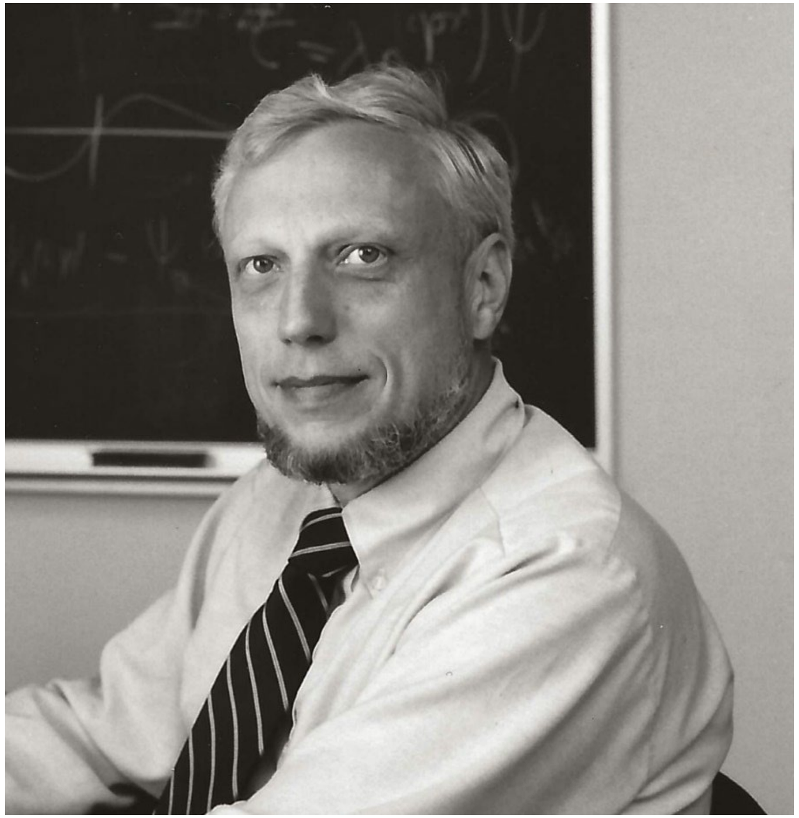
IN MEMORIAM

Bob Vandenbosch 1933-2024



University of Washington, Seattle, WA
Fellows of APS and ACS, Seaborg Award (1981)

Nuclear Fission, Robert Vandenbosch & John R. Huizenga

Nuclear Waste Stalemate: Political and Scientific Controversies, Robert Vandenbosch and Susanne E Vandenbosch

Vic Viola 1935-2024

Indiana University, Bloomington, IN
Fellows of APS and ACS, Seaborg Award (1986)

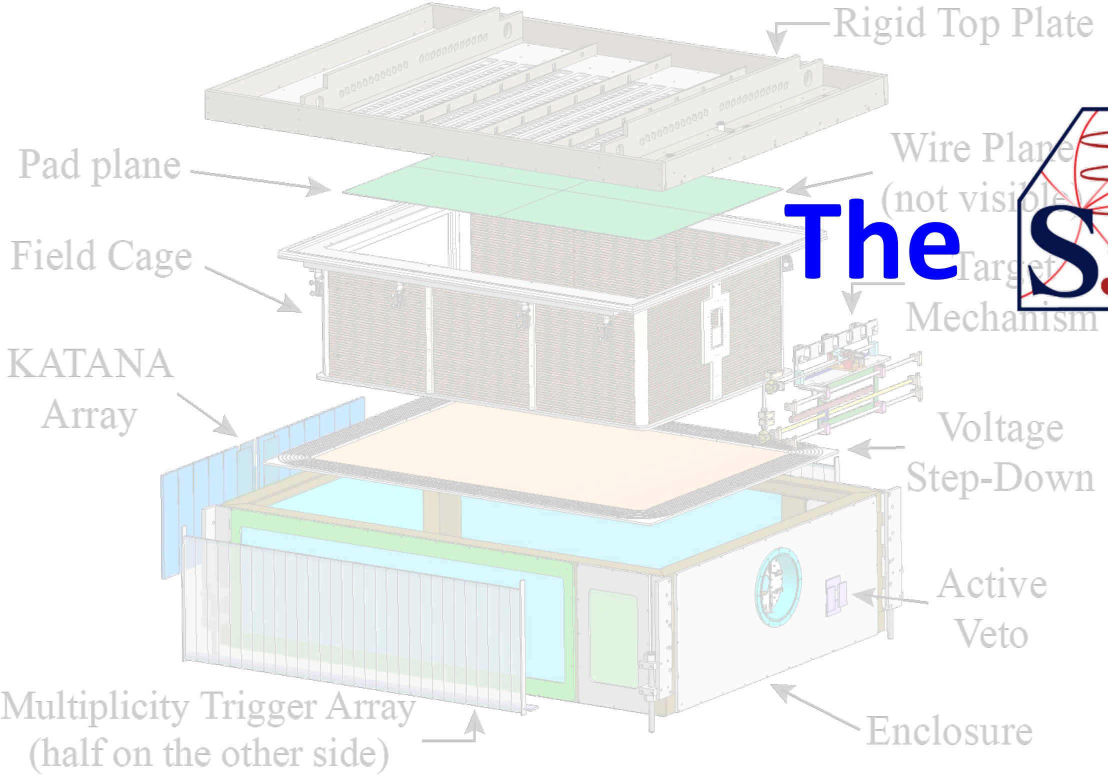
The Viola Systematics:

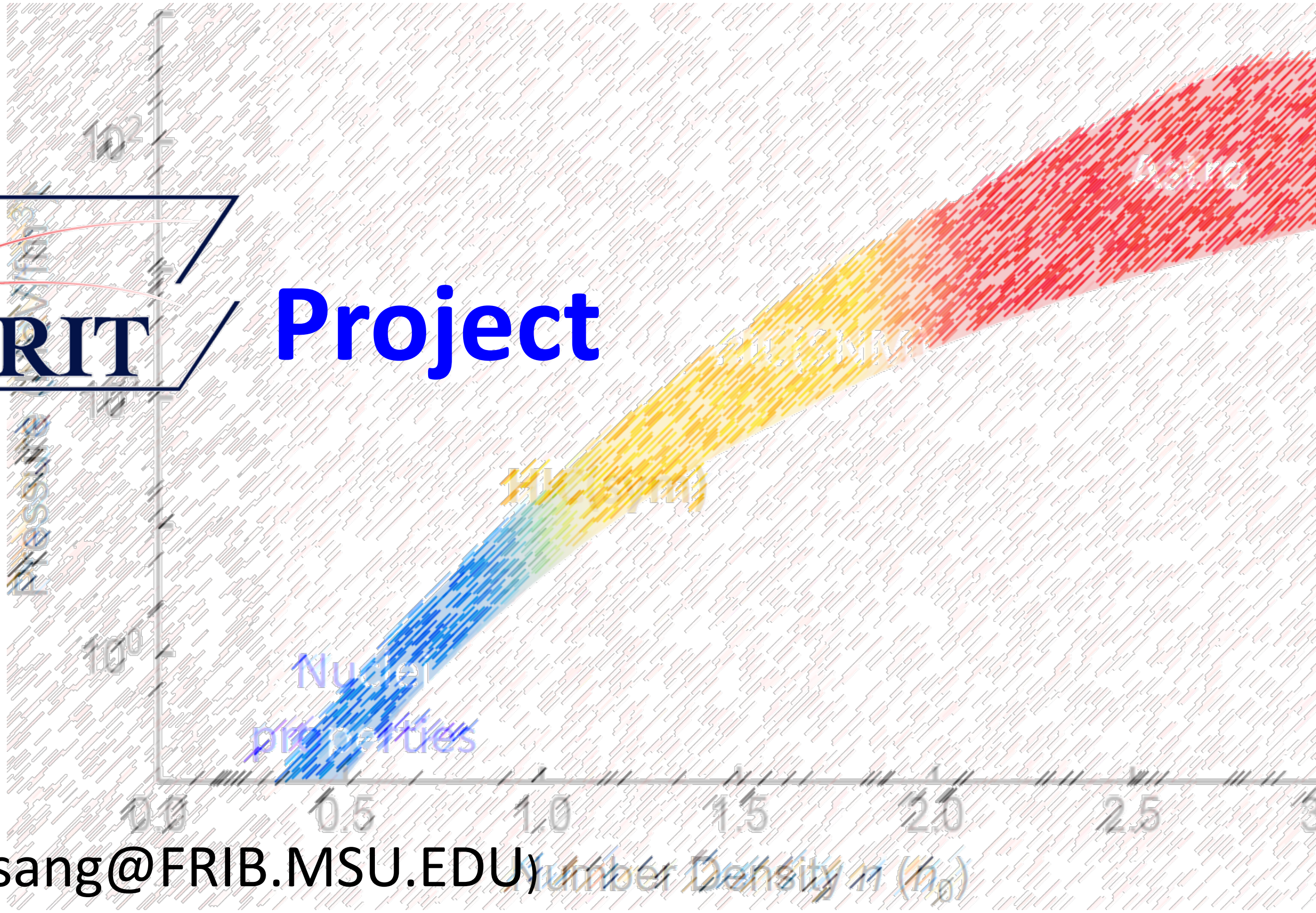
$\langle E_K \rangle = 0.1189 Z^2/A^{1/3} + 7.3$ MeV

NuSym2024

Caen, France, Sep 9-14, 2024

The SπRIT Project

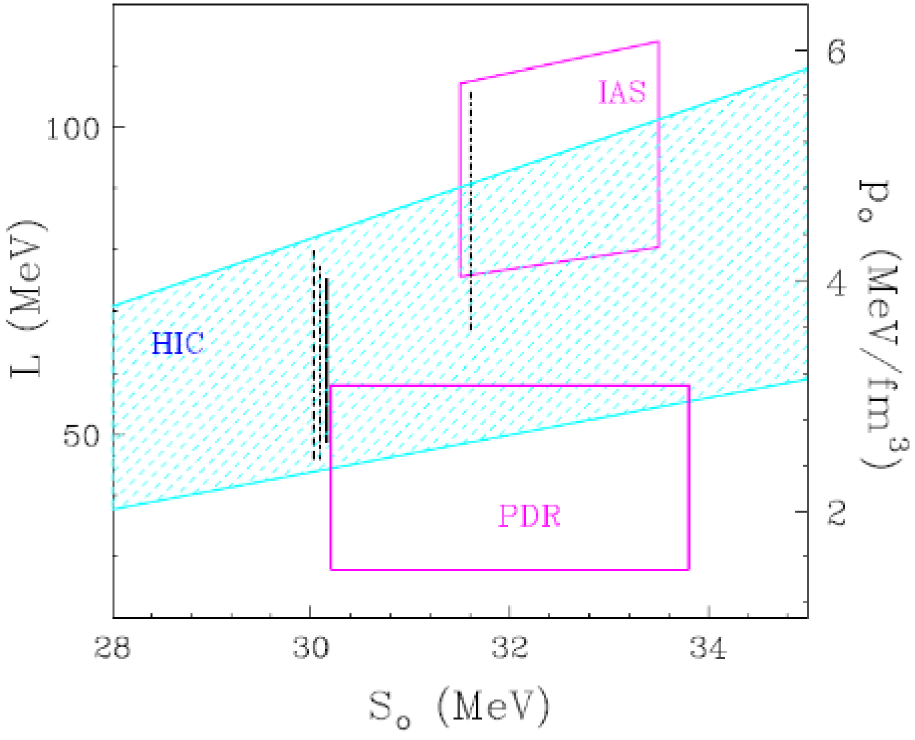




Betty Tsang (Tsang@FRIB.MSU.EDU)

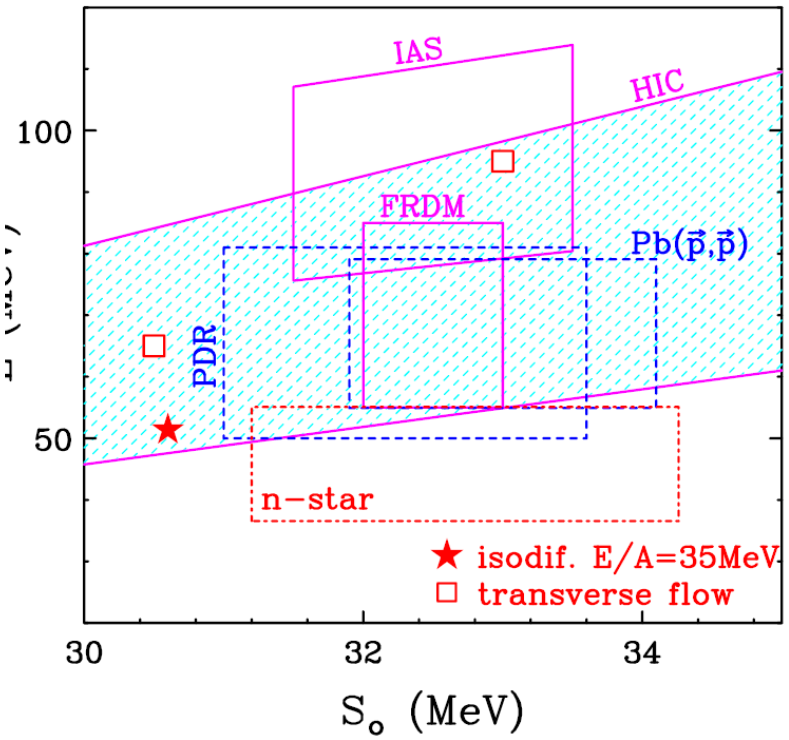
Status of Symmetry Energy Constraints using Heavy Ion Collisions

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



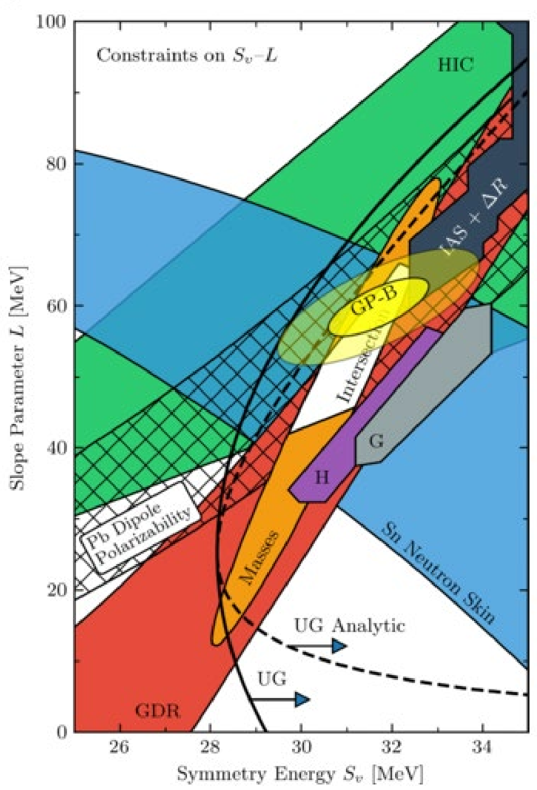
NuSYM10

Tsang, Zhang et al., PRL122, 122701(2009)



NuSYM11

Tsang et al., PRC **86**, 015803 (2012)



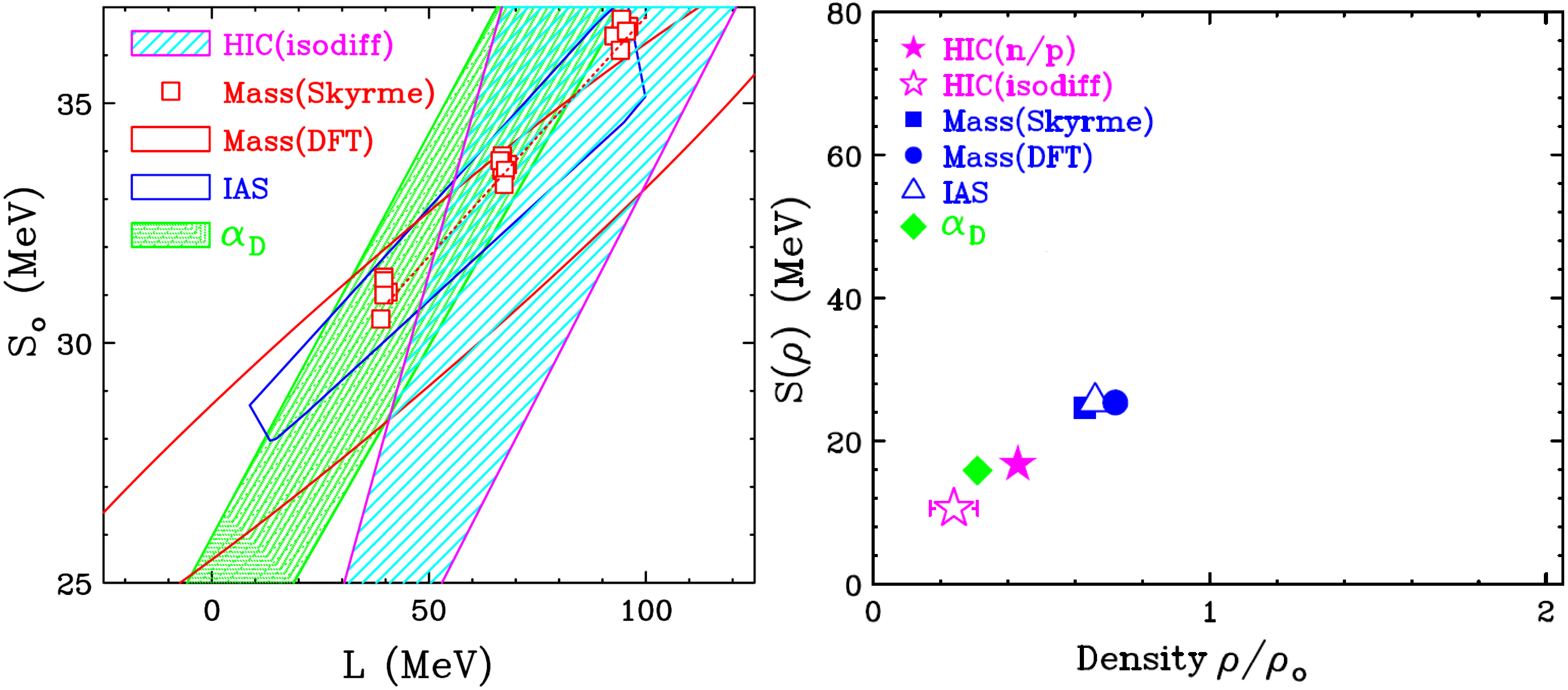
NuSYM13

Lim & Lattimer APJ 771, 51 (2013)

C. Drischler et al., PRL **125**, 202702 (2020)

Decoding the constraints on the Symmetry Energy

Lynch and Tsang, PLB 830, 137098 (2022)



~2009

Device: SAMURAI TPC (U.S. Japan Collaboration)

T. Murakami[a], Jiro Murata[b], Kazuo Ieki[b], Hiroyoshi Sakurai[c], Shunji Nishimura[c], Atsushi Taketani[c], Yoichi Nakai[c], Betty Tsang[d], William Lynch[d], Abigail Bickley[d], Gary Westfall[d], Michael A. Famiano[e], Sherry Yennello[g], Roy Lemmon[h], Abdou Chbihi[i], John Frankland[i], Jean-Pierre Wieleczko[i] , Giuseppe Verde[j], Angelo Pagano[i], Paulo Russotto[i], Z.Y. Sun[k], Wolfgang Trautmann[l]

