Latest results from T2K

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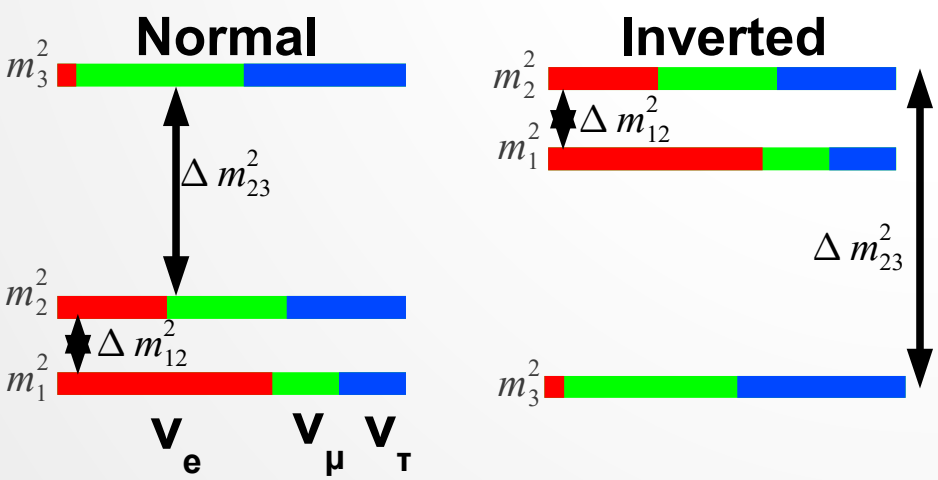
NCBJ

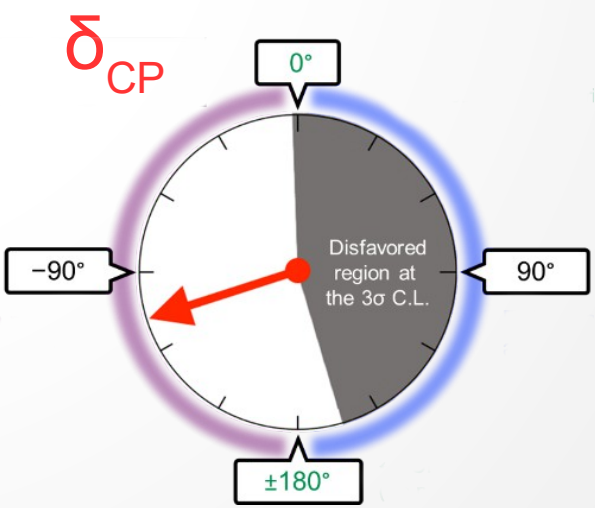
NuFact 2021

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 δ_{CP}
- most oscillation parameters measured with <10% precision
  - θ_{23} is known with 15% precision
- unknown parameters: mass hierarchy (ordering) and δ_{CP}

$$\sin^2(\theta_{13}) = (2.18 \pm 0.07) \times 10^{-2}$$
$$\sin^2(\theta_{12}) = 0.307 \pm 0.013$$
$$\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}\ \mathrm{eV}^2$$
$$\sin^2(\theta_{23}) = 0.547 \pm 0.021 \quad \text{(Inverted order)}$$
$$\sin^2(\theta_{23}) = 0.545 \pm 0.021 \quad \text{(Normal order)}$$
$$\Delta m^2_{32} = (-2.546^{+0.034}_{-0.040}) \times 10^{-3}\ \mathrm{eV}^2 \quad \text{(Inverted order)}$$
$$\Delta m^2_{32} = (2.453 \pm 0.034) \times 10^{-3}\ \mathrm{eV}^2 \quad \text{(Normal order)}$$





T2K Nature paper, spring 2020

T2K experiment

(plenary talk of C.Riccio)

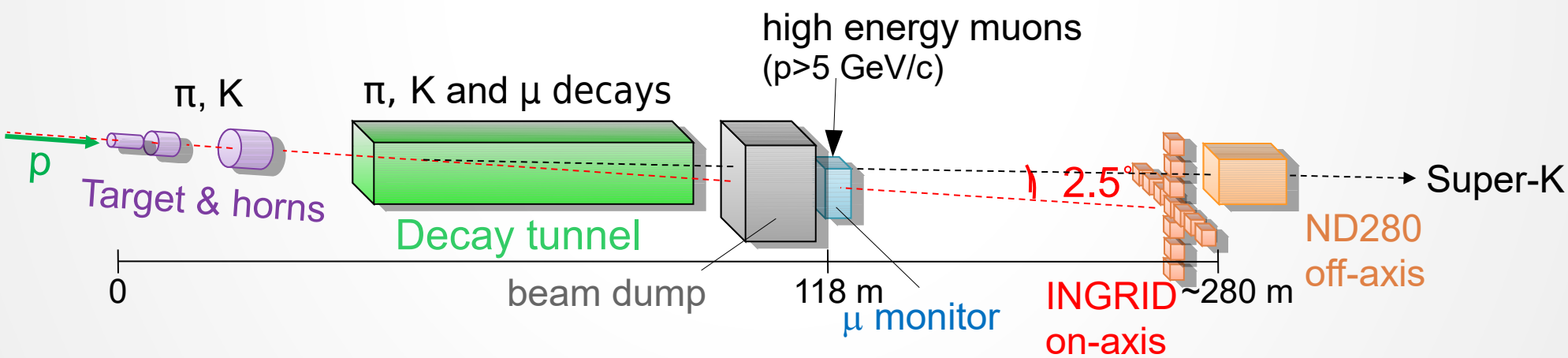
- located in Japan
- searches for oscillations in high purity (anti-)ν_μ beam

- 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 750kW
  - 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 280m from the target
  - **INGRID** (on axis), **WAGASCI** (1.5º off-axis) ← (talk of K.Yasutome)
  - **ND280** (same off axis angle as the Far Detector)

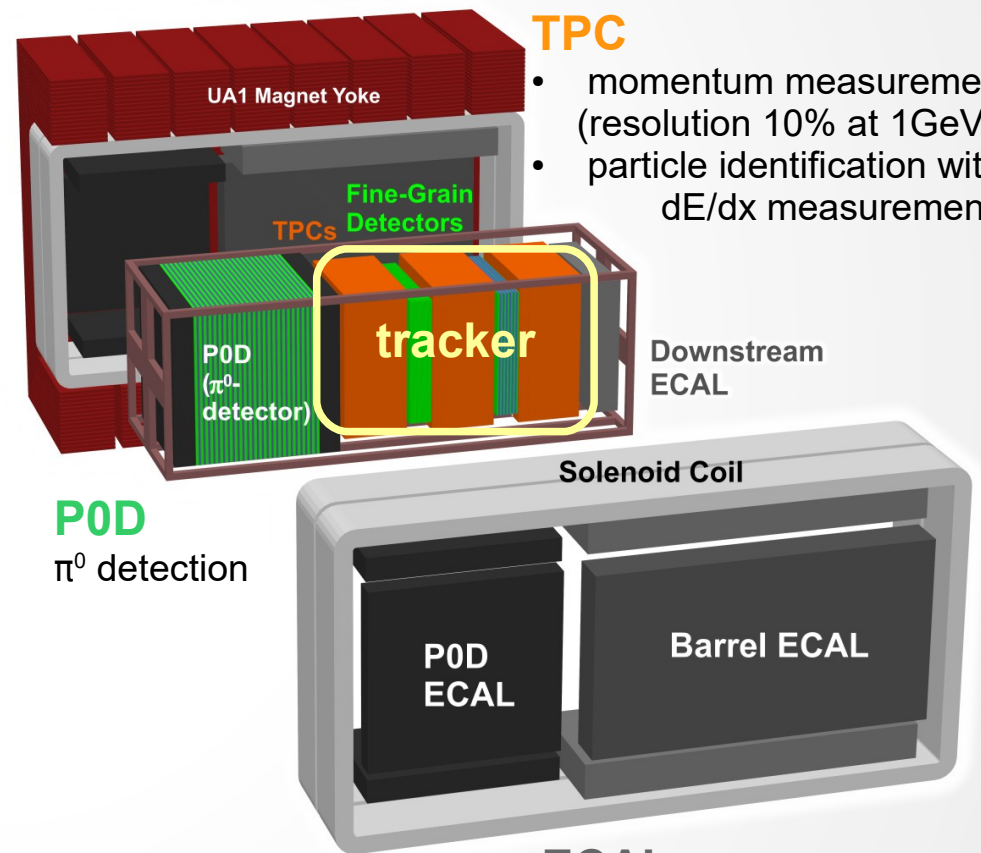
ND280

- 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 ν interaction rates and flavour → ν_μ and ν_e spectra
- focused on specific background processes to oscillation (NCπ^0, NC1π, CC1π…)
- compare interactions on **Carbon** and **Oxygen** (FGD2 and P0D)

SMRD
improvement of muon identification

FGD
- active target
- recoil protons detection

TPC
- momentum measurement (resolution 10% at 1GeV)
- particle identification with dE/dx measurement

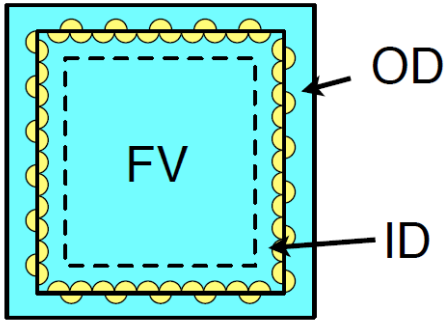


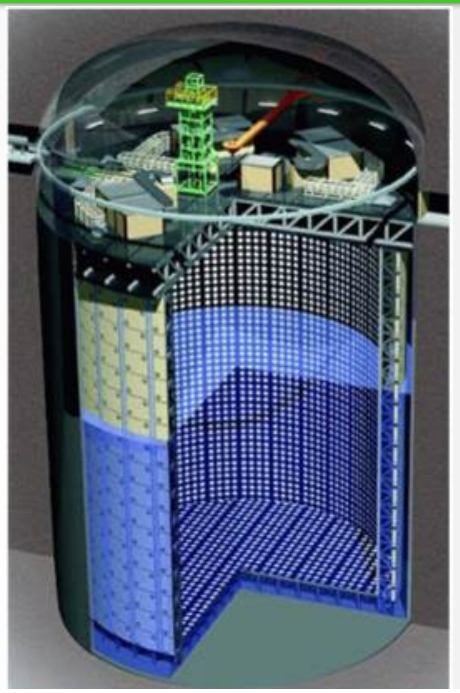
P0D
π^0 detection

ECAL
EM showers

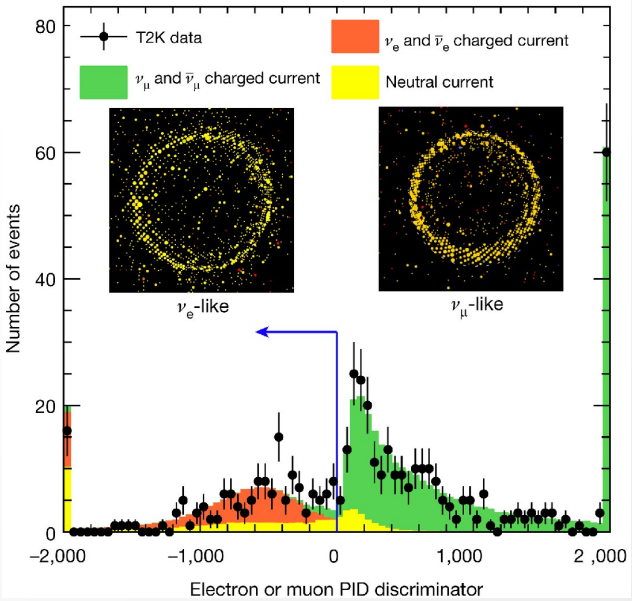
Super-Kamiokande as the Far Detector

- 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



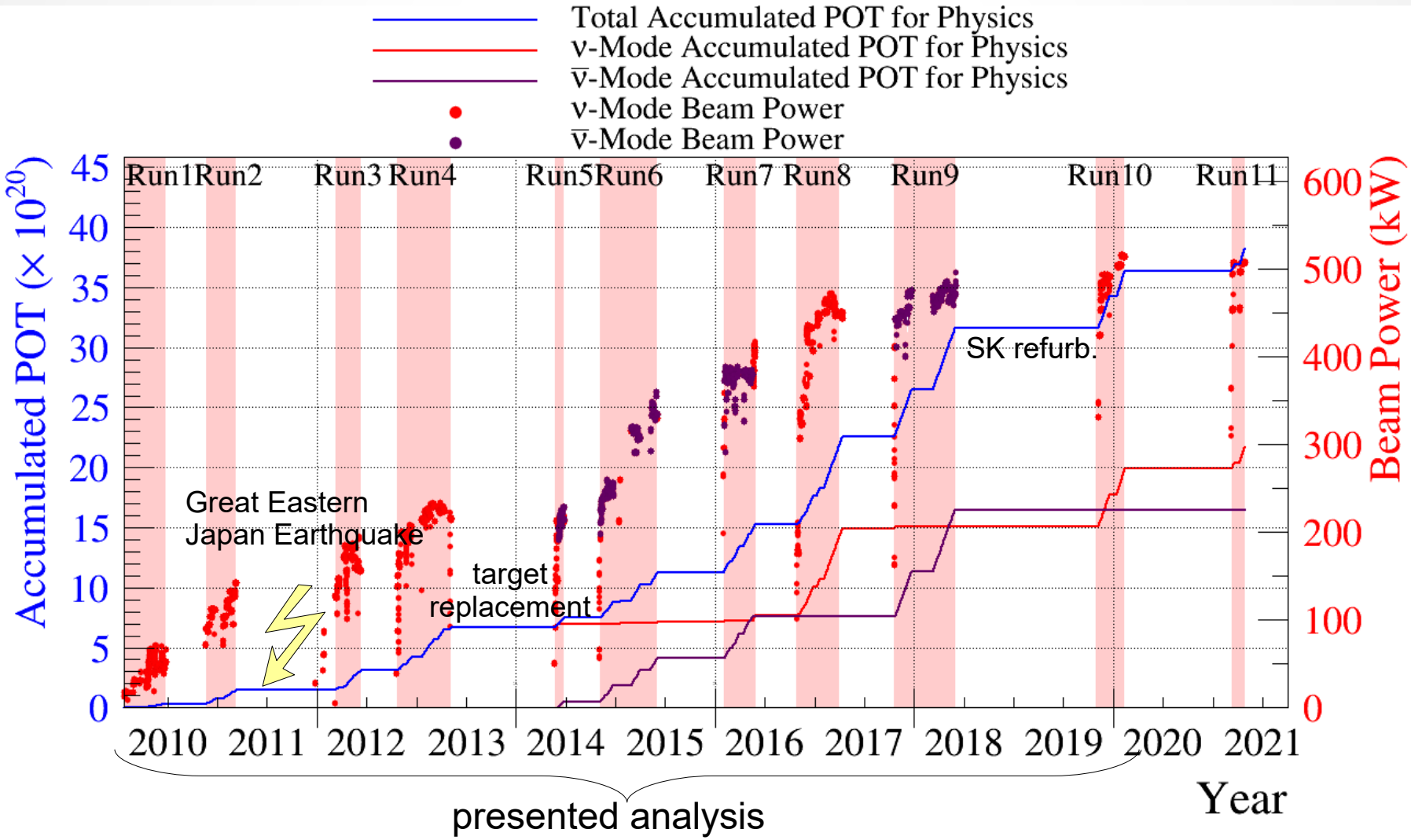


- particle identification capability:
  - muons misidentified as electrons <1%
- ν energy resolution ΔE/E~10% for two-body kinematics
- no charge identification

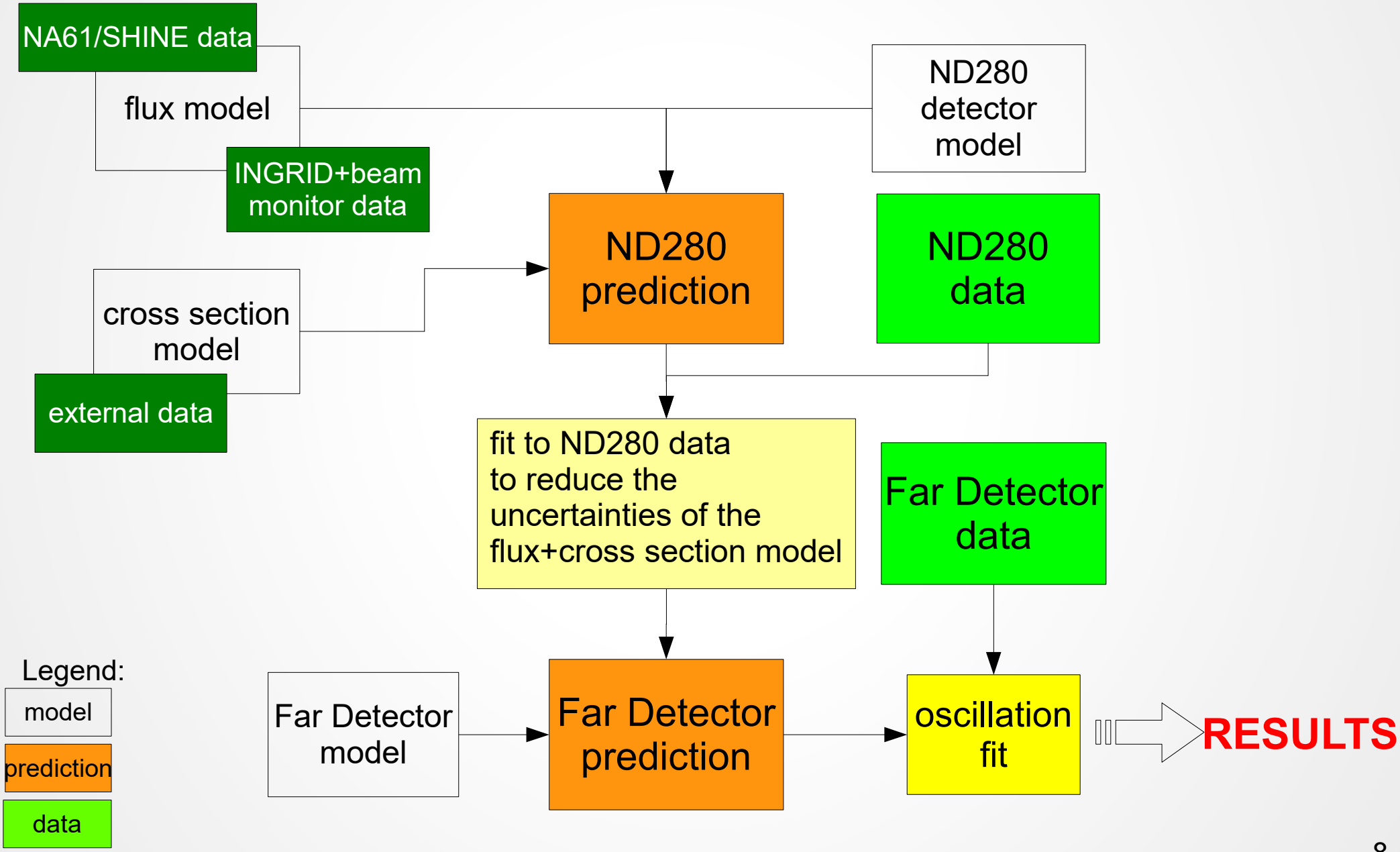


T2K data taking

- experiment started to take physics data in January 2010
- 515 kW stable operation
- 1.97×10^{21} protons on target (POT) in ν-mode and 1.63×10^{21} in $\bar{\nu}$-mode



