Search for $n \rightarrow \bar{n}$ in Large Neutrino Detectors

Linyan Wan, Fermilab

2025/01/13

Baryon Number Violation Workshop

Institute for Nuclear Theory

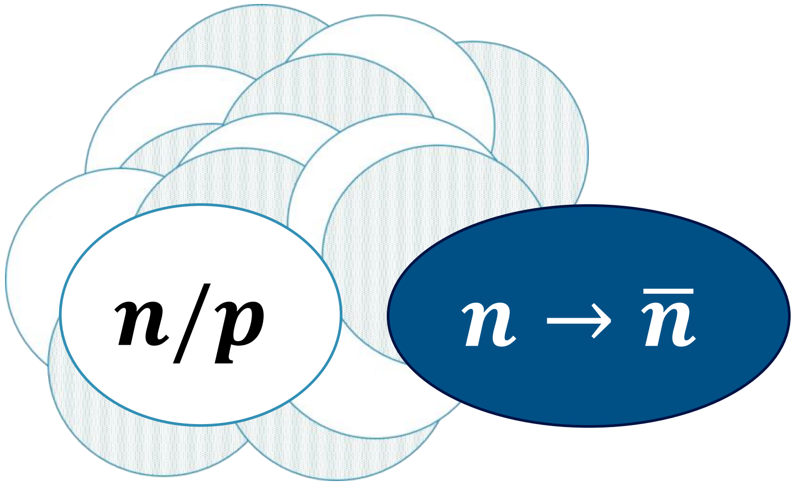
$n \to \bar{n}$ Search?

- Free neutron
  - Grenoble (1994), NNBAR@ESS (J. Womersley on Jan 15th)

- **Bound neutron in a nucleus**
  - **Large neutrino detectors**

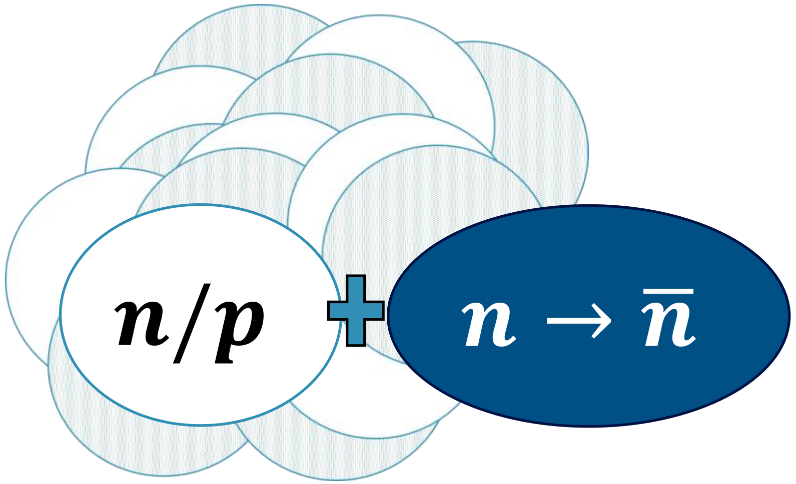
- Other neutron-dense environment
  - Neutron star (R. Shrock on Jan 17th)

Bound Neutron Transition



- $n \rightarrow \bar{n}$ transition (suppressed by nuclear potential)

Bound Neutron Transition



- $n \to \bar{n}$ transition (suppressed by nuclear potential)
- Antineutron annihilation with another nucleon

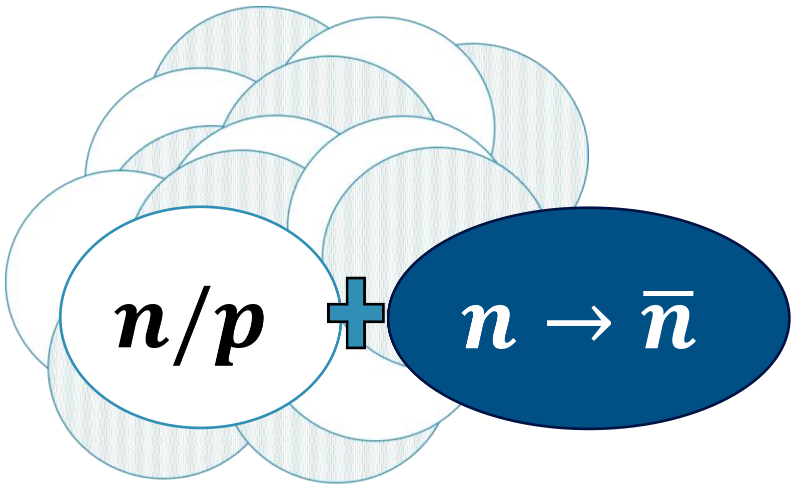
For $\bar{p}p$

- Bubble chambers (1978, 1983)

For $\bar{p}n$

- Bubble chambers (1969)

Bound Neutron Transition



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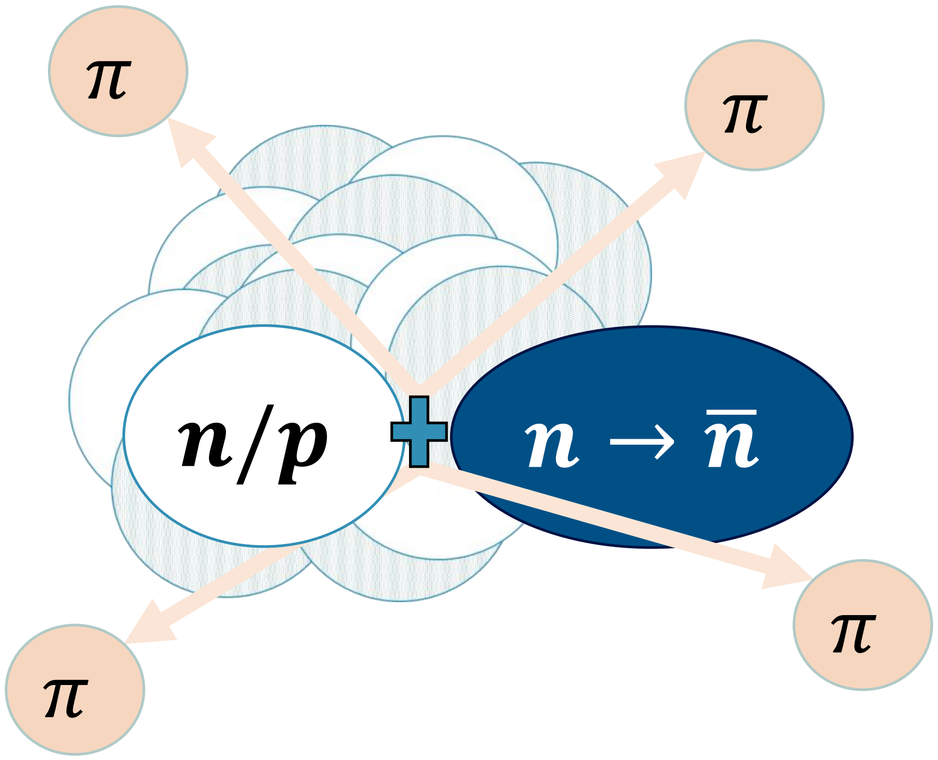
- $n \to \bar{n}$ transition (suppressed by nuclear potential)
- Antineutron annihilation with another nucleon

For $\bar{p}p$
- Bubble chambers (1978, 1983)
- Crystal Barrel (2003, 2005)

For $\bar{p}n$
- Bubble chambers (1969)
- OBELIX (2003)

Uncertainties
- Statistical, from these experiments

Bound Neutron Transition



- $n \rightarrow \bar{n}$ transition (suppressed by nuclear potential)
- Antineutron annihilation with another nucleon
- Final state interaction smears the kinetic features

$n \to \bar{n}$ in Large Neutrino Detectors

- Why?
  - Large volume (>> kton), long exposure (>> years), suitable energy range (2 GeV annihilation energy)

$n \to \bar{n}$ in Large Neutrino Detectors

- Why?
  - Large volume (>> kton), long exposure (>> years), suitable energy range (2 GeV annihilation energy)
- Where?
  - Deep underground
  - Only background: atmospheric nu's

		$T_{n-\bar{n}}(10^{32}$ years)
^{16}O	SK-I-IV (this study)	3.6
^{16}O	SK-I [15] (2015)	1.9
^{16}O	Kamiokande [18] (1986)	0.4
^{2}H	SNO [16] (2017)	0.1
^{56}Fe	Soudan II [17] (2002)	0.7
^{56}Fe	Frejus [21] (1990)	0.7
^{16}O	IMB [19] (1984)	0.2

$n \rightarrow \bar{n}$ in Surface Detectors

JINST 19 (2024) 07, P07032
DOI: 10.26153/tsw/13269

- There are attempts in surface detectors including NOvA & MicroBooNE
- Cosmic ray muons will introduce additional overwhelming background
  - Though NOvA managed to reduce cosmic muon rate at triggering, cosmogenic neutrons remain as the dominant background
- Results are not competitive even after scaling up the exposure
  - NOvA ~10 times worse than SK, MicroBooNE ~100 times worse

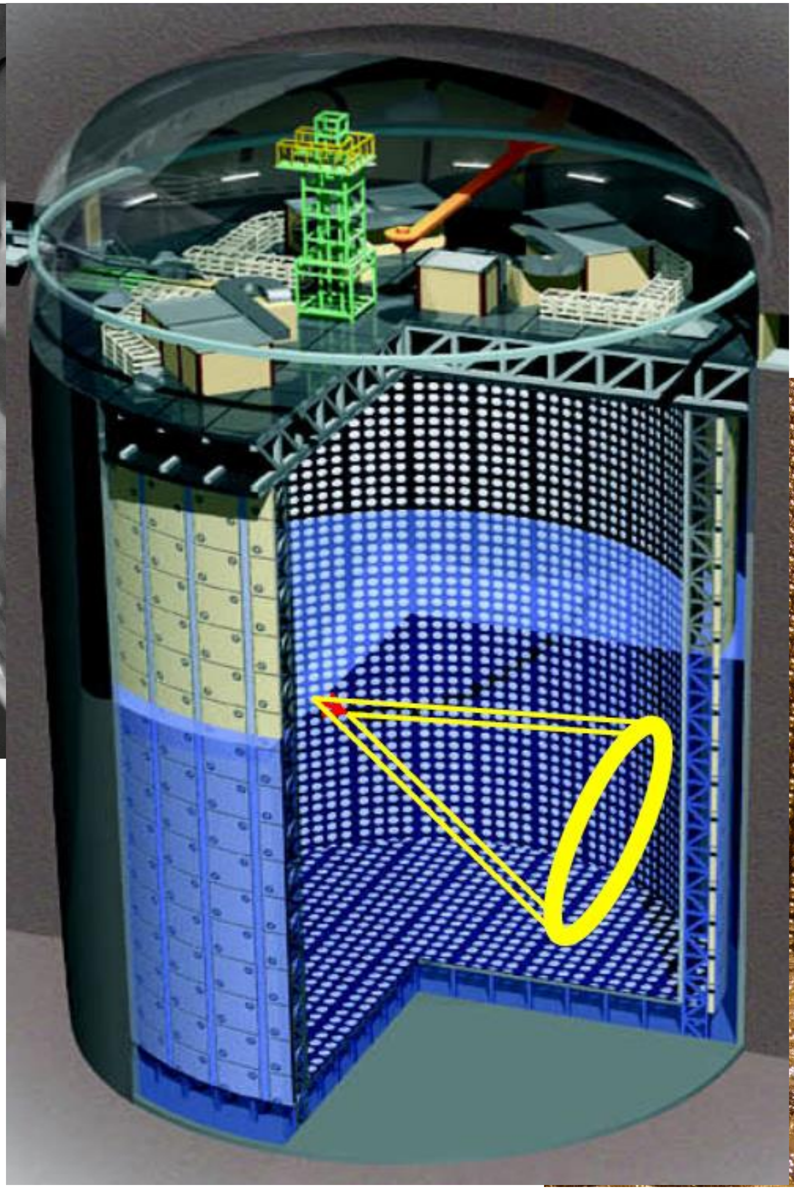
$n \to \bar{n}$ in Large Neutrino Detectors

- Why?
  - Large volume (>> kton), long exposure (>> years), suitable energy range (2 GeV annihilation energy)

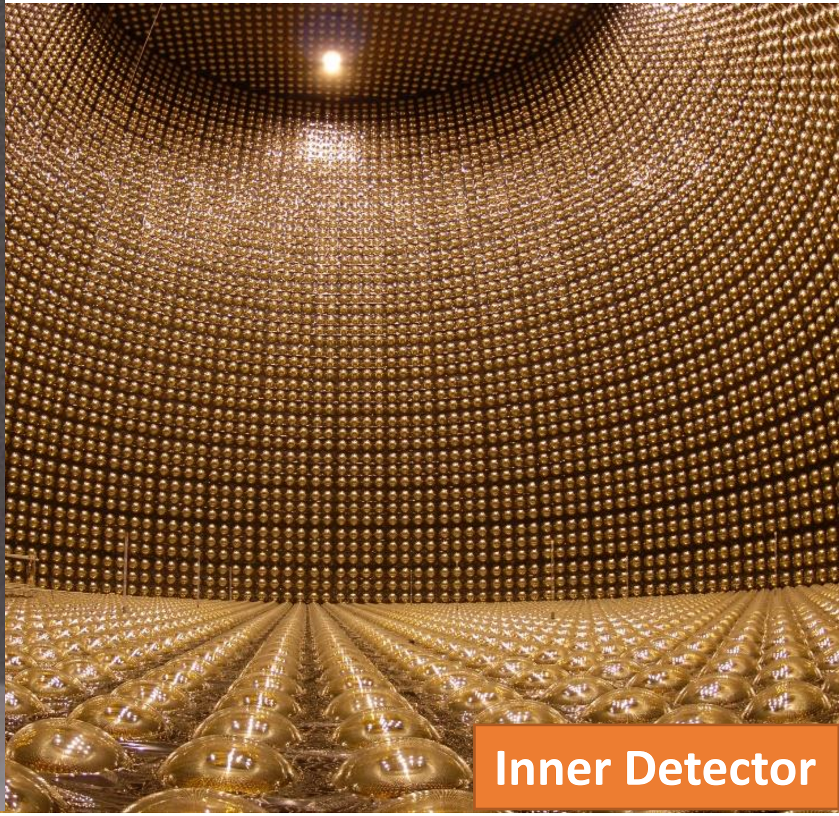
- Where?
  - Deep underground
  - Only background: atmospheric nu’s

