T2K & Nova chasing neutrino CP violation

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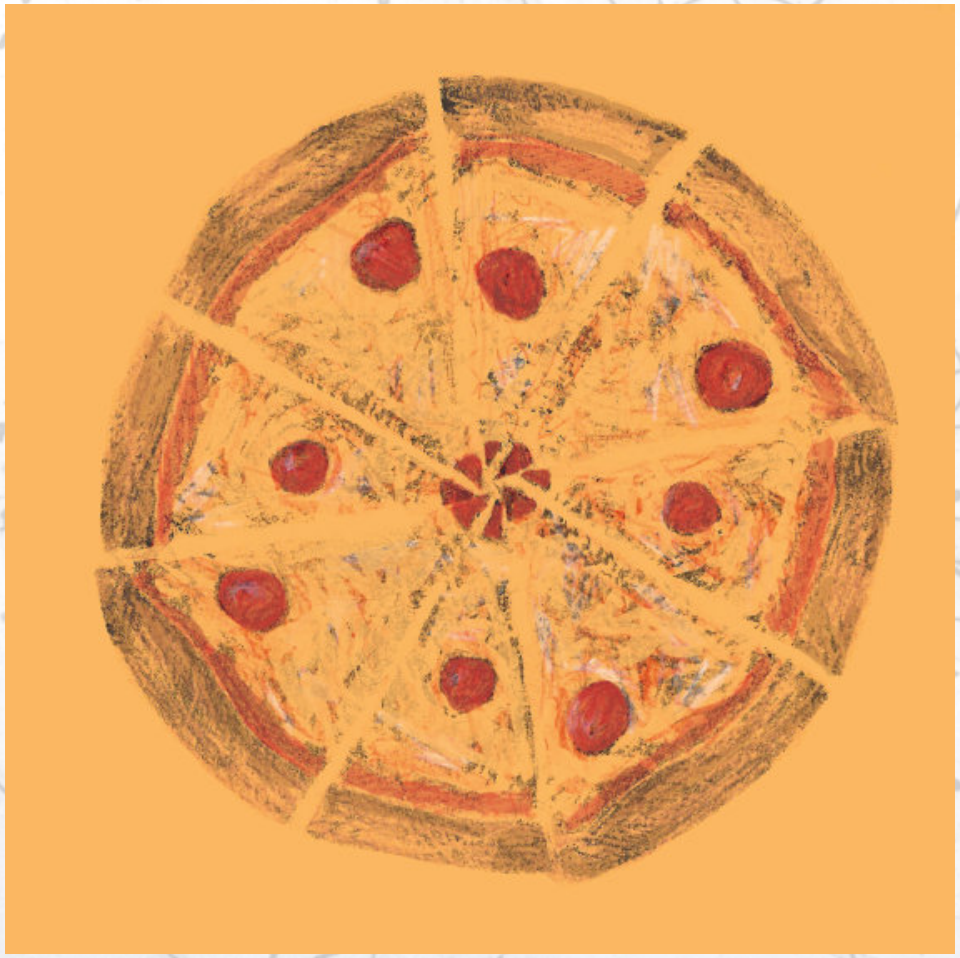
CP violation



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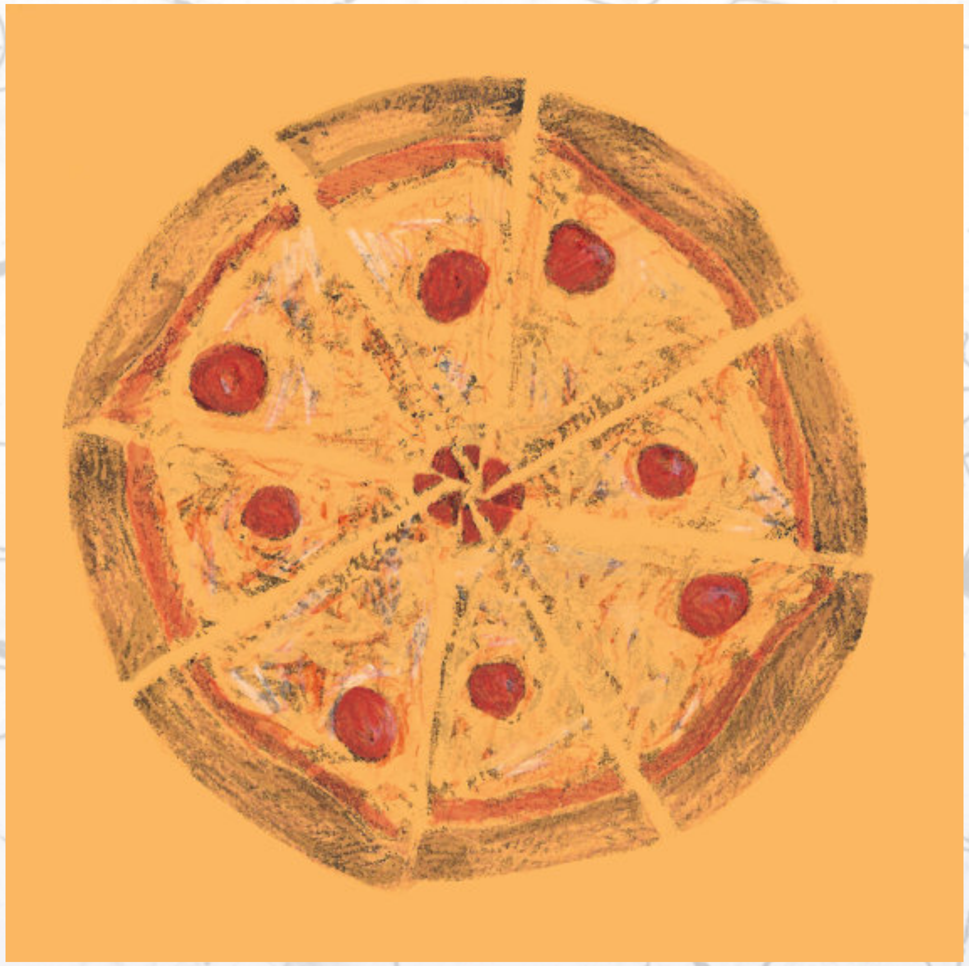

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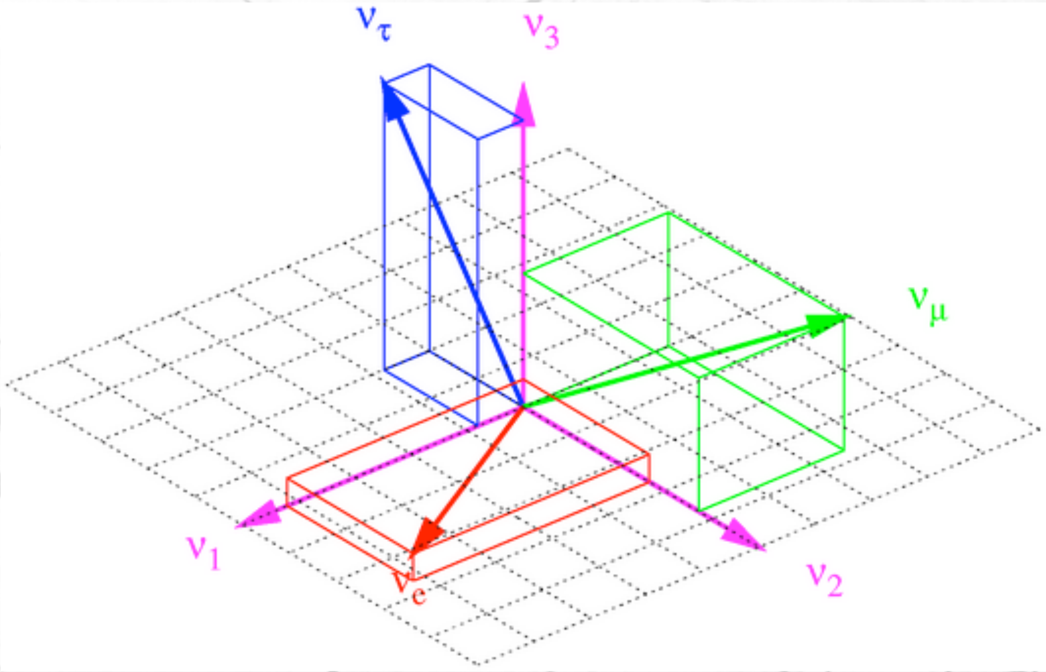
Neutrino oscillations

$$\begin{pmatrix}\nu_e & \nu_\mu & \nu_\tau\end{pmatrix} = U_{PNMS}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$



$$U_{PNMS} = \begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\begin{pmatrix}\cos\theta_{13} & 0 & e^{-\delta_{CP}}\sin\theta_{13}\\ 0 & 1 & 0\\ -e^{\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13}\end{pmatrix}\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}$$

- With 3ν, there are 3 angles and 1 imaginary phase:
- The phase allows for CP violation similar to the quark sector.
- There are also 2 values of Δm^2, traditionally Δm^2_{12} &Δm^2_{31}.

How to measure it ?

