Overview of Proton Decay Search Experiments

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Workshop on Grand Unified Theories: Phenomenology and Cosmology

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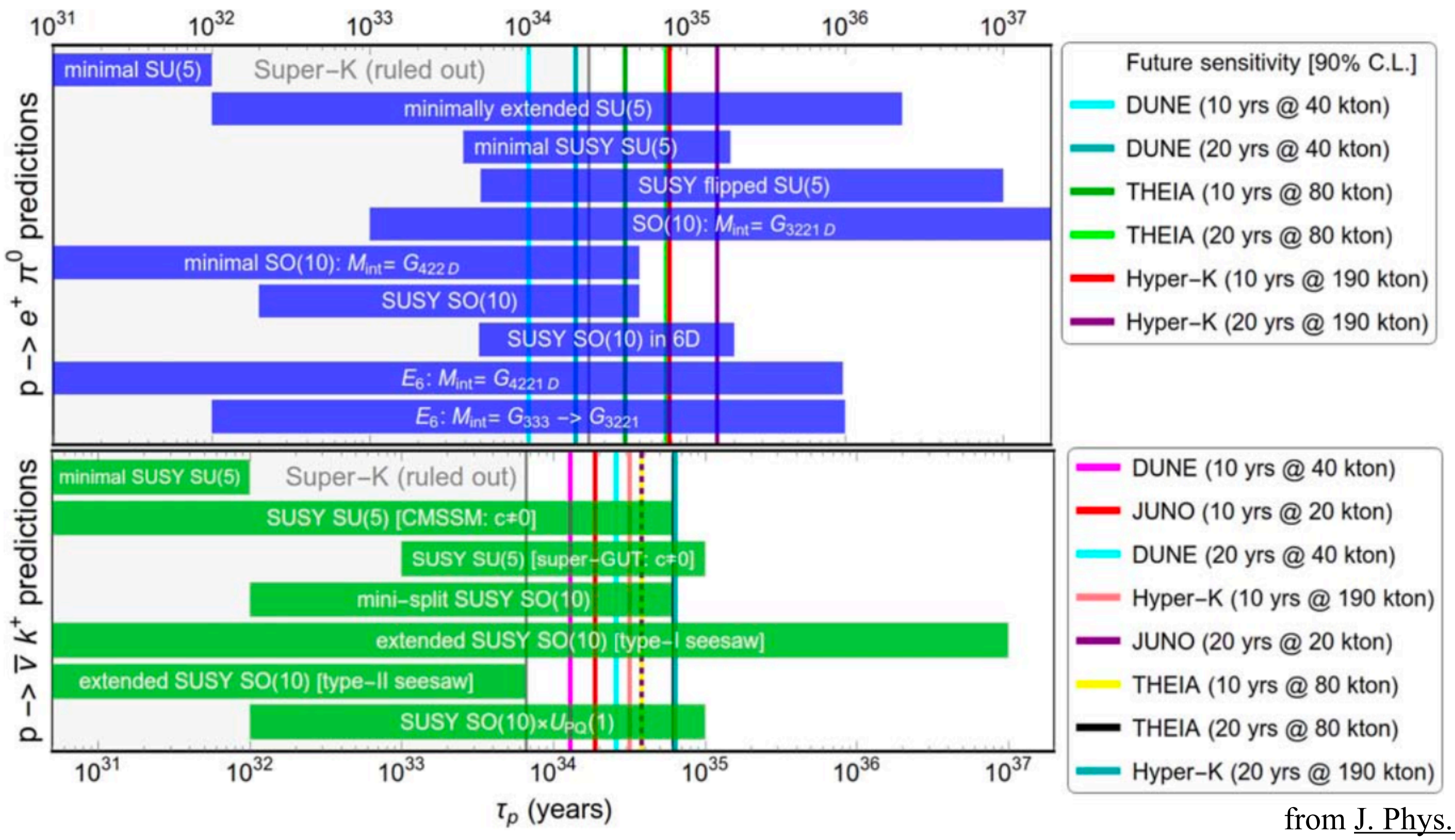
Introduction

- This presentation will overview the proton decay search experiments:
  - general detection principle/experimental challenges,
  - current limits on the proton lifetime,
  - future sensitivities.
- The speaker is an experimentalist, was working on Super-Kamiokande/Hyper-Kamiokande and now working on JUNO.

Work inside the Super-K detector

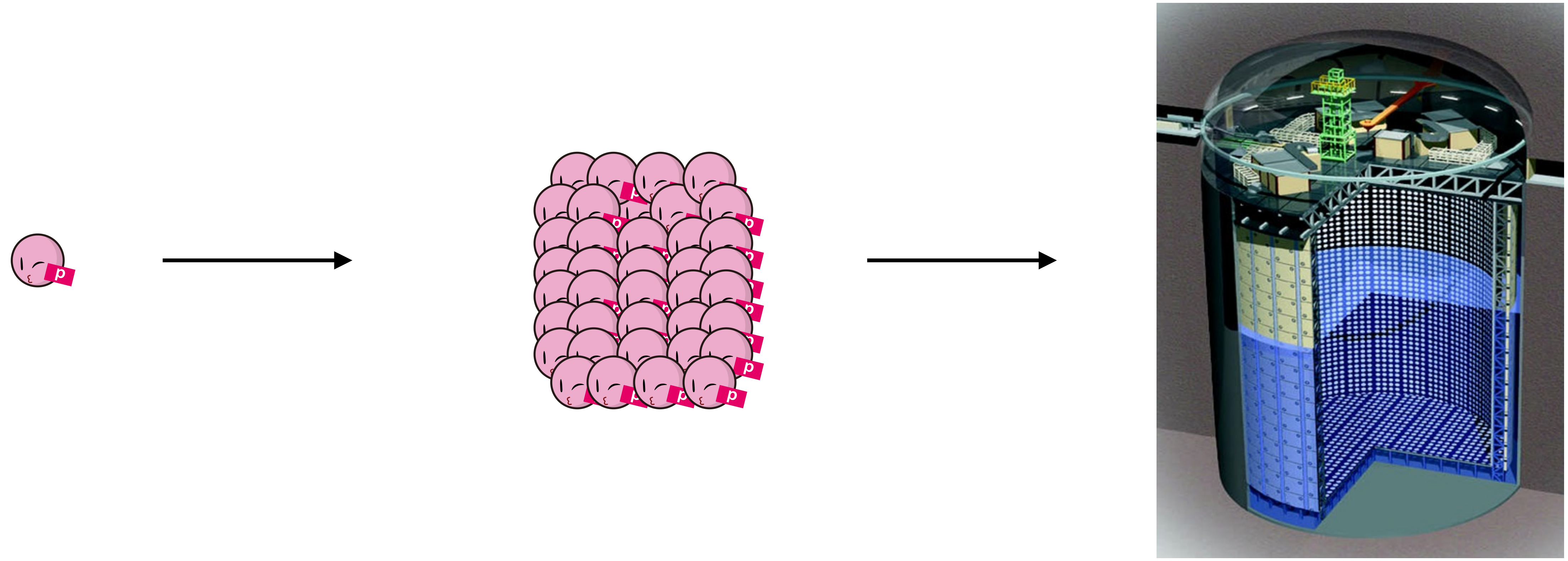
Proton Decay Search



from J. Phys. G: Nucl. Part. Phys., 51, 033001

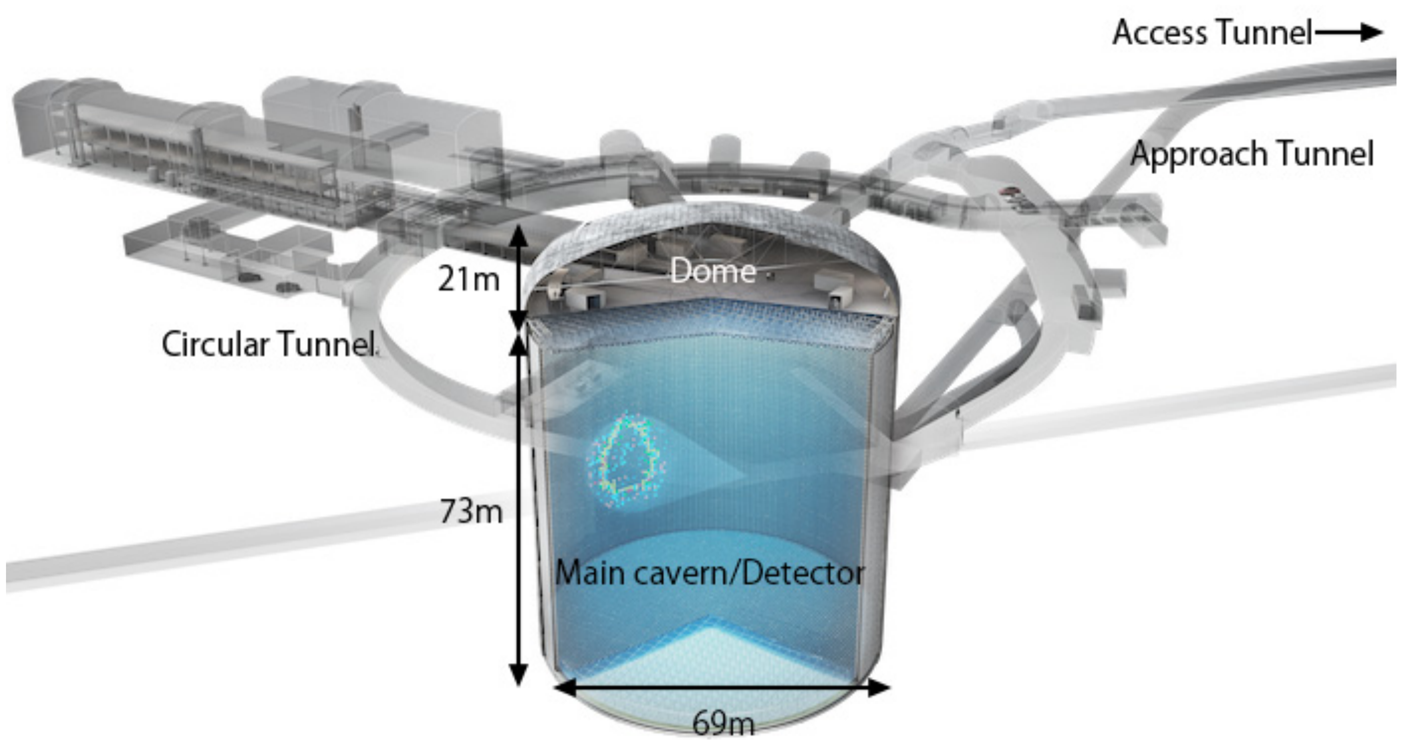
- The discovery of the proton decay would be strong evidence for Grand Unified Theories.
- Many experiments have searched for proton decay signals.
  - No positive observations so far…
- This presentation will describe the general characteristics of the proton decay experiments and introduce a few specific experiments.

Proton Decay Search Principles

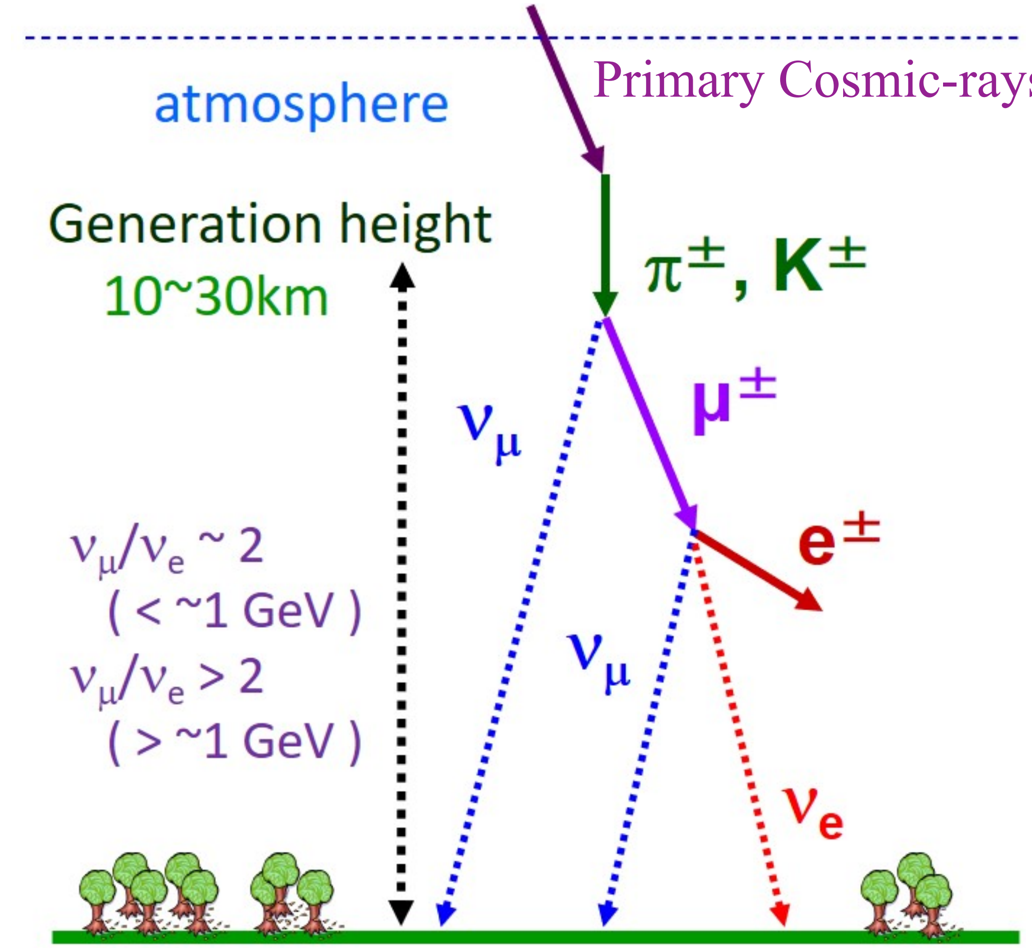


- Generally predicted proton lifetime ranges from $10^{\sim 30}$ years.
- It is impossible to discover its decay by monitoring a small number of protons.
  - It would take $10^{\sim 30}$ years to observe one proton decay.
- A gigantic detector is necessary to contain a huge number of protons as a detector material.
  - ex. Super-K contains $\sim 10^{34}$ protons in its water molecules.
- The proton decay search (discovery) potential basically depends on the size of the detector (number of protons) and background level.

Challenges in Proton Decay Search

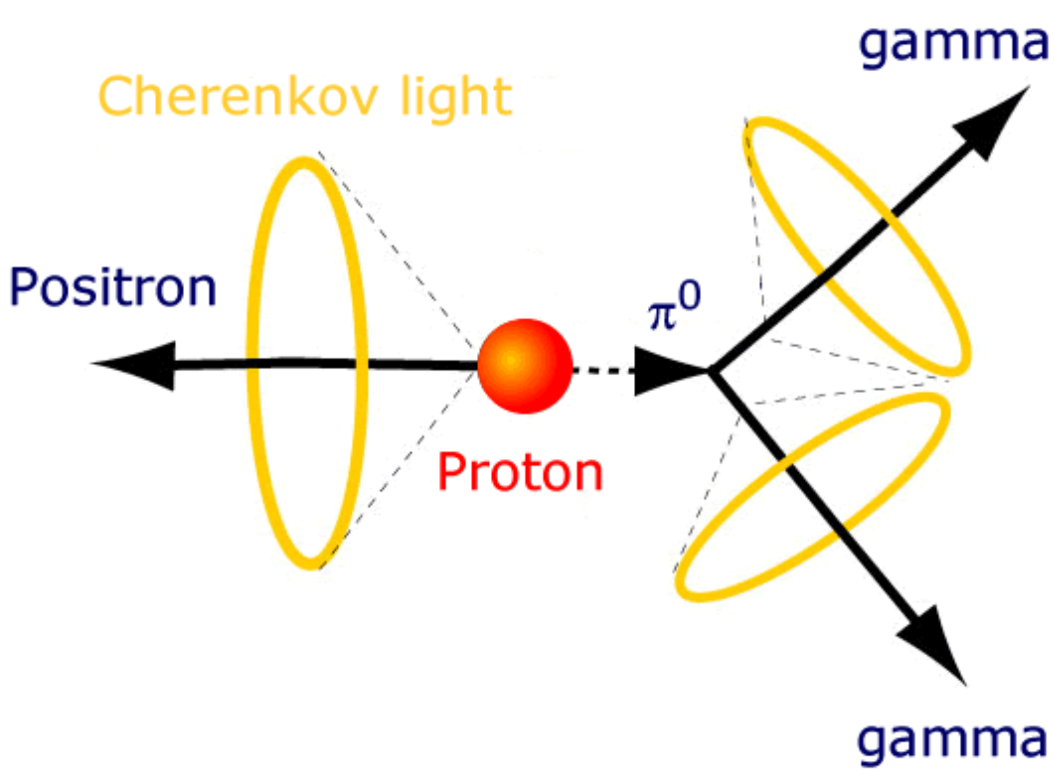


Hyper-K Illustration, world's largest cavern

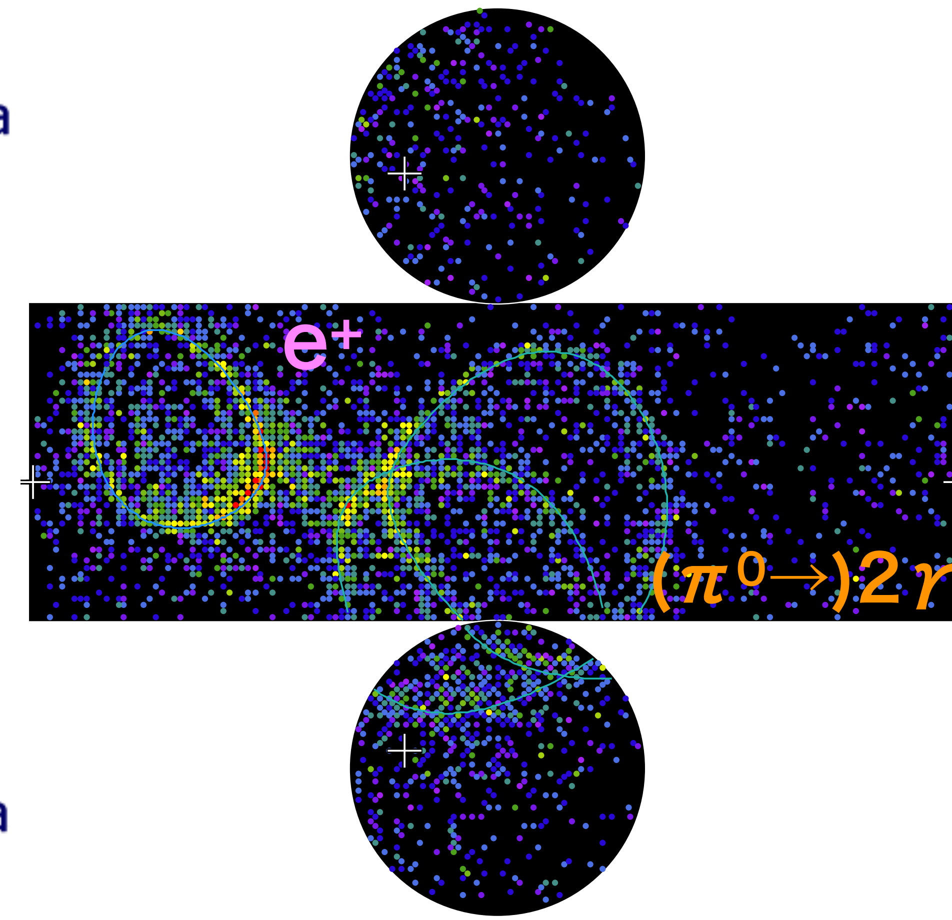


- **Practical challenge:** As a larger detector is required to enhance the proton decay search sensitivity, the financial and time costs for the experiment are increasing.
    - Hyper-K, JUNO, and DUNE: ~Billion RMB and several to ten years scale for the detector construction.
- **Scientific challenge:** Neutrinos produced in the atmosphere (atmospheric neutrinos) are the unavoidable backgrounds.
    - Atmospheric neutrinos interact with the detector material and the produced particles in the interaction mimic proton decay events

Current Proton Decay Search Status

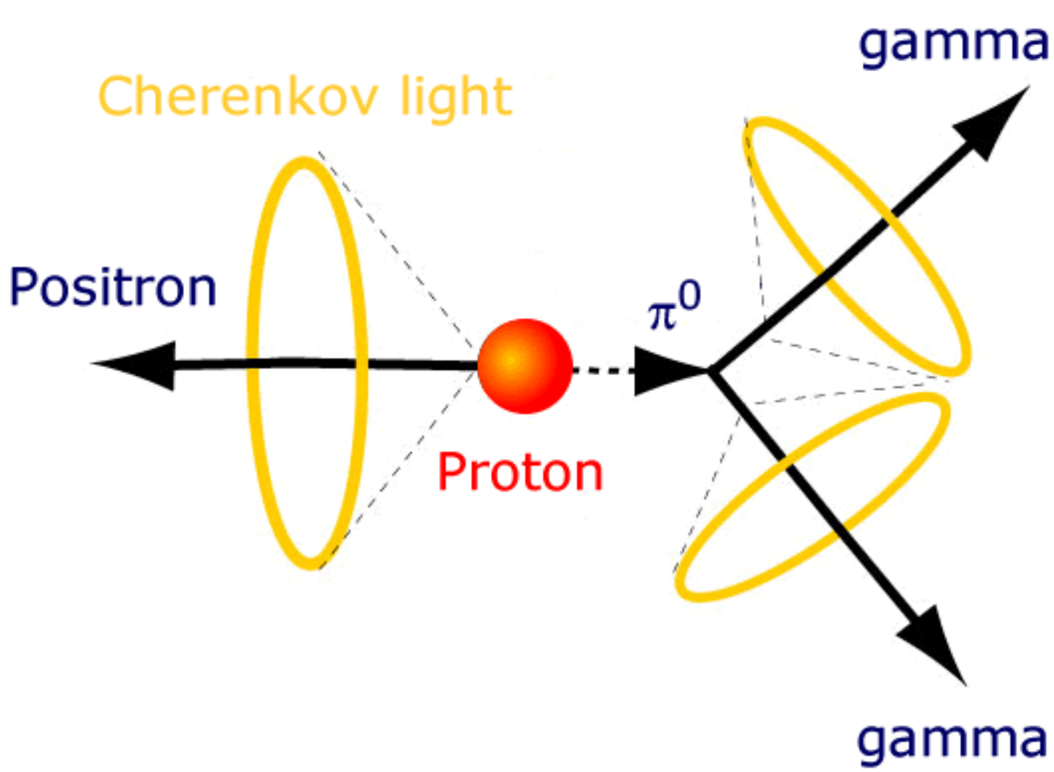


p→e+π0 MC event display

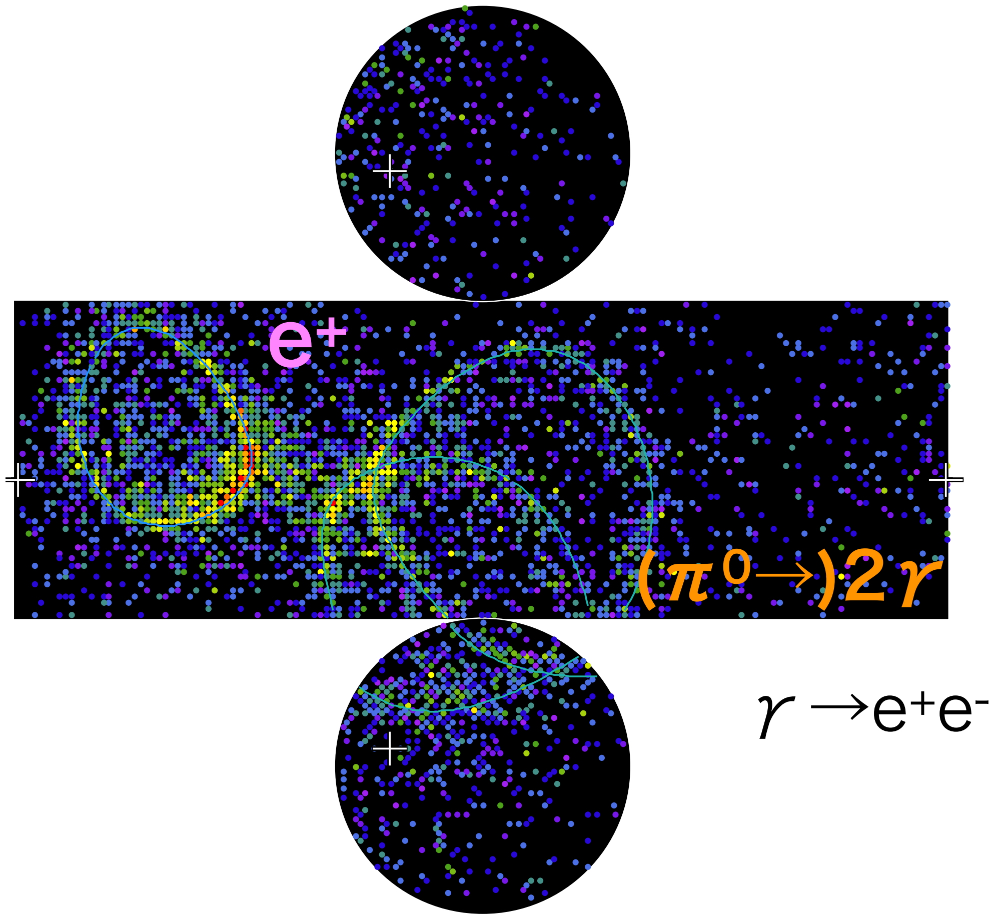


- The current lifetime limit for most of the proton decay modes is set by the Super-K experiment (~27 kton water mass).
  - A large water Cherenkov detector located in Kamioka, Japan.
  - ~11,000 photosensors are mounted on the detector wall.
- Lifetime limits for the two representative modes:
- $\tau/B(p \to e^+ \pi^0) > 2.4*10^{34}$ years (90% C.L.), Phys. Rev. D 102, 112011.
- $\tau/B(p \to \nu K^+) > 5.9*10^{33}$ years (90% C.L.), Phys. Rev. D 90, 072005.

Water Cherenkov Detector (1)



$p \rightarrow e^+\pi^0$ MC event display

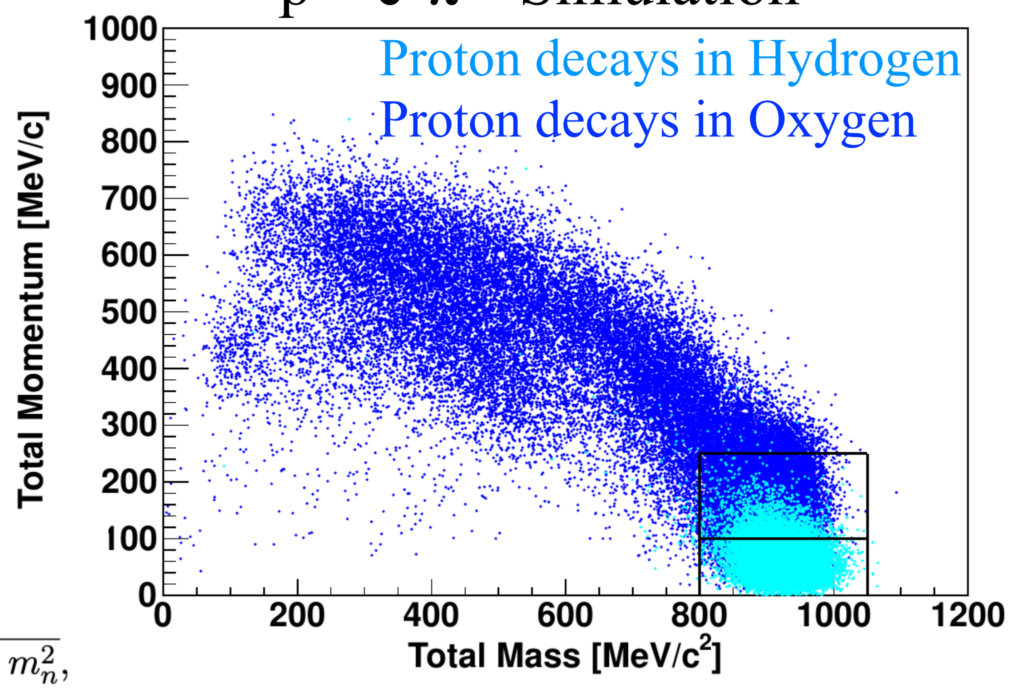


- Charged particles traveling faster than the speed of light in water emit Cherenkov light.
- By identifying the characteristic Cherenkov ring image obtained through the photosensors, the particle information is measured.
  - Particle type (either e or μ), direction, momentum/energy.
- Hyper-K (~200 kton water mass) is expected to launch in 2027.
  - The sensitivity will reach ~10^{35} years for the $p \rightarrow e^+\pi^0$ mode.

