Proton decays at JUNO

Wanlei Guo (IHEP)

On behalf of the JUNO collaboration

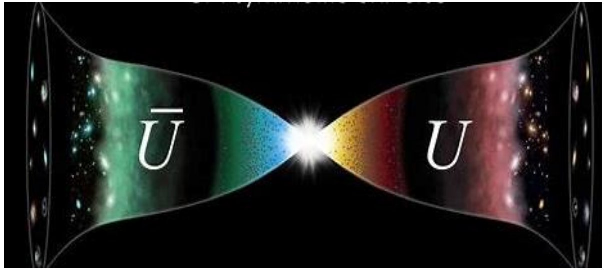
SSP 2025, Nara, Japan, Sep.23-28, 2025

Outline

1. Status of proton decay searches
2. JUNO sensitivity on $p \rightarrow \overline{\nu}\, K^{+}$
3. Neutron invisible decays in JUNO
4. Summary

Motivation

Experimental side: cosmological matter-antimatter asymmetry



Sakharov's three ingredients: JETP Letters 5,24 (1967)

1. *Baryon Number Violation*
2. *C and CP Violation*
3. *Non-Equilibrium Conditions*

B conservation from accidental global symmetry in SM

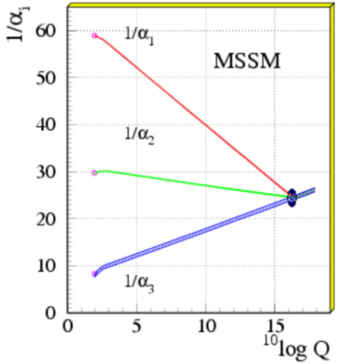
Lightest Baryon:

Proton

Stability?

Theoretical side: Grand Unified Theories (GUTs)

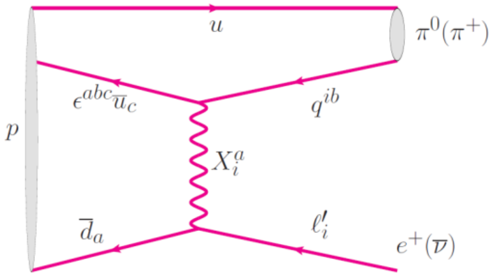
Phys. Rept. 441, 191 (2007)



A natural consequence

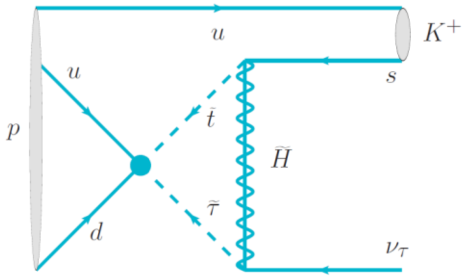
Proton decay

$$p \to e^+\pi^0$$



Non-SUSY GUTs

$$p \to \overline{\nu}\, K^+$$



SUSY GUTs

Searching for proton decays plays a key role to understand baryon asymmetry and test GUTs

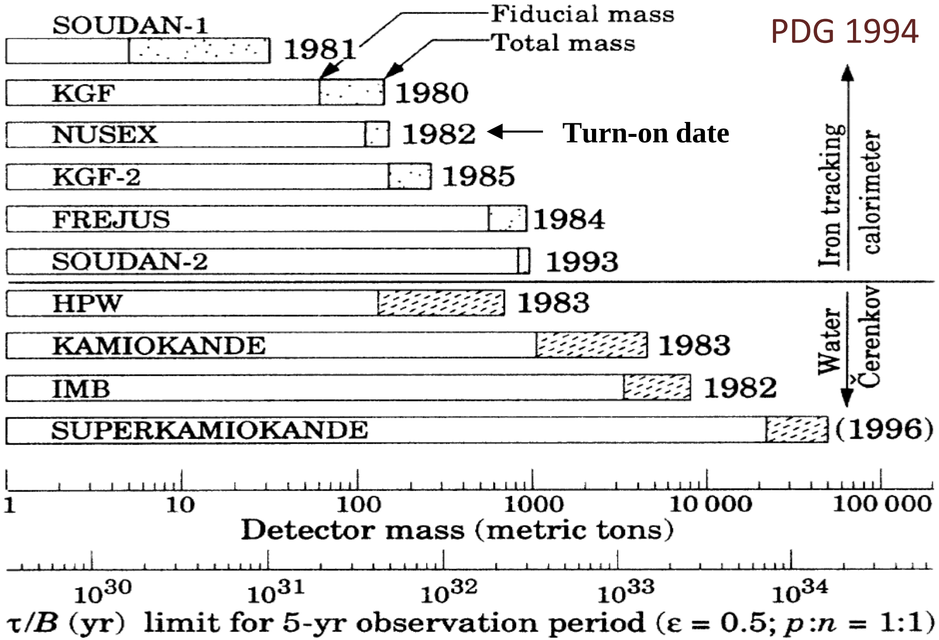
Search history of proton decays

In 1974, Georgi and Glashow propose the minimal SU(5) GUT → $\tau_p \approx 10^{28} - 10^{32}$ yrs

PRL 32,438 (1974)
Snowmass: 2203.08771

→ ***Detectors with about 1000 ton mass can test the SU(5) GUT***

The first generation of experiments (80s):



PDG 1994

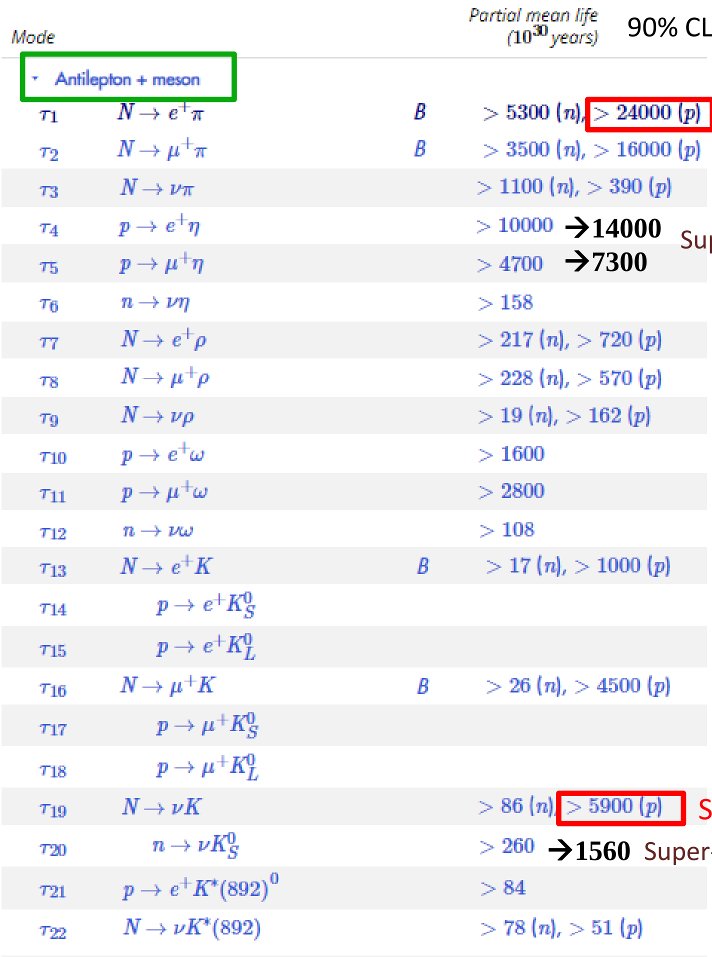
The second generation (90s):


Super-Kamiokande

After 2000, some neutrino experiments, Such as KamLAND, SNO and BOREXINO, have also searched for proton decays.

