Nucleon decay searches in JUNO

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On behalf of JUNO Collaboration

CoSSURF 2024

May 15, 2024

CONFERENCE **ON SCIENCE** AT THE

SANFORD UNDERGROUND RESEARCH FACILITY

South Dakota Mines campus, May 14-16, 2024

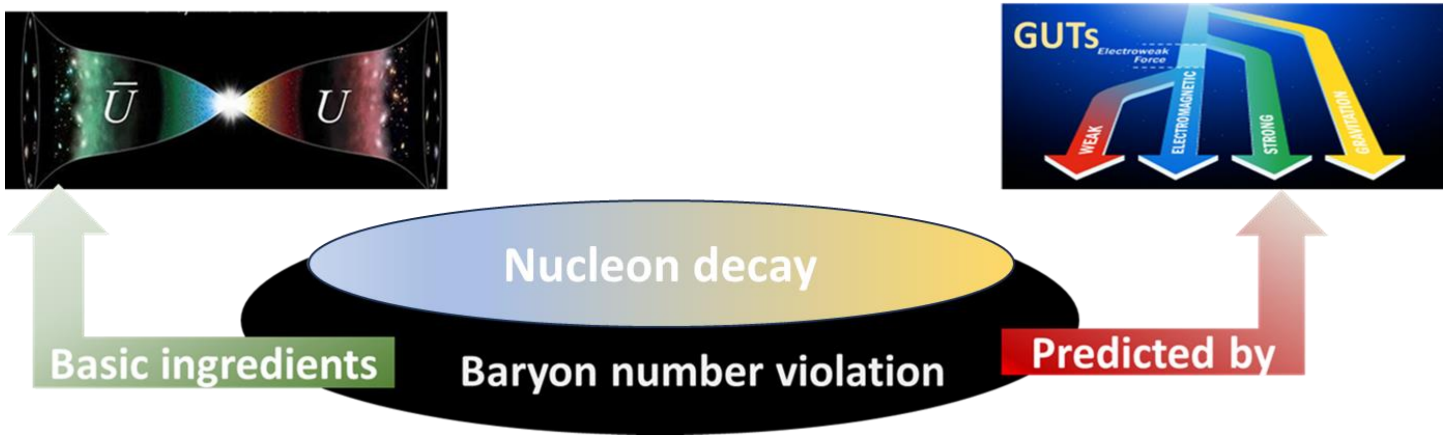
Outline

- Introduction
- JUNO experiment
- Nucleon decay
  - $p \rightarrow \overline{v} + K^{+}$
  - Invisible neutron decay
- Summary

Introduction

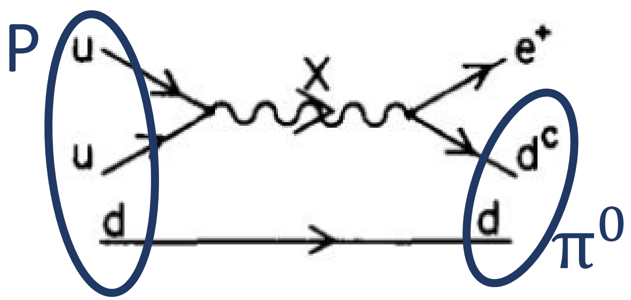
Motivation of nucleon decay

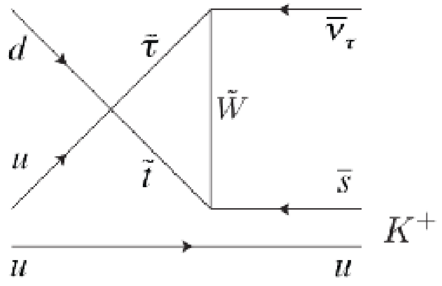
- GUTs unify the strong, weak and electromagnetic interactions
  - Predict the instability of nucleon
    - Search the nucleon decay to test the GUTs
- Matter-antimatter is asymmetric in universe
  - Sakharov conditions(to explain the asymmetry)
    - **Baryon number violation $\Delta B \neq 0$**
    - C and CP violation
    - departure from thermal equilibrium



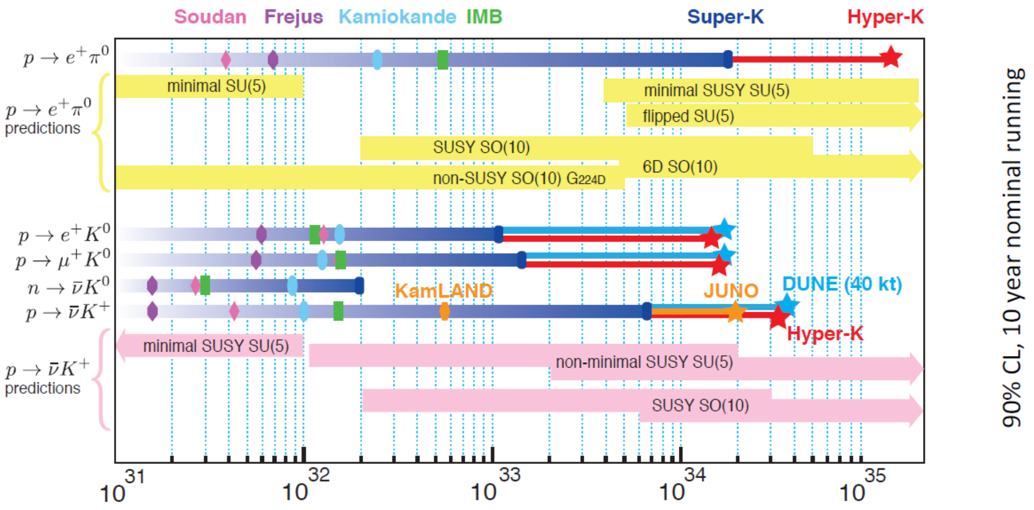
Nucleon decay in theory

- GUTs predict instability of nucleon
  - Protons can decay into lighter subatomic particles(hypothesis)
  - Examples
    - $p \rightarrow e^{+} + \pi^{0}$ **(Non-SUSY GUTs)**
    - $p \rightarrow \overline{\nu} + K^{+}$ **(SUSY GUTs)**





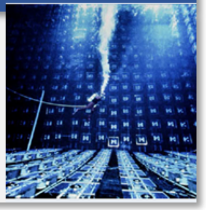
  - Invisible neutron decay: neutron decay into **undetected** particles (hypothesis)
  - Examples
    - $n \rightarrow$ neutrino, $n \rightarrow dark\ fermions$ …
    - Phys. Rev. D 67, 075015 (2003).
    - Phys. Lett. B 662, 259 (2008).
    - Phys. Rev. D 98, 035049 (2018).



DUNE: 2002.03005

Current searches for proton decay

IMB

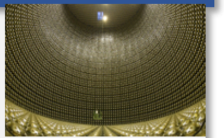


- 3.3 kton water-Cherenkov detector, 2000 PMTs
- $\tau/B(p \to e^+ \pi^0)$> $5.5 \times 10^{32} years$ (1990)
- No proton decay have been found

KamiokaNDE

- 0.88 kton water-Cherenkov detector, 948 PMTs
- $\tau/B(p \to e^+ \pi^0)$> $2.6 \times 10^{32} years$ (1989)
- No proton decay have been found

Super-Kamiokande (Super-K)

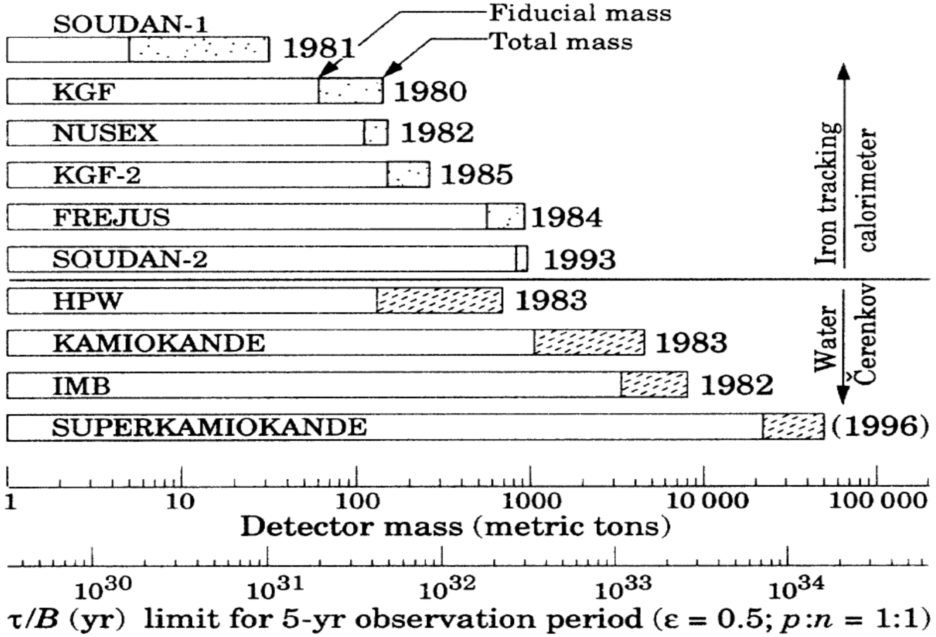


- 22.5 kton water-Cherenkov detector, 11146 PMTs
- $\tau/B(p \to e^+ \pi^0)$> $2.4 \times 10^{34} years$ (2020)
- $\tau/B(p \to \bar{\nu} K^+)$> $5.9 \times 10^{33} years$ (2014)
- No proton decay have been found

KamLAND

- 0.9 kton liquid scintillator detector
- $\tau/B(p \to \bar{\nu} K^+)$> $5.4 \times 10^{32} years$ (2015)
- No proton decay have been found

Past searches



Current searches for invisible neutron decay

KamLAND

- 0.9 kton liquid scintillator detector
- $\tau/B(n \rightarrow inv)$> $5.8 \times 10^{29} years$ (2006)
- $\tau/B(nn \rightarrow inv)$> $1.4 \times 10^{30} years$ (2006)
- No invisible neutron decay have been found

SNO+

- 0.9 kton liquid scintillator detcor
- $\tau/B(n \rightarrow inv)$> $9.0 \times 10^{29} years$ (2022)
- $\tau/B(nn \rightarrow inv)$> $1.5 \times 10^{28} years$ (2022)
- No invisible neutron decay have been found

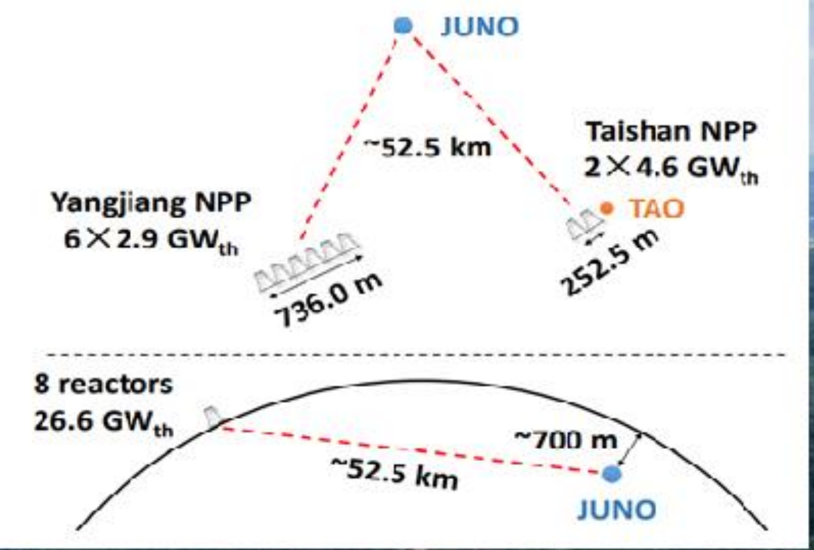
Future Nucleon Decay Experiments

Hyper-K | **DUNE** | **JUNO**

	Hyper-K	DUNE	JUNO
Mass (kton)	258 (186)	4*17 (4*10)	20
Target Nucleus	H2O	Ar40	12% H, 88% C12
Technology	Water Cherenkov	LAr TPC	Liquid Scintillator
Advantages	Large mass and cheap Good particle Identification Good direction resolution	Excellent track reconstruction Excellent particle Identification Good energy resolution	Excellent energy resolution 3% Excellent *E* threshold 0.7MeV
Shortcomings	Cerenkov threshold	Complex FSI for Ar40	Direction information lost

JUNO experiment

JUNO experiment overview

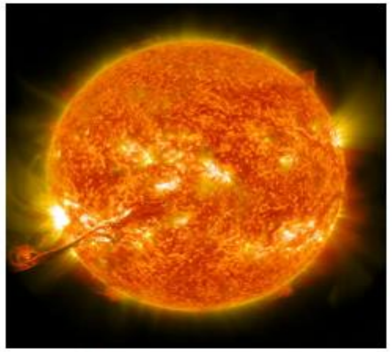


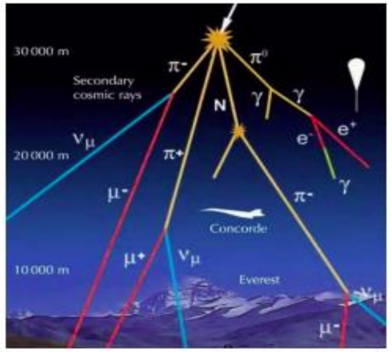
	JUNO
Photon Statistics	1200 p.e./MeV
PMT coverage	75%
LS transparency	> 20 m
Light yield(anthracene)	45%
Detection Eff.(QE×CE)	30%

JUNO experiment overview

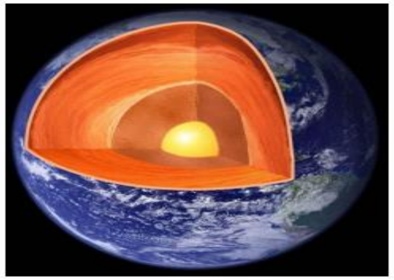
➢ **Jiangmen Underground Neutrino Observatory (JUNO)**, a **multi-purpose** neutrino experiment