Analysis flow



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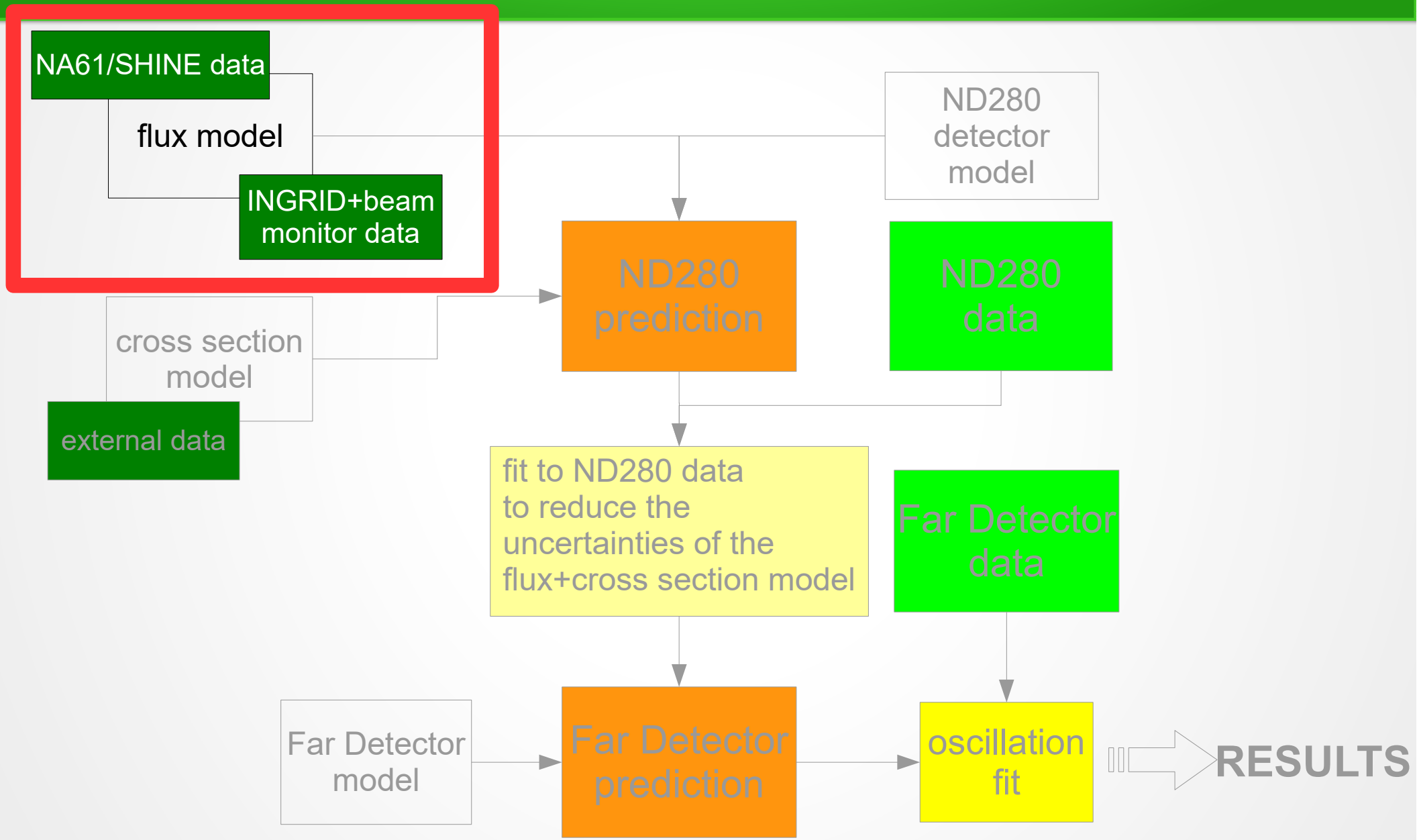
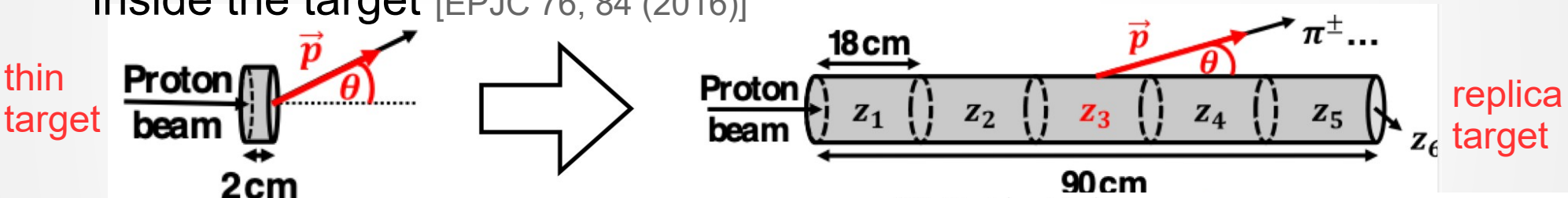
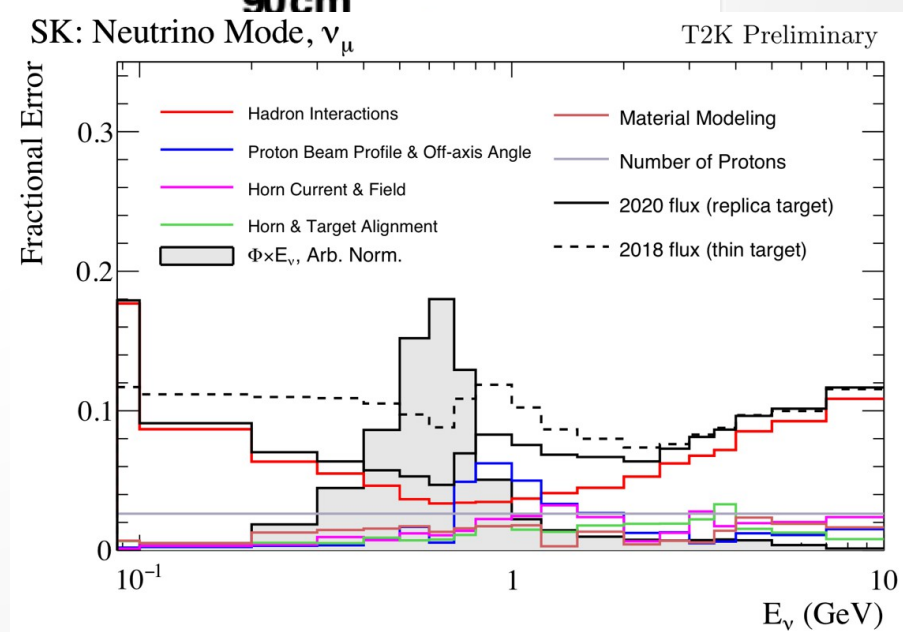


Beam simulation

- 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)]

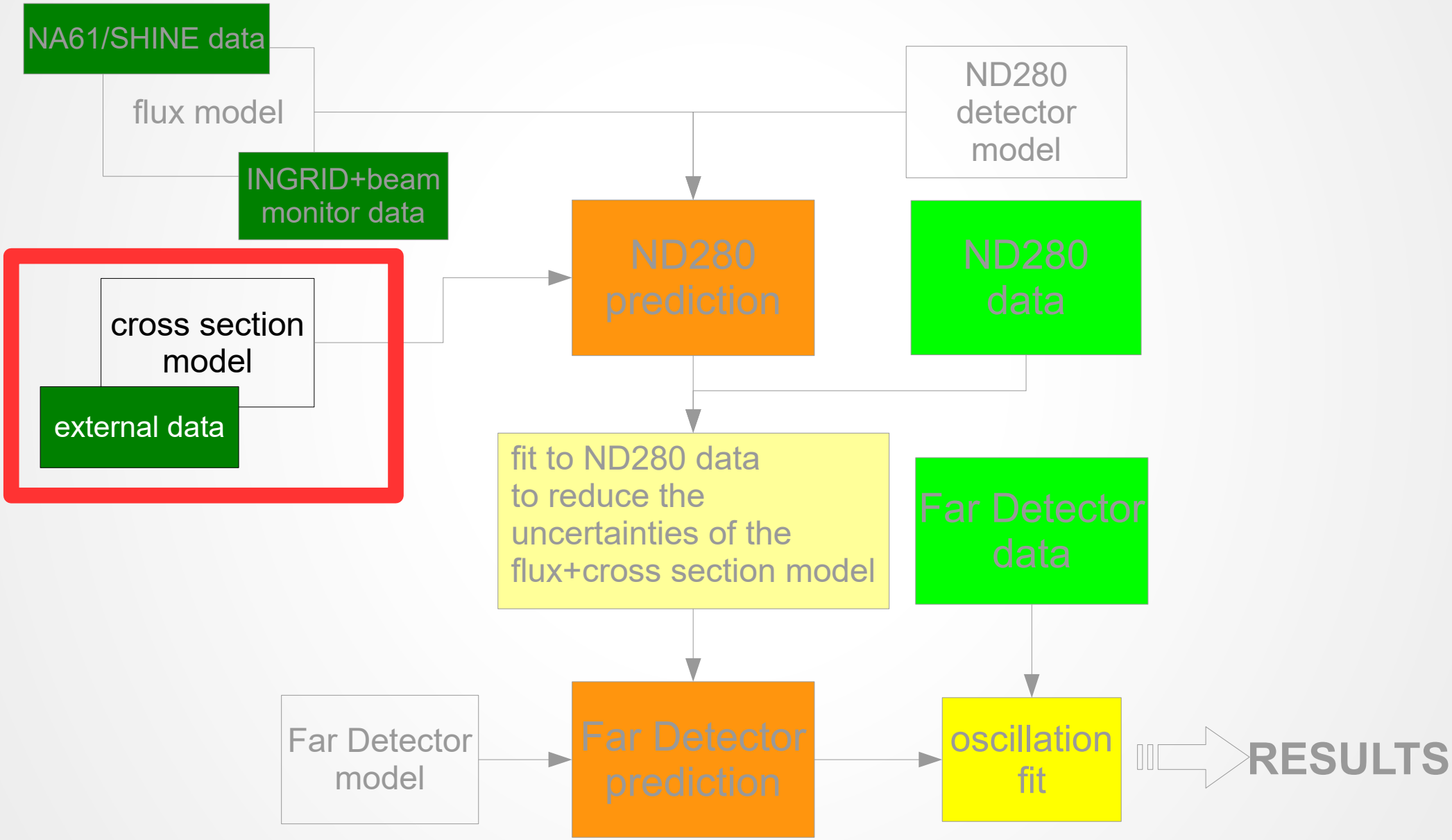


  - MC spectrum reweighted to match data in momentum, angle and target exit point



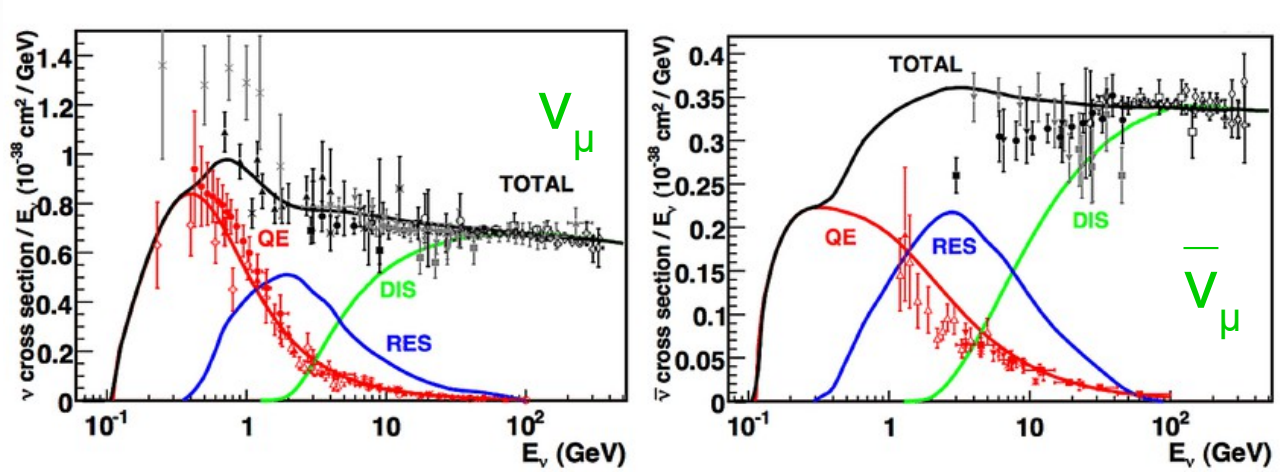
- Flux uncertainties reduced from 8% (thin) to 5% (replica) in flux peak

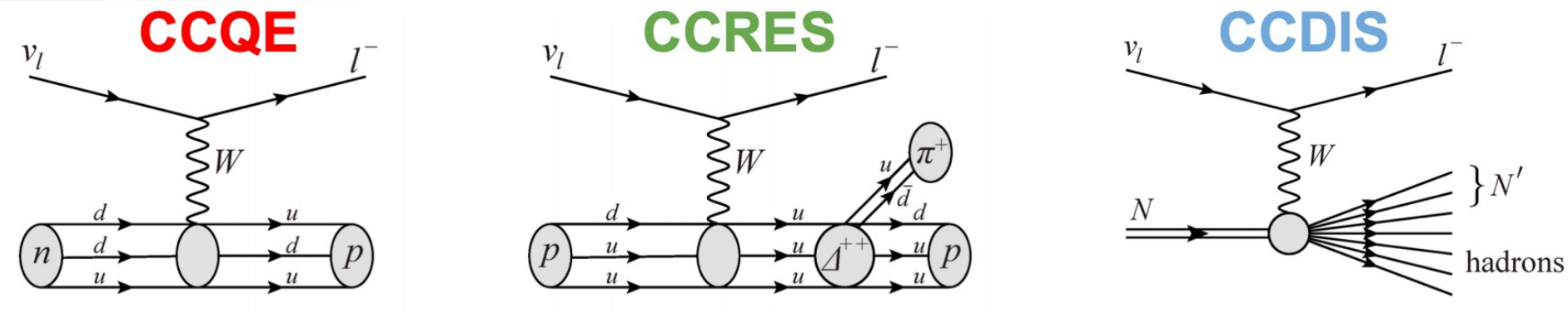
Analysis flow



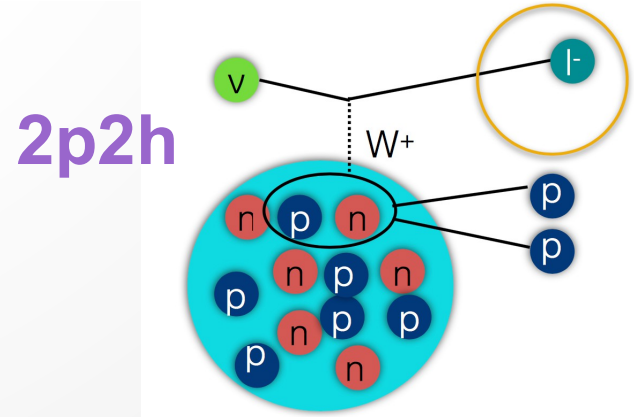
Cross section

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



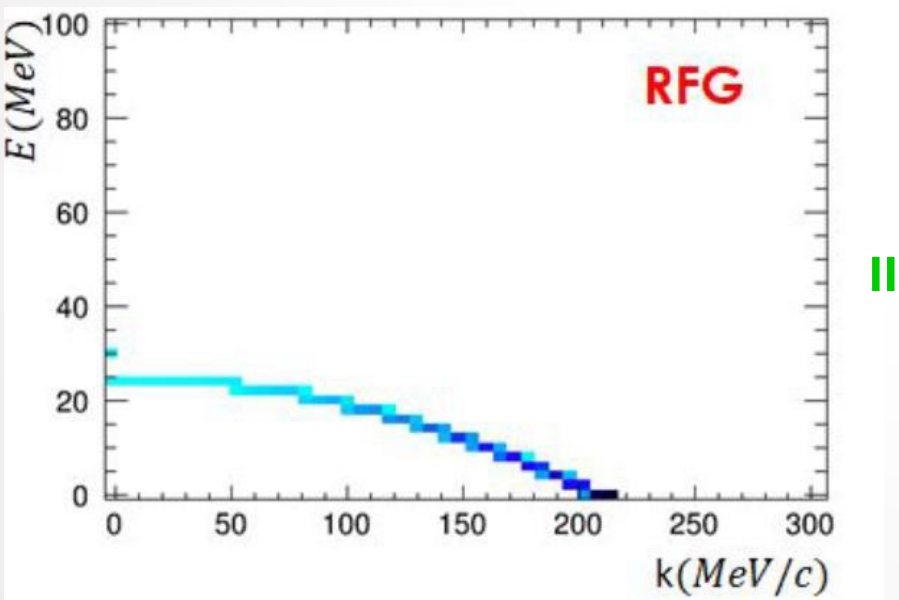


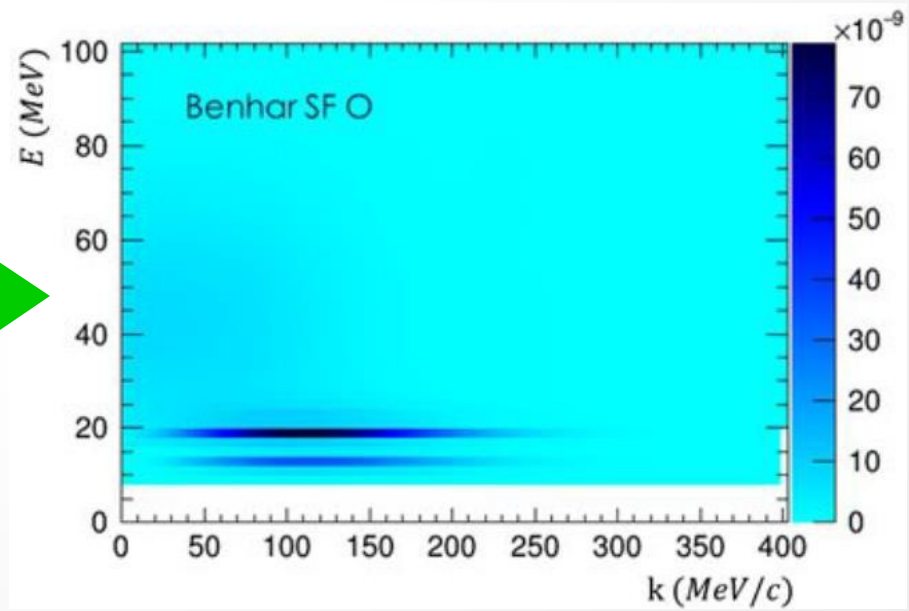
- at the nucleus level:
  - also multinucleon (2p2h) interactions
  - target nucleon initial state
  - Final State Interactions (FSI)



What's new in cross section models

- significant updates in interaction models (NEUT 5.4.0)
- most significant changes in the QE part
  - CCQE nuclear initial state model moved from Relativistic Fermi gas [Phys.Rept. 3 261] plus RPA [Phys. Rev. C 83, 045501] to tuned spectral function (SF) [Nuc. Phys. A 579, 493]
  - realistic shell-model-based description of the nucleus
  - can (almost) be interpreted as the initial state nucleon momentum (k) and binding energy (E)





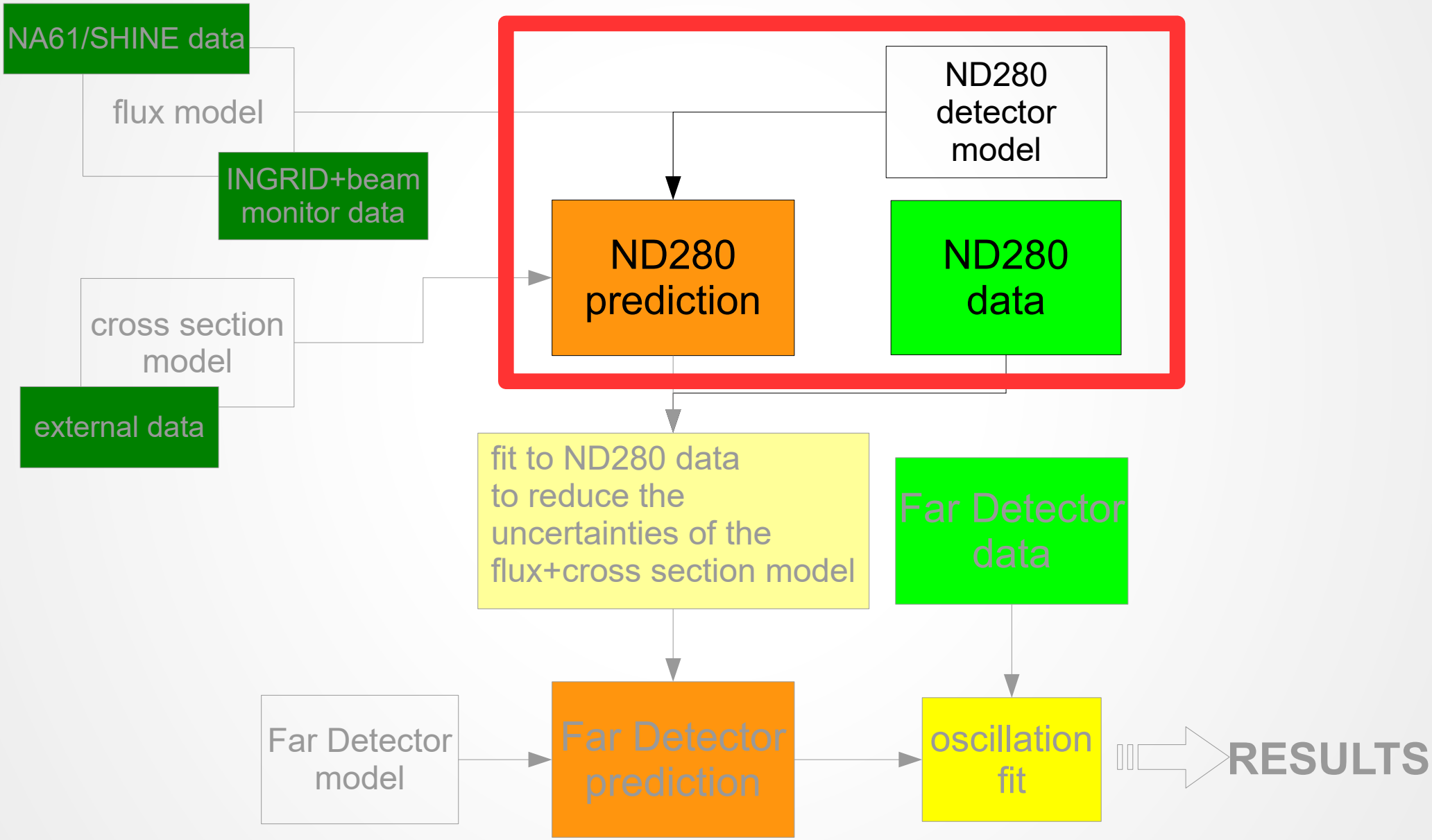
What's new in cross section models

- QE (cont.)
  - the Benhar SF is largely extracted from exclusive electron scattering data (on proton) → shift the position of shells for neutron
  - need for a suppression at low Q^2 from CC0π cross section measurements [Phys. Rev. D 101, 112004; Phys. Rev. D, 99, 012004] → parameters allowing ad-hoc low Q^2 suppression
  - 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



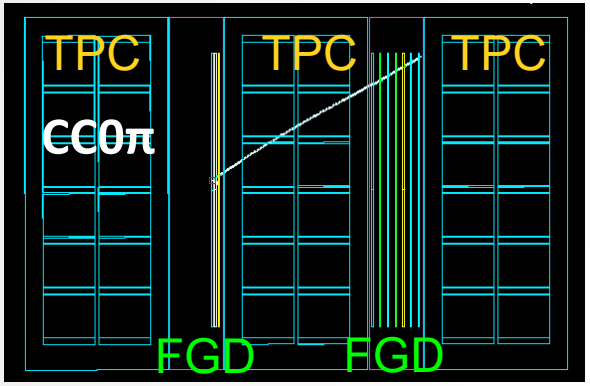
Near Detector samples

- analysis of ν_μ CC interactions in ND280 to constrain flux and cross section parameters and uncertainties
  - ν_μ measurement can constrain also ν_e flux
- **(anti)ν_μ CC selection in ND280 tracker**
  μ^- (μ^+) candidate: highest momentum negative (positive) track
  - starting in FGD FV with long segment in TPC
  - dE/dx compatible with muon hypothesis

