Using heavy-ion collisions to determine asymmetry dependence of nuclear energy and effective mass

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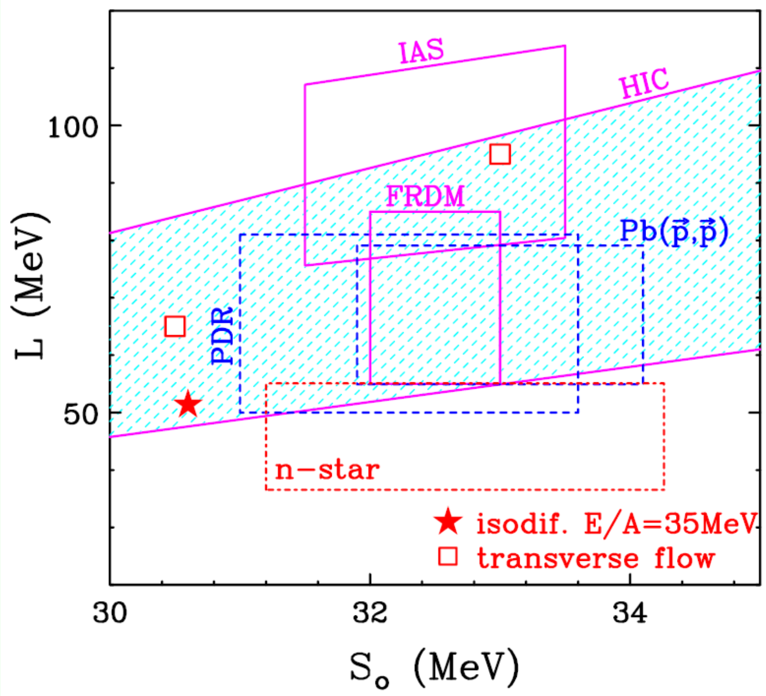
Outline

- **Introduction**
  - EOS, symmetry energy
- **Input from theory:**
  - sensitivity to symmetry energy and effective mass
- **Our experiment**
  - n/p and t/^{3}He (double-) ratios
- **Theory vs data**
  - pBUU and ImQMD



Tsang et al. PRC 86, 015803 (2012)

EOS and Symmetry Energy

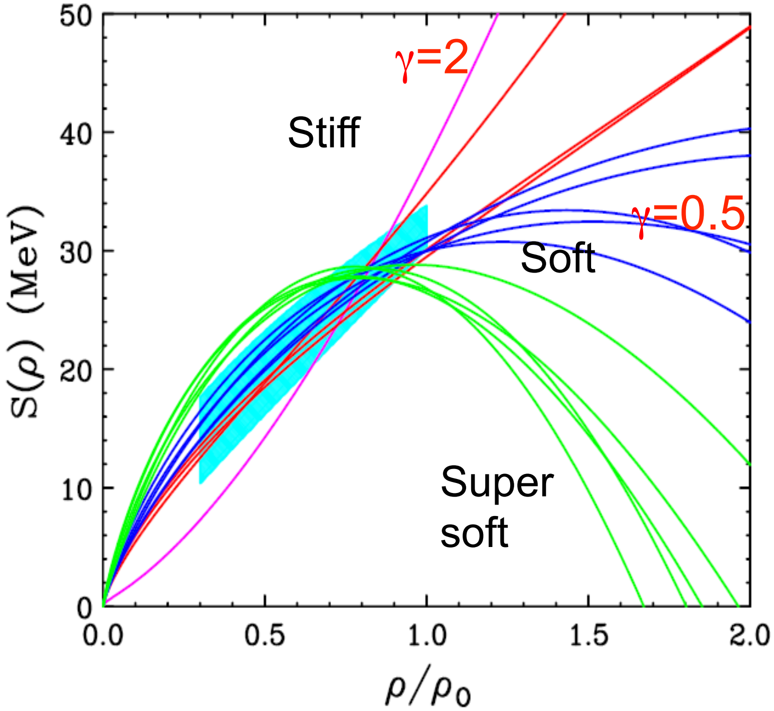
$$E/A(\rho,\delta) = E/A(\rho,0) + \delta^2 \cdot S(\rho)$$

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

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

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

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

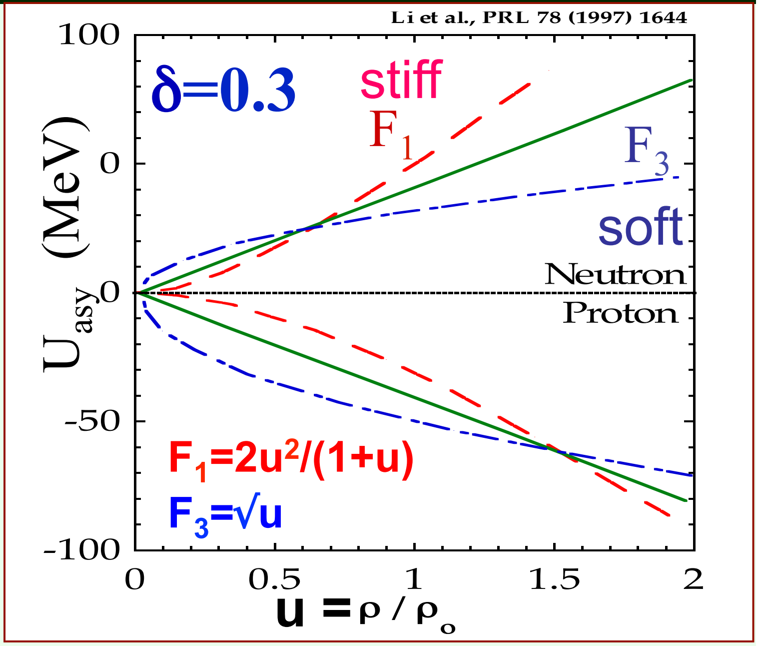


$$S(\rho) = S_k(\rho/\rho_0)^{2/3} + S_i(\rho/\rho_0)^{\gamma}$$

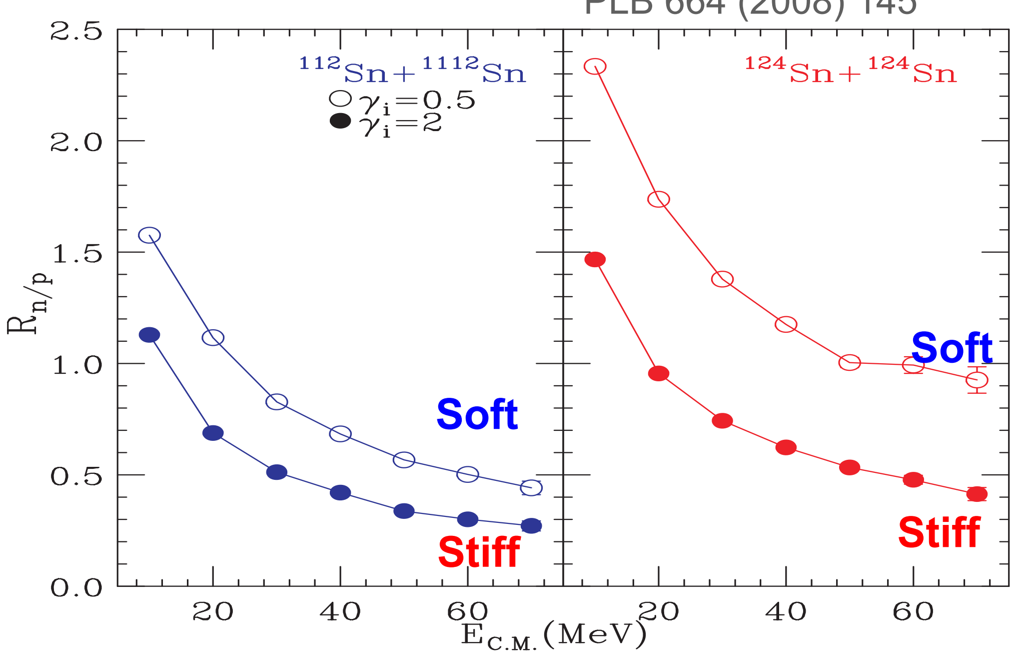
Reaction probes: isospin multiplets

Observables:

- Neutron vs. proton emission and flow
- Pion production
- Correlations
- Isospin transport ratios
- ….



PLB 664 (2008) 145



n and **p** potentials have opposite signs and slightly different density dependence

Soft: repulsive (attractive) potential for neutrons (protons) enhances (suppresses) the neutron (proton) emission ➔ **larger** double ratio

Stiff: the magnitude of the repulsive (attractive) potential for neutrons (protons) ➔ **smaller** double ratio

Reaction probes: isospin multiplets

Observables:

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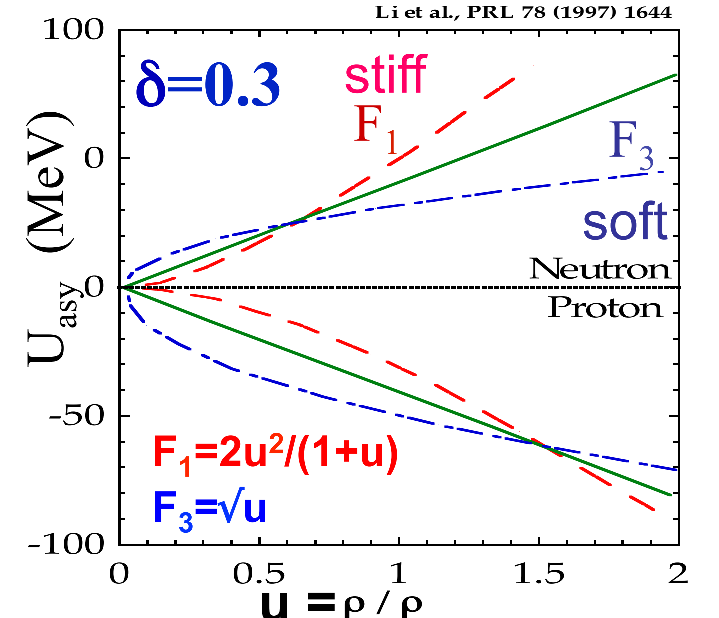
- ….



