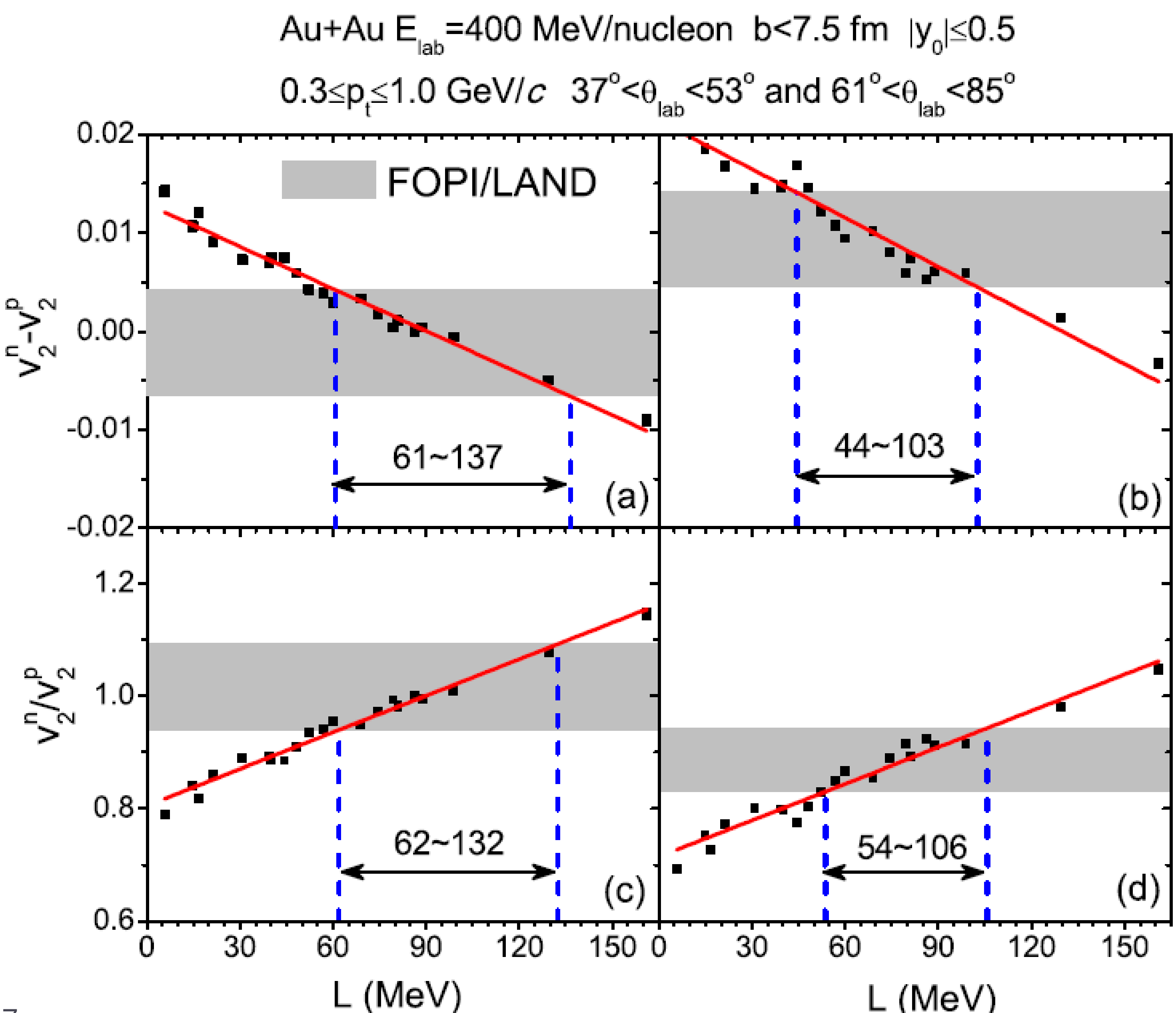


Background: on the experimental side

- Quite a few facilities working (partly) for this field:
  - **FRIB (or FRIB/China?) at MSU in USA**
  - **NUSTAR at FAIR/GSI in Germany**
  - **RIBF at RIKEN in Japan**
  - **CSR at HIRFL/Lanzhou in China**
  - KoRIA in Korea
  - …

ALADIN/FOPI/LAND existing flow data ~ UrQMD analysis

- List of Publications (Year 2009-2014):
  - **Prog. in Part. and Nucl. Phys.** 62 (2009) 425;
  - **Int. J. of Mod. Phys. E** 19 (2010) 1653;
  - **Phys. Lett. B** 697 (2011) 471;
  - **Phys. Rev. C** 83 (2011) 044617;
  - **SCIENCE CHINA Physics,** 55 (2012) 252 ;
  - **Phys. Rev. C** 88 (2013) 044912 ;
  - **Eur. Phys. J. A** 50 (2014) 38;
  - **Phys. Rev. C** 89 (2014), 034606;
  - **Phys. Rev. C** 89 (2014), 044603

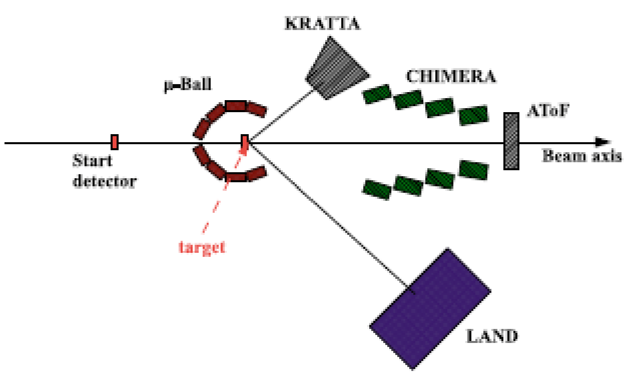


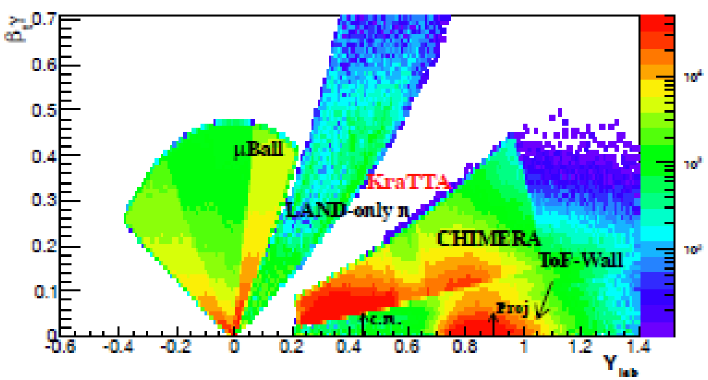
Au+Au E_{lab}=400 MeV/nucleon b<7.5 fm $|y_0|\leq0.5$
$0.3\leq p_t\leq1.0$ GeV/c $37^o<\theta_{lab}<53^o$ and $61^o<\theta_{lab}<85^o$
FOPI/LAND
$v_2^n-v_2^p$
$v_2^n-v_2^H$
v_2^n/v_2^p
v_2^n/v_2^H
61~137
44~103
62~132
54~106
(a)
(b)
(c)
(d)
L (MeV)
L (MeV)

ASY-EOS(S394) experiment at GSI

With the help of KraTTA from Krakow

- Au+Au; Zr+Zr; Ru+Ru
- E_b=400 MeV/nucleon
- Within a large impact parameter range
- Z≤4 (up to Be)
- nearly 4 π coverage
- Yield, yield ratios, flow parameters v_1,v_2
- Especially for neutrons with high precision.

