Towards the precise measurement of neutrino mixing parameters with long-baseline experiments

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LPNHE
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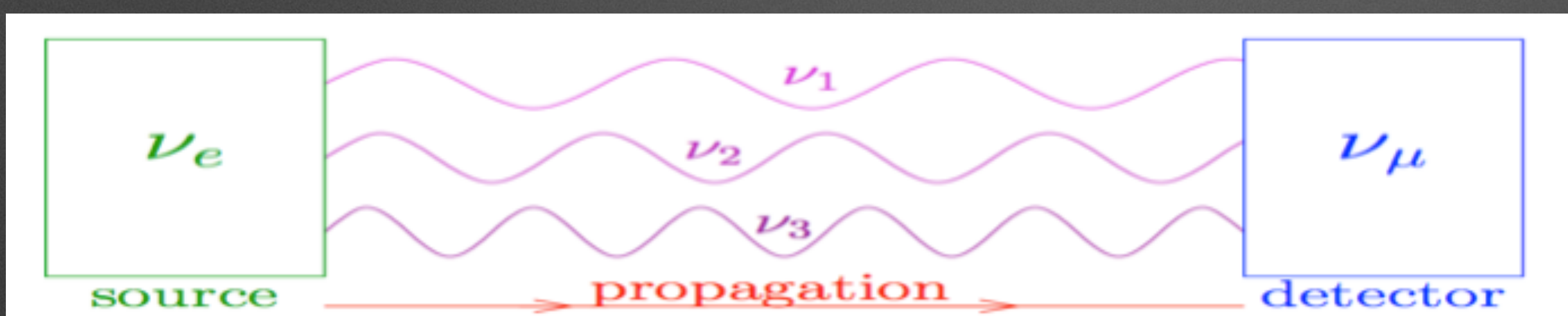
Outline

- Neutrino oscillations
- Long baseline experiments
  - Physics case
  - T2K and NOvA
- Different approaches to oscillation analyses
- Results
- Prospects

Most of NOνA results taken from Alexander Radovic wine&cheese seminar

Neutrino oscillations

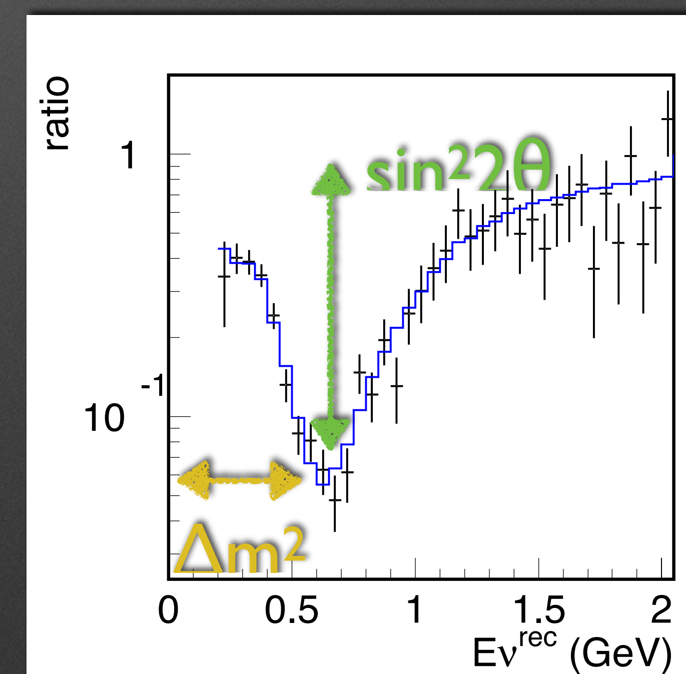
- First introduced by Bruno Pontecorvo in 1957
- Neutrinos are produced in flavor eigenstates ν_e, ν_μ, ν_τ that are linear combination of mass eigenstates ν_1, ν_2, ν_3
- Neutrinos propagate as mass eigenstates
- At the detection a flavor eigenstate is detected → it can be different from the one that was produced



ν_e produced in a mixture of $\nu_{1,2,3}$

$\nu_{1,2,3}$ travel at different speed because they have different masses → interference

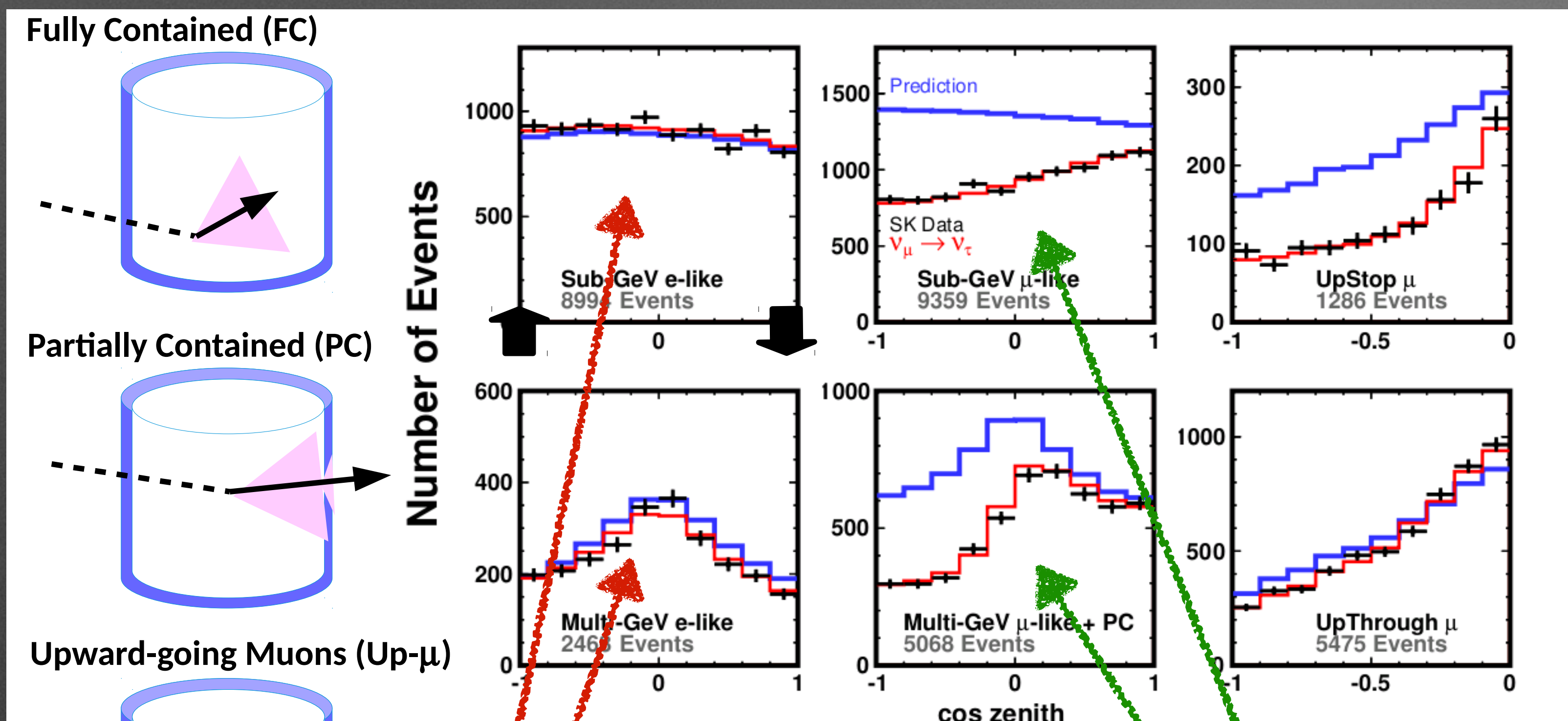
Different mixture of $\nu_{1,2,3}$ → μ from ν_μ is detected



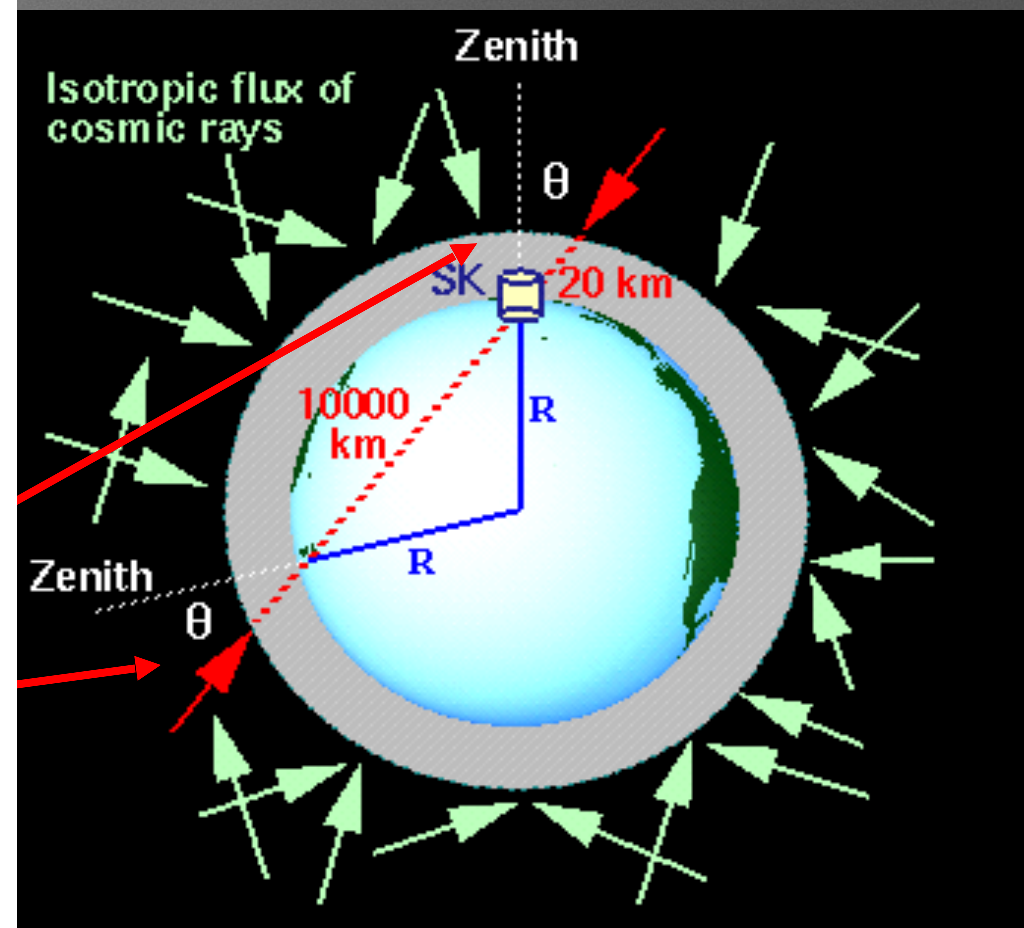
Neutrino oscillation implies massive neutrinos

$$P(\nu_e \to \nu_\mu) = \sin^2(2\theta)\sin^2(\Delta m^2_{12} L/E)$$

Super-Kamiokande (1998)



- In total **19** analysis samples: multi-GeV e-like samples are divided into ν-like and $\bar{\nu}$-like subsamples
- Dominated by $\nu_\mu \to \nu_\tau$ oscillations
- Interested in subdominant contributions to this picture
  - Ie three-flavor effects, Sterile Neutrinos, LIV, etc.



ν_e O.K. !

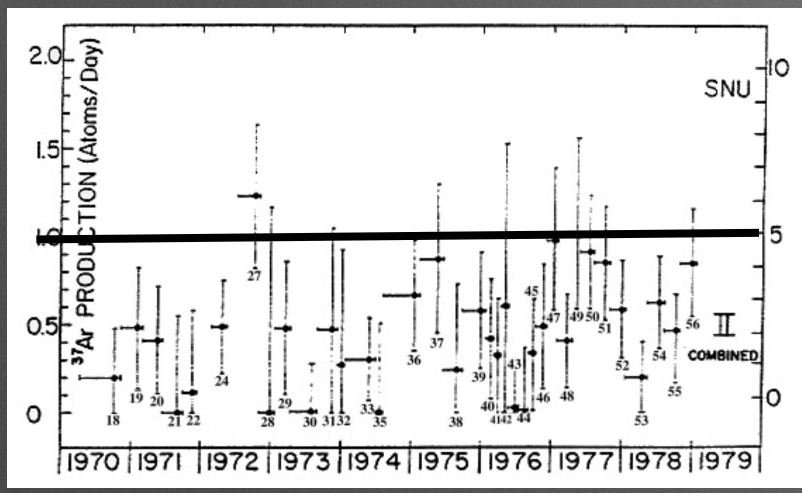
ν_μ deficit !

Neutrino oscillations!
2015 Nobel prize!

Discovery of neutrino oscillations: The ν_μ vary according to the direction (i.e. distance from the source). The ν_e are constant

Favorite scenario: $\nu_\mu \to \nu_\tau$

Solar neutrinos



Average over several decades:

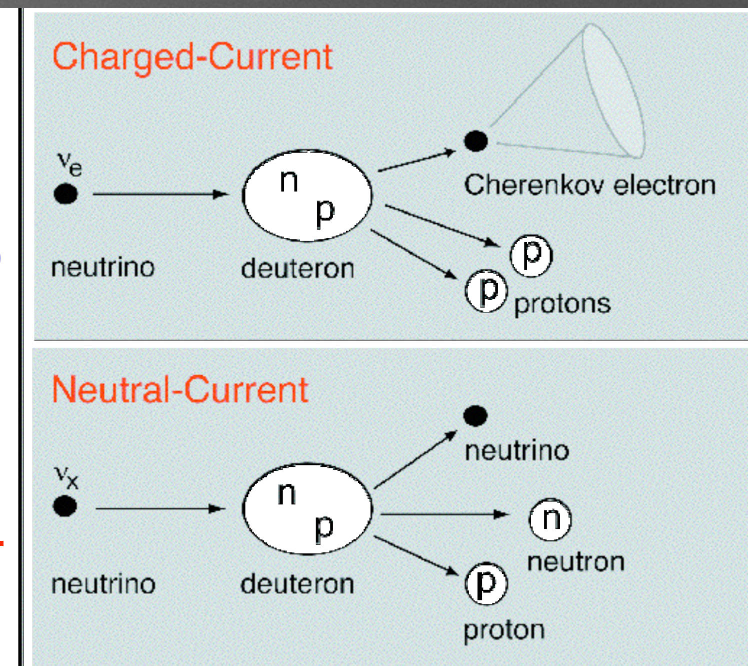
- Average (1970~1994) : $2.56 \pm 0.16_{stat} \pm 0.16_{sys}$
- Ratio(data/SSM) = **0.33**$\pm$0.3

CC $\nu_e + d \Rightarrow p + p + e^-$

-Gives ν_e energy spectrum well
-Weak direction sensitivity $\propto$ 1-1/3cos(θ)
- ν_e only.

NC $\nu_x + d \Rightarrow p + n + \nu_x$

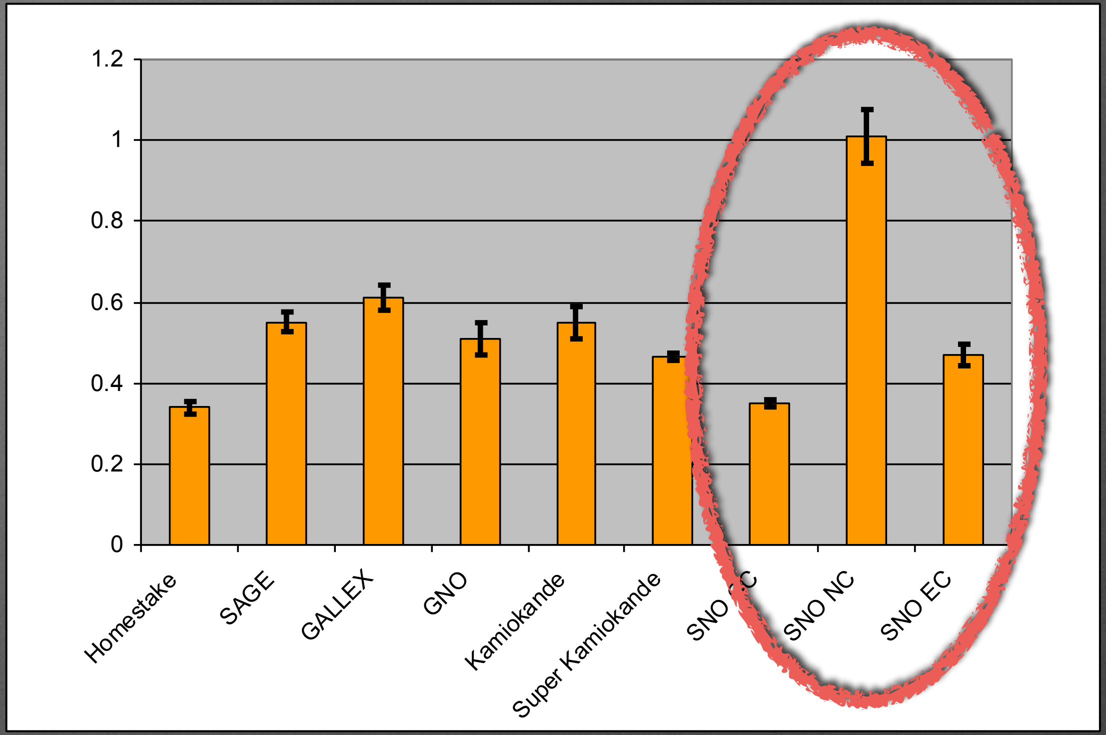
-Measure total ^{8}B ν flux from the sun.
- Equal cross section for all ν types

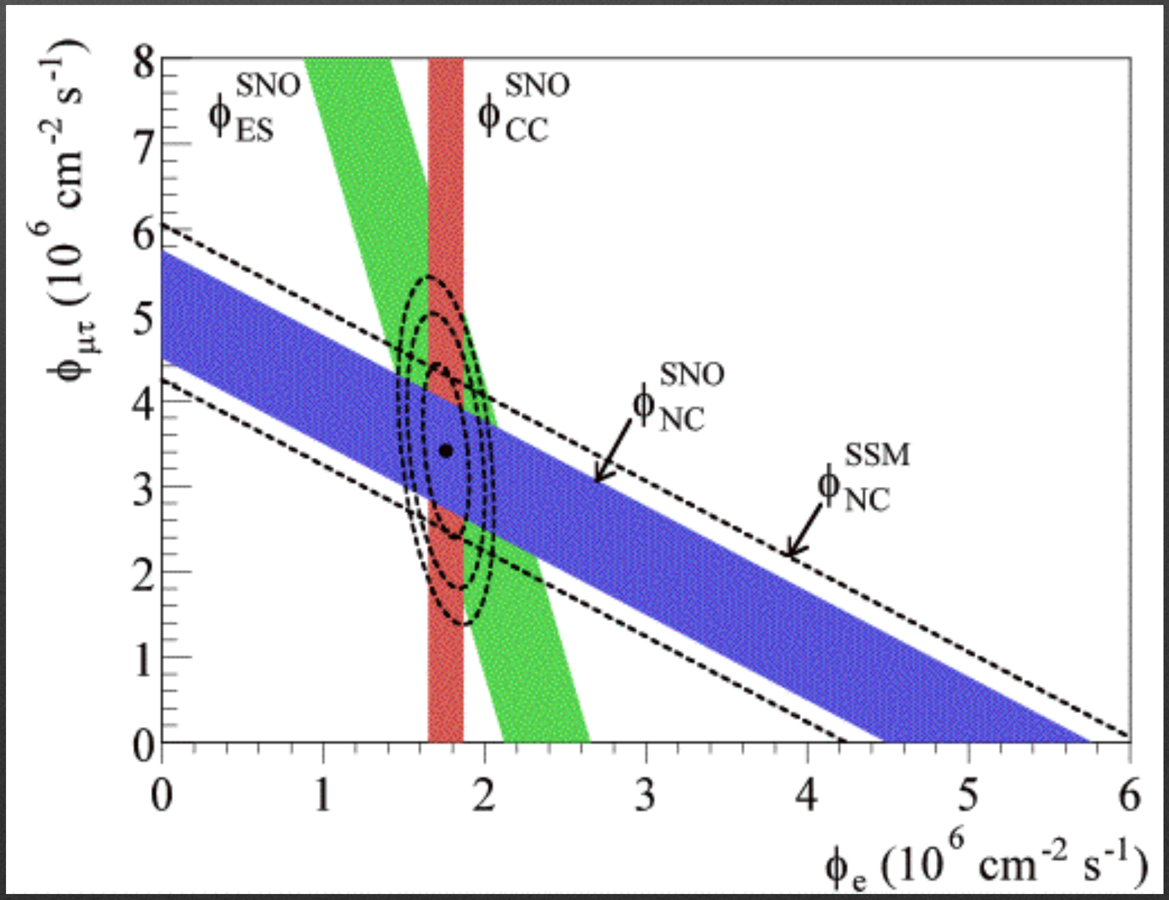


- The Sun is a source of electron neutrinos
- Several experiments since the sixties were sensitive to the Charged Current interactions
  - All consistently observed a deficit with respect to the expected neutrino flux
- SNO (2002): also sensitive to Neutral Current ($\nu_e+\nu_\mu+\nu_\tau$)

SNO results (2002)

- Solar neutrino problem solved by SNO
- Observe a lower flux of CC only but the expected flux of NC!
- ν_e oscillate into a mixing of ν_e, ν_μ, ν_τ





Charged current → only ν_e → deficit of ~2/3

Neutral current → ν_e, ν_μ, ν_τ → expected flux

Neutrino oscillations!
2015 Nobel prize!

Artificial sources of neutrinos

- Neutrino oscillations discovered with solar and atmospheric neutrinos
- Great sources of neutrinos → they come for free, just need to build a detector
  - Ideal for discoveries (span several ranges of Δm^2)
  - Cannot be tuned → you take whatever it's produced → Not the best sources for precision measurements
- Reactors → reactor spectrum is fixed but the distance can be tuned (KamLAND for θ_{12}, DayaBay/DChooz/RENO for θ_{13}, JUNO for Mass Ordering)
- Accelerators → can tune neutrino energy and the distance
  - Well defined L/E → maximize oscillation probability (knowing Δm^2)
  - Sensitive to 5 oscillation parameters (θ_{23}, θ_{13}, Δm^2_{23}, δ_{CP} and mass ordering)
  - Can alternatively produce beam of ν_μ or $\bar{\nu}_\mu$ → study CP violation

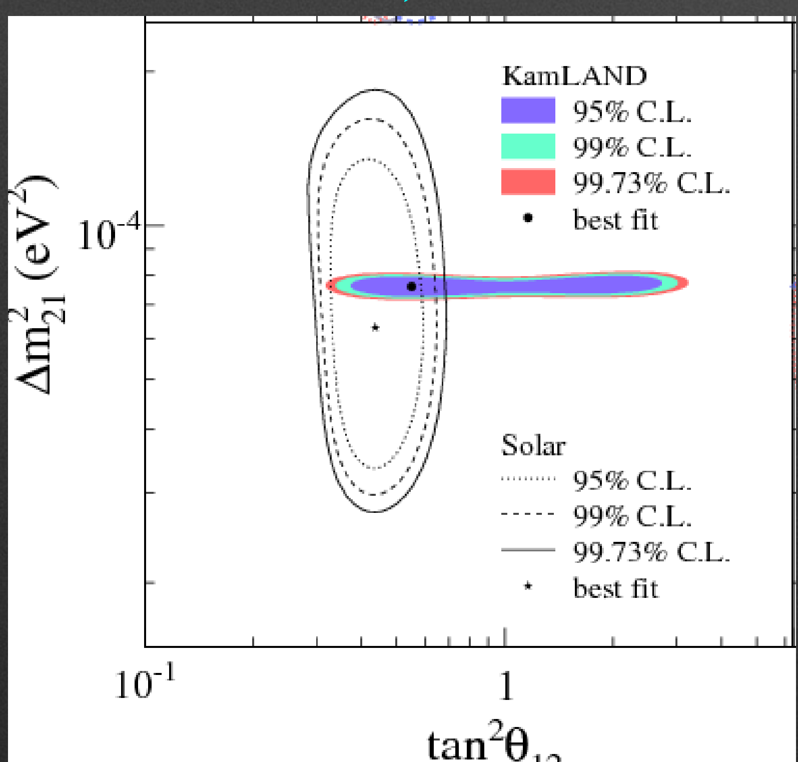
$$P(\nu_\mu \to \nu_x) = \sin^2(2\theta)\sin^2(\Delta m^2_{12} L/E)$$

Neutrino mixing ~ 2011

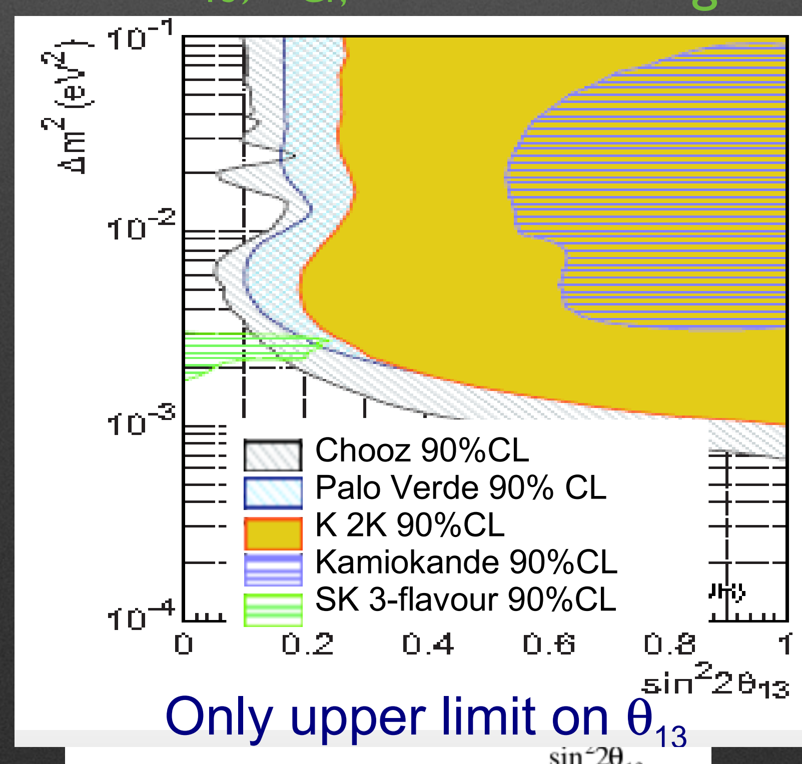
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} cos\theta_{12} & sin\theta_{12} & 0 \\ -sin\theta_{12} & cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} cos\theta_{13} & 0 & sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -sin\theta_{13}e^{i\delta} & 0 & cos\theta_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & cos\theta_{23} & sin\theta_{23} \\ 0 & -sin\theta_{23} & cos\theta_{23} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- 3 mixing angles
- 2 independent mass differences
- 1 CP violation phase

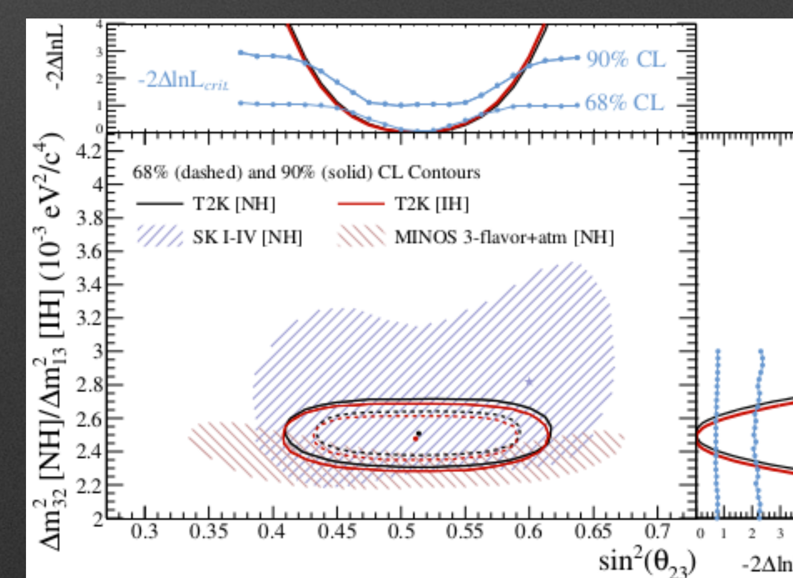
Solar (SNO, KamLand)
→ θ_{12}, Δm_{12}



Interference (Daya Bay, T2K)
→ θ_{13}, δ_{CP}, Mass Ordering



Atmospheric (SK, K2K, Minos, T2K)
→ θ_{23}, Δm_{32}



How to measure θ_{13}

Reactors (DChooz, RENO, Daya Bay)

- ✓ Disappearance of $\bar{\nu}_e$ $P(\bar{\nu}_e \to \bar{\nu}_e)$
- ✓ $\bar{\nu}_e$ produced in nuclear reactors
  - ✓ Neutrino energy few MeV
  - ✓ Distance L ~ 1 km
- ✓ Signature: disappearance of the $\bar{\nu}_e$ produced in the reactor → depends on θ_{13}

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - sin^2 2\theta_{13} sin^2\Delta_{13} - cos^4\theta_{13} sin^2 2\theta_{12} sin^2\Delta_{12}$$

Simple dependence on θ_{13} (and Δm_{31}^2

Accelerators (T2K, Nova):

- ✓ Appearance experiment: $P(\nu_\mu \to \nu_e)$
- ✓ ν_μ neutrino beam
  - ✓ Neutrino energy ~1 GeV
  - ✓ Distance L >~ 300 km
- ✓ Signature: ν_e appearance in ν_μ beam
- ✓ Degeneracy of θ_{13}, δ_{CP}, sign of Δm^2

1st order → θ_{13}

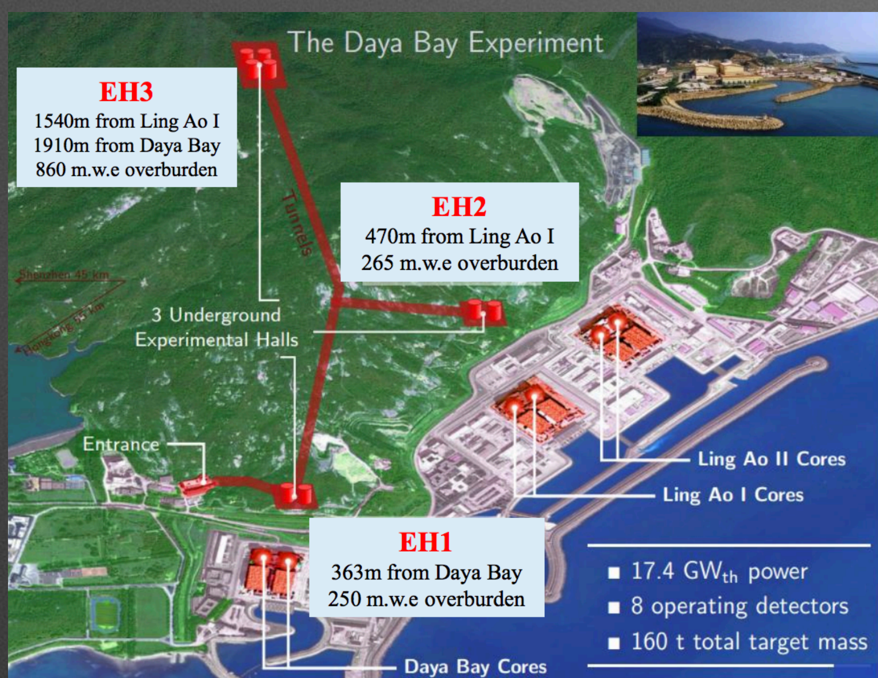
$$P(\nu_\mu \to \nu_e) \sim \sin^2\theta_{23} \frac{sin^2 2\theta_{13}}{(\hat{A}-1)^2} \sin^2((\hat{A}-1)\Delta)$$
$$+ \alpha \frac{8J_{CP}}{\hat{A}(1-\hat{A})} \sin(\Delta)\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)$$
$$+ \alpha \frac{8I_{CP}}{\hat{A}(1-\hat{A})} \cos(\Delta)\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)$$
$$\alpha^2 \frac{cos^2\theta_{23}\sin^2\theta_{12}}{\hat{A}^2} \sin^2(\hat{A}\Delta)$$

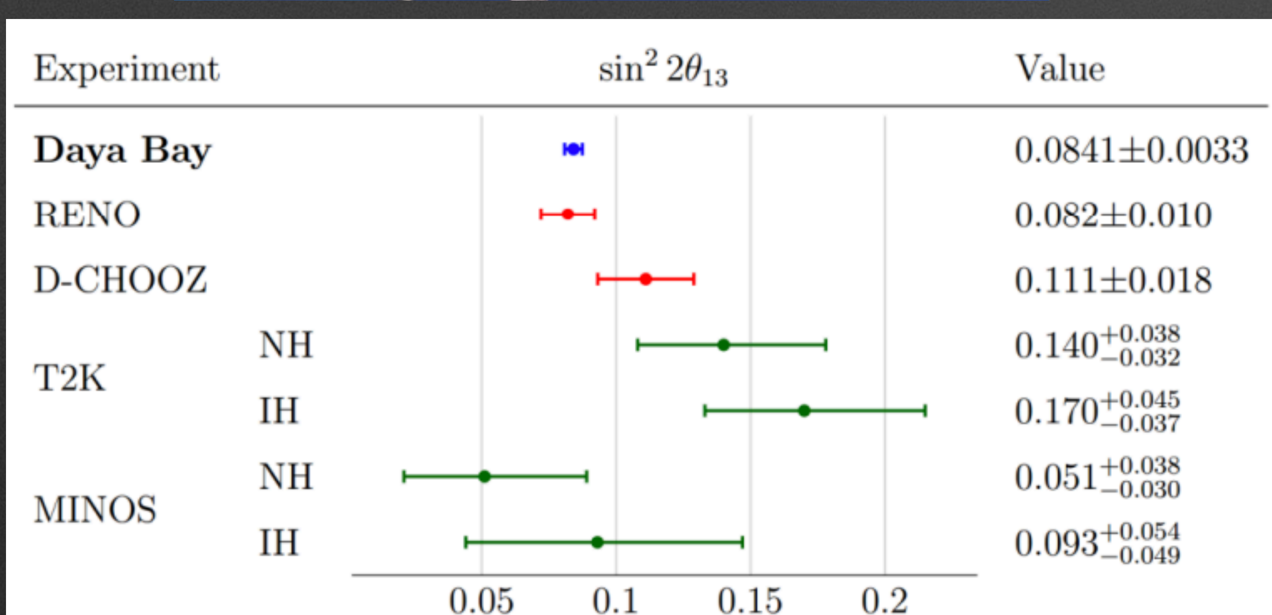
J_{CP} → CPV term
A depends on the sign of Δm^2

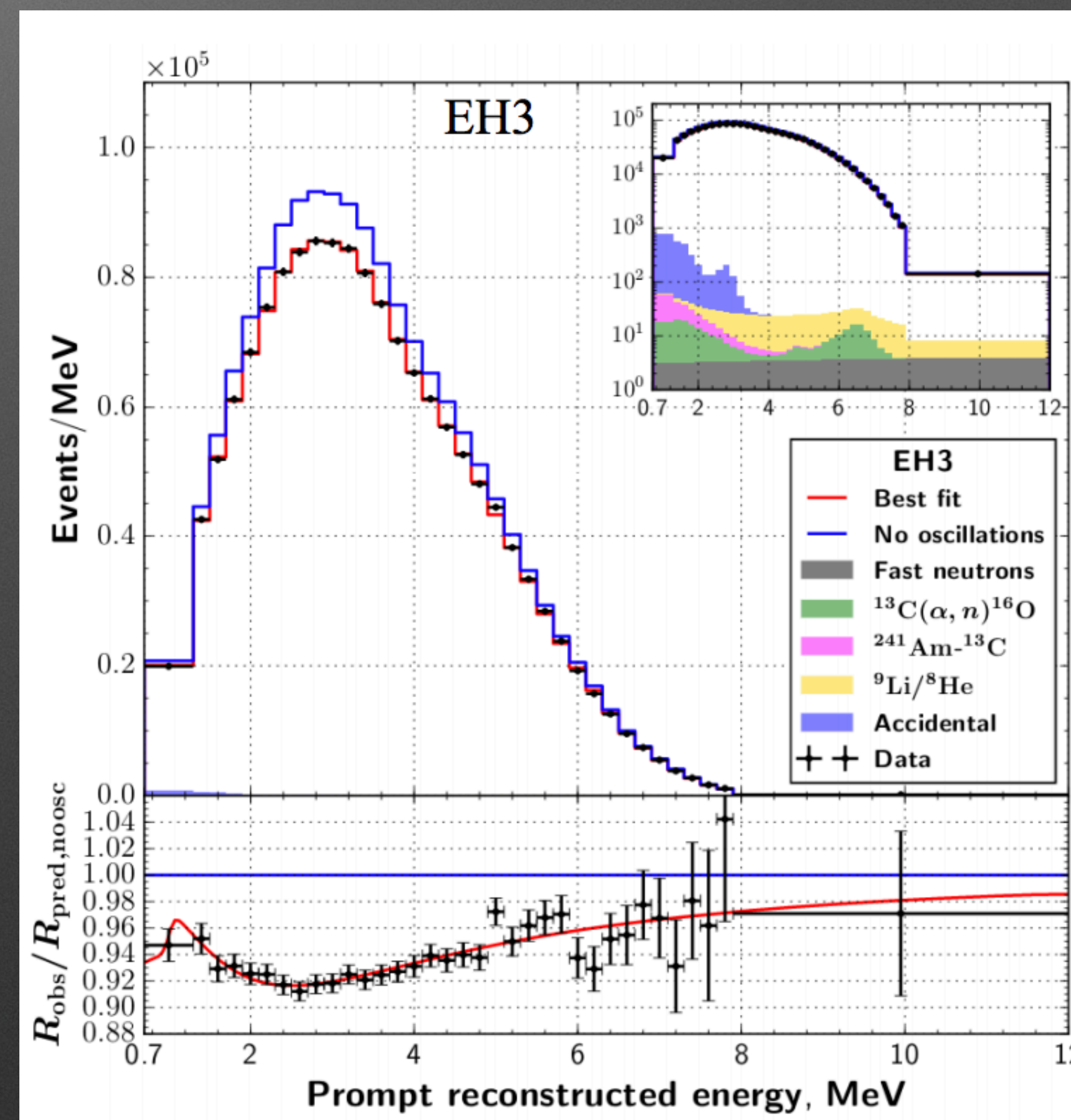
$\Delta = \Delta m_{32}^2 L/4E$ $\alpha = |\Delta m_{32}^2|/|\Delta m_{21}^2| \sim 1/30$

