Probing the symmetry energy and in-medium cross section via heavy ion collisions

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Outline

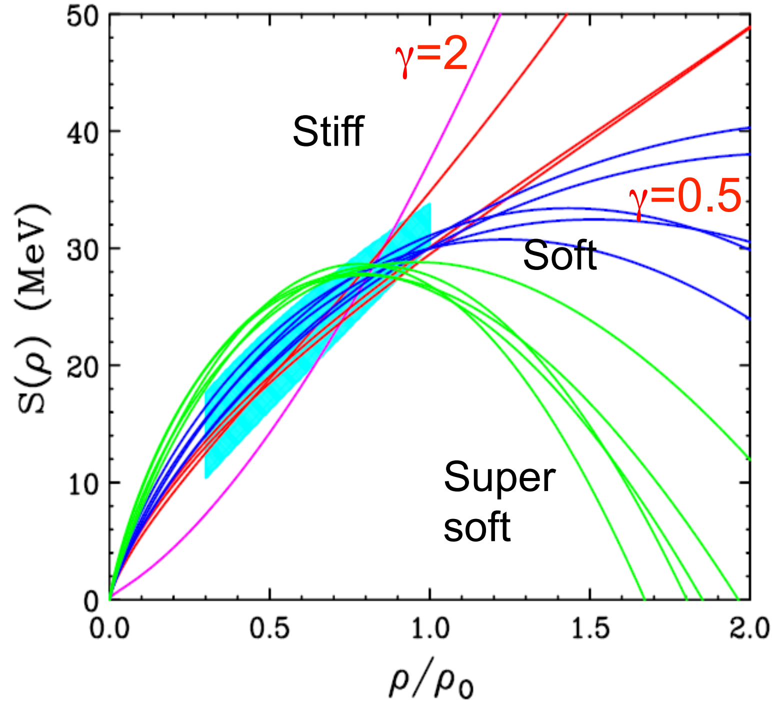
- Introduction
- Observables sensitive to the symmetry energy
- Current constraints
- How can we improve the constraints?
- Importance of cluster production, in-medium cross section and charge exchange in the transport model
- Summary

Symmetry Energy

adapted from
M.B. Tsang, Prog. Part.Nucl.Phys. 66, 400 (2011)
Brown, Phys. Rev. Lett. 85, 5296 (2001)

$$E/A(\rho,\delta) = E/A(\rho,0) + \delta^2 \cdot S(\rho)$$

$$\delta = (\rho_n - \rho_p)/(\rho_n + \rho_p) = (N-Z)/A$$



$$S(\rho) = S_k(\rho/\rho_0)^{2/3} + S_i(\rho/\rho_0)^{\gamma}$$

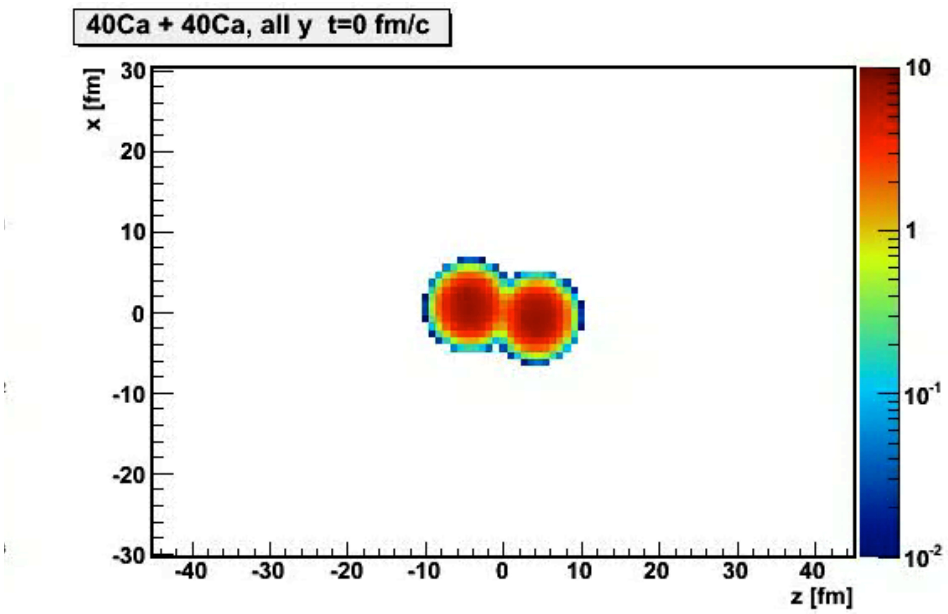
Both astrophysical and laboratory observables can constrain the EoS, $\varepsilon(\rho,T,\delta)$ or $P(\rho,T,\delta)$ indirectly

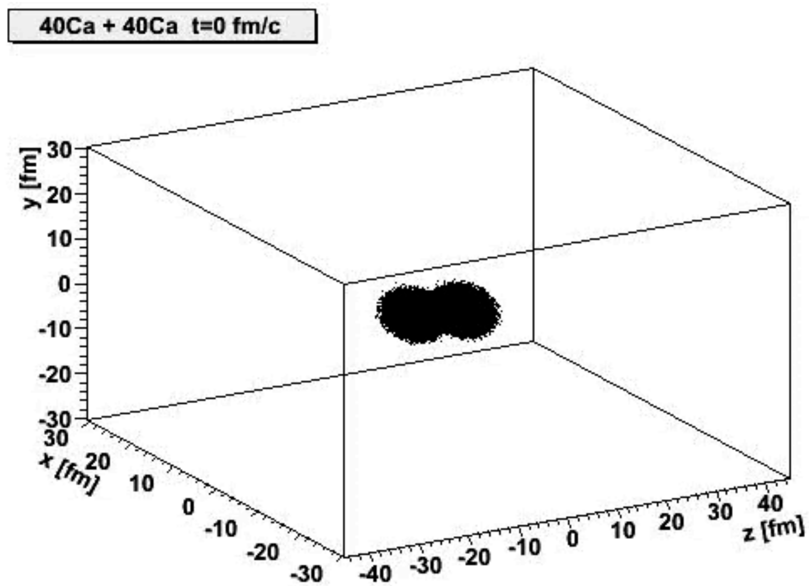
- What are the observables?
- What constraints have been obtained?
- At what densities or asymmetries do these constraints apply?
- What are the accuracies or model dependencies of these constraints?