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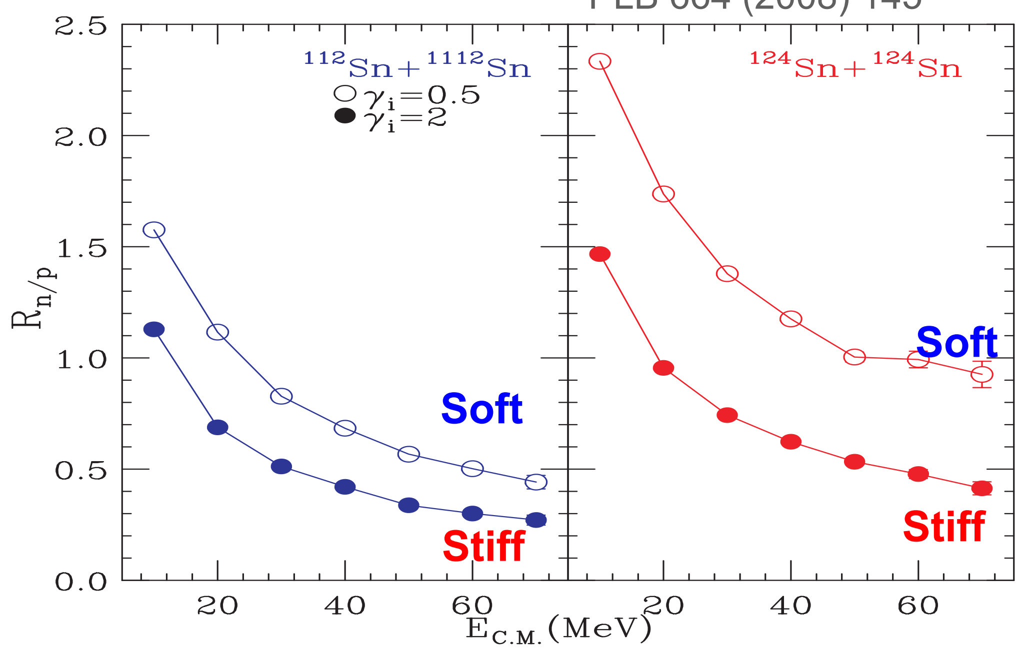
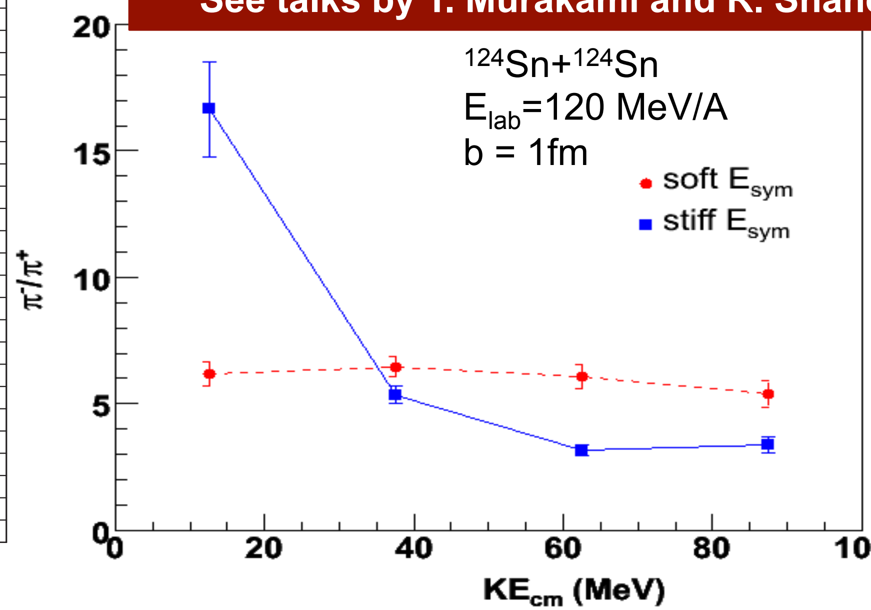


See talks by T. Murakami and R. Shane



Reaction probes: isospin multiplets

Observable

- Neutron vs. proto
- Pion production
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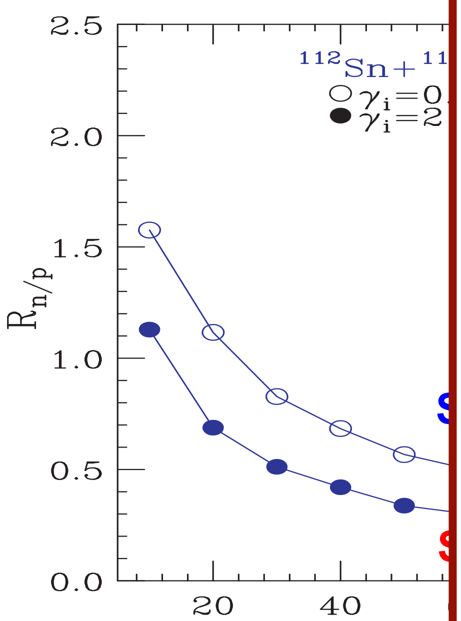
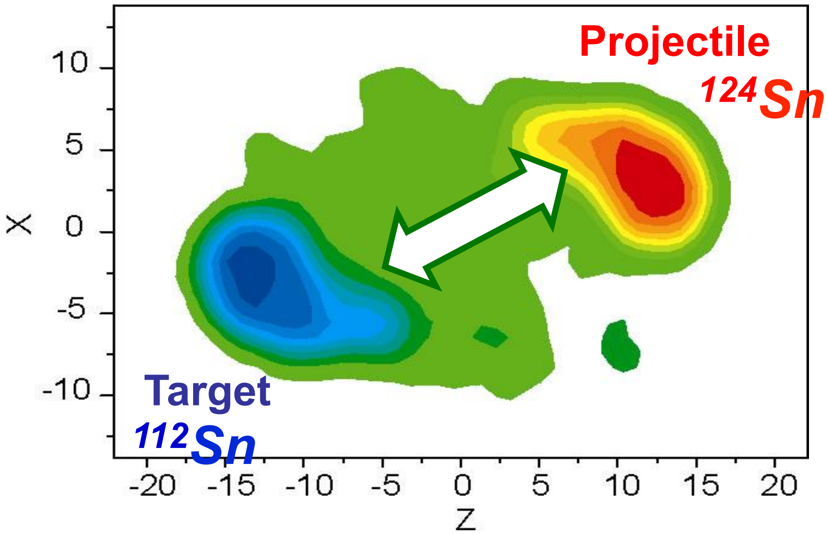
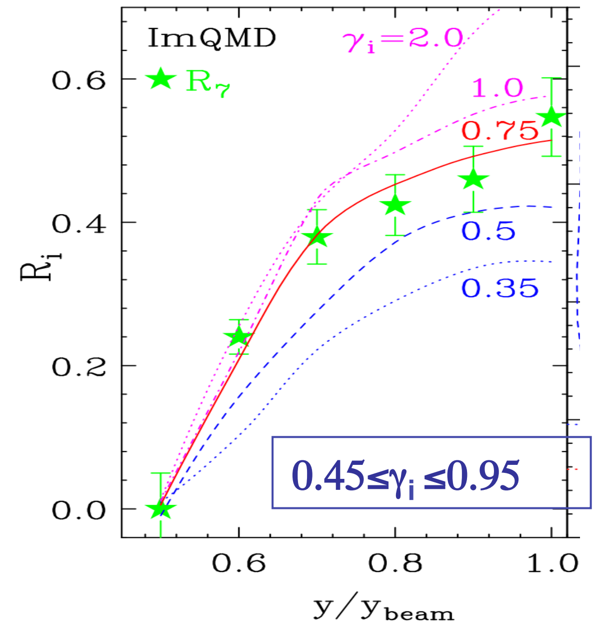
- Isospin transport
- ….



Isospin Diffusion





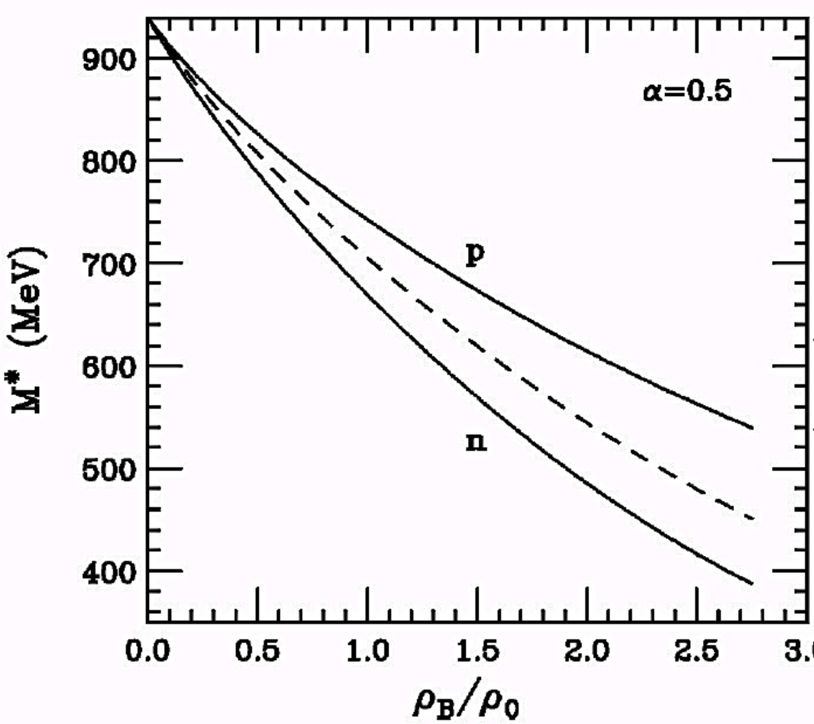
$$R_i(\delta_{AB}) = 2\cdot\frac{\delta_{AB}-(\delta_{AA}+\delta_{BB})/2}{\delta_{AA}-\delta_{BB}}$$