- Which (in this talk)?
  - Super-Kamiokande
  - DUNE

Super-Kamiokande

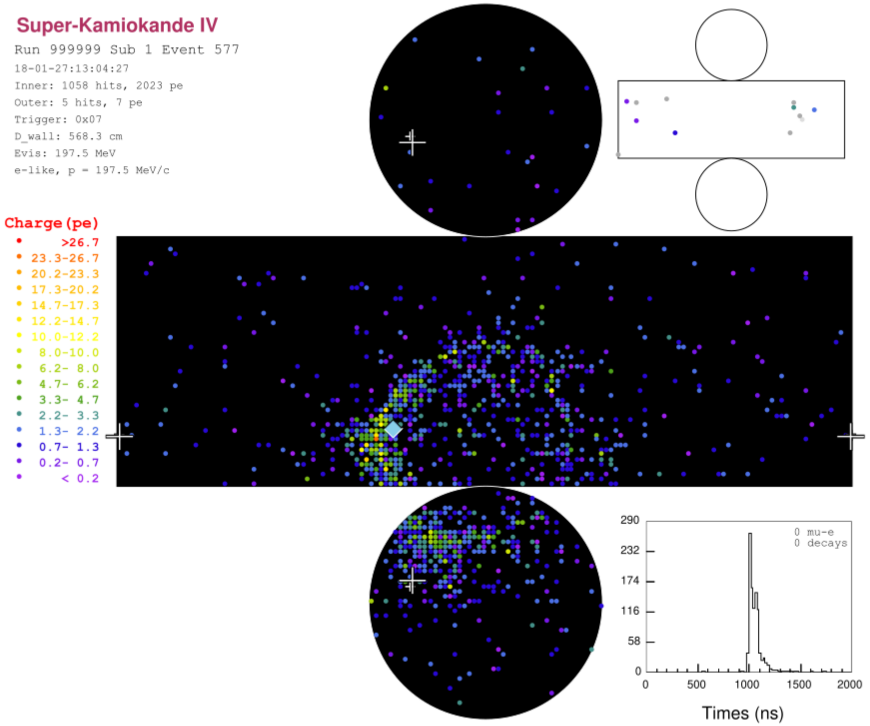


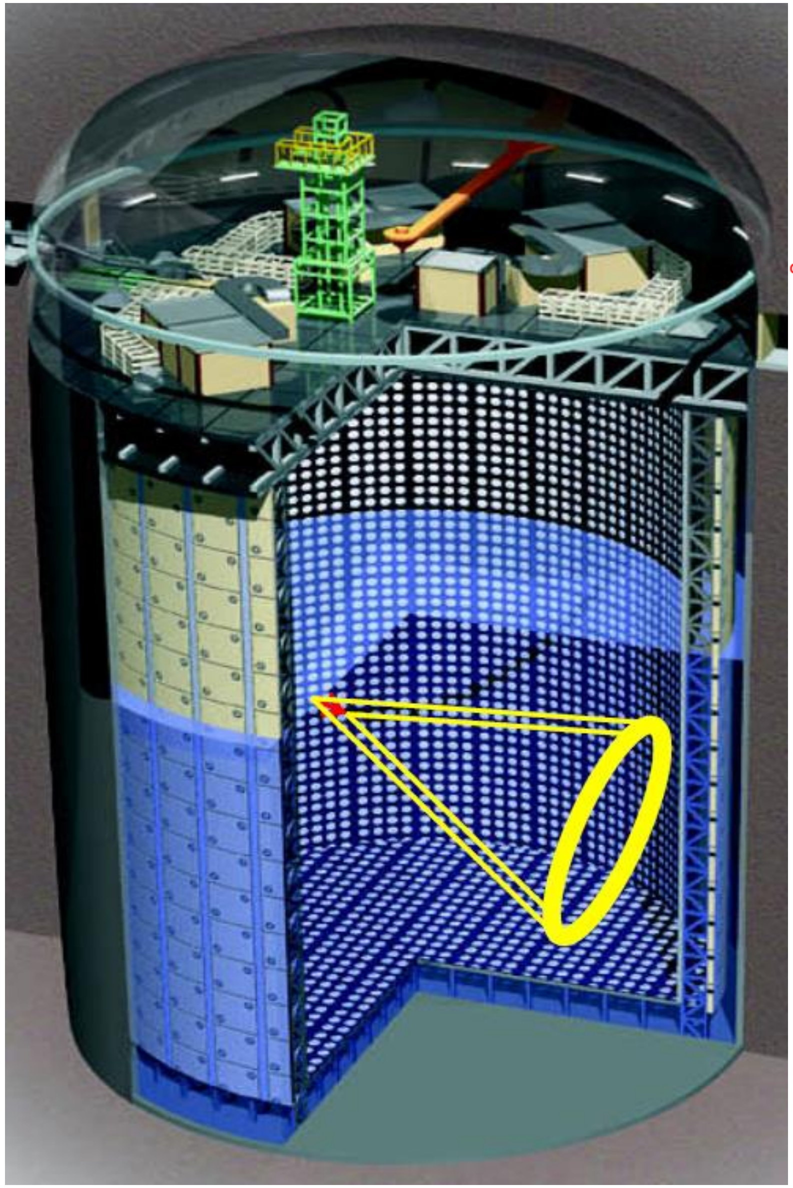
https://www-sk.icrr.u-tokyo.ac.jp/en/sk

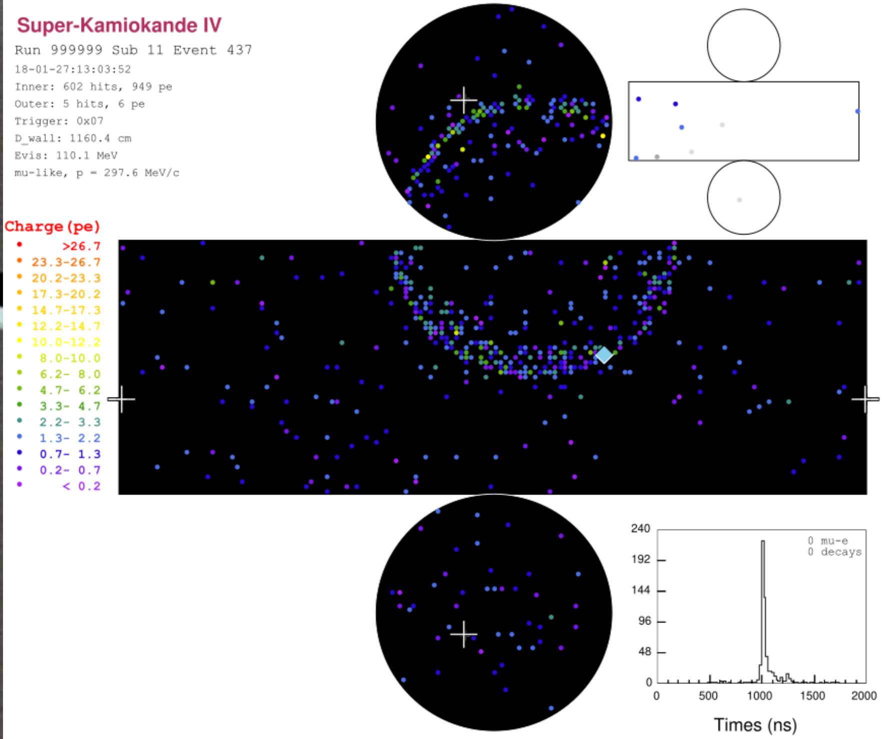


Super-Kamiokande
22.5 kton water

PID at Super-Kamiokande







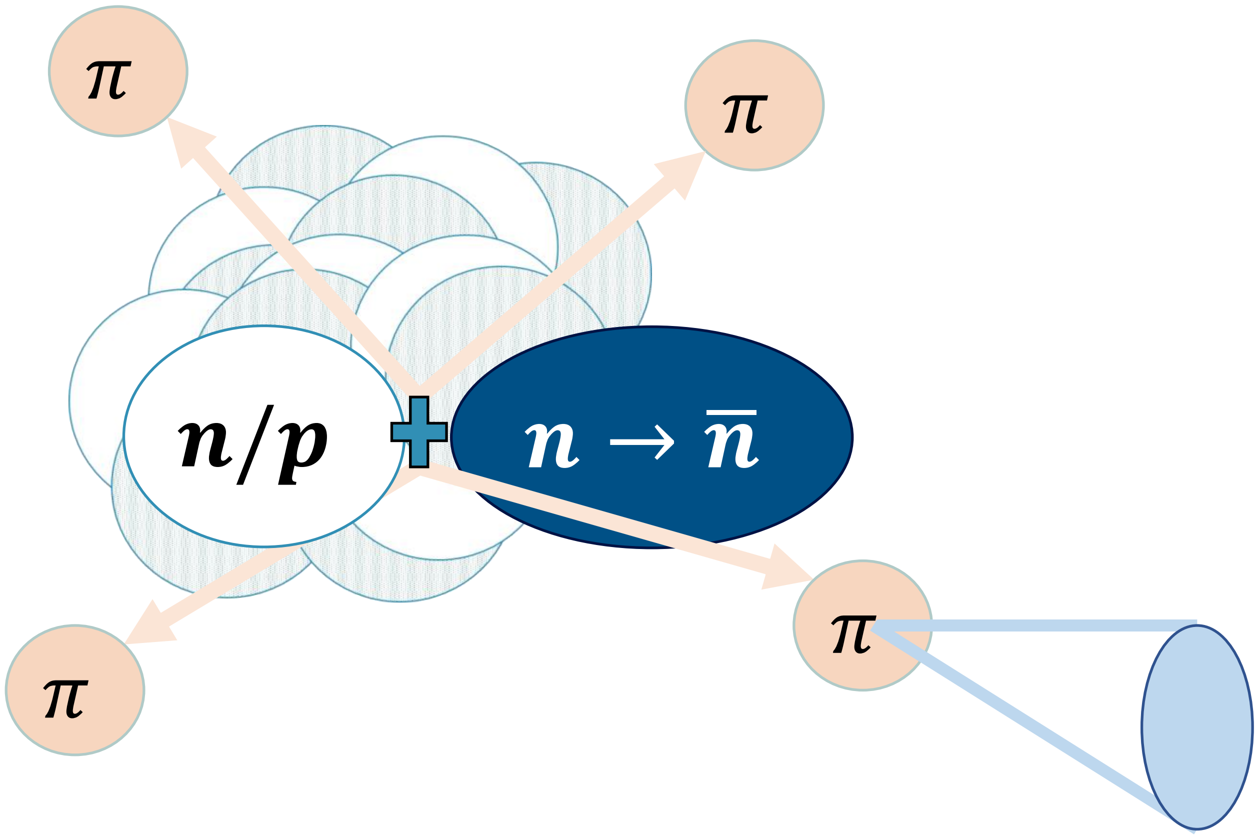
$e^{\pm}$

Fuzzy ring due to EM shower and multiple scattering

$\mu^{\pm}$

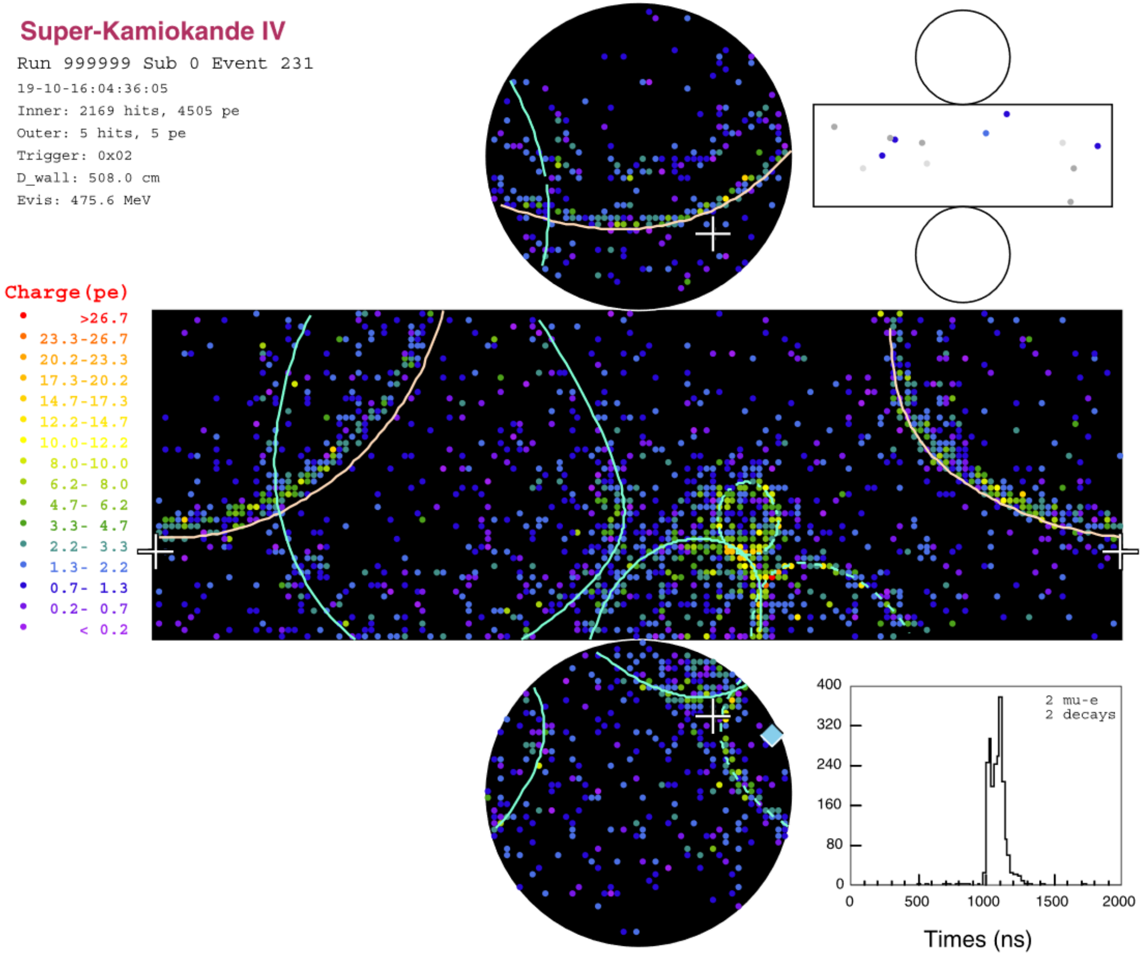
Sharp ring from minimum ionization

Bound Neutron Transition at SK



- $n \rightarrow \bar{n}$ transition (suppressed by the nuclear potential)
- Antineutron annihilation with another nucleon
- Final state interaction smears the kinetic features
- Outcoming charged particles produce Cherenkov light

$n \rightarrow \bar{n}$ at SK



- Multiple final state particles (rings)
- Highly isotropic
- Total energy around 2 GeV

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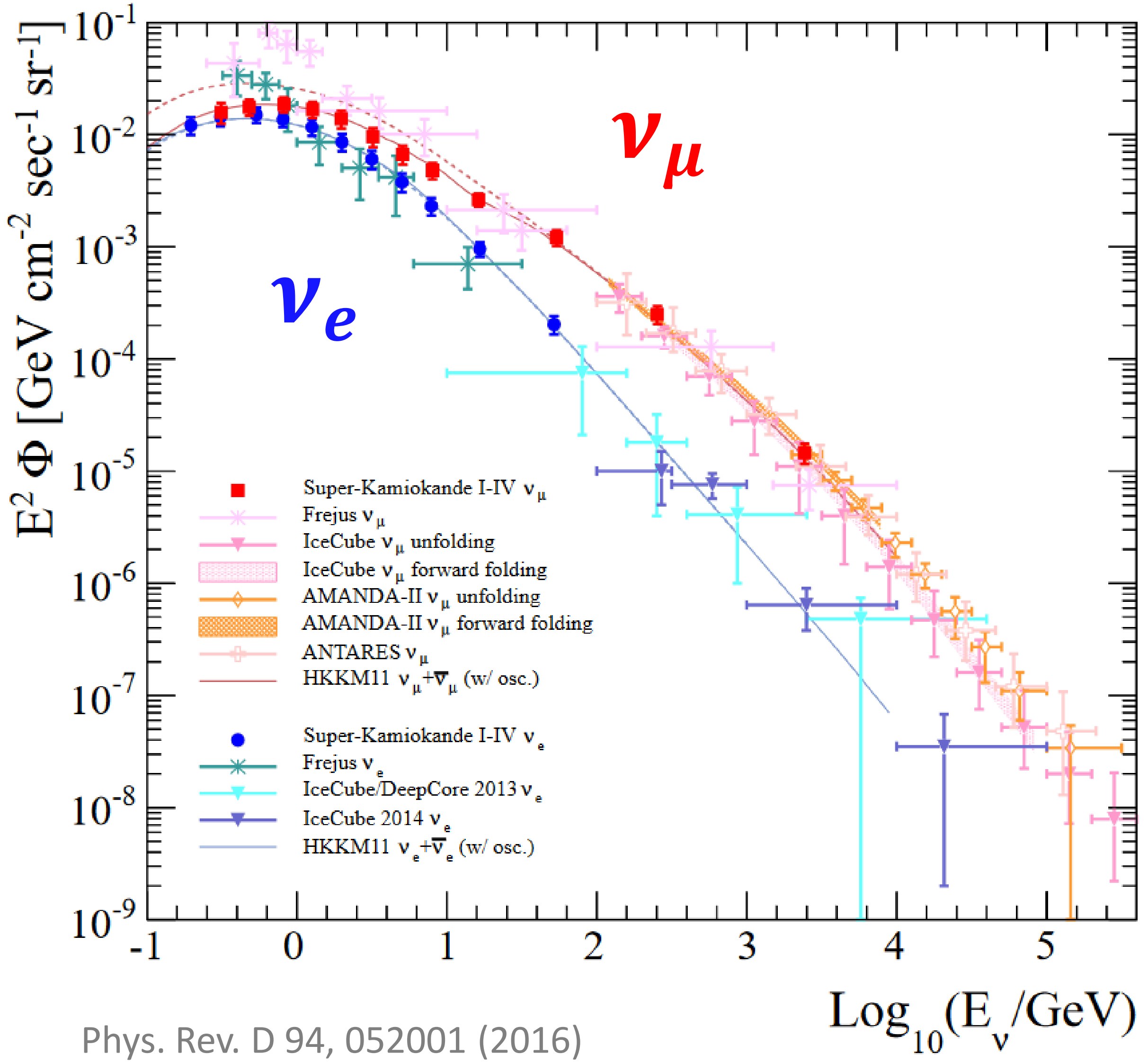
A simulated $\bar{n}p$ annihilation producing 6 pions.
5 rings were reconstructed.

Major Background: Atmospheric Neutrinos

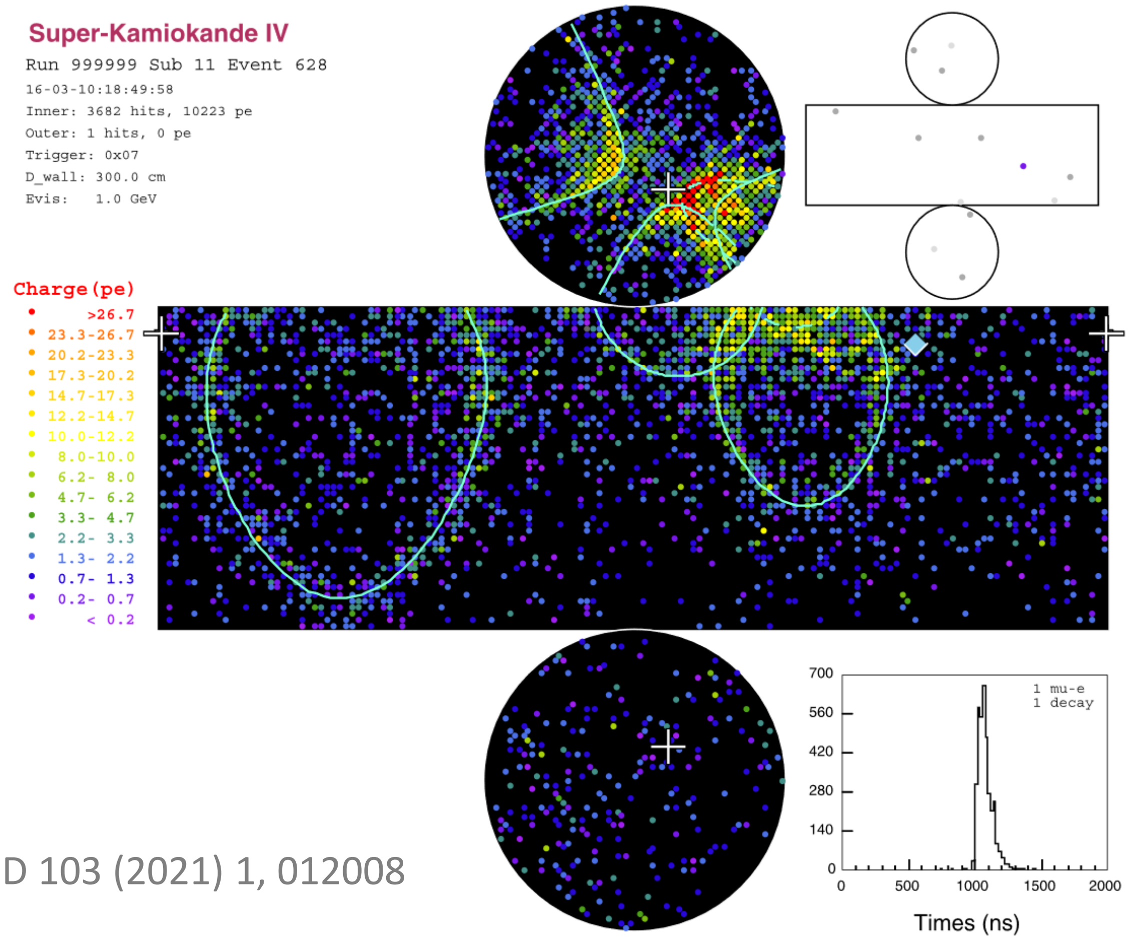
- Cosmic-ray muons can be vetoed with the outer-detector
- The major background is atmospheric neutrinos, in pion production channels and deep-inelastic scattering channels



Phys. Rev. D 94, 052001 (2016)

Atmospheric neutrinos at SK

- Typically fewer final state particles (rings)
- Directional
- Wider energy distribution



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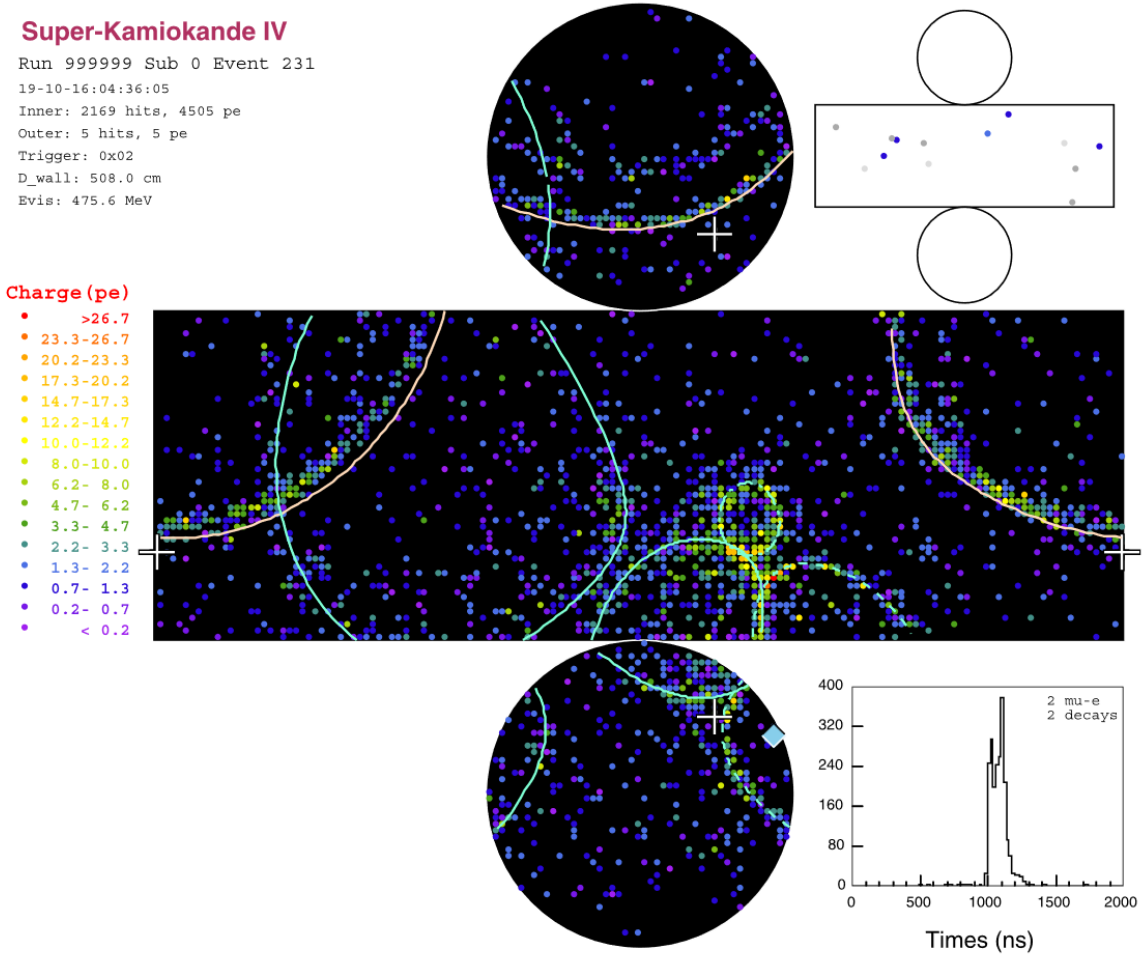
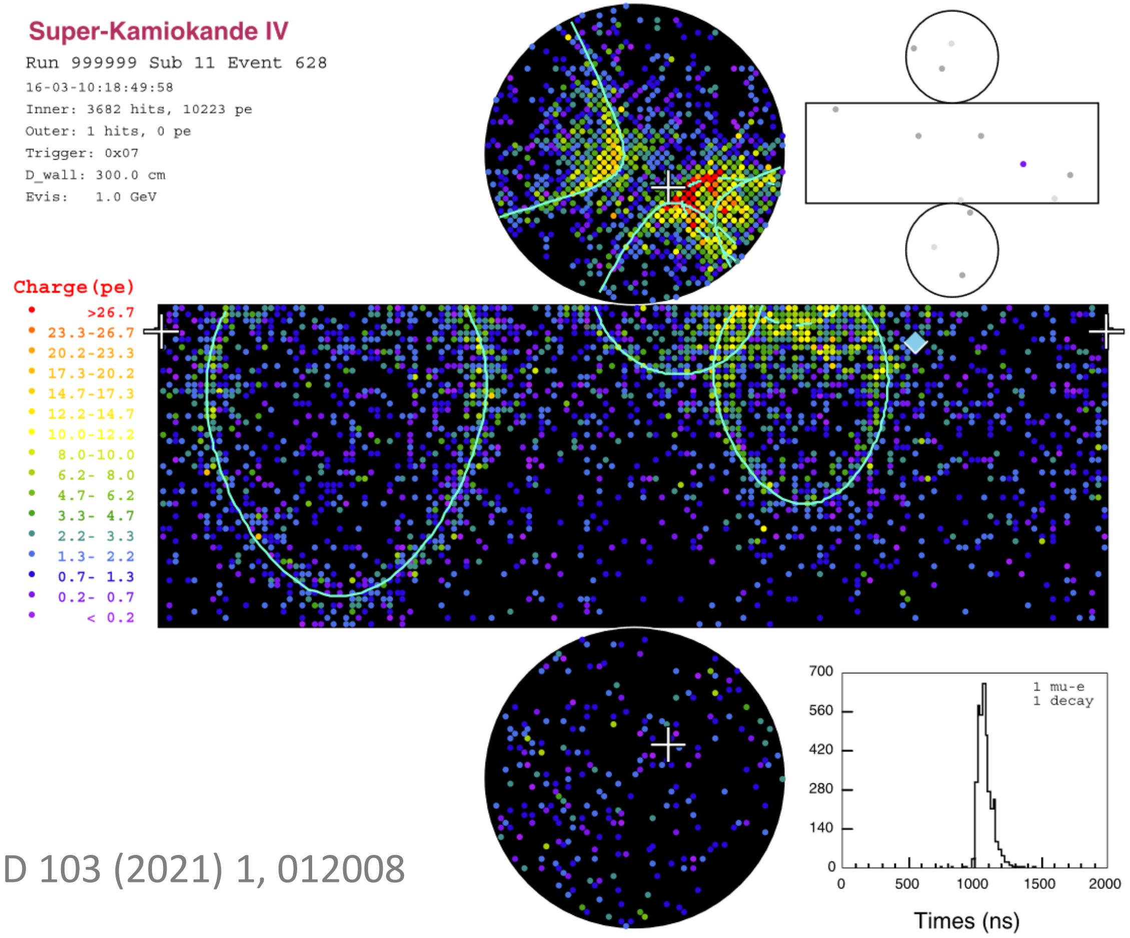
A simulated atmospheric neutrino event.
Neutral current deep inelastic scattering.