θ_{13} measurements

- Accelerators measured θ_{13} through νe appearance (T2K 2013, NOνA 2015)
- Most precise measurement from reactors (Daya Bay and RENO in 2012)





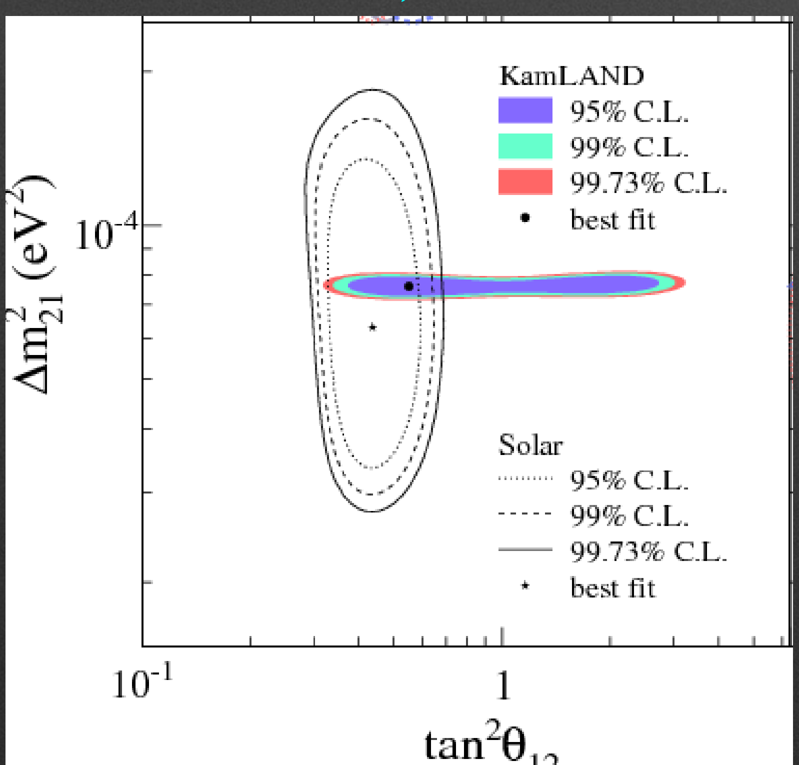


Neutrino mixing today

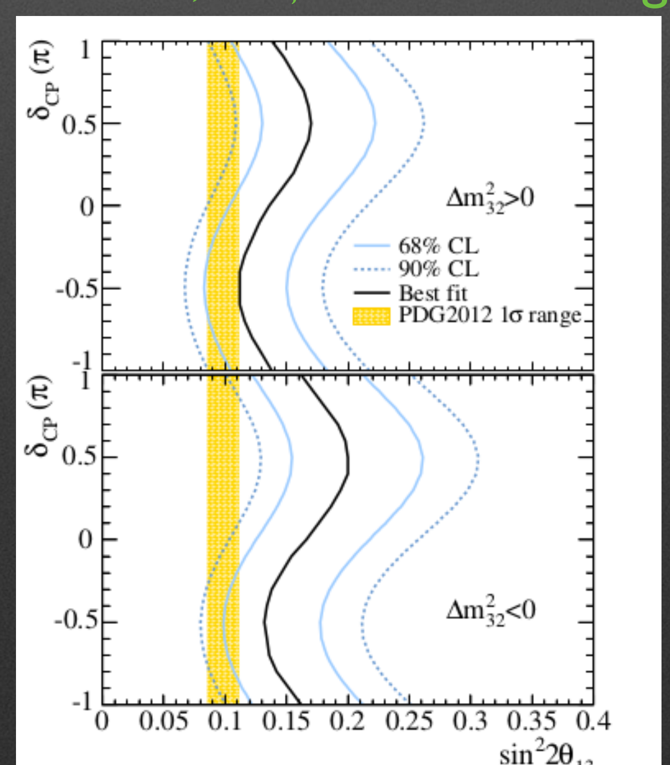
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} cos\theta_{12} & sin\theta_{12} & 0 \\ -sin\theta_{12} & cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} cos\theta_{13} & 0 & sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -sin\theta_{13}e^{i\delta} & 0 & cos\theta_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & cos\theta_{23} & sin\theta_{23} \\ 0 & -sin\theta_{23} & cos\theta_{23} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- 3 mixing angles
- 2 independent mass differences
- 1 CP violation phase

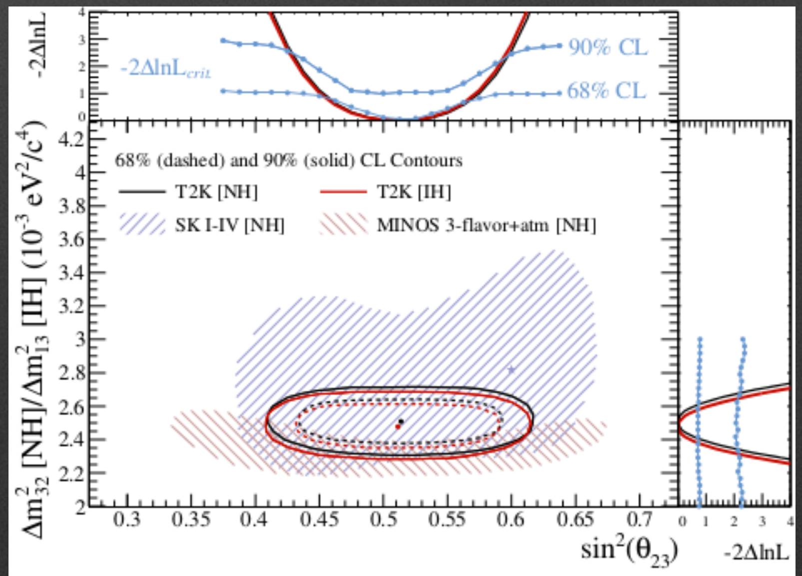
Solar (SNO, KamLand)
→ θ_{12}, Δm_{12}



Interference (Daya Bay, T2K)
→ θ_{13}, δ_{CP}, Mass Ordering

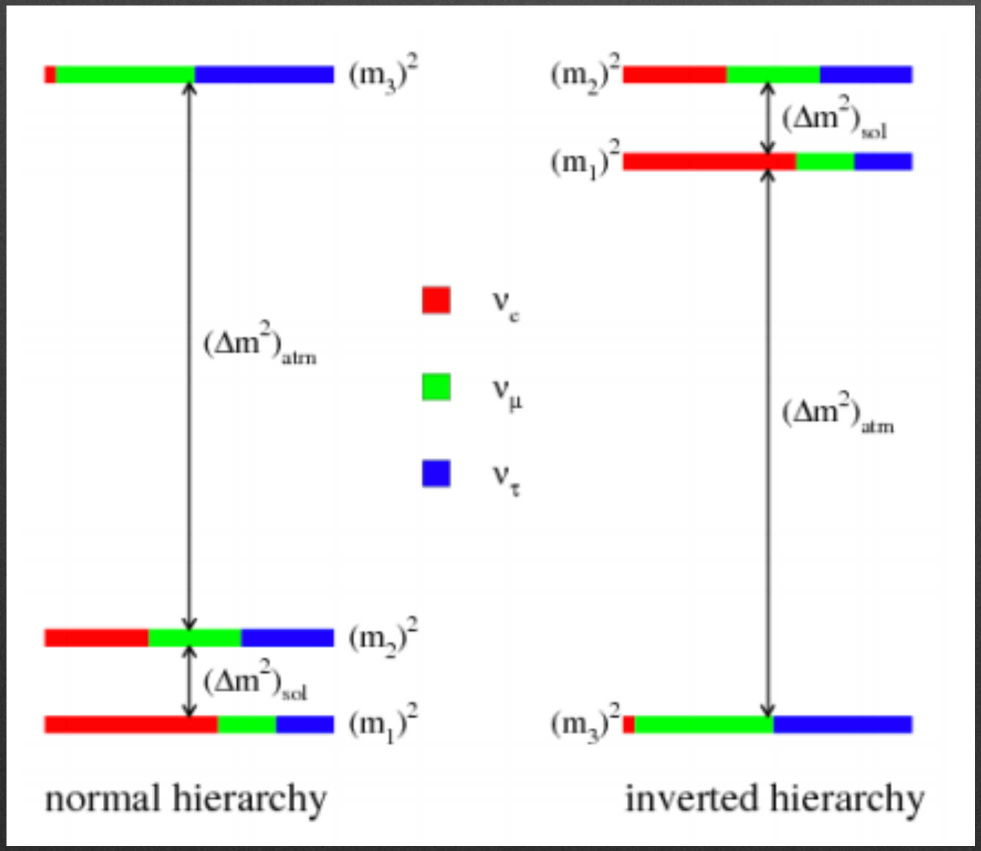


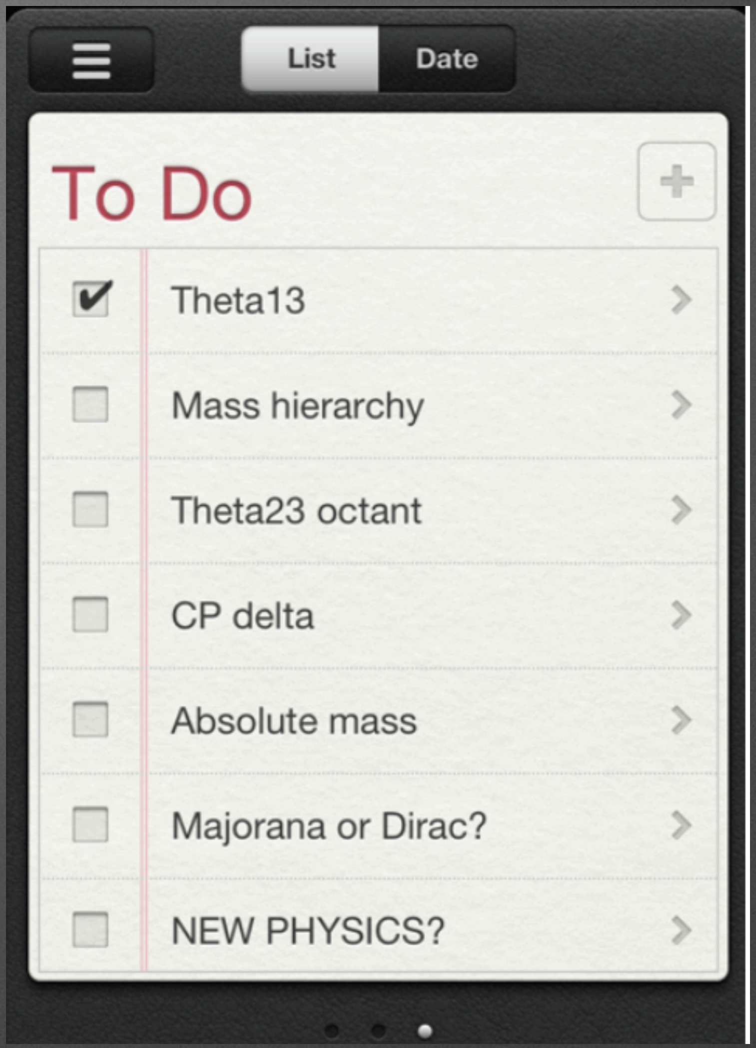
Atmospheric (SK, K2K, Minos, T2K)
→ θ_{23}, Δm_{32}

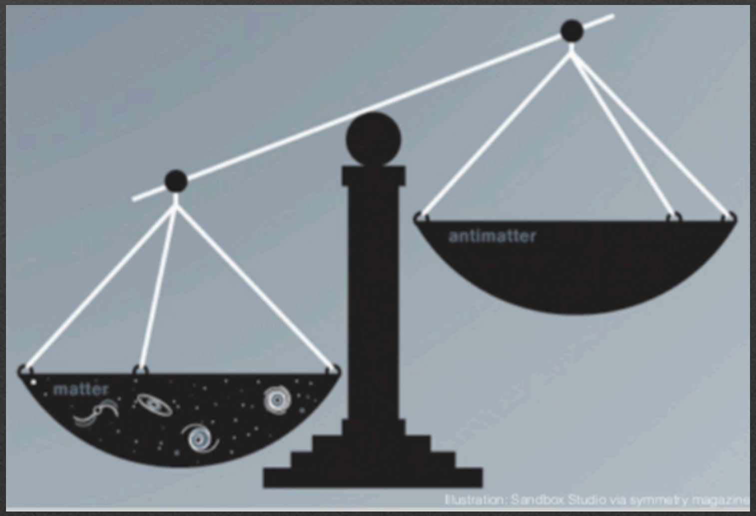


Main questions

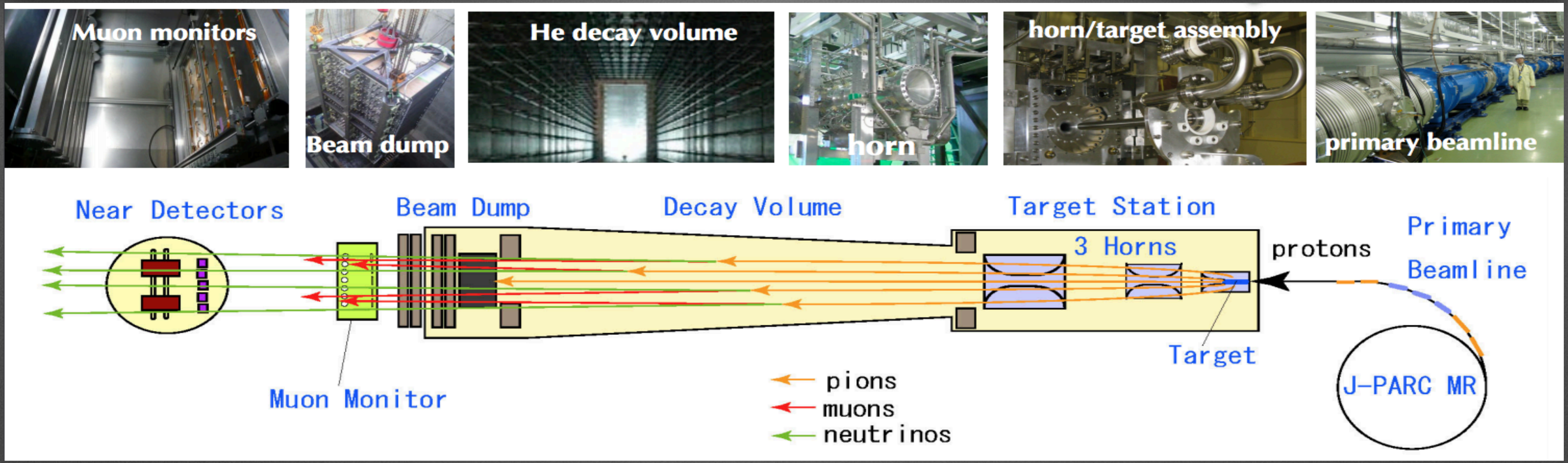
- Several question in neutrinos physics still to be addressed
- Most of them are accessible to accelerators
  - Why mixing so large with respect to CKM? Is θ_{23} maximal?
  - Which is the hierarchy of neutrino masses?
  - Is CP violated in the leptonic sector?

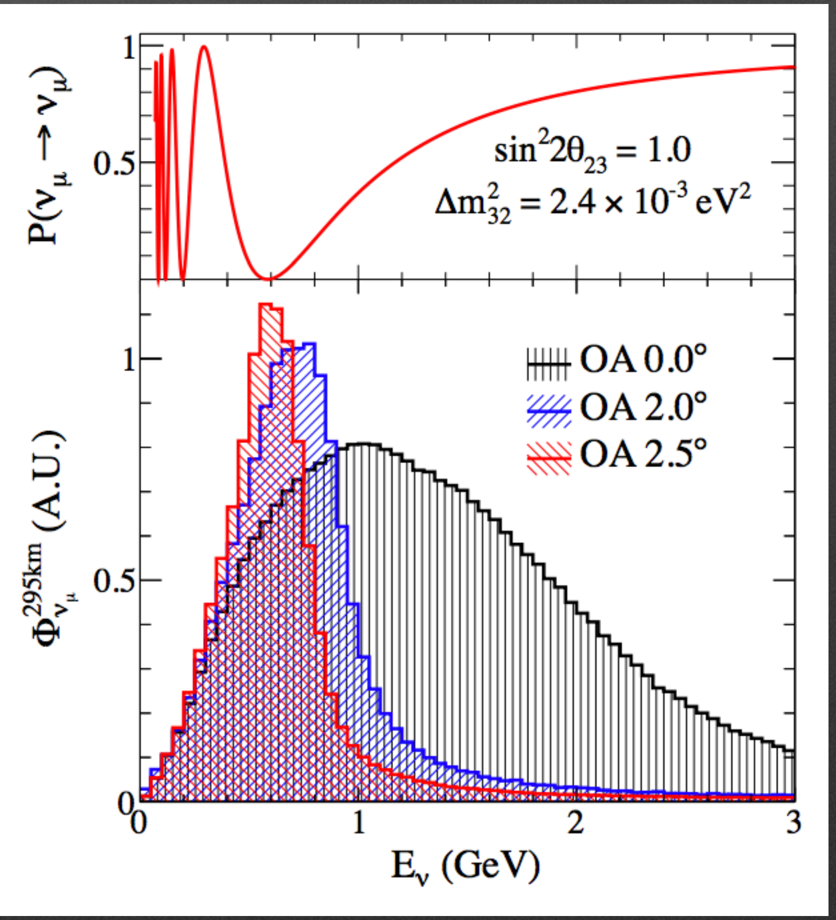






Neutrino beams





1. Accelerate protons and strike a target producing pions, kaons

2. The hadrons enter a system of magnetic horns where they are selected in charge and focused → mostly π^+ or π^-

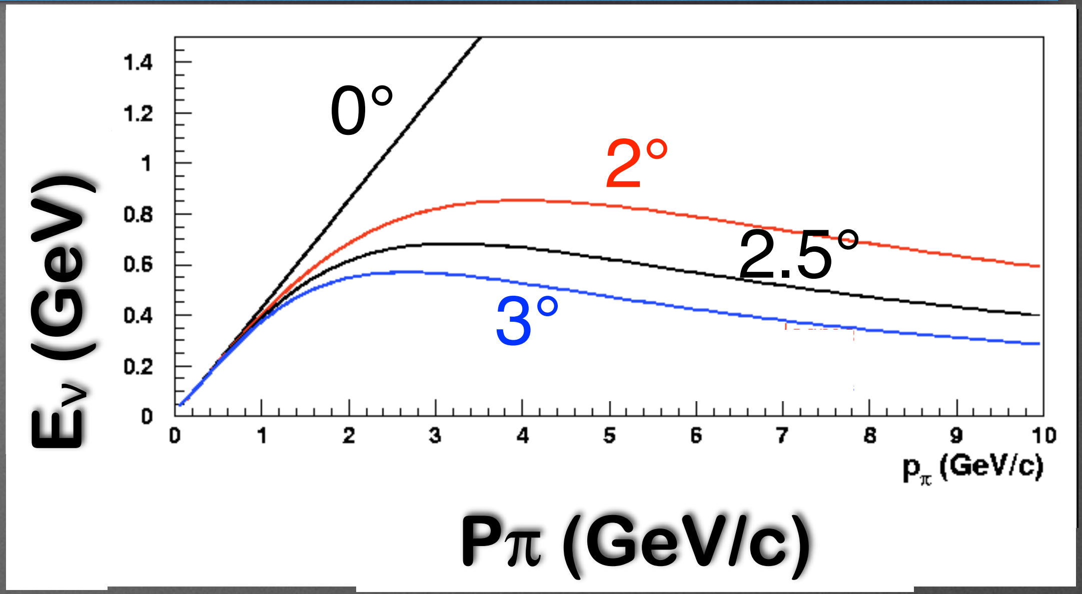
3. The hadrons enter a decay tunnel where they decay into neutrinos ($\pi^+ \to \mu^+ + \nu_\mu$)

4. At the end of the decay tunnel a beam dump stops all the particles that are not neutrinos

Off-axis technique

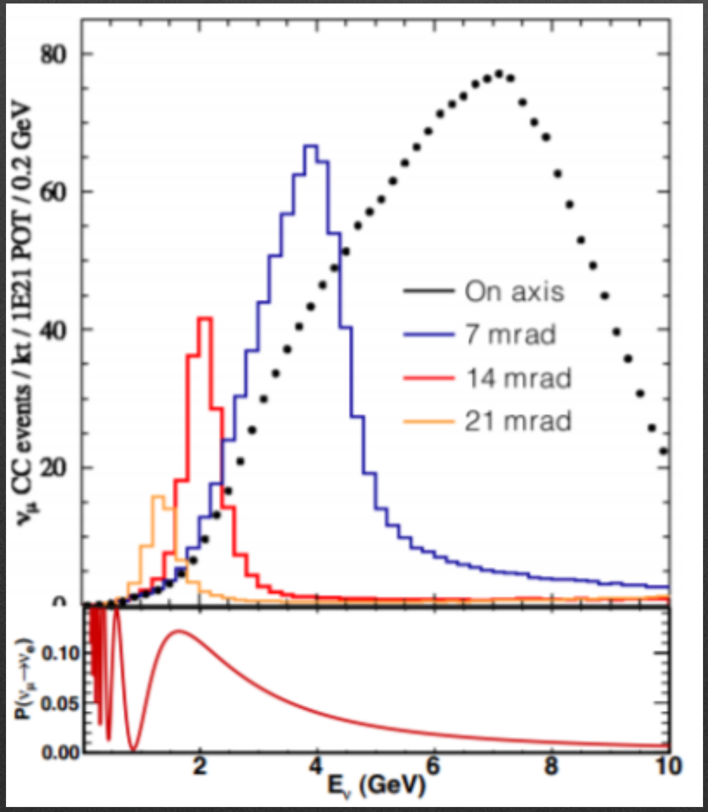
$\pi^+ \rightarrow \mu^+ + \nu_\mu$

- Off-axis technique allows to increase the intensity of the beam for at the desired L/E
- Maximise the oscillation probability, minimising the backgrounds from high energy neutrinos

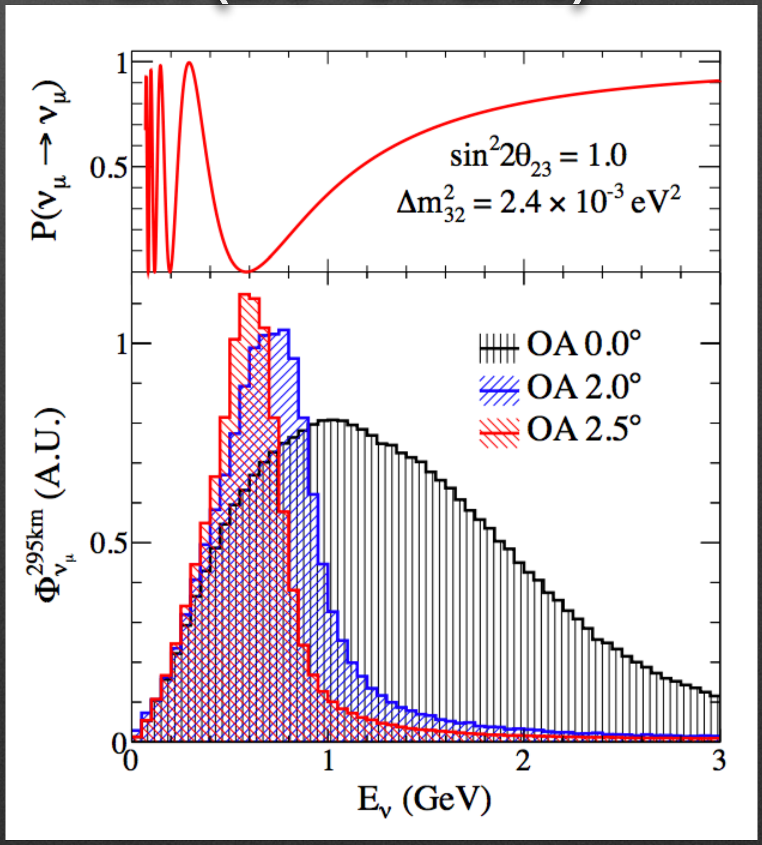


On-axis: E_ν proportional at P_π
Off-axis: different P_π contribute to the same E_ν

NOνA (14 mrad off axis)



T2K (2.5° off axis)

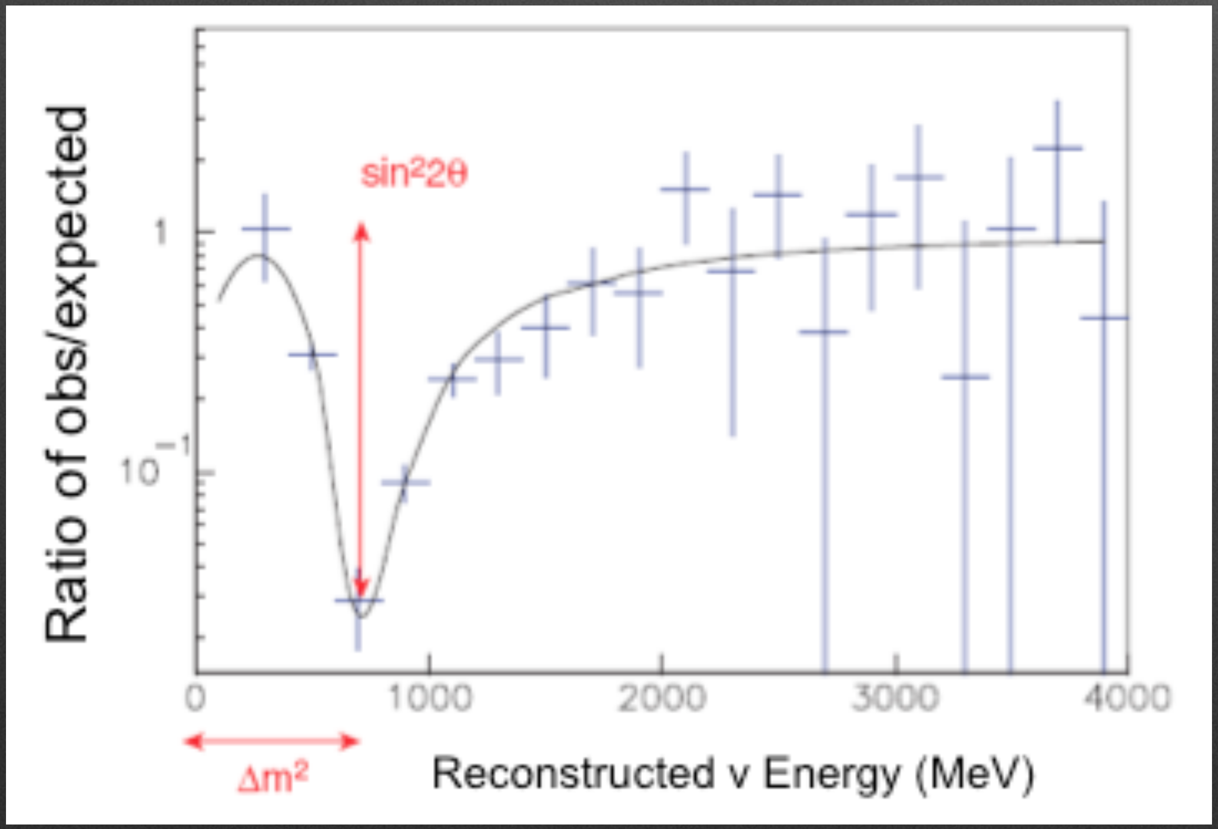


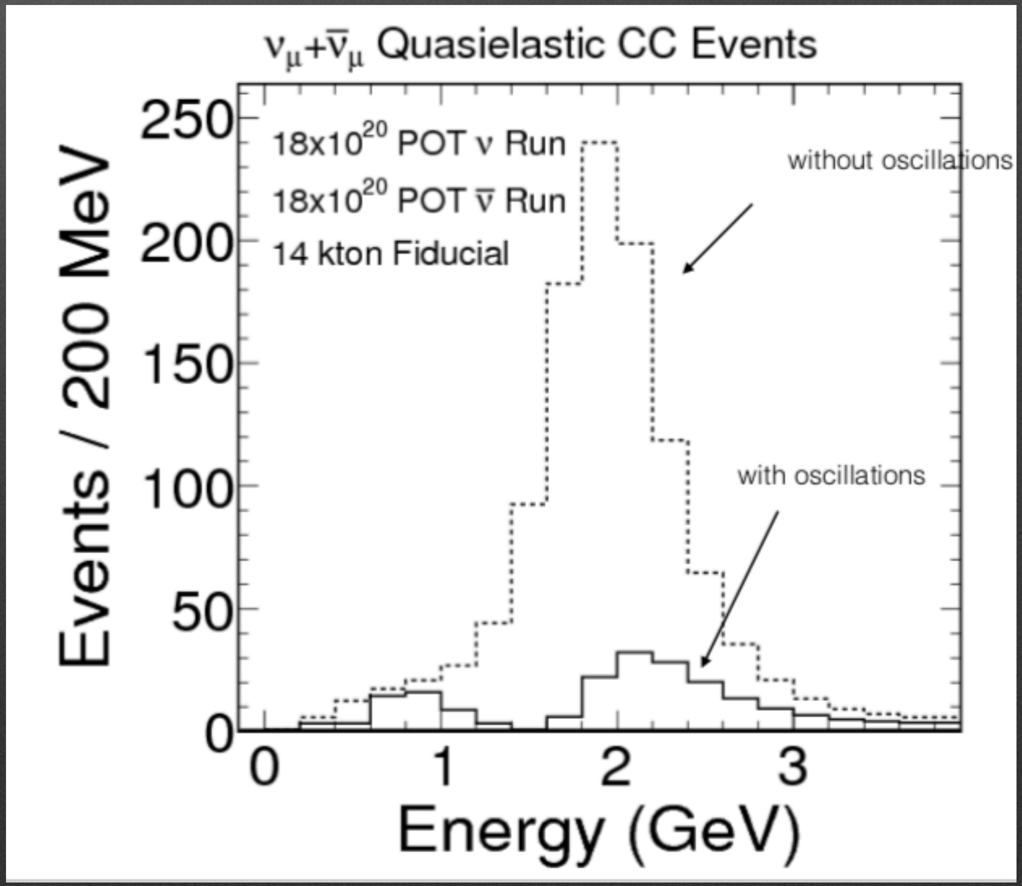
Physics case: ν_μ disappearance

- Produce a beam of ν_μ → most of the neutrinos goes into ν_τ → undetectable at T2K or NOνA energies

- But we can do a precise measurement of ν_μ disappearance that at first order depends on θ_{23} and Δm^2_{23}

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2(2\theta_{23}) \sin^2\left(\frac{1.27\Delta m^2_{atm} L}{E}\right)$$



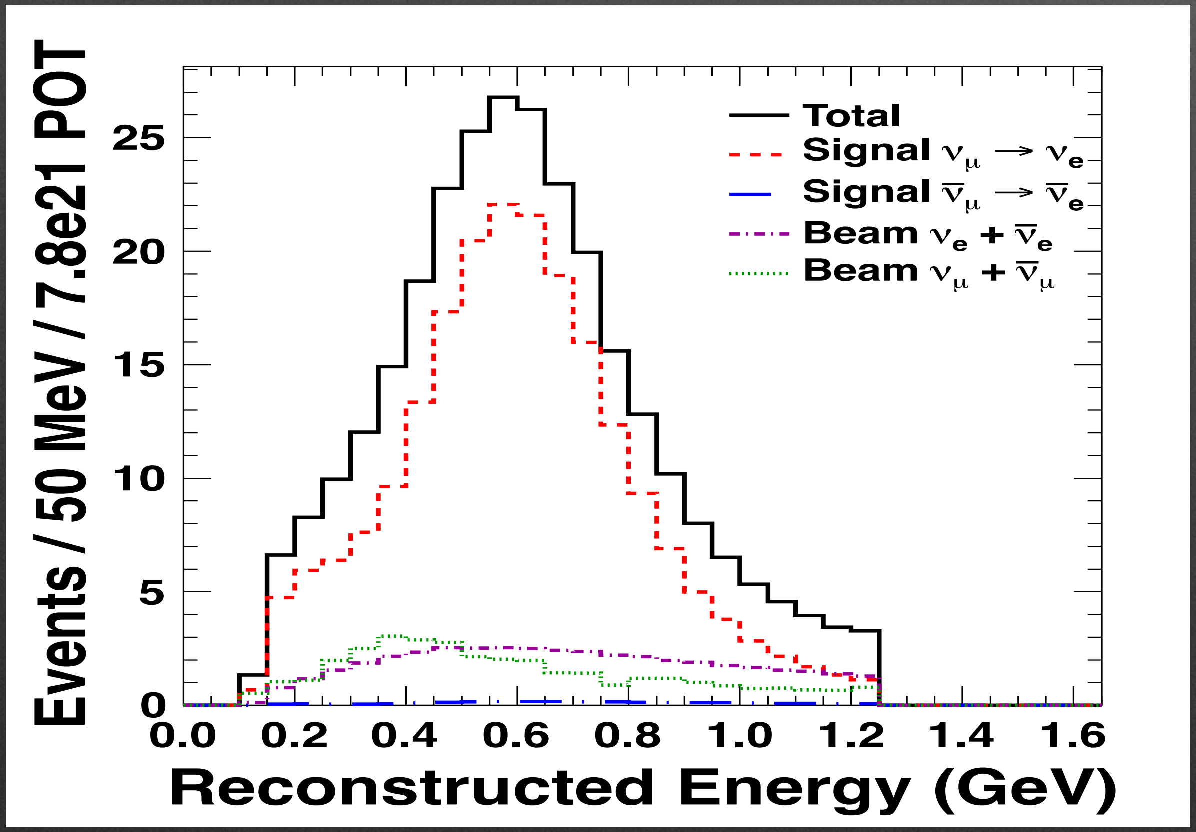


Physics case: ν_e appearance

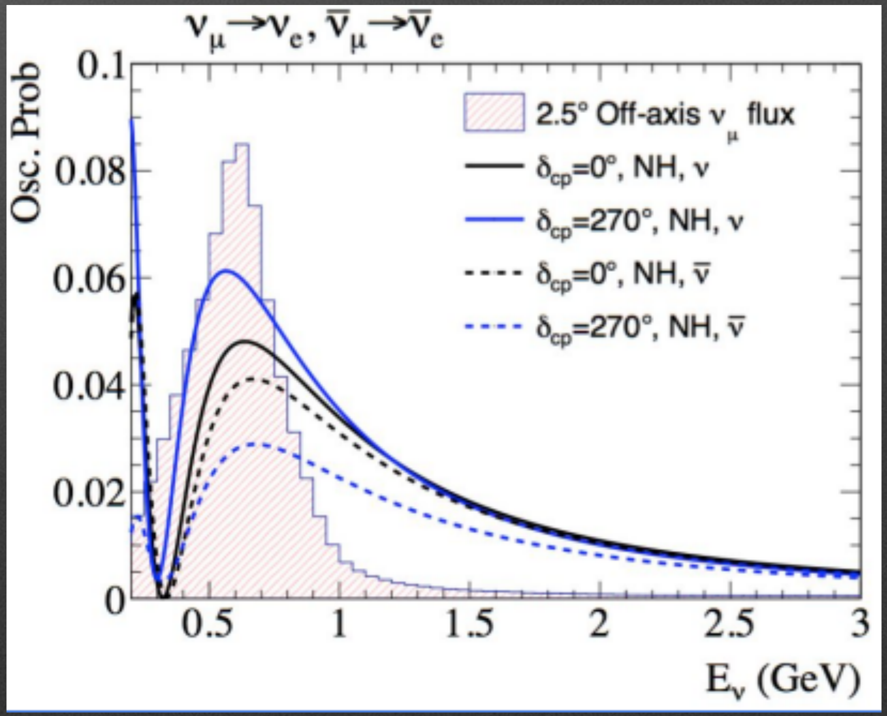
- When T2K and NOνA were designed their main goal was to search for ν_e appearance

- Now that we know that θ_{13} is different from zero the main goals of these experiments is to search for subleading effects