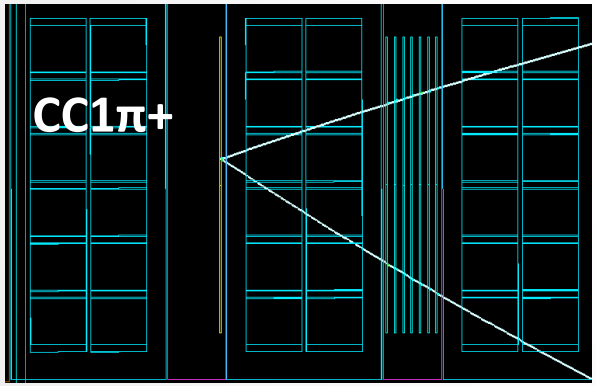
- 18 samples in total = sensitivity to different neutrino energy ranges and interactions modes
  - separate samples for **FGD1** and **FGD2** (interactions on CH/Water)
  - **separate multipion samples** ← presence of pions in final state topology
    - **NEW** for RHC beam mode
  - **dominant component** 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

18 = 2 * 3 * 3

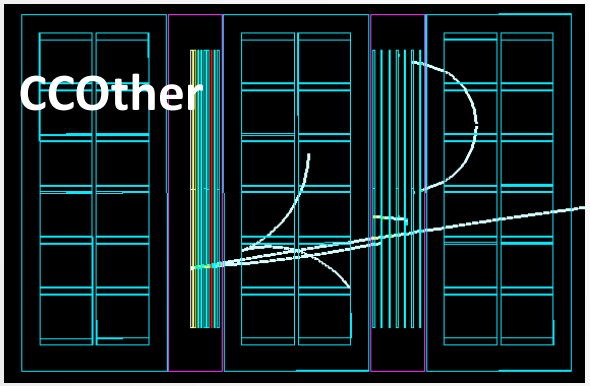
Example: FGD1 ν-mode (FHC) samples



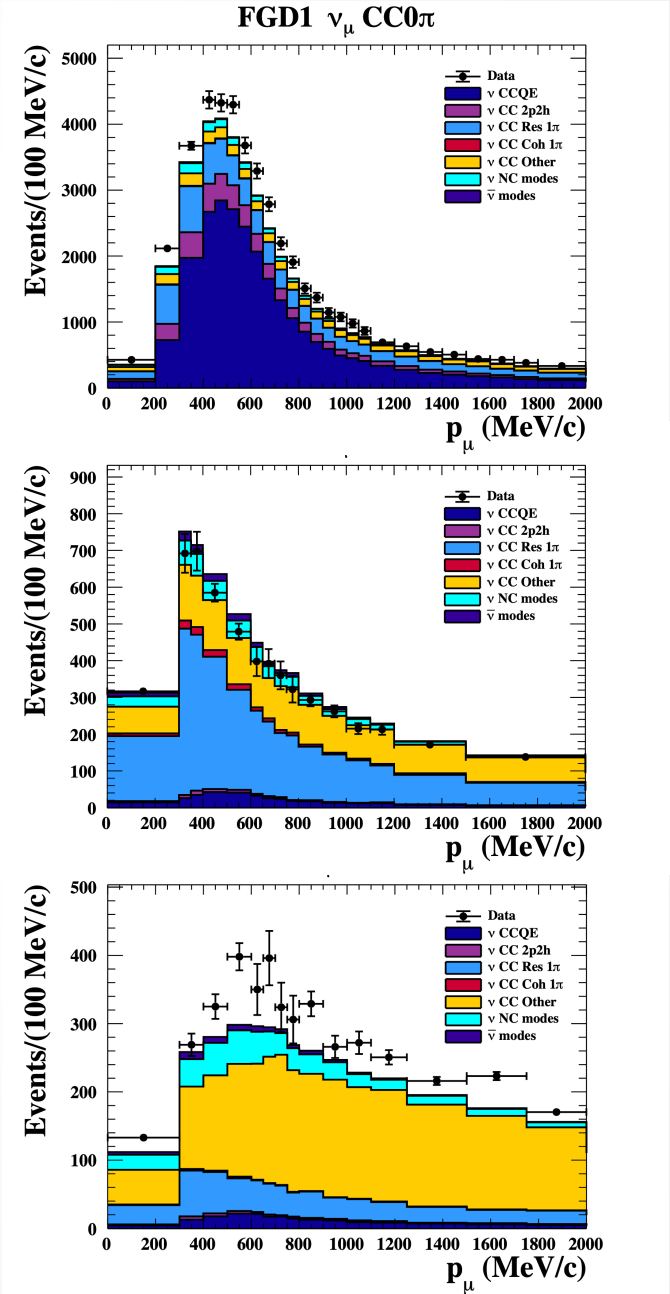
CC 0π – dominated by **CC QE**



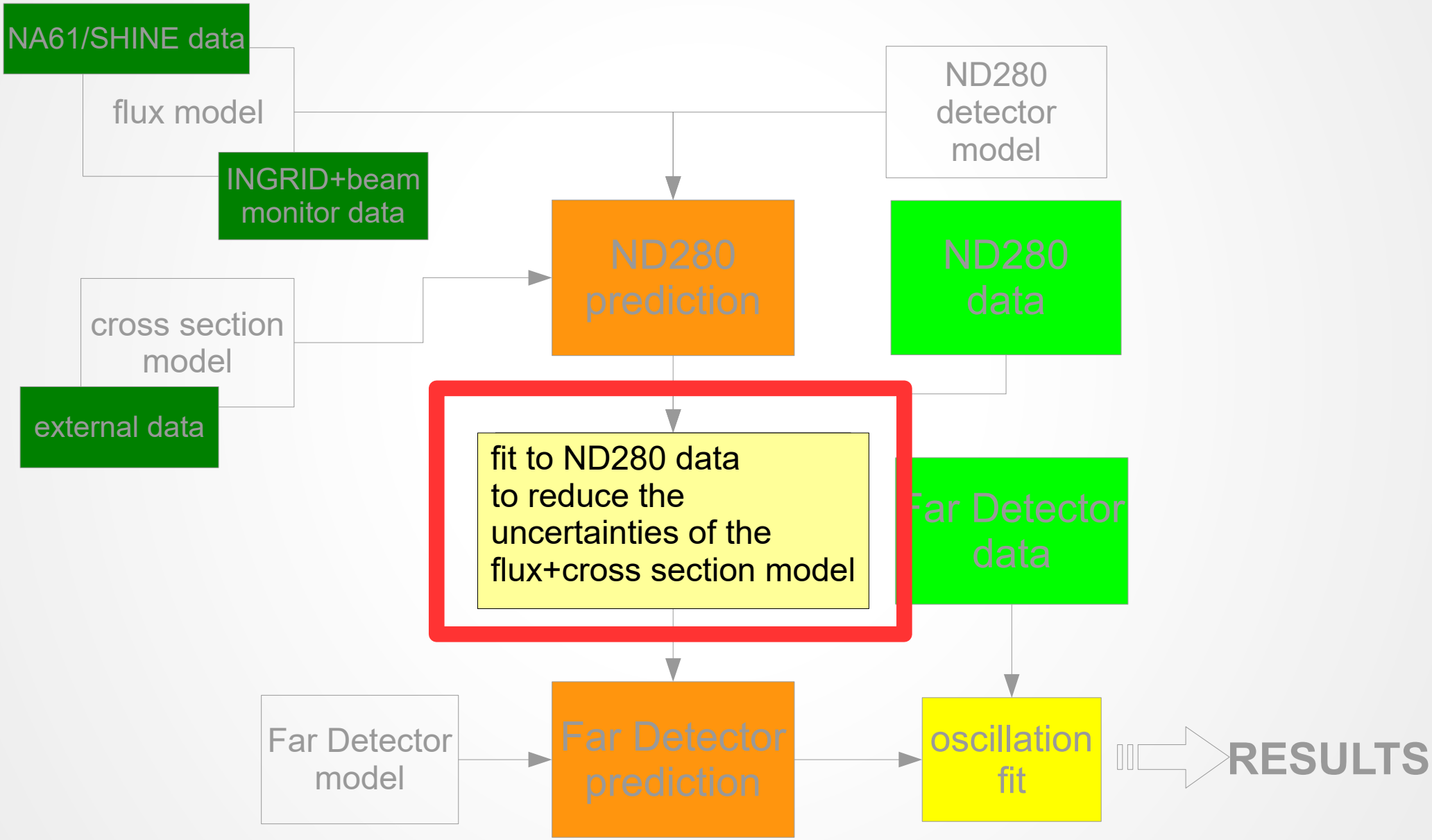
CC 1π⁺ – enhanced in **resonant pion production**



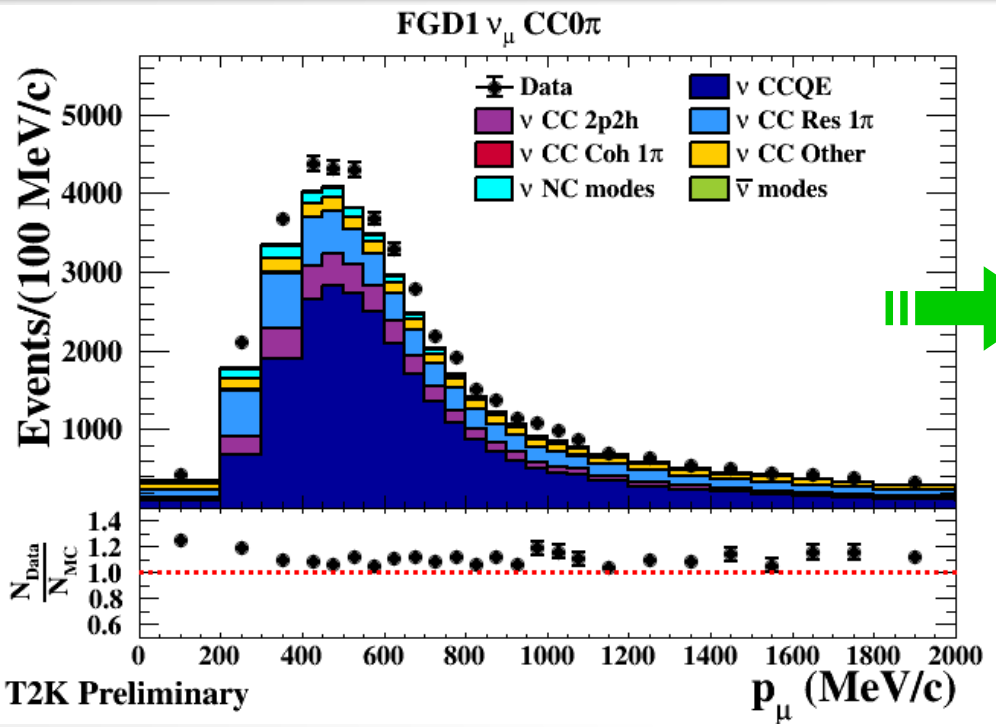
CC Other – mostly **DIS**

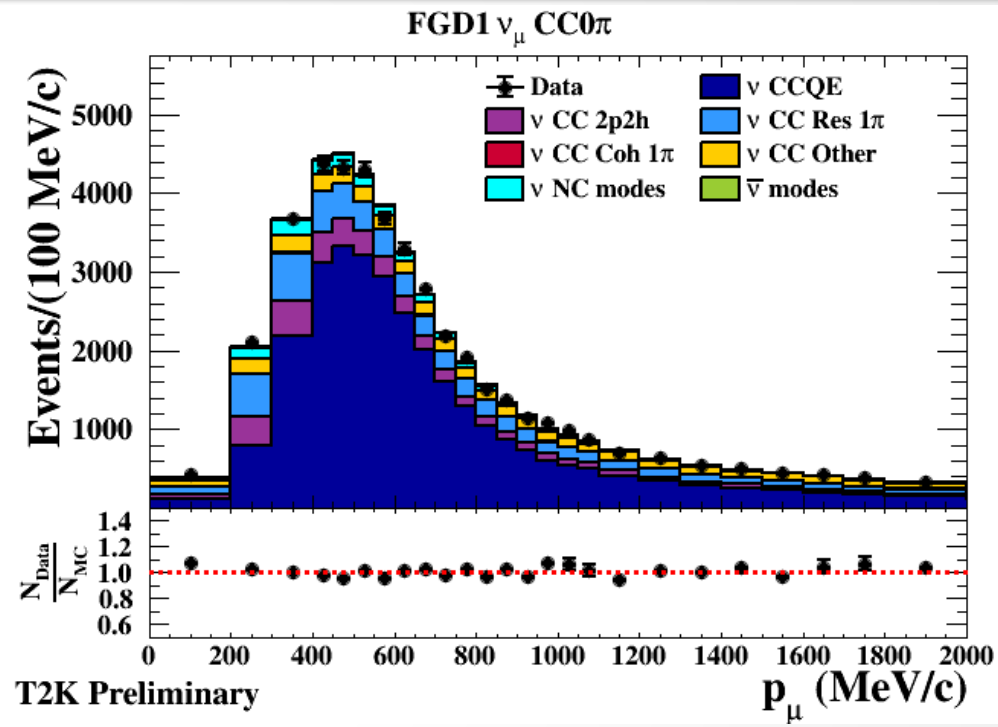


Analysis flow

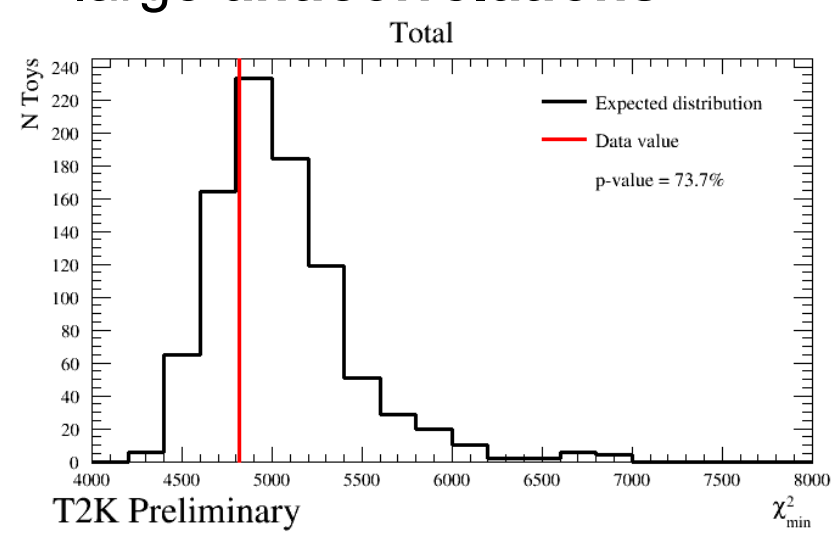


Post-fit

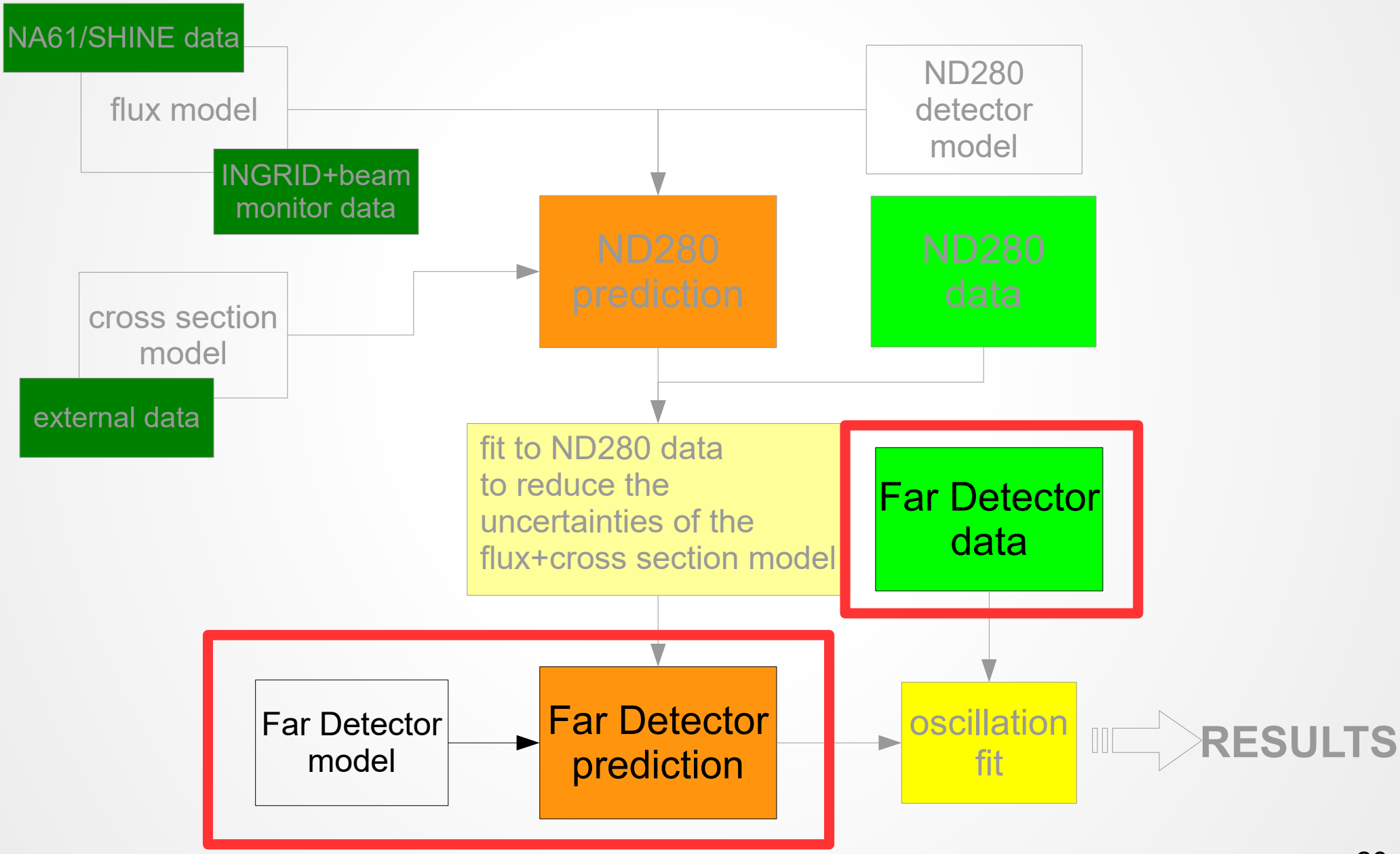




- ND fit constrains predicted number of events → large **anticorrelations** between flux and cross-section uncertainties
- good fit to data (prior model p-value=74%)
  - test the model ability to cover the phase space region which best describes the data.
  - "toy" data sets thrown from prior covariance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



Analysis flow

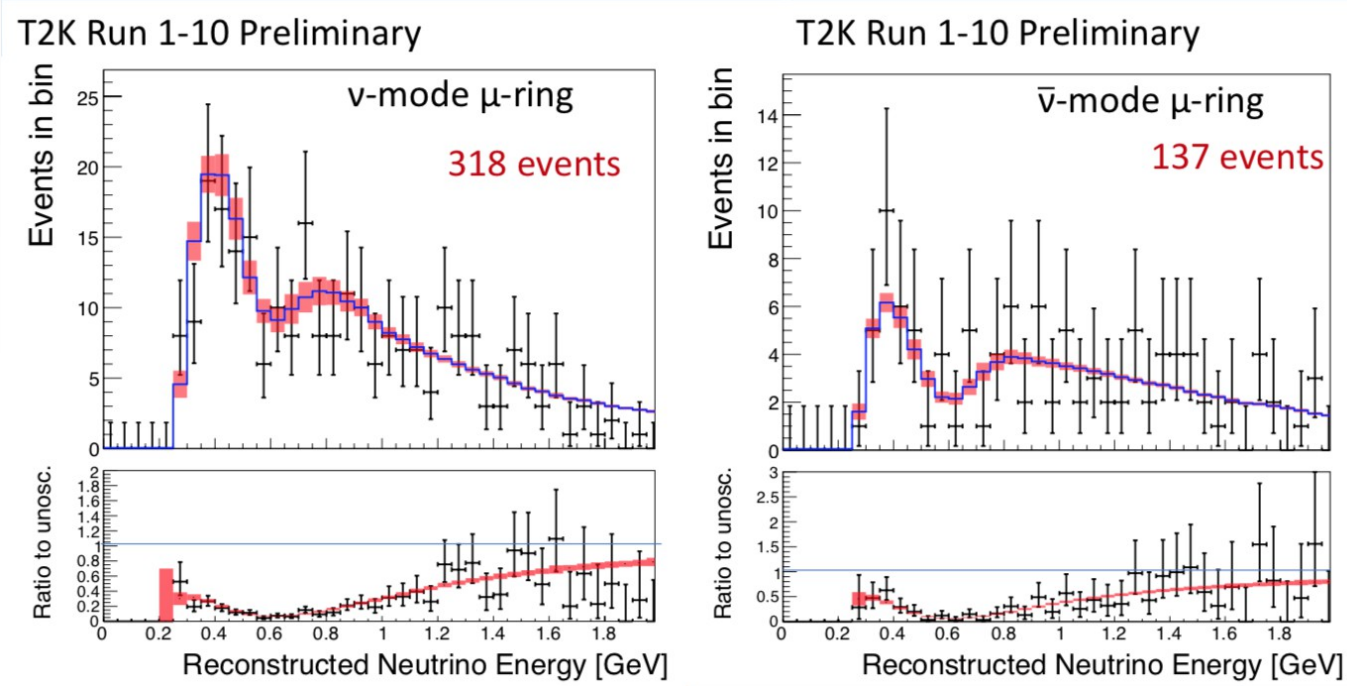


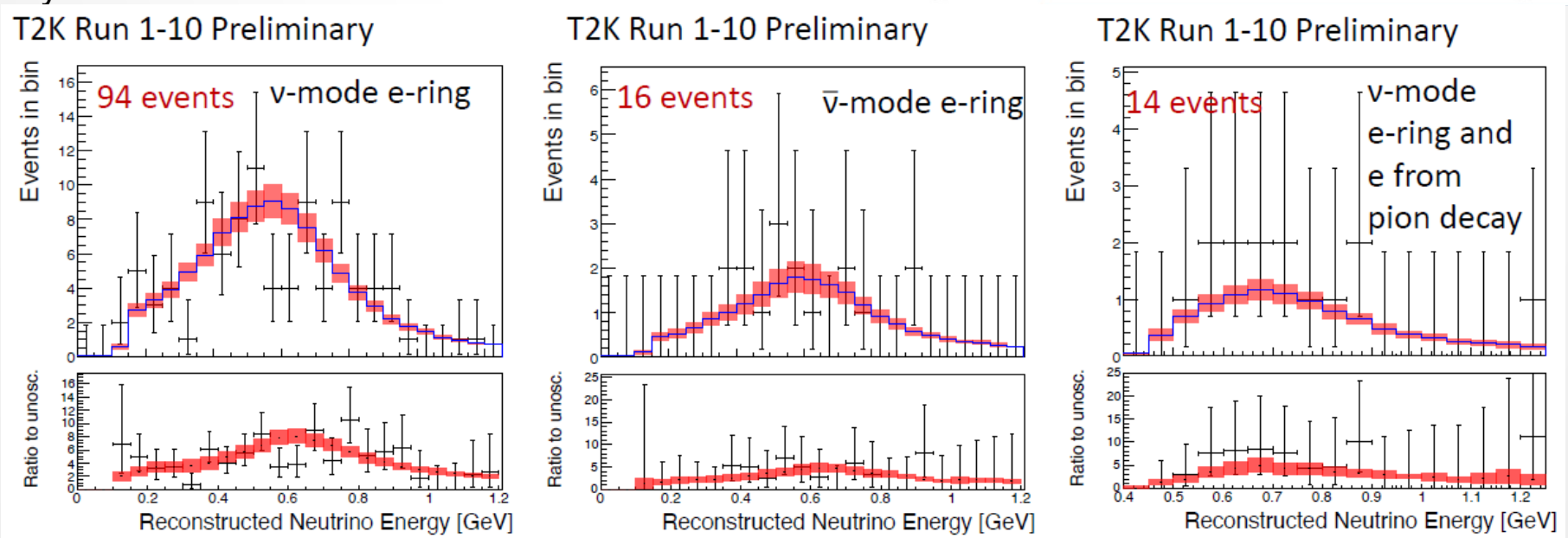
Far Detector samples

5 samples from the Far Detector are used:

- ν and $\bar{\nu}$-mode μ-ring
- ν and $\bar{\nu}$-mode e-ring
- ν-mode e-ring+Michel electron

red band = systematic uncertainty

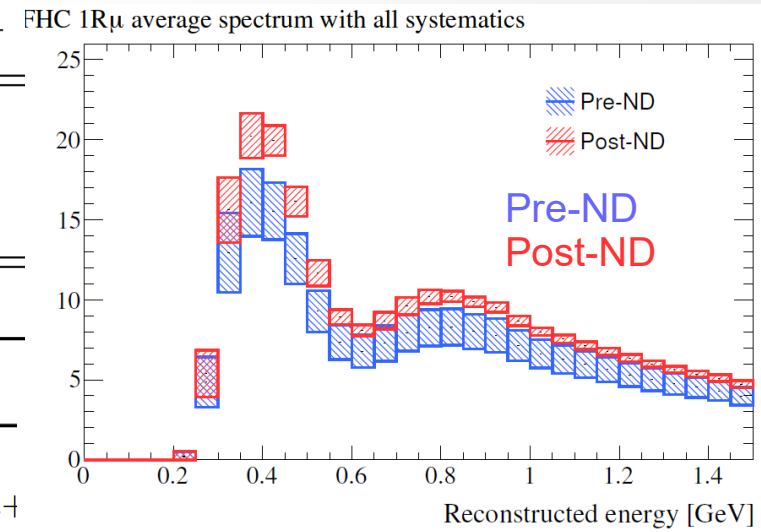


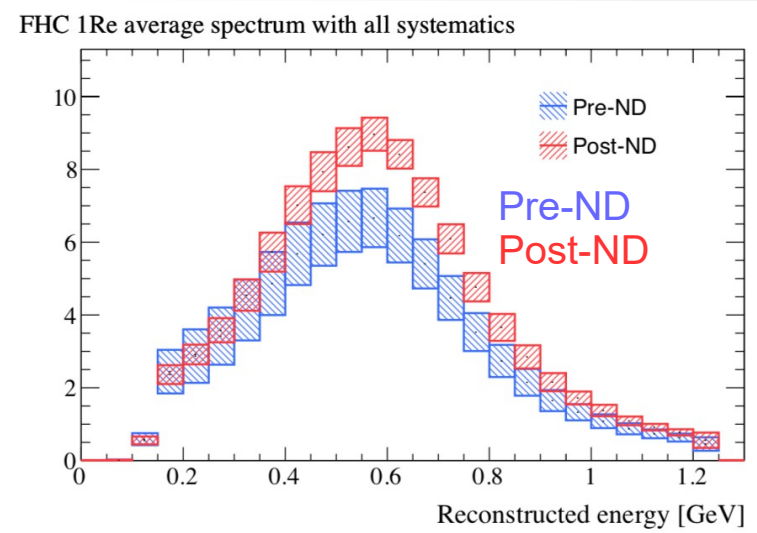


Effect of ND280 fit

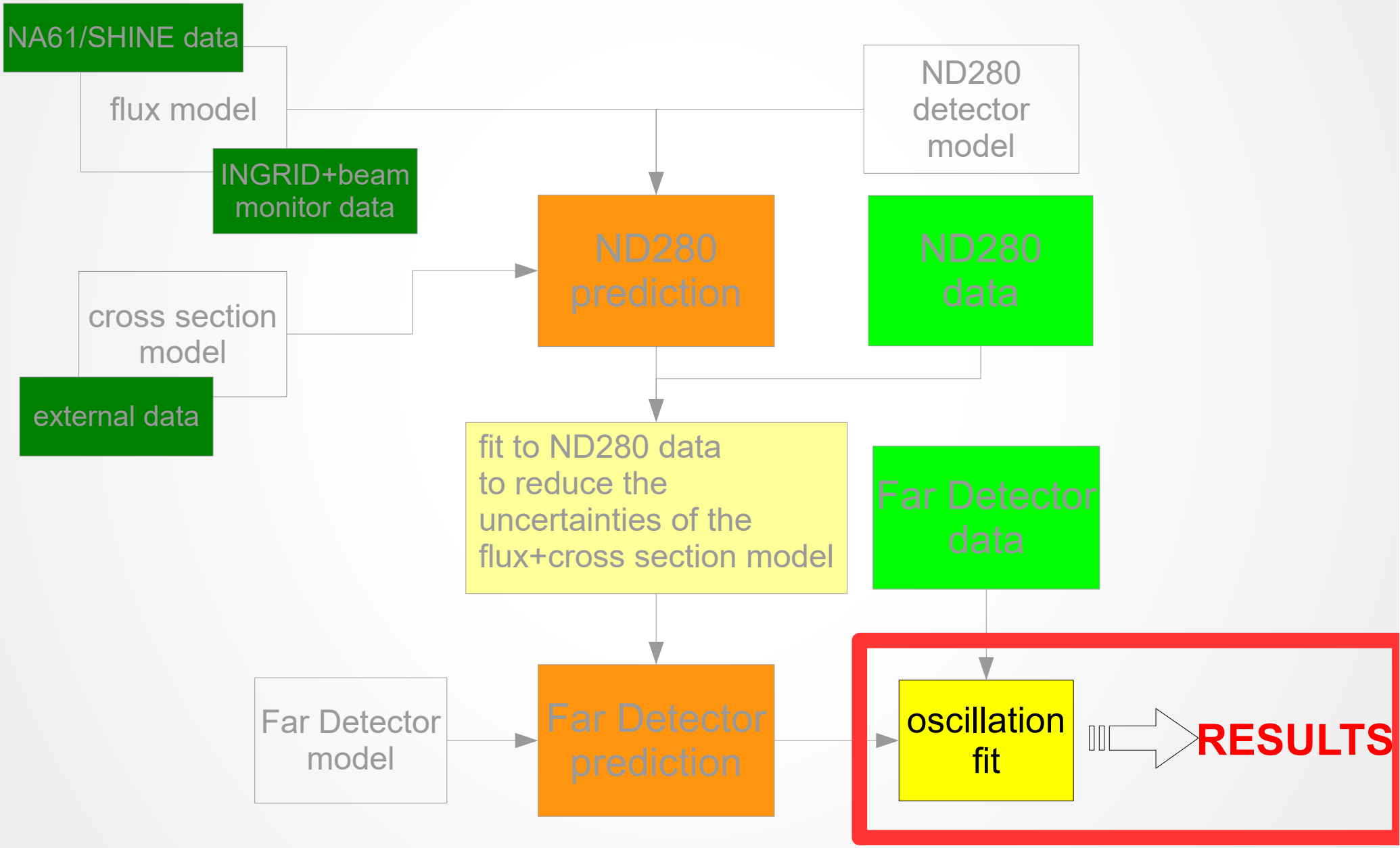
Pre fit Error source	1Rμ FHC	1Rμ RHC	1Re FHC	1Re RHC	1Re FHC CC1π^+
Flux	5.1%	4.7%	4.8%	4.7%	4.9%
Cross-section (all)	10.1%	10.1%	11.9%	10.3%	12.0%
SK+SI+PN	2.9%	2.5%	3.3%	4.4%	13.4%
Total	11.1%	11.3%	13.0%	12.1%	18.7%

Post fit Error source (units: %)	1Rμ FHC	1Rμ RHC	1Re FHC	1Re RHC	1Re FHC CC1π^+
Flux	2.9	2.8	2.8	2.9	2.8
Xsec (ND constr)	3.1	3.0	3.2	3.1	4.2
Flux+Xsec (ND constr)	2.1	2.3	2.0	2.3	4.1
Xsec (ND unconstrained)	0.6	2.5	3.0	3.6	2.8
SK+SI+PN	2.1	1.9	3.1	3.9	13.4
Total	3.0	4.0	4.7	5.9	14.3





Analysis flow



Oscillation fits

- $\nu_\mu \rightarrow \nu_\mu$ and $\nu_\mu \rightarrow \nu_e$ combined analysis within the 3ν 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 θ_{13}, θ_{23}, Δm^2_{32}, δ_{CP}
  - other oscillation parameters from PDG 2019 values
  - results with T2K data alone and using PDG 2019 constraint on θ_{13} from reactor experiments
- binned likelihood comparing data to MC predictions

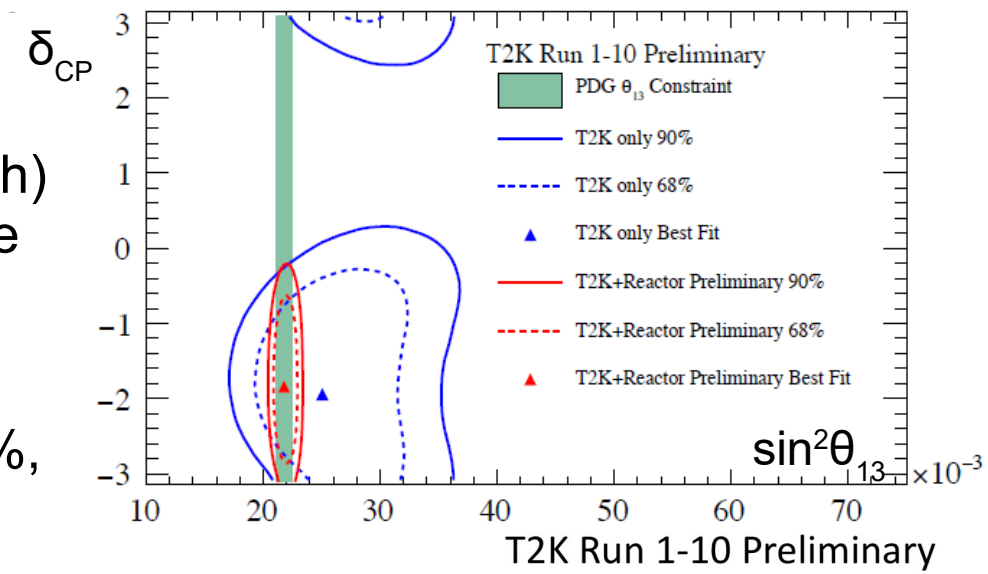
$$-2\ln\lambda\left(\delta_{CP};\boldsymbol{a}\right)=2\sum_{i=1}^{N}\left[n_i^{obs}\ln\left(\frac{n_i^{obs}}{n_i^{\exp}}\right)+n_i^{\exp}-n_i^{obs}\right]$$

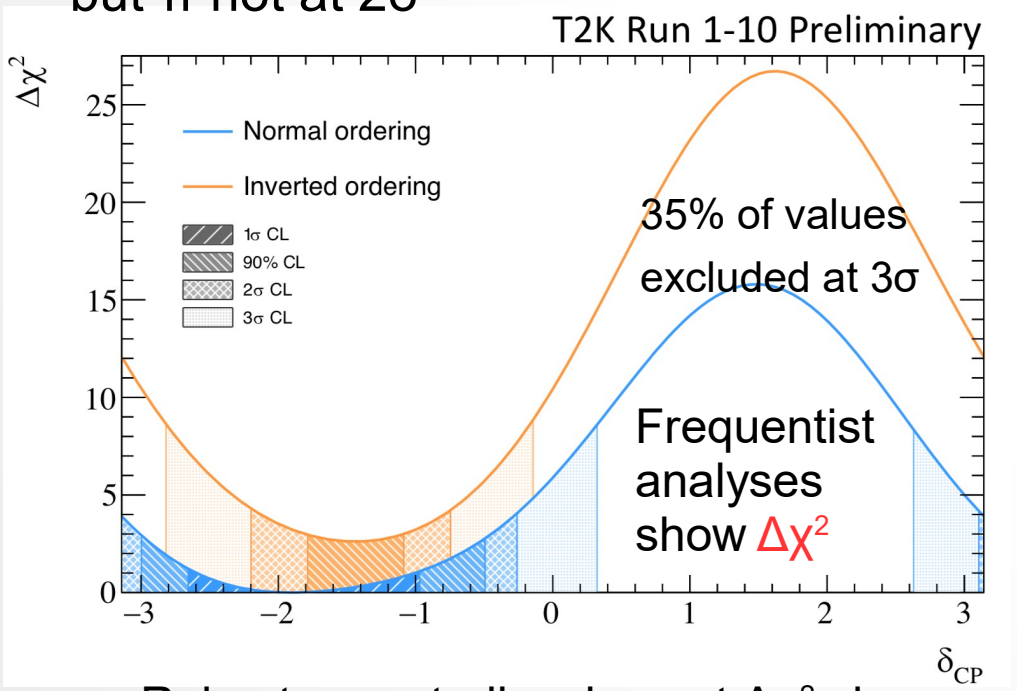
nuisance parameters
(flux, x-sec, detector)

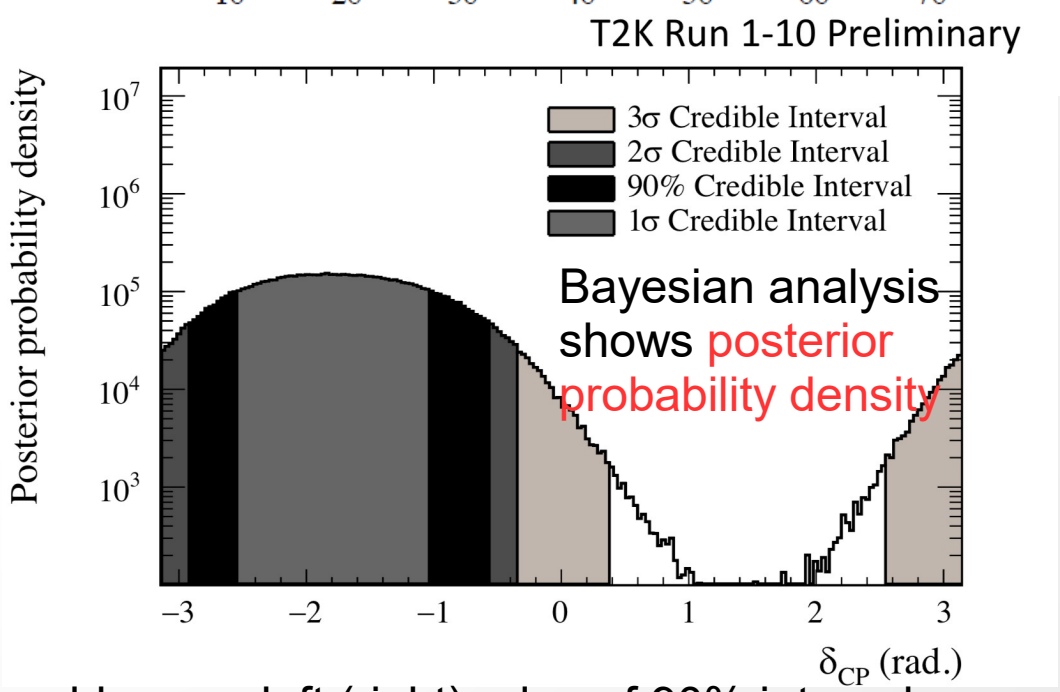
$$+\left(\boldsymbol{a}-\boldsymbol{a_0}\right)^T\boldsymbol{C}^{-1}\left(\boldsymbol{a}-\boldsymbol{a_0}\right)$$

δ_{CP} and θ_{13}

- T2K-only intervals compatible with PDG 2019 θ_{13} values
  - frequentists confidence intervals (grid search) agree with the Bayesian factors and credible intervals
- with reactor contraints:
  - CP conserving values (0,π) excluded at 90%, but π not at 2σ



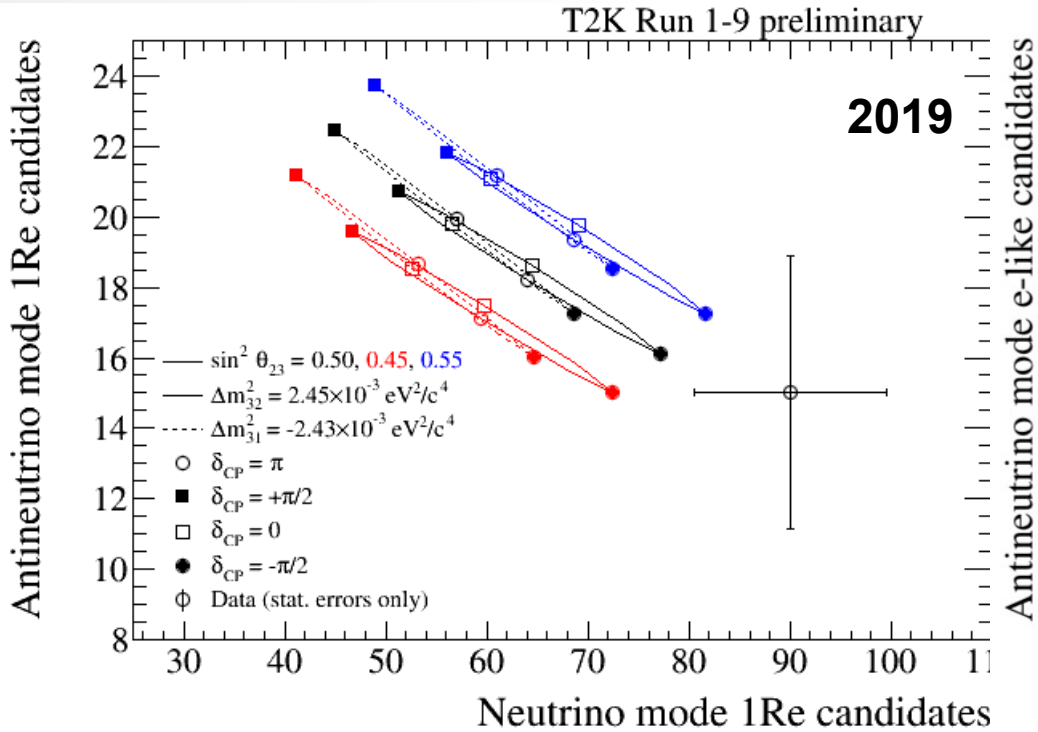


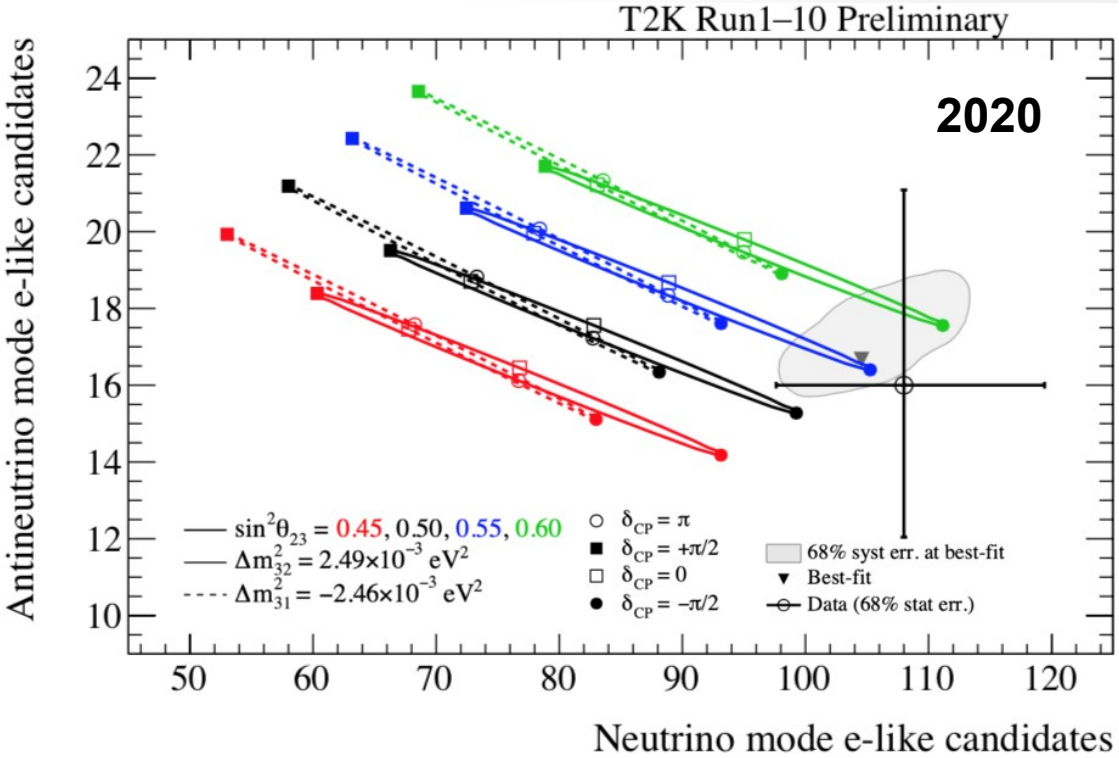


- Robustness studies: largest $\Delta\chi^2$ change would cause left (right) edge of 90% interval to move by 0.073 (0.080)

