Status of Accelerator-Based Neutrino Physics

Towards high precision measurements

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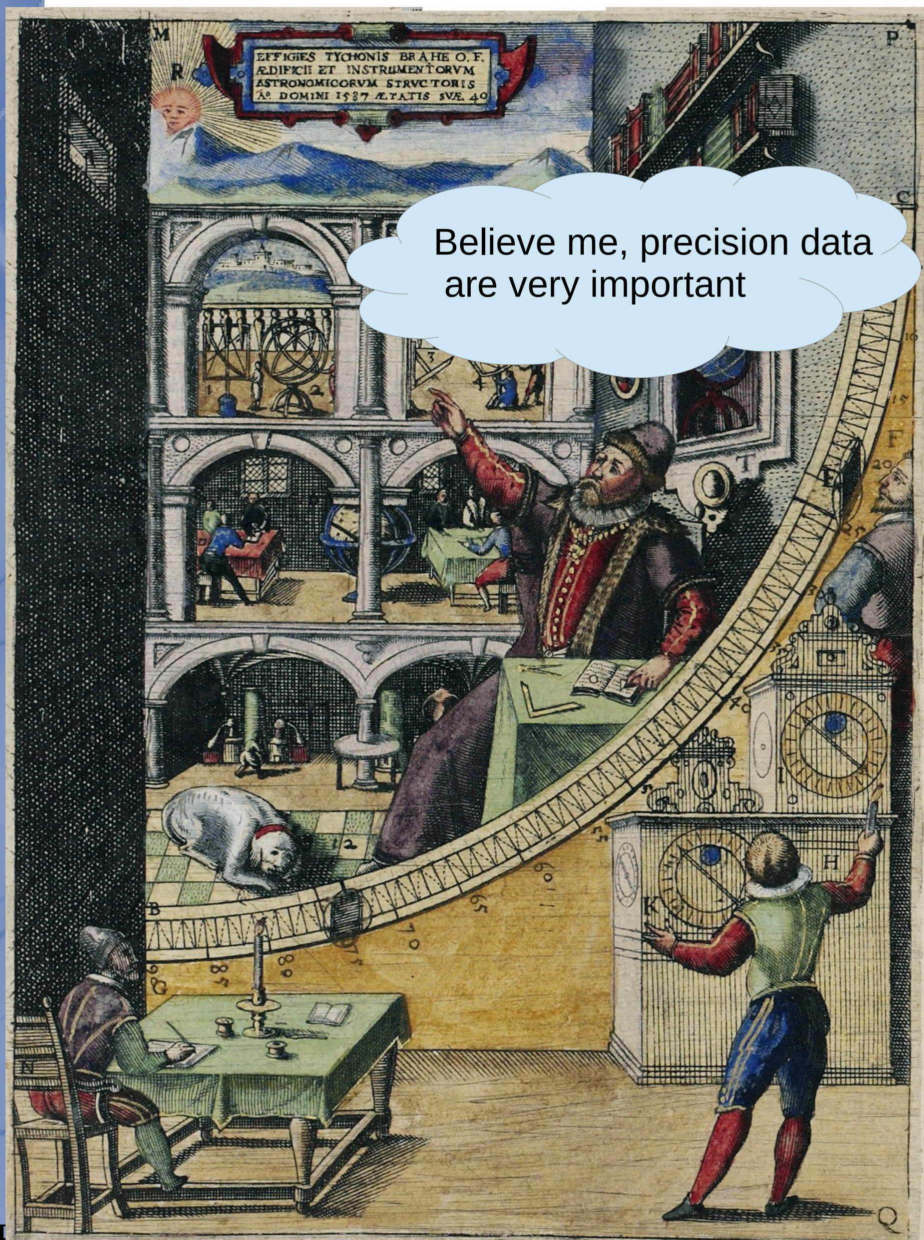
Outline

- Introduction
- Accelerator neutrinos experimental techniques
- Long Baseline recent results
- Short-baseline and neutrino cross section measurements
- A look into the future of long baselines exp.

Grateful acknowledgements to the NovA, T2K, OPERA, DUNE, Hyper-Kamiokande … collaborations for the plots and results

Tycho Brahe (1546-1601)



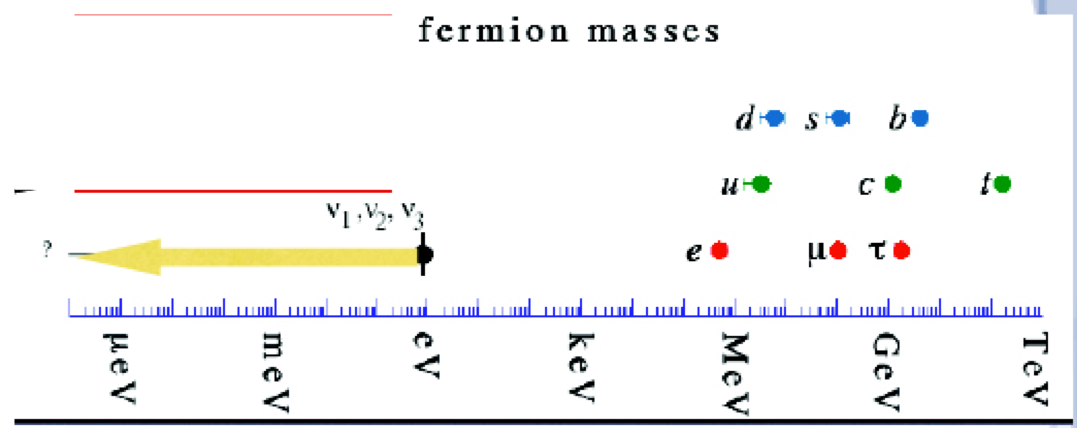
On the island of Ven (today Sweden), Tycho Brahe carefully observed the stars and planets. His accurate data (x5 smaller unc.) allowed Kepler to discover the laws behind the the planet orbits.

Timeline of recent discoveries

- 1998-2001 Neutrino oscillations : Super-Kamiokande, SNO, KamLAND (2015 Nobel Prize to T. Kajita and A. McDonald)
- 2012 The last mixing angle θ_{13}: Daya Bay, confirmed by RENO and Double Chooz
- 2013 $\nu_\mu \to \nu_e$ appearance: T2K, confirmed by NOvA
- 2015 $\nu_\mu \to \nu_\tau$ appearance: OPERA, confirmed by Super-Kamiokande

New phenomena through neutrino physics

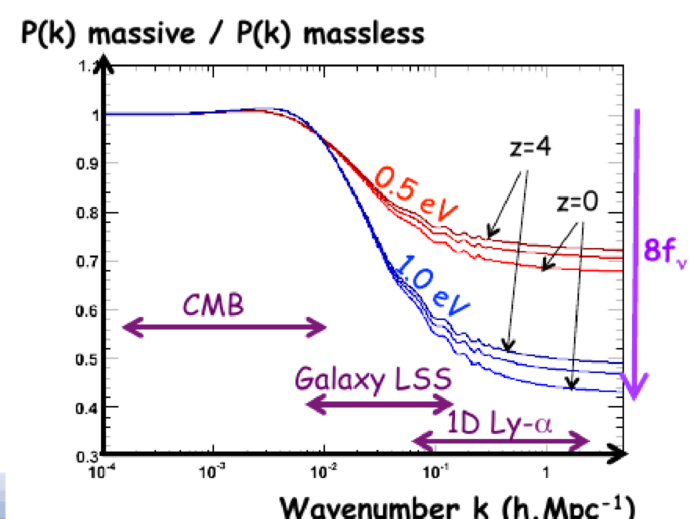
- The neutrino masses corresponds to a new mass scale requiring new degrees of freedom beyond the SM



- The neutrino mixing angles are large, at variance with the quark mixing angles: large CP violation effects are allowed

$$V_{PMNS} = \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \quad V_{CKM} = \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix}$$

- Neutrinos play an important role in the evolution of the Universe. Can they explain matter-antimatter asymmetry ?

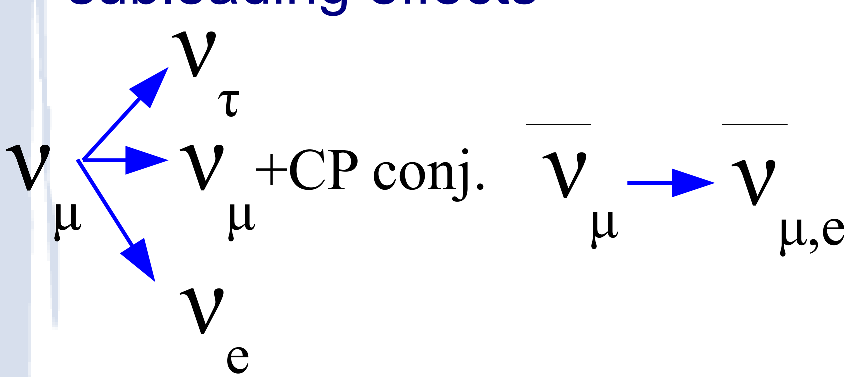


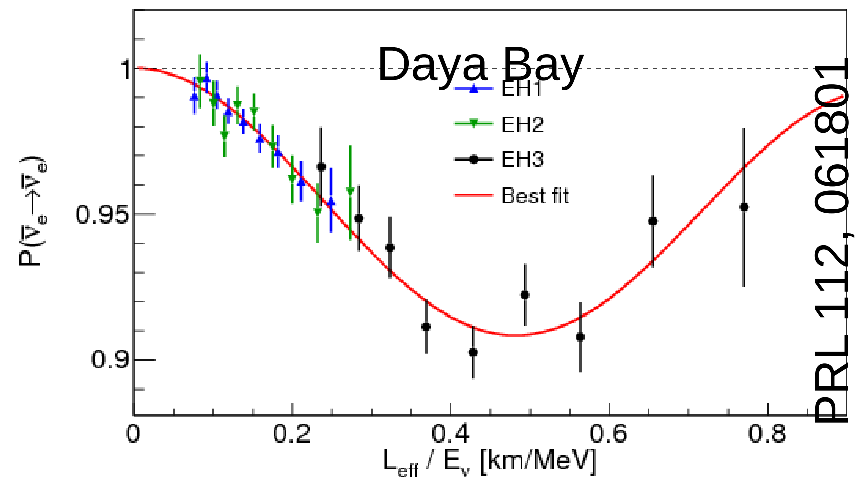
The Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix

$s_{ij}=\sin\theta_{ij}$

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\begin{pmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3}\\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3}\end{pmatrix}=\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 0\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

- The oscillation phenomena have been convincingly observed using solar, atmospheric (Nobel prize 2015), reactor and accelerator neutrinos, establishing the three neutrino SM paradigm
- Currently unveiling three-neutrino subleading effects





PRL 112, 061801

Parameter	Value	Precision (%)
Δm^2_{21}	$7.37\ 10^{-5}$ eV^2	2.3
θ_{12}	34°	5.8
Δm^2_{32}	$2.52\ 10^{-3}$ eV^2	1.6
θ_{23}	42°	~9
θ_{13}	8.4°	4

Capozzi et al. PRD 95, 096014 (2017)

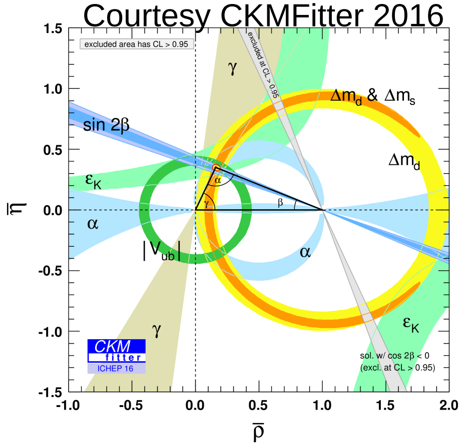
Outstanding questions in neutrino physics

1) Is θ_{23} =45°? which octant ?
2) Determine the mass ordering
3) Measure the CP violation parameter δ
4) Precision tests of the PMNS paradigm (at the % level, as for the CKM matrix)
5) Are there any new neutrino states ?
6) Nature of neutrinos: Dirac or Majorana ?

