# Pulse Shape Discrimination in Scintillator Detectors

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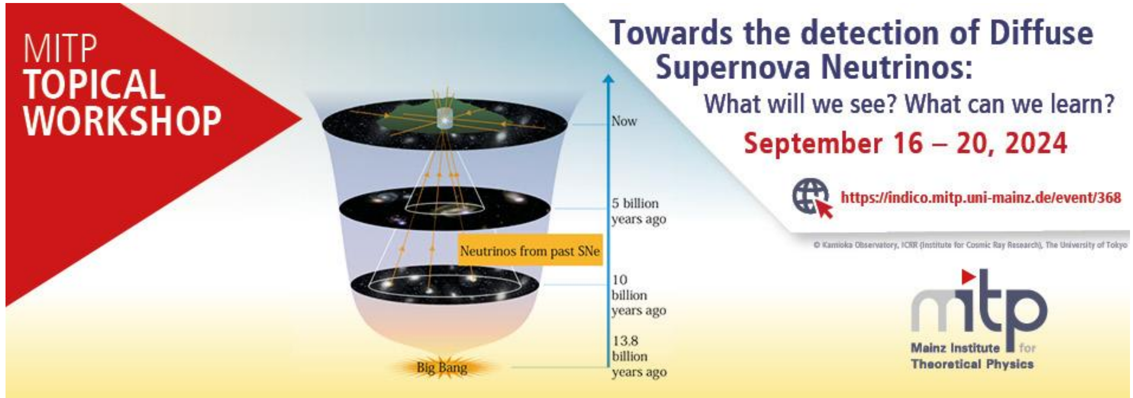
2024/09/20

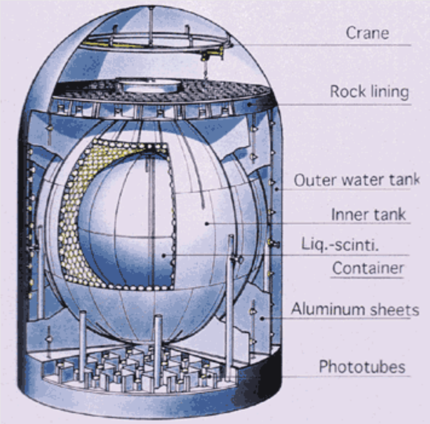


# Detecting Neutrino with Scintillator Detectors

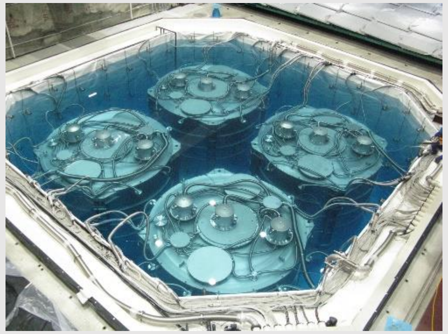
**Scintillator detection technique is popular for detecting neutrino**

- **Scintillator**: Material emits light after neutrino interactions.
- **Key Function**: Detect light flashes (scintillations) using photon sensors.
- **Advantage**: Highly sensitive to low-energy neutrinos.
- **Challenge**: Exclude backgrounds

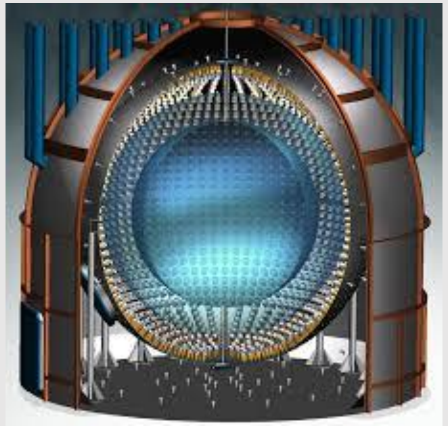
**KamLAND**



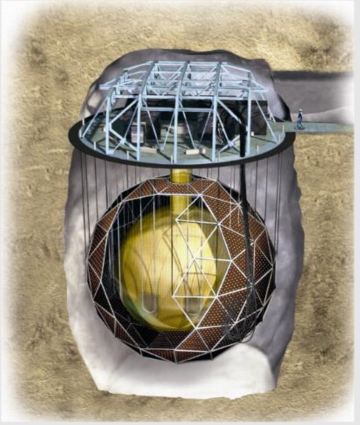

**Daya Bay**



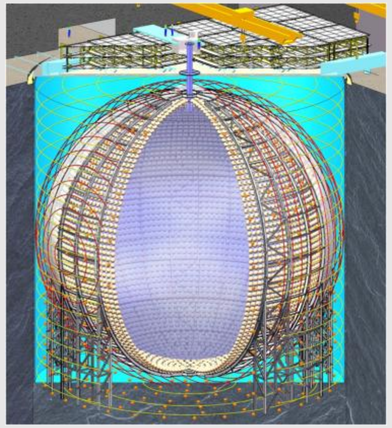
**Borexino**



**SNO+**



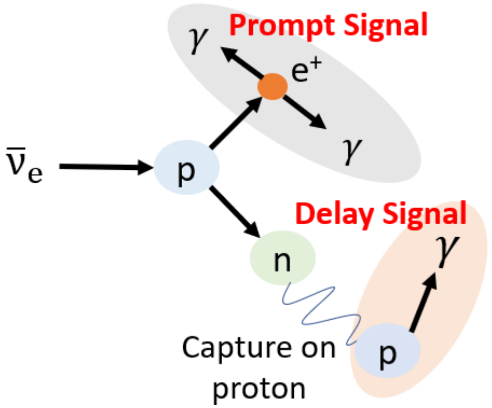
**JUNO**

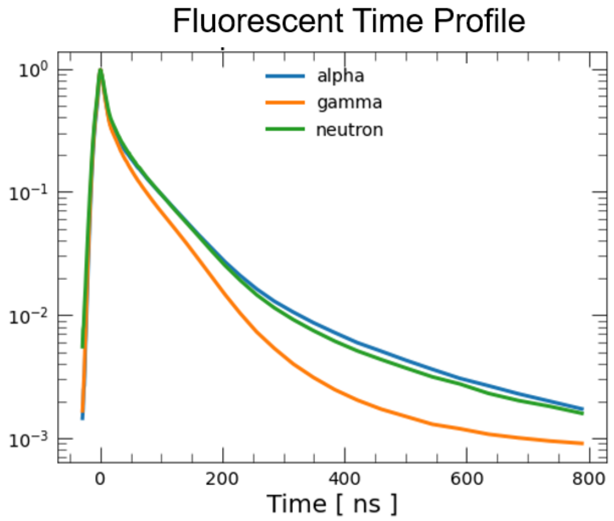


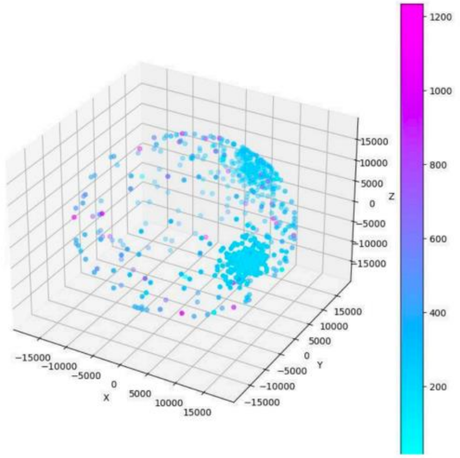
…

# Background Suppression in Scintillator Detectors

- Background shielding
- Muon veto
- Prompt-delayed coincident selection
  - Inverse Beta Decay(IBD): $\bar{\nu}_e$
  - Unstable isotopes(Bi-Po, $^{11}$C and so on)
- Pulse Shape Discrimination(PSD)
  - Utilize timing response to separate particles
  - Distinguish singles event(e/γ, p/n, α)
- Event topology
- And so on ...



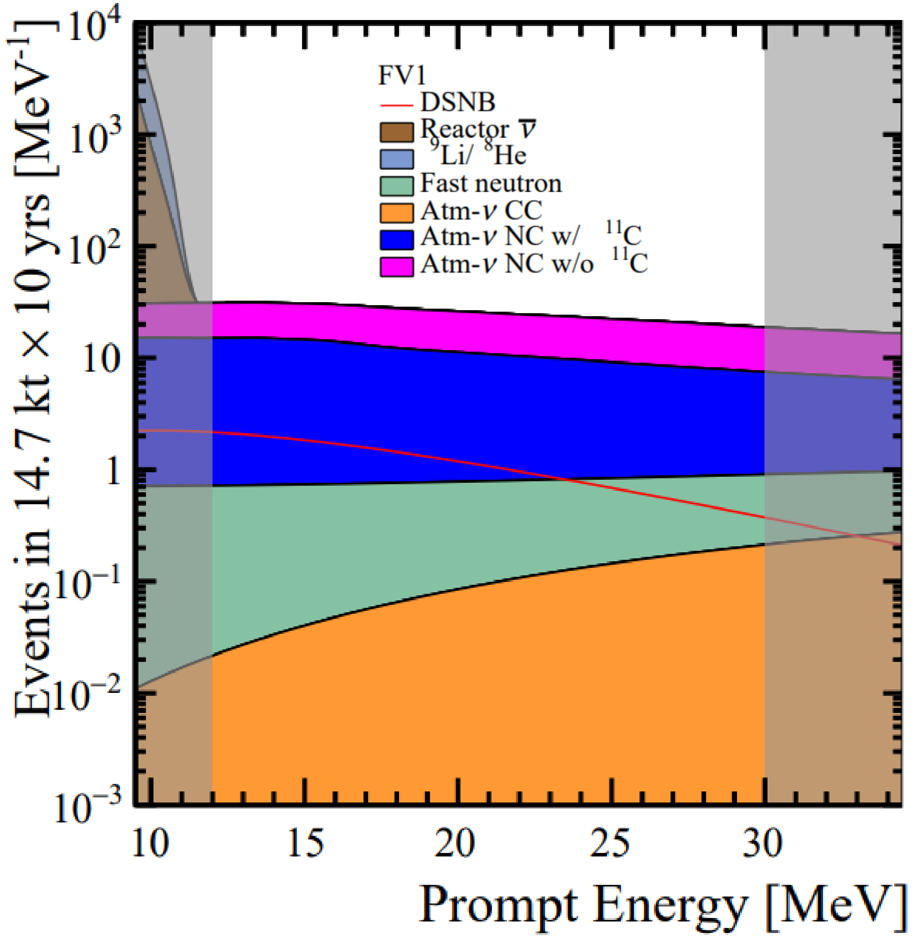



# Detecting DSNB with Scintillator Detectors

To detect DSNB $\bar{\nu}_e$ in scintillator detectors, it is essential to distinguish rare signals from plenty of backgrounds:

- Natural radioactivity background
- Atmospheric neutrino
    - Charge current (CC)
    - Neutral current (NC)
- Cosmic ray related backgrounds
    - Fast neutron (FN)
    - $^{9}Li/\ ^{8}He$
    - … …
- Reactor neutrino

**DSNB Detection @JUNO**
**Signal and Background Spectrum**



# Detecting DSNB with Scintillator Detectors

**Tangle with backgrounds:**

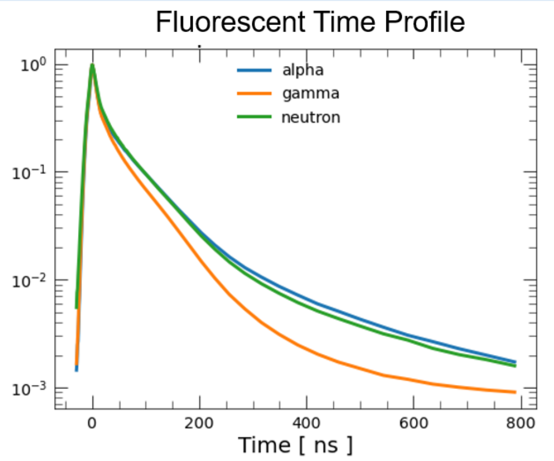
- Natural Radioactivity background
- Atmospheric neutrino
  - Charge current (CC)
  - Neutral current (NC)
- Cosmic ray induced backgrounds
  - Fast neutron (FN)
  - $^{9}$Li/ $^{8}$He
  - … …
- Reactor neutrino