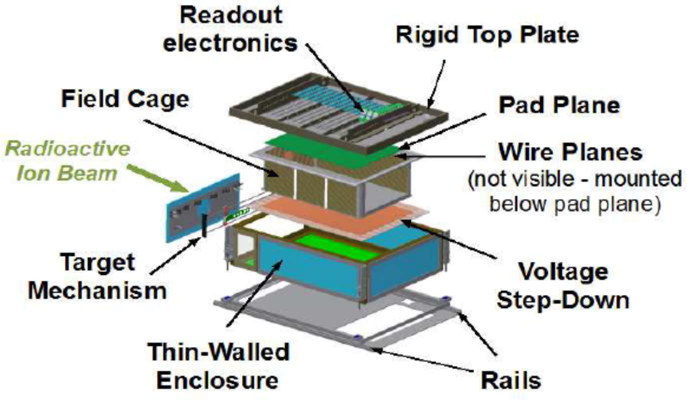




http://dx.doi.org/10.1016/j.nima.2015.01.026

Ability of SπRIT interested by theoretical workers

- $^{132}Sn+^{124}Sn$; $^{124}Sn+^{112}Sn$; $^{108}Sn+^{112}Sn$; $^{112}Sn+^{124}Sn$
- E_b up to 350 MeV/nucleon
- Central collisions
- $Z \leq 3$ (up to Li); charged π mesons
- nearly 4 π coverage
- Yield, yield ratios
- … to be learned from this workshop.

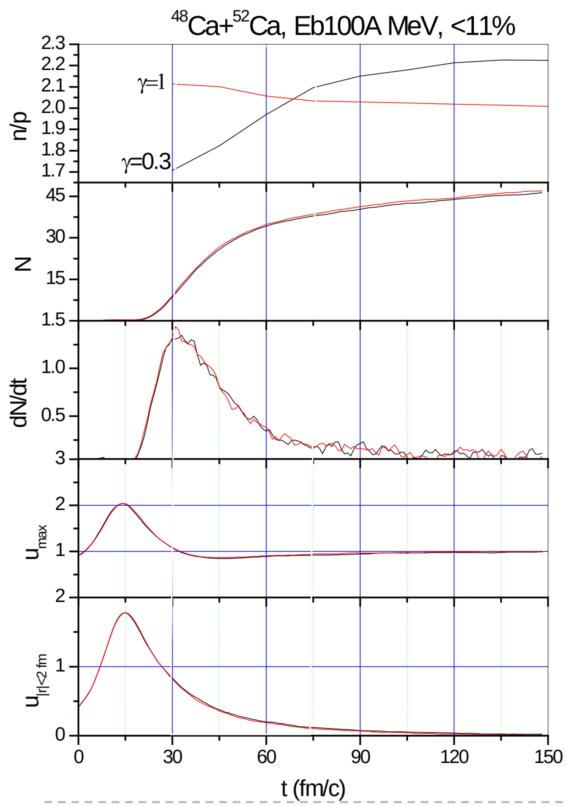


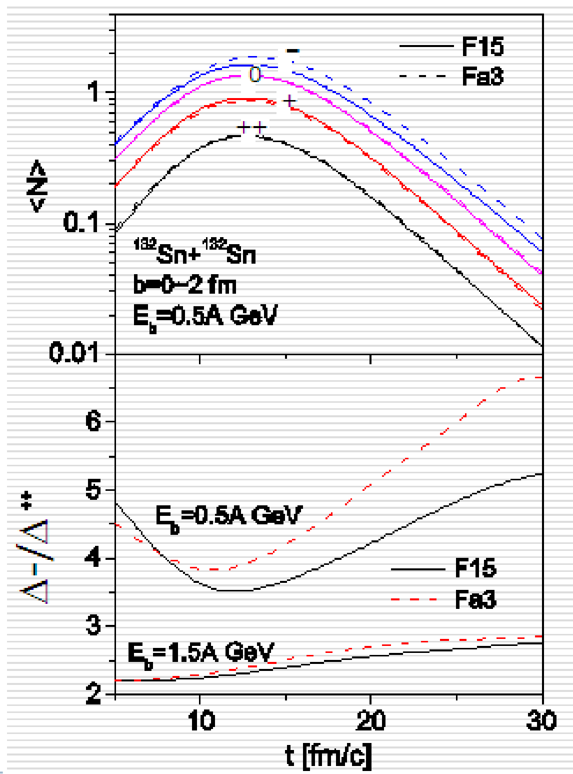
Theoretical concerns (partially)

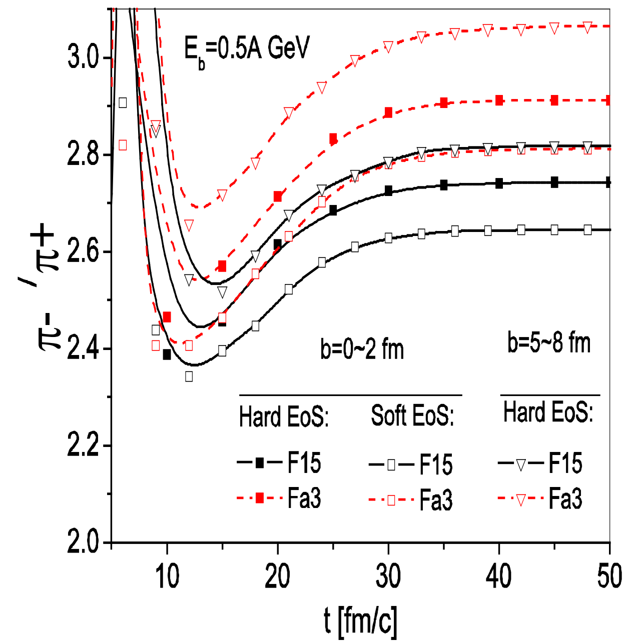
- Multi-systems √
  - From Zr+Zr, Sn+Sn, to Au+Au
  - From central to mid-central collisions
  - With beam energies up to 400 MeV/nucleon
- Multi-observables √
  - From neutron, proton, up to Li
  - From baryons to mesons
  - From yield, yield ratio, to flows
  - Within large rapidity y and transverse momentum p_t ranges
- Totally optimistic if all of these are measured with a high precision from experimental side.
- And, a close collaboration between us is essential

Theoretical concerns

- However, theoretically, the whole dynamical process should be investigated thoroughly, which makes the situation much more complicated.





