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Neutrino-Oxygen Neutral-Current Elastic Interaction as a Background in Supernova Relic Neutrino Search

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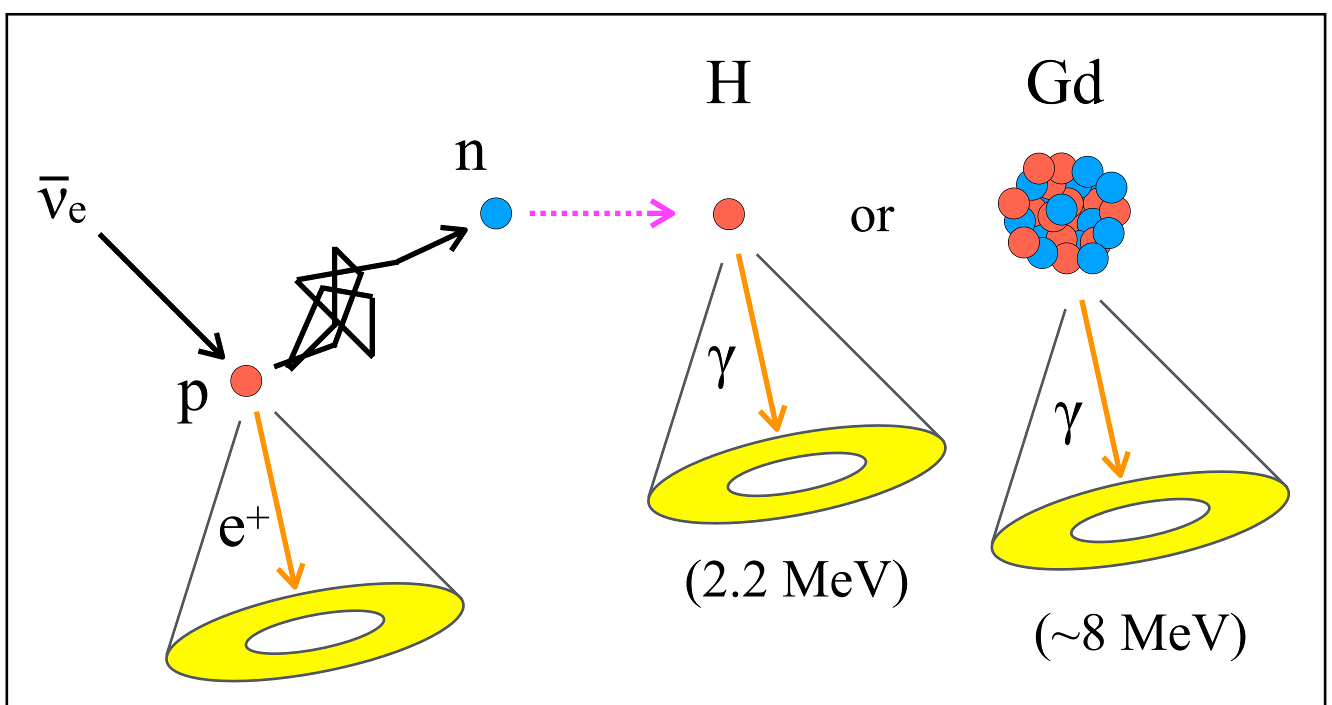
for the T2K and Super-Kamiokande Collaborations

Introduction

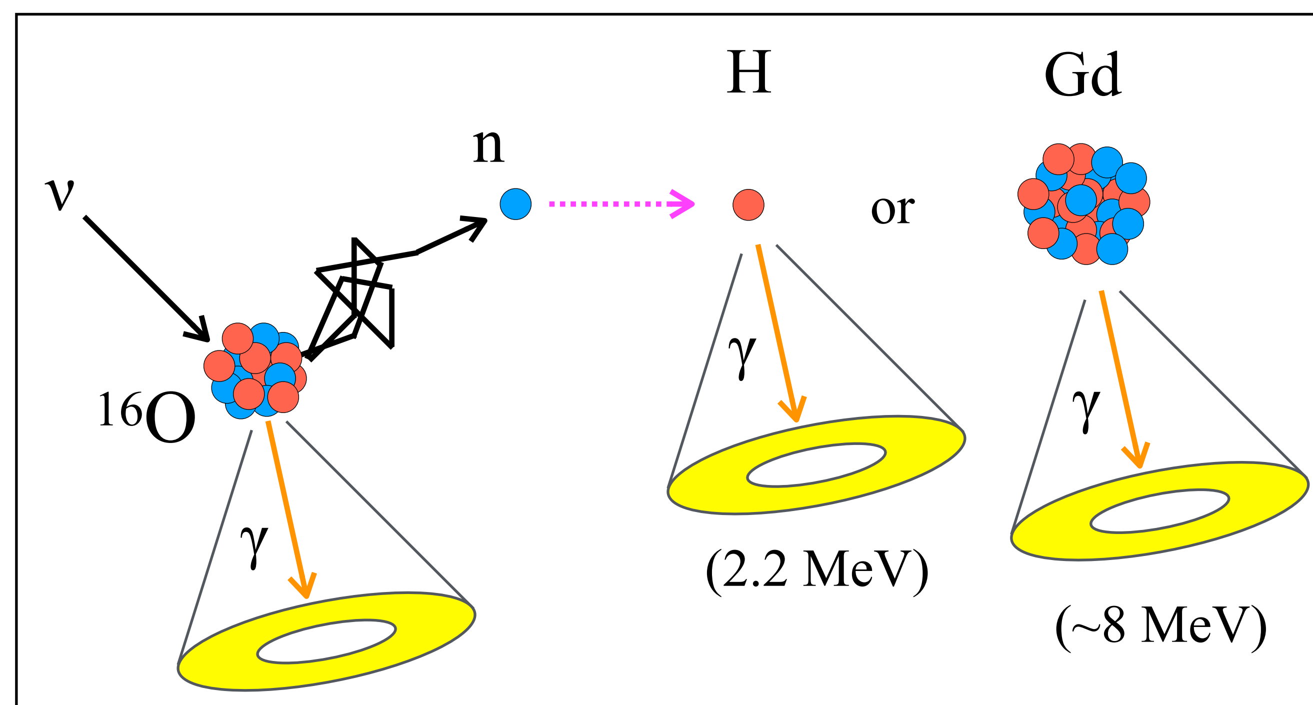
SRN Search & NC Elastic Interaction

- **"Neutron tagging"** analysis is implemented to obtain higher sensitivity.
  - **Delayed coincidence: e^+ & γ from n capture**
  - SK: 2.2 MeV gamma-ray by H (efficiency ~20%)
  - SK-Gd: ~8 MeV gamma-rays by Gd (efficiency ~80% @ 0.1%-Gd load)
- Many backgrounds can be reduced by neutron tagging, however, NC remains.
  - **NC at E_ν > 200 MeV usually involves nucleon knock-outs and mimics SRN signal.**
  - **NC is an irreducible background, so must be measured precisely (current: 100%!).**

Supernova relic neutrino (IBD)

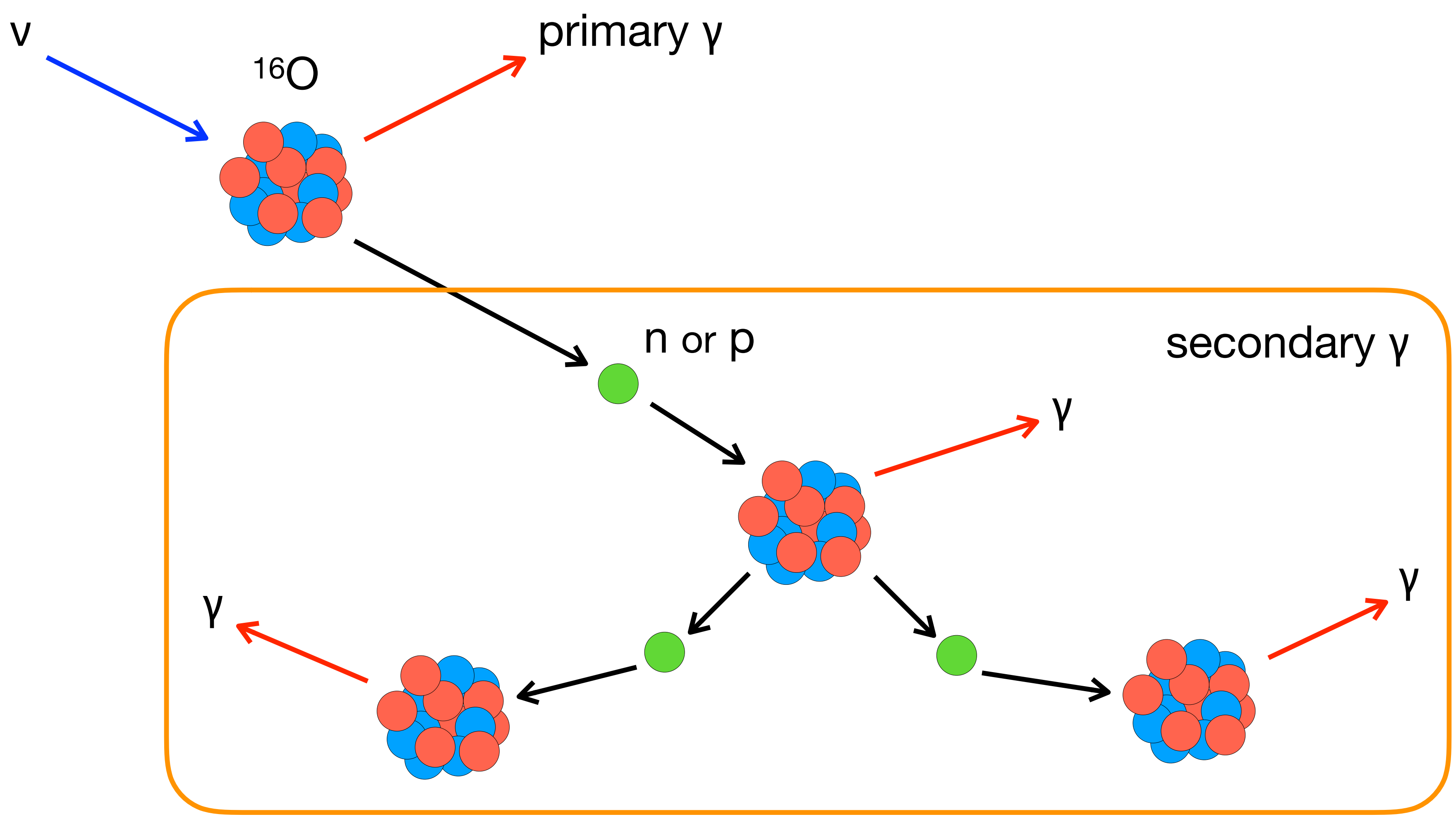


Atmospheric neutrino (NC elastic)