Option I

- $\nu_\mu \longrightarrow \nu_e$ with atmospheric Δm^2 (long base line: T2K, Nova)

$$
\begin{aligned}
P_{\nu_\mu,\nu_e} \approx \; & \sin^2 2\theta_{13} \sin^2 2\theta_{23} \sin^2 \frac{\Delta m^2_{31} L}{4E} \\
\pm \; & \frac{\Delta m^2_{12}}{\Delta m^2_{31}} \sin 2\theta_{13} \boxed{\sin\delta} \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin^3 \frac{\Delta m^2_{31} L}{4E} \\
- \; & \frac{\Delta m^2_{12}}{\Delta m^2_{31}} \sin 2\theta_{13} \cos\delta \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \cos \frac{\Delta m^2_{31} L}{4E} \sin \frac{2\Delta m^2_{31} L}{4E} \\
+ \; & \left(\frac{\Delta m^2_{12}}{\Delta m^2_{31}}\right)^2 \cos^2\theta_{23} \sin^2\theta_{12} \sin^2 \frac{\Delta m^2_{31} L}{4E}
\end{aligned}
$$

- Sensitive to violation of Charge Parity symmetry.
- We need to know: θ_{12} θ_{23} θ_{13} Δm^2_{31} & Δm^2_{31}

How to measure it ?

Option 2

- Compare P ($\nu_\mu \longrightarrow \nu_e$) with P ($\bar{\nu}_\mu \longrightarrow \bar{\nu}_e$)

$$\frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} = A(\theta_{13}, \theta_{23}, \theta_{12}, \delta_{CP}, \Delta m^2_{12}, \Delta m^2_{13}) \sin \delta_{CP}$$

- Any deviation from 0 is an evidence of CP violation.
- To extract the value of δ_{CP} we still need to know:
    - θ_{12} θ_{23} θ_{13} Δm^2_{31} & Δm^2_{31}

What is better ?

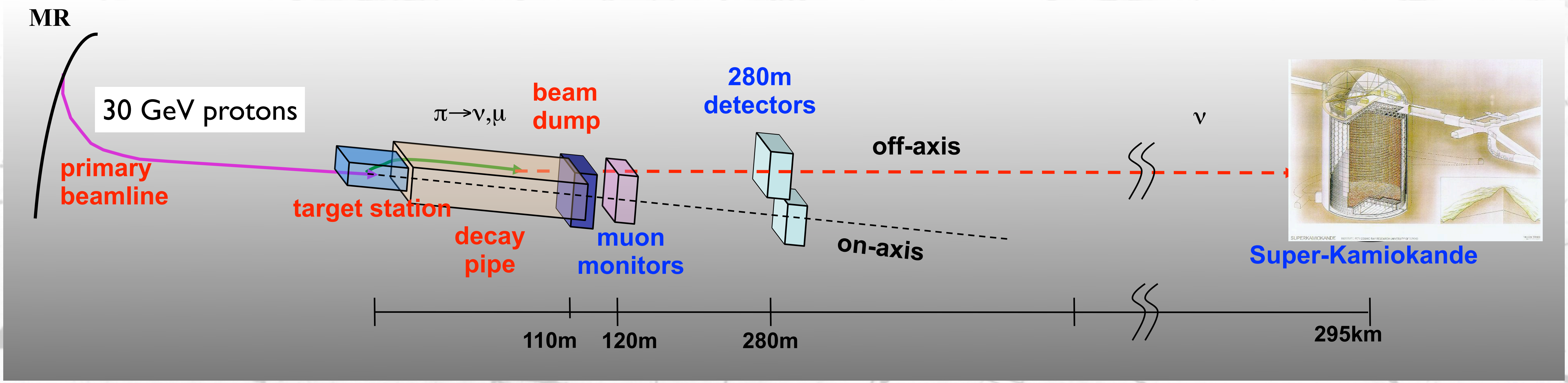
Method I

+ Production and detection of neutrinos is efficient.
- Model dependent.
- Systematic errors.

Method I

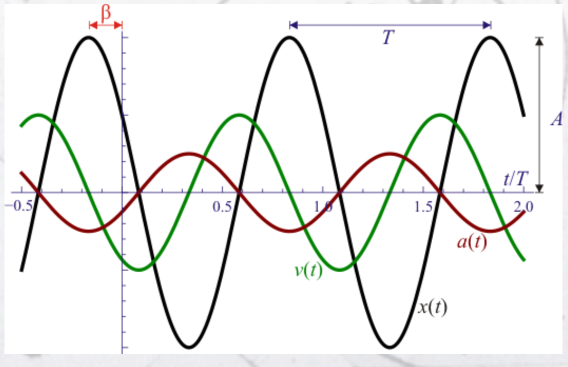
+ Model independent.
+ Cancellation of systematic errors (neutrino-antineutrinos).
- Production and detection of anti-neutrinos is 6 times less efficient than neutrinos.

T2K



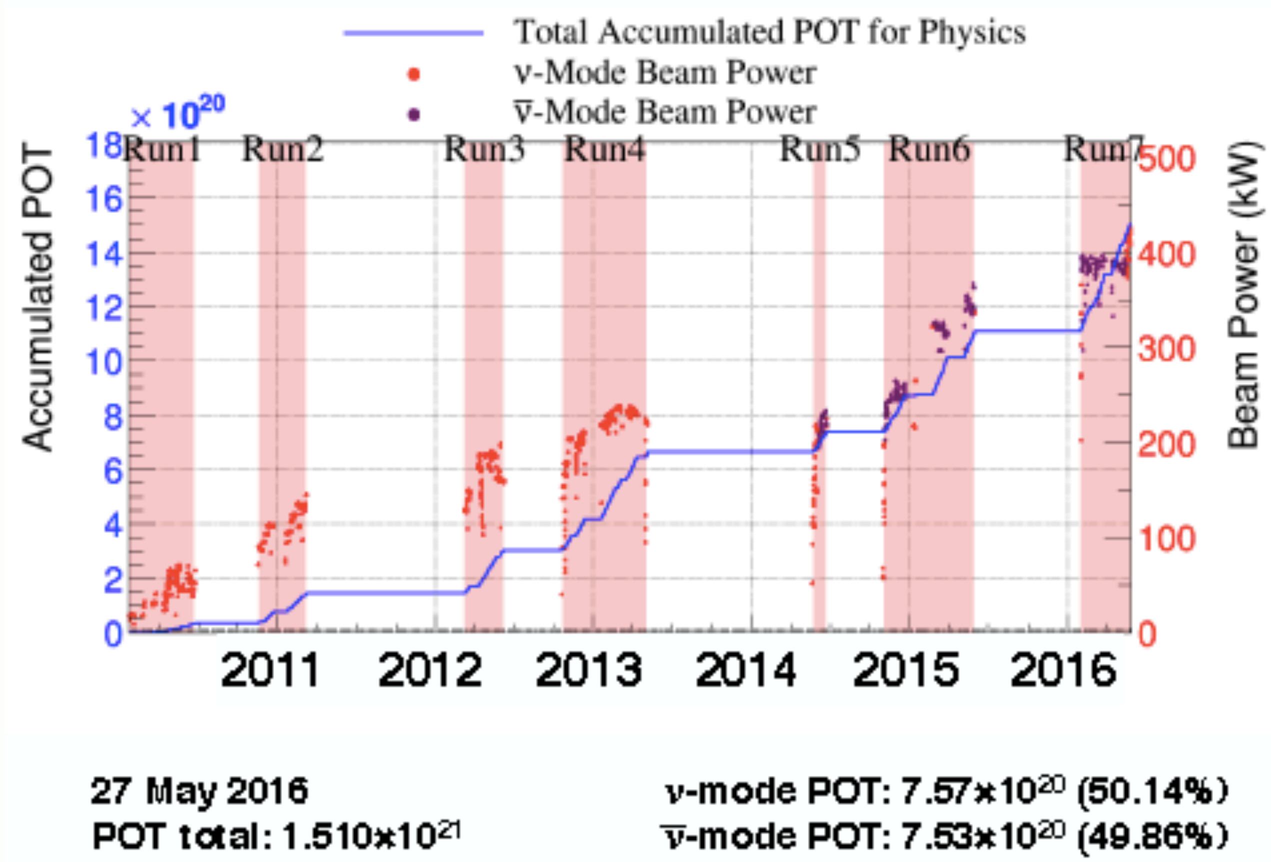
Neutrinos are produced in an accelerator:
1. Protons produce pions that decay into muon neutrinos.
2. Pions are focused with a magnetic horn.

