Highlights of nucleon decay searches at JUNO

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Supersymmetry Grand Unified Theory (SUSY-GUT) proton decay

Has SU(5) SUSY been ruled out?

Smoking gun of SUSY over classical GUT

If $p \to \bar{\nu} K^+$ dominates $p \to e^+ \pi^0$.

arXiv:2202.01404, 2203.08771

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- Minimal SUSY SU(5): 10^{28} year to 10^{32} year, ruled out.
- SUGRA SU(5): 10^{32} year to 10^{34} year.
- SUSY SU(5) in 5D: 10^{34} year to 10^{35} year.

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We need to reach 10^{35} year scale!

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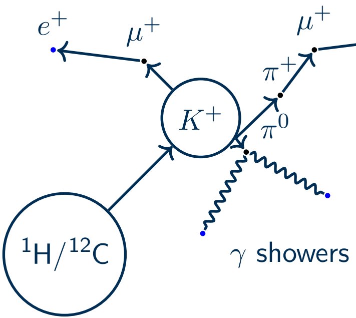
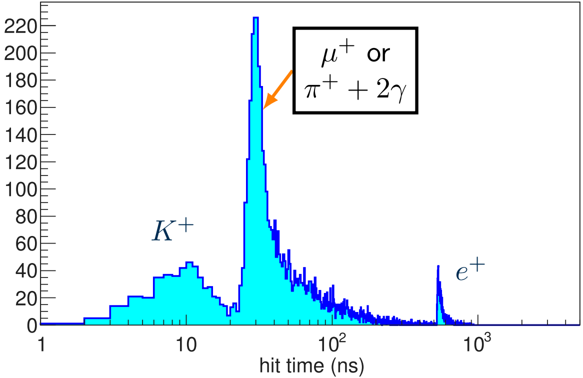
Signatures of K^+: need for large liquid scintillator





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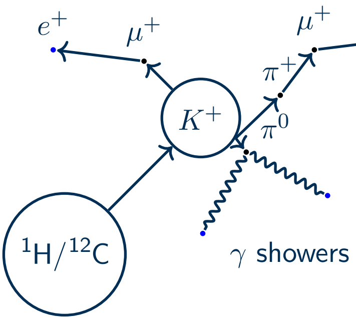
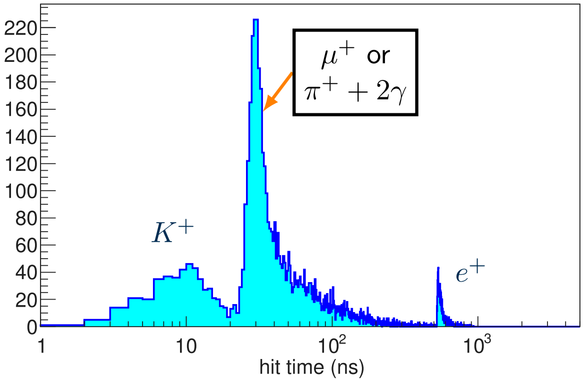
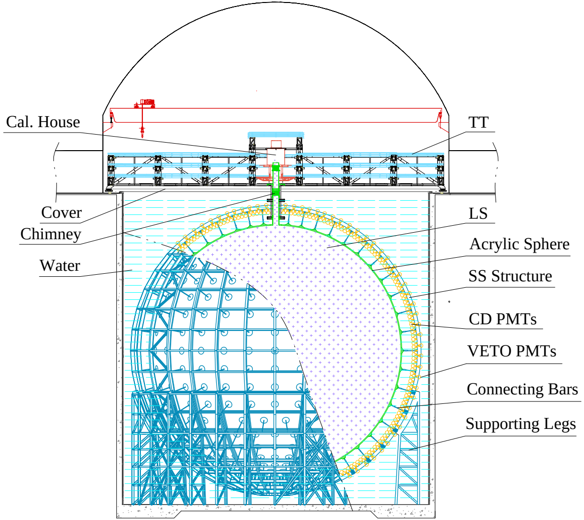




- K^+ is below Cherenkov threshold in water, invisible. So is μ^+ from π^+.
  - SK uses the γ ray from ^{15}N de-excitation.
- Liquid scintillator is ideal for identifying K^+.
  - Scintillation photons from mesons and muons with low kinetic energy.
- Investigated by Undagoitia et al. 2005 and realized by KamLAND 2015.