All these experiments don't find the evidence for proton decay, excluded minimal SU(5)

Current limits on proton decays



	Mode		Partial mean life (10^{30} years) 90% CL	
	Antilepton + meson			
τ_1	$N \to e^+\pi$	B	> 5300 (n), > 24000 (p)	Super-K
τ_2	$N \to \mu^+\pi$	B	> 3500 (n), > 16000 (p)	
τ_3	$N \to \nu\pi$		> 1100 (n), > 390 (p)	
τ_4	$p \to e^+\eta$		> 10000 →**14000**	Super-K 2024
τ_5	$p \to \mu^+\eta$		> 4700 →**7300**	
τ_6	$n \to \nu\eta$		> 158	
τ_7	$N \to e^+\rho$		> 217 (n), > 720 (p)	
τ_8	$N \to \mu^+\rho$		> 228 (n), > 570 (p)	
τ_9	$N \to \nu\rho$		> 19 (n), > 162 (p)	
τ_{10}	$p \to e^+\omega$		> 1600	
τ_{11}	$p \to \mu^+\omega$		> 2800	
τ_{12}	$n \to \nu\omega$		> 108	
τ_{13}	$N \to e^+K$	B	> 17 (n), > 1000 (p)	
τ_{14}	$p \to e^+K^0_S$			
τ_{15}	$p \to e^+K^0_L$			
τ_{16}	$N \to \mu^+K$	B	> 26 (n), > 4500 (p)	
τ_{17}	$p \to \mu^+K^0_S$			
τ_{18}	$p \to \mu^+K^0_L$			
τ_{19}	$N \to \nu K$		> 86 (n), > 5900 (p)	Super-K
τ_{20}	$n \to \nu K^0_S$		> 260 →**1560**	Super-K 2025
τ_{21}	$p \to e^+K^*(892)^0$		> 84	
τ_{22}	$N \to \nu K^*(892)$		> 78 (n), > 51 (p)	

Other modes include:

- ✓ *Antilepton + mesons*
- ✓ *Lepton + meson*
- ✓ *Lepton + mesons*
- ✓ *Antilepton + photon(s)*
- ✓ *Antilepton + single massless*
- ✓ *Three (or more) leptons*
- ✓ *Inclusive modes*
- ✓ *ΔB= 2 dinucleon modes*

https://pdglive.lbl.gov/Particle.action?init=0&node=S016&home=BXXX005#decays

Final state particles:

Mesons: $\pi^{\pm}, \pi^0, K^{\pm}, K^0,\ \eta,\ \rho,\ \omega,\ K^*(892);$

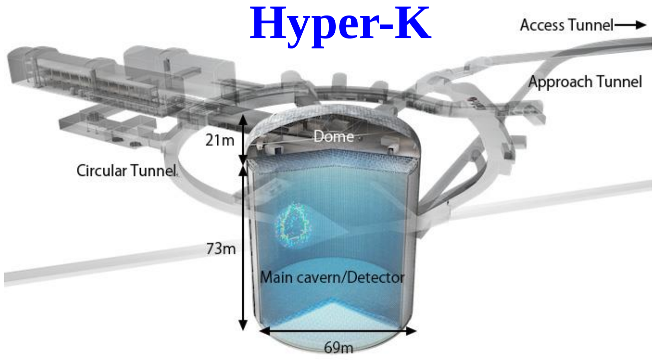
Leptons: $e^{\pm}, \mu^{\pm}, \nu$; ***Photon:*** γ

Total measured modes: 82

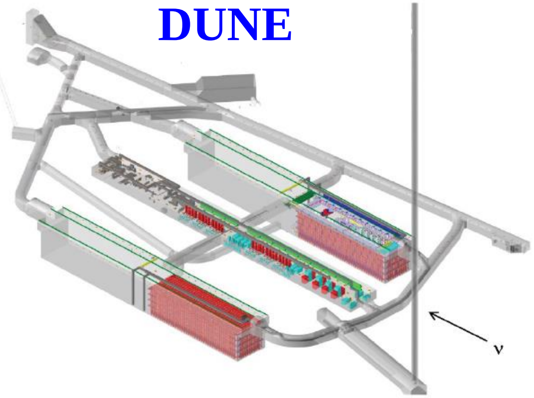
Super-K analyzed 38 modes!

Future proton decay experiments

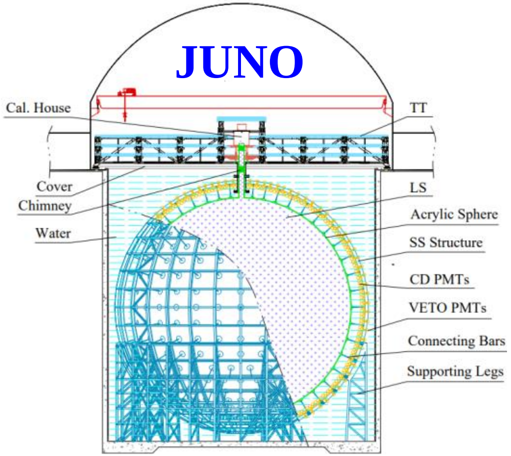
Hyper-K



DUNE

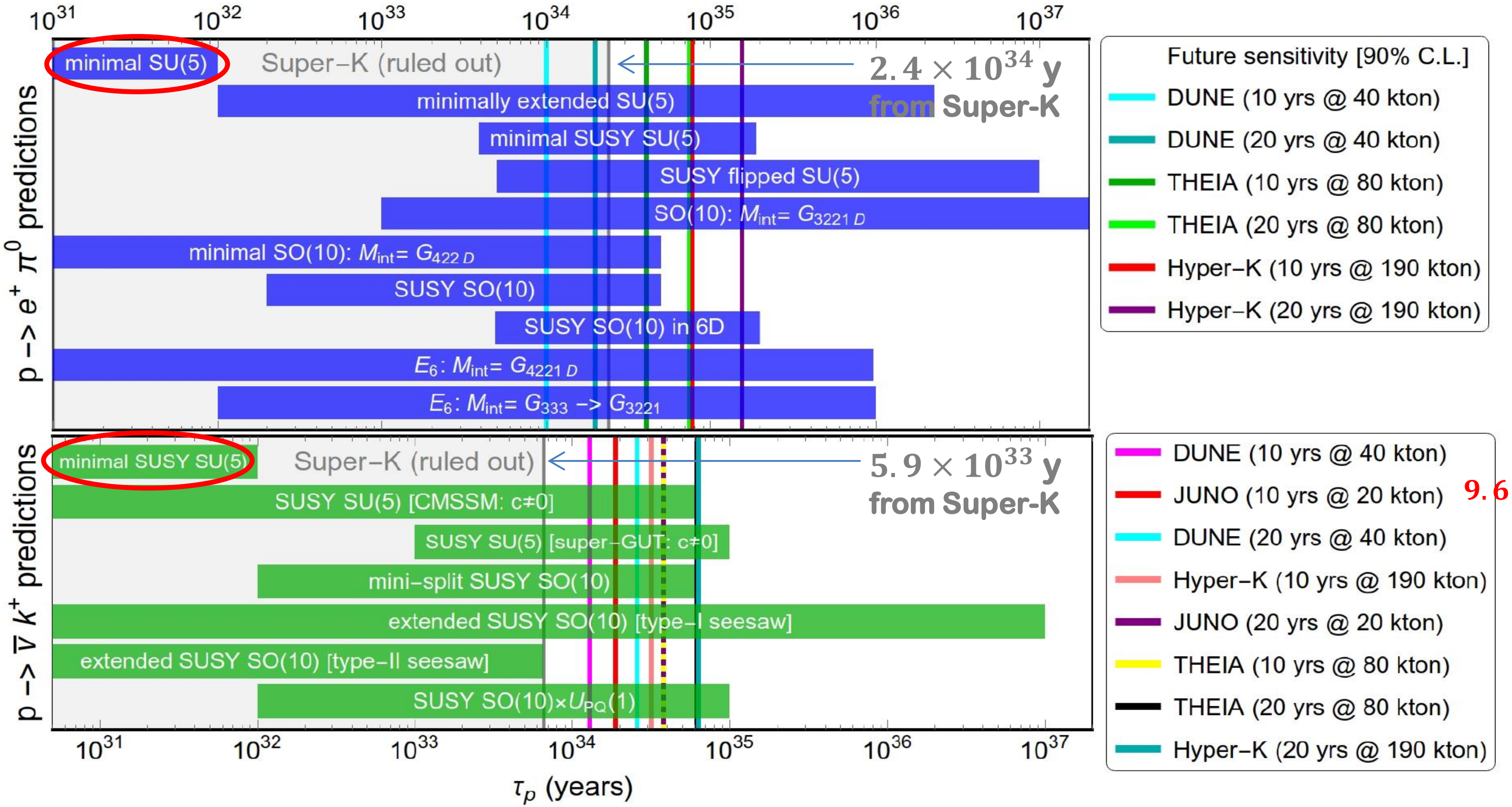


JUNO



	Hyper-K (arXiv:1805.04163)	**DUNE** (arXiv:2002.03005)	**JUNO** (JPG, 43 (2016) 3, 030401)
Total/Fiducial Mass (kton)	258/186	4*17 /4*10	20
Target Nucleus	H_2O	Ar40	12% H， 88% C12
Technology	Water Cerenkov	LAr TPC	Liquid Scintillator
Start Time	2028	2029	**Aug.26, 2025**
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

