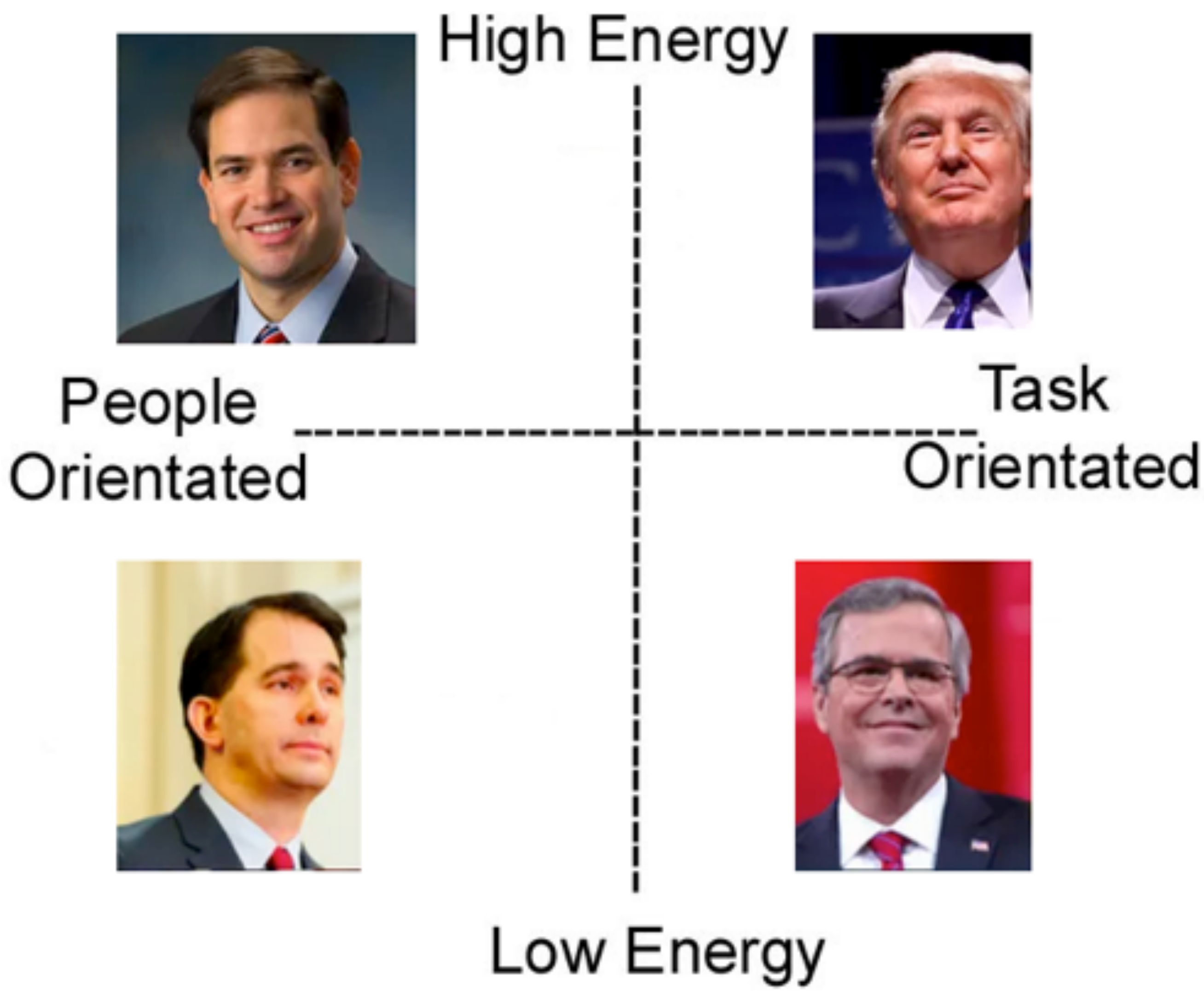
UNIVERSITY OF TORONTO
INSTITUTE OF PARTICLE PHYSICS
TRIUMF

H. A. TANAKA (U. TORONTO, IPP, TRIUMF)

OVERVIEW OF THEIA PHYSICS IN 2025 "HIGH ENERGY"

MY CHARGE



- Review the outlook of “high energy” c. 2025
  - Long baseline
  - Proton decay

“long shot”

“fundamental instability

LOOK INTO THE CRYSTAL BALL

LOOK INTO THE CRYSTAL BALL

- Caveats:

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  - there is no crystal ball . . . .

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  - I am myopic both literally and in outlook . . .
    - long range planning for me is "what should I eat for lunch?"

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  - start of Trump administration's third term . . . .

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  - particularly important given sentiment that "the world can only have one long-baseline experiment"
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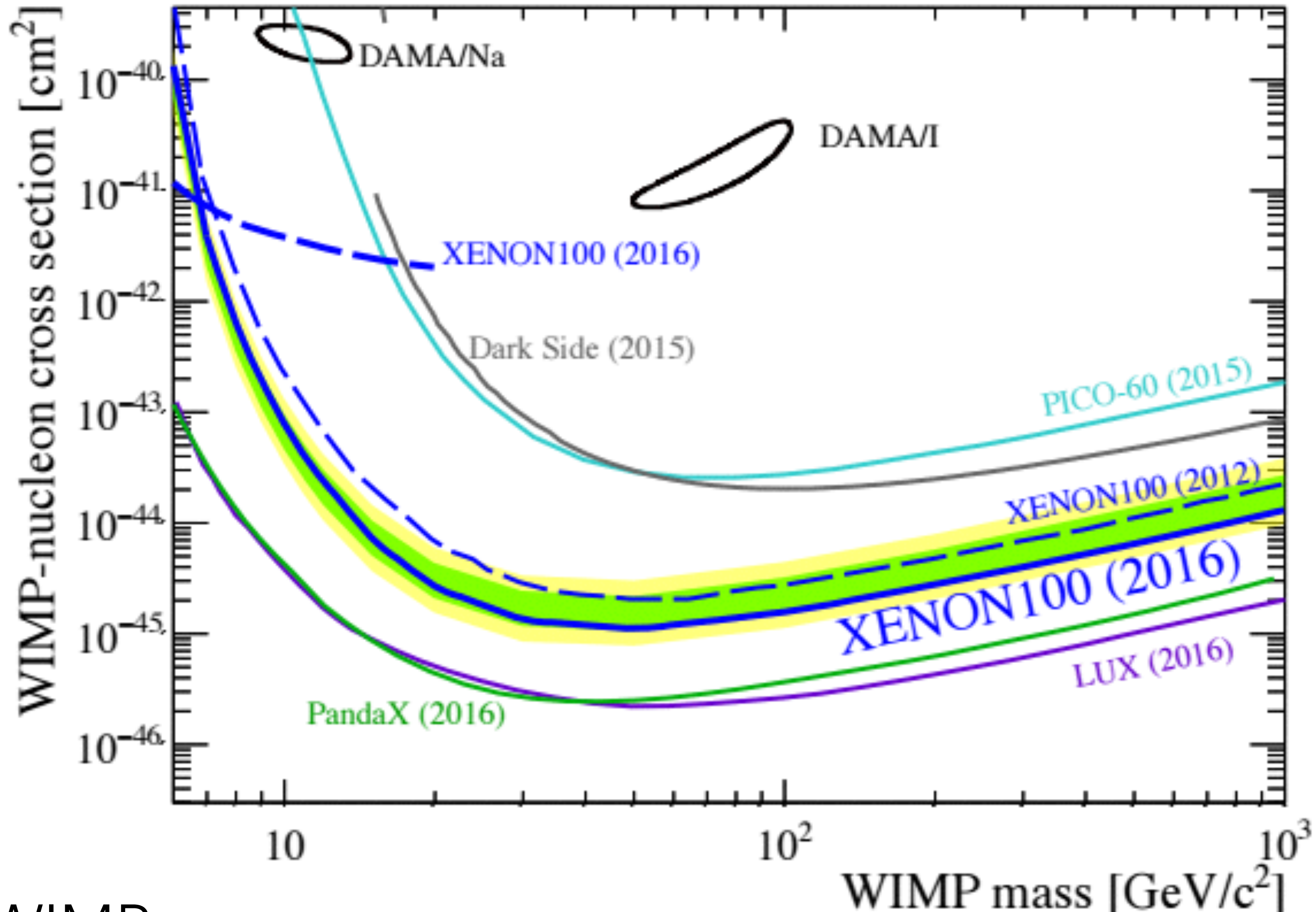
    - a broad program of important physics measurement
    - razor sharp focus on a few topics that can make the next "breakthrough"

SUMMER 2016

THE ENERGY FRONTIER

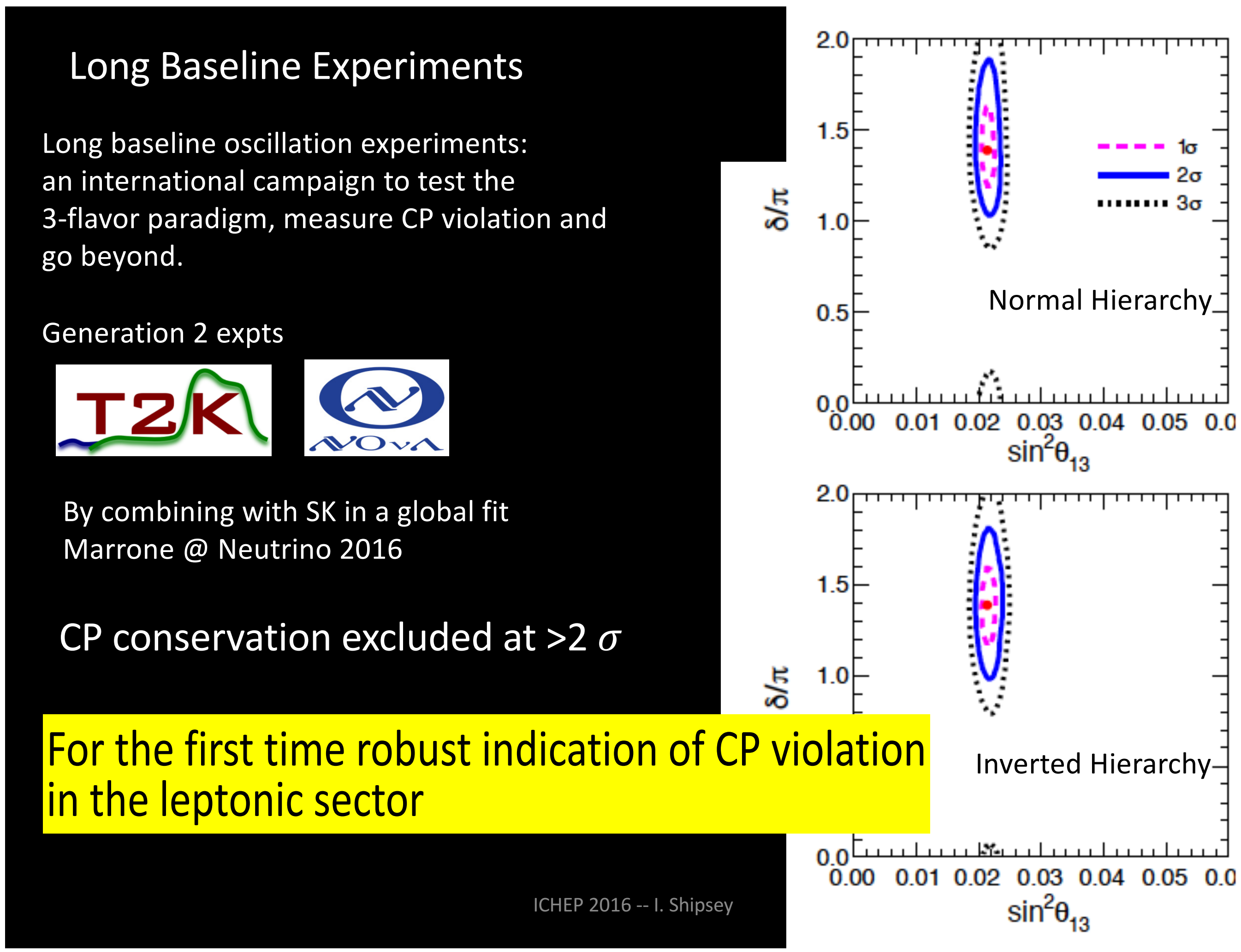
- The energy frontier has been silent on BSM physics for a while . . .
- BSM physics is hiding very effectively or possibly out of reach . . . .
- LHC has taken only a few percent of its planned integrated luminosity
  - any discovery will be more mysterious, dramatic then “conventional” scenarios that are not showing up
  - still, we are in the dark for now about possible TeV-scale BSM

DARK MATTER



- No signs of TeV-scale WIMPs
- Impressive march in sensitivity down to the "neutrino floor"
  - New frontier in low mass WIMPS and dark sector/portals
  - still in the"dark" about dark matter and potential BSM physics that is responsible for it.

NEUTRINOS



- One of the highlights from the summer
- Has CP violation been
    - “indicated”? “hinted”? “suggested”? “whispered”? “intimated”?

NEUTRINOS

Long Baseline Experiments

Long baseline oscillation experiments:
an international campaign to test the
3-flavor paradigm, measure CP violation and
go beyond.

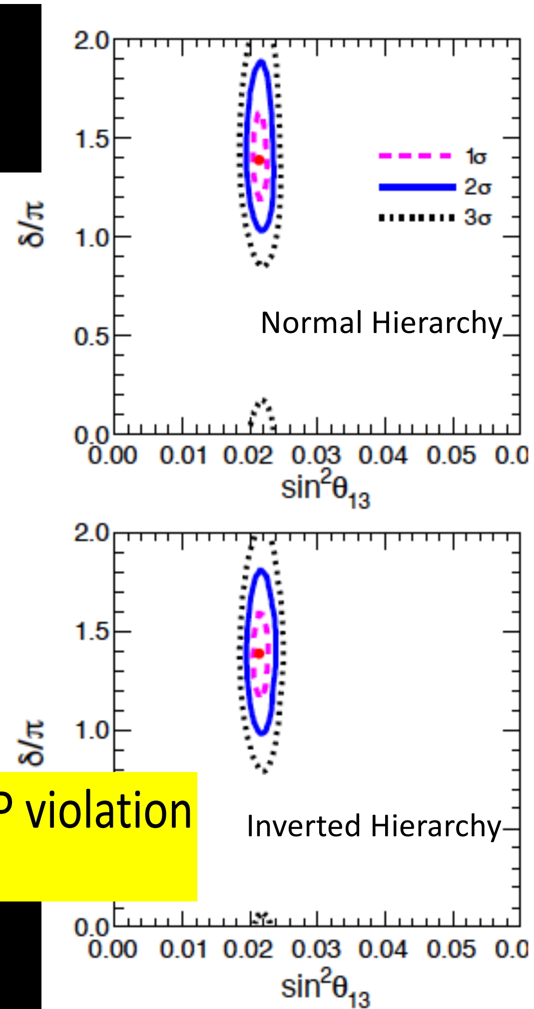
Generation 2 expts

By combining with SK in a global fit
Marrone @ Neutrino 2016

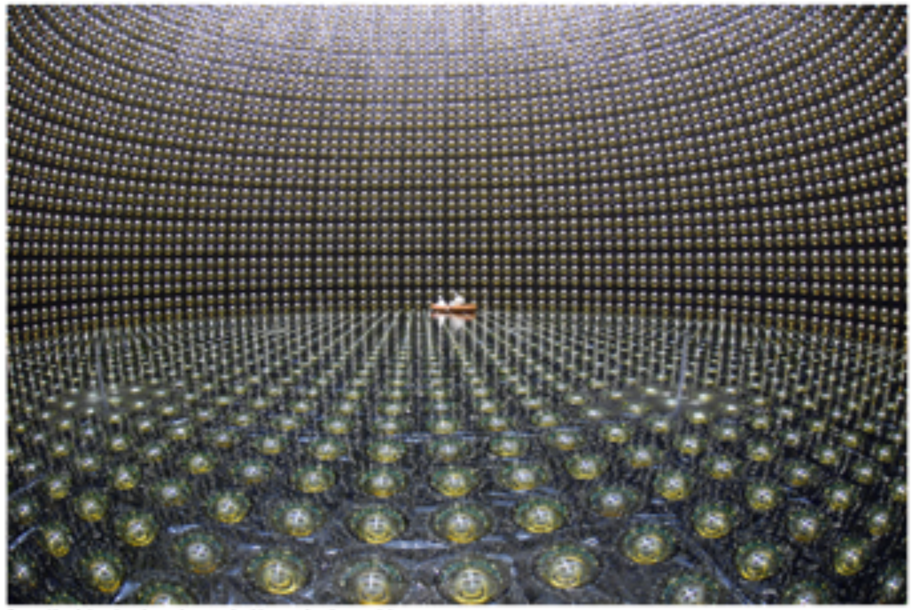
CP conservation excluded at >2 σ

For the first time robust indication of CP violation in the leptonic sector

ICHEP 2016 -- I. Shipsey



Neutrinos hint at why antimatter didn't blow up the universe



Super-Kamiokande: a huge detector looking out for tiny particles
Kamioka Observatory/ICRR(Institute for Cosmic Ray Research)/The University of Tokyo

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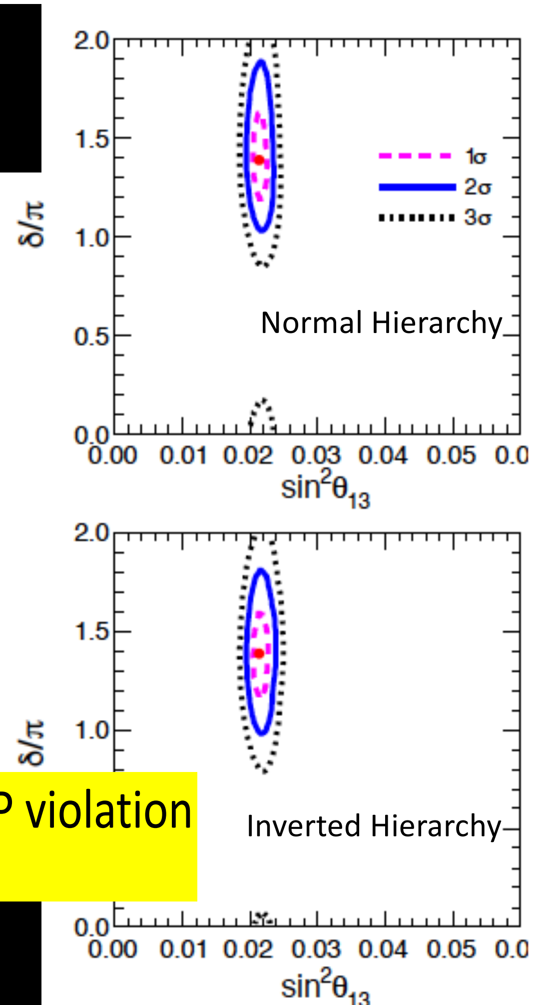

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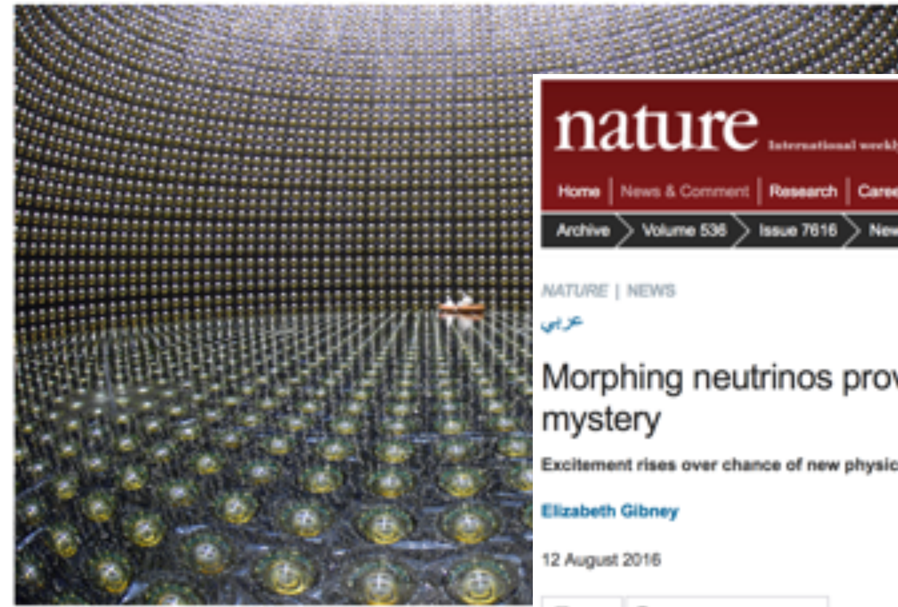

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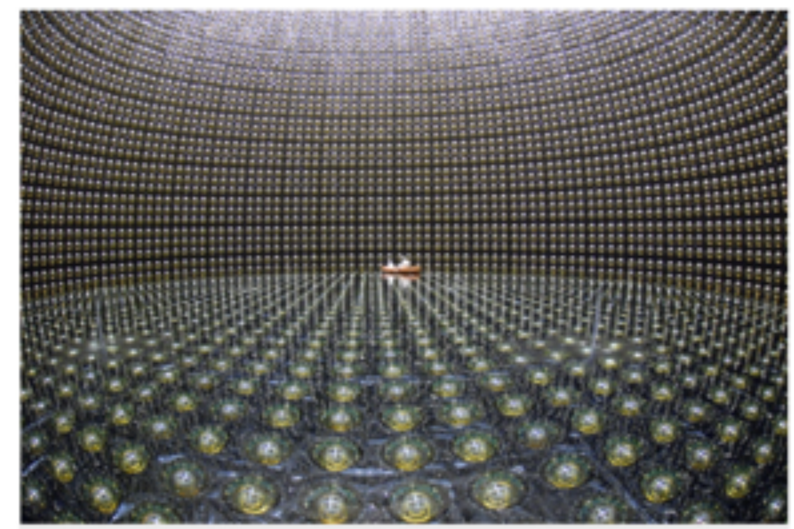

The Super-Kamiokande detector near Hida, Japan, is searching for differences in behaviour between matter and antimatter neutrinos.

