Sensitivity Study of Nucleon Decay Search at JUNO

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Department of Engineering Physics
Center for High Energy Physics
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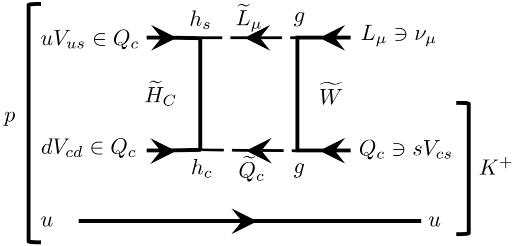
CoSSURF 2022-05-12

SUSY-GUT dimension-five proton decay



Smoking gun of SUSY over classical GUT

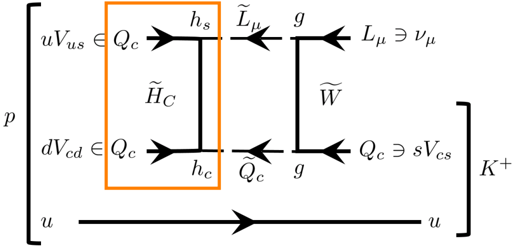
If $p \to \bar{\nu} + K^+$ (dimension-five) dominates $p \to e^+ + \pi^0$ (dimension-six).

- Has minimal SU(5) SUSY been ruled out by SuperK 2014?
  - Absence of SUSY partners at LHC $O(1\,\text{TeV})$.

arXiv:2202.01404

SUSY-GUT dimension-five proton decay

- Dimension-five operator with Colored Higgs exchange.



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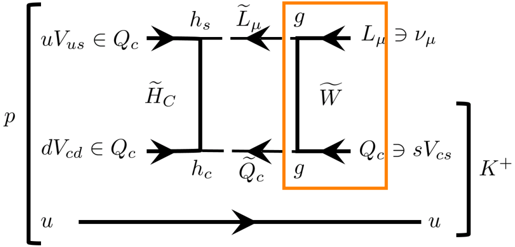

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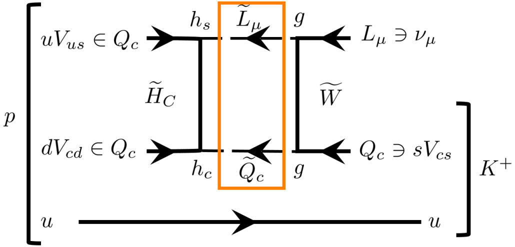

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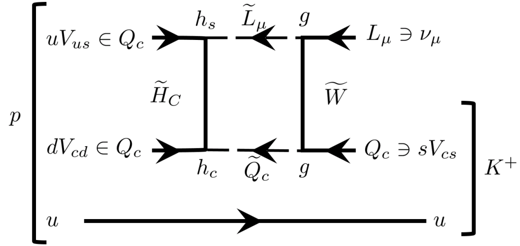

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  - Absence of SUSY partners at LHC $O(1\,\text{TeV})$.
- squark and slepton could be much heavier ($\sim$1000 TeV) than we thought.
- SU(5) SUSY-GUT possibly at 1×10^{35} year scale!

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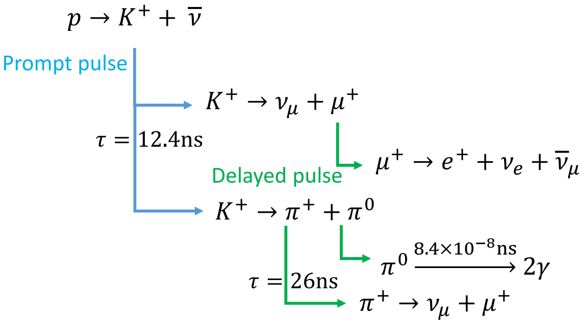
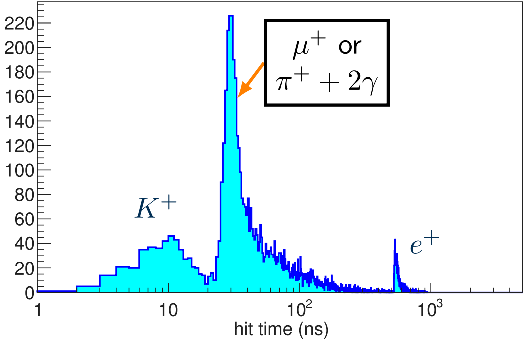
Signatures of K^+: need for large liquid scintillator





