Comparison of 2020 **T2K and NOVA** results

GDR Neutrino

22 Novembre 2020

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Outline

- Oscillation sensitivities: **how the LBL experiments measures the different parameters (δ_{CP} for CP-violation and Mass Hierarchy)**

- 2020 results of T2K and NOVA

  Neutrino 2020 results stored on Zenodo:

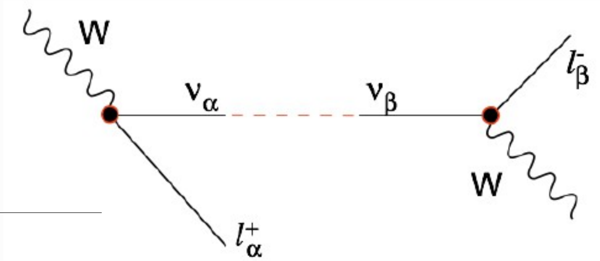
  DOI 10.5281/zenodo.3959557

  DOI 10.5281/zenodo.3959580

- **Statistical** uncertainties

- **Systematic** uncertainties: near and far detectors

Neutrino oscillations



- Standard 3-flavors formalism: PMNS matrix

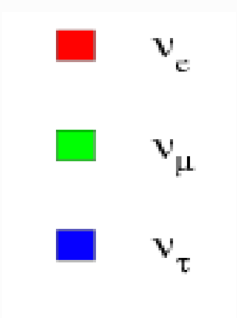
$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle$$

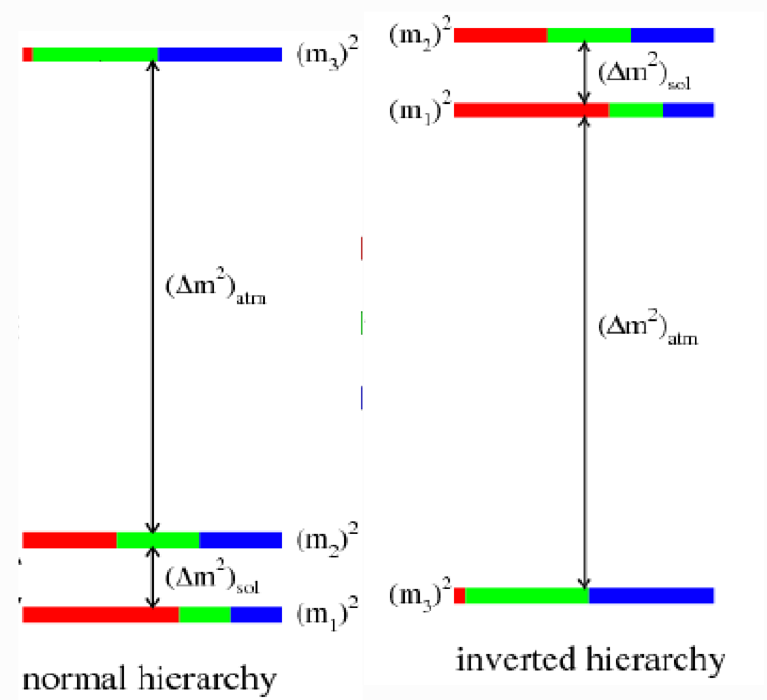
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U^*_{e1} & U^*_{e2} & U^*_{e3} \\ U^*_{\mu 1} & U^*_{\mu 2} & U^*_{\mu 3} \\ U^*_{\tau 1} & U^*_{\tau 2} & U^*_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$U_{\alpha i}$ are expressed in terms of 3 mixing angles (θ_{13}, θ_{23}, θ_{12}) and a phase δ_{CP}

- 3 mass states → two Δm^2: solar (small) and atm (large)

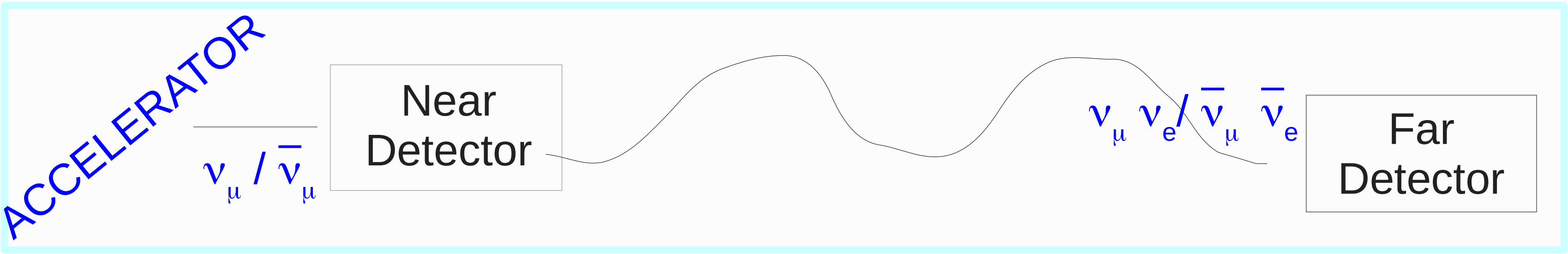
→ mass ordering unknown (normal = same as lepton ordering)

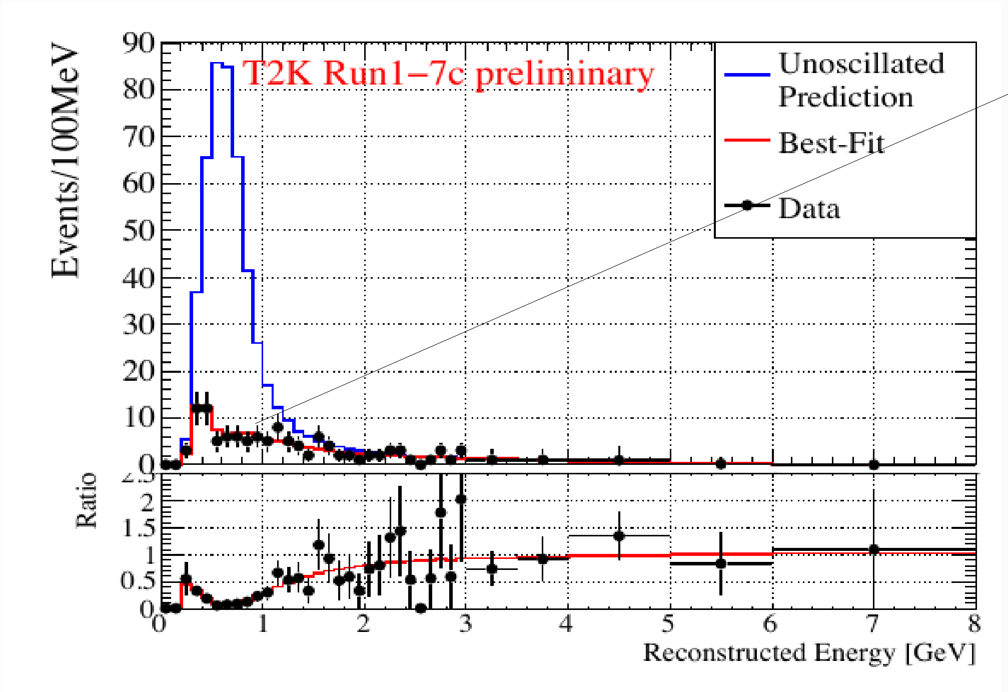


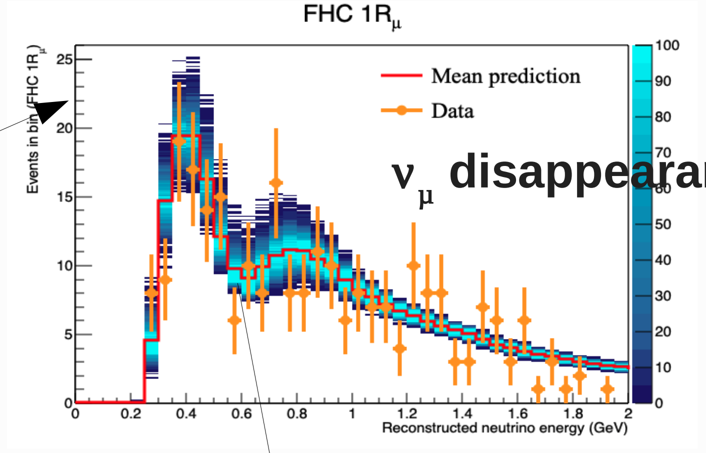


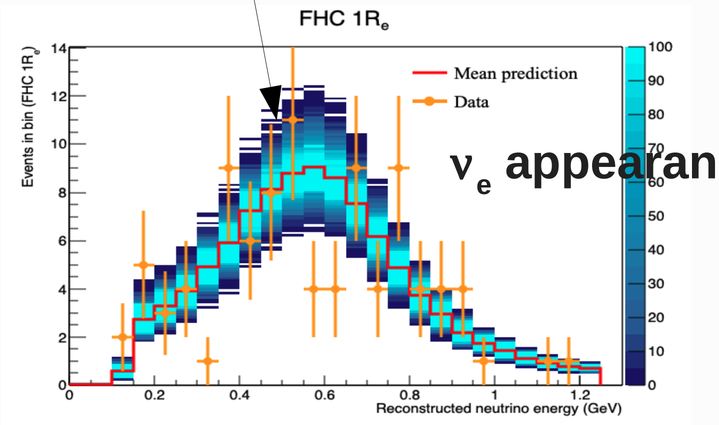
Long-baseline experiments

- **Oscillation probability estimated** by comparing ν (and $\bar{\nu}$) rate by flavor between source (near detectors) and far detectors:









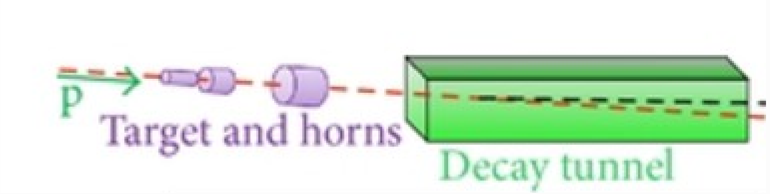
T2K preliminary Run1-10

ν_μ disappearance: $\sin\theta_{23}$, Δm^2_{32}

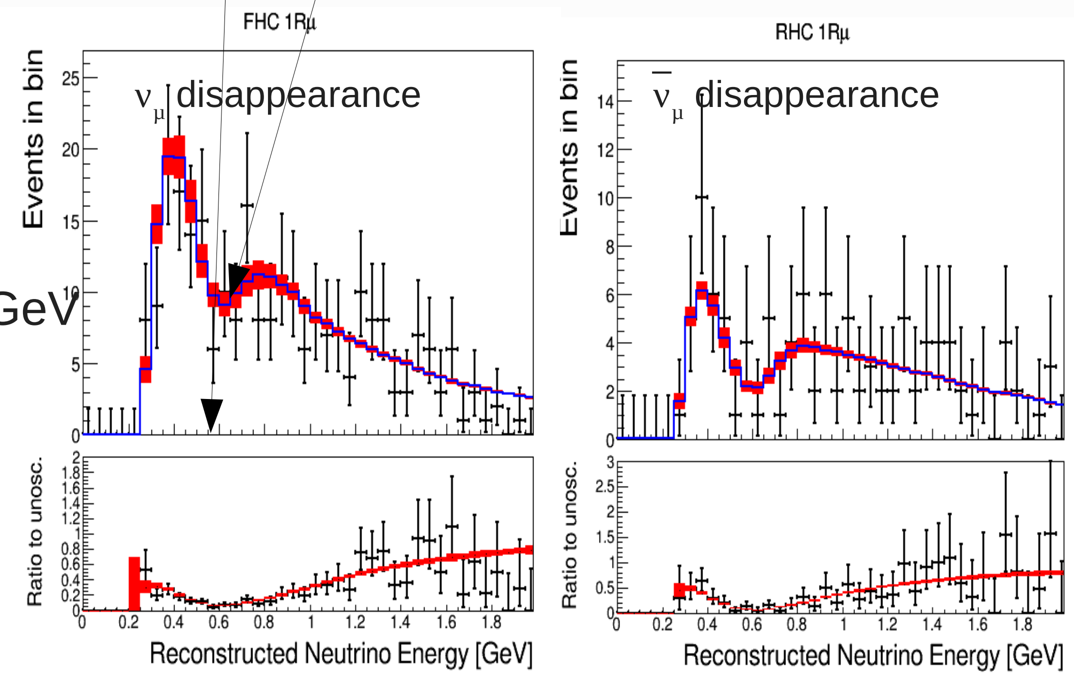
- $$P(\nu_\alpha \to \nu_\beta) = \underbrace{\sin^2(2\theta)}_{\textbf{amplitude}} \sin^2\underbrace{\left(1.27\frac{\Delta m^2_{ji}[\mathrm{eV}^2]L[\mathrm{km}]}{E_\nu[\mathrm{GeV}]}\right)}_{\textbf{frequency}}$$ (simplified 2-flavors approximation)
  - **$\sin\theta_{23}$ ~ amplitude of the ν_μ ($\bar{\nu}_\mu$) disappearance (height of spectrum minimum)**
  - **$\Delta m^2_{31(32)}$ ~ frequency of the disappearance (position of spectrum minimum)**

Experiment	Energy	Baseline
T2K (T2HK)	0.6 GeV	295 km
Nova	2 GeV	810 km

  Same oscillation maximum L/E ~ 0.5 km/GeV

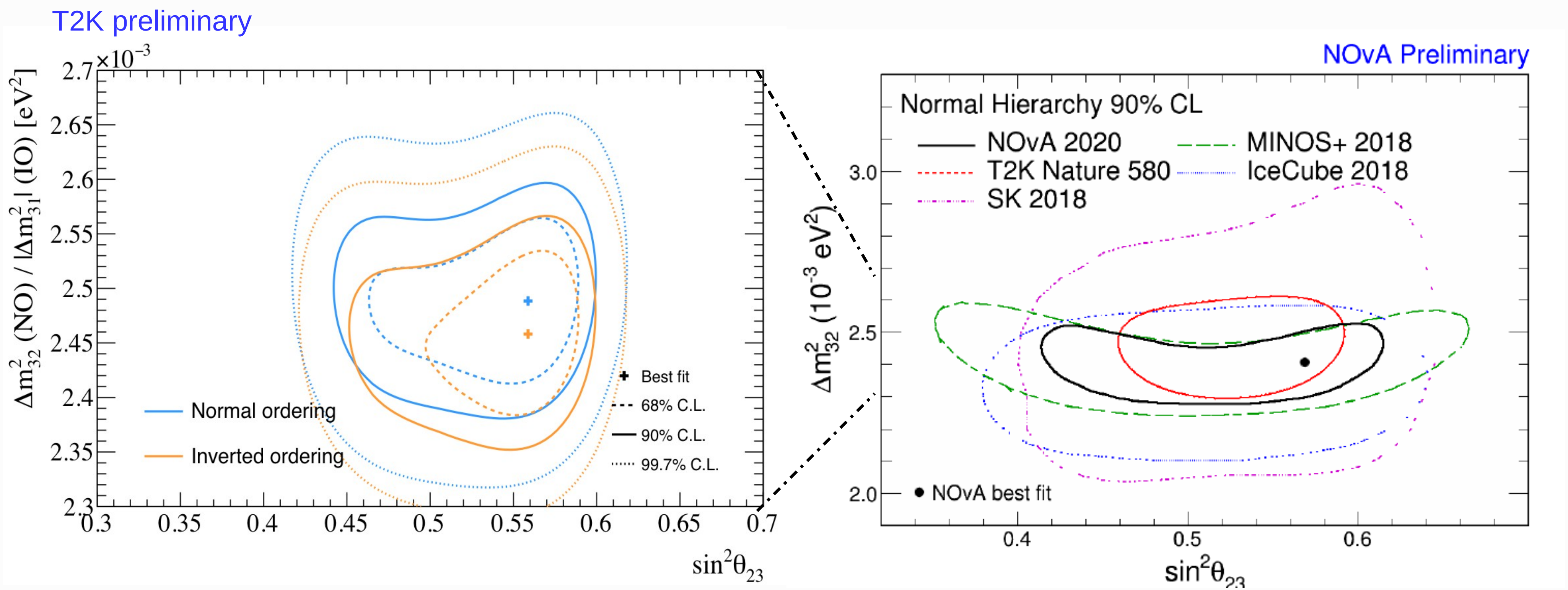
- 

  Both ν_μ and $\bar{\nu}_\mu$ enriched beam (by changing polarity of focusing horns)



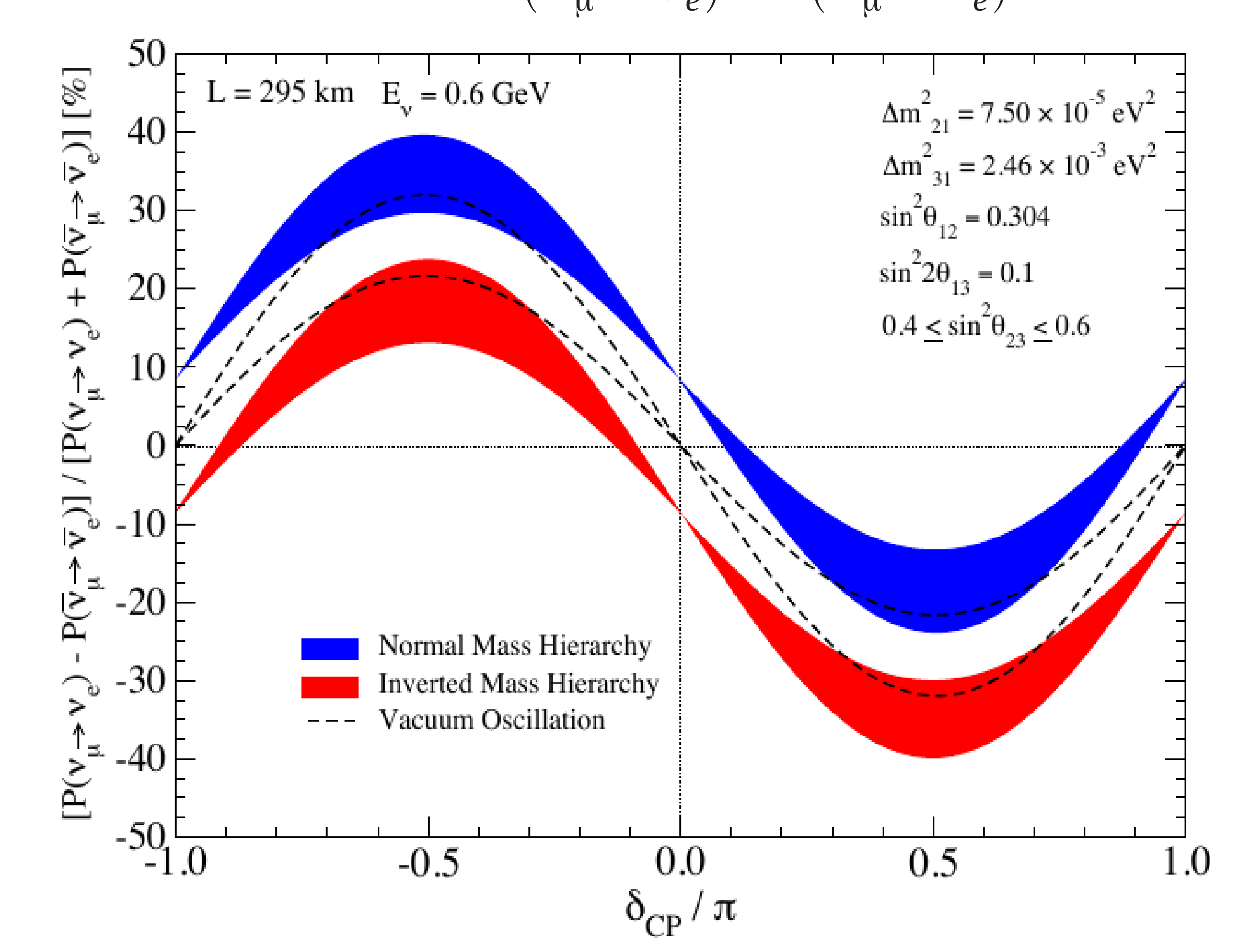
T2K preliminary Run1-10

ν_μ disappearance: $\sin\theta_{23}$, Δm^2_{32}



$\nu_e/\overline{\nu}_e$ appearance: δ_{CP}

$$\sin\delta_{CP} \approx \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)}$$



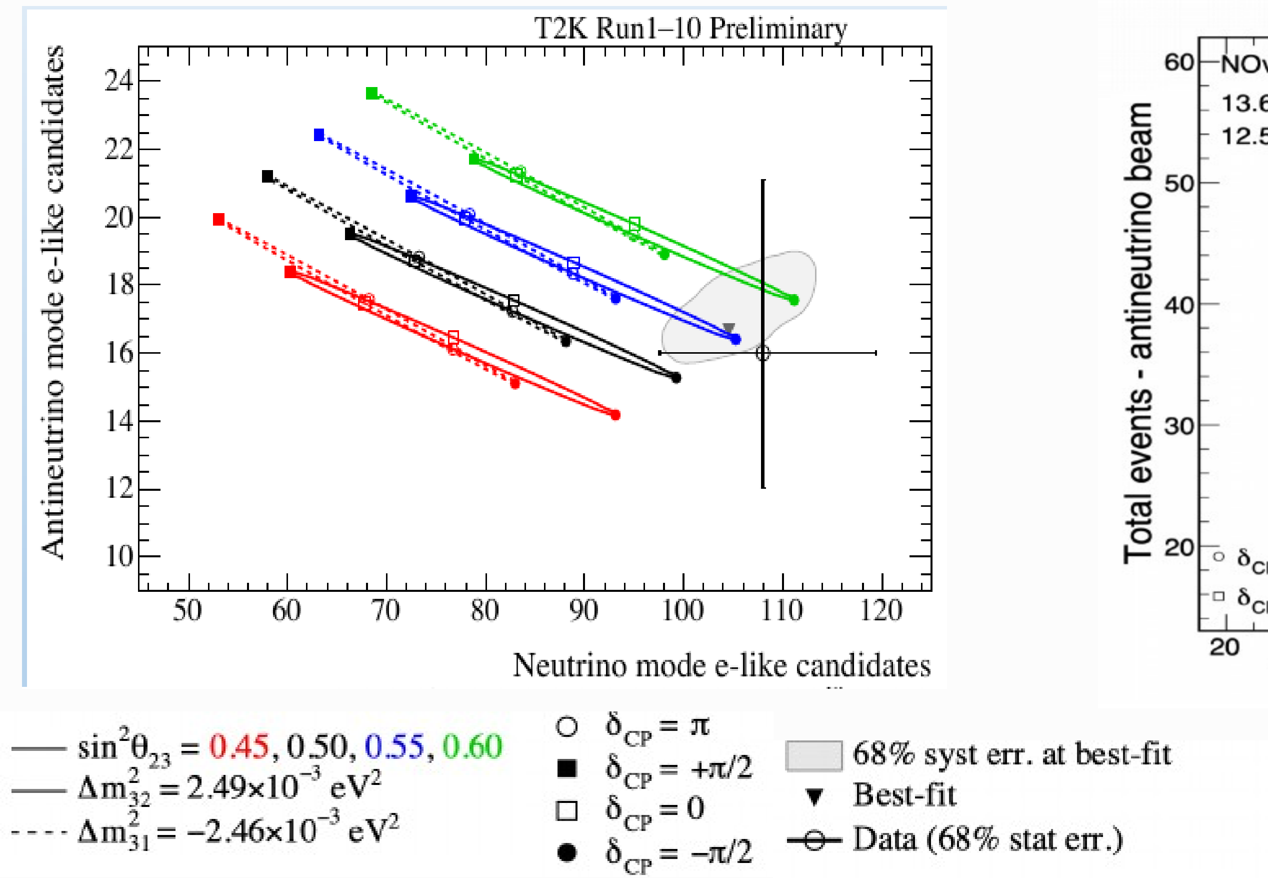
$$\mathcal{A}_{\rm CP} \equiv \frac{P(\nu_\mu \to \nu_e) - P(\overline{\nu}_\mu \to \overline{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\overline{\nu}_\mu \to \overline{\nu}_e)} \simeq -\frac{\sin 2\theta_{12} \sin\delta}{\sin\theta_{13}\tan\theta_{23}}\Delta_{21} + \boxed{\text{matter effects ,}} \longrightarrow$$ sensitivity to MH