A Comparison





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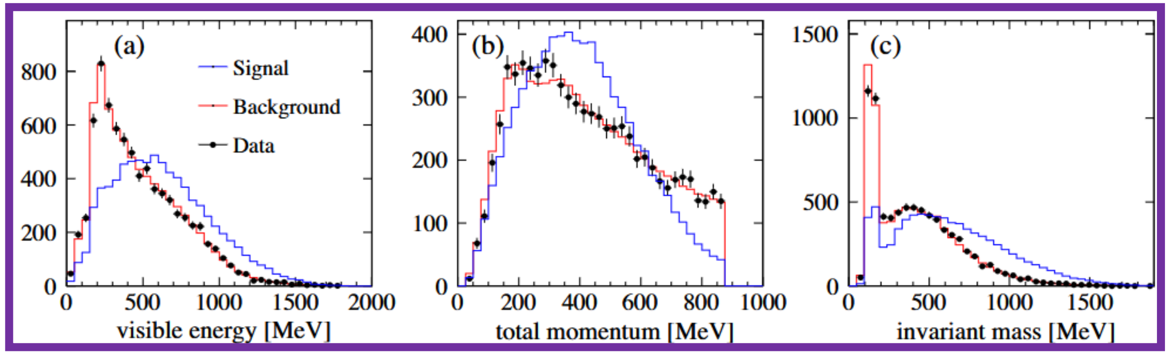
Signal / Background Features



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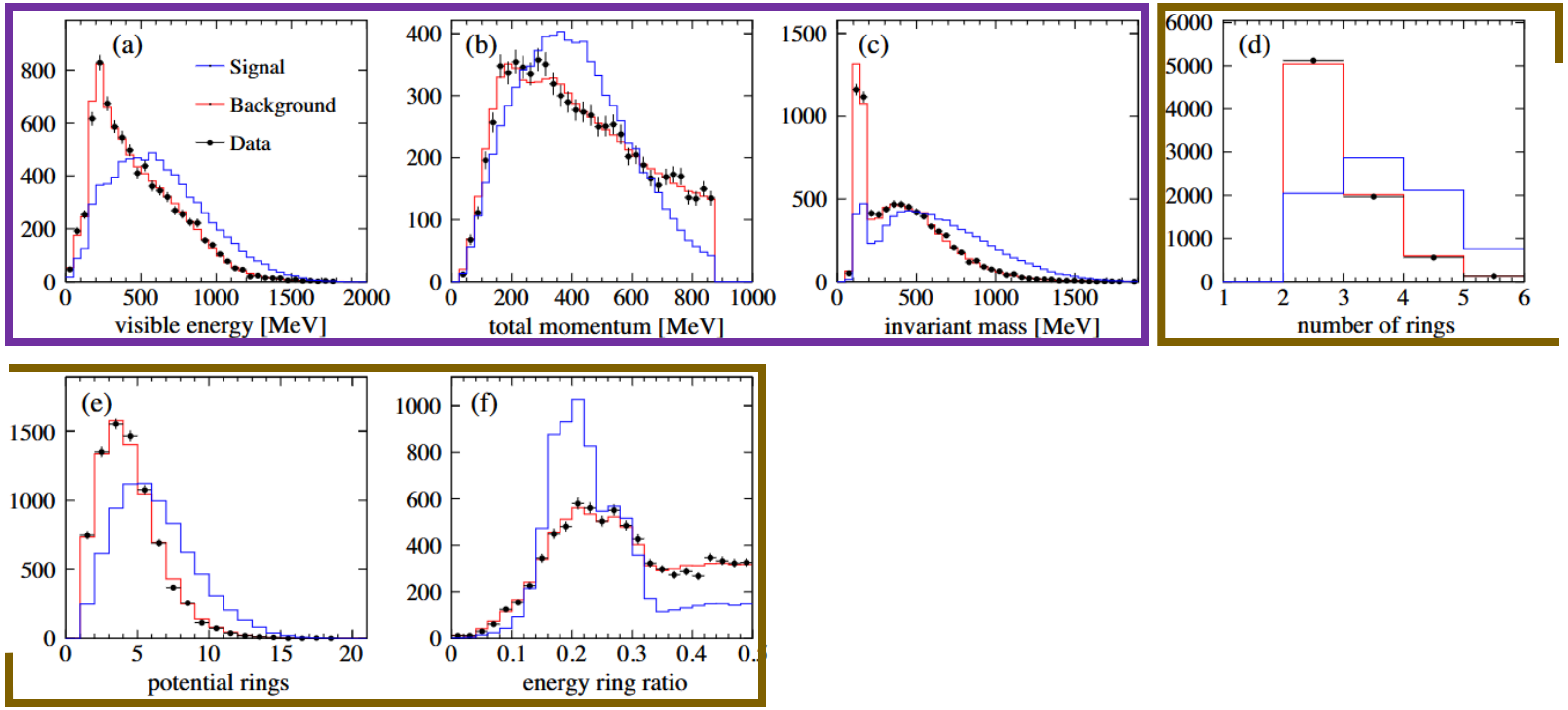
These features can be quantified by variables in the following categories:

- **kinetics**

Signal / Background Features



These features can be quantified by variables in the following categories:

- **kinetics**
- **number of rings**

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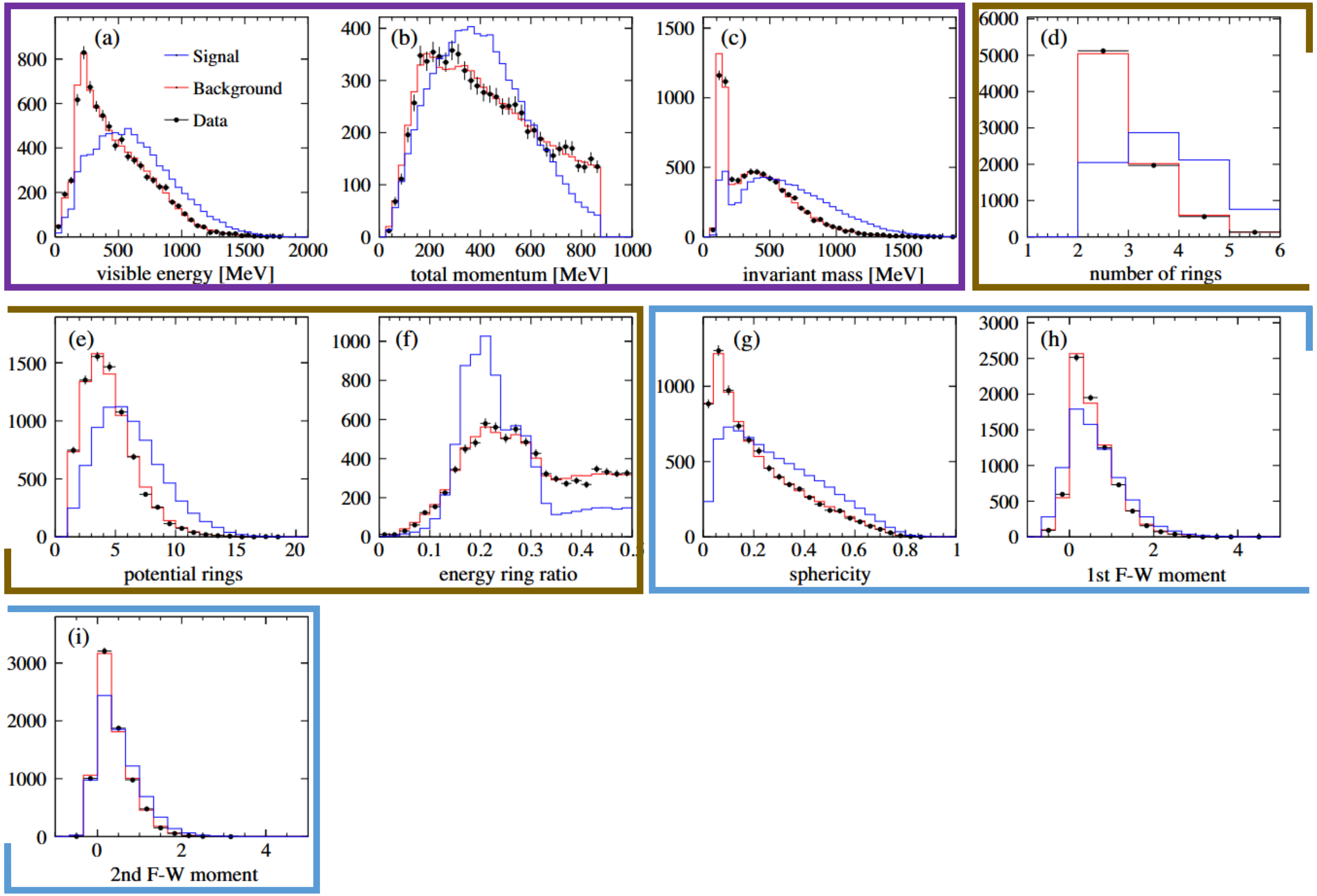
Signal / Background Features



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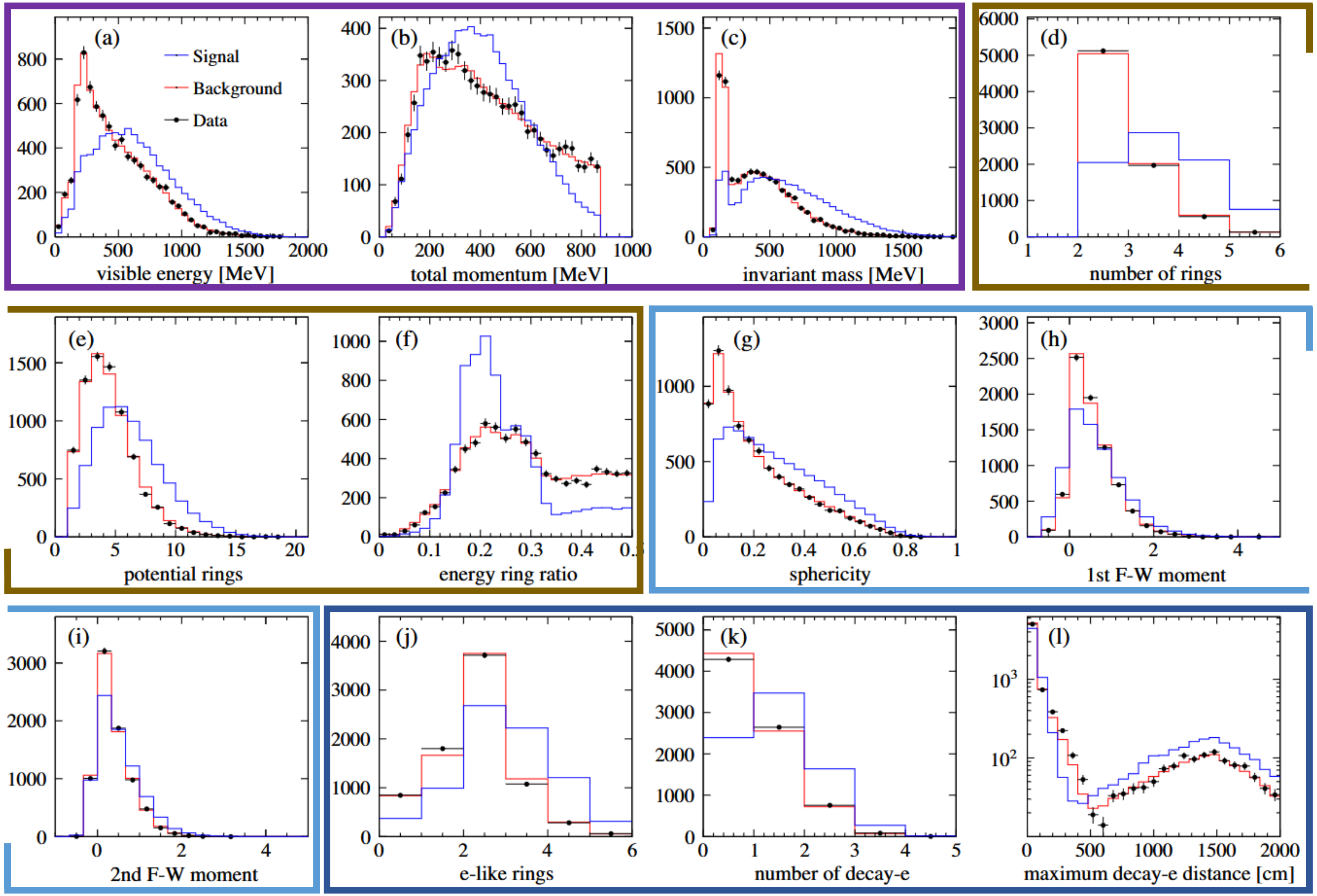
These features can be quantified by variables in the following categories:

- **kinetics**
- **number of rings**
- **isotropy**

Signal / Background Features



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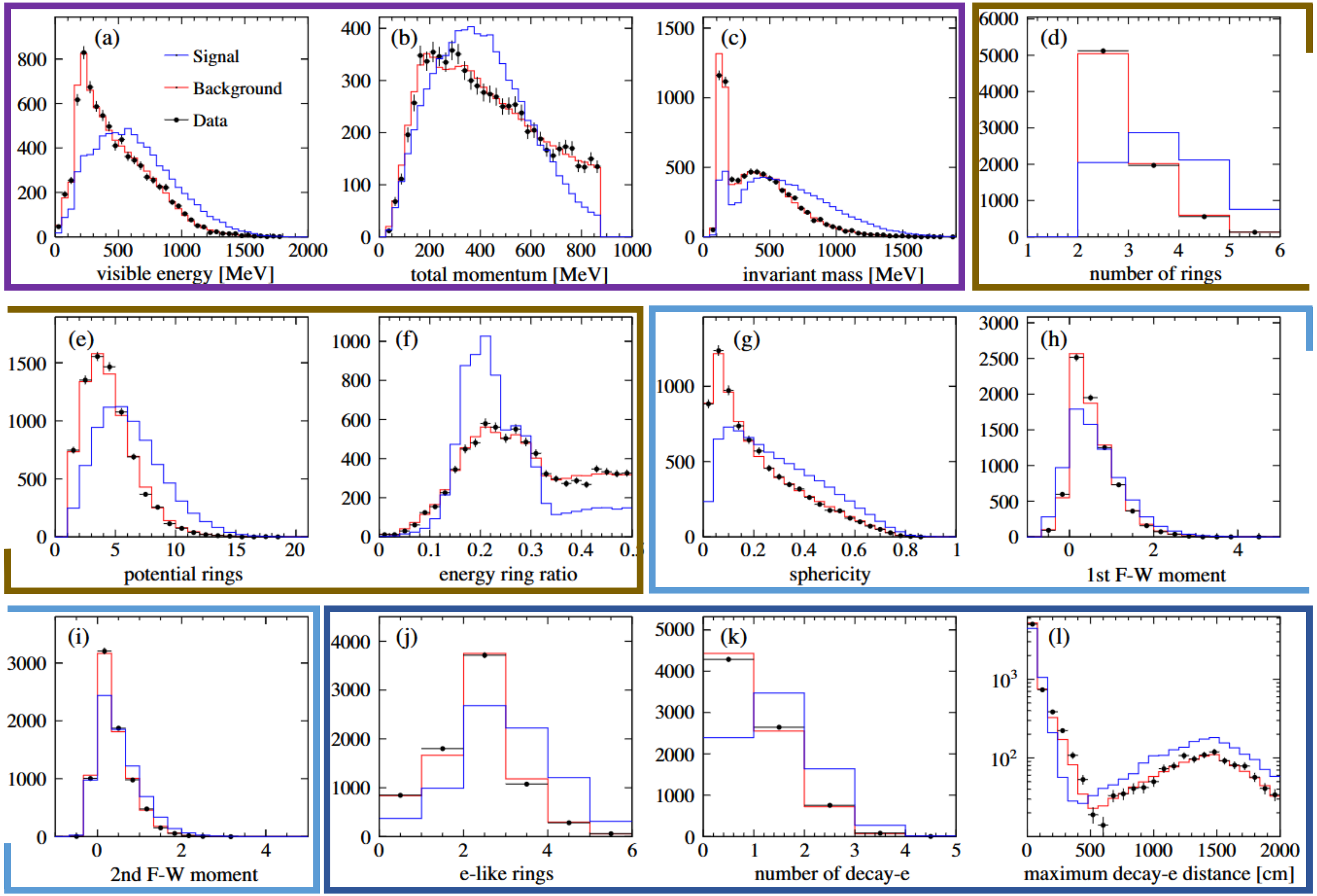
These features can be quantified by variables in the following categories:

- **kinetics**
- **number of rings**
- **isotropy**
- **PID**

Multi-Variate Analysis Construction



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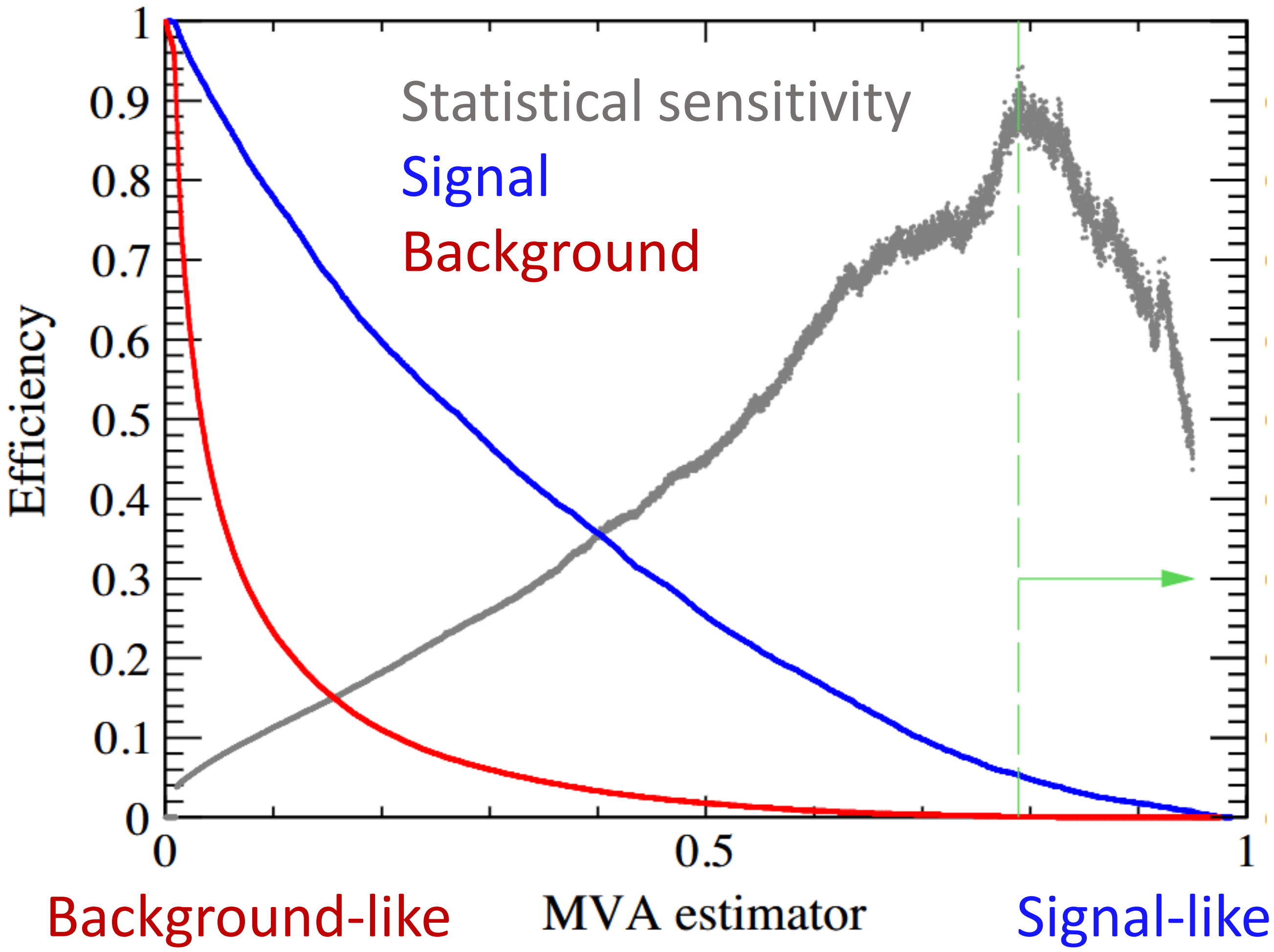
- Quantify these features by the 12 variables
- Apply pre-cuts to remove non-physics events
- Optimized a multi-variate analysis, evaluate sensitivity and set cuts

MVA Performance



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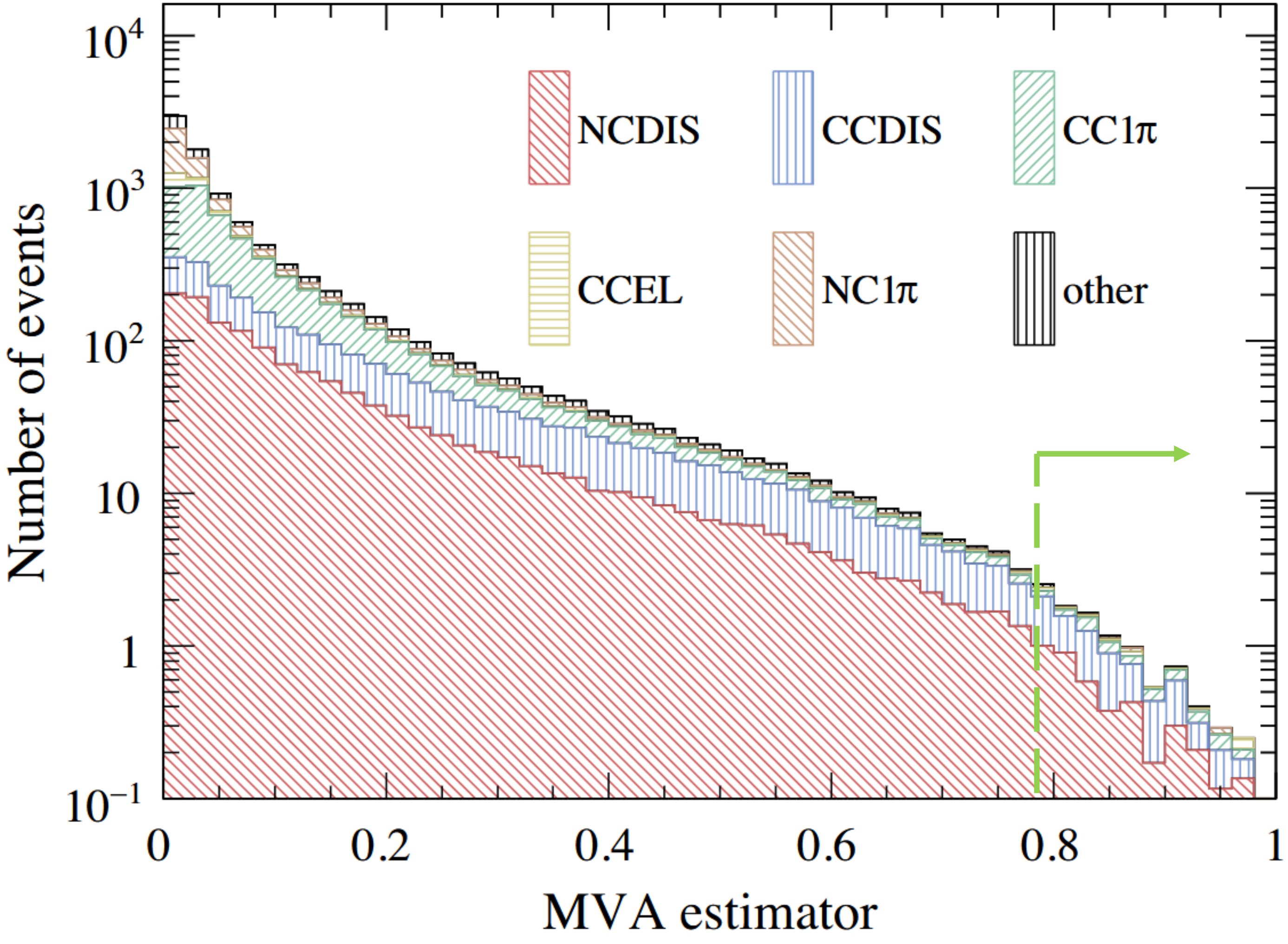
MVA cut optimized towards best statistical sensitivity

Signal Efficiency: 4.1%

Background Efficiency: 0.56 / year

Sensitivity: 4.3×10^{32} years

Remaining Background



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After pre-cuts
Dominated by CC 1π and NC 1π process.

After full selection
Dominated by deep inelastic scattering and CC pion processes.

Limitations:

- Low energy pions below the threshold
- Inability to separate CC from NC
- Large uncertainty from FSI

Systematic Uncertainties

	Signal Efficiency	Background
Physics		
Fermi motion	7%	…
Hadronization	4%	…
FSI	31%	…
Atmospheric ν	…	24%
Detector		
Energy scale	5%	11%
Non-uniformity	4%	6%
Ring counting	2%	2%
Other MVA variables	4%	7%
Total	33%	28%

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Signal:
dominated by **final state interaction**, especially pion absorption within nucleus.

Systematic Uncertainties

	Signal Efficiency	Background
Physics		
Fermi motion	7%	…
Hadronization	4%	…
FSI	31%	…
Atmospheric ν	…	24%
Detector		
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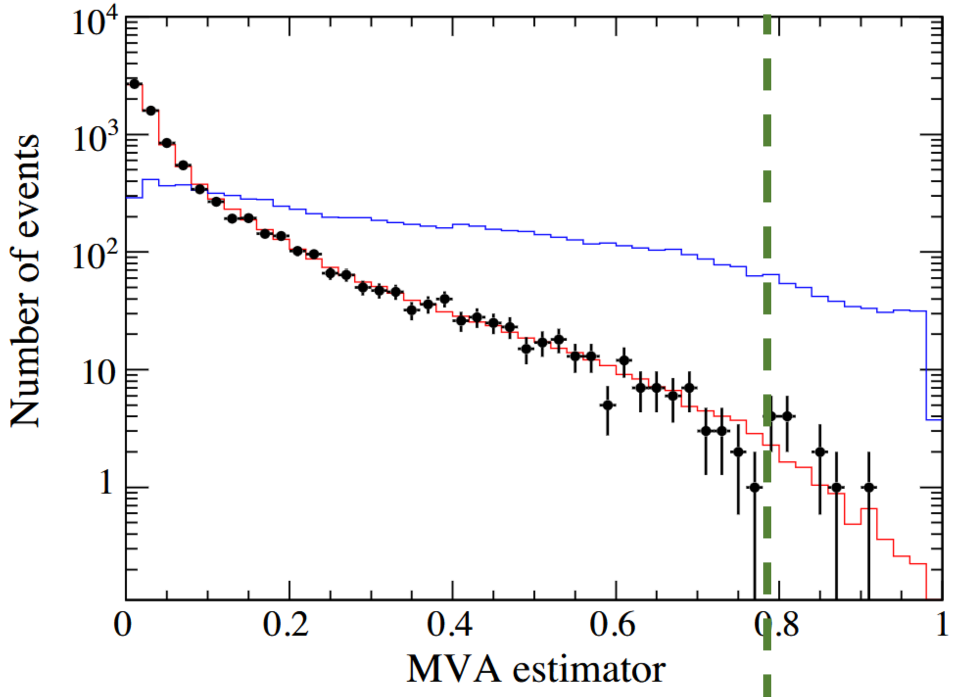
Background:
- dominated by **deep inelastic interaction** modeling
- subdominant flux uncertainty < 10%
- oscillation uncertainty not significant <5%

Open Data



Before selection

Data consistent w/ background MC.
No excess from signal seen.

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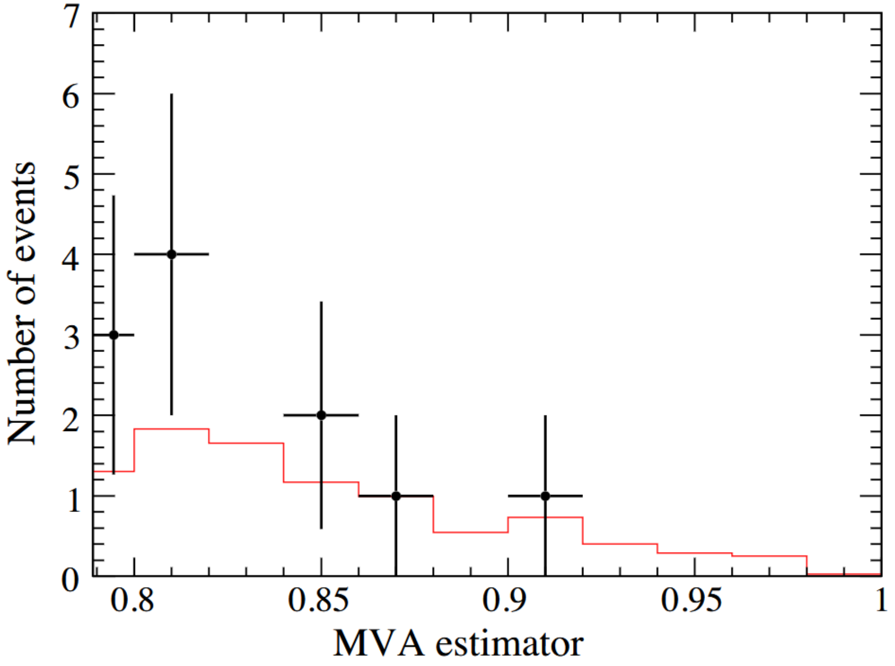
Signal-like

Remaining events after cut

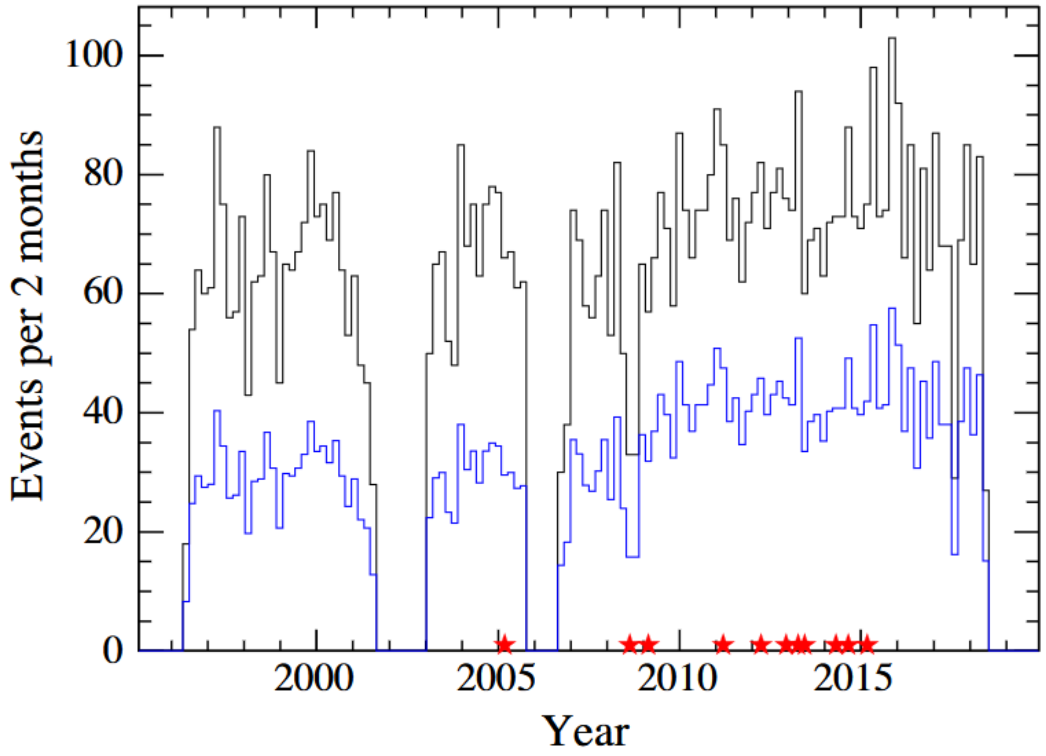
11 events observed in data, consistent w/ 9.3 events expected from background MC.

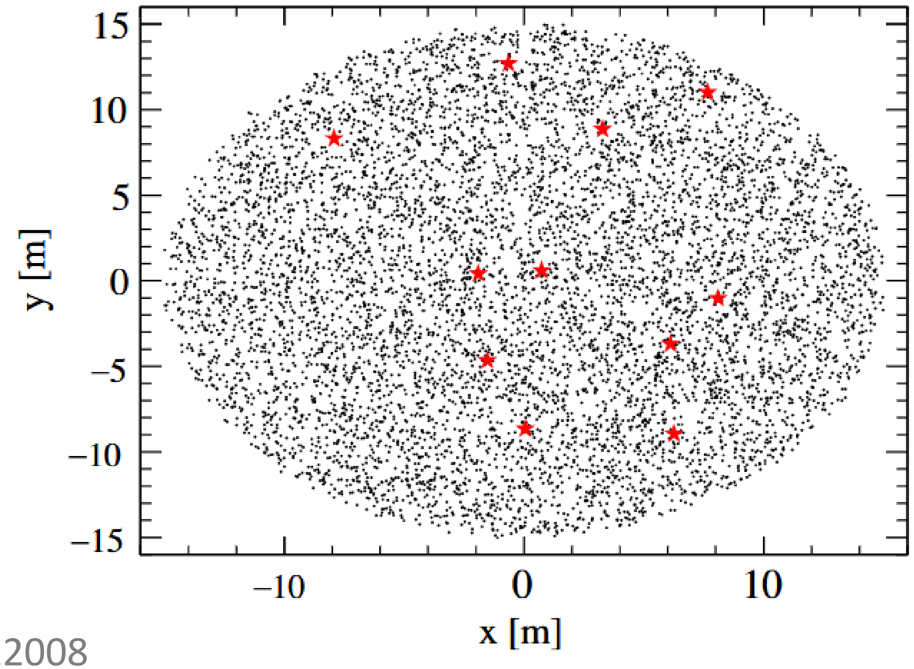


Sanity Check

Data after pre-cuts
Data after MVA cut

Time & spatial distribution is consistent with expectation.





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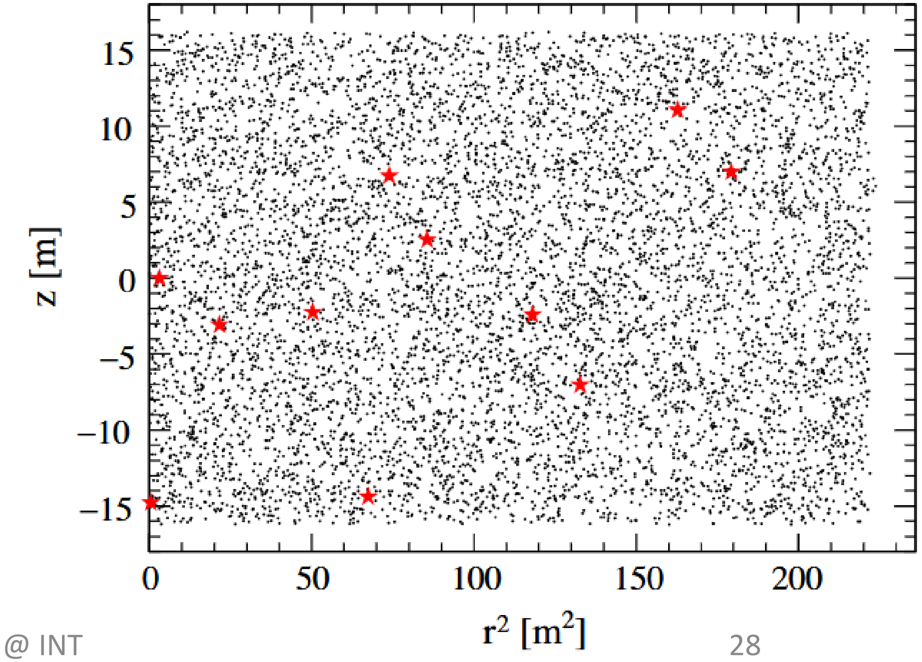

Result

	Events	$T_{n-\bar{n}}$ (10^{32} yrs)	$\tau_{n\to\bar{n}}$ (10^{8} s)
Expected	9.3	4.3	5.1
Observed	11	3.6	4.7

$$P_{\text{nuc}}(n \to \bar{n}) = \frac{1}{T_{\text{nuc}}} = \frac{1}{R\tau^2_{n-\bar{n}}}$$

No excess of events has been observed.

The observation limit is set at $\mathbf{3.6 \times 10^{32}}$ **years** at 90% C.L..

Assume $R = 0.517 \times 10^{23}$ / s, this corresponds to $\boldsymbol{\tau_{n\to\bar{n}} = 4.7 \times 10^{8}}$ **s**

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Comparison with Other Experiments

For better comparison and easier conversion, in this table $\tau_{n\to\bar{n}}$ is presented as $\sqrt{T_{n\bar{n}}/R}$, regardless of the reported value in corresponding paper.

