Electron Scattering in NEUT / Nuclear Deexcitation

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Institute for Cosmic Ray Research
University of Tokyo

Contents

Introduction: ν physics and interactions

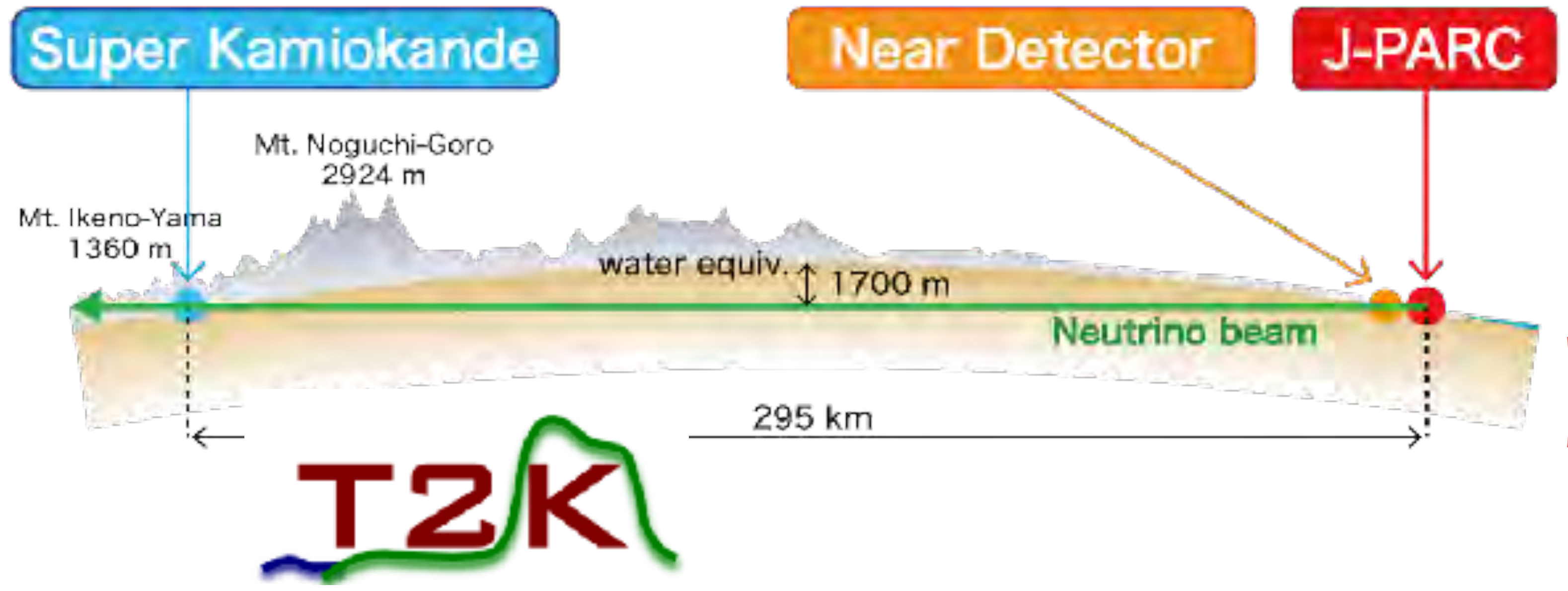
Neutrino CP-violation

Cosmogenesis physics

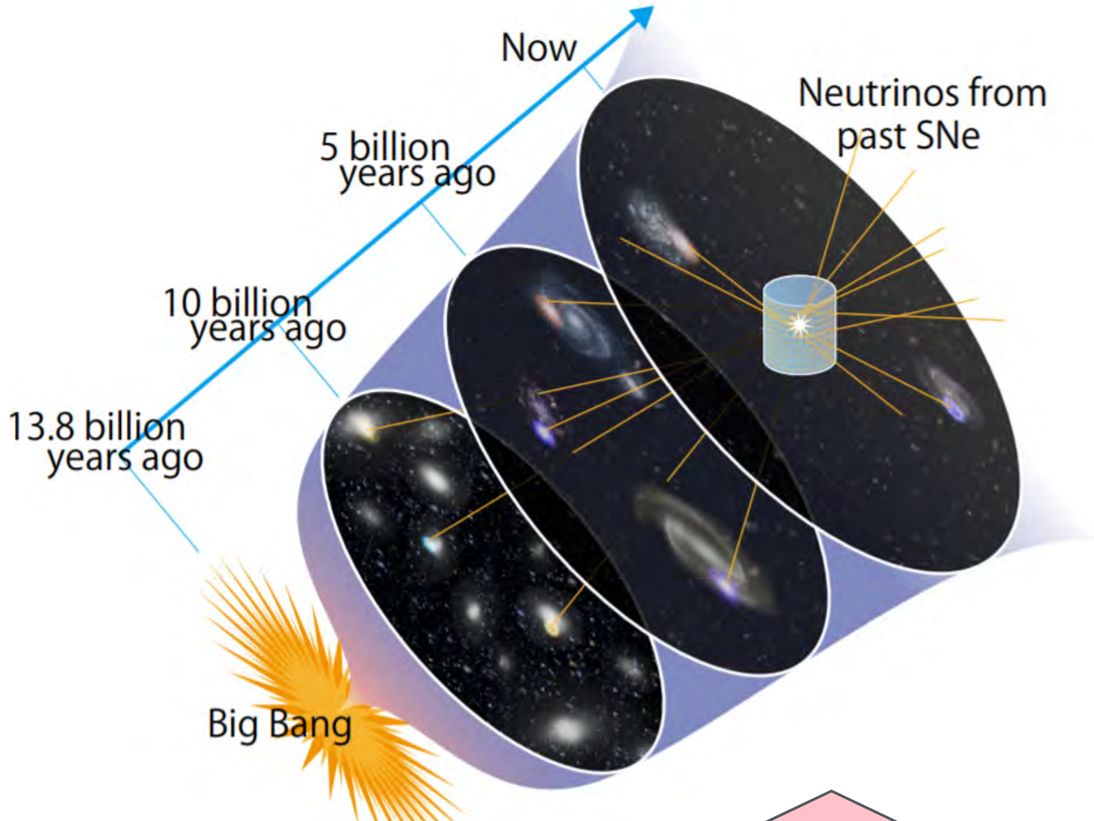
Osc. prob.

$$P(\nu_\mu \to \nu_e) \overset{?}{\neq} P(\bar{\nu}_\mu \to \bar{\nu}_e)$$

δ_{CP}



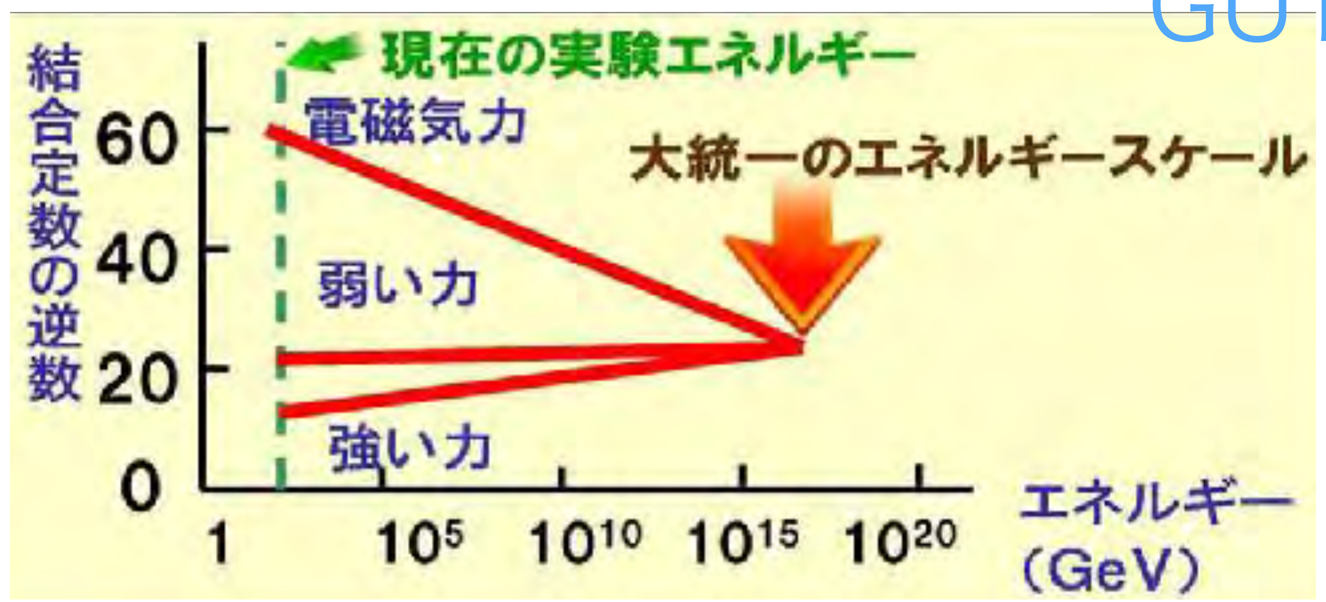
Diffused Supernova ν

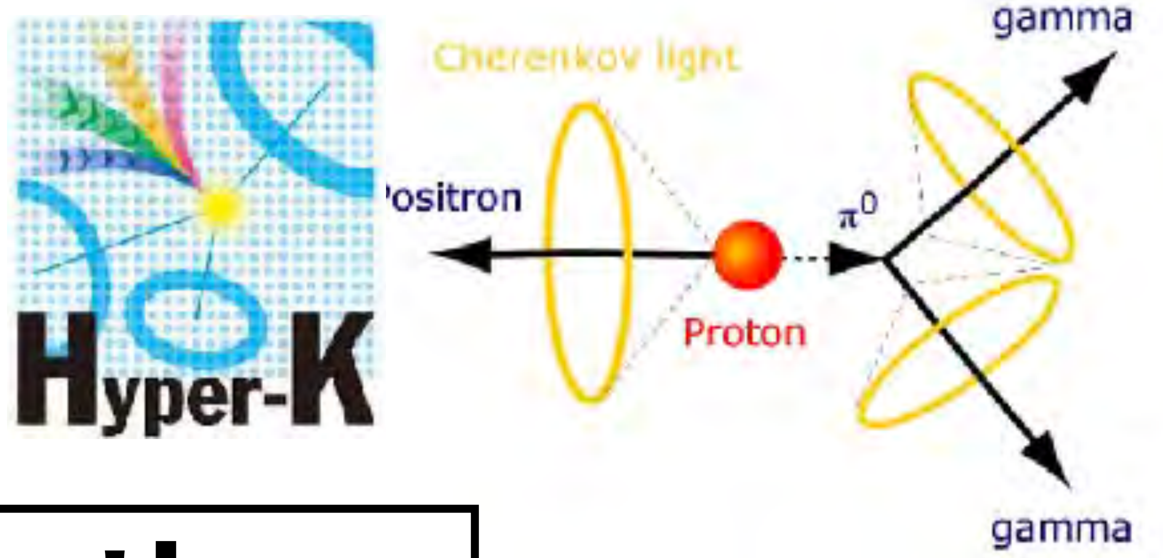


Astrophysics

Nucleaon Decay

GUT



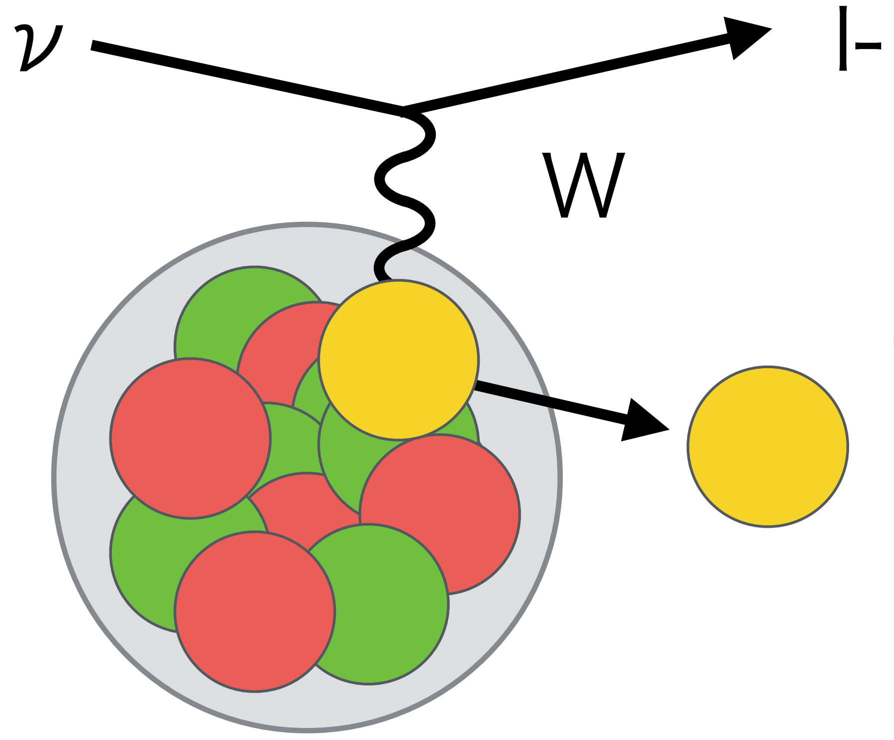


Develop neuturino physics

Understanding signal/BG

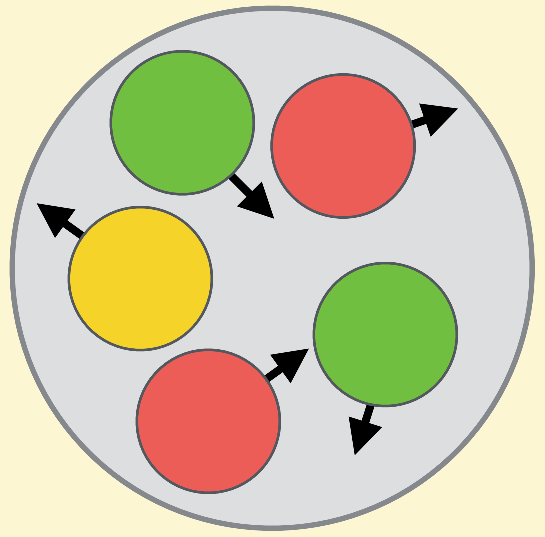
Understand ν-nucleus (νN) interactions

PWIA: Plane wave impulse approximation



$\simeq$

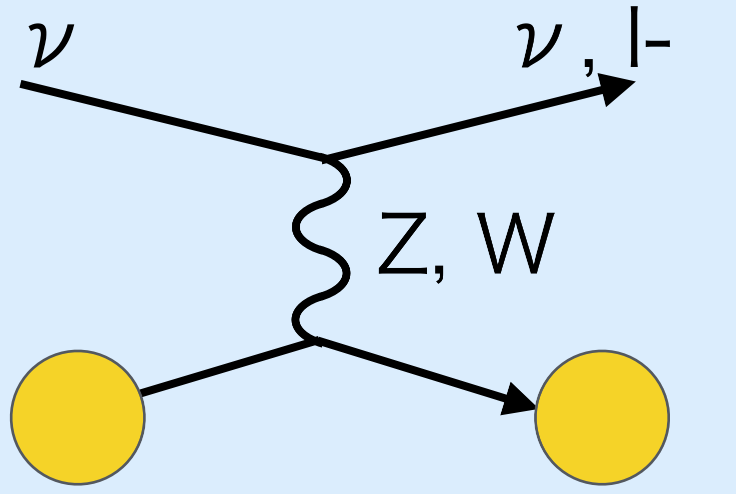
Initial state



Binding energy, momentum

X

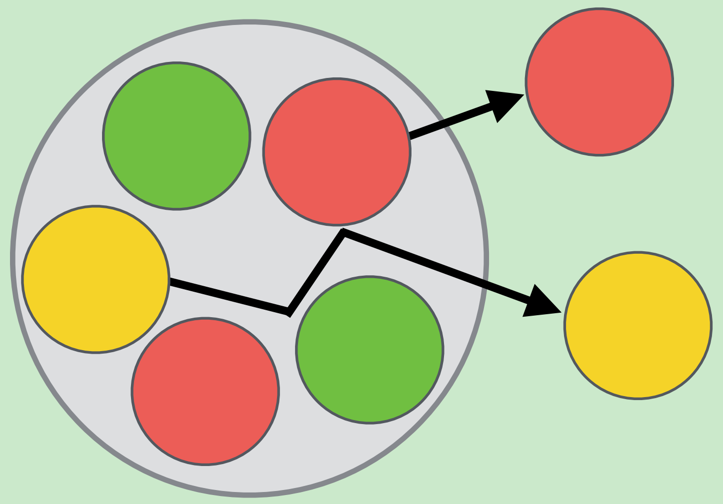
Weak interaction



V-A current

+

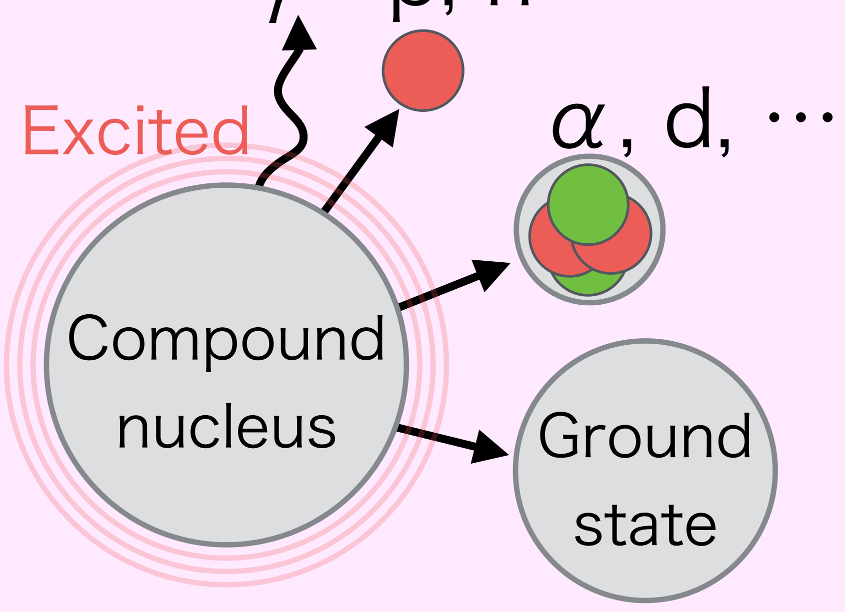
Final state interaction



Intranuclear cascade

+

Deexcitation



Compound process

Introduction: ν physics and interactions

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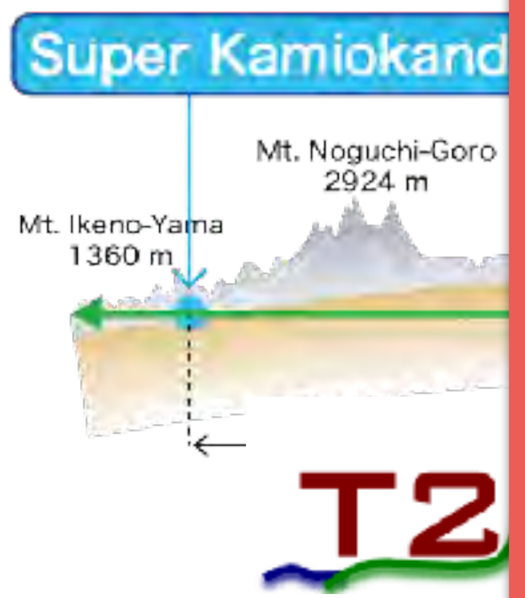
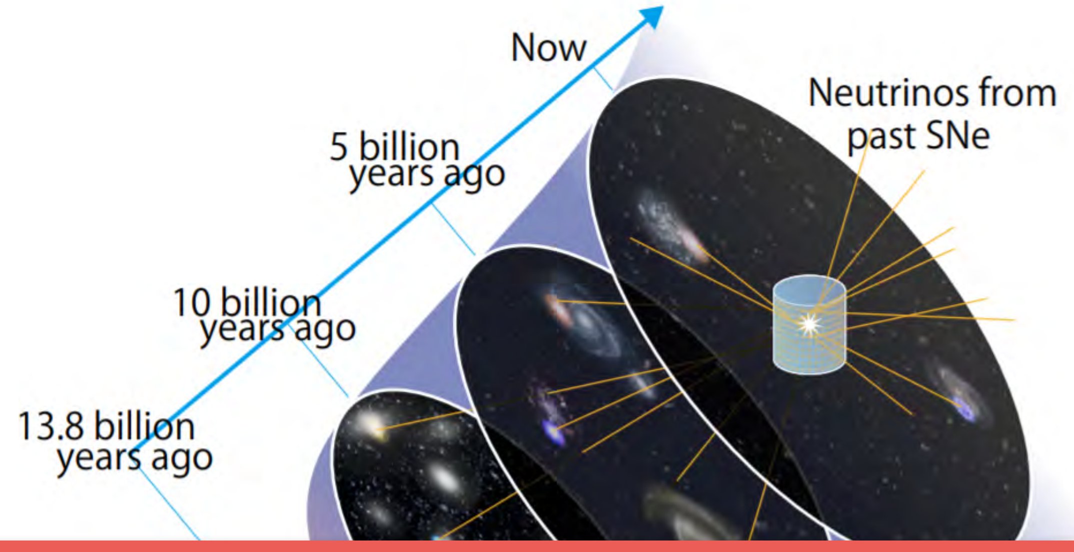