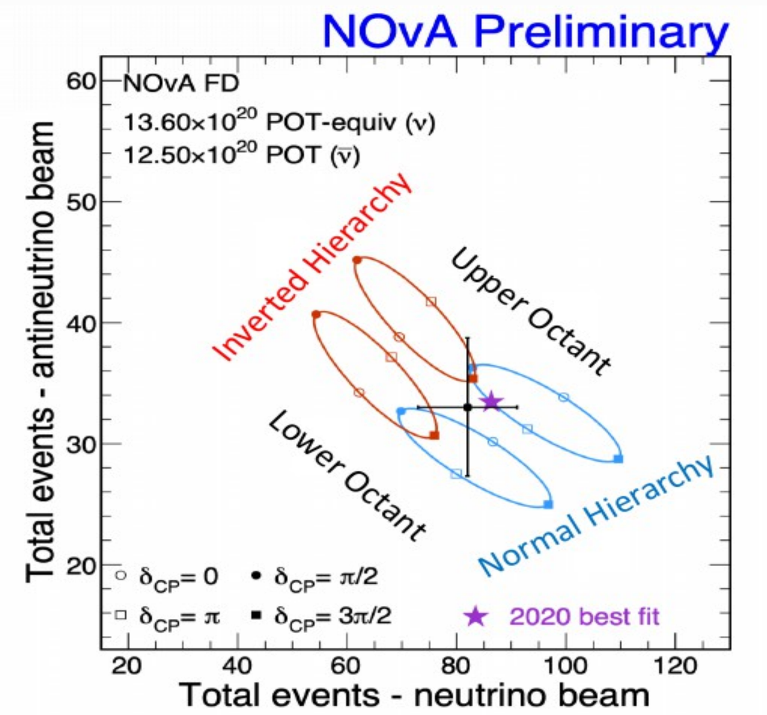
$\nu_e/\bar{\nu}_e$ apperance: MH

MH sensitivity comes from change of sign in term dominated by matter effects:
the longer the baseline → the larger the term

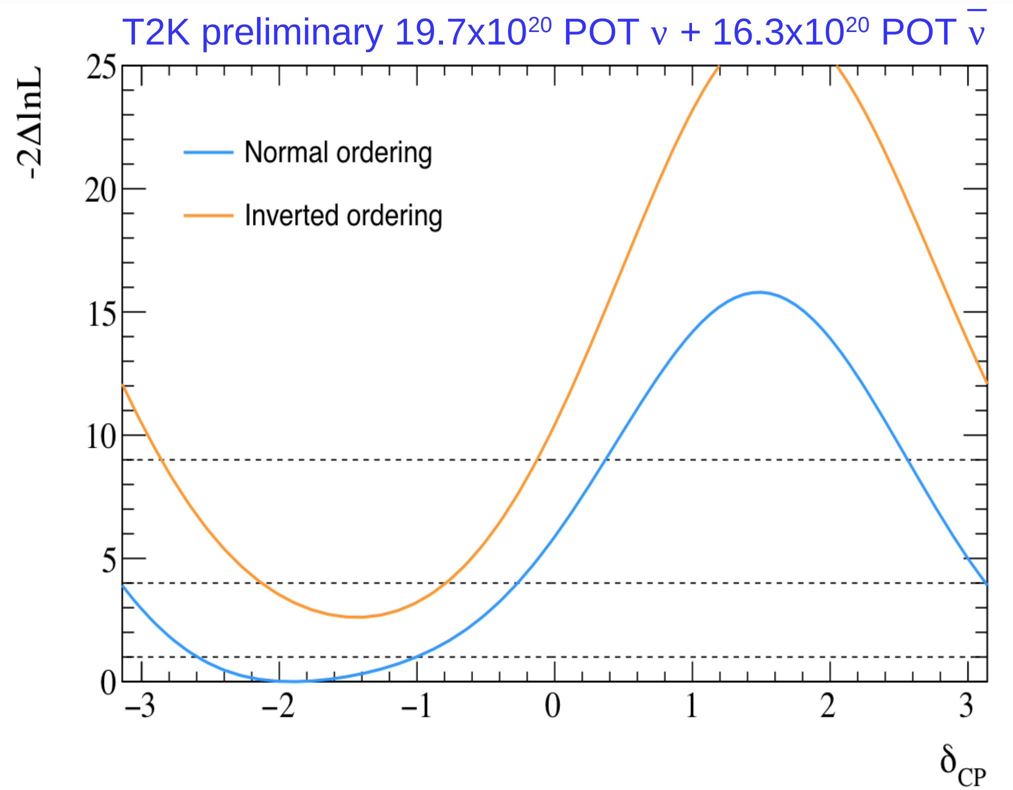
Experiment	CP asymmetry	Mass Hierarchy
T2K (T2HK)	~30%	~10%
Nova	~30%	~30%

- **T2K: clean δ_{CP} measurement with small MH sensitivity**
- **NOVA: degenerate δ_{CP} and MH:** (δ_{CP} $3\pi/2$ and IH = δ_{CP} $\pi/2$ and NH)

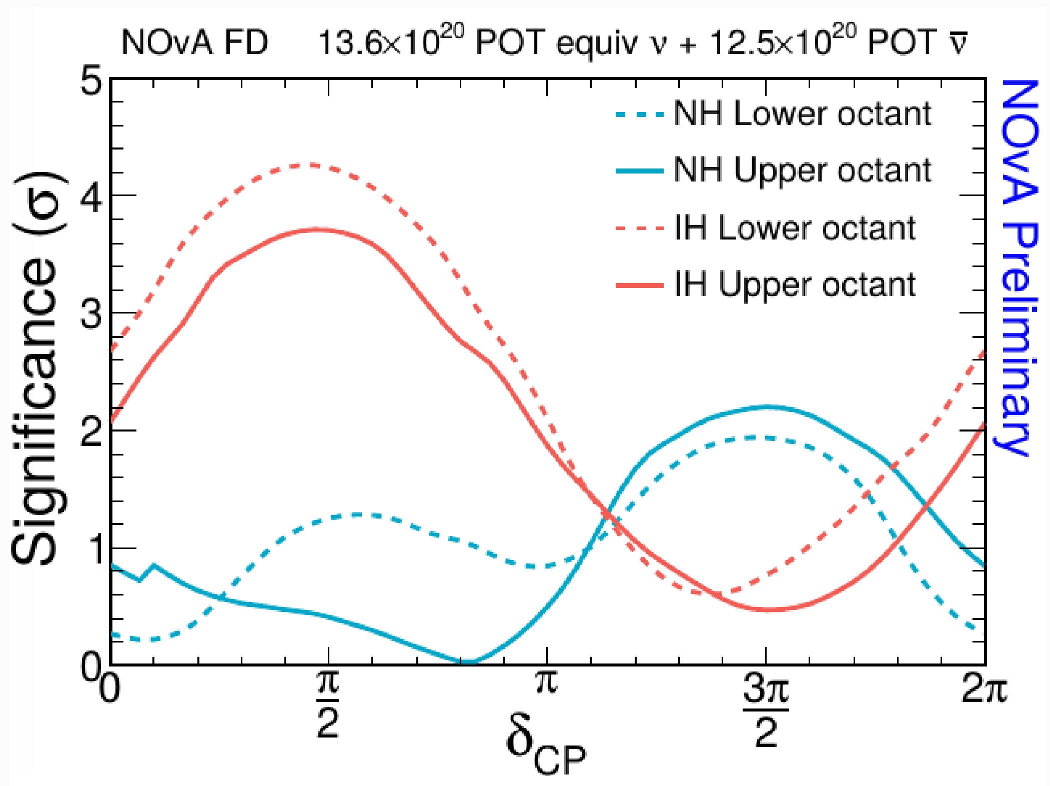




Results

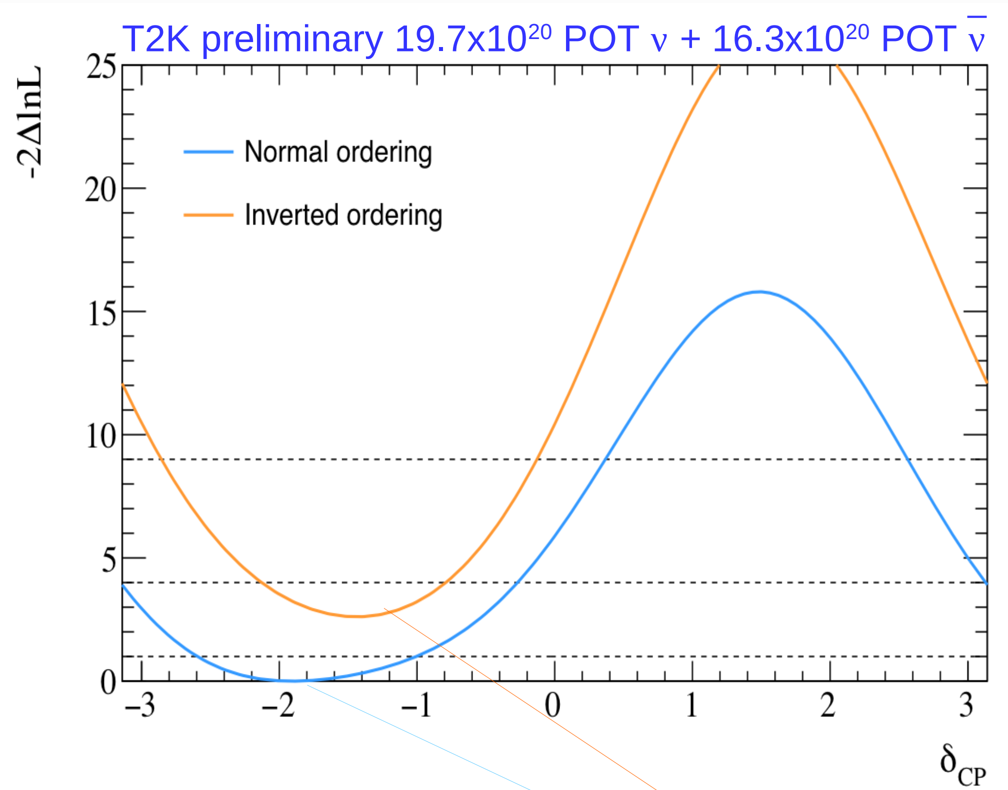


T2K preliminary 19.7x10^20 POT ν + 16.3x10^20 POT ν̄
-2ΔlnL
Normal ordering
Inverted ordering
0
5
10
15
20
25
−3
−2
−1
0
1
2
3
δCP



NOvA FD 13.6×10^20 POT equiv ν + 12.5×10^20 POT ν̄
NOvA Preliminary
Significance (σ)
NH Lower octant
NH Upper octant
IH Lower octant
IH Upper octant
0
1
2
3
4
5
0
π/2
π
3π/2
2π
δCP

Results



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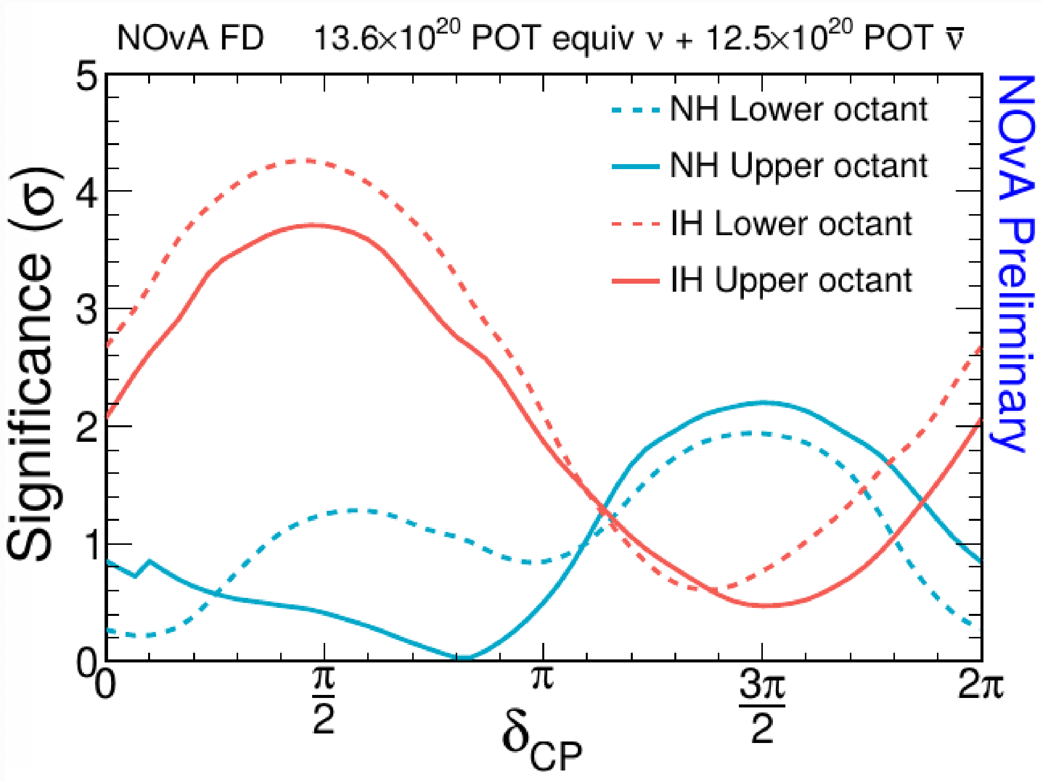
-2ΔlnL
Normal ordering
Inverted ordering
δCP



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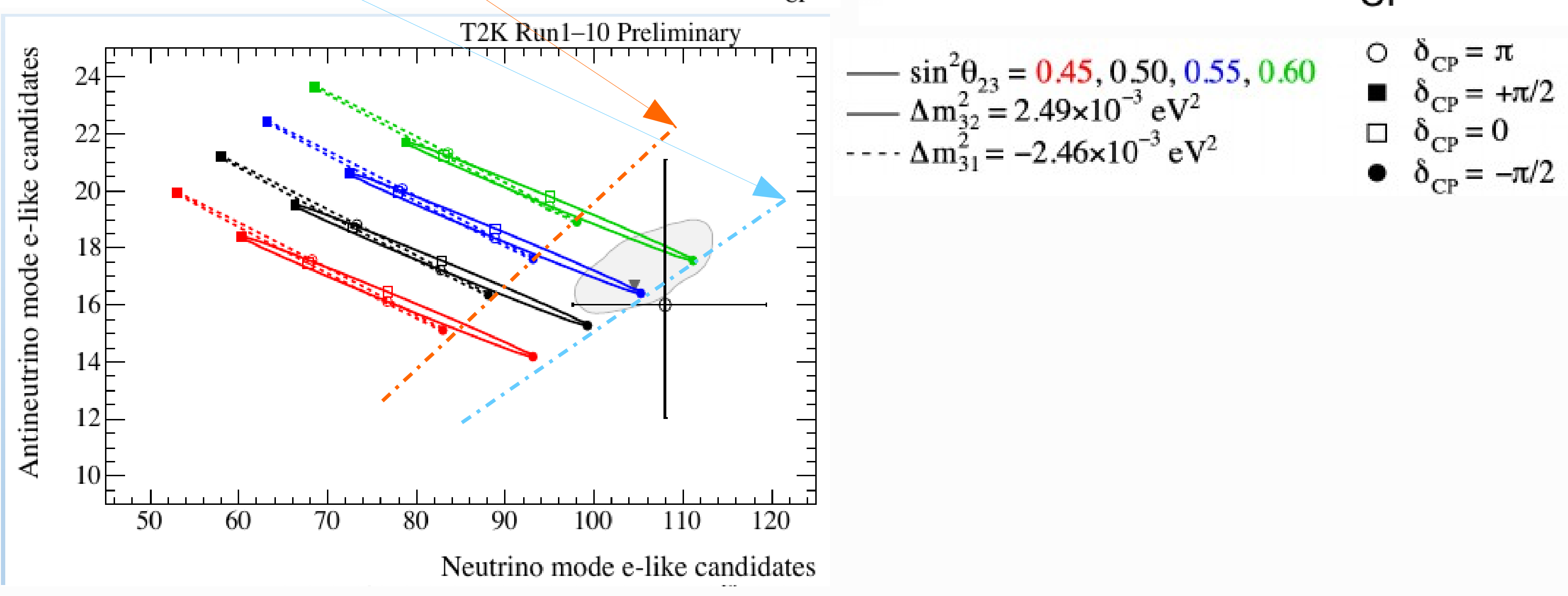
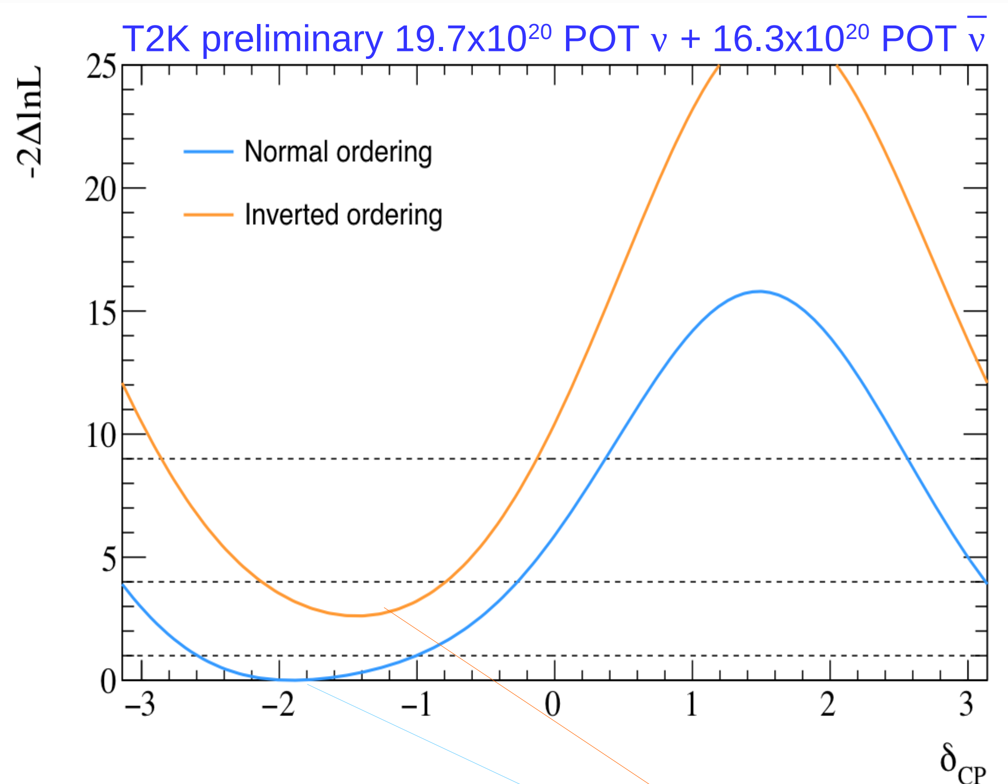
Significance (σ)
NH Lower octant
NH Upper octant
IH Lower octant
IH Upper octant
NOvA Preliminary
δCP

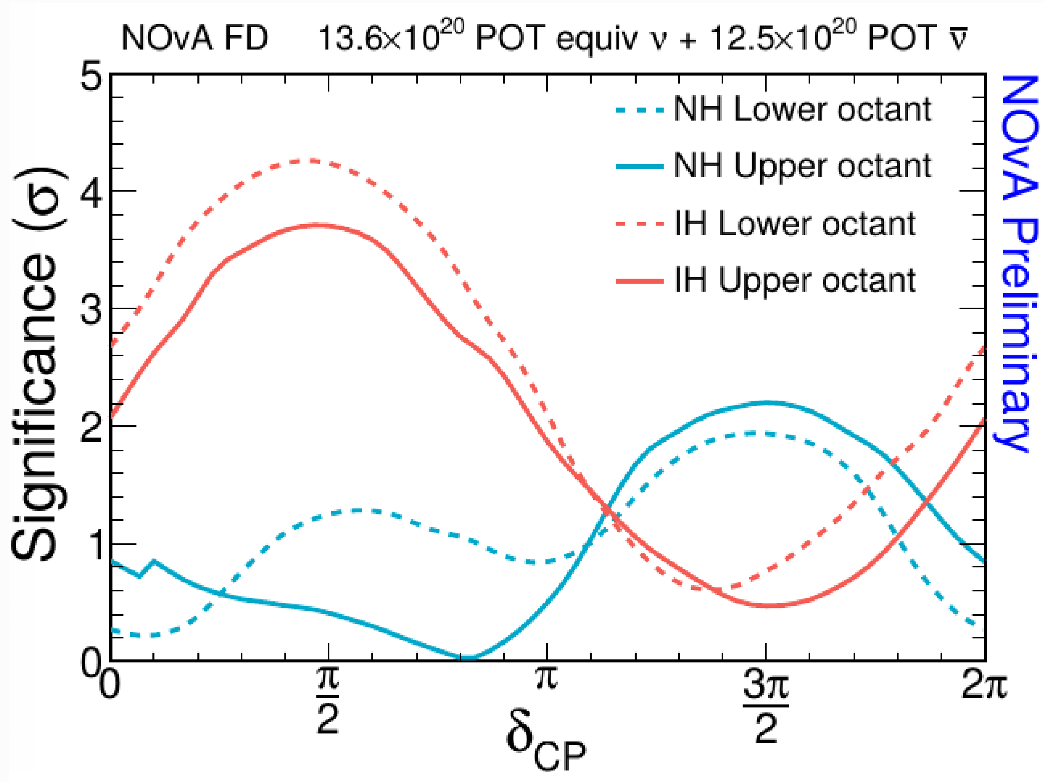


T2K Run1–10 Preliminary
Antineutrino mode e-like candidates
Neutrino mode e-like candidates
sin²θ23 = 0.45, 0.50, 0.55, 0.60
Δm²32 = 2.49×10^-3 eV²
Δm²31 = −2.46×10^-3 eV²
δCP = π
δCP = +π/2
δCP = 0
δCP = −π/2

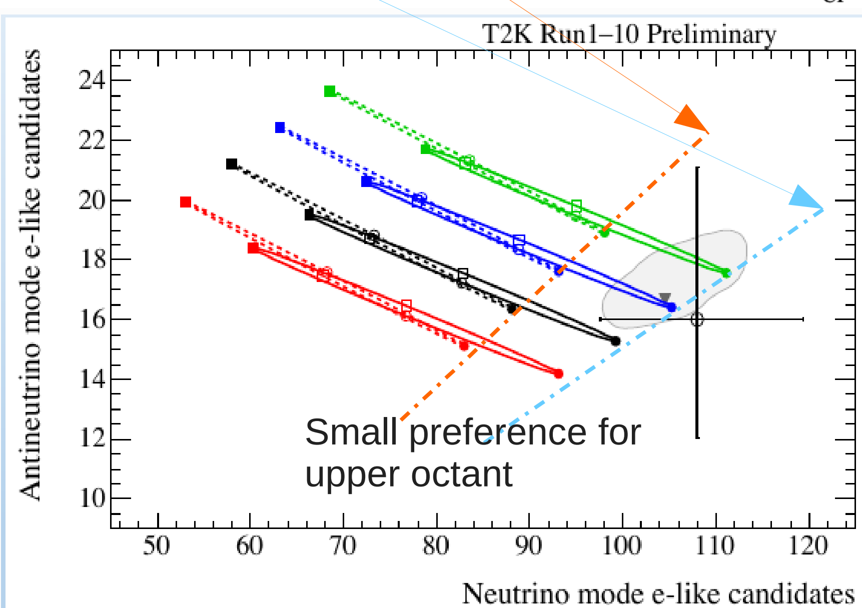
Results



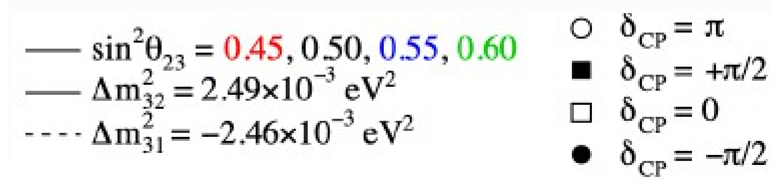
T2K preliminary 19.7x10^20 POT ν + 16.3x10^20 POT ν̄
-2ΔlnL
Normal ordering
Inverted ordering
δ_CP