ν_e appearance → θ_{13}



ν_e appearance → δ_{CP} and Mass ordering



Degeneracies

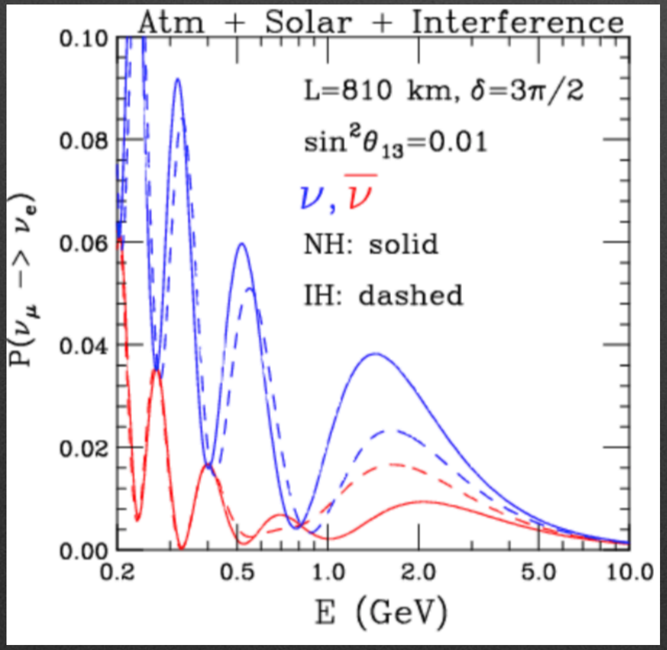
$$
\begin{aligned}
P(\nu_\mu \to \nu_e) = {} & 4C_{13}^2 S_{13}^2 S_{23}^2 \cdot \sin^2 \Delta_{31} \\
& + 8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21} \\
& - 8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \cdot \sin\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21} \\
& + 4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta) \cdot \sin^2\Delta_{21} \\
& - 8C_{13}^2 S_{13}^2 S_{23}^2 \cdot \frac{aL}{4E_\nu} (1 - 2S_{13}^2) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \\
& + 8C_{13}^2 S_{13}^2 S_{23}^2 \frac{a}{\Delta m_{31}^2} (1 - 2S_{13}^2) \cdot \sin^2\Delta_{31},
\end{aligned}
$$

Leading term → θ_{13}

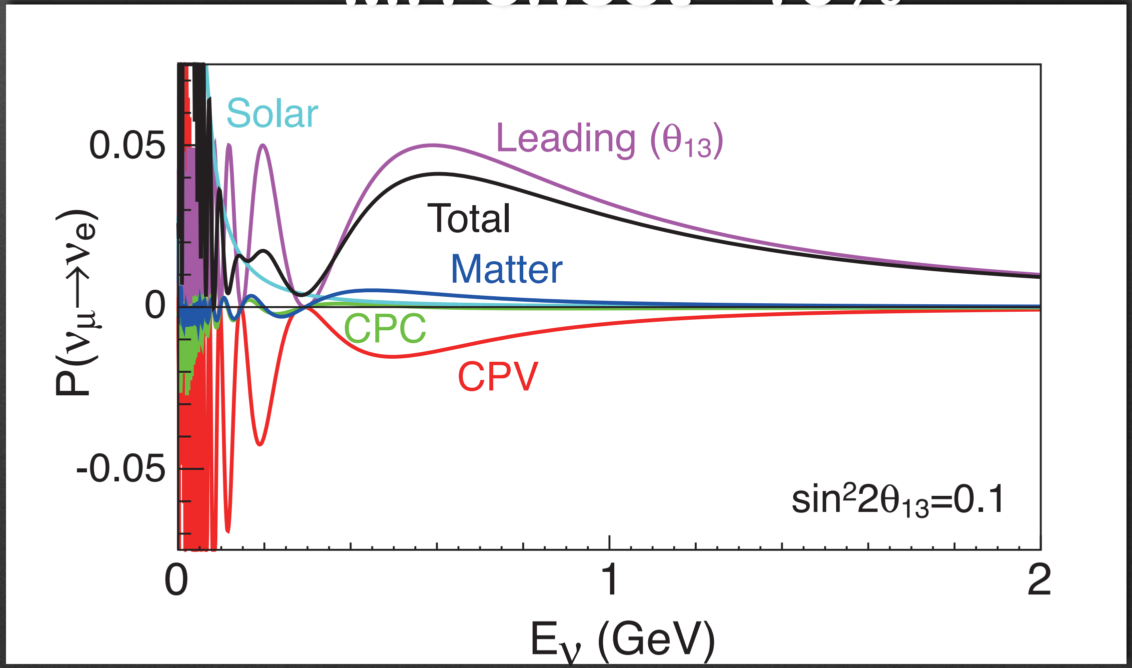
CPV term

Matter effects ∝ distance

NOνA: δ_{CP} effect ±20%
MH effect ~30%



T2K: δ_{CP} effect ±30%
MH effect ~10%



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& + 8C_{13}^2 S_{13}^2 S_{23}^2 \frac{a}{\Delta m_{31}^2} (1 - 2S_{13}^2) \cdot \sin^2 \Delta_{31},
\end{aligned}
$$

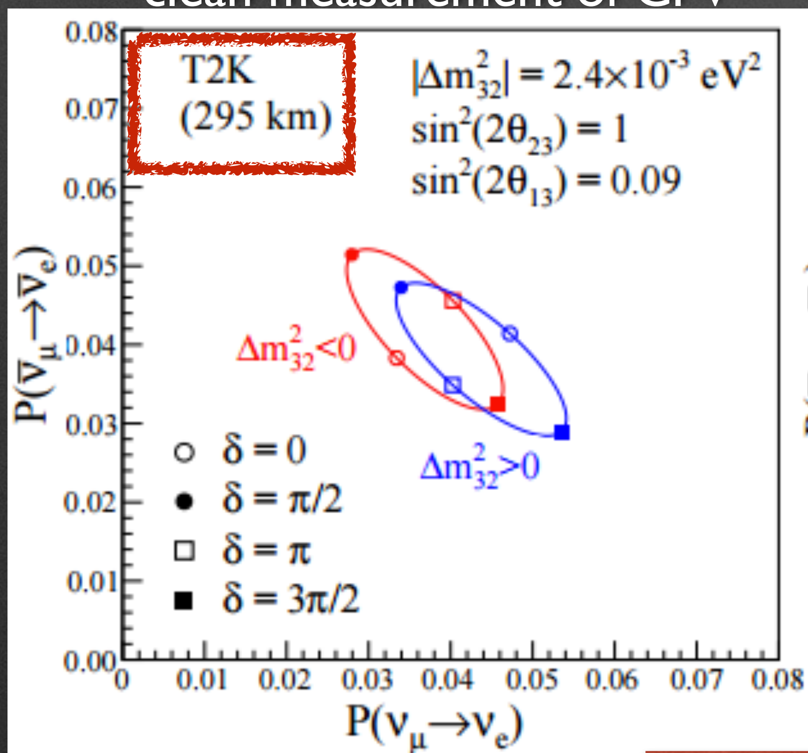
Leading term → θ_{13}

CPV term

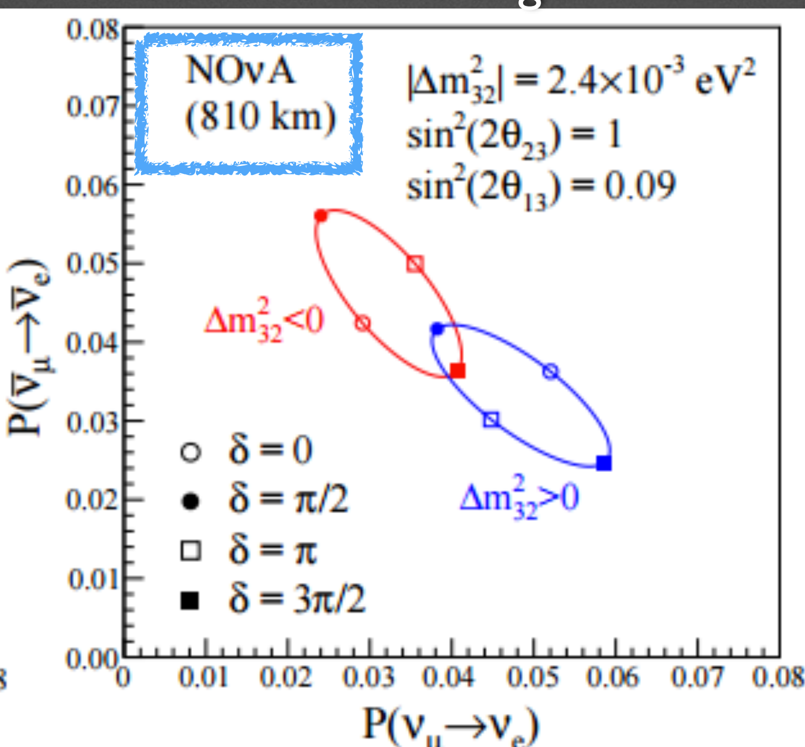
Matter effects

∝ distance

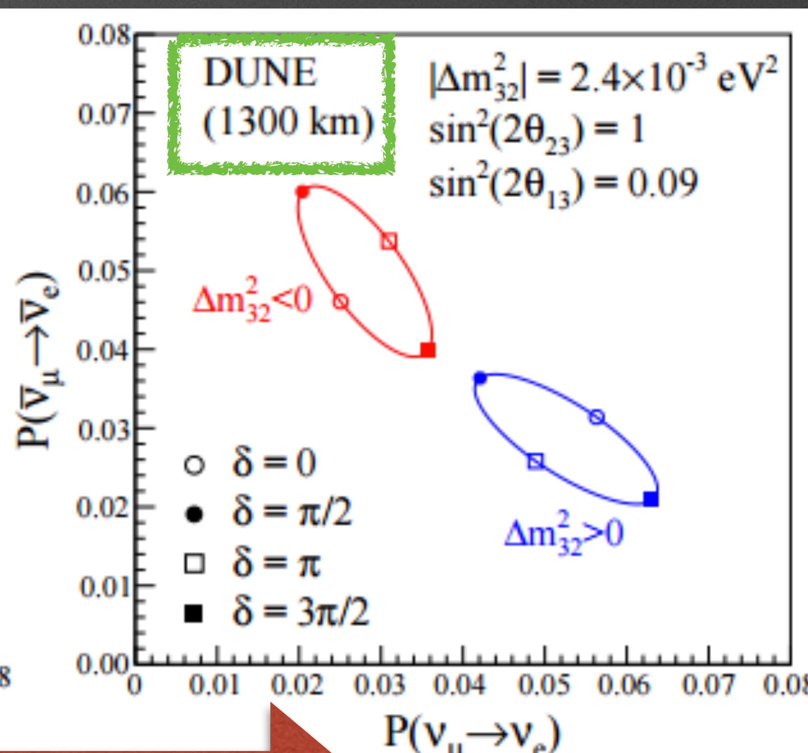
T2K(HK) almost no MH —> ~ clean measurement of CPV



NOVA sensitive to MH and CPV but with some degeneracies

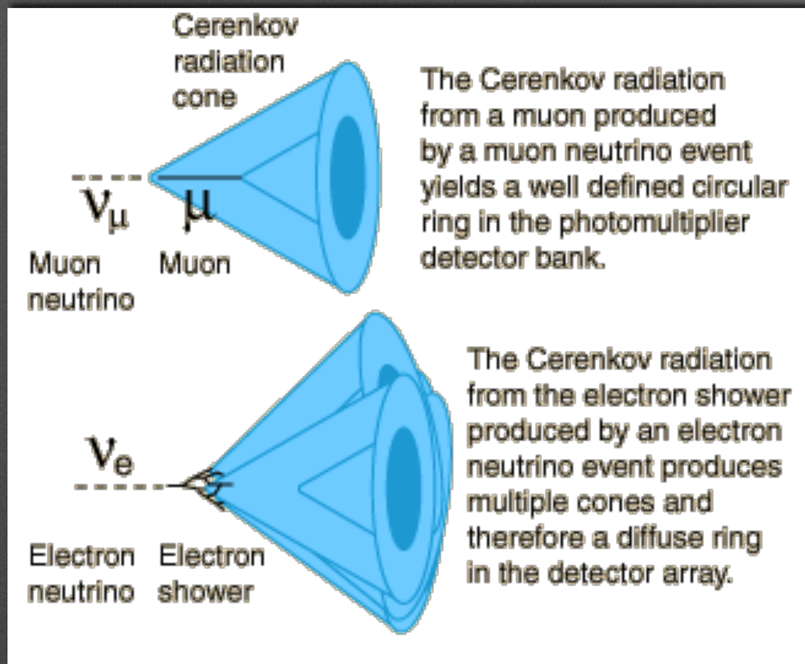


DUNE breaks the degeneracy between MH and CPV



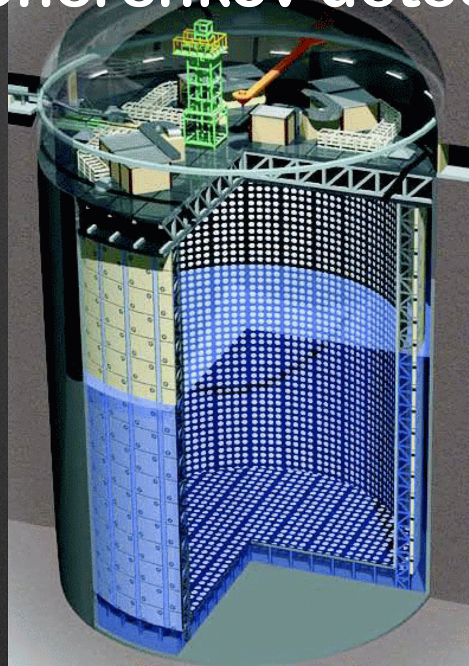
increasing baseline

T2K

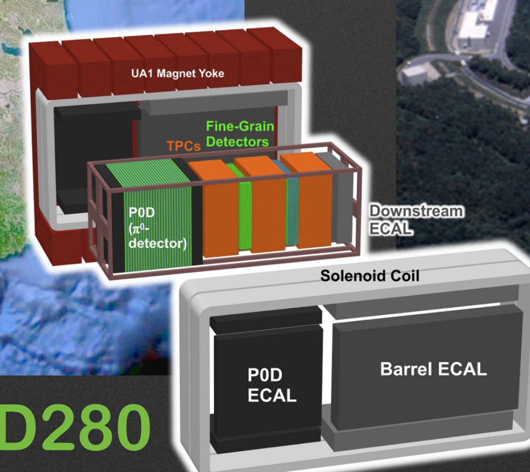


- L = 295 km
- E_ν ~ 600 MeV

Super-Kamiokande: 22.5 kt fiducial volume water Cherenkov detector



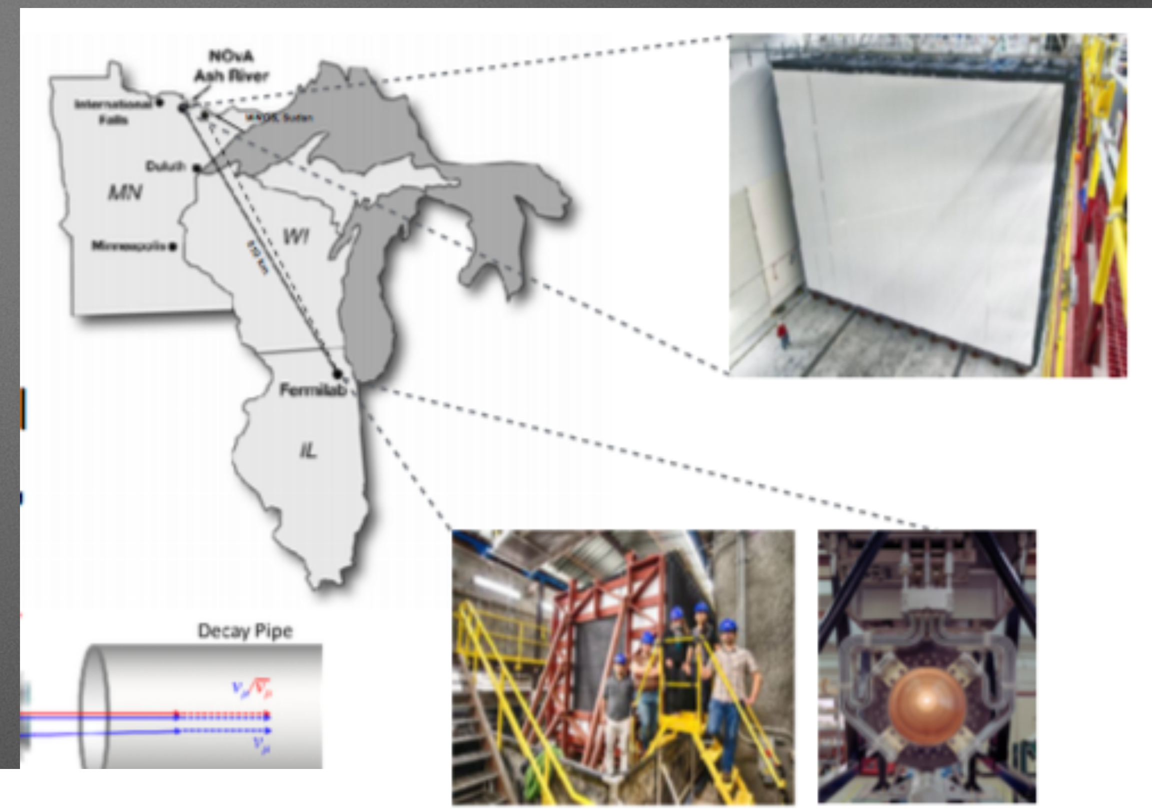
J-PARC accelerator: Design power: 750 kW

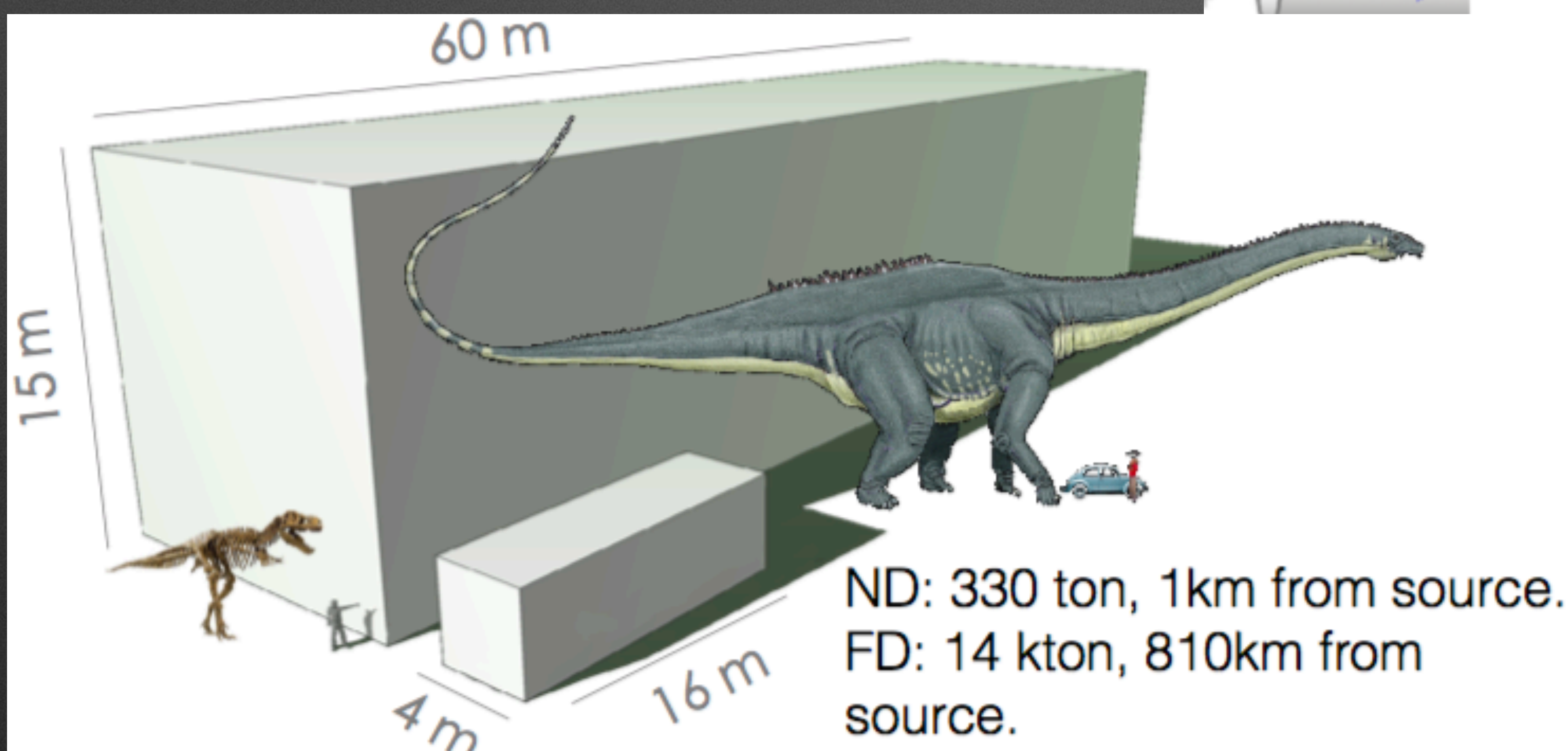


ND280

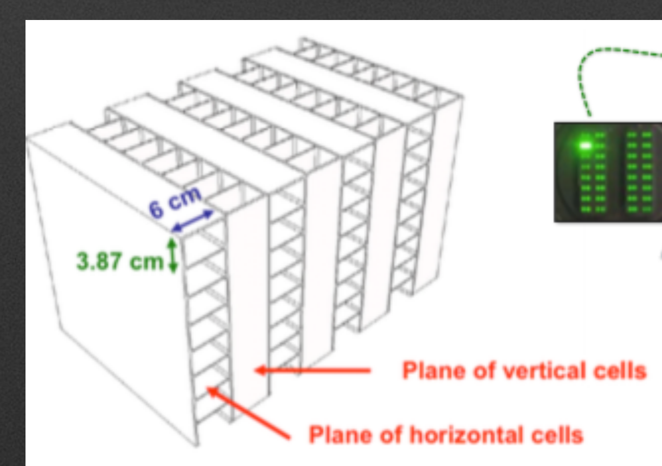
NOVA

- L = 810 km
- E_{ν} ~ 2 GeV





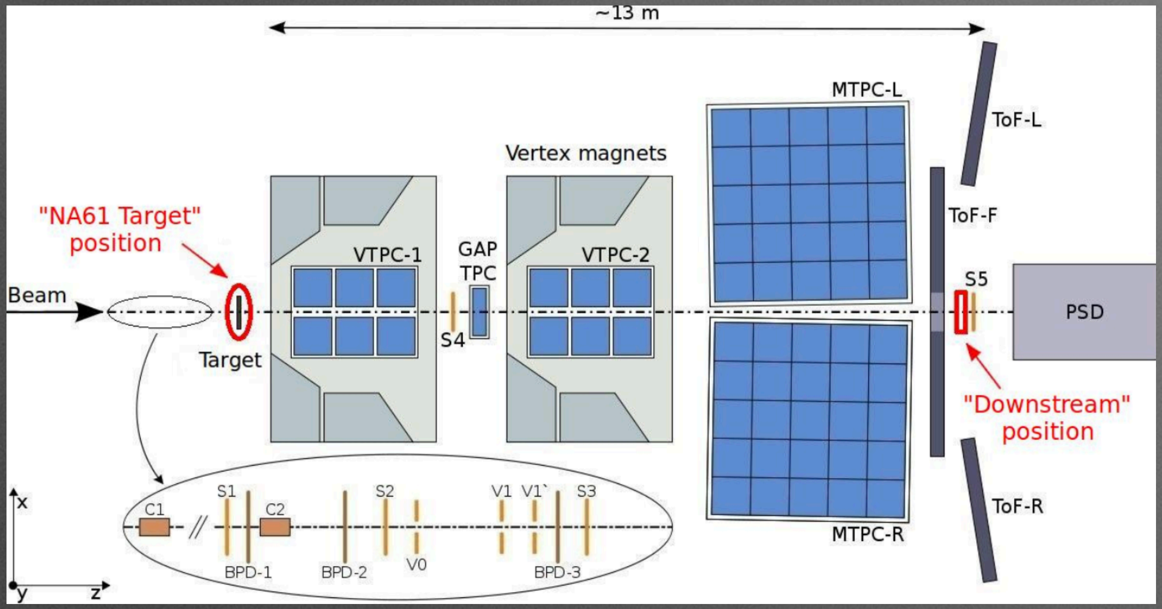
PCV extrusion + liquid scintillator: Ideal for electron identification

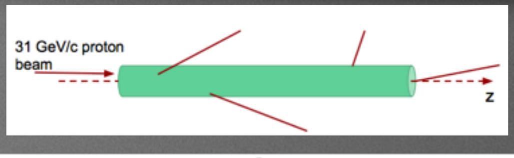


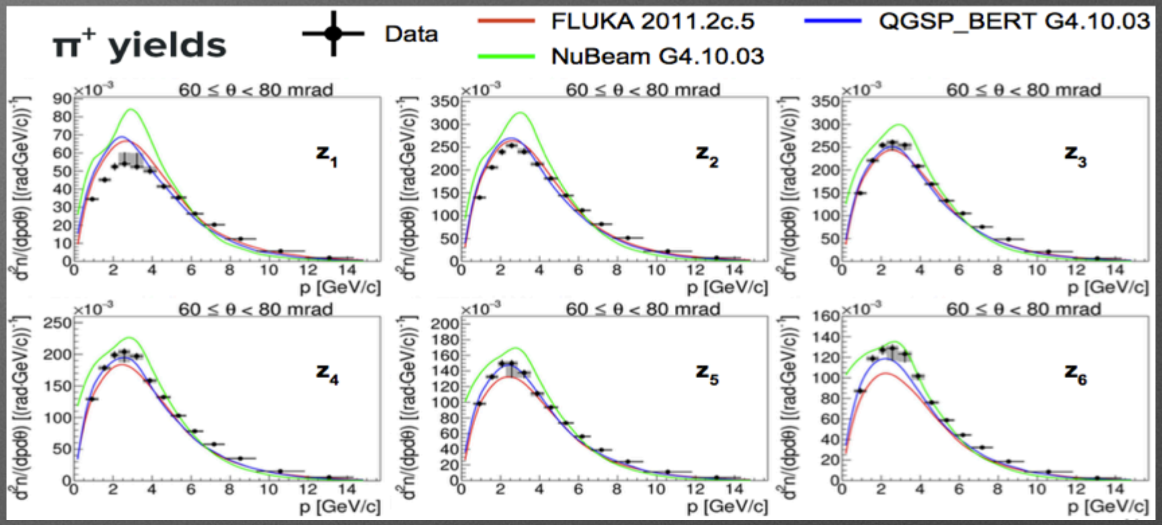
Common ingredients

- Flux prediction (NA61/SHINE for T2K, MIPP for NOvA)
- Cross-section models
- Near Detector analyses but used in very different ways
- Far detector $\nu\mu$ and νe selections
- Joint oscillation fits

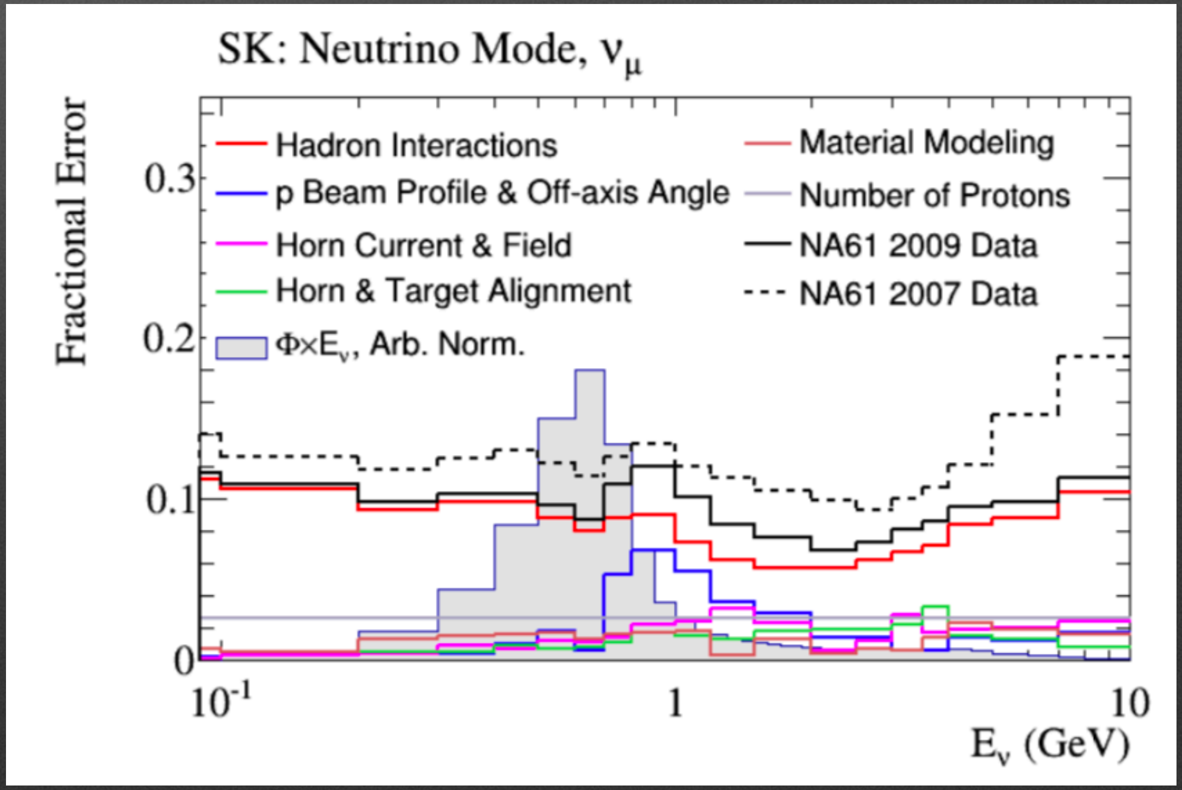
Flux prediction







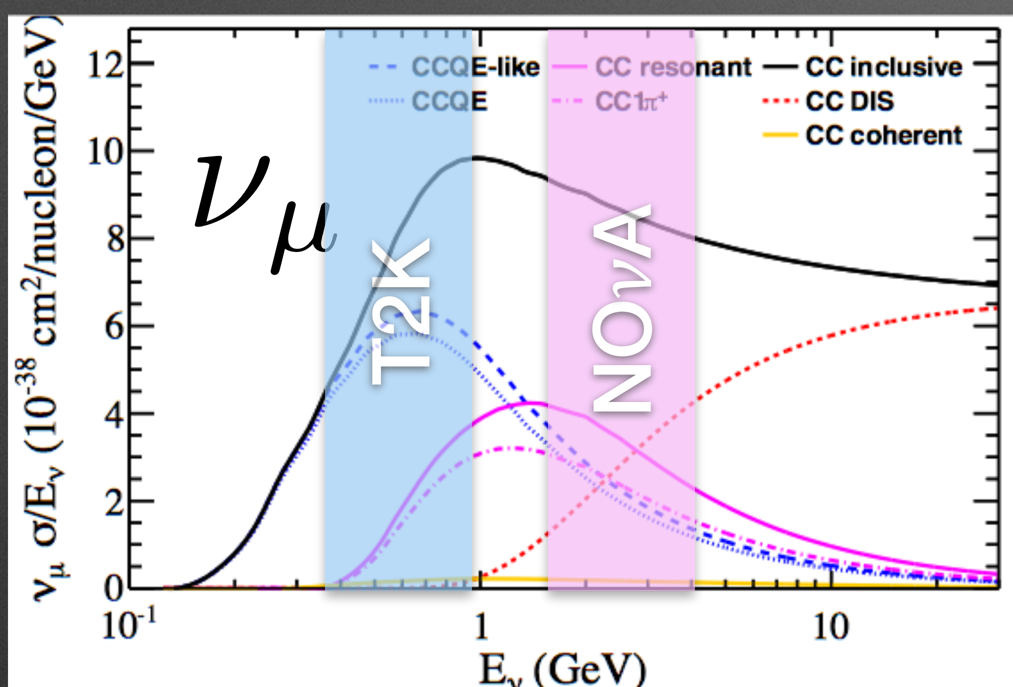
- Main uncertainty is the hadron-production cross-section
- This can be measured by dedicated experiments, such as NA61/SHINE for T2K
- Same proton energy, same target, measure double differential cross-section for hadrons production
- <10% uncertainty on neutrino fluxes, hope to go below 5% with more data

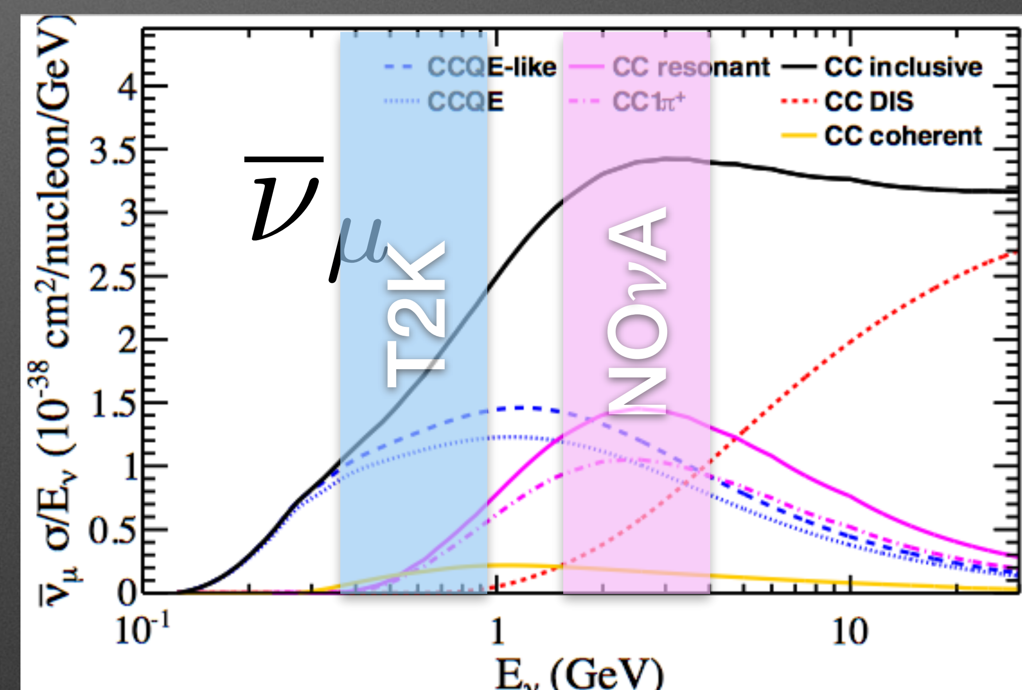


Cross-section models

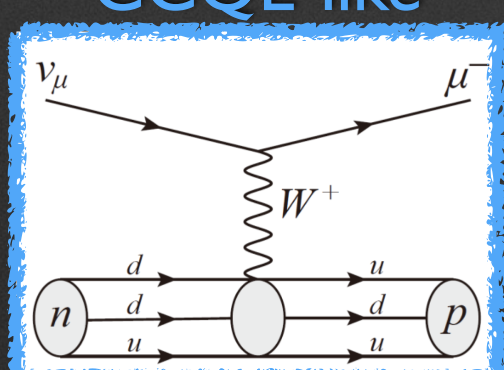
- T2K (700 MeV) → dominated by quasi-elastic processes (+ 2p2h) → look at lepton momentum and angle to reconstruct neutrino energy

- NOvA (~2 GeV) → dominated by CC interactions with pion production → need to measure also the hadronic part

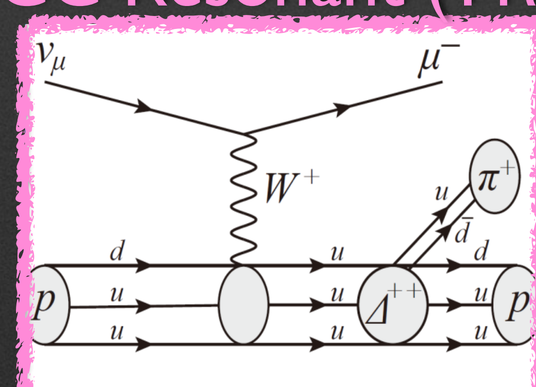




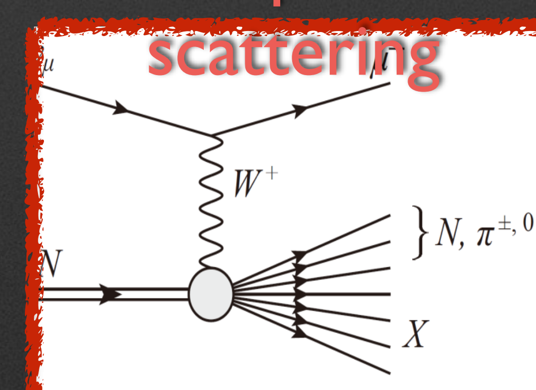
CCQE-like



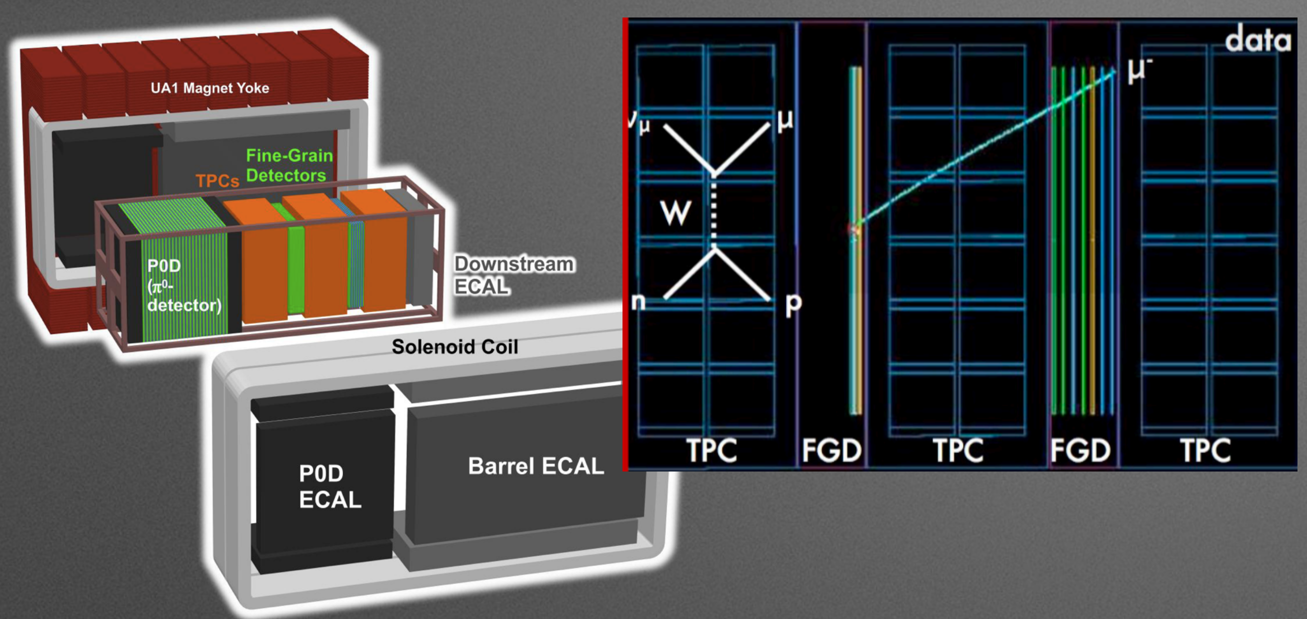
CC Resonant (1π)