Future sensitives on two favored decay modes



2.4×10^{34} y from Super-K

5.9×10^{33} y from Super-K

9.6×10^{33} y

Snowmass: 2203.08771

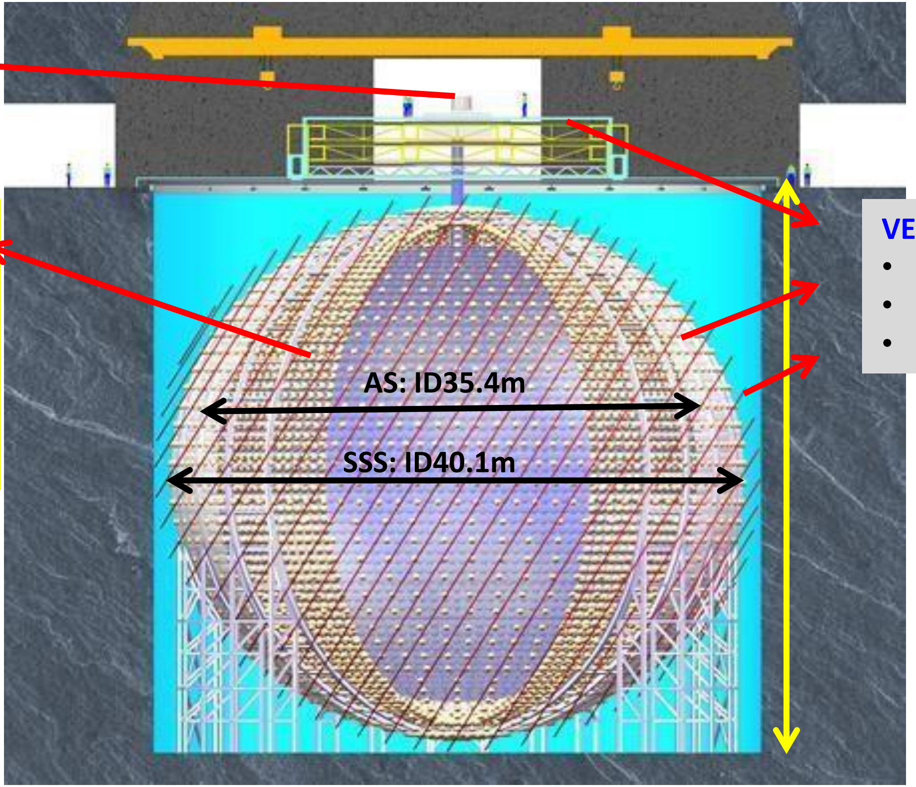
(2) JUNO sensitivity on $p \to \overline{\nu} K^+$

- Two-layers structure for simplicity and cost: stainless steel frame + Acrylic tank
- Water as VETO and Buffer(instead of oil) → radiopurity control of water

Calibration

Central detector

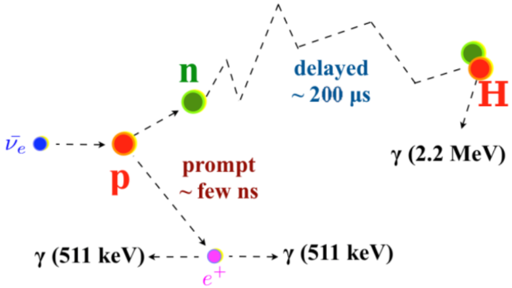
- Steel structure
- Acrylic sphere +
  20kt Liquid scintillator
- 17612 20” PMT
- 25600 3’’ PMT



VETO system (for cosmic muon detection)

- Top Tracker: plastic scintillator
- Water + 2400 20’’ PMT
- Earth Magnetic Field shielding coils

Detect reactor neutrinos → NMO



arXiv:1508.07166

Prog. Part. Nucl. Phys. 123(2022), 103927

$p \to \overline{\nu}\, K^+$ *in free and bound protons*

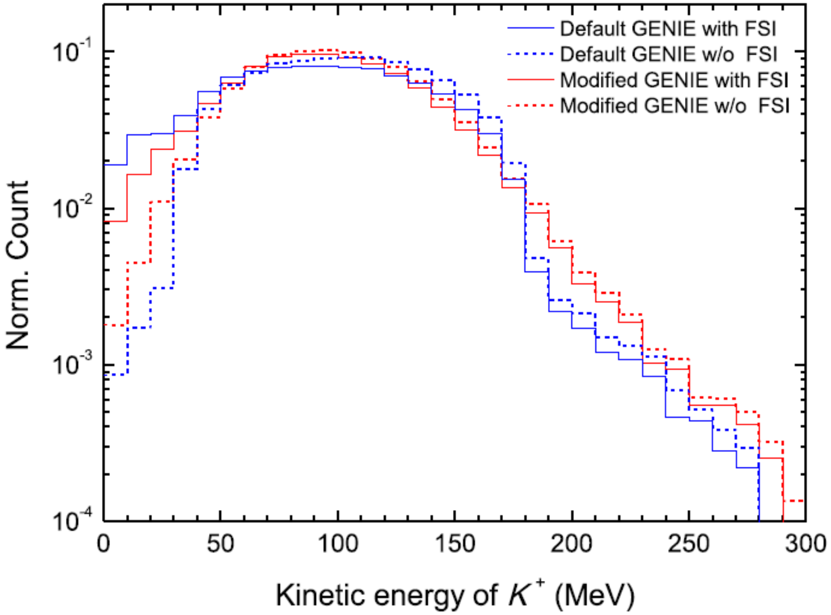
20 kton LS: Free proton: 1.45×10^{33}

Bound proton: 5.30×10^{33}

Kinetic energy of K^+

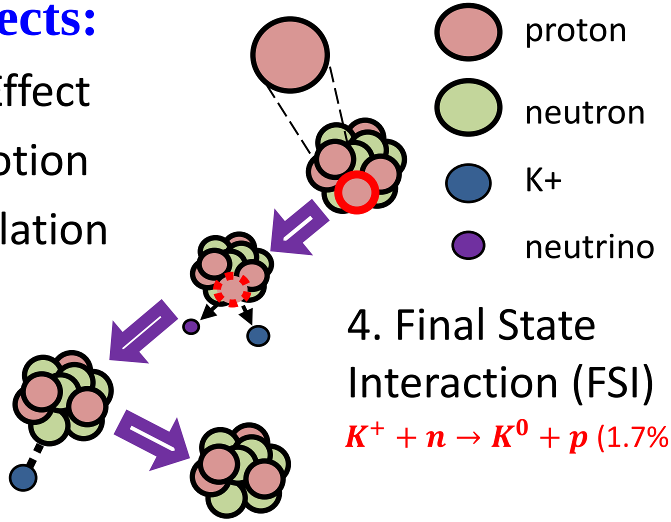
Free proton → 105 MeV

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%)

