Long baseline neutrino experiments

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Standard Model and Beyond

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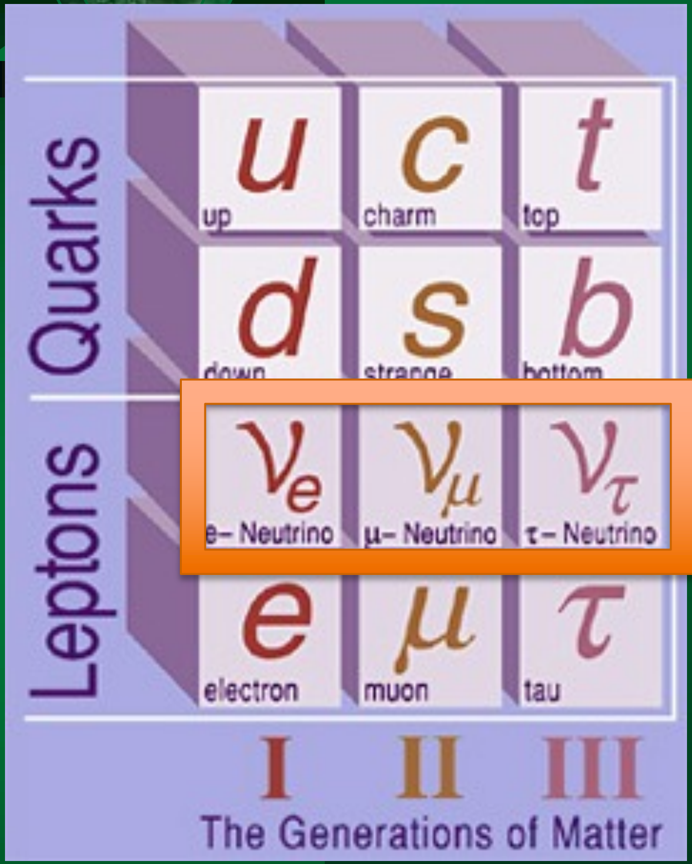
Building blocks in Standard Model



Neutrino?

- mass < 10^{-6} of the electron mass
- electric charge = 0
- difficalt to detect → participate only in weak interactions
- They can be Dirac or Majorana particles

Important role in the Standard Model

- form dublets with charged leptons
- neutrino flavour defined by lepton which participate in interaction via W exchange

As we know (from 1998) neutrinos oscillate

$\mathcal{O}(1)$

2 flavor-like oscillations

20 years ago

↓

Non-zero neutrino mass and mixing

Physics beyond Standard Model

Oscillation – sign of difference in velocity in mass states propagation

From sources to detectors (and in between)

→Neutrinos have non zero mass

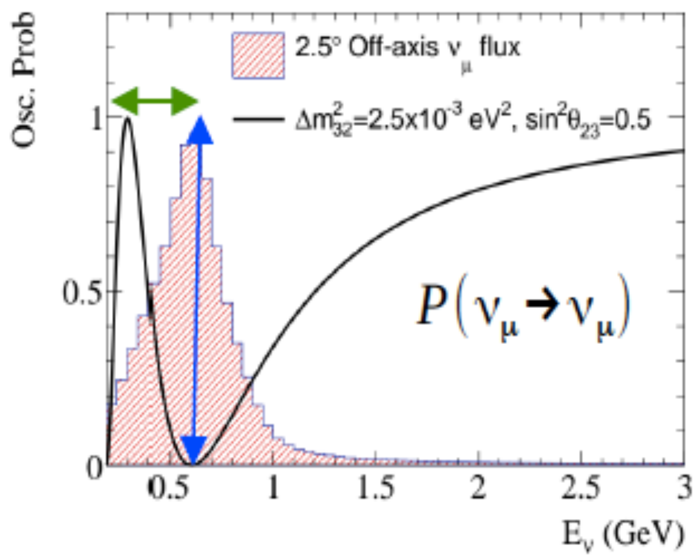
→ the only exception (failure) of the Standard Model

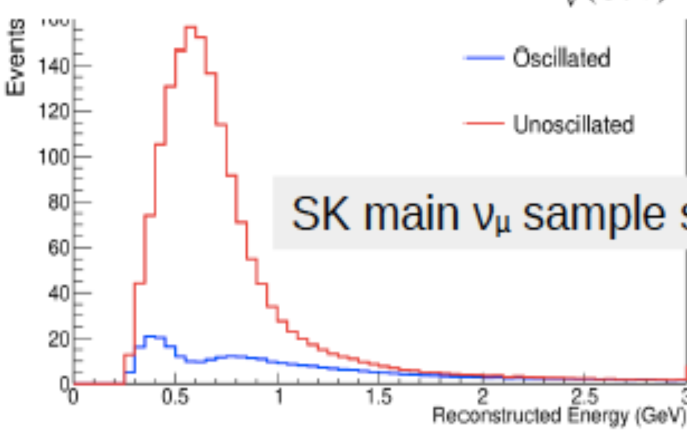
THE window to New Physics

Sensitivity to PMNS param.

disappearance

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





SK main ν_μ sample spectra

appearance

$$P(\nu_\mu \to \nu_e) \approx \sin^2(\theta_{23})\sin^2(2\theta_{13})\sin^2\left(1.27\frac{\Delta m^2 L}{E}\right)$$

if this is not zero we have 1-3 mixing

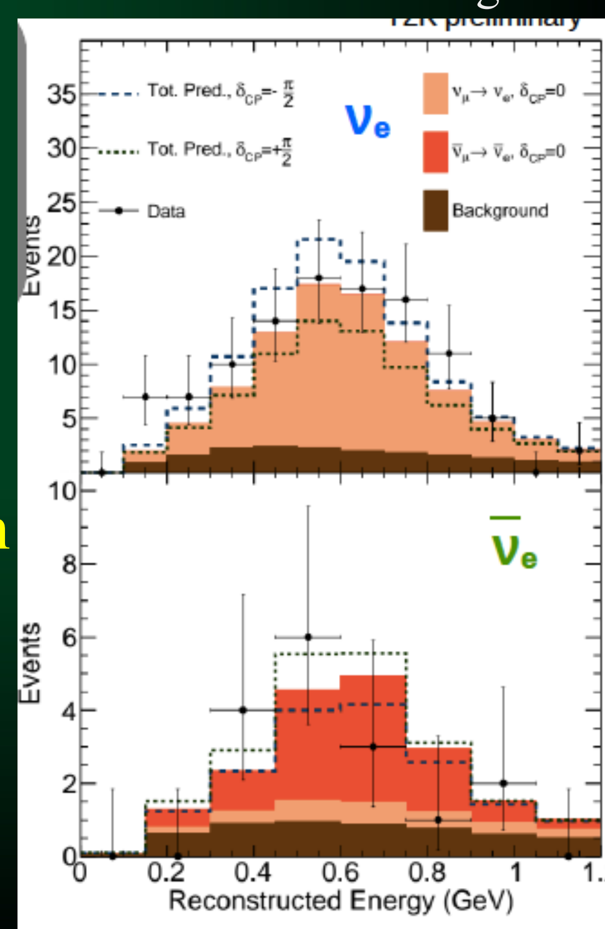
and

can

measure

CP

violation



Three-Flavour Neutrino Oscillations – picture as of today

FLAVOR **PMNS mixing matrix** **MASS**

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

„atmospheric”
SK, K2K, T2K, MINOS Nova

$\theta_{23} \sim 50°$
$|\Delta m_{32}^2| \sim 2.5\text{x}10^{-3}\ eV^2$

CHOOZ, DayaBay, Reno, DblChooz, T2K, Nova

$\theta_{13} \sim 8°$

„solar”
SNO, KamLand, SK, Borexino

$\theta_{12} \sim 34°$
$\Delta m_{12}^2 \sim 7.5\text{x}10^{-5}\ eV^2$

mixing angles,
squared mass differences,
CP violation phase
- fundamental parameters of nature

parameter θ_{13} non zero
→ sensitivity to CP phase

* $\Delta m^2_{ji} = m_j^2 - m_i^2$
Two free parameters for the three Δm^2's.
($\Delta m^2_{31} = \Delta m^2_{21} + \Delta m^2_{32}$)

Very different structure of mixing for quarks and leptons

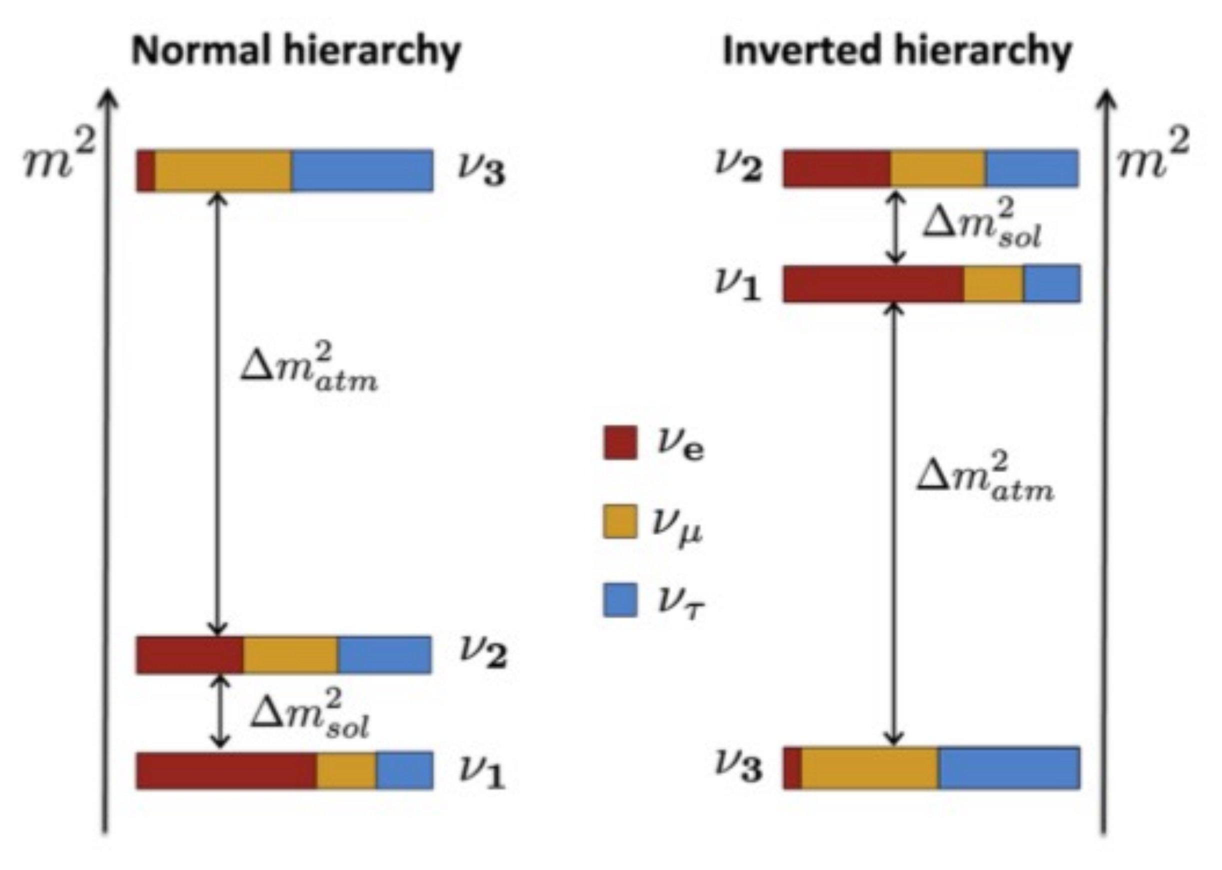
Mixing of leptons–Pontecorvo-Maki-Nakagawa-Sakata

