Latest results from T2K

Justyna Łagoda
Neutrino oscillations

- Flavor eigenstates are the linear combinations of mass eigenstates → Pontecorvo-Maki-Nakagawa-Sakata matrix
  - Parametrized by 3 mixing angles and CP-violating phase $\delta_{\text{CP}}$
- Most oscillation parameters measured with <10% precision
  - $\theta_{23}$ is known with 15% precision
- Unknown parameters: mass hierarchy (ordering) and $\delta_{\text{CP}}$

\[
\sin^2(\theta_{13}) = (2.18 \pm 0.07) \times 10^{-2} \\
\sin^2(\theta_{12}) = 0.307 \pm 0.013 \\
\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5} \text{ eV}^2 \\
\sin^2(\theta_{23}) = 0.547 \pm 0.021 \quad \text{(Inverted order)} \\
\sin^2(\theta_{23}) = 0.545 \pm 0.021 \quad \text{(Normal order)} \\
\Delta m^2_{32} = (-2.546 \pm 0.034) \times 10^{-3} \text{ eV}^2 \quad \text{(Inverted order)} \\
\Delta m^2_{32} = (2.453 \pm 0.034) \times 10^{-3} \text{ eV}^2 \quad \text{(Normal order)}
\]

T2K Nature paper, spring 2020
T2K experiment

- located in Japan
- searches for oscillations in high purity (anti-)ν_μ beam
- started to take data in 2010, with neutrino and antineutrino beam
- other measurements: cross sections, sterile ν search

(talks of K.Yasutome, S. Jenkins, C. Schloesser, D. Vargas' poster)
The beam and near detector complex

- Proton accelerator chain at J-PARC
  - 30 GeV proton beam, 2.5 s pulse period, 8 bunches,
  - Power achieved 515 kW, designed 750 kW
  - Position, profile and intensity of the proton beam monitored

- Graphite target, 3 horns focusing positively (FHC) or negatively (RHC) charged hadrons

- Near detectors located at the distance of 280 m from the target
  - INGRID (on axis), WAGASCI (1.5º off-axis)
    (talk of K. Yasutome)
  - ND280 (same off axis angle as the Far Detector)
ND280

- ND280 – multi-purpose detector with magnetic field
  - UA1/NOMAD magnet (magnetic field 0.2 T)
- measures the beam before the oscillations
- reconstructs final states to study neutrino interactions and beam properties
  - measures $\nu$ interaction rates and flavour $\rightarrow \nu_\mu$ and $\nu_e$ spectra
- focused on specific background processes to oscillation ($NC\pi^0$, $NC1\pi$, $CC1\pi\ldots$)
- compare interactions on **Carbon** and **Oxygen** (FGD2 and P0D)
Super-Kamiokande as the Far Detector

- 50 kton water Cherenkov detector
  - 22.5 kton fiducial volume, ultrapure water
- inner and outer detector
  - ~11,000 20" PMT for ID
    - 40% photo coverage
  - ~2,000 outward facing 8" PMT for OD
    - veto cosmics, radioactivity, exiting events
- particle identification capability:
  - muons misidentified as electrons <1%
- $\nu$ energy resolution $\Delta E/E \sim 10\%$ for two-body kinematics
- no charge identification
- Experiment started to take physics data in January 2010
- 515 kW stable operation
- $1.97 \times 10^{21}$ protons on target (POT) in $\nu$-mode and $1.63 \times 10^{21}$ in $\bar{\nu}$-mode

![Graph showing accumulated POT and beam power over years](image-url)

- Total Accumulated POT for Physics
- $\nu$-Mode Accumulated POT for Physics
- $\bar{\nu}$-Mode Accumulated POT for Physics
- $\nu$-Mode Beam Power
- $\bar{\nu}$-Mode Beam Power

- Great Eastern Japan Earthquake
- Target replacement
- SK-refurb.