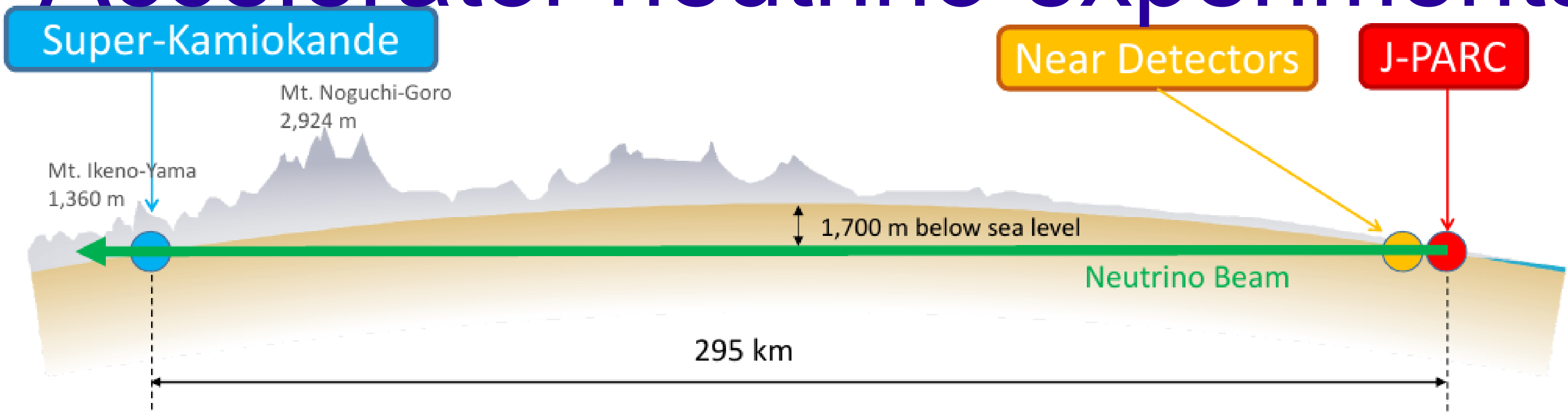
These questions can be solved with accelerator based neutrino oscillation experiments

How can we reach this level of precision in neutrino physics ?

Courtesy CKMFitter 2016



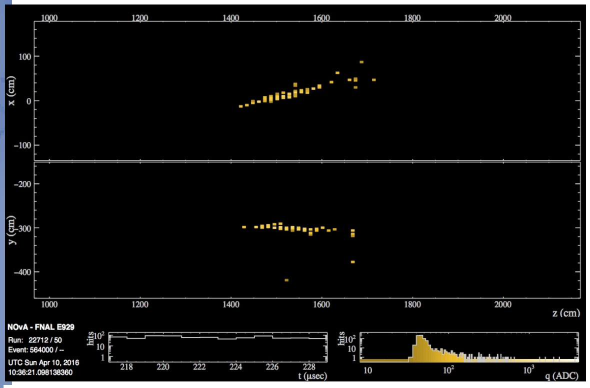
Accelerator neutrino experiments

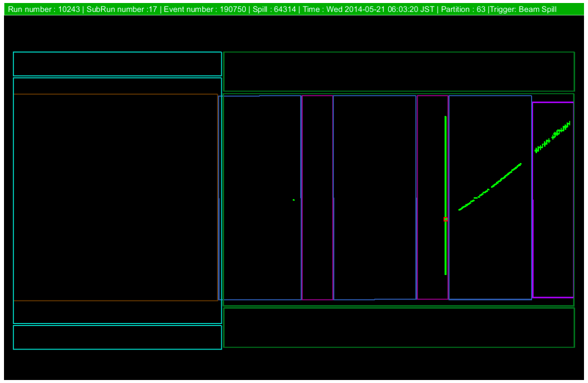


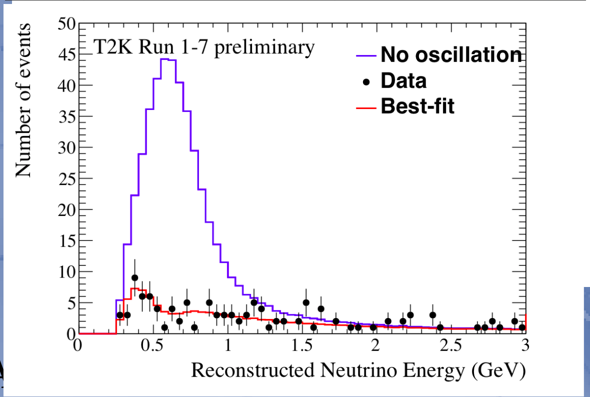
~20-100kt Far detector

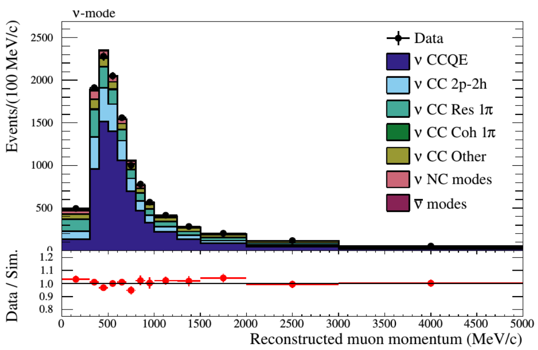
Near detector

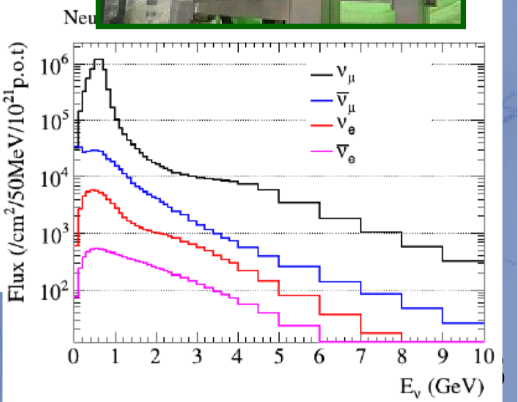
~MW proton driver





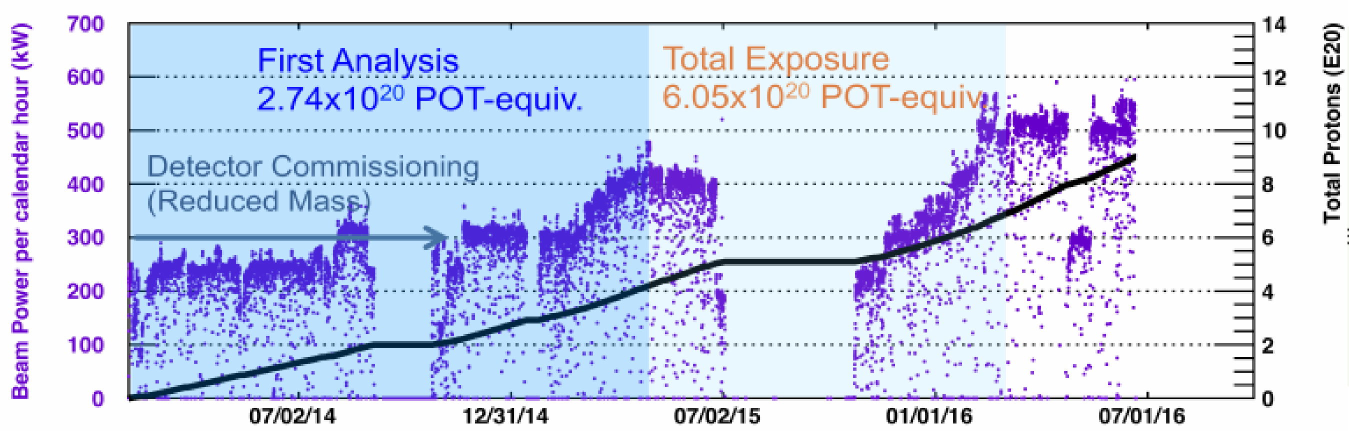




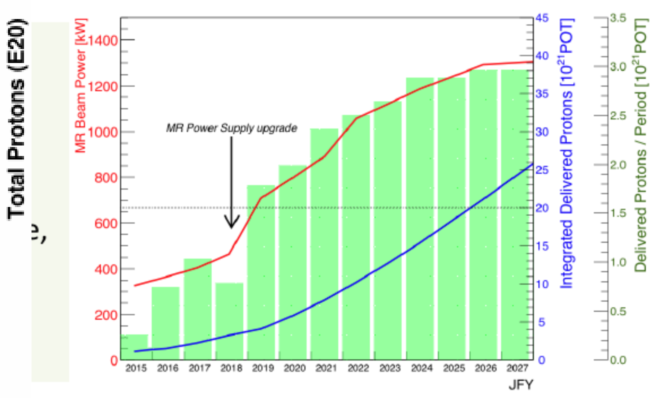


Super-beams: towards the Megawatt frontier

- See talks by Sato-san and C. Plostinar
- Most of the results still statistically limited!
- Important recent progress by JPARC (470 kW) and FNAL (700kW)
- An upgrade program underway (PIP 900 kW in 2021, JPARC towards 1.3 MW ~ 2025)



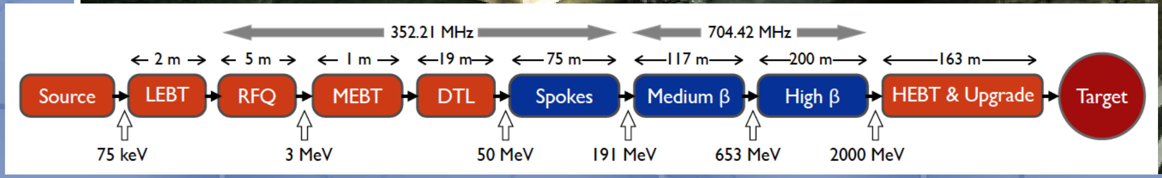
J-PARC MR expected performance
and T2K-2 POT accumulation scenario

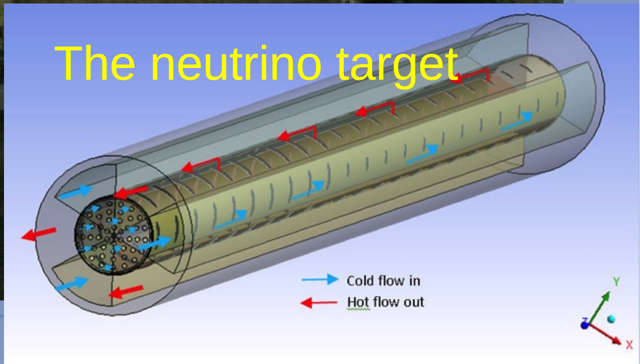


M. Dracos EPS 2017

The ESS NUSB Project

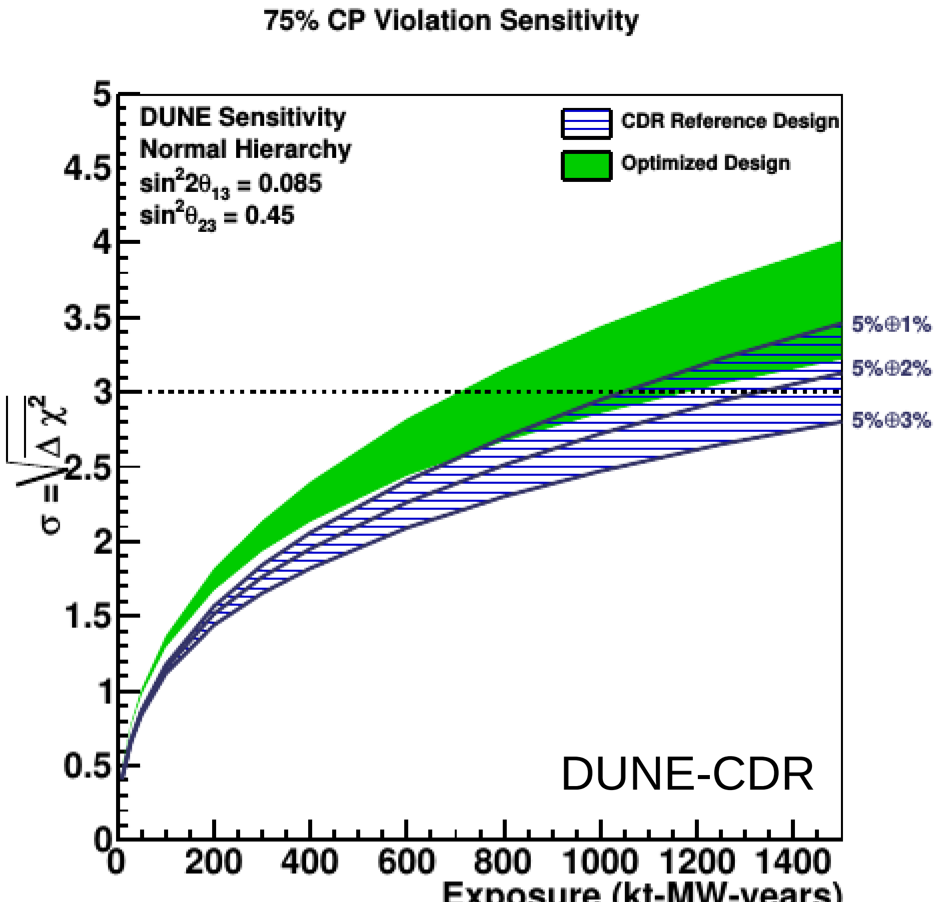
Based on the European Spallation Source 5 MW beam (Lund, Sweden)
Design study (H2020) approved by EU
Developing results obtained by the EURONU SB WG
Synergies with the T2K and HK program





