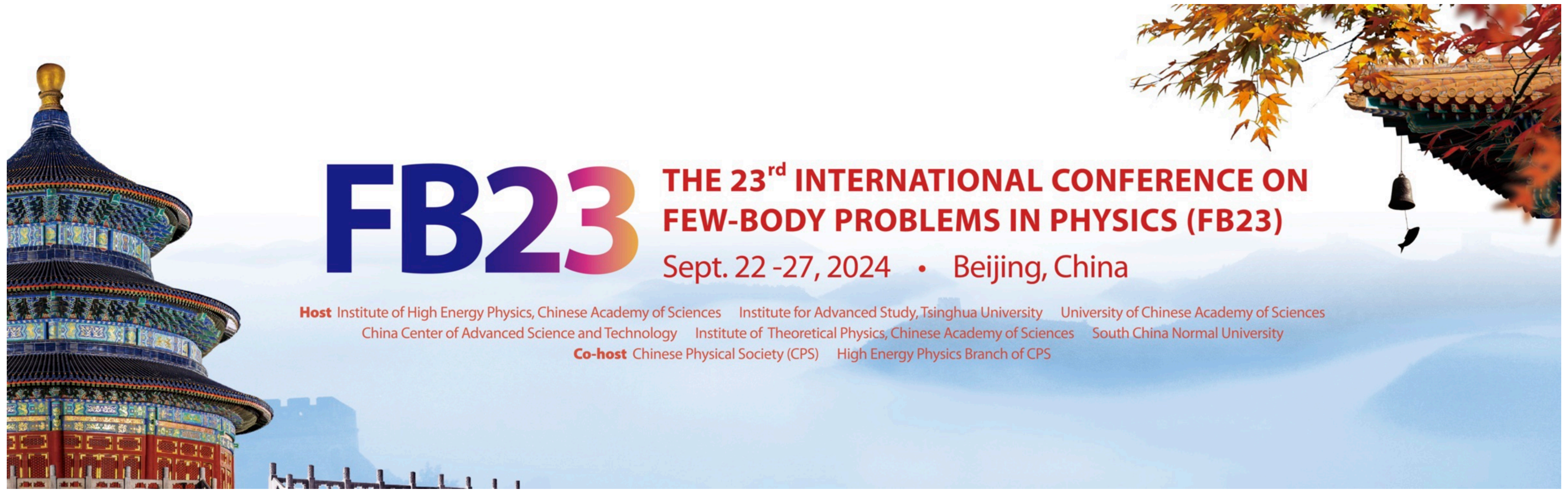
S. Abe, Phys. Rev. D 109, 036009 (2024)

https://github.com/SeishoAbe/NucDeEx

Validation and application of nuclear deexcitation event generator NucDeEx



Seisho Abe

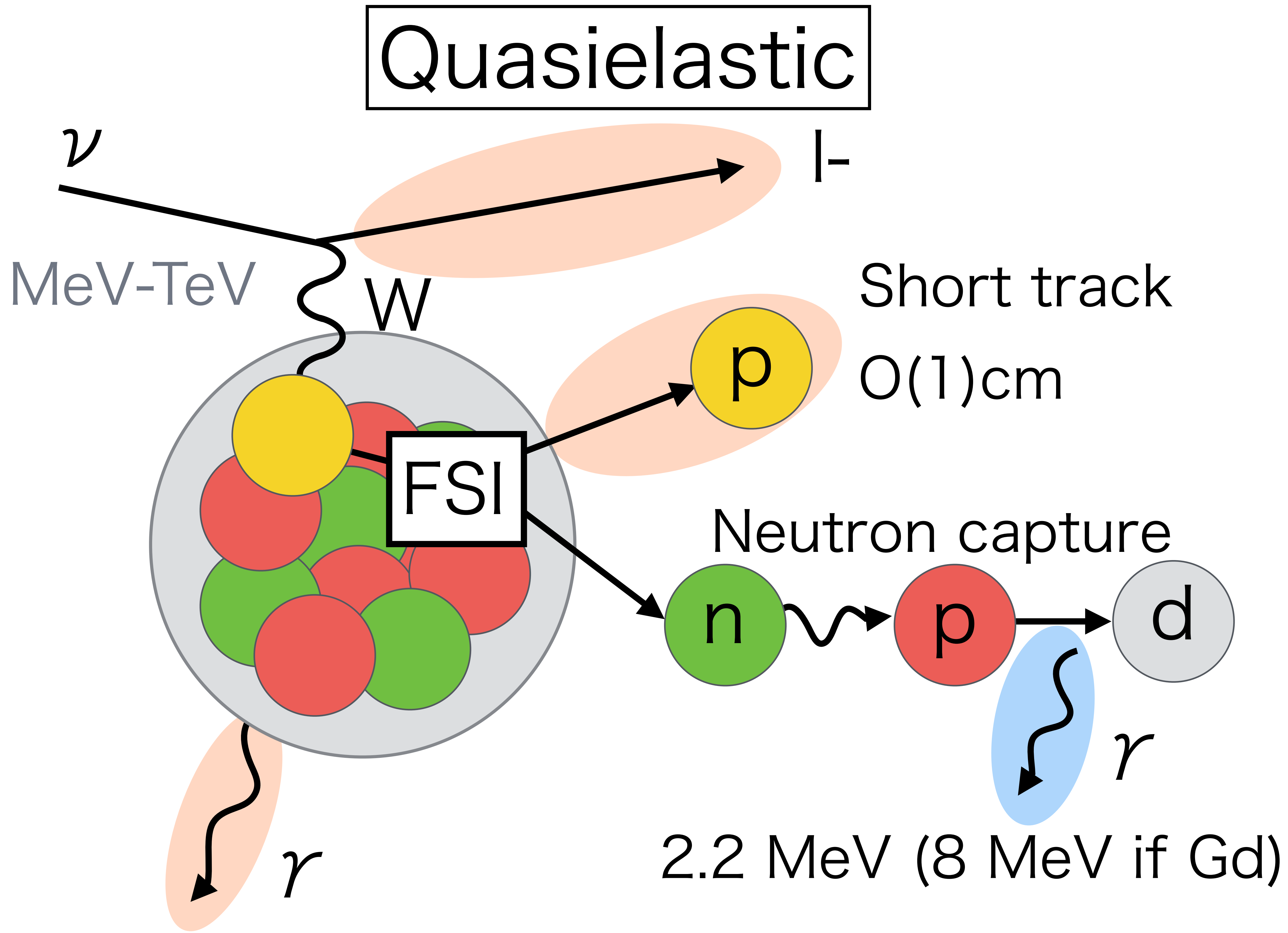
seisho@icrr.u-tokyo.ac.jp

Kamioka Obs., ICRR, the University of Tokyo

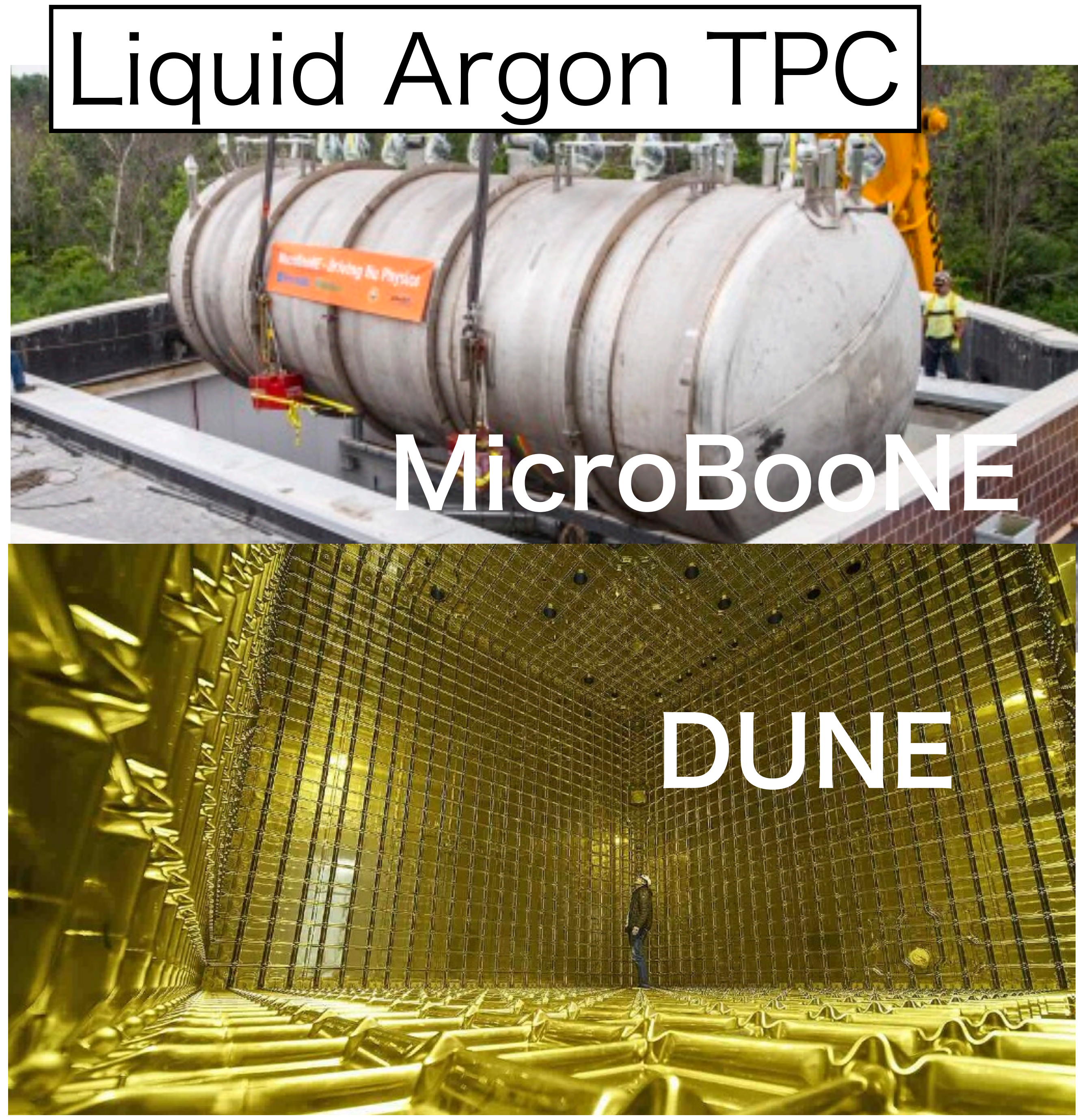
FB23 - 26th September, 2024

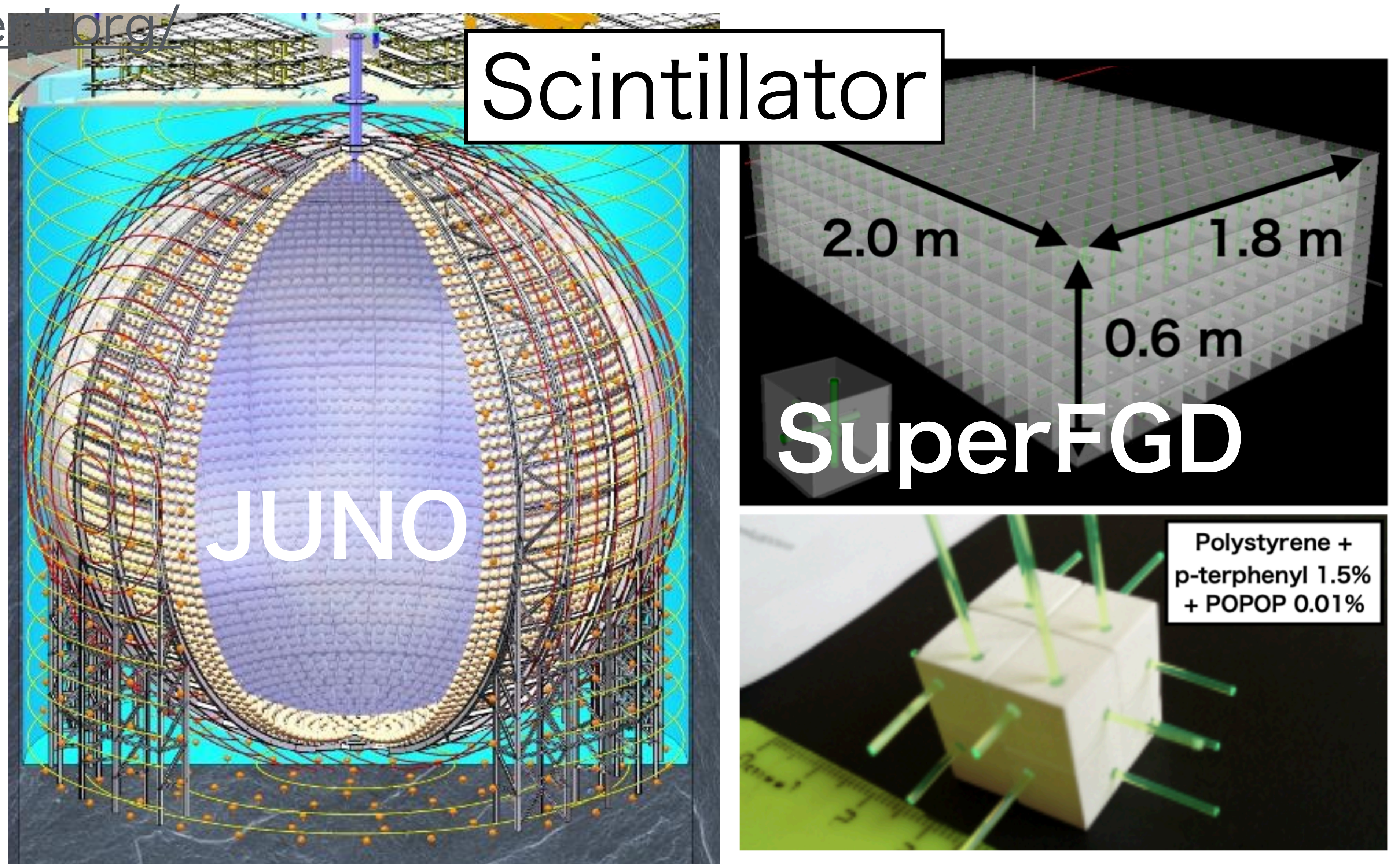
Contents

New era of neutrino experiments



C. Cerna et al., NIMA 958 162183 (2020).
https://www.fnal.gov/
https://www.t2k-experiment.org/





More **exclusive** measurements are coming!