JUNO: the large liquid scintillator to be online



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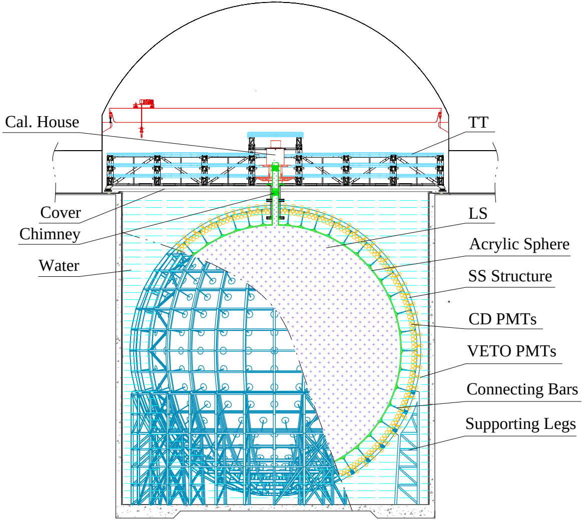

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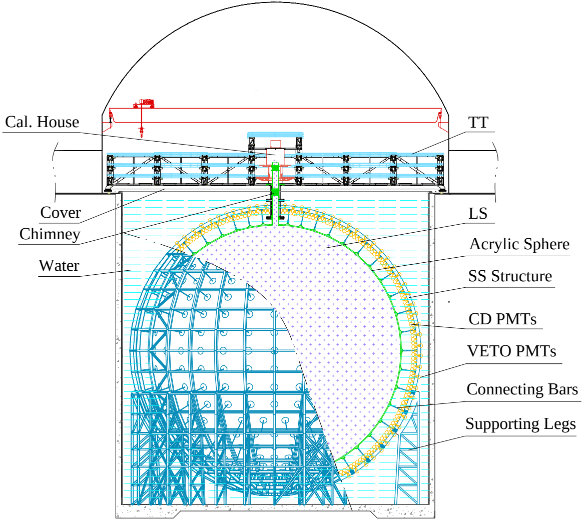

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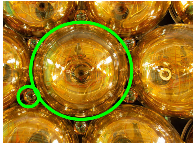

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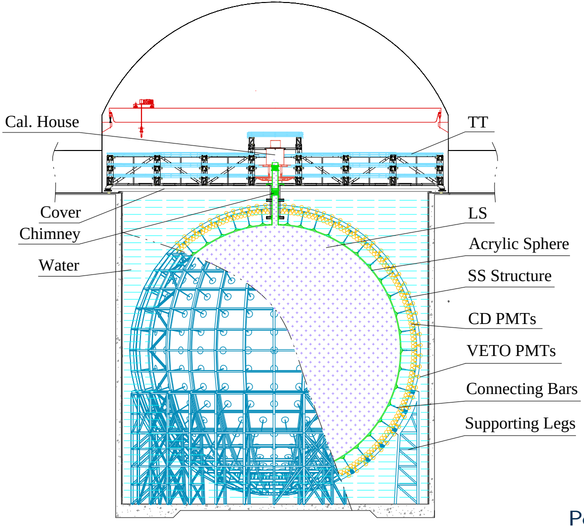

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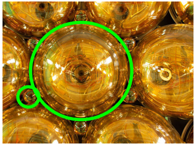
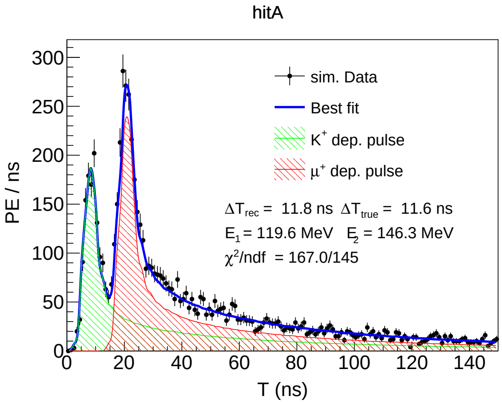
  - 3-inch PMTs' dynamic range is larger without saturation, suitable for K^+ ~ 0.5 GeV.



