A new de-excitation tool: GEMINI++4ν

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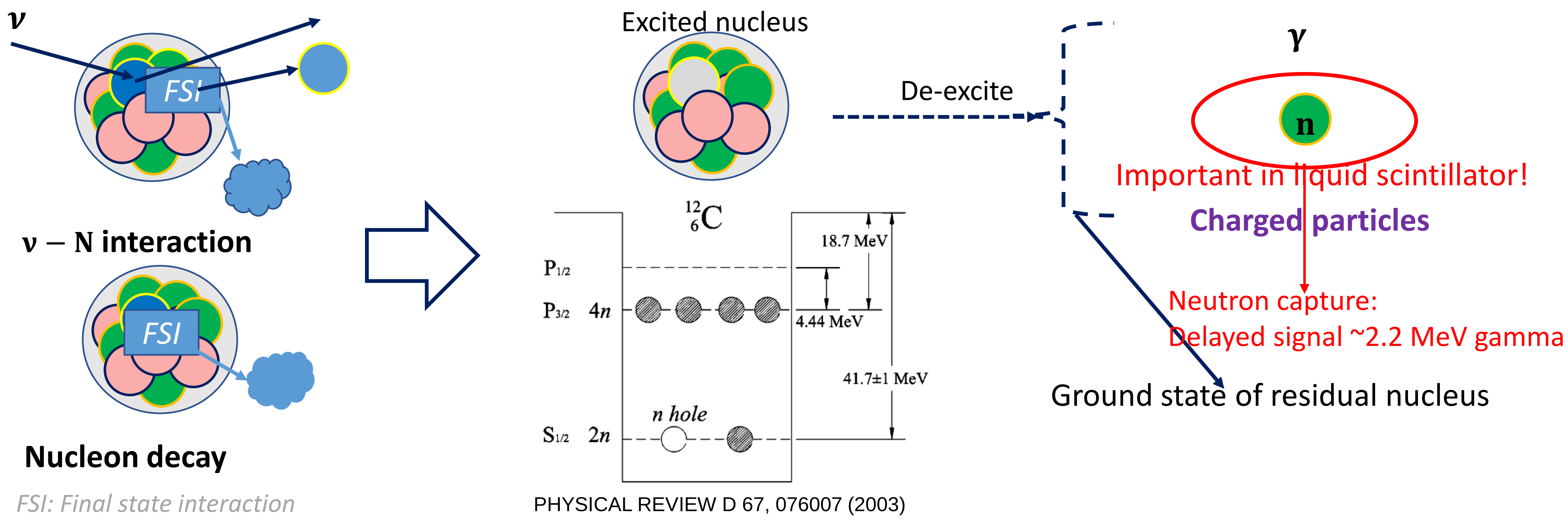
Outline

- What is / why de-excitation?
- De-excitation generators status and experiments
- GEMINI++ / Performance of GEMINI++
- GEMINI++4ν: Modified version of GEMINI++ for neutrino exp.
- Summary

GEMINI++/4v: **Y.J. Niu**, W.L. Guo, M. He, J. Su, arXiv: 2408.14955

What is / why de-excitation?

Nucleus de-excitation takes a significant part in neutrino experiment



- Emitting particles, especially neutrons from de-excitation contribute to **signal-background ratio** like **nucleon decay searching, DSNB, atmospheric ν** and so on
- But de-excitation is not considered well in widely-used ν generator such as GENIE and NuWro. De-excitation in GEANT4 is not reasonable compared to experimental result of light nucleus

De-excitation generators

How about the generator of de-excitation? Good performance?

Models used to calculate de-excitation probability of emitting particles :

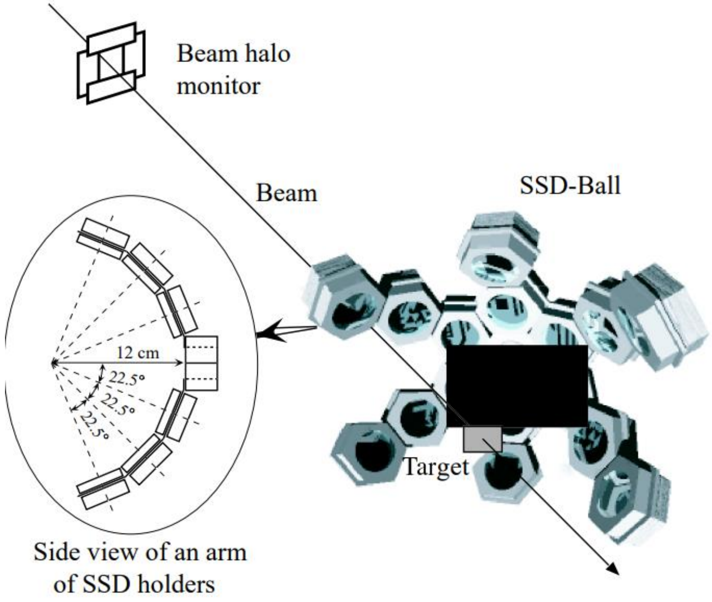
- **Weisskopf-Ewing (WE):** Angular momentum is not considered
- **Hauser-Feshbach (HF):** Angular momentum is considered

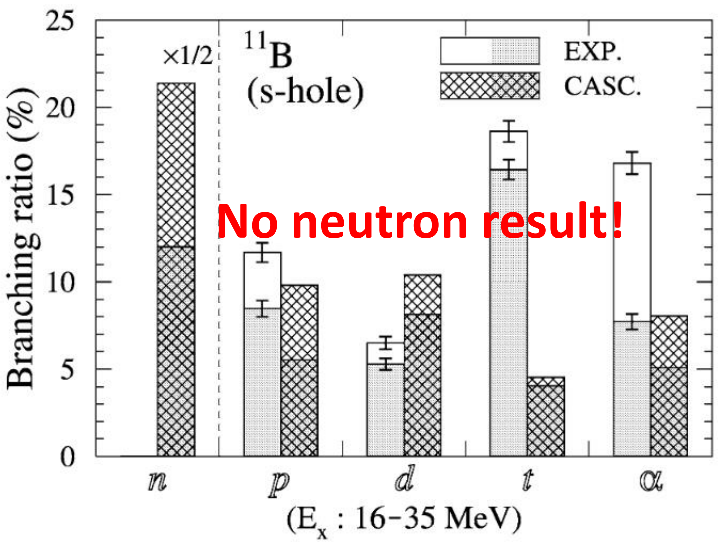
Generator	***Comments***	***Model***
TALYS	$p \rightarrow \bar{\nu}\, K^+$, DSNB, strange axial coupling constant	HF
ABLA	Energy resolution of accelerator neutrinos	WE
SMOKER	Neutron invisible decays	WE
CASCADE	Experimental data of $^{11}\mathrm{B}^*$ and $^{15}\mathrm{N}^*$ de-excitations	HF
GEMINI++	**Not used in neutrino experiments!**	HF / WE