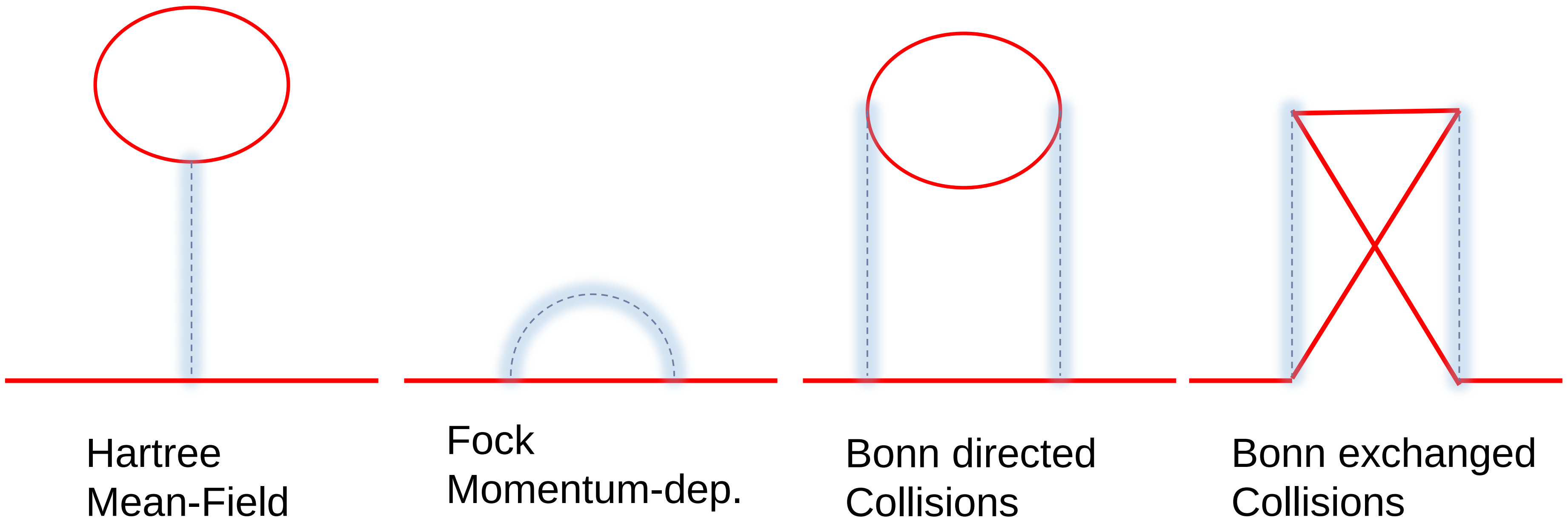


J. Phys. G **31** (2005) 1359

N-Δ-π dynamics

——in the view of Quantum Transport Theory based on RBUU

- time evolution of a many-particle quantum system→nonequilibrium field theory—QHD



2nd order

4th order

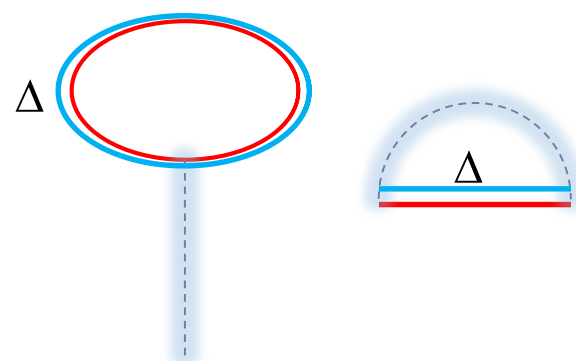
Mean-Field Term

- On-shell:

$$\bar{p}^{\mu}\bar{p}_{\mu} = M_{\mathrm{Re}}^{*\,2}$$

- And:

$$\begin{cases} \bar{p}^{\mu}(X,p,t) = p^{\mu} - \Sigma_{H}^{\mu}(X,t) - \mathrm{Re}\Sigma_{F}^{\mu}(X,p,t), \\ M_{\mathrm{Re}}^{*}(X,p,t) = M + \Sigma_{H}(X) + \mathrm{Re}\Sigma_{F}(X,p,t) 。\end{cases}$$



- For simplicity, for simplicity…

Mass-splitting

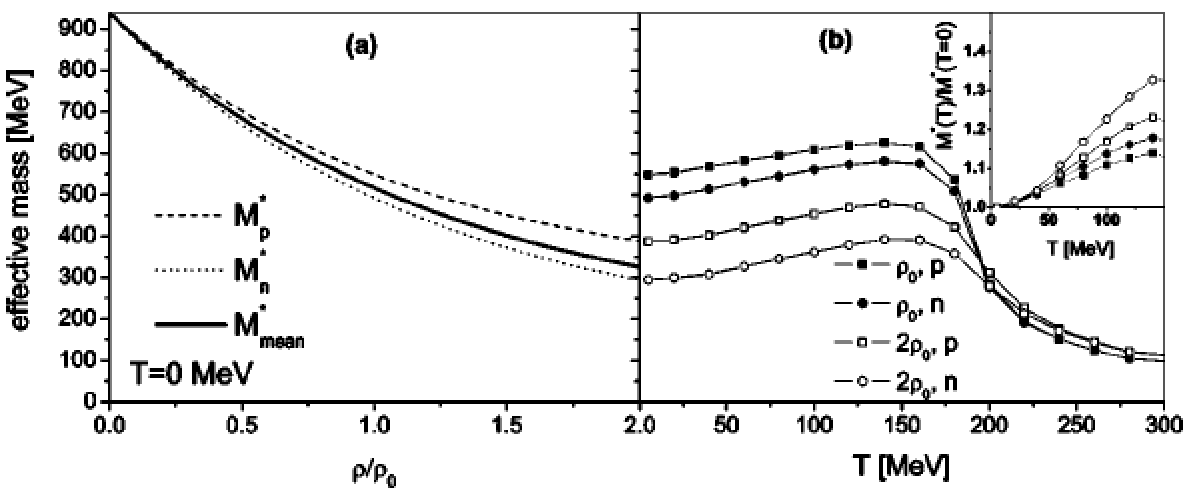
PRC **69**, 017601 (2004)