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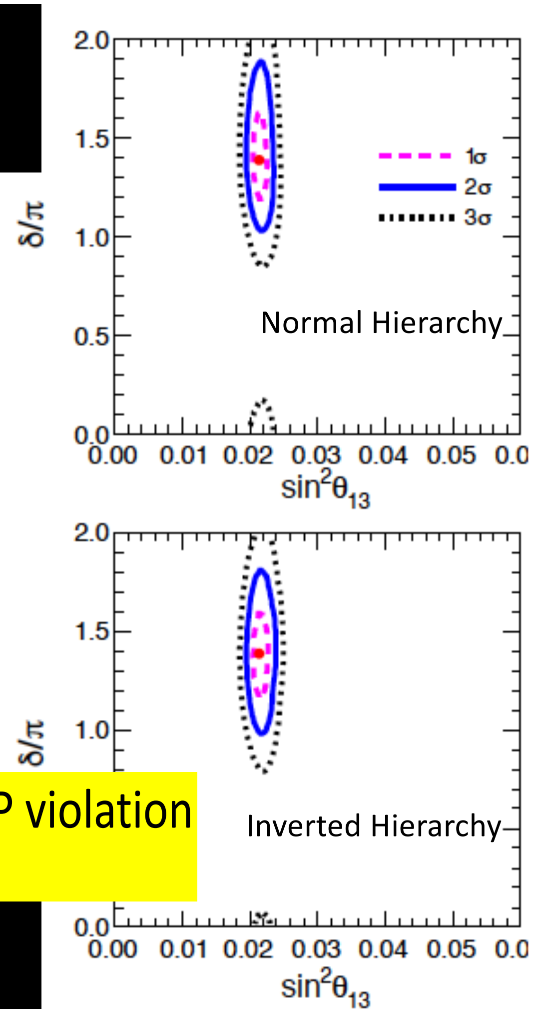

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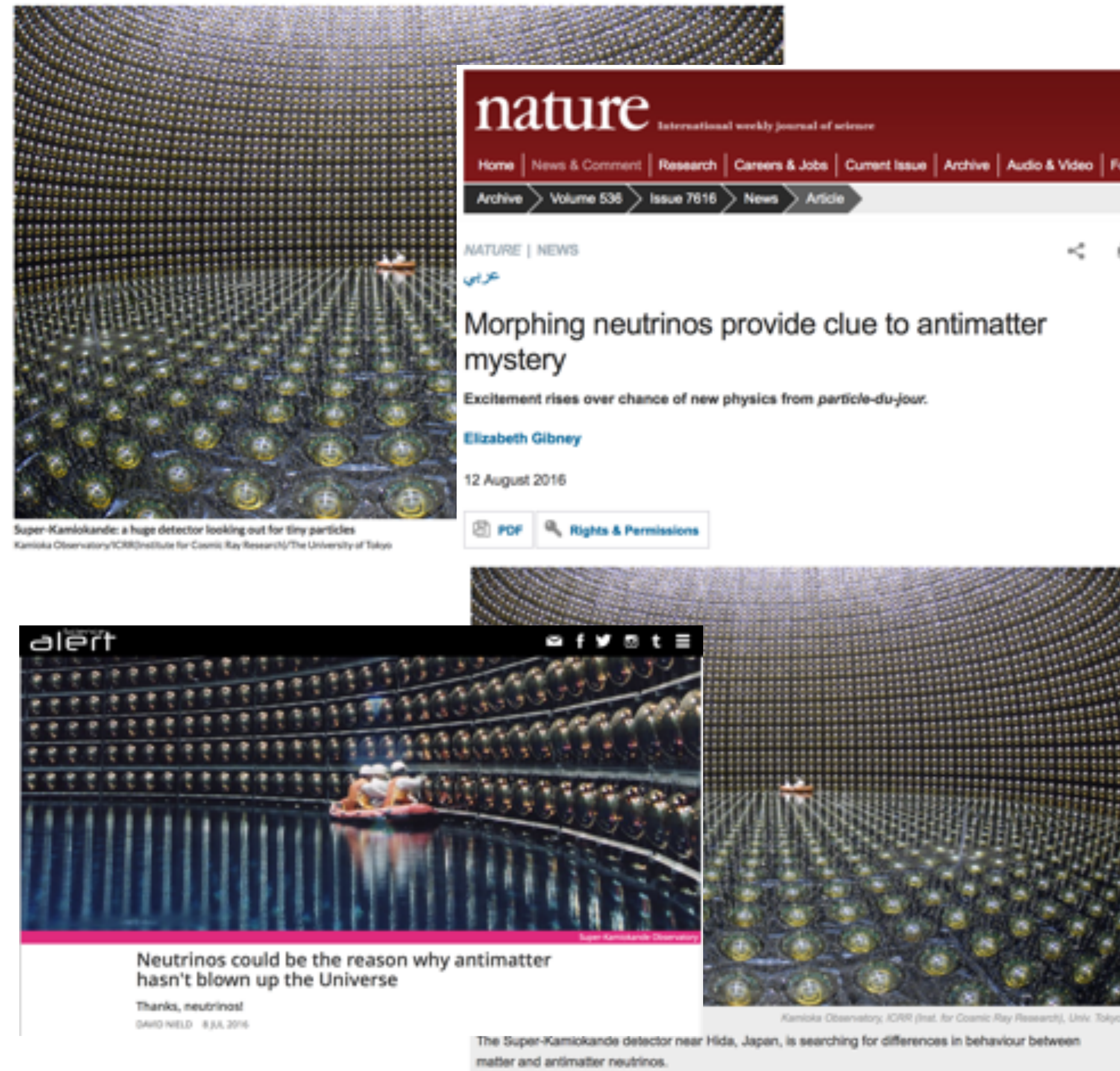

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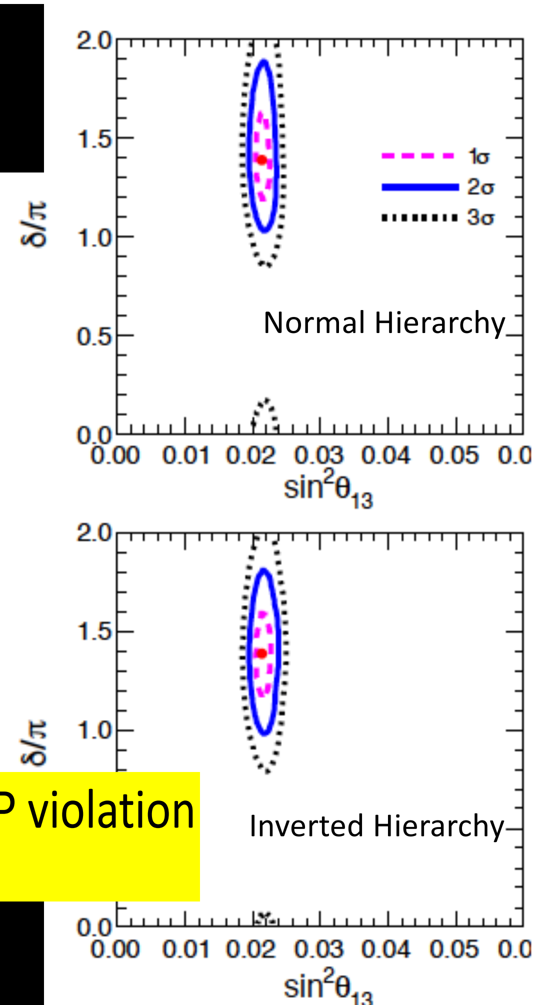

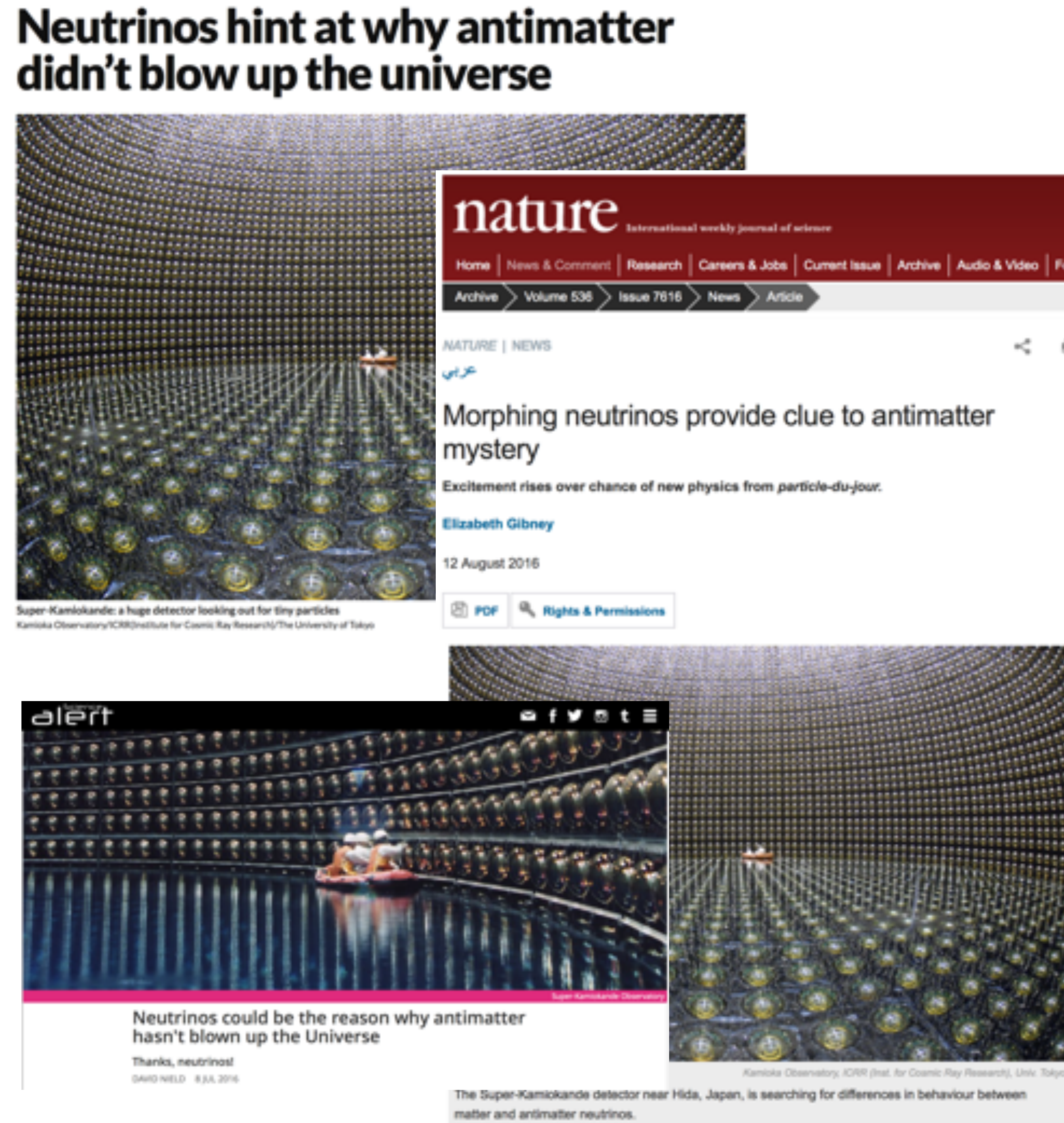

media bias?

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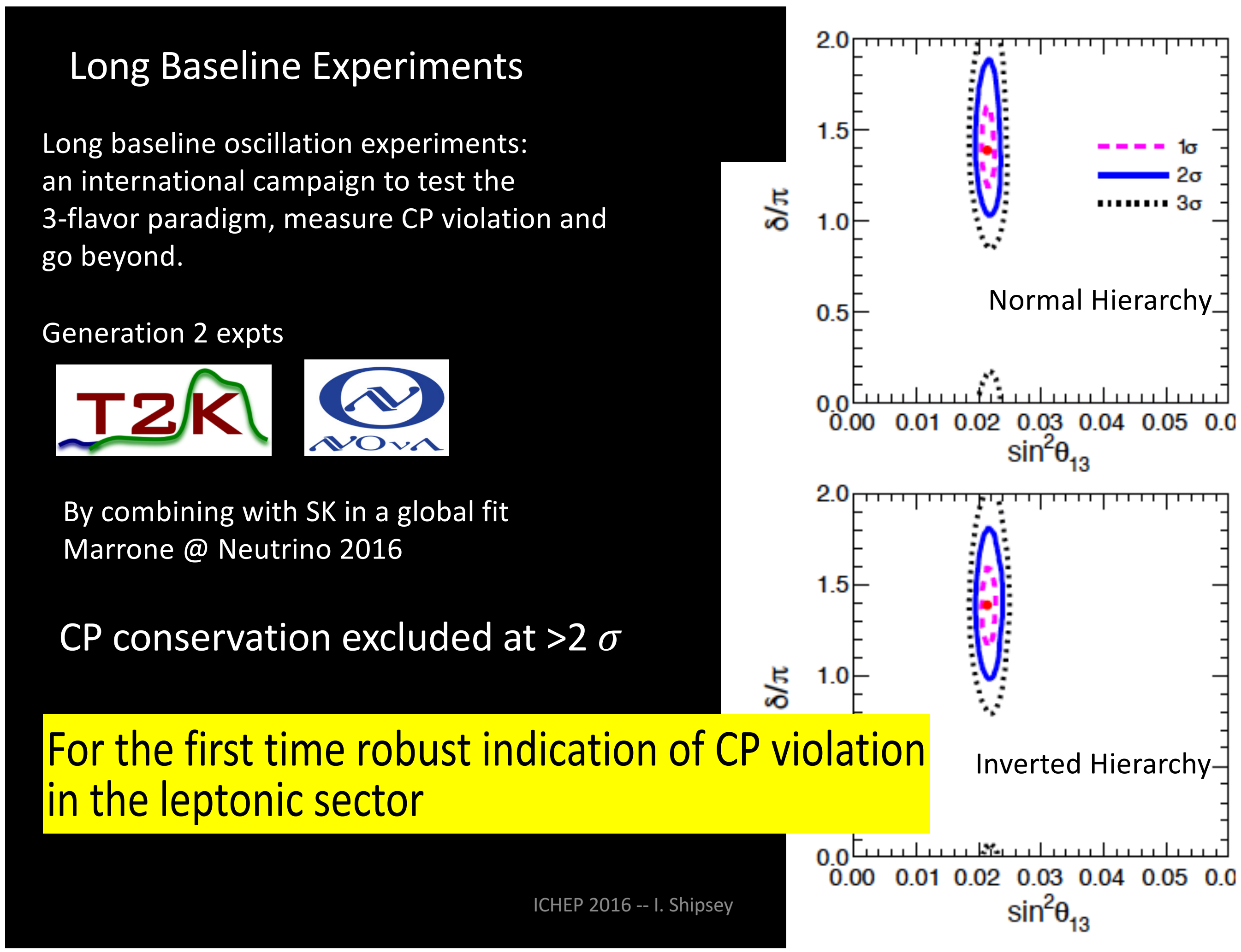

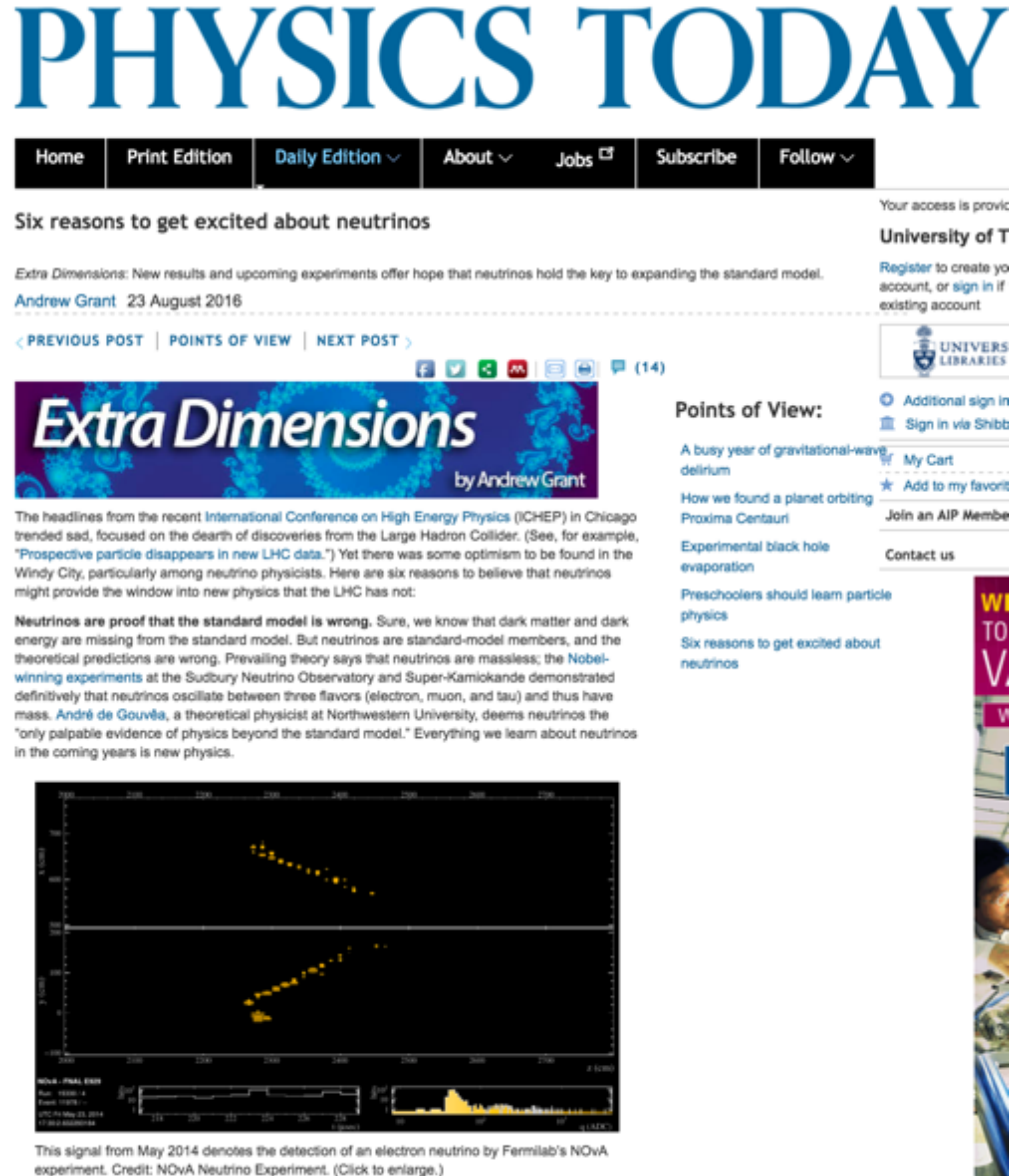

PHYSICS TODAY

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Six reasons to get excited about neutrinos

Extra Dimensions: New results and upcoming experiments offer hope that neutrinos hold the key to expanding the standard model.