Background shielding and prompt-delayed coincident selection

Pulse Shape Discrimination

NC and FN are the main backgrounds after prompt-delayed cut, that is why PSD is important

# Pulse Shape Discrimination

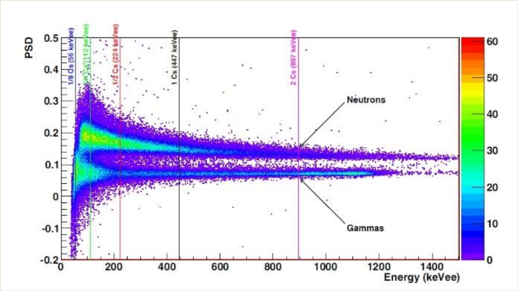



**Different particles has** **distinct fluorescent time profiles**

**Many methods to describe the timing shape:**

## Charge Integration Method

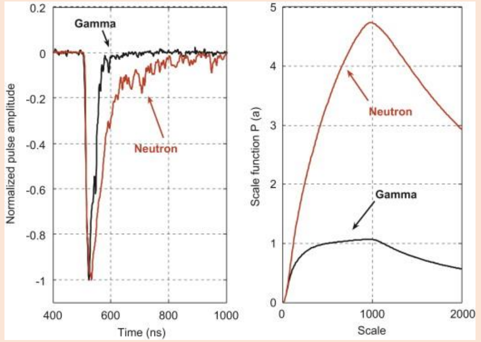
- Tail-to-Total Ratio
- Gatti's Method
- …




**CAEN DPP-PSD Firmware**

## Discrete Wavelet Transform

S. Yousefi et al. / Nuclear Instruments and Methods in Physics Research A 598 (2009) 551–555




## Zero-Crossing Method

M. Nakhostin, Nuclear Instruments and Methods in Physics Research Section A 672 (2012) 1-5.

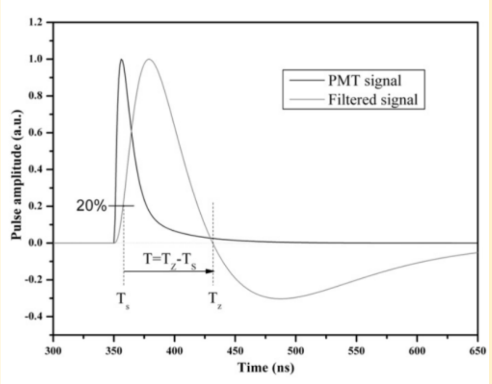



**Fig. 2.** Procedure of n/γ discrimination using the zero-crossing method.

## Machine Learning

- Boosted Decision Tree
- Multi-layer Perceptron
- …

**BOREXINO:** D. BASILICO et al. PHYS. REV. D 109, 112014 (2024)
**JUNO:** Cheng et al. Eur. Phys. J. C 84, 482 (2024).

… …

# Prospect for DSNB Detection with JUNO

Apply PSD on prompt signal to distinguish signal and background

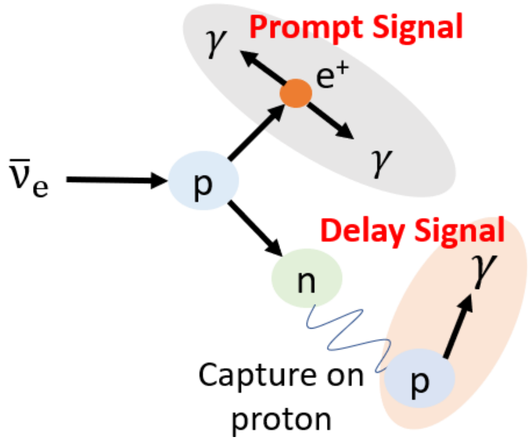
- DSNB → e+
- NC → Nuclei Recoil and Secondary γ ($e^+/e^-$)

Developed two Machine Learning (ML) based PSD techniques in JUNO:

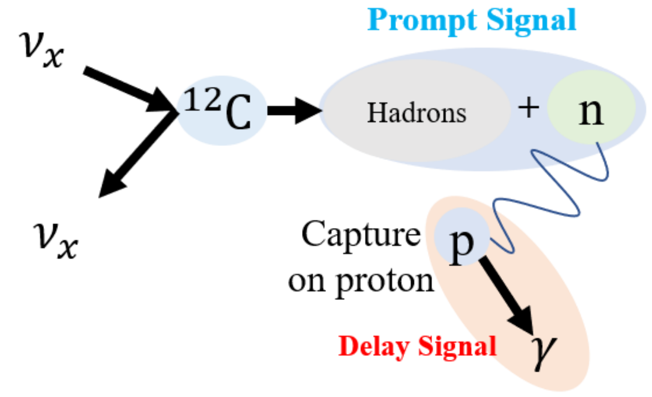
- ➢ Boosted Decision Trees (BDT)
- ➢ Neural Network (NN)

Cheng et al. Eur. Phys. J. C 84, 482 (2024).

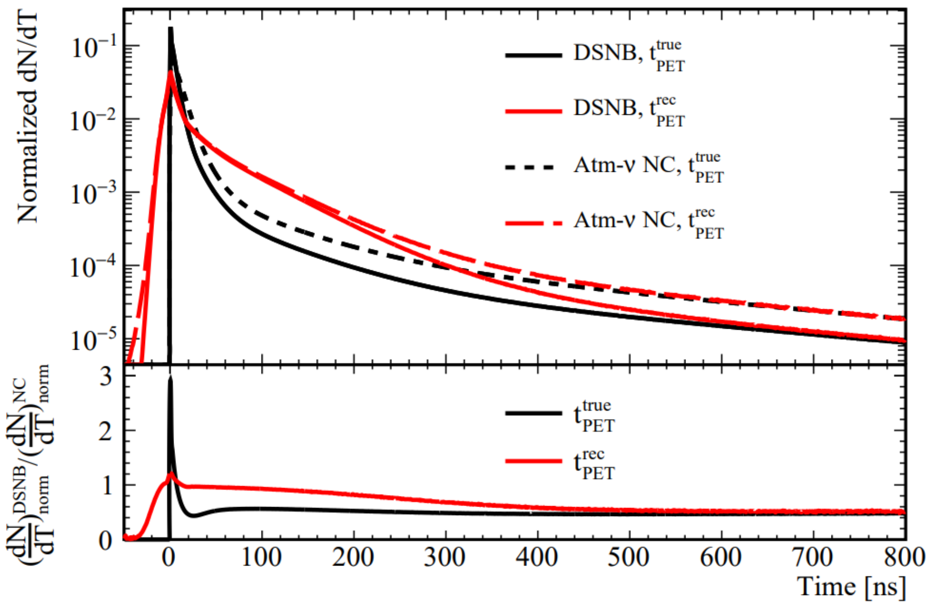
**DSNB Signal**




**NC Background**




**Emission Time Profiles in Simulation**



# Boosted Decision Trees

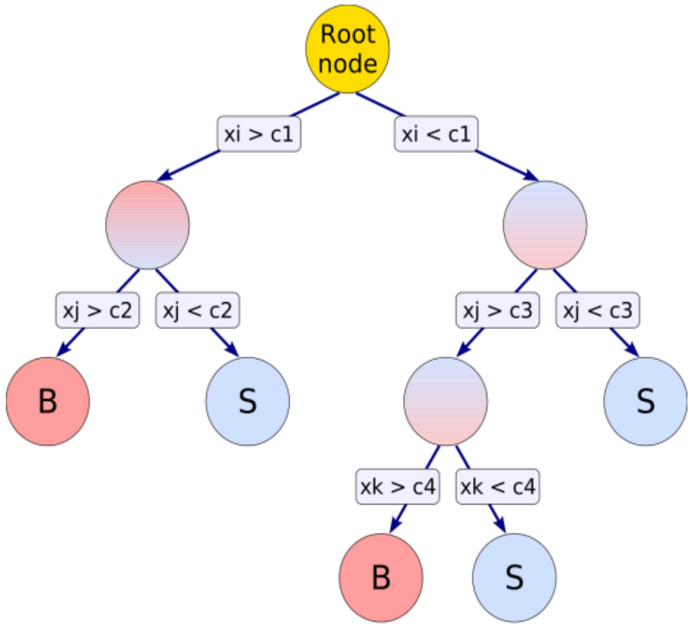
**Input:** Several discrimination variables (features)

**Basic idea:** Successive decision nodes are used to categorize the events

**How it Works:**

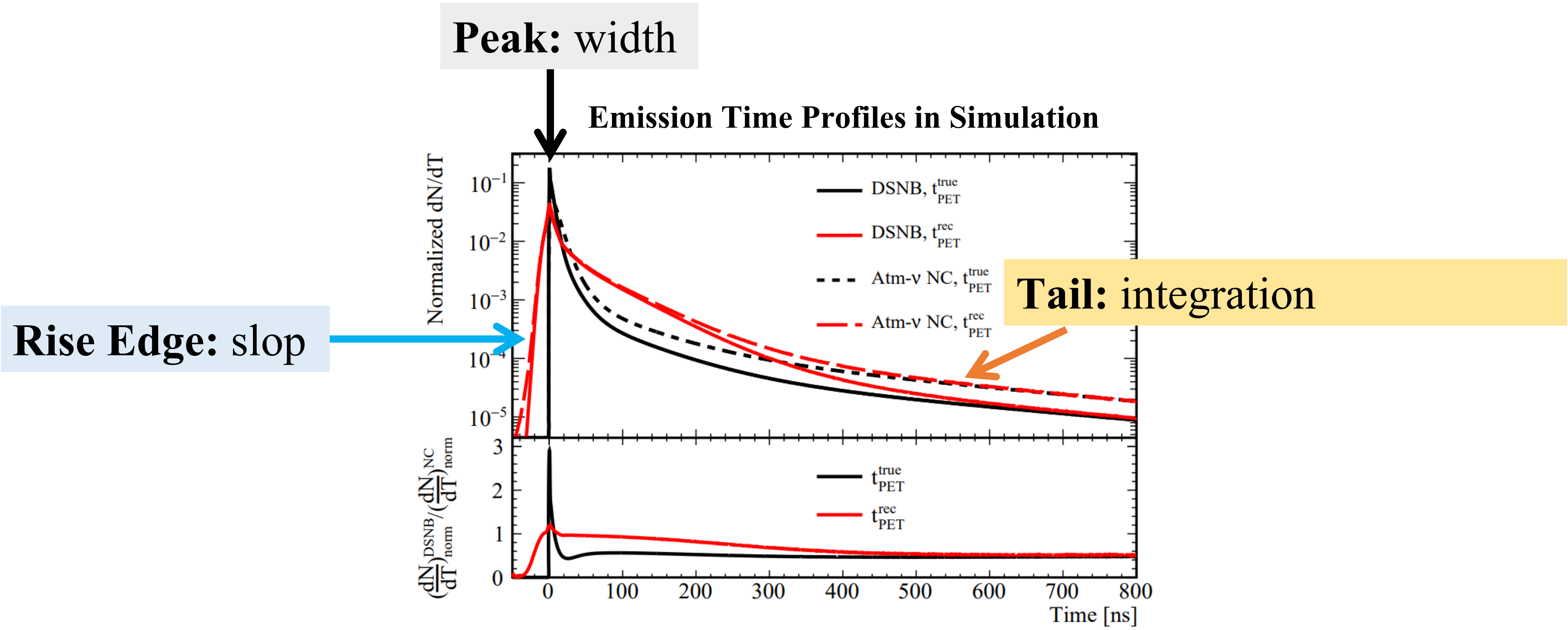
1. **Training**: The decision tree learns to split data at each node based on a variable that best separates signal from background.
2. **Boosting**: After each tree is created, misclassified events are given more weight, and a new tree is built to focus on these harder-to-classify cases.
3. **Prediction**: The final model applies these trees in sequence to classify target samples.

