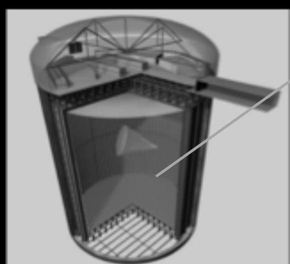
Future Oscillation Studies at Super-Kamiokande with Natural Sources



Roger Wendell
Kyoto University
2nd Snowmass NF01 Workshop
2020.09.11

Introduction :

- Super-K has been studying atmospheric and solar neutrino oscillations for more than 20 years

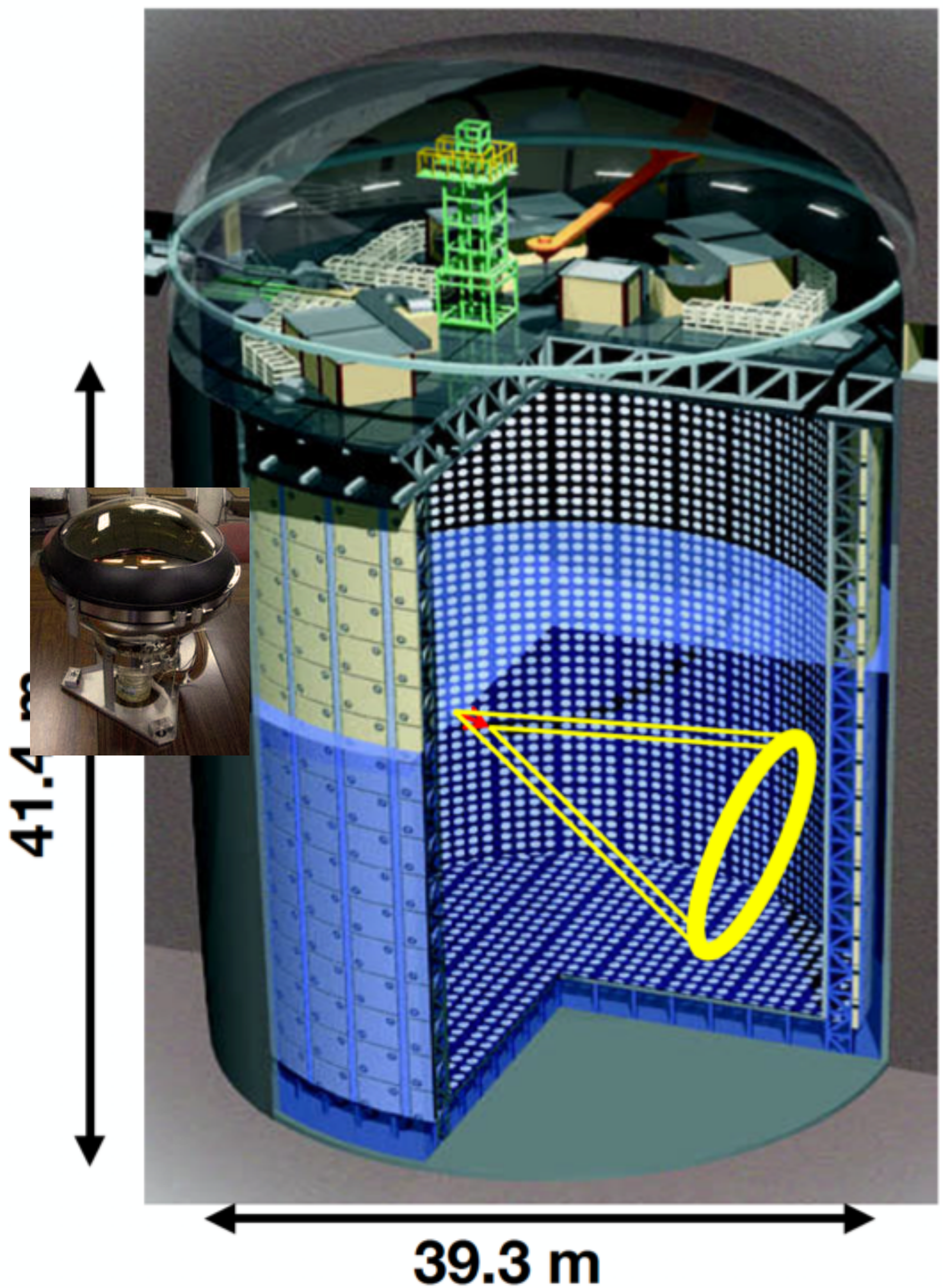
- … Statistical uncertainties are still dominant for the many interesting analyses

- Herein discuss briefly the latest results and expectations for the future, highlighting some challenges

- N.B. no discussion of accelerator neutrinos, please see T2K and Hyper-K talks in this series

- Content
  - Solar neutrino oscillations – present and future
  - Atmospheric neutrino oscillations – present and future
  - Summary

Super-Kamiokande: Introduction

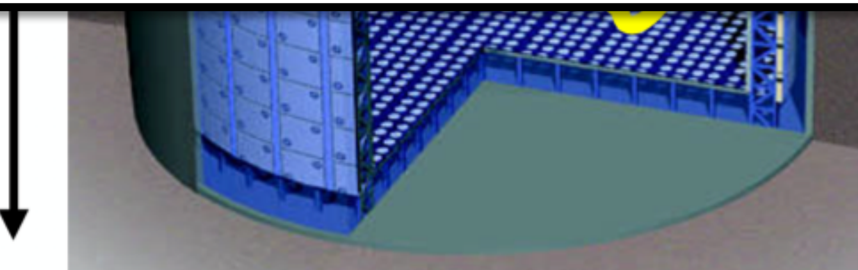


- 50 ktons, 22.5^{+} kton fiducial volume
- Optically separated into
  - Inner Detector 11,146 20” PMTs
  - Outer Detector 1885 8” PMTs

- No net electric or magnetic fields
- Excellent PID between showering (e-like) and non-showering (μ-like)
  - < 1% MIS ID at 1 GeV

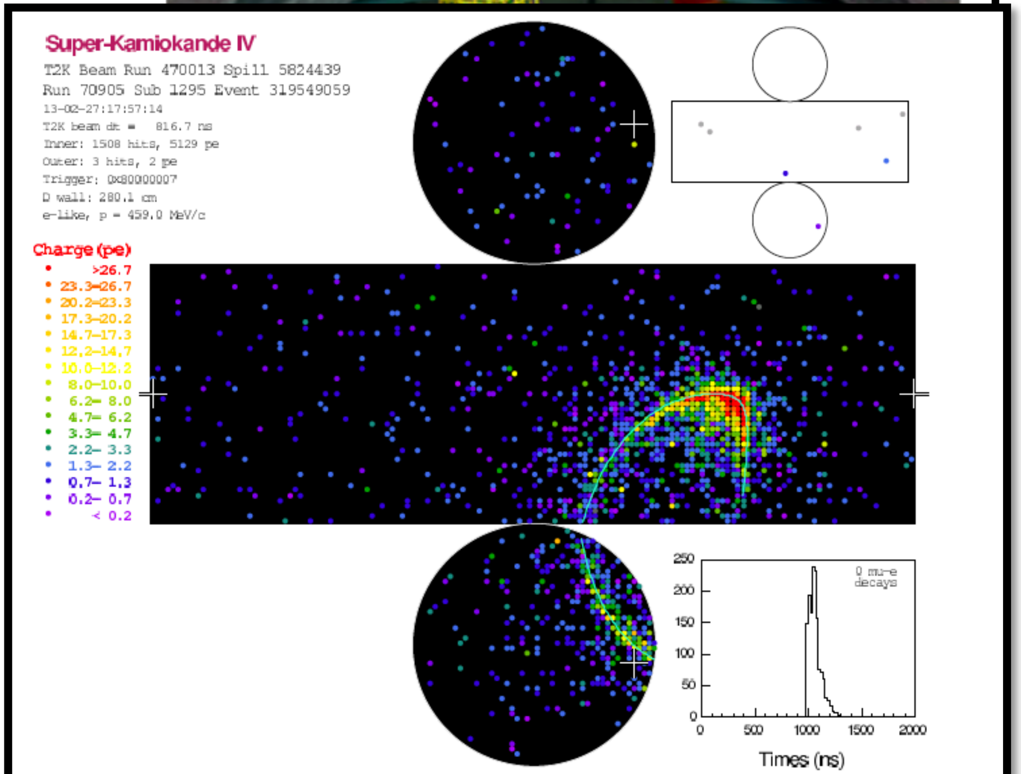
- Multipurpose detector
  - Solar Neutrinos (this talk)
  - Atmospheric Neutrinos (this talk)
  - Nucleon Decay Searches
  - T2K beam neutrinos
  - Supernova neutrinos
  - Indirect dark matter, GW coincidence,
  - …