- Low-energy particles
- neutrons via capture

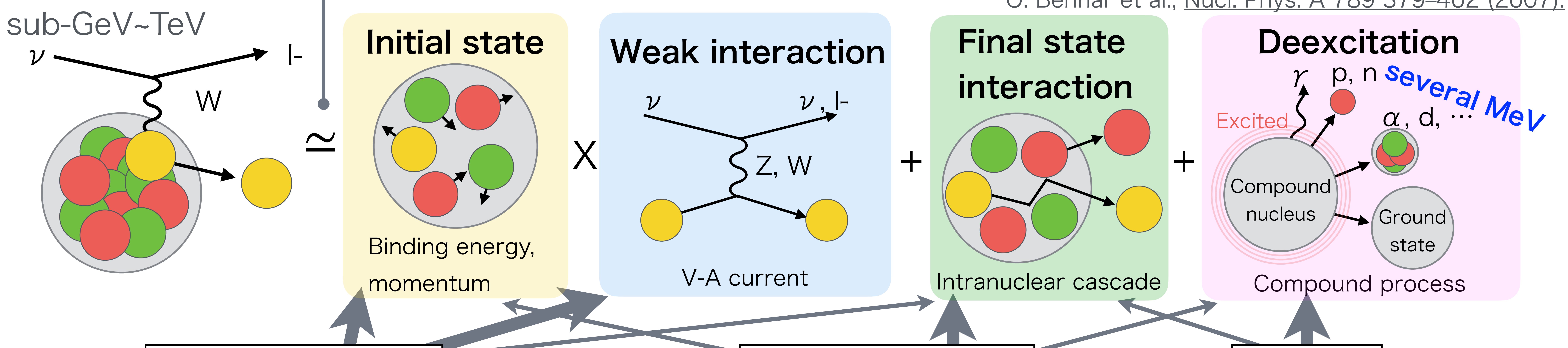
Strongly affected by **nuclear effects**

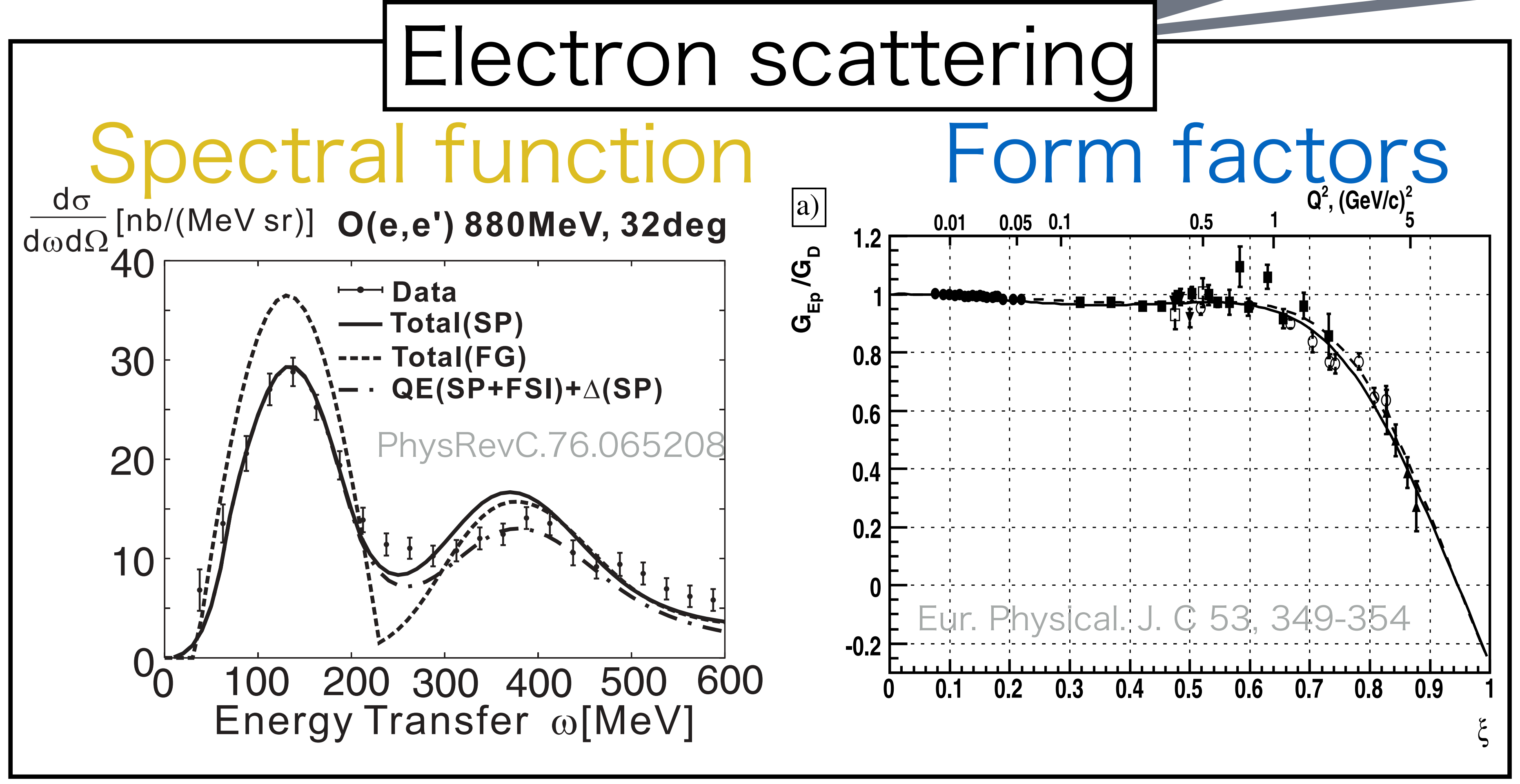
Needs **a precise understanding of interactions** to maximize performance.

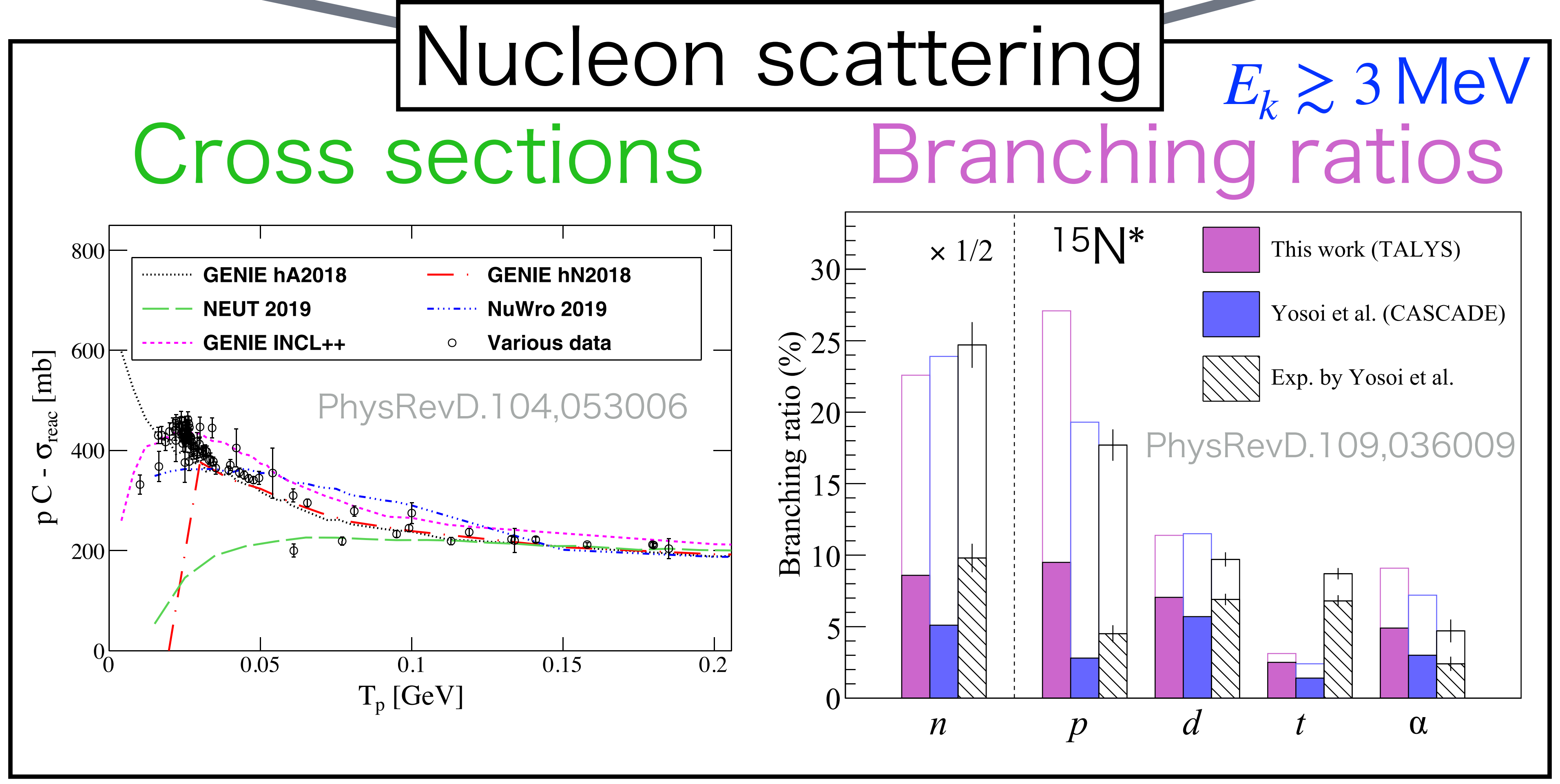
Neurino-nucleus interactions

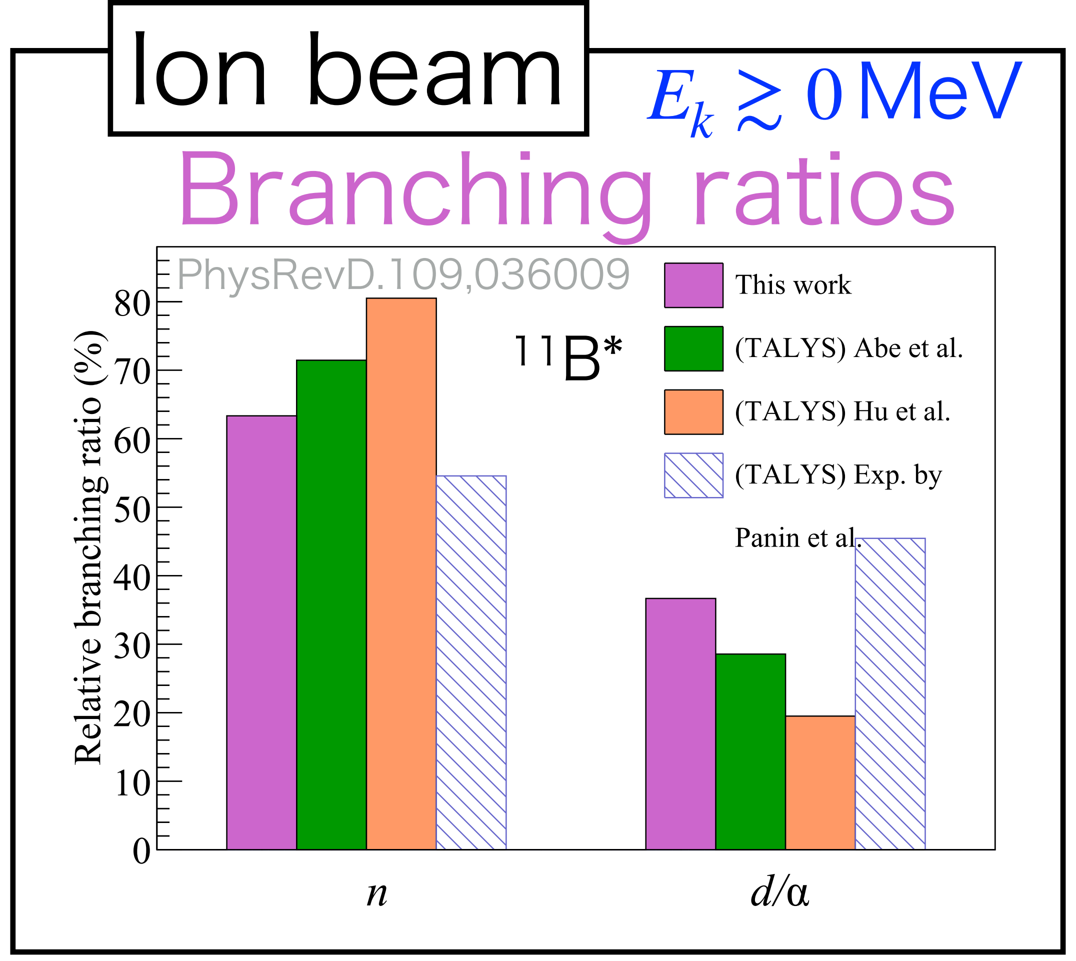
O. Benhar et al., Phys. Rev. D 72, 053005 (2005).
O. Benhar et al., Nucl. Phys. A 789 379–402 (2007).

PWIA: Plane wave impulse approximation



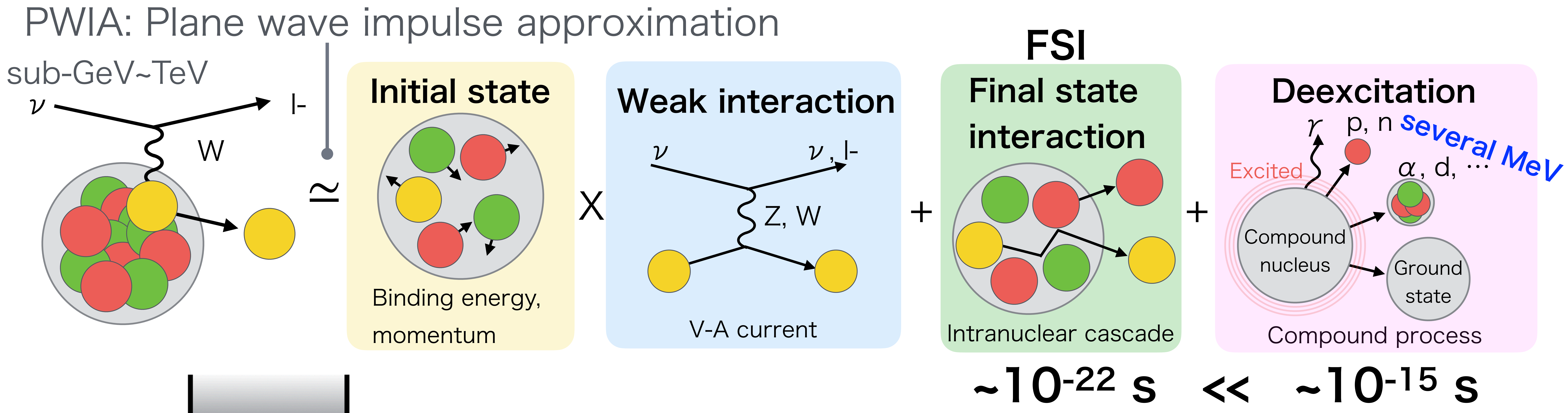


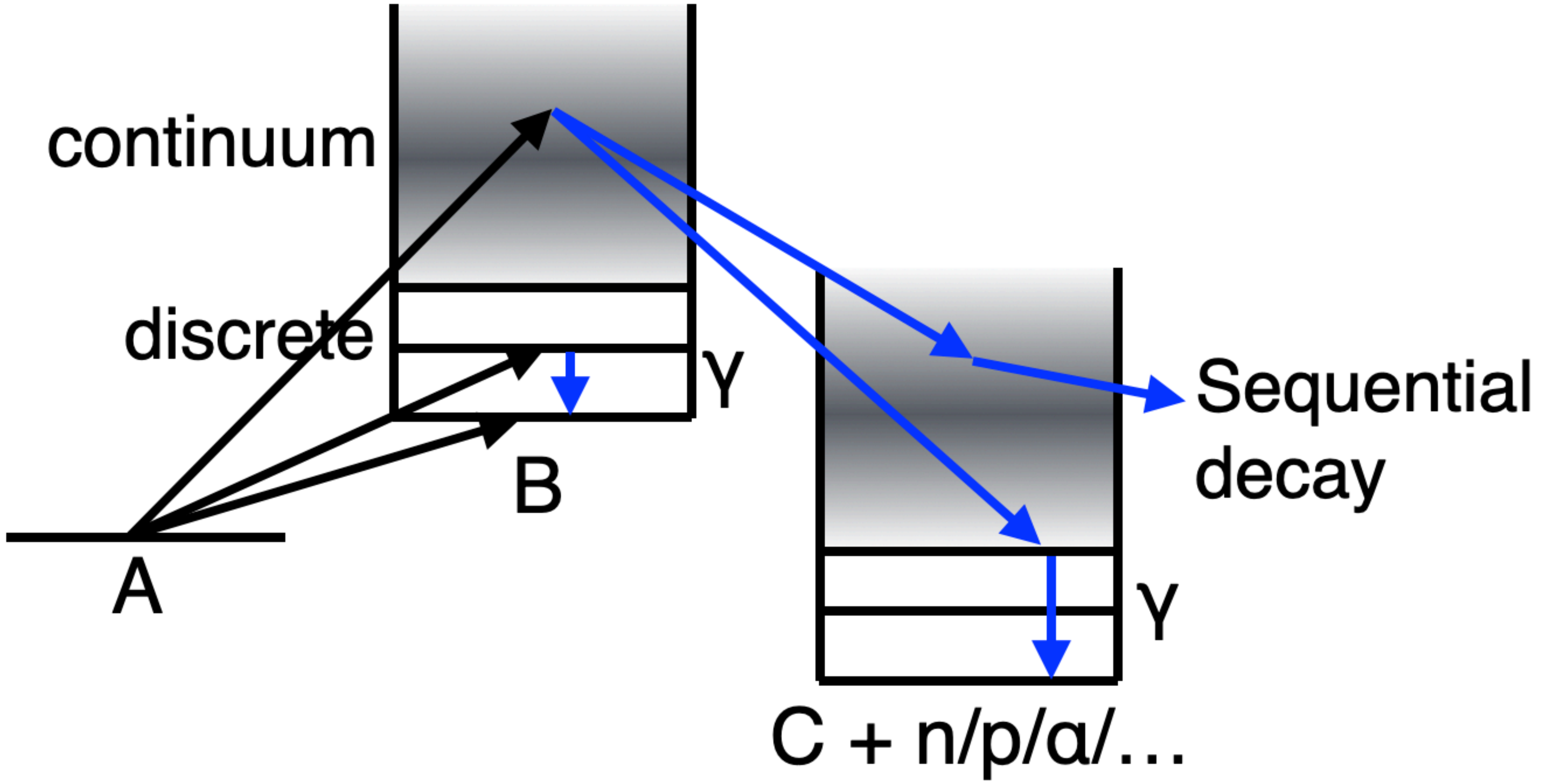




- Various experiments evaluate/constrain the models for each process.
- But, it's **the dominant syst. unc. in ν physics** (oscillation, DSNB, etc.)