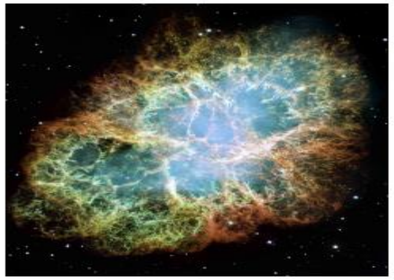

$\sim$ 50/day


$\mathcal{O}(1000)$/day

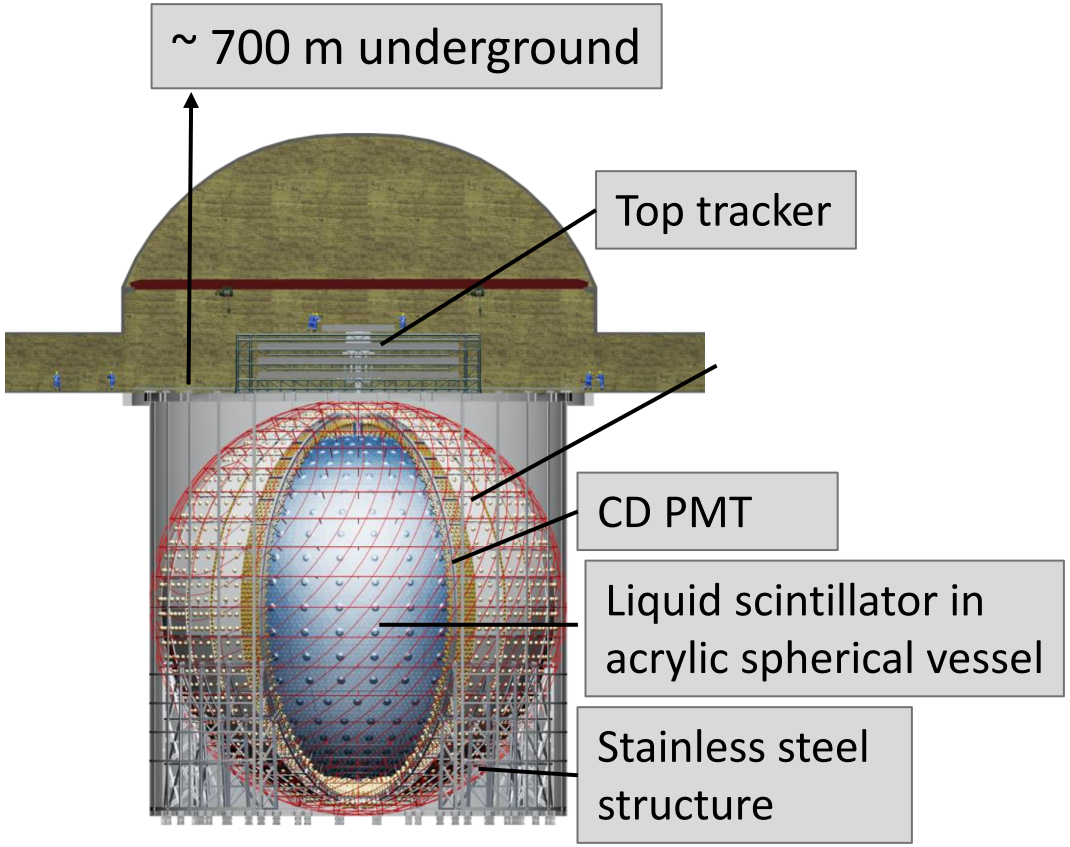


$\sim$ 10 - 20/day


$\sim$ 1 - 2/day


CCSN @10kpc : $\mathcal{O}(1000)$/s
DSNB: few/year

New Physics (Nucleon decay…)



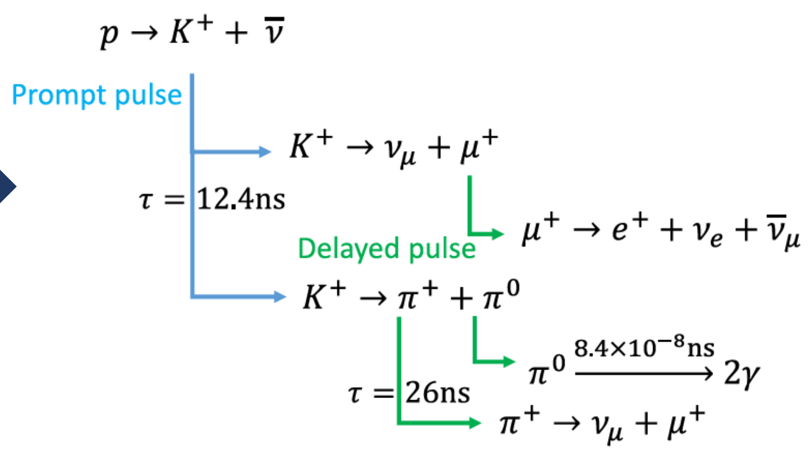
Nucleon decay: $p \rightarrow \overline{v} + K^{+}$

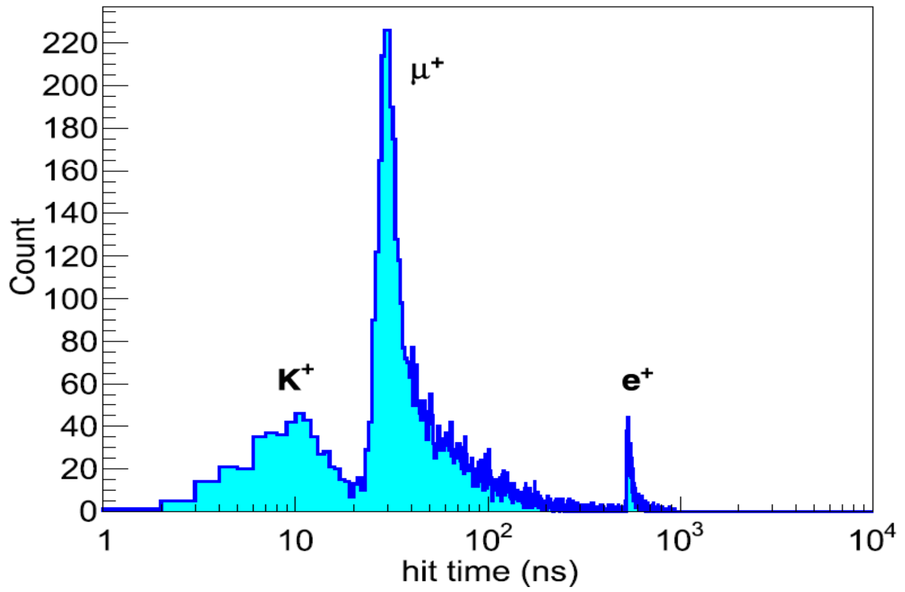
Signal characteristics of $p \to \overline{\nu} + K^+$

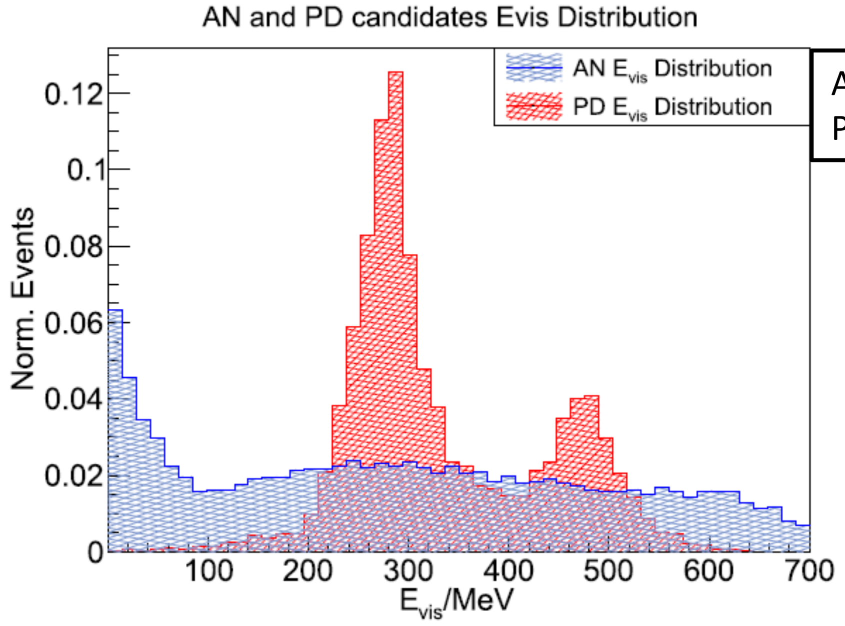
- Form triple coincident signals

Decay mode	Branching ratio (%)	Kinetic energy sum (MeV)
$K^+ \to \mu^+ \nu_\mu$	63.55 ± 0.11	152
$K^+ \to \pi^+ \pi^0$	20.66 ± 0.08	354
$K^+ \to \pi^+ \pi^+ \pi^-$	5.59 ± 0.04	75
$K^+ \to \pi^0 e^+ \nu_e$	5.07 ± 0.04	265–493
$K^+ \to \pi^0 \mu^+ \nu_\mu$	3.353 ± 0.034	200–388
$K^+ \to \pi^+ \pi^0 \pi^0$	1.761 ± 0.022	354

Two most dominant channels



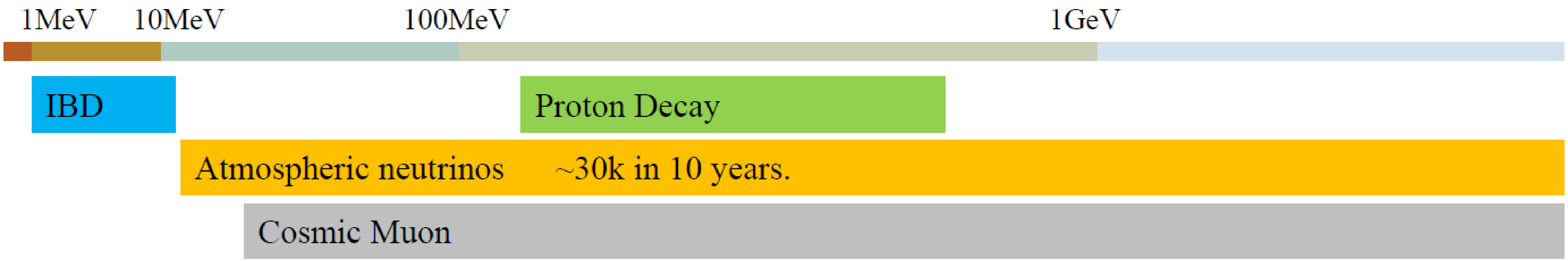




AN: Atmospheric neutrinos
PD: Proton decay

Backgrounds

➢Most dominant background: Atmospheric neutrinos



Type	Ratio (%)	Ratio with E_{vis} in [100 MeV, 600 MeV](%)	Interaction	Signal characteristics
NCES	20.2	15.8	$\nu + n \rightarrow \nu + n$ $\nu + p \rightarrow \nu + p$	Single Pulse
CCQE	45.2	64.2	$\bar{\nu}_l + p \rightarrow n + l^+$ $\nu_l + n \rightarrow p + l^-$	Single Pulse
Pion Production	33.5	19.8	$\nu_l + p \rightarrow l^- + p + \pi^+$ $\nu + p \rightarrow \nu + n + \pi^+$	Approximate Single Pulse (Second pulse too low)
Kaon Production	1.1	0.2	$\nu_l + n \rightarrow l^- + \Lambda + K^+$ $\nu_l + p \rightarrow l^- + p + K^+$	Double Pulse

Low energy background

- Removed by energy cut
  - IBD, solar-υ, geo-υ, and low energy atm-υ

Cosmic Muon

- Removed by muon veto and FV cut

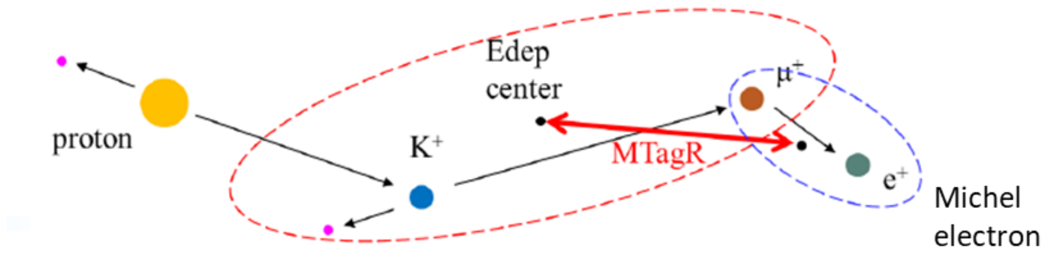
Event selection

➢Selection flow

Basic selection
- 200 MeV < E_{vis} < 600 MeV
- R_v < 17.5 m

Delayed signal selection
- $\Delta L_M < 0.8$ m
- $N_M = 1$
  - $N_n = 0$
  - $R_\chi > 1.1$
- $N_M = 1$
  - $1 \le N_n \le 3$
  - $\Delta L_n < 0.7$m
  - $R_\chi > 2$
- $N_M = 2$
  - $R_\chi > 1$

Time character selection
- $\Delta T > 7$ns
- 30 MeV < E_1 < 200 MeV
- 100 MeV < E_2 < 410 MeV