need a theory

Transport model

- BUU - Boltzmann-Uehling-Uhlenbeck
- Simulates the time-dependent evolution of the collision





Micha Kilburn, NSCL/MSU

pBUU: Danielewicz, Bertsch, NPA533 (1991) 712
IBUU: B. A. Li et al., PRL 78 (1997) 1644

Transport model

- BUU - Boltzmann-Uehling-Uhlenbeck
- Simulates the time-dependent evolution of the collision

In-medium cross section

Rostock

$$\sigma(\rho) = \sigma_{free} exp\Big(-0.6\frac{\rho}{\rho_0}\frac{1}{1+(KE_{cm}/150MeV)^2}\Big)$$

Screened

$$\sigma_\eta(\rho) = \sigma_0 tanh[\sigma_{free}/\sigma_0]$$

$$\sigma_0 = \eta\rho^{-2/3}$$

$\sigma_{0.9}(\rho_0) = .77\sigma_{free}$ and $\sigma_{0.5}(\rho_0) = .53\sigma_{free}$

P. Danielewicz, Acta. Phys. Pol. B 33, 45 (2002)

Main ingredients

- Nucleons in mean-field
- Symmetry energy
- In-medium cross section
- Momentum (in-) dependent nuclear interaction
- Cluster production (A≤3)

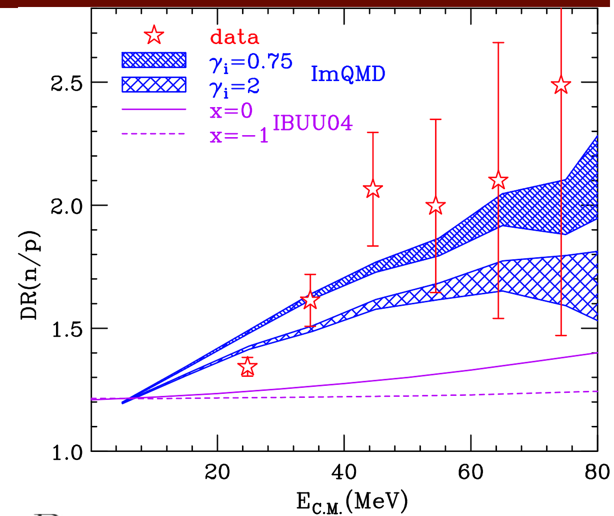
pBUU: Danielewicz, Bertsch, NPA533 (1991) 712
IBUU: B. A. Li et al., PRL 78 (1997) 1644

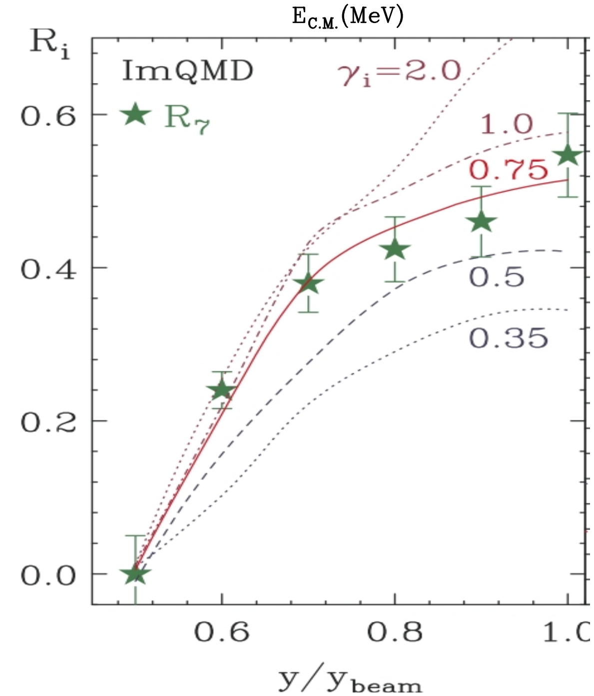
What observables have been used?

@ MSU/NSCL

- Simpler to interpret
  - n/p spectral double ratios
  - isospin diffusion – residual N/Z
- More difficult to interpret
  - fragment isotopic yields