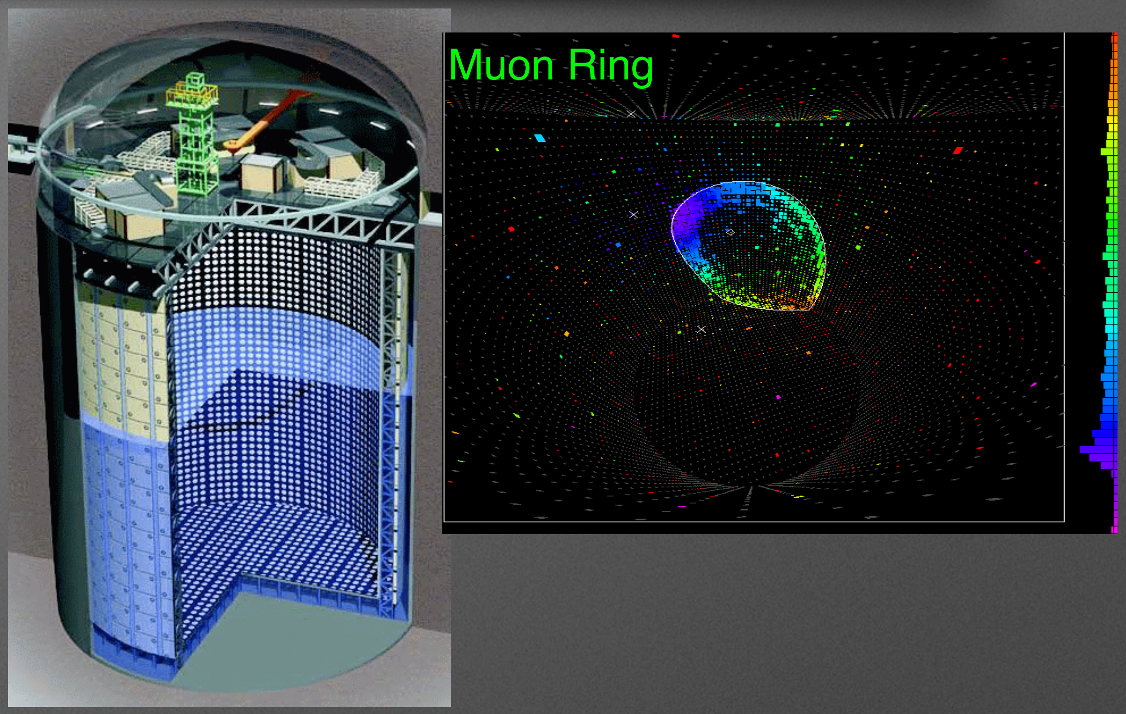


CC Deep Inelastic scattering



T2K

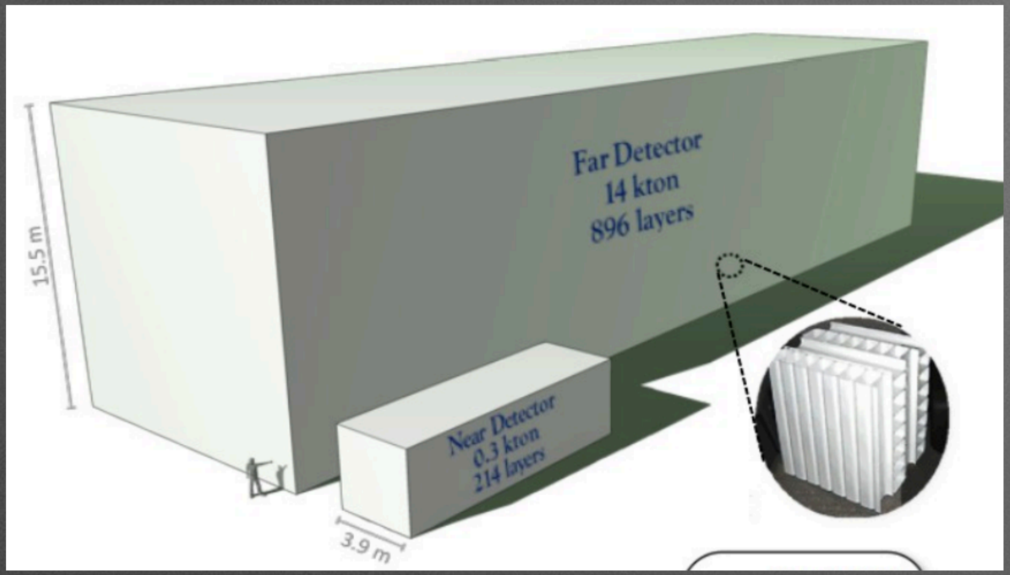


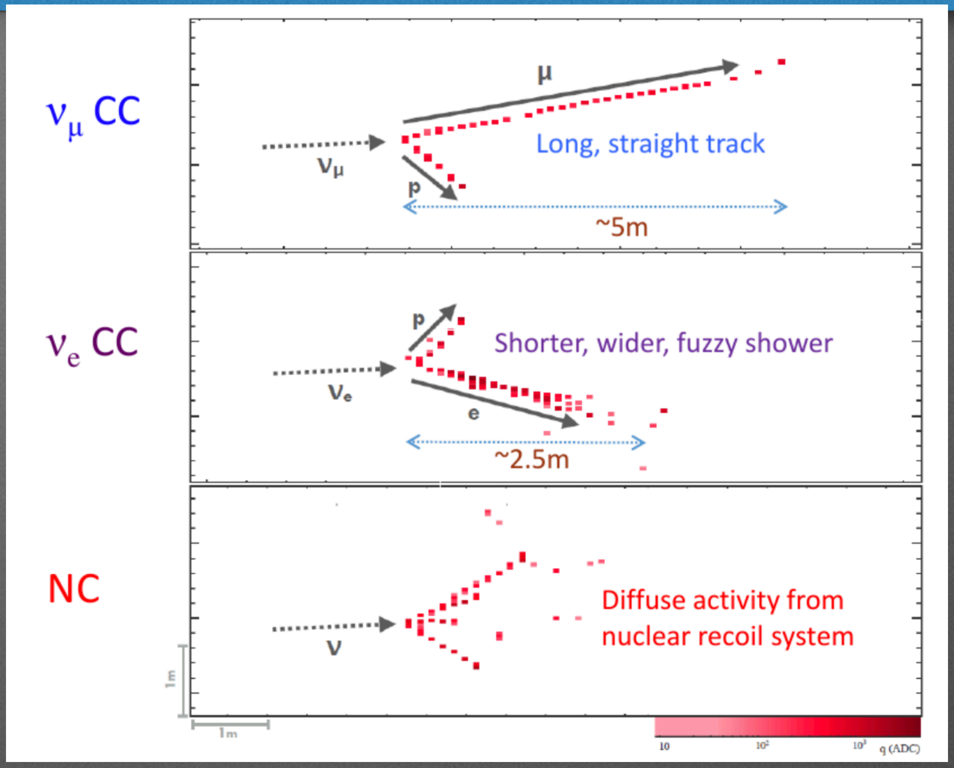


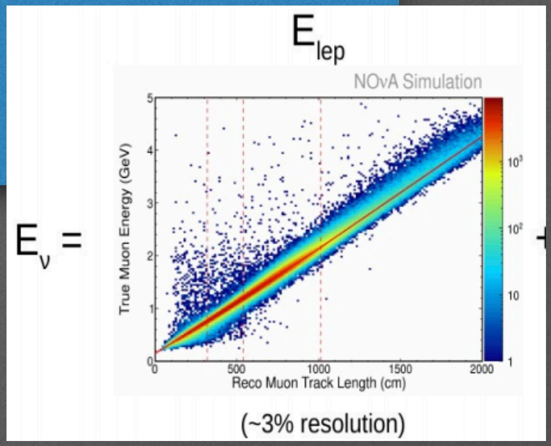
- Magnetized ND → distinguish ν from $\bar{\nu}$
- TPC for 3D track reconstruction and PID of all the charge particles
- Carbon and water target
- Mostly forward going acceptance

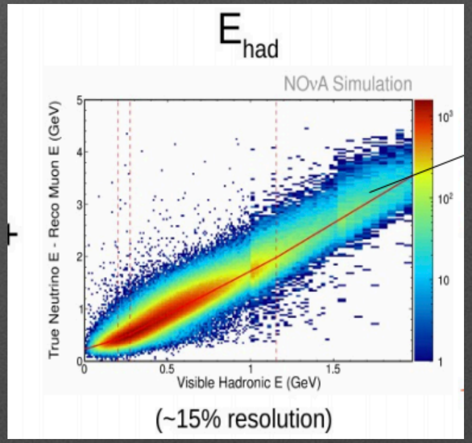
- Not magnetized FD → distinguish ν from $\bar{\nu}$
- Cherenkov effect → most of the time only the lepton is reconstructed → energy reconstructed assuming QE interactions
- 50 kton water target
- 4 π acceptance

NOνA









- Same technology near and far → but different size and so different acceptance
- Identical detector → easier to extrapolate near to far?
- Higher energy → Cannot assume QE interaction and need to reconstruct all the energy produced in a neutrino interaction
- Calorimetric energy reconstruction → Difficult to disentangle cross-section from detector effects
- Both detectors are not magnetised → no measurements of the wrong-sign component

T2K oscillation analysis

Flux prediction:

- ✓ Proton beam measurement
- ✓ Hadron production (NA61 and others external data)

ND280 measurements:

- ✓ ν_μ and $\overline{\nu}_\mu$ selections to constrain flux and cross-sections

Neutrino interactions:

- ✓ Interaction models
- ✓ External cross-section data

Prediction at the Far Detector:

- ✓ Combine flux, cross section and ND280 to predict the expected events at SK

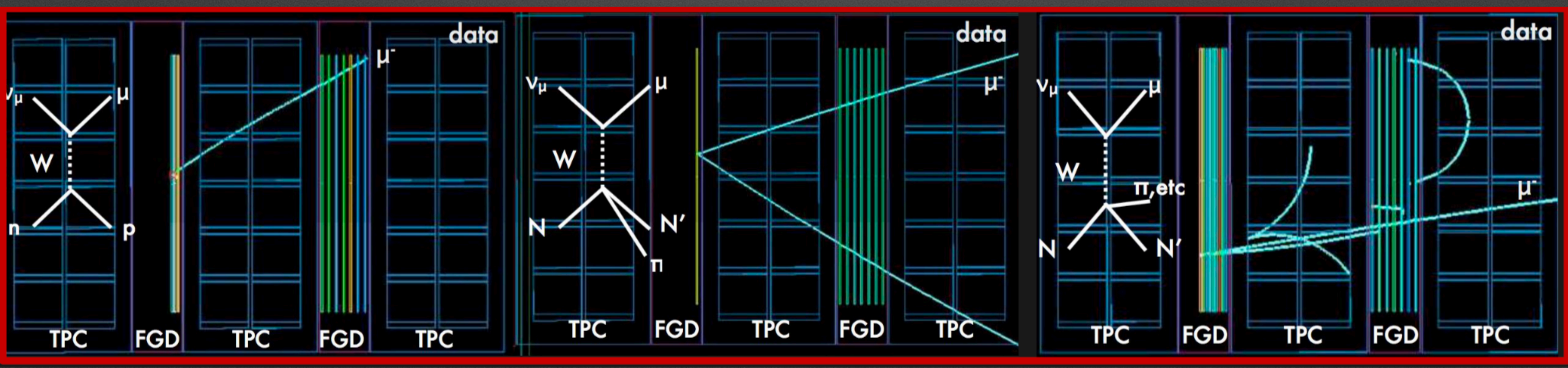
Extract oscillation parameters!

Super-Kamiokande measurements:

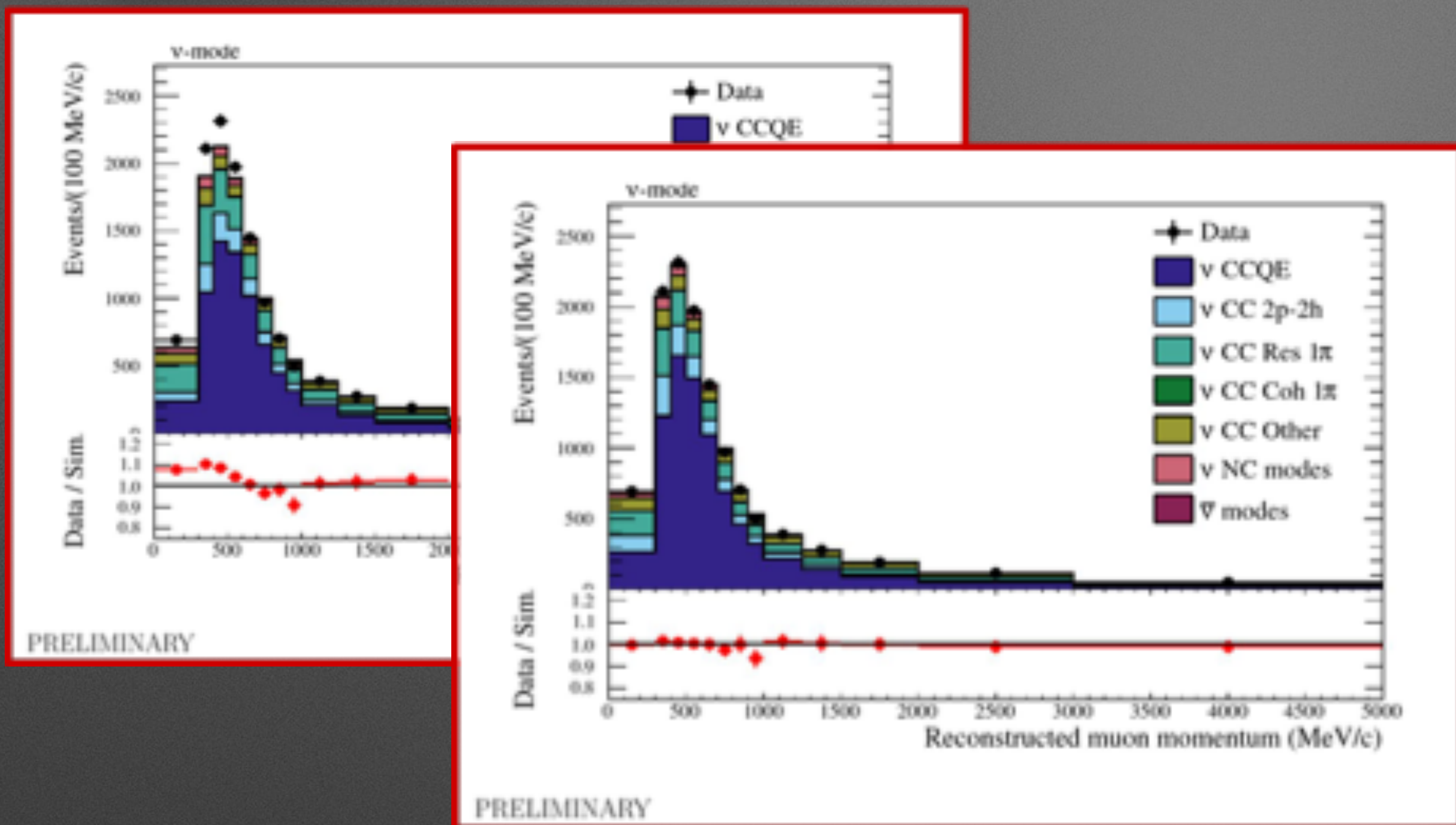
- ✓ Select CC ν_μ and ν_e candidates after the oscillations

ND280 selection

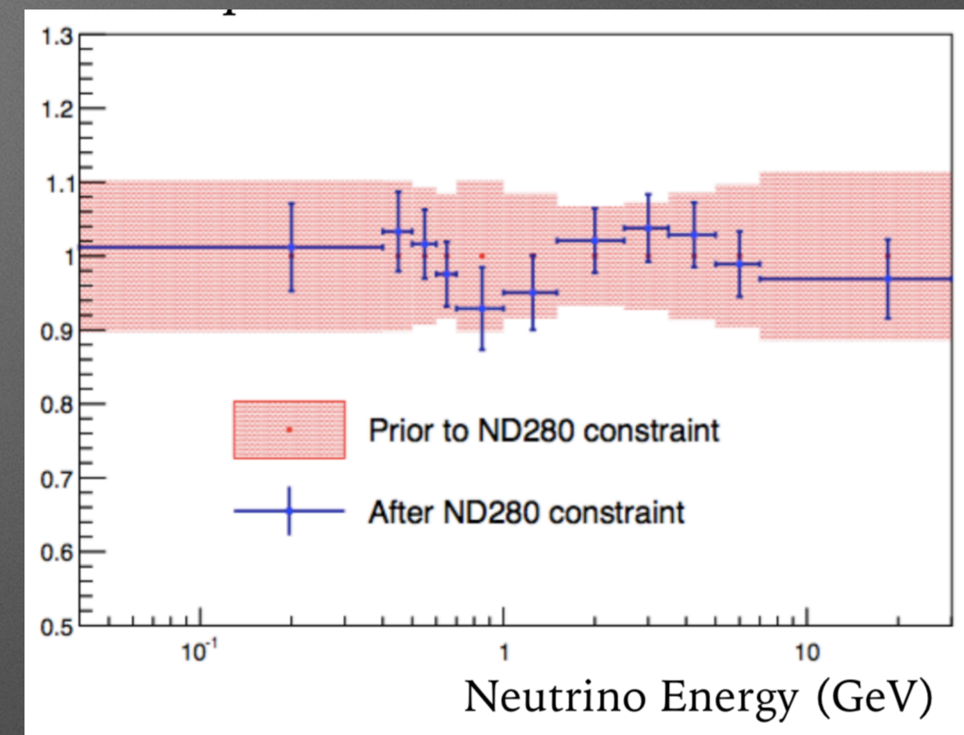
- Select charged current muon neutrino interactions in the tracker (FGD)
  - Use TPCs to reconstruct momentum, charge and particle ID
  - Further subdivide the sample according to the number of pions (0, 1, >1)
- ND280 is a magnetized detector → lepton charge reconstruction to distinguish ν_μ from $\overline{\nu}_\mu$ interactions
- 7 samples per FGD are used in the near detector fit (CC0π, CC1π and CCNπn ν-mode, CC1Track and CCNTrack for μ+ and μ- in $\bar{\nu}$-mode)

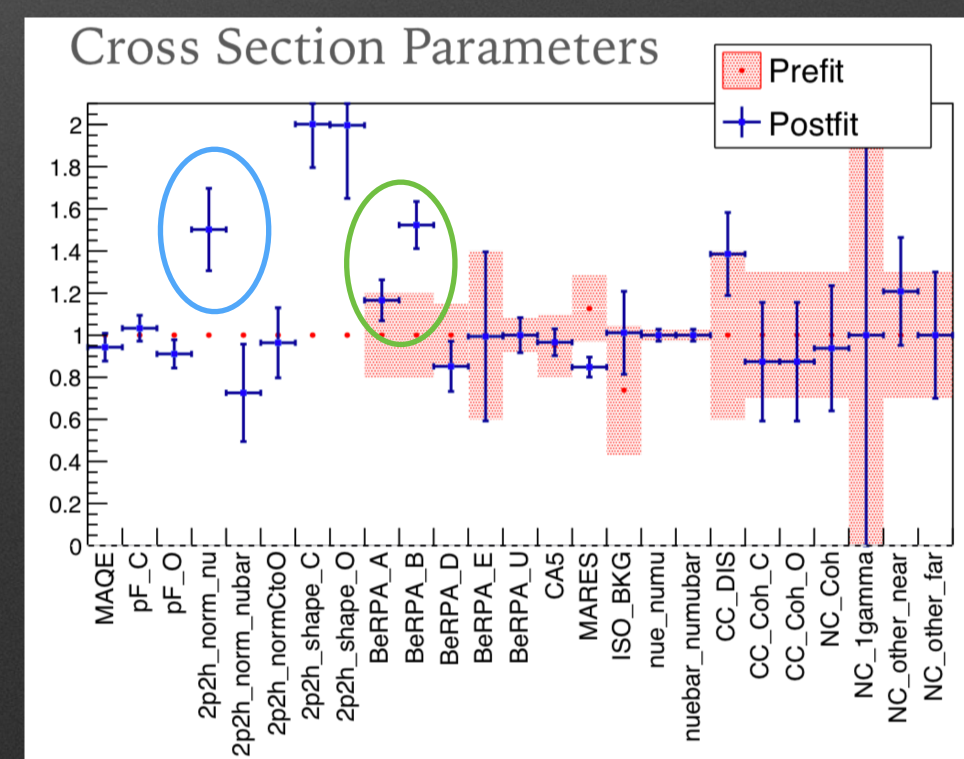


ND280 constraints



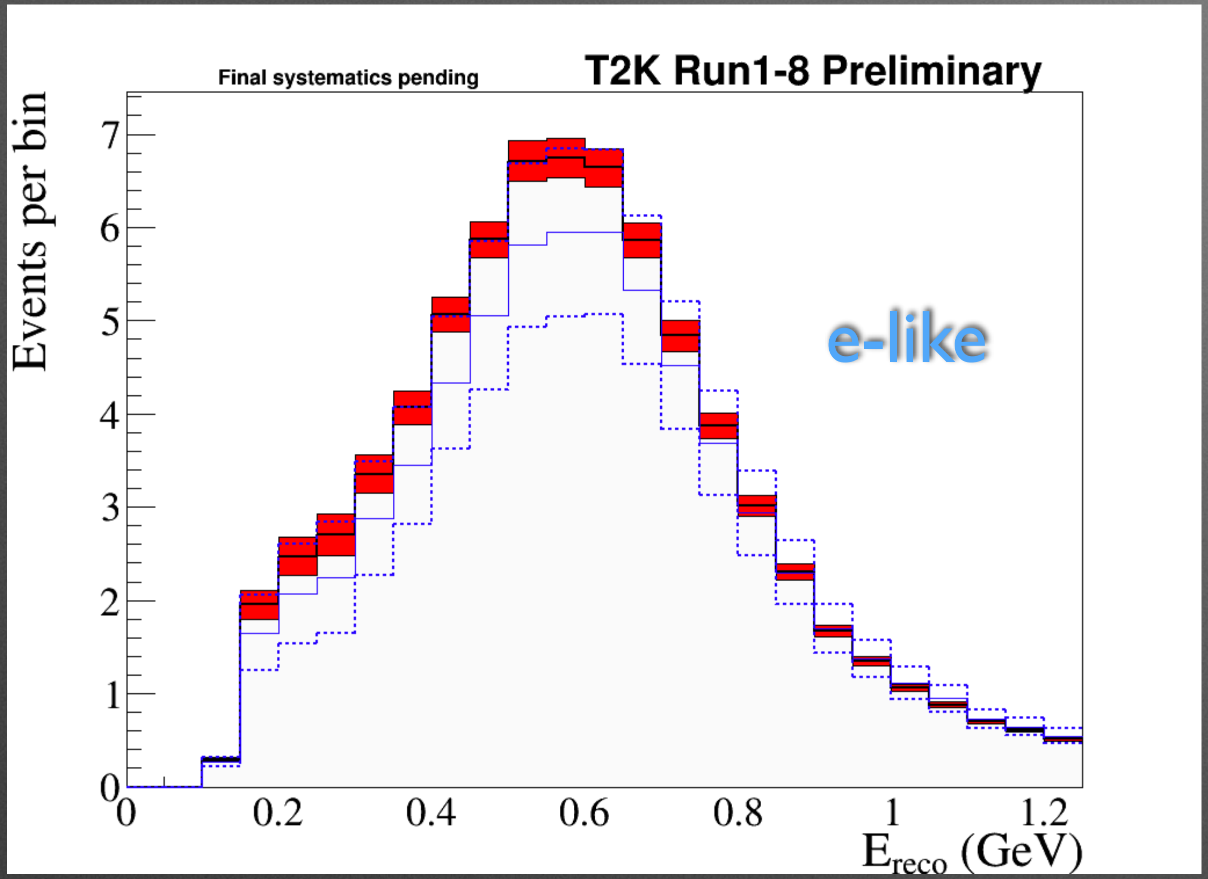
Flux parameters

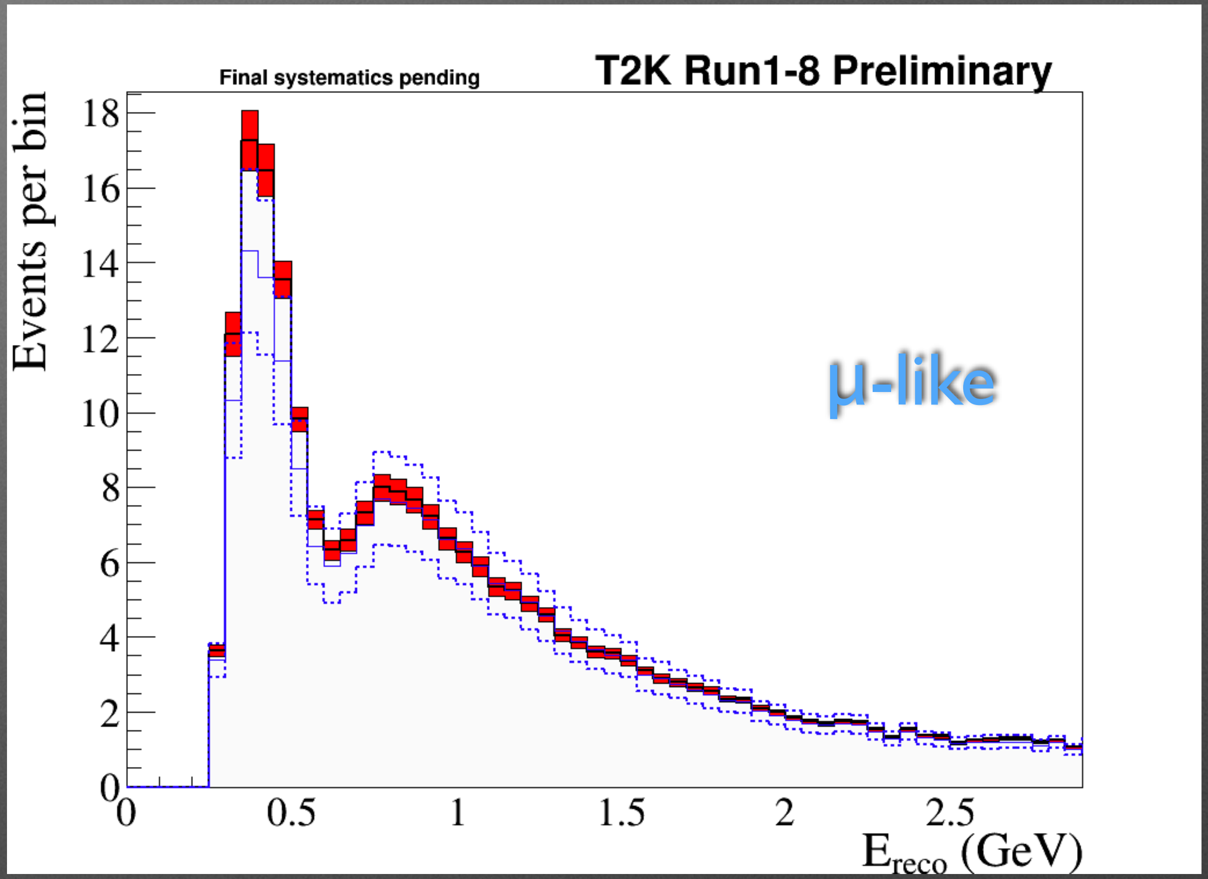




- Flux and cross-section parameters → mostly concentrated to the 0π component of the cross-section
- Different samples selected at ND280
- Adjust flux and cross-section parameters to predict spectra at SK

Reduction of systematics

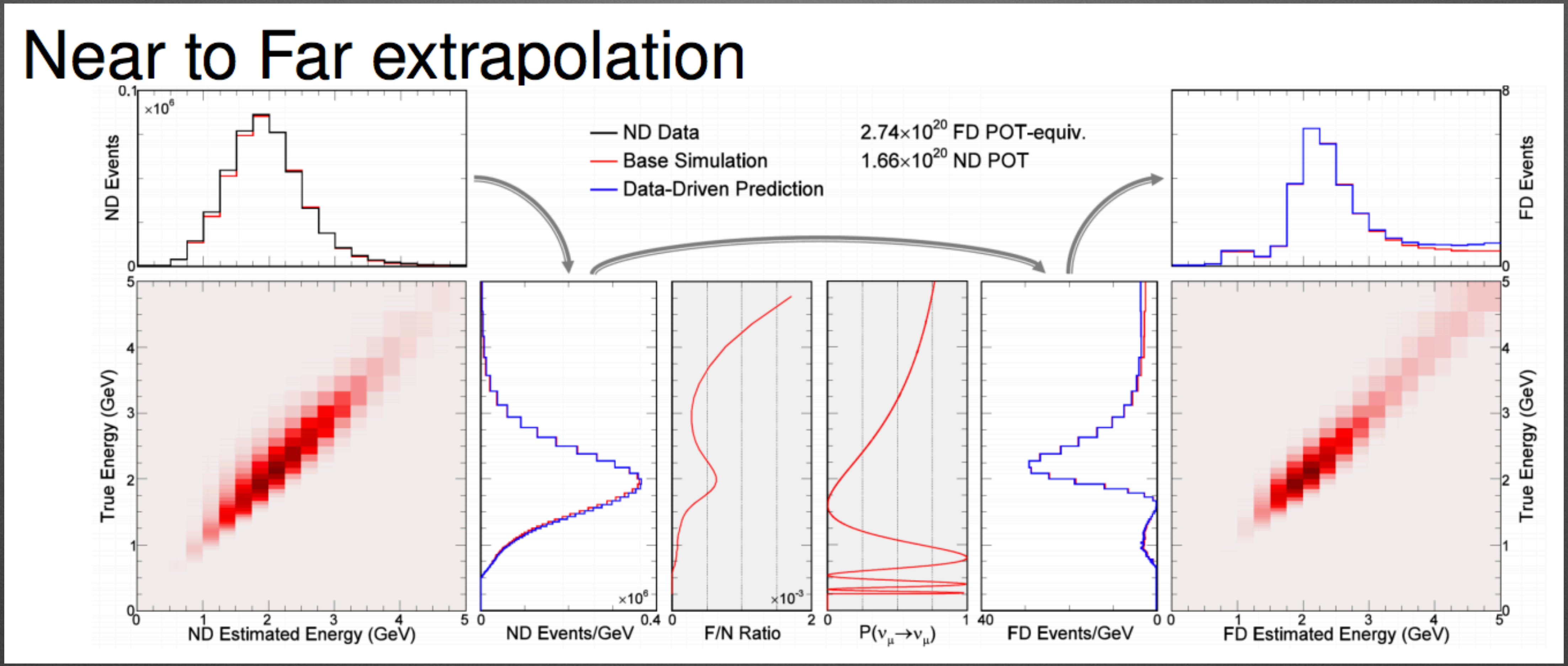




- Slightly increase the predicted number of events at SK → due to the small excess of events in ND280
- Errors are reduced from ~15% to ~4-7% thanks to the Near Detector fit

	μ-like ν-mode	e-like ν-mode	μ-like $\bar{\nu}$-mode	e-like $\bar{\nu}$-mode
Total Systematics (without ND280)	13.9 %	15.9 %	11.7 %	13.7 %
Total systematics (with ND280)	4.3 %	7.3 %	3.8 %	7.7 %

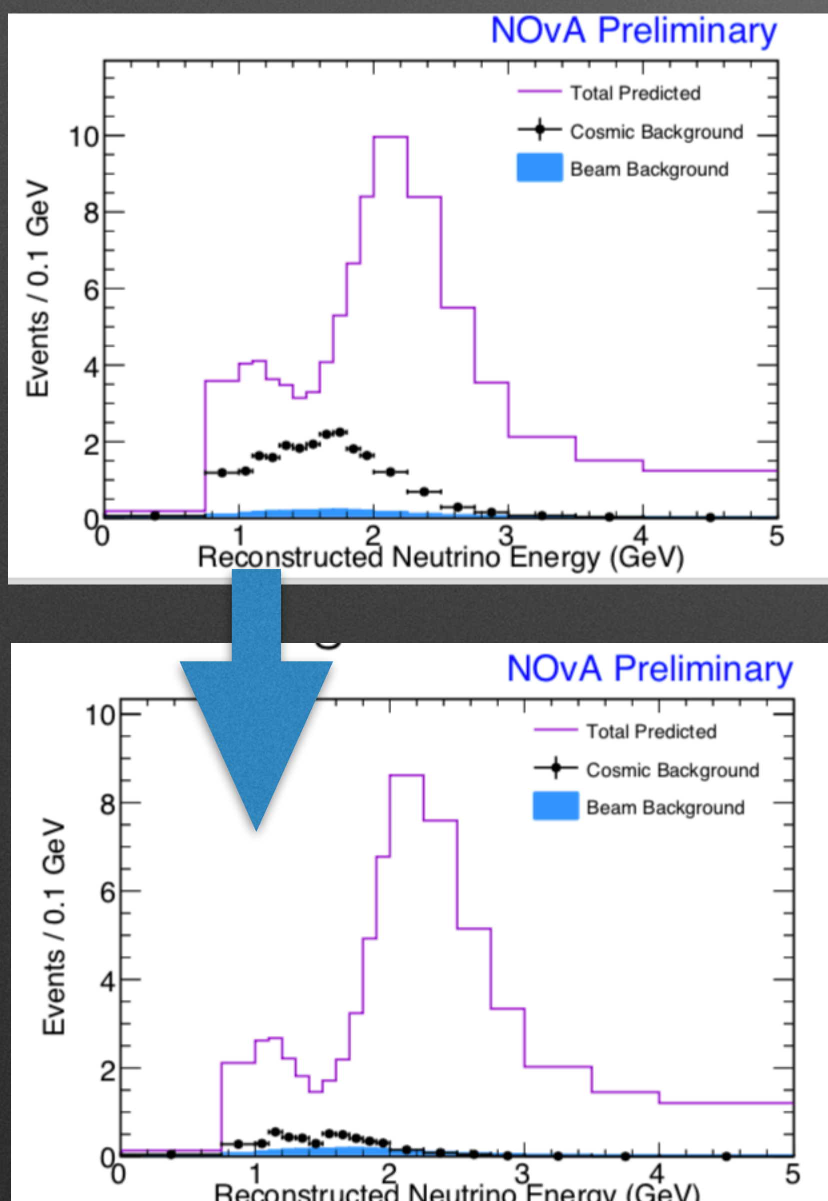
NOνA oscillation analysis

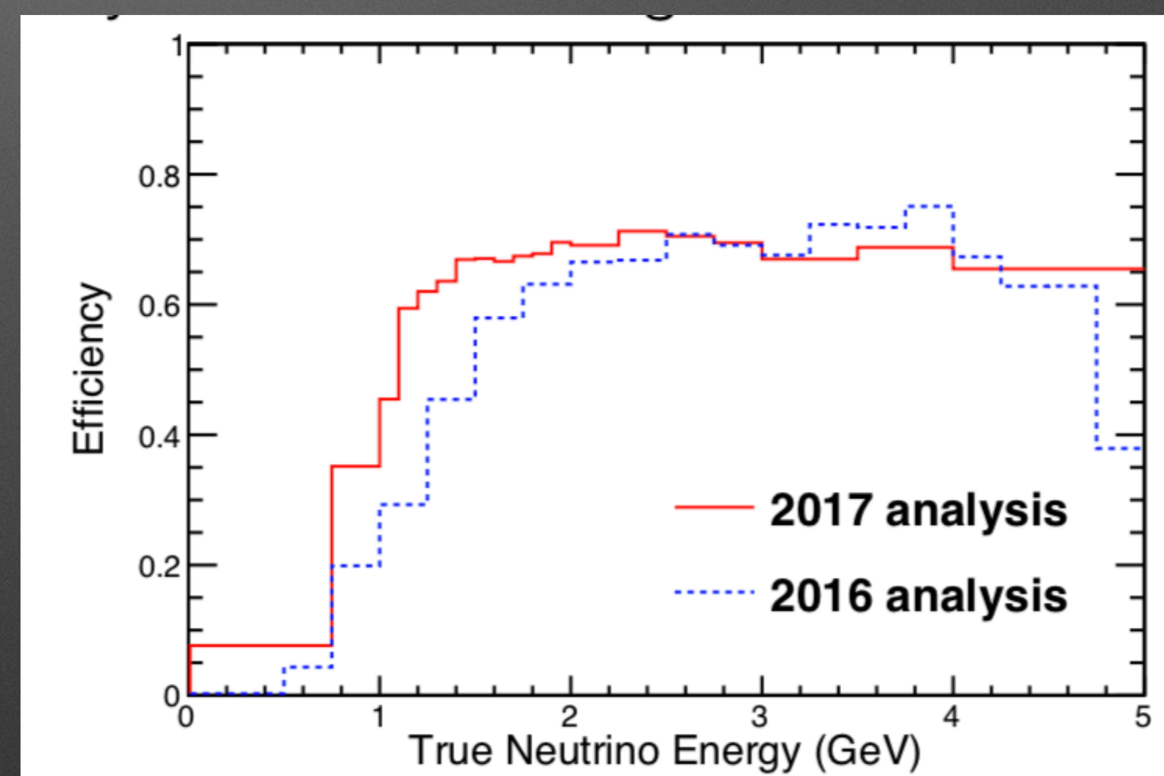


- Simpler than T2K, profiting of the two ~identical detectors
- Erec spectra at ND → Etrue spectra at ND → Far to Near ratio → Etrue spectra at FD → Erec spectra at FD
- But not so simple!