Poster #177

Fitting of multiple pulses on 3-inch PMT hits

1. Vertex reconstruction, with photon time-of-flight correction.



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- μ's form lines, time-of-flight correction is not perfect.

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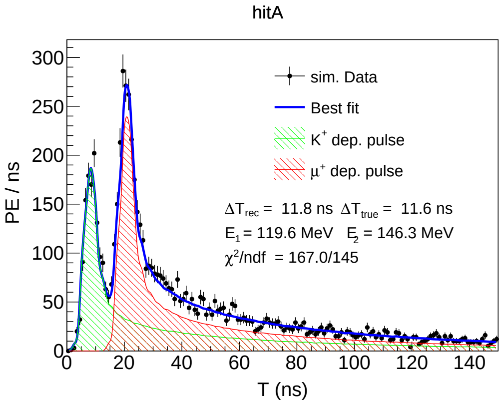

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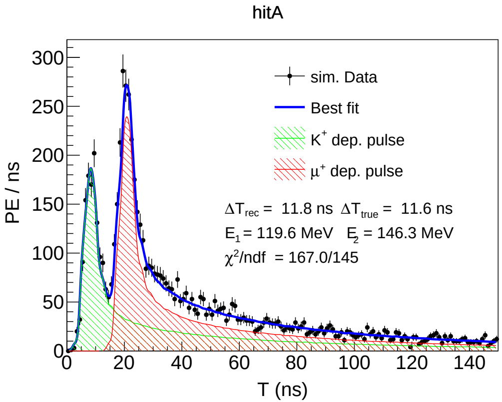

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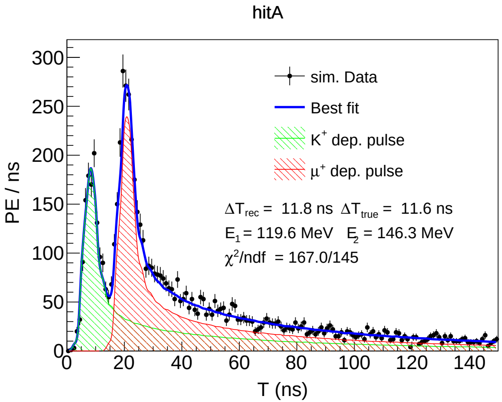

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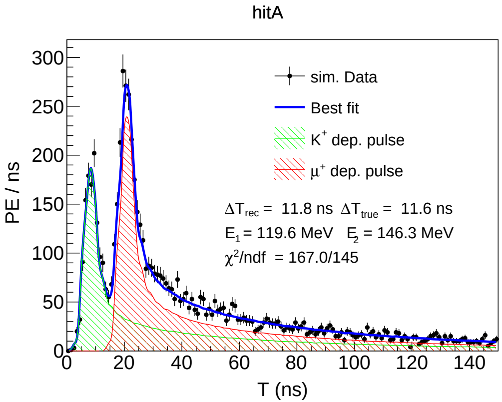
4. Discriminate among hypotheses by χ^2 ratios (F-statistic).



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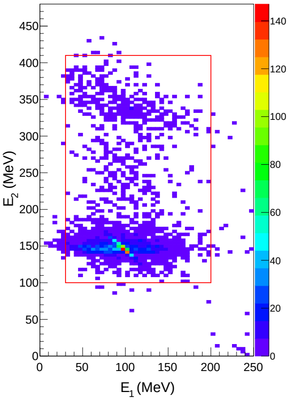
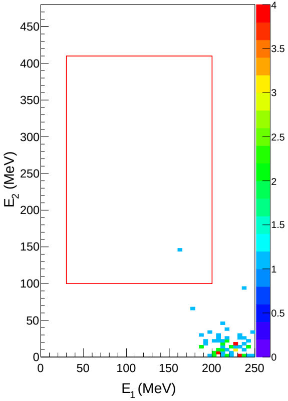
Individual pulse energies

- Scatter individual pulse energies on a plot.



