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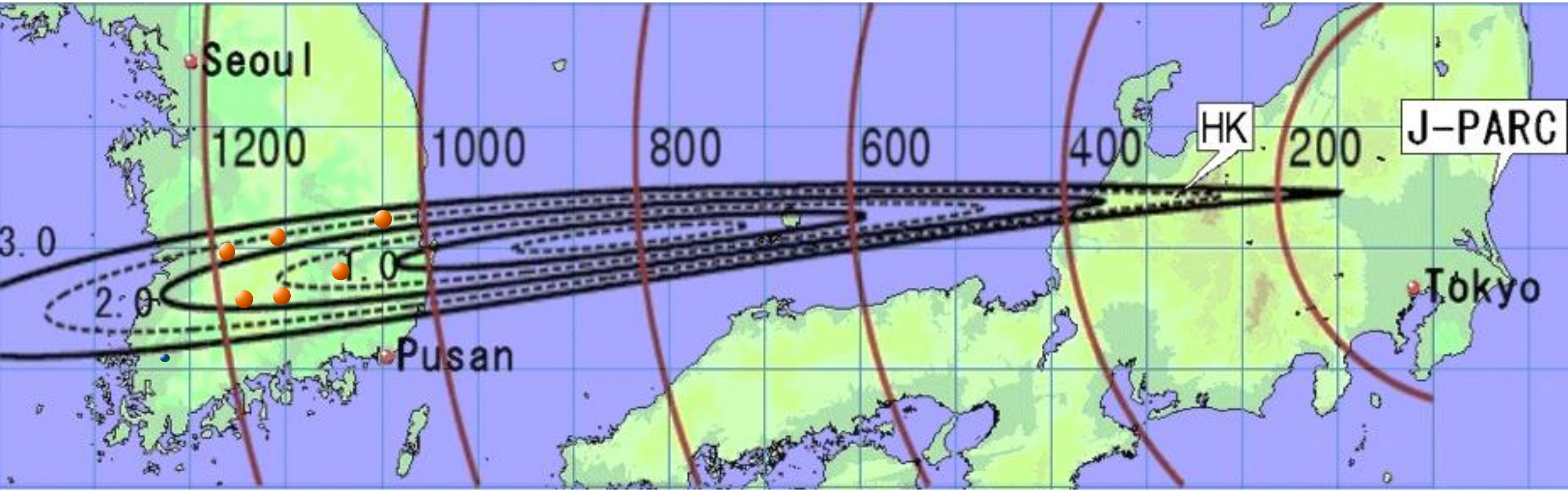
Hyper-Kamiokande 하이퍼 카미오칸데

Motivating a Korean detector: Biprobability plots



2017/02/15

Phill Litchfield

Motivation

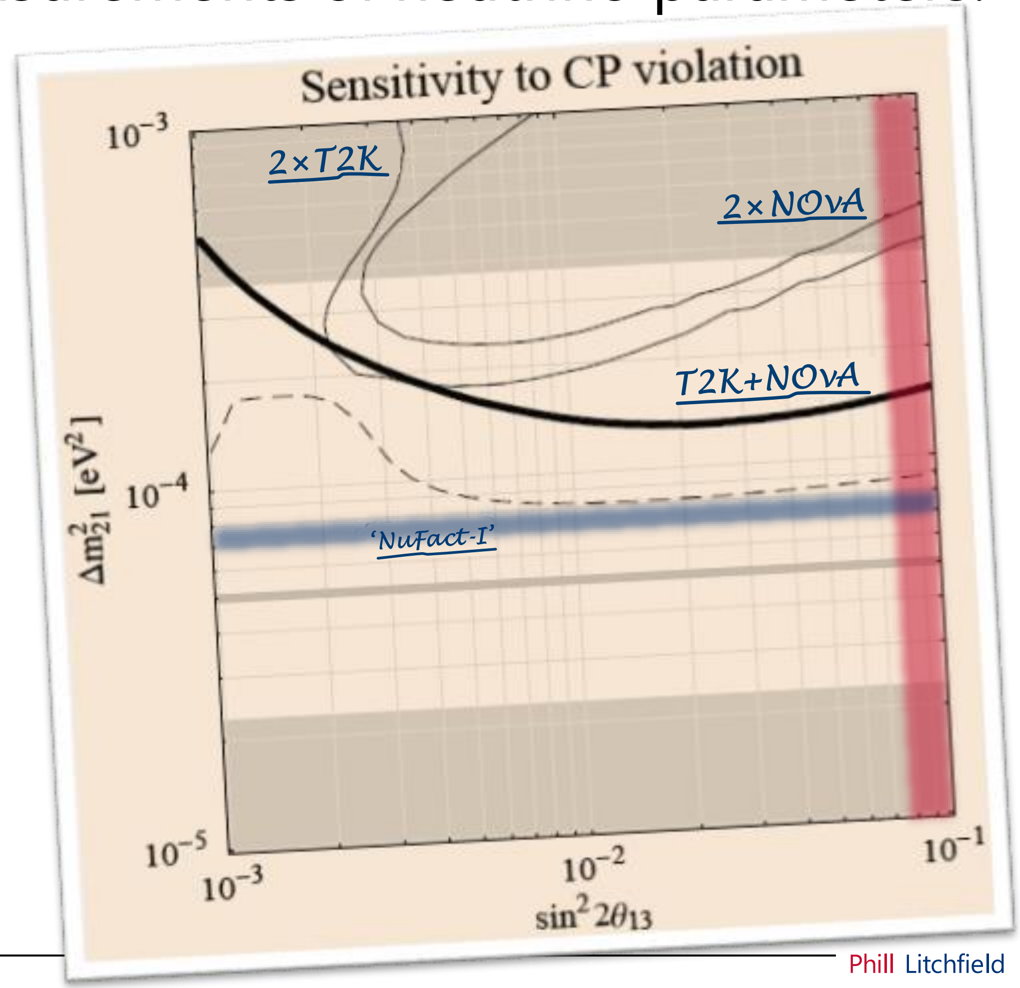
2

A Korean detector is exciting because…

…better measurements of neutrino parameters.

What is meant by "better"?

- More robust with respect to systematic errors
- Resolve degeneracies between oscillation parameters
- In pre-θ_{13} era, we talked about *synergies* (e.g. arXiv:0211300)



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Possible scenarios (my perspective)

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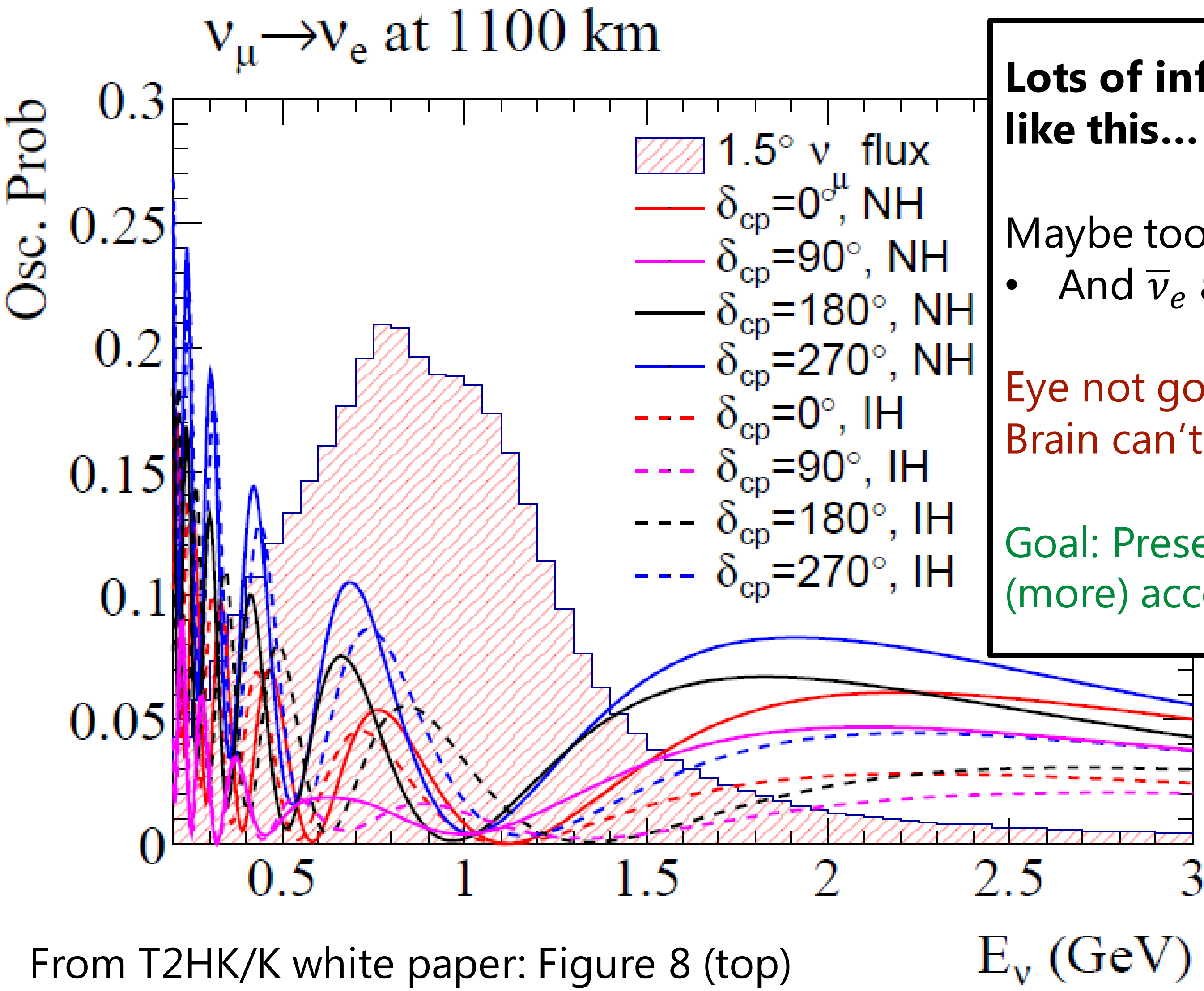
T2K best fit is one of the 'easy points'. Consider 2 options:

1. **T2K is correct, and other experiments agree**
   - Good chance that T2K + NOνA + Icecube together favour NH at $> 3\sigma$ [See back-up for NOνA sensitivities]
   - Most important goal is to establish CPv, and then *measure* δ.
   - **Korean detector can better resolve δ regions that are degenerate in 1st maximum experiments.**
2. **T2K is not correct, &/or other experiments disagree**
   - If so, just repeating T2K at higher statistics unlikely to resolve issue
   - Testing T2K best fit in other regimes is highly preferable over repeating at higher stats
   - **Korean detector provides only realistic access to other regimes with Water Cherenkov detector** (in next 20y)

Want to make straightforward demonstration of these benefits.

- Either way, would provide great 'closure tests' for our model

Argh, my brain hurts!



Lots of information in a figure like this… ***BUT***

Maybe too much information?

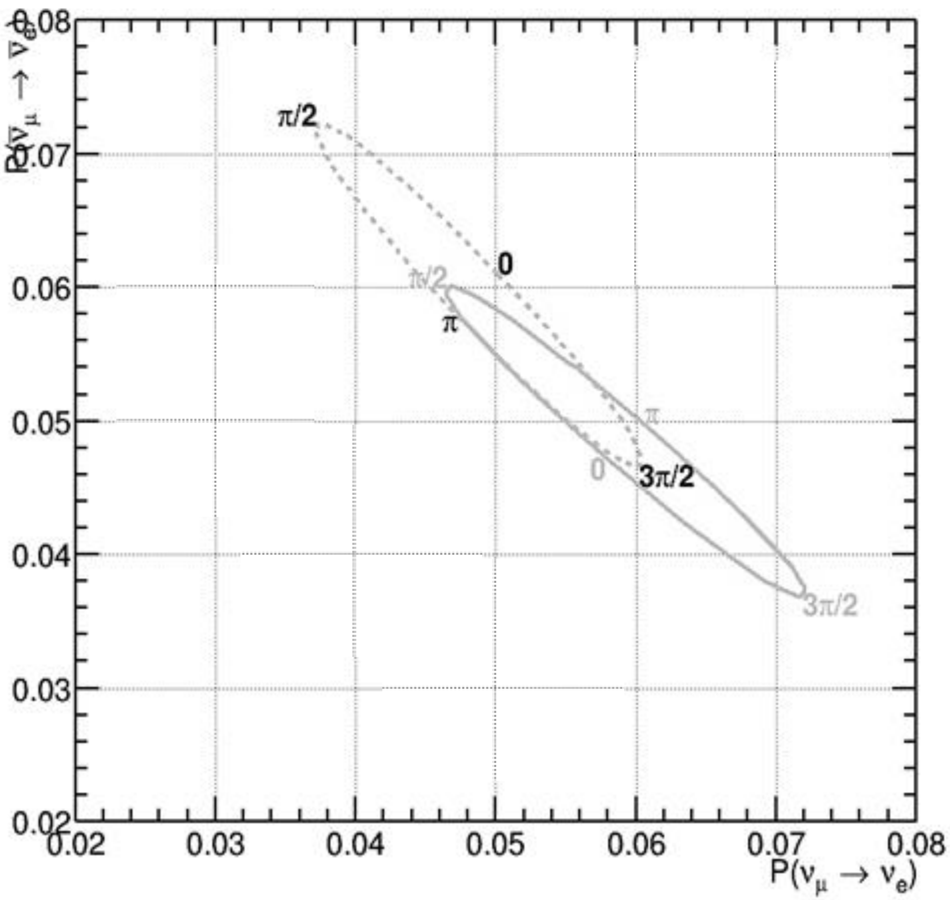
- And $\overline{\nu}_e$ aren't even shown…

Eye not good at following detail.
Brain can't retain information.