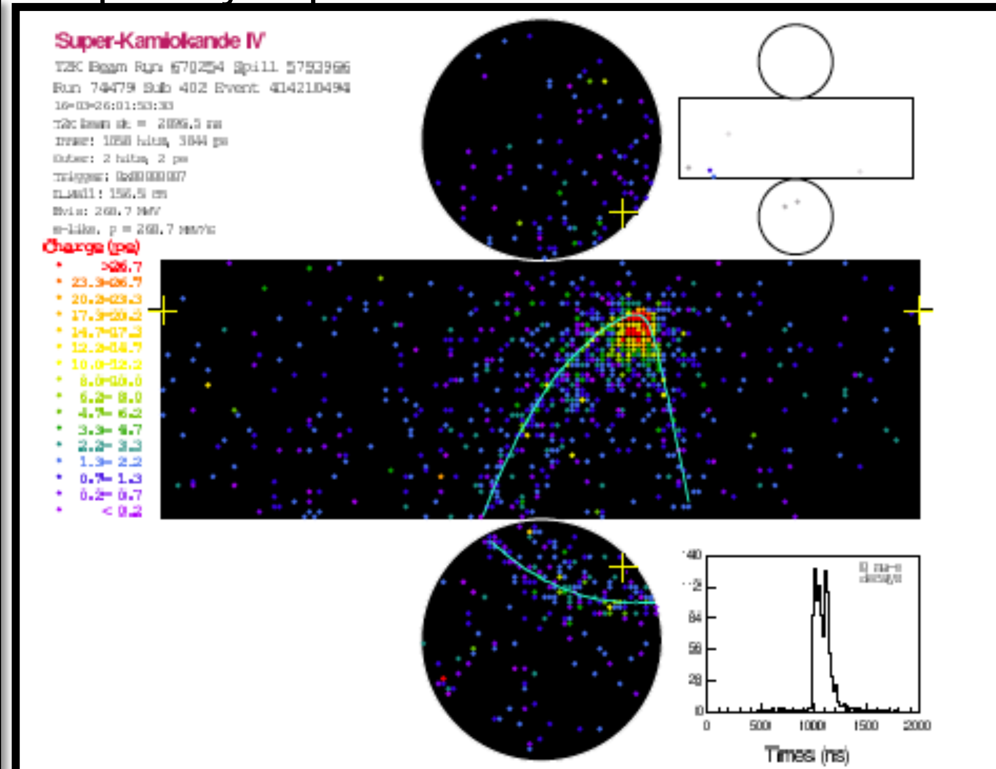
Super-Kamiokande: Introduction



39.3 m

Neutrino, Antineutrino?





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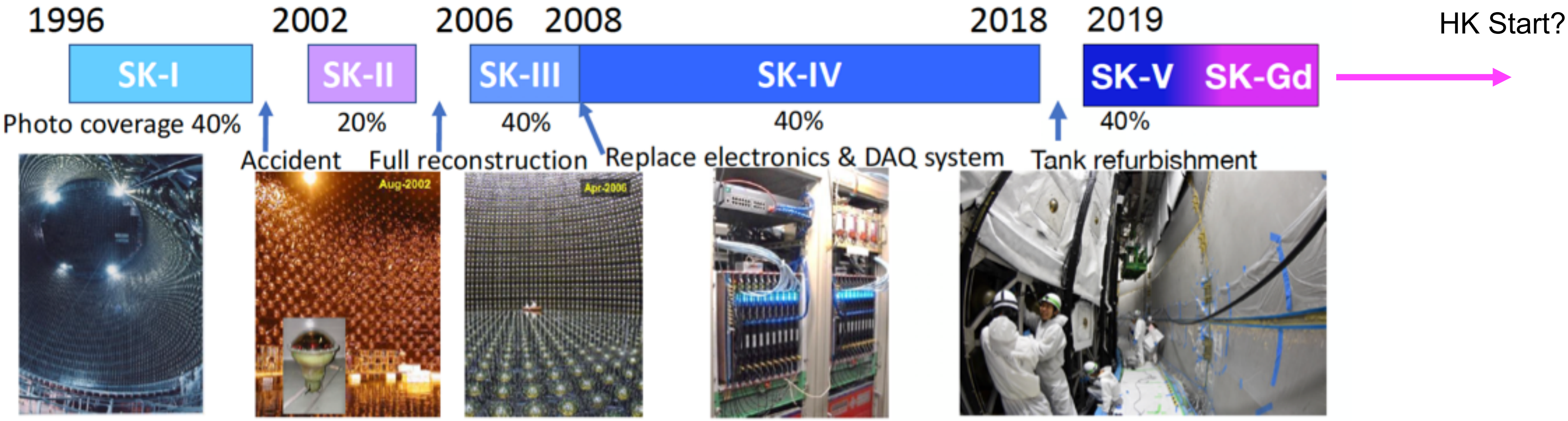
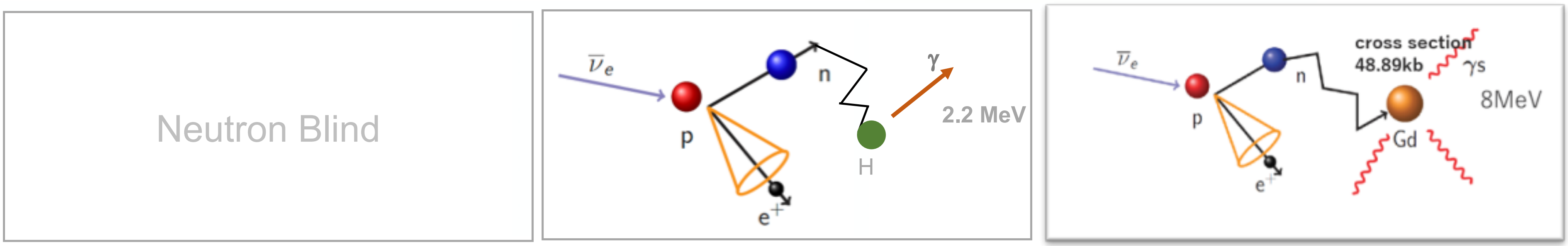
Optically separated into

- T2K beam neutrinos
- Supernova neutrinos
- Indirect dark matter, GW coincidence,
- …





- Running since 1996 , but many analyses remain statistics limited

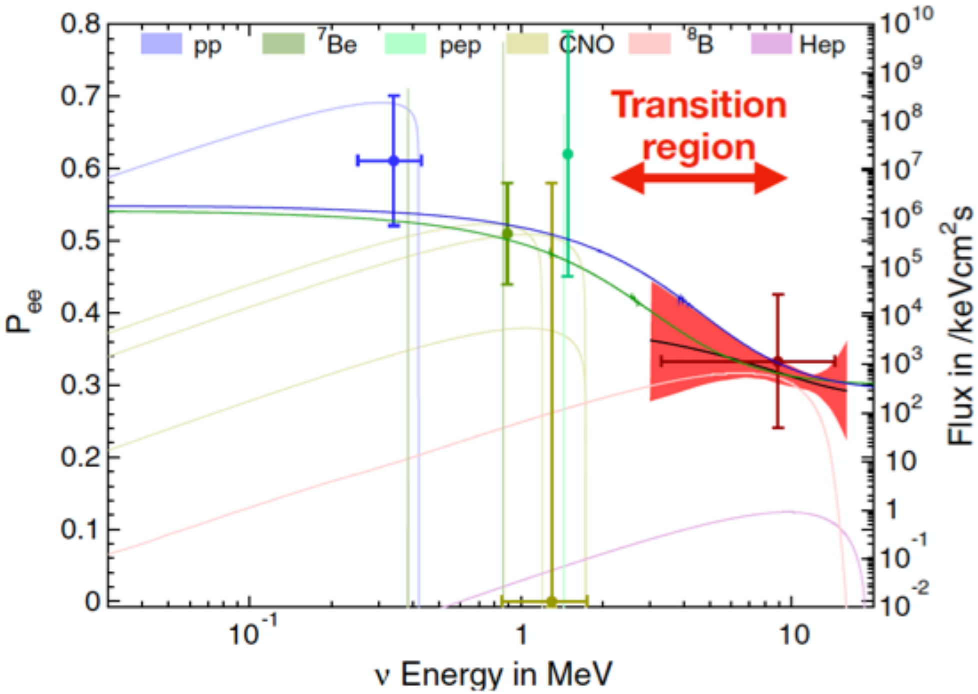
- During SK-IV and SK-V periods, neutron captures on hydrogen visible (~25% eff.)
- During SK-Gd period, neutron captures on Gd are dominant
  - Currently commissioning with 0.01% concentration allows for **50% capture eff**.
  - Goal is 0.1% concentration for **90% capture eff.**
- Separation of neutrino and antineutrino interactions …

Solar Neutrinos

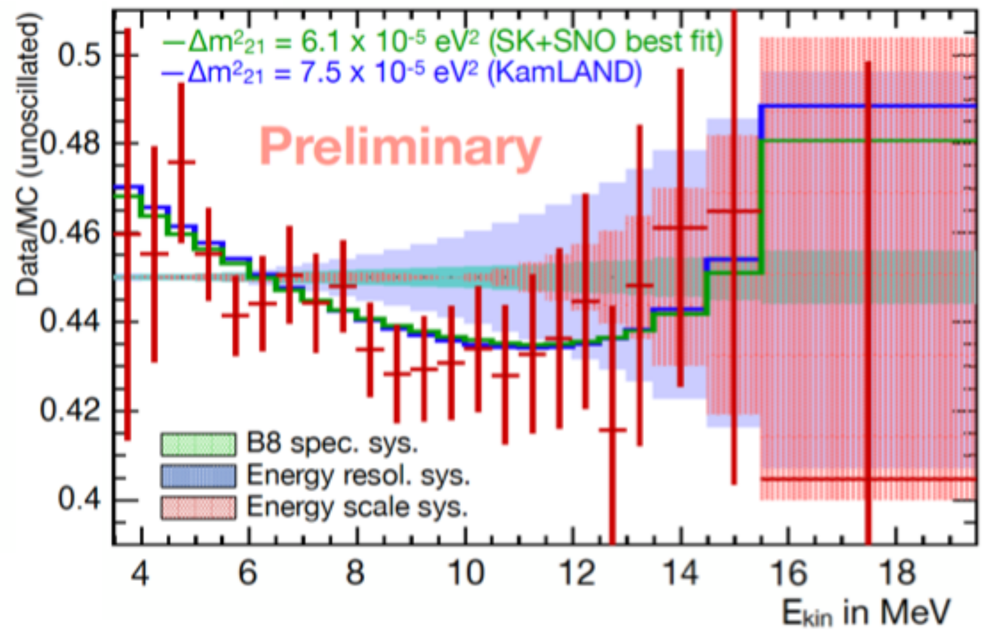
Solar Oscillations: Present

- Solar neutrino oscillations focused on precision measurements of MSW oscillation model
  - Low energy "upturn"
  - Day-night regeneration of νe flux in Earth