Andrew Grant 23 August 2016

PREVIOUS POST | POINTS OF VIEW | NEXT POST

Extra Dimensions by Andrew Grant

The headlines from the recent International Conference on High Energy Physics (ICHEP) in Chicago trended sad, focused on the dearth of discoveries from the Large Hadron Collider. (See, for example, "Prospective particle disappears in new LHC data.") Yet there was some optimism to be found in the Windy City, particularly among neutrino physicists. Here are six reasons to believe that neutrinos might provide the window into new physics that the LHC has not:

Neutrinos are proof that the standard model is wrong. Sure, we know that dark matter and dark energy are missing from the standard model. But neutrinos are standard-model members, and the theoretical predictions are wrong. Prevailing theory says that neutrinos are massless; the Nobel-winning experiments at the Sudbury Neutrino Observatory and Super-Kamiokande demonstrated definitively that neutrinos oscillate between three flavors (electron, muon, and tau) and thus have mass. André de Gouvêa, a theoretical physicist at Northwestern University, deems neutrinos the "only palpable evidence of physics beyond the standard model." Everything we learn about neutrinos in the coming years is new physics.

This signal from May 2014 denotes the detection of an electron neutrino by Fermilab's NOvA experiment. Credit: NOvA Neutrino Experiment. (Click to enlarge.)

Points of View:
A busy year of gravitational-wave delirium
How we found a planet orbiting Proxima Centauri
Experimental black hole evaporation
Preschoolers should learn particle physics
Six reasons to get excited about neutrinos

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ν OSCILLATIONS IN LBL EXPERIMENTS

$$P(\nu_\mu \to \nu_\mu) \sim 1 - (\cos^4 2\theta_{13} \sin^2 2\theta_{23} + \sin^2 2\theta_{13} \sin^2 \theta_{23}) \sin^2 \Delta m^2_{31} \frac{L}{4E}$$

- Precision measurement of $\sin^2 2\theta_{23}$.
- CPT tests with antineutrino mode ($\bar{\nu}_\mu \to \bar{\nu}_\mu$)

$$P(\nu_\mu \to \nu_e) \sim \sin^2 2\theta_{13} \times \sin^2 \theta_{23} \times \frac{\sin^2[(1-x)\Delta]}{(1-x)^2}$$

~30% max. effect

$$-\alpha \sin\delta \times \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \times \sin\Delta \frac{\sin[x\Delta]}{x} \frac{\sin[(1-x)\Delta]}{(1-x)}$$

$$+\alpha \cos\delta \times \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \times \cos\Delta \frac{\sin[x\Delta]}{x} \frac{\sin[(1-x)\Delta]}{(1-x)}$$

$$+\mathcal{O}(\alpha^2)$$

$$\alpha = \left|\frac{\Delta m^2_{21}}{\Delta m^2_{31}}\right| \sim \frac{1}{30} \qquad \Delta \equiv \frac{\Delta m^2_{31} L}{4E} \qquad x \equiv \frac{2\sqrt{2} G_F N_e E}{\Delta m^2_{31}}$$

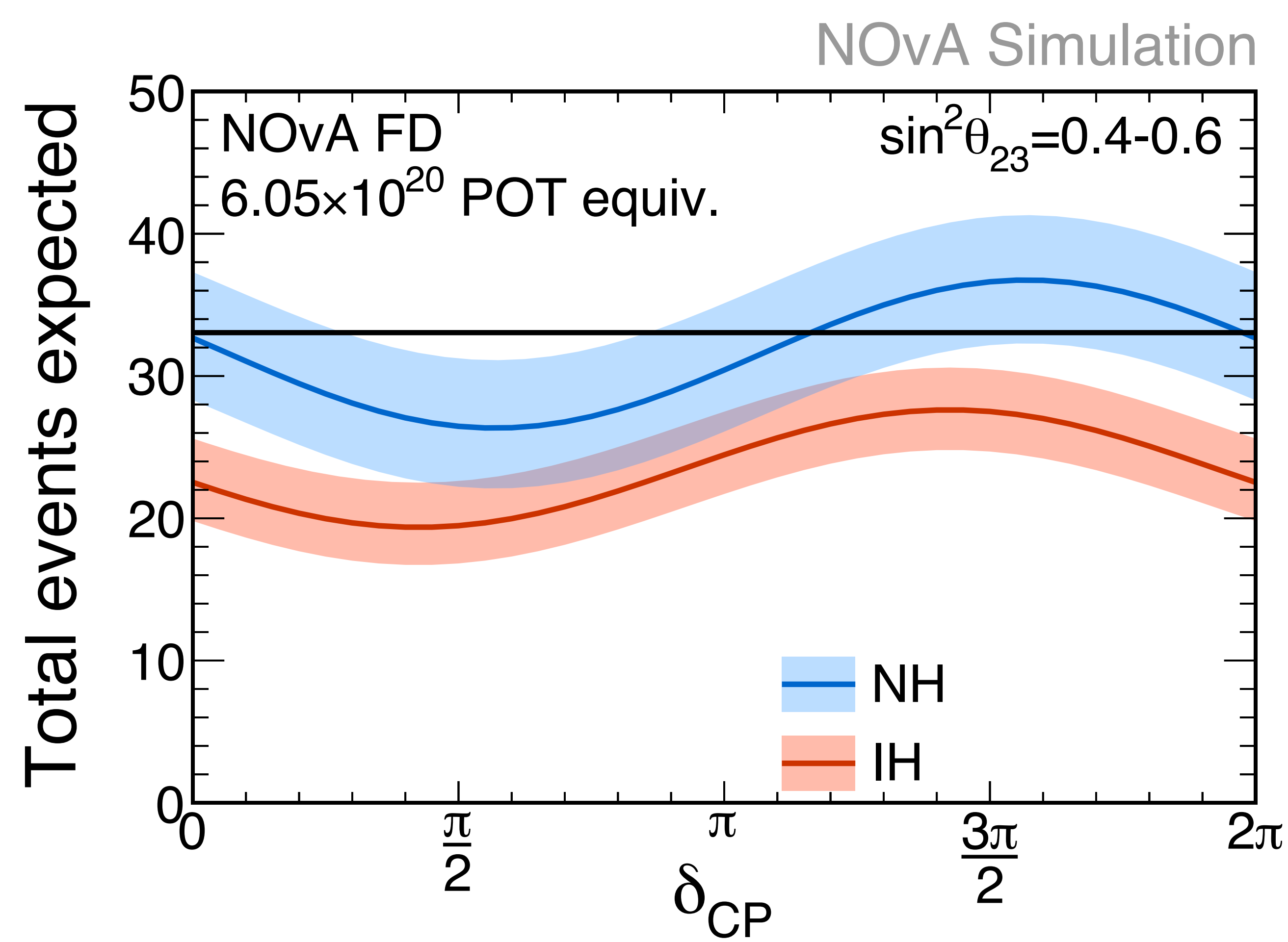
M. Freund, Phys.Rev. D64 (2001) 053003

- $\sin^2 2\theta_{13}$ dependence of leading term
- θ_{23} dependence of leading term: "octant" dependence (θ_{23}=/>/<45°?)
- CP odd phase δ: asymmetry of probabilities $P(\nu_\mu \to \nu_e) \neq P(\bar{\nu}_\mu \to \bar{\nu}_e)$ if sin δ ≠ 0
- Matter effect through x: ν_e ($\bar{\nu}_e$) enhanced in normal (inverted)

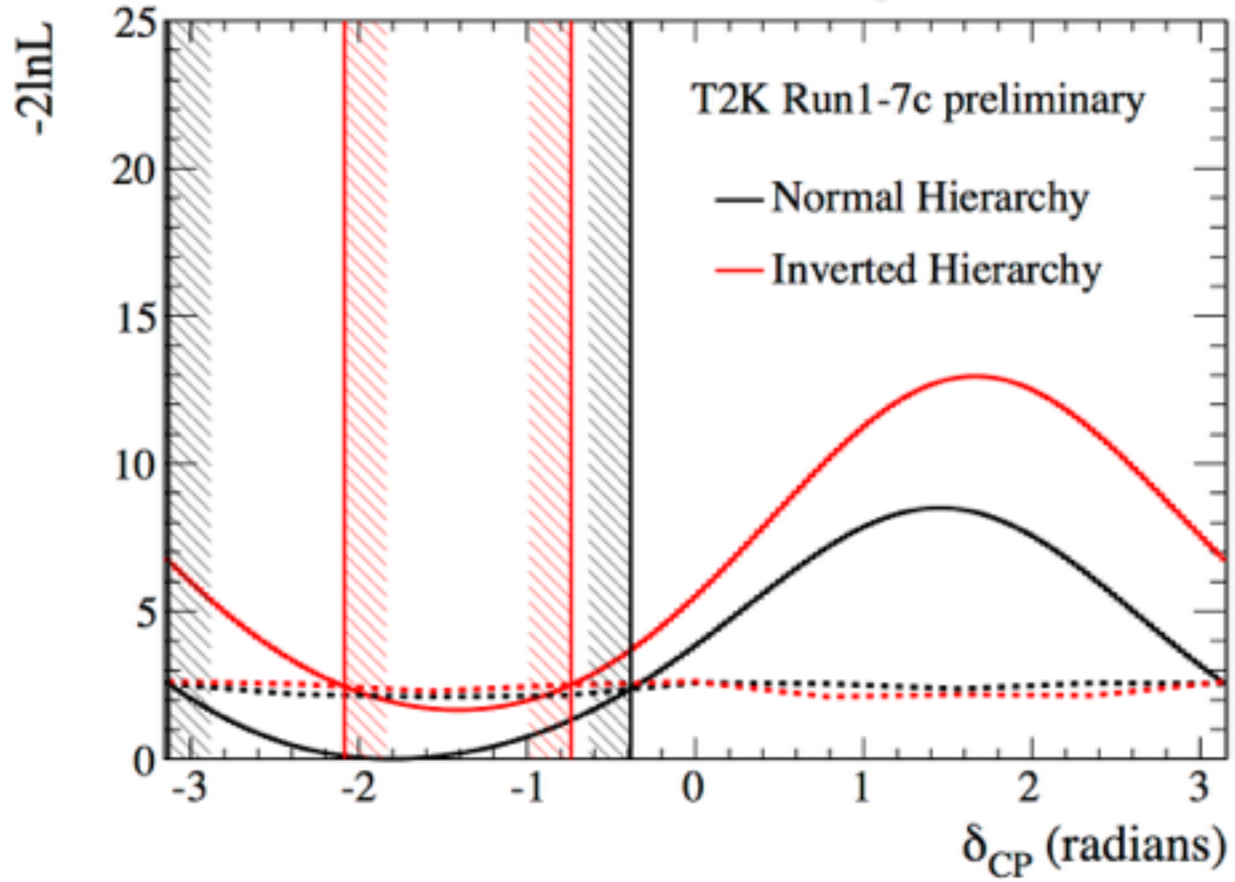
THE EVIDENCE:

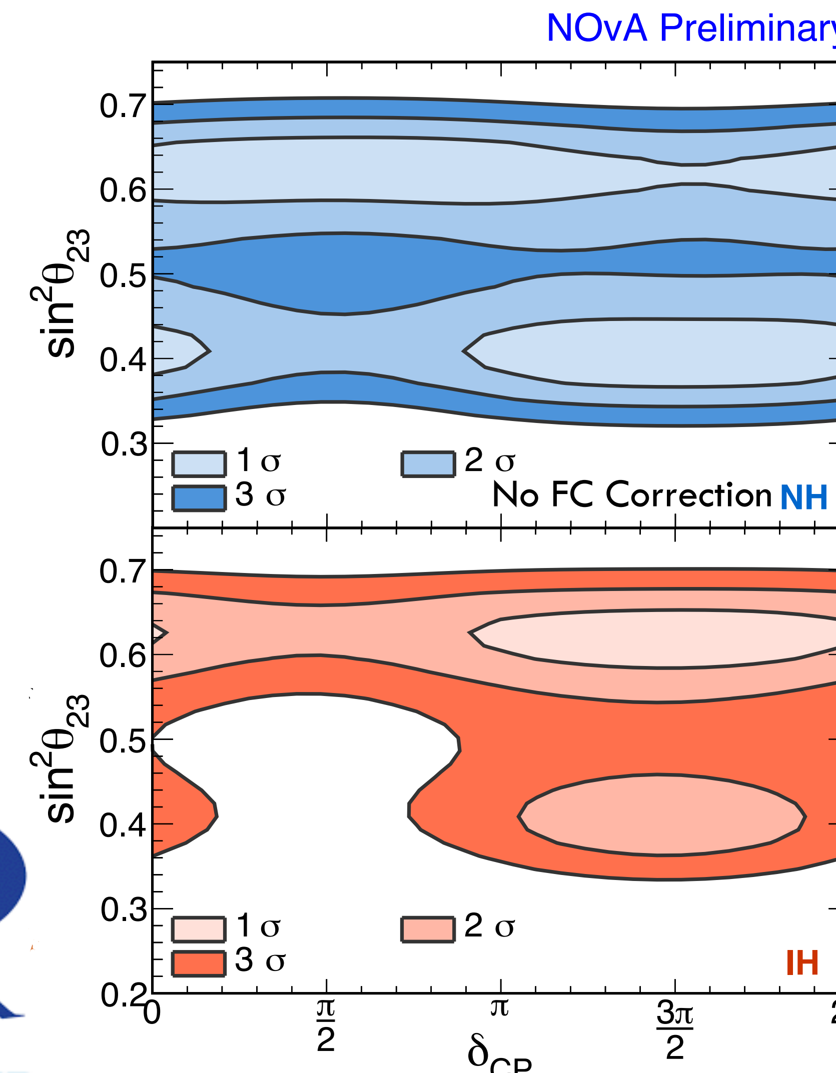
	MASS ORDER	$-\pi/2$	0	$+\pi/2$	π	OBS
ν_e	NH	28.7	24.2	19.6	24.1	32
	IH	25.4	21.3	17.1	21.3	
$\overline{\nu}_e$	NH	6.0	6.9	7.7	6.8	4
	IH	6.5	7.4	8.4	7.4	

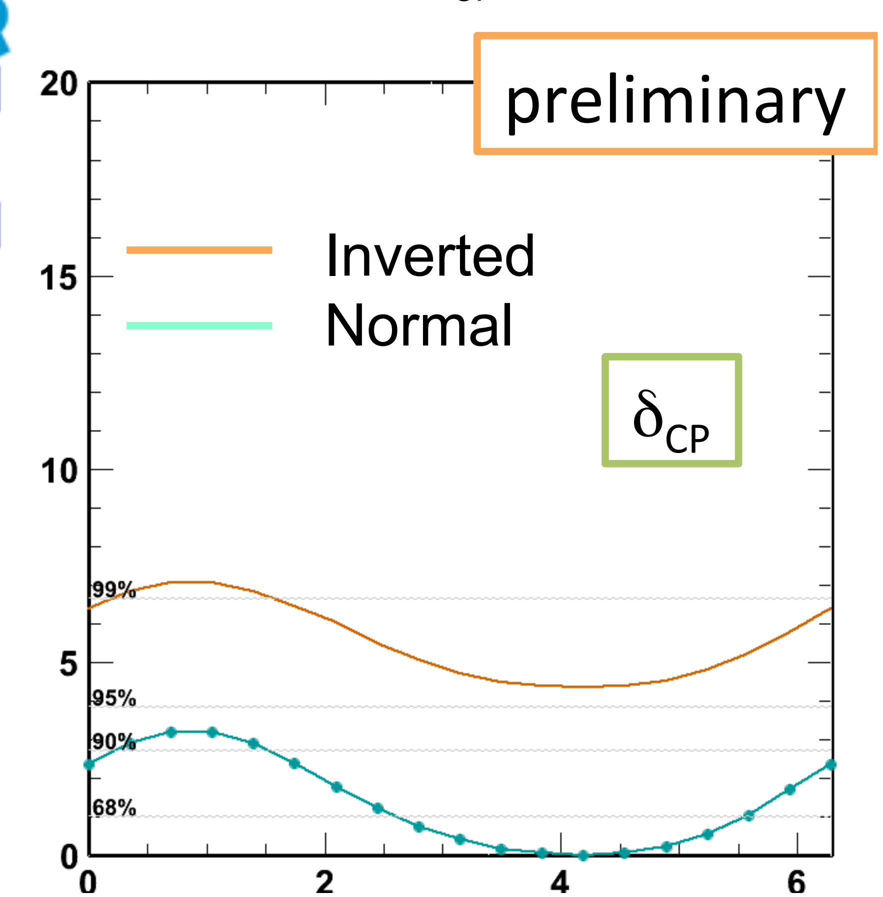
- Result is based mainly on
  - T2K:
    - 32 ν_e candidates in ν-mode
    - 4 $\overline{\nu}_e$ candidates in $\overline{\nu}$-mode
  - NOvA:
    - 33 ν_e candidates in ν-mode



TRENDS:



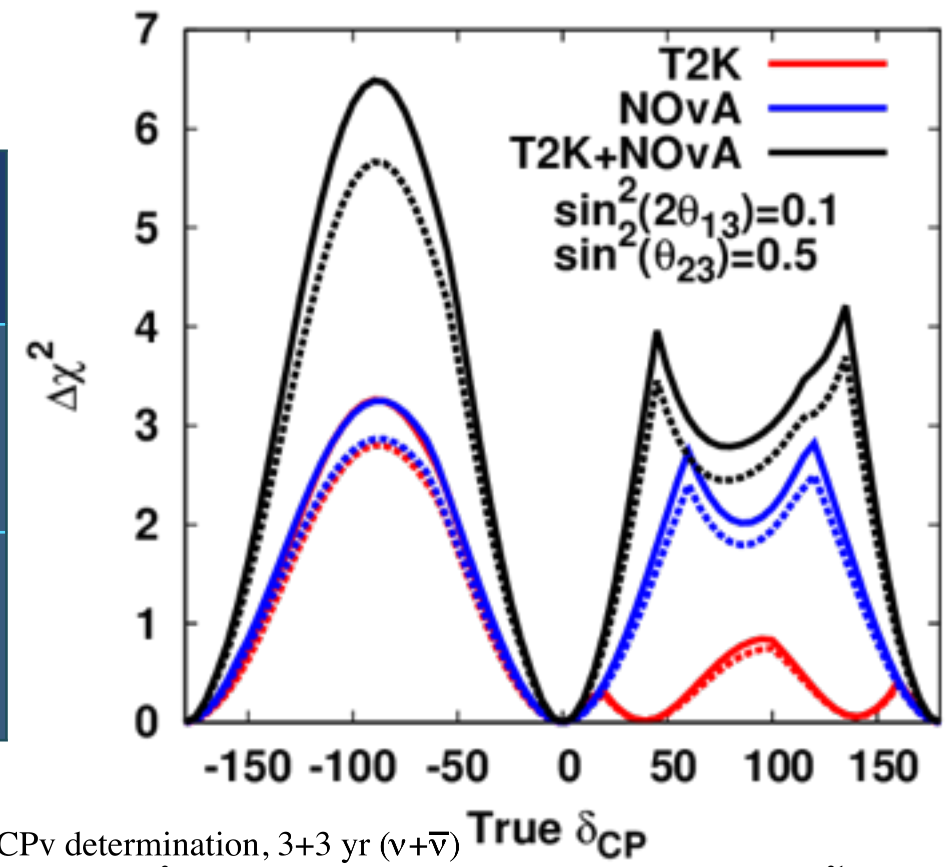


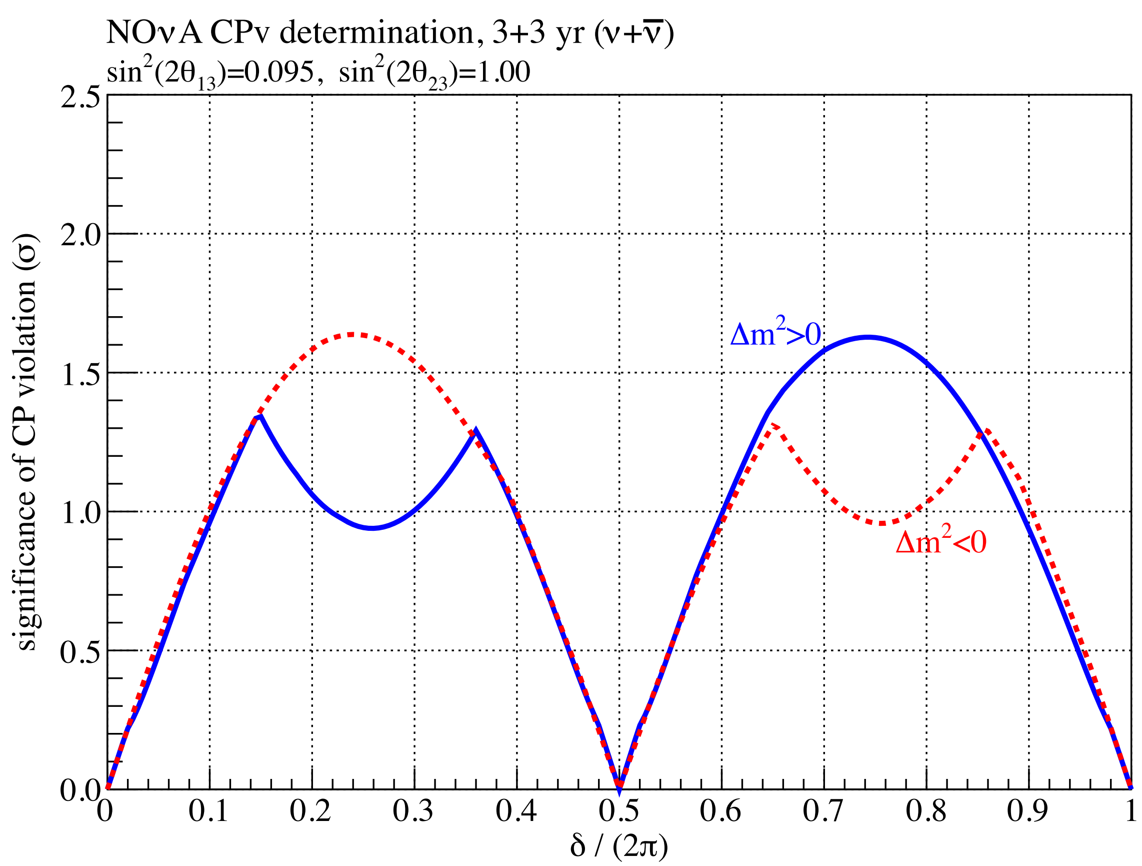


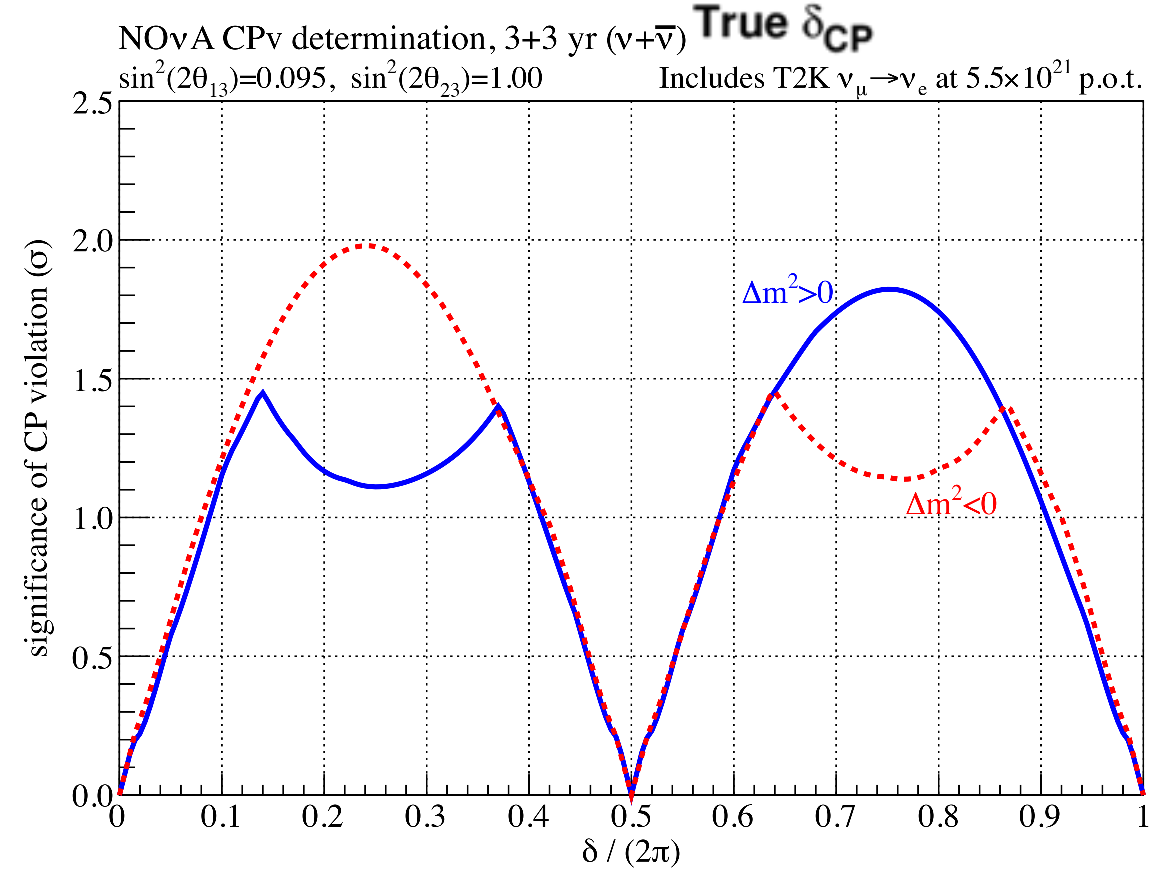
- T2K, SK (atm), NOvA are vaguely pointing in the same direction:
  - normal mass ordering
  - δ_{CP} = ~ -π/2 (maximal)
  - Both favor $\nu_\mu \to \nu_e$ over $\bar{\nu}_\mu \to \bar{\nu}_e$)
- do we accept that we have evidence for CP violation?
- "I will tell you after we have more data. I will keep you in suspense."

C. 2021 (SUSPENSE)

	δ_{CP}	TOTAL	SIGNAL $\nu_\mu \to \nu_e$	SIGNAL $\overline{\nu}_\mu \to \overline{\nu}_e$	BEAM ν_e	BEAM ν_μ	NC
ν	0	145.8	**106.0**	1.2	20.6	0.7	17.2
	$-\pi/2$	170.9	**131.4**	0.8			
$\overline{\nu}$	0	47.5	5.6	**24.4**	8.6	0.2	8.6
	$-\pi/2$	41.5	6.5	**17.5**			





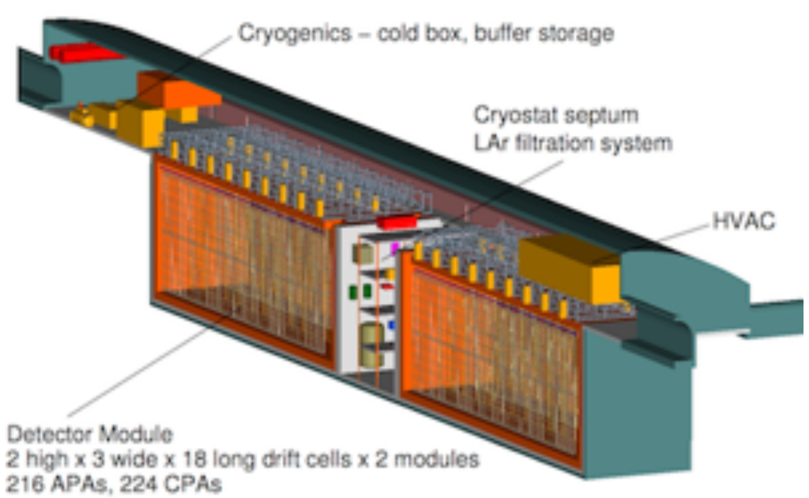


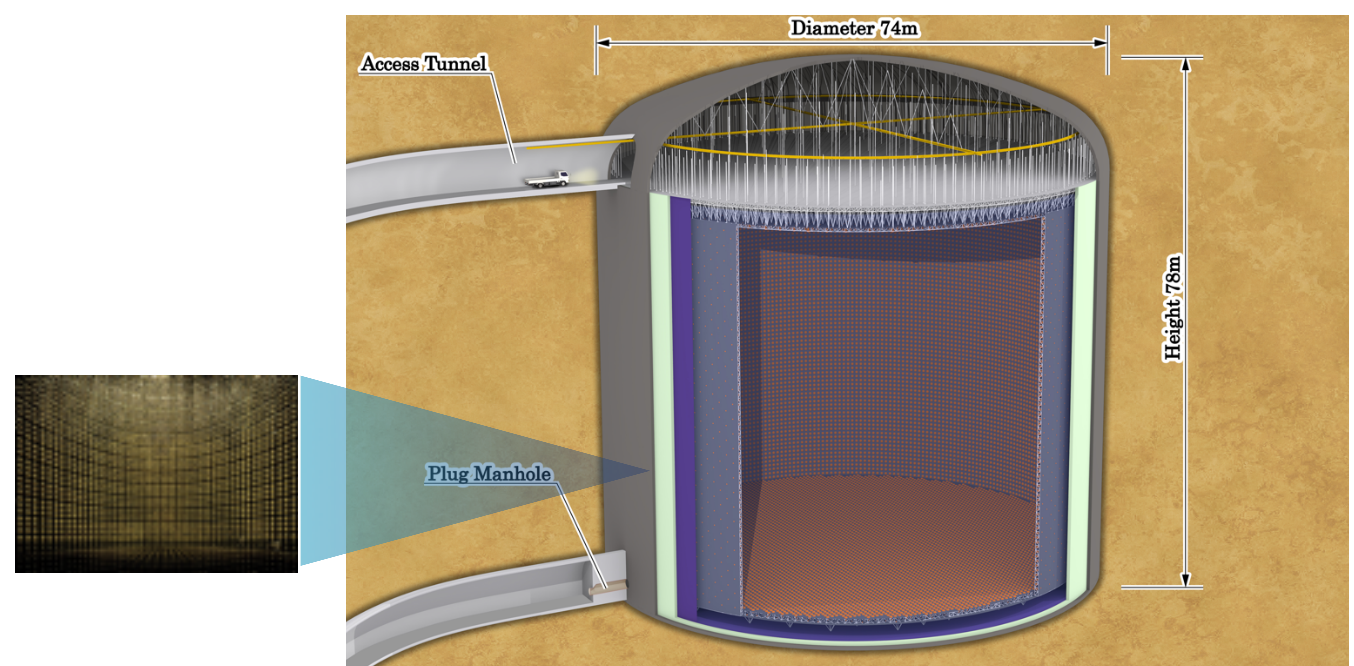
- 3.6×10^{21} POT at NOvA, 7.8×10^{21} POT at T2K

NEUTRINO ECONOMICS

Neutrino source upgrades

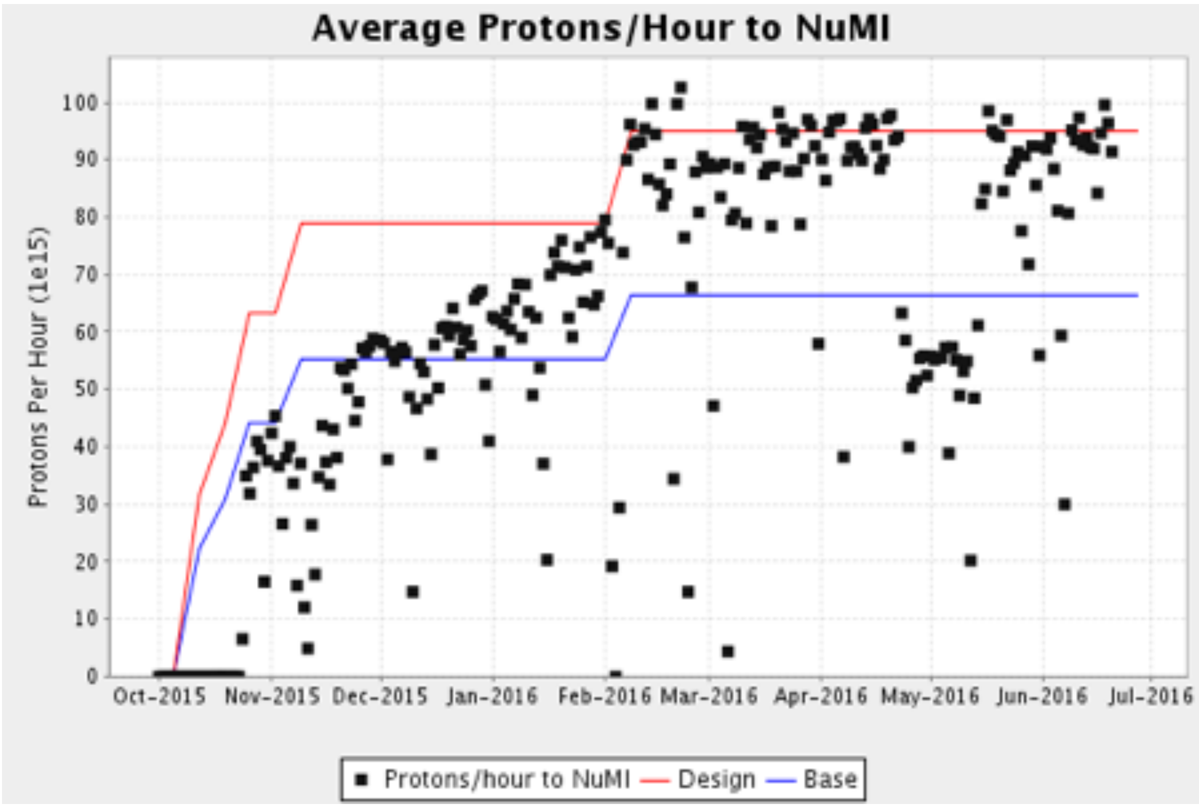
$$N \propto \boxed{\Phi_\nu} \times \boxed{V \times \rho \times \epsilon} \times \sigma_\nu$$