$$L = \overline{\Psi}[i\gamma_\mu\partial^\mu - M_N]\Psi + \tfrac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - \tfrac{1}{4}F_{\mu\nu}\cdot F^{\mu\nu} + \tfrac{1}{2}\partial_\mu\boldsymbol{\delta}\partial^\mu\boldsymbol{\delta} - \tfrac{1}{4}L_{\mu\nu}\cdot L^{\mu\nu} - \tfrac{1}{2}m_\sigma^2\sigma^2 + \tfrac{1}{2}m_\omega^2\omega_\mu\omega^\mu - \tfrac{1}{2}m_\delta^2\boldsymbol{\delta}^2 + \tfrac{1}{2}m_\rho^2\boldsymbol{\rho}_\mu\boldsymbol{\rho}^\mu + g_\sigma\overline{\Psi}\Psi\sigma - g_\omega\overline{\Psi}\gamma_\mu\Psi\omega^\mu + g_\delta\overline{\Psi}\boldsymbol{\tau}\cdot\Psi\boldsymbol{\delta} - \tfrac{1}{2}g_\rho\overline{\Psi}\gamma_\mu\boldsymbol{\tau}\cdot\Psi\boldsymbol{\rho}^\mu,$$

$$M^* = M_0 + \Sigma_{H(\sigma)}(x,\tau) + \Sigma_{H(\delta^0)}(x,\tau). \quad (1)$$

$\Sigma_{H(\sigma)}$ and $\Sigma_{H(\delta)}$ are the self-energy parts of nucleon contributed from σ and δ mesons, respectively. Because the self-energy $\Sigma_{H(\delta^0)}(x,\tau)$ has opposite sign for neutron and proton for isospin asymmetric medium the correction of the nuclear medium to proton mass and neutron mass from δ meson is of opposite sign. Thus the proton and neutron effective masses differ for isospin asymmetric systems. The effective chemical potential μ^* is

$$\mu_i^* = \mu_i + \Sigma^0_{H(\omega)}(x,\tau) + \Sigma^0_{H(\rho^0)}(x,\tau). \quad (2)$$



Mass-splitting puzzle

- "two definitions":
- Dirac one:

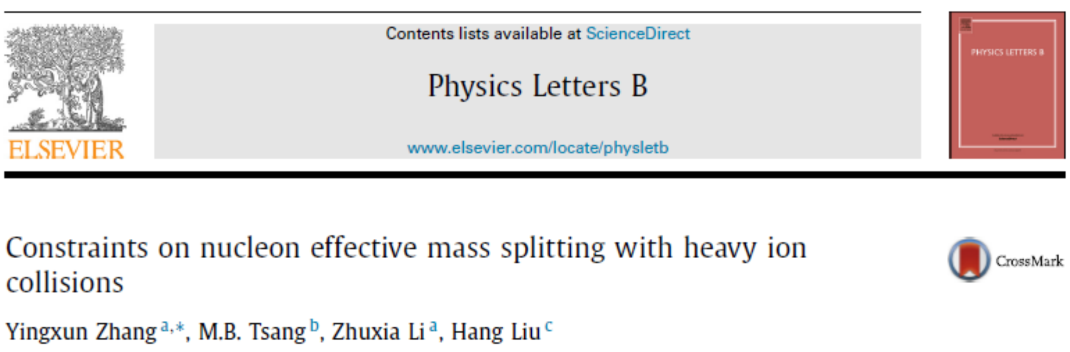
$$m^*_D(k, k_F) = \frac{M + \mathrm{Re}\,\Sigma_s(k, k_F)}{1 + \mathrm{Re}\,\Sigma_v(k, k_F)};$$

- Non-relativistic one:

$$m^*_{NR} = |\mathbf{k}|[dE/d|\mathbf{k}|]^{-1},$$

Phys. Rev. Lett. **95**, 022302 (2005)

- …


Contents lists available at ScienceDirect

Physics Letters B

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ELSEVIER

Constraints on nucleon effective mass splitting with heavy ion collisions

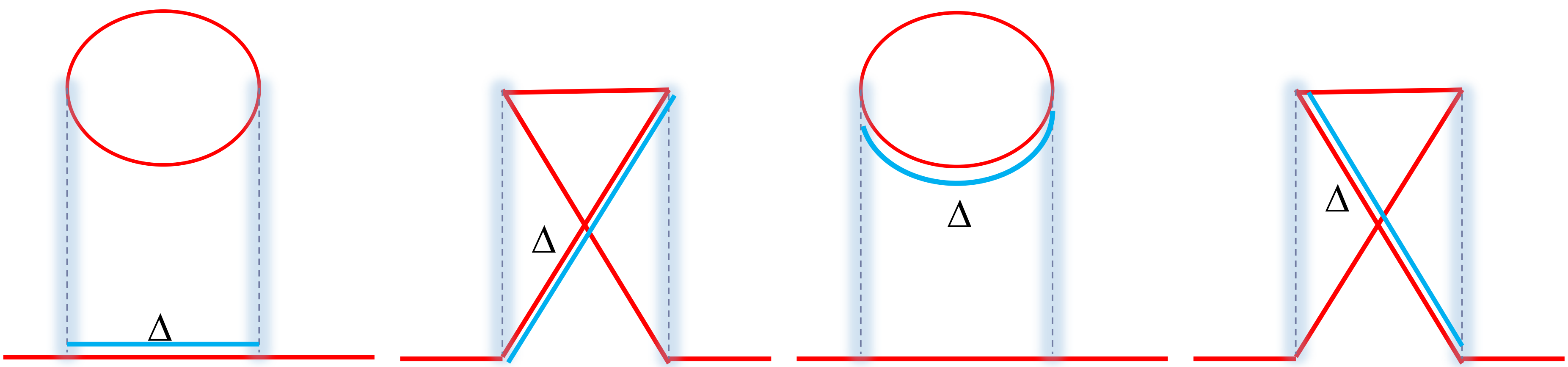
Yingxun Zhang[a,*], M.B. Tsang[b], Zhuxia Li[a], Hang Liu[c]

- Hence, a more consistent MF is urgently desired.