- Threshold $E_{kin} > 3.5$ MeV
  - (SK-IV) Disfavors no-upturn at 1-σ
  - 2.9σ preference for day-night asymmetry (All data 2016)

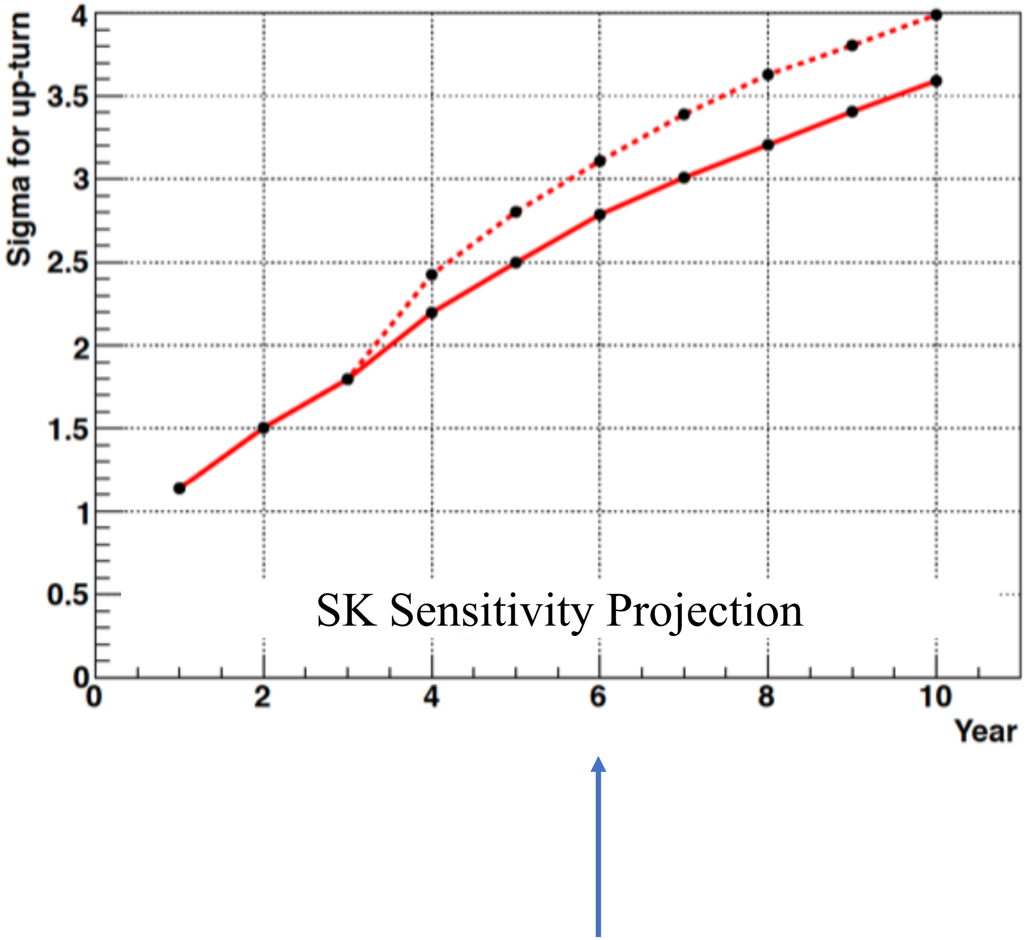


Energy spectrum fit (SK-IV)



$$A_{DN}^{fit,SK} = (-3.3 \pm 1.0(\text{stat}) \pm 0.5(\text{syst}))\%$$

Solar Oscillations: Future Sensitivity

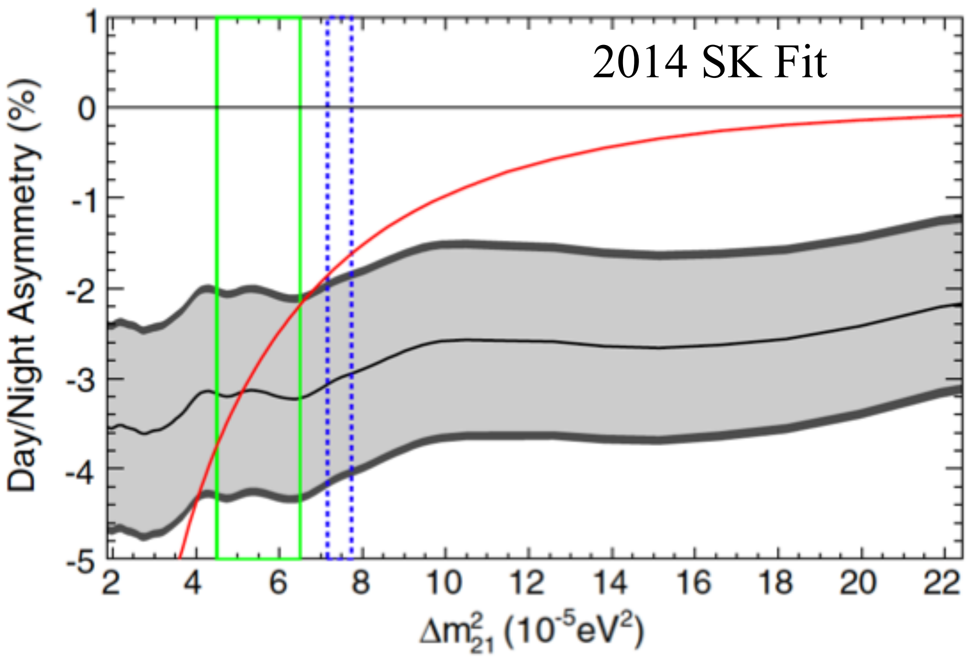


- <u>Assuming</u>
- Years 0-3
  - Same as SK-IV
  - 3.5 – 4.5 MeV : 8.8 kton
  - 4.5 - 5.0 MeV : 13.3 kton
- Years 3+
  - BG rate below 5.0 MeV cut 50%
  - 3.5 – 5.0 MeV : 22.5 kton
  - Energy correlated error reduced by 50% (dashed)
- Day-night : (very roughly) ~$3^{+}\sigma$ around 2026, depending upon value of Dm^2_{12}

Calculation from 2015, so we are already at year 6 in this plot

Solar Oscillations: Future Sensitivity

$$A_{DN}^{\text{fit,SK}} = (-3.3 \pm 1.0(\text{stat}) \pm 0.5(\text{syst}))\%.$$



JUNO?
Expect <1% measurement

- Assuming
- Years 0-3
  - Same as SK-IV
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  - 4.5 - 5.0 MeV : 13.3 kton
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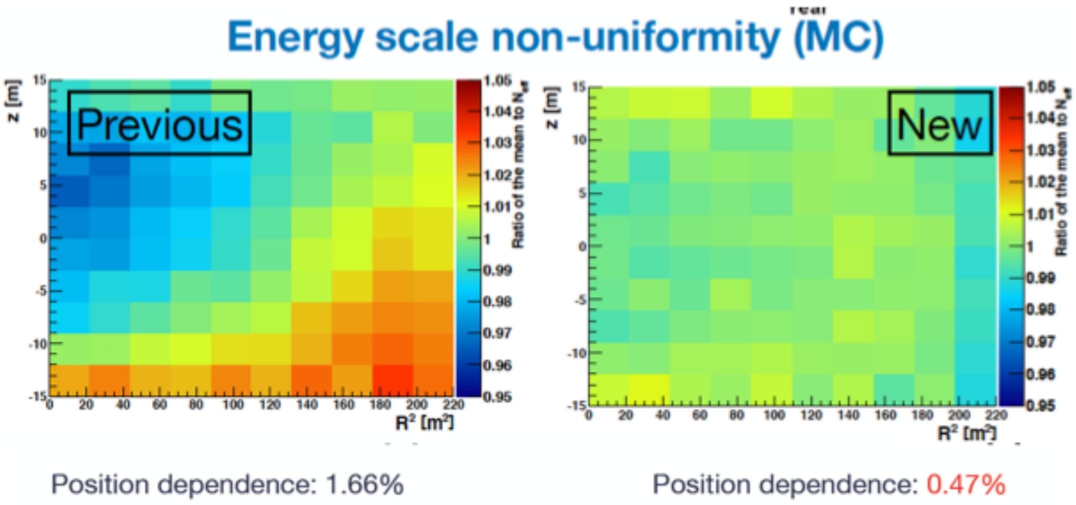
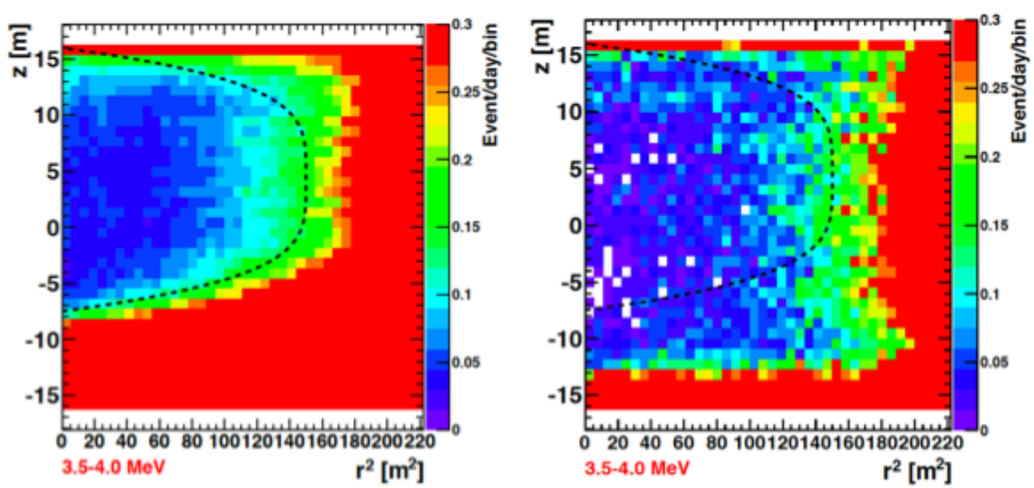
Solar Oscillations: Challenges



