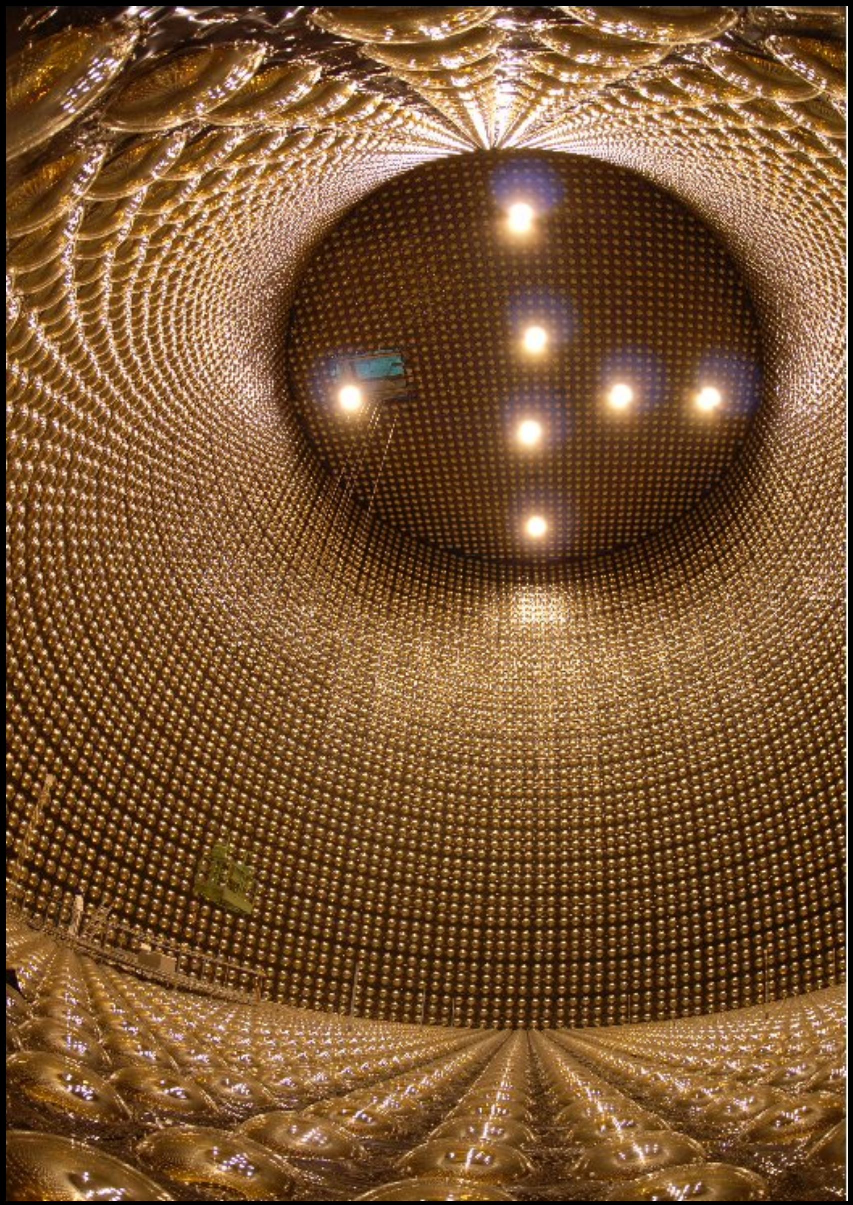
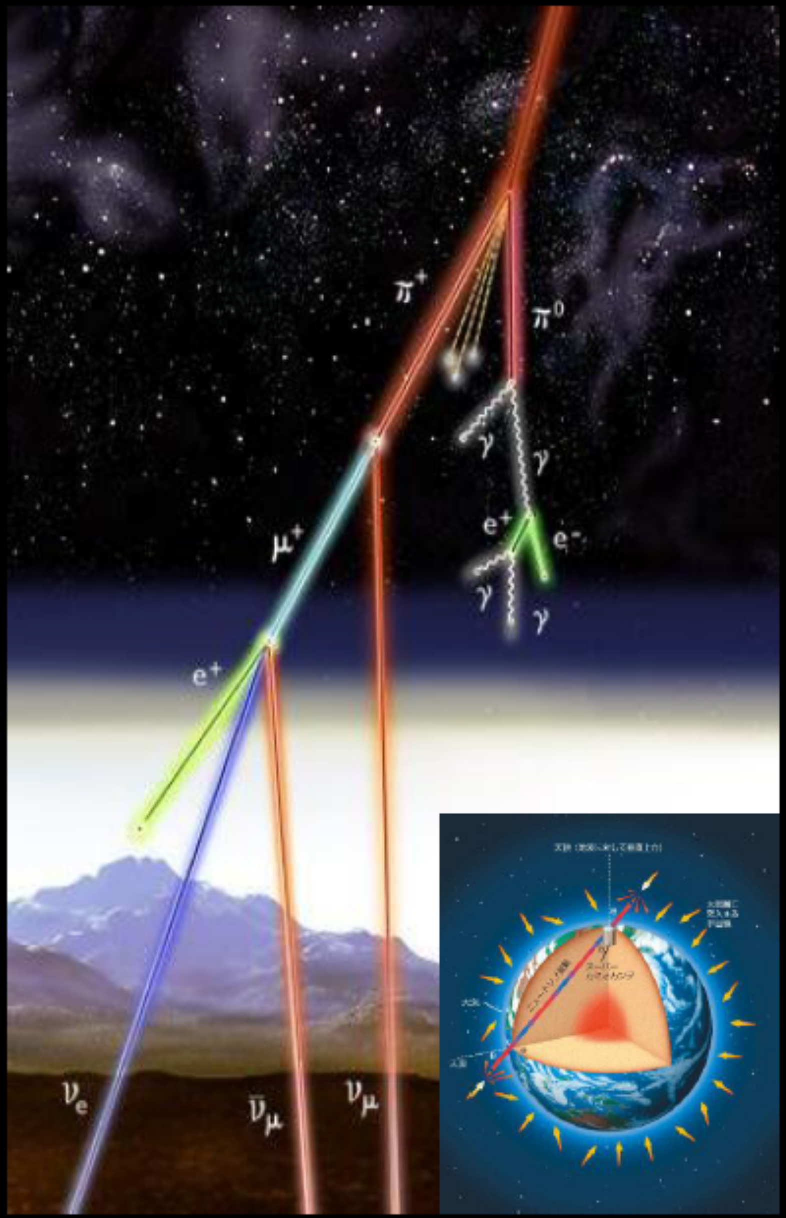
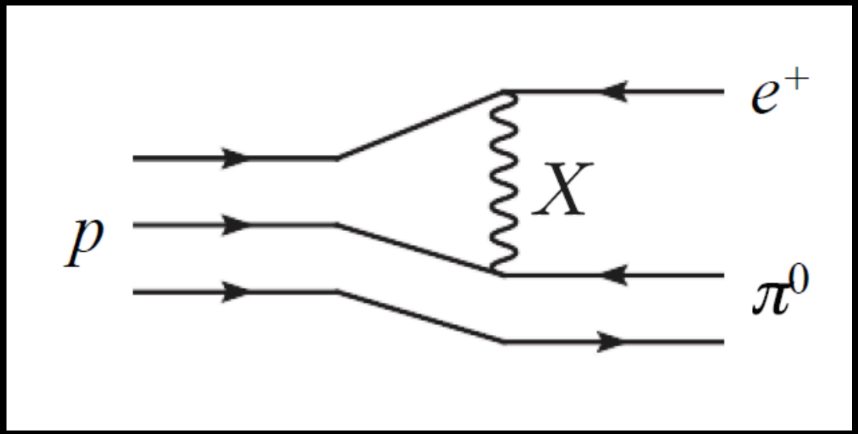
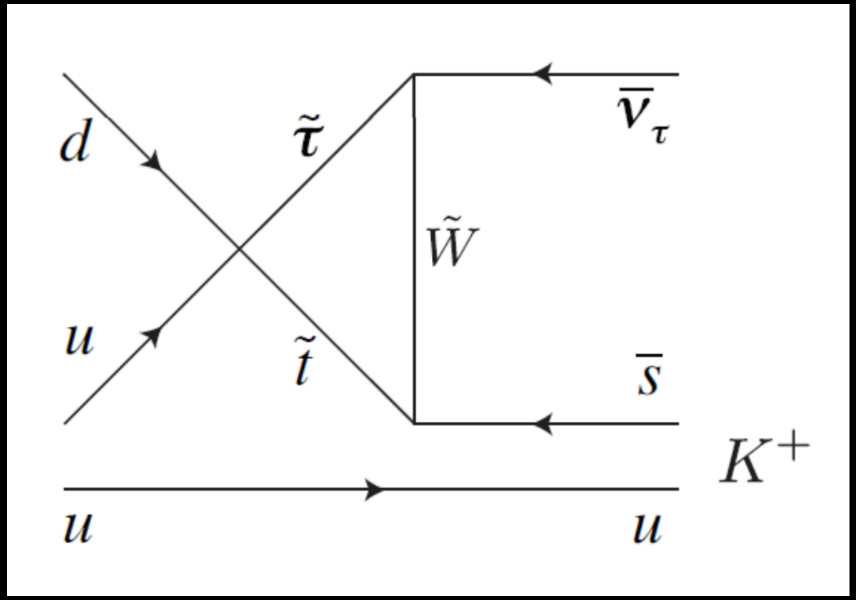
ATMPD-Gd

ATMospheric neutrinos and Proton Decay - Gd









Roger Wendell
The Gdfather Reborn Workshop
Kyoto University
2025.04.23

Introduction

- I'd like to give a brief tour of some *higher* energy physics topics at the Super-Kamiokande and how they benefit from the addition of gadolinum at SK

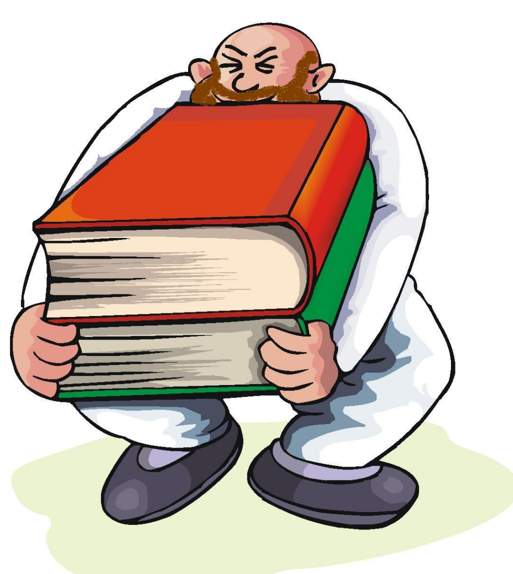
- For the most part this will cover Atmospheric Neutrino and Proton Decay studies at Super-Kamiokande as well as touching lightly on some accelerator neutrino topics
  - Certainly not an exhaustive list

Impressions from an End User

- Always up an interesting conversation on a variety of topics, both physics and otherwise
  - BICEP2 result (2014) stands out

- Plenty of interesting stories…
  - Tool belts and smiles, driving with colleagues and their wives, among many others

- Entertaining presentations (Win95 era clip art, animations)
  - Hawaiian shirts, Santa in Japan



共存共栄

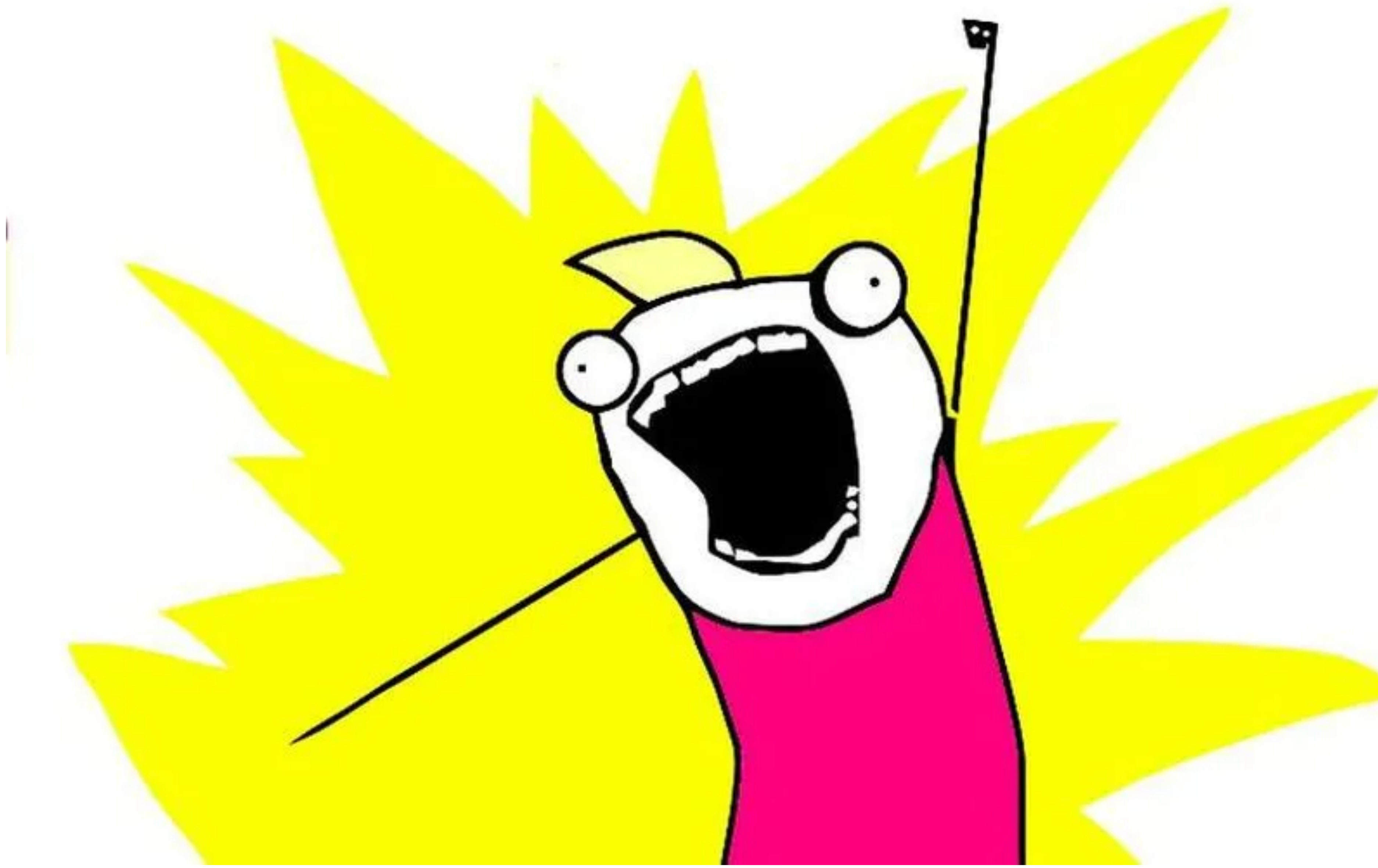
kyou son kyou ei

Coexistence and coprosperity

Happy Birthday Mark!

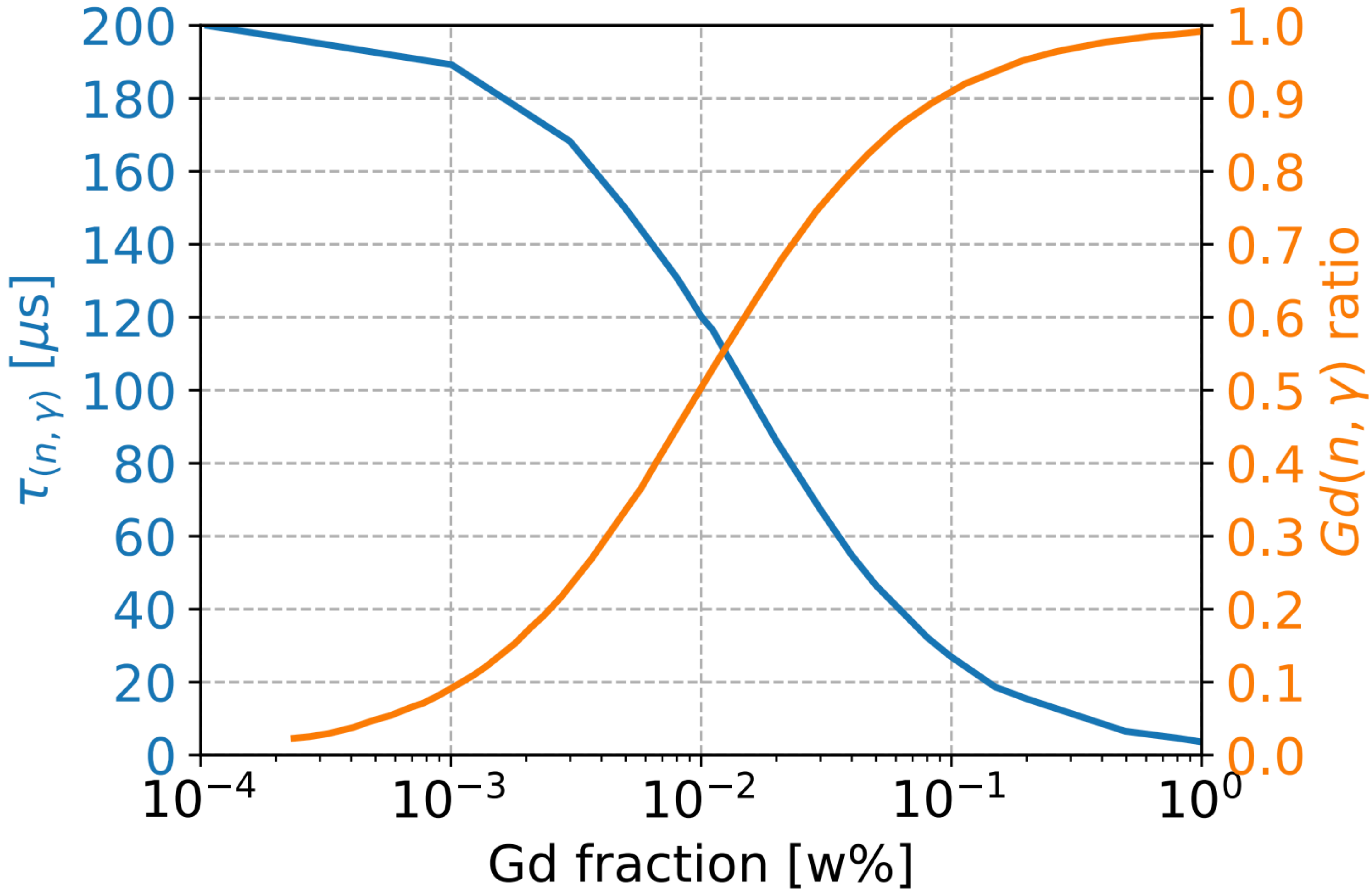
- ….and of course a deep passion for "gadiatiang" (and memes)

Gadiate all the detectors !



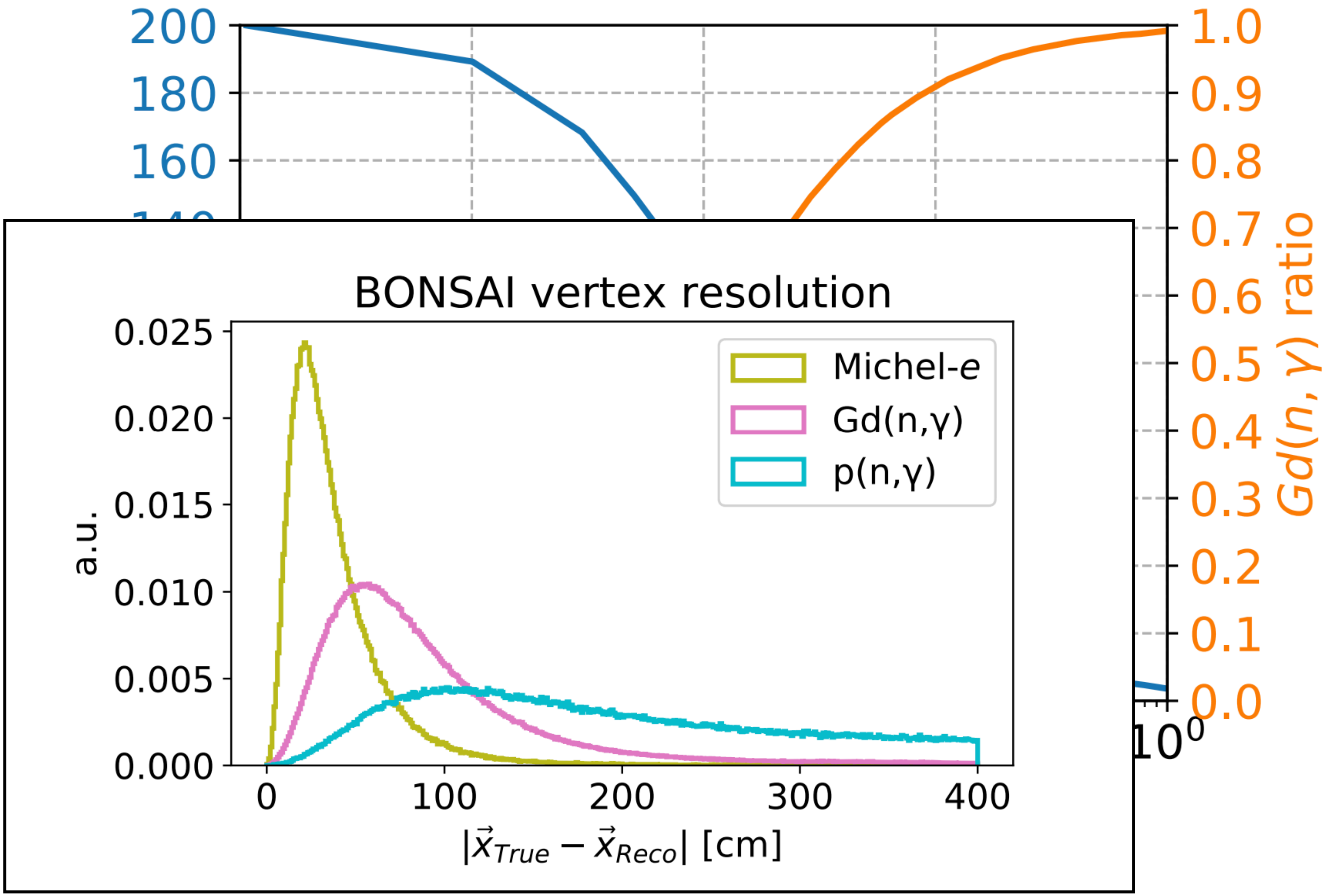
Gadolinium in Super-K
(ATMPD)

Expectation



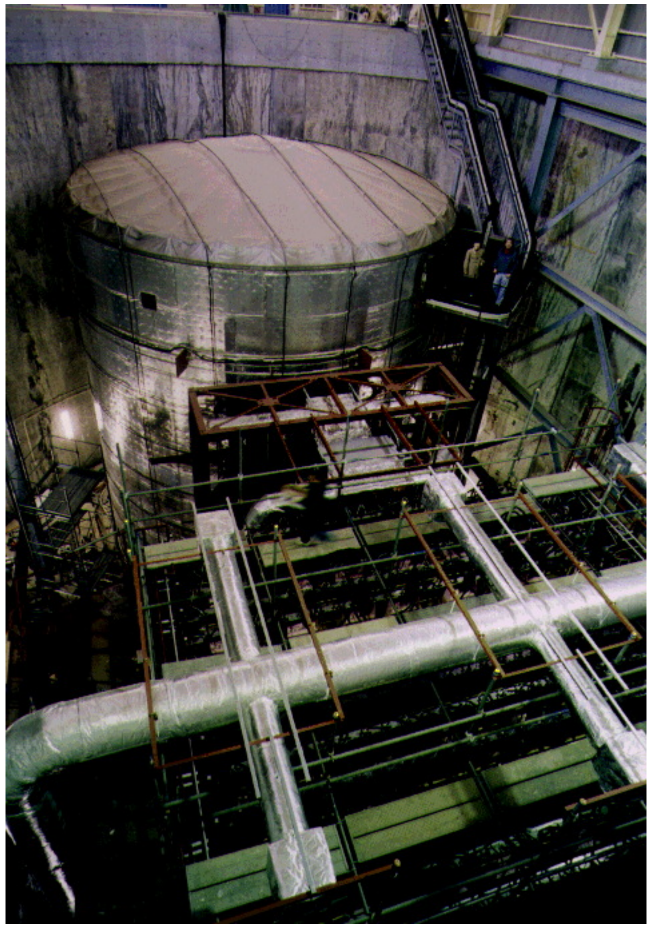
- For a little bit of Gd…
  - … one can get a lot of neutron captures at reconstructable energies

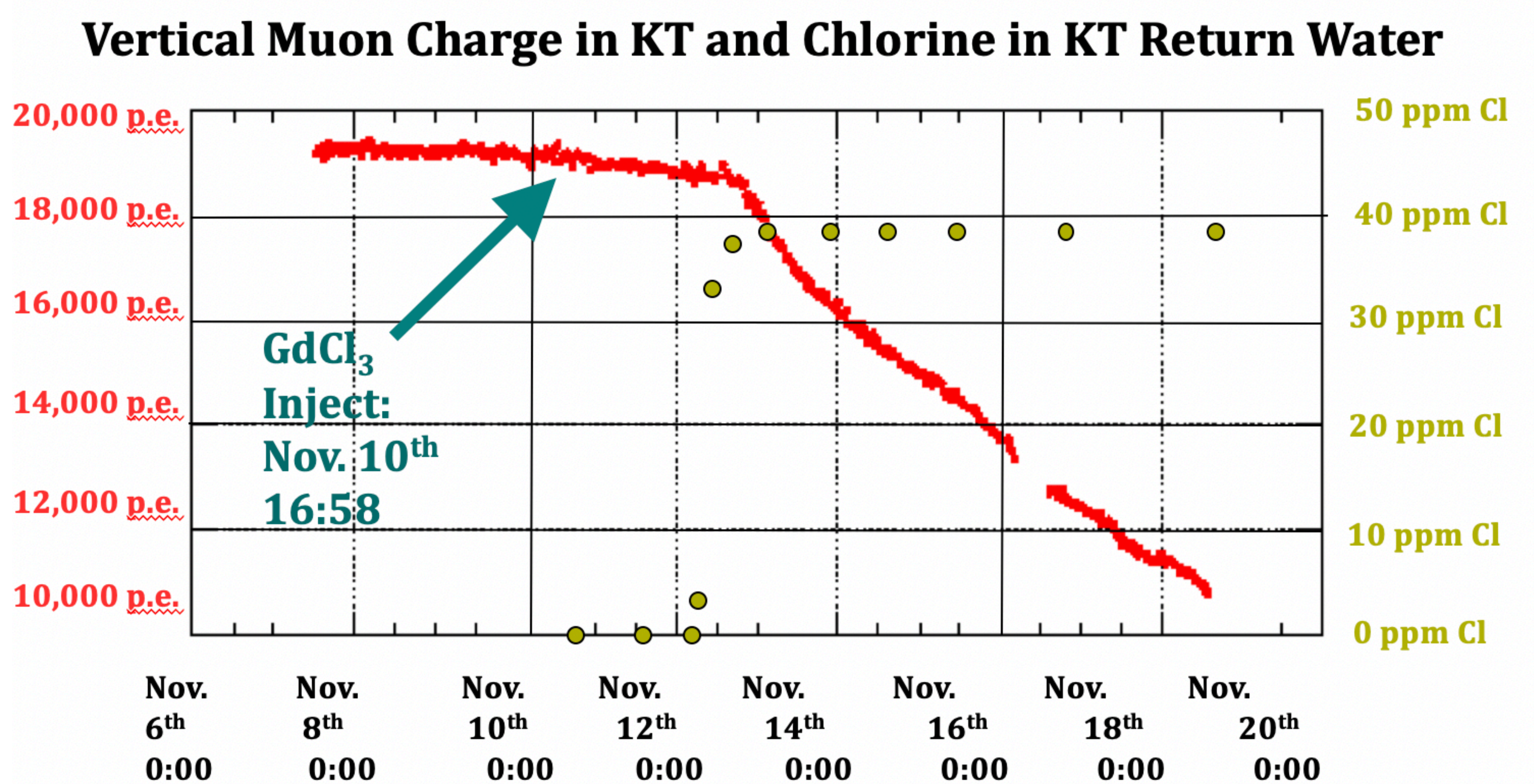
The Goal



- For a little bit of Gd…
  - … one can get a lot of neutron captures at reconstructable energies

A bit of Trepidation: The K2K 1 Kiloton Experience

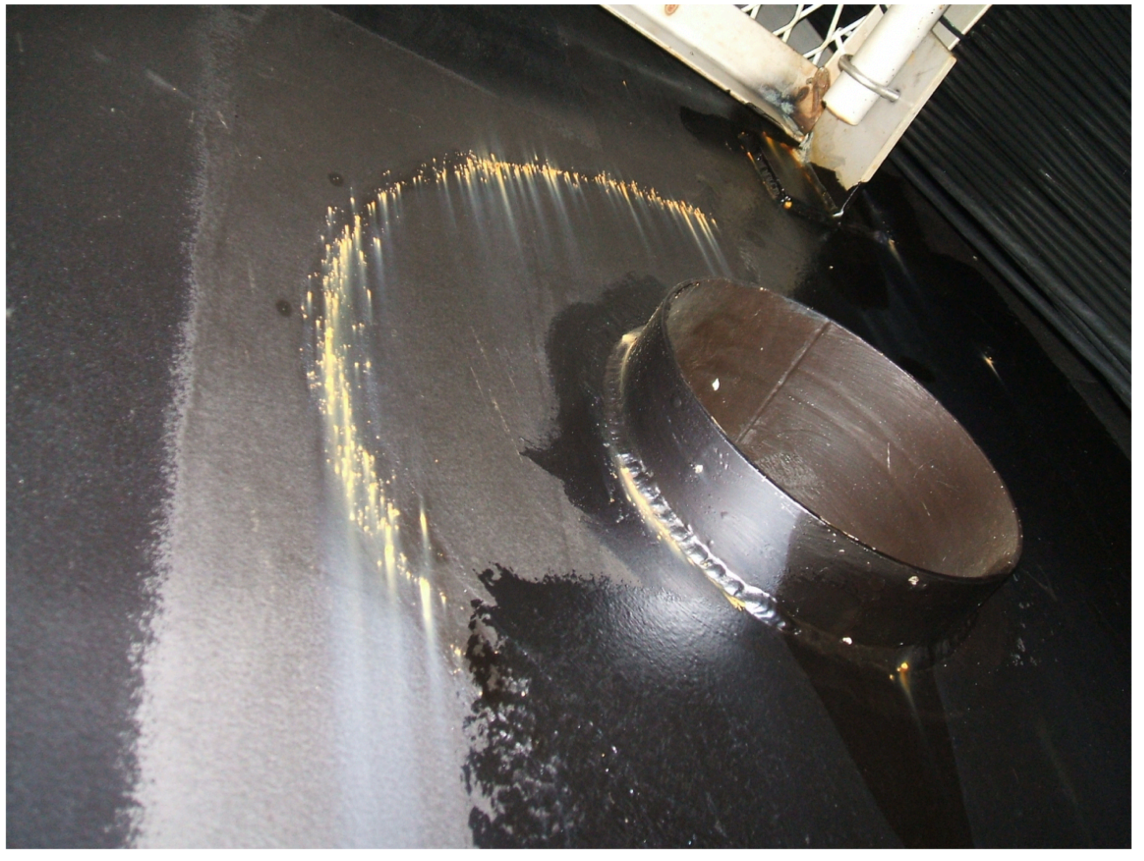


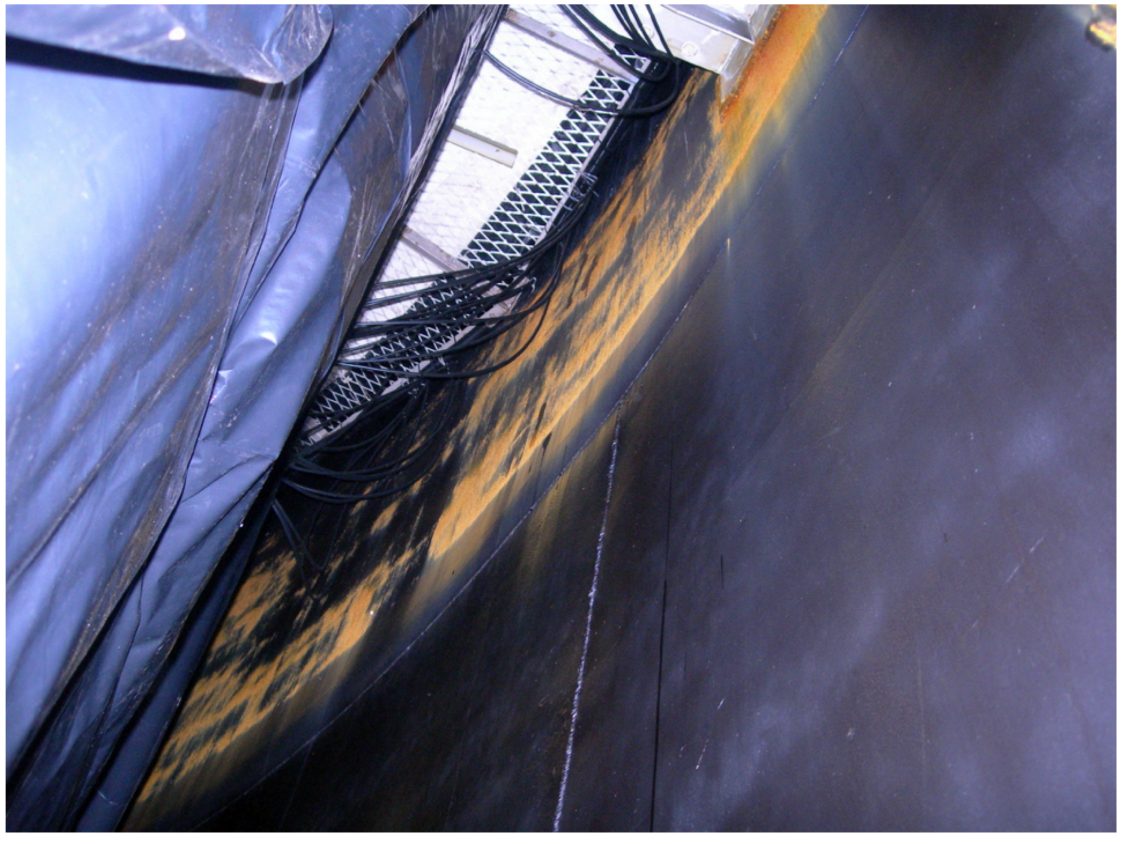


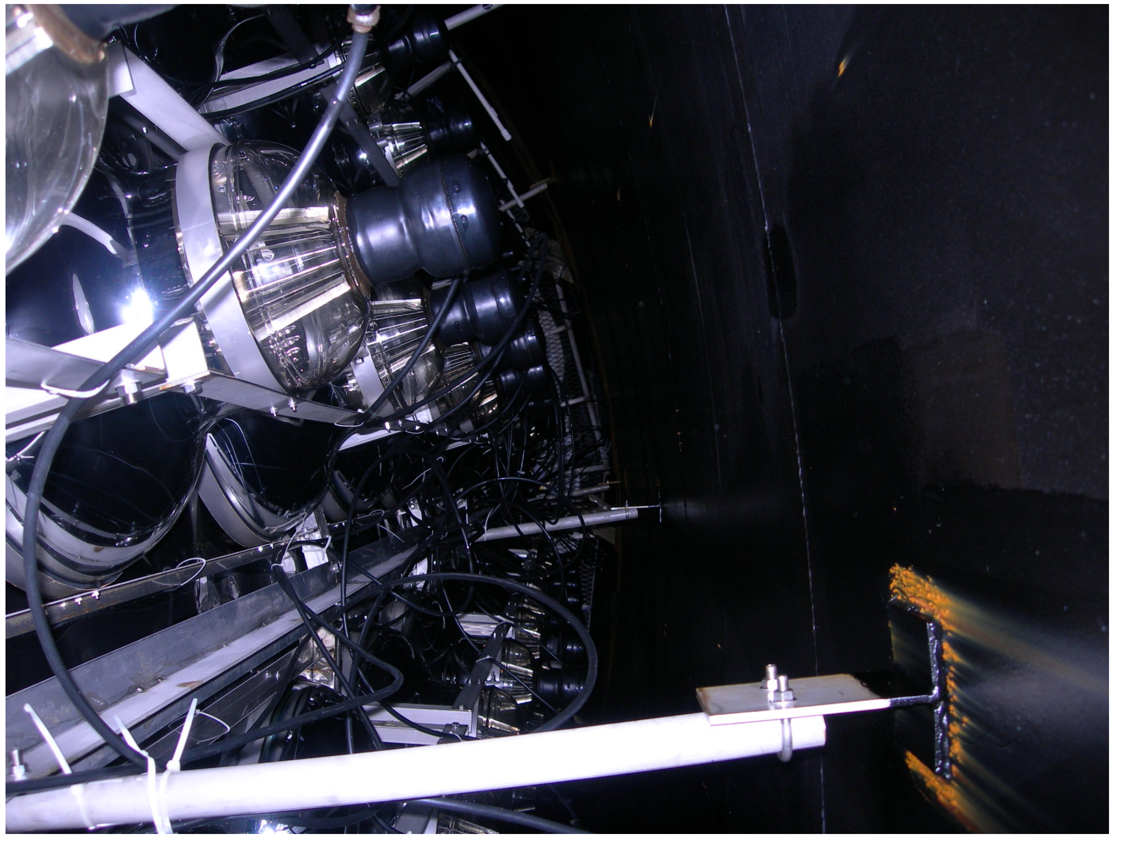
Circa 2005

- Initial tests of Gd ($GdCl_3$) in the K2K 1 kiloton detector raised my eyebrows

