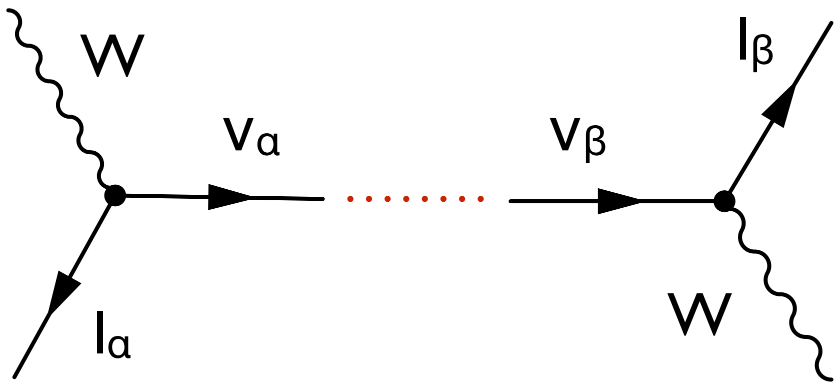
La misura della violazione di fase δ_{CP} nel settore leptonico: stato e prospettive

Lorenzo Magaletti (Politecnico di Bari & INFN Bari)
per il gruppo T2K di Bari

Congresso della sezione INFN e del Dipartimento di Fisica di Bari
22 Giugno 2021

Mixing of three neutrinos



Neutrinos produced in weak processes (ν_α) are linear combinations of mass eigenstates (ν_i)

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

where **U** is the **Pontecorvo-Maki-Nakagawa-Sakata (PMNS)** matrix

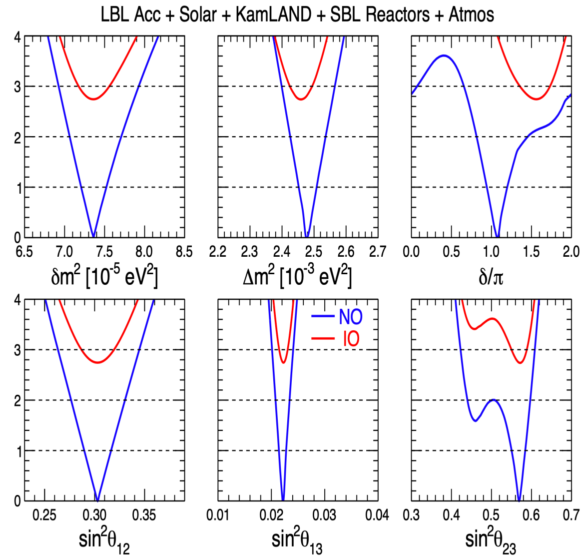
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & +c_{23} & +s_{23} \\ 0 & -s_{23} & +c_{23} \end{pmatrix} \begin{pmatrix} +c_{13} & 0 & +s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & +c_{13} \end{pmatrix} \begin{pmatrix} +c_{12} &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

Super-K, K2K, MINOS, OPERA, NOνA, **T2K**

DChooz, Daya Bay, RENO MINOS, NOνA, **T2K**

Super-K, SNO, KamLAND

Global Fits
A. Marrone @ NuTel 2021



$c_{ij} = \cos(\theta_{ij})$, $s_{ij} = \sin(\theta_{ij})$
(PMNS Neglecting possible Majorana phases)

Current knowledge:

- $\theta_{12} \approx 33^\circ$
- $\theta_{23} \approx 45^\circ$
- $\theta_{13} \approx 9^\circ$
- $\Delta m^2_{21} \approx 7.4 \times 10^{-5}$ eV^2
- $|\Delta m^2_{31}| \approx 2.5 \times 10^{-3}$ eV^2

Open questions:

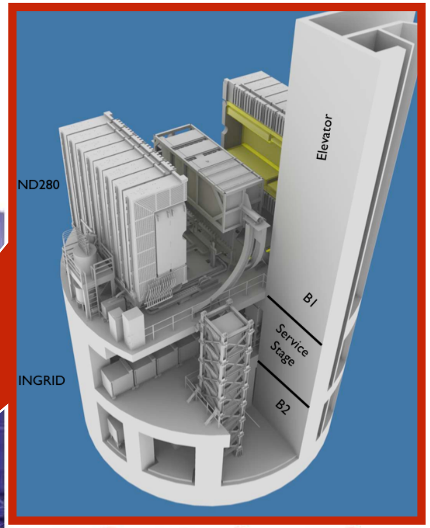
- CP violation?
- Mass hierarchy ($m_{1,2} \gtrless m_3$)?
- Is $\theta_{23} = 45^\circ$? If not is θ_{23} greater or lower than 45°?
- More PMNS symmetries?
- Majorana/Dirac?

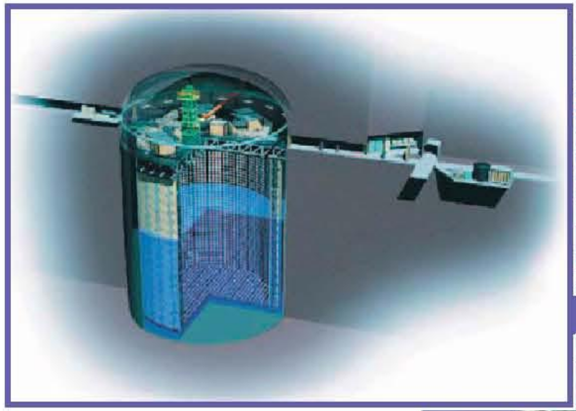
Neutrino oscillations at T2K

T2K

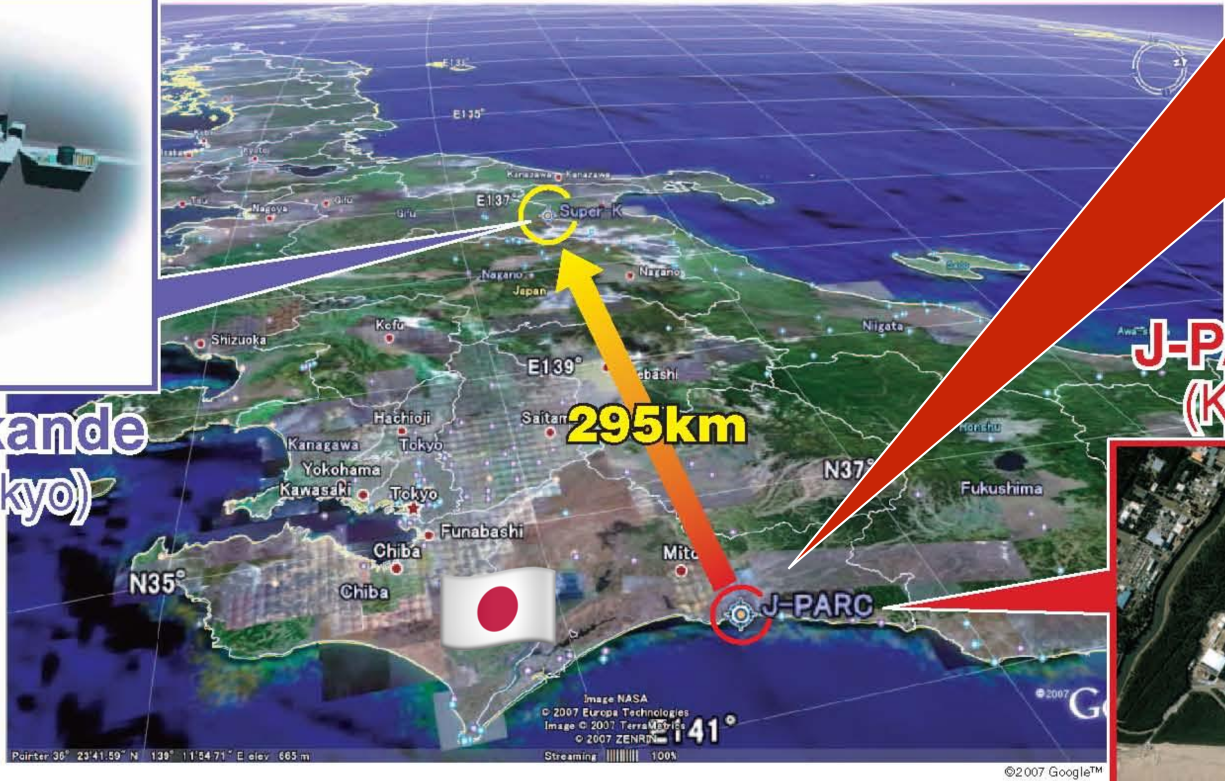
Near detector complex

at 280 m from the target





Super-Kamiokande
(ICRR, Univ. Tokyo)



J-PARC Main Ring
(KEK-JAEA, Tokai)

Intense high purity muon (anti)neutrino beam from J-PARC to Super-K to study:

- Muon (anti) neutrino disappearance $\nu_\mu \nrightarrow \nu_\mu$ ($\bar{\nu}_\mu \nrightarrow \bar{\nu}_\mu$)
- Electron (anti) neutrino appearance $\nu_\mu \rightarrow \nu_e$ ($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$)
- Rich program of:
  - neutrino cross sections studies with near detectors
  - “exotic” physics: sterile neutrinos, etc…

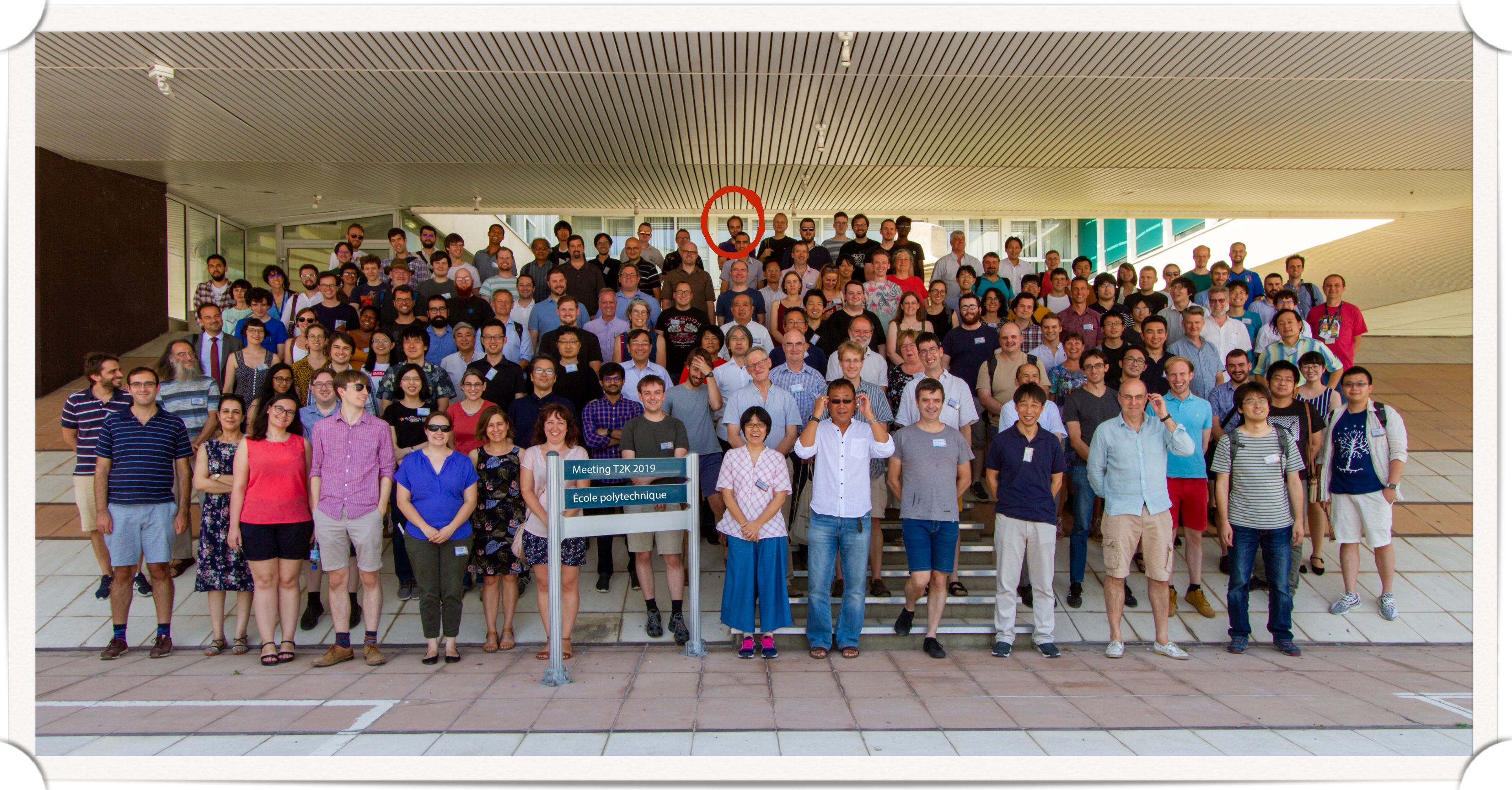
T2K one of the biggest international collaboration of neutrino LBL

~500 physicists, 69 institutions, 12 countries

Europe	261
France	38
Germany	5
Italy	28
Poland	28
Russia	19
Spain	14
Switzerland	30
UK	99

Americas	96
Canada	26
USA	70

Asia	117
Japan	114
Vietnam	3



Very strong European contribution including CERN

Neutrino oscillations at T2K

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

- Precision measurement of θ_{23} and Δm^2_{31}
- CPT test with anti-neutrino mode ($\bar{\nu}_\mu \to \bar{\nu}_\mu$)

$$\begin{aligned} P(\nu_\mu \to \nu_e) = \; & 4c^2_{13}s^2_{13}s^2_{23}\sin^2\frac{\Delta m^2_{13}L}{4E_\nu} \times \left[1 \pm \frac{2a}{\Delta m^2_{13}}(1 - s^2_{13})\right] \\ & +8c^2_{13}s_{12}s_{13}s_{23}(c_{12}c_{23}\cos\delta_{CP} - s_{12}s_{13}s_{23})\cos\frac{\Delta m^2_{23}L}{4E_\nu}\sin\frac{\Delta m^2_{13}L}{4E_\nu}\sin\frac{\Delta m^2_{12}L}{4E\nu} \\ & \mp 8c^2_{13}c_{12}c_{23}s_{12}s_{13}s_{23}\sin\delta_{CP}\sin\frac{\Delta m^2_{23}L}{4E_\nu}\sin\frac{\Delta m^2_{13}L}{4E_\nu}\sin\frac{\Delta m^2_{12}L}{4E_\nu} \\ & +4s^2_{12}c^2_{13}(c^2_{13}c^2_{23} + s^2_{12}s^2_{23}s^2_{13} - 2c_{12}c_{23}s_{12}s_{23}s_{13}\cos\delta_{CP})\sin\frac{\Delta m^2_{12}L}{4E_\nu} \\ & \mp 8c^2_{12}s^2_{13}s^2_{23}\cos\frac{\Delta m^2_{23}L}{4E_\nu}\sin\frac{\Delta m^2_{13}L}{4E_\nu}\frac{aL}{4E_\nu}(1 - 2s^2_{13}) \end{aligned}$$

Term labels (top to bottom): θ_{13} driven; CP even; CP odd; Solar driven; Matter effect (CP odd)

Change sign by changing ν with $\bar{\nu}$

B. Richter, SLAC-PUB-8587

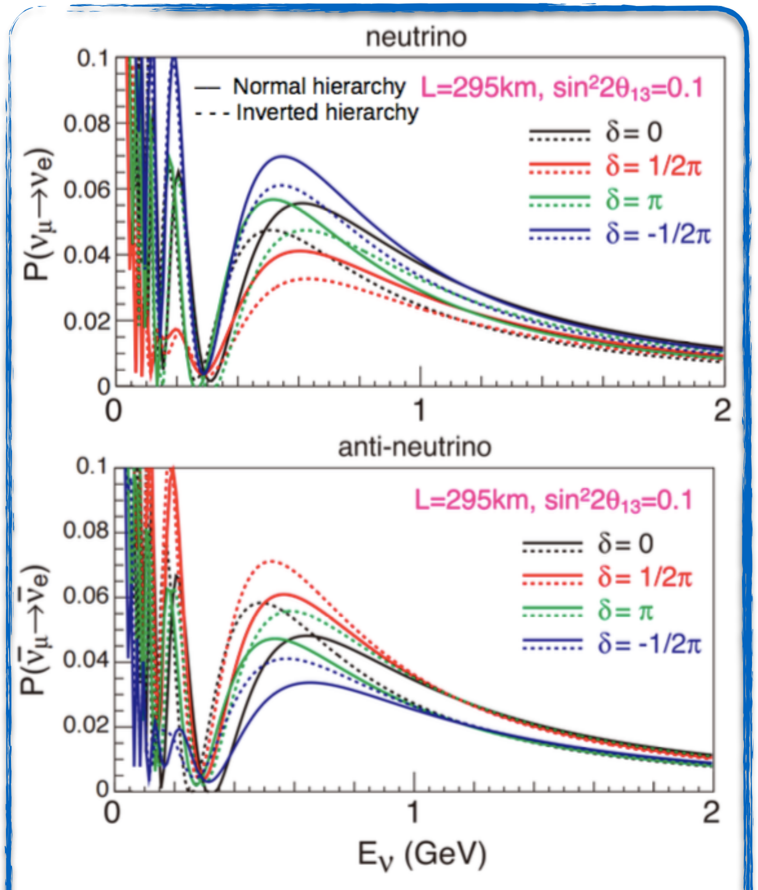
$a[\mathrm{eV}^2] = 2\sqrt{2}G_F n_e E_\nu = 7.6 \times 10^{-5}\rho[\mathrm{g/cm}^2]E_\nu[\mathrm{GeV}]$

- θ_{13} dependence of the leading term
- θ_{23} dependence of the leading term (θ_{23}=45° or $\theta_{23}\gtrsim$45°?)
- CP odd phase delta: asymmetry of probabilities $P(\nu_\mu \to \nu_e) \neq P(\bar{\nu}_\mu \to \bar{\nu}_e)$ if $\sin\delta \neq 0$
- Matter effect: ν_e ($\bar{\nu}_e$) appearance enhanced in normal (inverted) mass hierarchy

Learning from ν_e ($\bar{\nu}_e$) appearance

- $\sin^2 2\theta_{13}$ and $\sin^2\theta_{23}$
  - Enhance/suppress both ν_e and $\bar{\nu}_e$ appearance

- CP-violating phase δ_{CP} (**up to ±30% effect at T2K**)
  - **δ_{CP} = 0, π**⇒ no CP violation: $P(\nu_\mu\rightarrow\nu_e) = P(\bar{\nu}_\mu\rightarrow\bar{\nu}_e)$ in vacuo
  - **δ_{CP} ~ -π/2**: enhance $\nu_\mu\rightarrow\nu_e$ and suppress $\bar{\nu}_\mu\rightarrow\bar{\nu}_e$
  - **δ_{CP} ~ +π/2**: suppress $\nu_\mu\rightarrow\nu_e$ and enhance $\bar{\nu}_\mu\rightarrow\bar{\nu}_e$



PTEP 2015 (2015) 053C02

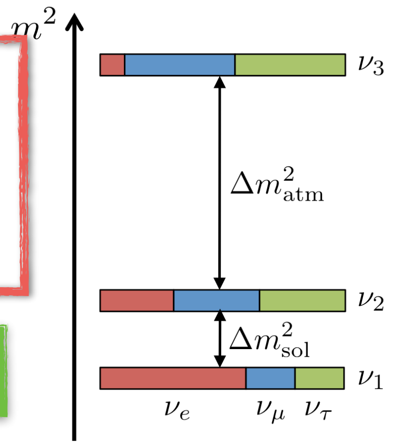
Normal hierarchy

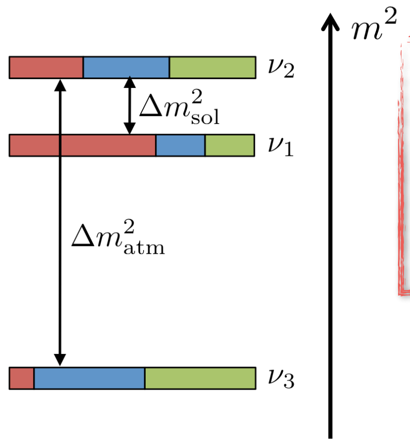
- Enhance $\nu_\mu\rightarrow\nu_e$
- Suppress $\bar{\nu}_\mu\rightarrow\bar{\nu}_e$

±10% effect at T2K

normal hierarchy (NH)

inverted hierarchy (IH)



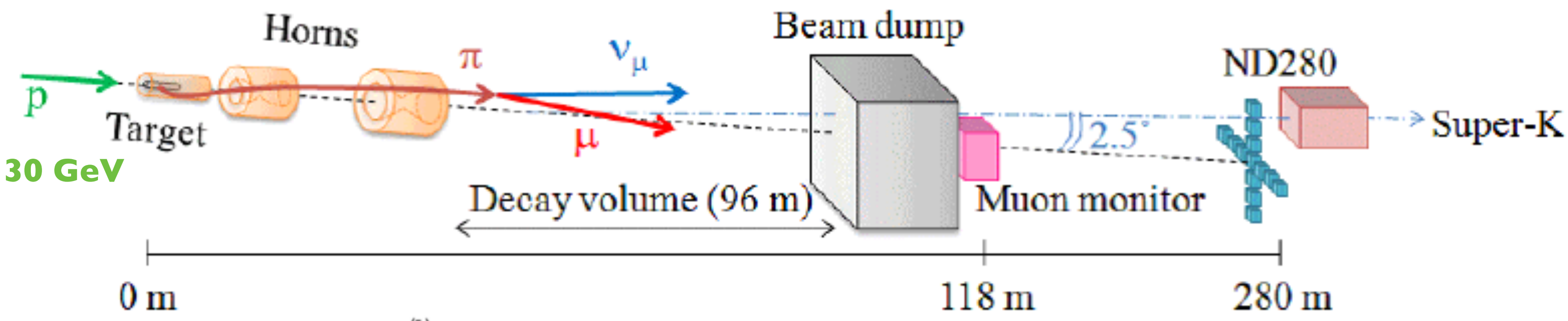


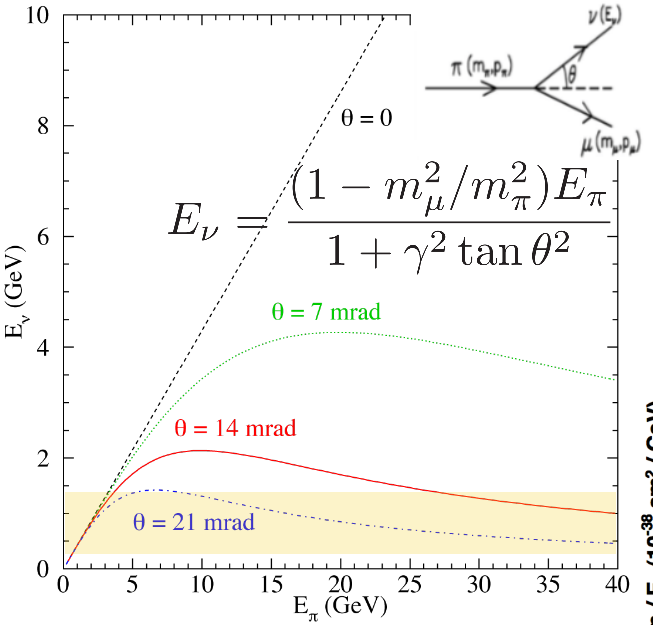
Inverted hierarchy

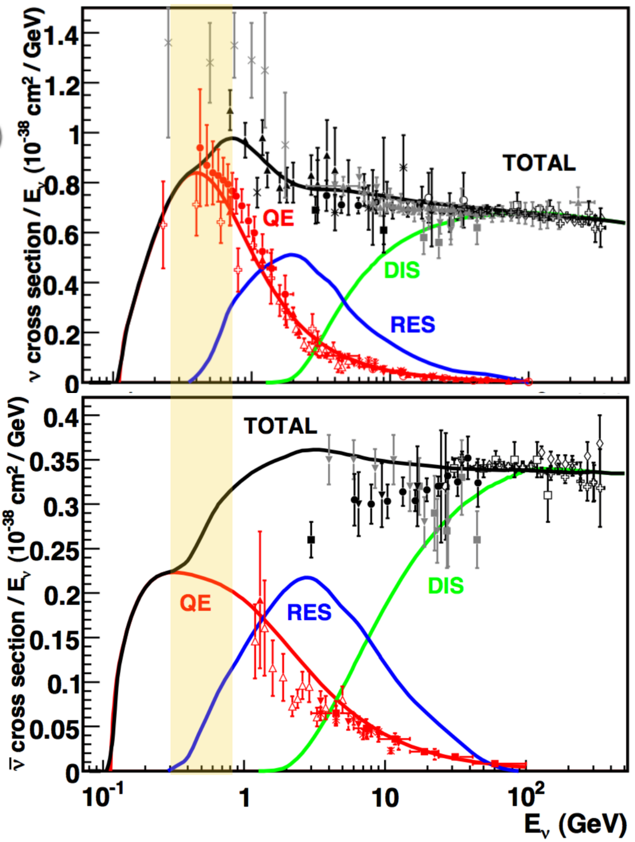
- Suppress $\nu_\mu\rightarrow\nu_e$
- Enhance $\bar{\nu}_\mu\rightarrow\bar{\nu}_e$