$R_i = \pm 1$ no diffusion
$R_i = 0$ equilibration

mixed $^{124}Sn+^{112}Sn$
n-rich $^{124}Sn+^{124}Sn$
p-rich $^{112}Sn+^{112}Sn$

See poster by R. Hodges

Influence of effective mass



B. Liu et al. PRC 65(2002)045201

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

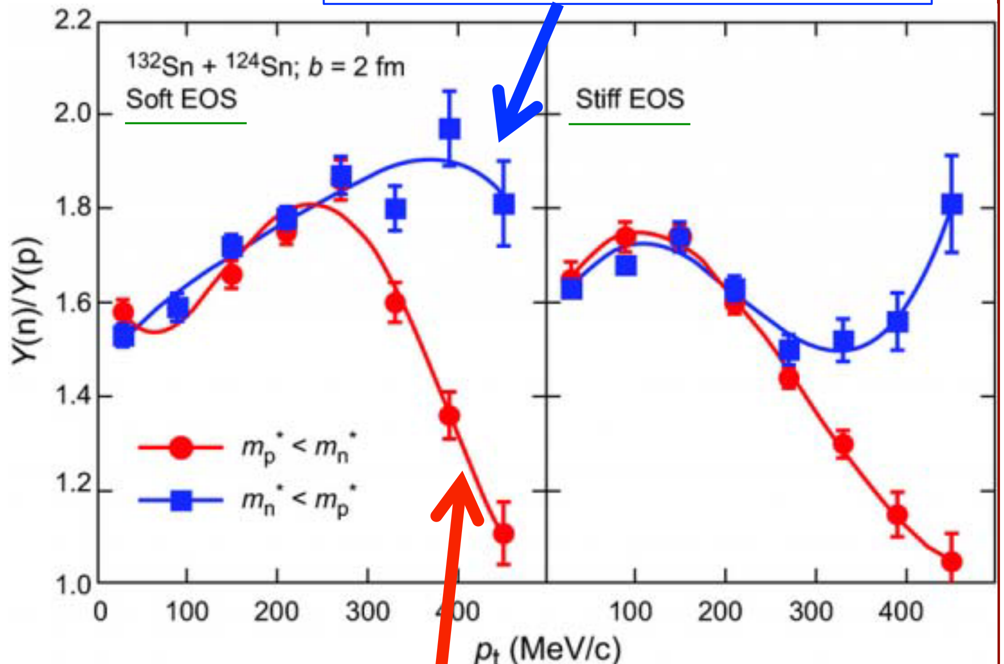
$$\text{if } U_{sym} = U_{sym}\left(\rho, \upsilon^2\right)$$

$$\frac{d\upsilon}{dt} = \frac{\nabla U}{m^*}$$

Transport simulations: $^{132}Sn+^{124}Sn$

J. Rizzo et al, Phys. Rev. C72, 064609 (2005)

$m^*_n<m^*_p$ - more neutrons accelerated to high energies



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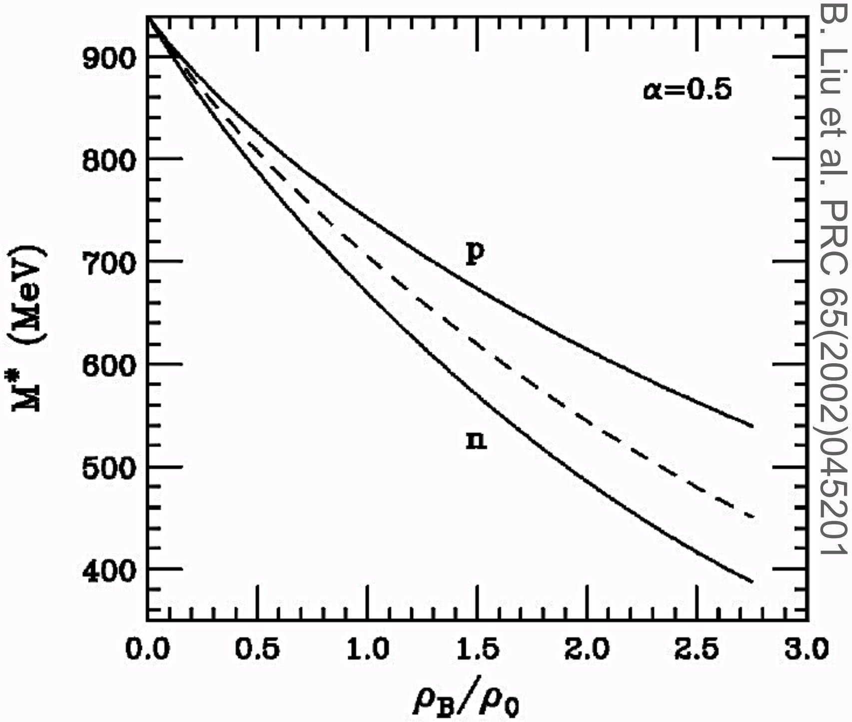
Influence of effective mass



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+ mean field

$$\text{if } U_{sym} = U_{sym}\left(\rho, \upsilon^2\right)$$

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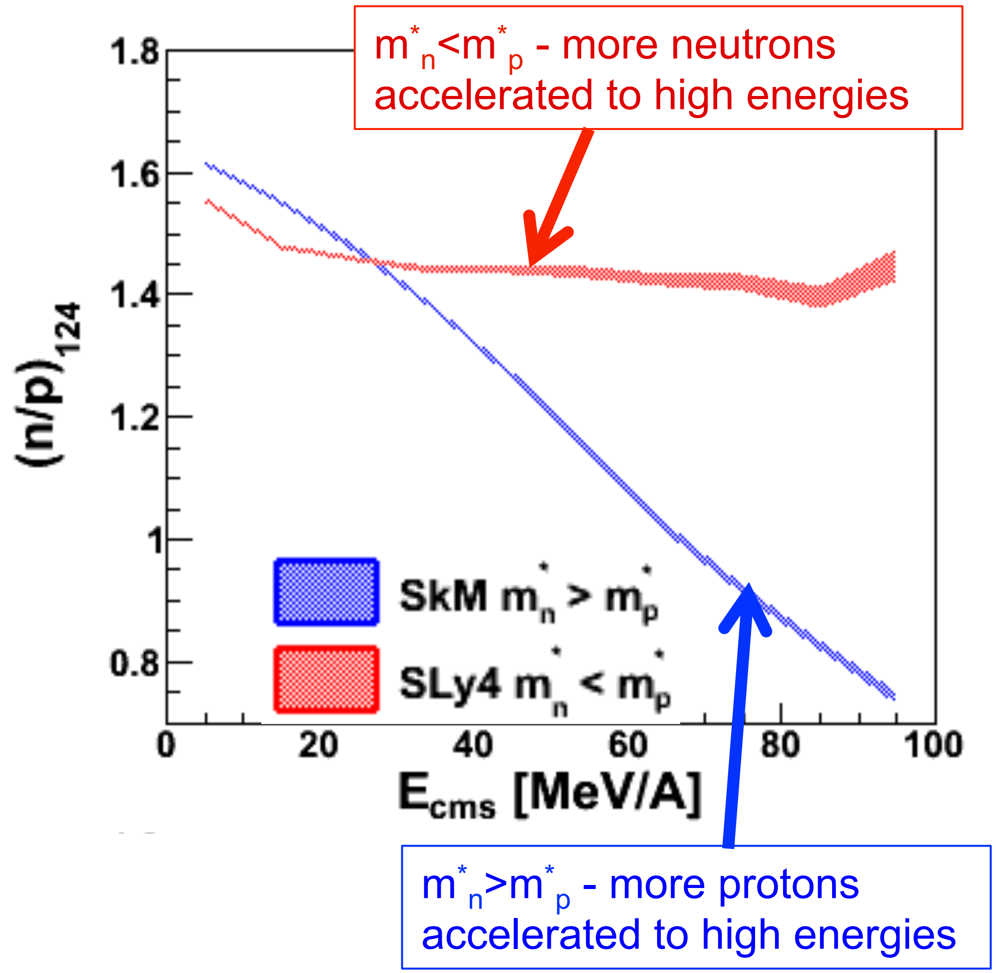
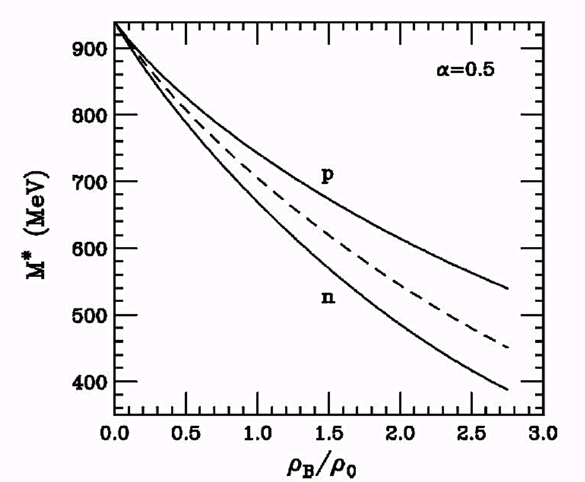
ImQMD simulations: $^{124}Sn+^{124}Sn$ @ 120 MeV/A



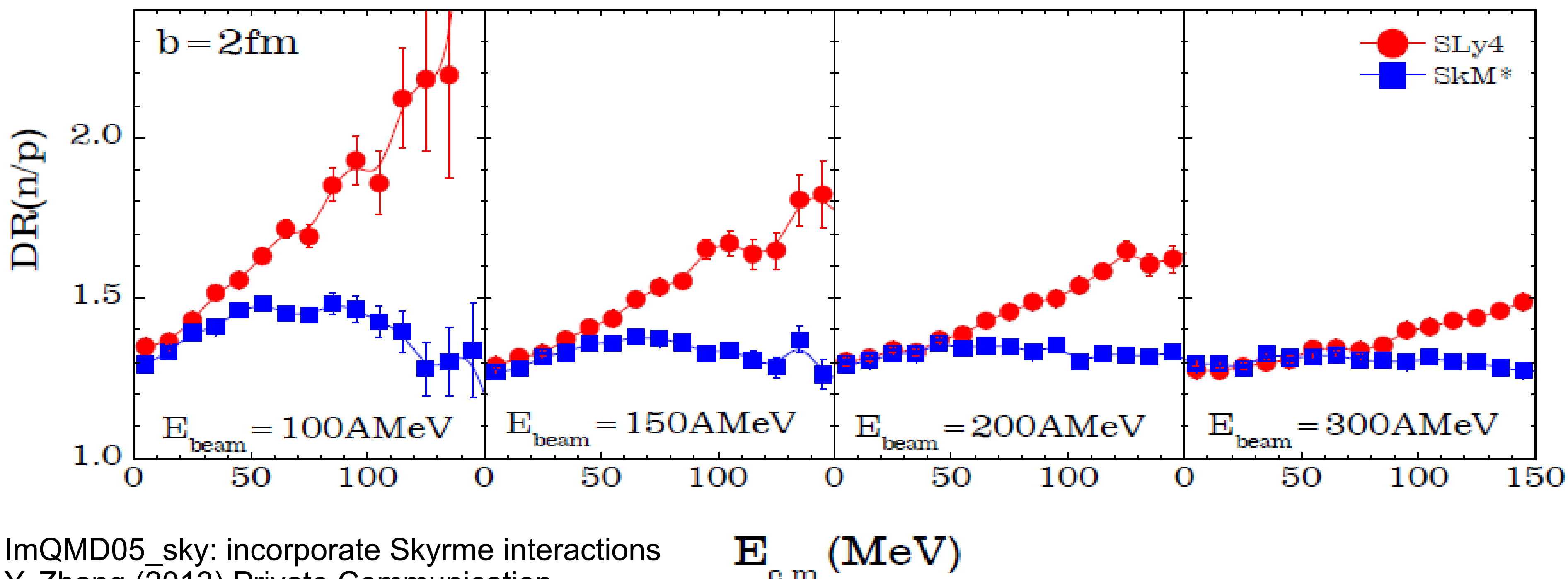
ImQMD: Nucleon Effective Masses



$S(\rho)=12.7(\rho/\rho_o)^{2/3} + 19(\rho/\rho_o)^{\gamma_i}$ + mean field in ImQMD05