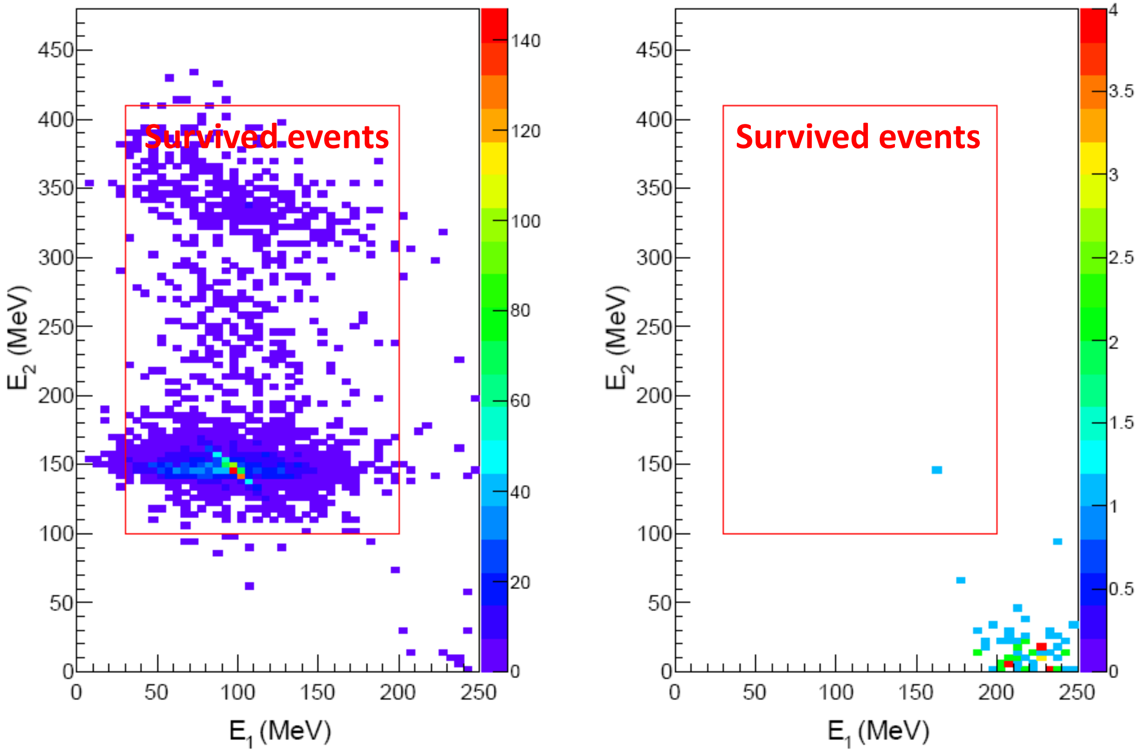
Prompt Edep Center to Michel birth place.

Selection result

Criteria		Survival rate of $p \to \bar{\nu}K^+$ (%) Sample 1	Sample 2	Sample 3	Survival count (fraction) of atmospheric ν Sample 1	Sample 2	Sample 3
basic selection	E_{vis}	94.6			51299 (32.1%)		
	R_V	93.7			47849 (29.9%)		
Delayed signal selection	N_M	74.4		4.4	20739 (13.0%)		1143 (0.7%)
	ΔL_M	67.0		4.4	13796 (8.6%)		994 (0.6%)
	N_n	48.4	17.9	–	5403 (3.4%)	6857 (4.3%)	–
	ΔL_n	–	16.6	–	–	4472 (2.8%)	–
Time character selection	R_χ	45.9	9.0	3.8	4326 (2.7%)	581 (0.4%)	716 (0.4%)
	ΔT	28.3	7.7	2.4	121 (0.07%)	18 (0.01%)	30 (0.02%)
	E_1, E_2	27.4	7.3	2.2	1 (0.0006%)	0	0
Total		36.9			1		

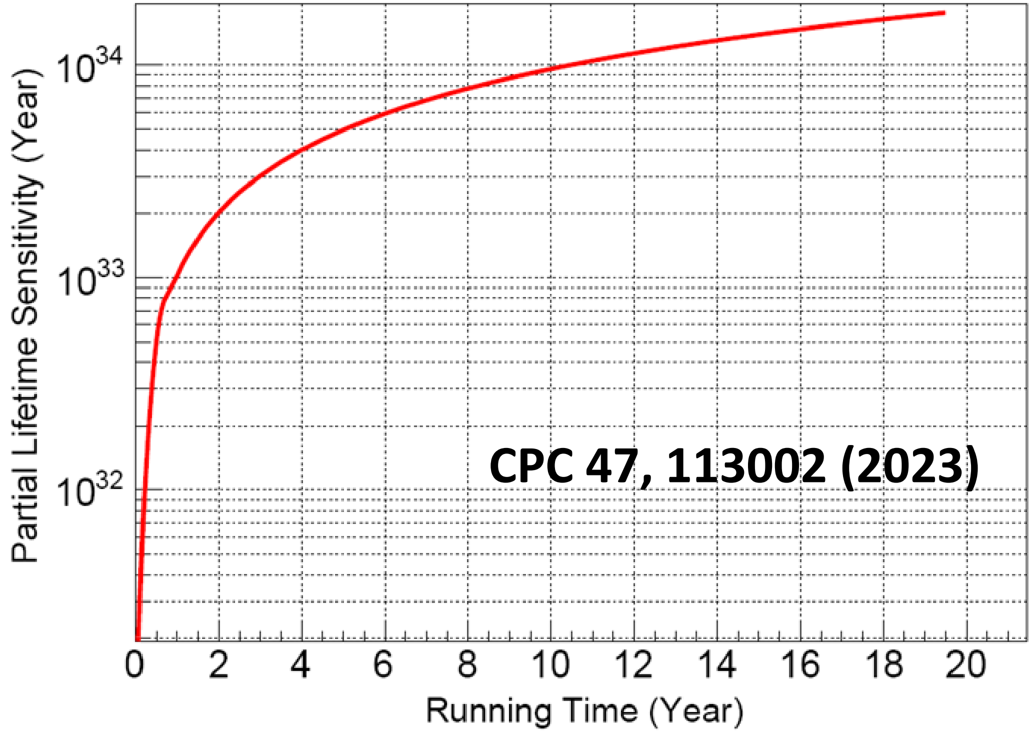
- R_v: Fiducial volume
- N_M: tagged Michel electron number
- ΔL_M: correlated distance to Michel electron
- N_n: tagged neutron number
- ΔL_n: correlated distance to neutron
- R_χ: χ^2 ratio

Sensitivity to $p \rightarrow \overline{\nu} + K^{+}$



(a) $p \rightarrow \bar{\nu}K^{+}$ (b) atmospheric ν

Background: 0.2/10 yrs
Signal efficiency : 36.9%



$\tau/B(p \rightarrow \overline{\nu}\, K^{+}) > 9.6 \times 10^{33}$ yrs/10 yrs

Best limit: 5.9×10^{33} **yrs from Super-K**

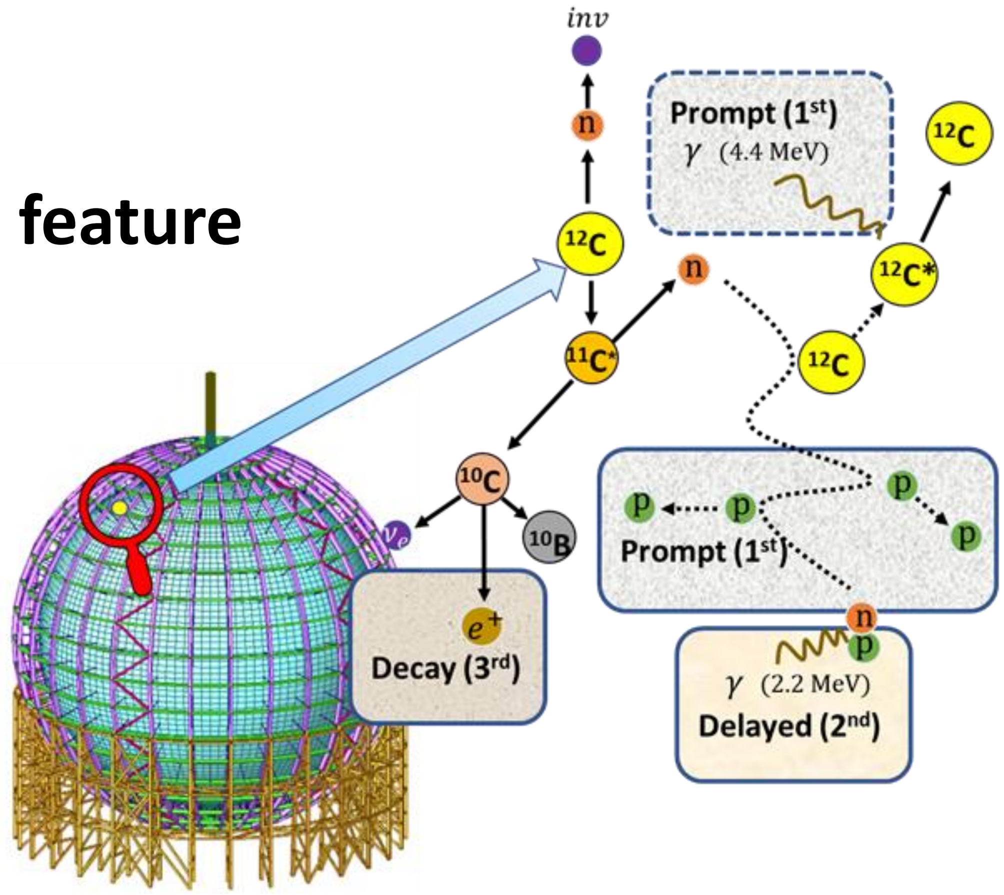
Nucleon decay: invisible neutron decay

Signal characteristic of invisible neutron decay

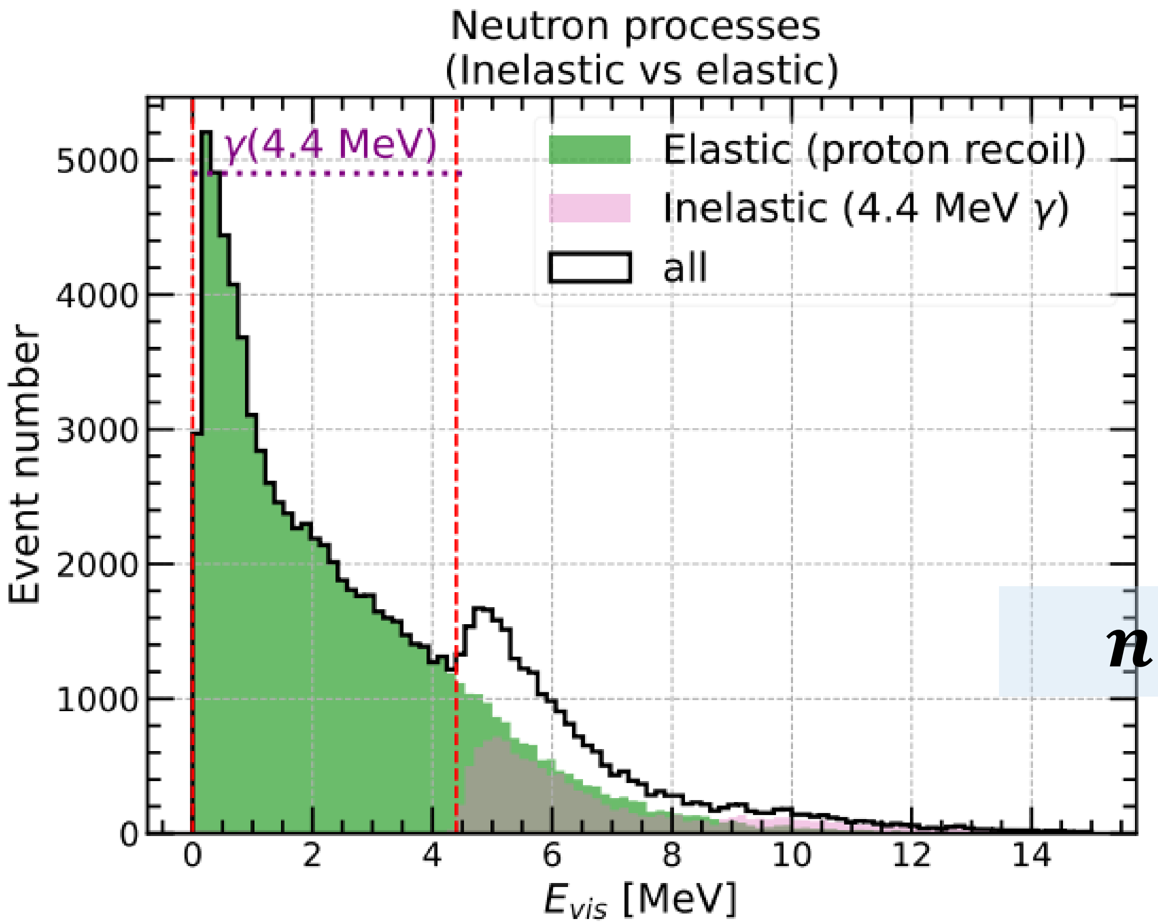
- Bounded neutrons in ^{12}C : two invisible decay modes
  - $n \to inv$ ($^{12}C \to {}^{11}C^{*}$)
  - $nn \to inv$ ($^{12}C \to {}^{10}C^{*}$)
- De-excitation modes have **triple coincidence feature**

$$^{11}C^{*} \to n + {}^{10}C \quad (Br_{n1} = 3.0\%)$$
$$^{11}C^{*} \to n + \gamma + {}^{10}C \quad (Br_{n2} = 2.8\%)$$
$$^{10}C^{*} \to n + {}^{9}C \quad (Br_{nn1} = 6.2\%)$$
$$^{10}C^{*} \to n + p + {}^{8}B \quad (Br_{nn2} = 6.0\%)$$

Yuri Kamyshkov, Edwin Kolbe PRD 67, 076007 (2003)