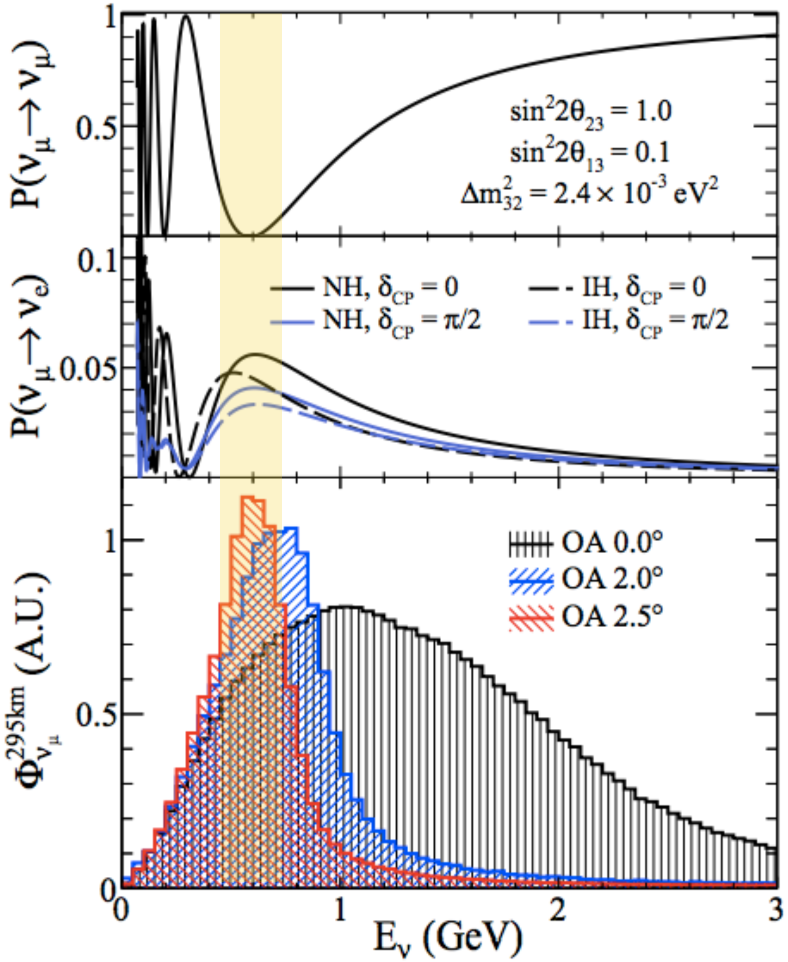
T2K experimental setup

The off-axis neutrino beam







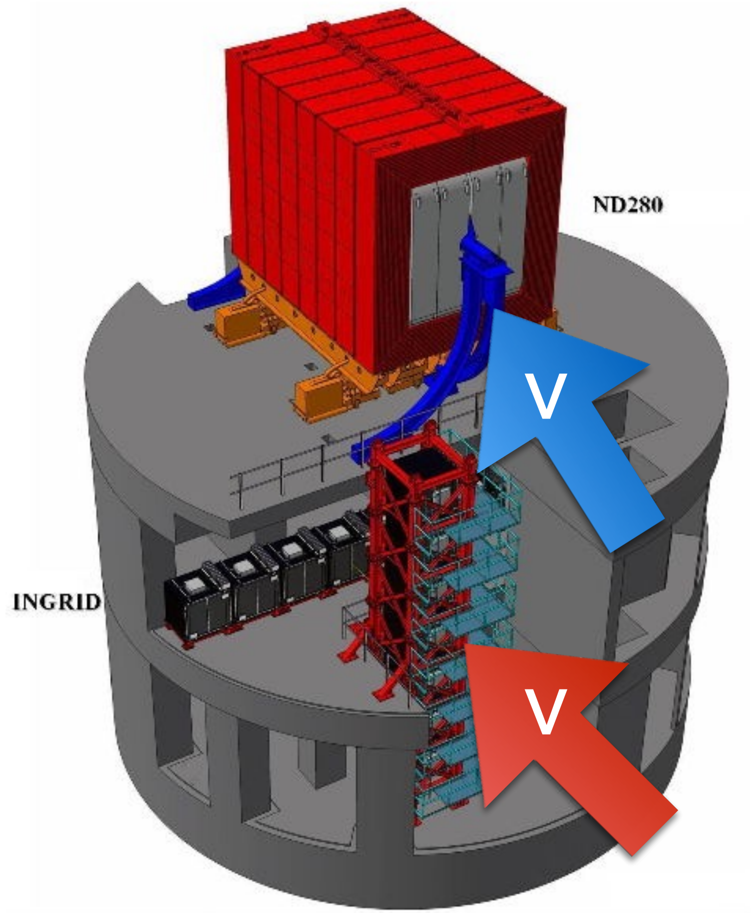


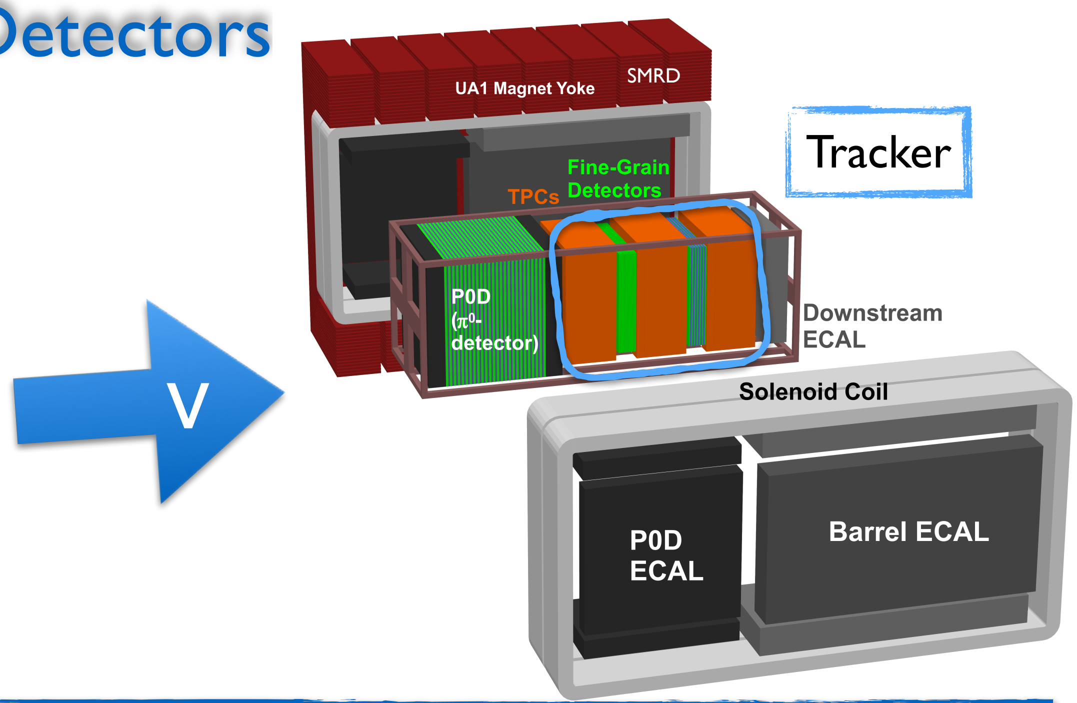
Charged Current Quasi-Elastic (CCQE)

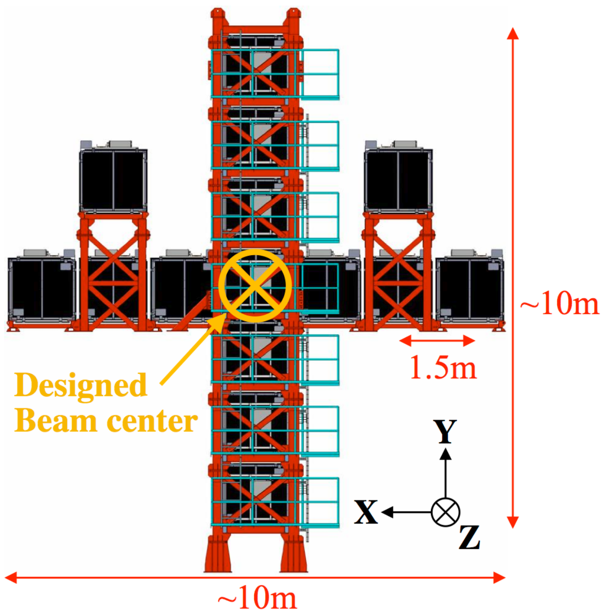
$$\nu_\mu + n \to \mu^- + p$$
$$\bar{\nu}_\mu + p \to \mu^+ + n$$

- Enhance neutrino oscillation effects
- Enhance CCQE-like interactions (signal at Super-Kamiokande)
- Reduces background from π^0 interactions
- Reduces ν_e contamination (less than 1%) at the peak

Near Detectors







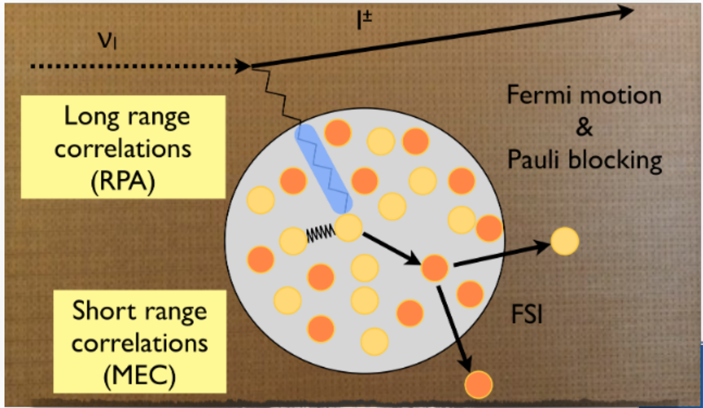
ND280 (off-axis)

- **Magnet:** B = 0.2 T
- **TPC:** p measurement + particle-ID with dE/dx
- **FGD:** Fine-grained detectors (2 x 0.8 t) → FGD1 (C), FGD2 (C+H_2O)
- **SMRD:** magnetized muon range detector
- **P0D:** pi-zero detector (Pb/brass-H_2O-scintillator)
- **ECal:** electromagnetic calorimeter

INGRID (on-axis)

- **ν_μ CC rate → monitor beam profile and stability**
- **Fe/Scintillator tracking calorimeter** (16 Fe/Scint modules + 1 central one made of scintillator only)

Neutrino cross sections at T2K energies

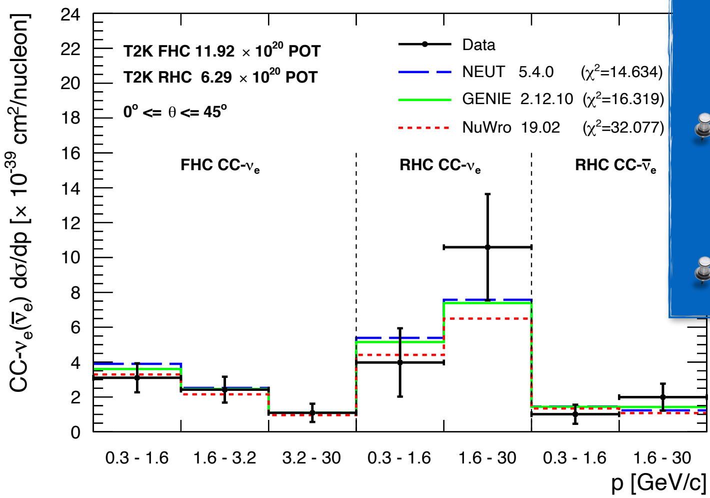


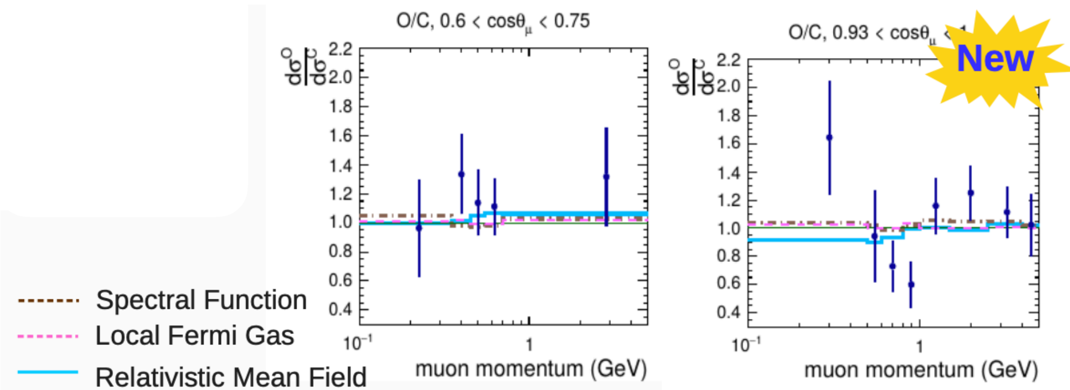
- At T2K energies the main kind of interactions are **CCQE**
  - Other neutrino interactions with production of **pions** in the final state are important as well
  - Discrepancies between different theoretical models
  - x-sec are not completely understood at T2K energies

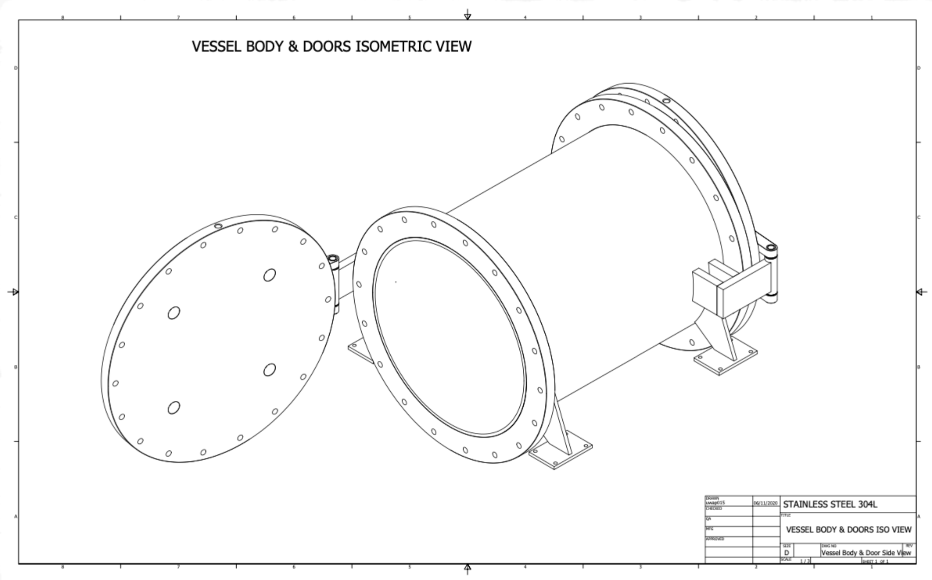
Latest x-sec measurement at ND280:

- ν_e and $\bar{\nu}_e$ measurement crucial for CPV
- $\nu_\mu/\bar{\nu}_\mu$ important for oscillation analysis
- Carbon/Oxigen Crucial for ND280 (CH, O) to SK (H_2O) extrapolation

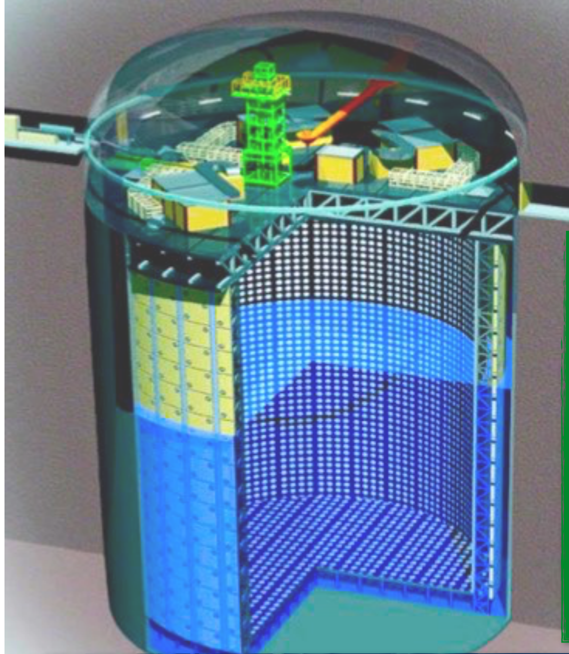
- **A dedicated experiment is needed in order to reduce these systematics → AIDA-Innova project (HPTPC with hybrid readout) started in Bari since April 2021**
- **Vessel design will be done by our CAD group here in Bari**







Far detector: Super-Kamiokande



Super-K (off-axis)

- Water Cherenkov (22.5 kt fiducial volume, > 11k PMT, ~40 m x 40 m)
- Excellent μ/e separation and π^0 detection (2 e-like rings)
- $\Delta E/E$ ~10% for Quasi-Elastic (QE) events

SIGNALS

$$\nu_l + n \rightarrow l^- + p \qquad \bar{\nu}_l + p \rightarrow l^+ + n$$

- Single μ/e like ring
- E_{rec} by energy/direction of lepton, 2-body kinematics

$$\nu_e + p \rightarrow e^- + \pi^+ + p$$

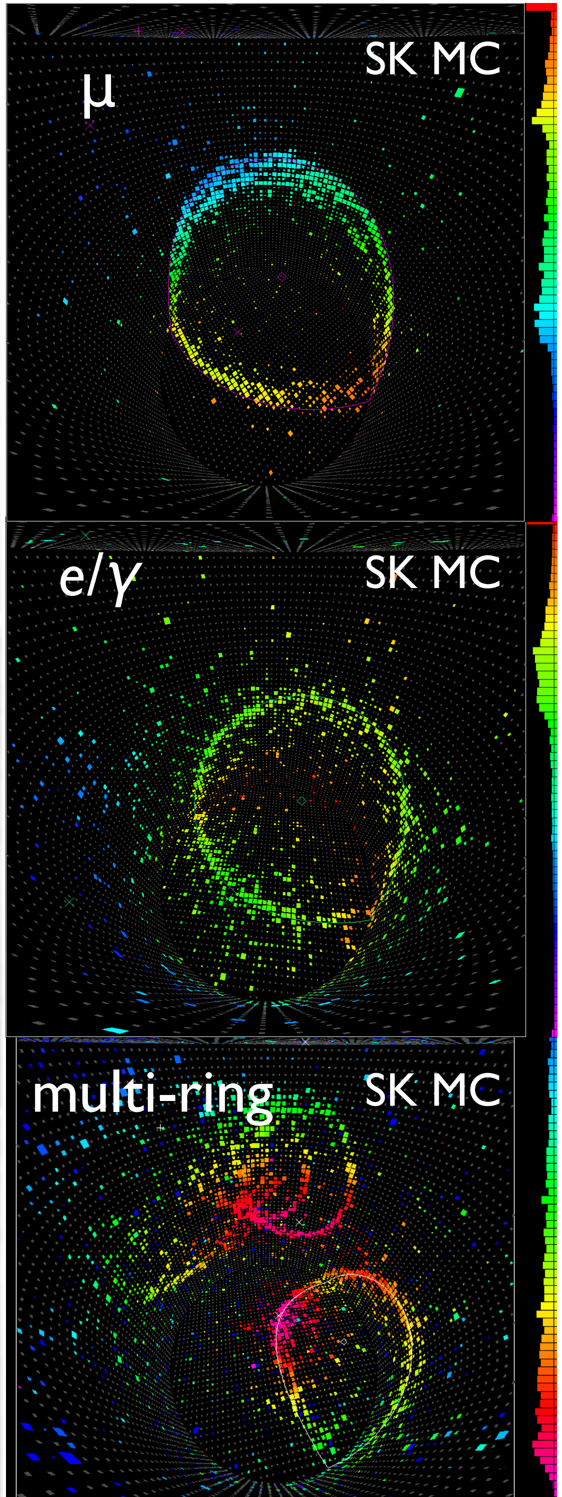
- Single e like ring
- E_{rec} by energy/direction of lepton, 2-body kinematics with a Δ^{++} recoil
- One decay electron

BACKGROUNDS

$$\nu_l + (n/p) \rightarrow \nu_l + (n/p) + \pi^0$$

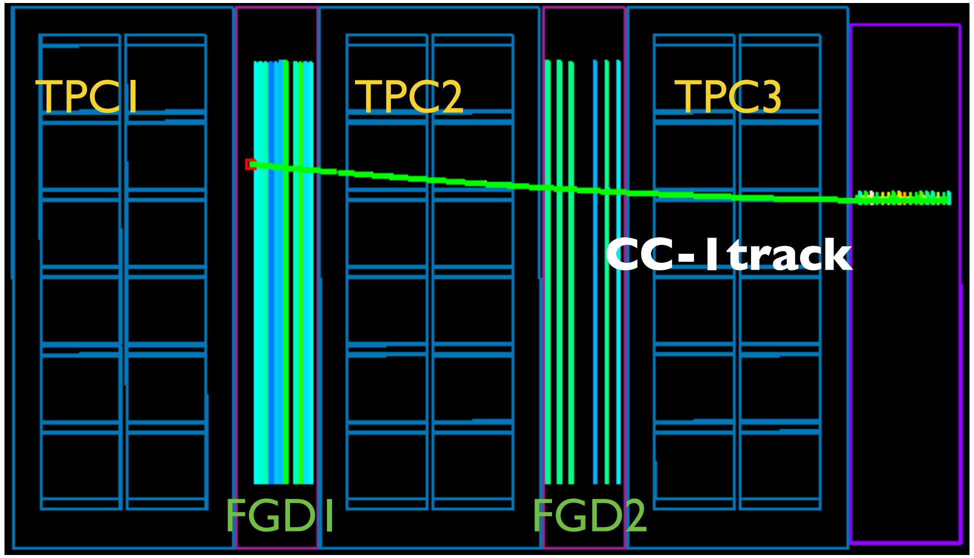
$$\nu_l + (n/p) \rightarrow l^- + (n/p) + \pi$$

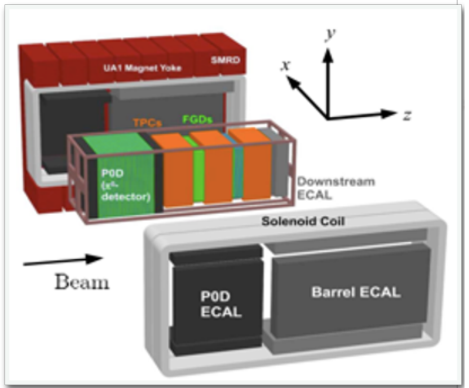
- $\pi^0 \rightarrow \gamma\gamma$: ring counting, 2-ring reconstruction
  - γ misidentified as e from ν_e CCQE
  - powerful rejection capabilities reduce this by $O(10^2)$
- Ring counting, decay electron cut to reject non-CCQE interactions