**Easy to use:** TMVA (Toolkit for Multivariate Analysis) in ROOT




S=Signal, B=Background

# Variables for Discrimination





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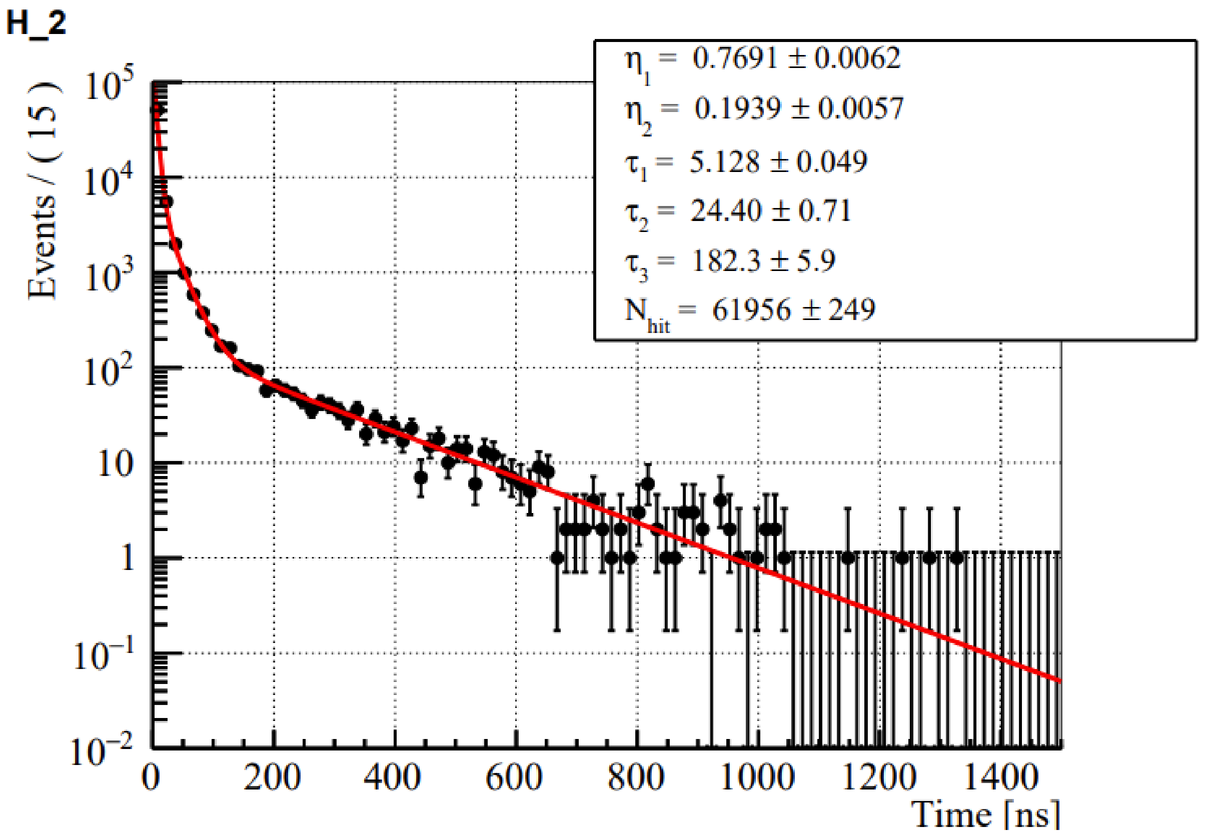
# Variables for Discrimination

***Also, we can fit the shape***

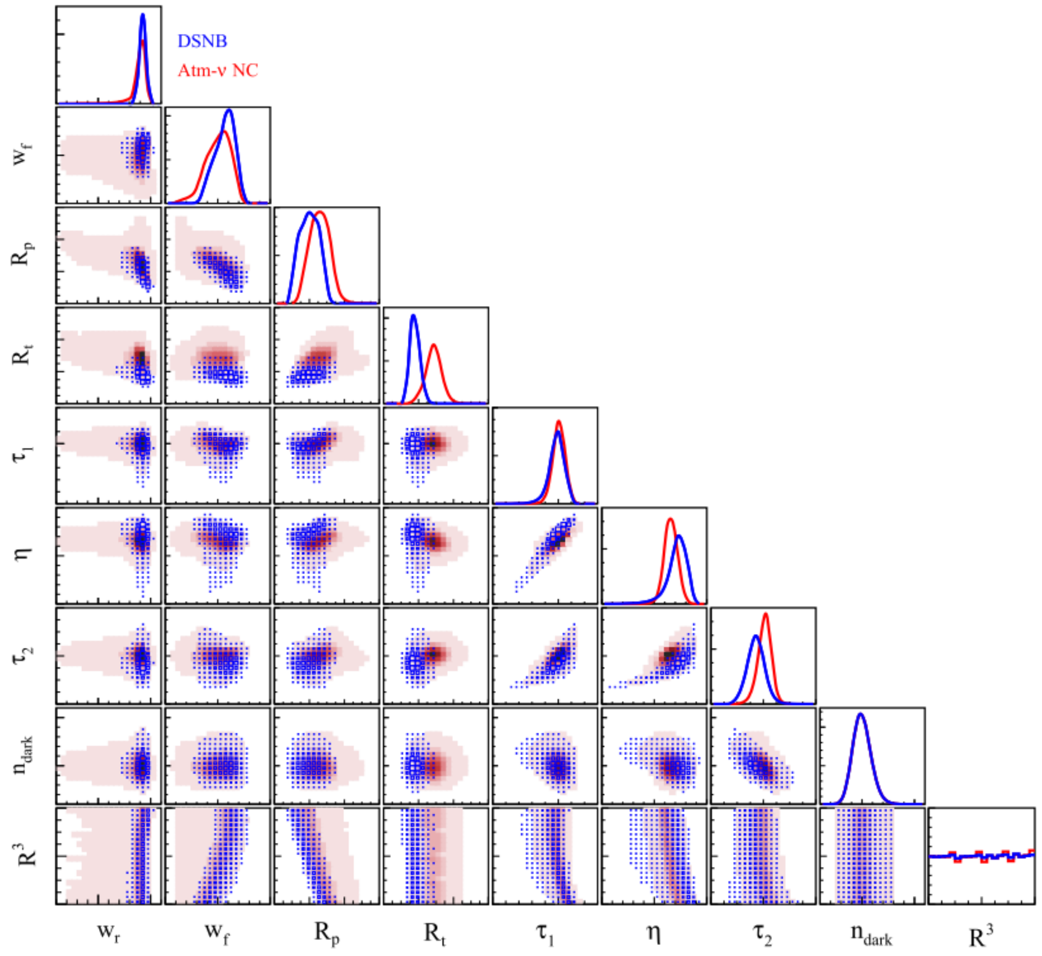



$$\tau_1, \tau_2, N_1, N_2 \ldots$$

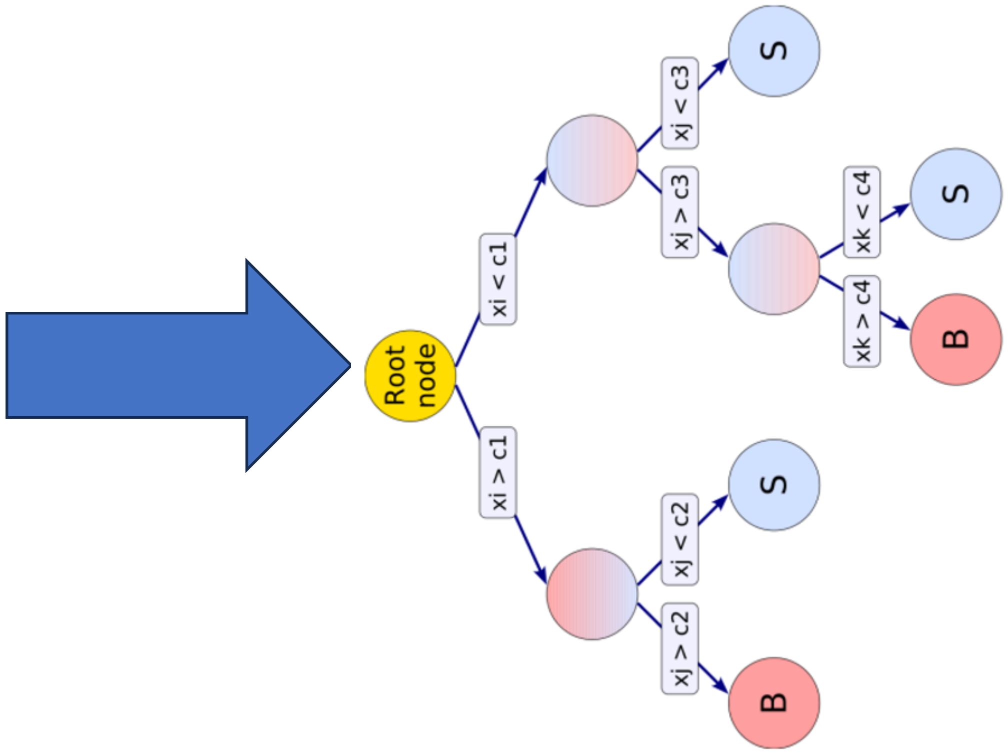
# PSD with Boosted Decision Trees

**Utilize multiple variables to describe the timing shape**

- Correlation between variables
- Combine advantages from several methods

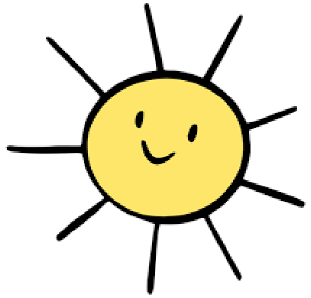


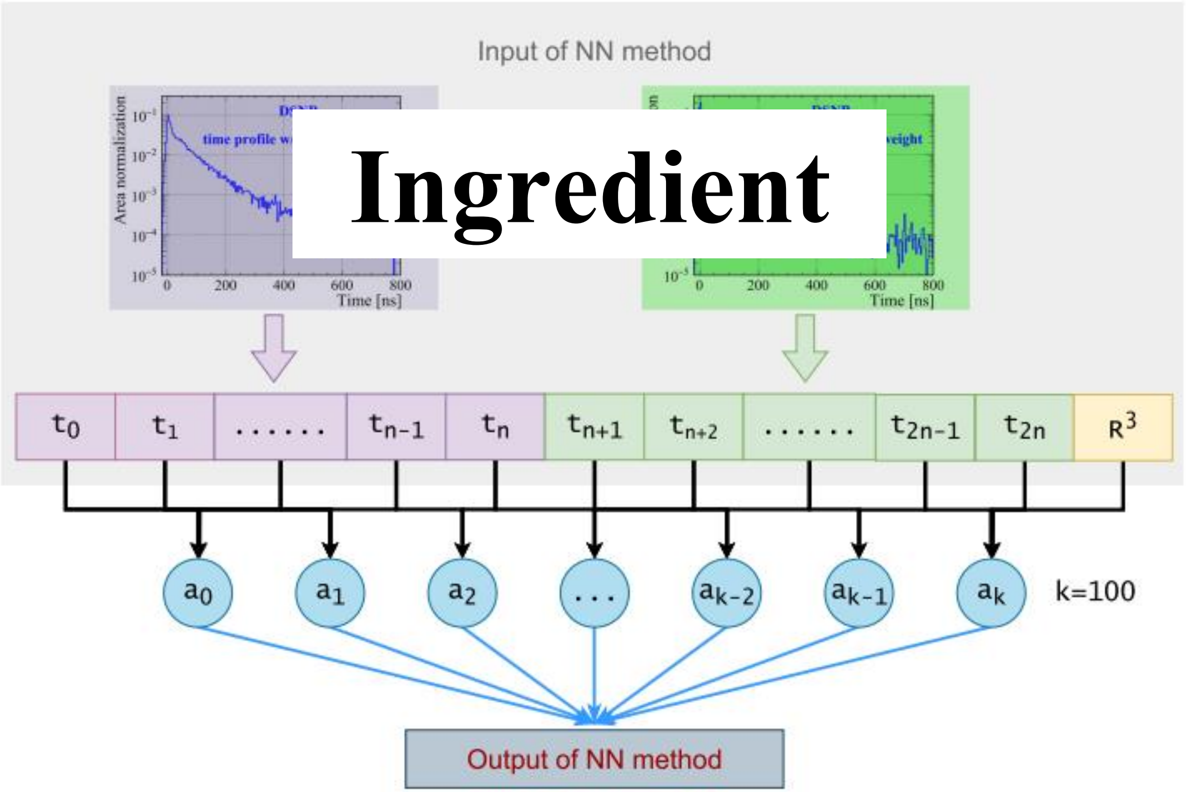

| |
|---|
| $\tau_1$ |
| $\tau_2$ |
| $\eta$ |
| $n_{dark}$ |
| $R_{tail}$ |
| $R_{peak}$ |
| $W_r$ |
| $W_f$ |
| $R^3$ |