NOvA FD 13.6×10^20 POT equiv ν + 12.5×10^20 POT ν̄
NOvA Preliminary
Significance (σ)
NH Lower octant
NH Upper octant
IH Lower octant
IH Upper octant
δ_CP



T2K Run1–10 Preliminary
Antineutrino mode e-like candidates
Neutrino mode e-like candidates
Small preference for
upper octant



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δCP = +π/2
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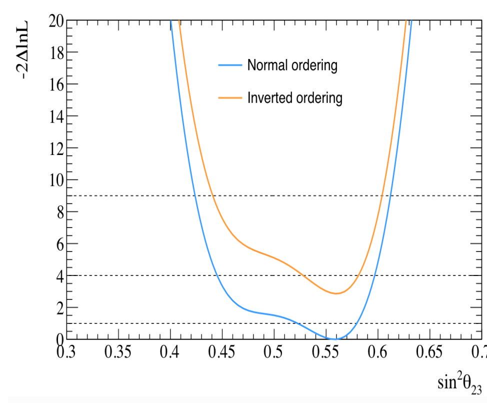
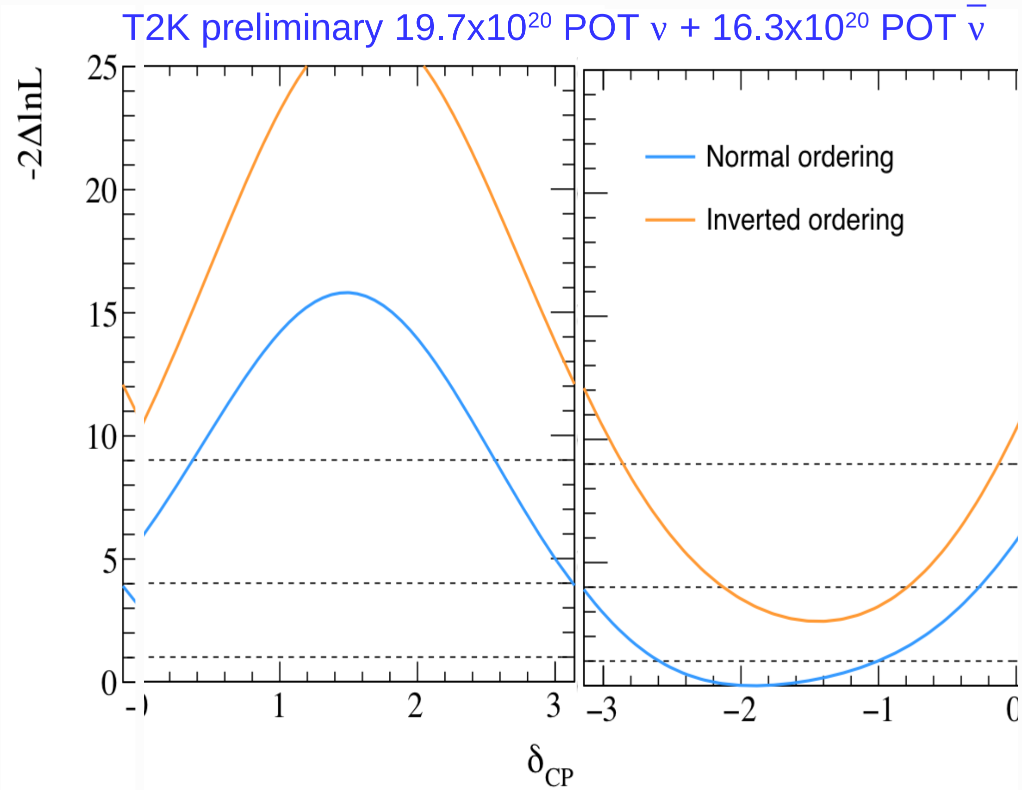
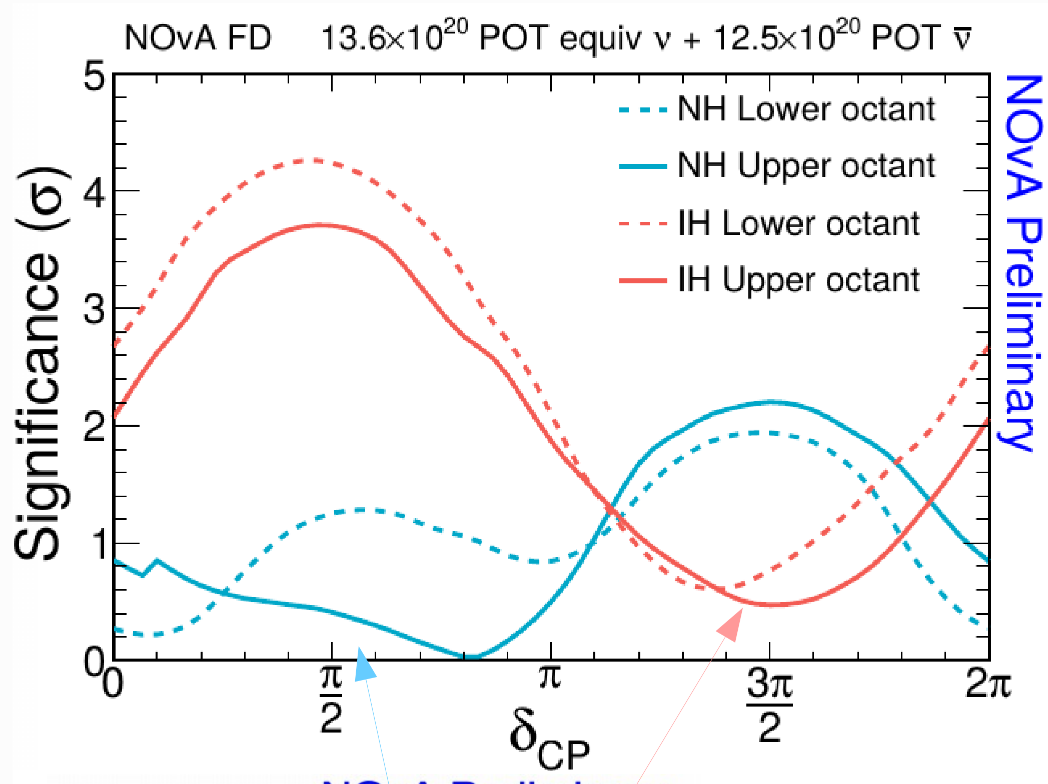


-2ΔlnL
Normal ordering
Inverted ordering
sin²θ23

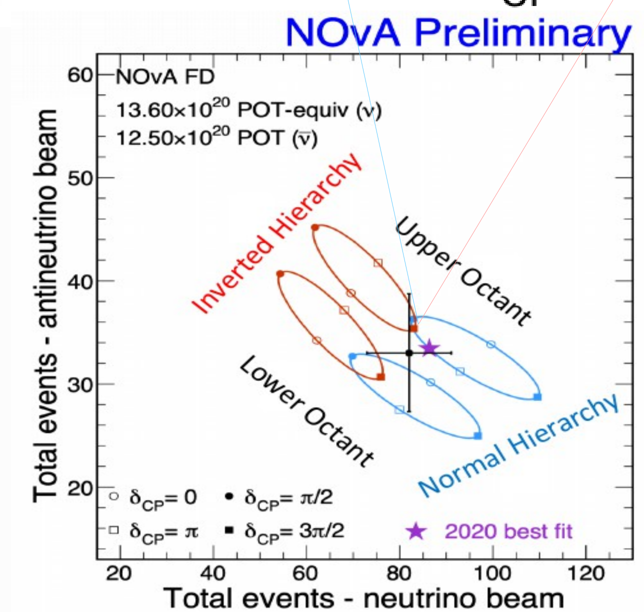
Results



T2K preliminary 19.7x10^{20} POT ν + 16.3x10^{20} POT $\bar{\nu}$
-2ΔlnL
Normal ordering
Inverted ordering
δ_{CP}

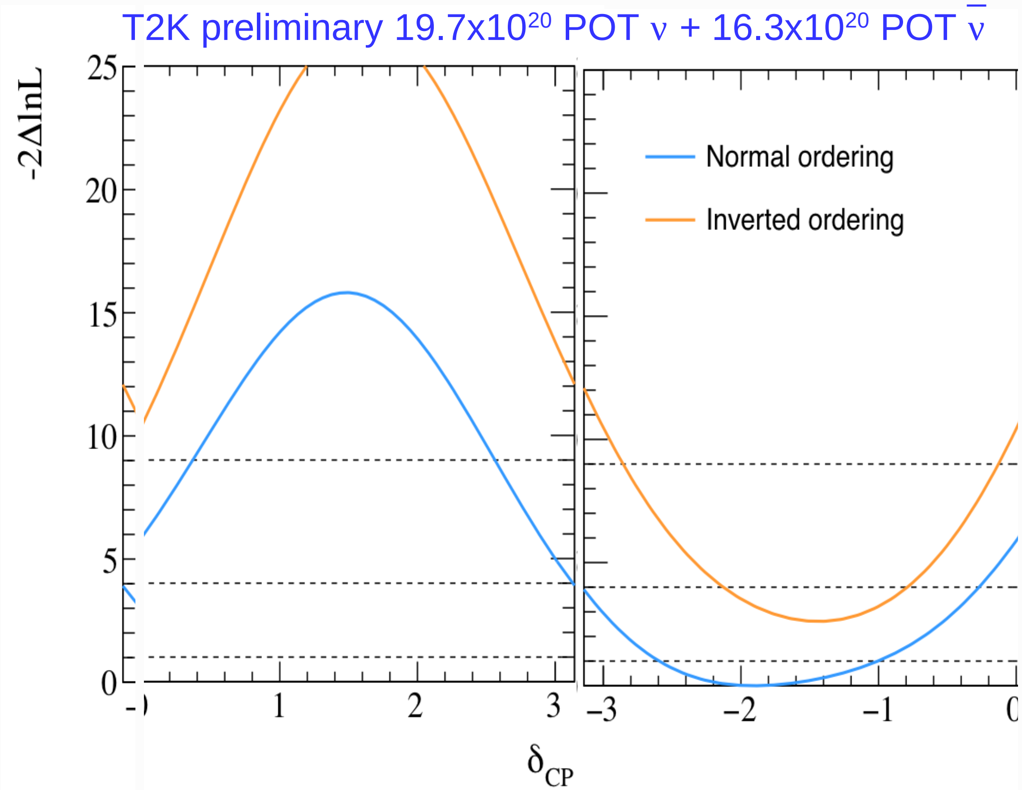


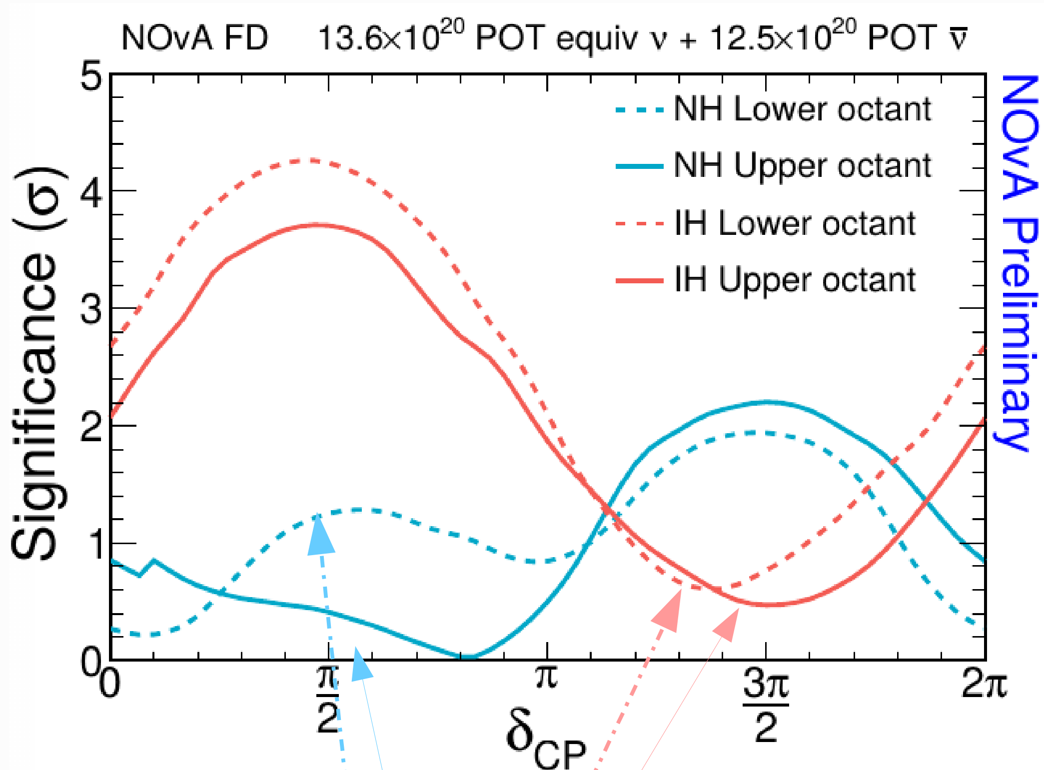
NOvA FD 13.6×10^{20} POT equiv ν + 12.5×10^{20} POT $\bar{\nu}$
Significance (σ)
NH Lower octant
NH Upper octant
IH Lower octant
IH Upper octant
NOvA Preliminary
δ_{CP}

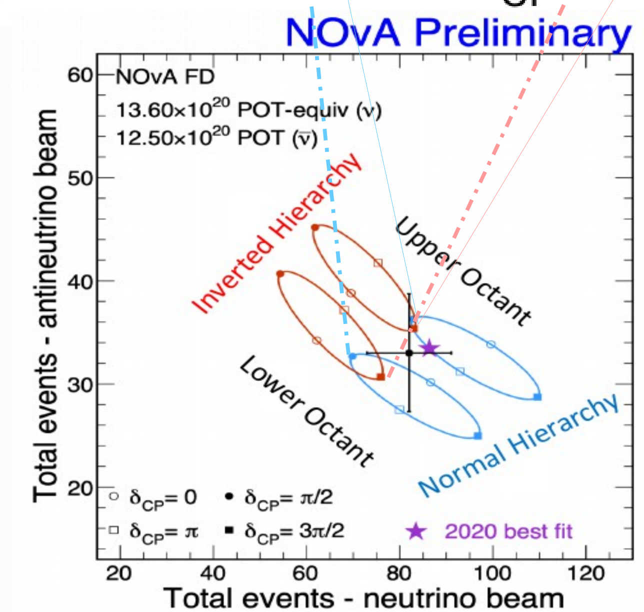


NOvA Preliminary
NOvA FD
13.60×10^{20} POT-equiv (ν)
12.50×10^{20} POT ($\bar{\nu}$)
Inverted Hierarchy
Upper Octant
Lower Octant
Normal Hierarchy
δ_{CP}= 0
δ_{CP}= π/2
δ_{CP}= π
δ_{CP}= 3π/2
2020 best fit
Total events - antineutrino beam
Total events - neutrino beam