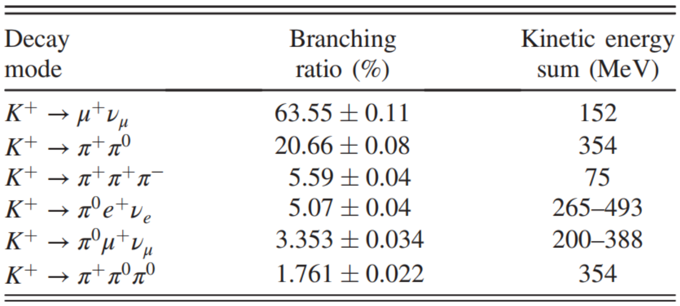
5. De-excitation of remaining nuclei could emit ***γ, p, n, …***

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

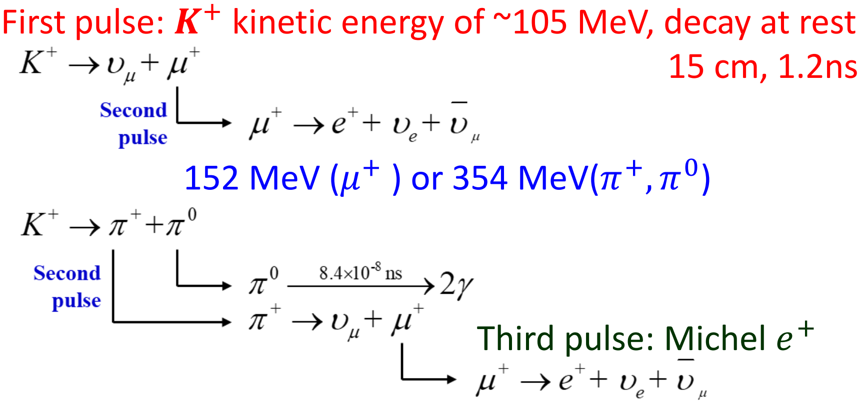
H. Hu, **W.L. Guo** et al, PLB 831, 137183(2022)

Signal characters of $p \to \bar{\nu} K^+$ in JUNO

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



First pulse: K^+ kinetic energy of ~105 MeV, decay at rest 15 cm, 1.2ns

$K^+ \to \upsilon_\mu + \mu^+$

Second pulse

$\mu^+ \to e^+ + \upsilon_e + \bar{\upsilon}_\mu$

152 MeV (μ^+) or 354 MeV(π^+,π^0)

$K^+ \to \pi^+ + \pi^0$

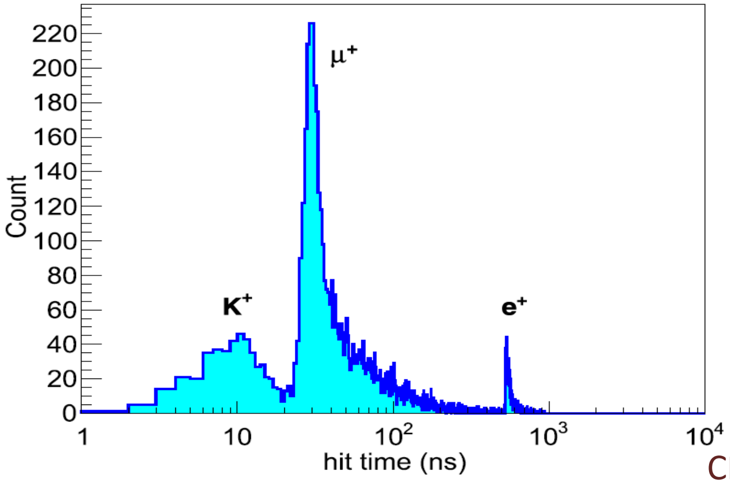
Second pulse

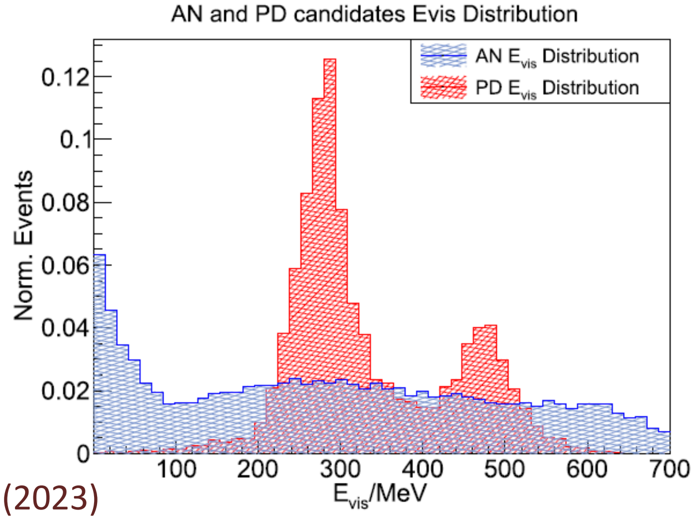
$\pi^0 \xrightarrow{8.4\times10^{-8}\,\mathrm{ns}} 2\gamma$

$\pi^+ \to \upsilon_\mu + \mu^+$

Third pulse: Michel e^+

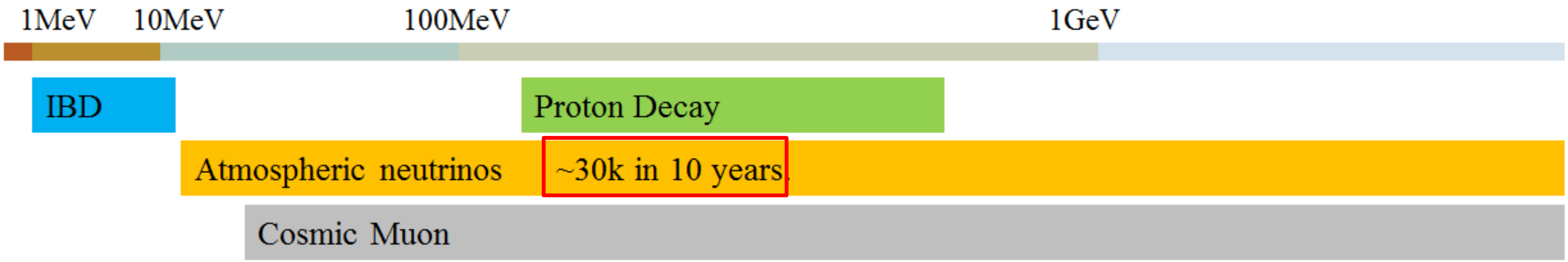
$\mu^+ \to e^+ + \upsilon_e + \bar{\upsilon}_\mu$





CPC 47, 113002 (2023)

Backgrounds of $p \to \overline{\nu} K^+$ in JUNO



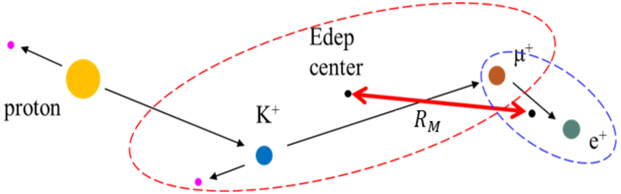
Type	Ratio (%)	Ratio with E_{vis} in [100 MeV, 600 MeV](%)	Interaction	Signal characteristics
NCES	20.2	15.8	$\nu + n \to \nu + n$ $\nu + p \to \nu + p$	Single Pulse
CCQE	45.2	64.2	$\bar{\nu}_l + p \to n + l^+$ $\nu_l + n \to p + l^-$	Single Pulse
Pion Production	33.5	19.8	$\nu_l + p \to l^- + p + \pi^+$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