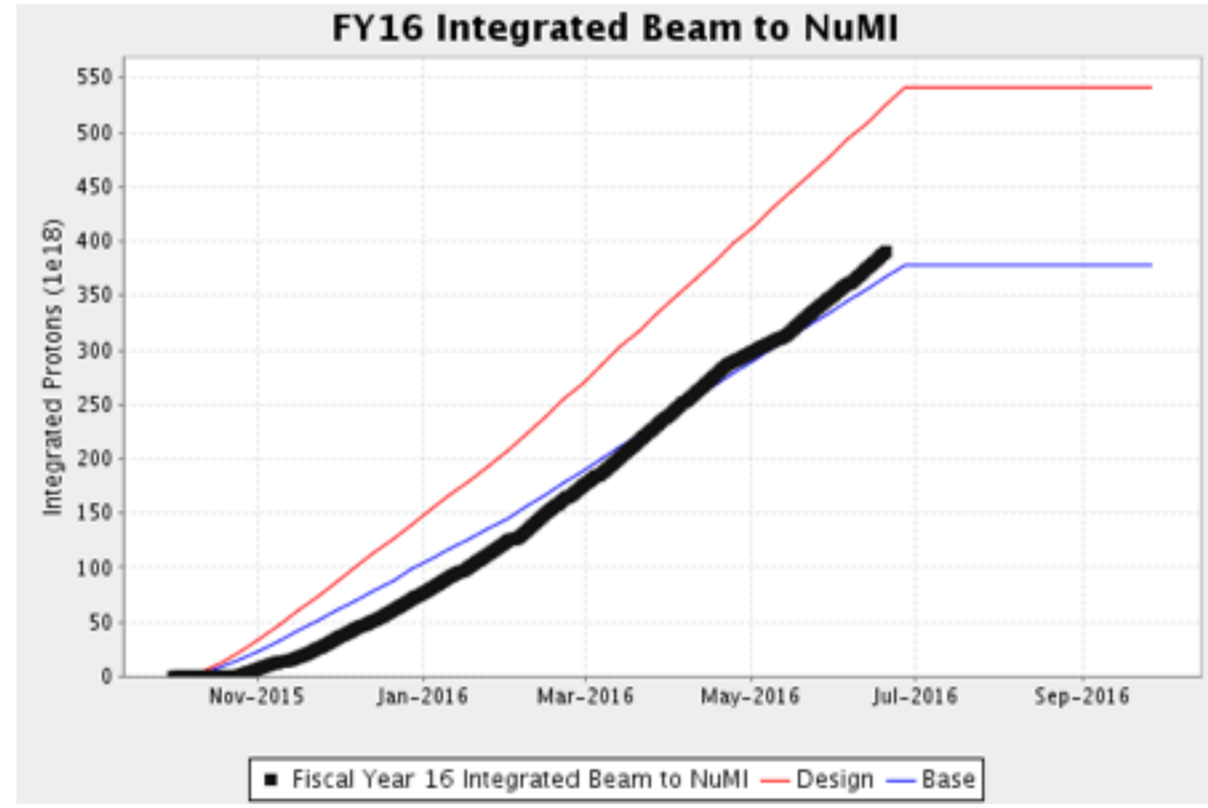




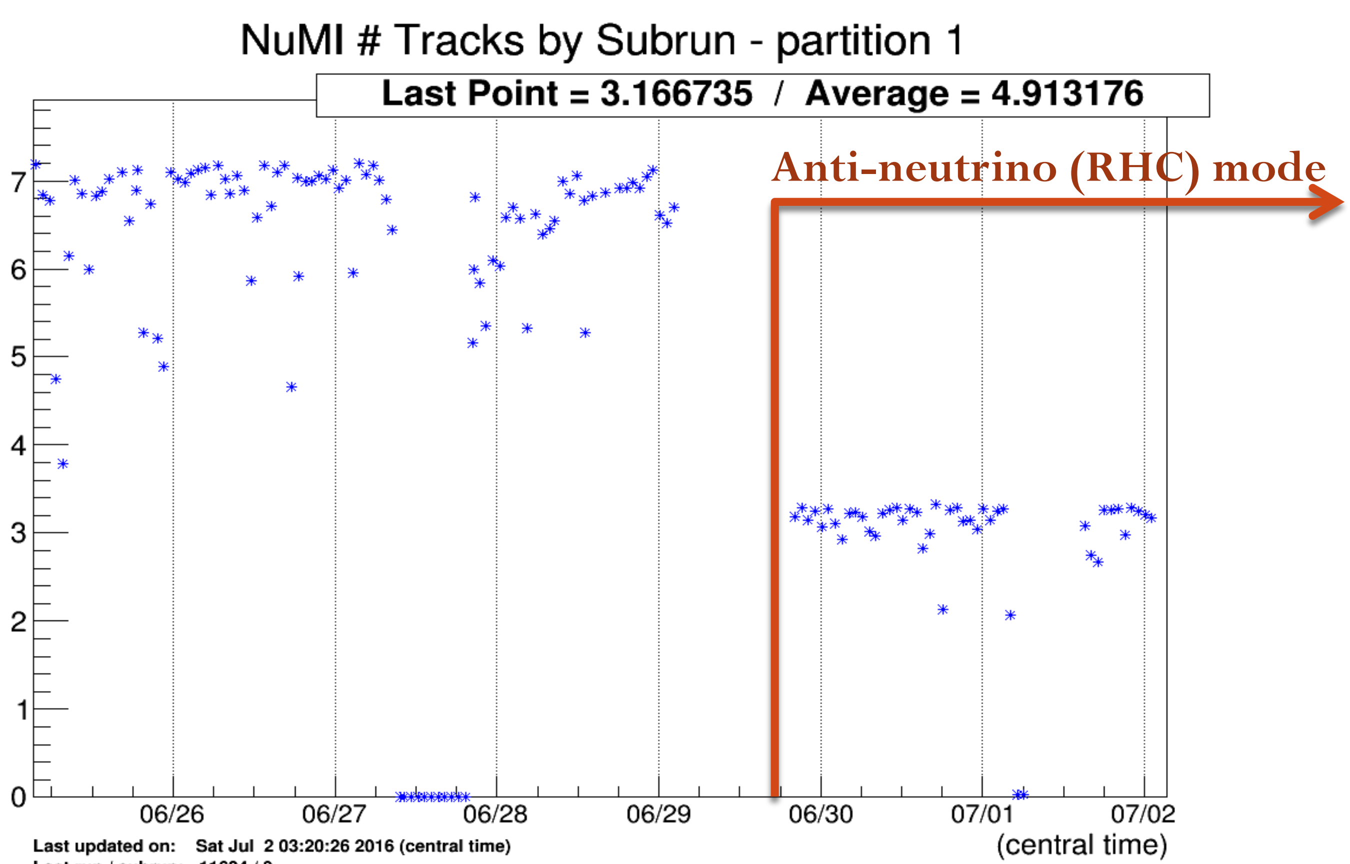
Detector upgrades

NOvA AND NUMI

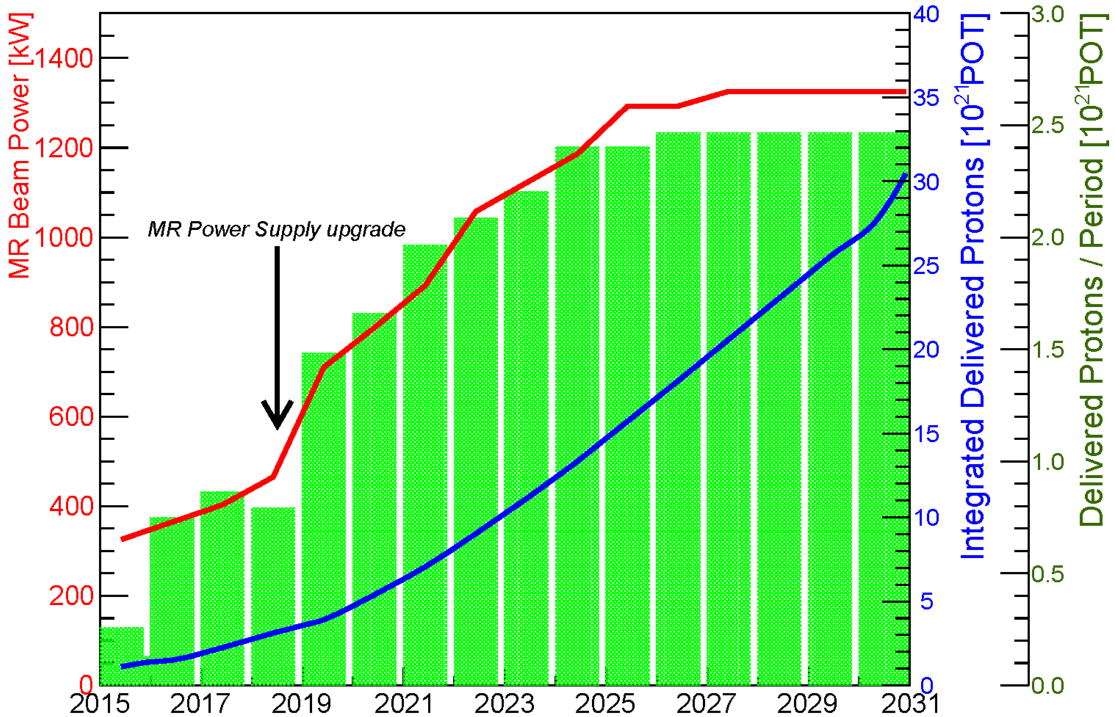




- Very impressive ramp up in beam power
  - >500 kW regularly achieved
- On the way to design power of 700 kW!
- Very promising for rapid accumulation of data at NOvA



J-PARC



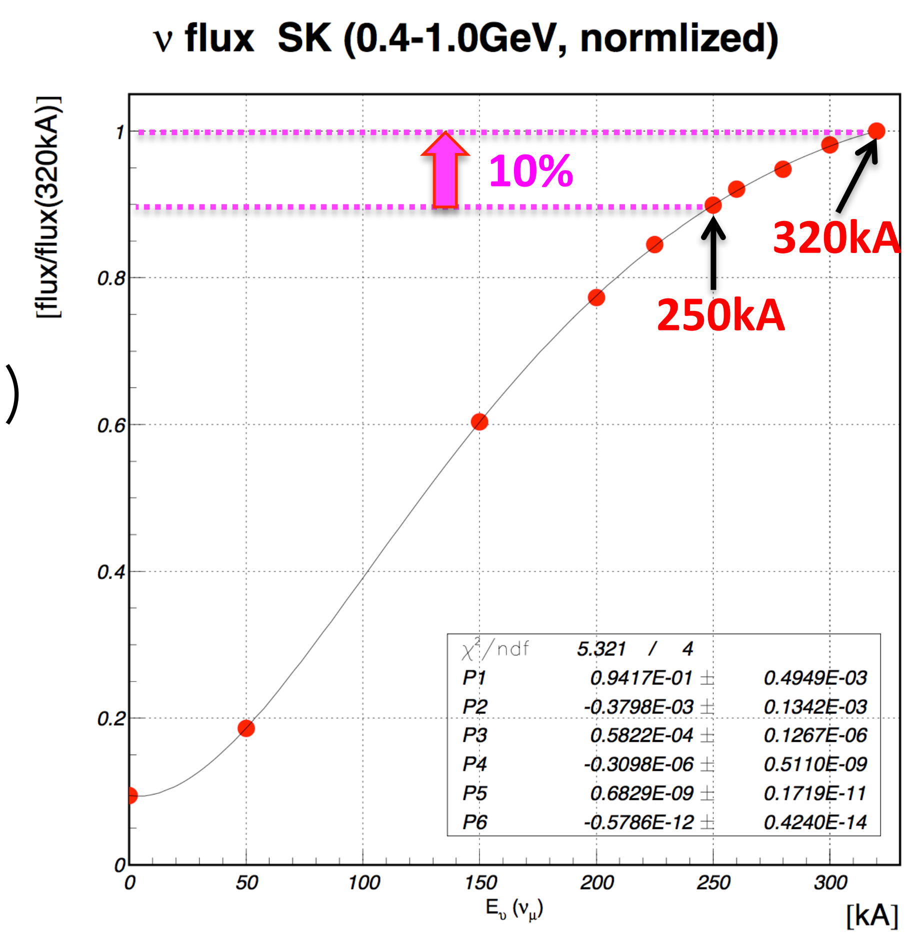
JFY	2014	2015	2016	2017	2018	2019	2020
	Li. current upgrade		New PS buildings				
FX power [kW] (study/trial)	320	> 360	400	450	700	800	900
SX power [kW] (study/trial)	-	33 - 40	50	50-70	50-70	~100	~100
Cycle time of main magnet PS New magnet PS	2.48 s R&D	Large scale 1st PS		Mass production installation/test	1.3 s	1.3 s	1.2 s
High gradient rf system 2nd harmonic rf system VHF cavity	Manufacture, installation/test R&D	R&D, manufacture, installation/test					
Ring collimators		Add.collimators (2 kW)	Add.collimators (3.5kW)				
Injection system FX system	Kicker PS improvement, Septa manufacture /test Kicker PS improvement, LF septum, HF septa manufacture /test						
SX collimator / Local shields			Local shields				
Ti ducts and SX devices with Ti chamber	Beam ducts	ESS					

- High power potential in J-PARC Main Ring
  - 420 kW operation in spring 2016 with 2.5 sec cycle
  - 1.3 sec cycle with MR PS upgrade would allow >800 kW beam
  - MW power possible
- **MR power supply upgrade approved!**
  - now looking to 1 MW power and beyond to **1.3 MW**
  - **Extension of T2K to 2026 to accumulate 20x10^{20} POT (3x current target)**
    - **"T2K-II"**

T2K-II STATISTICS

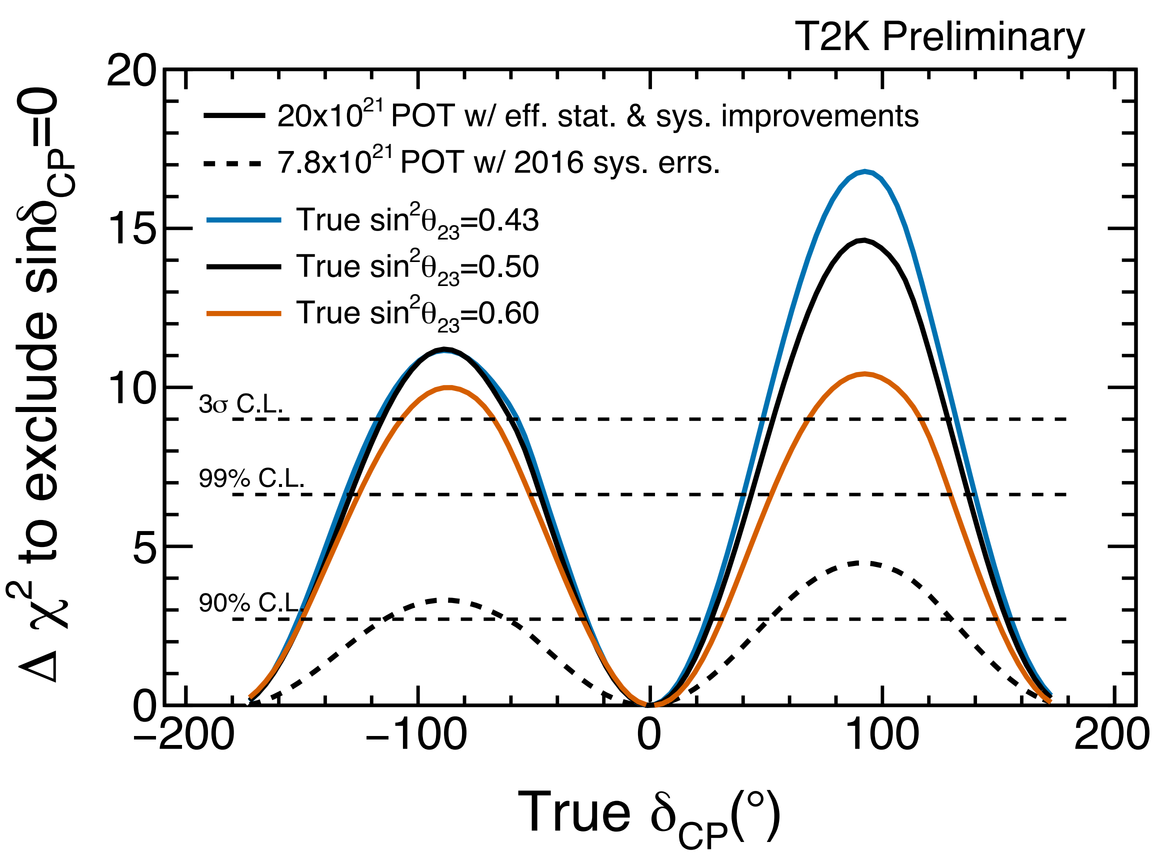
	δ_{CP}	TOTAL	SIGNAL $\nu_\mu \rightarrow \nu_e$	SIGNAL $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	BEAM ν_e	BEAM ν_μ	NC
ν MODE	0	454.6	**346.3**	3.8	72.2	1.8	30.5
	$-\pi/2$	545.6	**438.5**	2.7			
$\bar{\nu}$ MODE	0	129.2	16.1	**71.0**	28.4	0.4	13.3
	$-\pi/2$	111.8	19.2	**50.5**			

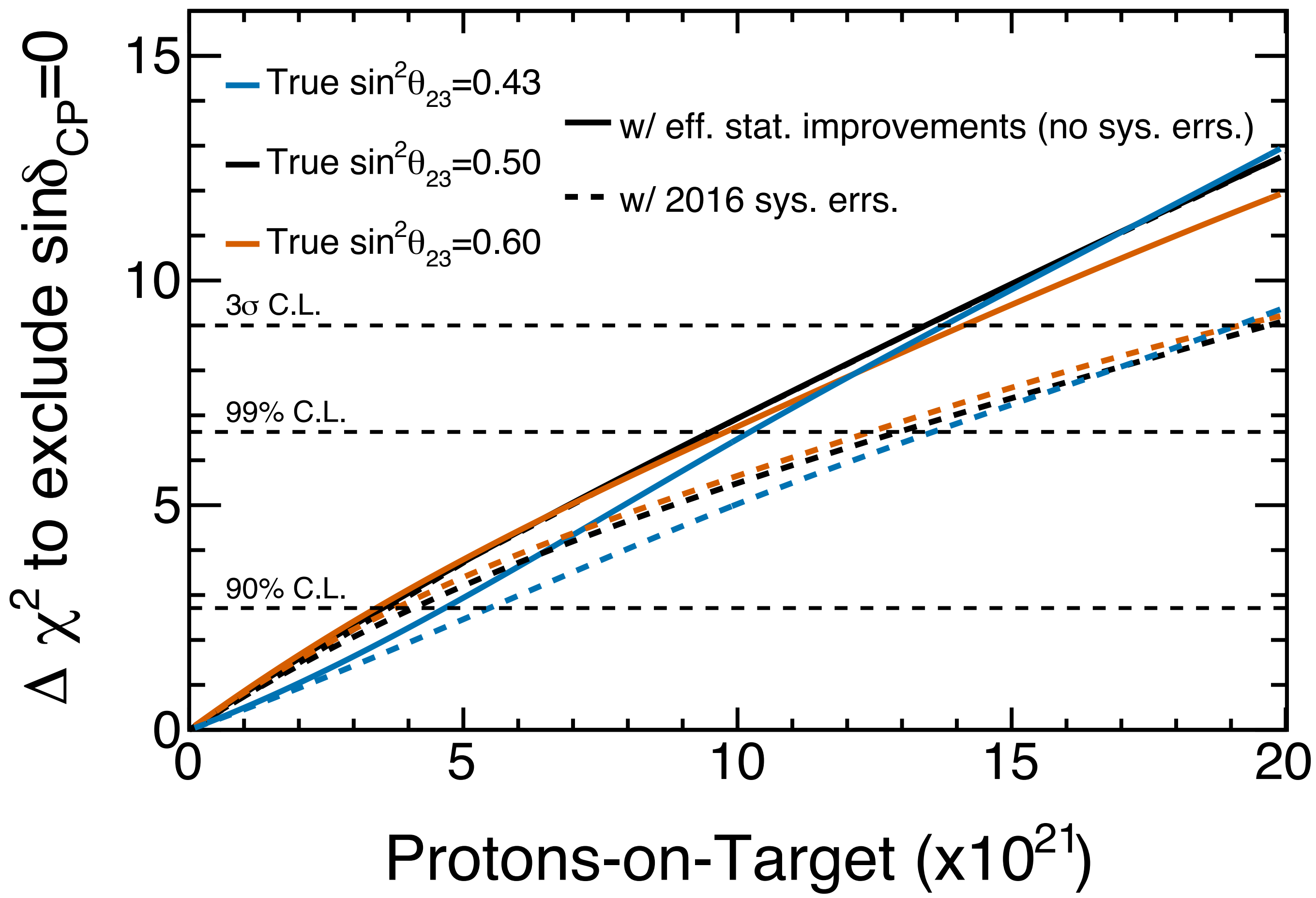
- Increased horn current (250 kA → 320 kA)
  - ~10% higher Φ_ν/POT
  - less "wrong sign" contamination (e.g. ν in $\bar{\nu}$ beam)
- Enlarged SK samples for higher statistics
  - Currently project assume 50% higher statistics/ POT relative to current T2K