Measurement Probe

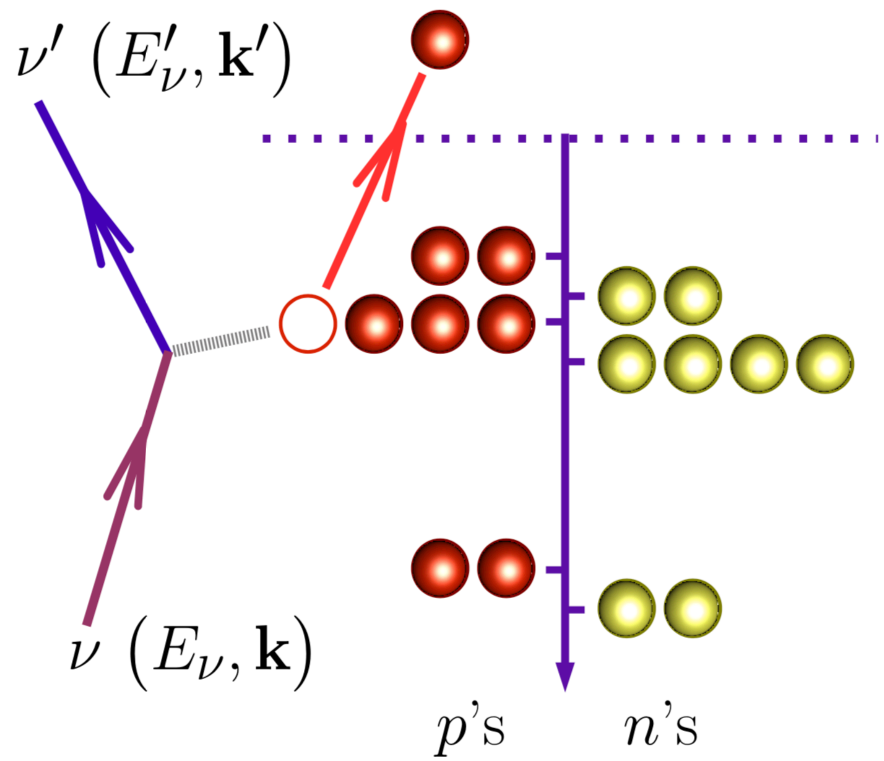
- NC elastic can be measured by adopting **nuclear de-excitation gamma-rays** as a signal (typical energy is <10 MeV).
- **“Key” is to reduce large background in a low energy region.**



Nuclear De-excitation Gamma-rays

- Probability of remaining nucleus having an excited state is calculated by Ankowski et al. based on the local density approximation (= spectroscopic strength).

- Basic three states (from the shell model) + *others* state;
  - **$(p_{1/2})^{-1}$**: no gamma emission
  - **$(p_{3/2})^{-1}$**: **gamma emission (6.18 MeV, 6.32 MeV, etc)**
  - **$(s_{1/2})^{-1}$**: particle (p, n, α, etc) decay + gamma emission
  - ***others***: **short range correlation** or higher excited state



Model or MC version	**$p_{1/2}$**	**$p_{3/2}$**	**$s_{1/2}$**	**others**
Simple shell model	0.25	0.50	0.25	0
Ankowski et al.	0.158	0.3515	0.1055	0.385

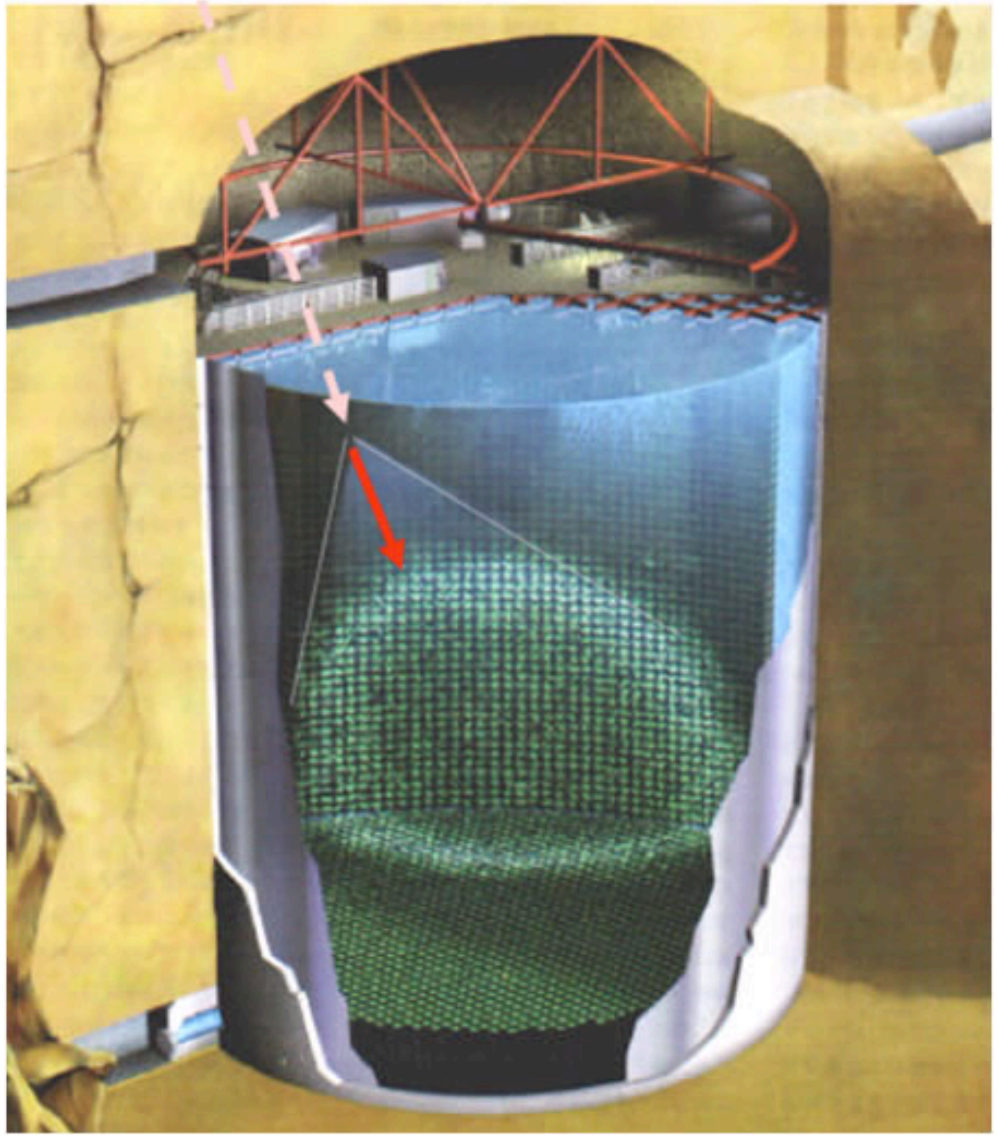
A. M. Ankowski, Phys. Rev. Lett. 108, 052505 (2012)