A bit of Trepidation: The K2K 1 Kiloton Experience

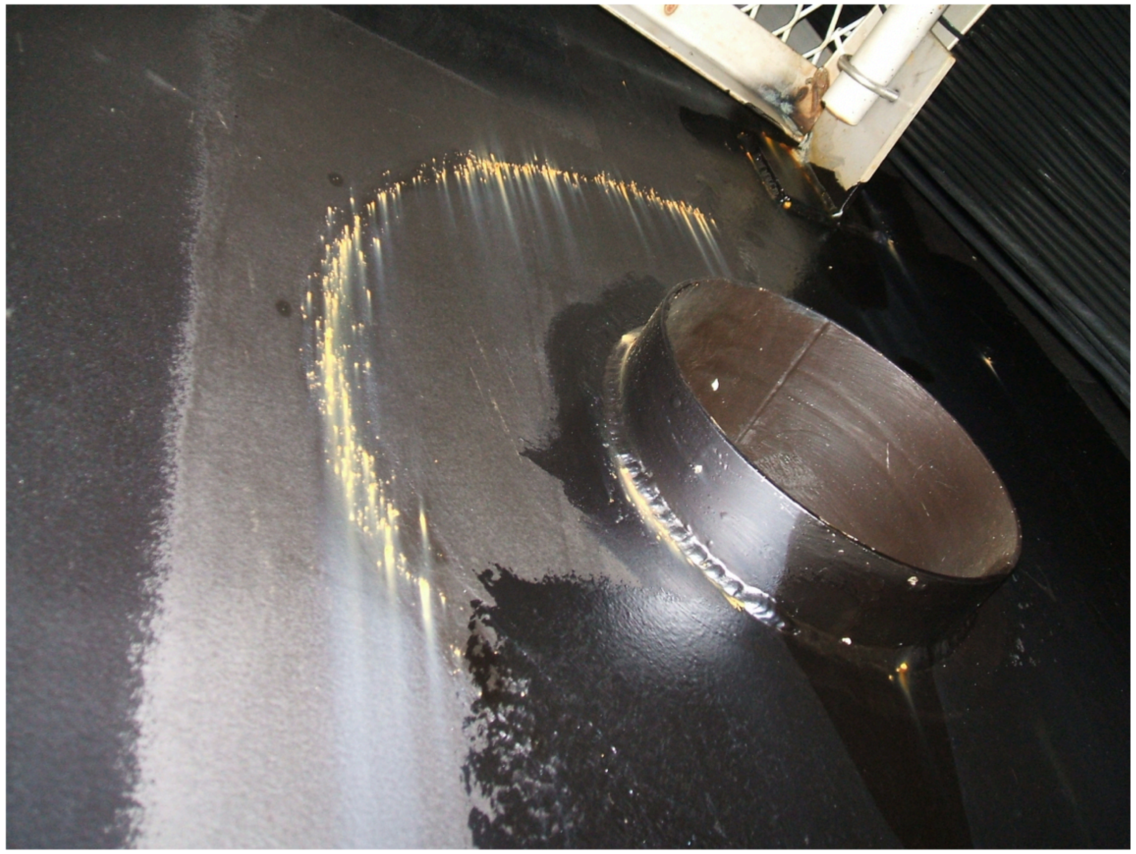


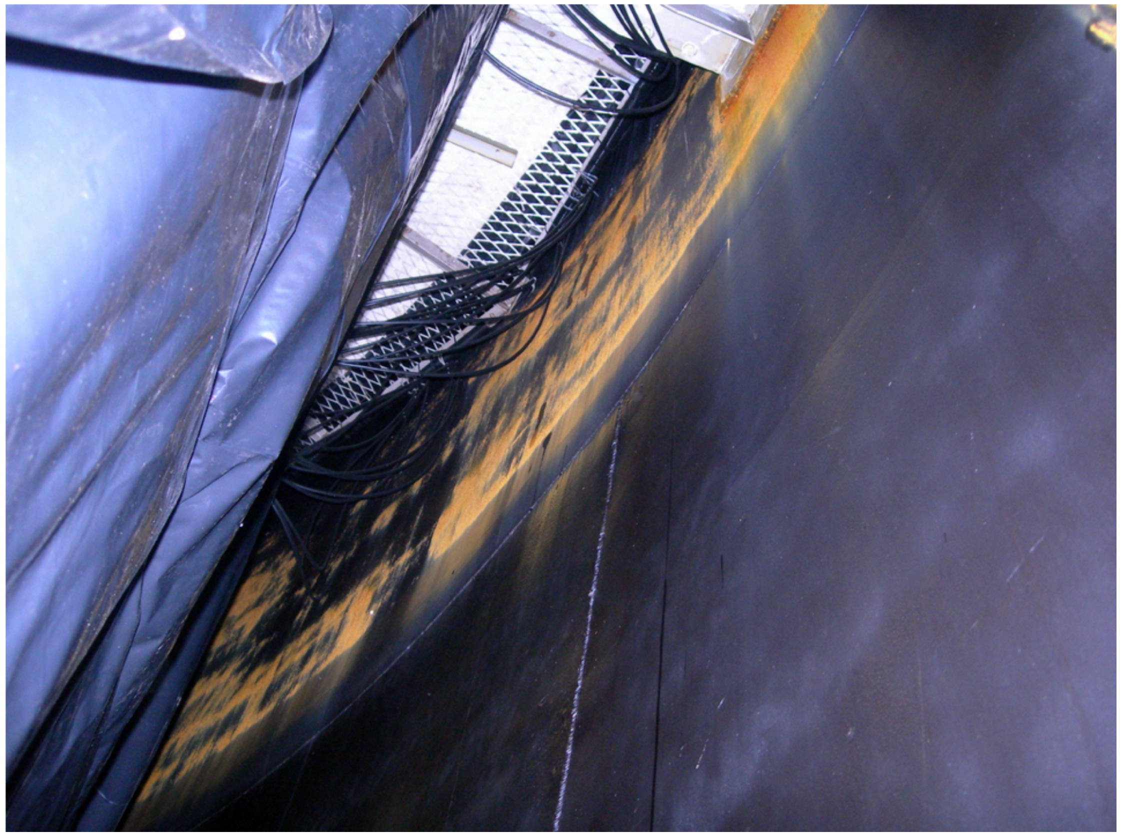


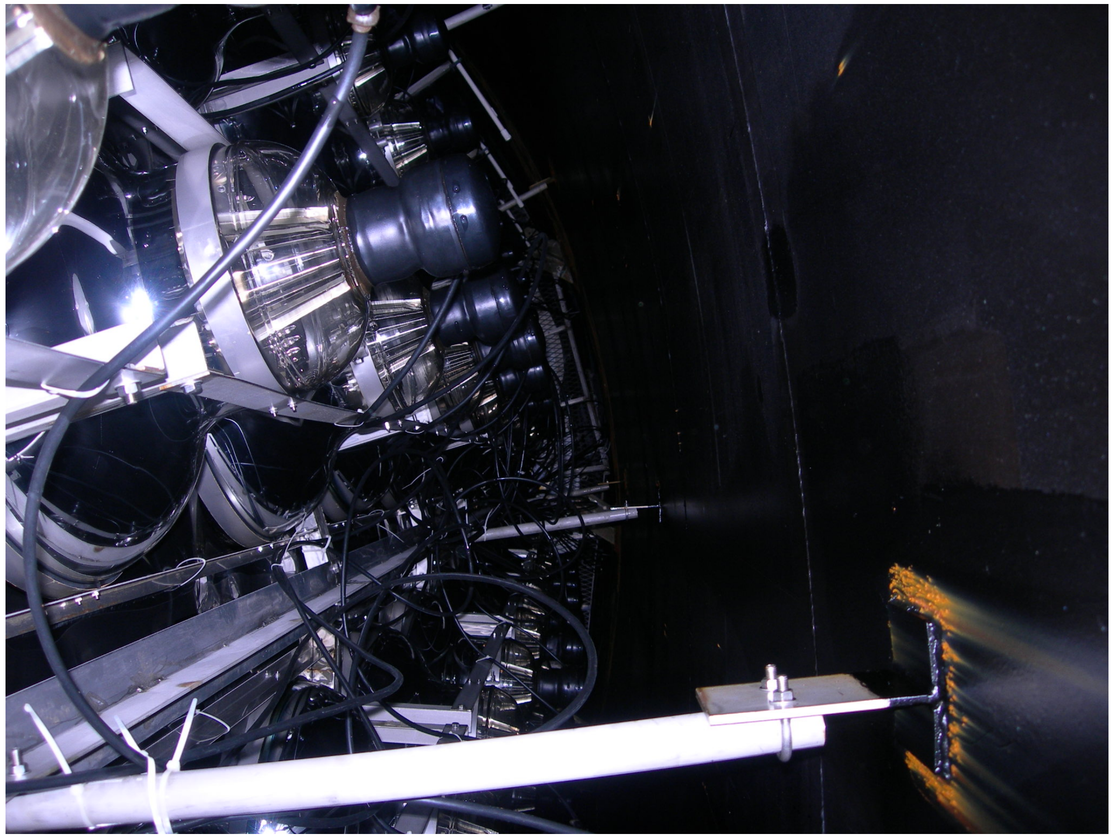


The atmosphere in the meeting was palpable

A bit of Trepidation: The K2K 1 Kiloton Experience







- Learned that coating of 1 kton (Iron) detector was probably not applied evenly…so rust!
  - Gd compound is good at bringing rust into solution

- For use in a real detector, material choice is extremely important (SK - SUS)!

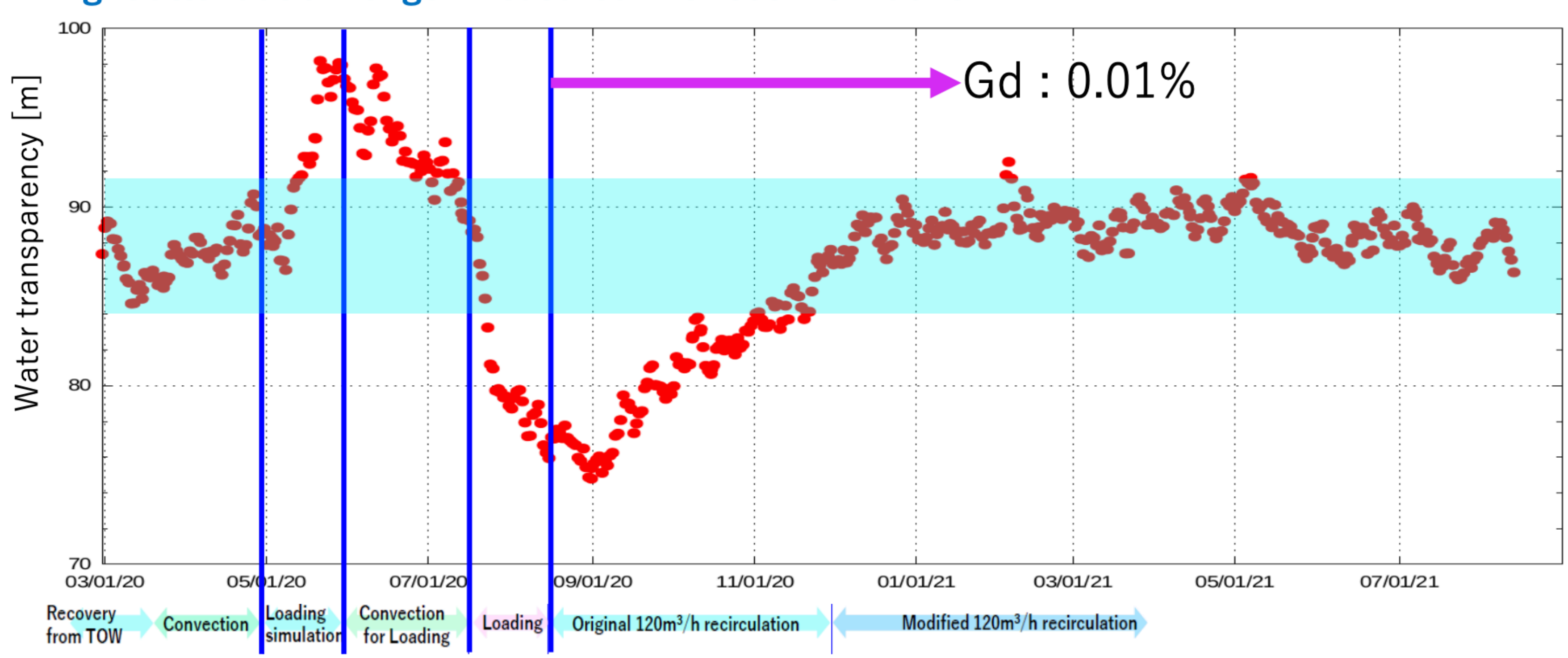
Fortunately…after a lot of R&D we achieved Gd loading

From Mark at 2017 SK Collaboration meeting

→ Since April 2015, EGADS has been fully loaded with the target goal of 0.2% (390.6 kg) of $Gd_2(SO_4)_3$. We have just looked in the tank for the first time in years – at first glance everything appears perfect. The tank will be drained and inspected next month.

→ As you will see in the coming talks, thanks to the efforts of many people over many years, gadolinium in Super-K is now well on its way to becoming a reality. <u>We are on track for the recently approved tank work during 2018.</u>

Light attenuation length measured with cosmic muons



M. Ikeda 2022 (LowBg)

Stable water transparency has been recovered few month after the loading

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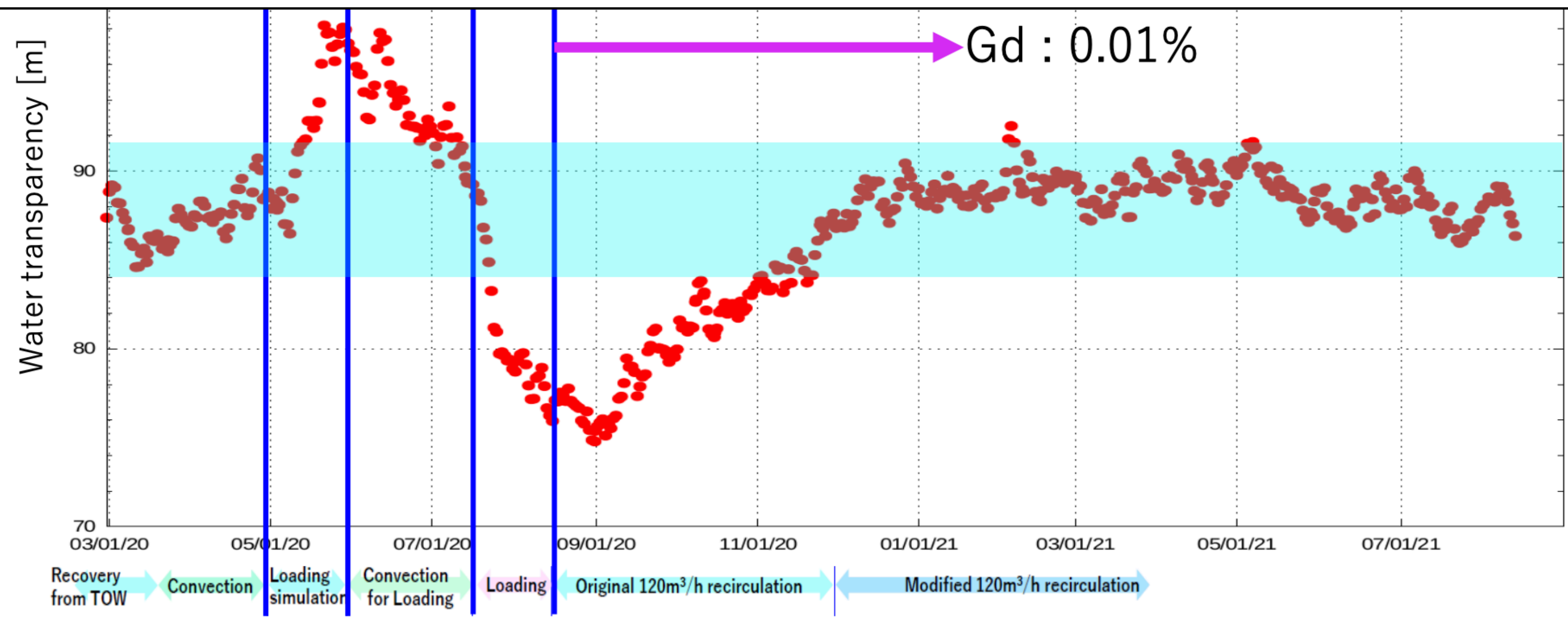
→ As you will see in the coming talks, thanks to the efforts of many peo… way… tank…

An important message about persistence and careful R&D!



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Stable water transparency has been recovered few month after the loading

Higher Energy Physics Overview

- Neutrino oscillations
  - CP Violation - difference in oscillation of ν and $\bar{\nu}$
  - Mass hierarchy - difference in matter effect between ν and $\bar{\nu}$
- Neutrino interactions
  - Neutron production in ν-nucleus interactions
- Proton decays
  - Signal is not expected to have final state neutrons, whereas primary backgrounds often do

Status of Neutrino Oscillations: PMNS Mixing

$c_{xy} = \cos\theta_{xy}$, $s_{xy} = \sin\theta_{xy}$,

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Atmospheric — Reactor — Solar

- Three mixing angles, two independent mass differences (Δm^2_{21} , Δm^2_{32}), and a CP-violating phase δ_{cp}
- Currently, ***all*** parameters have been measured, though δ_{cp} is the least well constrained and the topic of much interest

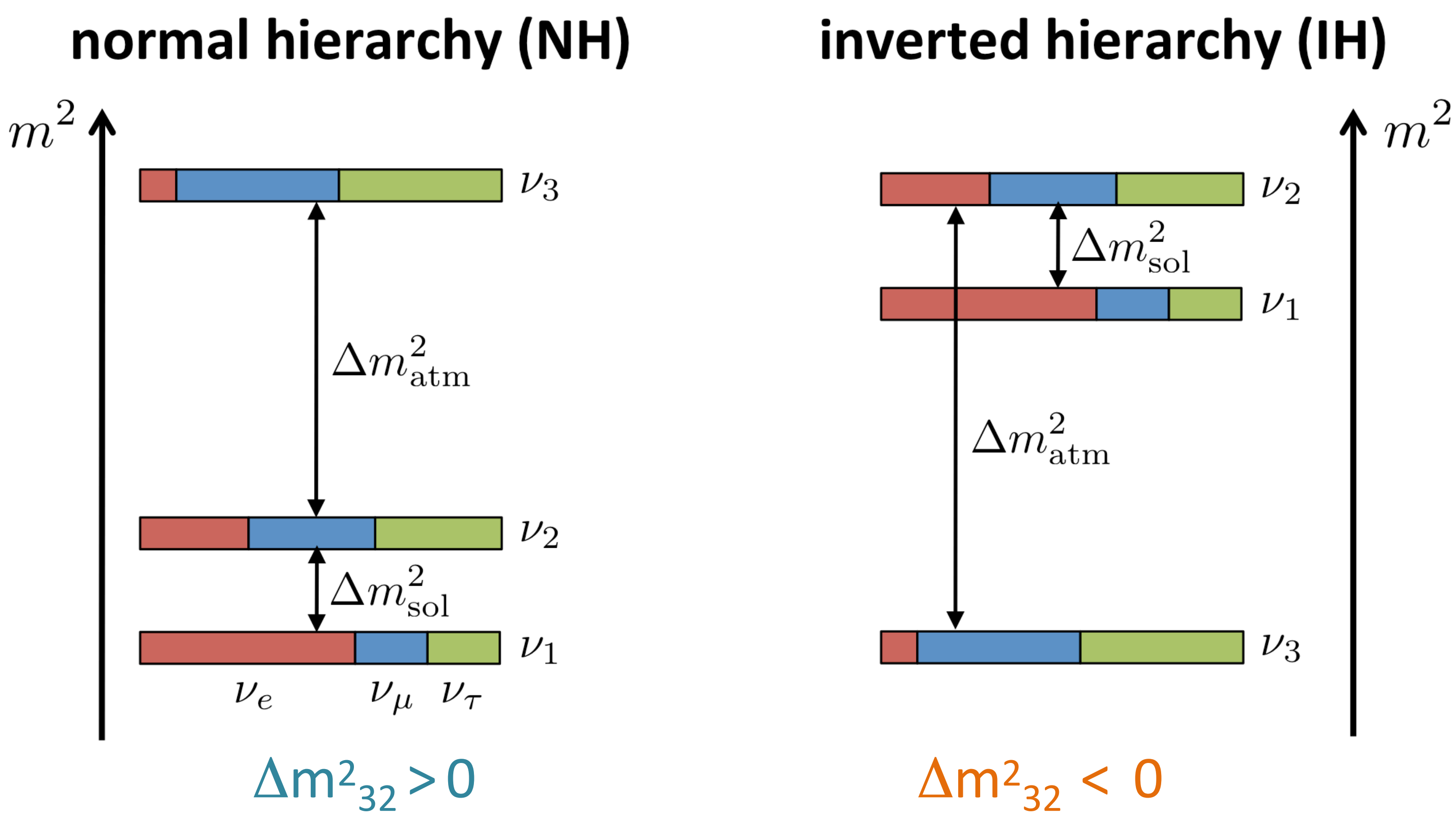
Open Questions:

- Precise value of θ_{23} ("octant"), nature of mass ordering, important parameters do address CPV.

Global Fit: JHEP 2021, 71 (2021)

parameter	best fit $\pm 1\sigma$	2σ range	3σ range
$\Delta m^2_{21}[10^{-5}\text{eV}^2]$	$7.50^{+0.22}_{-0.20}$	7.12–7.93	6.94–8.14
$\lvert\Delta m^2_{31}\rvert[10^{-3}\text{eV}^2]$ (NO)	$2.55^{+0.02}_{-0.03}$	2.49–2.60	2.47–2.63
$\lvert\Delta m^2_{31}\rvert[10^{-3}\text{eV}^2]$ (IO)	$2.45^{+0.02}_{-0.03}$	2.39–2.50	2.37–2.53
$\sin^2\theta_{12}/10^{-1}$	3.18 ± 0.16	2.86–3.52	2.71–3.69
$\theta_{12}/^\circ$	34.3 ± 1.0	32.3–36.4	31.4–37.4
$\sin^2\theta_{23}/10^{-1}$ (NO)	5.74 ± 0.14	5.41–5.99	4.34–6.10
$\theta_{23}/^\circ$ (NO)	49.26 ± 0.79	47.37–50.71	41.20–51.33
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.78^{+0.10}_{-0.17}$	5.41–5.98	4.33–6.08
$\theta_{23}/^\circ$ (IO)	$49.46^{+0.60}_{-0.97}$	47.35–50.67	41.16–51.25
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.200^{+0.069}_{-0.062}$	2.069–2.337	2.000–2.405
$\theta_{13}/^\circ$ (NO)	$8.53^{+0.13}_{-0.12}$	8.27–8.79	8.13–8.92
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.225^{+0.064}_{-0.070}$	2.086–2.356	2.018–2.424
$\theta_{13}/^\circ$ (IO)	$8.58^{+0.12}_{-0.14}$	8.30–8.83	8.17–8.96
δ/π (NO)	$1.08^{+0.13}_{-0.12}$	0.84–1.42	0.71–1.99
$\delta/^\circ$ (NO)	194^{+24}_{-22}	152–255	128–359
δ/π (IO)	$1.58^{+0.15}_{-0.16}$	1.26–1.85	1.11–1.96
$\delta/^\circ$ (IO)	284^{+26}_{-28}	226–332	200–353

Status of Neutrino Oscillations: PMNS Mixing



Several open questions

- What is the neutrino mass ordering (MO)
  - Normal Ordering (NO): $m_1 < m_2 < m_3$,
  - Inverted ordering (IO): $m_3 < m_1 < m_2$
- Why?
  - $0\nu\beta\beta$ - if process exists, rate ($\sim \langle m_{\beta\beta} \rangle$) depends on MO
  - Important implications for cosmology

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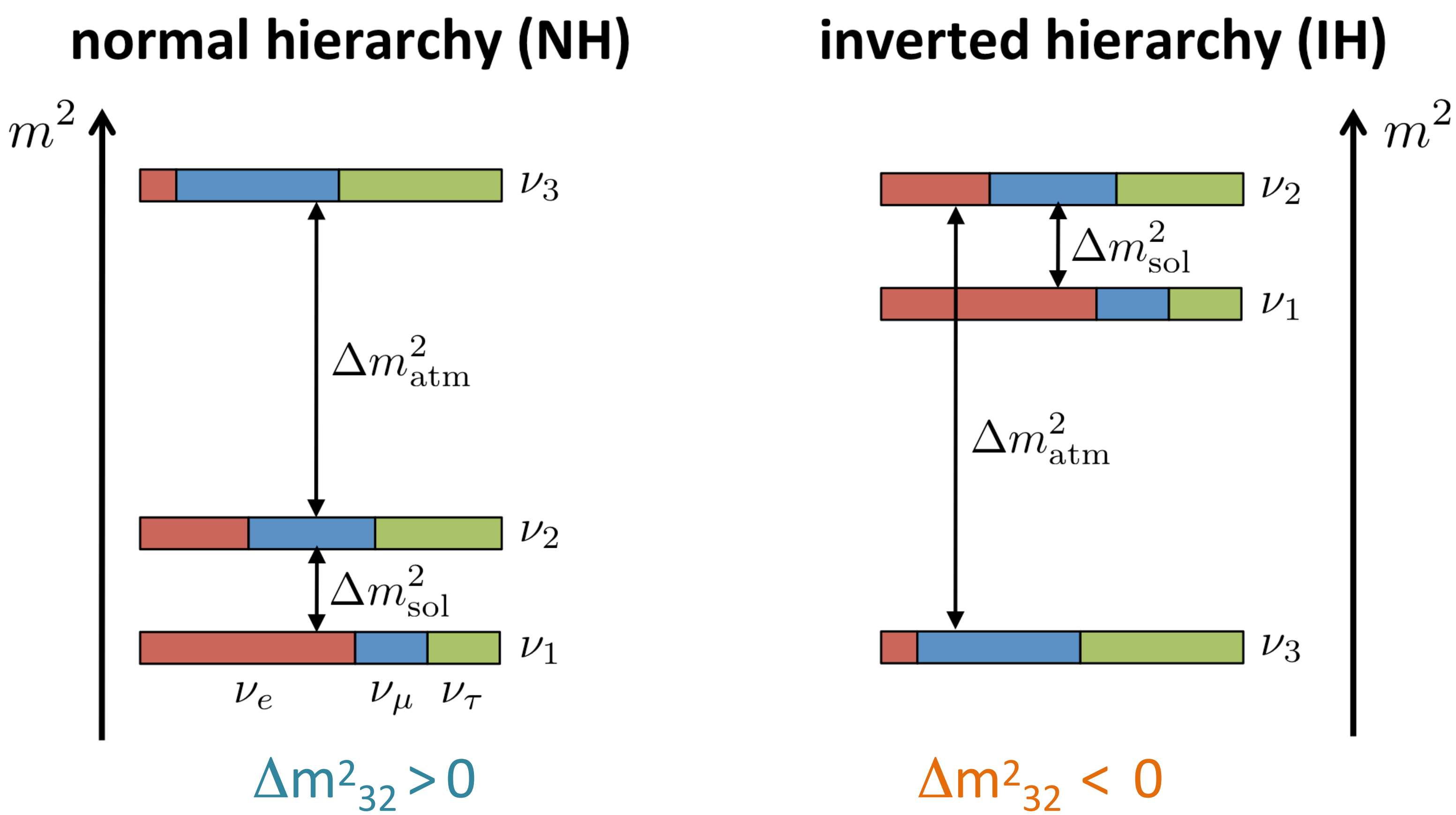

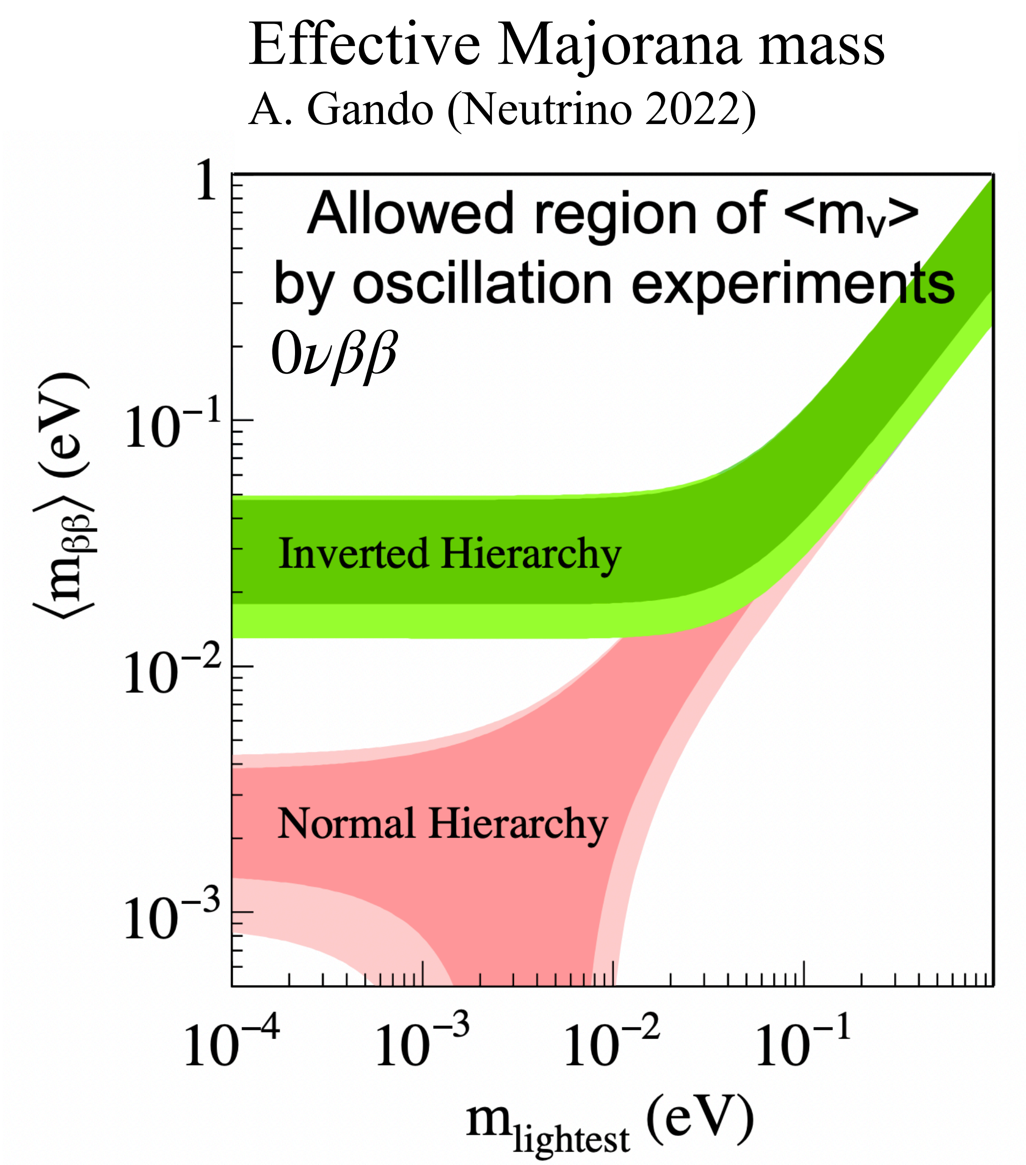

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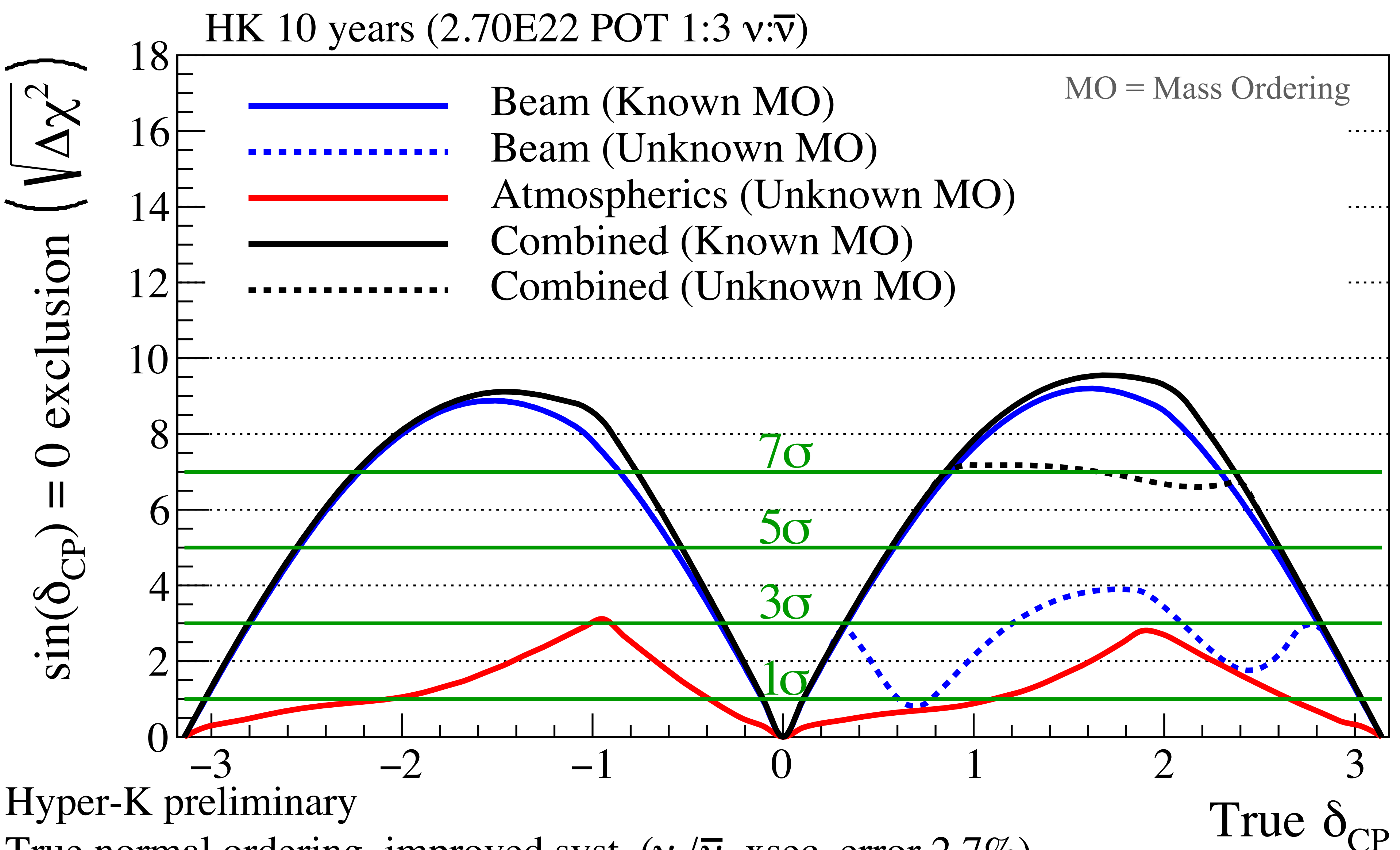
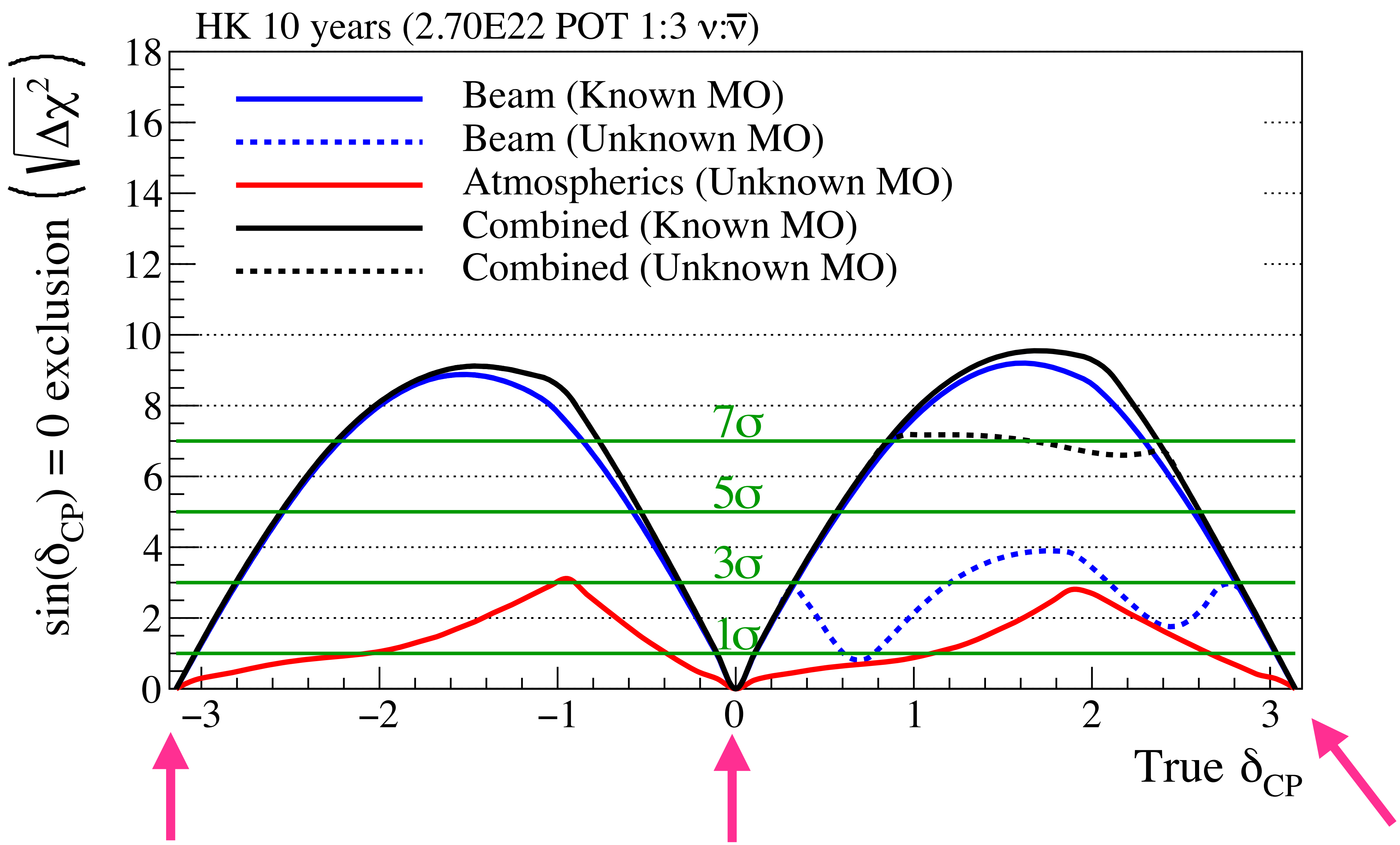
Goal: Observation of CP Violation - Hyper-K