Courtesy of T.Nakadaira

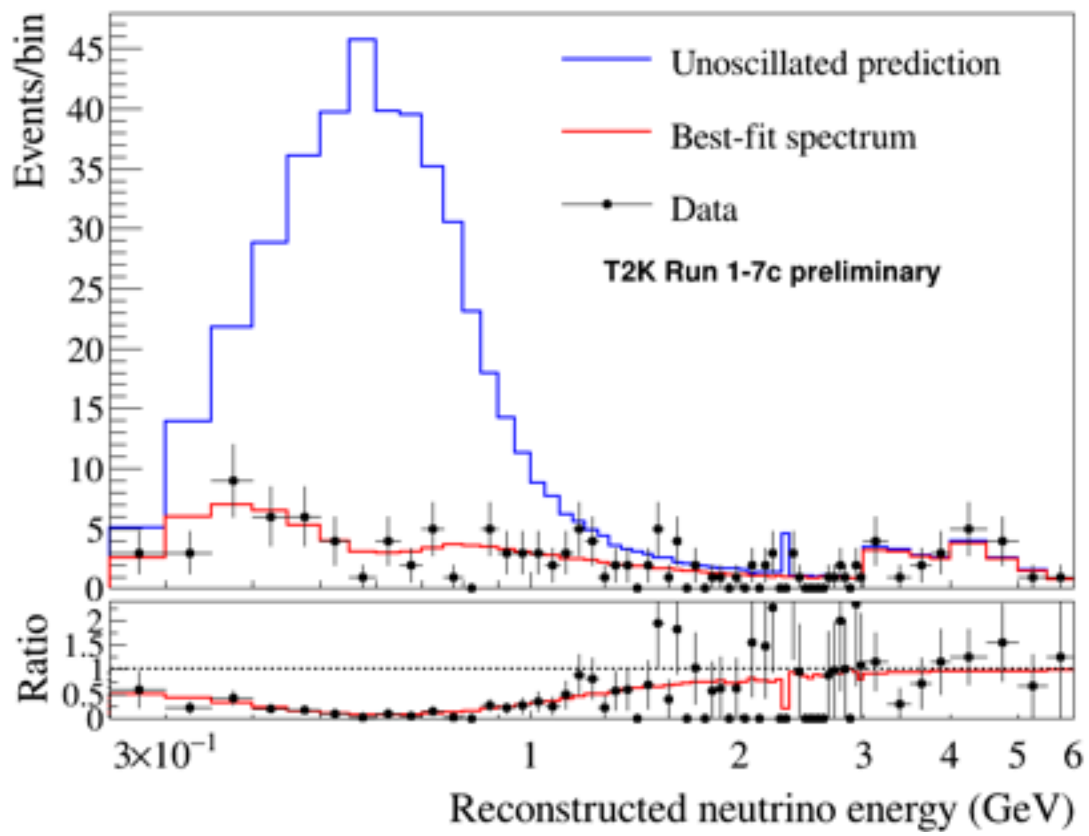
T2K-II SENSITIVITY

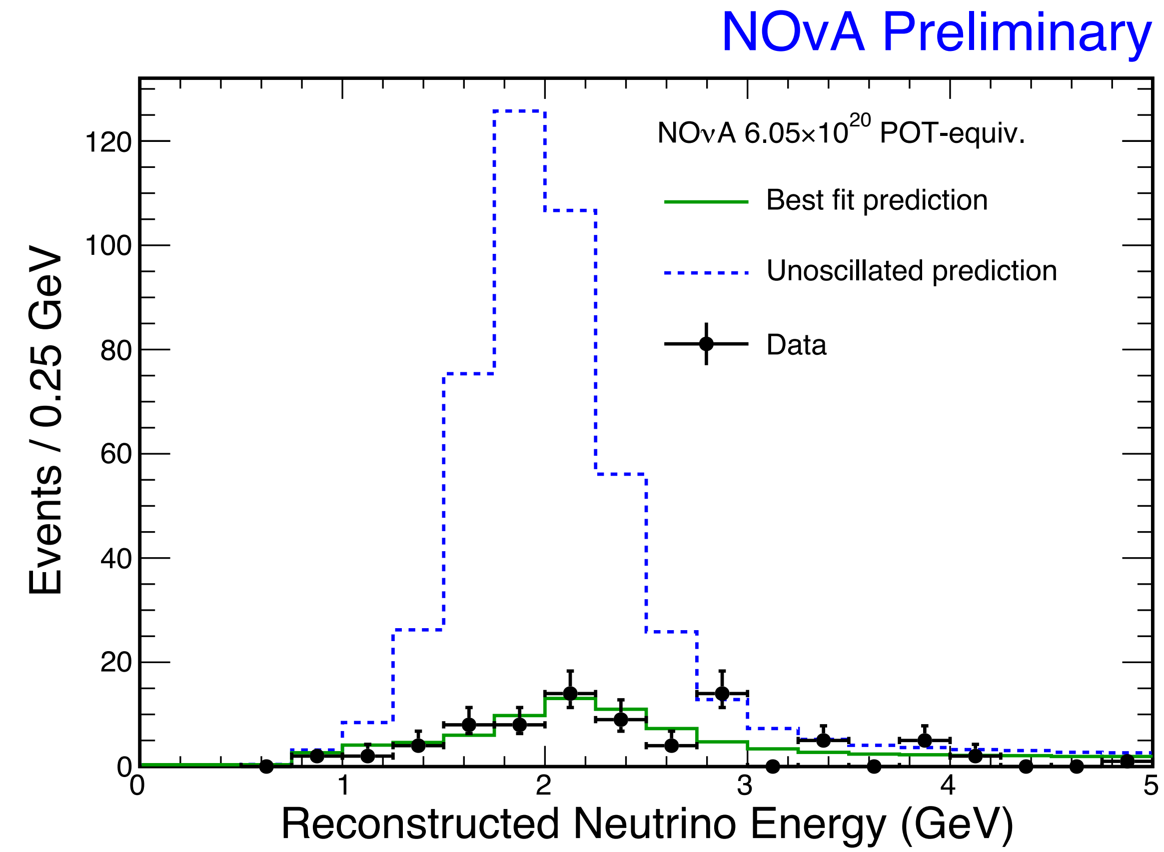


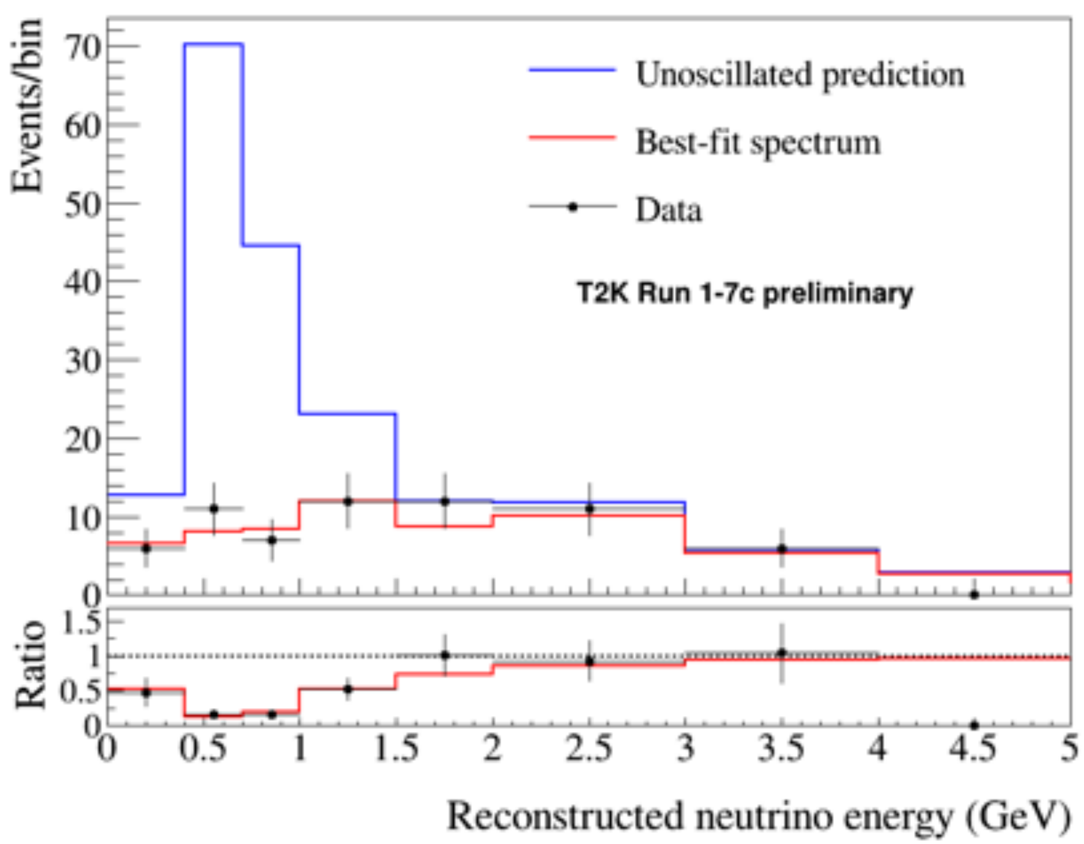


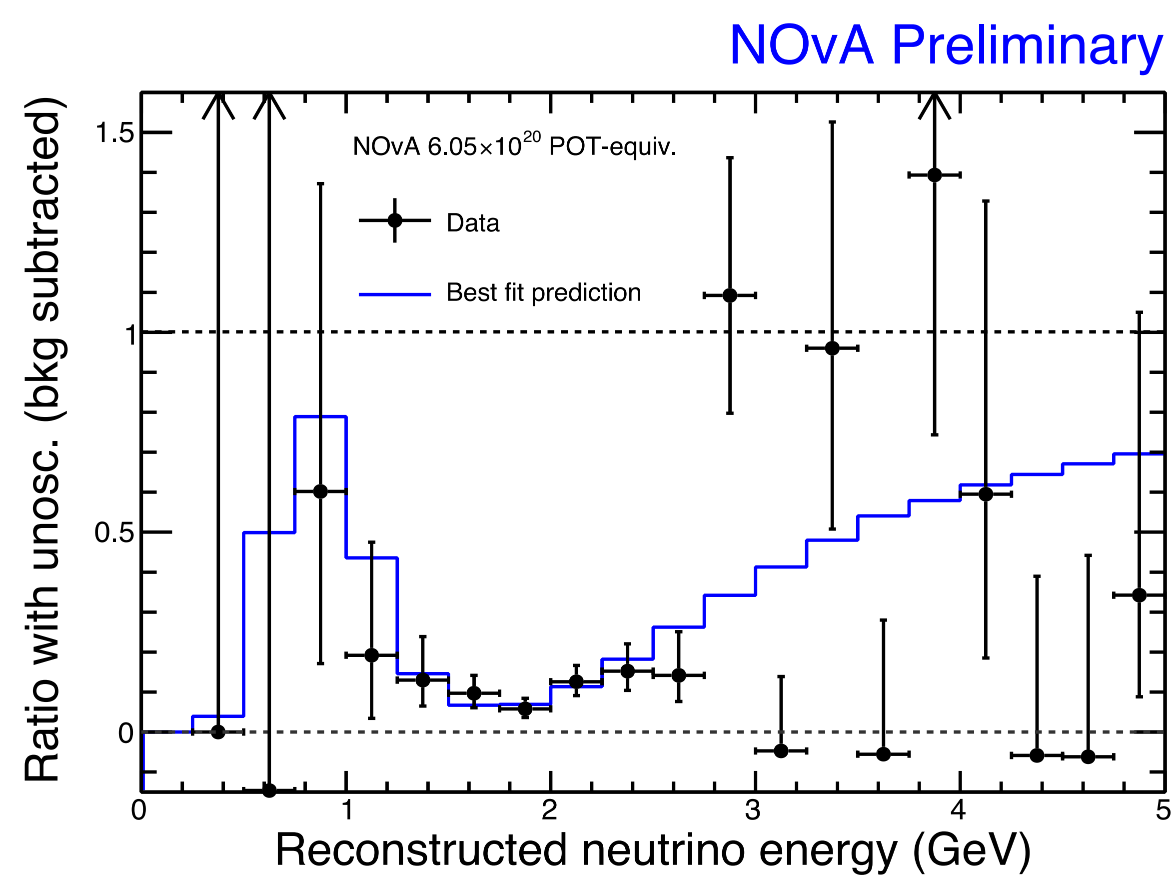
- Notes
  - Mass ordering assumed!
  - CP violation with δ_{CP} ~-π/2 can be observed with >3 x significance
- Control of systematics and analysis improvements are needed
- Combination with NOvA, SK, etc. should help significantly
  - we should lay the framework for a robust and rigorous combination of results