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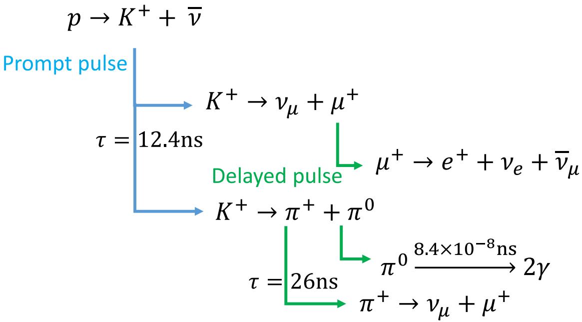
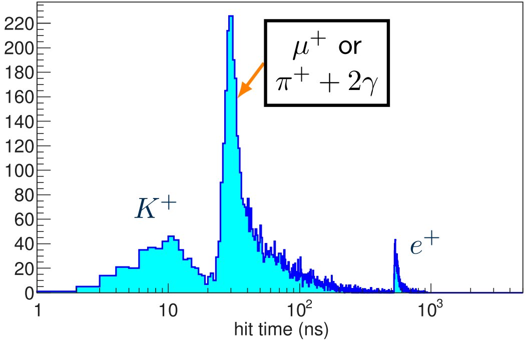
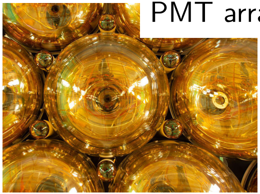
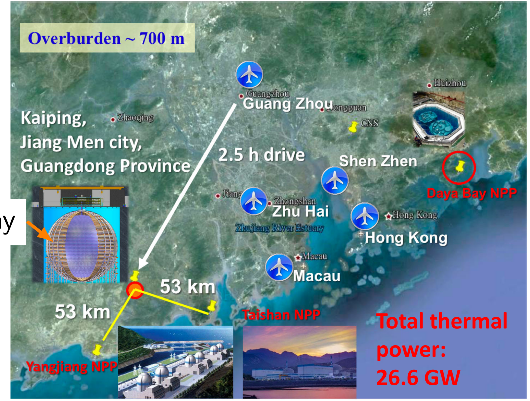


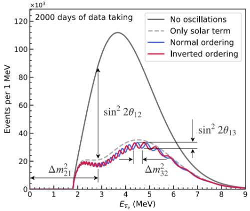


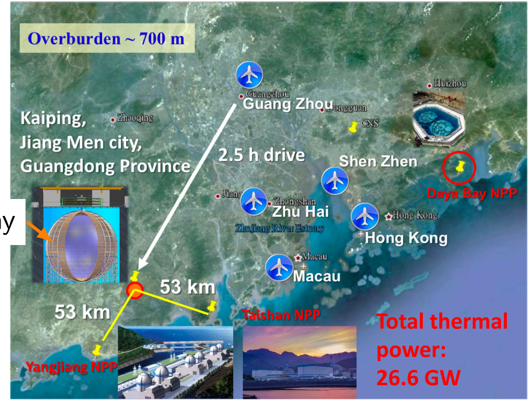
- K^+ is below Cherenkov threshold in water, invisible. So is μ^+ from π^+.
  - Searching for μ^+ or $\pi^+ + 2\gamma$ alone has background.
- Liquid scintillator is ideal for identifying K^+.
  - Scintillation photons from mesons and muons with low kinetic energy.
- Investigated by Undagoitia et al. 2005 and realized by KamLAND 2015.


PMT array


Overburden ~ 700 m
Kaiping,
Jiang Men city,
Guangdong Province
Zhaoqing
Guangzhou
Guang Zhou
Dongguan
CNS
Huizhou
2.5 h drive
Shen Zhen
Daya Bay NPP
Zhongshan
Zhu Hai
Zhujiang River Estuary
Hong Kong
Hong Kong
Macau
Macau
53 km
53 km
Taishan NPP
Yangjiang NPP
Total thermal
power:
26.6 GW

JUNO: the large liquid scintillator to be online





- Major target: neutrino massing ordering.
- Need unprecedented liquid-scintillator energy resolution of 3% at 1 MeV.