# More Lazy Way

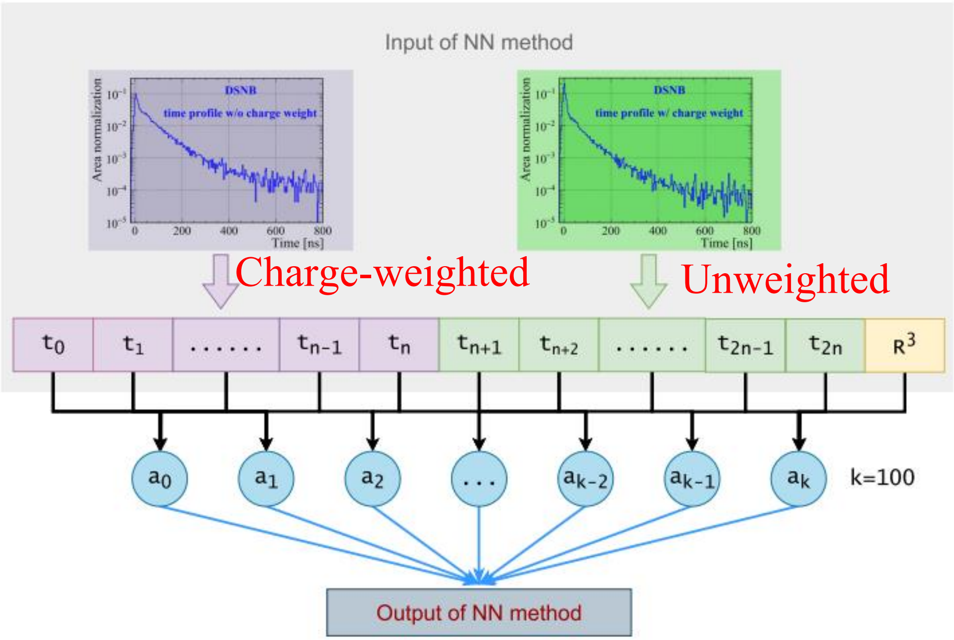
***How about directly inputing shape into "machine", let "machine" do the rest***



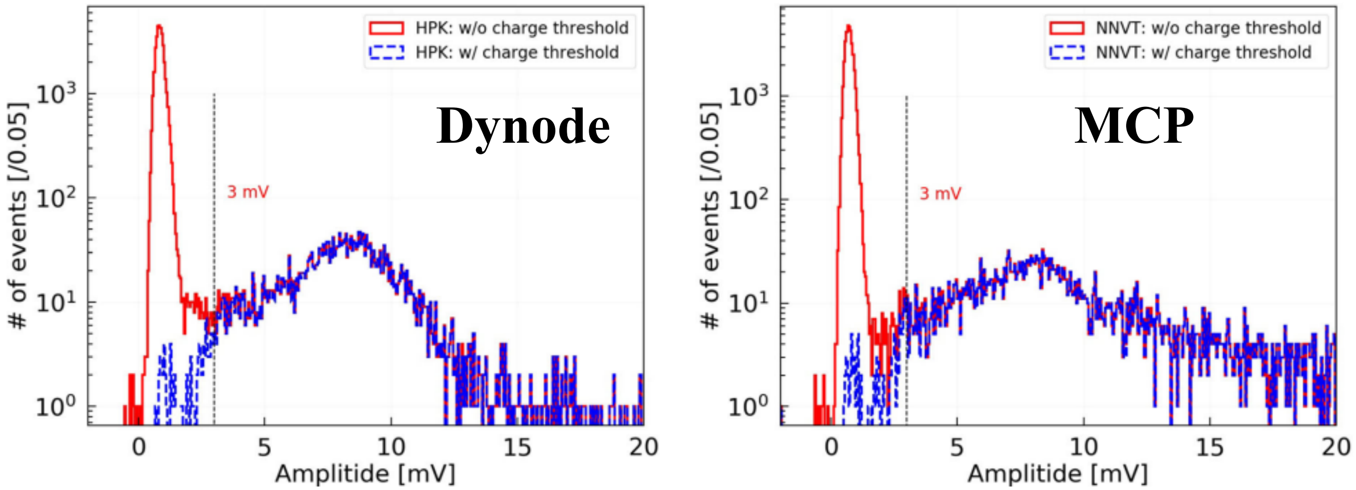


# Neural Network Method for PSD

- **Model:** Multi-layer Perceptron
- **Input:** binned time profile and event information
  - **Charge-weighted profile:** correct bias introduced by multi-PE hits
  - **Unweighted profile:** good for single-PE hits avoiding PMT charge smearing
  - **$R^3$:** vertex dependency




**Single Photon Electron(SPE) Response**




Abusleme *et al.* *Eur. Phys. J. C* **82**, 1168 (2022).

# PSD Performance

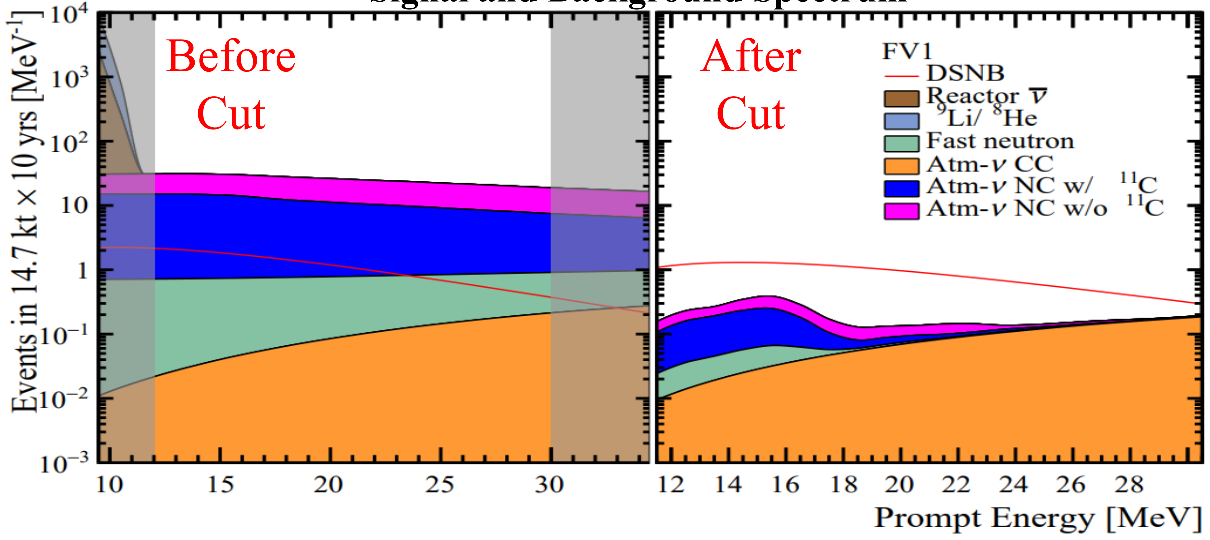
**For JUNO detector radius R<16m,**

Achieved NC background inefficiency:**1%**,

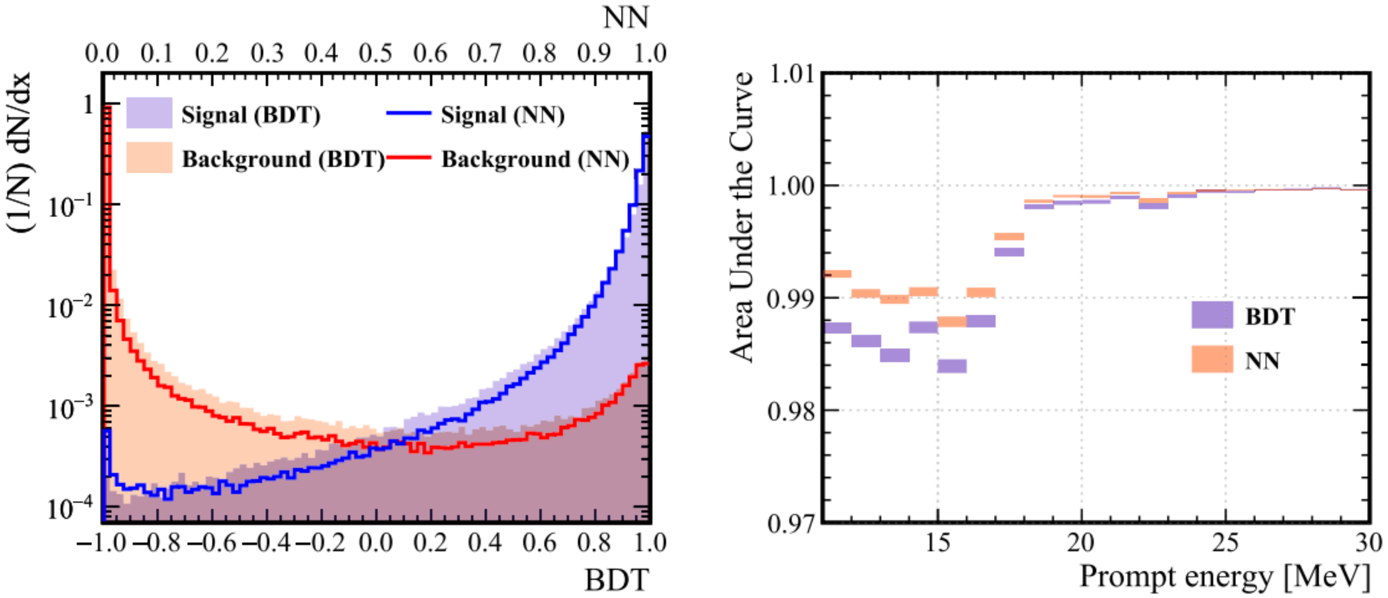
DSNB signal efficiency **~ 85%**

**Great improvement comparing with previous result (signal efficiency~50%) in JUNO(2015)**

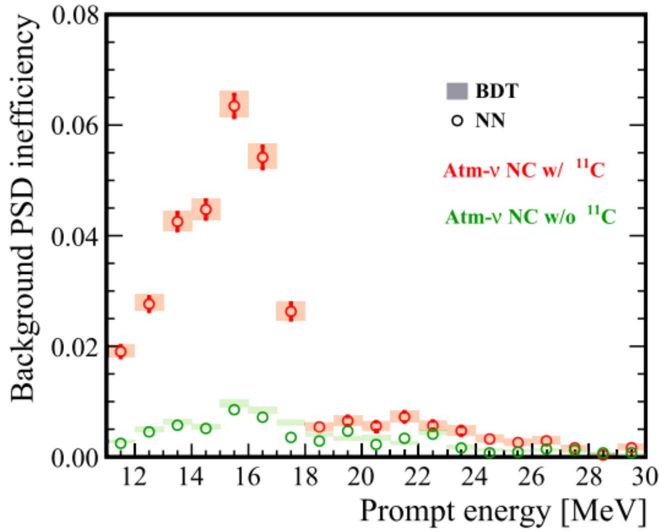
**DSNB Detection @JUNO**
**Signal and Background Spectrum**