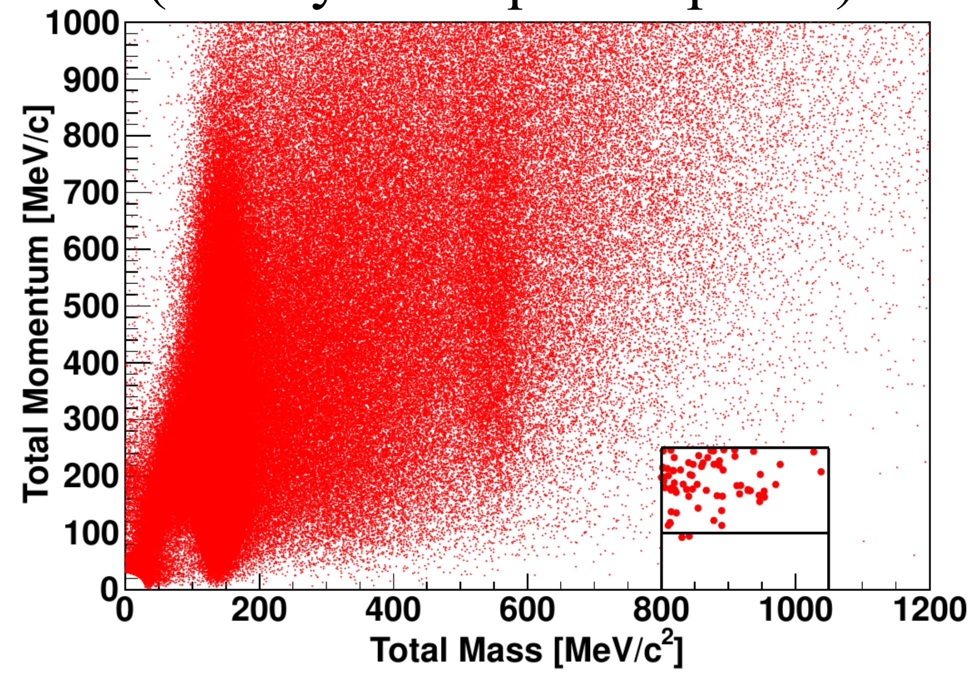
https://arxiv.org/abs/1805.04163

Water Cherenkov Detector (2)

p→e⁺π⁰ Simulation



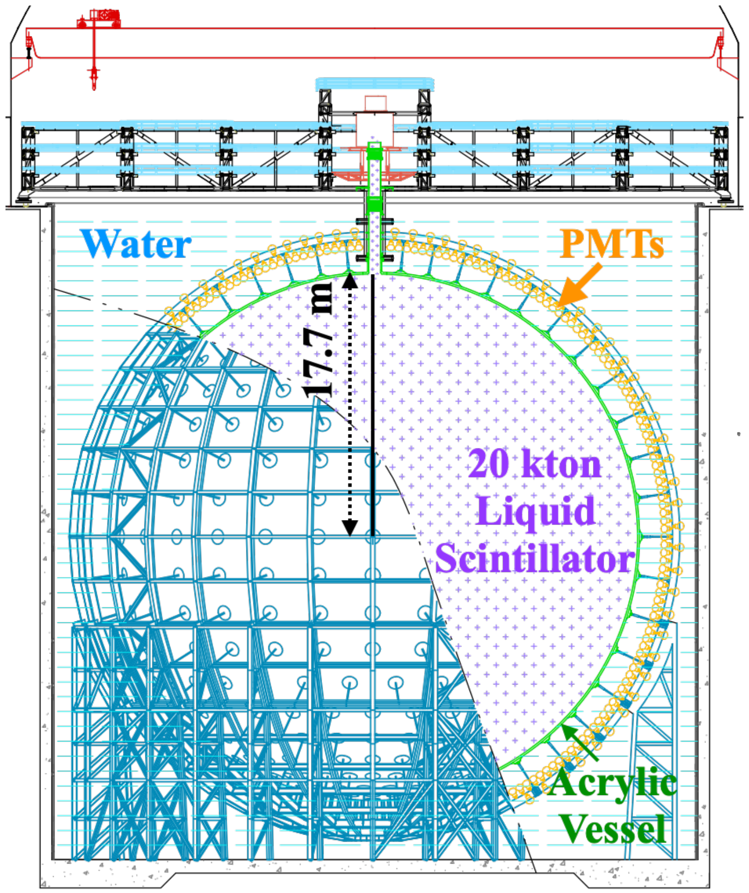
Atmospheric ν Simulation
(2000 years eq. in Super-K)



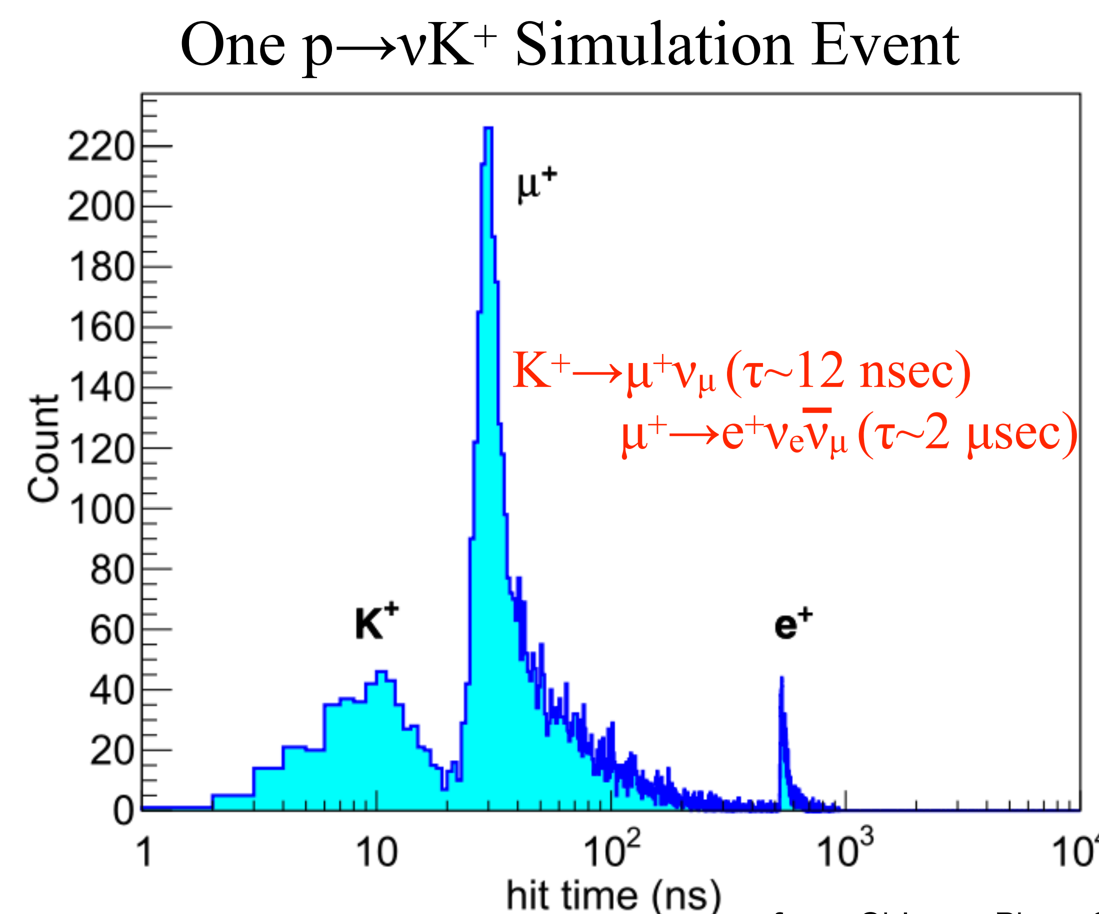
$$P_{\rm tot} = \left| \sum_n \vec{p}_n \right|,$$
$$E_{\rm tot} = \sum_n \sqrt{|p_n|^2 + m_n^2},$$
$$M_{\rm tot} = \sqrt{E_{\rm tot}^2 - P_{\rm tot}^2},$$

- Clear signal and background separation for $p \to e^+ \pi^0$.
  - Remaining backgrounds.
  - ex. $\nu_e n \to e^- \pi^0 p$ (p is below Cherenkov threshold, undetectable)
- It is relatively hard for water Cherenkov detectors to search for $p \to \nu K^+$.
  - The charged Kaon (K^+) is below the Cherenkov threshold and undetectable, resulting in a low signal efficiency of ~20%.

Liquid Scintillator Detector (1)



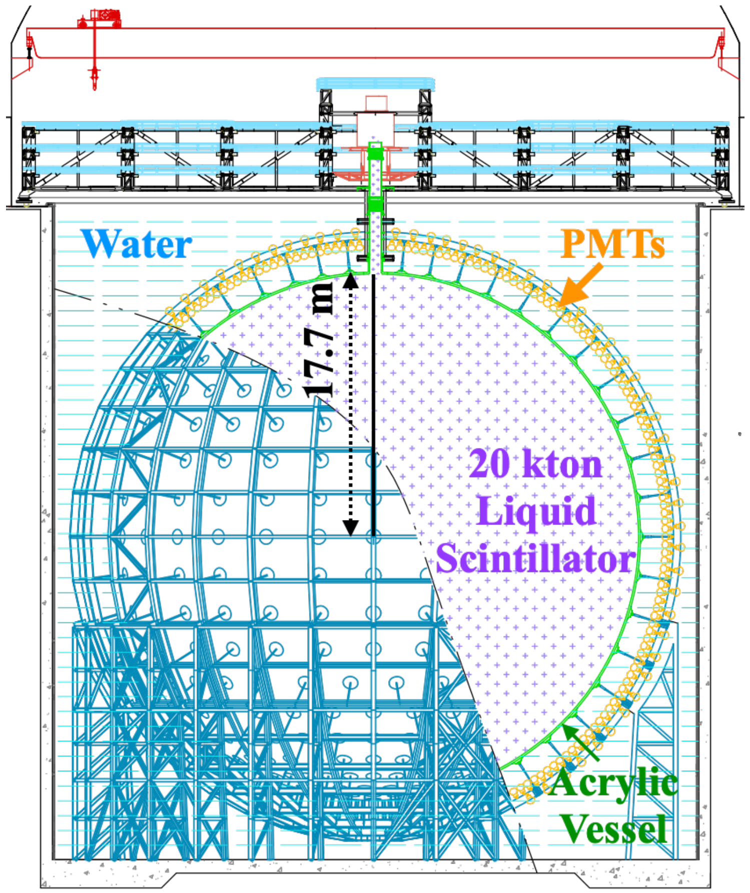
JUNO Detector



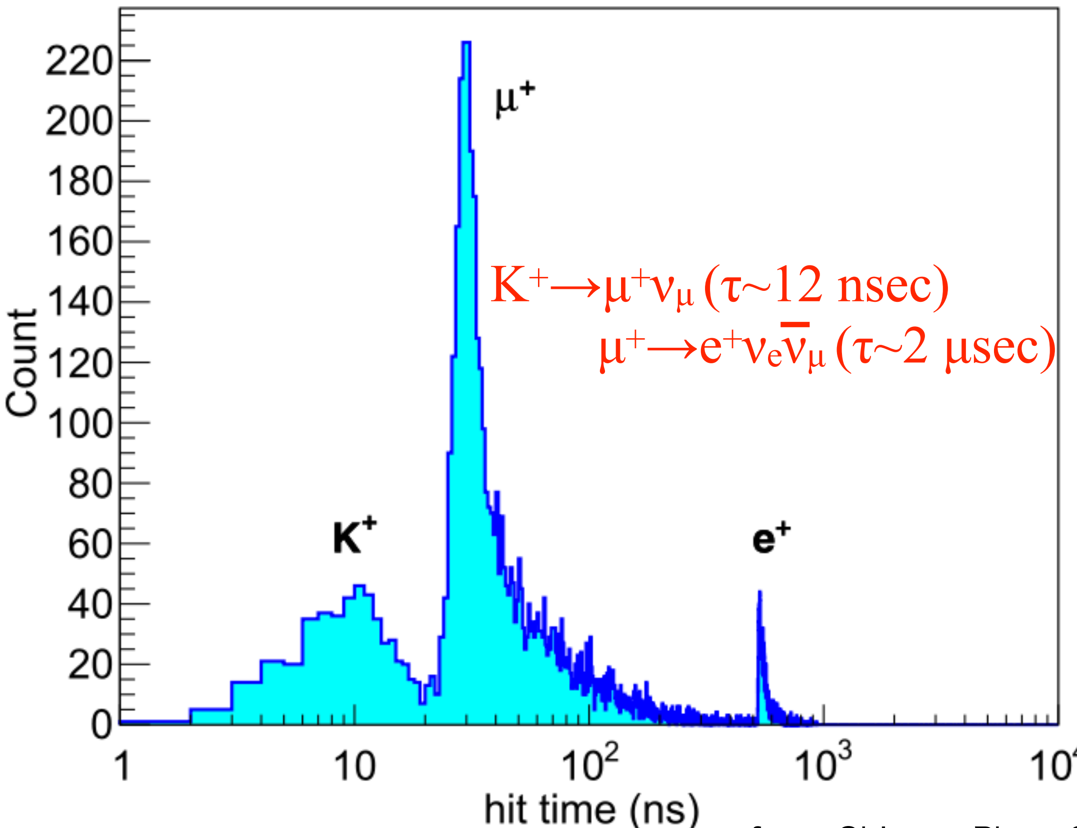
from Chinese Phys. C 47, 113002

- Liquid scintillator detectors do not have the issue regarding the Cherenkov threshold.
  - All of the charged particles inside emit scintillation light.
  - Good at searching for p→νK+ by requiring the triple coincidence.
- JUNO (~20 kton liquid scintillator) is under construction in Jiangmen, China, expected to start the physics run next year.
  - Will reach the sensitivity of ~10^{34} years for p→νK+.

Liquid Scintillator Detector (2)



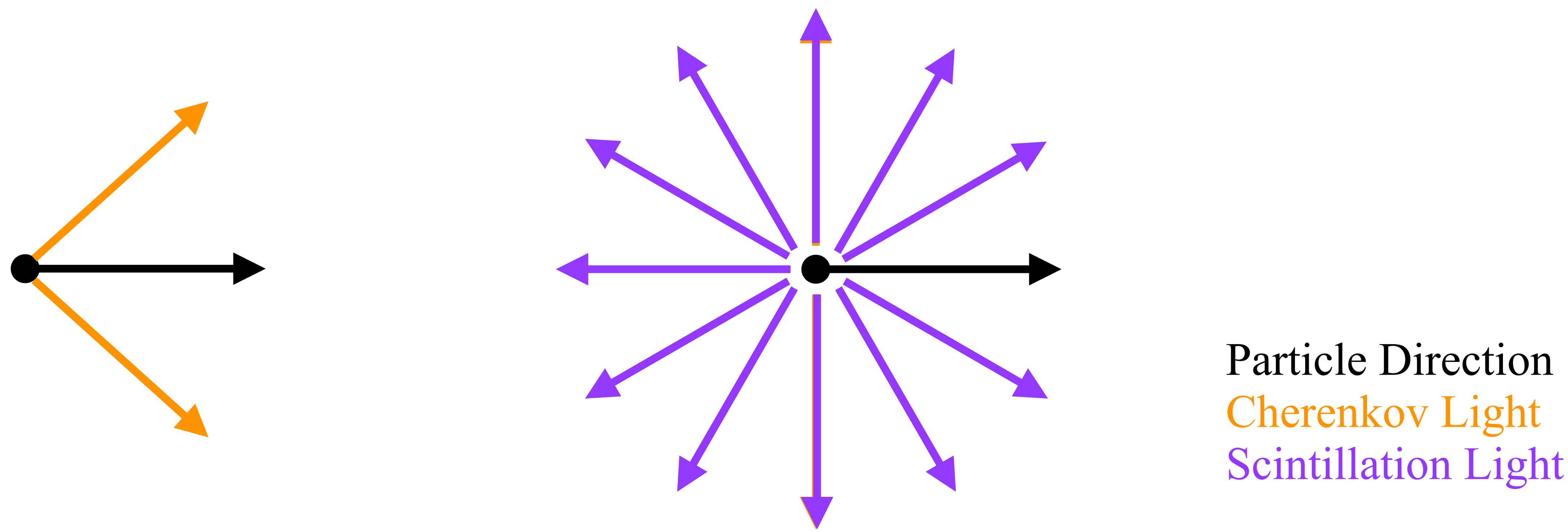
JUNO Detector



from Chinese Phys. C 47, 113002

- Background events for the p→νK+ search are also caused by atmospheric neutrinos.
  - ν_μn → μ^-p (p could mimic K+)
- With the triple coincidence technique, it is expected to be well suppressed.

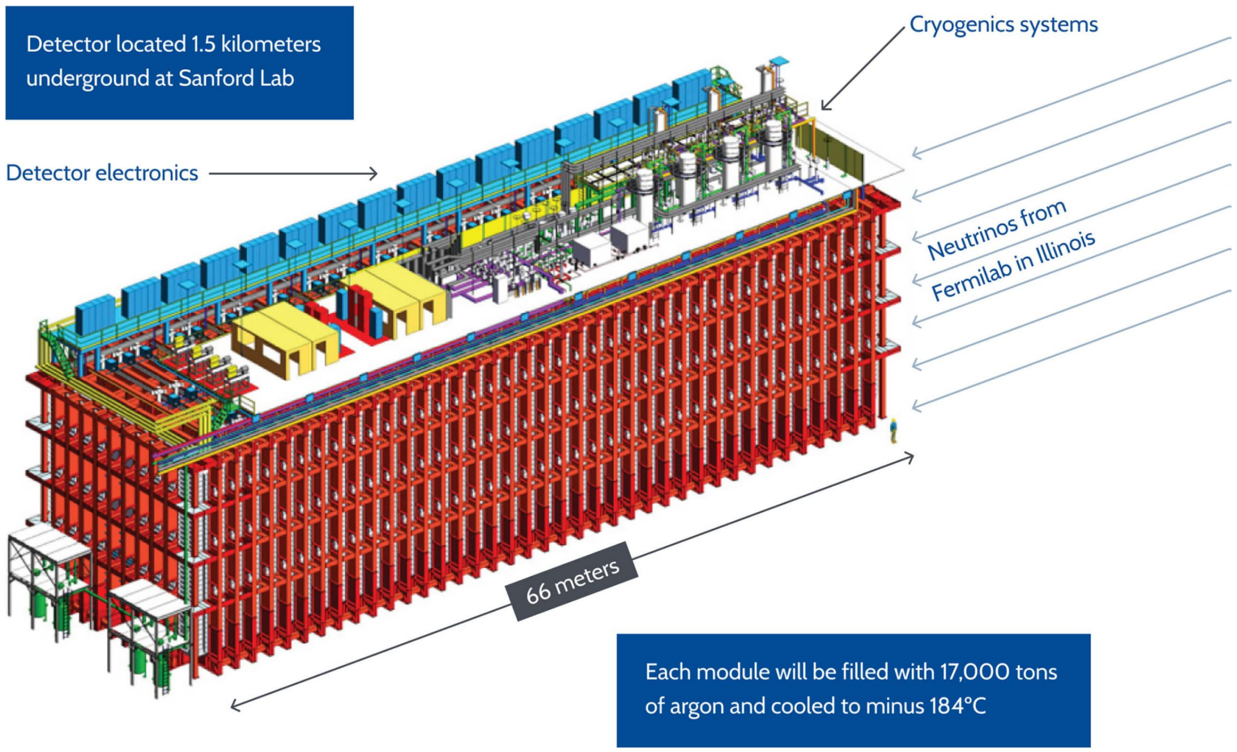
Liquid Scintillator Detector (3)



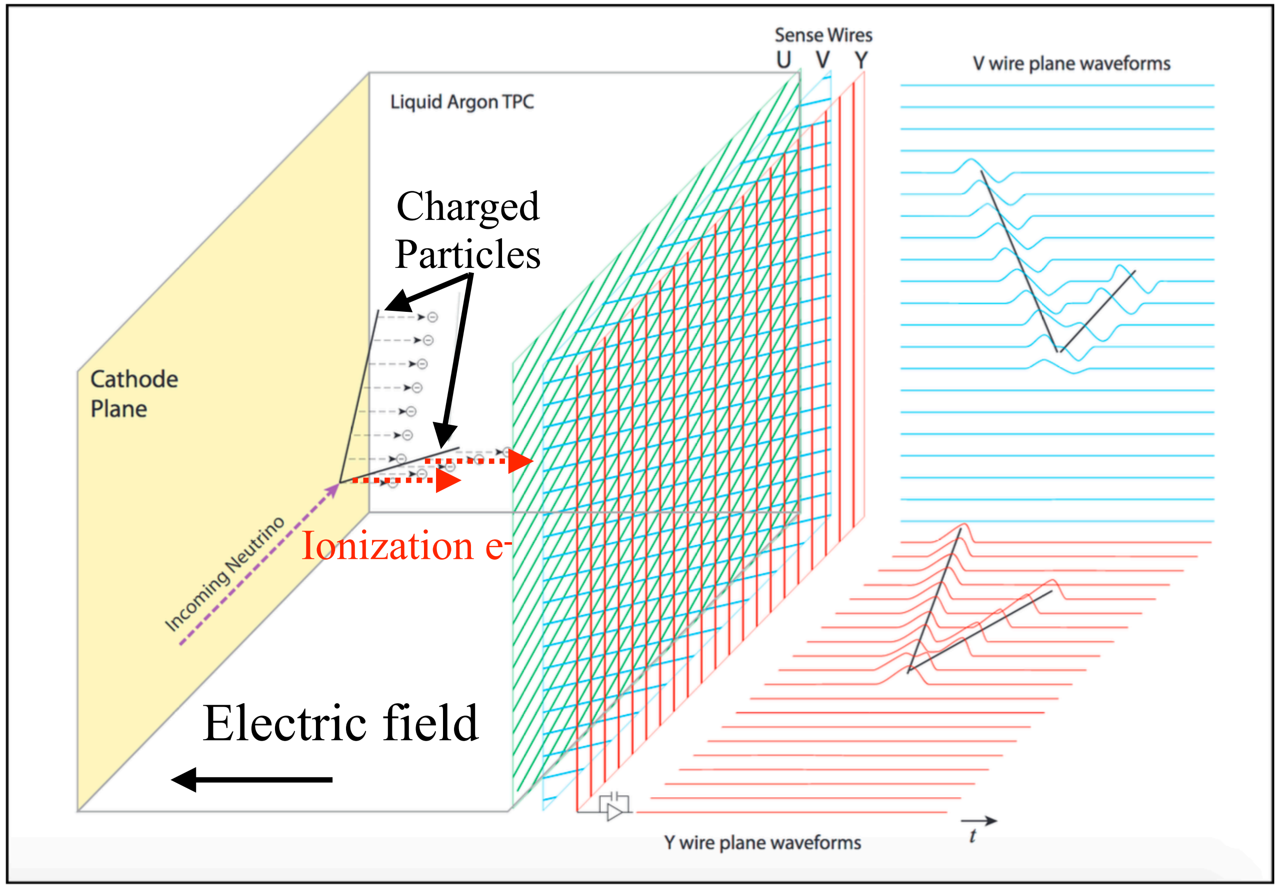
- In contrast to Cherenkov light, scintillation light is emitted isotropically from the particle.
- It is generically hard to estimate the particle direction in scintillator detectors and discern multiple particles appearing at the same time.
    - Therefore, the sensitivity for $p \to e^+ \pi^0$ is not very prospective in pure-scintillator detectors.
- In water-based liquid scintillator detectors, such as THEIA, both Cherenkov and scintillation light are observable.

Eur. Phys. J. C 80, 416

Liquid Argon Time Projection Chamber (1)

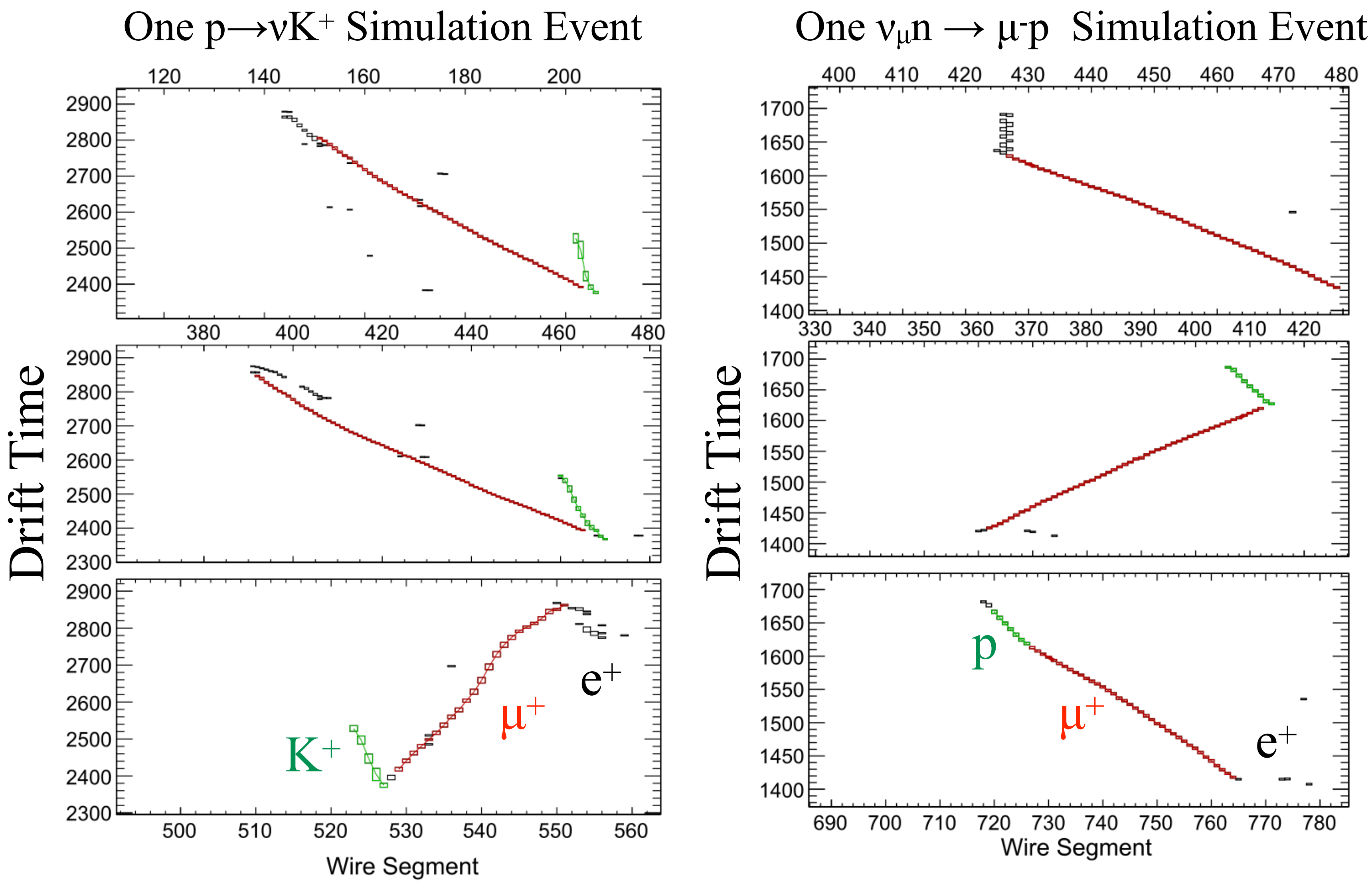


DUNE Detector



- Liquid Argon Time Projection Chamber (LArTPC) is another major detector technique for neutrino and proton decay search detectors.
  - Electrons produced by the ionizations of the charged particles drift the sensitive wire planes and leave signals.
  - By combining the information from multiple wire planes, a 3D particle track can be estimated.
- DUNE (~40 kton liquid argon) in the U.S. employs this technique and will be online around 2030.