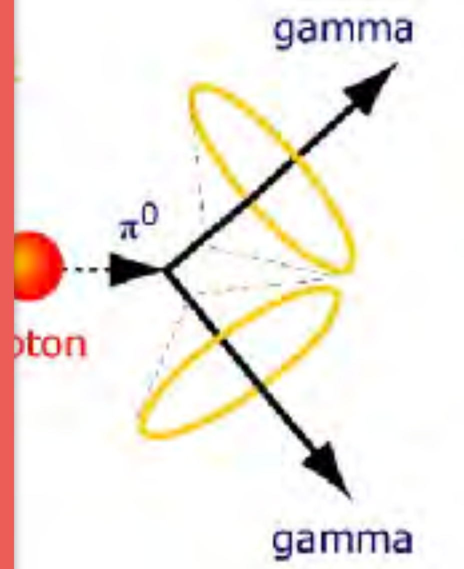
Diffused Supernova ν

Astrophysics



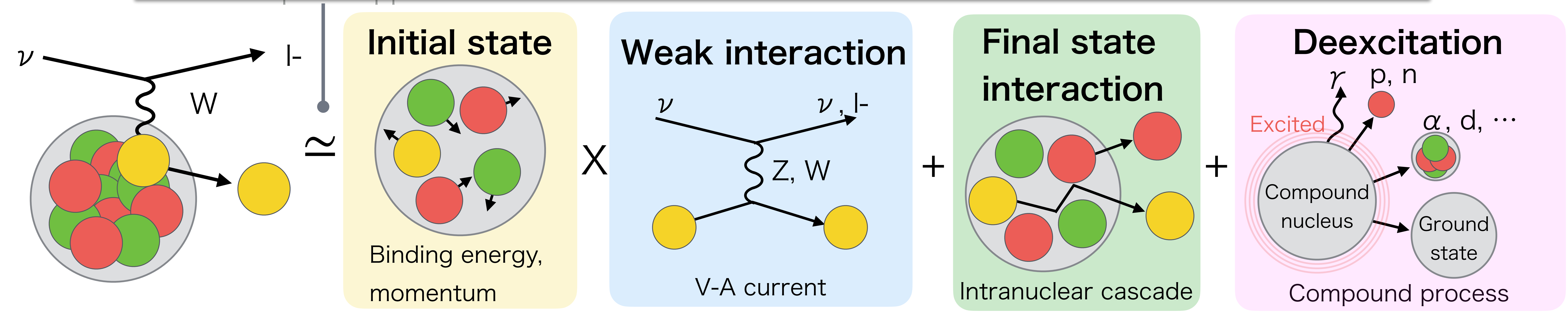
Nucleaon Decay

GUT



How can we accurately predict the response of νN interactions in detectors?

PWIA: Pla



ν detectors in the world

- Getting big…
- Target: O/C/Ar

- LS & H2O+Gd

→ Aim Neutron!

Neutrino event generators

Understanding νN interactions

Theory

Experiment

Generators:

Bridge to connect two pillars

NEUT, GENIE, NuWro, GiBUU, Achiless

* NEUT does not have official logo.

NEUT: A neutrino event generator

- Born for the Kamiokande experiment in the 1980s.

```
(Creation Date and Author)
  1983.??.?? ; M.NAKAHATA
  1987.08.?? ; N.SATO      FOR TAU
  1988.08.31 ; T.KAJITA    DATA UPDATE
  1988.09.06 ; T.KAJITA    R1314 IS ADDED
```

Source code comment.

- Mainly used in experiments in Japan: **Super-Kamiokande (SK), T2K**
  - The primary target is **water**, but it can be used for carbon, iron, etc.

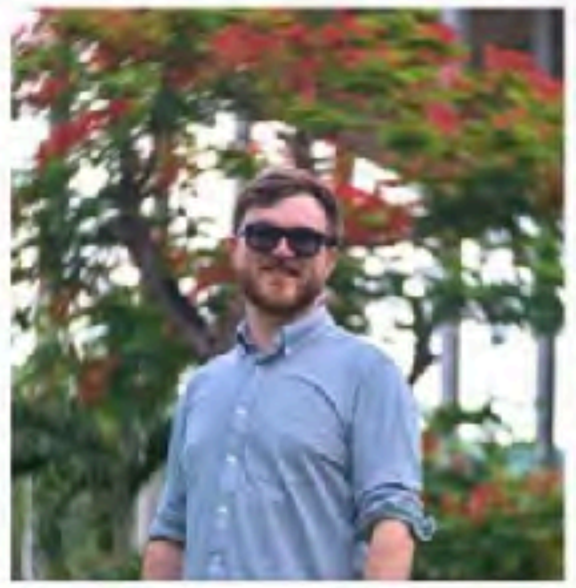
- Not open to the public, but distributed upon request.
  - e.g.) KamLAND, JUNO

Hayato (my boss)

- Recently developed by T2K NIWG members, mainly.

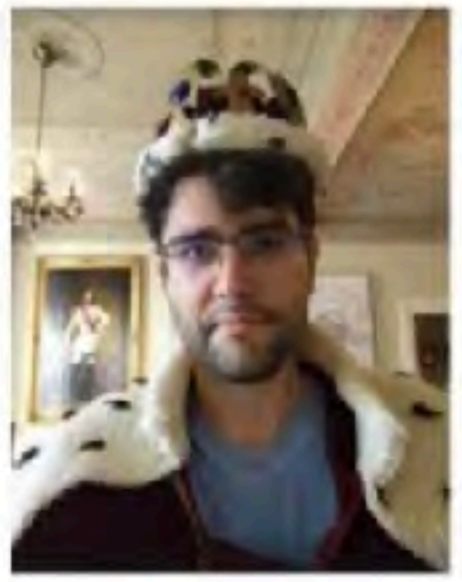
UK: Luke, Kamil, Patrick, Jake
Japan: Hayato, Abe
+ other contributors

T2K NIWG conveners (Neutrino Interaction Working Group)



Luke

Kevin



Kamil

Patrick

Abe

NEUT: Software

- **The core is written in Fortran.**
  - Old coding style 😇
  - C++ code provided by theorists is implemented by preparing an interface, e.g., the Valencia model.

- **Keep updating our coding style & build scripts for the next-generation experiments.**
  - e.g.) A major update, NEUT6
    - Built with CMAKE, supports NuHEPMC format, etc.

Current generation

Transition period!

Next generation

Hard time for developers due to strict compatibility requirements…

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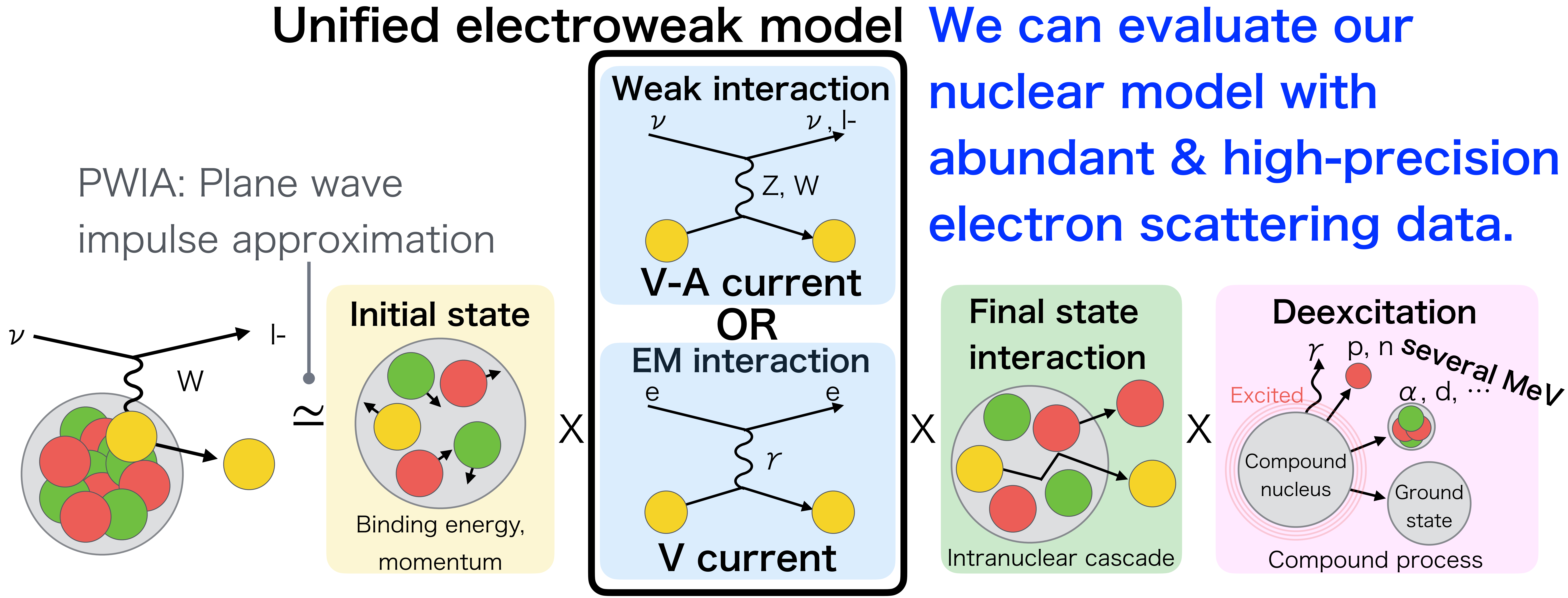
- **Electron scattering in the NEUT neutrino event generator**
  - Motivation of electron scattering (can be omitted).
  - Initial implementation & investigation.
  - S. Abe, PRD 109, 036009 (2024)

- **Nuclear deexcitation**
  - Signicance in Super-Kamiokande Gd experiment.
  - Nuclear deexcitation event generator NucDeEx.
  - How can we describe this process properly?
  - S. Abe, PRD 111, 033006 (2025)

Electron scattering for neutrino

- Great talk by Adi in this workshop.
- e4ν Collaboration focuses on GENIE.
- We would like to develop discussion also for **NEUT.**



We can evaluate our nuclear model with abundant & high-precision electron scattering data.

Extension to electron scattering of NEUT

- J. McElwee et al. implemented electron scattering in NEUT.
  - Not compliant with NEUT framework. QE only.
  - Not included in NEUT.

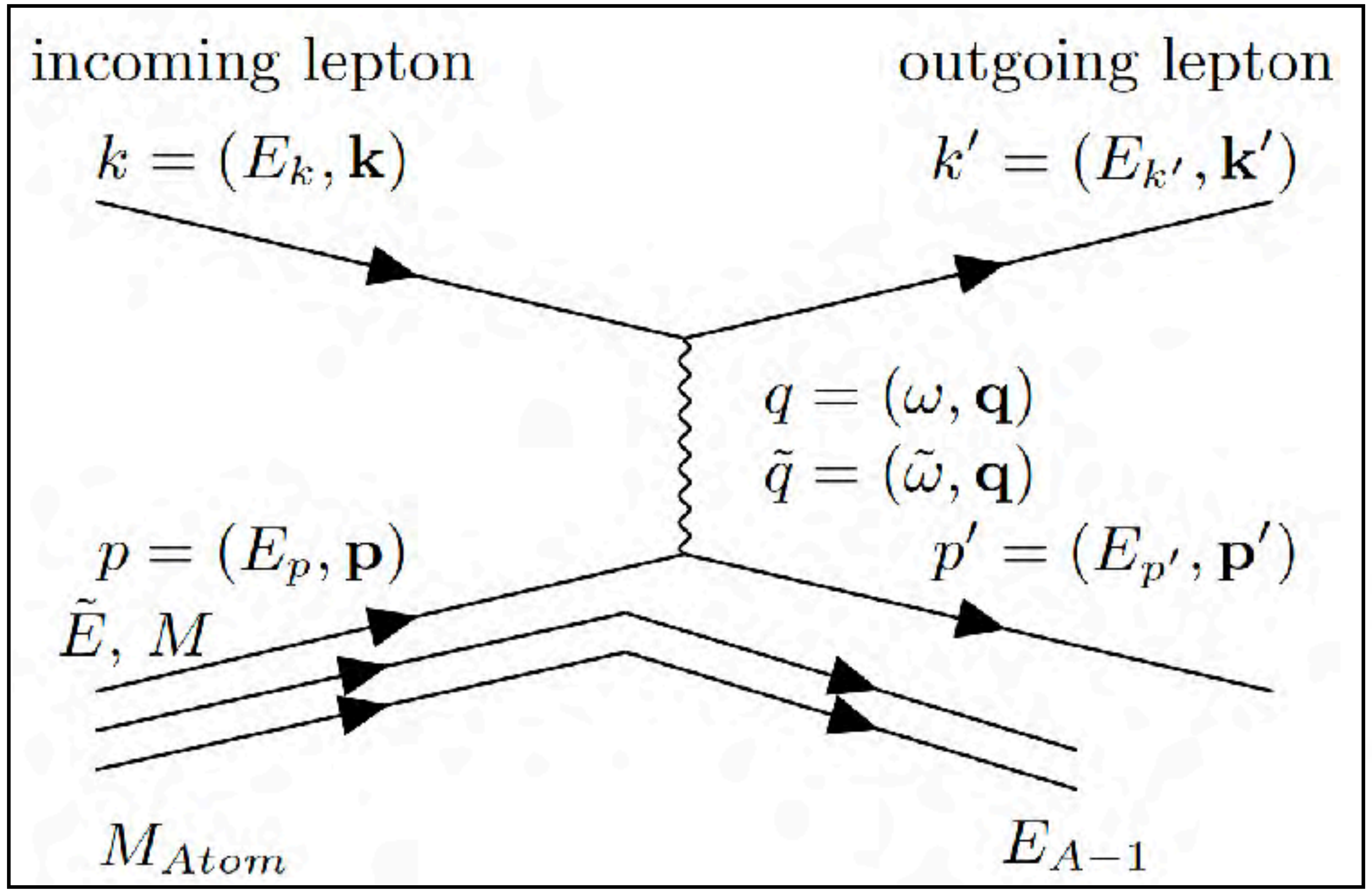
  - *J. McElwee, Ph.D. thesis, University of Sheffield (2022).*
  - *S. Dolan et al., Phys. Sci. Forum 8, 5 (2023).*

- **Newly implemented electron scattering to be compliant with NEUT framework.** *S. Abe, PRD 109, 036009 (2024)*
  - Included from version 5.9.0.
  - QE: Spectral Function
  - 1π: DCC
    - DCC is an electroweak interaction model, so quite straightforward to extend.

QE: Spectral function (SF) model

PWIA

- **Extend SF-based model used in T2K to electron scattering.**



Spectral function (SF) by Benhar et al.

Total cross section

Elementary cross section

$$\frac{d\sigma_{\mathrm{tot}}}{dQ^2} = \int d^3p\, d\tilde{E}\, P_{\mathrm{hole}}(\mathbf{p}, \tilde{E}) \frac{d\sigma}{dQ^2},$$

$$\frac{d\sigma}{dQ^2} = \frac{C}{E_k} \int d^3k'\, \delta(\omega + M - \tilde{E} - E_{p'}) \frac{L_{\mu\nu} H^{\mu\nu}}{E_p E_{p'} E_{k'}}.$$

Leptonic/hadronic tensors

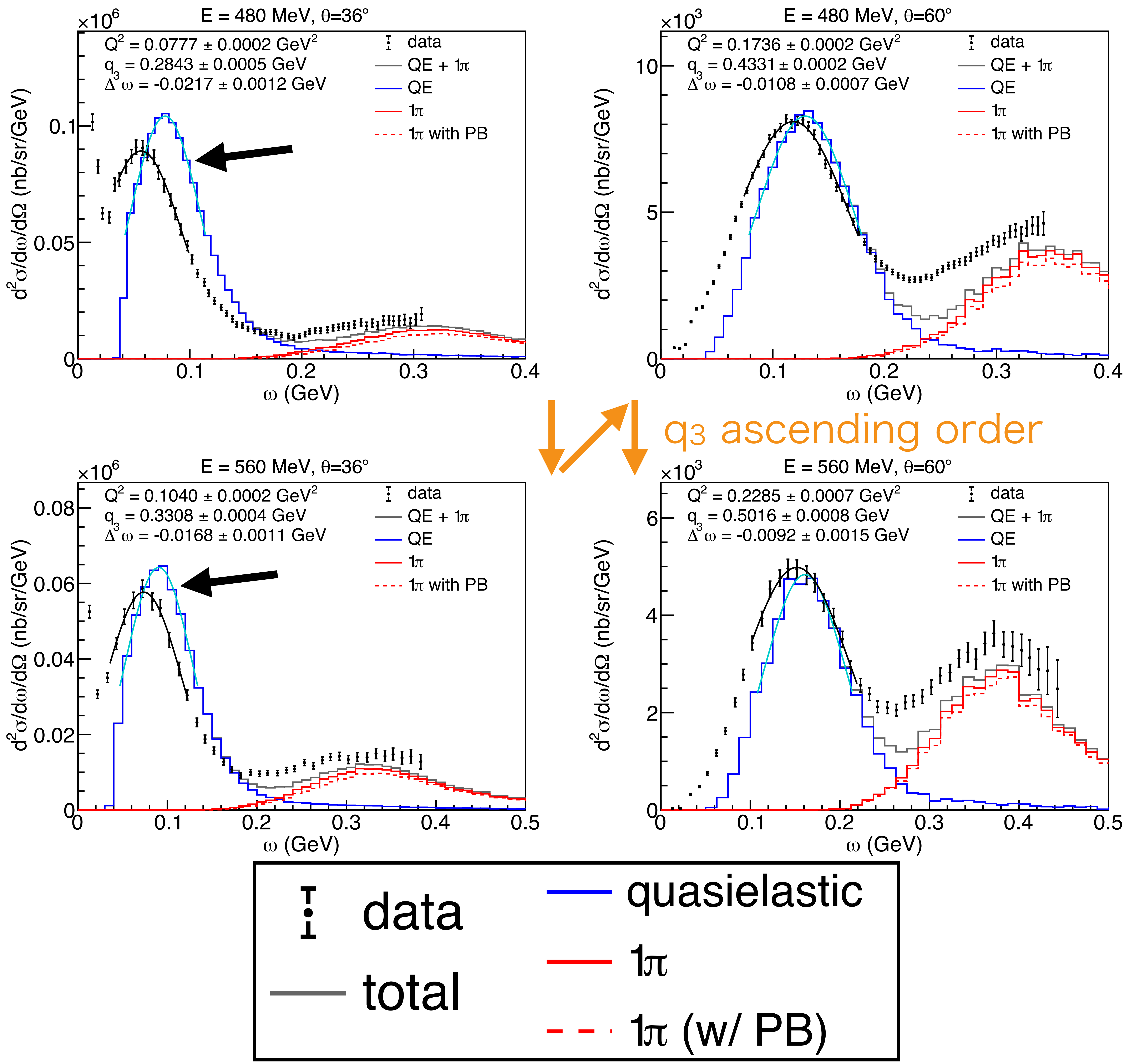
FFs appears here.

Coupling constant

$$C = \begin{cases} \dfrac{G_F^2 \cos^2\theta_C}{8\pi^2} & (\mathrm{CC}), \\ \dfrac{G_F^2}{8\pi^2} & (\mathrm{NC}), \\ \dfrac{\alpha^2}{Q^4} & (\mathrm{EM}), \end{cases}$$

- **We can simulate CC, NC, and EM by changing the coupling constant and FFs.**
  - The same method as GENIE and NuWro.

