Tau Neutrino Searches at Super-Kamiokande and Hyper-Kamiokande

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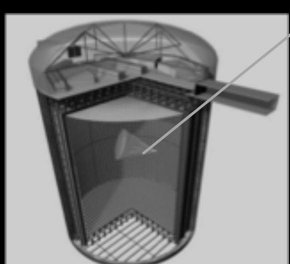
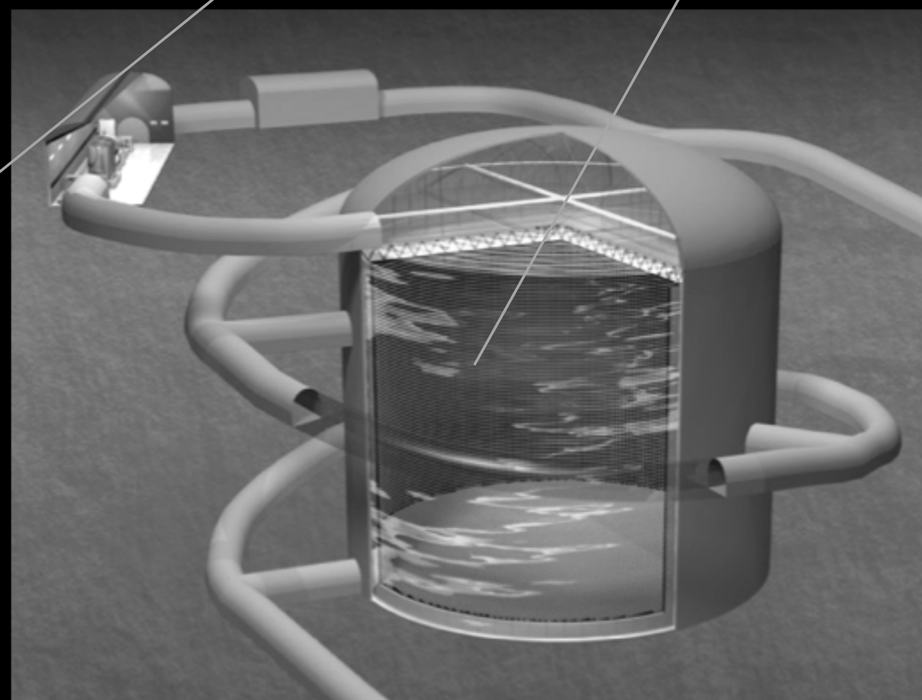
NuTau 2021
2021.09.29

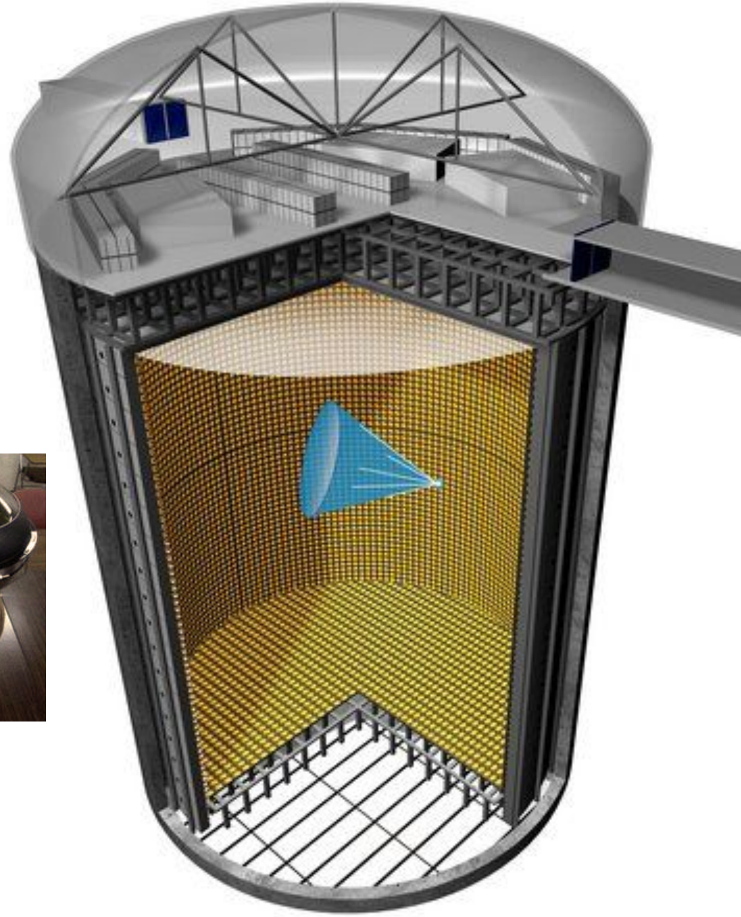


SK

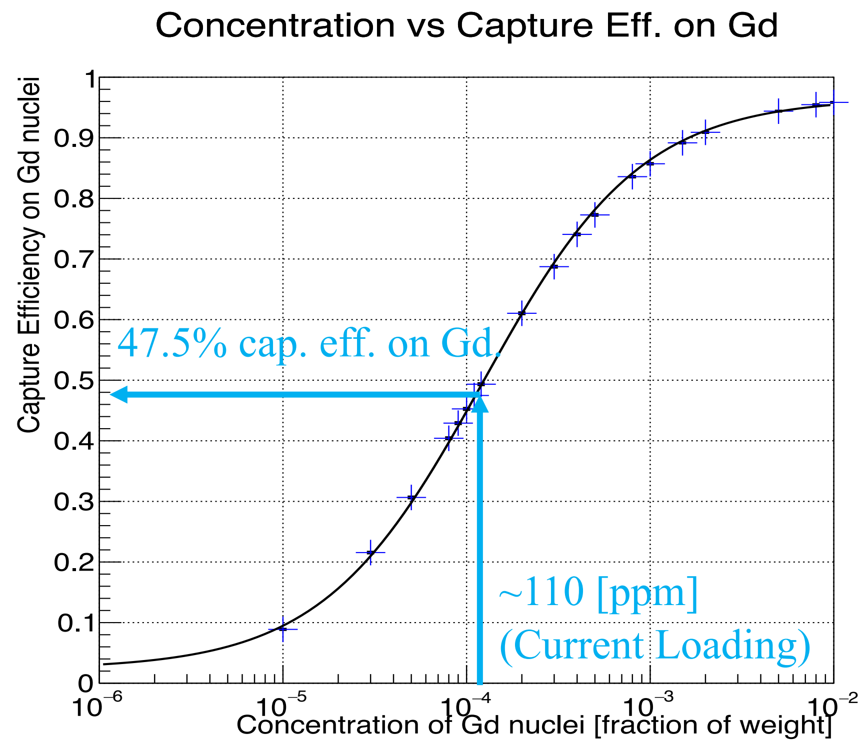


HK

Super-Kamiokande:



- 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 physics



Four Run Periods:

SK-I (1996-2001) SK-II (2003-2005)

SK-III (2005-2008) SK-IV (2008-2018)

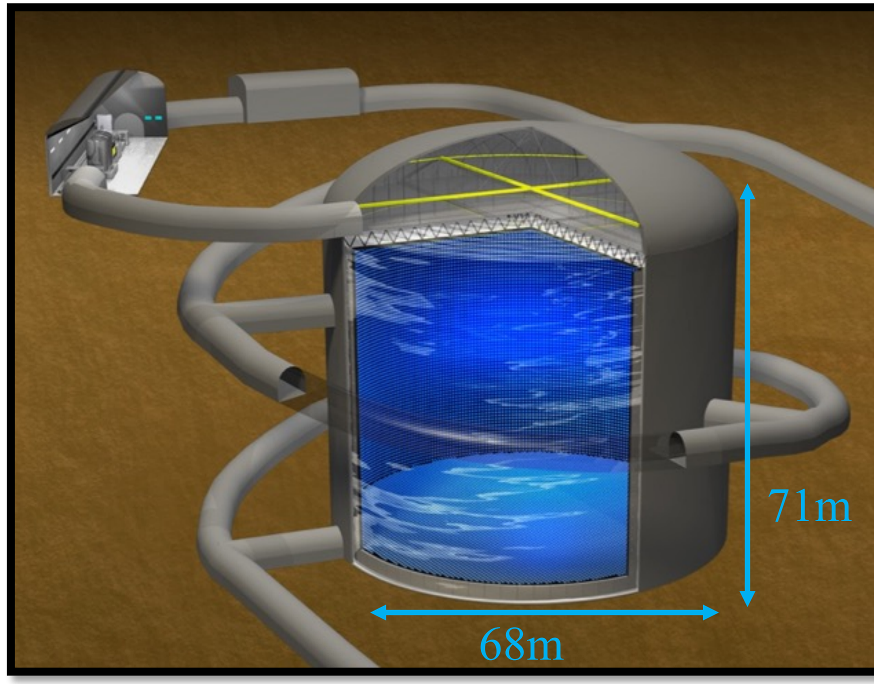
SK-V (2019-2020)

Upgrade Complete Now operating as (SK-Gd) !!

Hyper-Kamiokande:

- **186.5** kton fiducial volume (258 kton total)
- Optically separated into
  - Inner Detector
    - **20,000** 50cm High QE B&L PMTs
    - + O(1) k mPMT Modules
  - Outer Detector 1885 8” PMTs
- Pure water neutron tagging > 40%

