SORBONNE UNIVERSITÉ

T2K

Oscillation Analysis

- Latest results -

IRN Neutrino
2nd June 2026

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cnrs

LPNHE PARIS

Act I
Physics context and T2K

549 collaborators, 74 institutions and 14 countries!

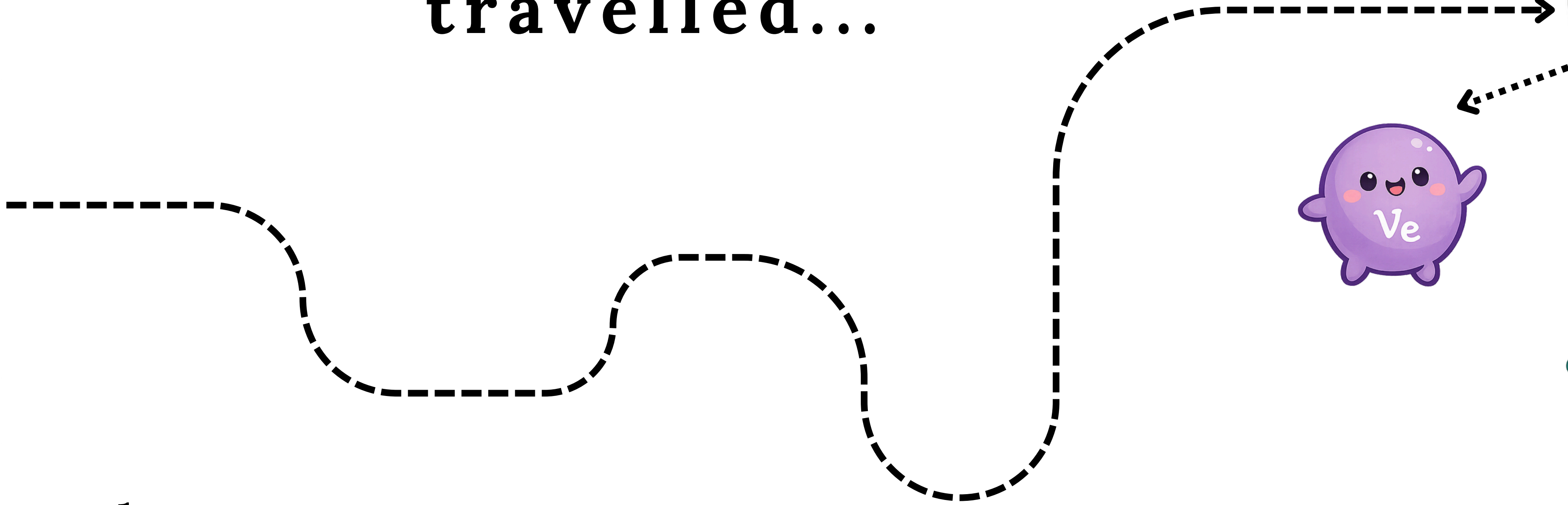
T2K Collaboration Meeting in Tokai (Japan) - April 2026

Recap on neutrino oscillation

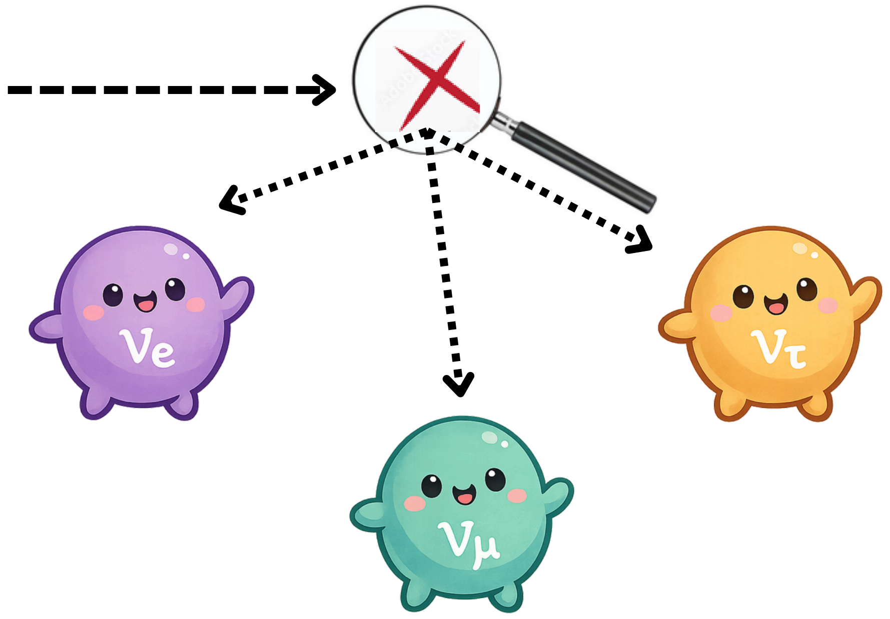
At source!

Numu is produced
(e.g. pion decay)

After a distance travelled...



At detection!

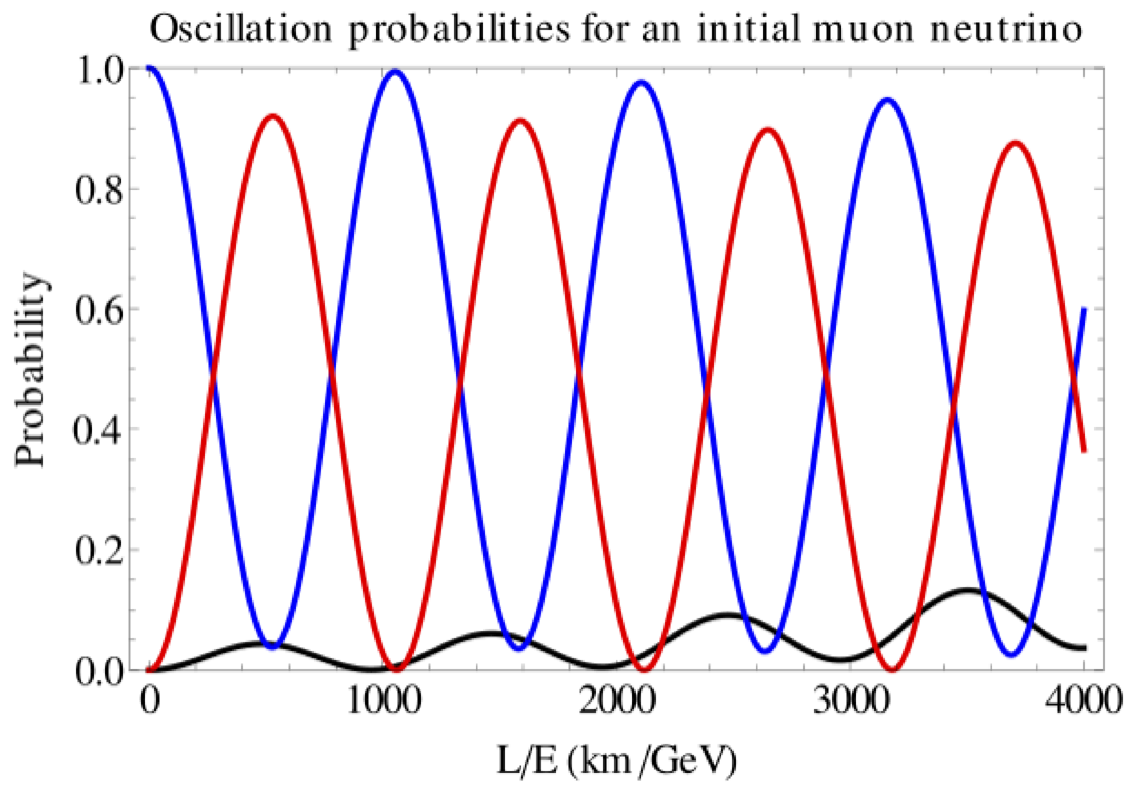


Possibility of
changing flavour

Flavour eigenstates | Mass eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

PMNS matrix



– to nuτ – to nuμ – to nue

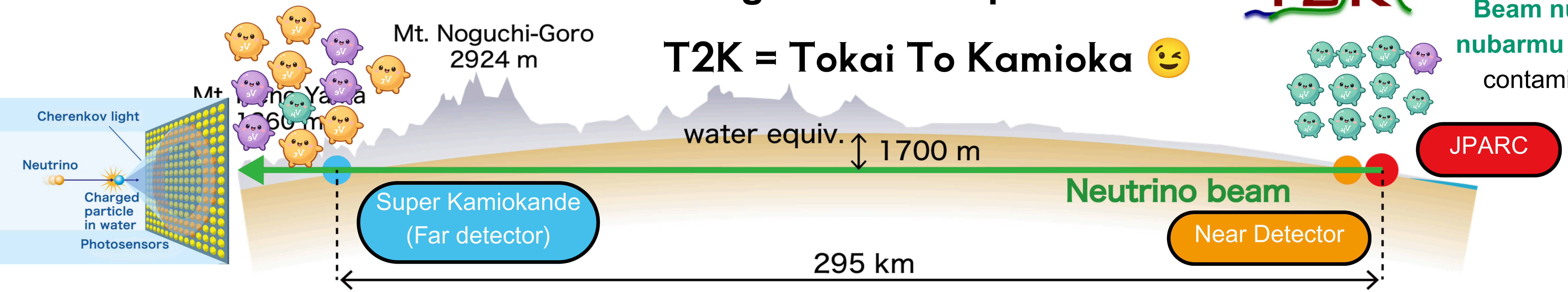
→ Neutrino oscillation parameters:

Pontecorvo-Maki-Nakagawa-Sakata
(PMNS) matrix

ν_τ ν_μ ν_e

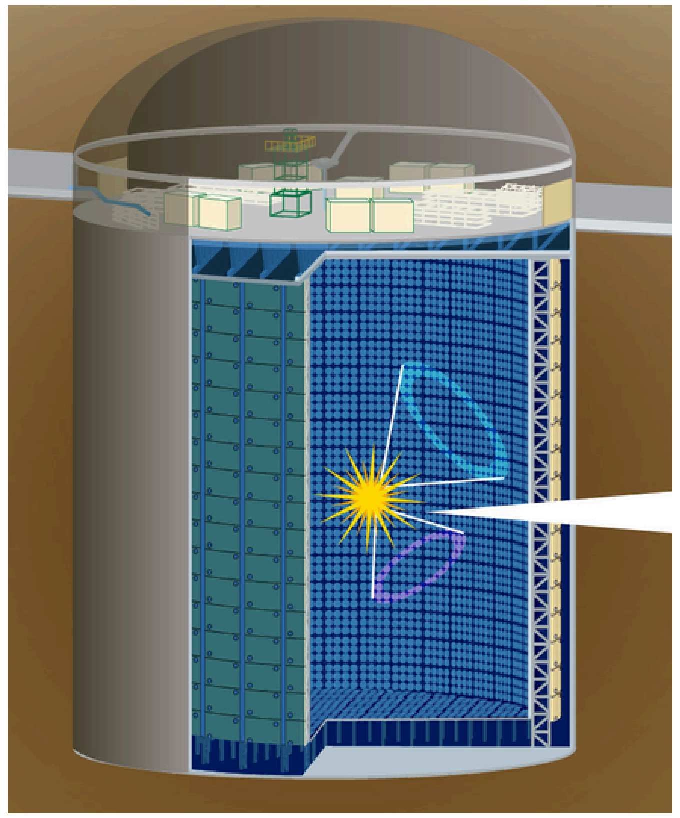
Neutrino oscillation → T2K

- Neutrino oscillation measured in **long baseline experiments** →



Beam numu or nubarmu with **nue** contamination

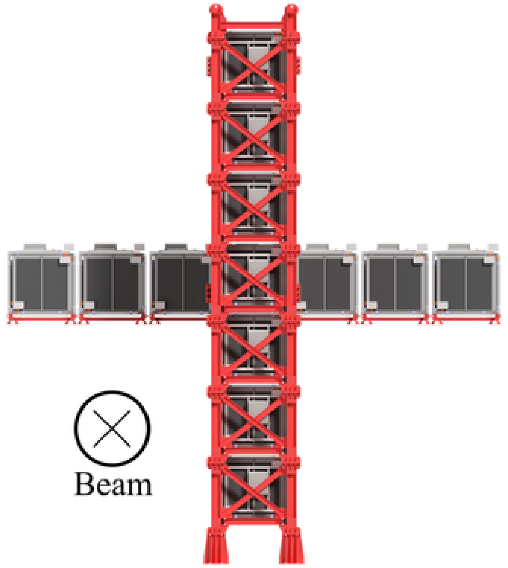
Super-Kamiokande (Far detector)