**Separation Power**



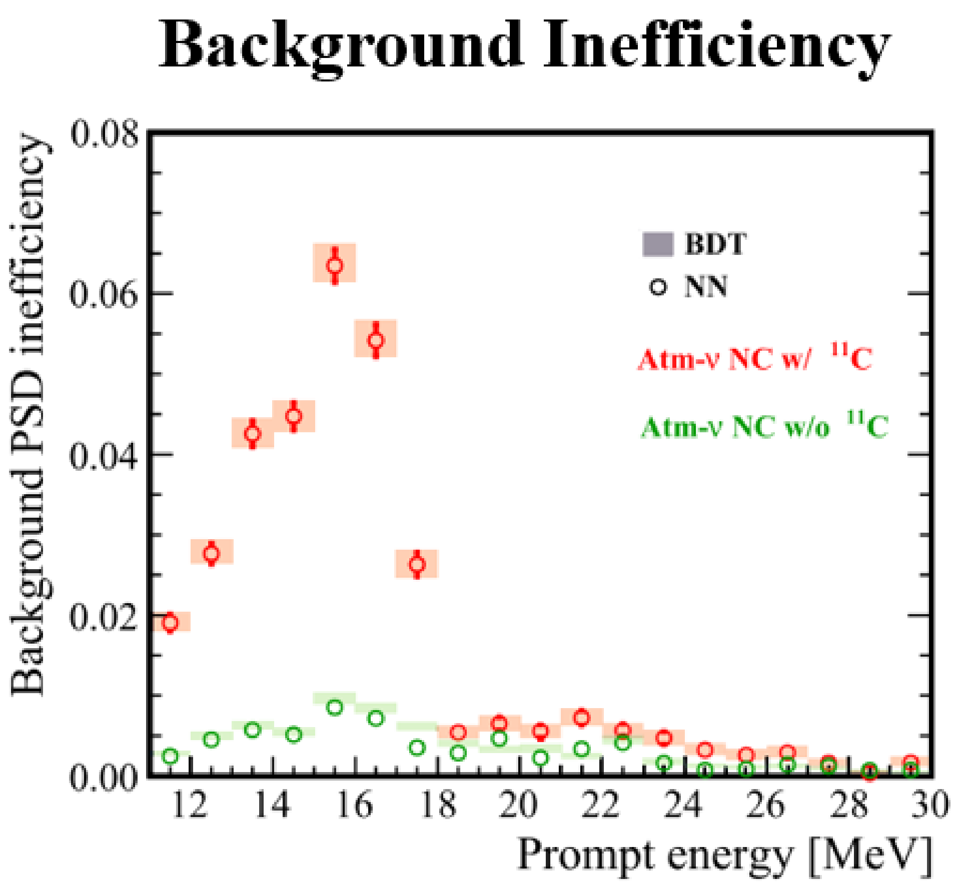

**Background Inefficiency**



# Physics Interpretations

***Seems very nice performance.***

***But why there is peak around ~16 MeV?***

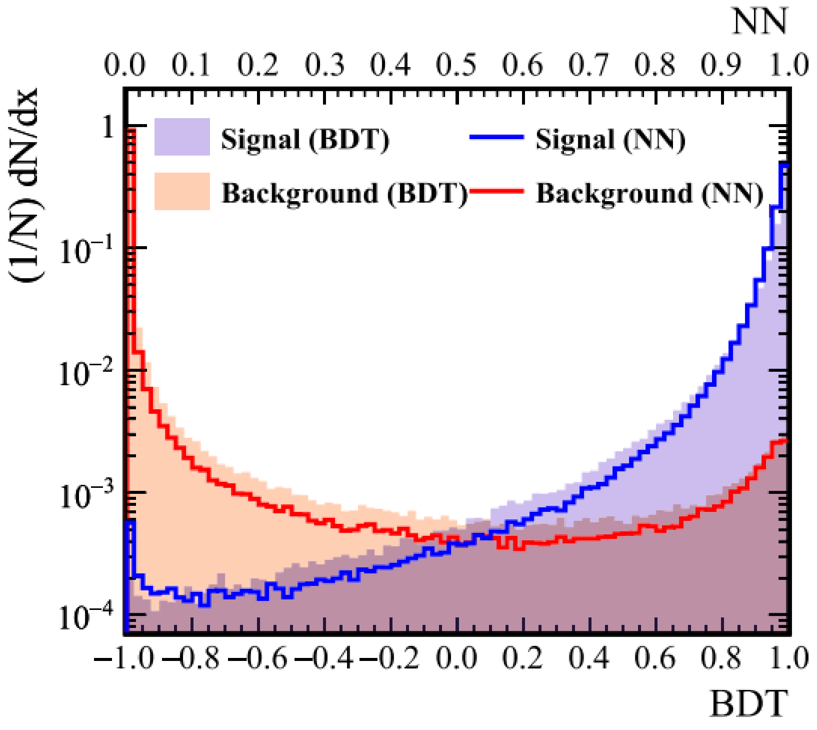


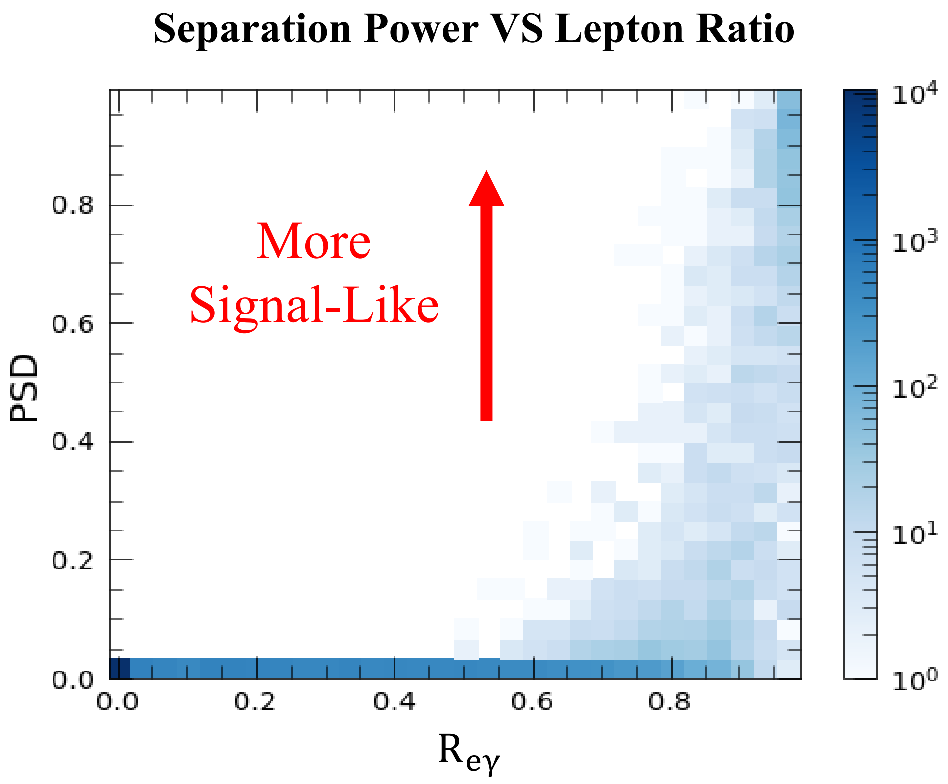
# Physics Interpretations

It is important to understand residual background, define lepton ratio in simulation:

$$R_{e\gamma} = \frac{\sum_{e^\pm,\gamma} E}{E_{total}}$$

Residual backgrounds tend to have large $R_{lepton}$ i.e. some $\gamma s$ generated during the interaction.





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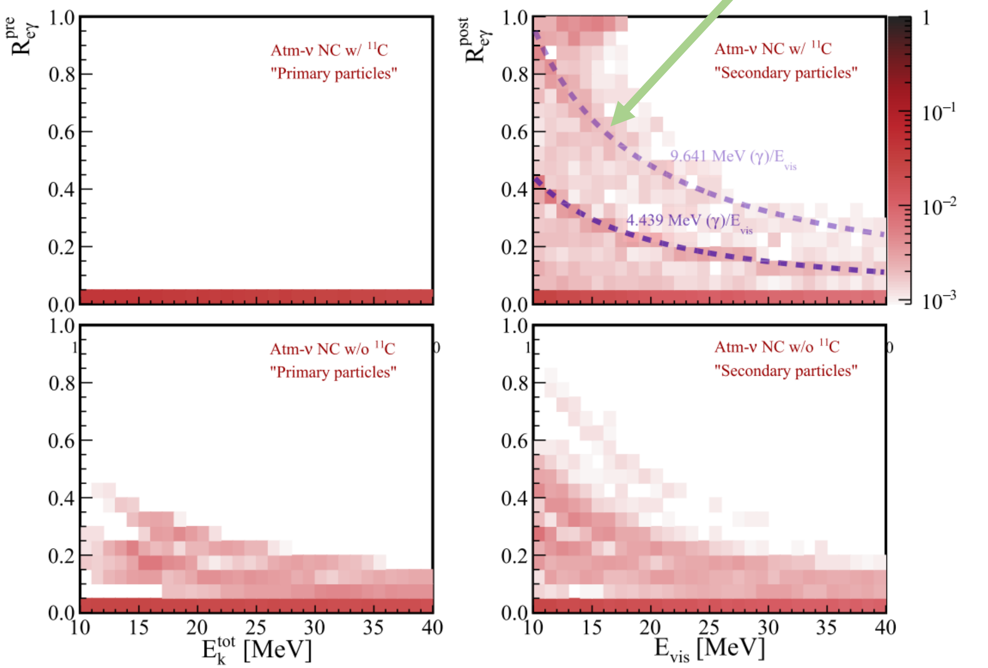
# Physics Interpretations

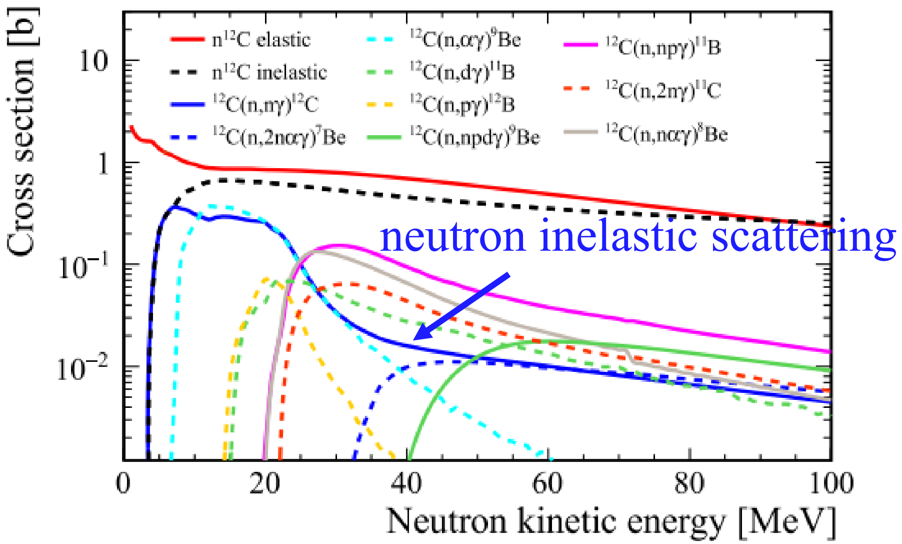
**Residual background mostly results from** **neutron inelastic scattering** in $^{11}$C channel of NC: $\nu_x + {}^{12}C \rightarrow {}^{11}C + n$

- Inelastic scattering generates $\gamma$ causing mixing up neutron background with $e^+$ signal
- Energy-dependent inefficiency origins from energy dependency of cross section.