Hyper-K preliminary
True normal ordering, improved syst. ($\nu_e/\bar{\nu}_e$ xsec. error 2.7%)
$\sin^2(\theta_{13})=0.0218$ $\sin^2(\theta_{23})=0.528$ $|\Delta m^2_{32}|= 2.509\times10^{-3}\ \mathrm{eV}^2/c^4$

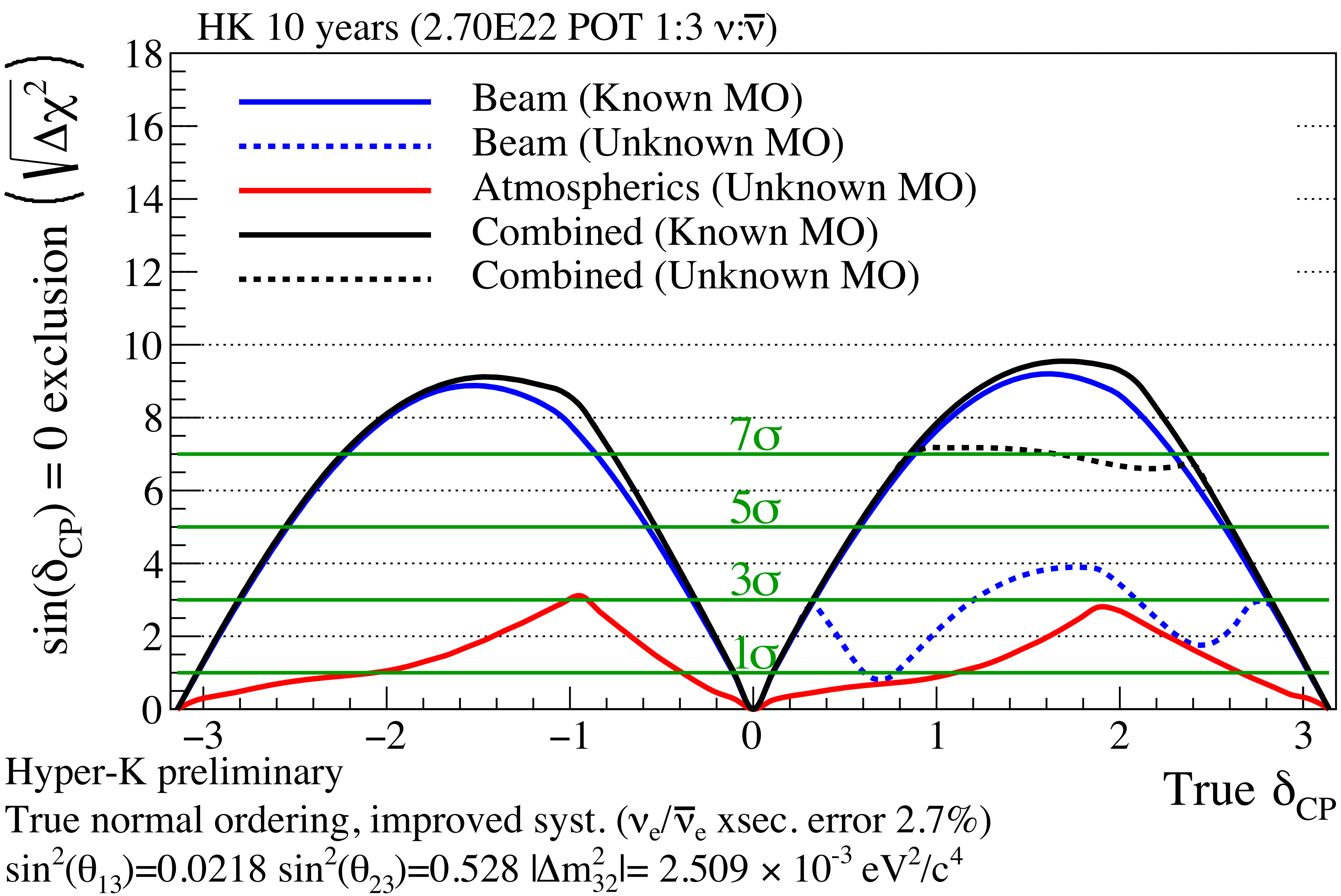
- Is there CP Violation (CPV) in the lepton sector?

Goal: Observation of CP Violation - Hyper-K



CP *conserving* values

Goal: Observation of CP Violation - Hyper-K



How to achieve this?

- Sensitivity to CP violation [$\sin(\delta_{CP,true}) \neq 0$] in neutrino oscillations by 2037 at Hyper-K :
- Assumes improvements in several systematic errors, O(1)% systematics

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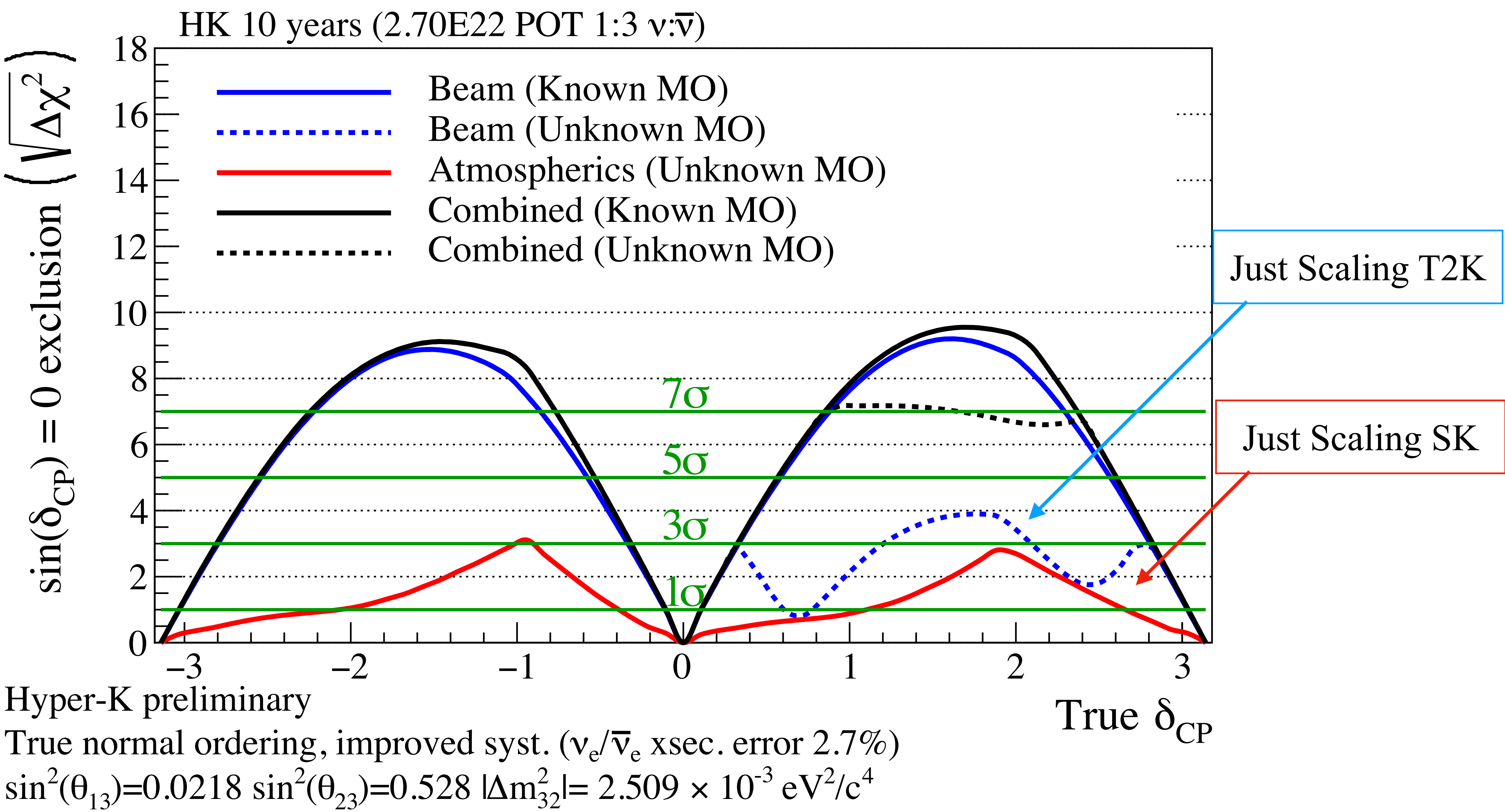

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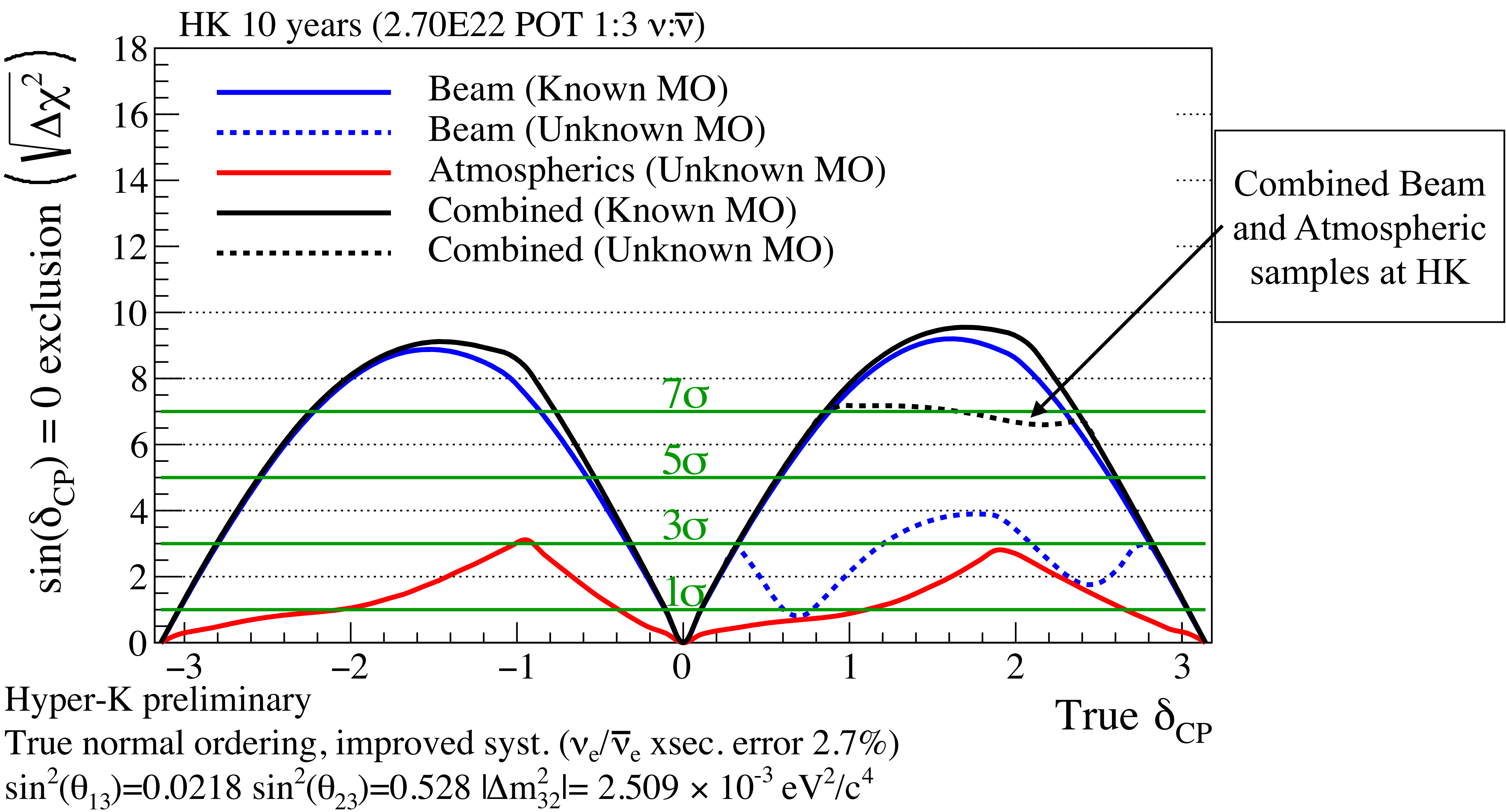

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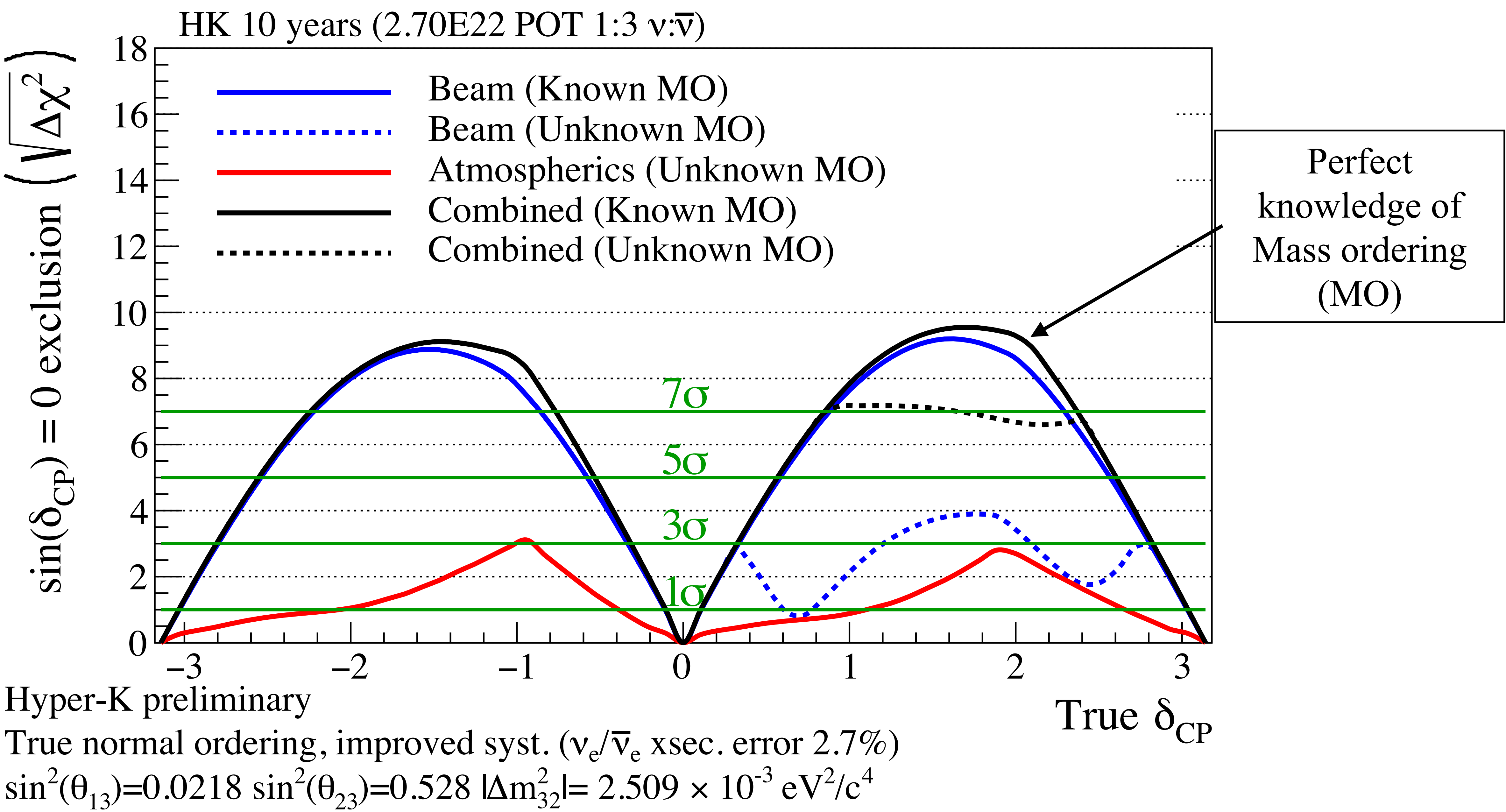

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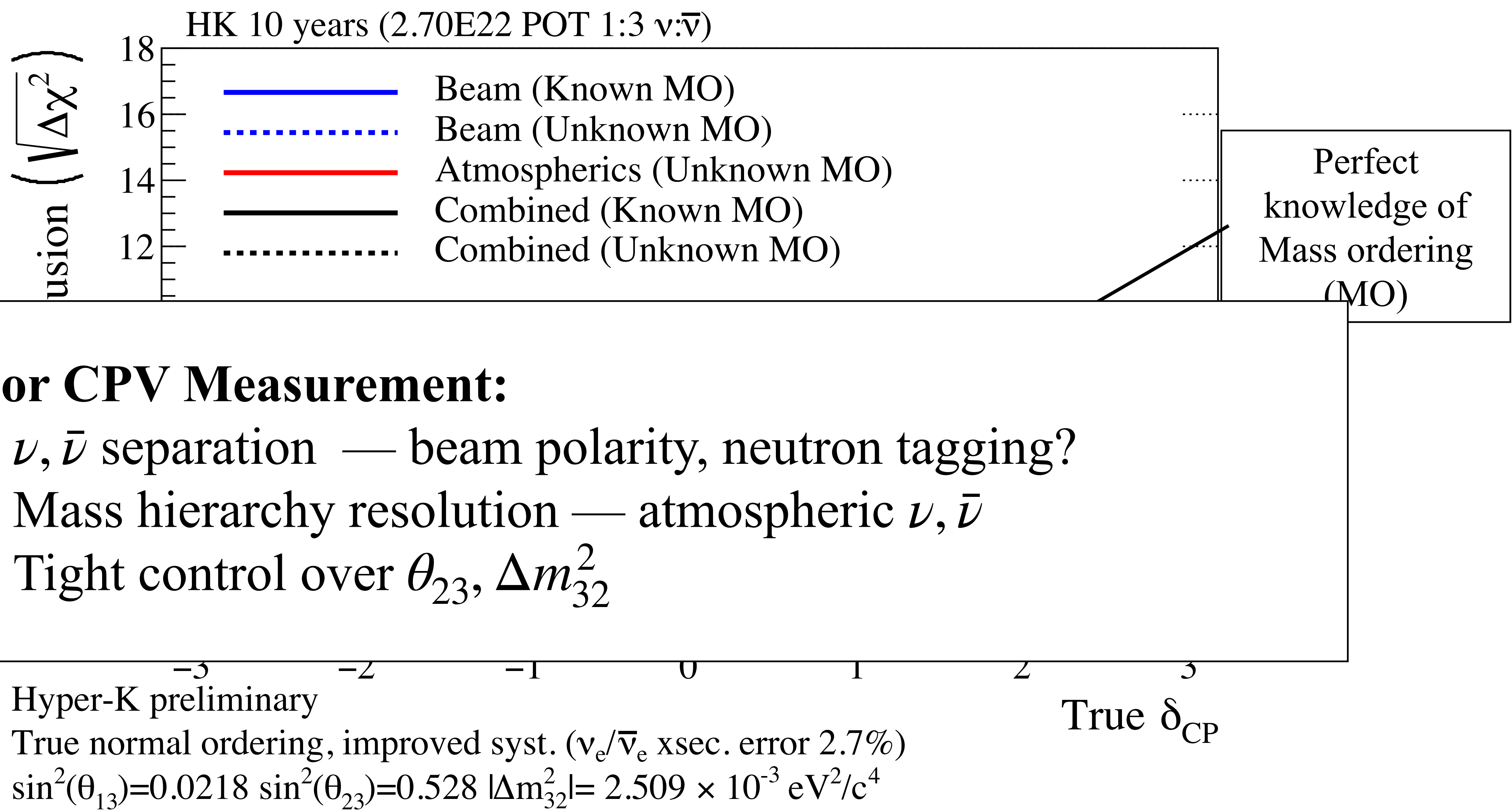


For CPV Measurement:

- $\nu, \bar{\nu}$ separation — beam polarity, neutron tagging?
- Mass hierarchy resolution — atmospheric $\nu, \bar{\nu}$
- Tight control over θ_{23}, Δm^2_{32}

How to achieve this?

- Sensitivity to CP violation [$\sin(\delta_{CP,true}) \neq 0$] in neutrino oscillations by 2037 at Hyper-K :
- Assumes improvements in several systematic errors, O(1)% systematics

Details

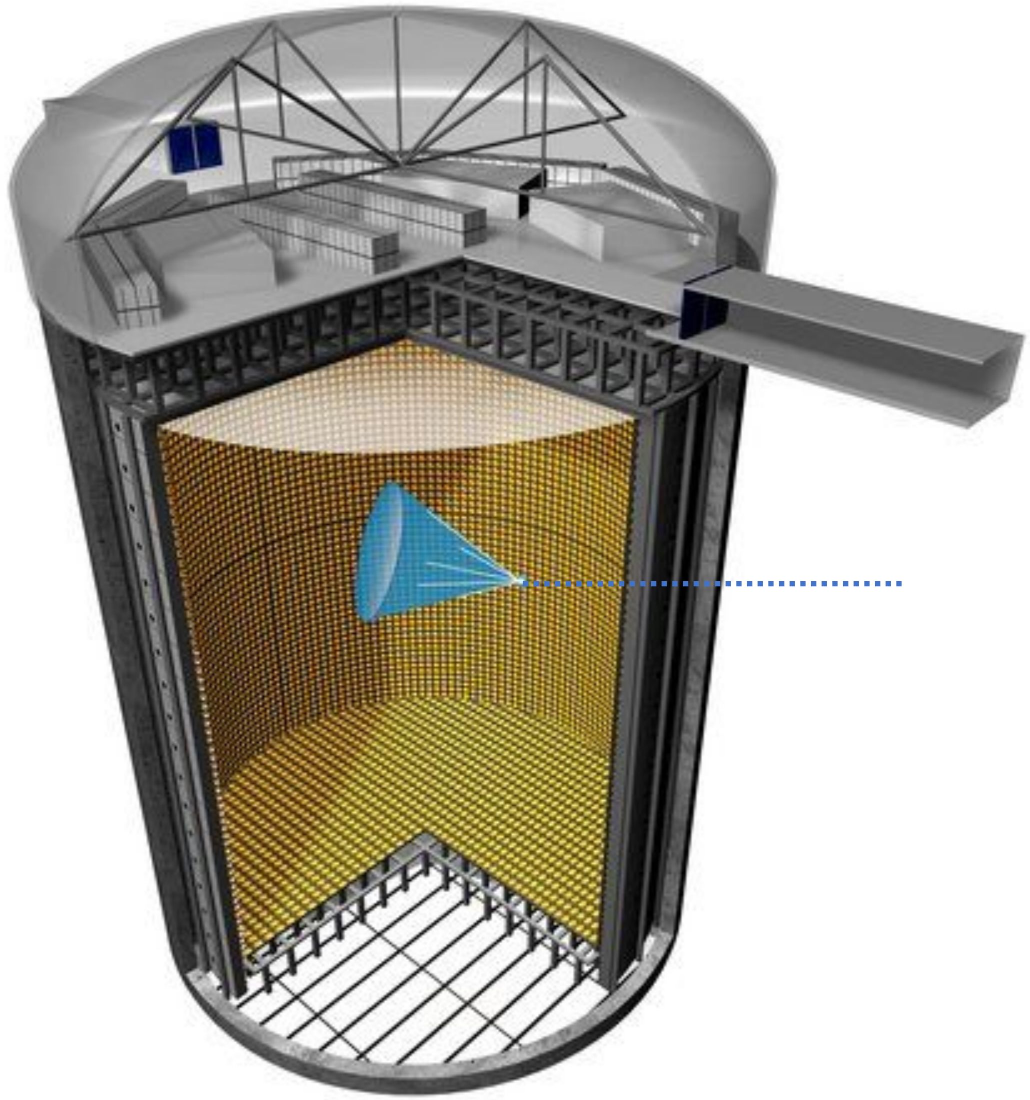
- Neutrino oscillations
  - CP Violation - difference in oscillation of ν and $\bar{\nu}$
  - Mass hierarchy - difference in matter effect between ν and $\bar{\nu}$
- Proton decays
  - Signal is not expected to have final state neutrons, whereas primary backgrounds often do

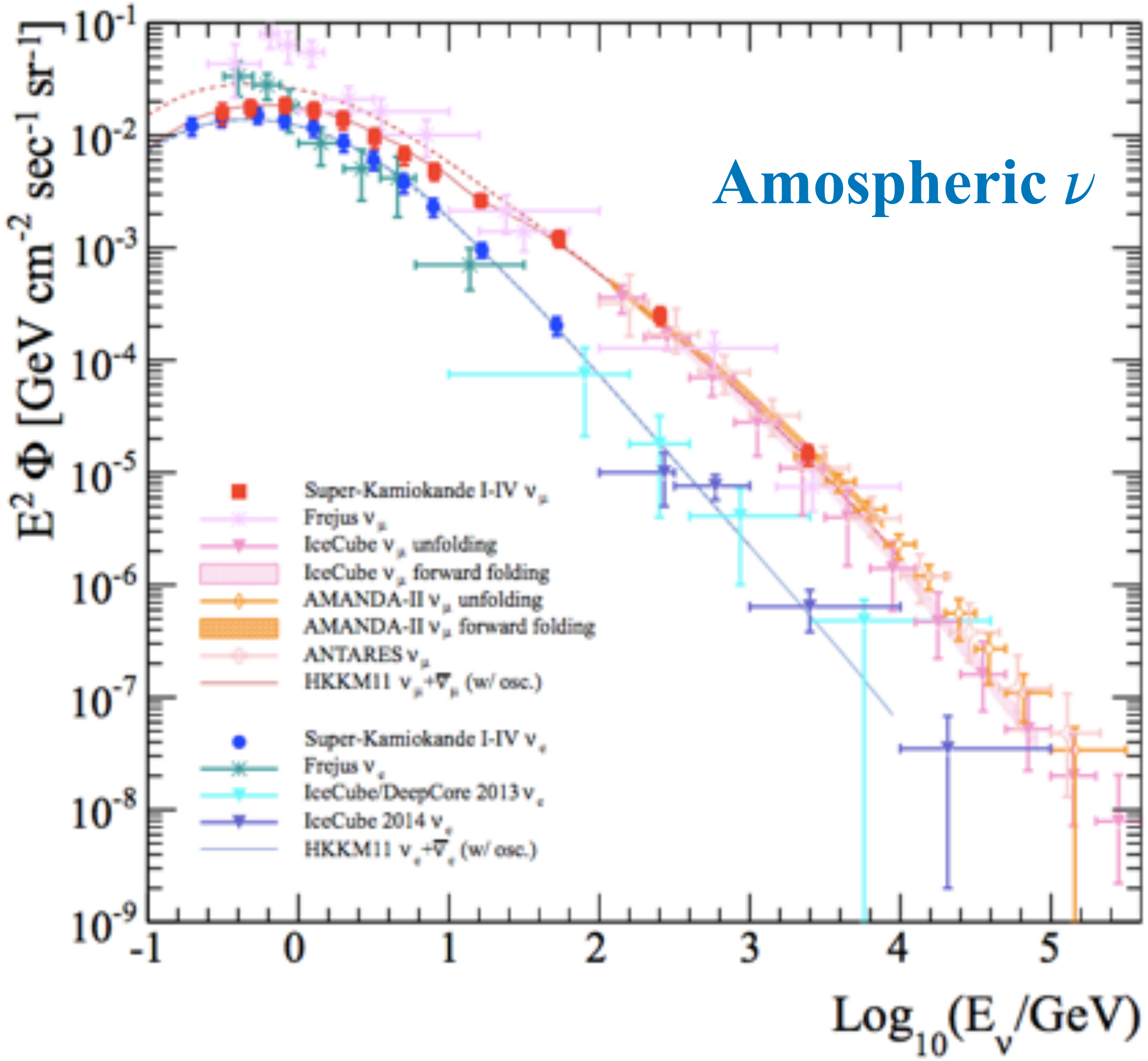
Ideal scenario:

Neutrino charged current : no neutrons in the final state

Antineutrino charged current : a single neutron in the final state

The Super-Kamiokande Experiment

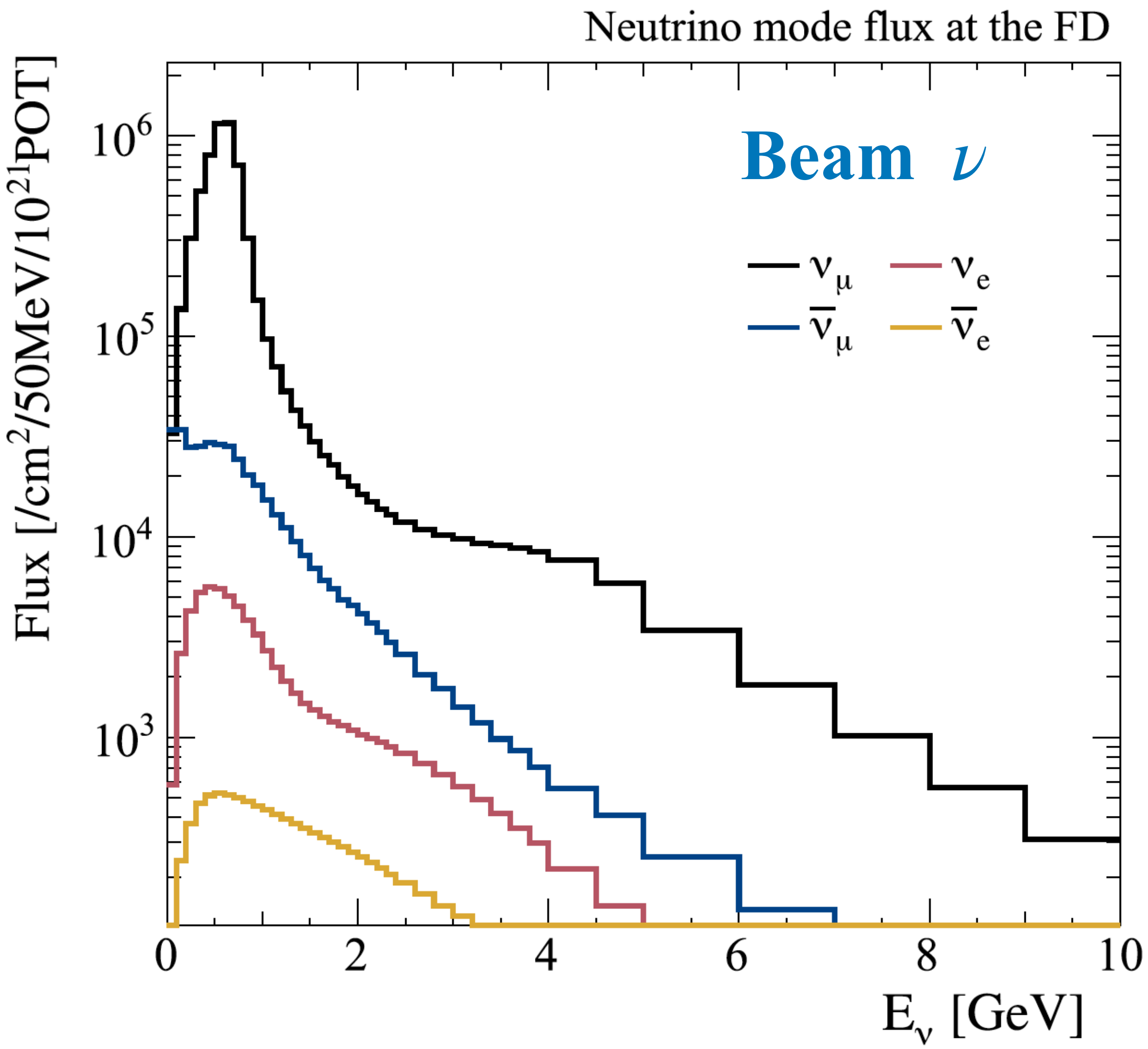


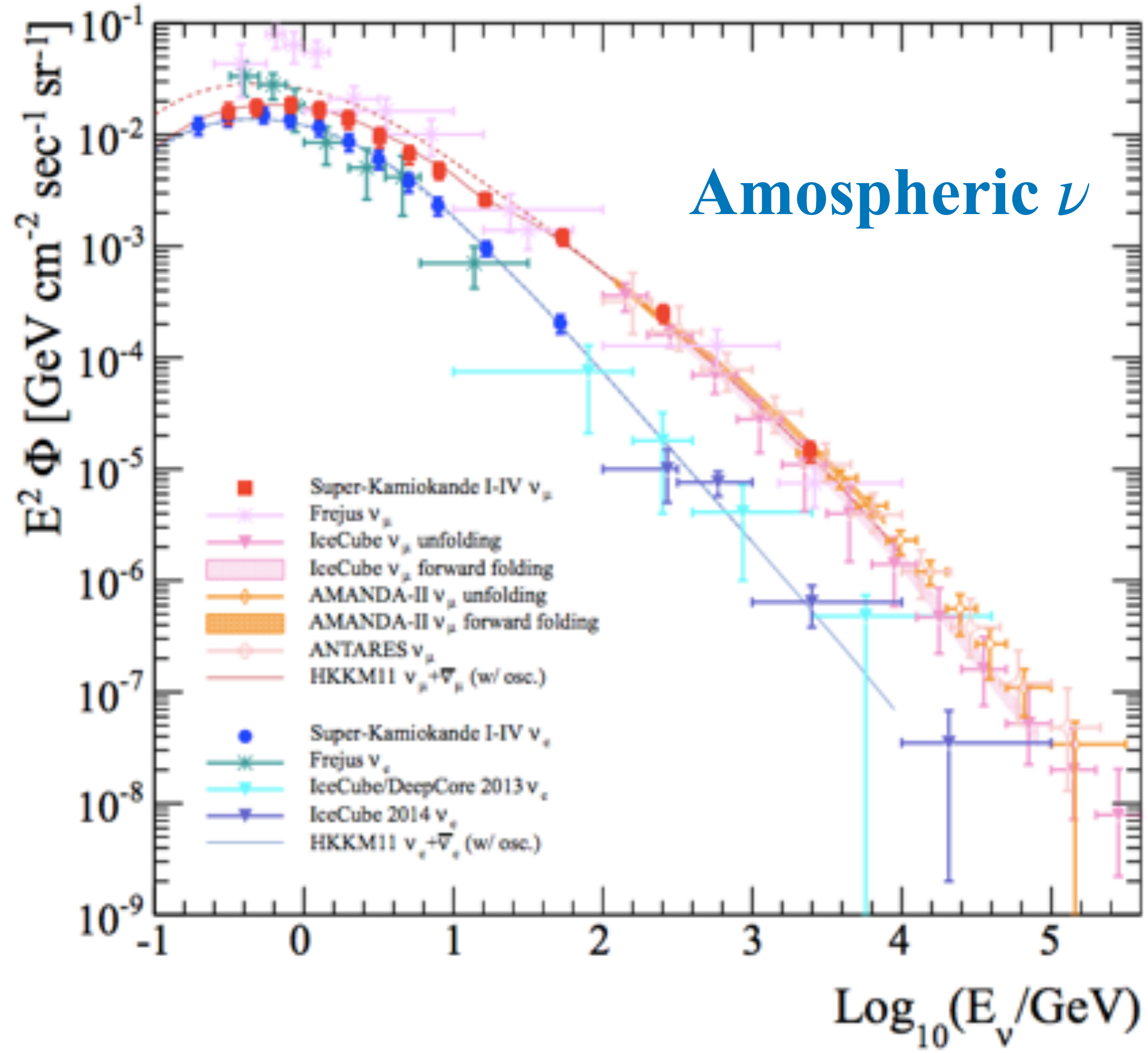


- 50,000 ton water Cherenkov
- Observes accelerator (**T2K**), **atmospheric**, solar, and supernova neutrinos
- Also: proton decay, indirect dark matter searches, exotic particle searches