		$T_{n-\bar{n}}(10^{32}$ years)	R $(10^{23}/\mathrm{s})$	$\tau_{n\to\bar{n}}(10^{8}$ s)
^{16}O	SK-I-IV (this study)	3.6	0.517	4.7
^{16}O	SK-I [15] (2015)	1.9	0.517	3.4
^{16}O	Kamiokande [18] (1986)	0.4	0.517	1.6
^{2}H	SNO [16] (2017)	0.1	0.25	1.4
^{56}Fe	Soudan II [17] (2002)	0.7	1.4	1.3
^{56}Fe	Frejus [21] (1990)	0.7	1.4	1.2
^{16}O	IMB [19] (1984)	0.2	0.517	1.2
Free neutron	Grenoble [14] (1994)	…	…	0.9

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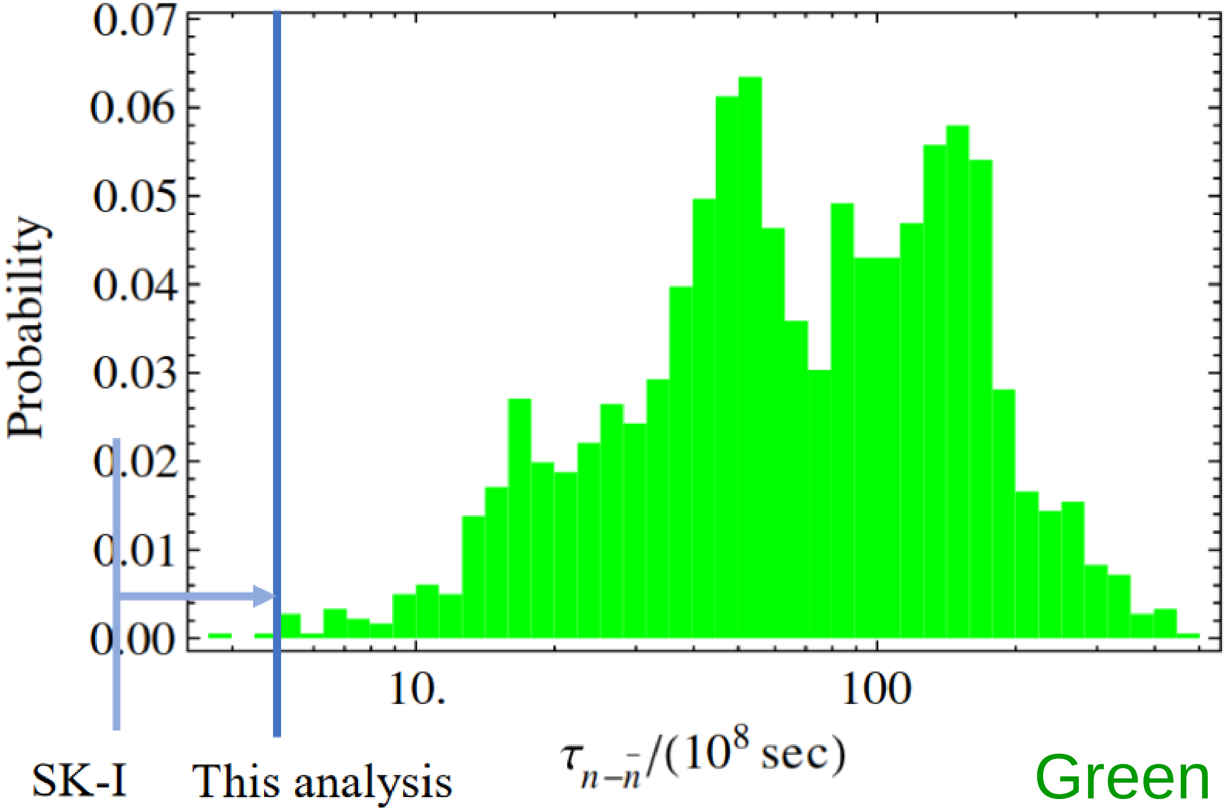
Comparison with Theoretical Prediction



Green from PSB model

K.S. Babu, et al, PRD 87 115019 (2013)

This result first reached the range of theoretical prediction.

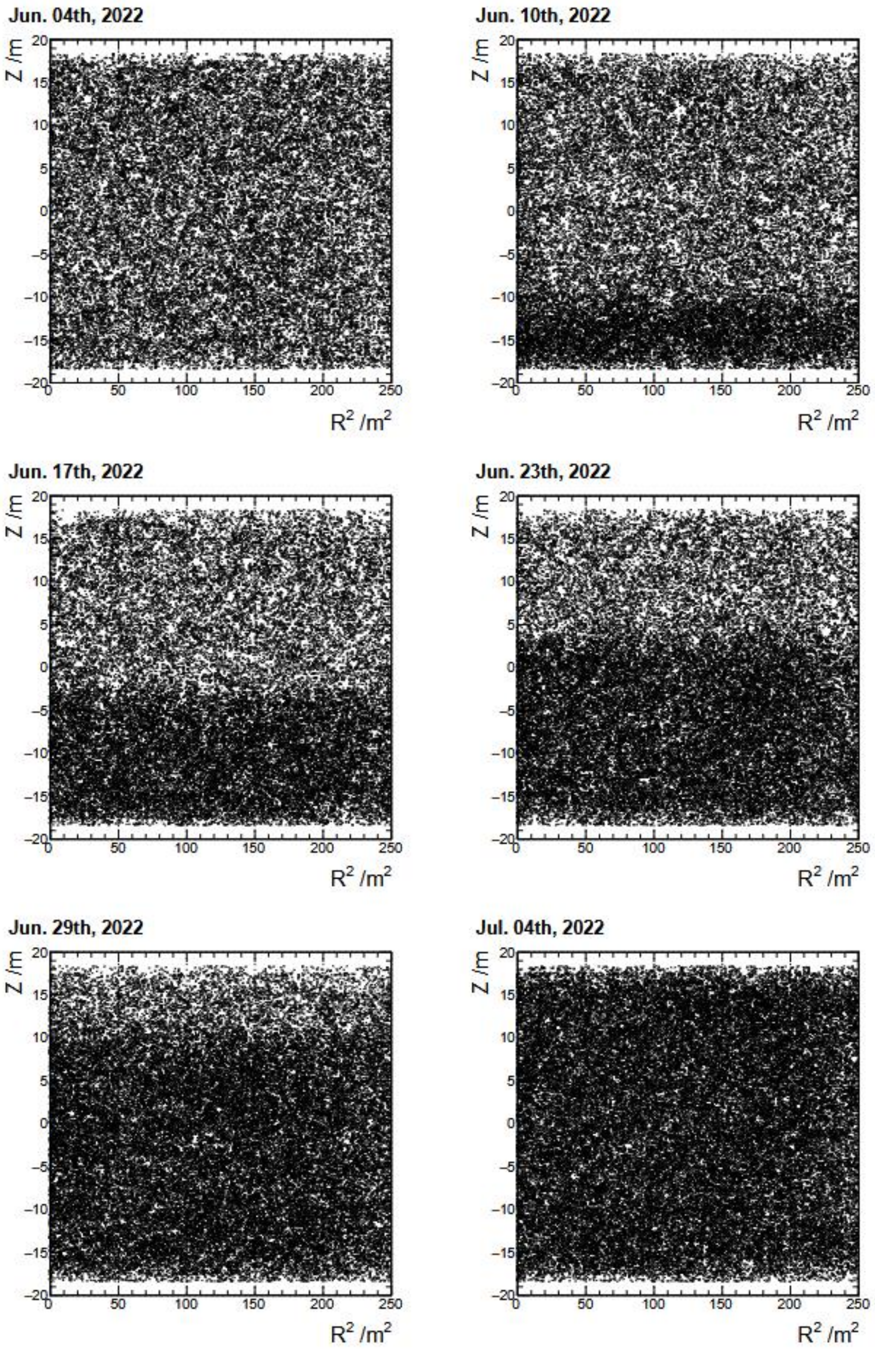
$n \rightarrow \bar{n}$ at SK-Gd

SK I-V: pure water | SK-Gd: Gd-loaded water

1996 → 2020 → 2022 →

- Neutron tagging efficiency increased from 25% (before 2020) to 50% (2020) to 75% (2022).

- Neutron multiplicity helps background rejection



Note on the Nuclear Suppression

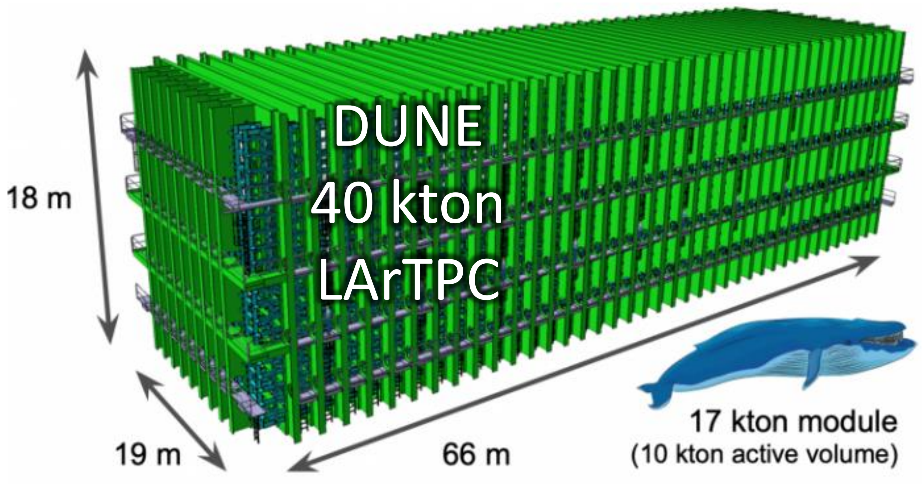
$$\tau_{n\to\bar{n}} = \sqrt{T_{n\bar{n}}/R}$$

	R (10^{23}/s)	Source
Oxygen	0.517	Phys. Rev. D **78**, 016002 (2008): Translationally Invariant model
	0.543	Phys. Rev. D **78**, 016002 (2008): Shell Model
	0.65	Phys. Rev. C **105**, 065501 (2022)
	0.8	Phys. Rev. D **27**, 1090 (1983)
Argon	0.56	Phys. Rev. D **101**, 036008 (2020)

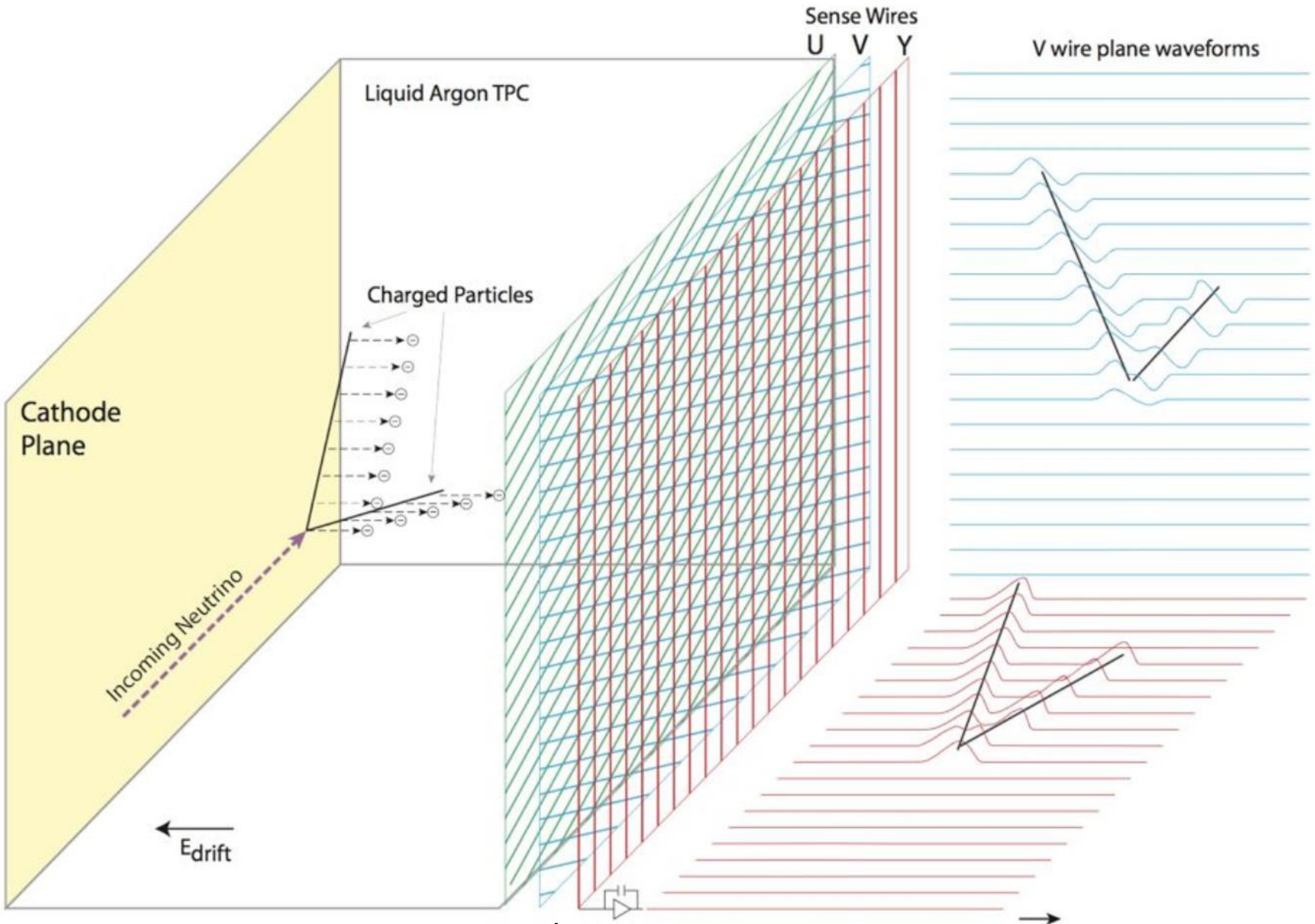
Although Ar has a larger nucleus, nuclear suppression in Ar is not necessarily larger than in O.

Future Detectors: DUNE

- Large statistics:
  - 40 kton liquid argon
- High efficiency:
  - Low threshold for hadrons



LArTPC: Liquid Argon Time Projection Chamber

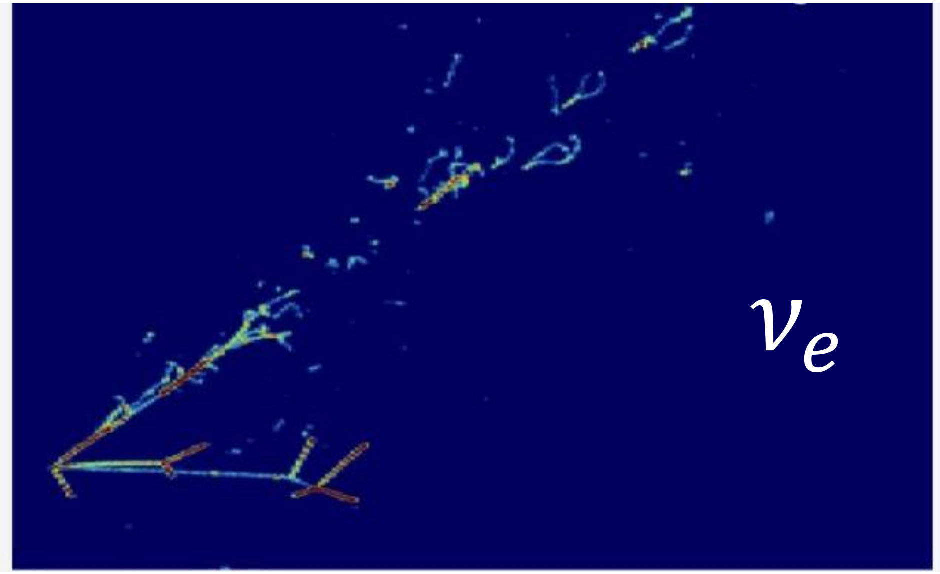


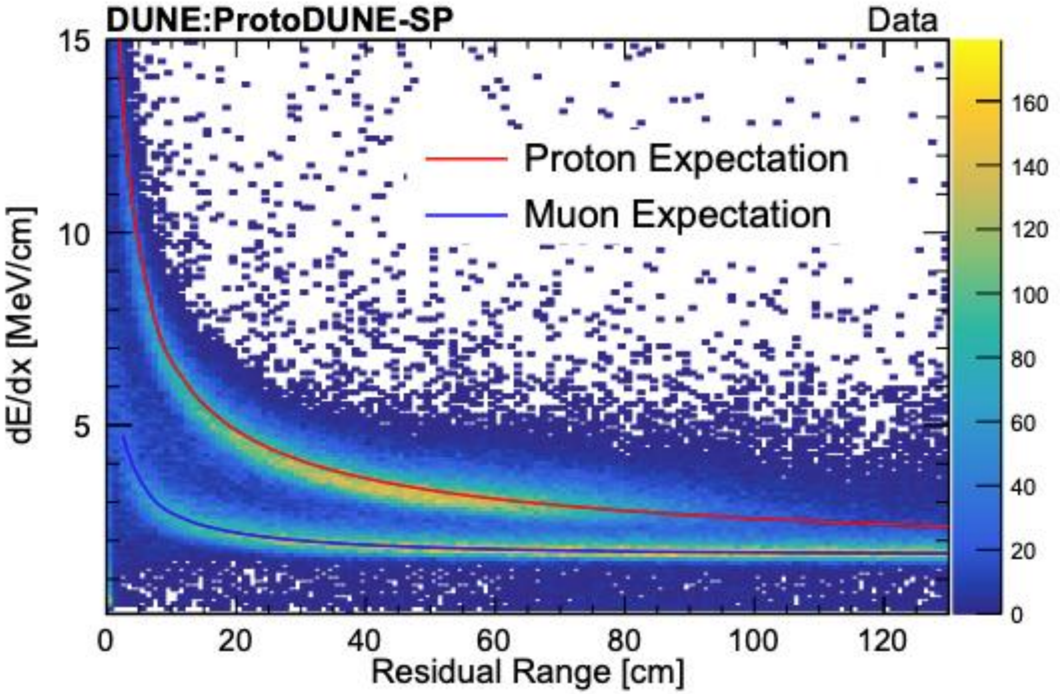
Anode Plane

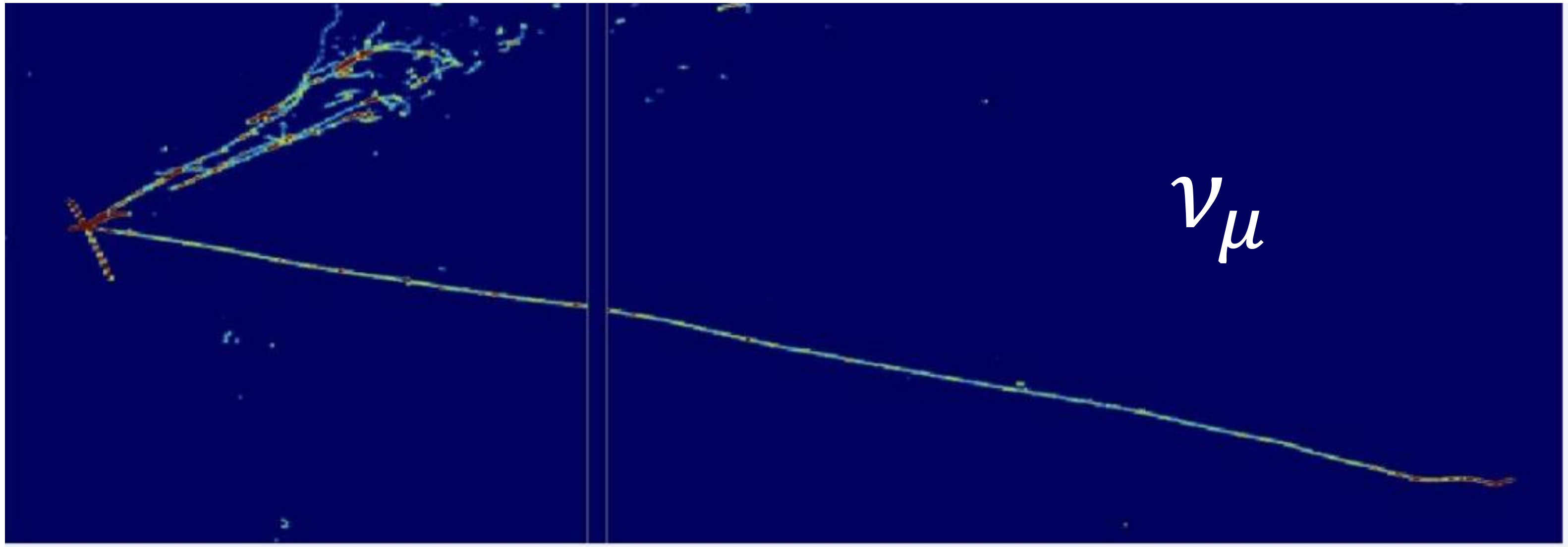
- Charged particles ionize the argon atoms as they traverse the detector