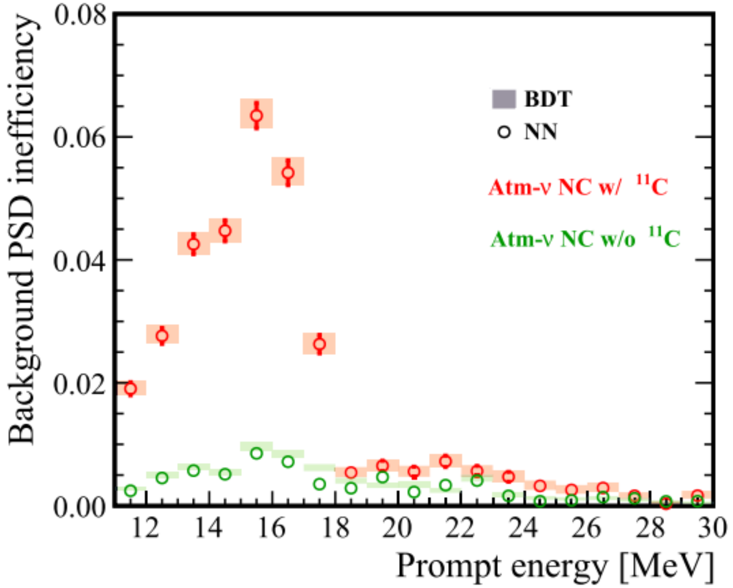
Fast neutrons excite the $^{12}$C causing γ emission with 4.4 MeV and 9.6 MeV




**Cross sections of exclusive $n-{}^{12}C$ reactions from TALAS**




**Energy dependency of NC background inefficiency**



# PSD Uncertainty Evaluation

**To evaluate the PSD systematic uncertainty:**

➢ Control samples

- Neutron sources: Spallation neutron, radioactivity calibration source
- e-/e+: Michael electron

➢ Well-tuned simulation

- Lab measurement input about scintillator properties

# Energy Dependency of Scintillator Time Property

- **For DSNB sensitivity study for JUNO, pulse shapes used for $E_{vis}$=10~30 MeV base on lowed energy sources[1]**

- **Time constants of scintillator could be energy dependent**
  - From previous study, some scintillators show energy dependency on timing property like liquid xenon

**Energy dependency of time constants in liquid xenon**

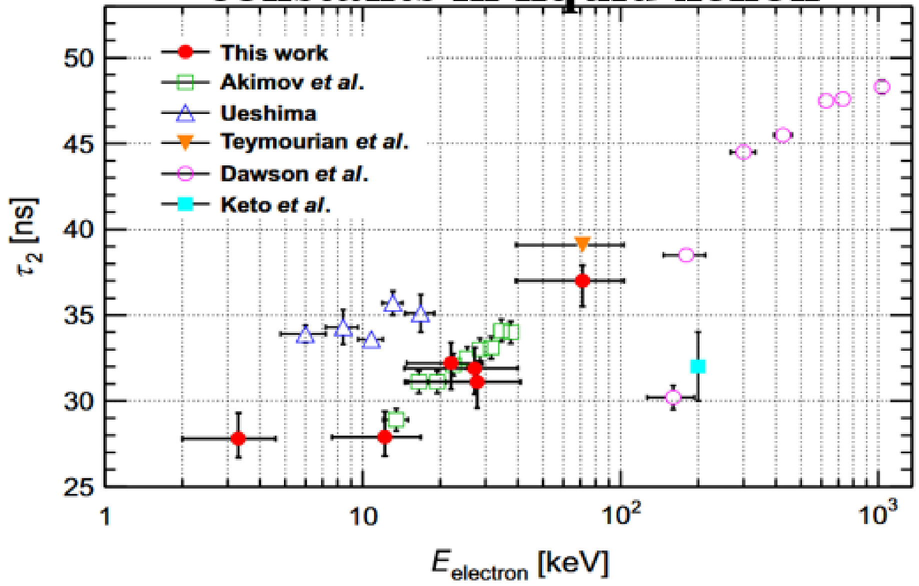



**Fig. 3.** $\tau_2$ as a function of incident electron energy $E_{electron}$. Teymourian et al. [17] used data from 122 keV gamma-ray from $^{57}Co$ so the same error as this work was applied. Dawson et al. [15] and Keto et al. [13] reported $\tau_2$ at higher the energy region $E_{electron}$ > 100 keV. Some Refs. [10,11,18] are not drawn because $E_{electron}$ is unknown.

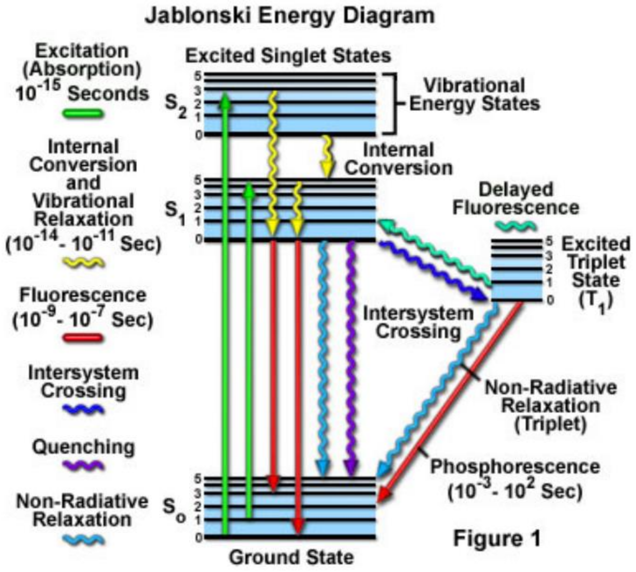
H. Takiya et al. / Nuclear Instruments and Methods in Physics Research A 834 (2016) 192–196

[1] https://zenodo.org/records/4122919

# Energy Dependency of Scintillator Time Property

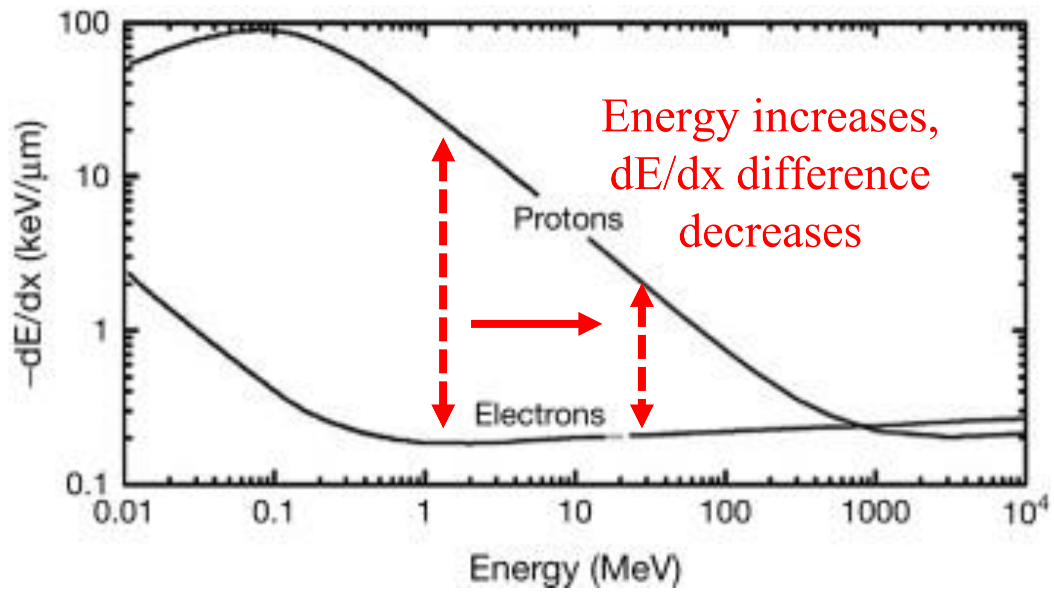
- Fluorescent process correlated to ionization
- Timing property of distinct particles could origin from ionization density(dE/dx) difference.
- **As energy of particles increases,** dE/dx difference decreases

→ **Separation power of timing property could be weaken**




[Fluorescence Excitation and Emission Fundamentals Fluorescence (studylib.net)]

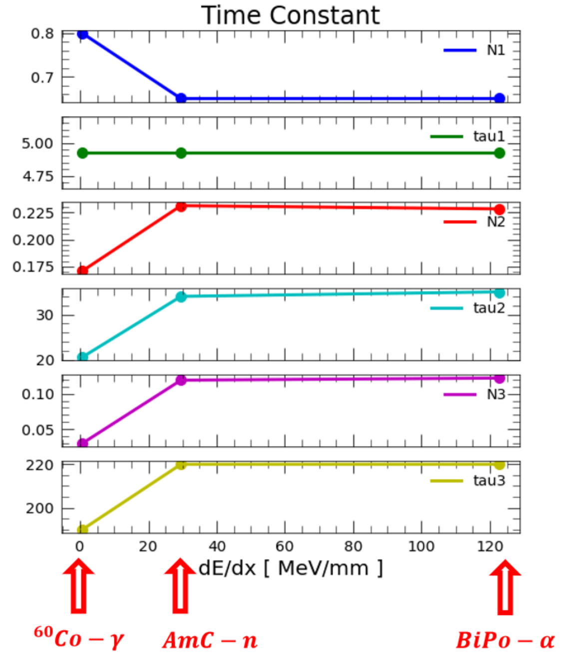
Stopping Power



# How could dE/dx Dependence be like?

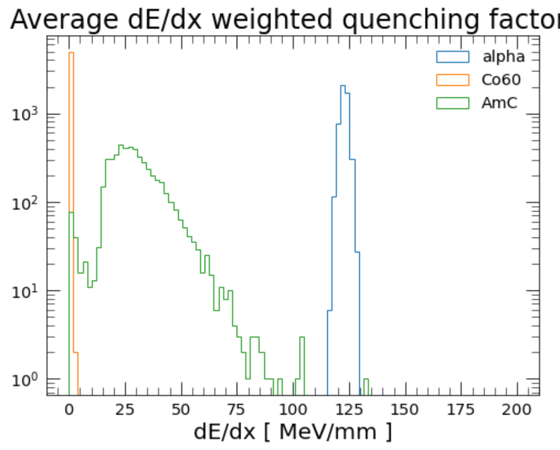
*If LS timing property is dE/dx dependent, how could it be like?*

**The most simple case:**

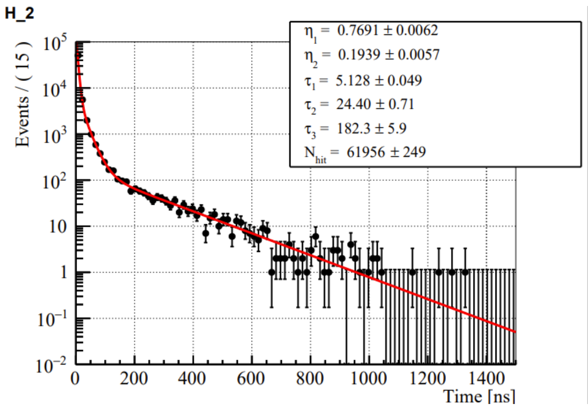



Mark particles with dE/dx

**Get dE/dx with Simulation**




**Parameterize time profile**




$\tau_1, \tau_2, N_1, N_2$ ….

fitting with multi-exponential function

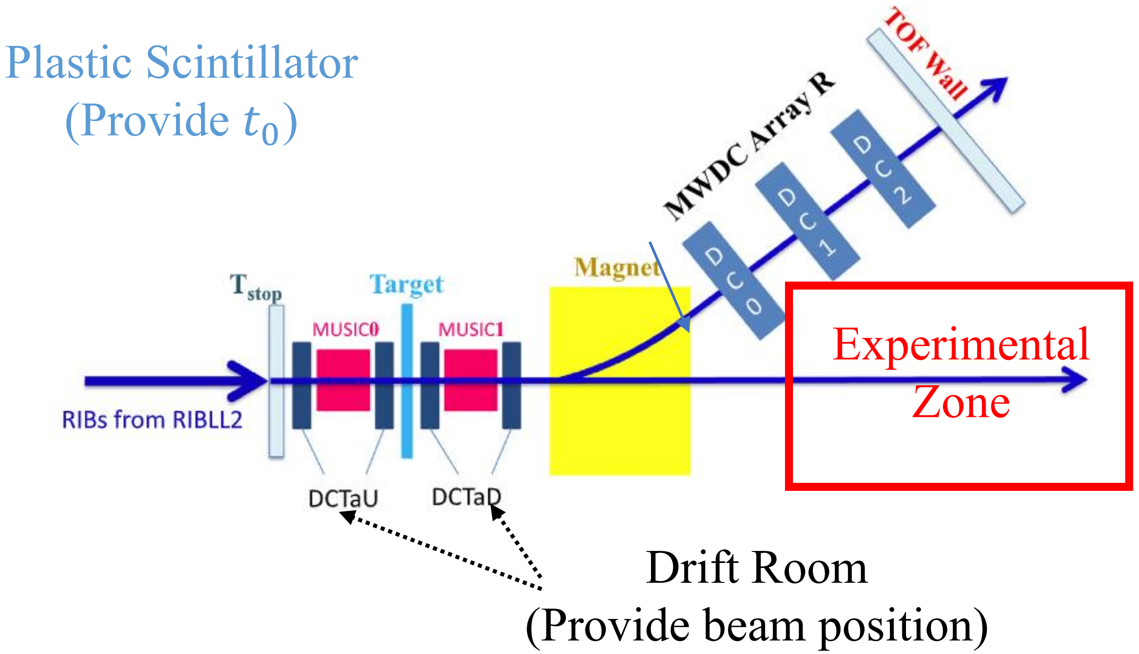
**Previous time constants used in JUNO software**