$$\begin{bmatrix} |U_{e1}| & |U_{e2}| & |U_{e3}| \\ |U_{\mu1}| & |U_{\mu2}| & |U_{\mu3}| \\ |U_{\tau1}| & |U_{\tau2}| & |U_{\tau3}| \end{bmatrix} = \begin{bmatrix} 0.801-0.845 & 0.513-0.579 & 0.143-0.156 \\ 0.233-0.507 & 0.461-0.694 & 0.631-0.778 \\ 0.261-0.526 & 0.471-0.701 & 0.611-0.761 \end{bmatrix}$$

Mixing for quarks – Cabibo-Kobayashi-Maskawa

$$\begin{bmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tv}| \end{bmatrix} = \begin{bmatrix} 0.9740 & 0.2265 & 0.0036 \\ 0.2264 & 0.9732 & 0.0405 \\ 0.0085 & 0.0398 & 0.9992 \end{bmatrix}$$

Mass Ordering



- Normal (NH) or inverted (IH) hierarchy??
- What is the mass of lightest neutrino?

→ Hints from cosmology

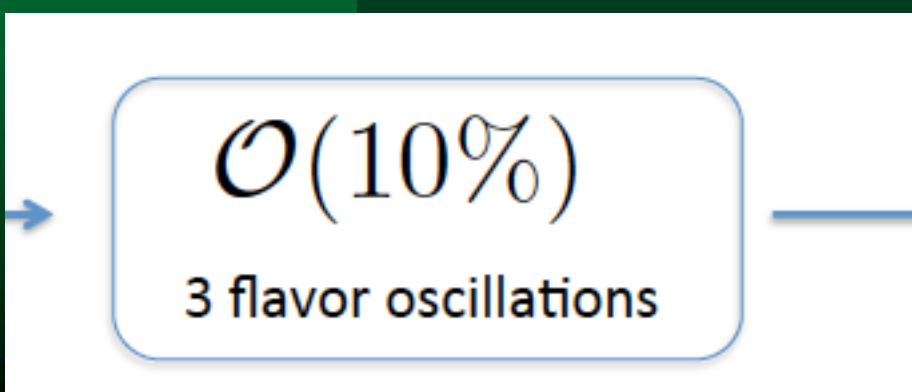
Possible answer on ordering from INO, IceCube-PINGU, KM3Net-ORCA

Combined fits to several Experiments with differnet MSW sensitivity

BIG QUESTIONS

- What is the origin of neutrino mass?
- What is the nature of the neutrino?
- Is there a theory of flavor?
- Why are lepton and quark mixings so different?
- Neutrino in cosmology, relation to baryon asymmetry, dark matter, …

Present situation – spacific questions (LBL):



- Precise oscillation parameters
- CP violation in the lepton sector? (measure phase)
- What is the mass ordering?
- precise parameters of mixing, octant for 2-3 angle

Oscillation results with present data (T2K and Nova)

Experiments currently taking data

here results presented at NEUTRINO 2022

and published reasently

Improved constraints on neutrino mixing from the T2K experiment with 3.13×10^{21} protons on target

T2K Collaboration • K. Abe (Kamioka Observ.) Show All(310)

Published in: *Phys.Rev.D* 103 (2021) 11, 112008

PHYSICAL REVIEW D **106,** 032004 (2022)

Featured in Physics

Improved measurement of neutrino oscillation parameters by the NOvA experiment

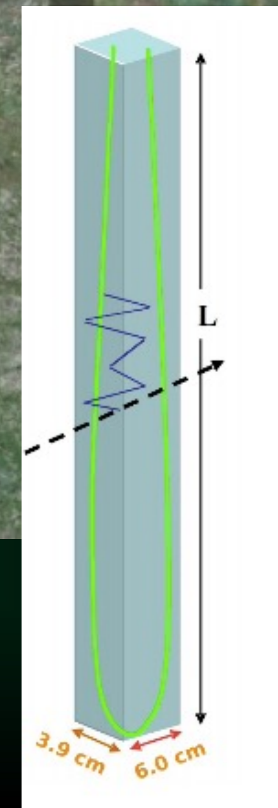
Actors on the scene: T2K

Tokai
To
Kamioka

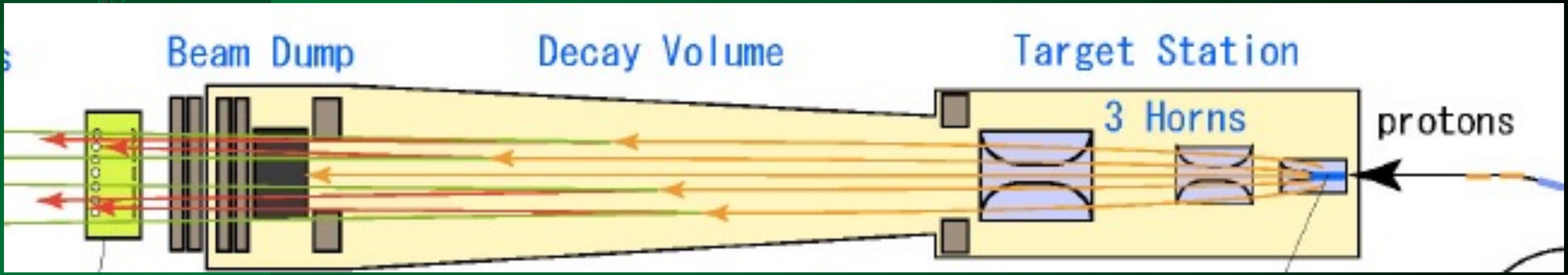
- Baseline – 300km → small matter effects
- Energy for first oscillation maximum below 1 GeV
- Far detector material - water

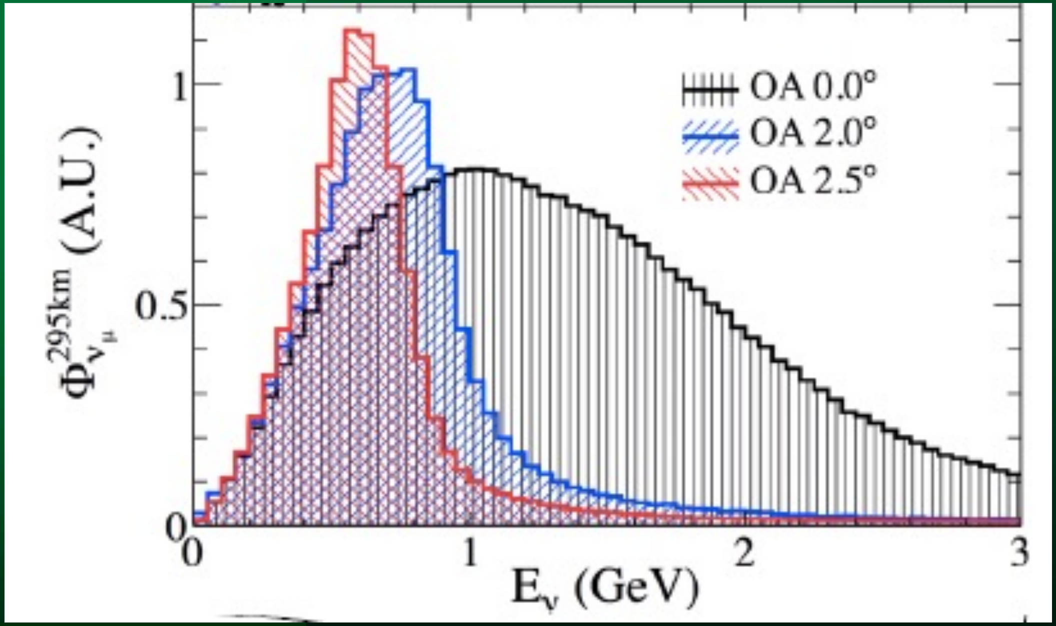
NOVA

- Mass effects important
- Higher beam energy peak around 2GeV
- Two detectors, same construction
  - → Tracking calorometers
  - → Plastic cels with liquid scintilator