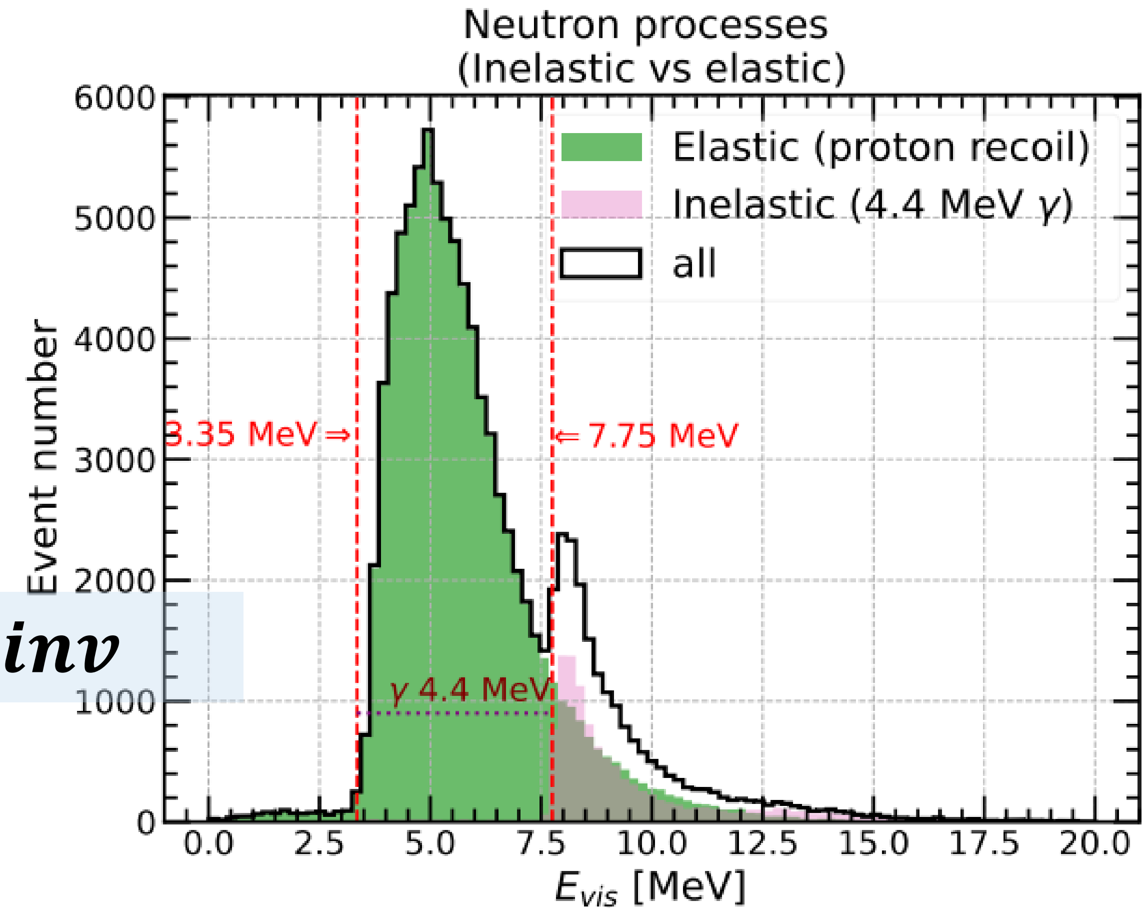


Signal characteristic of signal prompt energy



$^{11}C^{*} \rightarrow n + {}^{10}C$

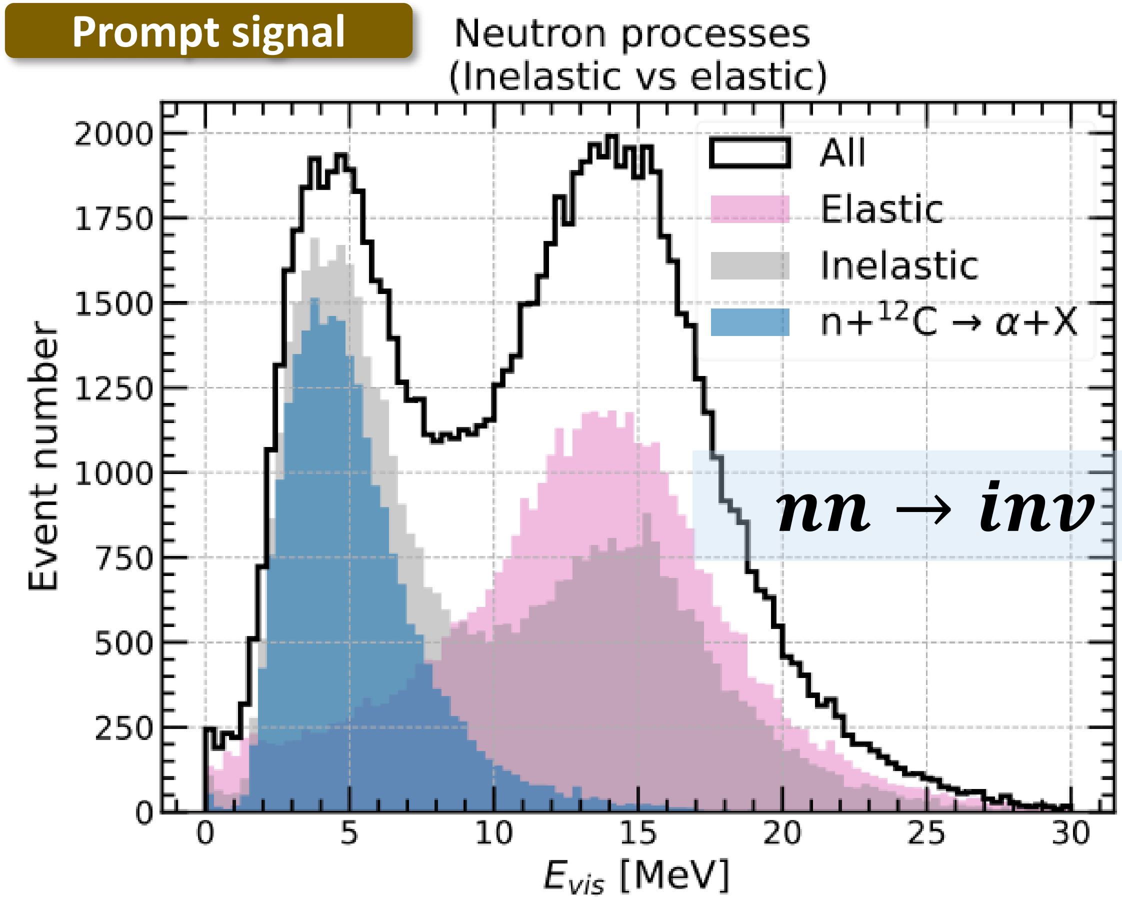
$$n \rightarrow inv$$



$^{11}C^{*} \rightarrow n + \gamma + {}^{10}C$

Signal characteristic of signal energy

Prompt signal

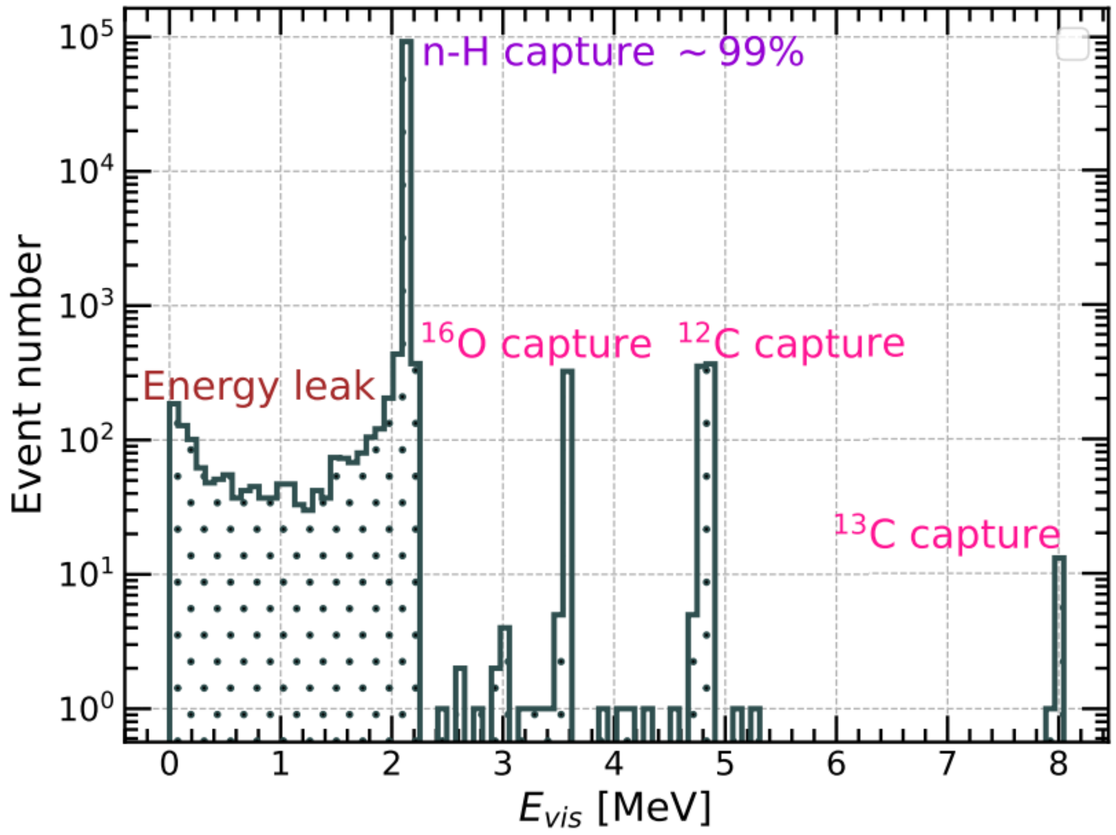


$nn \rightarrow inv$

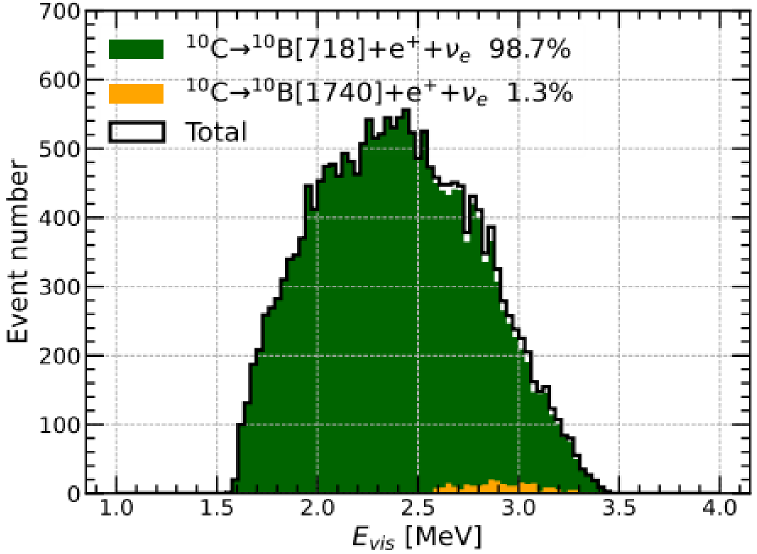
$^{10}\mathbf{C}^{*} \rightarrow n + {}^{9}\mathbf{C}$

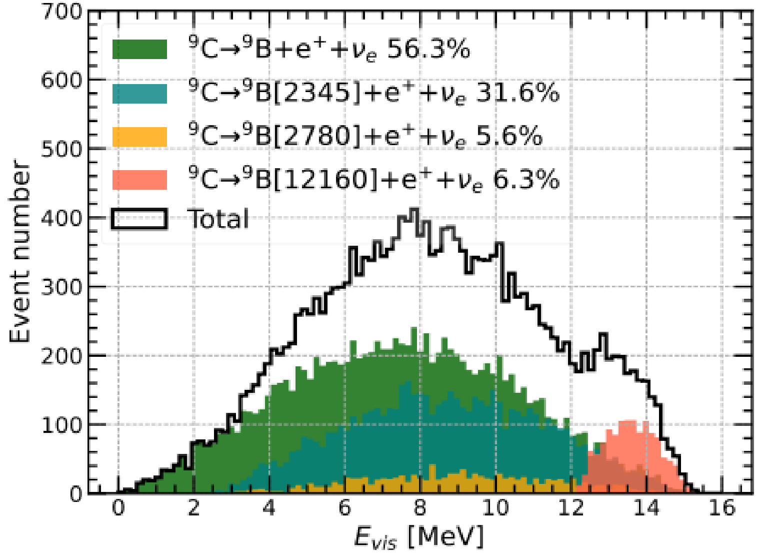
$^{10}\mathbf{C}^{*} \rightarrow n + p + {}^{8}B$ is similar

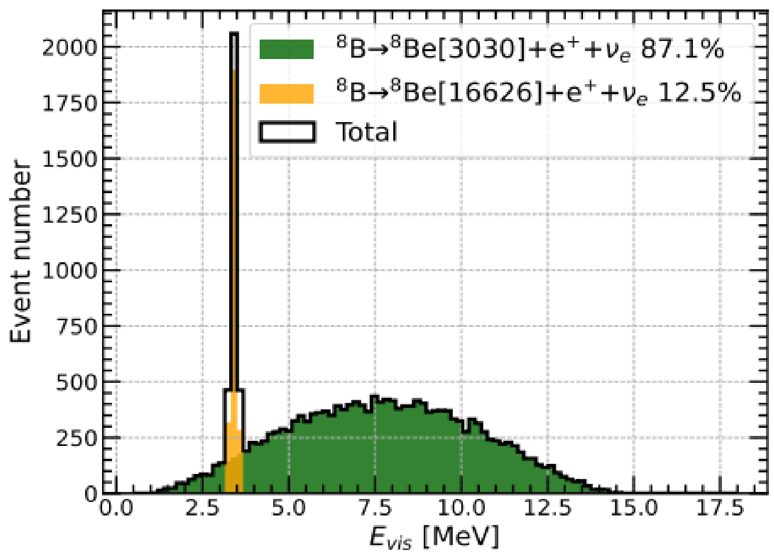
Delayed signal



Signal characteristic of signal decay energy







$n \to inv$

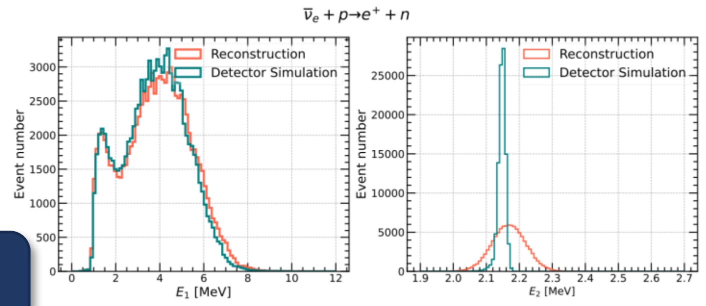
$nn \to inv$

Backgrounds

- ➢Six background **sources**
- ➢**Single**
  - Radioactivity
  - Long-lived isotopes
- ➢**Correlated (Prompt-Delayed)**
  - IBD (Inverse Beta decay)
  - Atm – ν NC (atmospheric neutrino neutral current)
  - Long-lived isotopes (Li9/He8) from cosmic muons
  - Fast neutron
  - Alpha-n
- ➢Triple (Prompt-Delayed-Decay)
  - Atm – ν NC