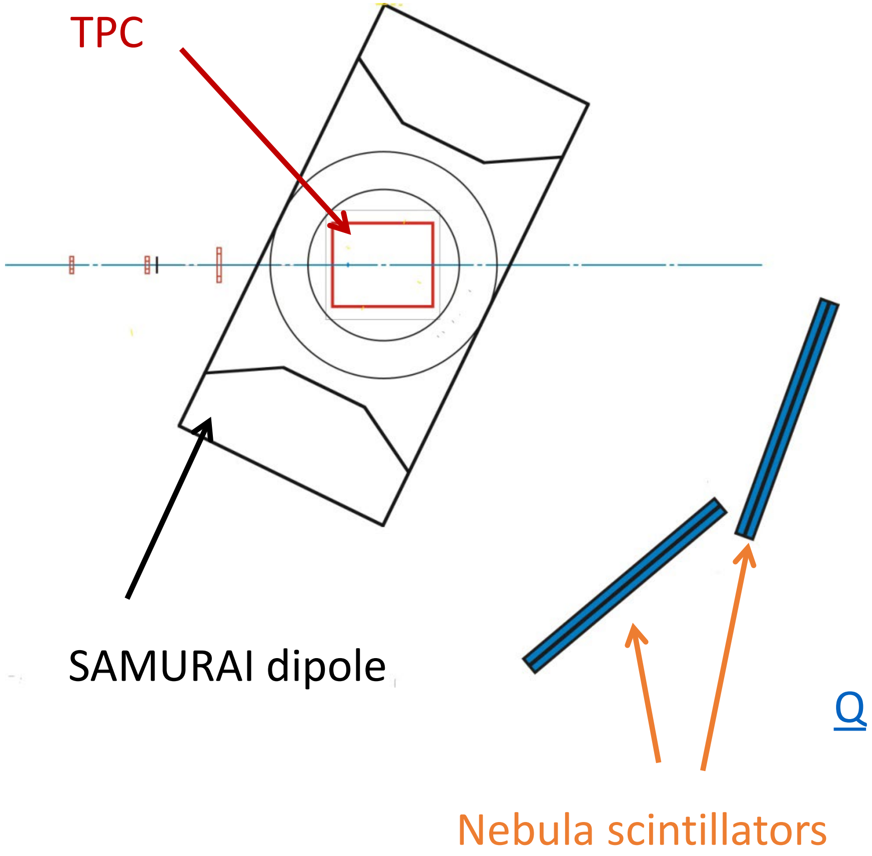
[a]Kyoto University, [b]Rikkyo University, [c]RIKEN, Japan, [d]NSCL Michigan State University, [e]Western Michigan University, [g]Texas A&M University, USA, [h]Daresbury Laboratory, [i]GANIL, France, UK, [j]LNS-INFN, Italy, [k]IMP, Lanzhou, China, [l]GSI, Germany

The SAMURAI TPC would be used to constrain the density dependence of the symmetry energy through measurements of:

- Pion production
- Flow, including neutron flow measurements with the nebula array.

The TPC also can serve as an active target both in the magnet or as a standalone device.

- Giant resonances.
- Asymmetry dependence of fission barriers, extrapolation to r-process.



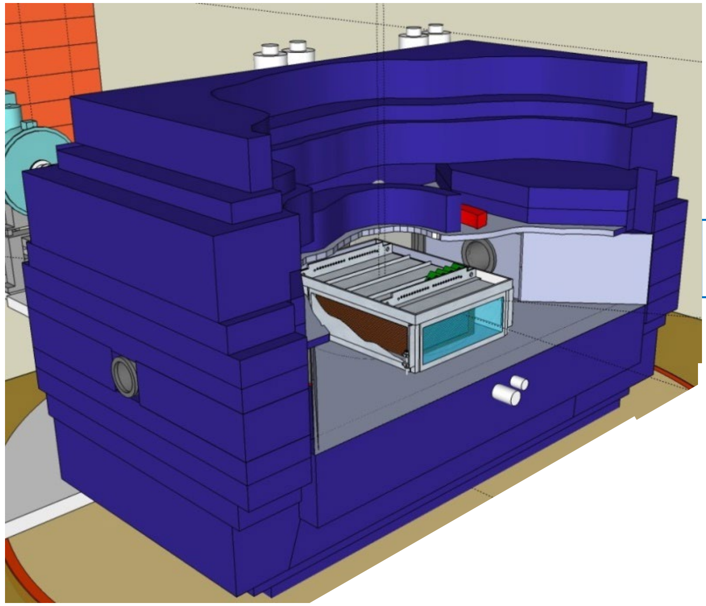
Q

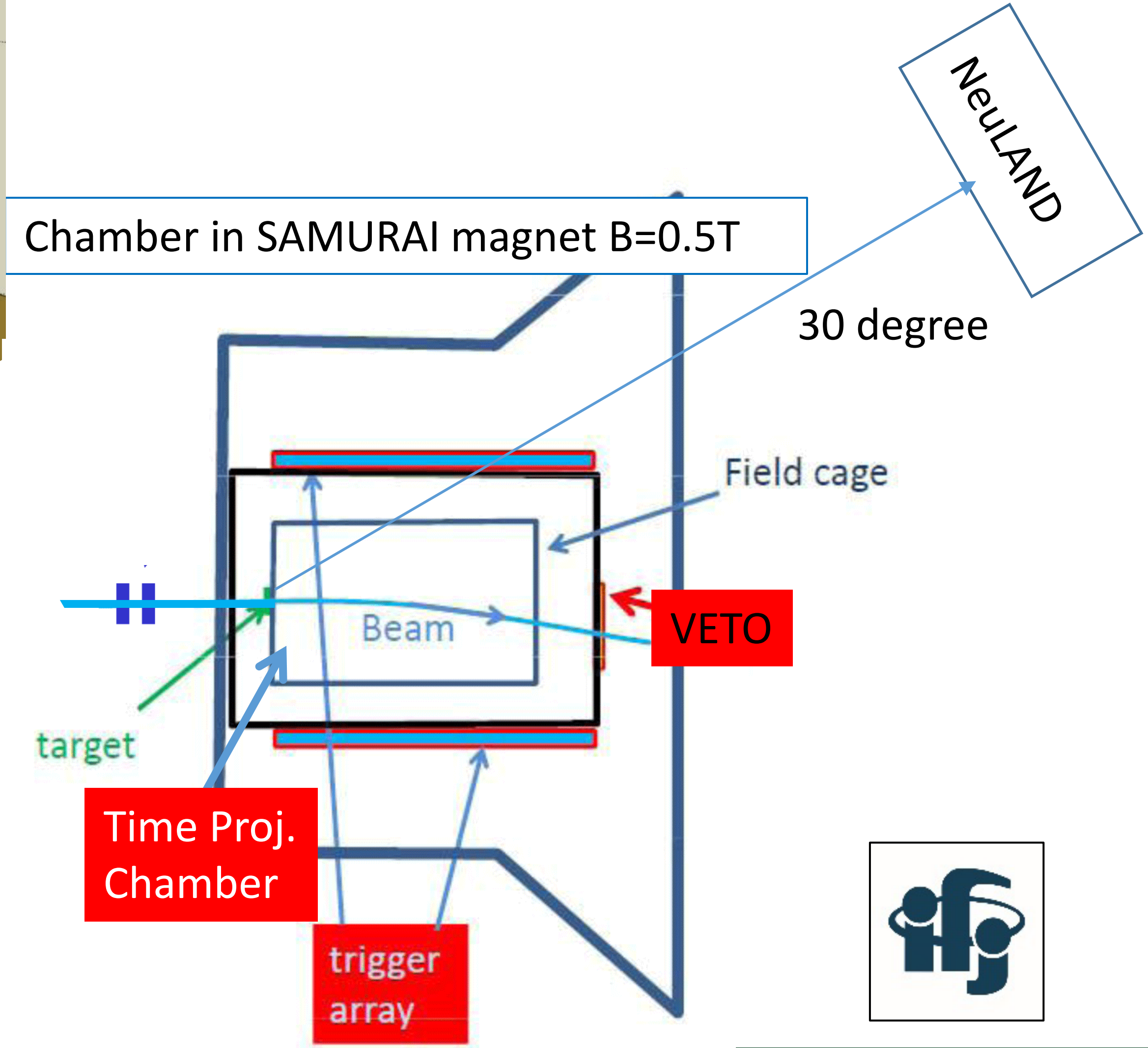
SπRIT

U.S. DEPARTMENT OF
ENERGY
Office of Science

文部科学省
MEXT
MINISTRY OF EDUCATION, CULTURE, SPORTS, SCIENCE AND TECHNOLOGY-JAPAN

SπRIT Experimental setup



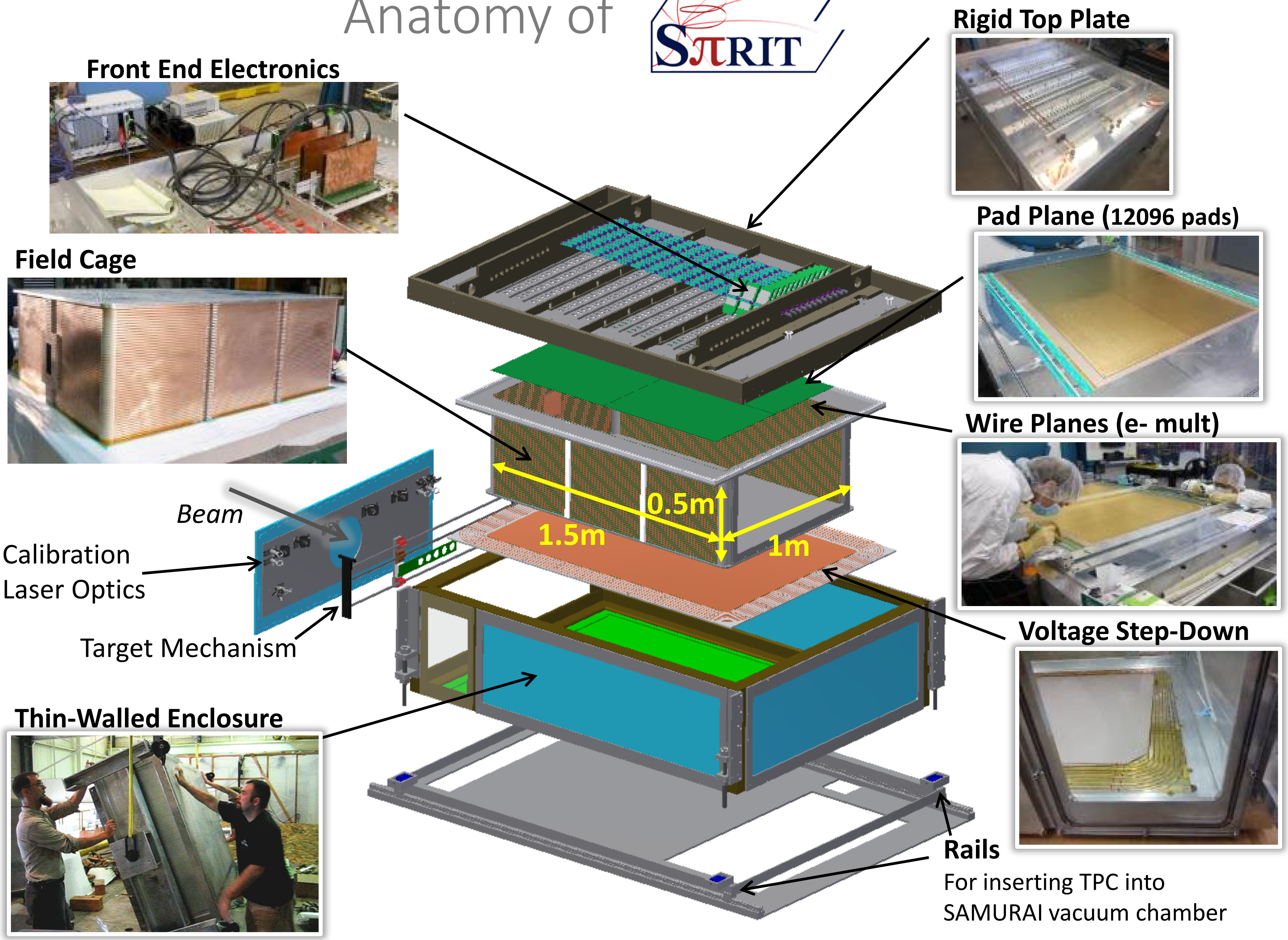


1. Detectors
   1. TPC
   2. Kyoto and Katana trigger arrays
   3. Katana VETO array
   4. Beam line detectors (BigRIPS, start counter, BDC)
   5. NeuLAND + its VETO
2. 3 DAQs: 5MB/event & 2ms dead time per event.