Goal: Present this info in an (more) accessible way…

From T2HK/K white paper: Figure 8 (top)

Biprobablility plots



Beloved of theorists, and FNAL people, but pretty much ignored by T2K (to date…)

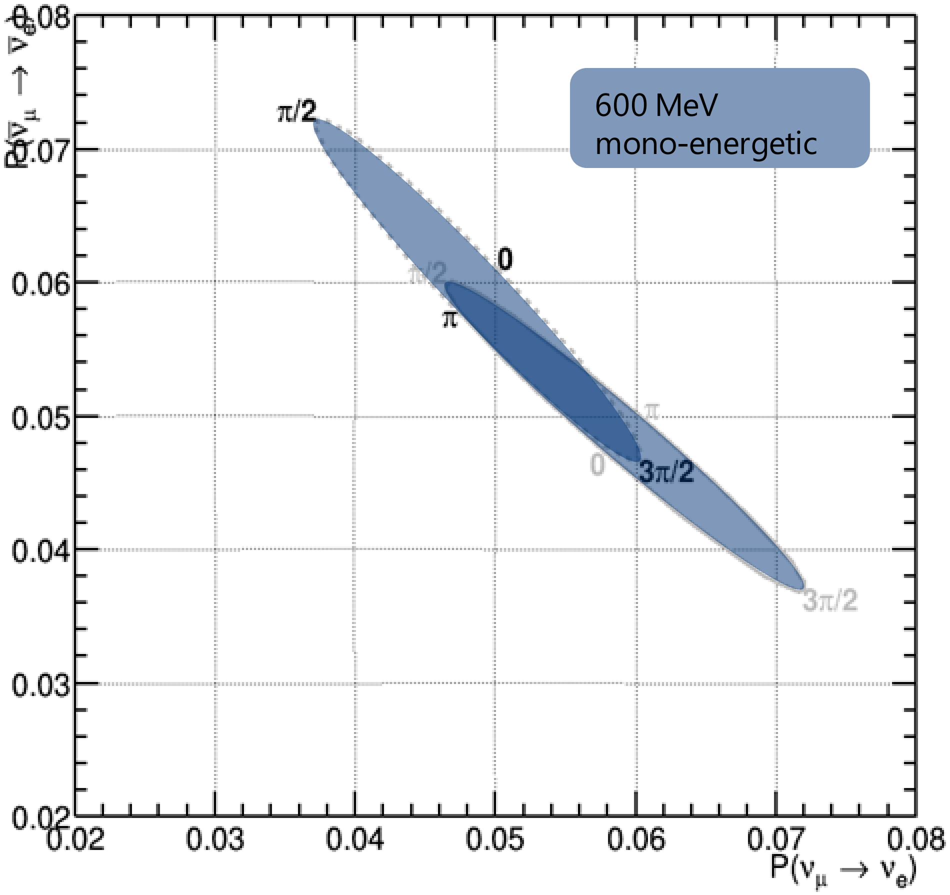
$$P(\nu_\mu \to \nu_e) \approx T_{\theta\theta} \sin^2 2\theta_{13} \frac{\sin^2([1-A]\Delta)}{[1-A]^2} + T_{\alpha\alpha} \alpha^2 \frac{\sin^2(A\Delta)}{A^2} + T_{\alpha\theta} \alpha \sin 2\theta_{13} \frac{\sin([1-A]\Delta)}{(1-A)} \frac{\sin(A\Delta)}{A} \cos(\delta + \Delta)$$

Ellipses show the $\nu_e(\overline{\nu}_e)$ appearance probabilities, for everything fixed except δ.

Common to show NH (solid) and IH (dash) on the same plot.

Mono-energetic plots?

"Kamioka-like": 295km, 600 MeV ν_μ



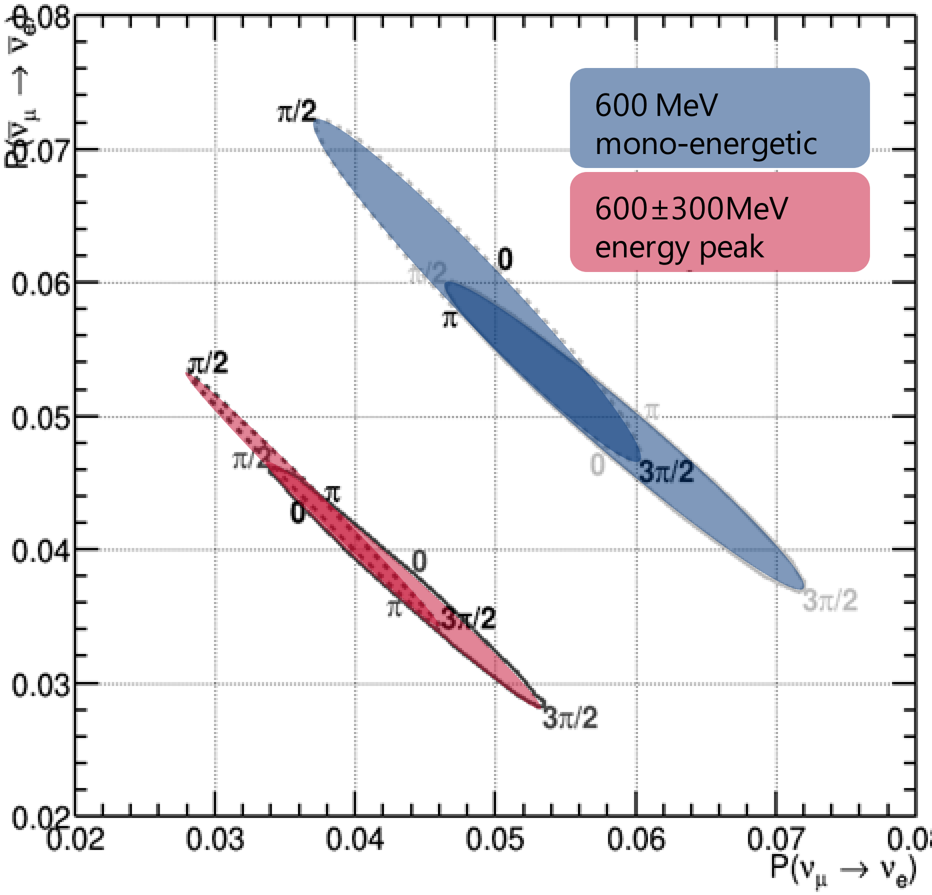
Commonly biprobability plots are **made for a single energy** (usually assume 1st maximum)

Not really representative of real experiments.

- e.g. for T2K $\delta E/E \sim 1/3$

Finite energy ranges

"Kamioka-like": 295km, 600 MeV ν_μ



Commonly biprobability plots are **made for a single energy** (usually assume 1st maximum)

Not really representative of real experiments.

- e.g. for T2K $\delta E/E \sim 1/3$

But **integrating over flux** is not helpful!

- Equivalent to doing a rate-only measurement

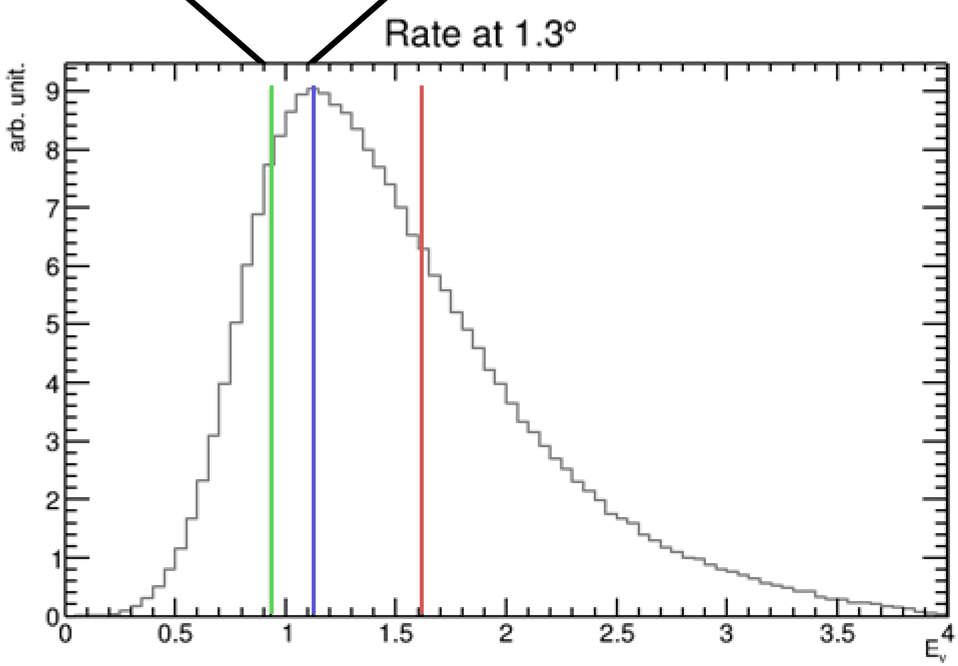
Instead try to find 'representative' points either side of the (non-oscillated) peak.

[Note: Retain a small (14MeV) smear to represent energy resolution]

Representing a spectrum with single points

Convert on-axis flux to off-axis assuming π parent:

$$f = \left[1 + (\gamma\theta)^2\right]^{-1}$$
$$E(\theta) = f\,E(0)$$
$$w(\theta) = f^2 w(0)$$



I use three energies:

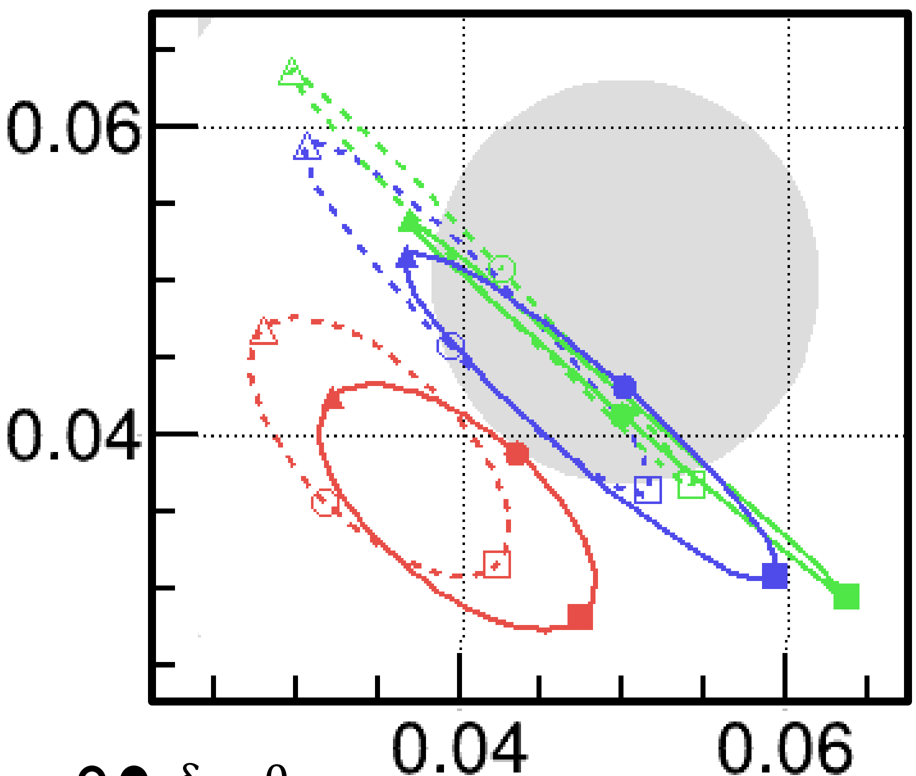
- **Blue:** Energy of peak QE rate
- **Red:** median of high-energy tail
- **Green:** " " low-energy "

Estimate these using a toy MC, which allows for range of angles to be considered.

- "O.A. angle = decay angle" only works for a parallel beam, so add angular smear and tune to existing flux histos.
- Ignores Kaon component, but gives a reasonable metric.

Conventions

Biprobability plots at Kamioka (Φ_{32} =0.874802)



○ ● $\delta = 0$

△ ▲ $\delta = \pi/2$

— $\delta = \pi$

□ ■ $\delta = 3\pi/2$ (T2K b.f.)

I use three energies:

- **Blue:** Energy of peak QE rate
- **Red:** median of high-energy tail
- **Green:** " " low-energy "

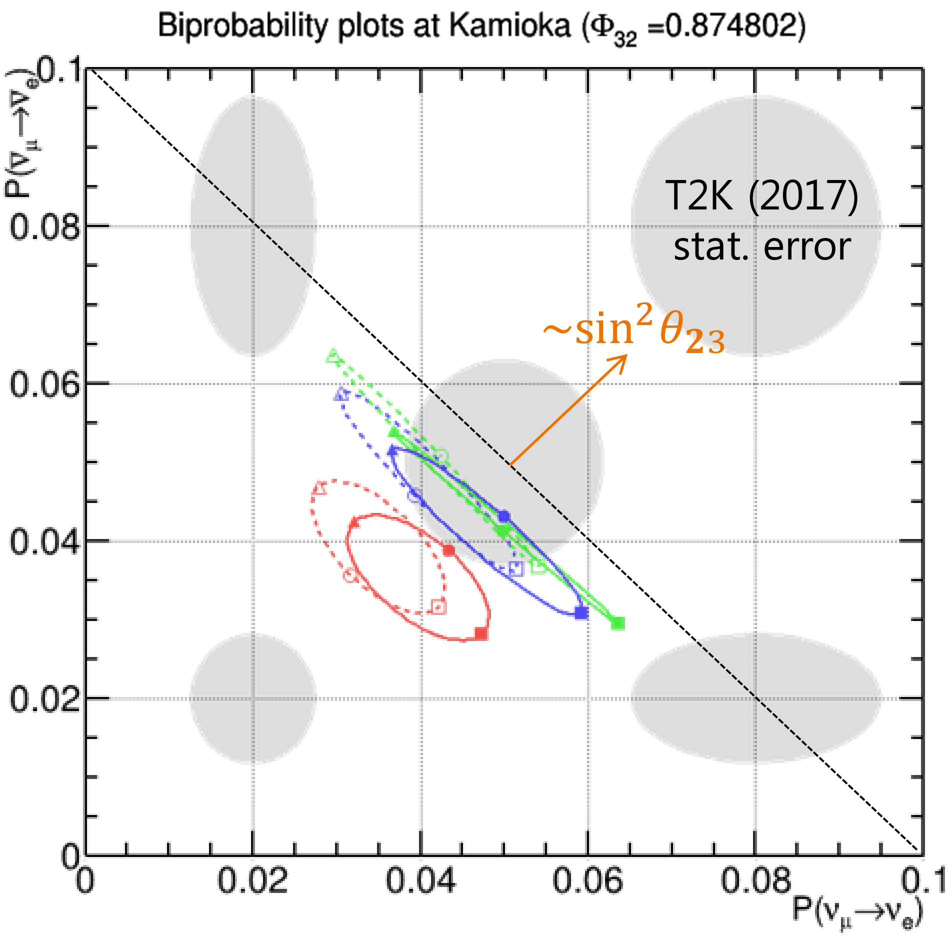
Filled grey ellipses are rough calculations of stat error (to be compared to peak ellipse).