ImQMD05_sky: incorporate Skyrme interactions

Skyrme	S_0(MeV)	L (MeV)	m_n^*/m_n	m_p^*/m_p	Δm_{n-p}
SLy4	32	46	0.68	0.71	-0.03
SkM*	30	46	0.82	0.76	+0.06

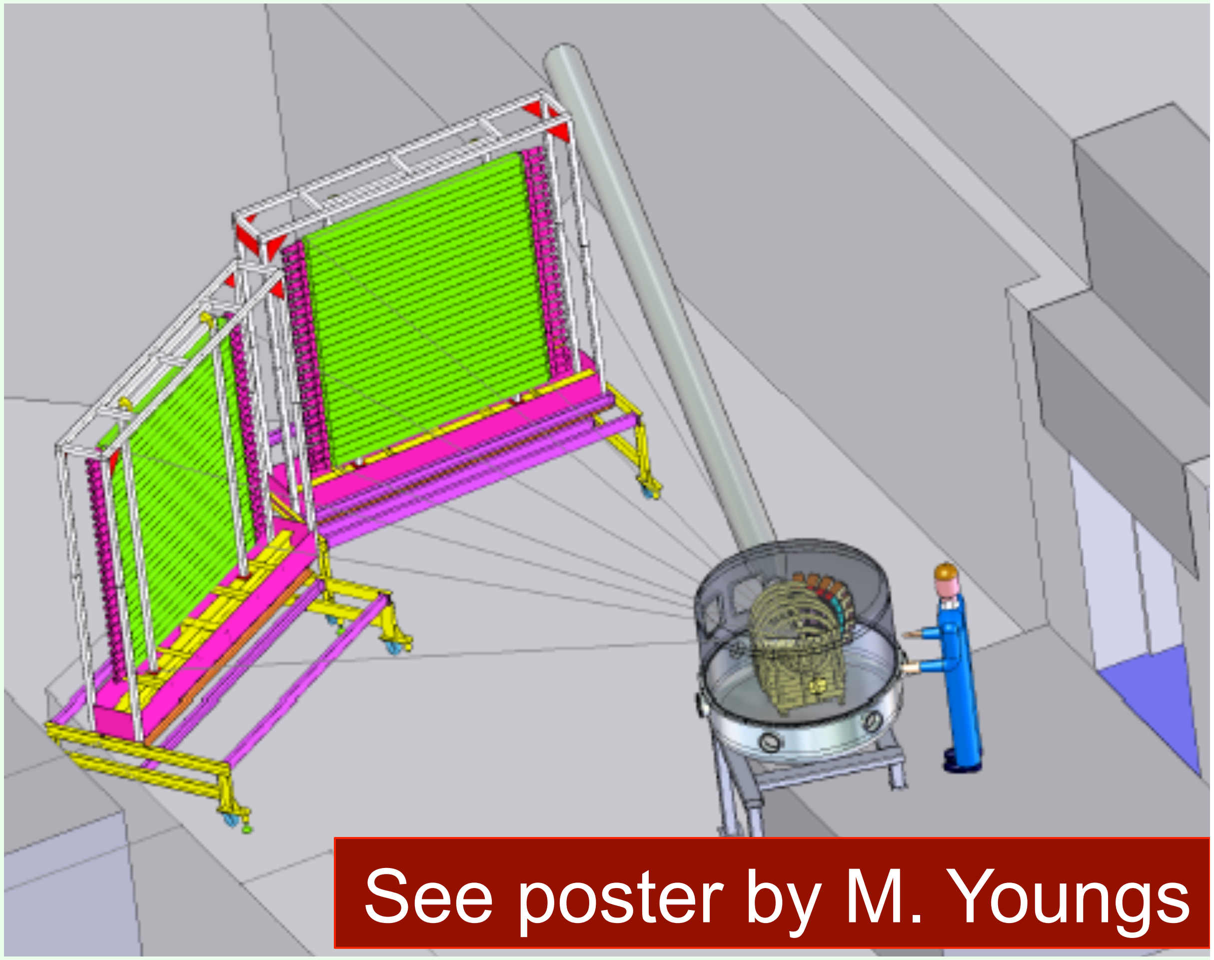


ImQMD05_sky: incorporate Skyrme interactions
Y. Zhang (2013) Private Communication
Tsang (2013) Private Communication

Experiment

$^{112}Sn+^{112}Sn$ and $^{124}Sn+^{124}Sn$ at 50 and 120 MeV/A

measure emitted neutrons, protons and light clusters from central collisions



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

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

^{112}Sn: $\delta = 0.108$

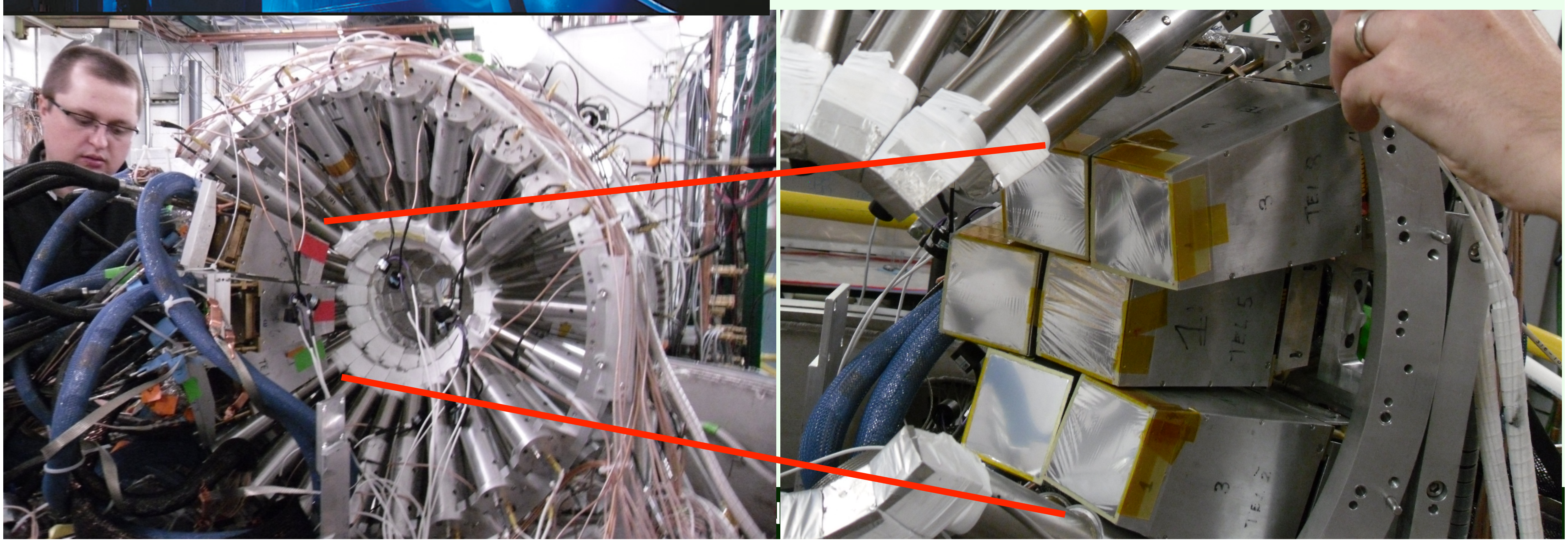
^{124}Sn: $\delta = 0.194$

e09042 NSCL: PhD Thesis Experiment Coupland & Youngs

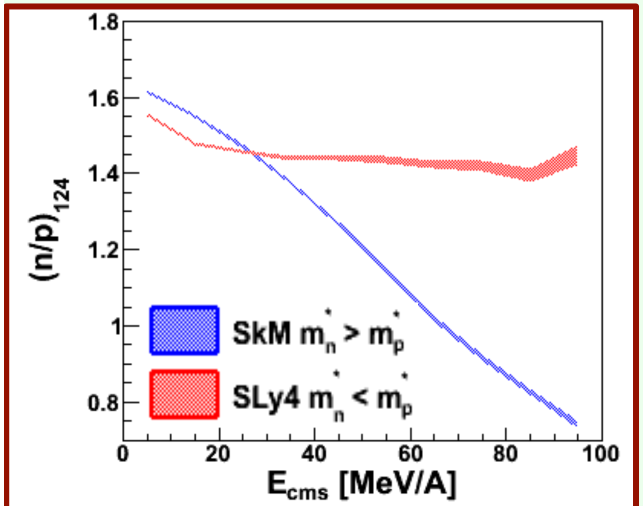
Experiment

5 detector systems:

- Neutron wall
- Miniball
- LASSA – Si Array
- Proton Vetos
- Forward Array



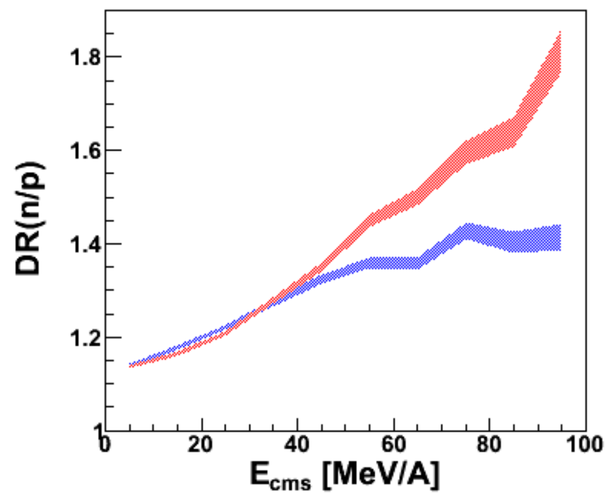
Our observables

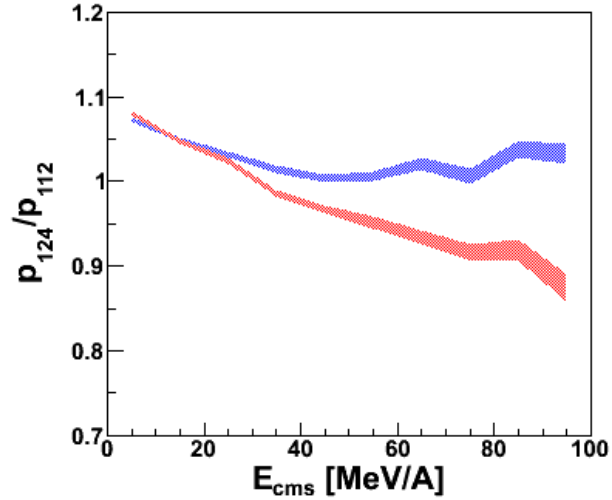


$$R(n/p) = \frac{Y(n)}{Y(p)}$$

Caveat:

- neutron measurements have known efficiency ~10%
- Effects we are going to measure are often of the same order





$$DR(n/p) = \frac{Y(n)/Y(p)\text{: asym}}{Y(n)/Y(p)\text{: sym}}$$

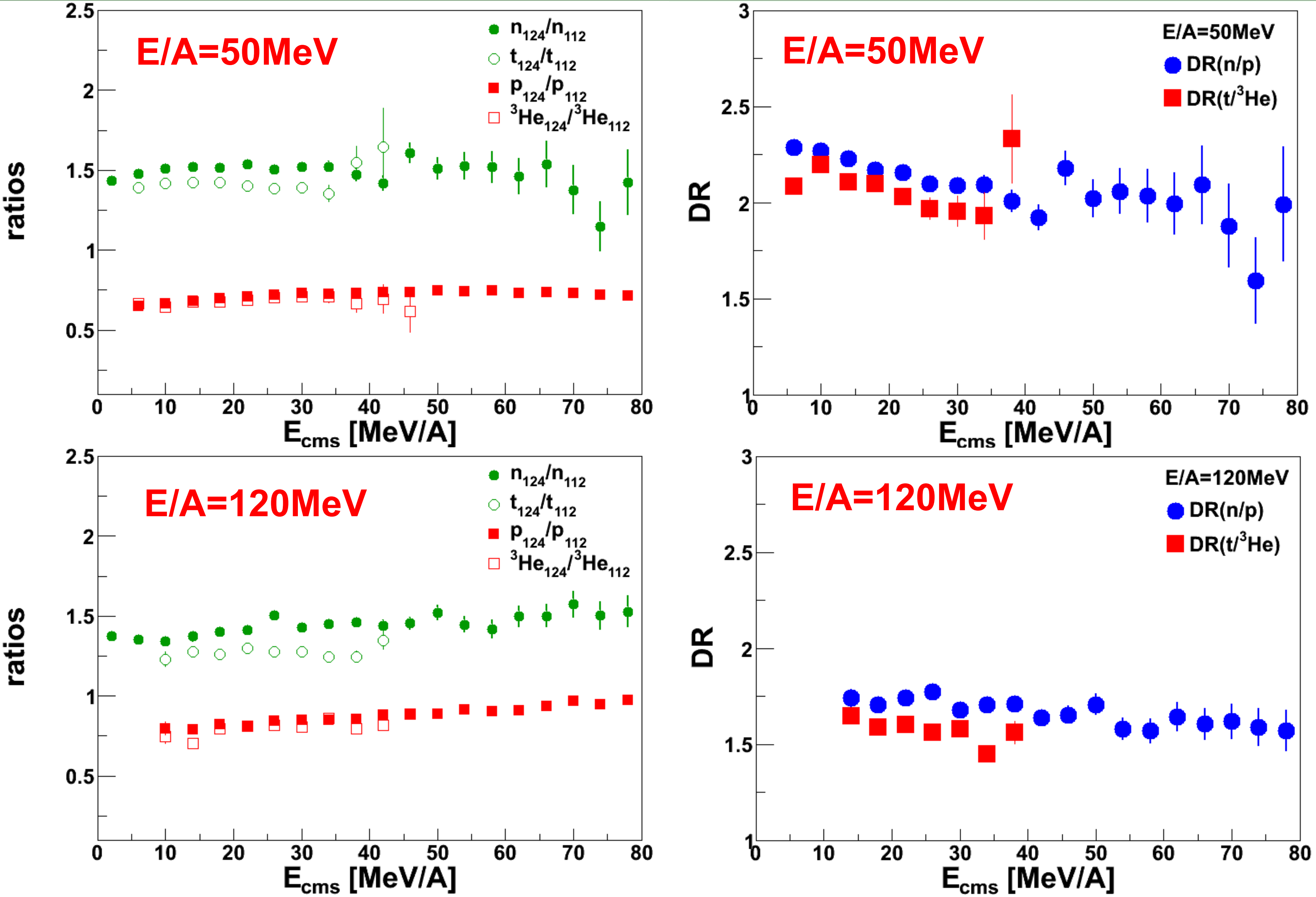
$$R(x/x) = \frac{Y(x)\text{: asym}}{Y(x)\text{: sym}}$$

e.g. x=p,n,t,...

Advantages:

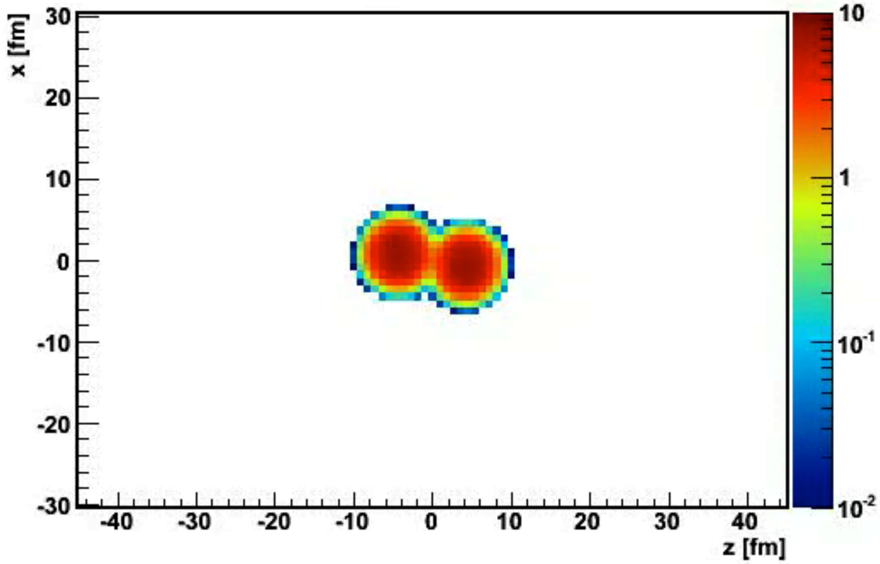
- reduce systematic uncertainties
- reduce differences in energy calibration
- Coulomb “cancels out”

Our experiment: particle ratios



Transport models

- BUU - Boltzmann-Uehling-Uhlenbeck
- QMD – Quantum Molecular Dynamics
- Simulates the time-dependent evolution of the collision



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

Danielewicz, Bertsch, NPA533 (1991) 712

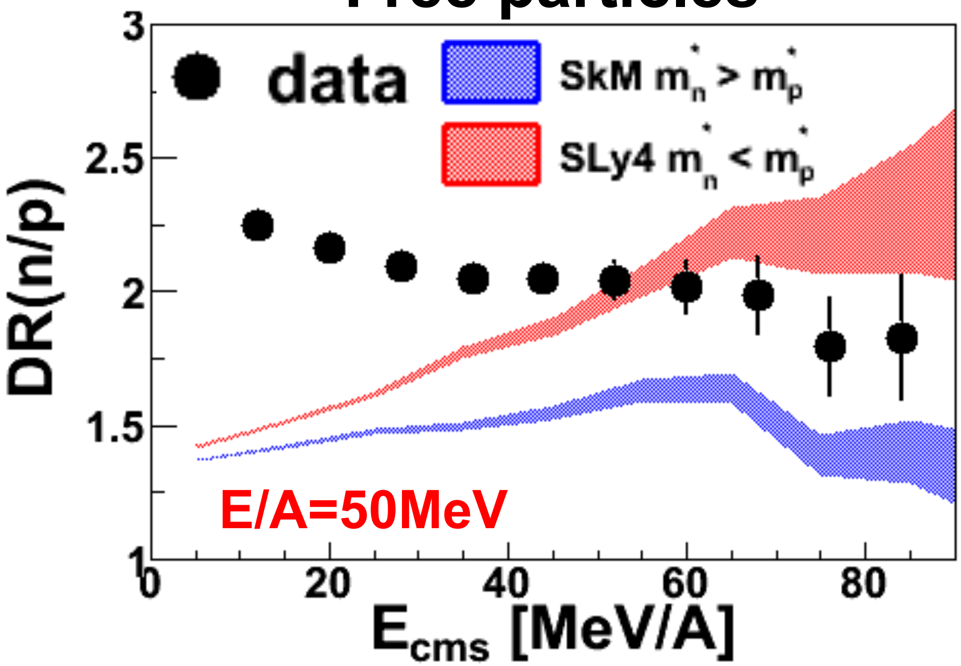
Main ingredients

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

We don't intend to fit our experimental data with theory.
Instead, we want to look for systematics in theory that may help us understanding the experimental data

ImQMD – effective mass

Free particles



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

ImQMD05_sky: incorporate Skyrme interactions
Y. Zhang (2013) Private Communication
Tsang (2013) Private Communication

ImQMD:

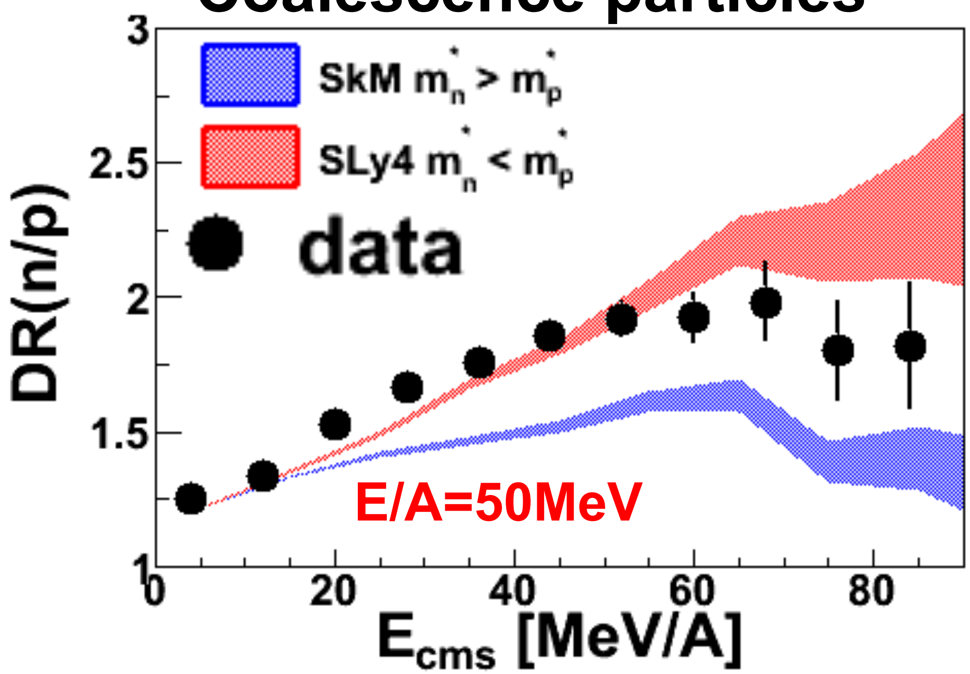
- Cluster production for alphas is not realistic
- *Possible solution:* Ignore the cluster production mechanism and look all the light particles (neutrons and protons) at a given velocity

Coalescence invariance:

- Coalescence protons (neutrons): Include protons (neutrons) from within clusters with the free proton (neutron) spectra
- Possibly a better match between simulation and experimental data

ImQMD – effective mass

Coalescence particles



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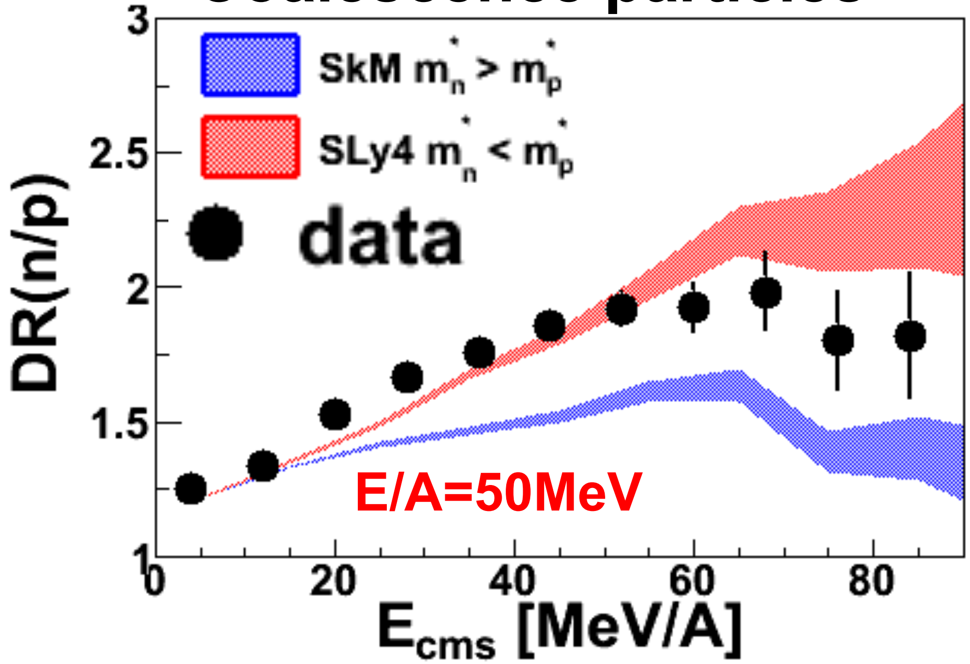

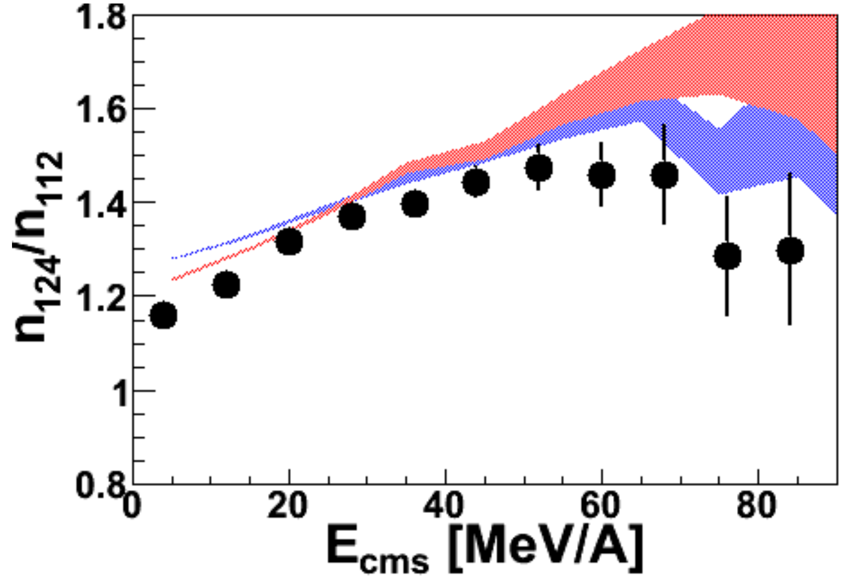

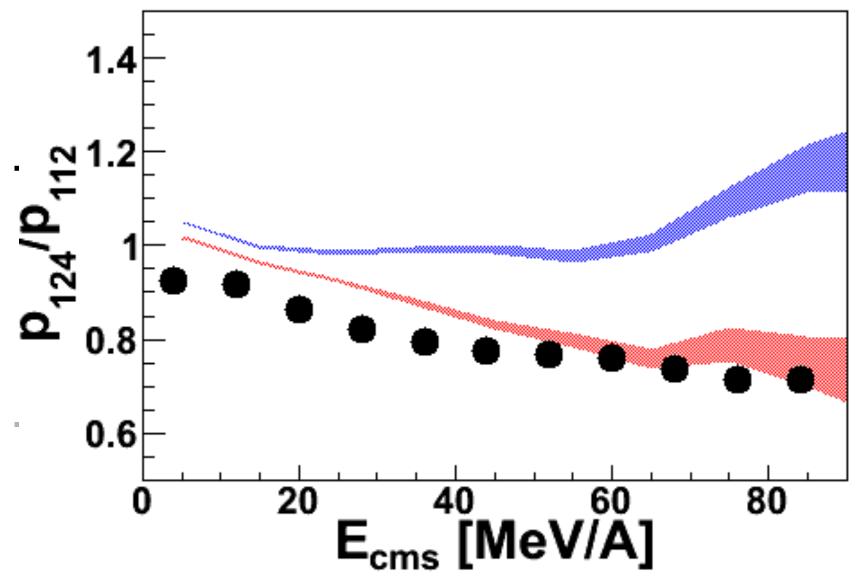

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Y. Zhang (2013) Private Communication
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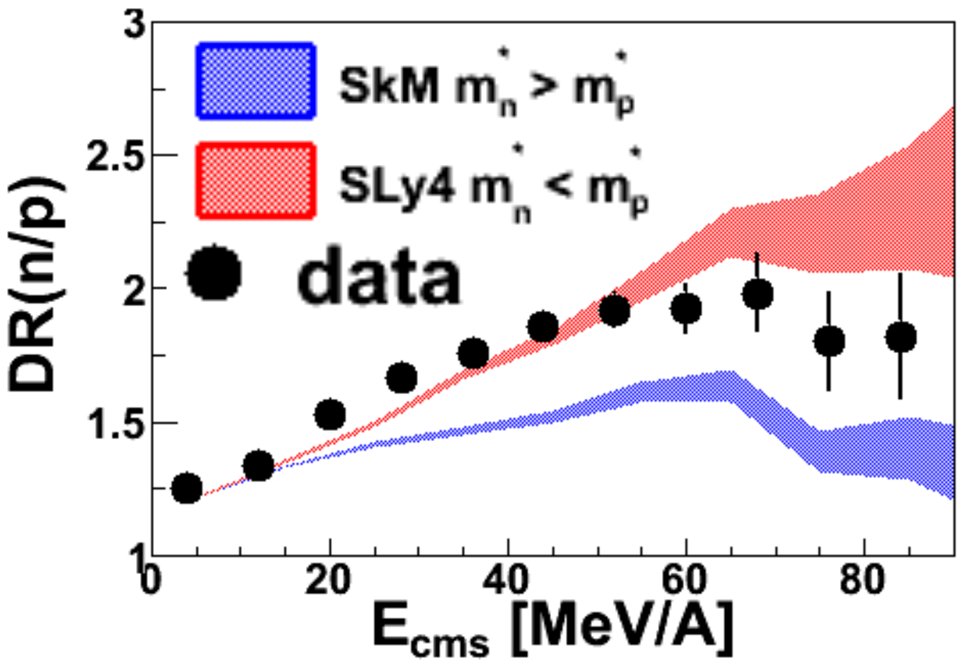
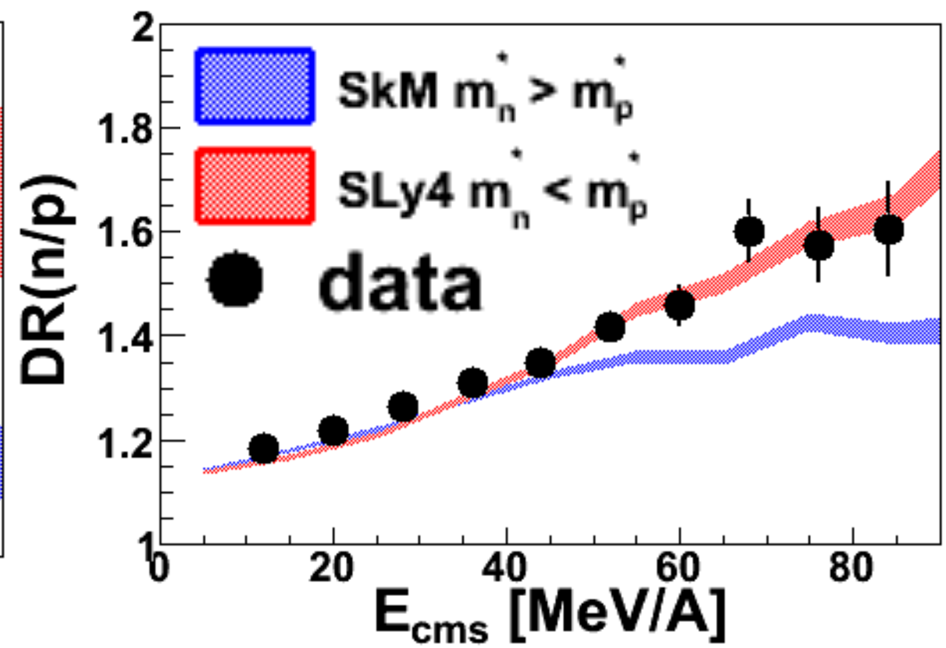
ImQMD - effective mass