Nuclear deexcitation

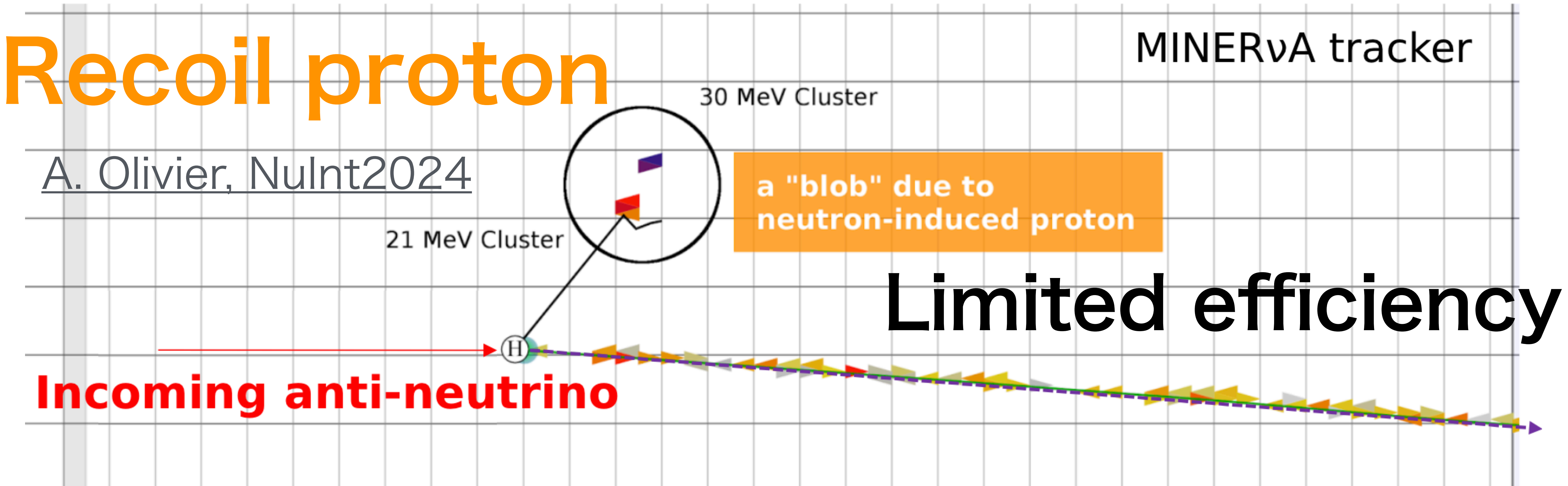




- The nucleus goes to excited states by weak interactions & FSI.
- It then decays emitting various particles: γ, n, p, α, etc.
- **Typical energy is several MeV.**

Example: Neutron detection via recoil/capture

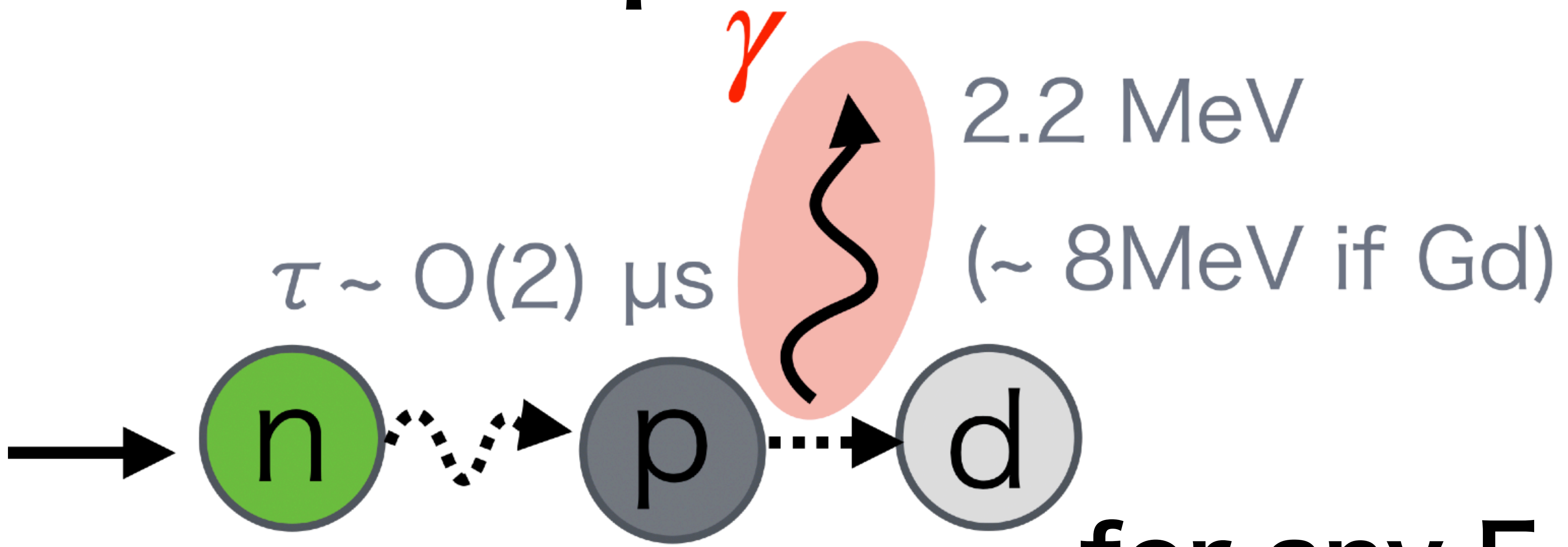
Recoil proton



Limited efficiency

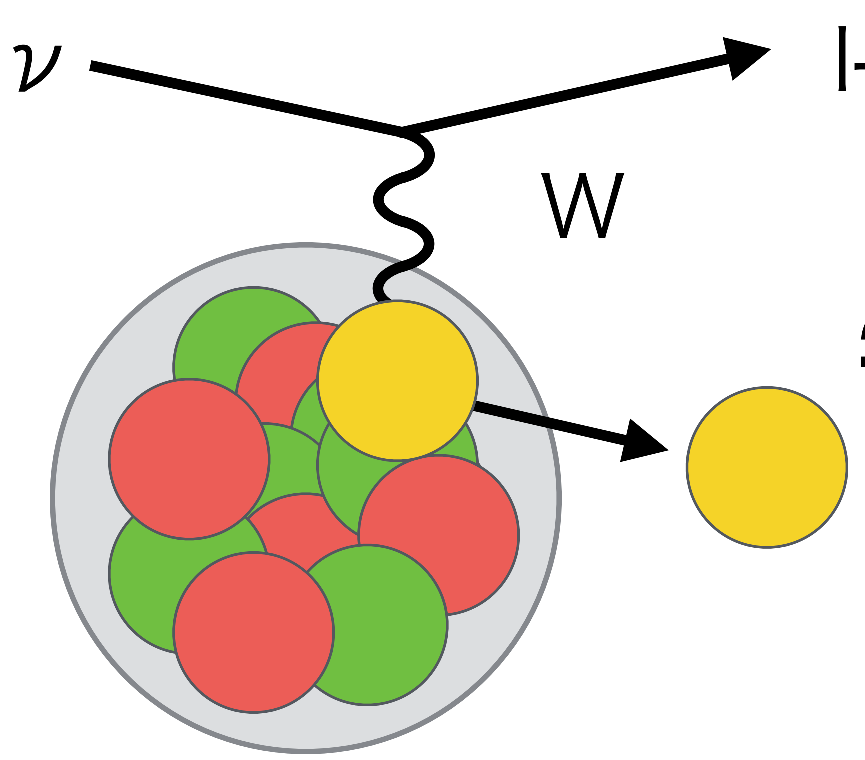
High-energy threshold: E_k > ~ 30 MeV
→ insensitive to deexcitation.