Results

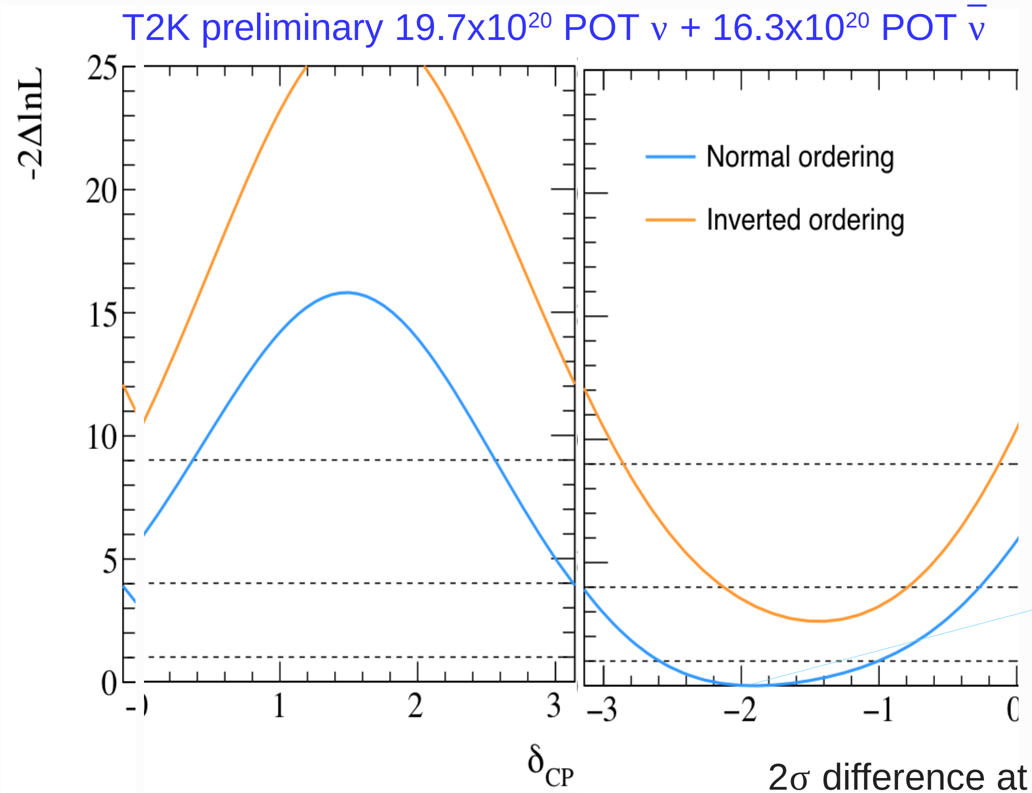


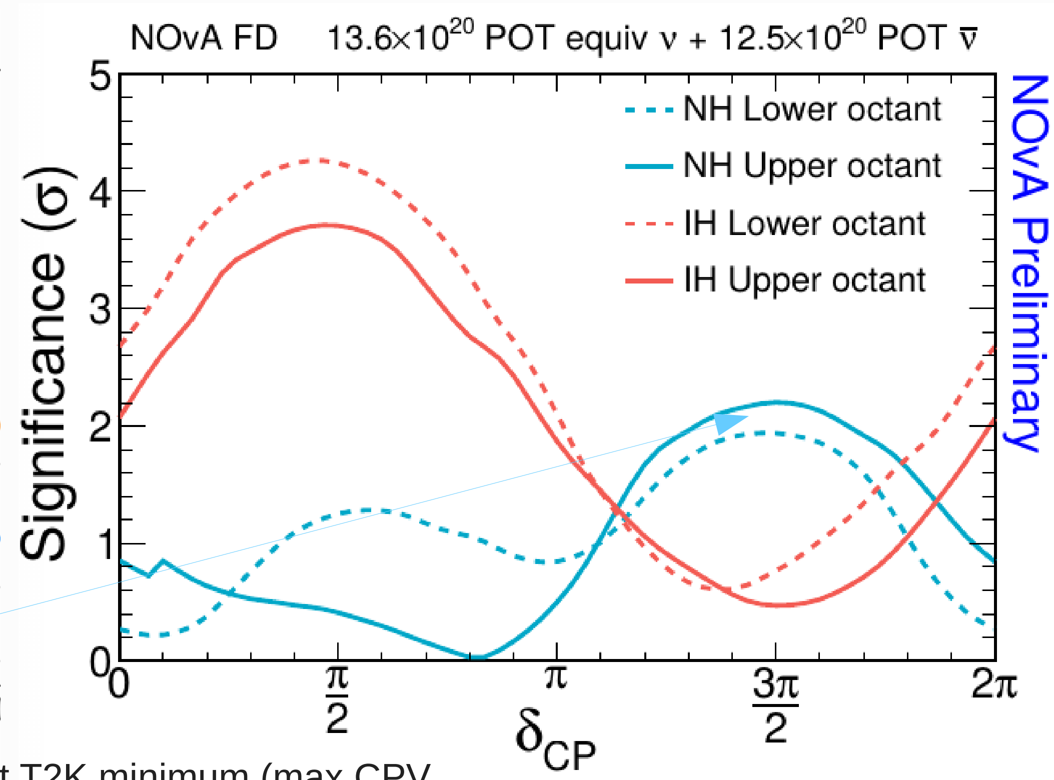




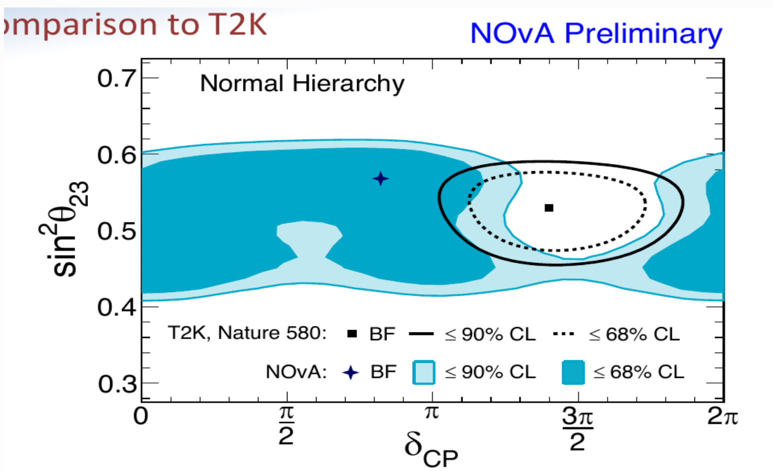
all these possibilities inside 1σ

Results

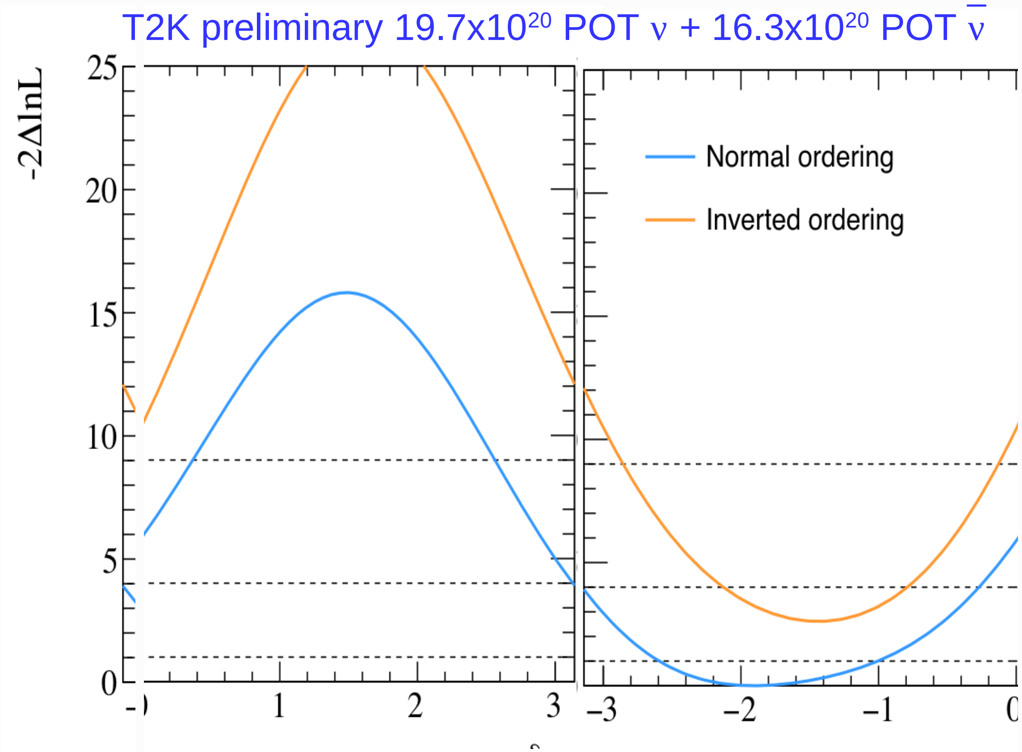


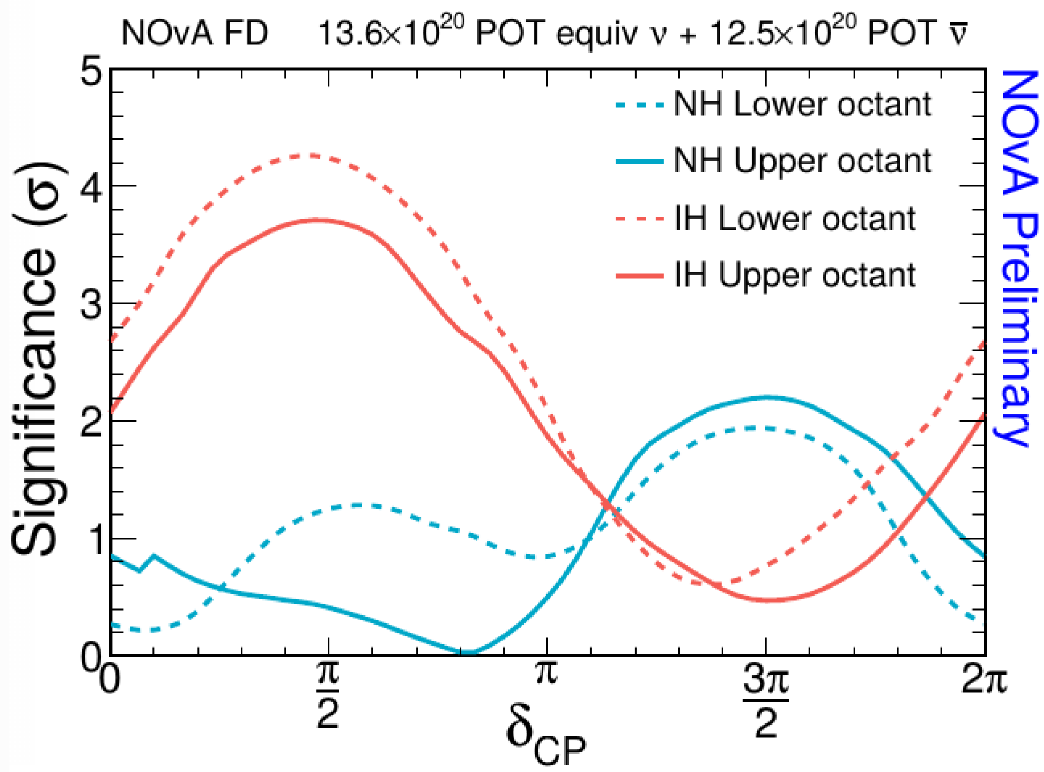


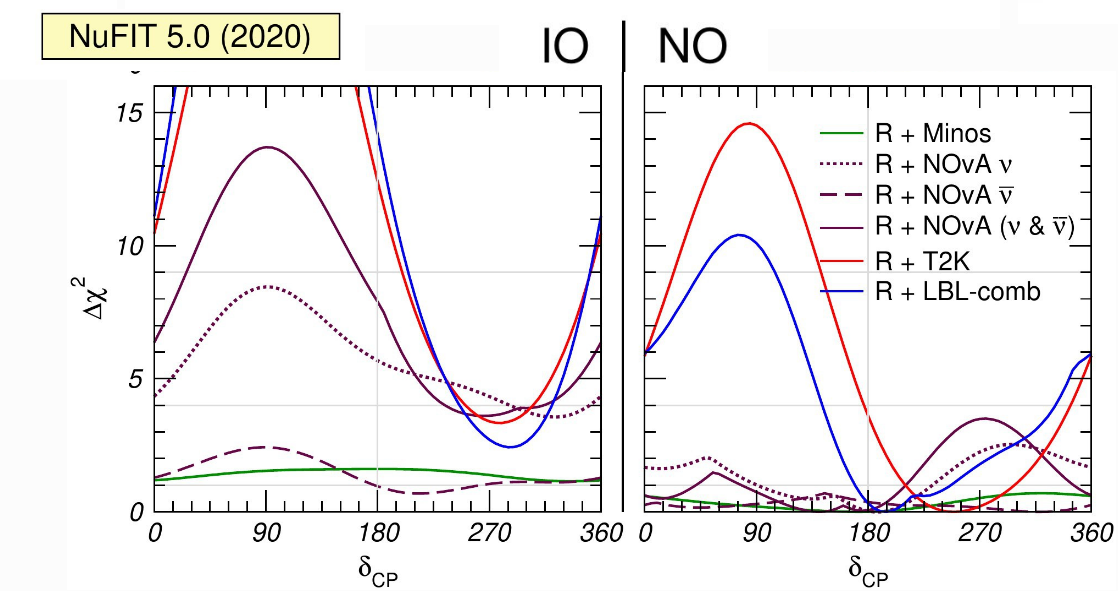
2σ difference at T2K minimum (max CPV, NH) but still common regions at 1σ

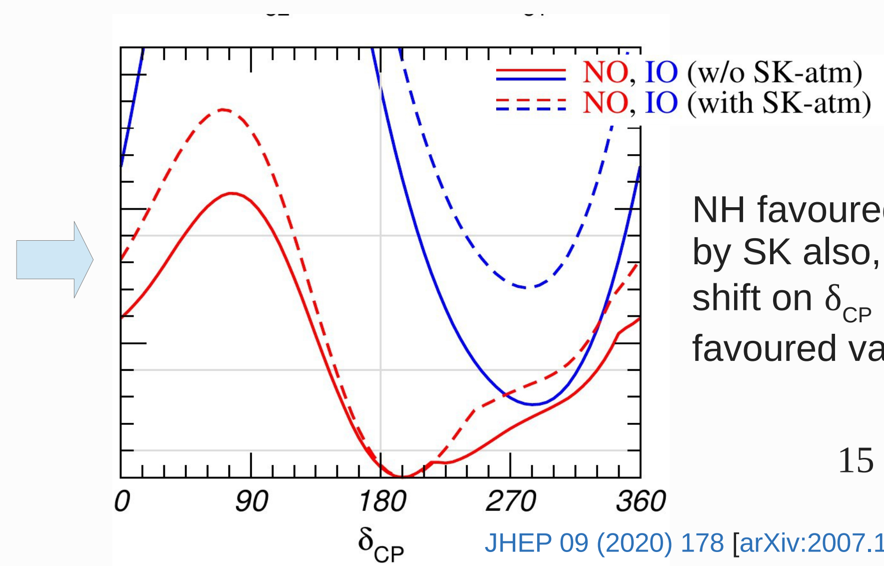


Results





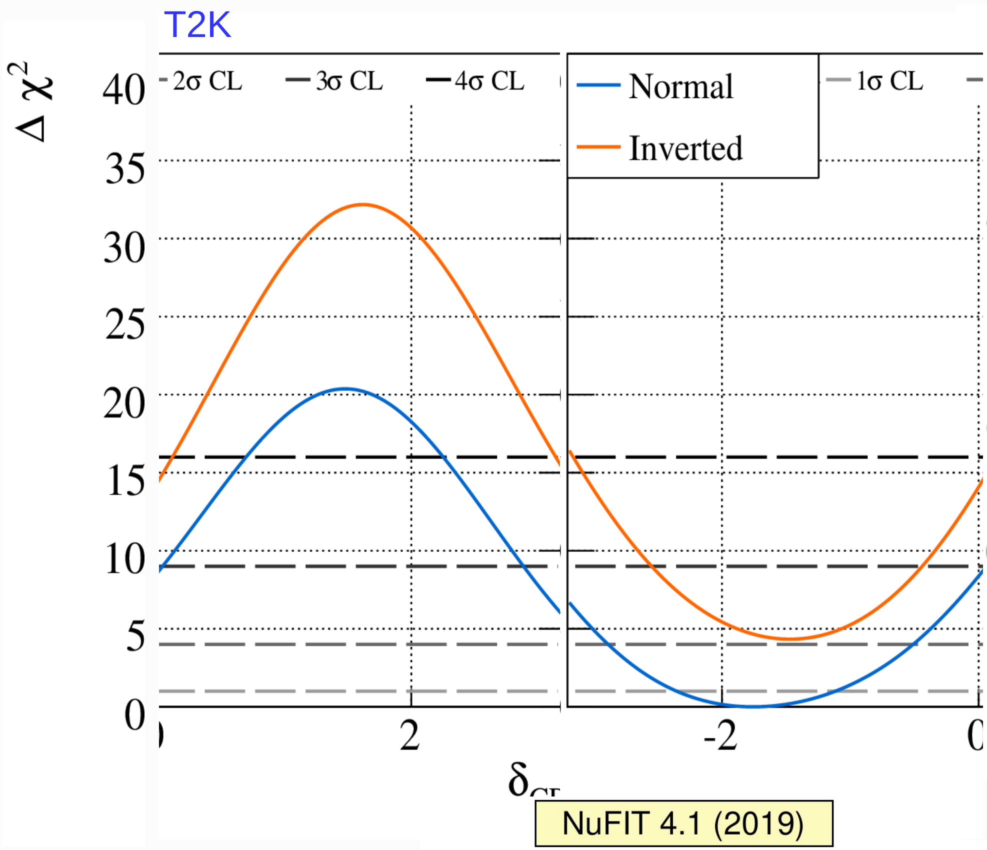


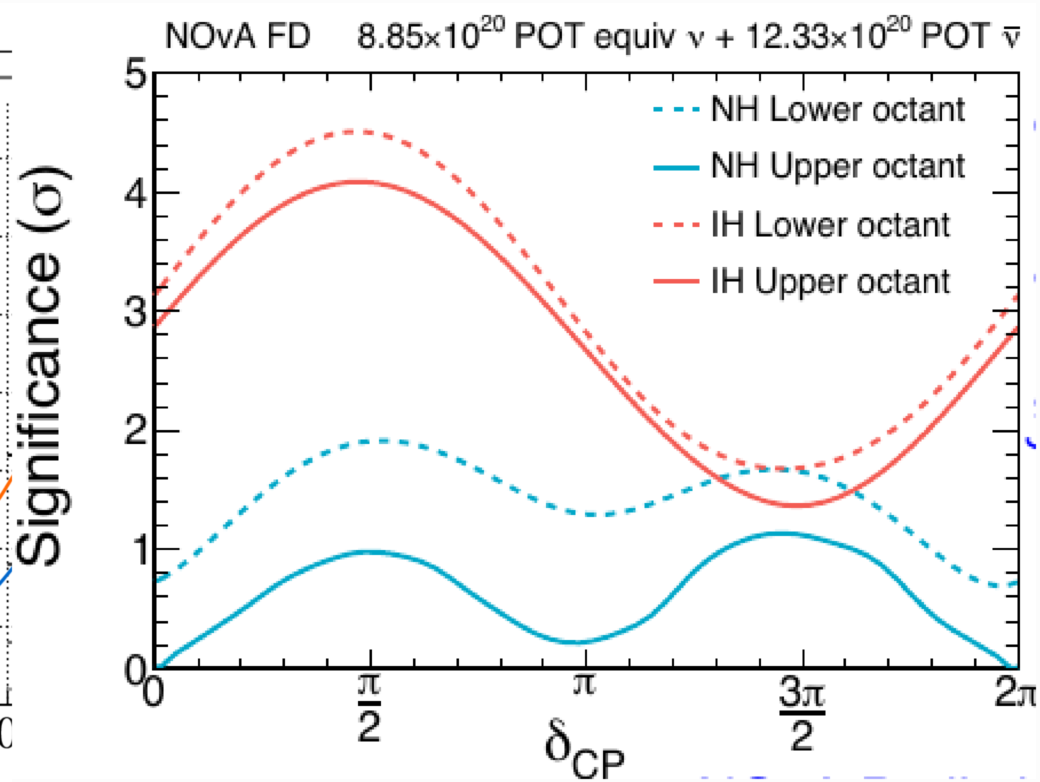


NH favoured by SK also, shift on δ_{CP} favoured value

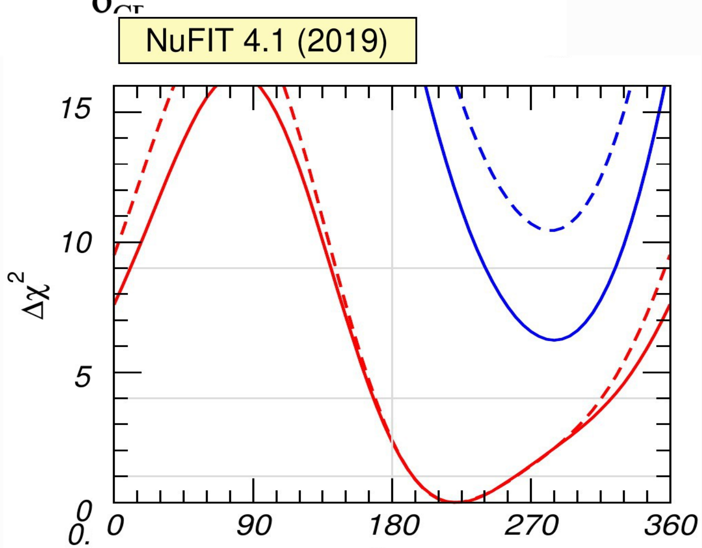
JHEP 09 (2020) 178 [arXiv:2007.14792]

Results *2019*

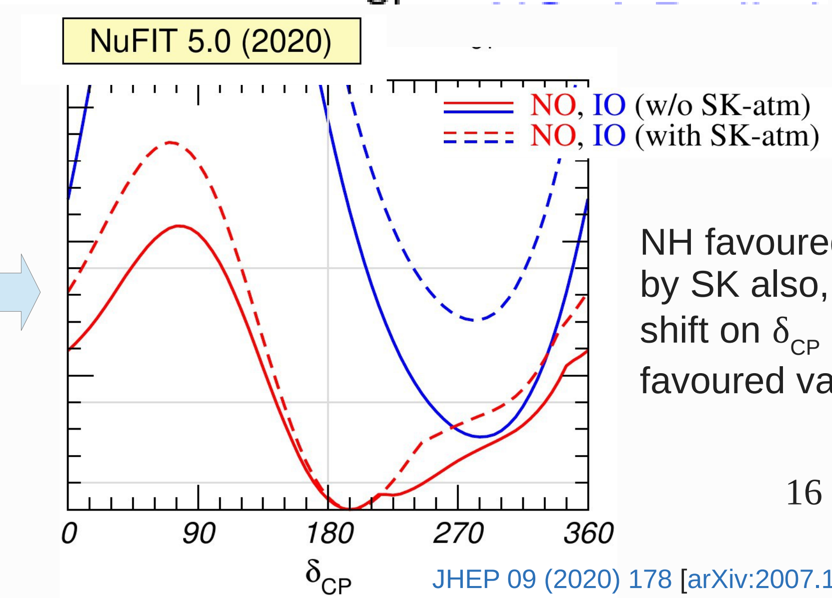




Something similar already visible last year



JHEP 01 (2019) 106 [arXiv:1811.05487]

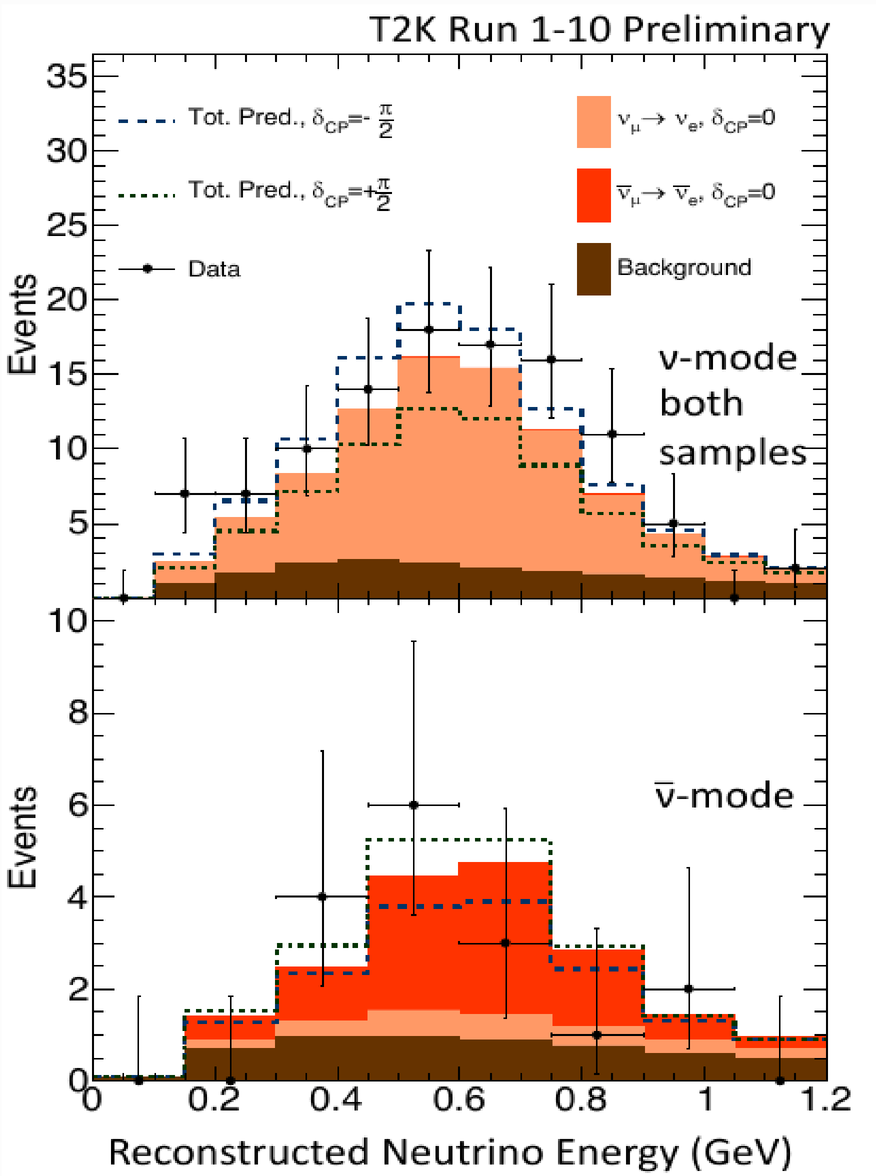


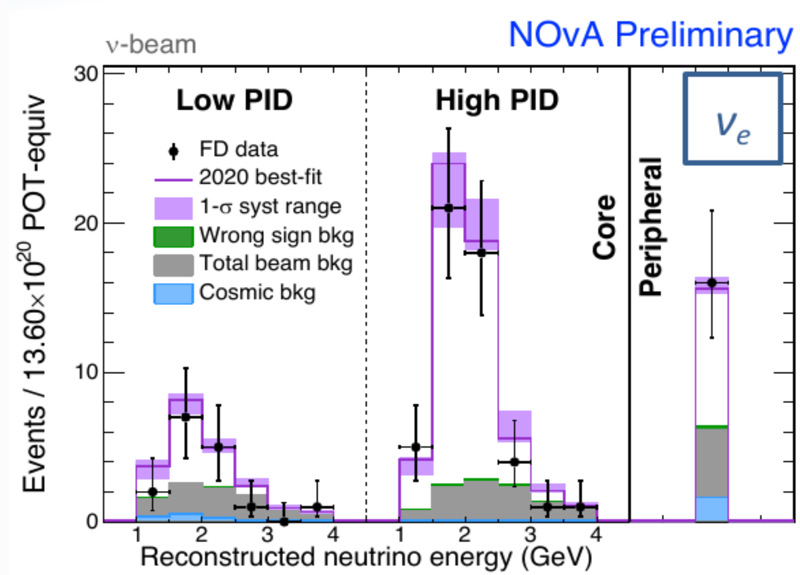
JHEP 09 (2020) 178 [arXiv:2007.14792]

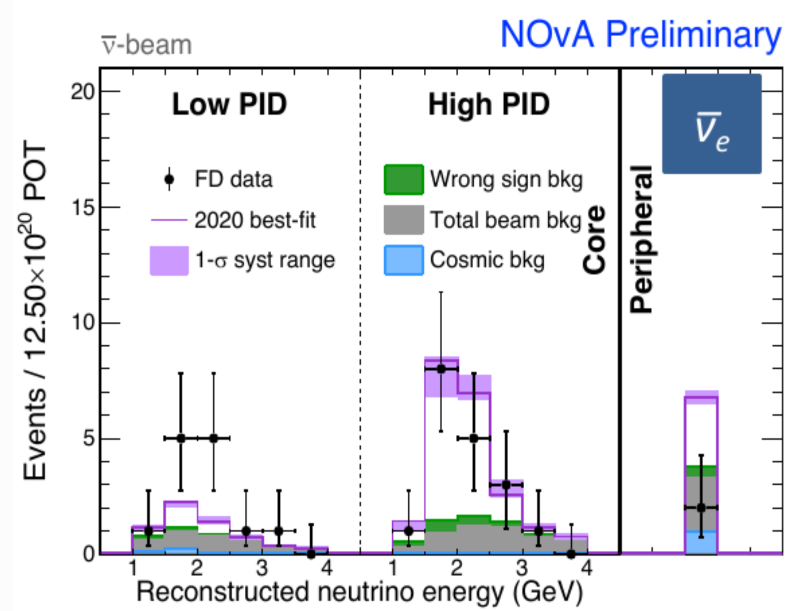
NH favoured by SK also, shift on δ_{CP} favoured value

Statistics

The δ_{CP} results are dominated by stat uncertainty (limited number of ν_e, $\bar{\nu}_e$ events)







Statistical treatment

Treatment of 'nuisances' = how to sample parameters in the fit which are profiled or marginalized (e.g. θ_{23} and Δm^2 in plots of δ_{CP}, MH sensitivity)
In Bayesian term: which priors for nuisances?

- Effect become more important in case of degeneracies and boundary effects

  Safe at 1σ but what about 2σ, 3σ, etc...? Studies on-going

- **Important effect at 5σ: in practice the region of 5σ exclusion may change with POT depending on sampling choice of nuisances.**
  Important for HK and DUNE!