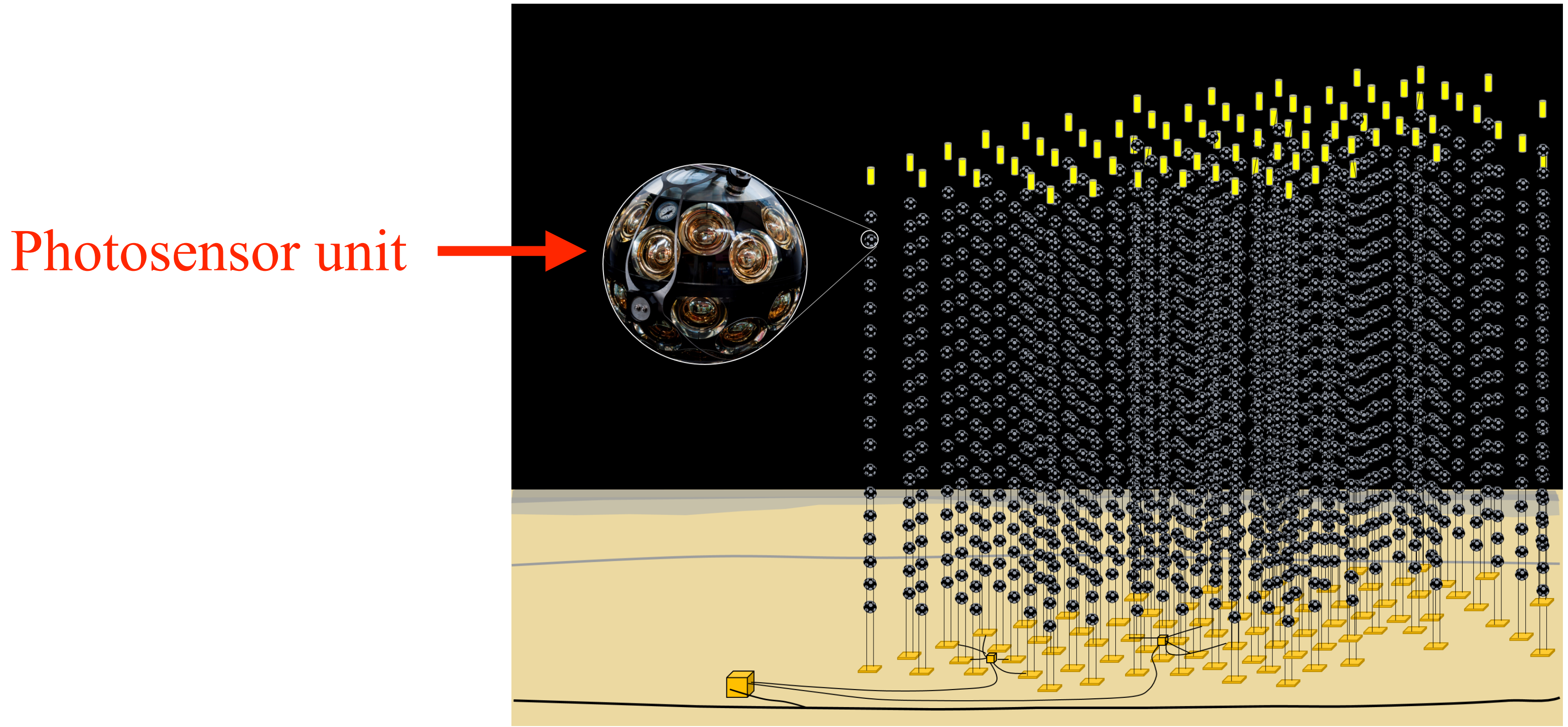
Liquid Argon Time Projection Chamber (2)



from Eur. Phys. J. C 81, 322

- The particle type of each track can be identified by the deposited energy over its track length (dE/dx).
- Here again, atmospheric neutrinos are the main background source.
- Machine-learning tools (CNN, BDT) are fully exploited to separate signals & backgrounds.
- The search sensitivity for $p \rightarrow \nu K^+$ will reach ~10^{34} years.

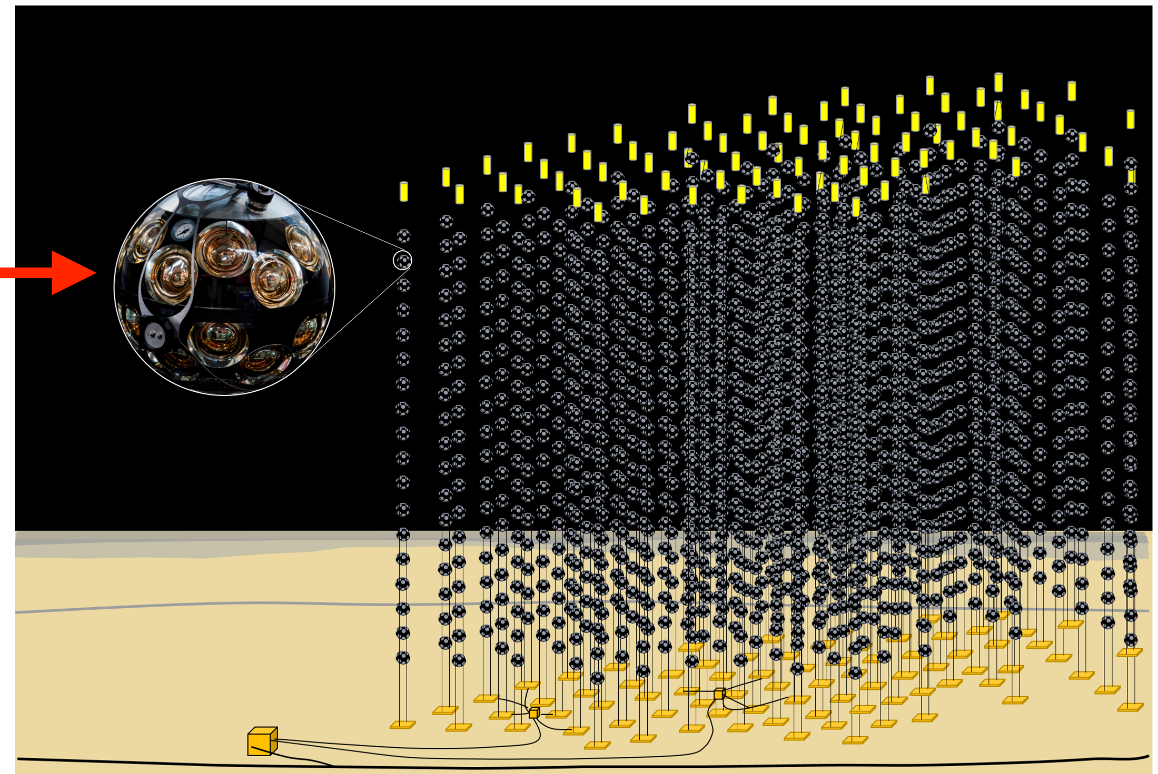
Next after Next Proton Decay Search Detector?



- Considering the predicted proton lifetime ranges beyond 10^{35} years, it may be nice to start to think of further future detectors.
- Neutrino telescopes (ex. KM3NeT) deploy photosensor units in the sea for quite high-energy neutrino observations (a few GeV or more).
  - Water Cherenkov detector in the sea.
- The target detector volume is extendable by deploying more and more photosensors with no rigid physical boundaries in the sea.

Next after Next Proton Decay Search Detector?

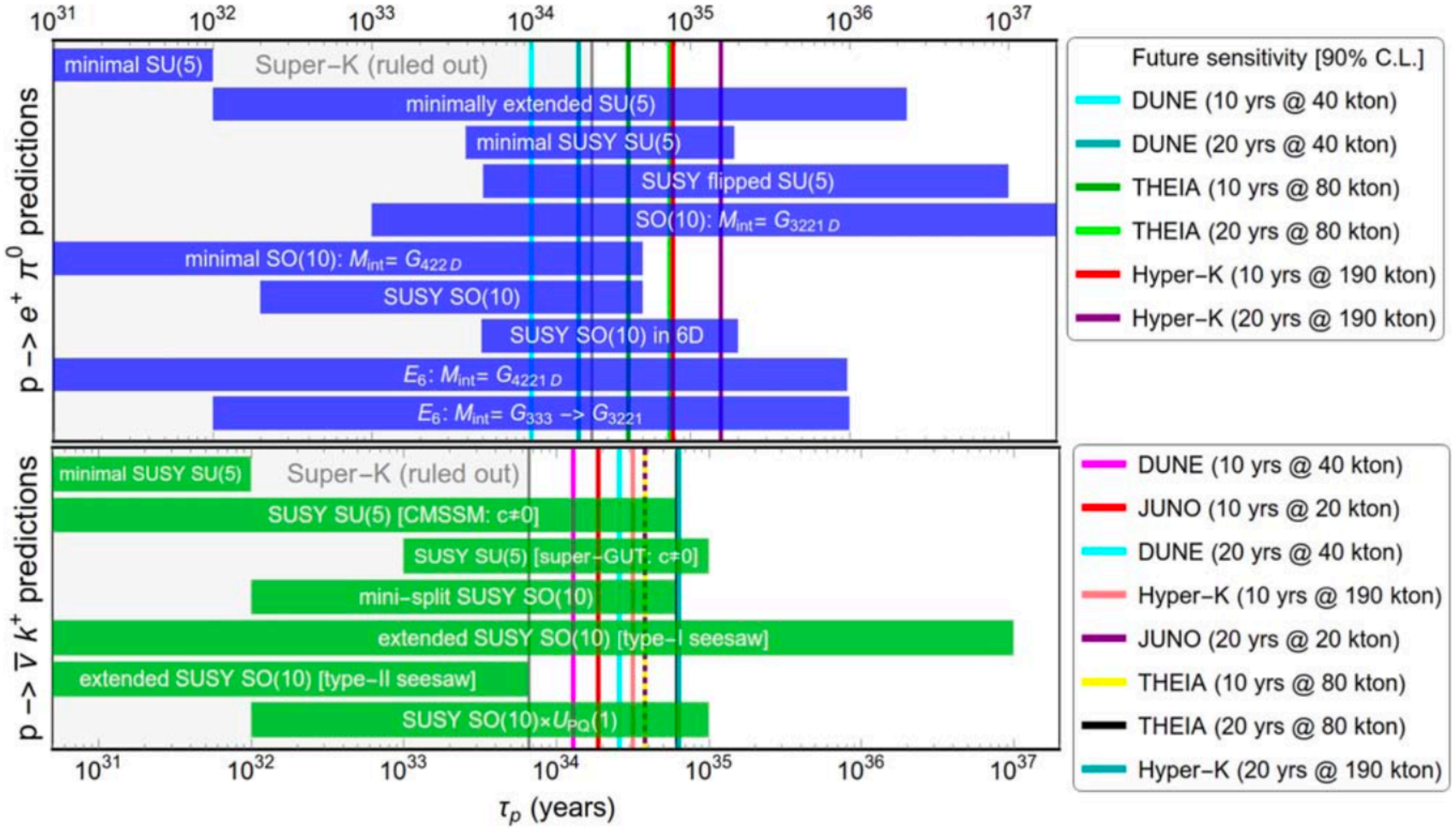
Photosensor unit



- By arranging photosensor units close enough, there may be chances to access the proton decay energy scale, ~1 GeV.
- A study to seek out the feasibility of this kind of proton decay search detector is ongoing.
  - Optimal photosensor units for proton decay search.
  - How well atmospheric neutrino backgrounds can be controlled.
  - Hardware feasibilities.

Summary

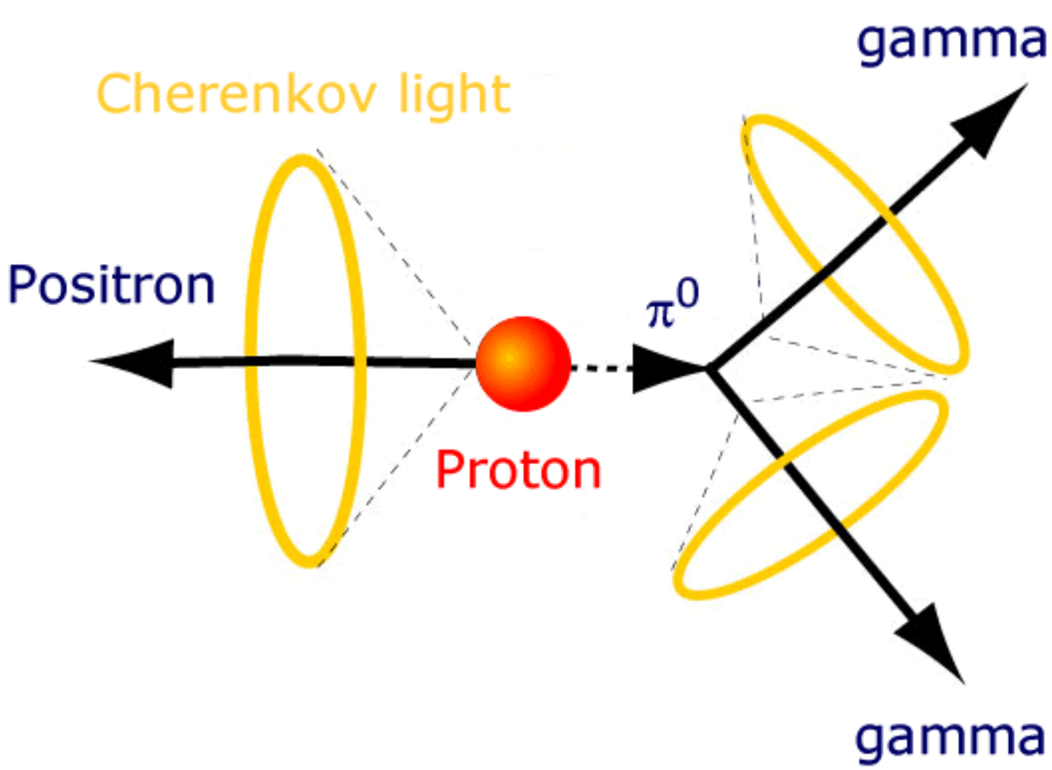
- Overviewed the current and near-future proton decay search detectors.



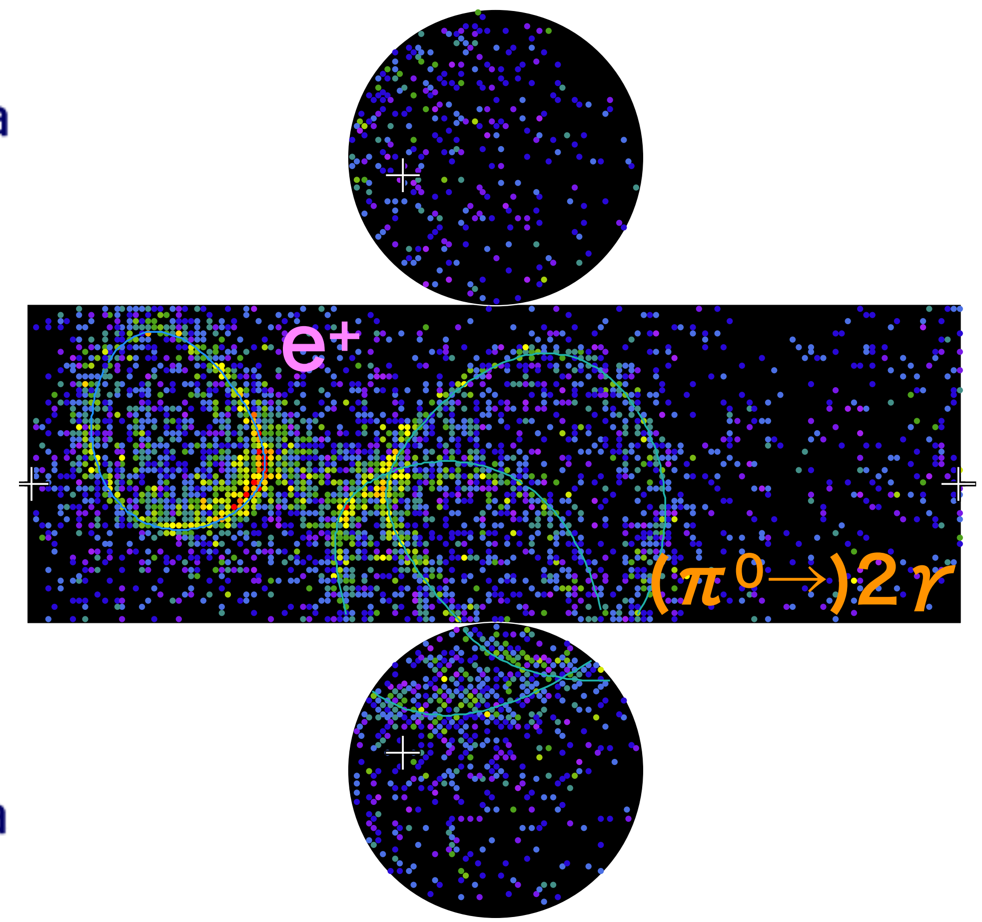
- Both the detector size and background control are crucial in the proton decay search study.
- Efforts in different directions are ongoing.
    - Improve the analysis in the existing and near-future detectors.
    - Study for further future gigantic detectors.

back-up

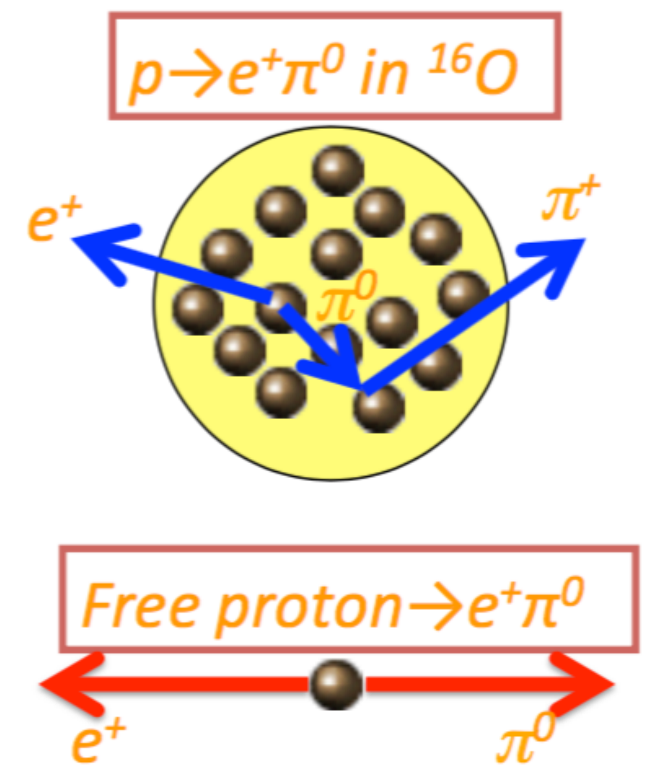
$p \to e^+ \pi^0$ Signal



$p \to e^+ \pi^0$ MC event display



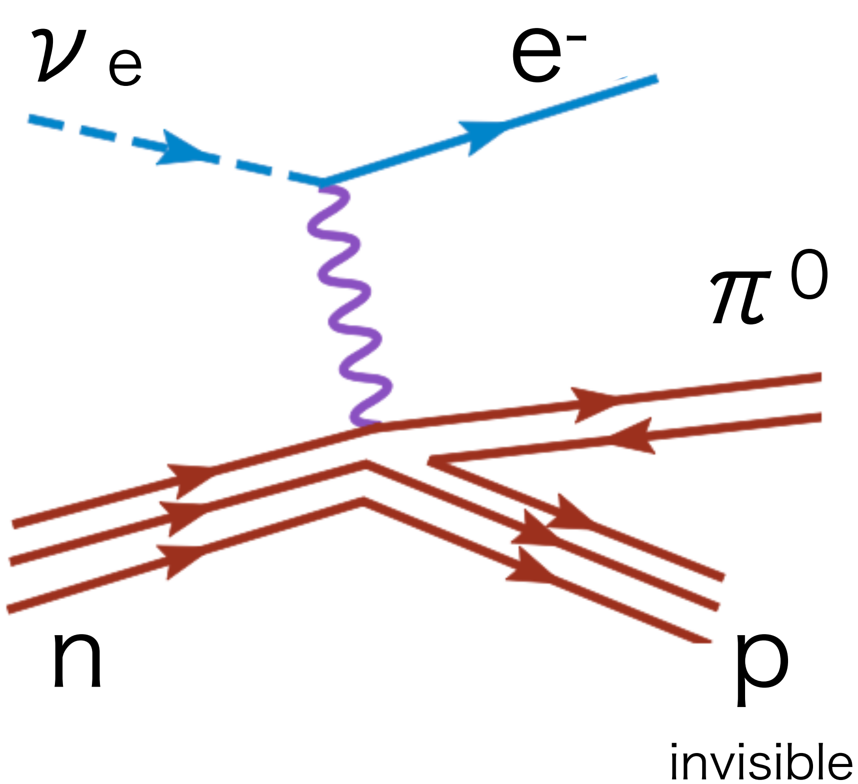
Protons in H_2O



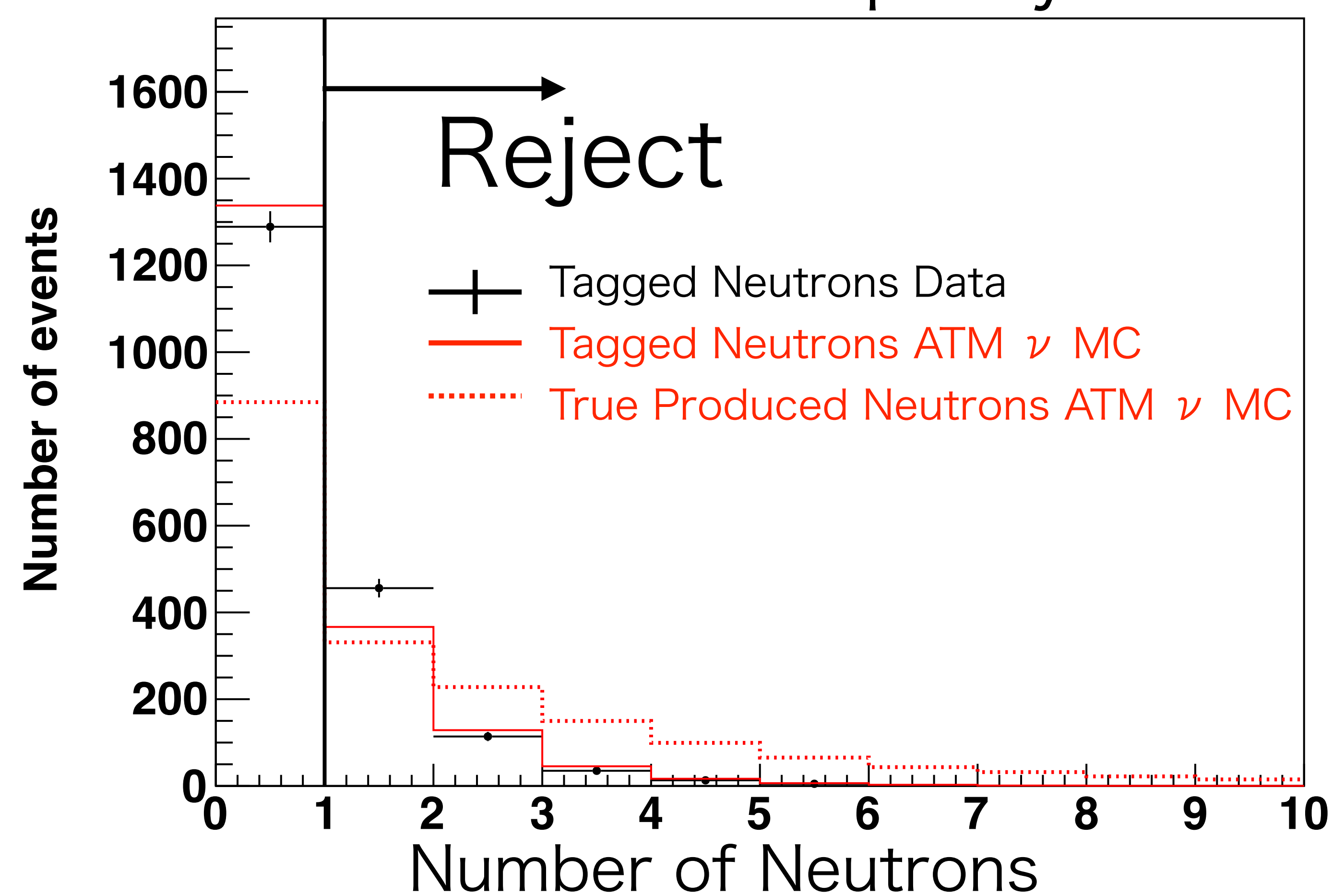
- All secondary particles (e^+, γ) can be reconstructed.
- From unique (back-to-back) event topology, signal and atmospheric ν background can be clearly discriminated.
- Free protons (H) are available in Super-K.
  - Free from the Fermi motion and various nuclear effects.