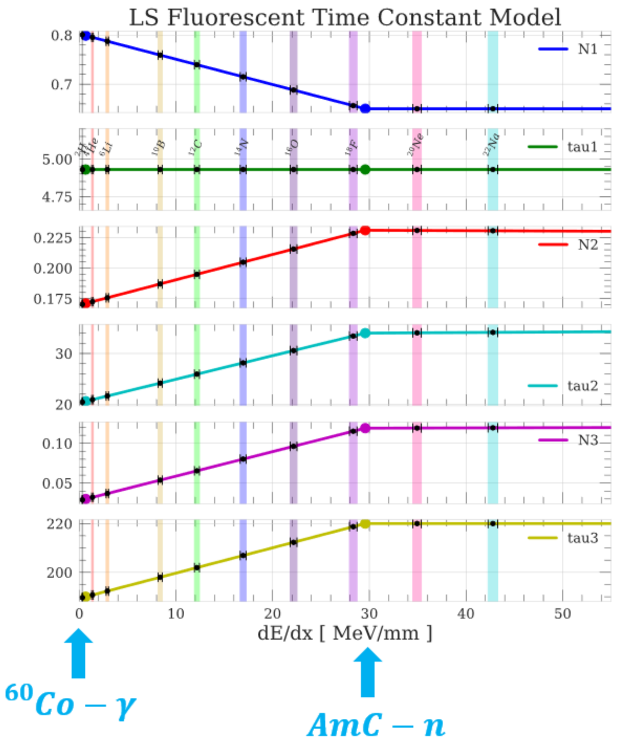
| Particles | $N_1$ [%] | $\tau_1$ [ns] | $N_2$ [%] | $\tau_2$ [ns] | $N_3$ [%] | $\tau_3$ [ns] |
|---|---|---|---|---|---|---|
| $\gamma$, $e^+$, $e^-$ | 79.9 | 4.93 | 17.1 | 20.6 | 3 | 190 |
| $n$, $p$ | 65 | 4.93 | 23.1 | 34 | 11.9 | 220 |
| $\alpha$ | 65 | 4.93 | 22.8 | 35 | 12.2 | 220 |

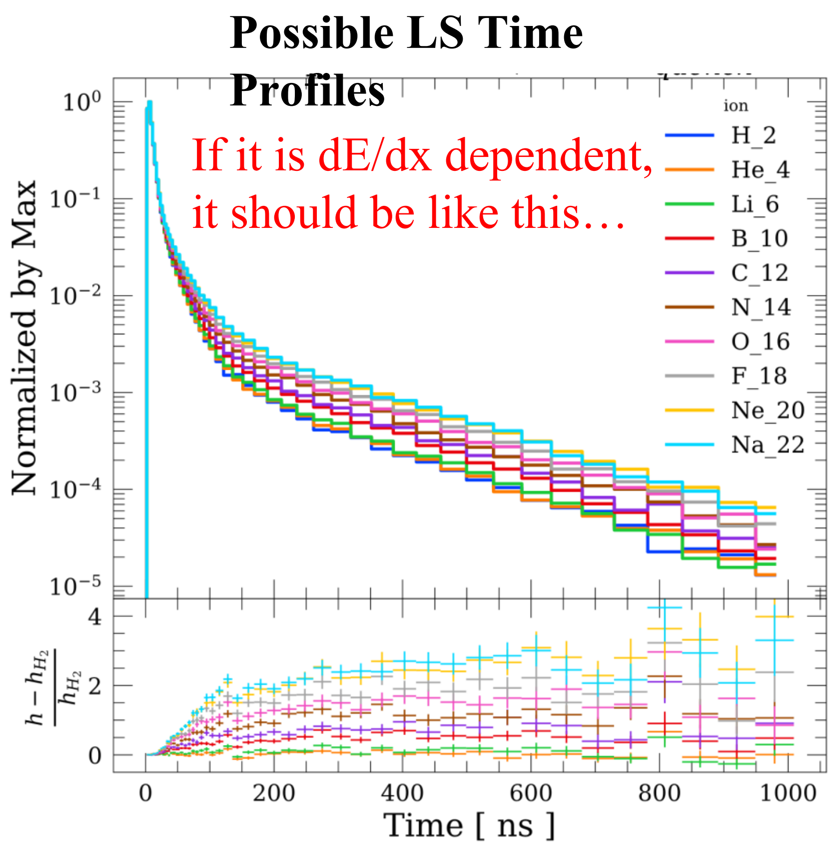
# dE/dx Dependence Measurement

**Measure time profile under various dE/dx**

- Ions beam with Z∈ [1,11] cover dE/dx ~ [0.3, 40] MeV/mm



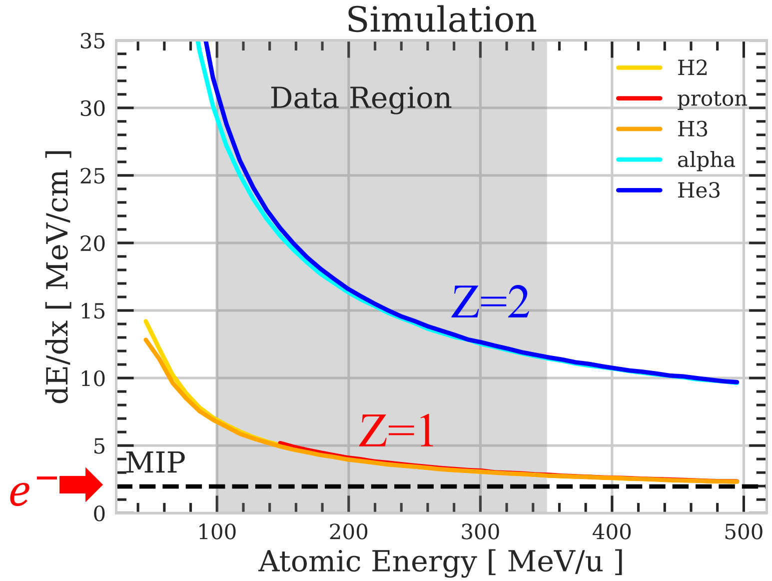



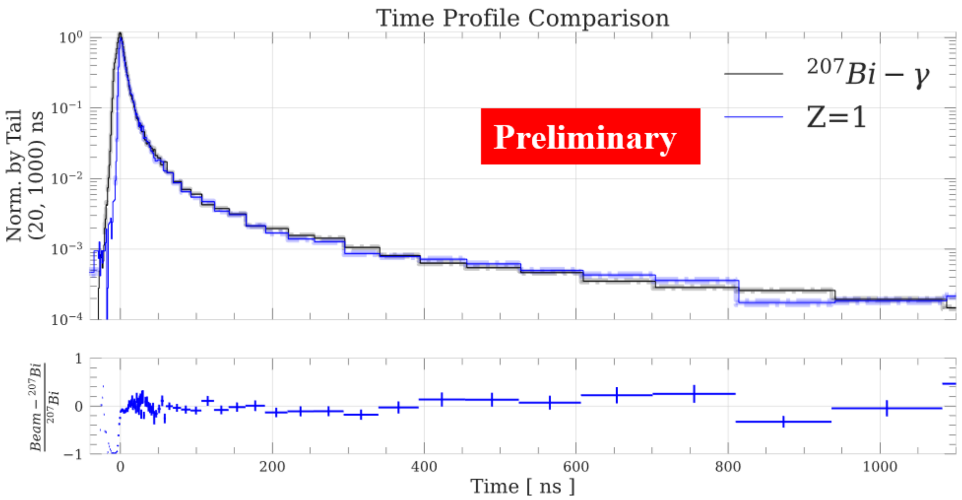

**So far, we are still waiting for the beam**

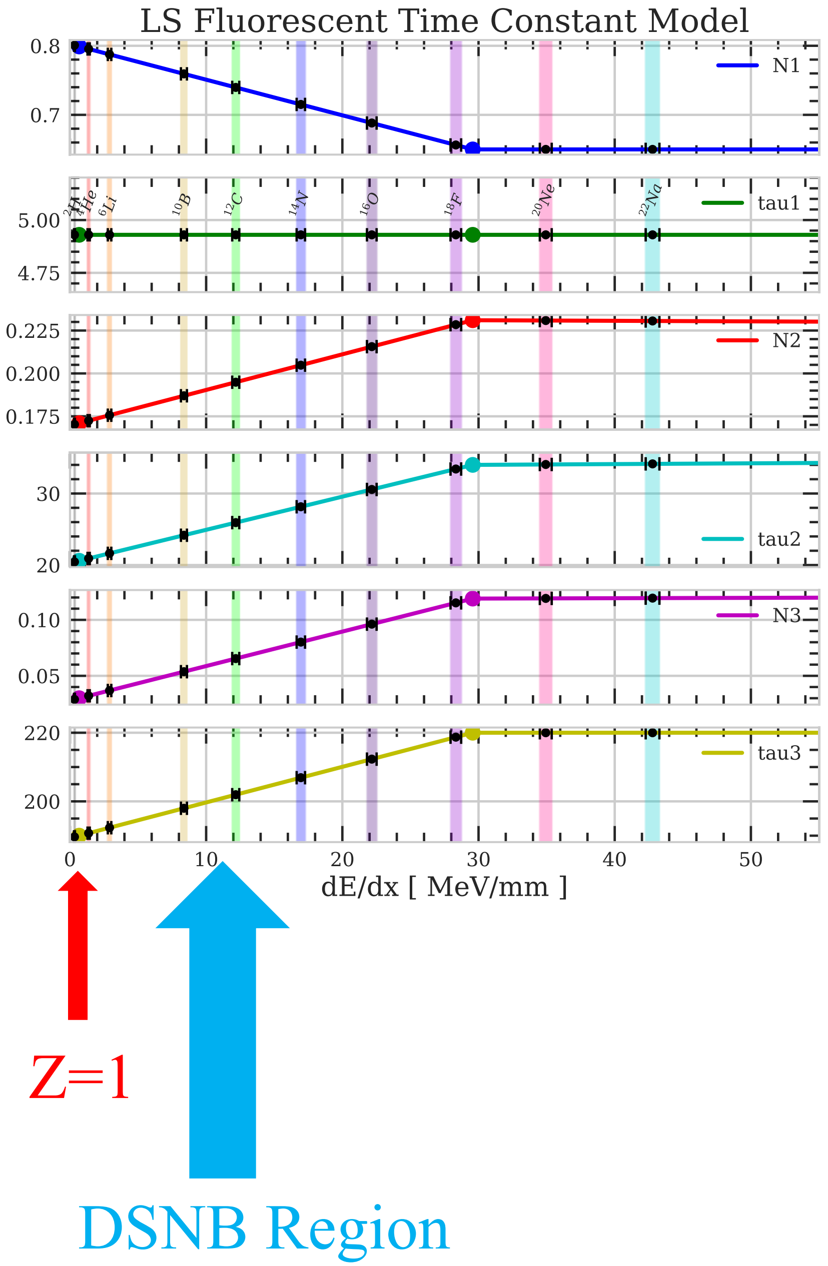
# dE/dx Dependence Measurement

## A hint for dE/dx dependence

- Measured time profile of JUNO under $E_k$ = 100~300 MeV/u isotope of hydrogen (Z=1) with dE/dx is close to e/$\gamma$
- Similar timing property between e/$\gamma$ and high energy hydrogen isotopes



# Energy Dependency of Timing Property

- Related effort in the lab is ongoing in JUNO group
  - Direct measurement on neutron timing property under DSNB energy region
  - Construct dE/dx dependent timing model for liquid scintillator

# Summary

- Pulse Shape Discrimination (PSD) is essential for distinguishing DSNB signal from backgrounds.
- The residual background in DSNB detection in scintillator detectors mainly results from neutron inelastic scattering.
- Timing property of scintillator could be energy dependent which could worse PSD performance, and related measurement is ongoing.