These generators must be validated with **experimental data!**

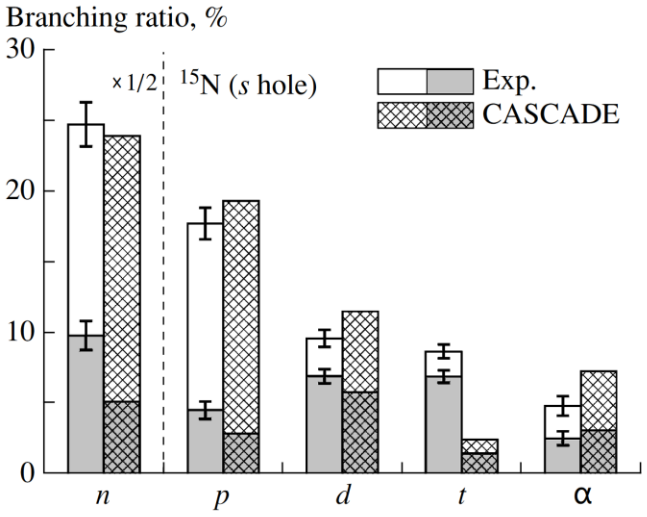
De-excitation experiments

(Yosoi et al.) Exp.1





M. Yosoi et al., Phys. Lett. B 551 (2003);



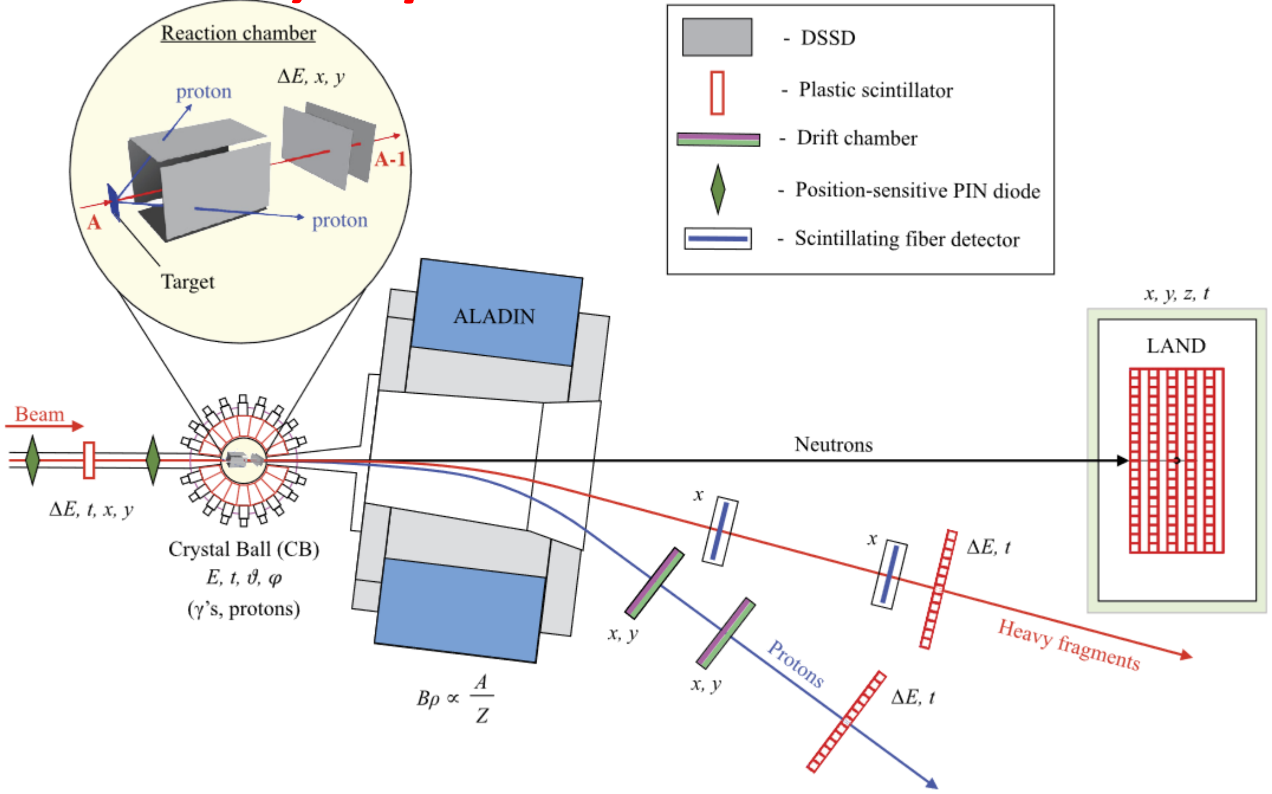
Phys. Atom. Nucl. 67, (2004) 1810

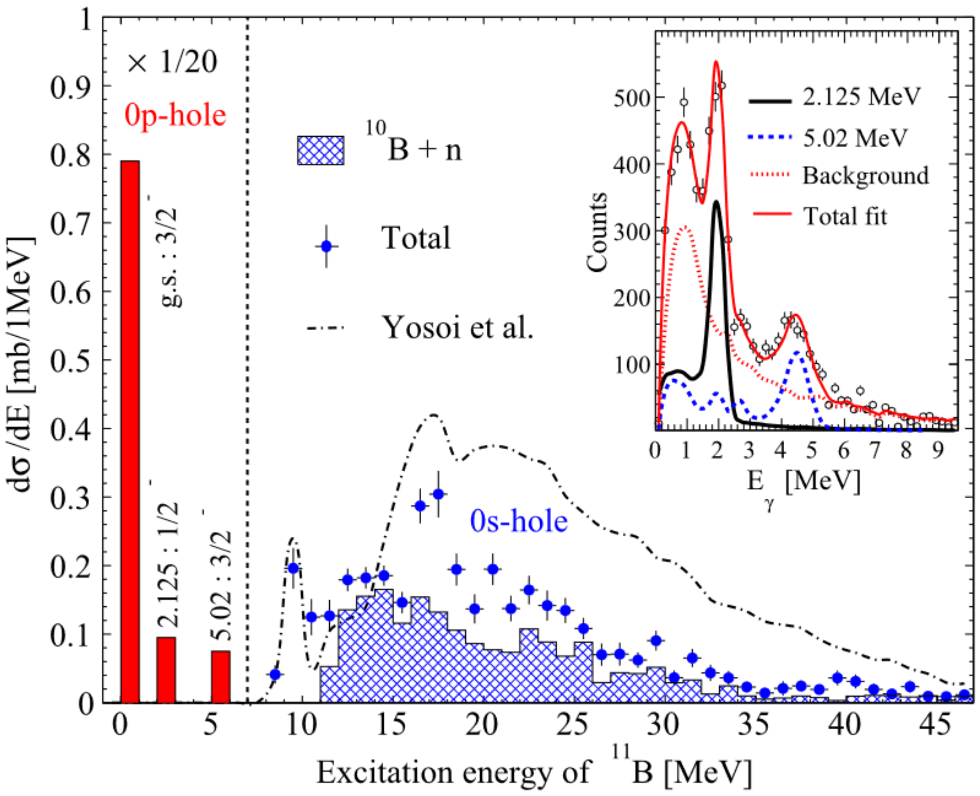
- **Quasi-free (p, 2p) reaction, targets are carbon ($^{12}C \rightarrow {}^{11}B^{*}$) and ice ($^{16}O \rightarrow {}^{15}N^{*}$)**
- JUNO (Liquid-scintillator→ ^{12}C), Super-Kamiokando / Hyper-Kamiokando (Water→ ^{16}O)
- **Different threshold for particles** from de-excitation
- Results shown above, darker color for ***'2-body decay' and lighter for '3-body decay'*** In a decay

De-excitation experiments

(Panin et al.) Exp.2

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

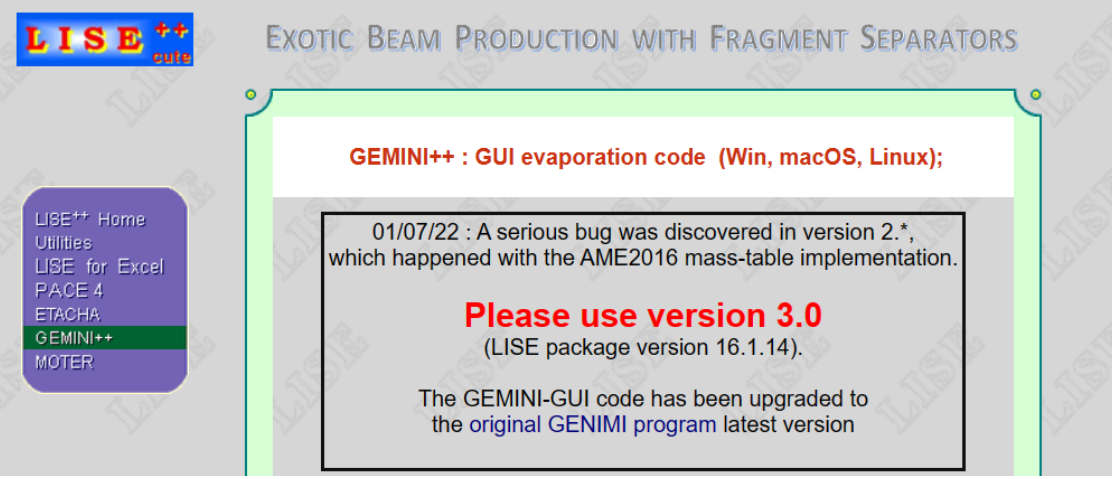




- $^{12}C(p,2p)\,^{11}B^*$
- Good energy resolution, **no threshold** for particle identification, even residue
- Only three **two-body decay channels** of ^{11}B were analyzed: $\mathbf{^{10}B + n}$, $\mathbf{^{9}Be + d}$ **and** $\mathbf{^{7}Li + \alpha}$