Background & Reduction Technique

Atmospheric ν



Neutron Multiplicity



- Atmospheric ν events can mimic p-decay signal.
  - ~60% of them are produced via charged current pion production interaction and often accompanied with neutrons.
- Since SK-IV (2008~2018), faint signature of neutrons (γs) can be recorded thanks to electronics upgrade. (n+p→d+γ (2.2 MeV))
  - Neutron tagging efficiency ~25%.
  - **Requiring no tagged neutrons reduces ATM ν BG by ~50%.**

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

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

1. Fully contained and vertex in fiducial mass region.
2. Cherenkov ring = 2 or 3
3. Particle identification

   all shower-like rings
4. No Michel-electron.
5. for 3-ring events, π^0 mass cut

   $85 < M_{\pi^0} < 185$ MeV/c^2
6. Total Mass cut

   $800 < M_{tot} < 1050$ MeV/c^2
7. Total Momentum Cut

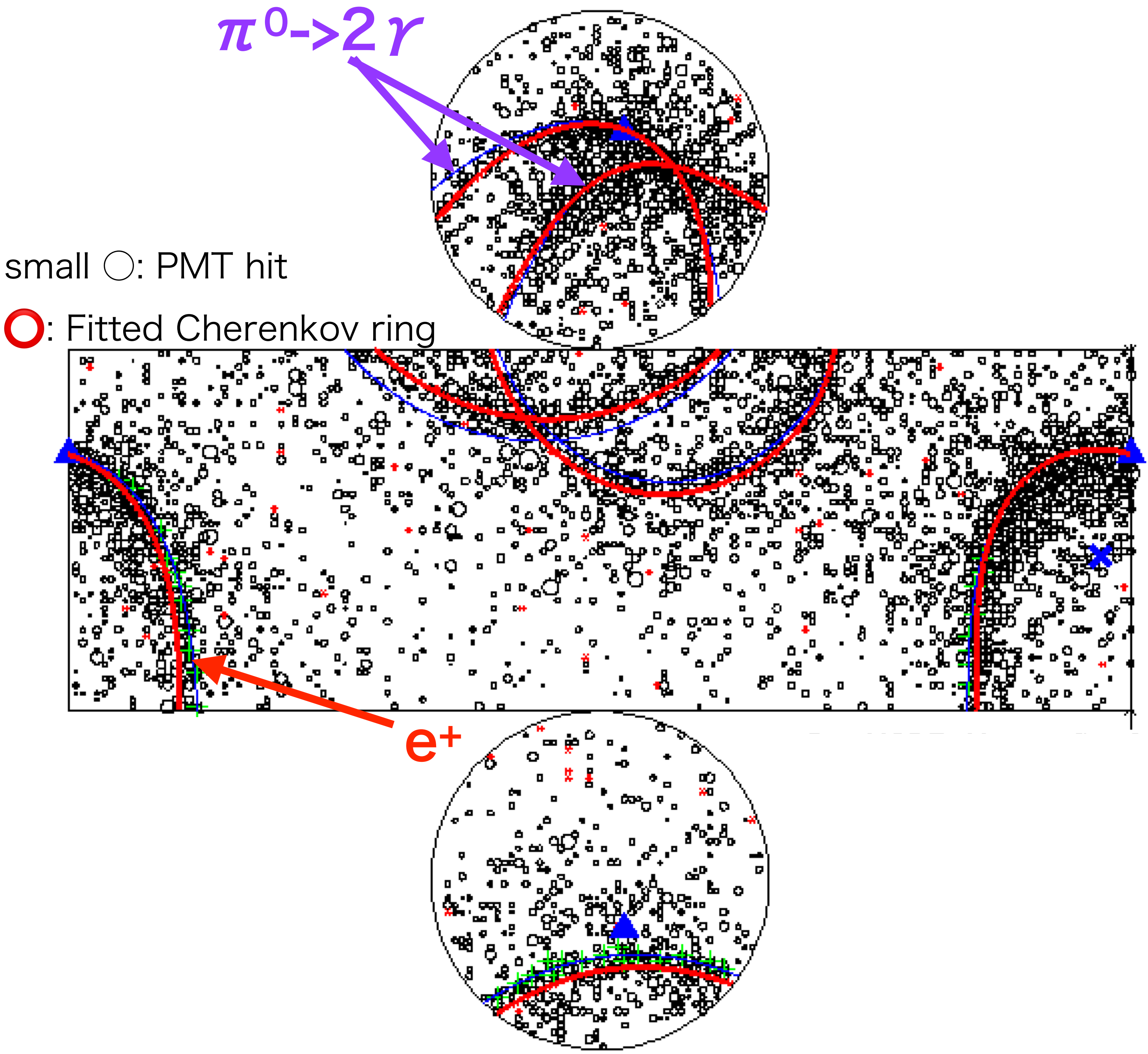
   Box1: $0 < P_{tot} < 100$ MeV/c

   (Free proton rich & Low ν BG)

   Box2: $100 < P_{tot} < 250$ MeV/c
8. For data since 2008, no tagged neutrons.

Typical free $p \to e^+ \pi^0$ event (MC)

Event display (e^+, $\pi^0 \to 2\gamma$)



Search Performance $p \rightarrow e^+ \pi^0$

$p \rightarrow e^+ \pi^0$ signal selection

1. Fully contained and vertex in fiducial mass region.
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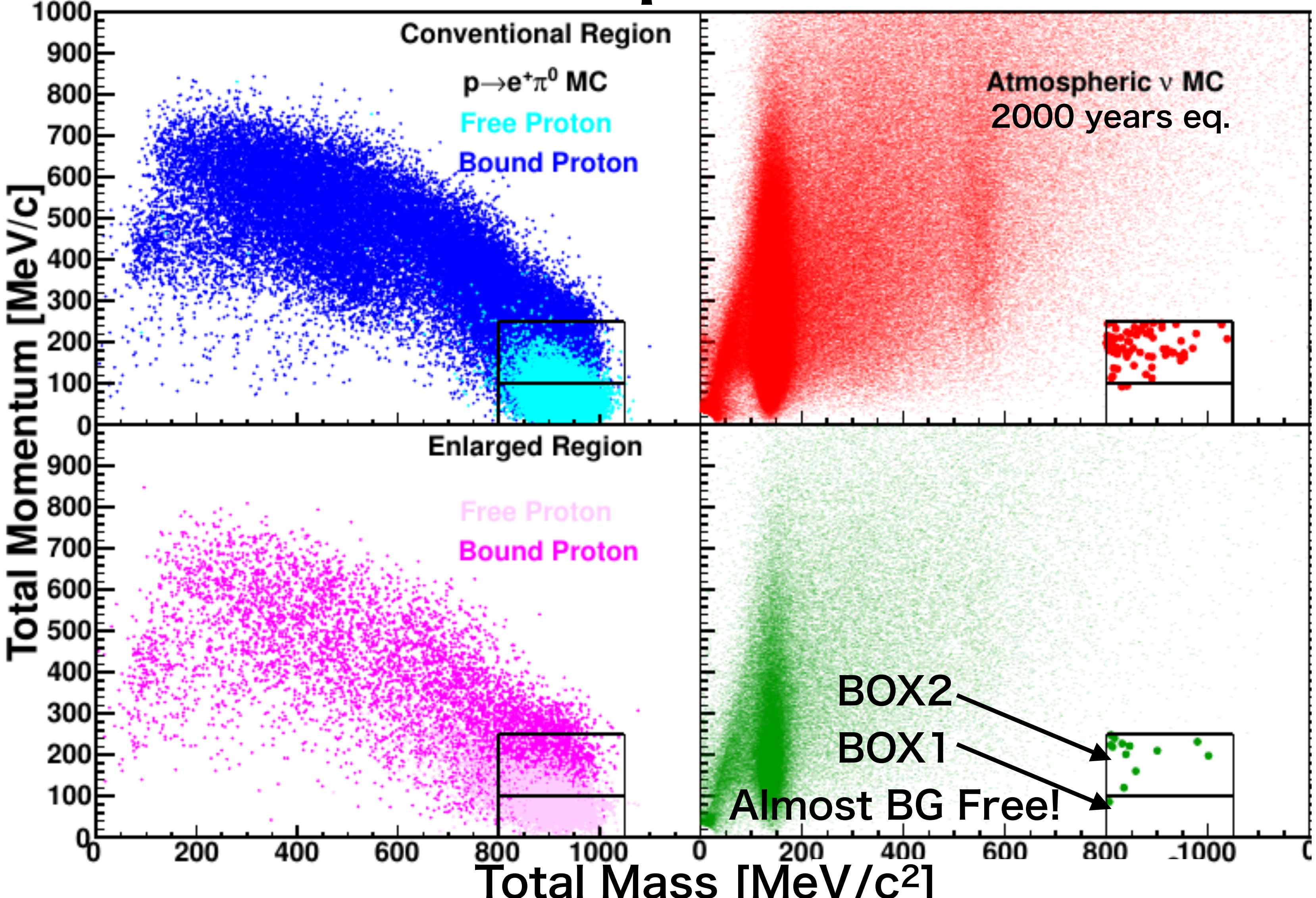


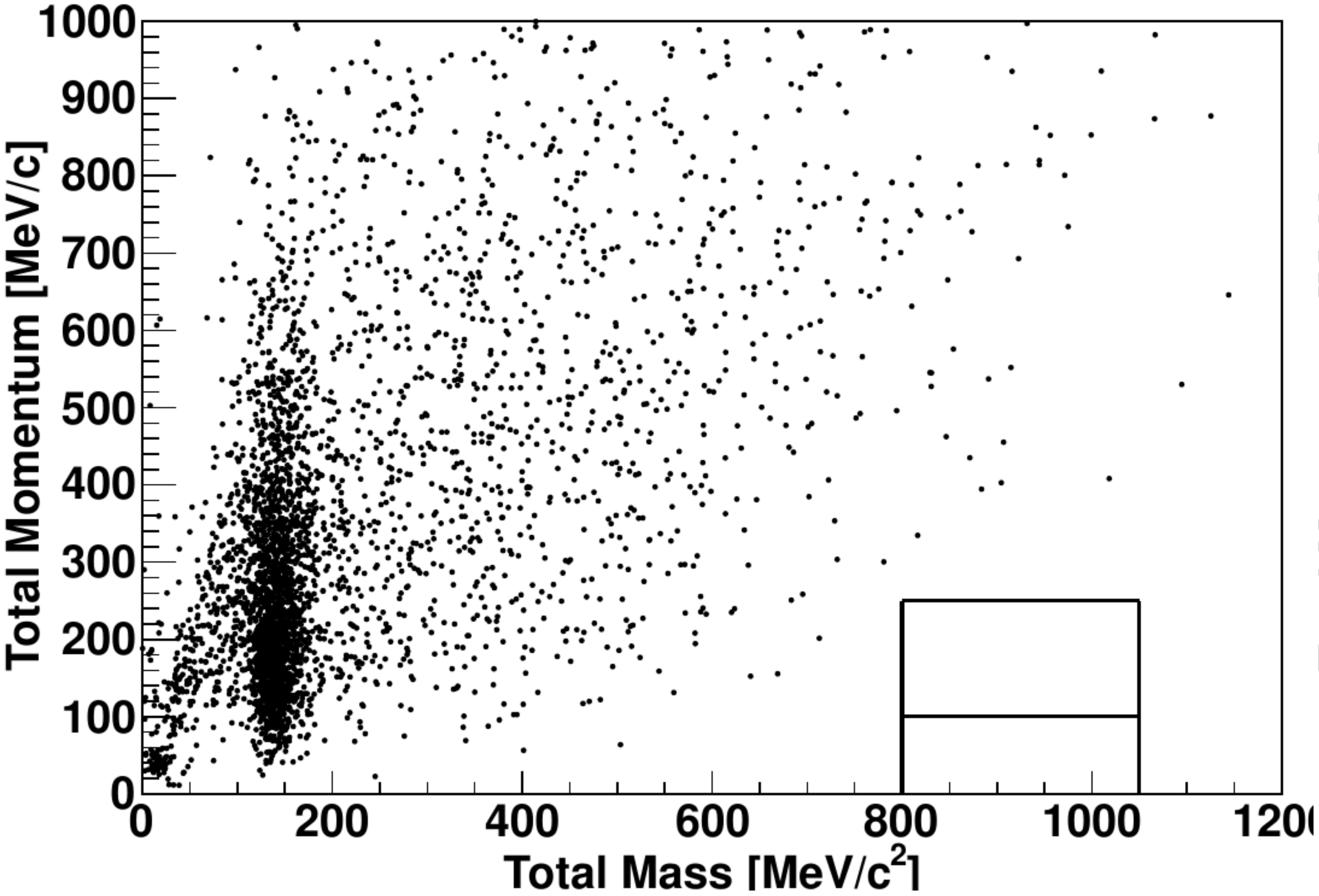
		Conventional	Enlarged
	Fiducial Mass	22.5 kton	4.7 kton
	Exposure	372 kton*years	78 kton*years
Signal Efficiency	BOX1	19.5+/-1.7%	10.3+/-1.4%
	BOX2	20.3+/-3.3%	15.5+/-2.6%
	TOTAL	39.8%+/-3.7%	25.8+/-3.0%
Expected BG [/livetime]	BOX1	0.01+/-0.01 ev	0.01+/-0.01 ev
	BOX2	0.48+/-0.21 ev	0.09+/-0.05 ev
	TOTAL	0.49+/-0.21 ev	0.10+/-0.05 ev

- **Enlarging fiducial mass increases p-decay search sensitivity by ~12%.**

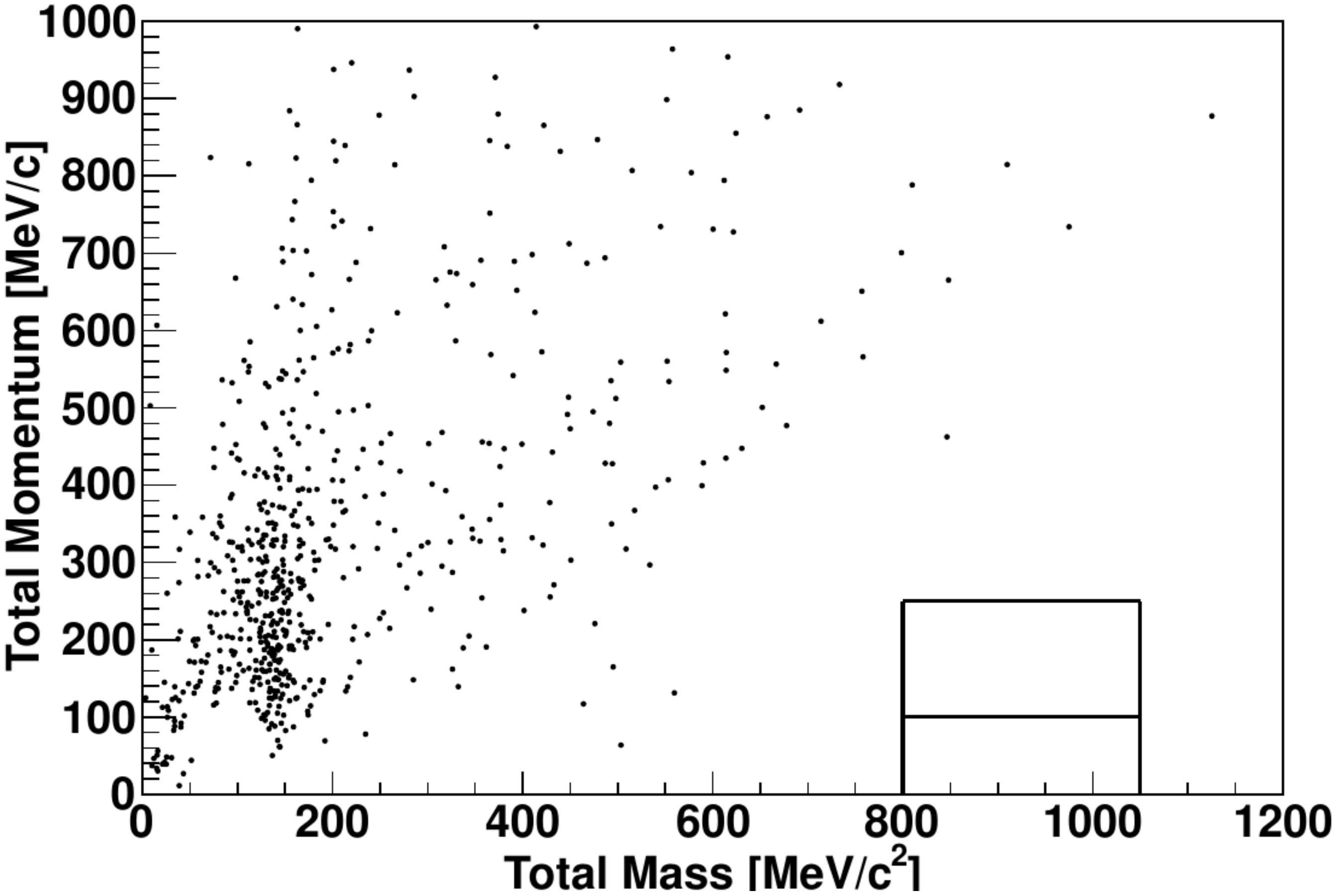
Data Result $p \rightarrow e^+ \pi^0$

Data SK-I to -IV 450 kton*years.

Conventional Region 372 kton*years

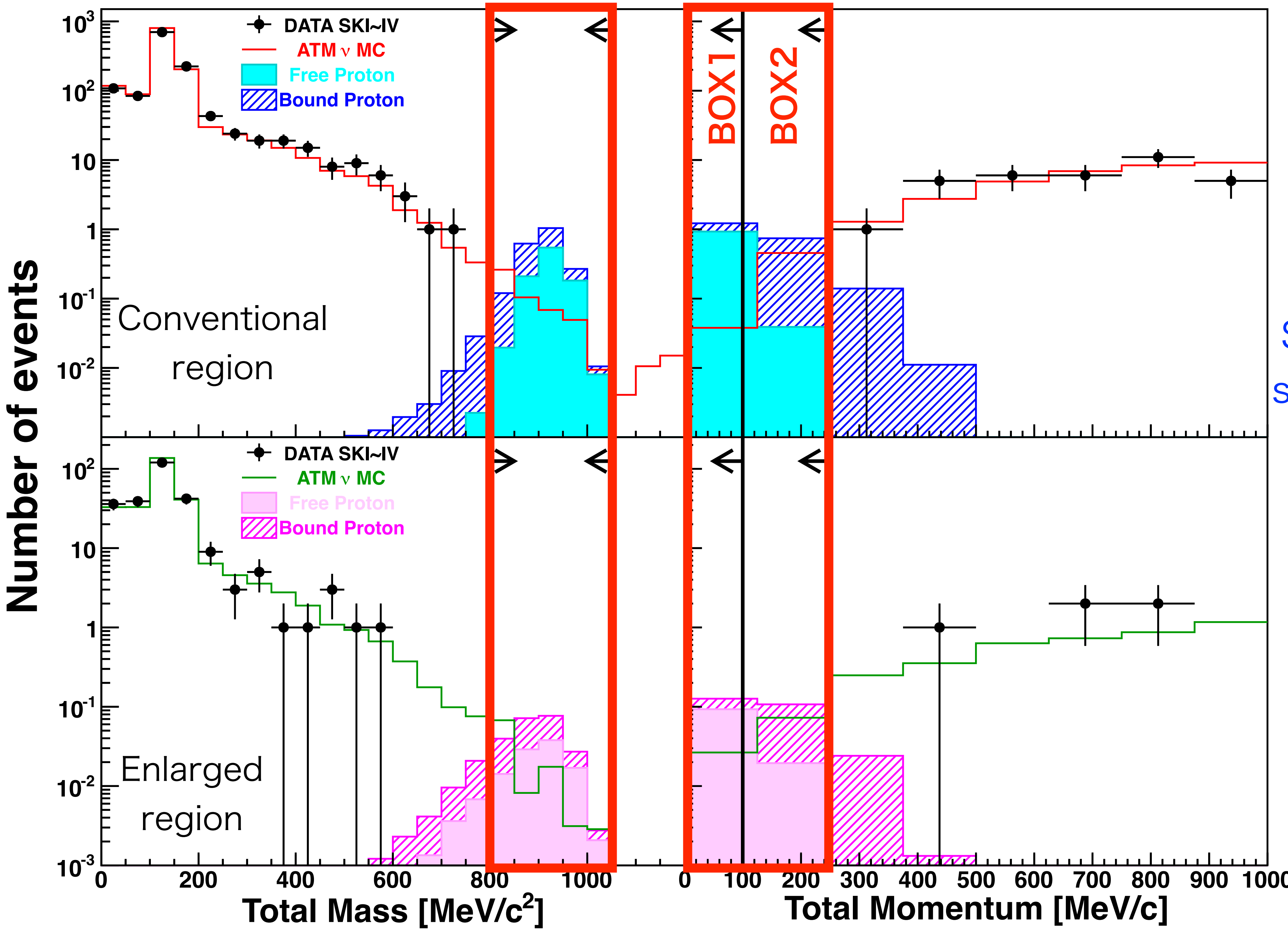


Enlarged Region 78 kton*years



- No candidates in signal box incl. enlarged region.
- Lower lifetime limit @90%C.L.
  - $\tau / B_{p \rightarrow e+\pi 0}$ > 2.4*10^{34} years **(published: 1.6*10^{34} years)**
- Most stringent constraint. **~1.5 times longer than published.**

Data Result $p \rightarrow e^+ \pi^0$



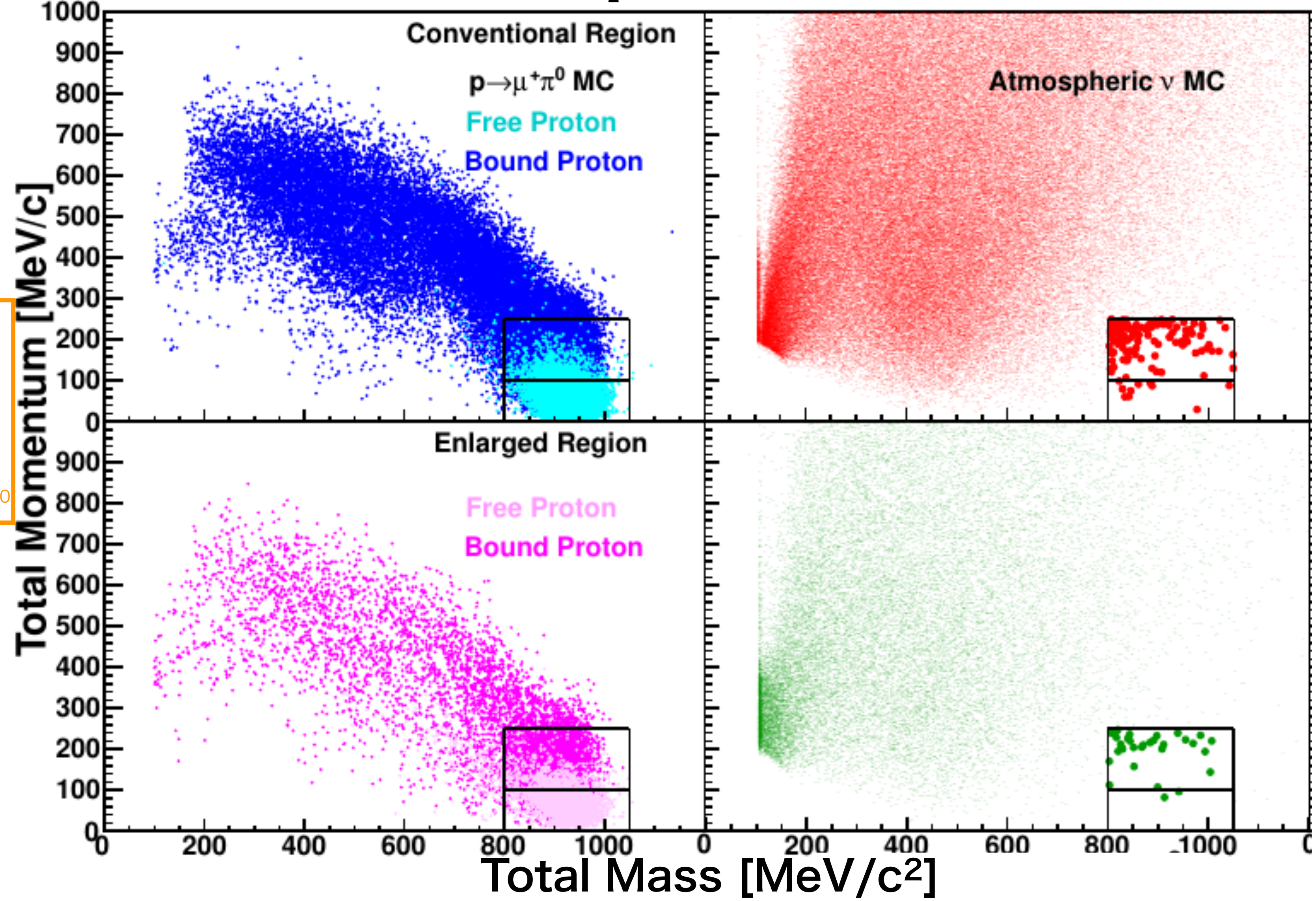
Signal hist: Normalized by signal upper limit (90%C.L.).

- No candidates in signal box incl. enlarged region.
- **$\tau / B_{p \rightarrow e^+ \pi^0} > 2.4*10^{34}$ years (90%C.L.)**
- Data is consistent with ATM ν MC prediction.

Search Performance $p \to \mu^+ \pi^0$

$p \to \mu^+ \pi^0$ signal selection

1. Fully contained and vertex in fiducial mass region.
2. Cherenkov ring = 2 or 3
3. Particle identification
   1 non-shower ring.
4. 1 Michel-electron. Differences from $p \to e^+ \pi^0$
5. for 3-ring events, π^0 mass cut
   $85 < M_{\pi^0} < 185$ MeV/c^2
6. Total Mass cut
   $800 < M_{tot} < 1050$ MeV/c^2
7. Total Momentum Cut
   Box1: $0 < P_{tot} < 100$ MeV/c
   (Free proton rich & Low ν BG)
   Box2: $100 < P_{tot} < 250$ MeV/c
8. For data since 2008, no tagged neutrons.



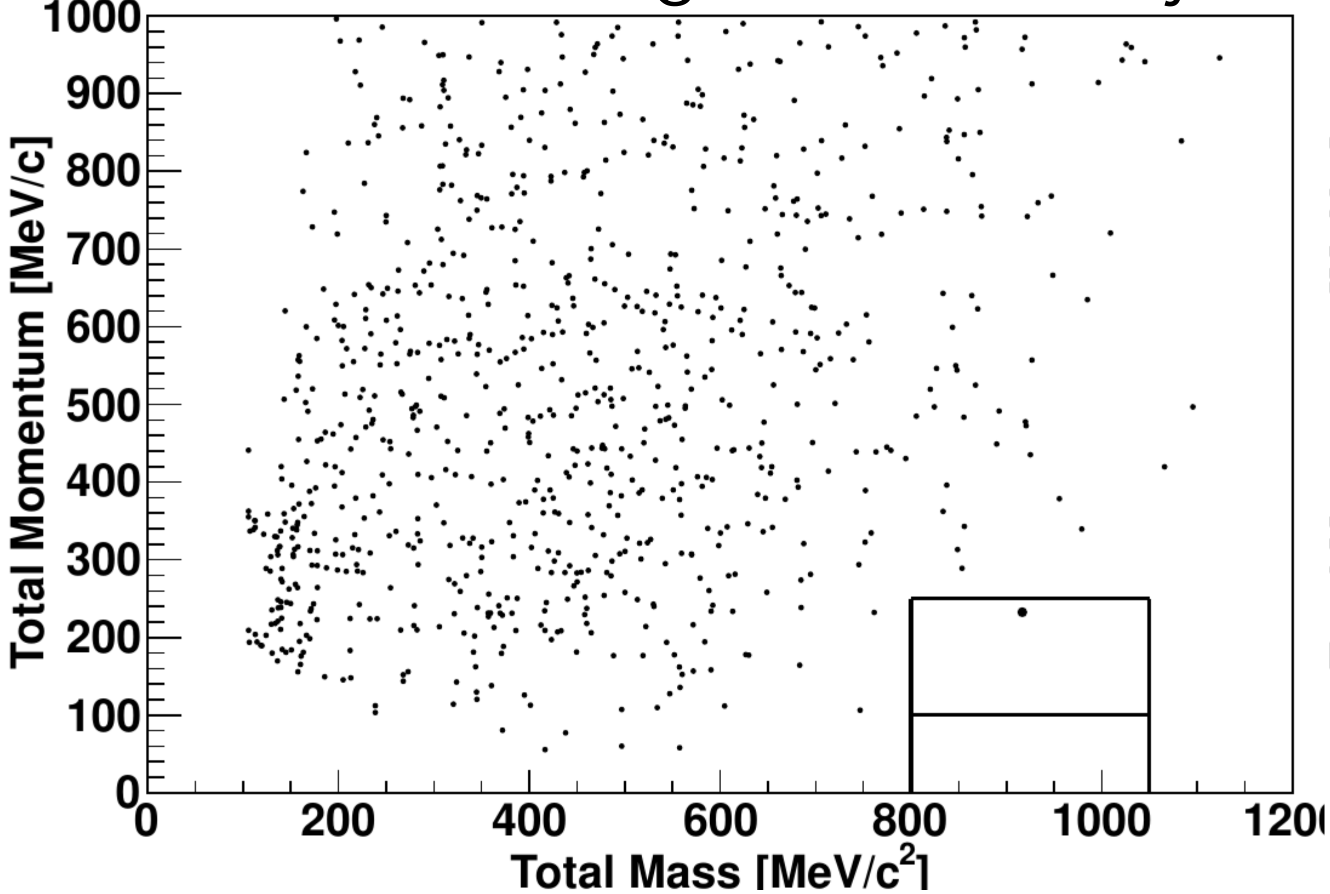
	Fiducial Mass	Conventional 22.5 kton	Enlarged 4.7 kaon
	Exposure	372 kton*years	78 kton*years
Signal Efficiency	BOX1	18.5+/-1.7%	11.7+/-1.2%
	BOX2	17.8+/-3.3%	13.5+/-2.4%
	TOTAL	36.3%+/-3.7%	25.2+/-2.7%
Expected BG [/livetime]	BOX1	0.04+/-0.03 ev	0.01+/-0.01 ev
	BOX2	0.70+/-0.24 ev	0.19+/-0.08 ev
	TOTAL	0.74+/-0.24 ev	0.19+/-0.08 ev

- Enlarging fiducial mass increases p-decay search sensitivity by ~12%.