K^+



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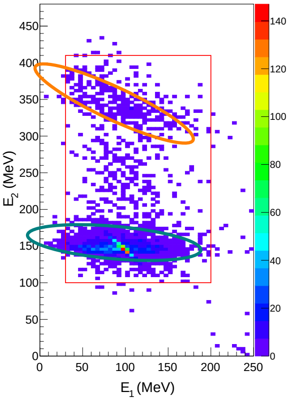

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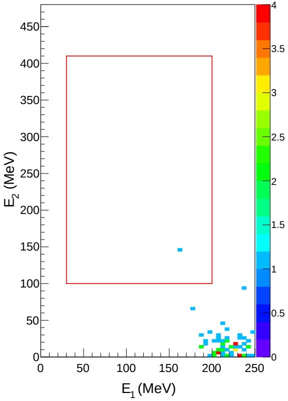

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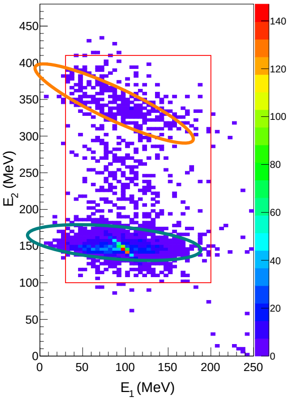

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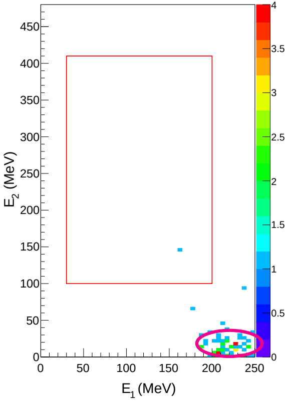

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- Mostly only one peak for background.

Simulation setup

Event generator

- GENIE[1] 3.0.2 for atmospheric ν events.
  - Final state interaction taken into account.

Excited residual nuclei

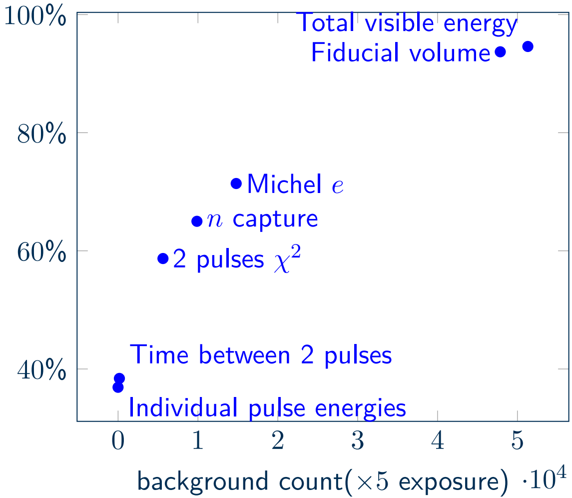
- Customize GENIE to generate K^+ and the excited energy spectrum of residual nuclei.
  - TALYS[2] 1.95 with excited energy spectrum as input to handle de-excitations.

Detector response simulation

- JUNO-customized GEANT4[3] for energy deposition and scintillation optics.
- K^+ and atmospheric ν are uniformly distributed in the liquid-scintillator sphere.