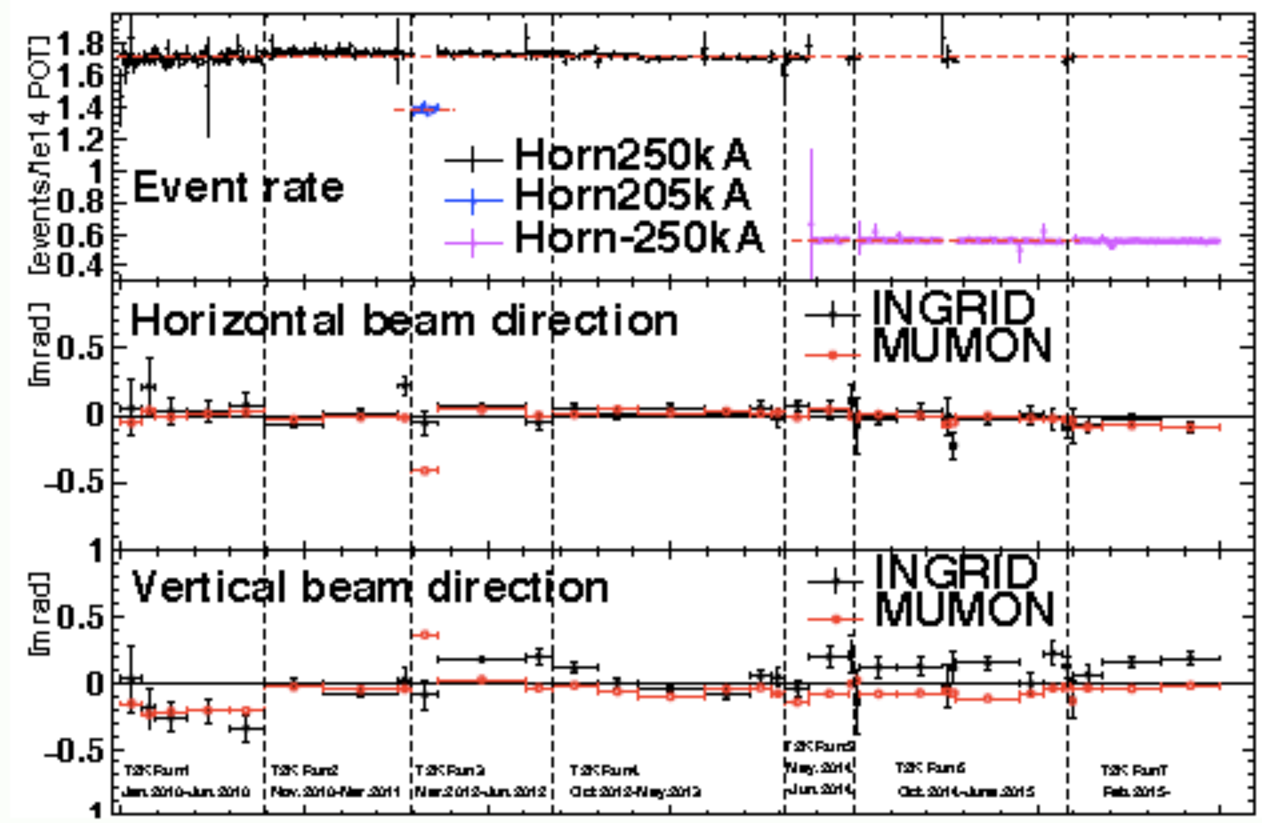
The flux is measured to reduce errors.



Measurement of oscillated flux.

T2K

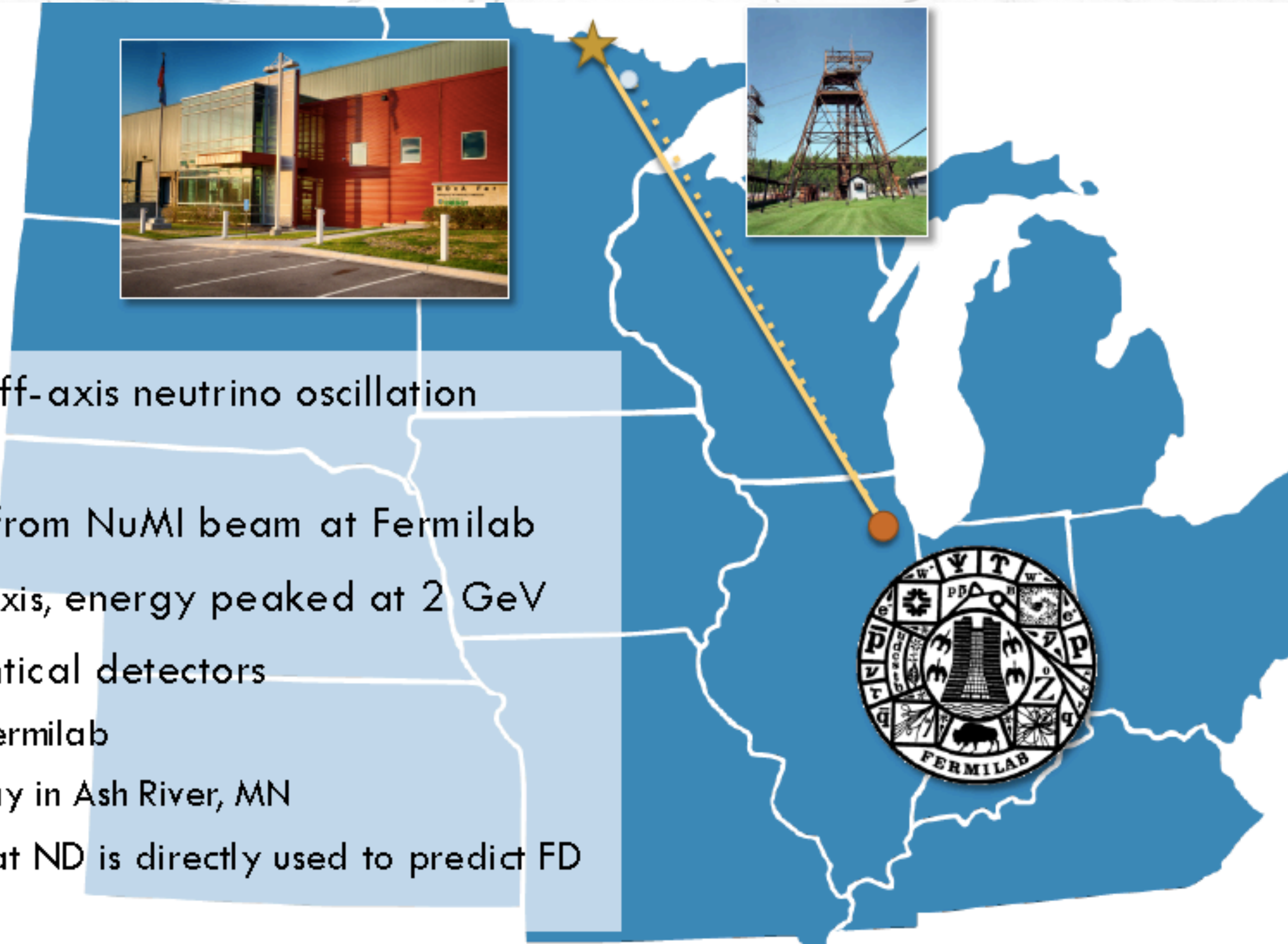




- Continuous rise in beam power from ~225 kW (2014) to 420 kW (2016)
  - Stable beam operations from muon monitor and INGRID measurements
- Total of 15.1×10^{20} POT accumulated as of end of May
- Results presented today with:
  - ν-mode: 6.91×10^{20} POT
  - $\bar{\nu}$-mode: 7.53×10^{20} POT (~2 x previous $\bar{\nu}$-mode results)

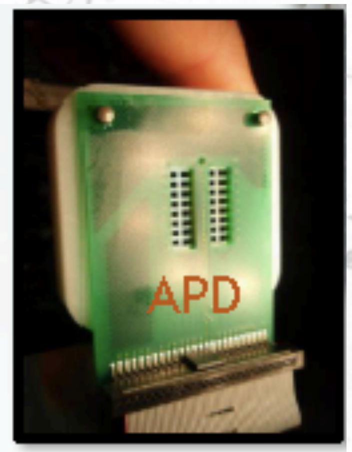
$\sim 0.5\ \bar{\nu}\ /\ 0.5\ \nu$

Nova

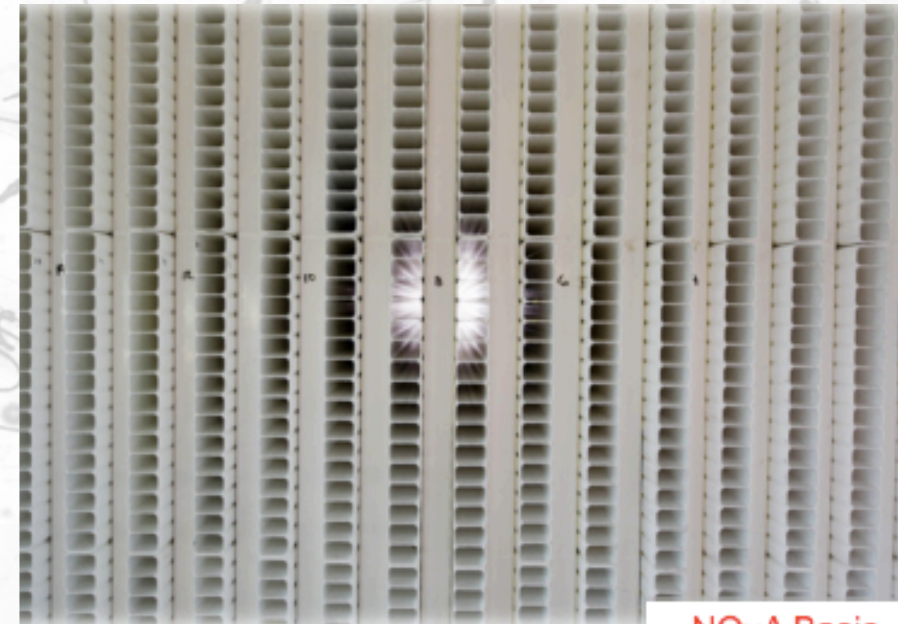


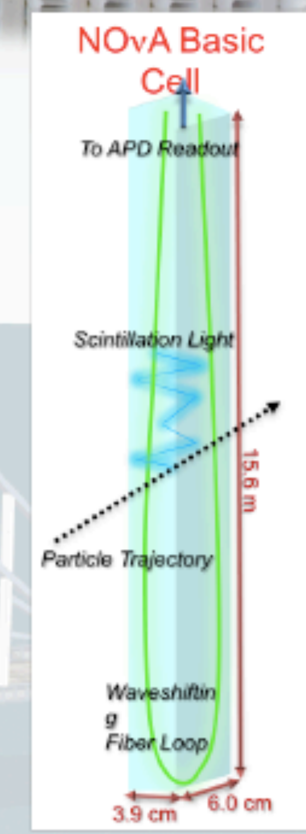
- Long-baseline, off-axis neutrino oscillation experiment
- Study neutrinos from NuMI beam at Fermilab
- At 14 mrad off-axis, energy peaked at 2 GeV
- Functionally identical detectors
  - ND on site at Fermilab
  - FD 810 km away in Ash River, MN
  - Measurement at ND is directly used to predict FD

