Accelerator Neutrinos

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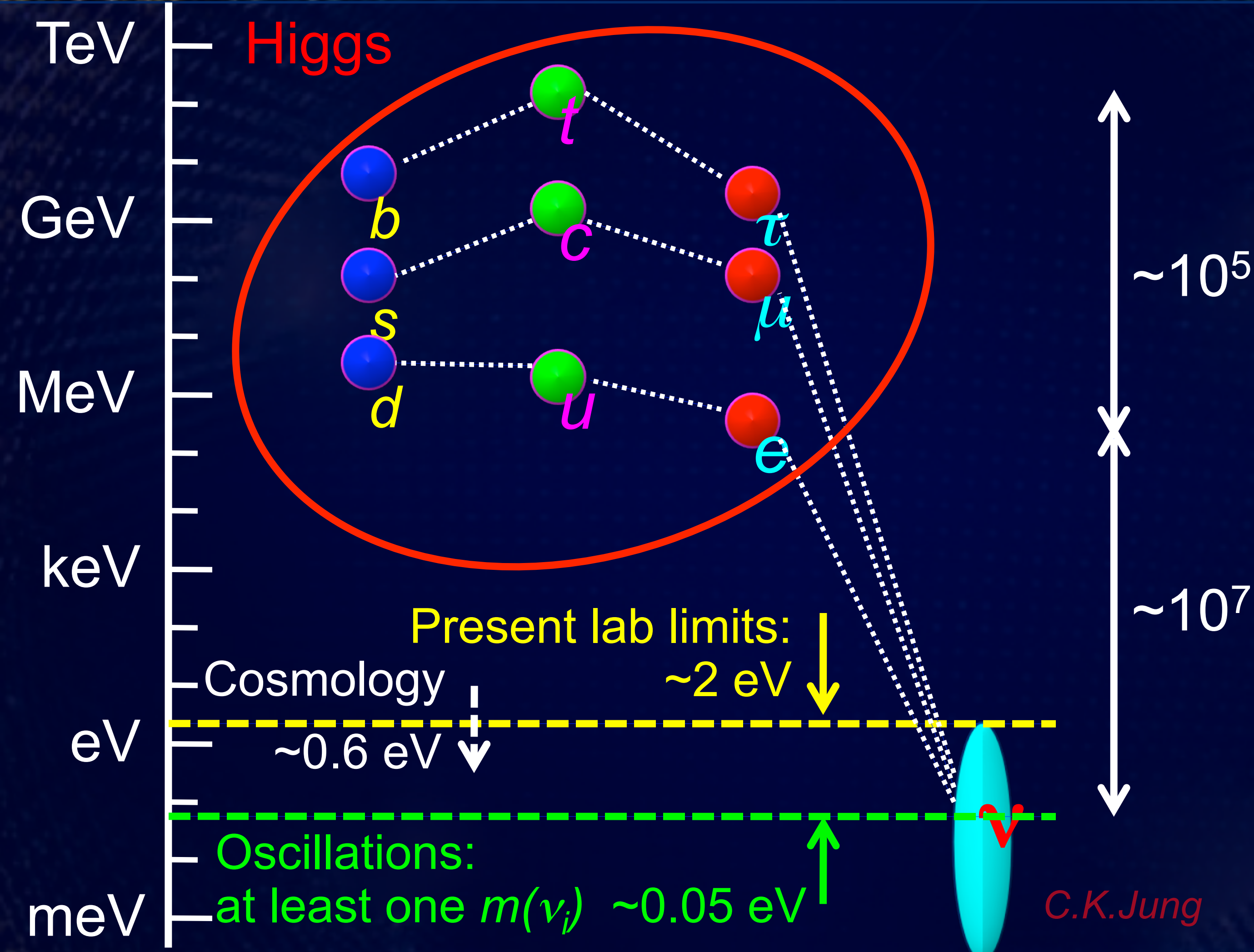
ICFA Seminar
October 26, 2014

Spin ½ Matter Field Particle Mass Spectrum



Are neutrino masses suppressed by new physics at very high energy?

$m(\nu_i) = m^2_{Di} / M$

Seesaw in SO(10)

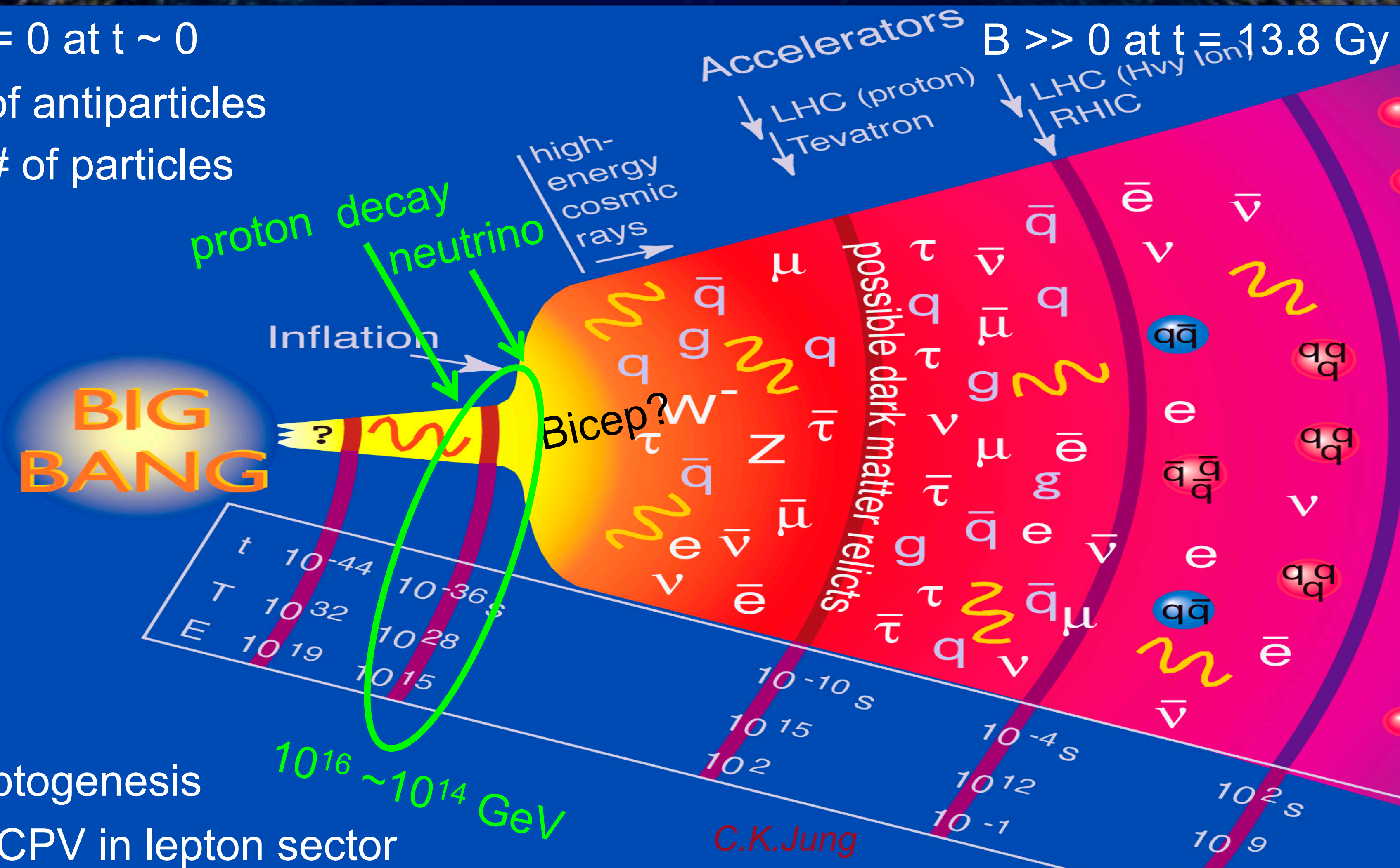
Nucleon decay and Neutrino Experiments: Probing the earliest time and the highest energies

B = 0 at t ~ 0

# of antiparticles

= # of particles

B >> 0 at t = 13.8 Gy



Leptogenesis

→ CPV in lepton sector

3-flavor Neutrino Oscillations (in Vacuum) under PMNS Framework

In general,

$$P_{\alpha\to\beta}=\delta_{\alpha\beta}-4\sum_{i>j}\Re(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2\left(\frac{\Delta m^2_{ij}L}{4E}\right)$$
$$+2\sum_{i>j}\Im(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin\left(\frac{\Delta m^2_{ij}L}{2E}\right)$$

For three generation, ν_e appearance (accelerator experiments)

$$P(\nu_\mu\to\nu_e)=\sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{32}L}{4E_\nu}+\text{subleading terms}$$

Sensitivity to θ_{23} octant

Full appearance probability includes term that goes as sin(δ):

CPV term $\propto \pm\sin\theta_{12}\sin\theta_{13}\sin\theta_{23}\sin\delta$

Sensitivity to CPV-δ

Sign flip for neutrino vs. antineutrino

Need non-zero value for all three mixing angles including θ_{13}

Complementary

For anti-ν_e disappearance (reactor experiments)

$$P(\bar{\nu}_e\to\bar{\nu}_e)=1-4C^2_{13}S^2_{13}\cdot\left(C^2_{12}\sin^2\Delta_{13}+S^2_{12}\sin^2\Delta_{23}\right)+4S^2_{12}C^2_{12}C^4_{13}\sin^2\Delta_{12}$$

No CPV-δ dependence, Pure θ_{13} measurement

Current Status of Neutrino Oscillation Parameter Measurements

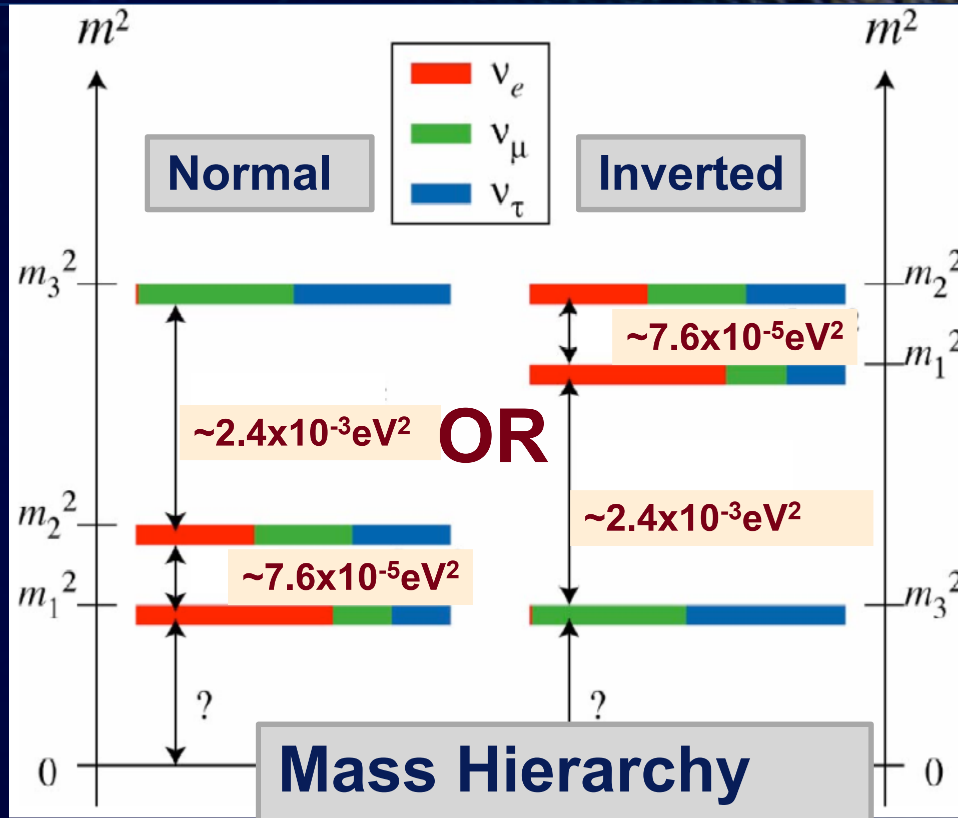
- Remarkable progress!
- All mixing angles are now known
  - $\theta_{12} = 33.9^o \pm 1.0^o$
  - $\theta_{13} = 8.7^o \pm 0.4^o$
  - $\theta_{23} = 45^o \pm 6^o$ (90% C.L.)
    → largest uncertainty

All three angles are non-zero and relatively large

→ allows exploration of CPV in the lepton sector

$P(\nu_\mu \to \nu_e)$
$\propto$ leading term + …
+ term($\sin\theta_{12} \sin\theta_{23} \sin\theta_{13} \sin\delta_{CP}$)

Why is nature so kind to us?