- Now under construction – Data taking in 2027



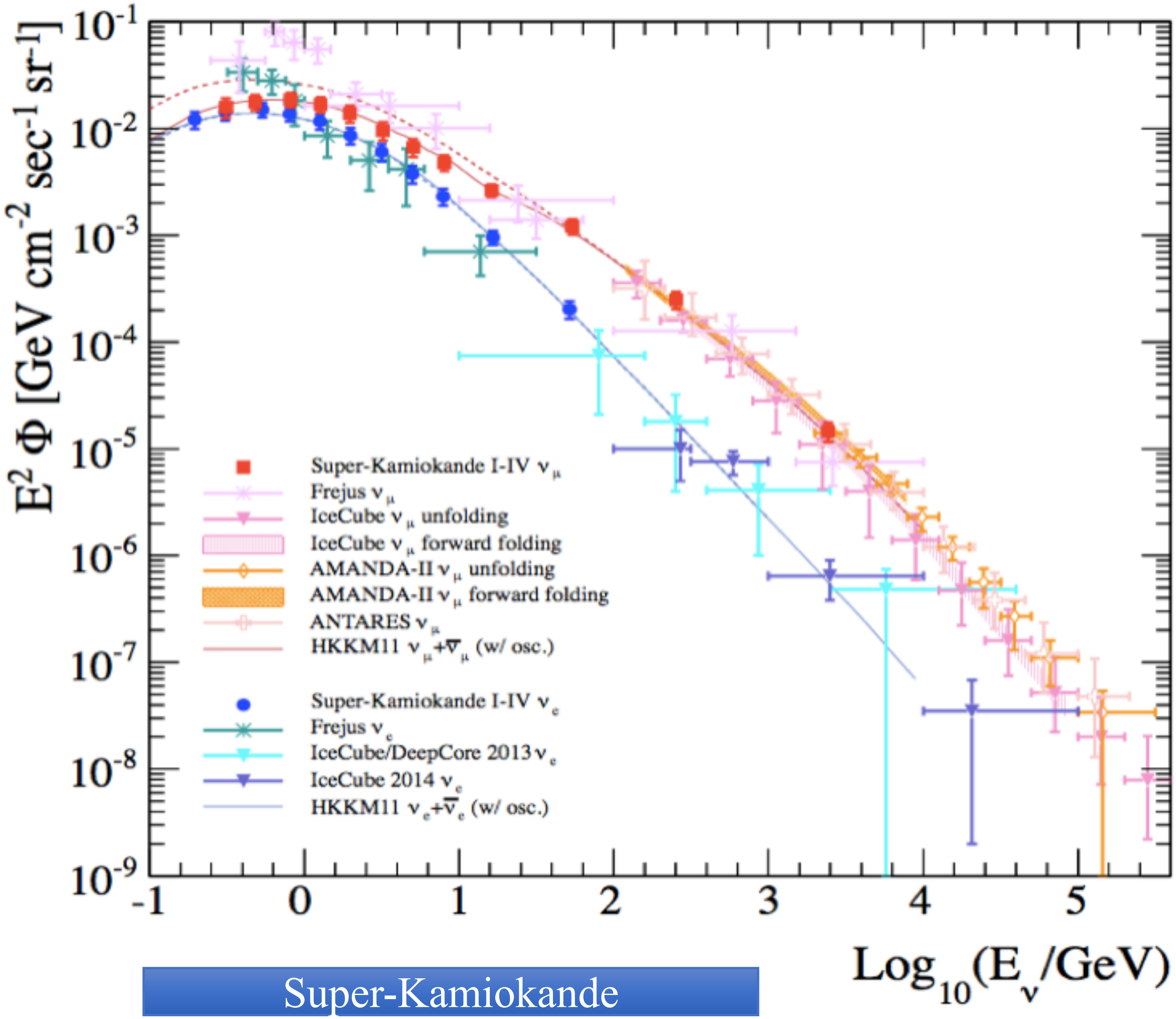
SK QE × 2
SK σ_τ × 2
SK Pres. Tol × 2

Multi-PMT

Current Hyper-K analysis uses the same methodology as Super-K,
In 10 years of data expect
→ A factor of **~6 times** the current SK data set
→ No improvements assumed in systematic errors or detector performance…yet

Atmospheric Neutrino Flux:

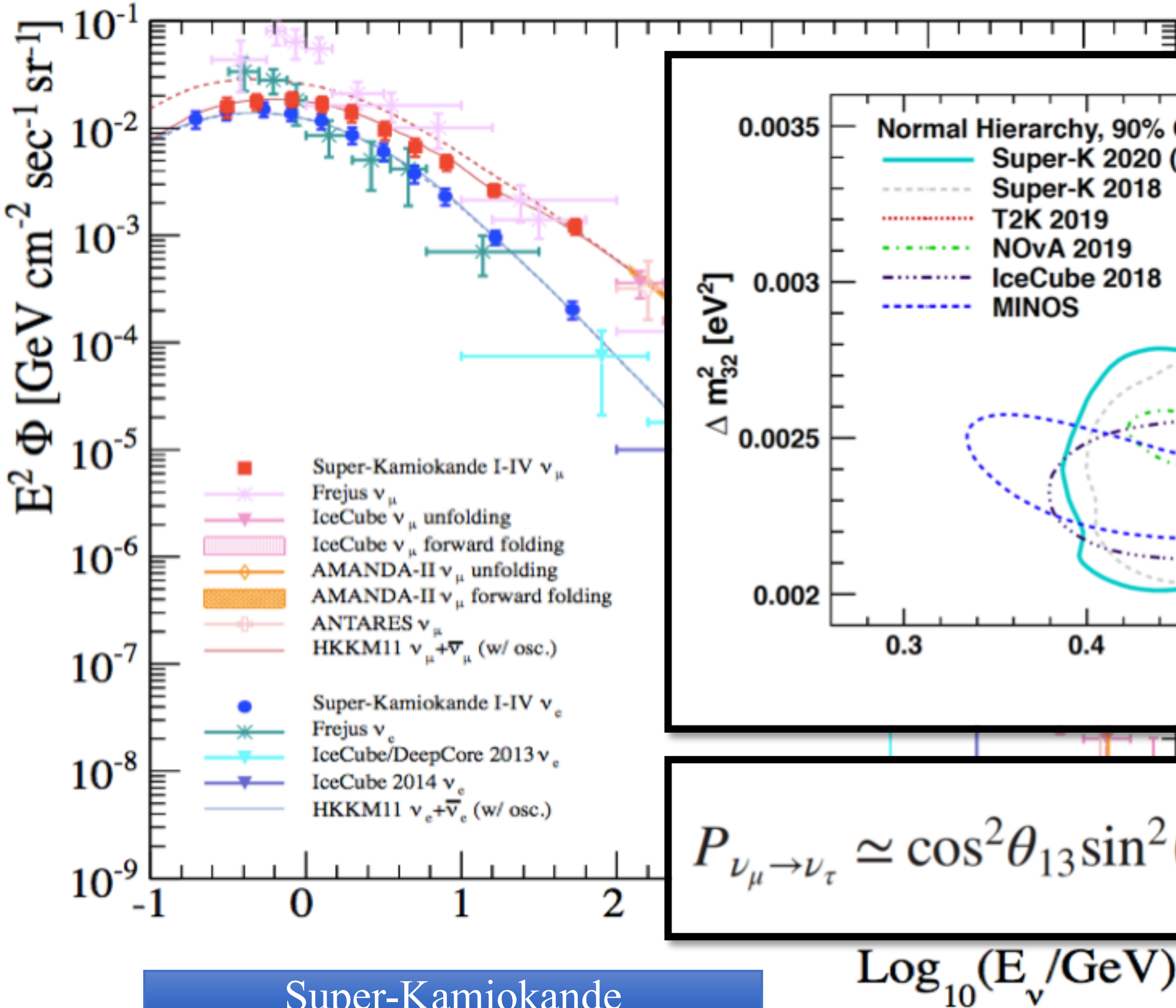
PHYSICAL REVIEW D 94, 052001 (2016)

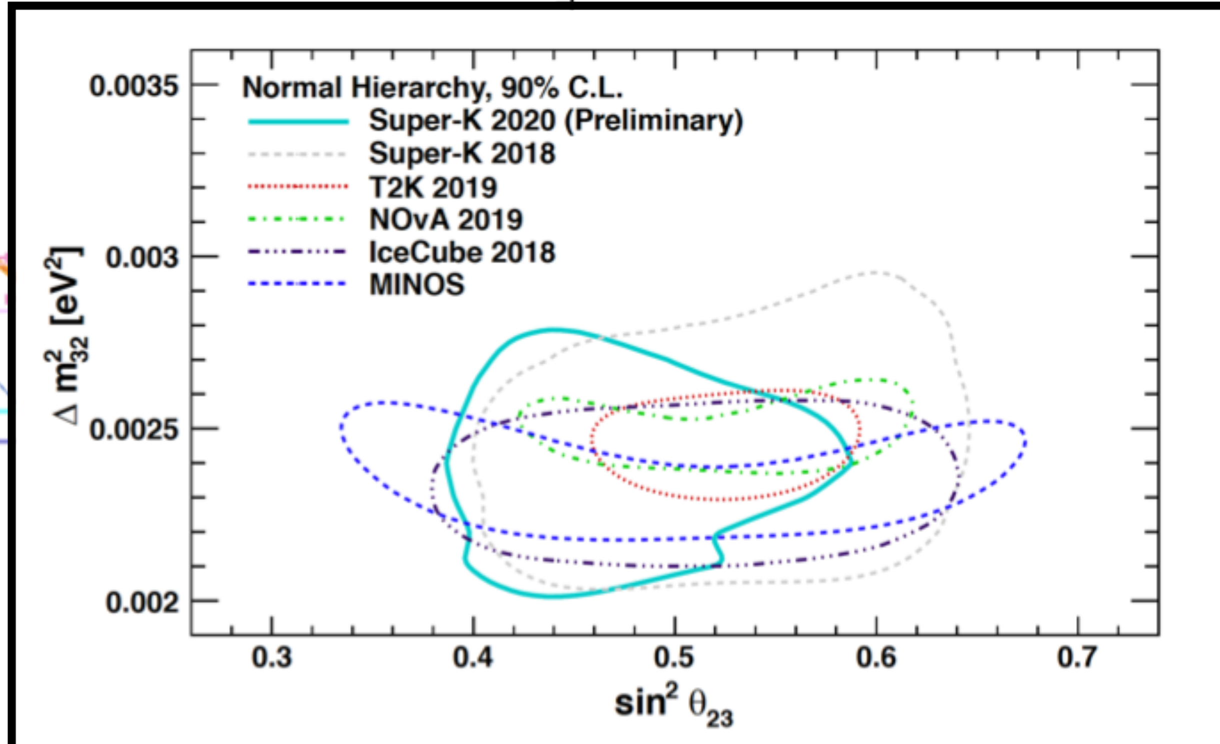


No ν_τ in the flux at SK/HK energies

Atmospheric Neutrino Flux: ν_μ Disappearance

PHYSICAL REVIEW D 94, 052001 (2016)





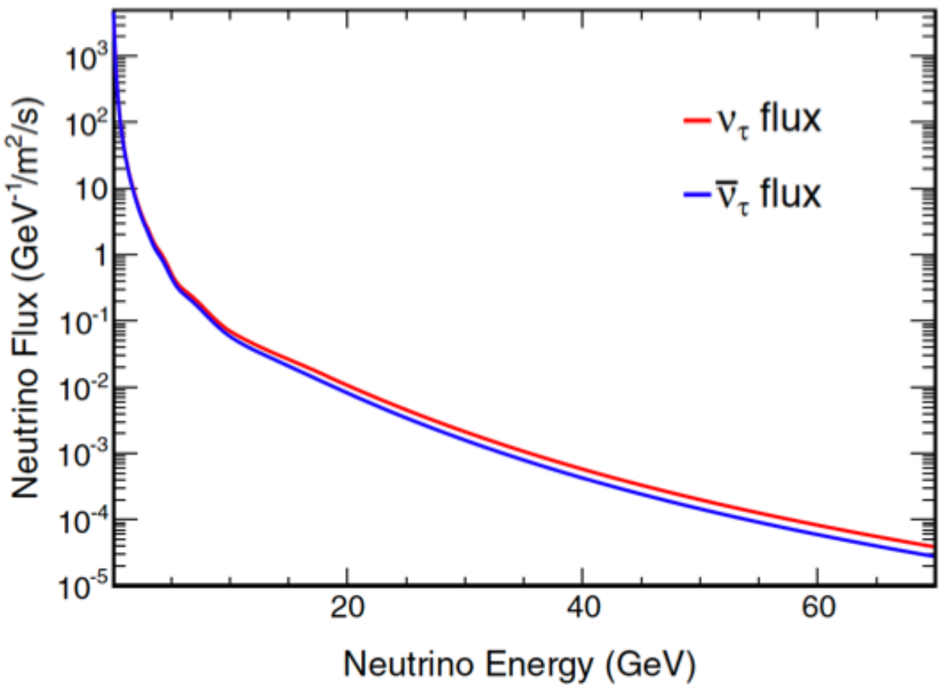
$$P_{\nu_\mu \to \nu_\tau} \simeq \cos^2\theta_{13} \sin^2(2\theta_{23}) \sin^2\left(1.27 \Delta m^2_{32} \frac{L}{E}\right)$$