Taken from white paper Tab. II, and extrapolated for O.A. angle and baseline.

Summary of L/E:

$$\Phi_{32} = \frac{1.267\ \Delta m^2_{32} L}{(\pi/2)\ E_p}$$

Suppressed variables



Most important is the $\mu - \tau$ mixing (θ_{23})

- Scale (1st term) set by $\sin^2\theta_{23}$
- Also affects size of ellipse through $\sim\sin 2\theta_{23}$

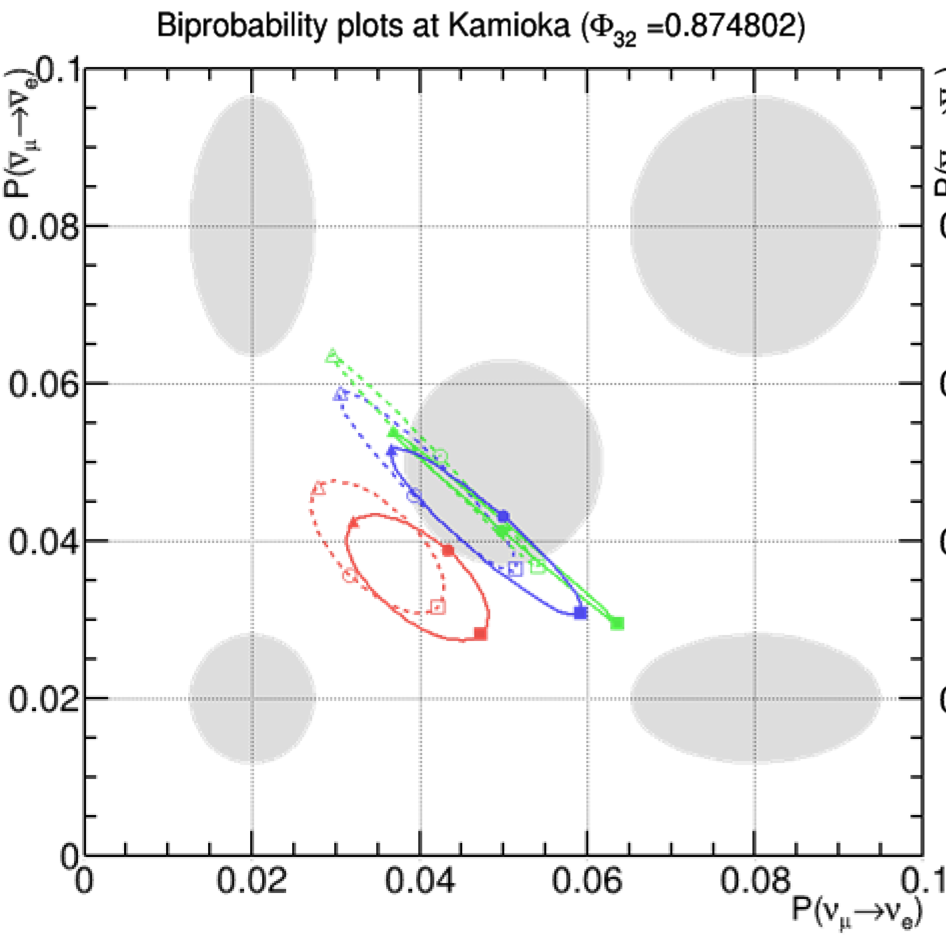
For Korean detector, Δm^2_{3x} will be interesting too…

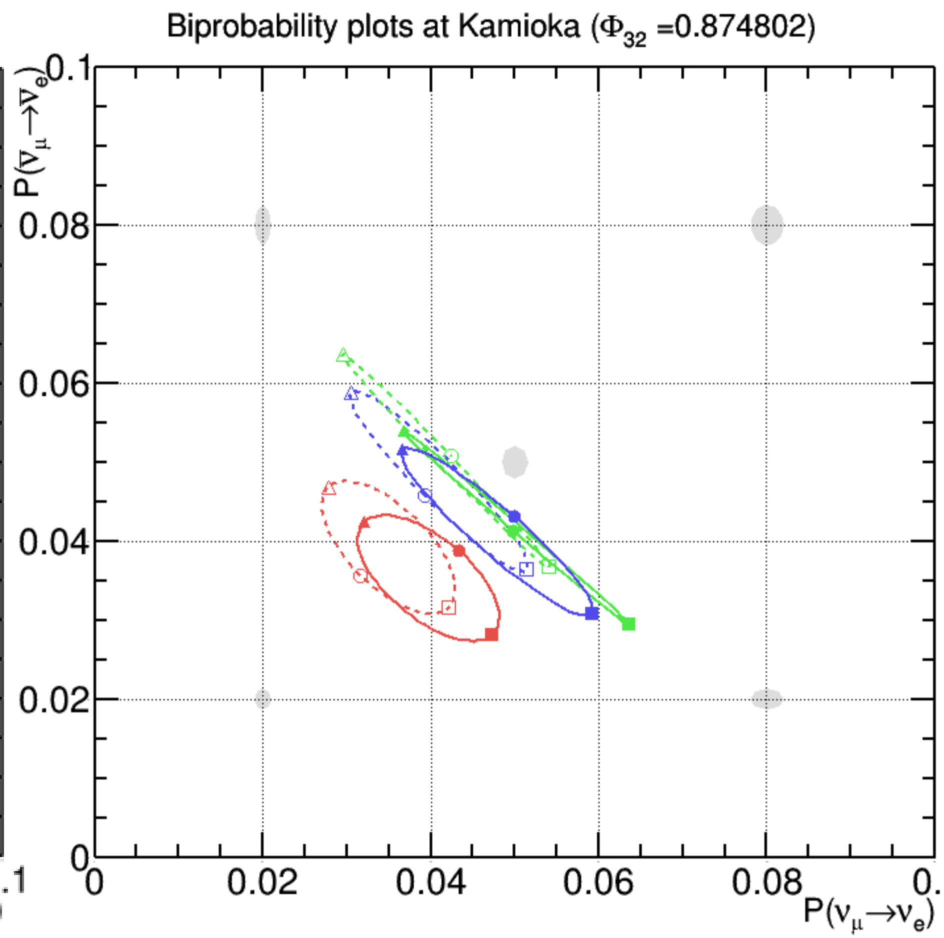
Uniform density assumed

- 2.6 g/c.c. for Kamioka
- 2.9 g/c.c. for all Korean sites

Other parameter uncertainties are smaller.

Super-K (2017) to Hyper-K





Korea candidate sites

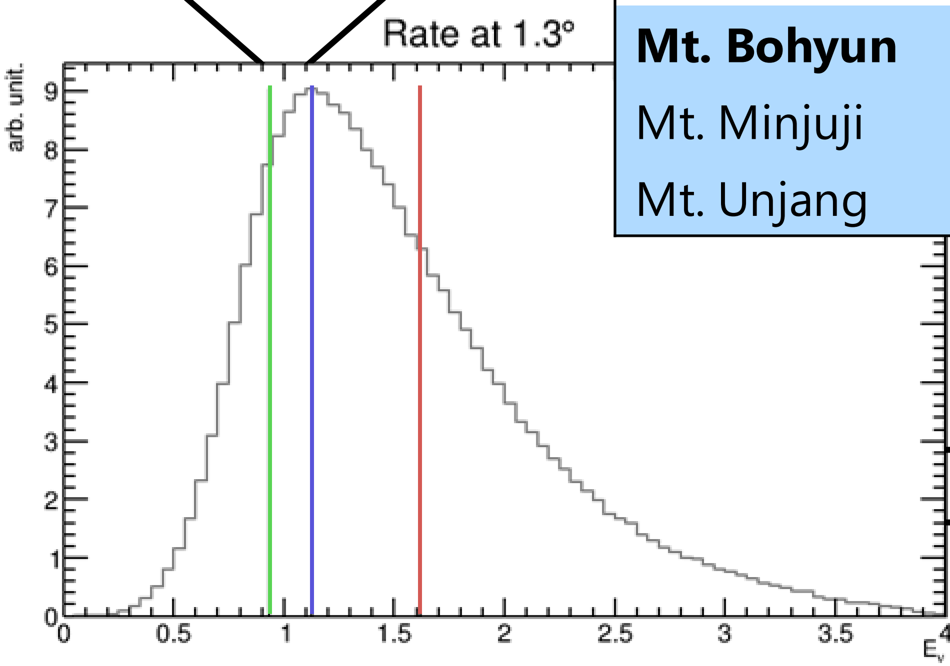
Convert on-axis flux to off-axis assuming π parent:

$$f = \left[1 + (\gamma\theta)^2\right]^{-1}$$

$$E(\theta) = f E(0)$$

$$w(\theta) = f^2 w(0)$$

Site	Distance /km	Angle	LM /MeV	Peak /MeV	UM /MeV
Kamioka	295	2.5°	590	680	840
Mt. Bisul	**1088**	**1.3°**	**930**	**1130**	**1620**
Mt. Hwangmae	1140	1.8°	740	870	1180
Mt. Sambong	1180	1.9°	710	830	1110
Mt. Bohyun	**1040**	**2.2°**	**640**	**730**	**950**
Mt. Minjuji	1140	2.2°	640	730	950
Mt. Unjang	1190	2.2°	640	730	950



Peak Energy /GeV	$1.25\theta^{-1} + 0.17$
Lower Median /GeV	$0.95\theta^{-1} + 0.21$
Upper Median /GeV	$2.17\theta^{-1} + 0.03$

HK/K Option 1: Mt. Bisul

琵瑟山

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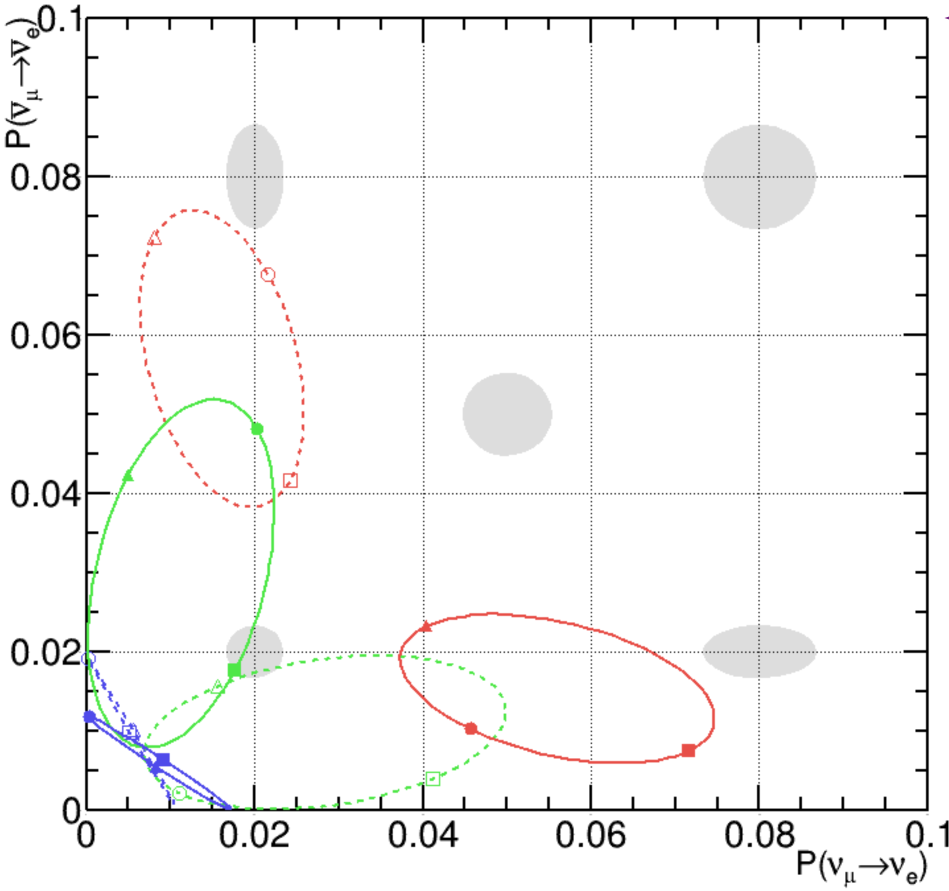
Energy /MeV 930 1130 1620

Biprobability plots at Mt. Bisul (Φ_{32} =1.941544)



This is the high energy option.