- Electrons drift under an electric field & deposit charge on the anode planes

PID in LArTPC



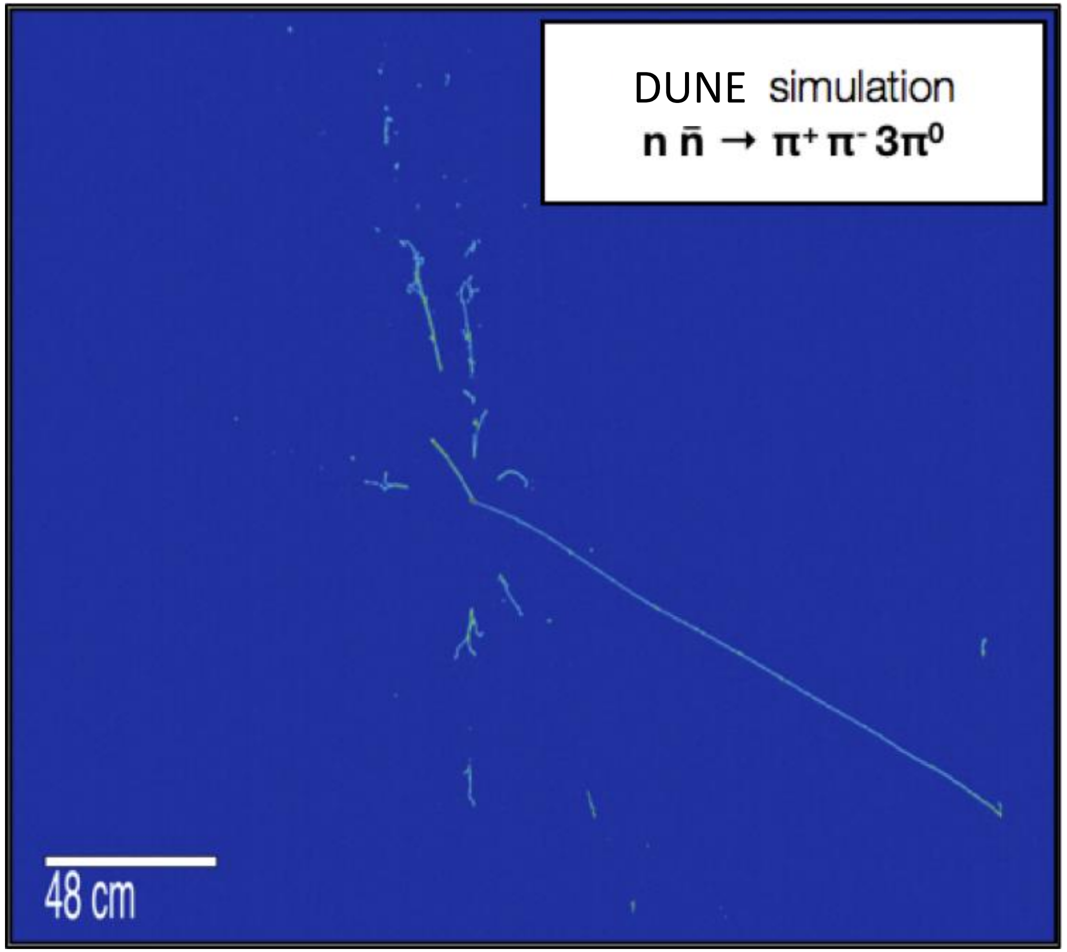


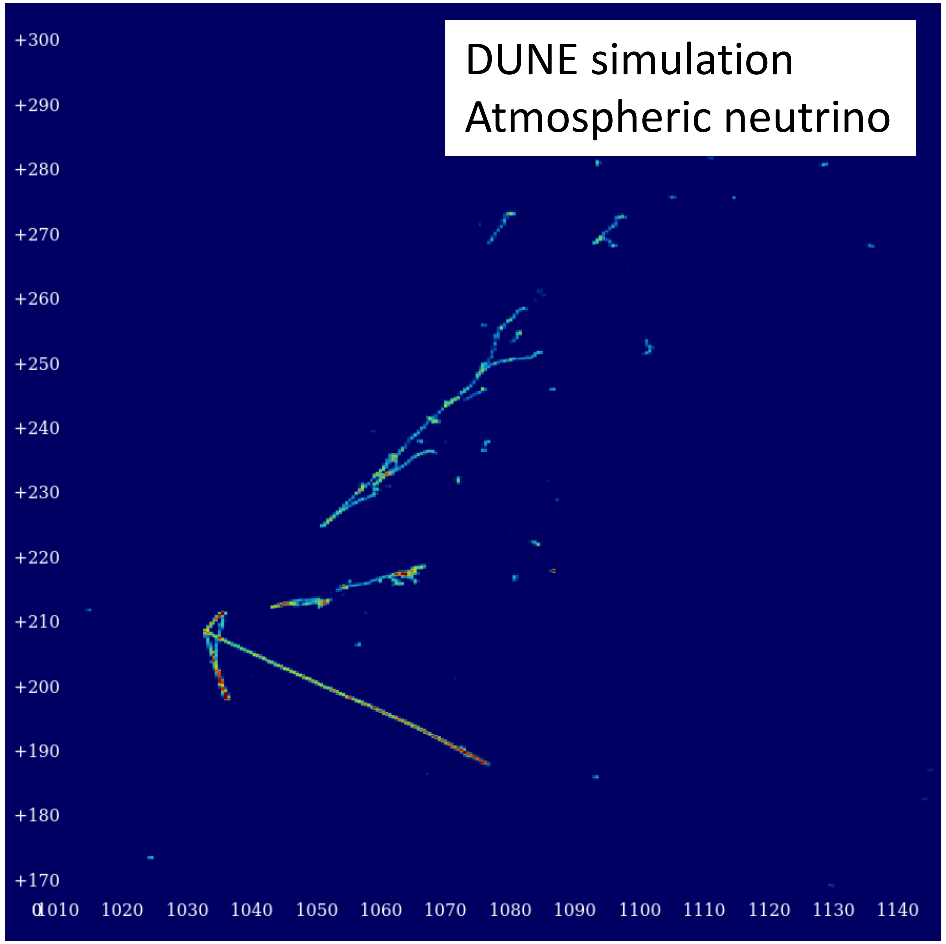


- p/μ separation
- μ/e separation

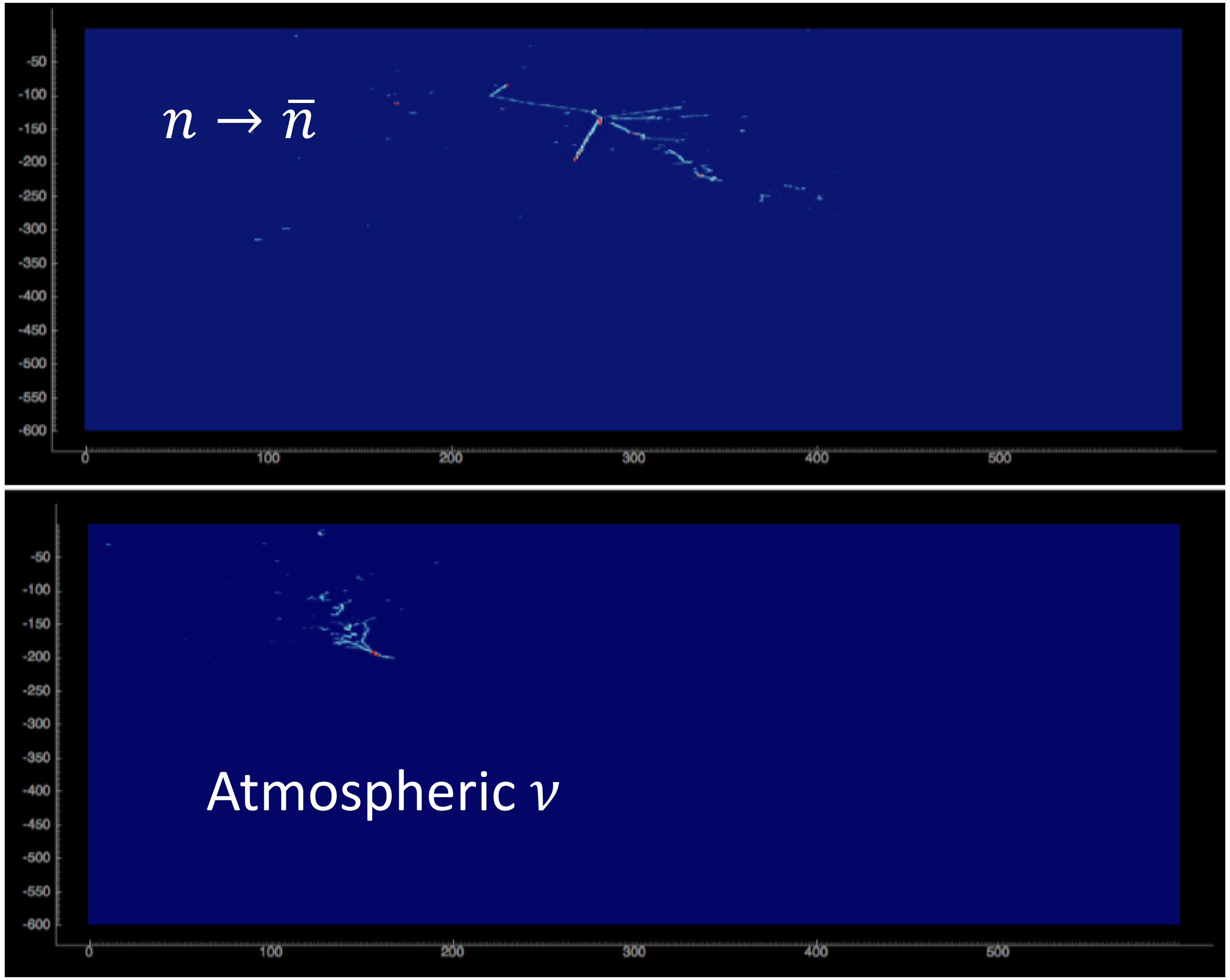
Chris Marshall, Neutrino 2024

$n \to \bar{n}$ in LArTPC





Initial Studies at DUNE (TDR)



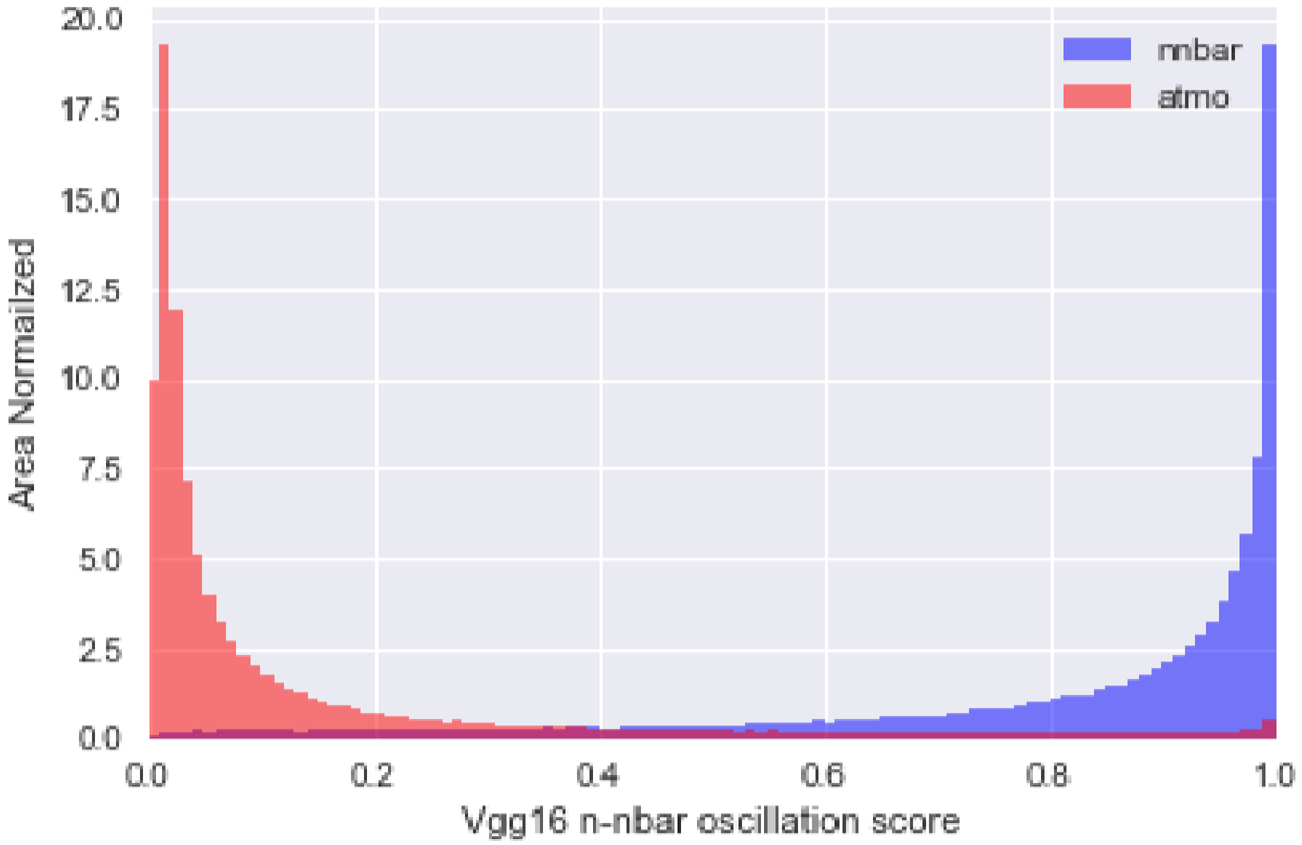
- Convolutional Neural Network:

CNN with downsized 2D image from the collection plane

- Study by Yeon-jae Jwa

DOI: 10.7916/a1dh-gh90

Initial Studies at DUNE (TDR)



- CNN performance

Score cut	Signal efficiency	Background rejection
0.99986	2.22 %	99.931 %
0.9999	1.86 %	99.943 %
0.99995	1.316 %	99.959 %
0.9999	0.614 %	99.980 %
0.99995	0.442 %	99.984 %
0.99999	0.2085 %	99.991 %

- Study by Yeon-jae Jwa

DOI: 10.7916/a1dh-gh90

Initial Studies at DUNE (TDR)

For easier comparison:

- ~0.5% efficiency
- 10 bkgs / 400 kton*yrs

- Efficiency 10 times worse than SK when scaled to the same exposure

- CNN performance

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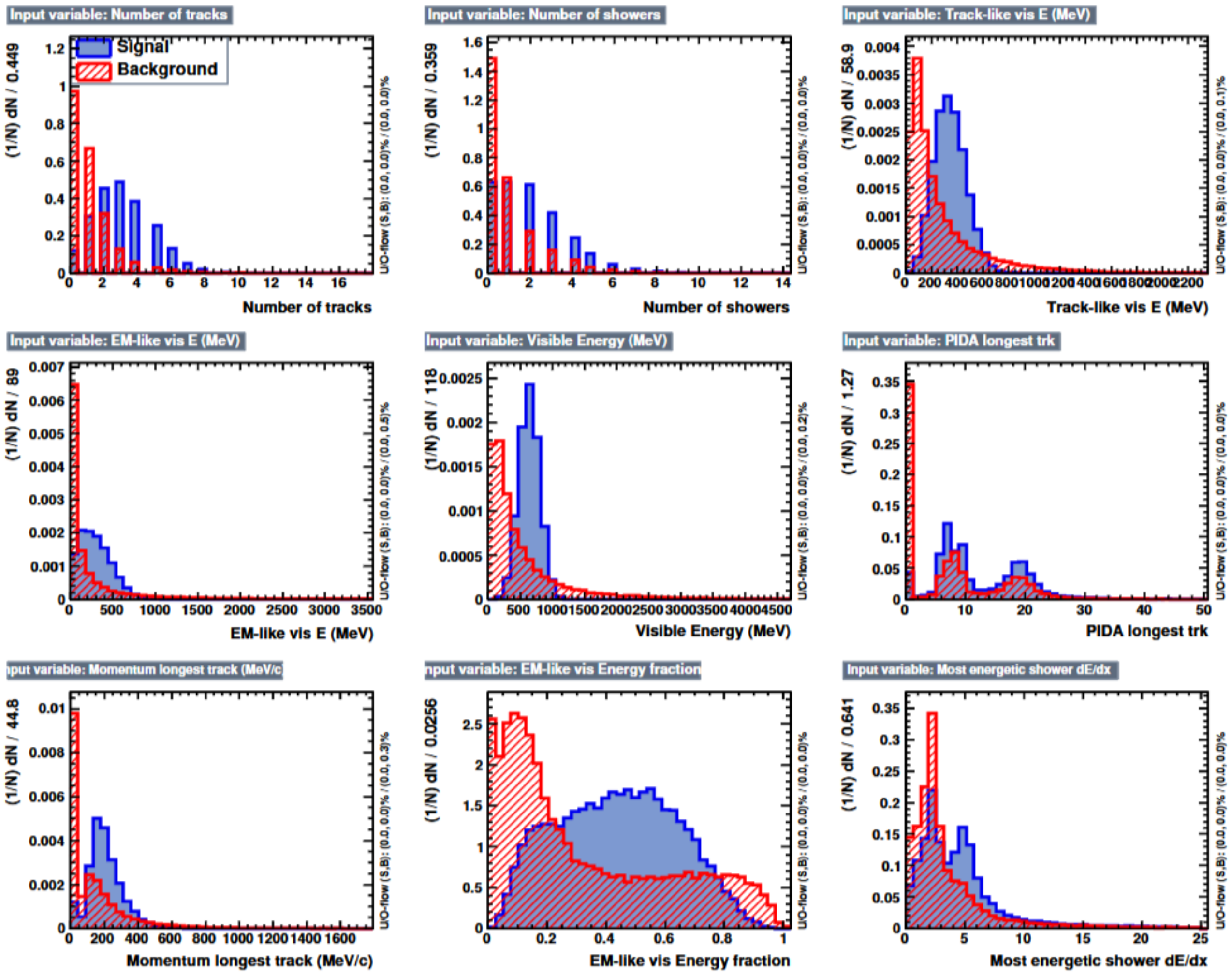
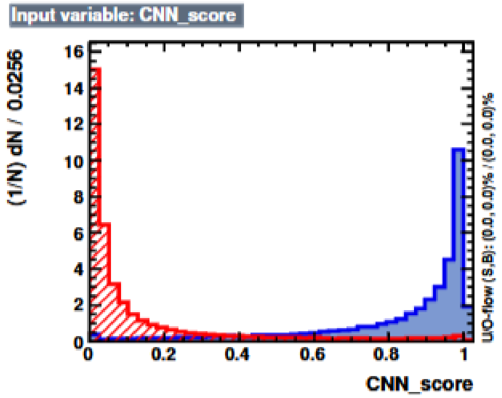


Additional step with a SK-like BDT

- Kinematic + PID
- Using the CNN score as a variable



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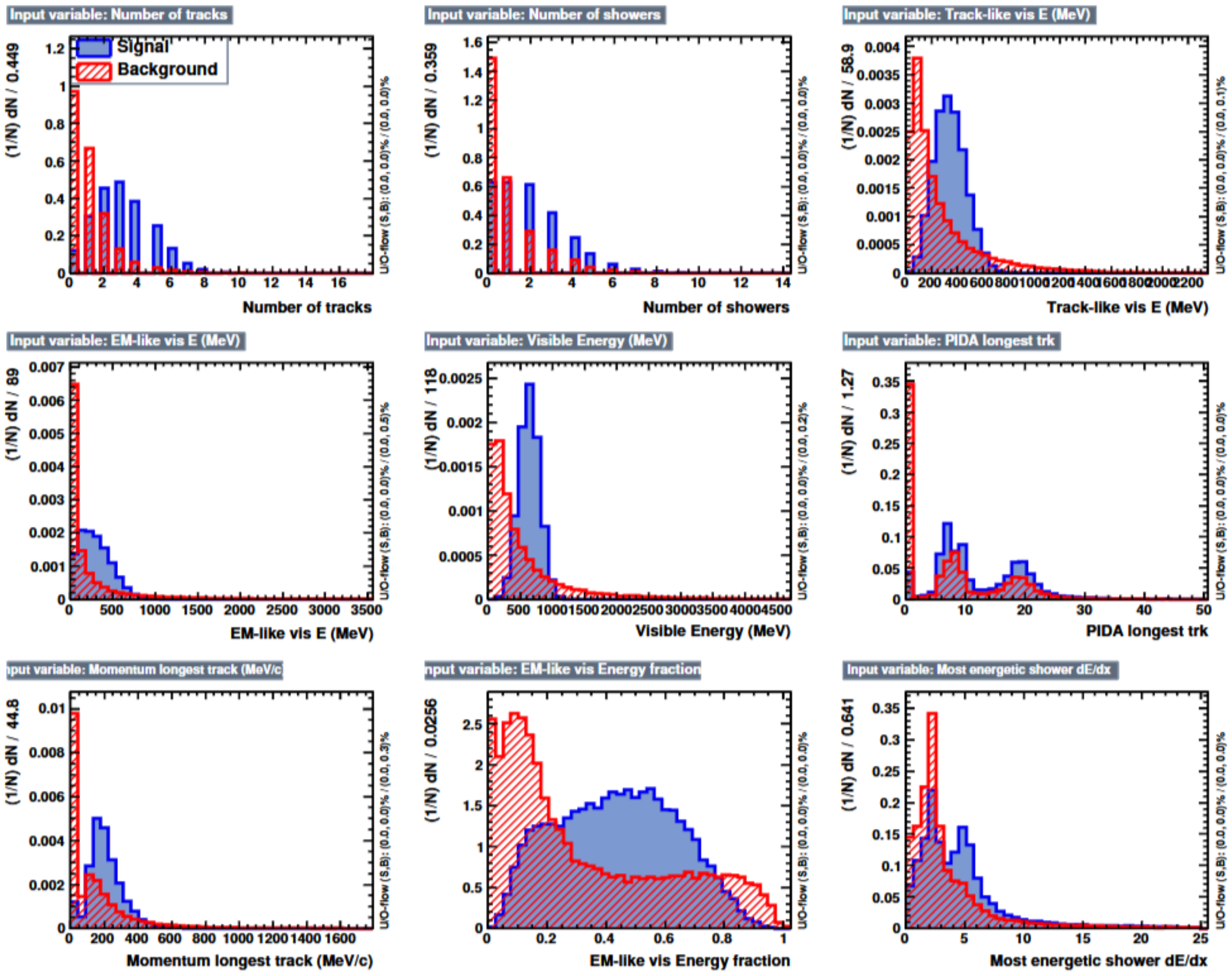


BDT + CNN Performance

- ~8% efficiency
- 10 bkgs / 400 kton*yrs

- Efficiency 2 times better than SK when scaled to the same exposure

- Study by Yeon-jae Jwa

DOI: 10.7916/a1dh-gh90

Comments on Potential Improvements

- This study was done in 2020. Since then, the simulation/reconstruction tools have evolved more realistic

- More BDT variables should be explored, for example adding the isotropy variables

- The CNN workflow can be improved (not just utilizing the collection plane image / switch to use 3D info / cluster-level identification etc)

Since Then, $n \to \bar{n}$ Updates in Sim/Reco at DUNE

Nuclear model: new GENIE version

- FSI model (major uncertainty source) remains as *hA* (the effective model), produces more high-momentum π's, fewer p's and n's.
- *hN* (the full cascade model) is used for systematic study

Study by Linyan, with help from Josh B. and Tyler S.