Comparison to previous result

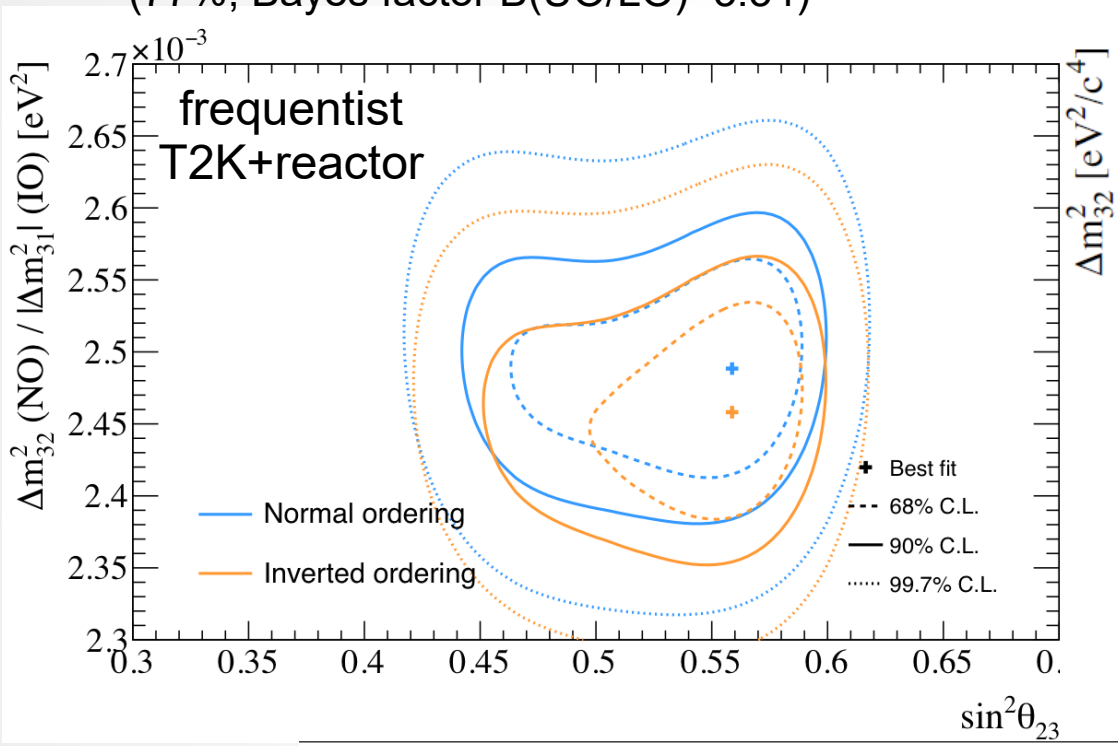
- data in 2020 analysis closer to PMNS prediction
  - previously, excess of neutrinos was seen → reduced with new data
  - consistent with slight upwards statistical fluctuation?
  - largest change in δ_{CP} comes from new data (see backup slides)

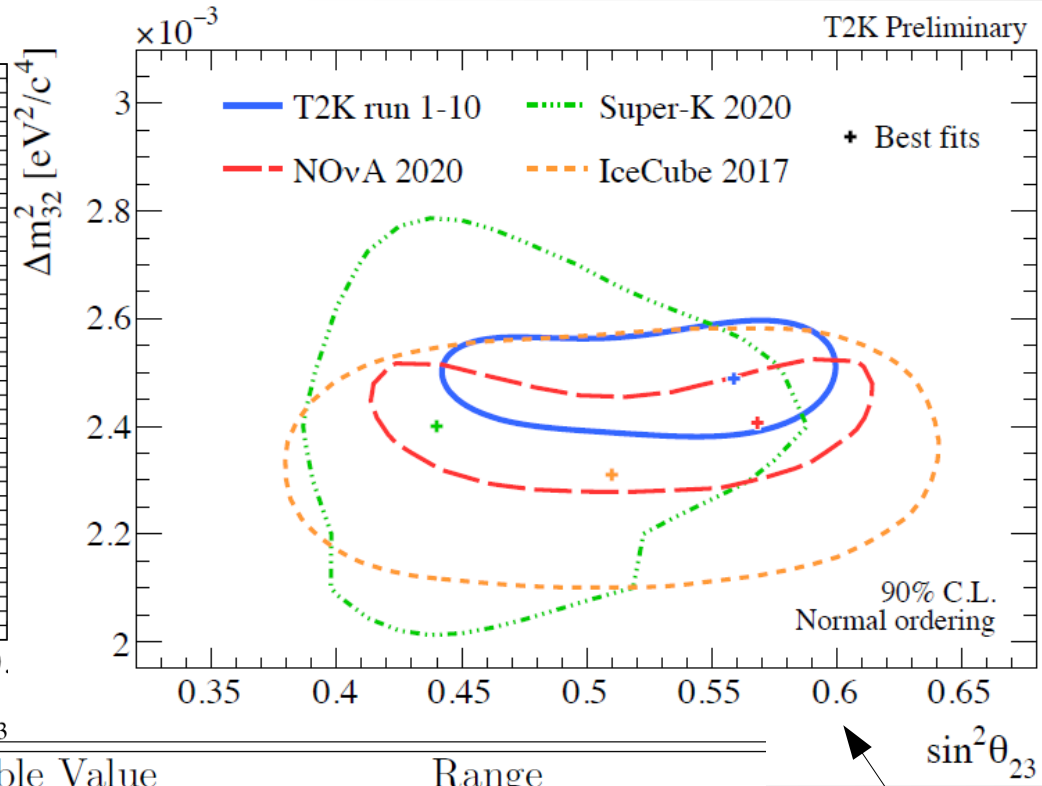




θ_{23} and Δm^2_{32}

- slight preference for non-maximal $\sin^2\theta_{23}$
- preference for normal hierarchy (80.8%, Bayes factor B(NH/IH)=4.21) and upper octant (77%, Bayes factor B(UO/LO)=3.34)



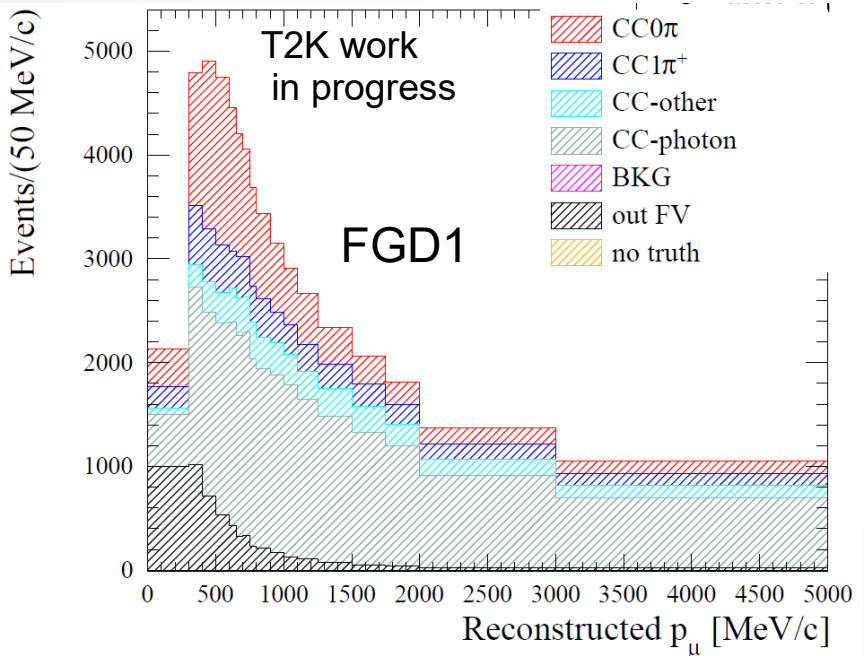


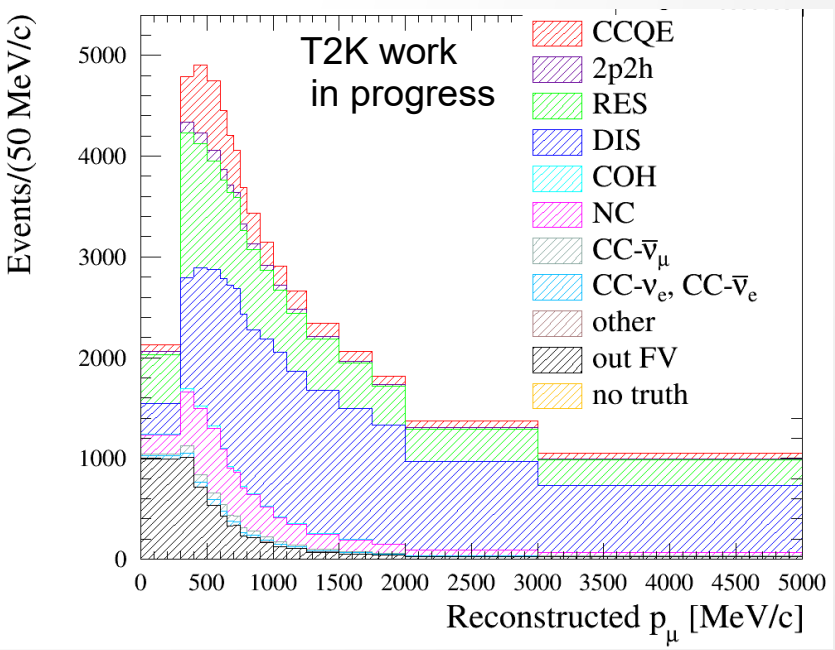
Bayesian	Hierarchy	Most Probable Value	Range
T2K only	Normal	0.471	[0.452, 0.508] and [0.530, 0.568]
	Inverted	0.469	[0.449, 0.508] and [0.531, 0.565]
	Both	0.471	[0.451, 0.508] and [0.530, 0.567]
T2K + reactor	Normal	0.559	[0.504, 0.583]
	Inverted	0.560	[0.519, 0.585]
	Both	0.559	[0.507, 0.584]

for references see backup

Plans for the next OA analysis

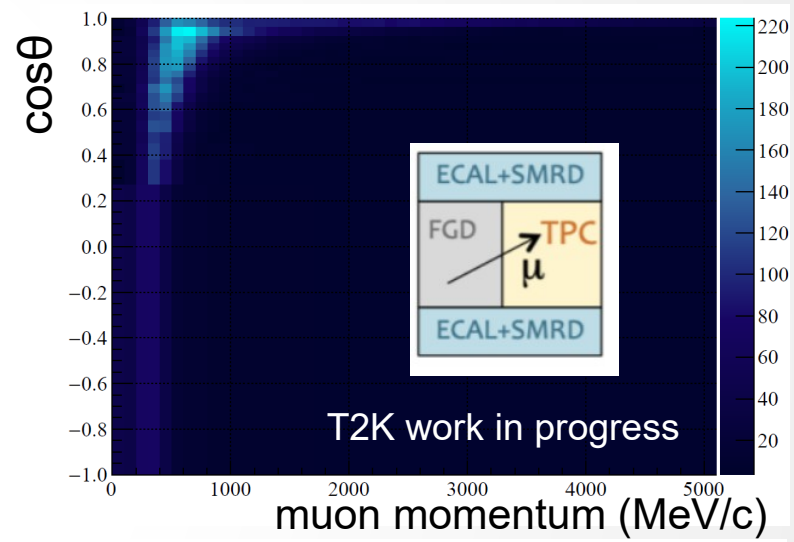
- new analysis ongoing
- new samples will be included, both from ND280 and Far Detector
- **ND280 CC Photon sample**: tagging photon conversion in ECal
  - mostly photons from π^0 decays
  - dominated by DIS (30%) and multipion production (20%), with contribution from resonant π^0 production (24%)
  - photon tag increases the purity of CC0π and CC1π samples by ~10%

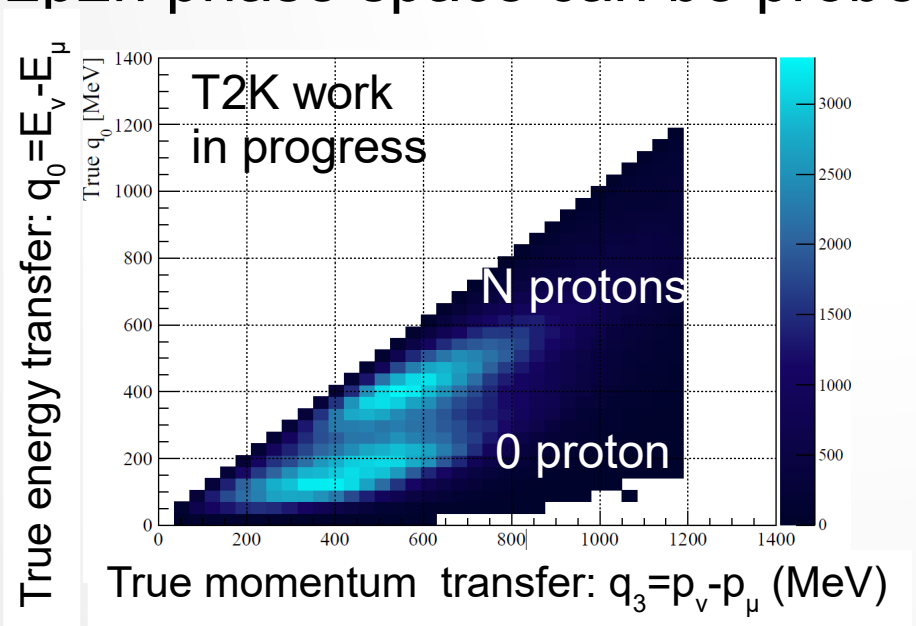


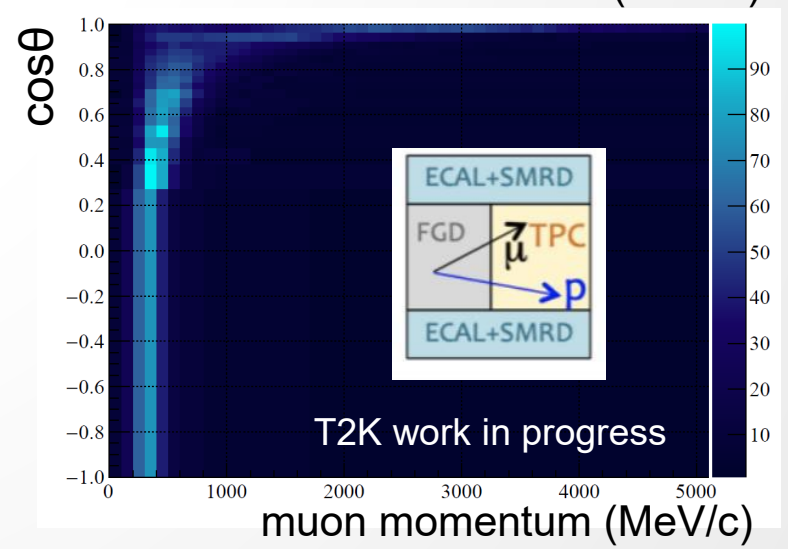


New samples from ND280 (cont.)

- "proton samples" from **ND280**: **CC0π-0p** and **CC0π-Np**
  - based on proton multiplicity, proton tracking threshold 450-500 MeV/c
  - different phase space of muon kinematics
  - different fraction of reactions
- Nieves et al. model describing 2p2h interactions has two peak structure (Phys. Lett., B 707:72-75, 2012)
- using proton samples different regions of 2p2h phase space can be probed:



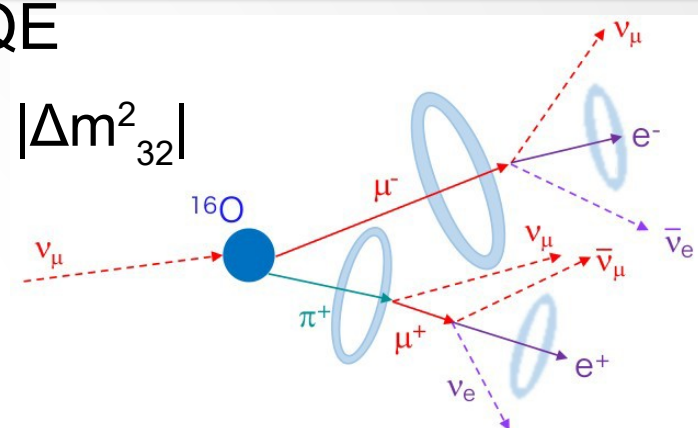


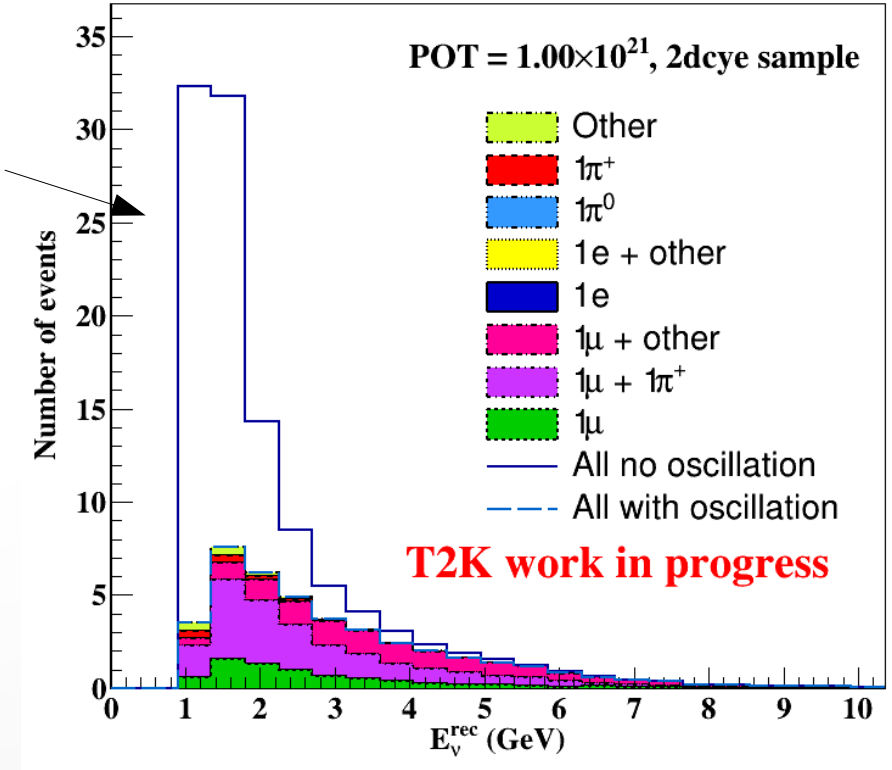


(see K.Skwarczynski's poster)

"Multiring sample" from Far Detector

- $\nu_\mu CC1\pi^+$ - second largest sample after $\nu_\mu CC$ QE
  - expected slightly increased sensitivity to θ_{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

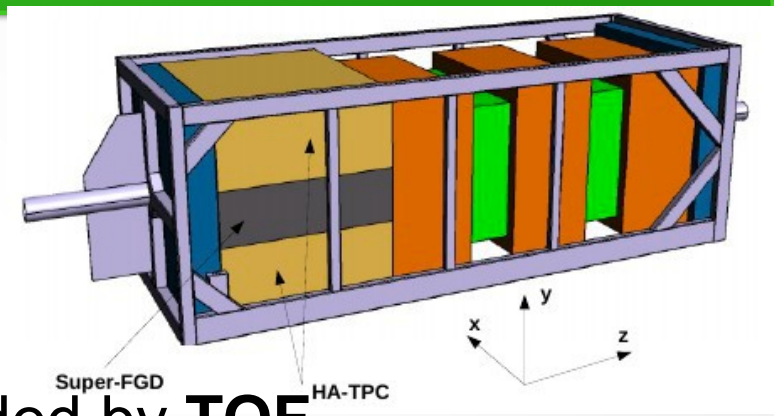


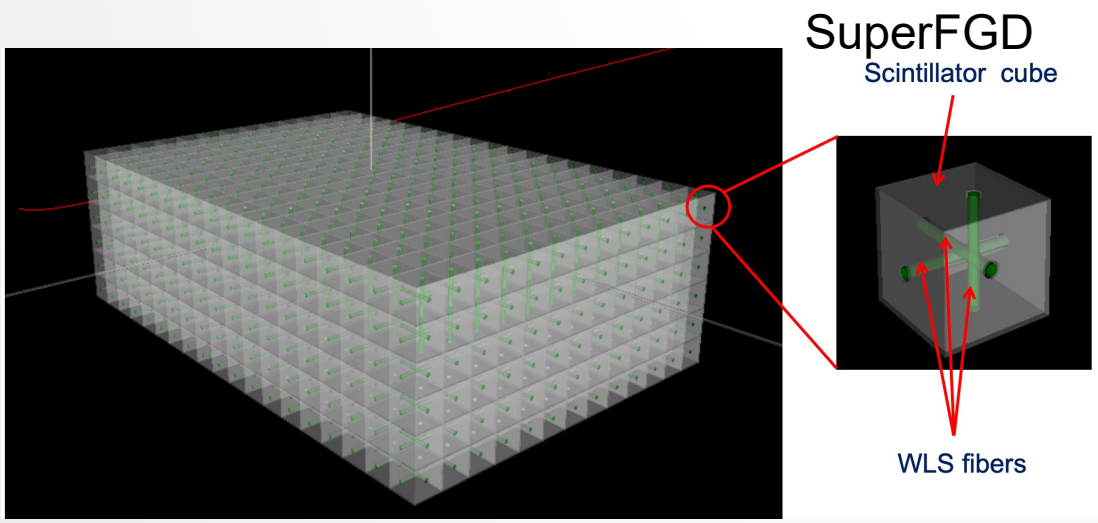


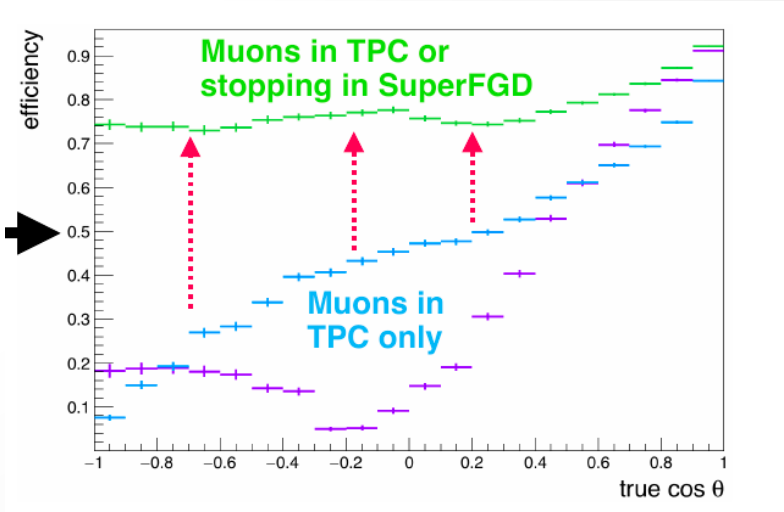
- SK loaded with $Gd_2(SO_4)_3$:
  0.01% concentration of Gd by weight
- enhanced neutron detection
  → more samples in the future?