Measurement with Atmospheric Neutrinos

L. Wan et al. (Super-Kamiokande Collaboration), Phys. Rev. D 99, 032005 (2019)

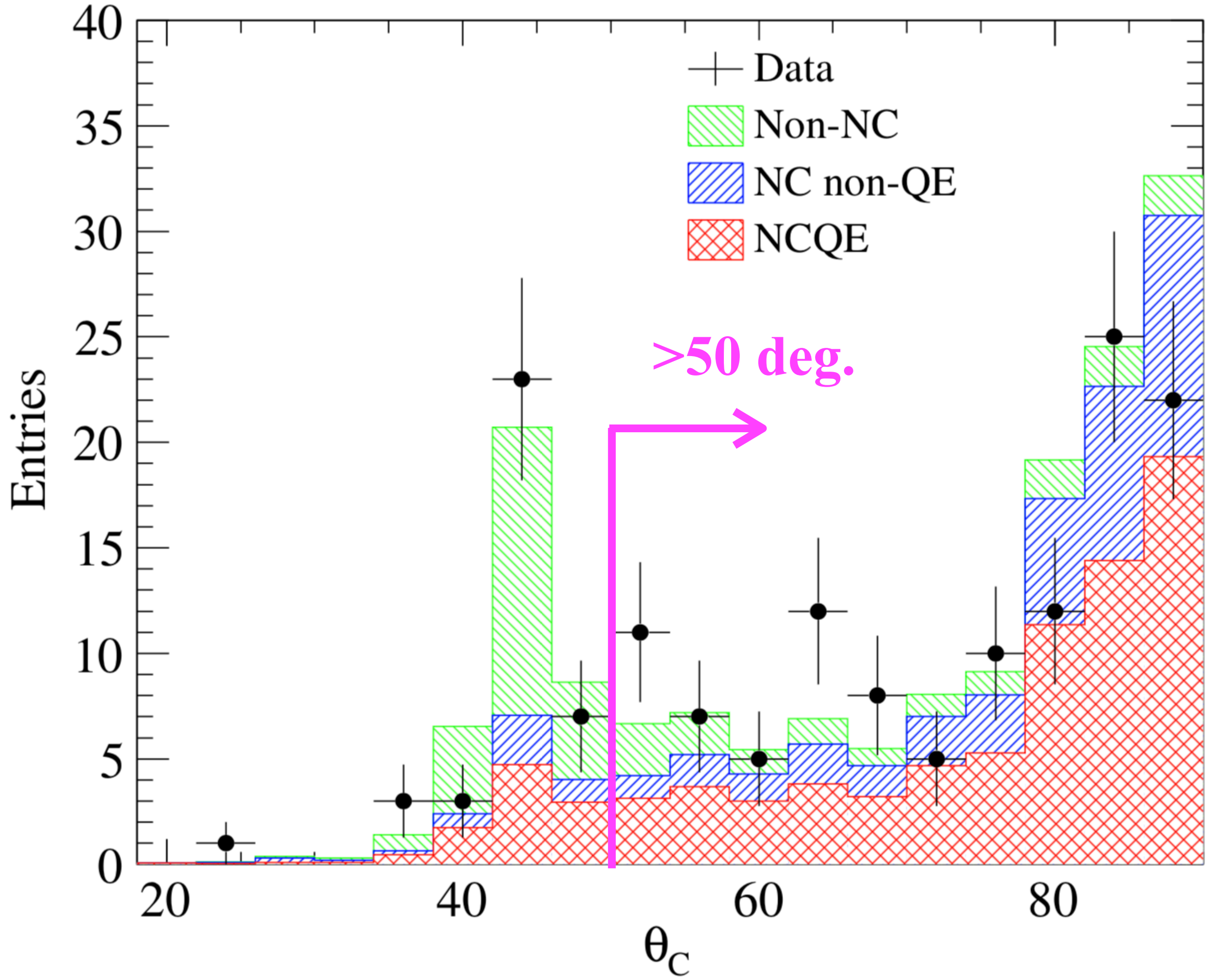
Super-Kamiokande

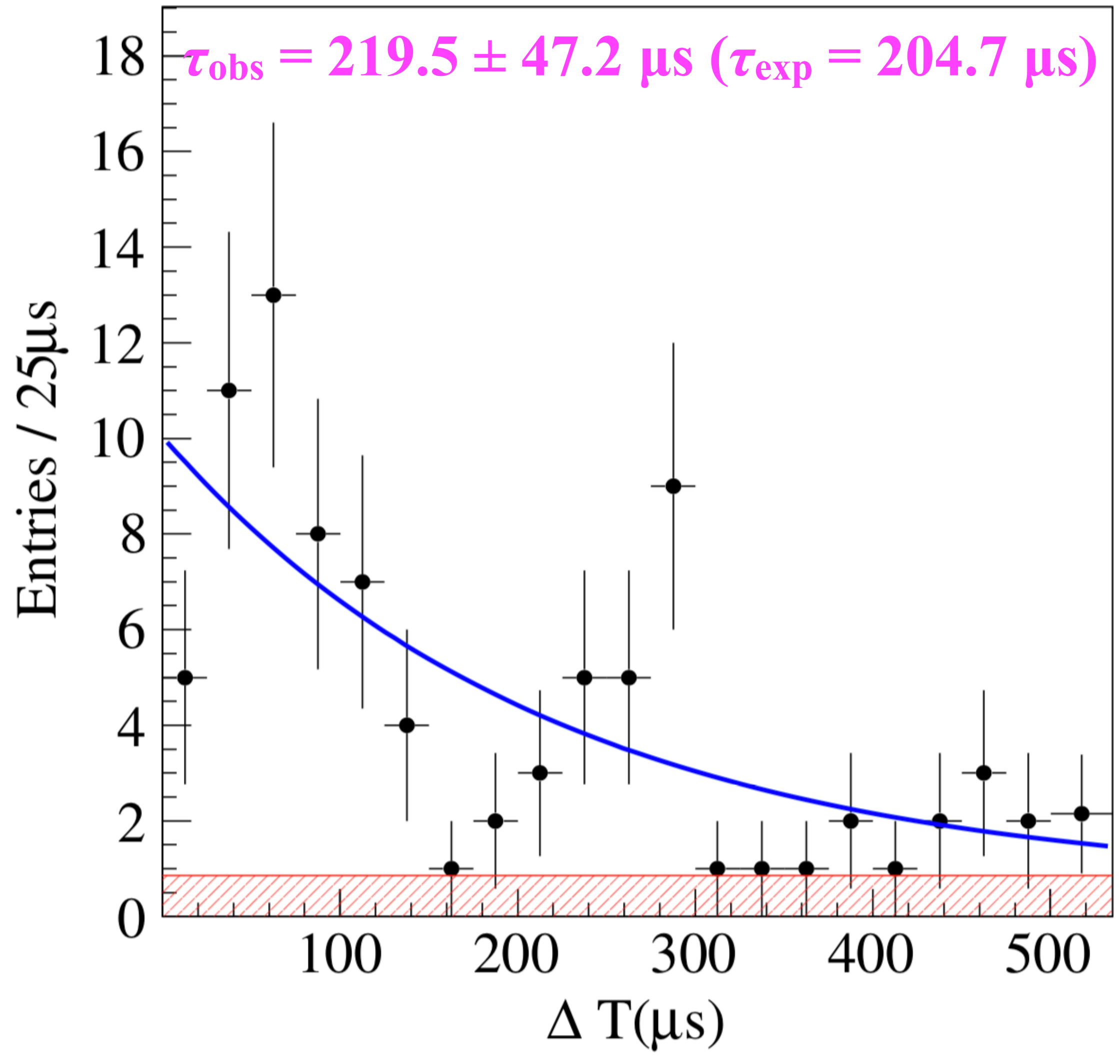
- Large water Cherenkov detector scaling ~40 m in diameter and ~40 m height.
- ~11,000 20-inch PMTs used to detect Cherenkov photons emitted by charged particles.
- Running since 1996; Run after October/2008 has a neutron tagging capability.
- Data between October/2008 and October/2017 is used in the analysis.



Measurement Method

- Basically SRN analysis cut is applied in order to reduce large backgrounds (Neutron tagging is also applied).
- Different from SRN IBD, NCQE is expected to involve many gamma-rays via secondary neutron interactions. This leads to larger reconstructed Cherenkov angle (angle cut).





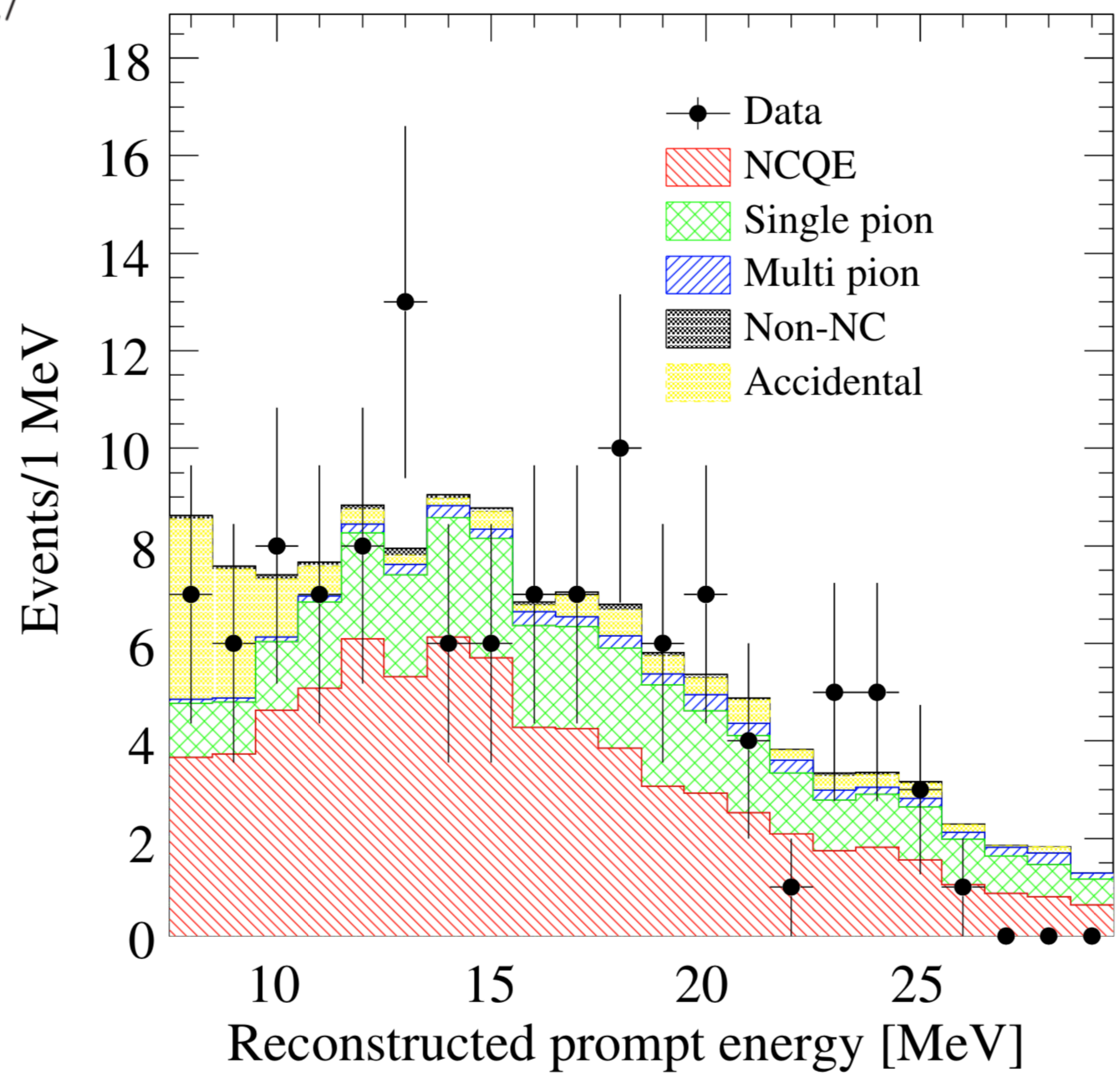
Cross Section Result

$$\langle \sigma^{\text{observed}}_{\text{NCQE}} \rangle = \frac{N^{\text{obs}}_{\text{tot}} - N^{\text{exp}}_{\text{acc}} - N^{\text{exp}}_{\text{others}} - N^{\text{exp}}_{\text{NCothers}}}{N^{\text{exp}}_{\text{NCQE}}} \times \langle \sigma^{\text{theory}}_{\text{NCQE}} \rangle$$
$$= (1.01 \pm 0.17_{\text{stat.}}) \times 10^{-38}\ \text{cm}^2,$$

TABLE III. Predictions of components in the final data sample and the comparison with signal MC.