Super-Kamiokande

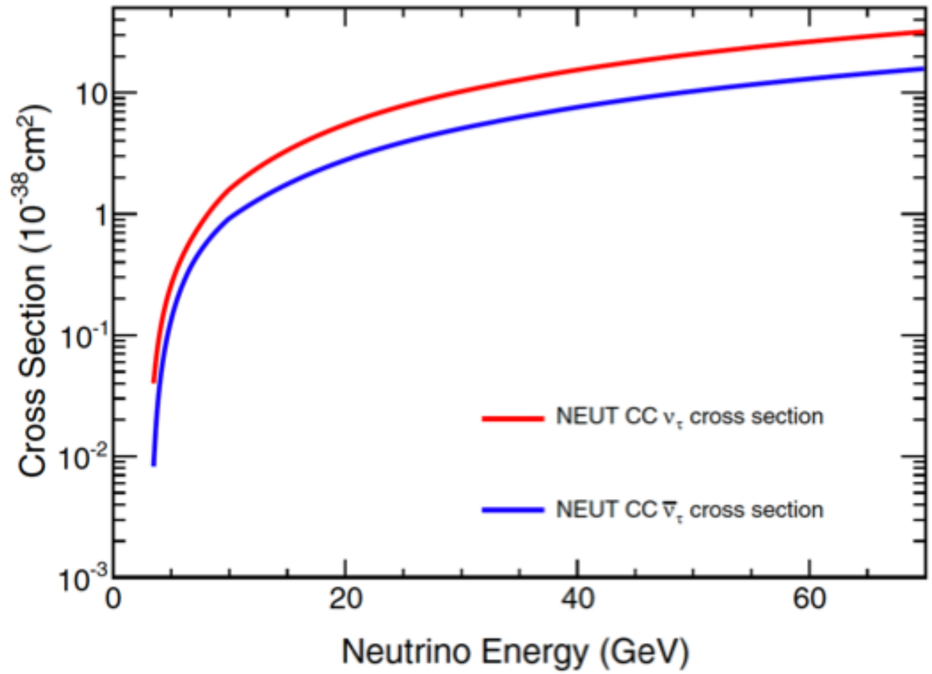
Well known that this best explained by $\nu_\mu \to \nu_\tau$ oscillations

Tau Expectation:

Honda 2011



NEUT 5.3.6



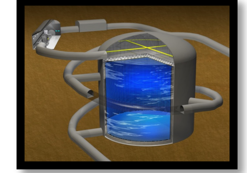
- Assuming current values of oscillation parameters expect roughly (CC)

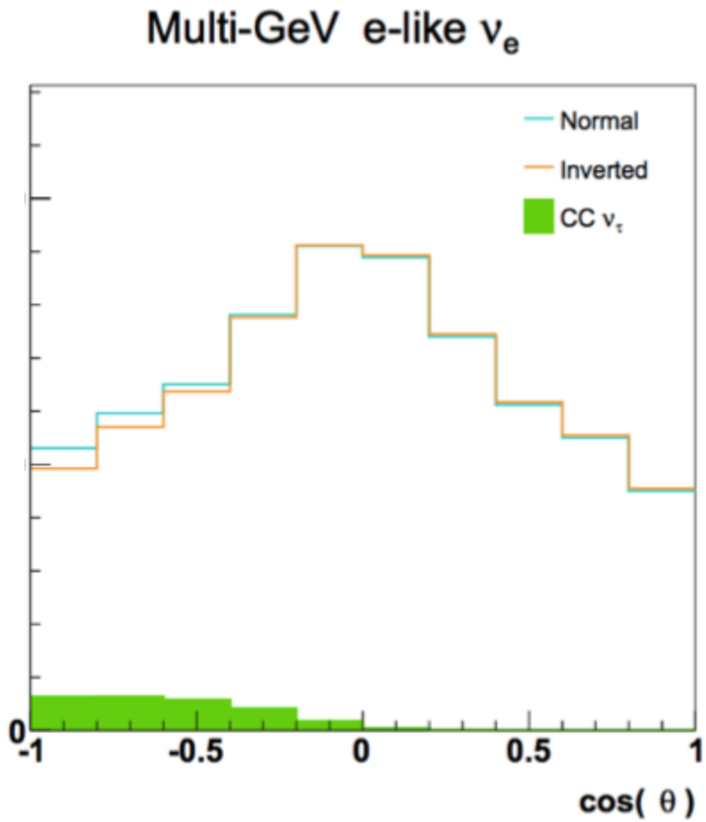
$$\Gamma_\tau \sim 1/\mathrm{yr}/\mathrm{kton}$$

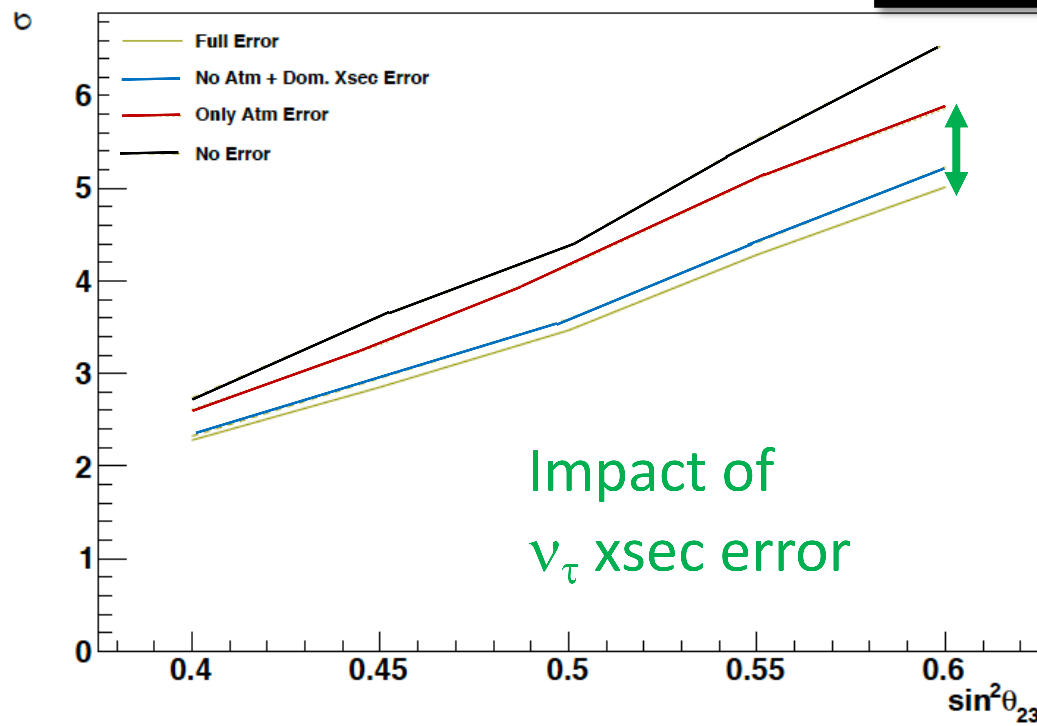
- Current SK data set spans1996-2016 representing 328 kton-yrs
- Assumed **HK** data set 1.86 **M**ton-yrs

Impact of ν_τ

Hyper-Kamiokande : Mass Hierarchy Prospects



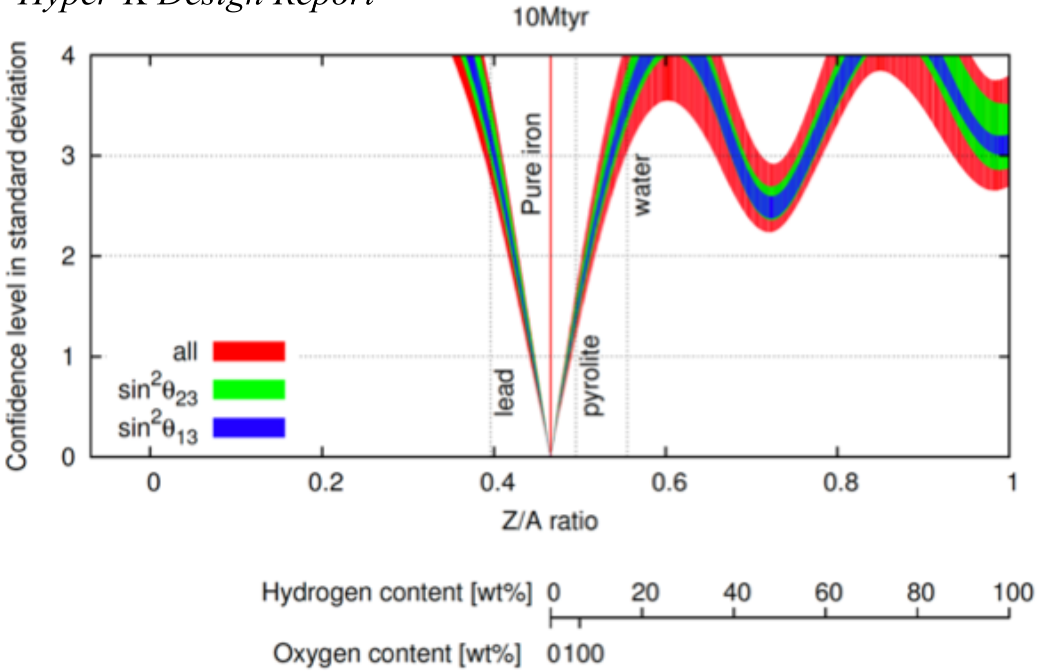




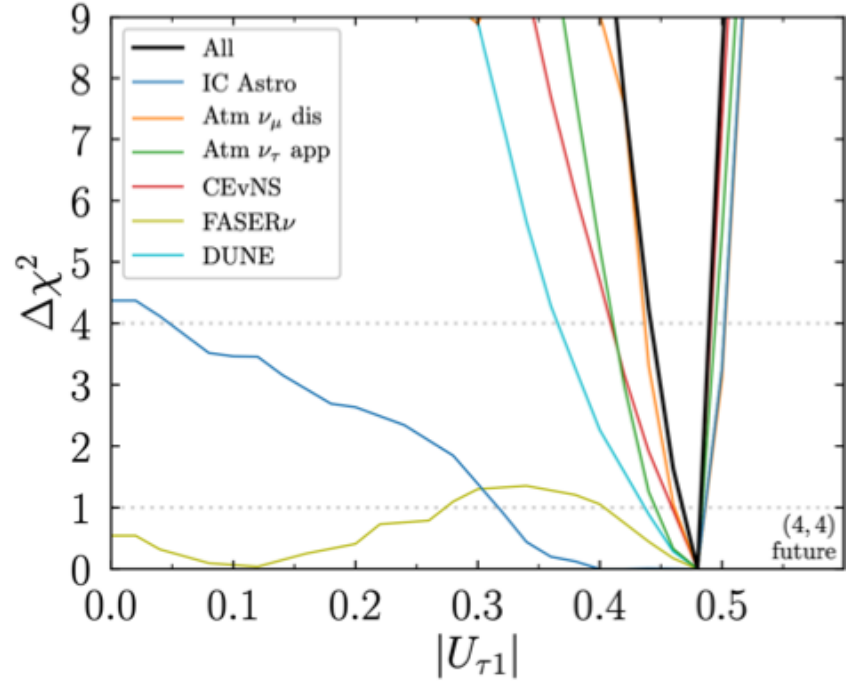
- Tau neutrinos are expected to appear in the same kinematic region as the mass hierarchy signal
- Uncertainty in the tau cross section (currently using ~25%) has a large impact on expected sensitivity
- → Secondary impact on q23 octant sensitivity