- No net magnetic field to separate ν and $\bar{\nu}$
- Excellent PID: showering (e-like) and non-showering (μ-like)
  - < 1% MIS ID at 1 GeV

The Super-Kamiokande Experiment

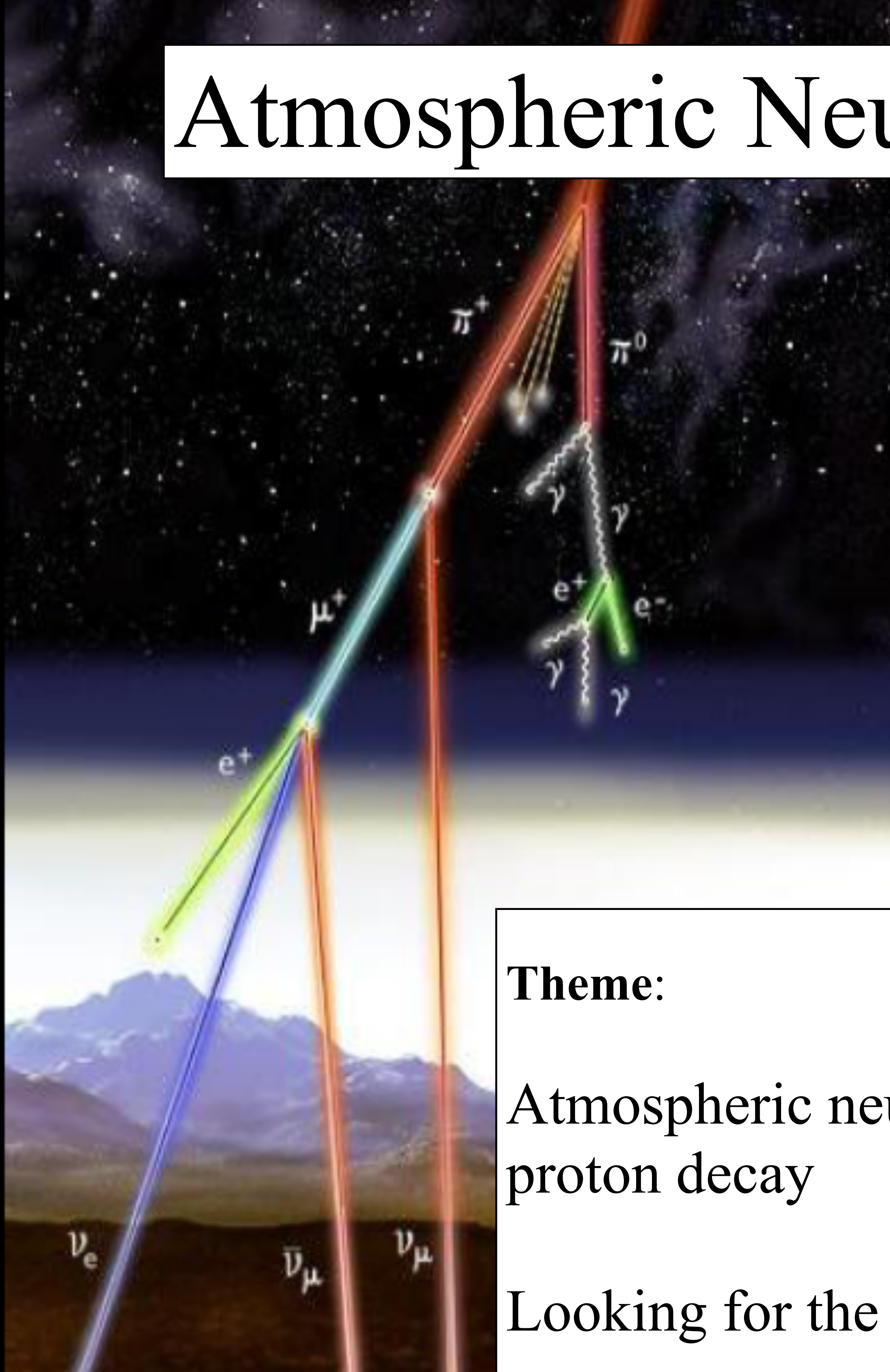


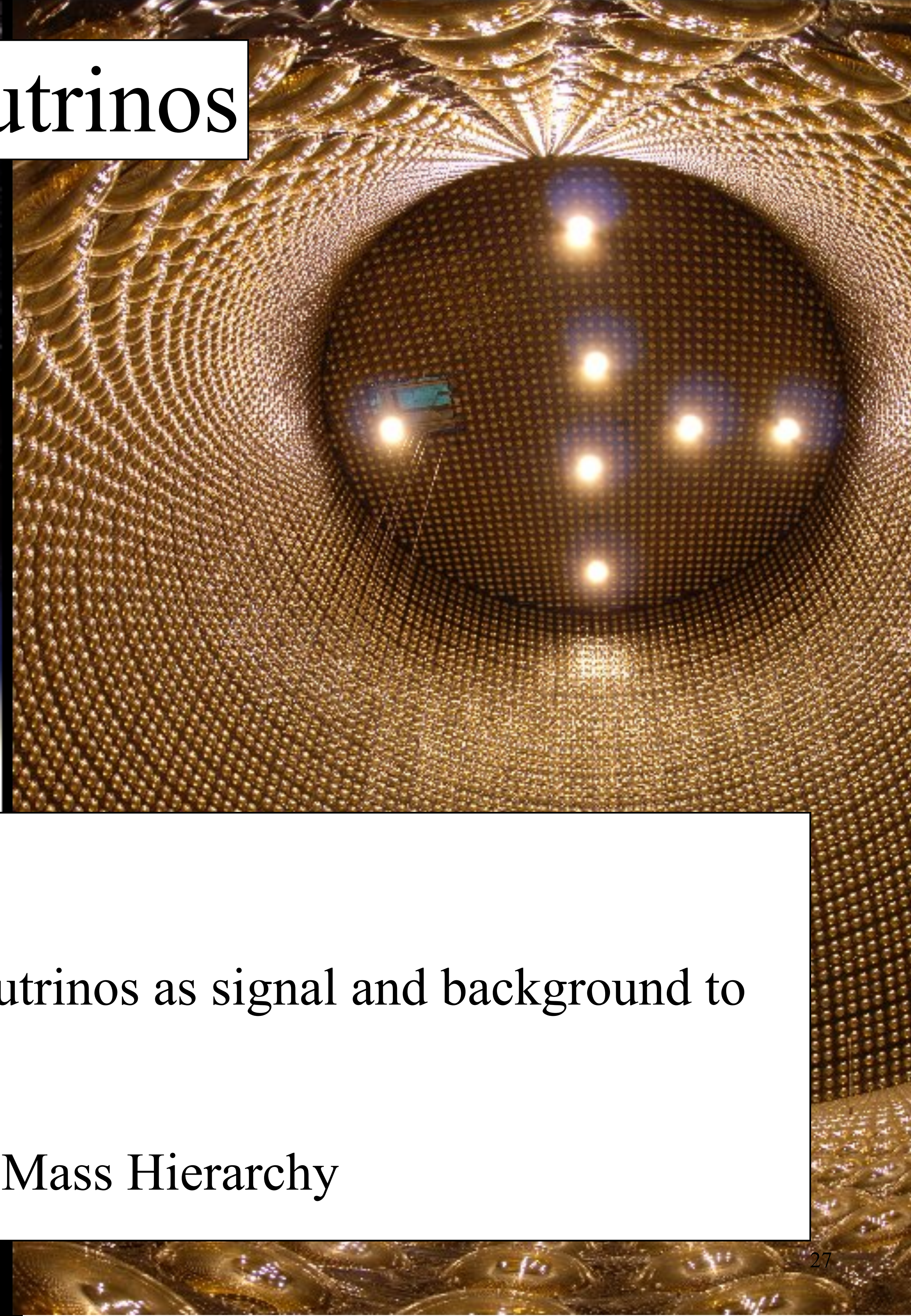


- T2K beam: narrow flux, peak around ~600 MeV
  - Known neutrino direction, dominated by ν_μ (or $\bar{\nu}_\mu$)
  - → Reconstruct neutrino energy from outgoing lepton kinematics

- Atmospheric neutrino flux much broader
  - ν arrive from all directions, but event-by-event direction is unknown
  - $\nu_{\mu,e} + \bar{\nu}_{\mu,e}$ present in the flux (no ν_τ below ~ 100 GeV)

Atmospheric Neutrinos



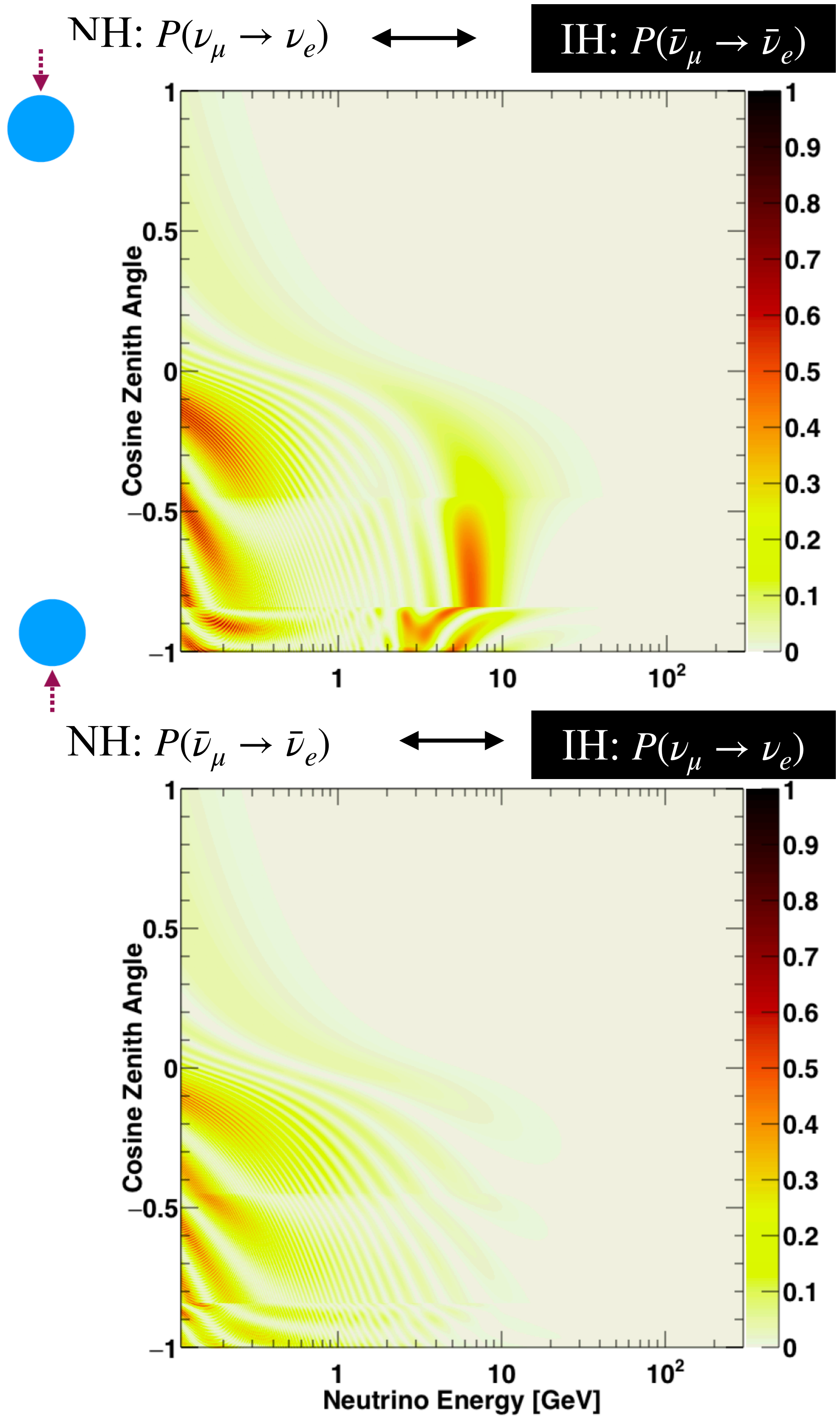


Theme:

Atmospheric neutrinos as signal and background to proton decay

Looking for the Mass Hierarchy

Atmospheric Neutrino Oscillations :



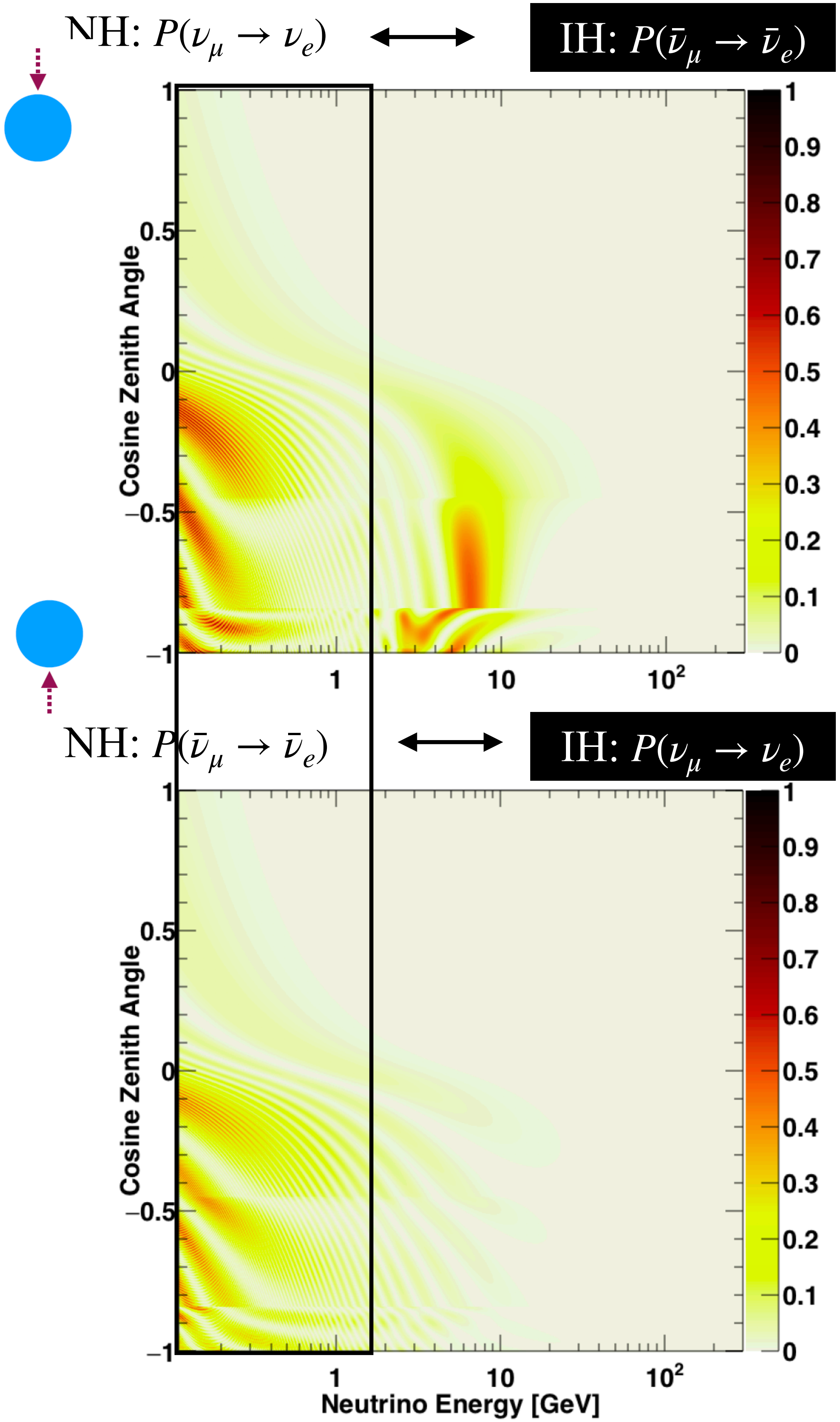
- Plots assume the Normal Hierarchy
  - Under the inverted hierarchy the neutrino and antineutrino plots reverse roles

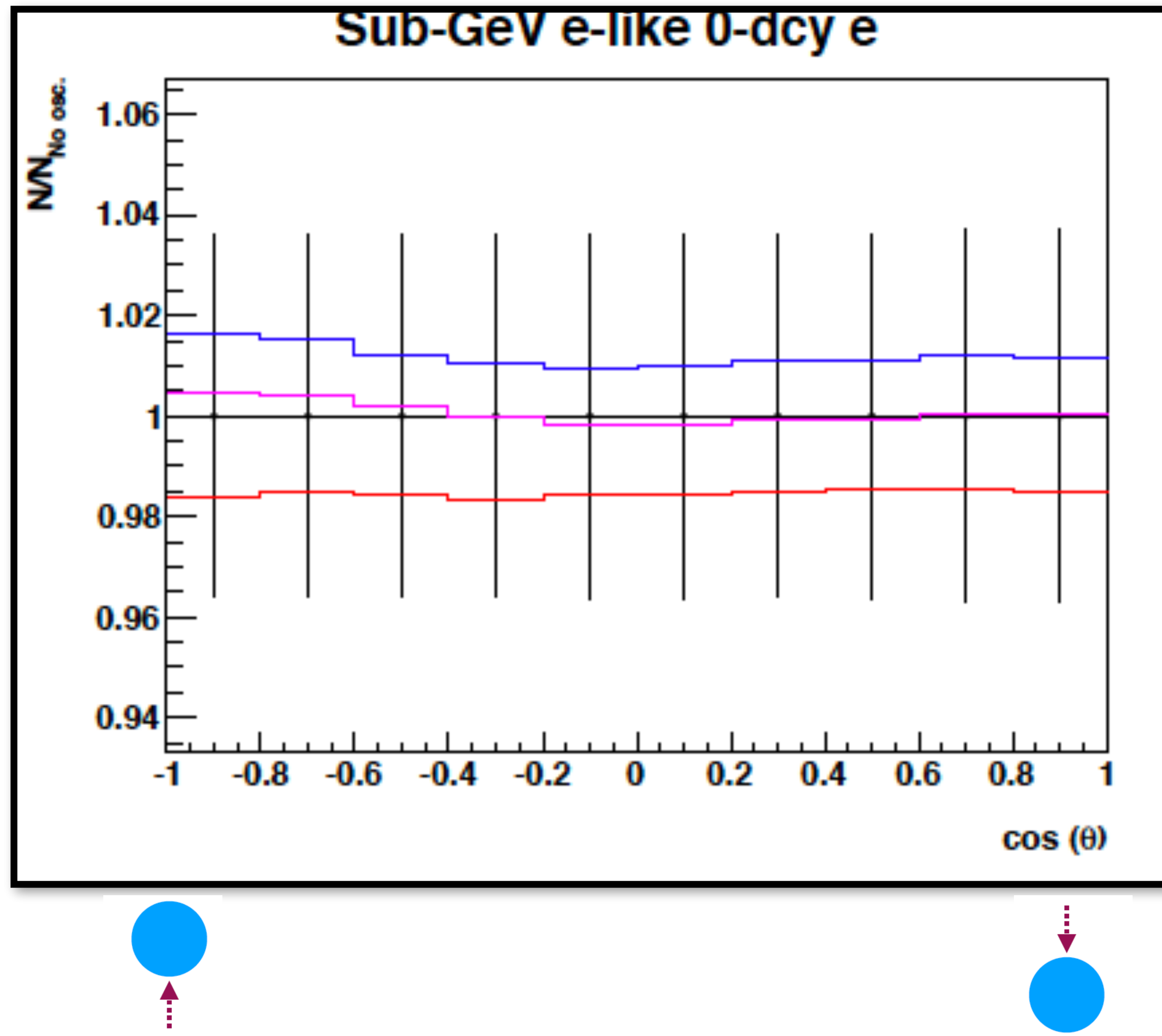
- Size of matter effects depends on θ_{13}, θ_{23}, δ_{CP} (in order of importance)

- Mass hierarchy sensitivity:
  - 2 ~ 10 GeV

- CP sensitivity
  - Below 2 GeV , strongest effects (400~600 MeV)

Atmospheric Neutrino Oscillations :





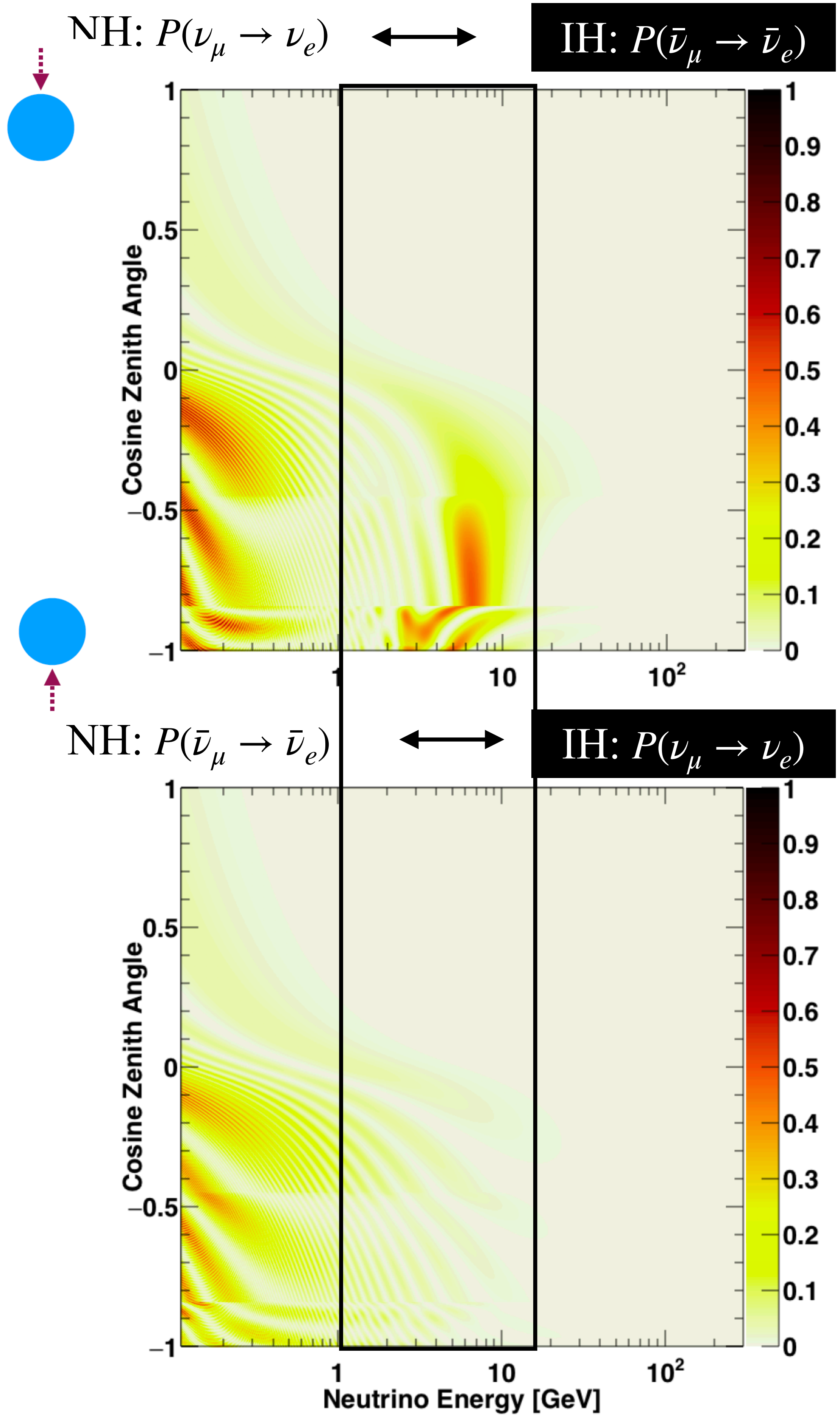
Statistical Error

$\delta_{CP} = 0^{\circ}$

$\delta_{CP} = 80^{\circ}$

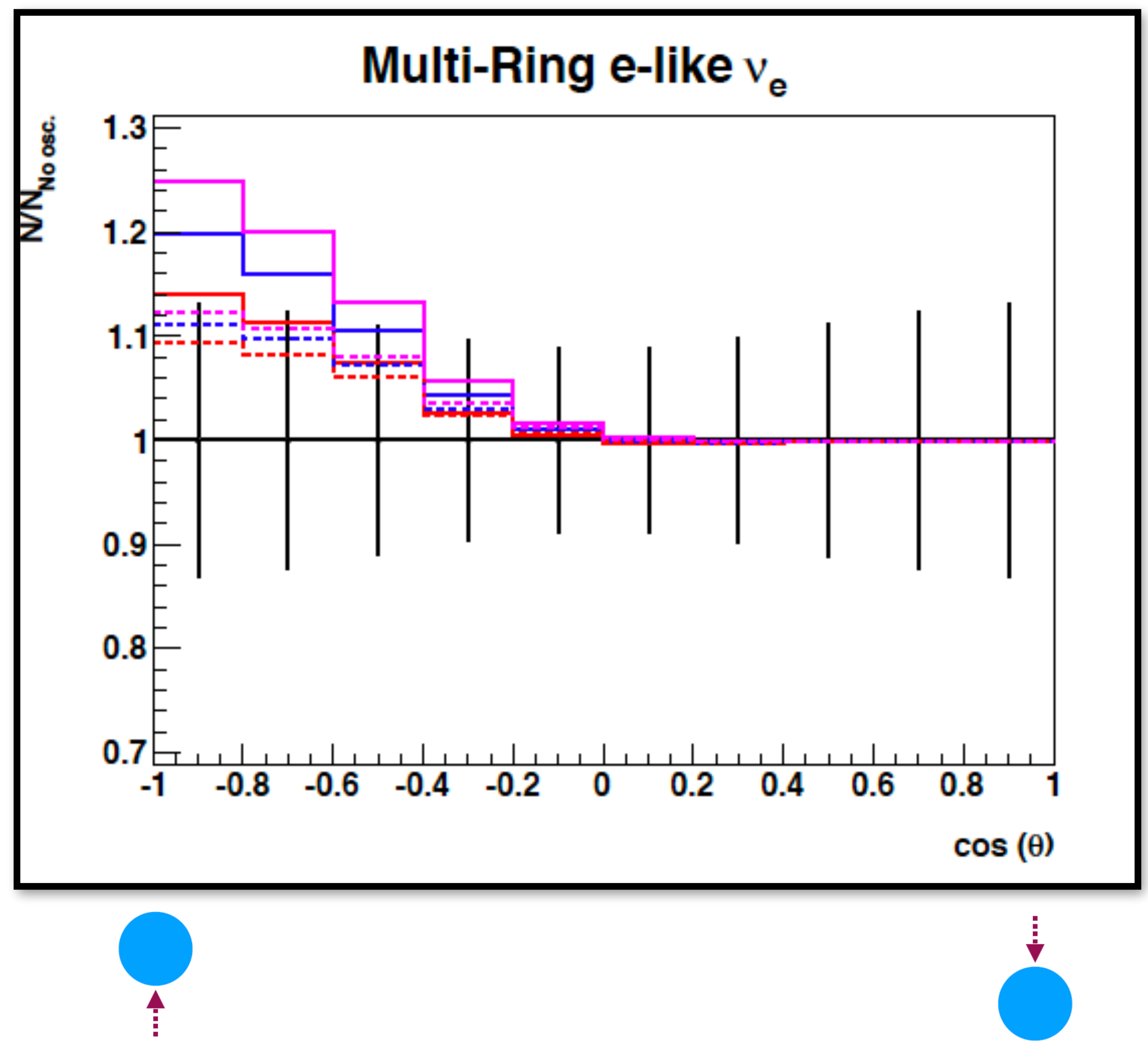
$\delta_{CP} = 300^{\circ}$

Atmospheric Neutrino Oscillations :

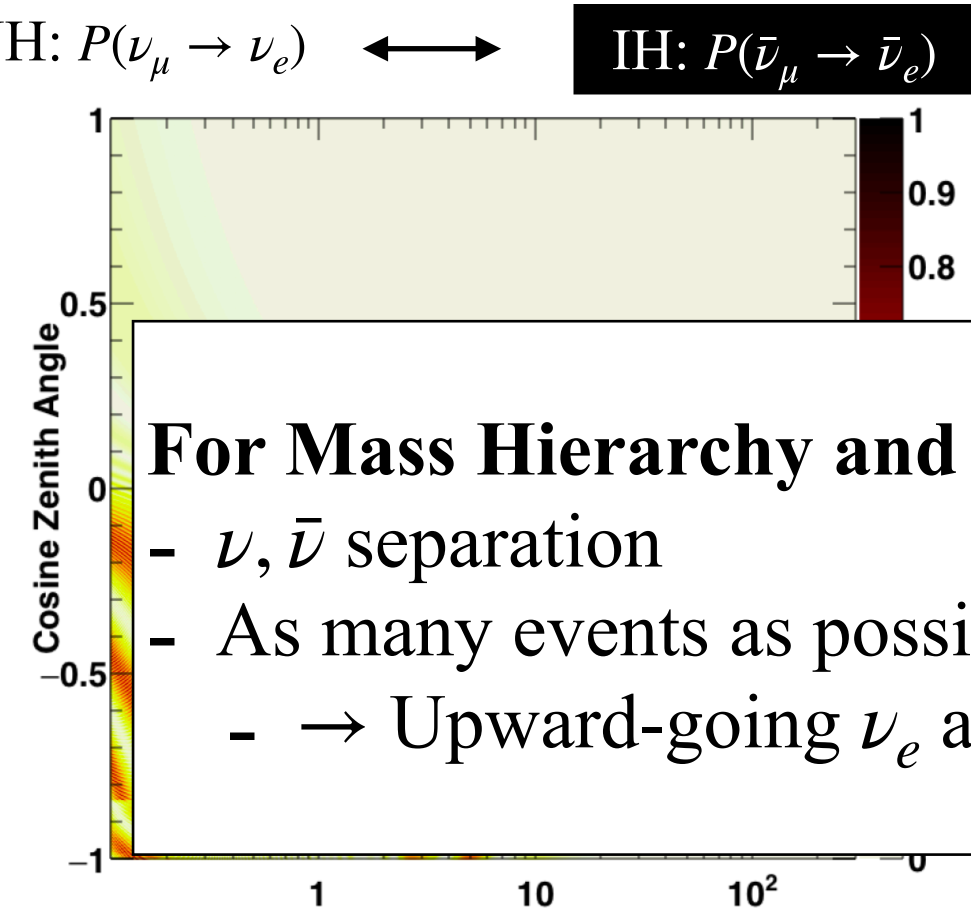


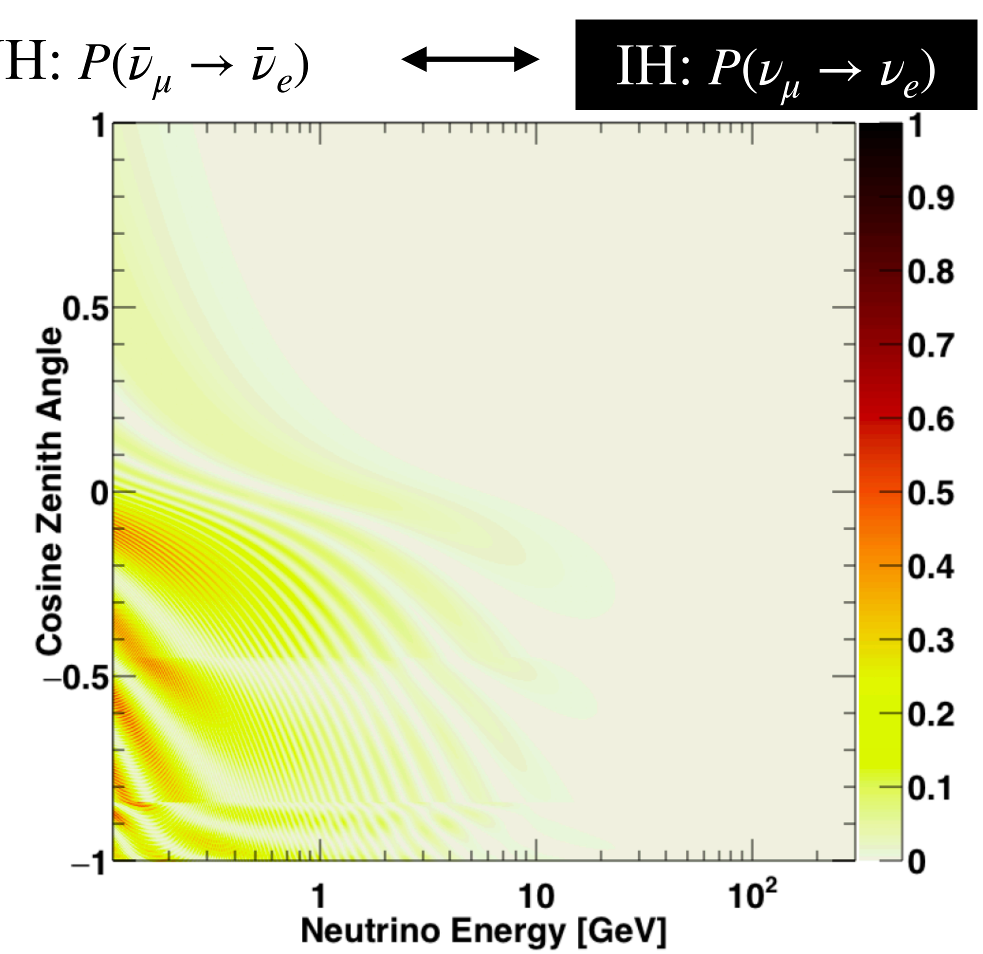
Solid: Normal Hierarchy
Dash: Inverted Hierarchy

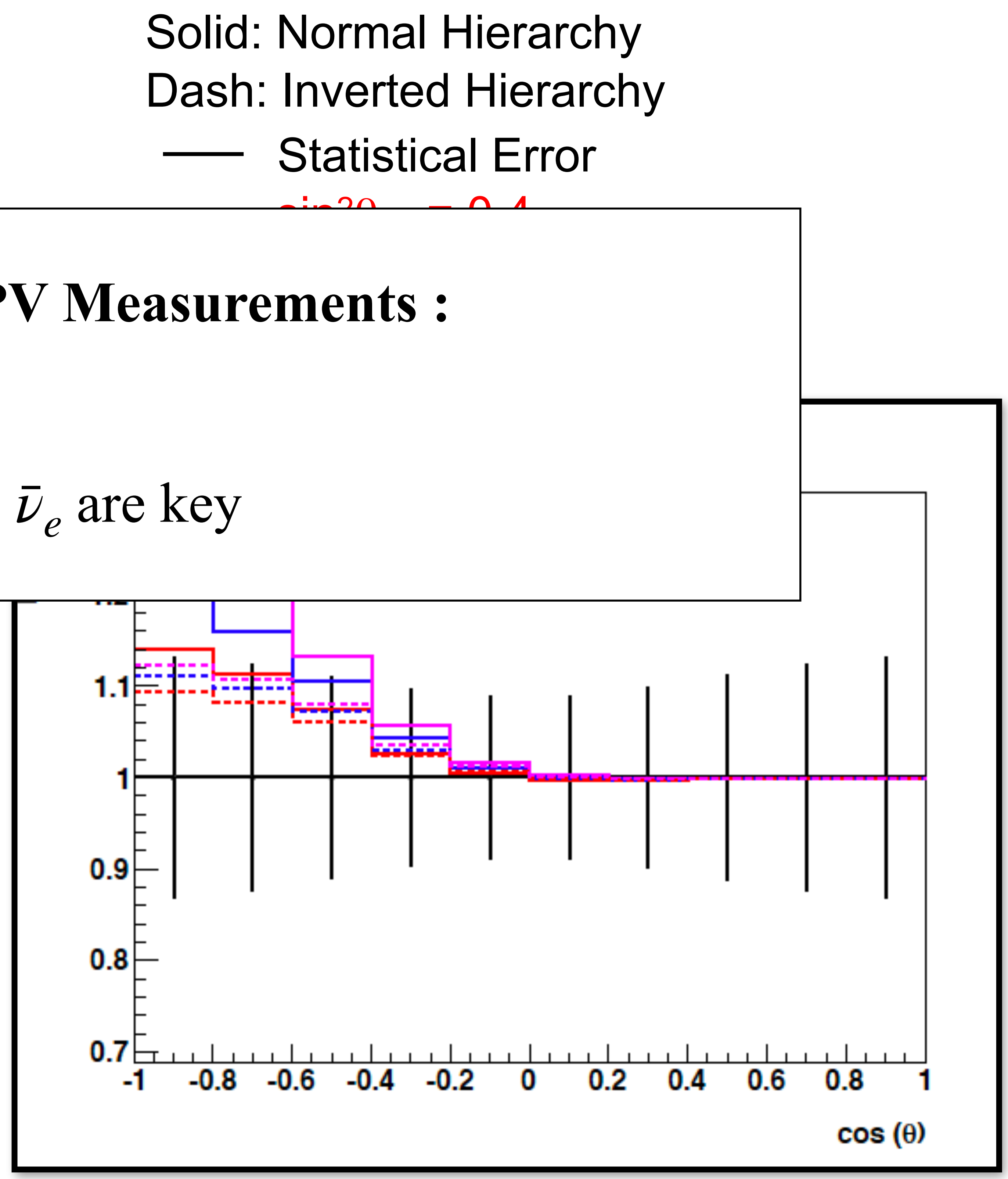
Statistical Error
$\sin^2\theta_{23} = 0.4$
$\sin^2\theta_{23} = 0.5$
$\sin^2\theta_{23} = 0.6$