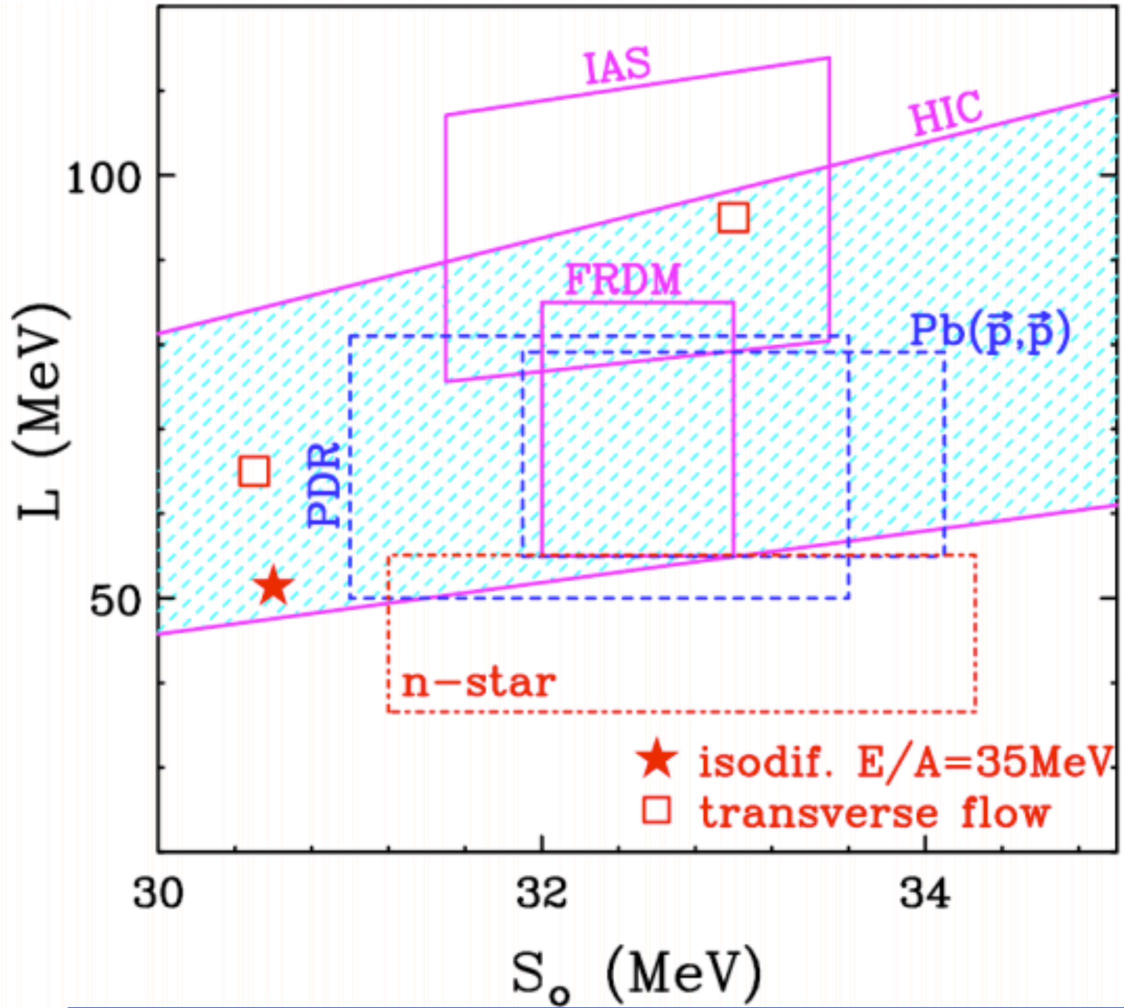
other observables: pion ratios, transverse flow, …





M. B. Tsang et al., PRL 102, 122701 (2009)
M. A. Famiano et al., PRL 97, 052701 (2006)

Current constraints



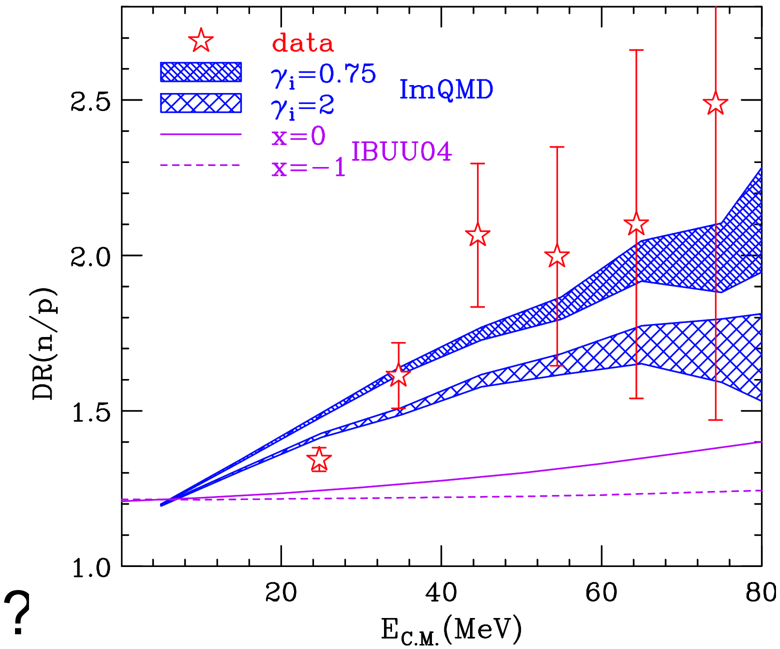
B. Tsang et al., arXiv:1204.0466

$$S(\rho) = S_0 + \frac{L}{3}\frac{\rho - \rho_0}{\rho_0} + \frac{K_{sym}}{18}\left(\frac{\rho - \rho_0}{\rho_0}\right)^2 + \cdots$$

How to improve constraints?

- reduce the statistical uncertainties
- what new observables?
- transport model
  - include cluster production
  - what other physics can be missing?