Comparison between NEUT and exp. data



- **QE peak shift is observed.**
- It's known to depend on three-momentum transfer q_3.
  - A smaller q_3 gives a larger peak shift.
  - From effects beyond the PWIA.

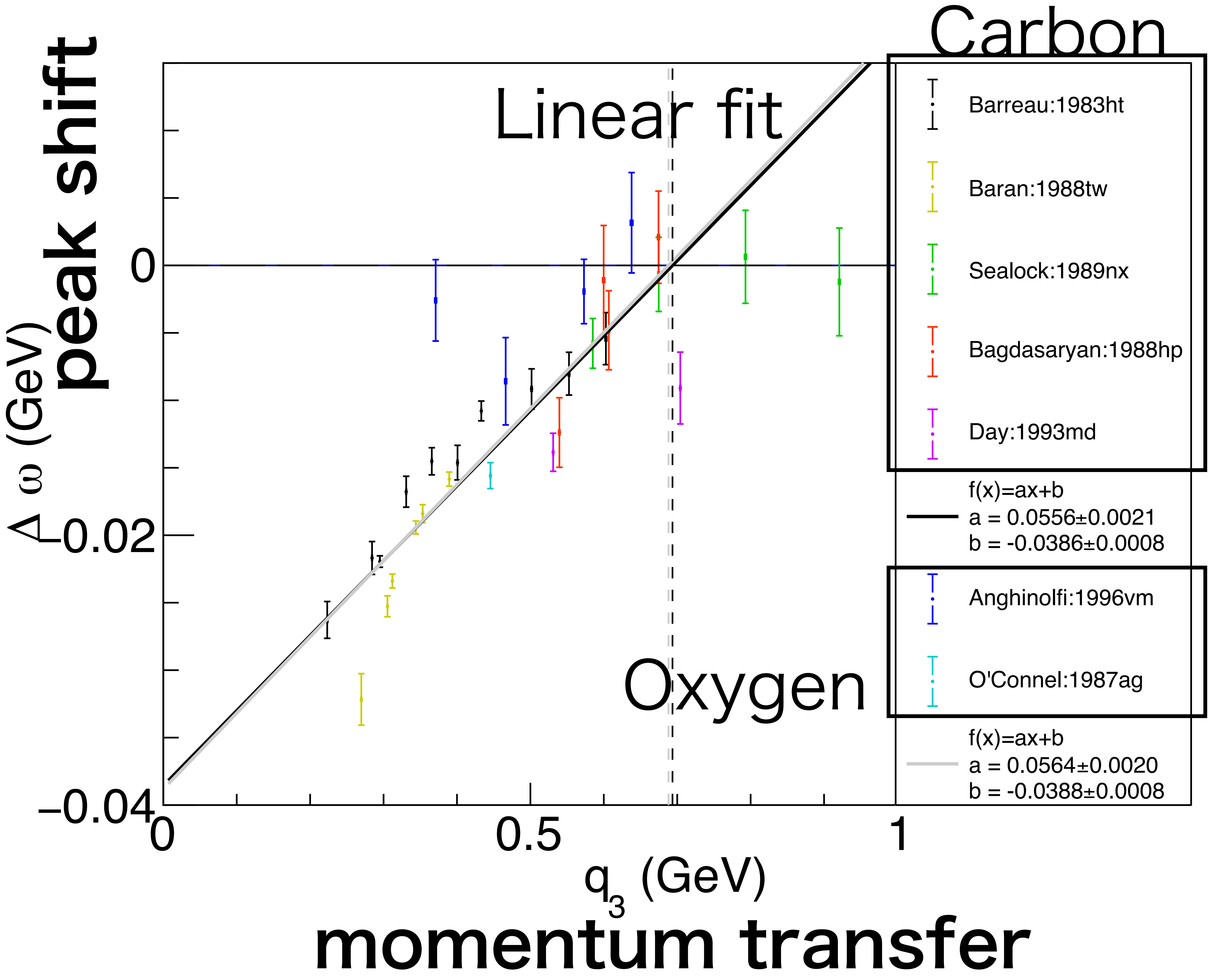
- Analyze the relation between q_3 and peak shift $\Delta\omega$.
- Fit the QE peaks with Gaussian.

peak positions

$$\Delta\omega = \omega_{data} - \omega_{neut}$$

- Calculate q_3 from ω_{data}

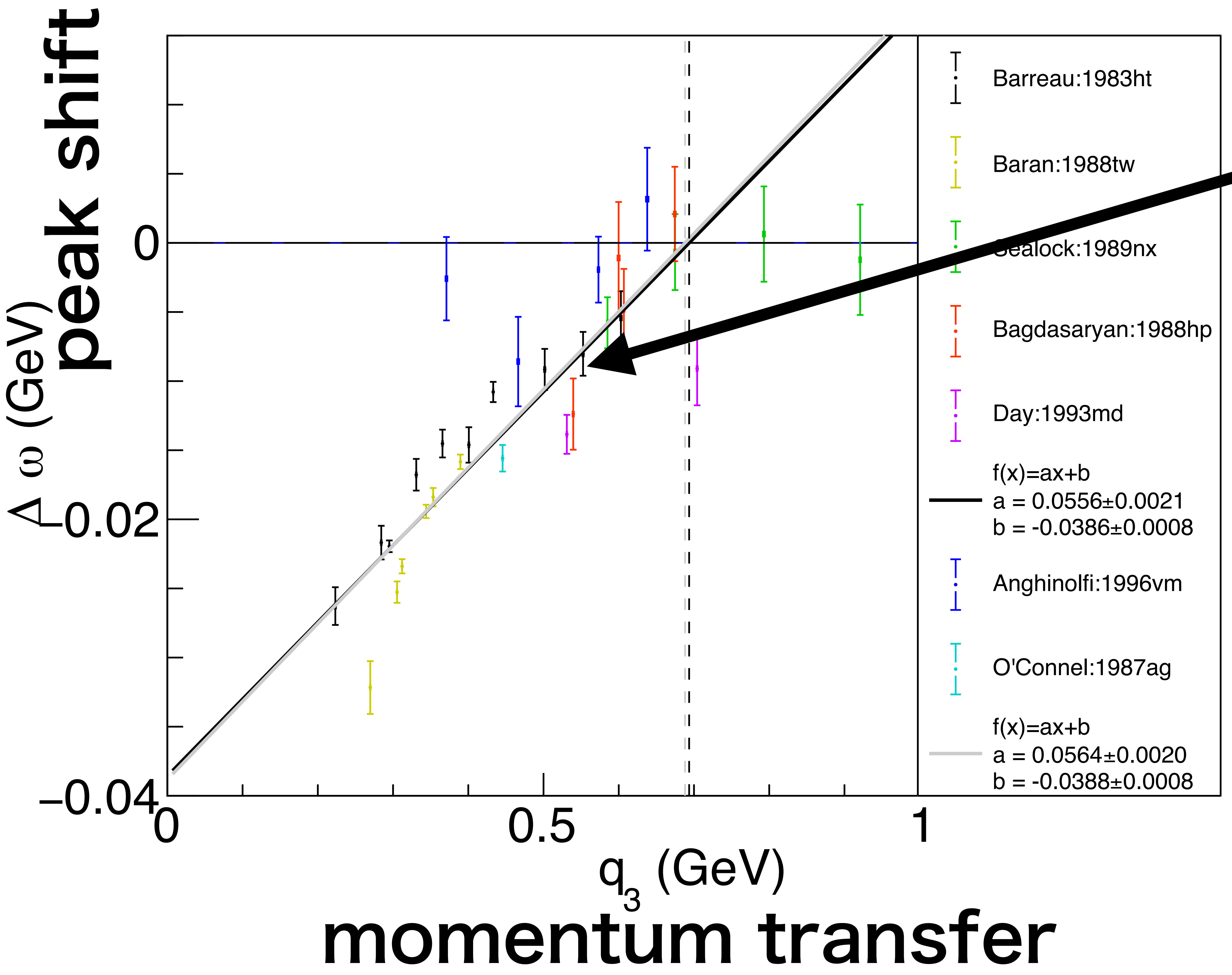
Peak shift vs momentum transfer



- Non-zero $\Delta\omega$ can be interpreted as **an additional term to the removal energy** due to effects beyond the PWIA.
  - Smaller momentum transfer results in smaller effective removal energy.
- Correlation is parameterized by a linear function.

It can be used as **“momentum transfer dependent removal energy correction” to empirically introduce effects beyond the PWIA.**

Correction to removal energy $\tilde{E}$



$f(q_3)$: Linear function

$$\Delta\tilde{E} = \begin{cases} f(q_3) & (f(q_3) \le 0), \\ 0 & (f(q_3) > 0), \end{cases}$$

truncate to be negative

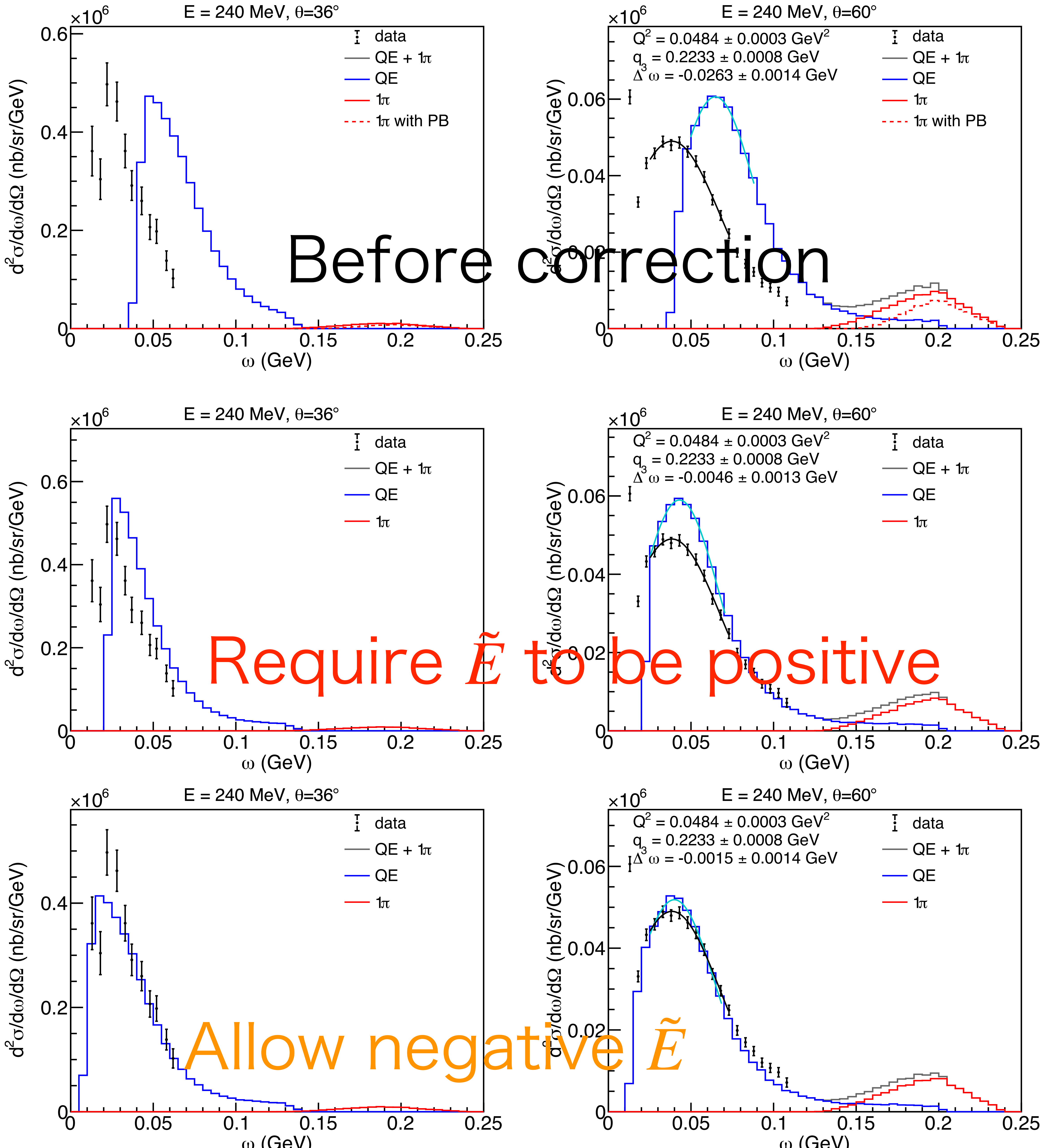
$$\tilde{E} \to \tilde{E} + \Delta\tilde{E}.$$

From SF From e scat.

- Removal energy can be negative.
- Two ways of correction:
  - Allow negative $\tilde{E}$
  - Require $\tilde{E}$ to be positive

Impact of correction

- **Allowing negative $\tilde{E}$ gives much better agreement.**
  - Both in peak position and height.
- But this is empirical.
- **Better to have an alternative way to maintain physics consistency.**
  - e.g.) Theory-driven correction for real optical potential. A. M. Ankowski et al., PRD 91, 033005 (2015)



Impact on neutrino energy reconstruction

Assuming CCQE

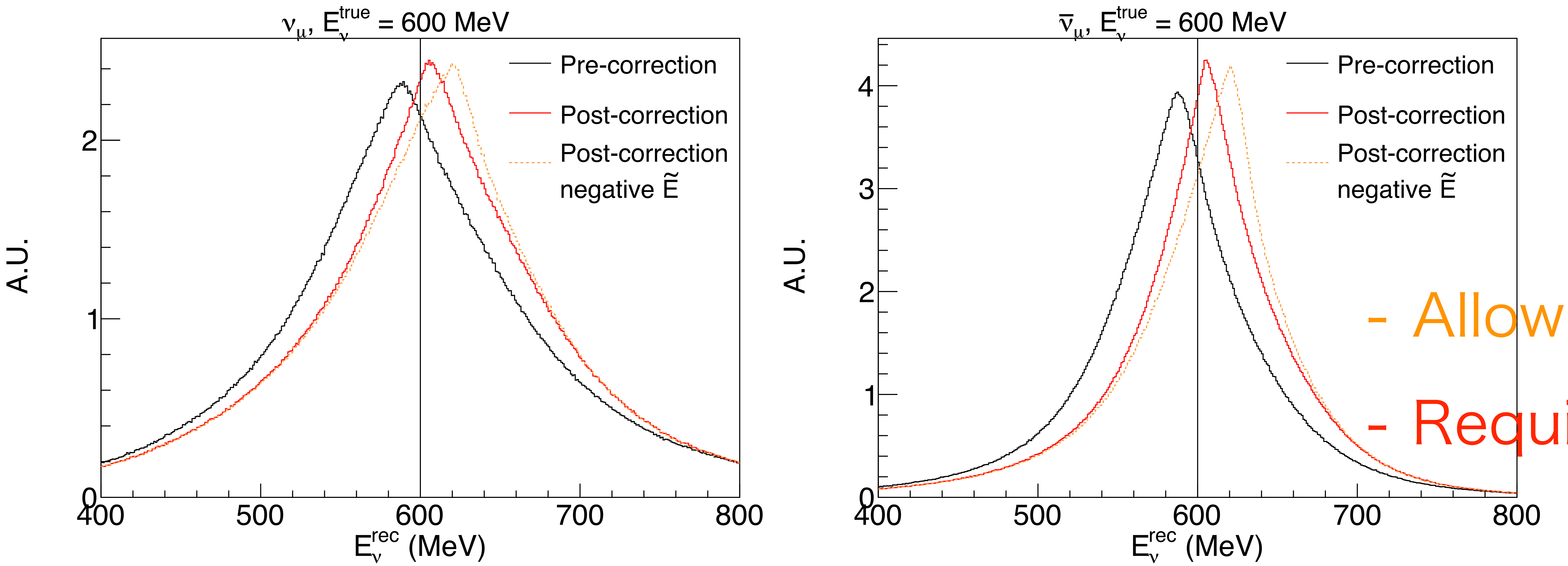
Charged lepton

$$E_\nu^{rec} = \frac{2E_l\tilde{M} - (m^2 + \tilde{M}^2 - M_f^2)}{2(\tilde{M} - E_l + p_l\cos\theta_l)},$$

$$\tilde{M} = M_i - E_b, \quad E_b = 27\,\mathrm{MeV}$$

- Shifted by ~20-30 MeV.
- Consistent with similar studies
  - A. M. Ankowski et al., PRD 91, 033005 (2015)
  - A. Bodek and T. Cai, Eur. Phys. J. C 79, 293 (2019).

CCQE @ True E_ν=600 MeV



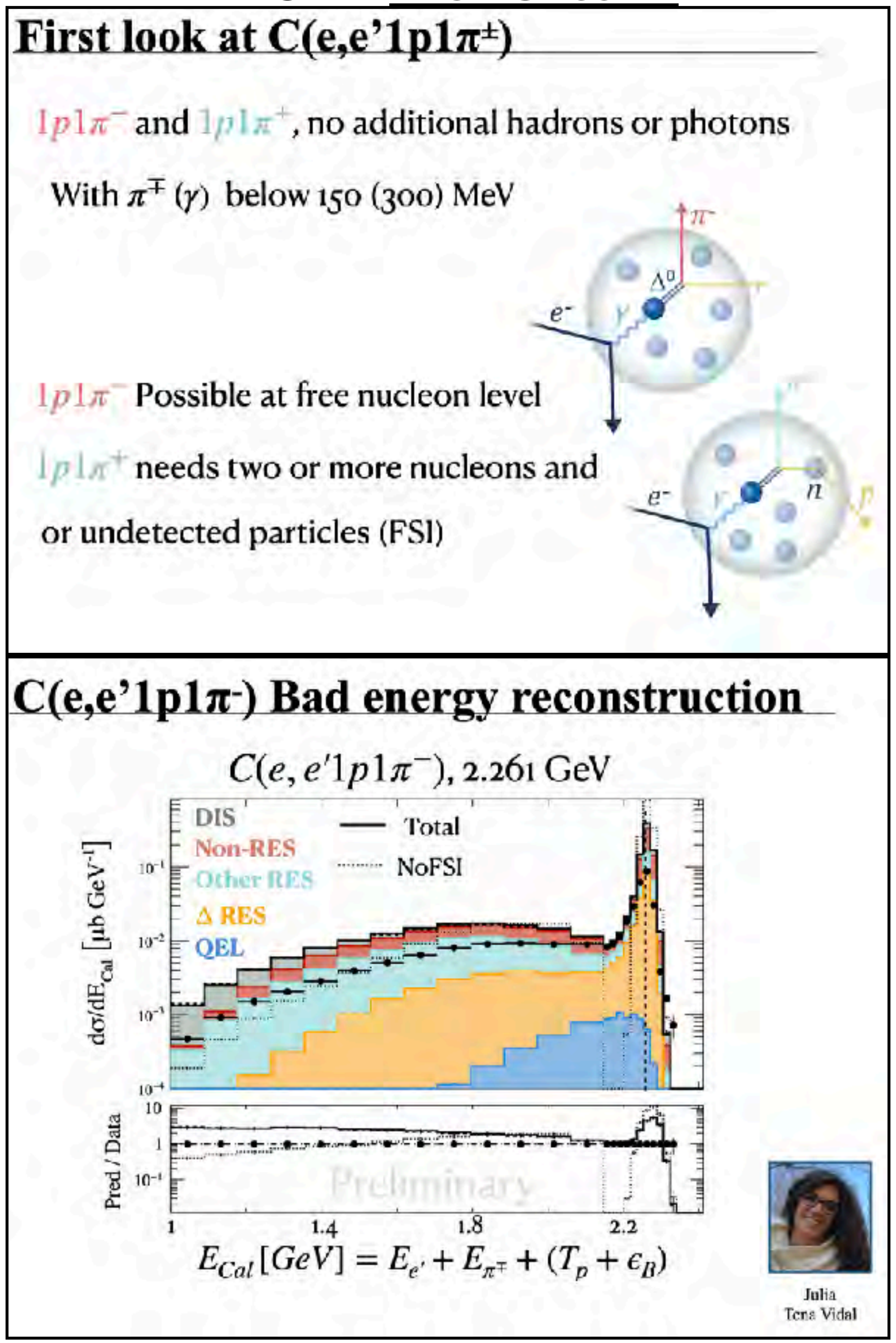
- Allow negative $\tilde{E}$
- Require $\tilde{E}$ to be positive

Further studies: Go to “exclusive”

- Comparison with e4nu data in JLab.
  - C(e,e’p)$_{1p0\pi}$
  - C(e,e’1p1$\pi^{\pm}$) in Adi’s talk.