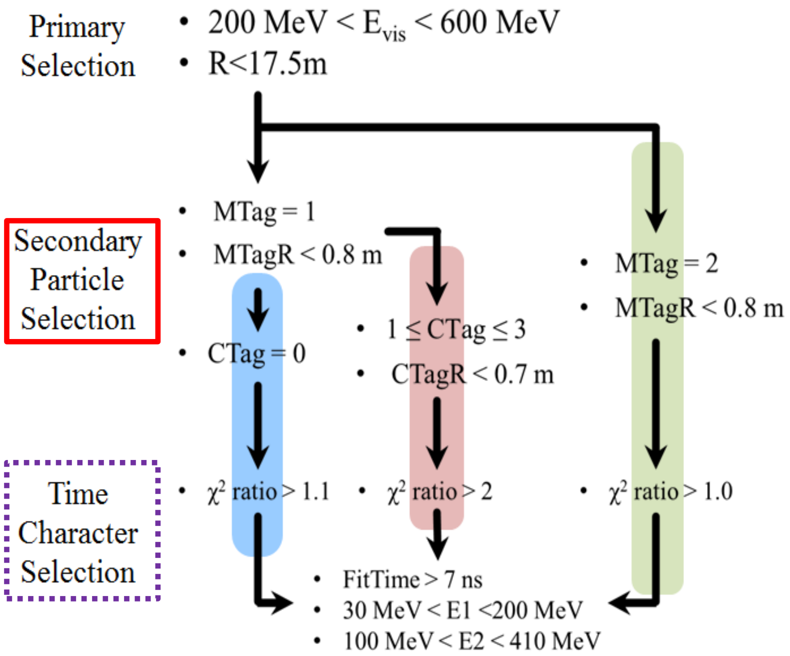
- ➢ **If energetic neutrons do not lost most of the energy within ~10 ns**
- ➢ **Kaon Production has a negligible contribution!**

Event Selection of $p \to \overline{\nu} K^+$ in JUNO

Three chains based on delayed signals:

- ✓ **Michel electrons → MTag**
- ✓ **Captured neutrons→ CTag**





Firstly

Primary Selection

- 200 MeV < E_{vis} < 600 MeV
- R<17.5m

Then

Secondary Particle Selection

- MTag = 1
- MTagR < 0.8 m

- CTag = 0

- 1 ≤ CTag ≤ 3
- CTagR < 0.7 m

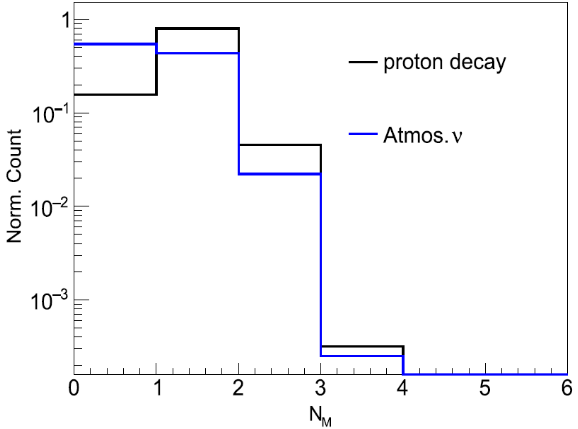
- MTag = 2
- MTagR < 0.8 m

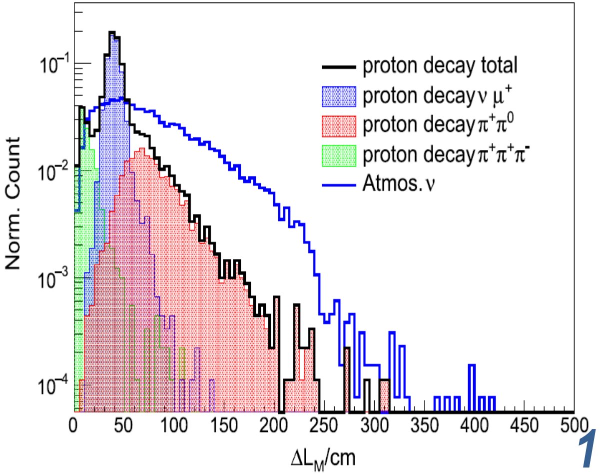
Finally

Time Character Selection

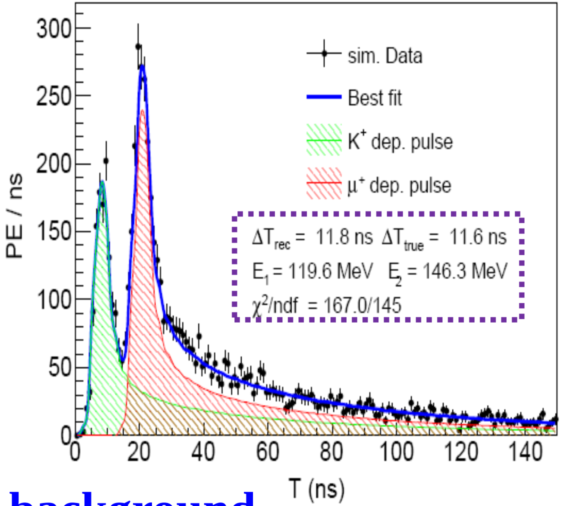
- χ^2 ratio > 1.1
- χ^2 ratio > 2
- χ^2 ratio > 1.0

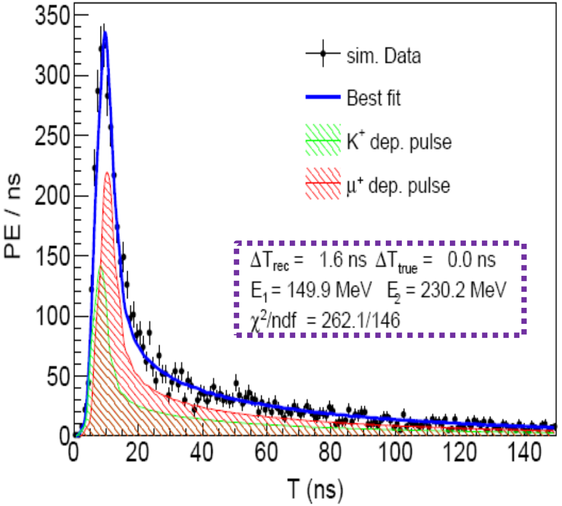
- FitTime > 7 ns
- 30 MeV < E1 <200 MeV
- 100 MeV < E2 < 410 MeV





Multi-pulse fitting of $p \to \bar{\nu}\, K^+$ in JUNO





Efficiency vs background

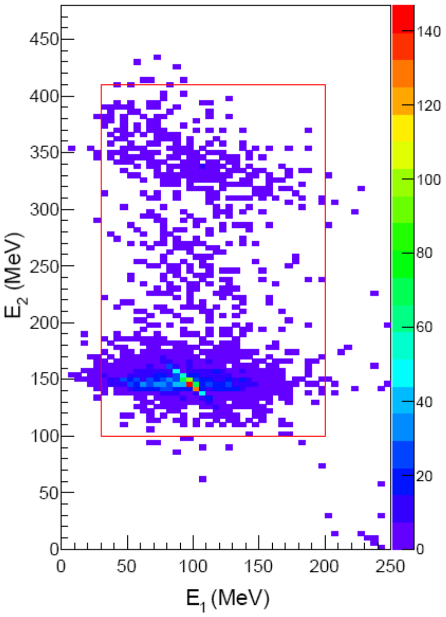
Criteria		Survival rate of $p \to \bar{\nu}K^+$ (%)			Survival count (fraction) of atmospheric ν		
		Sample 1	Sample 2	Sample 3	Sample 1	Sample 2	Sample 3
basic selection	E_{vis}	94.6			51299 (32.1%)		
	R_V	93.7			47849 (29.9%)		
Delayed signal selection	N_M	74.4		4.4	20739 (13.0%)		1143 (0.7%)
	ΔL_M	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		

Only 1 left form 16k MC events

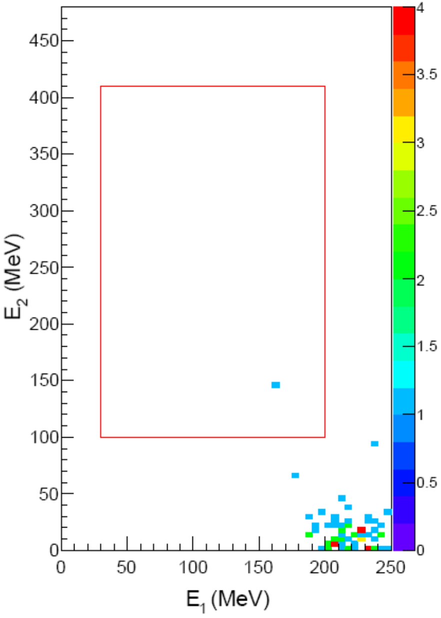
Efficiency uncertainties:

Source	Uncertainty
Statistic	1.6%
Position reconstruction	1.7%
Nuclear model	6.8%
Energy deposition model	11.1%
Total	13.2%

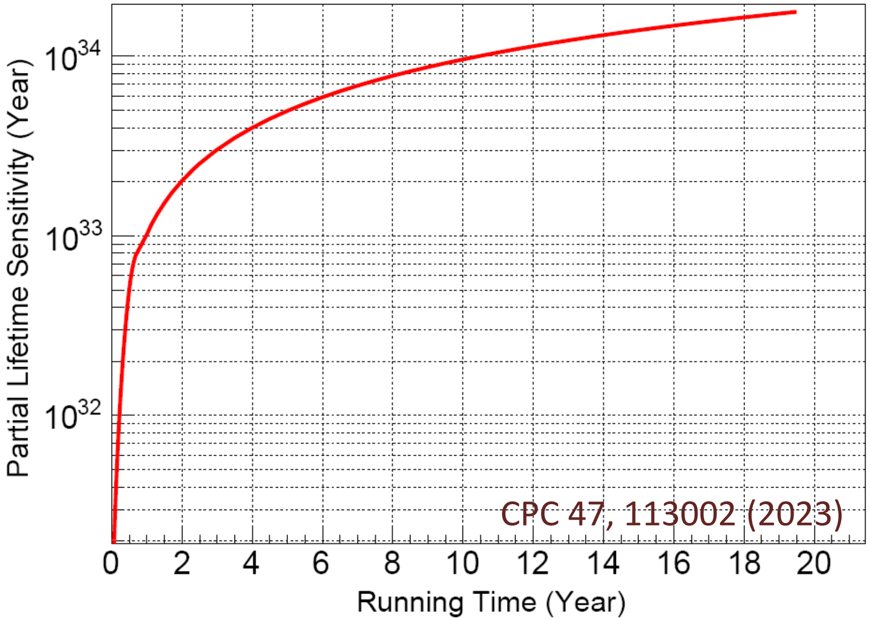
Sensitivity of $p \to \overline{\nu}\, K^+$ in JUNO



(a) $p \to \bar{\nu} K^+$



(b) atmospheric ν



CPC 47, 113002 (2023)

Background： 0.2/10years

Efficiency： 36.9%

$$\tau/B(p \to \overline{\nu}\, K^+) > 0.96 \times 10^{34}\ \mathrm{yrs}$$

$$n \to \mu^- K^+, \quad p \to e^+ K^*(892)^0, \quad n \to \nu K^*(892)^0, \quad \text{and} \quad p \to \nu K^*(892)^+$$

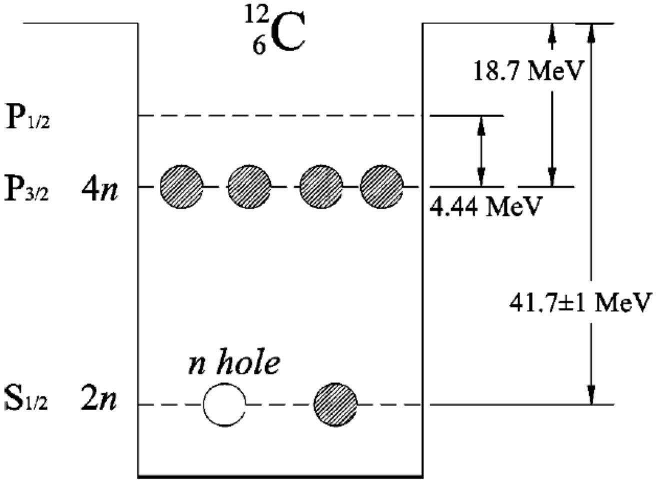
(3) Neutron invisible decays in JUNO

Bound neutrons in ^{12}C :

- ➢ $n \rightarrow inv$ ($^{12}\mathrm{C} \rightarrow {}^{11}\mathrm{C}^*$)
- ➢ $nn \rightarrow inv$ ($^{12}\mathrm{C} \rightarrow {}^{10}\mathrm{C}^*$)

Invisible particle:
neutrinos, NP particles

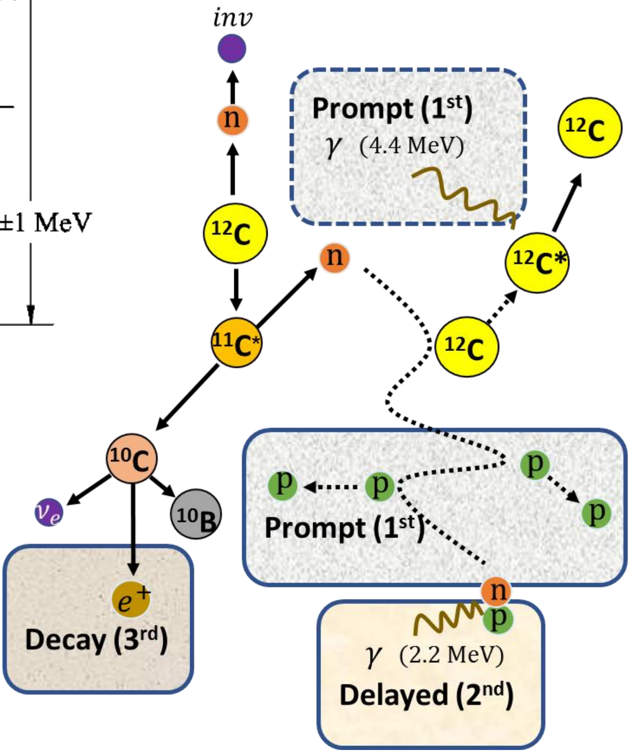
Detect de-excitation products of $^{11}\mathrm{C}^*$ and $^{10}\mathrm{C}^*$



Triple coincident signals :

		Half-life Q value
$^{11}\mathrm{C}^* \rightarrow n + {}^{10}\mathrm{C}$	$(Br_{n1} = 3.0\%)$	[19.3 s, 3.65 MeV]
$^{11}\mathrm{C}^* \rightarrow n + \gamma + {}^{10}\mathrm{C}$	$(Br_{n2} = 2.8\%)$	[19.3 s, 3.65 MeV]
$^{10}\mathrm{C}^* \rightarrow n + {}^{9}\mathrm{C}$	$(Br_{nn1} = 6.2\%)$	[0.13 s, 16.5 MeV]
$^{10}\mathrm{C}^* \rightarrow n + p + {}^{8}\mathrm{B}$	$(Br_{nn2} = 6.0\%)$	[0.77 s, 18.0 MeV]

Y. Kamyshkov and E. Kolbe, PRD 67, 076007 (2003)



Backgrounds of neutron invisible decays in JUNO

Five background sources:

1. Reactor neutrinos; 2. Natural radioactivity; 3. Long-lived isotopes;
4. Fast neutrons; 5. Atmospheric neutrinos

Background combinations:

Single signal

- *Natural radioactivity*
- *Long-lived isotopes*

Single+Single+Single

Double signal

- *IBD from reactor neutrinos*
- *He8/Li9 from long-lived isotopes*
- *Fast neutrons*
- *Alpha-N from radioactivity*
- *Atmospheric neutrino NC*