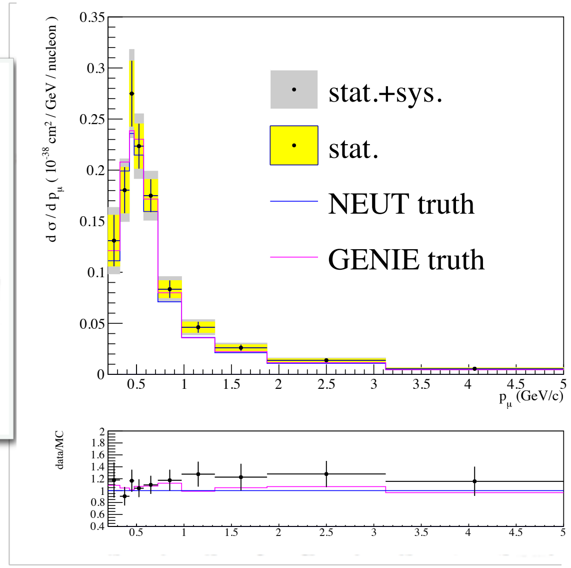


INFN-Bari’s group activities

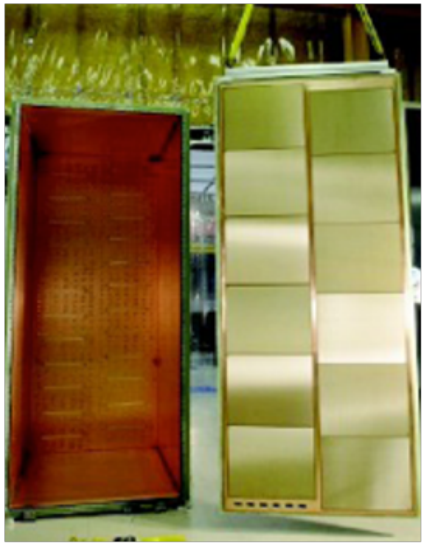
ND280



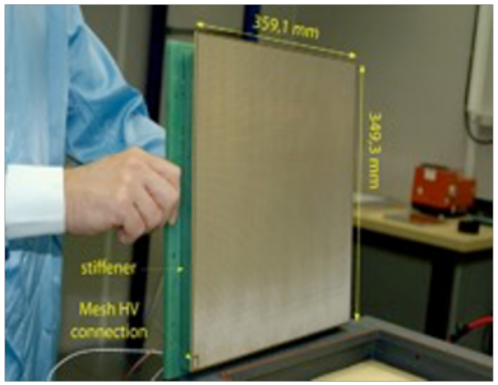




First large TPC with MPGD



TPC assembling



TPC design with advanced detectors (MPGD)

INFN Bari activities in T2K

- TPC design, assembling, calibration, maintenance and operation
- Leading role on TPCs (Emilio Radicioni)
- Leading in $\bar{\nu}_\mu$ analysis @ ND280
- Since 2012 our group is leading the T2K activities in Italy and in the executive committee of the T2K experiment (Gabriella Catanesi)

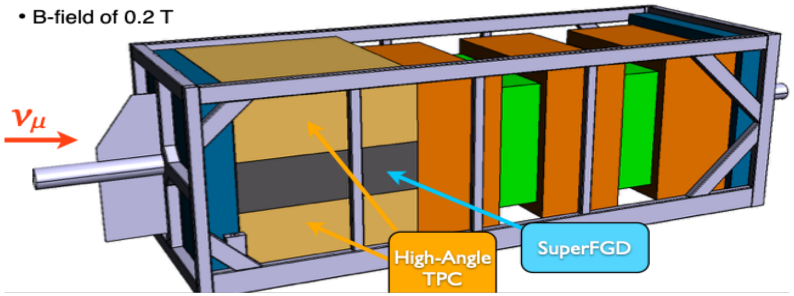
ND280-upgrade

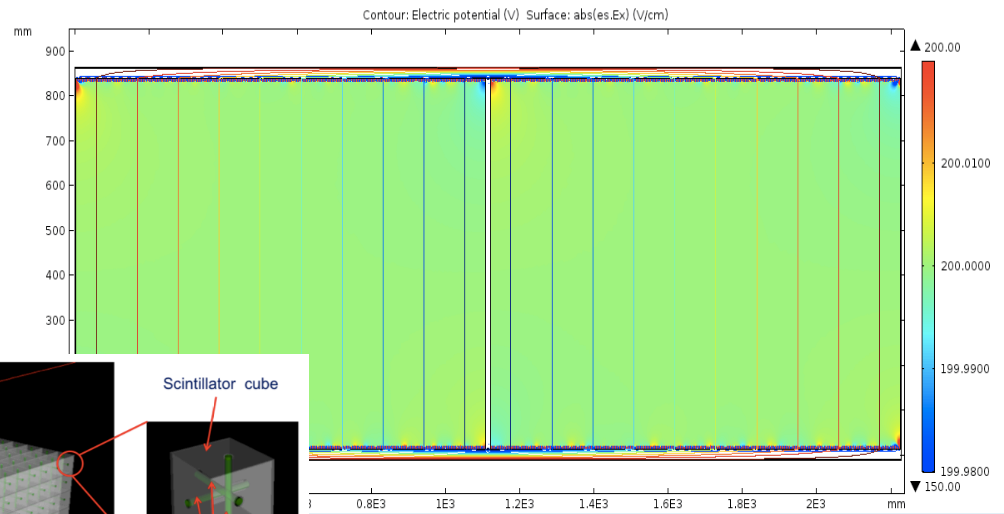
- **Our group is heavily involved in the new Horizontal TPC fir the ND280 upgrade**
- **COMSOL simulations:**
  - Good E filed uniformity up to 10^{-4}
  - Non uniformity <10 mm from the field strips
- 2020-2021: CAD design and **MOLD** produced for the HTPC at the **mechanical workshop** here in Bari
- 2022-2023: final design and construction of HTPCs, assembling, integration and test at CERN and J-PARC
- Leading role in the ND280-upgrade global reconstruction

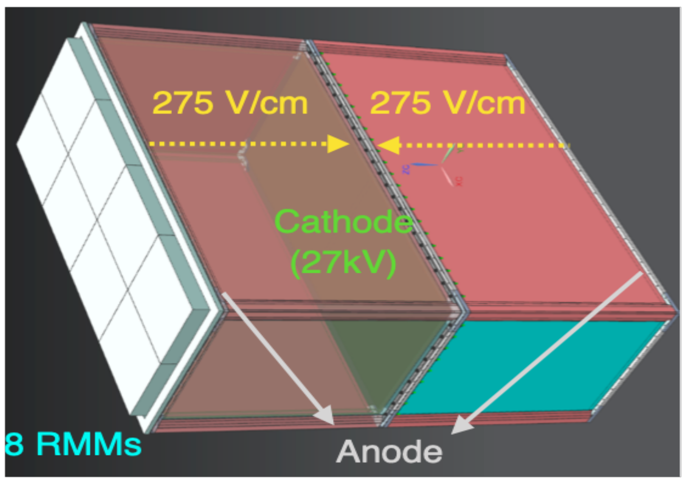
The T2K Near Detector upgrade

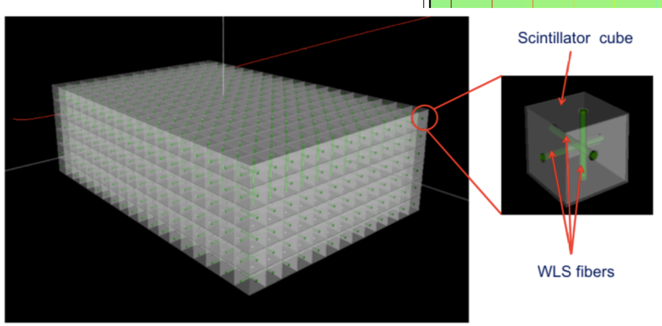
- Keep the electromagnetic calorimeter
- Horizontal active target detector: SuperFGD
- Two High-Angle TPCs
- Time-of-Flight detector around new tracker
- B-field of 0.2 T

	Current	Upgrade
Target Mass (tons)	2.2	4.3

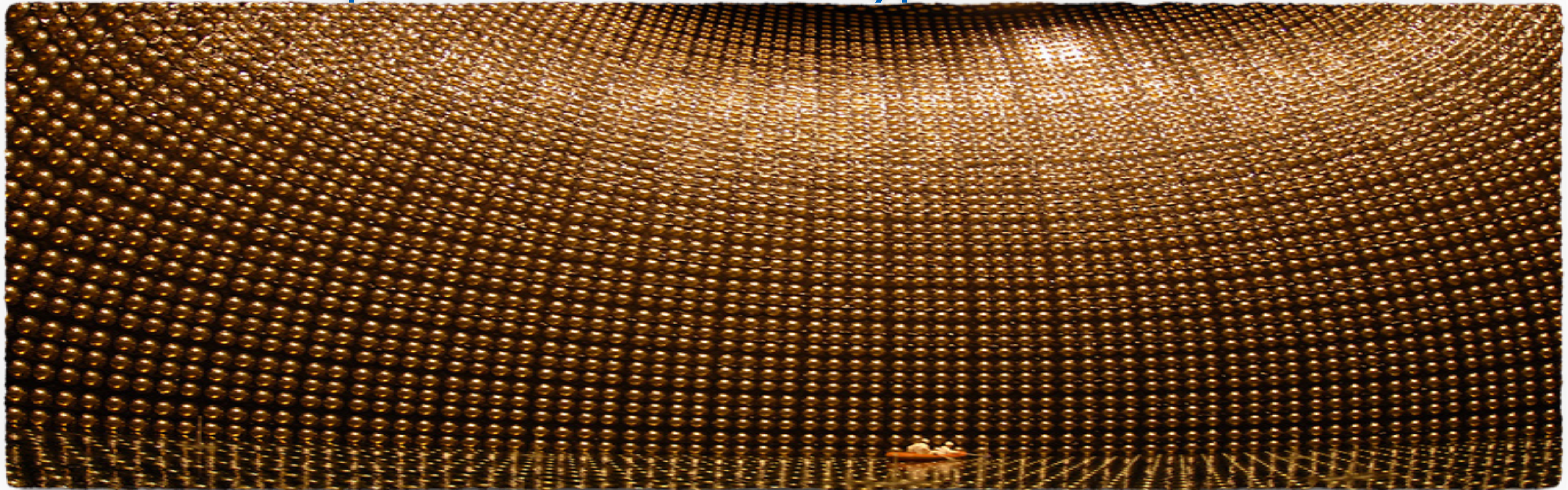


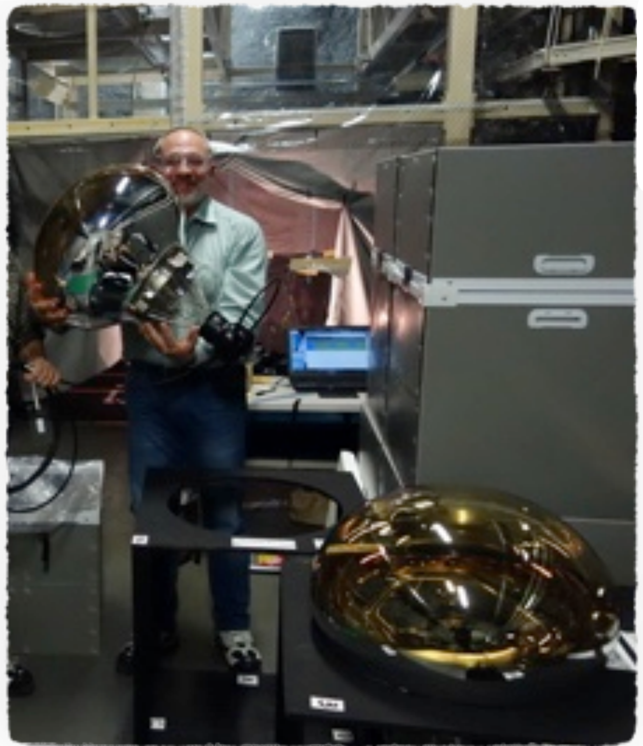


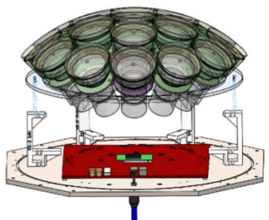




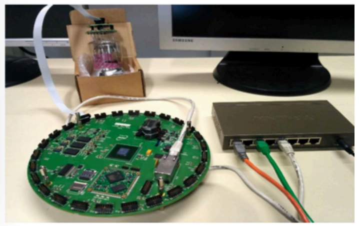
Super-Kamiokande and Hyper-Kamiokande





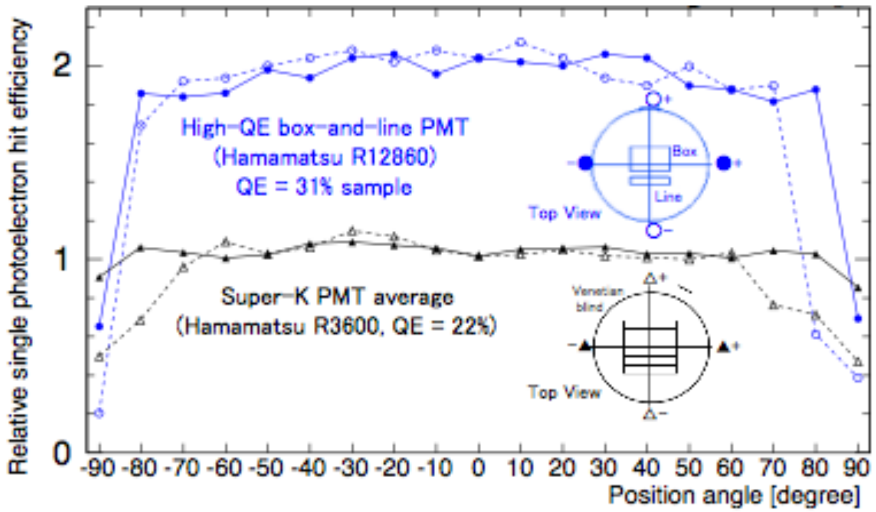


Prototype at TRIUMF



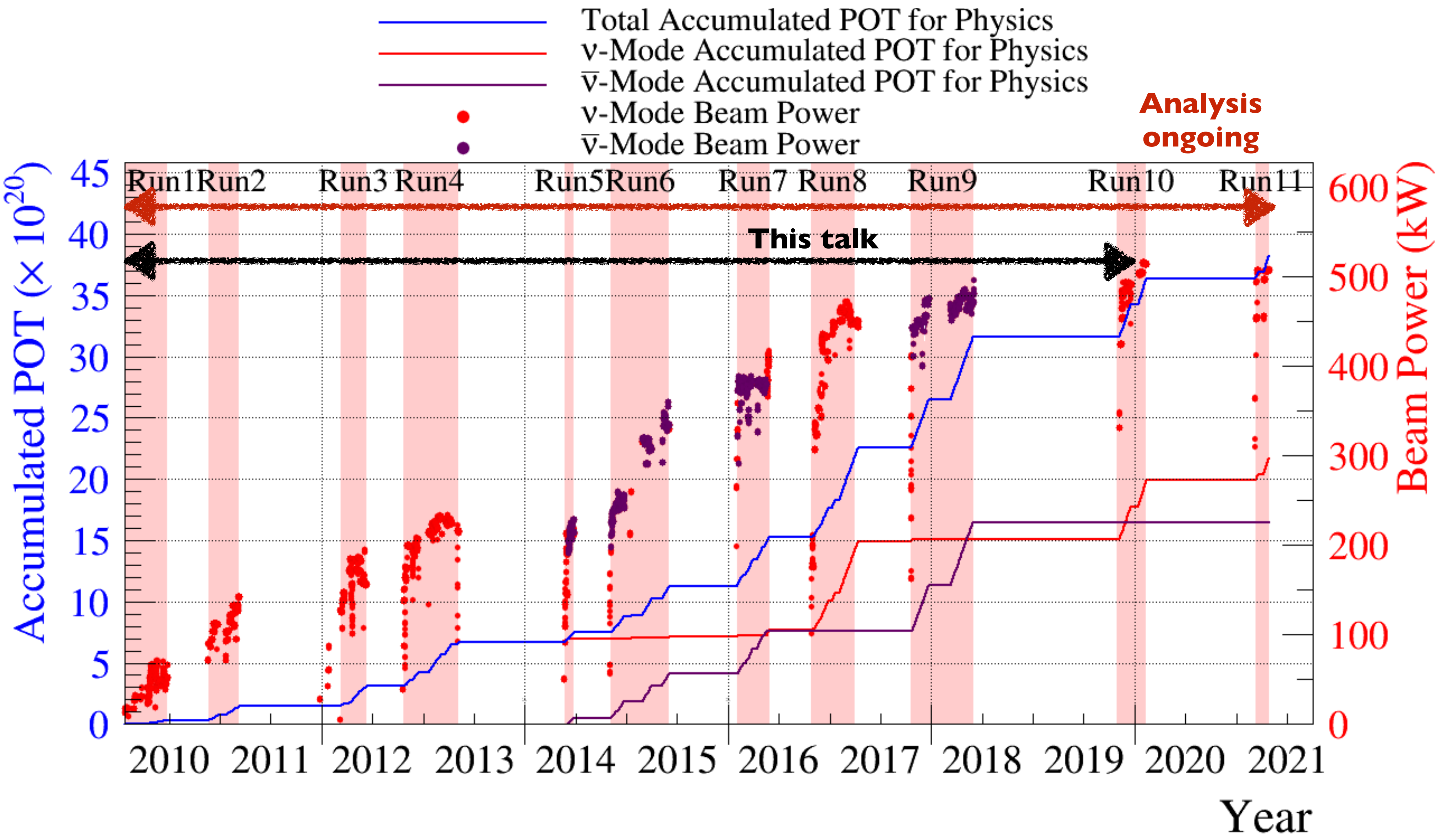
Electronics at INFN

- Participation to the SK refurbishment operations in Japan
- Proton decay channel analysis
  - $p \rightarrow \nu K^+ \rightarrow \nu \pi^+\pi^0$
- design Multi-PMTs for H-K (INFN+Poliba)



T2K oscillation results

Collected data analyzed



23 Jan 2010 - 12 Feb 2020

POT Total : 3.64059×10^{21}
(maximum power 522.627 kW)

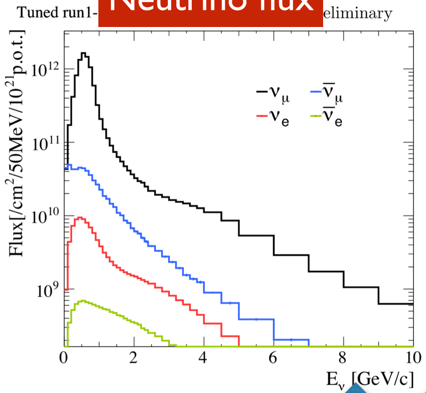
ν mode : 1.99006×10^{21} (54.7%)

$\bar{\nu}$ mode : 1.65053×10^{21} (45.3%)