Neuron capture



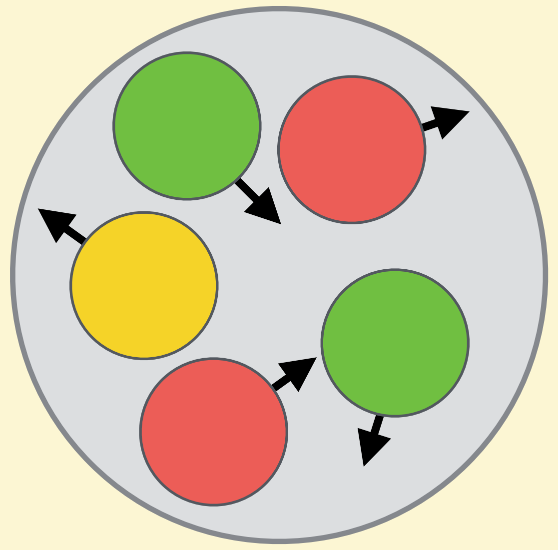
for any E_k

Occurs with **all neutrons.**



≃

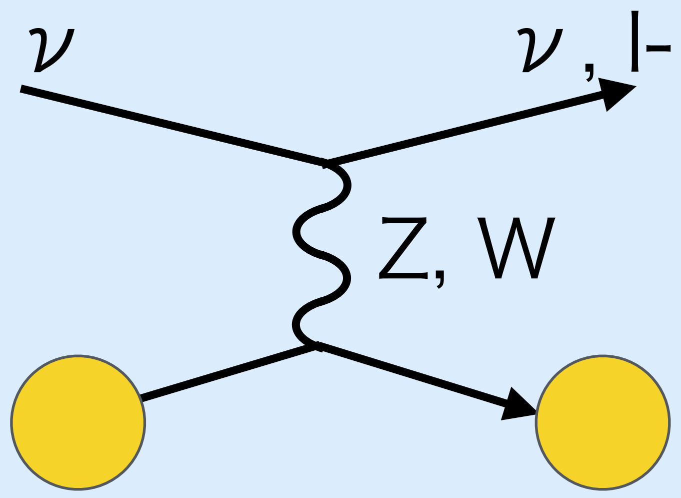
Initial state



Binding energy, momentum

X

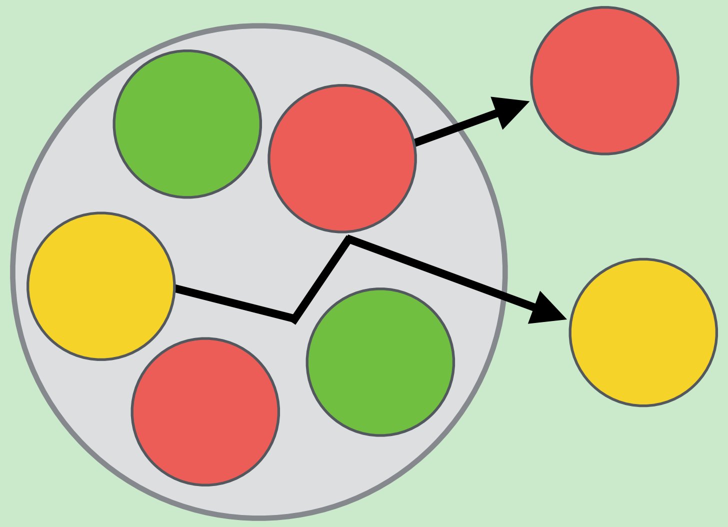
Weak interaction



V-A current

+

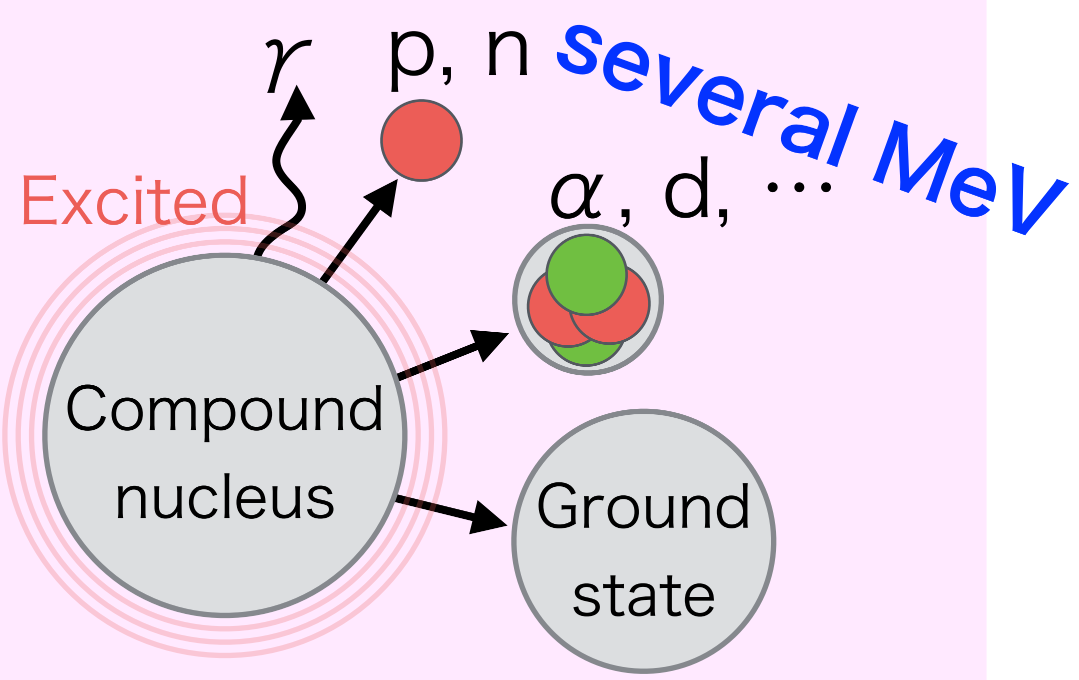
Final state interaction



Intranuclear cascade

+

Deexcitation

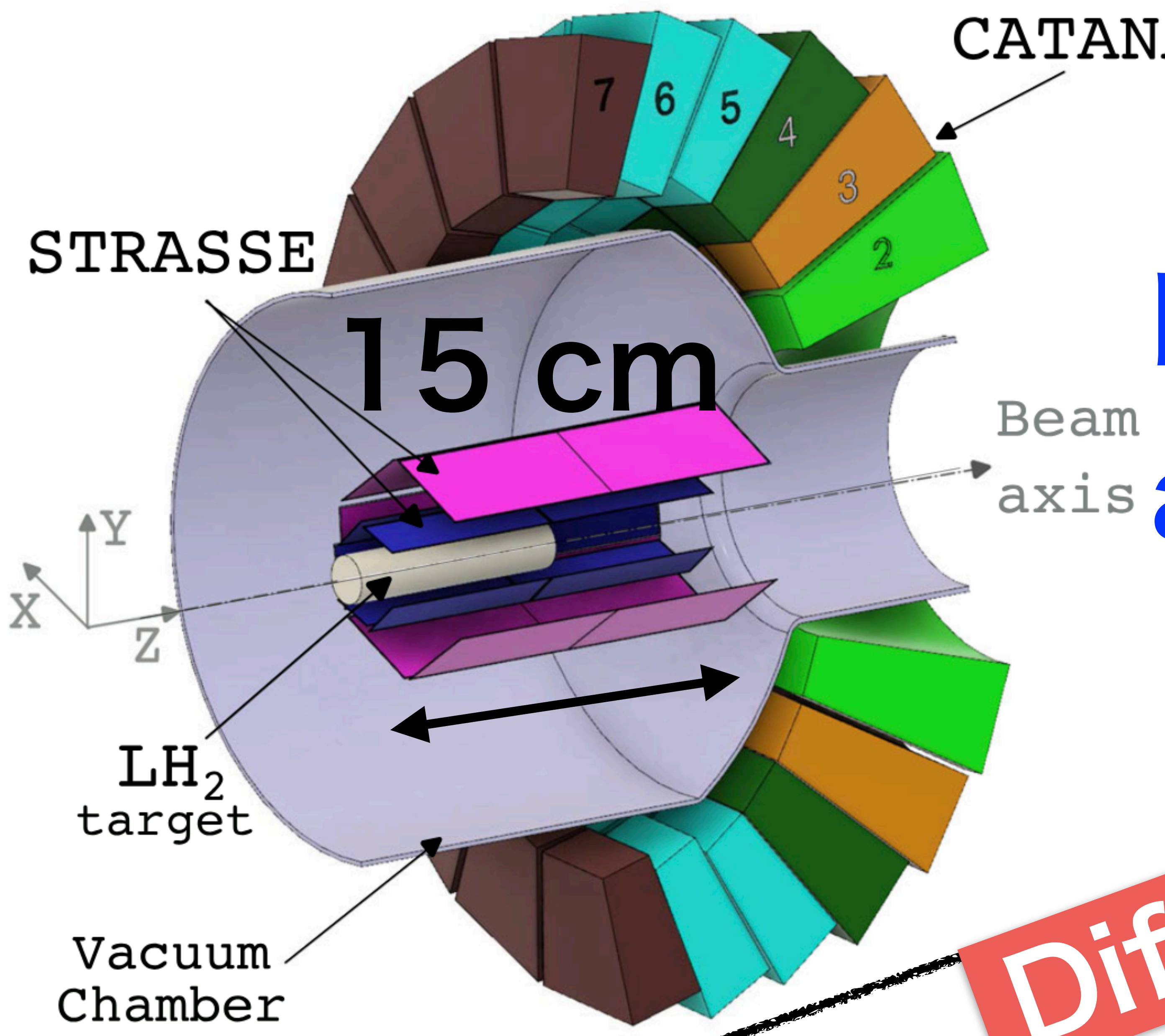


Compound process

Precise understanding of deexcitation is essential for capture.

Importance of nuclear experiments and theory

Nuclear experiments for deexcitation



H. N. Liu et al., Eur. Phys. J. A 59, 6, 121 (2023).

RIKEN RIBF O(10) cm

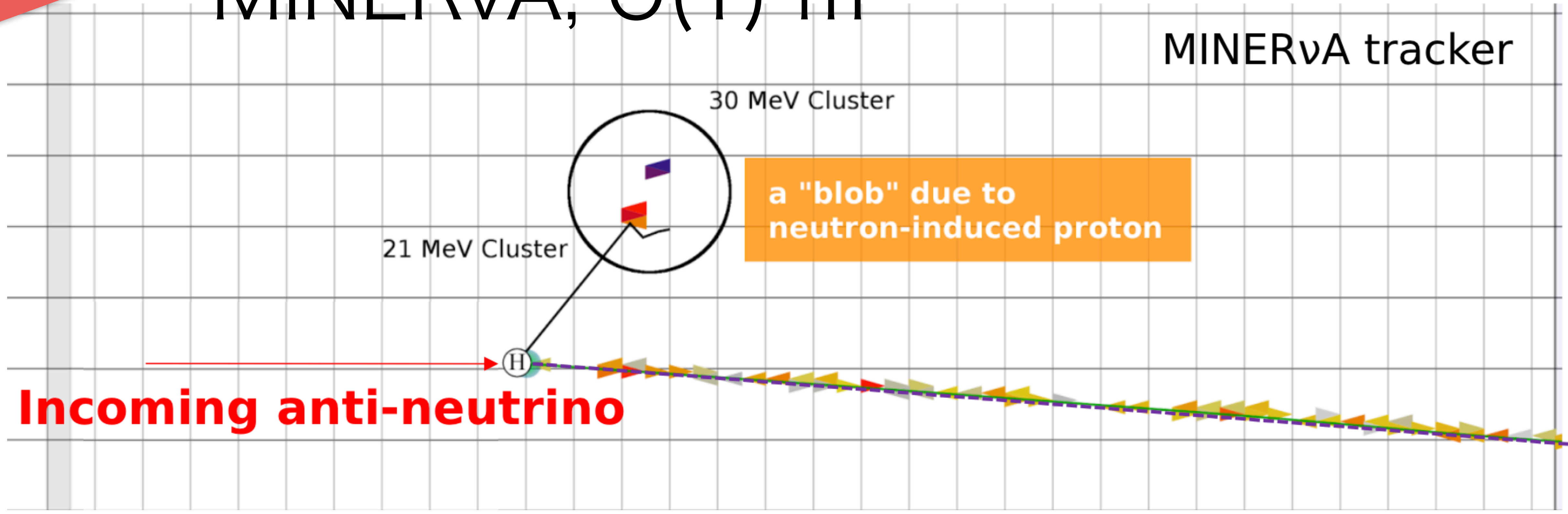
Precise measurements around target

Different purpose & optimization

Large targets for statistics

A. Olivier, NuInt2024.

MINERνA, O(1) m



ν experiments

- **Difficult to constrain deexcitation model by ν experiments.**
- We need **nuclear theory and experiments** to precisely simulate deexcitation process and estimate errors.

Deexcitation in ν generators

- **Deexcitation is not simulated in major ν generators (NEUT, GENIE, NuWro)** with a few exceptions*.

* NEUT employs a naive data-driven model for ^{16}O only.
* A study of ABLA coupled with INCL++ was conducted in NuWro.
  - A. Ershova et al., Phys. Rev. D 108, 112008 (2023).

A dedicated software of deexcitation is necessary.

Therefore, I developed…

NucDeEx: S. Abe, Phys. Rev. D 109, 036009 (2024)
- GitHub: https://github.com/SeishoAbe/NucDeEx

Unique features:
- Open-source & standalone.
  - Easy to be integrated into ν generators.
- Based on the nuclear reaction calculator TALYS.
- Supports ^{12}C and ^{16}O.

A. Koning et al., Eur. Phys. J. A 59, 131 (2023).

Contents

Deexcitation (evaporation) models

Model	Features
Weisskopf-Ewing (WE)	Angular momentum is NOT conserved. V. F. Weisskopf and D. H. Ewing Phys. Rev. 57 472, 935 (1940).
Hauser-Feshbach (HF)	**It considers angular momentum conservation.** W. Hauser and H. Feshbach, Phys. Rev. 87, 366 (1951).
Generalized Evaporation Model (GEM)	A specific model based on WE prescription. S. Furihara, Nucl. Instrum. and Meth. B 171(2000) 251.
Fermi breakup (FB)	All decays happen at the same time. Frequently used for light nuclei ($A \leq 16$). E. Fermi, Prog. Theor. Phys. 5 570 (1950).

- **The more sophisticated HF model is known to be generally favored,** but that's for heavy nuclei.
- **It's not clear which model is the best for light nuclei**, carbon and oxygen.

Deexcitation generators

Generator	Model	Comments
NucDeEx v2.1	HF	Open-source & standalone event generator based on **TALYS.**
INCL++/FB	FB	Default model for light nuclei (A ≤ 16) in INCL++
INCL++/ABLAv3p	WE	Alternative model in INCL++. **Not considers low-lying discrete excited states.**
G4PreCompundModel	GEM and FB	Default model in **Geant4.**
CASCADE	HF	Closed-source. Citing values of branching ratio from paper.

Deexcitation generators

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CASCADE	HF	Closed-source. Citing values of branching ratio from paper.

- Hauser-Feshbash (HF) base.
- NucDeEx is open-source, but CASCADE is closed.

S. Abe, Phys. Rev. D 109, 036009 (2024).
F. Pühlhofer, Nucl. Phys. A 280 267 (1977).

Deexcitation generators

Generator	Model	Comments
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G4PreCompundModel	GEM and FB	Default model in **Geant4.**
CASCADE	HF	Closed-source. Citing values of branching ratio from paper.

- From INCL++ cascade simulators.
- Simulate deexcitation part individually

S Leray, et al., J. Phys. Conf. Ser. 420, 012065 (2013).
J. Benlliure et al., Nucl. Phys. A628, 458-478 (1998).
A.R. Junghans et al., Nucl. Phys. A629, 635-655 (1998).

Deexcitation generators

Generator	Model	Comments
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G4PreCompundModel	GEM and FB	Default model in **Geant4.**
CASCADE	HF	Closed-source. Citing values of branching ratio from paper.

- Many neutrino experiments use Geant4 for detector simulation.

J. M. Quesada et al., Progress in Nuclear Science and Technology 2, 936 (2011).

Contents

- Introduction: Neutrino experiments & ν-nucleus interaction

The reason why we need a precise description of deexcitation.

- Deexcitation models/generators
- Novel deexcitation generator NucDeEx
- Validations with nuclear experiments
- Application to Geant4, neutrino generators, etc.

Concepts of NucDeEx

- **Open-source** and **standalone**
- **^{12}C and ^{16}O**
- Branching ratios are calculated with **TALYS.**

- Opened in GitHub: https://github.com/SeishoAbe/NucDeEx
- Easy to be integrated into **ν generators and nucleon decay generators.**

Because it's standalone

NucDeEx → ν generators

Provide library

NEUT, GENIE, NuWro

UNIVERSAL NEUTRINO GENERATOR & GLOBAL FIT

NuWro * Wroclaw Neutrino Event Generator *

Y. Hayato et al., Eur. Phys. J. Special Topics 230, 4469 (2021).

C. Andreopoulos et al., Nucl. Instrum. Methods Phys. Res., Sect. A 614, 87 (2010).

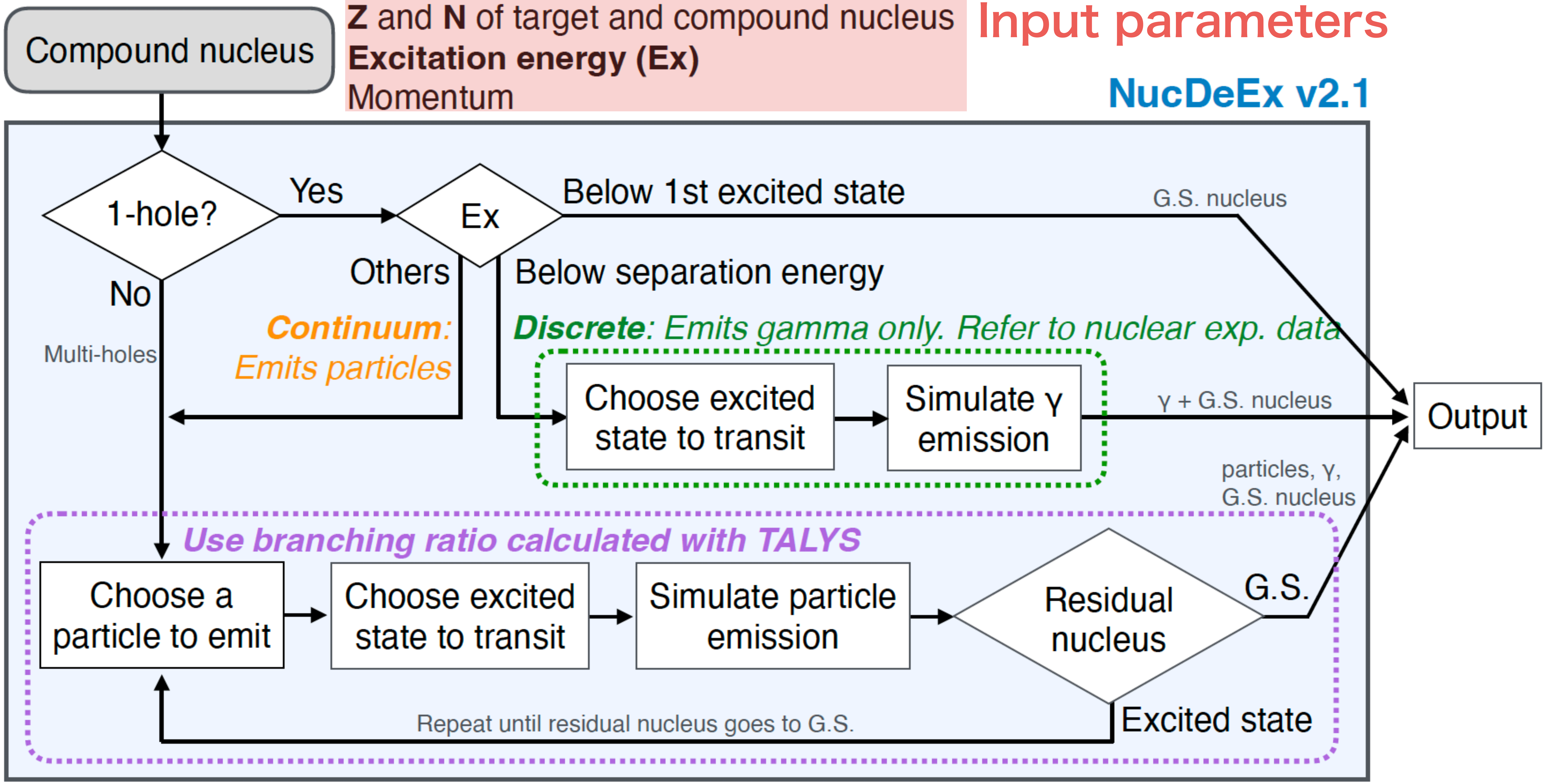
T. Golan et al., Phys. Rev. C 86, 015505 (2012).