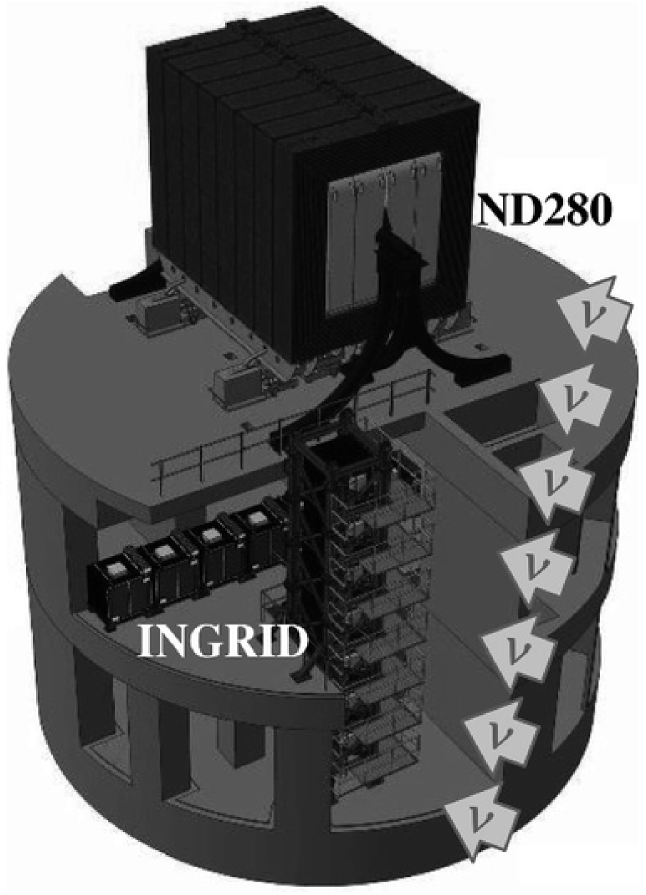
Large water tank
22.5 ktons

Particle detection using Photomultiplier Tubes (PMTs) for Cherenkov radiation

INGRID (on-axis)



Monitoring neutrino beam intensity and direction

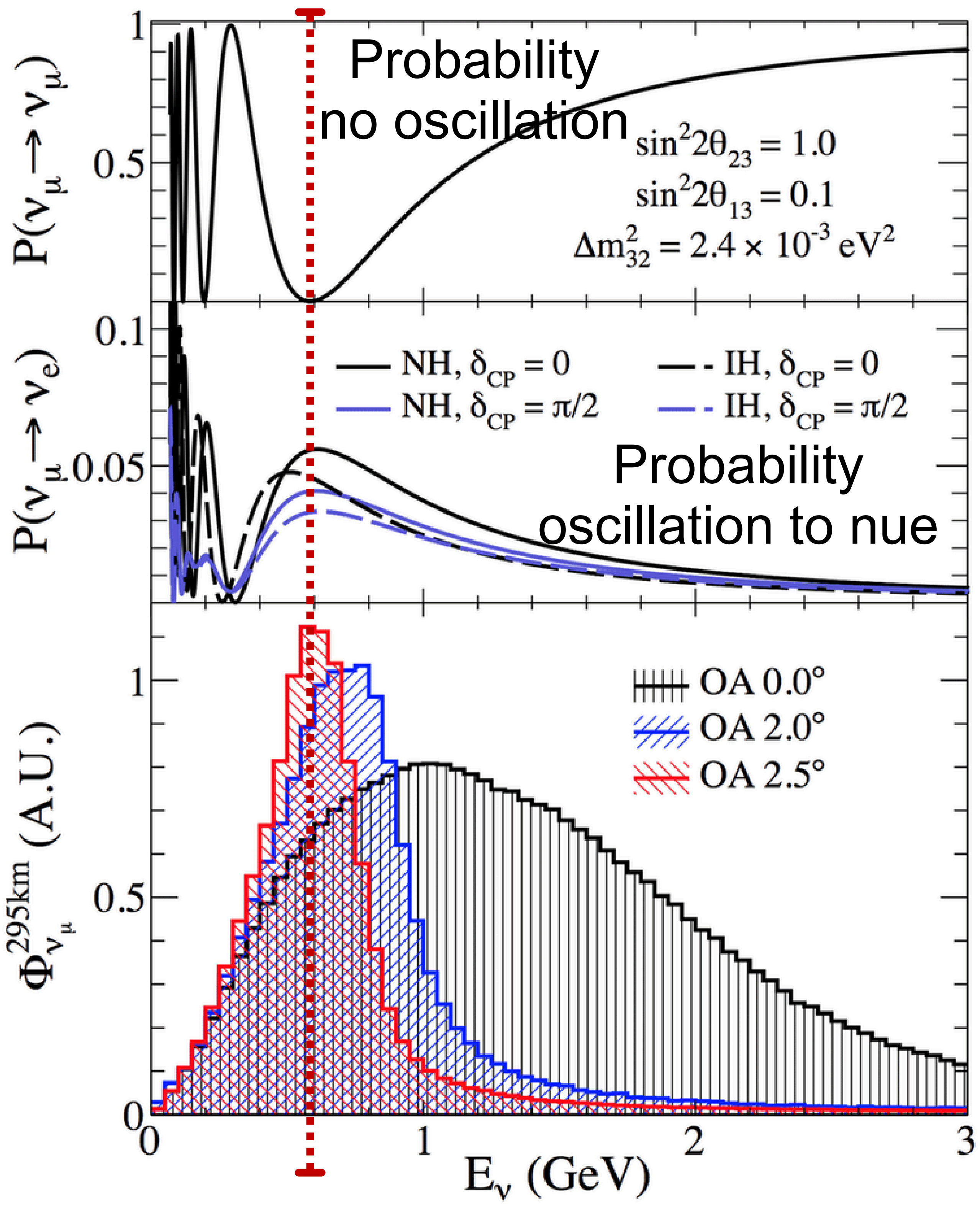


ND280
(off-axis, main complex)
Explained later on
Measuring neutrino spectra (numu/numubar and nue)

WAGASCI-babyMIND
X-sec mesurements in **water**, same target as Super-K!

T2K physics results

- Beam is off-axis (~2.5°) → Intended for **maximum oscillation probability** at Far Detector!



numu disappearance + nue appearance

$$\Delta m^2_{32} = (2.506^{+0.039}_{-0.052}) \times 10^{-3}\ \mathrm{eV}^2$$

$$\sin^2(\theta_{23}) = 0.559^{+0.018}_{-0.078}$$

The T2K Collaboration et al.
Phys. Rev. Lett. 135 (2025)

Nu/Nubar x-secs in different targets (e.g. $H_2O, {}^{12}C$)

The T2K Collaboration et al. Phys. Rev. D 108 (2023)

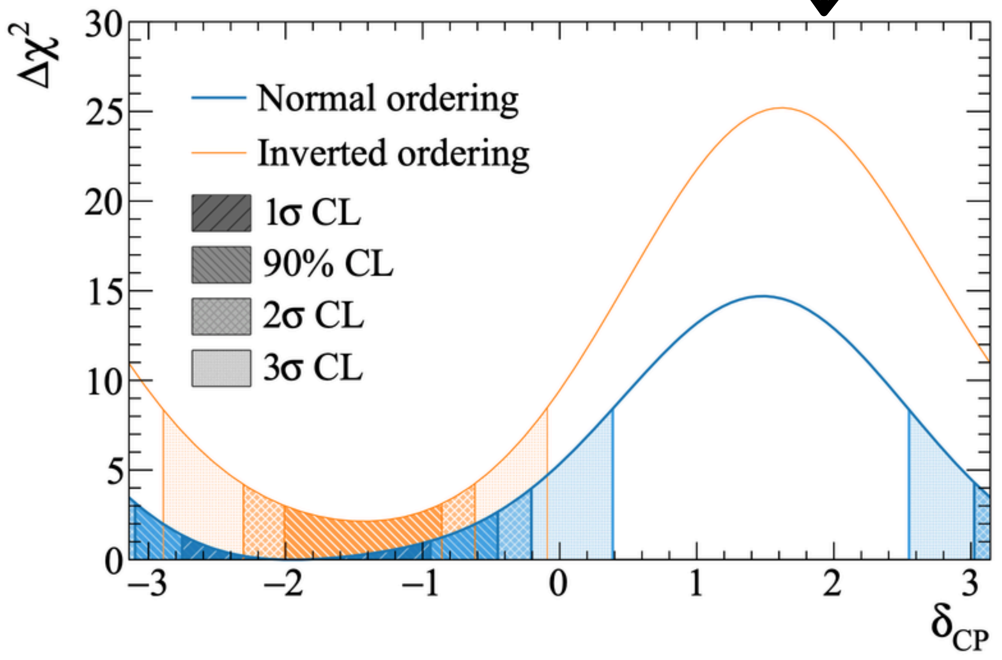
The T2K Collaboration et al. PTEP Vol 2021, Issue 4 (2021)

Since we also have nubar beam

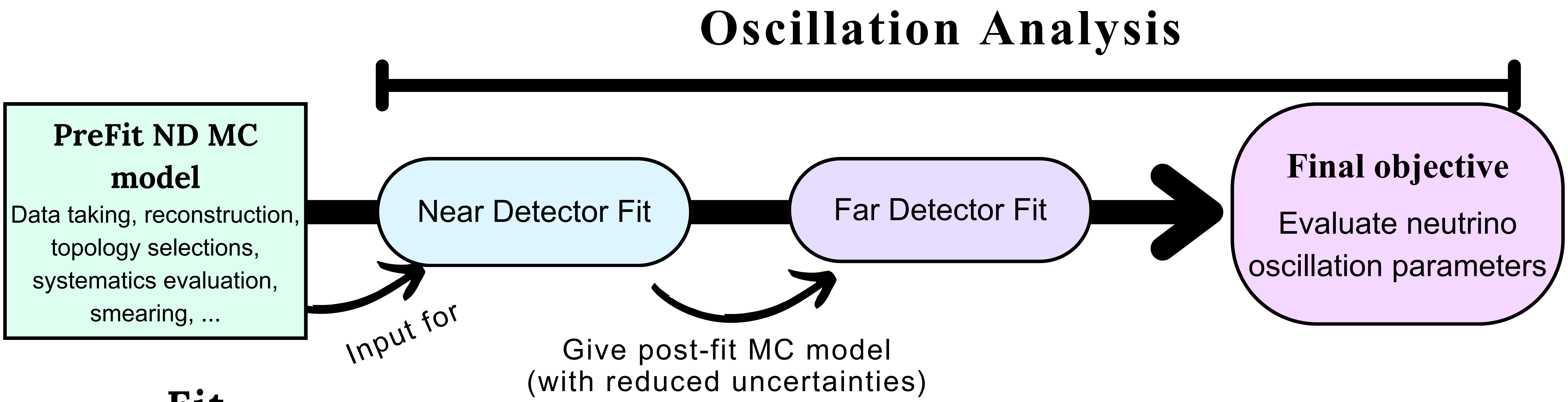
Charge-Parity Violation
(CPV)

$$\delta_{CP}$$

(=0 → No CPV)



Act II
Fundamentals for Oscillation Analysis (OA) in T2K



Fit

Finding best-fit MC parameter values to reproduce the data and reduce uncertainties