Future : Other Physics with Atmospheric Neutrinos

Hyper-K Design Report



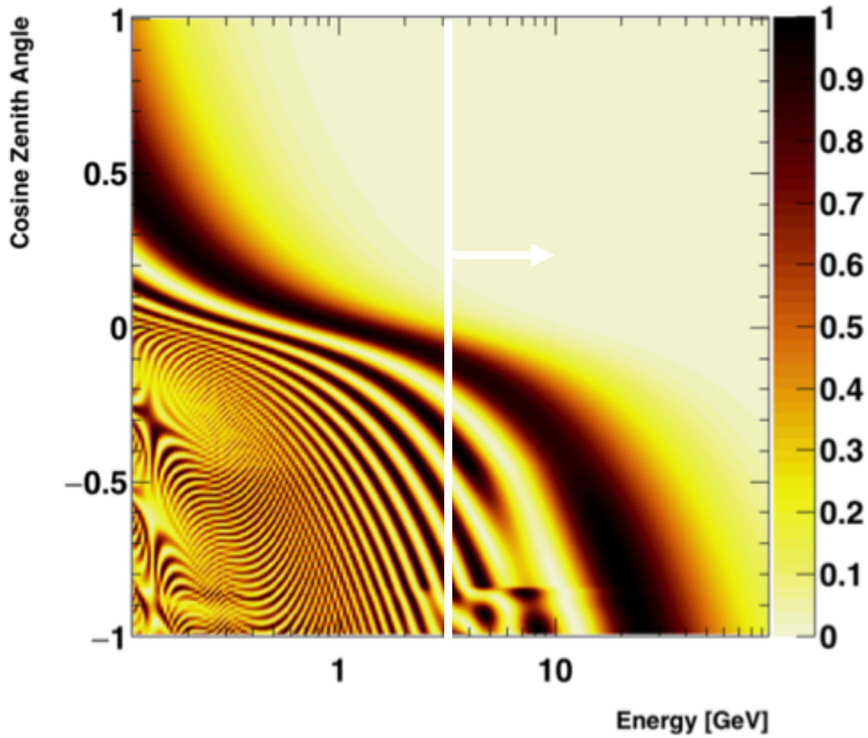
J. Gehrlein, TAUP 2021



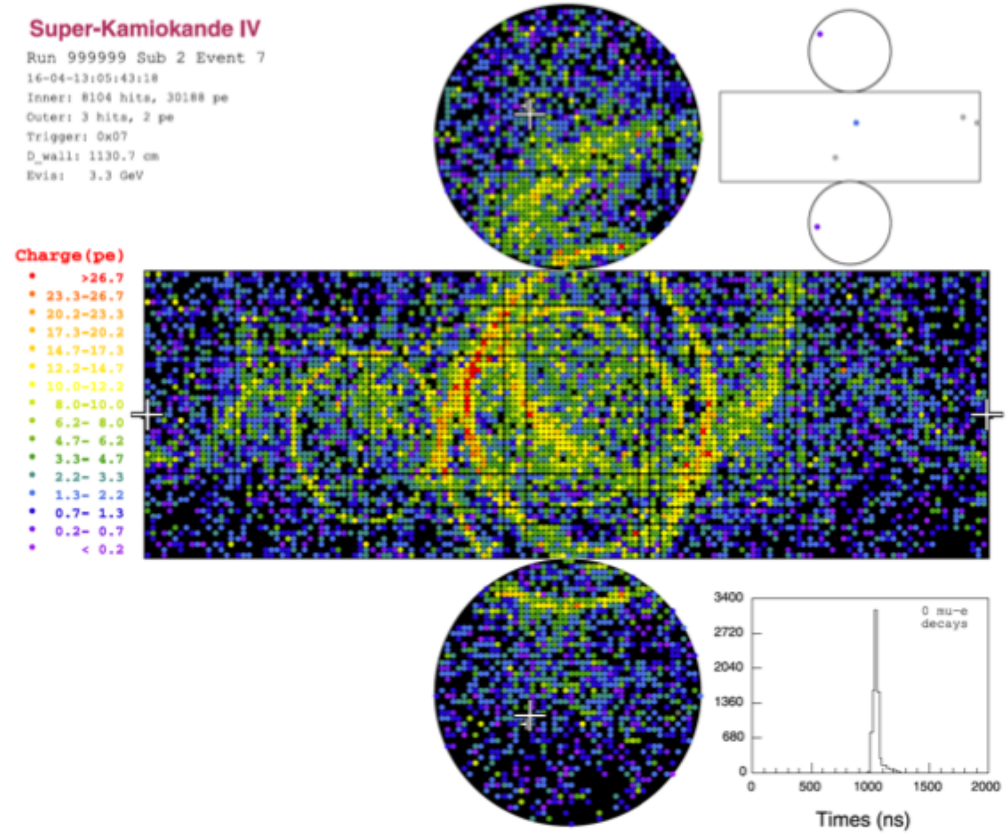
- Core-crossing atmospheric neutrinos can probe electron density of the core via its impact on their oscillations
  - General test of earth matter effects – not living on a vacuum, probably
- High-statistics observations can be used to constrain the electron content of the Earth
  - Important in geophysics for understanding the origin of the Earth's magnetic field
- Tau appearance contribution to (non-)unitarity studies

Searching for ν_τ

3 Flavor $P(\nu_\mu \to \nu_\tau)$

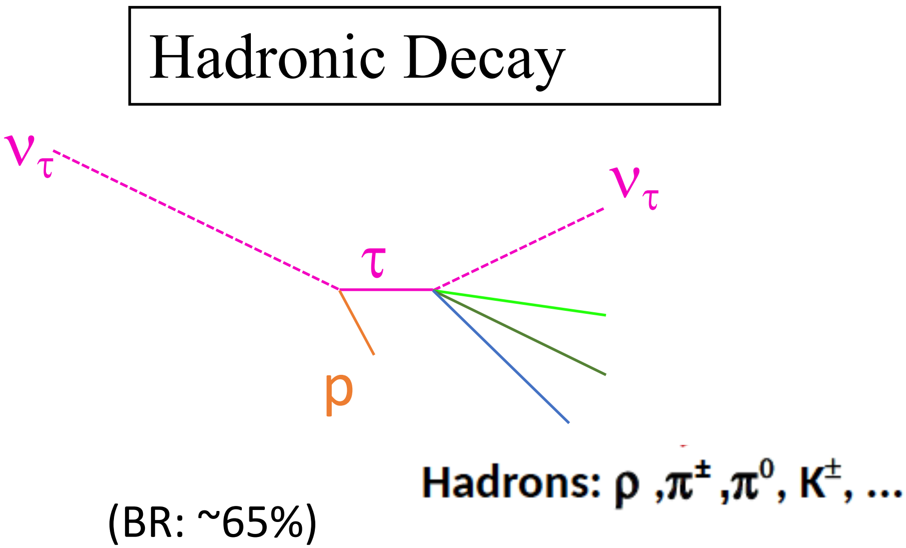


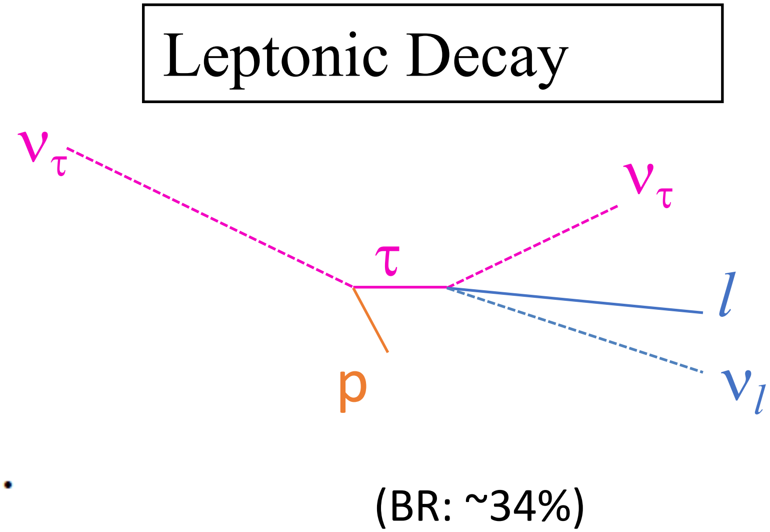
CC ν_τ



- Complicated event topologies with many overlapping charged particles

Search for Tau Neutrinos at SK



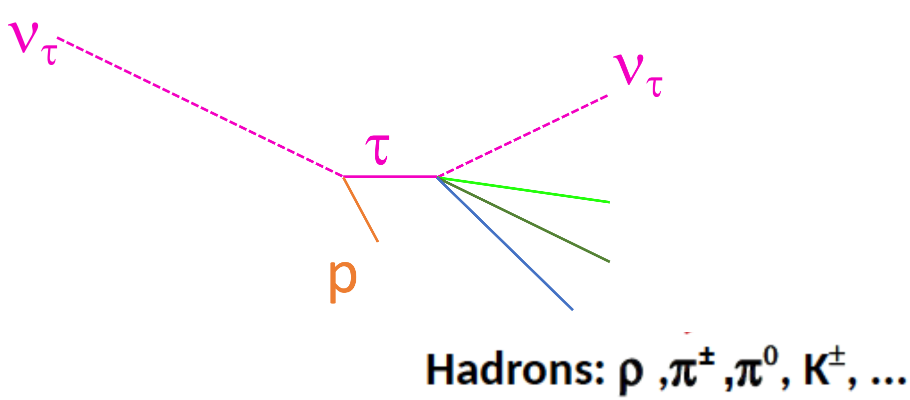


Visible Final State identical to that of a primary ν_l

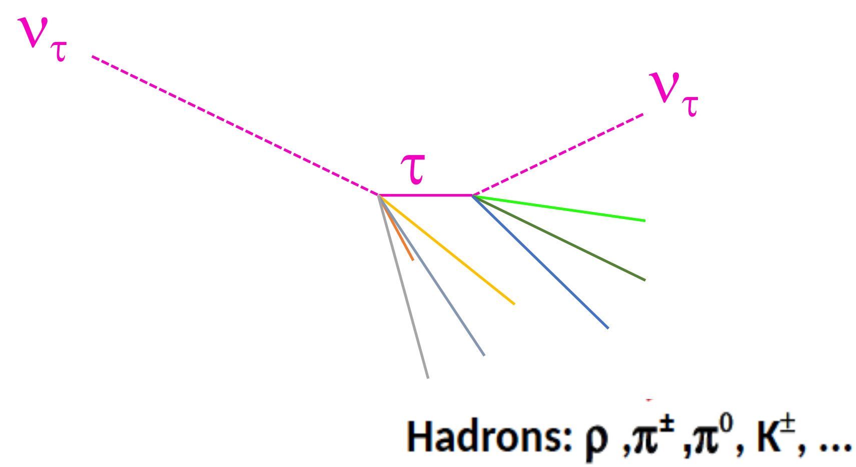
- A 10 GeV τ will travel about 0.5 mm in tank before decaying
- Leptonic decay
  - Swamped by charged current backgrounds from other atmospheric neutrinos, ν_l
- Hadronic decay
  - Expect more isotropic distribution of final state particles
  - Due to production threshold many interactions are DIS, so additional forward-going hadrons