- Branching ratios (BR) calculated with **TALYS (Hauser-Feshbash) are pre-tabulated** (it does not link TALYS library)

Algorithm

Z and **N** of target and compound nucleus
Excitation energy (Ex)
Momentum

Input parameters



- **Discrete:** Simple→Refer to experimental data.
- **Continuum + Multi-holes:** Complicated→Use **TALYS (Hauser-Feshbach model).**

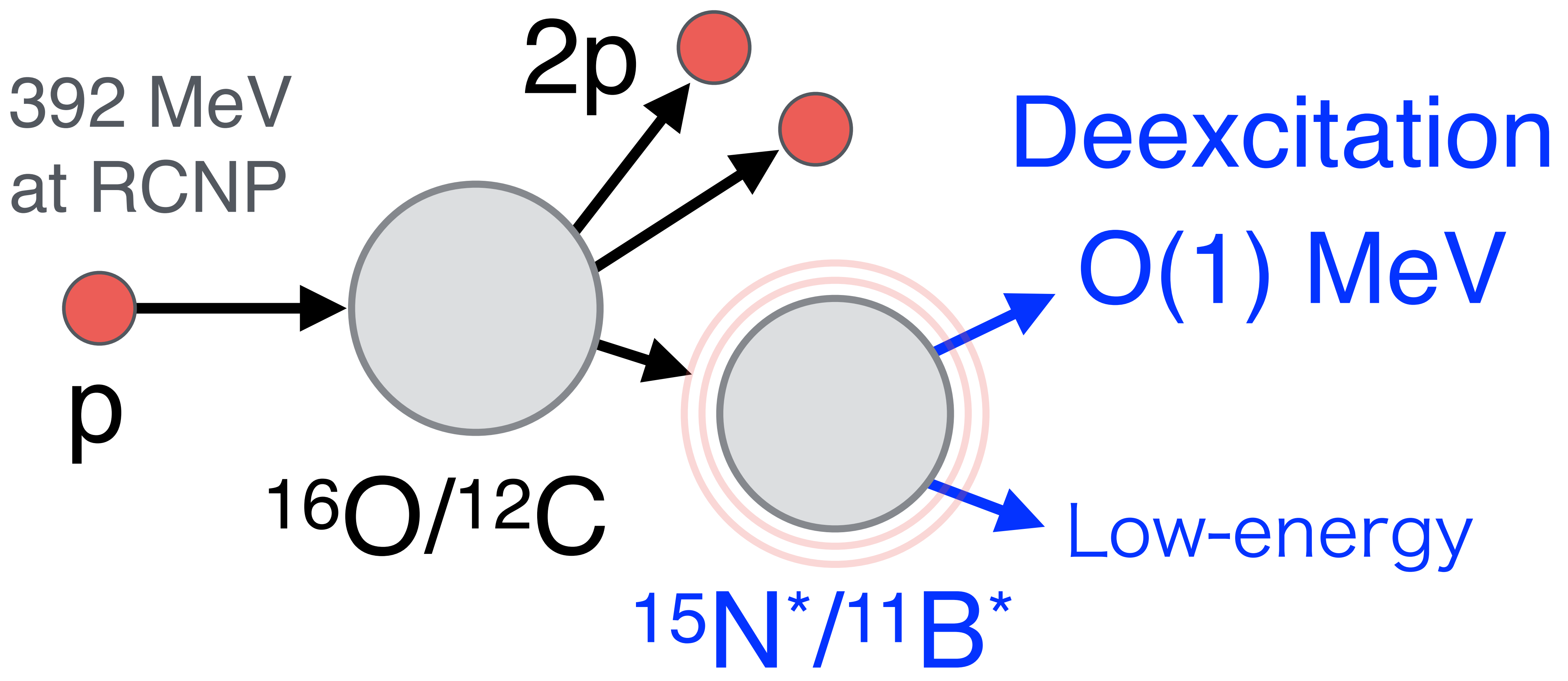
To be discussed later

Contents

Validation with experimental data

Two types of experiments: Both (p,2p)

Normal kinematics: nucleon beam



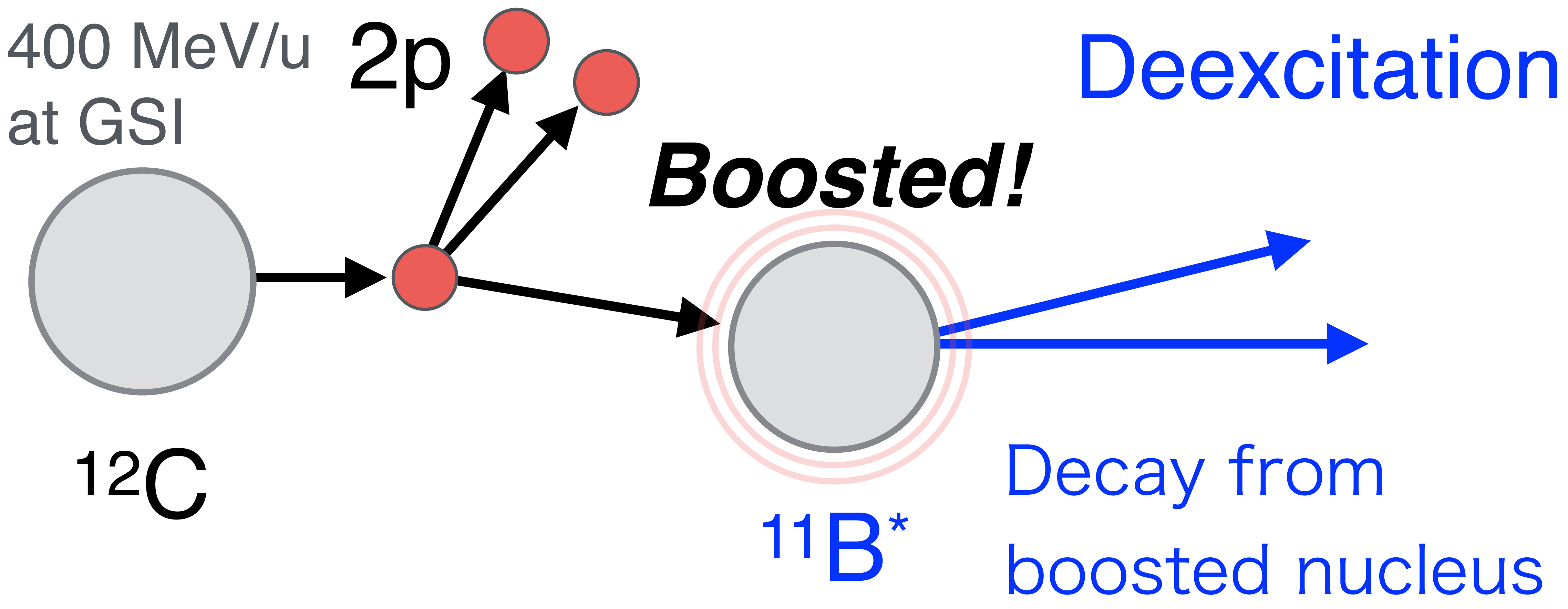
High detection energy threshold ~4 MeV

→ **~50% inefficiency**

M. Yosoi et al., Phys. Atom. Nucl. 67, 1810 (2004).

VS

Inverted kinematics: ion beam



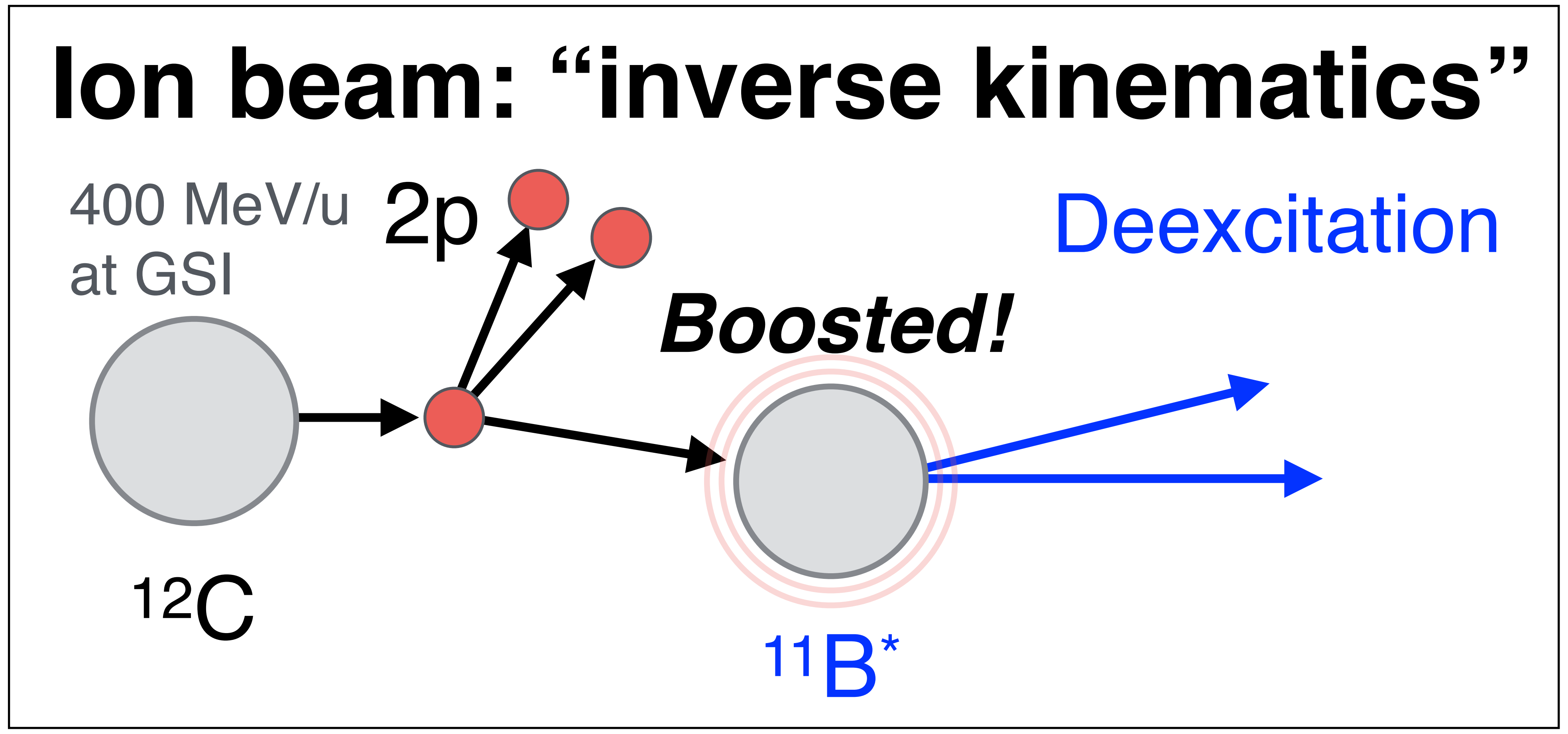
High energy in LAB frame.

→ **Can measure almost all deexcited particles**

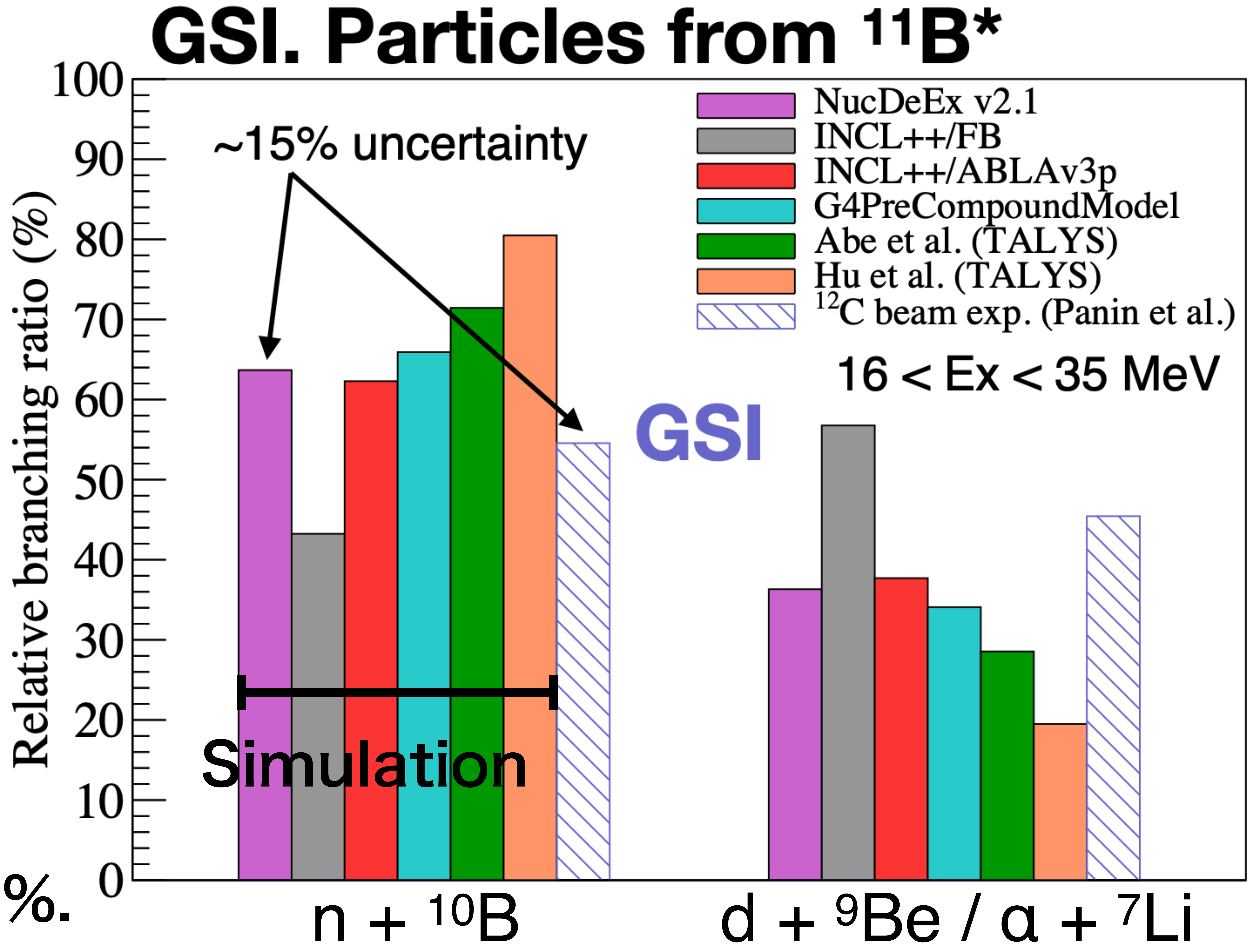
Panin et al., Phys. Lett. B 753, 204 (2016).

- **Inverted kinematics (ion beam) is powerful experiment.**
- But, facilitiies are limited (GSI, RIKEN RIBF).

Validation with GSI (inverted) result



- Inverted. $^{12}C(p,2p)^{11}B^*$
- Measures n, d, and α only.
- **Relative** BRs
- NucDeEx agrees within **~15%.**
- FB shows different trends.



S. Abe et al., Phys. Rev. D 107, 072006 (2023).
H. Hu et al., Phys. Lett. B 831, 137183 (2022).
Panin et al., Phys. Lett. B 753, 204 (2016).