ν_μ DISAPPEARANCE

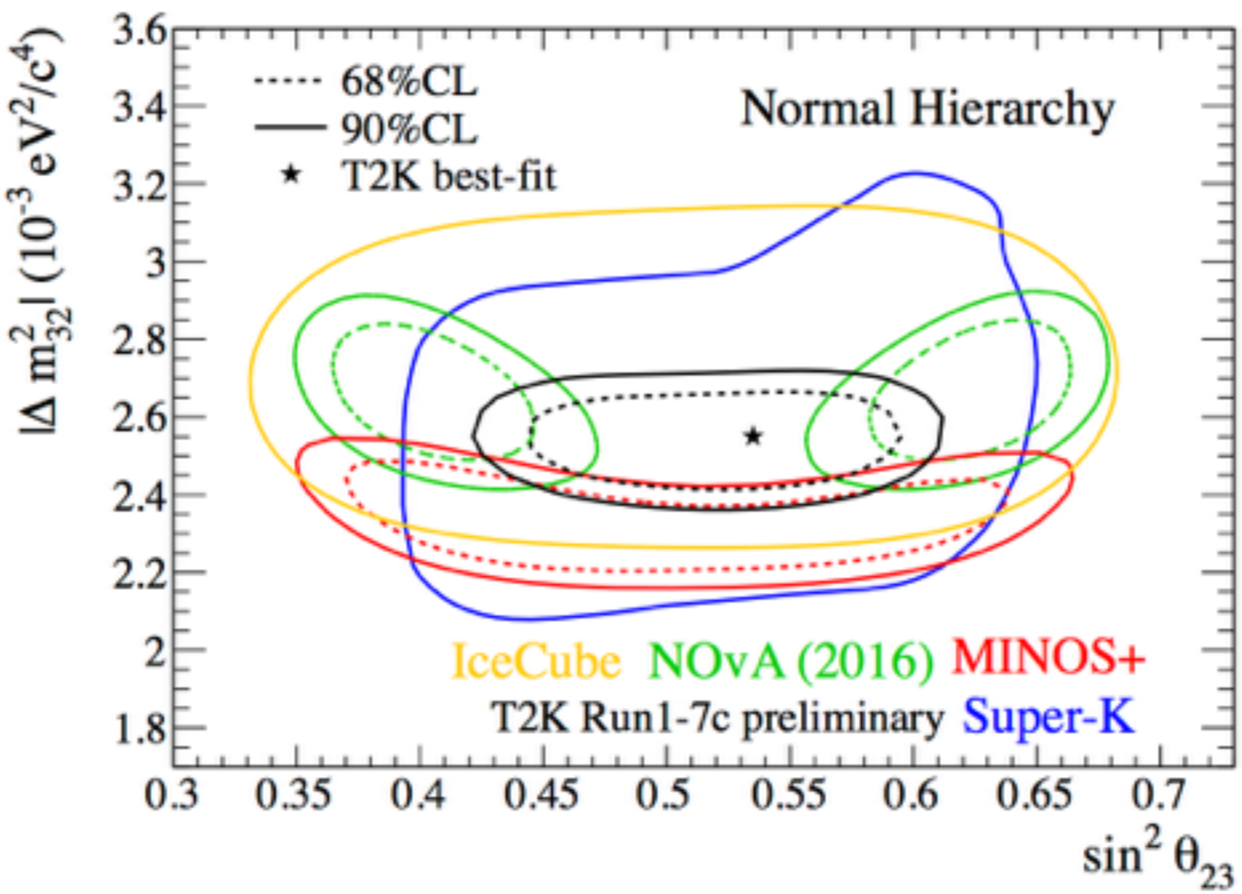


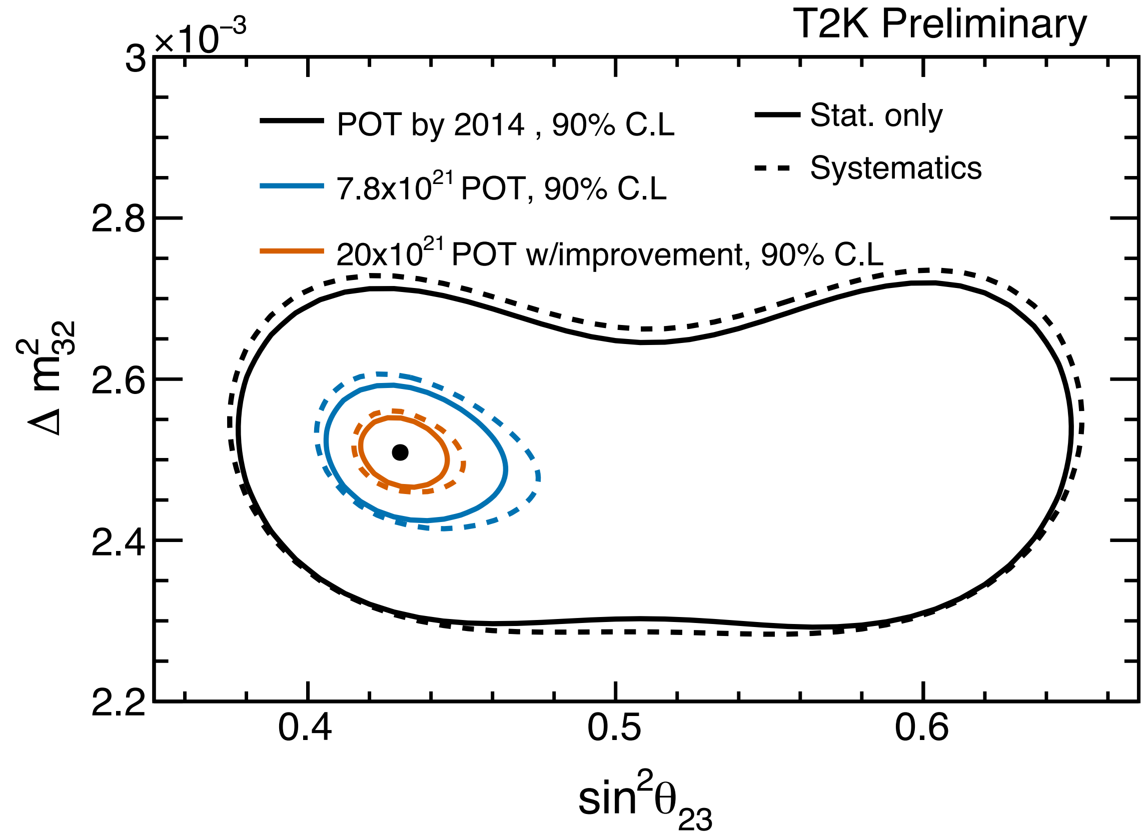


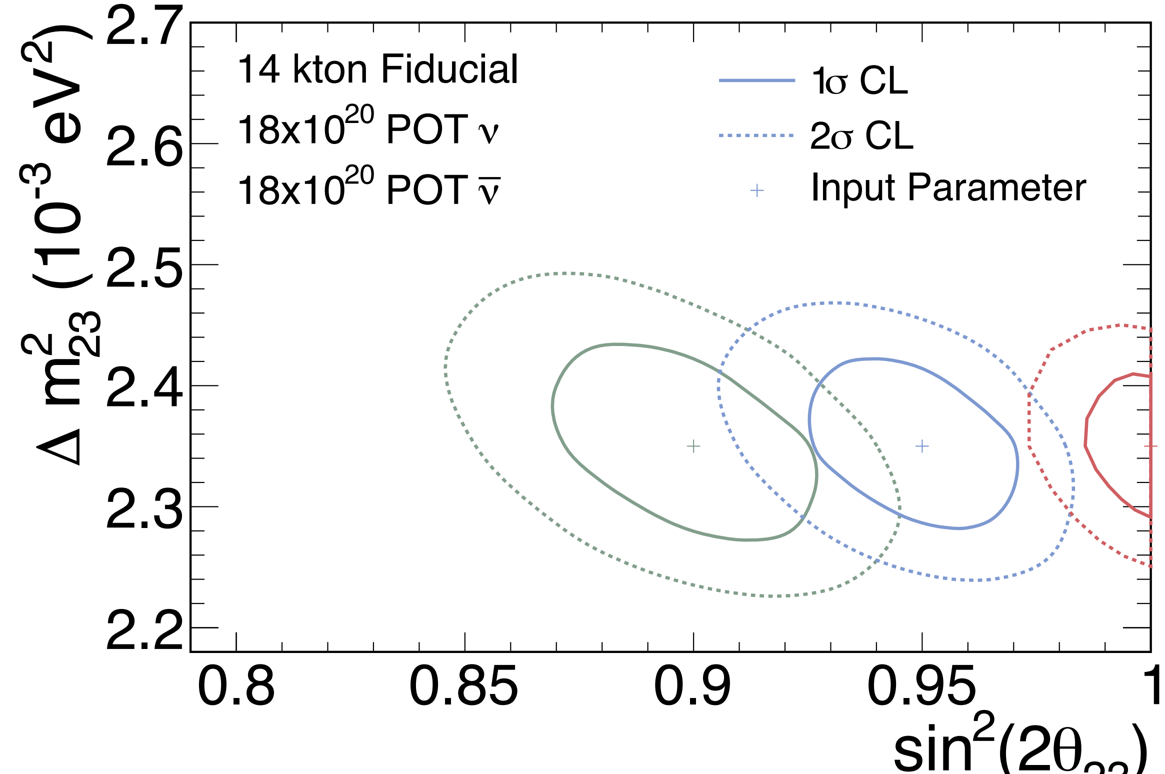




θ_{23} c. 2025

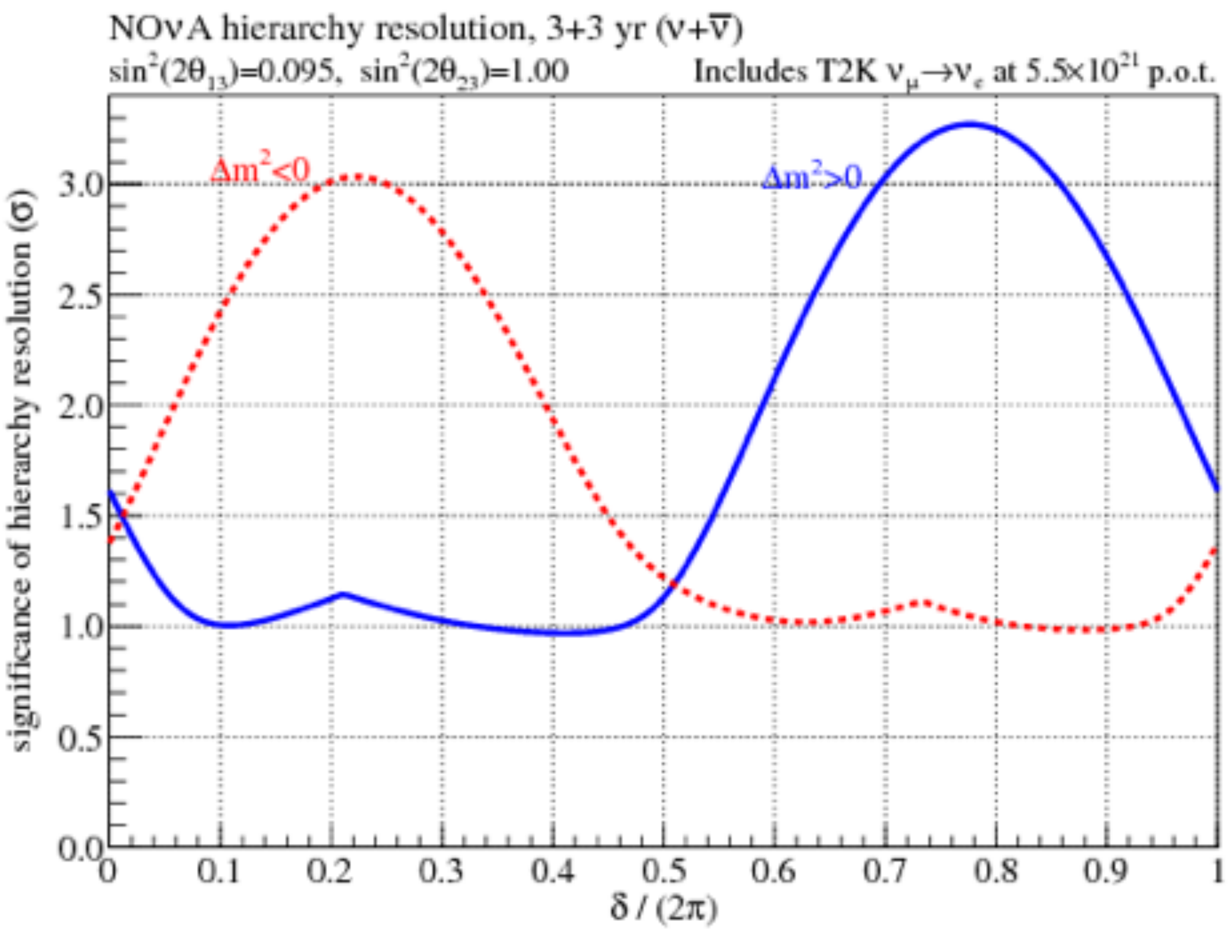


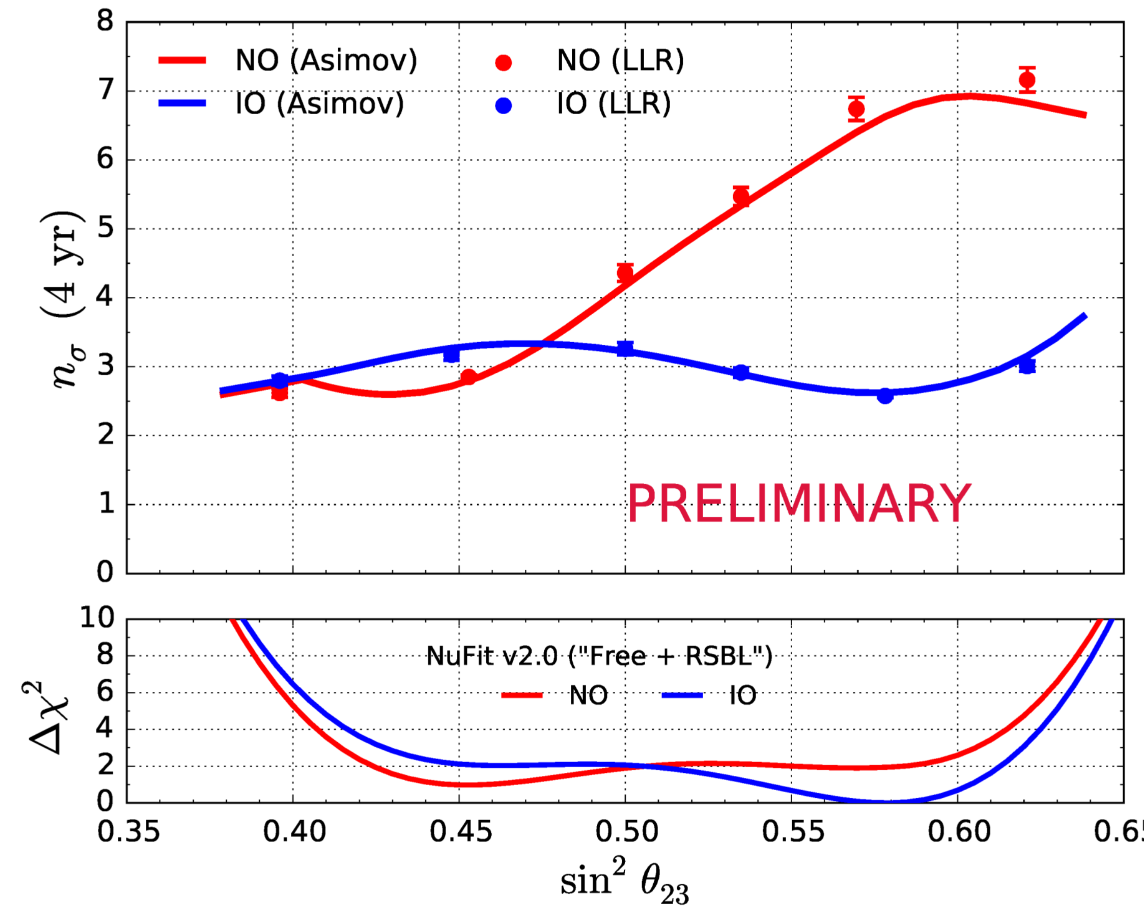


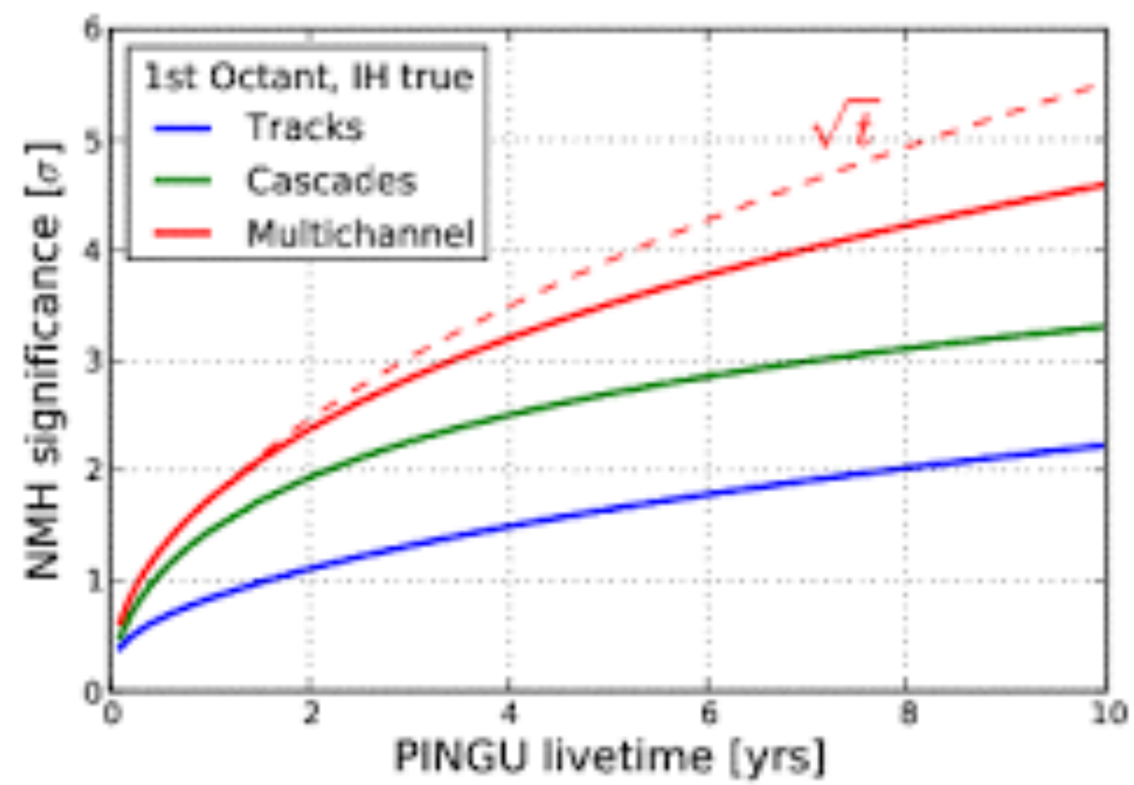


- By 2025, $\delta(\theta_{23})$ should be< 2°:
  - $\delta(\sin^2\theta_{23}$ ~0.03)
  - $\delta(\sin^2 2\theta_{23}$ ~0.005)
- Current indications of non-maximal mixing with $\sin^2\theta_{23}$ ~0.4 should be resolved

MASS ORDERING/HIERARCHY



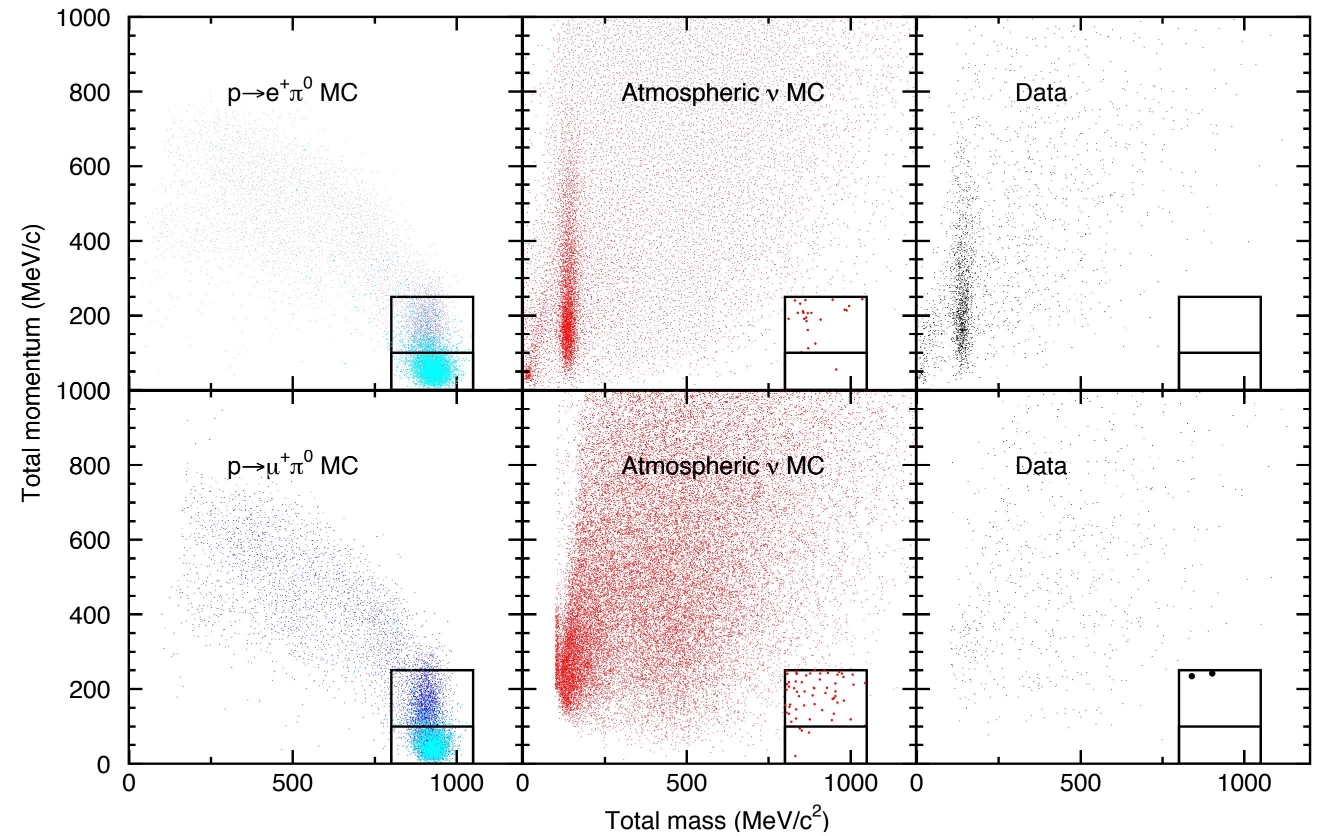


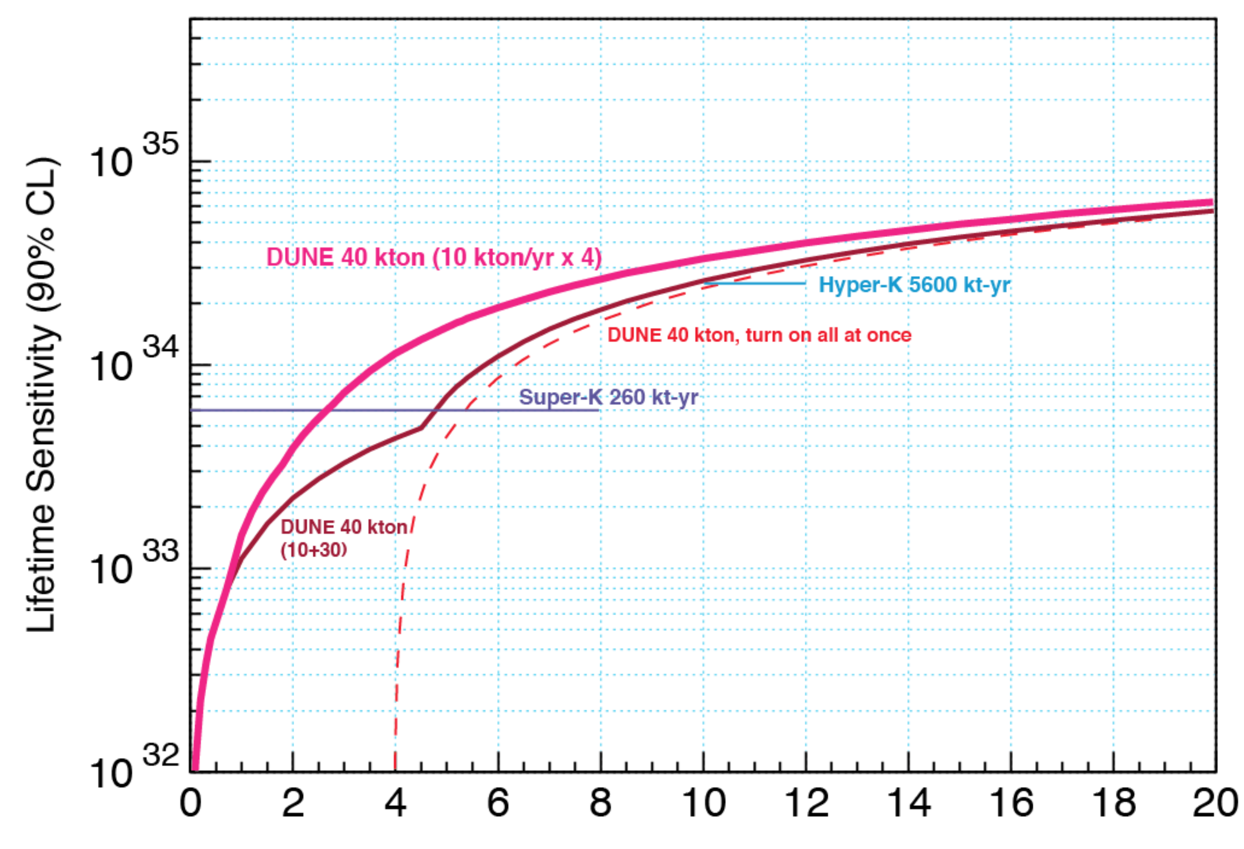


- Several opportunities by 2025
  - NOvA + T2K
  - JUNO
  - ORCA, PINGU (hope at least one goes forward)
- If all these “agree” we may consider mass ordering to be “resolved”
- Very important input LBL CPV searches

PROTON DECAY

- New SK results with 0.3 MT-year exposure
  - $\tau(p \rightarrow e^{+}+\pi^{0}) > 1.6 \times 10^{34}$ years
  - $\tau(p \rightarrow \mu^{+}+\pi^{0}) > 0.77 \times 10^{34}$ years
- Other results with 0.26 MT-year
  - $\tau(p \rightarrow K^{+}+\nu) > 0.59 \times 10^{34}$
- Another ~0.2 MT-year at SK by 2025
- Important to keep looking, improve analyses
  - Fully explore potential of SK-Gd
- Establish ~background free $p \rightarrow K^{+}+\nu$ searches in DUNE
  - also channels currently not accessible in WČ detectors





BEYOND

ELUCIDATING CPV

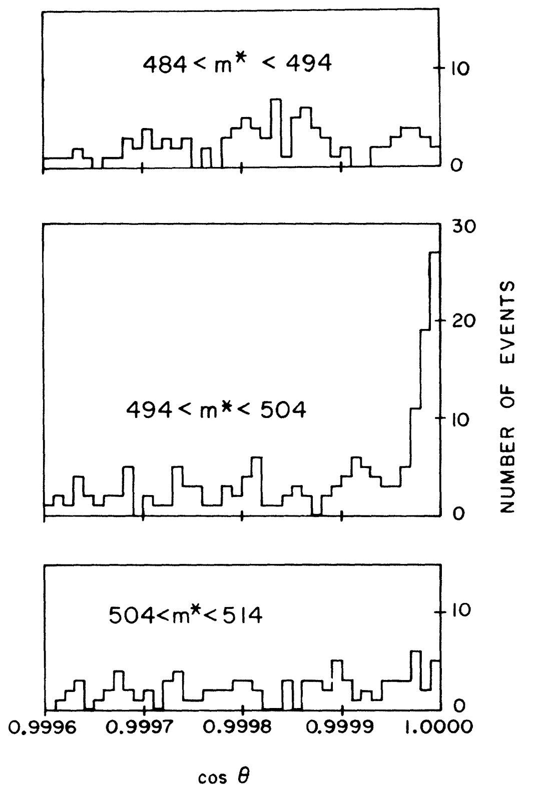


FIG. 3. Angular distribution in three mass ranges for events with cosθ > 0.9995.