Search for Tau Neutrinos at SK

CCQE + Hadronic



CC DIS + Hadronic



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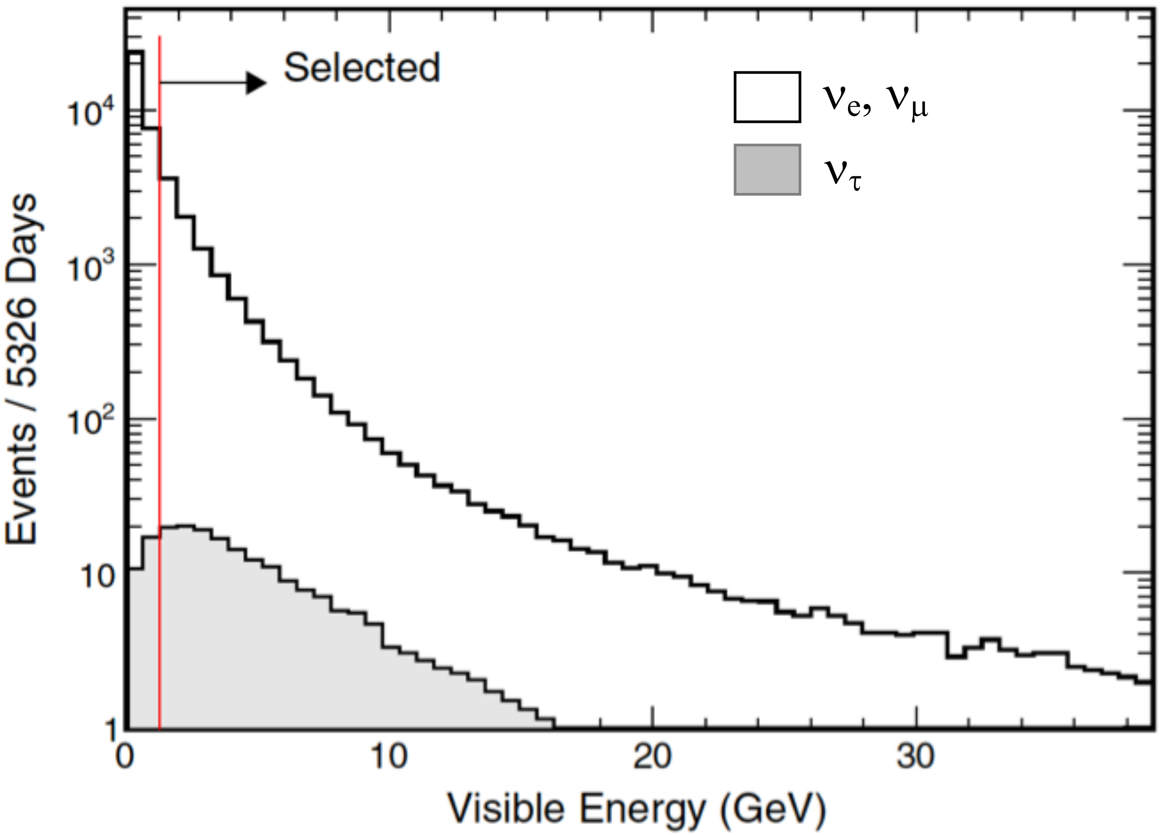
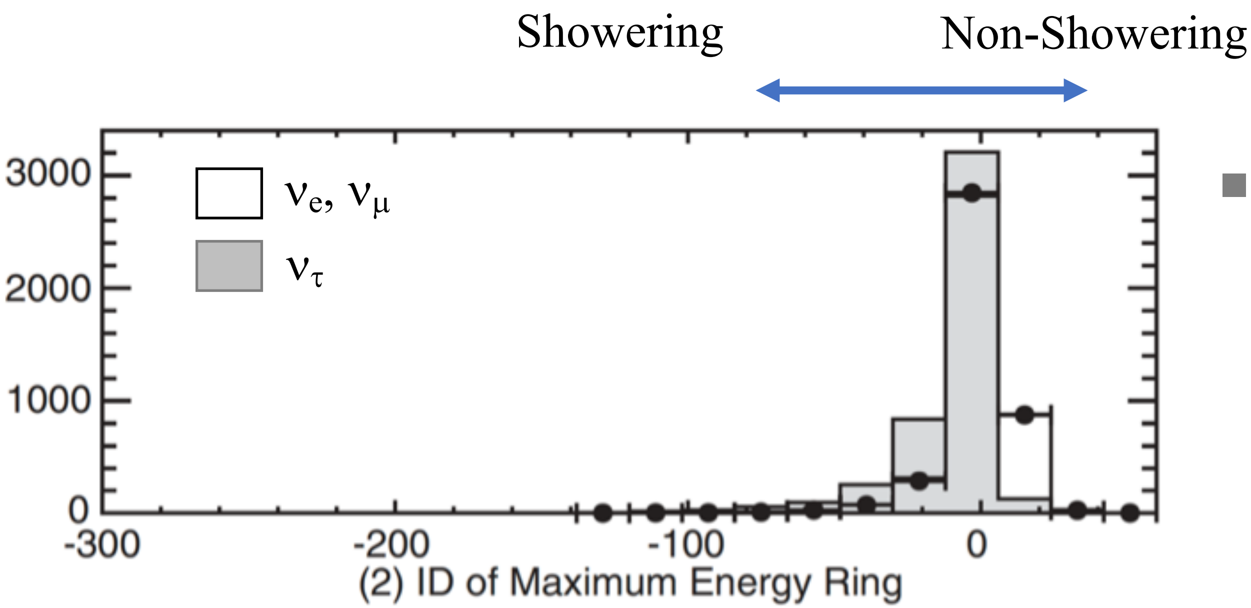
Search for Tau Neutrinos at SK: Selection



- Pre-selection
  - Fully-Contaned
  - Fiducial Volume (22.5kton)
  - Visible Energy > 1330.0 MeV
- Seven Neural Network Variables
  - Log10 (Visible Energy)
  - Particle ID Likelihood
  - Number of Decay Electrons
  - Distance to farthest electron
  - Event sphericity
  - Number of Ring Candidates
  - Fraction of momentum in leading ring

- Select ν_τ above production threshold

Search for Tau Neutrinos at SK: Selection



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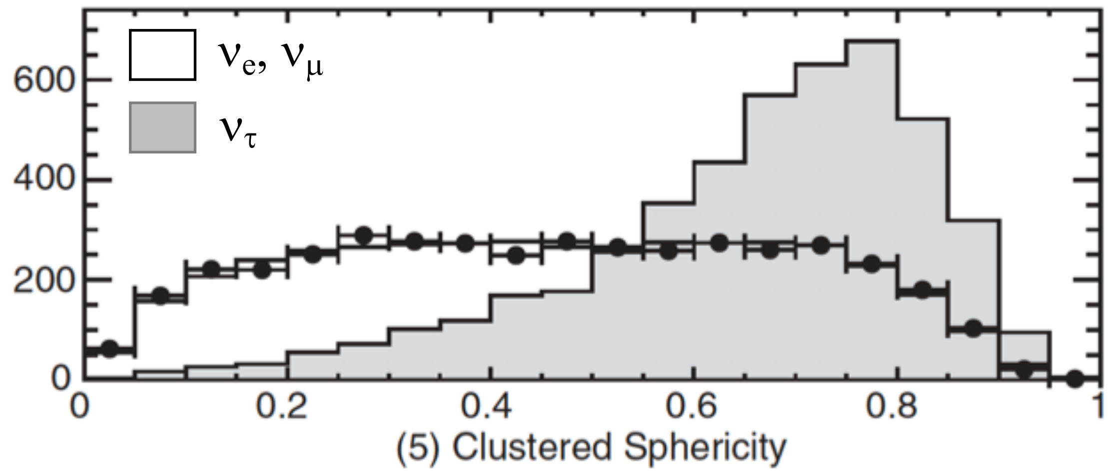
  - Fraction of momentum in leading ring

- Dependent upon reconstruction to find most energetic ring
- Many tau decays produce showering particles (via e or π^0)
  - CC ν_μ likely to have non-showering

Search for Tau Neutrinos at SK: Selection

* Data points are downward-going atm. ν



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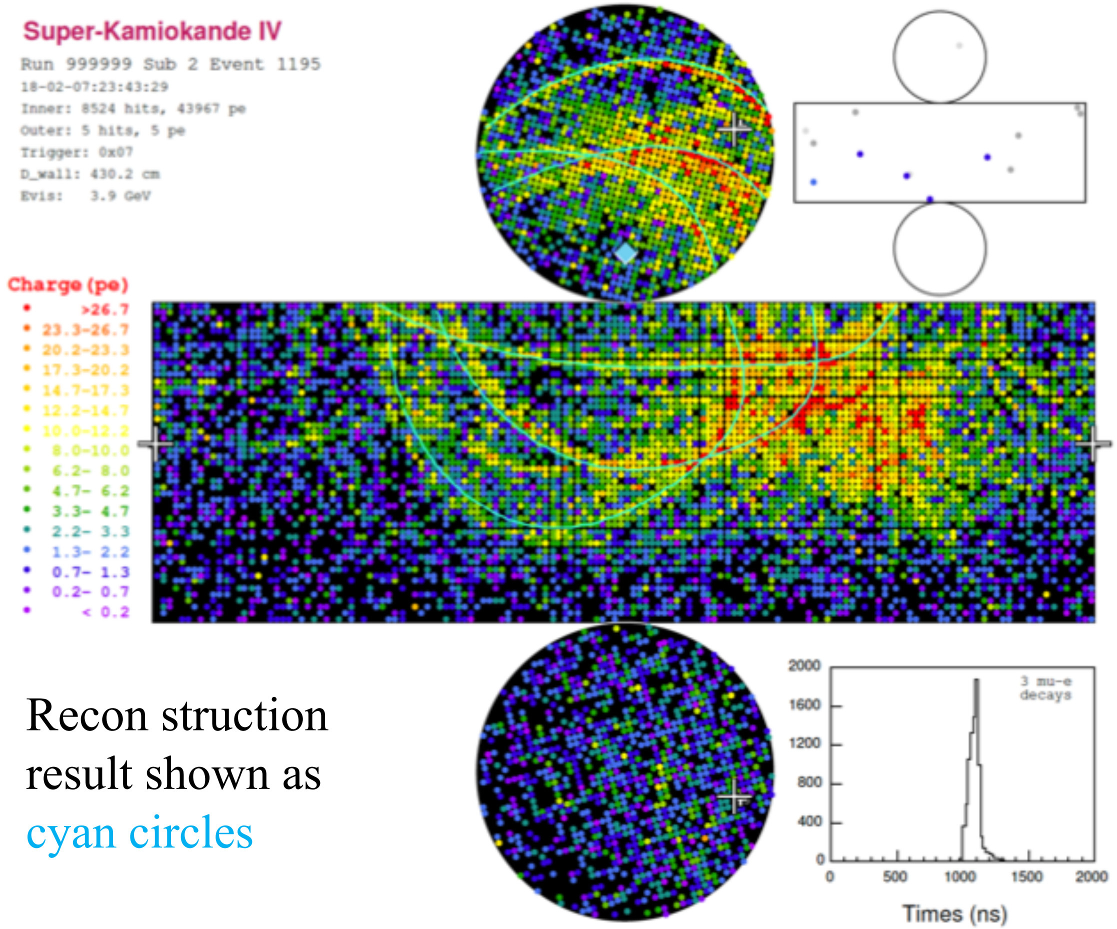
$$S^{\alpha\beta} = \frac{\sum_i p_i^\alpha p_i^\beta}{\sum_i p_i^2}$$

$$S = \frac{3}{2}(\lambda_2 + \lambda_3)$$

- Calculated based on distribution of charge seen in event COM
- S = 0 : linear event , S = 1 isotropic charge
- → Decay of heavy τ produces more isotropic charge