- Interesting topic
  - Compare with NEUT.
    - Talking with Julia about this.
  - Implement other channels (MEC, DIS)

From Adi's talk.



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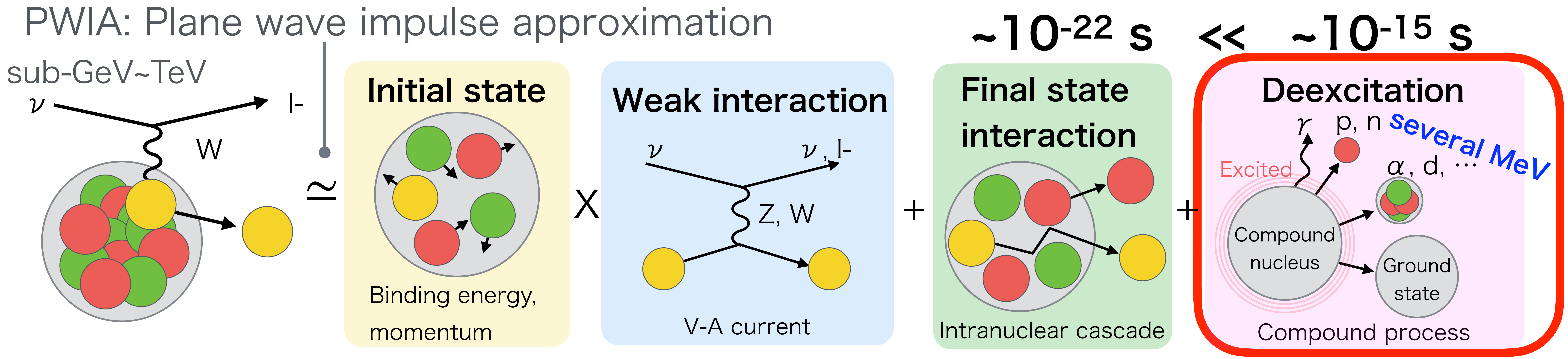
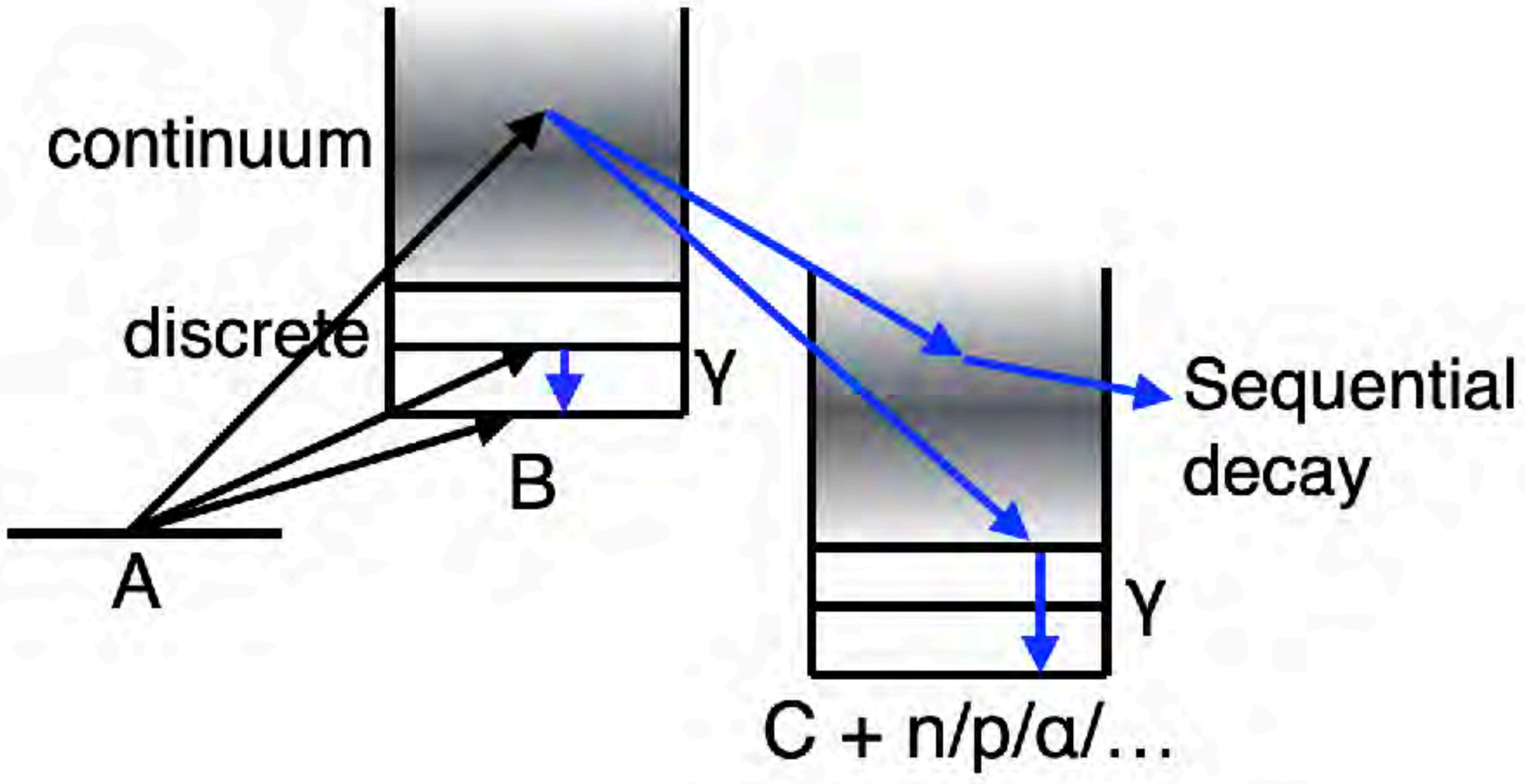
  - Signicance in Super-Kamiokande Gd experiment.
  - Nuclear deexcitation event generator NucDeEx.
  - How can we describe this process properly?
  - S. Abe, PRD 111, 033006 (2025)

Nuclear deexcitation

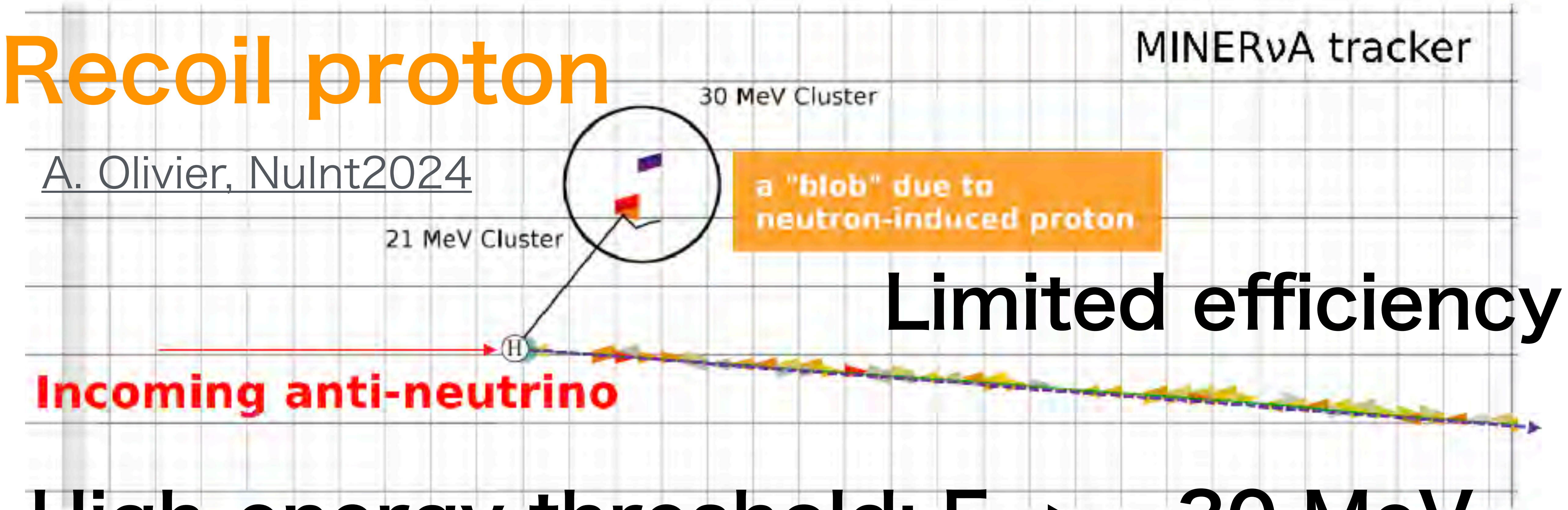




- The last process.
- It emits various particles: γ, n, p, α,⋯
- **Typical energy is several MeV.**
  - Invisible at many ν detectors.
  - Neglected in many generators so far, but becoming a hot topic recently.

Example: Neutron detection via recoil/capture

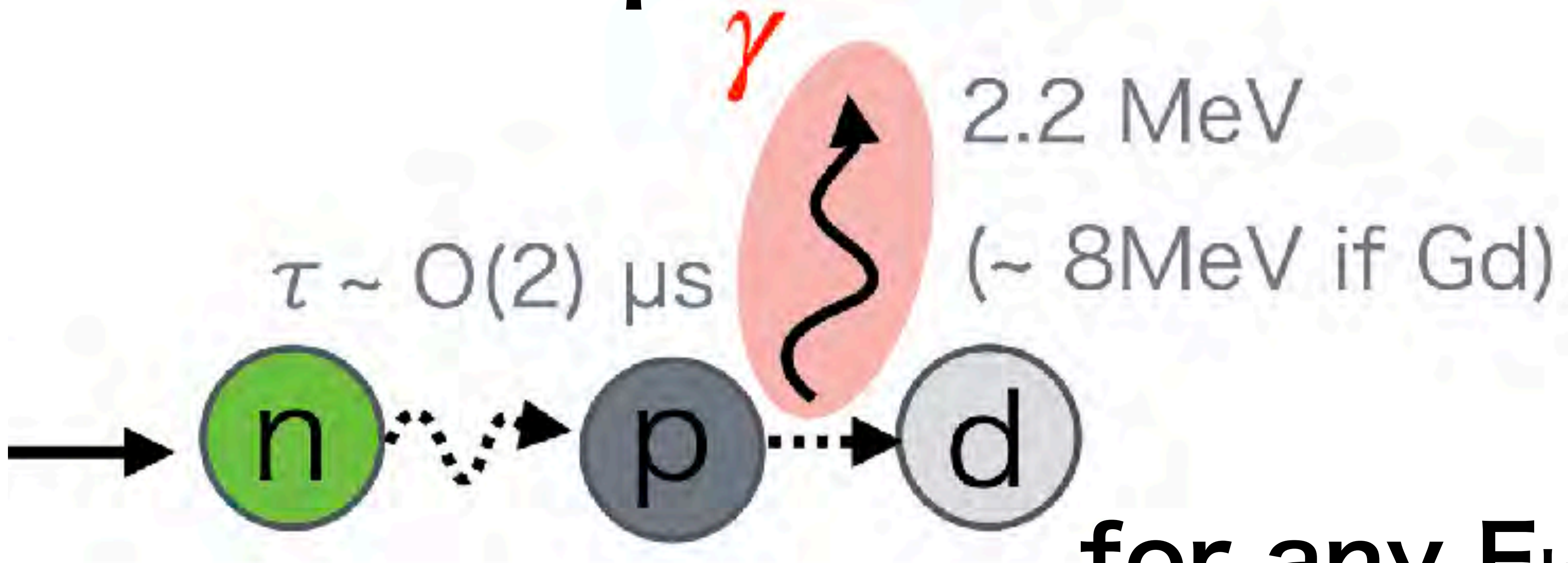
Recoil proton



Limited efficiency

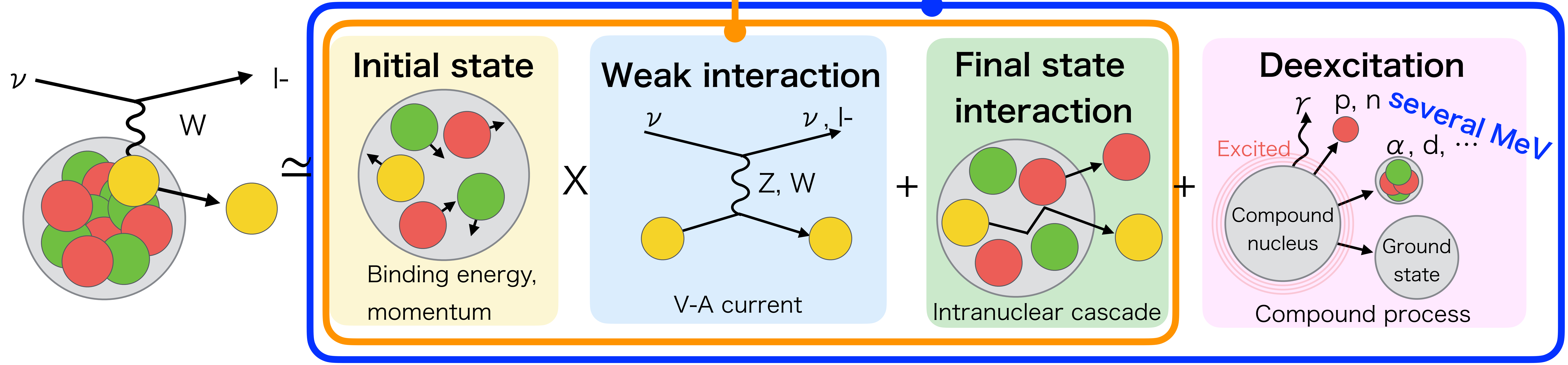
High-energy threshold: E_k > ~ 30 MeV
→ insensitive to deexcitation.

Neuron capture



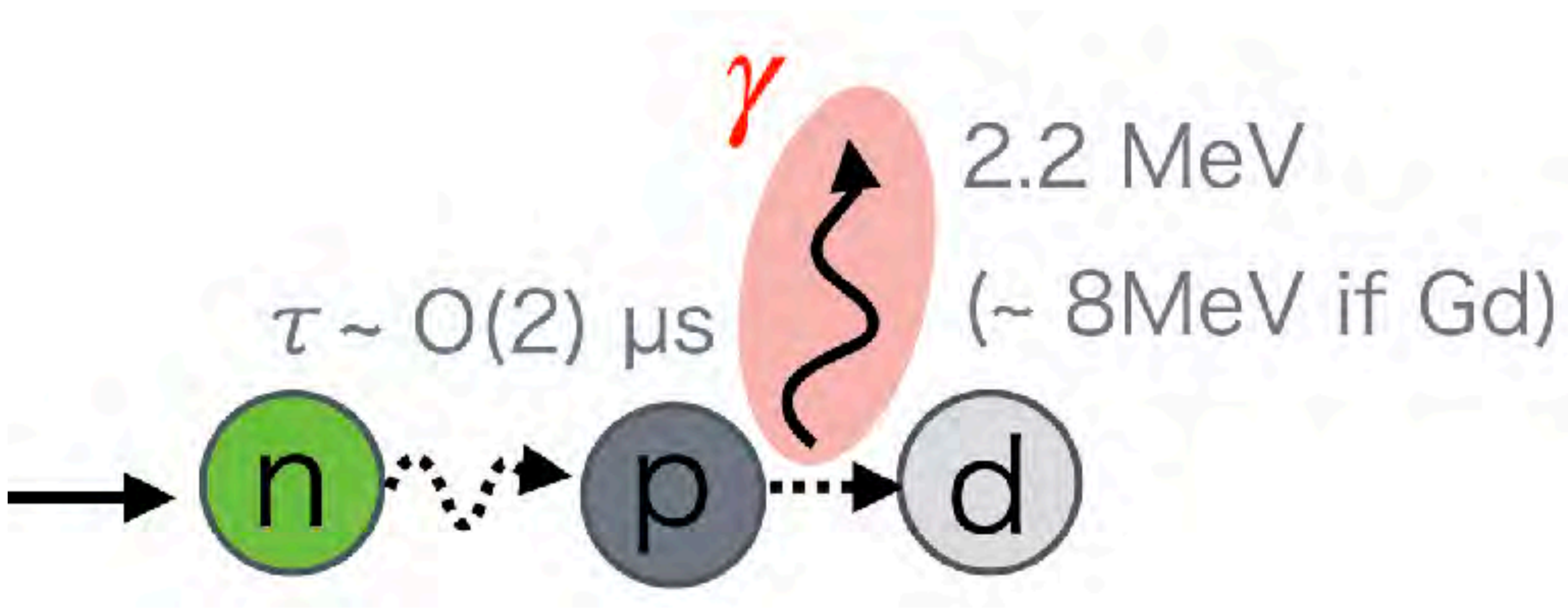
for any E_k

Occurs with **all neutrons.**



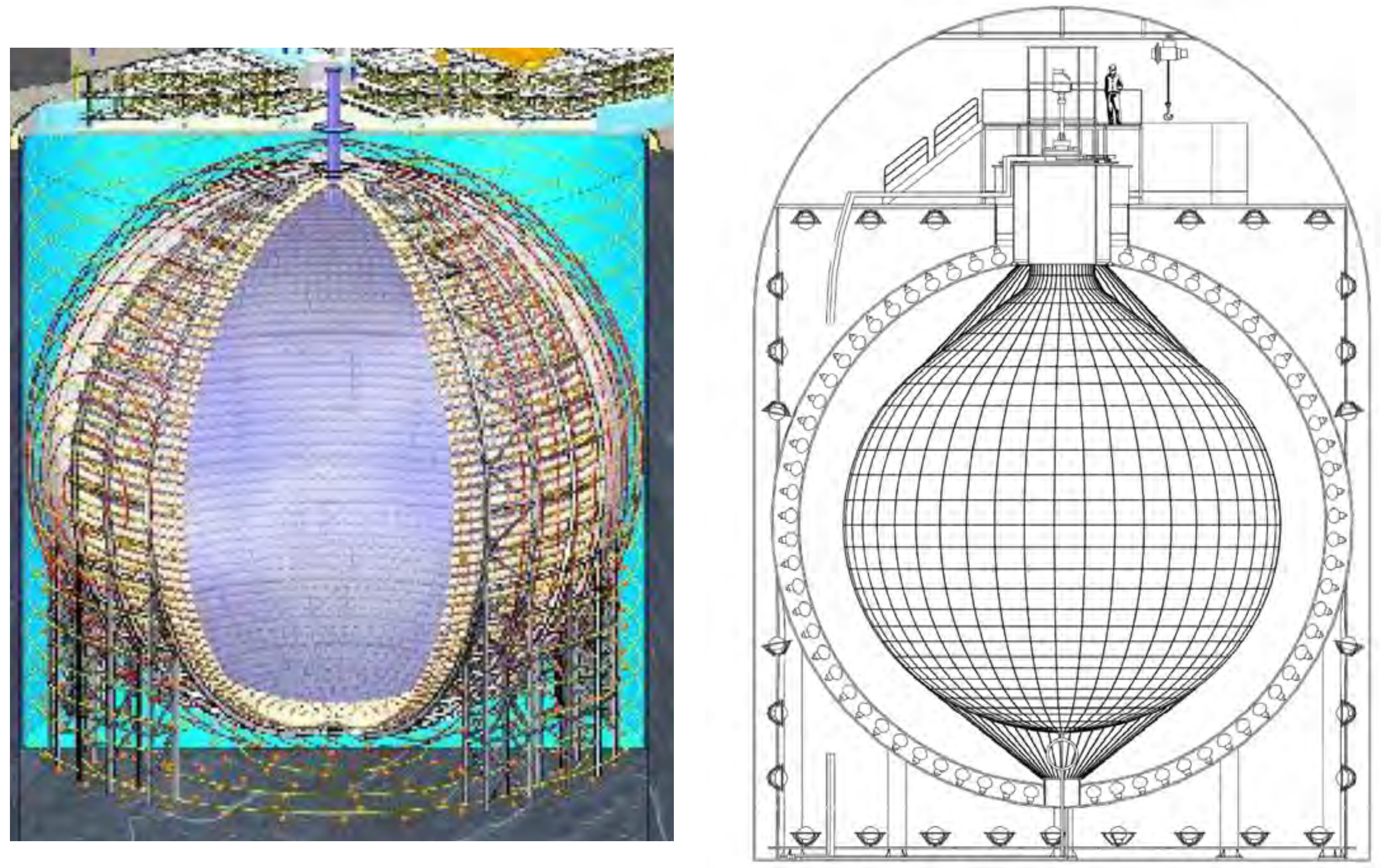
Precise understanding of deexcitation is essential for capture.