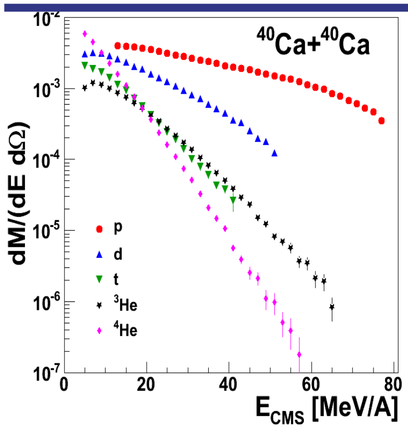
$^{112,124}Sn+^{112,124}Sn$@50 MeV/A

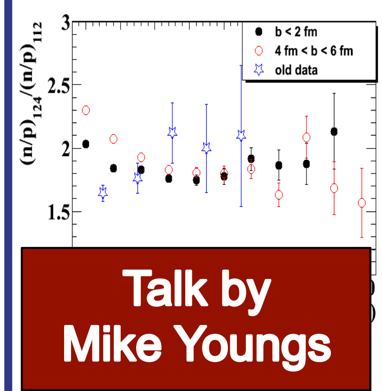


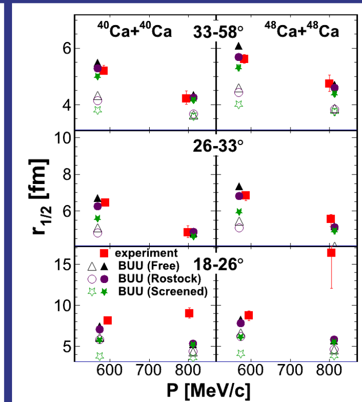
Talk by M. Youngs

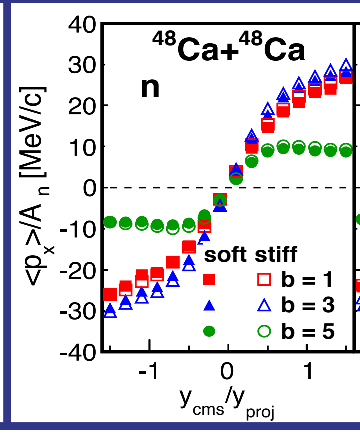
SEP at NSCL: Our current focus

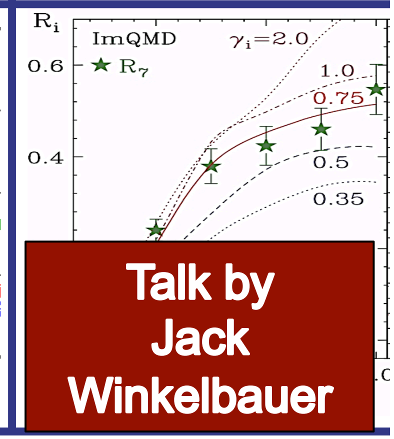
Spectra	(Double-) ratios	Femtoscopy	Flow	Isospin diffusion









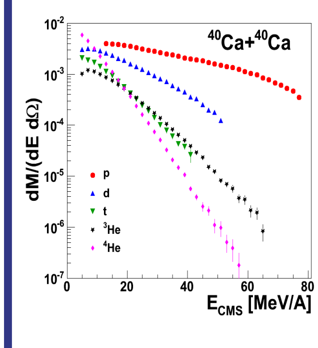


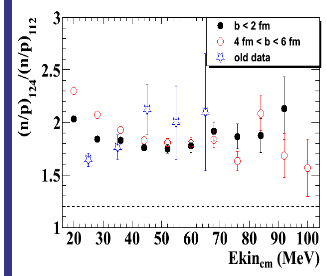
	Energy [MeV/A]	Spectra	n/p (double) ratios	t/^{3}He (double) ratios	Femto-scopy	Flow	Isospin diffusion
^{40,48}Ca+^{40,48}Ca	80						
^{112,124}Sn+^{112,124}Sn	50,120						
^{112,124}Sn+^{48}Ca	140						
^{112,118,124}Sn+^{112,118,124}Sn	30,50,70						

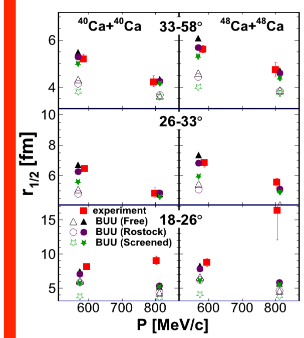
Analysis in progress

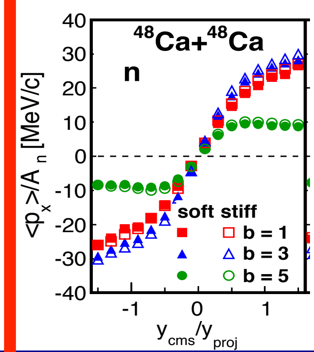
SEP at NSCL: What we hope to learn?

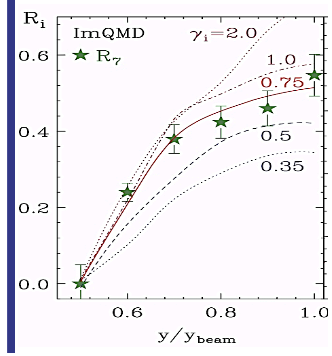
	Spectra	(Double-) ratios	Femtoscopy	Flow	Isospin diffusion
pBUU Transport model ingredients ↓					
Symmetry energy		✔			✔
Cross section	✔	✔	✔	✔	✔
Cluster production	✔	✔	✔	✔	✔