Presented analysis
Analysis flow

Legend:
- model
- prediction
- data

NA61/SHINE data

flux model

INGRID+beam monitor data

cross section model

external data

ND280 prediction

fit to ND280 data to reduce the uncertainties of the flux+cross section model

Far Detector data

Far Detector prediction

oscillation fit

RESULTS
Analysis flow

- NA61/SHINE data
  - flux model
  - INGRID+beam monitor data
- cross section model
- external data

**ND280 prediction**
- fit to ND280 data to reduce the uncertainties of the flux+cross section model

- ND280 detector model
- ND280 data

**Far Detector data**

**Far Detector model**
- Far Detector prediction

**RESULTS**
- oscillation fit
Beam simulation

- primary interactions of protons in target simulated with FLUKA, propagation through horns and decay volume with GEANT3 (GCALOR)
- reweighed to match NA61/SHINE data
  - latest measurements with T2K replica target to account for re-interactions inside the target [EPJC 76, 84 (2016)]
  - MC spectrum reweighted to match data in momentum, angle and target exit point
- Flux uncertainties reduced from 8% (thin) to 5% (replica) in flux peak
NA61/SHINE data
flux model
INGRID+beam monitor data
cross section model
external data

ND280 prediction
fit to ND280 data to reduce the uncertainties of the flux+cross section model

ND280 detector model
ND280 data
Far Detector data
Far Detector prediction
oscillation fit

RESULTS
Cross section

- CC QE interactions dominate at the energies of T2K
- significant resonant contribution

at the nucleus level:
  - also multinucleon (2p2h) interactions
  - target nucleon initial state
  - Final State Interactions (FSI)
What's new in cross section models

- **significant updates** in interaction models (NEUT 5.4.0)
- most significant changes in the QE part
  - realistic shell-model-based description of the nucleus
  - can (almost) be interpreted as the initial state nucleon momentum (k) and binding energy (E)
What’s new in cross section models

- QE (cont.)
  - the Benhar SF is largely extracted from exclusive electron scattering data (on proton) → shift the position of shells for neutron
  - improvements of nucleon binding energy (shift in lepton momentum)
    - smaller uncertainty from better understanding of removal energy in spectral function

- other changes
  - improvement parametrization of CC DIS and CC Nπ models
  - 2p2h modeling: new uncertainty on neutrino energy dependence

  (more details in C.Wret's and J.McElwee's talks later today)

- more sophisticated treatment, more parameters to fit!
  - 47 cross-section parameters
Analysis flow

NA61/SHINE data

flux model

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cross section model

external data

ND280 prediction

ND280 detector model

ND280 data

fit to ND280 data to reduce the uncertainties of the flux+cross section model

Far Detector data

Far Detector model

Far Detector prediction

oscillation fit

RESULTS
Near Detector samples

- analysis of $\nu_\mu$ CC interactions in ND280 to constrain flux and cross section parameters and uncertainties
  - $\nu_\mu$ measurement can constrain also $\nu_\mathrm{e}$ flux
- (anti)$\nu_\mu$ CC selection in ND280 tracker
  $\mu^-$ ($\mu^+$) candidate: highest momentum negative (positive) track
  - starting in FGD FV with long segment in TPC
  - dE/dx compatible with muon hypothesis

- 18 samples in total = sensitivity to different neutrino energy ranges and interactions modes
  18 = 2 * 3 * 3
  - separate samples for FGD1 and FGD2 (interactions on CH/Water)
  - separate multipion samples ← presence of pions in final state topology
  - NEW for RHC beam mode
- dominant component for (anti)neutrino beam, and also neutrino component of the antineutrino beam (wrong sign)
  - NEW: doubled both neutrino and anti-neutrino data in the fit
Example: FGD1 $\nu$-mode (FHC) samples

CC $0\pi$ – dominated by CC QE

CC $1\pi^+$ – enhanced in resonant pion production

CC Other – mostly DIS
Analysis flow

- NA61/SHINE data
  - flux model
  - INGRID+beam monitor data
  - cross section model
  - external data

- ND280 detector model
- ND280 data
- Far Detector data
- Far Detector model
- Far Detector prediction
- oscillation fit

RESULTS

fit to ND280 data to reduce the uncertainties of the flux+cross section model
Post-fit

- ND fit constrains predicted number of events → large **anticorrelations** between flux and cross-section uncertainties
- good fit to data (prior model p-value=74%)
  - test the model ability to cover the phase space region which best describes the data.
  - “toy” data sets thrown from prior covariance and the nominal model is fit to each toy.
  - p-value: the fraction of fits with a $\chi^2_{\text{min}}$ greater than that of the data
Analysis flow

- **NA61/SHINE data**
- **flux model**
- **INGRID+beam monitor data**
- **cross section model**
- **external data**