Neutron capture is so sensitive to nuclear deexcitatioin

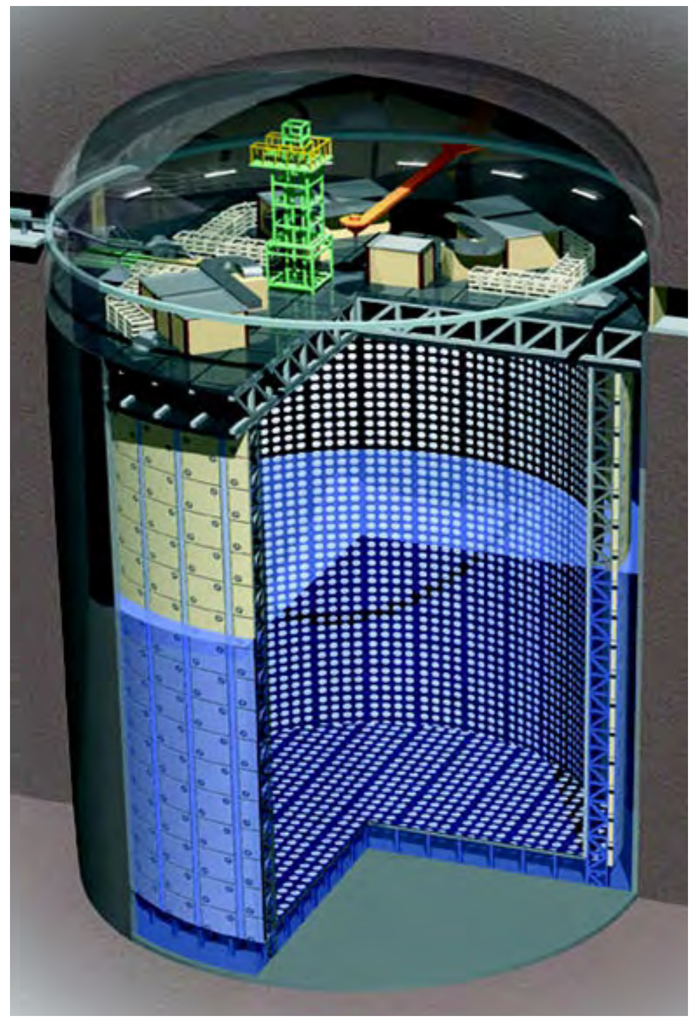


- Identical signal with delayed coincidence.
- It occurs for all neutrons,
  i.e., no threshold for neutrons

JUNO, KamLAND
(liquid scintillator)



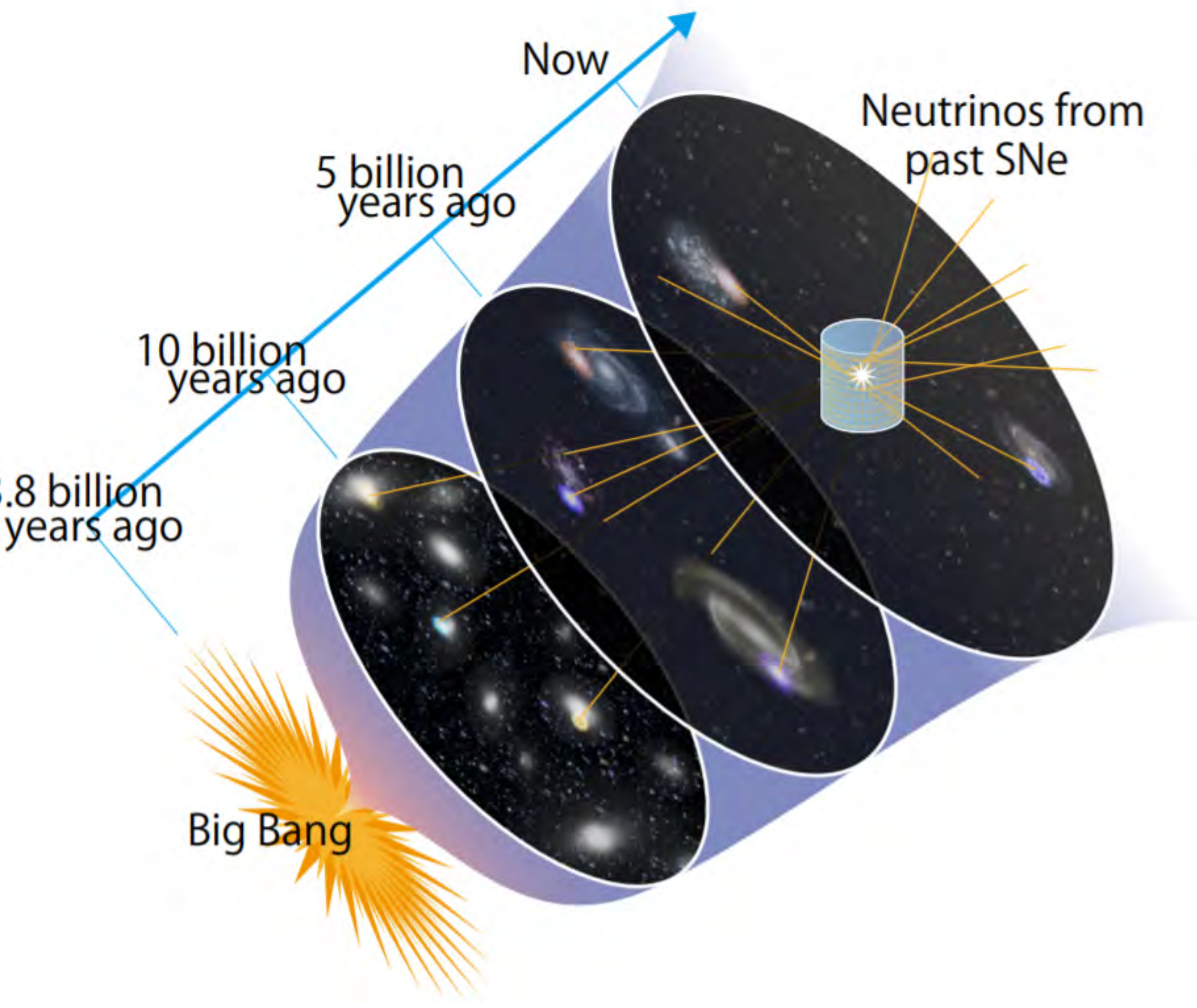
SK-Gd



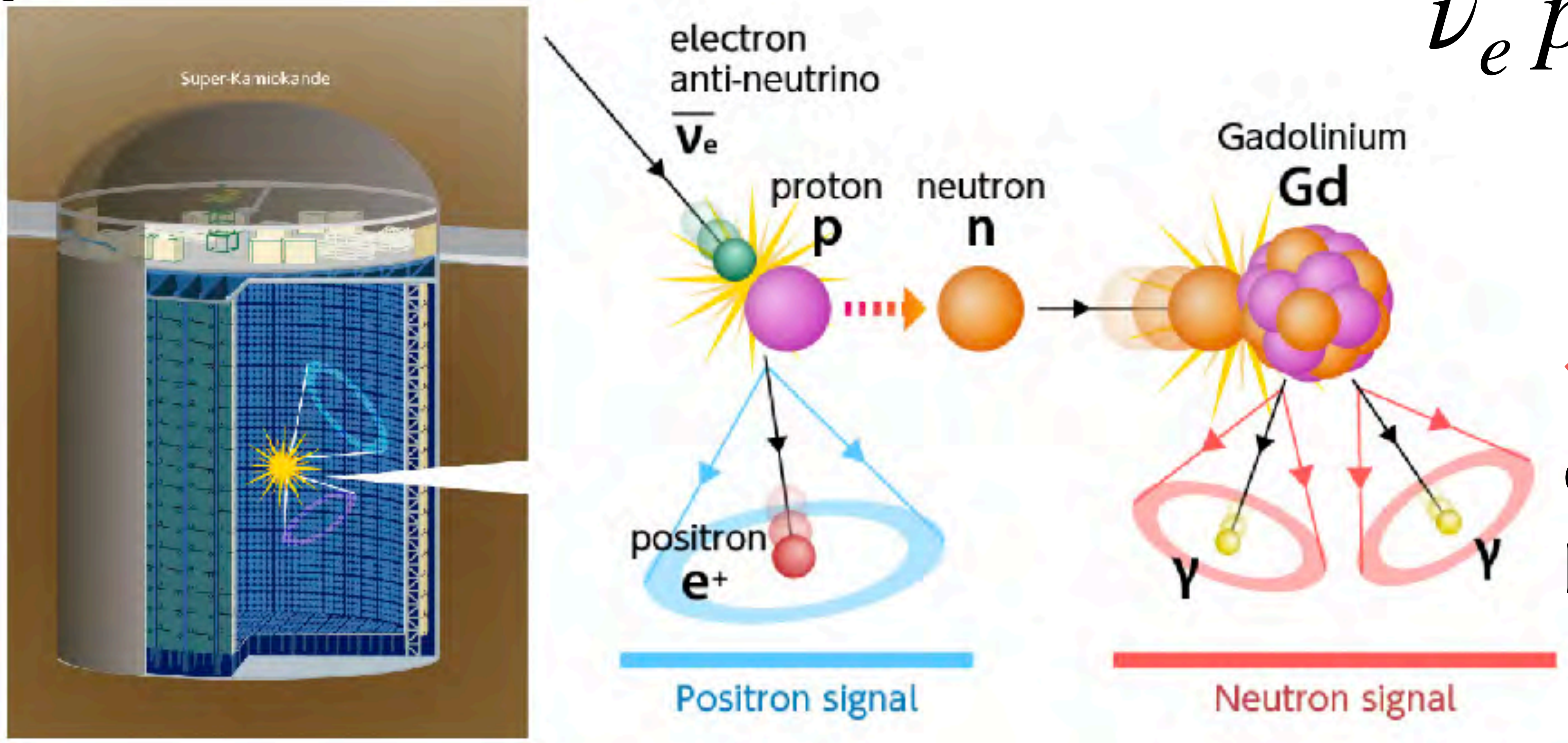
- **Important to precisely describe deexcitation process.**
- **Highly in demand to maximize the ability of these detectors.**

e.g.) Diffused Supernova Neutrino Background (DSNB)

Neutrino background from past supernova bursts.
Undiscovered yet, but SK-Gd leads the world.

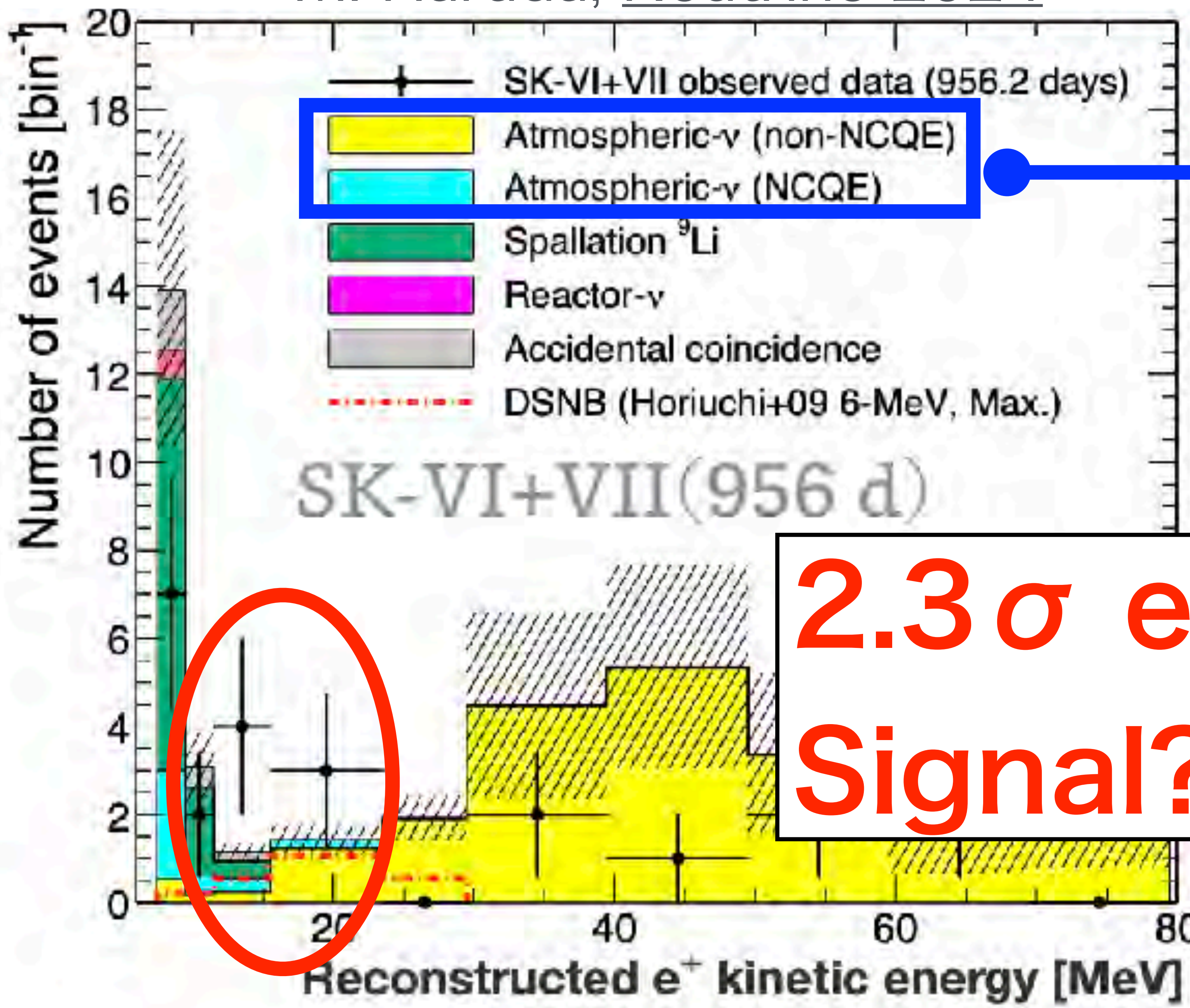


$$\bar{\nu}_e\, p \rightarrow e^+\, n$$



~ 8 MeV
only 2 MeV if hydrogen.

M. Harada, Neutrino 2024



2.3σ excess
Signal?

- BG: Atmospheric ν
  - Large sys. unc. from γ and n: ~60%
- SK will run until the end of 2028 JFY.
- Need to reduce the systematic to reach 3σ.

deexcitation simulations

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).

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.

Note:

- GEMINI++4ν is not listed here.

Y. Niu et al., Phys.Lett.B 860 139203 (2025)

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- 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).

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- 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).

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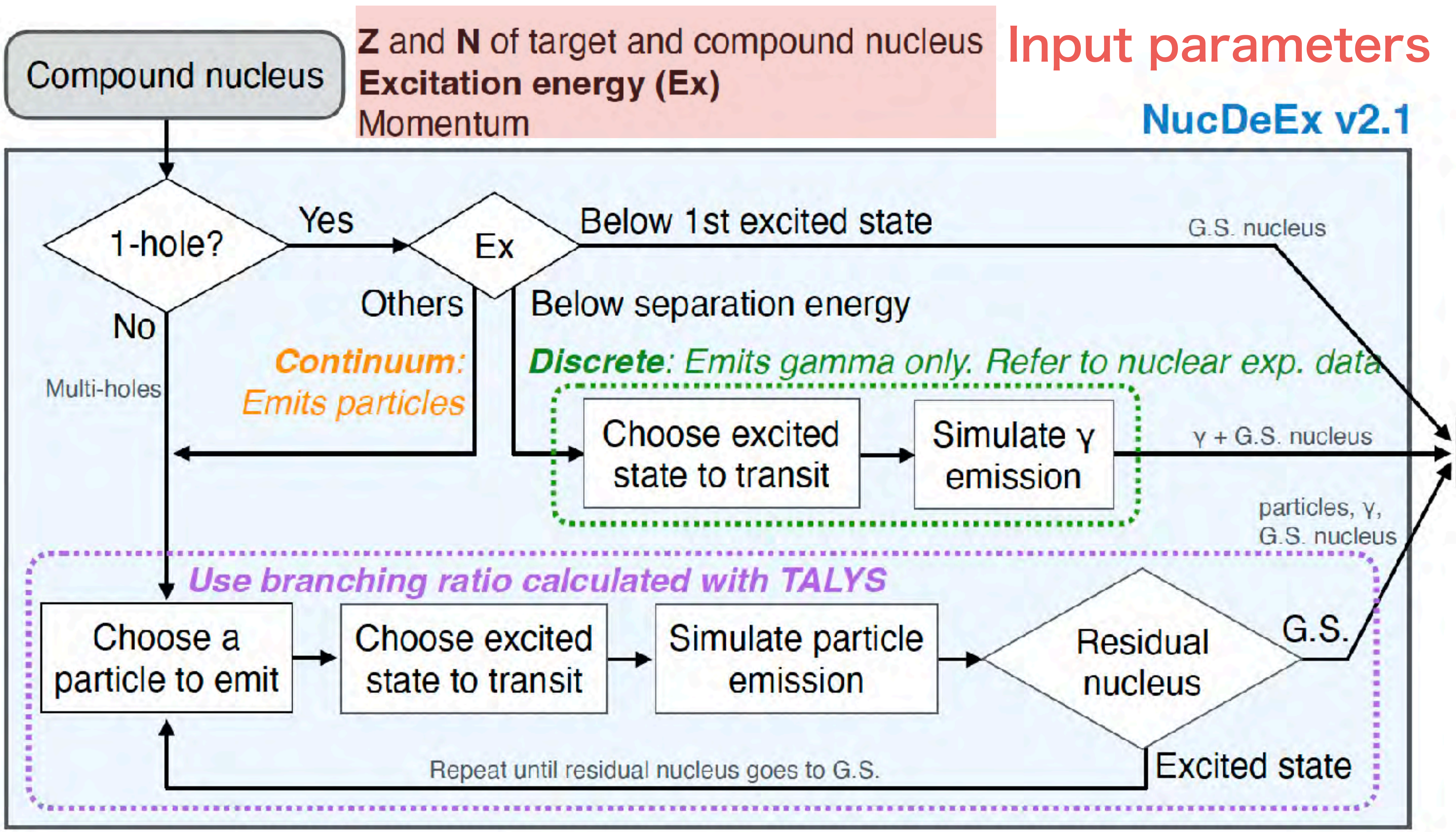
CASCADE	HF	Closed-source. Citing values of branching ratio from paper.

- Many neutrino experiments use Geant4 for detector simulation.

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

Algorithm



- **Discrete:** Simple→Refer to experimental data.