- Understanding of the energy scale and related systematic uncertainties important for solar upturn
- Reconstruction biases and relate uncertainties important for day-night asymmetry

Event Rate



SK-IV

SK-V

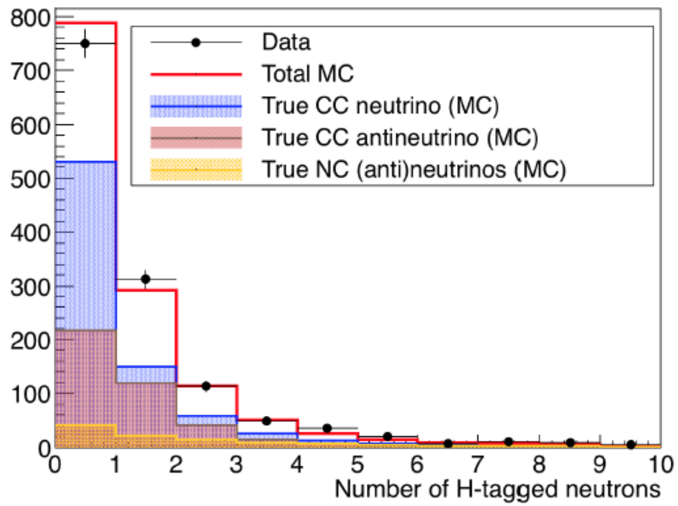
- Low energies incur larger backgrounds (Rn), so desire:
  - Clean detector materials
  - Improved understanding of
    - water transport in the detector
  - Control of spallation backgrounds
- Maintain water quality and BGs in the event of a dissolved solvent (Gd, WBLs)…

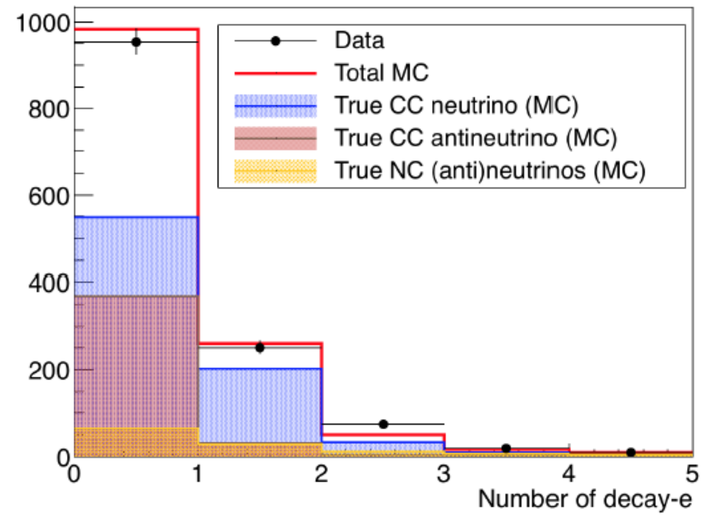
Atmospheric Neutrinos

Atmospheric Oscillations: Present

- Atmospheric oscillations: mass ordeing, θ_{23} octant, and δ_{CP} , exotic oscillations
- Most of these improve with neutrino/antineutrino separation
  - Directly below 1 GeV (δ_{CP})
  - Matter resonance 2~10 GeV (MO)
- Now using neutron information for this purpose

Single-Ring Multi-GeV e-like Cut Variables :

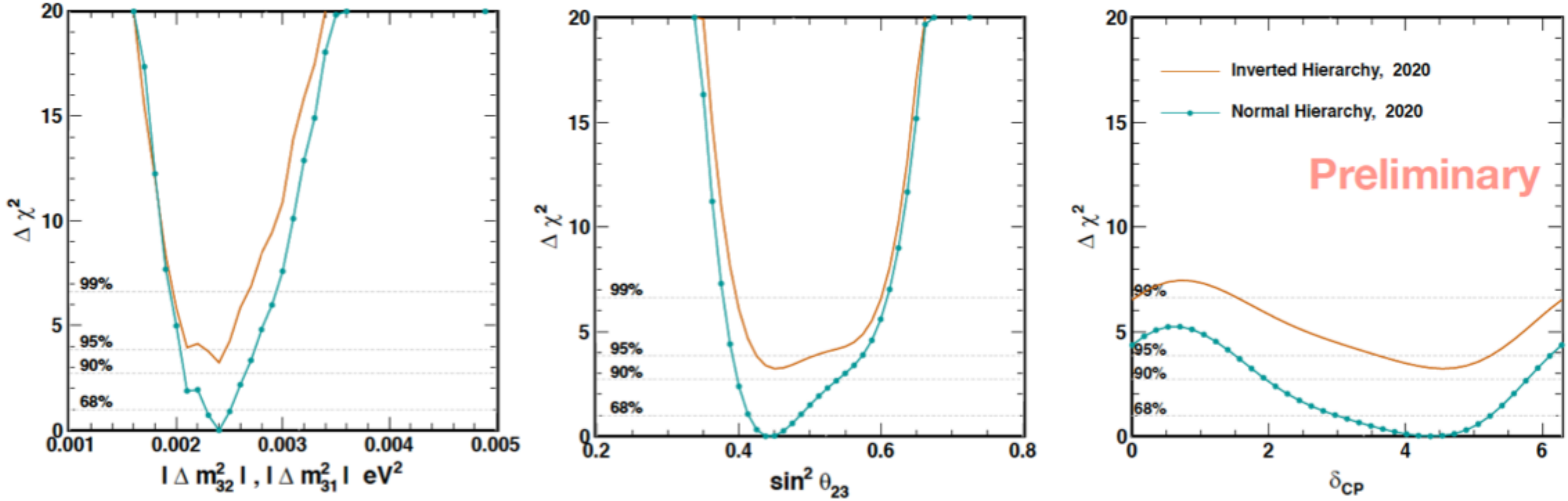




25% tagging eff.

Sample	nue	nuebar	numu (tot)	Tau (tot)	NC
2018 nu-like	0.604	0.088	0.100	0.033	0.156
2018 nubar-like	0.546	0.372	0.009	0.010	0.063
2020 nu-like	0.592	0.086	0.110	0.033	0.159
2020 e-like	0.628	0.281	0.007	0.007	0.057
2020 nubar-like	0.423	0.460	0.010	0.014	0.077