MICHIGAN STATE UNIVERSITY

Anatomy of SπRIT

J. Barney et al., RSI **92**, 063302 (2021)

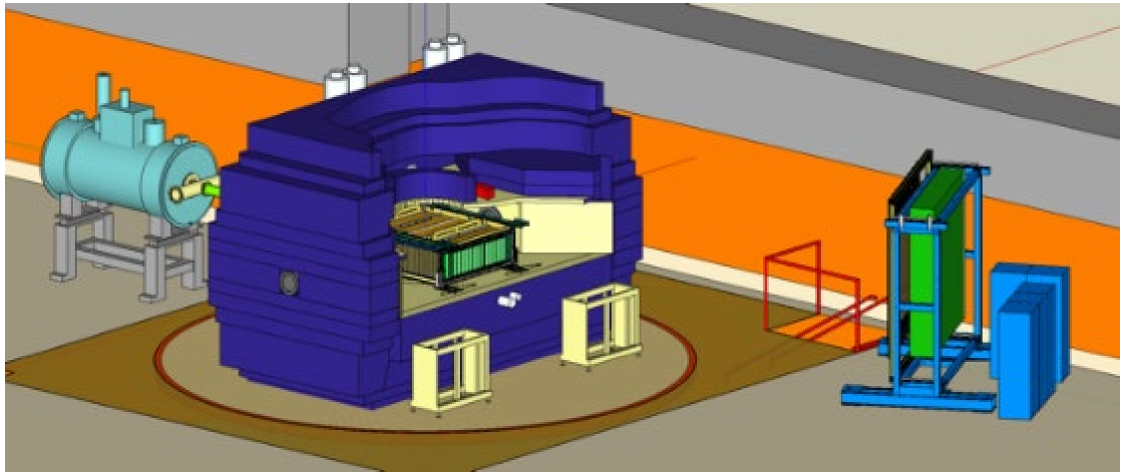


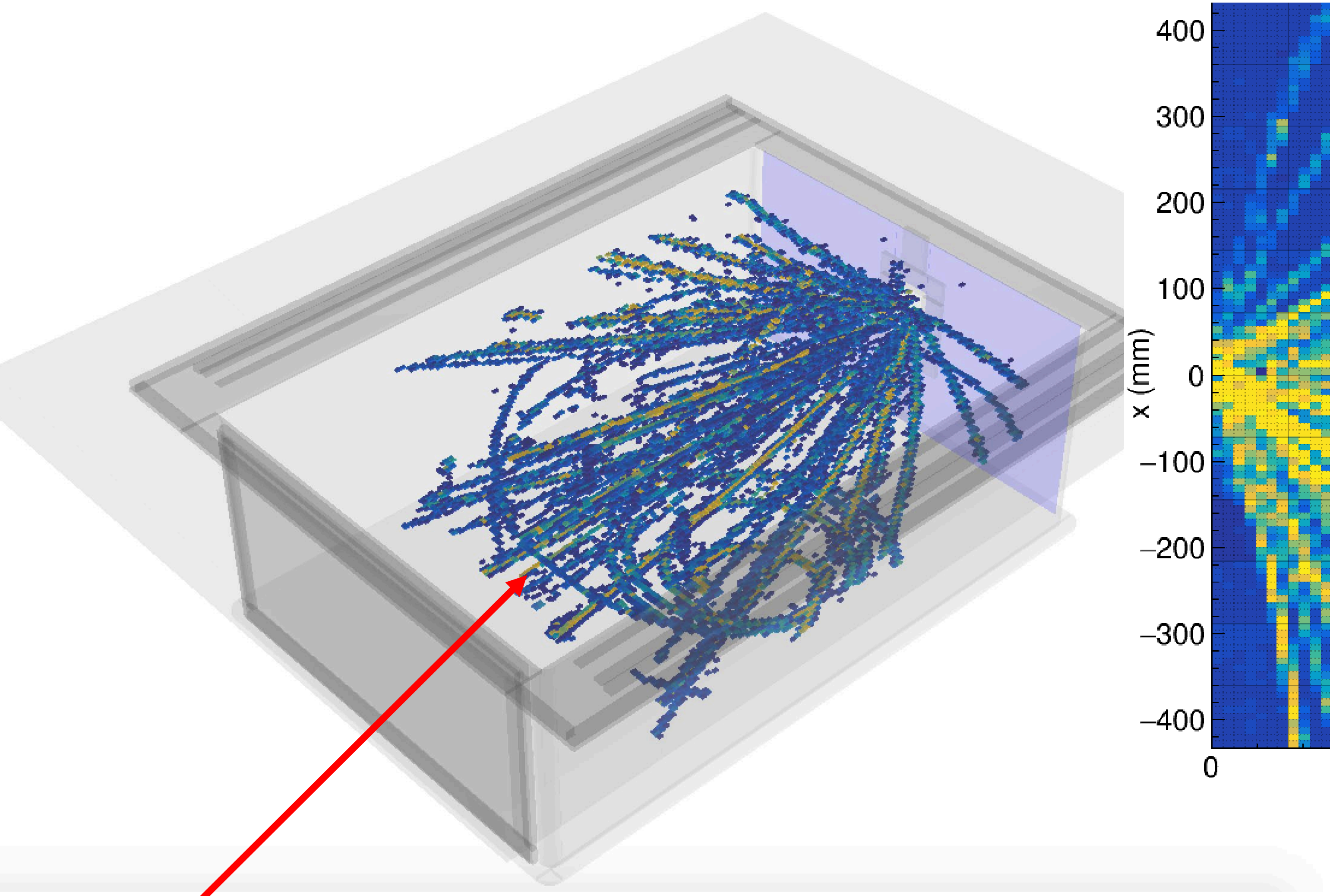
July, 2014

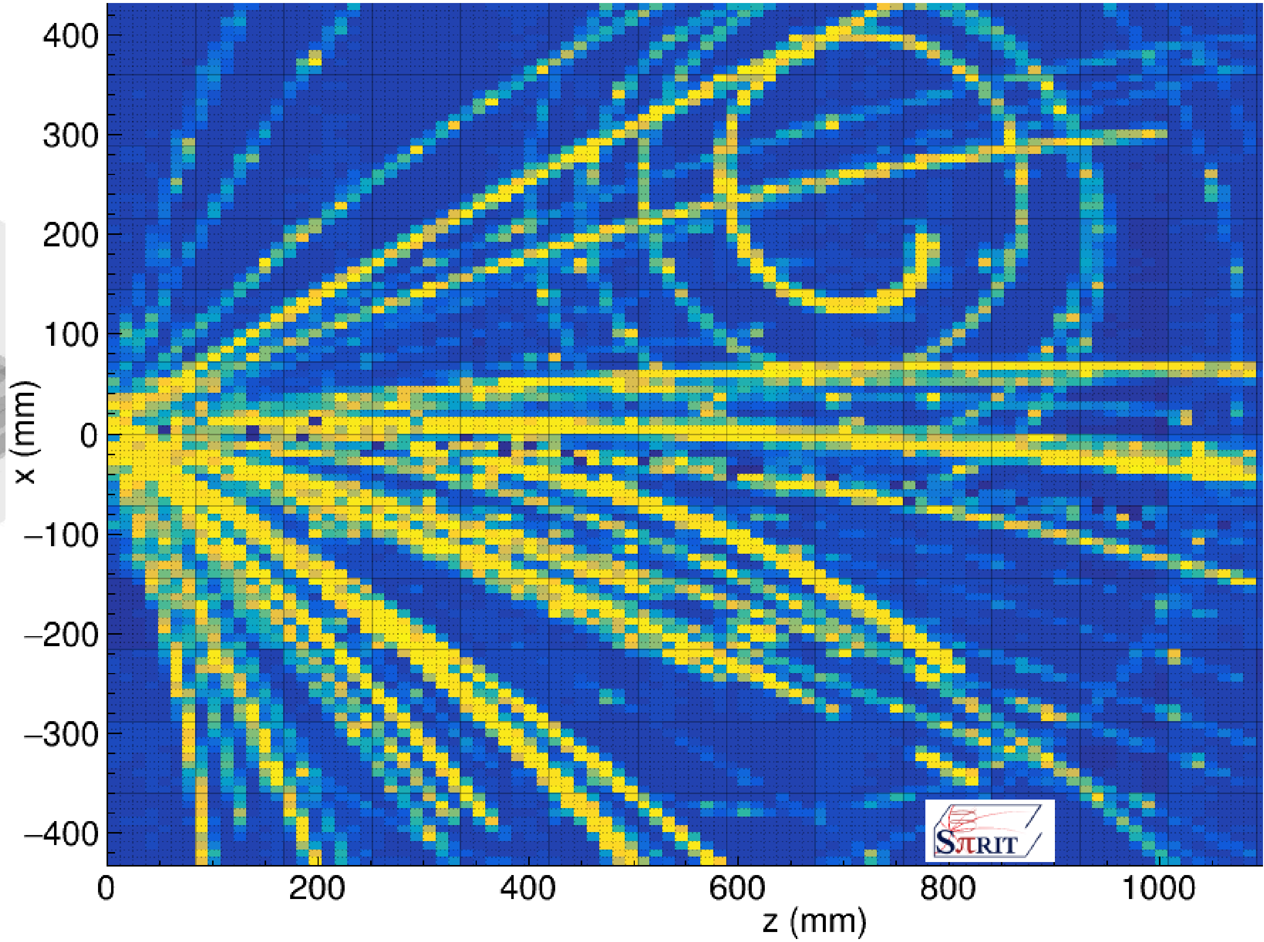
Feb, 2015

Experimental Setup
April 2016

Primary	Beam	Target	E_{beam}/A	δ_{sys}	evt(M)	2016
^{124}Xe	^{108}Sn	^{112}Sn	269	0.09	8	4/30-5/4
	^{112}Sn	^{124}Sn	270	0.15	5	5/4-5/6
238 U	^{132}Sn	^{124}Sn	269	0.22	9	5/25-5/29
	^{124}Sn	^{112}Sn	270	0.15	5	5/30-6/1
Z=1,2,3			**100, 200**		**0.6**	**6/1**



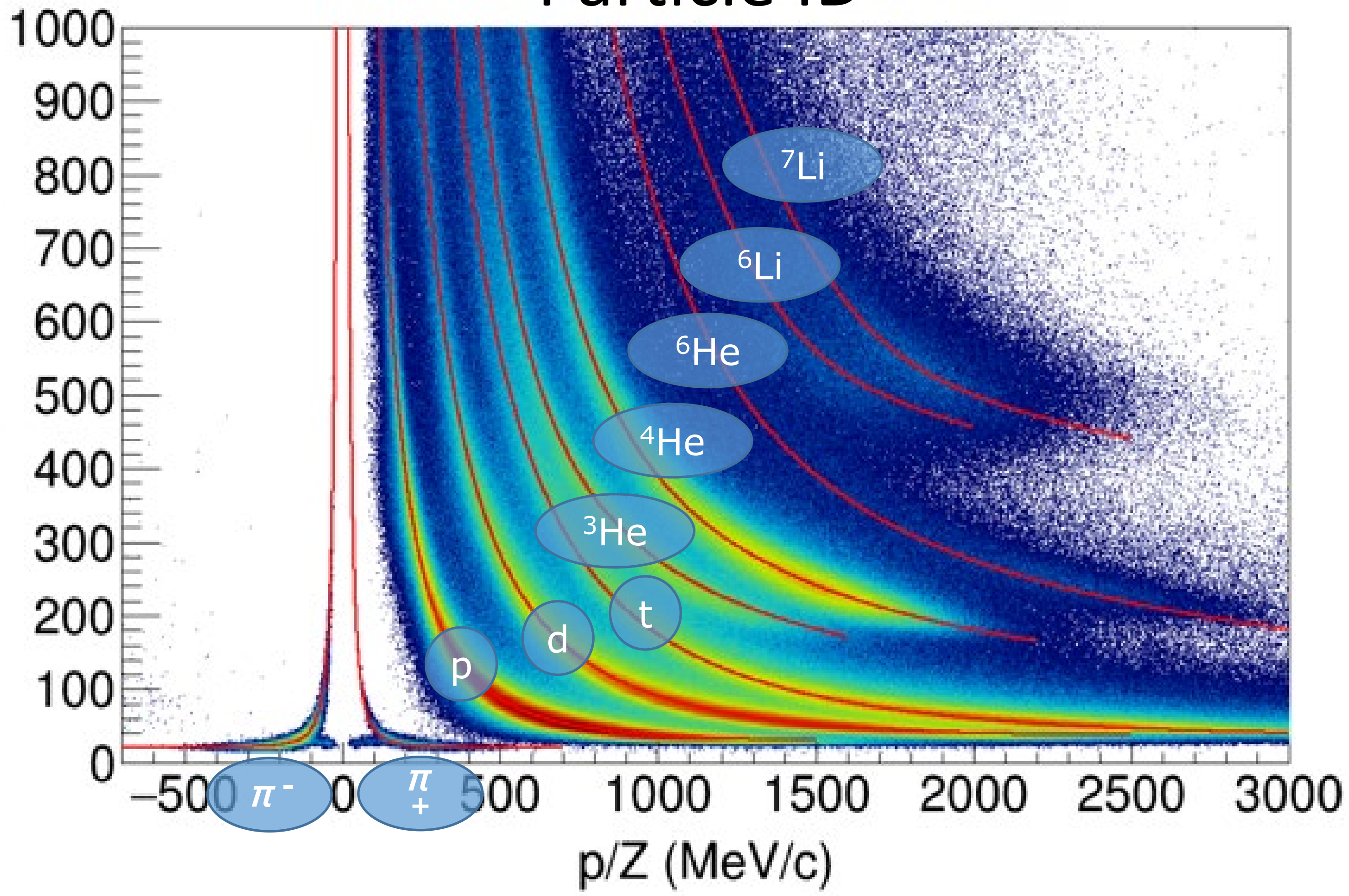




Big spiral of a pion

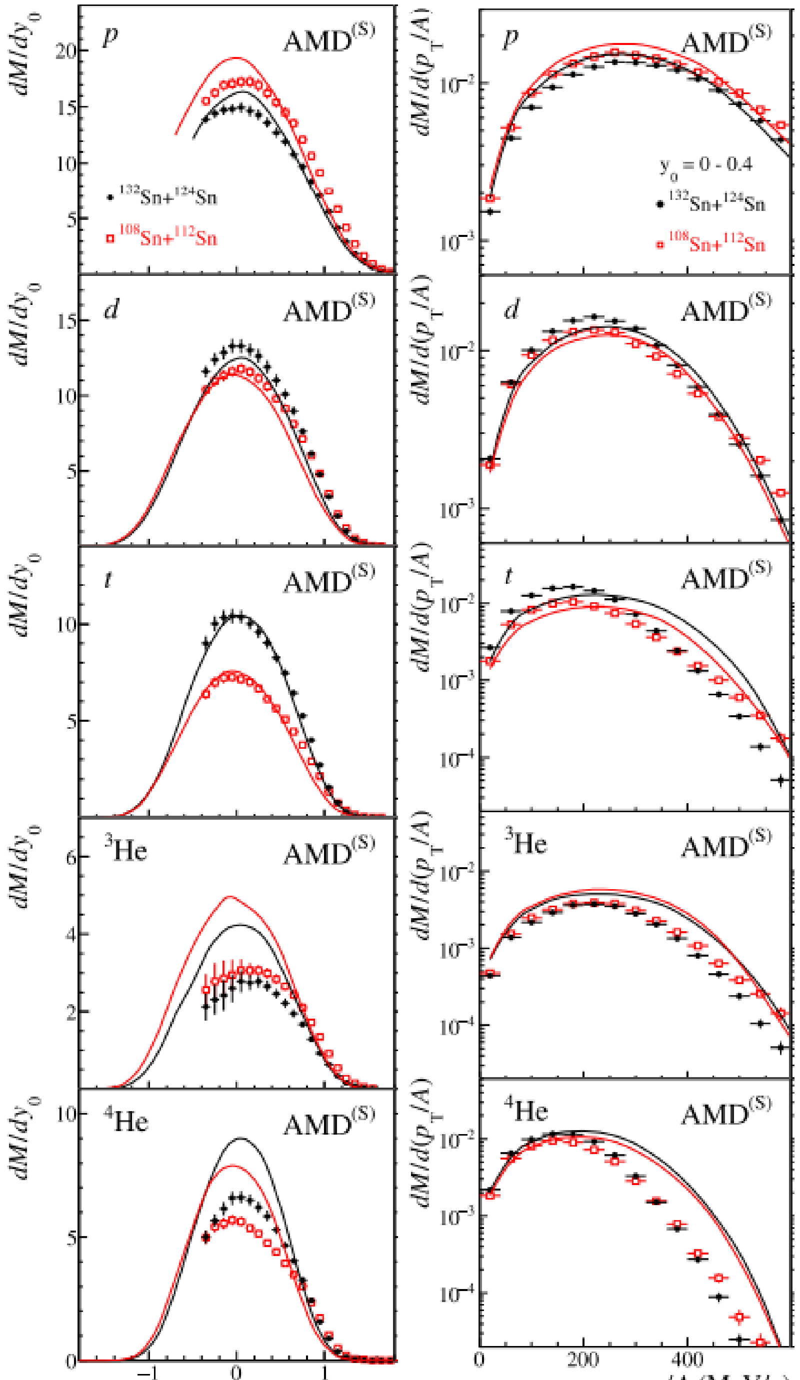
SπRIT Collaboration

Particle ID



R. Shane et al., NIMA **784**, 513 (2015).
G. Jhang et al., JKPS 69, 144–151 (2016).
S. Tangwangchoren et al. NIMA 853, 44–52 (2017).
P. Lasko et al., NIMA 856, 92 (2017).
T. Isobe et al., NIMA 899, 43 (2018).
J. Estee et al., NIMA 944, 162509 (2019).
C.Y. Tsang et al. NIMA 959, 163477 (2020).
J.W. Lee et al., NIMA 965, 163840 (2020).
J. Barney et al., RSI **92**, 063302 (2021);
G. Jhang et al., PLB 813, 136016 (2021).
J. Estee et al., PRL 126, 162701 (2021).
M. Kaneko, PLB 822, 136681 (2021).
M. Kaneko, NIM A 1039, 167010 (2022).
J.W. Lee et al., Eur. Phys. J. A 58, 201 (2022).
C.Y. Tsang et al., PLB 853, 138661 (2024)
Kurada-Nishimura et. al., PLB

Genie Jhang



Kaneko; JungWoo Lee

J.W. Lee et al., Eur. Phys. J. A 58, 201 (2022).

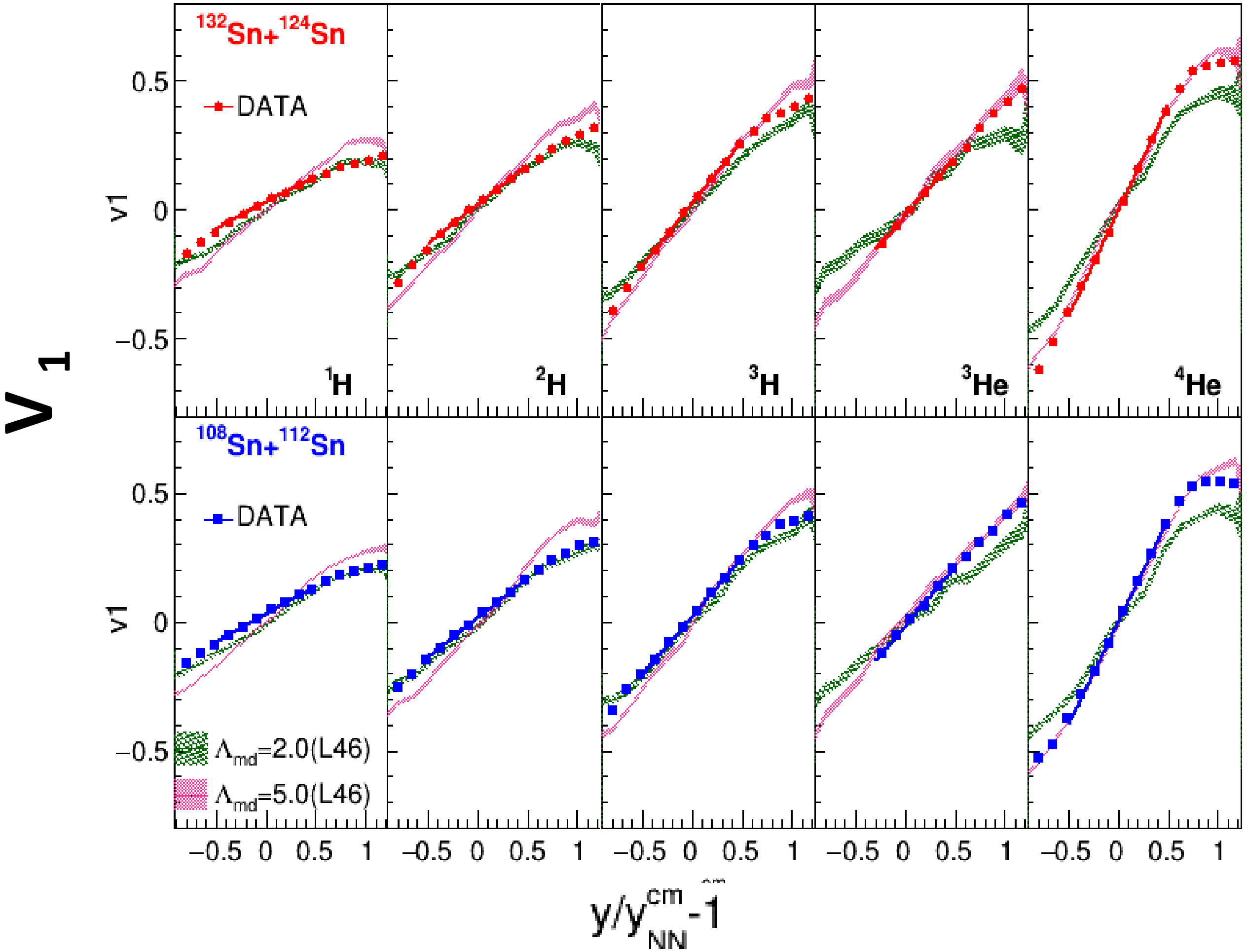
M. Kaneko, PLB 822, 136681 (2021).

p, d, t, 3He, alpha particle momentum and rapidity spectra.

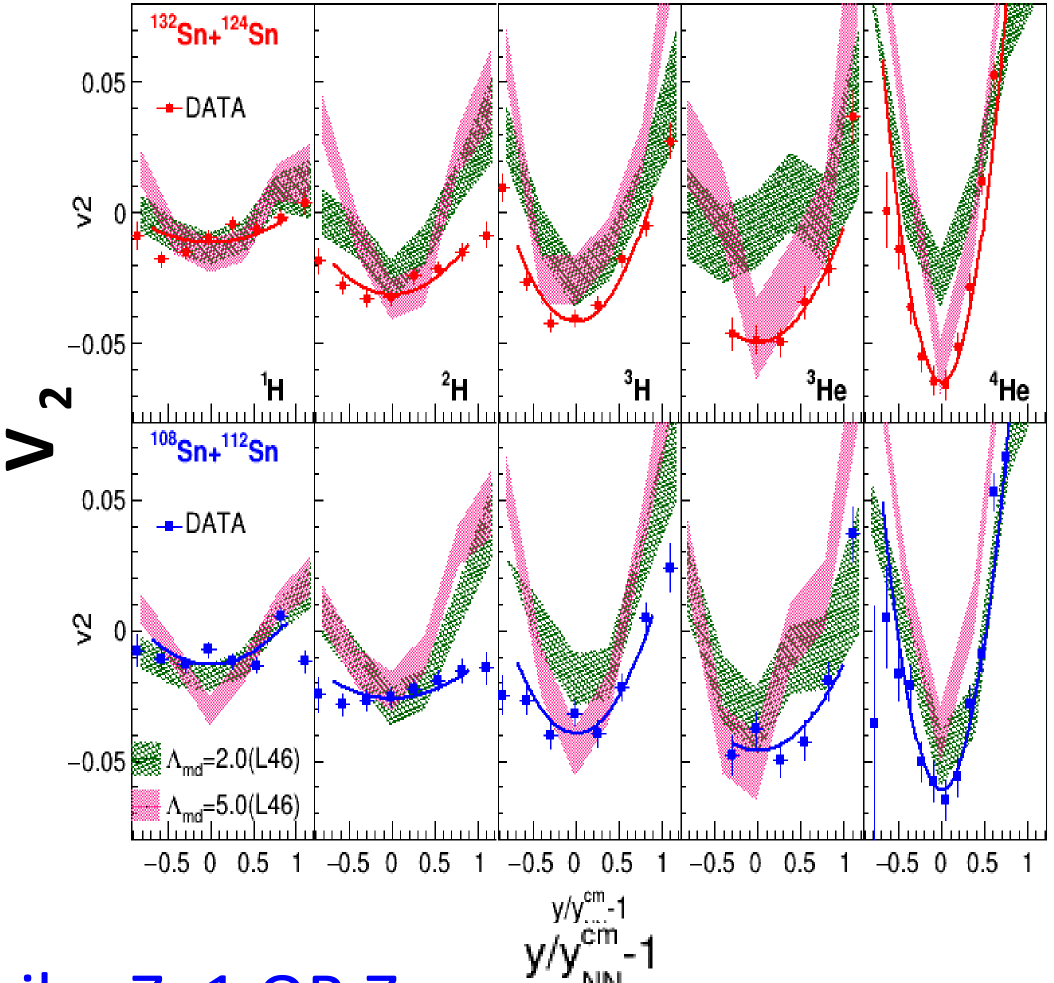
Comparison to AMD depends on parameter sets to obtain reasonable agreements

Mizuki Kurata-Nishimura, under review

Directed Flow



Squeeze out Flow



Parameter sets in AMD either describe Z=1 OR Z=2 particle momentum and rapidity flow spectra but not both.

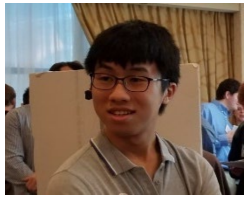
More work on clusters in transport models.