Gamma-ray BRs at RCNP

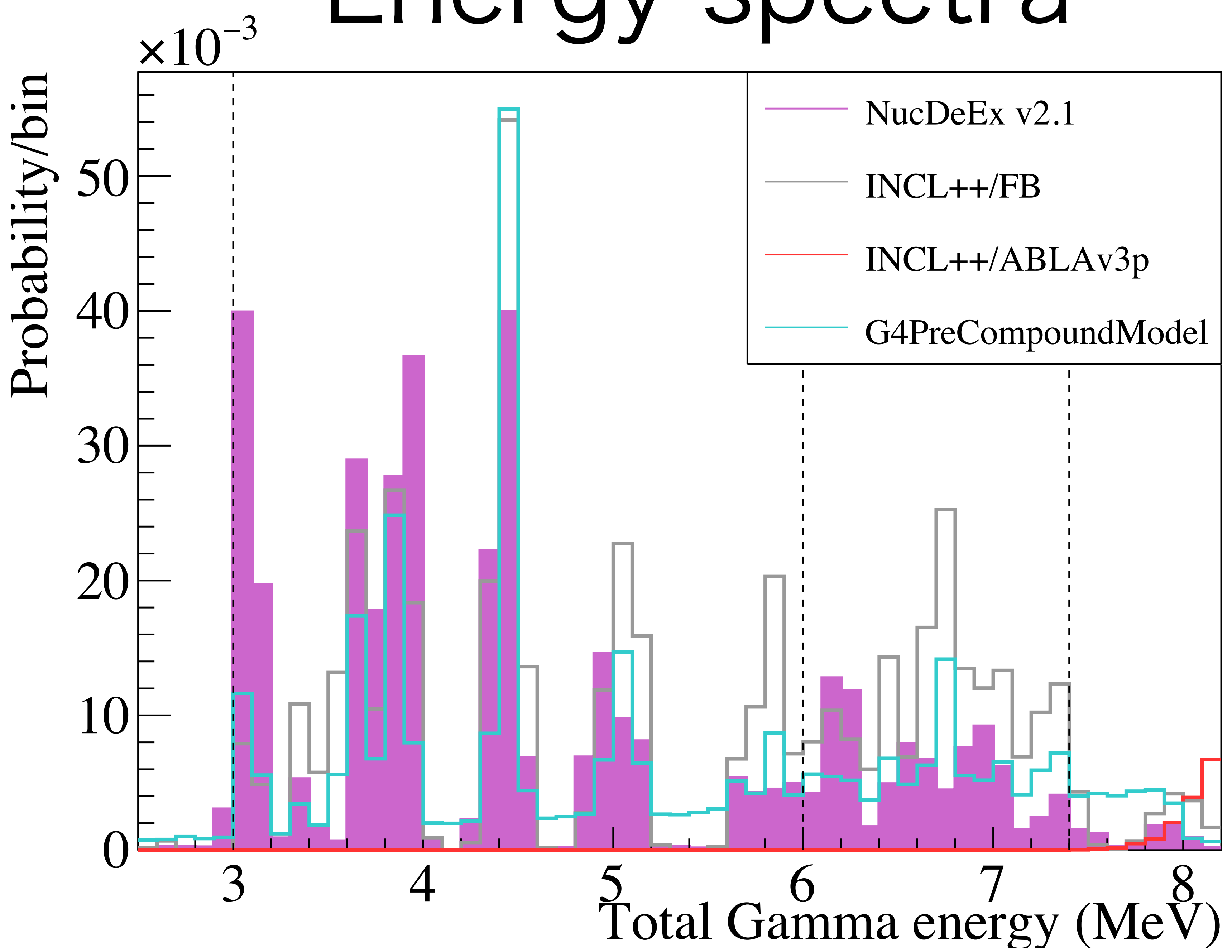
Normal, $^{16}O(p,2p)^{15}N^*$

K. Kobayashi et al., arXiv:nucl-ex/0604006 (2006)

16 < Ex < 40 MeV

	γ branching ratio (%)	
	$3 < E_{\gamma,tot} < 6$ MeV	$6 < E_{\gamma,tot} < 7.4$ MeV
NucDeEx v2.1	**31.1**	**8.5**
INCL++/FB	31.1	16.4
INCL++/ABLAv3p	**0 ***	
G4PreCompundModel	22.9	8.7
Experiment (RCNP)	$27.9 \pm 1.5^{+3.4}_{-2.6}$	$15.6 \pm 1.3^{+0.6}_{-1.0}$

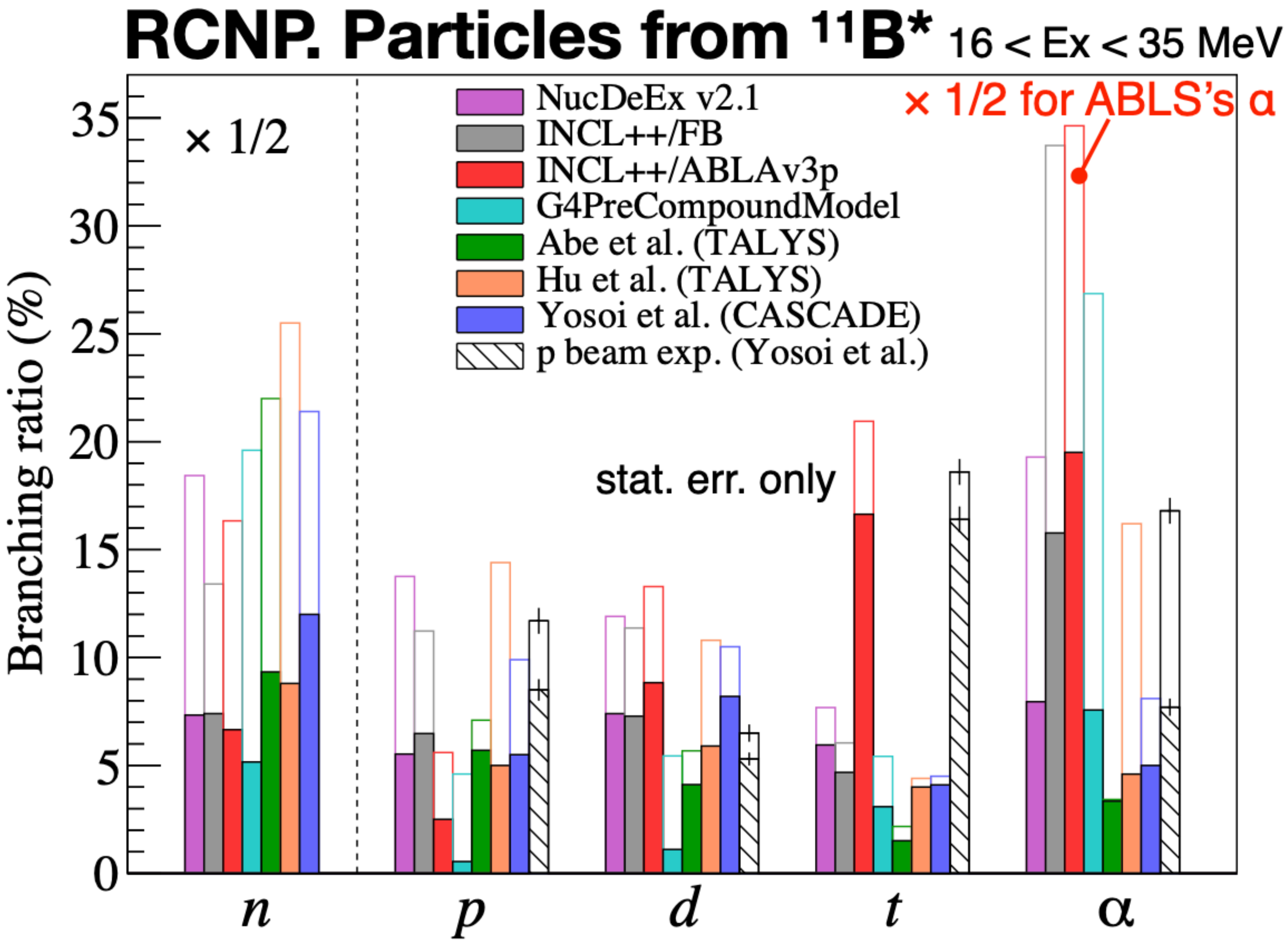
Energy spectra

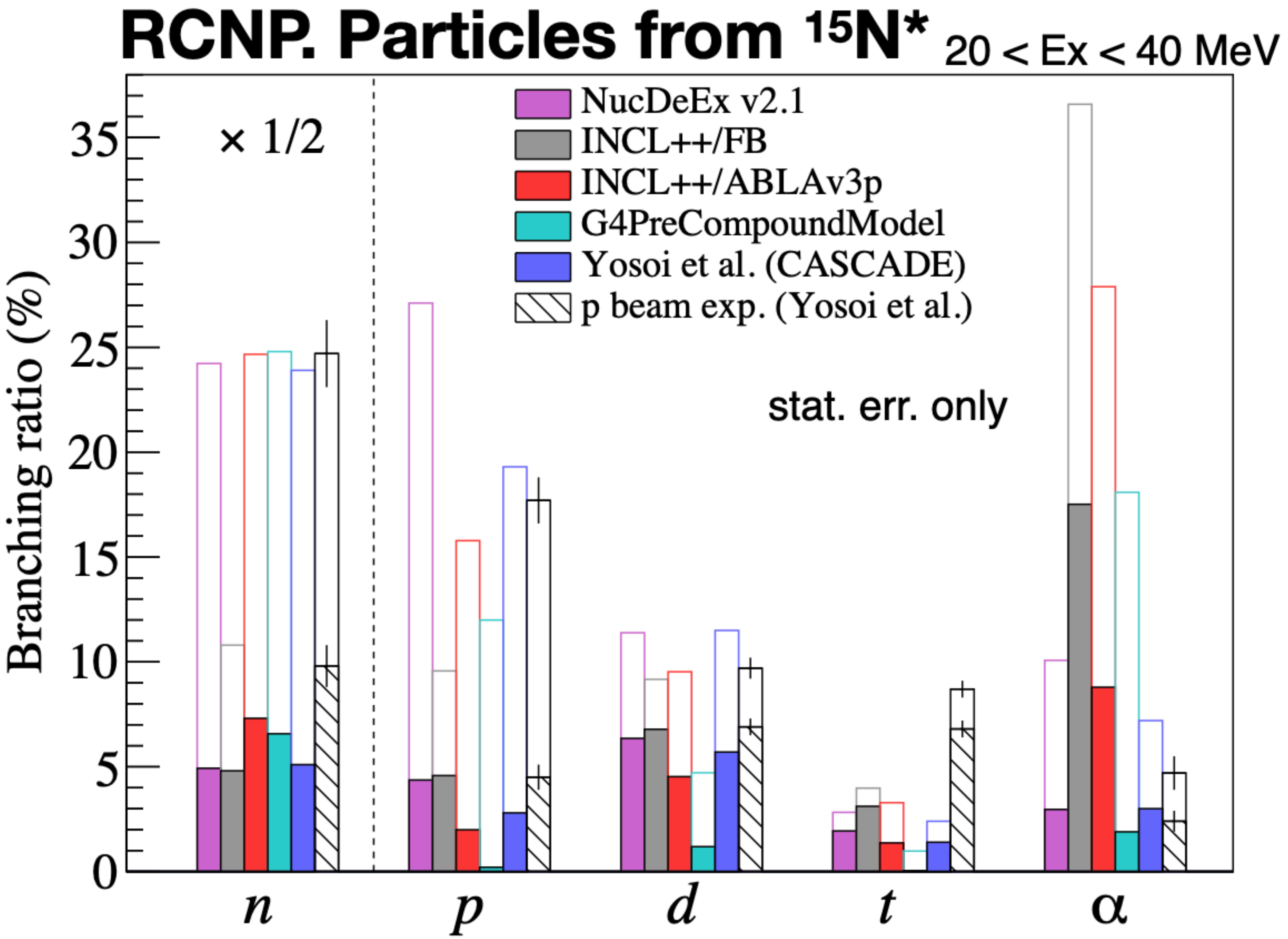


Deviation is visible in spectra,
but the experiment had poor resolution

- NucDeEx: Underestimates BR above 6 MeV (unknown reason).
- FB: Looks nice, but not good for hadronic particles (next page).
- ABLA: Has no predictive power for γ. **Not suitable for Super-K.**
- G4PreCo: **Neither BR reproduces well.**

Hadronic particle BRs at RCNP





Solid/hatched: Two-body decays.
Open: Three or more body decays (sequential decay).

M. Yosoi et al., Phys. Lett. B 551, 255 (2003).
M. Yosoi et al., Phys. Atom. Nucl. 67, 1810 (2004).
S. Abe et al., Phys. Rev. D 107, 072006 (2023).
H. Hu et al., Phys. Lett. B 831, 137183 (2022).

Hadronic particle BRs at RCNP

Solid/hatched: Two-body decays.
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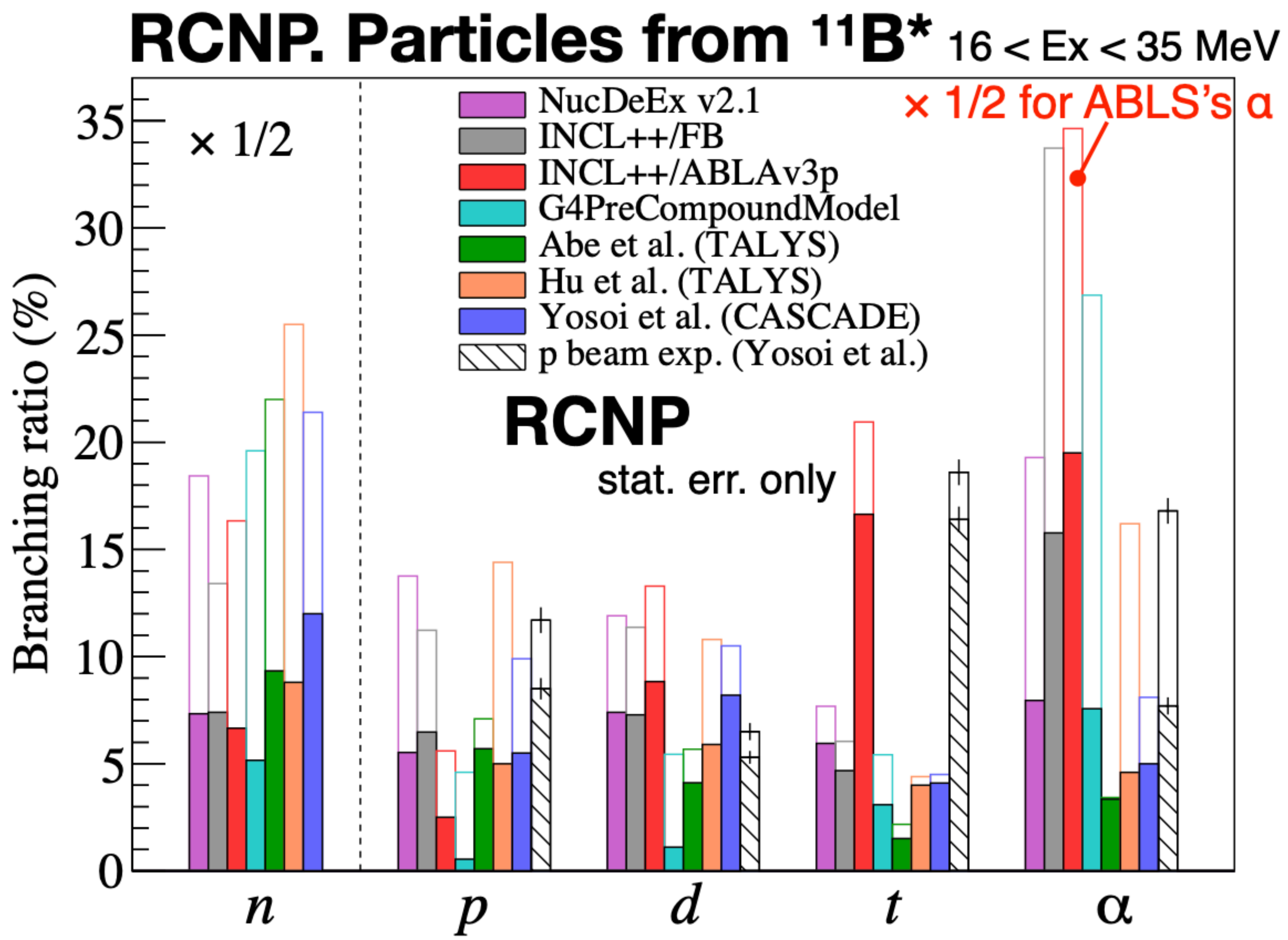