Critical for the ν-less double-β decay searches that would determine the Majorana-nature of ν

Remaining Unknown Neutrino Properties

- θ_{23}> 45°, = 45° (maximal) or < 45°
  → maximal mixing may indicate a profound hidden symmetry
- δ_{CP} (≠ 0, i.e. CPV?)
- Mass ordering (NH or IH?)
- Any sterile ν
- Is PMNS matrix correct description of the lepton sector?
- Absolute m_ν
- Dirac/Majorana

Accelerator Based Neutrino Experiments

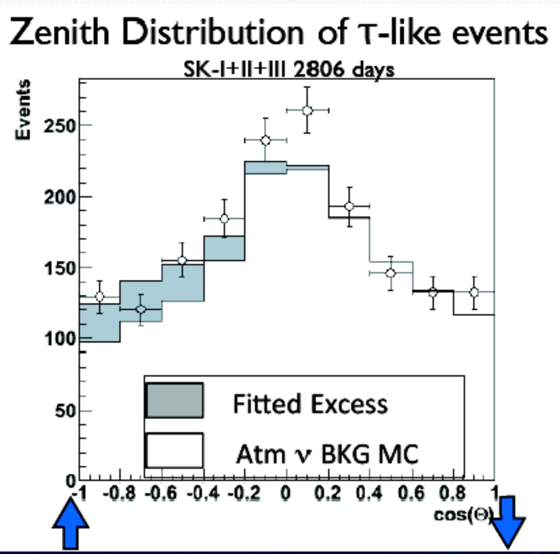
Status of Experiments	US-based	Japan-based	Europe-based
Recently Completed	MINOS MiniBooNE		ICARUS OPERA
Currently Running	ArgoNeuT MINERvA NOvA, MINOS+	T2K	
Approved	MicroBooNE LBNE/LBNF (CD1)		
Proposed		Hyper-Kamiokande	LBNO

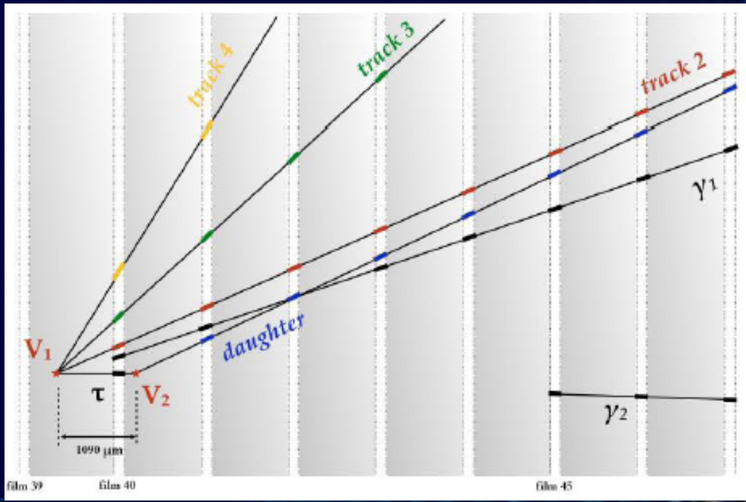
(Not a complete list. Some R&D type experiments and sterile neutrino search experiment proposals are missing in this list.)

This talk will concentrate on the recent results from the currently running experiments and prospects of future experiments in terms of neutrino oscillation parameter measurements

Tau Neutrino Appearance

- Super-K published a 3.8 s C.L. evidence for ν_τ appearance using events resulting from hadronic tau decays
  - Phys. Rev. Lett. **110**, 181802 (2013)
- OPERA published results based on 2008-2012 data
  - Phys. Rev. D **89**, 051102 (2014)
- 4th ν_τ appearance event found in more recent data
  - No oscillation is excluded at the 4.2 σ C.L.

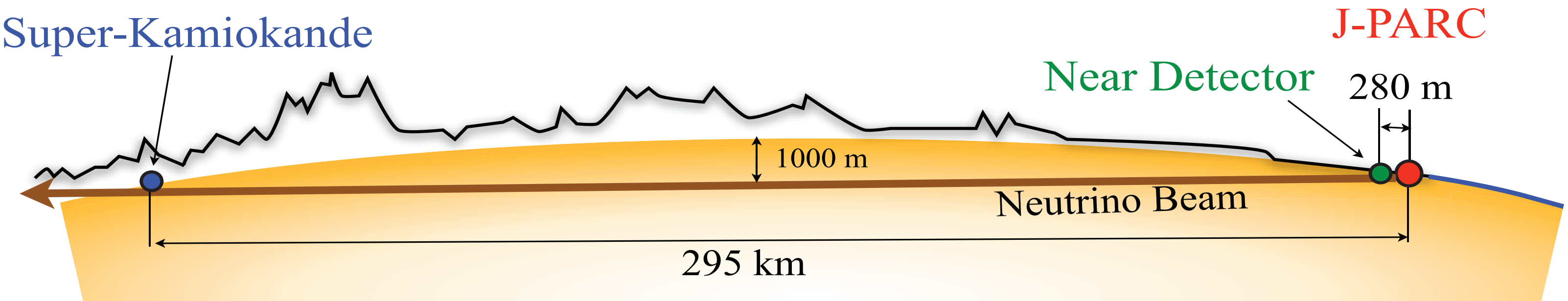




OPERA ν_τ appearance 4th candidate event

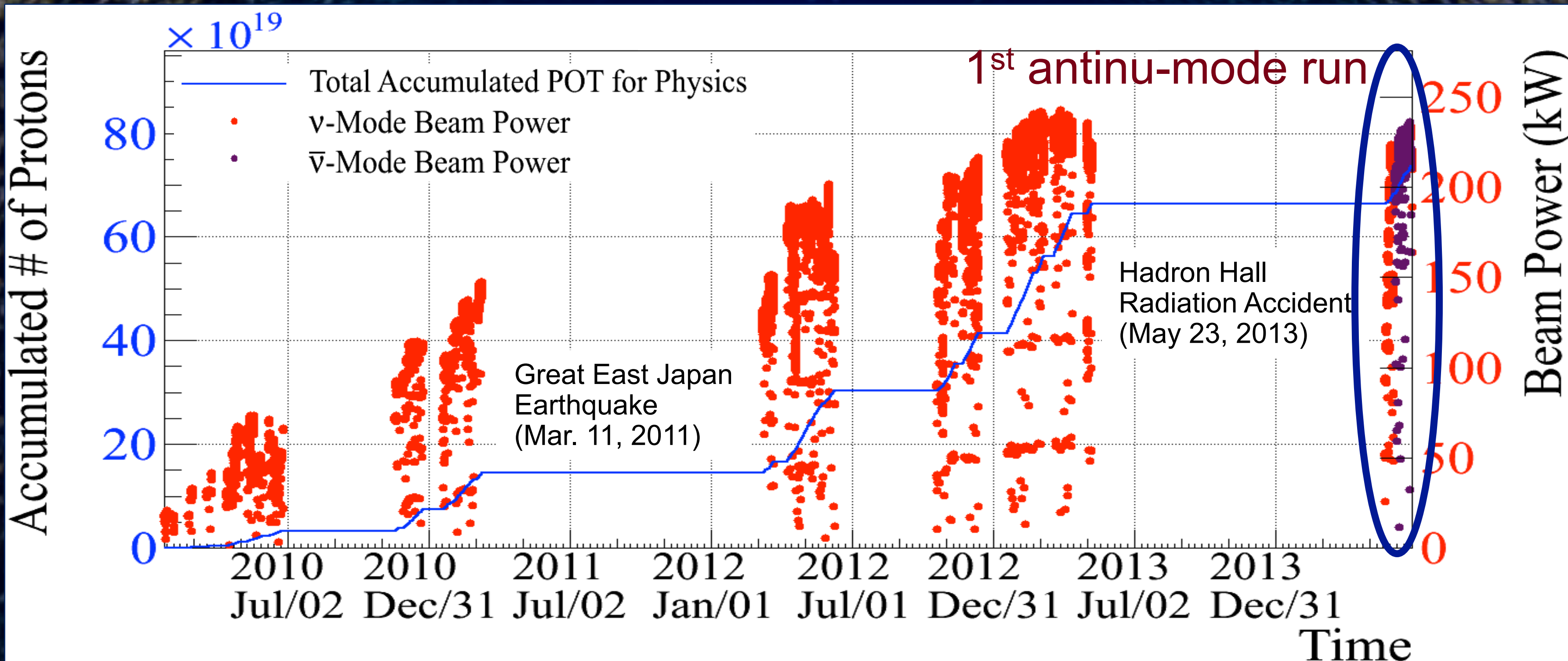
- *S. Dusini, Neutrino 2014*

The T2K (Tokai to Kamioka) Experiment
(http://t2k-experiment.org/)



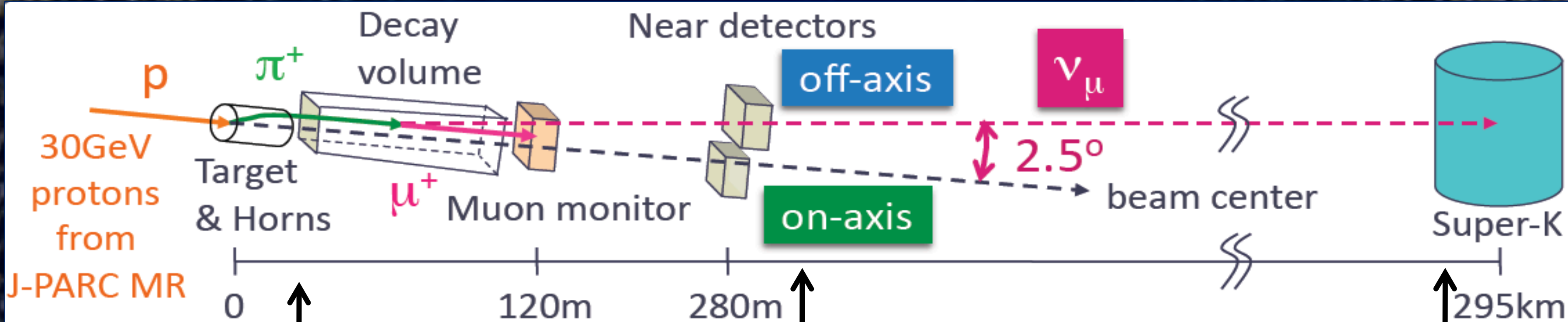
"The T2K Experiment", K. Abe, et al., Nucl. Instr. and Meth. A **659**, 106 (2011)

T2K Accumulated # Protons on Target (POT), and J-PARC Main Ring Beam Power



- Stable operation at ~230 kW achieved
- Antineutrino-mode run (Run 5) in June 2014
- Total POT for physics: 6.88×10^{20} (nu-mode), 0.51×10^{20} (antinu-mode)
  → ~ 10% of the total approved POT (7.8×10^{21})

T2K Experimental Setup and Oscillation Analysis Strategy



Tracking inside horns and He vessel

GEANT3+GCALOR

Proton beam interaction in the target

→Hadron production

FLUKA, NA61, etc.

Φ

Near detector data

Fit

Constrained Φ σ

σ

Neutrino-nucleus interactions (NEUT)

MiniBooNE, MINERvA

SK data and uncertainties (detector and uncorrelated σ)

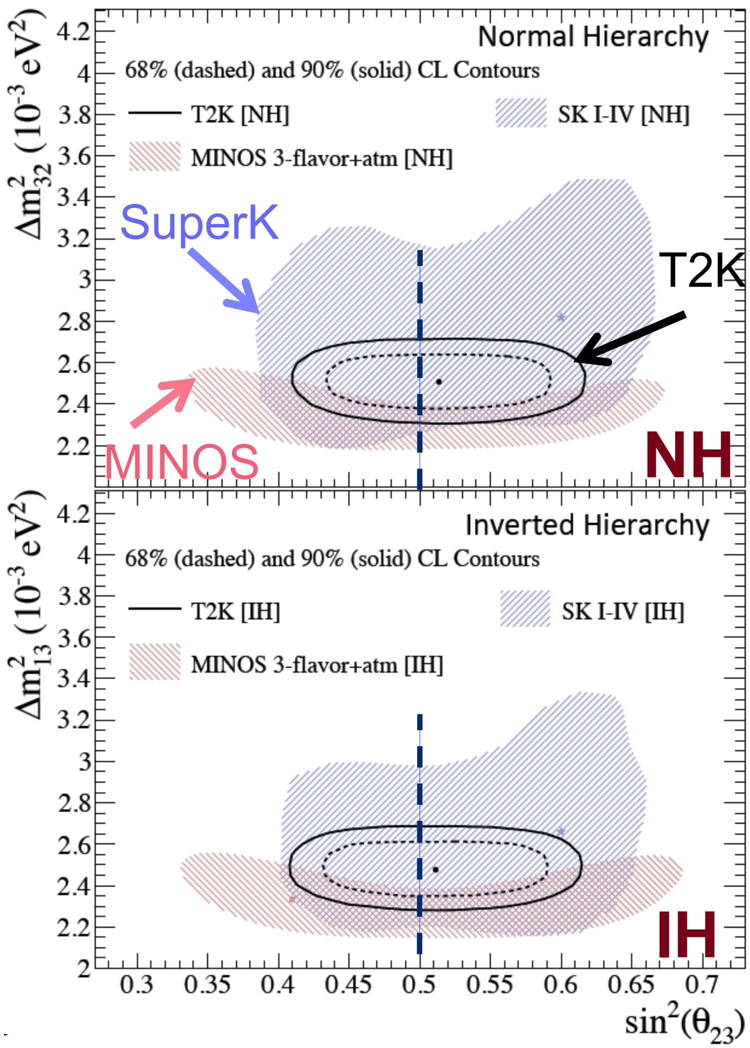
Fit

Measured oscillation parameters

Predicted Φ and correlated σ at SK

$$\Phi^{SK} \cdot P_{osc} \cdot \sigma^{H2O}_{reaction} \cdot \varepsilon_{SK} dE_{\nu}$$

ν_μ Disappearance Confidence Regions



T2K and SuperK: Separate C.L. for NH & IH
MINOS: C.L. from the global minimum

T2K Run 1-4 Best Fit Point (NH):

$\Delta m^2_{32} = 2.51 \pm 0.1 \times 10^{-3}$ eV^2

$\sin^2\theta_{23} = 0.514^{+0.055}_{-0.056}$

- The best fit is consistent with the maximal mixing but not exactly at the maximal mixing
- T2K now has the smallest error on θ_{23}, (~3°)

Note: osc. Max for $\sin^2 2\theta_{13} = 0.098$:

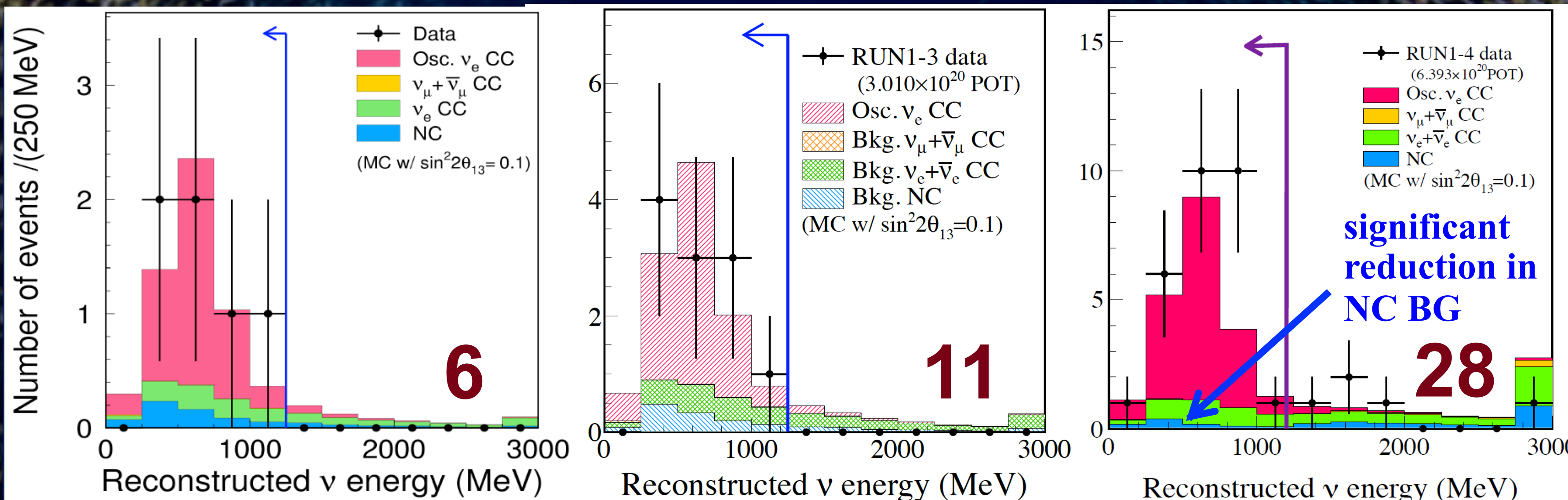
$\sin^2\theta_{23} = 0.513$ (or $\theta_{23} = 45.74°$)

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

Leading: $c_{13}^4 \sin^2 2\theta_{23}$

Next-to-leading: $s_{23}^2 \sin^2 2\theta_{13}$ is different between 1st/2nd octants

T2K Reconstructed E_ν Spectrum of the Final Selected Events



Year	2011	2012	2013
POT (10^{20})	1.43	3.01	6.57
$N_{\nu_e}^{obs.}$	6	11	28
N_{BG}^{exp}	1.5 ± 0.3	3.3 ± 0.4	4.92 ± 0.55
$\sin^2 2\theta_{13}$(T2K)	0.11	$0.088^{+0.049}_{-0.033}$	$0.140^{+0.038}_{-0.032}$
Significance	2.5σ	3.1σ	7.3σ
Systematic Error (%) on N_{tot}^{exp}	17.5	9.9	8.8

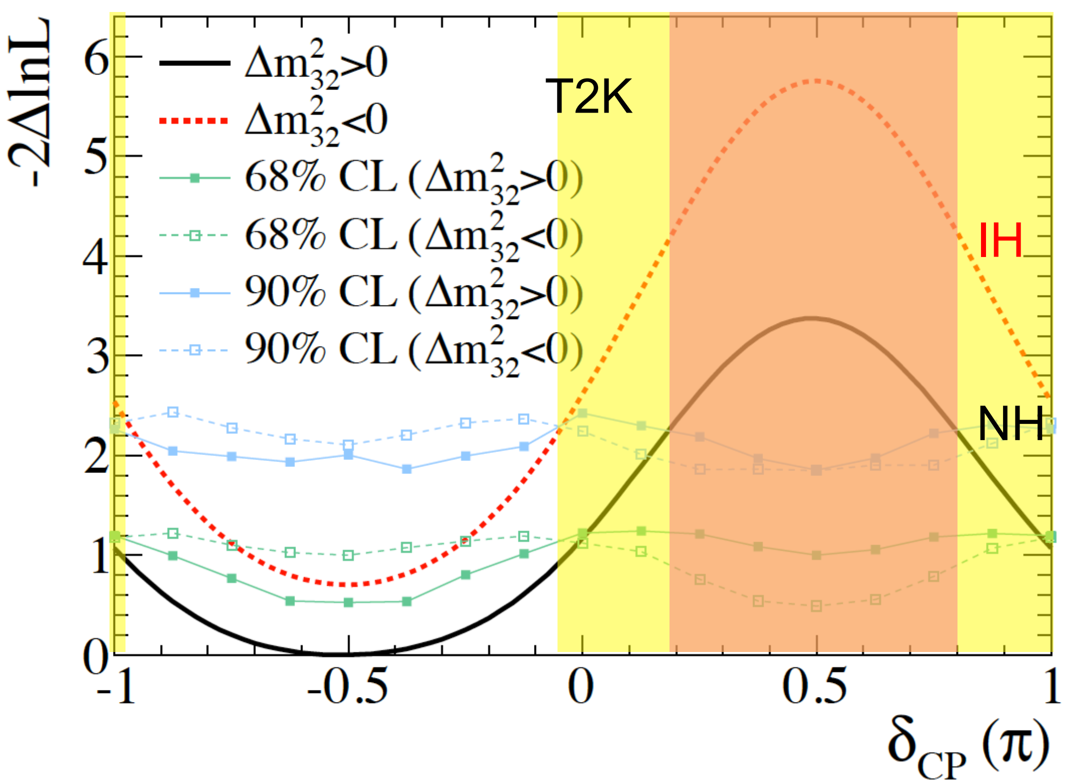
- θ_{13}= 0 is excluded at 7.3σ level of significance

→ Observation of ν_e appearance from a ν_μ beam!

First step to measure δ_{CP}
T2K ν_e Appearance Analysis

T2K: Marginalized over Δm^2_{32}, $\sin^2\theta_{23}$ and $\sin^2 2\theta_{13}$

Best fit values of δ_{CP}: −1.65 (NH), −1.57 (IH)
(Note the physical boundaries at $\pm\pi/2$)



90% C.L. excluded regions using Feldman-Cousins method:

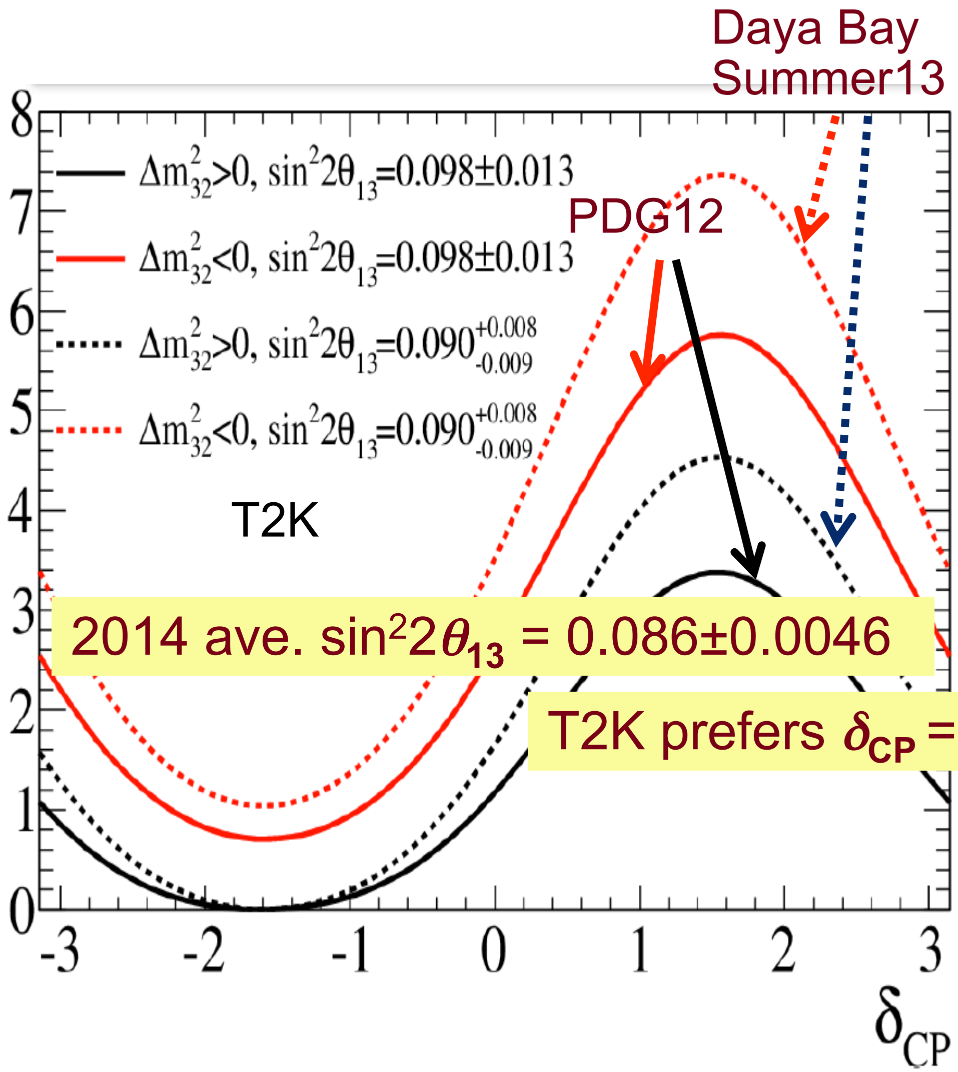
$$\Delta\chi^2 = \chi^2_{true} - \chi^2_{min}$$

(global minimum)

$$\Delta\chi^2 < \Delta\chi^2_{crit}$$

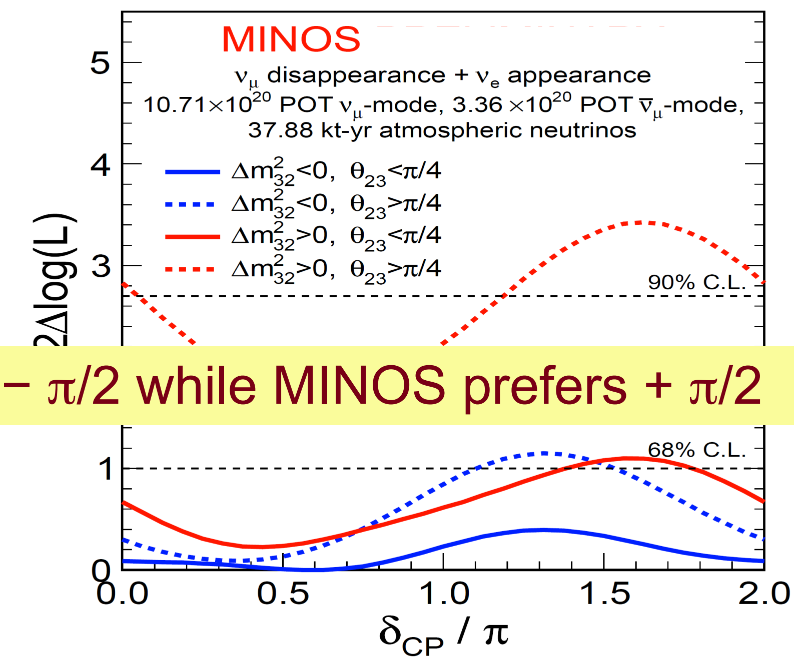
NH: $0.19\pi < \delta_{CP} < 0.80\pi$,
IH: $-\pi < \delta_{CP} < -0.97\pi$
and $-0.04\pi < \delta_{CP} < \pi$

Impact of Reactor Measurement of θ_{13} on δ_{CP} and Comparison with MINOS



T2K: Marginalized over Δm^2_{32}, $\sin^2 2\theta_{23}$ and $\sin^2 2\theta_{13}$

Note the x-axis scales are different and the y-axis scales are adjusted to be same



2014 ave. $\sin^2 2\theta_{13} = 0.086\pm0.0046$

T2K prefers $\delta_{CP} = -\pi/2$ while MINOS prefers $+\pi/2$

What does this mean?

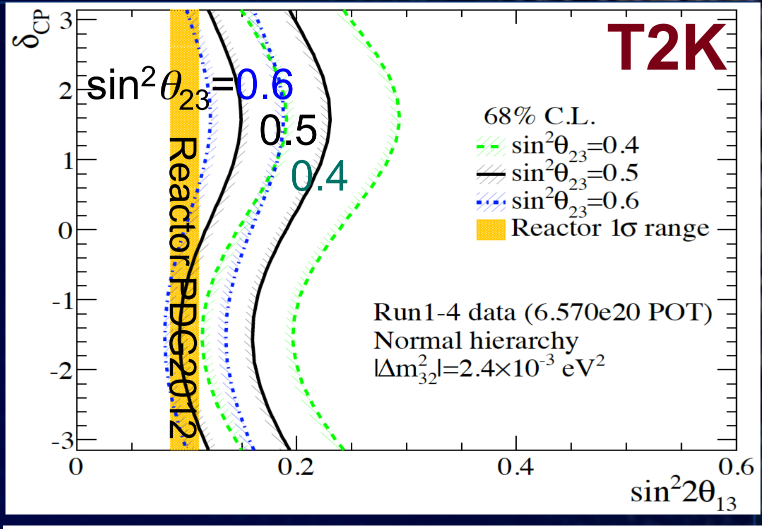
- An intriguing and encouraging results stemming from the strong tension between the T2K and the reactor $\sin^2 2\theta_{13}$ measurements
- An excellent news for the current and future accelerator-based neutrino oscillation experiments
  - T2K, NOvA, LBNE and HyperK

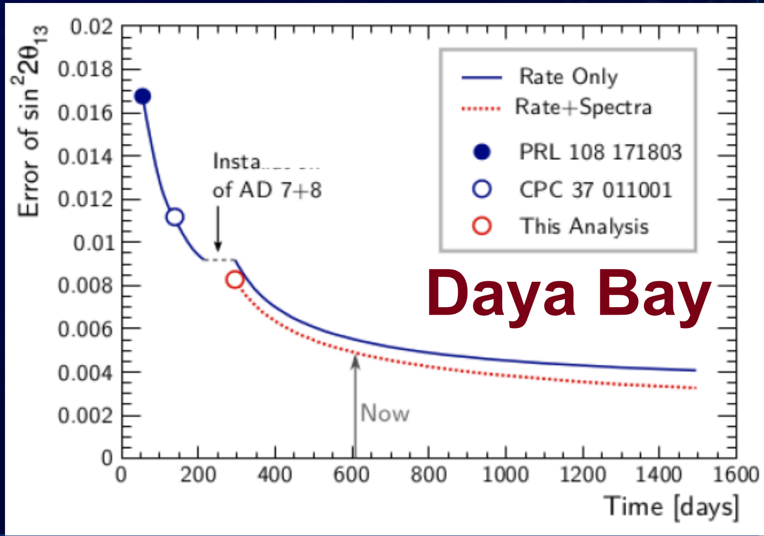
→ Need continued precision measurements of θ_{13} by the reactor experiments