Atmospheric Neutrino Oscillations :



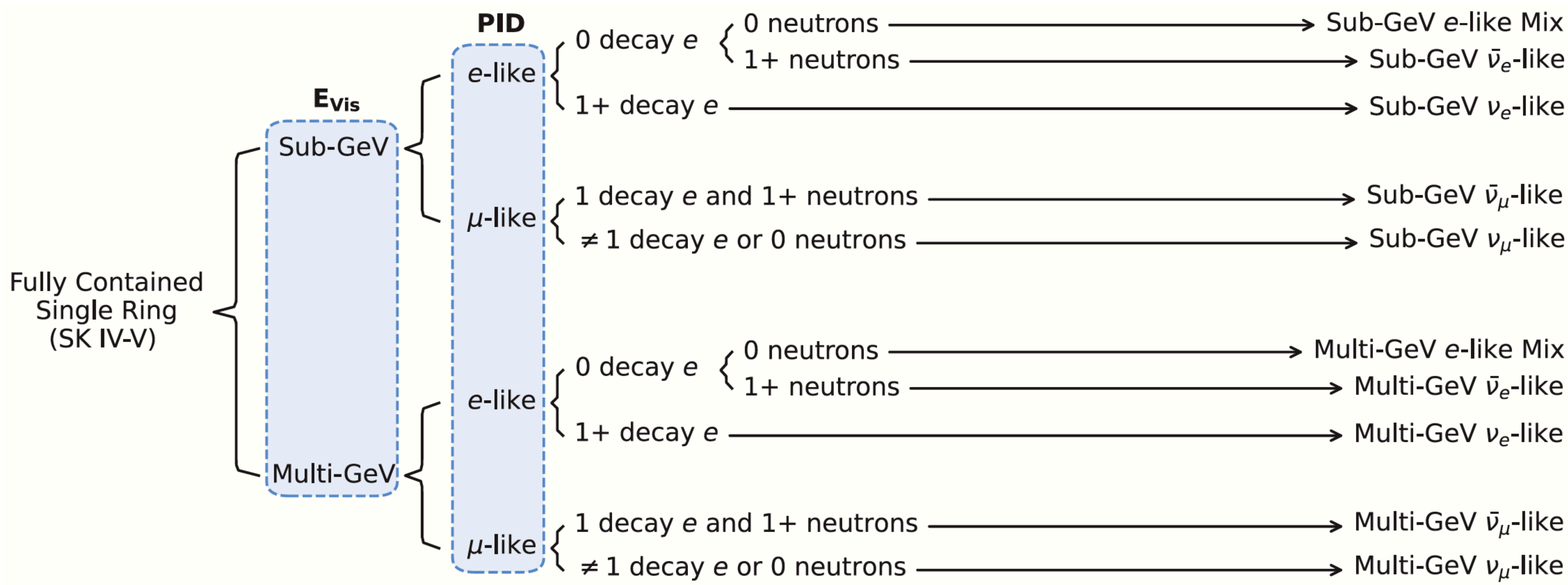




For Mass Hierarchy and CPV Measurements :

- $\nu, \bar{\nu}$ separation
- As many events as possible
  - $\rightarrow$ Upward-going ν_e and $\bar{\nu}_e$ are key

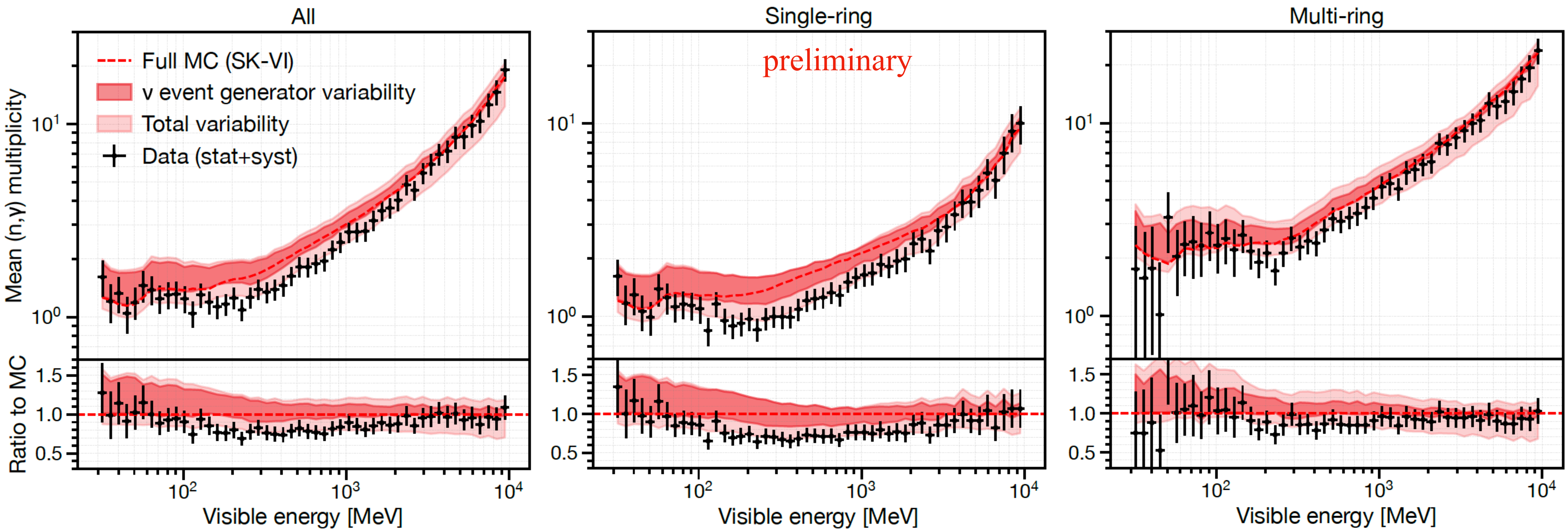
Aiming for Sensitivity Improvement:



- Try to purify atmospheric event sample using cuts on number of Michel electrons and tagged <u>neutrons</u>
  - Single-ring events only

Neutron Production in Atmospheric ν Interactions

S. Han (ICRR)

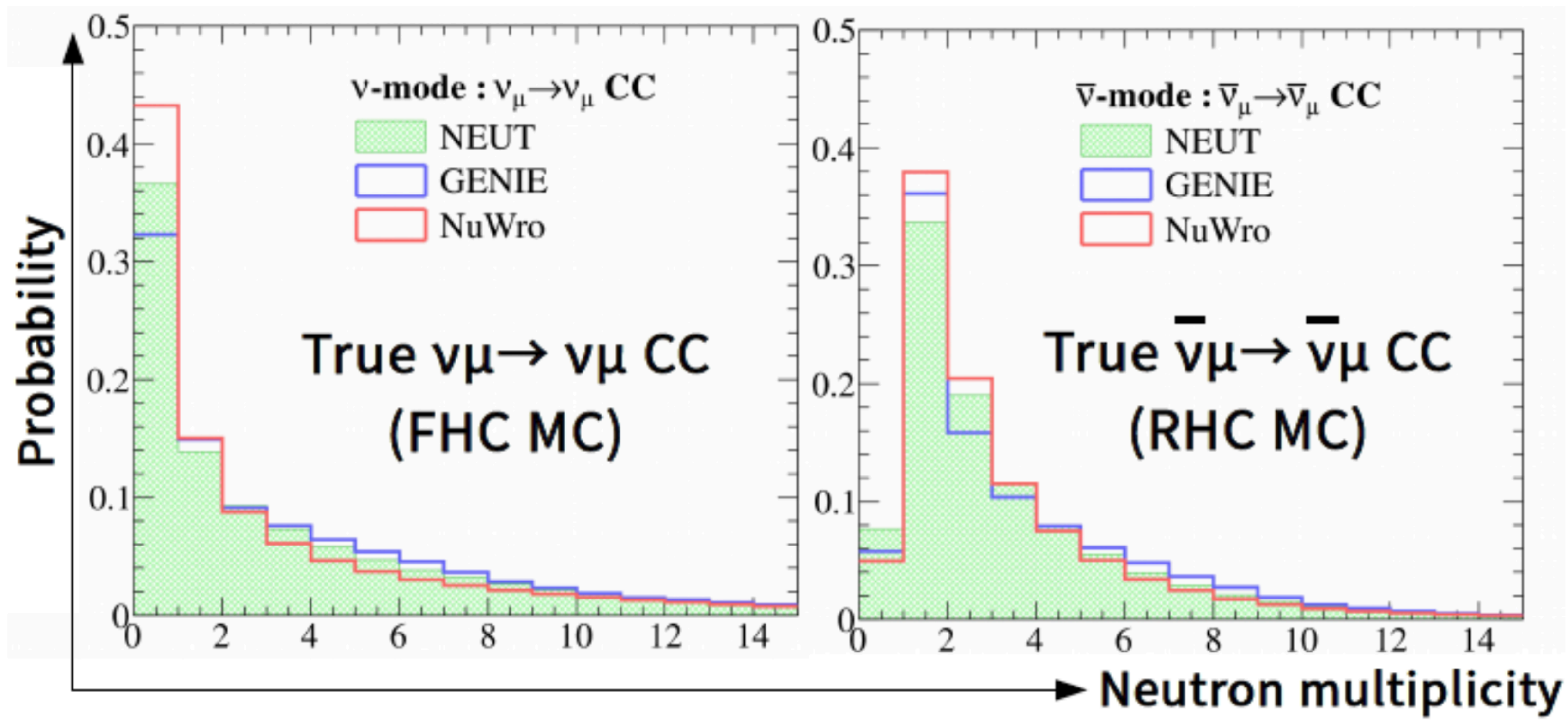


- Neutron capture at Super-K has enabled high statistics measurements of neutron production in atmospheric neutrino interactions

- In general, model predictions roughly describe the observation though there is considerable variation among models
  - Final state interactions, secondary hadronic interactions produce more hadrons… but less in data

- Sizable corrections applied to data during analysis

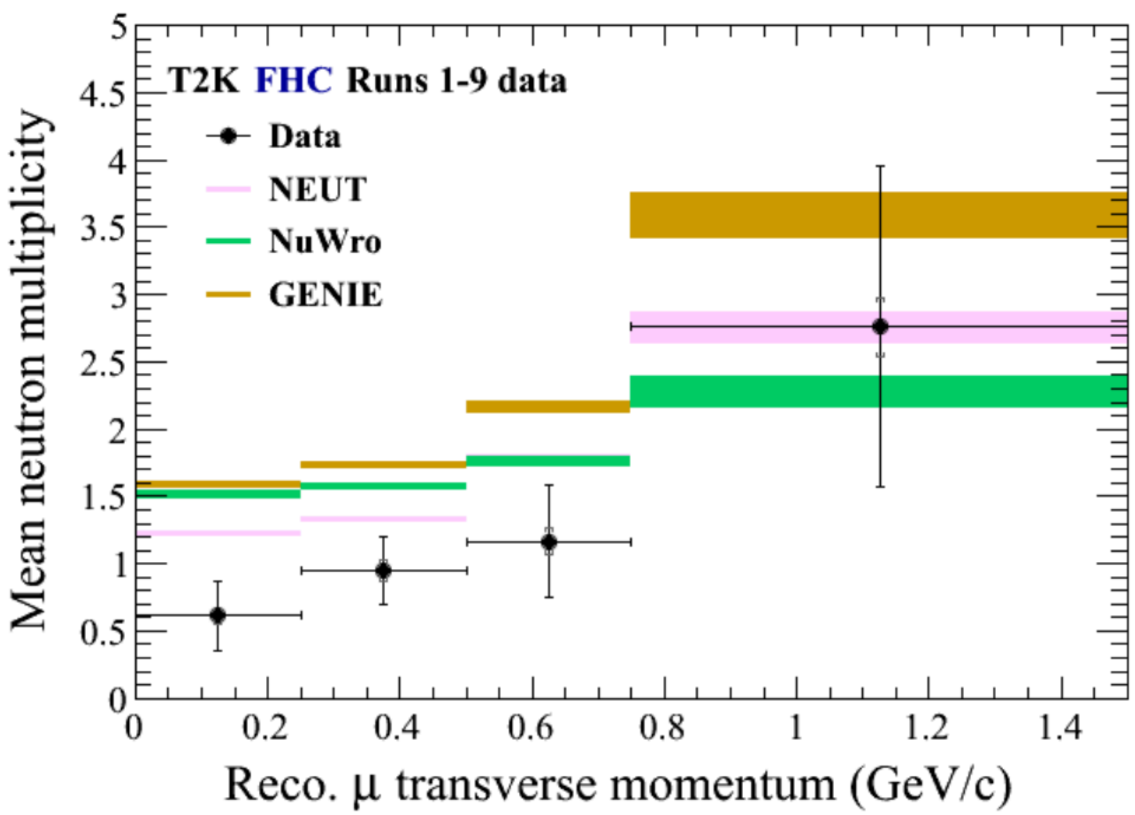
Neutron Production in Beam ν Interactions : Pure Water

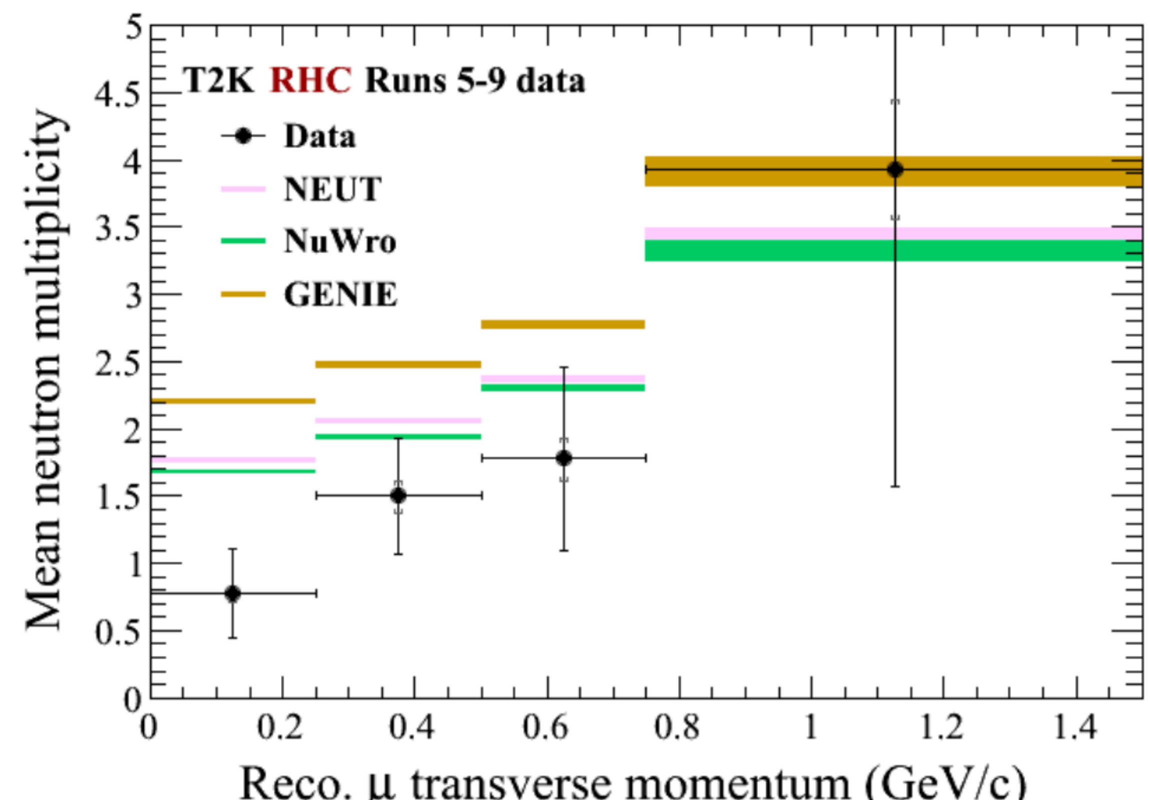


- To get more out of the atmospheric neutrino data set detailed information on neutrino-induced neutron production would be helpful

R. Akutsu (KEK)

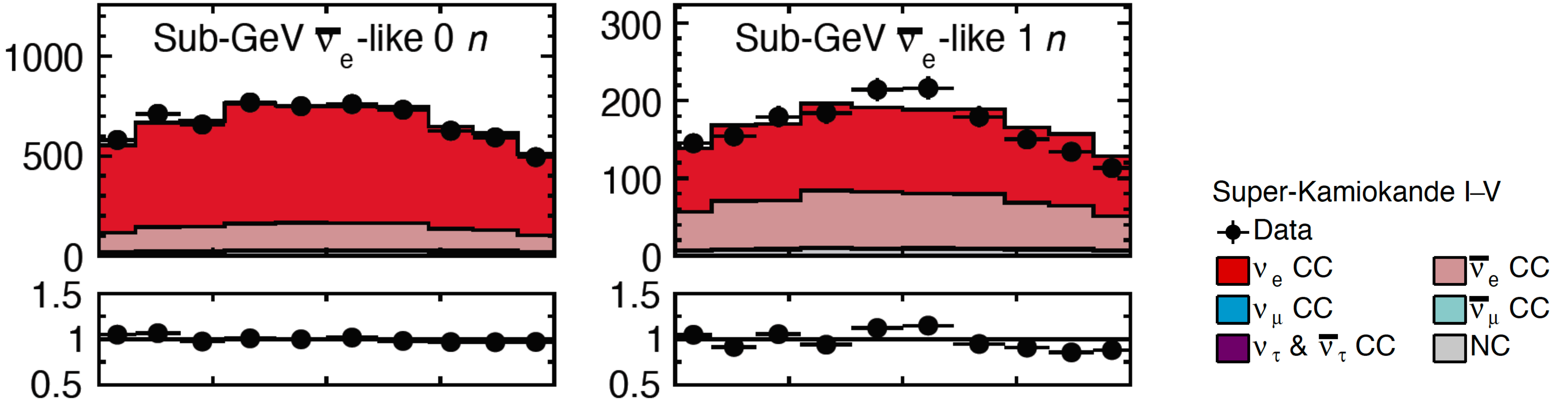
T2K preliminary



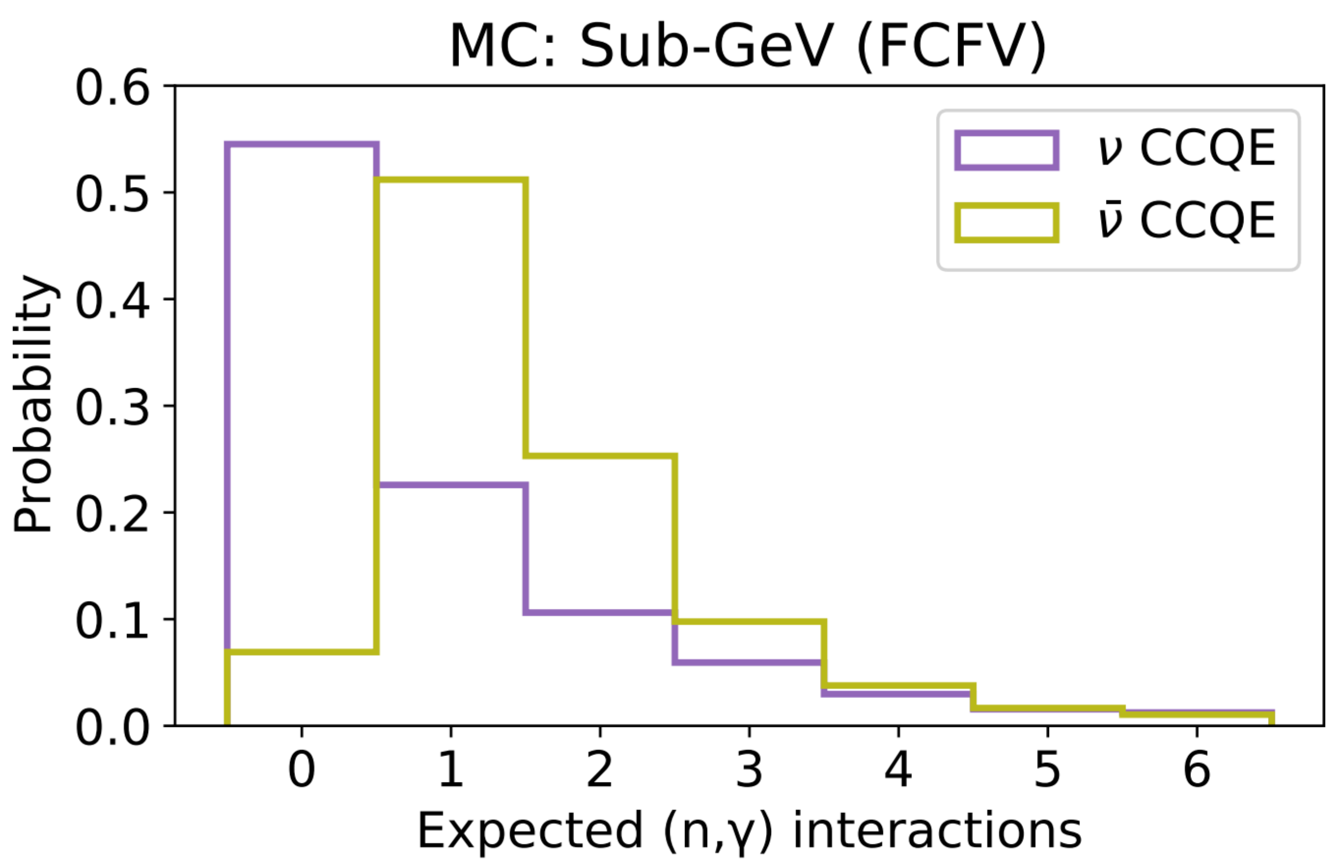


Neutrino-Antineutrino Separation : Neutrons

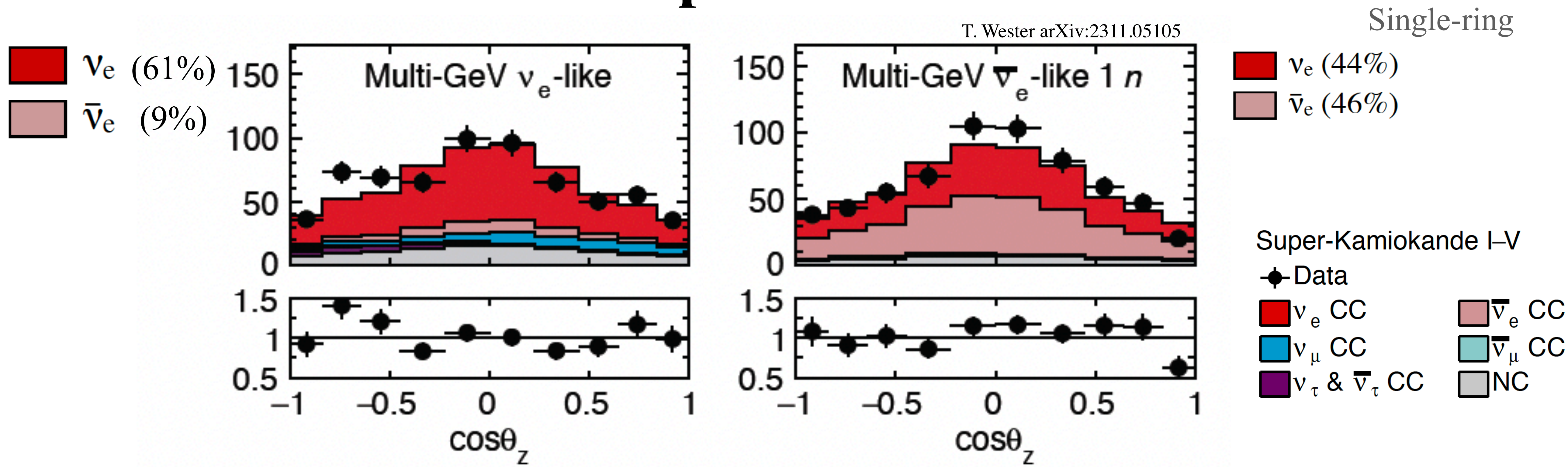
Single-ring



- Separate analysis samples into $\nu/\bar{\nu}$ using number of neutrons ☑ new in 2023
  - → $\bar{\nu}$ purity is modest due to hadron-induced n production



Neutrino-Antineutrino Separation : Neutrons



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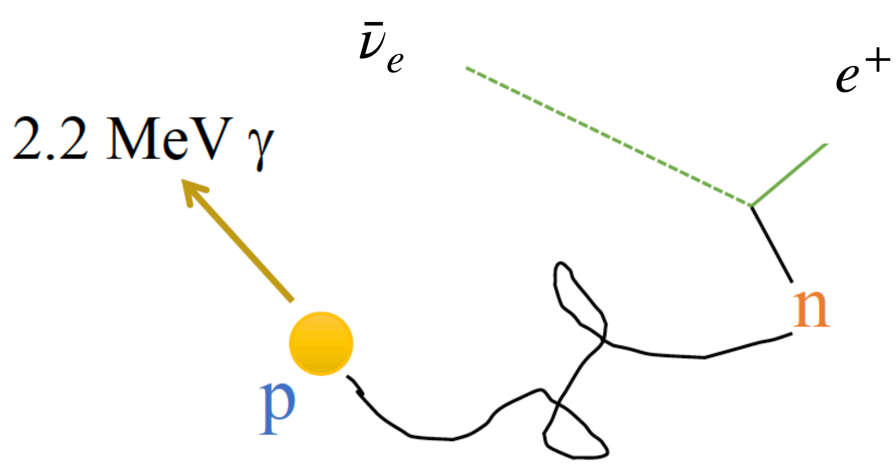


Neutron tagging

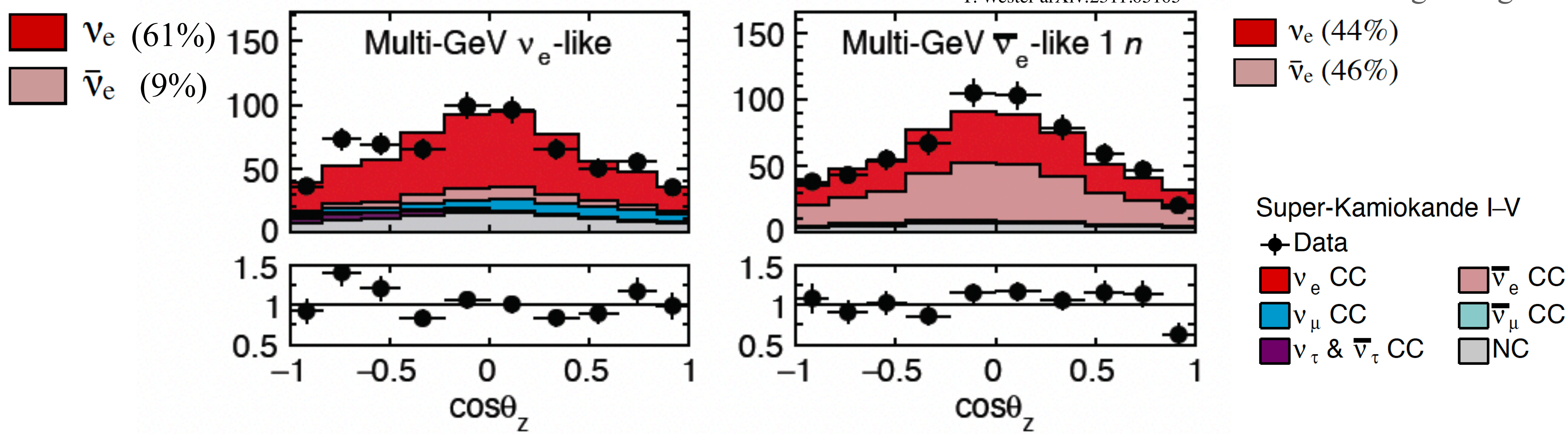
$\varepsilon \sim 25\ \%$

Neutrino-Antineutrino Separation : Neutrons

Preliminary

Single-ring

T. Wester arXiv:2311.05105



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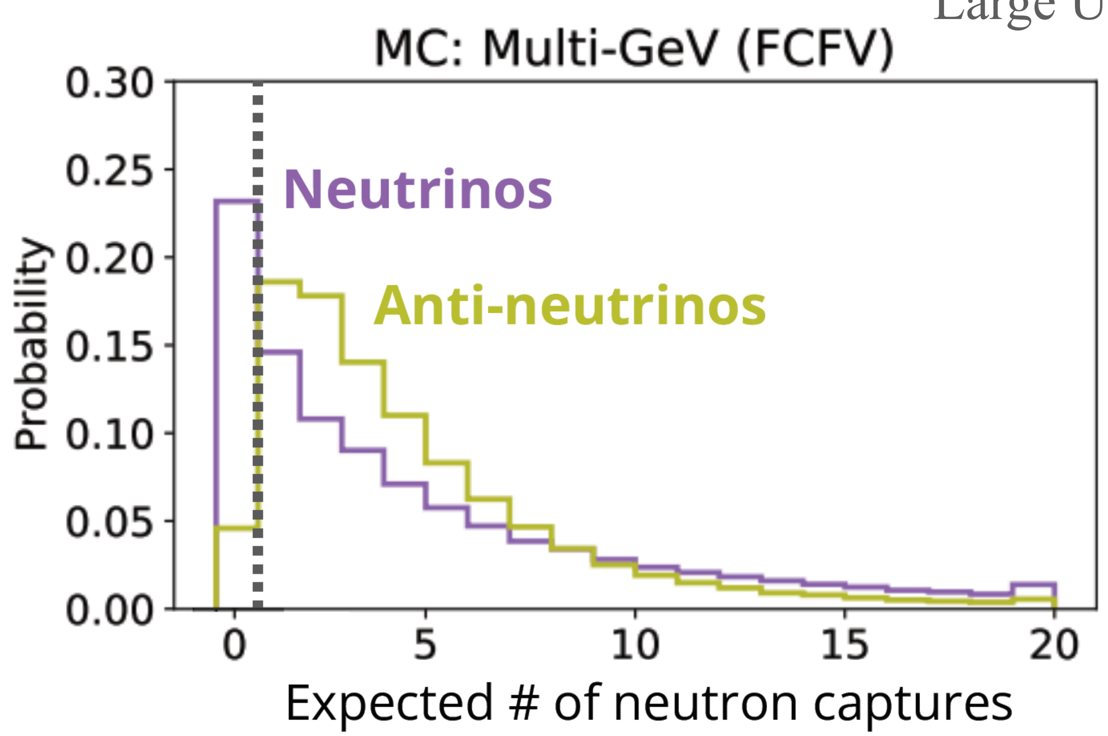
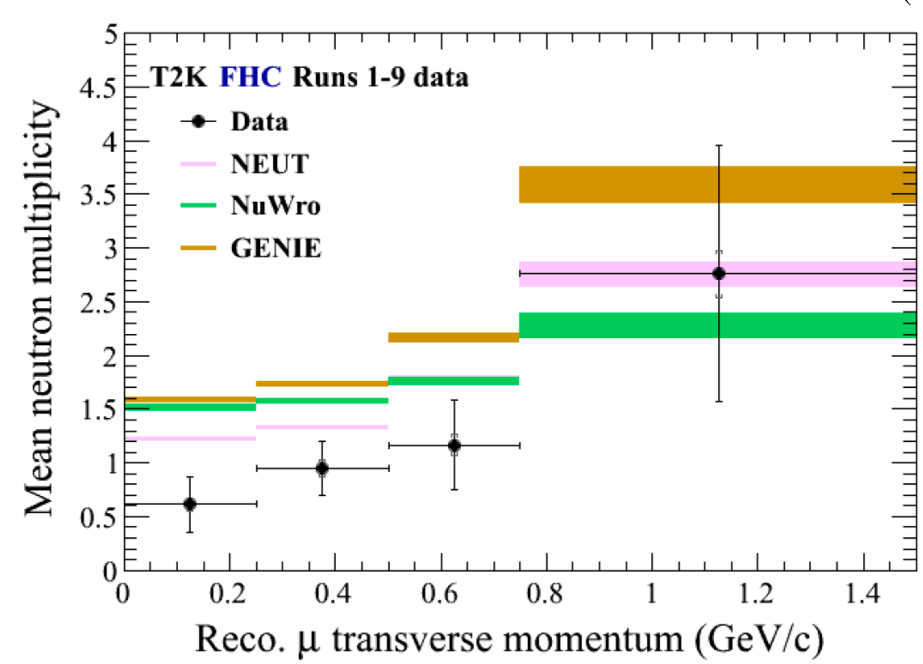
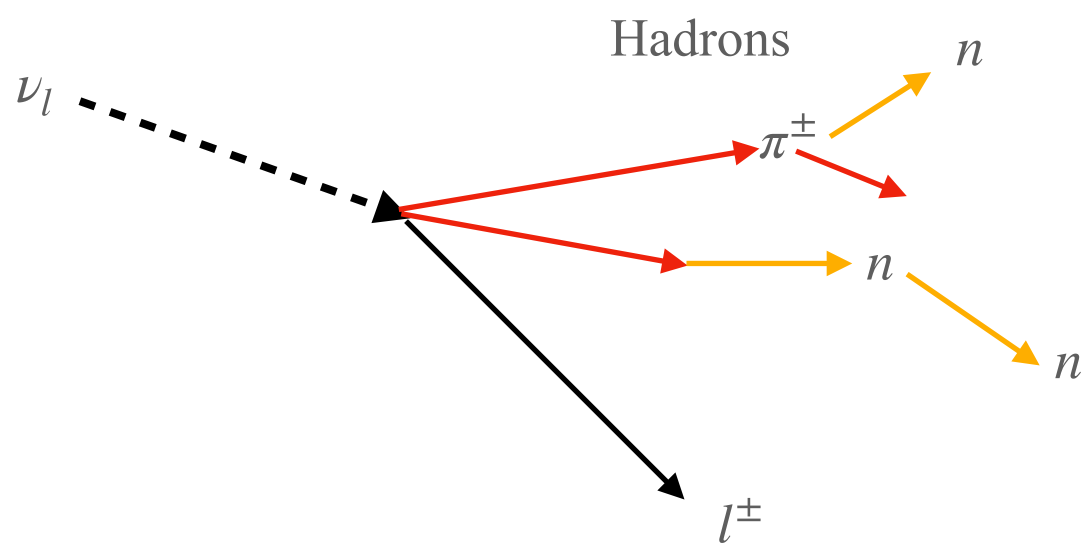
Large Uncertainties…



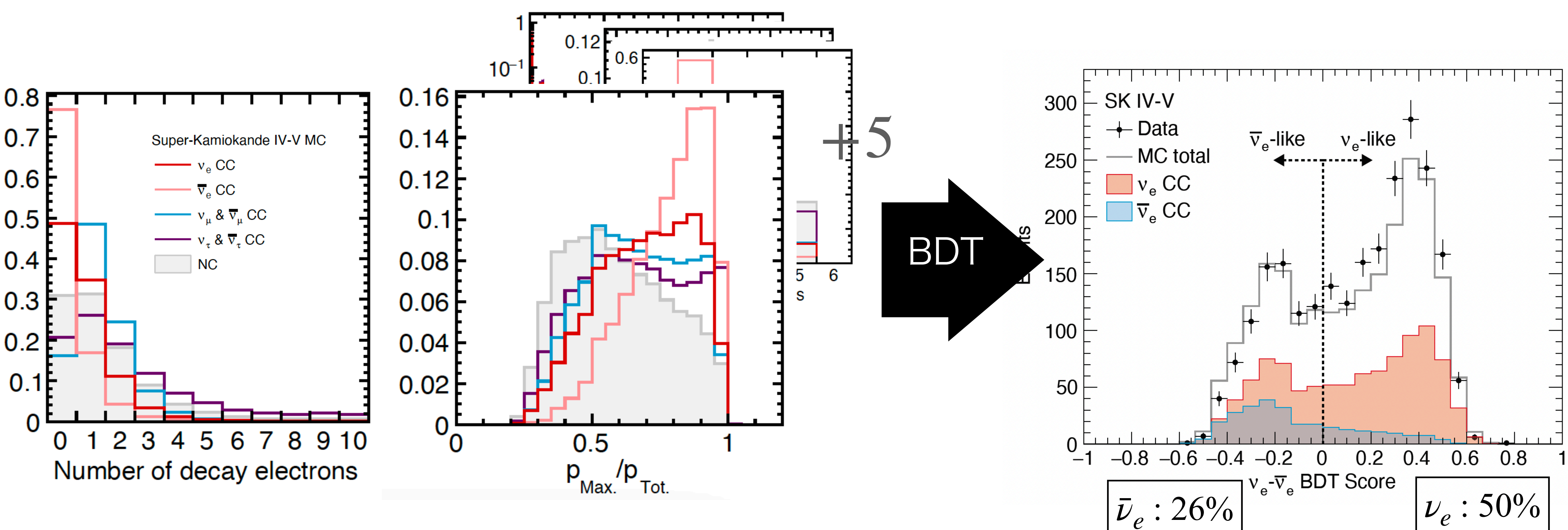
R. Akutsu Ph.D. Thesis (2019)