Atmospheric Oscillations: Present

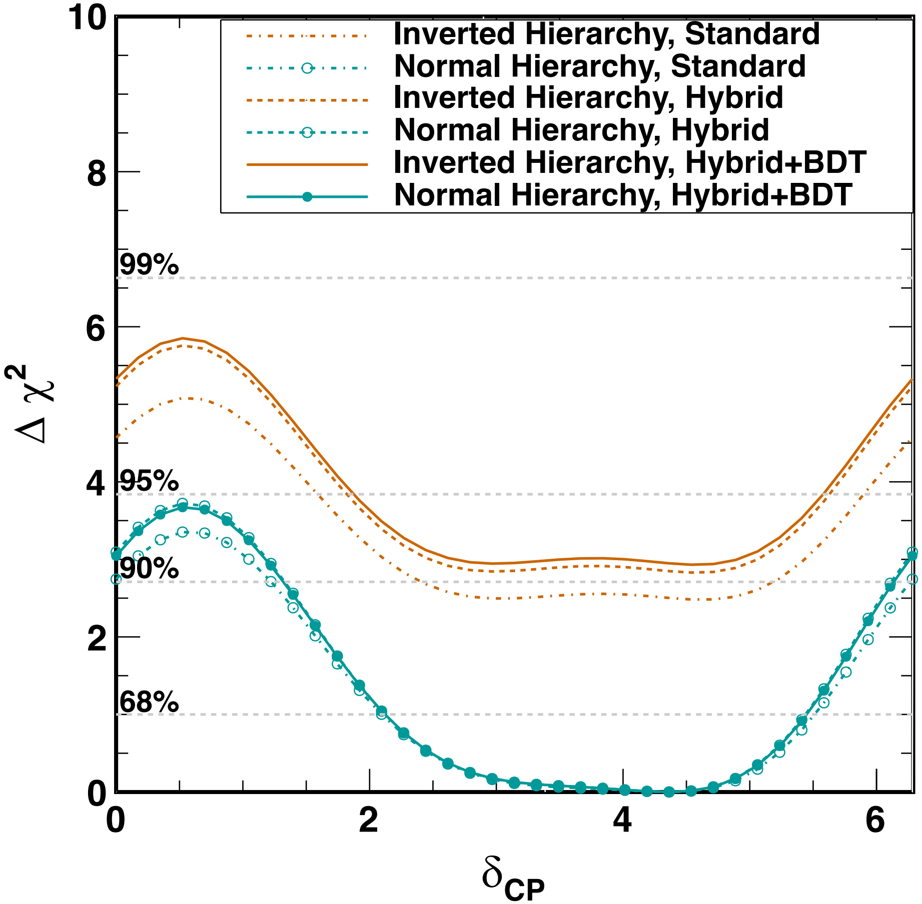


930 Bins	$\chi 2$	θ_{13}	δ_{cp}	θ_{23}	Δm_{23} ($x10^{-3}$)
SK (NH)	**1037.5**	0.0218	$4.36^{+0.88}_{-1.39}$	$0.44^{+0.05}_{-0.02}$	$2.40^{+0.11}_{-0.12}$
SK (IH)	**1040.7**	0.0218	$4.54^{+0.88}_{-1.32}$	$0.45^{+0.09}_{-0.03}$	$2.40^{+0.09}_{-0.32}$

SK data disfavors Inverted Hierarchy at 71.4-90.3% CL_s (was 81.9-96.1% in 2018)

Also prefers: 1st θ_{23} octant and $\delta_{CP}\sim 3/2\pi$

Atmospheric Oscillations: Challenges



Sensitivity

Reduce NC and numu backgrounds

2020 Neutrons + Multi-ring Lilkehood

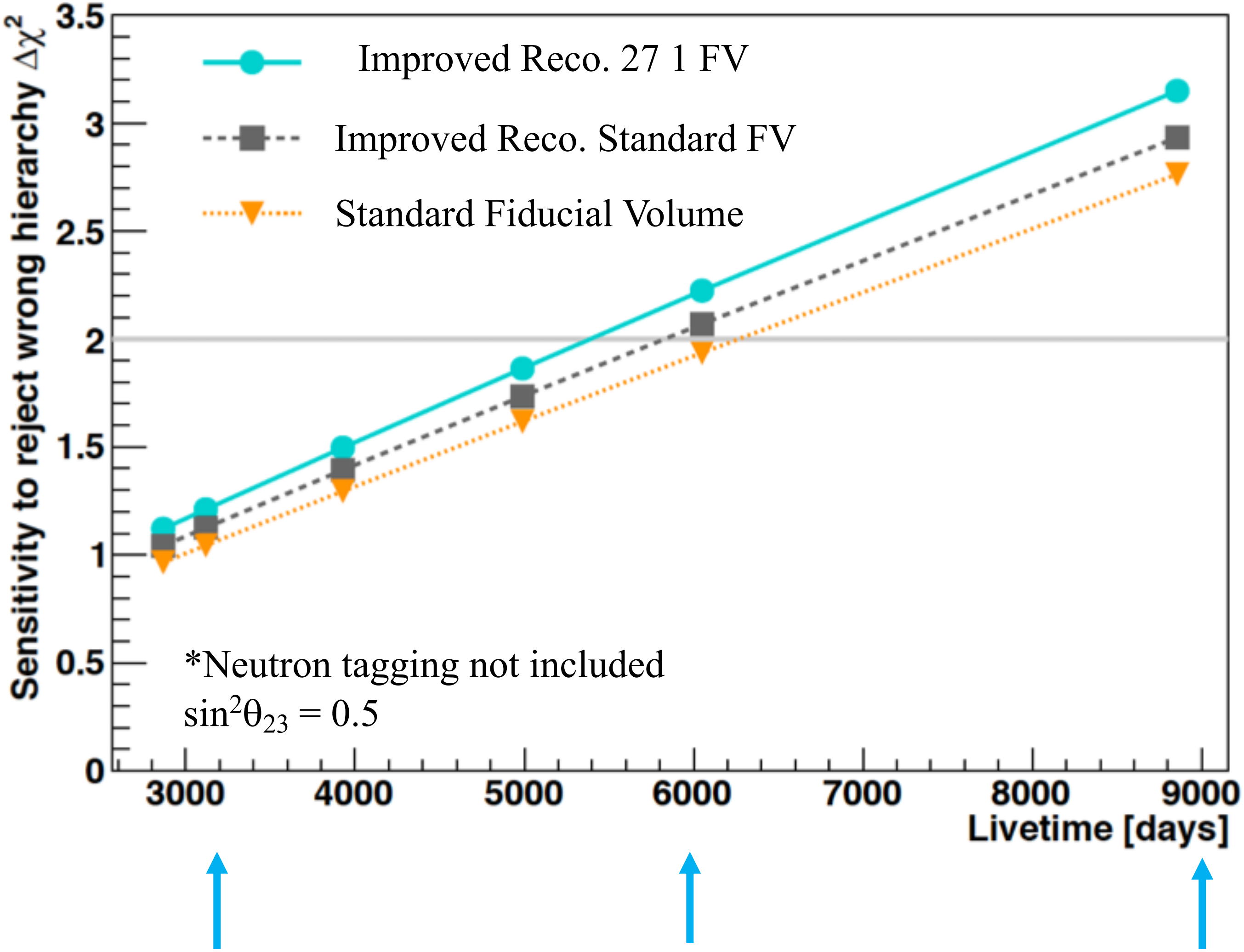
Add Neutron Tagging (single-ring)

2018 Event Selection

- Current event selection is quite simple: binary
  - Tagging efficiency of 25% improves MH sensitivity by about 20%
  - Increasing the efficiency to 70% improves sensitivity by about 30%
- **Perfect separation** would yield **3σ** sensitivity with current statistics and systematics
  - → Use more of neutron shape information? Multi-ring? Other kinematic variables?

Summary

Atmospheric Oscillations: Future Sensitivity



SK-IV Data

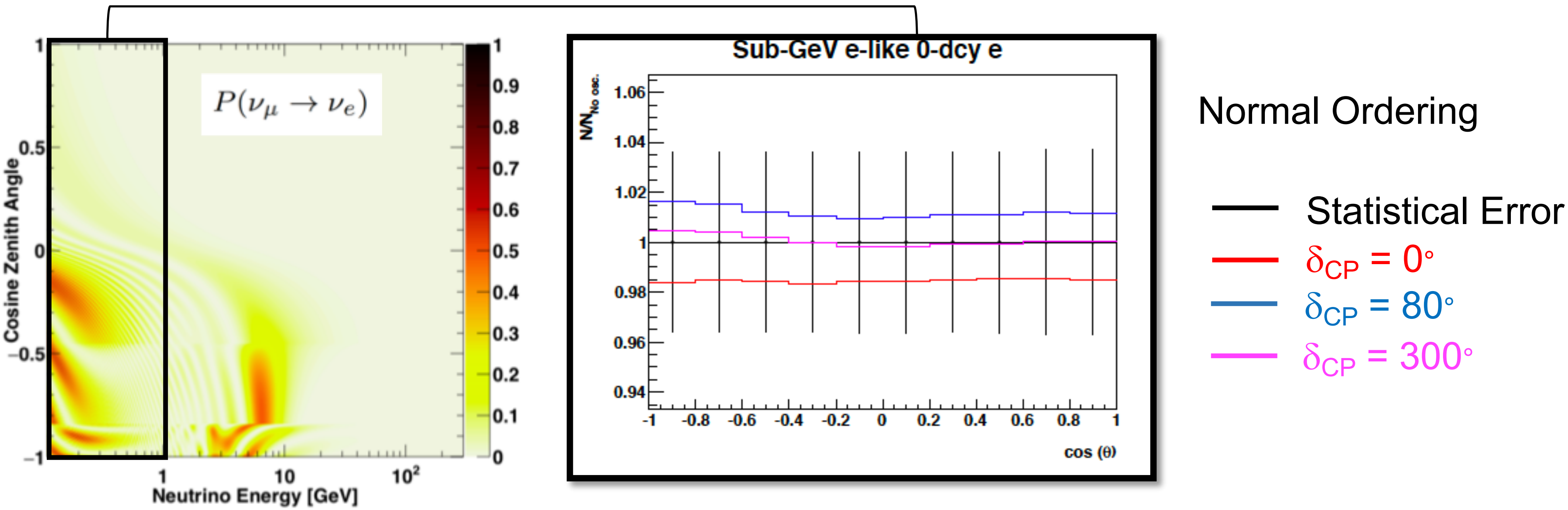
SK-I~IV Data

Projected Data Set by 2026

Expect another +20% sensitivity with neutron tagged analysis

- Median sensitivity will reach < 2σ by the time Hyper-K starts assuming $\sin^2\theta_{23}$ = 0.5, more (less) for larger (smaller) values