[1] https://hep.ph.liv.ac.uk/~costasa/genie/
[2] https://www-nds.iaea.org/talys/
[3] https://geant4.web.cern.ch/ https://sniper-framework.github.io/

Evolution of signal efficiency



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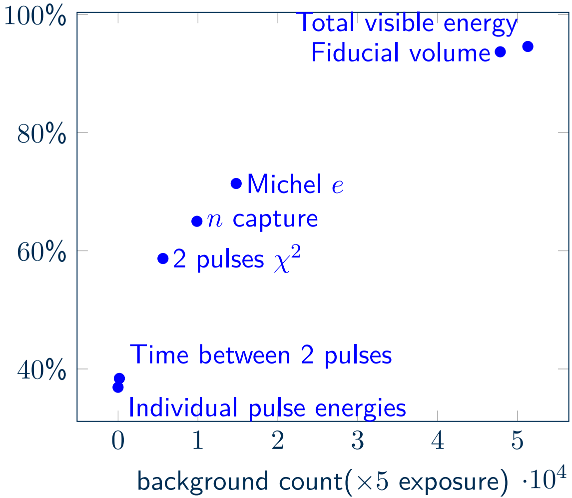

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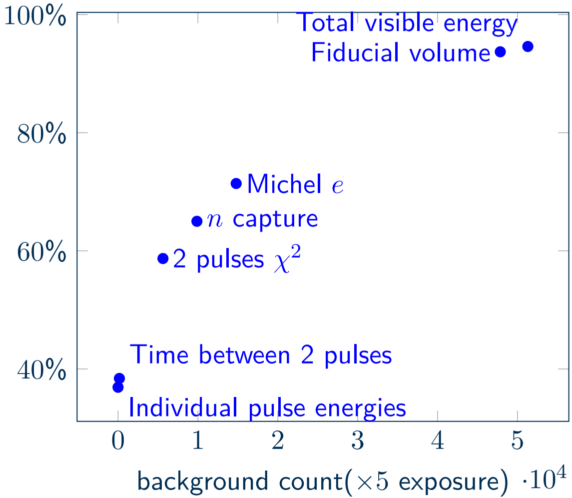

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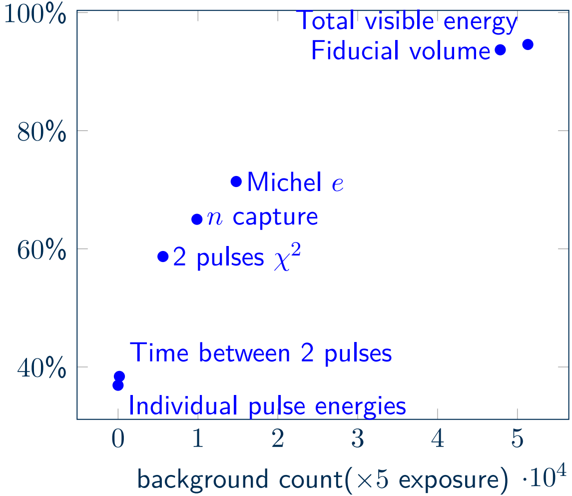

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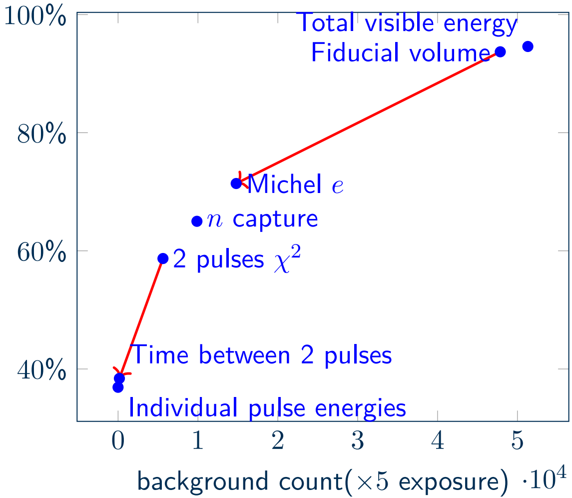

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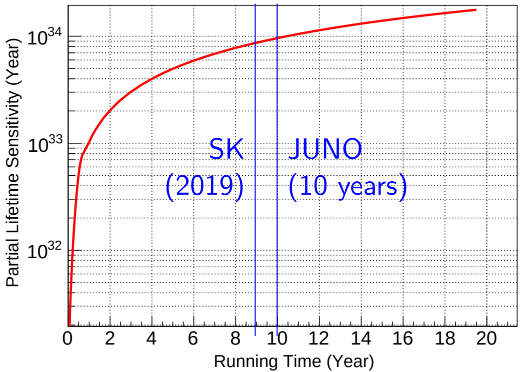
Sensitivity for $200\,\mathrm{kt}\cdot$ year exposure[4]

- JUNO $20\,\mathrm{kt}$ for 10 years.