Branching ratios

- New branching ratios implemented. PR submitted to GENIE
- Expect lower π momentum and slightly fewer p's and n's.

Signal simulation/reconstruction:

- Include 2D simulation / signal processing

more realistic simulation & better input to reconstruction

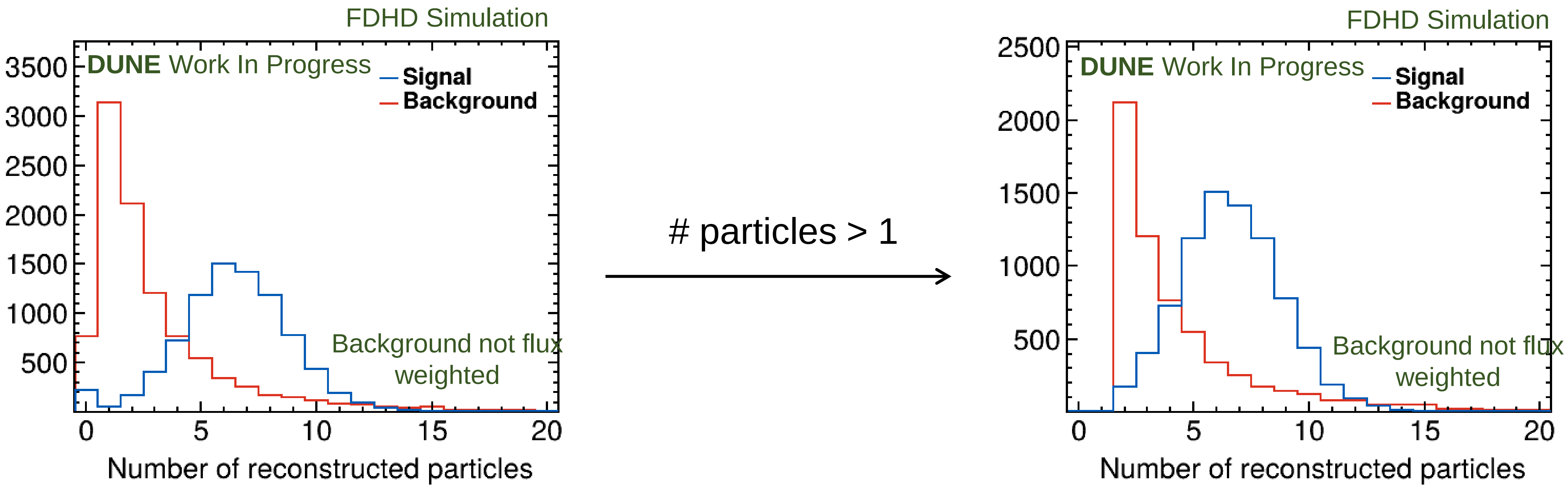
New Attempts on $n \to \bar{n}$ / Background Separation


Justin Wheeler at Fermilab

Work by SULI student Justin Wheeler
Supervisor: L. Wan

Multiplicity and precuts

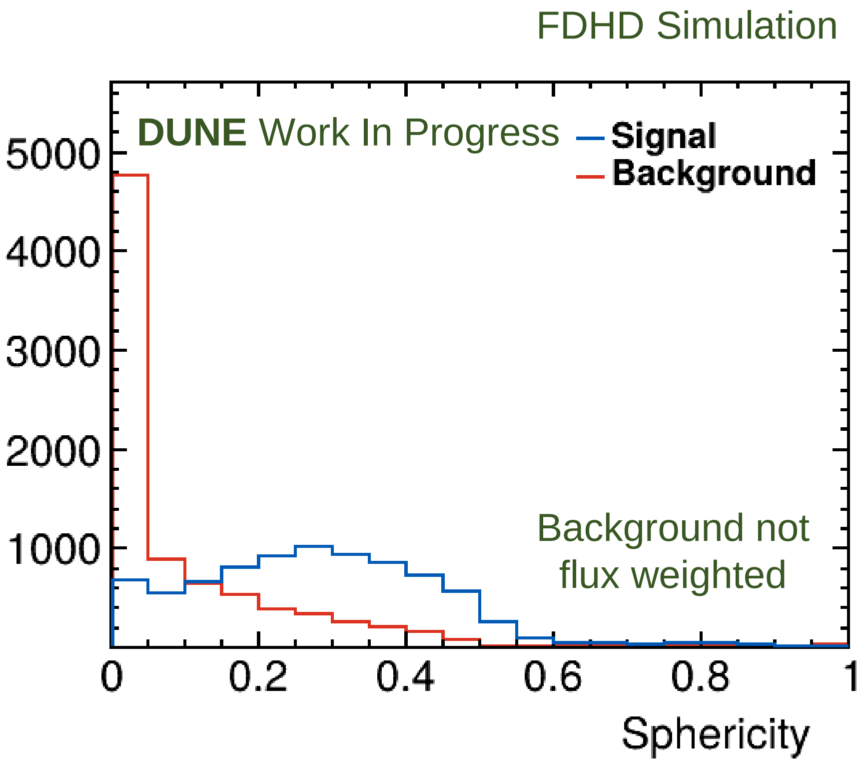
Work by SULI student Justin Wheeler

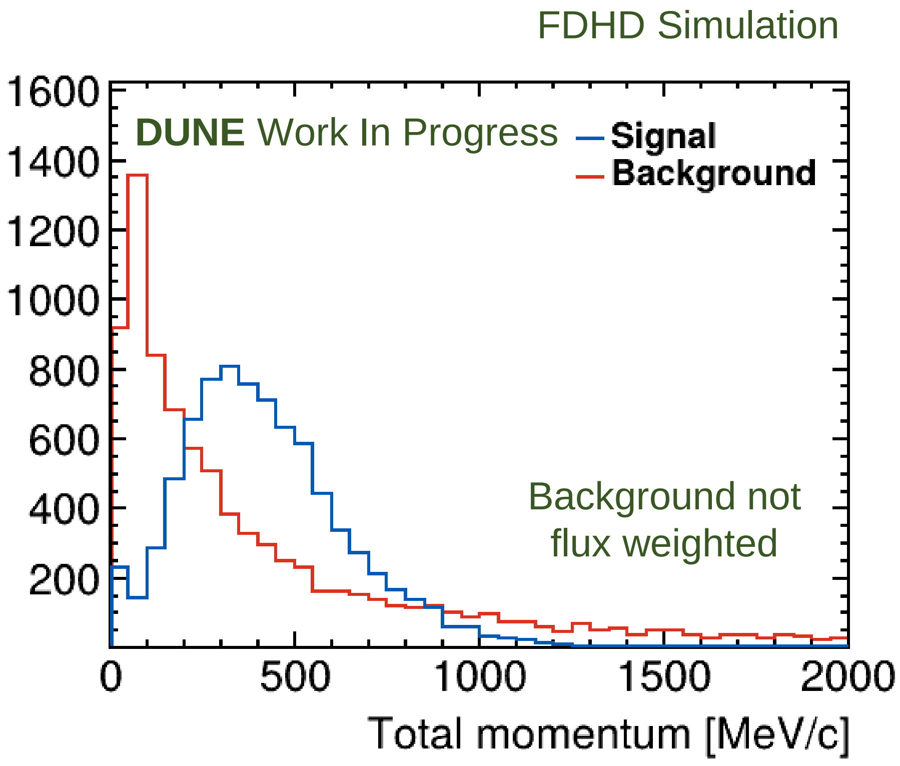


- Apply precut of number of reconstructed particles > 1
- Signal efficiency: 96.7%
- Cut out 39.0% background
- Signal events have higher multiplicity

Isotropy and kinematics

Work by SULI student Justin Wheeler





- Signal events are more isotropic
- Background exhibits directionality

- Background events have wider kinematic range
- Signal events have total momentum around fermi momentum

Comments on This Ongoing Study

- π^0/e separation
  - Some ν_e CC events leak into the sample, indicating insufficient π^0/e separation
  - Potential enhancement from flavor tagging

- $p/\mu/\pi$ separation
  - Similarly, some ν_μ CC events leak in

- Proton rejection

Next Step

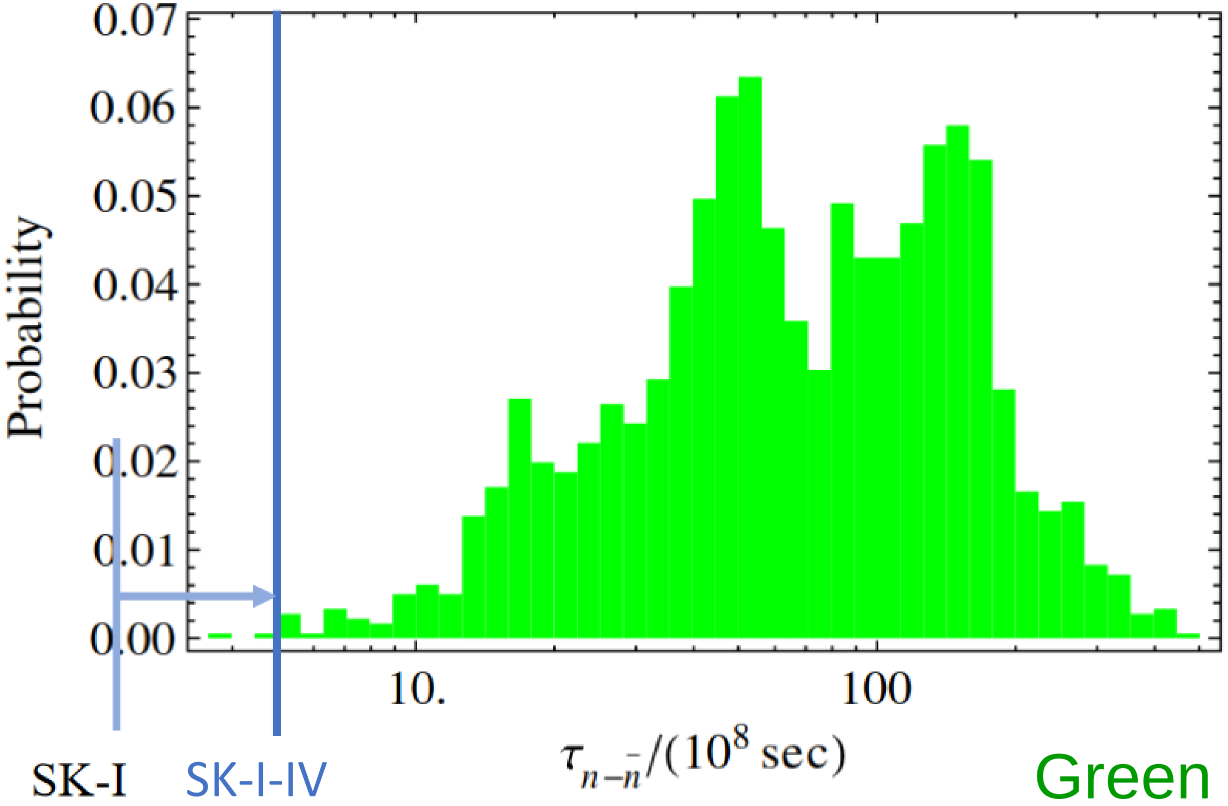
Enhance PID & calorimetry via alternative methodologies:

- Machine learning in LArTPC could use more advanced techniques than putting 2D time-wire images into CNN

- Clustering & cluster-level semantic labeling helps

- CVN (convolutional visual network) for flavor tagging also helps

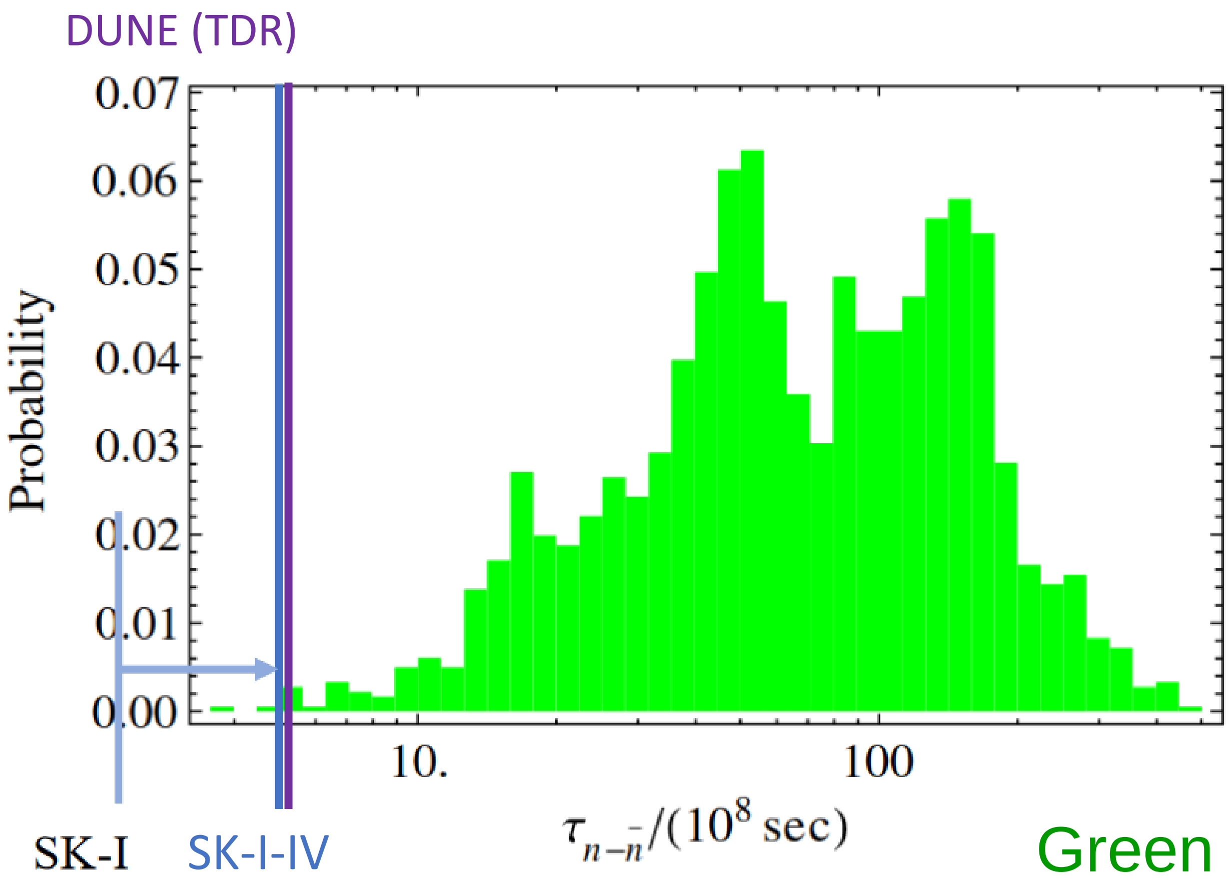
Where Will We Be?



Green from PSB model

K.S. Babu, et al, PRD 87 115019 (2013)

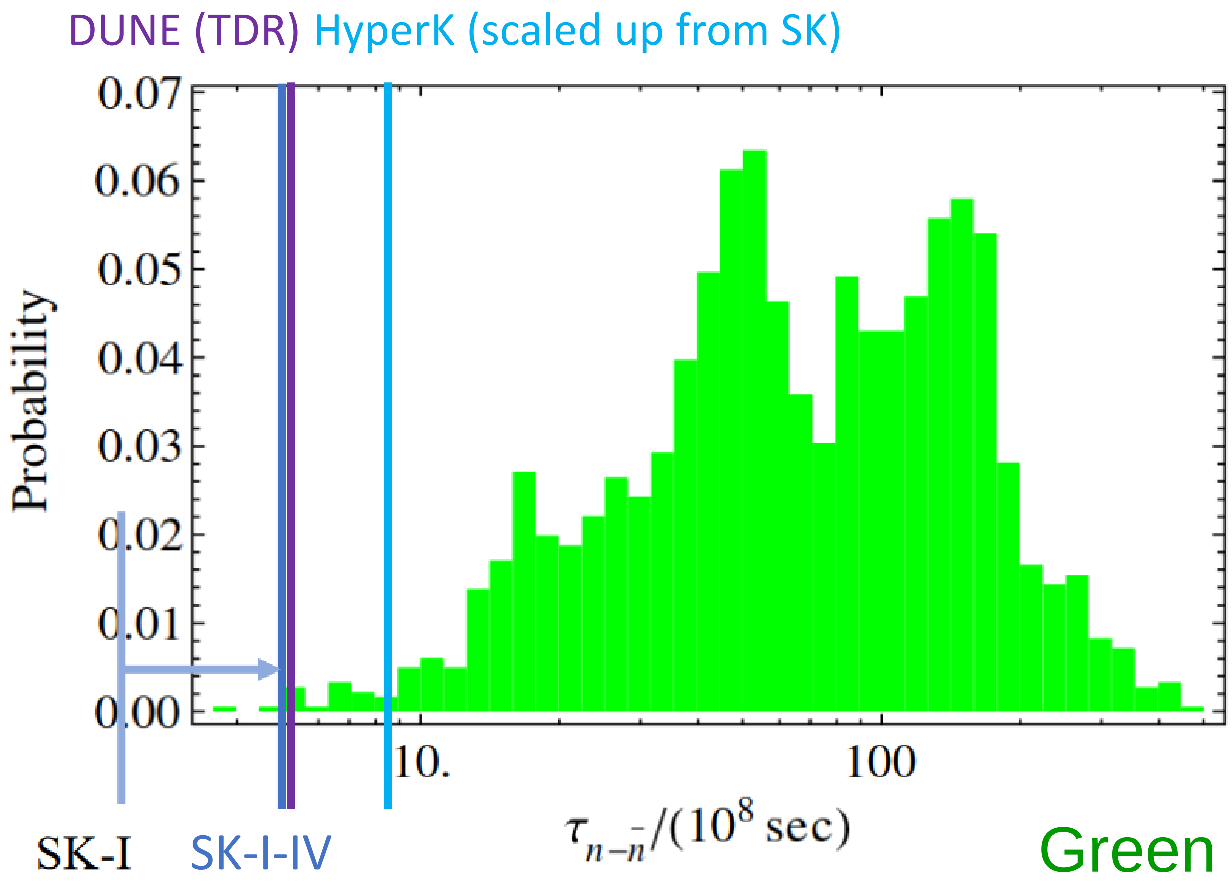
Where Will We Be?