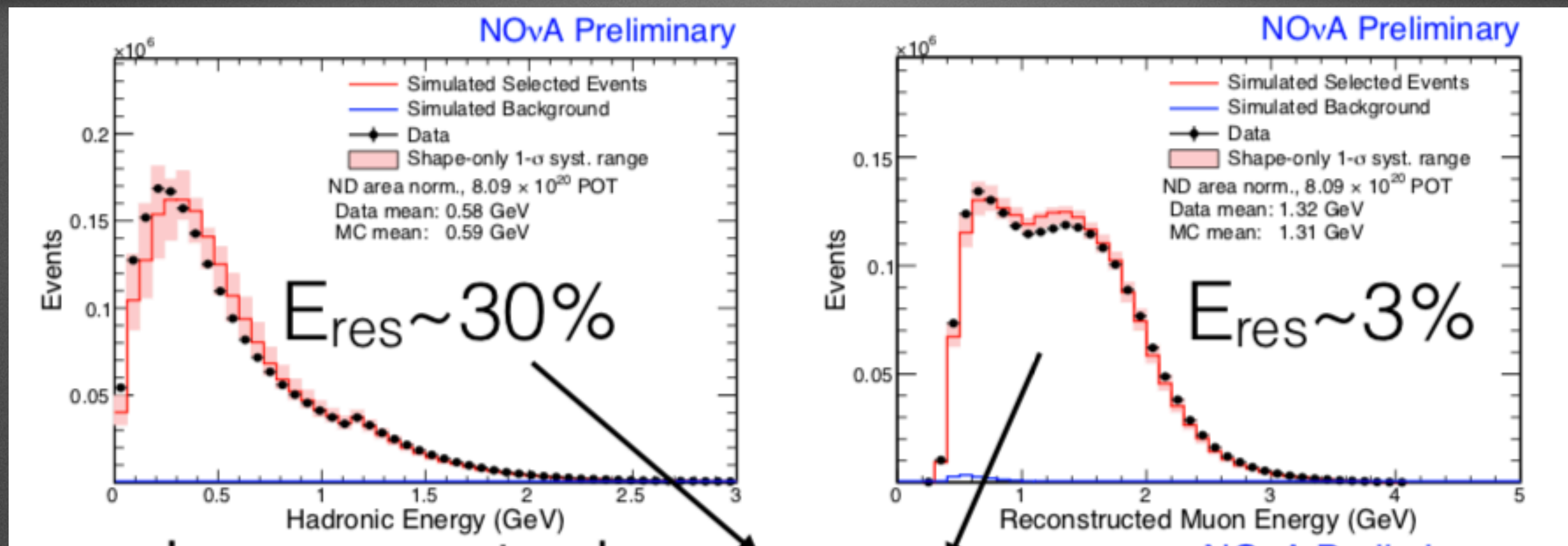
NOνA event selection

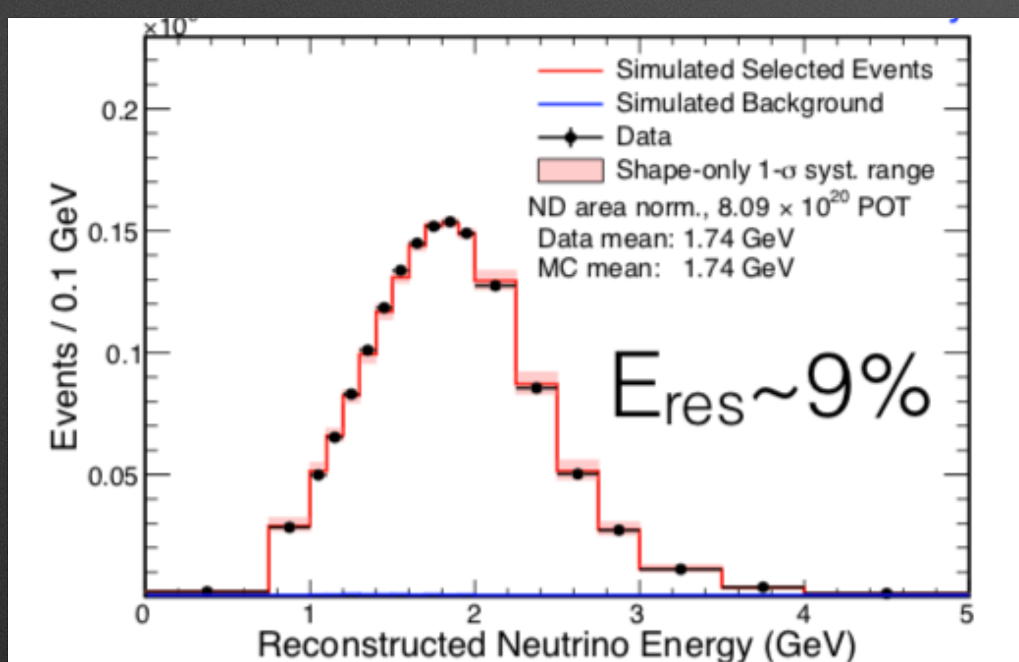
- NOνA far detector is operated on-surface so cosmics constitutes an important source of background
- Continouos development of reconstruction algorithm to reduce the cosmic background and select clean samples of μ and e





NOνA energy reconstruction



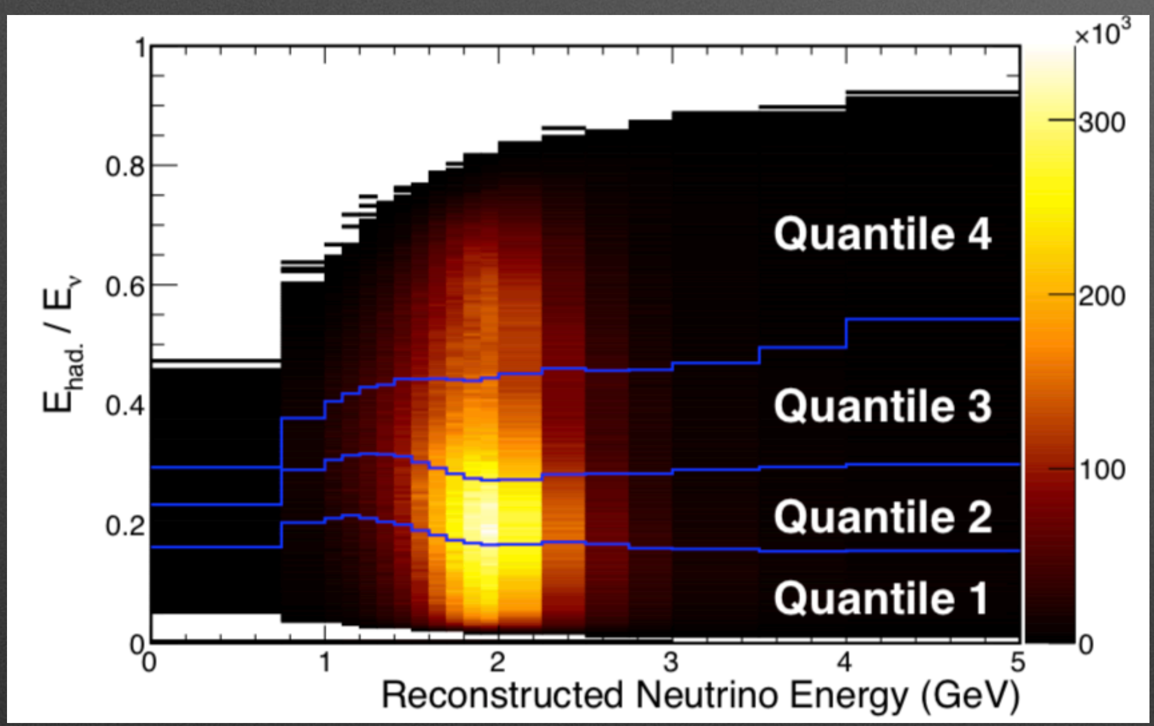


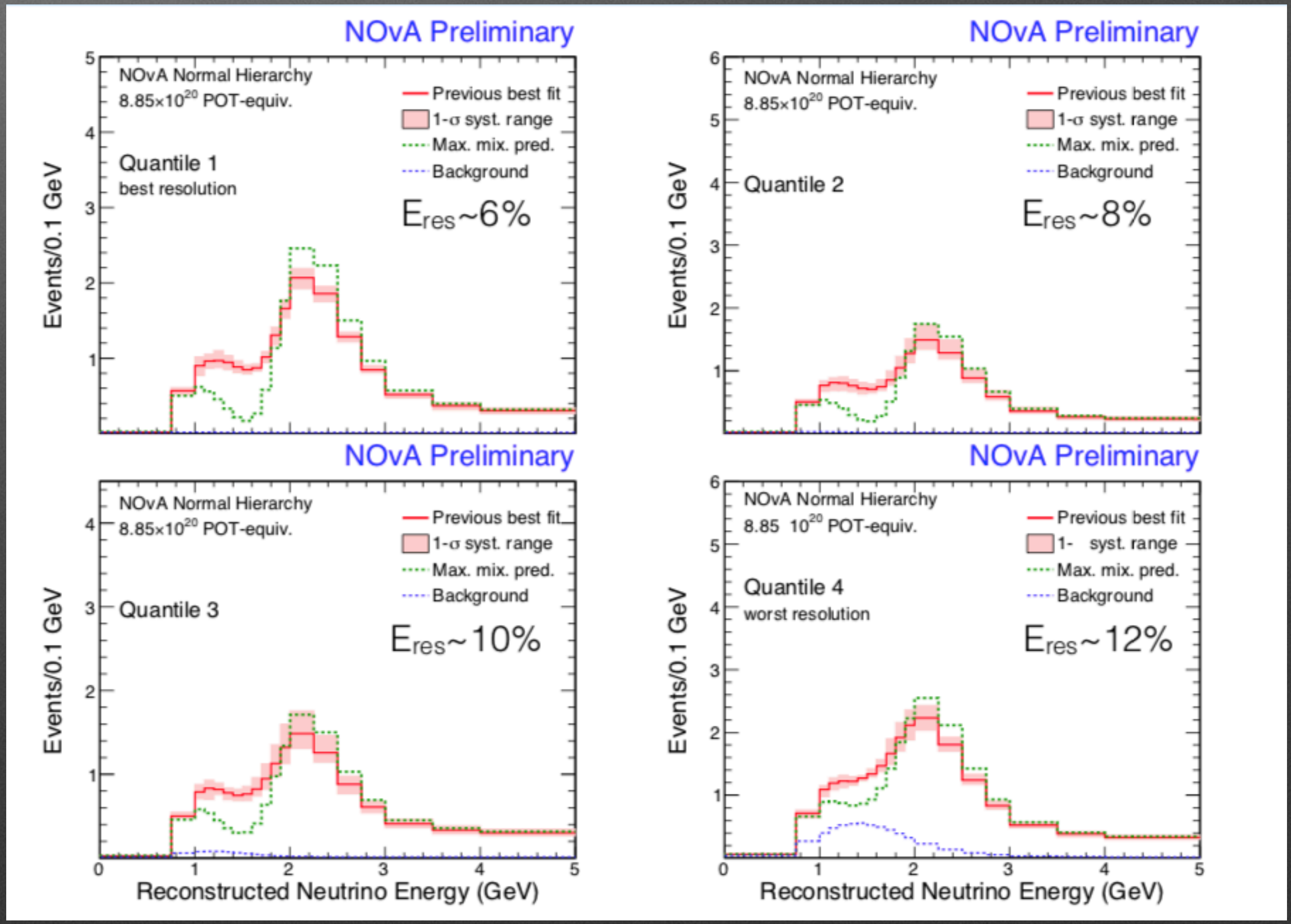
- Reconstructed energy combines E_{had} and E_{μ}
- Observed ND spectrum is converted into true and then extrapolated to far
- It might be more difficult to distinguish between detector and cross-section effects → if it's a detector effect far/near ratio is unchanged, if it's a cross-section effects should also affect the far/near ratio!

New NOνA analysis

- Do something more refined to separate detector from cross-section effects by separating the sample in different bins of hadronic energy

- The far to near ratio is then propagated independently for each bin





Oscillation analysis

- Both collaborations now do a full joint analysis
- T2K: ν_e, $\overline{\nu}_e$, ν_μ and $\overline{\nu}_\mu$
- NOνA: ν_e and ν_μ → antineutrinos samples coming soon

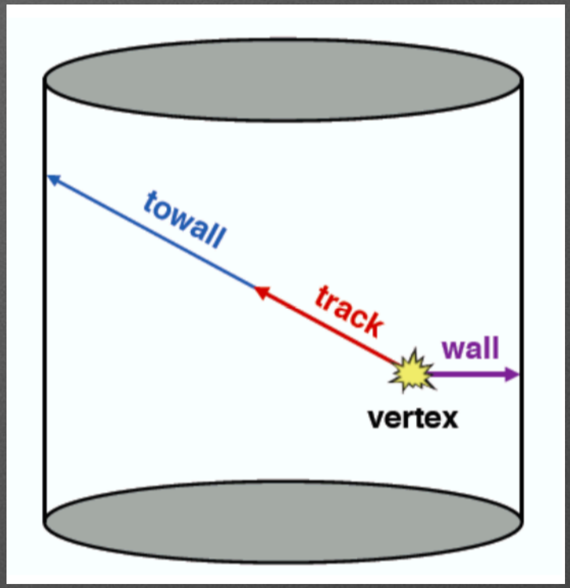
$$-ln(L) = \sum_{i}^{N_{SKbins}} N_i^{SK}(\vec{o},\vec{p}) - M_i^{SK} + M_i^{SK} ln[M_i^{SK}/N^{SK}(\vec{o},\vec{p})]$$
$$+\frac{1}{2}\sum_{i}^{N_o}\sum_{j}^{N_o}\Delta o_i (V_{ij}^{o})^{-1}\Delta o_j + \frac{1}{2}\sum_{i}^{N_p}\sum_{j}^{N_p}\Delta p_i (V_{ij}^{p})^{-1}\Delta p_j$$

N → expected events
M → observed events
o → oscillation parameters
p → other nuisance parameters

- In order to make the presentation clearer I'll show first ν_μ disappearance (θ_{23}, Δm_{23}) and then appearance (θ_{13}, δ_{CP}, Mass Ordering) results

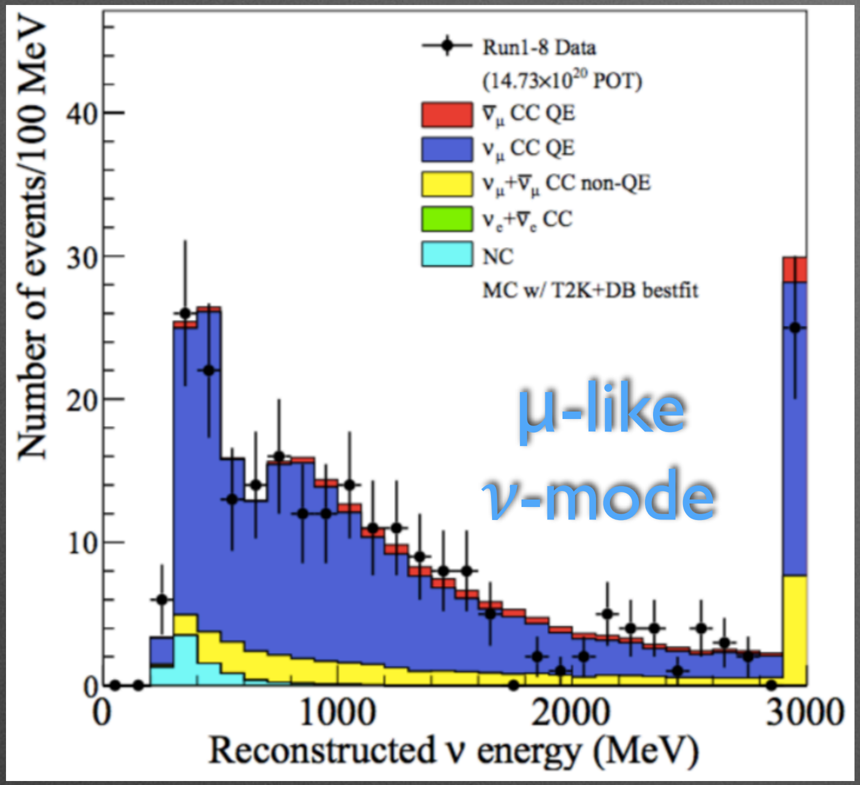
T2K Far Detector event selection

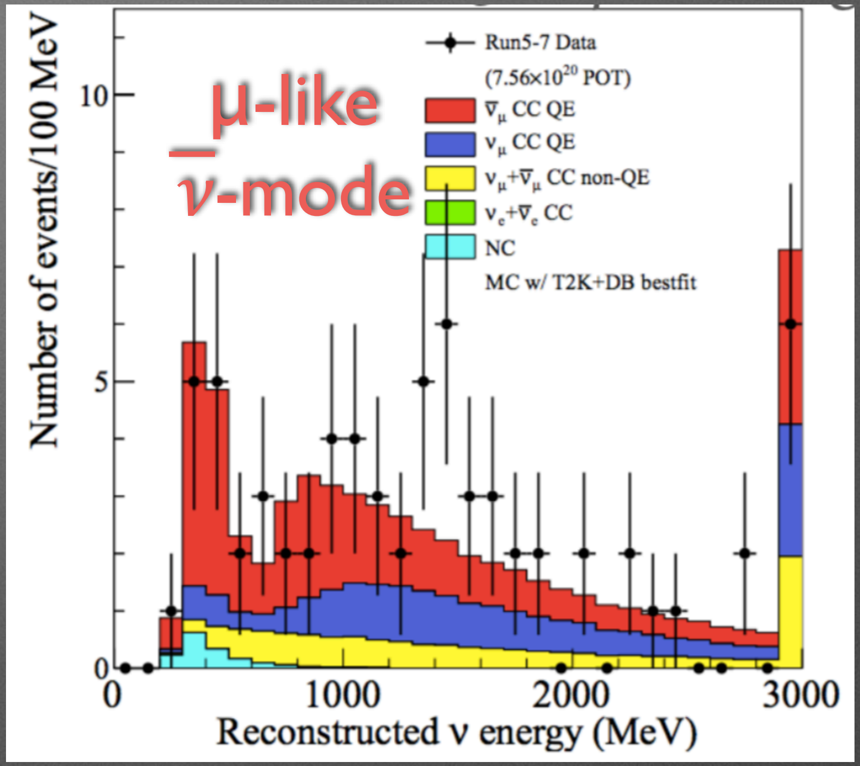
MC exp	New SK selection		Old SK selection	
	Candidate	Purity	Candidate	Purity
ν-mode e-like	69.5	81 %	56.5	81 %
ν-mode e-like	6.9	79 %	5.6	72 %
$\bar{\nu}$-mode e-like	7.6	62 %	6.1	64 %
ν-mode μ-like	261.6	80 %	268.7	68 %
$\bar{\nu}$-mode μ-like	62.0	80 %	65.4	71 %



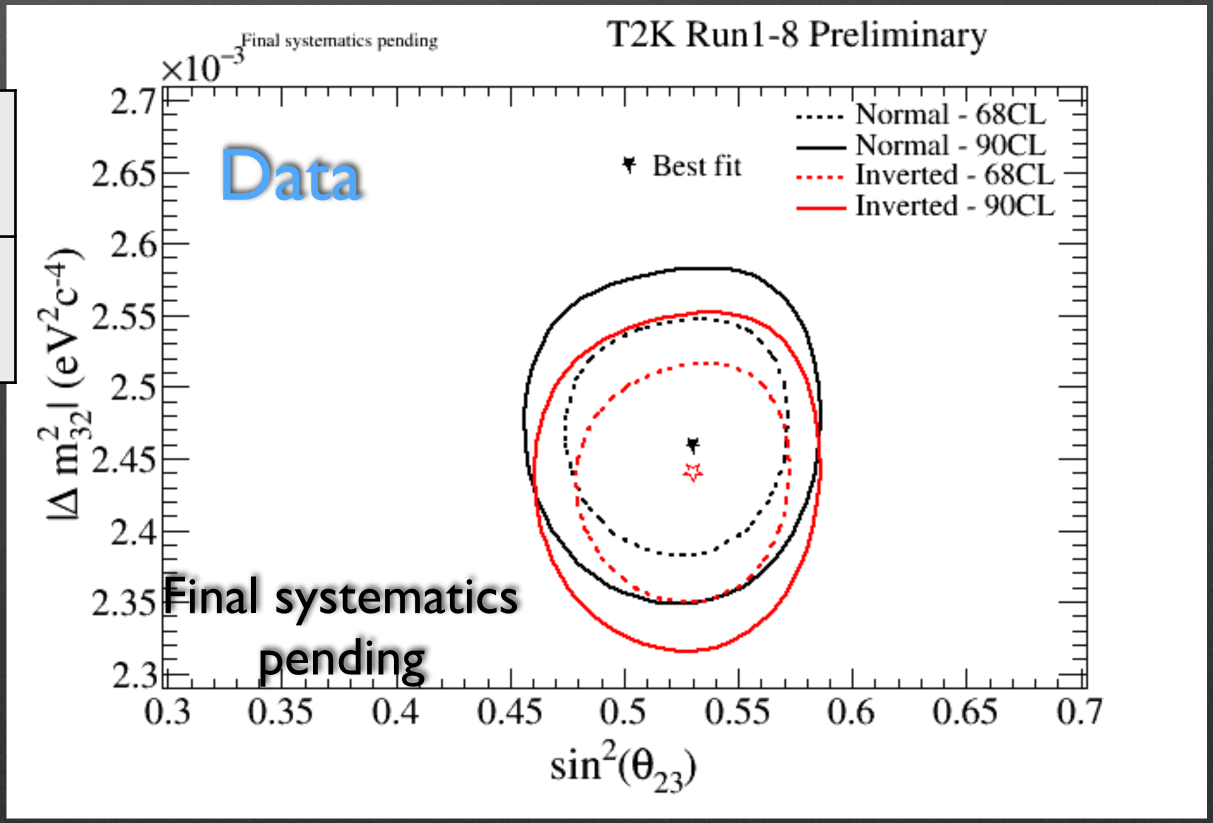
- Select single-ring events at SK
- Separate them according to their PID in μ-like and e-like
- New optimisation of the selection allowed to increase by ~30% the statistics

T2K ν_μ disappearance



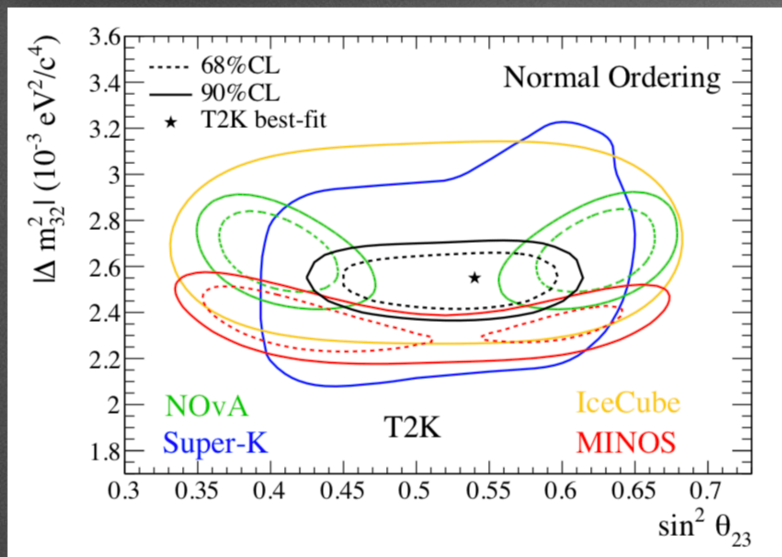


ν-mode μ-like	240	267.8
$\bar{\nu}$-mode μ-like	68	63.1



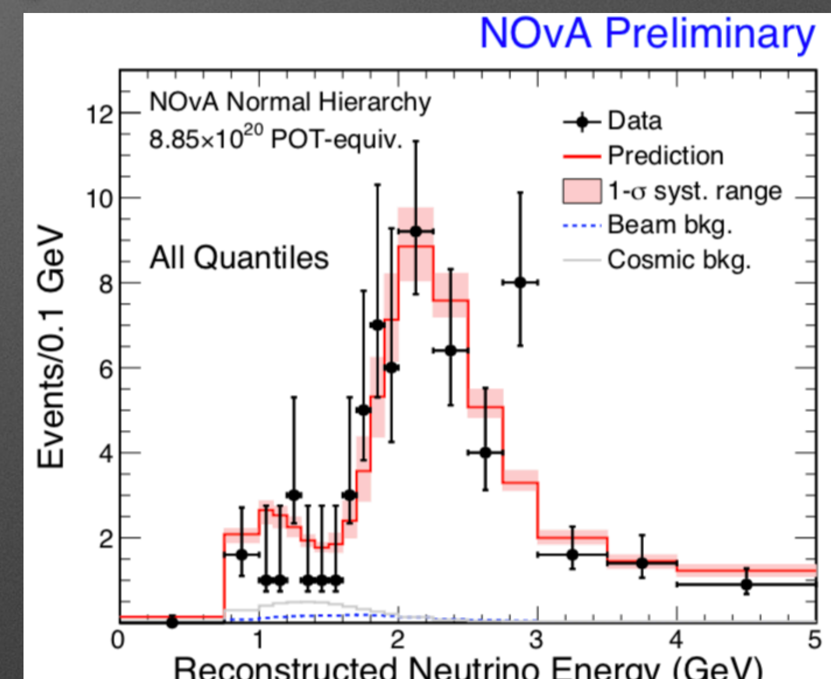
- Results still preliminary → we are doing careful job to finalise the systematics uncertainties
- Plan to publish within the next month

NOνA ν_μ disappearance



- Some (mild) tension between T2K and NOνA with NOνA old analysis

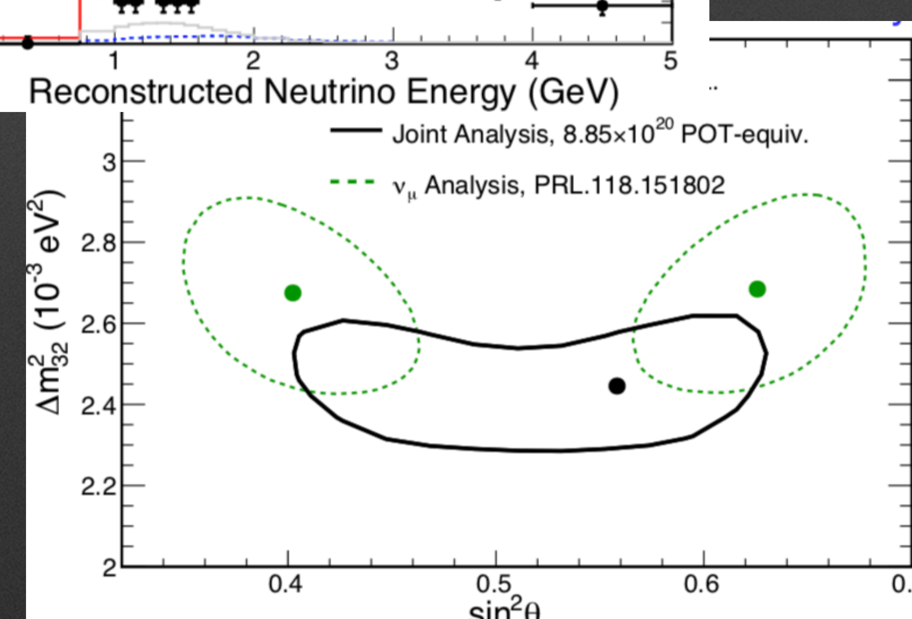
- Claim to exclude maximal mixing at 2.6σ while T2K is compatible with maximal mixing



- Also global fits prefer non-maximal θ_{23}

- New analysis from NOνA with more stat. and new method for Near to Far extrapolation show that they are now compatible with maximal mixing!

- Approaching T2K level of precision.. is θ_{23} maximal?



How to be sure

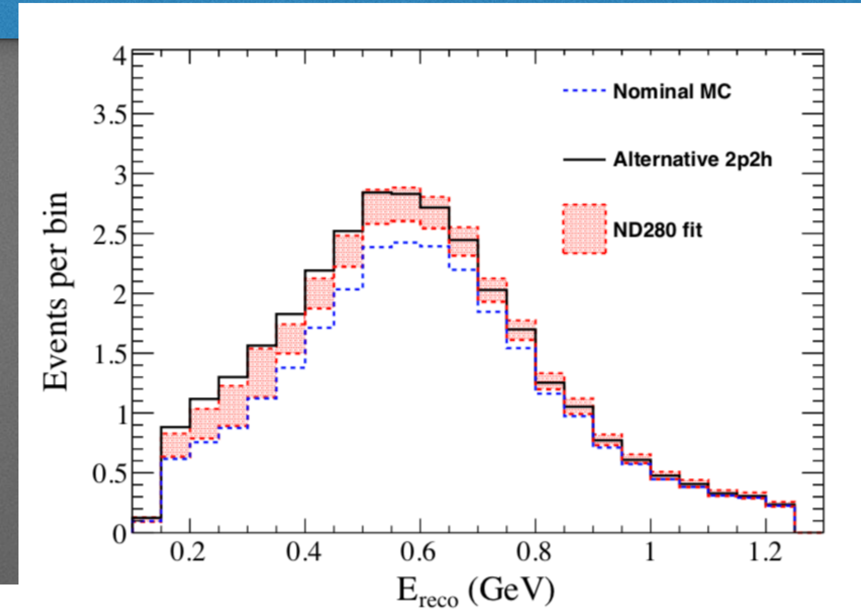
* In T2K we developed a procedure to test the robustness of our limits against model dependencies

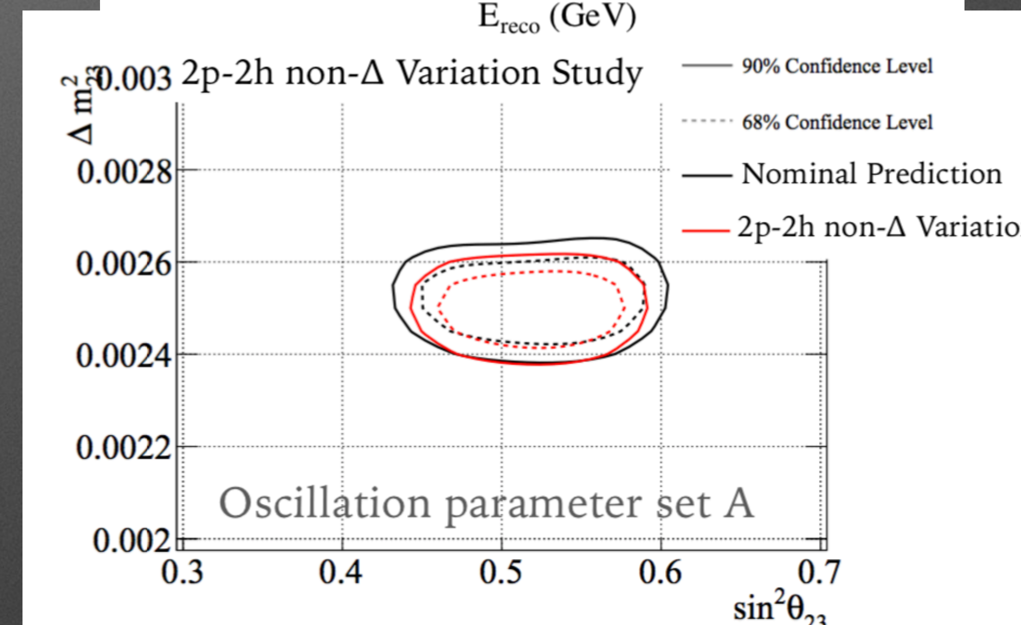
* Change cross-section model and produce expected spectra at near and far detector

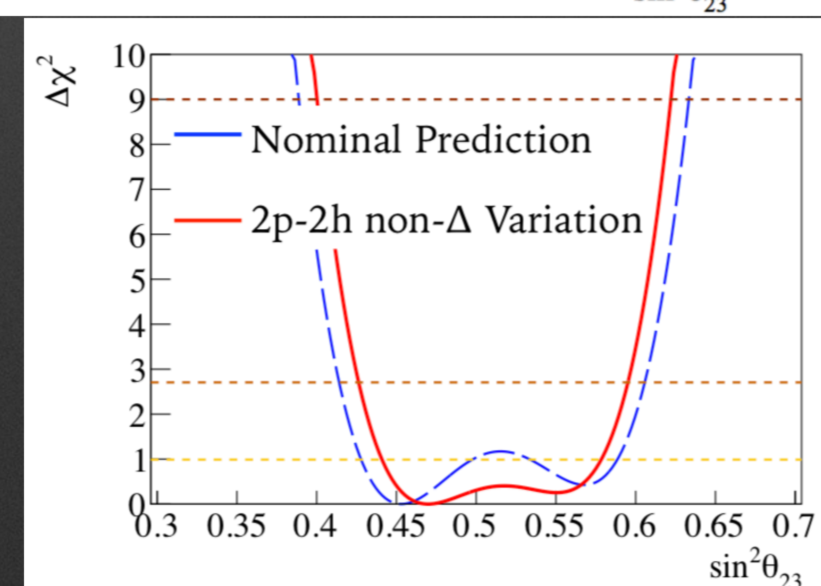
* Fit ND with our nominal model and propagate constraints to FD