**ND280**
- **ND280 detector model**
- **ND280 data**

**Far Detector**
- **Far Detector data**

**fit to ND280 data to reduce the uncertainties of the flux+cross section model**

**RESULTS**
5 samples from the Far Detector are used:
- $\nu$ and $\bar{\nu}$-mode $\mu$-ring
- $\nu$ and $\bar{\nu}$-mode $e$-ring
- $\nu$-mode $e$-ring+Michel electron

Red band = systematic uncertainty
# Effect of ND280 fit

## Pre fit

<table>
<thead>
<tr>
<th>Error source</th>
<th>$1R_\mu$ FHC</th>
<th>$1R_\mu$ RHC</th>
<th>$1Re$ FHC</th>
<th>$1Re$ RHC</th>
<th>$1Re$ CC1π⁺</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flux</td>
<td>5.1%</td>
<td>4.7%</td>
<td>4.8%</td>
<td>4.7%</td>
<td>4.9%</td>
</tr>
<tr>
<td>Cross-section (all)</td>
<td>10.1%</td>
<td>10.1%</td>
<td>11.9%</td>
<td>10.3%</td>
<td>12.0%</td>
</tr>
<tr>
<td>SK+SI+PN</td>
<td>2.9%</td>
<td>2.5%</td>
<td>3.3%</td>
<td>4.4%</td>
<td>13.4%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>11.1%</strong></td>
<td><strong>11.3%</strong></td>
<td><strong>13.0%</strong></td>
<td><strong>12.1%</strong></td>
<td><strong>18.7%</strong></td>
</tr>
</tbody>
</table>

## Post fit

<table>
<thead>
<tr>
<th>Error source (units: %)</th>
<th>$1R_\mu$ FHC</th>
<th>$1R_\mu$ RHC</th>
<th>$1Re$ FHC</th>
<th>$1Re$ RHC</th>
<th>$1Re$ CC1π⁺</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flux</td>
<td>2.9%</td>
<td>2.8%</td>
<td>2.8%</td>
<td>2.9%</td>
<td>2.8%</td>
</tr>
<tr>
<td>Xsec (ND constr)</td>
<td>3.1%</td>
<td>3.0%</td>
<td>3.2%</td>
<td>3.1%</td>
<td>4.2%</td>
</tr>
<tr>
<td>Flux+Xsec (ND constr)</td>
<td>2.1%</td>
<td>2.3%</td>
<td>2.0%</td>
<td>2.3%</td>
<td>4.1%</td>
</tr>
<tr>
<td>Xsec (ND unconstrained)</td>
<td>0.6%</td>
<td>2.5%</td>
<td>3.0%</td>
<td>3.6%</td>
<td>2.8%</td>
</tr>
<tr>
<td>SK+SI+PN</td>
<td>2.1%</td>
<td>1.9%</td>
<td>3.1%</td>
<td>3.9%</td>
<td>13.4%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>3.0%</strong></td>
<td><strong>4.0%</strong></td>
<td><strong>4.7%</strong></td>
<td><strong>5.9%</strong></td>
<td><strong>14.3%</strong></td>
</tr>
</tbody>
</table>
Analysis flow

- **NA61/SHINE data**
  - flux model
  - INGRID+beam monitor data
  - cross section model
  - external data

- **Far Detector model**
  - Far Detector prediction
  - ND280 prediction
  - fit to ND280 data to reduce the uncertainties of the flux+cross section model

- **ND280 detector model**
  - ND280 data
  - Far Detector data
  - oscillation fit

**RESULTS**
Oscillation fits

- $\nu_\mu \rightarrow \nu_\mu$ and $\nu_\mu \rightarrow \nu_e$ combined analysis within the 3v oscillation paradigm (PMNS)
- several fitter groups with some analysis differences:
  - sequential ND-FD fit ↔ simultaneous ND+FD fit
  - Bayesian MCMC approach ↔ frequentist approach
  - reconstructed neutrino energy ↔ lepton kinematics assuming 2-body interactions
- fit for $\theta_{13}$, $\theta_{23}$, $\Delta m^2_{32}$, $\delta_{CP}$
  - other oscillation parameters from PDG 2019 values
  - results with T2K data alone and using PDG 2019 constraint on $\theta_{13}$ from reactor experiments
- binned likelihood comparing data to MC predictions