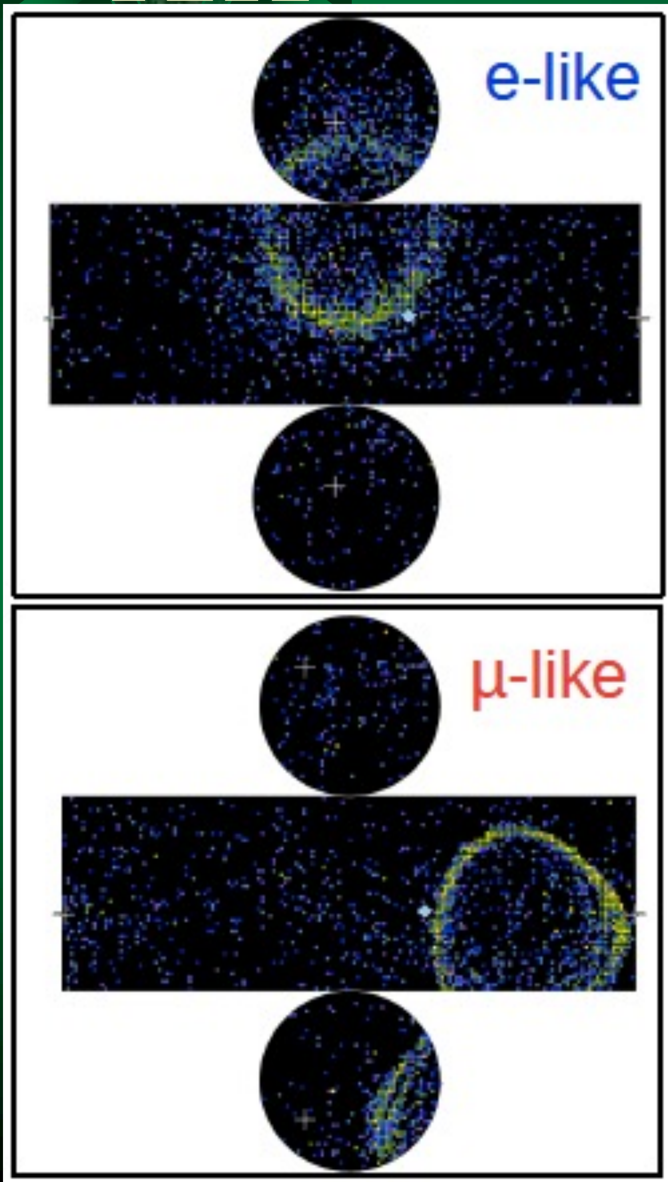
Both experiments use off axis beam from π and K decays



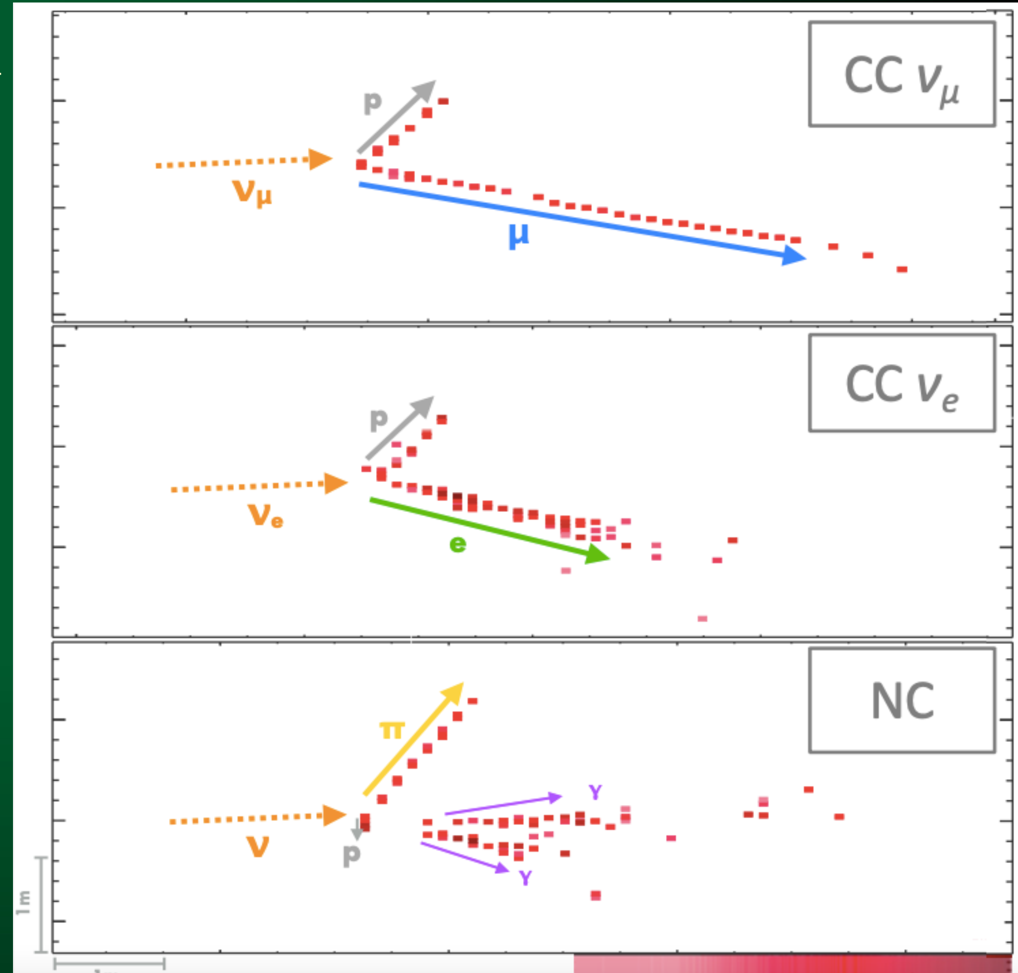


- Narrow beam
- Smaller high energy tail
- Almost pure ν_μ

T2K



NOνA



- Electrons and muons can be distinguished
- Neutrino Energy determination
- NC is a background for oscillation as we do not know ν flavour

What we measure?

Neutrino interaction → particles in the detector

→ charged lepton defines neutrino flavour

→ final state particles help to estimate energy

ND – high statistics of ν interactions

No oscillation

Measurement = (*flux* × *interaction*) ⊕ detector effects

FD - observe events after oscillation

Flux is modified by oscillation probability

Oscillation parameters fitting

What is fitted?

→ Simple answer: mixing matrix angles + Δm^2

$$N_{pred}(E_\nu^{reco}) = \Phi(E_\nu^{true})\,\sigma(E_\nu^{true})\,P(\alpha\rightarrow\beta, E_\nu^{true})\,\epsilon(E_\nu^{true})\,S(E_\nu^{true}, E_\nu^{reco})$$

$N_{pred}(E_\nu^{reco})$ = Expected number of events

$\Phi(E_\nu^{true})$ = Neutrino flux

$\sigma(E_\nu^{true})$ = Interaction cross sections

$P(\alpha\rightarrow\beta, E_\nu^{true})$ = Oscillation probability

$\epsilon(E_\nu^{true})$ = Selection efficiency

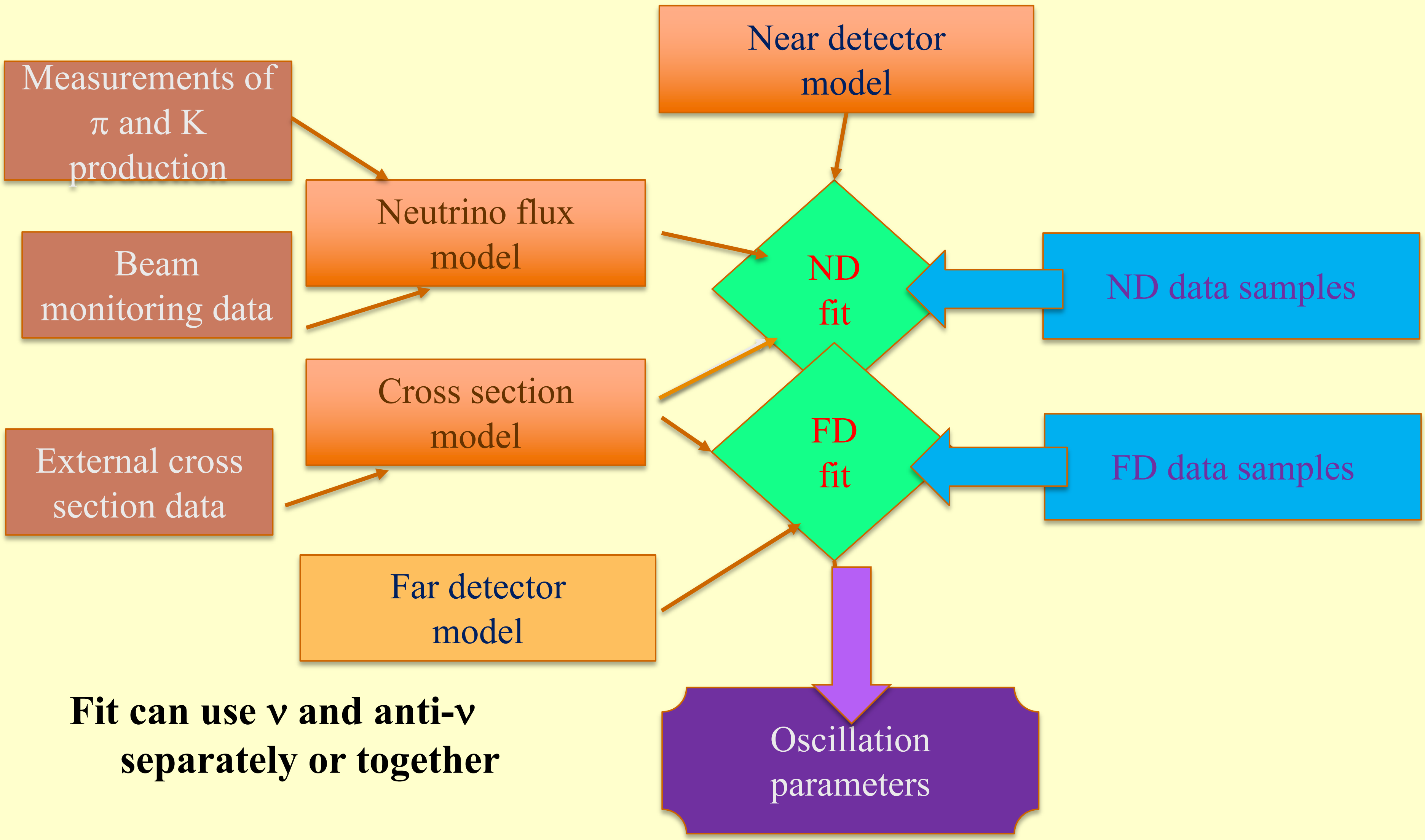
$S(E_\nu^{true}, E_\nu^{reco})$ = Smearing matrix

Compare numer of events observed and predicted can be done as a function of kinematic variables

Change PMNS parameters to find best agreement

In practice – more complicated as flux and cross sections not precisely known and controlled by near detector ….