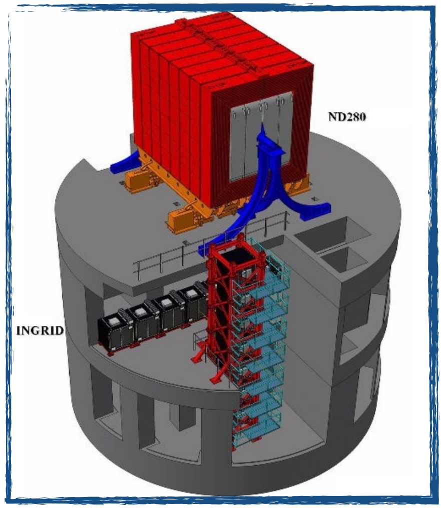
Analysis Model

T2K Run 1-10 Prelimi

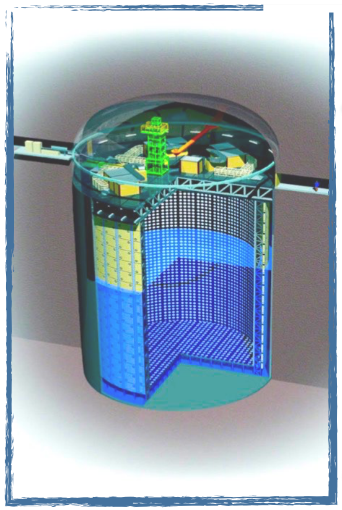
Neutrino flux

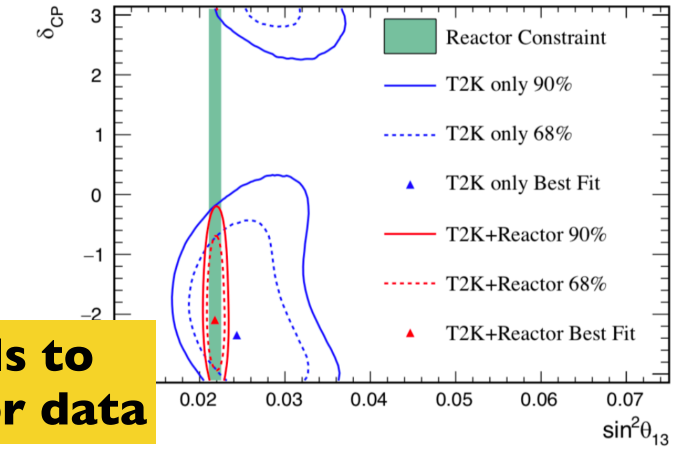


Tune models with Near detectors



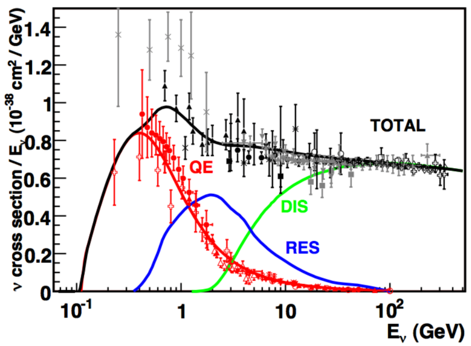
Fit models to Far detector data

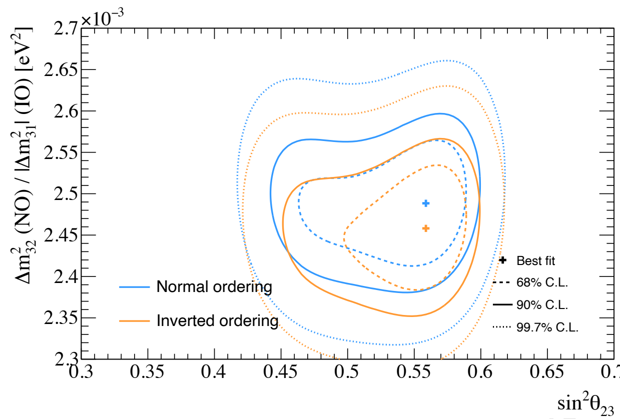




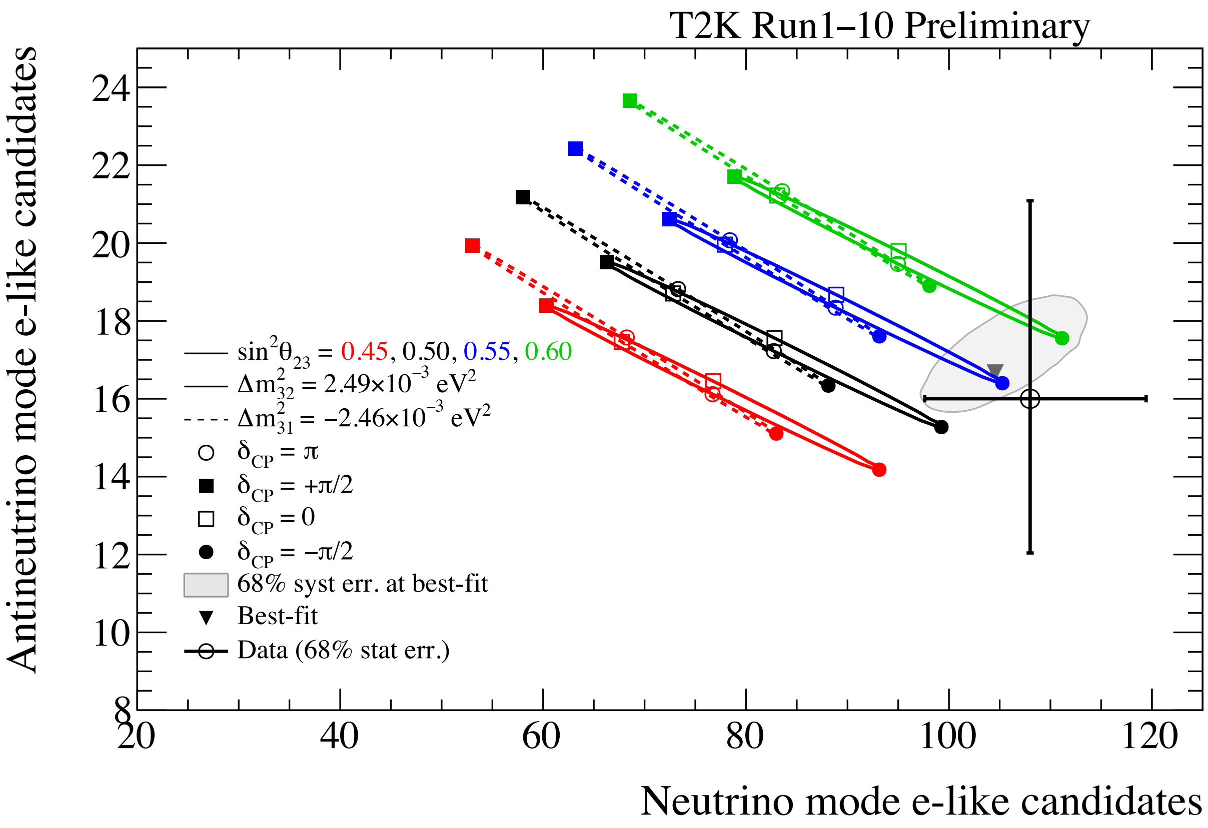
Oscillation parameter extraction

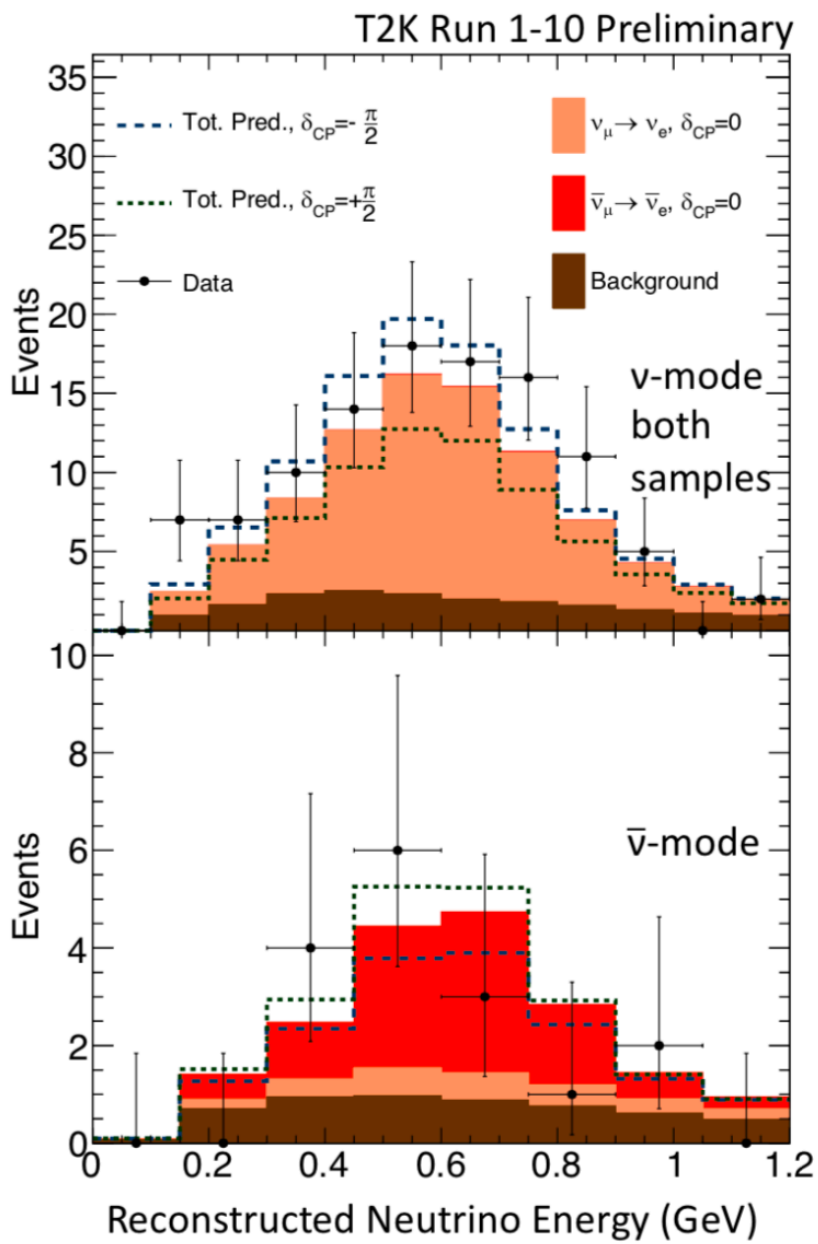
Neutrino x-sec model





SK ν_e and $\bar{\nu}_e$ data and PMNS predictions

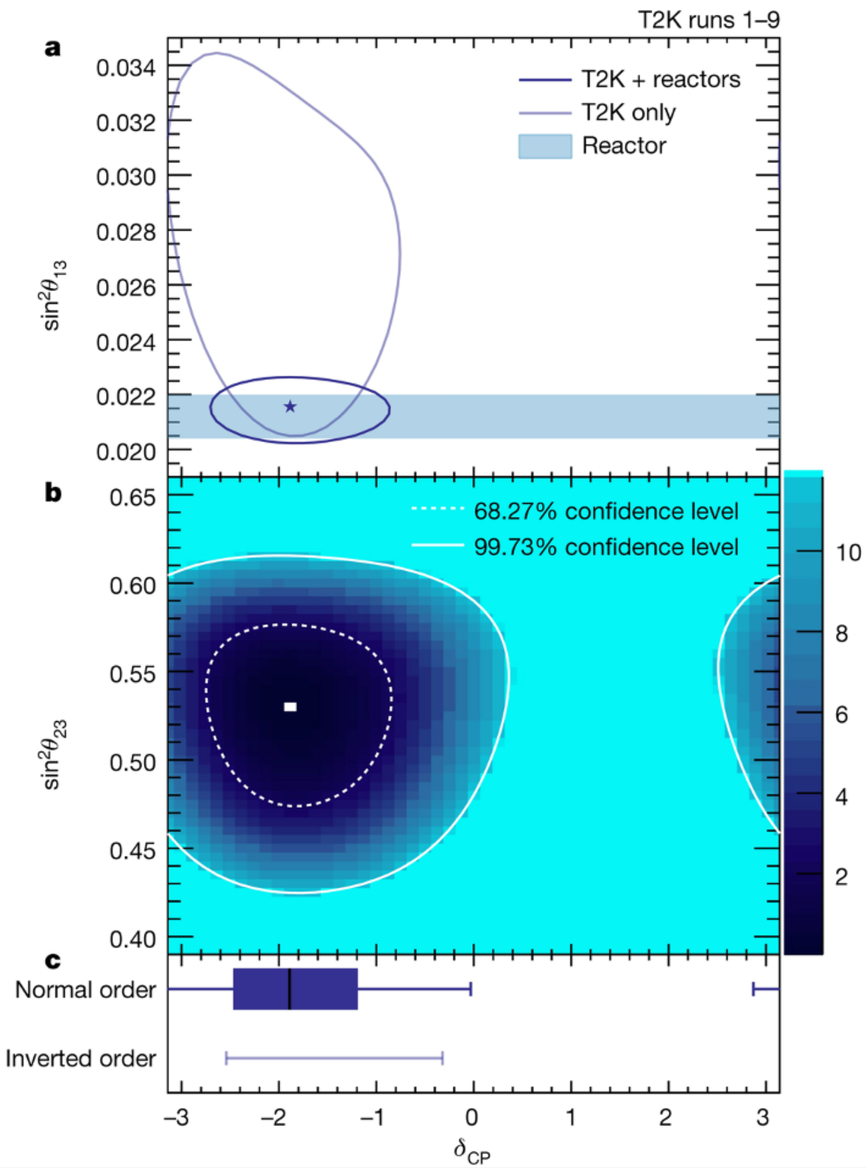


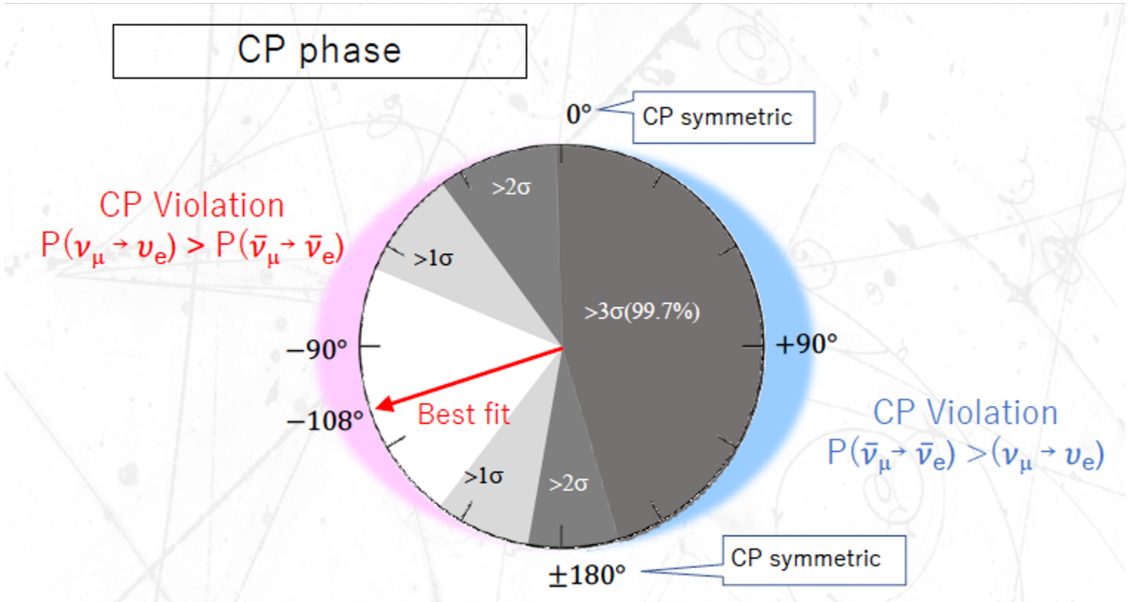


- We see an **excess of electron neutrinos** when compared to CP conserving case.
- Suggests a preference for **δ_{cp} = -π/2** and **Normal Ordered Masses**

Nature paper results (2019)

Our results show an indication of CP violation in the lepton sector!





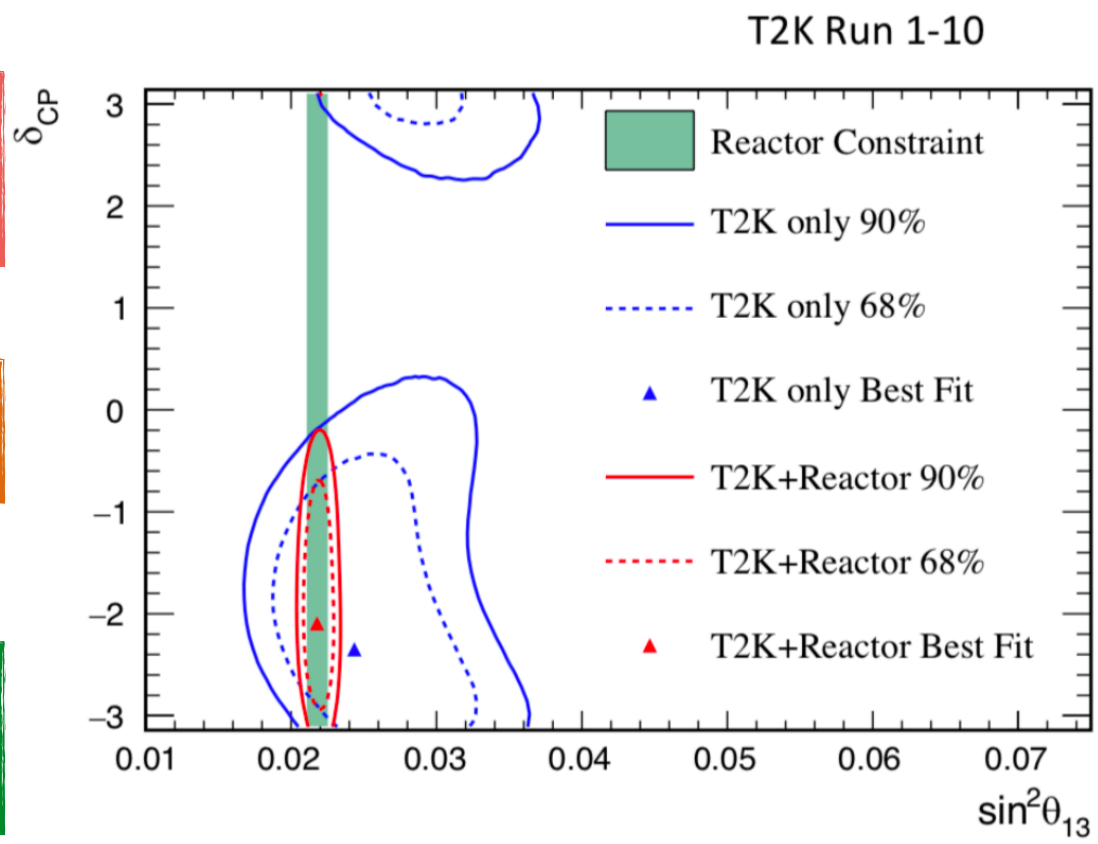
First 3σ limits on 46% (65%) of the δ_{cp} values in Normal (Inverted) Ordering

New results: T2K vs T2K + Reactor

T2K produces results with only T2K data and with the global reactor constraint on θ_{13}.

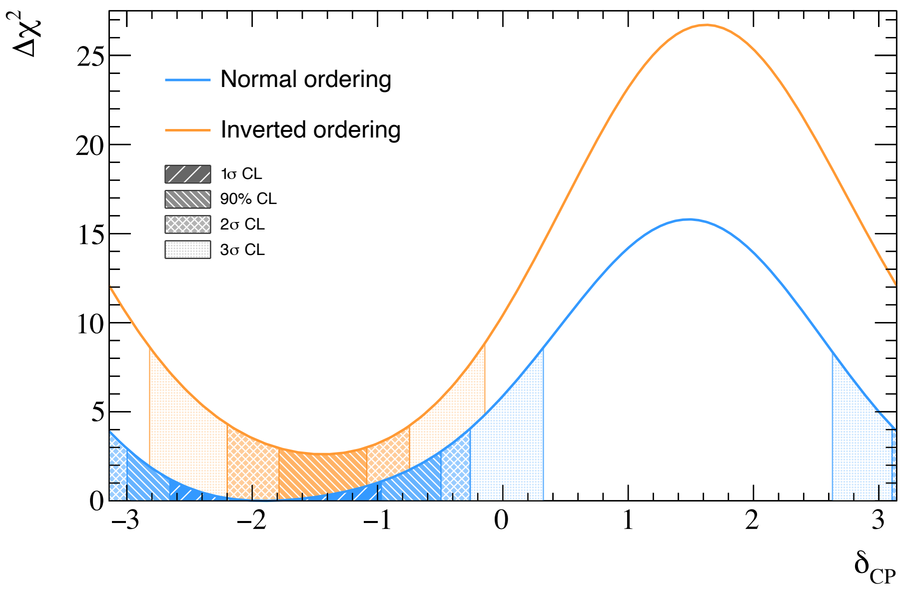
T2K ONLY result is consistent with reactor constraint to 1σ.

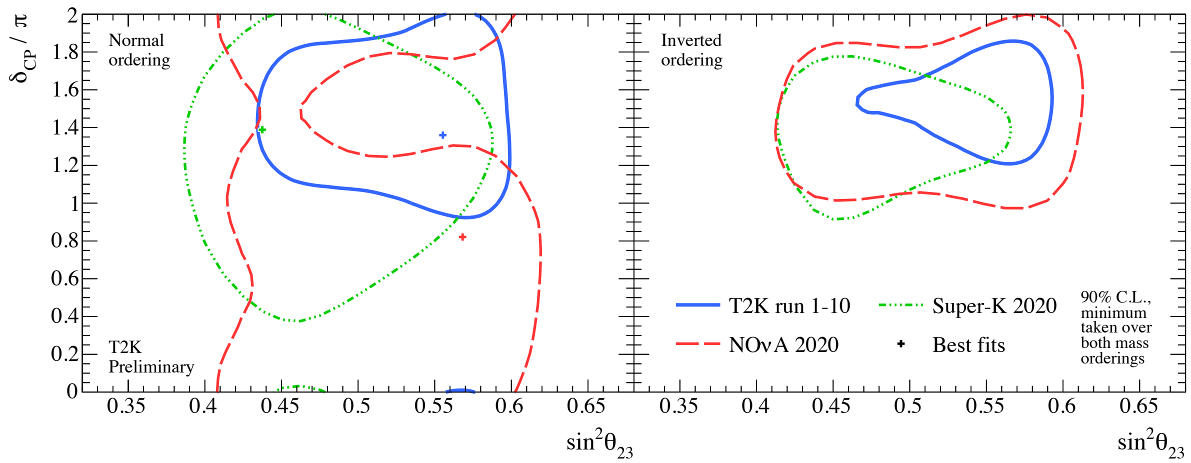
Results from here onward are with REACTOR CONSTRAINT APPLIED.

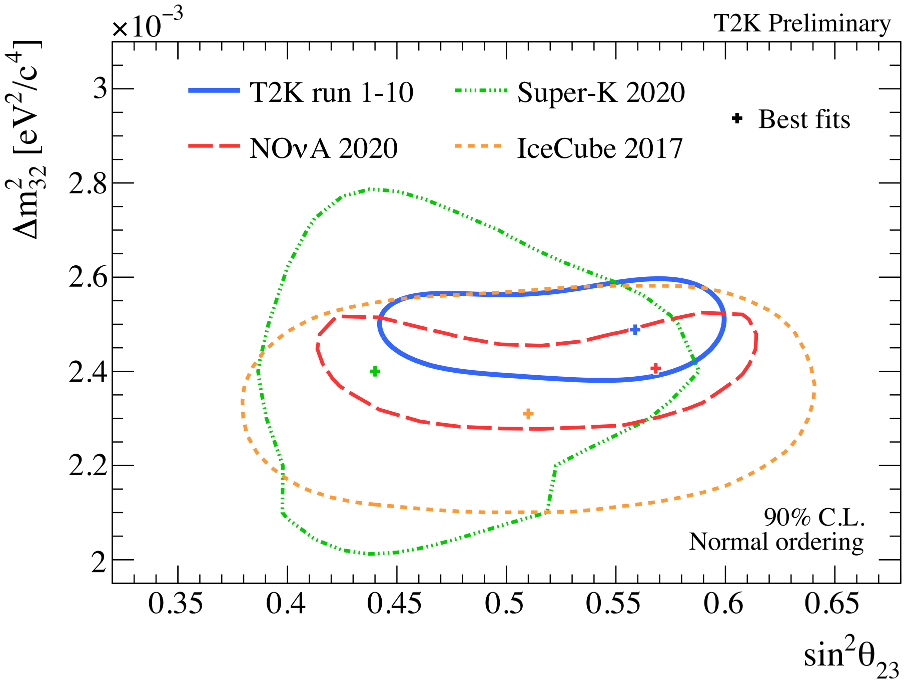


PDG 2019 reactor constraint:
https://pdg.lbl.gov/2019/reviews/rpp2019-rev-neutrino-mixing.pdf

New results and comparison with other experiments







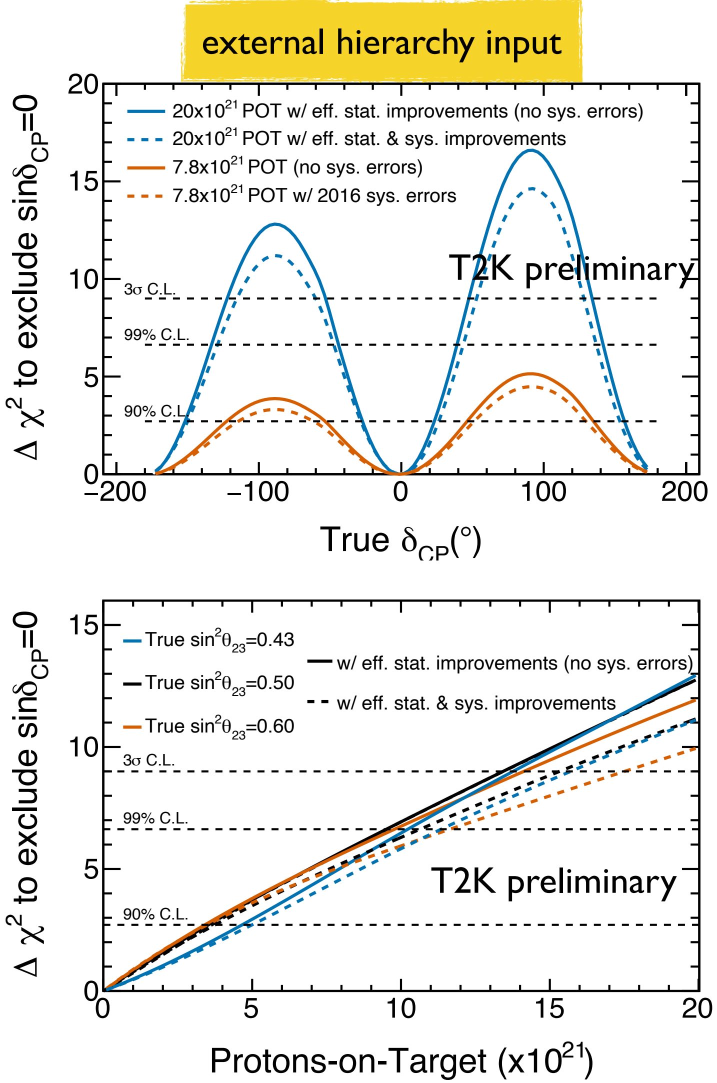
Our data still prefer a maximal CP violation ($\delta_{CP} = -\pi/2$) and Normal Ordered Masses

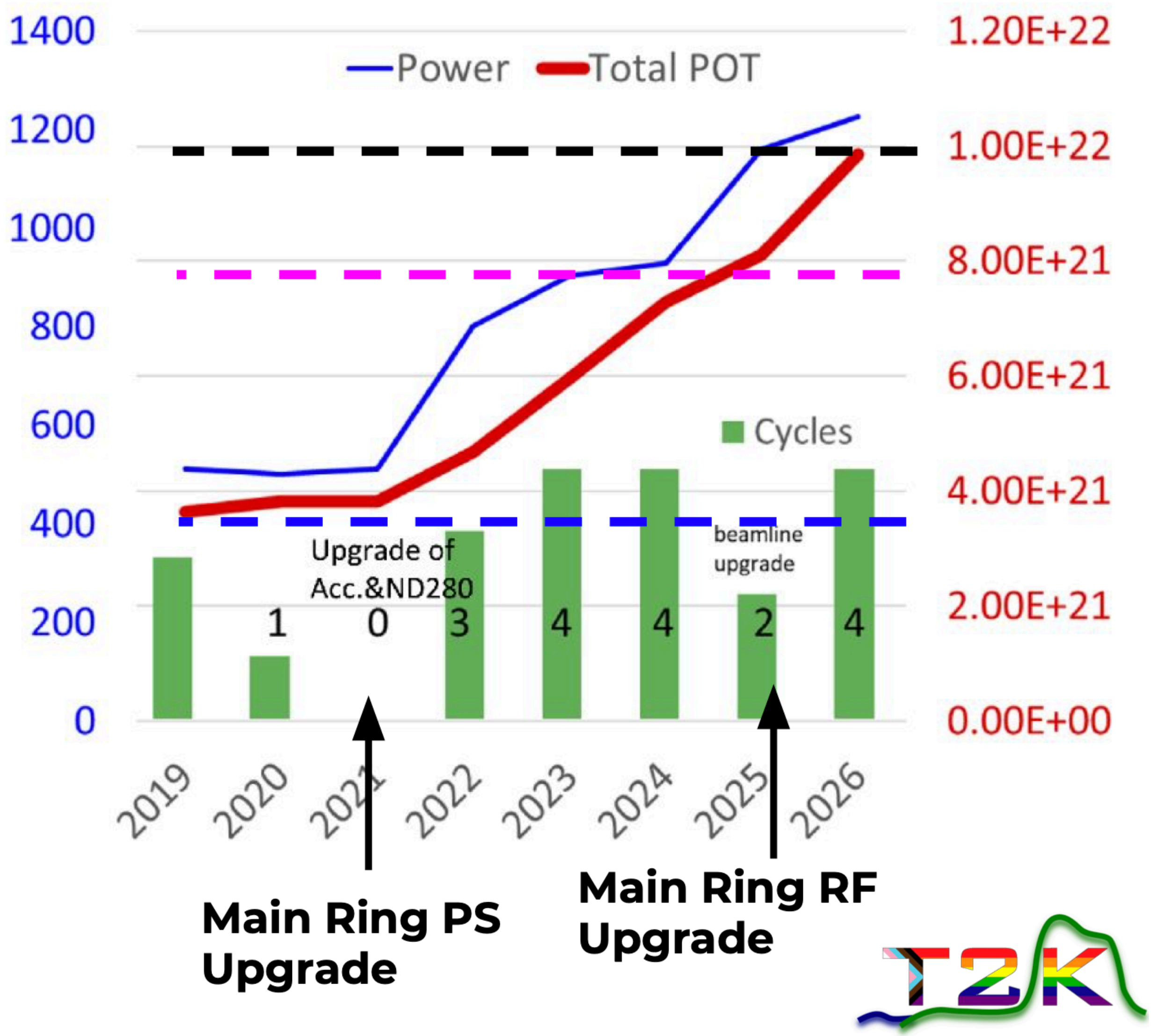
Preference for upper octant of θ_{23}

- **Slight tension with NOvA on δ_{CP}**
- **T2K has the world leading measurement of δ_{CP} and $\sin^2\theta_{23}$**

Prospects

T2K phase II with beam and ND280 upgrade (2022)

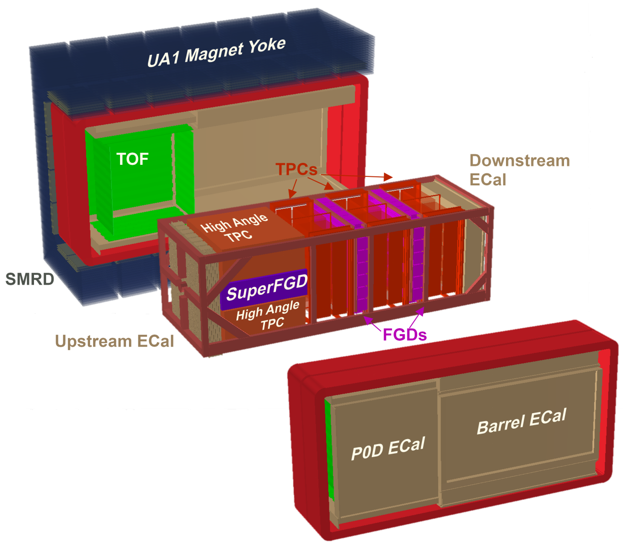


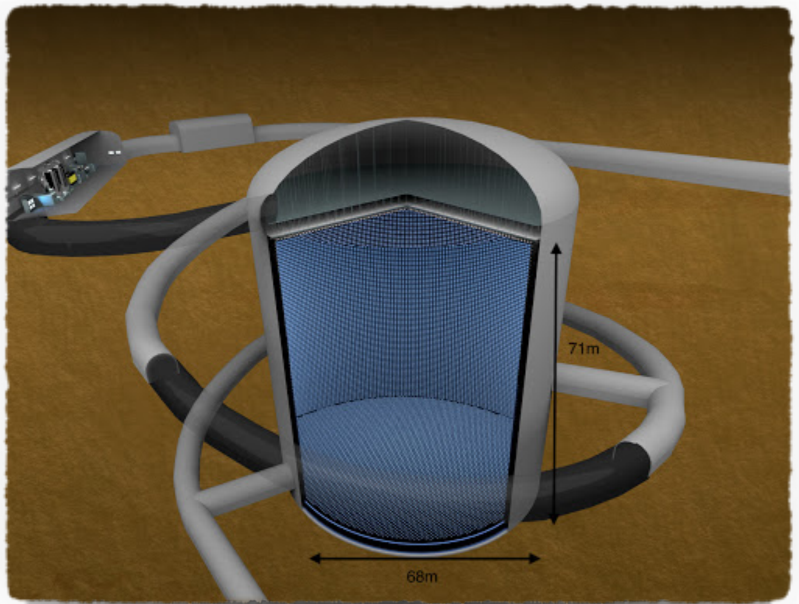


- Agreements signed with **NOvA and T2K collaborations and work on joint fits** have begun
- **Very different sensitivities, may break apart degeneracies**.
- KEK now has budget for collecting **10^{22} POT** with the second phase of T2K
- **Continued rich physics program and improved oscillation sensitivity until Hyper-K and DUNE (expected 5σ sensitivity to δ_{cp})**

Conclusions

- T2K has the world leading result for δ_{cp} measurement (we exclude 35% of δ_{cp} values at 3σ)
- Preference for upper octant θ_{23} and Normal Ordering
- Slight preference for non maximal $\sin^2\theta_{23}$ mixing
- Next step T2K-II (ND280 and beam upgrade), long term Hyper-Kamiokande approved by MEXT and under construction
- The final INFN approval is expected by the end of this year
- Lots of exciting work and results to come in the next few years!