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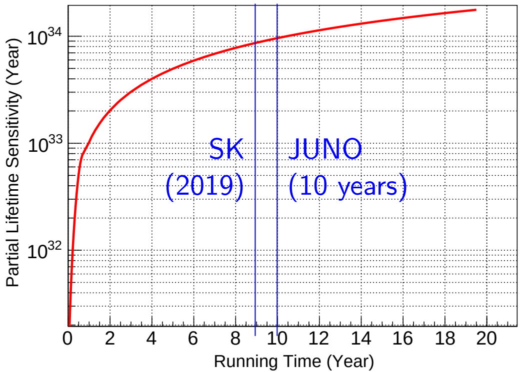

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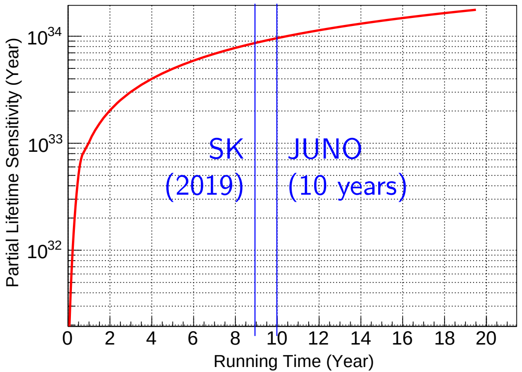

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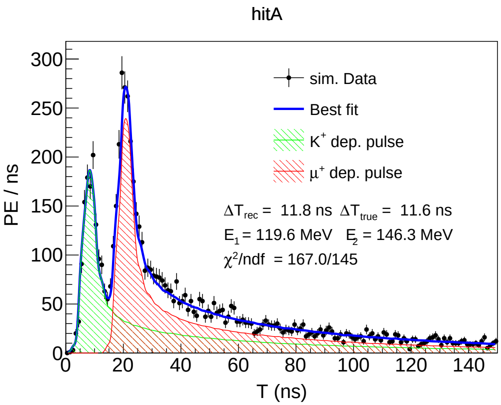
Future developments

- Better K-π and K-μ templates sensitive to event locations and directions.



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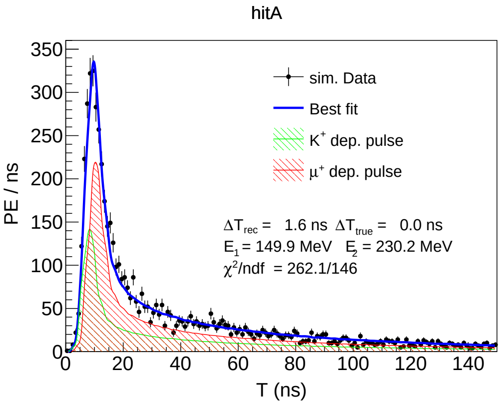

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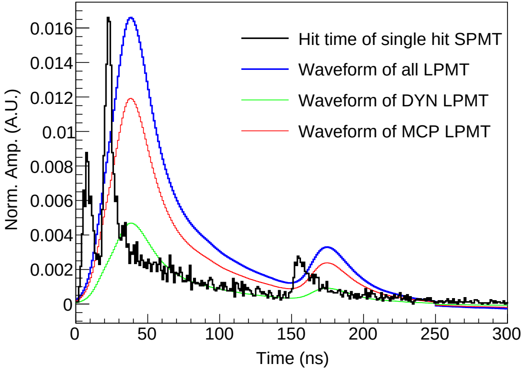