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 δ_{CP} values around $+\pi/2$ excluded at 99.7%
- most precise measurement of θ_{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

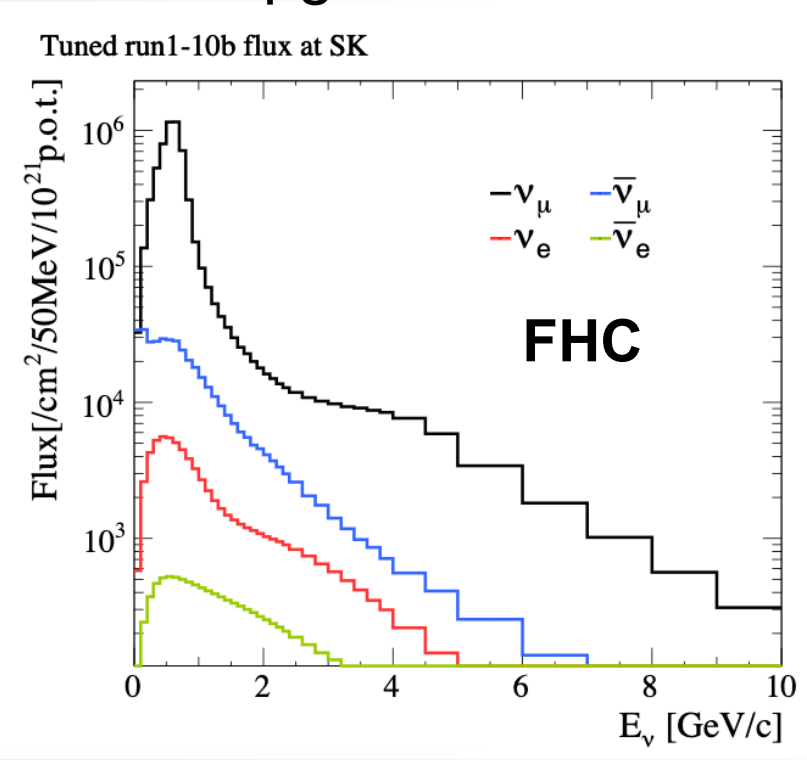
- very exciting neutrino physics possibilities ahead of us!

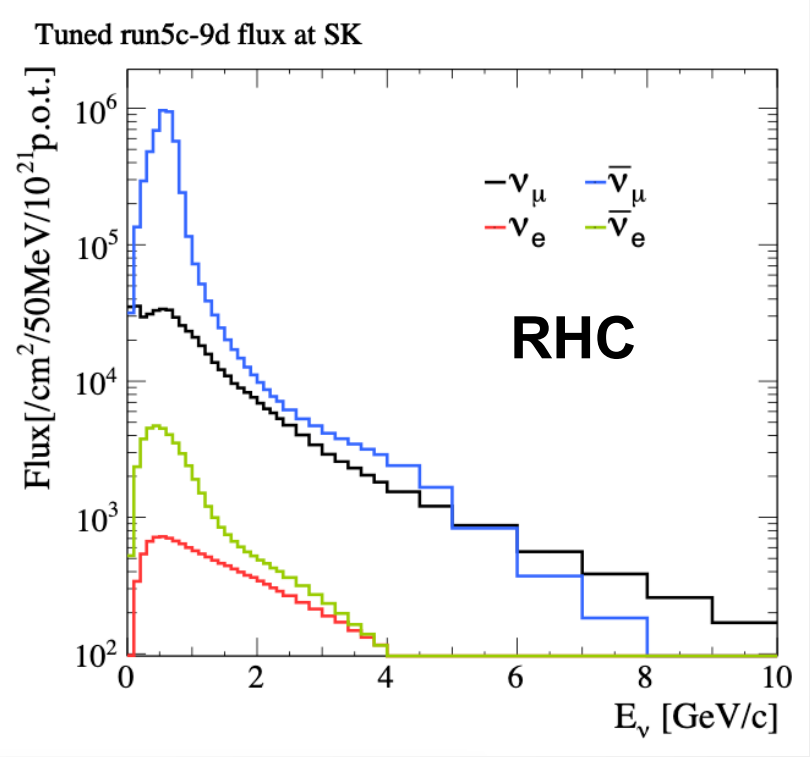
Acknowledgements: National Science Centre, GA: UMO-2018/30/E/ST2/00441

Backup slides

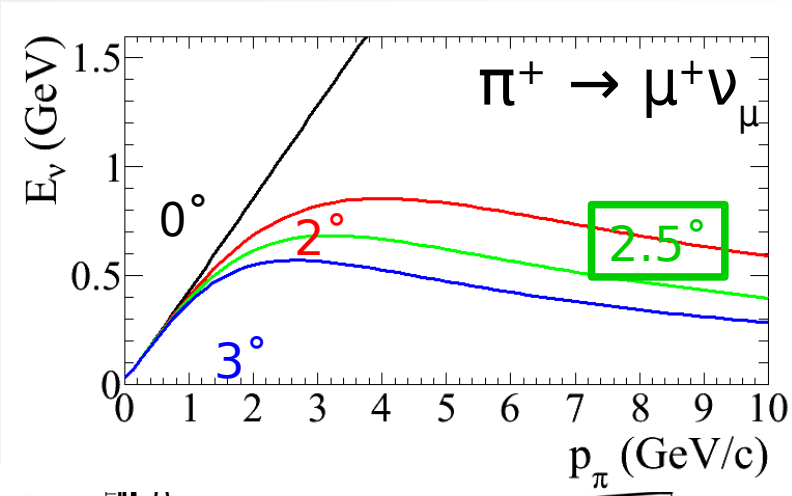
The fluxes

- 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% ν flux





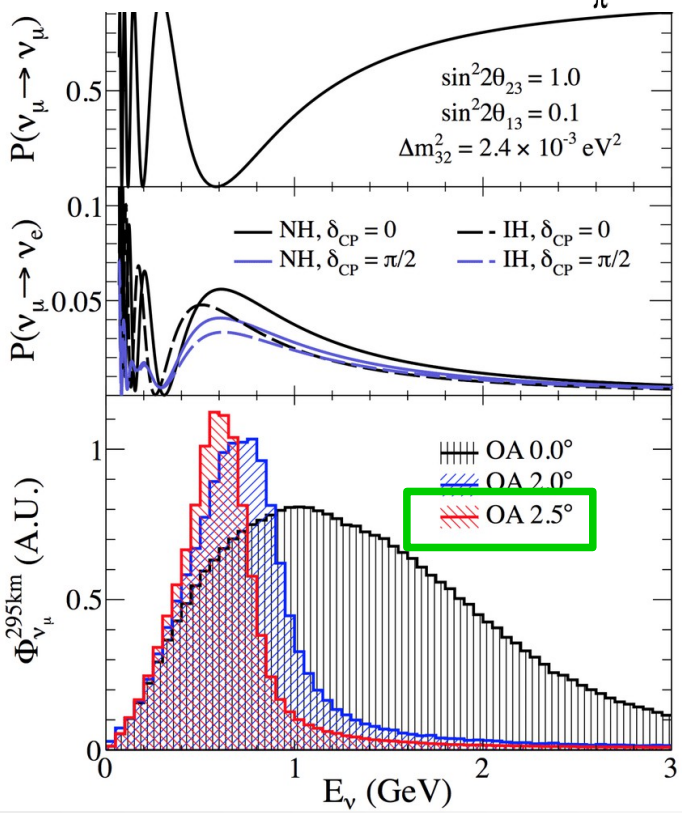
Off-axis beam



for angles ≠ 0
the dependence of
E_ν from E_π is
reduced

⇒

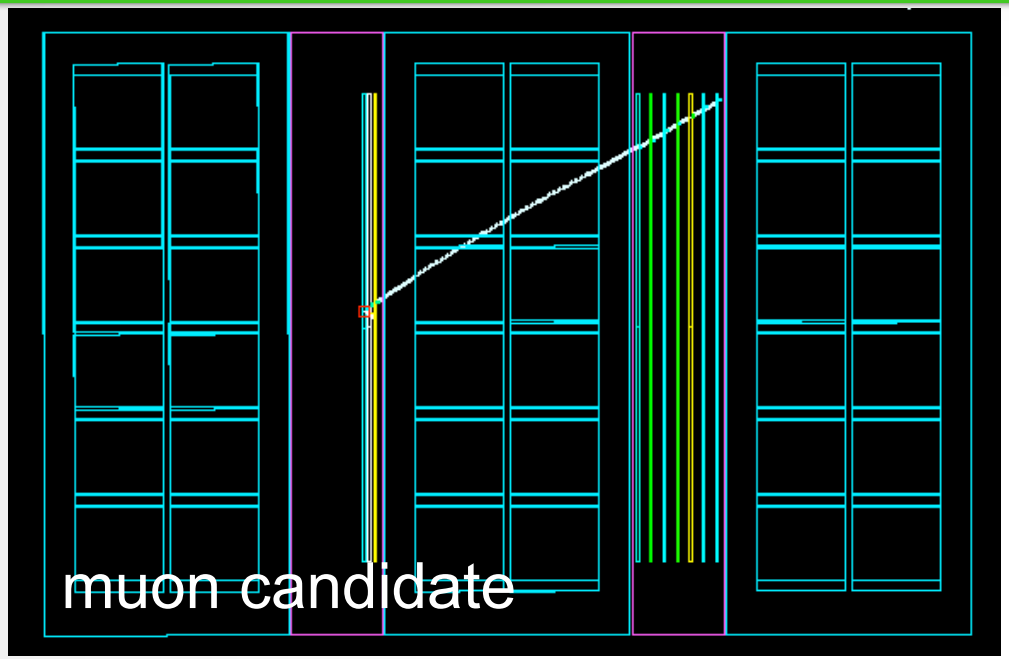
narrow spectrum,
tuned at the first
oscillation maximum

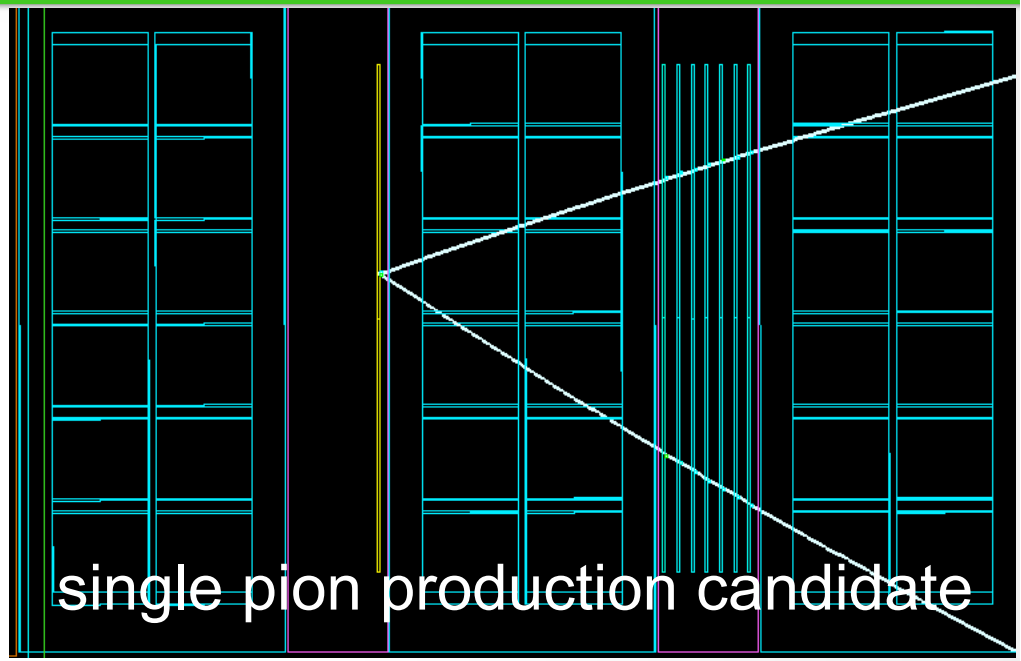


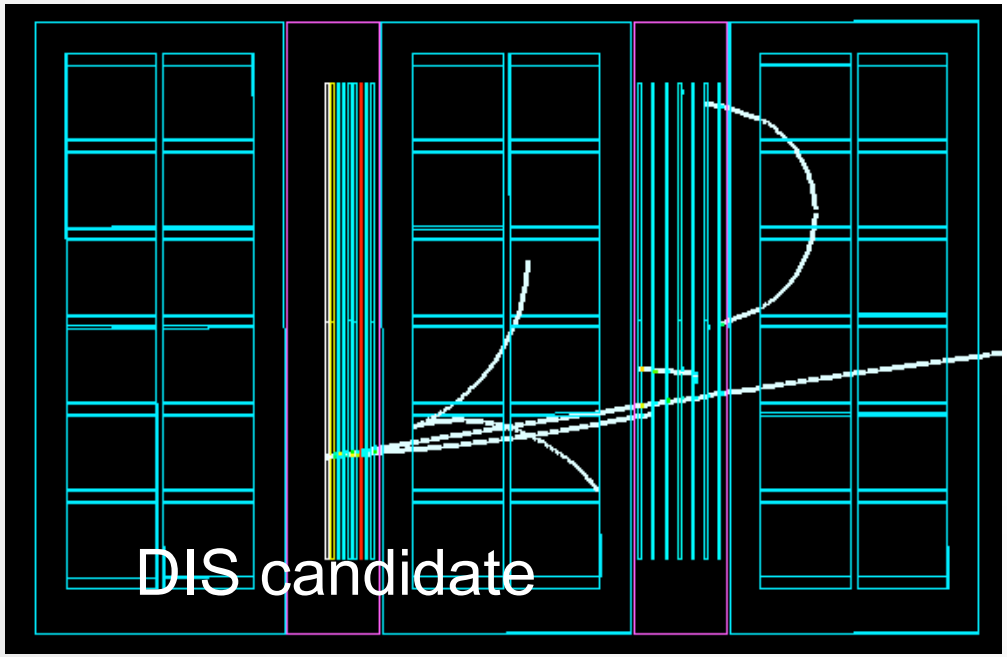
- CC QE sample enhanced
- background from intrinsic ν_e reduced
- background from NC π^0 production reduced

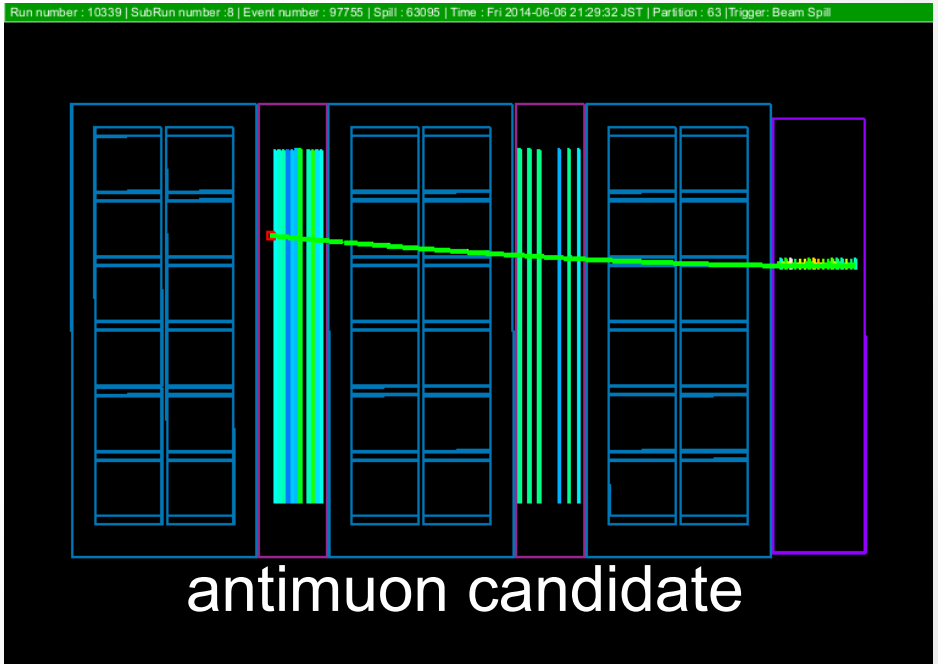
the direction must be precisely controlled
(<1mrad to keep peak energy stable
δE/E ~2% at far detector)

ND280 events in tracker









What so special about $\nu_\mu \to \nu_e$ channel?