ポイント! [Points]

- Good separation between hierarchies especially at **high-energy**
- $\Phi_{32}\sim2$ means very little appearance at **flux peak**. Instead most effect is in "tail" regions.
- **Stats** are quite good because of small OA angle.
- Inversion of Hierachy enhancement for **low-energy** events

Referring back to the energy picture

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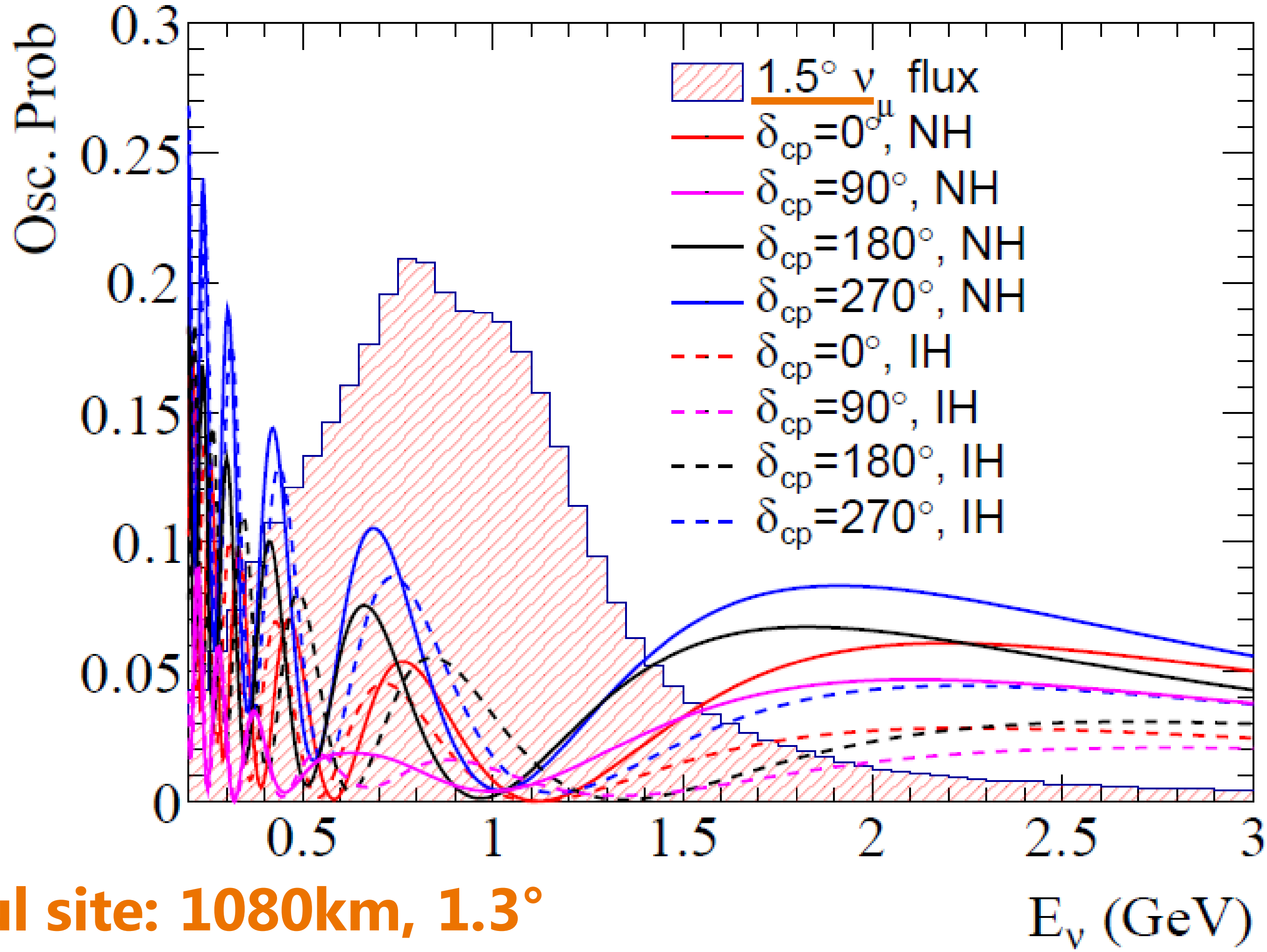
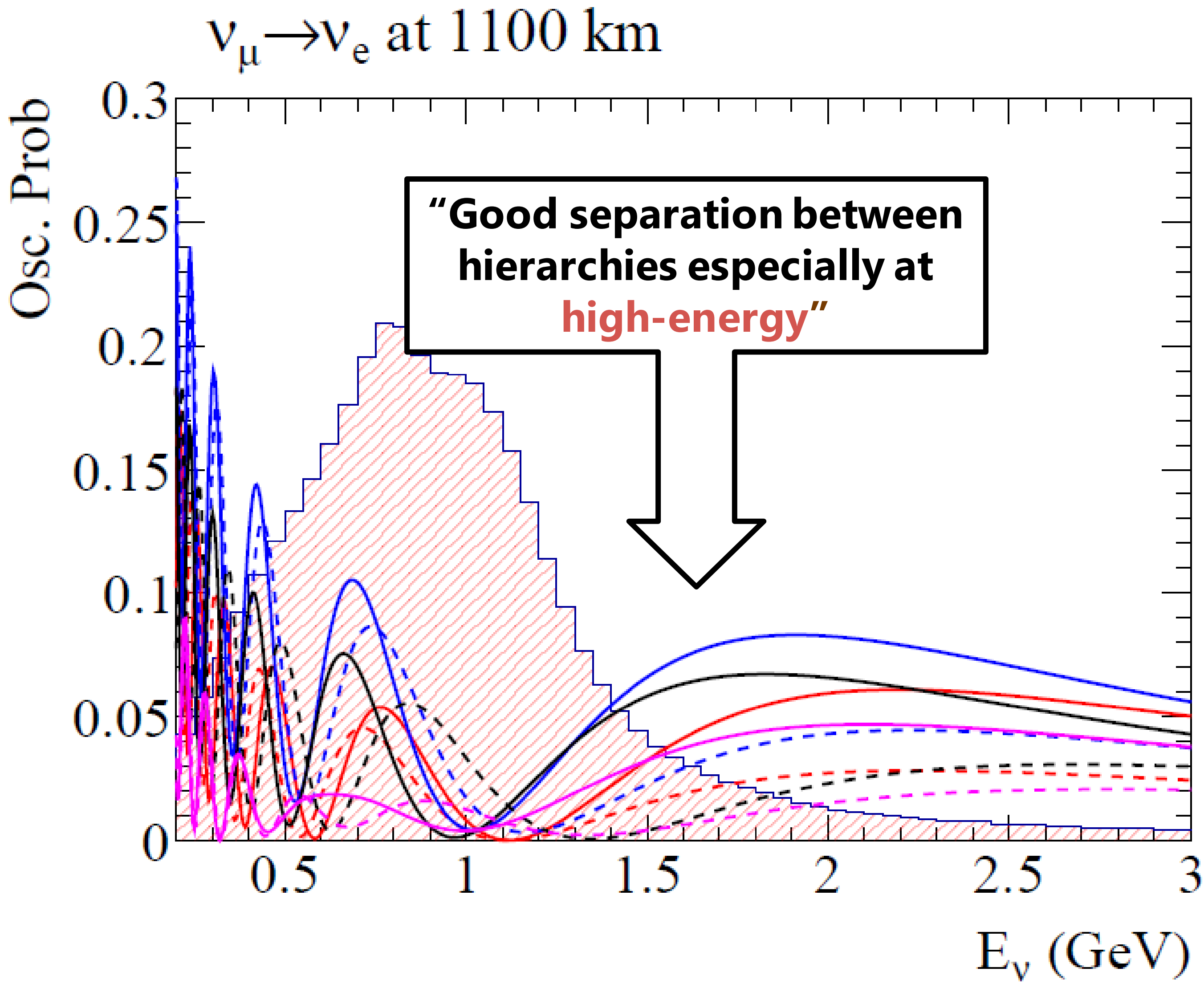
$\nu_\mu \rightarrow \nu_e$ at 1100 km



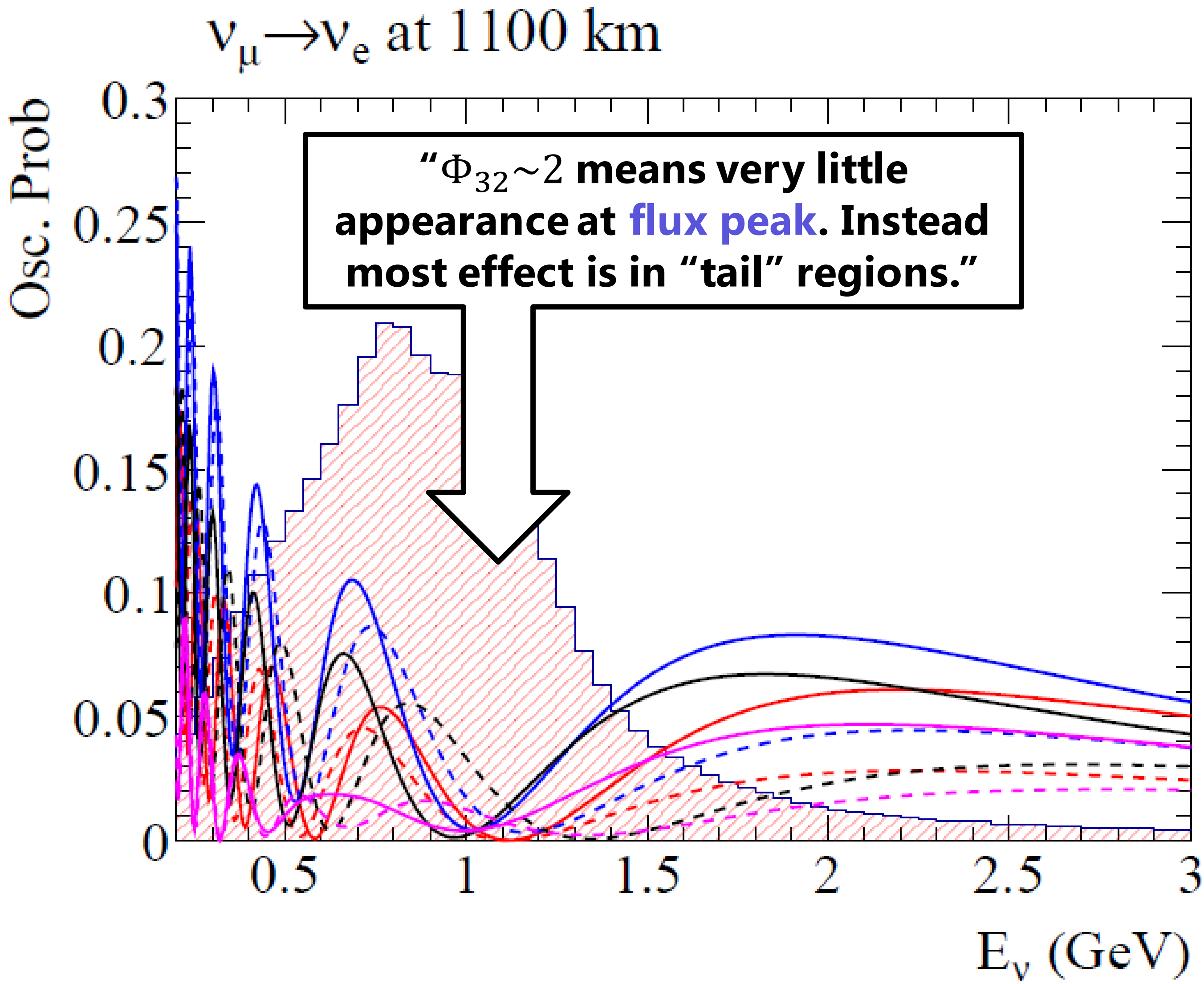
White Paper: Figure 8 (top)