[5] based on arXiv:2403.03156, poster #210

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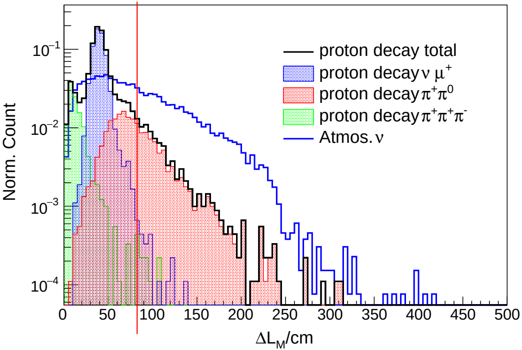
- Deploy 20-inch PMTs, solve waveform pile-up and saturation[5].
- Multi-point & line-shaped reconstruction for μ and Michel electrons.
  - The $N_M \in [1, 2]$ and $\Delta L_M \leq 80\,\text{cm}$ cut may be replaced by a better μ reconstruction.

ΔL_M cut



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Ongoing studies: invisible neutron decay

- Two invisible decay modes of neutron in ^{12}C:
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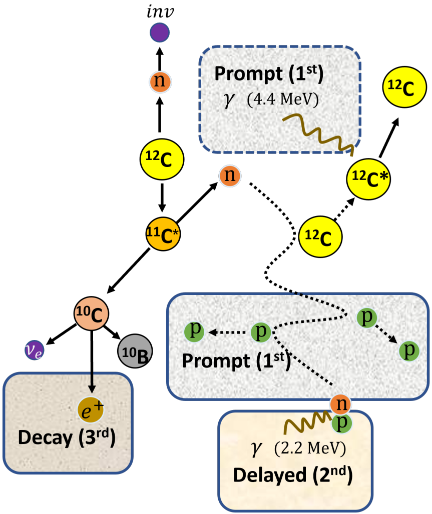

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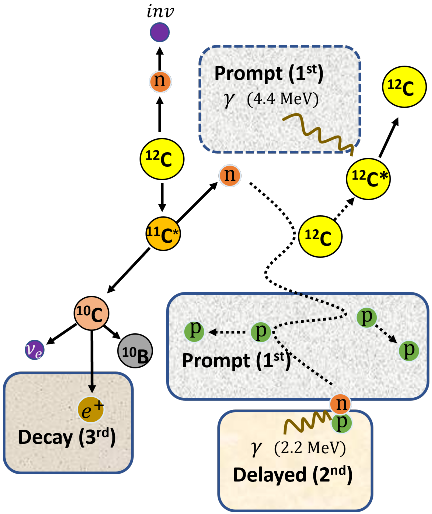

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- Sensitivity of 10 years data taking, at $90\,\%$ C.L.:
  - $\tau/B(n \rightarrow \mathrm{inv}) > 5.0 \times 10^{31}$ year
    - ★ ...at $26.7\,\%$ efficiency.
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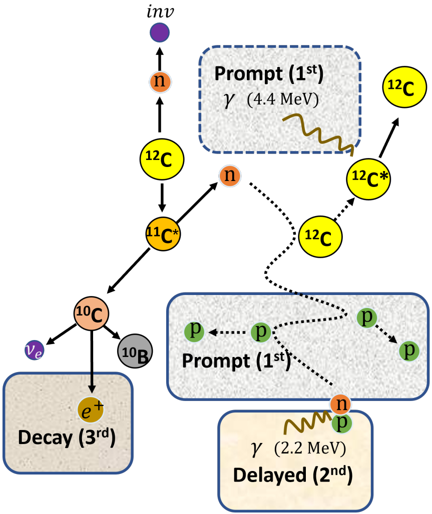
    - ★ ...at $42.3\,\%$ efficiency.



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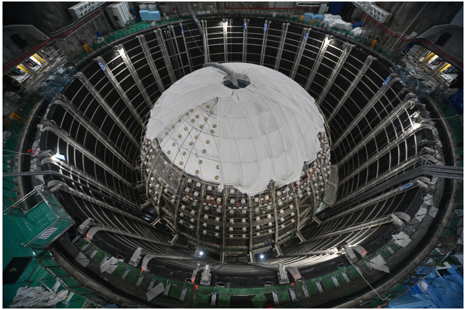