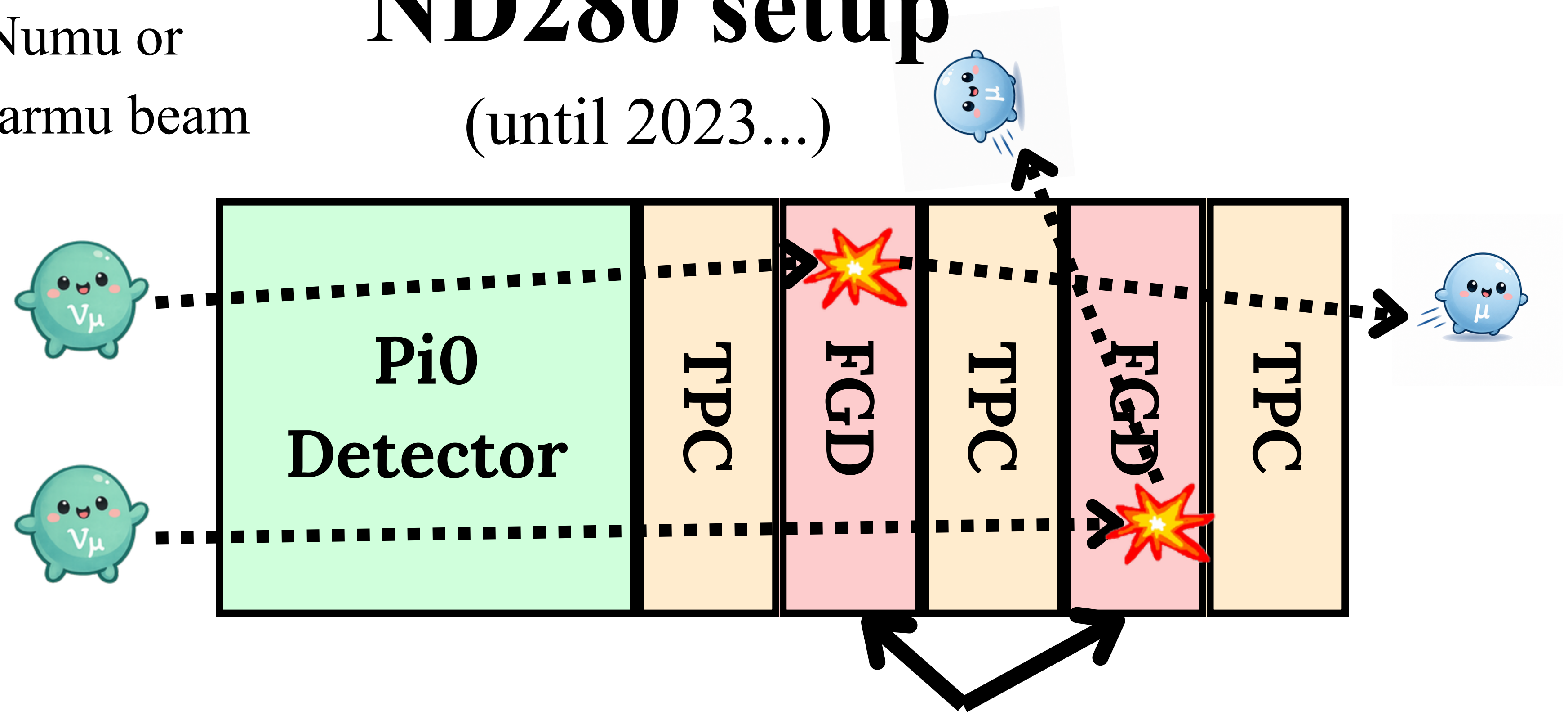
My work:
Near Detector Fit

What do we measure in ND280?

Numu or
nubarmu beam

ND280 setup

(until 2023...)

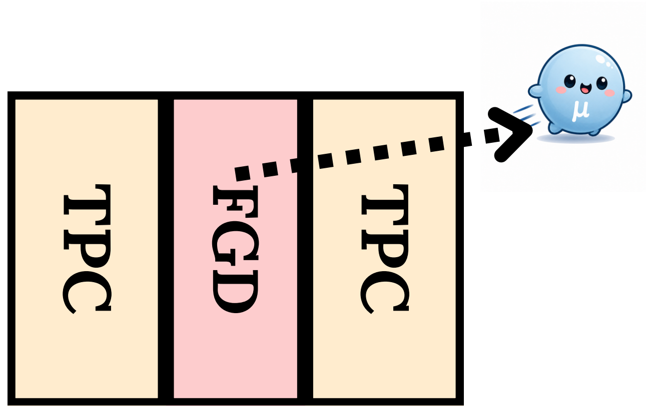


Active targets

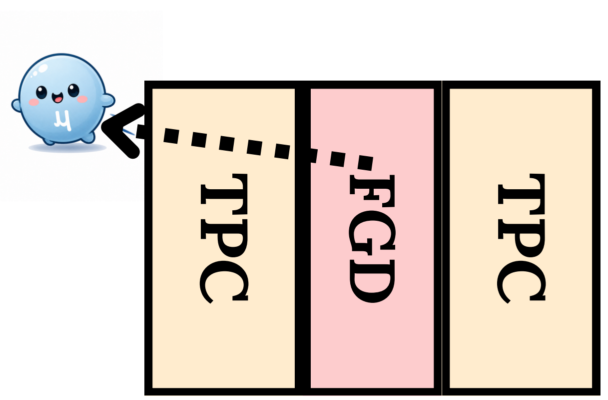
(**mainly C**, but some H20 in right FGD)

TPC = Time Projection Chamber

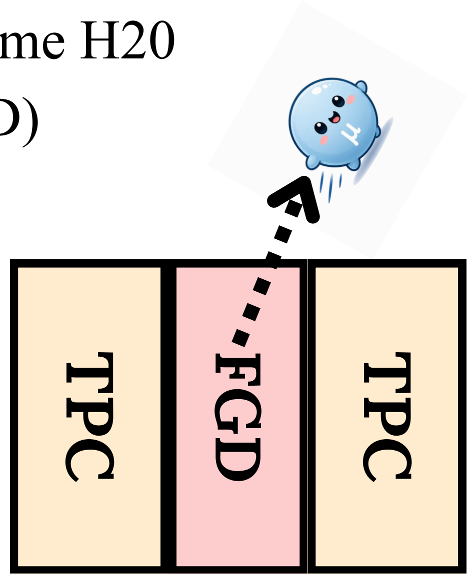
FGD = Fine-Grained Detector



Forward (Fwd)

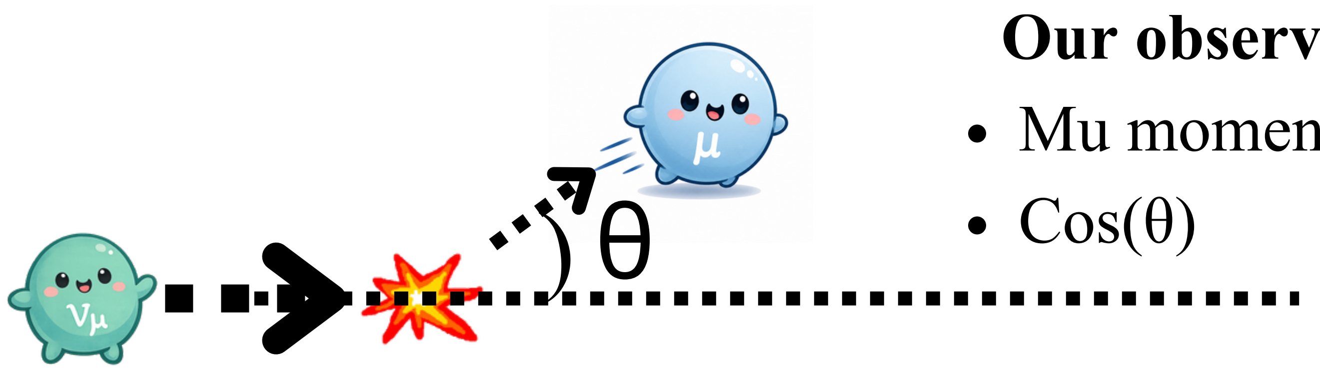


Backward (Bwd)



High -Angle (HA)

For **Charged Current (CC) interactions,** our main decay product is **muon**



Our observables:

- Mu momentum
- Cos(θ)

Samples selected and studied are divided per:

- FGD
- Nu or nubar interaction
- Topology (CC0pi, CC1pi, CCmultipi)
- Other products (0proton, 0gamma, ...)
- Angular orientation (Fwd, Bwd, HA)

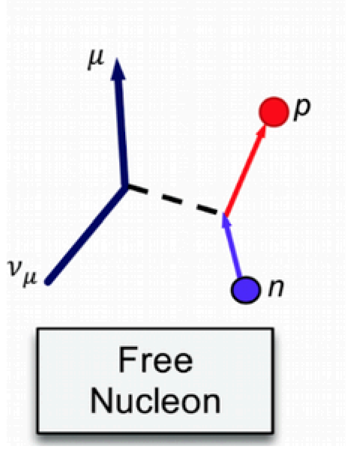
Total of 32 samples at ND280!

Cross-section model at T2K

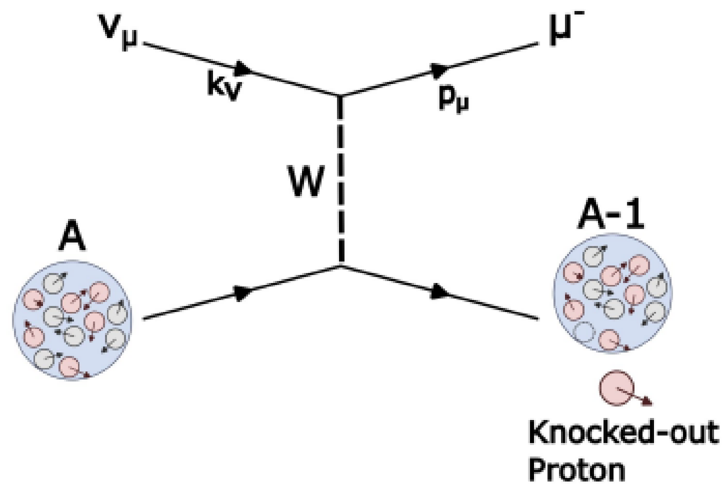
- We need to model in MC neutrino interactions in target → Assign parameters for:

Interaction modes

Only for reaction modes, for example:

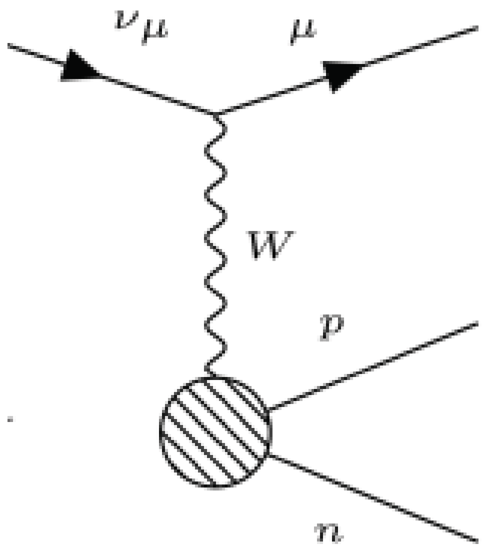


Charged-Current in Quasi-Elastic regime (CCQE)



Only 1 nucleon is ejected from nucleus
(32 parameters)

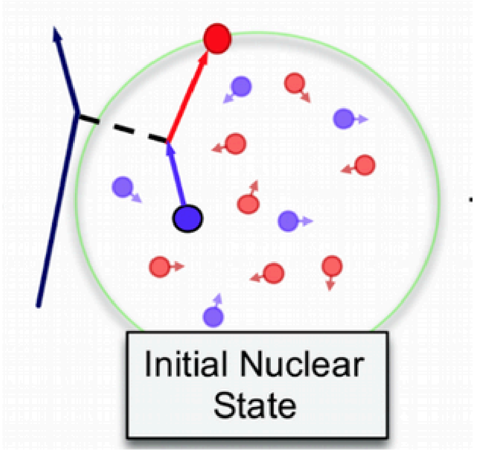
Meson Exchange Current for 2particles-2holes (MEC-2p2h)



2 nucleons are ejected from nucleus
(8 parameters)

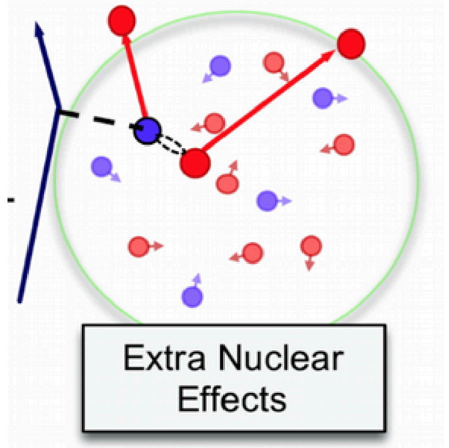
Nuclear effects:

Nucleus before interaction



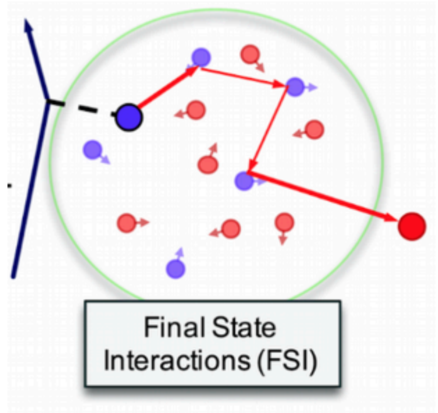
Spectral Function (SF)

Nuclear medium corrections



Modifications in the neutrino interaction, e.g. Coulomb Correction

Final State Interactions (FSI)



How outgoing hadrons interact within nucleus

Total of 83 parameters for our xsec model!