Generator GEMINI++

GENIMI++: a Monte Carlo code, is an improved C++ version based on GEMINI



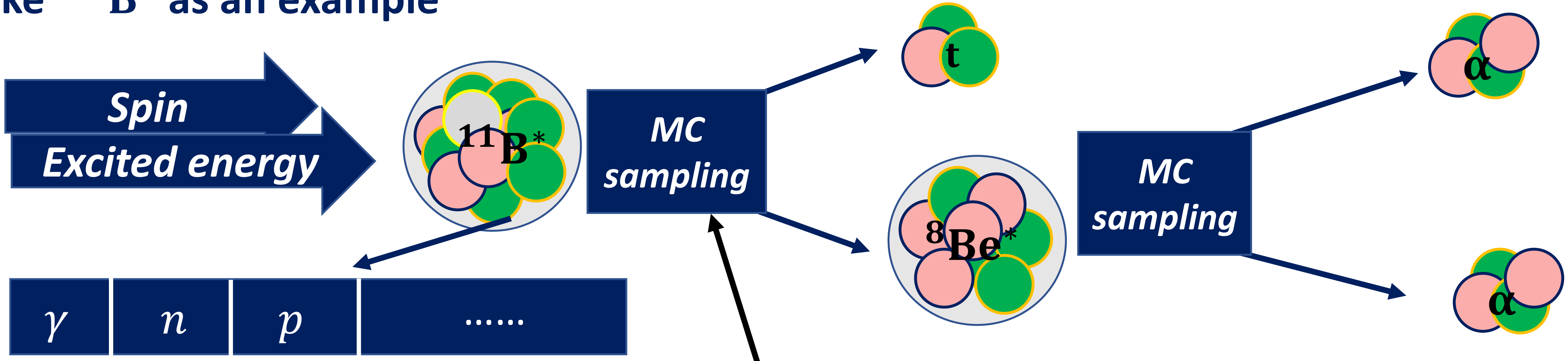
R. J. Charity, PRC 82 (2010), 014610; PRC 82 (2010) 044610
https://lise.frib.msu.edu/gemini.html

Code	***GEMINI++***
Input	**Nucleus, Excited energy, Spin**
Formulism of width Γ_i	HF or WE
Output	Complete de-excitation cascade information
Convenience	**Event-by-event, Convenience**

- GEMINI++ is designed for **heavy nucleus** process, like fission, fusion and so on
- GEMINI++ had been widely used in nuclear physics area, getting **cheerful** achievements!

Generator GEMINI++

Take $^{11}\mathrm{B}^*$ as an example



WE formulism

$$\Gamma_i^W(E_i) = \frac{2s_v+1}{2\pi\rho_i(E_i)}\int\sum_{l=0}^{\infty}T_l(\epsilon)\,\rho(U)\,d\epsilon$$

i means different emitting particles

Γ_i^{WE}: the partial decay width for evaporation of particle *i*

$S_i,\ l$: the spin and orbital angular momenta

$T_l(\varepsilon)$: the transmission coefficient, ε: the kinetic energy of *i*

U : $E_x - B_i - E_{rot} - \epsilon$

ρ^0, ρ: the level densities of the parent and daughter nuclei

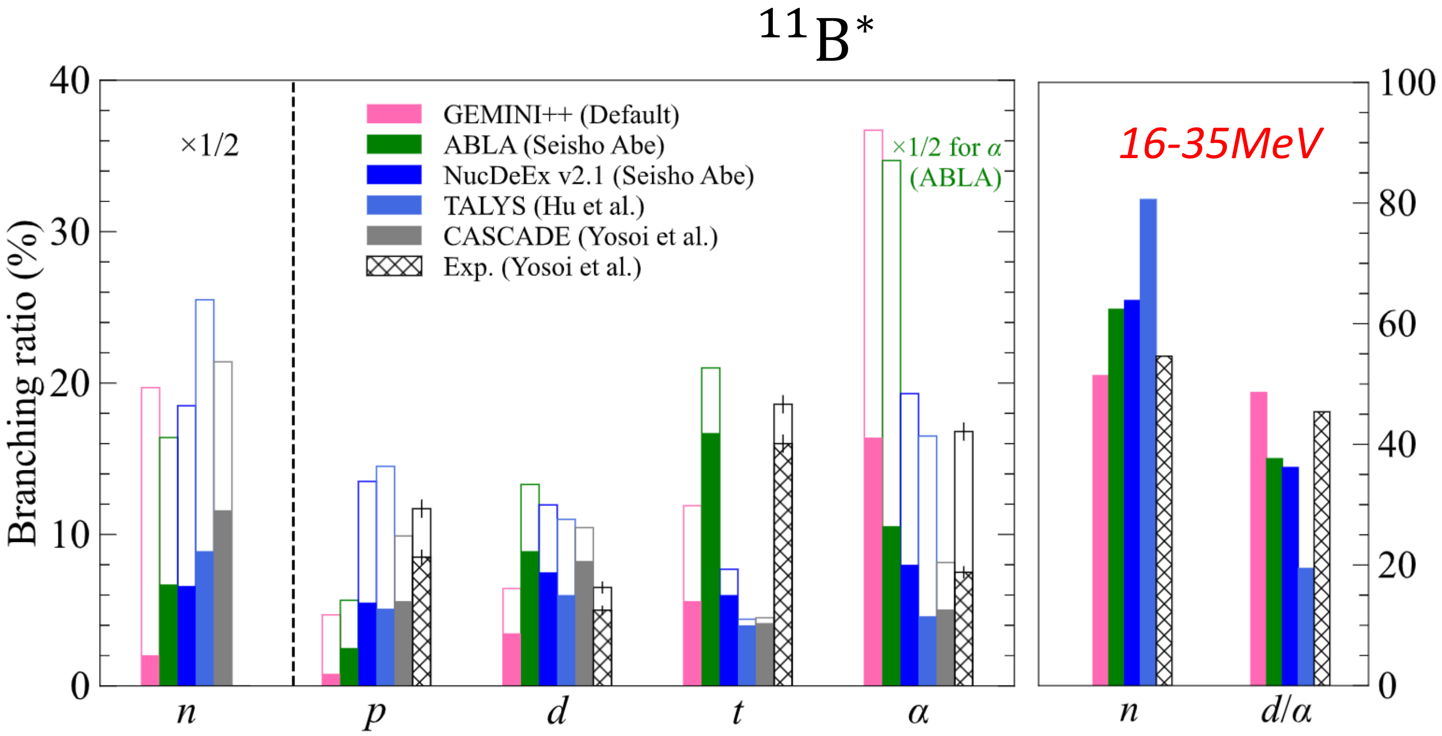
$$\rho(U) \propto \frac{\exp\left[2\sqrt{a(U-E_1)}\right]}{a^{\frac{1}{4}}(U-E_1)^{5/4}}$$