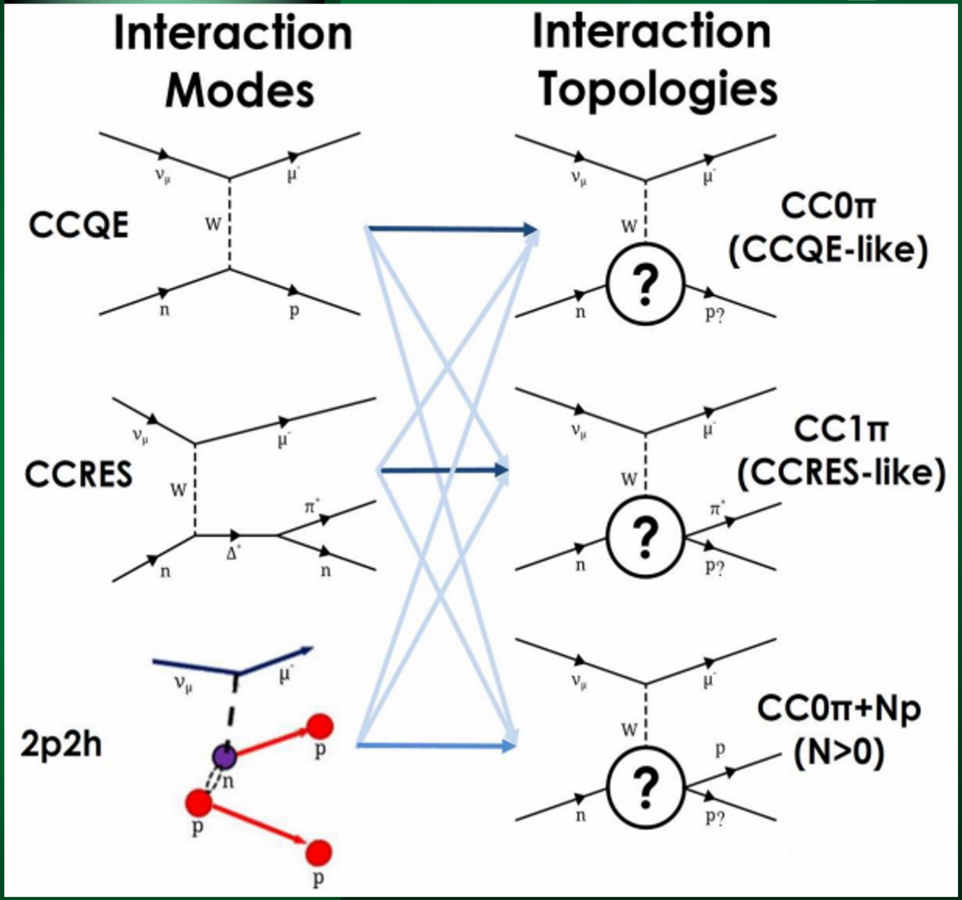
What goes into oscillation fit?



Fit can use ν and anti-ν separately or together

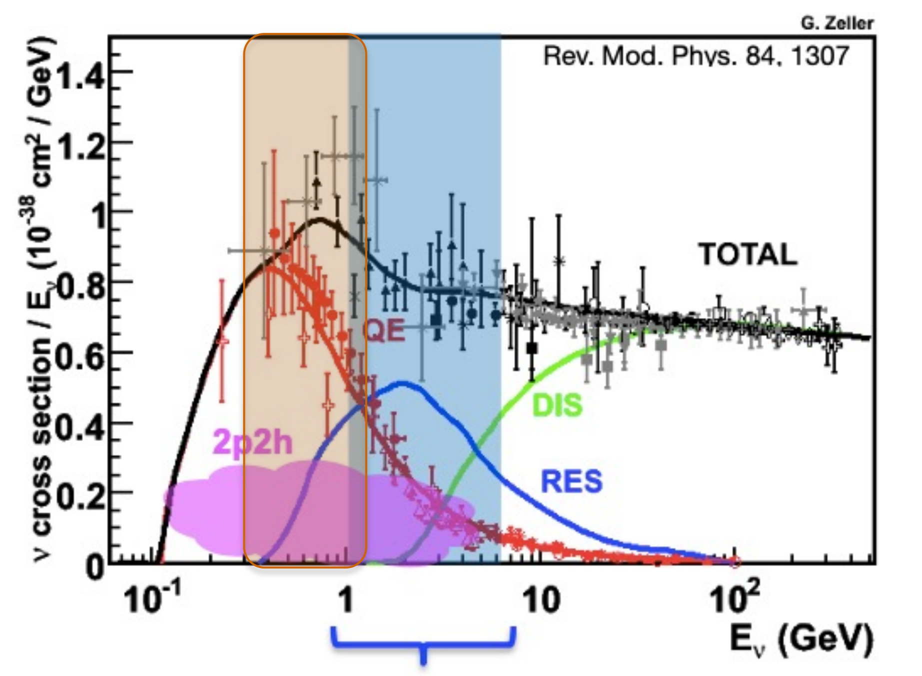
ND fit improves knowledge on flux and cross sections → can be done separately or together with FD fit

How cross section knowledge can be improved?

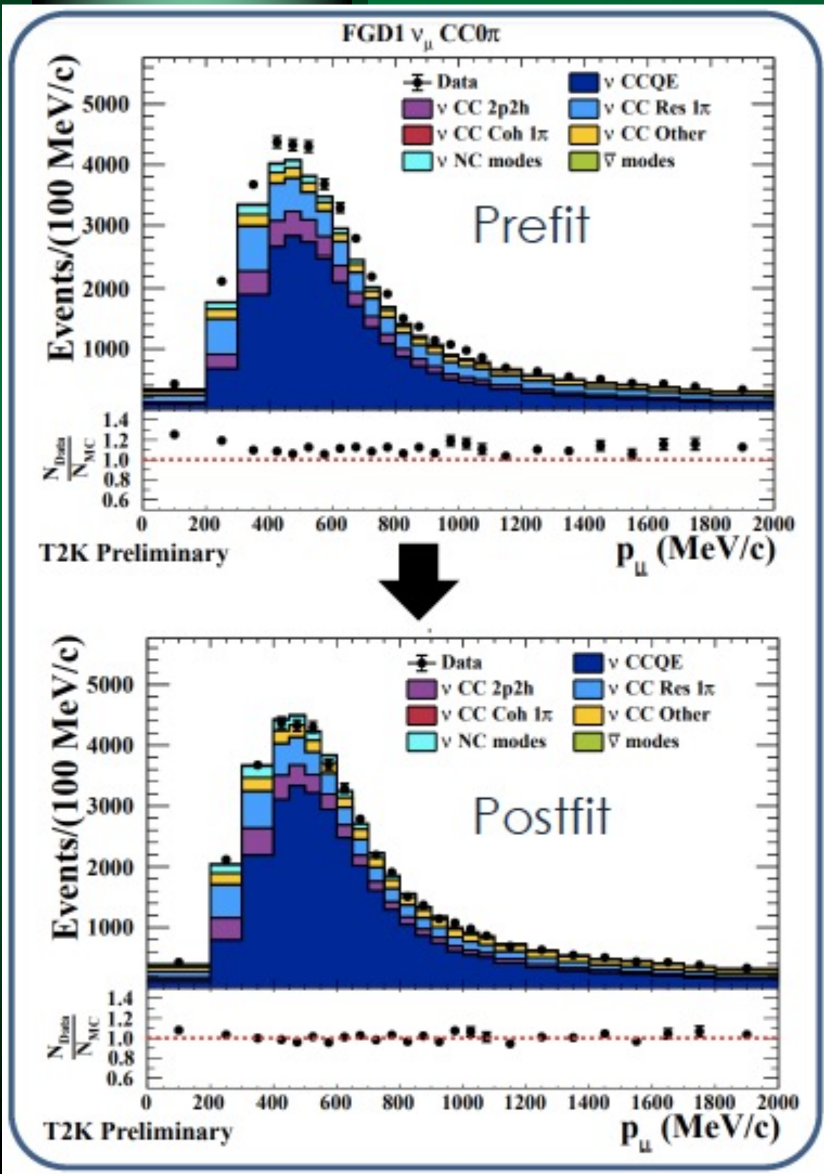


- Measured in near detector
- Parametrize models
- Allow change of processes contributions