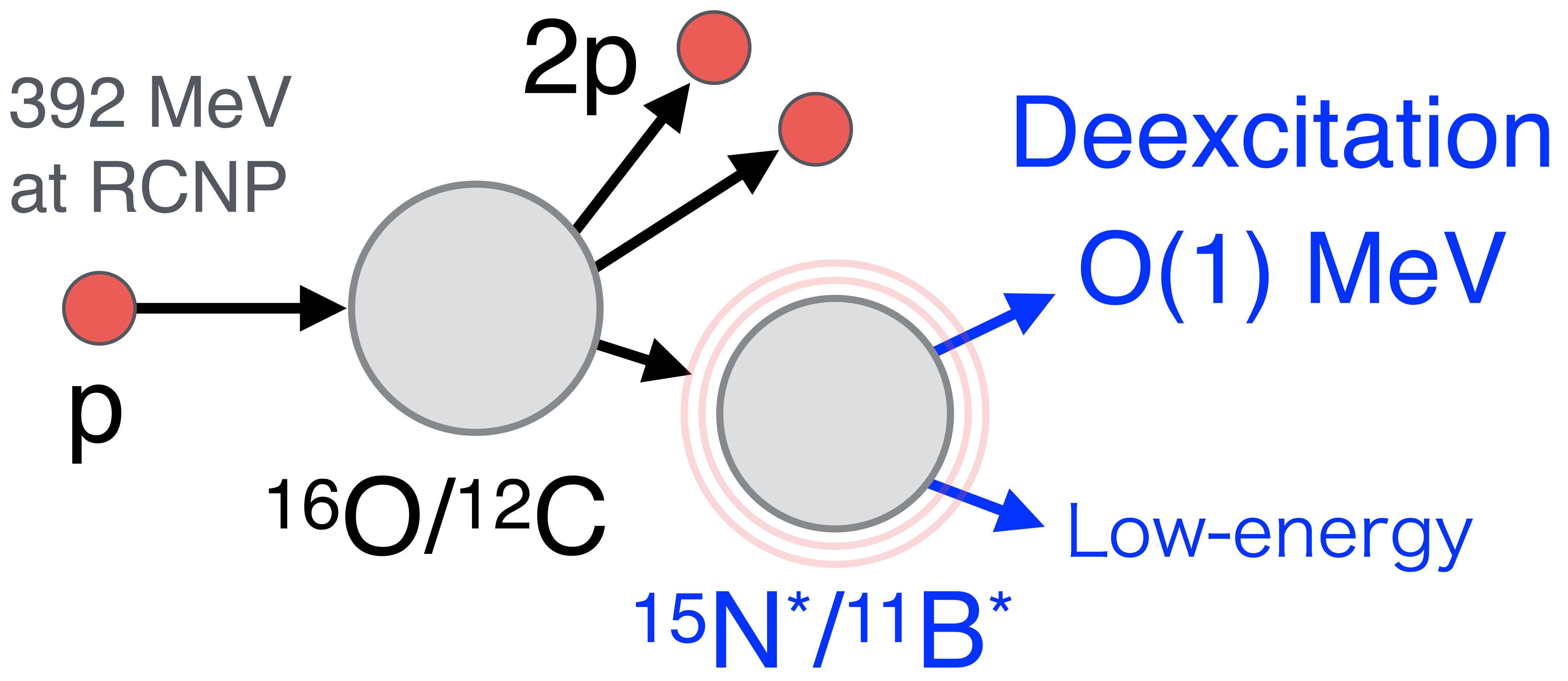
To be discussed later

- **Continuum + Multi-holes:** Complicated→Use **TALYS (Hauser-Feshbach model).**

Validation with experimental data

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

Normal kinematics: nucleon beam



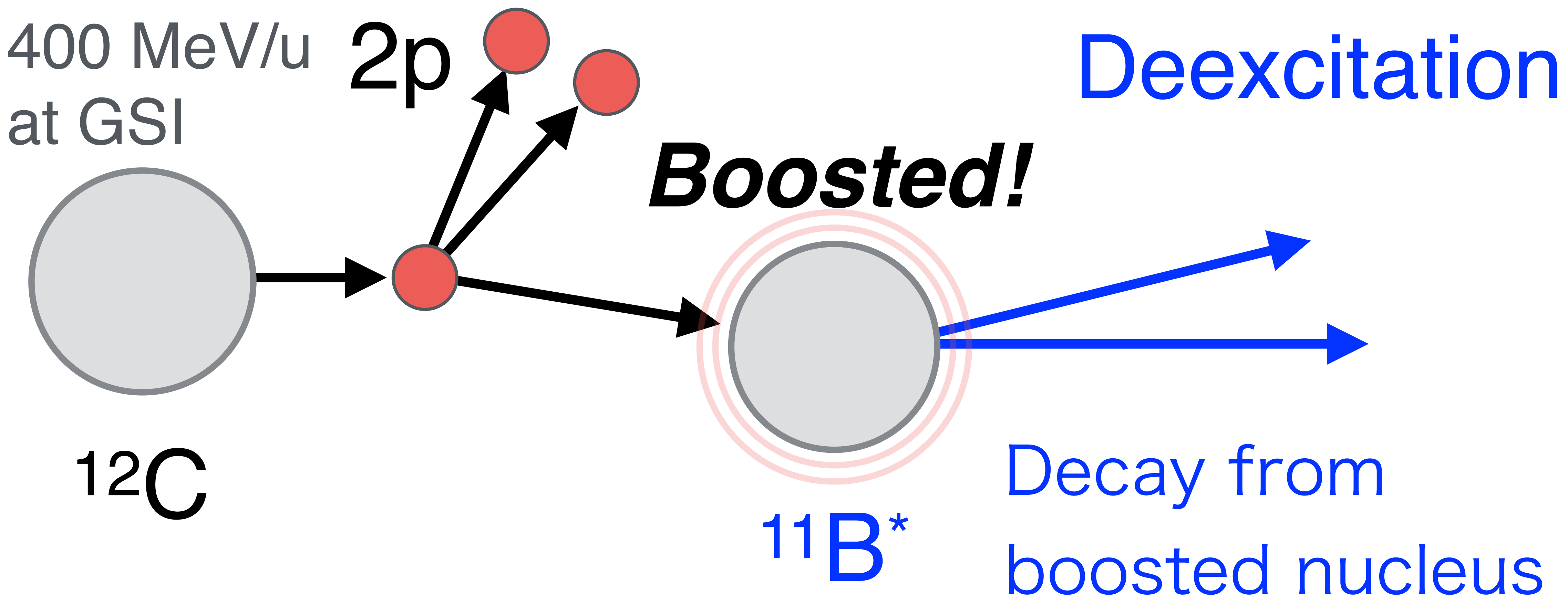
High detection energy threshold ~4 MeV

→ **~50% inefficiency**

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

VS

Inverted kinematics: ion beam



High energy in LAB frame.

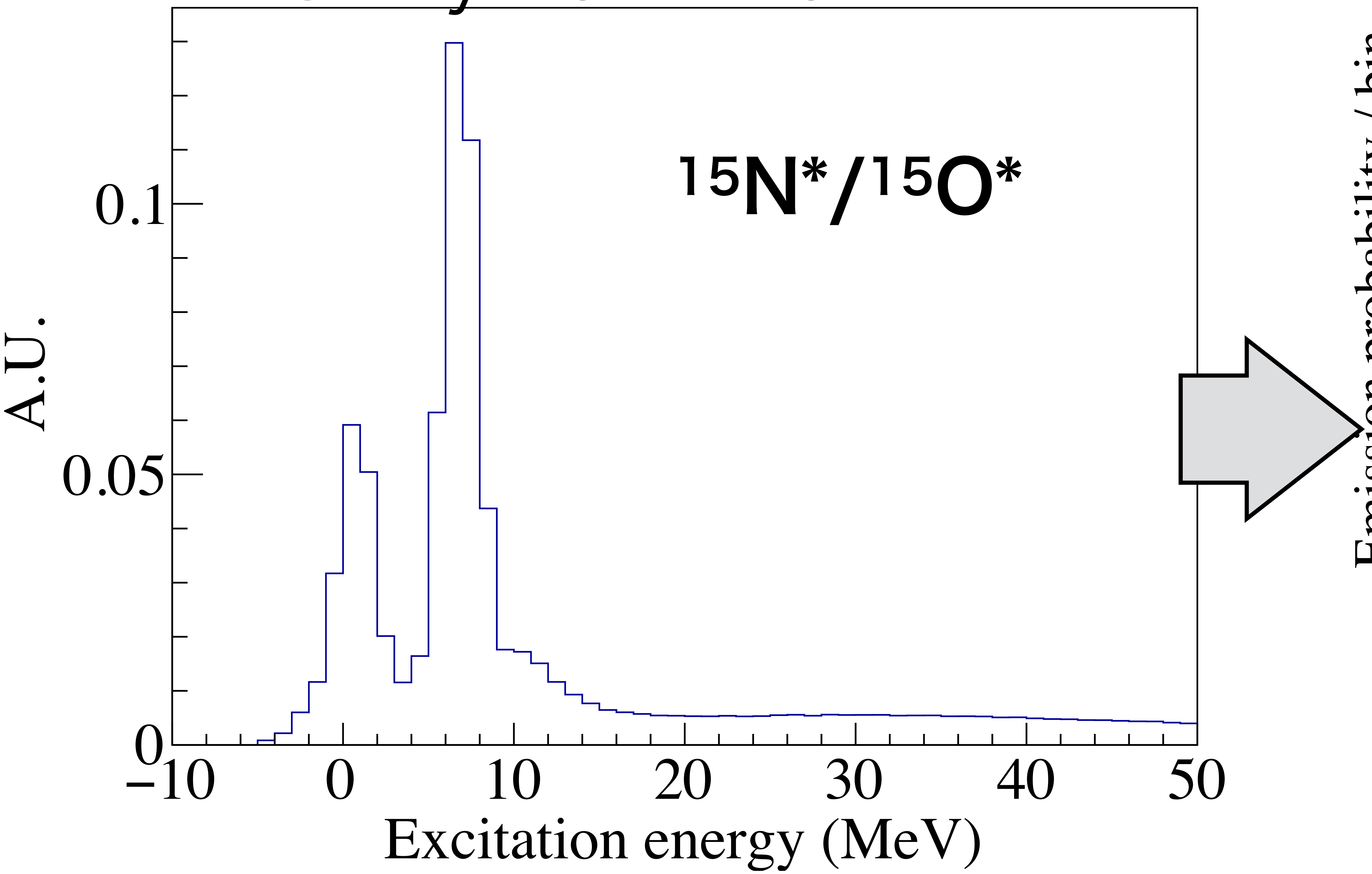
→ **Can measure almost all deexcited particles**

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

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

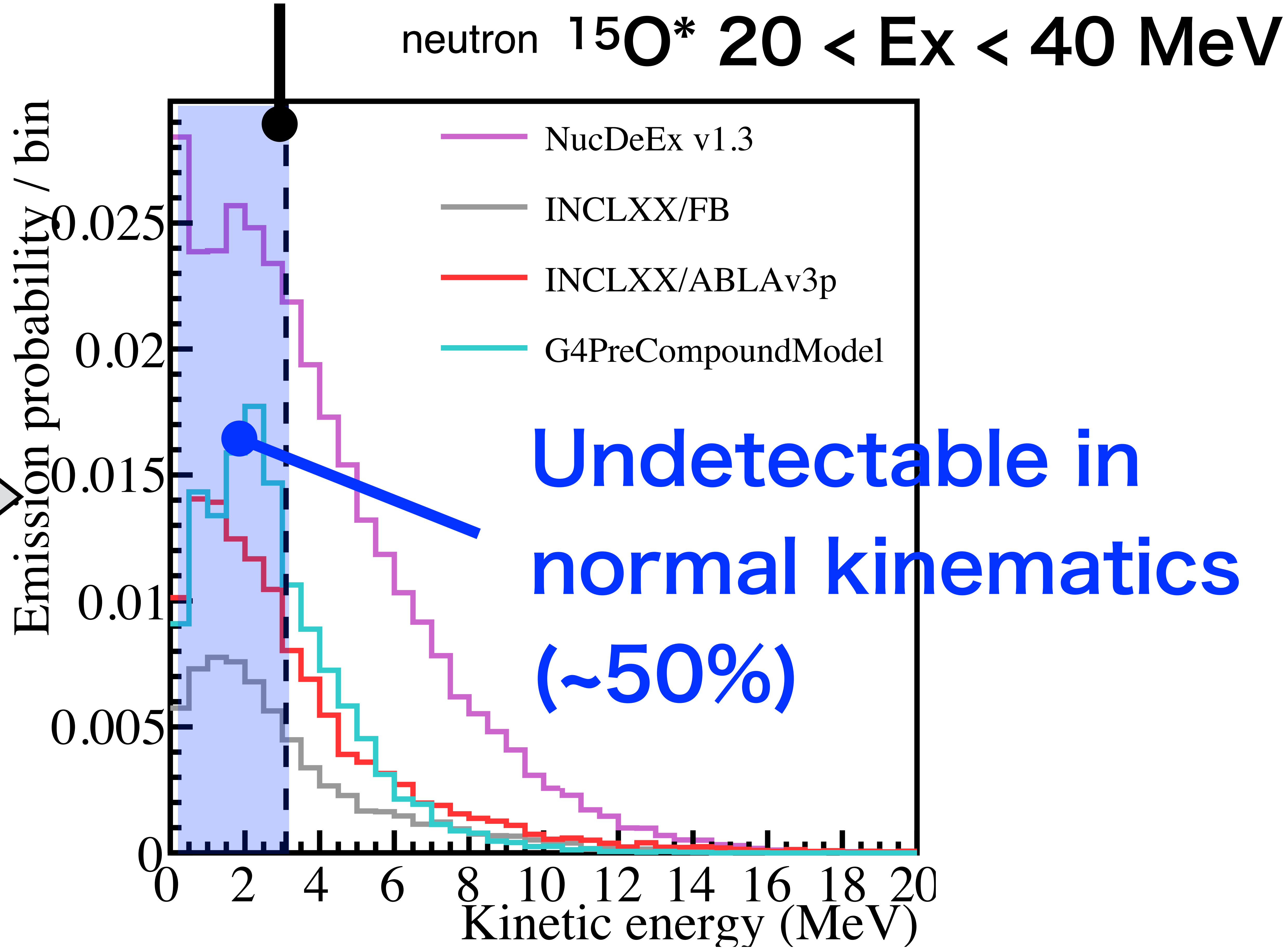
e.g) Energy spectra of neutrons from deex

SF by Benhar et al.



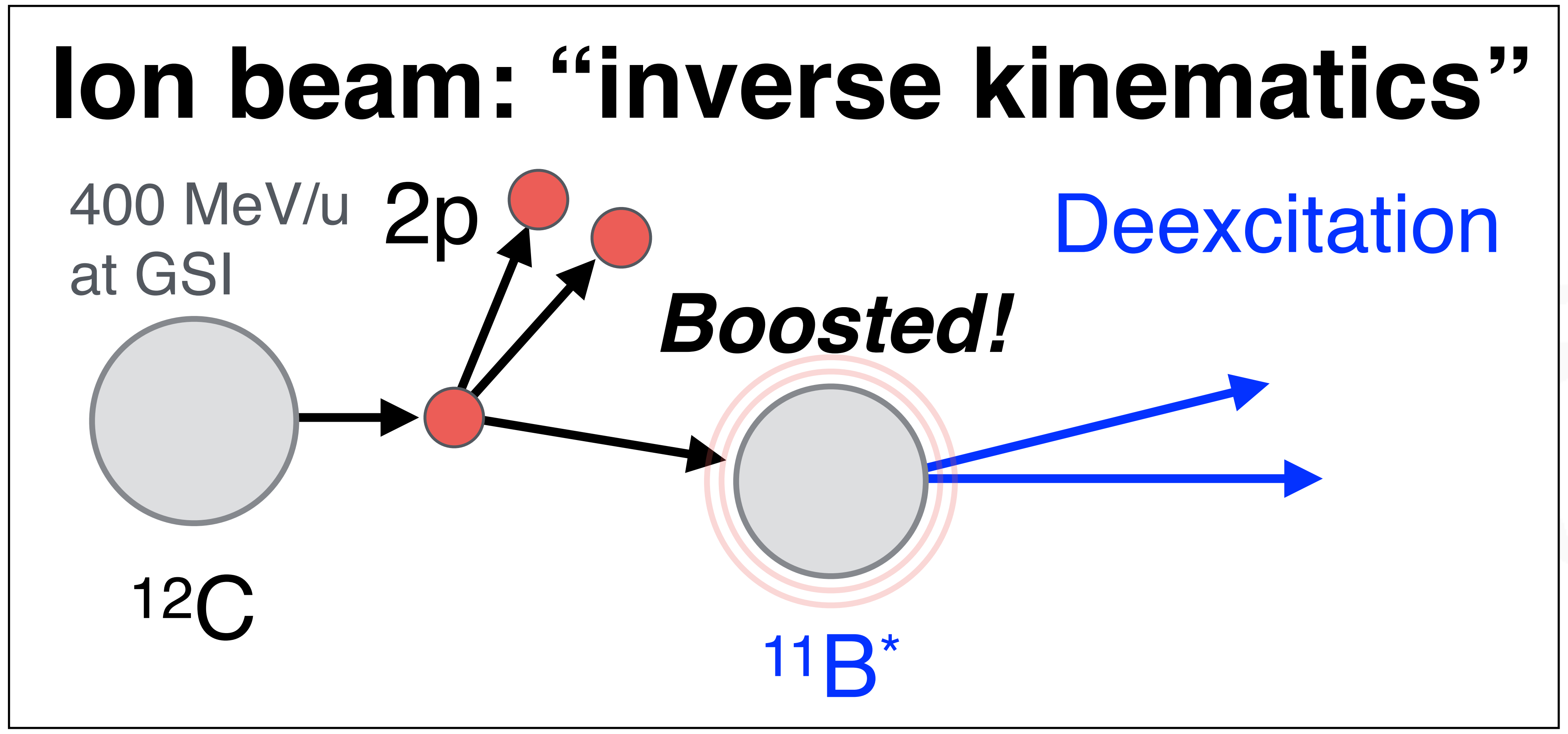
threshold in RCNP exp. (Yosoi et al.)

neutron $^{15}O^*$ 20 < Ex < 40 MeV

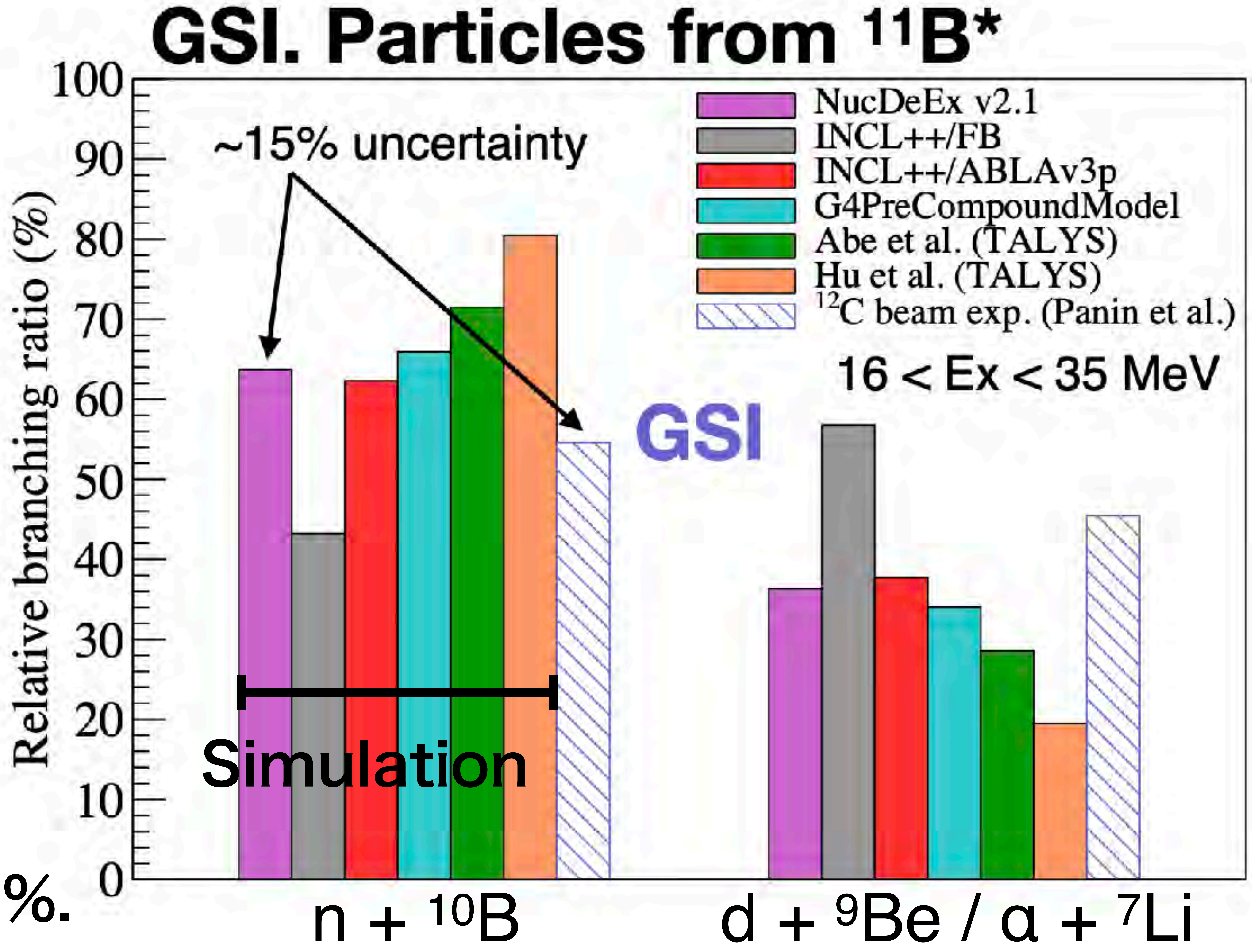


- obtained by subtracting the separation energy.
- Inverted kinematics is essential.