* Check effect on oscillation parameters

* If difference is large account for it in the systematics evaluations



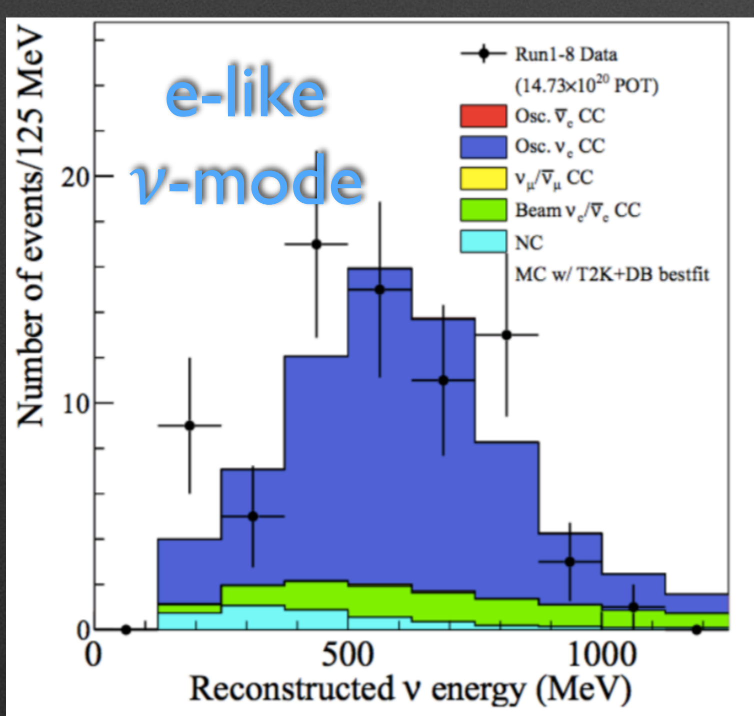


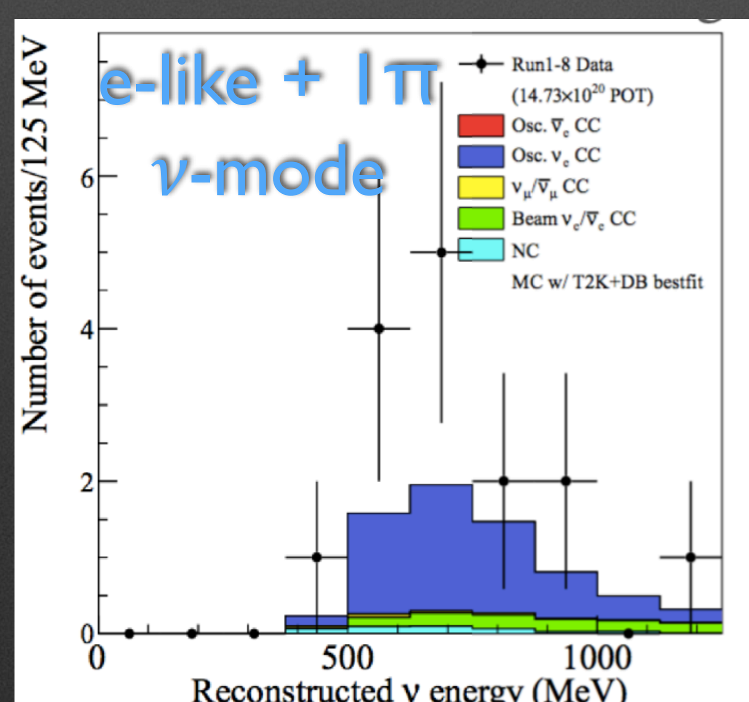


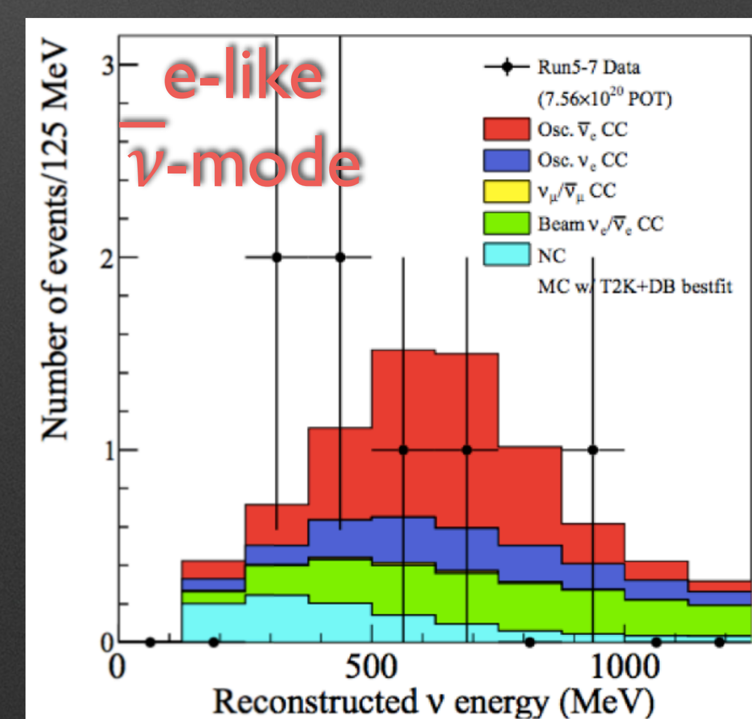
T2K e-like selection

	Data	MC expected Number of events			
		δCP=-π/2	δCP=0	δCP=+π/2	δCP=π
ν-mode e-like	74	73.5	61.5	49.9	62.0
ν-mode e-like+1π	15	6.9	6.0	4.9	5.8
$\bar{\nu}$-mode e-like	7	7.9	9.0	10.0	8.9

- δCP gives ~20% asymmetry in the event rate
- ν-mode Signal/Background ~4.4 at $\delta_{CP}=-\pi/2$



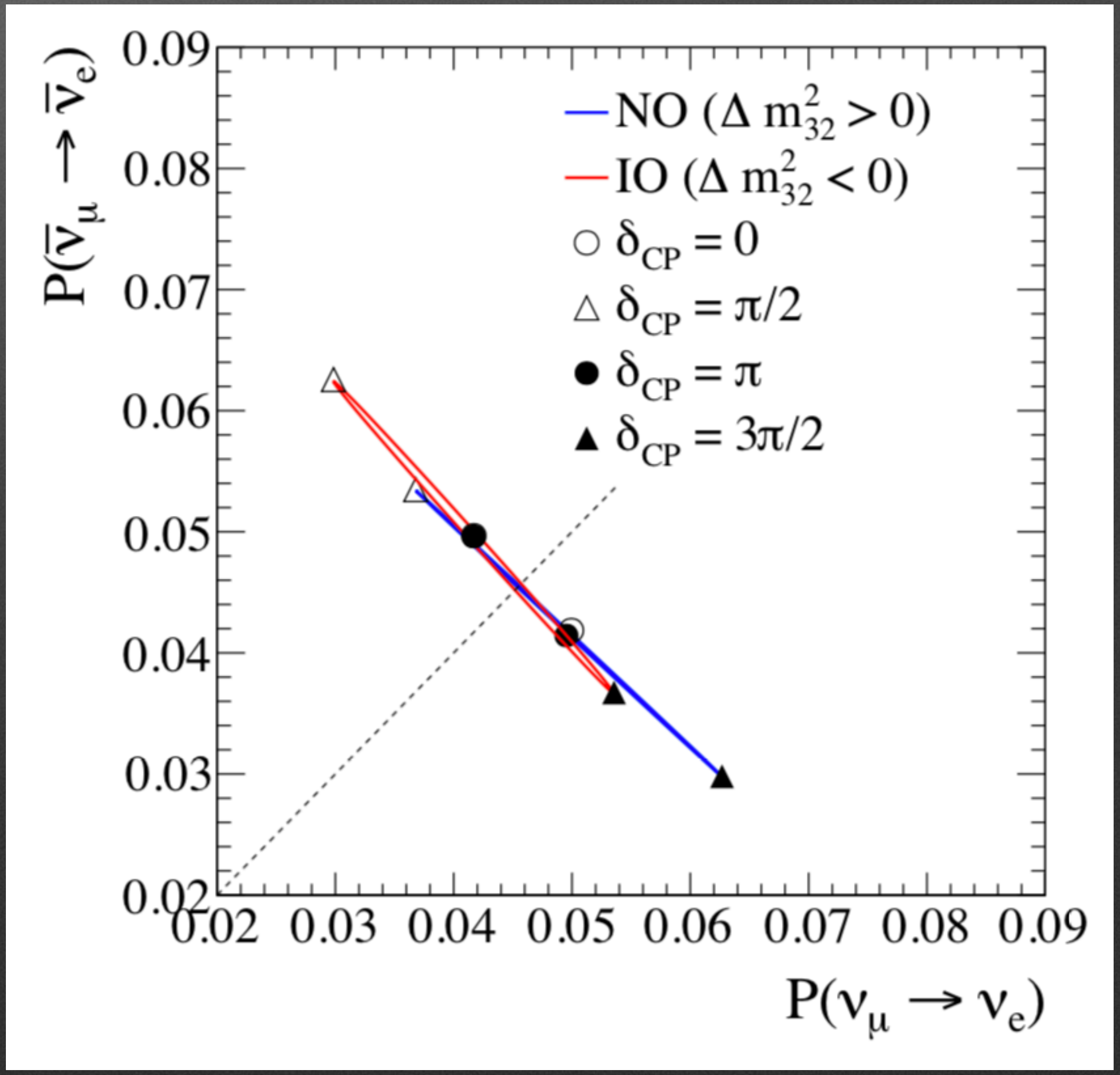




T2K appearance

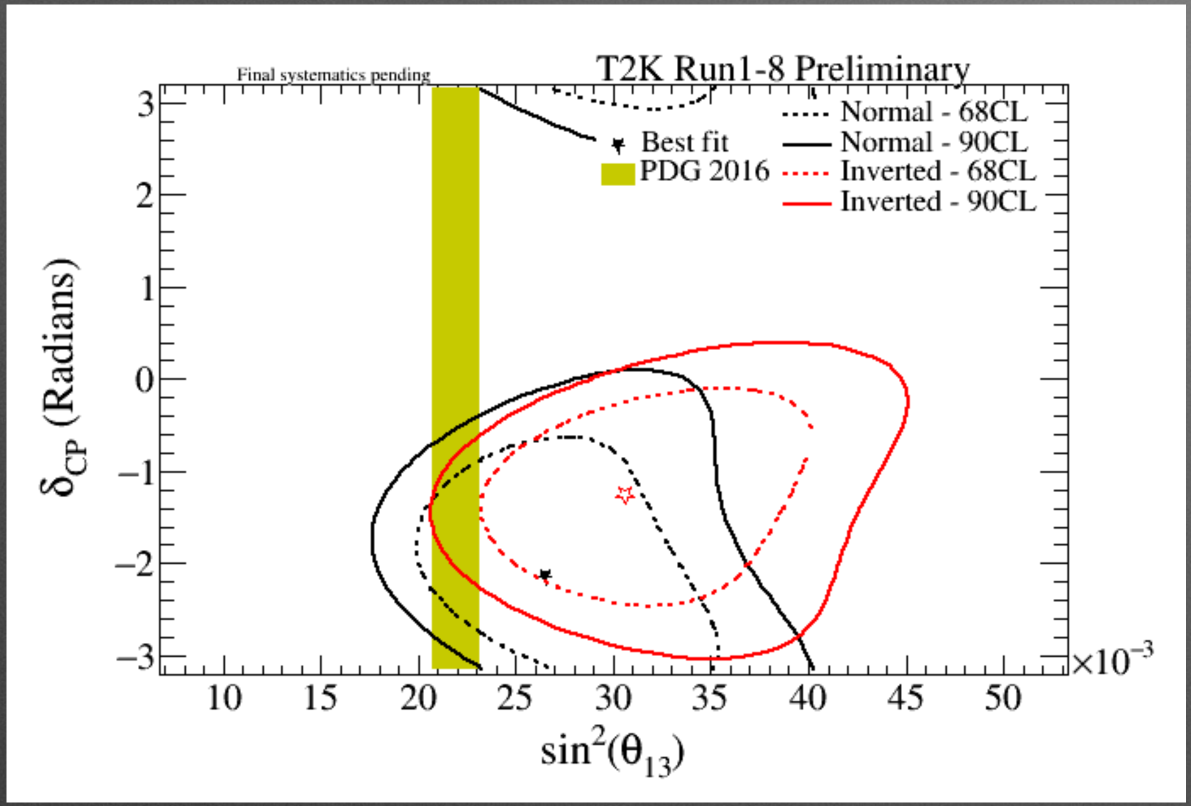
	Data	MC expected Number of events			
		δCP=-π/2	δCP=0	δCP=+π/2	δCP=π
ν-mode e-like	74	73.5	61.5	49.9	62.0
ν-mode e-like+1π	15	6.9	6.0	4.9	5.8
$\bar{\nu}$-mode e-like	7	7.9	9.0	10.0	8.9

- θ_{23} → ν_e and $\overline{\nu}_e$ appearance probabilities are affected in the same way
- δ_{CP} = $-\pi/2$ → maximize ν_e appearance, minimize $\overline{\nu}_e$ (~30%)
- δ_{CP} = $\pi/2$ → maximize $\overline{\nu}_e$ appearance, minimize ν_e (~30%)
- Normal hierarchy → same as δ_{CP}=$-\pi/2$ but smaller effect in T2K (~10%)

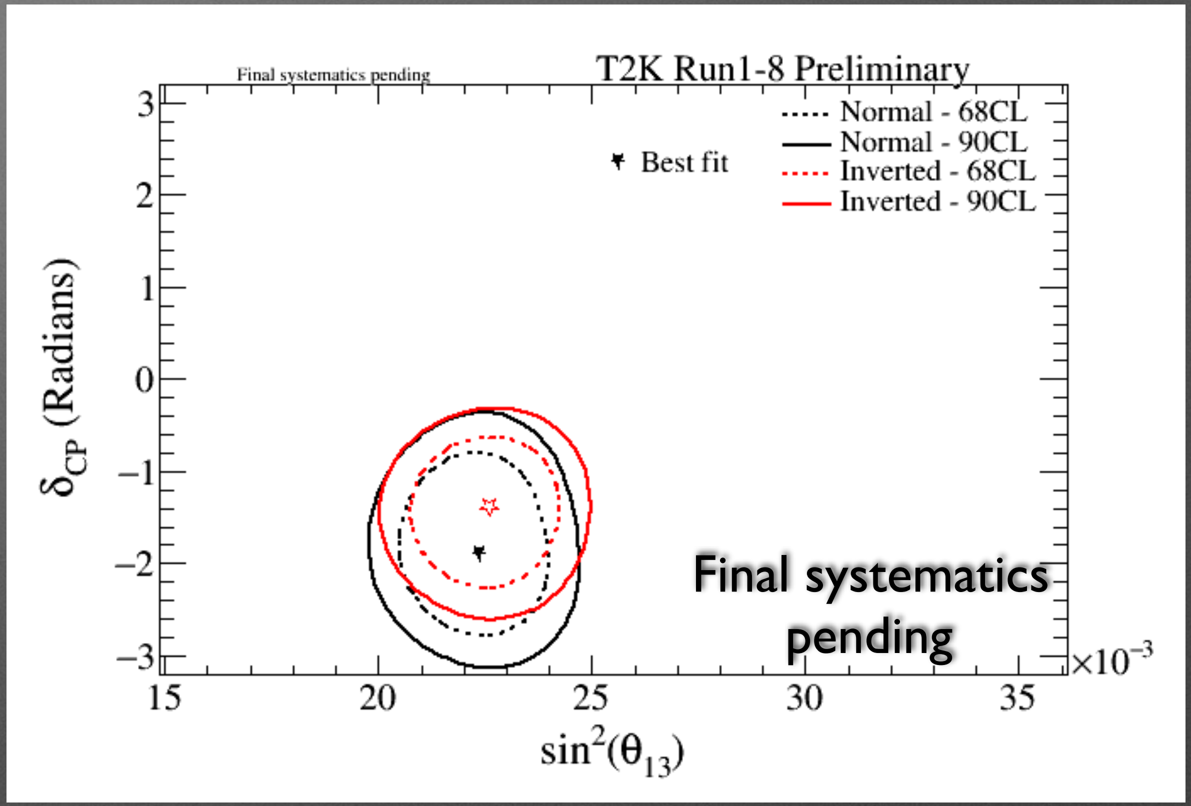


(θ_{13}, δ_{CP})

without reactor



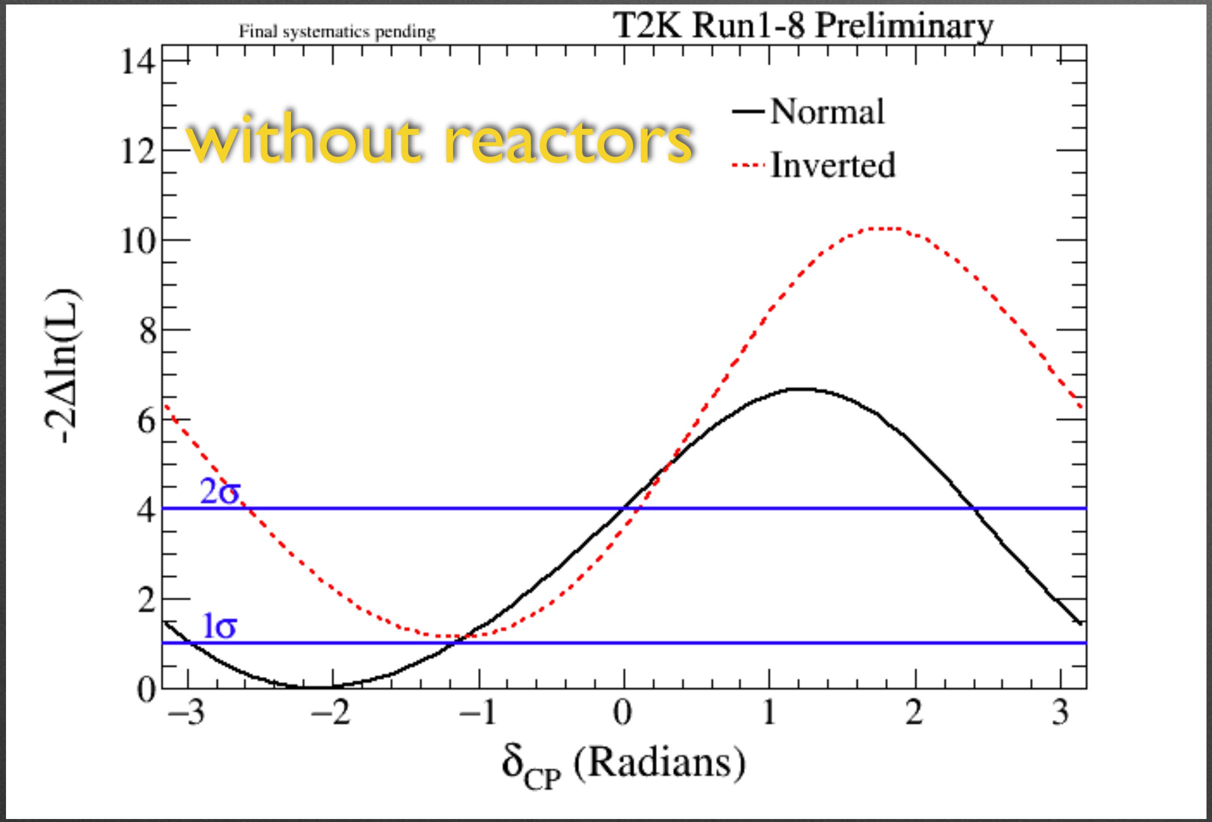
with reactor

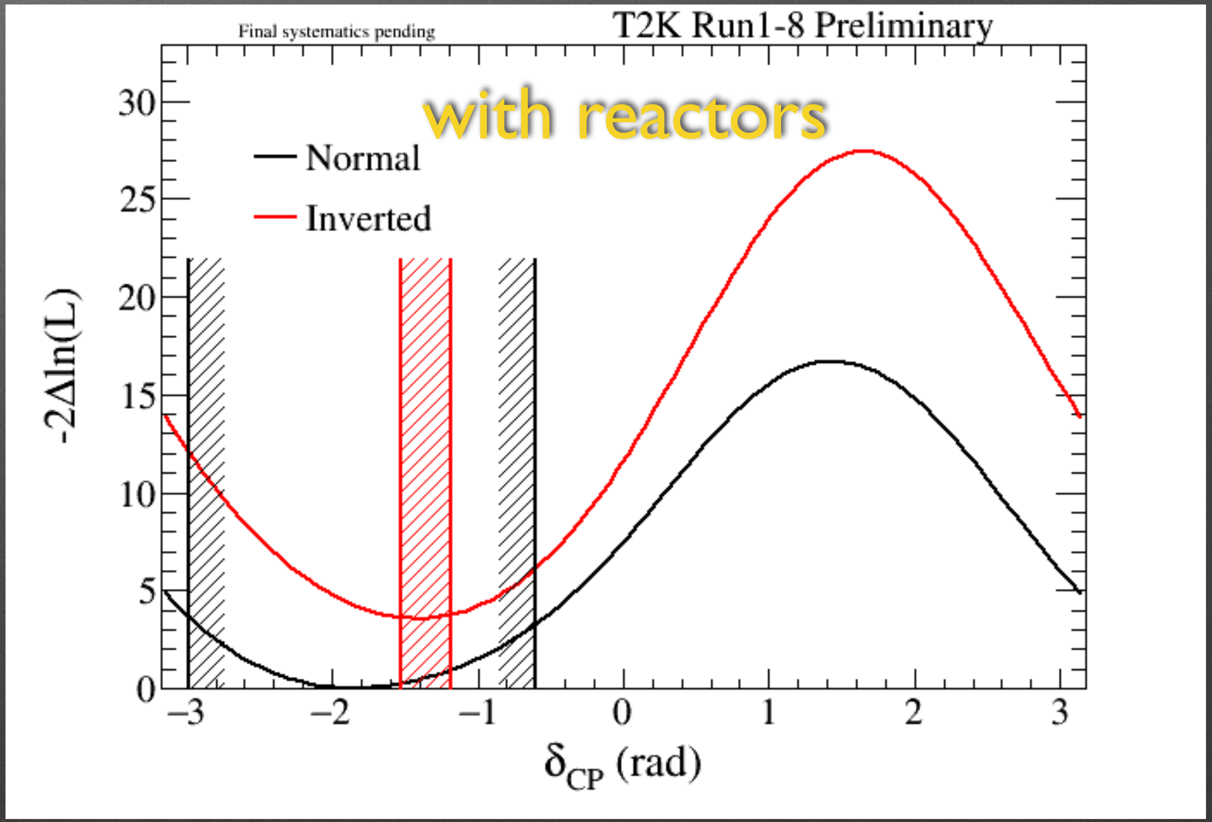


- Without reactor constraints: $\sin^2\theta_{13}$ compatible with the one measured by reactors. Prefer values of δ_{CP} in the region around $-\pi/2$
- With reactor constraints: stronger preference for values of $\delta_{CP} \sim -\pi/2$
- As expected given the observed number of e-like events in ν and $\bar{\nu}$ mode

T2K δ_{CP} measurement

	Normal hierarchy	Inverted hierarchy
68% CL	[-2.49, -1.23]	-
90% CL	[-2.80,-0.83]	-
2σ	[-2.98,-0.60]	[-1.53,-1.19]

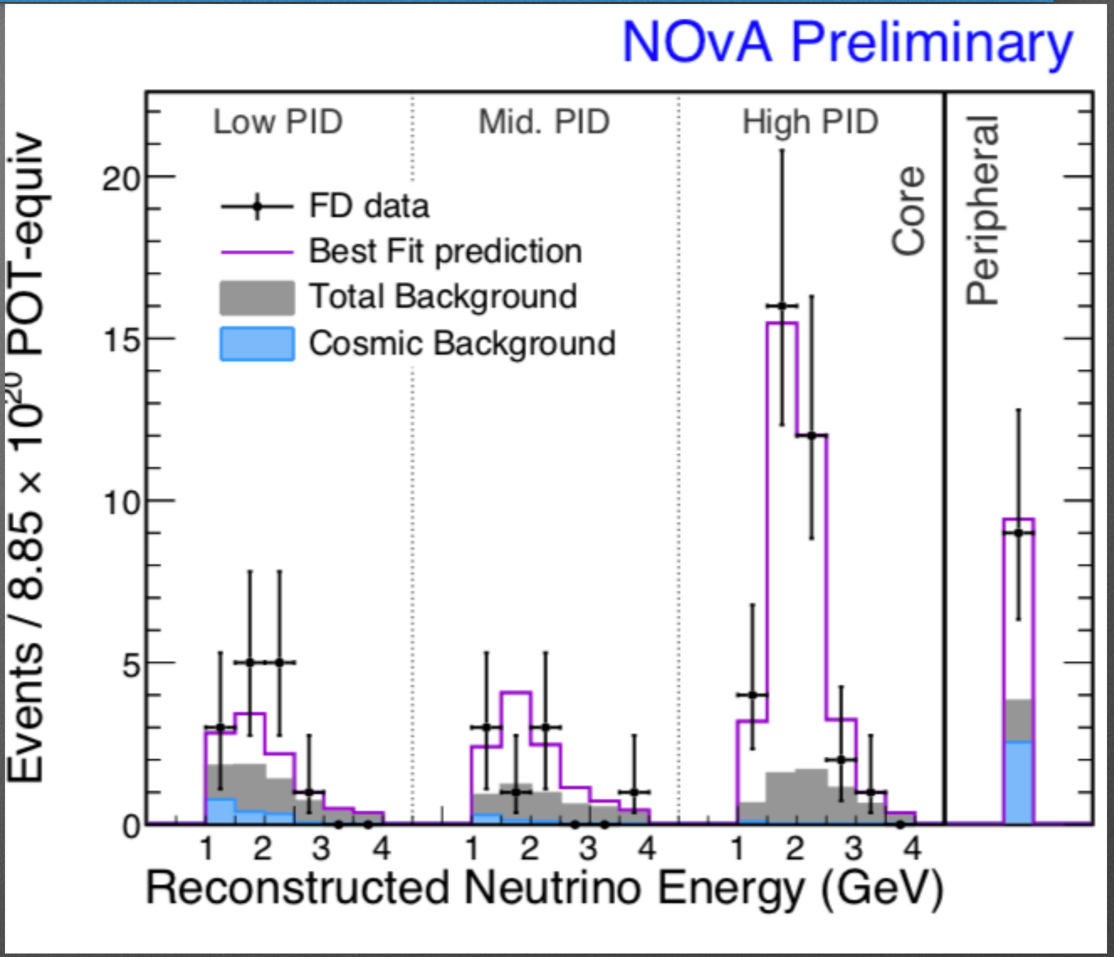


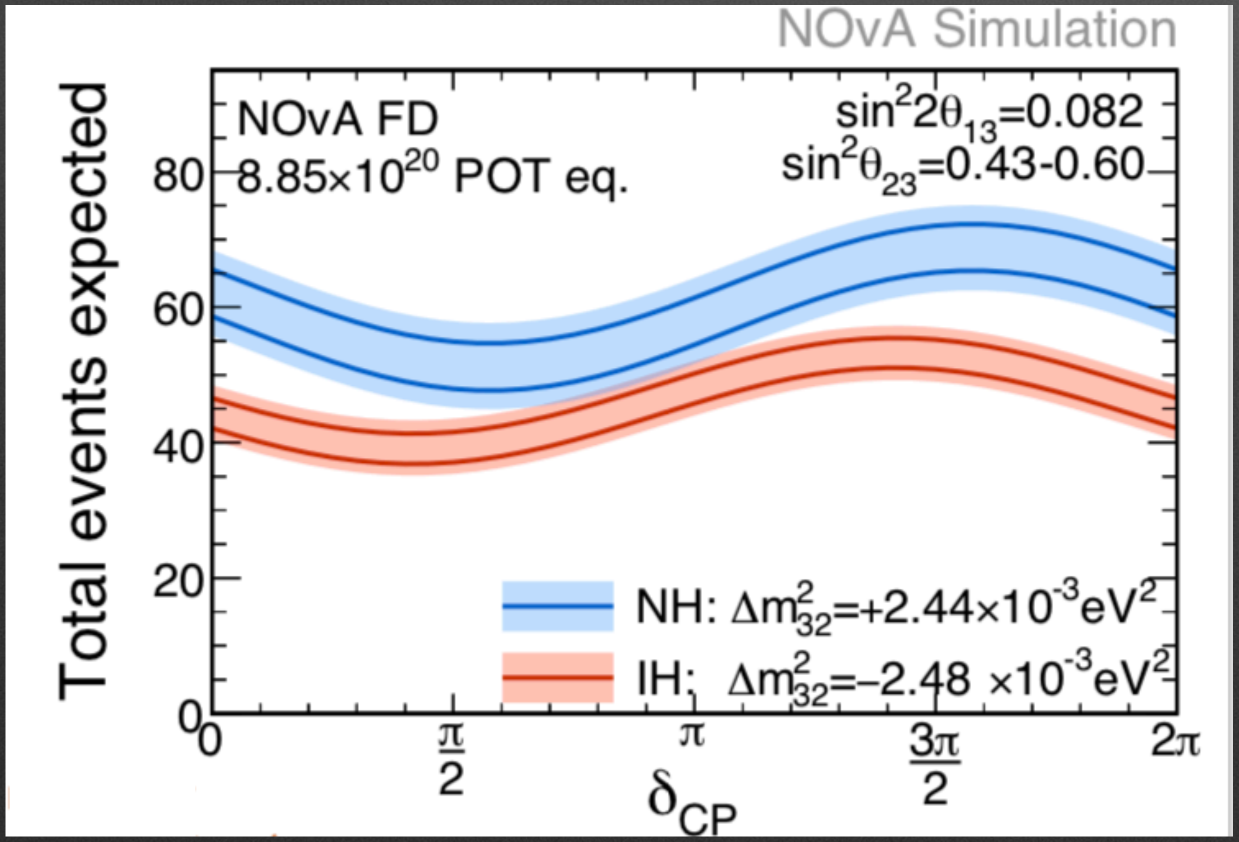


- Our data prefer values of δ_{CP}~-π/2 mostly driven by the large number of events observed in the e-like sample in ν-mode
- Feldman-Cousins method used to define confidence intervals for δ_{CP} → CP conserving values (0,π) excluded at 2σ

NOνA ν_e selection

- Convolutional neural network (CVN) to select e-like events
- Signal/Background of 2.3 at δ_{CP}=-π/2 (3π/2)





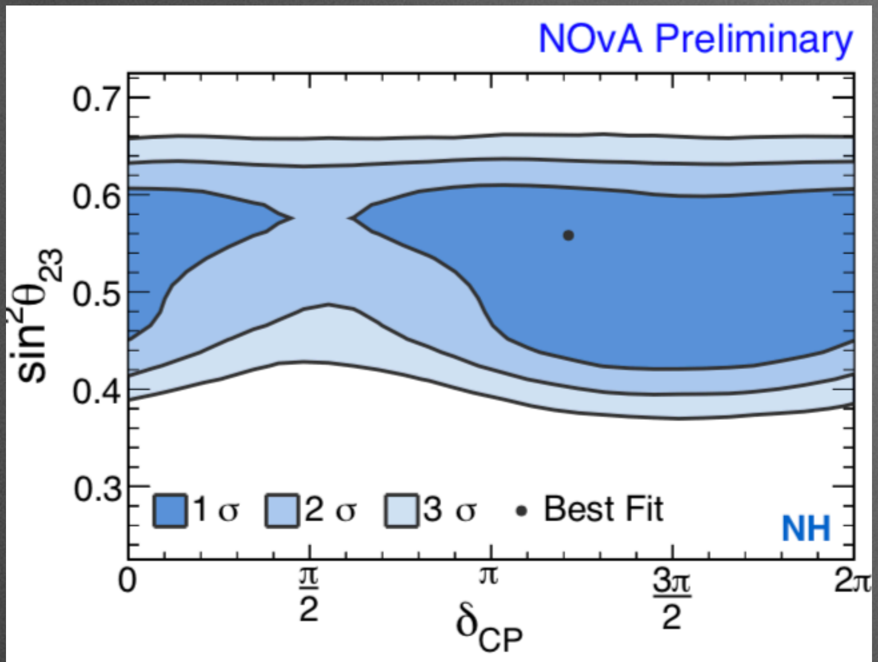
Signal events
(±9% systematic uncertainty

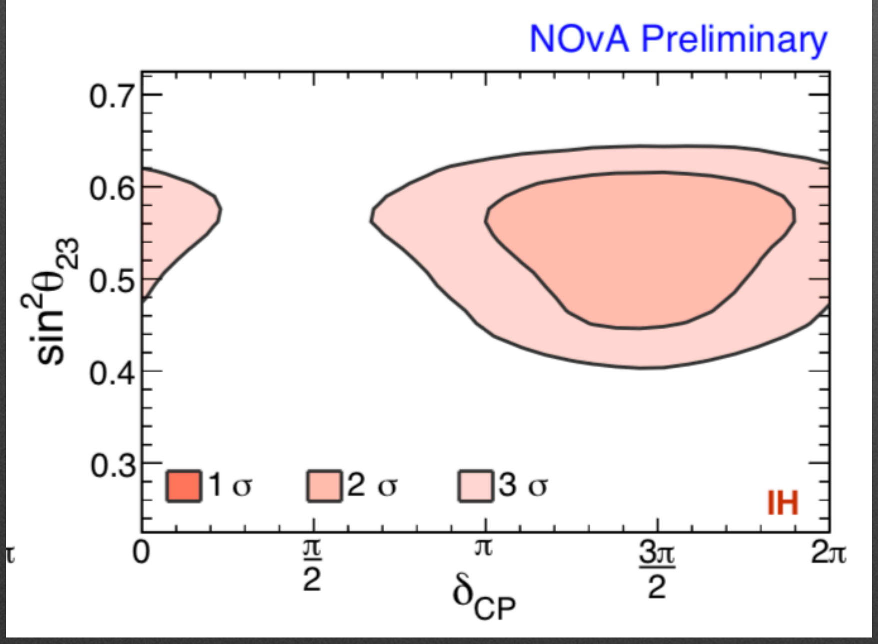
NH, 3π/2,	IH, π/2,
48	20

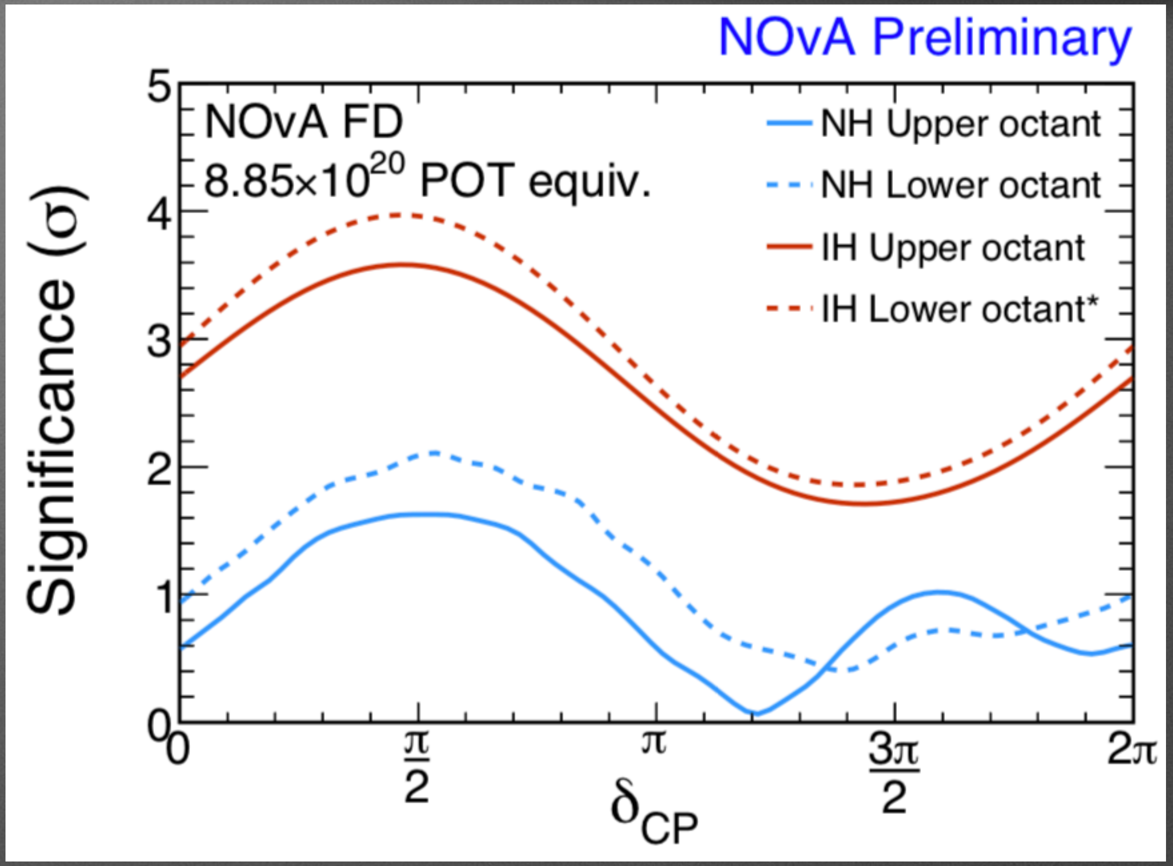
Background by component
(±10% systematic uncertainty):