Nova



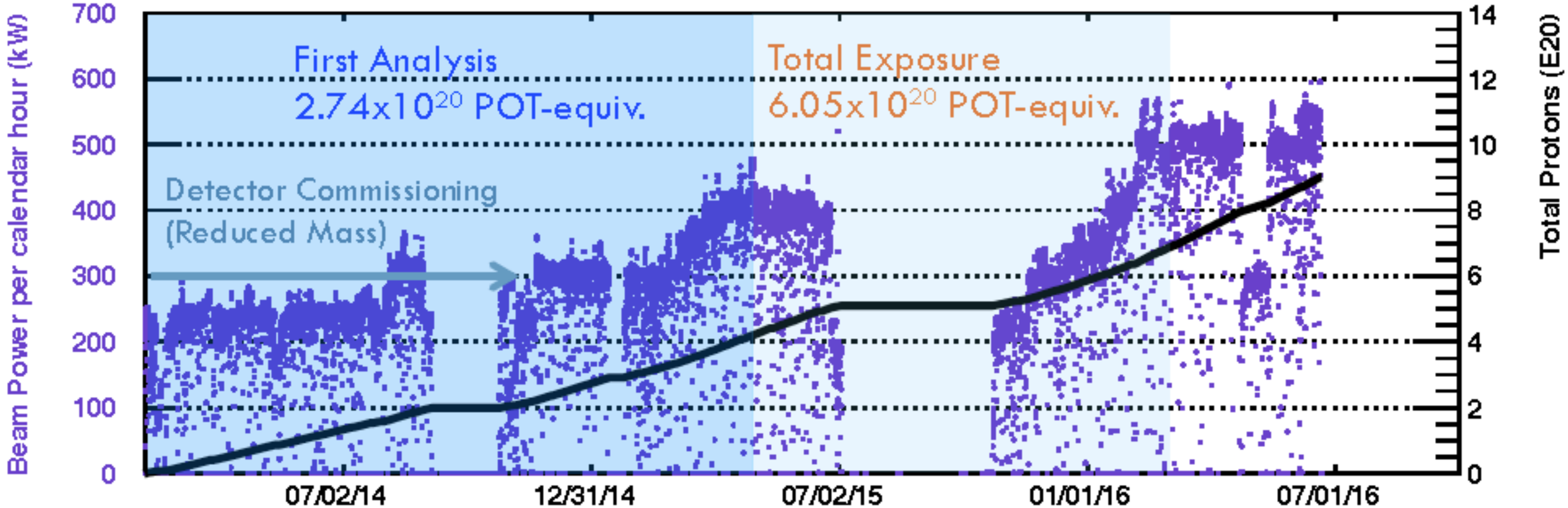
- PVC+Liquid Scintillator
  - Mineral Oil
  - 5% pseudocumene
- Read out via WLS fiber to APD
- Layered planes of orthogonal views
  - muon crossing far end ~40 PE
  - 0.17 X_0 per layer
- DAQ runs with zero deadtime
  - triggers for beam, SNEWS, cosmic ray calibration samples, exotic searches
  - 150kHz of cosmic induced events





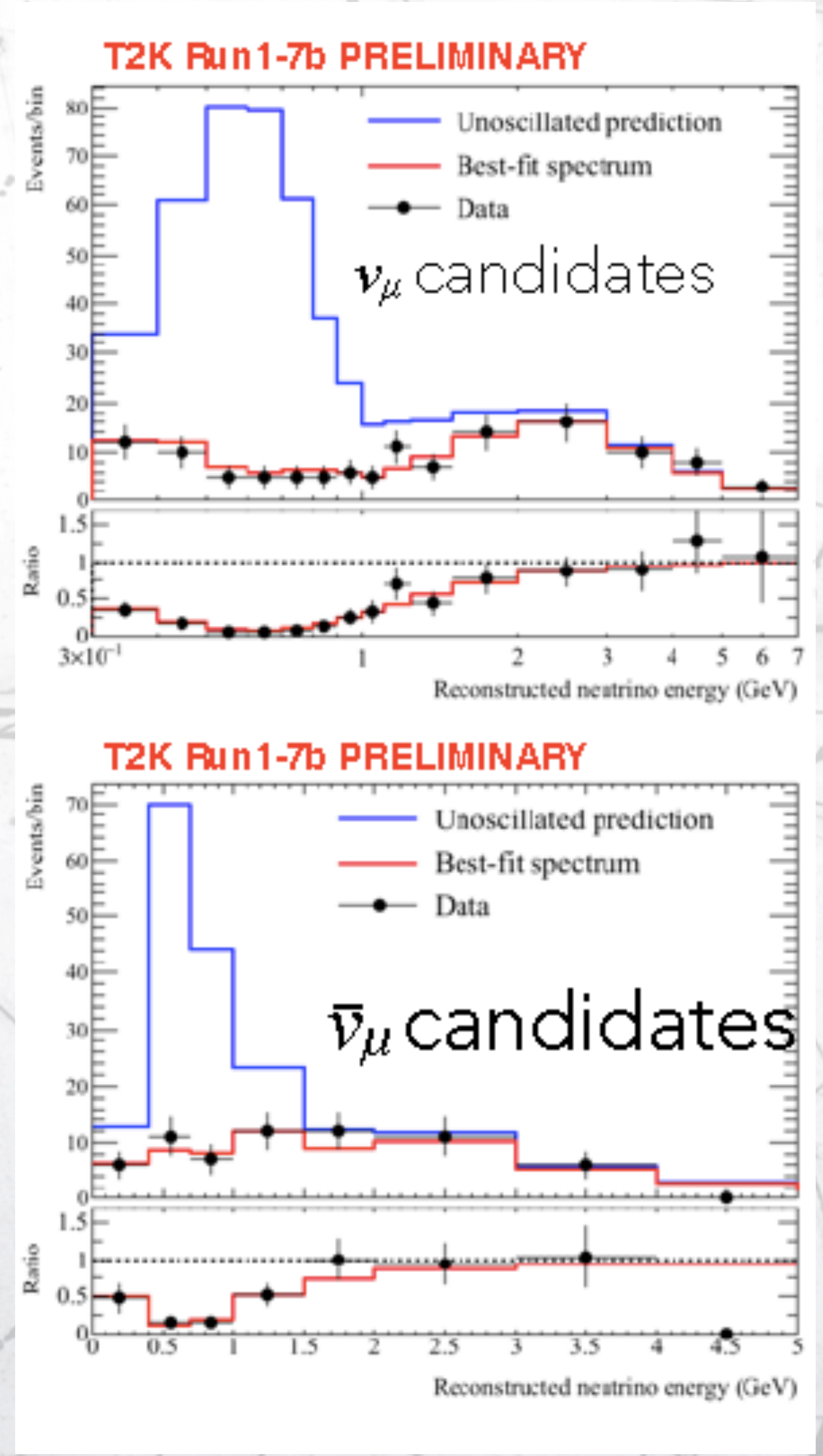
Nova

- 6.05×10^{20} POT in 14 kton equivalent detector
  - More than double exposure of 2015 analysis
- Currently running at 560 kW
- Achieved 700 kW design goal in tests on June13!