c.f. Bisul site: 1080km, 1.3°

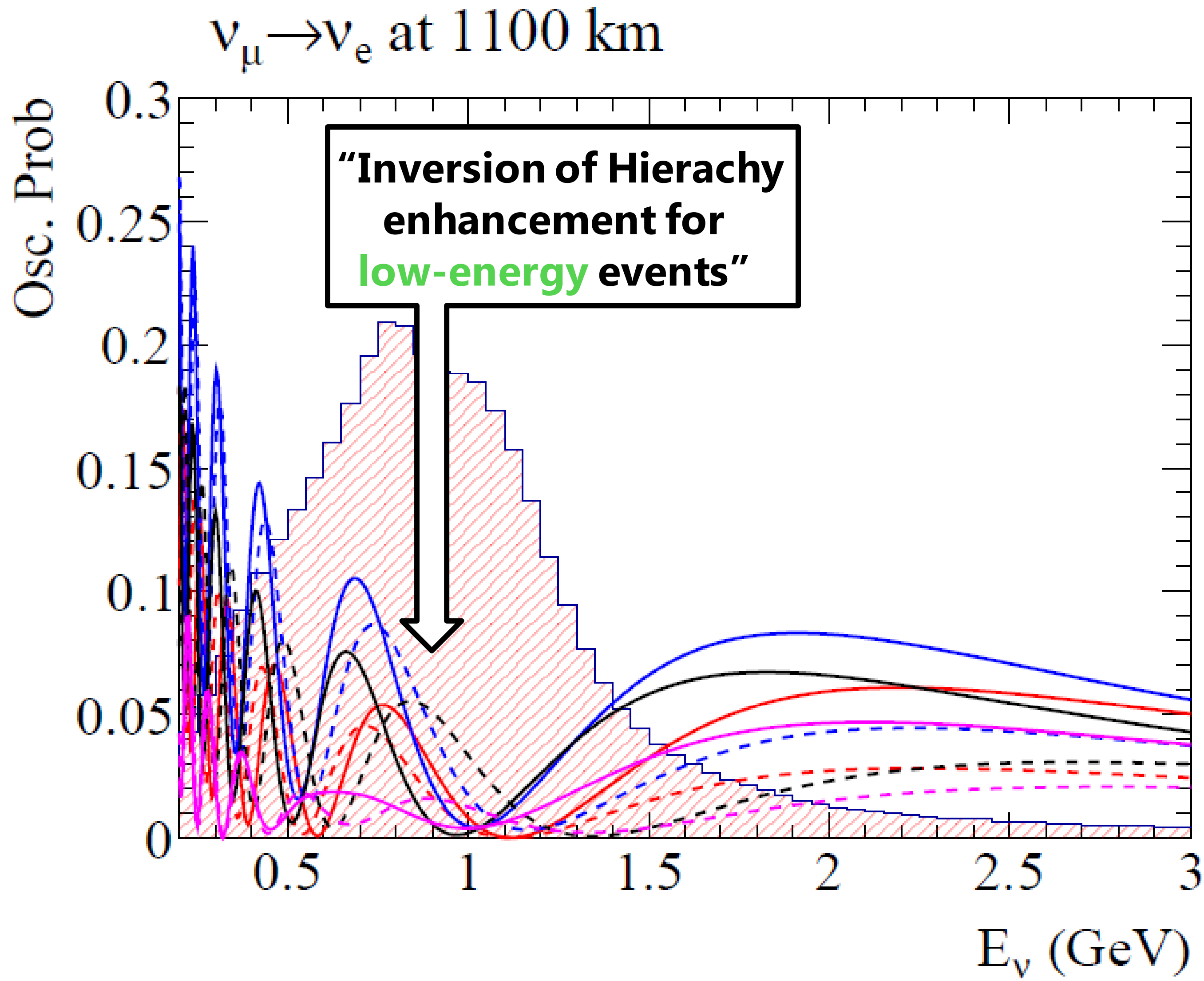
The energy picture



The energy picture

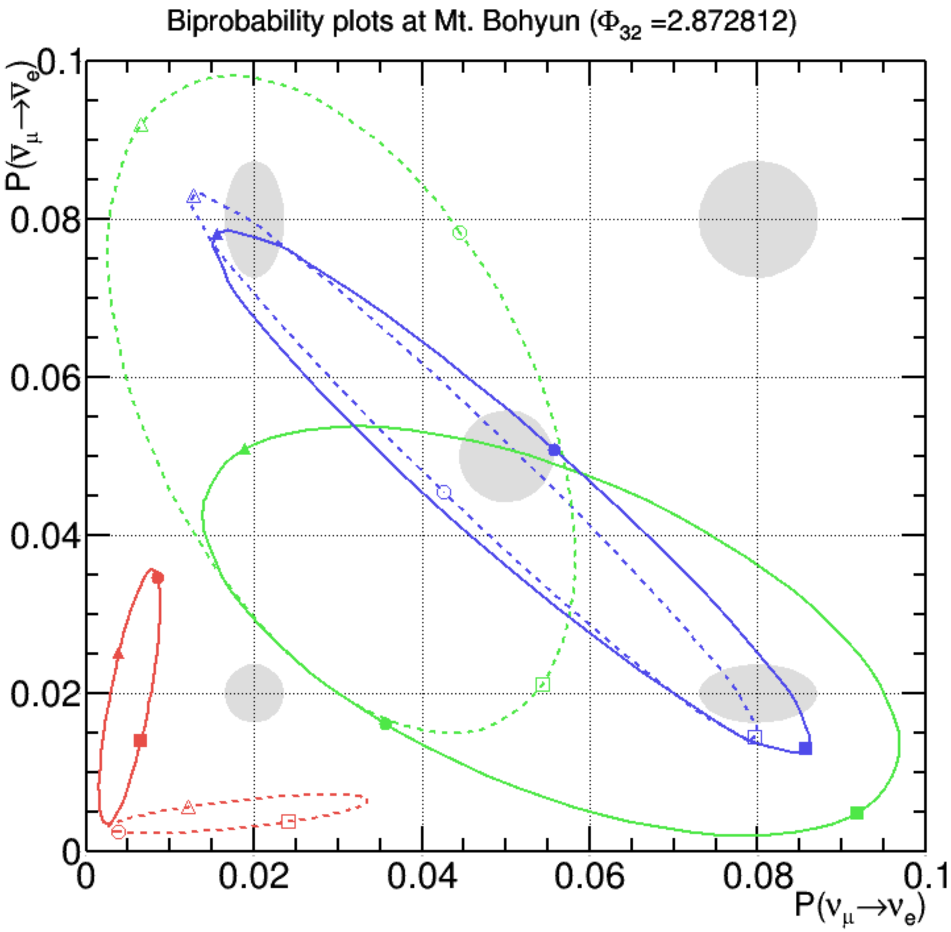


The energy picture



HK/K Option 2: Mt. Bohyun

Energy /MeV 640 730 950



This is the other primary option.

- At **flux peak** hierarchy almost doesn't matter for CPv (but note CPc difference)
- **Stats** are a bit worse than at Bisul
- Large ellipses = Large CPv effect. Therefore can make good measurement even though larger stat errors.
- 'Fat' ellipses = better at $\cos\delta$ (precision on δ near CPv-max) especially at **low-energy**

HK/K : Mt. Sambong

三峯山

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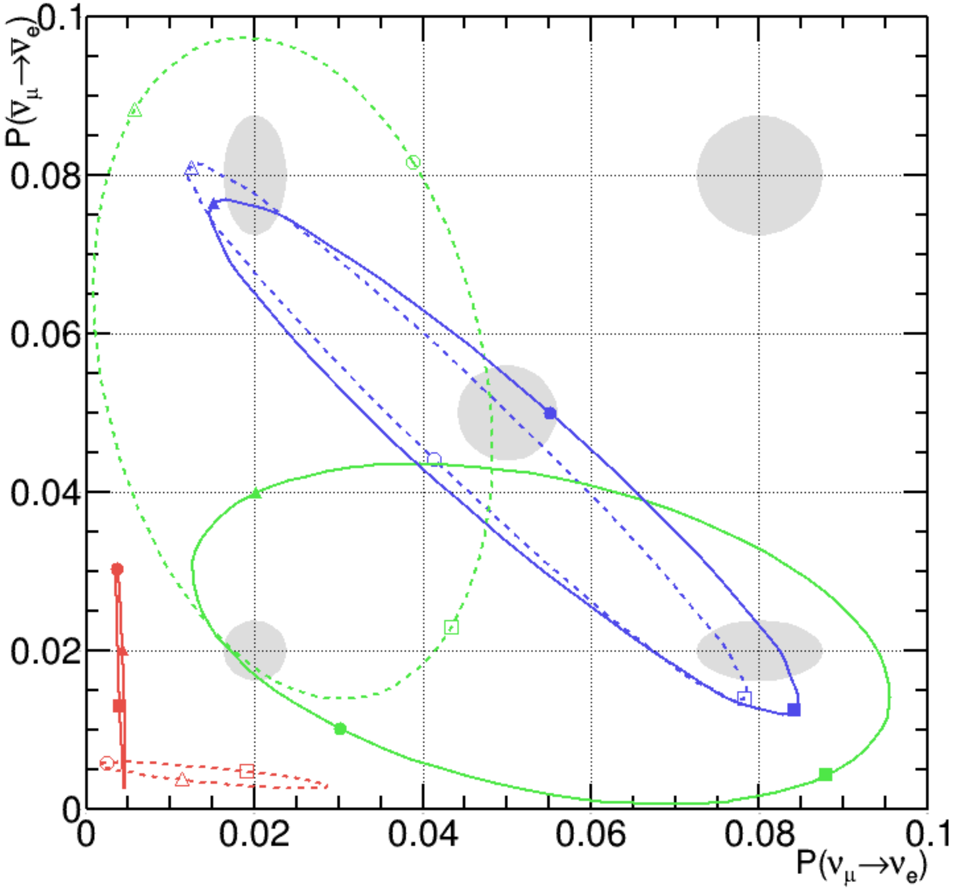
Energy /MeV 710 830 1110

Biprobability plots at Mt. Sambong (Φ_{32} =2.866822)



Alternative at 1180km & 1.9°

- Baseline and energy are both slightly higher, but L/E matches Bohyun very closely:

  $$\Phi_{32}(\text{Sambong}) = 2.866$$
  $$\Phi_{32}(\text{Bohyun}) = 2.878$$

  As a result, site is overall very similar to Bohyun site.

- Interesting effect for **HE** events. $P(\nu_\mu \to \nu_e)$ is almost independent of δ for NH (& similarly for $\overline{\nu}_e$ in IH)

HK/K : Mt. Hwangmae 黄梅山

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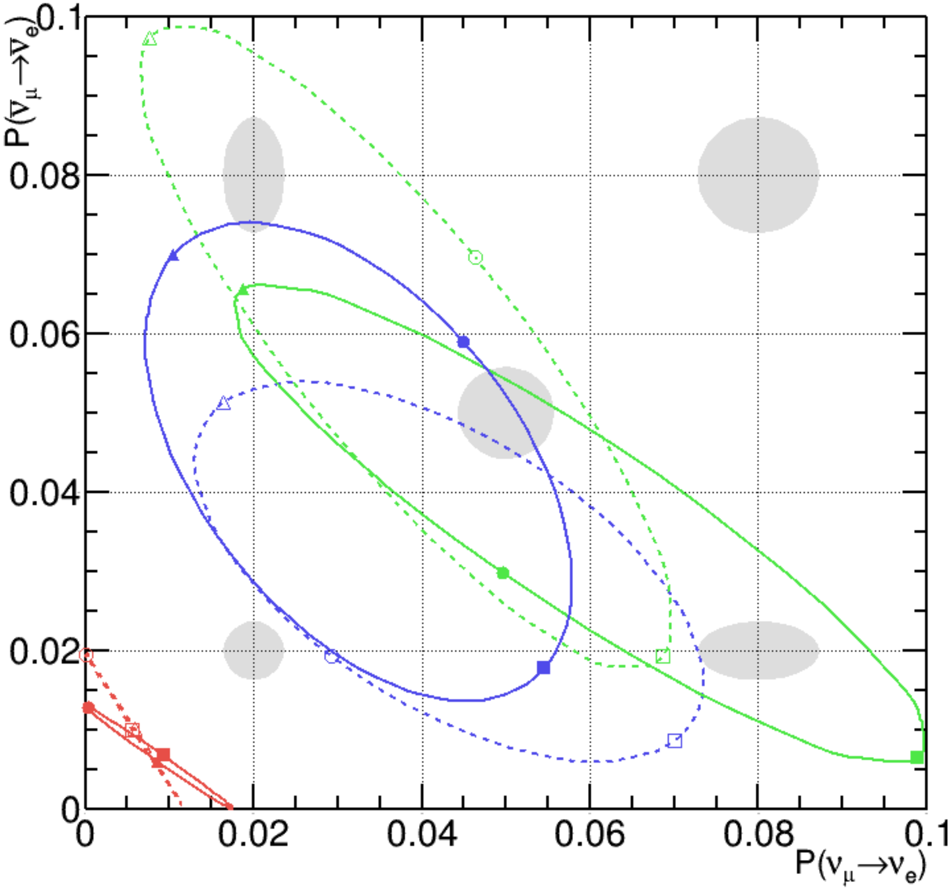
Energy /MeV **740** **870** **1180**

Biprobability plots at Mt. Hwangmae (Φ_{32} =2.642301)



Alternative at 1140km & 1.8°

- Overall somewhat similar to Bohyun and Sambong sites (e.g. in the dominance of **peak** and **LE** tails). Difference due to slightly lower L/E
- **HE** events have $\Phi_{32} \sim 1.94$ (similar to Bisul peak).
  As with that case, there is interesting dependence on δ: almost identical probs from $\pi/2$ and $3\pi/2$. But its hard to make use of due to low rate.

HK/K : Mt. Minjuji

岷周之山

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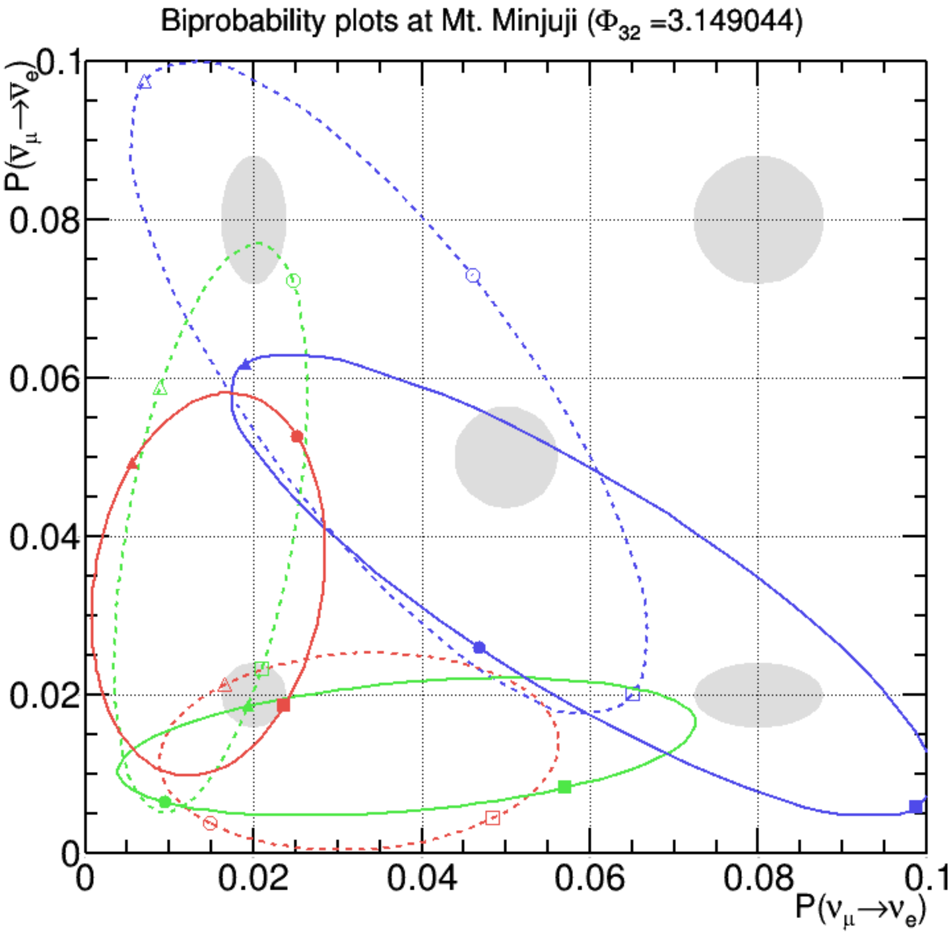
Energy /MeV 640 730 950



Alternative at 1140km & 2.2°

- Highest appearance probability for events **near peak** (*assuming* T2K best fit point)
- Lots of orientation difference between ellipses. Maybe this makes it more robust to θ_{23} &/or systematic uncertainties? *Interesting question to study…*

HK/K : Mt. Unjang 雲長山

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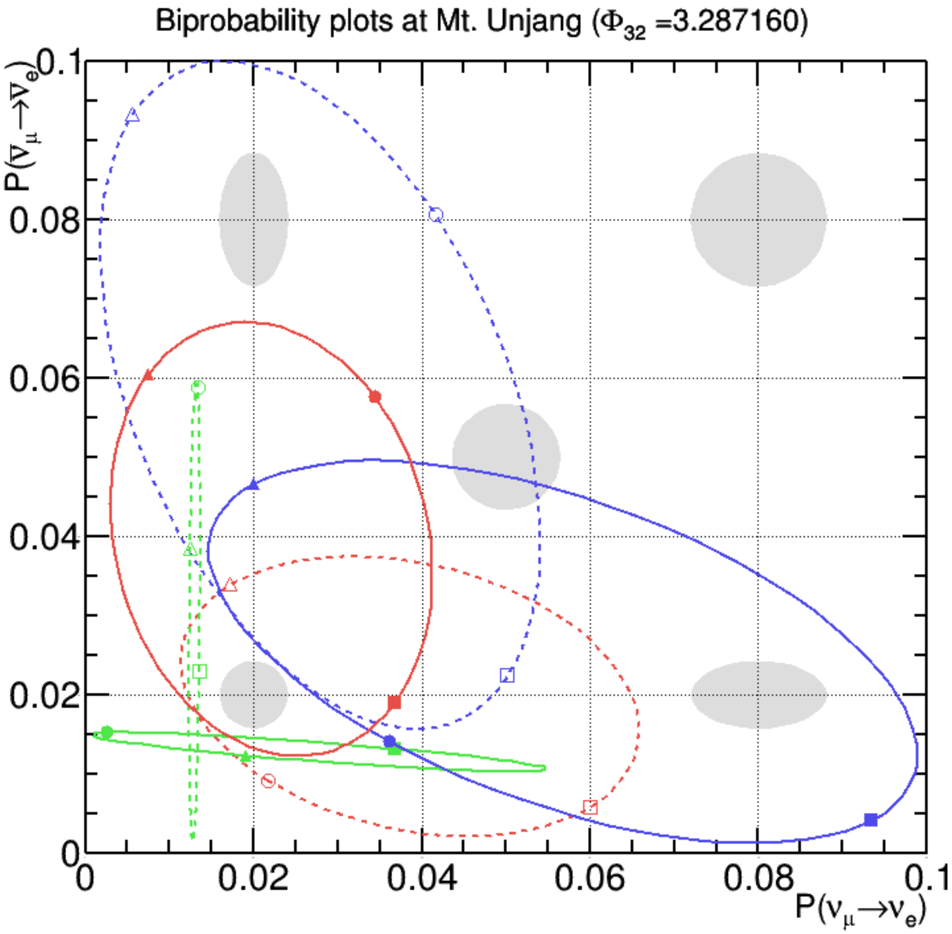
Energy /MeV 640 730 950



Alternative at 1190km & 2.2°

- Most distant site (most Reno-50 like) **LE** events are almost at 4th node! (aka 2nd min)
- 'Fat' ellipses may be good for measurement of δ
- Largest range of L/E (High oscillation order can beat wide spectrum.)
  - But note caveat about Kaon contribution.
  - And need to consider energy resolution.