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

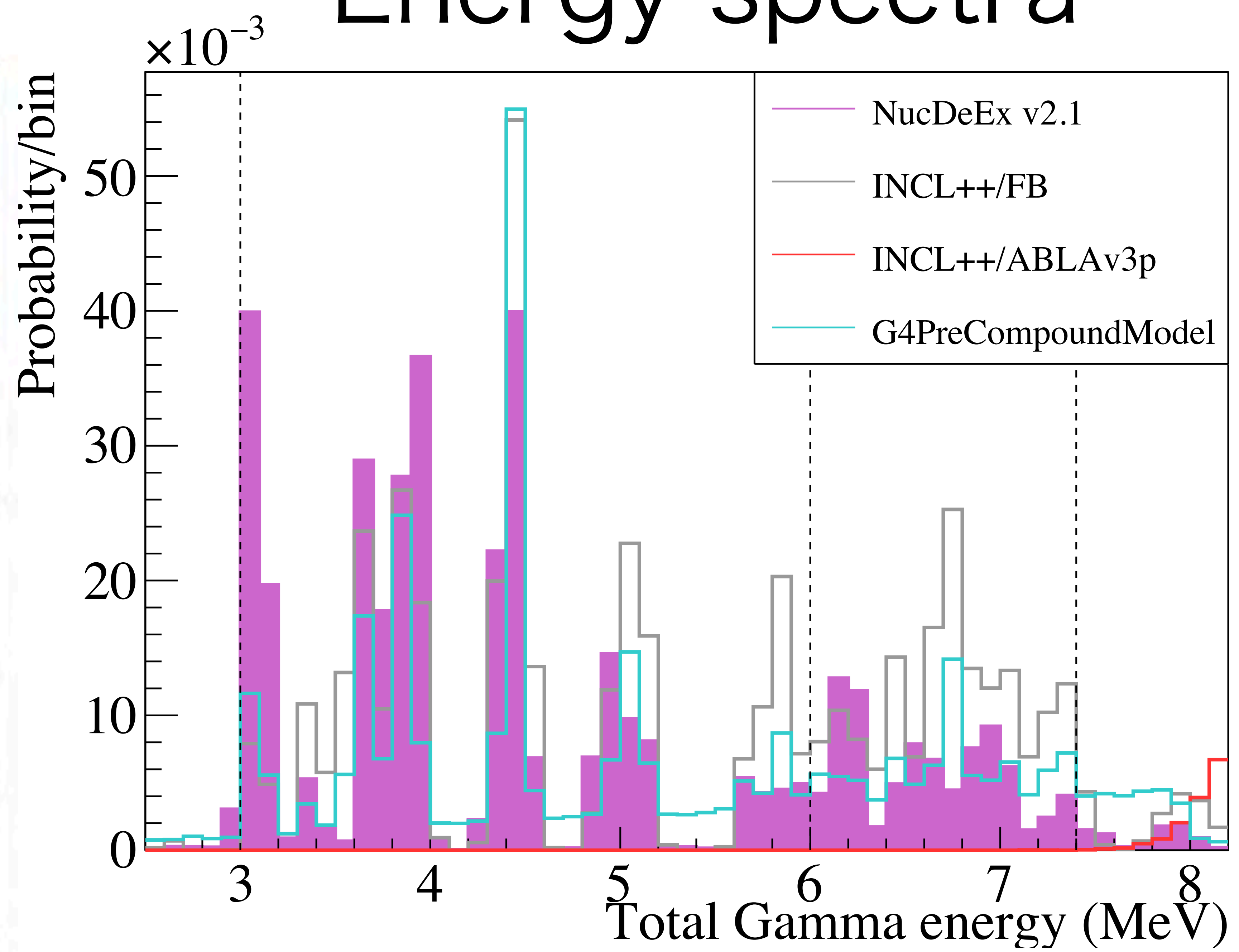
Normal, $^{16}O(p,2p)^{15}N^*$

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)	$27.9 \pm 1.5^{+3.4}_{-2.6}$	$15.6 \pm 1.3^{+0.6}_{-1.0}$

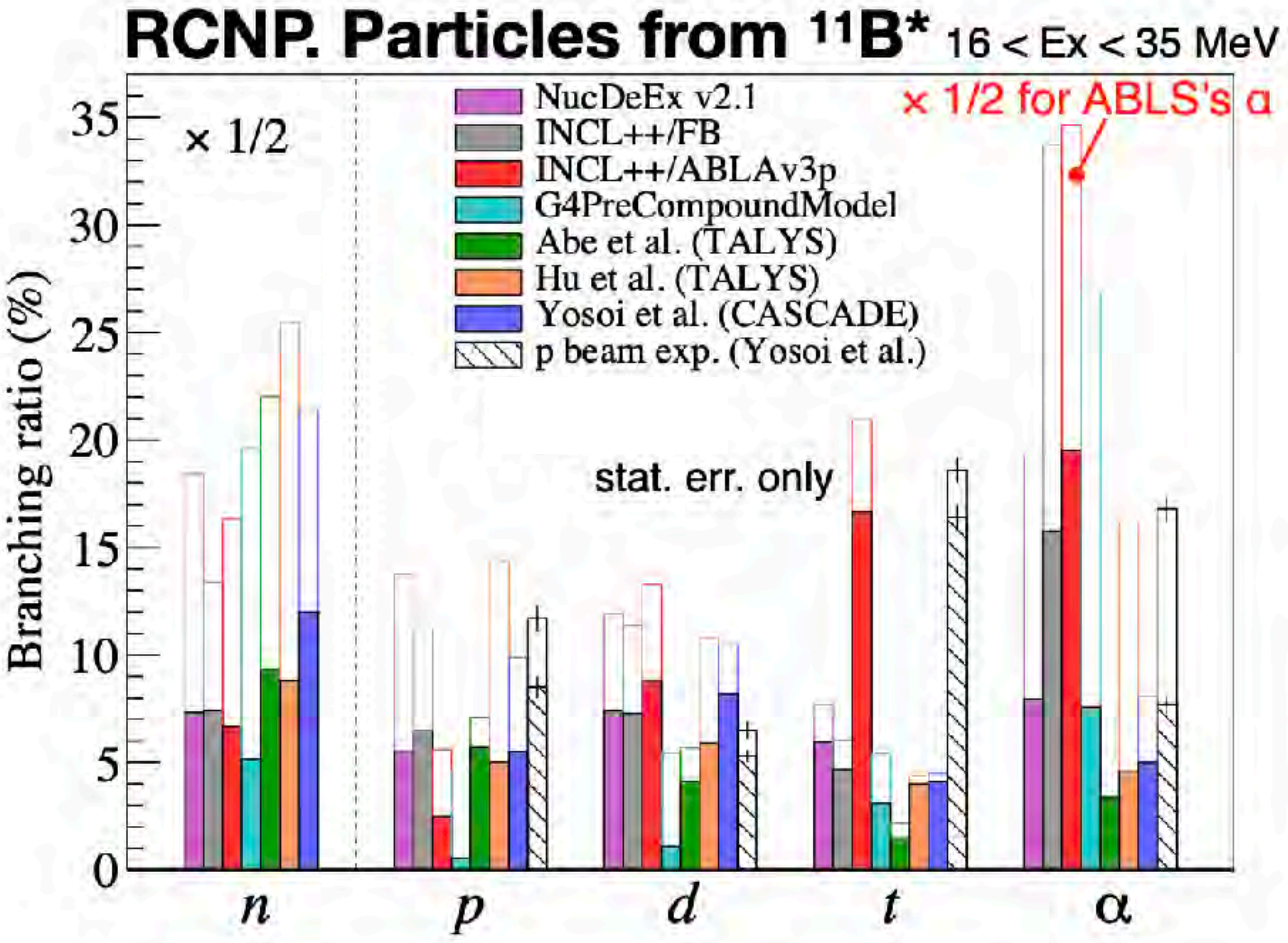
Energy spectra

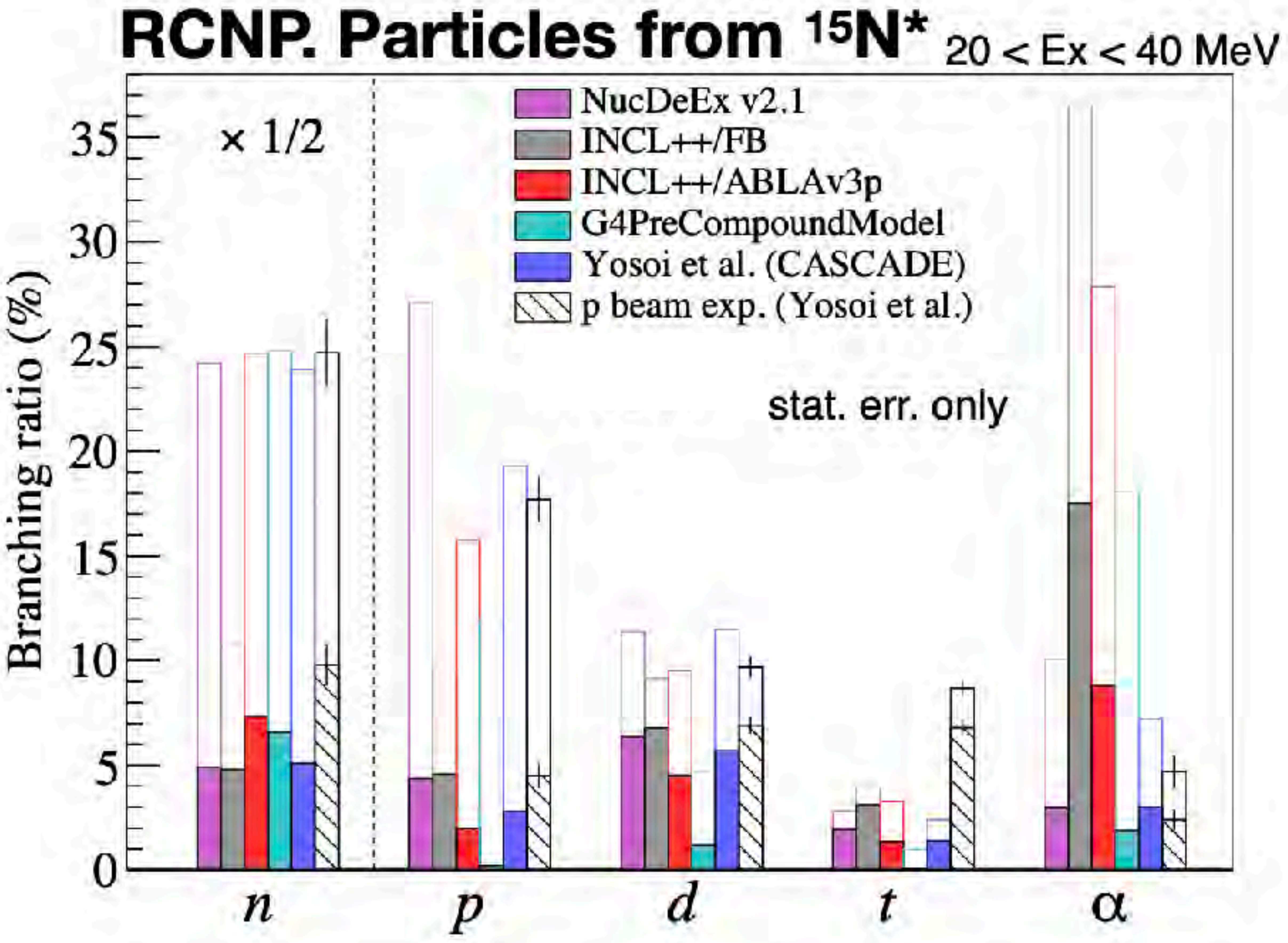


Deviation is visible in spectra,
but the experiment had poor resolution

- 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

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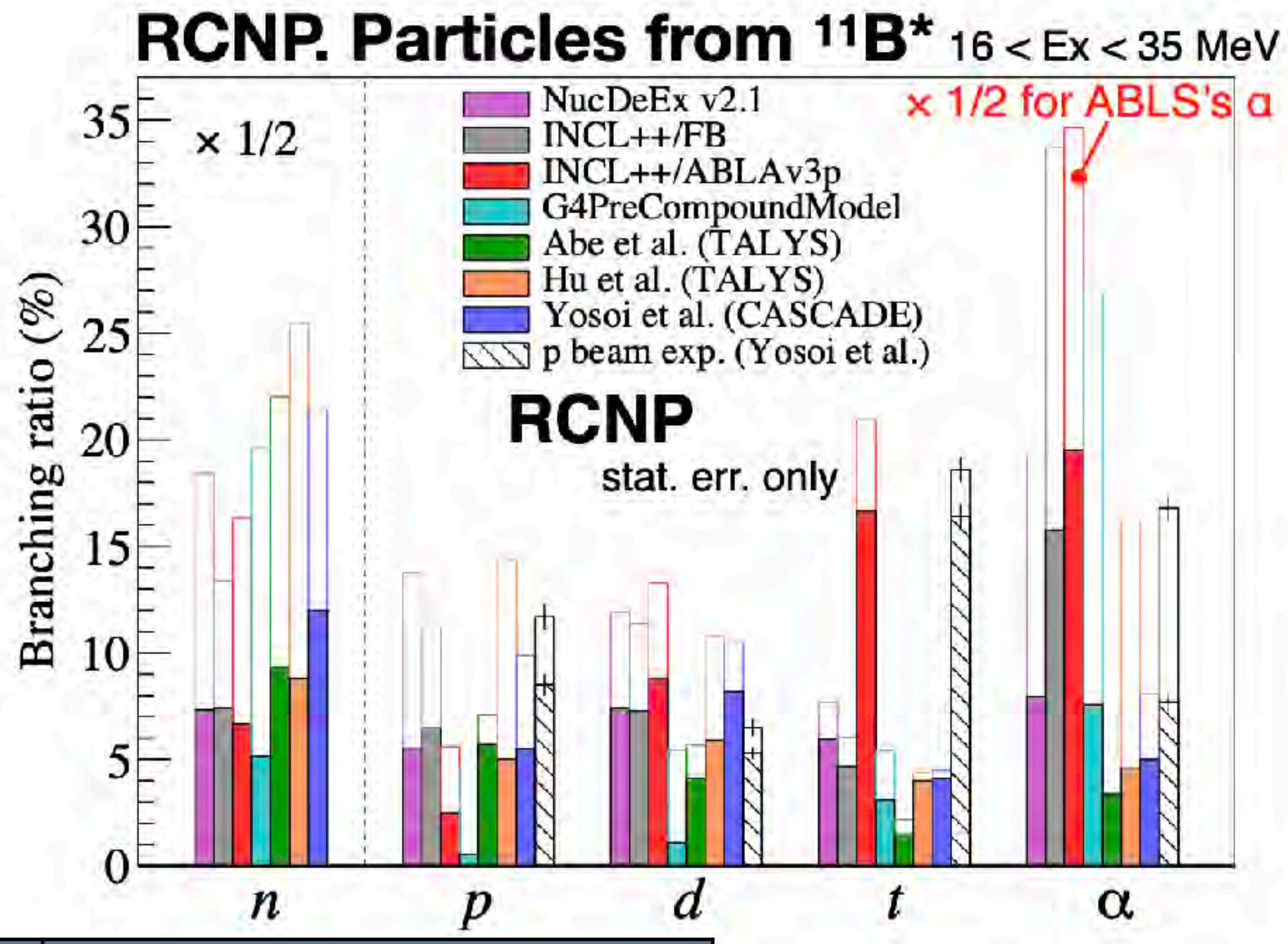

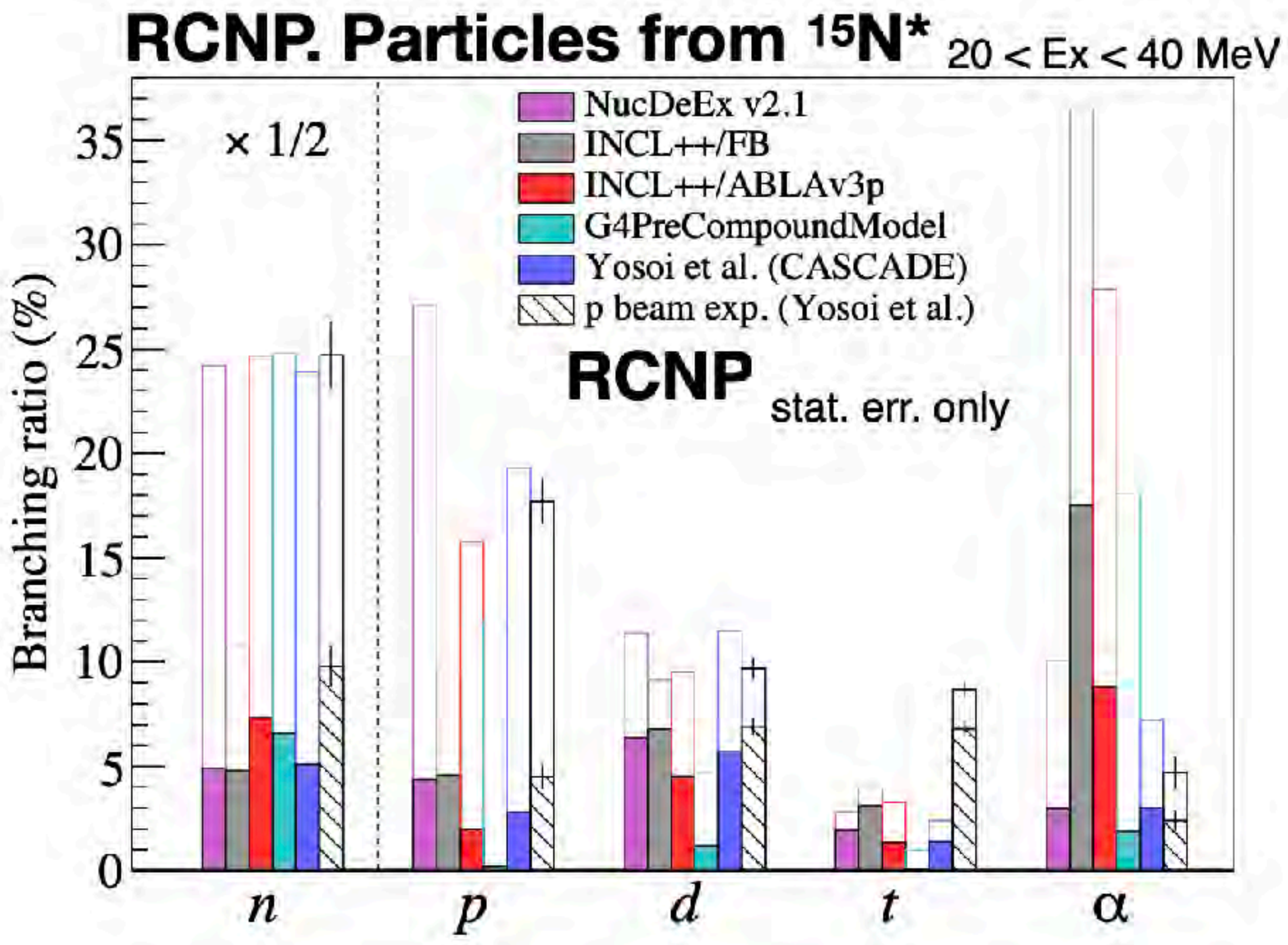

Generator	χ^2/ndf (stat. err. only)	
	RCNP ^{11}B*	RCNP ^{15}N*
NucDeEx v2.1	**483 / 8**	**280 / 10**
INCL++/FB	1038 / 8	1409 / 10
INCL++/ABLAv3p	7320 / 8	737 / 10
G4PreCompundModel	1181 / 8	777 / 10
Abe et al. (TALYS)	947 / 8	-
Hu et al. (TALYS)	674 / 8	-
Yosoi et al. (CASCADE)	676 / 8	263 / 10

The best (or comparable to the best) reproducibility.