- **Single + Single + Single**
- **Correlated + Single**

Combination



Atm – ν NC (correlated):

$$\nu/\bar{\nu} + {}^{12}\mathrm{C} \to \nu/\bar{\nu} + n + p + {}^{10}\mathrm{B}\,,$$
$$\nu/\bar{\nu} + {}^{12}\mathrm{C} \to \nu/\bar{\nu} + n + p + \alpha + {}^{6}\mathrm{Li}\,,$$
$$\nu/\bar{\nu} + {}^{12}\mathrm{C} \to \nu/\bar{\nu} + n + 2p + {}^{9}\mathrm{Be}\,,$$
$$\nu/\bar{\nu} + {}^{12}\mathrm{C} \to \nu/\bar{\nu} + n + p + d + {}^{8}\mathrm{Be}\,.$$

Atm – ν NC (triple):

$$\nu/\bar{\nu} + {}^{12}\mathrm{C} \to \nu/\bar{\nu} + n + {}^{11}\mathrm{C}\,,$$
$$\nu/\bar{\nu} + {}^{12}\mathrm{C} \to \nu/\bar{\nu} + 2n + {}^{10}\mathrm{C}\,,$$
$$\nu/\bar{\nu} + {}^{12}\mathrm{C} \to \nu/\bar{\nu} + 3p + n + {}^{8}\mathrm{Li}$$

Event selection

➢ Consider **10 years** data taking

- Signal rate
  - from the final sensitivity result

Selection criteria

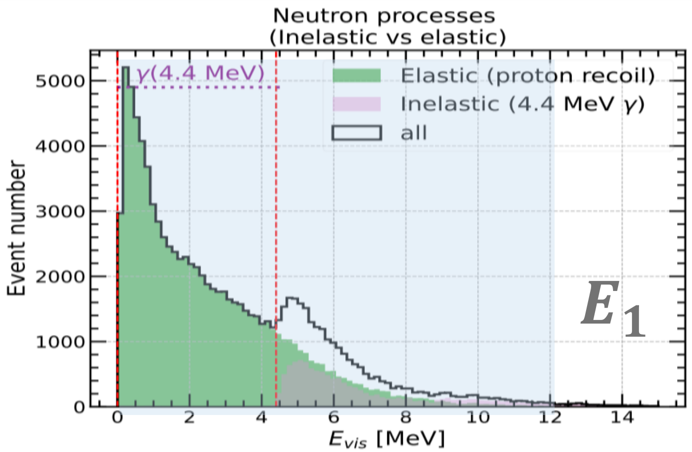
Quantity	$n \to inv$	$nn \to inv$
$R_{1,2,3}$ [m]	< 16.7	< 16.7
E_1 [MeV]	0.7-12	0.7-30
E_2 [MeV]	1.9-2.5	1.9-2.5
E_3 [MeV]	1.5-3.5	3.0-16.0
ΔT_{12} [ms]	< 1	< 1
ΔT_{23} [s]	0.002-100	0.002-3.0
ΔR_{12} [m]	< 1.5	< 1.5
ΔR_{23} [m]	< 1.5	< 1.5
ΔR_{13} [m]	< 1.0	< 1.0

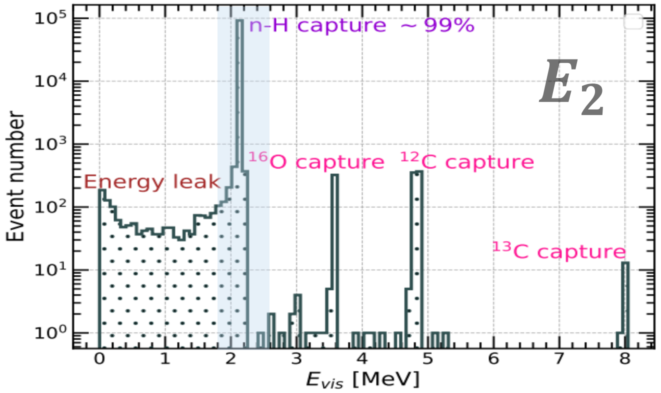
$i = 1, 2, 3$ represents the Prompt, Delayed, Decay signal

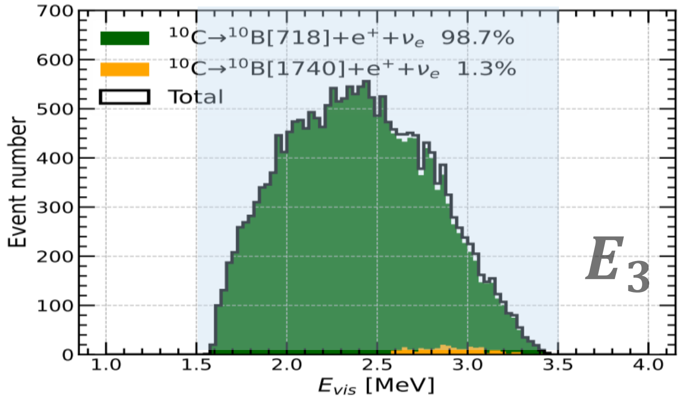
Notations of the interested parameters

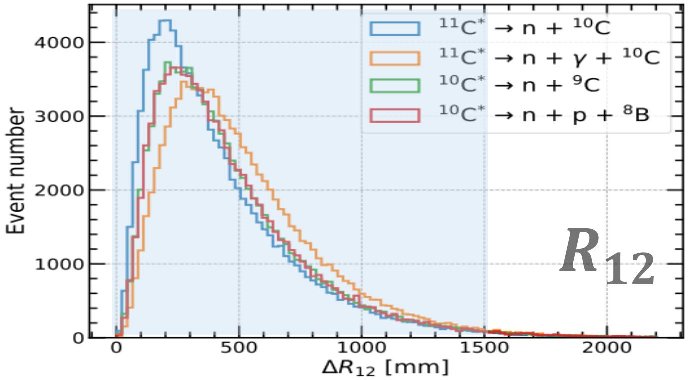
E_i $(i = 1, 2, 3)$: Reconstruct energy
R_i $(i = 1, 2, 3)$: Radial position
$\Delta R_{ij}(i, j = 1, 2, 3, i < j)$: Distance between signal pair (i^{th}, j^{th})
$\Delta T_{ij}(i, j = 1, 2, 3, i < j)$: Time interval between signal pair (i^{th}, j^{th})

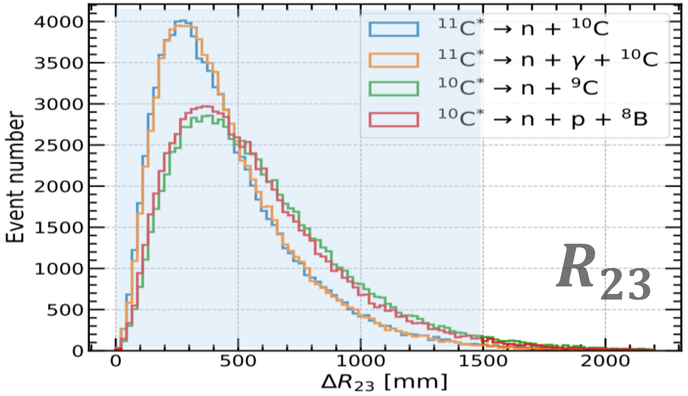
Signal characteristic of ($n \rightarrow inv$)