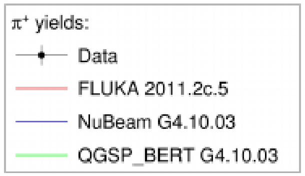
The high precision challenge

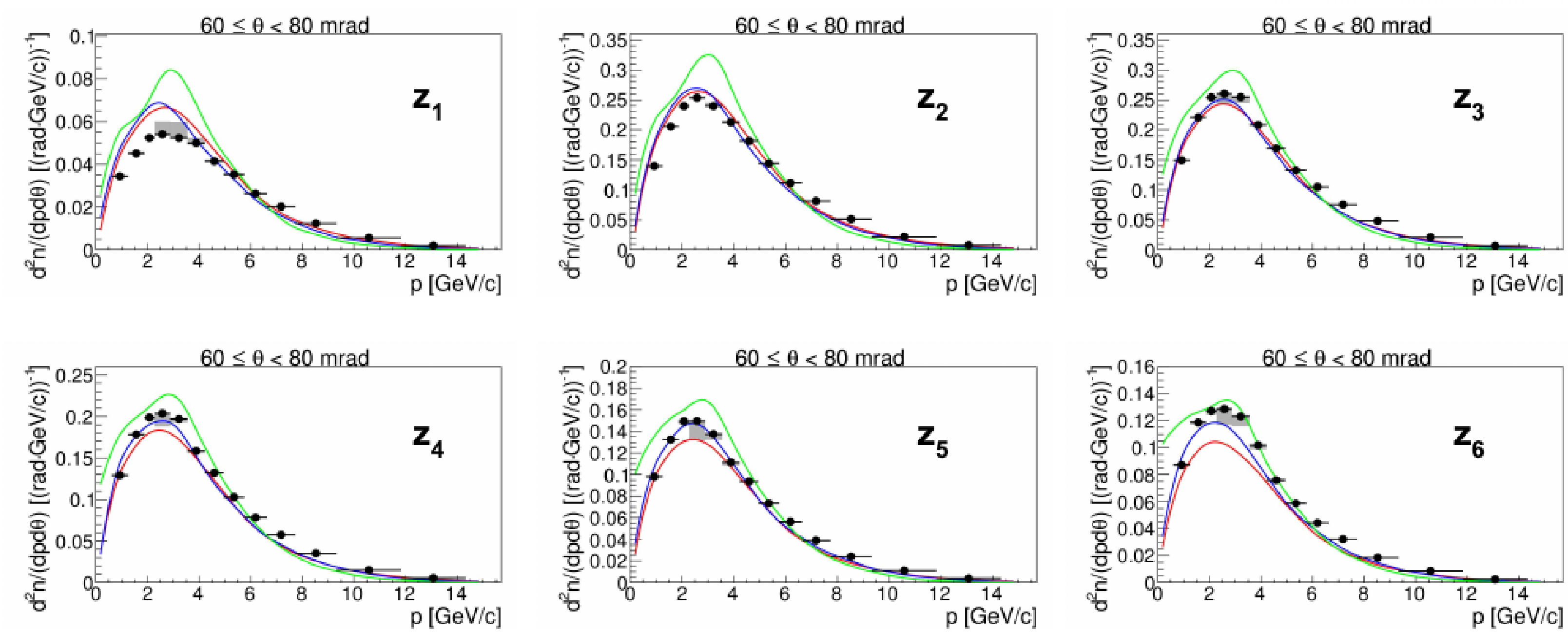
Controlling systematic uncertainties at the %-level (flux, cross-sections, detector response) is crucial for extracting precision information on neutrino oscillations

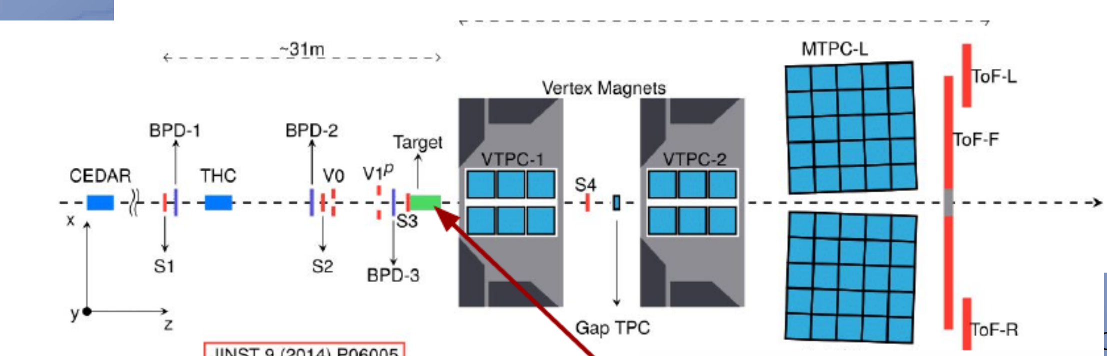


NA61/SHINE hadroproduction measurement

π^+ yields





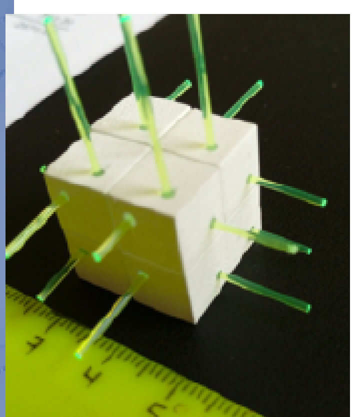


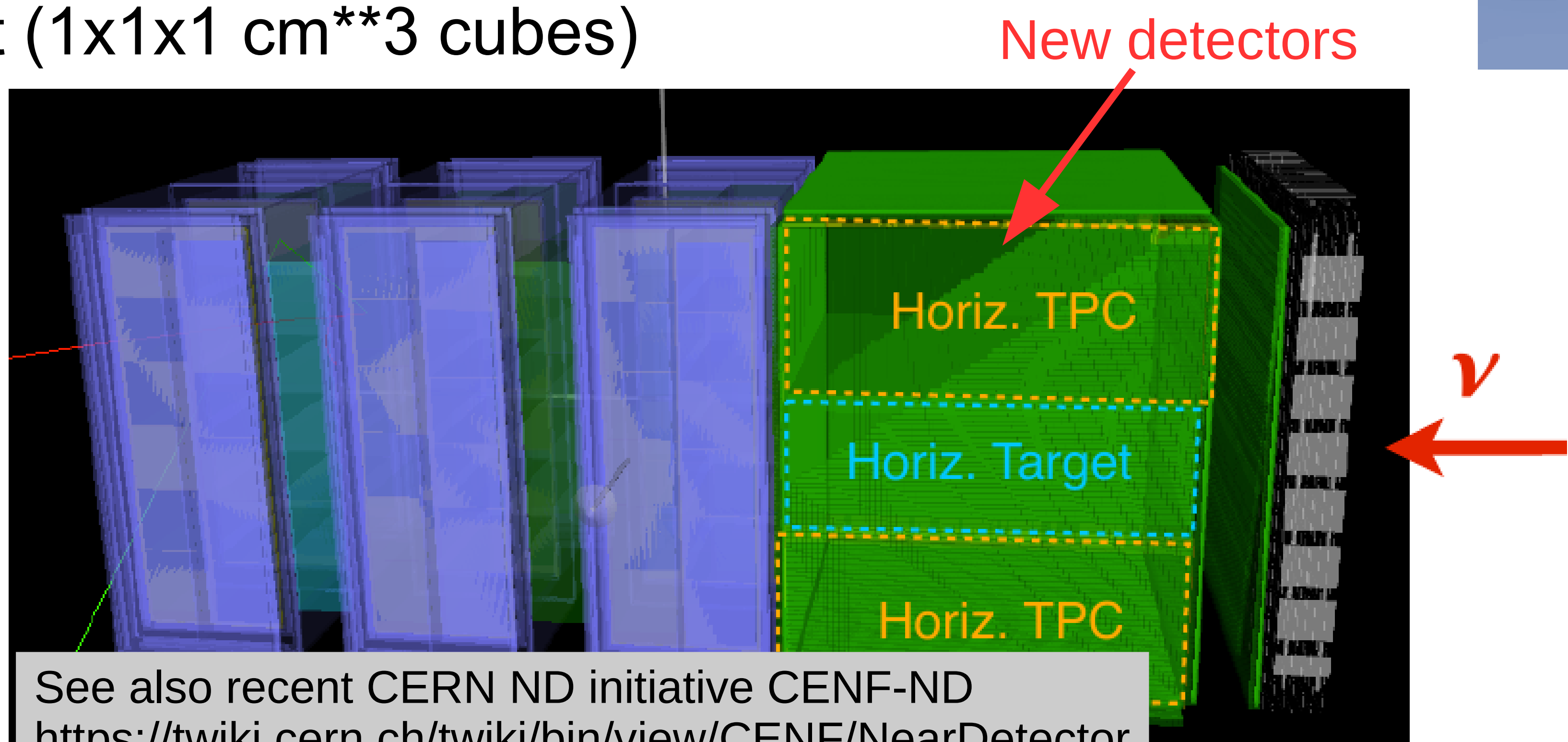
These data with a T2K replica target will allow to predict the T2K flux at the 5% level

SPSC-EOI-15
arXiv:1707.01785

T2K Near Detector Upgrade

- Upgrade of the near detector for T2K-II (installation in 2021)
- Extend the tracker angular acceptance at high angles
- 2 TPCs with resistive Micromegas (ILC TPC design)
- R&D for SuperFGD, a high granularity totally active target (1x1x1 cm**3 cubes)