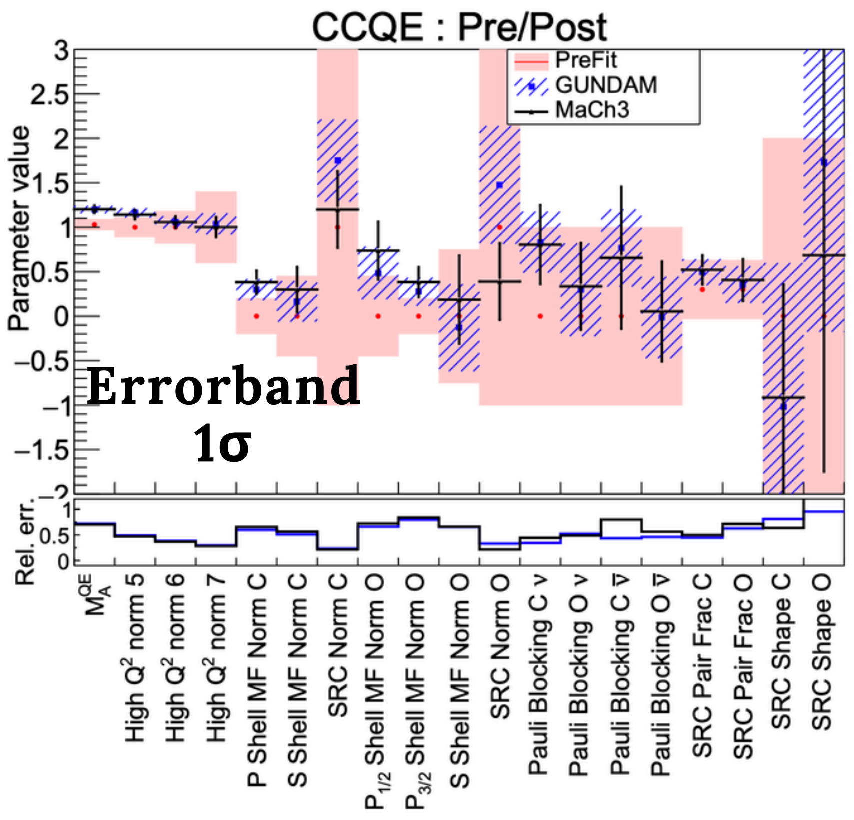
Act III

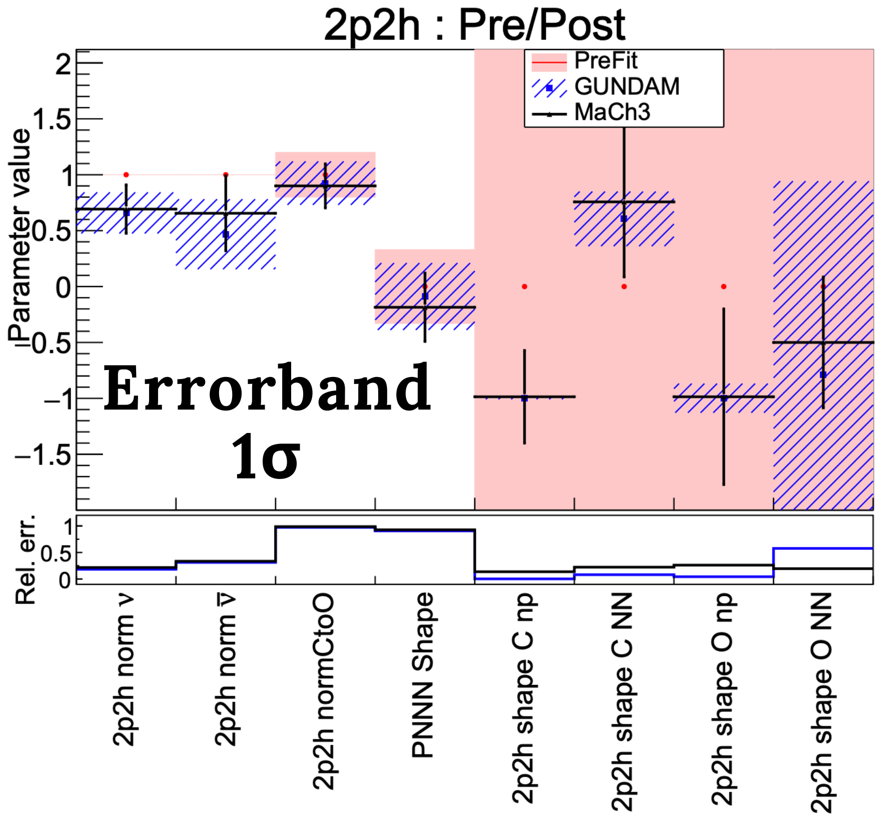
Near Detector Fit + New studies

Near Detector Fit strategy

- **Fitter: GUNDAM*** *Generalized and Unified Neutrino Data Analysis Methods*
  - Semi-frequentist approach → Profiling over MC parameters
  - Gradient descent method (Minuit2): find minimum χ^2
  - HESSE to build post-Fit covariance matrix
- **MC systematic model** → 842 parameters (Flux, X-sec, detector)
- **Fit =** Finding best-fit MC parameter values to reproduce the data and reduce uncertainties

PreFit GUNDAM MaCh3

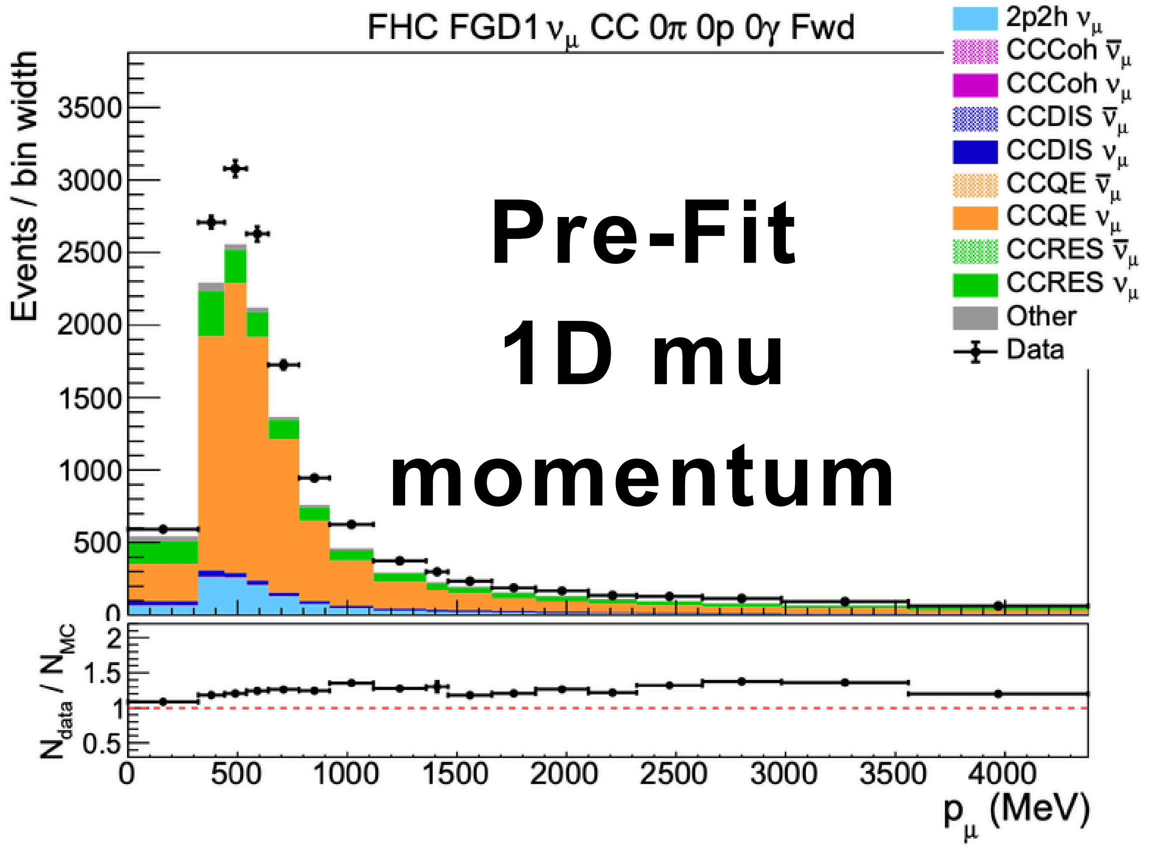




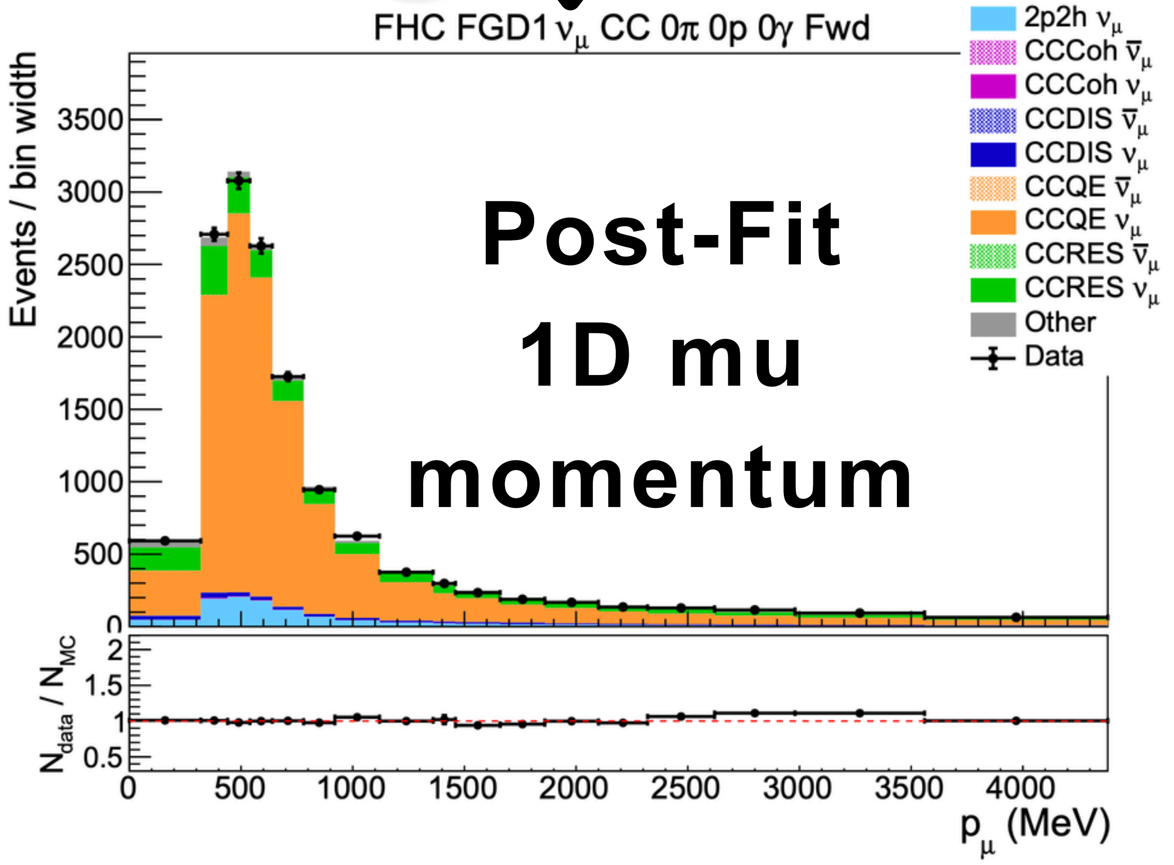
Datafit discussed previously in IRN

[Link to Lena's slides]