Tommy Tsang et al. Physics Letters B 853 (2024) 1386613

To by-pass cluster problem, use of the coalescence invariance observables (weighed by A or Z) to extract EOS parameters in transport models, S_0, L, η, m_v^*, m_s^*.
Observables calculated with ImQMD model.

Observable	Exp. $\langle b \rangle$	System
C.I. v_1 v.s. y_0	5.0 fm	$^{108}Sn+^{112}Sn$
	5.0 fm	$^{132}Sn+^{124}Sn$
C.I. v_1 v.s. p_T	5.0 fm	$^{108}Sn+^{112}Sn$
$(0.3 < y_0 < 0.8)$	5.0 fm	$^{132}Sn+^{124}Sn$
C.I. v_2 v.s. y_0	5.0 fm	$^{108}Sn+^{112}Sn$
	5.0 fm	$^{132}Sn+^{124}Sn$
VarXZ	1.0 fm	$^{112}Sn+^{124}Sn$

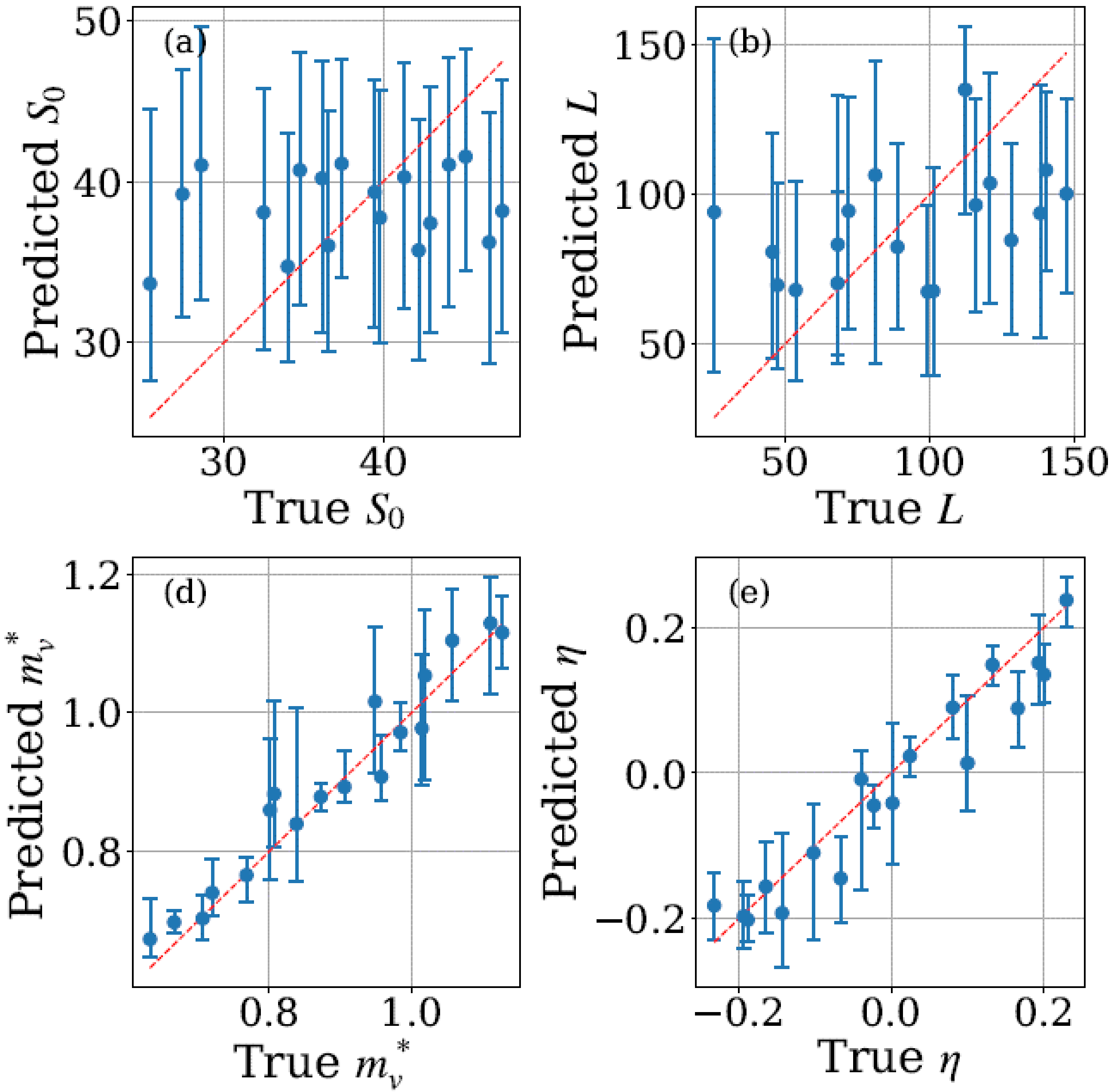
YingXun Zhang

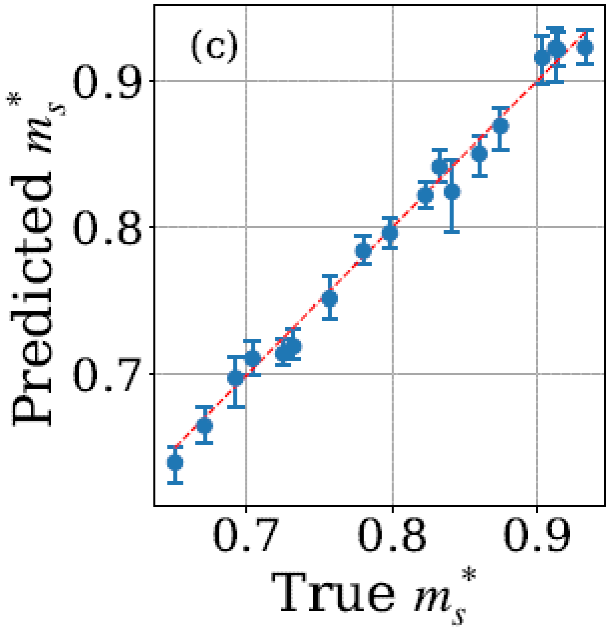


Chun Yuen Tsang

Closure Tests with ImQMD

Observable	Exp. $\langle b \rangle$	System
C.I. v_1 v.s. y_0	5.0 fm	$^{108}Sn+^{112}Sn$
	5.0 fm	$^{132}Sn+^{124}Sn$
C.I. v_1 v.s. p_T $(0.3 < y_0 < 0.8)$	5.0 fm	$^{108}Sn+^{112}Sn$
	5.0 fm	$^{132}Sn+^{124}Sn$
C.I. v_2 v.s. y_0	5.0 fm	$^{108}Sn+^{112}Sn$
	5.0 fm	$^{132}Sn+^{124}Sn$
VarXZ	1.0 fm	$^{112}Sn+^{124}Sn$

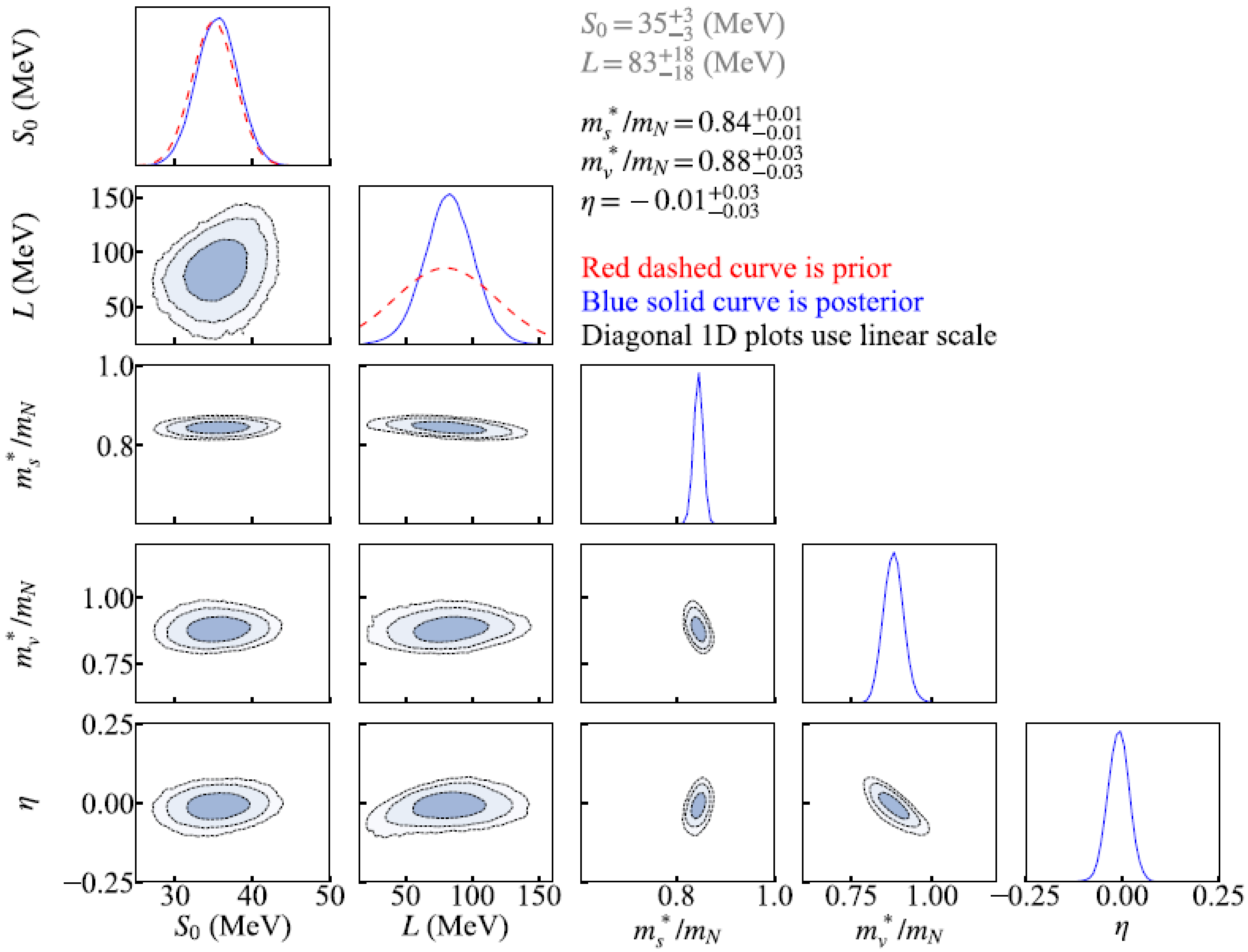




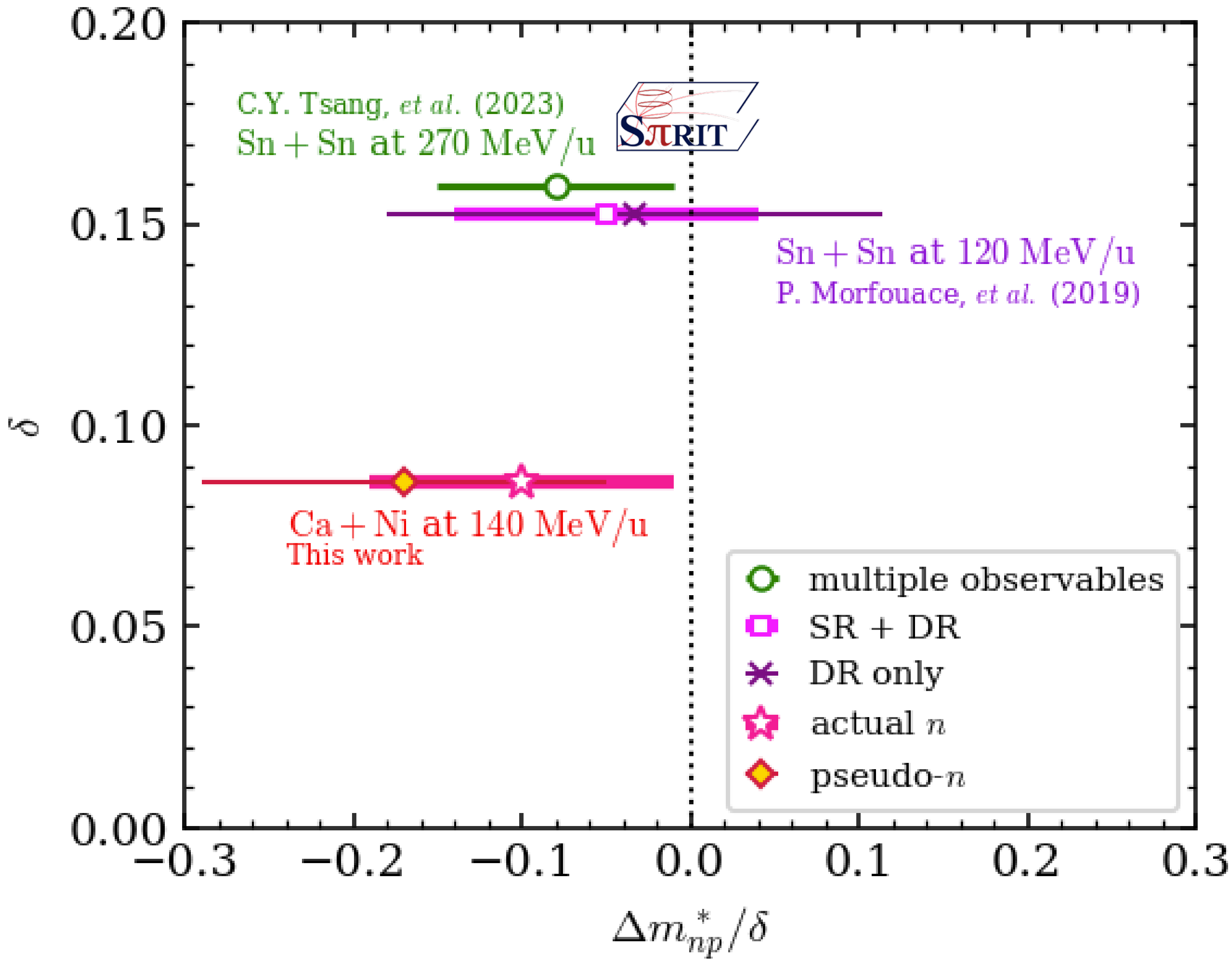
Tommy Tsang et al. Physics Letters B 853 (2024) 1386613, thesis

Tommy Tsang et al. Physics Letters B 853 (2024) 1386613

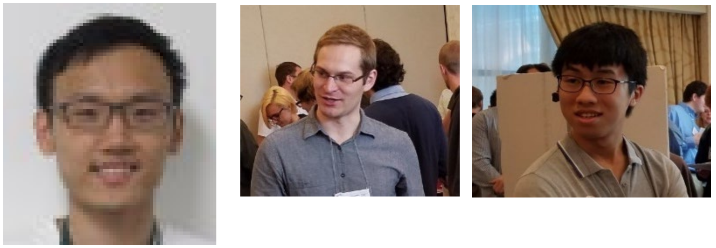
Observable	Exp. $\langle b \rangle$	System
C.I. v_1 v.s. y_0	5.0 fm	$^{108}Sn+^{112}Sn$
	5.0 fm	$^{132}Sn+^{124}Sn$
C.I. v_1 v.s. p_T $(0.3 < y_0 < 0.8)$	5.0 fm	$^{108}Sn+^{112}Sn$
	5.0 fm	$^{132}Sn+^{124}Sn$
C.I. v_2 v.s. y_0	5.0 fm	$^{108}Sn+^{112}Sn$
	5.0 fm	$^{132}Sn+^{124}Sn$
VarXZ	1.0 fm	$^{112}Sn+^{124}Sn$



Observables+ImQMD➔Bayesian analysis



Fanurs Teh   Estee   Tsang



- Diverse set of data with different systems, different observable at different energy
- Results are consistent with b/p splitting slightly negative
- Data is consistent

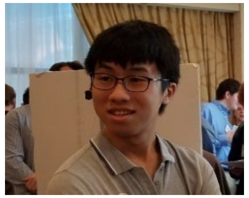
Transport Model Proof?