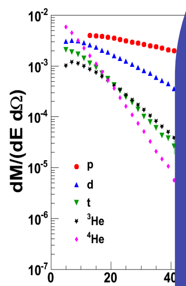






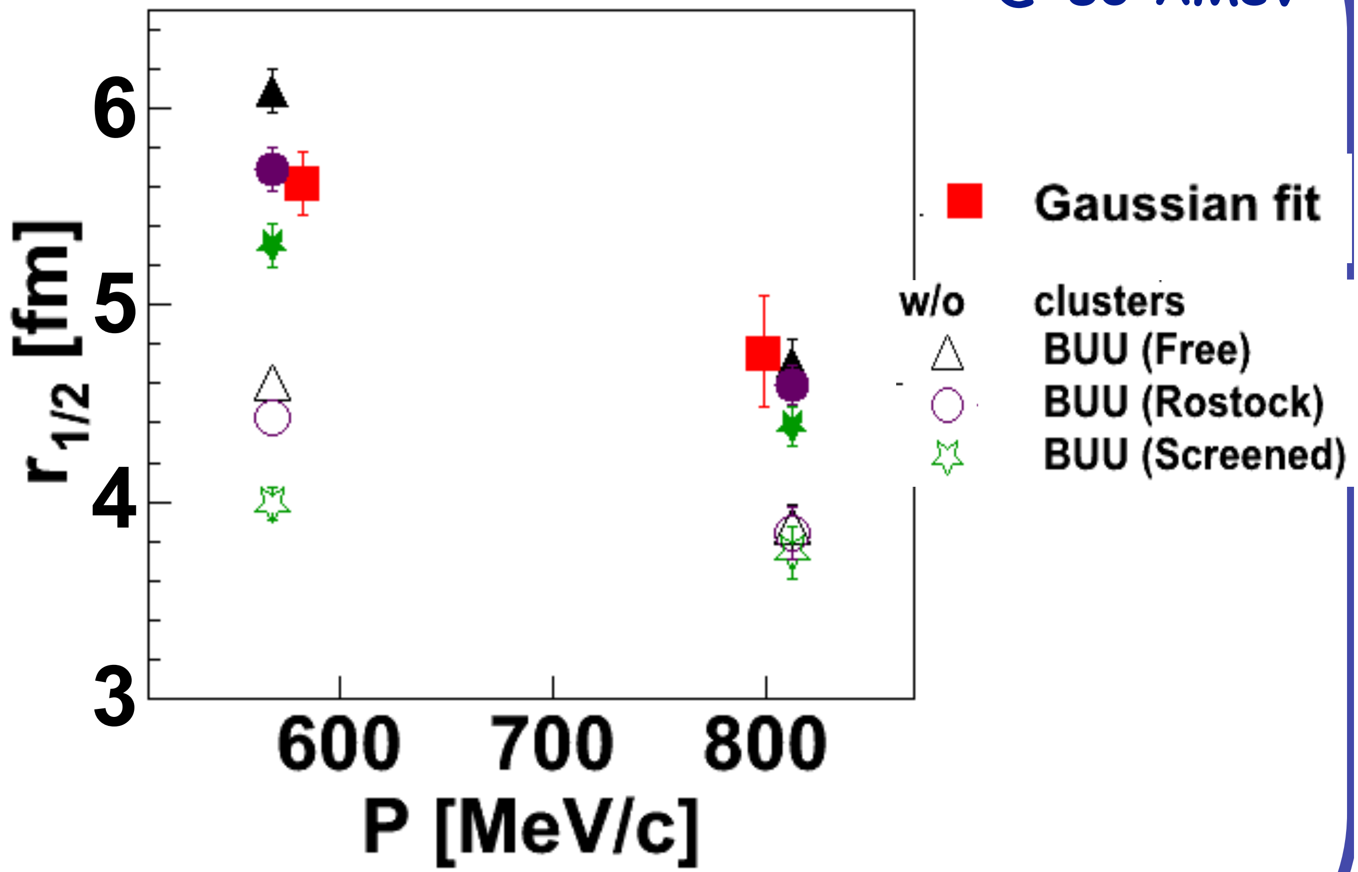


SEP at NSCL: What we hope to learn?

	Spectra
pBUU Transport model ingredients	
Symmetry energy	
Cross section	✔
Cluster production	✔

In this talk,
I will focus on s

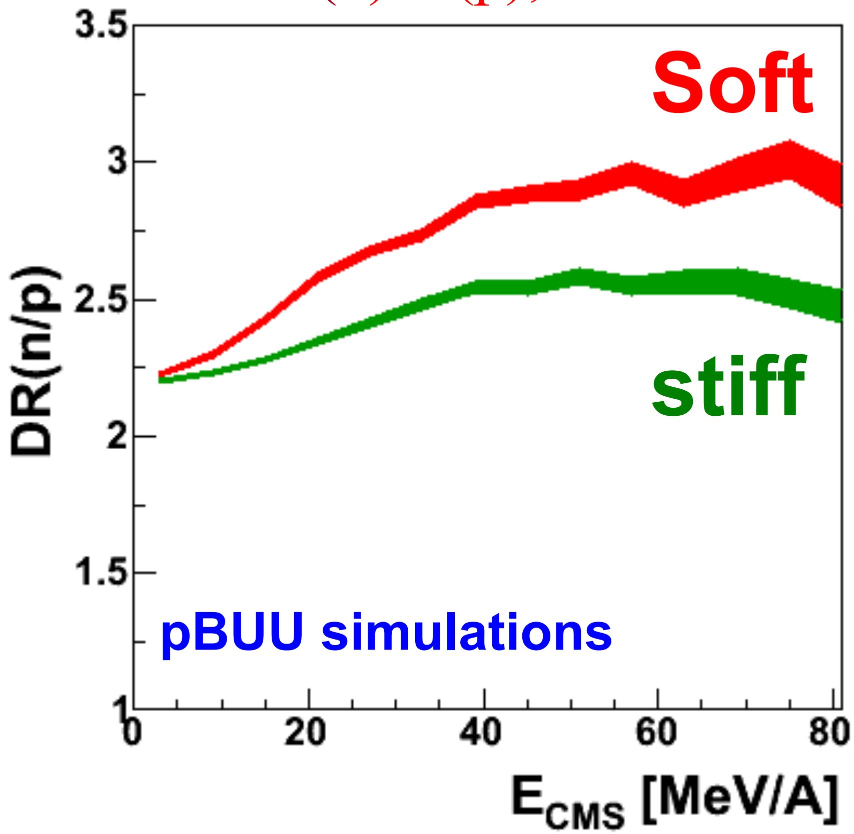
Proton femtoscopy in $^{48}Ca+^{48}Ca$ @ 80 AMeV