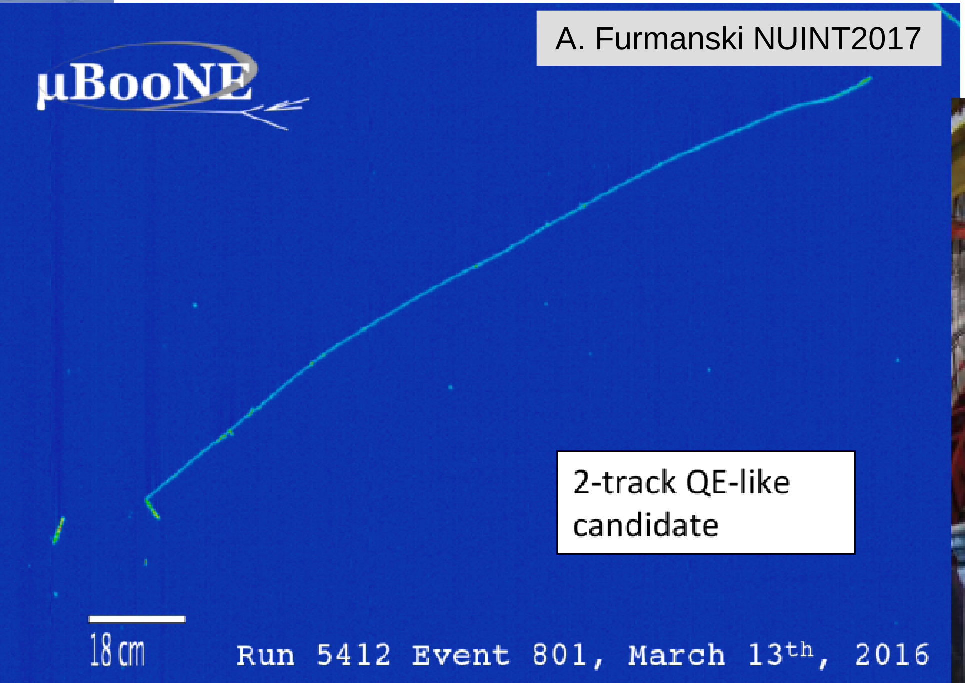


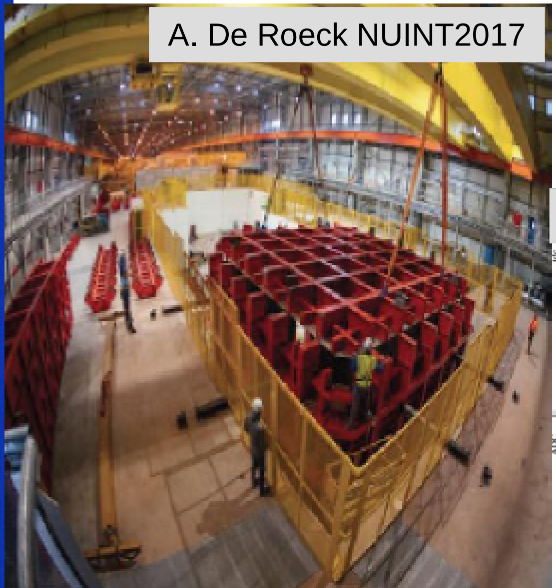


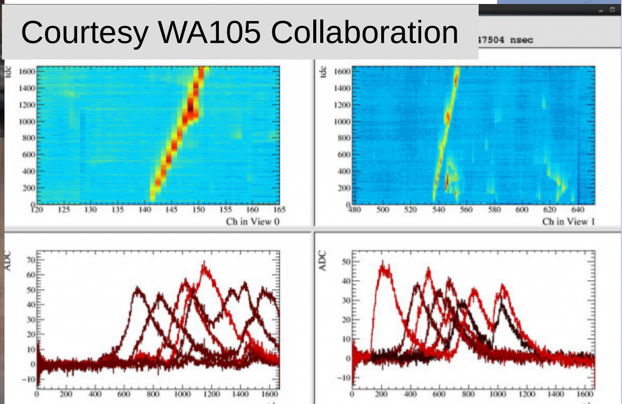
See also recent CERN ND initiative CENF-ND
https://twiki.cern.ch/twiki/bin/view/CENF/NearDetector

Progress with Liquid Argon TPCs

- The MicroBooNE experiment at FNAL (170 tons of LAr) has recently showed its first results on neutrino interactions
- CERN Neutrino Platform: 800 t cryostats for the two ProtoDUNE detectors (det. inst. 2018), first CR tracks for the large ($3x1x1m^3$) double phase WA105 prototype







Neutrino oscillations : LB observables

$\nu_\mu \longrightarrow \nu_\mu$

$$P(\nu_\mu \to \nu_\mu) = 1 - (\cos^4\theta_{13}\sin^2 2\theta_{23} - \sin^2 2\theta_{13}\sin^2\theta_{23})\sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$$

$\nu_\mu \longrightarrow \nu_e$

$$P(\nu_\mu \to \nu_e) \approx \sin^2 2\theta_{13}\sin^2\theta_{23}\sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) - \frac{\sin 2\theta_{12}\sin 2\theta_{23}}{2\sin\theta_{13}}\sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)\sin\delta_{CP} \ldots$$

Disappearance channel : sensitivity to θ_{23} and Δm^2_{32}

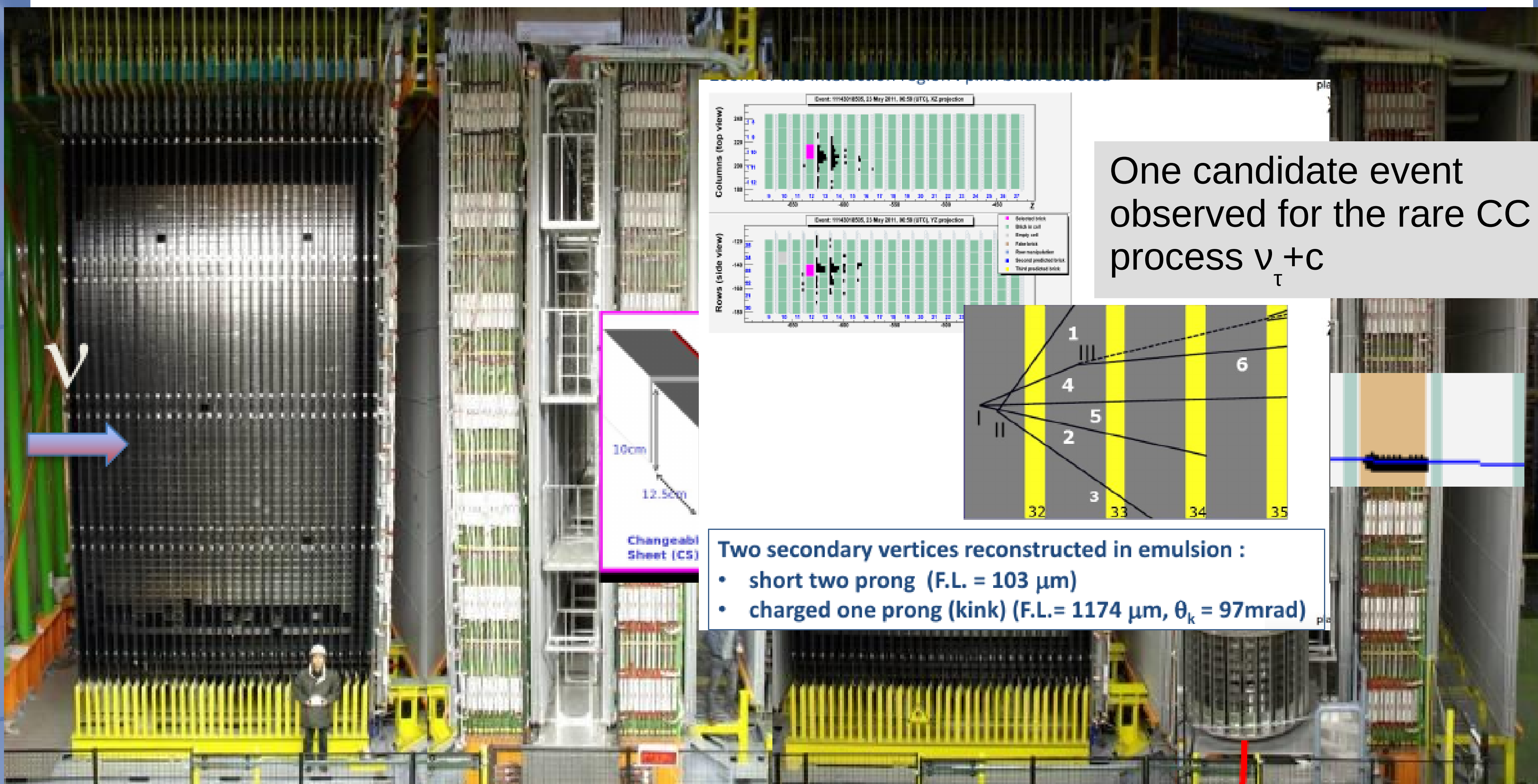
Appearance channel : sensitivity to θ_{13} and (subleading) to the CP phase, octant

C. Sirignano EPS-HEP 2017

OPERA (CNGS): $\nu_\mu \to \nu_\tau$

New selection of „silver“ ν_τ sample:

10 ev observed (6.8 exp ν_τ 2 bck.)



CP violation effects

$\nu_\mu \to \nu_e$: beyond the leading term in vacuum

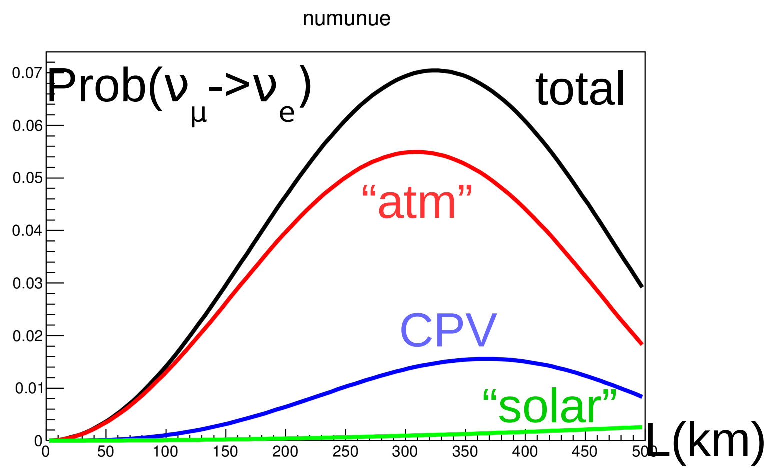
$$P(\nu_\mu \to \nu_e) \approx 4 C^2_{13} S^2_{13} S^2_{23} \sin^2 \Phi_{31}$$ "Atmospheric" term

$$\pm 8 C^2_{13} C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin\Phi_{32} \sin\Phi_{31} \sin\Phi_{21}$$ CP violating term

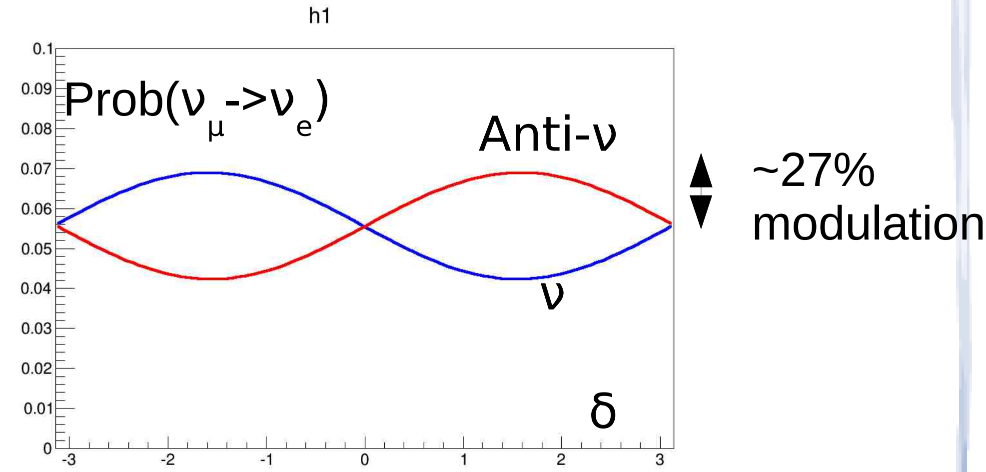
$$+4 S^2_{12} C^2_{13} (C^2_{12} C^2_{23} + S^2_{12} S^2_{23} S^2_{13} - 2 C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta) \sin^2 \Phi_{21}$$ "Solar" term

$$C_{ij} = \cos(\theta_{ij})$$
$$\Phi_{ij} = \Delta m^2_{ij} L / 4E$$

Change sign from nu to anti-nu! An accelerator based neutrino beam is ideal to study this, as either neutrinos or antineutrinos can be produced



E=0.6 GeV



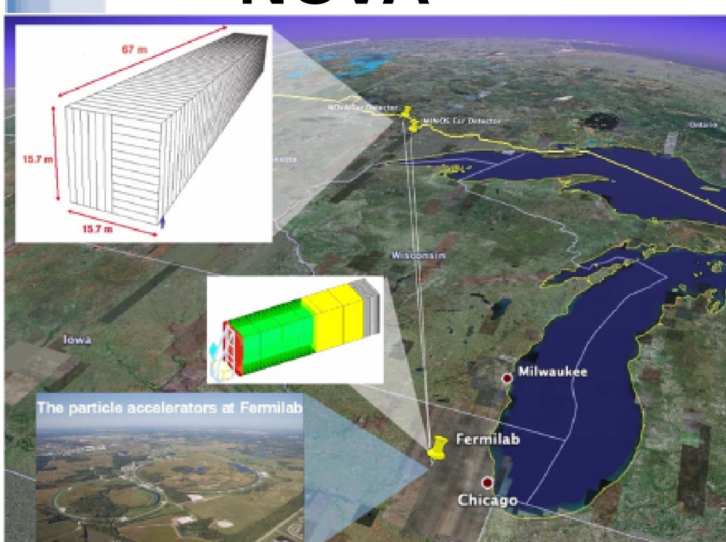
Caution: indicative plots !!