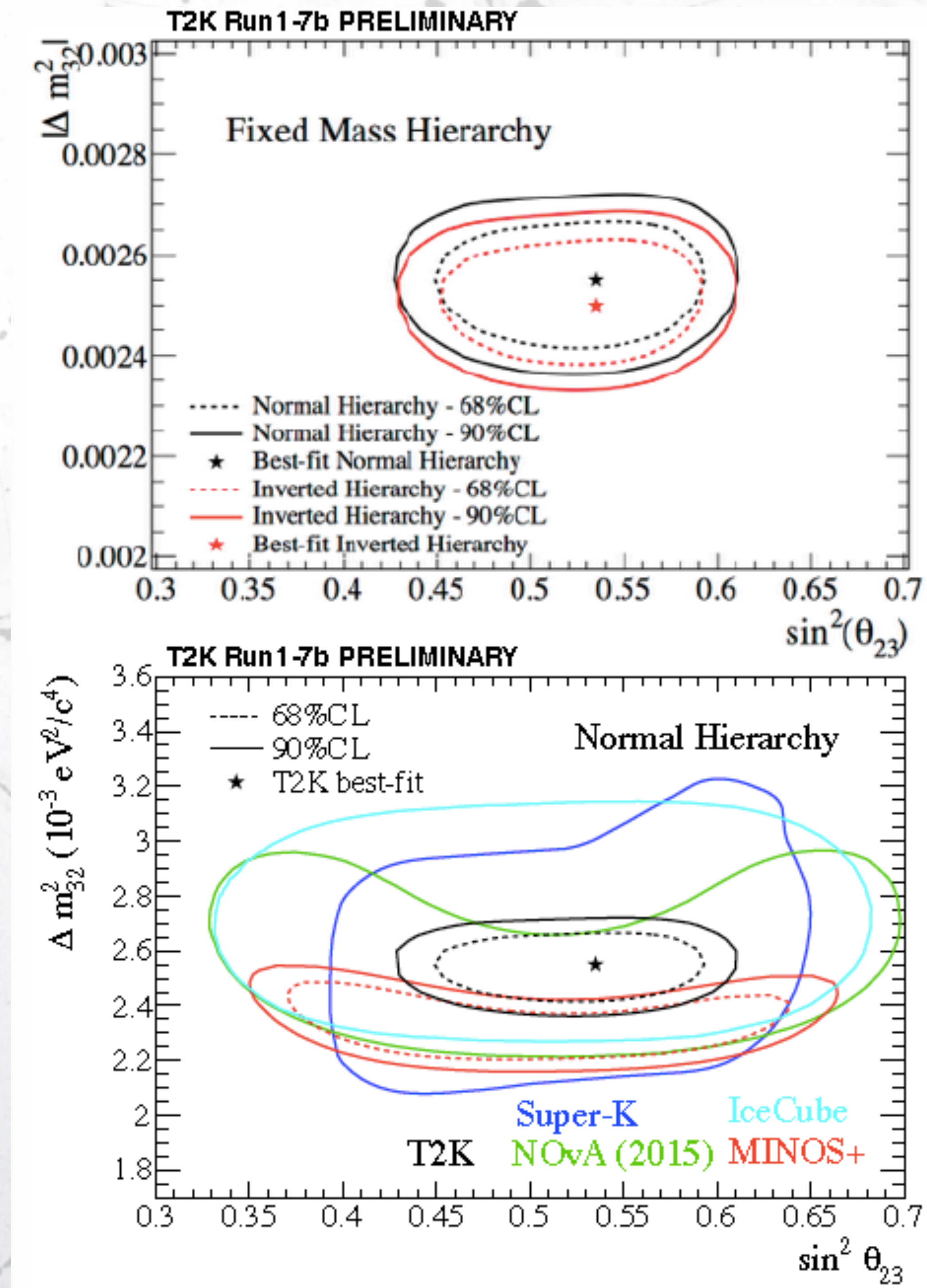
$$P(\nu_\mu \to \nu_\mu)$$

T2K



	Exp. $\sin^2\theta_{23}=0.528$ NH	Obs.
ν_μ	127.9	125.
$\bar{\nu}_\mu$	64.3	66.

T2K



	NH	IH
$\sin^2\theta_{23}$	$0.532^{+0.044}_{-0.060}$	$0.534^{+0.041}_{-0.059}$
$\lvert\Delta m^2_{32}\rvert$ ($/10^{-3}$eV^2)	$2.545^{+0.084}_{-0.082}$	$2.510^{+0.082}_{-0.083}$

Results are consistent with maximal mixing!

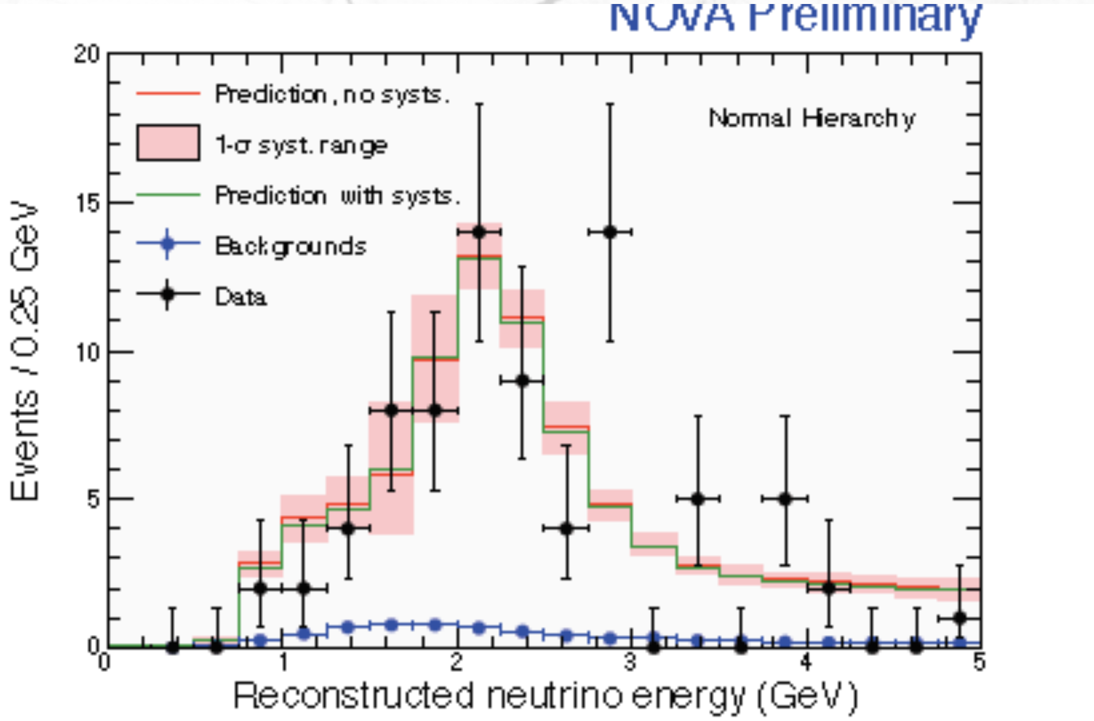
Nova P($\nu_\mu \rightarrow \nu_\mu$)

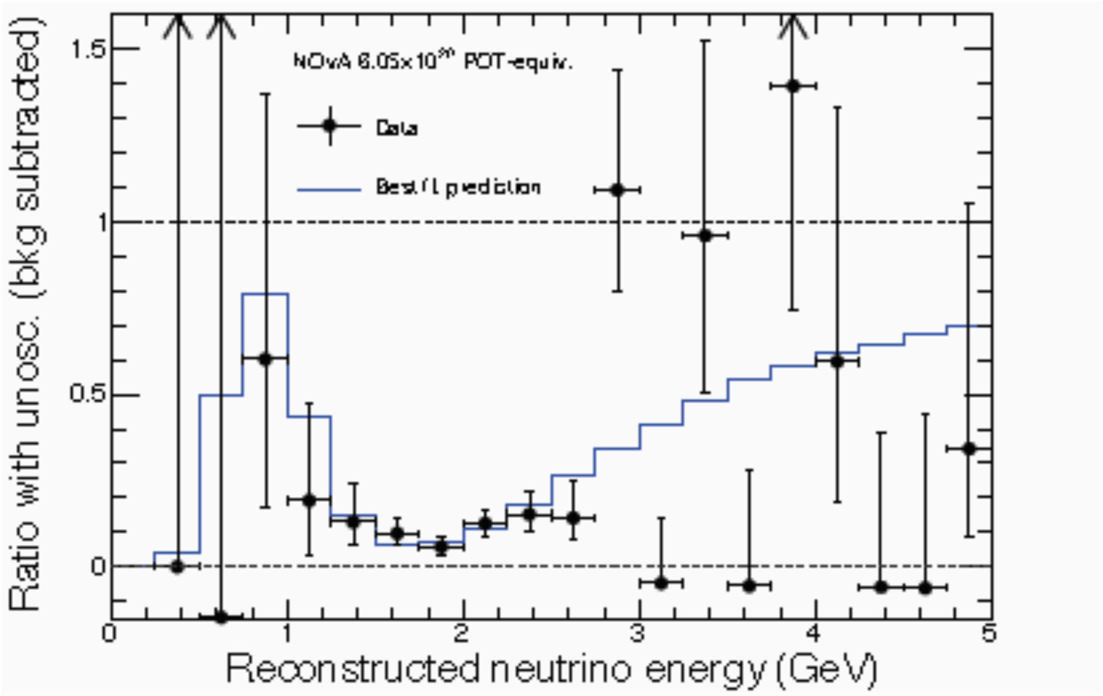
- 78 events observed in FD
  - 473±30 with no oscillation
  - 82 at best oscillation fit
  - 3.7 beam BG + 2.9 cosmic