Back-shifted term E_1: modification of U

Final width ← $\Gamma_i = F_s \times \Gamma_i^W$

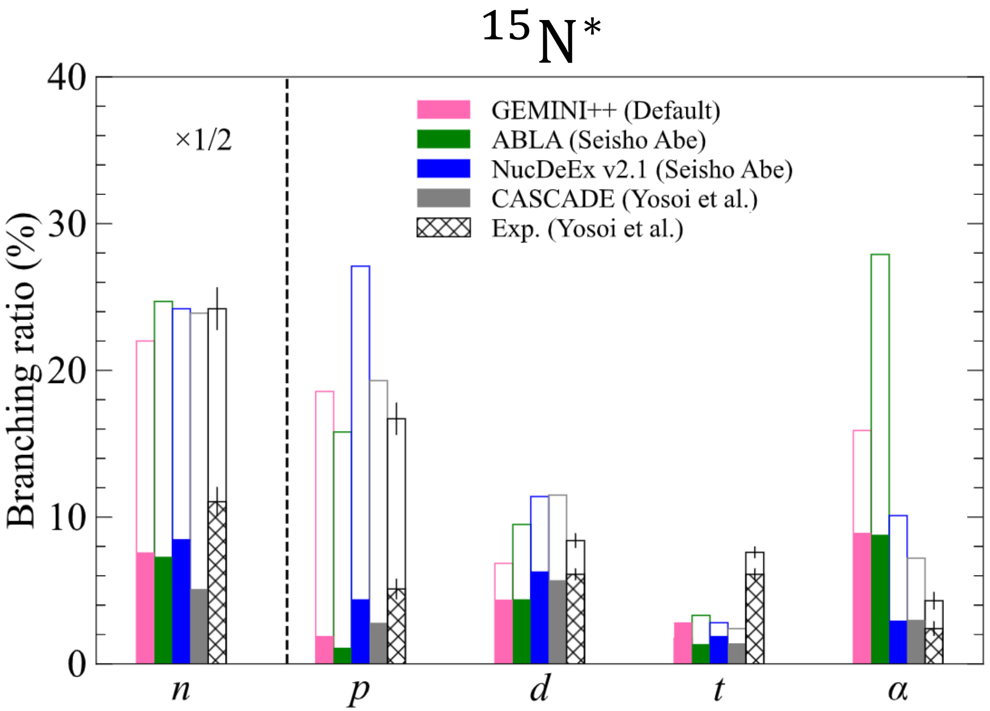
Suppression factor：Tuning width

Performance of GEMINI++



(Yosoi et al.) Exp.1

(Panin et al.) Exp.2



(Yosoi et al.) Exp.1

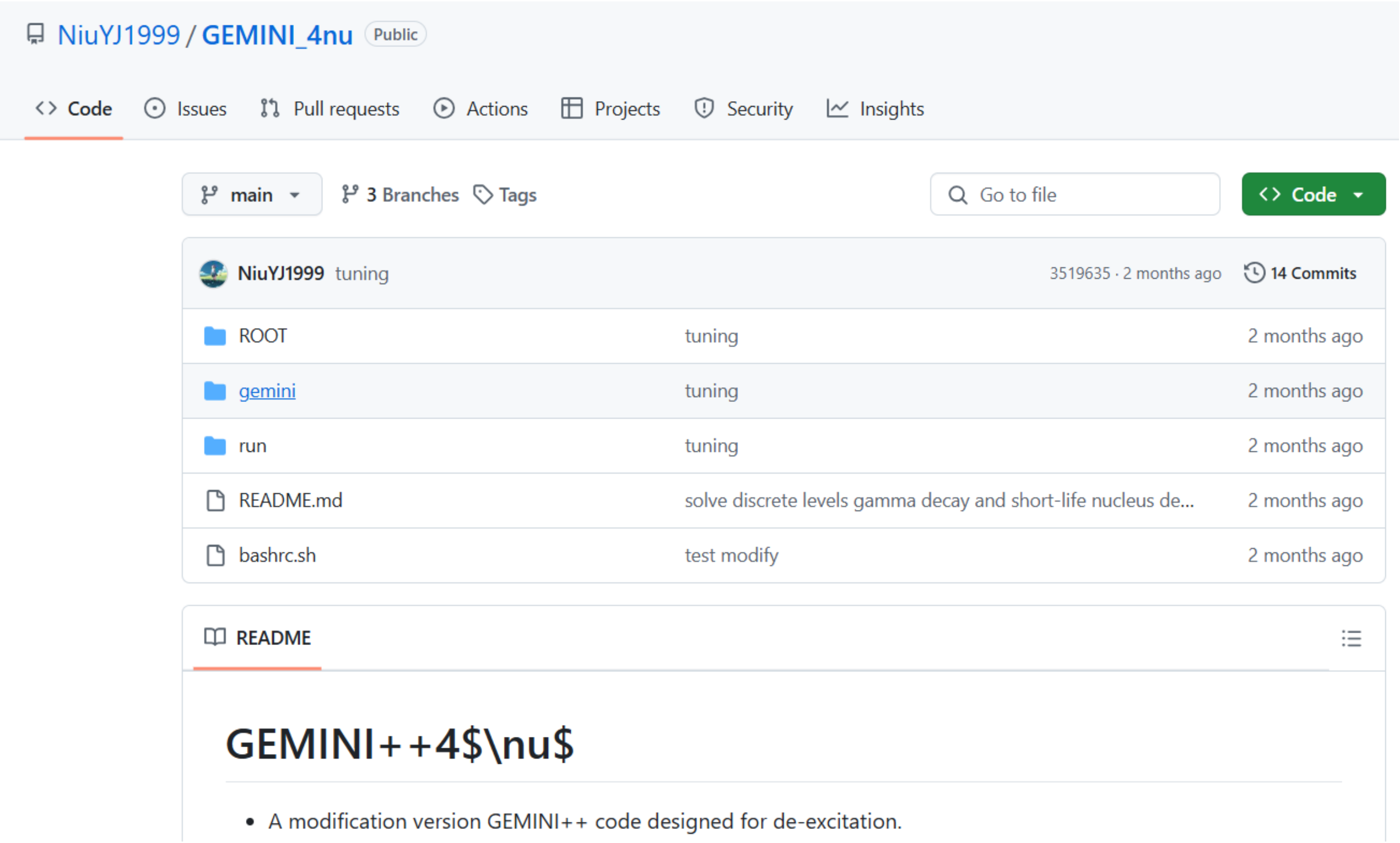
- Bad agreement with Exp.1
- Good prediction to Exp.2, but not enough
- GEMINI++ is designed for heavy nucleus, for light nucleus, modifications are required

Generator GEMINI++4ν

GENIMI++4ν is developed for neutrino experiments to handle de-excitations of residual nuclei associated with ν interaction and nucleon decay based on GEMINI++ code

Open source:

https://github.com/NiuYJ1999/GEMINI_4nu



Three modifications are carried:

- ***Removing Back-shifted term***
- ***Add discrete levels***
- ***Adjust suppression factor***

Removing Back-shifted term

5000 events for every interval of 0.1 MeV are simulated (0 MeV ≤ Ex ≤ 50 MeV) to determine the critical energy $\mathrm{E_c}$ of particle-emitting for 2-body decay

	Separation energy	critical energy	
Modes	Theory	GEMINI++	GEMINI++4ν
$n+{}^{10}\mathrm{B}$	11.5	12.2	12.2
$p+{}^{10}\mathrm{Be}$	11.2	17.1	12.2
$d+{}^{9}\mathrm{Be}$	15.8	16.6	16.6
$t+{}^{8}\mathrm{Be}$	11.2	20.5	12.1
${}^{3}\mathrm{He}+{}^{8}\mathrm{Li}$	27.2	28.6	28.6
$\alpha+{}^{7}\mathrm{Li}$	8.7	10.1	10.1

difference!

Improved!

$$\rho\,(U) \propto \frac{\exp\left[2\sqrt{a(U-E_1)}\right]}{a^{\frac{1}{4}}(U-E_1)^{5/4}}$$

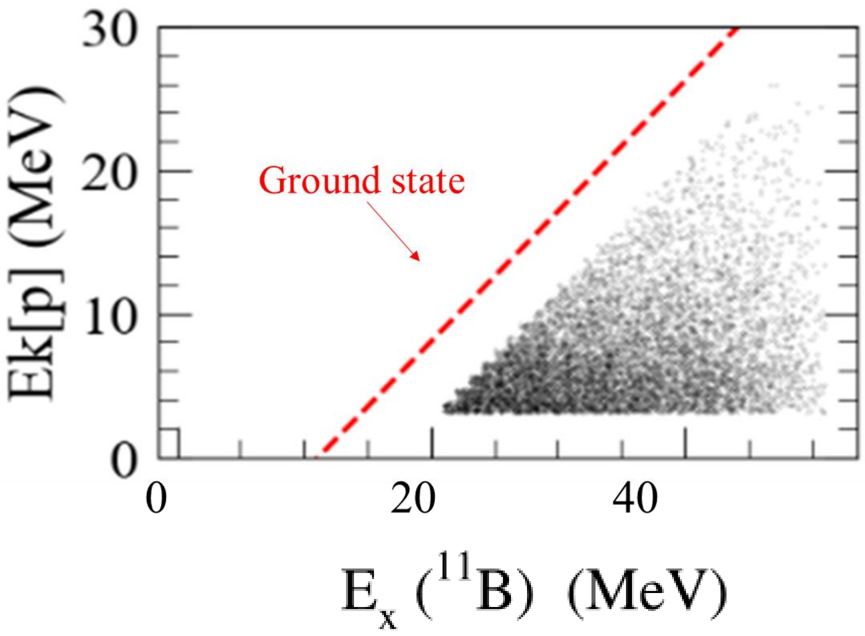
Modification of $\mathrm{E_1}$ equals to tune excited energy:

- $\mathrm{E_c}$ can be changed due to this modification
- Winner in competition can be changed

- **No available experimental $\boldsymbol{E_1}$** for ${}^{11}\mathrm{B}^*$ and ${}^{15}\mathrm{N}^*$ and their daughter nucleus can be used (only $\boldsymbol{E_1}$ of nucleus mass > ${}^{19}\mathrm{F}$ can be found)
- $\rho\,(U)_{E_1\neq 0}$ and $\rho\,(U)_{E_1=0}$ are used to do χ^2 calculation to fit existing discrete levels
- $\rho\,(U)_{E_1=0}$ gives a better result, this modification is reasonable

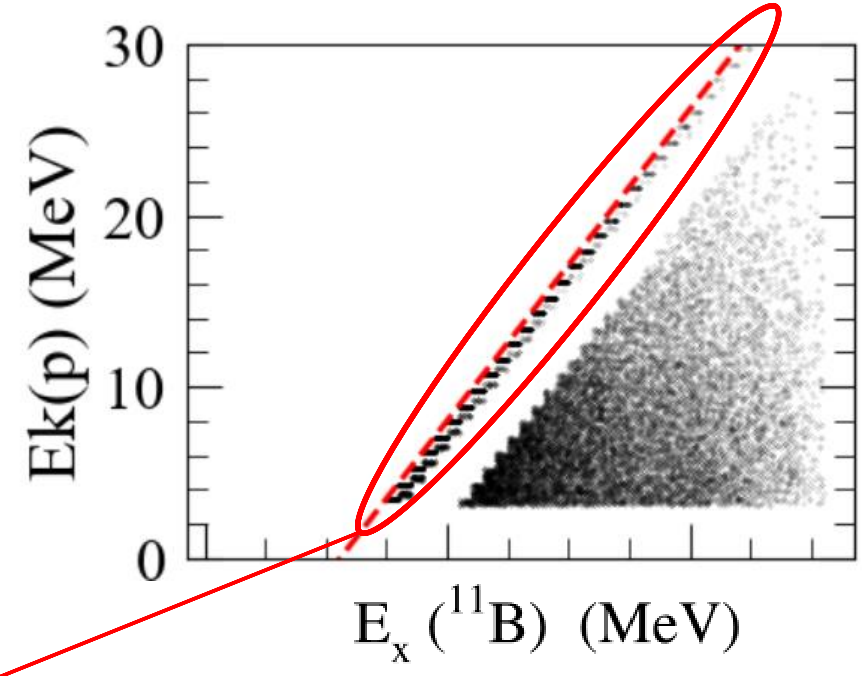
Add discrete levels

- **GEMINI++ does not consider discrete levels**
- Decayed nucleus always has low excited energy at the last decay
- Modifying the de-excitation result by adding the clearly known discrete levels in NNDC



Absence of discrete levels

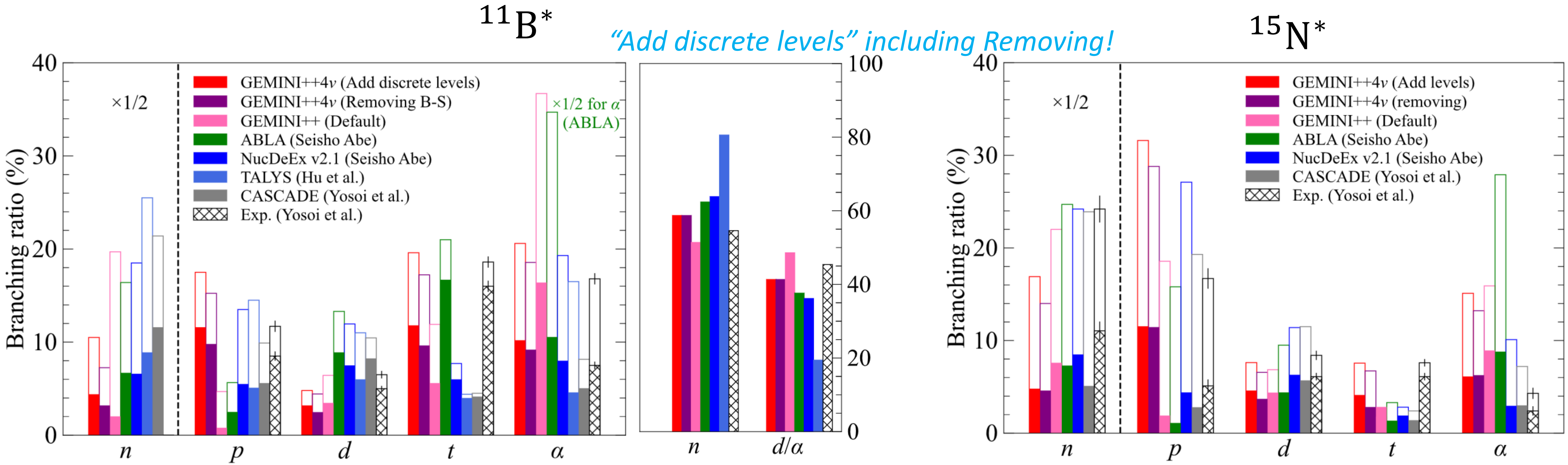
Add discrete levels



Discrete levels occur

Kinematic energy of some particles can be **increased** to **cross the detection threshold** in Exp.1

Impact of modification 1 and 2



(Yosoi et al.) Exp.1 **(Panin et al.) Exp.2** **(Yosoi et al.) Exp.1**

- Besides more reasonable E_c can be given, removing E_1 obviously provides a better result
- Adding discrete levels provides higher "2-body decay" and "3-body decay" ratios for almost all particles