The running LB experiments: T2K and NOvA

Exp.	L (km)	E ν	FD mass	Det	#Events
T2K	295	0.6	22.5kt	Water Cher.	74+15 ν_e 7 anti-ν_e
NOvA	810	2	14kt	Scintillator	33 ν_e

- Deep complementarity between the two experiments: baseline, energy, detection technique, …
- Healthy and friendly competition

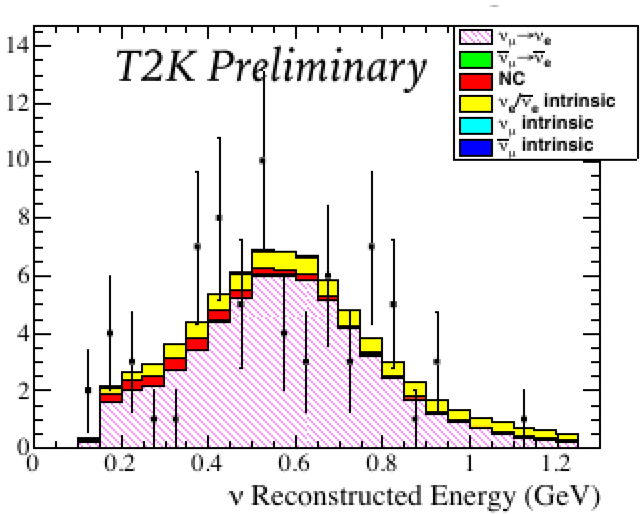
NOvA



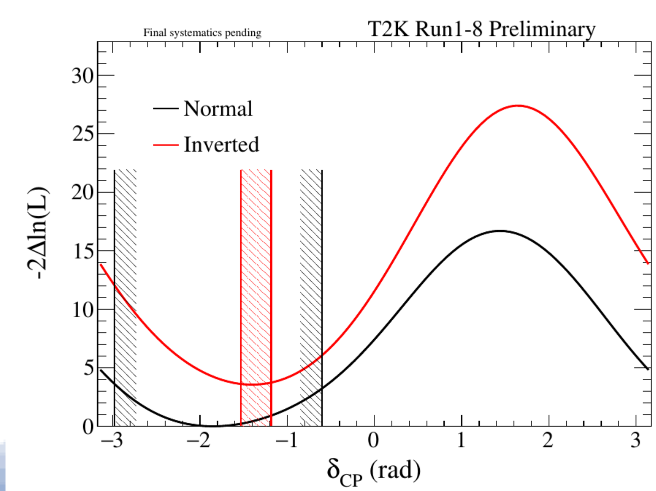
T2K

T2K $\nu_\mu \to \nu_e$

- Recently preliminary results shown results based on 2017 data (nu-mode 14.7 10^{20}, antinu-mode 7.6 10^{20}POT, 29% of the approved T2K POT). Nu-mode statistics doubled in one year.
- Addition of a new CC1pi sample in the far detector
- and new optimization of cuts: 30% increase in statistics
- 89 ν_e (67 exp for δ=0), 7 antiν_e (9 exp for δ=0)
- Exclude at 2 σ the CP conserving values δ=0,π

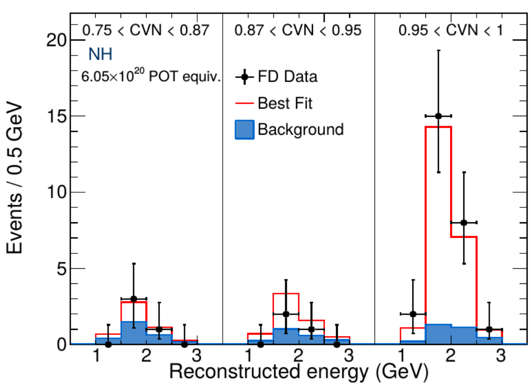


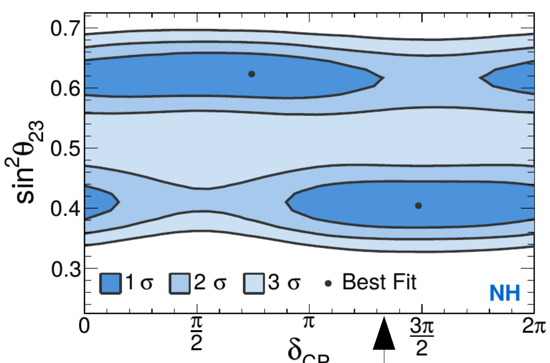
Intervals at 2 σ:
NO[-2.98, -0.60]
IO [-1.54, -1.19]



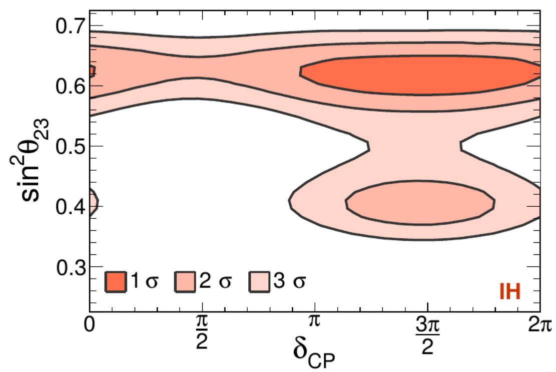
NOvA $\nu_\mu \rightarrow \nu_e$

- Results based on 6.05 10^{20} POT in neutrino-mode
- 33 ν_e candidates (bck 8.2) (19-36 exp. for extreme osc. scenarios)
- Two best fit points in the normal ordering
- Inverted ordering with θ_{23} in the lower octant is disfavored (93%CL) for all values of δ
- Stay tuned for antinu-mode data!





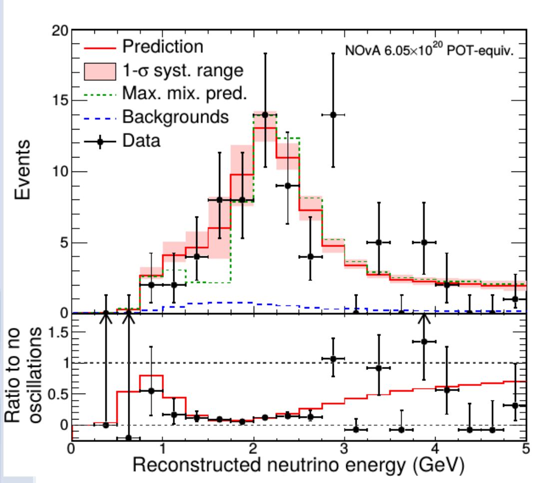
T2K best fit

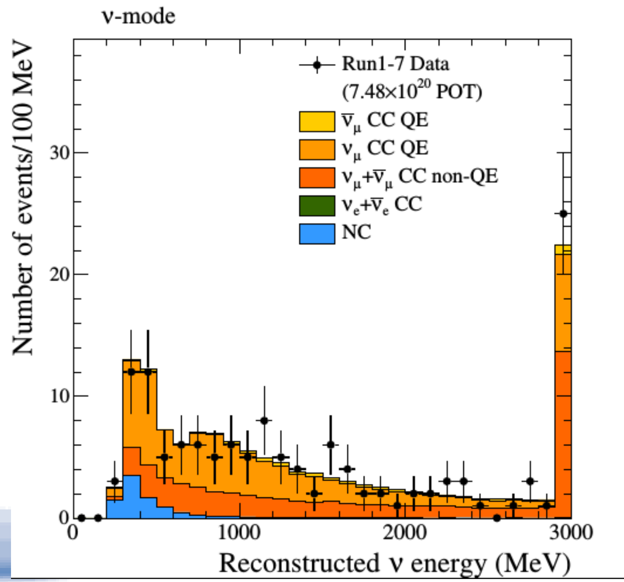


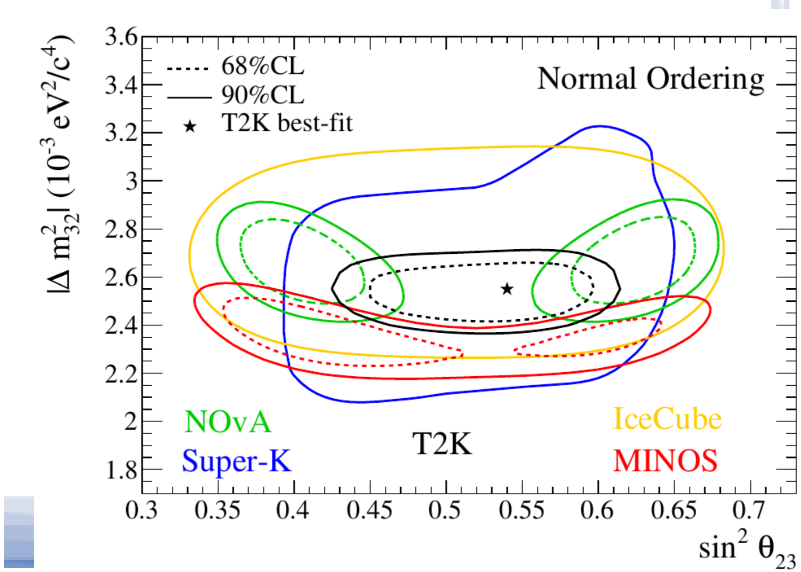
T2K arXiv:1707.01048
NovA:PRL 118, 151802 (2017)

T2K-NOvA ν_μ->ν_μ

- T2K: 135 ev obs. (446 exp. no osc.)
- NOvA: 78 ev obs. (484 exp. no osc.)
- Mild tension in θ_{23} values: T2K prefers almost maximal value (best fit $\sin^2\theta_{23}$ = 0.532), while NOvA non-maximal ($\sin^2\theta_{23} = 0.404^{+0.030}_{-0.022}$)
- This could also point to a mismodelling of nuclear effects





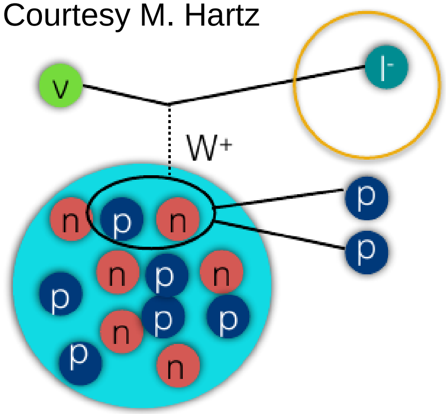


P. Coloma et al 2013 arXiv: 1307.1243
A. Ankowski, arXiv:1704.07835

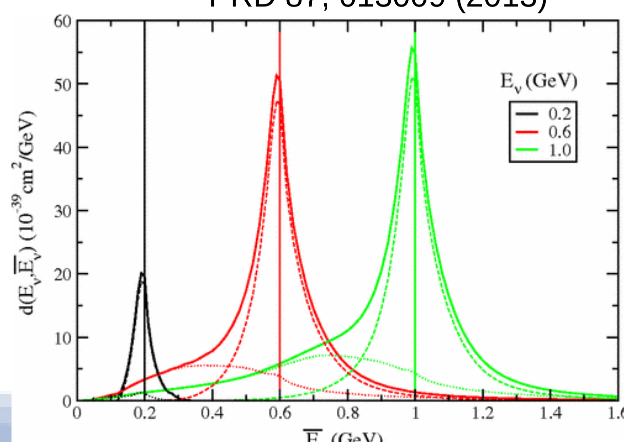
Nuclear effects and impact on oscillation measurement

- Sizeable contribution (~15% of CCQE) to ν-nucleus interaction from 2p-2h processes
- Mismodelling it could affect the energy reconstruction of both T2K and NOvA (although through different mechanisms)
- Both collaborations take into account a contribution from 2p-2h and estimate it from near detector data
- Improvements are expected from 4π data in ND, near detector upgrade, external data, better theoretical models