Collision Term (also complicated)

- $C = \frac{1}{2} \int \frac{dp_2}{(2\pi)^3} \int \frac{dp_3}{(2\pi)^3} \int \frac{dp_4}{(2\pi)^3}$
- $(2\pi)^4 \delta^{(4)}(p + p_2 - p_3 - p_4)$
- $W \; (F_2 - F_1)$

Transition probability



NN→NΔ

Transition probability W ~ spin+isospin matrices

- Spin matrix: Φ;Iso-spin matrix: T
- Directed: D; Exchanged: E

- $W = \sum_{p_3 \leftrightarrow p_4} \frac{1}{16 E_1 E_2 E_3 E_4} (T_D \Phi_D - T_E \Phi_E)$

Transition probability W ~ differential cross section dσ/dΩ

- From W based on RBUU
- $\int \nu \frac{d\sigma}{d\Omega} d\Omega = \frac{\int dp_3}{(2\pi)^3} \frac{\int dp_4}{(2\pi)^3} (2\pi)^4 \delta^{(4)}(p + p_2 - p_3 - p_4)\, W$
- ν is Moller velocity.

$$\nu = \frac{\sqrt{(p.p_2)^2 - p^2 p_2^2}}{p^0 p_2^0}$$

- In the c.o.m of two particles:

- $\frac{dp_3 dp_4}{E_1 E_2 E_3 E_4} = \frac{\nu}{s} \frac{|p_3|}{|p_1|} d\Omega dQ$
  - $s = (p + p_2)^2; t = (p - p_3)^2; u = (p - p_4)^2$

(s,t,u)→(s,cos(θ))

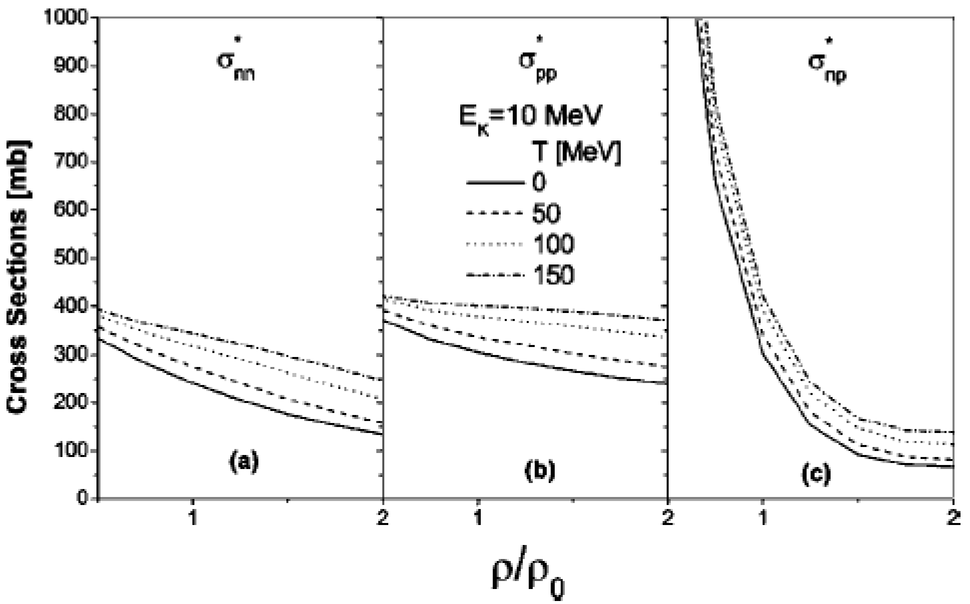
differential cross section dσ/dΩ ~integral cross section

- $$\sigma_{NN\to B_3B_4} = \frac{1}{8(1+\delta_{B_3B_4})}\int \frac{d\sigma}{d\Omega}d\Omega$$

$$d \le d_0 = \sqrt{\frac{\sigma_{\rm tot}}{\pi}}, \qquad \sigma_{\rm tot} = \sigma(\sqrt{s},\ {\rm type}).$$

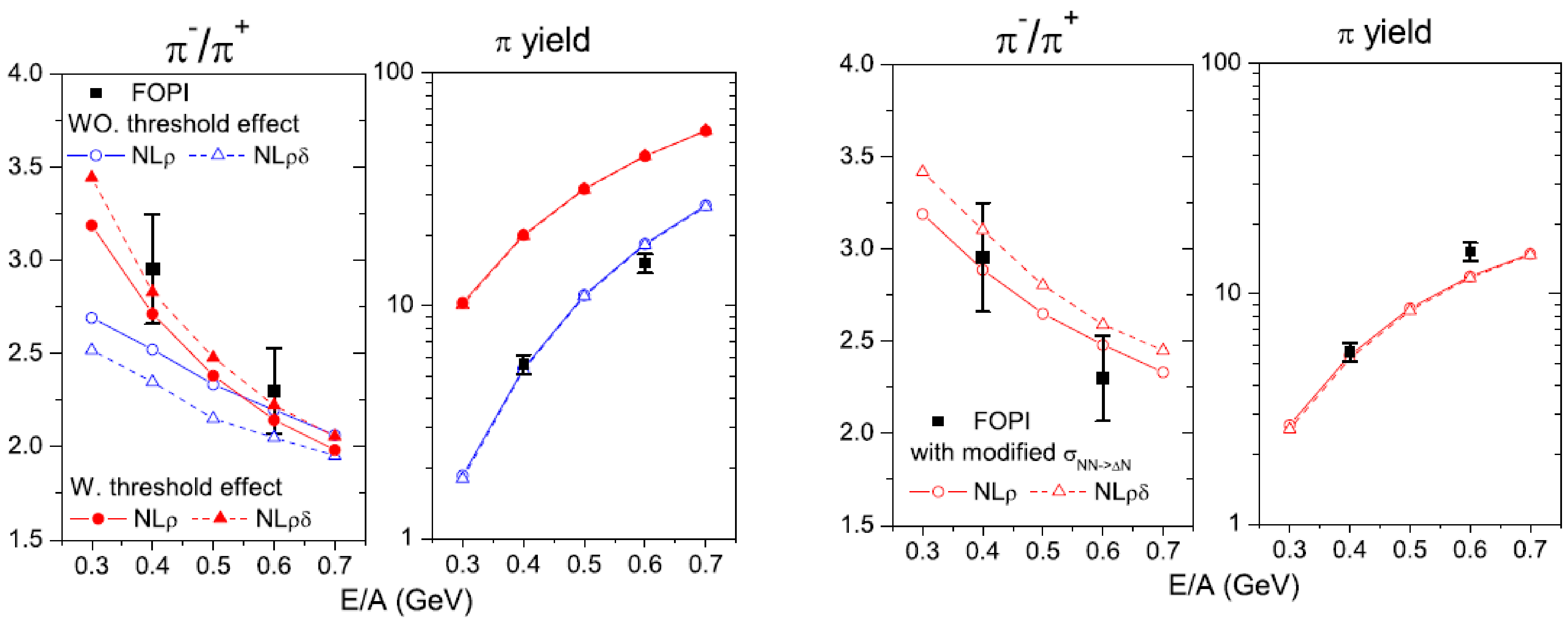
Threshold: $s \to s - (m_1^* + m_2^*)^2 + 4{m^*}^2$