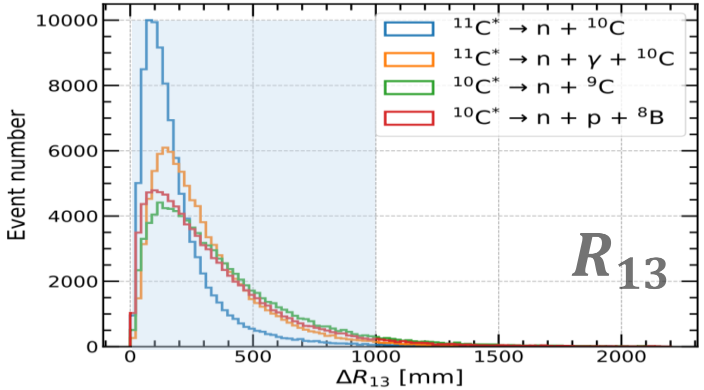


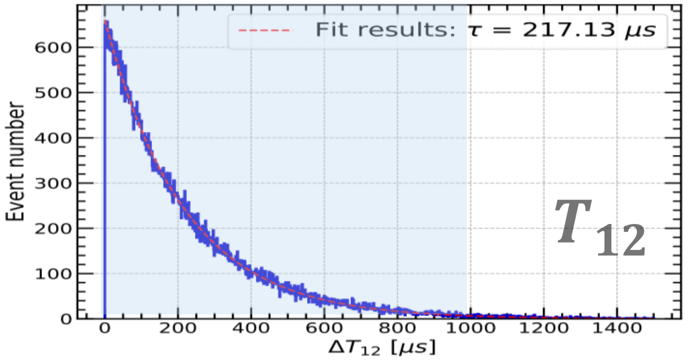


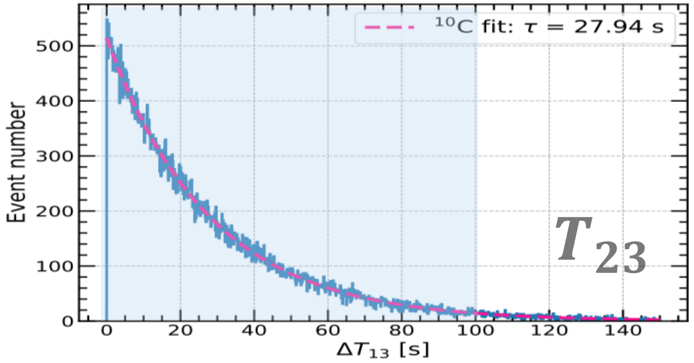






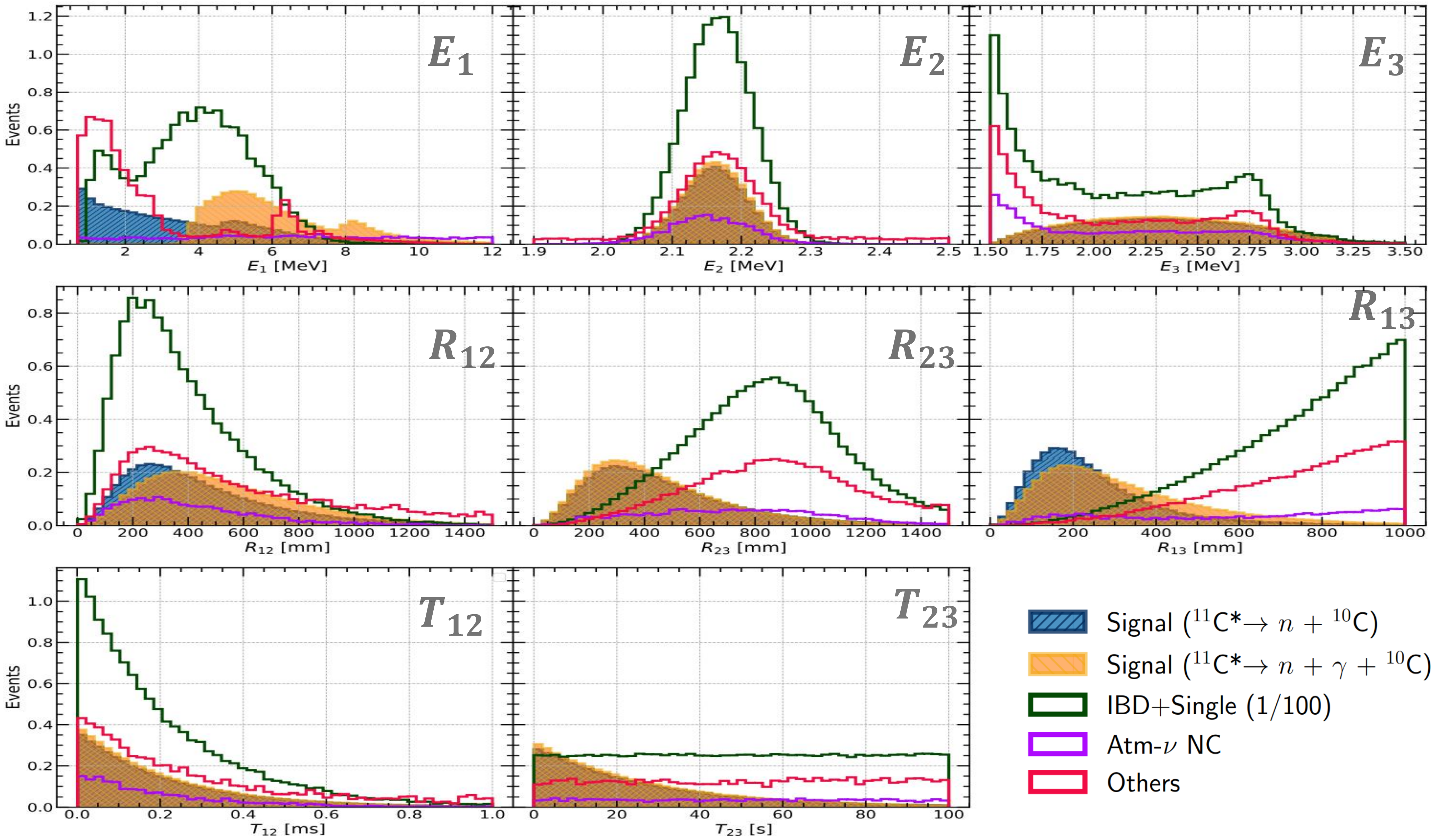




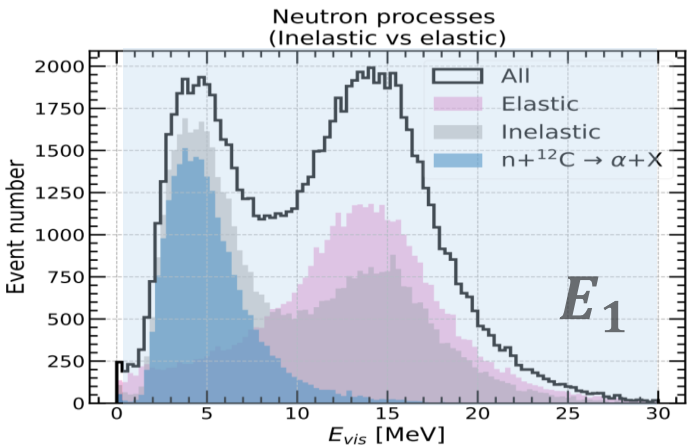


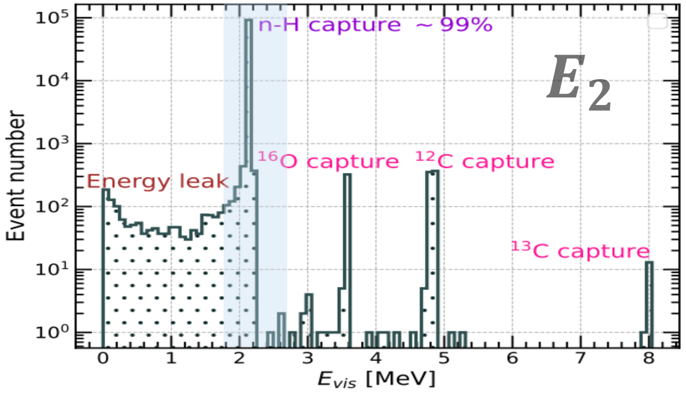
Select region

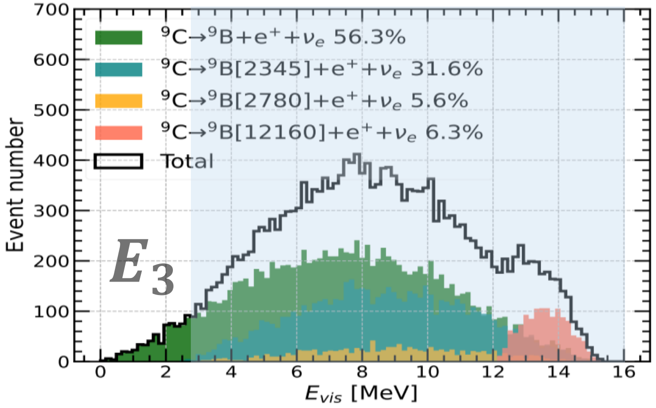
Event selection ($n \to inv$)

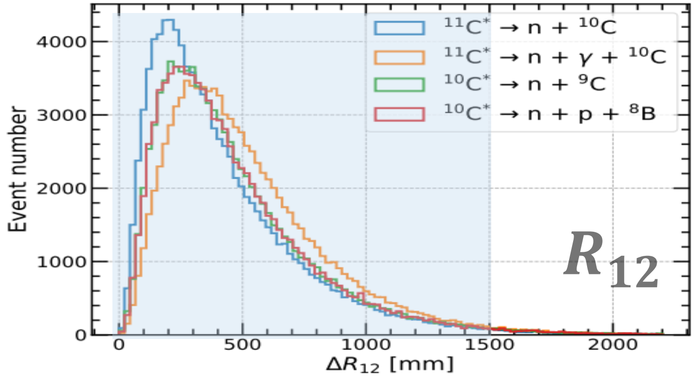


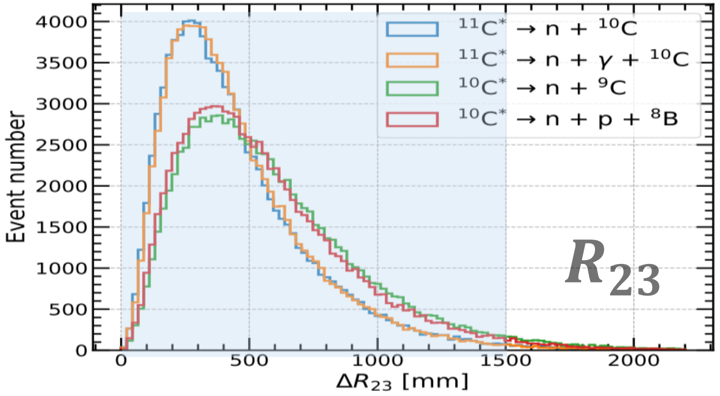
Signal characteristic of signal energy

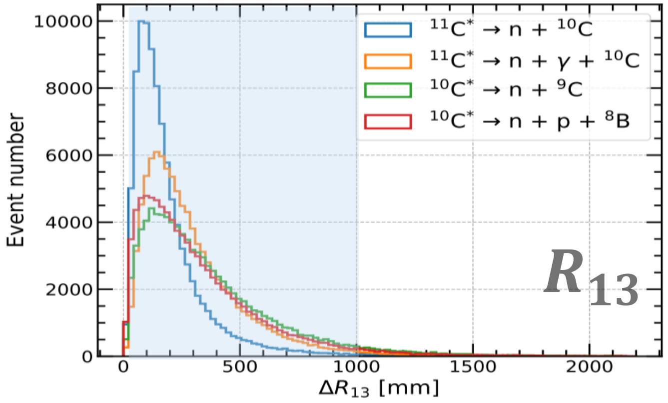


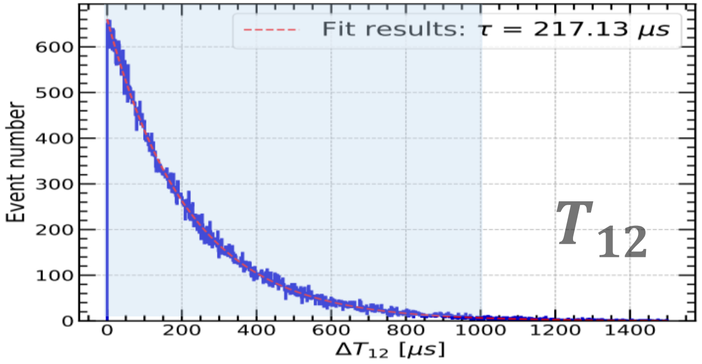


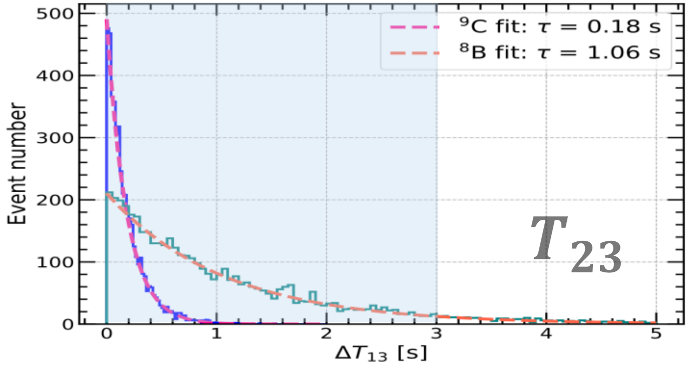






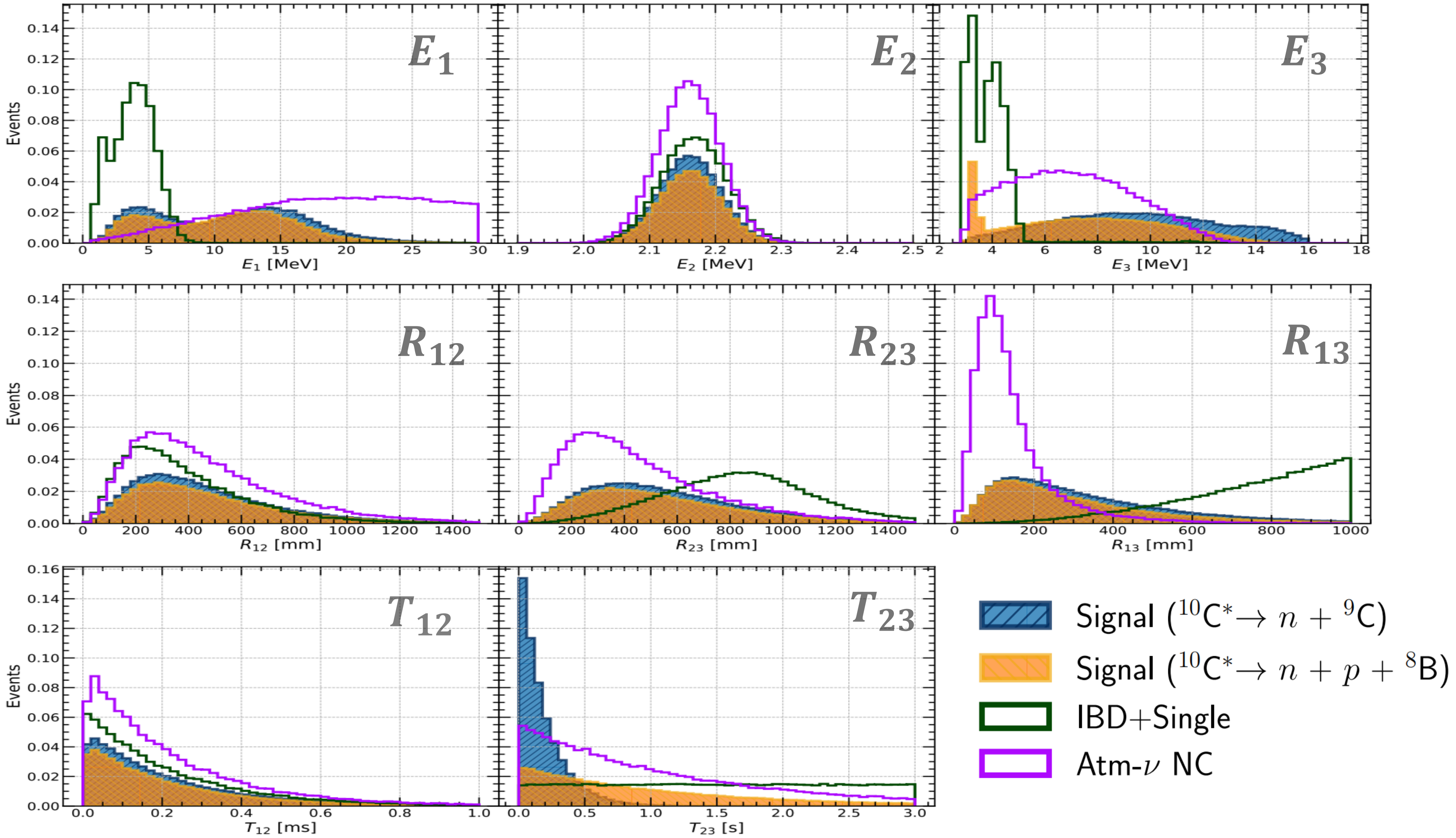






Select region

Event selection ($nn \rightarrow inv$)



Event selection

➢Consider **10 years** data taking
- Signal rate
  - from the final sensitivity result