$$-2 \ln \lambda (\delta_{CP}; a) = 2 \sum_{i=1}^{N} n_i^{obs} \ln \left( \frac{n_i^{obs}}{n_i^{exp}} \right) + n_i^{exp} - n_i^{obs} + (a-a_0)^T C^{-1} (a-a_0)$$

nuisance parameters (flux, x-sec, detector)
$\delta_{CP}$ and $\theta_{13}$

- T2K-only intervals compatible with PDG 2019 $\theta_{13}$ values
  - frequentists confidence intervals (grid search) agree with the Bayesian factors and credible intervals
  - with reactor constraints:
    - CP conserving values $(0, \pi)$ excluded at 90%, but $\pi$ not at 2$\sigma$

- Robustness studies: largest $\Delta \chi^2$ change would cause left (right) edge of 90% interval to move by 0.073 (0.080)
**Comparison to previous result**

- data in 2020 analysis closer to PMNS prediction
  - previously, excess of neutrinos was seen $\rightarrow$ reduced with new data
  - consistent with slight upwards statistical fluctuation?
  - largest change in $\delta_{CP}$ comes from new data (see backup slides)
• slight preference for non-maximal $\sin^2\theta_{23}$
• preference for normal hierarchy (80.8%, Bayes factor $B(\text{NH}/\text{IH})=4.21$) and upper octant (77%, Bayes factor $B(\text{UO}/\text{LO})=3.34$)

<table>
<thead>
<tr>
<th>Bayesian</th>
<th>Hierarchy</th>
<th>Most Probable Value</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>T2K only</td>
<td>Normal</td>
<td>0.471</td>
<td>$[0.452, 0.508]$ and $[0.530, 0.568]$</td>
</tr>
<tr>
<td></td>
<td>Inverted</td>
<td>0.469</td>
<td>$[0.449, 0.508]$ and $[0.531, 0.565]$</td>
</tr>
<tr>
<td></td>
<td>Both</td>
<td>0.471</td>
<td>$[0.451, 0.508]$ and $[0.530, 0.567]$</td>
</tr>
<tr>
<td>T2K + reactor</td>
<td>Normal</td>
<td>0.559</td>
<td>$[0.504, 0.583]$</td>
</tr>
<tr>
<td></td>
<td>Inverted</td>
<td>0.560</td>
<td>$[0.519, 0.585]$</td>
</tr>
<tr>
<td></td>
<td>Both</td>
<td>0.559</td>
<td>$[0.507, 0.584]$</td>
</tr>
</tbody>
</table>

T2K Preliminary

for references see backup
Plans for the next OA analysis

- new analysis ongoing
- new samples will be included, both from ND280 and Far Detector
- **ND280 CC Photon sample**: tagging photon conversion in ECal
  - mostly photons from $\pi^0$ decays
  - dominated by DIS (30%) and multipion production (20%), with contribution from resonant $\pi^0$ production (24%)
  - photon tag increases the purity of CC0$\pi$ and CC1$\pi$ samples by $\sim$10%

![Graph 1](image1.png)

![Graph 2](image2.png)
New samples from ND280 (cont.)

- “proton samples” from ND280: CC0\(\pi\)-0p and CC0\(\pi\)-Np
  - based on proton multiplicity, proton tracking threshold 450-500 MeV/c
  - different phase space of muon kinematics
  - different fraction of reactions
- using proton samples different regions of 2p2h phase space can be probed:

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True energy transfer: \(q_0 = E_\nu - E_\mu\) (MeV)

T2K work in progress

N protons

0 proton

True momentum transfer: \(q_3 = p_\nu - p_\mu\) (MeV)

(see K.Skwarczynski's poster)
“Multiring sample” from Far Detector

- $\nu_\mu\text{CC}1\pi^+ - \text{second largest sample after } \nu_\mu\text{CC QE}$
  - expected slightly increased sensitivity to $\theta_{23}$ and $|\Delta m^2_{32}|$
  - more robust analysis, check of the interaction model

- preliminary selection:
  - 2 mu-like rings (muon and pion)
  + 1 delayed signal from Michel electrons
  OR
  1 or 2 mu-like rings + 2 Michel electrons
  - exp. numbers of signal events for $10^{21}$ POT: 11.15 and 23.97, respectively