χ^2/NDF=41.6/17

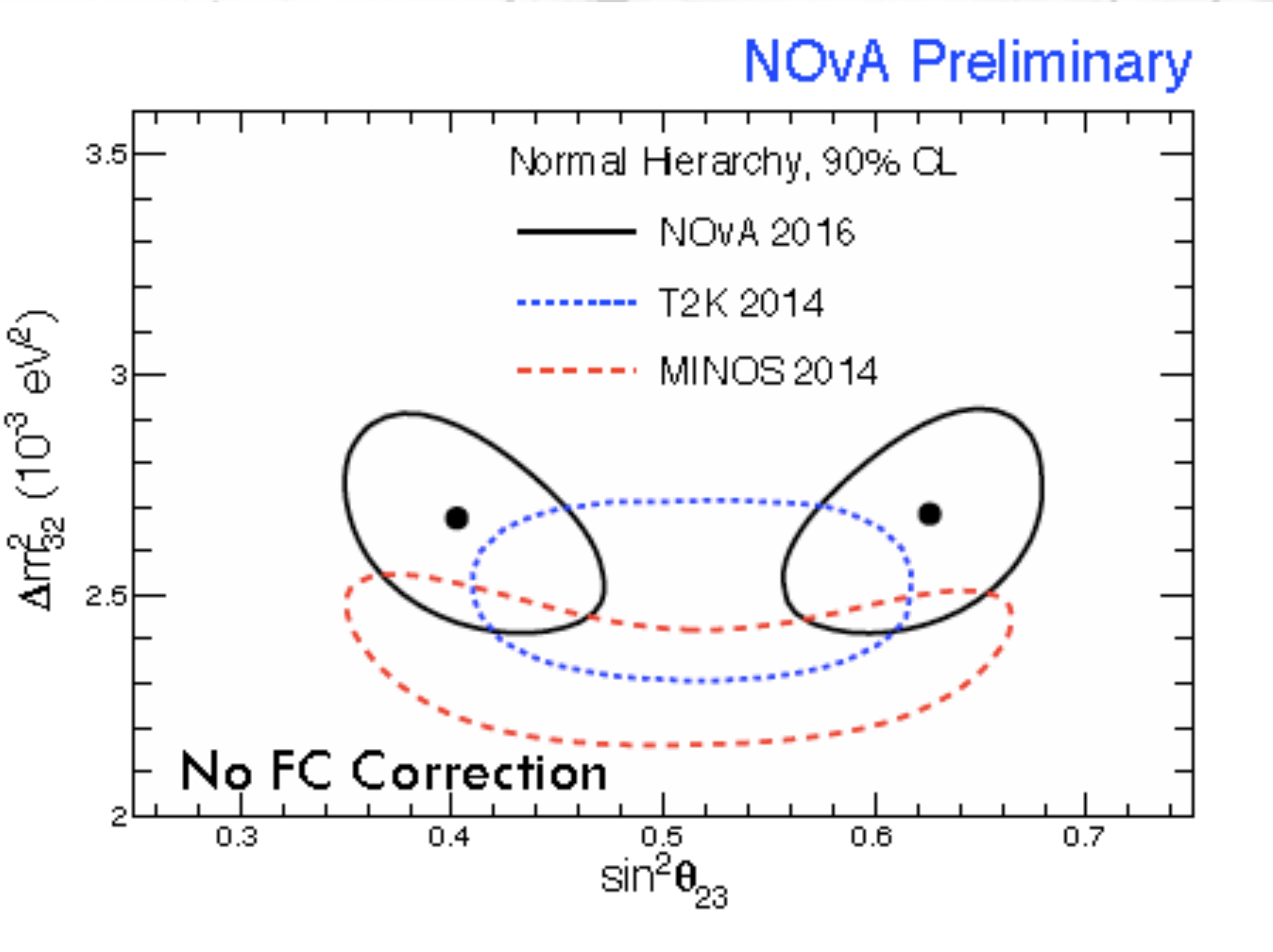
Driven by fluctuations in tail,

no pull in oscillation fit





Nova



Best Fit (in NH):

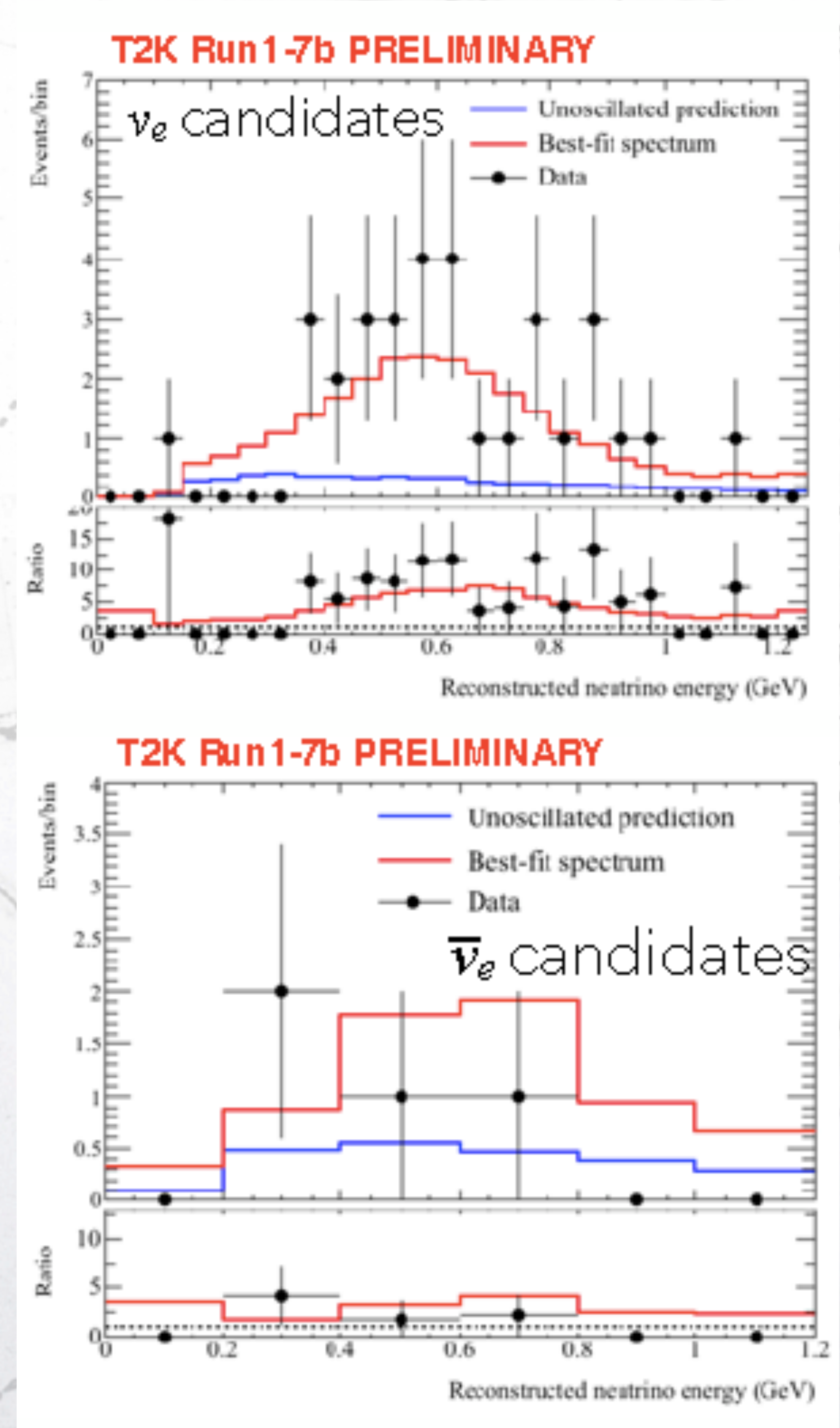
$$\left|\Delta m^2_{32}\right| = 2.67 \pm 0.12 \times 10^{-3}\mathrm{eV}^2$$
$$\sin^2\theta_{23} = 0.40^{+0.03}_{-0.02}(0.63^{+0.02}_{-0.03})$$

Results exclude maximal mixing at 2.5σ

	NH	IH
$\sin^2\theta_{23}$	$0.532^{+0.044}_{-0.060}$	$0.534^{+0.041}_{-0.059}$
$\lvert\Delta m^2_{32}\rvert$ ($/10^{-3}$eV^2)	$2.545^{+0.084}_{-0.082}$	$2.510^{+0.082}_{-0.083}$

Results are compatible in a region where maximal mixing is excluded!

$$P(\nu_\mu \to \nu_e)$$



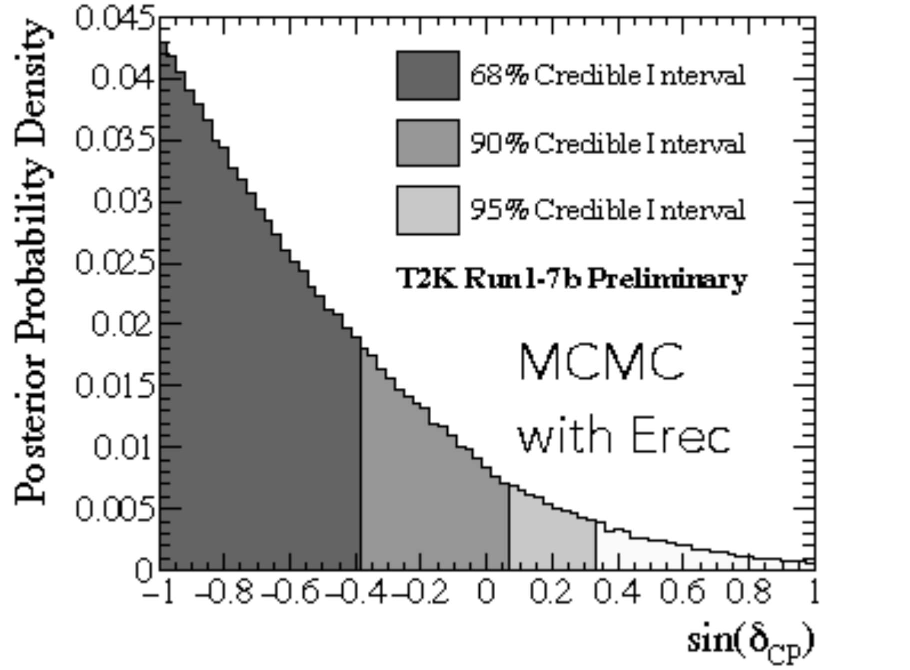
		NH $\sin^2\theta_{23}$=0.528 $\sin^2\theta_{13}$=0.085 (Reactor)			
	Obs.	δ_{CP}=-π/2	δ_{CP}=0	δ_{CP} =π/2	δ_{CP} =π
ν_e	32.	27.0	22.7	18.5	22.7
$\bar{\nu}_e$	4.	6.0	6.9	7.7	6.8