Green from PSB model

K.S. Babu, et al, PRD 87 115019 (2013)

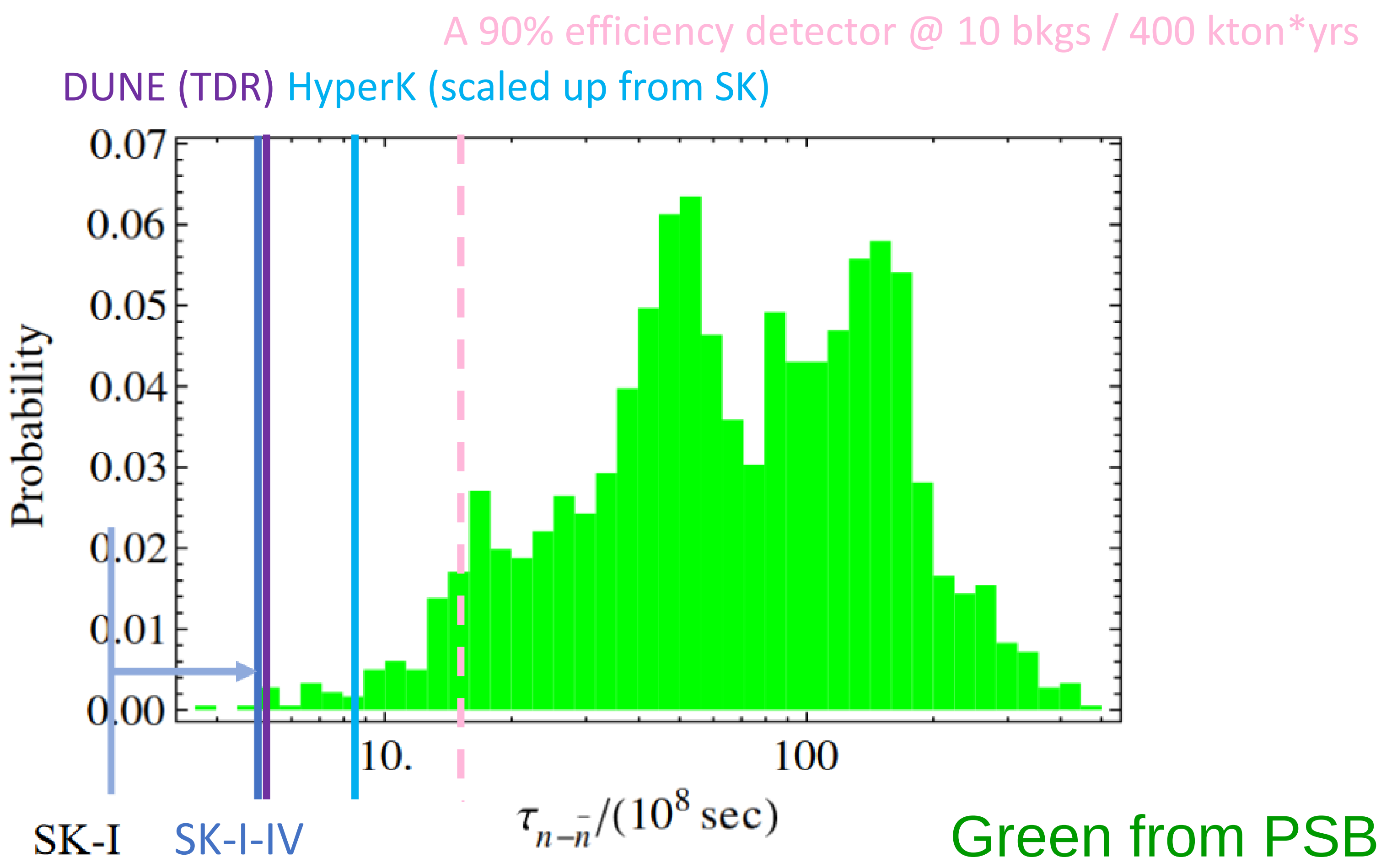
Where Will We Be?



Green from PSB model

K.S. Babu, et al, PRD 87 115019 (2013)

Where Will We Be?



Green from PSB model

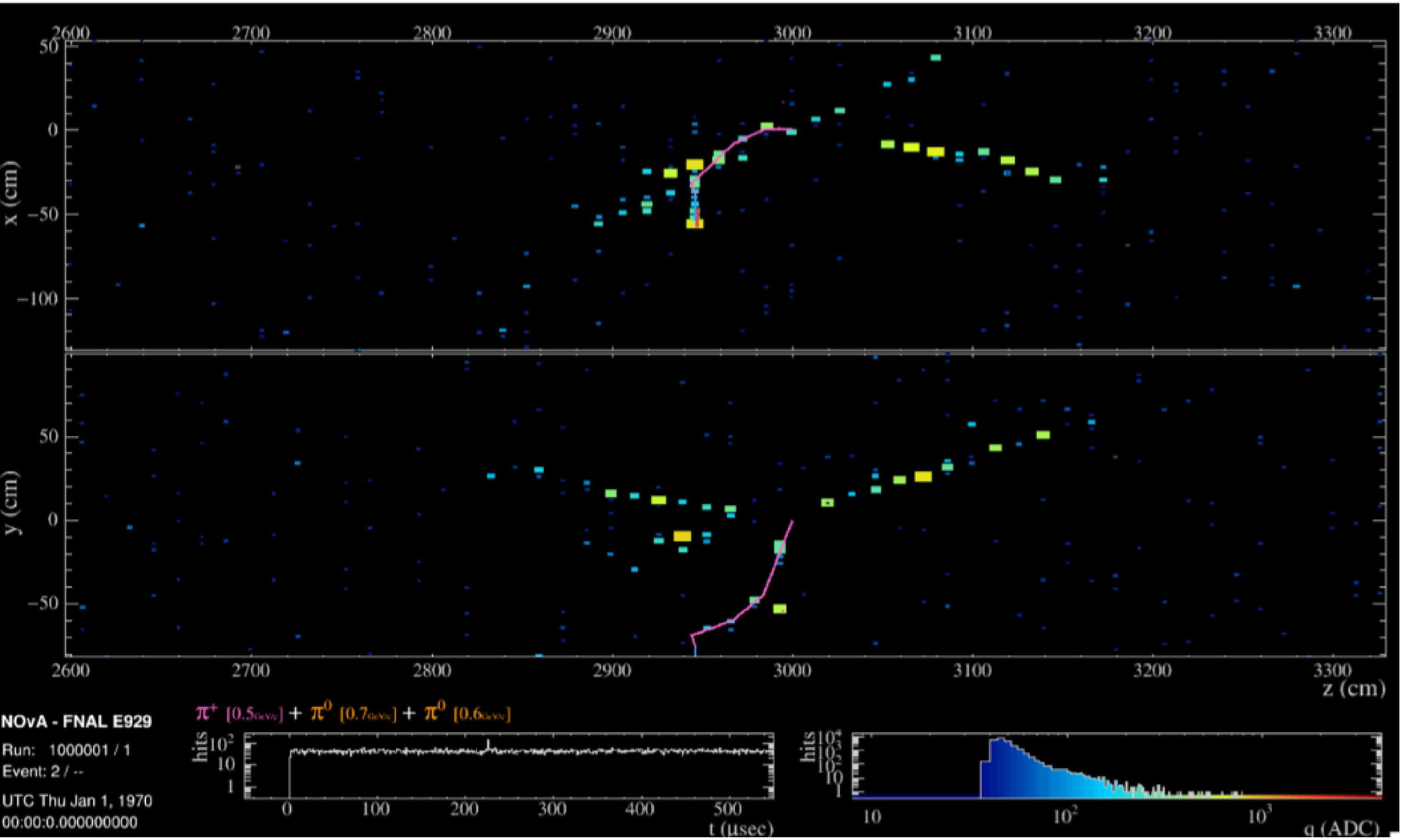
K.S. Babu, et al, PRD 87 115019 (2013)

Summary

- $\boldsymbol{n} \rightarrow \overline{\boldsymbol{n}}$ search at SK has begun to rule out the theoretical predicted parameter space by the PSB model scenario

- Ongoing and past work suggests that $\boldsymbol{n} \rightarrow \overline{\boldsymbol{n}}$ search at DUNE is promising.
  - Work to do (being done NOW!)

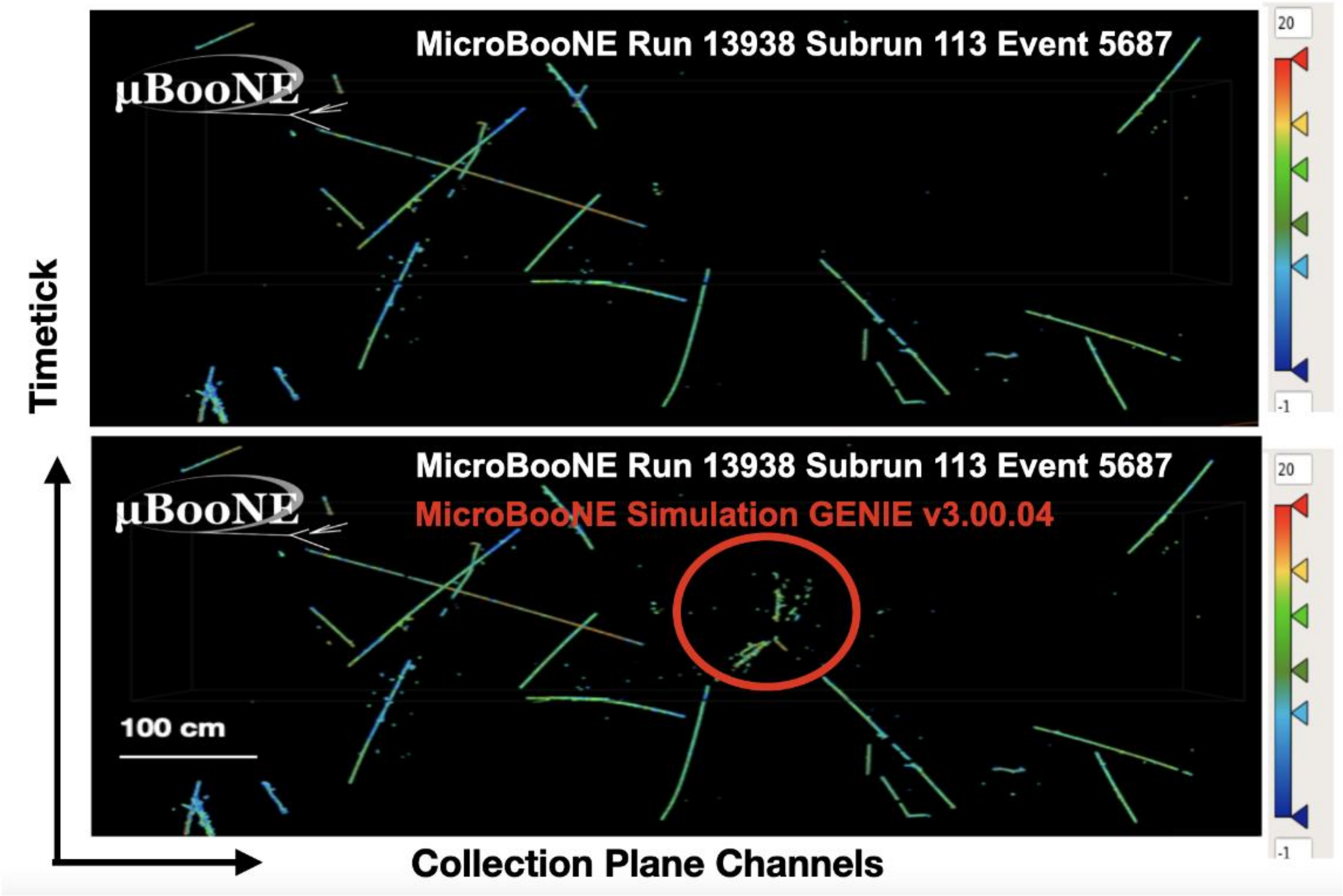
$n \to \bar{n}$ in NOvA



DOI: 10.26153/tsw/13269

- Trigger improvement reduced cosmic mu event rate from 120 kHz to 8 Hz
- Major background is cosmogenic neutrons
- Event selection
  - ~10% efficiency
  - ~100 bkgs / 10 kton*yr
- Bound neutron lifetime limit ~100 times worse than SK (~10 times worse after scaling to same exposure as SK)

$n \rightarrow \bar{n}$ in MicroBooNE



JINST 19 (2024) 07, P07032

- A small surface detector with small exposure, major background = cosmic ray muons

- Analysis:

1. Precut using event size in 3 anode planes & time
2. Sparse CNN with 2D image from the 3 planes
3. Bad reconstruction rejection

- Performance not competitive, ~100 times worse than SK after scaling to the same exposure

Super-Kamiokande Detector

Large water Cherenkov detector: 1996 ~ so far

In Gifu, Japan

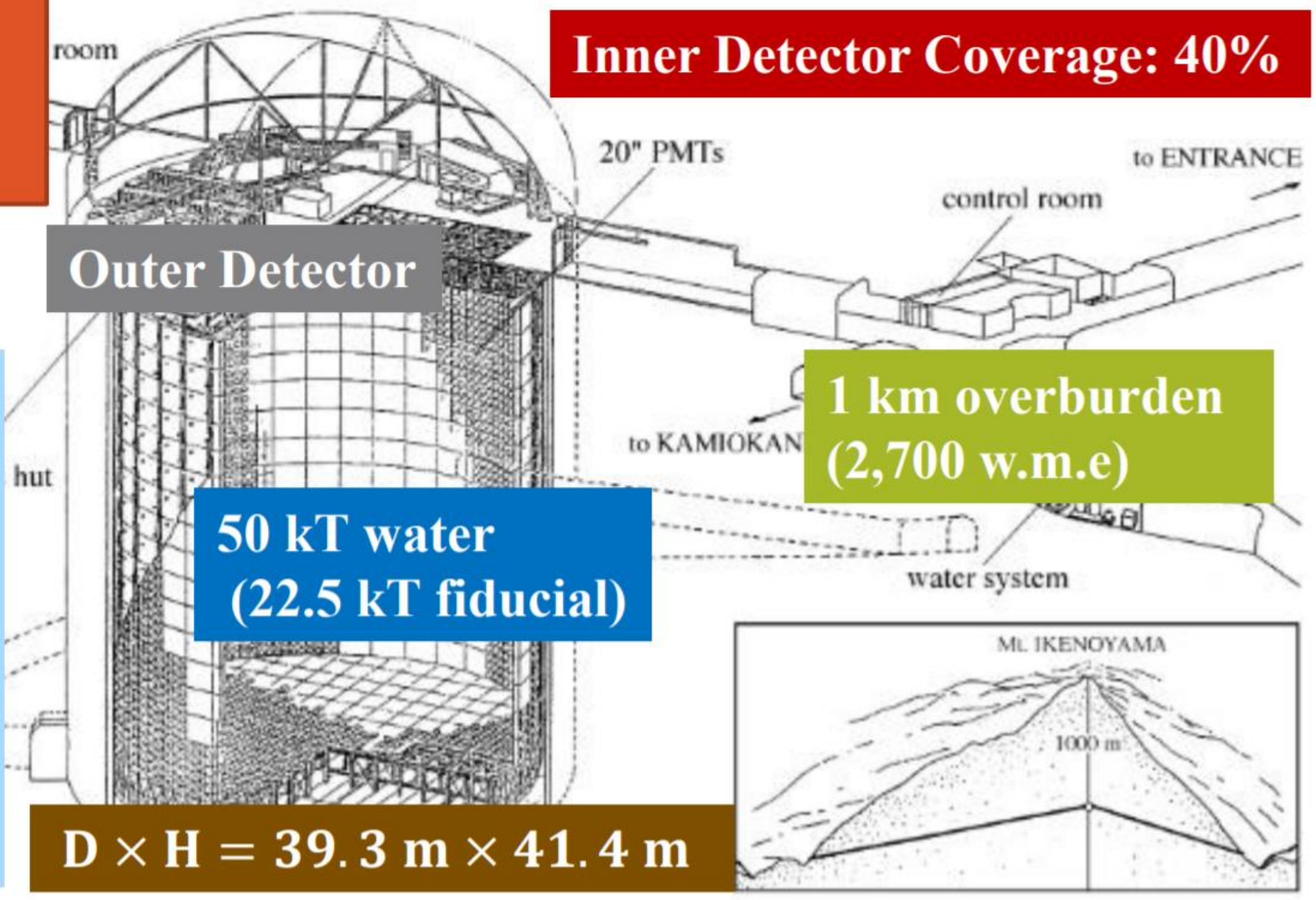
Inner Detector Coverage: 40%

Outer Detector

1 km overburden (2,700 w.m.e)

50 kT water (22.5 kT fiducial)

D × H = 39.3 m × 41.4 m



Nucl. Instr. & Meth, A 737C (2014)

Comparison with Previous Analysis

	SK-I Paper	Box-cut method	This analysis
Data set	SK I (1489 days)	SK I-IV (6050.3 days)	
Hadron production	Bubble chamber	Crystal Barrel + Obelix + Bubble chamber	
Final state interaction	ORNL[1]	NEUT π FSI model [2]	
Analysis method	Box cut		Multi-layer perceptron
Signal eff.	12.1%	3.7%	4.1%
Background rate	5.91 / year	0.90 / year	0.56 / year
Sensitivity	$\mathbf{1.9 \times 10^{32}}$ **years**	$\mathbf{2.0 \times 10^{32}}$ **years**	$\mathbf{4.3 \times 10^{32}}$ **years**

[1] ORNL-6910

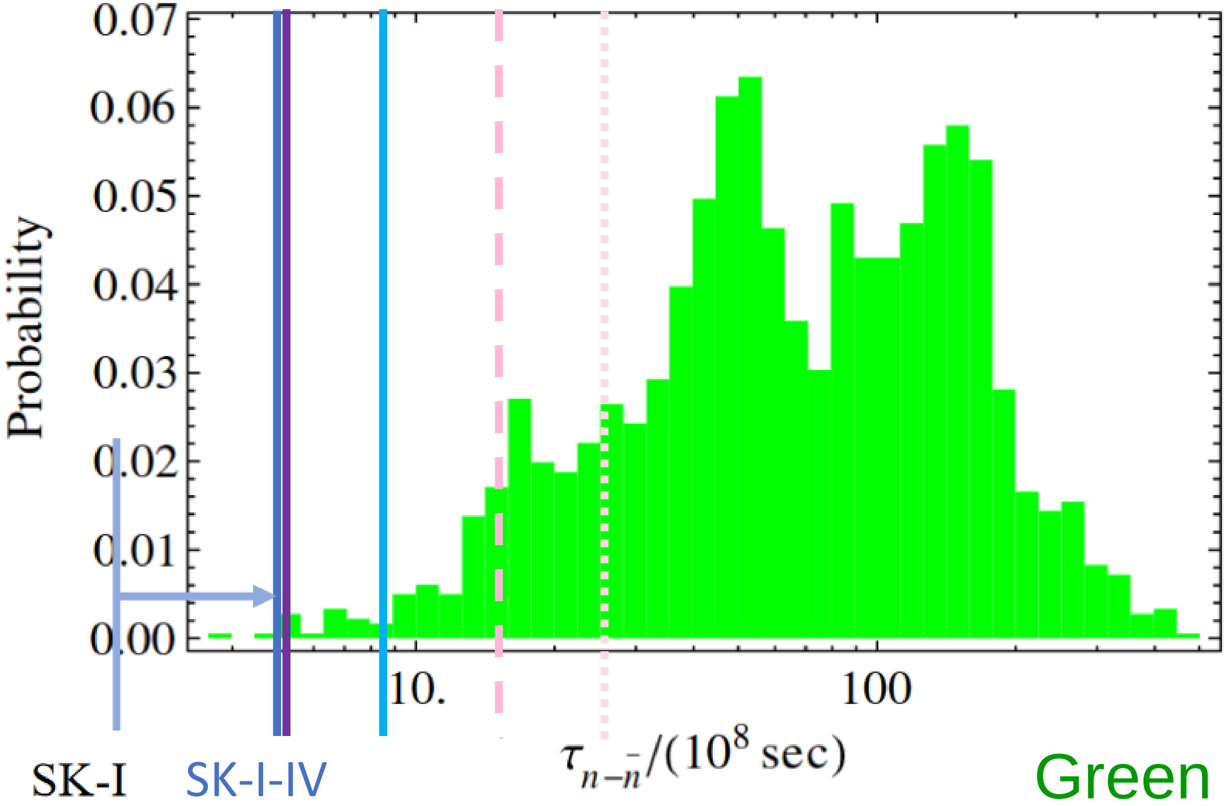
[2] arXiv: 1405.3973

Where Will We Be?

A 100% efficiency background-free detector @ 400 kton*yrs

A 90% efficiency detector @ 10 bkgs / 400 kton*yrs

DUNE (TDR) HyperK (scaled up from SK)



Green from PSB model

K.S. Babu, et al, PRD 87 115019 (2013)