→ Both the central value and the error size are important

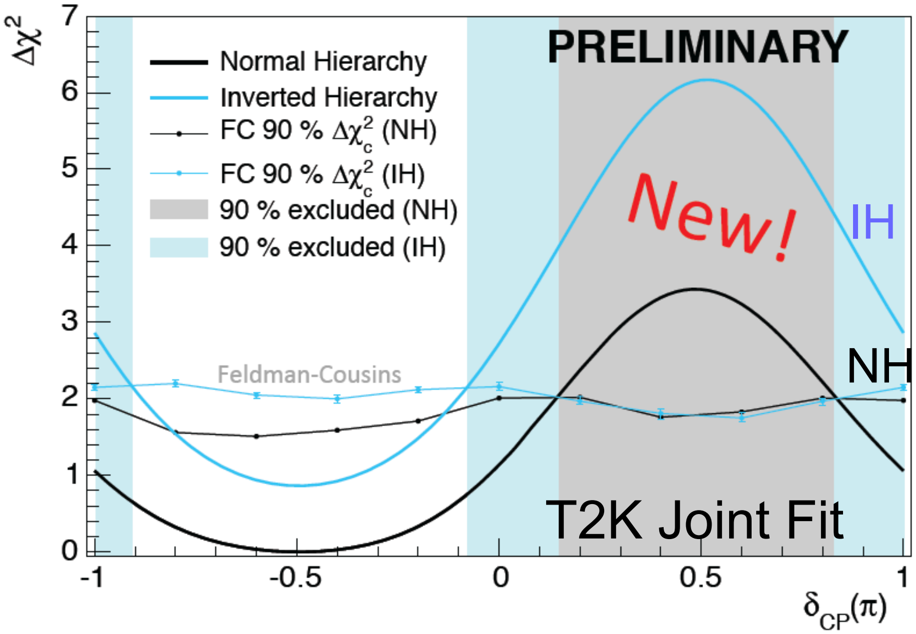
Daya Bay projected error on $\sin^2 2\theta_{13}$

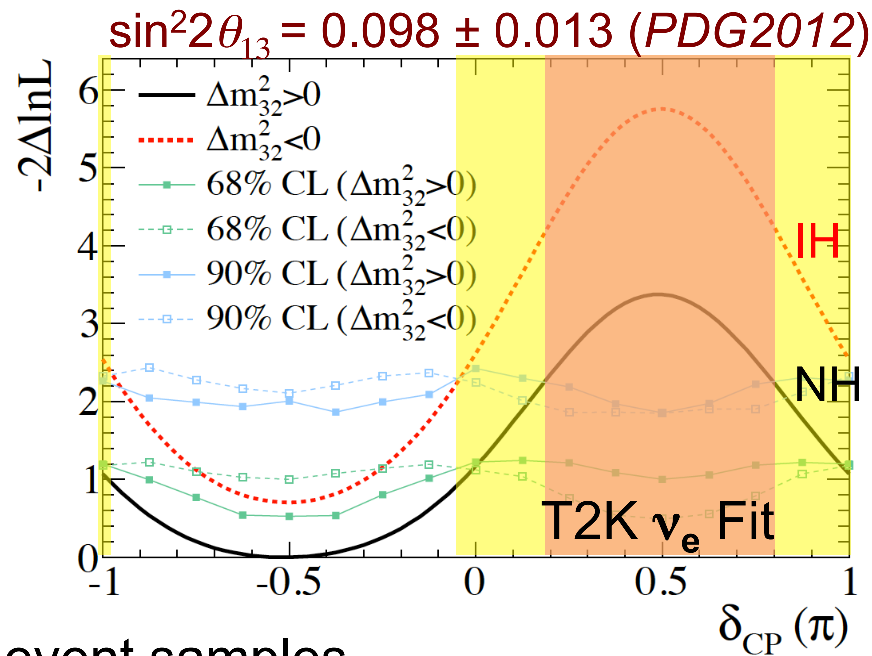
→ ~0.003 (4%) ultimately





T2K Joint ν_μ and ν_e Analysis





- Likelihood ratio fit to both candidate event samples
- Full representation of correlations among oscillation parameters:
  θ_{13}, θ_{23}, Δm^2_{32} and δ_{CP}
- Constraint on θ_{13} from reactor measurements
  $\sin^2 2\theta_{13} = 0.095 \pm 0.010$ (*PDG2013*)

→ No qualitative difference compared to ν_e fit

	90% CL Inclusion
NH	$\delta_{CP} \in [-1.18, 0.15]\pi$
IH	$\delta_{CP} \in [-0.91, -0.08]\pi$

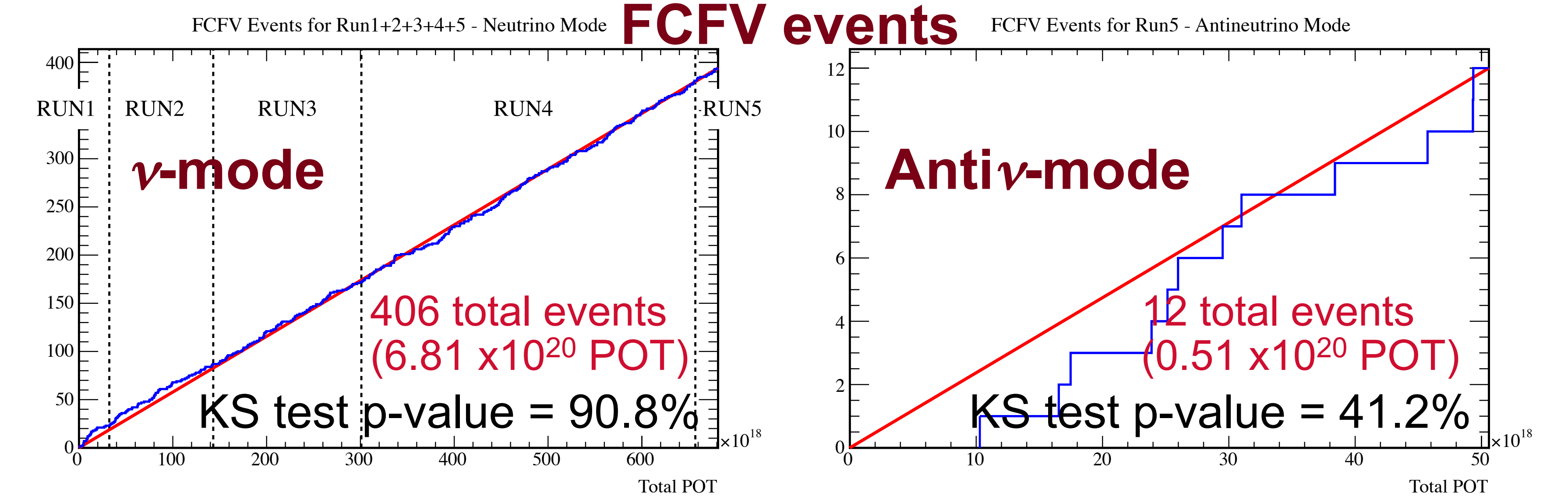
PRELIMINARY

T2K Joint Fit Systematic Uncertainties

		ν_μ sample	ν_e sample
ν flux and cross section	w/o ND measurement	21.8%	26.0%
	w/ ND measurement	2.7%	3.1%
ν cross section due to difference of nuclear target btw. near and far		5.0%	4.7%
Final or Secondary Hadronic Interaction		3.0%	2.4%
Super-K detector		4.0%	2.7%
total	w/o ND measurement	23.5%	26.8%
	w/ ND measurement	7.7%	6.8%

- An excellent progress has been made in reducing systematic uncertainties
  - T2K has now surpassed the original sys. error goal (~10% overall)
- Important contributions
  - Dedicated Hadron production experiment (NA61)
  - Good near detector
  - Available external data
  - Theoretical modeling

T2K Data Collected at SuperK (Far Detector)

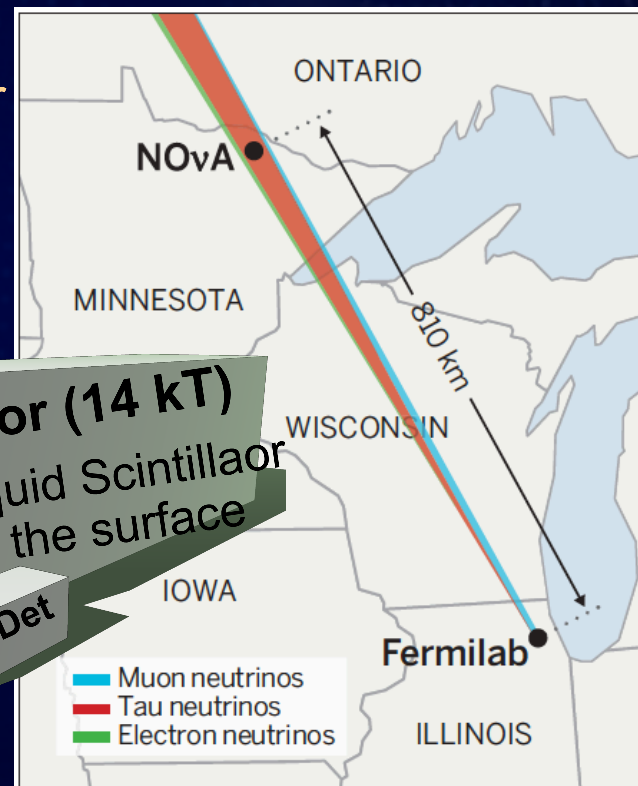


Optimum Run Strategy to Sustain the Best Sensitivity on δ_{CP} throughout T2K Runs

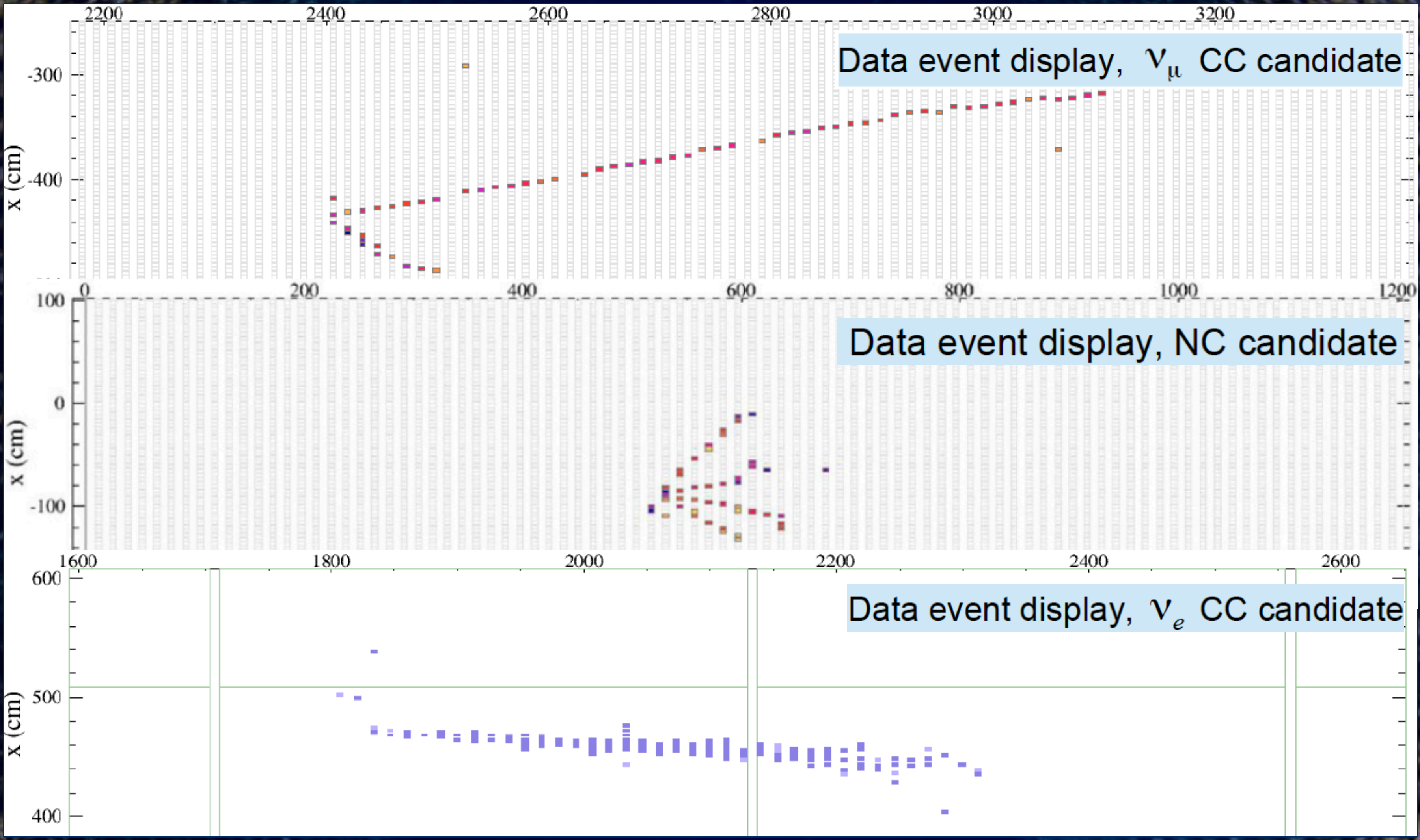
- Through extensive sensitivity studies, It was found that approximately 50%:50% nu-mode to antinu-mode run ratio is a reasonable optimal choice to sustain the best sensitivity on δ_{CP} throughout T2K runs