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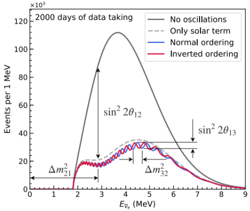

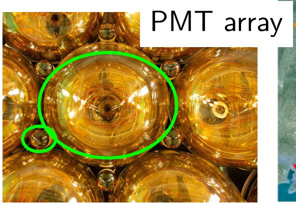

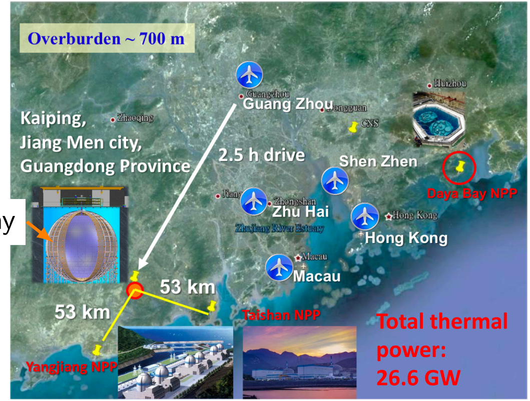

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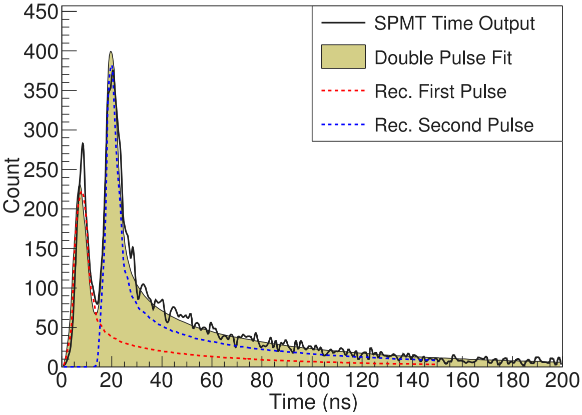
- 17612 20-inch PMTs and 25600 3-inch PMTs cover 78% of the liquid-scintillator sphere.
  - 3-inch PMTs dynamic range is larger without saturation, suitable for K^+ ~0.5 GeV.

Fitting of multiple pulses on 3-inch PMT hits

1. Vertex reconstruction, subtract photon time-of-flights.



Caveat

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

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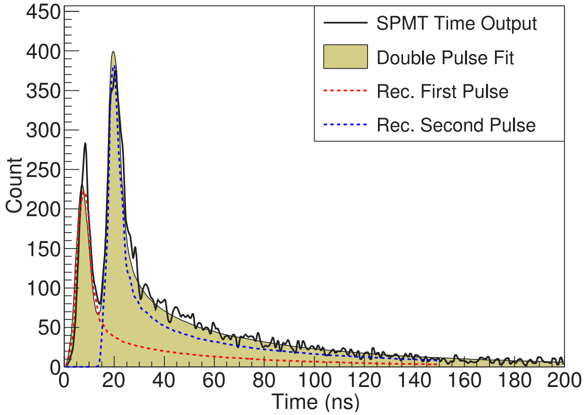

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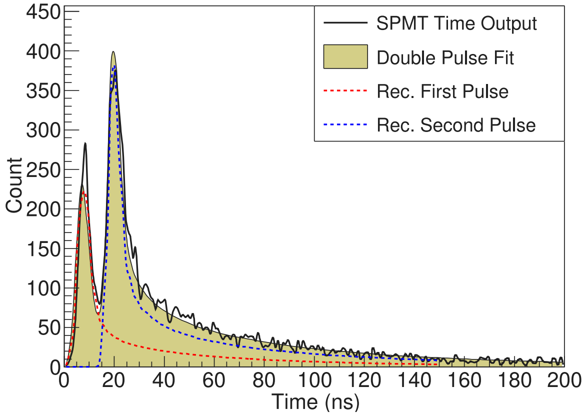

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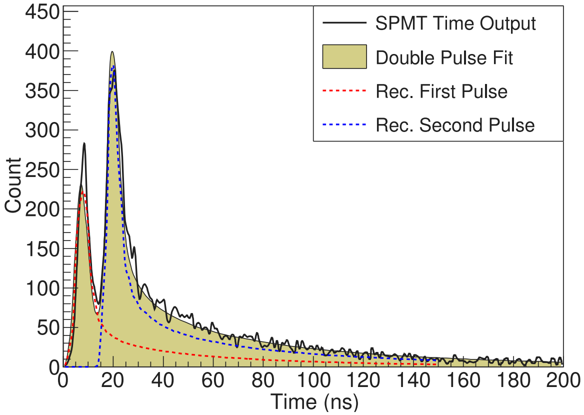

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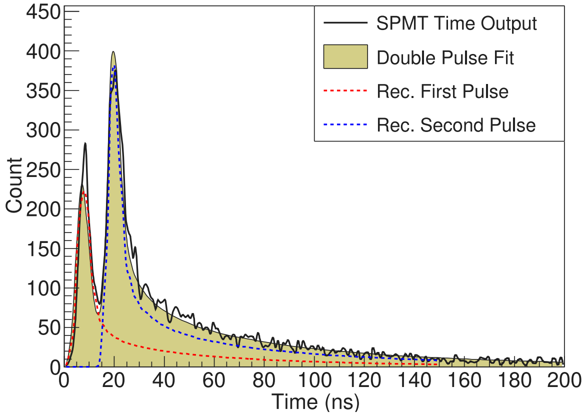
4. Discriminate among hypotheses by χ^2 ratios (F-statistic).