Neutrino-Antineutrino Separation : Multi-Ring BDT

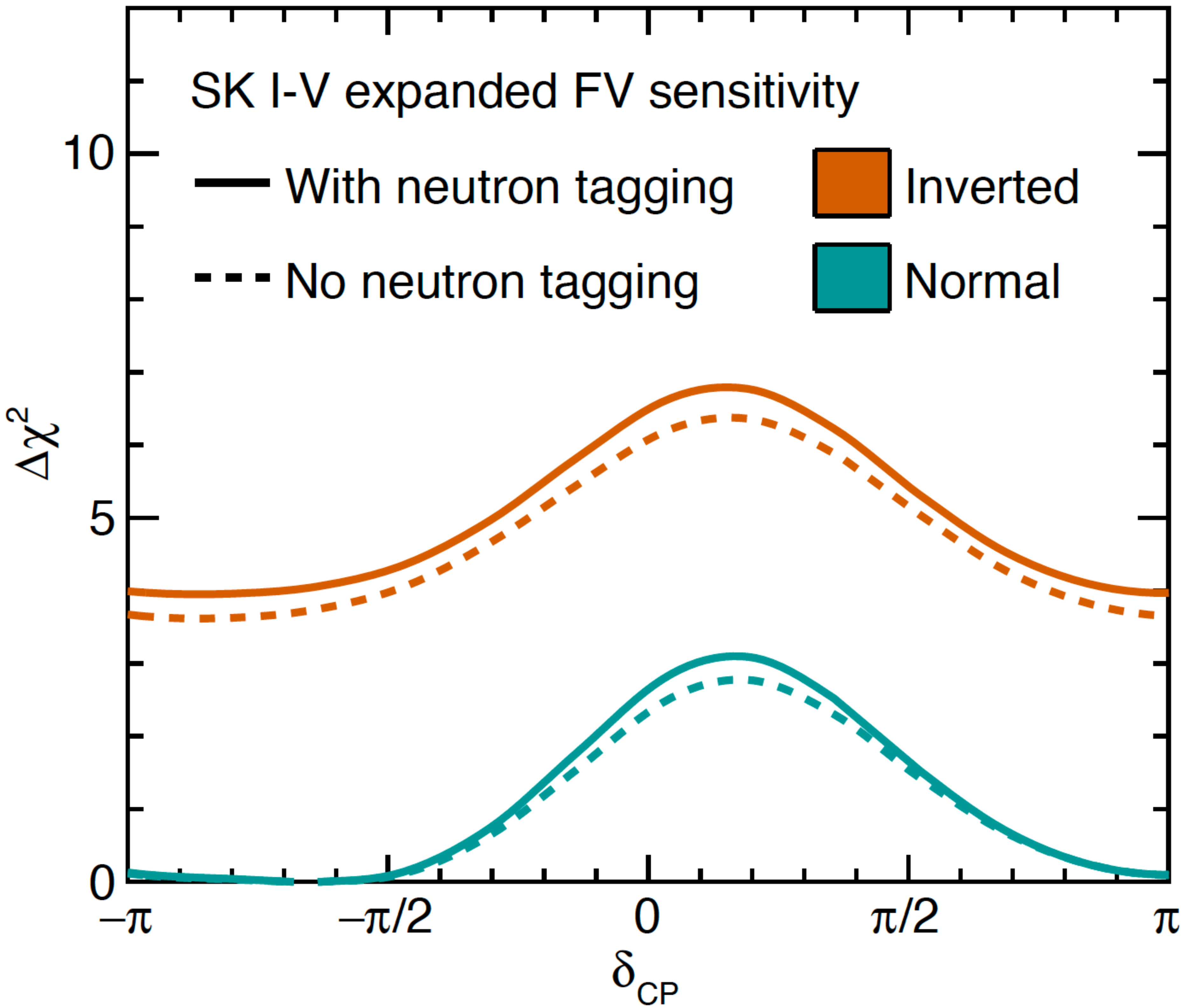


- Too many neutrons — no $\nu/\bar{\nu}$ separation power…
- Multi-variate BDT, decay electrons, rings, momentum, at high energy



https://arxiv.org/abs/2311.05105

Sensitivity With Neutrons (Pure Water Only)

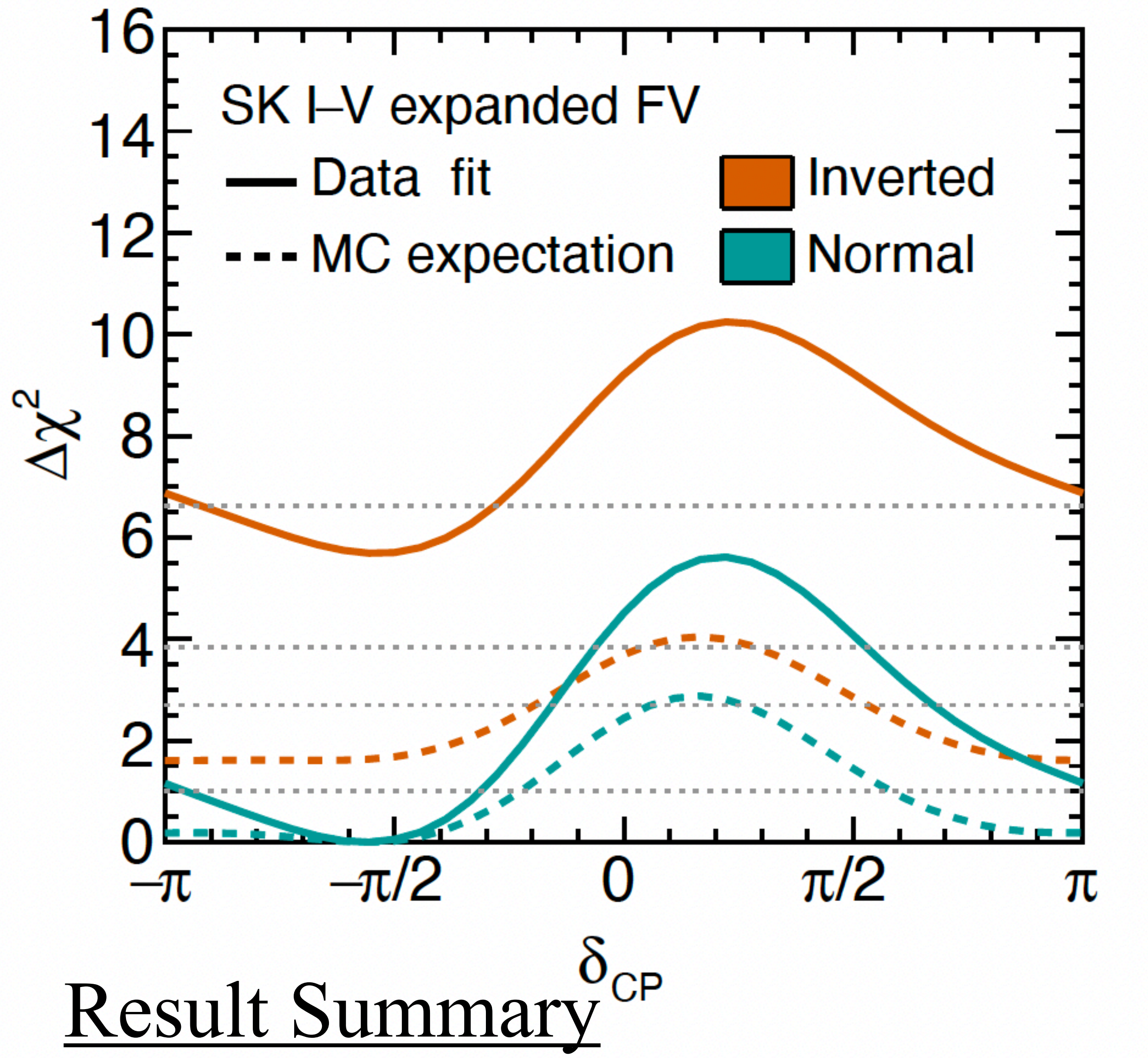


Neutron tagging
$\varepsilon \sim 25\,\%$

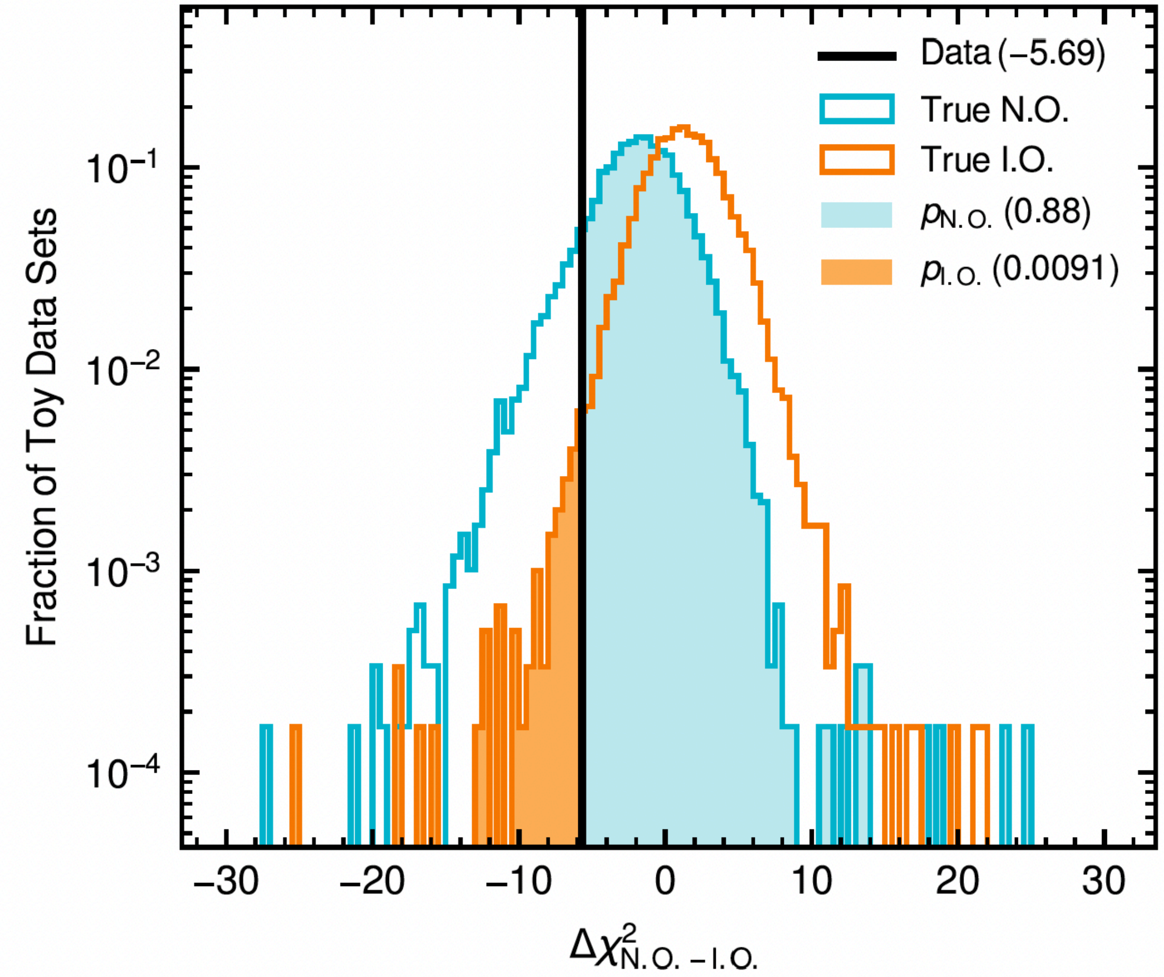
Uncertainties are large

- Lack of sub-GeV neutrino pointing and flux errors limit atmospheric sensitivity to CPV

Atmospheric Neutrino Measurement: Result (Pure Water)



Mass Ordering Preference

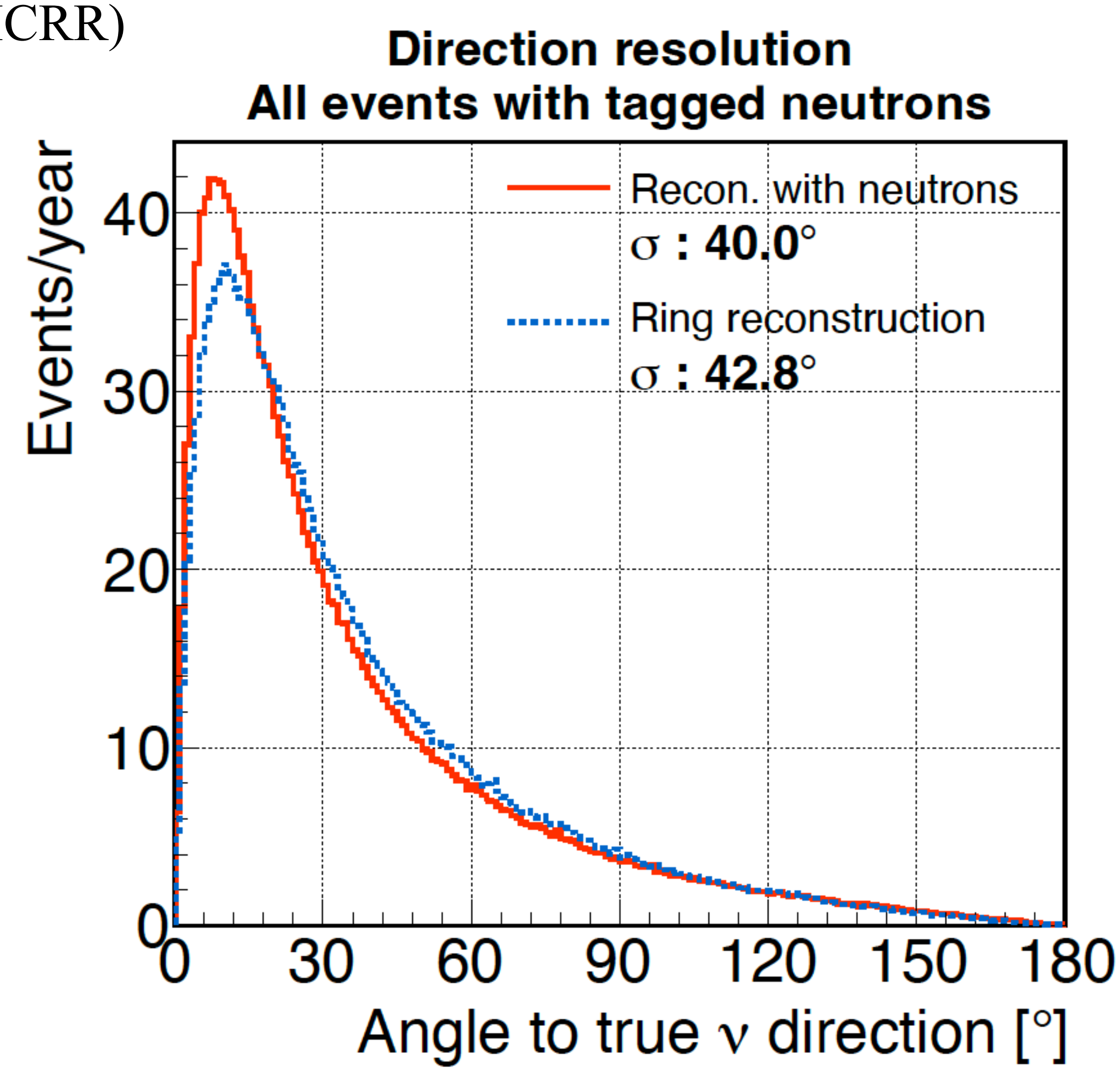


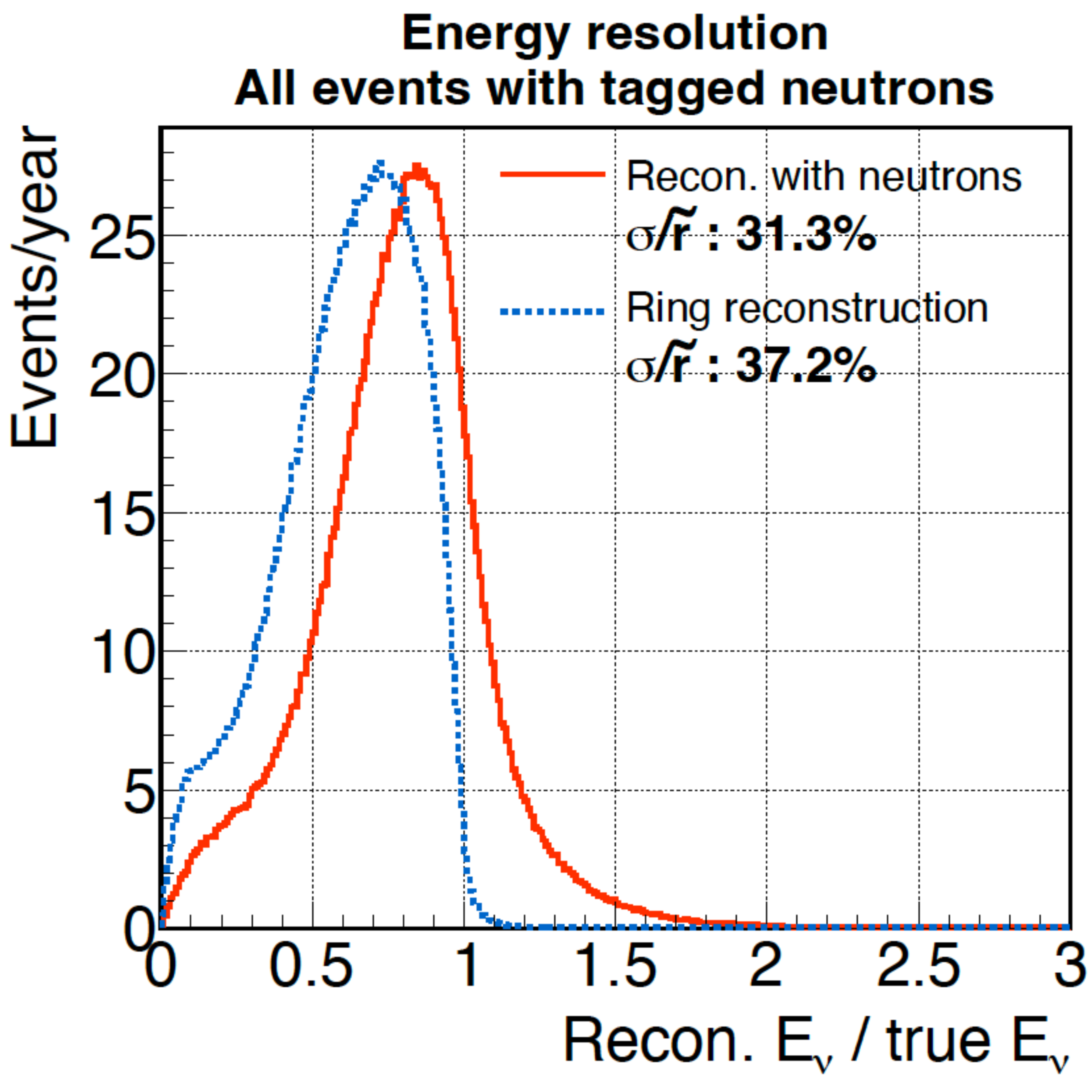
Result Summary

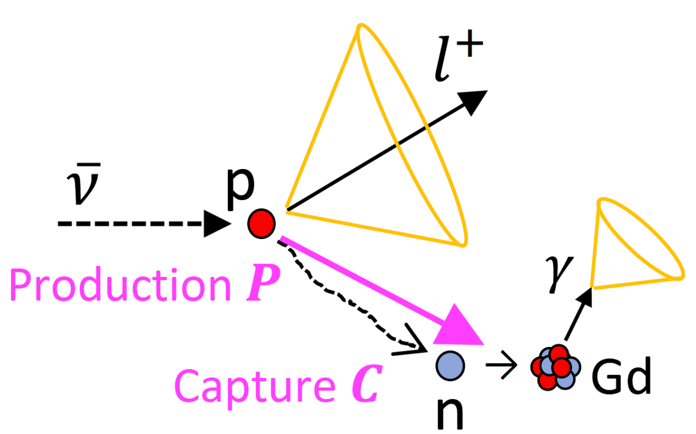
- Preference for $\delta_{CP} \sim -\dfrac{\pi}{2}$, CP conservation not excluded
- Weak preference for $\sin^2\theta_{23} < 0.5$ (*first octant*): $\sim 1\sigma$
- Weak preference for *normal* mass ordering: $\mathrm{CL}_s = 0.077$

Neutrino Reconstruction : Gd Neutrons (SK6, 0.01w%)

S. Miki (ICRR)







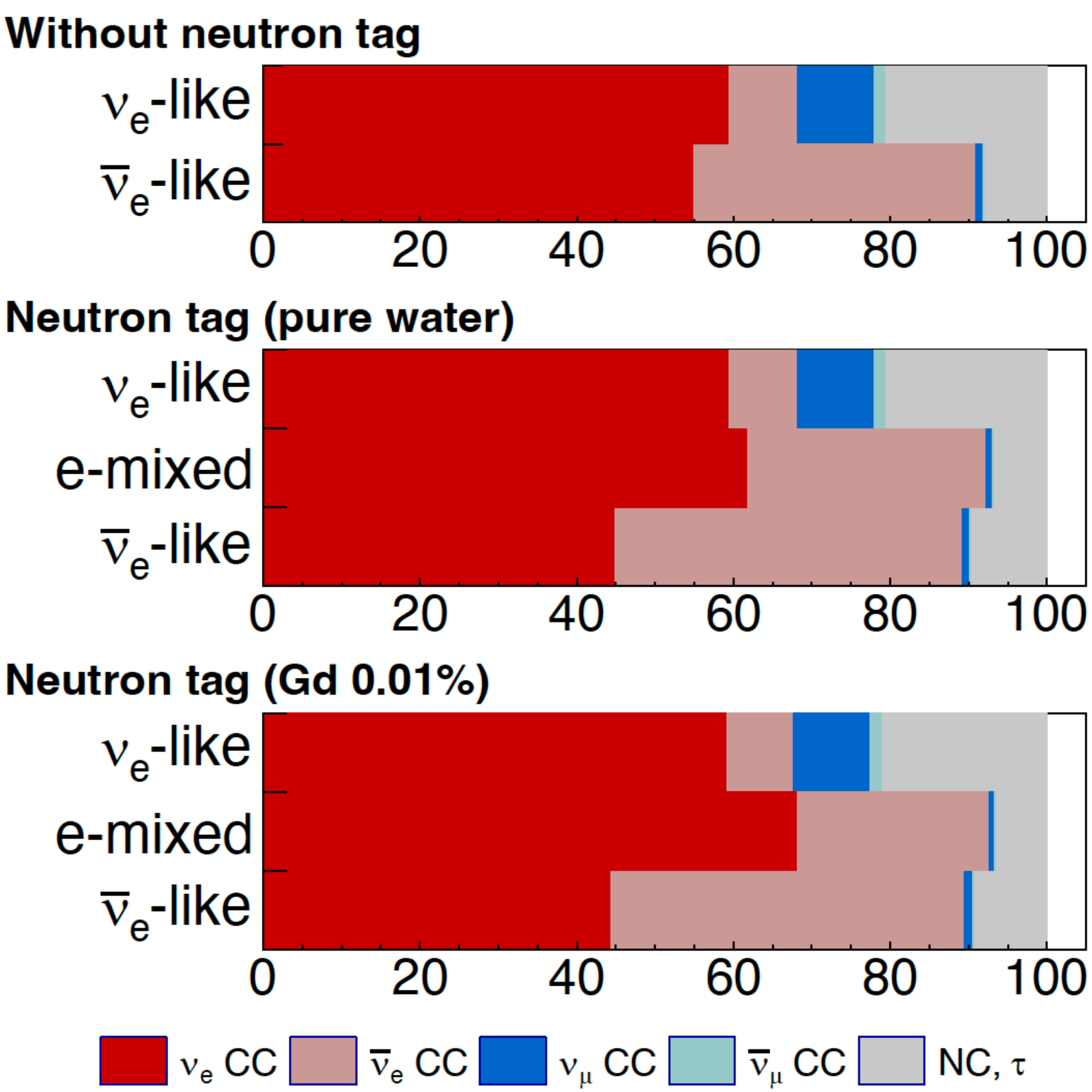
Assume $\overrightarrow{p_n} \propto \overrightarrow{PC}$

- First touch with Gd
- Improve energy estimator by counting neutrons
- Improve direction reconstruction using neutron capture vertex

Neutron tagging
$\varepsilon \sim 50\ \%$

Neutrino-Antineutrino Separation : Gd Neutrons (SK6)

S. Miki (ICRR)



Neutron tagging

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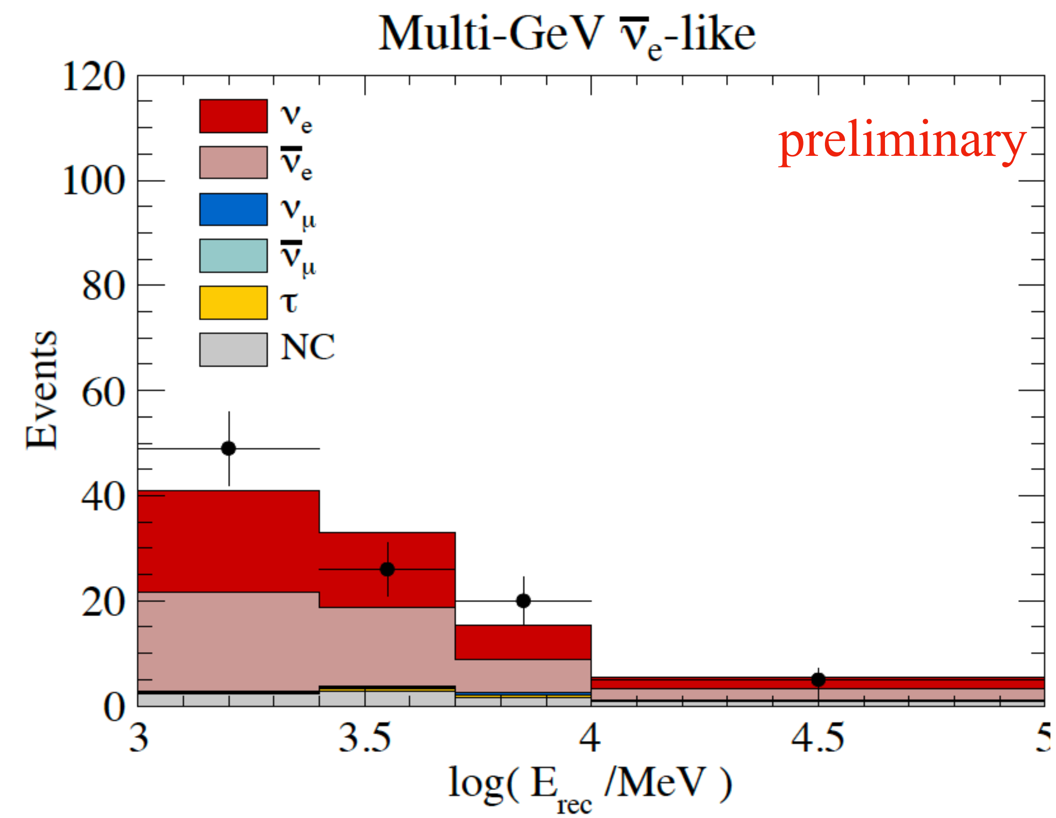
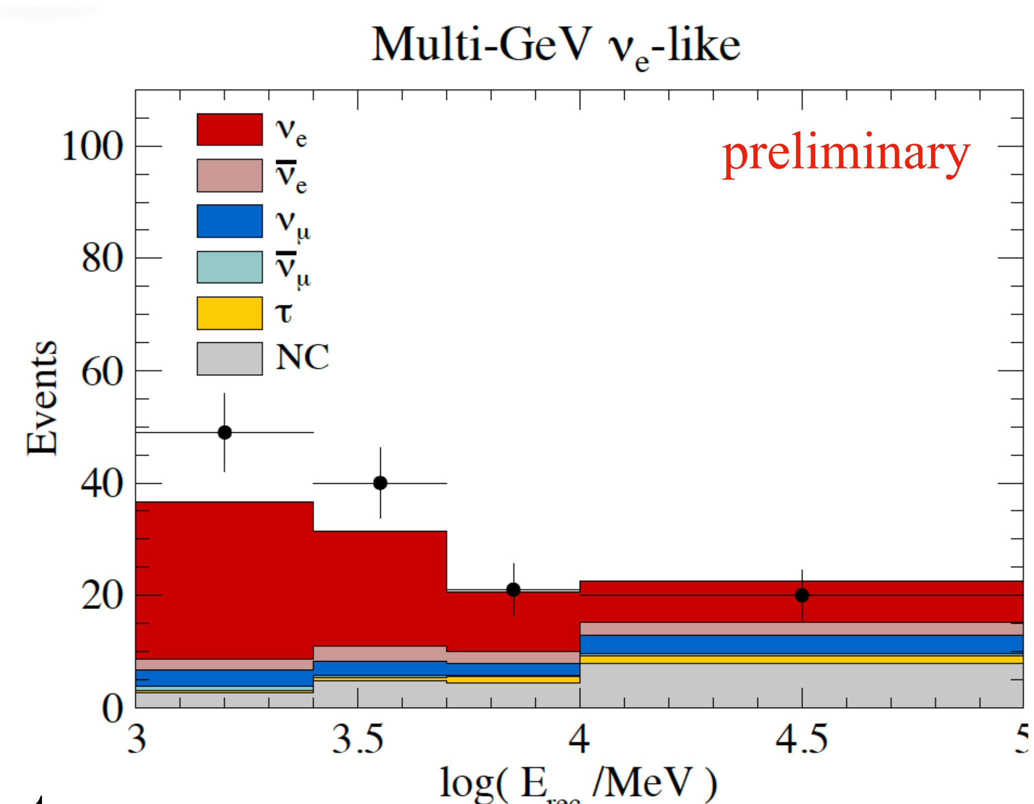
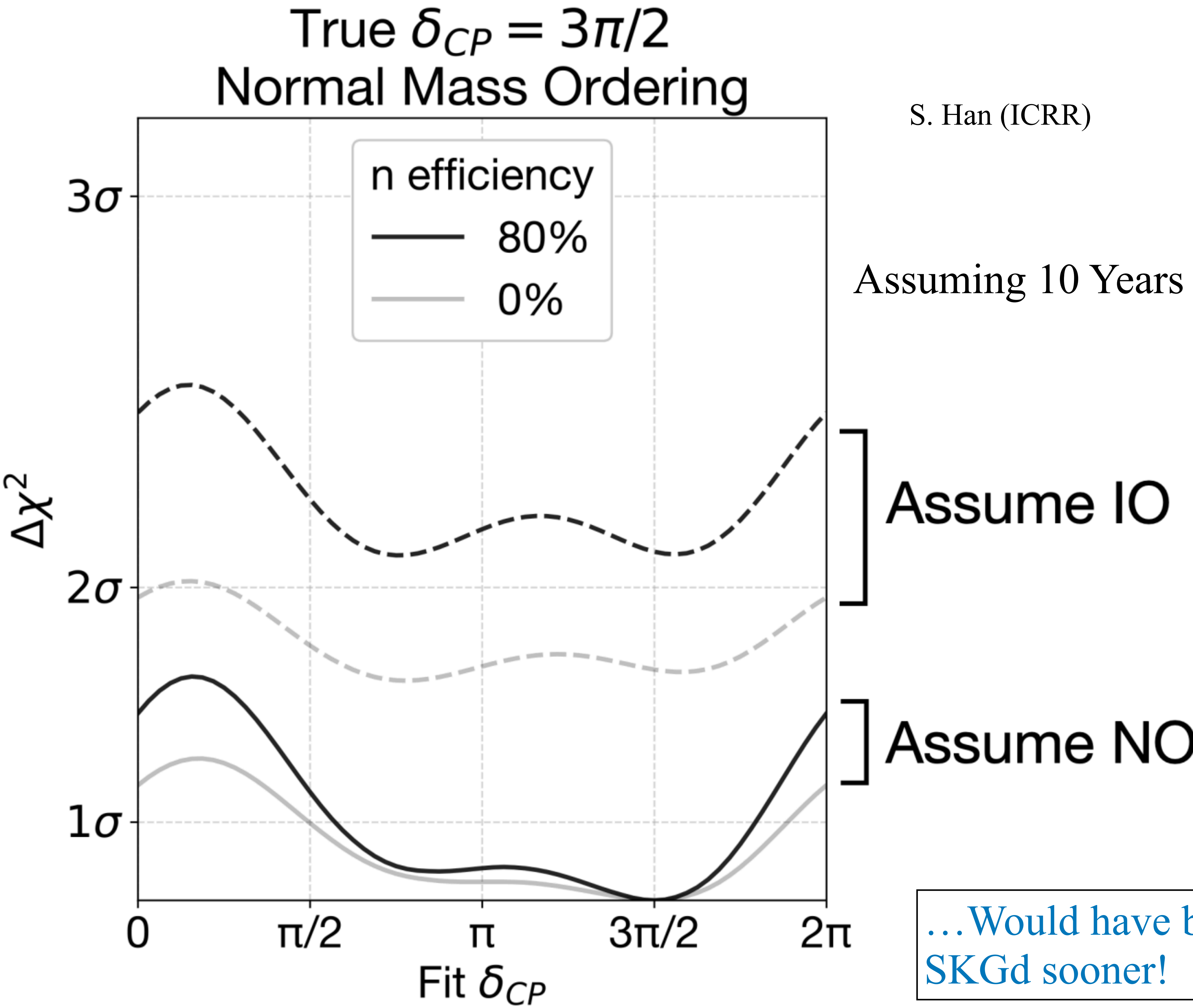




- Now adding SK6 to the rest of the pure water data set

Ultimately What Gadolinium Can Do for This Analysis : **Sensitivity**

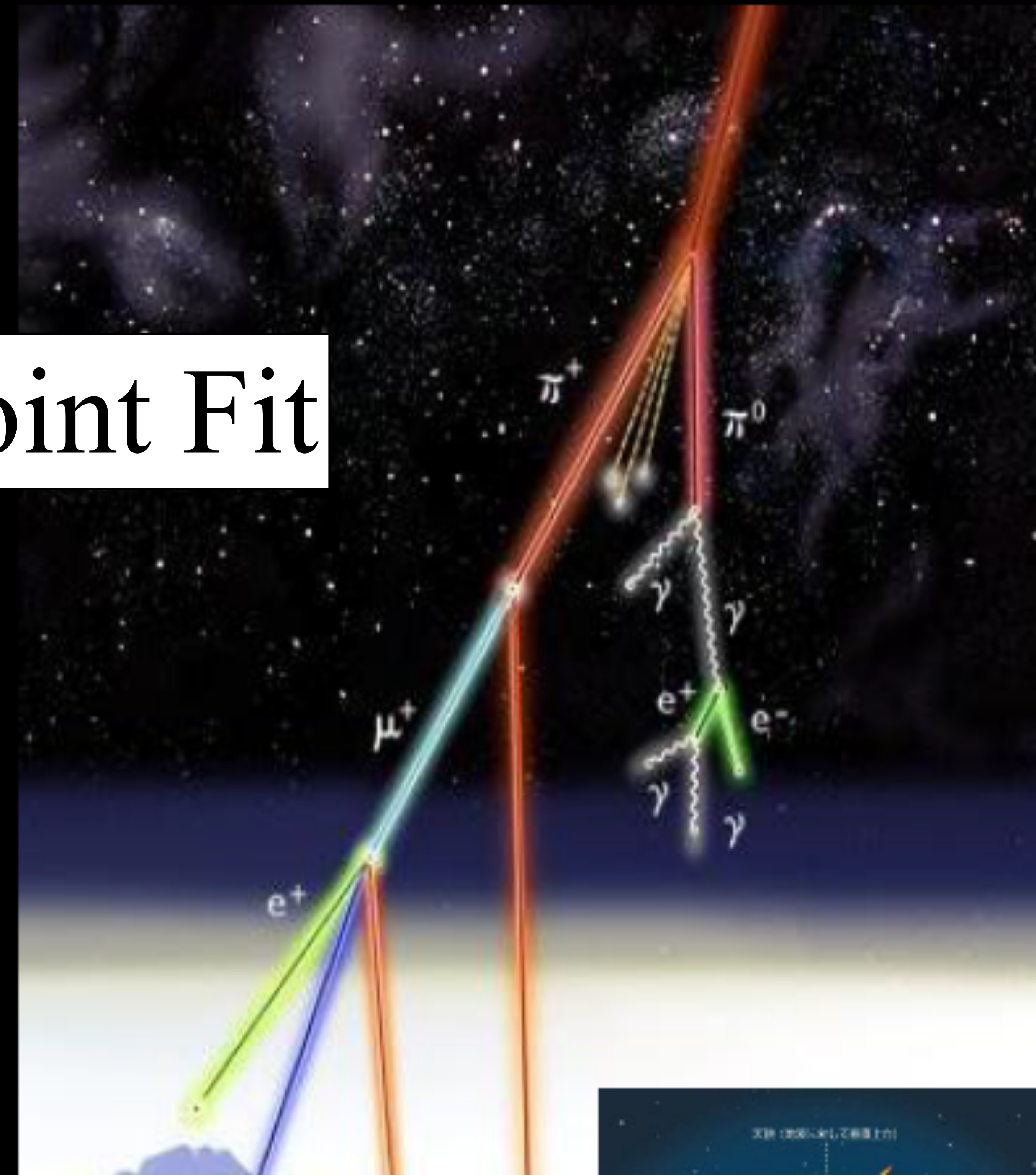


S. Han (ICRR)

Assuming 10 Years of data after 2019

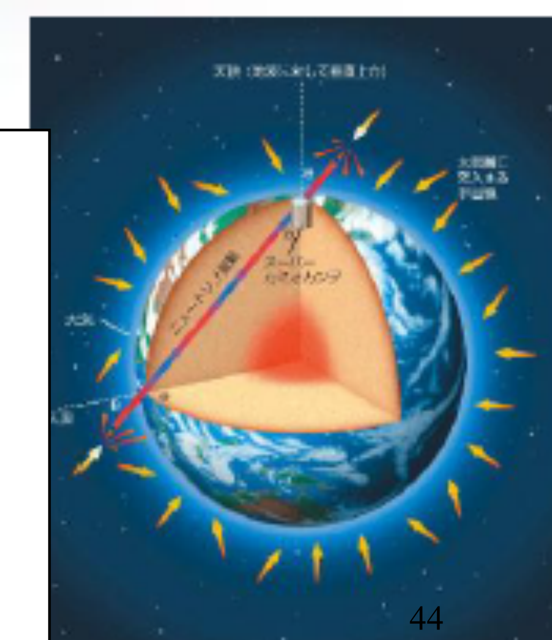
…Would have been nice to have SKGd sooner!