NOvA Status

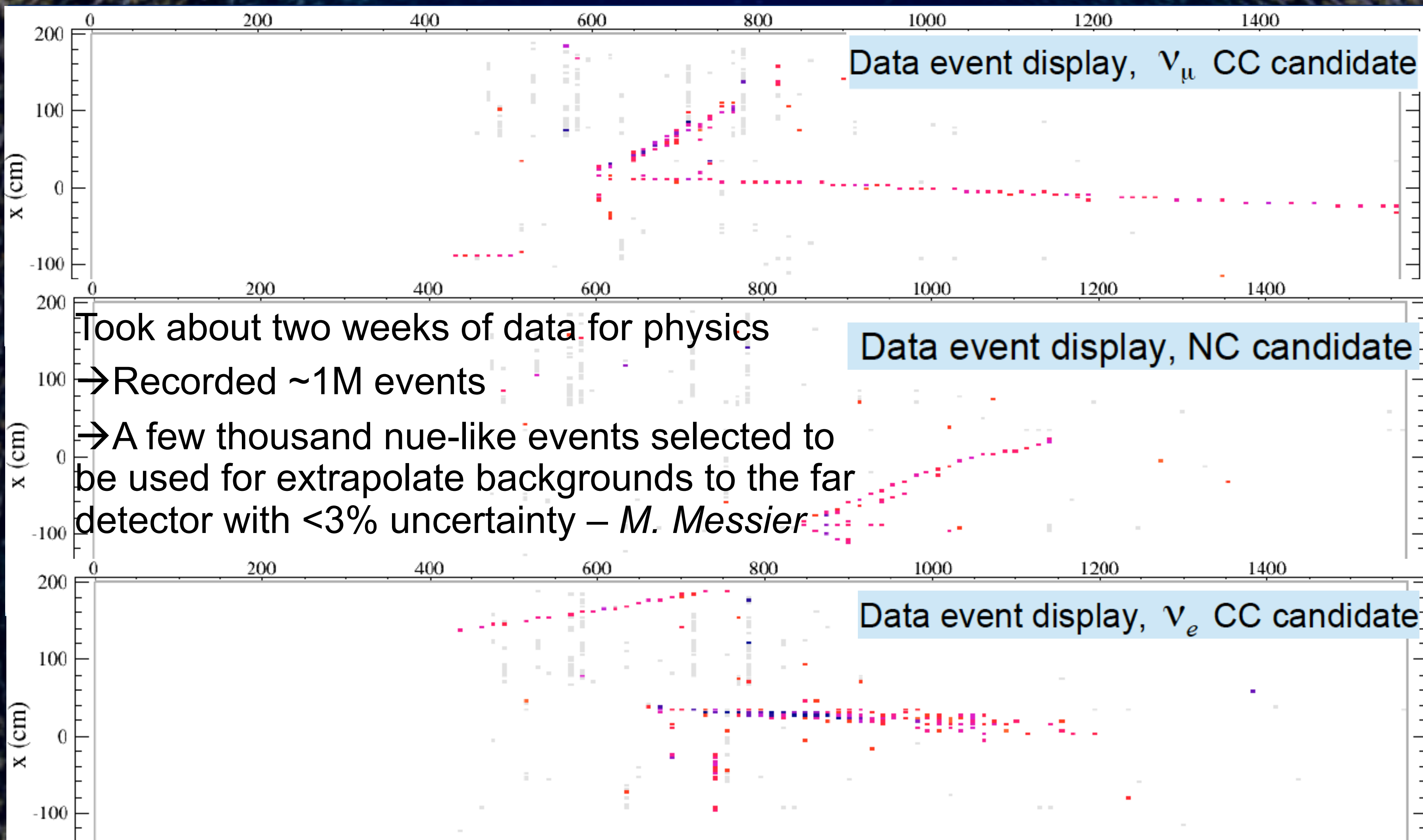
- Detector construction is complete; Received DOE CD4 in Sep. 2014
- Beam Status: Delivered 3×10^{20} POT in 2014, Restarted on Oct. 25, 2014
- Beam power: 320 kW (peak in 2014), 410 kW (expected in 2015), 700 kW (expected in 2016 after booster ring refurbishment)
- 40M:1 cosmic rejection for ν_e selection
- First oscillation results expected early next year



NOvA Far Detector Events



NOvA Near Detector Data and Events

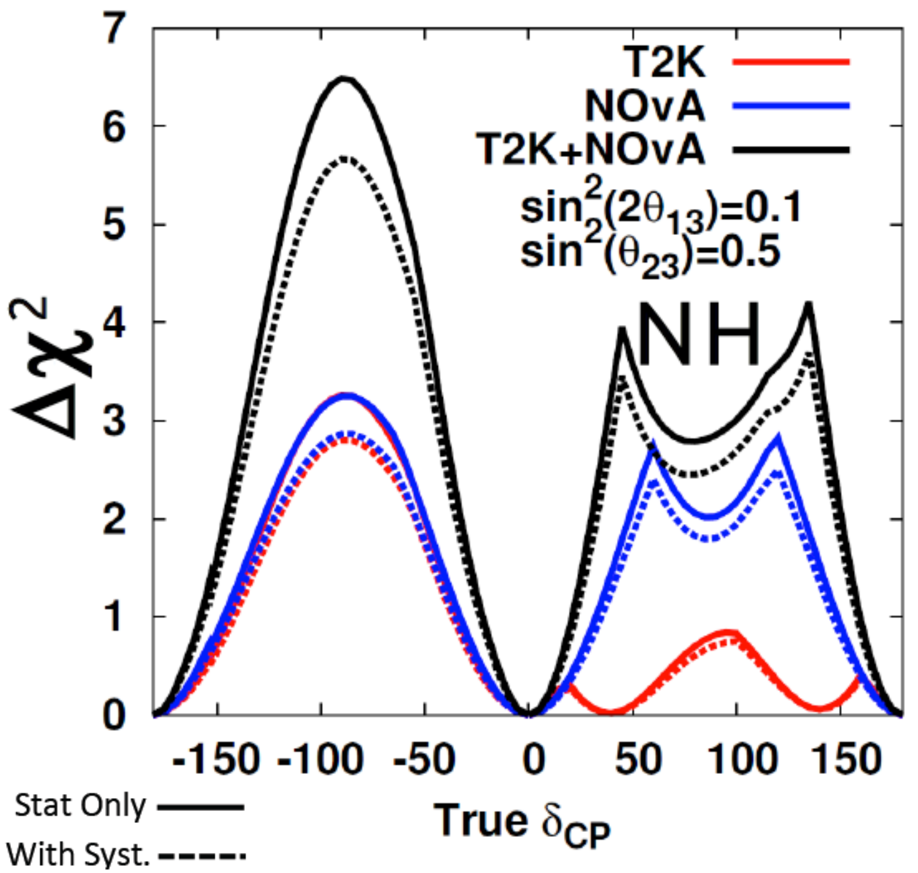


Took about two weeks of data for physics

→Recorded ~1M events

→A few thousand nue-like events selected to be used for extrapolate backgrounds to the far detector with <3% uncertainty – *M. Messier*

T2K and NOvA Sensitivity to Resolve $\delta_{CP} \neq 0$

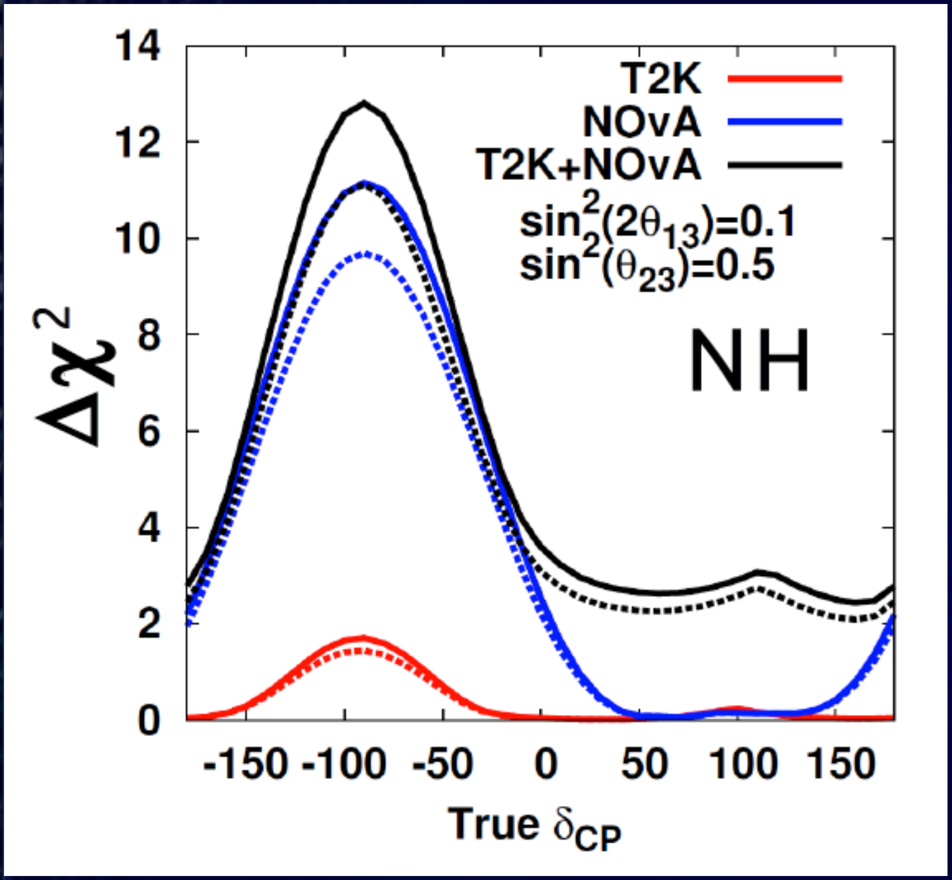


Syst. assuming 5% (10%) normalization uncertainty on signal (background)

- The combined fit improves the sensitivity significantly
- The combined sensitivity to CPV could reach up to 2~3 σ for some values of δ_{CP}

T2K: full data (7.8 x 10^{21} POT)
50% ν + 50% anti-ν runs
NOvA: 3 yrs ν + 3 yrs anti-ν runs
@design beam power

T2K and NOvA Sensitivity to Resolving MH

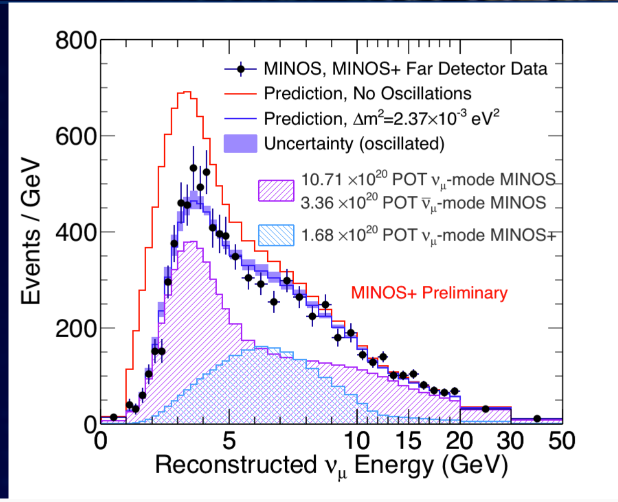


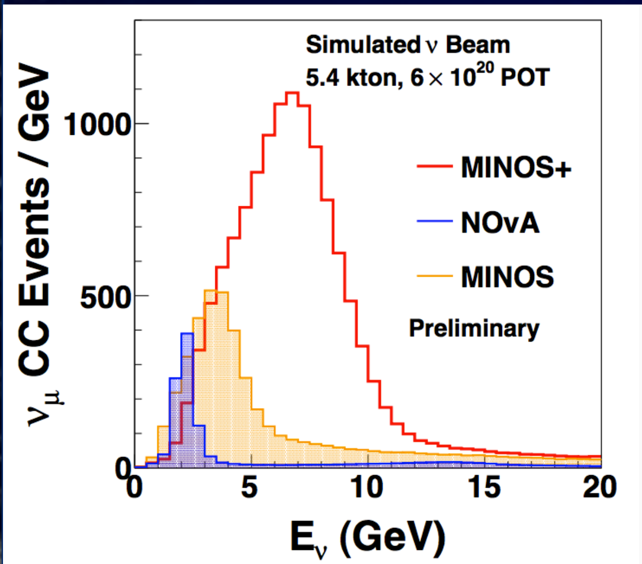
- T2K alone has almost no sensitivity
- The combined fit improves the sensitivity substantially

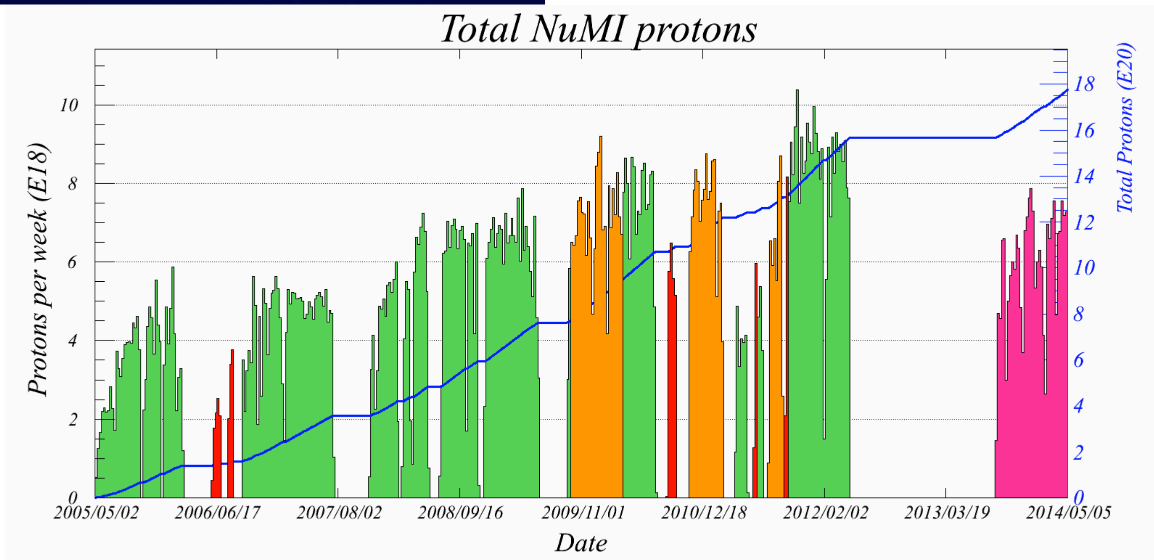
  → Adding SuperK to the fit should further enhance the sensitivity
- The combined sensitivity to MH could reach up to ~3σ for some values of δ_{CP}