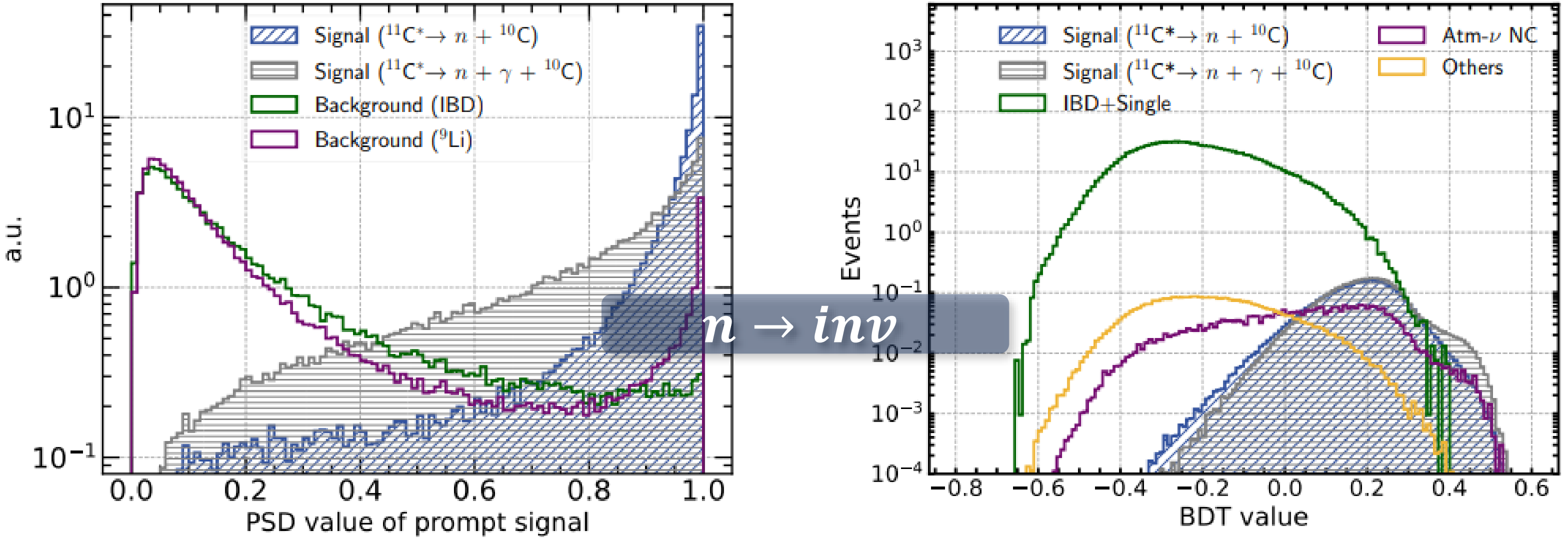
Signal efficiencies

Selection Criterion	$n \to inv$		$nn \to inv$	
	${}^{11}\mathrm{C}^* \to n + {}^{10}\mathrm{C}$	${}^{11}\mathrm{C}^* \to n + \gamma + {}^{10}\mathrm{C}$	${}^{10}\mathrm{C}^* \to n + {}^{9}\mathrm{C}$	${}^{10}\mathrm{C}^* \to n + p + {}^{8}\mathrm{B}$
All triple signals	100	100	100	100
Muon Veto	65.7 ± 0.2	65.5 ± 0.2	80.8 ± 0.2	78.3 ± 0.2
Fiducial Volume	83.5 ± 0.4	82.7 ± 0.4	82.9 ± 0.4	83.1 ± 0.4
Event Selection	75.4 ± 0.9	89.7 ± 0.3	89.2 ± 0.3	83.5 ± 0.3
Multiplicity Cut	93.8 ± 0.1	93.8 ± 0.1	$99.9 \pm \mathcal{O}(10^{-4})$	$99.9 \pm \mathcal{O}(10^{-4})$
Combined Selection	38.8 ± 0.5	45.6 ± 0.3	59.7 ± 0.4	54.3 ± 0.4

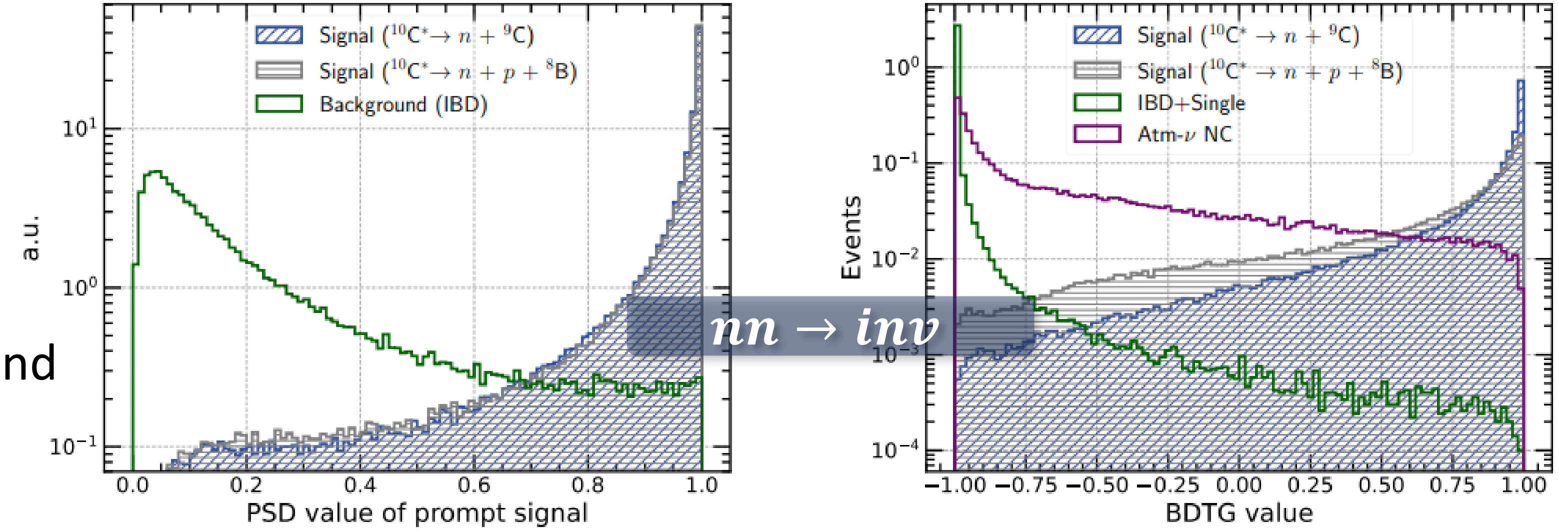
Background suppression

➢ **Two** suppression method

- **P**ulse **S**hape **D**iscrimination
  - Particle's emission photon time are different
- **M**ulti **V**ariate **A**nalysis
  - Combine multidimensional features



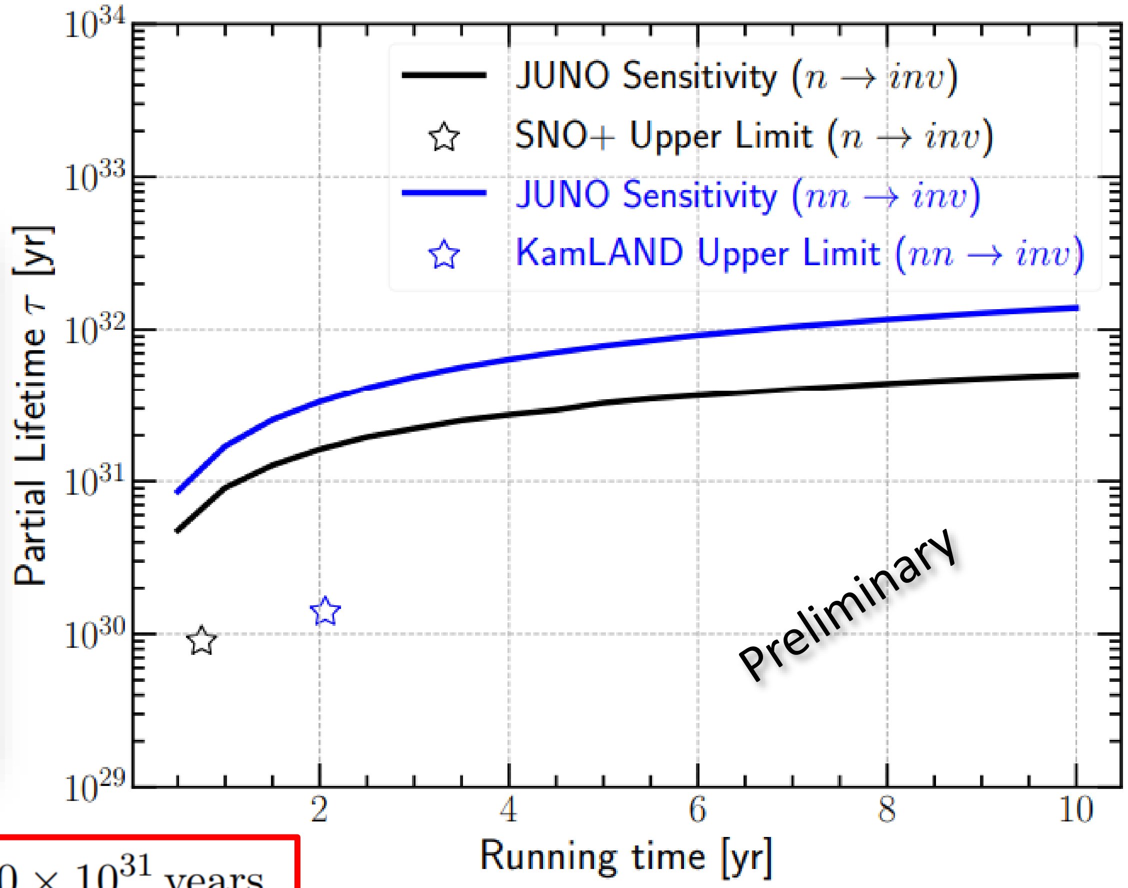
- Both PSD and MVA have **good** performance
  - Effectively suppress background



Sensitivity

Summary of Signal and background

Backgrounds (10 years)	$n \to inv$		$nn \to inv$	
	Basic selection	PSD + MVA	Basic selection	PSD + MVA
IBD + Single	1235 ± 50	2.72 ± 0.10	3.01 ± 0.09	0.0110 ± 0.0003
Atm-ν NC	3.0 ± 1.1	0.93 ± 0.67	4.3 ± 3.5	0.55 ± 0.63
^{13}C(α,n)^{16}O + Single	3.4 ± 1.4	0.036 ± 0.013	–	–
^{9}Li/^{8}He + Single	1.55 ± 0.39	0.29 ± 0.17	0.13 ± 0.13	0.13 ± 0.13
Accidental	1.46 ± 0.05	0.095 ± 0.004	–	–
Total	1244 ± 50	4.07 ± 0.68	7.4 ± 3.5	0.69 ± 0.64
Signal efficiency (%)	$n \to inv$		$nn \to inv$	
	Basic selection	PSD + MVA	Basic selection	PSD + MVA
$\epsilon_{n(nn)1}$	35.6 ± 0.2	23.5 ± 0.2	54.0 ± 0.3	48.2 ± 0.3
$\epsilon_{n(nn)2}$	43.6 ± 0.3	30.3 ± 0.3	49.2 ± 0.3	36.3 ± 0.3



$$\tau/B(n \to inv) > 5.0 \times 10^{31} \text{ years},$$
$$\tau/B(nn \to inv) > 1.4 \times 10^{32} \text{ years}.$$

10 years

An order of magnitude improvement to the current best limits in 2 years data taking

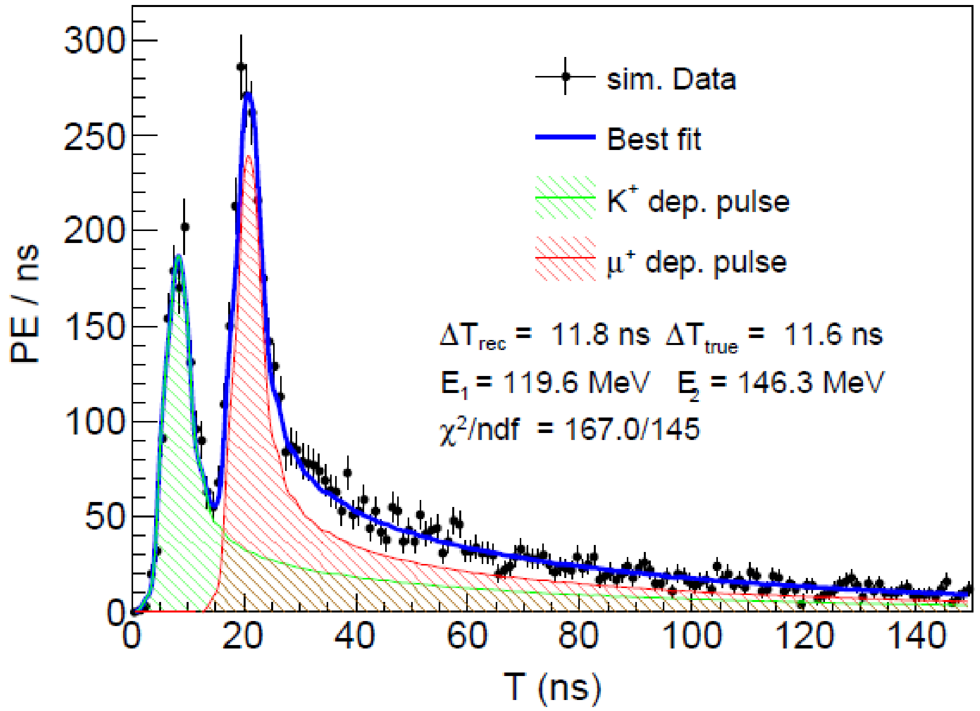
Summary

- JUNO is a large LS detector
  - 20 kton LS
    - 1.45×10^{33} free protons, 5.30×10^{33} bound protons/neutrons
- Competitive sensitivities for nucleon decay (some channels)
  - **Nucleon decay** (JUNO 10-year sensitivity**)**
    - $\boldsymbol{\tau/B(p \to \bar{\nu}\, K^{+}) > 9.6 \times 10^{33}}$ **year at 90% C.L.**
    - $\boldsymbol{\tau/B(n \to inv) > 5.0 \times 10^{31}}$ **year at 90% C.L.**
    - $\boldsymbol{\tau/B(nn \to inv) > 1.4 \times 10^{31}}$ **year at 90% C.L.**
- JUNO construction near completion, overcoming challenges
- JUNO has the potential to study nucleon decay and test new physics

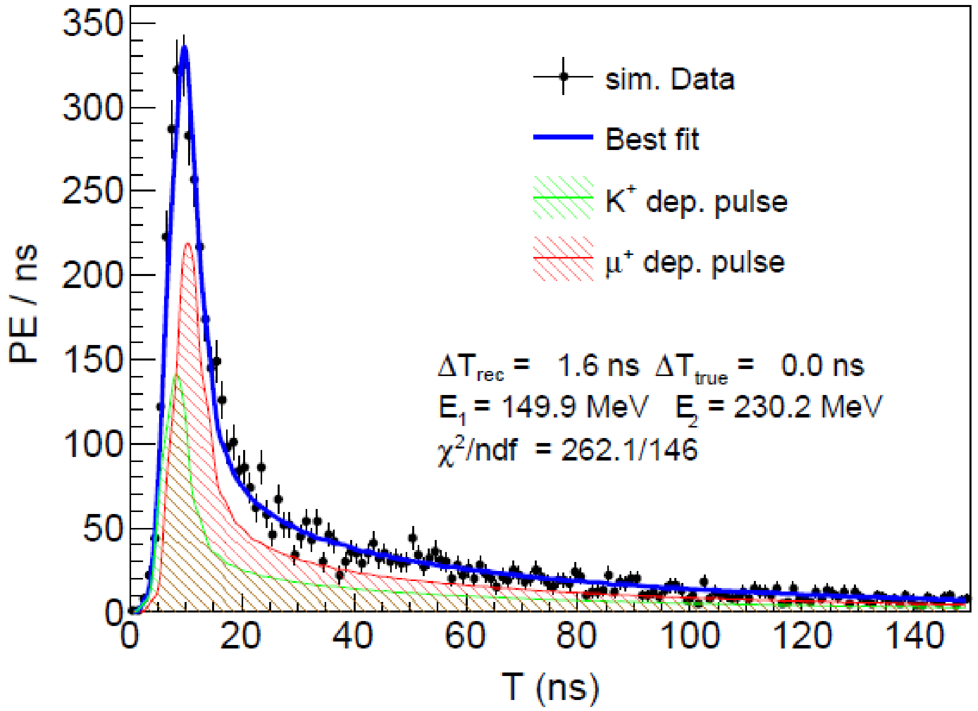
Thank you for your attention!