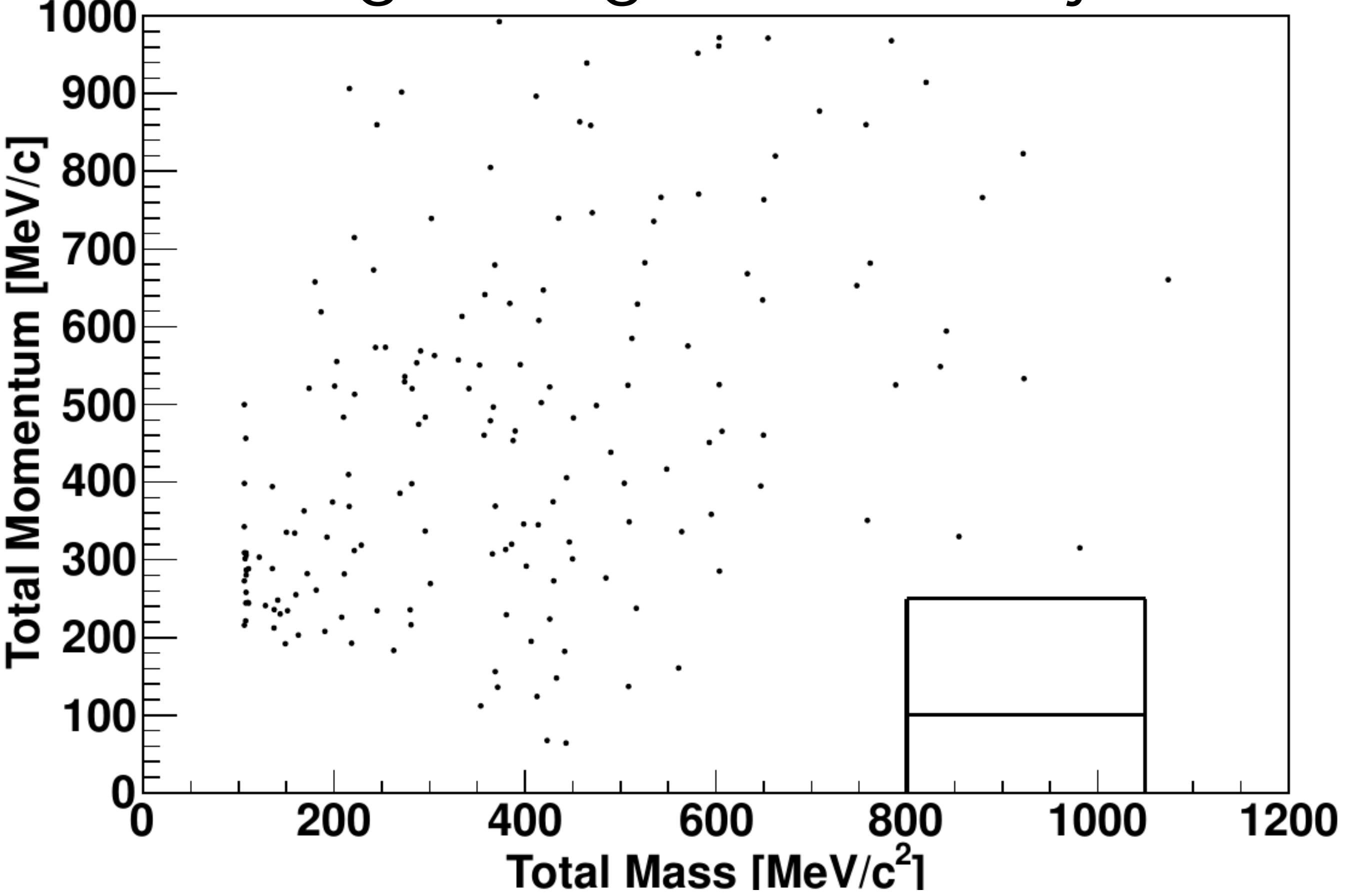
Data Result $p \to \mu^+ \pi^0$

Data SK-I to -IV 450 kton*years.

Conventional Region 372 kton*years

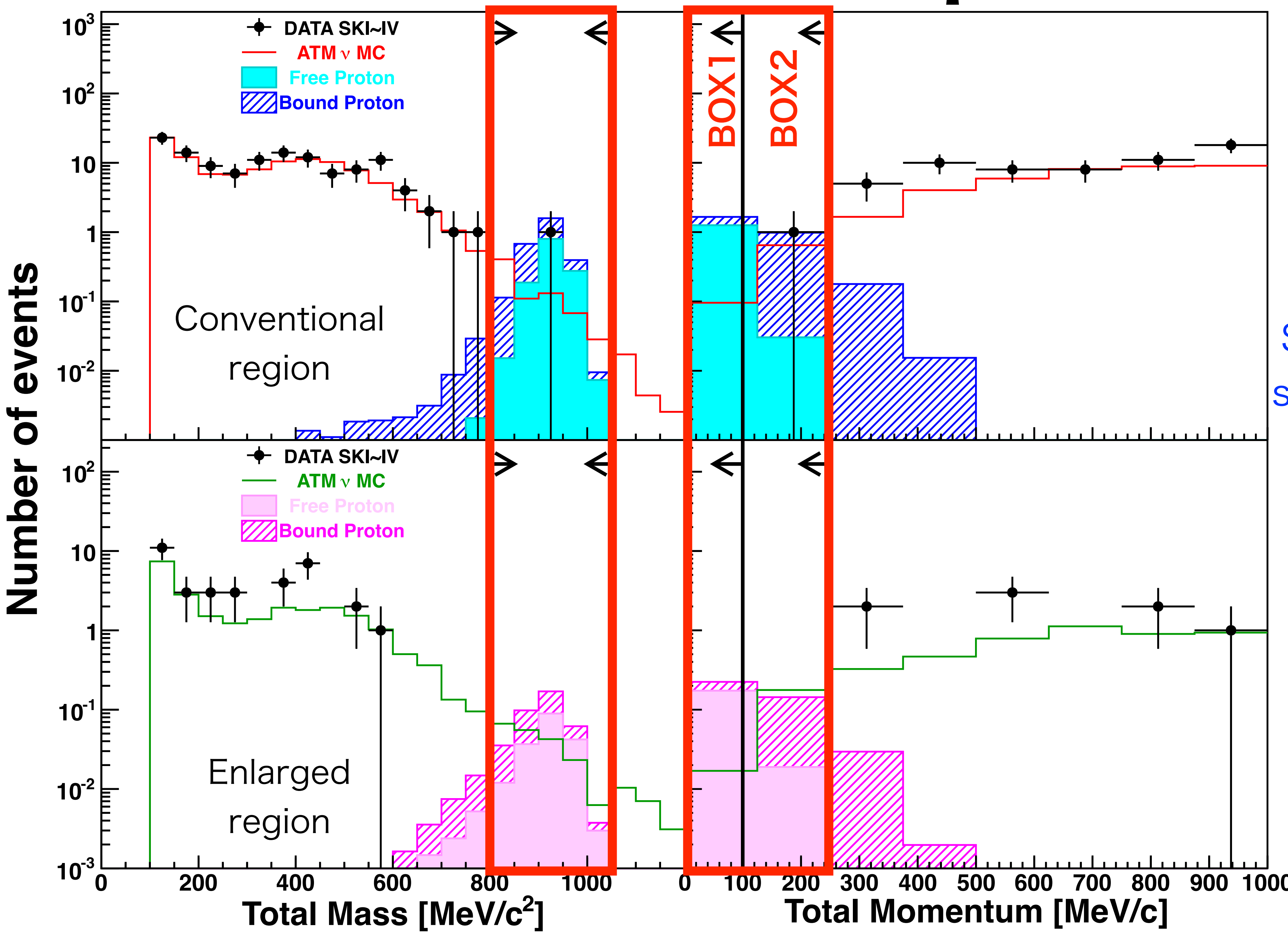


Enlarged Region 78 kton*years



- 1 candidate in BOX2. Same event reported in the last paper. **PRD 95, 012004 (2017)**
- No new candidates incl. in enlarged region.
- No significant data excess compared to expected BG, 0.94.
- Lower lifetime limit @90%C.L.
  - **$\tau / B_{p \to \mu + \pi 0} > 1.6*10^{34}$ years** **(published: $7.7*10^{33}$ years)**
- Most stringent constraint. **~2 times longer than published.**

Data Result $p \to \mu^+ \pi^0$



Signal hist: Normalized by signal upper limit (90%C.L.).

- 1 candidate in BOX2 (With BG 0.94).
- **$\tau / B_{p\to\mu+\pi0}$ > 1.6*10^{34} years (90%C.L.)**
- Data is consistent with ATM ν MC prediction.

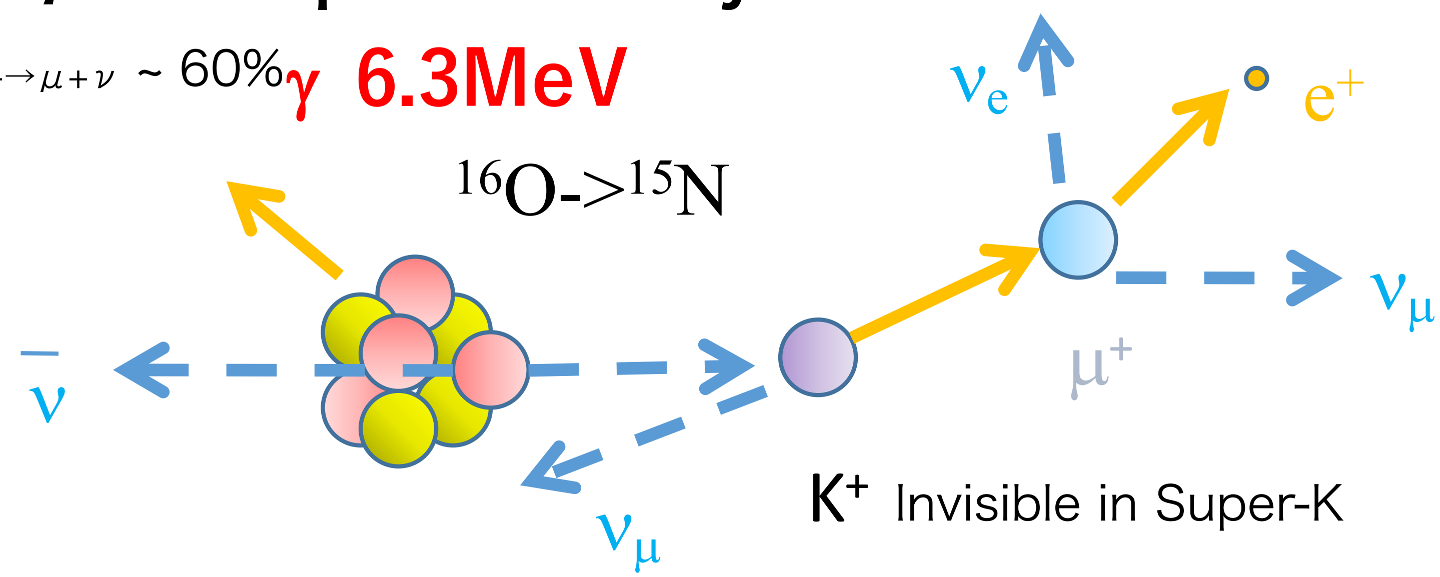
Other Decay Modes (Conventional Fiducial Mass Analysis Results)

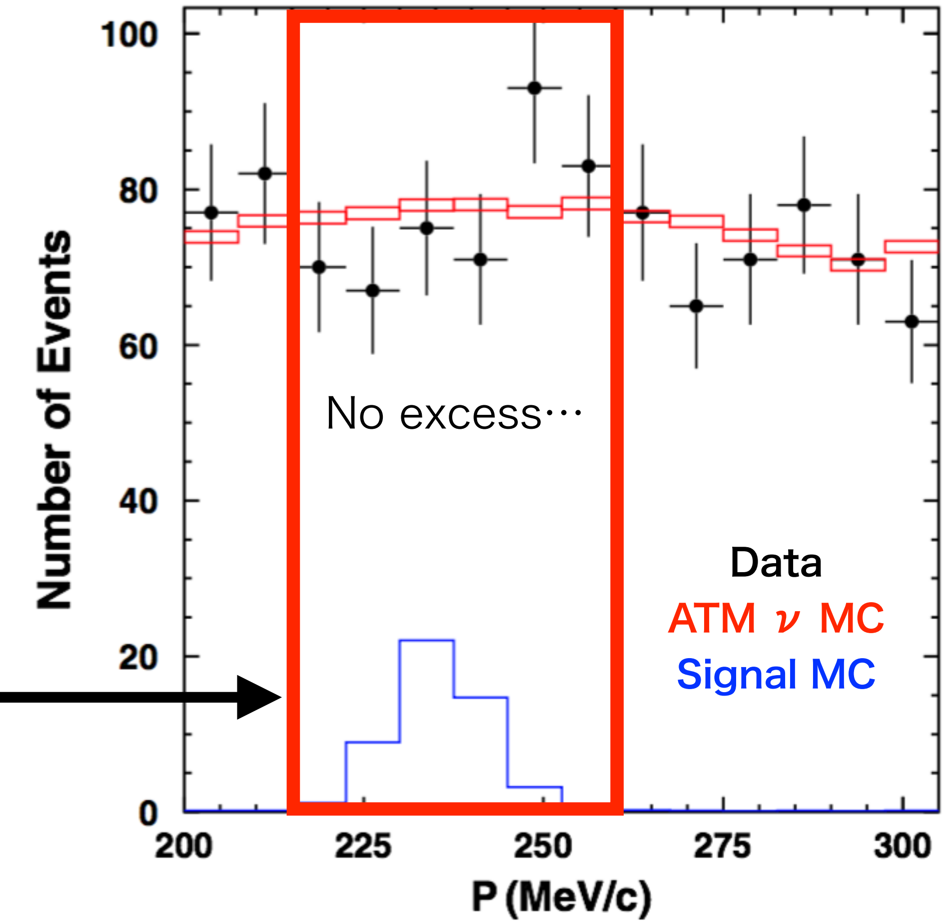
Search for p→$\overline{\nu}$K+

Favored in SUSY.

K+→μ+ν: Leptonic decay channel

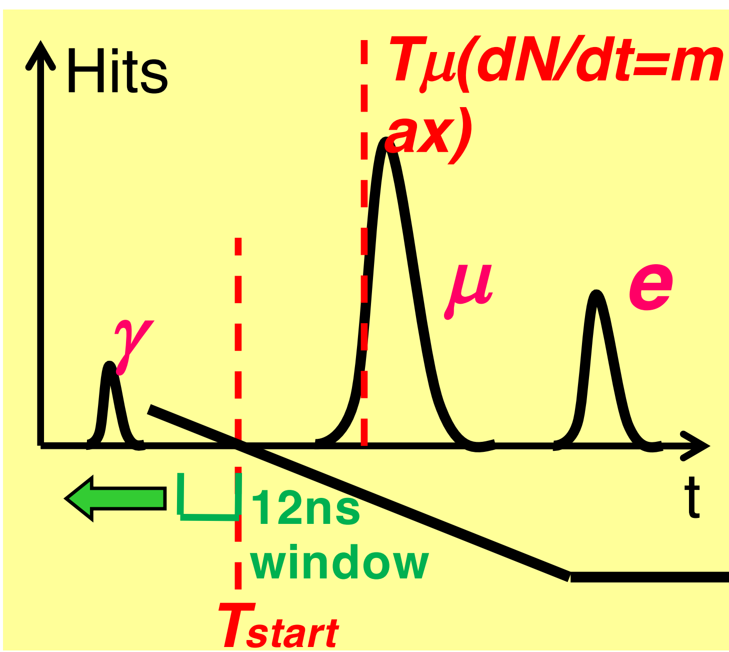
BR$_{K+\to\mu+\nu}$ ~ 60%

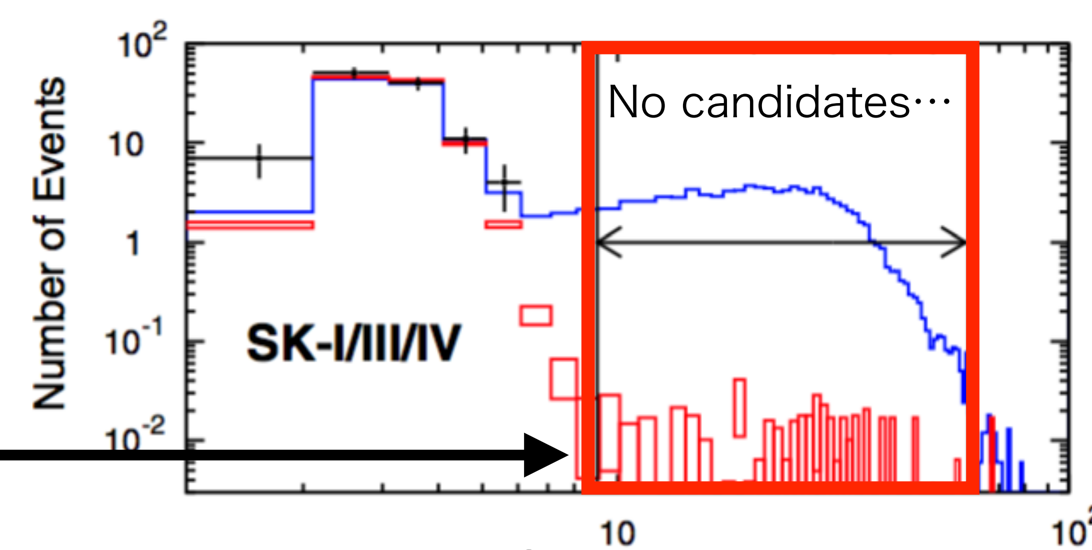




(a) Mono-energetic (236 MeV/c) μ search

- ε ~35%. No significant excess…





(b) Tag De-excitation 6.3 MeV γ and Michel-e

- Require γ, μ, and Michel-e triple coincidence.
- ε ~9%. No candidates…

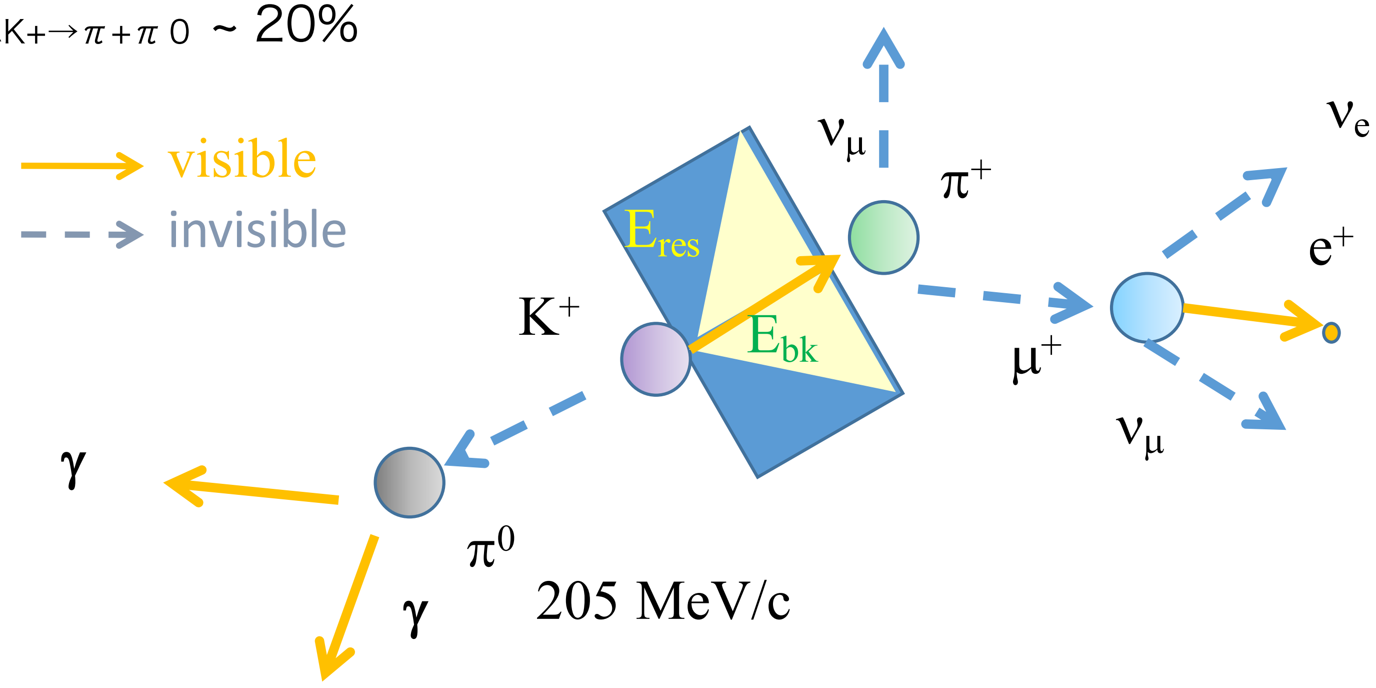
PRD 90, 072005 (2014)

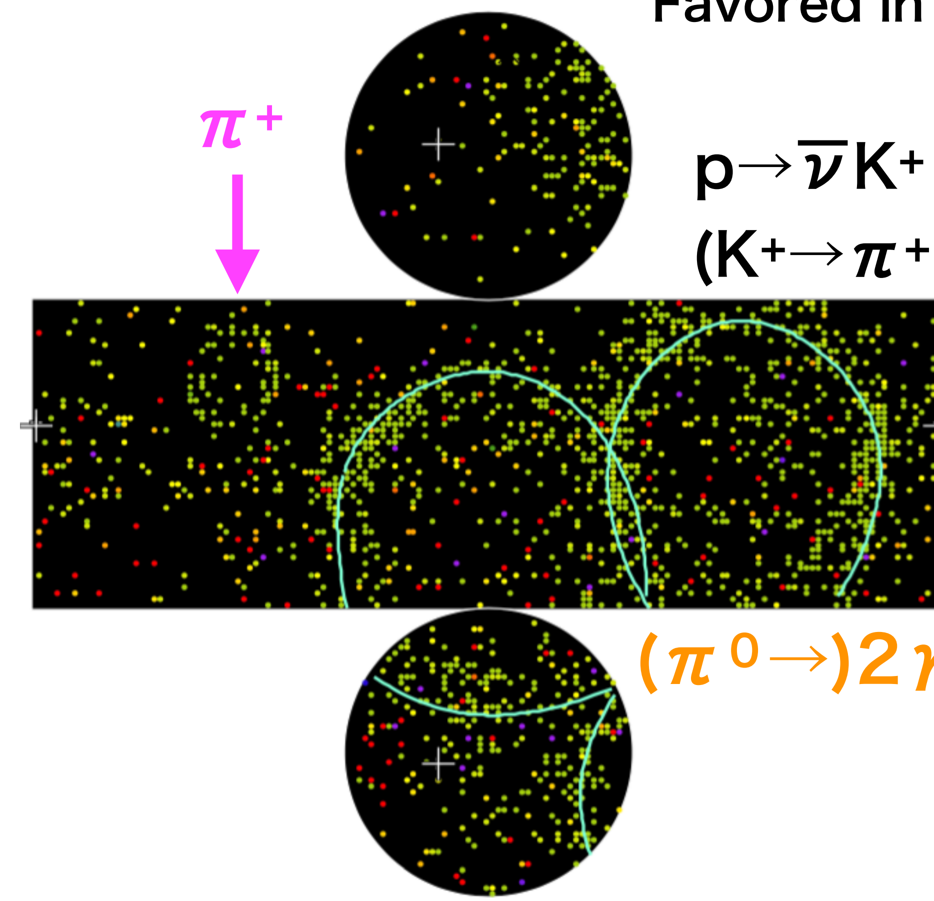
Search for $p \to \overline{\nu} K^+$

Favored in SUSY.