MINOS+

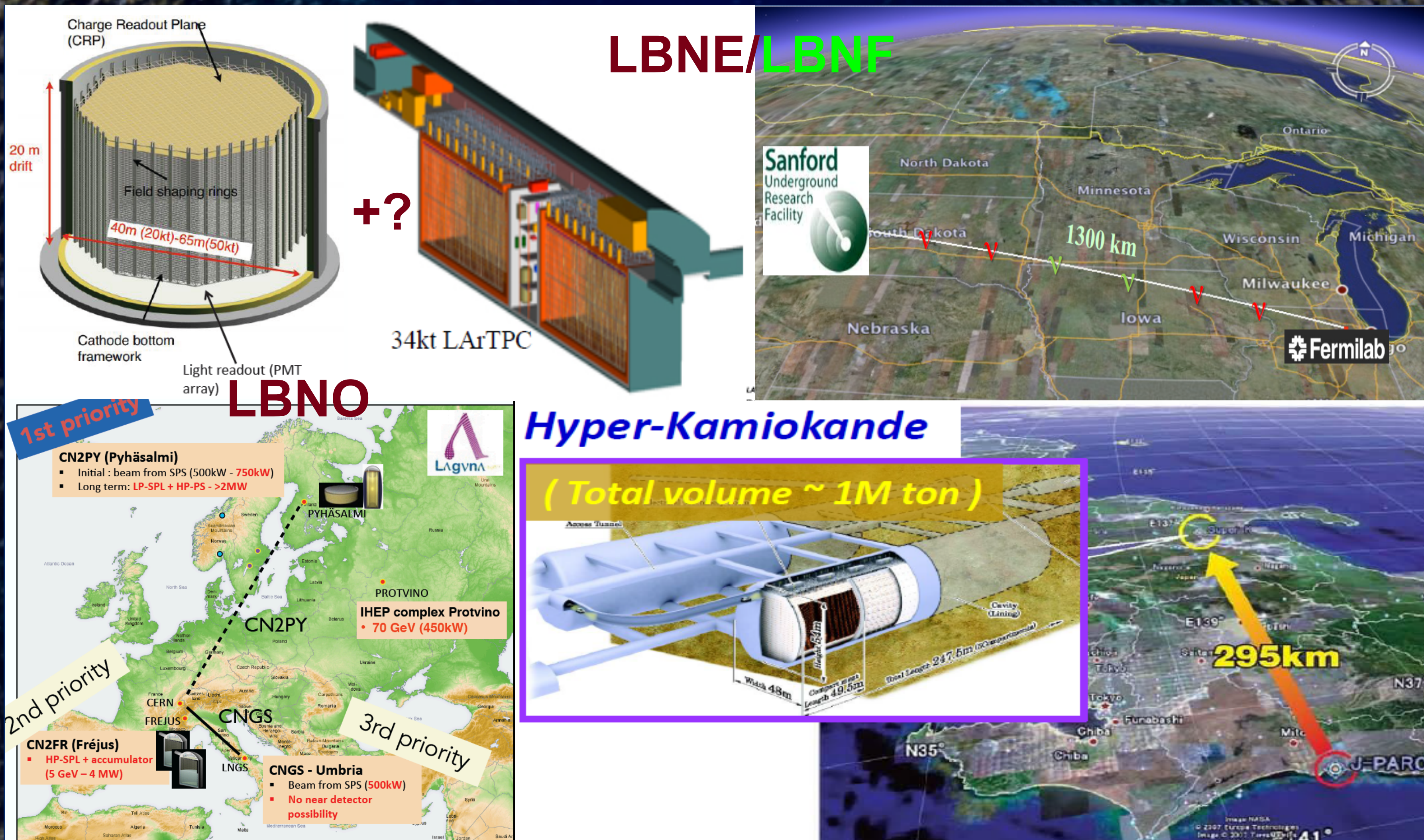
- Physics Goals:
  - – precision 3-flavor mixing tests
  - – sterile neutrinos
  - – non-standard interactions
  - – neutrino cross-section measurements







LBNE, LBNO, LBNF and Hyper-Kamiokande



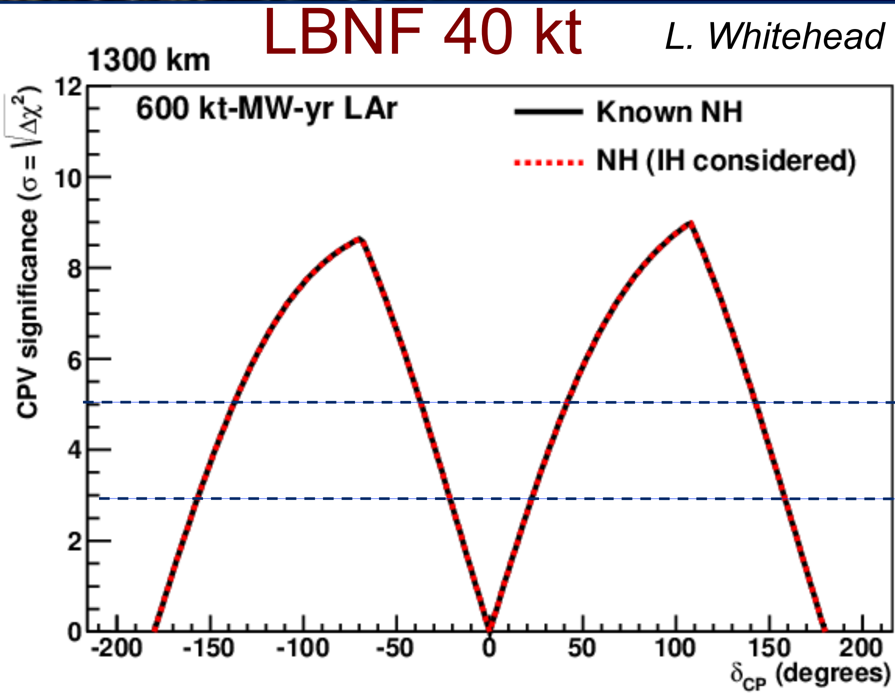
Experiment@LBNF and Hyper-Kamiokande

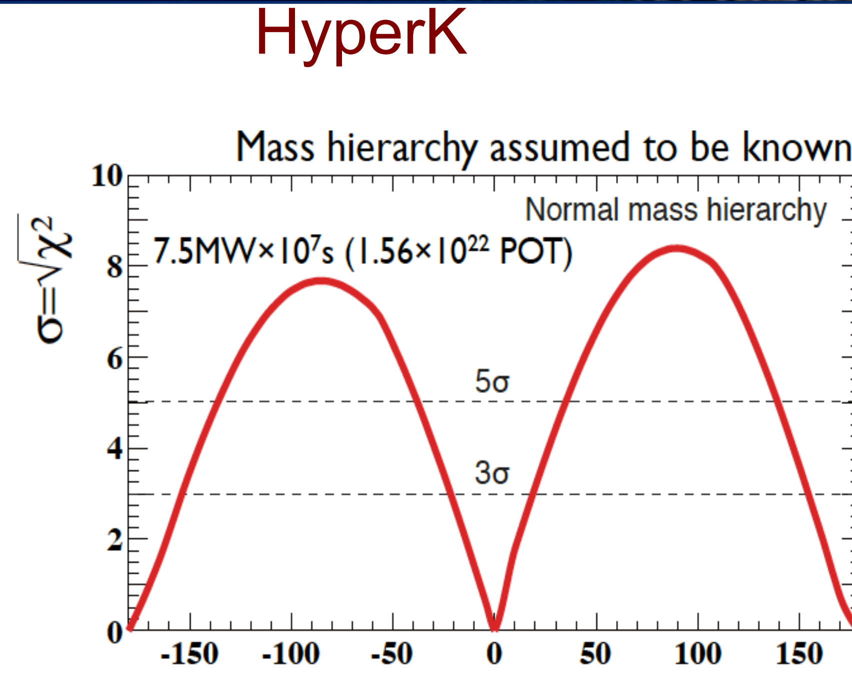
	Experiment@LBNF	Hyper-Kamiokande
Beam Energy	120 GeV (60 – 120 GeV)	30 GeV
Beam Power	≥ 1.2 MW	≥ 750 kW
Beam Configuration	On-axis, Wide-band	Off-axis (2.5^o), Narrow-band
Baseline	1300 km (default)	300 km
Detector Technology	Liquid Ar	Water Cherenkov
Far detector F.V.	35 kt (LBNE) → 40 kt (P5)	560 kt
Near Detector	Yes	Yes
Estimated Cost (to be re-evaluated)	~$1.5B* (Full Costing* for beamline, near and far detectors)	~$800M (only for far detector)
Proposal Status	DOE CD1 approval (in the process of reformulation)	In discussion w/ MEXT (See M. Shiozawa's talk)

(* includes: project management, contingency and escalation)

These two proposed experiments are complementary to each other in many aspects. However, the science goals of each experiment must be compelling on its own. And in my opinion they are.

LBNE and HyperK Sensitivities to CPV





Exposure of
600 kt-MW-yr
(~ 40 kt x 1.2MW x 12.5 yrs)

>3σ CPV sensitivity for 75% of δ

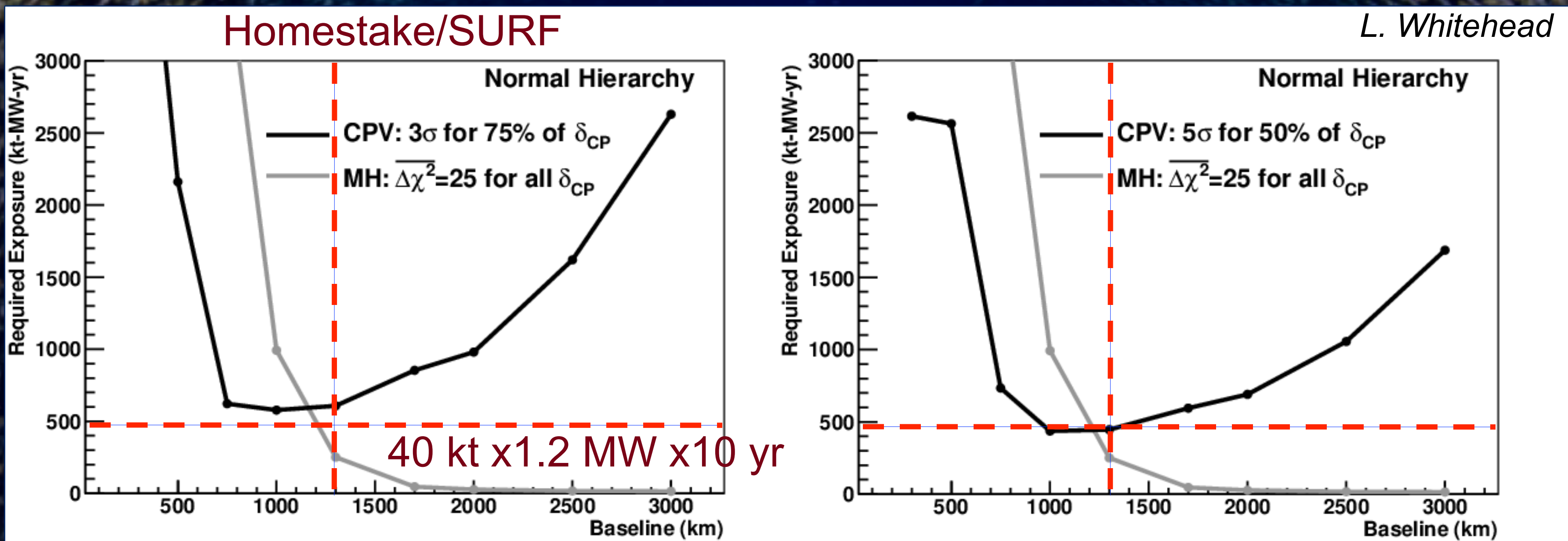
>5σ CPV sensitivity for 56% of δ

Exposure of
7.5 MW x 10^7 s (~ 750 kW x 10 yr)
w/ 560 kt F.V. allows:

>3σ CPV sensitivity for 76% of δ

>5σ CPV sensitivity for 58% of δ

Required Exposure for Given Sensitivities vs. Baseline (LBNE/LBNF Studies)



- Baselines of at least 1000 km are optimal for determining the mass hierarchy and observing CP violation in a wide-band muon neutrino beam from Fermilab
- At the Fermilab to Homestake baseline (1300 km) observing CPV is close to optimum and determining the mass hierarchy at >5σ level can be made in a reasonable time frame (~5 years)