→ fit to improve agreement



Examles of ND fit results

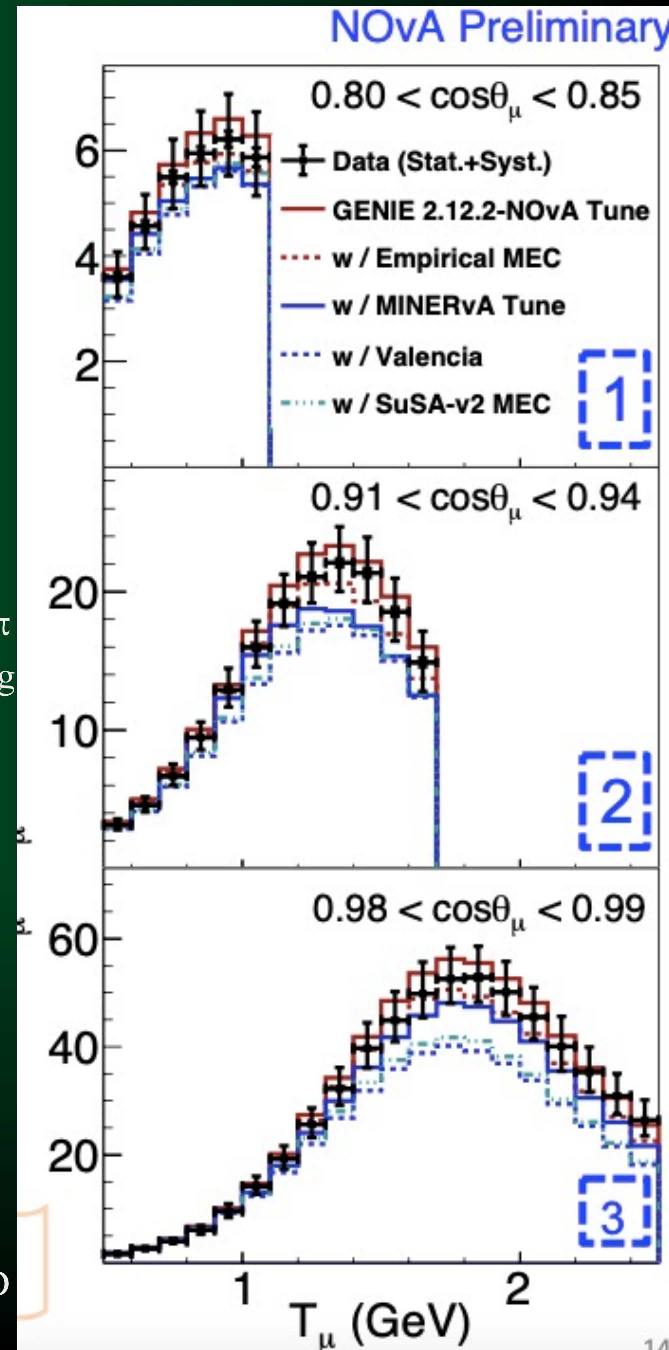


Improved data/MC
by tuning model param.
or contributions from
processes
for example:
2p2h contribution to CC0π
treatment of Pauli blocking
Fermi motion of nucleons
nucleon bounding Energy
…….

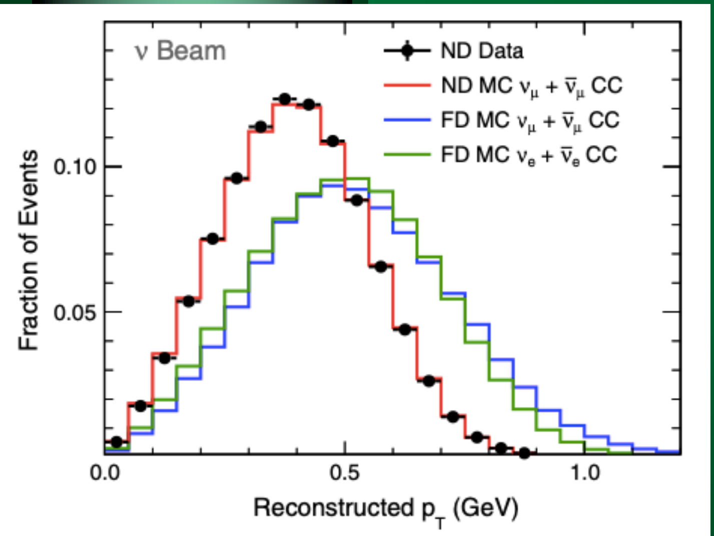
Two approaches:

Separate fit for ND and
Modification in s used in
Oscillation fit

Single fit using ND and FD
data together



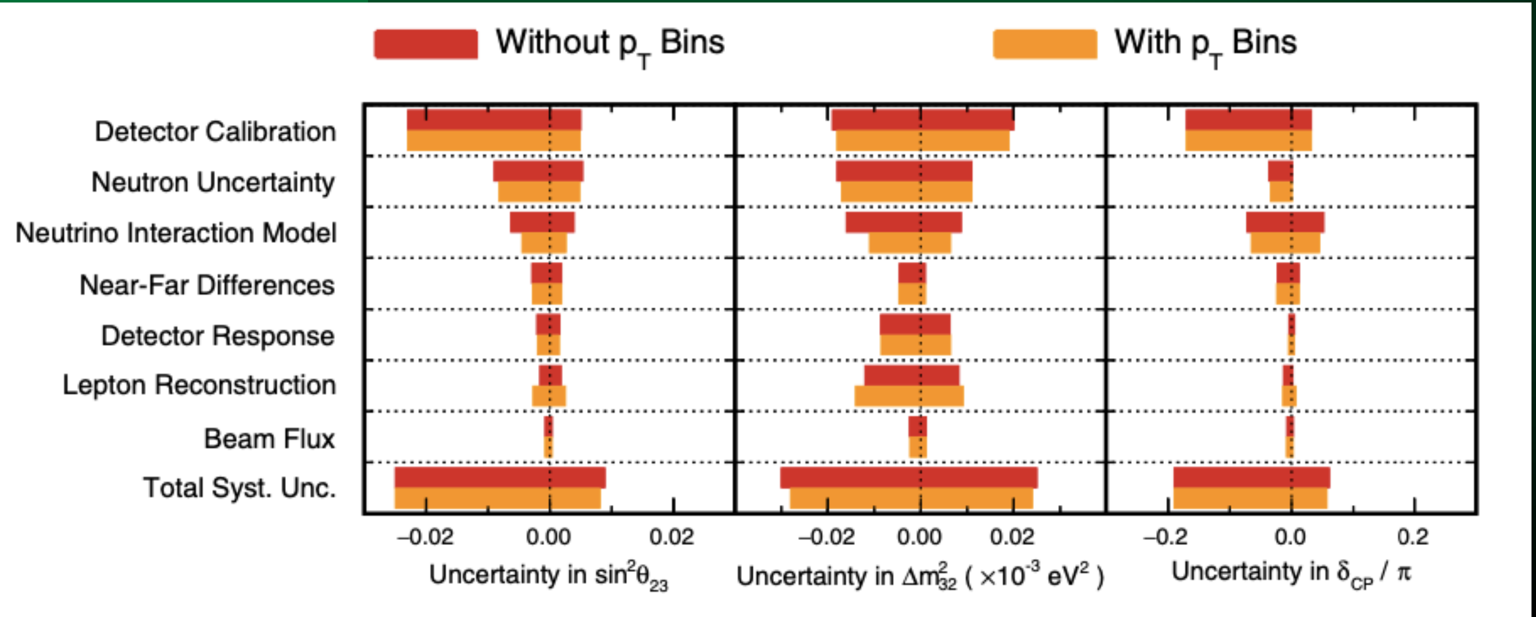
Biases reduction and checks



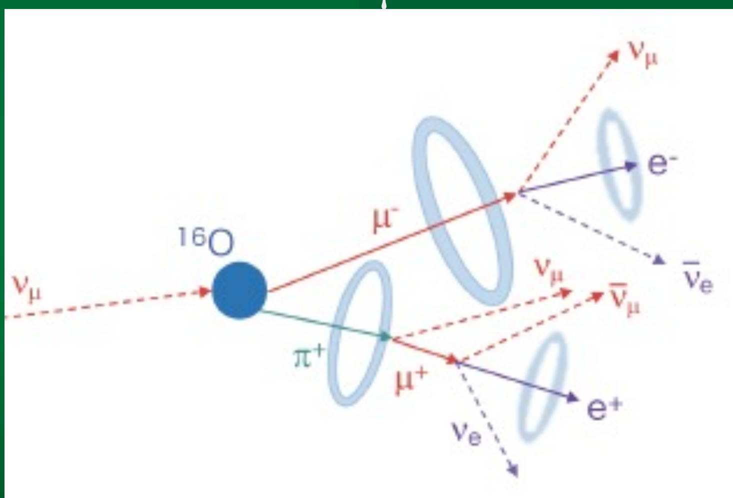
for flux prediction - NOνA

As example – difference in pT distribution at ND and FD

For check – use binning in pT

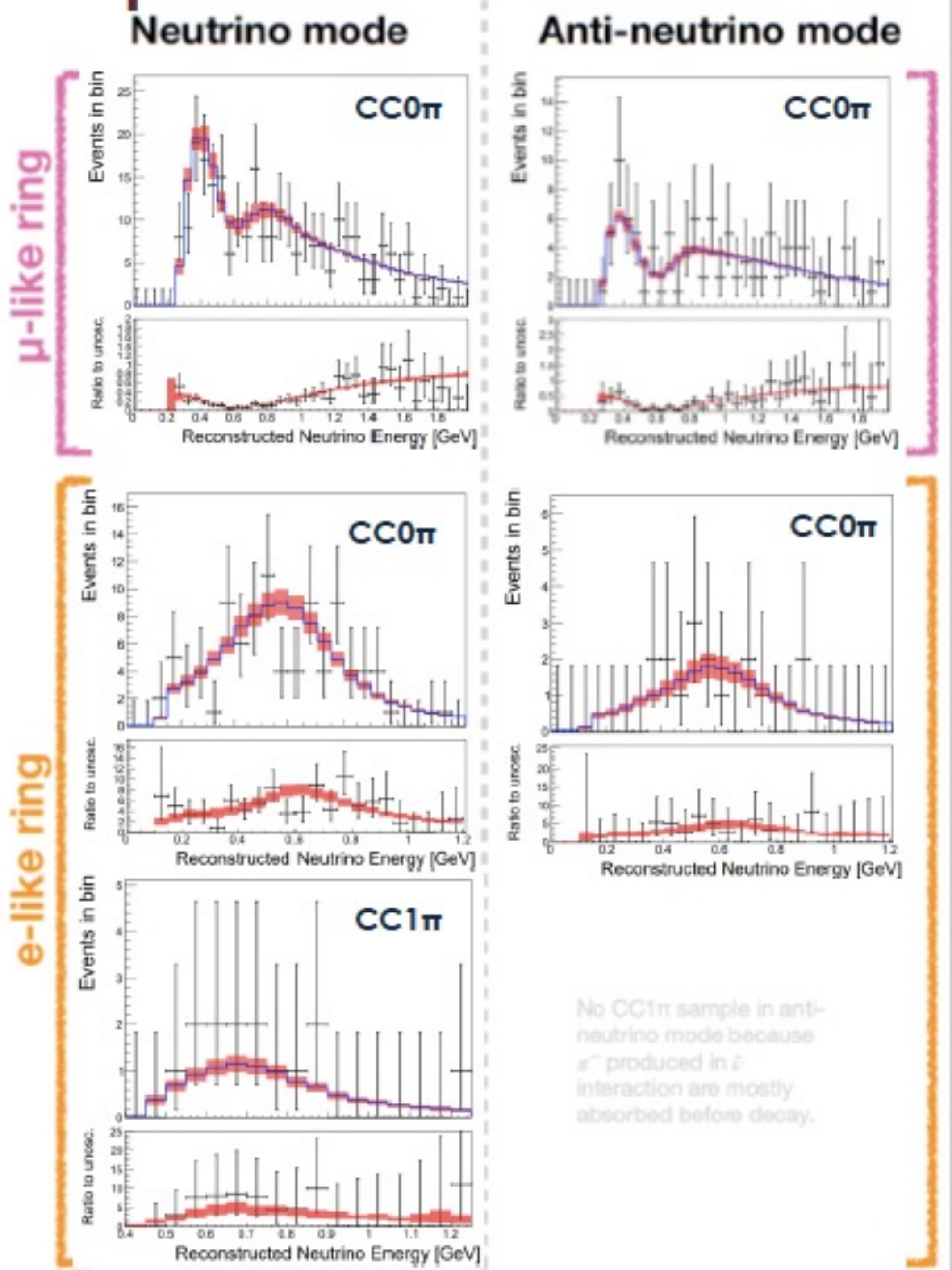


T2K – samples used (FD) and first time ν_μ CC $1\pi^+$



Fit together neutrinos and anti-neutrinos

3 analysis



T2K - fitted parameters

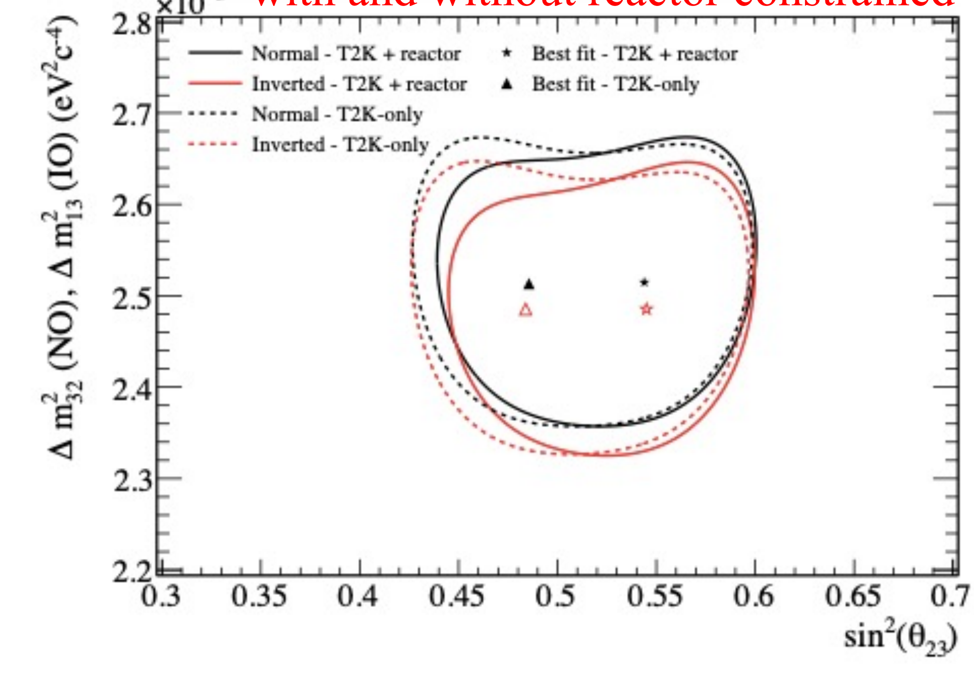
Parameter	Best-fit and 1σ interval NO	IO
δ_{CP}	$-1.89^{+0.70}_{-0.58}$	$-1.38^{+0.48}_{-0.55}$
$\sin^2\theta_{23}$	$0.532^{+0.030}_{-0.037}$	$0.532^{+0.029}_{-0.035}$
Δm^2_{32} $/10^{-3}\mathrm{eV}^2c^{-4}$	$2.45^{+0.07}_{-0.07}$	
$\mid\Delta m^2_{13}\mid$ $/10^{-3}\mathrm{eV}^2c^{-4}$		$2.43^{+0.07}_{-0.07}$

From paper – data until 2018 pot 3.13×10^{21}

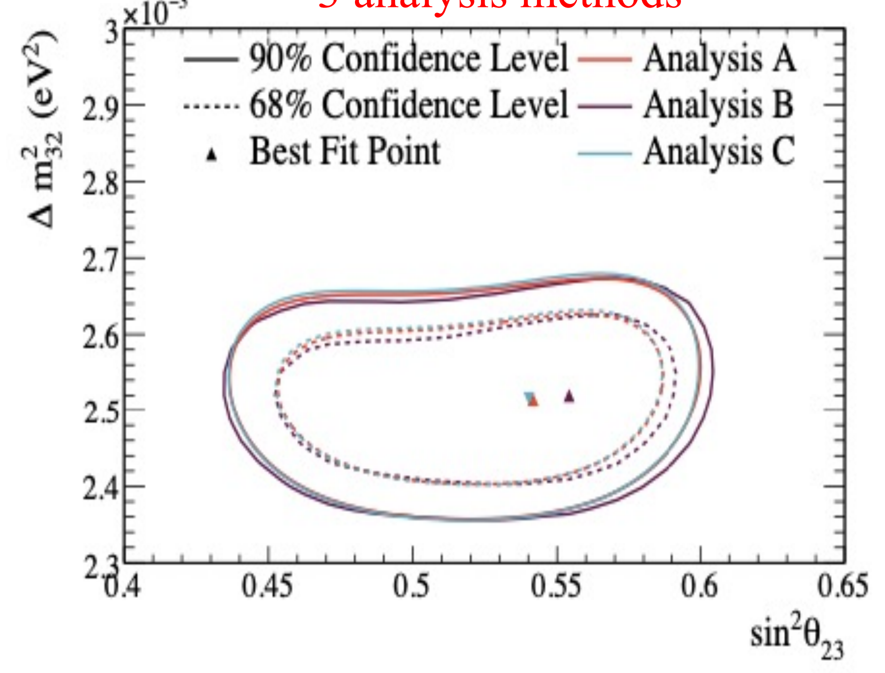
Neutrino and anti-neutrino beam settings

Best fit results:

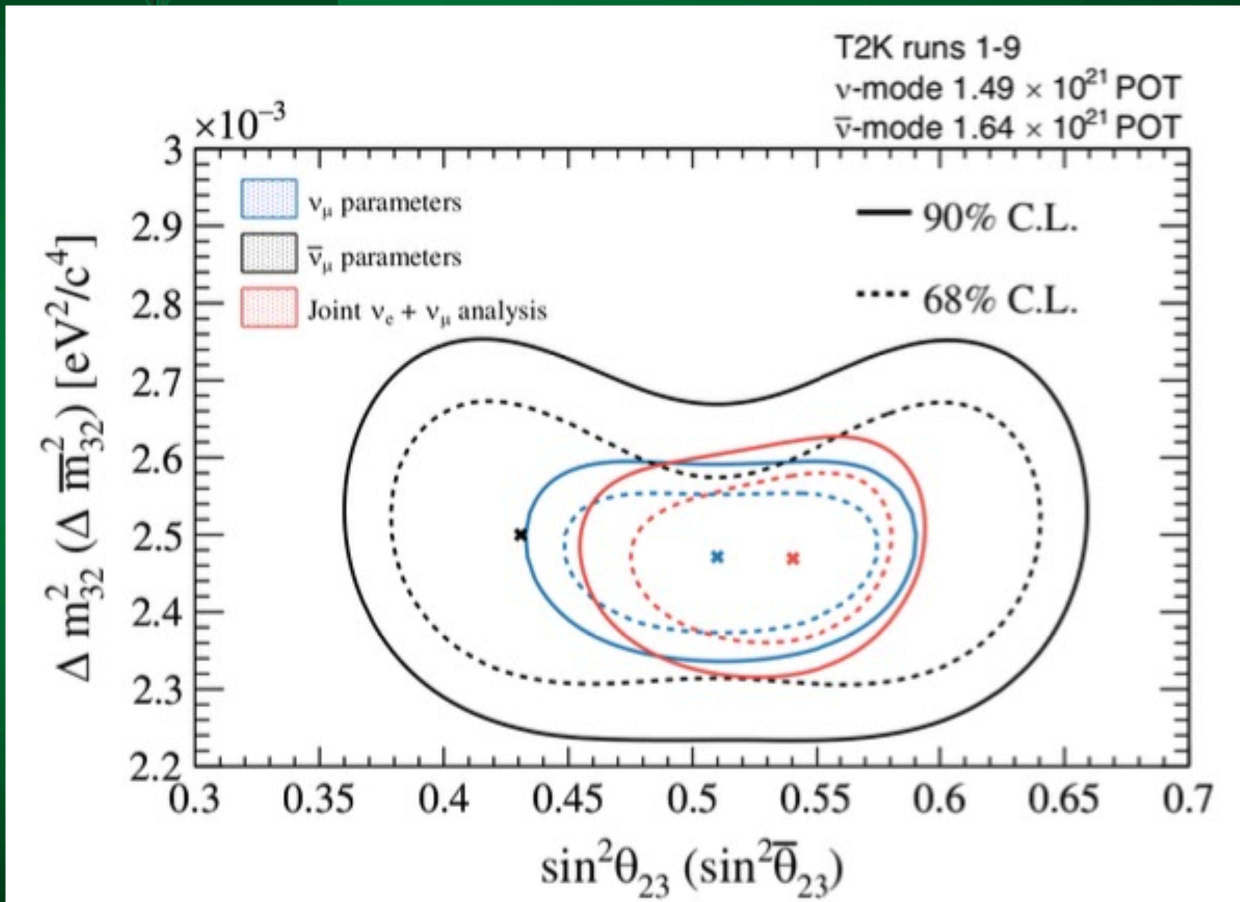
with and without reactor constrained



3 analysis methods



Separate fits for ν and $\bar{\nu}$

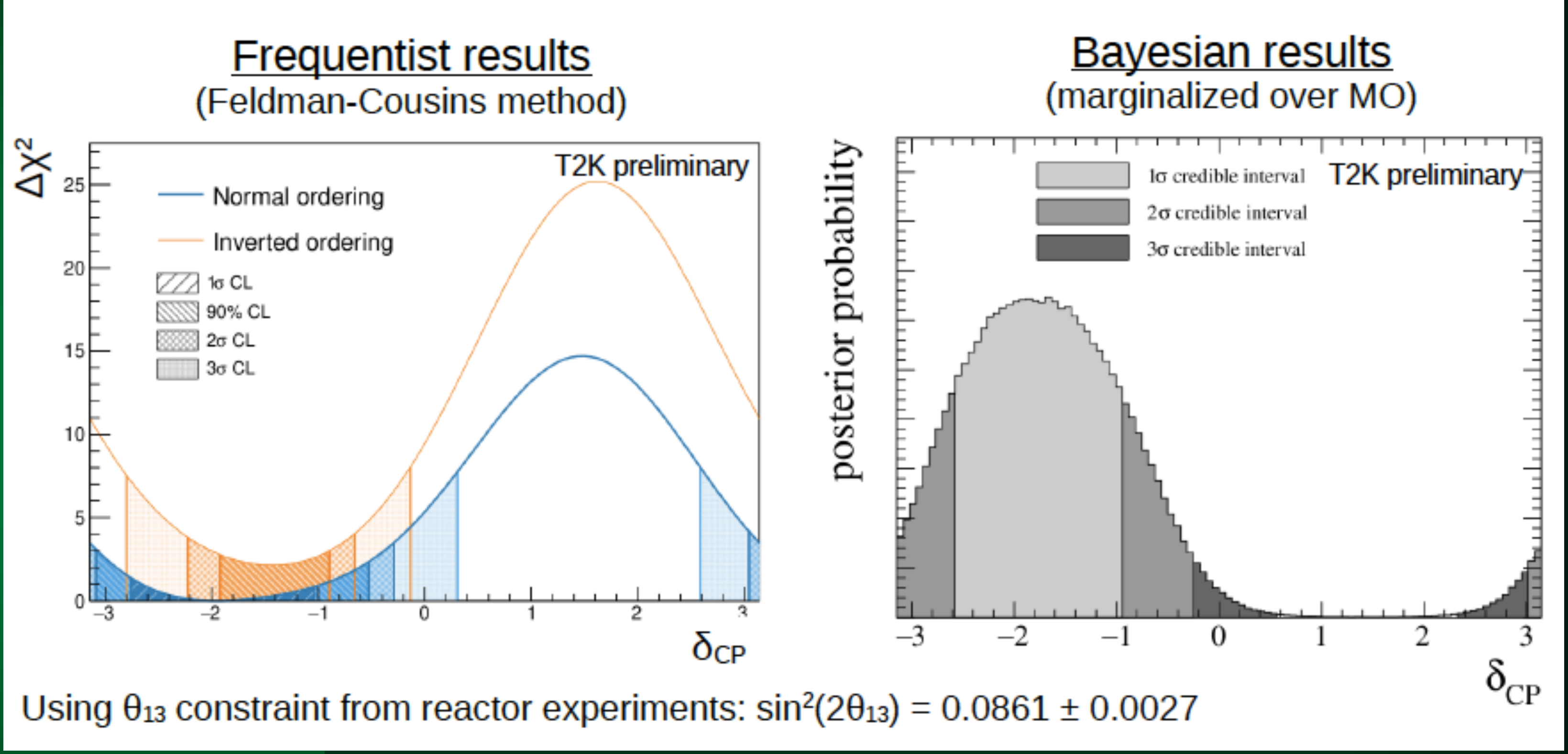


Phys. Rev. D 103, L011101 (2021)

Results consistent

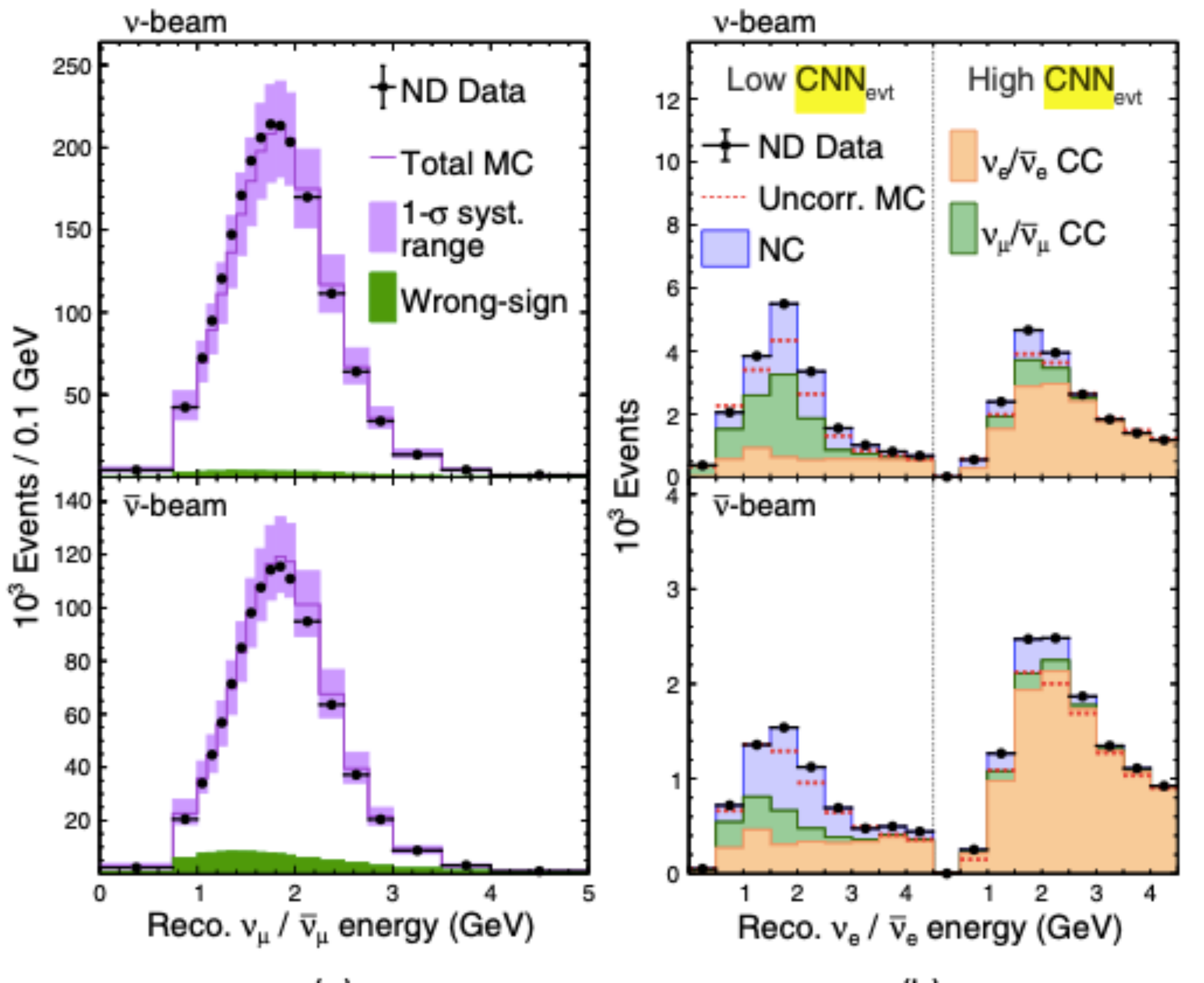
Both octants are still allowed at 1 sigma level

CP violation ????