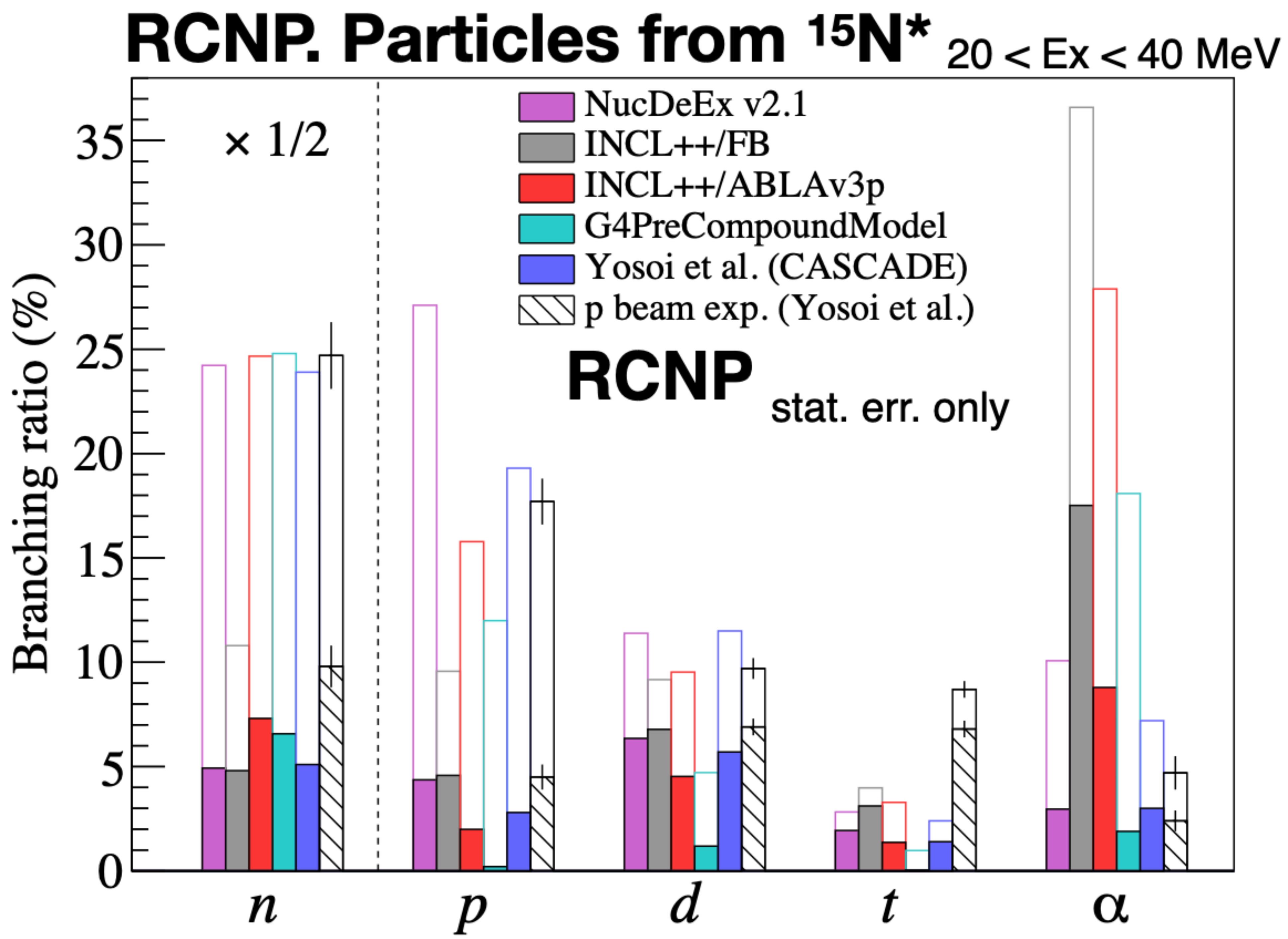

Generator	χ^2/ndf (stat. err. only)	
	RCNP $^{11}B^*$	RCNP $^{15}N^*$
NucDeEx v2.1	**483 / 8**	**280 / 10**
INCL++/FB	1038 / 8	1409 / 10
INCL++/ABLAv3p	7320 / 8	737 / 10
G4PreCompundModel	1181 / 8	777 / 10
Abe et al. (TALYS)	947 / 8	-
Hu et al. (TALYS)	674 / 8	-
Yosoi et al. (CASCADE)	676 / 8	263 / 10

The best (or comparable to the best) reproducibility.

Overestimates α emission.

Bonus?

Not so good. **Better to replace it with NucDeEx!**

Predecessor of NucDeEx

Closed-source. Quality is comparable to NucDeEx
→ It can be replaced with NucDeEx

Hadronic particle BRs at RCNP

Generator	χ^2/ndf (stat. err. only)	
	RCNP ^{11}B*	RCNP ^{15}N*
NucDeEx v2.1	**483 / 8**	**280 / 10**
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Yosoi et al. (CASCADE)	676 / 8	263 / 10

considers angular momentum conservation

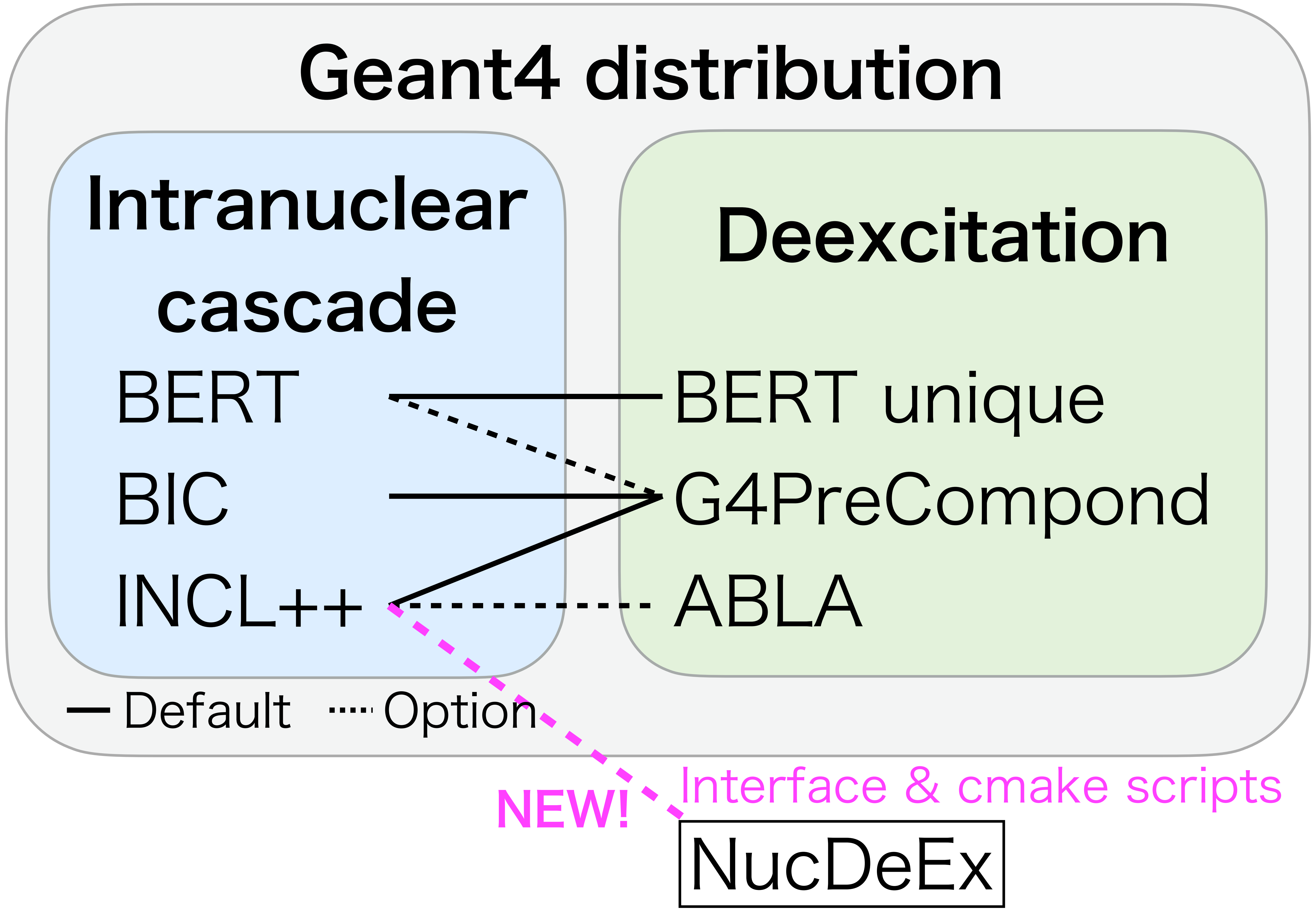
- It seems that **the Hauser-Feshbach model tends to give better agreements also for carbon & oxygen (light nuclei)**
  - The same conclusion with heavy nuclei.

Contents

Bonus study: Application to Geant4

- Geant4 has an original deexcitation model G4PreCompoundModel.
- But, **it does not agree with experimental data well**

What happen if we use NucDeEx instead of G4PreCo?



- Super-K and E525/E487 (neutron beam) reported that **INCL++ & G4PreCo** gives better agreement with data than BIC and BERT.
- I developed **an interface of NucDeEx for INCL++ in Geant4.**

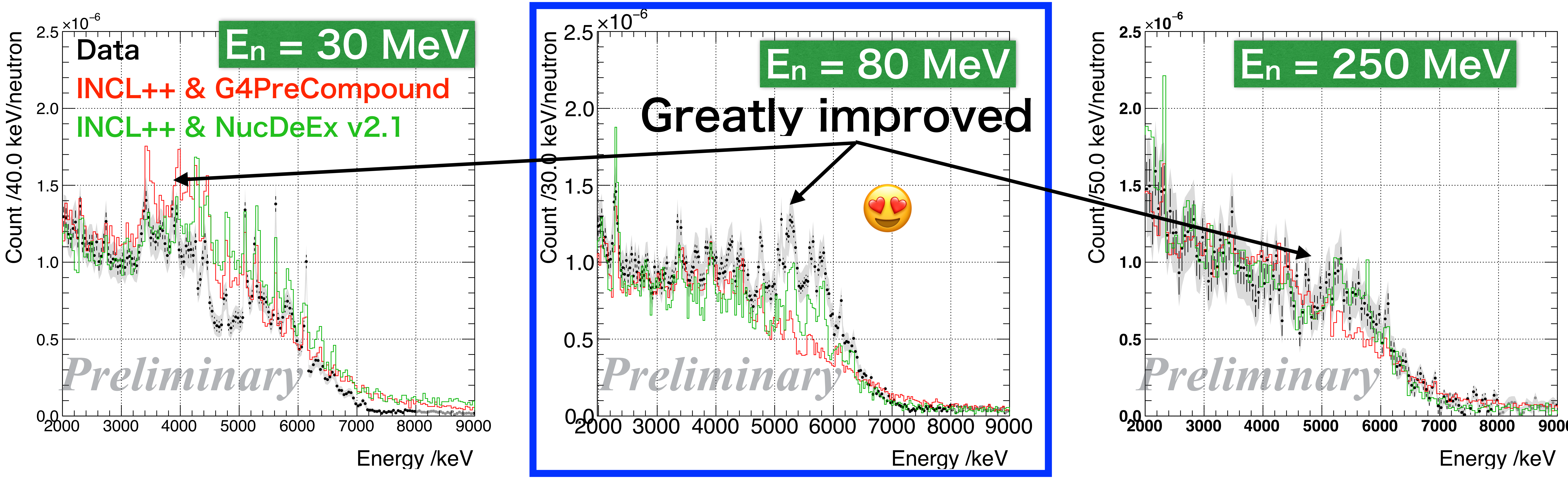
S. Sakai et al., Phys. Rev. D 109, L011101 (2024).
Y. Hino, poster at Neutrino2024.

Validation by E525/E487 @ RCNP (neutron beam)

- **Inclusive γ measurement with n+^{16}O.**
- Compare observed energy spectra of γ.

Y. Ashida et al., PRC 109, 014620 (2024).
T. Tano et al., arXiv:2405.15366 (2024).
Y. Hino, poster at Neutrino2024 (paper in preparation).
Whole Geant4 scripts are given in private comm.

Median neutron energy from atm. ν NCQE ↓



Model	χ^2/ndf @30 MeV	χ^2/ndf @80 MeV	χ^2/ndf @250 MeV
G4PreCompound	1063.7 / 151	3599.6 / 201	303.1 / 121
NucDeEx v2.1	925.7 / 151	647.3 / 201	200.9 / 121

NucDeEx is better than G4PreCo in all n energies!

Future prospects

- **Integration into ν generators**
  - 1st interface for NEUT is almost done.
    - Planning to be included in the next release.
  - Other generators? Welcome to use.

- **Application to SKG4 (Super-K Geant4)**
  - Initial investigation is ongoing.

- **Extension to argon for MicroBooNE & DUNE etc. ?**
  - The larger atomic number, the harder to prepare tables.
  - An effective method is necessary. Still under consideration.

Summary

- We need to understand neutrino-nucleus interactions further for ongoing/coming neutrino experiments ("exclusive" measurements).
- **A dedicated deexcitation generator based on reliable (and validated) nuclear models is necessary.**

- **NucDeEx** is released with many nice features:
  - **Open-source & standalone.** For ^{12}C & ^{16}O
  - Based on **TALYS (Hauser-Feshbach model)**
- Validations with nuclear exp. show **good reproducibility.**

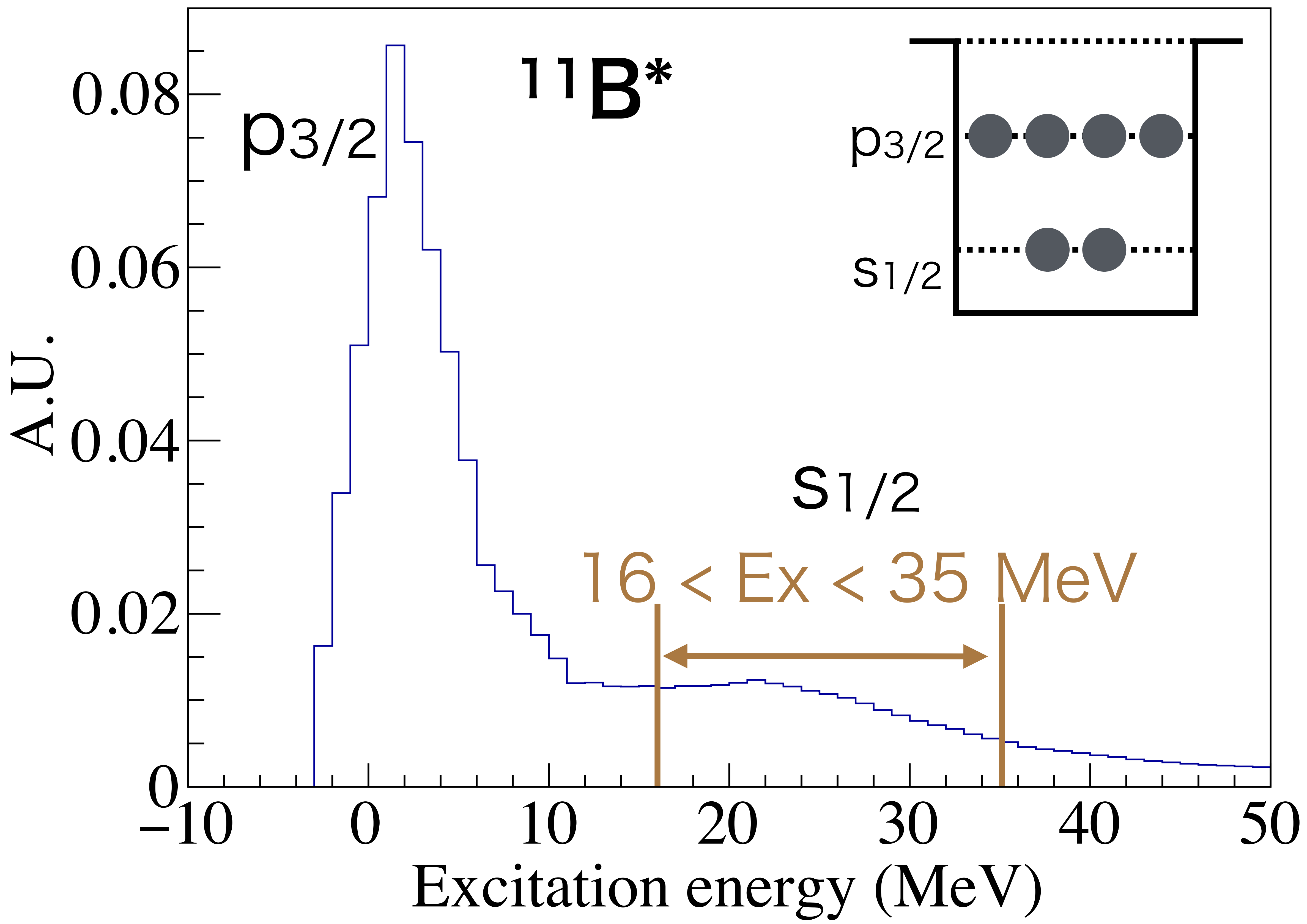
- **Application to NEUT & Geant4 is ongoing.** Stay tuned!