p-value=57.5%



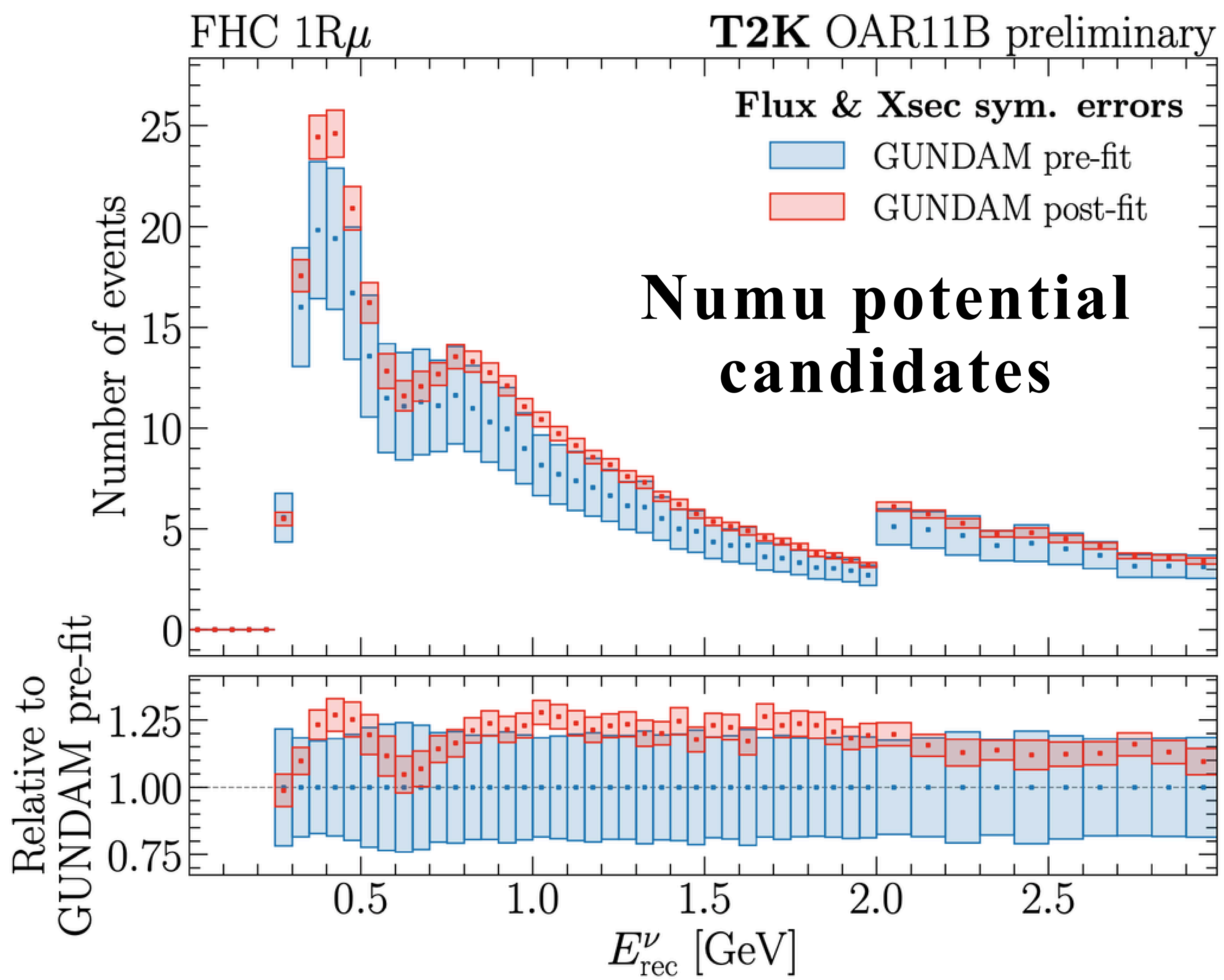
Fit!

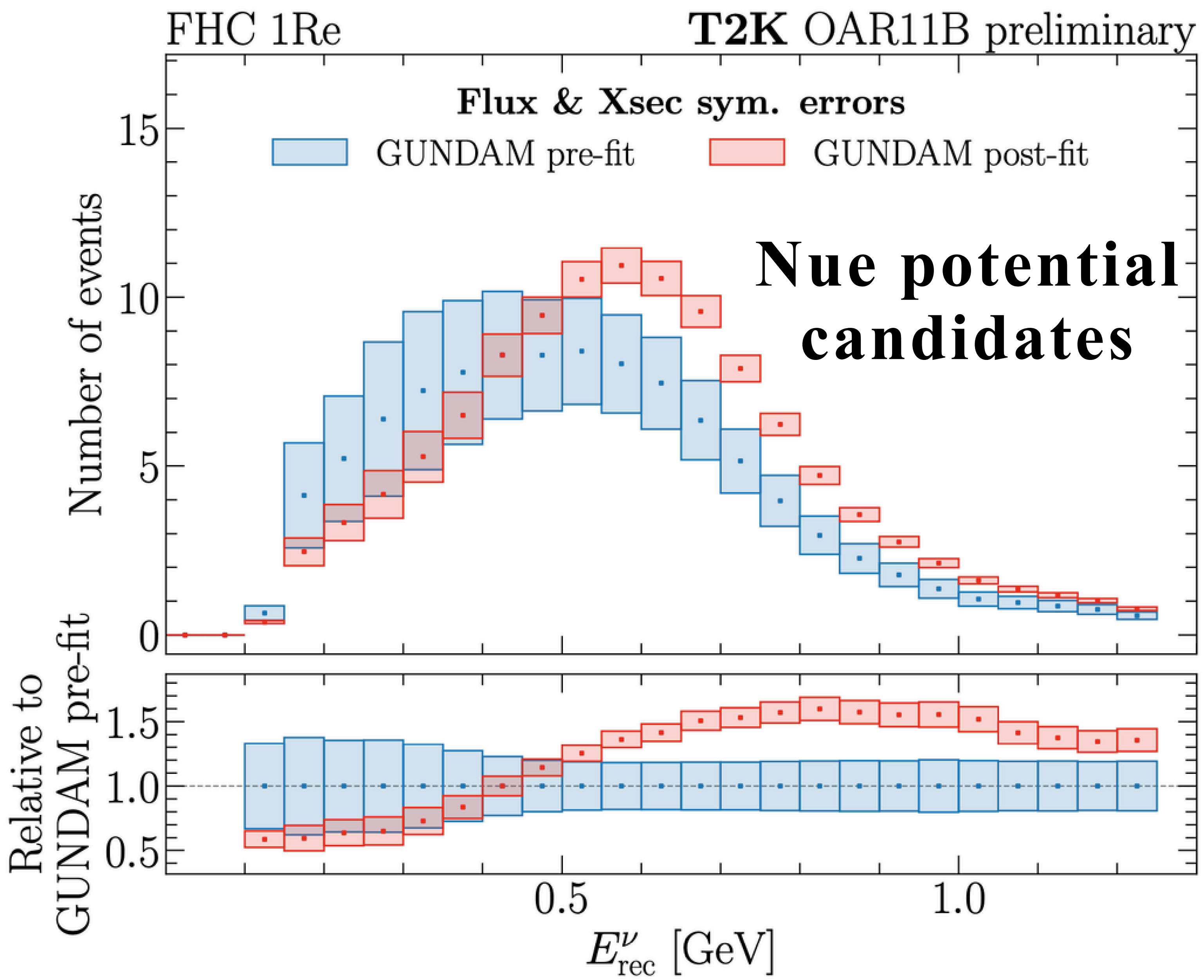


* MaCh3 fitter is also widely employed within T2K → Bayesian approach

How ND datafit is useful for Super-K (Far Detector)

Neutrino energy spectra at Super-K, pre-Fit
(6 samples in total)





ND Fit has an important role in constraining uncertainties at Super-K → Far Detector Fit will be **more precise** for best-fit values in **oscillation parameters**

New studies for this analysis!

- This looks great, but what if **we are wrong** in our xsec model? **How can we know?**

Fake Data Studies (FDS)

- Fake data = MC reweight event per event to match a different xsec model
- FDS = Fit T2K preFit MC to “**fake data**”
  - If fit is good = amazing :) our current MC systematic model can absorb this alternative model
  - If fit is poor = bias in neutrino oscillation parameters
- **Main objective: evaluate possible bias!**

For this year @Neutrino 2026

Name	Applied to
SFtoLFG	1p1h
non-QE	pi-abs, 2p2h
1pi hadron kinematics	RES
CRPA	1p1h

(we have 14 more fake datas 😉)

For today :)

Fake data SF to LFG:

Joint probability P of finding a nucleon with momentum p and bound energy E

Spectral Function (SF)

Reweighting in CCQE (=1p1h)

Nucleons with equally likely momentum p below Fermi momentum

Local Fermi Gas (LFG)

= Fake data

Fitting T2K MC model to LFG fake data

- **Fake data** reduces (increases) xsec at low (high) energies w.r.t. **T2K MC model**
- Fake data: lower events for small mu angles (and higher events for high mu angles → spare)
- **GUNDAM reproduces well the fake data**, except at high energies and forward angles