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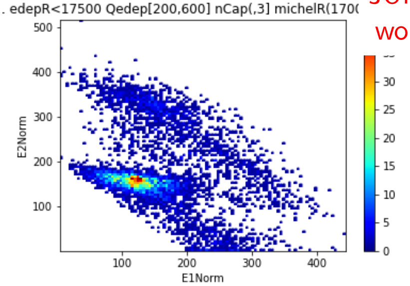
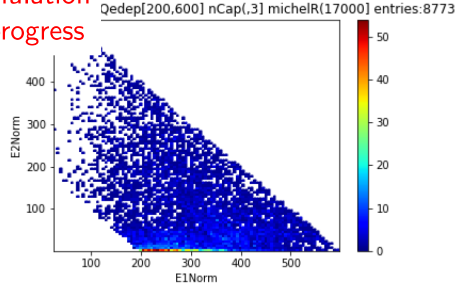
Individual peak energies

- Scatter individual peak energies on a plot.

JUNO simulation
work in progress



K^+



atmospheric ν

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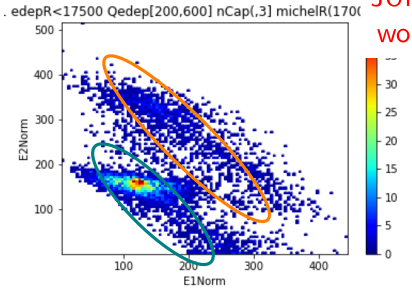

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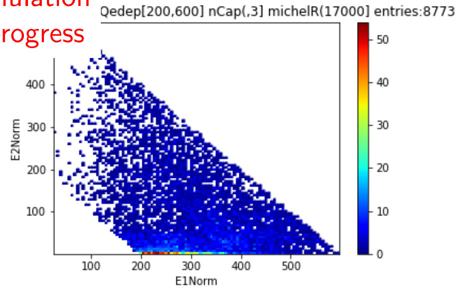

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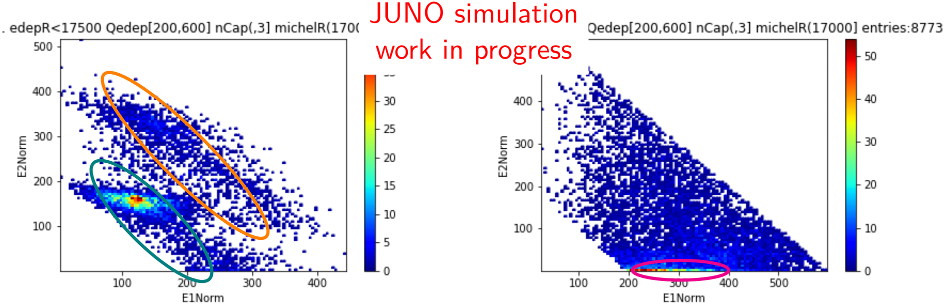

K^+ atmospheric ν

- $K^+ \to \pi^+ + \pi^0(2\gamma)$
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- mostly only one peak for background.

Simulation setup

Event generator

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

Excited residual nuclei

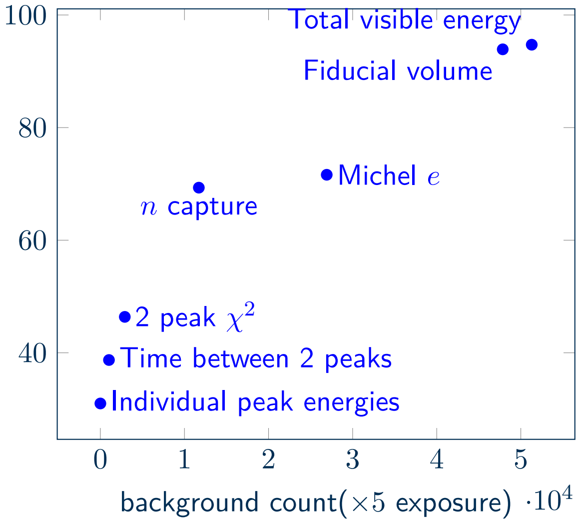
- Customize GENIE to handle the excited states of residual nuclei.
  - Supplimented by TALYS[2] for $^{11}B^*$.