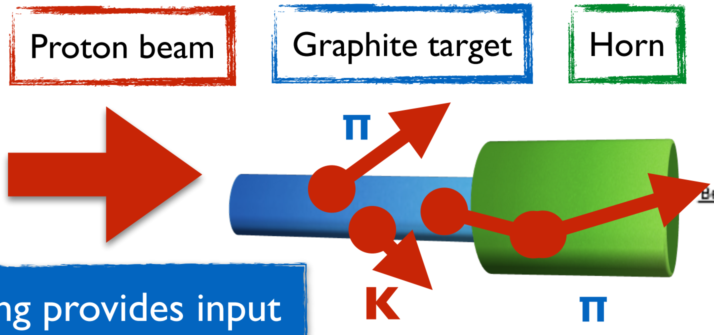


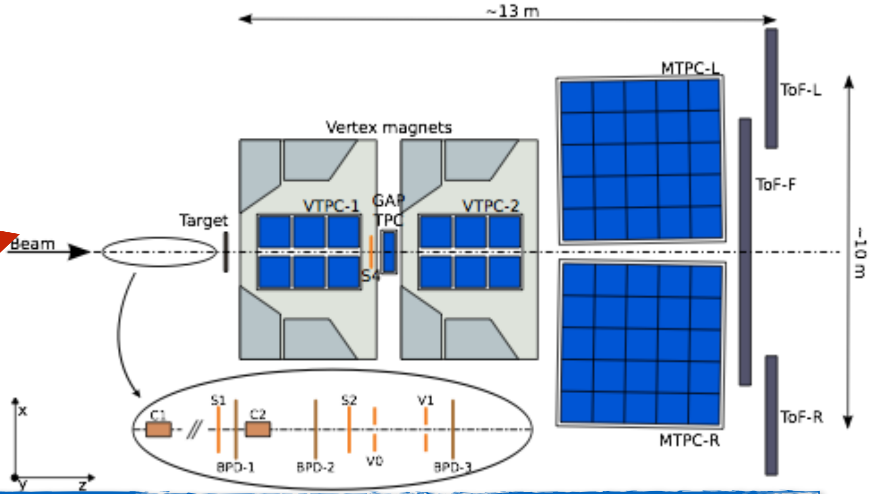
Backup

The neutrino beam: flux predictions

- Fluxes are predicted from a data-driven simulation → **NA61/SHINE experiment** measures hadron production cross sections using a thin carbon and a T2K replica target

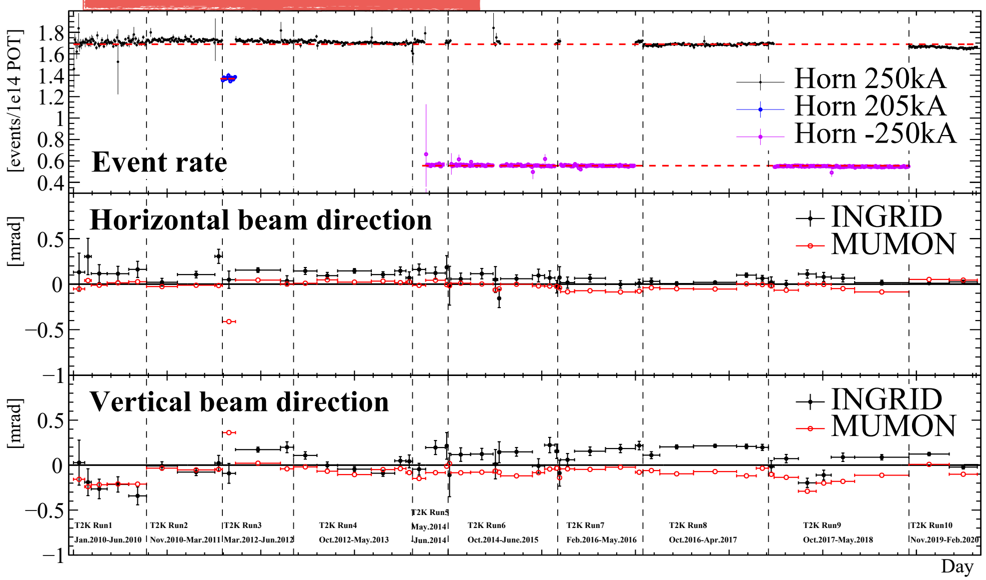
Flux error reduction from ~25% to ~5% (was ~8% with thin carbon target)





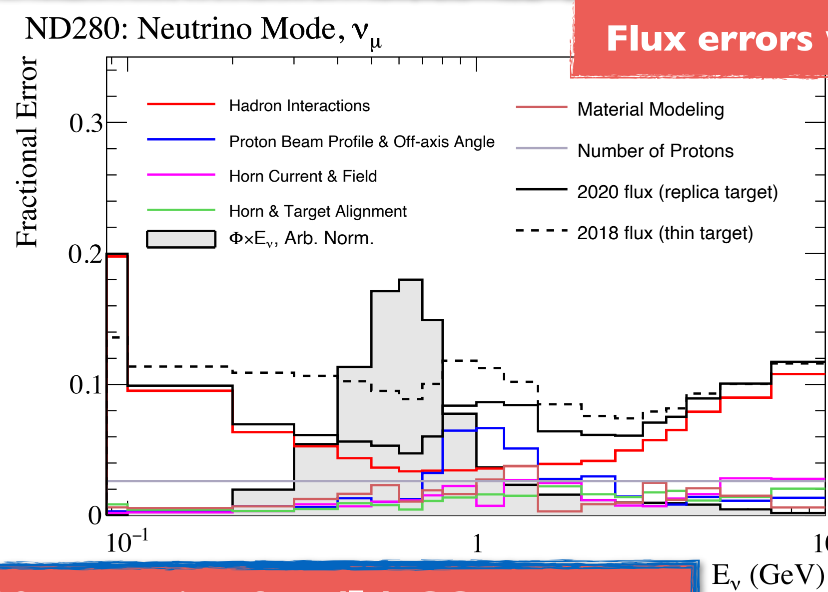
- Beam alignment monitoring provides input to estimations of beam systematics

ν daily event rate



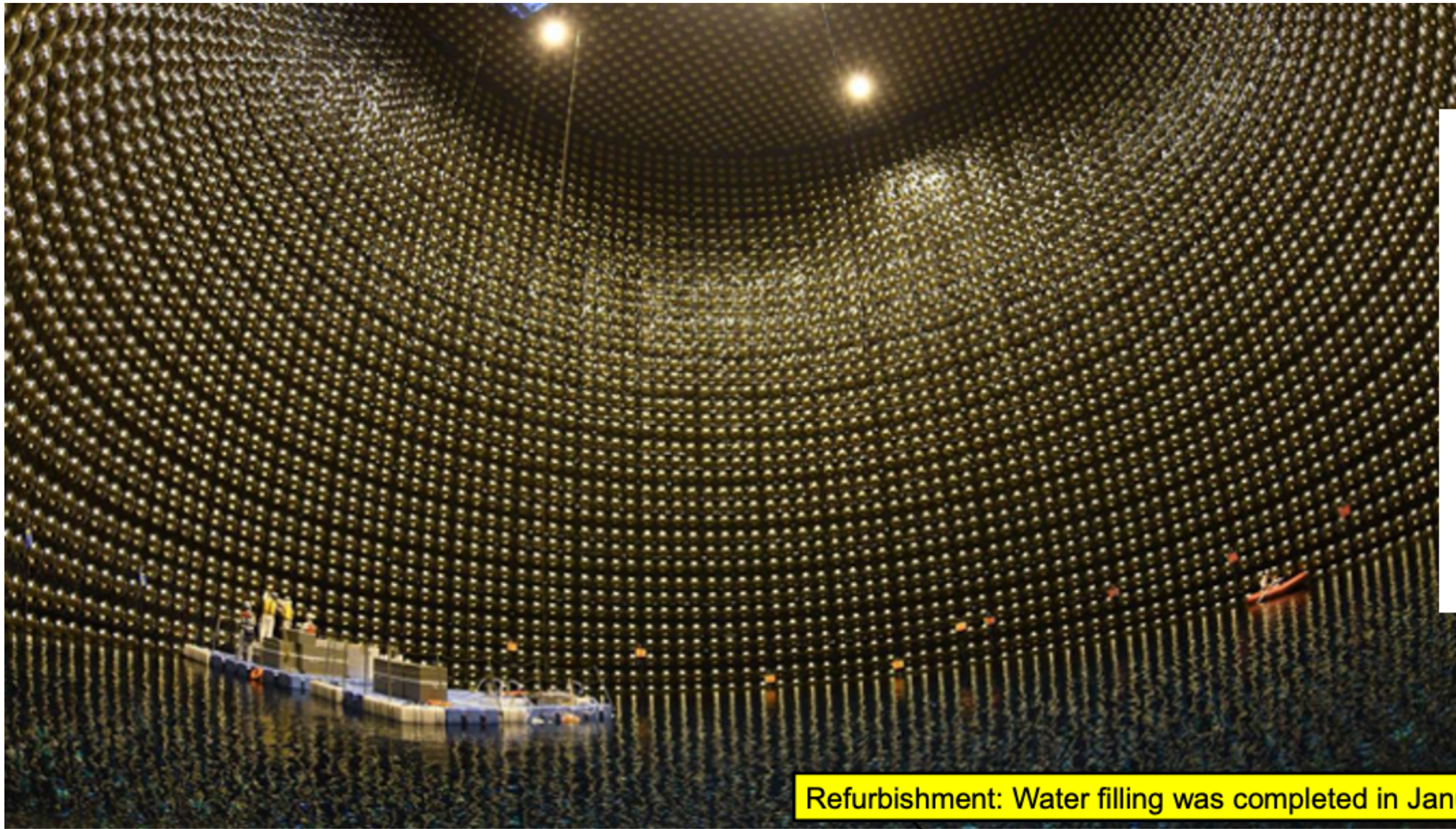
- INGRID detector provides high-statistics monitoring of the beam intensity, direction, profile and stability

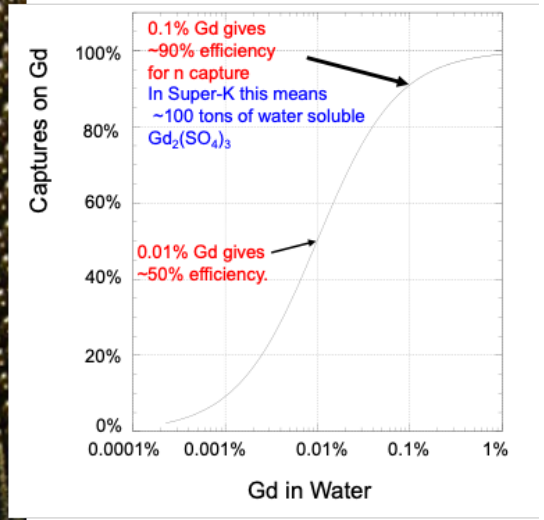
Flux errors ν mode



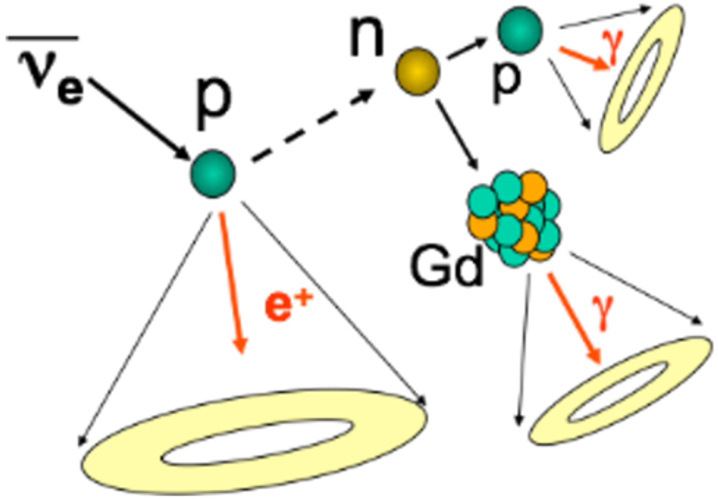
Flux errors are further constrained with the ND280 analysis of ν_μ ($\bar{\nu}_\mu$) CC events
Higher constraint on ν_e component with tagged beam (ENuBET)

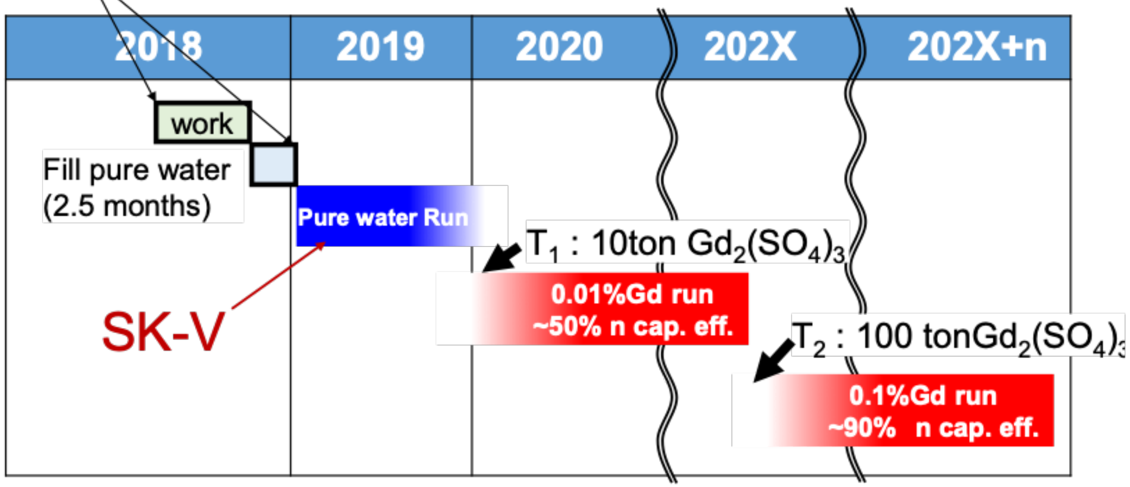
SK-V with Gd





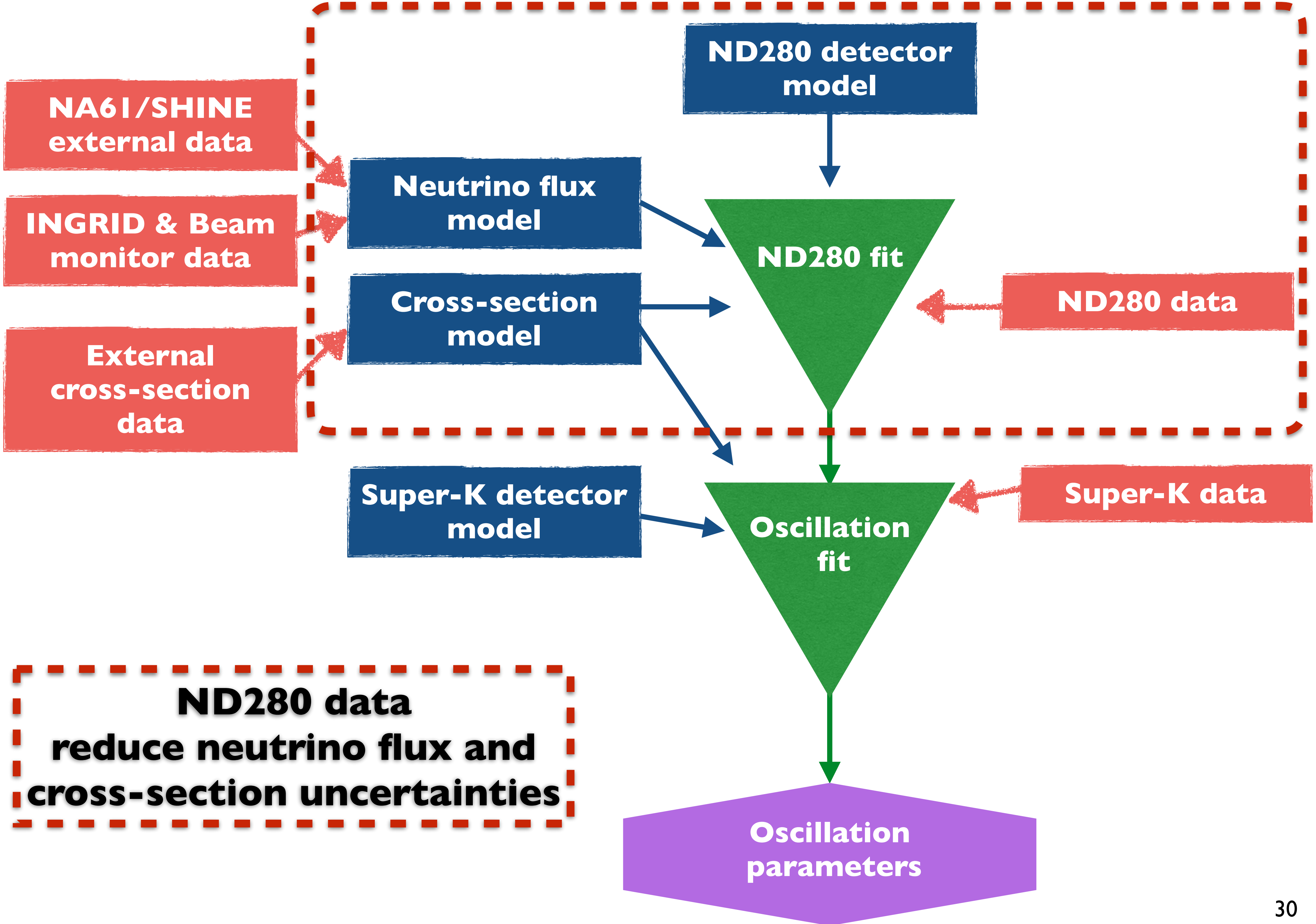
Refurbishment: Water filling was completed in January 2019.