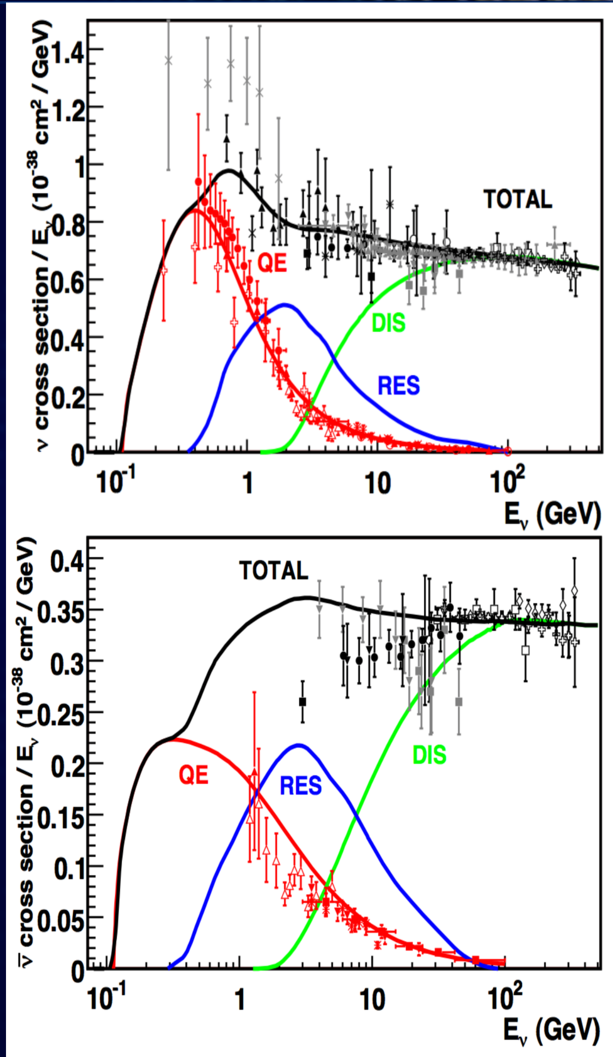
Reformulation of LBNE to an Experiment at LBNF w/ Broad International Participation

- 2008: P5 recommendation to move ahead with a long baseline neutrino experiment
- Dec. 2012: CD1 by DOE ($867M)
- May 2014: P5 Recommendation 13:
  - Form a new international collaboration to design and execute a highly capable Long-Baseline Neutrino Facility (LBNF) hosted by the U.S. To proceed, a project plan and identified resources must exist to meet the minimum requirements in the text. LBNF is the highest-priority large project in its timeframe.
- July 2014: "Neutrino Summit" at Fermilab
  - Formation of interim International Executive Board (iIEB)
- Sep 2014: 1st iIEB meeting at Fermilab
  - Agree to prepare an LOI to form a new international collaboration for an experiment at LBNF
- Dec. 2014: community meeting at CERN (5th) and at Fermilab (12th) to discuss and sign the LOI, and proceed to form a collaboration
- Early 2015: Formation of new broad international collaboration
- Physics LOI to PAC in Jan. 2015 and CDR in summer 2015

Measurements of Neutrino-Nucleus Interactions

- Understanding few-GeV neutrino interactions with nuclei is vital for precision oscillation measurements
  - Such understanding requires understanding complex strongly-bound systems
  - historic data is sparse and at times inconsistent
- Interesting effects from nuclear environment
  - coherent scattering
  - initial state binding/Fermi motion
  - final state interactions in target nucleus (absorption, scattering, charge exchange, etc.)
  - multi nucleon effects
    - directly impact oscillation observables e.g. reconstructed E_ν

➔ Precise and robust measurements and modeling of ν-nucleus interactions are more important than ever



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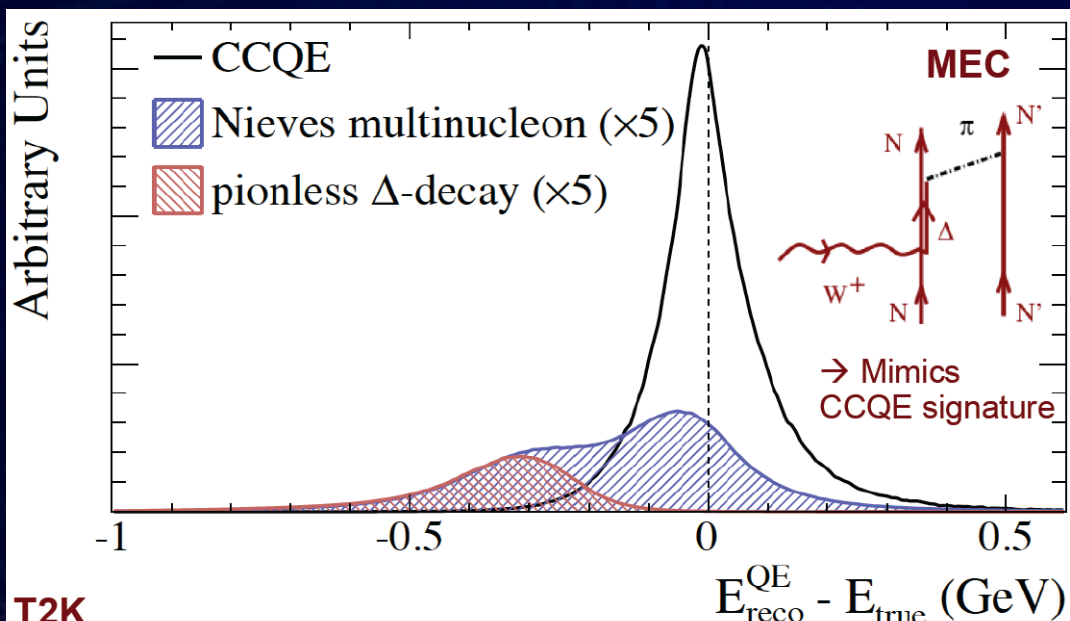
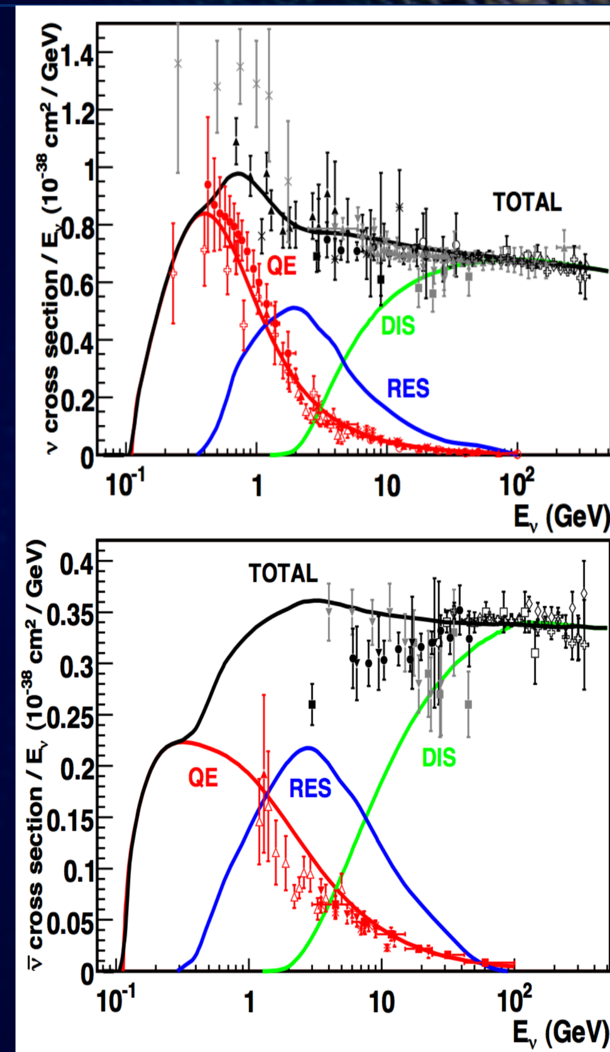
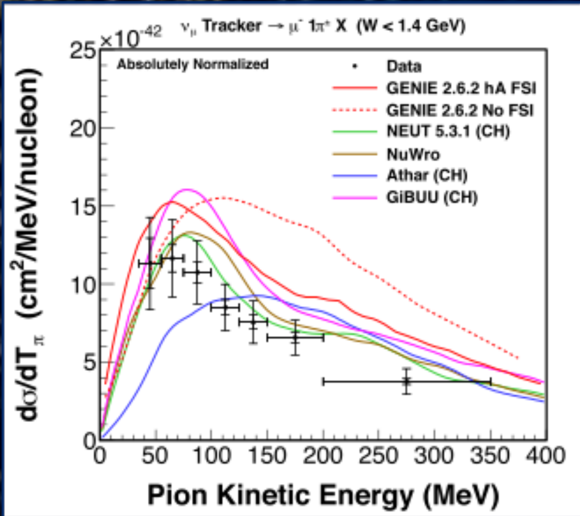
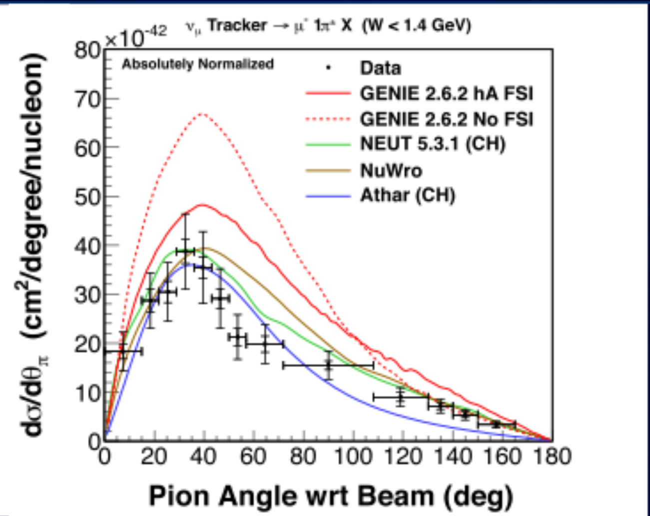




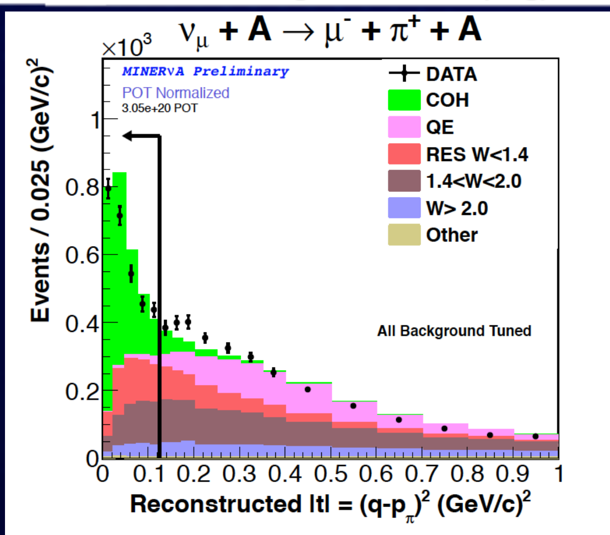
MINERvA CC Single and Coherent Pion Production Results

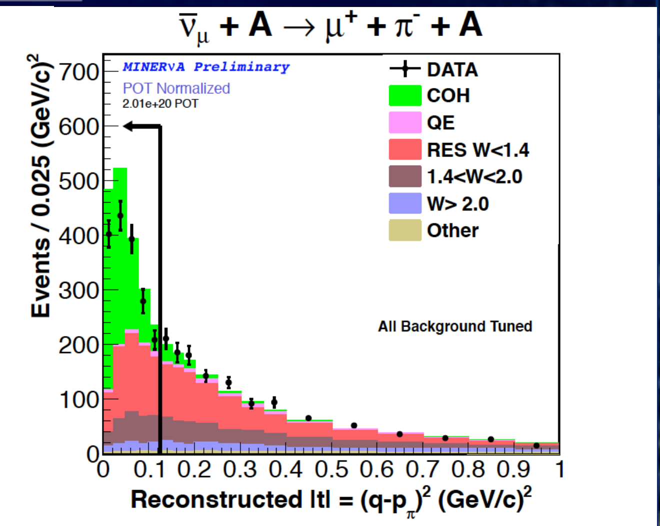




In CC single π+ production, MINERvA pion kinematics show broad agreement with models disagreeing with MiniBooNE results

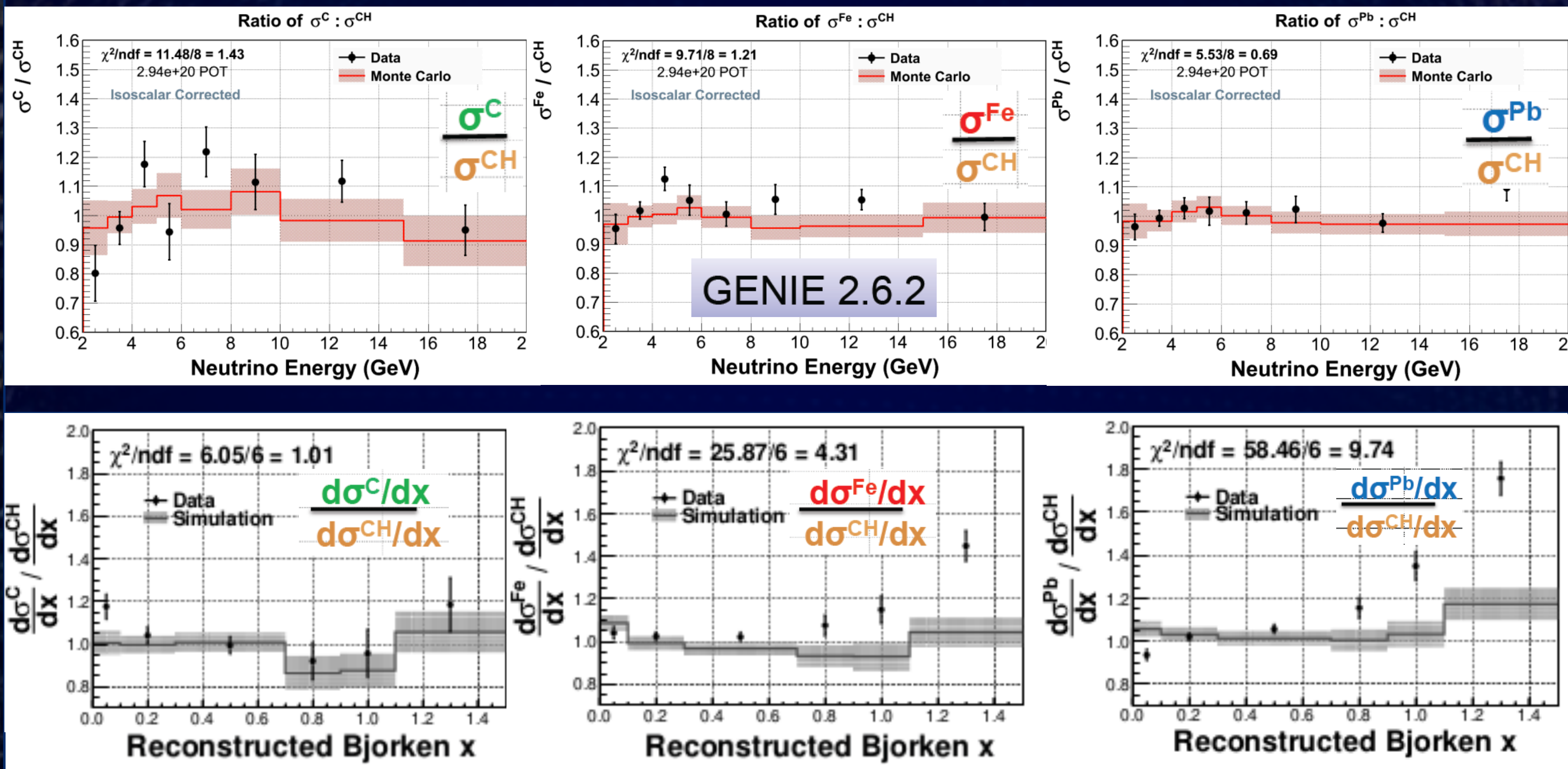
MINERvA sees clear evidence of coherent pion production disagreeing with previous results from K2K and SciBooNE