- allows for CP violation studies

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

$$+8 c_{13}^2 s_{12} s_{13} s_{23} (c_{12} c_{23} \cos\delta_{CP} - s_{12} s_{13} s_{23}) \cos\Delta_{32} \sin\Delta_{31} \sin\Delta_{21}$$

$$-8 c_{13}^2 c_{12} c_{23} s_{12} s_{13} s_{23} \sin\delta_{CP} \sin\Delta_{32} \sin\Delta_{31} \sin\Delta_{21}$$ CP violation

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

matter

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

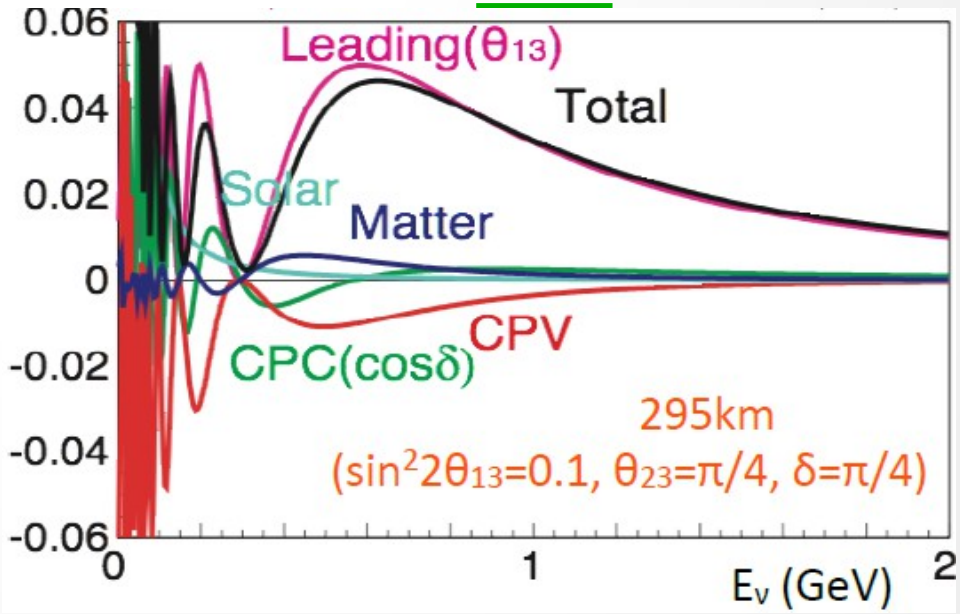
for $\bar{\nu}$

$$\delta_{CP} \to -\delta_{CP}$$

$$a \to -a \qquad a = 2\sqrt{2} G_F n_e E_\nu$$

n_e related to matter density

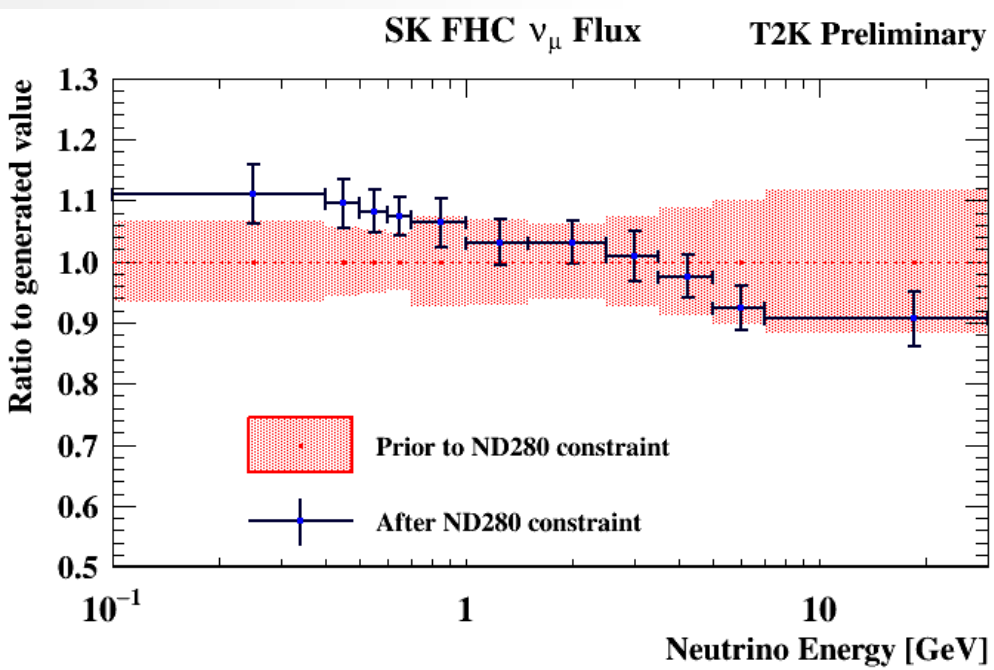
subleading effect,
can be as large as 30%
of dominant



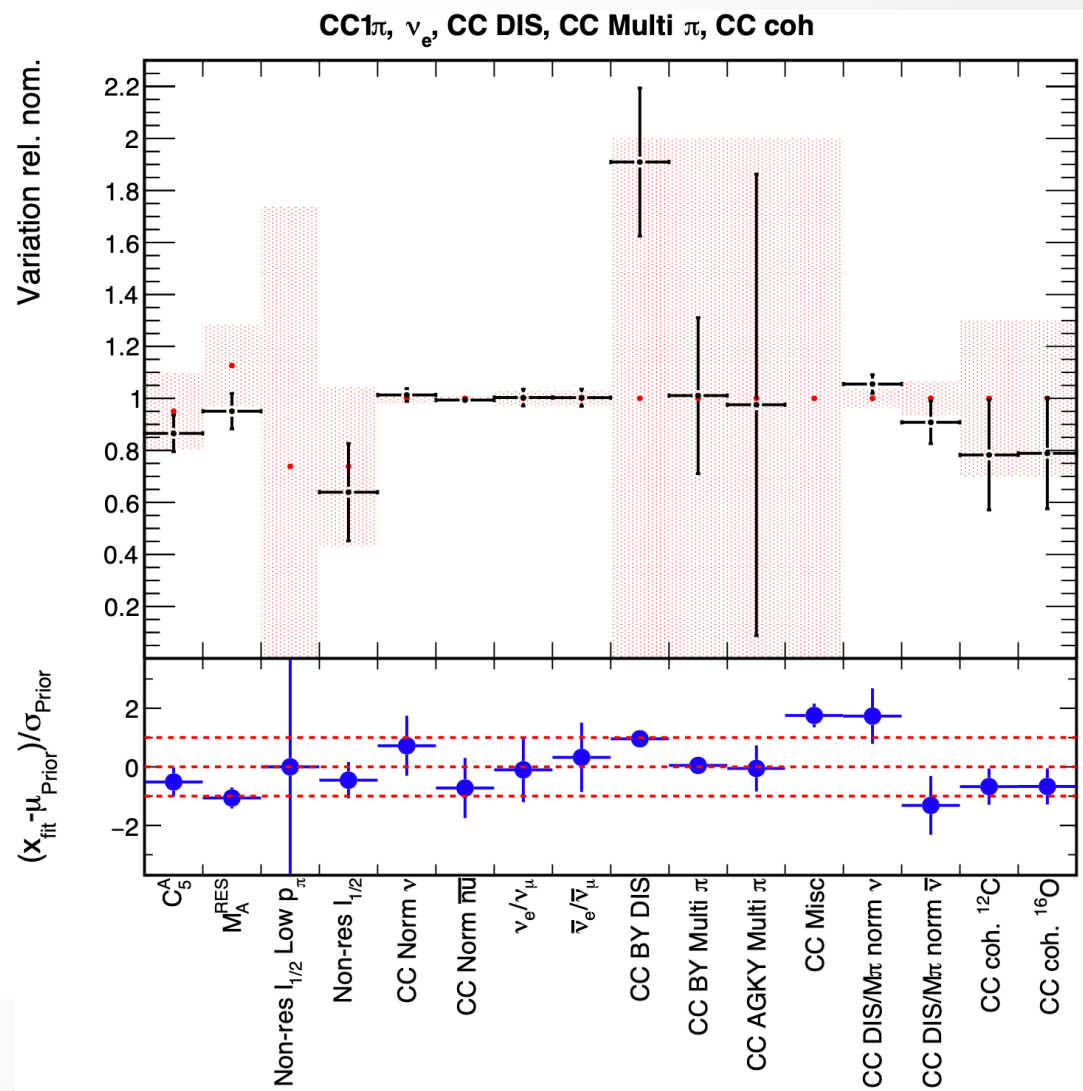
Examples of ND280 fits

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

Example of flux parameters

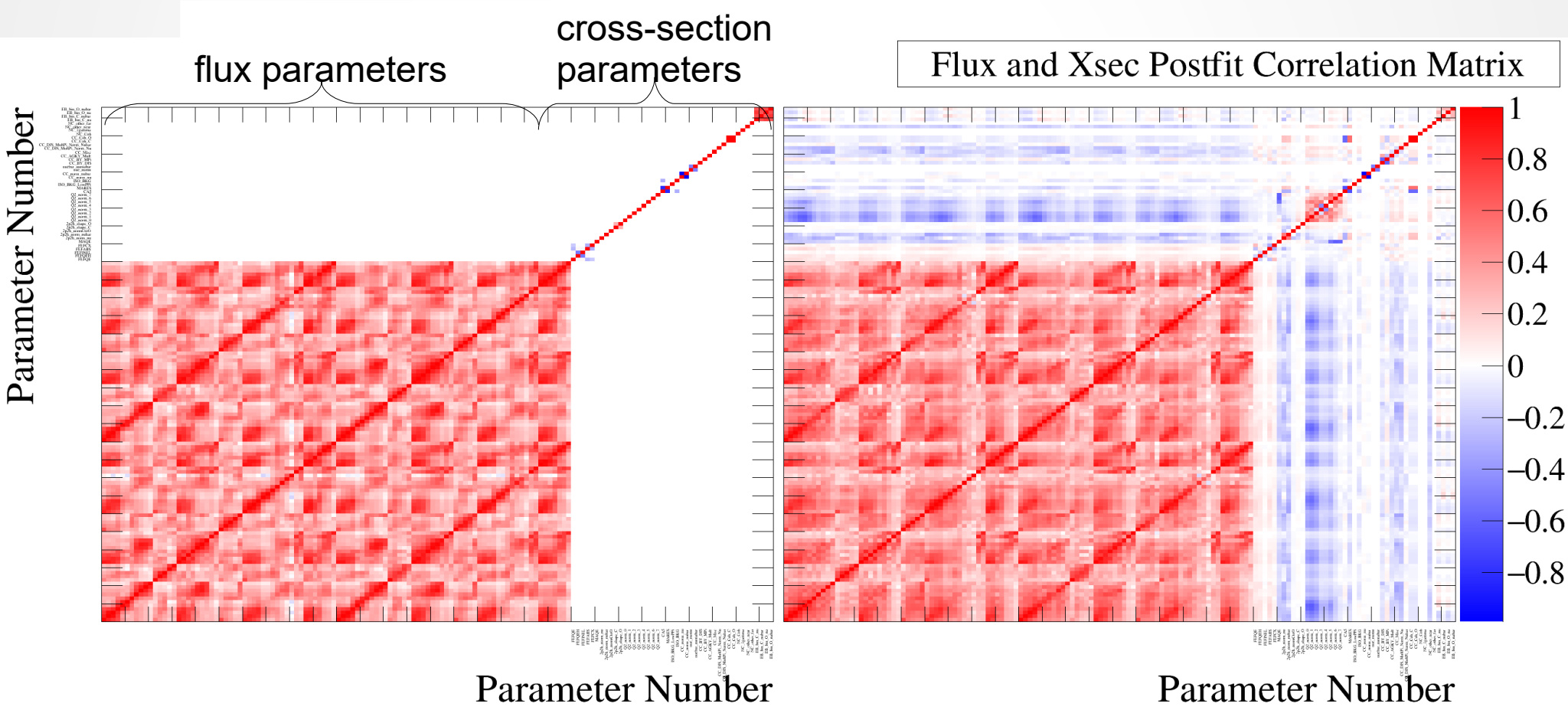


Some of cross section parameters



Error covariance matrix

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

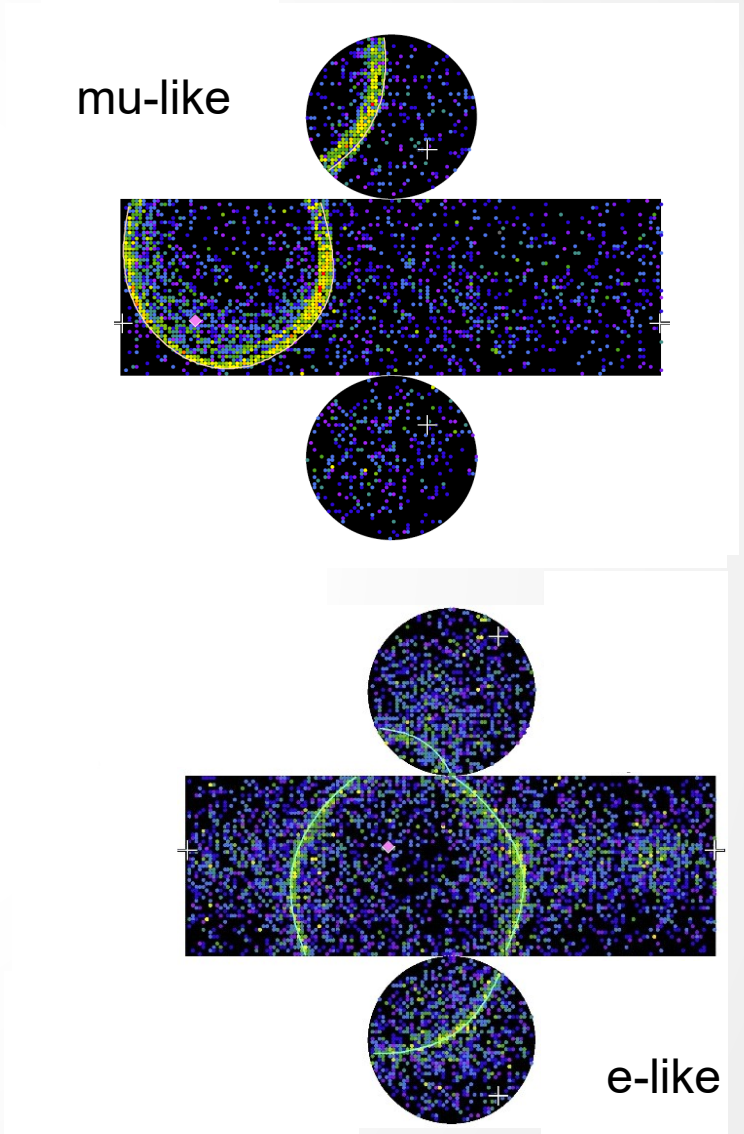


Far Detector Samples

- 5 samples of single ring events
  - muon candidate, ν-mode (FHC)
  - muon candidate, $\bar{\nu}$-mode (RHC)
    - μ-like PID
    - p_μ > 200 MeV/c
    - Michel electron 1 or 0

CC 0π

  - electron candidate, ν-mode
  - electron candidate, $\bar{\nu}$-mode
    - e-like PID
    - p_e > 100 MeV/c
    - E_{rec} < 1250 MeV
    - π^0 rejection
  - electron candidate with a Michel electron from decay of π, ν-mode



Statistical methods

	Analysis 1	Analysis 2	Analysis 3
Kinematic variables for 1Re sample at SK	Erec-θ	p_e-θ	Erec-θ
Likelihood	Binned Poisson Likelihood Ratio	Binned Poisson Likelihood Ratio	Binned Poisson Likelihood Ratio
Likelihood Optimization	Markov Chain Monte Carlo	Gradient descent and grid scan	Gradient descent and grid scan
Contours/limits produced	Bayesian Credible Intervals	Frequentist Confidence Intervals with Feldman-Cousins (credible intervals supplemental)	Frequentist Confidence Intervals with Feldman-Cousins
Mass Hierarchy Analysis	Bayes factor from fraction of MCMC points in each hierarchy	Bayes factor from likelihood integration	Frequentist p-value from generated PDF
Near Detector Information	Simultaneous joint fit	Constraint Matrix	Constraint Matrix
Systematics Handling	Simultaneous fit then marginalization	Marginalization during fit	Marginalization during fit

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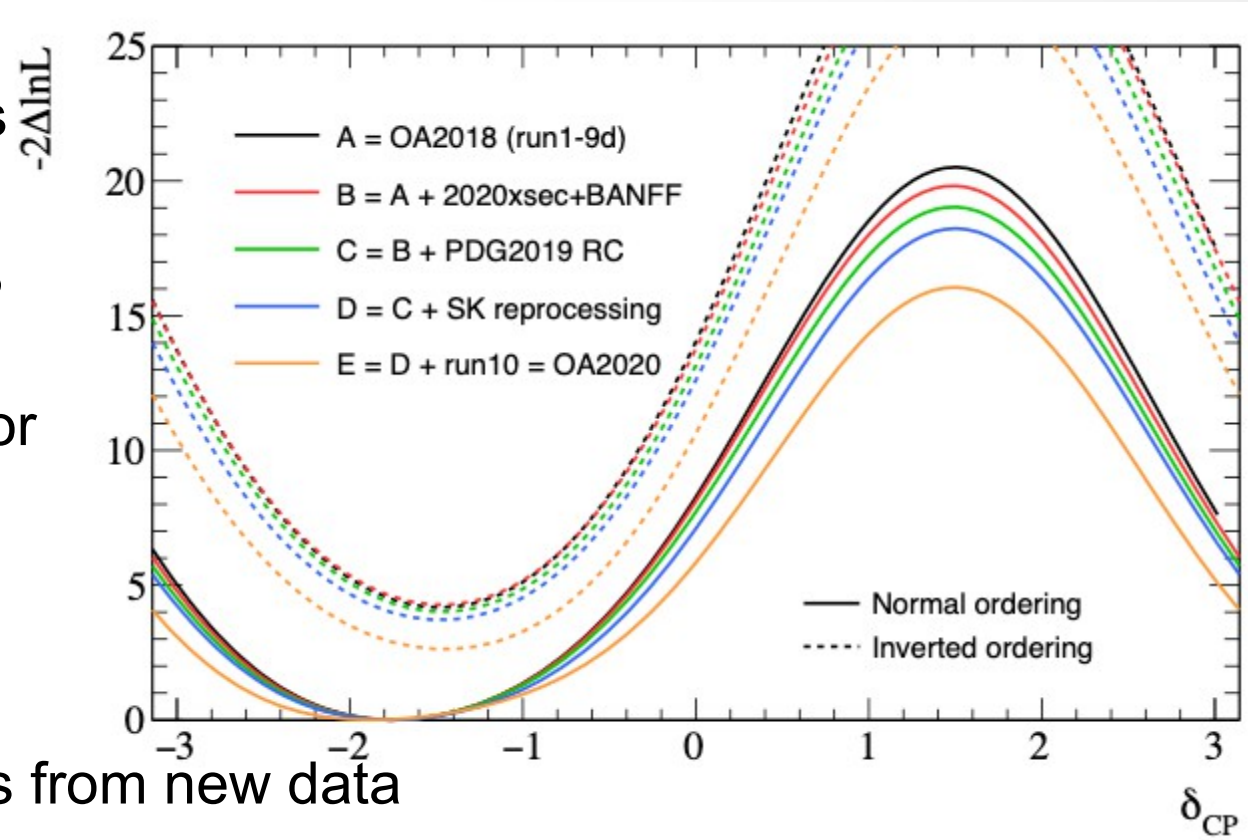
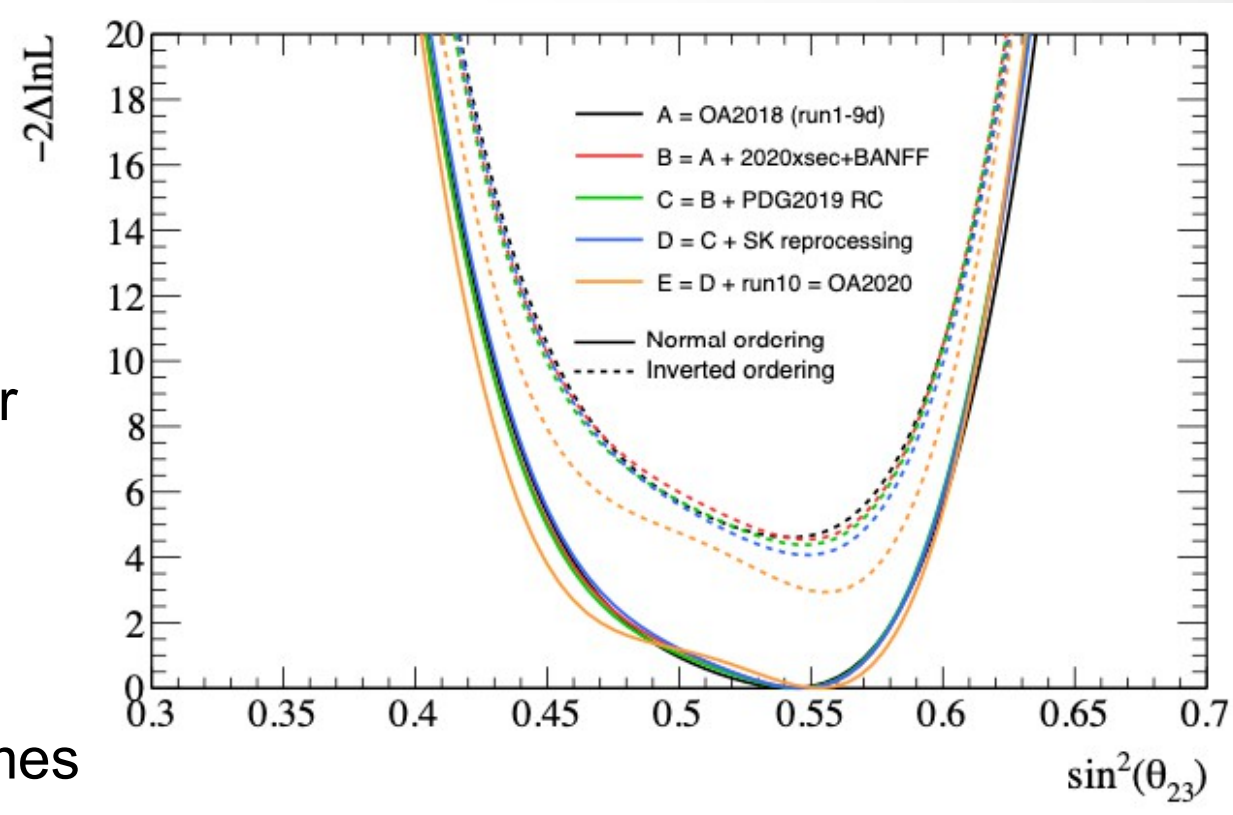
Difference wrt previous analysis

- 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 θ_{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

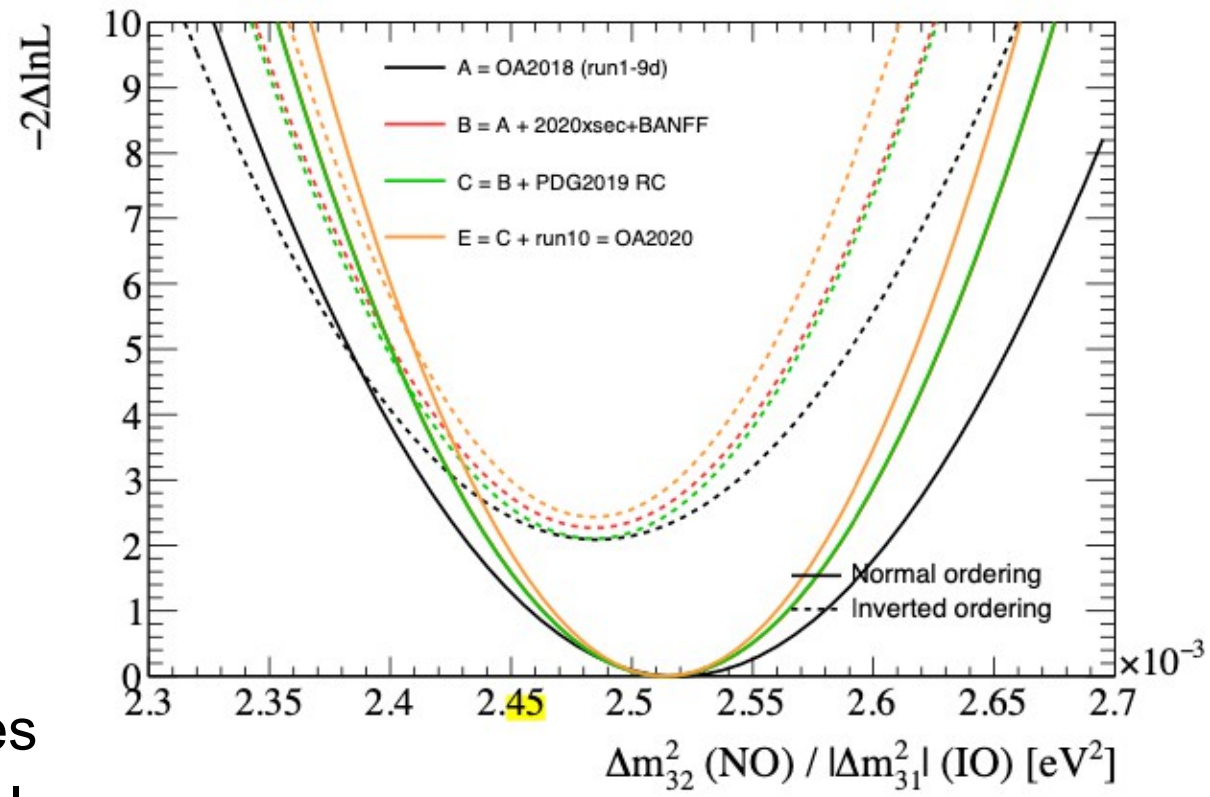


- largest change in δ_{CP} comes from new data
- new data collected in spring 2021, will be included in the next analysis