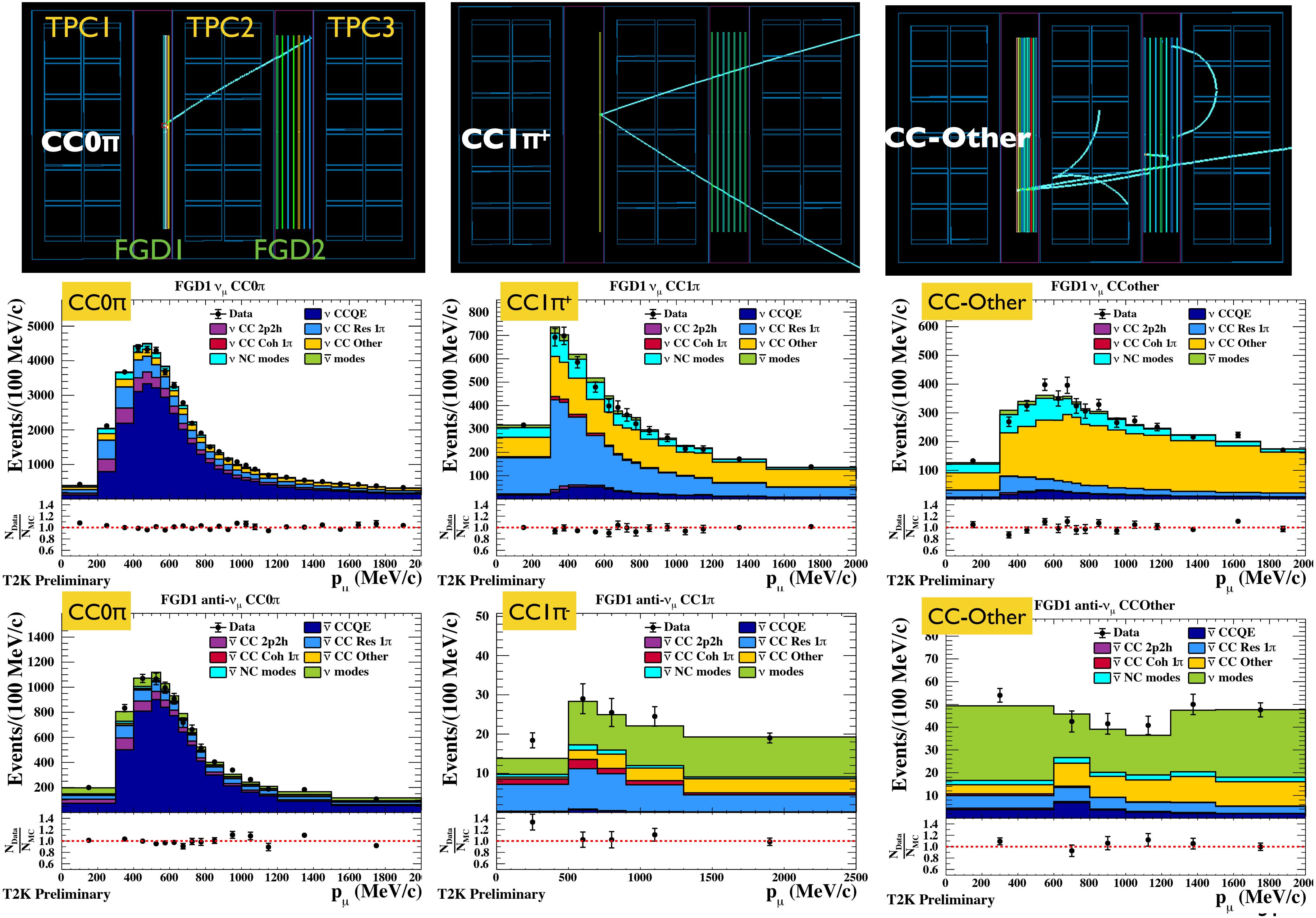
Plan to start 0.01% Gd run in early 2020.
(Adjusting schedule with T2K)

Analysis strategy



ND280 data reduce neutrino flux and cross-section uncertainties

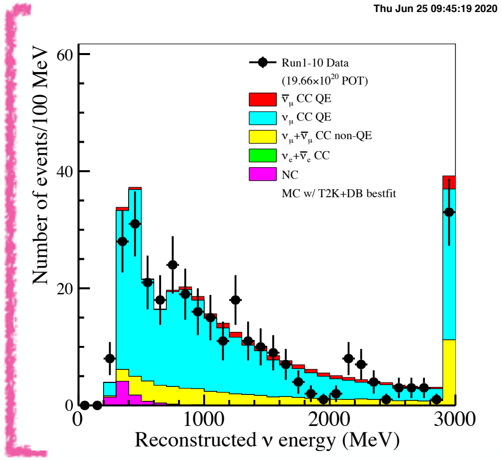
ND280 samples in ν and $\bar{\nu}$ beam mode (post-ND280 fit)

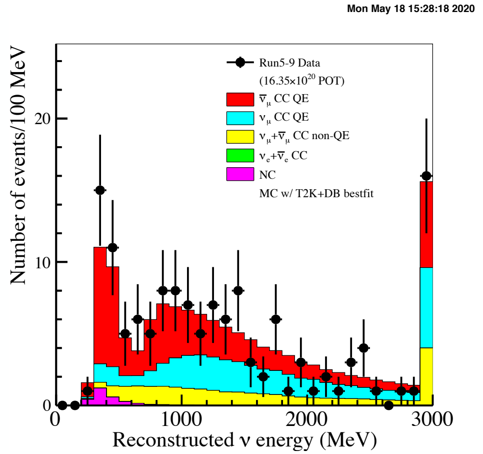


Samples collected at Super-Kamiokande

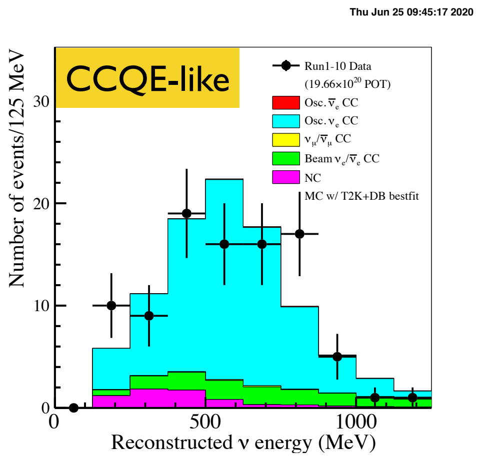
Neutrino mode | **Anti-neutrino mode**

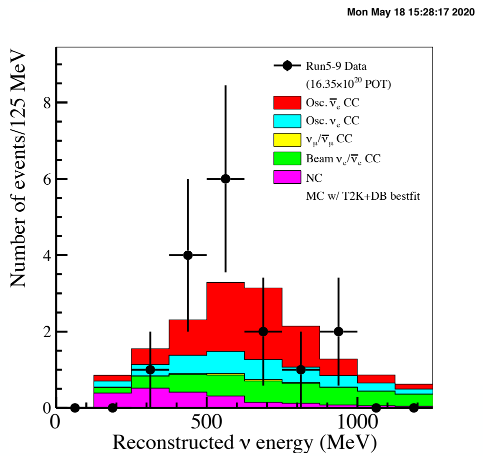
μ-like ring

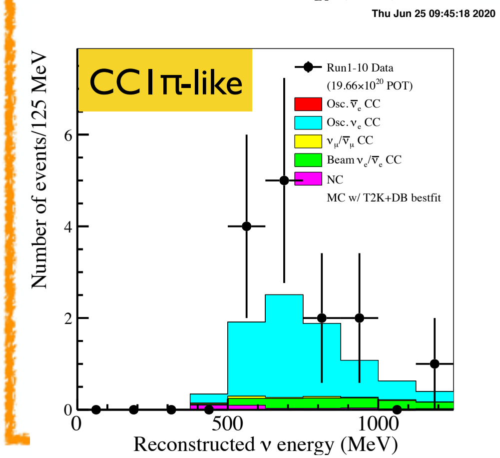




e-like ring







No CC1π sample in anti-neutrino mode because π^- produced in $\bar{\nu}$ interaction are mostly absorbed before decay.

	$\delta_{CP}=-\pi/2$	$\delta_{CP}=0$	$\delta_{CP}=\pi/2$	$\delta_{CP}=\pi$	Data
FHC 1Rμ	356.48	355.76	356.44	357.27	318
RHC 1Rμ	138.34	137.98	138.34	138.73	137
FHC 1Re	97.62	82.44	67.56	82.74	94
RHC 1Re	16.69	18.96	20.90	18.63	16
FHC 1R ν_e CC1π^+	9.20	8.01	6.51	7.71	14
FHC 1Rμ ($E_{rec}<1.2$ GeV)	213.40	213.06	213.36	213.81	191
RHC 1Rμ ($E_{rec}<1.2$ GeV)	68.53	68.34	68.53	68.74	71

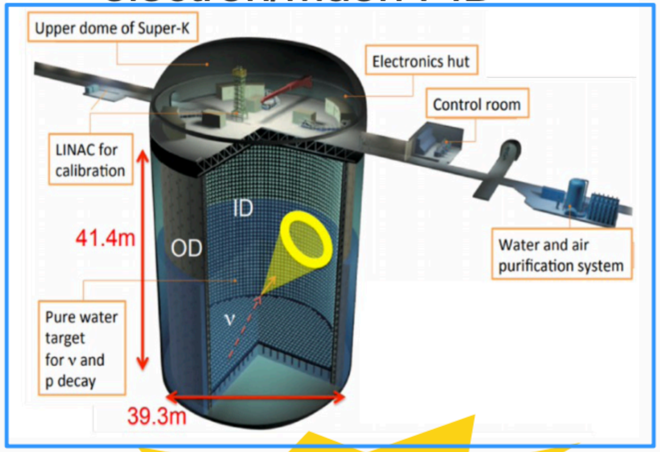
- **Data prefer δ_{CP} inducing the largest ν-ν̄ asymmetry: -π/2**
- **Differences in μ-like events** are **consistent with statistical and systematic errors**

- **Oscillation and systematic parameters are shared between the 5 samples**
- **Fit simultaneously the 5 samples to maximize the sensitivity to the oscillation parameters**

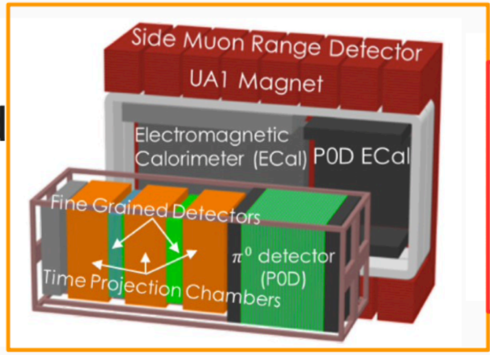
- **Error reduction with near detector fit on the number of expected events at SK**
  - ν_μ event rate uncertainty **from 11% to 3%**
  - ν_e event rate uncertainty **from 13% to 5%**

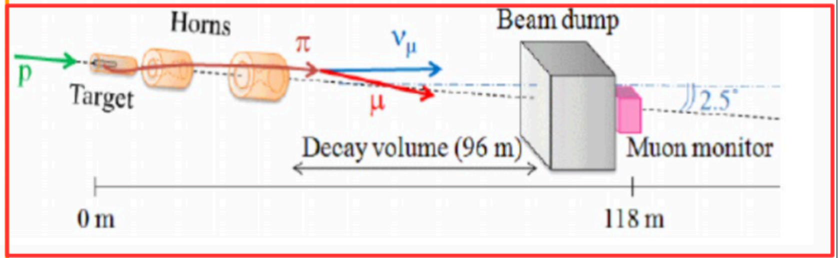
What is new in the current analysis

- **SuperKamiokande:** samples with Chrenkov ring counting and electron/muon PID



New ! +33% ν statistics





- **Neutrino flux:** simulation tuned to NA61 measurements

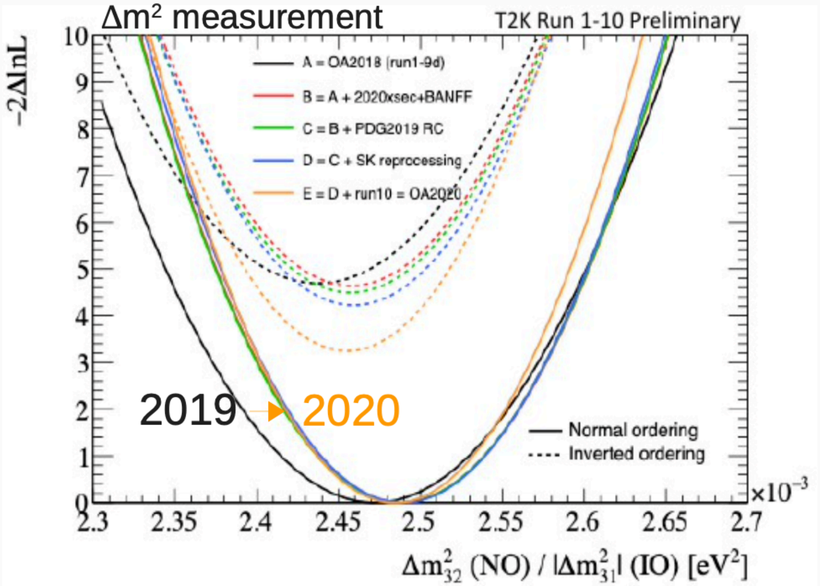
New ! NA61 replica target *Flux constraints improved from 8% to 5%*

- **Model of neutrino-nucleus interactions:** informed by external and T2K cross-section measurements

New ! Improved model *Spectral Function nuclear model from e-scattering data → more physical treatment of binding energy*

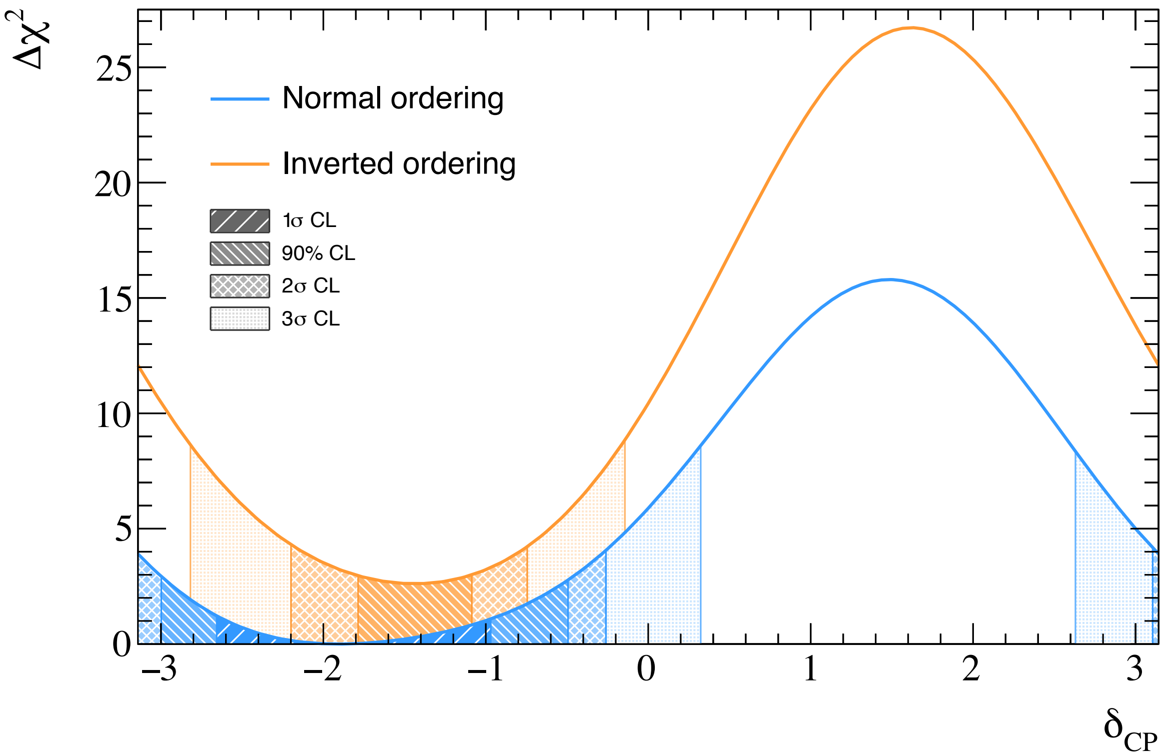
- **ND280** data to tune flux and interaction model

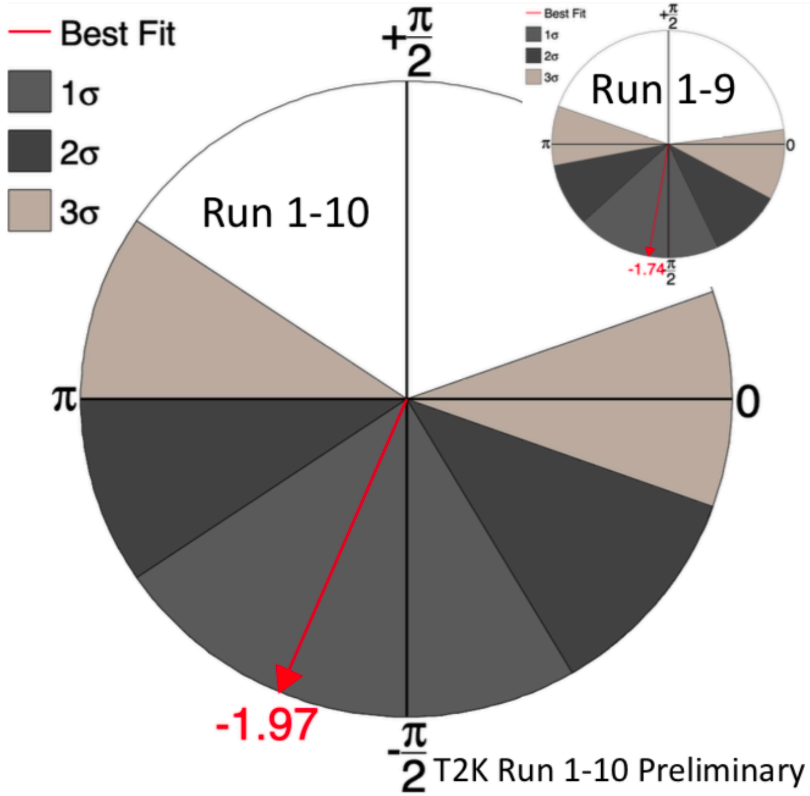
New ! Doubled statistics and improved analysis



Improvement of Δm^2_{32} measurement thanks to improved neutrino-interaction model and ND280 constraints!

δ_{cp} constraints

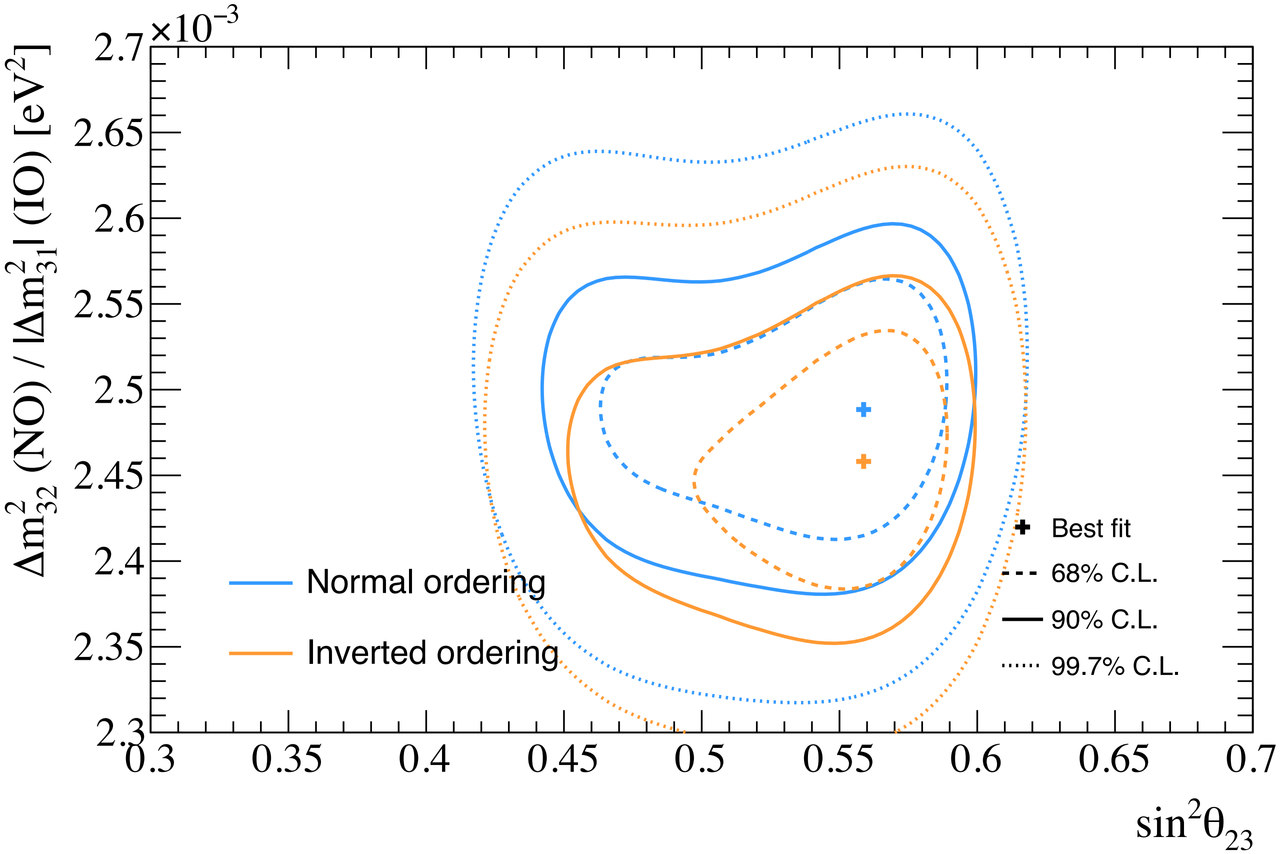




CP conserving values (0, π) excluded at 90% C.L. but π not quite at 2σ

35% of all values excluded at 3σ when marginalised over both hierarchies

Atmospheric parameters



- **Preference for upper octant of θ_{23} and normal ordered neutrino masses**
- **Slight preference for non maximal $\sin^2\theta_{23}$**
- **World leading measurement of theta23**

Posterior Probabilities

	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Sum
NO ($\Delta m^2_{32} > 0$)	0.195	0.613	0.808
IO ($\Delta m^2_{32} > 0$)	0.034	0.158	0.192
Sum	0.229	0.771	1.000

Systematic uncertainties

Pre ND280 constraint

Error source (units: %)	$1R\mu$ FHC	$1R\mu$ RHC	$1Re$ FHC	$1Re$ RHC	$1Re$ FHC CC$1\pi^+$	$1Re$ FHC/RHC
Flux	5.1	4.7	4.8	4.7	4.9	2.7
Cross-section (all)	10.1	10.1	11.9	10.3	12.0	10.4
SK+SI+PN	2.9	2.5	3.3	4.4	13.4	1.4
Total	11.1	11.3	13.0	12.1	18.7	10.7

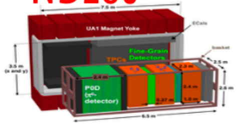
Post ND280 fit

Error source (units: %)	$1R\mu$ FHC	$1R\mu$ RHC	$1Re$ FHC	$1Re$ RHC	$1Re$ FHC CC$1\pi^+$	$1Re$ 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

T2K vs NOvA

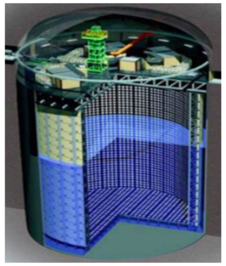
J-PARC Main Ring (30 GeV) ~500 kW
<E> ~ 0.6 GeV (2009)

ND280

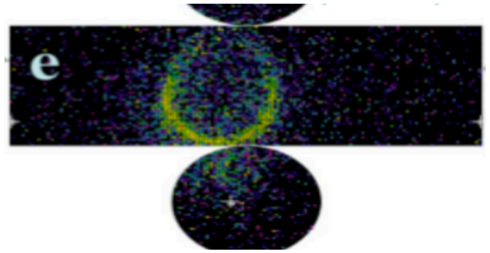


295 km
2.5° off-axis

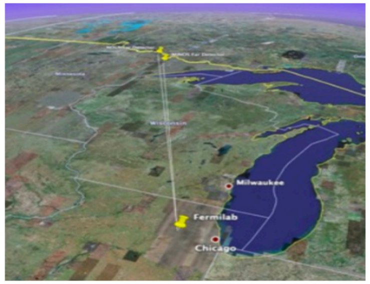
underground
Super-K 22.5 kt



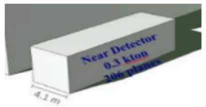
Water Cherenkov



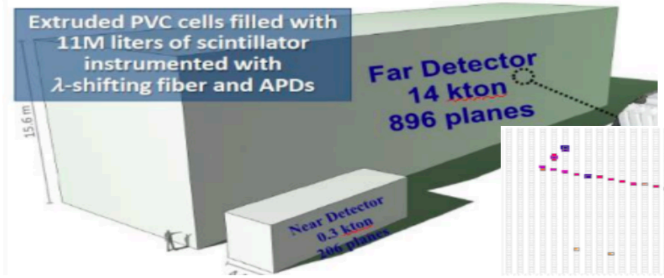
FNAL Main Injector (120 GeV) 670 kW
<E> ~ 2 GeV (2013)