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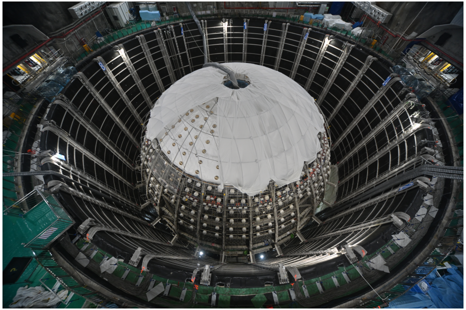

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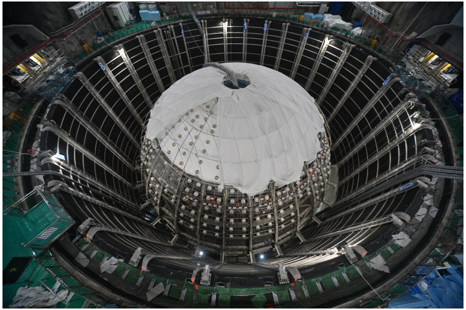

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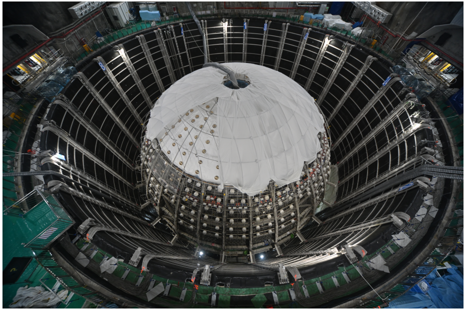

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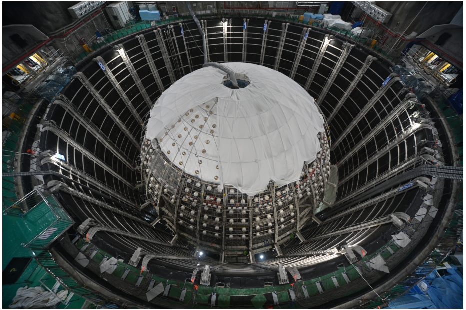

Summary and Outlook

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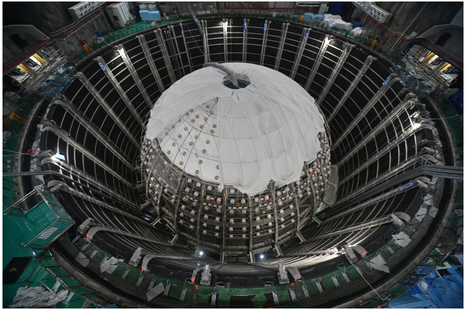

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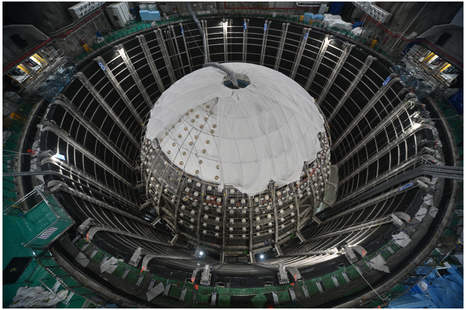
- JUNO is under detector assembly. Stay tuned!



Pre-fitting cuts

$E_{\text{vis}} \in [200, 600]$MeV reconstructed visible energy, smeared with $\mathcal{N}(0, \sigma_E)$ on MC truth.

$R \in [0, 17.5]$m reconstructed radius, smeared with $\mathcal{N}(0, 0.3)$m on MC truth.

$N_M \in [1, 2]$ number of Michel electrons.

$\Delta L_M \leq 80\,\text{cm}$ average distance between Michel electrons and locations of energy deposition

$\forall N_M = 1, N_n \leq 3$ number of neutron captures.

$\forall N_M = 1 \& N_n \in [1, 3], \Delta L_n \leq 70\,\text{cm}$ average distance between neutron captures position and location of energy deposition

Customize GENIE

- Consider nuclear shell structure. Calculate proton mass considering binding energy.
- Turn on the hadron-nucleon model, for $K^{+}n \rightarrow K^{0}p$ interaction.
  - FSI: final state interaction