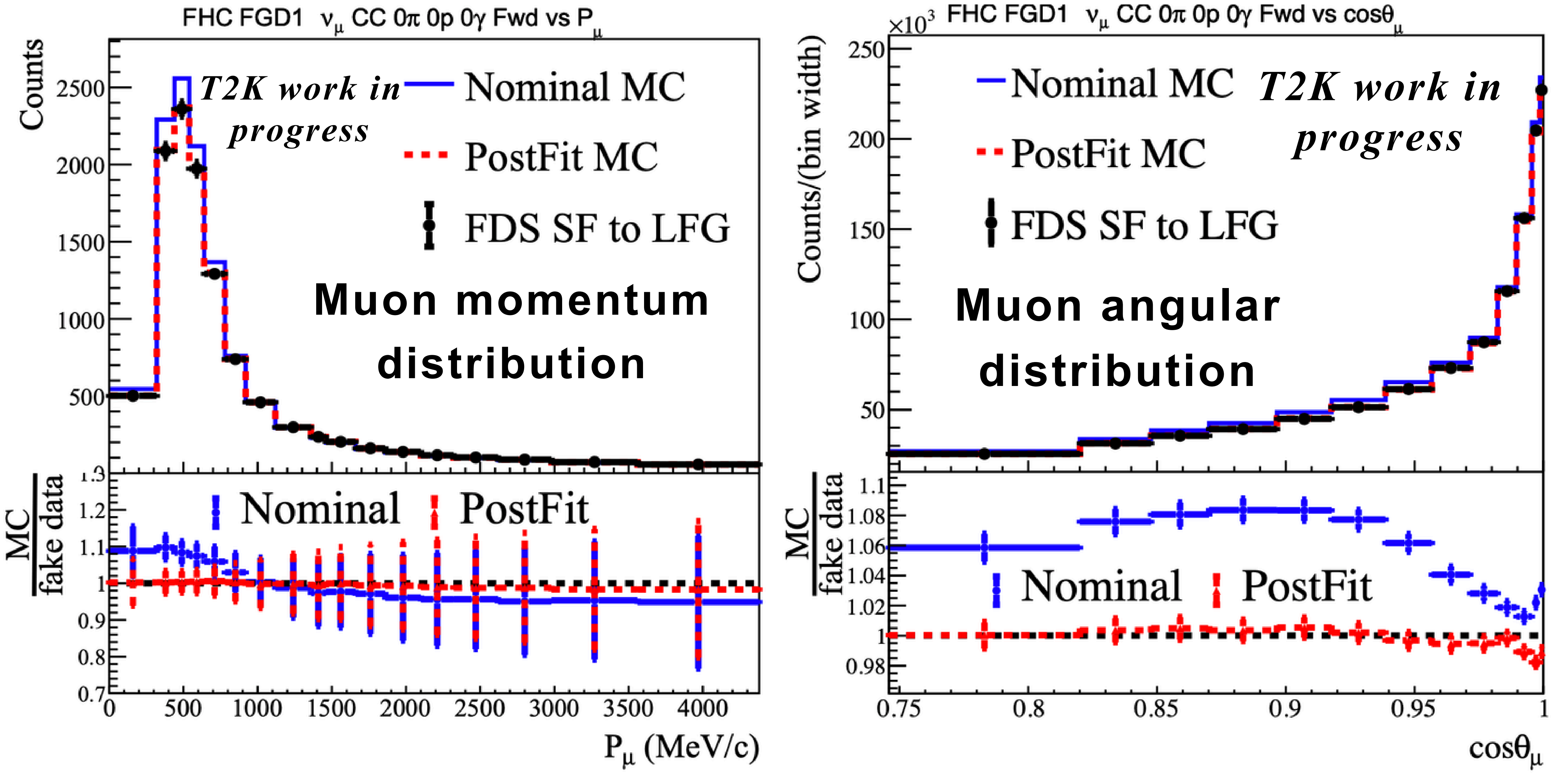
Fit **ND preFit MC** to **fake data**

↓

PostFit MC

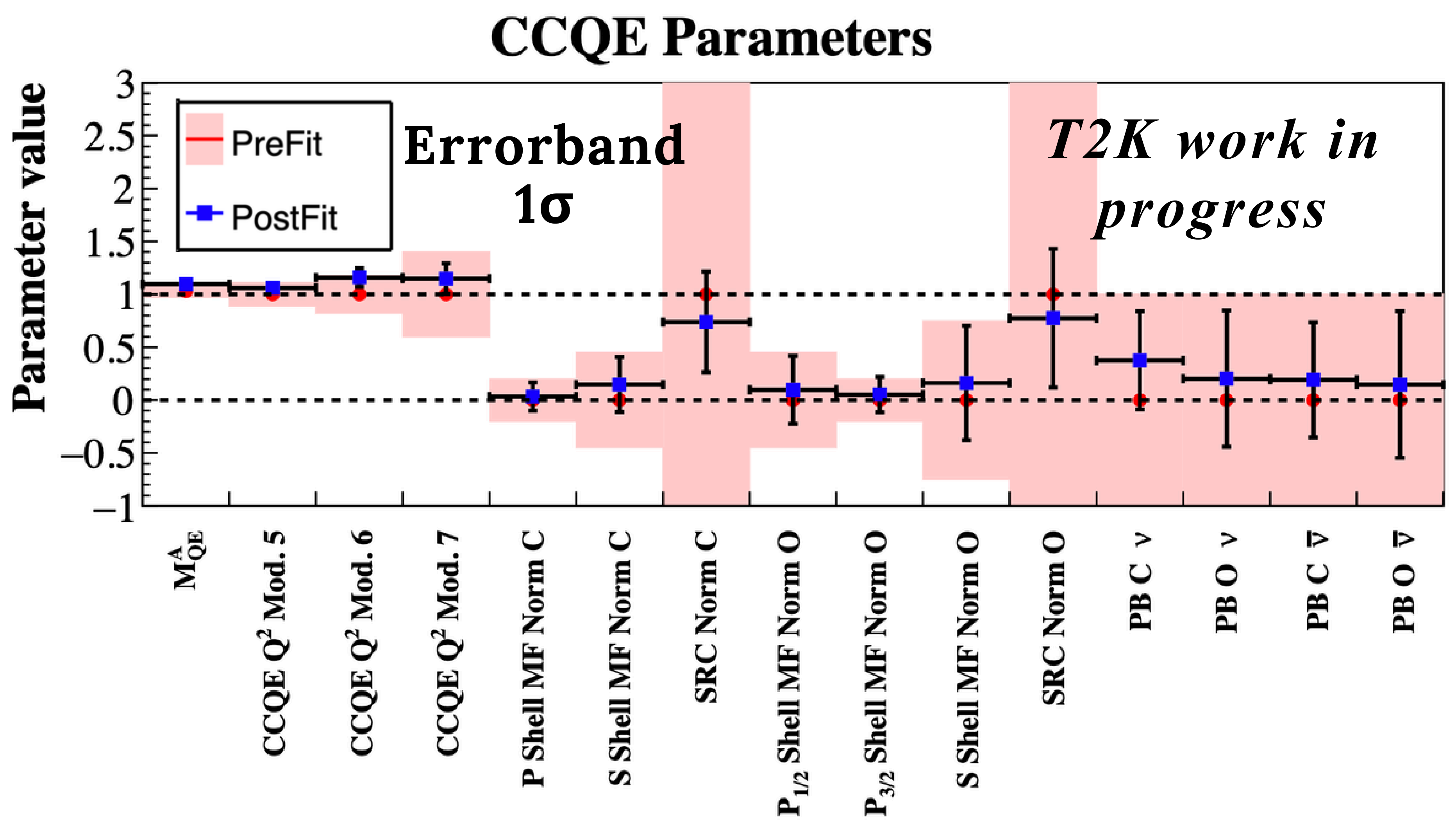
Event rates

(most representative CC0pi sample)



LFG fake data → What changes in MC parameters?

This is how GUNDAM best-reproduce the **LFG fake data**



This fake data is applied to model differently CCQE interactions, it makes sense CCQE parameters differ from pre-Fit!

Rest of parameters in spare

Some of the interpretations for post-Fit

- Increase Axial Mass form factor for CCQE: **higher xsec at high energies**
- Increase in Q^2 dials: Higher x-sec, especially for Q^2>0.50 GeV^2
- Lower Short Range Correlations (SRC): Less multi-nucleon interactions
- Increase Pauli Blocking probability: **Suppresion at low energies** (part of the Fermi momentum effect from LFG)

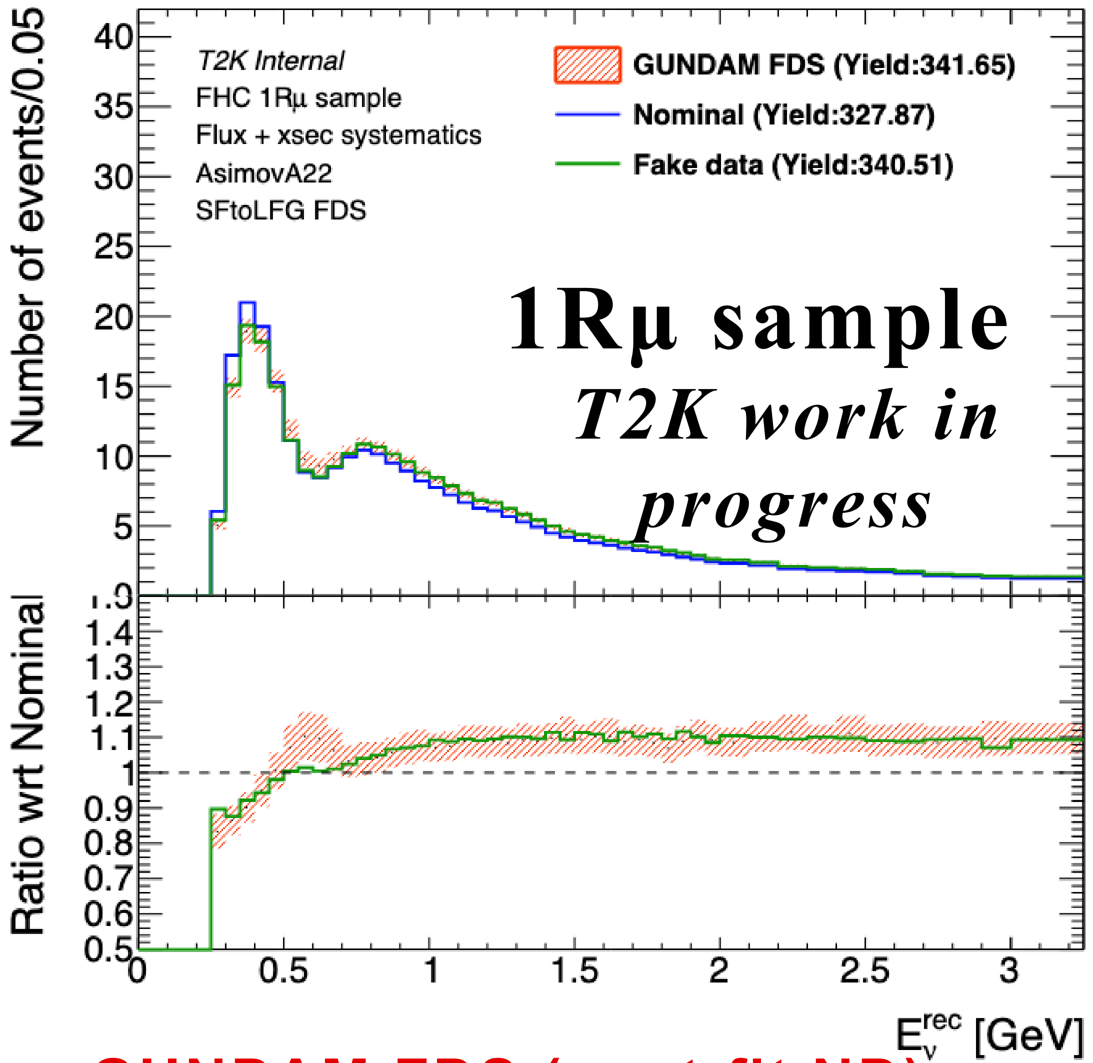
We see this is **consistent with 1D event rates**: fewer events at low pmu while higher at bigger energies

FDS SF to LFG - results in oscillation parameters

(preFit)

Energy spectra at SK

Fit → Far Detector

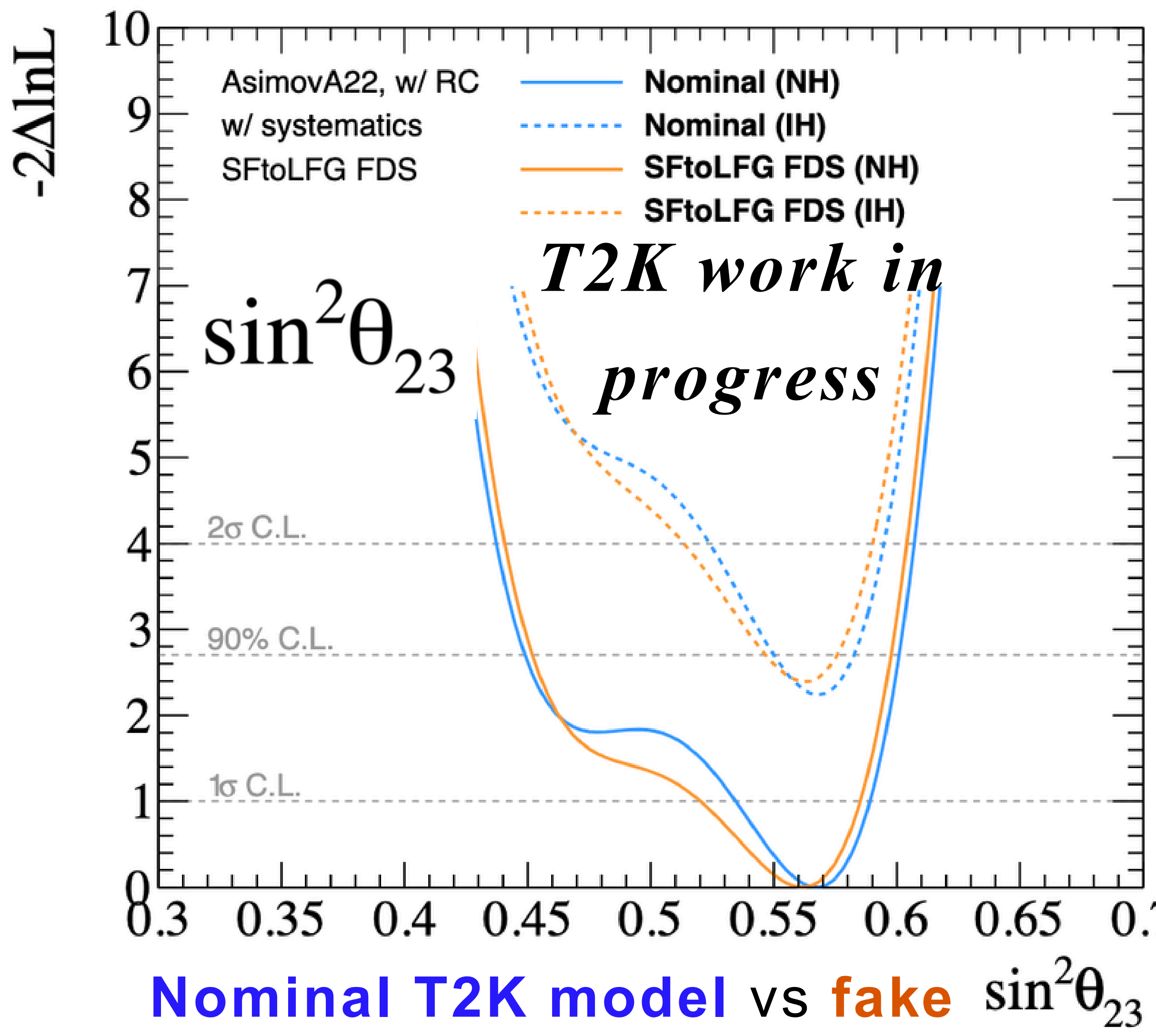


GUNDAM FDS (post-fit ND) vs **fake data**

If T2K model is good, they should be aligned

LLH distribution for neutrino oscillation parameters!