Total BG	NC	Beam ν_e	ν_μ CC	ν_τ CC	Cosmics
20.5	6.6	7.1	1.1	0.3	4.9

NOνA appearance results





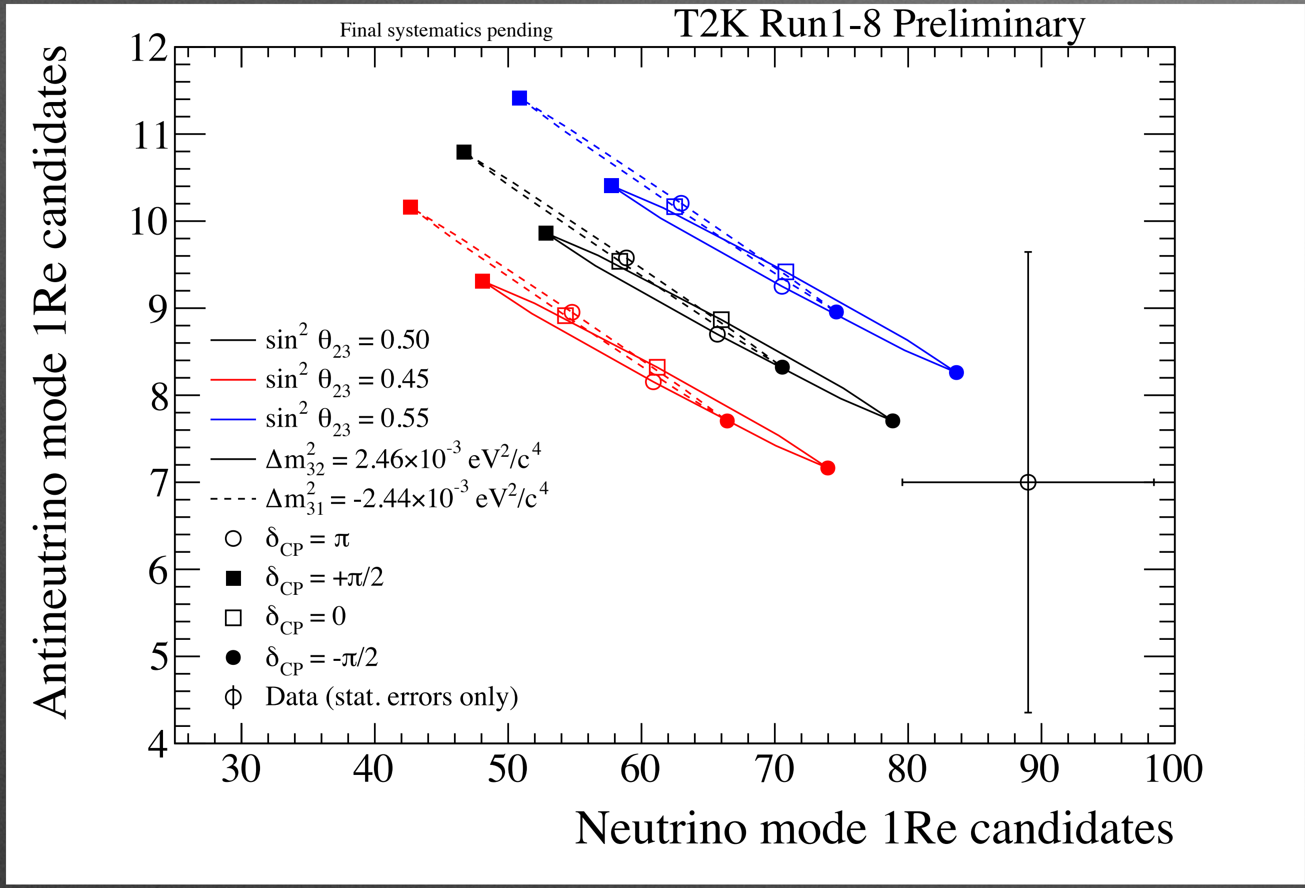


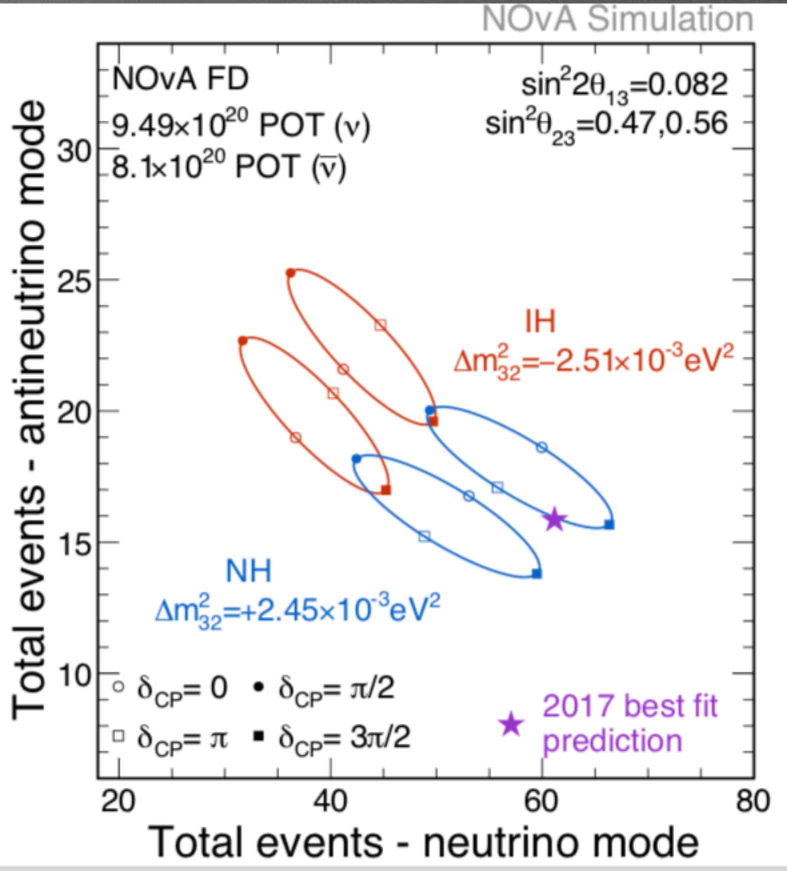
- Also NOνA prefer values of δCP ~ $-\pi/2$ (or $3/2\pi$) that maximise ν_e appearance

- Also prefer normal ordering → exclude inverted ordering at almost 2σ for all the values of δ_{CP}

- No antineutrino data yet

T2K/NOνA comparison

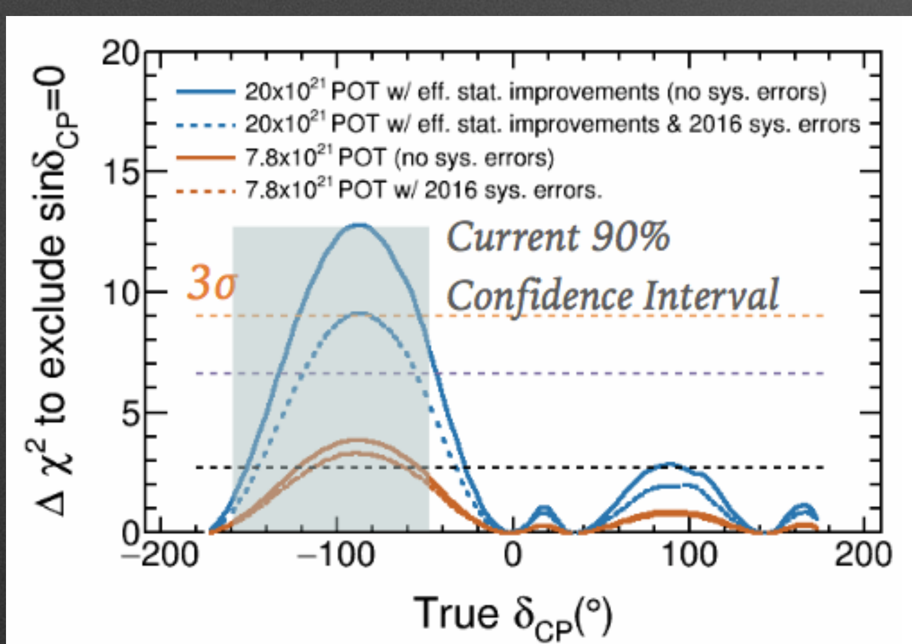


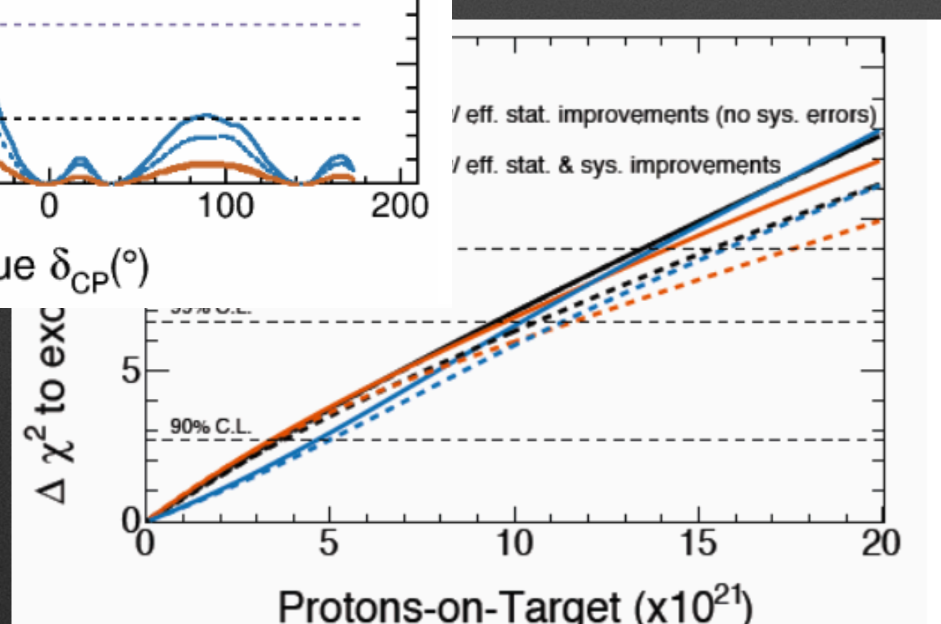


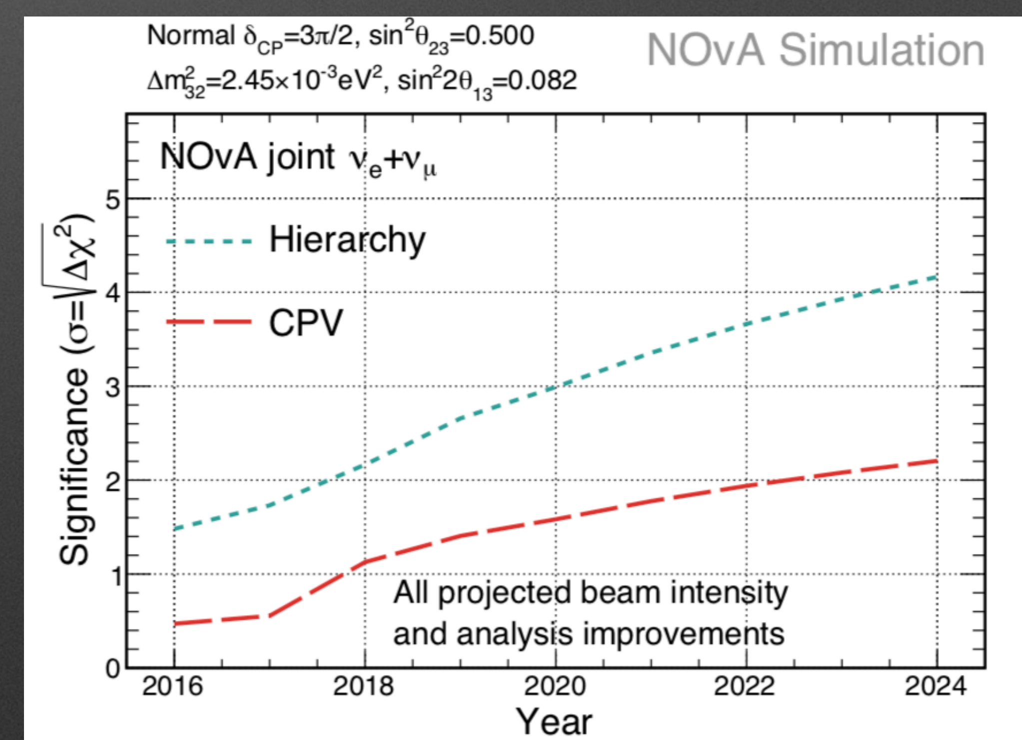
- Both experiments see a large appearance of νe → Compatible with maximal CP violation !
- Both are still statistically limited!
  - More data will help
  - NOνA antineutrino data, summer 2018!

The future

- T2K and NOνA are both seeing appearance rates compatible with normal ordering and δ_{CP}~-π/2 → This would be the luckiest combination in order to measure both!
- NOνA is most sensitive to MO and will release first results with $\bar{\nu}$ this summer!
- T2K will double its statistics in $\bar{\nu}$ by this summer and have 3σ sensitivity to CPV if enough data will be collected
- The two collaborations are also working towards a combined analysis (~2021)



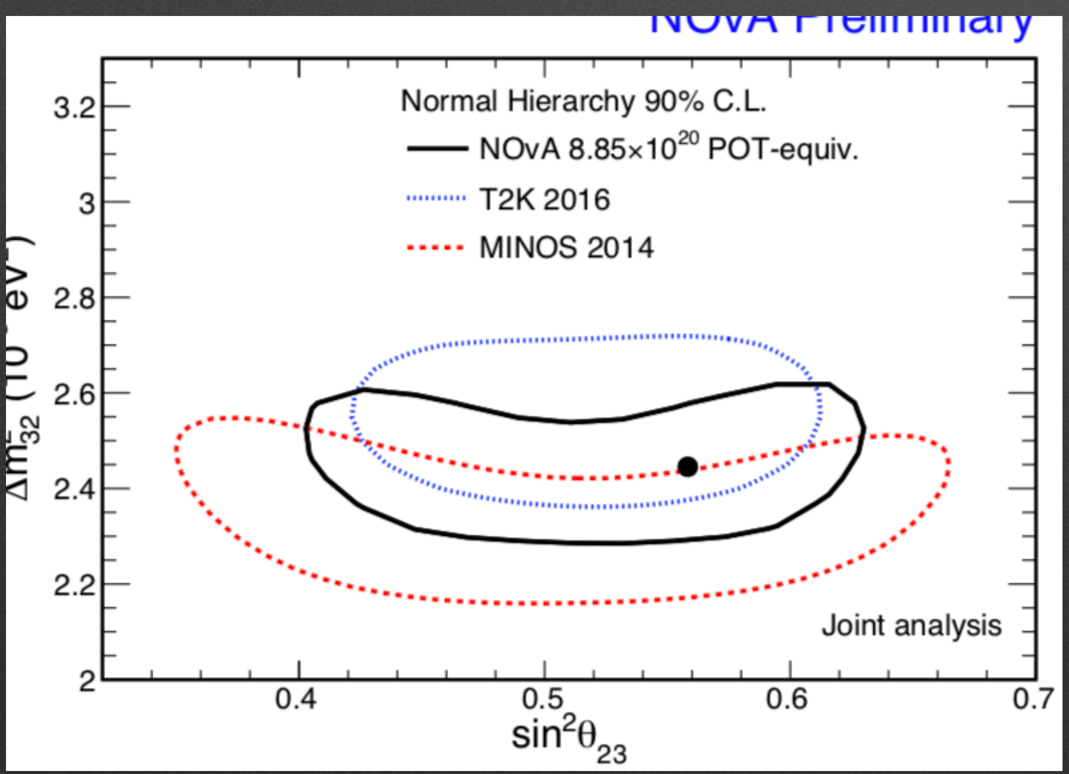


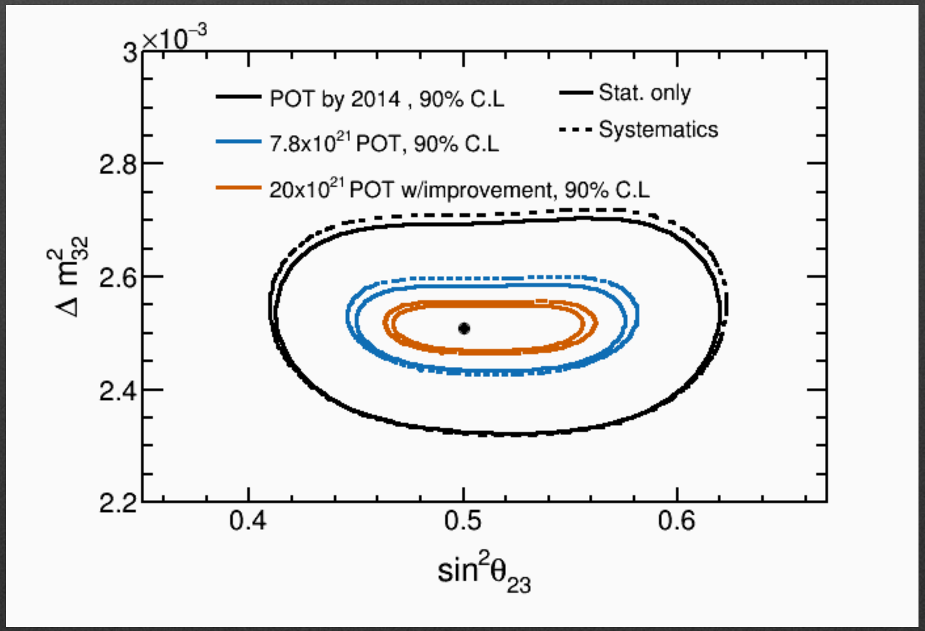


ν_μ disappearance

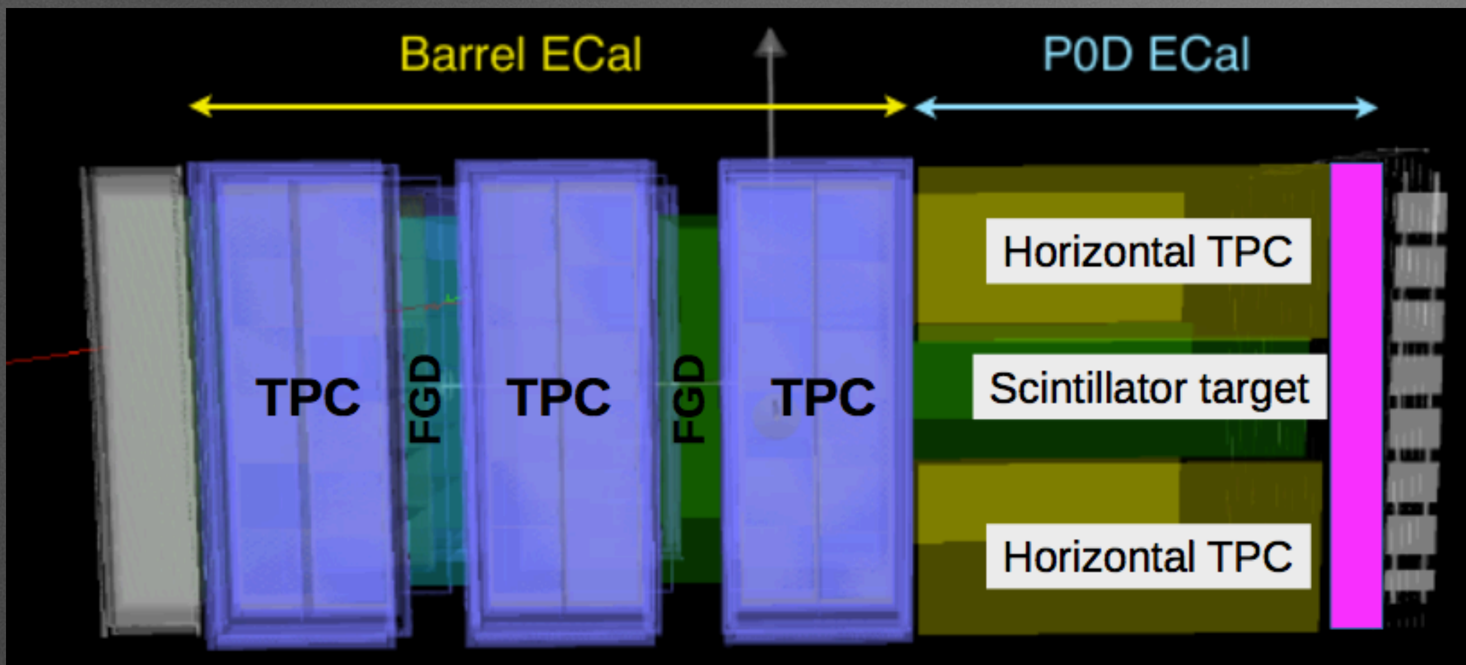
- More data will also allow precise measurements of the disappearance parameters

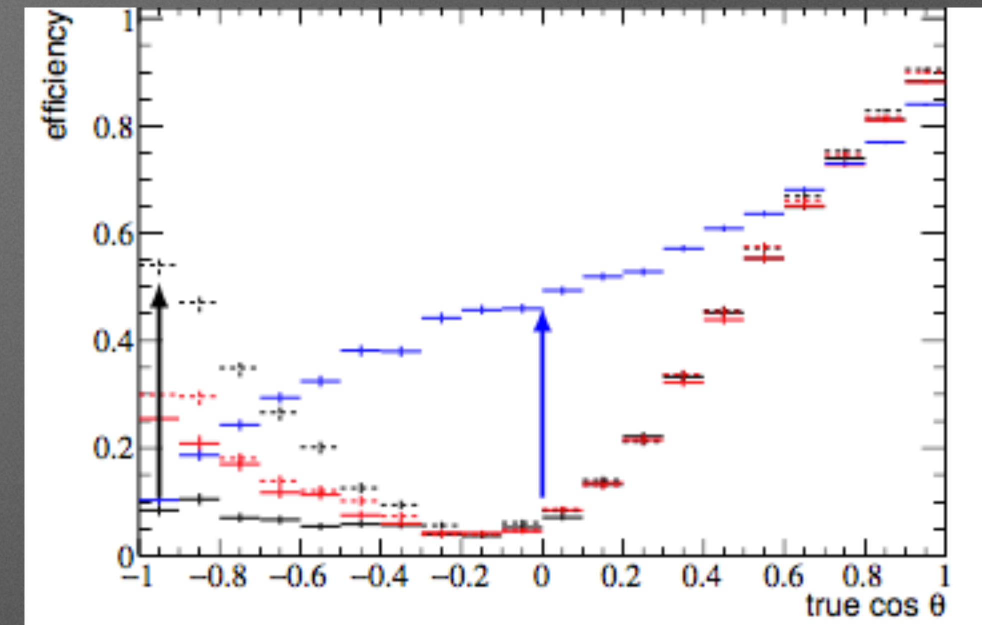
- Investigate if θ_{23} is really maximal or not!



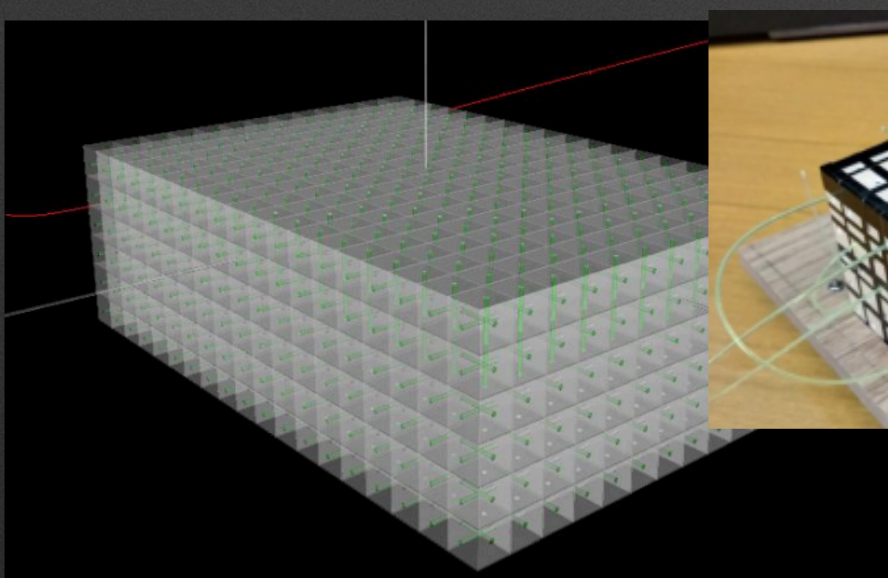


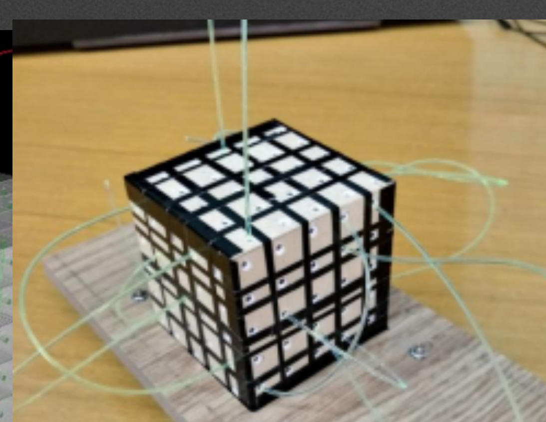
T2K and the ND280 upgrade



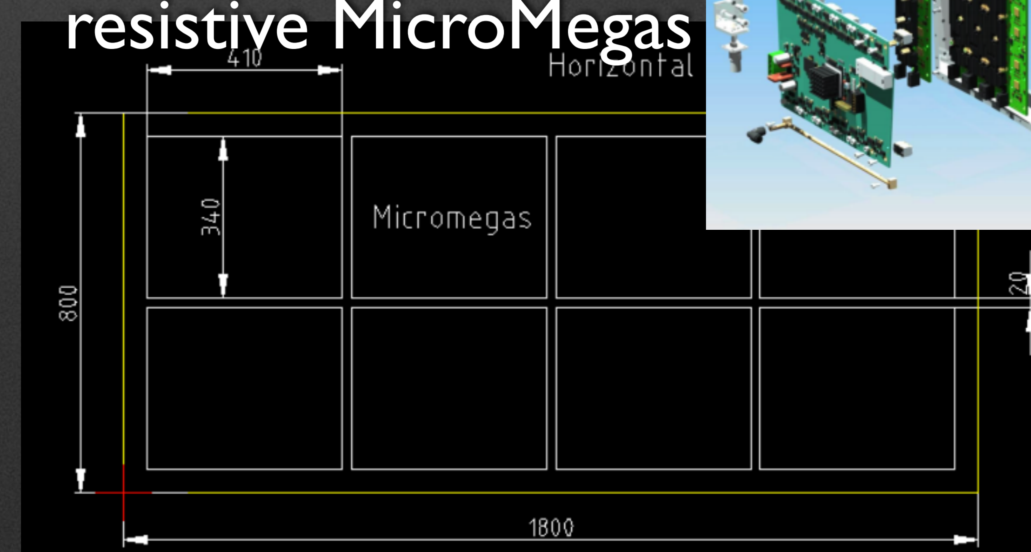


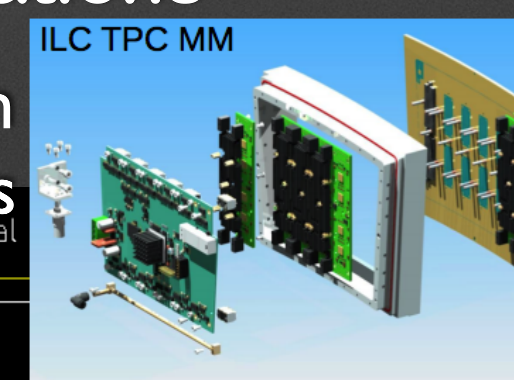
- Goal of the upgrade project: replace the P0D with an horizontal totally active target and 2 horizontal TPCs by 2021
- Currently working on R&D and prototypes + simulations





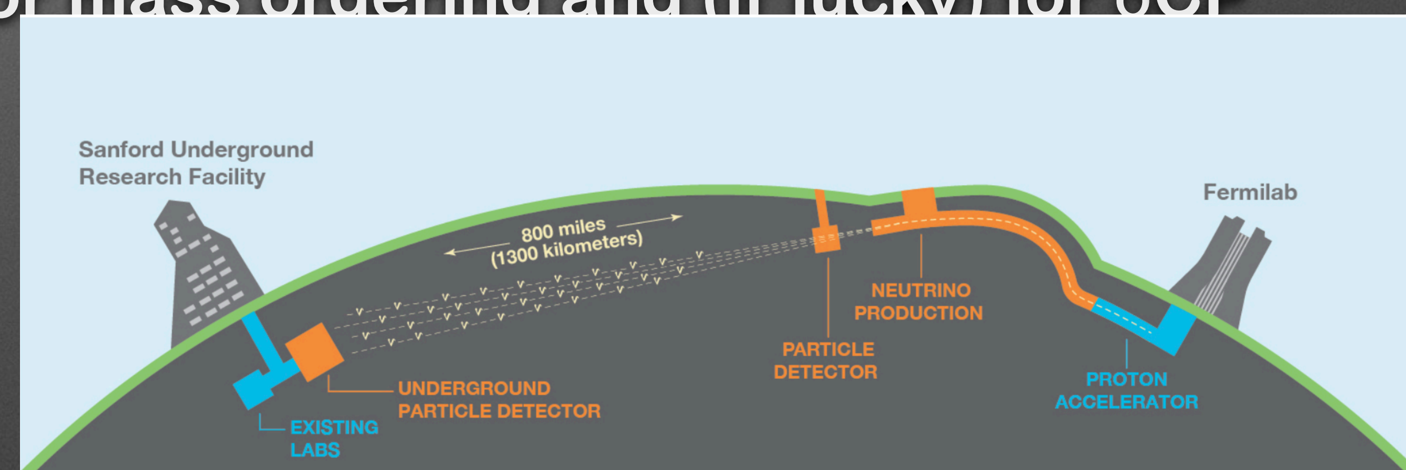
Horizontal TPC with resistive MicroMegas





Longer term future

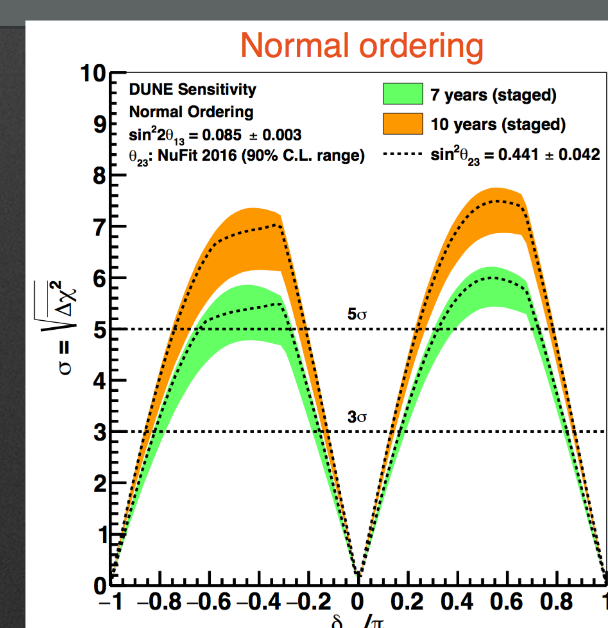
- NOνA and T2K will continue to take data, leading the search for δ_{CP} until 2026 → more than 3 σ for both, δCP and Mass Ordering
- Then 2 next-generation LBL experiments will come online: DUNE (US) and Hyper-K (Japan)
- I don't have time to discuss them today.. but they will collect thousands of neutrino interactions → >5 σ for mass ordering and (if lucky) for δCP



Hyper-K Design Report (7E21 POT for nu and 20E21 POT for anti-nu)

		signal		BG						Total
		$\nu_\mu \to \nu_e$	$\bar{\nu}_\mu \to \bar{\nu}_e$	ν_μ CC	$\bar{\nu}_\mu$ CC	ν_e CC	$\bar{\nu}_e$ CC	NC	BG Total	
ν mode	Events	2300	21	10	0	347	15	188	560	2880
	Eff.(%)	63.6	47.3	0.1	0.0	24.5	12.6	1.4	1.6	—
$\bar{\nu}$ mode	Events	289	1656	3	3	142	302	274	724	2669
	Eff. (%)	45.0	70.8	0.03	0.02	13.5	30.8	1.6	1.6	—

assuming $\delta_{CP}=0$



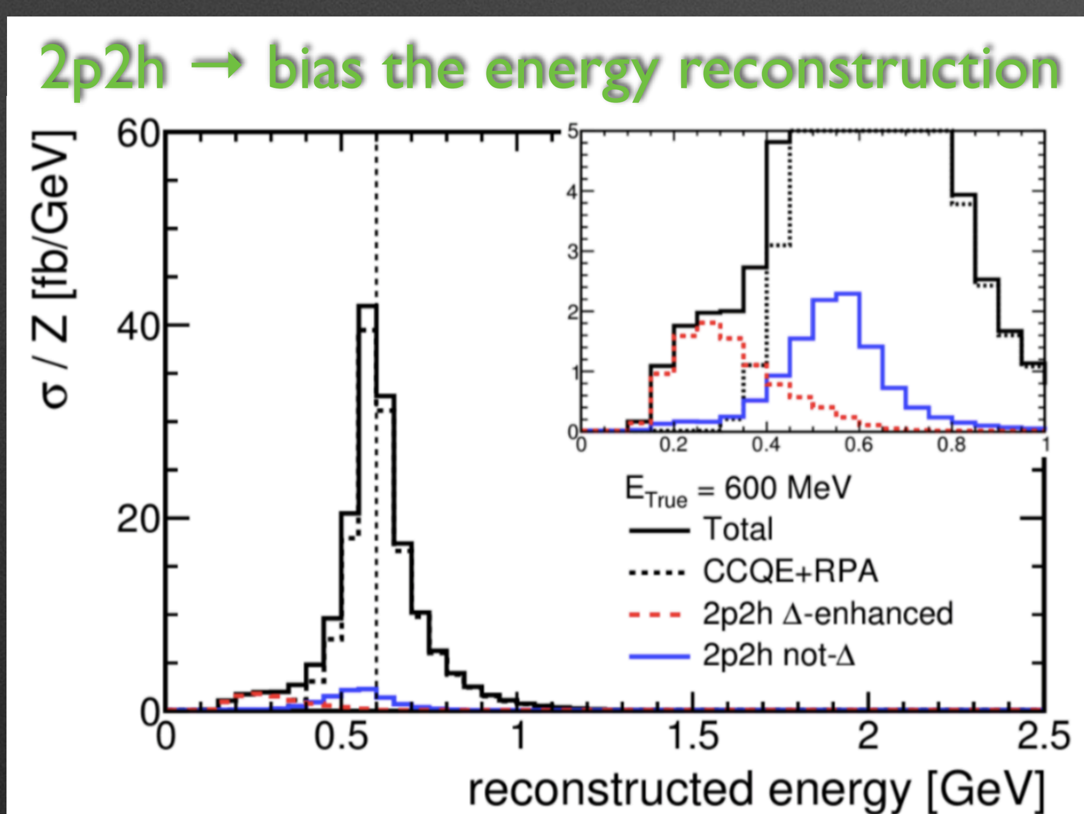
Conclusions

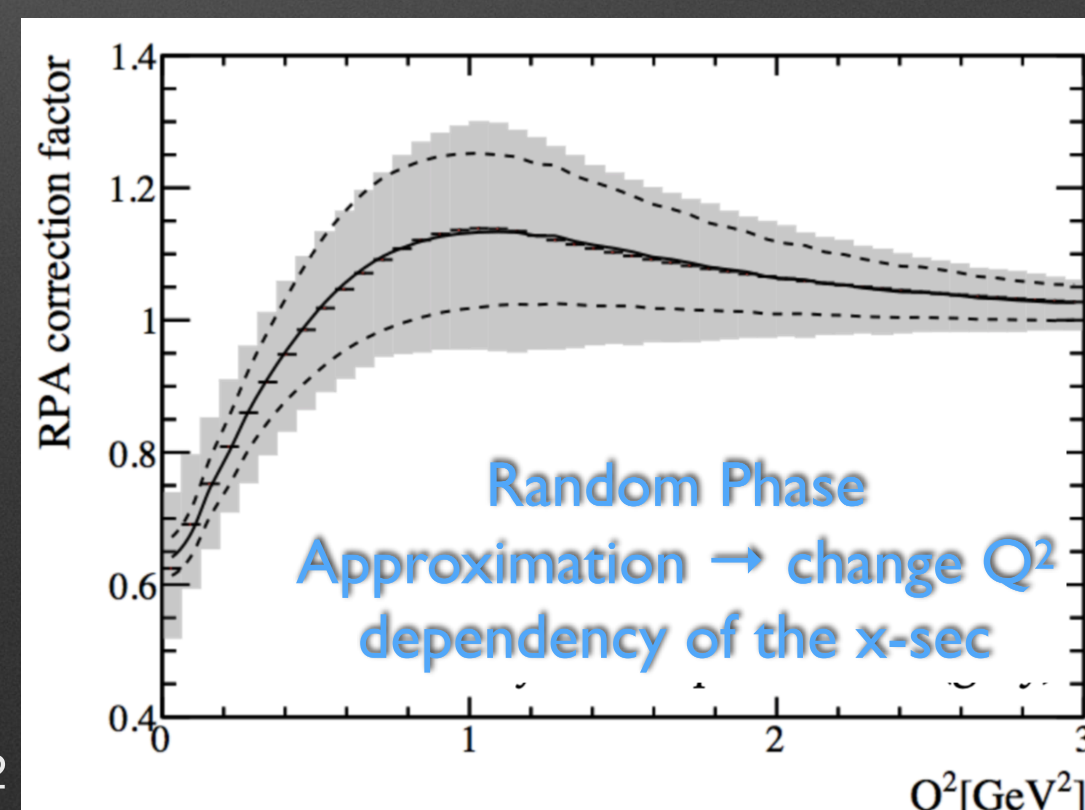
- Neutrino oscillations have entered the precision era
- Long-Baseline experiments are the best experiments to precise measure oscillation parameters, investigating sub-leading order effects
- T2K and NOνA are currently seeing (very) first hints of δ_{CP}~$-\pi/2$, mass ordering ~ normal and θ_{23} ~ maximal
  - Fully compatible results with two very different experiments
  - Still statistically limited → more data will come in the next years
  - We hope to have 3σ measurements for δCP and MO with the currently running experiments
- Precision measurements and 5σ discovery of δCP will need a next generation of experiments → DUNE and Hyper-K