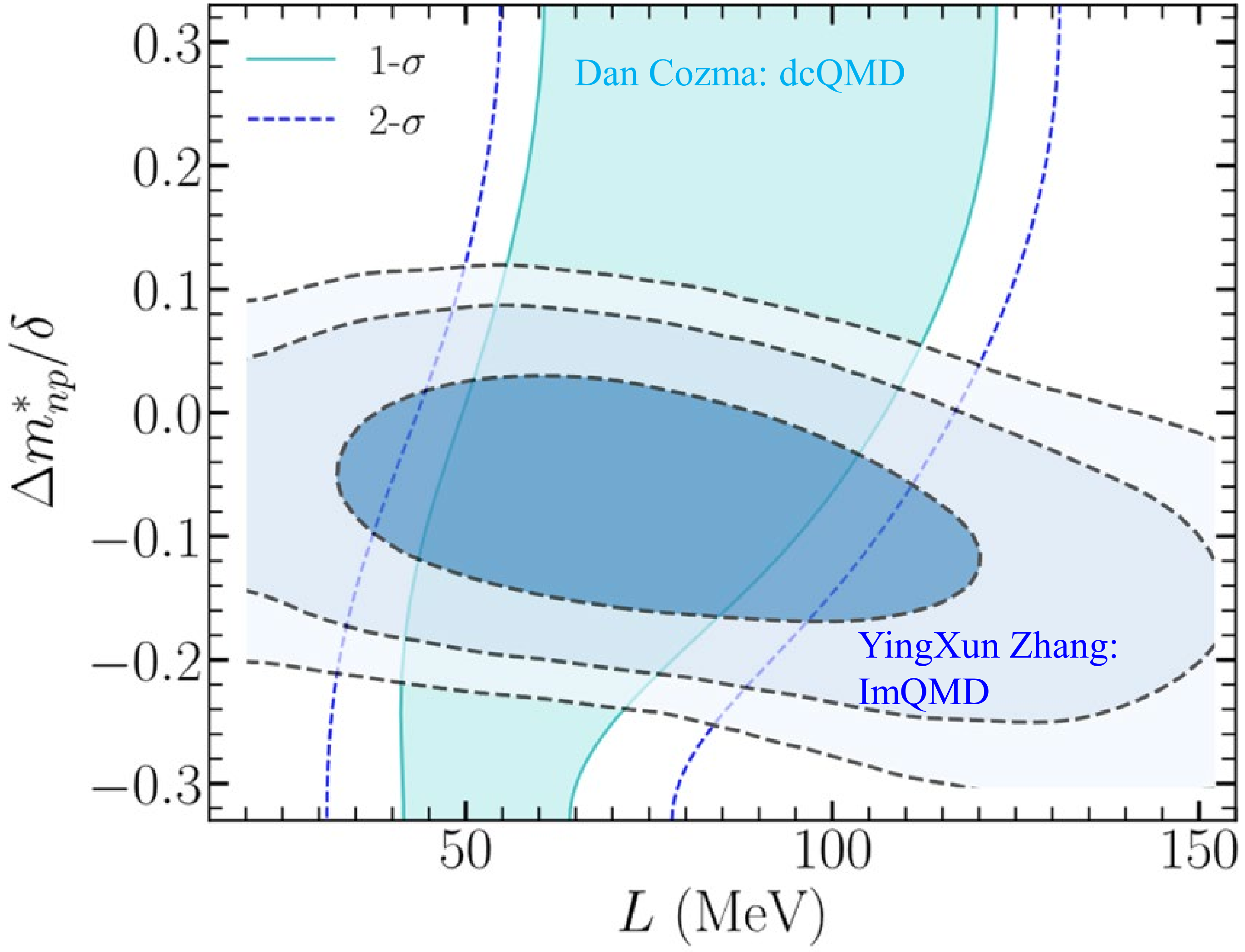
Collaboration

YingXun


Cozma


Estee


Tsang




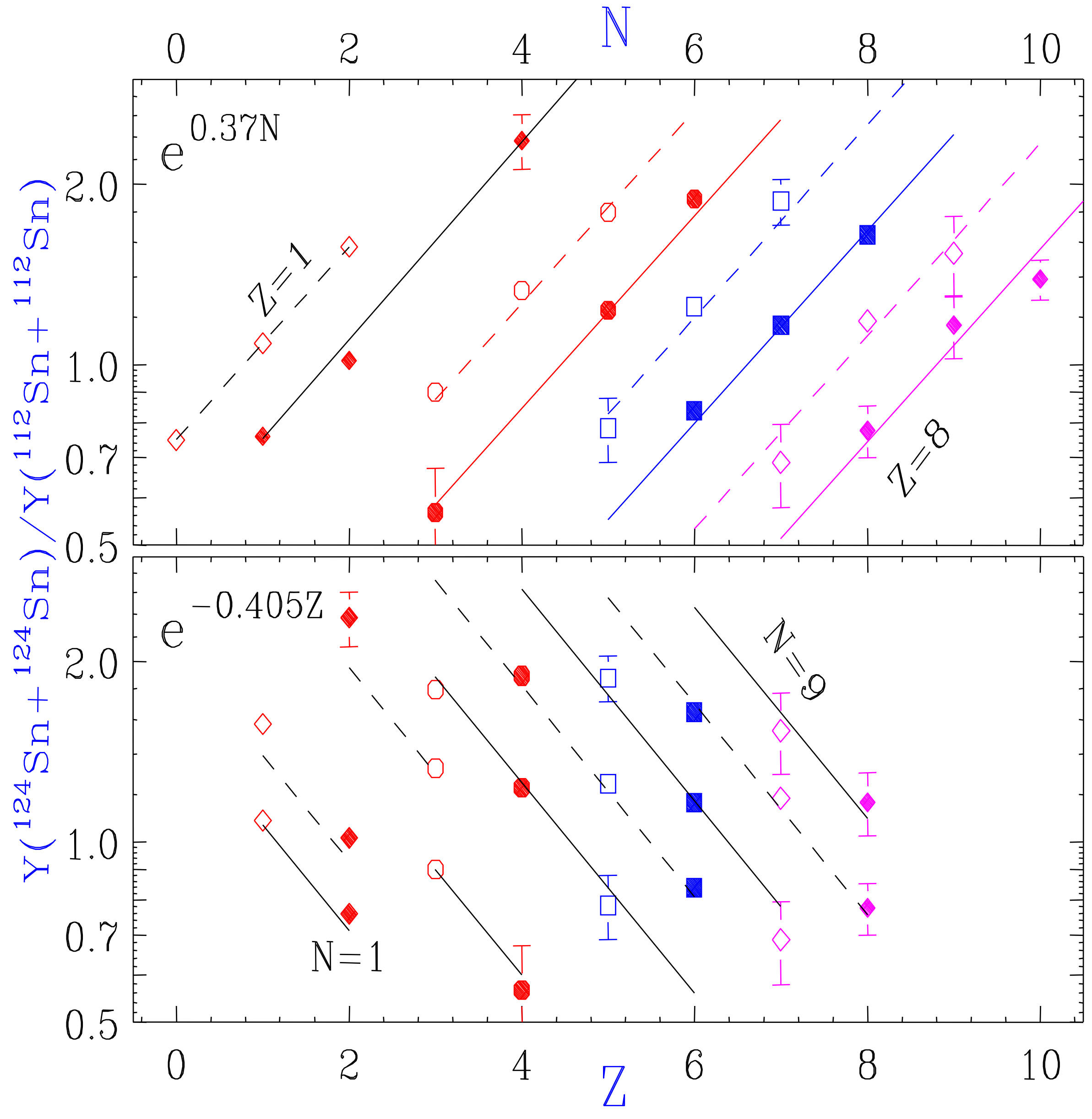
Estee et al, PRL **126**, 162701 (2021)

Two different constraints correlations are orthogonal to each other producing a nice overlapped region.

Different definitions of effective masses splitting in different codes

Need to be resolved in transport codes – in progress

Isoscaling from Relative Isotope Ratios



$R_{21} = Y_2(N,Z)/Y_1(N,Z)$

$R_{21} = C\exp(\alpha N + \beta Z)$

$\alpha = \frac{\Delta\mu_n}{T}, \qquad \beta = \frac{\Delta\mu_p}{T}$

Factorization of yields into p & n densities

Cancellation of effects from sequential feedings

Robust observables to study isospin effects

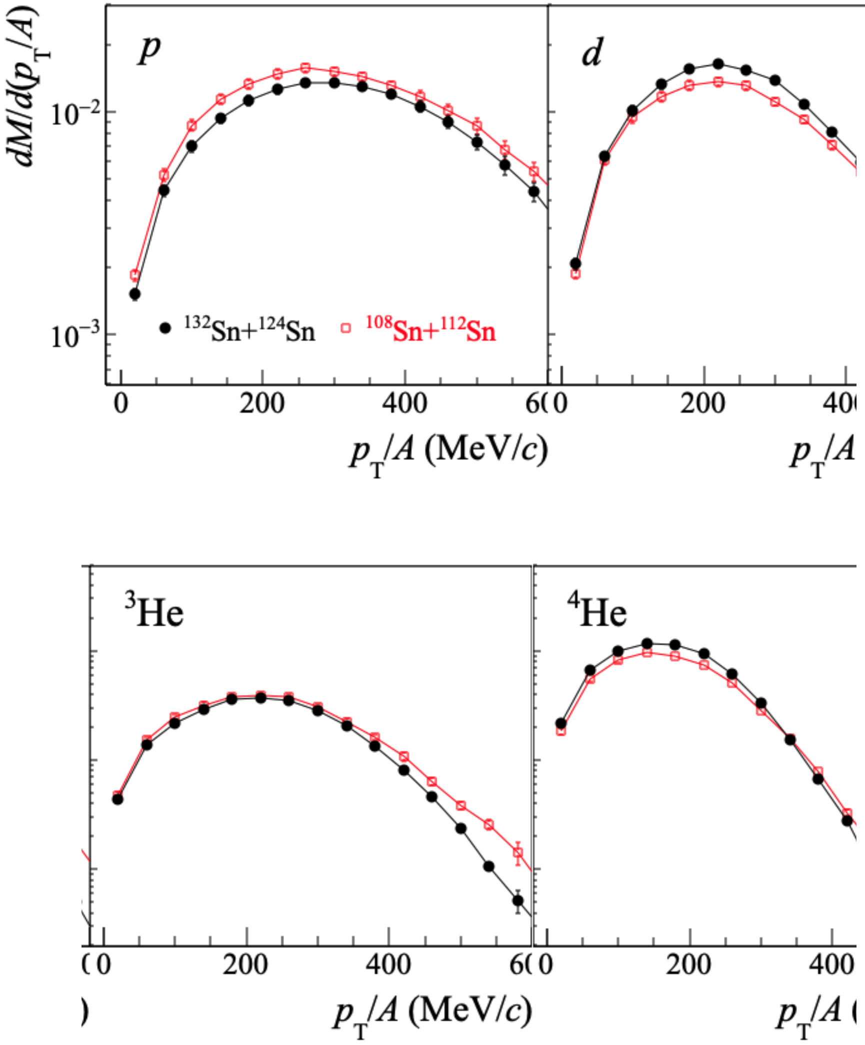
Tsang et al., PRC 64 (2001) 054615

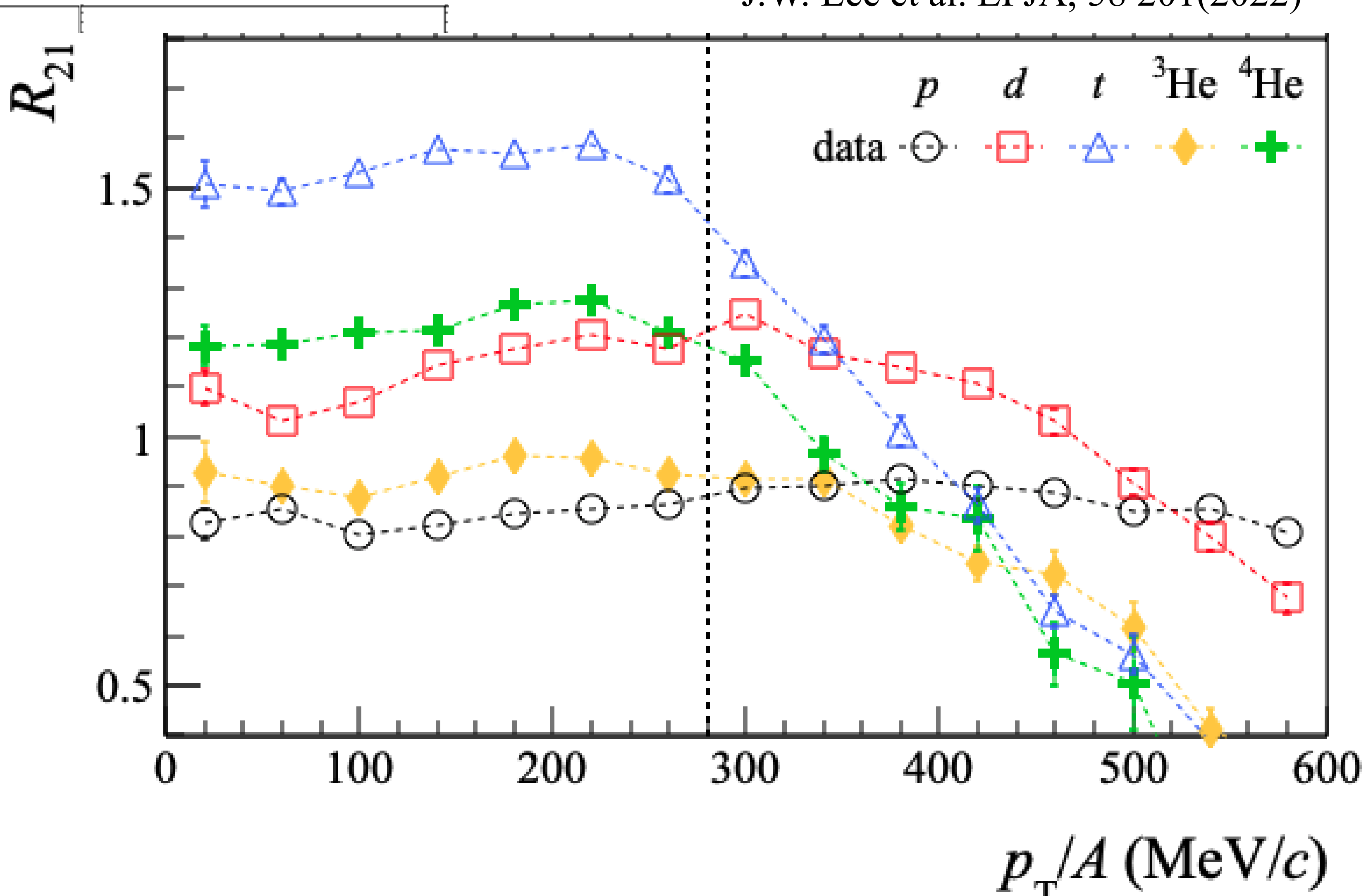
Isoscaling $R_{21} = \frac{Y_2(N,Z)}{Y_1(N,Z)} = C \exp(\alpha N + \beta Z)$

$^{132}Sn+^{124}Sn$ □ $^{108}Sn+^{112}Sn$ at 270 MeV/u

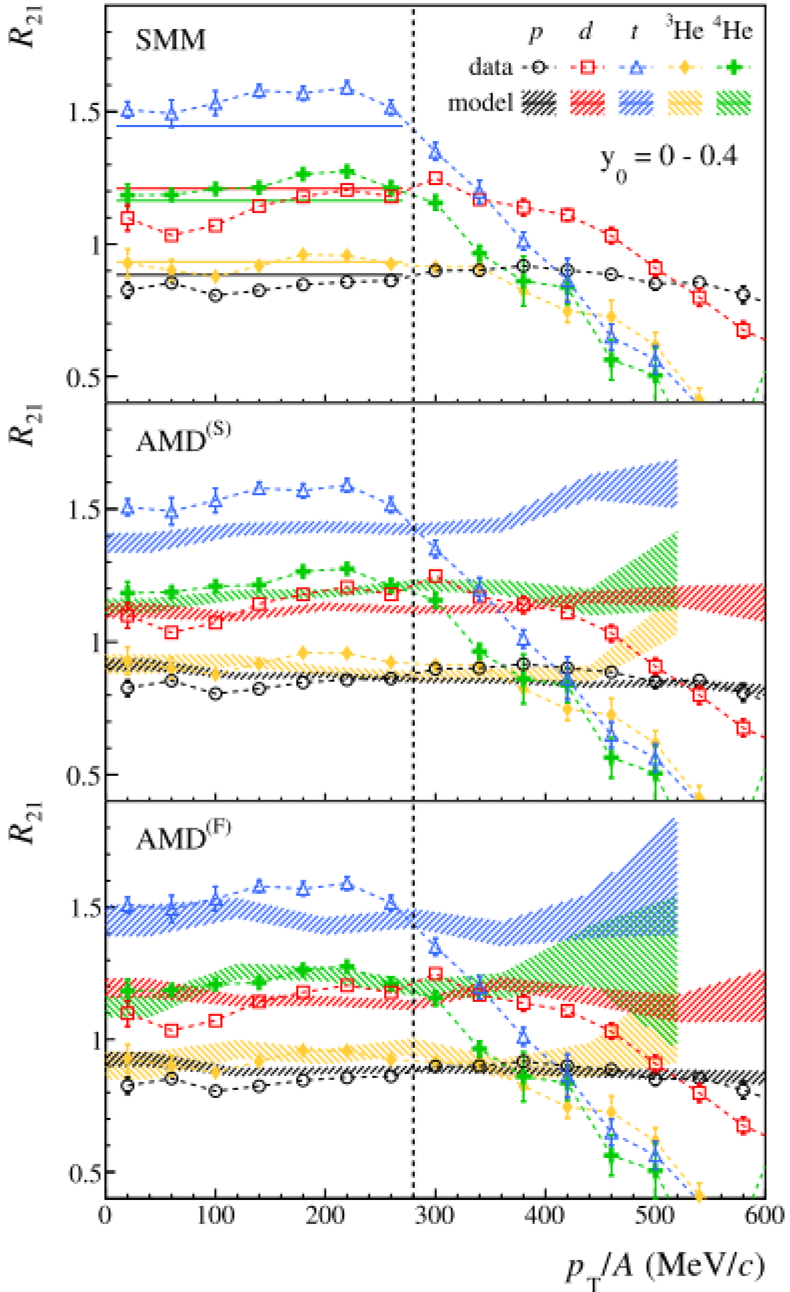
JungWoo Lee

J.W. Lee et al. EPJA, 58 201(2022)





J.W. Lee et al., Eur. Phys. J. A 58, 201 (2022).



Break at p_t/A~270 MeV/c cannot be explained by statistical or transport models.

Clustering around (N-Z)=0, 1 & -1

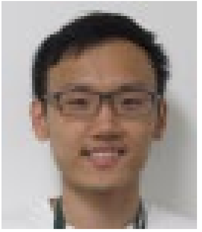
Is t/³He the same as n/p?