- systematic errors evaluation ongoing

- SK loaded with $\text{Gd}_2(\text{SO}_4)_3$: 0.01% concentration of Gd by weight

- enhanced neutron detection
  $\rightarrow$ more samples in the future?
Starting soon: upgrades for T2K-II

- J-PARC main ring power supply upgrade
  - 2x higher repetition rate (2.5s→1.3s)
  - power increased from 515 kW up to 1.3 MW
- ND280 upgrade: replacing P0D with **SuperFGD** and **High Angle TPCs**, surrounded by **TOF**
  - quasi-3D imaging
  - improved high angle acceptance
  - improved proton detection threshold
  - neutron detection capabilities

(for details see M.Tzanov's talk tomorrow and V.Nguyen's poster)
Summary

- recent results from T2K were presented
  - with 33% more data for FHC beam mode (Runs 1-10)
  - significant upgrades to the flux and interaction modelling
  - multipion ND280 samples for RHC beam mode
  - doubled ND280 data used in the fit
  - improved statistical and systematic errors control
- large range of $\delta_{CP}$ values around $+\pi/2$ excluded at 99.7%
- most precise measurement of $\theta_{23}$
- data taking and analysis continues, more improvements planned
  - new parameters for interactions modelling
  - new ND280 and FD samples
- plans of T2K+NOvA and T2K+SK joint fits
- planned upgrades of beam and ND280
- very exciting neutrino physics possibilities ahead of us!
Backup slides
The fluxes

- system of 3 horns with 250 kA current sinusoidal ~3ms pulse.
- Forward Horn Current (FHC) → neutrino enhanced beam
  \( \pi^+ \rightarrow \mu^+ \nu_\mu \)
- Reversed Horn Current (RHC) → anti-neutrino enhanced beam
  \( \pi^- \rightarrow \mu^- \bar{\nu}_\mu \)
- planned upgrade to reach 320kA → +~20% \( \nu \) flux
Off-axis beam

for angles $\neq 0$
the dependence of $E_\nu$ from $E_\pi$ is reduced

narrow spectrum, tuned at the first oscillation maximum

- CC QE sample enhanced
- background from intrinsic $\nu_e$ reduced
- background from NC $\pi^0$ production reduced

the direction must be precisely controlled
(<1 mrad to keep peak energy stable $\delta E/E \sim 2\%$ at far detector)
ND280 events in tracker

- Muon candidate
- Single pion production candidate
- DIS candidate
- Antimuon candidate
What so special about $\nu_\mu \rightarrow \nu_e$ channel?

- allows for CP violation studies

$$P(\nu_\mu \rightarrow \nu_e) = 4 \, c_{13}^2 \, s_{13}^2 \, s_{23}^2 \, \sin^2 \Delta_{31}$$

$$+ 8 \, c_{13} \, s_{12} \, s_{13} \, s_{23} \left( c_{12} \, c_{23} \, \cos \delta_{CP} - s_{12} \, s_{13} \, s_{23} \right) \cos \Delta_{32} \sin \Delta_{31} \sin \Delta_{21}$$

$$- 8 \, c_{13} \, c_{12} \, c_{23} \, s_{12} \, s_{13} \, s_{23} \sin \delta_{CP} \sin \Delta_{32} \sin \Delta_{31} \sin \Delta_{21}$$

$$+ 4 \, s_{12} \, c_{13} \left( c_{12}^2 \, c_{23}^2 + s_{12}^2 \, s_{23}^2 \, s_{13}^2 - 2 \, c_{12} \, c_{23} \, s_{12} \, s_{23} \, s_{13} \, \cos \delta_{CP} \right) \sin^2 \Delta_{21}$$

$$- 8 \, c_{13} \, s_{13}^2 \, s_{23}^2 \, \frac{a \, L}{4 \, E_\nu} \left( 1 - 2 \, s_{13}^2 \right) \cos \Delta_{32} \sin \Delta_{31} + 8 \, c_{13} \, s_{13}^2 \, s_{23}^2 \, \frac{a}{\Delta m_{31}^2} \left( 1 - 2 \, s_{13}^2 \right) \sin^2 \Delta_{31}$$

For $\bar{\nu}$:

$$\delta_{CP} \rightarrow -\delta_{CP}$$

$$a \rightarrow -a \quad a = 2 \sqrt{2} \, G_F \, n_e \, E_\nu$$

$n_e$ related to matter density

Subleading effect, can be as large as 30% of dominant CP violation

Matter

Solar

CPV

CPC(cos$\delta$)

Leading($\theta_{13}$)

Total

295km

$\sin^2 2\theta_{13} = 0.1$, $\theta_{23} = \pi/4$, $\delta = \pi/4$
Examples of ND280 fits

- corrected flux and cross-section model
- significant reduction in parameter uncertainties.