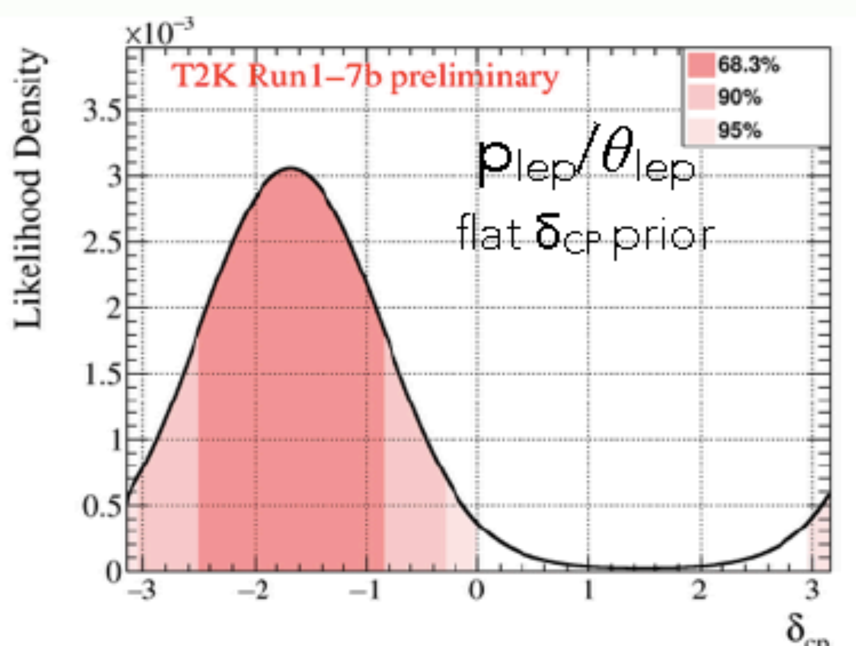
Without any analysis:

- δ_{CP}=-π/2 is preferred by neutrinos and antineutrinos.
- Neutrinos has 5 more than expected @ δ_{CP}=-π/2
- Antineutrinos has 2 less than expected @ δ_{CP}=-π/2
- Result will be at the edge of T2K sensitivity.

BAYESIAN POSTERIOR PROBABILITIES

P4.023 K. Duffy





- Left: posterior probability distribution in δ_{CP} marginalizing over all other parameters
  - negligible dependence on priors except for δ_{CP}
    - (flat in δ_{CP} vs. sin δ_{CP})
- Bottom: posterior probability distributions for θ_{23} octant and hierarchy with MCMC analysis
  - mild preference for $\theta_{23} > \pi/4$ and normal hierarchy

FLAT δ_{CP}	NH	IH	SUM
$\sin^2\theta_{23} \leq 0.5$	0.218	0.072	0.290
$\sin^2\theta_{23} > 0.5$	0.529	0.181	0.710
SUM	0.747	0.253	1.000

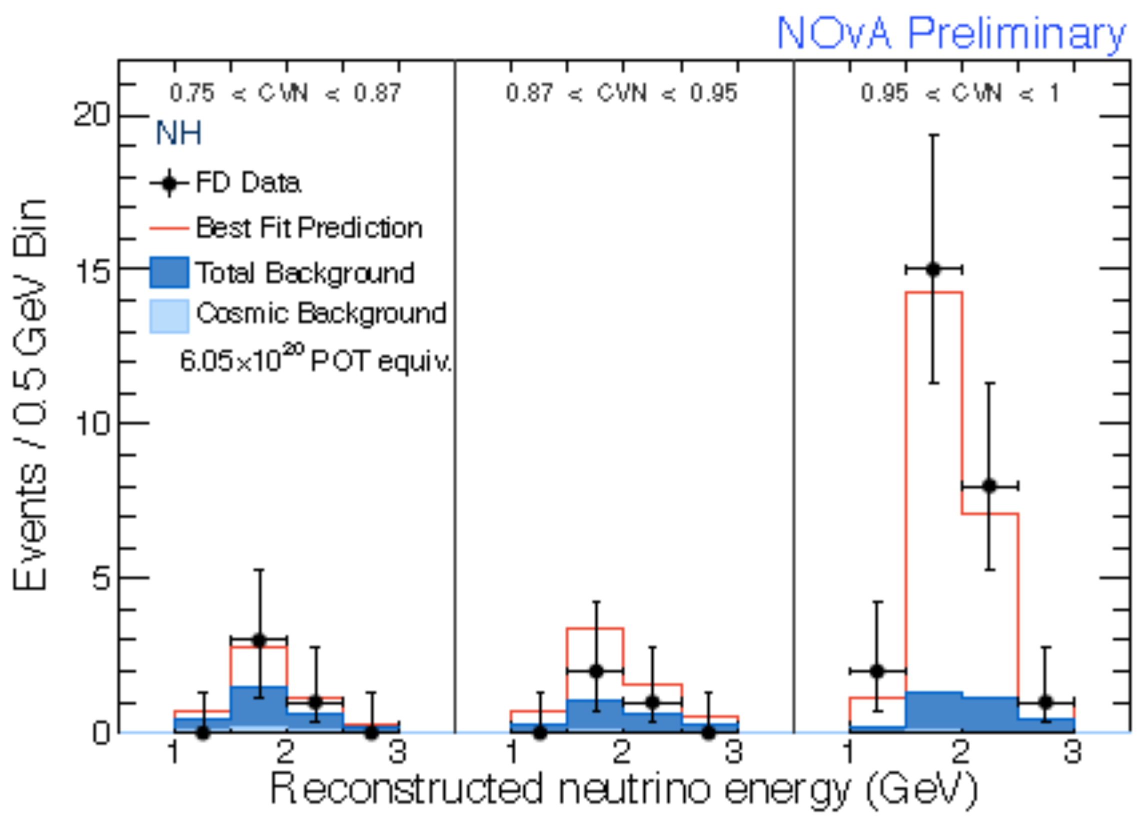
expected sensitivity (NO, $\sin^2\theta_{23}$=0.528, δ_{CP}=-1.601)

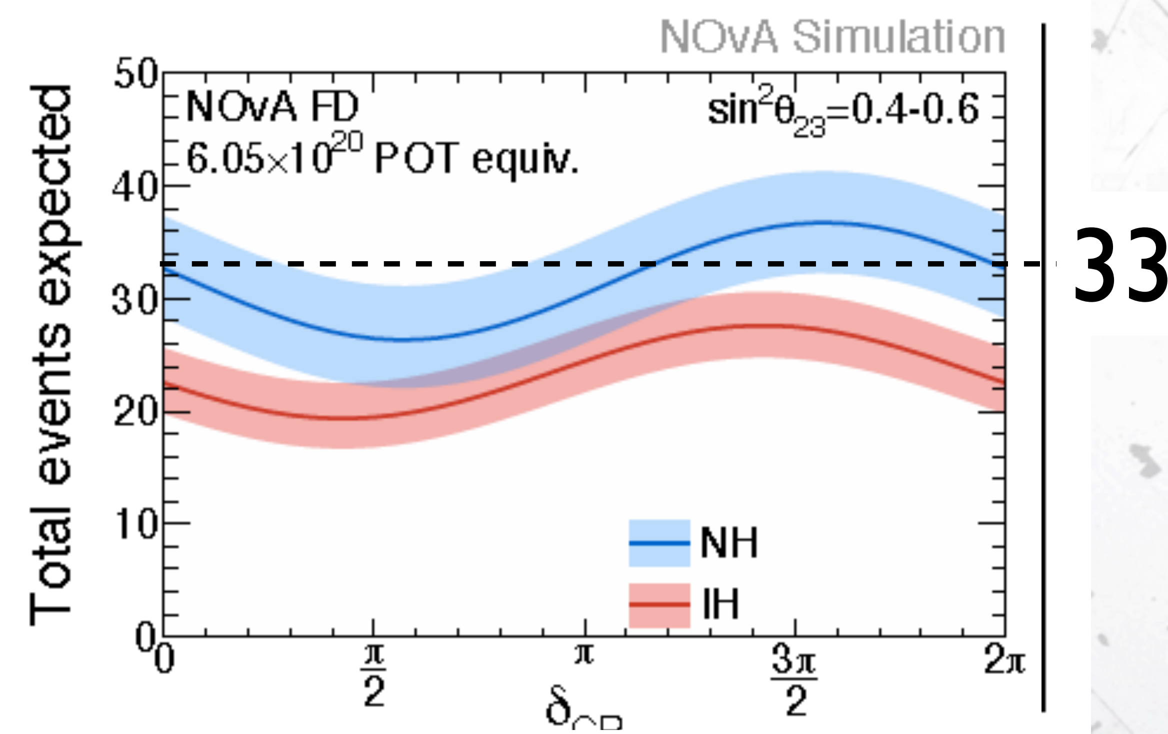
FLAT δ_{CP}	NH	IH	SUM
$\sin^2\theta_{23} \leq 0.5$	0.223	0.125	0.347
$\sin^2\theta_{23} > 0.5$	0.405	0.248	0.653
SUM	0.628	0.373	1.000