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

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

Double+Single

Triple signal

- *Atmospheric neutrino NC*

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

Triple

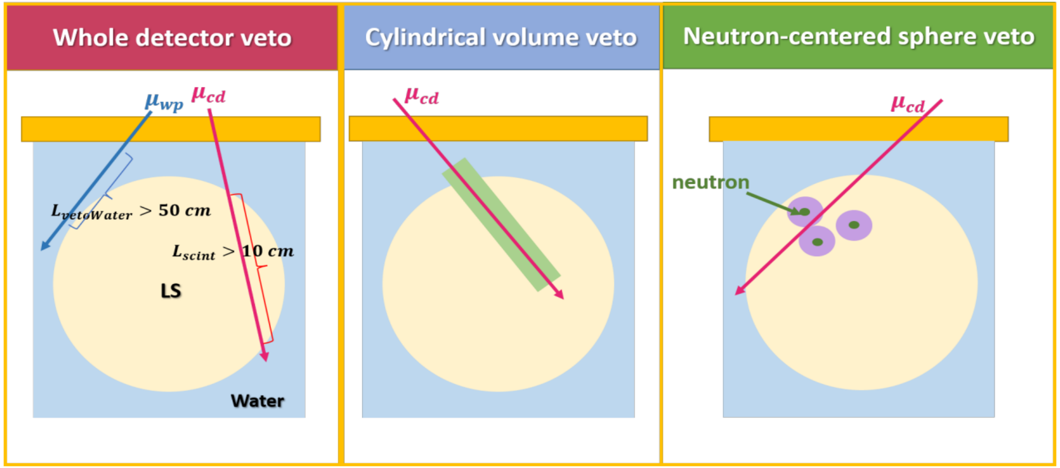
Event selection of neutron invisible decays in JUNO

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

FV cut and selection criteria:

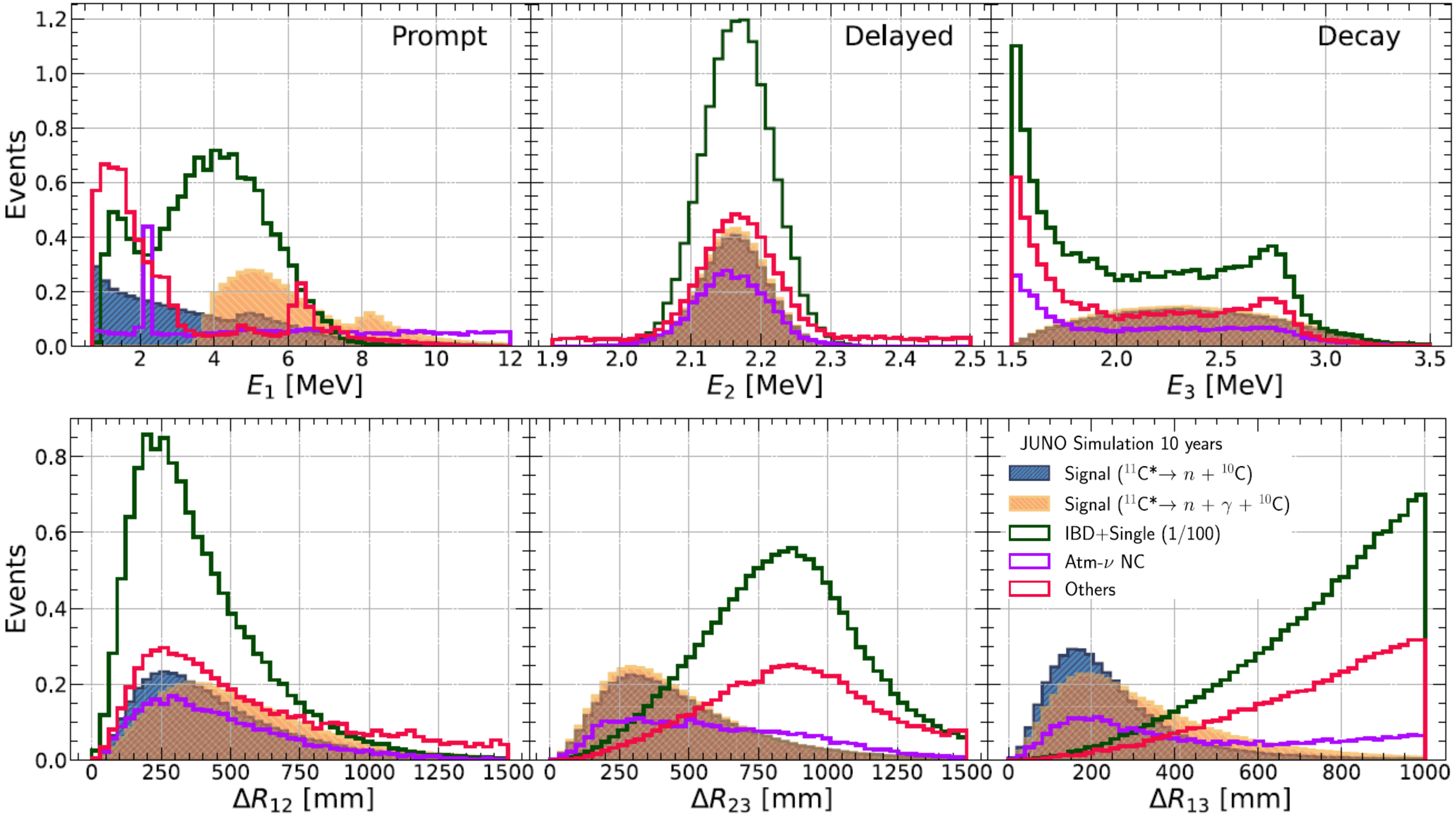
Quantity	$n \to inv$	$nn \to inv$
$R_{1,2,3}$ [m]	< 16.7	< 16.7
E_1 [MeV]	0.7-12	0.7-30
E_2 [MeV]	1.9-2.5	1.9-2.5
E_3 [MeV]	1.5-3.5	3.0-16.0
ΔT_{12} [ms]	< 1	< 1
ΔT_{23} [s]	0.002-100	0.002-3.0
ΔR_{12} [m]	< 1.5	< 1.5
ΔR_{23} [m]	< 1.5	< 1.5
ΔR_{13} [m]	< 1.0	< 1.0

Muon veto strategy:



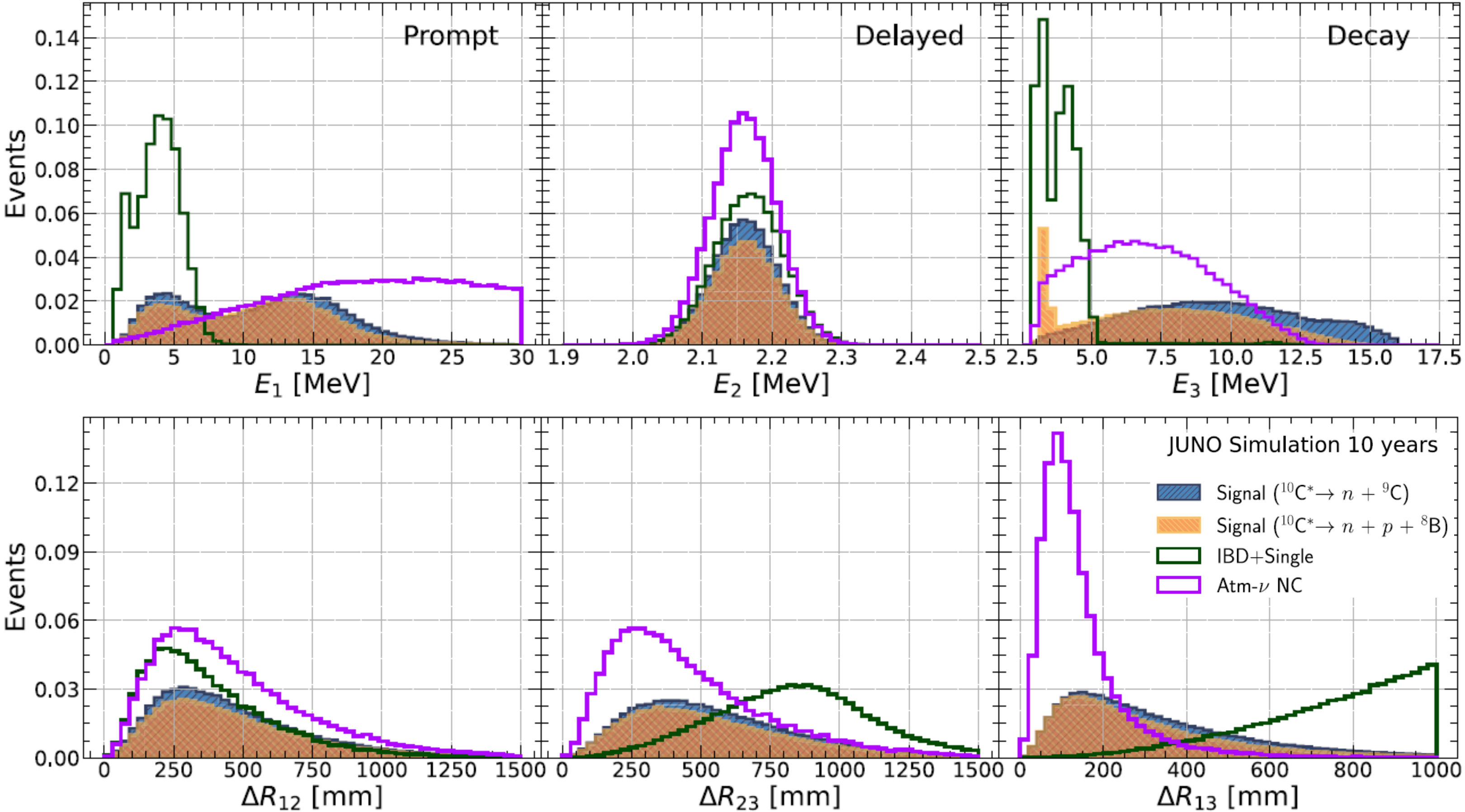
$n \to inv$ signal vs backgrounds in JUNO