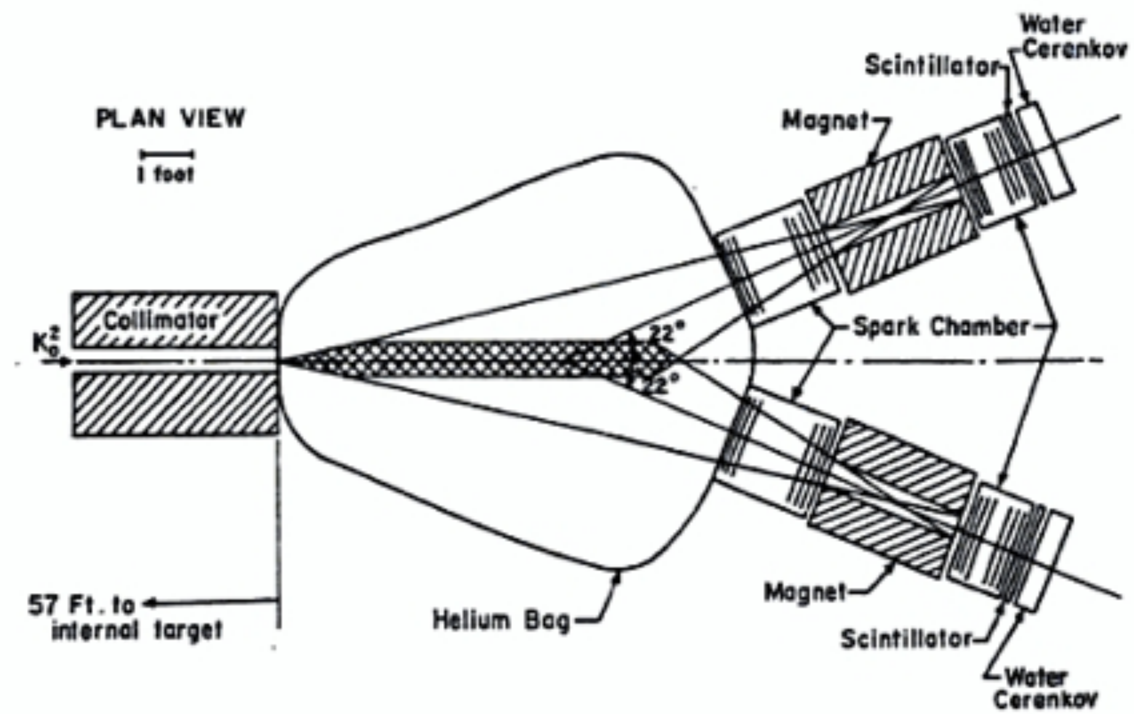
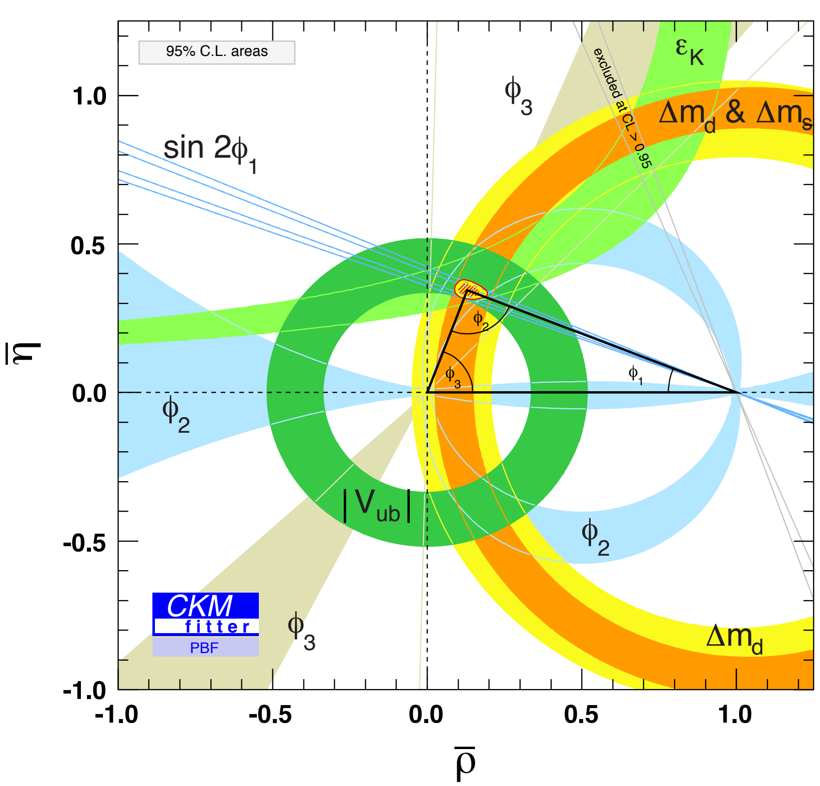
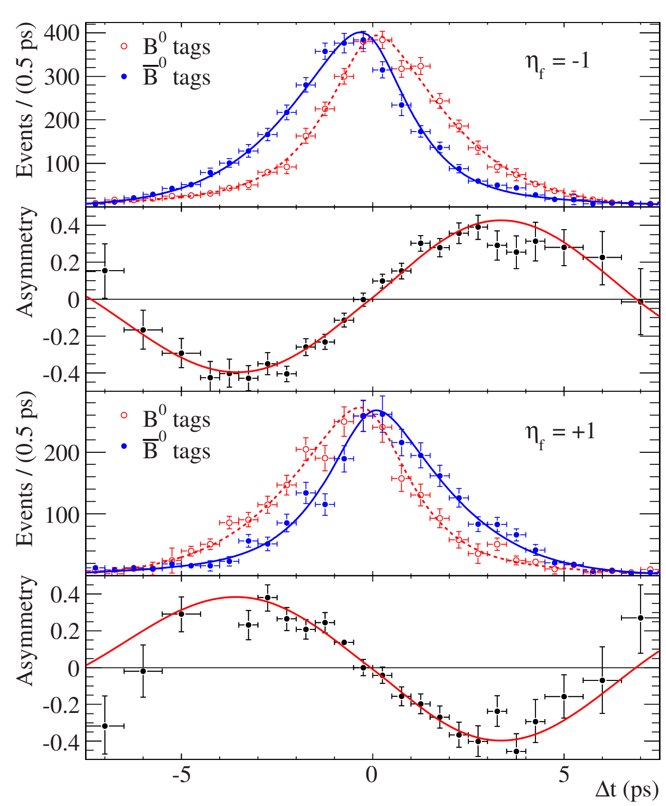


Fig. 9a. Set-up used to detect $K_2 \to \pi^+\pi^-$.

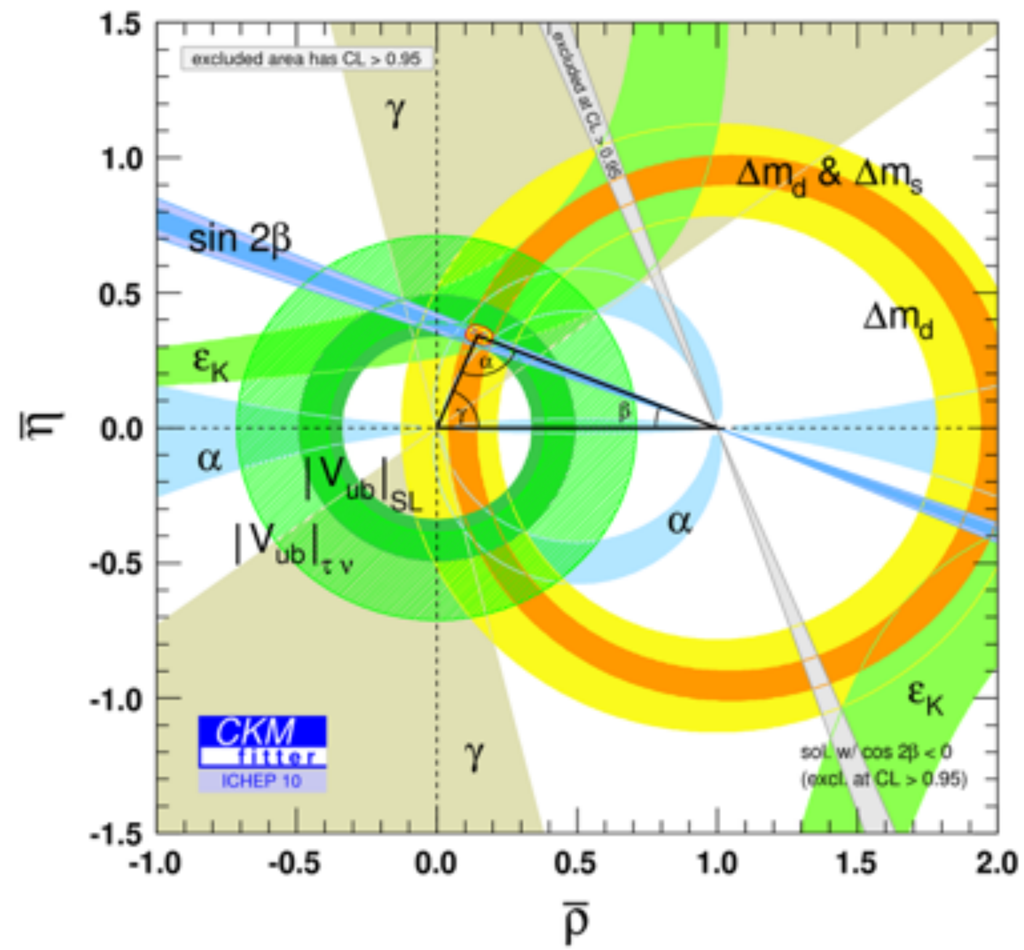


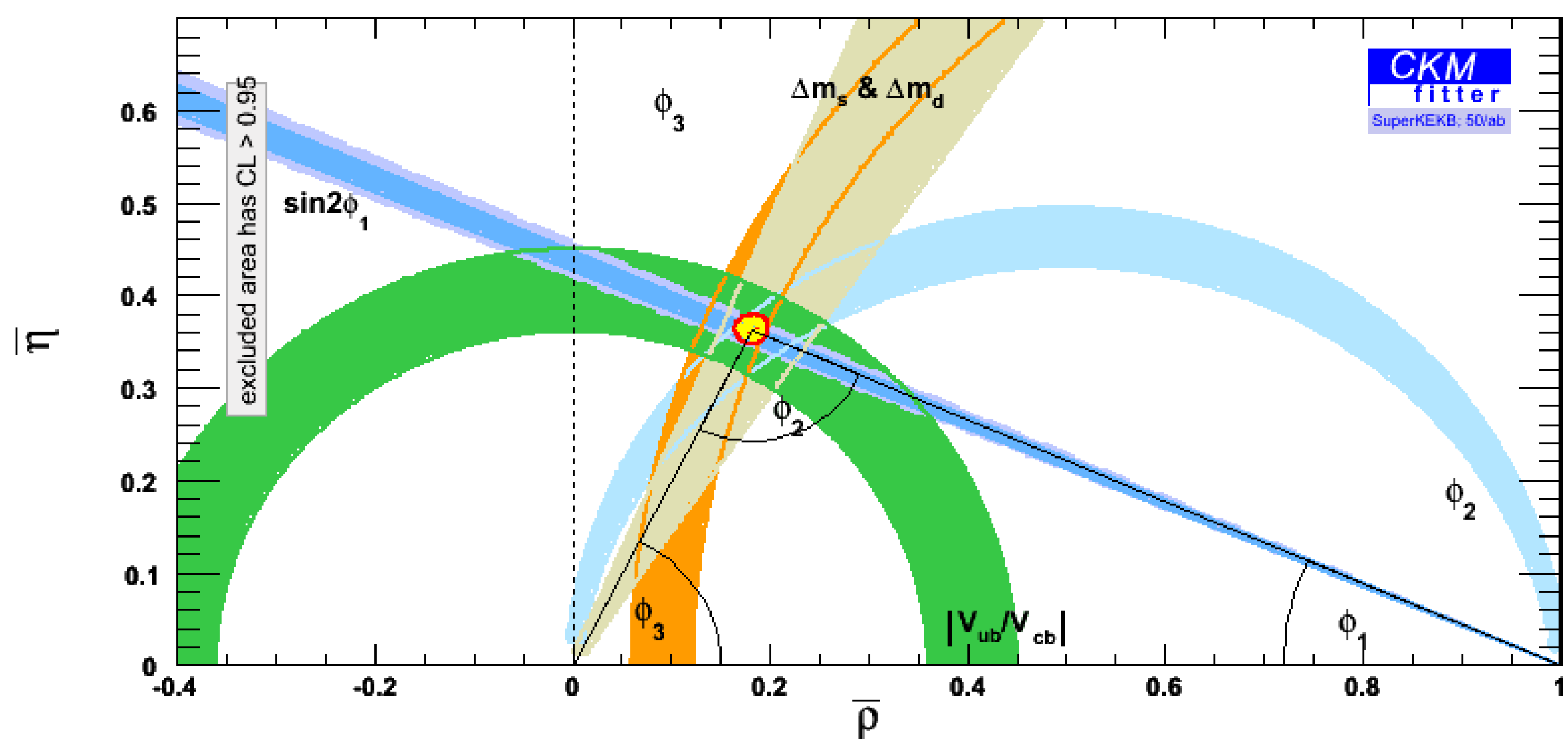


- 1964: Initial discovery of CP violation in $K_L \to \pi^+ + \pi^-$
- Nearly 50 years later, we know that this arises from a complex phase in quark mixing
- Observing CPV in neutrinos is the **beginning** of a program . . .

QUARK SECTOR

- Expect significant improvement in CKM measurements with Belle2
- What would violation of unitarity or other evidence of new physics in quark flavour mean for lepton mixing?





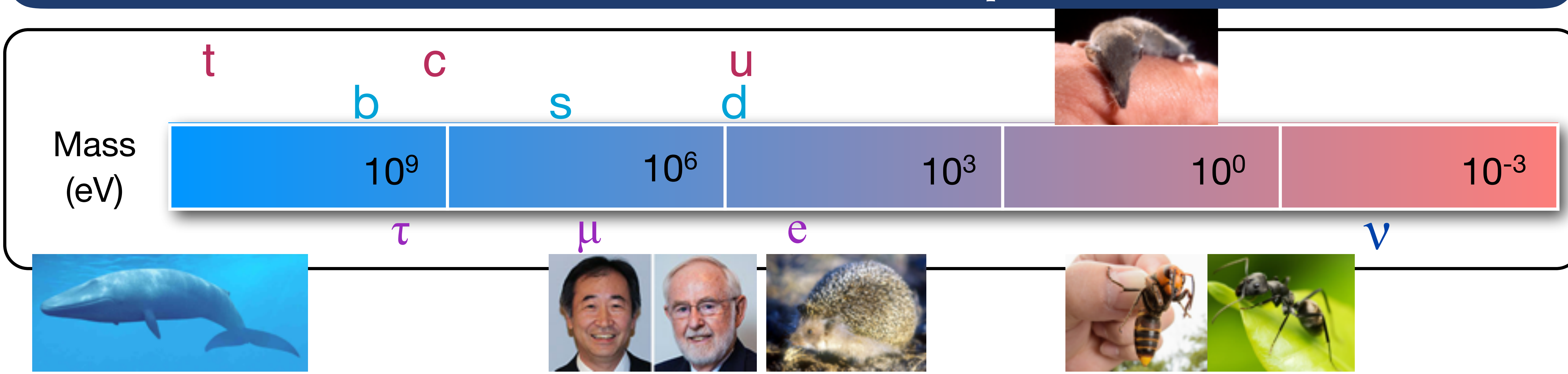
ANSWERS?

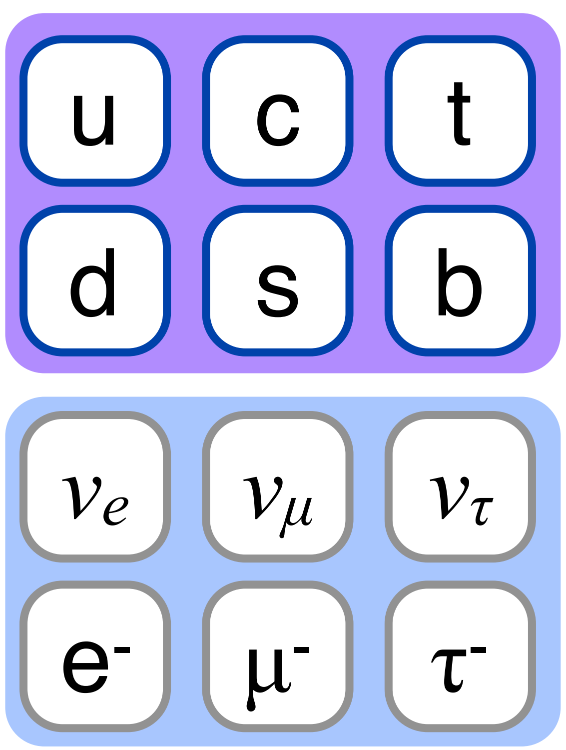
Quark

$$|U_{CKM}| \sim \begin{pmatrix} 0.97428 & 0.2253 & 0.0034 \\ 0.2252 & 0.93745 & 0.0410 \\ 0.00862 & 0.0403 & 0.99915 \end{pmatrix}$$

Lepton

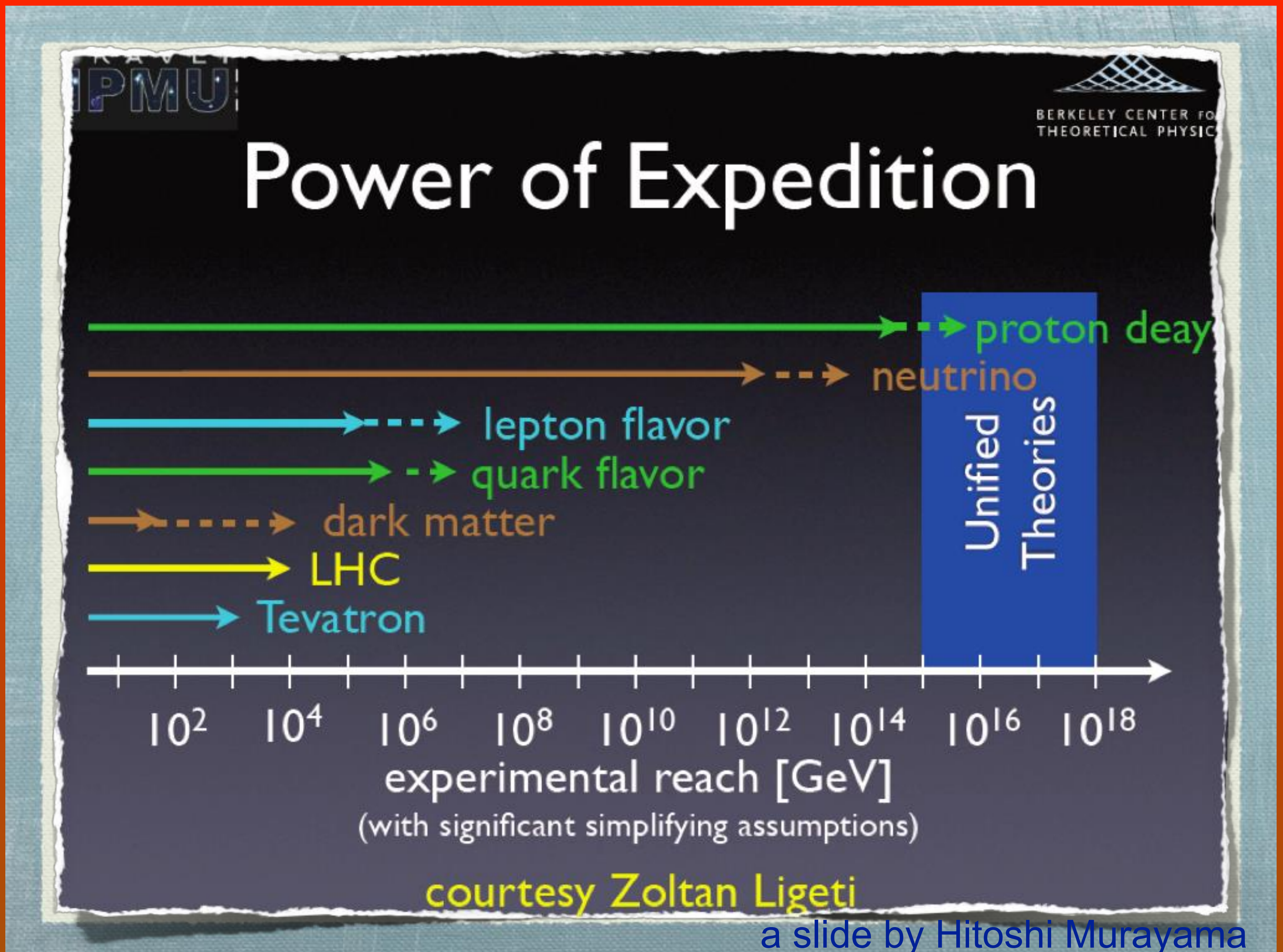
$$|U_{MNSP}| \sim \begin{pmatrix} 0.8 & 0.5 & 0.15 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$





- Why is quark and lepton mixing so different?
  - is neutrino mixing "maximal"?
- Why are neutrino masses so tiny?
  - quarks/charged leptons masses from Higgs mechanism
  - do neutrinos get mass some other way?

PHYSICS SCALES



presented at ICHEP 2016

FRoST 2016

What is the new physics of neutrino mass as proton decay

HEARD IN THE HALLWAYS:

- "Looks like the mass ordering is normal . . . "
- "Mass ordering is no longer a compelling physics topic"
  - ???
  - the mass ordering is far from resolved . . . .
  - even then, mass ordering is just one outcome from the study of neutrino matter effects
- "neutrinoless double beta decay looks less promising"
  - ???
  - Majorana mass and lepton flavour violation in $0\nu 2b$ is a fundamental question that must be addressed . . . period.

CONCLUSIONS (LBL)

- Exciting summer for LBL physics
  - T2K: first fully joint analysis across all $\nu/\bar{\nu}$ appearance/disappearance modes
  - NOvA: new ν-mode results with 2x data, significant analysis improvements
  - weak hints of CP violation? non-maximal mixing?
- If parameters are near currently favoured values:
  - we may establish strong evidence for CP violation by 2025
  - strong indications on the mass ordering may come from several sources
  - a robust joint analysis of results may be needed to convince ourselves we have this right.
- If not . . . we will leave plenty to do for the next generation
- ' would accept a clear CP violation or mass ordering result"
  - "but reserve my right to contest questionable results or propose a new experiment."

CONCLUSIONS: PROTON DECAY

- I'm very excited about proton decay
- But it seems unlikely that we will make leaps in sensitivity
  - SK has been running for 20 year already
  - DUNE will have only been running for a few years
- Needless to say, it is important to keep looking
  - we may have surprises
  - we may get "lucky" (or correspondingly been "unlucky" so far
- This is a game of discovery
  - upper limit sensitivity difficult to improve but
  - lot of work to do to improve analyses, backgrounds, etc. so that discovery potential with even a few events remains high
  - demonstrate that we are ready for a big leap once DUNE and HK start.