Search for Tau Neutrinos at SK: Selection



Recon struction result shown as cyan circles

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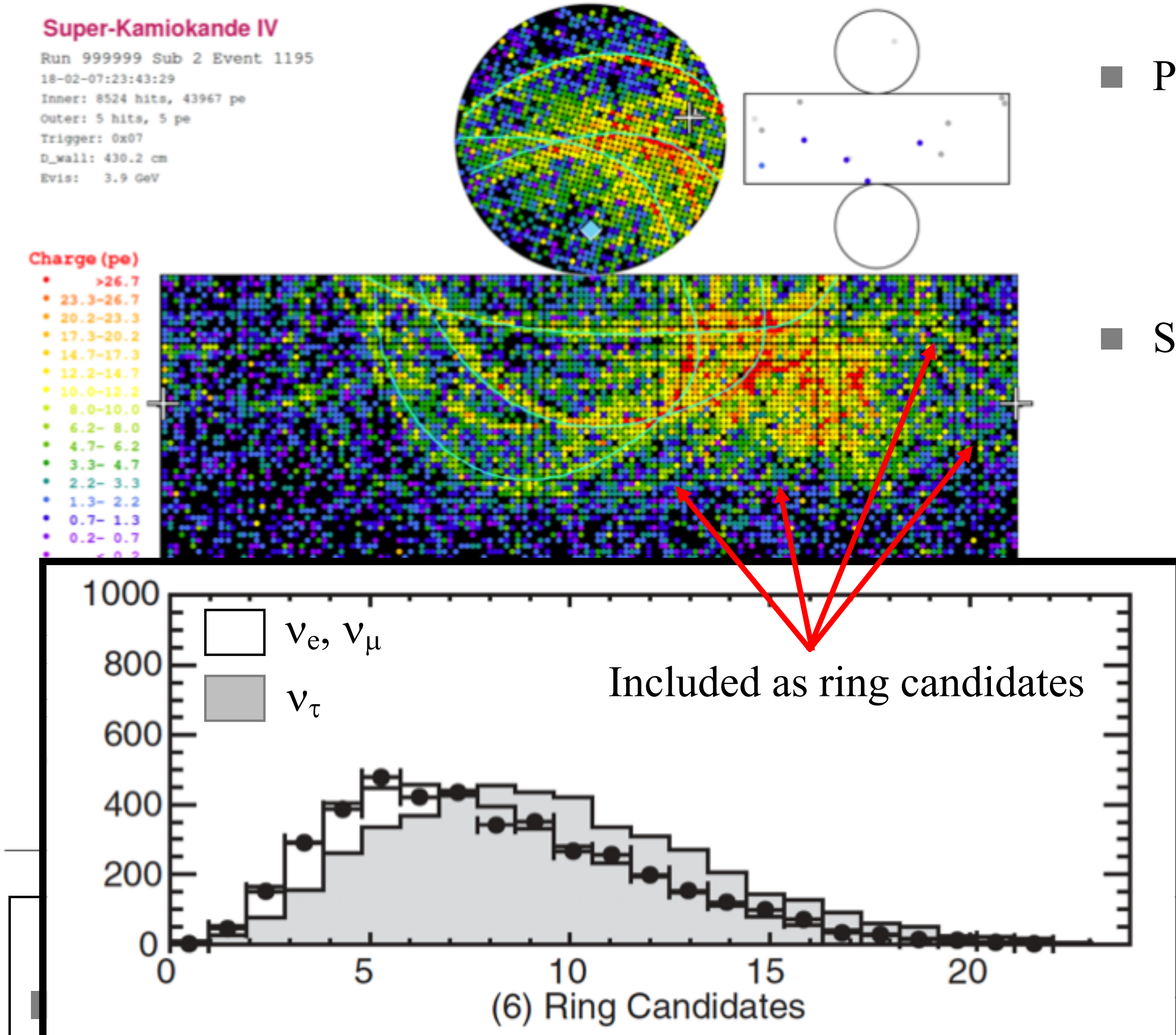
  - Fraction of momentum in leading ring

- Difficult to fully reconstruct all particles, so count ring pieces
- Typically τ decay produces more pions above C threshold

Search for Tau Neutrinos at SK: Selection



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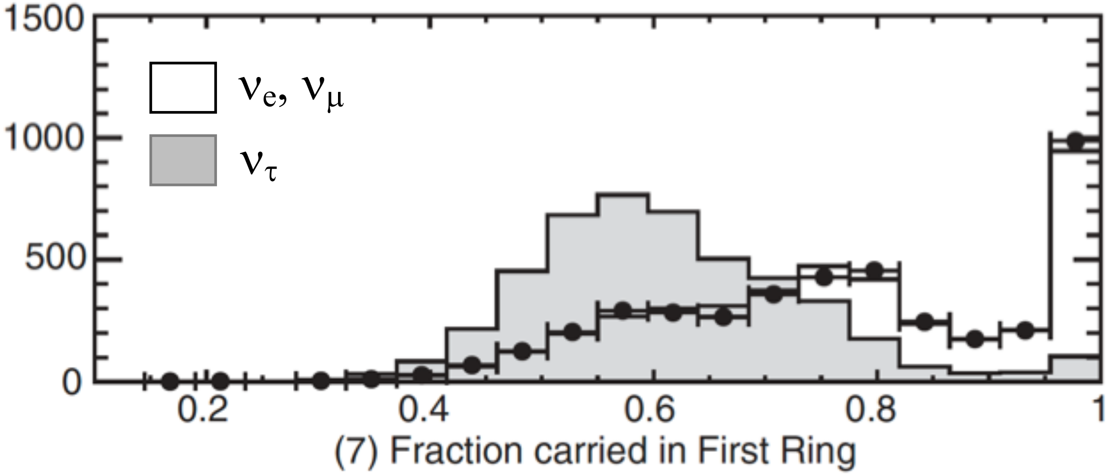

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  - Particle ID Likelihood
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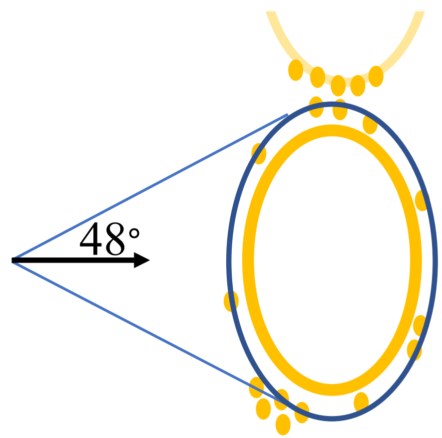
  - Fraction of momentum in leading ring

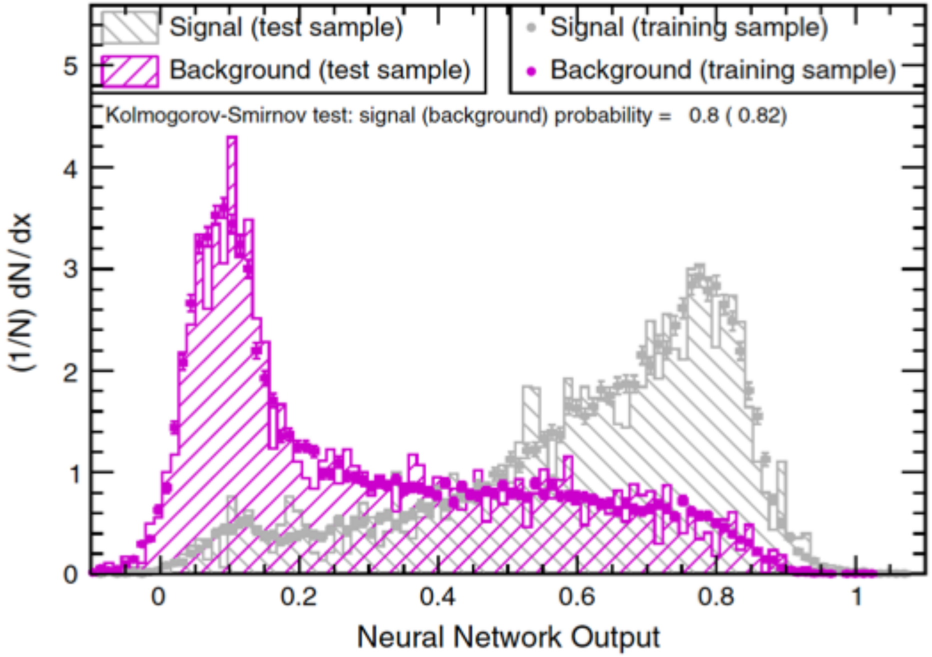
$$= \frac{\sum_{\theta_i < 48^\circ} q_i}{\sum q_i}$$



- Calculate charge with 48 degrees of highest momentum particle
- Expect more even energy distribution in ν_τ events → small fractions

Search for Tau Neutrinos at SK: Performance

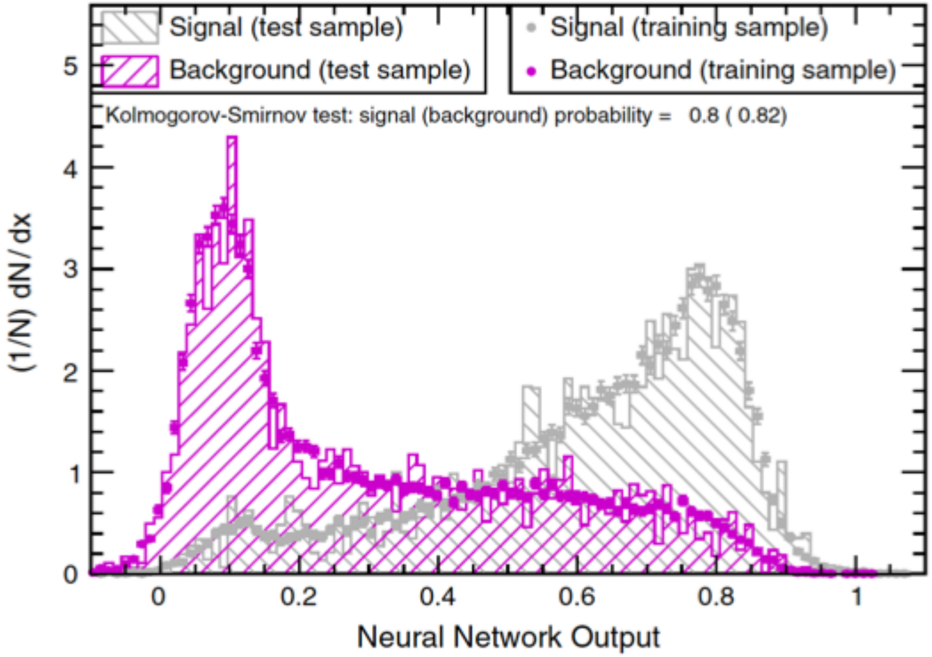
PHYS. REV. D 98, 052006 (2018)