Commentary: Things we knew already

Feature space is *very* different from existing experiments.

- Potential for resolving degeneracies and robustness against systematics (but does need to be demonstrated.)

Larger CP ellipses & larger stat errors roughly compensate. But systematic uncertainties should be less important.

Mt Bisul should be strongest for unambiguous hierarchy determination.

- It has the smallest L/E (except Kamioka) which reduces 'true' CPv
- OTOH it has higher energy than Kamioka, enhancing matter effect

Other options look better for CPv & measurement of δ, but it is difficult to intuit. Variation in stats is surprisingly unimportant.

Commentary: Things I didn't know

(LBL-ν) physics at Mt Sambong and Mt Bohyun is very similar.

- (Guess) preference for Bohyun, due to smaller *L*, and 2.2° angle.

For *any* Korean baseline, matter effect causes a relative enhancement of *anti*-neutrinos for NH at some energy.

- Nice 'non-trivial' dependence if we can resolve it.
- Closure test of matter-enhanced oscillations?

1242m

If T2K is correct (NH & $\delta \sim 3\pi/2$)**, a longer baseline** (Mt. Minjuji, Unjang) **and anti-neutrino running looks like promising approach for measuring δ near $3\pi/2$**

- Again, needs more careful study, especially of constraints from ν_μ channel (i.e. parameters θ_{23} , Δm^2_{3x})

Would be interesting to consider even longer (1250km) baseline, but may need to bring our own overburden…

Important point, but maybe I ran out of time?

Δm^2 dependence

Δm^2_{3x} (Mea culpa)

Atmospheric mass splitting is much more important for Korean detector. N^{th} max = $(2N-1)^{th}$ node so:

$$\frac{dE_N}{d(\Delta m^2)} = (2N-1)\frac{dE_1}{d(\Delta m^2)}$$

Complete analysis must also treat Δm^2 correctly. But I have assumed (value is T2K & PDG 'best fit'): $\boldsymbol{\Delta m^2 = \Delta m^2_{32}}(= 2.5 \times 10^{-3}\,\mathrm{eV}^2)$

In reality "The experiment measures an unresolved mixture of $|\Delta m^2_{31}|$ and $|\Delta m^2_{32}|$, which we refer to as $|\Delta m^2_{32}|$ for brevity."

Expansion of vacuum terms gives (T2K note):

$$\Delta m^2_{\mu\mu} = \frac{|U_{\mu 2}|^2 \Delta m^2_{32} + |U_{\mu 1}|^2 \Delta m^2_{31}}{|U_{\mu 1}|^2 + |U_{\mu 2}|^2}$$

Justify ignoring this because **measurement error is still large…**

Δm^2_{3x} measurement error

T2K Best fit ~ PDG average = $\mathbf{2.5 \times 10^{-3} eV^2}$

3 sigma range (2015 global fit) extends around $2.18 \sim 2.82 \times 10^{-3} \mathrm{eV}^2$

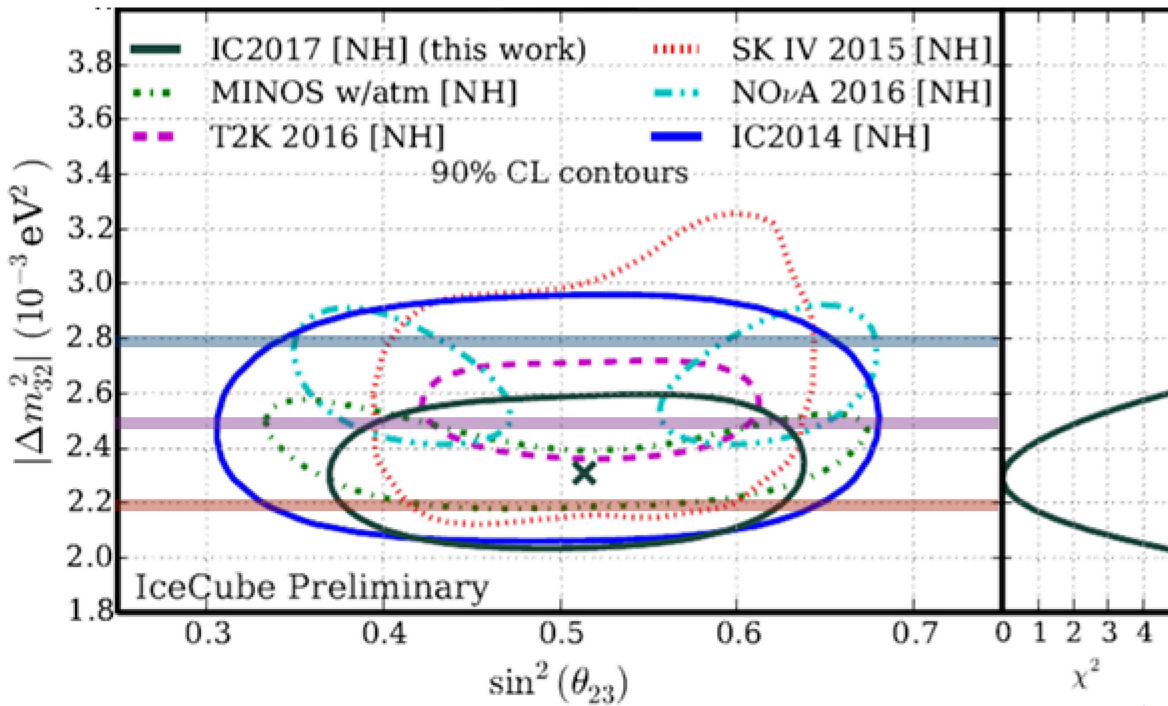
[rough, eliding definition changes for NH/IH]

Choose **Lower at $\mathbf{2.2 \times 10^{-3} eV^2}$** (MINOS, IceCube consistent)

and **Upper at $\mathbf{2.8 \times 10^{-3} eV^2}$** (NO$\nu$A ~ consistent)

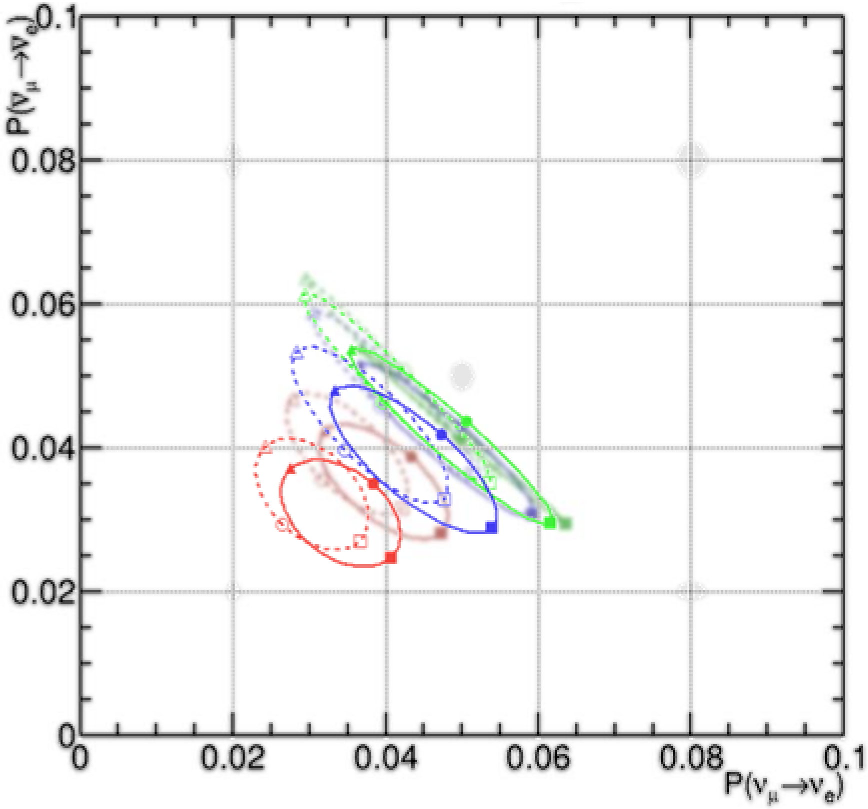
In retrospect, closer test points would be better

Not because points are low probability, but that effect is too large to visualise the transition paths!

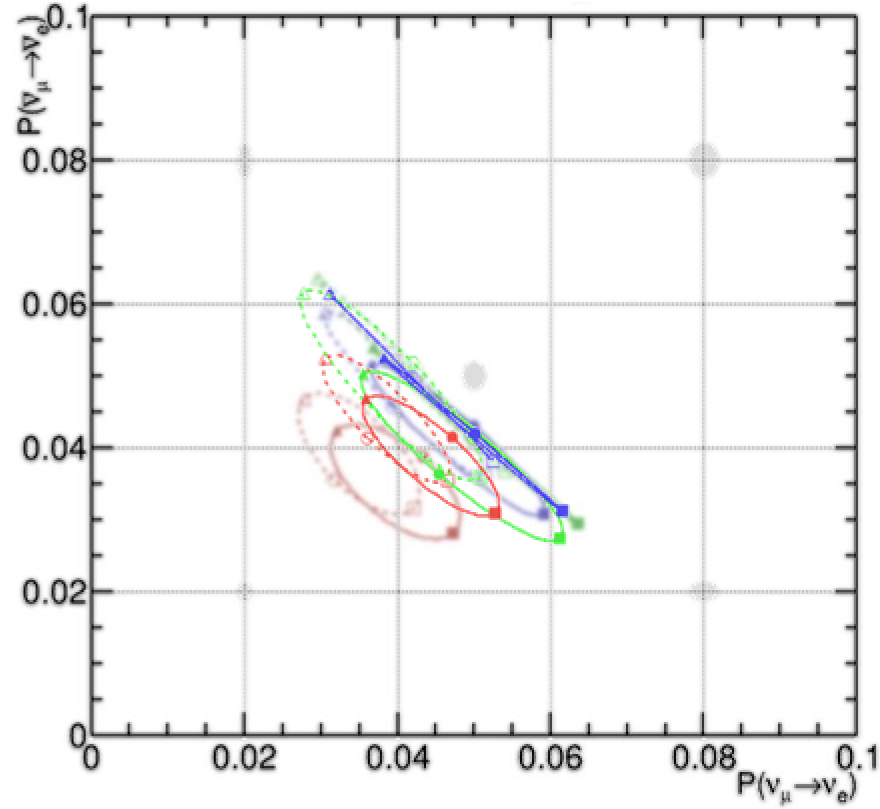


Δm^2_{32} shifts at Kamioka

$\Delta m^2_{32} = 2.2 \times 10^{-3}\,\mathrm{eV}^2$



$\Delta m^2_{32} = 2.8 \times 10^{-3}\,\mathrm{eV}^2$



[Side note: Hakama-goshi site has same leading-order effect: $1.1 \times \Phi_{32}$]