- 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 θ_{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

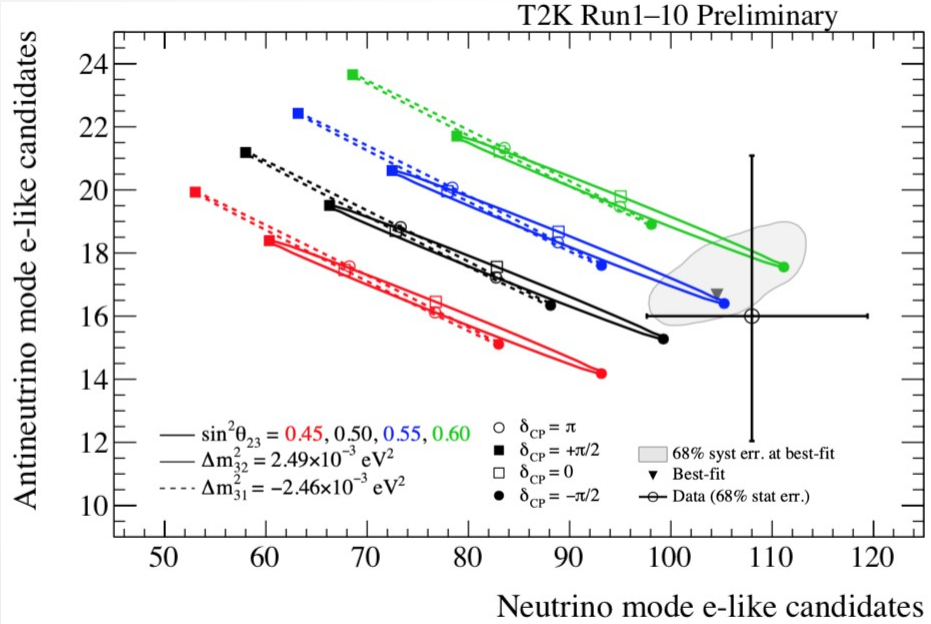


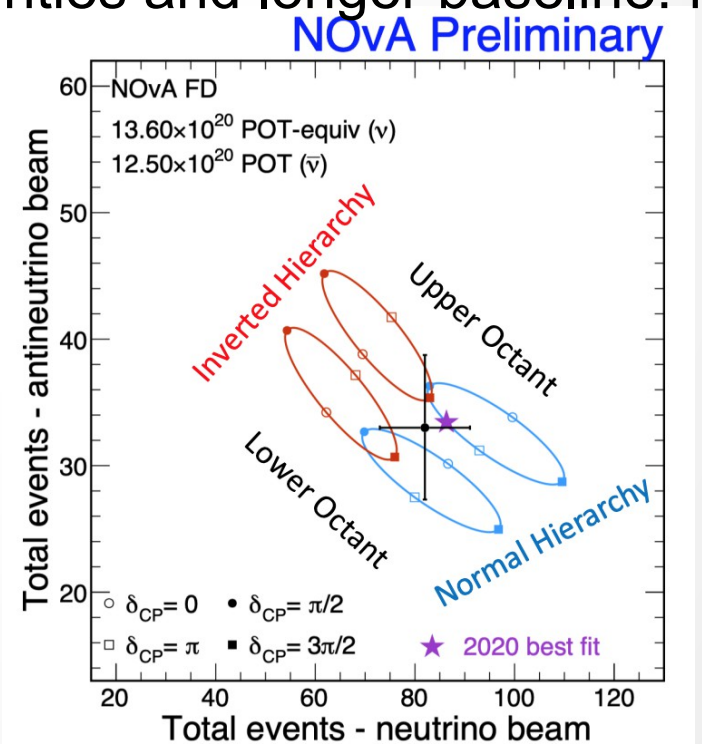
- changes from previous to recent analysis made sequentially one by one
  - **A** – previous result
  - **B** = A + changes in flux and cross-section models
  - **C** = B + update on θ_{13} constraint from PDG2018 to PDG2019
  - **D** = C + new calibration for SK (caused some events to migrate in and out of samples
  - **E** = D + new run 10 data
- largest change in Δm^2_{32} comes from new cross-section model (primarily better removal energy treatment)



Joint fits

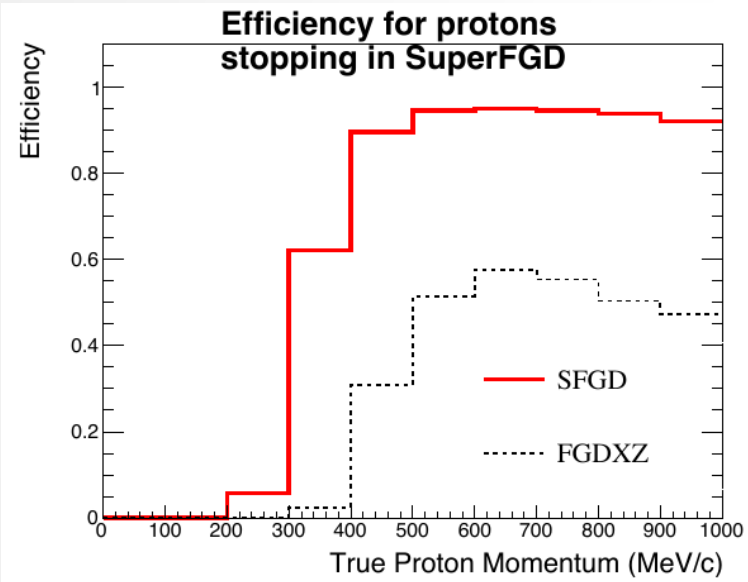
- different baselines and neutrino energies → different oscillation patterns and systematic uncertainties
- combined analysis of data allows degeneracies to be broken
- two ongoing combined analyses:
  - T2K+SK atm. data: longer baseline and higher energy neutrinos, shared detector systematics: more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

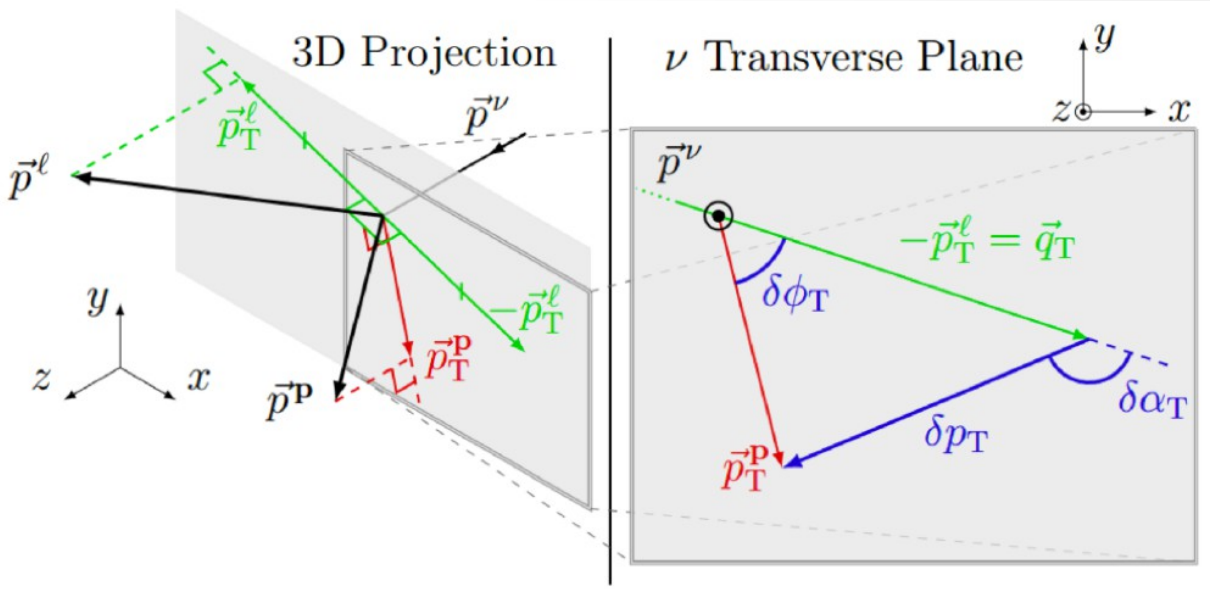




ND280 upgrade

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

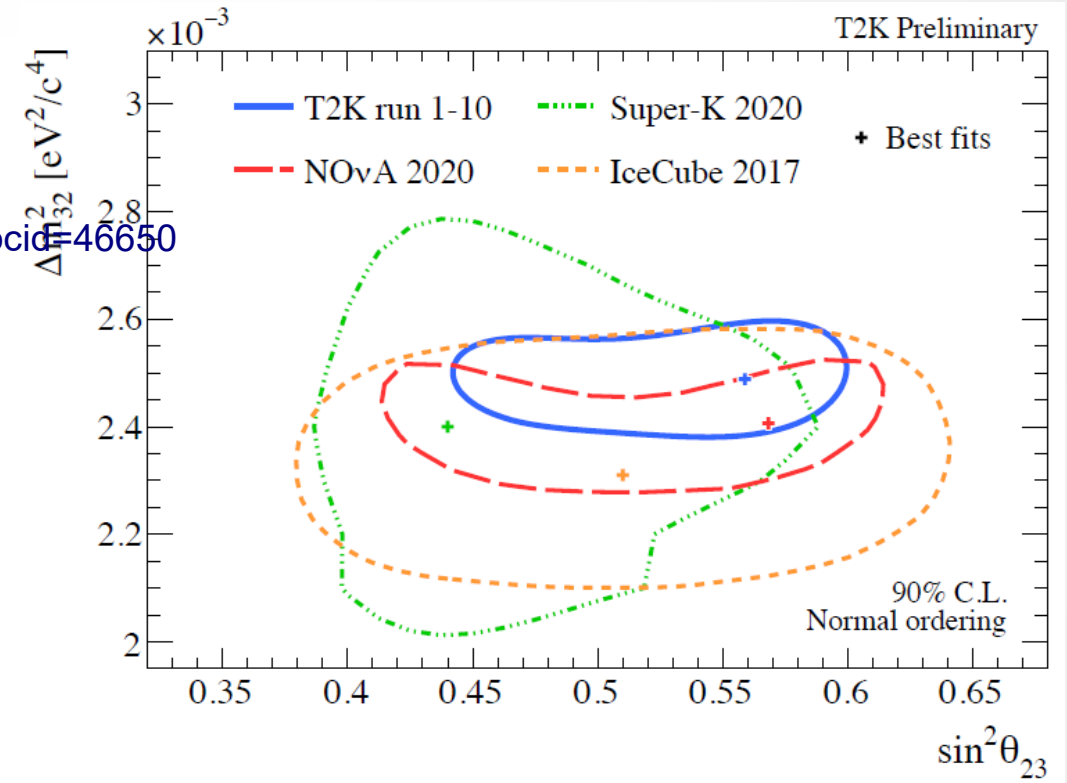




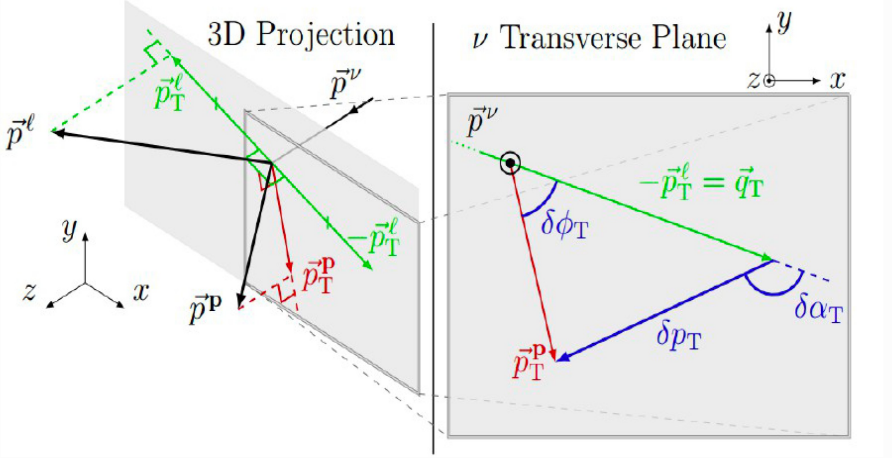
- better tracking:
  - gamma conversions in superFGD: important to tag $\pi^0 \rightarrow \gamma\gamma$,
  - Bragg peak: μ/proton discrimination by dE/dx
  - neutron tagging capabilities for isolated delayed clusters (~60% eff.)

Comparison for θ_{23}

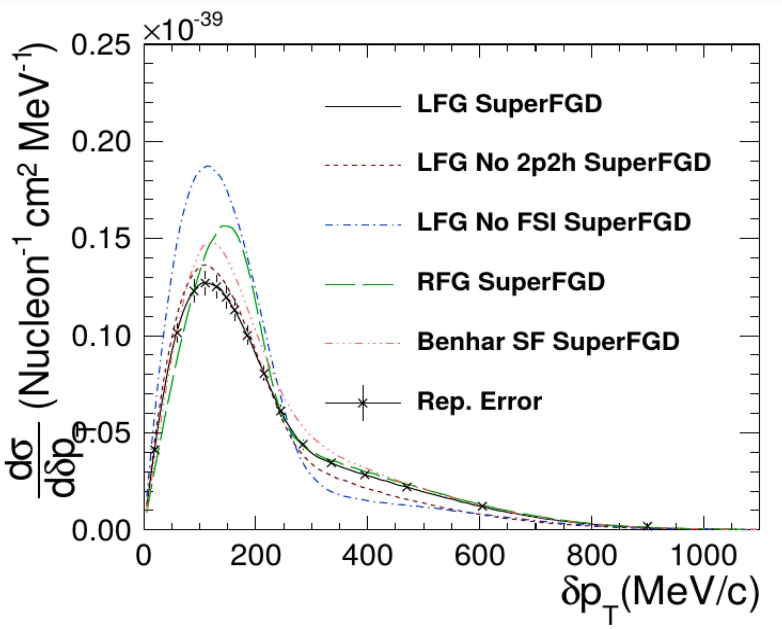
- References:
  - T2K: OA2020 data release, with reactor constraint.
  - NOvA: https://nova-docdb.fnal.gov/cgi-bin//ShowDocument?docid=46650
  - SK: https://doi.org/10.5281/zenodo.4134680 (Neutrino 2020, preliminary results), data release can be found at http://indico-sk.icrr.u-tokyo.ac.jp/event/5517/
  - 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. https://icecube.wisc.edu/data-releases/2018/02/measurement-of-atmospheric-neutrino-oscillations-with-three-years-of-data-from-the-full-sky/ , 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



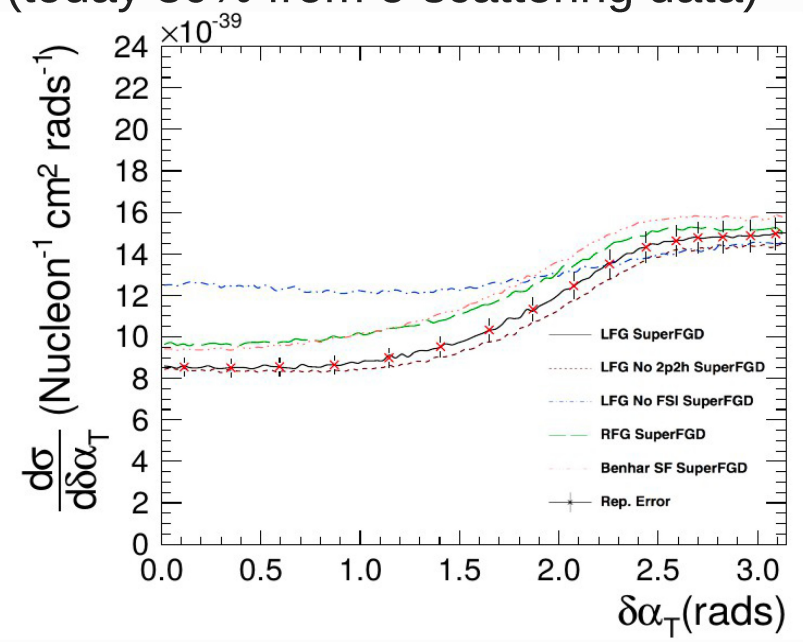
How to use this proton information:
"Single Transverse Variables" and beyond!
→ measurements of Fermi momentum, binding energy, 2p2h...



δp_T is a direct measurement of Fermi momentum: shape measurement <10% precision in each bin with 8×10^{21} POT

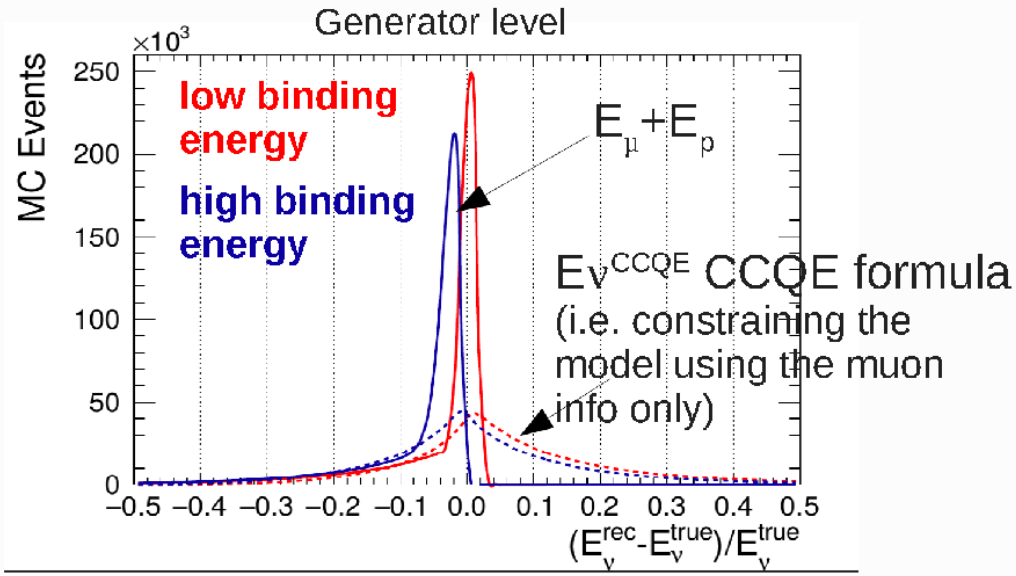


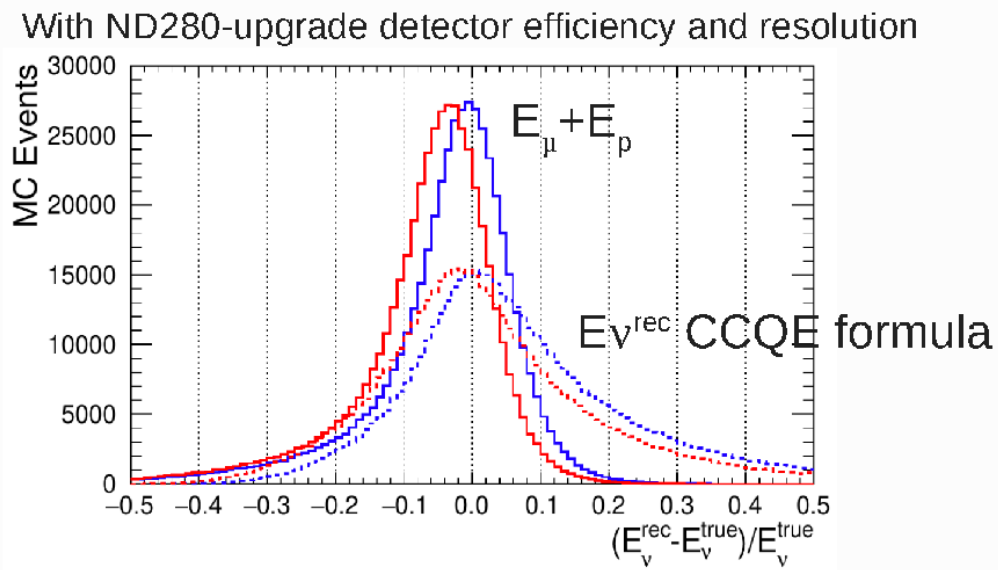
$\delta\alpha_T$ shape is highly sensitive to proton FSI
→ allows to constrain it to ~1% : **not anymore an issue to use protons in the ND fit for the oscillation analysis!**
(today 30% from e-scattering data)



Another variable: total energy

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





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

smearing of $E\mu+Ep$ is dominated by flux (and detector effects)

→ **$E\mu+Ep$ 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 electroproductiondata.
- 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±0.06 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