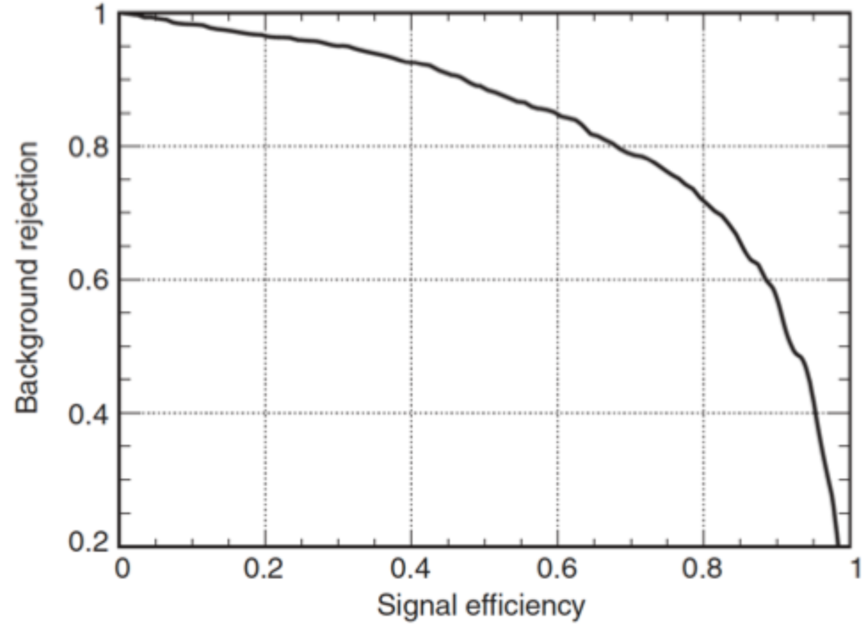


NN > 0.5	Background	Signal (ν_τ)
Efficiency	28%	76%
Purity	95.3%	4.7%
Rate [Mton· year]$^{-1}$	8467	422

Search for Tau Neutrinos at SK: Performance

PHYS. REV. D 98, 052006 (2018)





NN > 0.5	Background	Signal (ν_τ)
Efficiency	28%	76%
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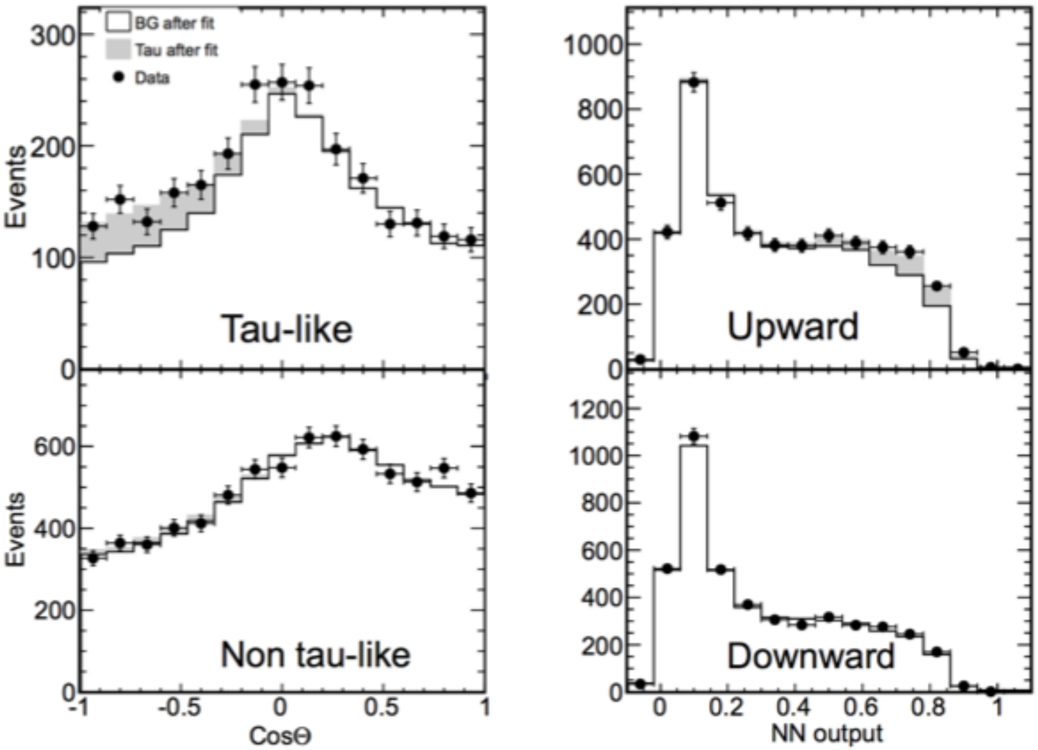
Decay mode	Branching ratio (%)	Tau-like fraction (%)
$e^-\bar{\nu}_e\nu_\tau$	17.83	67.3 ± 2.2
$\mu^-\bar{\nu}_\mu\nu_\tau$	17.41	42.6 ± 2.6
$\pi^-\nu_\tau$	10.83	84.7 ± 3.8
$\pi^-\pi^0\nu_\tau$	25.52	81.0 ± 2.1
$3\pi\nu_\tau$	18.29	88.7 ± 2.5
Others	10.12	90.5 ± 3.4

Search for Tau Neutrinos at SK :

PHYS. REV. D **98,** 052006 (2018)



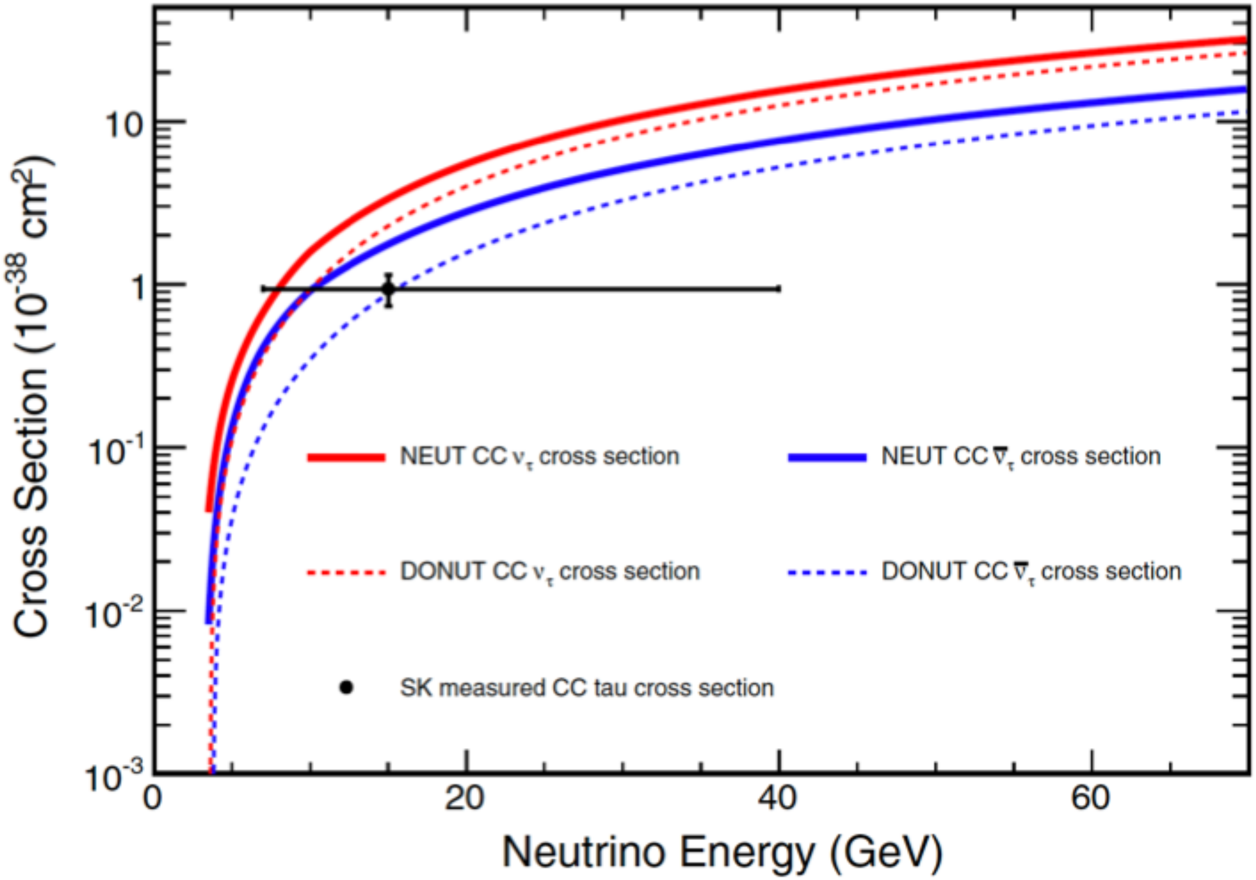
$$\text{Data} = \text{PDF}_{\text{BG}} + \alpha \times \text{PDF}_{\text{tau}} + \sum \epsilon_i \times \text{PDF}_i$$

$\alpha = 1.47 \pm 0.32$ (stat+syst)

4.6σ rejection of no τ appearance

- Fit 2-dimensional PDFs (cos θ, Neural Network), while simultaneously varying systematic error templates
  - No cut to separate tau-like and non-tau-like
- Uses 328 kton-yr exposure (SK-I ~ SK-IV)

Systematic Errors in Search for Tau Neutrinos



- Flux-averaged cross section:
- Consistent with model at about 1σ

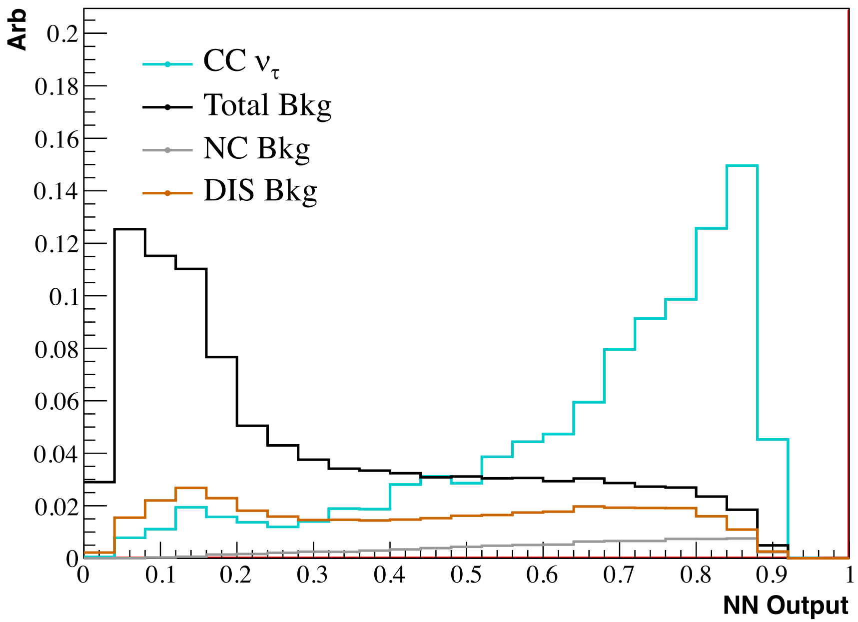
$$\sigma_{measured} = (1.47 \pm 0.32) \times \langle \sigma_{theory} \rangle$$

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

Stat+Syst.