24

$>8\sigma$ electron neutrino appearance signal

- Observe 33 events in FD
  - background 8.2 ± 0.8





Alternate selectors from 2015 analysis show consistent results

LID: 34 events, 12.2 ± 1.2 BG expected

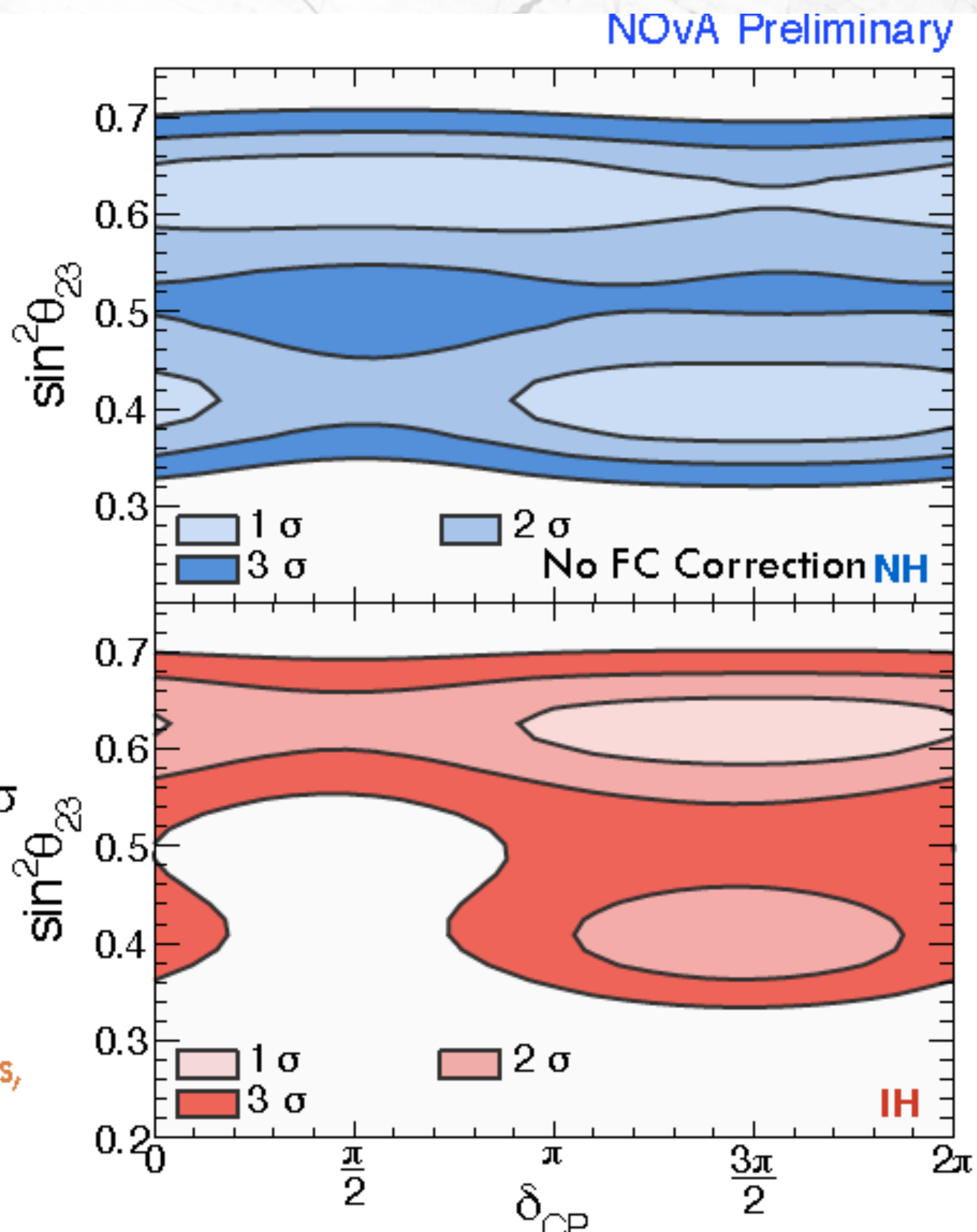
LEM: 33 events, 10.3 ± 1.0 BG expected

Slight preference for $-\pi/2$ and NH.

- Fit for hierarchy, δ_{CP}, $\sin^2\theta_{23}$
  - Constrain Δm^2 and $\sin^2\theta_{23}$ with NOvA disappearance results
  - Not a full joint fit, systematics and other oscillation parameters not correlated
- Global best fit Normal Hierarchy

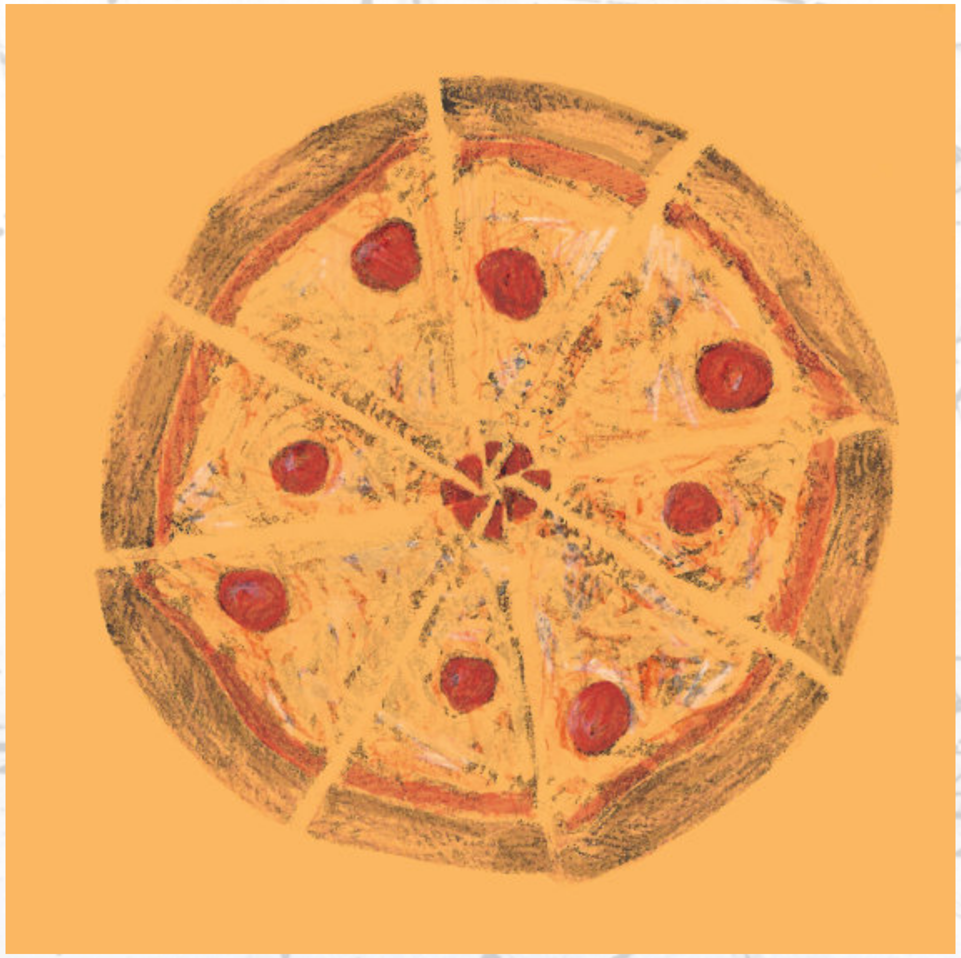
$$\delta_{CP} = 1.49\pi$$
$$\sin^2(\theta_{23}) = 0.40$$

  - best fit IH-NH, $\Delta\chi^2$=0.47
  - both octants and hierarchies allowed at 1σ
  - 3σ exclusion in IH, lower octant around $\delta_{CP}=\pi/2$



Antineutrino data will help resolve degeneracies, particularly for non-maximal mixing

Planned for Spring 2017



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Too early to say:
Consistent results from Nova and T2K
Wait for Nova anti-neutrinos.
Sensitivity is still low: combining results is a must!
But, if CP is maximal Nova and T2K will be able to say something in few years.

Conclusions II

Is the θ_{23} mixing maximal ?

No mixing

Maximal mixing

Combination of Nova and T2K points to non-maximal mixing.
More data needed.
Which is the octant ? $\theta_{23} < 45°$ or $\theta_{23} > 45°$
Impact on the determination of δ_{CP}