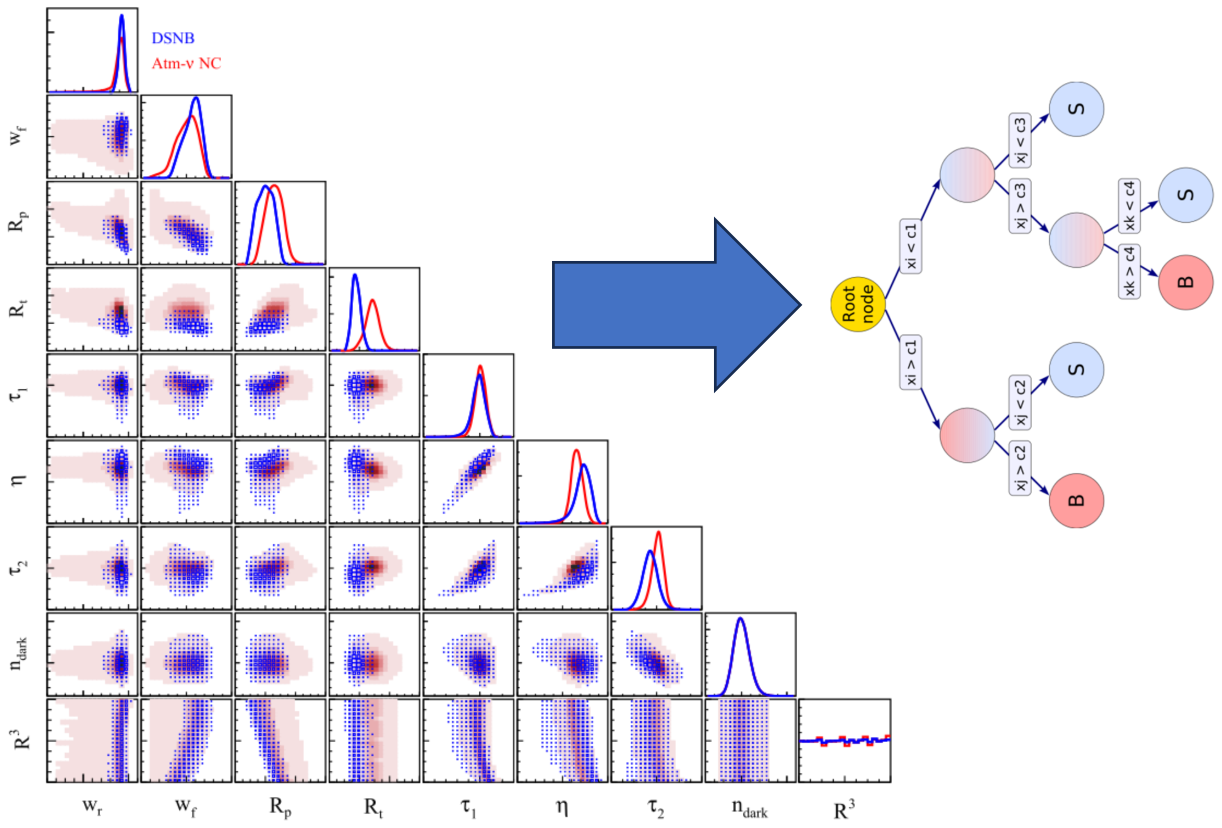
**THANK YOU!**

# Backup

# Boosted Decision Trees for PSD

**Utilize multiple variables to describe the timing shape**

- Utilize correlation between variables to optimize cut
- Combine variables from several methods like TTR to benefit from distinct methods




The LS time profile can be described by **sum of several exponential functions** (Atm-$\nu$ NC: a larger portion of long decayed components)

**Evaluate decayed components by fitting the tail (Time∈[0,800]):**

$$f(t) = N \times \left[\frac{\eta}{\tau_1}\exp\left(-\frac{t}{\tau_1}\right) + \frac{1-\eta}{\tau_2}\exp\left(-\frac{t}{\tau_2}\right)\right] + n_{dark}$$

**Demarcated shape with Integral:**

$$R_{peak} = \frac{\int_{20ns}^{1100ns} F(t)dt}{\int_{0ns}^{1100ns} F(t)\,dt}, \mathrm{R_{tail}} = \frac{\int_{400ns}^{1100ns} F(t)dt}{\int_{0ns}^{1100ns} F(t)\,dt}$$

NC backgrounds (Flatten peak and thick tail) correspond to larger $\mathrm{R_{peak}}$ and $\mathrm{R_{tail}}$

**Evaluate peak width by:**

$$\frac{\int_{-20ns}^{-20ns+W_r} F(t)dt}{\int_{-20ns}^{20ns} F(t)dt} = 0.1 \text{(rising edge)}$$

$$\frac{\int_{20ns-W_f}^{20ns} F(t)dt}{\int_{-20ns}^{20ns} F(t)dt} = 0.1 \text{ (falling edge)}$$

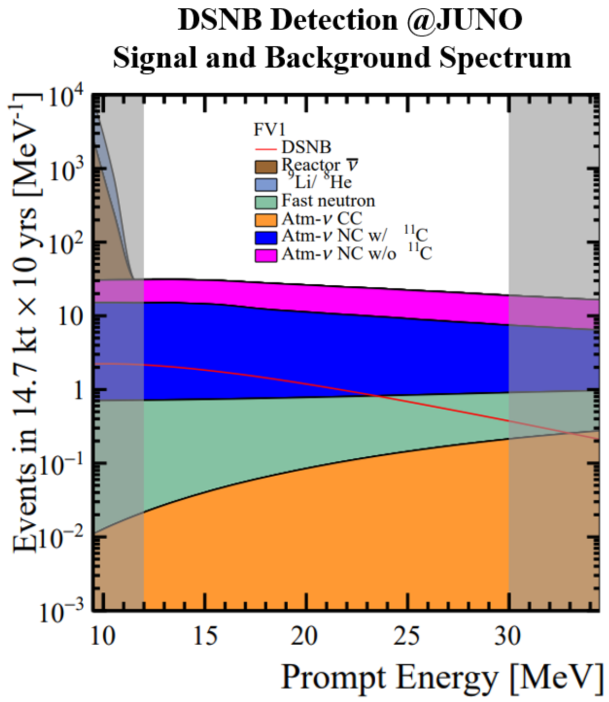
**Vertex $R^3$**
adapt to shape differences caused by event vertex.

| |
|---|
| $\tau_1$ |
| $\tau_2$ |
| $\eta$ |
| $n_{dark}$ |
| $R_{tail}$ |
| $R_{peak}$ |
| $W_r$ |
| $W_f$ |
| $R^3$ |

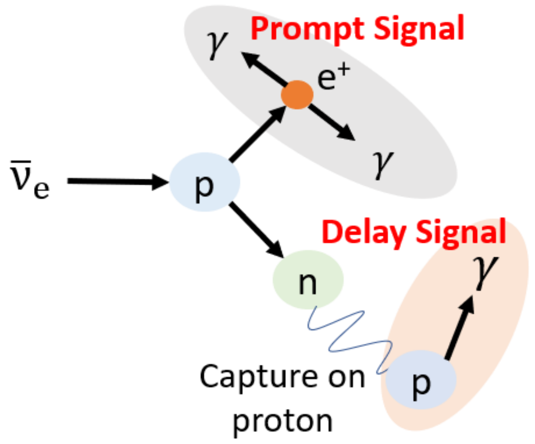
# Prospect for DSNB Detection with JUNO

**Detect $\bar{\nu}_e$ of DSNB**

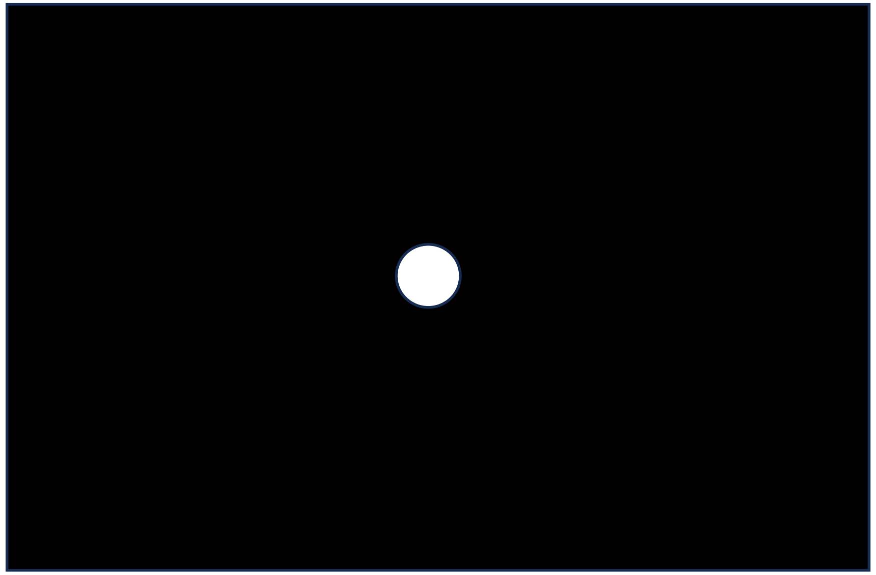
- **Detection channel:** Inverse Beta Decay(IBD)
- **Signal event rate:** 2~4 events per year
- **Backgrounds after prompt-delayed cut:**
  - Atmospheric neutrino
    - Charge current (CC)
    - Neutral current (NC)
  - Cosmic ray related background
    - Fast neutron (FN)
    - $^{9}Li/\ ^{8}He$
  - Reactor neutrino

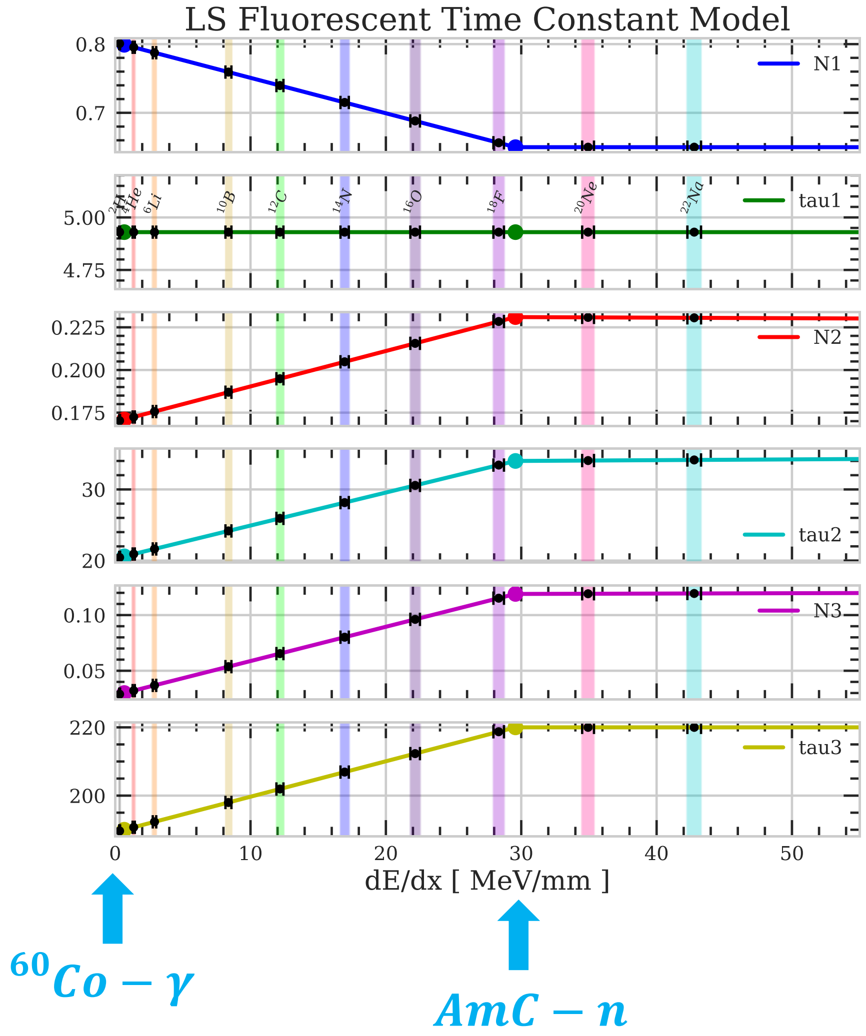



**Prompt-delayed coincident selection**




Despite applying prompt-delayed cut, the DSNB signal remains obscured by backgrounds.
**That is why PSD is important in DSNB detection.**




LS Fluorescent Time Constant Model
N1
tau1
N2
tau2
N3
tau3
dE/dx [ MeV/mm ]
$^{60}Co-\gamma$
$AmC-n$