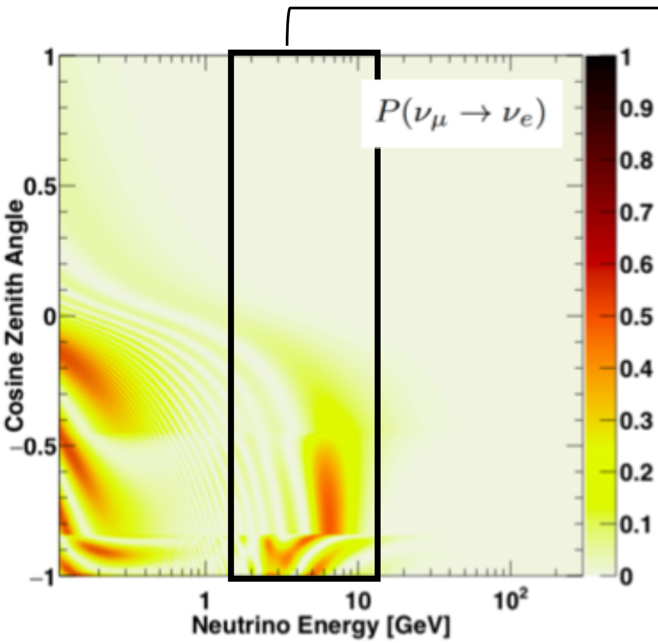
Atmospheric Oscillations: Challenges, CP Measurement

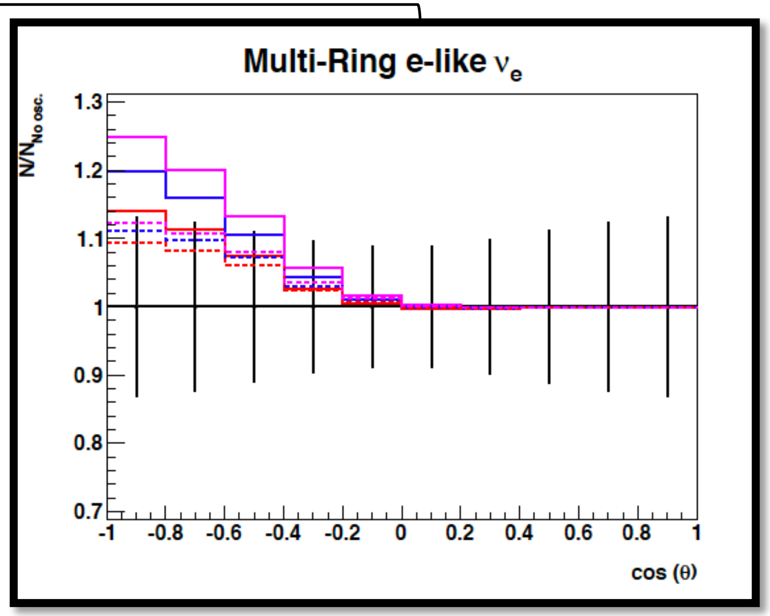


- CP precision limited by lack of direction information (mostly CCQE events)
  - Complementary (not competitive) with accelerators

  - Subject to flux systematic errors → requires better prediction
    - Neutrino/Antineutrino ratios below 1 GeV (currently ~5-15%)
    - Muon/electron cross section ratio 2~10%
  - Neutron multiplicity distribution largely unknown…
    - Large ("conservative") systematic errors used at present, … external measurements
- Ideas for future mitigation
  - Neutrons for direction reconstruction?
  - Proton identification at higher energies?

Atmospheric Oscillations: Challenges, MH and Octant





Solid: Normal
Dash: Inverted

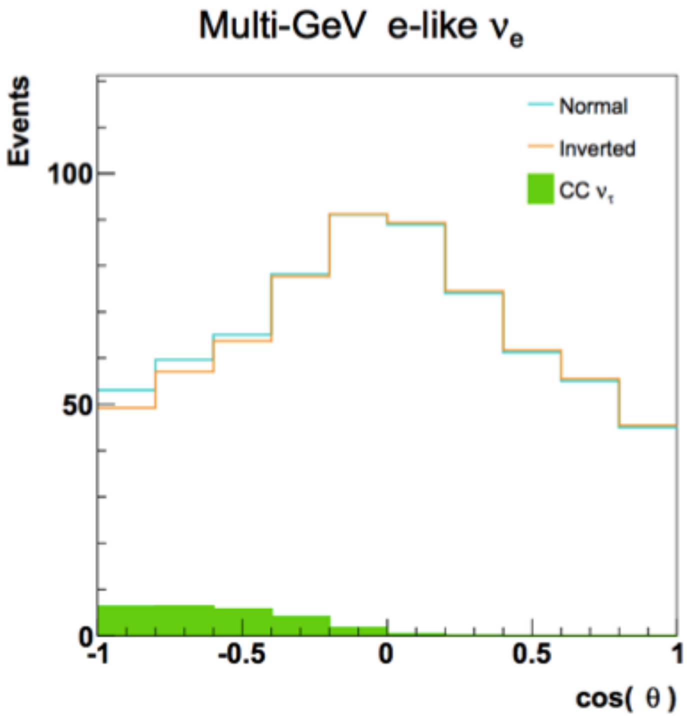
- Statistical Error
- $\sin^2\theta_{23} = 0.4$
- $\sin^2\theta_{23} = 0.5$
- $\sin^2\theta_{23} = 0.6$

- Following statements are true for both Mass Hierarchy and θ23 octant sensitivity

- Statistics are currently the largest uncertainty
  - → Use as many events and as much volume as possible
  - → Moving towards using every neutrino interaction in the detector within 27kton volume

- Oscillation uncertainties are the next largest, so sensitivity improves as
  - External constraints become stronger (T2K, NOvA)
  - Collaborative fits between experiments become realized (SK+T2K underway)
    - Roughly 2~3 σ sensitivity expected by 2026

Atmospheric Oscillations: Challenges and Tips, MH and Octant



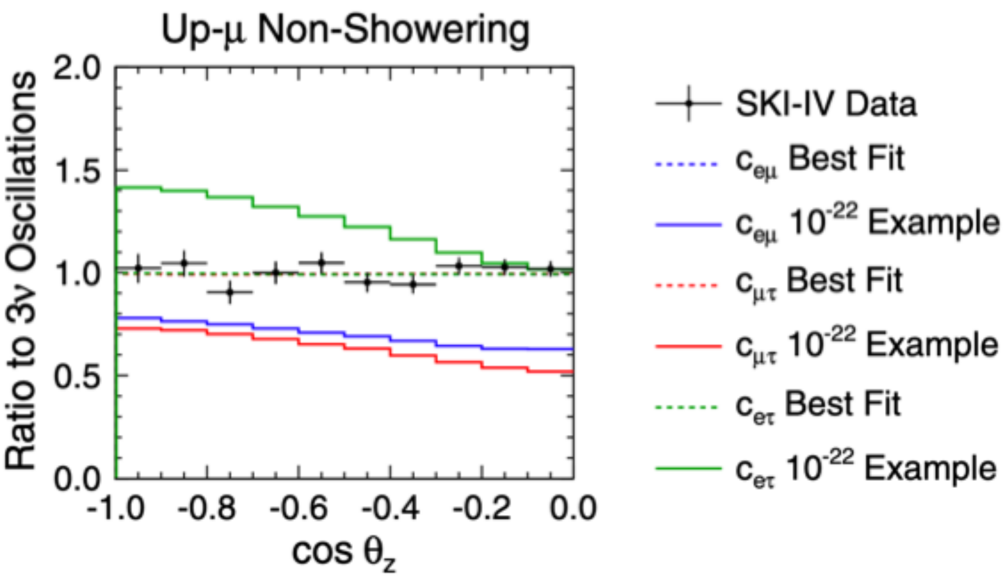
Sample	CC ν_e	CC $\bar{\nu}_e$	CC $\nu_\mu + \bar{\nu}_\mu$	CC ν_τ	NC
Multi-ring					
ν_e-like	0.588	0.117	0.054	0.036	0.204
$\bar{\nu}_e$-like	0.526	0.300	0.021	0.020	0.134
μ-like	0.010	0.001	0.959	0.004	0.026
Other	0.283	0.026	0.342	0.053	0.295

Remove these

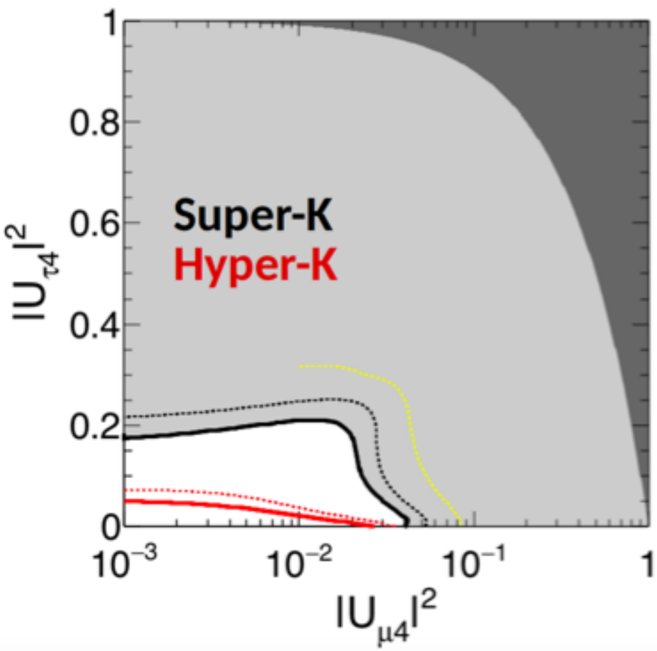
Recoverable?