Systematics

- **T2K-NOVA**: very different detectors → very different analysis and treatment of systematics

- Crucial **role of Near Detectors:**

$$R_{ND}^{\nu'} = \int \boxed{\Phi^{\nu}(E_\nu)\frac{d\sigma^{\nu'}}{dE_\nu}} dE_\nu$$

ND measures rate vs neutrino energy

$$R_{FD}^{\nu'} = \int \boxed{\Phi^{\nu}(E_\nu)} \, P_{osc}^{\nu\to\nu'}(E_\nu) \boxed{\frac{d\sigma^{\nu'}}{dE_\nu}} dE_\nu$$

~same flux at ND and FD

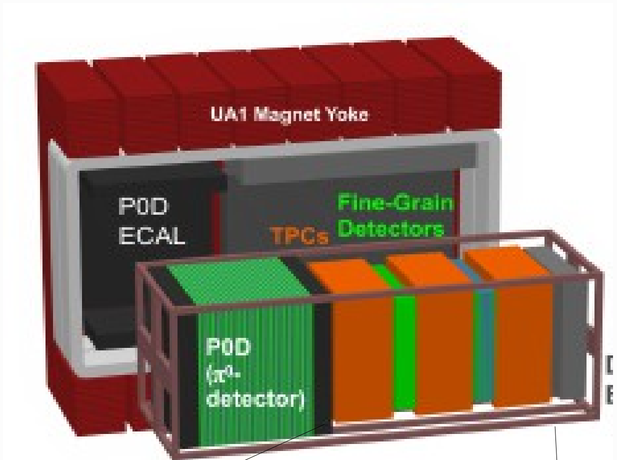
what we want to measure:
oscillation probability

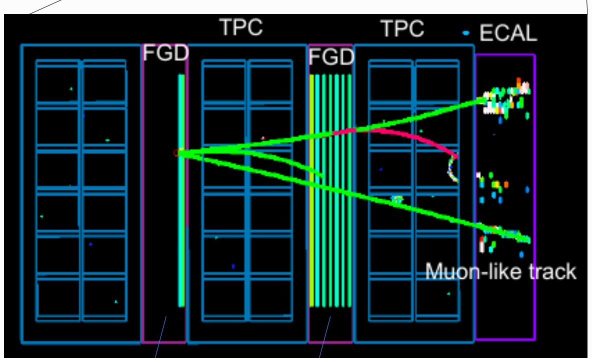
cross-section must be extrapolated from ND to FD (different neutrino energy distribution)

- Important systematics for δ_{CP} (MH):
  - **difference between ν and $\bar{\nu}$ (xsec and flux)**
    Notably, **"wrong sign" background:** ν in $\bar{\nu}$ mode (π^+ focused beam)
  - **ν_e intrinsic background:** ν_e produced in the beam by K / π->μ decays

T2K

ND280





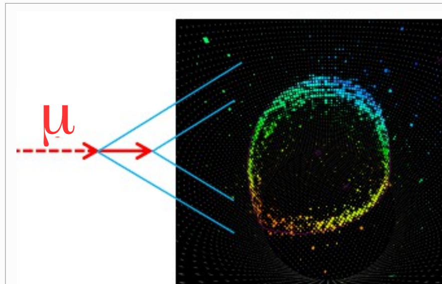
carbon target

water target

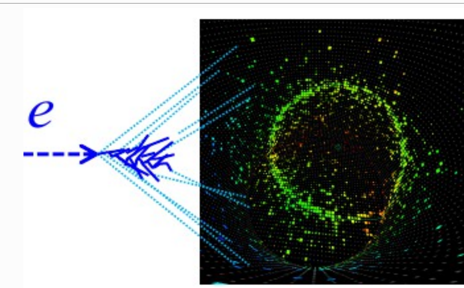
Full tracking and particle reconstruction (**<u>magnetized!</u>**): measure precisely neutrino and antineutrino rate before oscillation

SuperKamiokande

Huge water cherenkov detector (50 kTon) with optimal μ/e identification to distinguish ν_e, ν_μ



<u>clear ring</u>



<u>fuzzy ring</u>

T2K ND fit

- **Near detector measurement**

$$R^{\nu'}_{ND}(E_\nu) = \Phi^{\nu}(E_\nu)\frac{d\sigma^{\nu'}}{dE_\nu} = F\left(\boxed{p_\mu, \cos\theta_\mu}; \alpha_{ND}, \alpha_{model}\right)$$

nuisances = parametrization of (detector systematics), flux and nuclear physics uncertainties

Reconstruction of energy at the far detector

$$E_\nu = R\left(p_\mu, \cos\theta_\mu; \alpha_{FD}, \alpha_{model}\right)$$

- magnetized ND: separate uncertainties for ν and $\bar{\nu}$

- constrain on ν_e rate from ND ~8% → ν_e / ν_μ xsec uncertainty from theory ~3%

- **Crucial improvement expected from upgrade of ND280 (2022 → HK)**

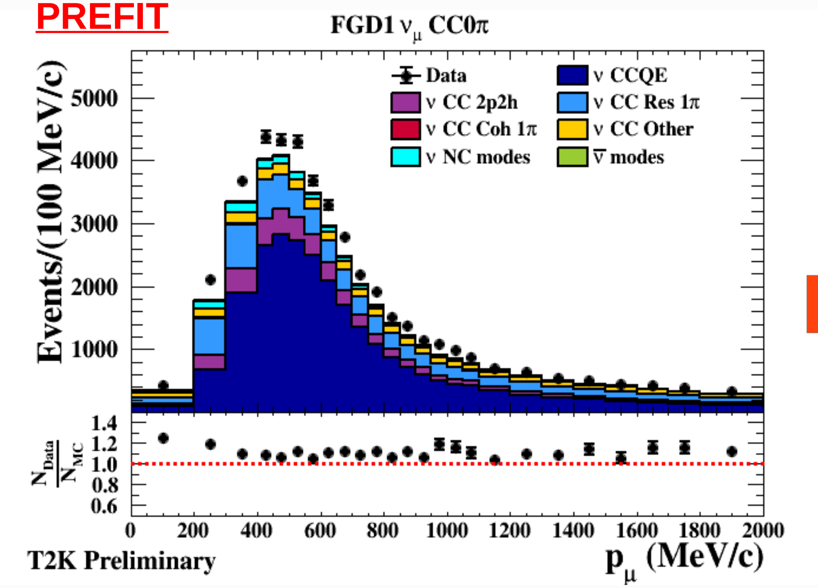
  - measurement of low momentum protons and neutrons to “validate” neutrino energy reconsctruction

  - larger statistics (beam upgrade) and better ν_e efficiency and purity (~4%)

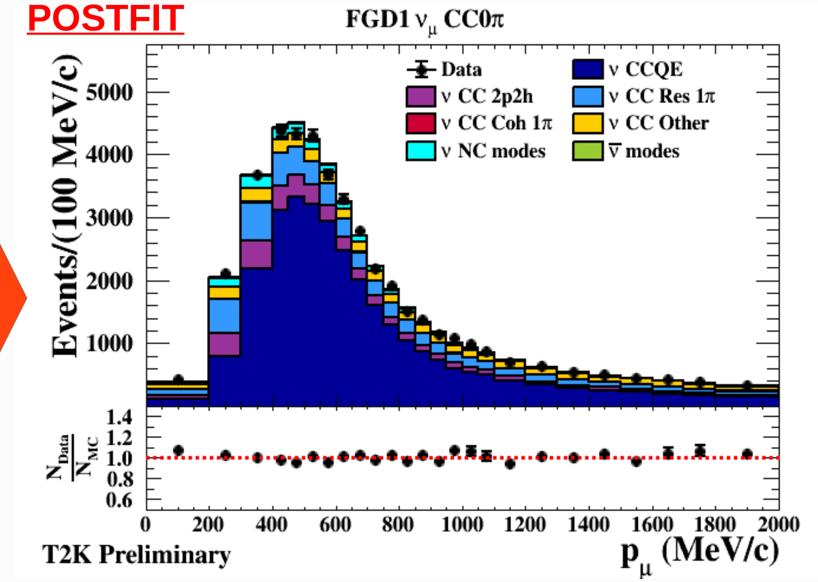
T2K ND: data fit

Fit to samples with 0,1,N pions in the final state, on C and C+O **for nu and antinu selection in opposite beam focusing**

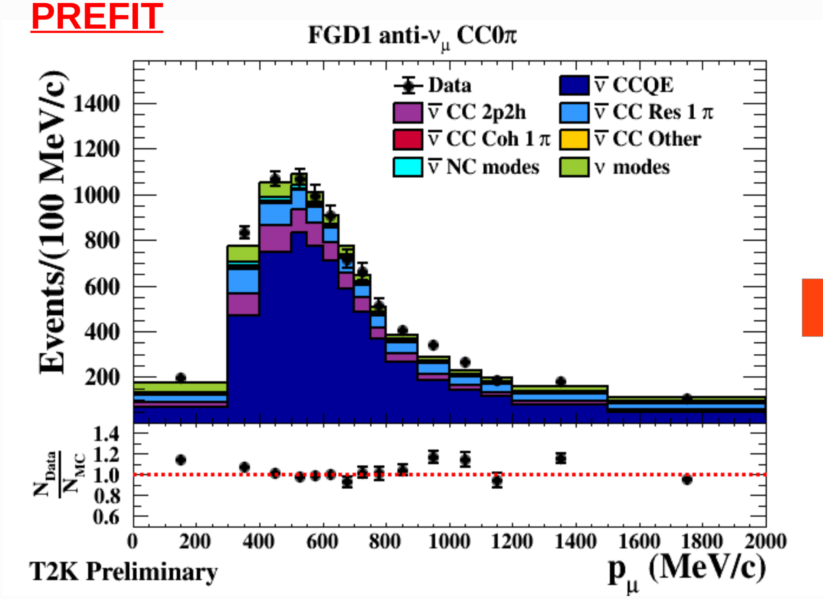
PREFIT



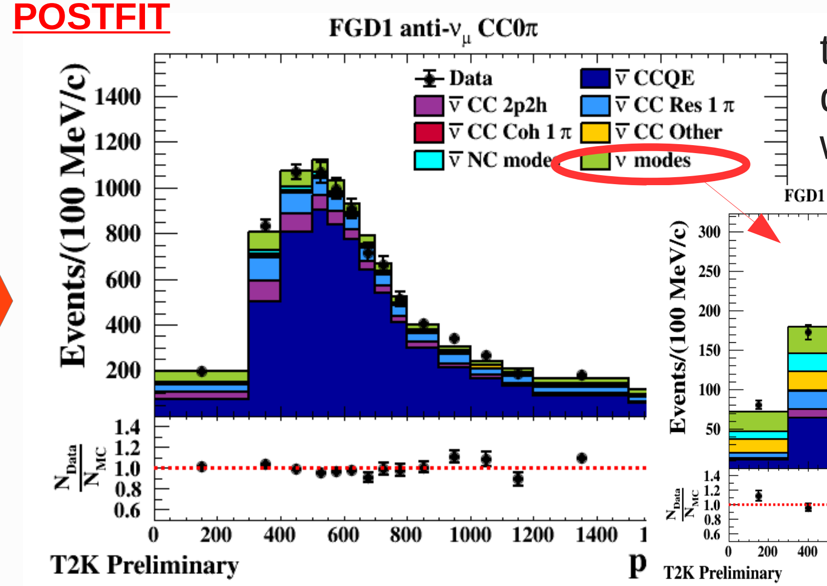
POSTFIT



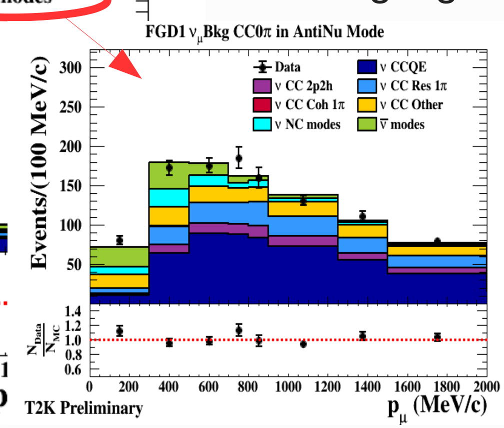
PREFIT

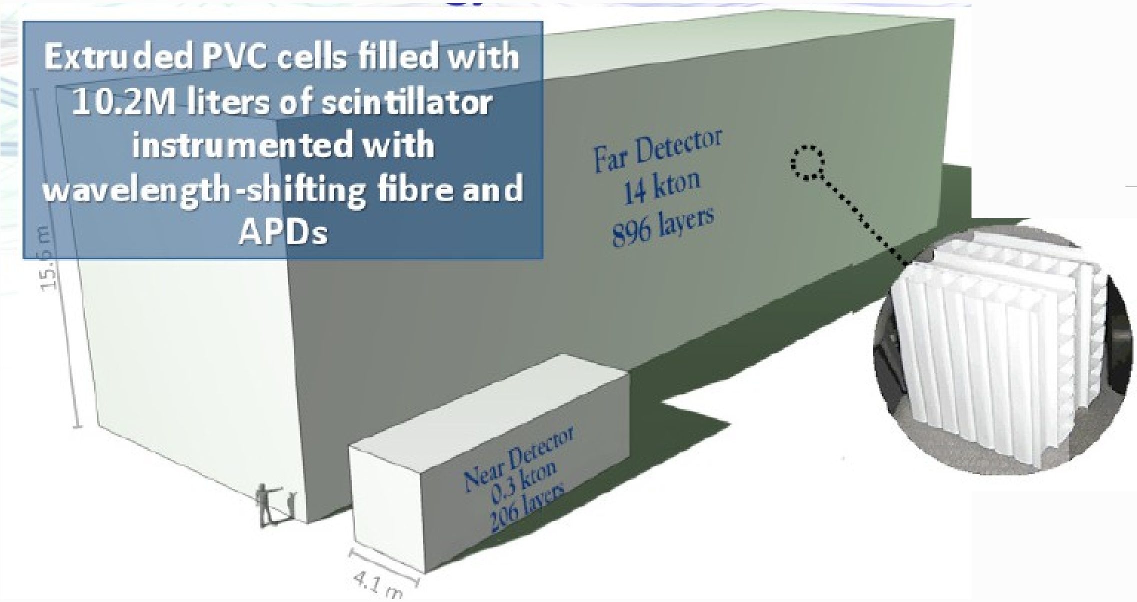


POSTFIT



tuned to dedicated sample with 'wrong sign'

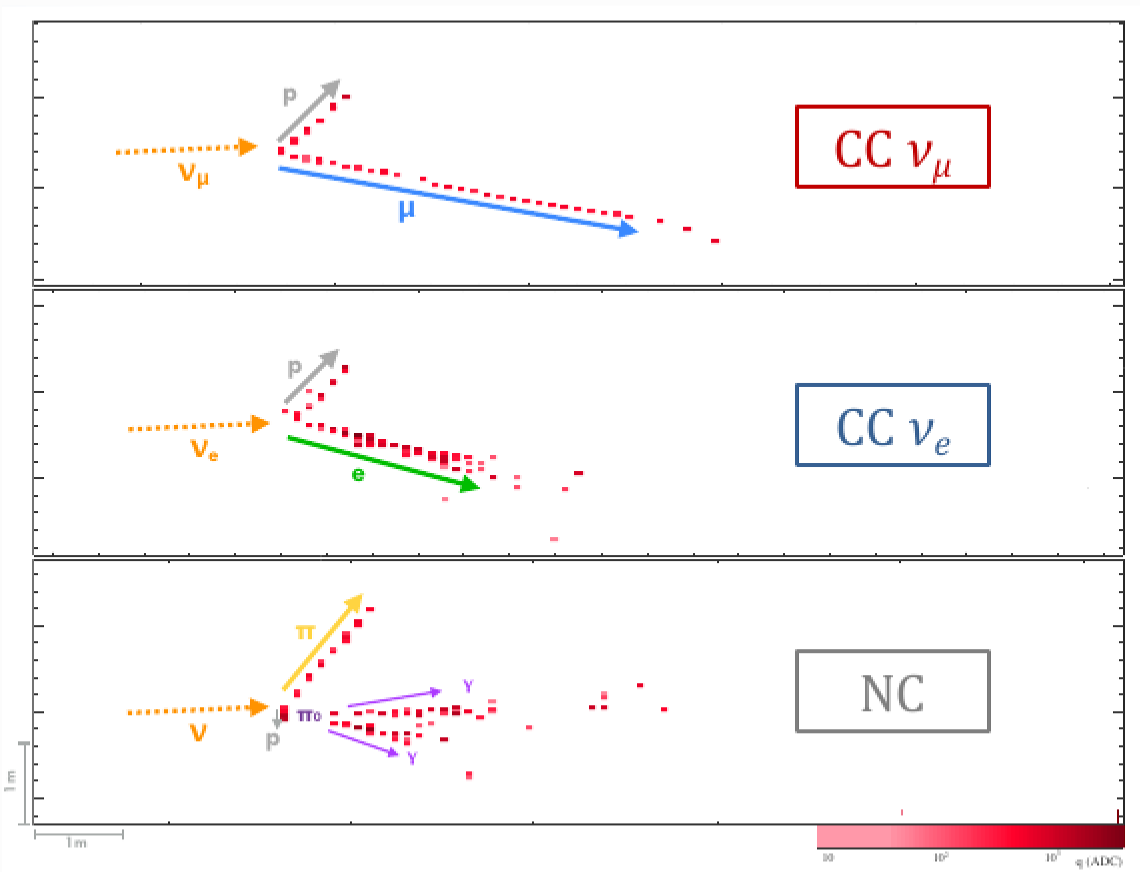




NOVA

- **Very same technology (liquid scintillator) for near and far detector**

Extrapolation from near to far detector does not rely on a detailed theoretical interpretation/understanding of the nuclear effects



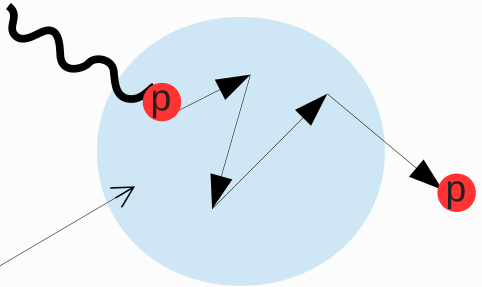
- **How systematics on nuclear effects still affect ND to FD extrapolation:**

  - different Eν at ND and FD (before and after oscillation) → different $E_{had}/E\nu$, different resolution...

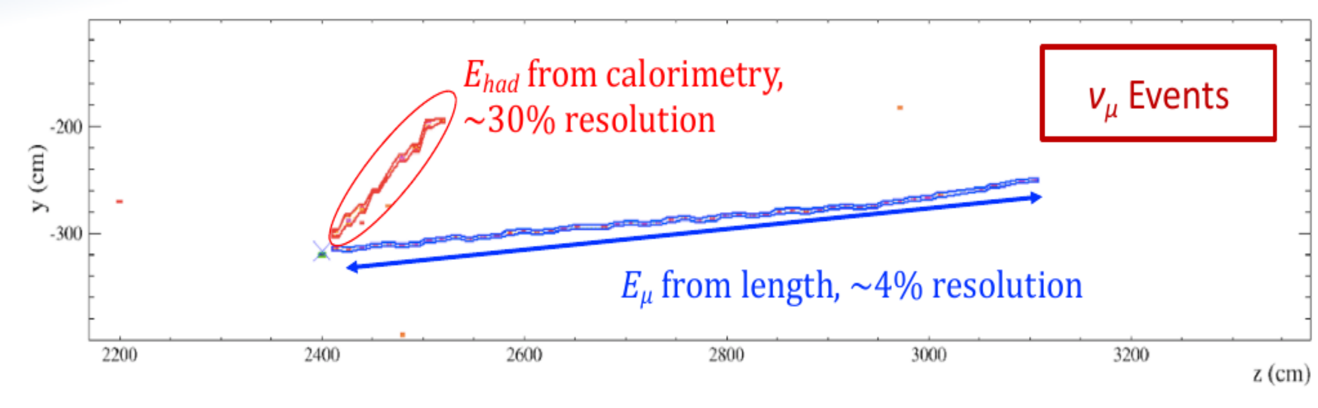
  - different acceptance (in p_T) at ND and FD due to different size

  - still need to disentangle flux and xsec since they depends on Eν differently

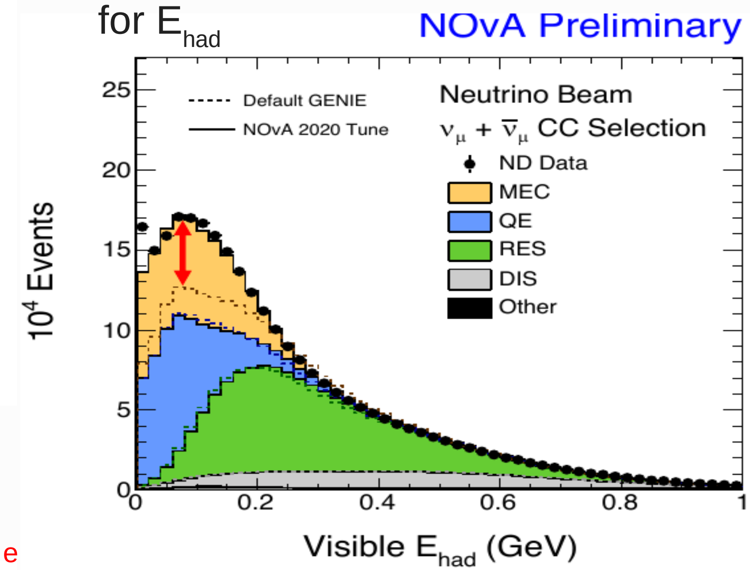
Eν reconstruction



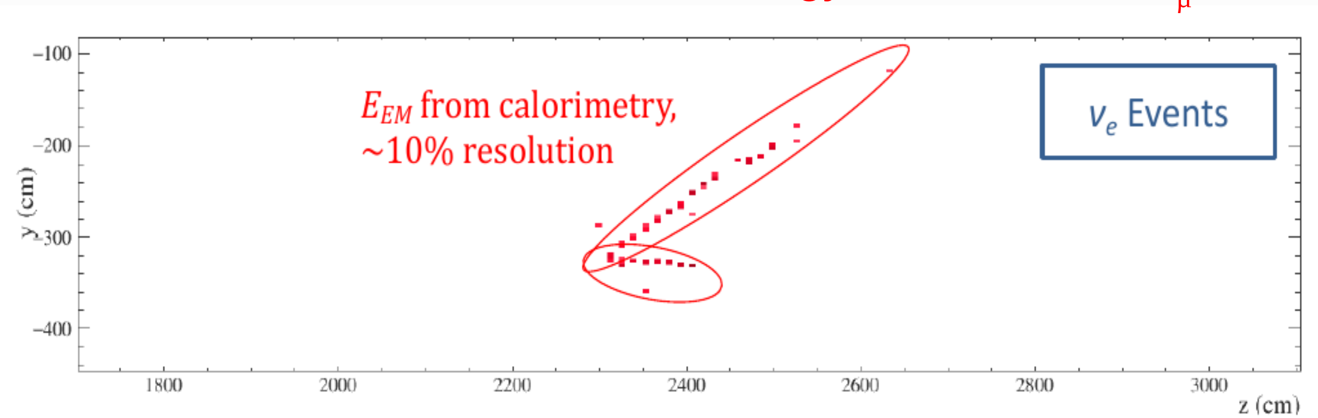
- **Eν reconstructed with hadronic deposits:**
  - important difference $\nu - \bar{\nu}$: proton vs neutron (~undetected)
  - proton/pion energy smeared by Final State Interactions



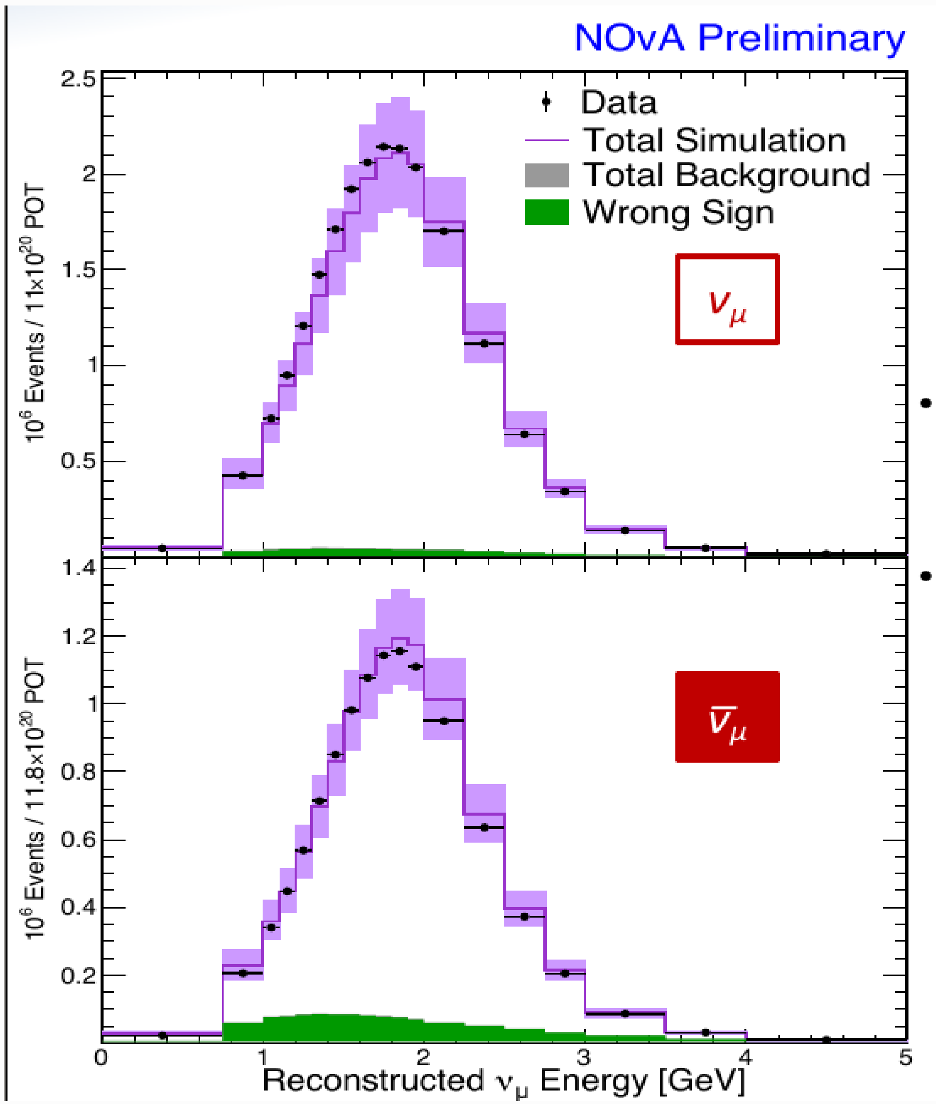
Important to tune model predictions for E_{had}