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/

Evolution of signal efficiency



- 31% efficiency for background level 0.3.

Remarks

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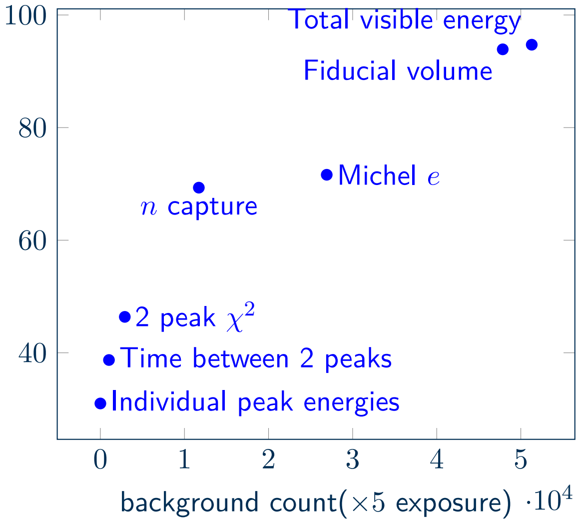

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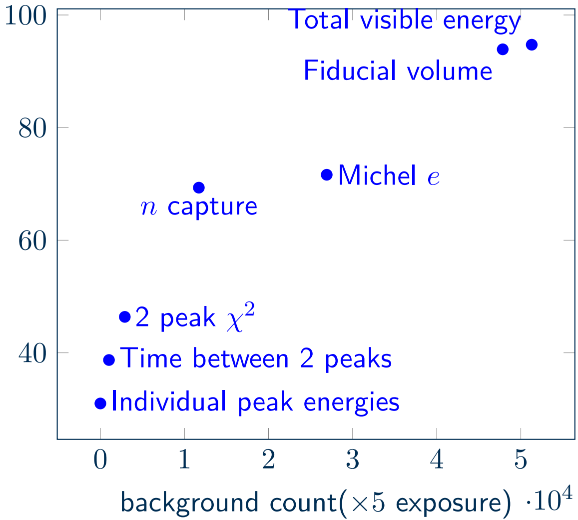

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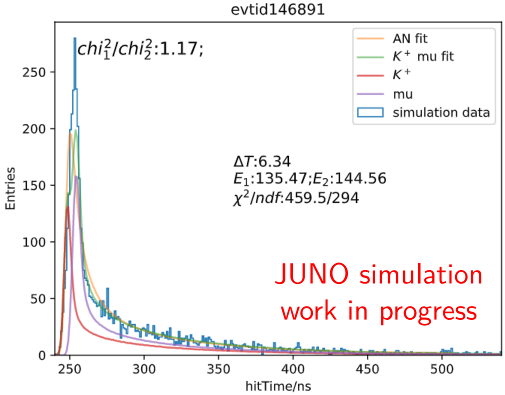
- SuperK searches by prompt deexitation γ at 9.1%, $\pi^+\pi^0$ at 10% and mono-energetic μ with background.

Background example: quasi-elastic scattering of atmospheric ν

$$\nu_\mu + {}^{12}\text{C} \to p + \mu^- + {}^{11}\text{C}$$



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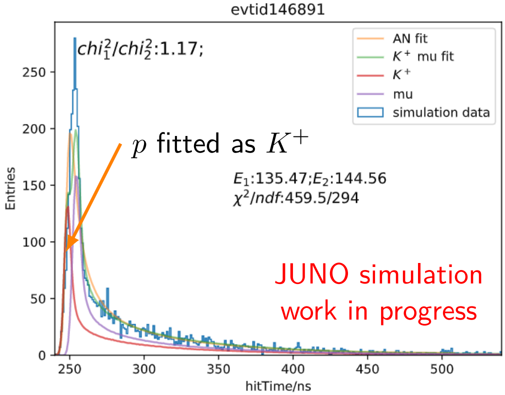