Δm_{32}^2 shifts at Mt. Bisul

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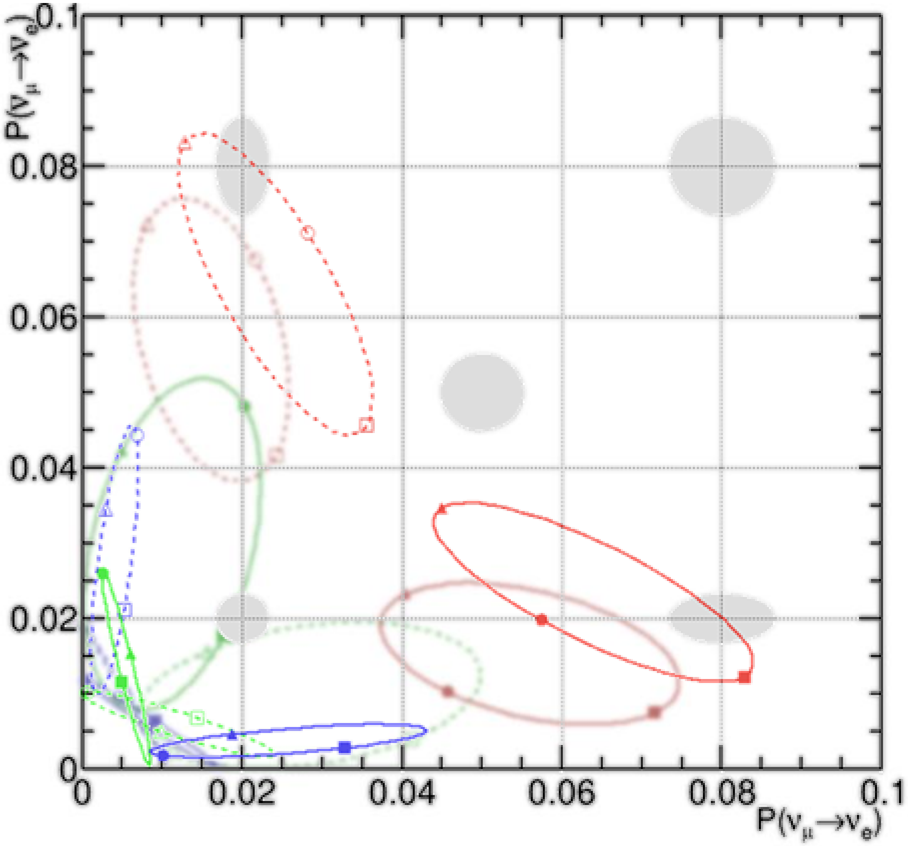
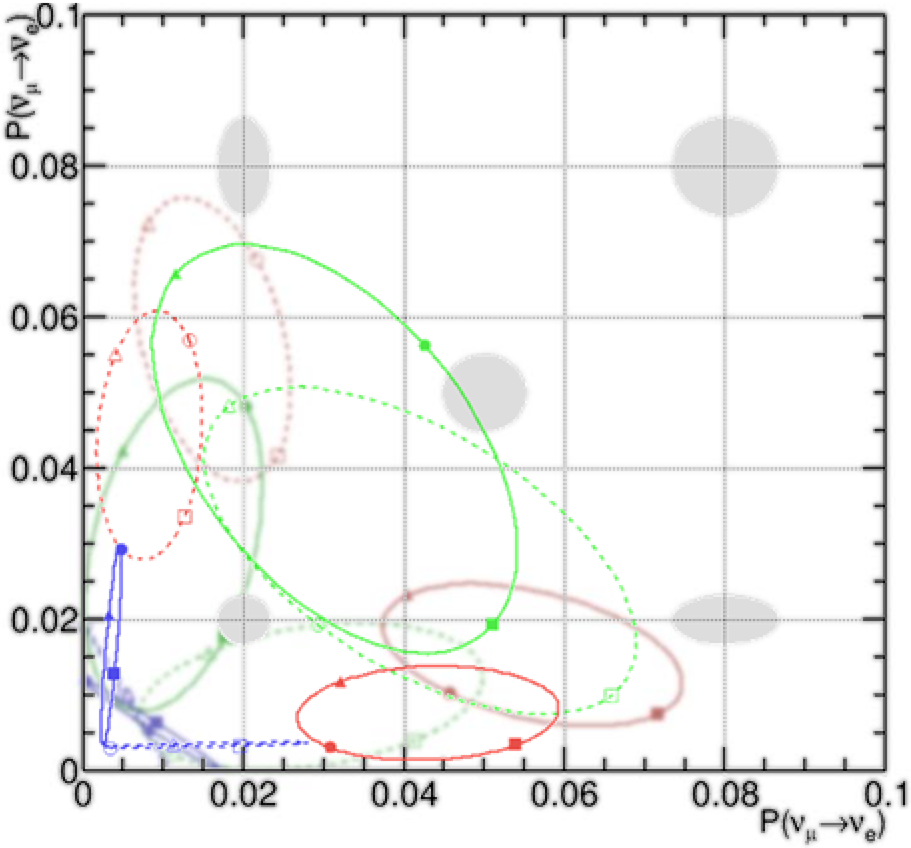
$\Delta m_{32}^2 = 2.2 \times 10^{-3} \mathrm{eV}^2$



$\Delta m_{32}^2 = 2.8 \times 10^{-3} \mathrm{eV}^2$



Δm^2_{32} shifts at Mt. Bohyun

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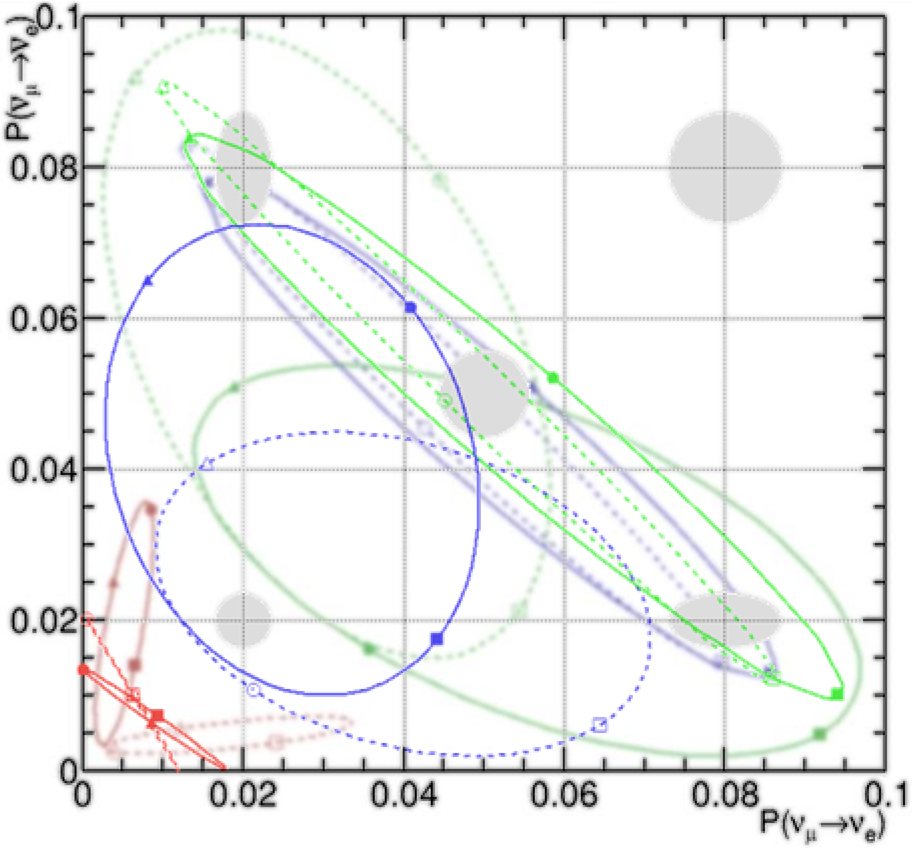
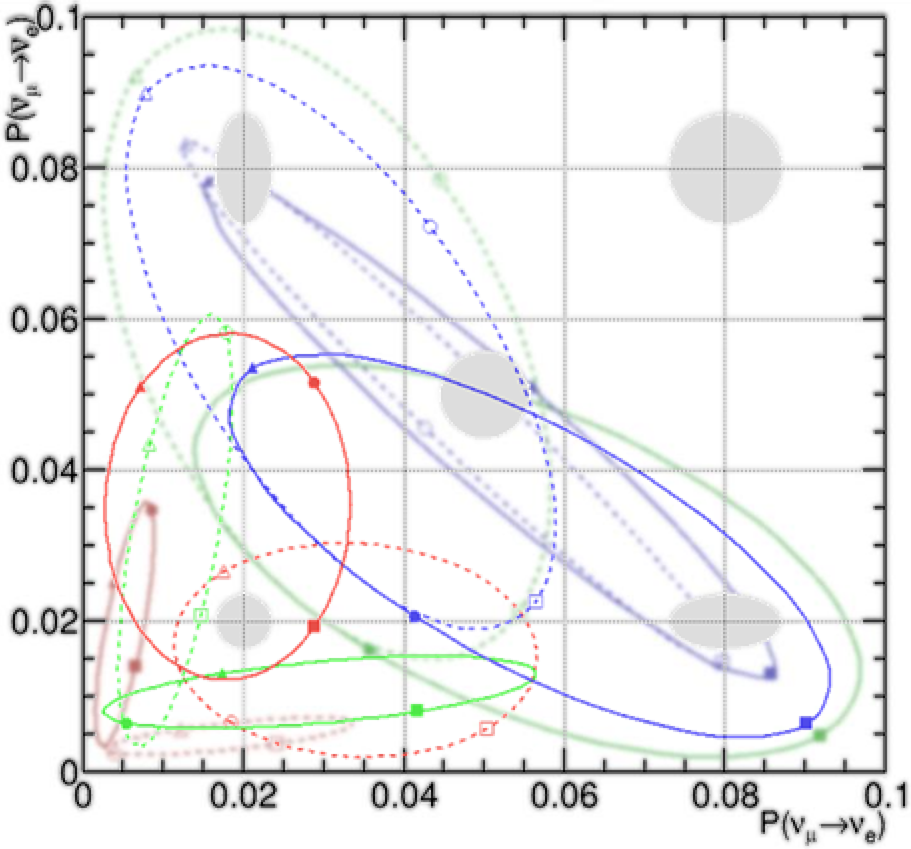
$\Delta m^2_{32} = 2.2 \times 10^{-3}\,\mathrm{eV}^2$



$\Delta m^2_{32} = 2.8 \times 10^{-3}\,\mathrm{eV}^2$



Δm^2_{32} shifts at Mt. Unjang

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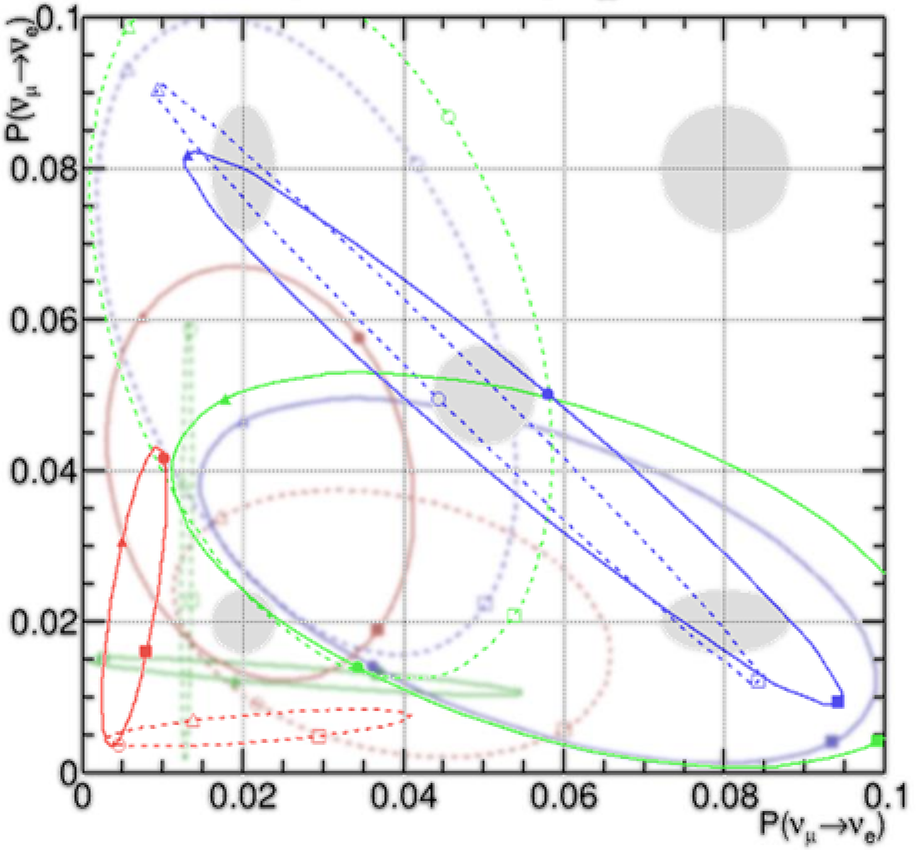
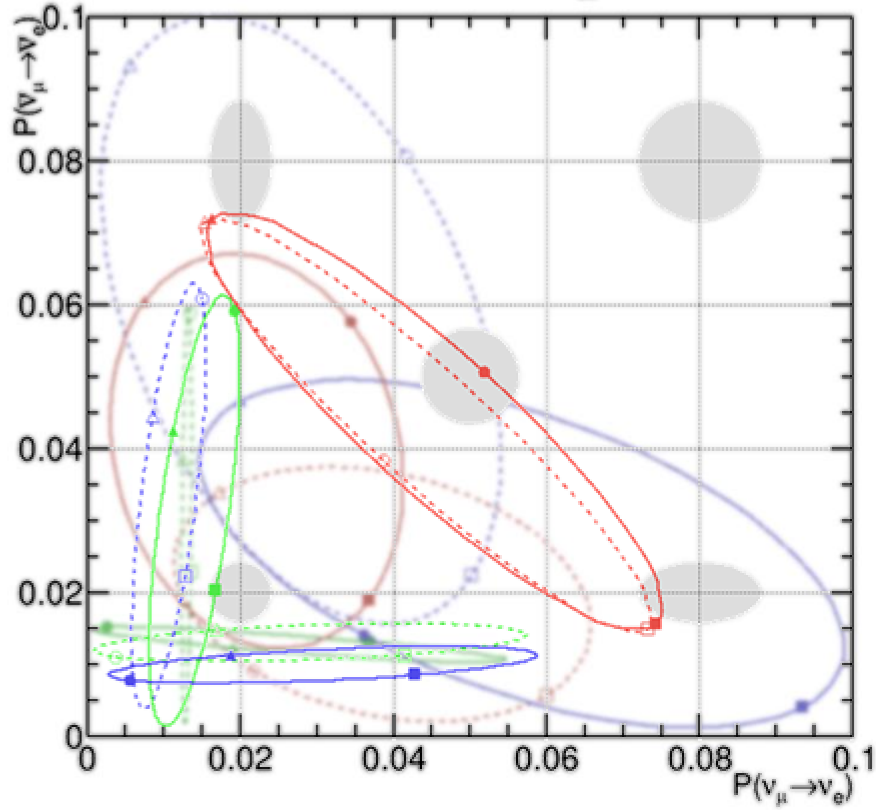
$\Delta m^2_{32} = 2.2 \times 10^{-3} \mathrm{eV}^2$