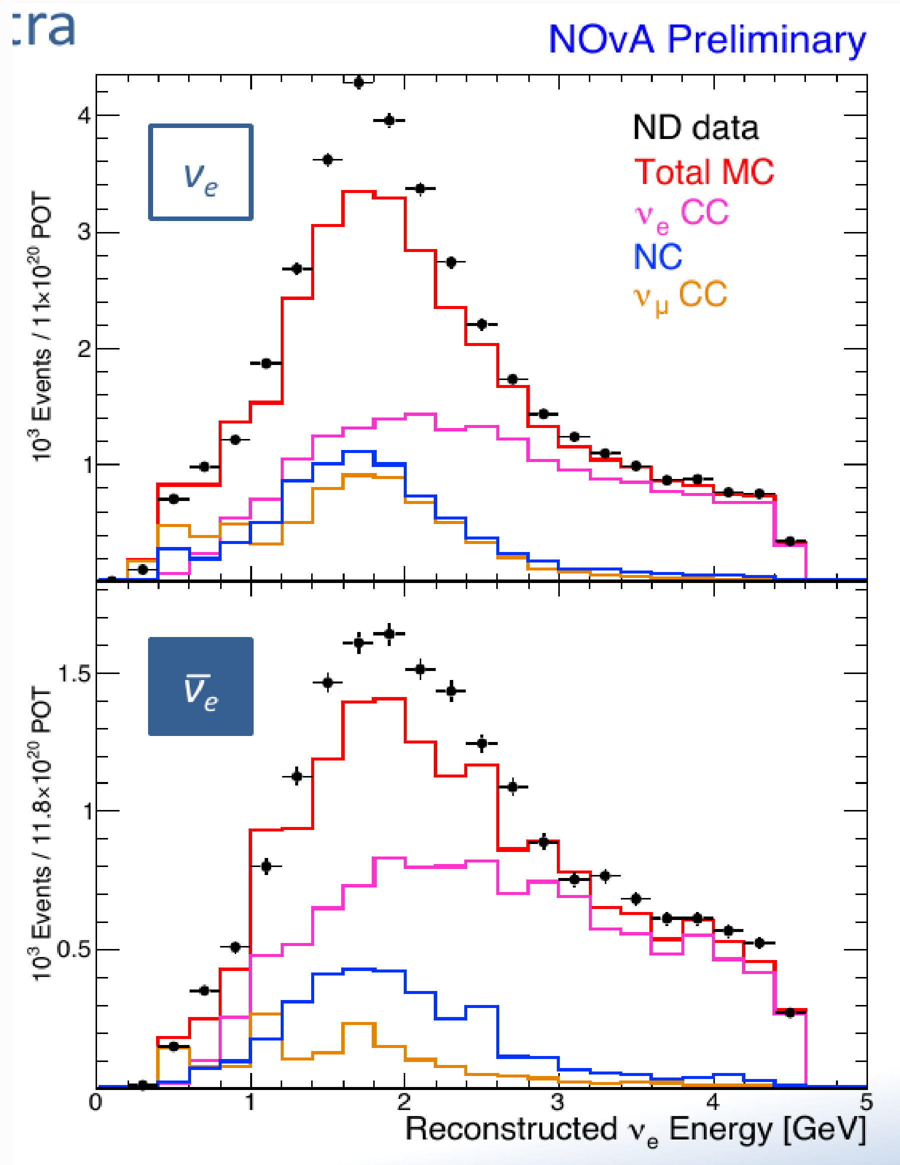


- Different reconstruction and energy resolution for ν_μ and ν_e

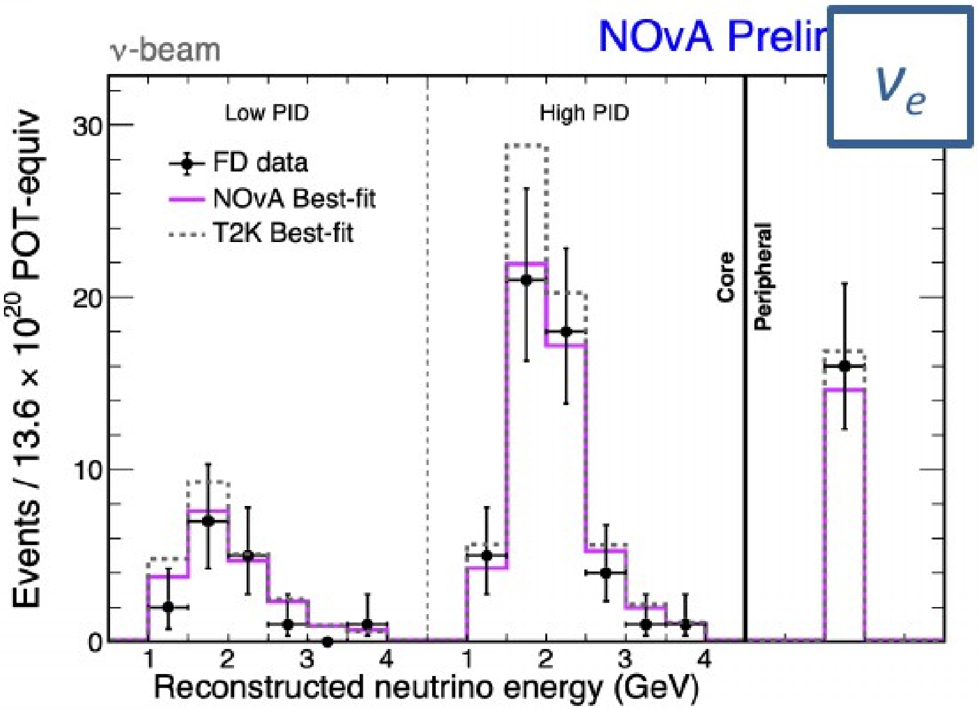


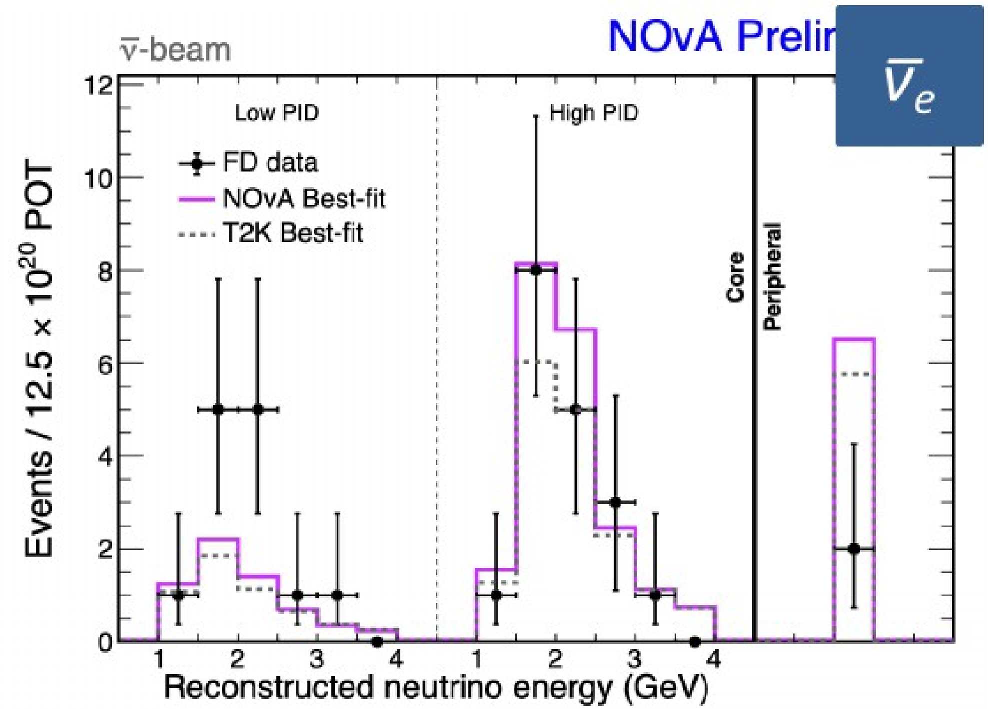
Near Detector data vs prediction





~~Conclusions~~ → Stay tuned for more data!





- Still in ν_e / $\bar{\nu}_e$ (so δ_{CP} measurements) **the statistic uncertainties at the far detector is dominant over the systematics**

- The model of systematics is extremely different in T2K and NOVA and their impact and treatment is extremely different

- The evaluation of systematics is the big challenge for the next years: **T2K and NOVA are crucial to open the road to higher-statistics future LBL**

Volume 580 Issue 7803, 16 April 2020 - Nature

T2K is a statistically-limited experiment which just got the Nature cover!

The next years T2K and NOVA will have an extremely interesting physics program
(eg, beam and ND280 upgrade, joint T2K-NOVA and T2K-SK fits, … → sensitivity for 3σ CP-violation and MH determination)

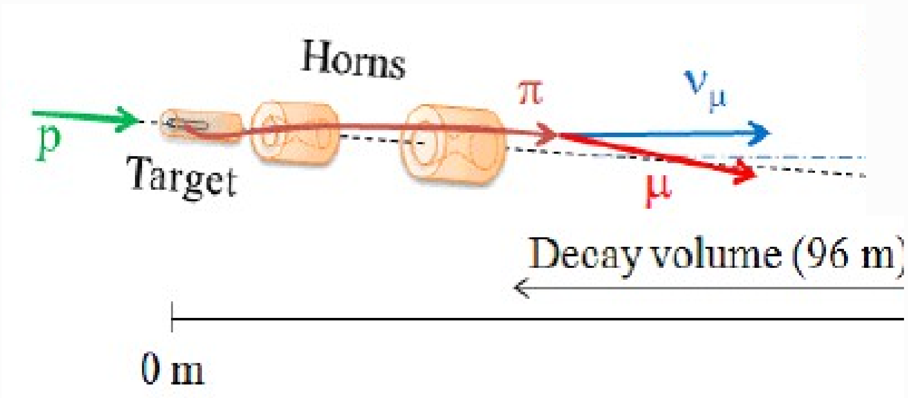
COME AND JOIN US!

If you are interested in HyperKamiokande and DUNE, then T2K and NOVA is where you can pave the road to the future!!

BACK-UP

Decay volume

- **Let the hadrons to decay in (μ and) ν:**



Decay volume (T2K: He filled):

- longer to let most of the pion decaying
- not too long to avoid muon decay (ν_e pollution)

- most ν_μ's from 2-body decays:

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

$K^+ \rightarrow \mu^+\nu_\mu$

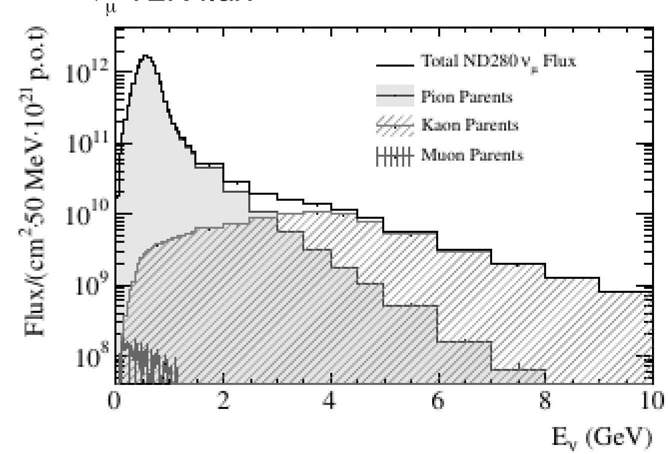
- most ν_e's from body decays:

$\mu^+ \rightarrow e^+\nu_e\nu_\mu$

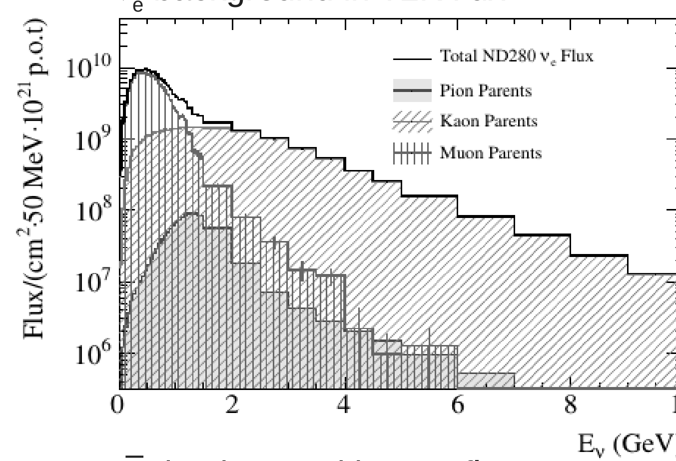
$K^+ \rightarrow \pi^0 e^+\nu_e$

- $\bar{\nu}_\mu$ / ν_μ larger at high energy due to high p_L π- which cannot be (de-) focused