SK+T2K Joint Fit

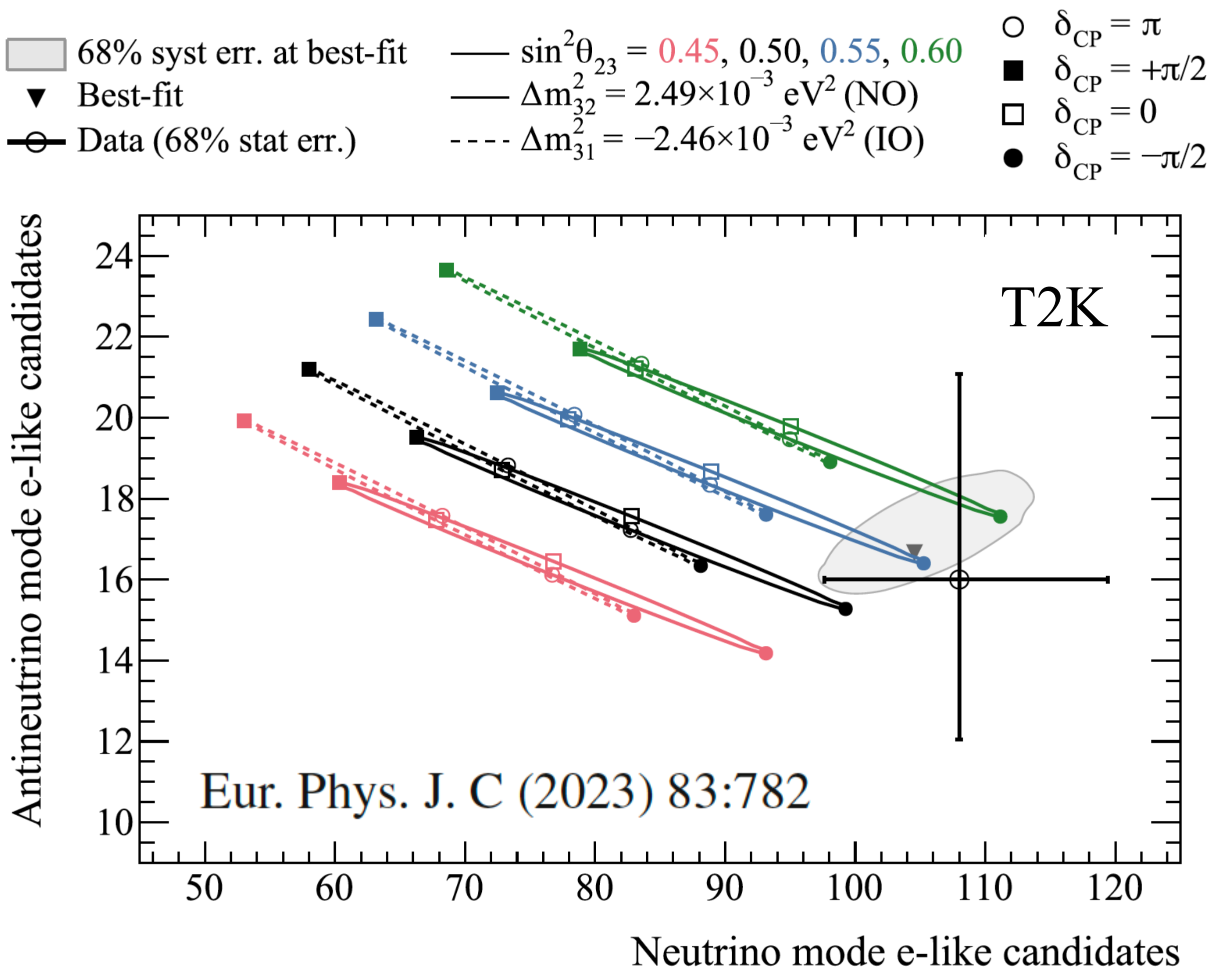


Theme:

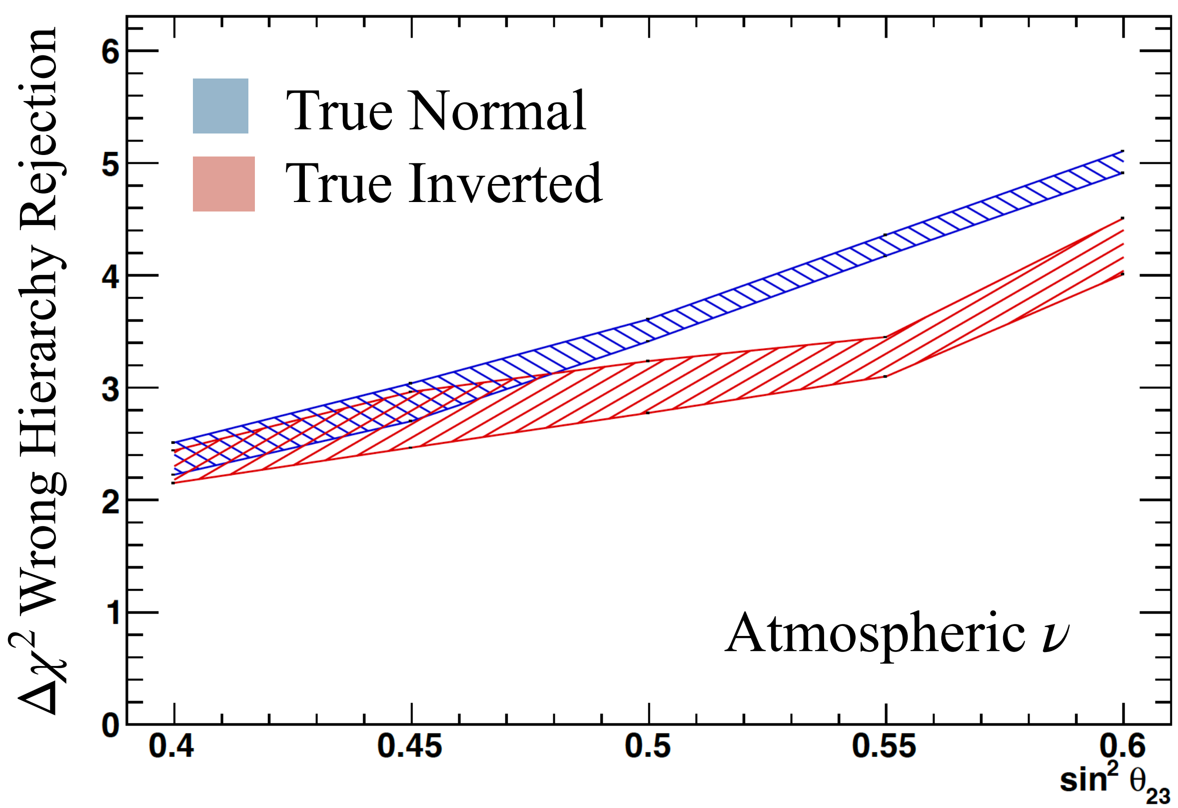
- Best of both worlds!
- …Preparation for Hyper-K



Motivation for A Combined SK+T2K Analysis



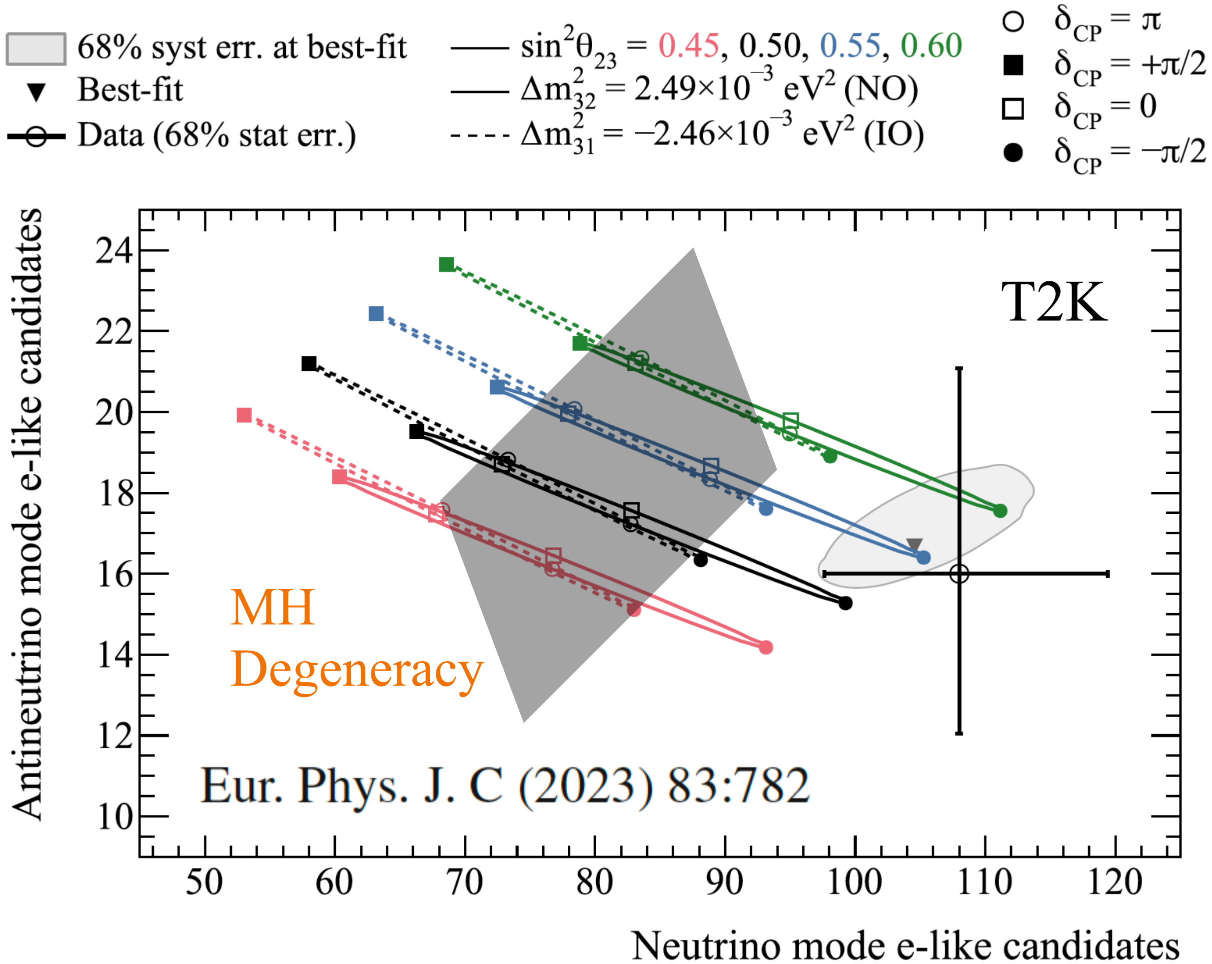
- T2K's Relatively short baseline means limited matter effect
  - → limited hierarchy sensitivity
  - Parameter degeneracies
- Off-axis beam measures atmospheric parameters precisely



- Super-K has large matter effect
  - → good hierarchy sensitivity
  - Strong dependence on atmospheric mixing

Width of bands is effect of δ_{cp}

Motivation for A Combined SK+T2K Analysis



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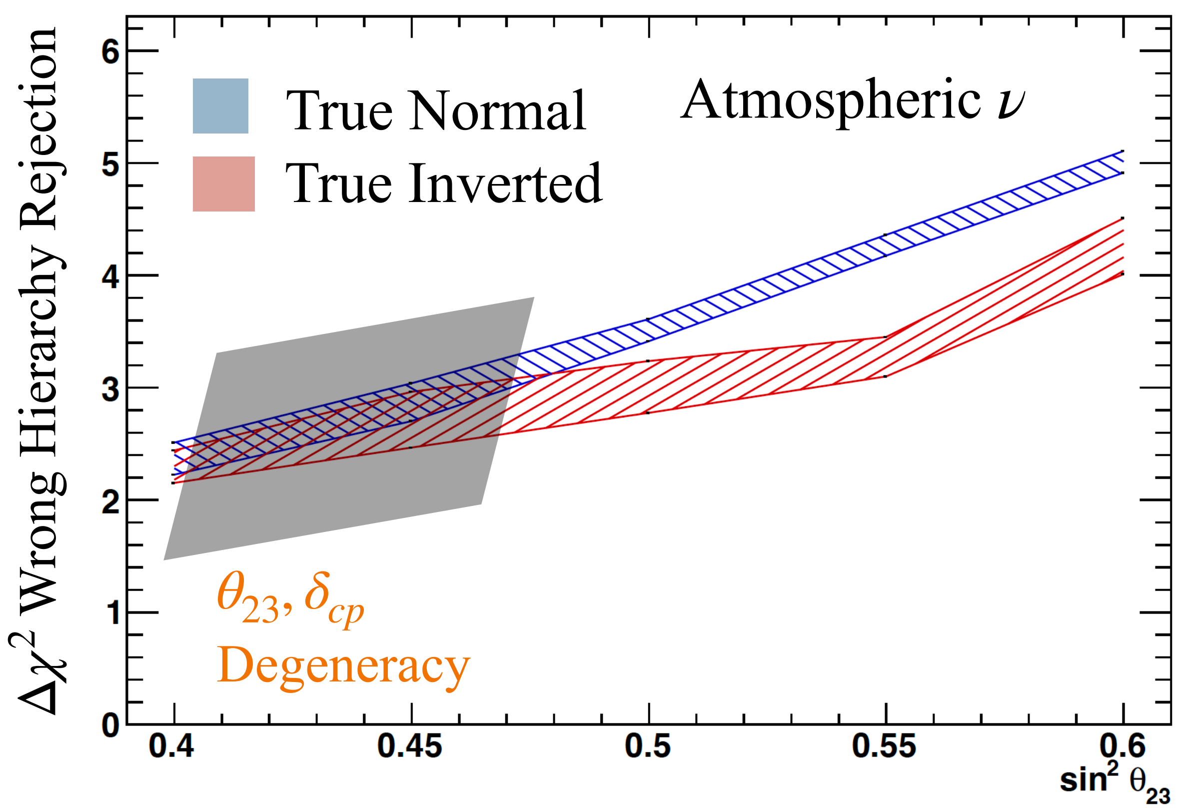

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Width of bands is effect of δ_{cp}

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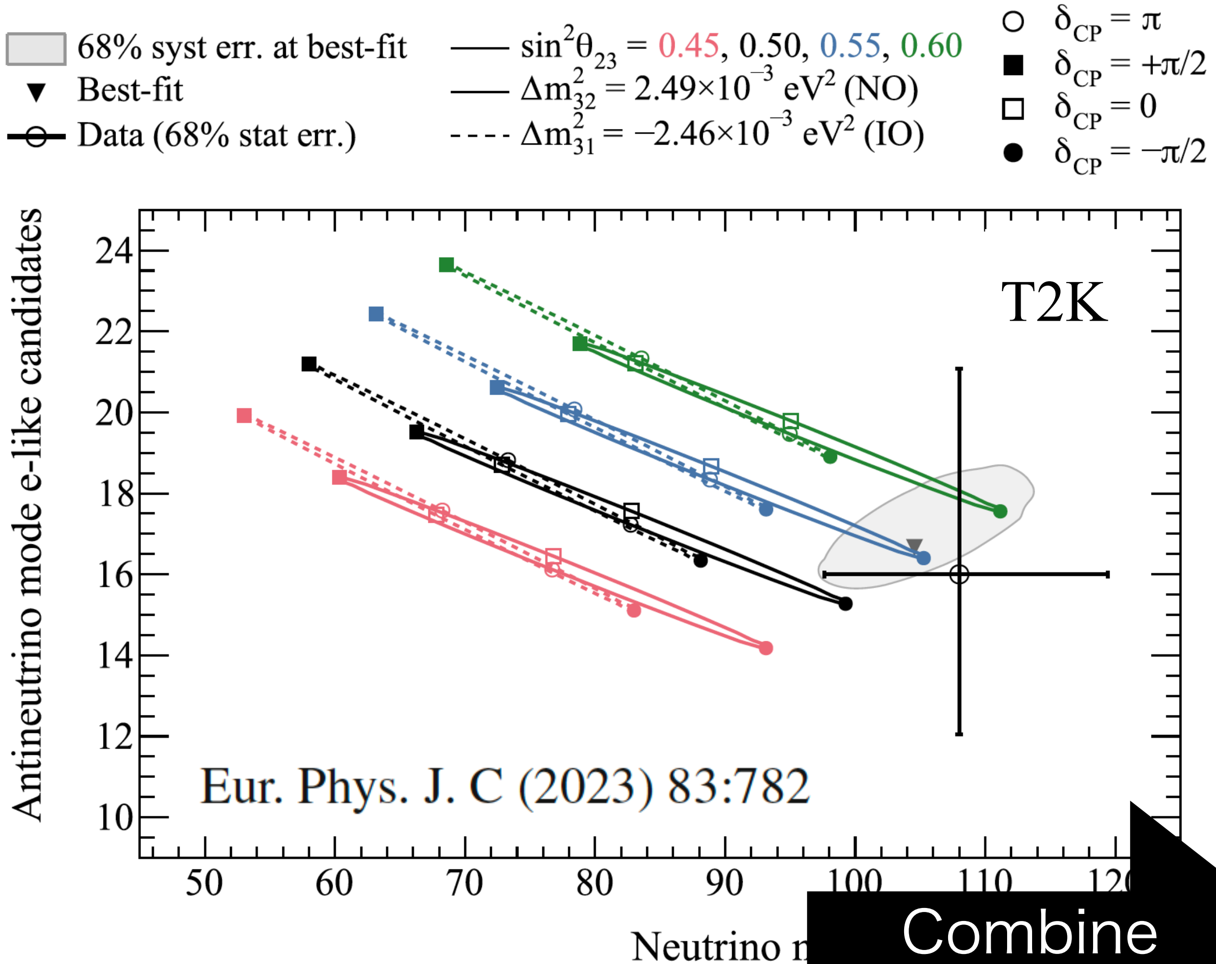
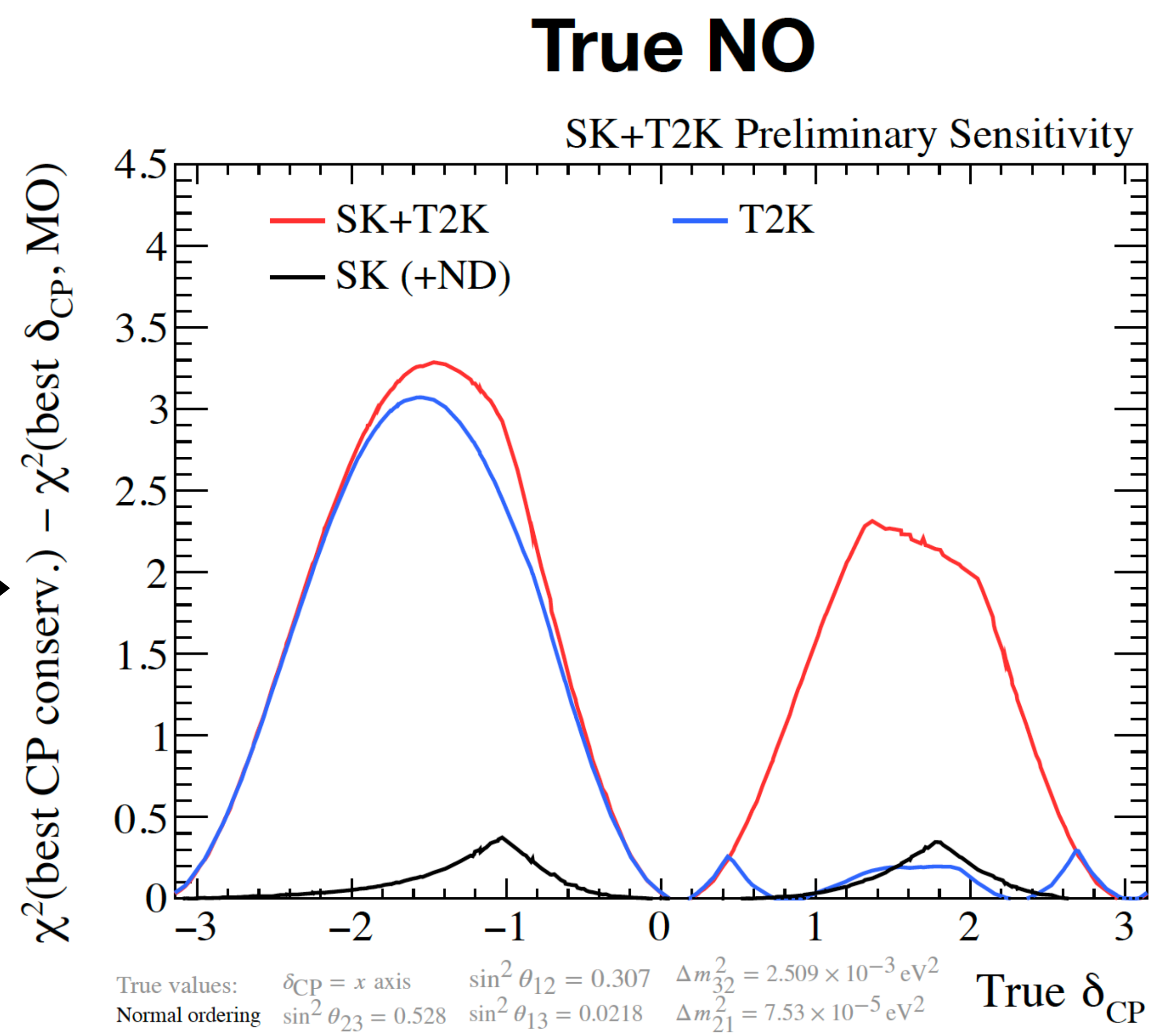
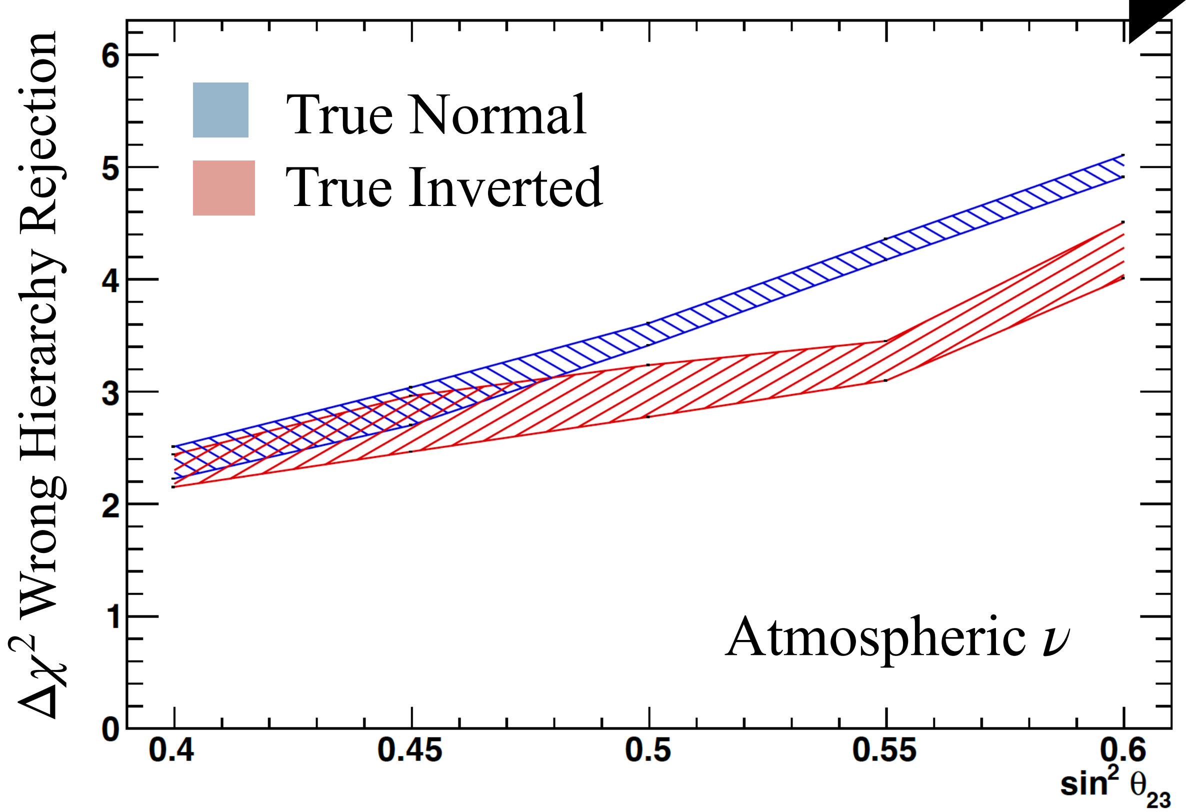


Combine



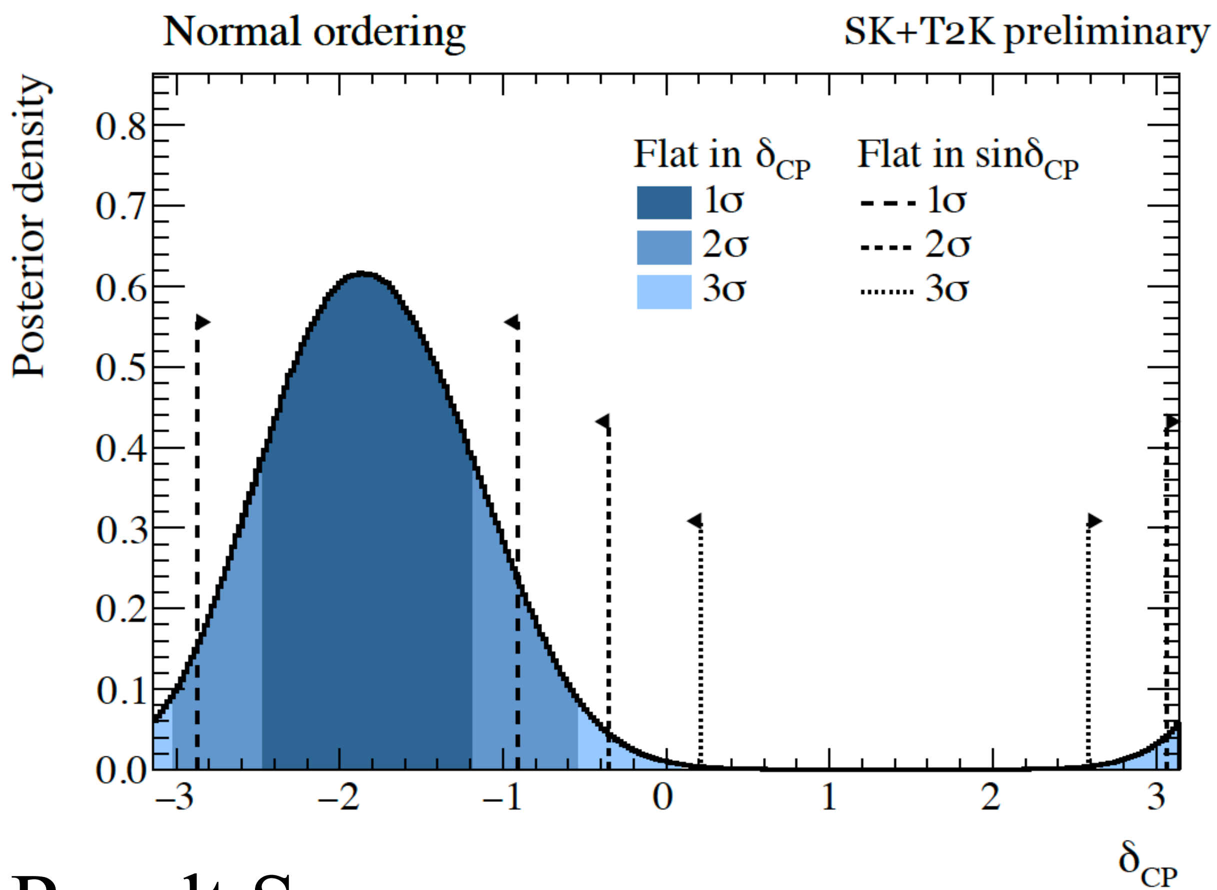


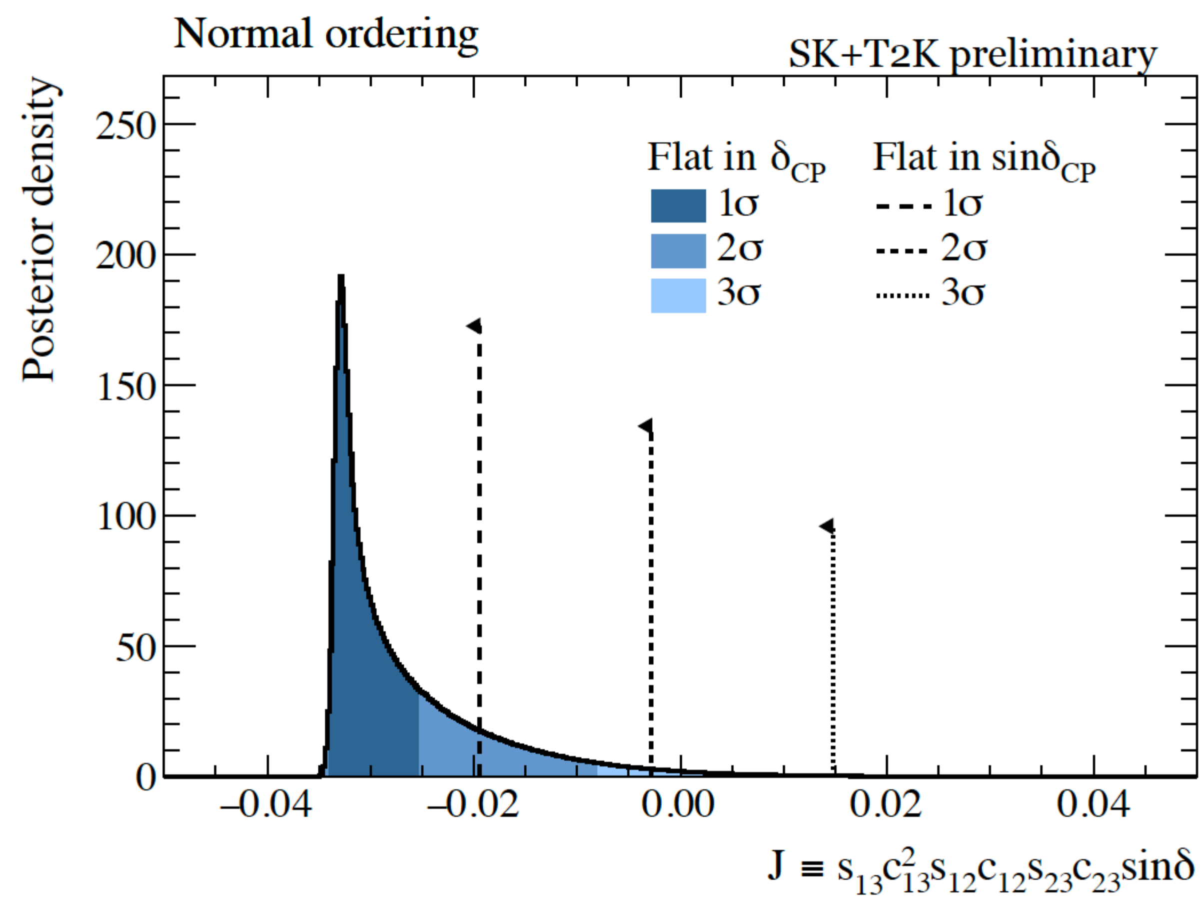
Width of bands is effect of δ_{cp}

SK+T2K Result Summary 2023

Preliminary

- 4 fits representing Bayesian and Frequentist analyses from SK and T2K
  - → All show similar conclusions

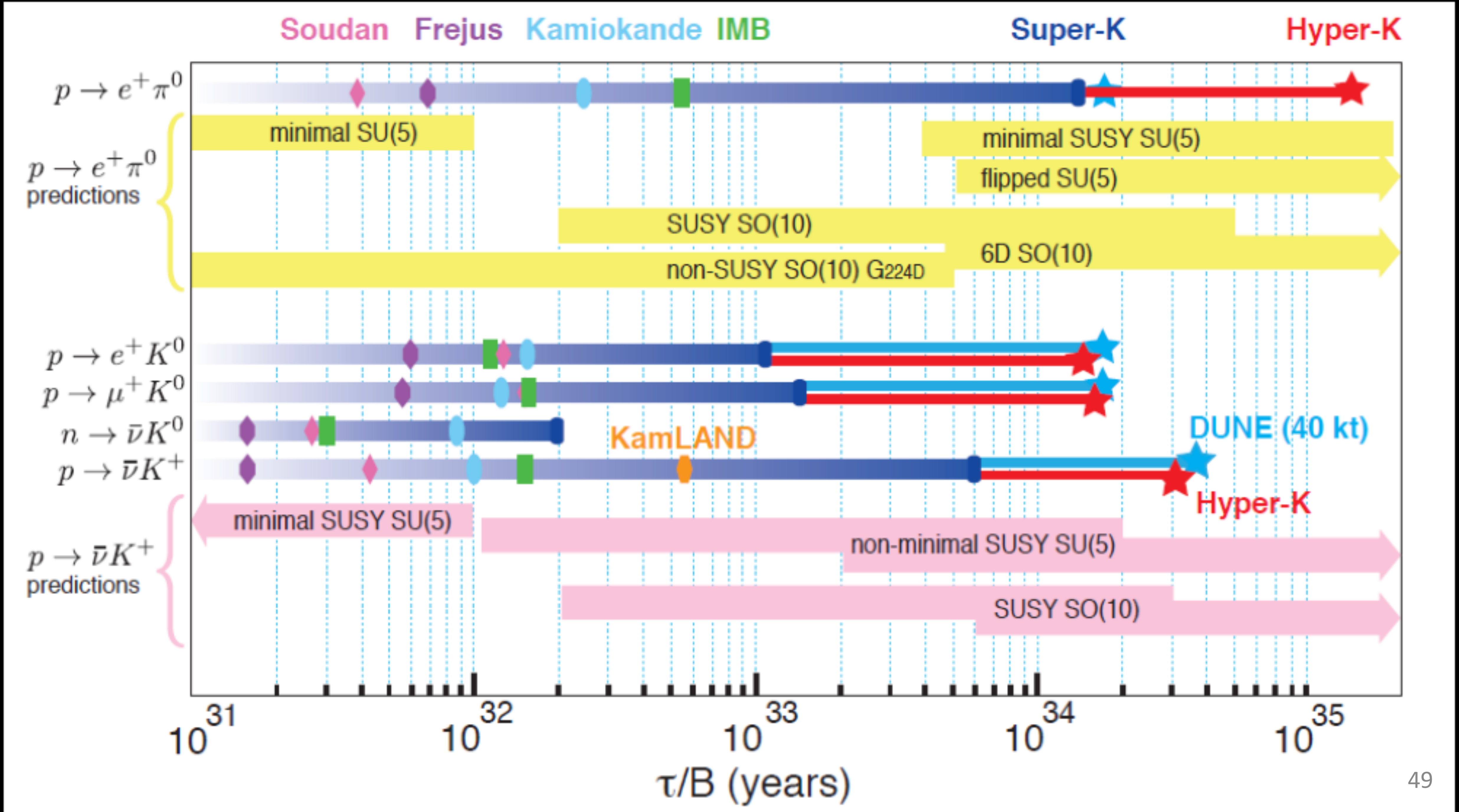




Result Summary

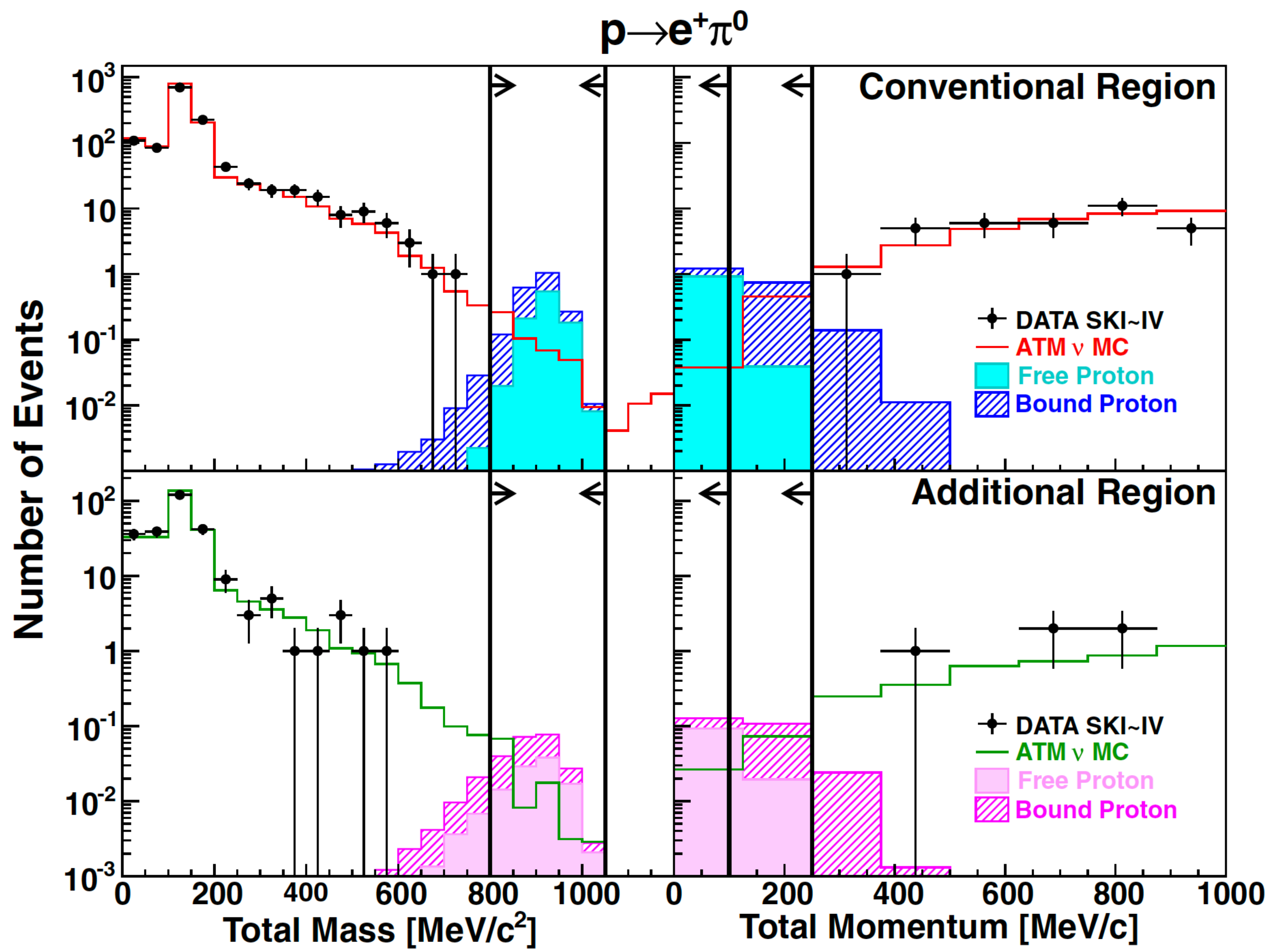
- Preference for $\delta_{CP} \sim -\dfrac{\pi}{2}$, CP conservation *excluded* at 2σ
- Weak preference for *normal* mass ordering: Bayes Factor: 8.98
- No real preference for θ_{23} octant
- So far…no neutron information used — next iteration, now in progress will!