Some of cross section parameters

Example of flux parameters
Error covariance matrix

ND fit constrains predicted number of events, which introduces large anticorrelations between flux and cross-section uncertainties
Far Detector Samples

- 5 samples of single ring events
  - muon candidate, $\nu$-mode (FHC)
  - muon candidate, $\bar{\nu}$-mode (RHC)
    - $\mu$-like PID
    - $p_\mu > 200$ MeV/c
    - Michel electron 1 or 0
  - electron candidate, $\nu$-mode
  - electron candidate, $\bar{\nu}$-mode
    - e-like PID
    - $p_e > 100$ MeV/c
    - $E_{\text{rec}} < 1250$ MeV
    - $\pi^0$ rejection
  - electron candidate with a Michel electron from decay of $\pi$, $\nu$-mode
<table>
<thead>
<tr>
<th>Statistical methods</th>
<th>Analysis 1</th>
<th>Analysis 2</th>
<th>Analysis 3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Kinematic variables for 1Re sample at SK</strong></td>
<td>Erec-θ</td>
<td>pE-θ</td>
<td>Erec-θ</td>
</tr>
<tr>
<td><strong>Likelihood</strong></td>
<td>Binned Poisson Likelihood Ratio</td>
<td>Binned Poisson Likelihood Ratio</td>
<td>Binned Poisson Likelihood Ratio</td>
</tr>
<tr>
<td><strong>Likelihood Optimization</strong></td>
<td>Markov Chain Monte Carlo</td>
<td>Gradient descent and grid scan</td>
<td>Gradient descent and grid scan</td>
</tr>
<tr>
<td><strong>Contours/limits produced</strong></td>
<td>Bayesian Credible Intervals</td>
<td>Frequentist Confidence Intervals with Feldman-Cousins (credible intervals supplemental)</td>
<td>Frequentist Confidence Intervals with Feldman-Cousins</td>
</tr>
<tr>
<td><strong>Mass Hierarchy Analysis</strong></td>
<td>Bayes factor from fraction of MCMC points in each bin</td>
<td>Bayes factor from likelihood integration</td>
<td>Frequentist p-value from generated PDF</td>
</tr>
<tr>
<td><strong>Near Detector Information</strong></td>
<td>Simultaneous joint fit</td>
<td>Constraint Matrix</td>
<td>Constraint Matrix</td>
</tr>
<tr>
<td><strong>Systematics Handling</strong></td>
<td>Simultaneous fit then marginalization</td>
<td>Marginalization during fit</td>
<td>Marginalization during fit</td>
</tr>
</tbody>
</table>
Difference wrt previous analysis

- changes from previous to recent analysis made sequentially one by one
  - $A$ – previous result
  - $B = A +$ changes in flux and cross-section models
  - $C = B +$ update on $\theta_{13}$ constraint from PDG2018 to PDG2019
  - $D = C +$ new calibration for SK (caused some events to migrate in and out of samples)
  - $E = D +$ new run 10 data
- largest change in $\delta_{CP}$ comes from new data
- new data collected in spring 2021, will be included in the next analysis
• changes from previous to recent analysis made sequentially one by one
  - A – previous result
  - B = A + changes in flux and cross-section models
  - C = B + update on $\theta_{13}$ constraint from PDG2018 to PDG2019
  - D = C + new calibration for SK (caused some events to migrate in and out of samples)
  - E = D + new run 10 data
• largest change in $\sin^2 \theta_{23}$ comes from new data
- changes from previous to recent analysis made sequentially one by one
  - **A** – previous result
  - **B** = A + changes in flux and cross-section models
  - **C** = B + update on $\theta_{13}$ constraint from PDG2018 to PDG2019
  - **D** = C + new calibration for SK (caused some events to migrate in and out of samples)
  - **E** = D + new run 10 data
- largest change in $\Delta m^2_{32}$ comes from new cross-section model (primarily better removal energy treatment)
Joint fits