$K^+ \to \pi^+ \pi^0$: Hadronic decay channel

$BR_{K^+ \to \pi^+ \pi^0}$ ~ 20%





(c) Search for $\pi^+ \pi^0$ back-to-back signal

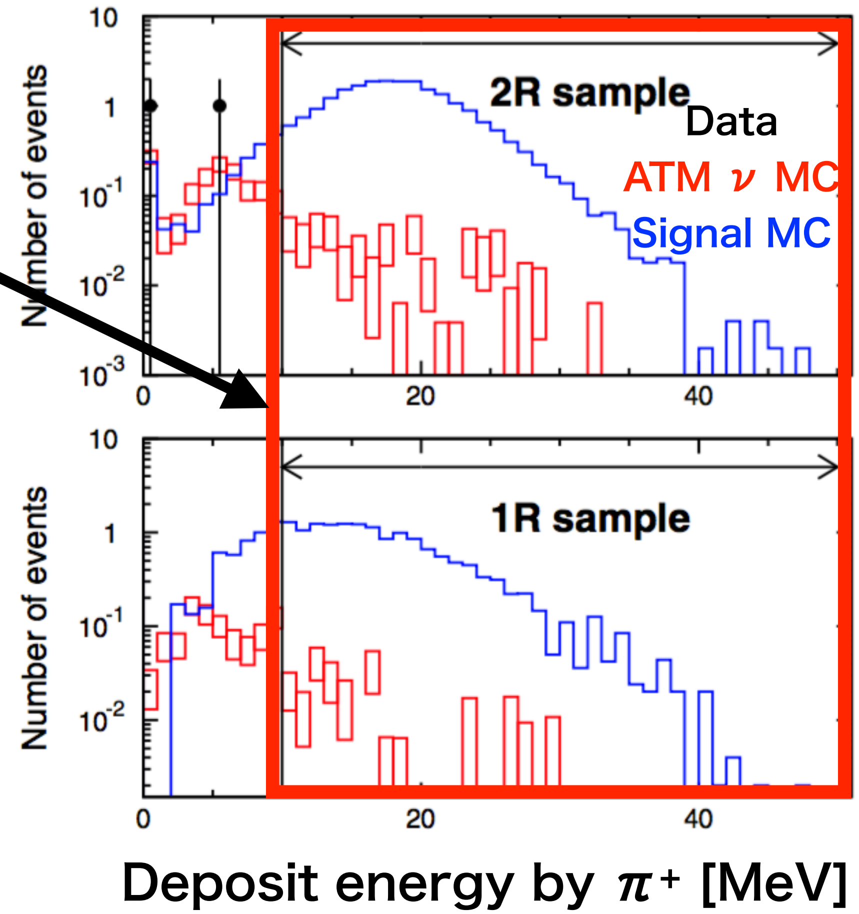
- ε ~9%. No candidates …

PRD 90, 072005 (2014)

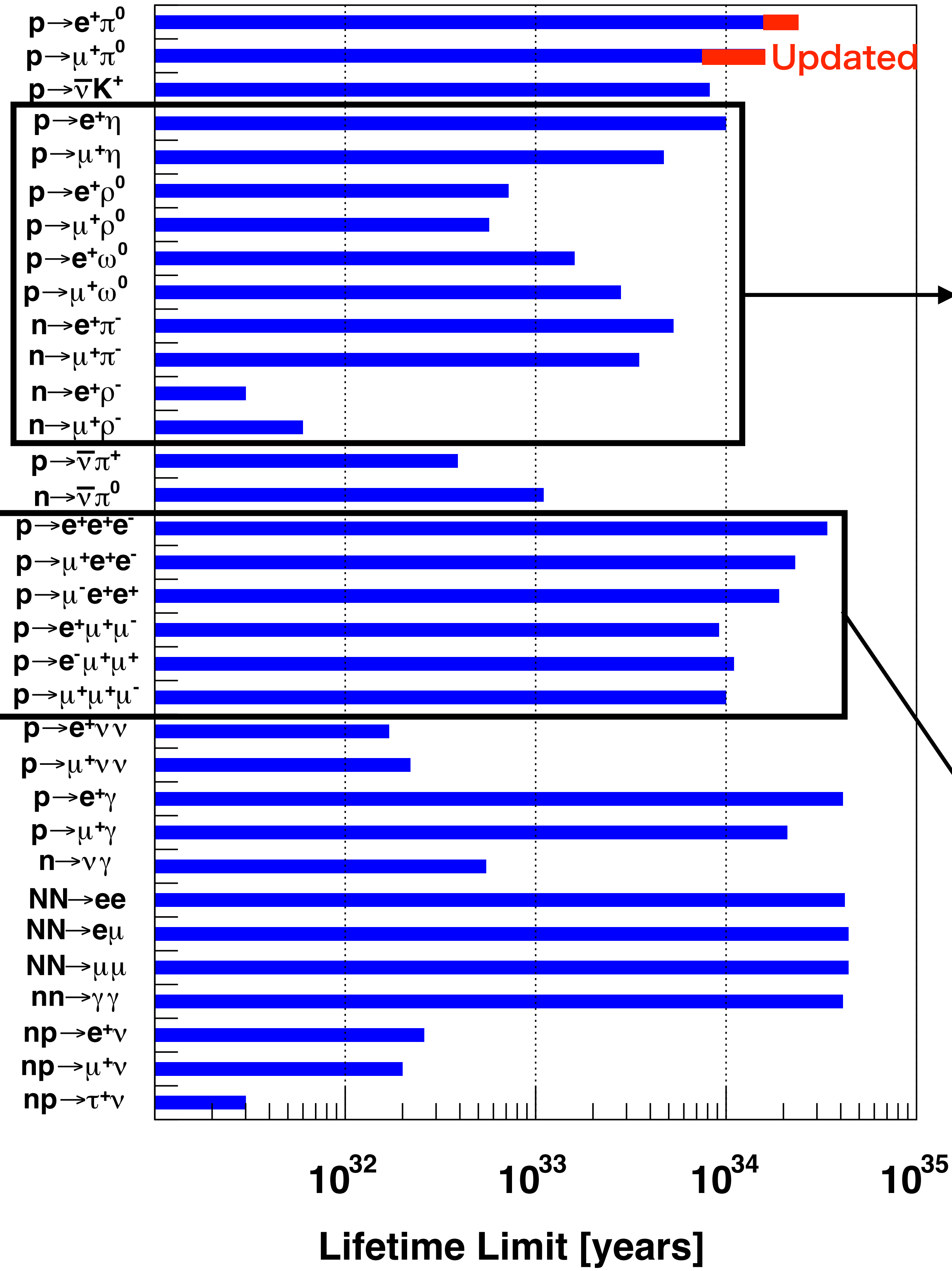
- Combining three search methods with SKI~IV data (365 kton*years)
- **$\tau / B_{p \to \nu K^+}$ > 8.2*10^{33} years (90%C.L.)**

[Super-K Preliminary]

- Studying feasibility of enlarging fiducial mass for this search.



Nucleon Decay Search Summary



Systematic [e^+, μ^+] × [η, ρ, ω, π] searches

PRD 96, 012003 (2017)

Modes	Eff (%)	Background (events)	Candidate (events)	Probability (%)	Lifetime Limit ($\times 10^{33}$ years) at 90% CL
$p \to e^+\eta$	16.0	0.78 ± 0.30	0	···	10.
$p \to \mu^+\eta$	23.3	0.85 ± 0.23	2	20.9	4.7
$p \to e^+\rho^0$	3.8	0.64 ± 0.17	2	13.5	0.72
$p \to \mu^+\rho^0$	1.9	1.30 ± 0.33	1	72.7	0.57
$p \to e^+\omega$	4.8	1.35 ± 0.43	1	74.1	1.6
$p \to \mu^+\omega$	7.9	1.09 ± 0.52	0	···	2.8
$n \to e^+\pi^-$	12.6	0.41 ± 0.13	0	···	5.3
$n \to \mu^+\pi^-$	13.4	0.77 ± 0.20	1	53.7	3.5
$n \to e^+\rho^-$	1.5	0.87 ± 0.26	4	1.2	0.03
$n \to \mu^+\rho^-$	1.2	0.96 ± 0.28	1	61.7	0.06
total		8.6	12	15.7	···

Three charged leptons searches

PRD 101, 052011 (2020)

Modes	Eff (%)	Background (events)	Candidate (events)	Probability (%)	Lifetime limit ($\times 10^{34}$ years) at 90% CL
$p \to e^+e^+e^-$	63.5	0.58±0.08	0	-	3.4
$p \to \mu^+e^+e^-$	47.9	0.50±0.06	0	-	2.3
$p \to \mu^-e^+e^+$	40.8	0.50±0.06	0	-	1.9
$p \to e^+\mu^+\mu^-$	32.6	0.27±0.04	1	18.4	0.92
$p \to e^-\mu^+\mu^+$	38.6	0.27±0.04	1	18.4	1.1
$p \to \mu^+\mu^+\mu^-$	32.6	0.40±0.07	1	25.8	1.0

- No evidence of N-decay so far …. There is still room for statistic improvement (livetime & enlarging the fiducial mass) for these modes.

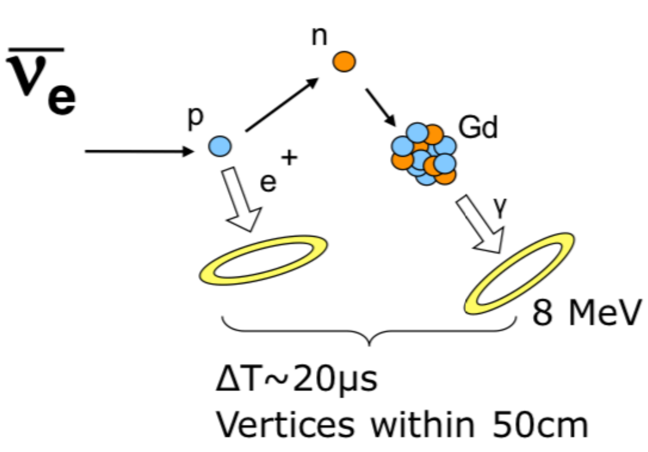
Future Prospect (SK-Gd)

- To increase the search sensitivity, atmospheric ν background rejection and larger exposure are crucial.
- We have loaded Gd into Super-K (SK-Gd), $Gd_2(SO_4)_3$ 0.02%.
- 8 MeV γ emitted from Gd-n capture is much easier to be detected.
  → Increase the neutron tagging efficiency.

  → **We can significantly improve the atmospheric ν rejection power.**

Relation between Neutron tagging efficiency and ATM ν BG rejection power

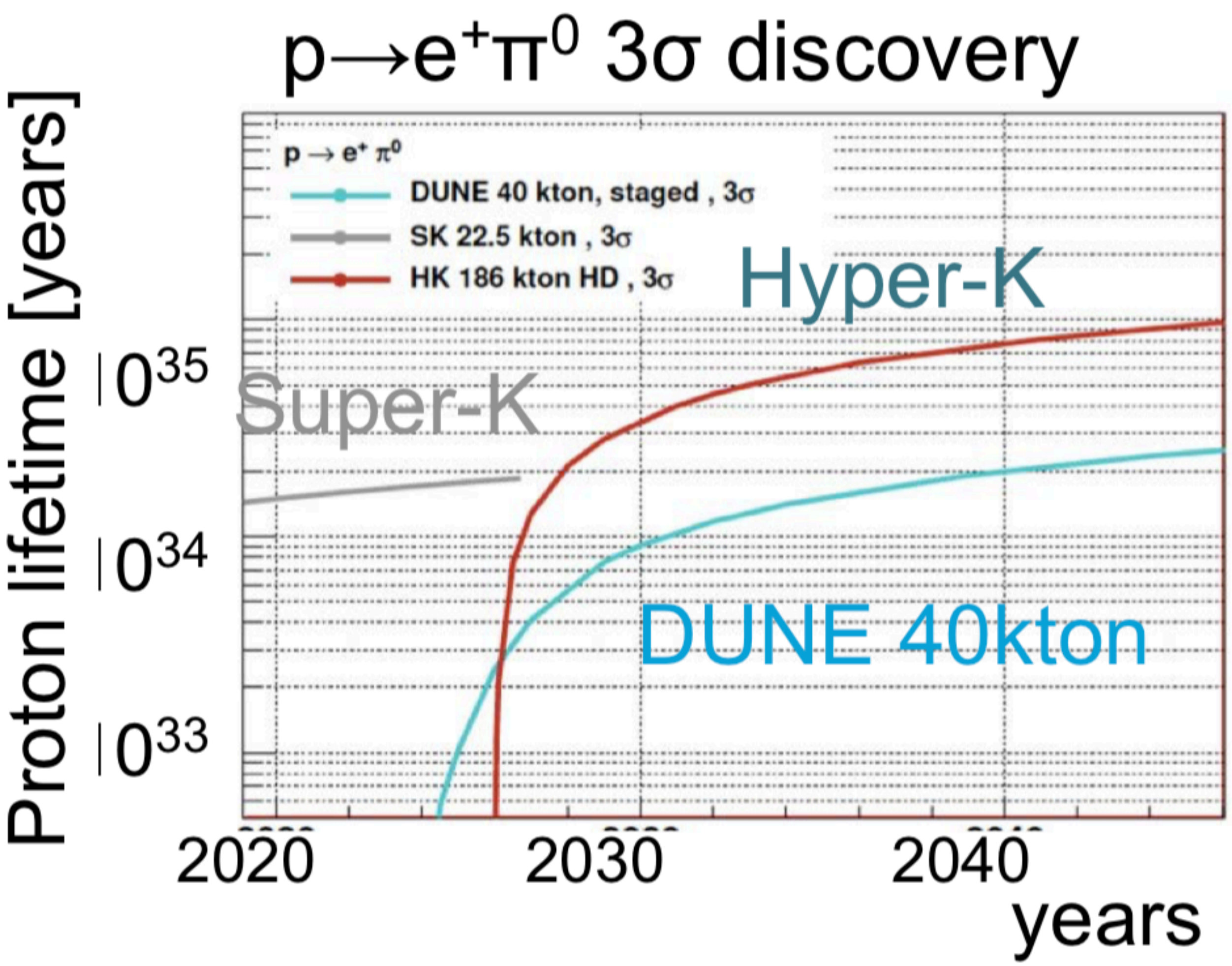
Neutron Tagging efficiency	~25% (H capture)	~50% ($Gd_2(SO_4)_3$ 0.02%)	~90% ($Gd_2(SO_4)_3$ 0.2%)
ATM ν BG Rejection by Ntag	~50%	~65%	~80%

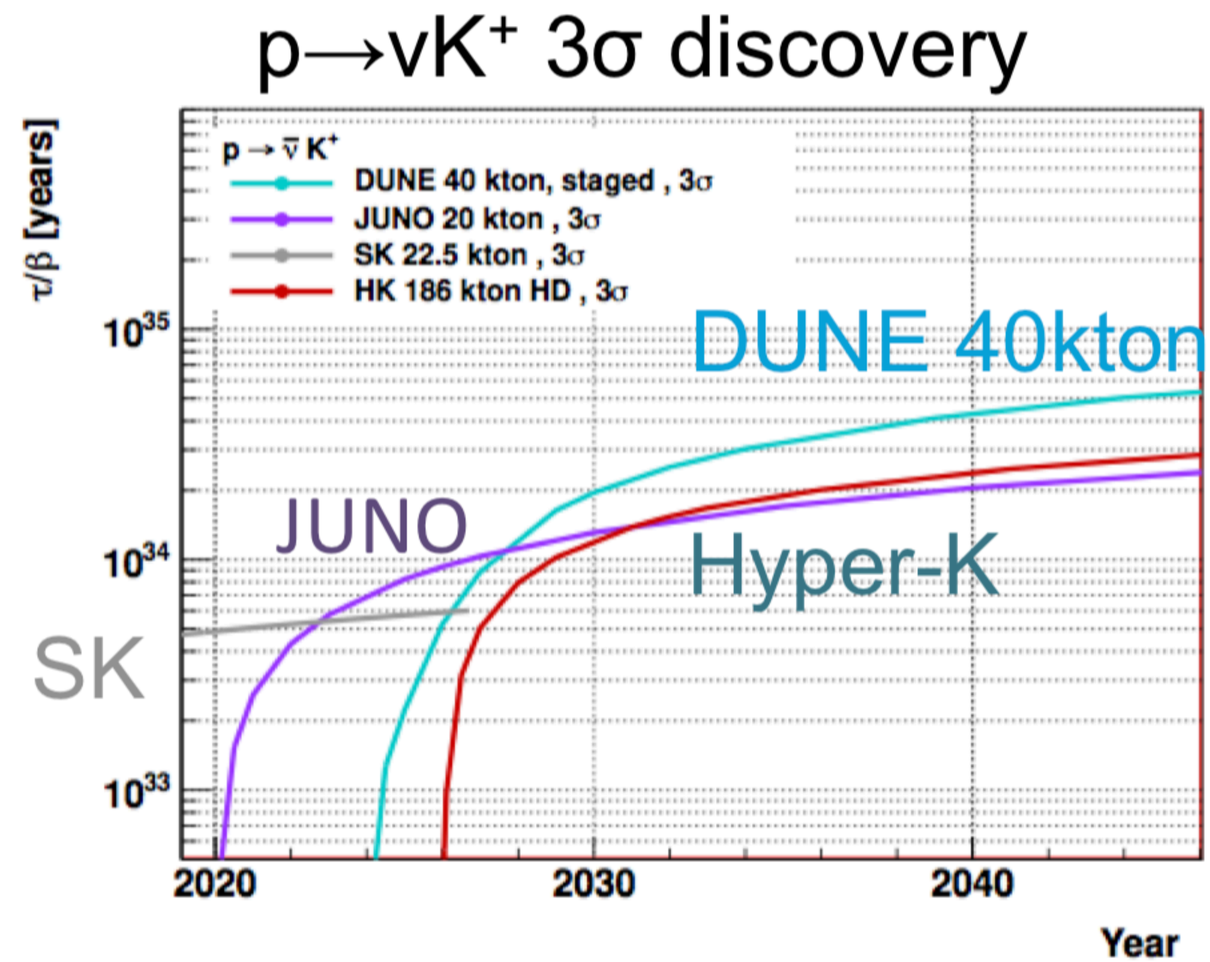


DUNE arXiv:1601.05471
HK arXiv:1805.04163v1
JUNO arXiv:1507.05613

Further Step Forward

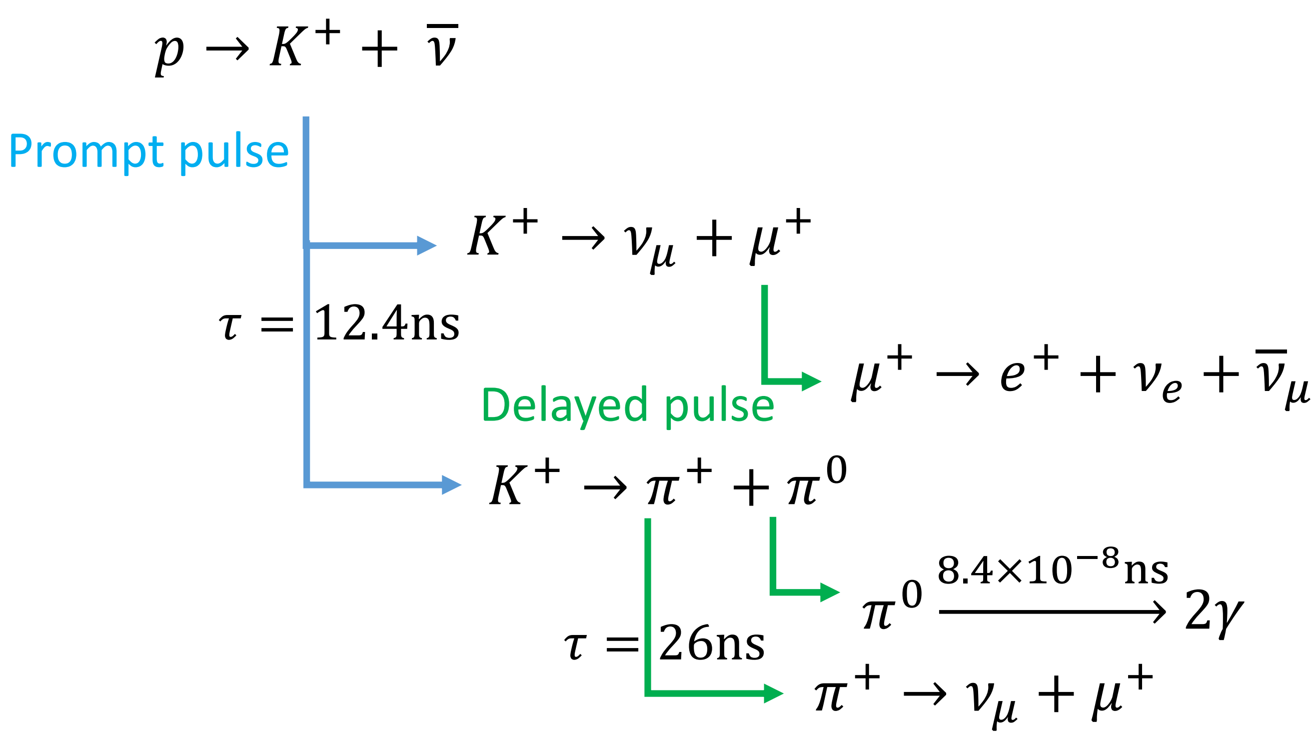
- Different types of gigantic detectors are being constructed and will start operation in this decade.

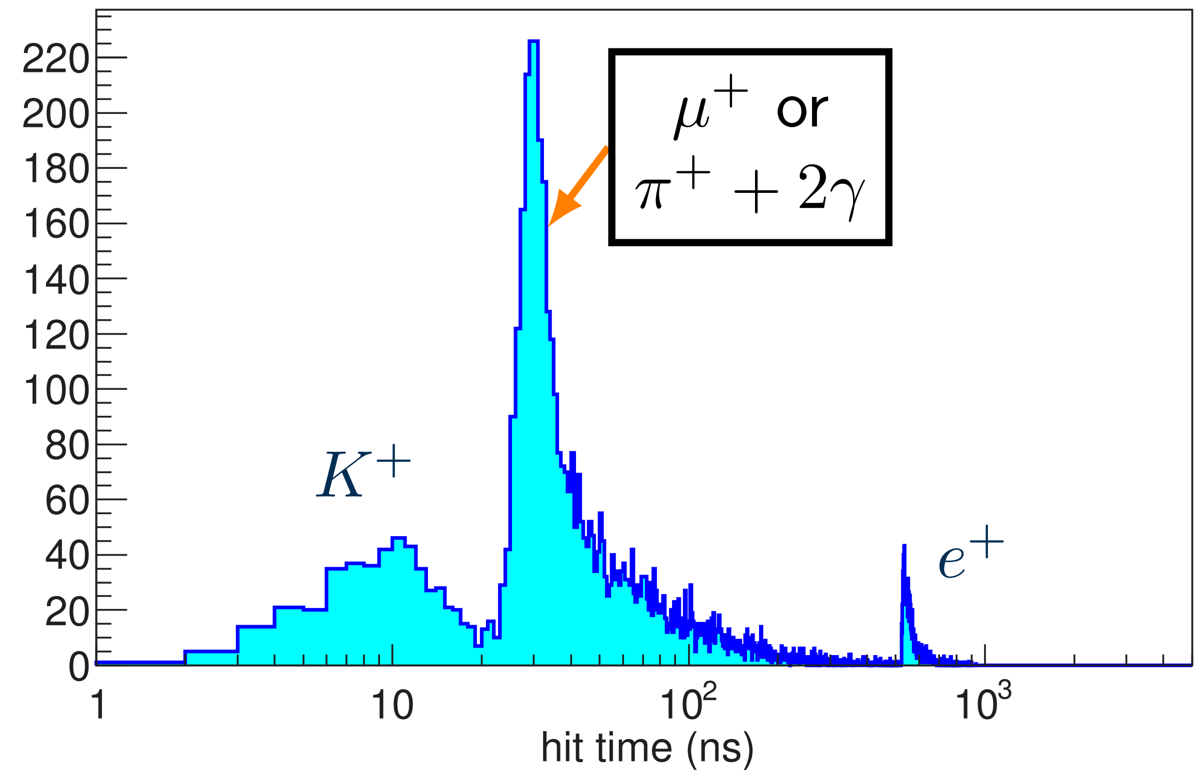




- **3σ discovery potential is expected to reach 10^{35} years for $p \rightarrow e^{+}\pi^{0}$ and 10^{34} years for $p \rightarrow \nu K^{+}$.**

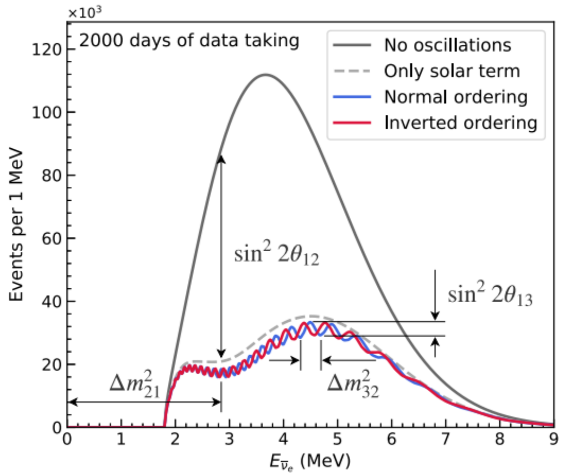
Signatures of K^+: need for large liquid scintillator

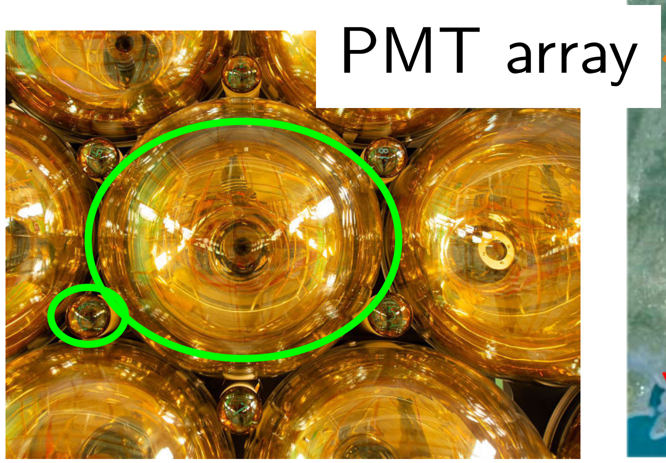


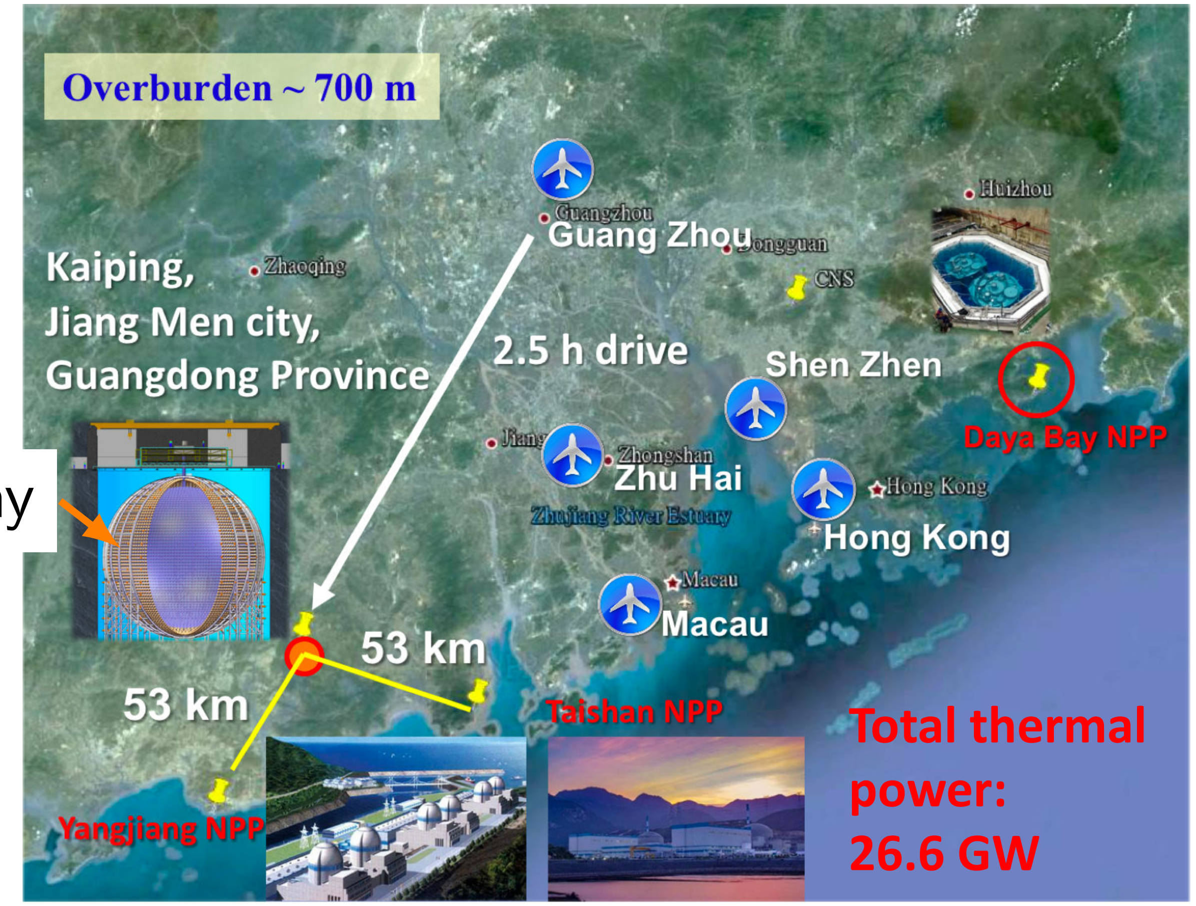


- K^+ is below Cherenkov threshold in water, invisible. So is μ^+ from π^+.
  - Searching for μ^+ or $\pi^+ + 2\gamma$ alone has background.
- Liquid scintillator is ideal for identifying K^+.
  - Scintillation photons from mesons and muons with low kinetic energy.
- Investigated by Undagoitia et al.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