Modification of GEMINI++

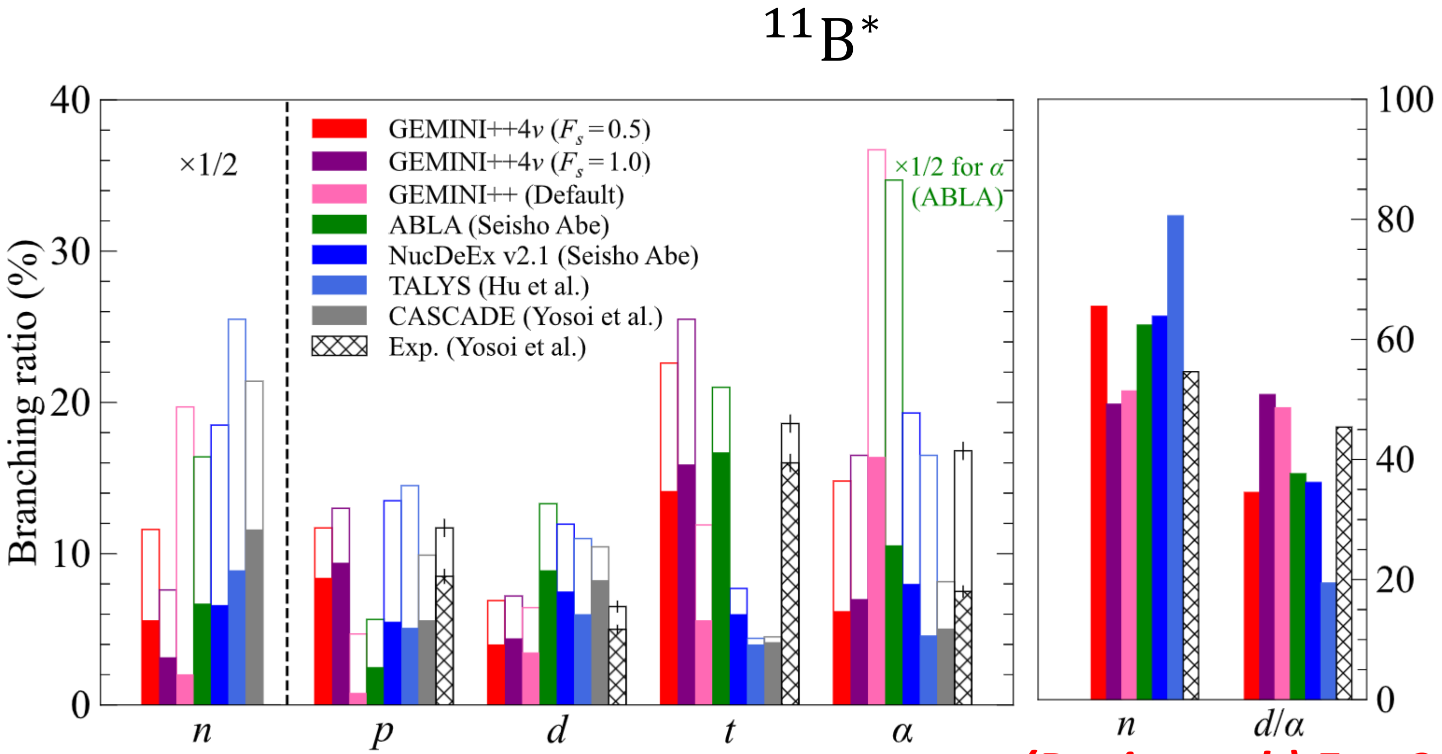
Default F_s settings originate from the de-excitations of heavy nuclei

Settings	n	p	d	t	^{3}He	α
Default	1.0	1.0	0.5	0.5	0.5	1.0
$F_s = 1.0$	1.0	1.0	1.0	1.0	1.0	1.0
$F_s = 0.5$	1.0	0.5	0.5	0.5	0.5	0.5

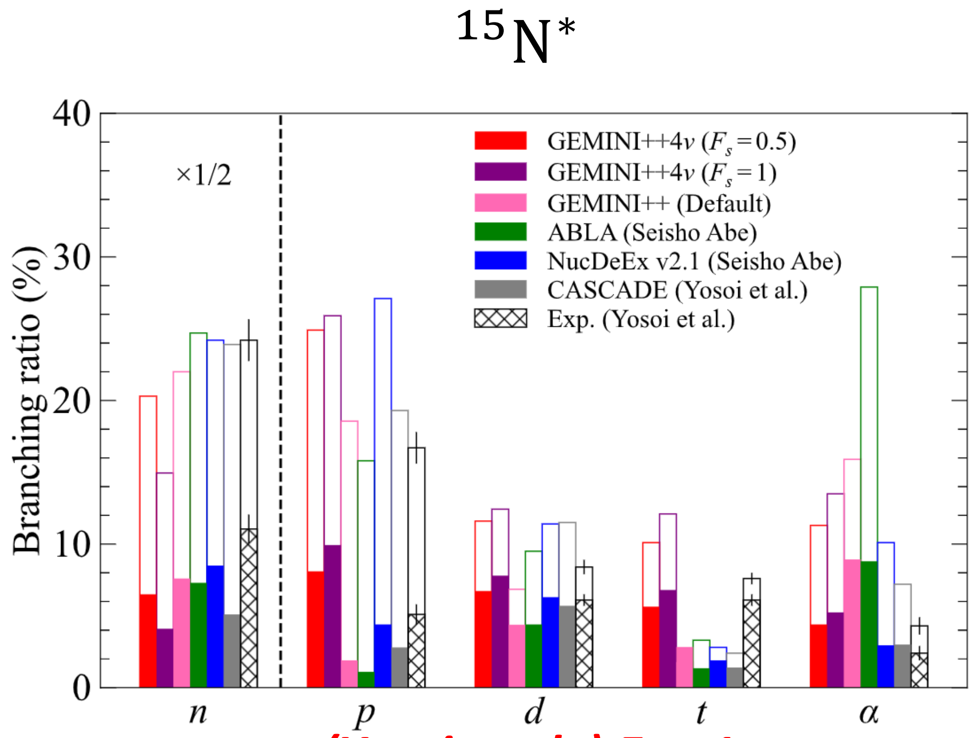
Are default settings reasonable for light nuclei?

- Don’t use suppression factor to adjust results, namely $F_s = 1.0$ for all particles
- $F_s = 0.5$ for all charged particles. Compared with default, only two changes

Modification of GEMINI++



(Yosoi et al.) Exp.1 (Panin et al.) Exp.2



(Yosoi et al.) Exp.1

GEMINI++4v with $F_s = 1.0$:

- Good agreement with $^{11}B^*$ data
- Can't account for $^{15}N^*$ data well

GEMINI++4v with $F_s = 0.5$ (Recommend!)

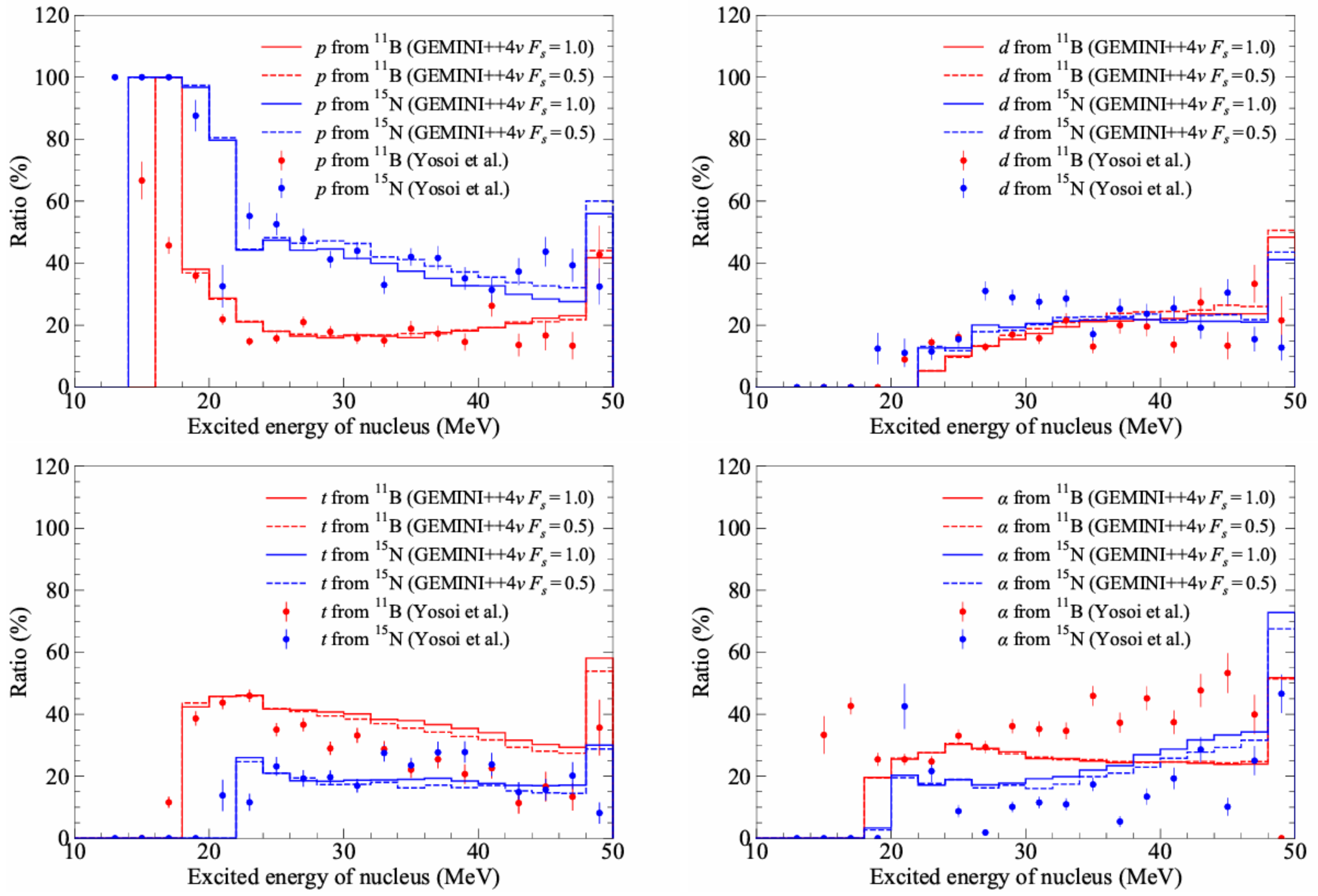
- Better agreement with $^{11}B^*$ data
- Partially account for $^{15}N^*$ data, include *n*