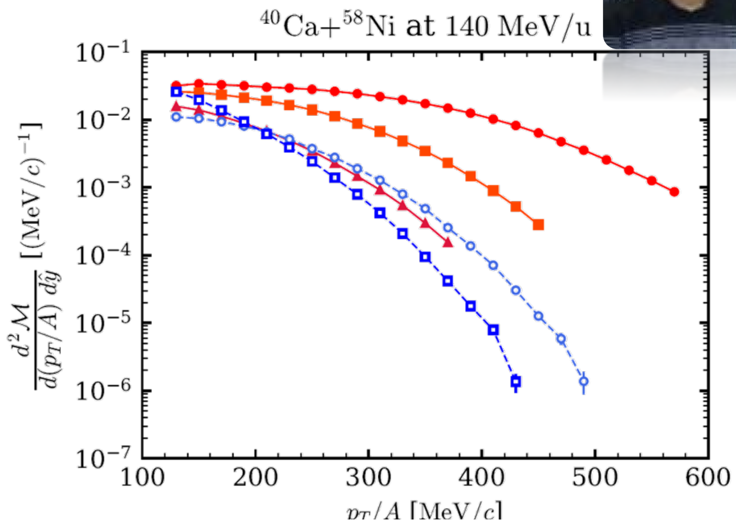
JungWoo Lee

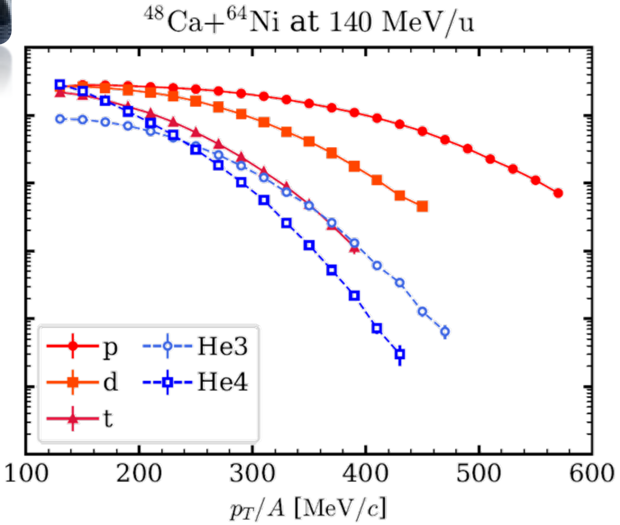
Isoscaling

Rensheng Wang

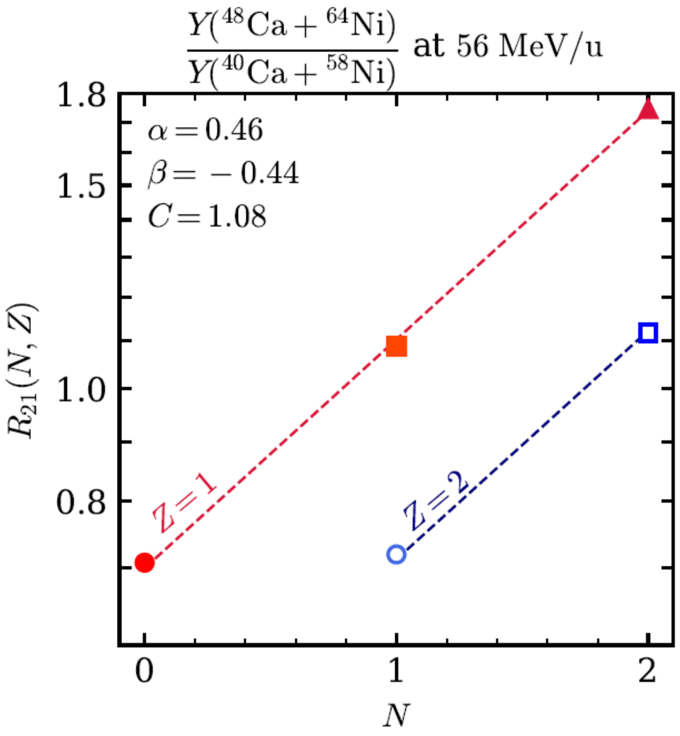
Fanurs Teh

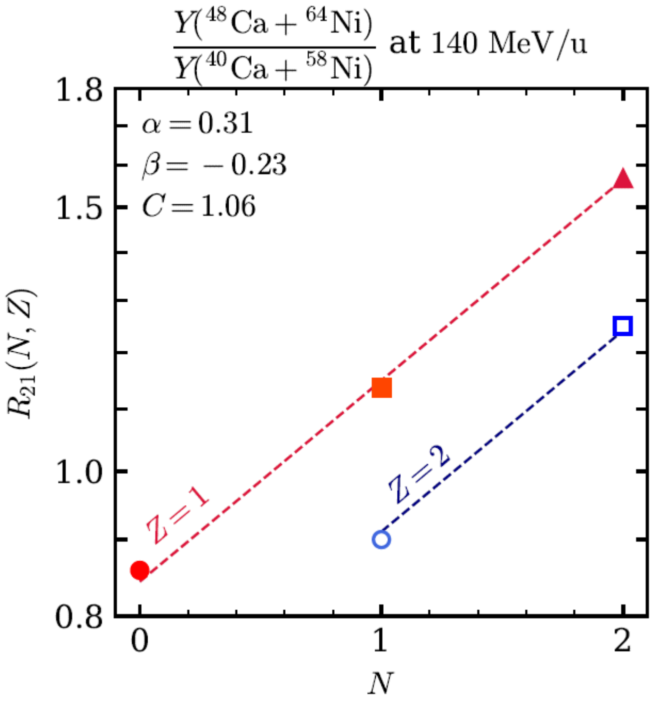




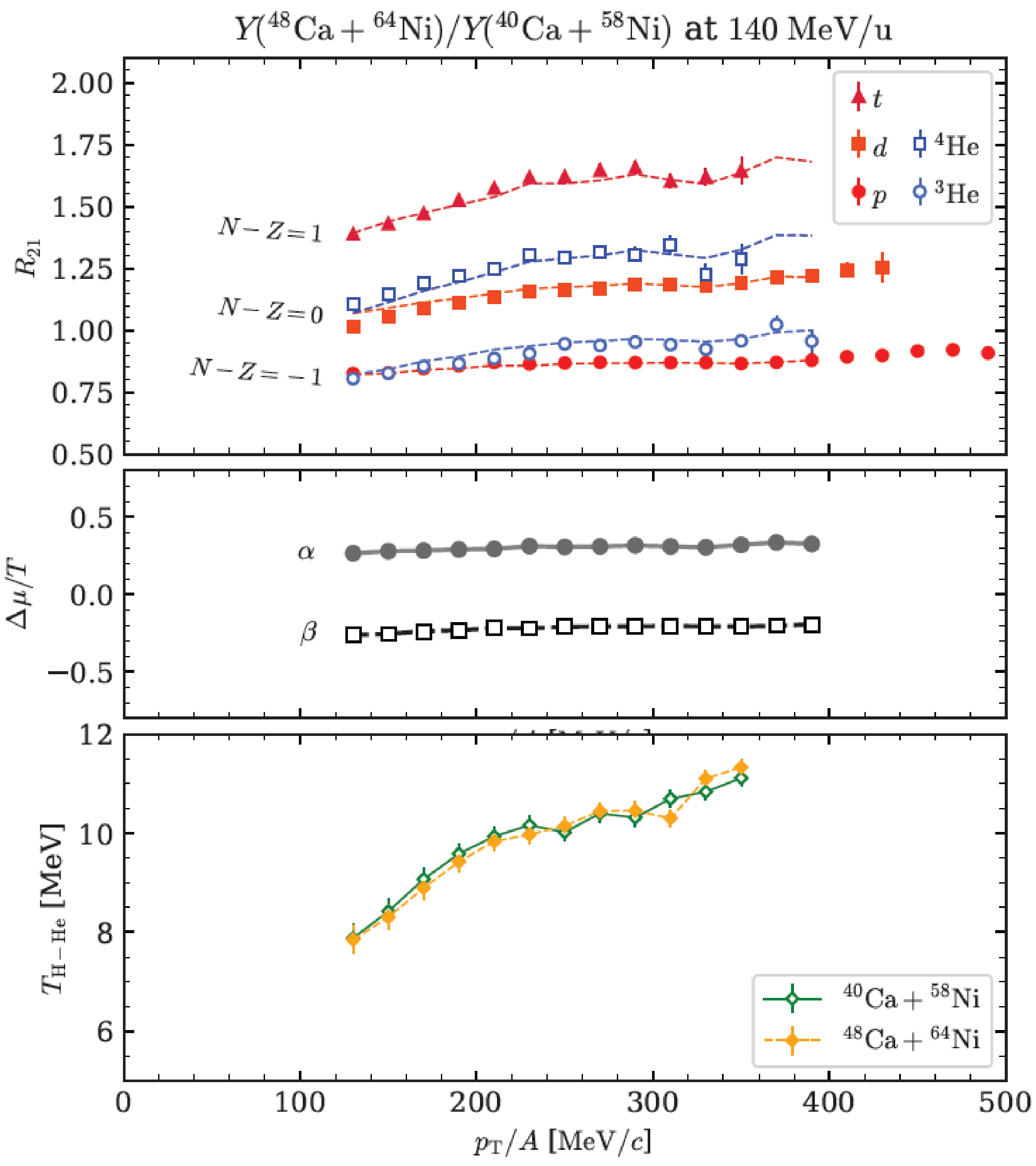


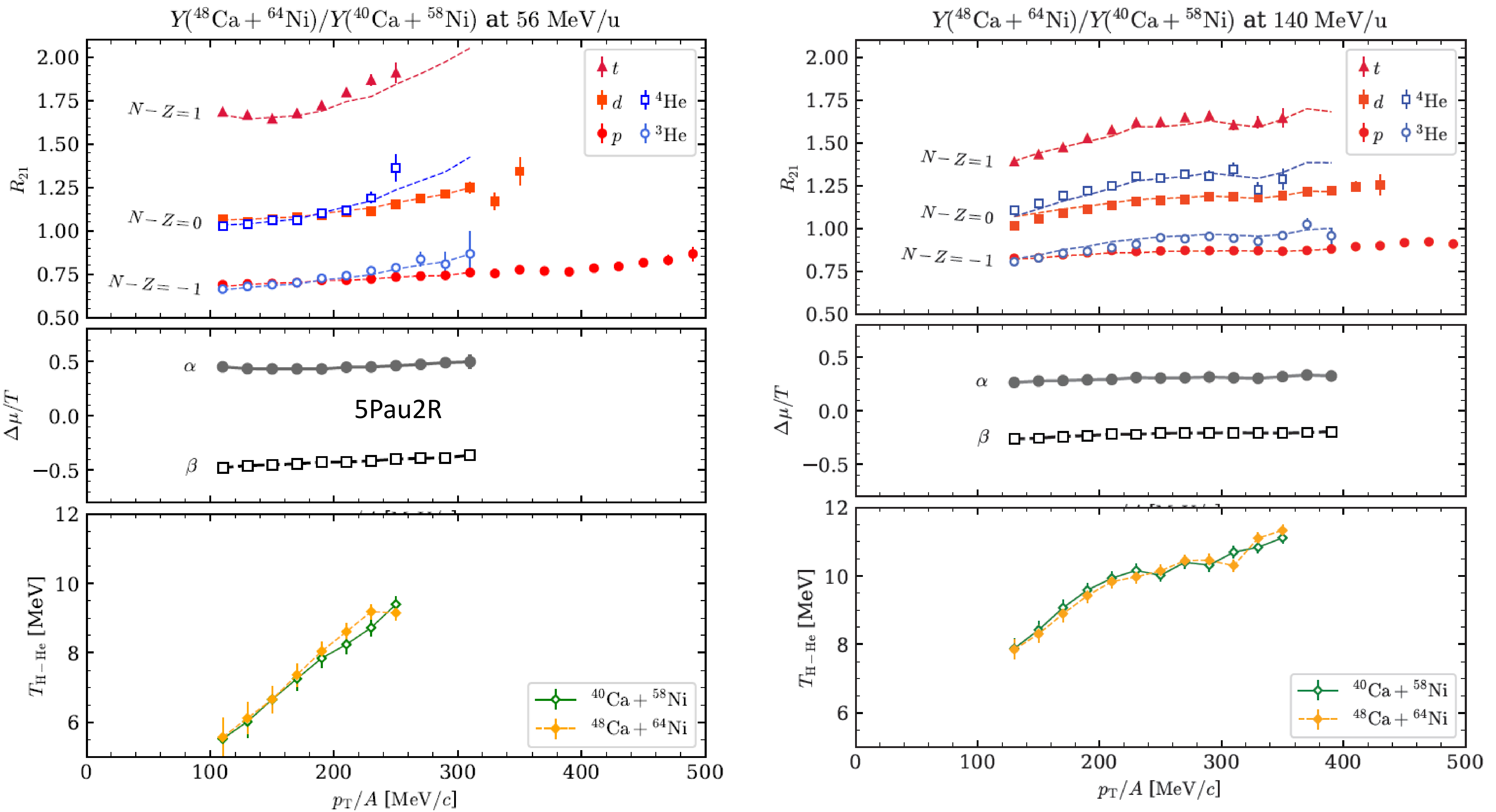
$$R_{21} = \frac{Y_2(N,Z)}{Y_1(N,Z)} = C\,\exp(\alpha N + \beta Z)$$





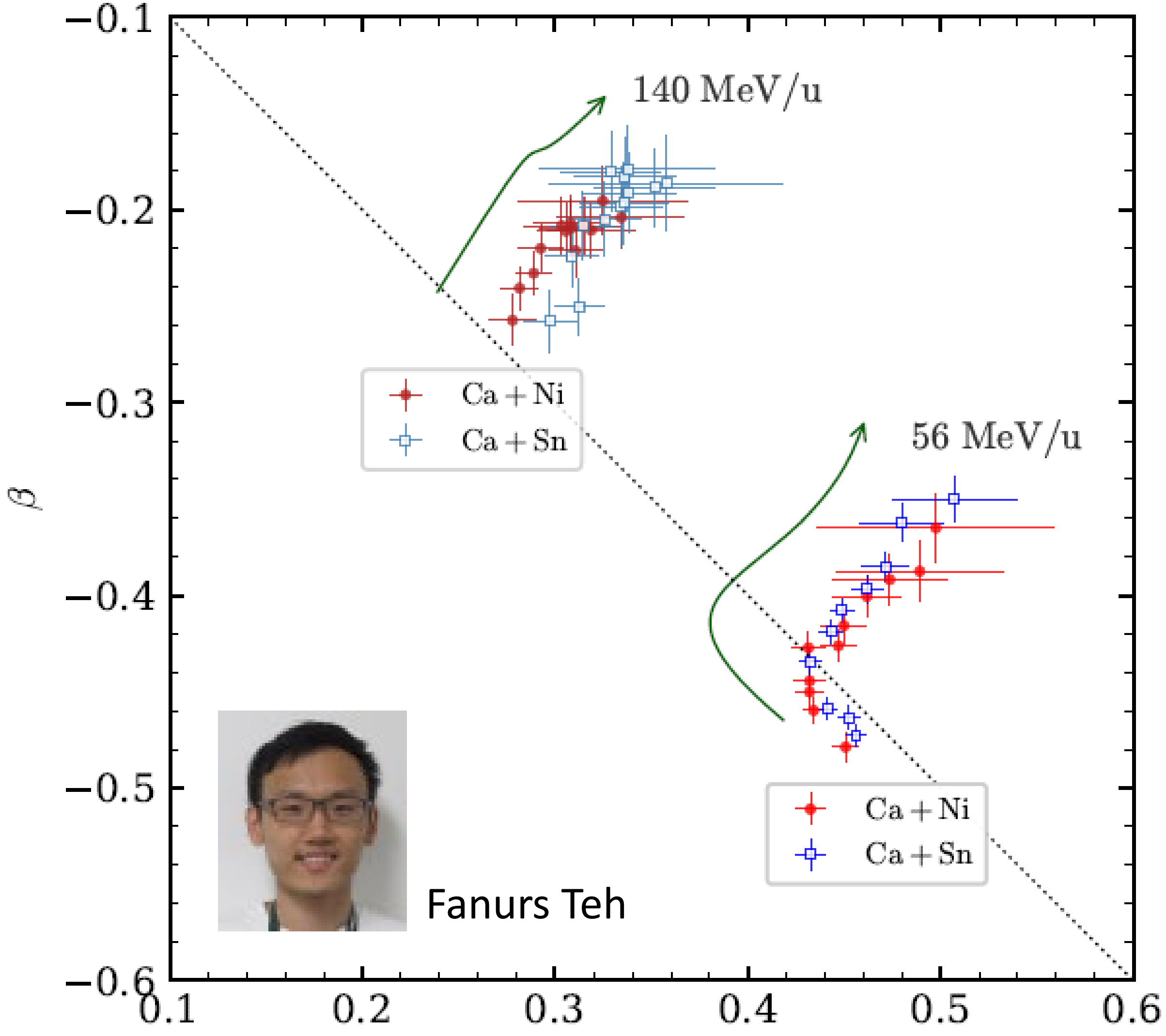
$$R_{21} = Y_2(N,Z)/Y_1(N,Z)$$
$$R_{21} = C\exp(\alpha N + \beta Z)$$
$$\alpha = \frac{\Delta\mu_n}{T}, \qquad \beta = \frac{\Delta\mu_p}{T}$$





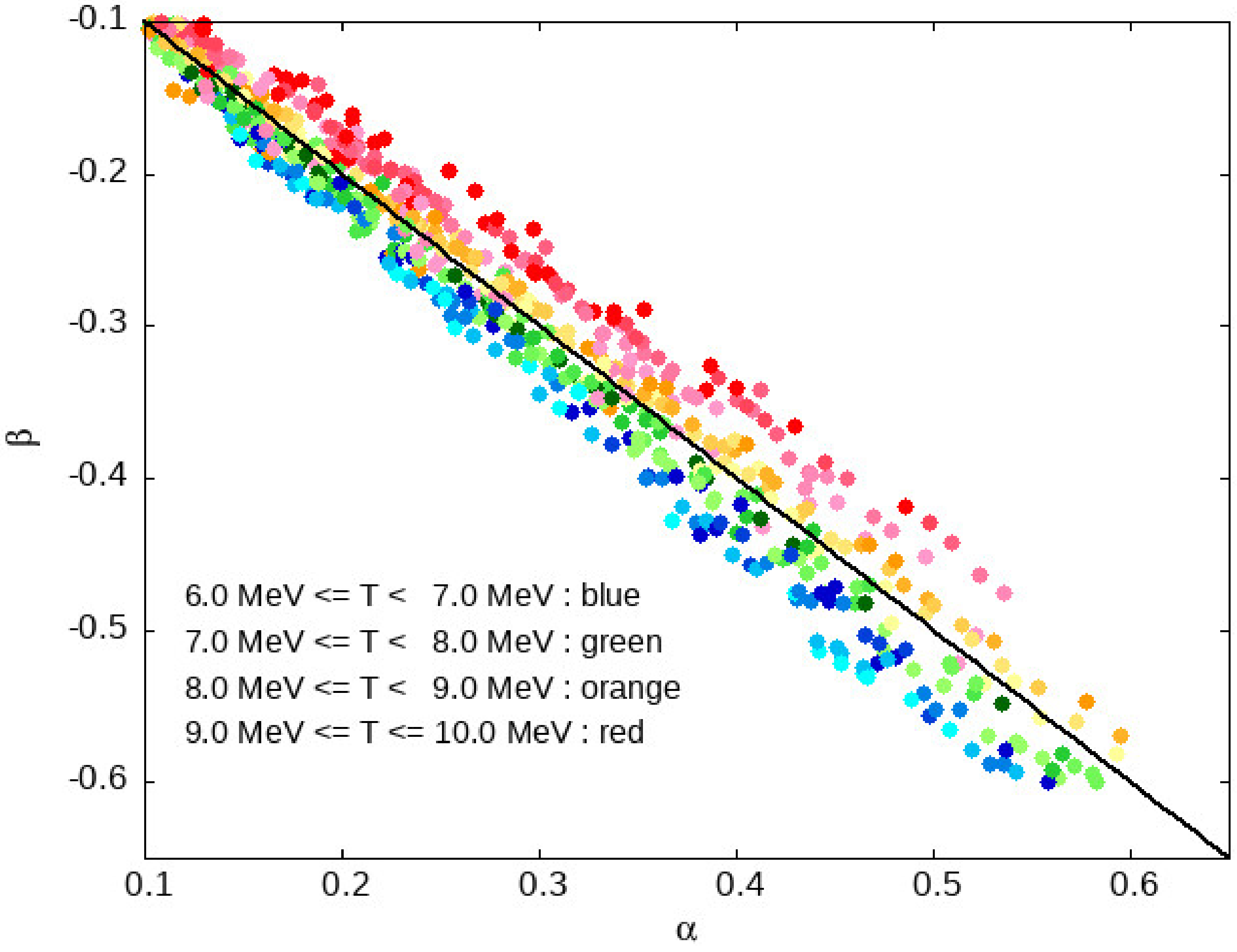
$Y(^{48}Ca+^{64}Ni)/Y(^{40}Ca+^{58}Ni)$ at 56 MeV/u
$Y(^{48}Ca+^{64}Ni)/Y(^{40}Ca+^{58}Ni)$ at 140 MeV/u
R_{21}
$N-Z=1$
$N-Z=0$
$N-Z=-1$
t
d
p
^4He
^3He
$\Delta\mu/T$
α
β
5Pau2R
T_{H-He} [MeV]
$^{40}Ca+^{58}Ni$
$^{48}Ca+^{64}Ni$
p_T/A [MeV/c]

Temperature Dependence of isoscaling parameters

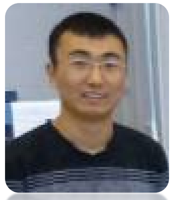


Fanurs Teh

SMM by S. Souza



Isoscaling



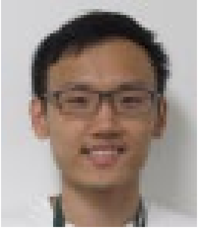
Renshеng Wang

What about neutrons?

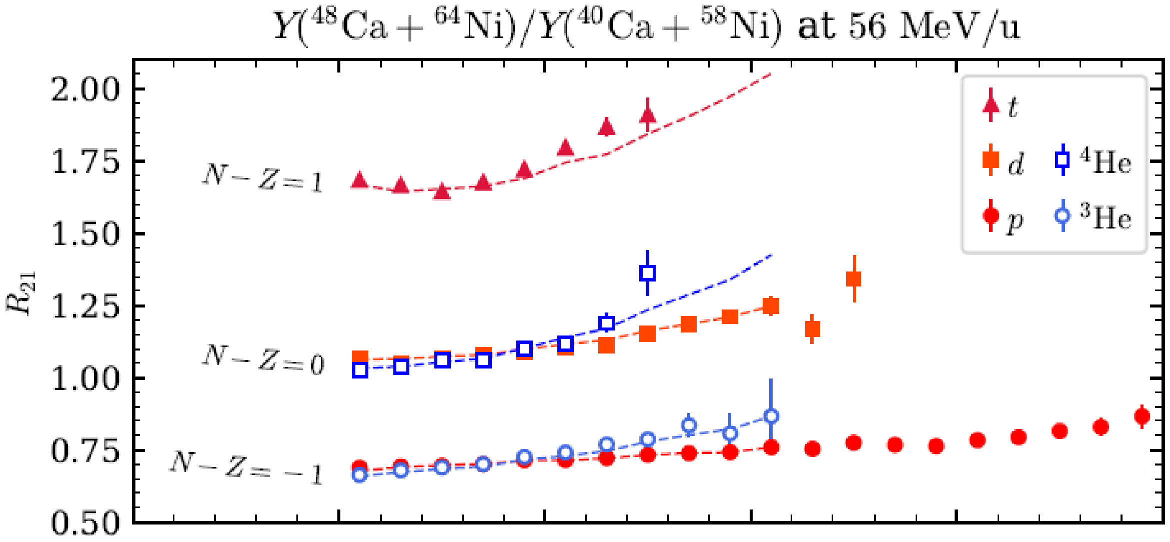
Is t/³He the same as n/p?