JUNO: the large liquid scintillator to be online





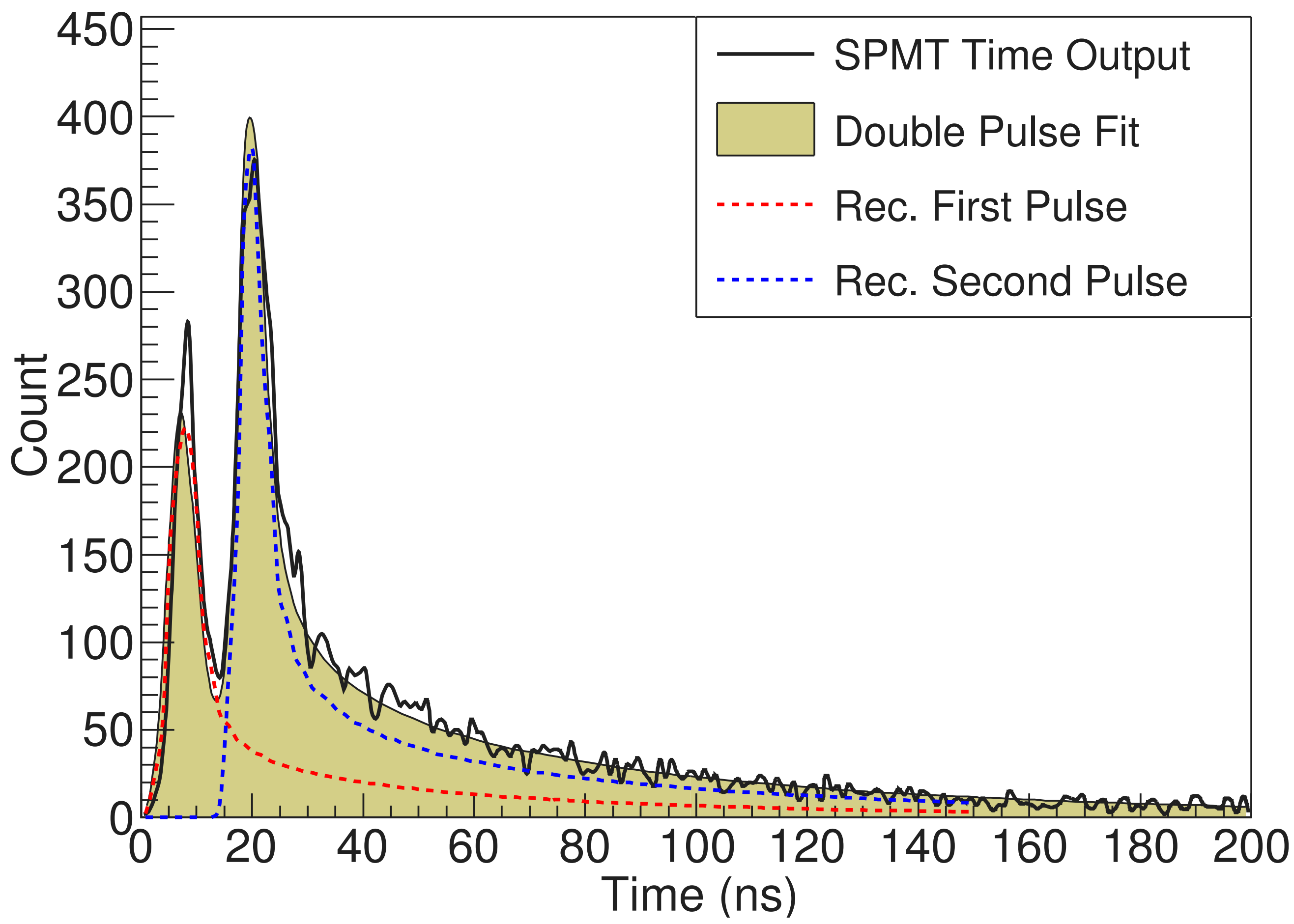


- Major target: neutrino massing ordering.
- Need unprecedented liquid-scintillator energy resolution of 3% at 1 MeV.

- 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.
2. At the residual time histogram, find the rising edge.
3. Fit with K-π , K-μ and single-peak atmospheric ν templates.
   - Require a minimal separation between two peaks to avoid degeneracy.
4. Discriminate among hypotheses by χ^2 ratios (F-statistic).

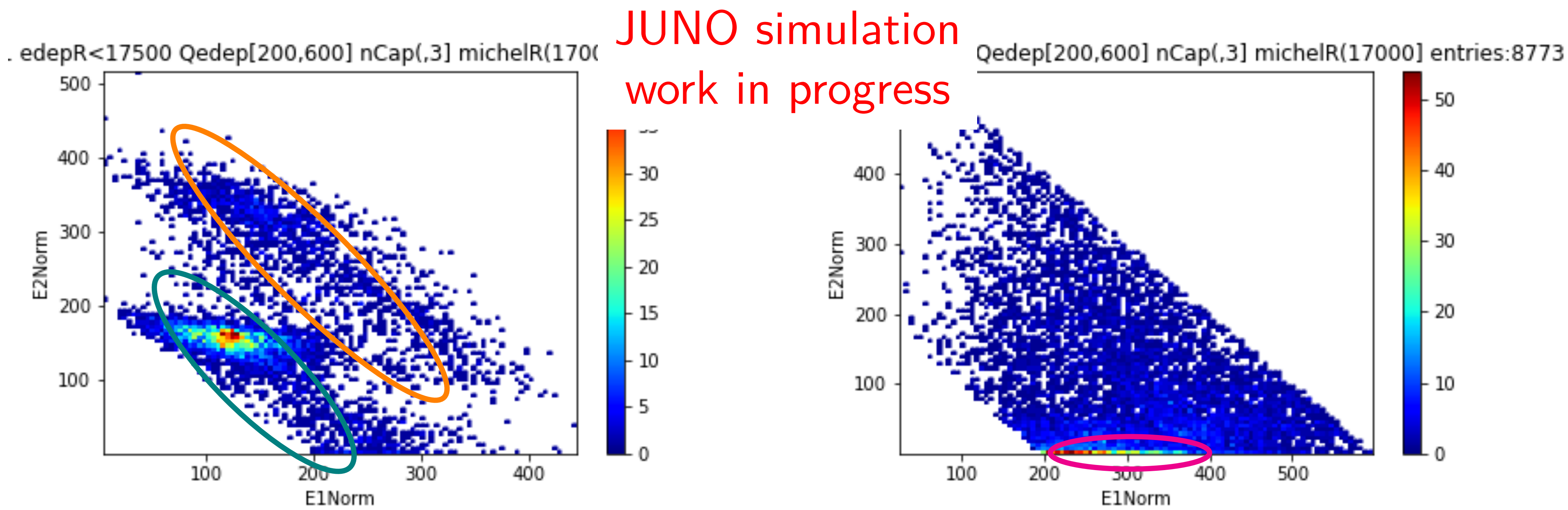


Caveat

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

Individual peak energies

- Scatter individual peak energies on a plot.



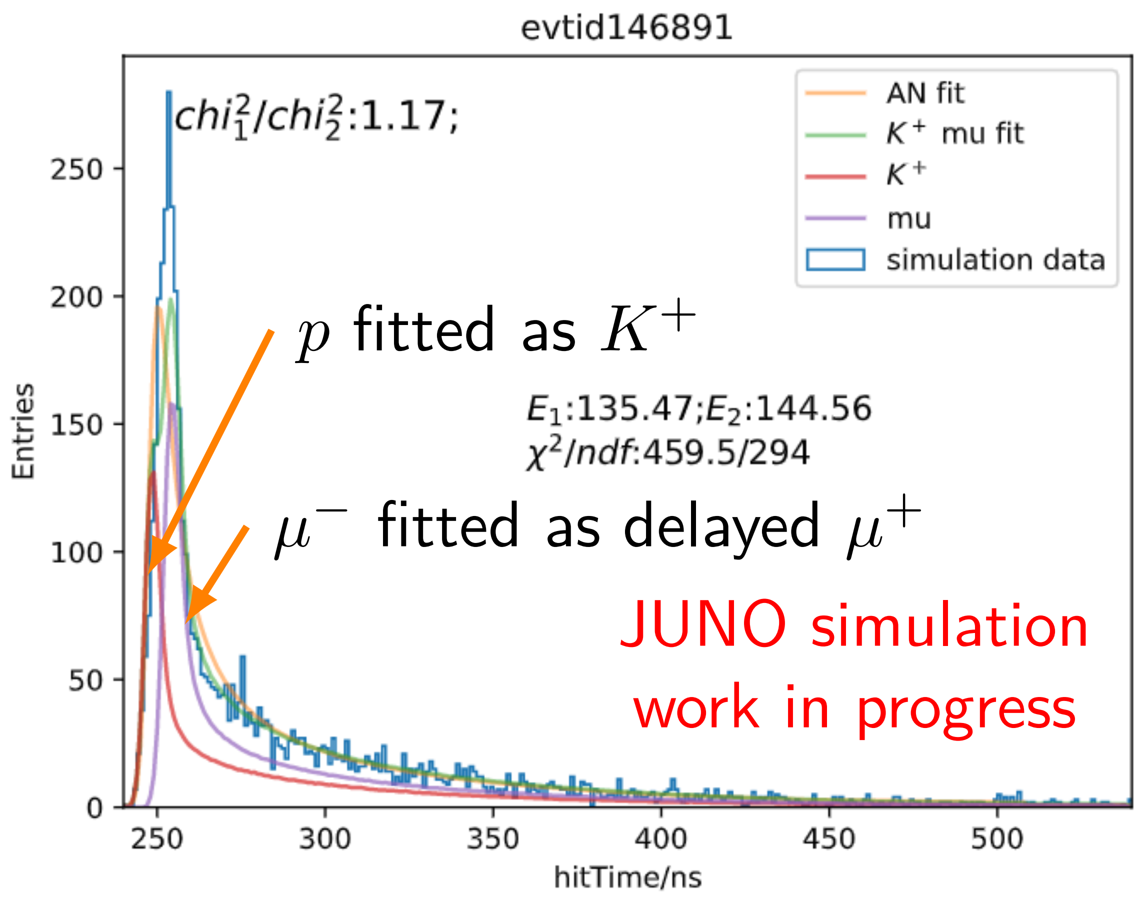
K^+ atmospheric ν

- $K^+ \rightarrow \pi^+ + \pi^0(2\gamma)$
- $K^+ \rightarrow \mu^+ + \nu_\mu$, missing energy carried by ν_μ.
- mostly only one peak for background.

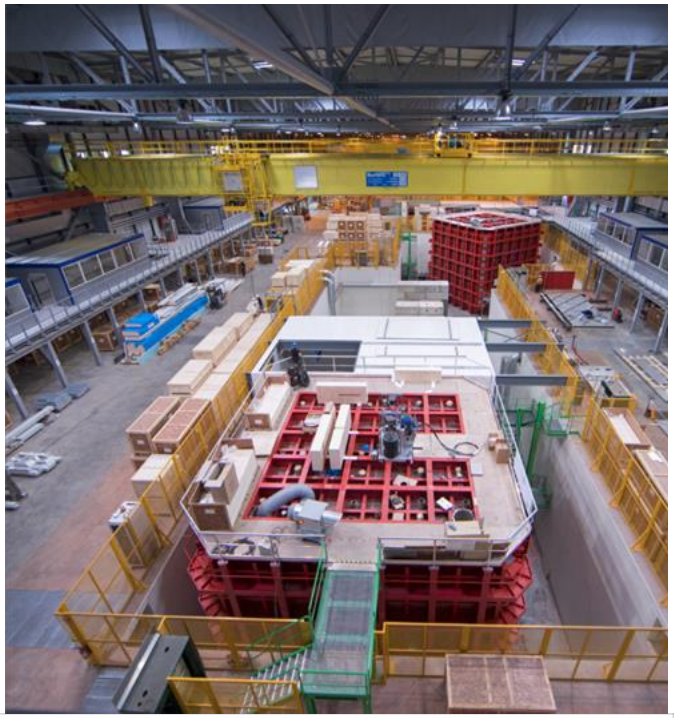
Background example: quasi-elastic scattering of atmospheric ν

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

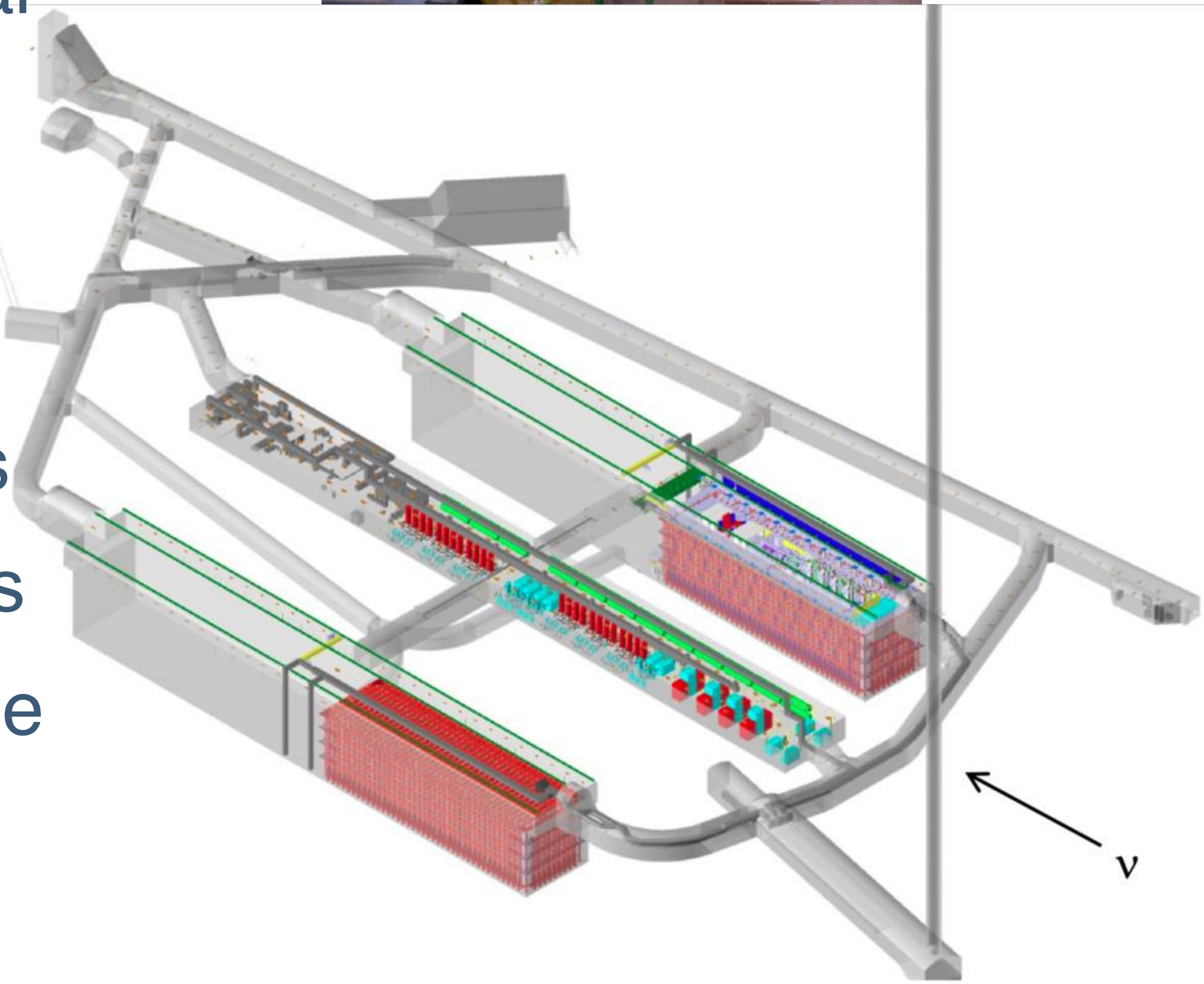
- Prompt p peak minicing K^+. Possible improvement:
  - p-K discrimination
- "Delayed" μ^- peak is simultaneous as p but starting time is mis-identified. Possible improvements:
  - line-shaped energy deposition model for μ^-.
  - $\mu^\pm$ discrimination.



DUNE Far Detector



- Deep underground cavern (1.5 km) at SURF
- Four 17-kiloton Liquid argon TPC (LArTPC) modules (70-kiloton total mass)
  - Each cryostat is 65.8 m long, 18.9 m wide and 17.8 m tall
- Photon Detection System system to provide t_0 for non-beam physics
- Expect FD to turn on in late 2020's
- Successful operation of large-scale DUNE prototypes at CERN (ProtoDUNE)

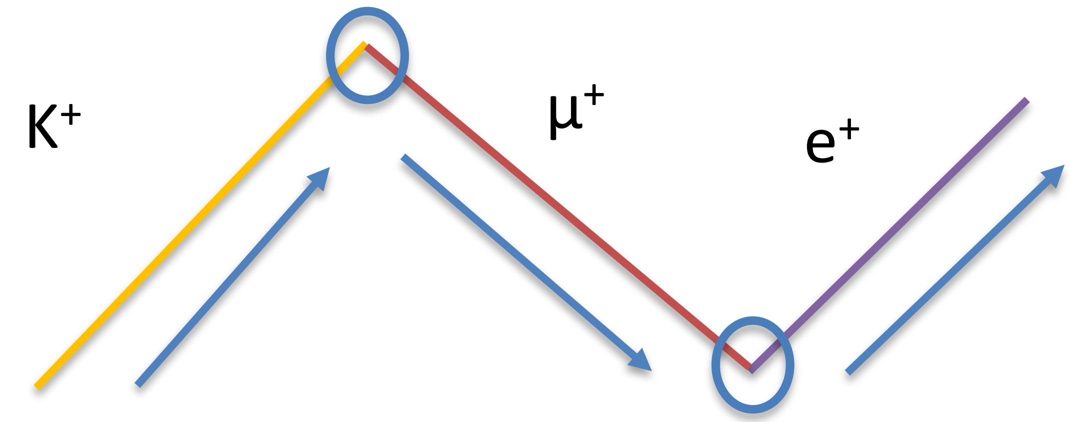


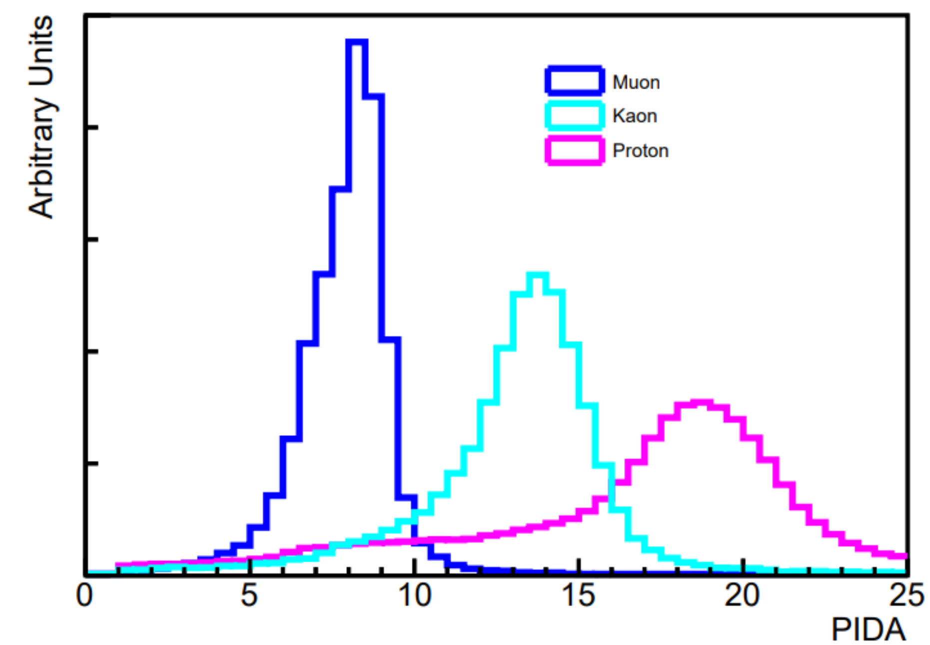
Nucleon Decay

- Observation of baryon number violating processes such as nucleon decay and neutron-antineutron oscillation would provide evidence of physics beyond the Standard Model
  - Benchmark proton decay modes from grand unified theories:
    - $p \rightarrow e^{+}\pi^{0}$
    - $p \rightarrow K^{+}\bar{\nu}$
- Large mass, deep underground location, and excellent imaging and particle ID capabilities in LArTPCs make the DUNE FD ideal for nucleon decay searches
- The most stringent limits in most decay channels are set by the Super-Kamiokande experiment (water Cherenkov detector, 50 kiloton total mass, in operation for more than 25 years)
  - Improvements on these limits will require long exposure times coupled with larger sensitive mass and/or improved efficiency and background rejection
- Two other large detectors will be operating in the DUNE era: Hyper-Kamiokande (water Cherenkov) and JUNO (liquid scintillator)
  - Highly complementary searches

$p \rightarrow K^+ \bar{\nu}$

- DUNE's initial focus is on proton decay modes producing charged kaons
  - Kaon is typically below threshold in a water Cherenkov detector, but can be identified by dE/dx and decay in a LArTPC
- Signature: single kaon with origin in the fiducial volume followed by decay products
  - 64% branching fraction for decay to muon
- Background due to cosmic-ray muons can be controlled by requiring no activity close to the edges of the TPCs
- Atmospheric neutrinos make up the dominant background
  - Most significant background is not neutrino-induced kaon production, but charged-current quasi-elastic events where the proton is misID-ed as a kaon
  - Look for kaon Bragg peak near muon vertex



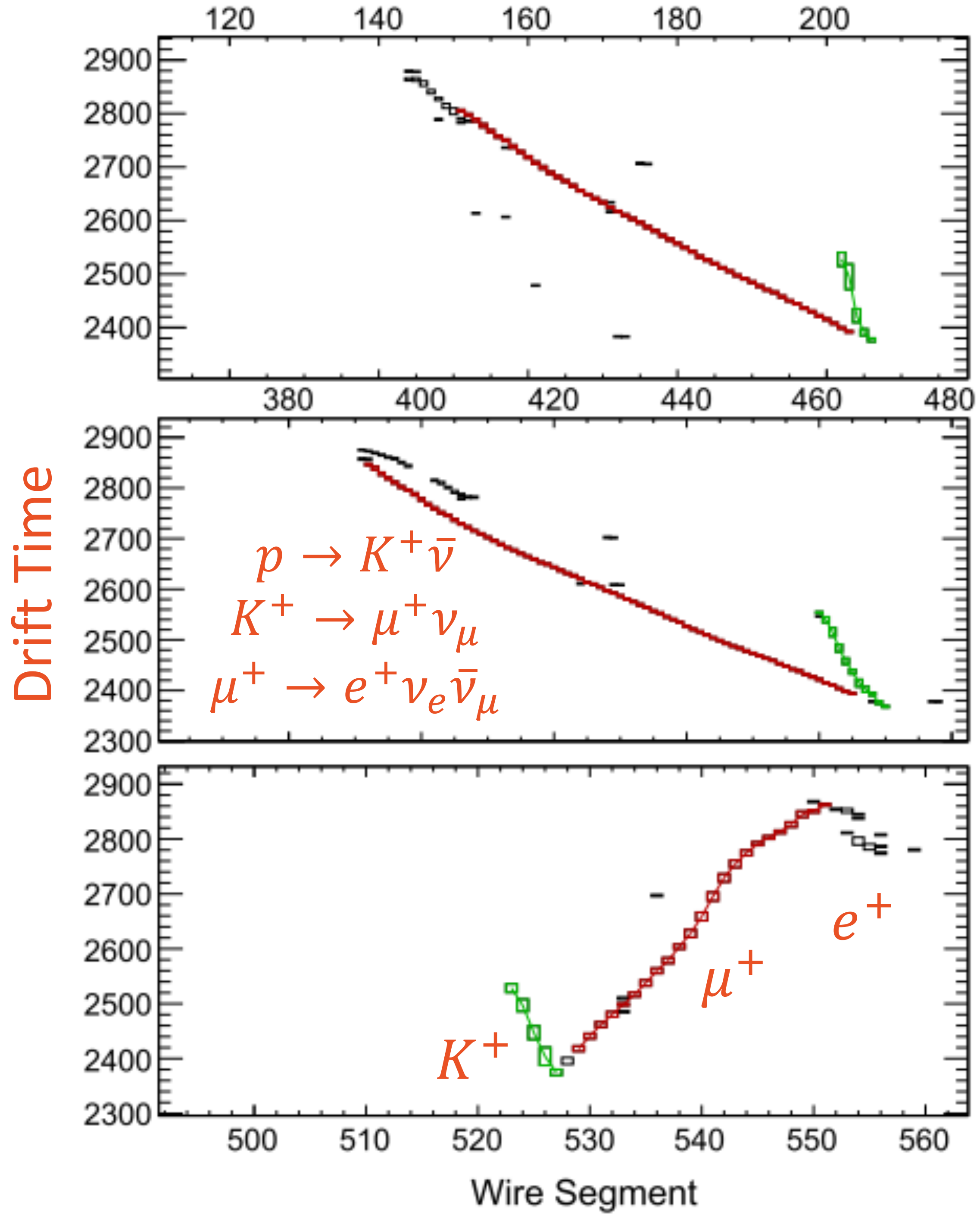


Analysis:

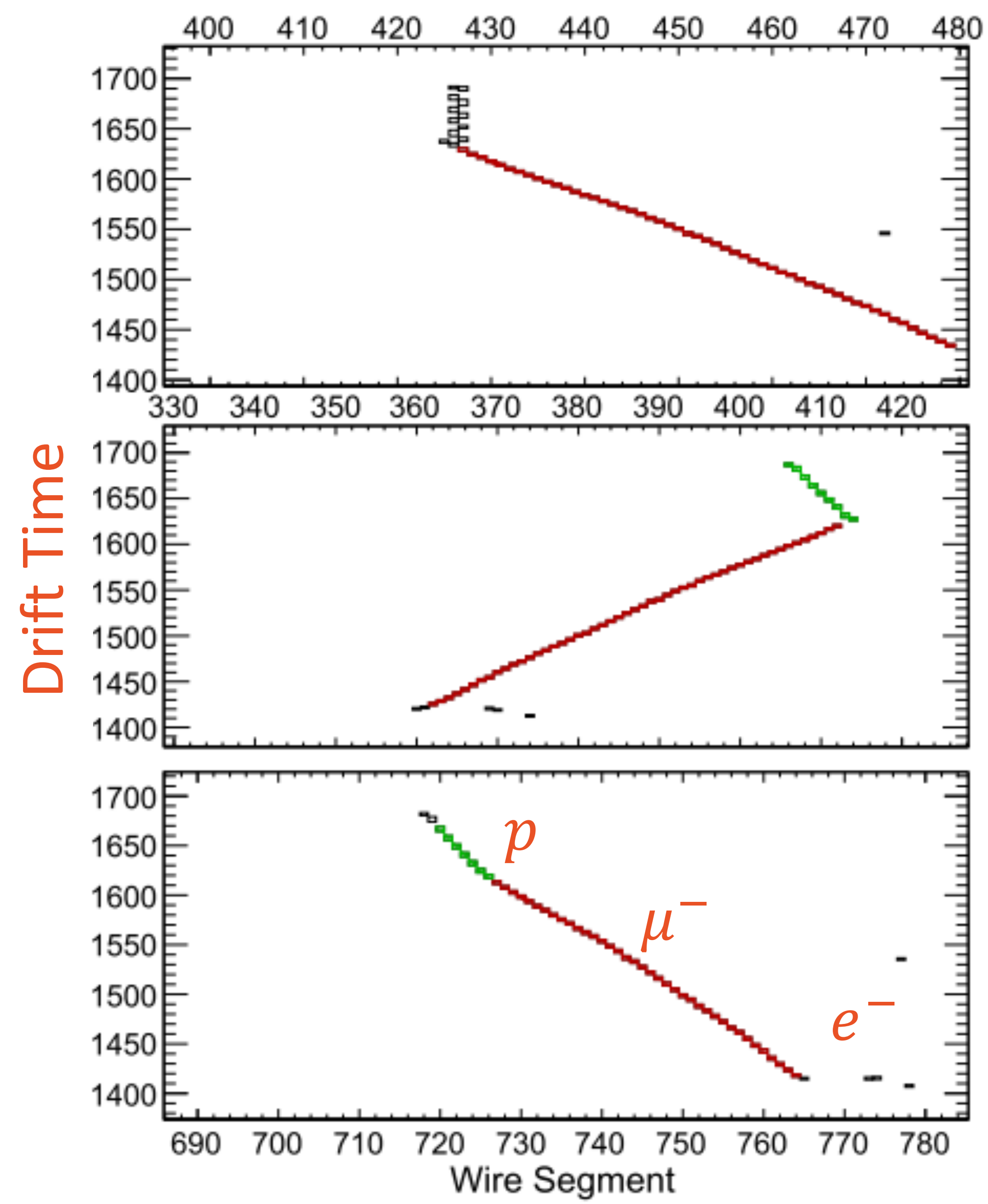
- At least two tracks (kaon + decay product, usual muon), longest track <100 cm (removes background from high-energy nus)
- Boosted Decision Tree identifier with 14 input variables

p→K⁺$\bar{\nu}$ Event Displays

A high scoring signal MC event



A high scoring atmospheric MC event



https://link.springer.com/article/10.1140/epjc/s10052-021-09007-w

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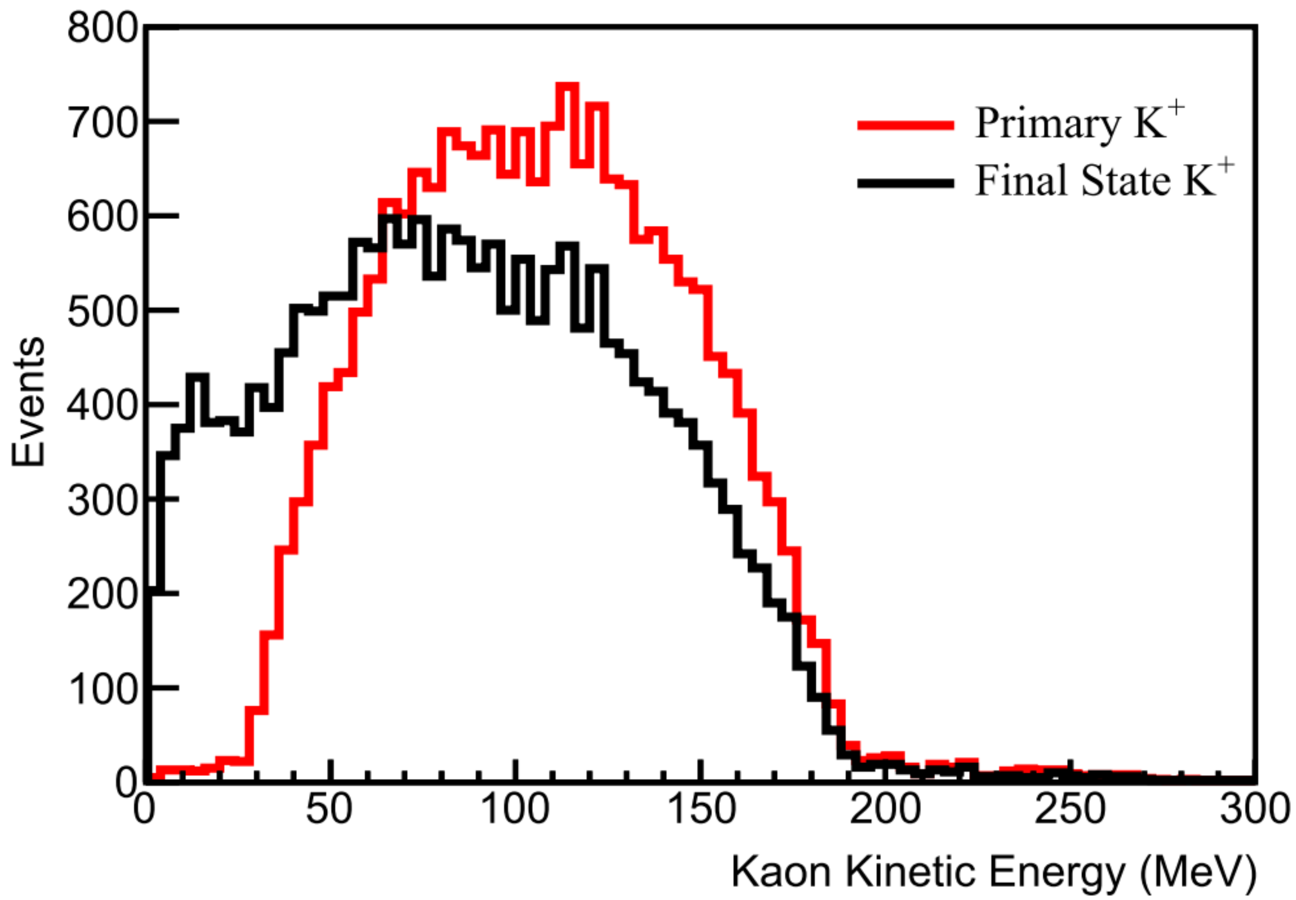
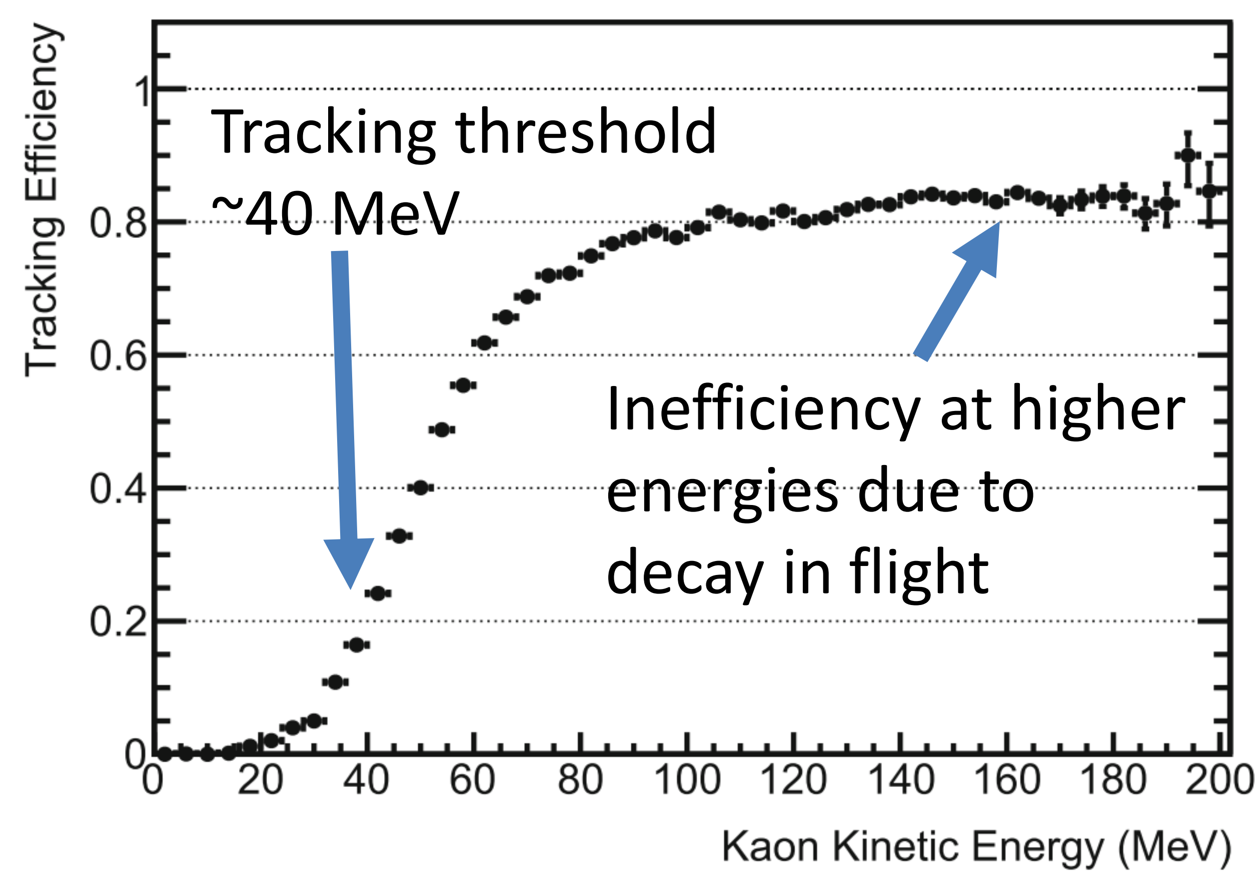
Effect of Final State Interactions

- Limiting factor in kaon identification is the kaon tracking efficiency
- Kaons from proton decay are ~100 MeV and strongly affected by final state interactions (FSI)
  - After FSI, ~25% of kaons have kinetic energy <50 MeV
  - FSI can also cause nucleons to be emitted; presence of these nucleons can also affect kaon reco





$p \rightarrow K^+\bar{\nu}$ Sensitivity

- Assumed a 30% signal efficiency (including expected tracking improvements)
- Applied same cuts to atmospheric neutrino events to get an expected background of one event per megaton-year (3×10^{-6} background suppression)
- Systematics: 2% on signal (FSI uncertainty); 20% on background (flux and cross section uncertainty)
- DUNE sensitivity (90% CL lower limit on proton lifetime in this channel):
  - 1.3×10^{34} years (400 kiloton-year exposure)
  - Current published limit from Super-K: 5.9×10^{33} years (260 kiloton-year exposure)

Other Nucleon Decay Channels

- $n \rightarrow e^- K^+$
- Applied similar analysis techniques as $p \rightarrow K^+\bar{\nu}$ analysis, with requirement of electron shower in addition to kaon ID
- Signal efficiency: 47%
- DUNE sensitivity:
  - 1.1x10^{34} years (400 kiloton-year exposure)
  - Current published limit (Frejus experiment): 3.2x10^{31} years

- $p \rightarrow e^+\pi^0$
- Preliminary analysis based on Monte Carlo truth variables (approximated reconstruction)
- Must identify 3 electromagnetic showers
- DUNE sensitivity:
  - 8.7x10^{33} – 1.1x10^{34} years depending on reconstruction performance (400 kiloton-year exposure)
  - Current published limit from Super-K: 2.4x10^{34} years (450 kiloton-year exposure)

p→ ν π^+ & n→ ν π^0

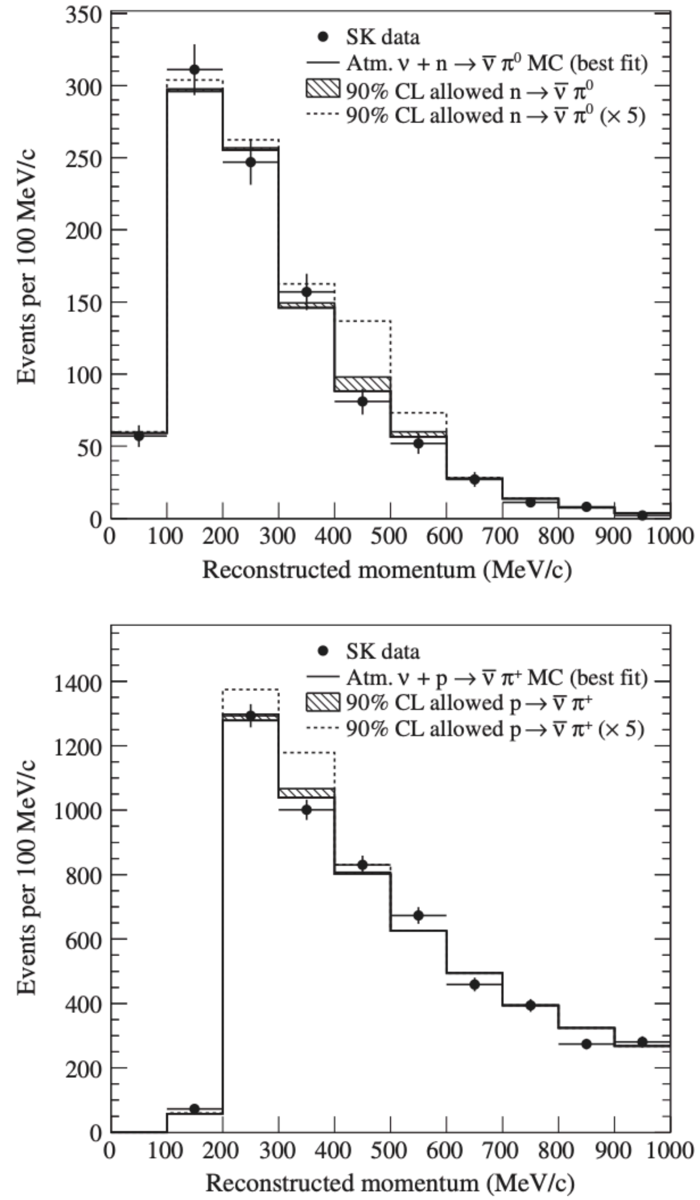


FIG. 3. Reconstructed momentum for 172.8 kt · yr of SK-I + II + III data (black dots), best fit result of atmospheric neutrino plus nucleon decay MC simulation (solid line), and the 90% C.L. allowed amount of nucleon decay (hatched histogram) for $n \to \bar{\nu}\pi^0$ (top) and $p \to \bar{\nu}\pi^+$ (bottom). The dashed line shows how a positive signal of nucleon decay would look, corresponding to five times the limit we set on the decay partial lifetimes. The $p \to \bar{\nu}\pi^+$ nucleon decay contribution in the bottom figure is reconstructed at lower momentum than the expected value (458.8 MeV/c) because a muon hypothesis is assumed in the reconstruction.

Dinucleon Decay (1)

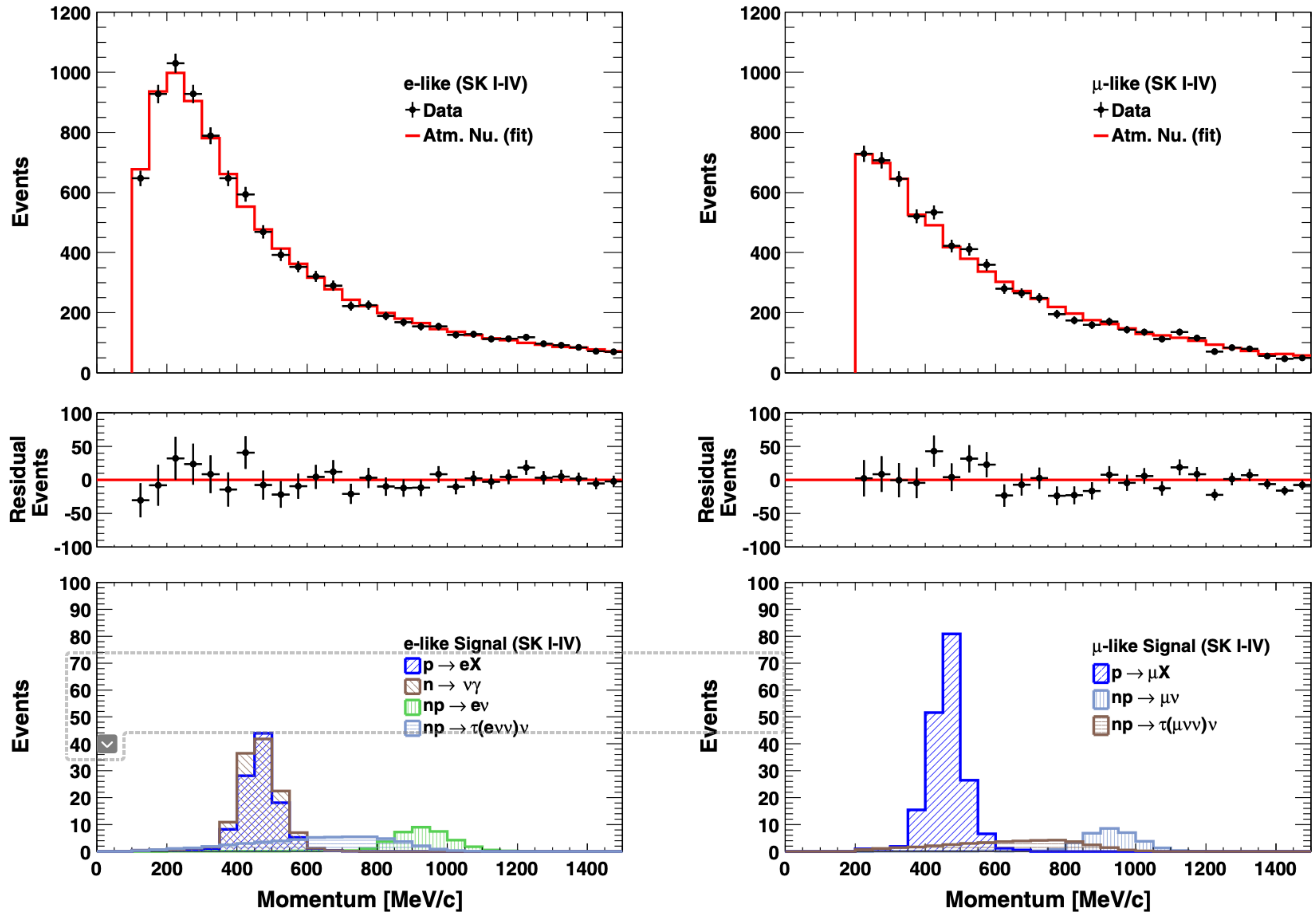


FIG. 1 (color online). (Top) Reconstructed momentum distribution for 273.4 kton yr of combined SK data (black dots) and the best-fit result for the atmospheric neutrino background Monte Carlo simulations (solid line). The corresponding residuals are shown below, after fitted background subtraction from data. (Bottom) The 90% confidence level allowed nucleon decay signal (hatched histograms), from the signal and background MC fit to data. All modes are shown (overlaid), with e-like channels on the left and μ-like channels on the right.

Dinucleon Decay (2)

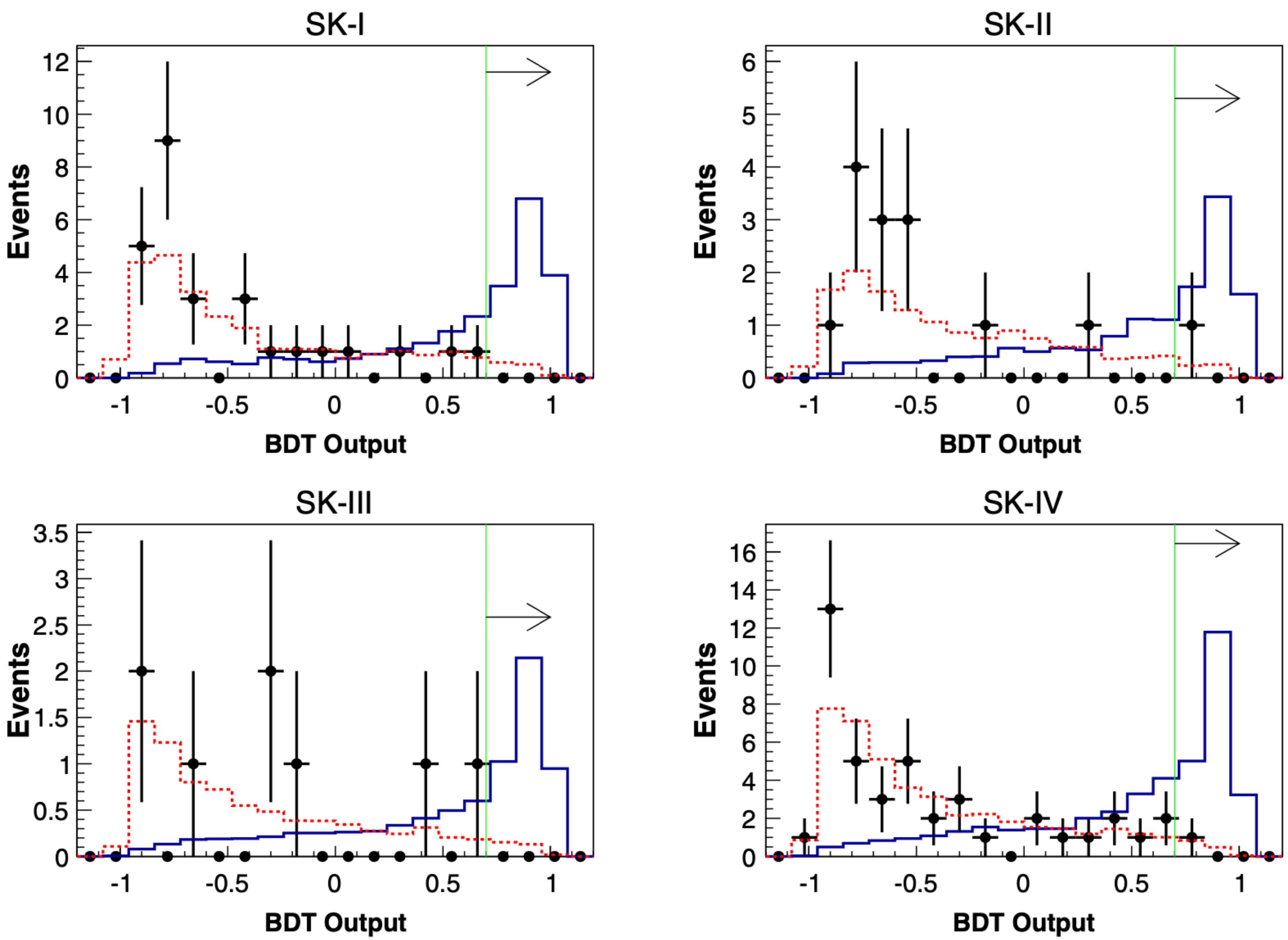


FIG. 4 (color online). BDT output for $pp \to \pi^+\pi^+$ signal MC (solid), atmospheric neutrino background MC (dashed), and data (crosses). The vertical green line indicates the BDT cut value, and the arrow indicates that only events to the right of the cut are kept.

Dinucleon Decay (3)

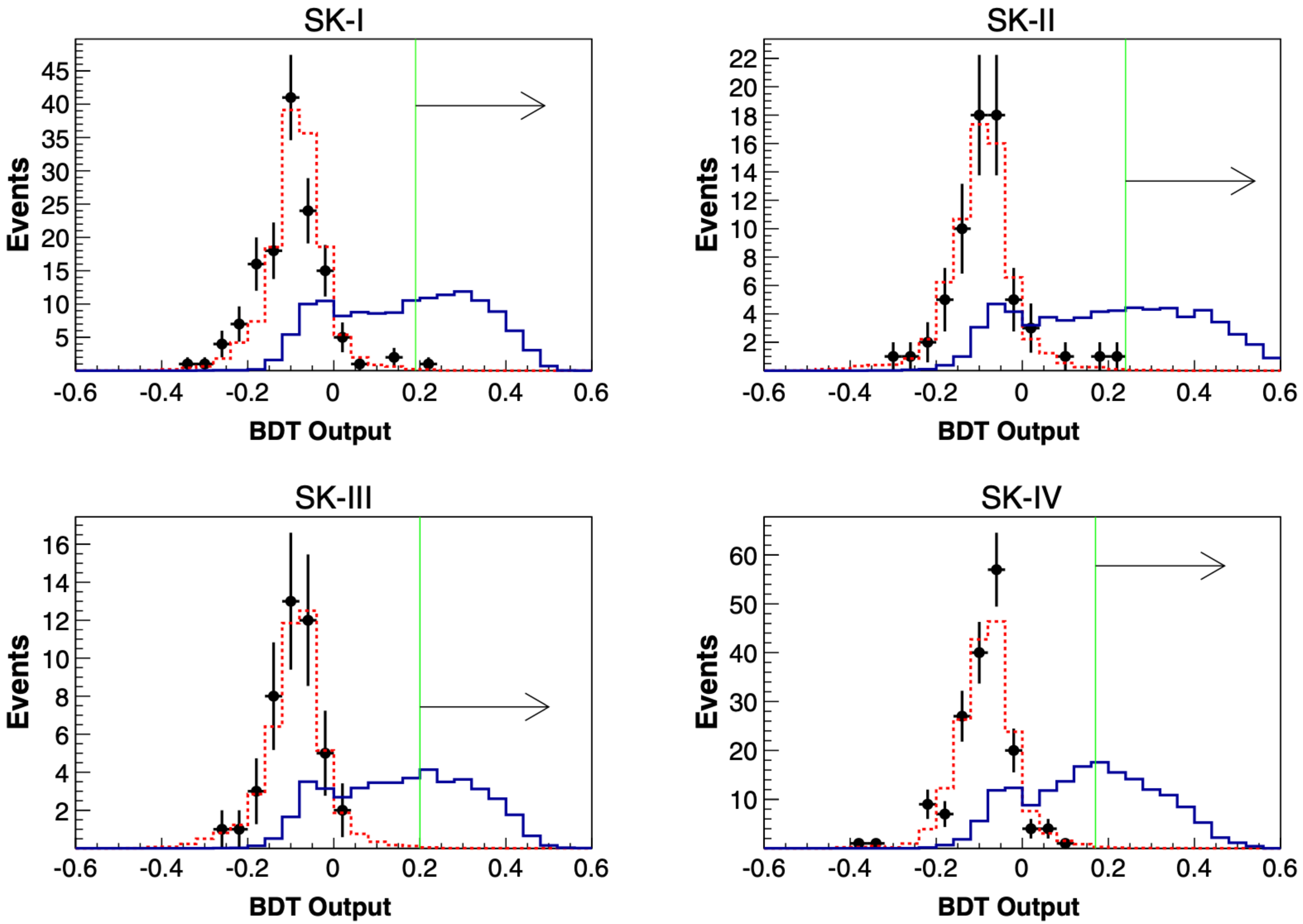


FIG. 10 (color online). BDT output for $pn \to \pi^+\pi^0$ signal MC (solid), atmospheric neutrino background MC (dashed), and data (crosses). The green vertical line indicates the BDT cut value, and the arrow indicates that only events to the right of the cut are kept. One candidate event can be seen in the SK-I data distribution, just to the right of the cut at 0.19.