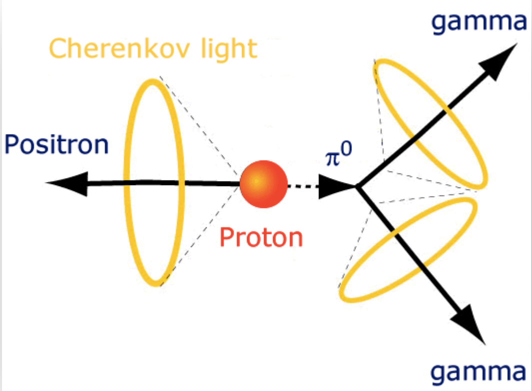
Nucleon Decay Physics Potential



Proton Decay : $p \rightarrow e^{+}\pi^{0}$

PHYS. REV. D **102**, 112011 (2020)





- 2 or 3 e-like rings
- No decay-e
- $85 < M_{\pi^0} < 185$ MeV/c^2 (3ring)
- $800 < M_p < 1050$ MeV/c^2
- $p_{tot} < 250$MeV/c

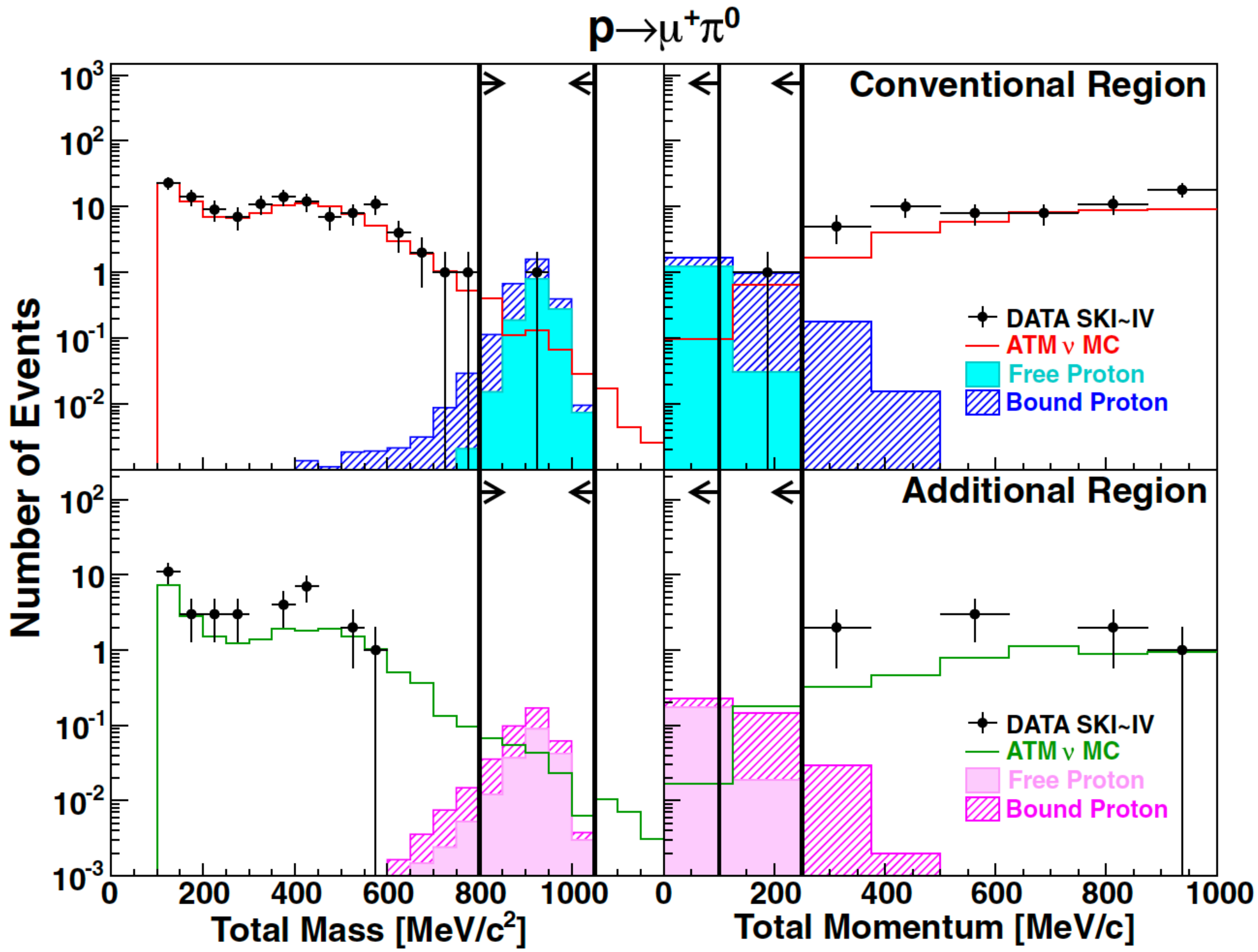
- **No tagged neutrons**

$\varepsilon \sim 25\,\%$ **(purewater)**

SK 450 kton-yr	Signal Effic.	BKG [/Mton yr.] no neutron tag	BKG [/Mton yr.] 25% neutron tag	Data
Low (p< 100MeV)	~ 18%	0.09	< 0.04	0
High (100 < p <250)	~20%	1.36	1.03	0

Proton Decay : $p \rightarrow \mu^+\pi^0$

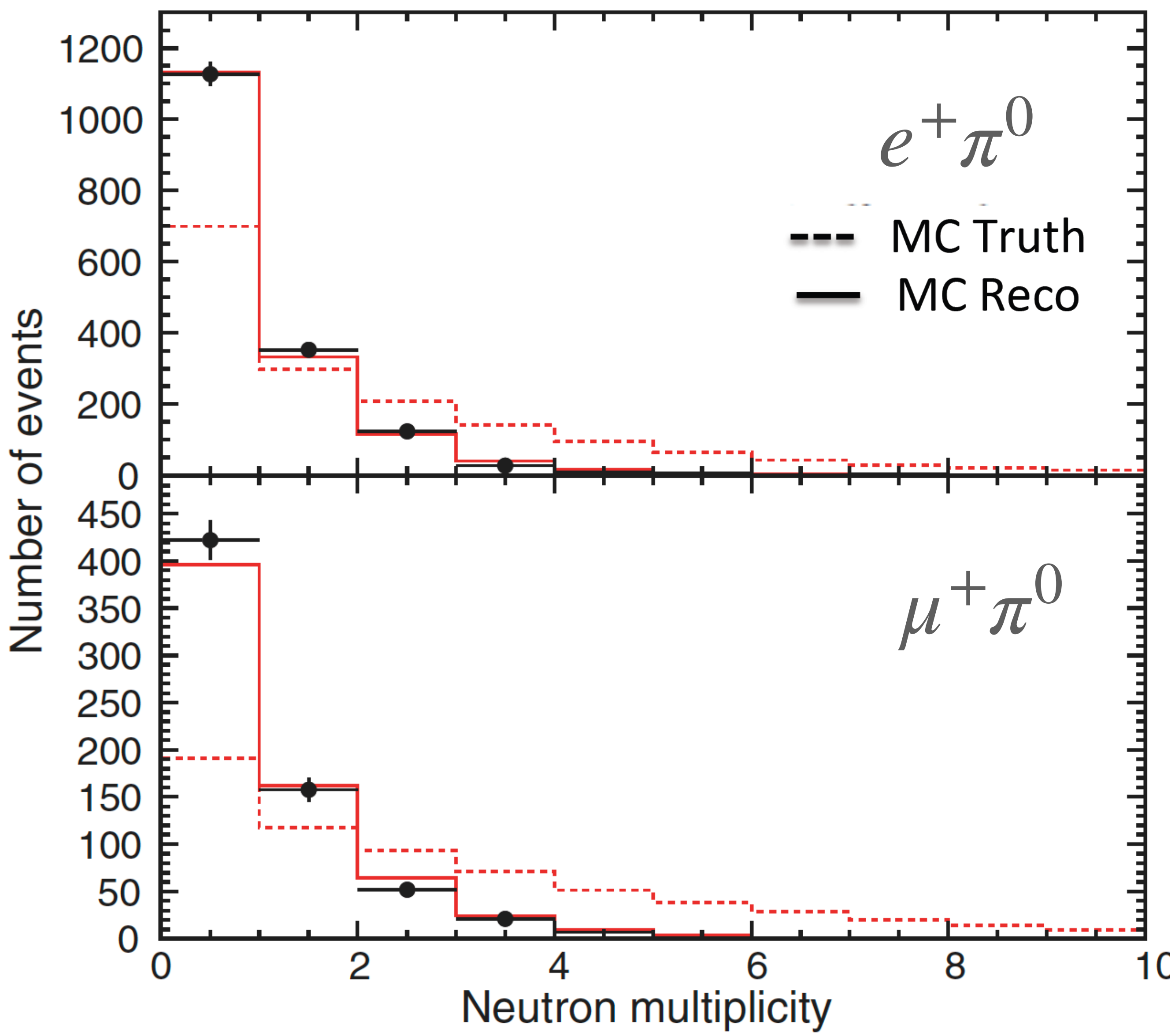
PHYS. REV. D **102**, 112011 (2020)

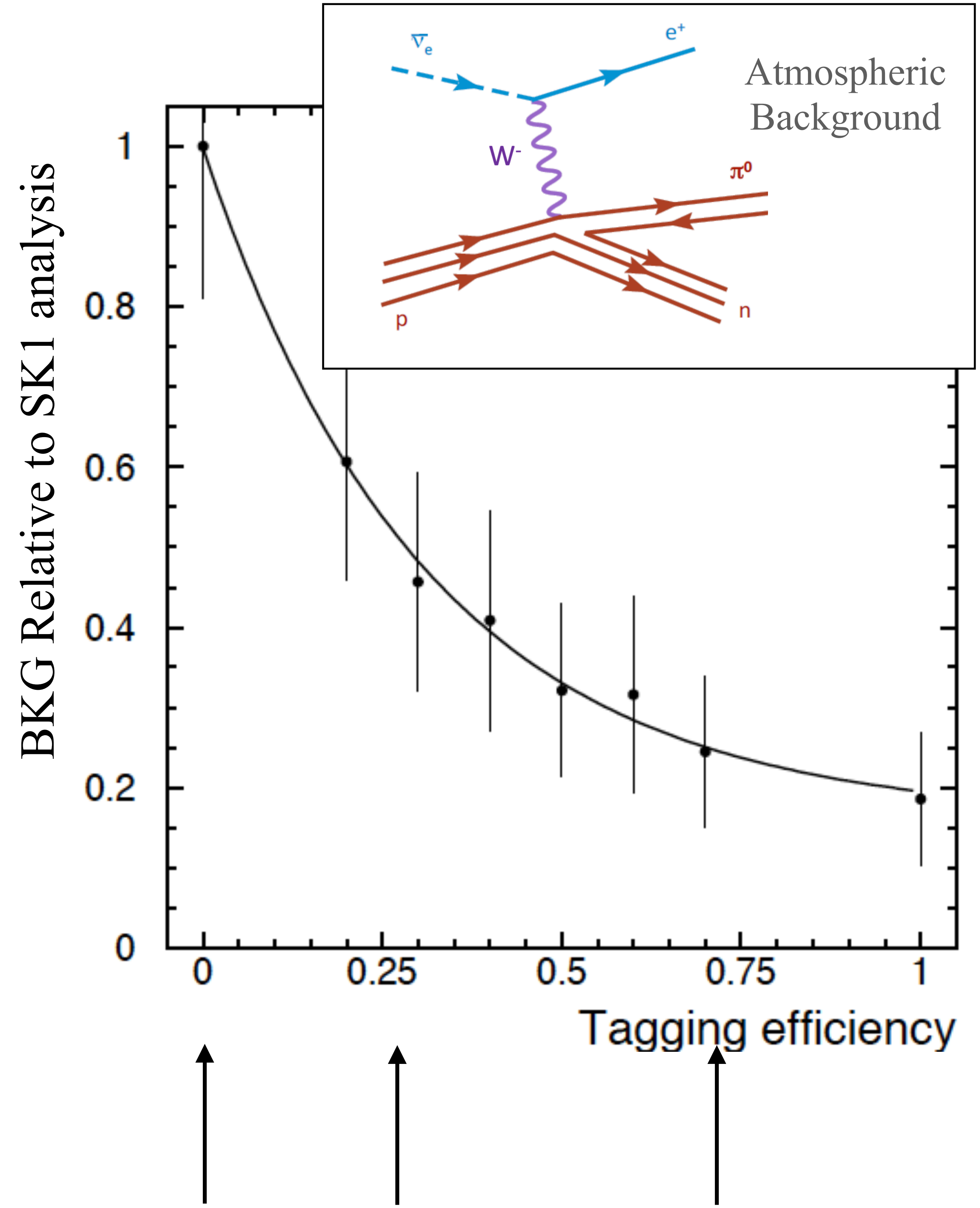


SK 450 kton-yr	Signal Effic.	BKG [/Mton yr.] no neutron tag	BKG [/Mton yr.] 25% neutron tag	Data
Low (p< 100MeV)	~ 16%	0.27	< 0.04	0
High (100 < p <250)	~ 16 %	1.9	1.9	**1**

Proton Decay : Importance of Neutron Tagging

PHYSICAL REVIEW D **95,** 012004 (2017)





SK1 SK4 SKGd (0.03w%)

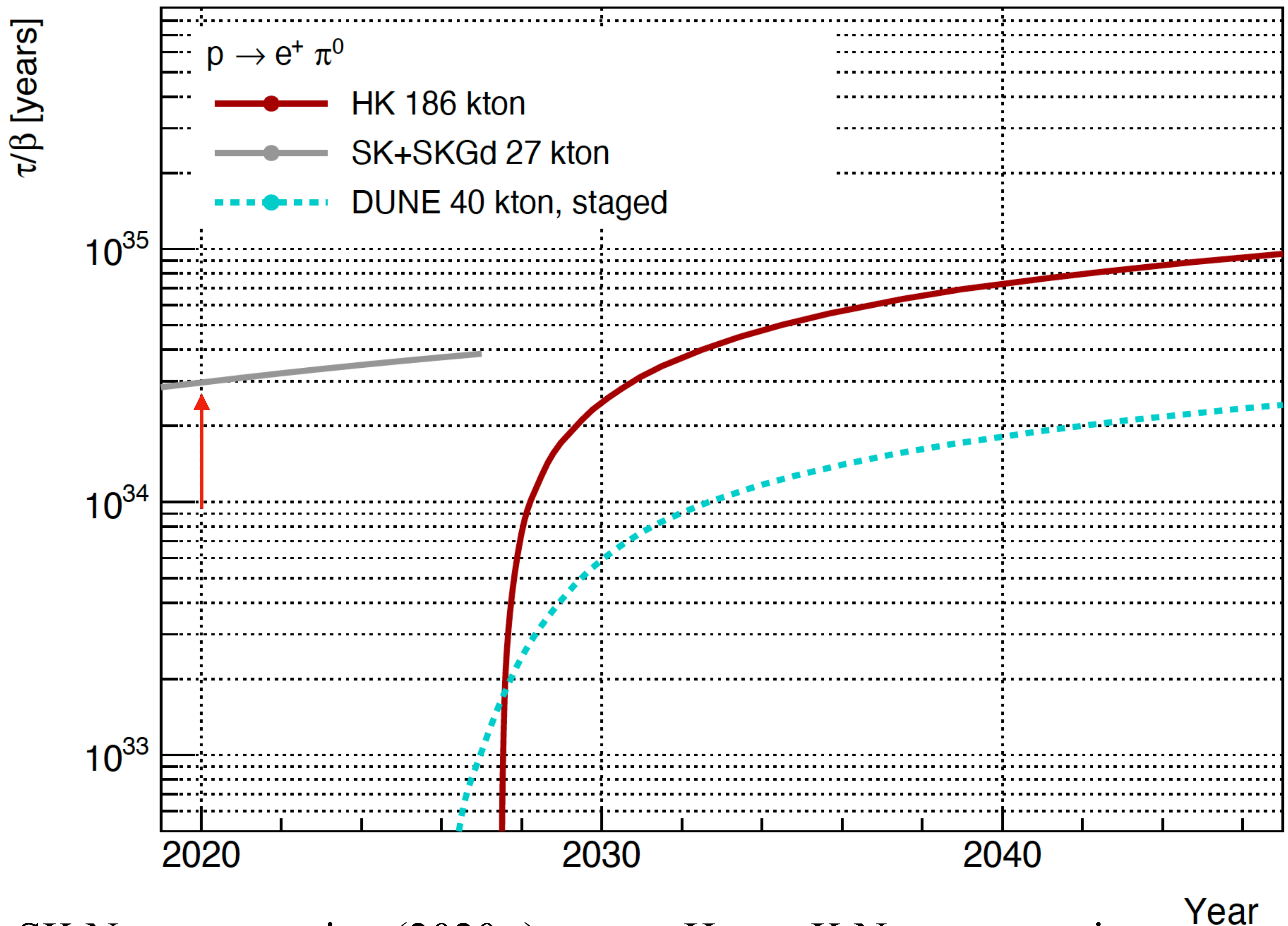
Neutron tagging

$\varepsilon \sim 25\ \%$

- Impact on efficiency expected to be negligible

Proton Decay : $p \rightarrow e^+\pi^0$

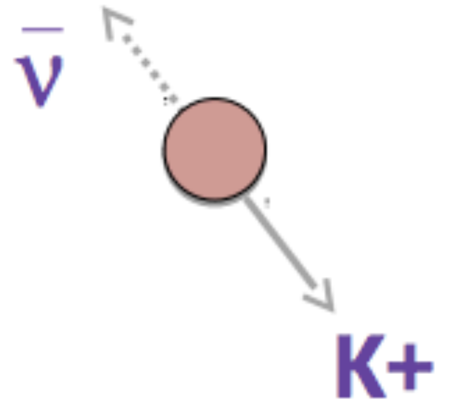
Discovery Potential



SK Neutron tagging (2020+)
$\varepsilon \sim 25\ \%$

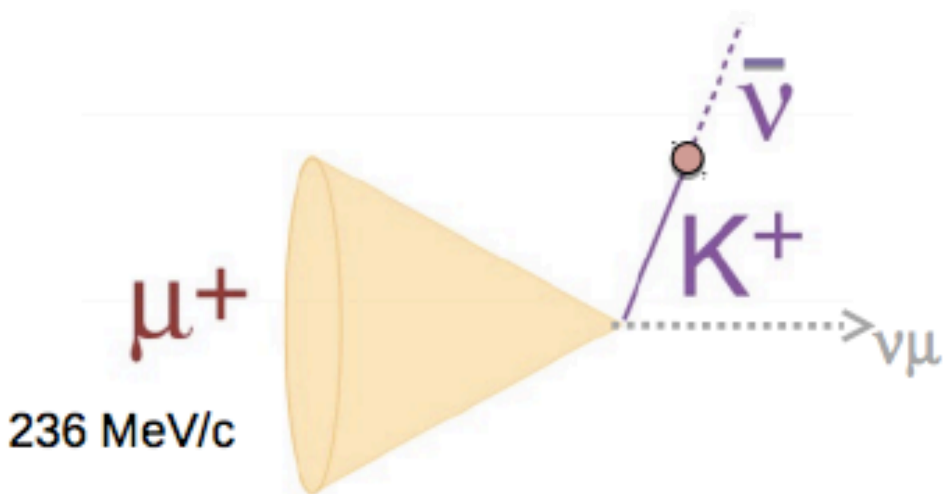
Hyper-K Neutron tagging
$\varepsilon \sim 40\ \%$

Proton Decay : $p \rightarrow \nu\ K+$



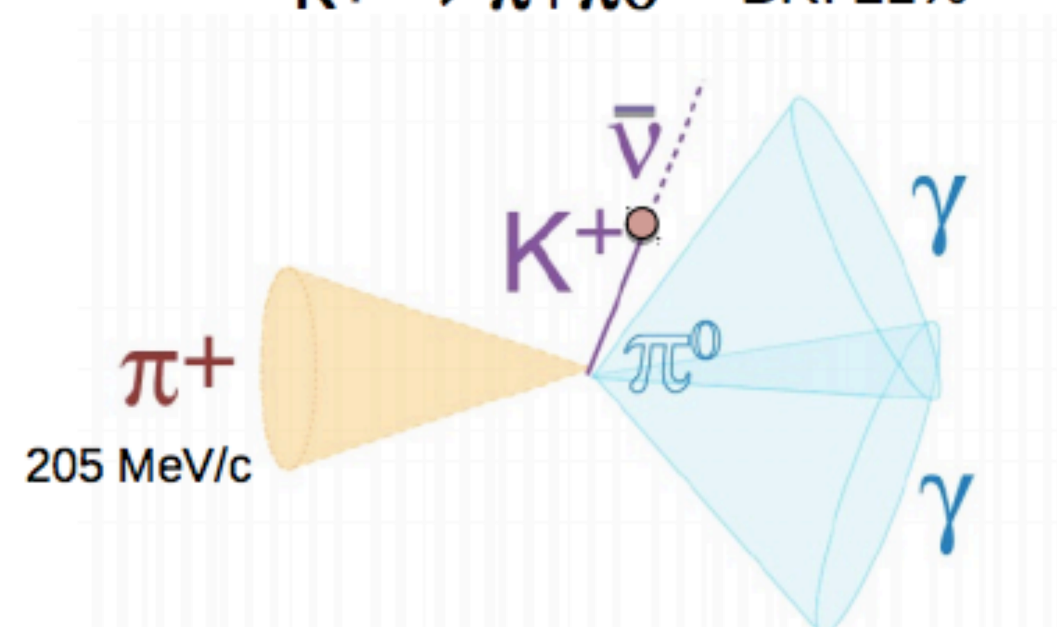
- K+ momentum is 340 MeV/c
  - Below Cherenkov threshold (749 MeV/c)
- However, K+ experiences no nuclear interactions and escapes
- Strategy: search for evidence of isolated K+ via its decays
- Cannot reconstruct the original proton mass

$K+ \rightarrow \mu+\nu\mu$ BR: 65%



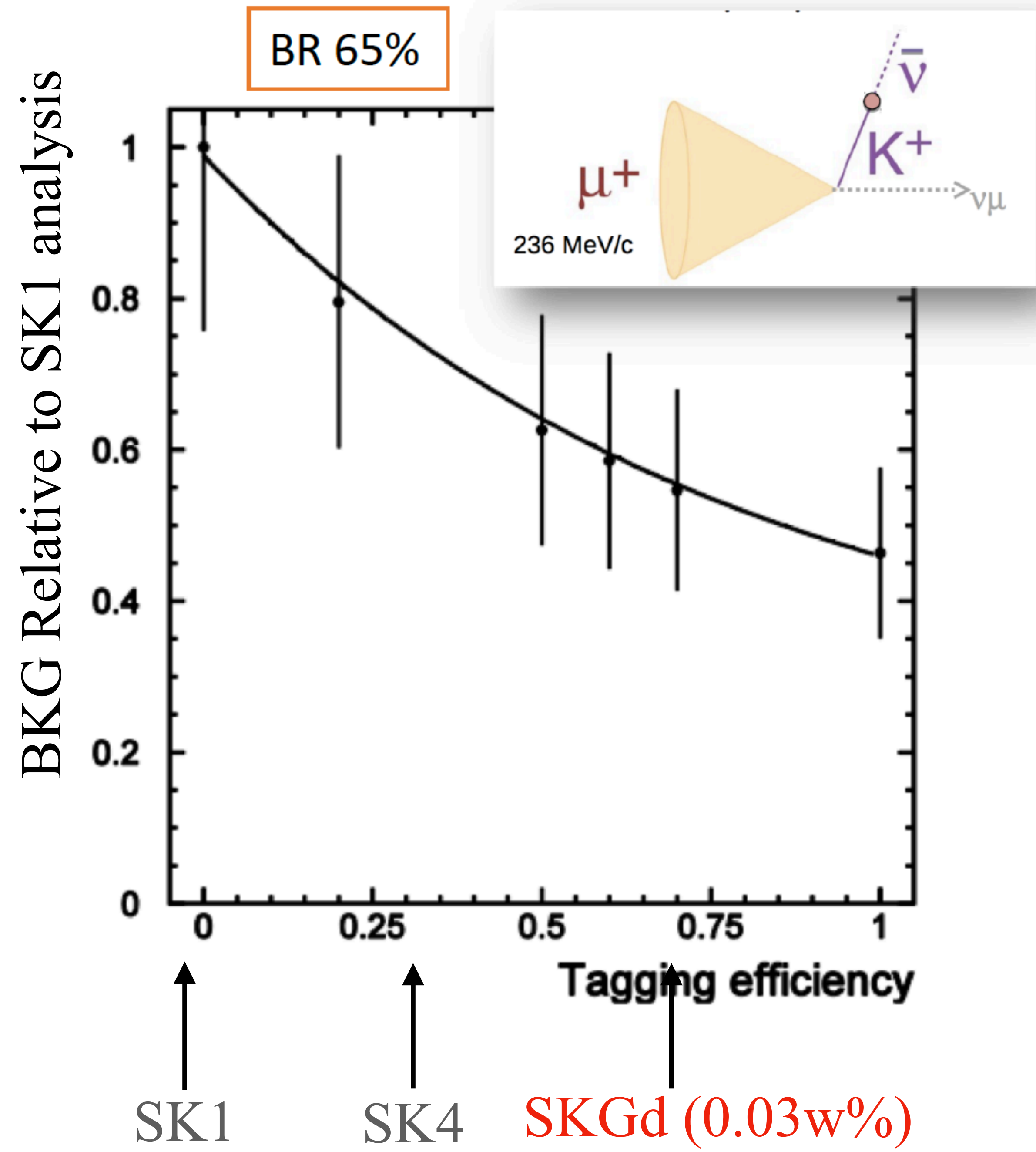
Search Methods
- 1) Nuclear deexitation γ, μ, and decay e+
- 2) Monochromatic μ from K+ decay

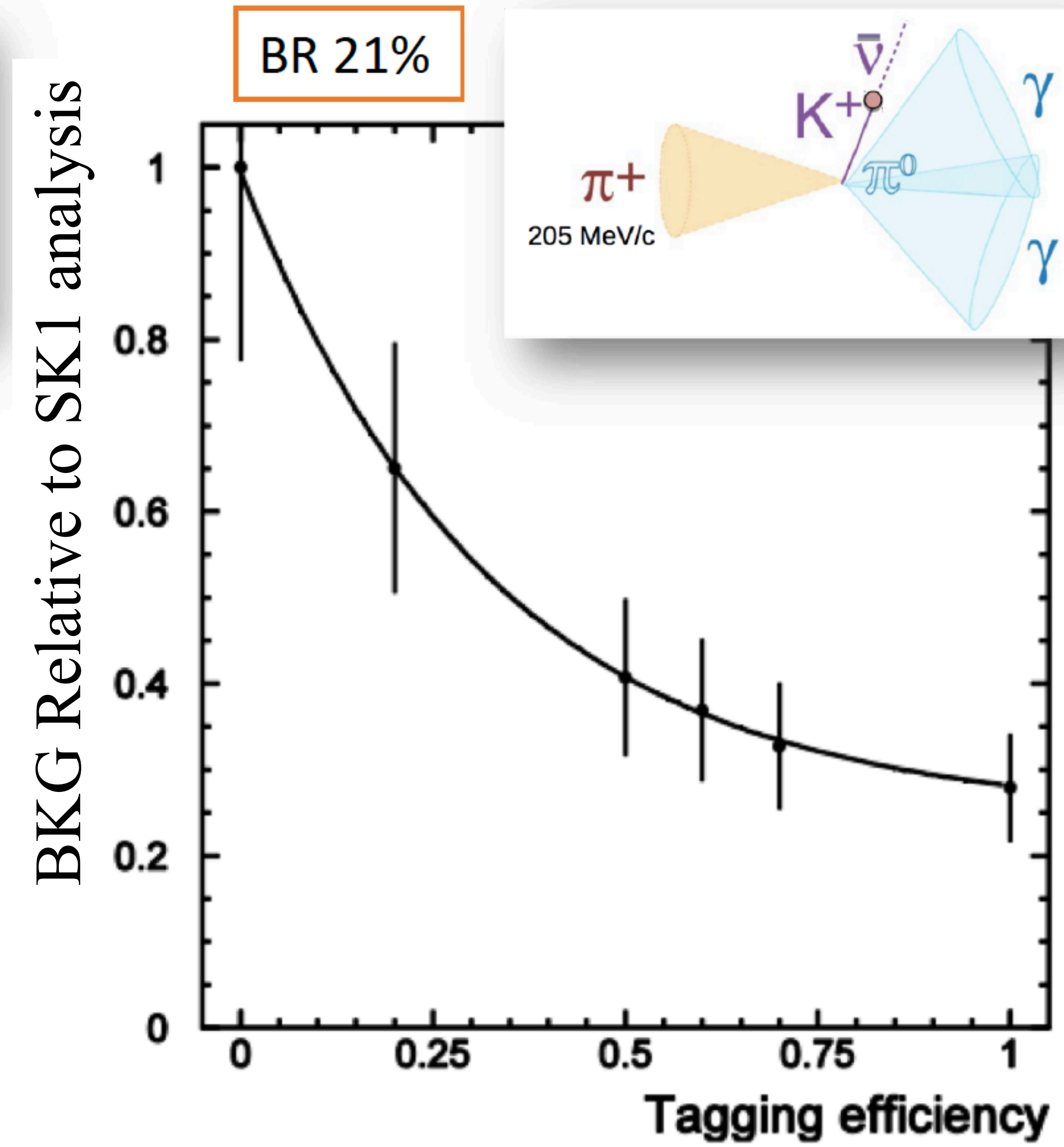
$K+ \rightarrow \pi+\pi0$ BR: 21%



Search Method
- 3) π^+ and two γ from π^0 decay

Proton Decay : Importance of Neutron Tagging



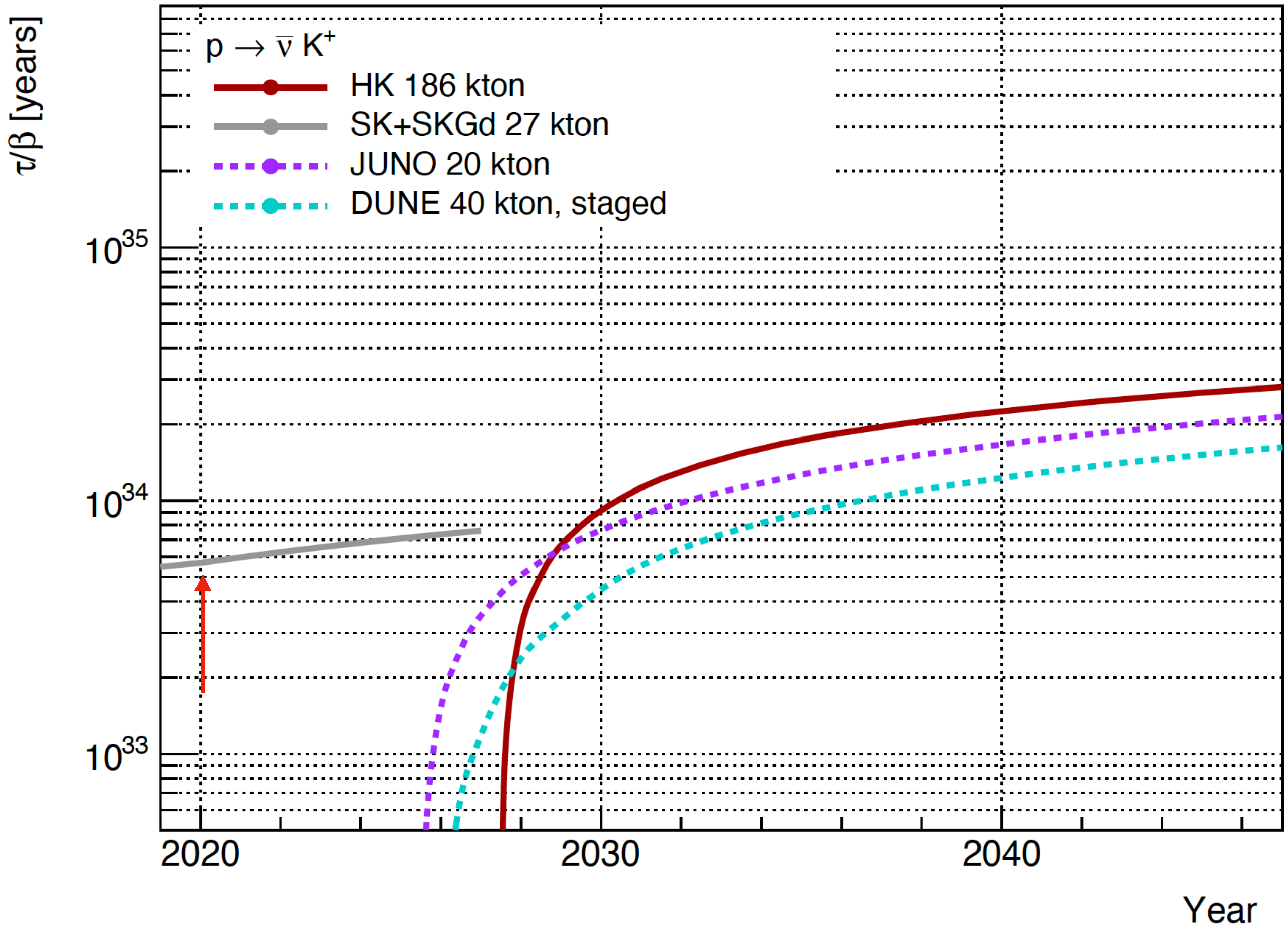


SK	Signal Effic.	BKG [/Mton yr.] no neutron tag	Data
Prompt Gamma	~ 16%	0.89	0
Pi+ Pi0	~ 16 %	1.97	0

- Impact on efficiency expected to be negligible

Proton Decay : $p \to \nu K+$

Discovery Potential



…Would have been nice to have SKGd sooner!

Summary

- Neutrino oscillations - neutron tagging is starting to make an impact in atmospheric oscillation and proton decay studies

- Generator neutron predictions vary wildly and just barely cover observations
  - $\rightarrow$ Large corrections and systematics

- Expect improvements in sensitivity with better neutron tagging

- Just now starting to make use of neutrons from SK-Gd in ATMPD…promising!

- Accumulation of statistics is slow…

At first I worried about Gd, but now…it would have been nice to have SKGd sooner!

Thanks, Mark - Happy Birthday!