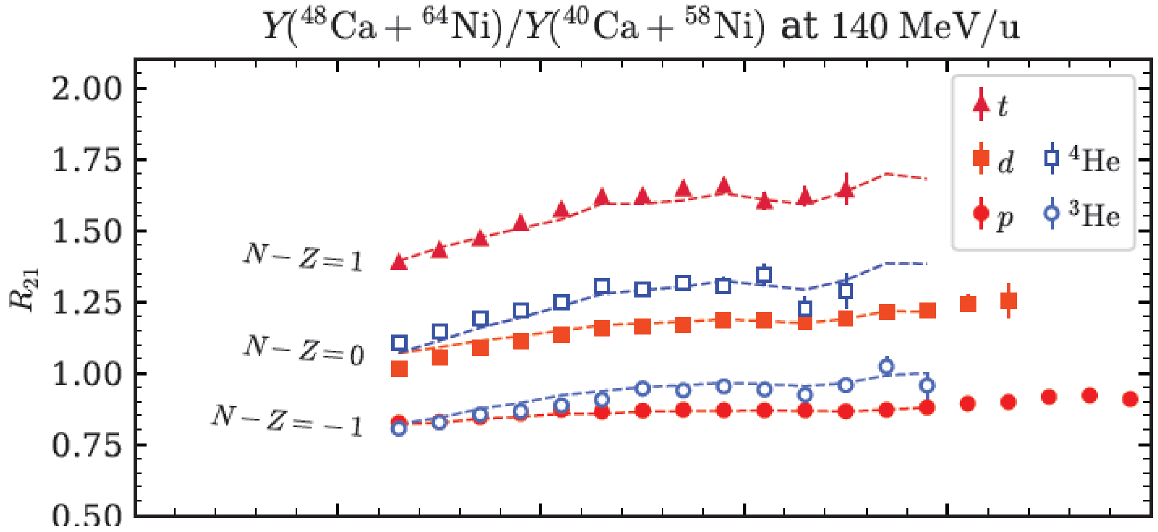
Is Y(n) ∝Y(p)*Y(t)/Y(3He)?

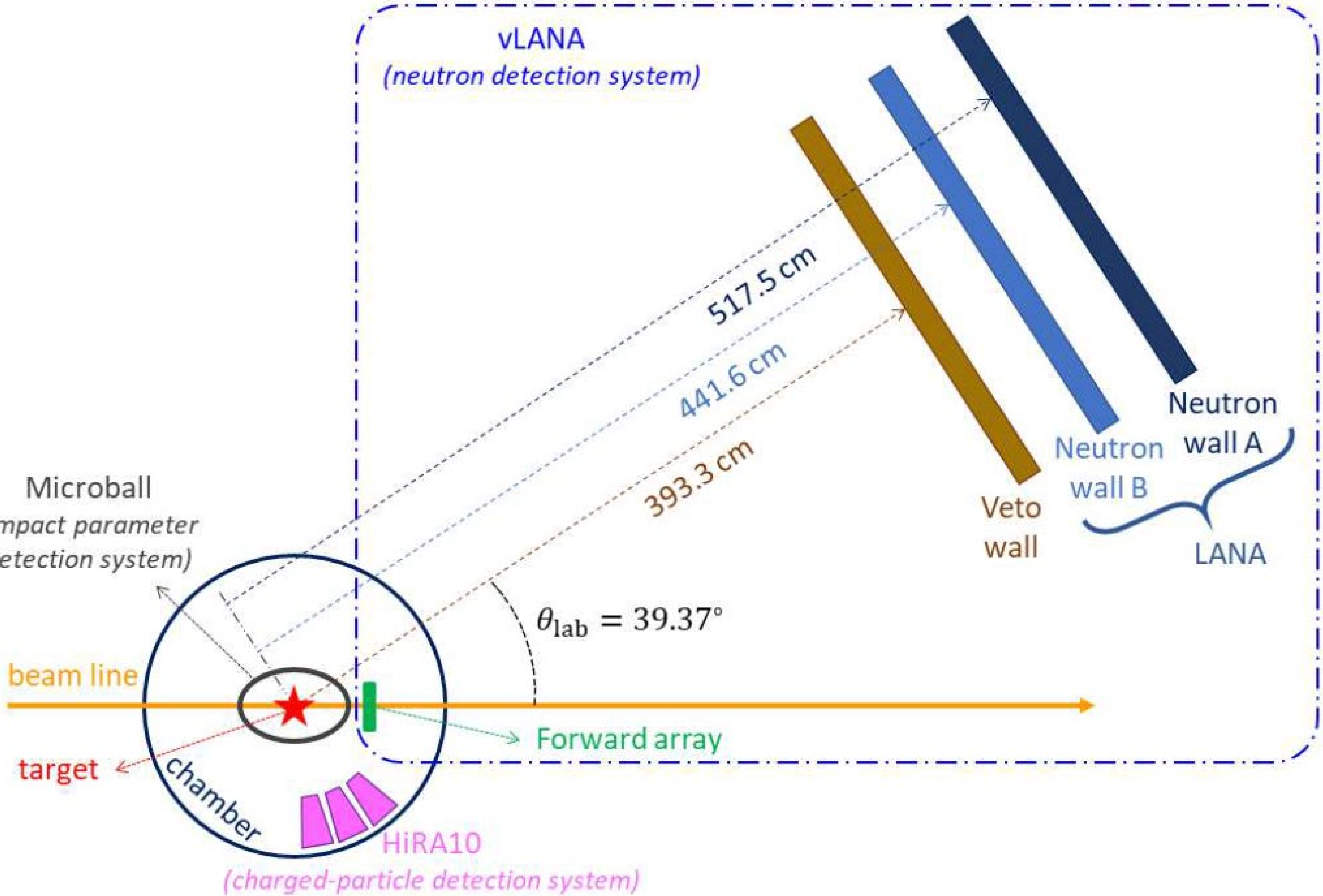
Pseudo-neutron



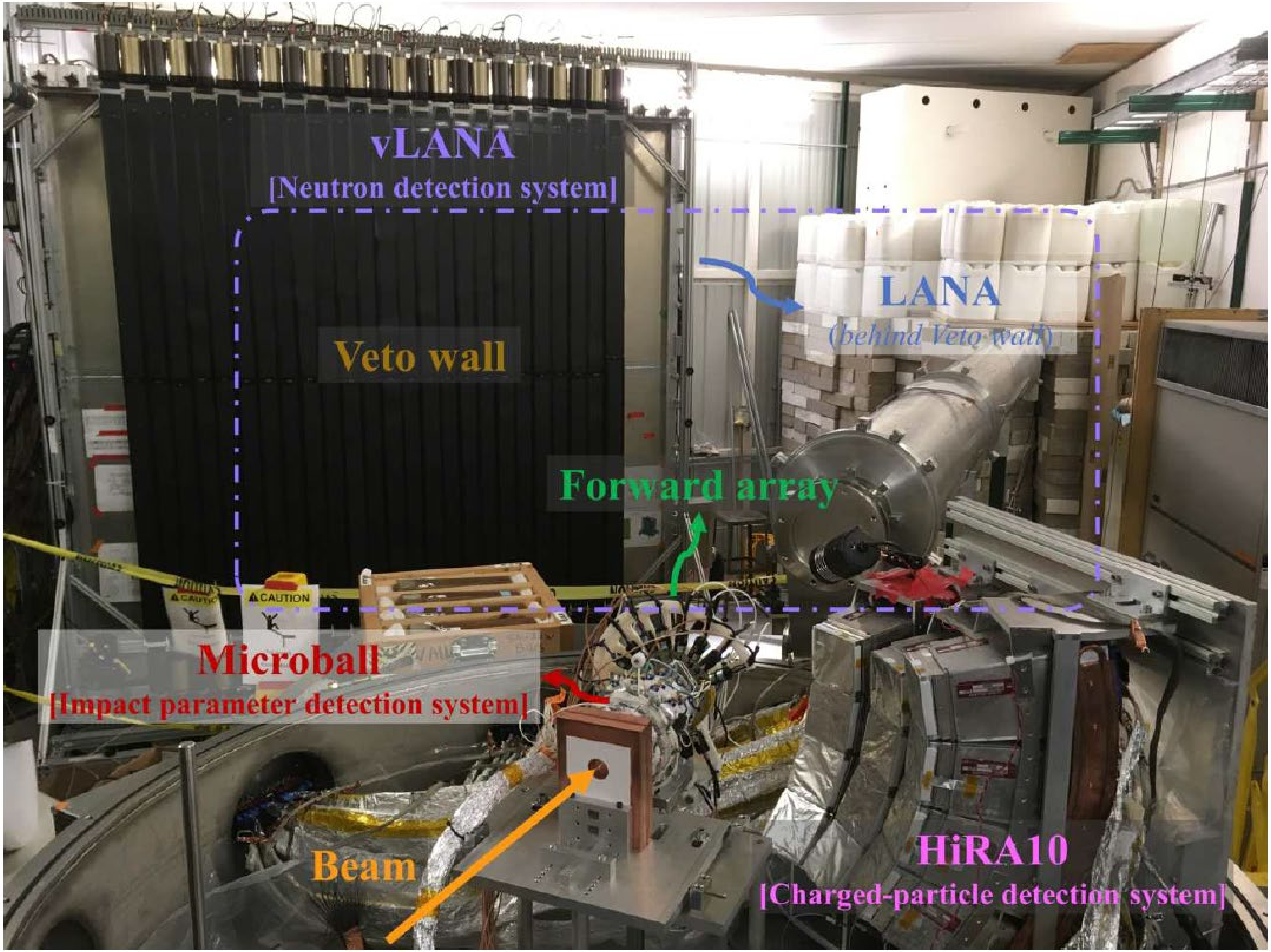
Fanurs Teh







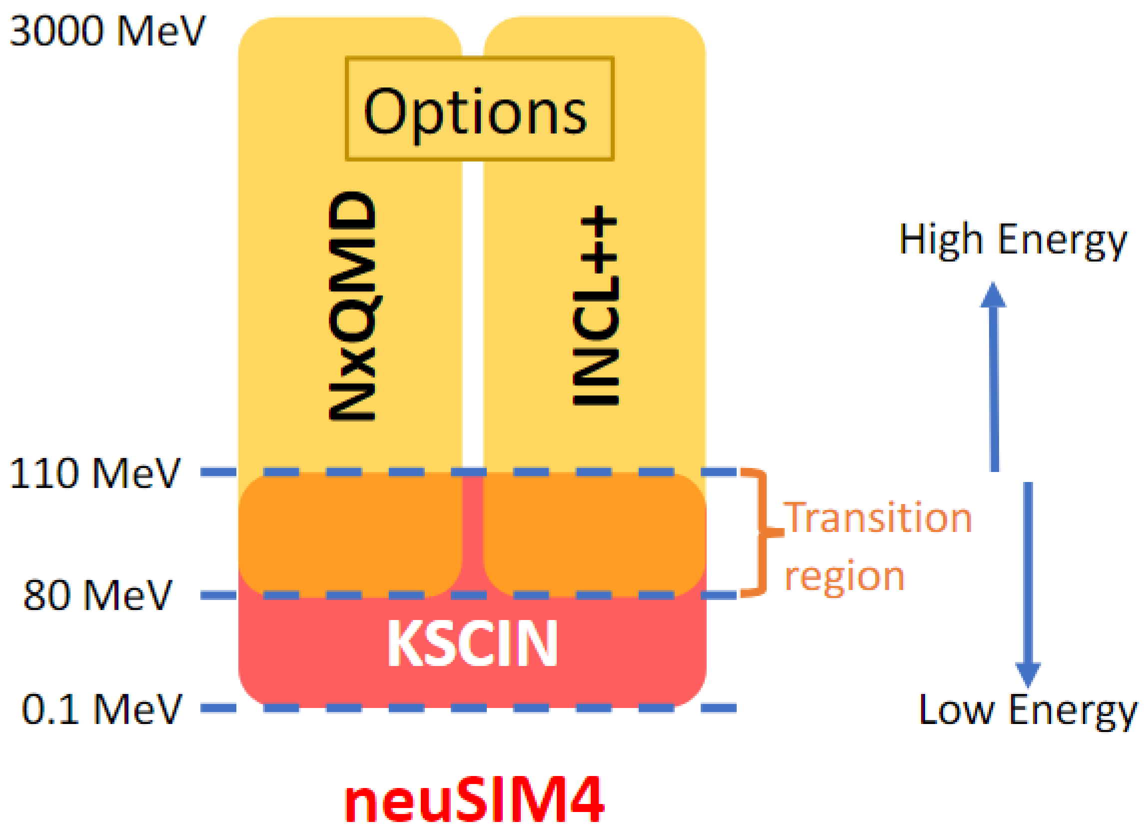
vLANA
(neutron detection system)
517.5 cm
441.6 cm
393.3 cm
Neutron wall A
Neutron wall B
Veto wall
LANA
Microball
(impact parameter detection system)
$\theta_{\mathrm{lab}} = 39.37^{\circ}$
beam line
Forward array
target
chamber
HiRA10
(charged-particle detection system)

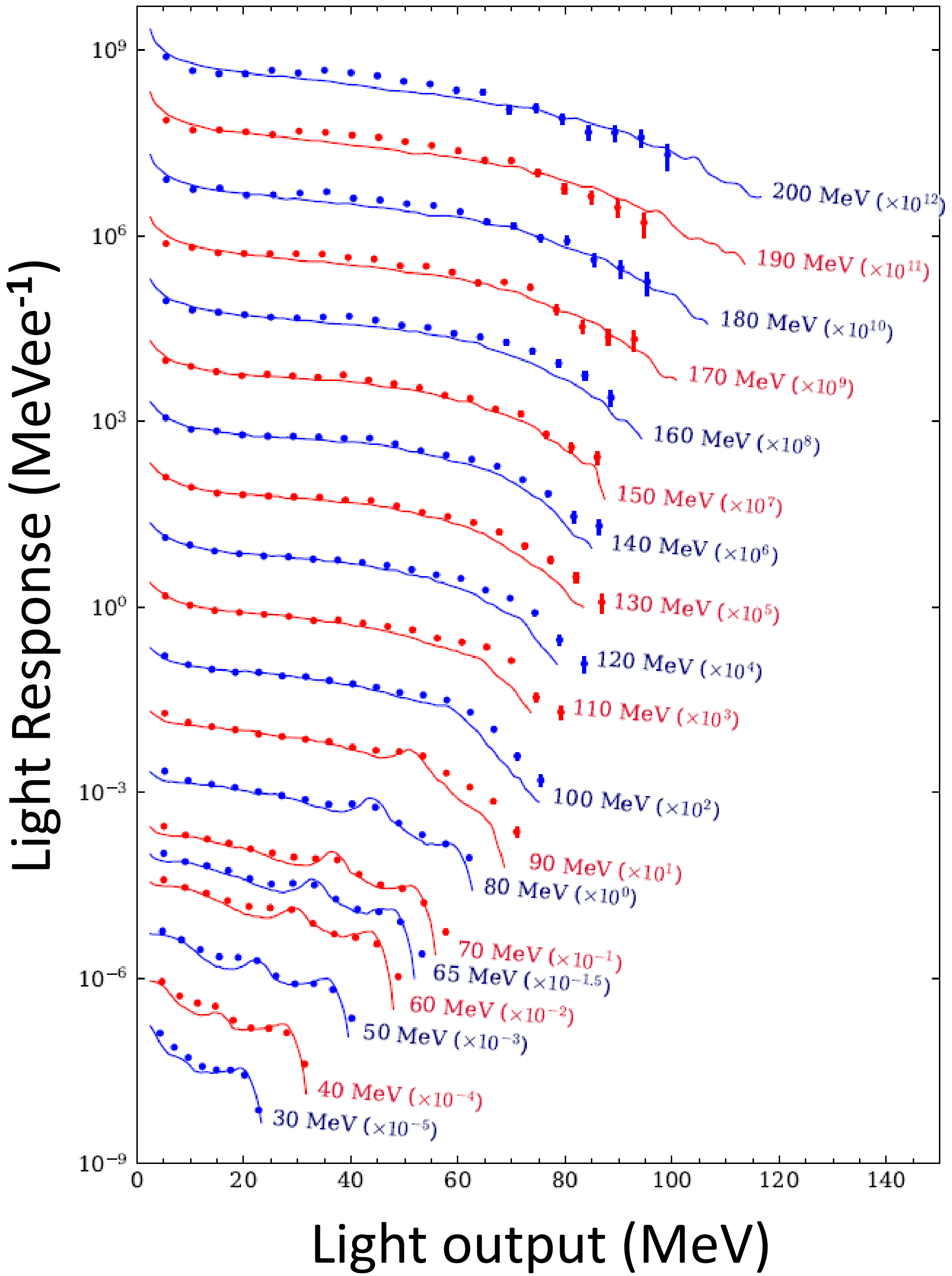

vLANA
[Neutron detection system]
LANA
(behind Veto wall)
Veto wall
Forward array
Microball
[Impact parameter detection system]
Beam
HiRA10
[Charged-particle detection system]