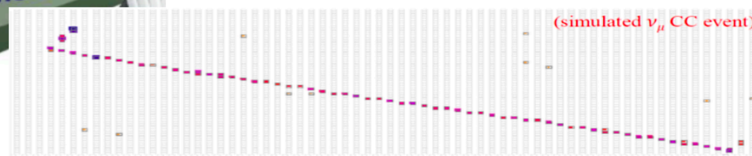
810 km
0.84° off-axis



~ at surface
NOvA 14 kt

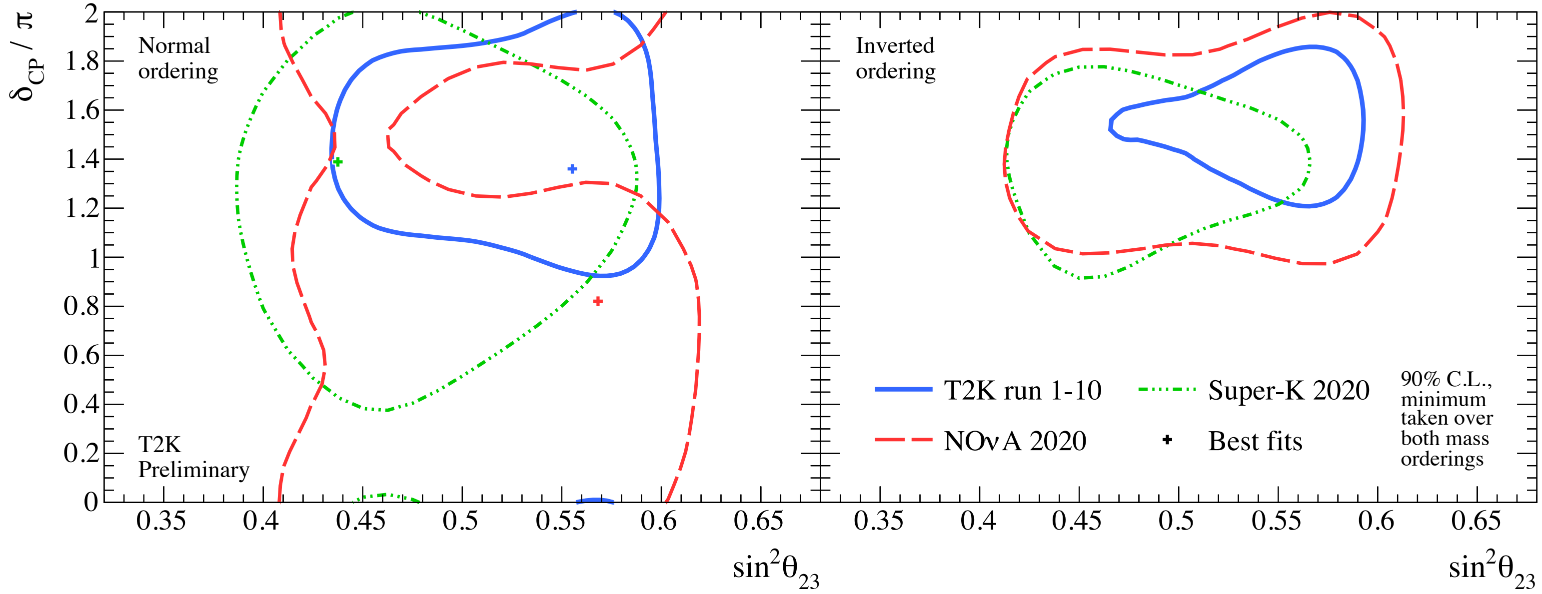


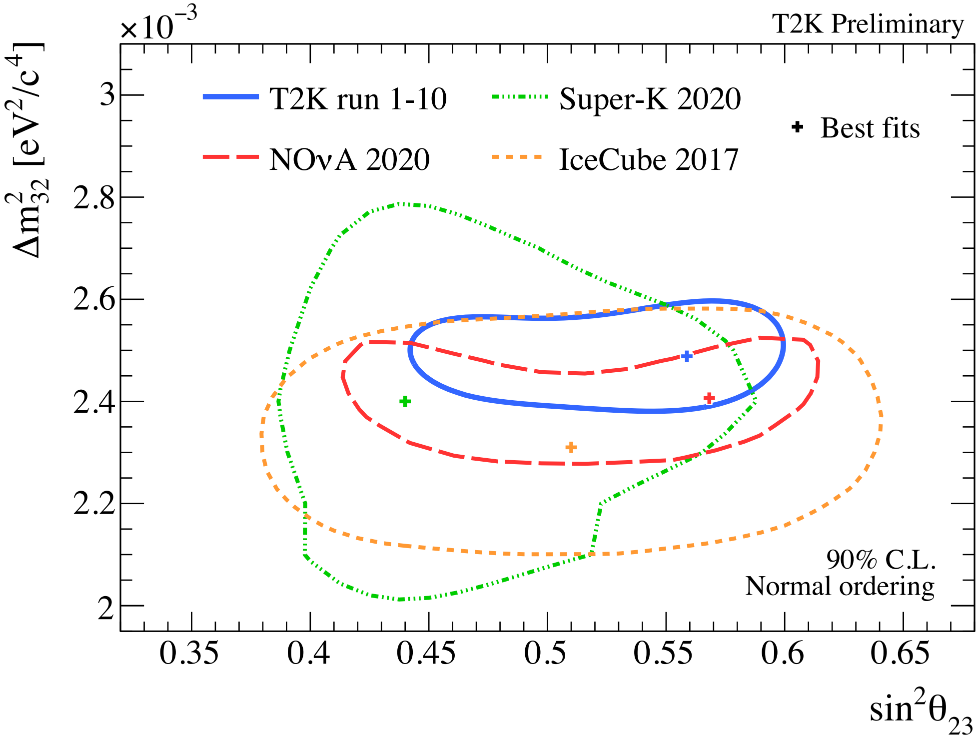
Liquid scintillator

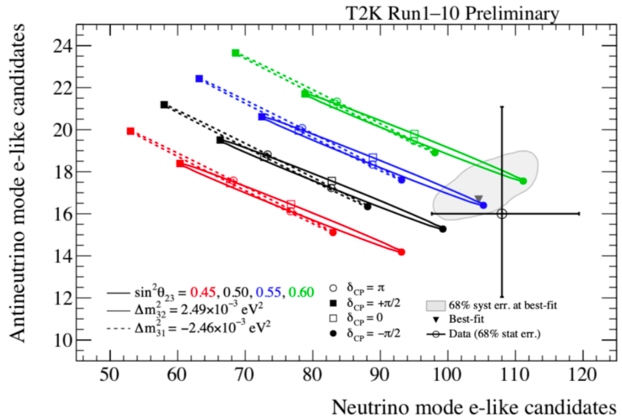


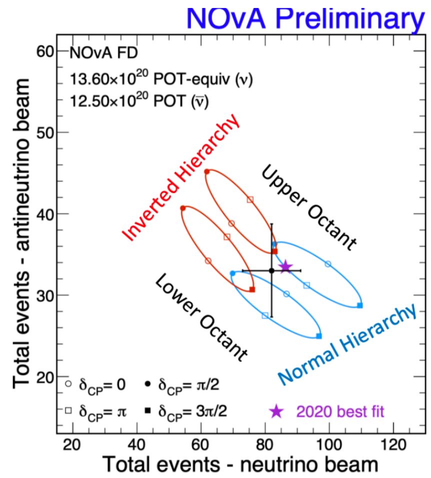
$$\frac{\dfrac{dN^{far}_{\nu_e}}{dE_{rec}}}{\dfrac{dN^{near}_{\nu_\mu}}{dE_{rec}}} = \frac{\int P_{\nu_\mu\to\nu_e}(E_\nu) * \phi^{near}_{\nu_\mu}(E_\nu) * F_{far/near}\,(E_\nu) * \sigma^{Ar}_{\nu_e}\,(E_\nu) * D^{far}_{\nu_e}(E_\nu, E_{rec})\; dE_\nu}{\int \phi^{near}_{\nu_\mu}(E_\nu) * \sigma^{Ar}_{\nu_\mu}\,(E_\nu) * D^{near}_{\nu_\mu}(E_\nu, E_{rec})\; dE_\nu}$$

Comparison with other experiments





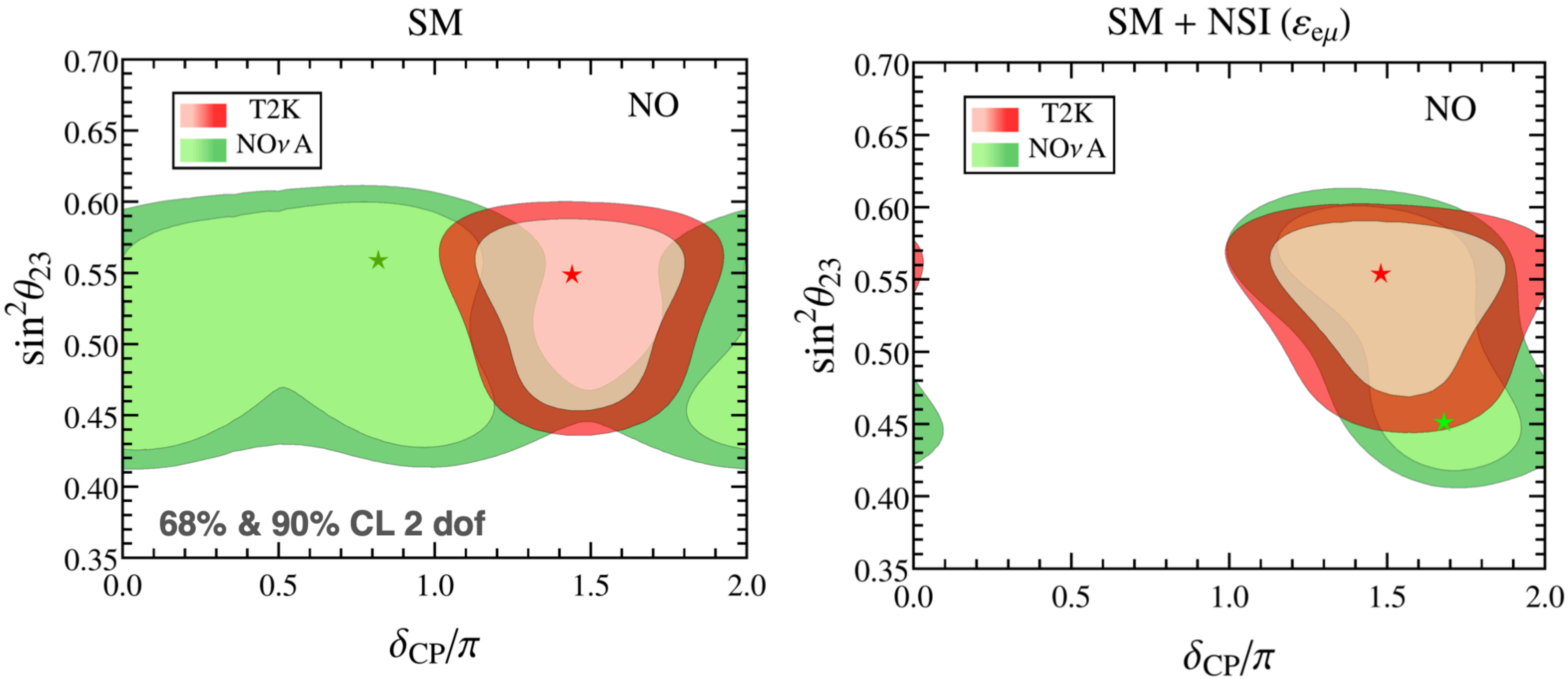




- **Slight tension with NOvA on δ_{CP}**
- **T2K has the world leading measurement of δ_{CP} and $\sin^2\theta_{23}$**

Theory may explain differences between T2K and NOvA on δ_{cp}

NSI bring the estimates of δ_{CP} in agreement



Contours obtained for the best fit of T2K + NOvA: $[\varepsilon_{e\mu} = 0.15,\ \phi_{e\mu} = 1.38\pi]$

T2K region almost unaltered

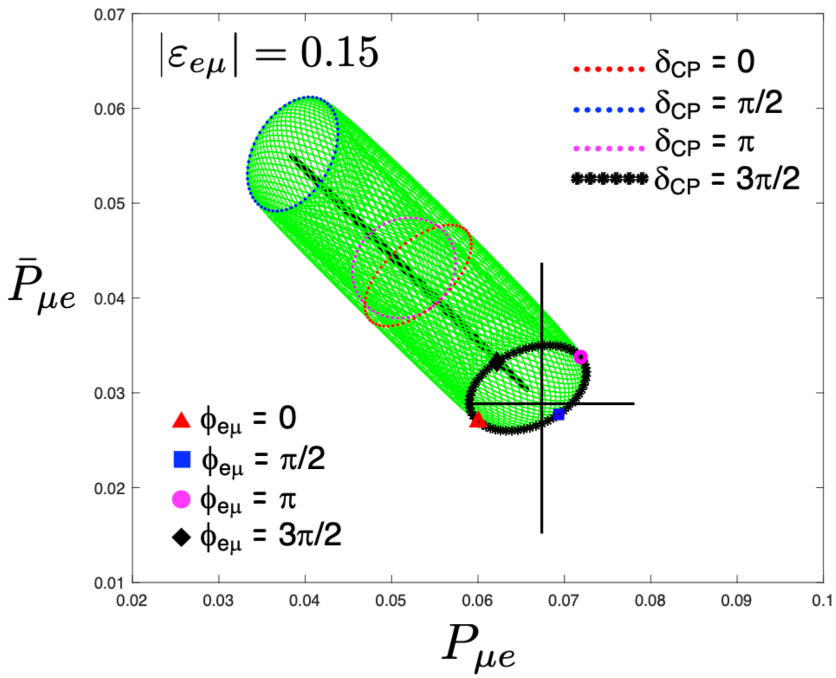
NOvA region strongly modified

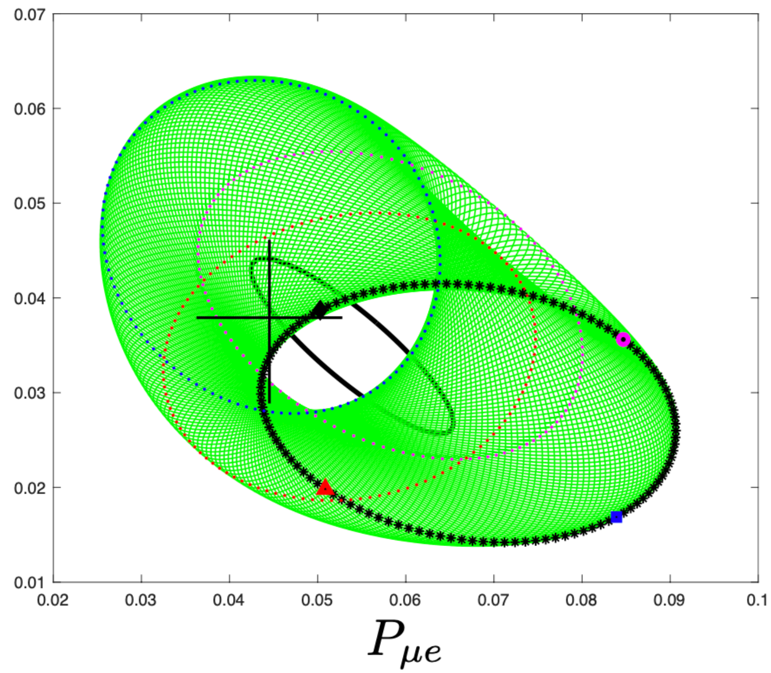
A. Palazzo @ NuTel 2021

Theory may explain differences between T2K and NOvA on δ_{cp}

Biprobability plots in the presence of NSI

T2K	NOνA
Strongly favors $\delta_{CP} \sim 3\pi/2$ ellipse (almost no sensitivity to $\phi_{e\mu}$)	In agreement with $\delta_{CP} \sim 3\pi/2$ ellipse. On this ellipse it pins down $\phi_{e\mu} \sim 3\pi/2$





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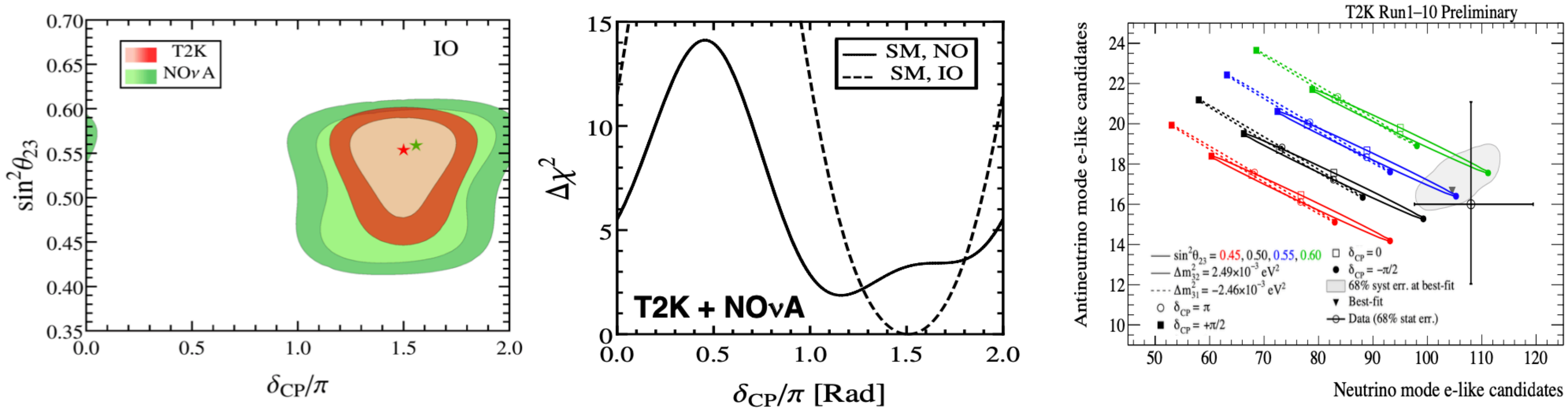
Theory may explain differences between T2K and NOvA on δ_{cp}

Can the tension be resolved assuming IO?



For IO the best fit of δ_{CP} is the same in T2K and NOvA (left panel).

However, IO gains only $\chi^2_{IO} - \chi^2_{NO} \sim -2$ in T2K + NOvA combination (middle panel).

The reason is that T2K disfavors IO (dotted ellipses) (right panel).

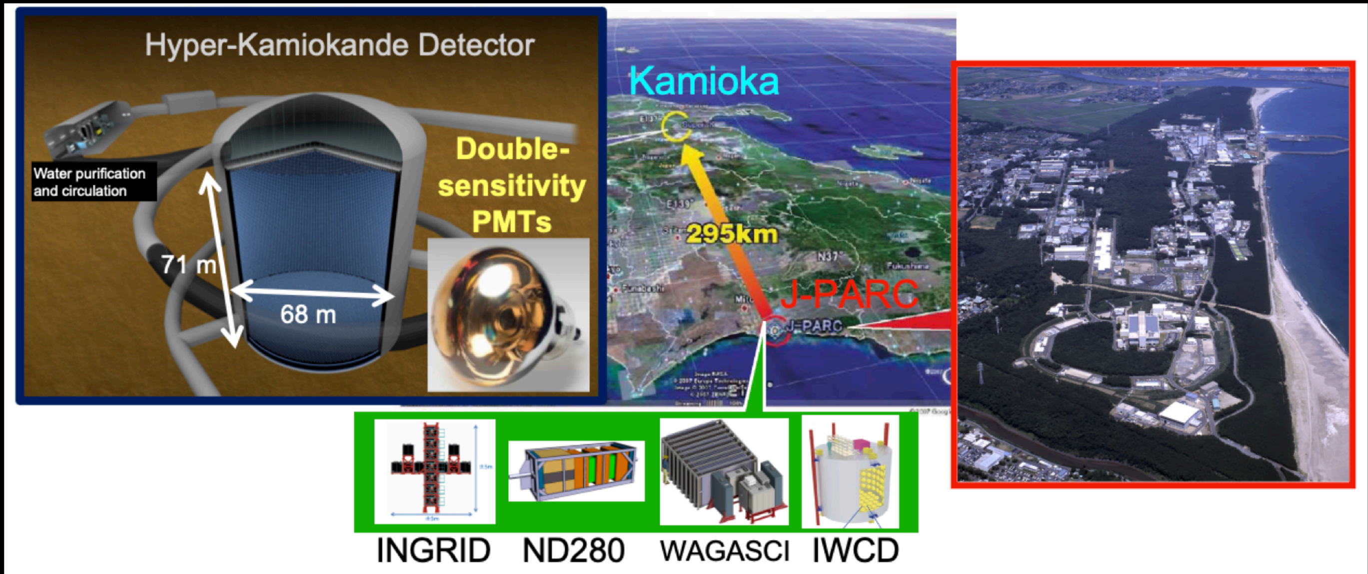
T2K and NOvA disappearance channel + Reactors prefer NO ($\chi^2_{IO} - \chi^2_{NO} \sim 4$).

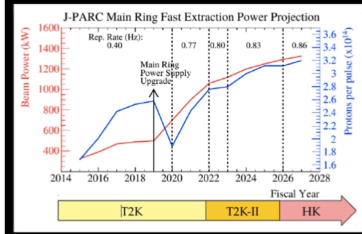
SK atmospheric data (ν 2020) prefer NO ($\chi^2_{IO} - \chi^2_{NO} \sim 3$).

Therefore, IO seems not to be the favored solution

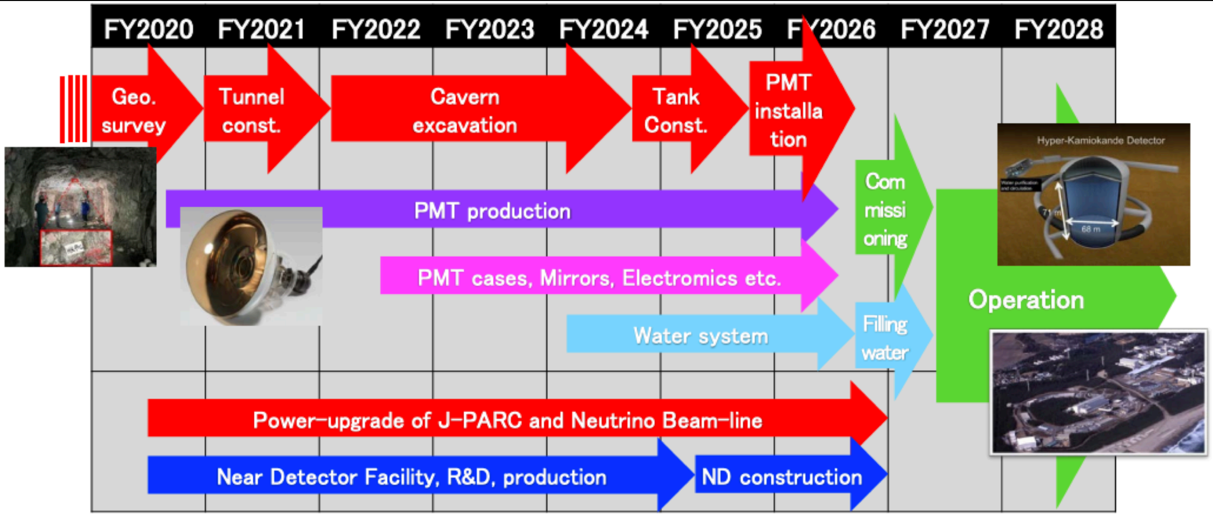
A. Palazzo @ NuTel 2021

Hyper-Kamiokande Experiment





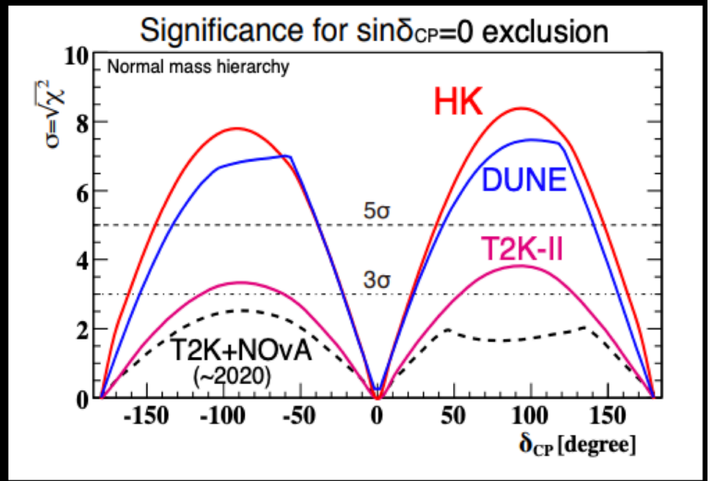
- Hyper-K detector will be built with **8.4 times larger fiducial mass** (190 kiloton) than Super-K and will be instrumented with **double-sensitivity PMTs**
- J-PARC neutrino beam will be upgraded from 0.5 to 1.3 Mega Watt **x8** Natural Neutrino Rate and **x20** Accelerator Neutrino Rate
- New (IWCD) and upgraded (@280m) near detectors to control systematic errors



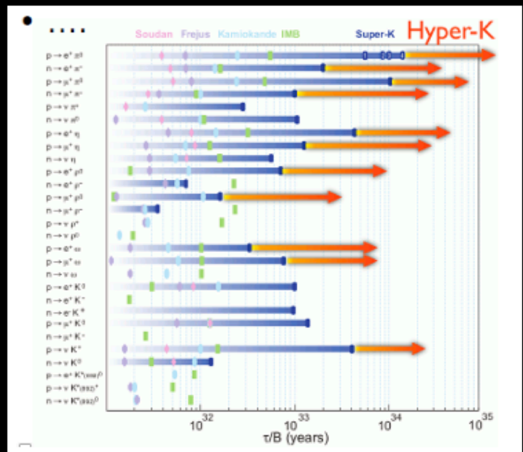
Hyper-Kamiokande

Broad Science and Discovery Potential

Matter Antimatter asymmetry:
- Provide CP conservation exclusion versus δ_{CP}
- Large samples provide high statistics
- Limited by systematics
- Pin down the δ_{CP} size with a $10^\circ - 20^\circ$ accuracy