Henzl et al., Phys.Rev. C85 (2012) 014606

Sensitive probe: n/p double ratio

$$DR(n/p) = \frac{Y(n)/Y(p);\ ^{48}Ca+^{48}Ca}{Y(n)/Y(p);\ ^{40}Ca+^{40}Ca}$$



Free cross section,
<u>free neutrons and protons</u>
Cluster production included

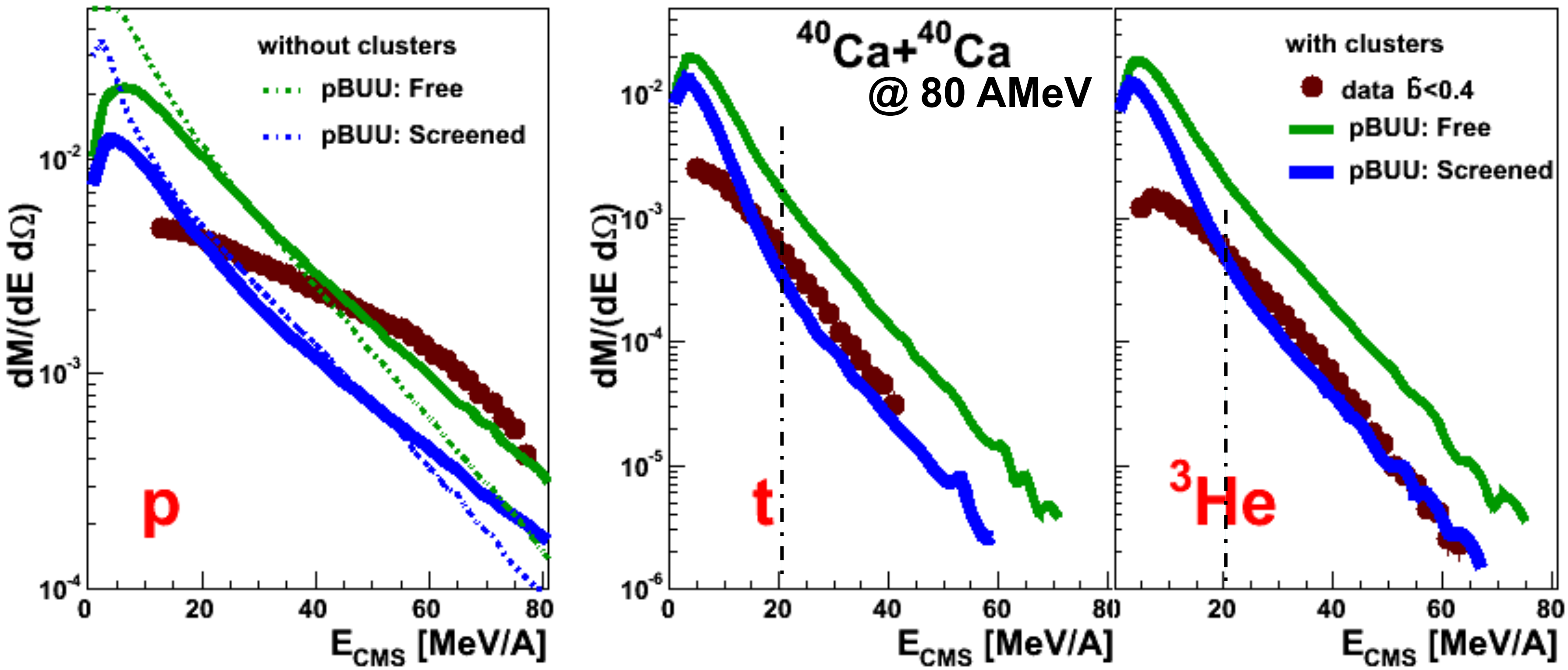
Soft: repulsive (attractive) potential for neutrons (protons) enhances (suppresses) the neutron (proton) emission resulting in **<u>larger</u>** double ratio

Stiff: the magnitude of the repulsive (attractive) potential for neutrons (protons) is smaller thus, the n/p double ratio is **<u>smaller</u>**

- **n/p ~ t/^{3}He ?** easier to detect charge particles
- coalescence?

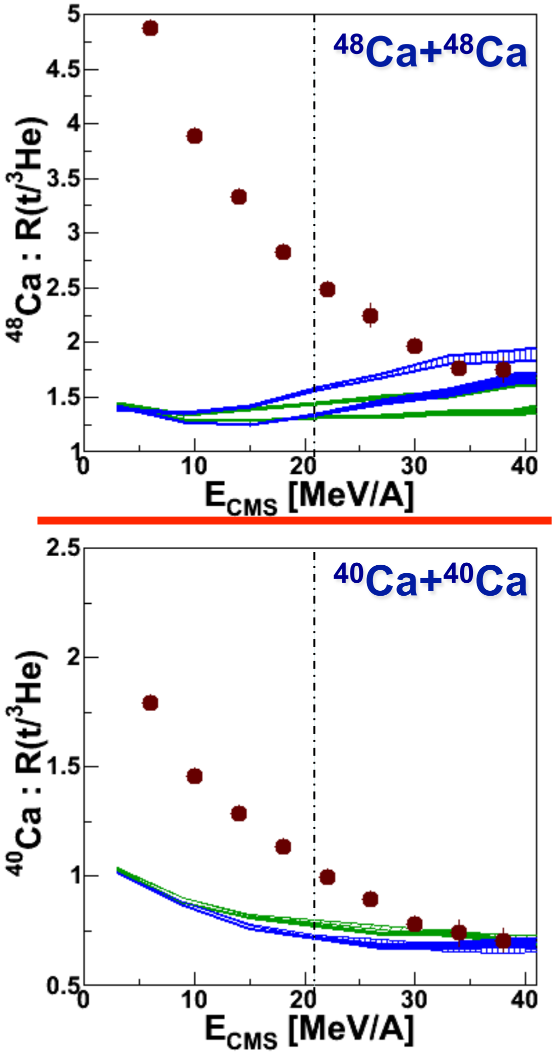
\- used in many theories

Charge particle spectra

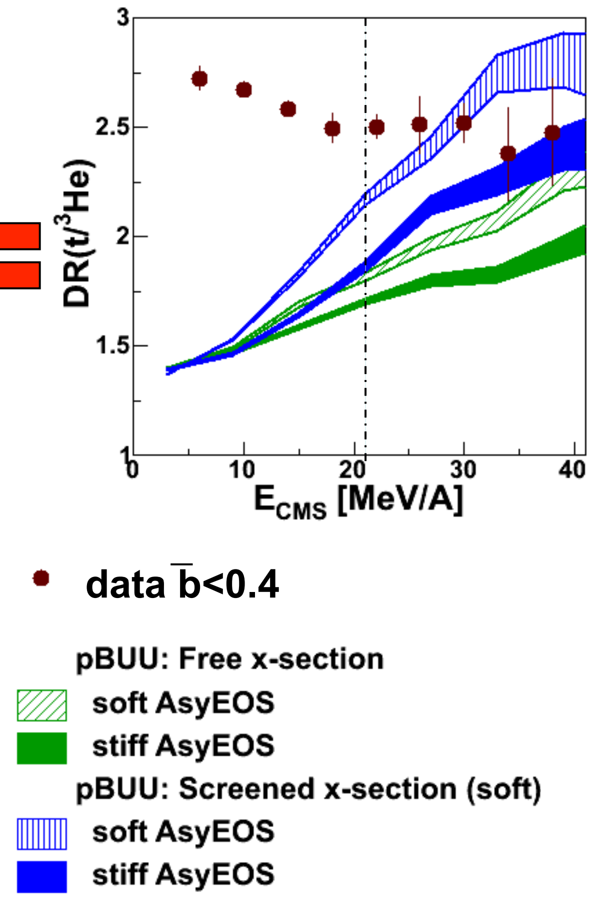


- More particles produced at lower energies in pBUU comparing to experimental results
- Better agreement at E_{CMS} > 20 MeV/A,
  where the phase space density is not high

t/³He (double) ratio $^{40,48}Ca+^{40,48}Ca$ @ 80MeV/u



$$DR(t/^{3}He) = \frac{Y(t)/Y(^{3}He);\ ^{48}Ca+^{48}Ca}{Y(t)/Y(^{3}He);\ ^{40}Ca+^{40}Ca}$$ @80 AMeV