Very consistent for NO and IO, >3 σ from 0, 2π

Samples used in Nova analysis



CNN – convolutional neural network

→ Selects sample reach in electron (anty)neutrino interactions

Using also boosted decision tree – BDT

→ To reduce cosmic background in near detector

Efficiency ν_e ($\bar{\nu}_e$) is 63% (75%)

results

	Neutrino beam		Antineutrino beam	
	ν_μ CC	ν_e CC	$\bar{\nu}_\mu$ CC	$\bar{\nu}_e$ CC
Signal	$214.1^{+14.4}_{-14.0}$	$59.0^{+2.5}_{-2.5}$	$103.4^{+7.1}_{-7.0}$	$19.2^{+0.6}_{-0.7}$
Background	$8.2^{+1.9}_{-1.7}$	$26.8^{+1.6}_{-1.7}$	$2.1^{+0.7}_{-0.7}$	$14.0^{+0.9}_{-1.0}$
Best fit	222.3	85.8	105.4	33.2
Observed	211	82	105	33

Fitted parameters

For mass ordering (normal and inverted) and sin2t23 (upper and lower octant)

	Normal order		Inverted order	
Parameter	UO	LO	UO	LO
$\Delta m^2_{32}(10^{-3}\ \mathrm{eV}^2)$	$+2.41 \pm 0.07$	+2.39	−2.45	−2.44
$\sin^2\theta_{23}$	$0.57^{+0.03}_{-0.04}$	0.46	0.56	0.46
$\delta_{\mathrm{CP}}(\pi)$	$0.82^{+0.27}_{-0.87}$	0.07	1.52	1.41

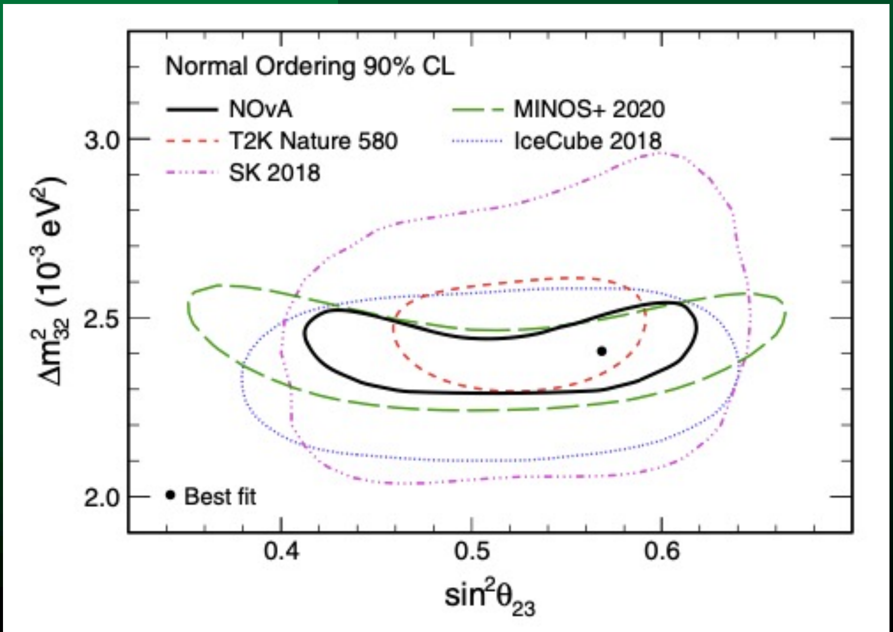
results

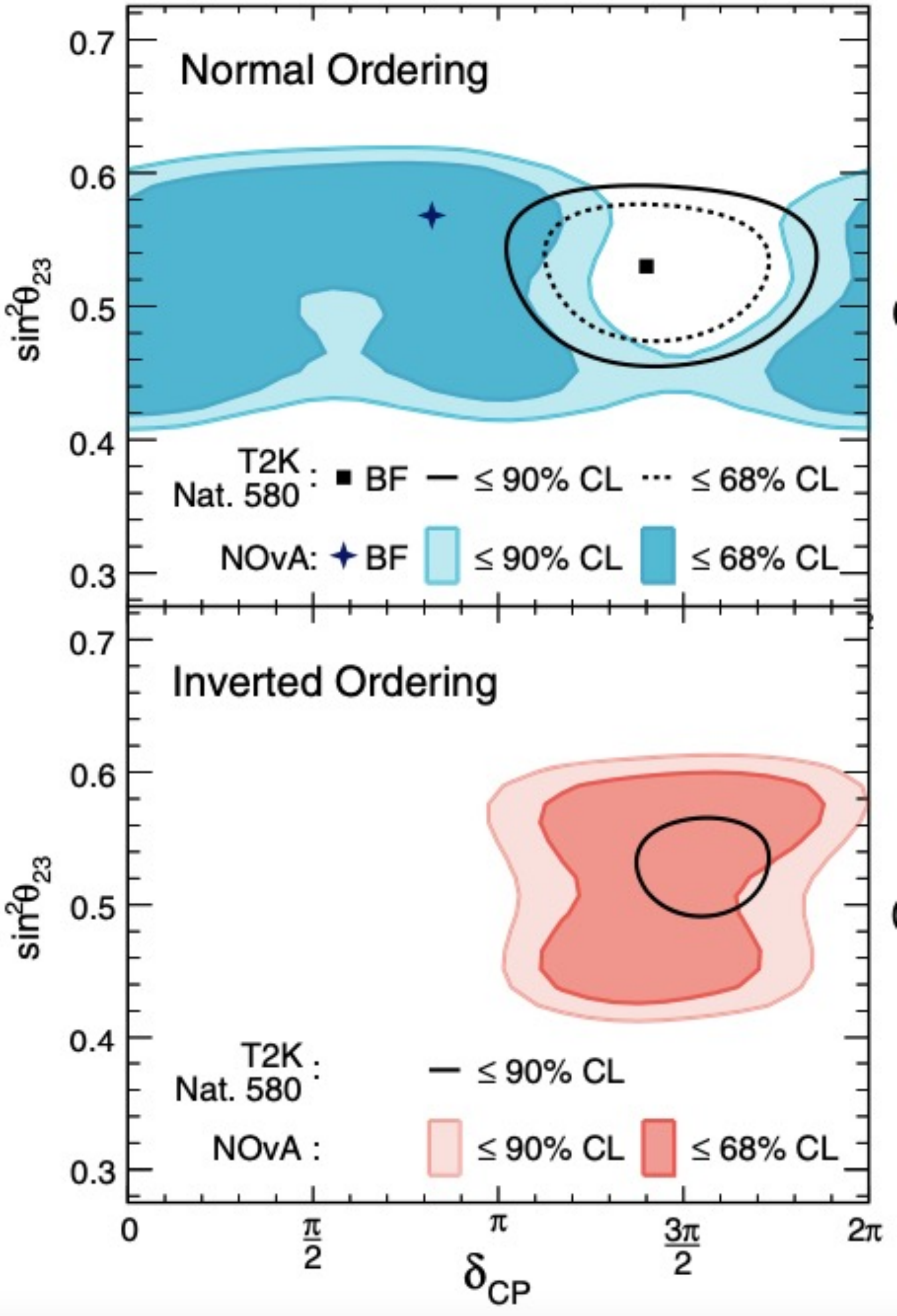
Comparison with T2K

→ Consistent for IO

→ For NO the best fit δ_{CP}

Different at more than 90%CL

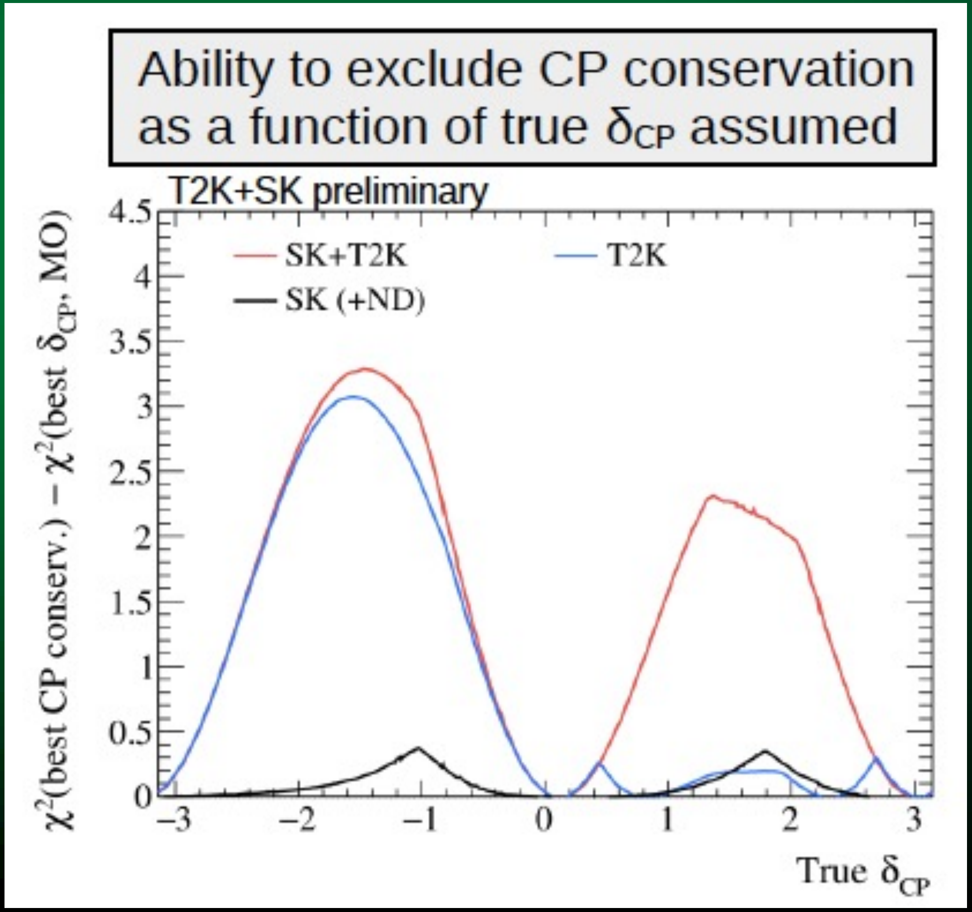




What more can be done ?

Combined analysis of T2K+NOnA

- Preparation in progres
- Well advance



Combine LBL data and atmospheric neutrino data

T2K + SK

(sensitivity)

$\mathcal{O}(1)$ → $\mathcal{O}(10\%)$ → $\mathcal{O}(1\%)$

20 years ago	now	future
$\mathcal{O}(1)$ 2 flavor-like oscillations	$\mathcal{O}(10\%)$ 3 flavor oscillations	$\mathcal{O}(1\%)$

next generation neutrino experiments:

Hyper-K; DUNE

→CP sensitivity

$\gg 3\,\sigma$ (7–8)

Why we need more precise data?

Test oscillation framework:

- more light neutrinos??
- more interactions (NSI)
- other exotic phenomena
  LIV, CPTV, decays, decoherence…
- test Unitarity of mixing matrix

LBL prospects

- Experiments running with higher beam intensity
- In T2K :
  - Gadolinium in SK (neutron tagging)
  - upgrade for ND (2023)
- Dedicated measurements for flux and σ_ν
- Combined analysis:
  - NOνA+T2K in preparation
  - T2K+SK atmospheric
- Next generation LBL under construction to start in 2027