Components	Events
NC single π	33.4
NC multi-π's	4.2
DIS	0.0
$\bar{\nu}_e$ CC	0.4
$\bar{\nu}_\mu$ CC	0.8
Accidental	13.7
Spallation	0.5
Reactor	0.1
Total background	53.1
Observed data	117
Background subtracted data	63.9
NEUT NCQE prediction	71.9

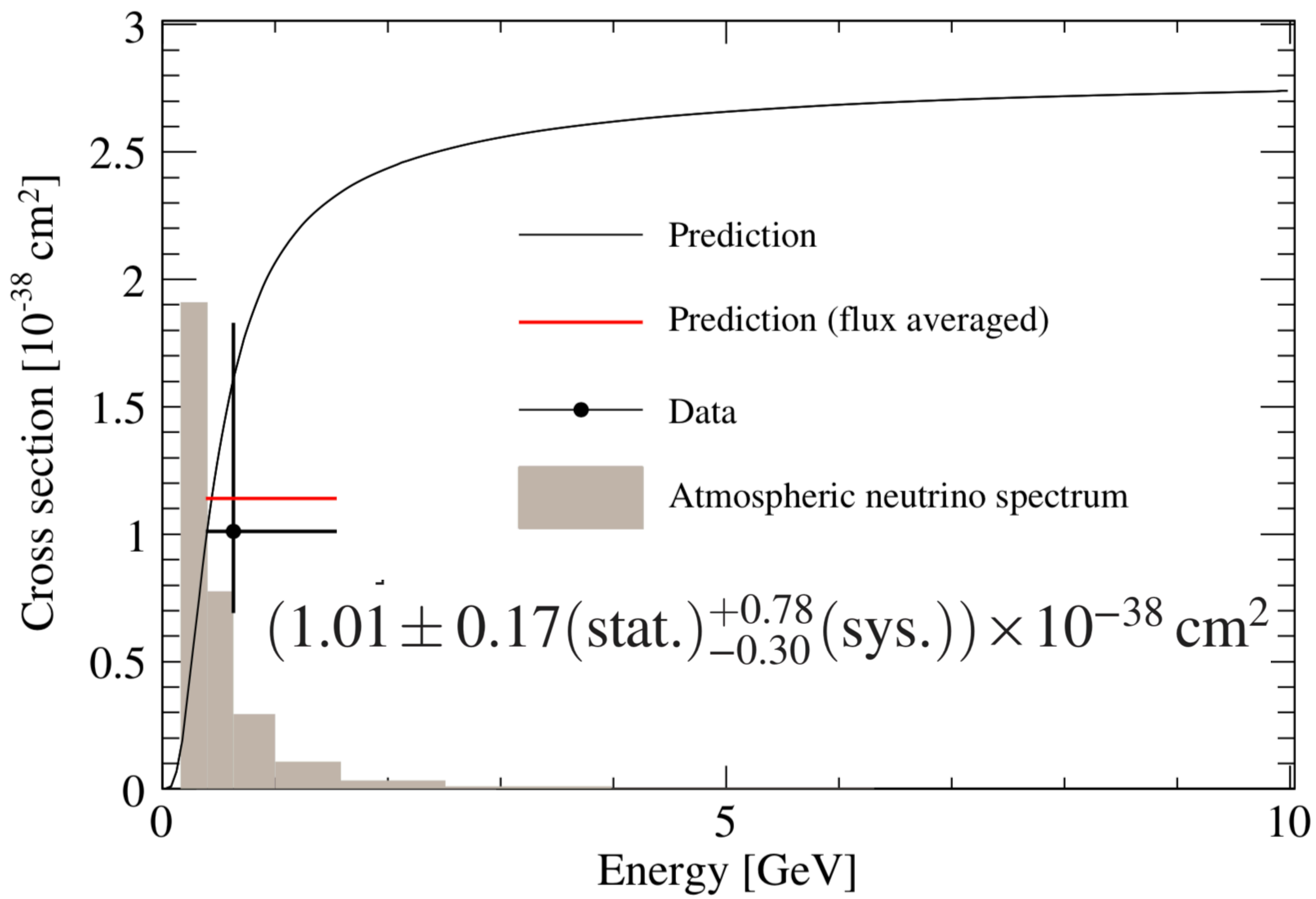
Signal purity ~ 58%



Systematic Uncertainty

TABLE IV. Uncertainties in NCQE measurement.

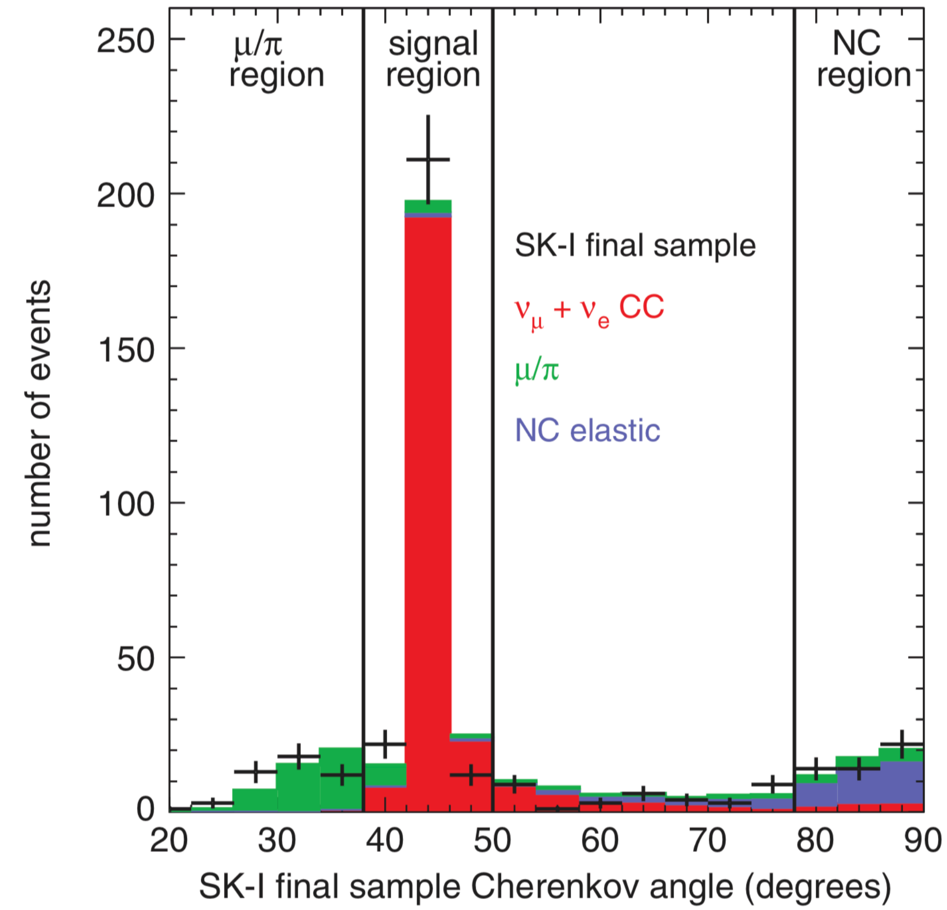
	NCQE		NC non-QE
ν_{atm} flux		18%	
$\nu/\bar{\nu}$ ratio		5%	
Cross-section			18%
Primary γ's	15%		3%
Secondary γ's	13%		13%
Neutron multiplicity	21%		16%
Neutron energy	18%		14%
Neutron transportation	+7%		+4%
Data reduction		3%	
Neutron tagging		10%	
Others		0.7%	



- Neutrino flux (HKKM model) error is large.
- Neutron-related errors are very large.
- **Final systematic error size is +77.2/–29.7%, while statistical error is ±16.8%.**

Comments on SK Measurement

- Atmospheric neutrino is used with almost the same cuts as SRN analysis, then **a direct comparison is possible.**



- **Very large systematic error** (flux, neutron tagging, still large background).
- Large statistical error even with ~10 years data.
- Inclusive measurement for neutrino and antineutrino, thus not ideal from a stand point of neutrino interaction study.
- Cherenkov angle cut strongly depends on the secondary nuclear interaction model (bias?).

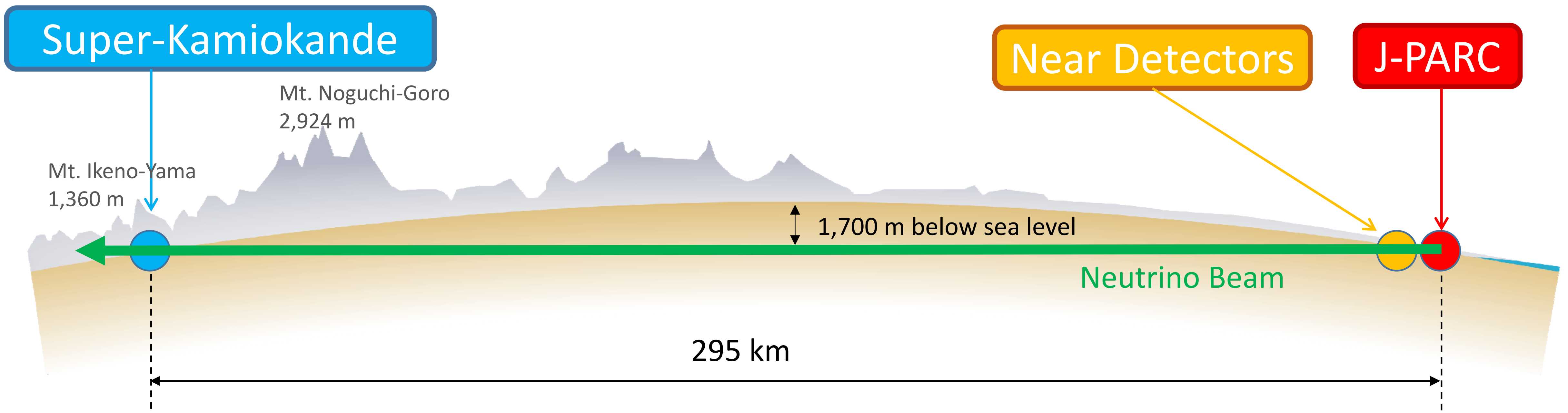
K. Bays et al. (Super-Kamiokande Collaboration), Phys. Rev. D 85, 052007 (2012)