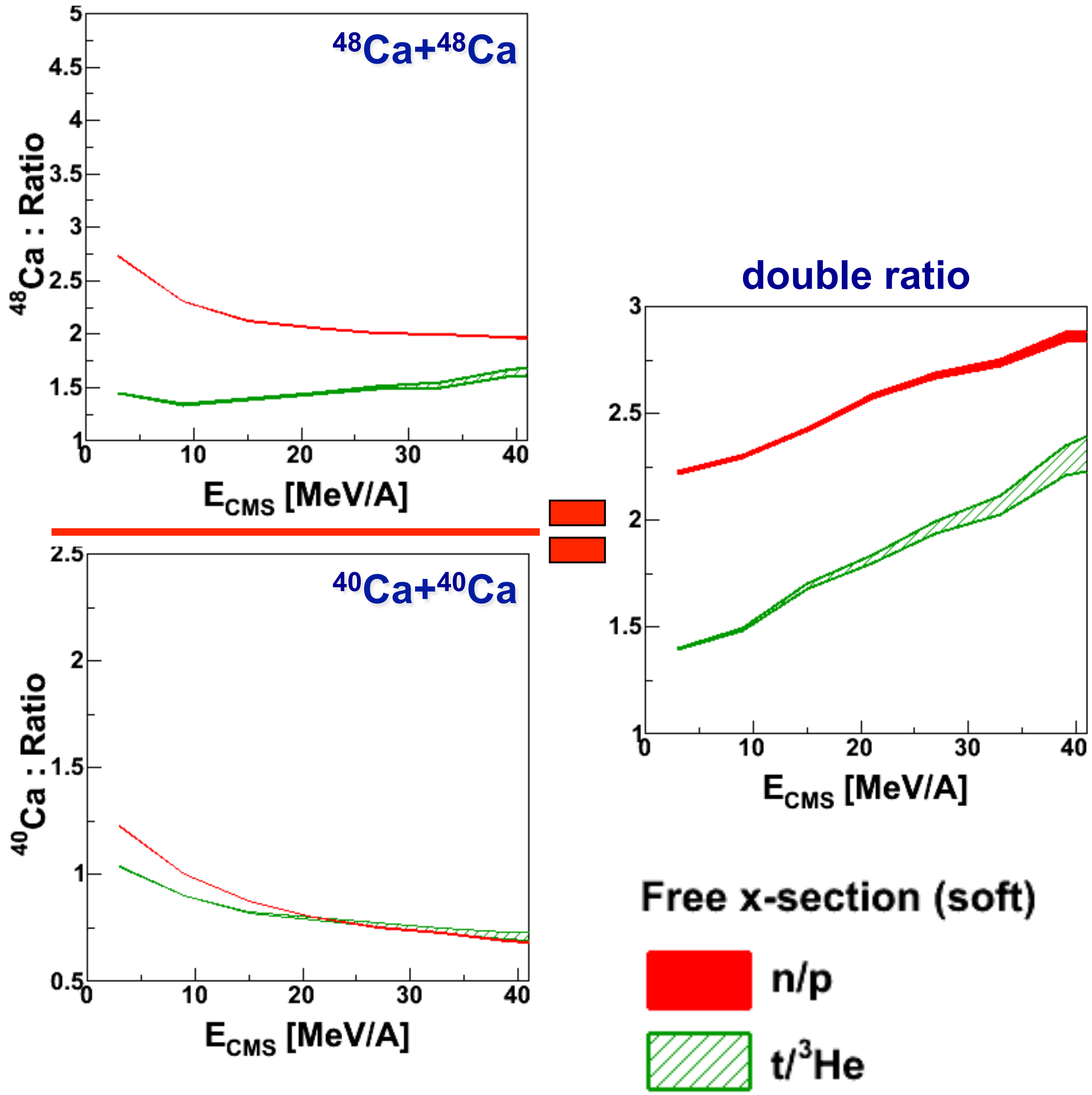


- higher energies are better for comparison
- t/³He (double) ratio sensitive to both the symmetry energy and in-medium cross section

What about comparing t/³He to n/p double ratio in transport model?

Transport model: n/p ≠ t/^{3}He

pBUU simulations



Coalescence doesn't come up

what can be "missing"

in the model?

Charge exchange

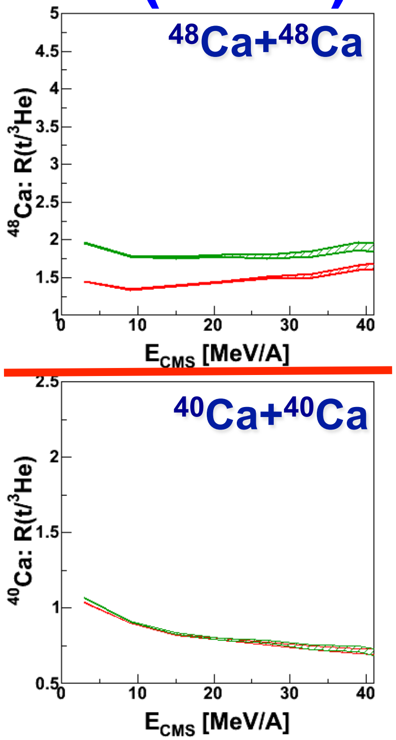
- 50% probability of the charge exchange reaction
- no energy dependence
- same mass for n & p, and t & ^{3}He

(educational purpose)