Systematic Errors in Search for Tau Neutrinos

Phys. Rev. D 98, 052006 (2018)



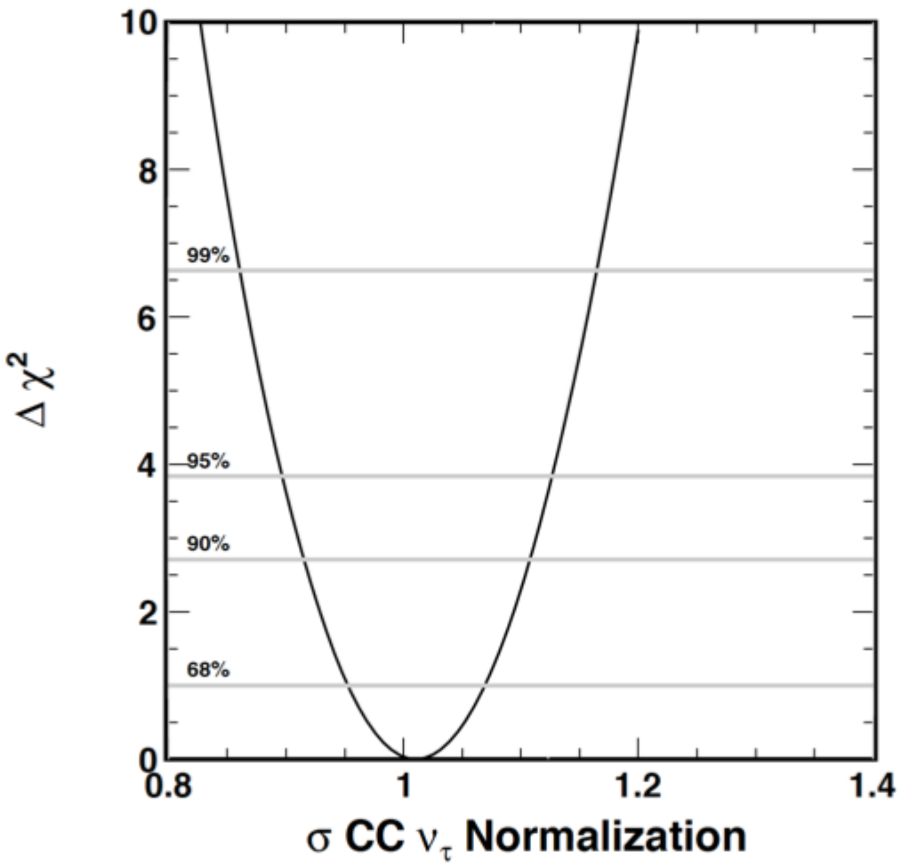
- Dominant systematics are cross section related but flux errors also play a role
- Total systematic uncertainty is ~8% impact on normalization
- Present analysis is dominated by statistical uncertainty ~20%

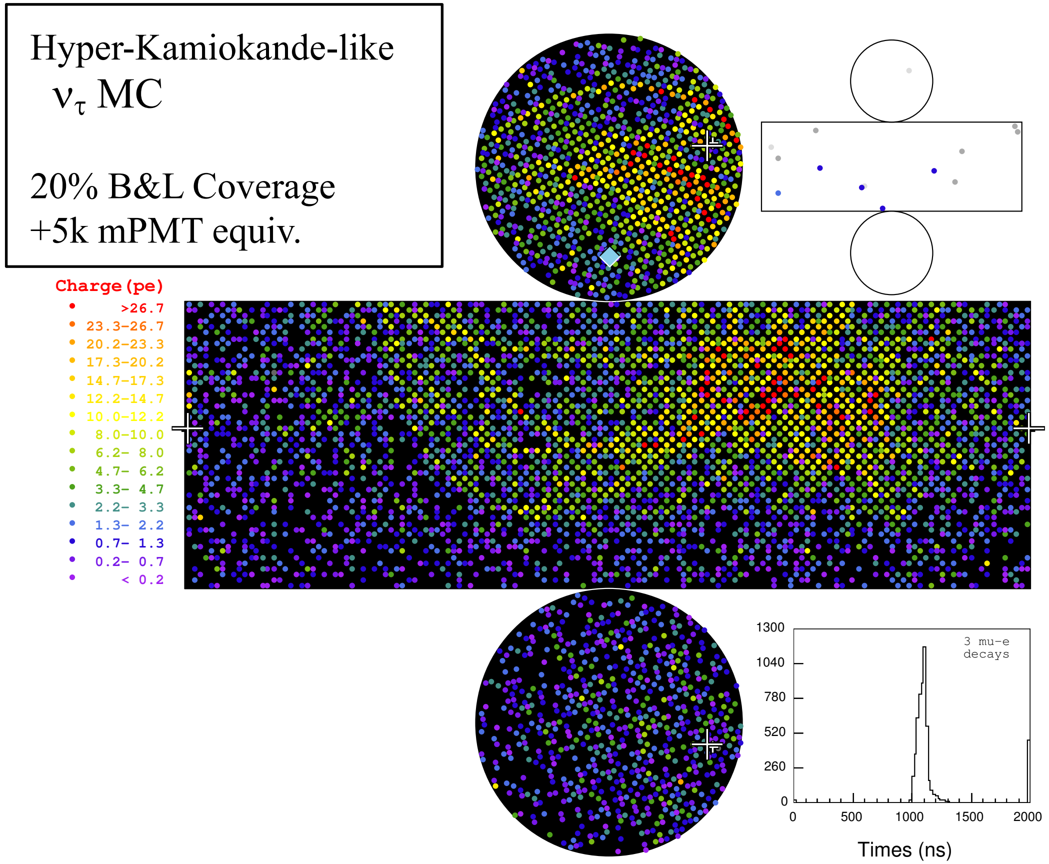
In decreasing order of impact

Systematic error		σ (%)
NC/CC ratio	20%	20
DIS q^2 dependence for low W	15%	10
Meson exchange current		10
1π axial coupling		10
DIS q^2 dependence for high W		10
Coherent π cross section		100
Flux normalization ($E_\nu > 1$GeV)	11%	15
1π background scale factor		10
1π axial form factor		10
CCQE cross section		10
Single pion $\pi^0/\pi^\pm$ ratio		40
$\bar{\nu}_\mu/\nu_\mu$ ratio ($E_\nu > 10$ GeV)	5.6%	15
$\nu/\bar{\nu}$ ratio ($E_\nu > 10$ GeV)	5.3%	5
DIS cross section ($E_\nu < 10$ GeV)		10
FC multi-GeV normalization		5
$\bar{\nu}_e/\nu_e$ ratio ($E_\nu > 10$GeV)	4.6%	8
K/π ratio	4.5%	10
Single meson cross section		20
Single-pion $\bar{\nu}/\nu$ ratio		10
Horizontal/vertical ratio	3%	1
CCQE $\nu/\bar{\nu}$ ratio		10
DIS cross section		5
Matter effect		6.8
Neutrino path length		10

* Numbers in red are maximum impact on analysis bins, red boxes are flux-related errors

Expanding Analysis to Hyper-Kamiokande



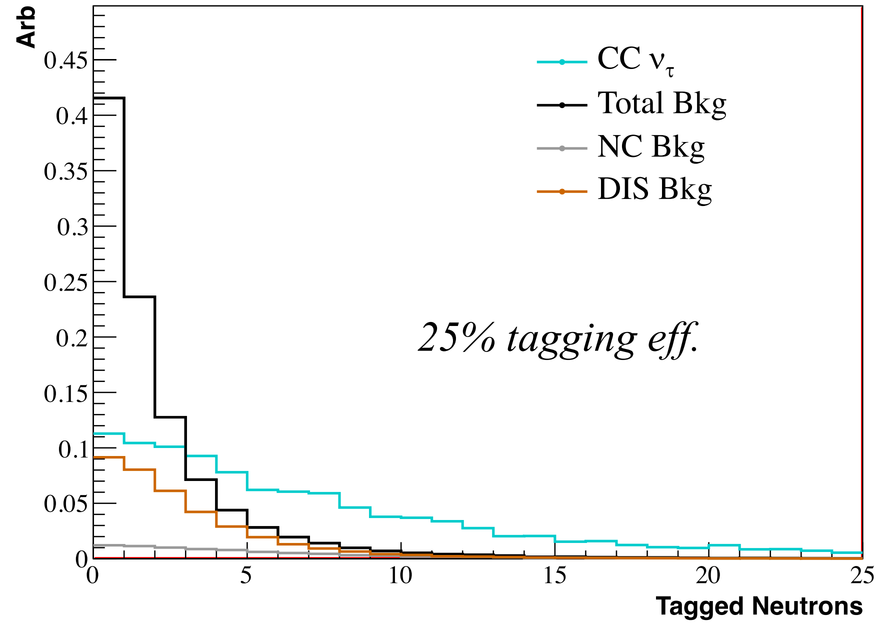


* Same event as above, viewed in HK-like display

- Simple scaling of analysis above to 5.6 Mton-yr
  - … or 30 years of Hyper-K
- Corresponds to ~8% uncertainty on normalization → limit of current assumptions

Prospects and Ideas

- Neutron Information
  - Tau events: more hadrons → more neutrons
  - Another handle on isotropy?
  - *Unknown and potentially large systematics*
- Improved reconstruction algorithm
  - SK Fiducial volume 22.5 → 27.0^{+} kton
  - Better ring identification
  - Better allotment of charge among rings
  - "New" algorithm is current default for HK
- Improved multi-variate methods
  - Graduate from TMVA…
- Hyper-K specific tools are under development
  - Take advantage of improve QE PMTs
  - Complementary information from mPMTs
  - Machine Learning-based reconstruction



True Number of Rings	New Reco. 1R	New Reco. 2R	New Reco. ≥ 3R	SK Standard 1R	SK Standard 2R	SK Standard ≥ 3R
True 1R	95.0%	4.64%	0.41%	95.9%	3.85%	0.29%
True 2R	27.8%	66.7%	5.56%	42.5%	52.8%	4.63%
True ≥3R	7.04%	25.5%	67.5%	20.2%	33.0%	46.8%

Reconstruction efficiency

Summary and Conclusions

- Tau neutrinos appearing in the SK atmospheric neutrino data at 4.6σ
  - Currently statistics limited measurement

- At Hyper-K level exposures sensitivity to reach 8% error on tau normalization
  - Assumes SK analysis → currently being ported to HK specific tools

- Prospects for improved reconstruction, additional NN variables, are expected to improve the S/N for short-term and can be extended in principle to long-term

- Techniques presented here can equally be applied to HK beam neutrinos from J-PARC
  - Stay tuned….

Super-Kamiokande collaboration

Kamioka Observatory, ICRR, Univ. of Tokyo, Japan
RCCN, ICRR, Univ. of Tokyo, Japan
University Autonoma Madrid, Spain
University of British Columbia, 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
NFN Bari, Italy
INFN Napoli, Italy
INFN Padova, Italy
INFN Roma, Italy
Kavli IPMU, The Univ. of Tokyo, Japan
KEK, Japan
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
Osaka University, Japan
University of Oxford, UK
Queen Mary University of London, 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
The University of Winnipeg, Canada
Yokohama National University, Japan

178 collaborators
from 45 institutes
10 countries


ハイパーカミオカンデ　着工記念式典
Hyper-Kamiokande Groundbreaking Ceremony
ICRR
宇宙線研
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