Back-up

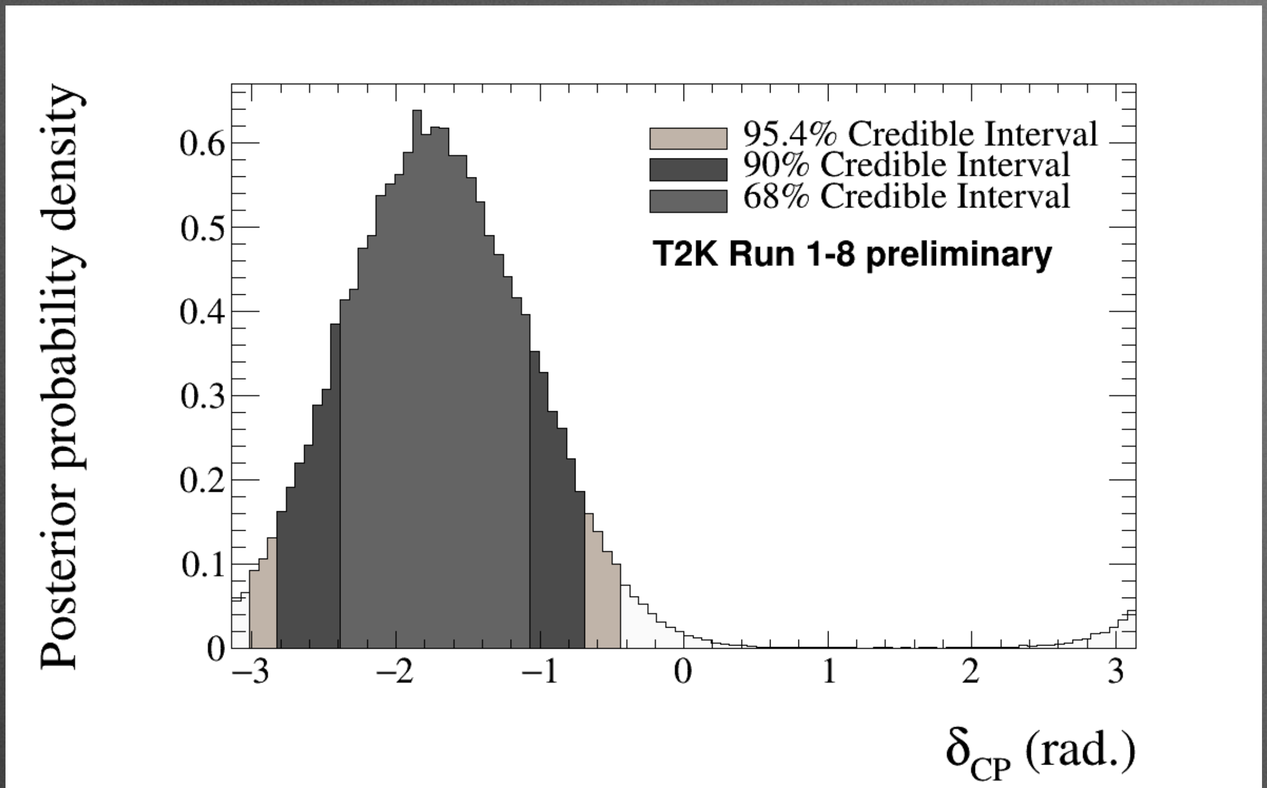
Neutrino cross sections

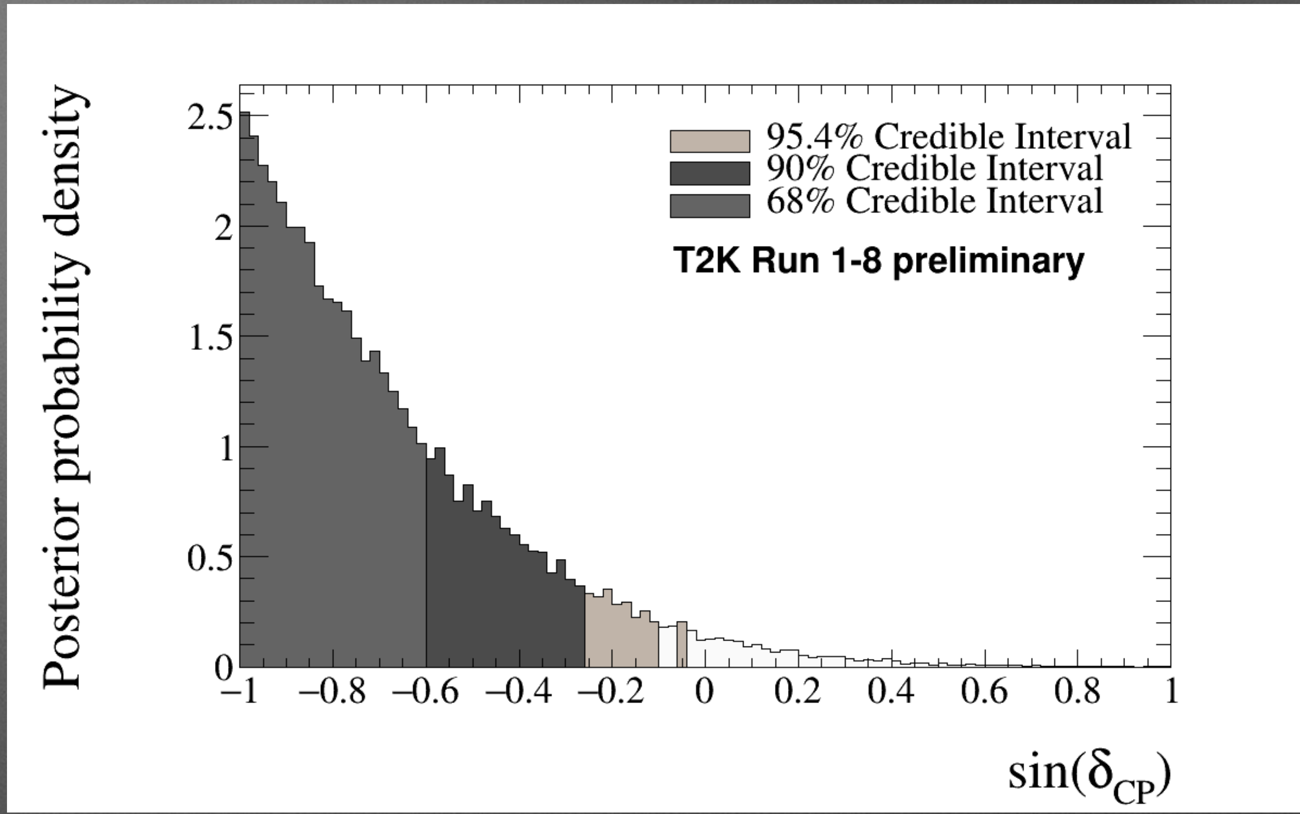
- At T2K energies the dominant contributions to the cross section are quasi-elastic
- Other contributions with production of pions in the final state are also important
- Need to take into account nuclear effects (2p-2h, FSI that might lead to pion absorption, …)
- New parametrisation of the cross-section modelling





Bayesian analysis





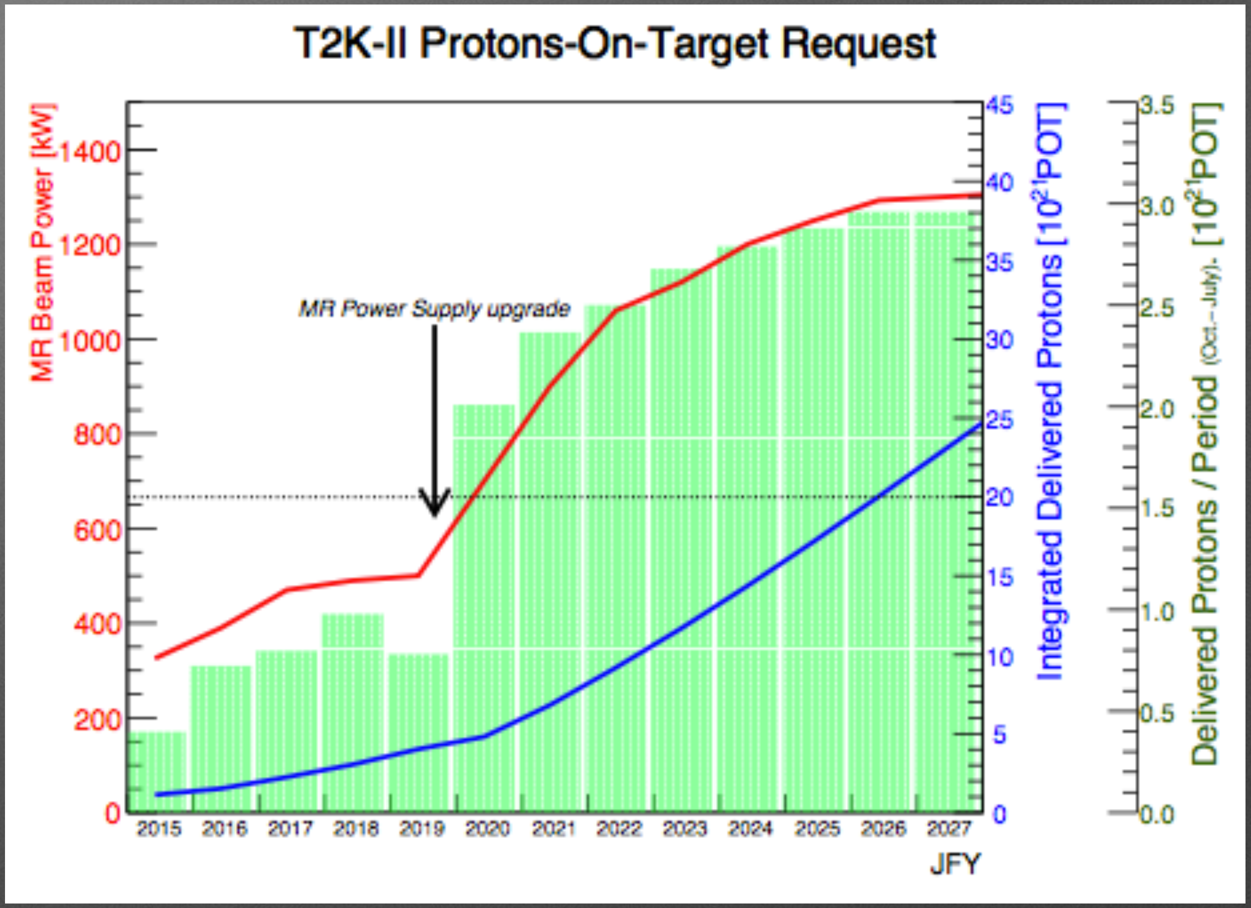
* Dependence of the δ_{CP} exclusion on the prior (flat in δ_{CP} or $\sin(\delta_{CP})$) → CP conserving values outside 94.5% Credible Intervals

* From posterior probability weak preference for NH and second octant (as for the frequentist analysis)

	$\sin^2\theta_{23}<0.5$	$\sin^2\theta_{23}>0.5$	Sum
Normal hierarchy ($\Delta m^2_{32}>0$)	0,193	0,674	0,868
Inverted hierarchy ($\Delta m^2_{32}>0$)	0,026	0,106	0,132
Sum	0,219	0,781	

Towards T2K-II

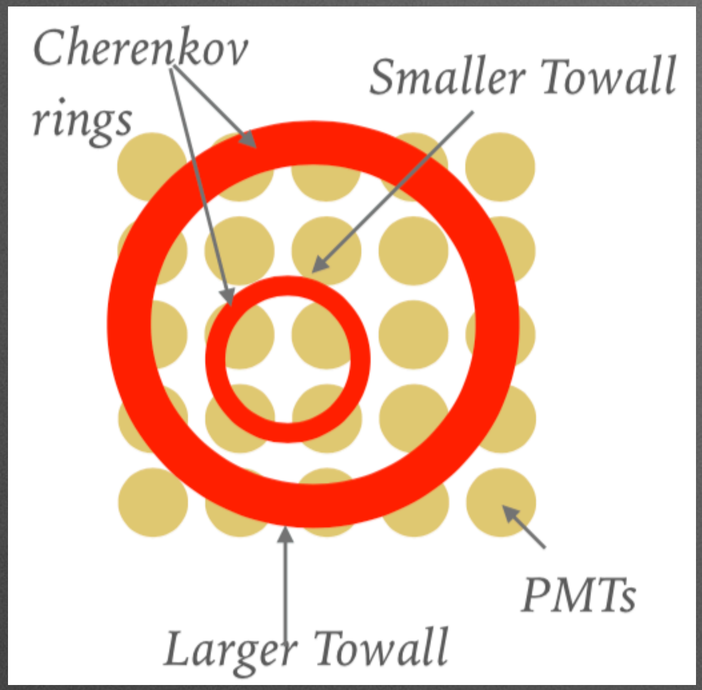
- T2K was originally approved to collect 7.8x10^{21} pot
  - Driven by sensitivity to θ_{13}
- Proposal for an extended run
  - T2K-II → 20x10^{21} pot
- SK will also be upgraded with Gadolinium → start preparation work in June 2018

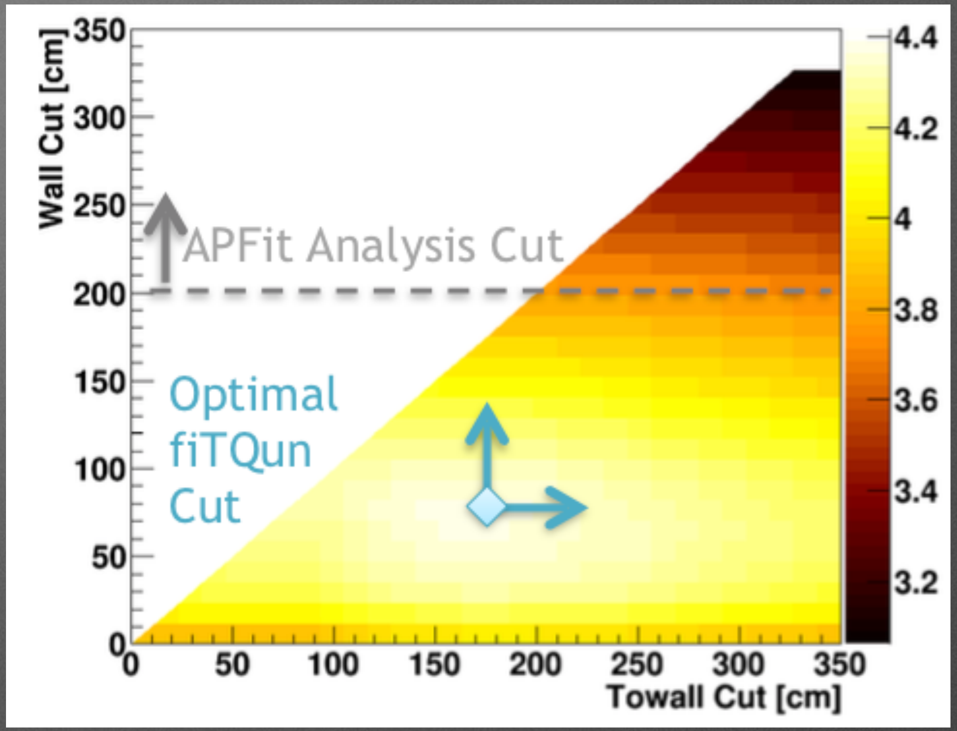


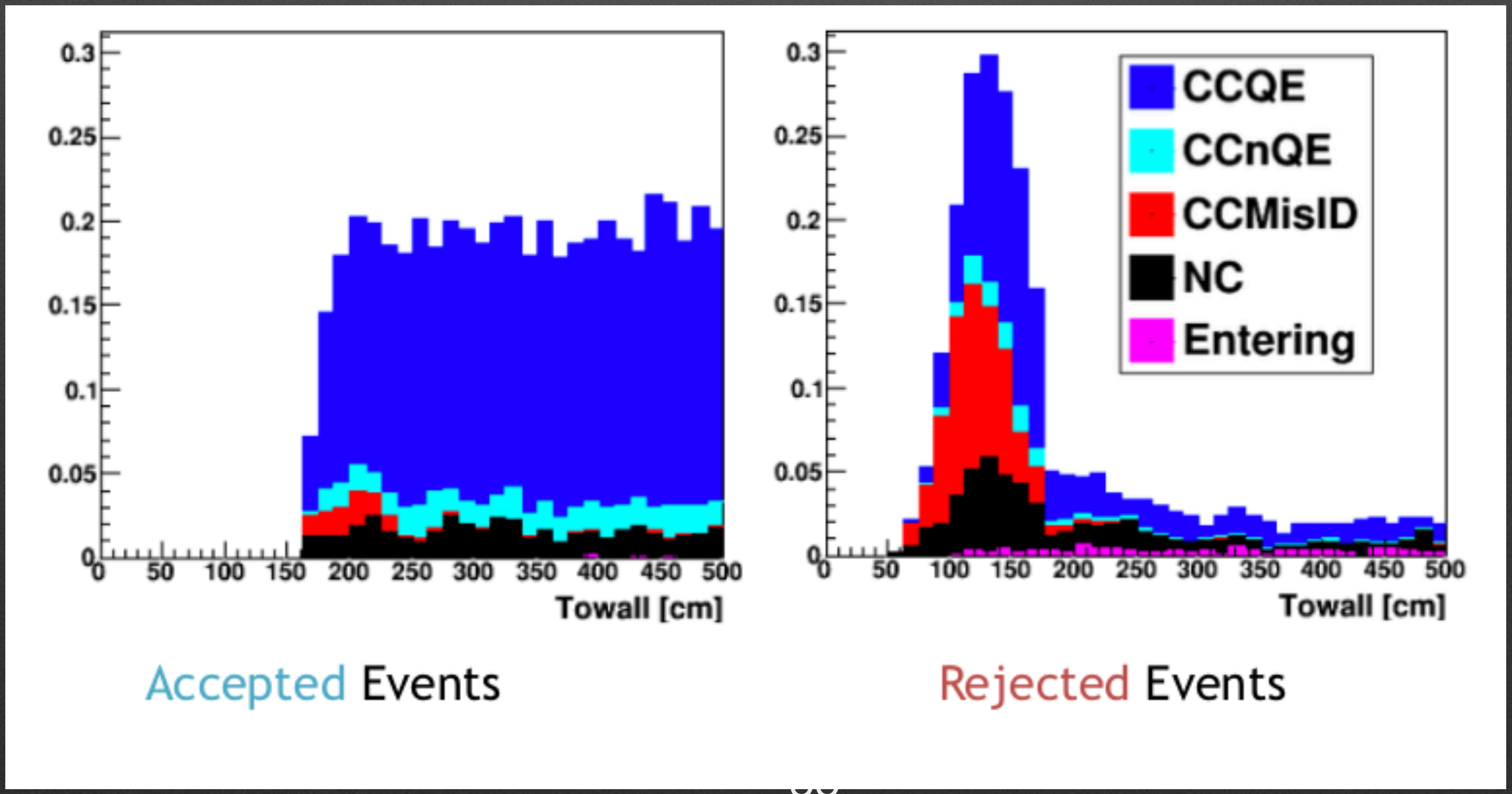
- To reach such statistics (and be ready for HK) we will upgrade the Main Ring power supply to reach 1.3 MW operations

	True δ_{CP}	Total	Signal $\nu_\mu \to \nu_e$	Signal $\bar{\nu}_\mu \to \bar{\nu}_e$	Beam CC $\nu_e + \bar{\nu}_e$	Beam CC $\nu_\mu + \bar{\nu}_\mu$	NC
ν-mode	0	454.6	346.3	3.8	72.2	1.8	30.5
ν_e sample	$-\pi/2$	545.6	438.5	2.7	72.2	1.8	30.5
$\bar{\nu}$-mode	0	129.2	16.1	71.0	28.4	0.4	13.3
$\bar{\nu}_e$ sample	$-\pi/2$	111.8	19.2	50.5	28.4	0.4	13.3

New SK selection

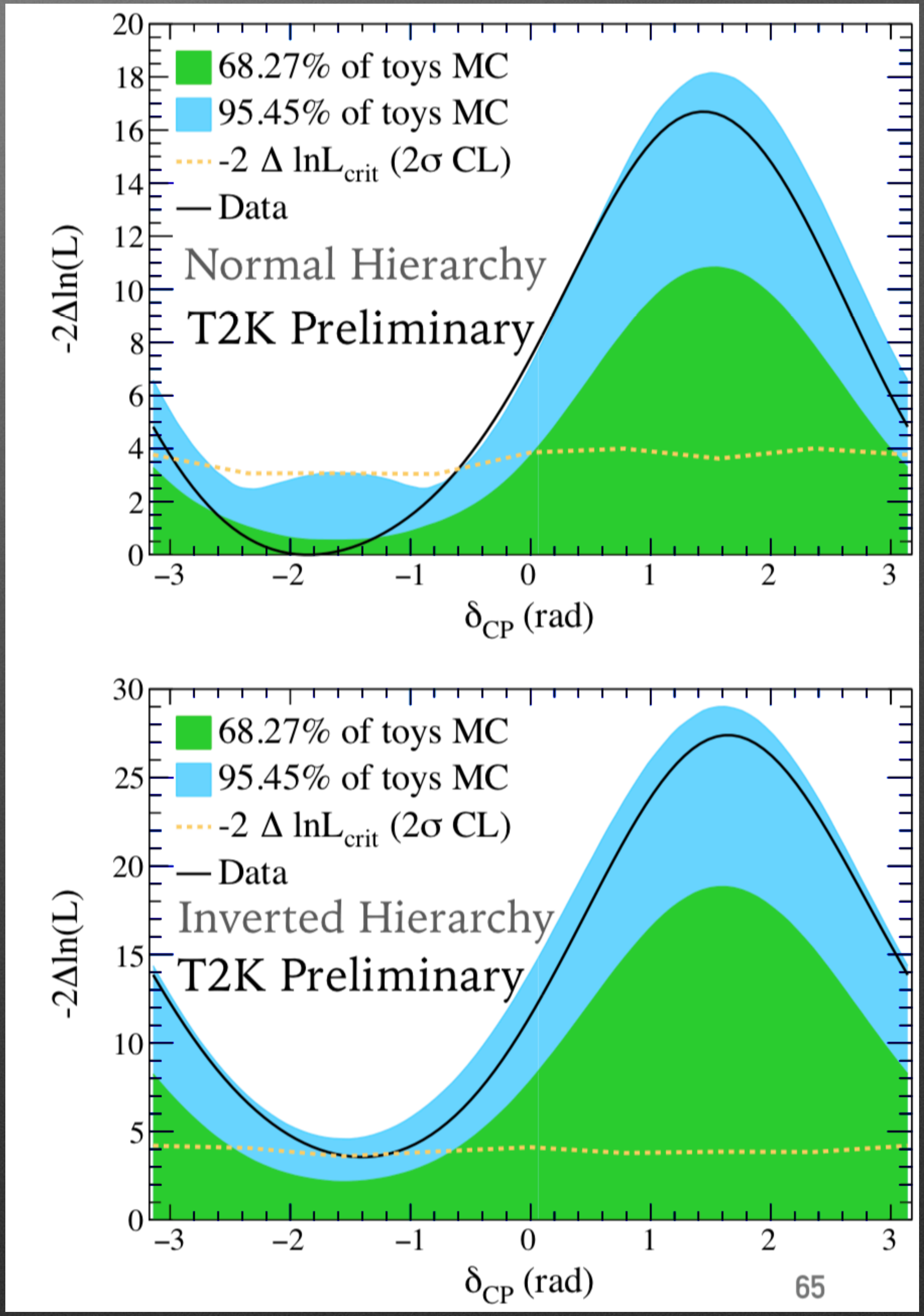


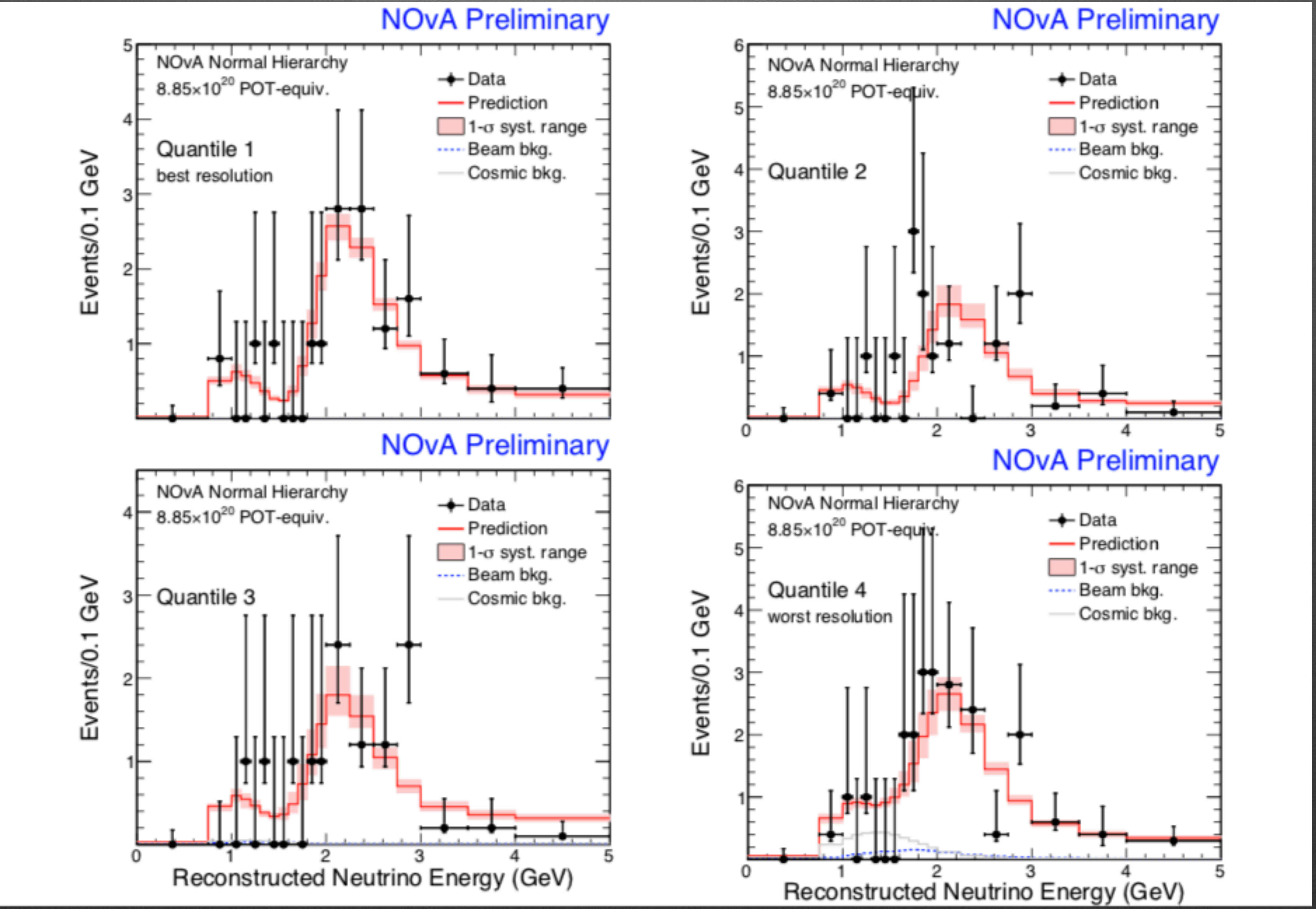




δCP exclusion

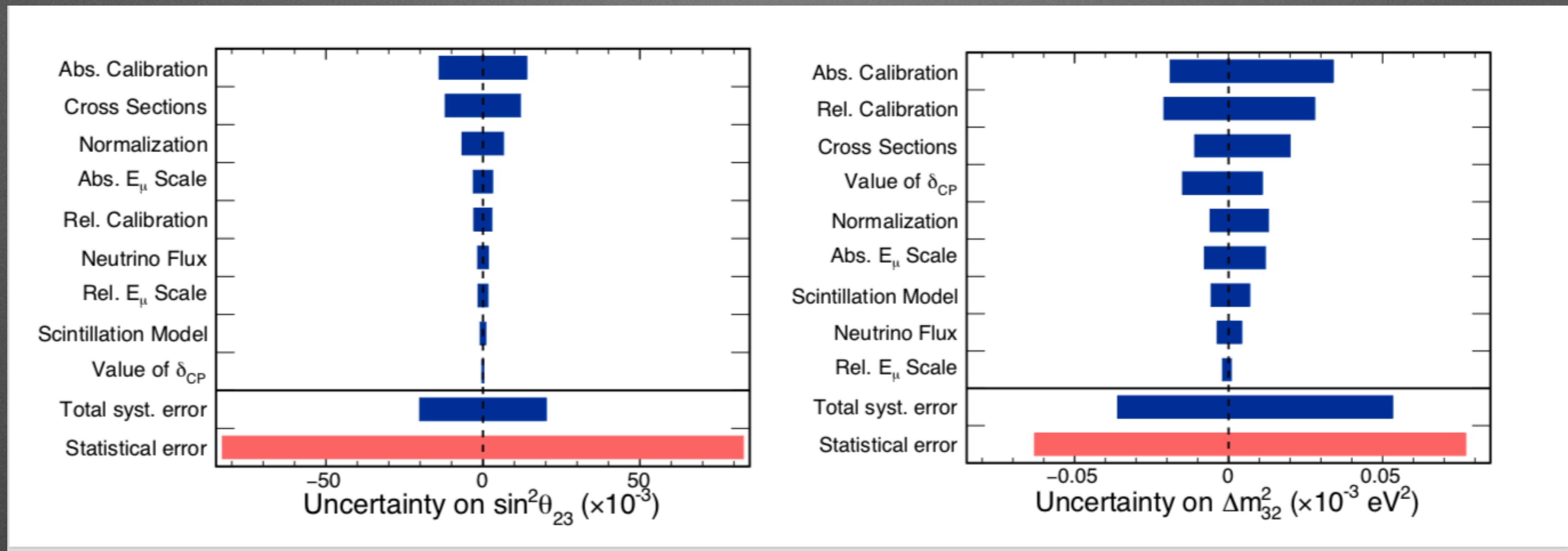
- The exclusion of CP conserving values is stronger than the expected sensitivity
  - Is it reasonable?
- We run many toys for different oscillation parameters with statistical and systematics variation → NH and $\delta_{CP}=-\pi/2$
- 30% of the experiments exclude $\delta_{CP}=0$ at $>2\sigma$
- 20% of the experiments exclude $\delta_{CP}=\pi$ at $>2\sigma$





NOvA Preliminary
NOvA Normal Hierarchy
8.85×10^20 POT-equiv.
Quantile 1
best resolution
Data
Prediction
1-σ syst. range
Beam bkg.
Cosmic bkg.
Events/0.1 GeV
NOvA Preliminary
NOvA Normal Hierarchy
8.85×10^20 POT-equiv.
Quantile 2
Events/0.1 GeV
NOvA Preliminary
NOvA Normal Hierarchy
8.85×10^20 POT-equiv.
Quantile 3
Events/0.1 GeV
Reconstructed Neutrino Energy (GeV)
NOvA Preliminary
NOvA Normal Hierarchy
8.85×10^20 POT-equiv.
Quantile 4
worst resolution
Events/0.1 GeV
Reconstructed Neutrino Energy (GeV)

NOνA systematics



	Total Observed	Expectation at Best Fit	Total Background	Cosmic	Neutral Current	Other Beam
All Q Events	126	129	9.24	5.82	2.50	0.96

Our previous result*: **2.6σ**

↓

New simulation & Calibration: ~1.8σ

↓

New selection and analysis: ~0.5σ

↓

Full dataset: ~0.4σ → Full dataset*: **0.8σ**

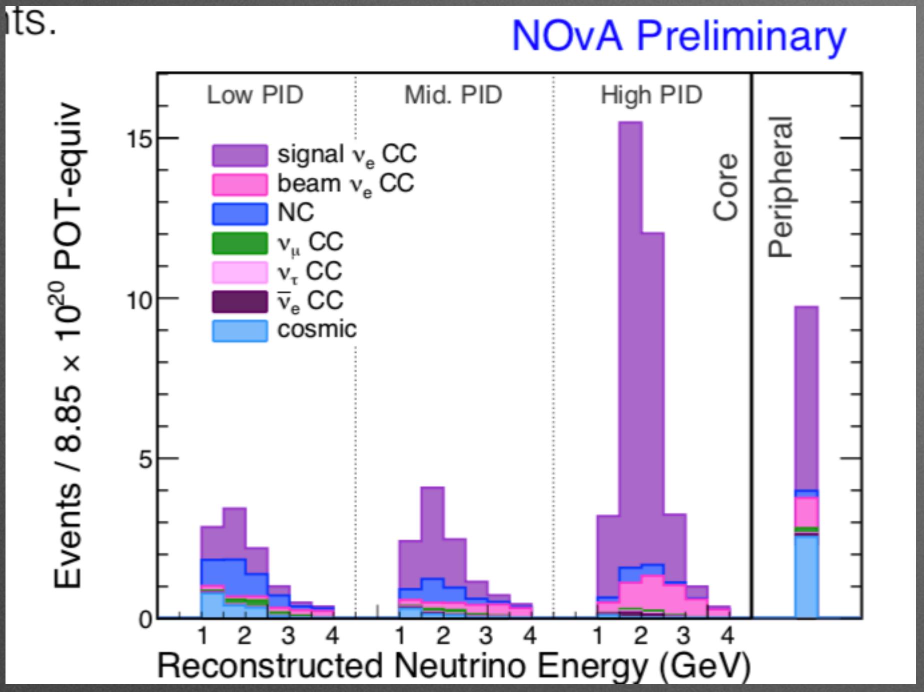
Our rejection of maximal mixing has moved from 2.6σ to 0.8σ. This change in the character of our result comes from a few key changes which I'll break down below.

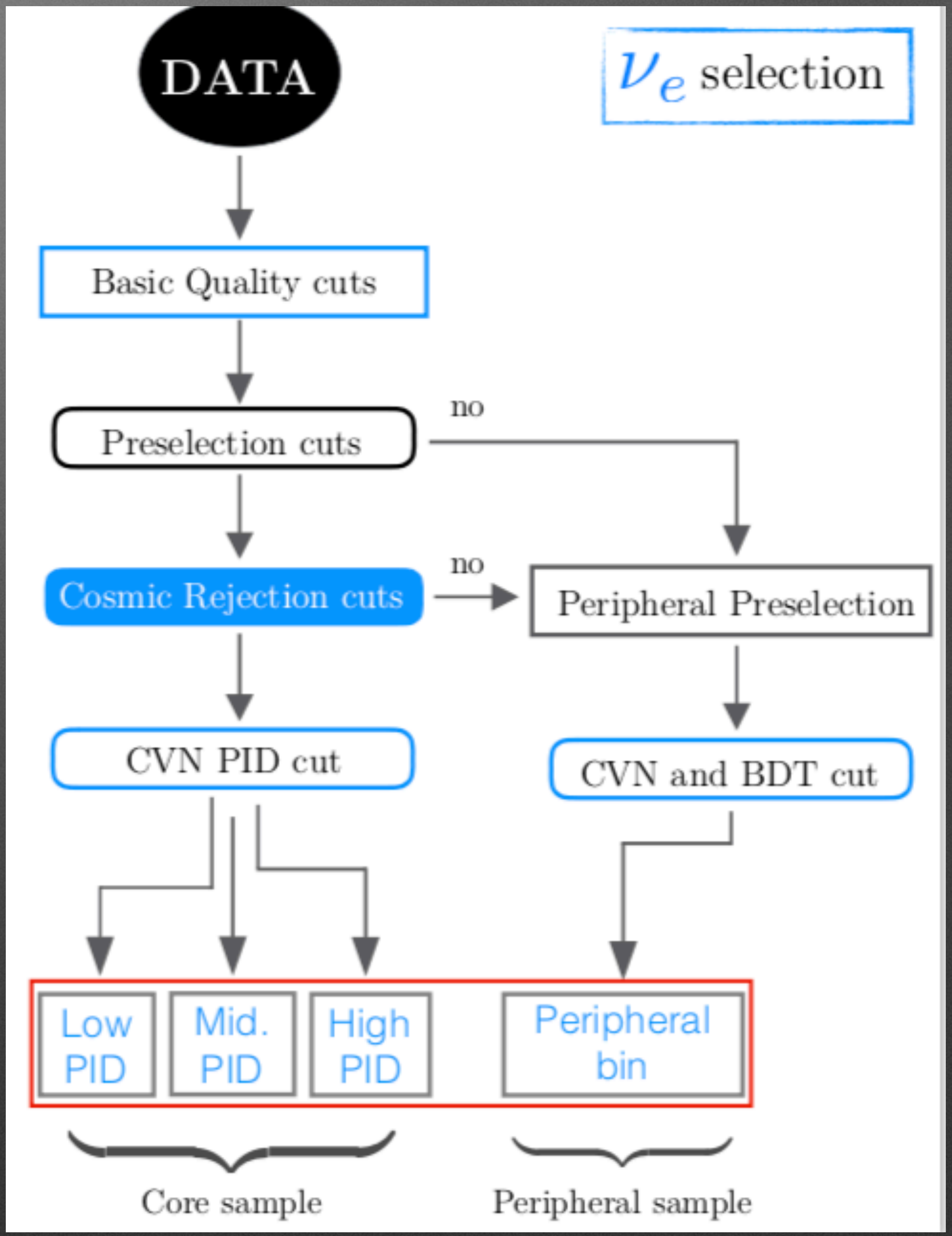
Driven by updates to energy response model. Drop to 2.3σ expected due to new energy resolution. Additionally we have a <70 MeV> shift in our hadronic energy response. This energy shift would be expected to move 0.5 events out of the "dip" region. However it instead pushes 3 "dip" events past a bin boundary.

For combined analysis changes 5% of pseudo-experiments in a MC study had this size shift or larger. This probability is driven by a low expected overlap in background events, and to second order the addition of resolution bins.

New, 2.8×10^{20} POT, data prefers maximal mixing.

*Feldman-cousins corrected significance.


nts.
NOvA Preliminary
Low PID
Mid. PID
High PID
Core
Peripheral
signal ν_e CC
beam ν_e CC
NC
ν_μ CC
ν_τ CC
$\bar{\nu}_e$ CC
cosmic
Events / 8.85 × 10^{20} POT-equiv
Reconstructed Neutrino Energy (GeV)


DATA
ν_e selection
Basic Quality cuts
Preselection cuts
no
Cosmic Rejection cuts
no
Peripheral Preselection
CVN PID cut
CVN and BDT cut
Low PID
Mid. PID
High PID
Peripheral bin
Core sample
Peripheral sample