- Other issues:
  - Uncertainty in tau neutrino cross section ~25% is next leading systematic
    - Mitigate with external measurements (e.g. SHiP, IceCube)
    - and/or constrain in-situ with edicated algorism (in progress)
  - CC and NC contamination of few GeV (multi-ring) samples
    - PID confusion in e-like signal samples next-next leading systematic
    - Mitigate with improved reconstruction methods, in progress

A word about *Exotic* Oscillation Scenarios



- Lorentz invariance-violating oscillation effects are strongest at high energies
- E > 30 GeV flux uncertainties and poor energy resolution limit sensitivity



- Sterile neutrino oscillation sensitivity limited by uncertainties in flux (and cross section) around 1 GeV
- Particularly $U_{\mu 4}$

Systematic uncertainty	No steriles (σ)	Best fit (σ)
$(\nu_\mu + \bar{\nu}_\mu)/(\nu_e + \bar{\nu}_e)$, < 1 GeV	−0.49	−0.13
$(\nu_\mu + \bar{\nu}_\mu)/(\nu_e + \bar{\nu}_e)$, 1–10 GeV	−0.50	−0.09
CCQE ν_μ/ν_e	0.36	0.01

Summary

- Solar neutrino oscillation studies aimed at observing upturn in the low energy part of spectrum
  - Currently 1σ rejection of no-upturn, expect between 3-4 sigma significance by 2026
  - Challenges: Maintain precise understanding of water quality, energy-related systematics, and reconstruction in an era of a Gd-loaded target

- Atmospheric oscillations are working towards MH, θ_{23} octant, and dCP
  - Weak (~1σ) preferences for all
  - Expect 2~3 sigma sensitivity by 2028, depending on true values of osc. parameters and constraints from other experiments
  - Challenges: Flux uncertainties, neutrino/anti-neutrino separation, and reconstruction of multi-particle final states

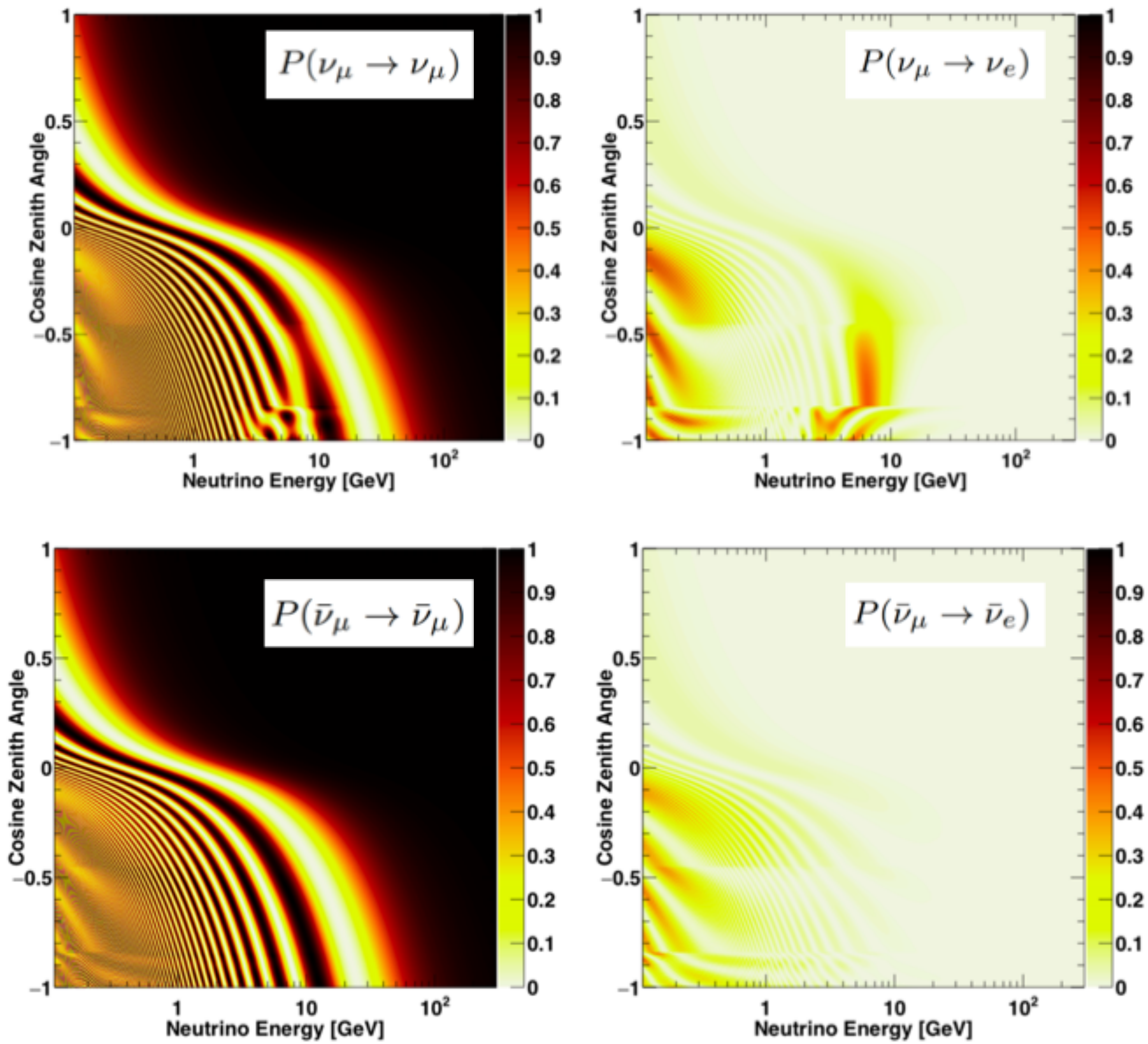
Supplements

The Super-Kamiokande Collaboration

~190 collaborators from 49 institutes in 10 countries

Kamioka Observatory, ICRR, Univ. of Tokyo, Japan
RCCN, ICRR, Univ. of Tokyo, Japan
University Autonoma Madrid, Spain
BC Institute of Technology, Canada
Boston University, USA
University of California, Irvine, USA
California State University, USA
Chonnam National University, Korea
Duke University, USA
Fukuoka Institute of Technology, Japan
Gifu University, Japan
GIST, Korea
University of Hawaii, USA
Imperial College London, UK
INFN Bari, Italy
INFN Napoli, Italy
INFN Padova, Italy
INFN Roma, Italy
Kavli IPMU, The Univ. of Tokyo, Japan
Keio University, Japan
KEK, Japan
King's College London, UK
Kobe University, Japan
Kyoto University, Japan
University of Liverpool, UK
LLR, Ecole polytechnique, France
Miyagi University of Education, Japan
ISEE, Nagoya University, Japan
NCBJ, Poland
Okayama University, Japan
University of Oxford, UK
Queen Mary University of London, UK
Rutherford Appleton Laboratory, UK
Seoul National University, Korea
University of Sheffield, UK
Shizuoka University of Welfare, Japan
Sungkyunkwan University, Korea
Stony Brook University, USA
Tokai University, Japan
The University of Tokyo, Japan
Tokyo Institute of Technology, Japan
Tokyo University of Science, japan
University of Toronto, Canada
TRIUMF, Canada
Tsinghua University, Korea
University of Warsaw, Poland
Warwick University, UK
The University of Winnipeg, Canada
Yokohama National University, Japan

Atmospheric Neutrino Oscillations :



- Plots assume the Normal Hierarchy
- Under the inverted hierarchy the neutrino and antineutrino plots reverse roles
  - Resonance effects in the antineutrino channels
- Size of matter effects depends on θ_{13}, θ_{23}, δ_{CP} (in order of importance)
- Mass hierarchy sensitivity:
  - 2 ~ 10 GeV
- CP sensitivity
  - Below 2 GeV , strongest effects (400~600 MeV)
- *Exotic* Scenarios
  - Lorentz-Invariance: > 5 GeV
  - Sterile Neutrinos > 1 GeV

Search for Tau Neutrinos at SK :