$\sin^2\theta_{23}$ δ_{CP} Δm^2_{32}



Nominal T2K model vs **fake data model**

We spot here some differences (~2% bias)

Assess carefully if these differences will be meaningful in oscillation parameters

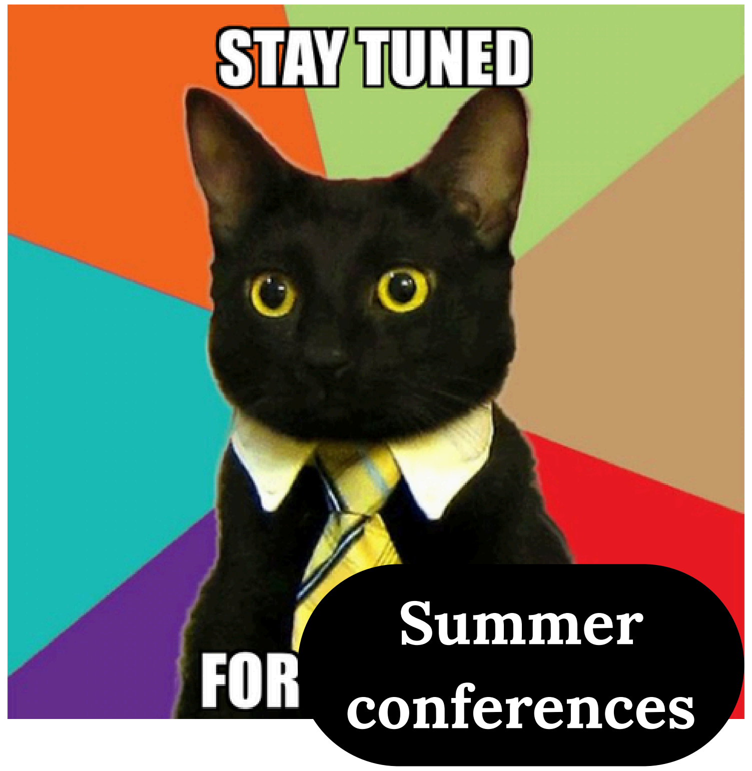
If yes → Smearing

If not → Good news :)

More details on this FDS and the others in...

Act IV
Why future looks bright :)

New OA analysis including more data in Far Detector!



Upgrades!

Beam:

from 250kA to 320kA

See Jean-Baptiste presentation just after this one! Click me

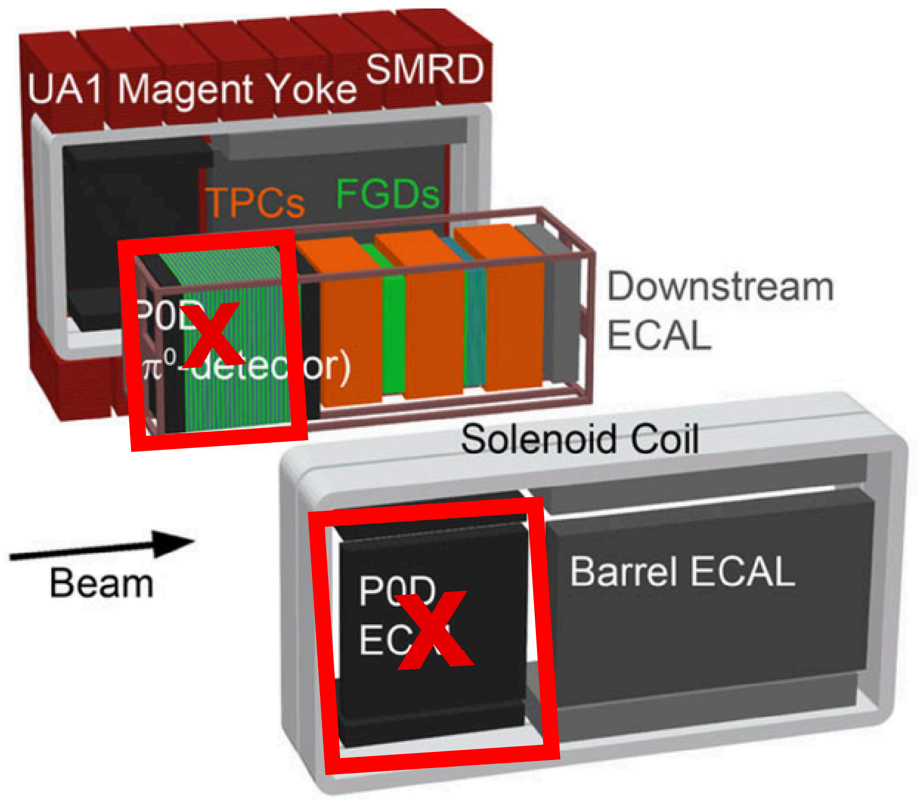
Near Detector:

new subdetectors!

Next slides...

T2K Near Detector (ND280) Upgrade

Pre-upgrade



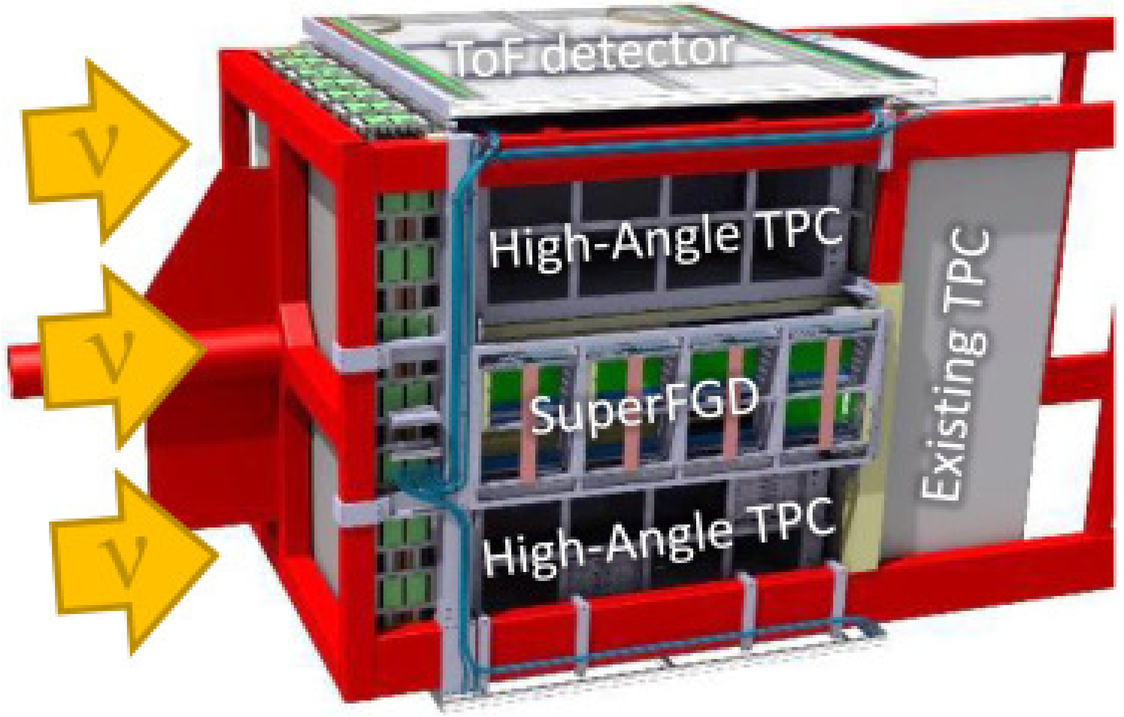
Used for all OA results so far

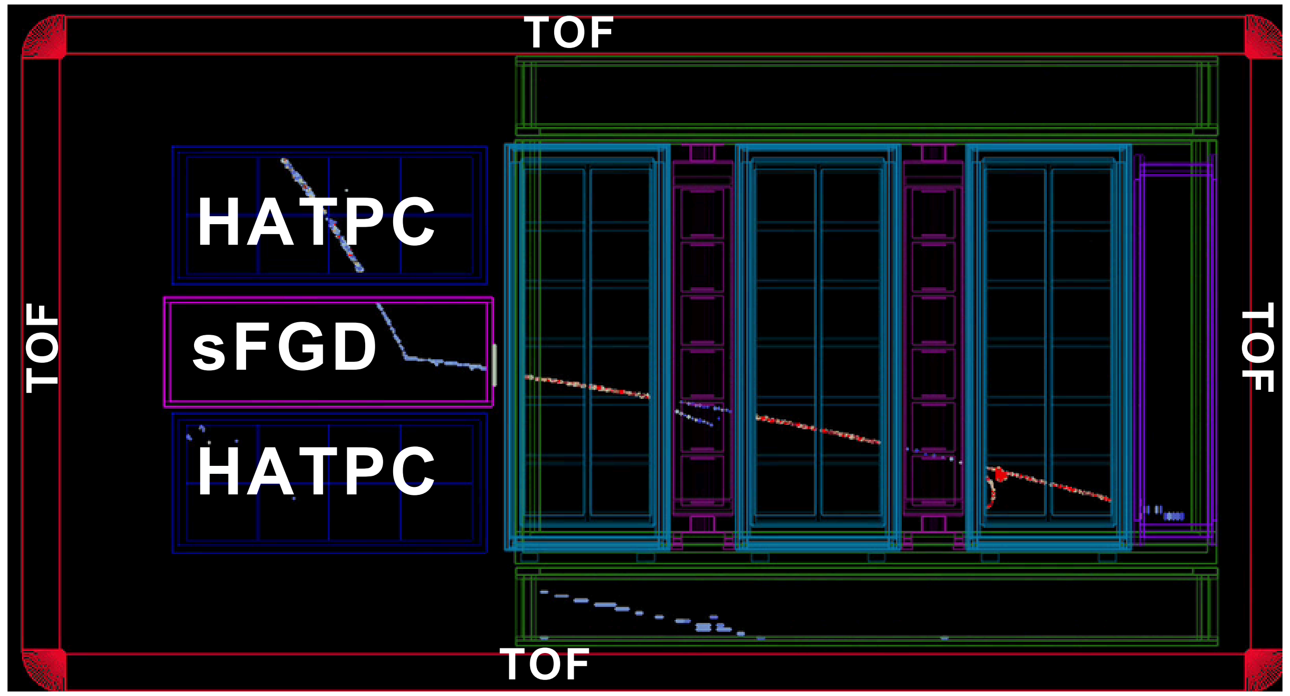
X **Not in the upgrade**

This will be employed for Hyper-K experiment :)

Post-upgrade

Project started in 2018, construction finished in 2022, **data taking since 2023!**