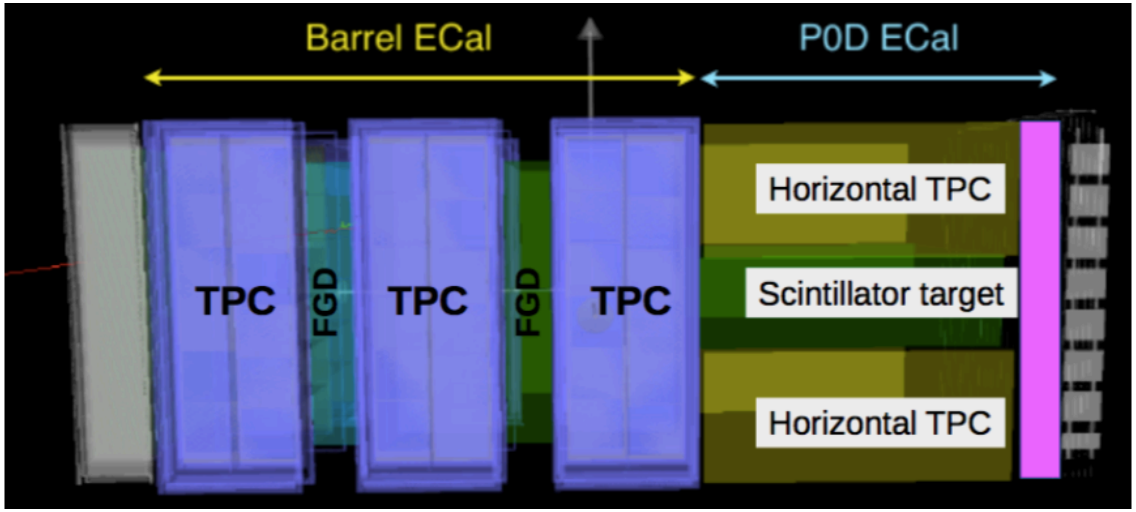
Proton decay:
- Best capability to address proton decays
- Only realistic approach beyond proton lifetime of 10^{35} years

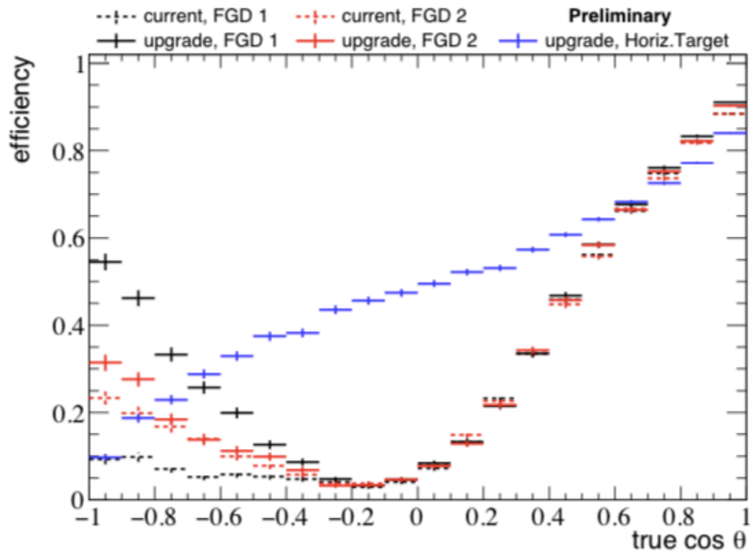


Unique astrophysical capabilities to address:
- Tension in solar neutrinos
- Supernova neutrino observation and capability to provide direction at 1°

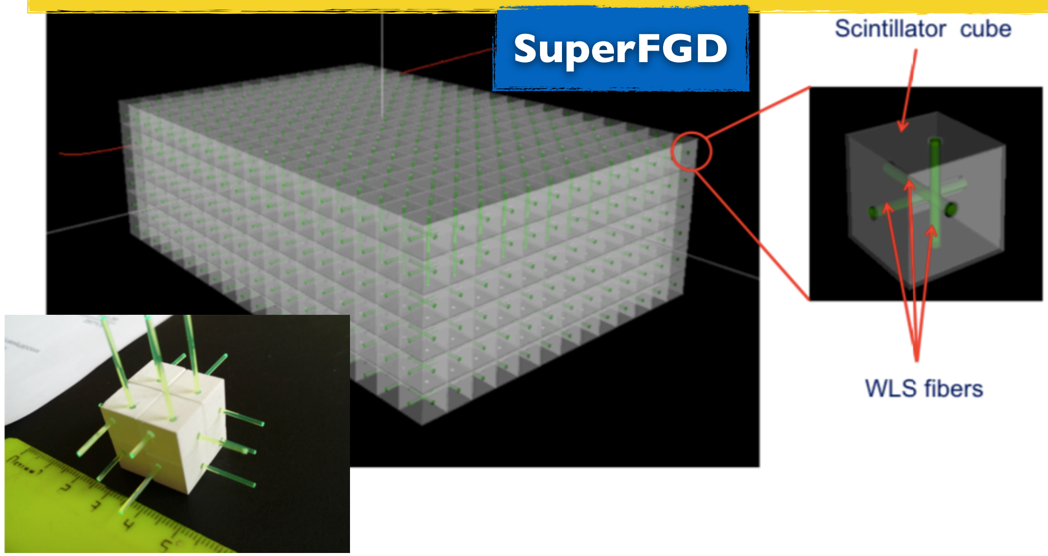
T2K Collaboration Meeting 5

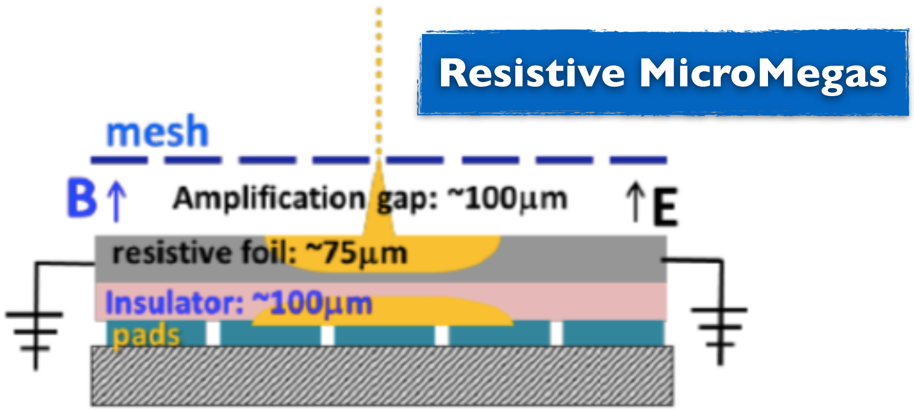
Towards T2K phase II: ND280 upgrade



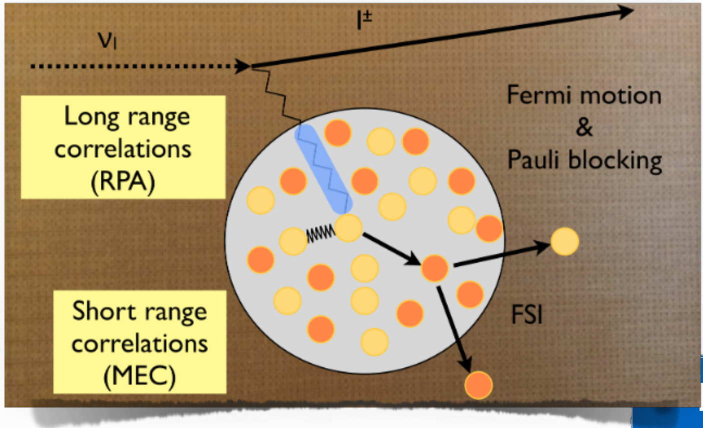


- Goal of the upgrade project: replace the P0D with an **horizontal totally active target** (SuperFGD) and **2 horizontal TPCs** equipped with resistive MicroMegas by 2021
- Increase the current phase-space and reduce the cross-section systematics
- Currently working on R&D and prototypes + simulations





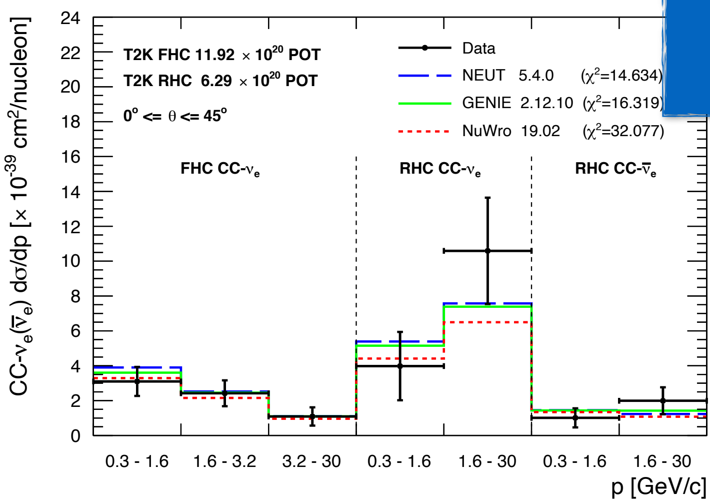
Neutrino cross sections at T2K energies

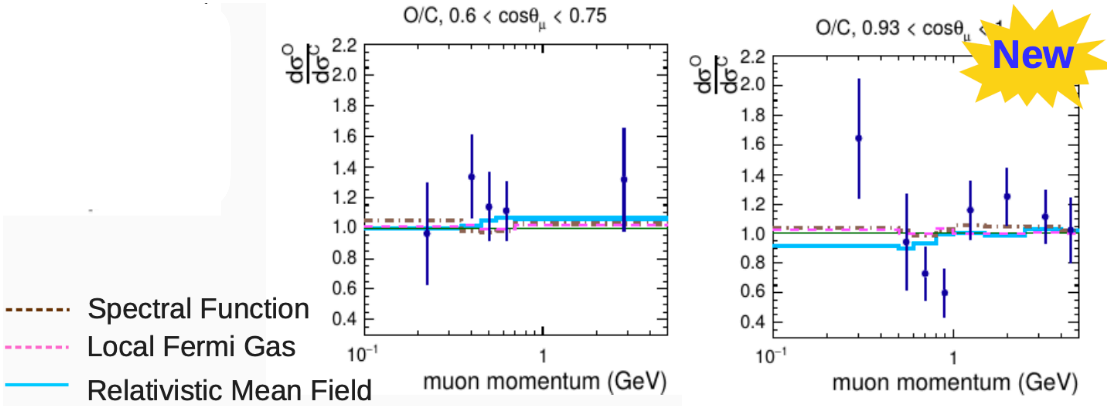


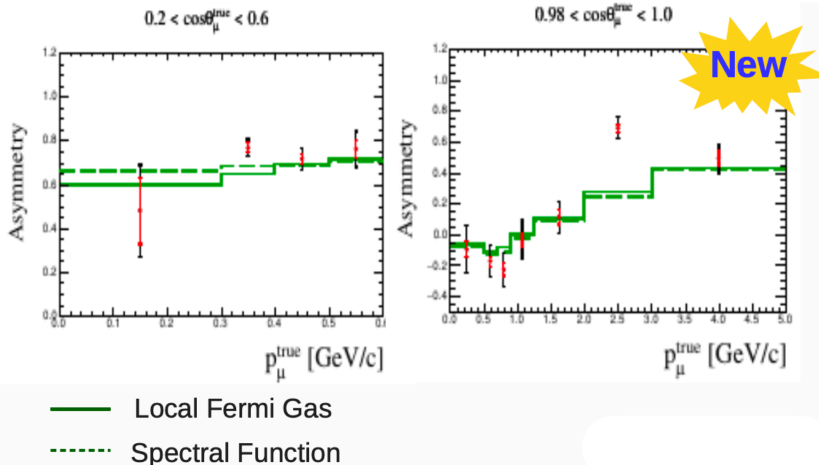
- At T2K energies the favoured interactions are **CCQE**
  - Other neutrino interactions with production of **pions** in the final state are important as well
  - Discrepancies between different theoretical models
  - x-sec are not completely understood at T2K energies

Latest x-sec measurement at ND280:

- ν_e and $\bar{\nu}_e$ measurement crucial for CPV
- $\nu_\mu/\bar{\nu}_\mu$ important for oscillation analysis
- Carbon/Oxigen Crucial for ND280 (CH, O) to SK (H_2O) extrapolation

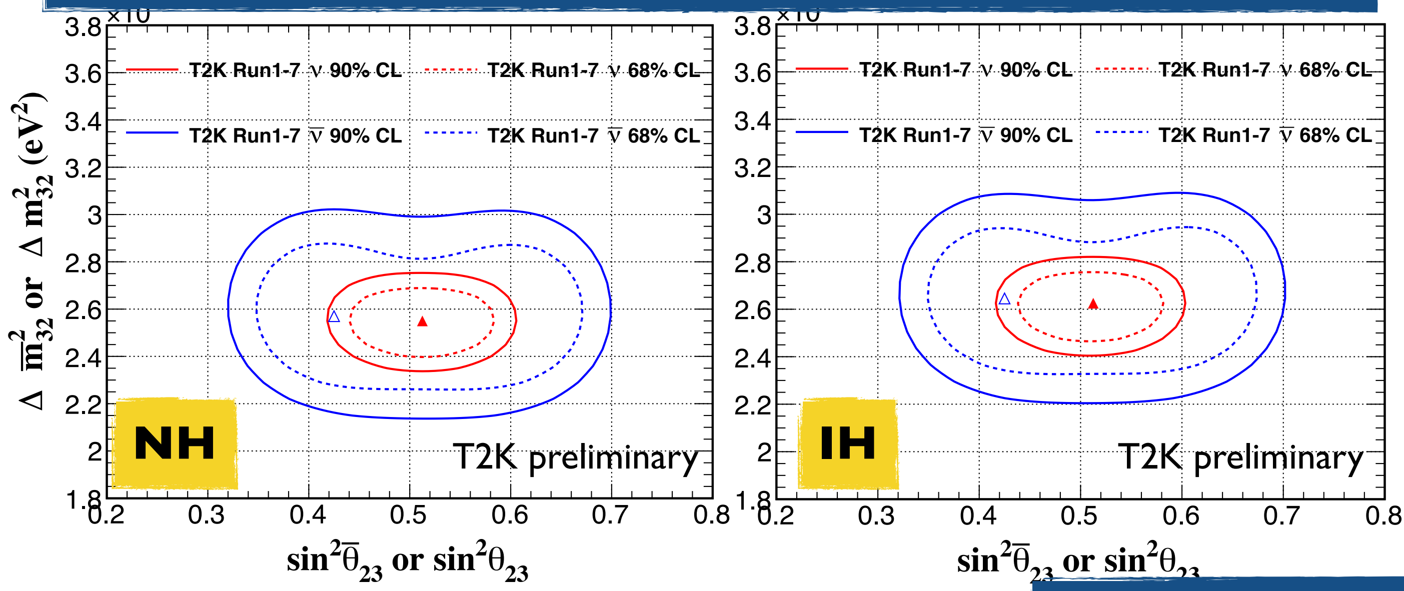






ν_μ and $\bar{\nu}_\mu$ disappearance results

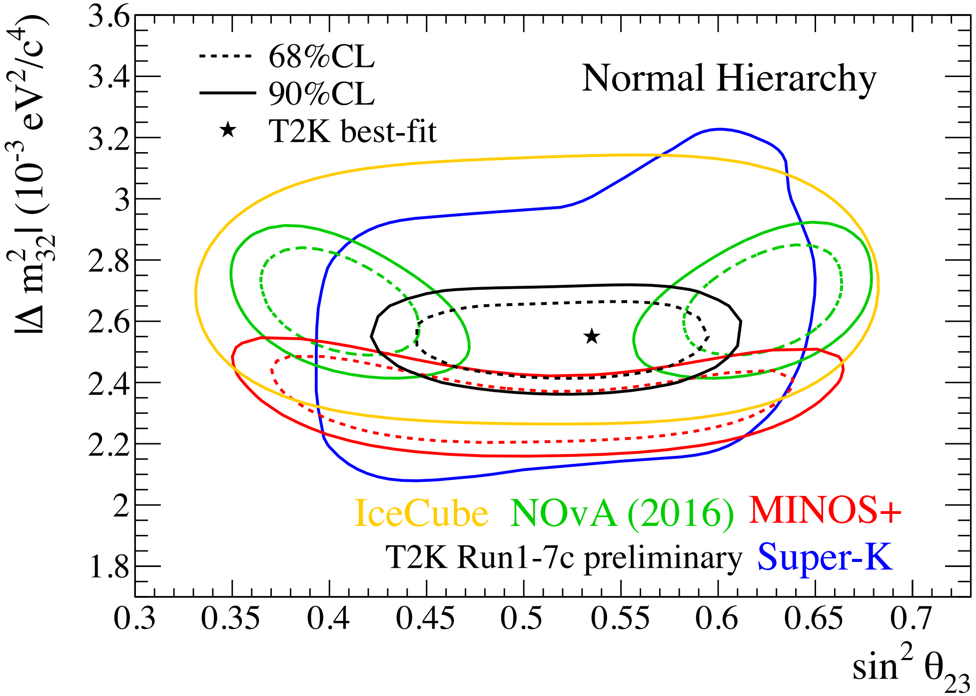
Constraints on the atmospheric parameters: θ_{23} and Δm^2_{31}



- **CPT theorem:**

$P(\nu_\mu \rightarrow \nu_\mu) = P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu)$

if $P(\nu_\mu \rightarrow \nu_\mu) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu) \Rightarrow$
CPT theorem is violated

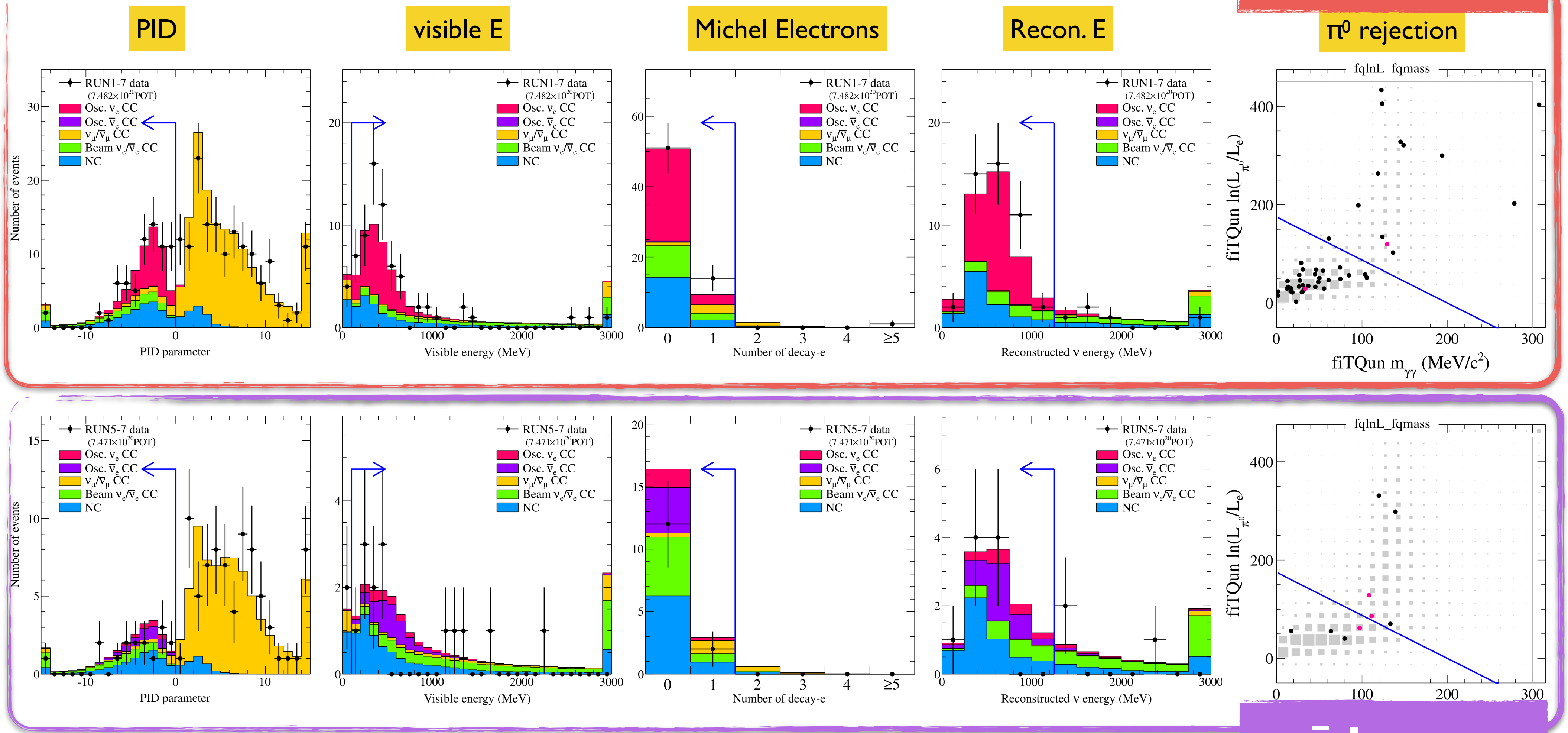


- **World-leading measurement of $\sin^2\theta_{23}$**
- **Results continue to be consistent with maximal mixing/oscillation**
- **No significant differences between ν and $\bar{\nu}$**

	NH	IH
$\sin^2\theta_{23}$	$0.532^{+0.046}_{-0.068}$	$0.534^{+0.043}_{-0.007}$
$\lvert\Delta m^2_{32}\rvert$ ($\times 10^{-5}$ eV^2/c^4)	$254.5^{+8.1}_{-8.4}$	$251.0^{+8.1}_{-8.3}$

Event selection at Super-Kamiokande

ν beam mode



ν̄ beam mode

Selection cuts

Osc. ν_e CC

Osc. $\bar{\nu}_e$ CC

$\nu_\mu/\bar{\nu}_\mu$ CC

Beam $\nu_e/\bar{\nu}_e$ CC

NC

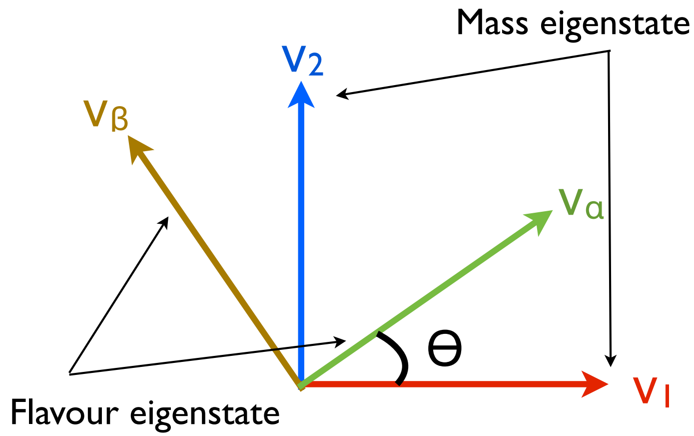
A well understood selection/detector

Two flavour ν oscillation in vacuum

Considering two flavor ν_α and ν_β the PMNS matrix become a 2 X 2 matrix: $\mathbf{U} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$

Flavour eigenstate are superposition of mass eigenstates:

$$|\nu_\alpha\rangle = |\nu_1\rangle \cos(\theta) + |\nu_2\rangle \sin(\theta), \quad \alpha = e, \mu, \tau$$



The Schrödinger equation implies that massive neutrino eigenstate evolves in time as plane wave, so:

$$|\nu_\alpha(t)\rangle = |\nu_1\rangle e^{-iE_1 t} \cos(\theta) + |\nu_2\rangle e^{-iE_2 t} \sin(\theta)$$

in the ultrarelativistic neutrinos ($E = |\vec{p}|$, $t = L$), it is possible to approximate:

$$E_k = \sqrt{\vec{p}^2 + m_k^2} \simeq E + \frac{m_k^2}{2E} \qquad E_k - E_j \simeq \frac{\Delta m_{kj}^2}{2E}, \; \Delta m_{kj}^2 \equiv m_k^2 - m_j^2$$

Then the probability that a ν_α becomes a ν_β is given by:

$$P(\nu_\alpha \to \nu_\beta) = |\langle \nu_\beta | \nu_\alpha \rangle|^2 = \sin^2(2\theta) \sin^2\left(\Delta m^2 \frac{L}{4E}\right)$$

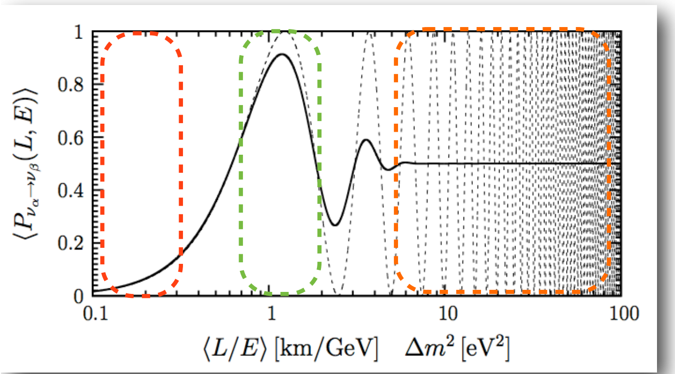
Introducing the speed of light and the Plank costant:

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \times \sin^2\left(1.27 \frac{L[km]}{E[GeV]} \Delta m^2 [eV^2]\right)$$

The maximum oscillation amplitude

Controlled parameters in LBNO experiment

Oscillation frequency



L/E << Δm^2 no time for the oscillation to develop,

L/E >> Δm^2 oscillation probability averages to $1/2 \sin^2 2\theta$,

L/E ≈ Δm^2 best sensitivity to oscillation