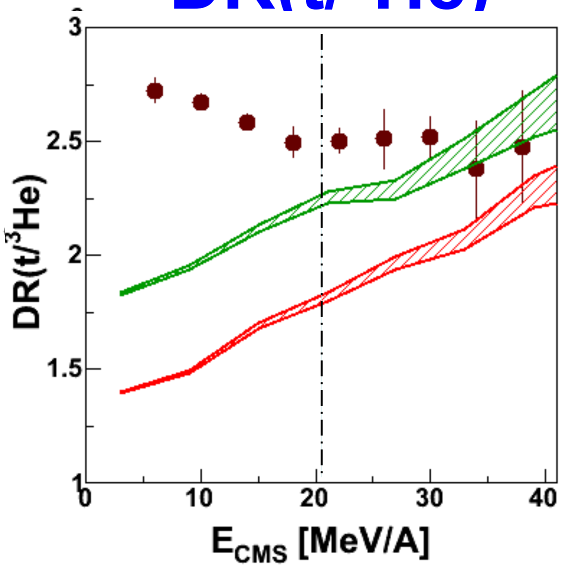
- should have no effect for symmetric system (e.g.^{40}Ca+^{40}Ca) as long as n & p, and t & ^{3}He are emitted at *similar* densities
- expects more p's and t's produced in n-rich in the charge exchange reaction **=> should affect both n/p and t/^{3}He (double-) ratios**

Charge exchange : n/p and t/^{3}He

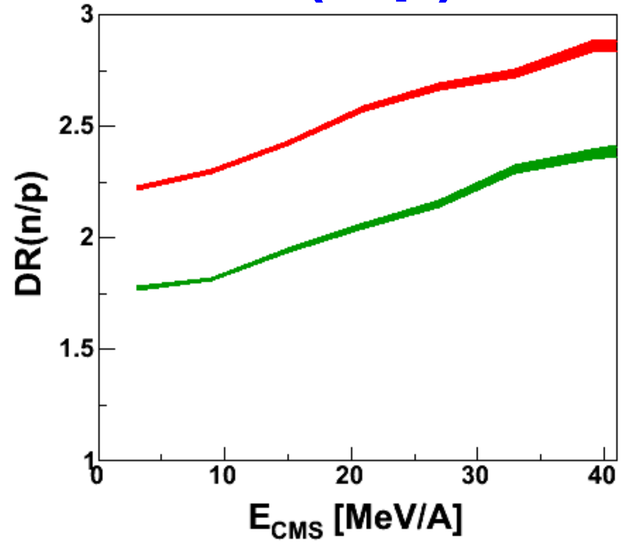
R(t/^{3}He)



DR(t/^{3}He)



DR(n/p)



pBUU: Free x-section

without charge exchange

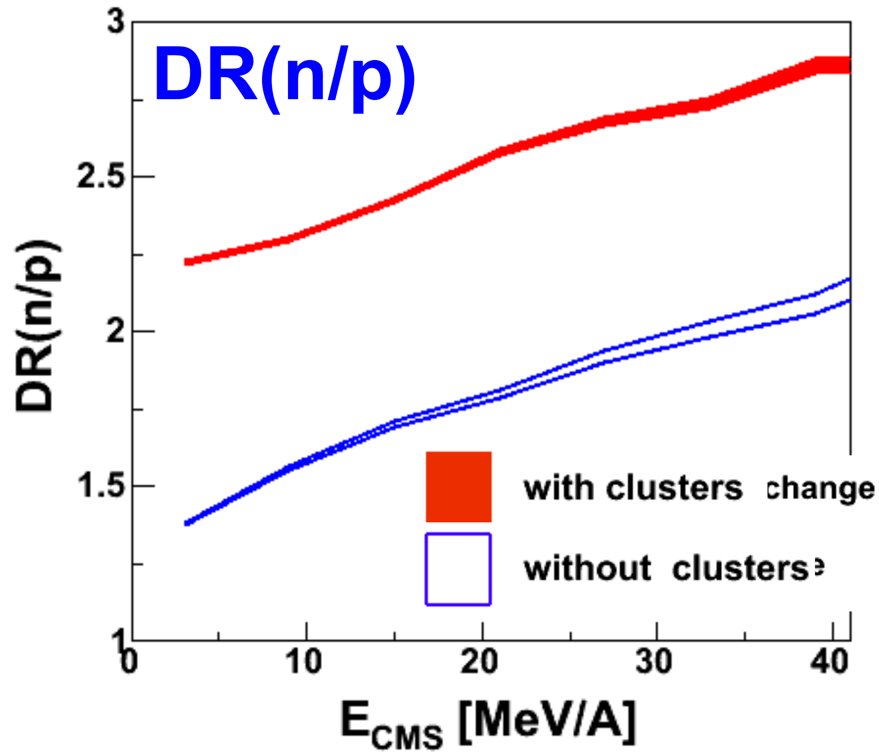
Including charge exchange reaction

- has an opposite effect on t/^{3}He and n/p double ratio
- improves comparison to the model

Cluster production & n/p double ratio

Do we need to include the cluster production?

Why not just do coalescence?



Yes, we need to include the cluster production,

as n/p double ratio is strongly sensitive to the cluster production

(as well as charge exchange and symmetry energy)

Summary

- Finding constraints on symmetry energy relies on comparison of the experimental observables to the theoretical calculations
- However, not only the effect of symmetry energy is not fully understood; importance of
  - cluster production
  - cross section
  - charge exchange reaction
- Need systematic studies of the models – that's why we need such a wide range of observables and measurements
- Understand the differences between theoretical models

Collaborators

*V. Henzl, M. Kilburn, D. Henzlova, **W.G. Lynch**, D. Brown, **D. Coupland, P. Danielewicz**, C. Herlitzius, R. Hodges, A. Rogers, A. Sanetullaev, J. Lee, **B. Tsang**, A. Vander Molen, M. Wallace, J. Winkelbauer, **M. Youngs**, Y. Sun, G. Verde, Z.S. Hudan, M. Famiano, R. deSouza, A. Chbihi, S. Lukyanov, L. Sobotka*

Thank you.