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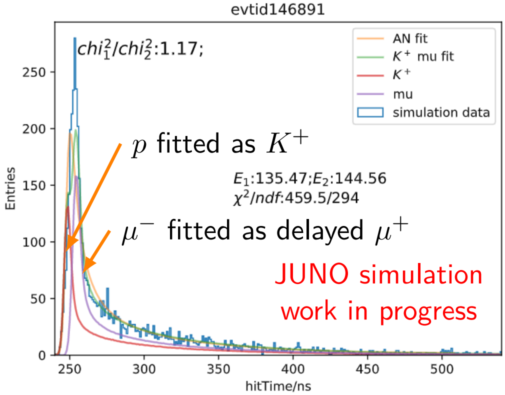
- "Delayed" μ^- peak is simultaneous as p but starting time is mis-identified. Possible improvements:
  - line-shaped energy deposition model for μ^-.
  - $\mu^\pm$ discrimination.



Projected sensitivity

- Sensitivity for 200 kton · year exposure
  - JUNO 20 kt for 10 years.
  - $\tau(p \to K^+ + \bar{\nu}) > 0.834 \times 10^{34}$ year at 90% C.L.
  - Background-free search: scales linearly with exposure.
- on *JUNO physics and detector*, Progress in Particle and Nuclear Physics 2022

[4] based on `https://arxiv.org/abs/2112.06913`

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Future developments

- Identify μ with both Michel e and line-shaped energy deposition.
- Better K-π and K-μ templates sensitive to event locations and directions.
- Deploy 20-inch PMTs, solve waveform pile-up and saturation[4].
- Other K^+ decay modes: 3π , $e^+ + \nu_e$, semileptonic.

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On-going studies

- $n \to 3\nu$
- $p \to \mu^+ + \mu^- + \mu^+$

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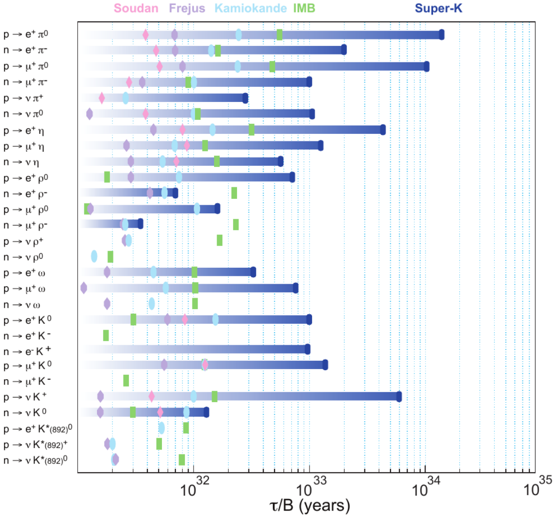
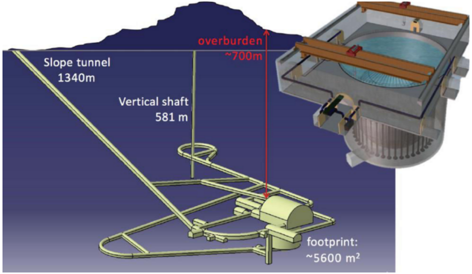


How to build a 20 kt detector: project status



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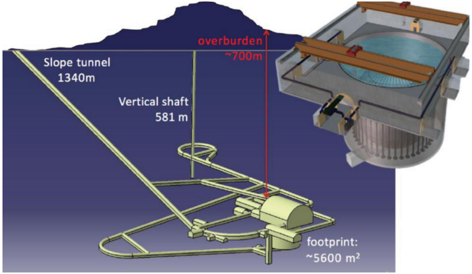

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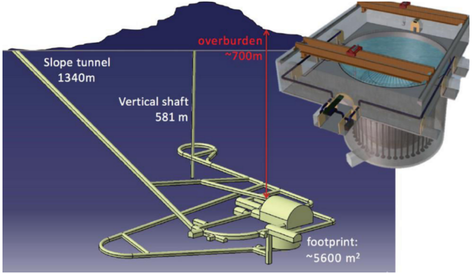

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Next key milestones

1. Central detector installation
2. PMT installation
3. Filling

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- JUNO is under detector assembly. Stay tuned!

Pre-fitting cuts

$Q_{edep} \in [200, 600]$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.

nMichel number of Michel electrons.

michelR average distance between Michel electrons and locations of energy deposition

nCapture number of neutron captures.

nTagR average distance between neutron captures position and location of energy deposition

Grand Unification Theory (GUT)

- Towards string theory, maximal subgroup in each step.

$$E_8 \to E_7 \to E_6 \to SO(10) \to SU(5) \to SU(3) \times SU(2) \times U(1)$$