Measurement with T2K Neutrino Beams

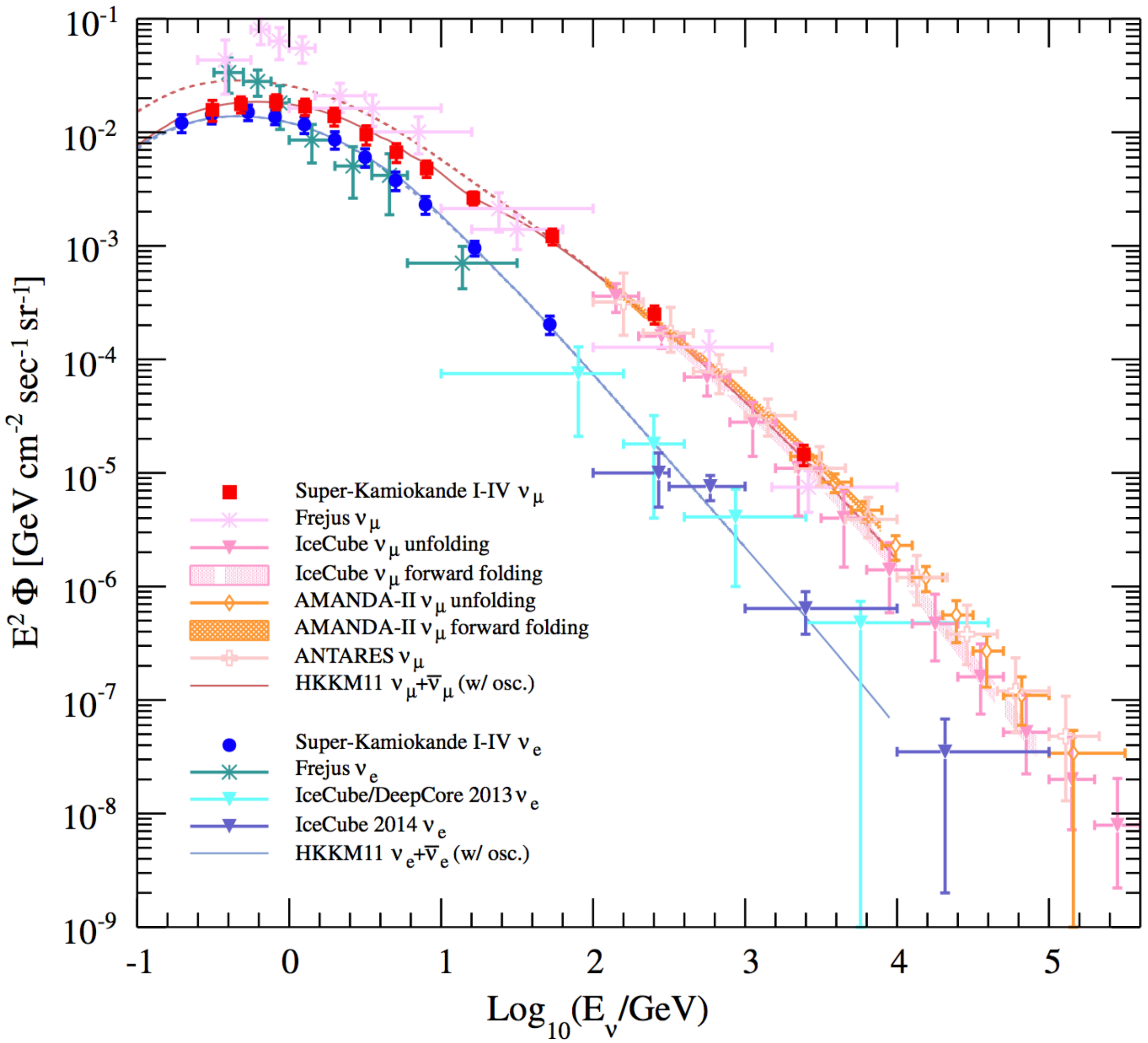
K. Abe et al. (T2K Collaboration), Phys. Rev. D 90, 072012 (2014) +α

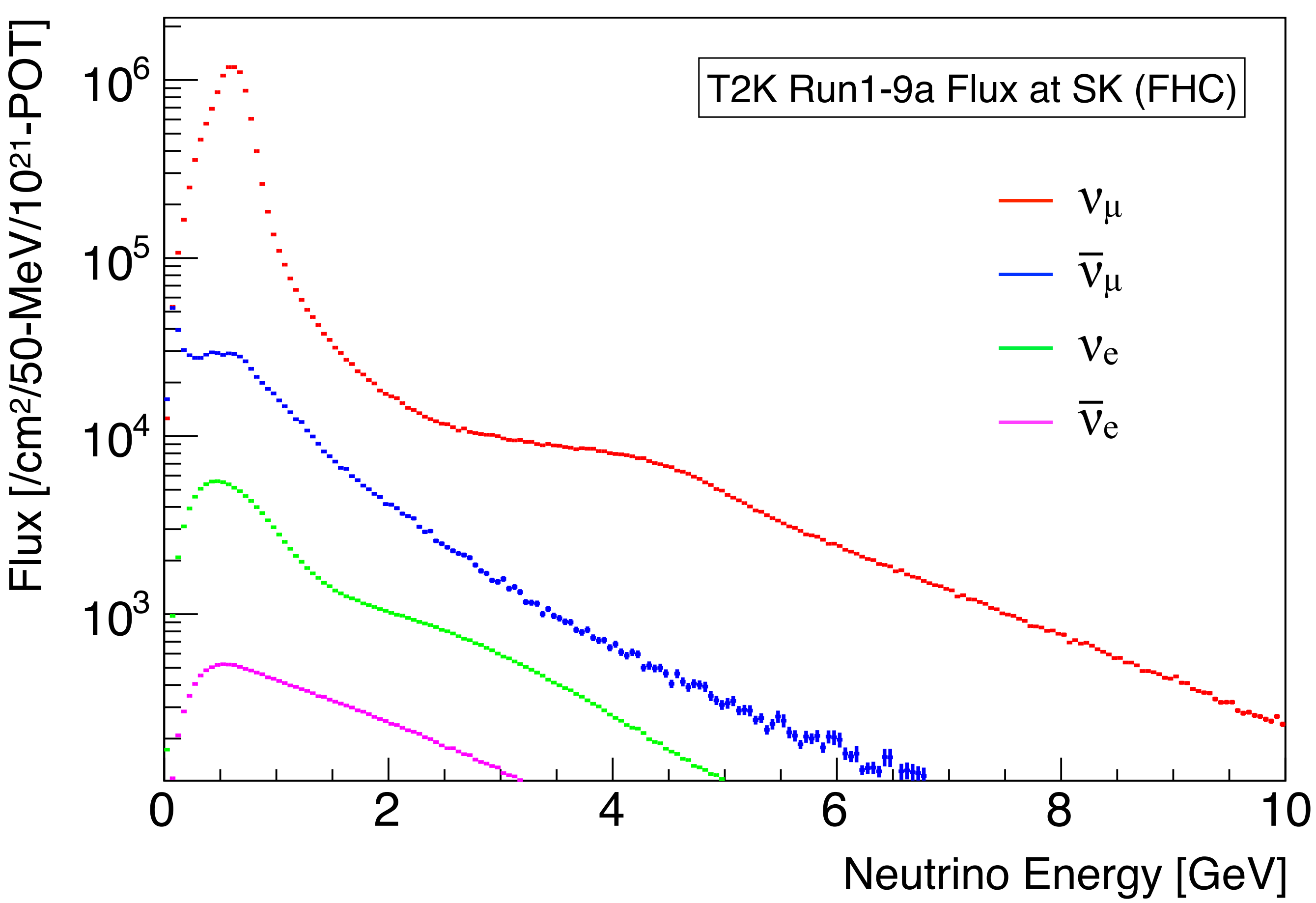
T2K Experiment

- T2K is a long baseline neutrino experiment.
  - Beam produced at J-PARC (8 bunch beam structure being separated by 581 ns), and detected at 295 km away Super-Kamiokande.
  - **Two operation modes: neutrino-dominant (FHC) or antineutrino-dominant (RHC)**
  - **Flux peak ~630 MeV is close to the atmospheric neutrino flux peak.**
- Use FHC 3.07×10^{20} protons-on-target data in the analysis.