CS:



See, PRC69, 017601 (2004), for NN→NN case

Medium modified threshold-energy and cross section effects on pion production



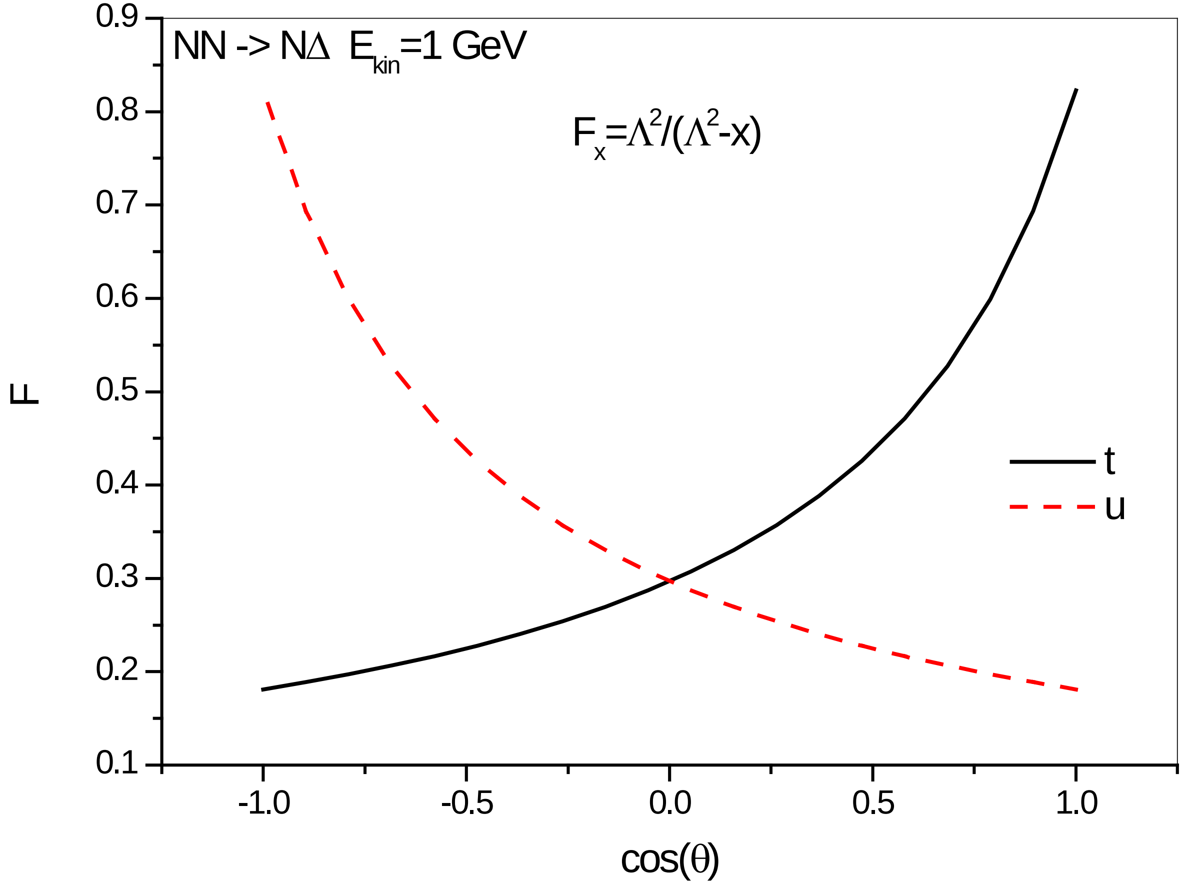
See, TS&CK, PRC91, 014901(2015)

Hold on… Is that all done?

Form Factors at vertices

- Considering of the effect of finite size of hadrons (to model the deviations from the point-like couplings due to the quark structure of nucleons and resonances.)
  - $F_{NNA}(t) = \frac{\Lambda^2}{\Lambda^2 - t}$
- Λ is the cut-off parameter and governs the range of suppression of the contributions of high momenta.

It is angular-dep.:



- $$\frac{d\sigma}{d\Omega} \rightarrow \frac{d\sigma}{d\Omega} F_{NNA}^2 F_{NNB}^2$$

- Because it is not clear *a priori* which form these additional factors should have, they introduce a source of systematical error in all models. And the parameters extracted can depend strongly on the functional form used for the form factors.

For NN->NΔ

- $\frac{d\sigma}{d\Omega} \rightarrow \frac{d\sigma}{d\Omega} F^2_{NNA} F^2_{NNB}\ \mathrm{F}^2_{res}$
- because of the decay of the Δ resonance and the existence of the distribution function

- $F_{res} = \left(\frac{\frac{1}{4}\Gamma^2(<q>)}{(<M_\Delta - M_0>)^2 + \frac{1}{4}\Gamma_0^2} \right)^{\frac{1}{4}}$

Angular distributions in UrQMD

- It is assumed that the angular distributions for all relevant two-body processes are similar and can be described approximately by the differential cross-section of in-medium NN elastic scattering derived from the collision term of the RBUU equation.
- It only uses free cross sections and free on-shell particles.
- It is only used for the angular distributions of all elementary two-body processes but not for the corresponding total cross sections.

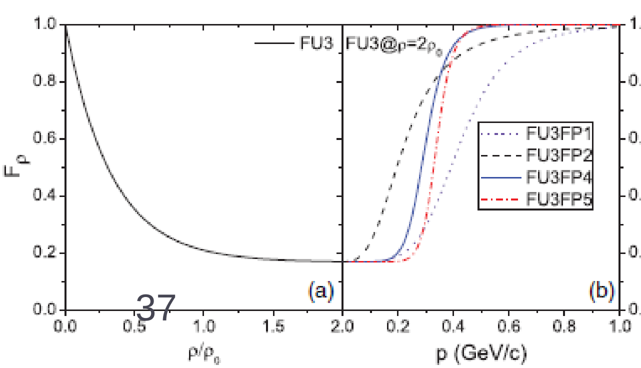
Medium Modifications on NNECS

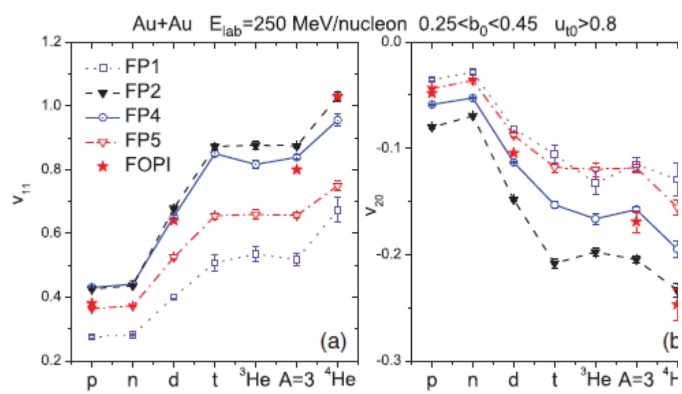
- PHYSICAL REVIEW C, **62, 014606 (2000)**
- PHYSICAL REVIEW C **69, 017601 (2004)**