This is the first time that a code can basically reproduce both $^{11}B^*$ and $^{15}N^*$ data

Accidental coincidence check

Fixed energy ranges of $16 \leq \mathrm{Ex} \leq 35$ MeV for $^{11}\mathrm{B}^{*}$ and $20 \leq \mathrm{Ex} \leq 40$ MeV for $^{15}\mathrm{N}^{*}$

Compare the ratio of each type of charged particle emission among four types for every energy bin



- $F_s = 1.0$ and $F_s = 0.5$ differences are relatively small
- Predicted shapes are basically consistent with data except α
- Discrepancy maybe come from $^{11}\mathrm{B}^{*} \rightarrow t + \alpha + \alpha$

Not coincidental!

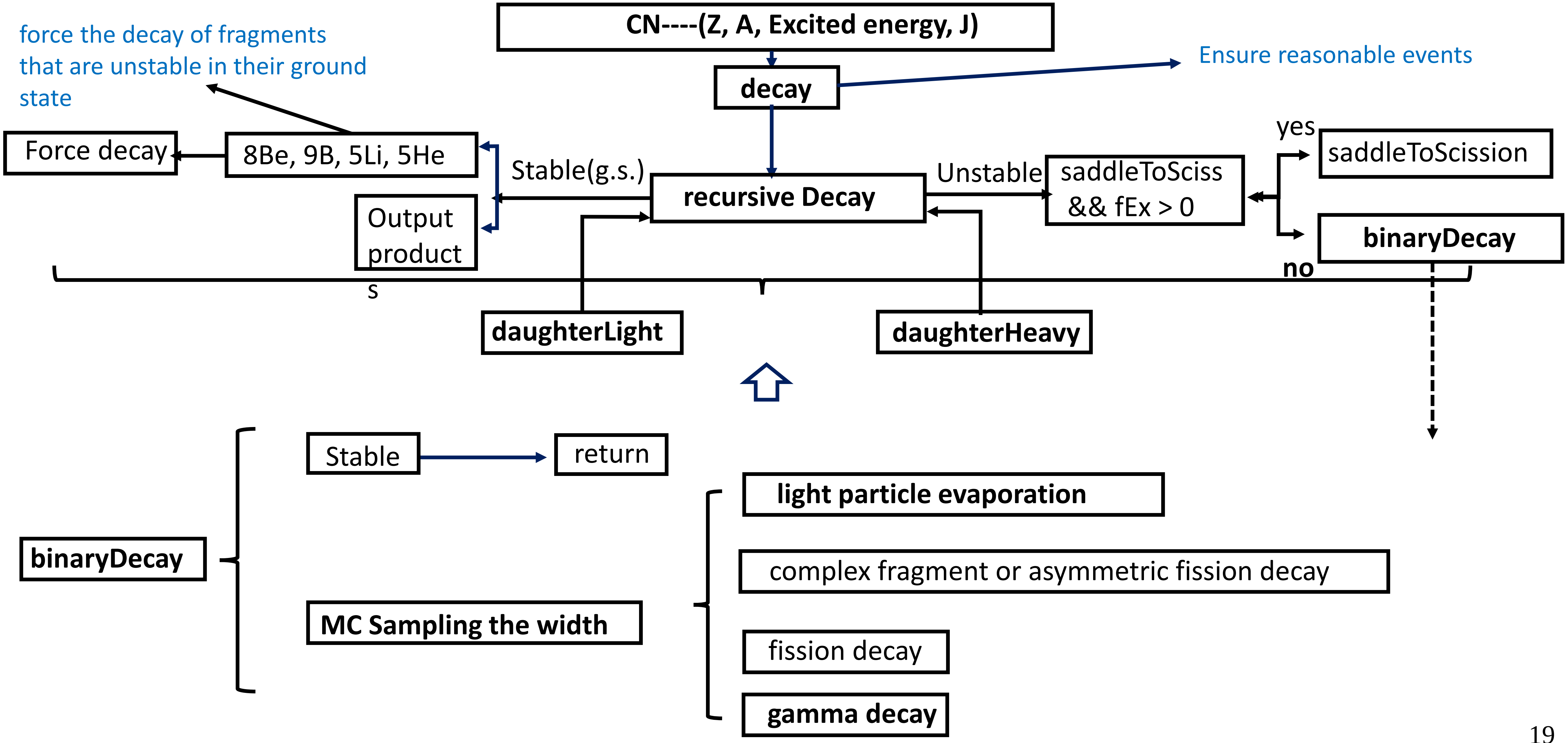
Summary

- De-excitation plays an more and more important role in ν experiments
- GEMINI++ is a potential event-by-event de-excitation generator
- Three modifications provide the best agreement with experiments in $^{11}\mathrm{B}^*$ and $^{15}\mathrm{N}^*$, the modified generator is named **GEMINI++4ν**
- More work is on-going, such as the predictions of gamma emitting from de-excitation
- Plan to combine GEMINI++4ν into widely-used ν generator such as GENIE and NuWro

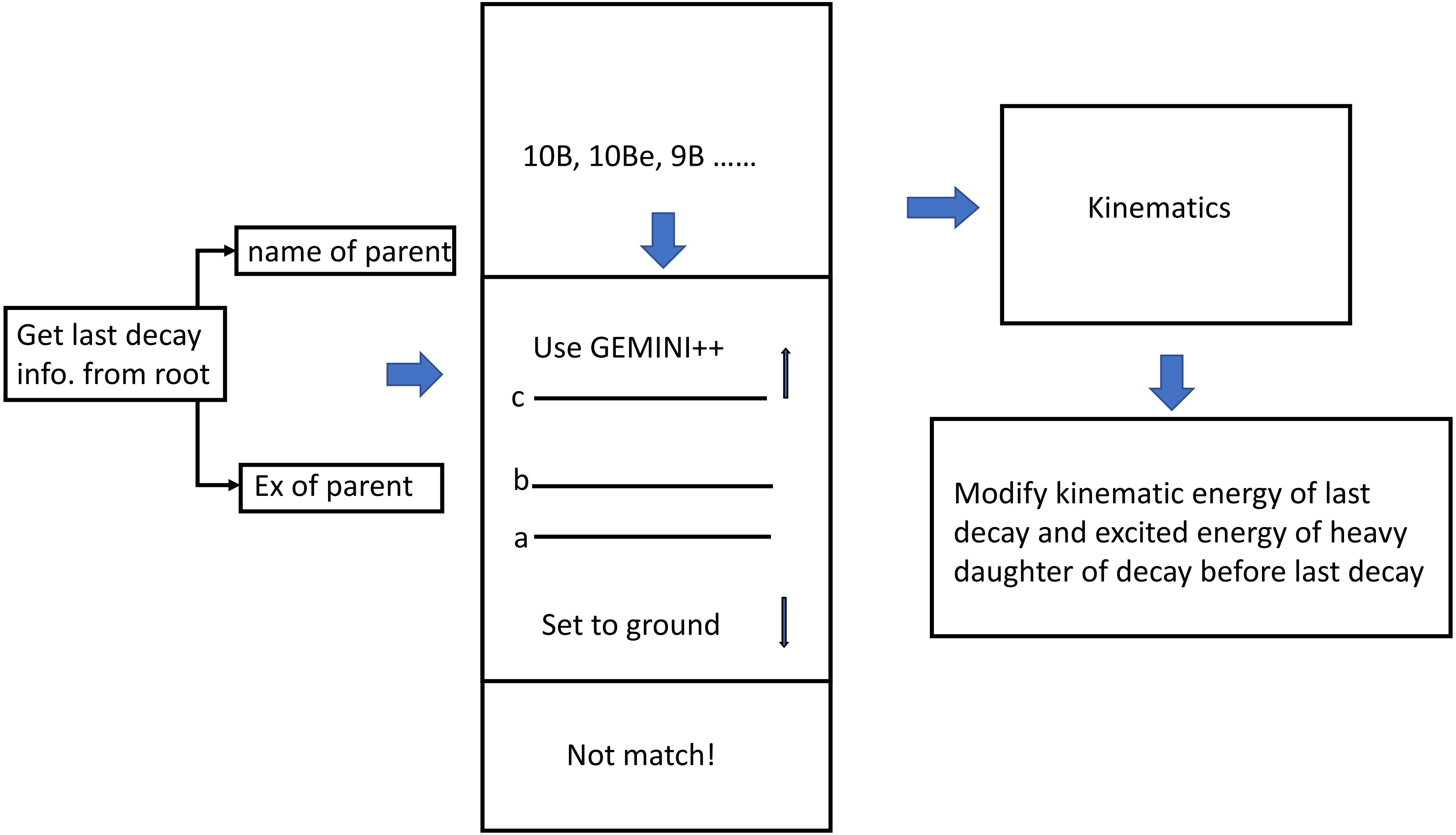
Thanks for your attention!