Overestimates α emission.

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

Bonus?

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)	
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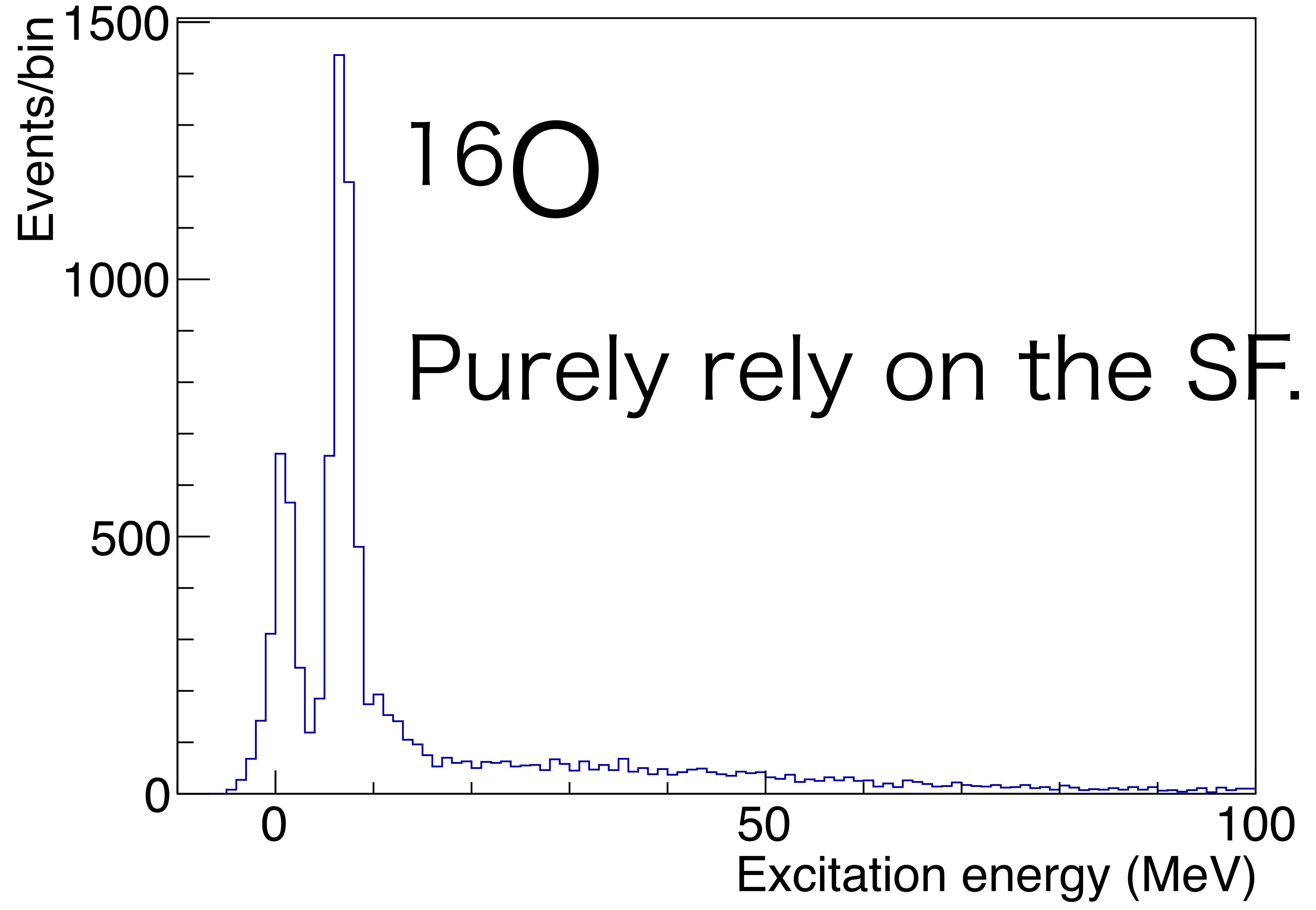
considers angular momentum conservation

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

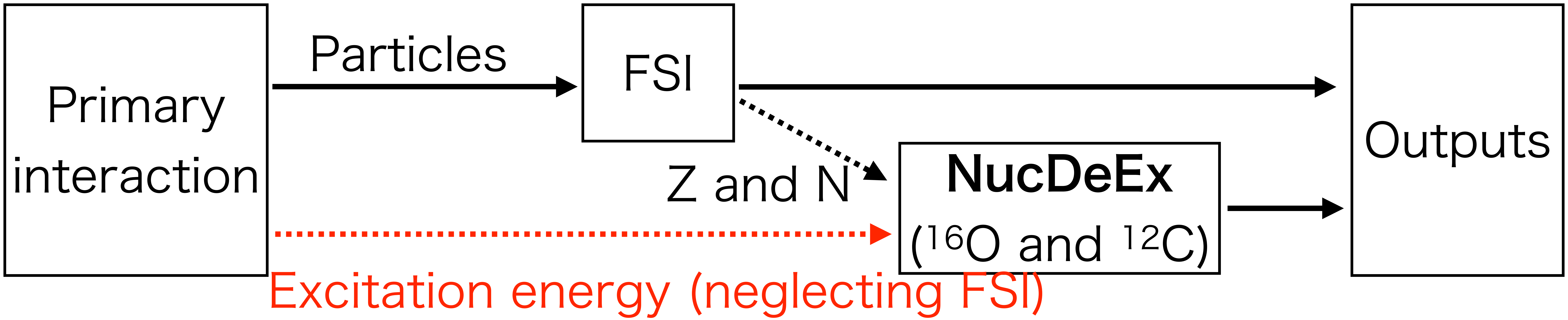
Implementation in ν generators

- NucDeEx is relatively easy to implement into ν generators.
- **It is implemented in NEUT from version 5.9.0.**
  - Limited to QE.
  - Excitation energy is determined by pre-FSI*.



* Can be improved with a method in A. Ershova et al, PRD 108, 112008 (2023).

Lots of room to be improved!



What’s the next step?

- Inverted kinematics is essential.
- Plan to take the data with inverted kinematics in Japan.
- SAMURAI-79 experiment!

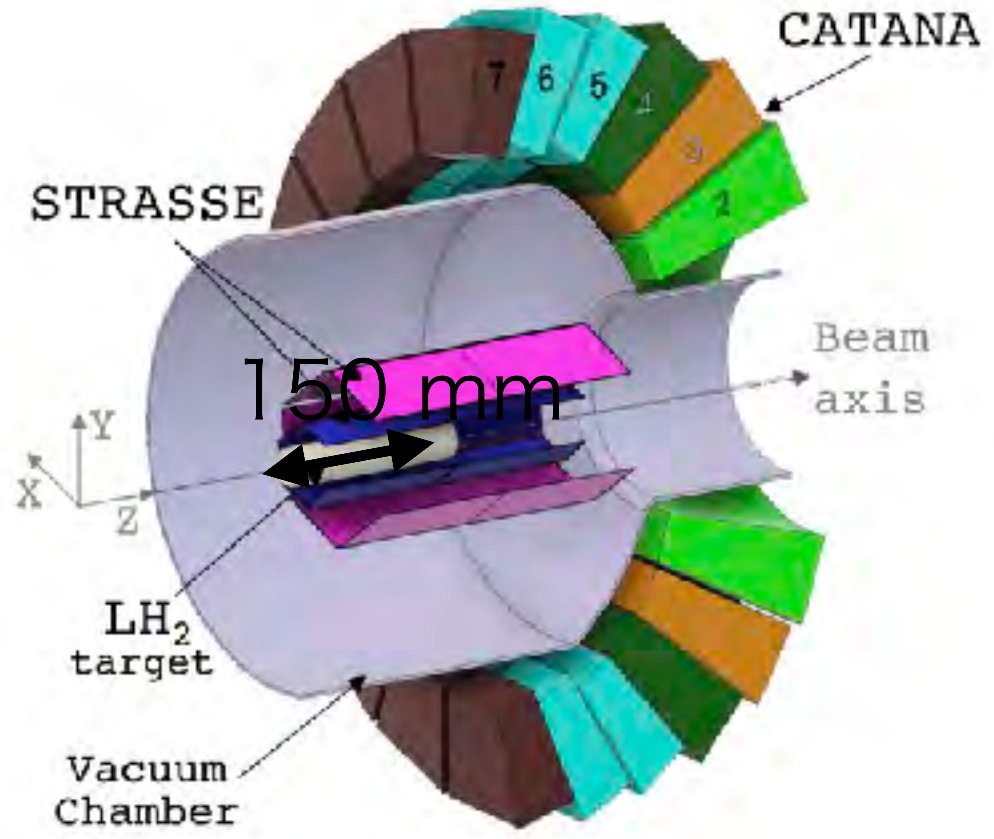
SAMURAI-79 experiment at RIKEN RIBF, Japan

RIKEN RIBF can generate ion beam, like GSI.

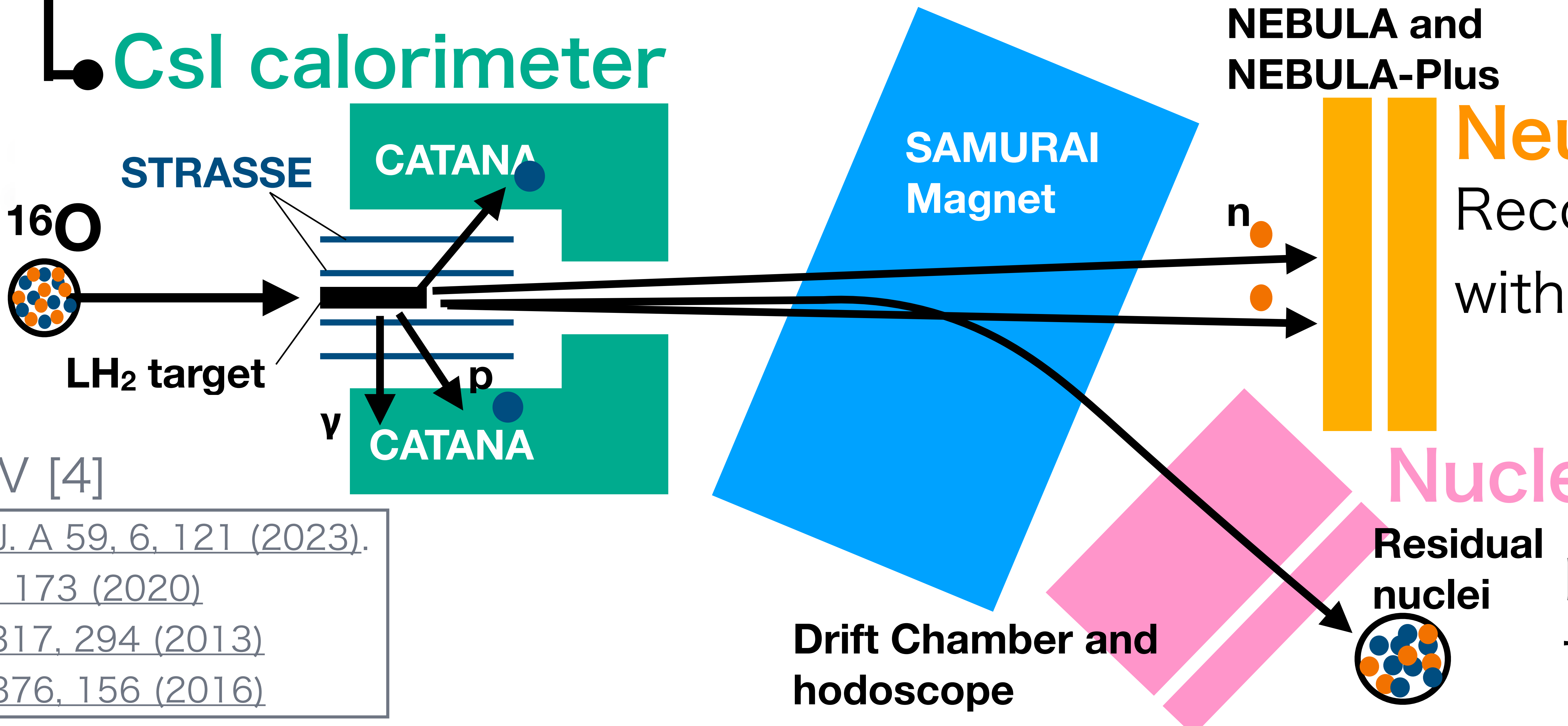
Target	Energy	Setup
$^{16}O(p,2p)^{15}N^*$	200 MeV/u	See below.
$^{16}O(p,pn)^{15}O^*$		**Newly construct knockout neutron detectors downstream of the magnet.**
$^{17}O(p,pn)^{16}O^*$		

Measure excitation energy

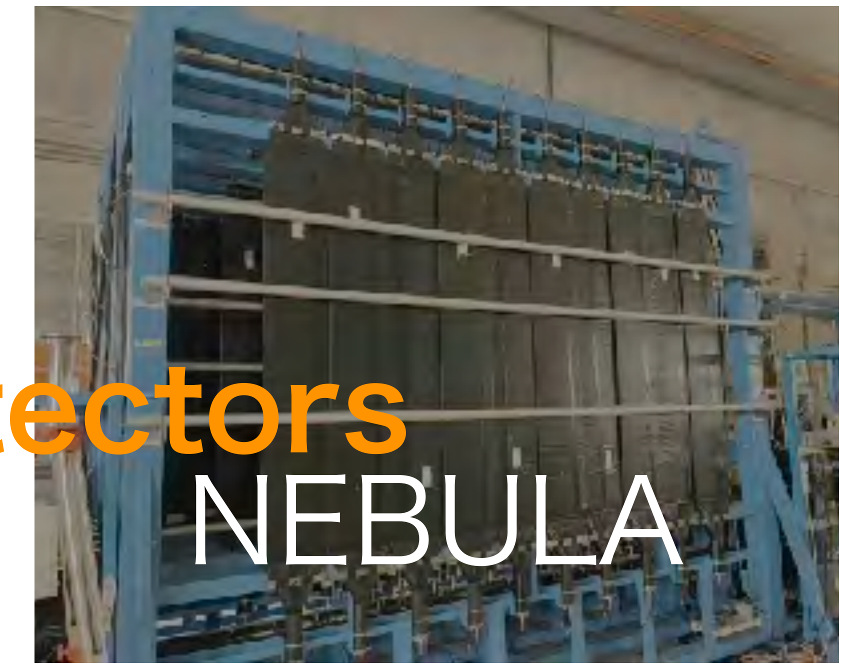
knockout proton
- **Si tracker**
- **CsI calorimeter**



Missing mass res. 2 MeV [4]



Efficiency: 32.5%/2 layers,
E resolution: 2.72 MeV [5]



Neutron detectors
Recon. energy with ToF.

decay particles

Nuclei detectors
Identify nuclear species with ToF, charge, and vertex.

[4] H. N. Liu et al., Eur. Phys. J. A 59, 6, 121 (2023).
[5] Y. Kondo et al., NIMB 463, 173 (2020)
[6] T. Kobayashi et al., NIMB 317, 294 (2013)
[7] T. Nakamura et al., NIMB 376, 156 (2016)

It's really comming!

Center for Nuclear Study, The University of Tokyo
RIKEN NISHINA CENTER

January 10, 2025

Dear Dr. Yasuhiro Nakajima,

We are grateful for your proposal submission at the 25th program advisory committee meeting for nuclear physics experiments at the RI Beam Factory (NP-PAC). The committee reviewed your proposal

⋮

NP2412-SAMURAI79R1

Title: **Study of ^{16}O(*p*,2*p*) and ^{16}O(*p*,*np*) reactions for precise neutrino observation at giant water Cherenkov detectors**

Spokesperson(s): **Yasuhiro Nakajima**

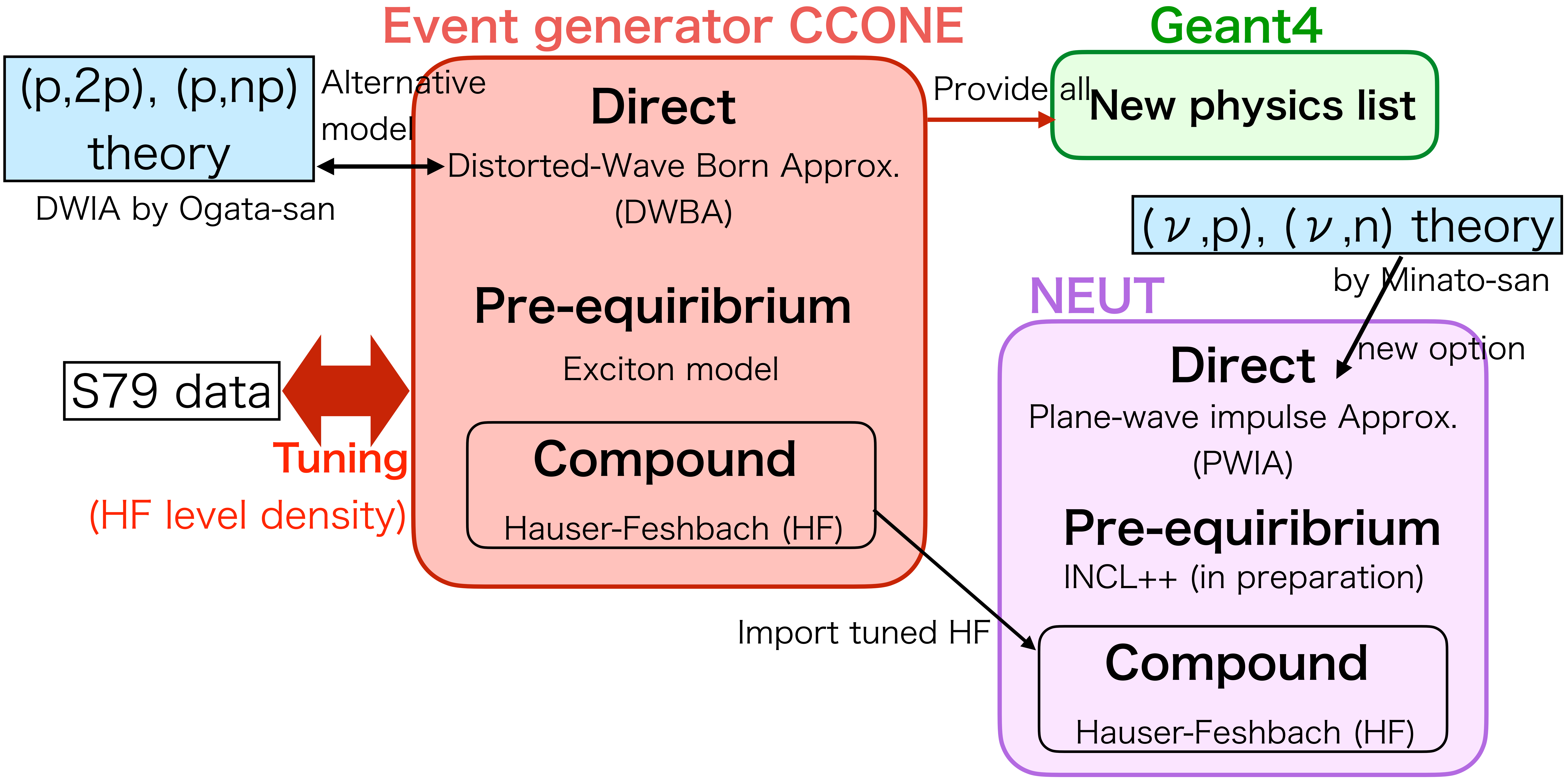
Approved — Grade A
5 days (including 0.5 days of BigRIPS tuning time)

- Our beam time request is approved by the PAC in 2024 JFY.
- We are discussing when we have the beam.

Spokes: Yasuhiro Nakajima

T2K Analysis Coordinator
(with Stephen Dolan)

Strategy



CCONE (calculates Japanese nuclear data library JENDL) has the key.

Summary

- NEUT is in a transition period, together with experiments.

- Electron scattering in NEUT.
  - "inclusive" is discussed, wants to go "exclusive" like e4nu.
  - Need further development: implementing MEC & DIS.

- Deexcitation:
  - Actively growing these days.
  - NucDeEx is developed and implemented in NEUT.
  - Further topics to be studied:
    - More careful treatment of excitation energy.
    - SAMURAI-79 experiment (inverted kinematics) to tune the model.