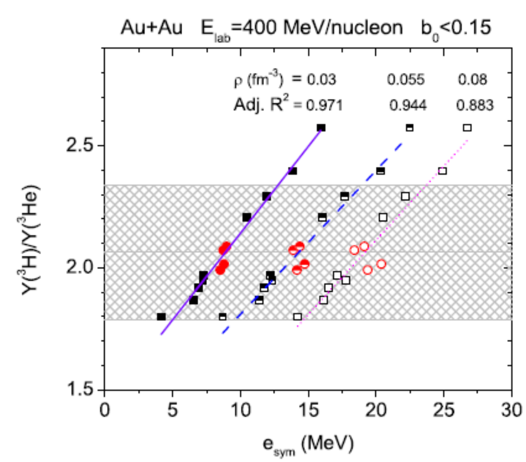
Obtained from RBUU

- J. Phys. G: Nucl. Part. Phys. **32 (2006) 407**
- PHYSICAL REVIEW C **81, 034913 (2010)**
- PHYSICAL REVIEW C **83, 044617 (2011)**
- PHYSICAL REVIEW C **89, 034606 (2014)**
- PHYSICAL REVIEW C **89, 044603 (2014)**
- Eur. Phys. J. A **51 (2015) 37**

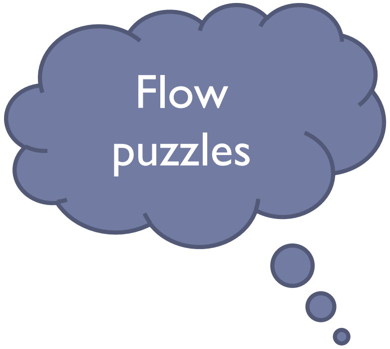
Used in UrQMD

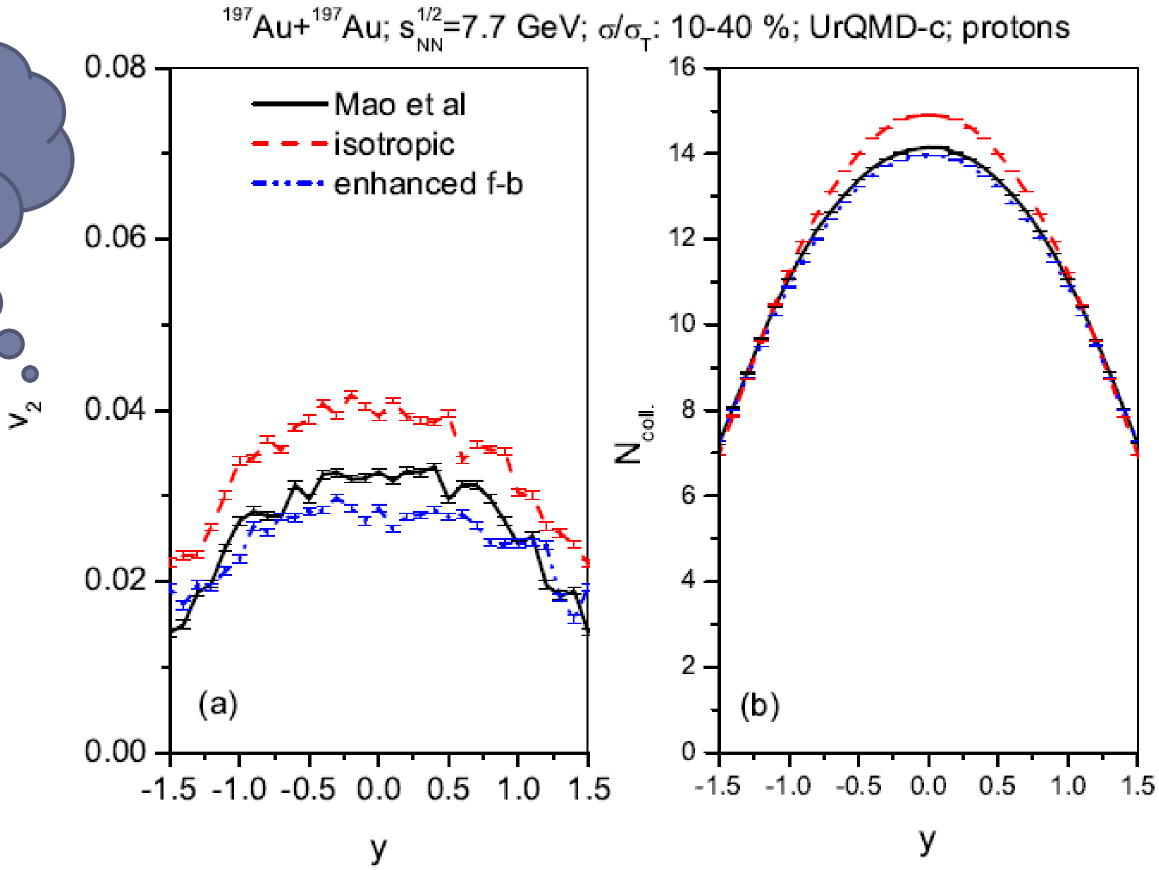






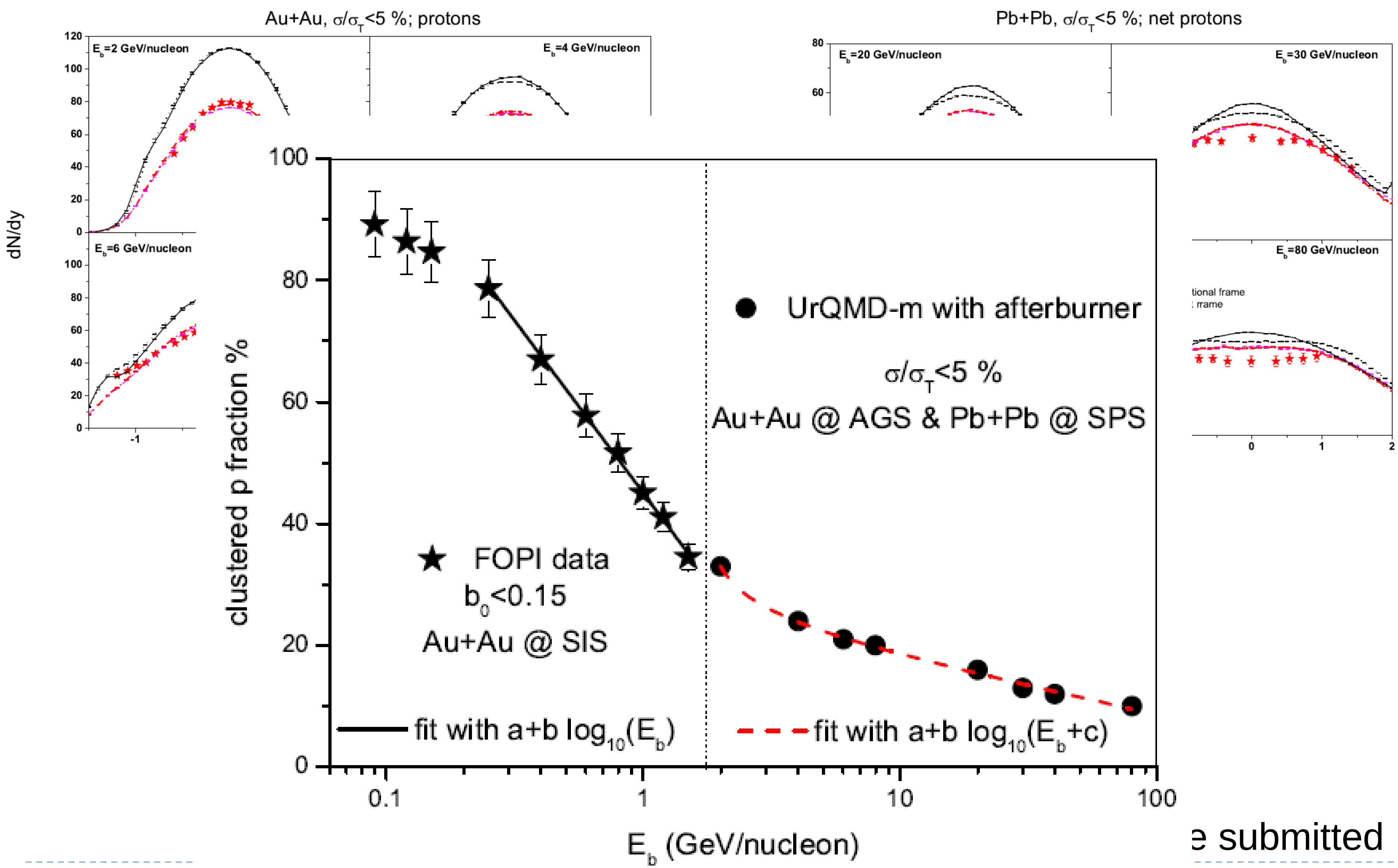
NNCS even at higher energies…





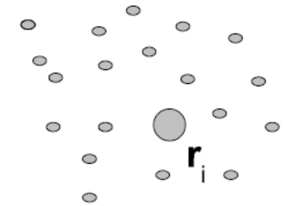
To be submitted

After-burner:
is important in a large beam energy region



e submitted

Coalescence after-burner



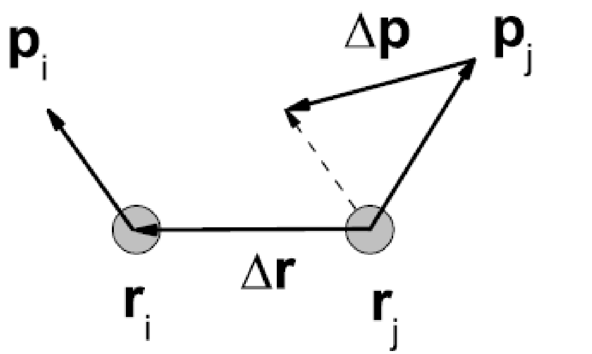
$\rho_i > \rho_0 / c$

- How to construct clusters?

- δr? But if too excited?
- δp? But if gays or lesbins?

Coalescence Model
(Minimum Spanning Tree)

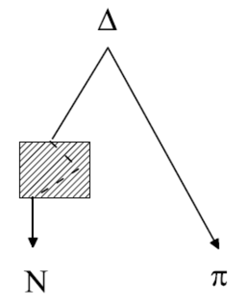
- More polishments on:
  - Isospin-dependence
  - Excitation energy