Backup

➢ Muti-pulse Fitting

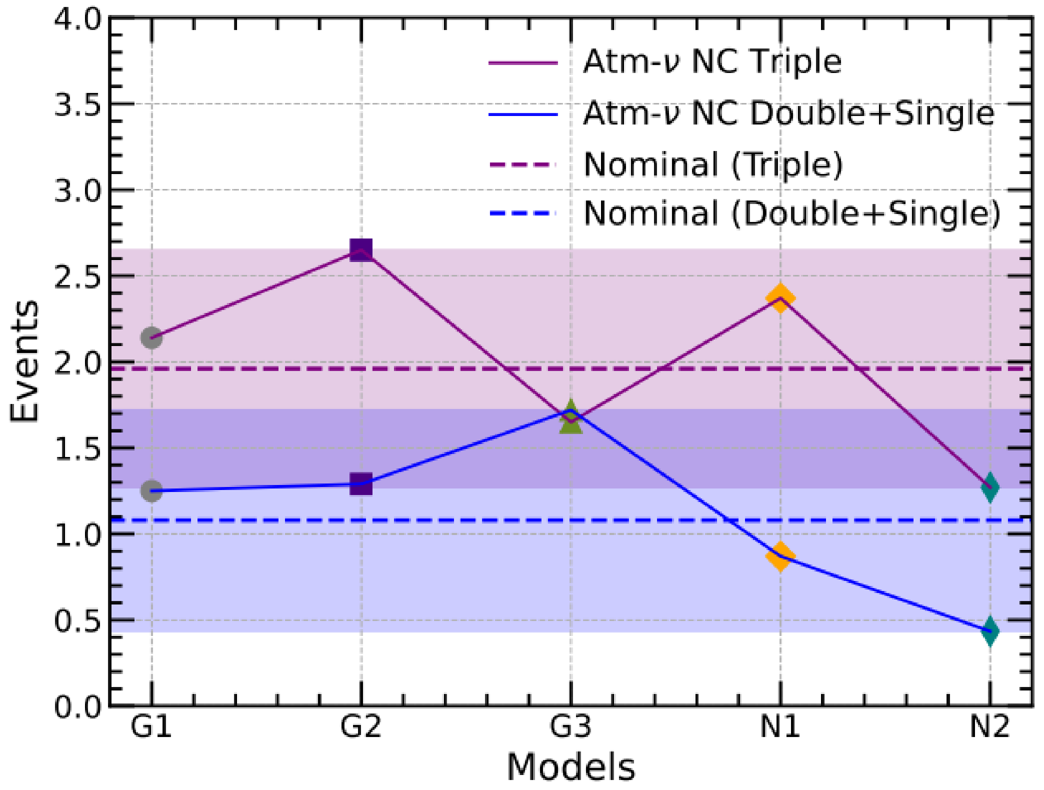


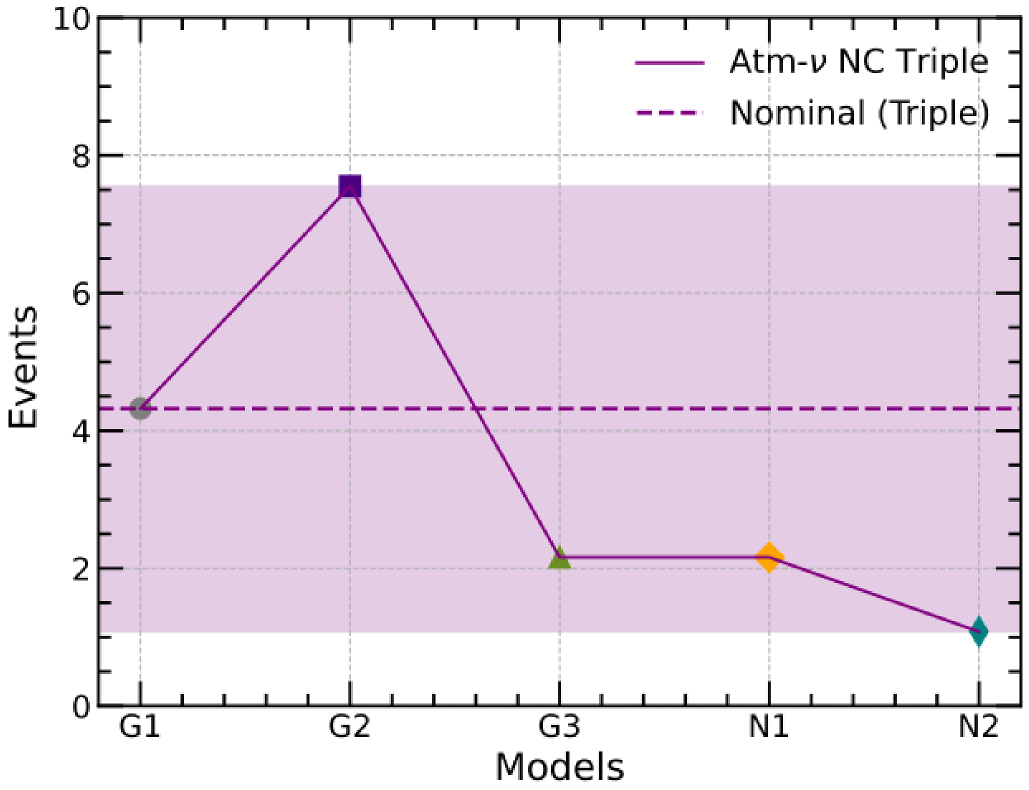
(a) Hit time spectrum of a proton decay event

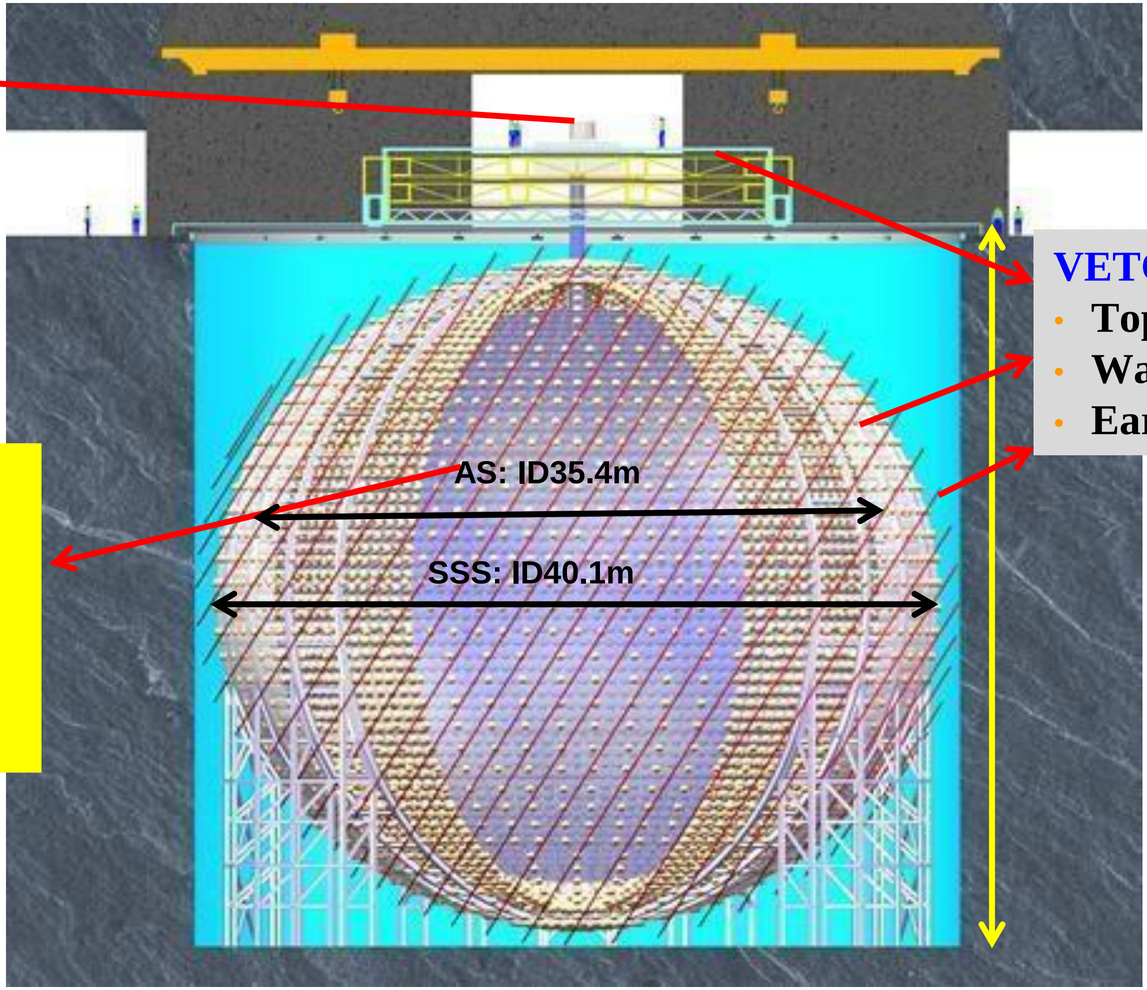


(b) Hit time spectrum of an atmospheric ν event

➢NC background







Calibration

VETO system
- Top Tracker
- Water VETO with 2400 20’’ PMT
- Earth Magnetic Field shielding coils

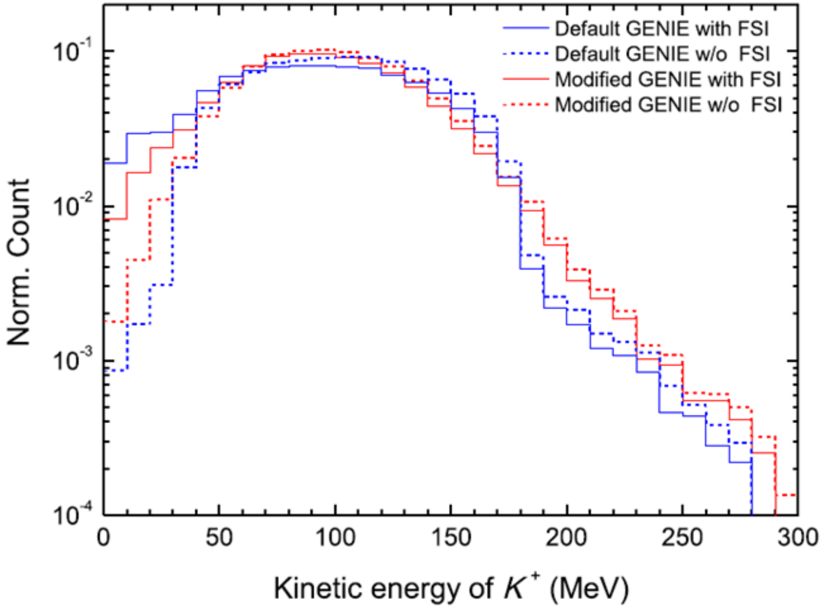
Central detector
- Steel structure (SSS)
- Acrylic sphere(AS) + 20kt Liquid scintillator
- 17612 20” PMT
- 25600 3’’ PMT

➢Search for $p \to \bar{\nu} K^{+}$ in JUNO

20 kton LS: Free proton: 1.45×10^{33}
Bound proton: 5.30×10^{33}

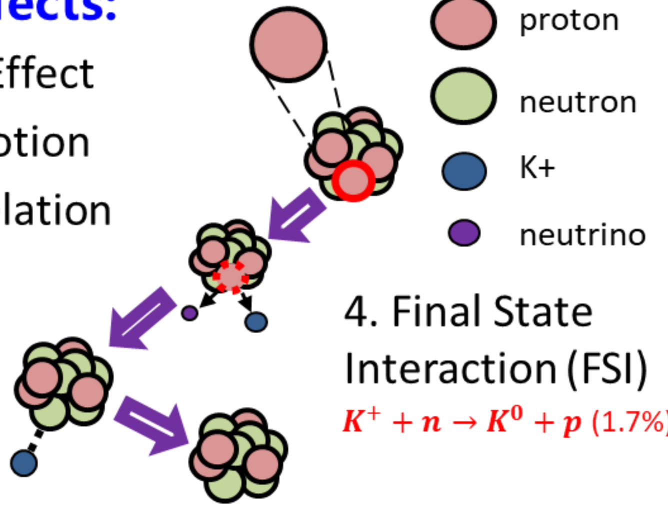
Kinetic energy of K^{+}

Free proton → 105 MeV
Bound proton: ↓



Nuclear Effects:

1. Binding Effect
2. Fermi Motion
3. *NN* correlation



4. Final State Interaction (FSI)
$K^{+} + n \to K^{0} + p$ (1.7%)

5. De-excitation of remaining nuclear: could emit **γ/p/n.**

- ➢ **Modify GENIE generator**
- ➢ **Implement de-excitation with TALYS**

H. Hu, W.L. Guo et al, PLB 831, 137183(2022)

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