Energy dependence

E/A=50MeV



E/A=120MeV



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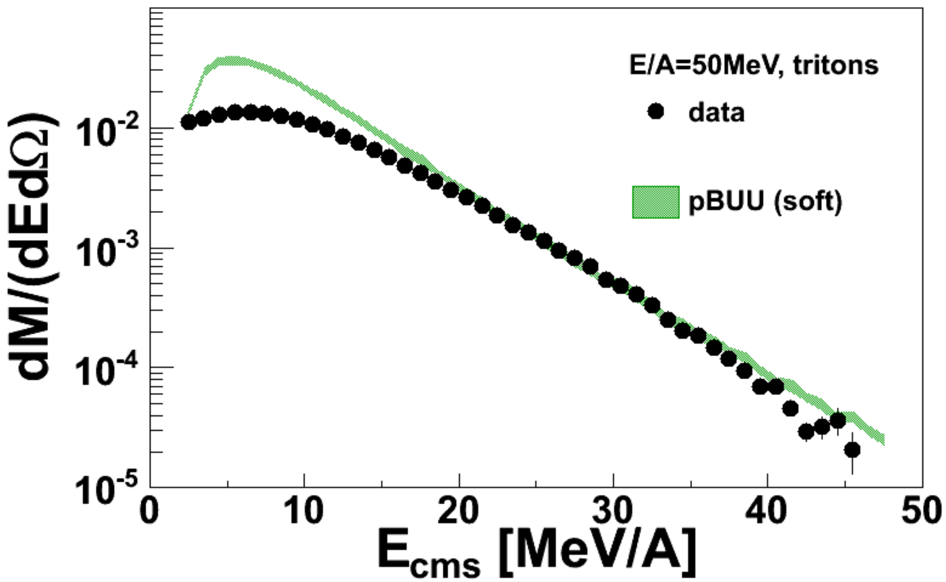
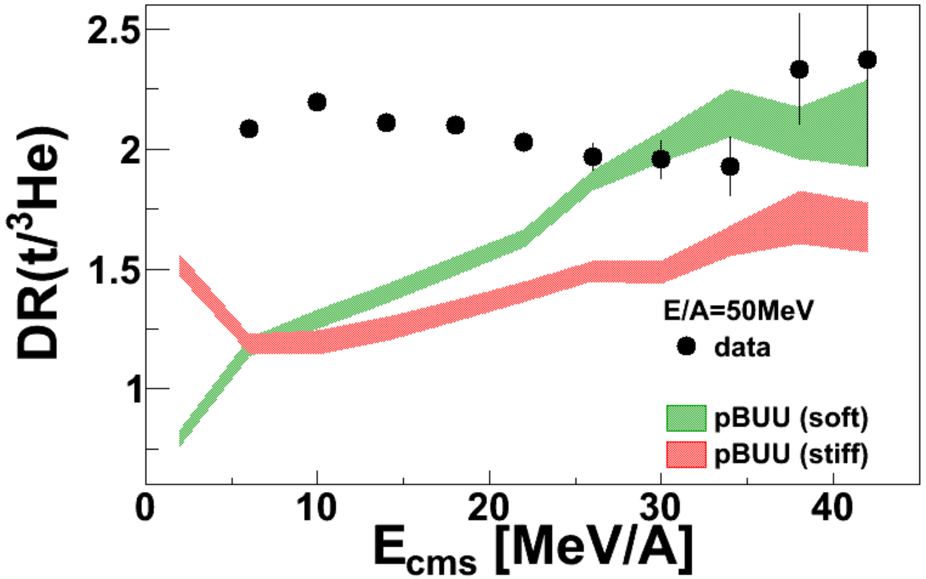
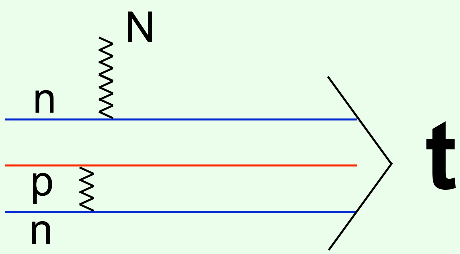
Coalescence ratios

pBUU: light clusters

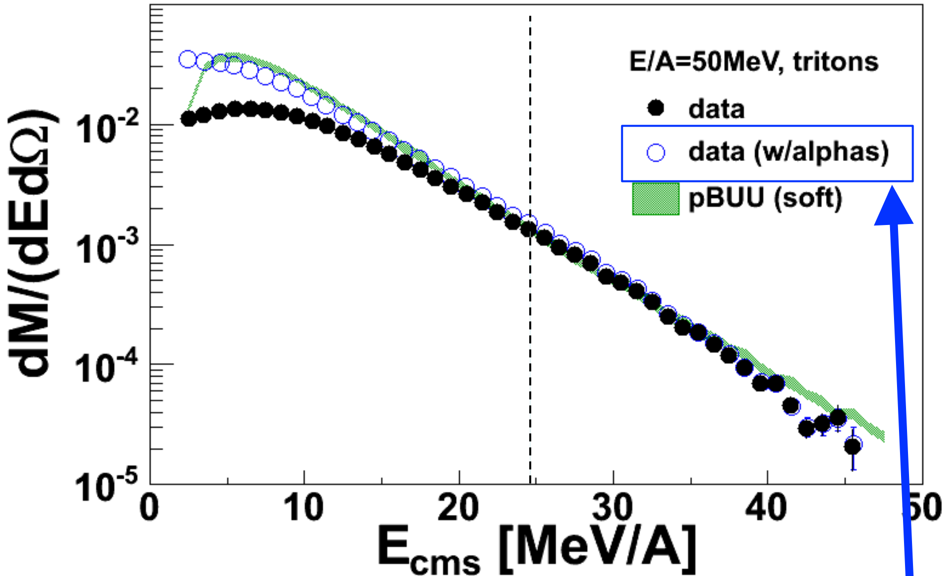


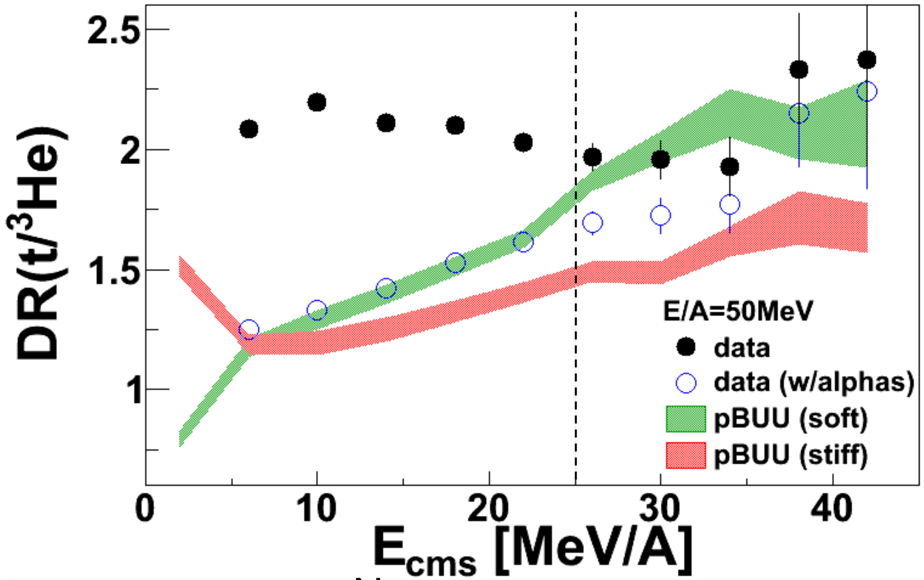


- Includes dynamical production of clusters up to A=3 (but not beyond)
- $m^{*}=0.7m_{0}$, $m^{*}_{p}= m^{*}_{n}$
- Calculations underpredict the double-ratio at low energies



pBUU: light clusters





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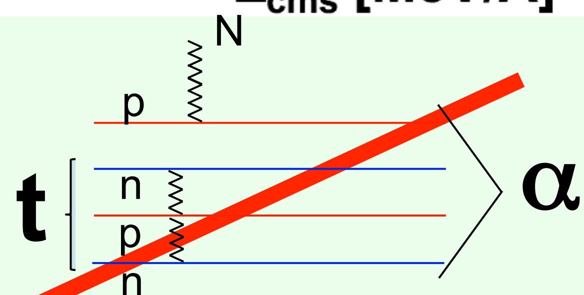
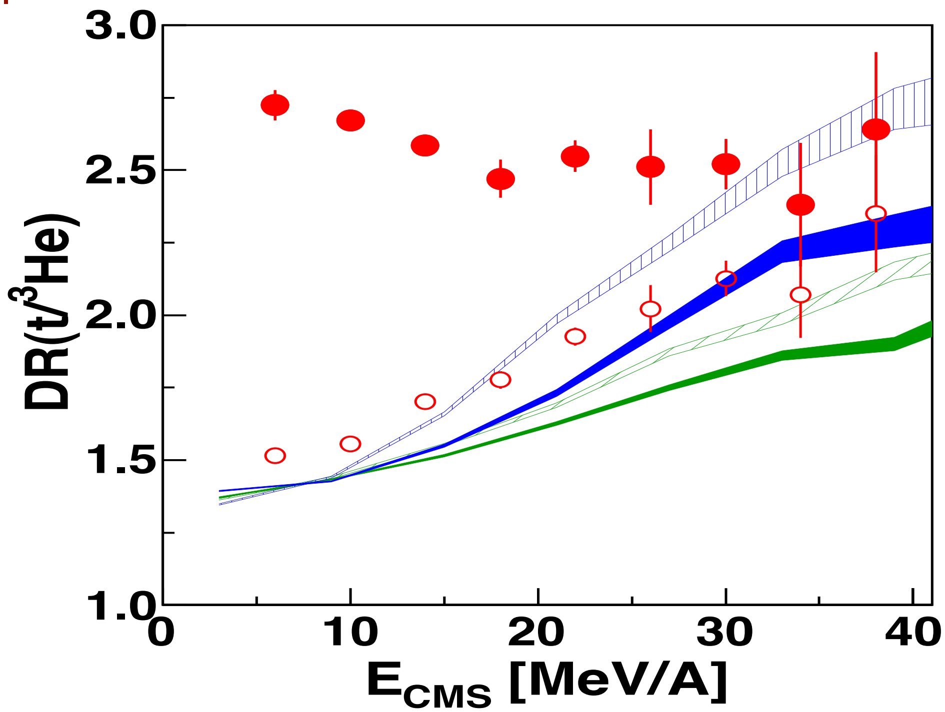