- different baselines and neutrino energies → different oscillation patterns and systematic uncertainties
- combined analysis of data allows degeneracies to be broken
- two ongoing combined analyses:
  - T2K+SK atm. data: longer baseline and higher energy neutrinos, shared detector systematics: more sensitive to mass ordering
  - T2K+NOvA: different systematic uncertainties and longer baseline: more sensitive to mass ordering
ND280 upgrade

- better proton detections: tool for studying transverse variables
  - access nuclear effects: nuclear initial state and final state interactions

- better tracking:
  - gamma conversions in superFGD: important to tag $\pi^0 \rightarrow \gamma\gamma$,
  - Bragg peak: $\mu$/proton discrimination by $dE/dx$,
  - neutron tagging capabilities for isolated delayed clusters (~60% eff.)
Comparison for $\theta_{23}$

References:
- **T2K**: OA2020 data release, with reactor constraint.
- **NOvA**:
- **SK**:
  https://doi.org/10.5281/zenodo.4134680
  (Neutrino 2020, preliminary results), data release can be found at
  http://indico-sk.icrr.u-tokyo.ac.jp/event/5517/
- **IceCube**: IceCube Collaboration (2018):
  Measurement of atmospheric neutrino oscillations with three years of data from
  the full sky. IceCube Neutrino Observatory. Dataset. DOI: 10.21234/B4105H.
  , corresponding to paper “Measurement of Atmospheric Neutrino Oscillations at 6-56
  GeV with IceCube DeepCore,” IceCube Collaboration: M. G. Aartsen et al., Physical
  Review Letters 120, 071801 (2018). DOI: 10.1103/PhysRevLett.120.071801
How to use this proton information:
“Single Transverse Variables” and beyond!
→ measurements of Fermi momentum, binding energy, 2p2h...

$\delta p_T$ is a direct measurement of Fermi momentum: shape measurement <10% precision in each bin with $8 \times 10^{21}$ POT

$\delta \alpha_T$ shape is highly sensitive to proton FSI
→ allows to constrain it to $\sim 1\%$: not anymore an issue to use protons in the ND fit for the oscillation analysis!
(today 30% from e-scattering data)
Another variable: total energy

- The $E_{\nu}^{\text{rec}}$ CCQE formula does not include information on the outgoing proton → $E_{\mu}+E_p$ is a much better estimator of the true neutrino energy.

![Graph showing the comparison between $E_{\nu}^{\text{rec}}$ and $E_{\nu}$](image)

Smearing of $E_{\nu}^{\text{rec}}$ is dominated by Fermi momentum,

smearing of $E_{\mu}+E_p$ is dominated by flux (and detector effects)

→ $E_{\mu}+E_p$ is a much more robust estimator of true $E_{\nu}$ and of binding energy.

- This is just the appetizer! We are starting investigating possible other variables and combinations → a lot of new sensitivity

A good example of the 'iterative' process: new detector + *DATA* → new ways of doing analysis / looking at our systematics → improvements of oscillation analysis!
Spectral function

- moved from an RFG+RPA to a SF nuclear ground state model
- At higher $Q^2$ axial form factor effects become more important. Our default model is a single parameter ($M_{AQE}$) dipole form factor which be constrained to the level of <10% from bubble chamber and pion electroproduction data.
- However, at higher $Q^2$ the dipole approximation is known be insufficient (TN315). Previous analyses then used a large $M_{AQE}$ uncertainty to effectively account for variations of the dipole form factor.
- For this analysis we opt to use a value and prior of $M_{AQE}$ as constrained by bubble chamber experiments ($M_{AQE}=1.03\pm0.06$ GeV) with three additional “high” $Q^2$ parameters to account for variations from a dipole form factor.
- These have priors to cover differences in the higher $Q^2$ behaviour of the dipole and “z-expansion” form factor parametrisations (z-expansion is a much more free parametrisation which can describe higher $Q^2$ bubble chamber data)
- In RFG freedom at low $Q^2$ was offered via RPA, for SF we instead allow 5 free ad-hoc “low” $Q^2(<0.25$ GeV$^2$) bin normalisation parameters (every 0.05 GeV$^2$) with central values set from neutrino scattering data