    - (due to strong phase-space
    - correlation, excitation energy
    - has been almost decided by δr&δp)



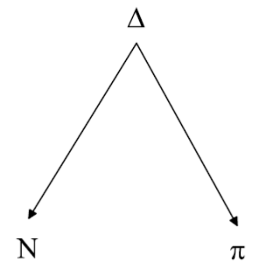
$|\Delta \mathbf{r}| < R_0$ and $|\Delta \mathbf{p}| < P_0$

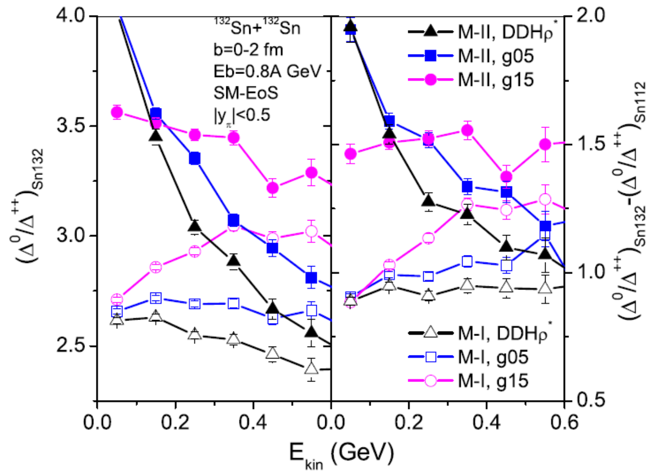
How to reconstruct Δ from Δ→Nπ channel ?

- "**contaminated**" one from one-π pt distribution



- "**pure**" one from correlated protons and charged pion pairs





See MPLA 24 (2009) 41 for more details.

Suggestions for upcoming SπRIT experiments

- ✓ How about the determination of the reaction plane and impact parameter?
- ✓ How about the systematic and statistic errors?

① n/p, π^-/π^+ , $^3H/^3He$, v_1, and v_2? *(multi-observables)*

② y and p_t distributions; y-p_t- correlated distribution? *(window-cut sensitivity)*

③ To reconstruct Δ? *(high density SE, and a better after-burner)*

Thank you for your attention!

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