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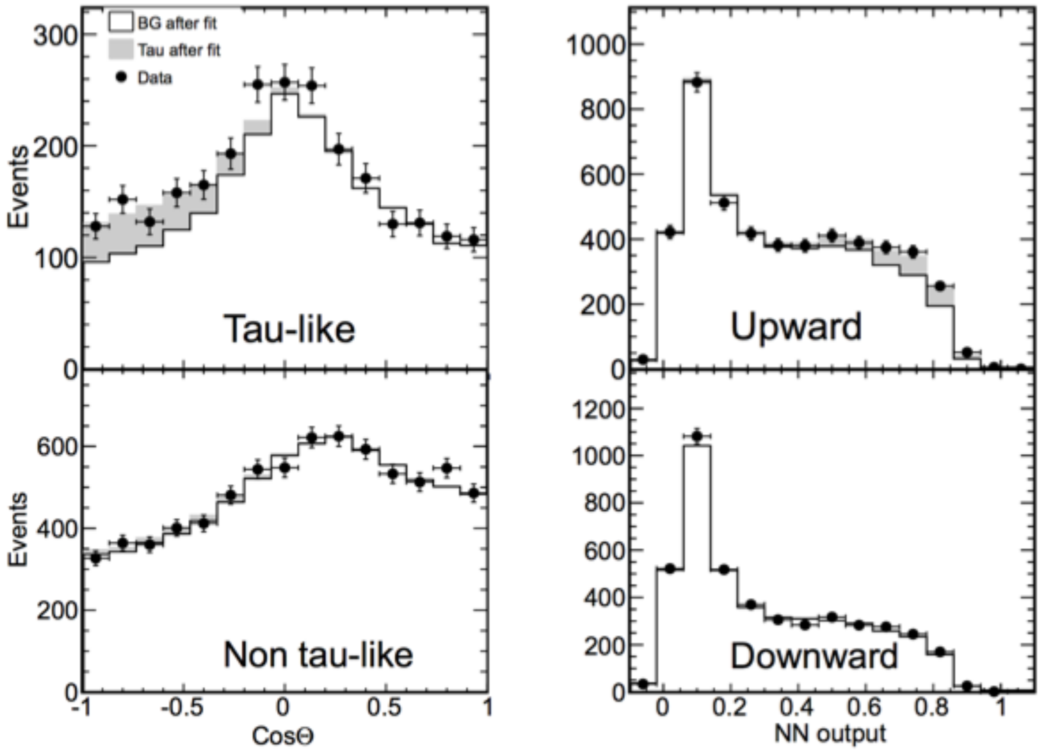

$$\text{Data} = \text{PDF}_{\text{BG}} + \alpha \times \text{PDF}_{\text{tau}} + \sum \epsilon_i \times \text{PDF}_i$$

α = 1.47 ± 0.32 (stat+syst)

4.6σ rejection of no τ appearance

- Fit 2-dimensional PDFs (cos θ, Neural Network), while simultaneously varying systematic error templates
- Uses 328 kton-yr exposure (SK-I ~ SK-IV)

Systematic Errors in Search for Tau Neutrinos

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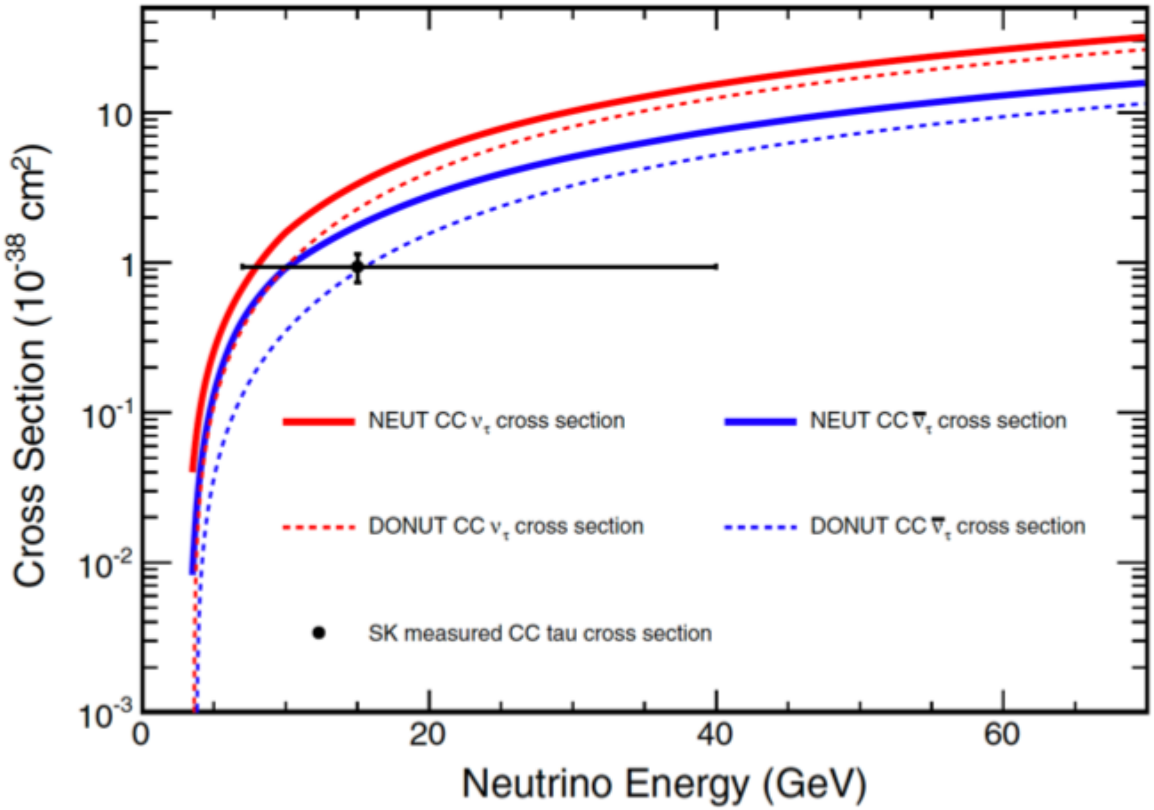
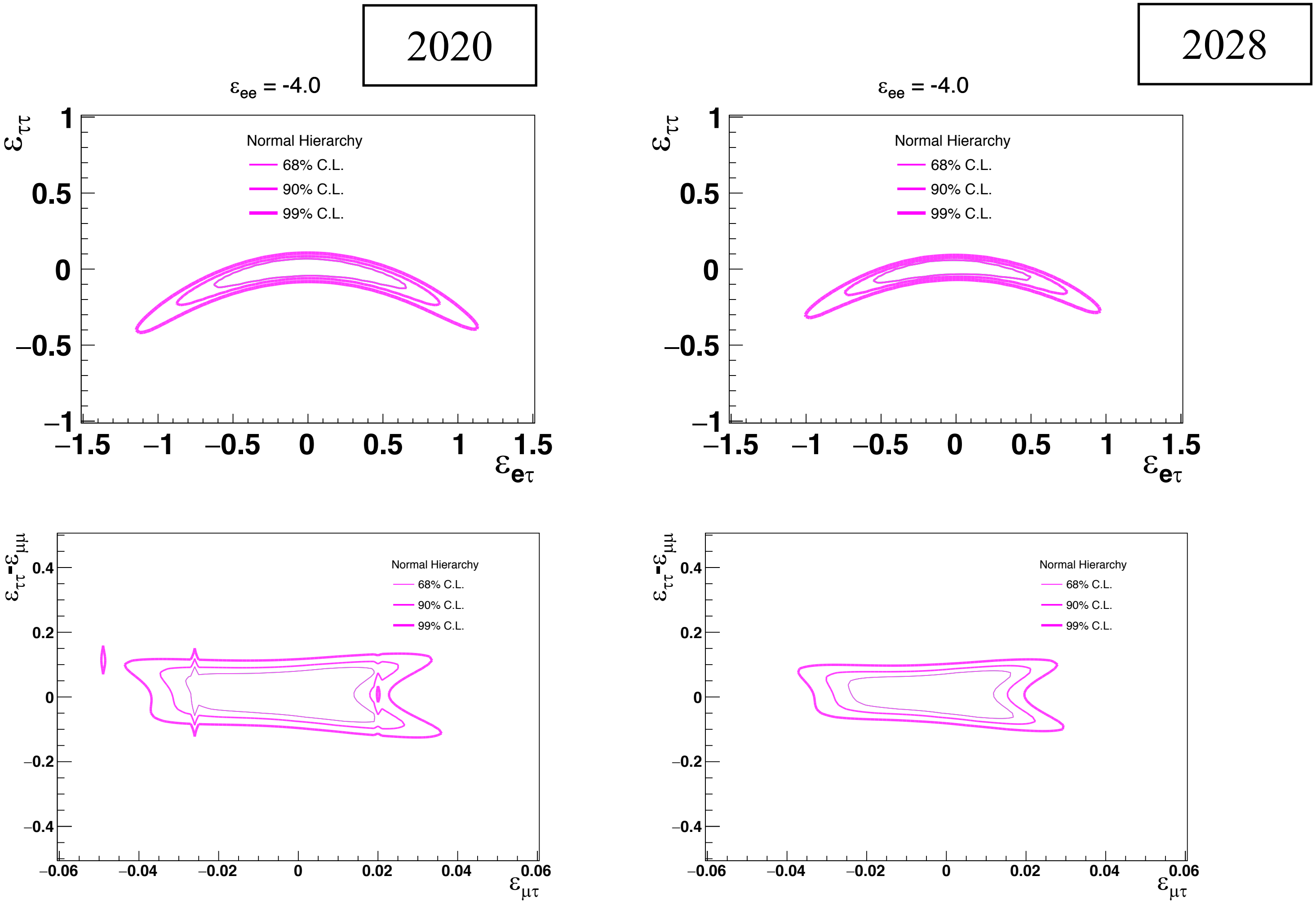


- Flux-averaged cross section: $\sigma_{measured} = (1.47 \pm 0.32) \times \langle \sigma_{theory} \rangle$

$$= (0.94 \pm 0.20) \times 10^{-38}\ \mathrm{cm}^2$$

Stat+Syst.

Atmospheric NSI Sensitivity



- Modest sensitivity improvements with increased exposure
- Similar limitations due to flux uncertainties at highest energies