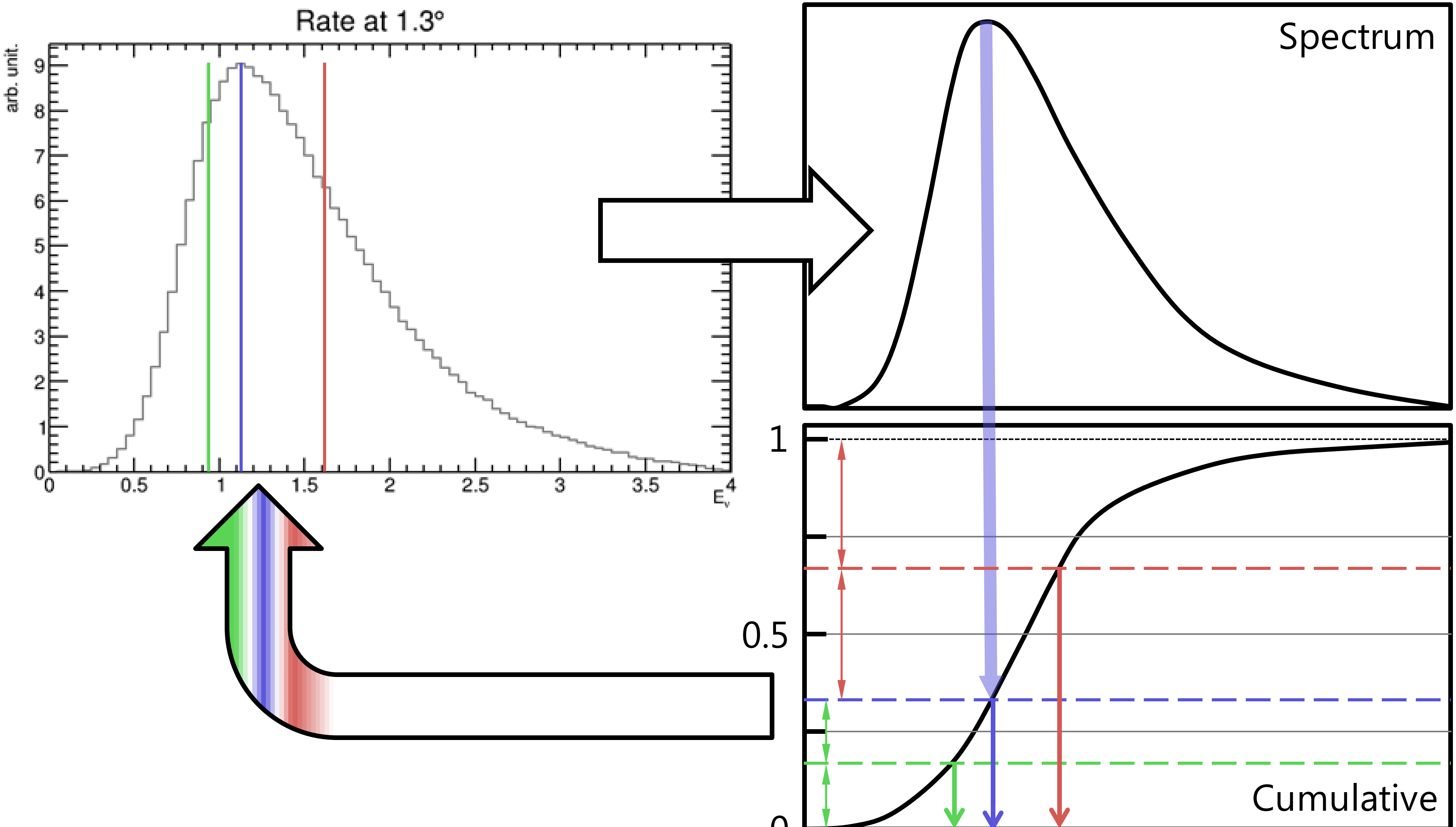
$\Delta m^2_{32} = 2.8 \times 10^{-3} \mathrm{eV}^2$



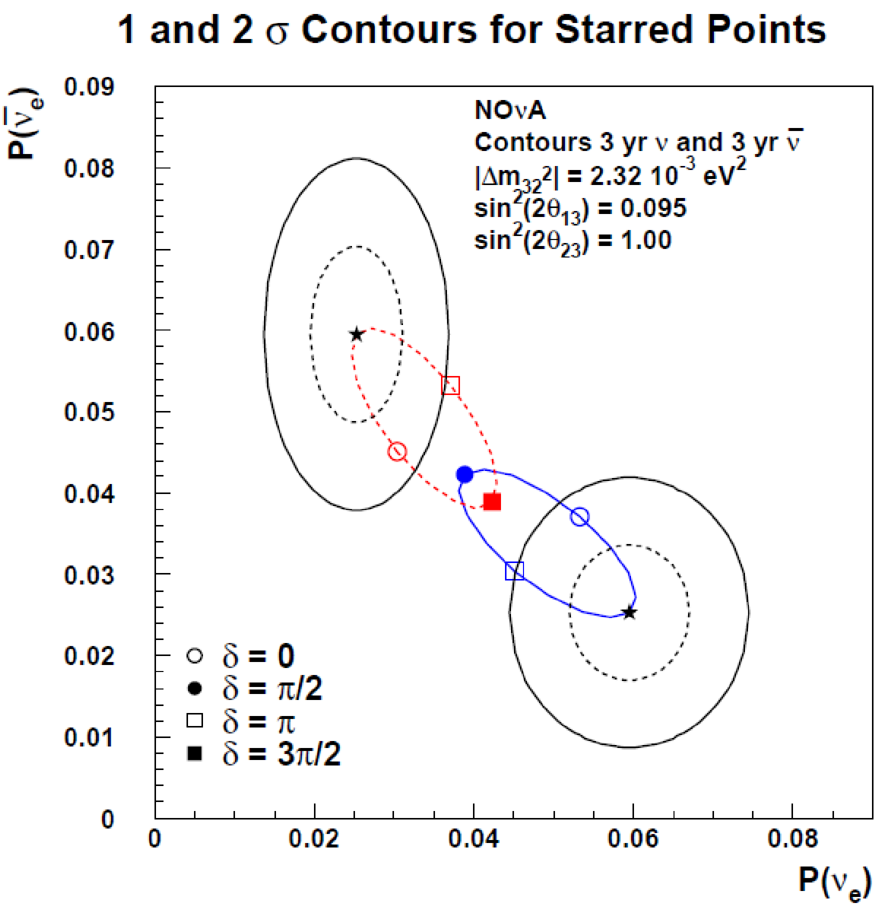
Backup

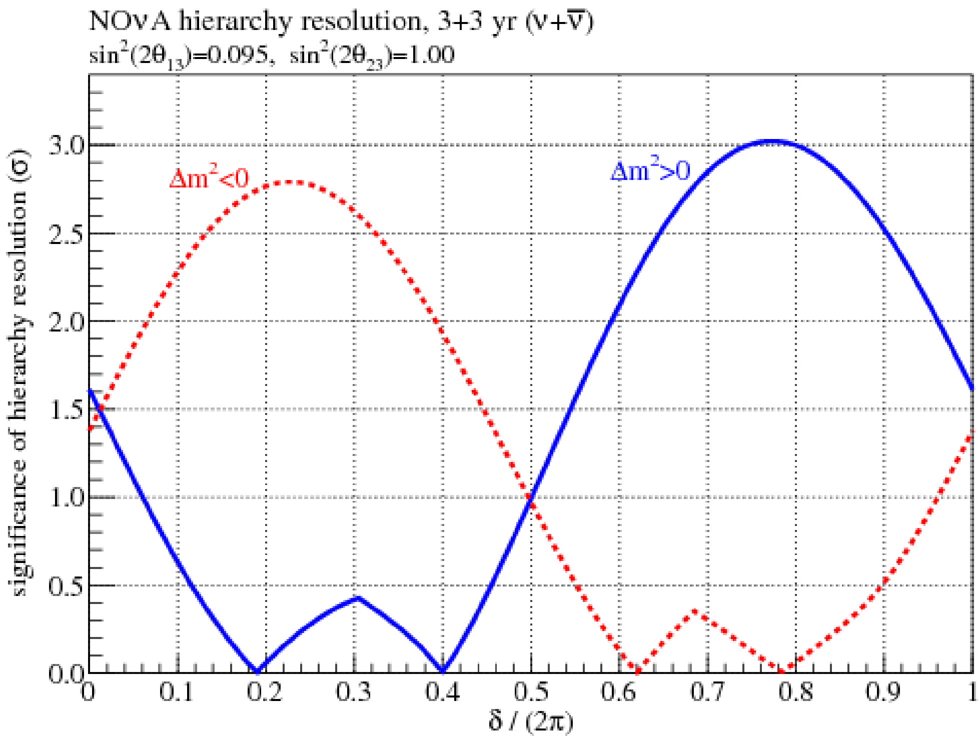
2017/02/15

"Tail medians"



NOνA



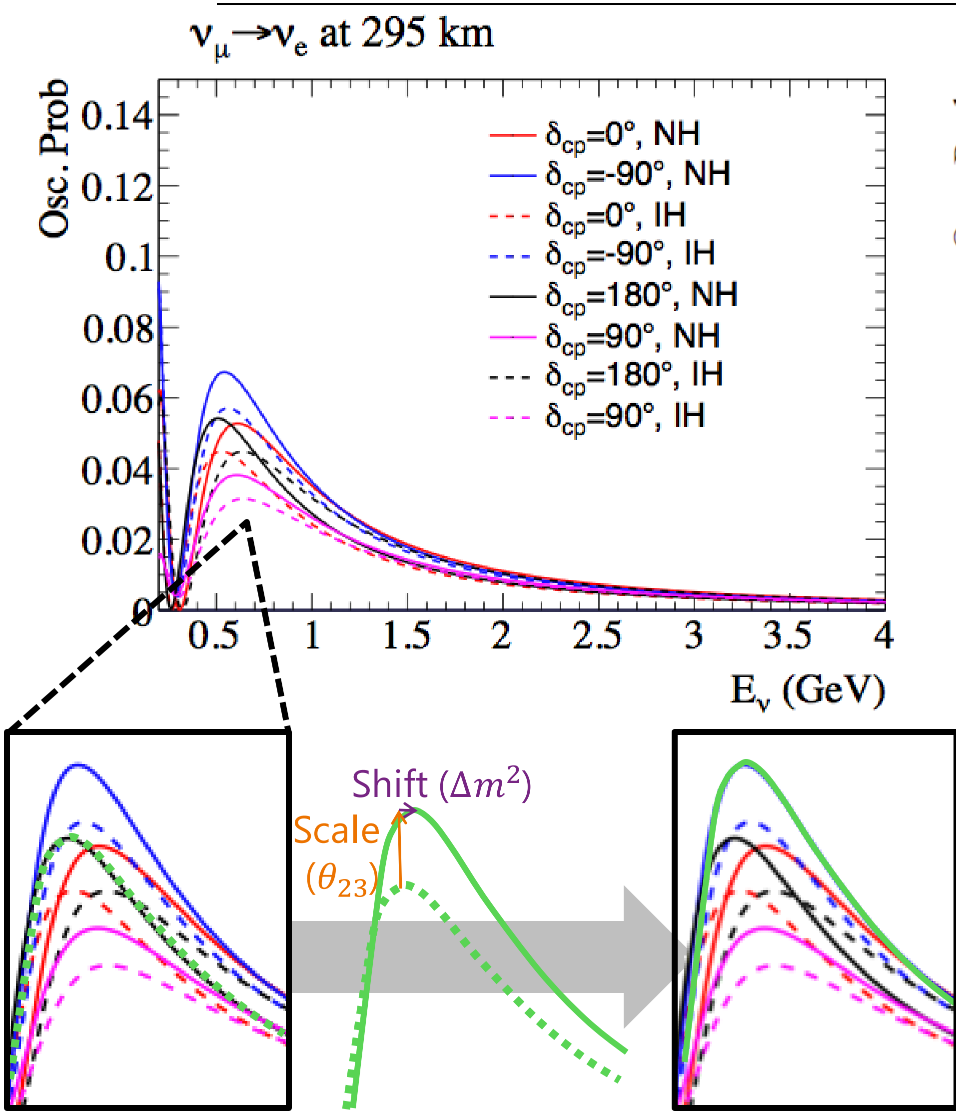


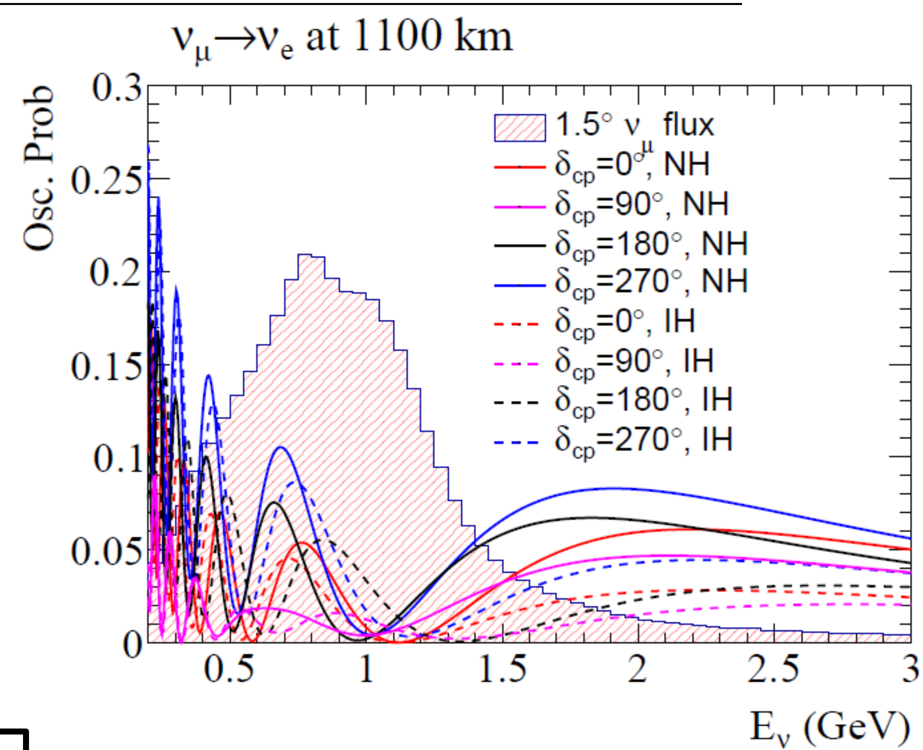
From PhyStat-ν

BC: "Two 3.5 results are better than one 5 result."

DvD: "Calibrated 3.5 result is better than uncalibrated 5."

Δm^2 and θ_{23} degeneracies





- Degeneracies are partially resolved with $\overline{\nu}_e$ data
- But also resolved by covering larger range of Φ_{32}