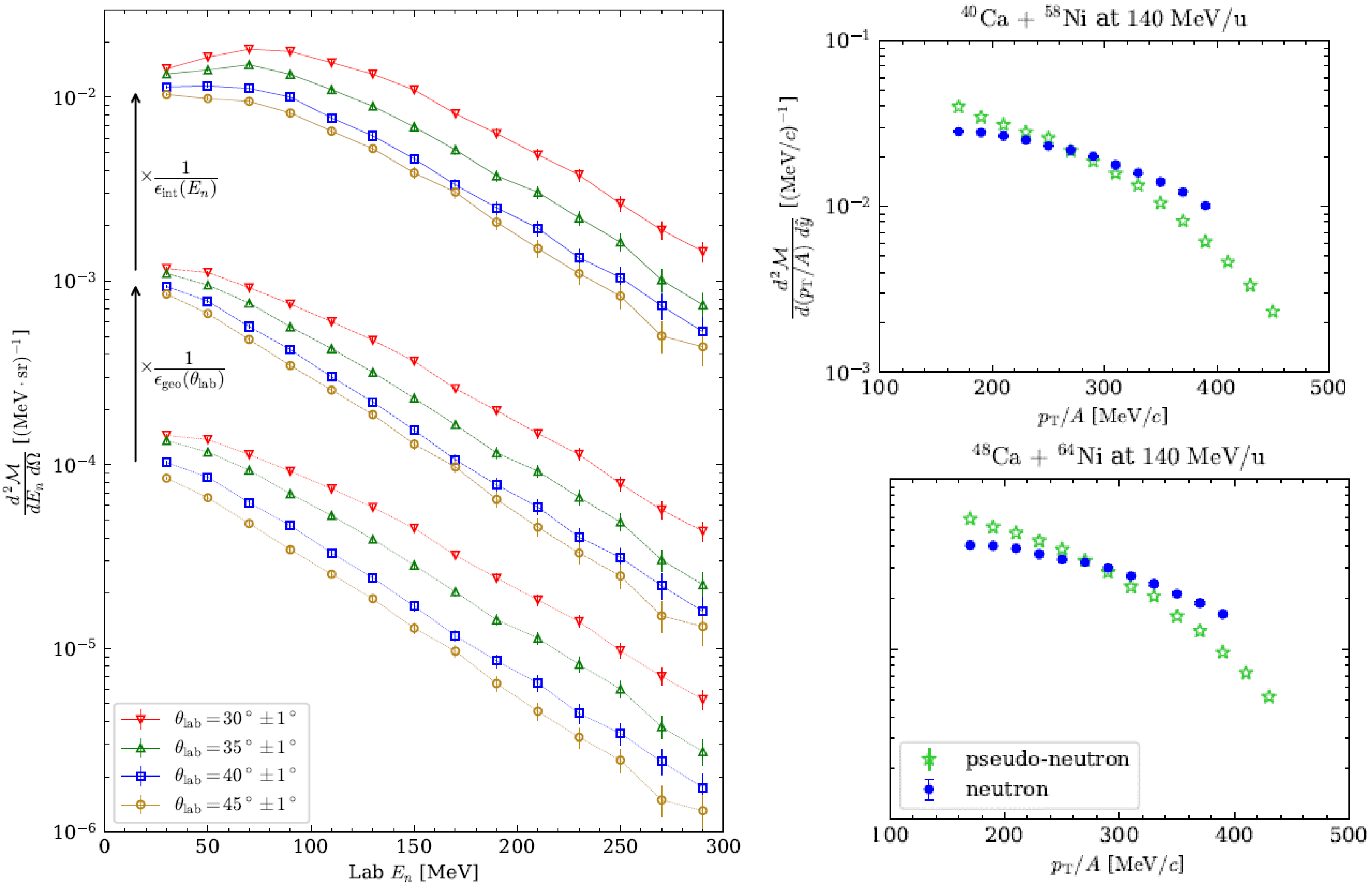
neuSIM4 : Neutron Simulation programs

Jeonghyeok Park et al.,

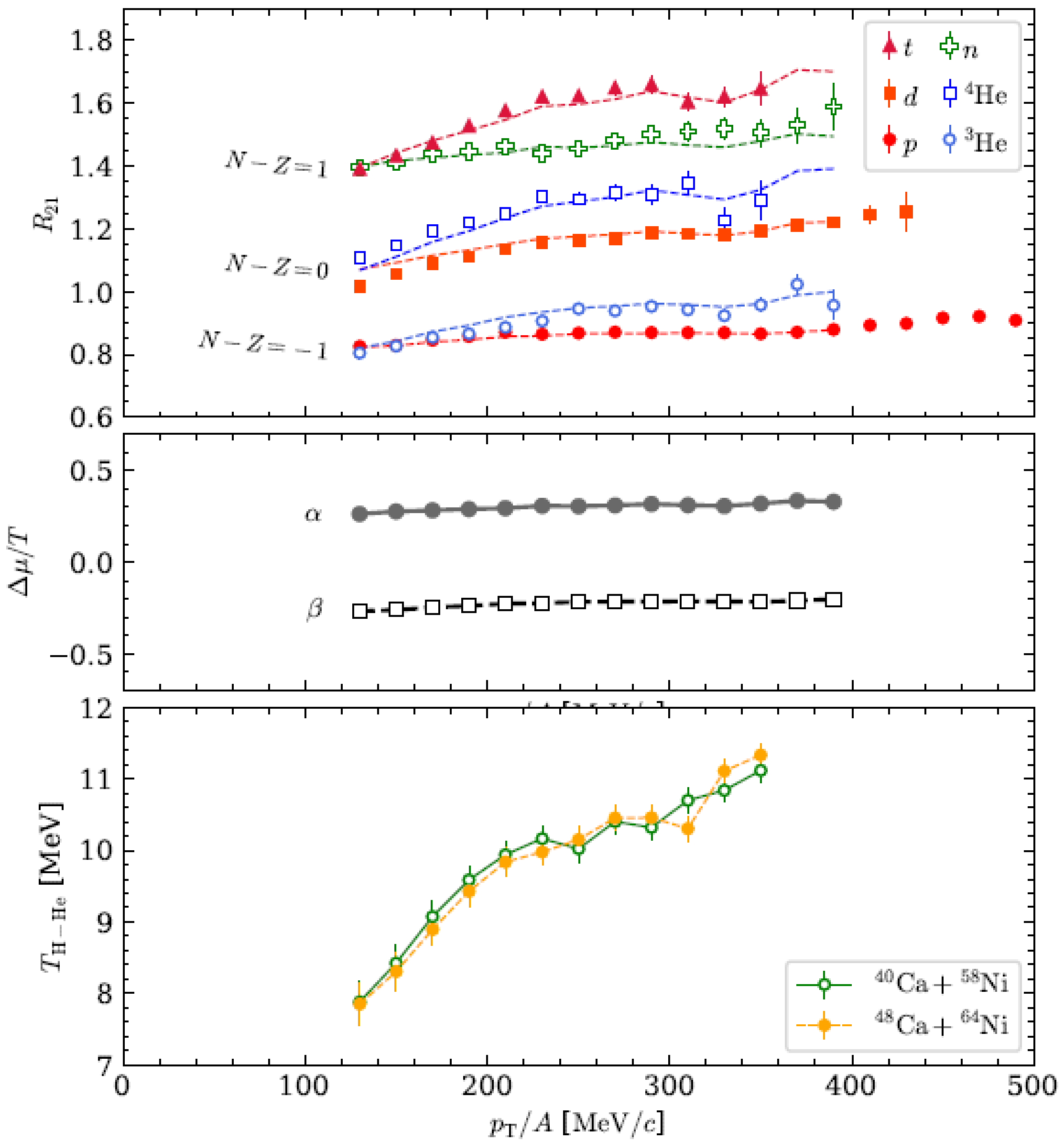
NIMA 1065, (2024), 169475



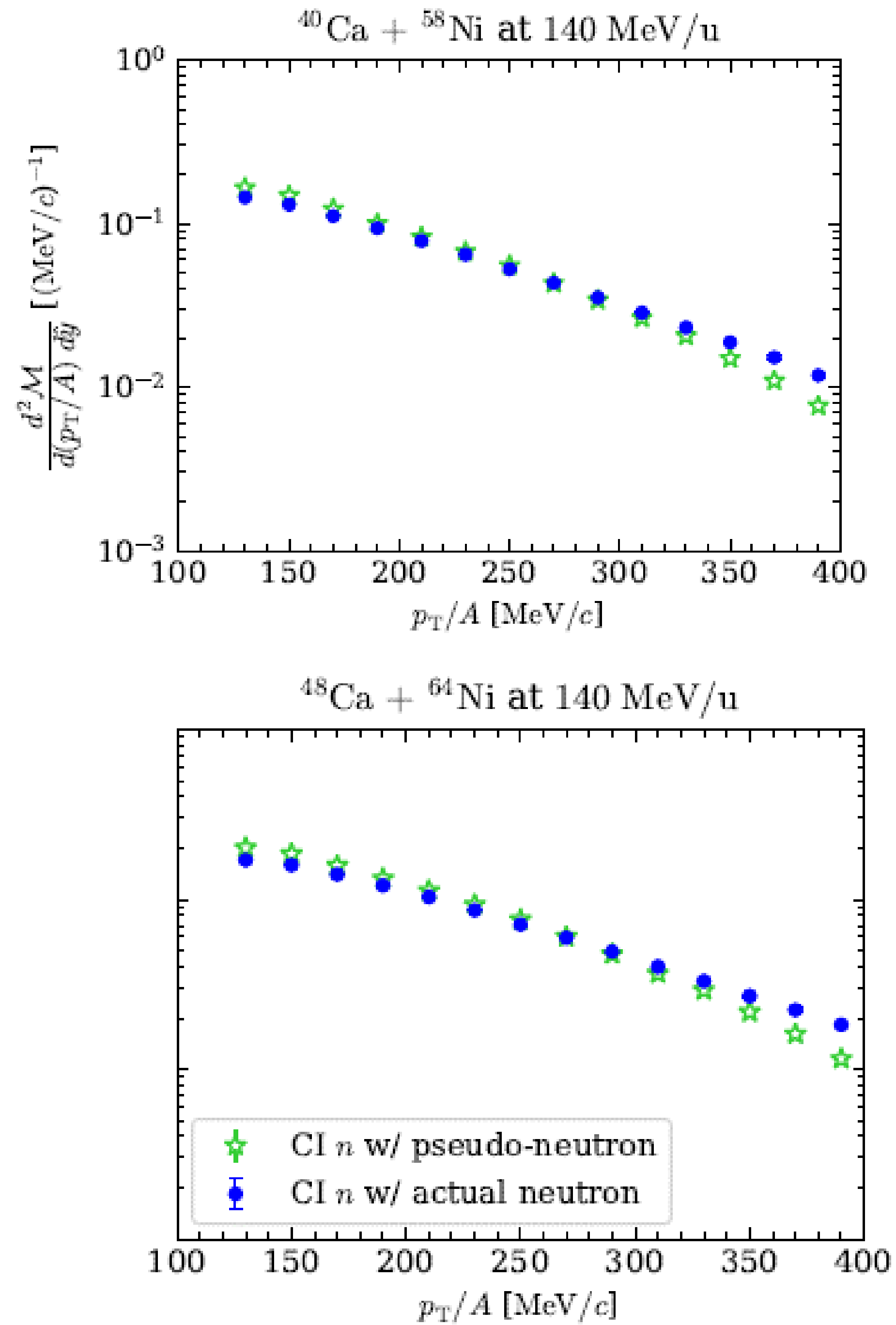




$\frac{d^2\mathcal{M}}{dE_n\, d\Omega}$ [(MeV · sr)$^{-1}$]
$\times \frac{1}{\epsilon_{\text{int}}(E_n)}$
$\times \frac{1}{\epsilon_{\text{geo}}(\theta_{\text{lab}})}$
$\theta_{\text{lab}} = 30° \pm 1°$
$\theta_{\text{lab}} = 35° \pm 1°$
$\theta_{\text{lab}} = 40° \pm 1°$
$\theta_{\text{lab}} = 45° \pm 1°$
Lab E_n [MeV]
^{40}Ca + ^{58}Ni at 140 MeV/u
$\frac{d^2\mathcal{M}}{d(p_T/A)\, d\hat{y}}$ [(MeV/c)$^{-1}$]
p_T/A [MeV/c]
^{48}Ca + ^{64}Ni at 140 MeV/u
pseudo-neutron
neutron
p_T/A [MeV/c]

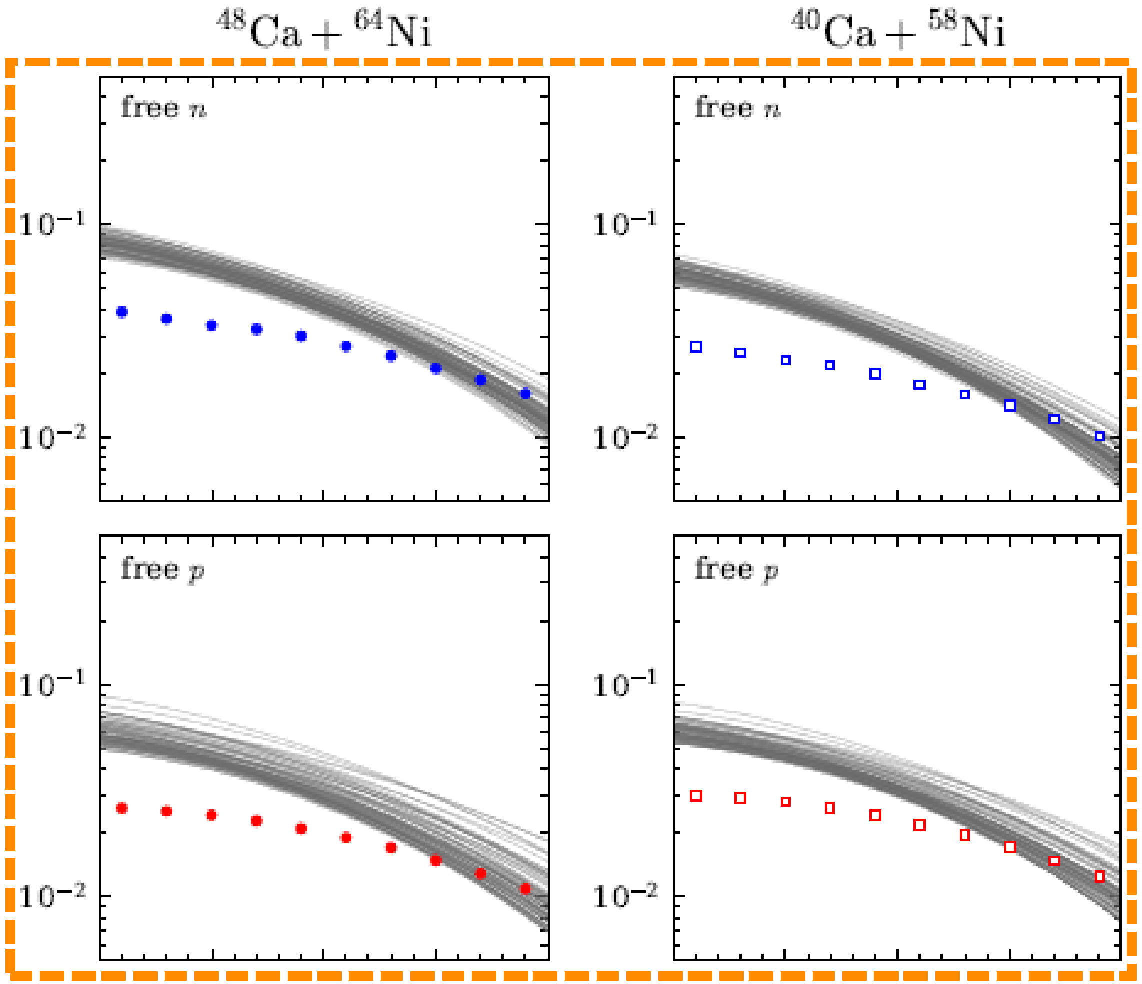


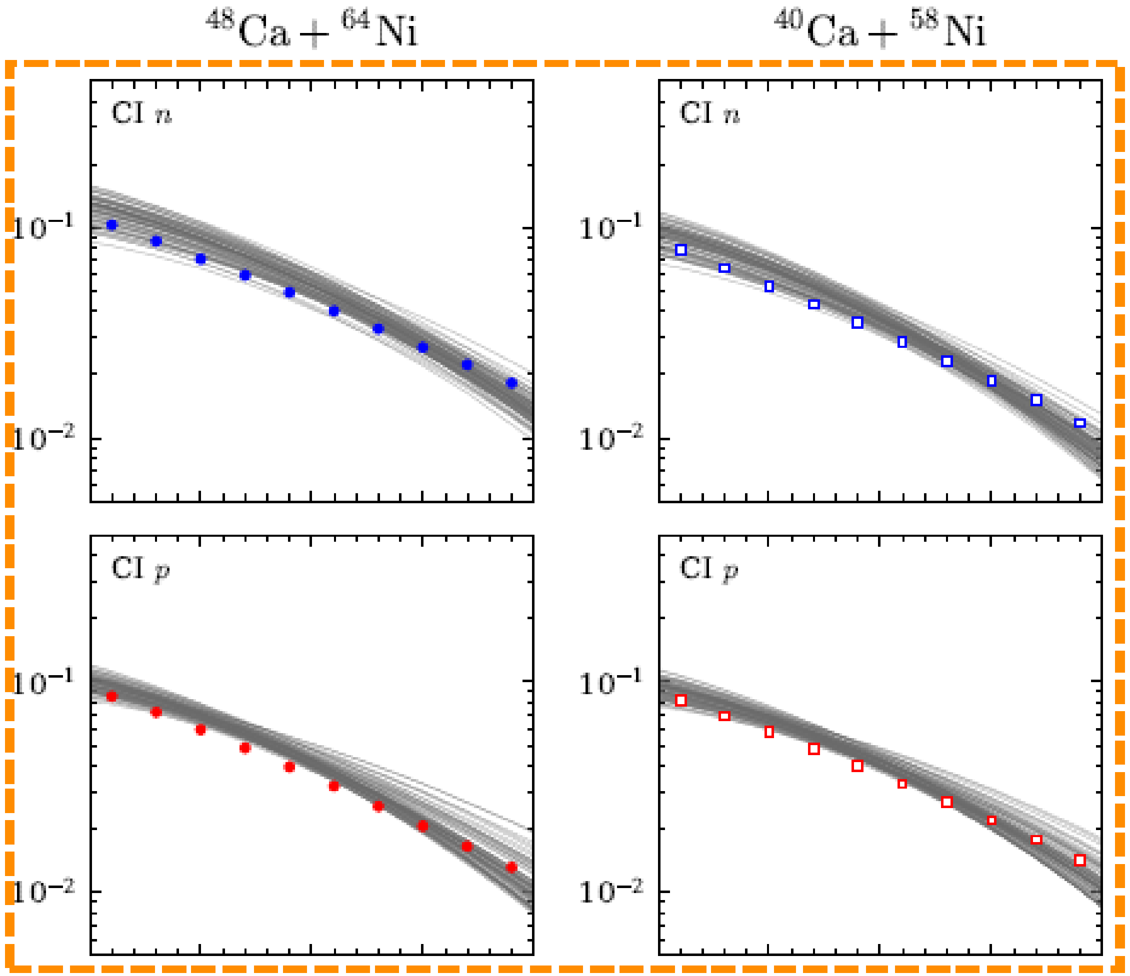
t
n
d
4He
p
3He
N − Z = 1
N − Z = 0
N − Z = −1
R21
α
β
Δμ/T
T H−He [MeV]
40Ca + 58Ni
48Ca + 64Ni
pT/A [MeV/c]



40Ca + 58Ni at 140 MeV/u
48Ca + 64Ni at 140 MeV/u
pT/A [MeV/c]
CI n w/ pseudo-neutron
CI n w/ actual neutron

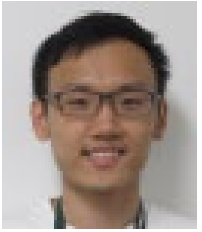
n-productions from transport models needs Work





YingXun Zhang

Fanurs Teh



Conclusion:

- **Data from SpiRIT I is available**
  - ^{108}Sn + ^{112}Sn @ 270 MeV (May 2016)
  - ^{132}Sn + ^{124}Sn @ 270 MeV (May 2016)
- **Moving Forward : SpiRIT II in Progress**
  - ^{124}Xe + ^{112}Sn @ 320 MeV (June 2024)
  - ^{136}Xe + ^{124}Sn @ 320 MeV (Oct 2024)
- **Evaluate the neutron detection and production mechanism**
- **Transport Models – panel discussions & TMEP meeting**

U.S. DEPARTMENT OF ENERGY Office of Science
SπRIT
文部科学省 MEXT MINISTRY OF EDUCATION, CULTURE, SPORTS, SCIENCE AND TECHNOLOGY-JAPAN
NSF U.S. National Science Foundation