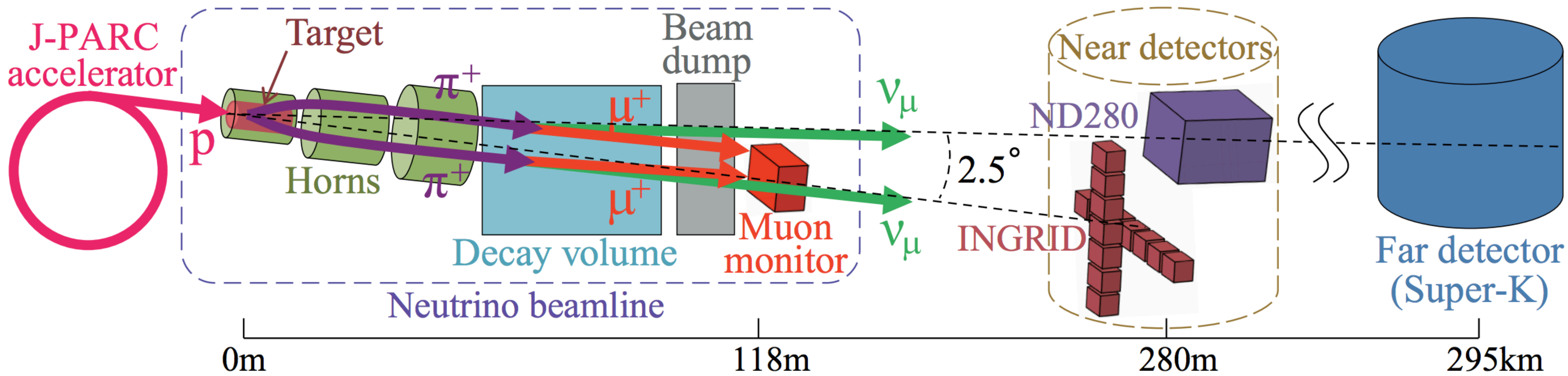


Atmospheric vs. T2K Beam Neutrino Flux

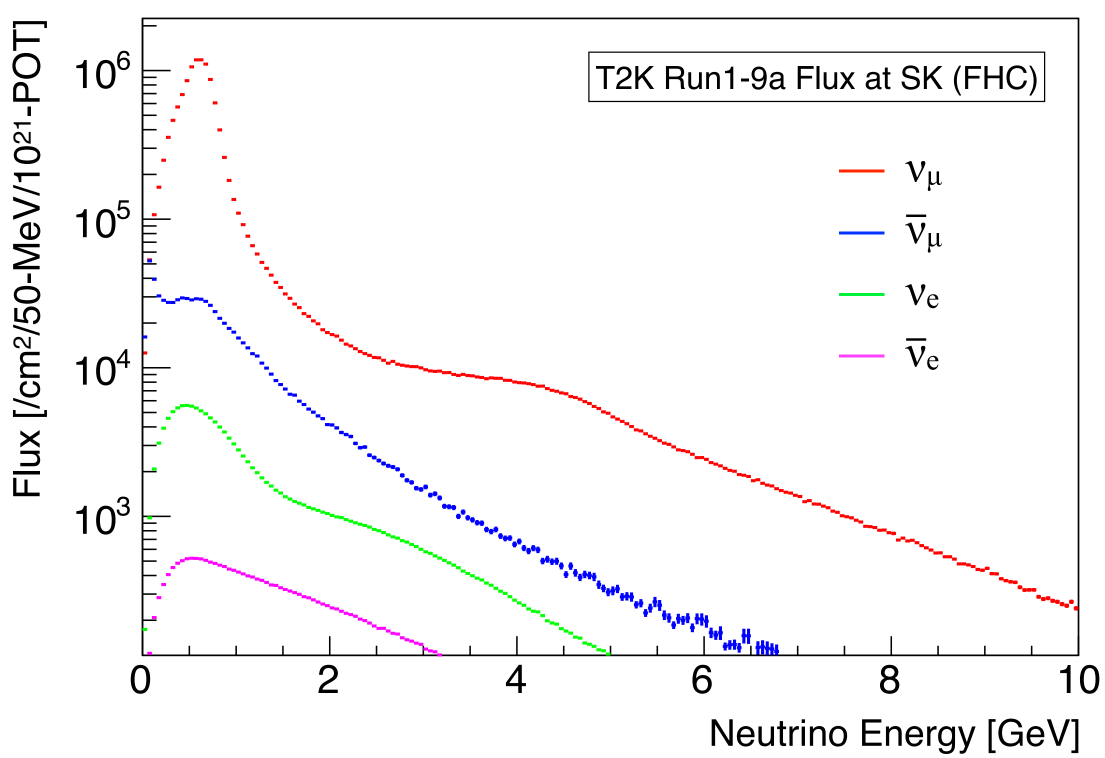


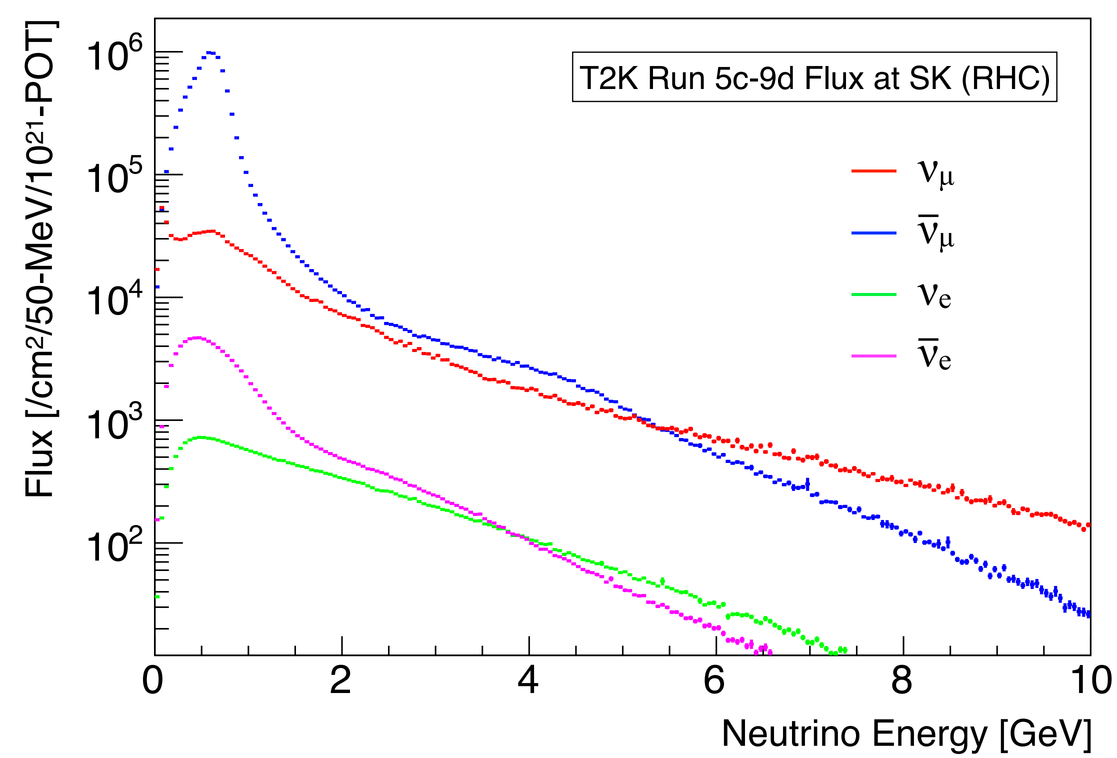


Neutrino Beam



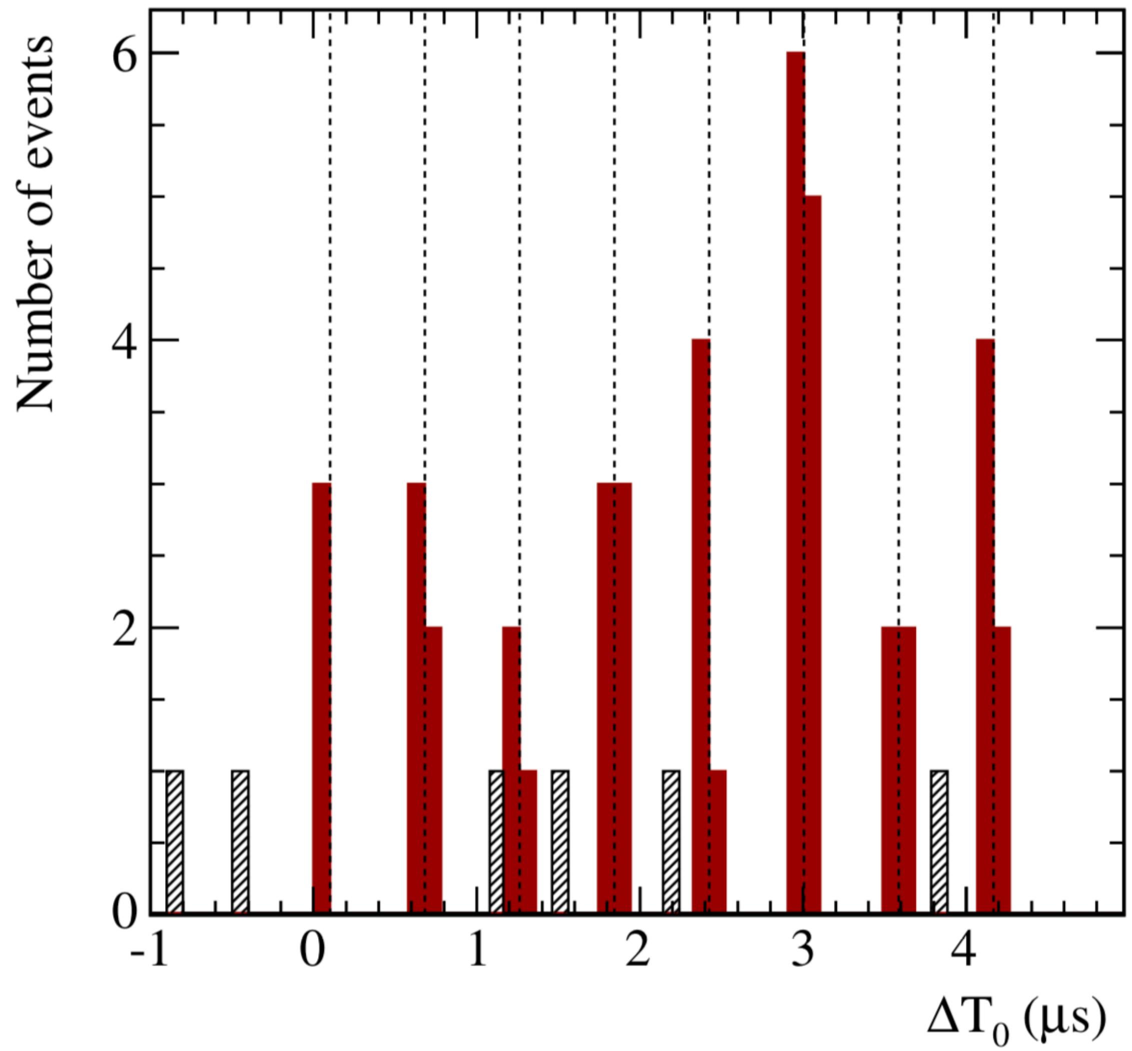
- Neutrino beam is simulated by FLUKA (hadronic interaction) + GEANT3 (transportation).
- **Hadron interaction cross section and kinematics are tuned by NA61/SHINE data.**