MINERvA "A" Dependent Relative Cross-section Measurements

MINERvA passive target data shows consistency with model in *E but* not *x*

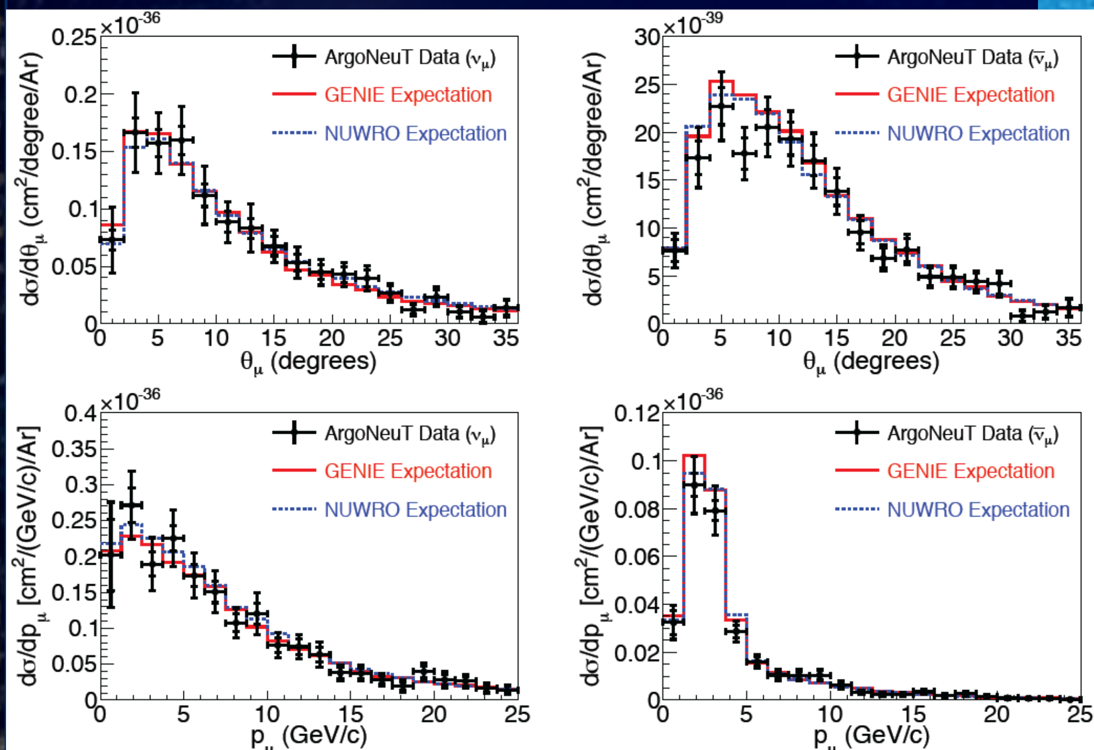


Increasing *A* →

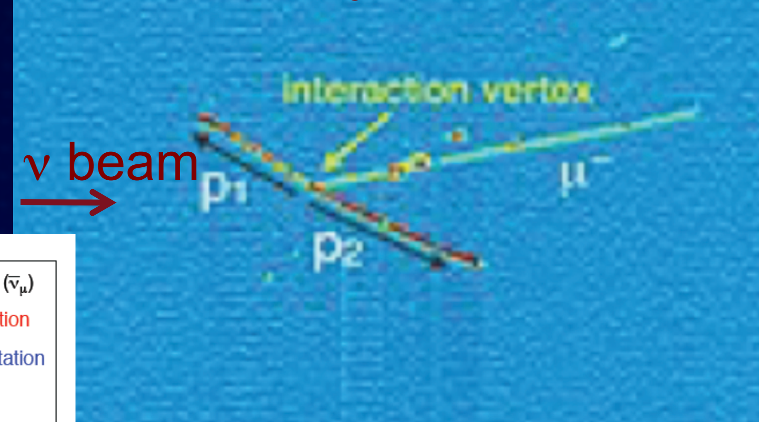
Results from ArgoNeuT

CC inclusive differential cross sections

→ Good agreement w/ models



Multi-baryon final state

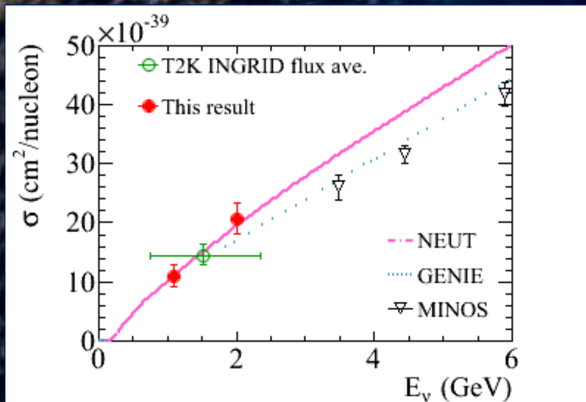


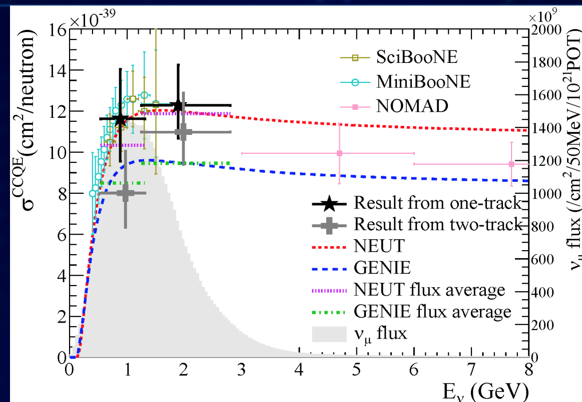
Demonstration of power of LAr TPC

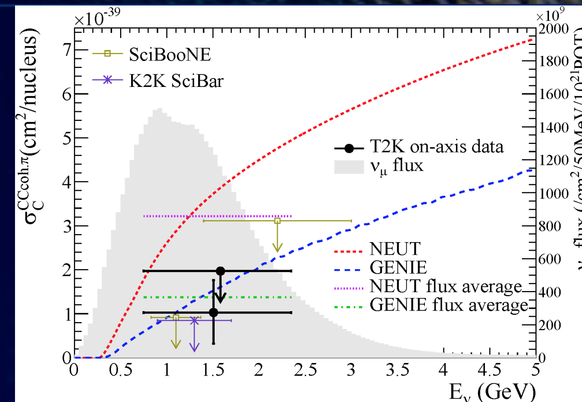
→Low threshold tracking (down to 20 MeV) and excellent PID

→Despite small volume (175 liter), relevant physics produced

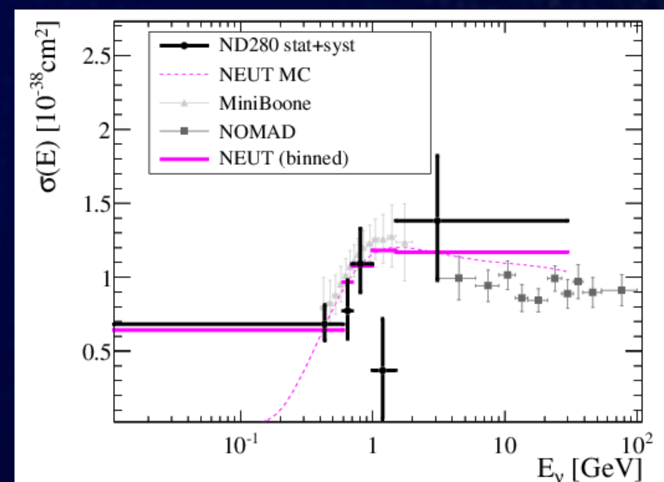
T2K ν_μ CC Cross-section Measurements





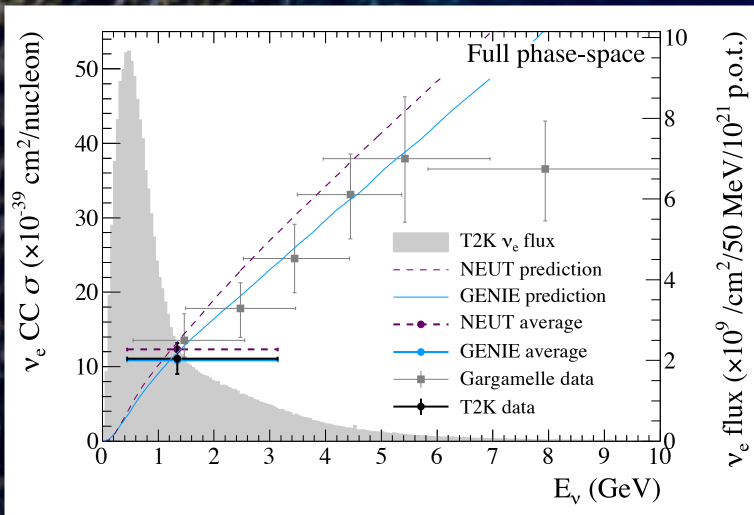


- Top: INGRID (on-axis) measurements:
  - left: inclusive ν_μ CC using varying off-axis spectrum
  - center: ν_μ CCQE in μ, μ+p topologies
  - right: coherent pion production off ^{12}C
- Right: ND280 tracker (off-axis) ν_μ CCQE cross section vs. neutrino energy



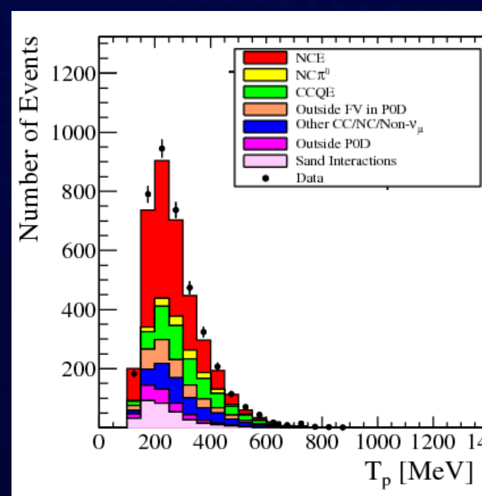
ν_μ CC: primary channel for studying ν-nucleus interactions due to high statistics (beam is ~99% ν_μ/anti-ν_μ)

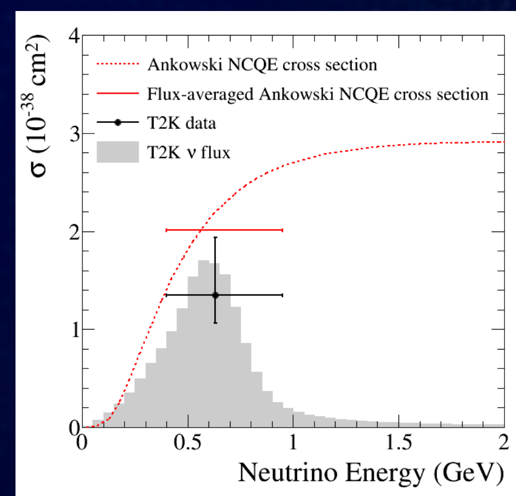
T2K ν_e CC and NC Cross-section Measurements



- ND280 tracker ν_e cross section measurement
  - First ν_e cross section measurement since bubble chamber days
  - First ν_e differential measurement
- Important cross check on signal process in $\nu_\mu \rightarrow \nu_e$ oscillations, modeling of differences in ν_μ/ν_e interactions

- NC elastic:
  ν + (n/p) → ν + (n/p)
  - Left: recoil p identified in P0D
  - Right: de-excitation γ from n/p knockout in ^{16}O in SK (far det.!)





Conclusions

- **“Observation of ν_e appearance from a ν_μ beam”** has now been made
  - This opens the door to study CPV in neutrinos
- Physics goals for the post non-zero θ_{13} /ν_e appearance era are now clearly defined for the world neutrino oscillation community
  - Determination of δ_{CP}, mass hierarchy and θ_{23} (=45°, <45°, >45°?)
    - We may have an initial hint that $\delta_{CP} = -\pi/2$
  - T2K and NOvA will lead the world in determining these parameters for the next decade
  - Next generation experiments should follow in order to ensure the discoveries
- Neutrino oscillation (i.e. the existence of massive neutrino states) is the only phenomena beyond the SM observed in laboratory venue today
- Measurement of CPV will provide critical experimental input to our understanding of the matter–antimatter asymmetry in the universe
- Nature kindly gave us the non-zero neutrino mixing angles and ν_e **appearance** in order for us to be able to probe CP violation

State of Neutrino