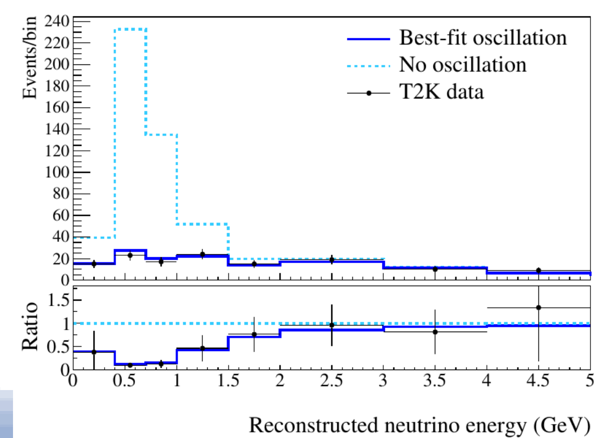
Courtesy M. Hartz



M. Martini et al
PRD 87, 013009 (2013)



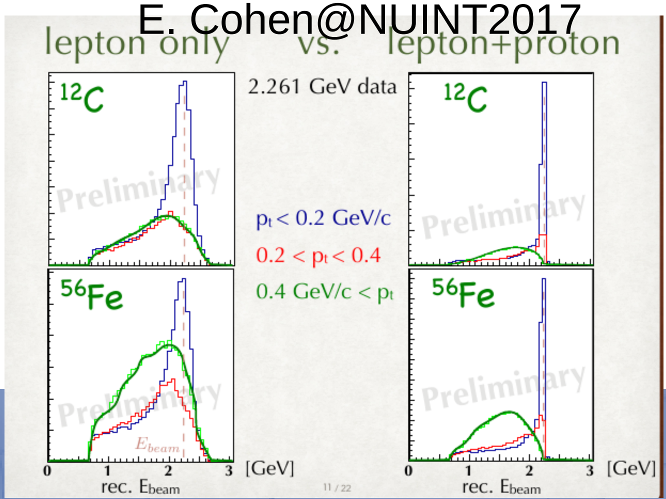
T2K arXiv:1707.01048



Neutrino-nucleus cross-sections

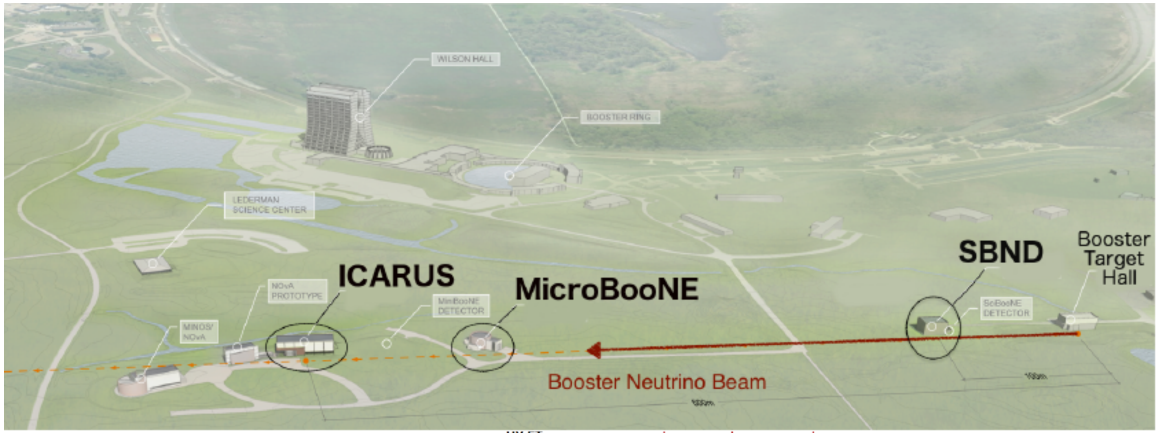
- Healthy progress reported at NUINT 2017: many cross-sections results (MINERVA, MicroBoone, Argoneut, T2K, LARIAT, DUET, …) in cc-inclusive, 0-pion, 1-pion channels
- NUSTEC white paper arXiv:1706.03621 (recommended reading!) charting the way towards an in-depth understanding and modelling of ν-nucleus interactions
- Collaboration with electron-scattering community picking-up: e.g. study of nuclear effects in electron energy reconstruction (CLAS)

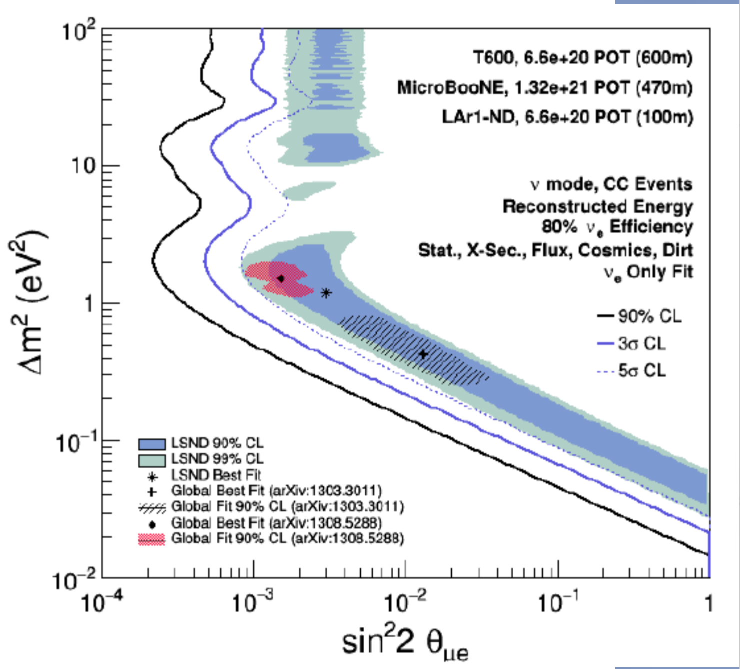
E. Cohen@NUINT2017

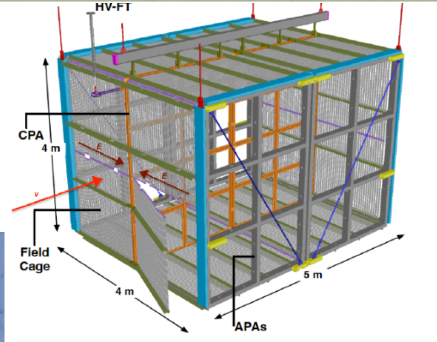


SBN program at FNAL

- Three LAr detectors (SBND, MicroBooNE, ICARUS) in the Booster neutrino Beam.
- ~ 5 10^6 ν interaction events in the SBND detector (112t active mass, start in 2019)
- 5 σ sensitivity to the LSND/MiniBooNE allowed region for sterile ν

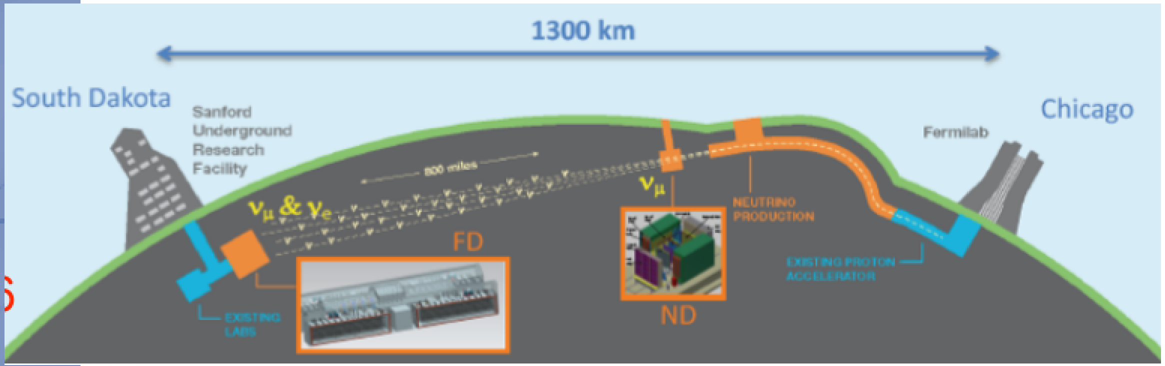


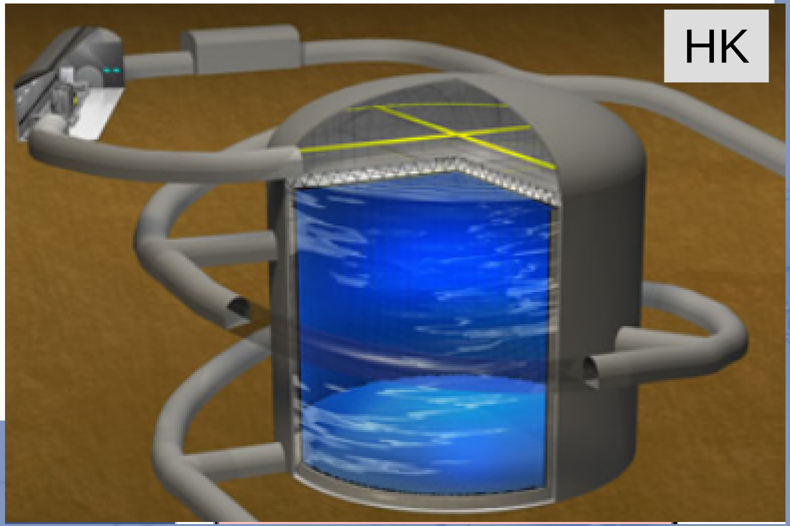




Future long baselines

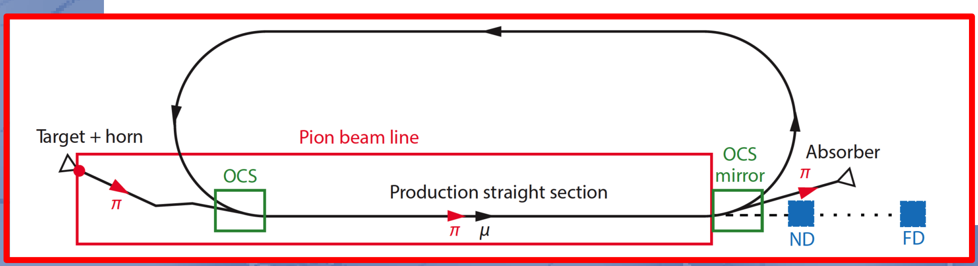
- DUNE 1300 km from FNAL to SURF (South Dakota), 40 kt Lar TPCs: recent far laboratory groundbreaking event (21/07/17)
- Hyper-Kamiokande: 190 kt Water Cherenkov in the Kamioka region: recently selected for the Japanese MEXT roadmap 2017 (7/28), funding request in progress
- Both aim to start data-taking around 2026

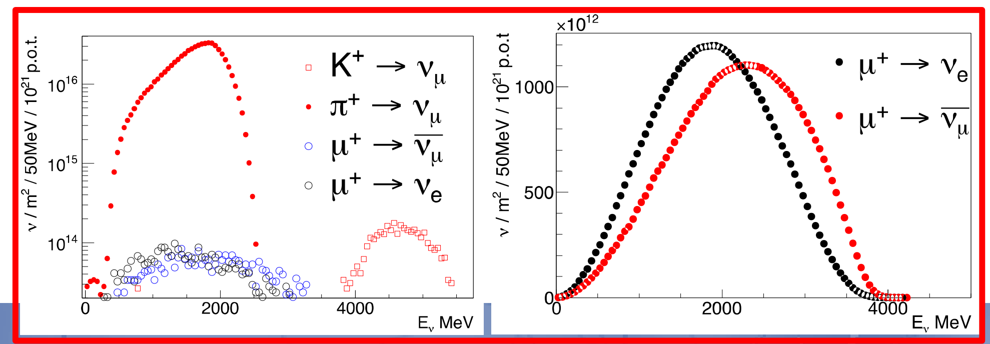




nuSTORM

- Aim: measure ν_e-nucleus cross-sections at the % level (see also the ENUBET R&D), SB oscillations studies
- Precisely known ν_μ and ν_e fluxes from muon decays
- Study ongoing for siting at CERN in the Physics Beyond Collider framework, report planned for end 2018





Conclusions

- Accelerator-based neutrino experiments played a major role in the study of neutrino properties since the 1960's
- Today T2K and NOvA are narrowing down on δ, the mass ordering, Δm^2_{32}, θ_{23}
- A number of experiments are crucial for the precision study of neutrino cross-sections including future projects like nuSTORM
- The SBN program at FNAL will explore possible short baseline oscillations at high significance
- Long baselines: DUNE and Hyper-Kamiokande starting data-taking from ~2026