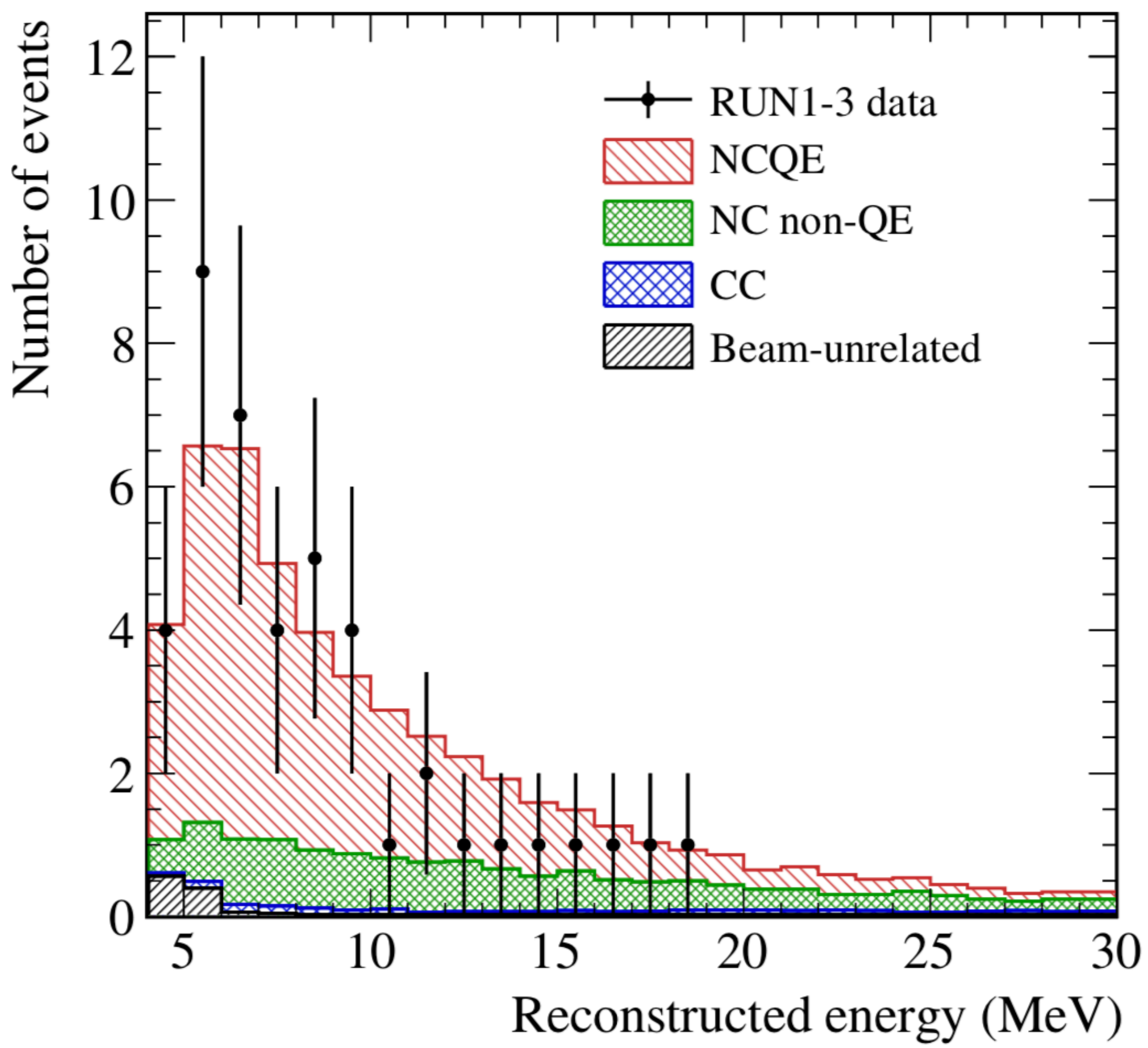


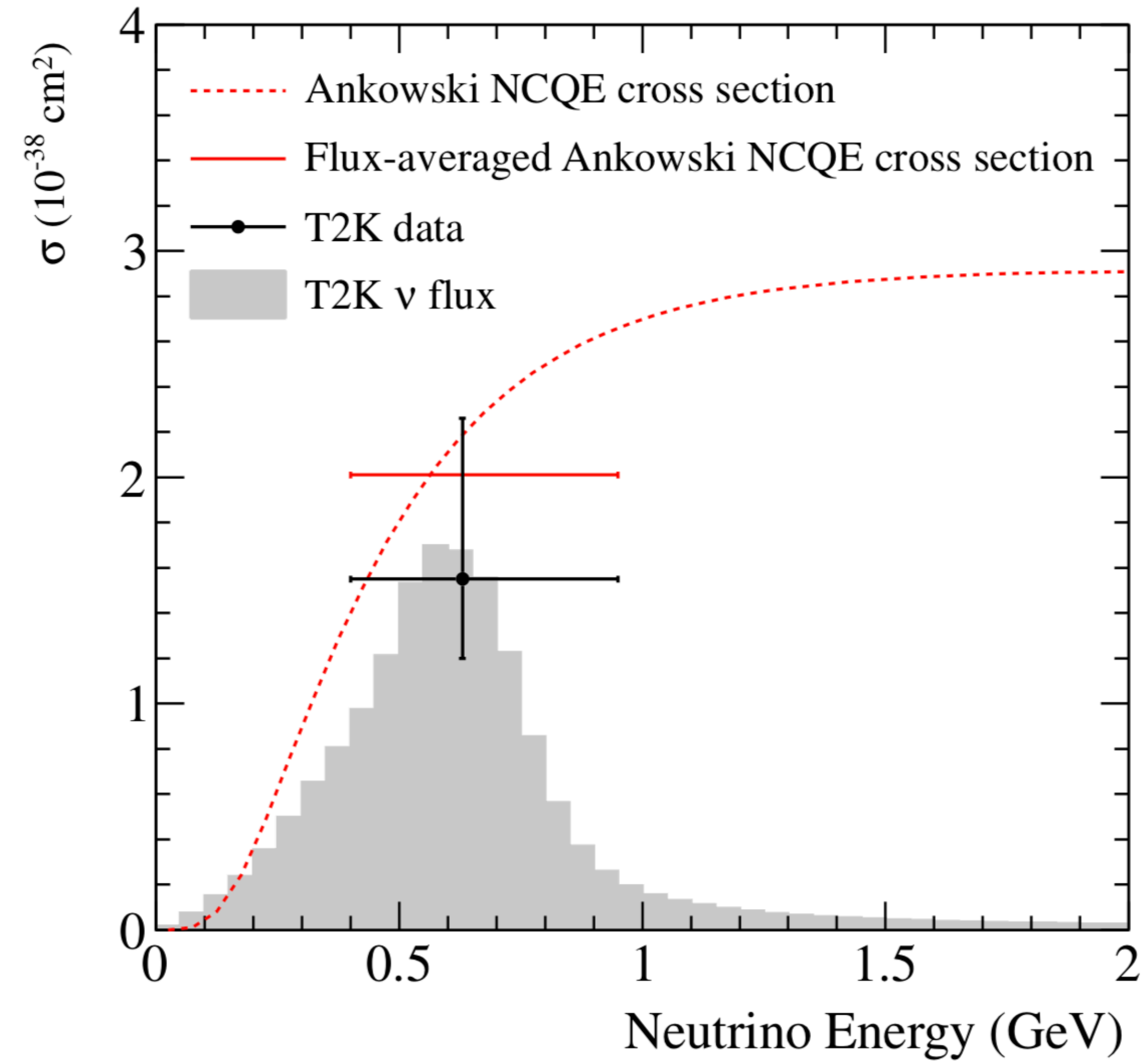
Measurement Method

- **By using beam timing information, large part of backgrounds can be removed.**
- **Energy threshold can be lower than the atmospheric case (7.5 MeV → 4 MeV).**
- Furthermore, cut parameters are optimized by using MC and off-timing data.
- In the final sample, **only 2% beam-unrelated events** are contaminated.



Cross Section Result

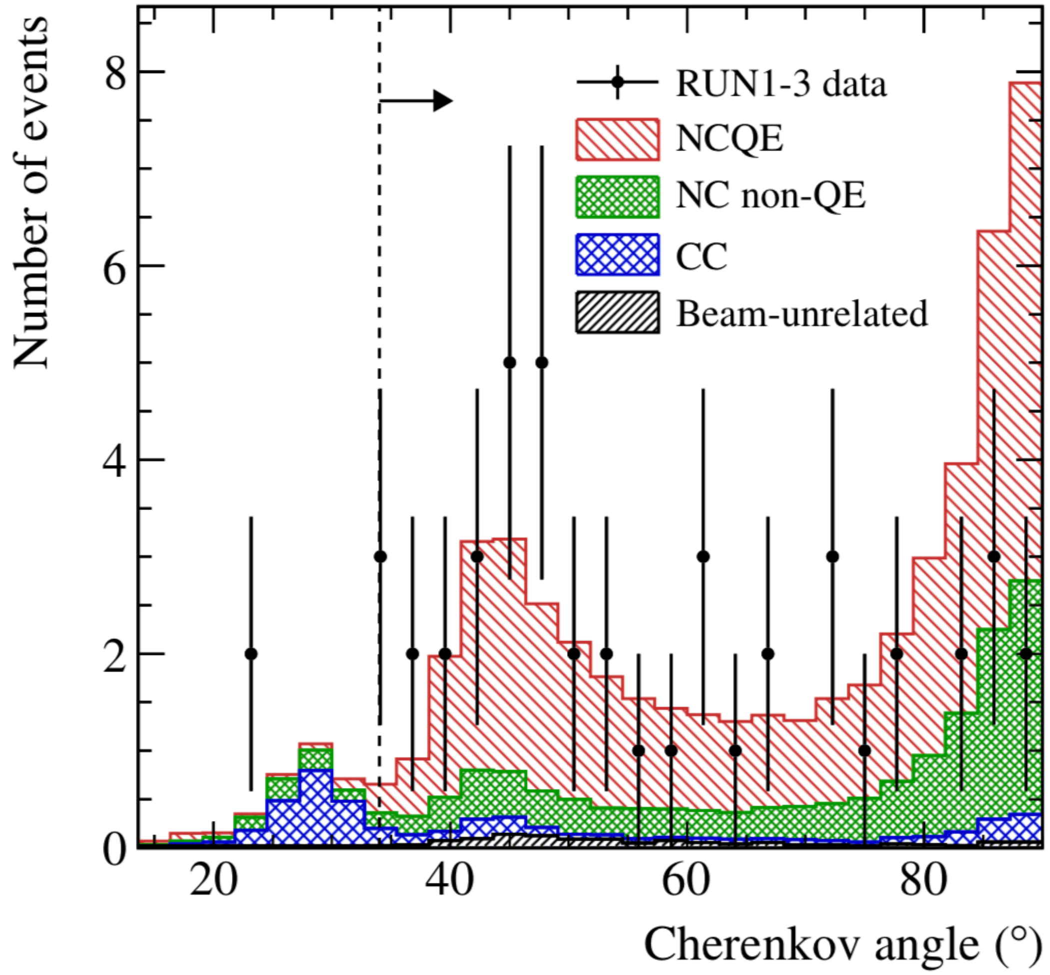




$$< \sigma^{obs}_{\nu,NCQE} >= 1.55 \pm 0.395(stat.)^{+0.65}_{-0.33}(sys.) \times 10^{-38} cm^2$$

Systematic Uncertainty

	Signal	Background		
	NCQE	NC non-QE	CC	Unrel.
Fraction of sample	68%	26%	4%	2%
Flux	11%	10%	12%	···
Cross sections	···	18%	24%	···
Primary γ production	15%	3%	9%	···
Secondary γ production	13%	13%	7.6%	···
Detector response	2.2%	2.2%	2.2%	···
Oscillation parameters	···	···	10%	···
Total systematic error	23%	25%	31%	0.8%



- Flux error is smaller than the atmospheric case.
- Large error on primary-γ production (mainly on *others* state because of no data).
- Second dominant is secondary-γ production. A gap is seen in large Cherenkov angle region.

Comments on T2K Measurement

- **Smaller background and well-known flux (→ better precision).**
- Larger statistics with an intense beam.
- Neutrino and antineutrino cross sections can be measured separately.