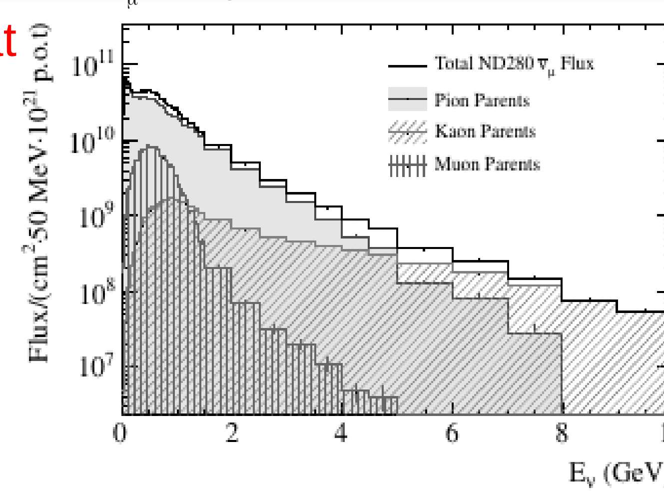
ν_μ T2K flux



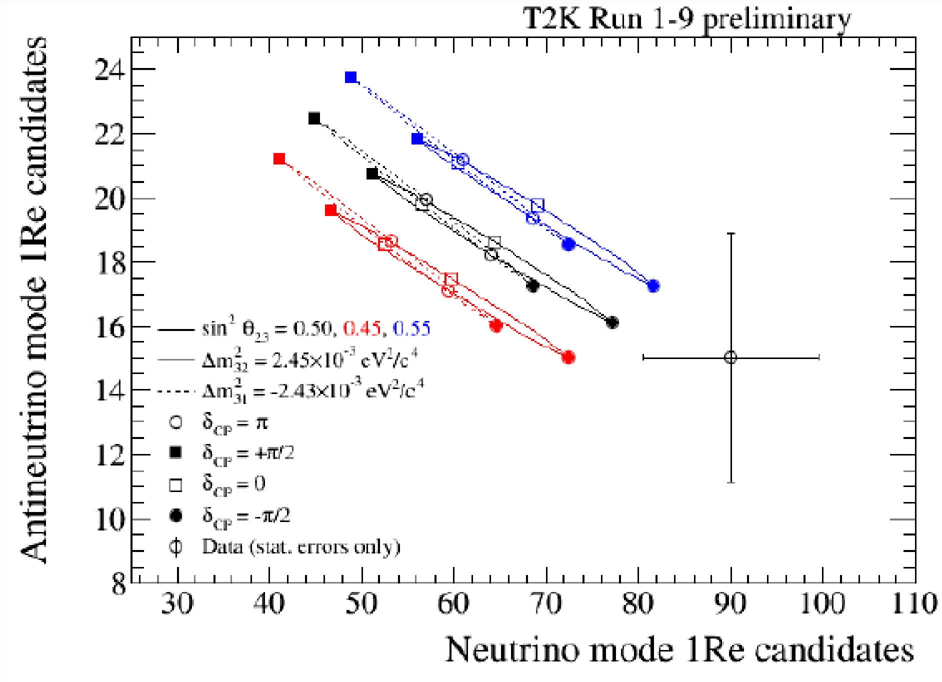
ν_e background in T2K flux

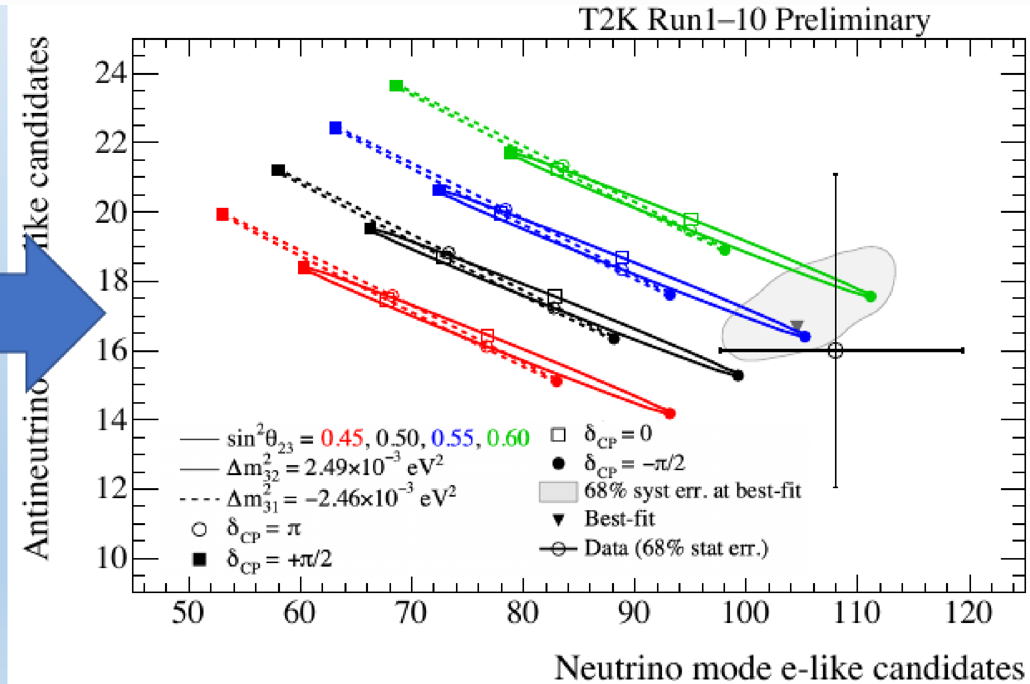


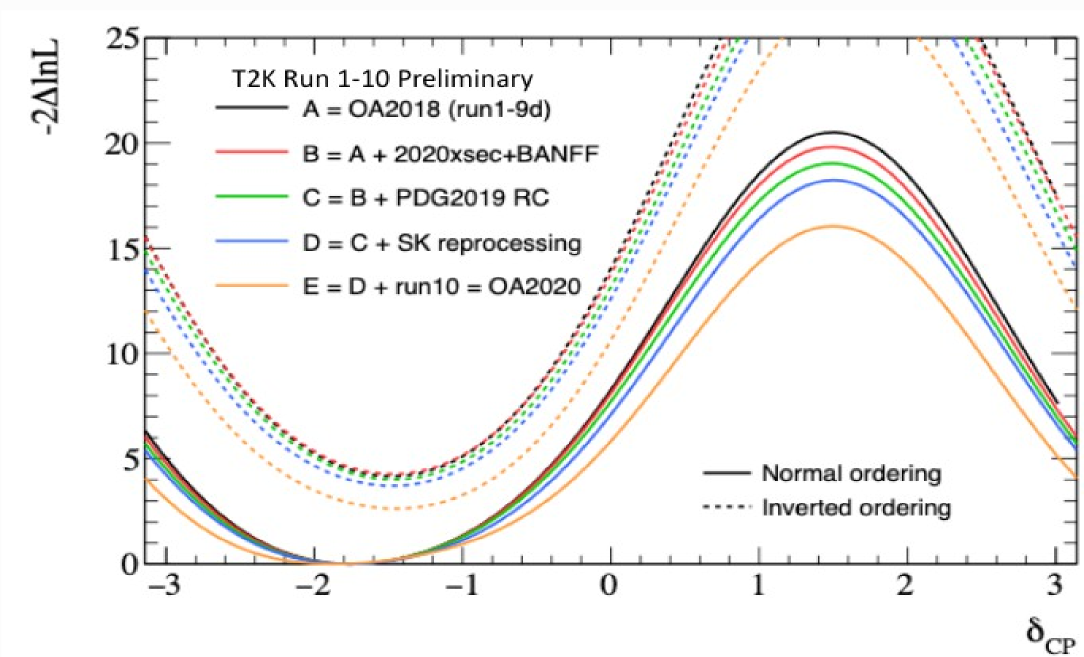
$\bar{\nu}_\mu$ background in T2K flux



2019 → 2020: T2K

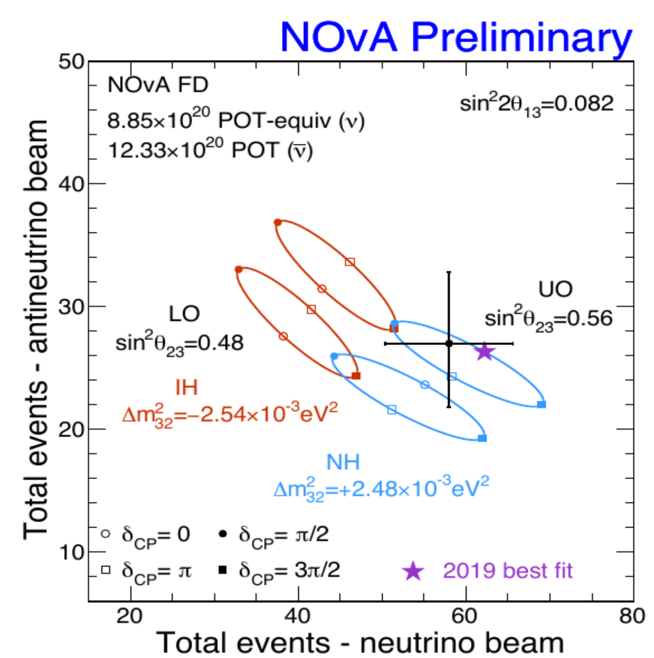


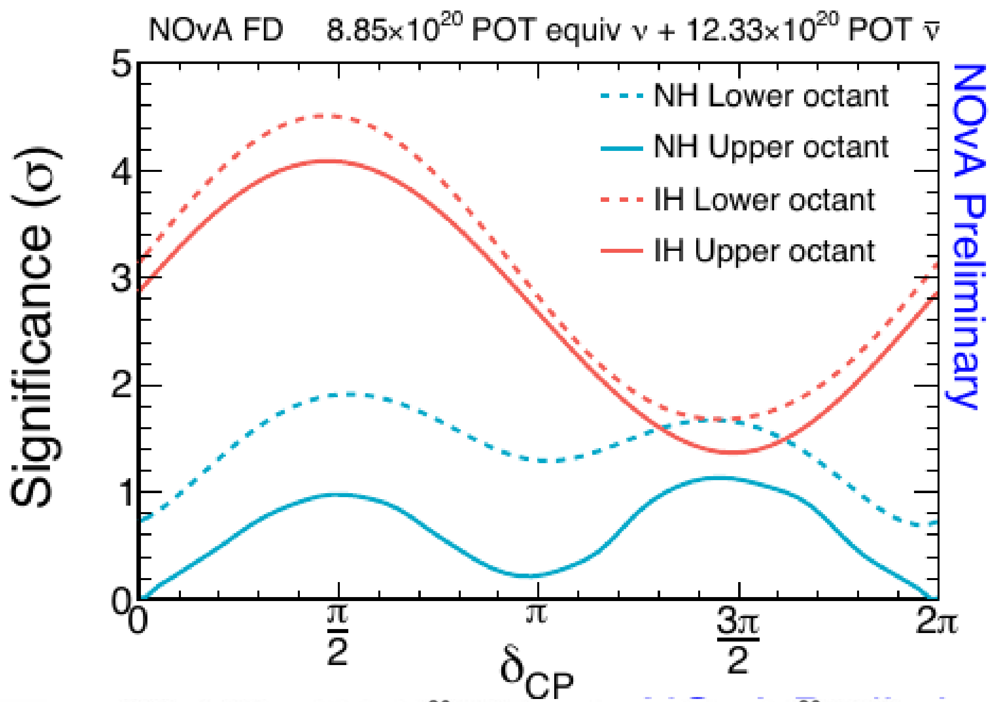




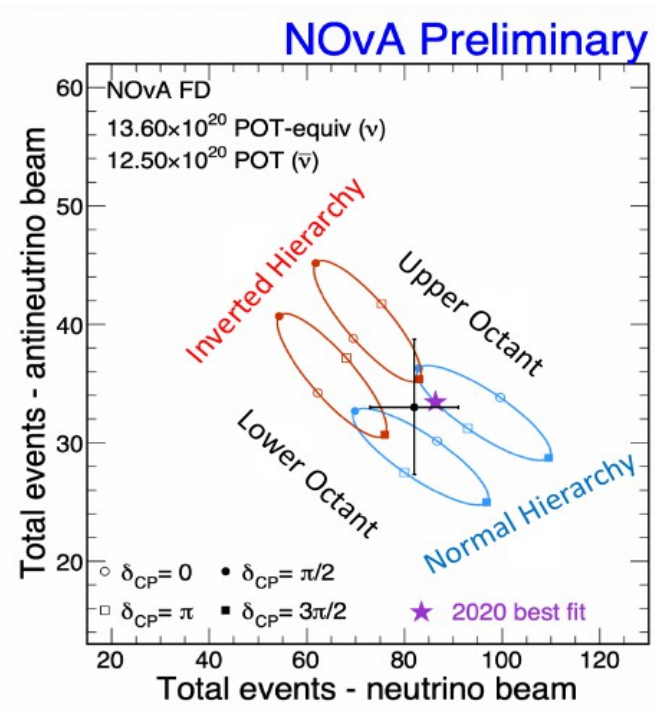
2019 → 2020: NOVA

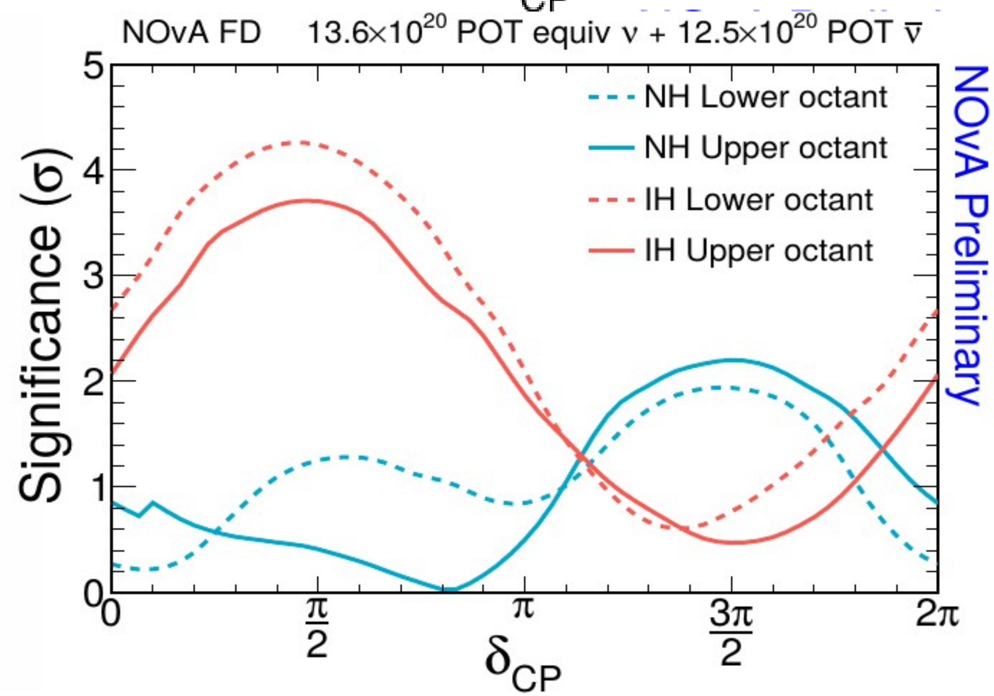
2019





2020





Oscillation formulas for ne/nebar appearance

Given an accelerator-driven neutrino beam, the long-baseline oscillation experiments are also sensitive to the neutrino mass ordering. Because of the interaction of neutrinos with terrestrial matter as they pass through the Earth, the probability of $\nu_\mu \to \nu_e$ oscillations can be approximately expressed as[59]

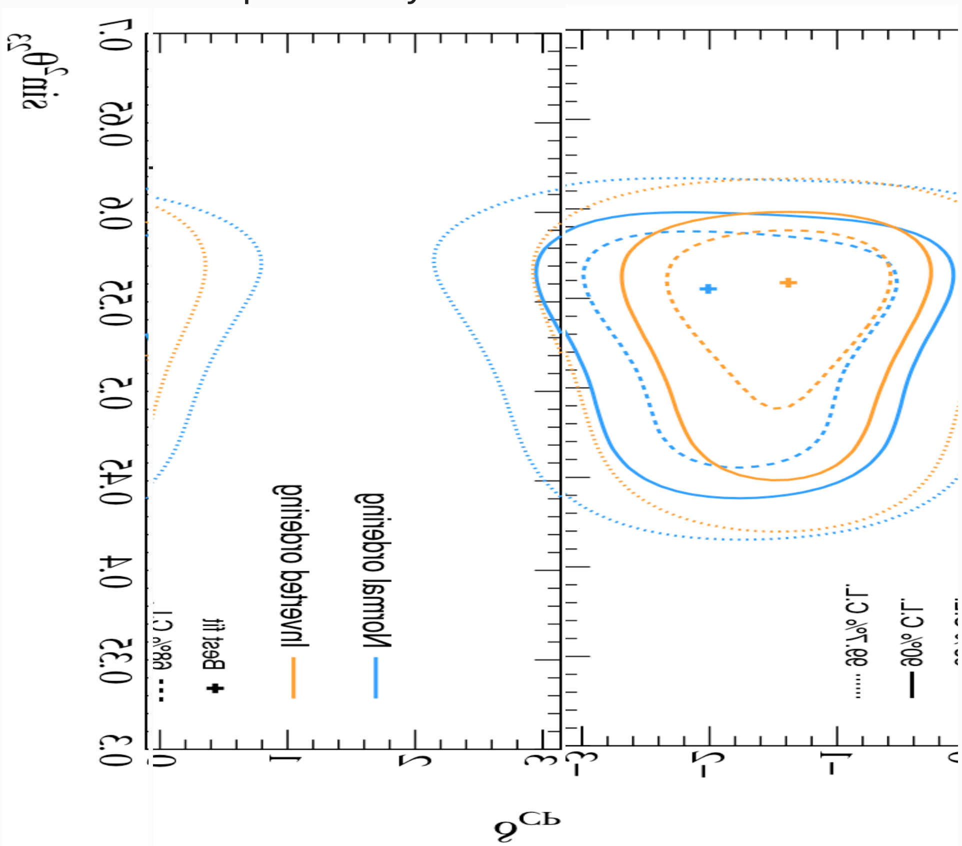
$$
\begin{aligned}
P(\nu_\mu \to \nu_e) \simeq \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2 (x-1)\Delta_{31}}{(x-1)^2} + \alpha \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \\
\times \cos(\Delta_{31} + \delta) \frac{\sin x\Delta_{31} \sin (x-1)\Delta_{31}}{x(x-1)} \\
+\alpha^2 \sin^2 2\theta_{12} \cos^2 \theta_{23} \frac{\sin^2 x\Delta_{31}}{x^2} \ ,
\end{aligned}
\tag{7}
$$

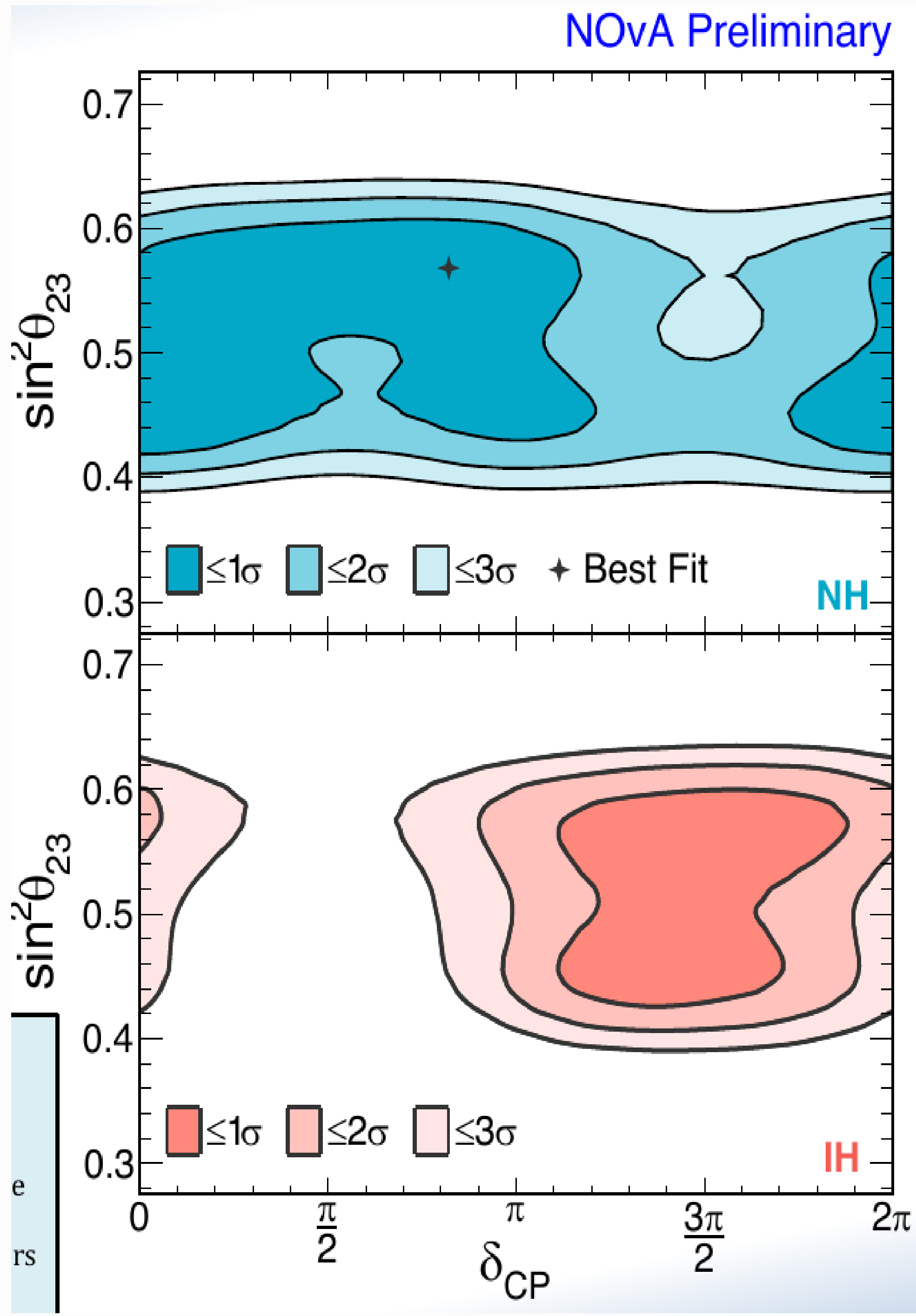
where $x \equiv 2\sqrt{2} G_{\rm F} N_e E / \Delta m^2_{31}$ and $\alpha \equiv \Delta m^2_{21} / \Delta m^2_{31}$. One may easily obtain the expression of $P(\overline{\nu}_\mu \to \overline{\nu}_e)$ from Eq. (7) with the replacements $\delta \to -\delta$ and $x \to -x$. So the sign of Δm^2_{31} affects the behaviors of neutrino oscillations via the signs of x and α. That is why the matter-induced resonant conversion can only occur for neutrinos in the normal mass hierarchy ($x > 0$) or for antineutrinos in the inverted mass hierarchy ($x < 0$), similar to the case of atmospheric neutrino or antineutrino

$$
\mathcal{A}_{\rm CP} \equiv \frac{P(\nu_\mu \to \nu_e) - P(\overline{\nu}_\mu \to \overline{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\overline{\nu}_\mu \to \overline{\nu}_e)} \simeq -\frac{\sin 2\theta_{12} \sin\delta}{\sin\theta_{13} \tan\theta_{23}} \Delta_{21} + \text{matter effects} \ ,
$$

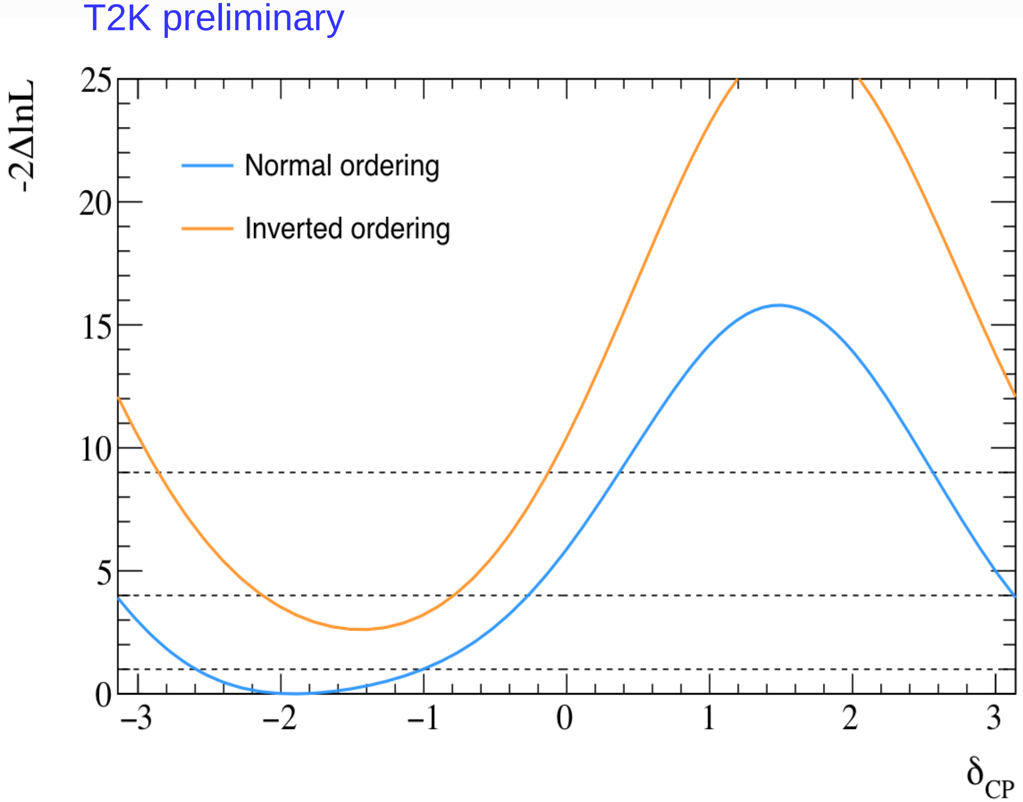
Results

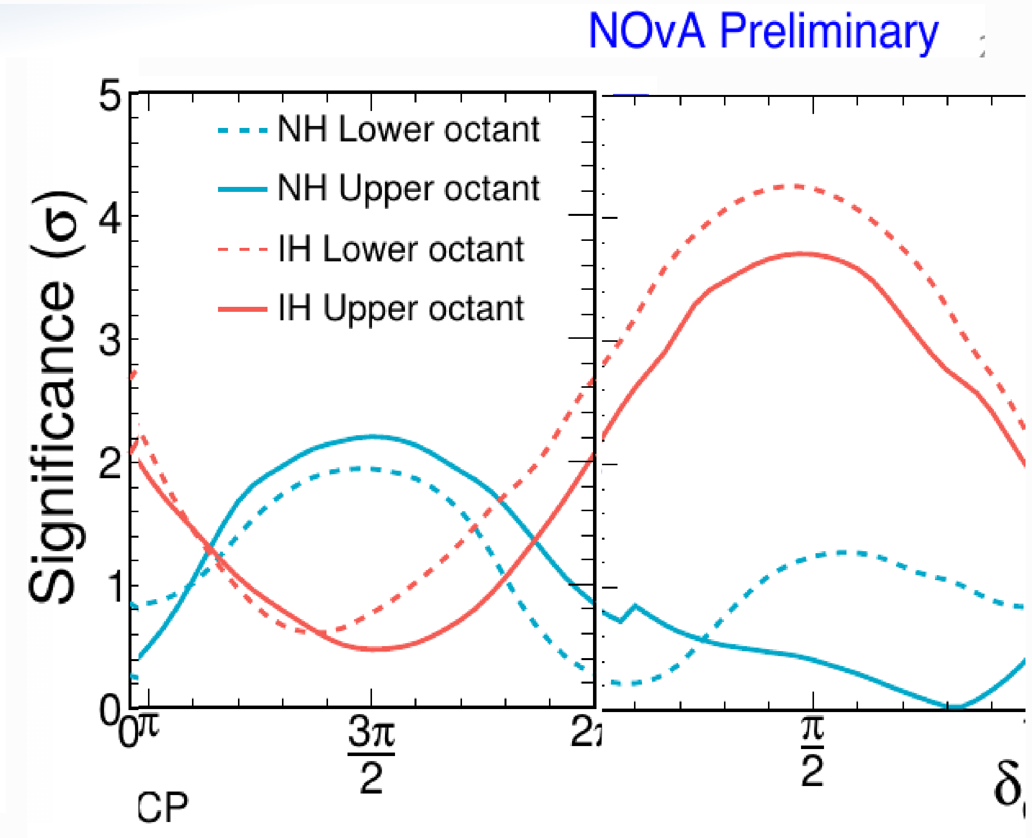
T2K preliminary



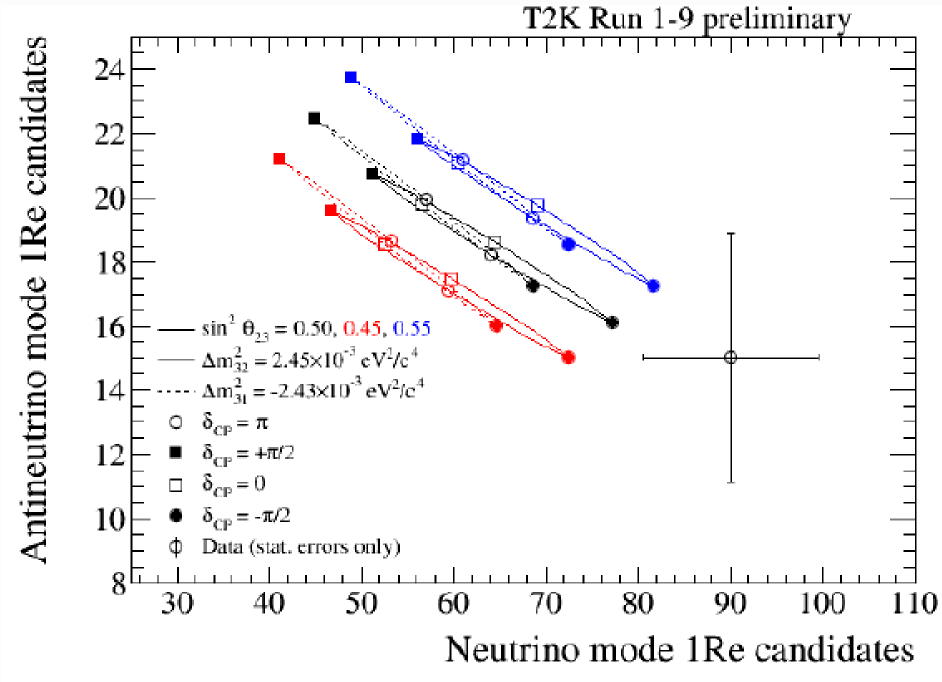


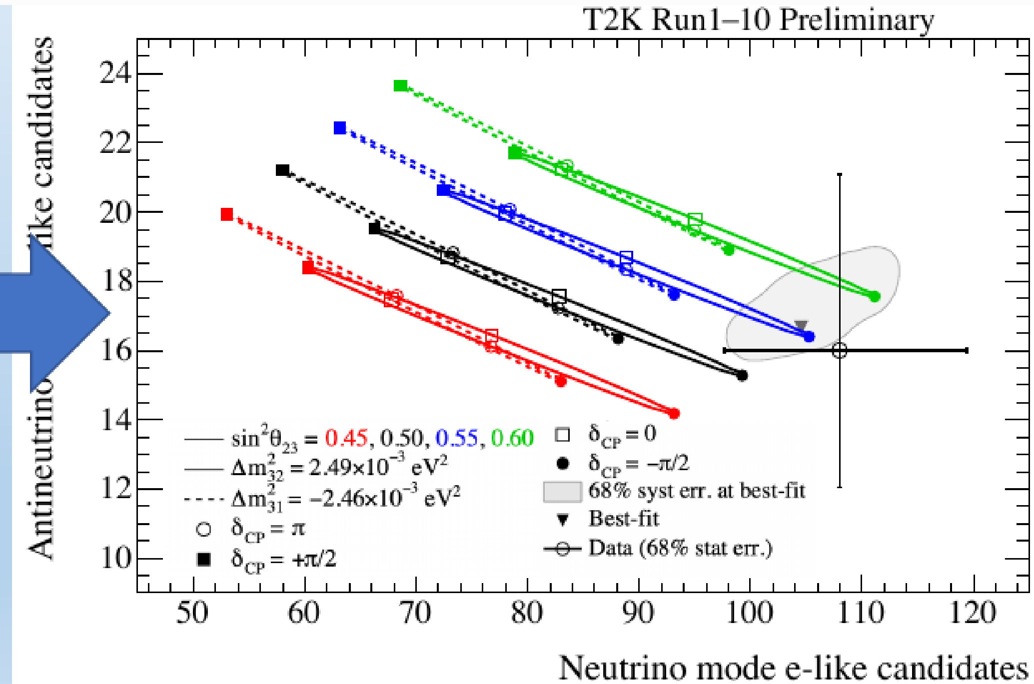
Results

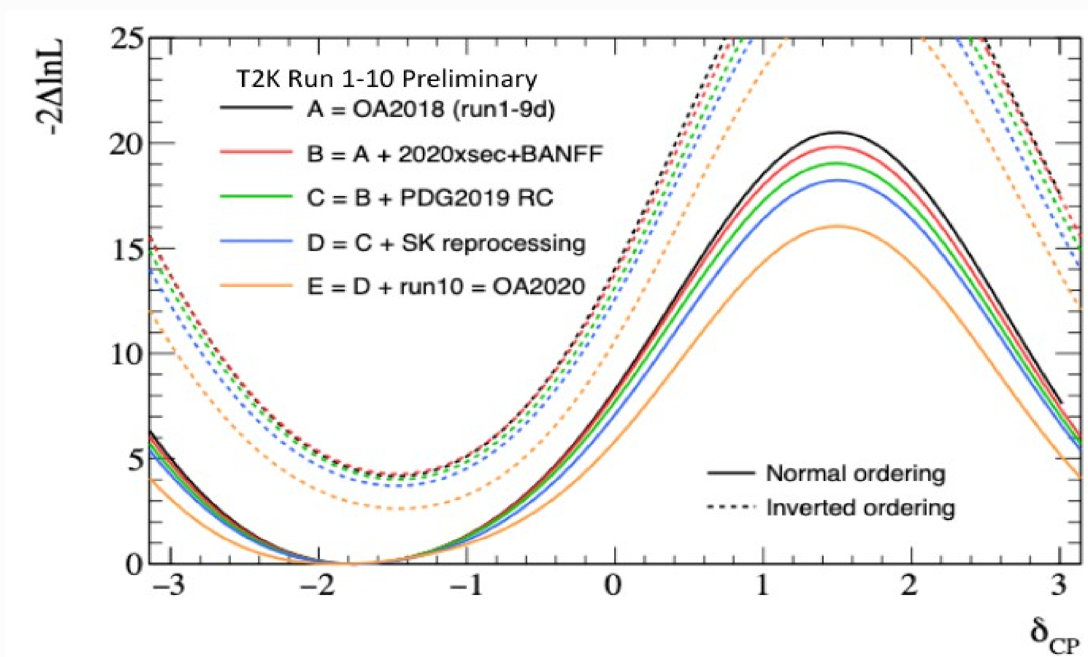

T2K preliminary
-2ΔlnL
Normal ordering
Inverted ordering
δ_{CP}


NOvA Preliminary
Significance (σ)
NH Lower octant
NH Upper octant
IH Lower octant
IH Upper octant