Neutrino oscillations

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

If neutrino flavor eigenstates are different from mass eigenstates, propagation induces a phase shift with the appearance of a new flavor

$$\nu_\mu = -\sin\theta\, \nu_1 + \cos\theta\, \nu_2$$

Propagation

Source

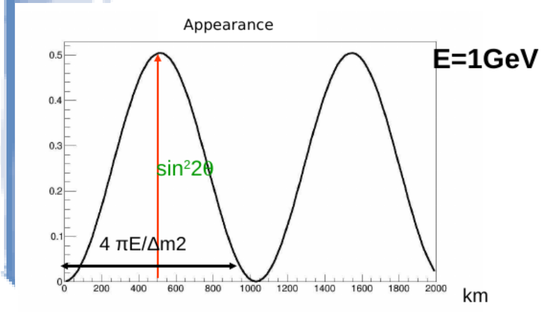
W ν_μ μ

$$\nu_1 \rightarrow \exp(-ip_1 x)\, \nu_1$$
$$\nu_2 \rightarrow \exp(-ip_2 x)\, \nu_2$$
$$\Delta\varphi = \Delta m^2 L/(4E)$$

ν_e e

Detector

L

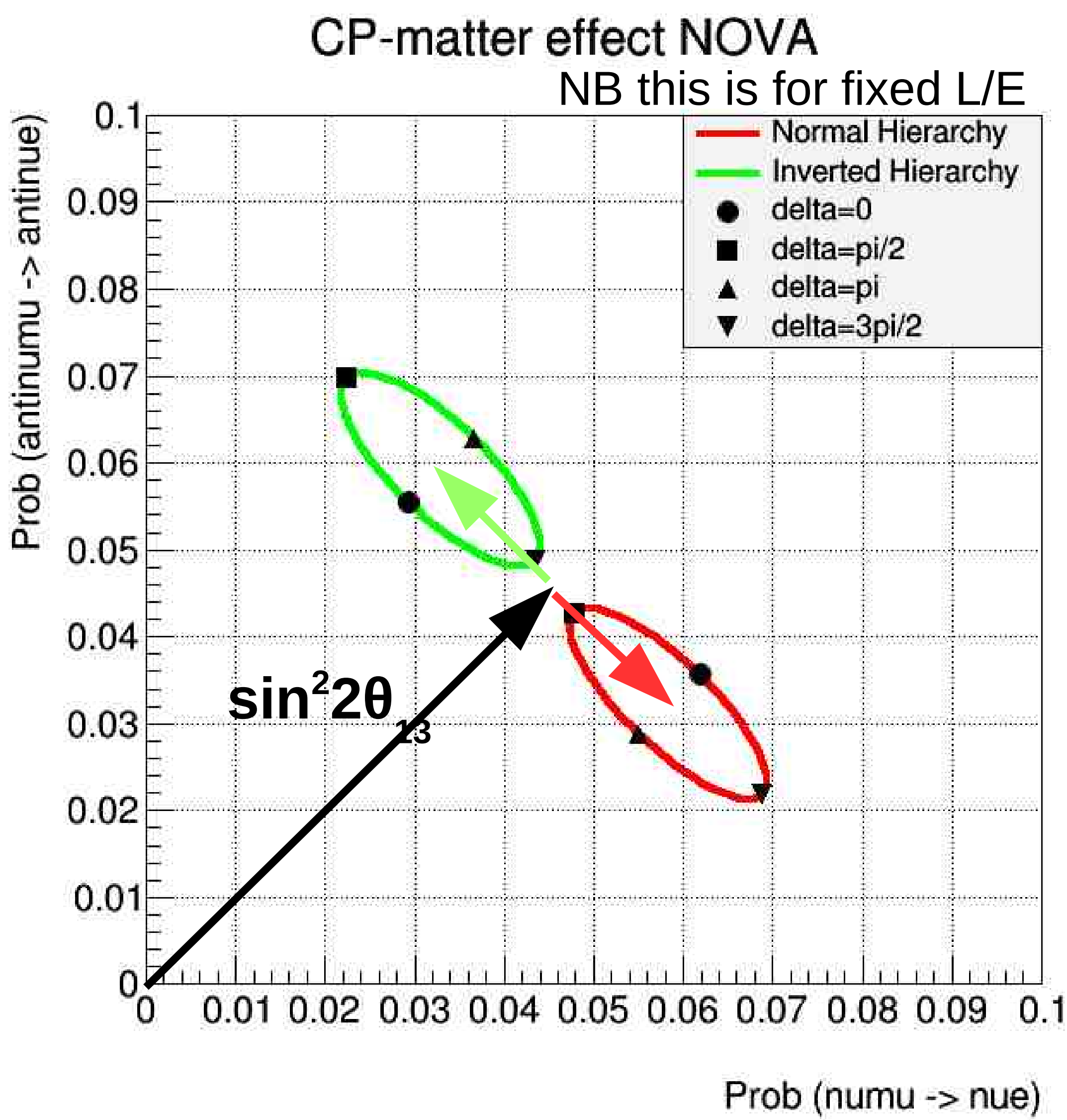


$$\mathrm{Prob}(\nu_\mu \rightarrow \nu_e) = \sin^2(2\theta)\,\sin^2(\Delta m^2 L/4E)$$

This is a simplified two neutrino scenario

Notice that the expression is invariant replacing Deltam**2 → -Deltam**2

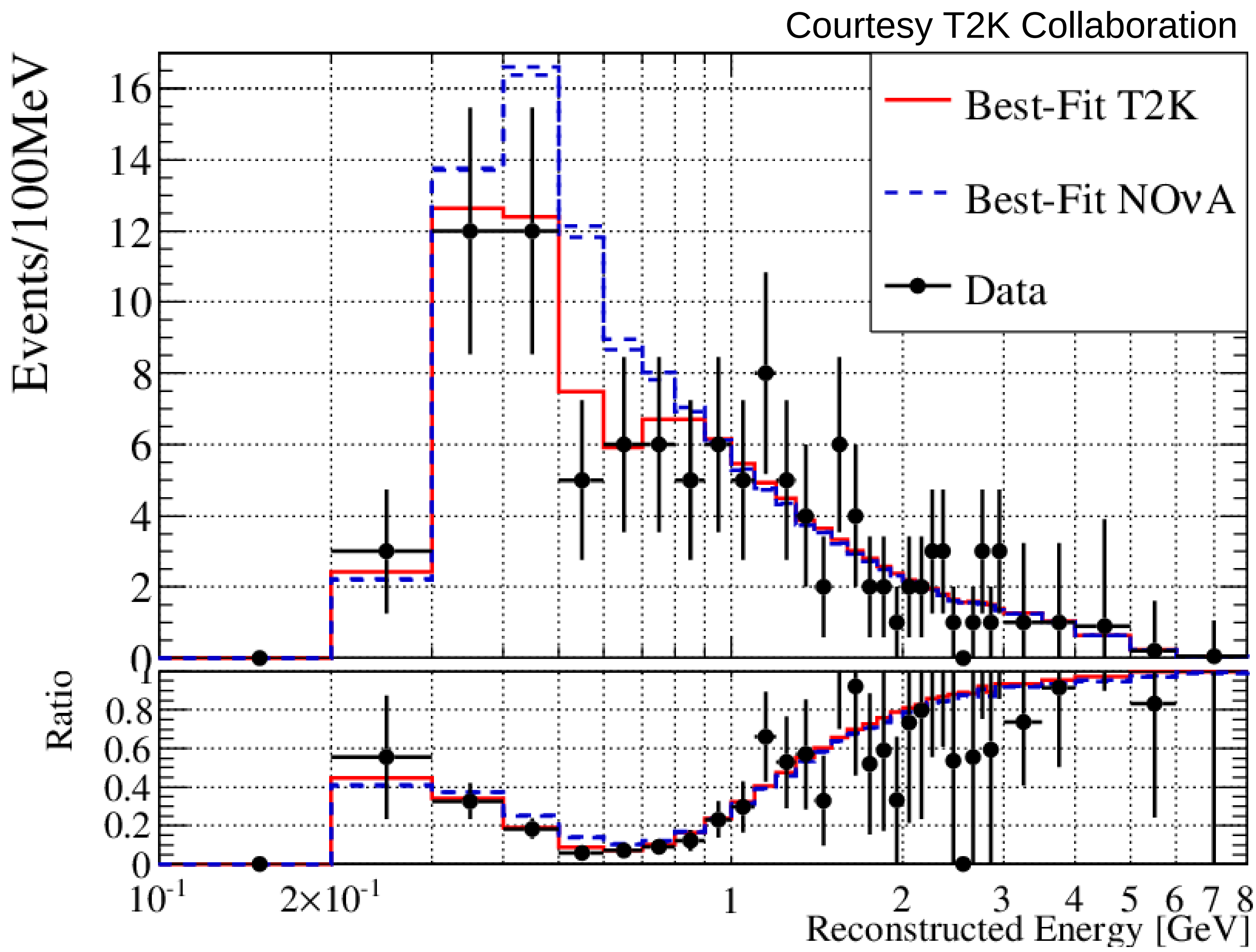
Combined CP and matter effects



Effect of inverse or direct mass ordering

CP violation

NB A precise measurement in this plane can determine theta13, MH, delta, octant


Courtesy T2K Collaboration
Best-Fit T2K
Best-Fit NOνA
Data
Events/100MeV
Ratio
Reconstructed Energy [GeV]

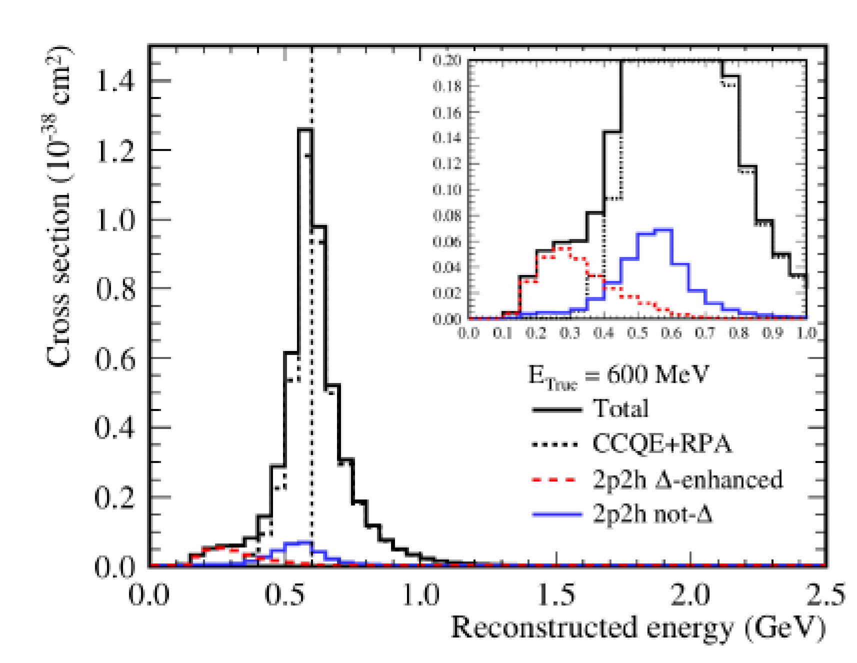
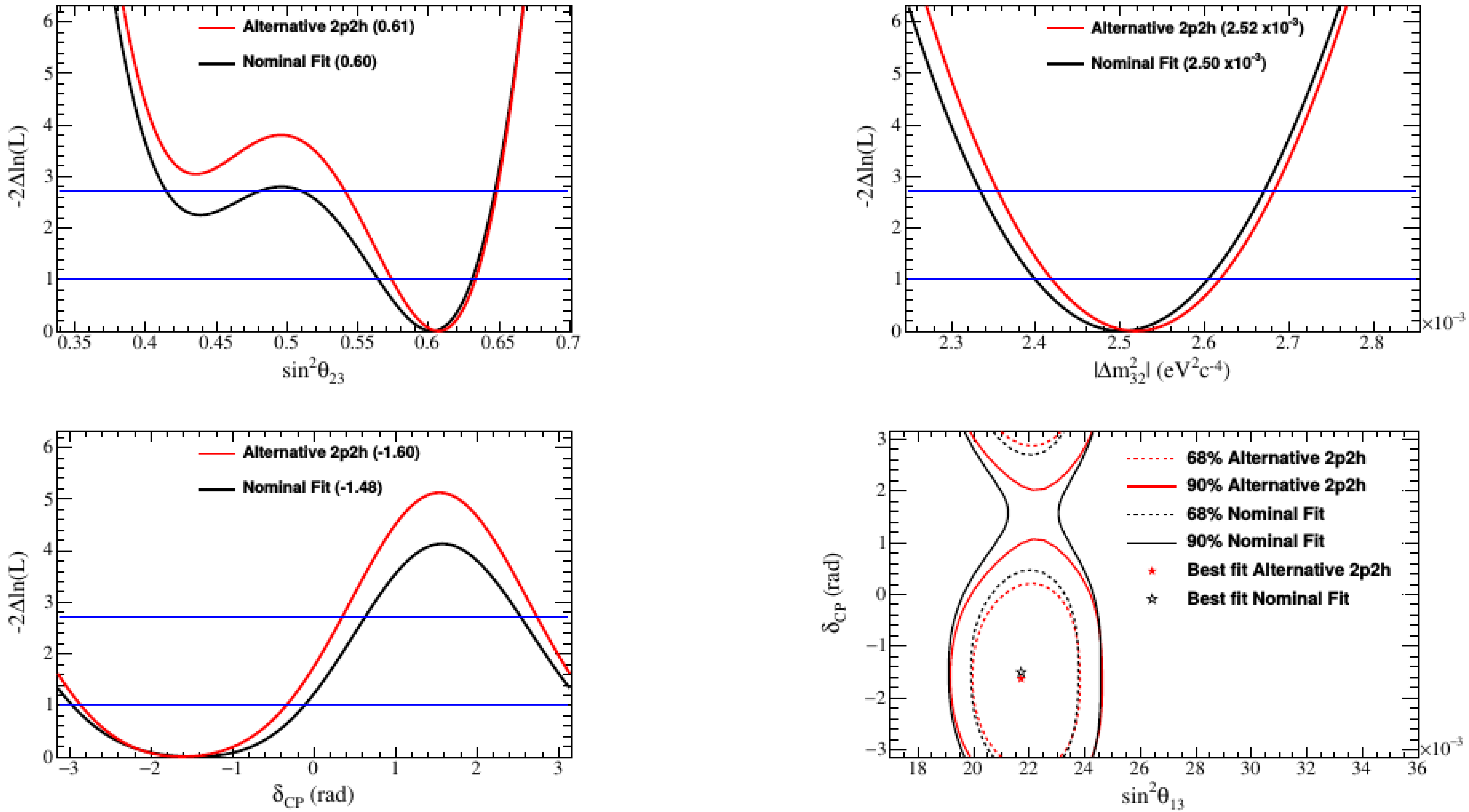