Alpha production not included in the model => alpha ends up being t or ^{3}He

Solution: combine experimental alpha spectra with tritons and helium-3 and compare to the model predictions

pBUU: light clusters

$^{48,40}Ca+^{48,40}Ca$ @ 80MeV/A



● data b̂<0.4

○ data b̂<0.4 (with ^{4}He)

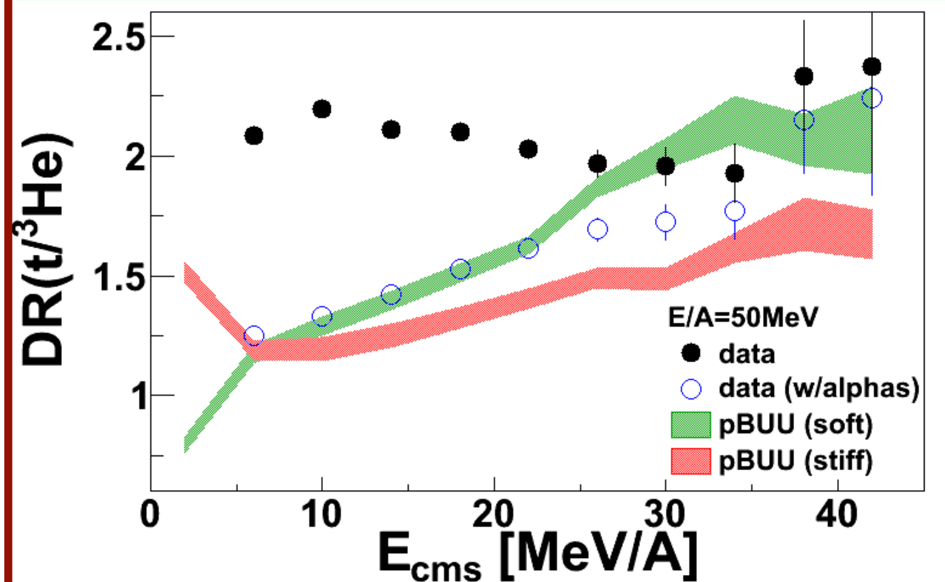
pBUU: Free x-section

- soft AsyEOS
- stiff AsyEOS

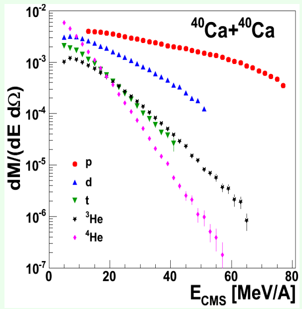
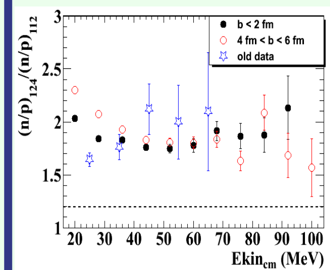
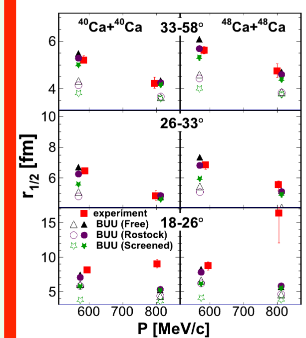
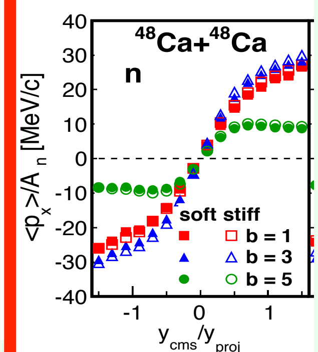
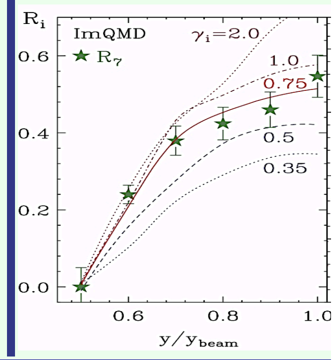
pBUU: Screened x-section

- soft AsyEOS
- stiff AsyEOS

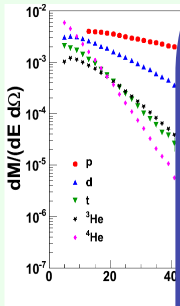
$^{112,124}Sn+^{112,124}Sn$ @ 50MeV/A



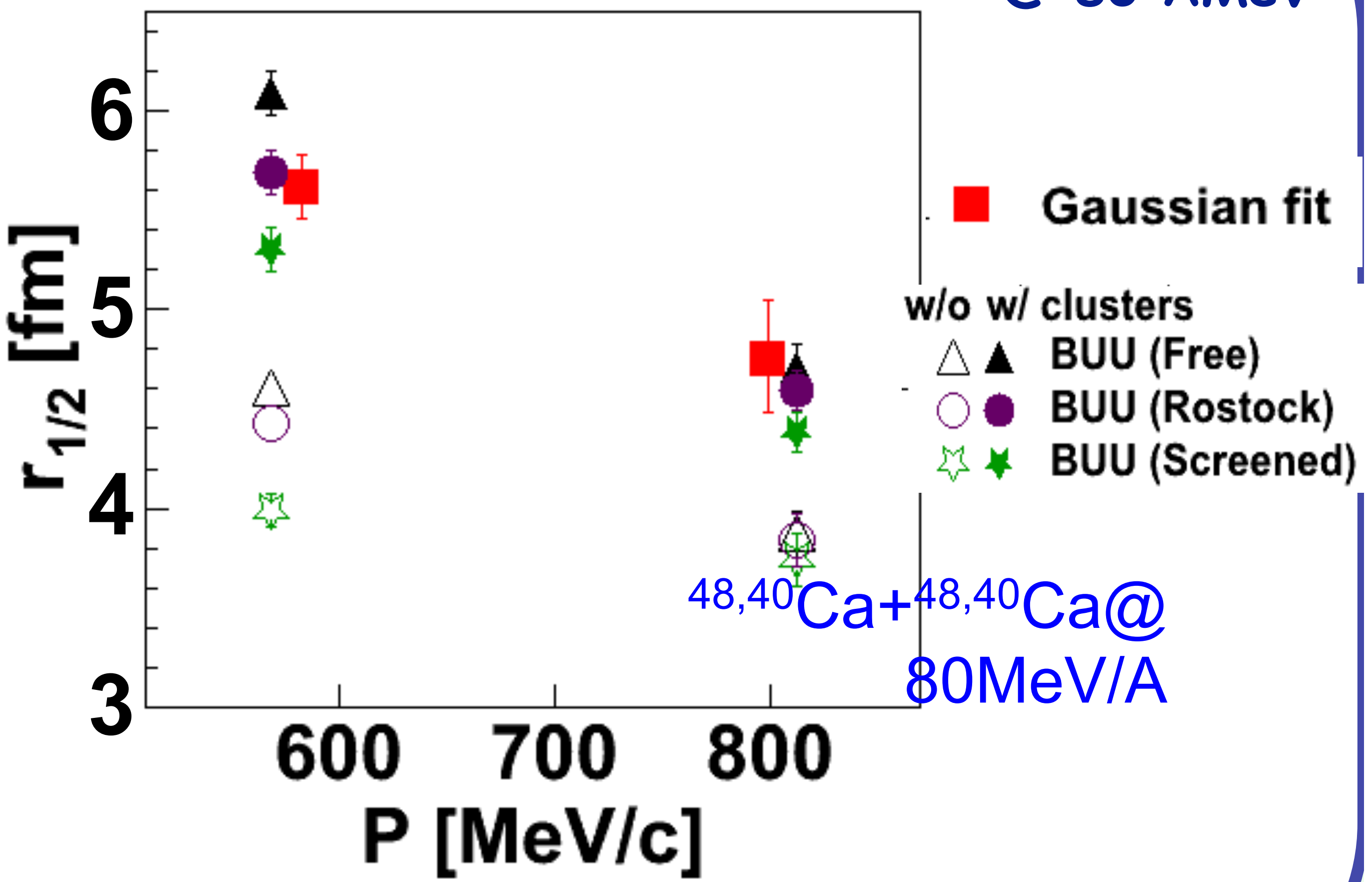
SEP at NSCL: What we hope to learn?

	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?

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

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



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

Summary

- The density dependence of the symmetry energy is of fundamental importance to nuclei, nuclear matter and neutron stars
- **We presented results on n/p and t/^{3}He double-ratios from ^{112,124}Sn+^{112,124}Sn collisions at E/A=50 and 120 MeV.**
- Calculations show a sensitivity of the n/p (double-) ratio to the symmetry energy and **effective mass** and the sensitivity of the t/^{3}He (double-) ratio to the symmetry energy
- There are more ingredients of the transport models than just symmetry energy that have to be better constrained (x-section, cluster production, …) - need more observables and systematics
- Differences between models have to be understood

Thank you collaborators!

- **Dan Coupland**
- **Mike Youngs**
- William Lynch
- Betty Tsang
- Zbigniew Chajecki
- Michael Famiano
- Brenna Giacherio
- Tilak Ghosh
- Rachel Showalter
- Micha Kilburn
- Jenny Lee
- Fei Lu
- John Novak
- Paulo Russotto
- Alisher Sanetullaev
- Concettina Sfienti
- Giuseppe Verde
- Jack Winkelbauer