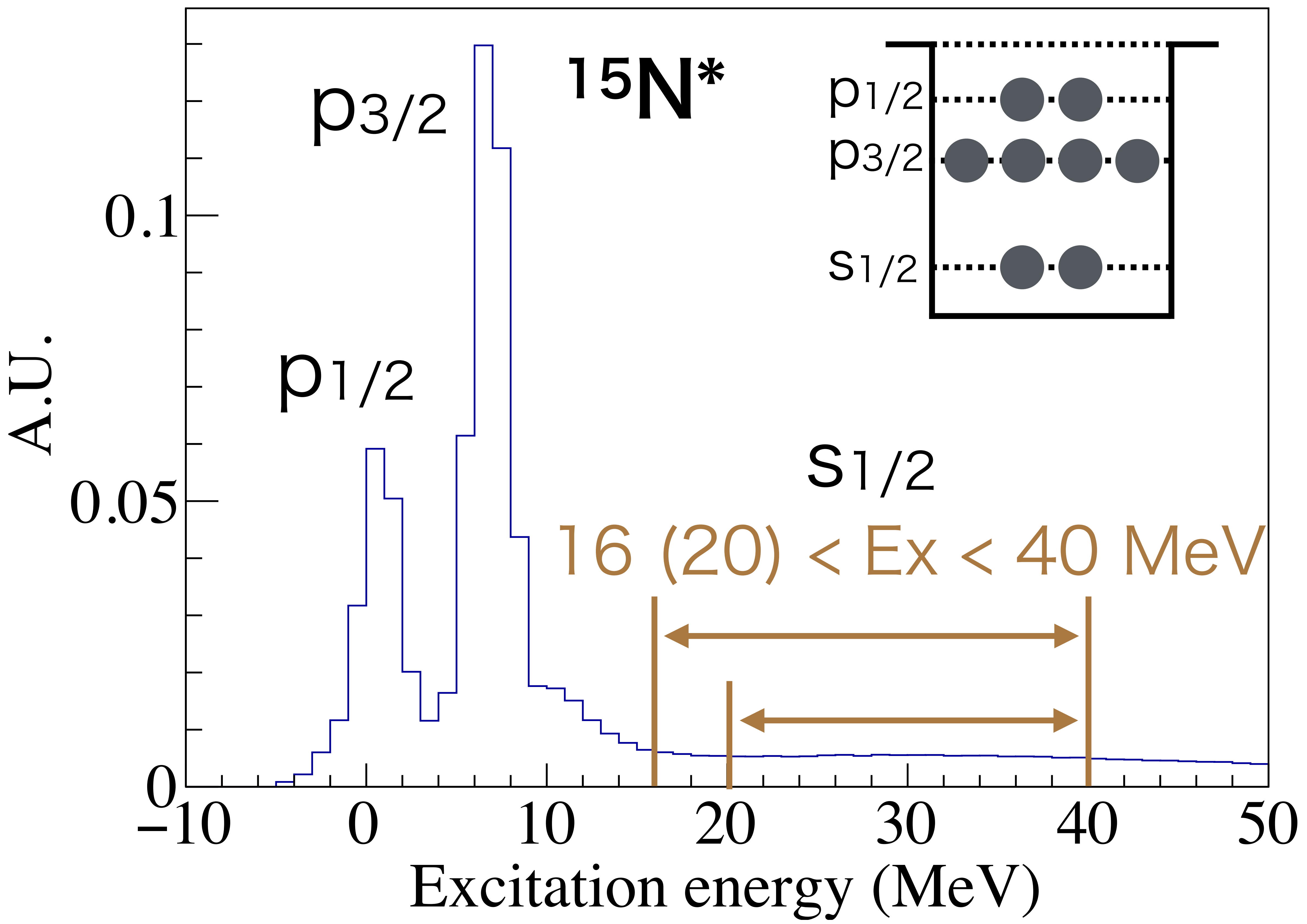
backup

Excitation energy (Ex) distribution from Benhar SF

- Benhar SF provides missing energy.
- Ex is obtained by subtracting the separation energy.

O. Benhar et al., Phys. Rev. D 72, 053005 (2005).



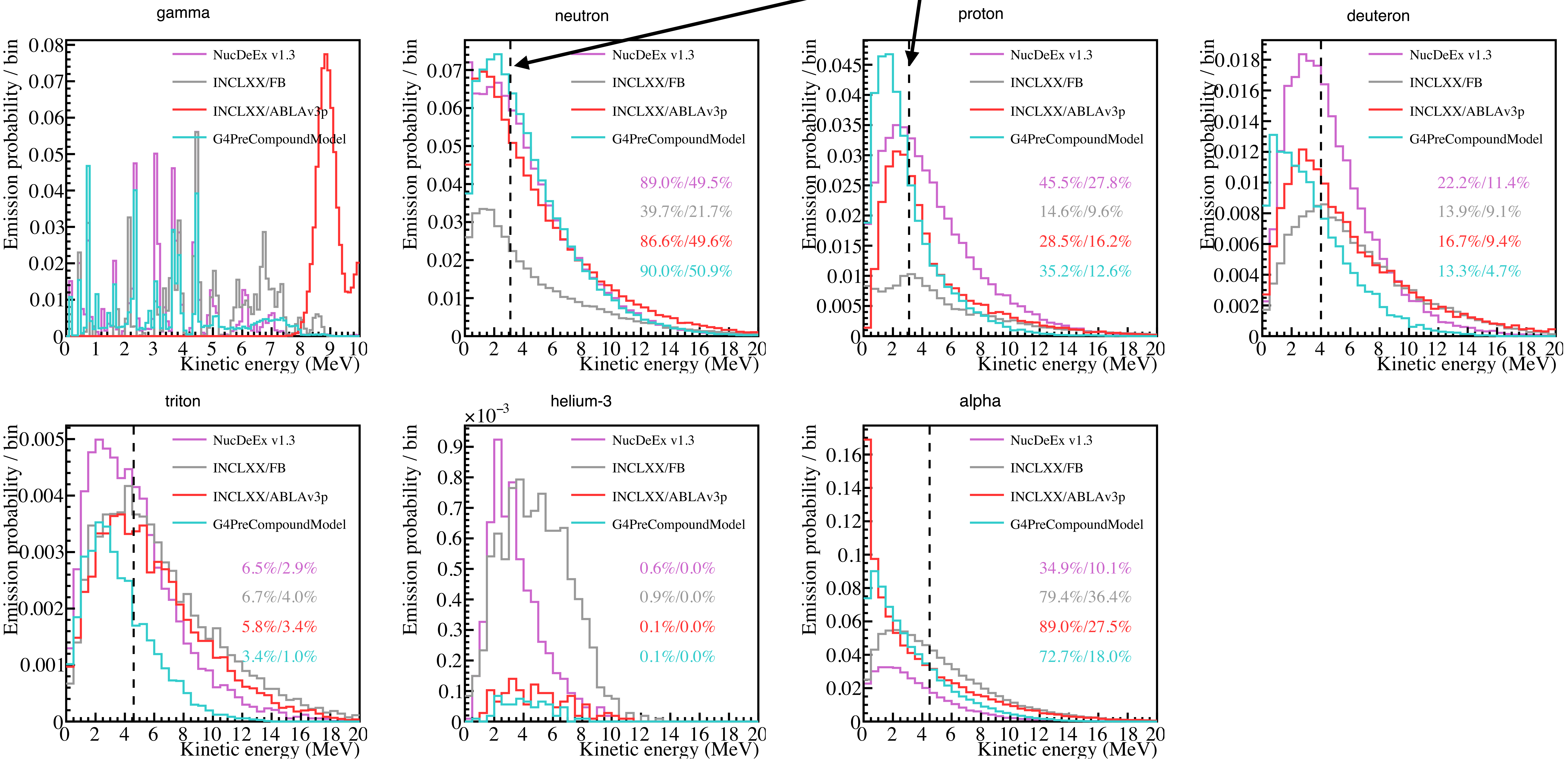


Selected for comparison with experiment as $s_{1/2}$-hole states.

Energy spectra of deexcited particles

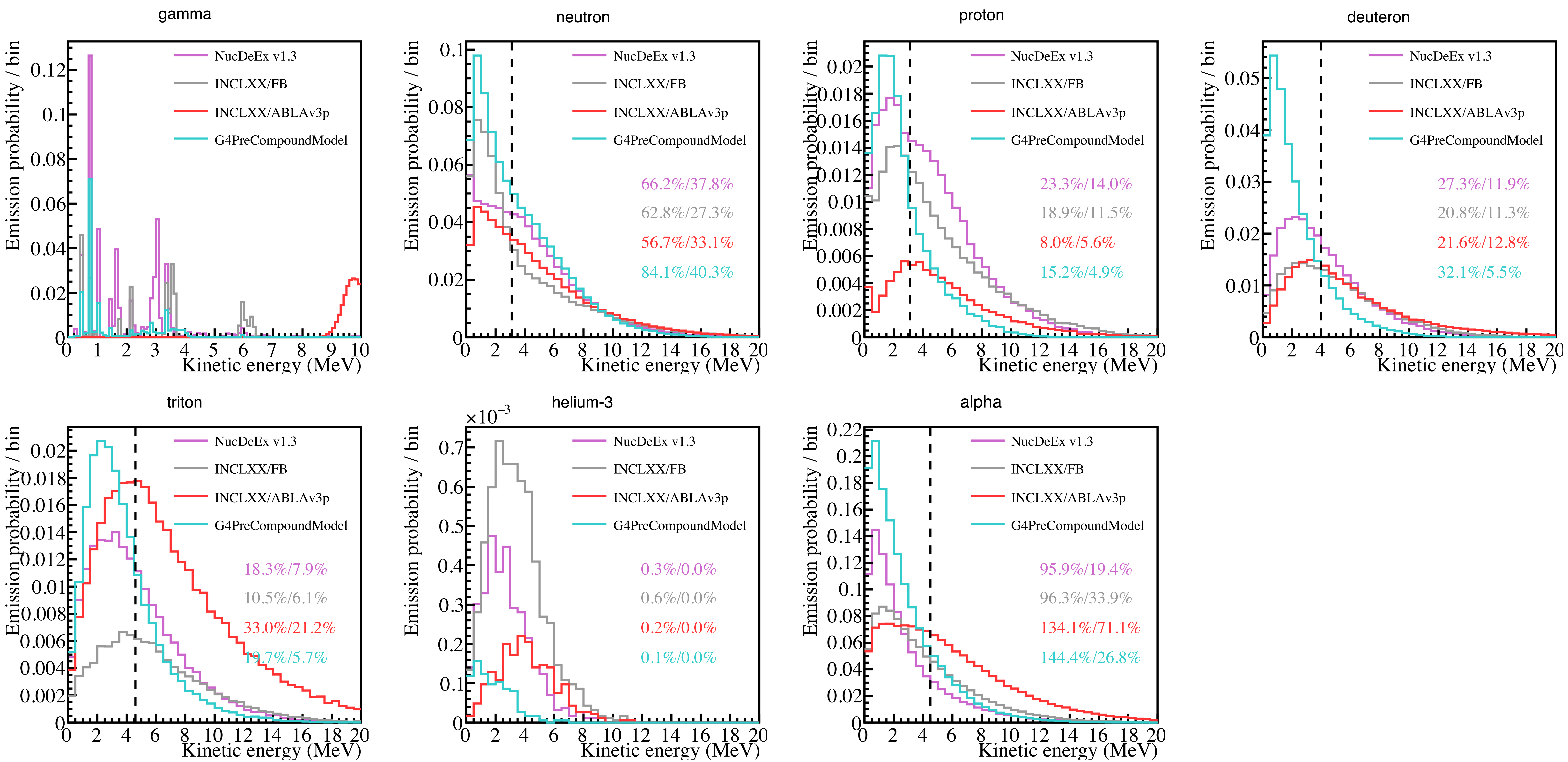
$^{15}N^*$ 20 < Ex < 40 MeV

Detection threshold in exp. by Yosoi et al.



Energy spectra of deexcited particles

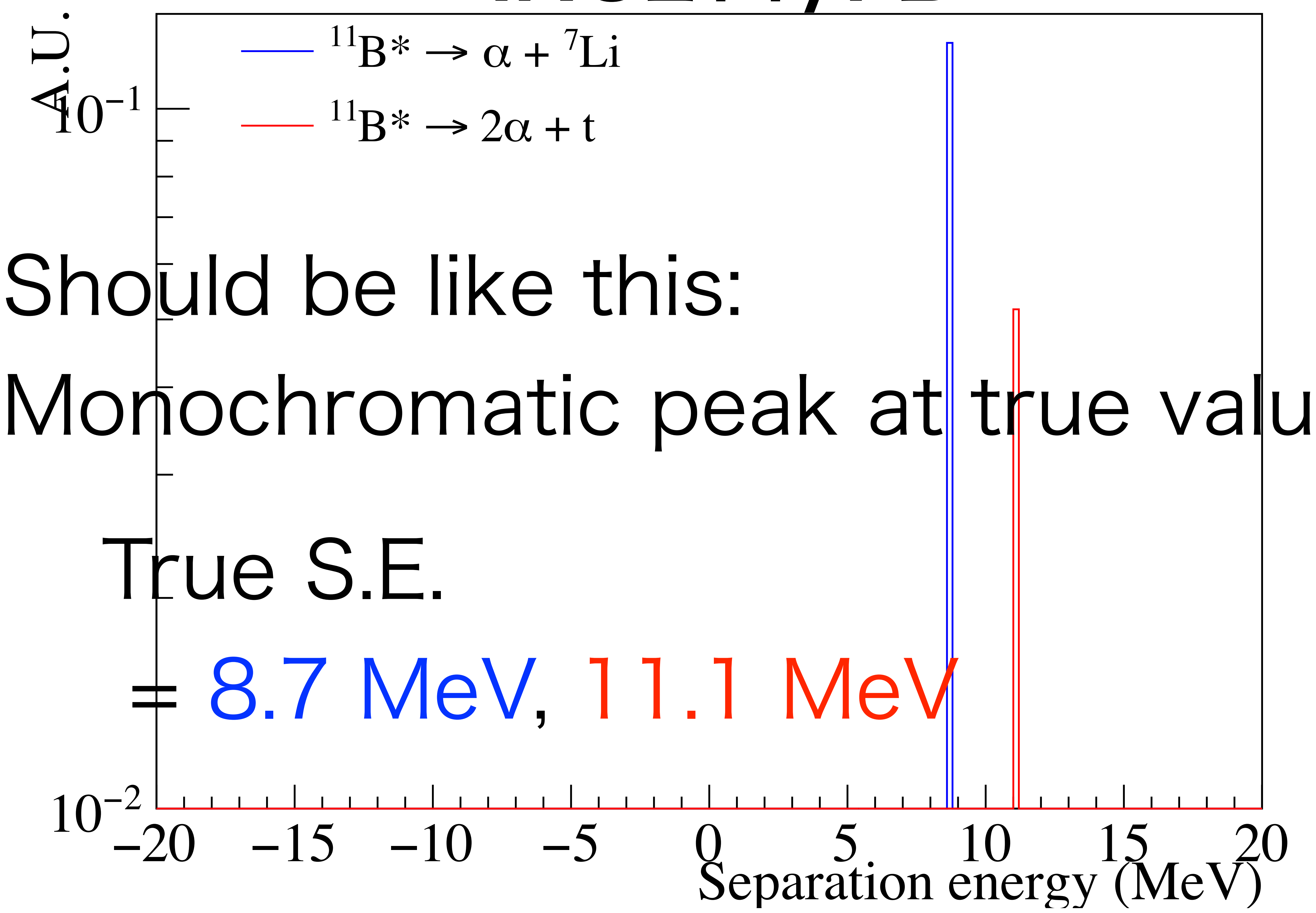
$^{11}B^*$ 16 < Ex < 35 MeV



Issue in ABLAv3p

- Very large α branching ratios in ABLAv3p
- Calculate S.E. using energies of generated particles
- Found energy is not conserved in α emissions
- Might overestimate the phase space

INCL++/FB



Should be like this:
Monochromatic peak at true value

True S.E.
= 8.7 MeV, 11.1 MeV

INCL++/ABLA