Back up

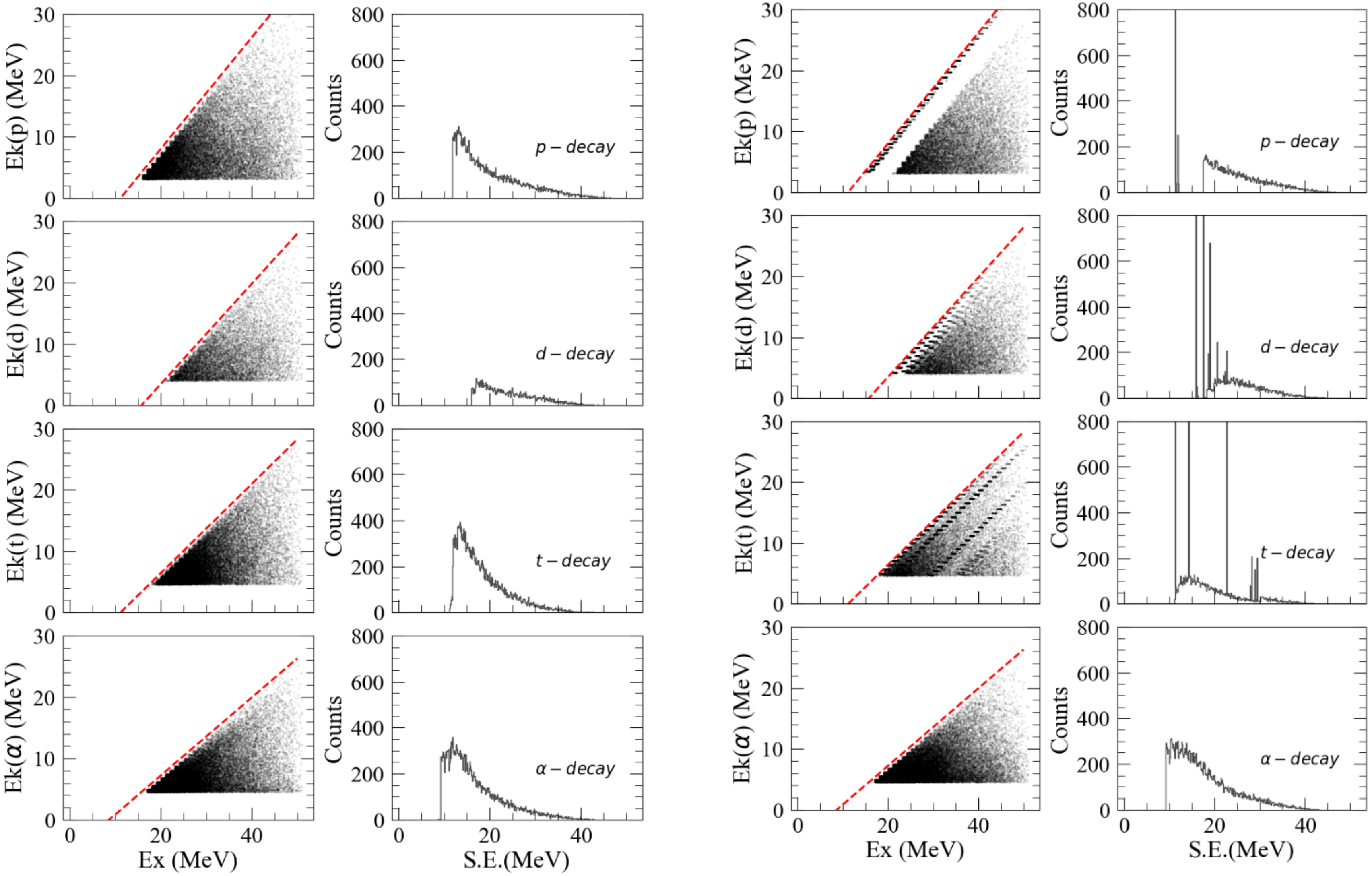
Code detail (picture)



Modification of the last decay



Modification of the last decay



Modify some residues to G.S.

Modify with p

Usually the decay for 8Be

Width calculation

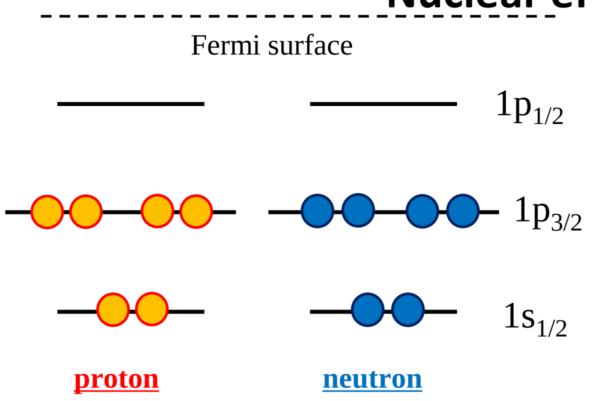
Hauser-Feshbach formulism

$$\Gamma_i^{HF} = \frac{1}{2\pi\rho(E^*, S_{CN})} \int d\epsilon \sum_{S_d=0}^{\infty} \sum_{J=|S_{CN}-S_d|}^{S_{CN}+S_d} \sum_{l=|J-S_i|}^{J+S_i} T_l(\epsilon)\rho(E^* - B_i - \epsilon, S_d)$$

- S_i, J, l for the evaporated particle, T_l is transmission coefficient, ϵ for kinematic energy, B_i for separation energy
- S_d is the spin of residue, S_{CN} is the spin of CN, ρ for level density
- Evaporation channels include n, p, d, t, 3He, α and so on
- **Ignore the effect of angular momentum, gives Weissikopf formulism**

$$\Gamma_i^W(E_i) = \frac{2s_v + 1}{2\pi\rho_i(E_i)} \frac{2m_v}{\pi\hbar^2} \int_0^{E_i - S_v - B_v} \sigma_c(\epsilon_v)\rho_f\left(E_f\right) \times (\epsilon_v - B_v) d\epsilon$$

Nuclear effects considered



- **Shell correction**
- **Pairing**

Back-shifted Fermi Gas model

$$\rho_F(E_x, J, \Pi) = \frac{1}{2} \frac{2J+1}{2\sqrt{2\pi}\sigma^3} \exp\left[-\frac{(J+\frac{1}{2})^2}{2\sigma^2}\right] \frac{\sqrt{\pi}}{12} \frac{\exp\left[2\sqrt{aU}\right]}{a^{1/4}U^{5/4}}$$

- $U = E^* - \Delta_{BFM}$, Δ_{BFM} is the parameter affected by shell correction and pairing, in fact, an adjustable parameter to fit experiment data in theory
- Parameter $\boldsymbol{a}$ has relationship with shell correction and A in GEMINI++