Dominant BKGs of $n \to inv$: *IBD + Single (1235), Atm-ν NC (3.0) per 10 years*



$nn \to inv$ signal vs backgrounds in JUNO

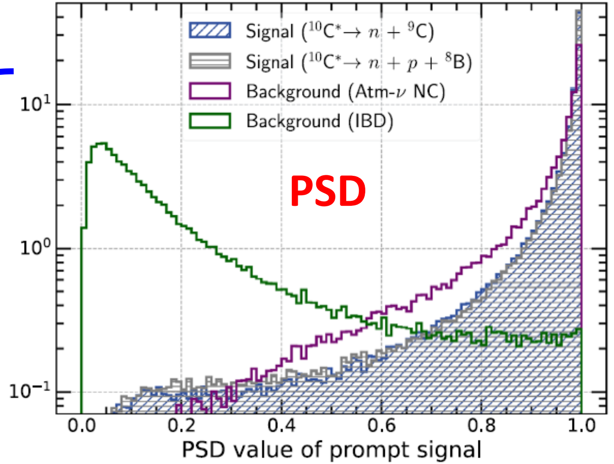
Dominant BKGs of $nn \to inv$: ***IBD + Single (3.0), Atm-ν NC (4.3) per 10 years***

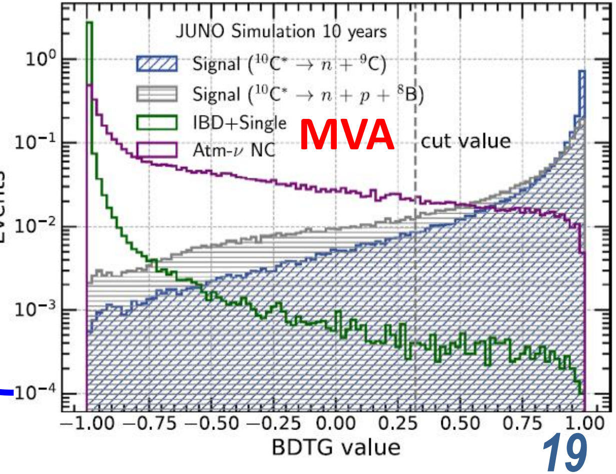


Summary of Backgrounds and Signal efficiency in JUNO

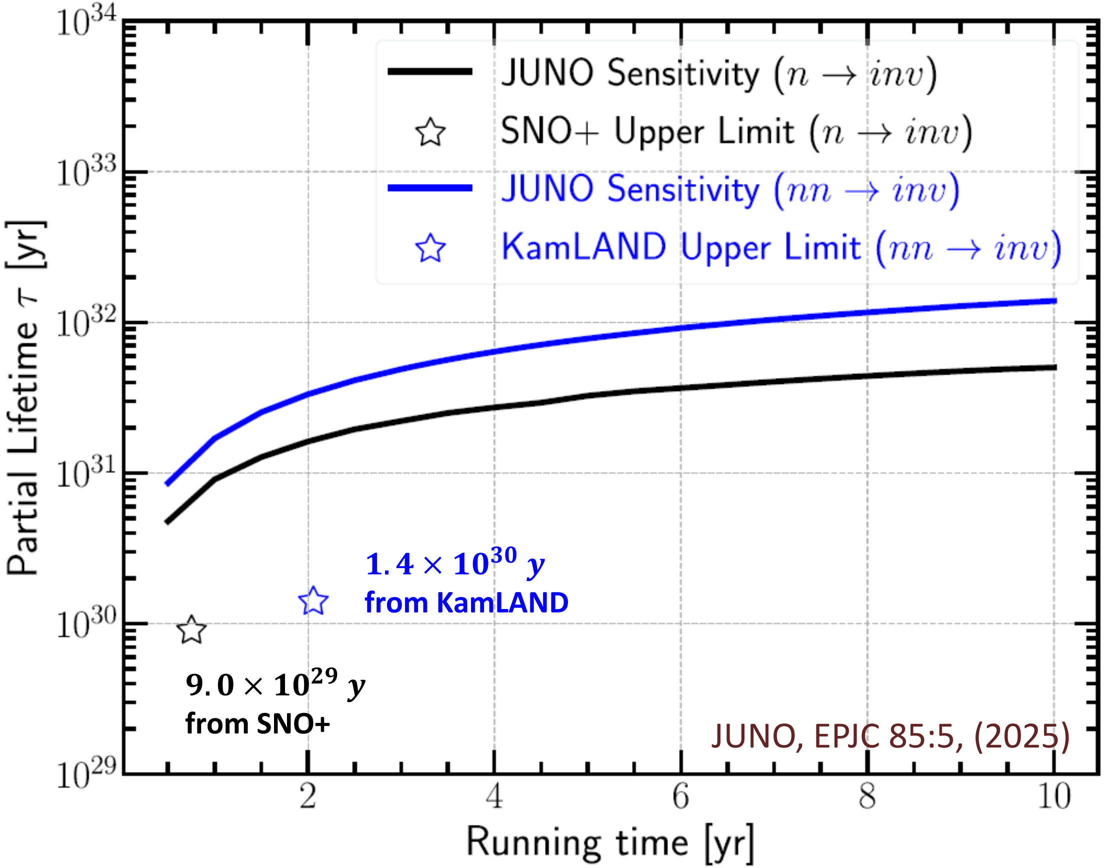
There are still lots of backgrounds after the basic selection. We employ the Pulse Shape Discrimination (PSD) and the Multivariate Analysis (MVA) techniques to suppress further.

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	0.89 ± 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	4.03 ± 0.70	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





JUNO sensitivity



$1.4\times 10^{32}\ y$

5.0×10^{31} y

$1.4\times 10^{30}\ y$
from KamLAND

$9.0\times 10^{29}\ y$
from SNO+

JUNO, EPJC 85:5, (2025)

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

Summary

- **JUNO has competitive sensitivities for some proton decay modes**
  - ✓ $\tau/B(p \to \bar{\nu}\, K^+) > 0.96 \times 10^{34}\ \mathrm{yrs}$
  - ✓ $\tau/B(n \to inv)\ > 5.0 \times 10^{31}\ \mathrm{yrs}$
  - ✓ $\tau/B(nn \to inv) > 1.4 \times 10^{32}\ \mathrm{yrs}$

90% CL

- **After 17 years efforts, from idea to construction, JUNO detector is fully completed, despite numerous challenges**

- **Initial testing and performance studies show that key specifications have been mostly met**

- **More physics results on proton decays and relevant new physics will come in future**