2019 → 2020: T2K

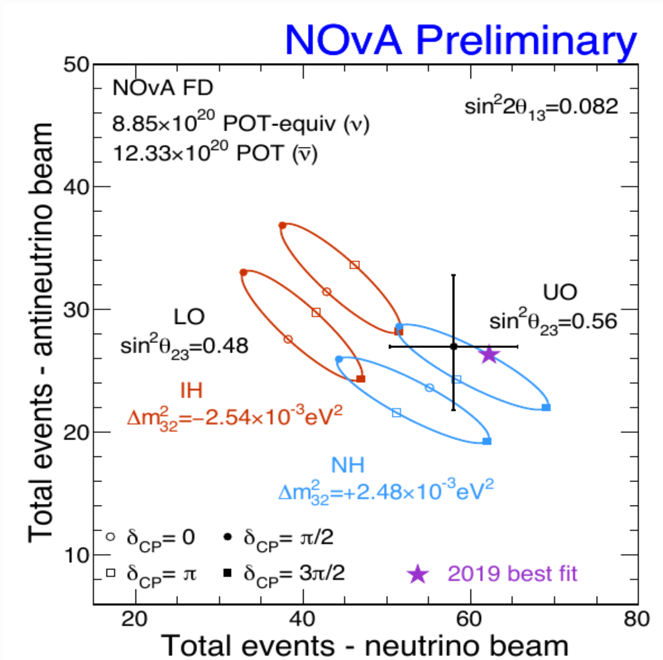


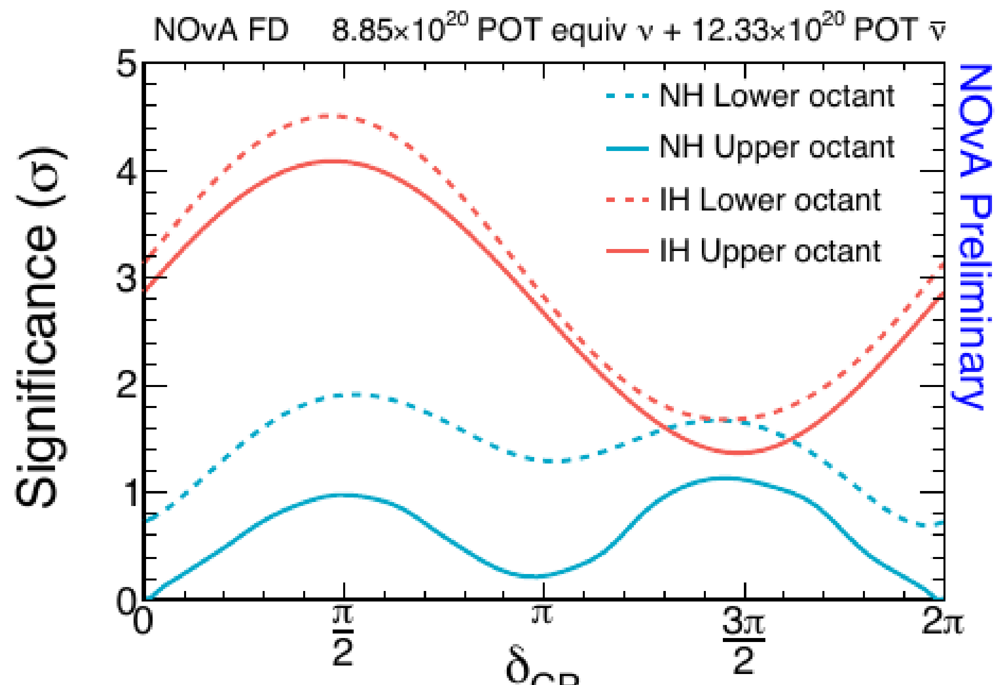




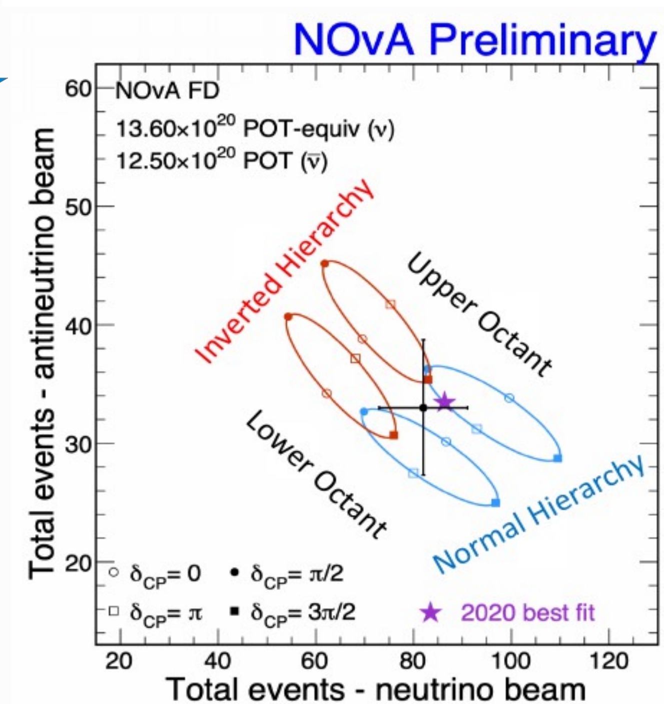
2019 → 2020: NOVA

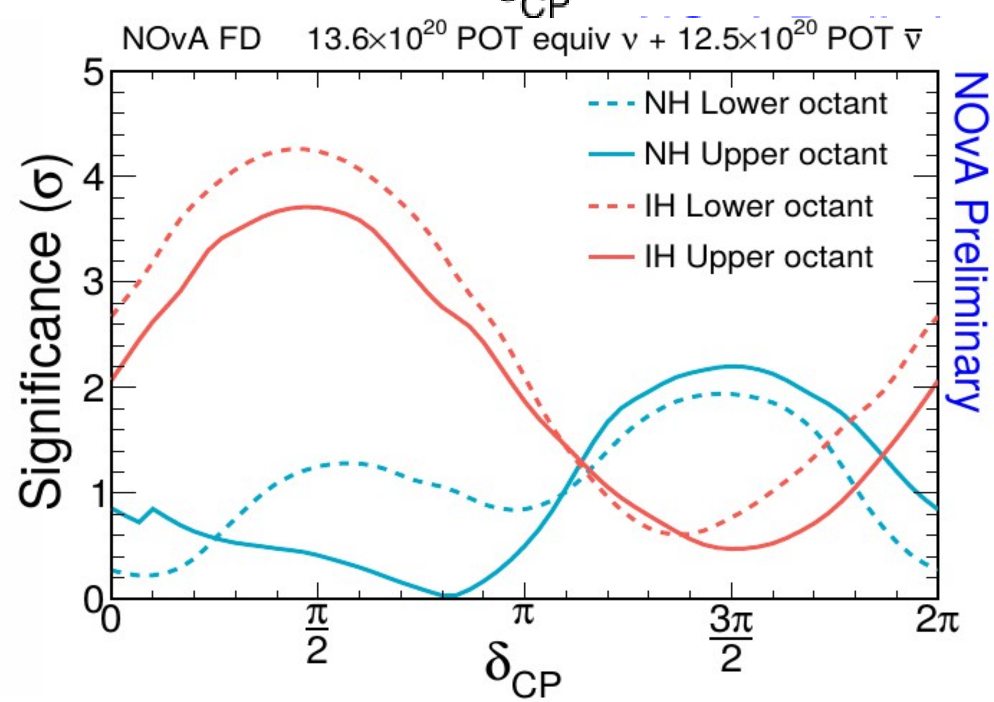
2019





2020

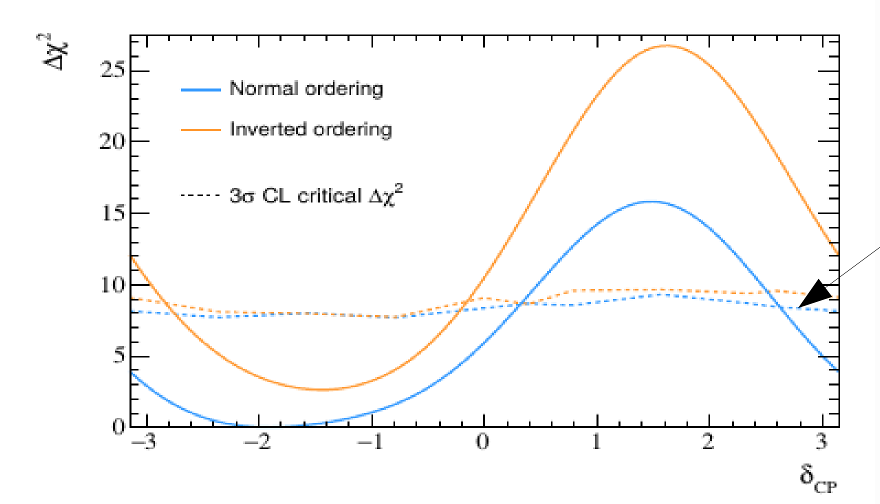




Statistical treatment: Fieldman Cousin

Treatment of 'nuisances' = parameters in the fit which are profiled or marginalized (e.g. θ_{23} and Δm^2 in plots of δ_{CP}, MH sensitivity)

When uncertainties are not Gaussian, you cannot simply calculate σ as units of $\delta\chi^2$ (i.e. the test-statistic has not χ^2 distribution → need to run toys over all the parameters)



For each values of true δ_{CP} → look which χ^2 corresponds to 68%, 95% ...

How to sample nuisances?
[In Bayesian terms: which prior on nuisances?]

- Near the δ_{CP} minimum, obviuos way to sample the nuisances: from data results

  Far from minimum is less obvious: eg, sample over nuisances distribution for Asimov at that true δ_{CP} value? (different in T2K and NOVA)

  Safe at 1σ but what about 2σ, 3σ, etc...? Studies on-going

- Effect become more important in case of degeneracies and boundary effects

- Important effect at 5σ: in practice the region of 5σ exclusion may change! Important for HK and DUNE!

T2K ND fit

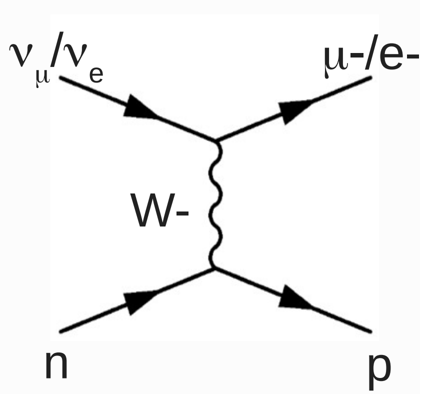
- **Near detector measurement**

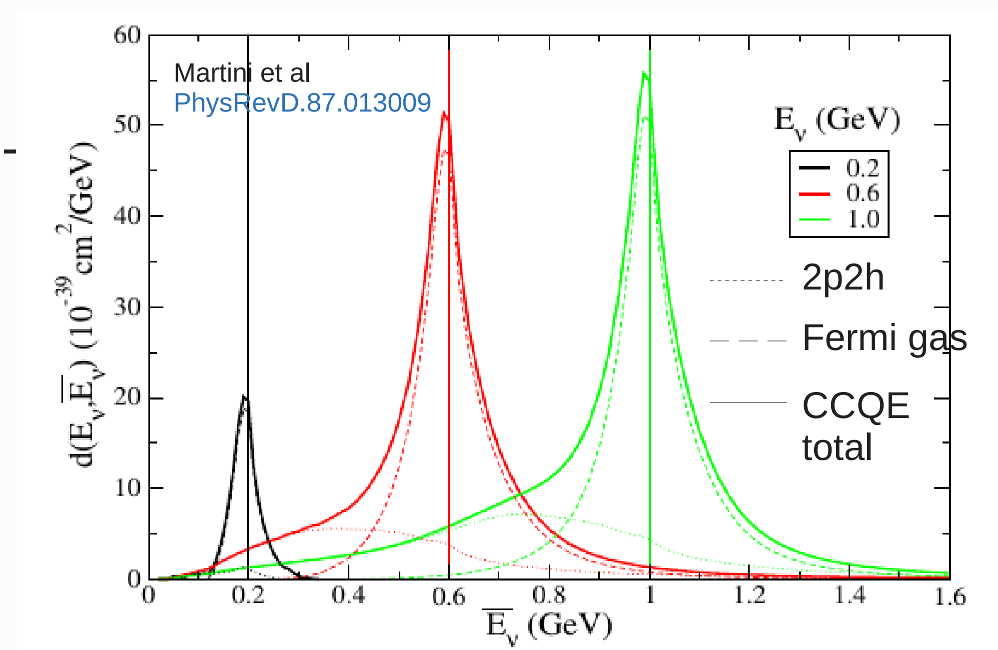
$$R^{\nu'}_{ND}(E_\nu)=\Phi^{\nu}(E_\nu)\frac{d\sigma^{\nu'}}{dE_\nu}=F(\boxed{p_\mu,\cos\theta_\mu};\alpha_{ND},\alpha_{model})$$

nuisances = parametrization of detector systematics and nuclear effects uncertainties

- **Reconstruction of energy at the far detector**

$$E_\nu=R(p_\mu,\cos\theta_\mu;\alpha_{FD},\alpha_{model})$$





- smearing due to nucleon motion in the nucleus

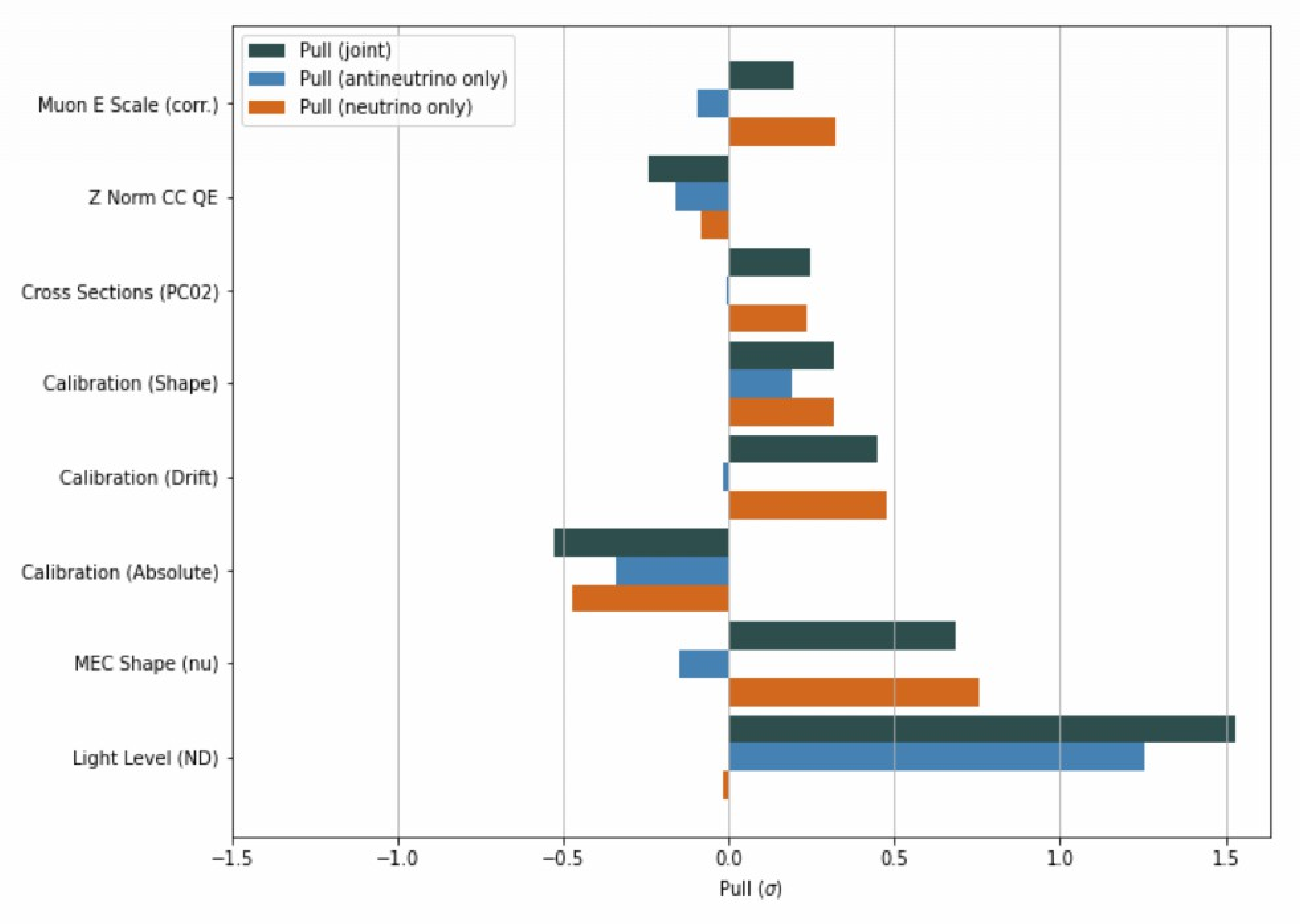
- bias due to energy to extract the nucleon from the nucleus

- tail due to 0π non-QE (eg. 2p2h)

separate uncertainties for nu and nubar constrained by ND

- Constrain on ν_e rate from ND ~8% . **ν_e / ν_μ xsec uncertainty from theory ~3%**

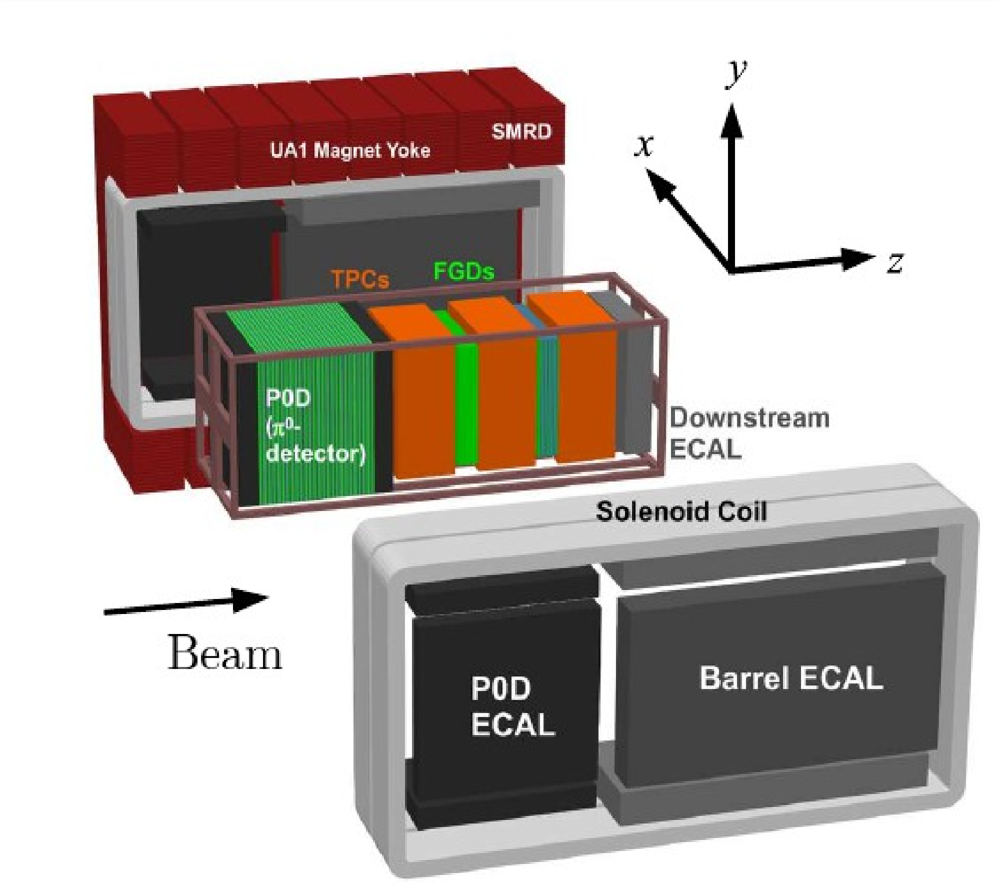
Systematic pulls from NOVA FD fit

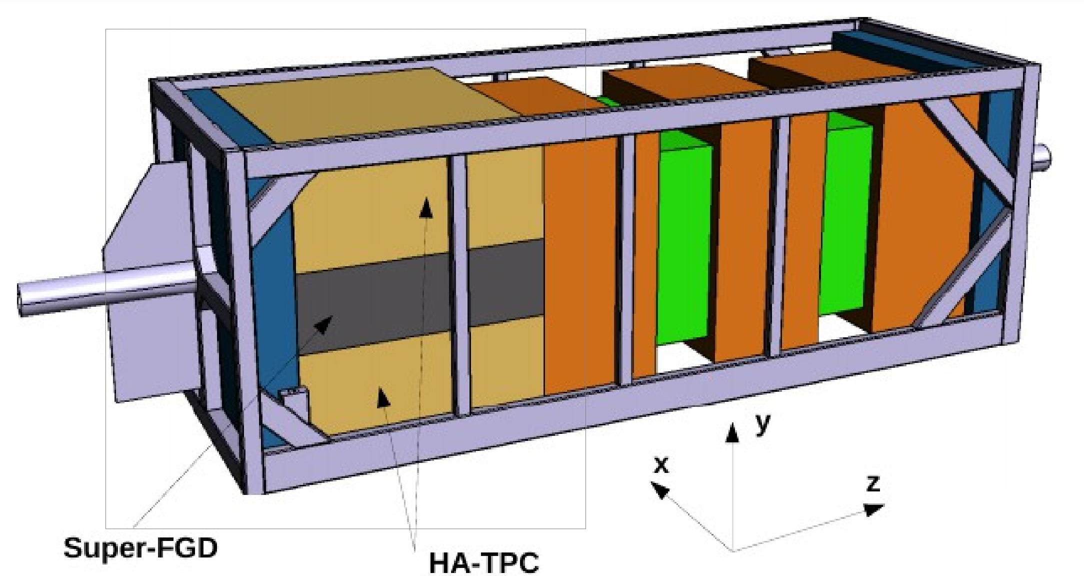


Systematics for T2K FD samples

Error source (units: %)	$1R\mu$ FHC	$1R\mu$ RHC	$1Re$ FHC	$1Re$ RHC	$1Re$ FHC $CC1\pi^+$	$1Re$ FHC/RHC
Flux	2.9	2.8	2.8	2.9	2.8	1.4
Xsec (ND constr)	3.1	3.0	3.2	3.1	4.2	1.5
Flux+Xsec (ND constr)	2.1	2.3	2.0	2.3	4.1	1.7
Xsec (ND unconstrained)	0.6	2.5	3.0	3.6	2.8	3.8
SK+SI+PN	2.1	1.9	3.1	3.9	13.4	1.2
Total	3.0	4.0	4.7	5.9	14.3	4.3

ND280 (left) → ND280 upgrade (right)





+Time of Flight modules all around the new tracker

Vertical TPCs: instrumented with Standard Bulk Micromegas.
Running with astonishing stability and reliability since 11 years

New HA-TPC: to increase acceptance at high angle (→ lower momentum particles)
Required same performances (momentum resolution and PID) as “old” vertical TPCs