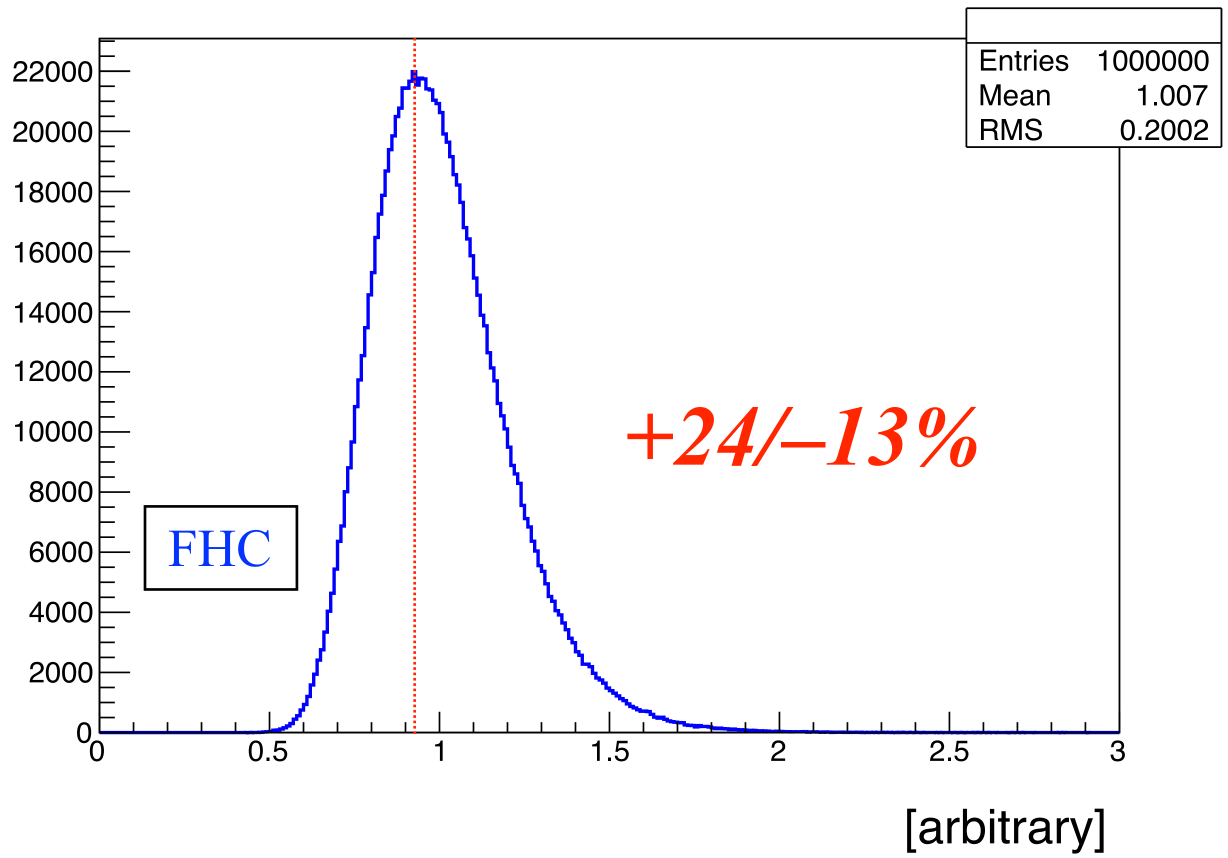
- No neutron tagging (as of now), then **different phase space is seen from SRN (?).**

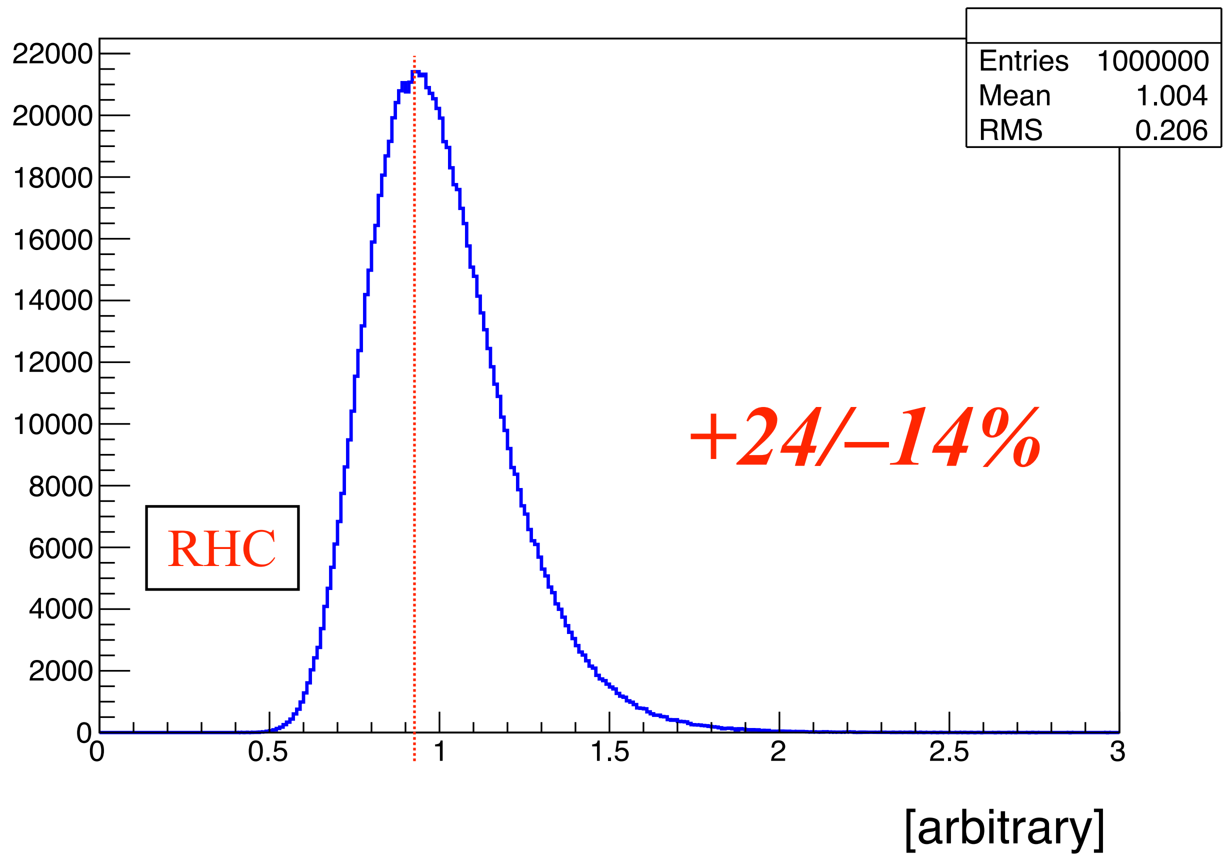
Updates On-going …

WORK-IN-PROGRESS

- Larger statistics (×5 for FHC) & additional RHC data.
- Reduced systematic error by referring to latest data (~60% of the previous result).
- By treating both data set simultaneously, the systematic error can be constrained.

Number of expected events (fraction)	All	nu NCQE	nubar NCQE	NCother	CC
T2K Run1-9 FHC	243.3	180.1 (74.0%)	4.9 (2.0%)	46.2 (19.0%)	12.1 (5.0%)
T2K Run1-9 RHC	95.7	18.3 (19.2%)	57.2 (59.8%)	17.1 (17.9%)	3.0 (3.1%)



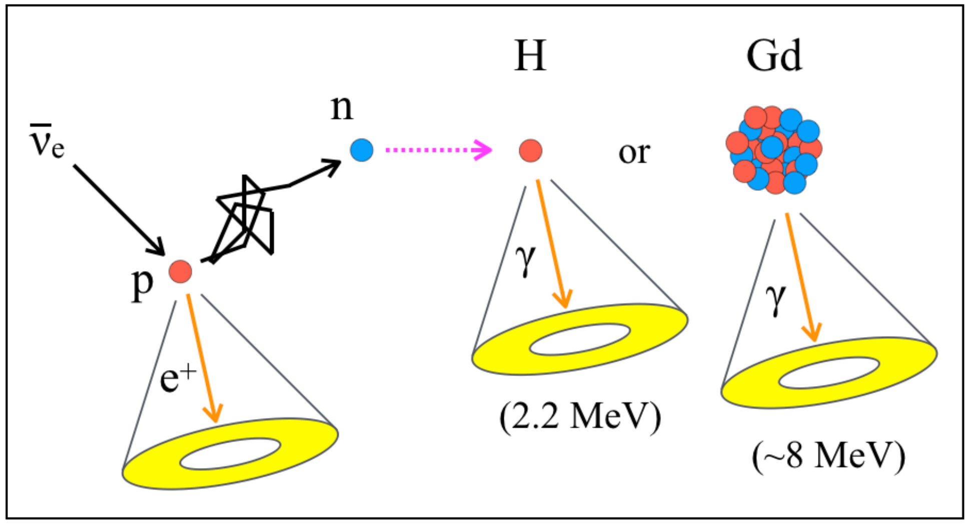


Summary

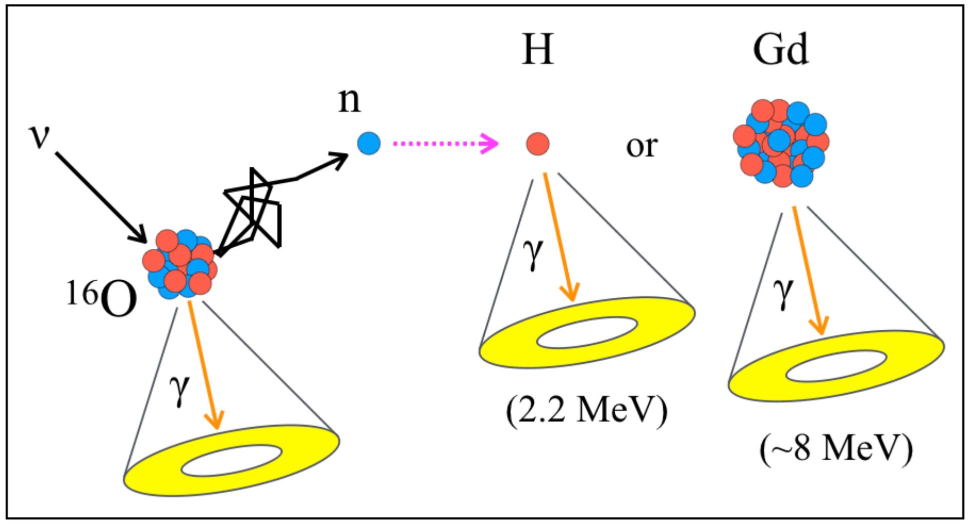
- Understanding of neutrino-oxygen NC elastic interaction is important especially in the phase of SK-Gd to improve SRN sensitivity.
- SK atmospheric neutrinos and T2K beam neutrinos can be used to measure such interaction.
- Results from both experiments and merit/demerit are shown.
- **T2K updated measurements will come very soon!**

- Possible updates;
  - Error reduction by RCNP measurements (Next talk)
  - Neutron tagging analysis
  - Separation between NC and IBD in vertex difference in the phase of SK-Gd (?)

Supernova relic neutrino (IBD)



Atmospheric neutrino (NC elastic)



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