FIG. 5. Neutrino energy calculated with the CCQE two-body assumption for CCQE and 2p2h interactions of 600 MeV muon neutrinos on ^{12}C simulated with the reference model. The different components of 2p2h show differing amounts of bias.

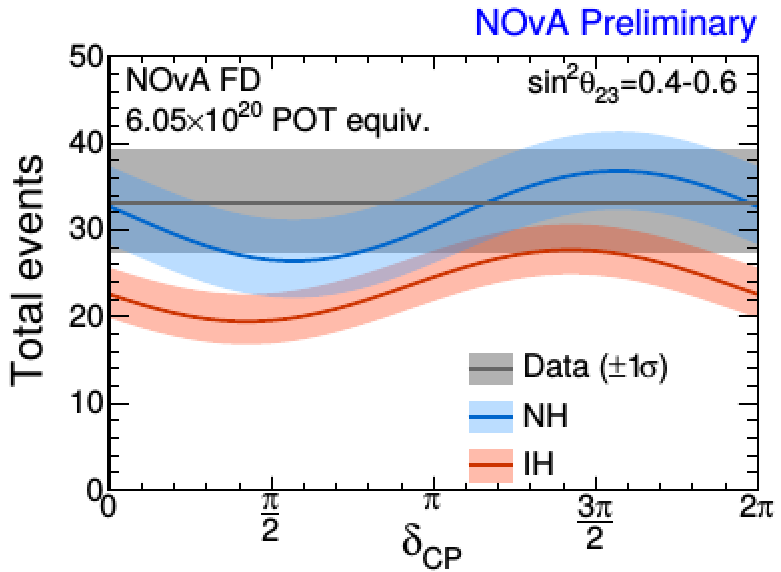
T2K arXiv:1707.01048

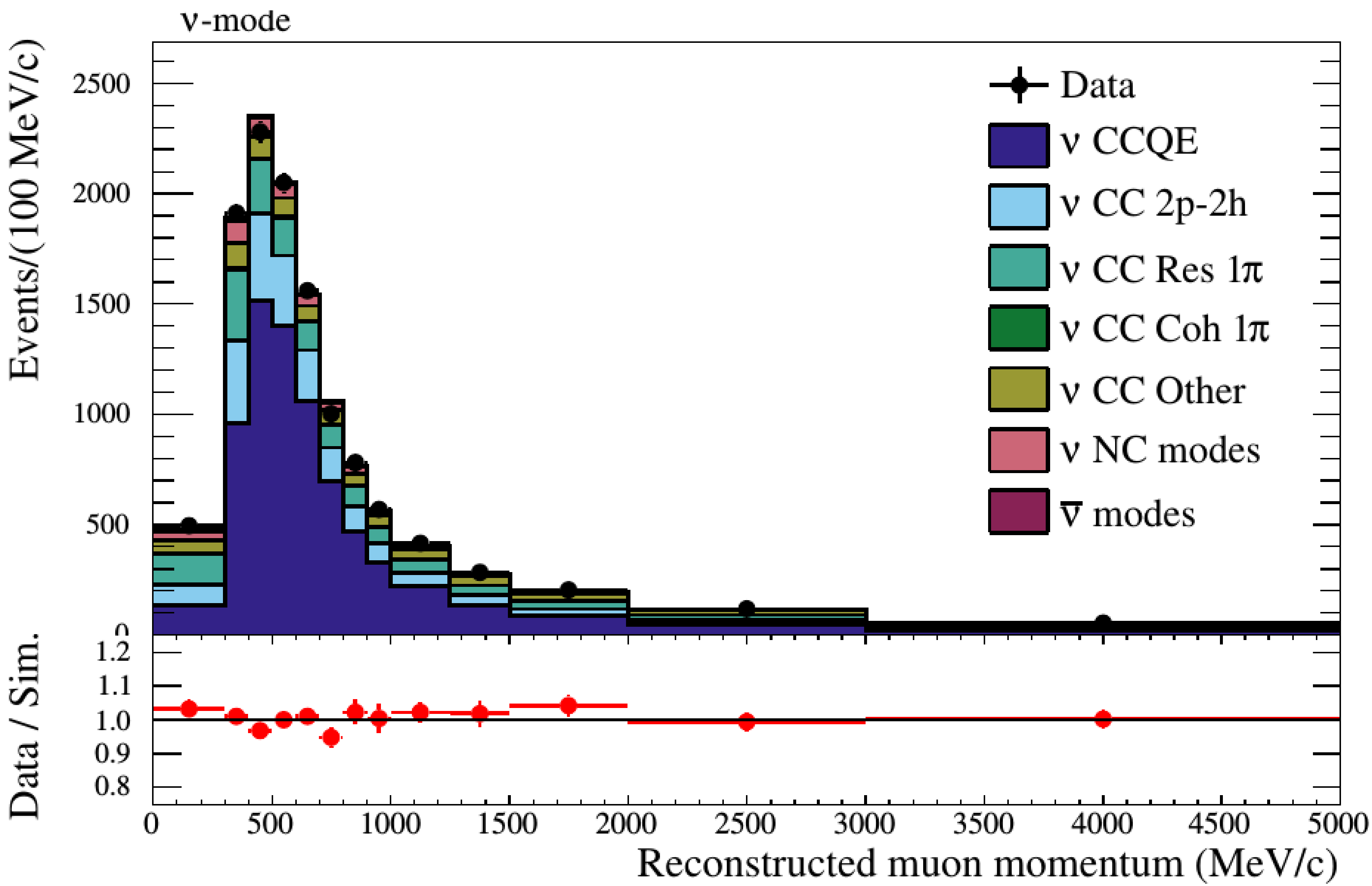


T2K arXiv:1707.01048

TABLE XXII. Summary of the maximum bias seen in oscillation parameters when fitting simulated datasets (defined in Sect. III B), presented as a fraction of the expected 1σ uncertainty on each parameter. Fits were performed for a number of true oscillation parameter assumptions. The numbers shown here are the maximum bias found for a given parameter and alternative model across all true oscillation parameter values tested.

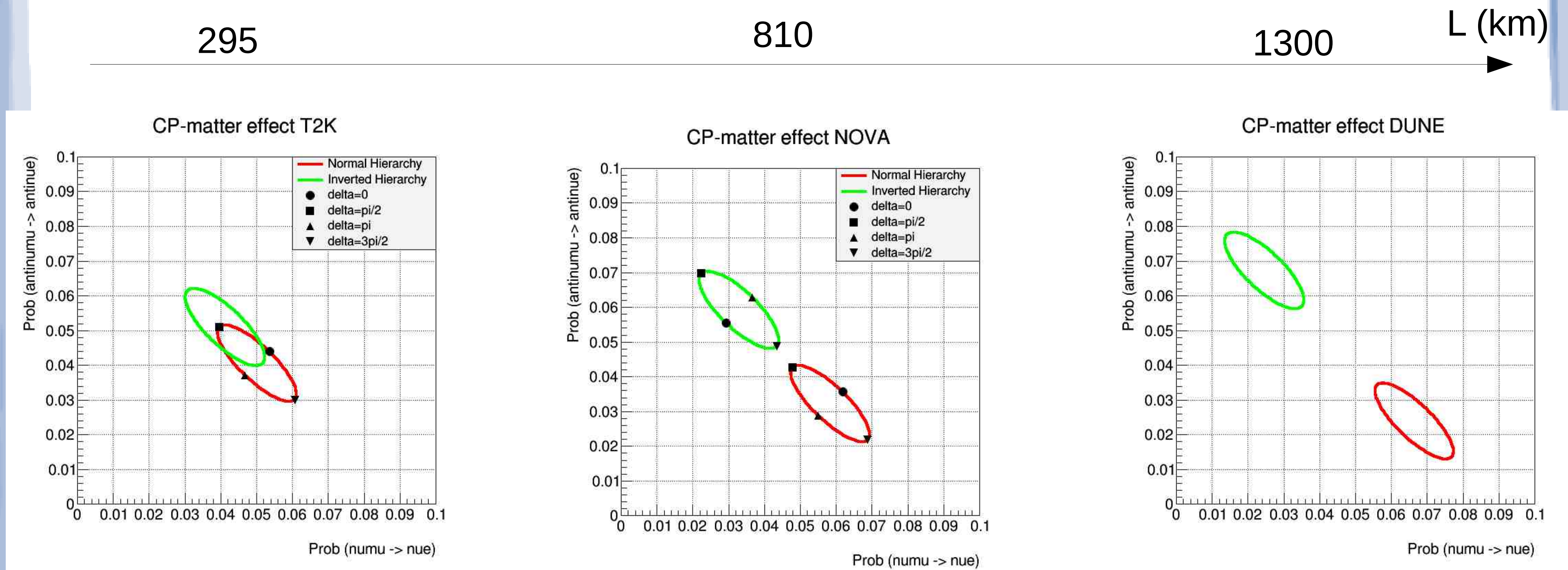
Alternative model	Maximum bias on parameter (σ)		
	Δm^2_{32}	$\sin^2\theta_{23}$	$\sin^2\theta_{13}$
SF	0.09	0.17	0.17
Effective RPA	0.00	0.06	0.00
Alternative 1p1h	0.20	0.09	0.07
Alternative 2p2h	0.20	0.21	0.18
Delta-enhanced 2p2h	0.10	0.10	0.00
Not-Delta 2p2h	0.11	0.07	0.05


NOvA Preliminary
NOvA FD
6.05×10^20 POT equiv.
sin^2θ23=0.4-0.6
Total events
0
10
20
30
40
50
0
π/2
π
3π/2
2π
δCP
Data (±1σ)
NH
IH



ν-mode
Events/(100 MeV/c)
2500
2000
1500
1000
500
0
Data
ν CCQE
ν CC 2p-2h
ν CC Res 1π
ν CC Coh 1π
ν CC Other
ν NC modes
ν̄ modes
Data / Sim.
1.2
1.1
1.0
0.9
0.8
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
Reconstructed muon momentum (MeV/c)

Combined effect of CP and matter



The relative increase of matter effect versus CP effect is due to the fact that these experiments are tuned to the L/E of the first oscillation maximum. The increasing L and E are such that Prob (numu->nue) climbs the slope of the MSW resonance.

For T2K, CP modulation +-27%, Matter effect ~10%