What is **new**

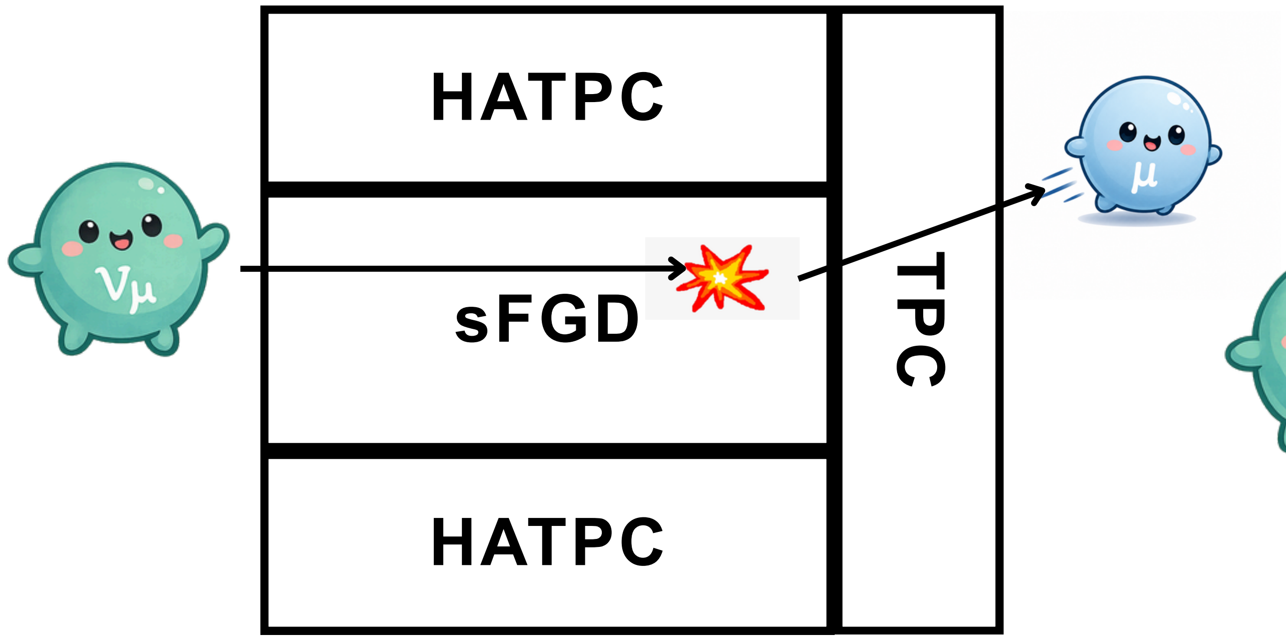
- **Super Fine Grained Detector (sFGD)**: active target, measuring information of neutrino vertex, low momentum protons, … → **reduced systematic uncertainties**
- **2 High-Angle Time Projection Chambers (HATPCs)**: precise momentum resolution outgoing leptons and PID + **4pi angular coverage**
- **Time-of-Flight system (TOF)**: outgoing particle information (complementary to sFGD)

Detectors performance publications on HAT (link) and sFGD (link)

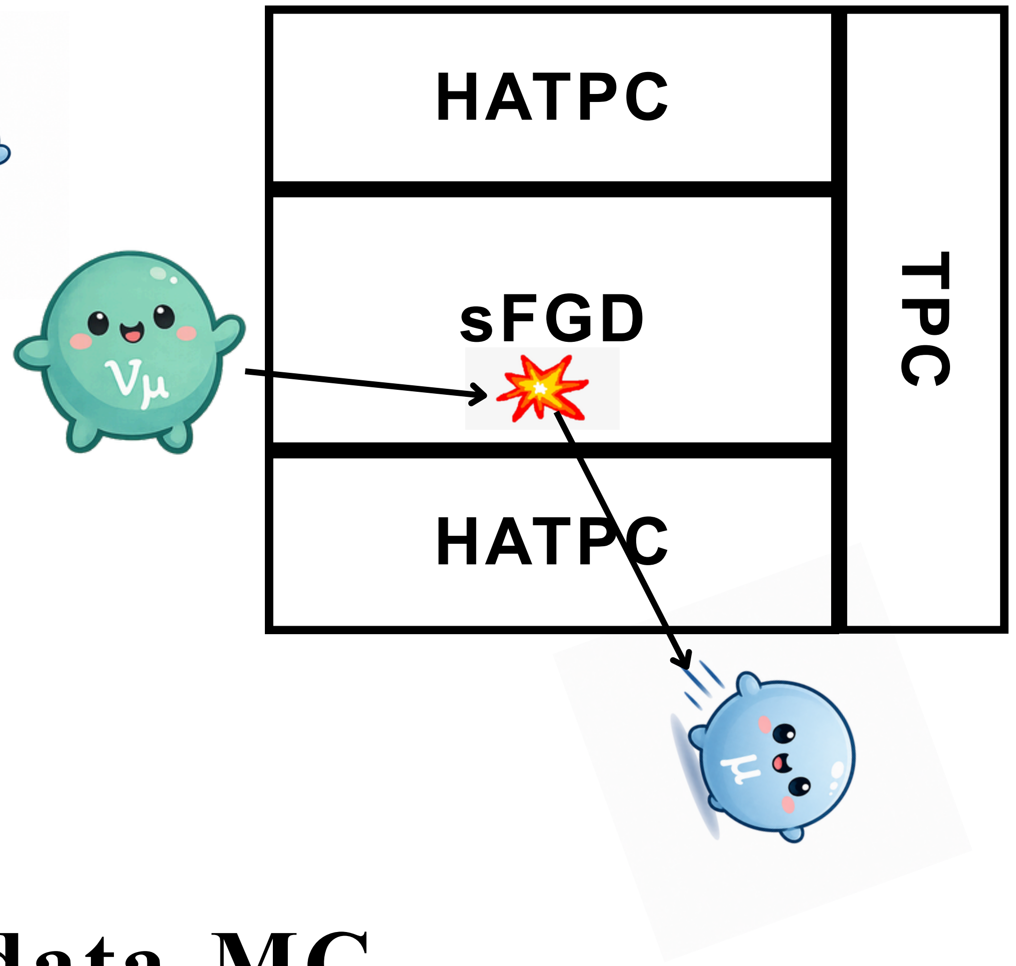
ND280 Upgrade current status

- Recently finished **CC Inclusive selection** and **systematics evaluation** with the upgrade

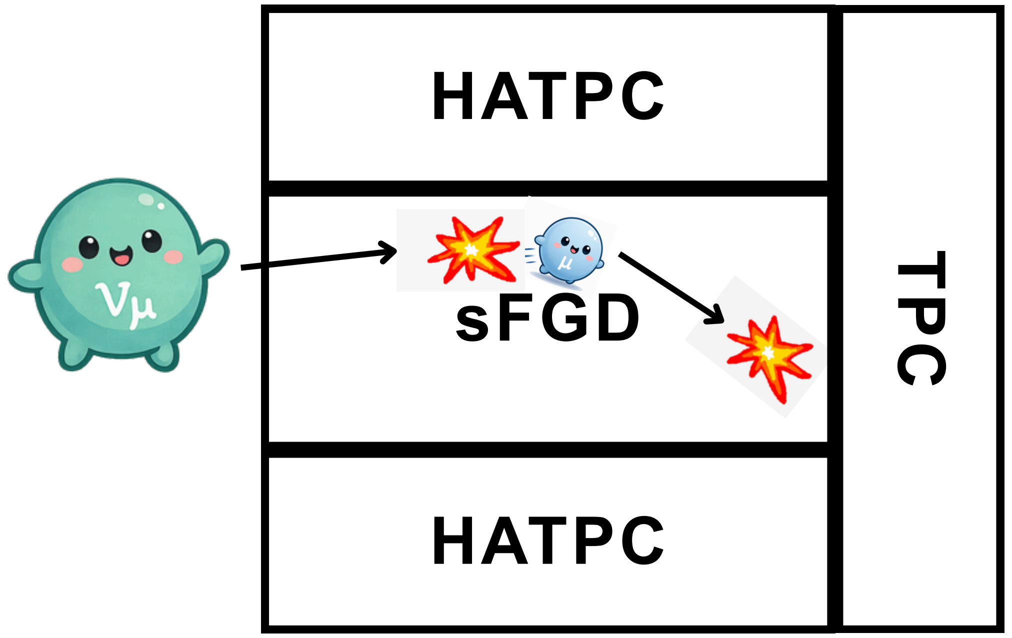
Muon going to TPC



Muon going to HATPC



Muon stopping in sFGD



Many results data-MC comparisons in →

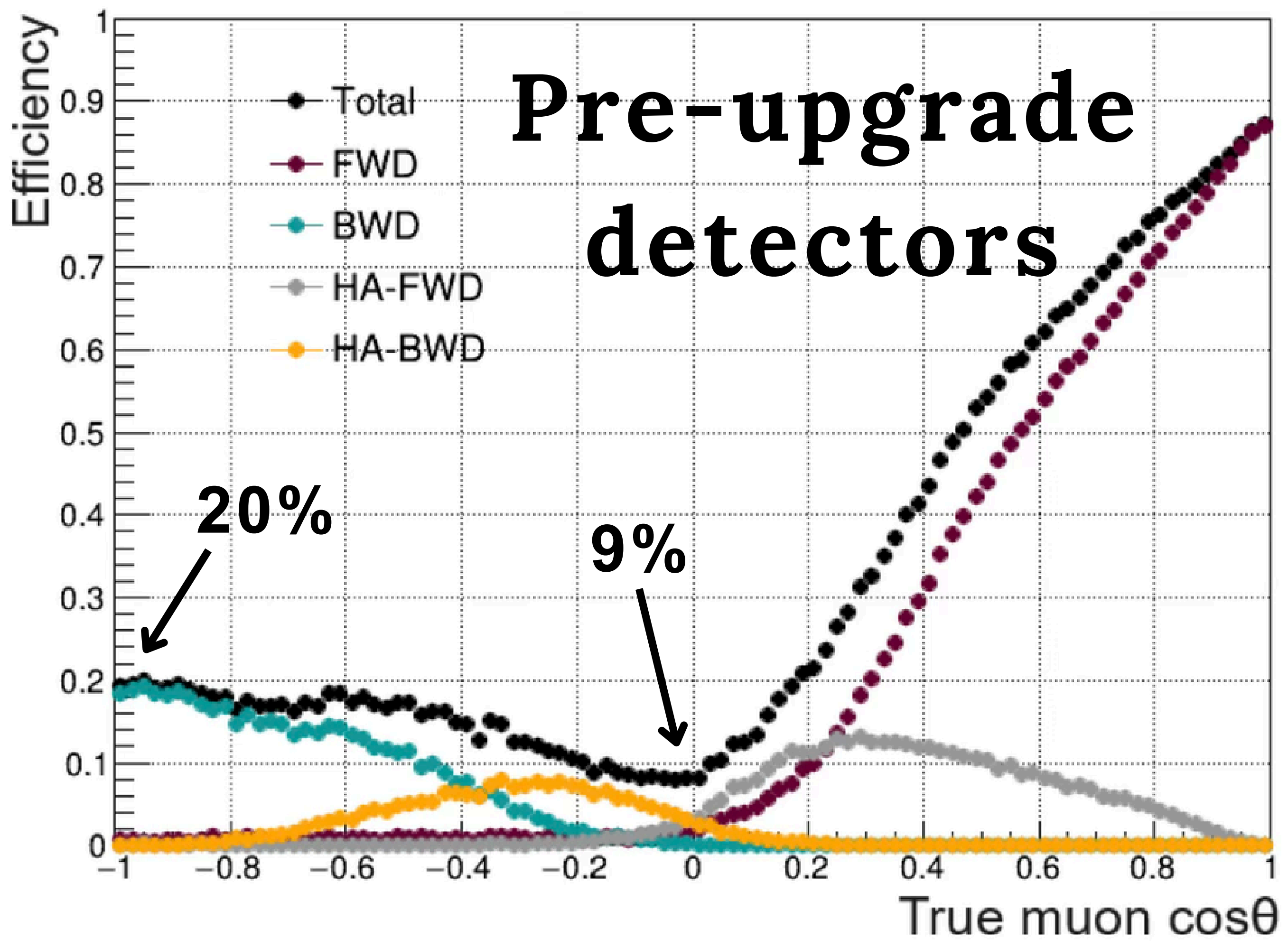
[Jean-Baptiste presentation]

\+

Why this matters to OA

- Recently finished **CC Inclusive selection** and **systematics evaluation** with the upgrade

Efficiency in angular distribution



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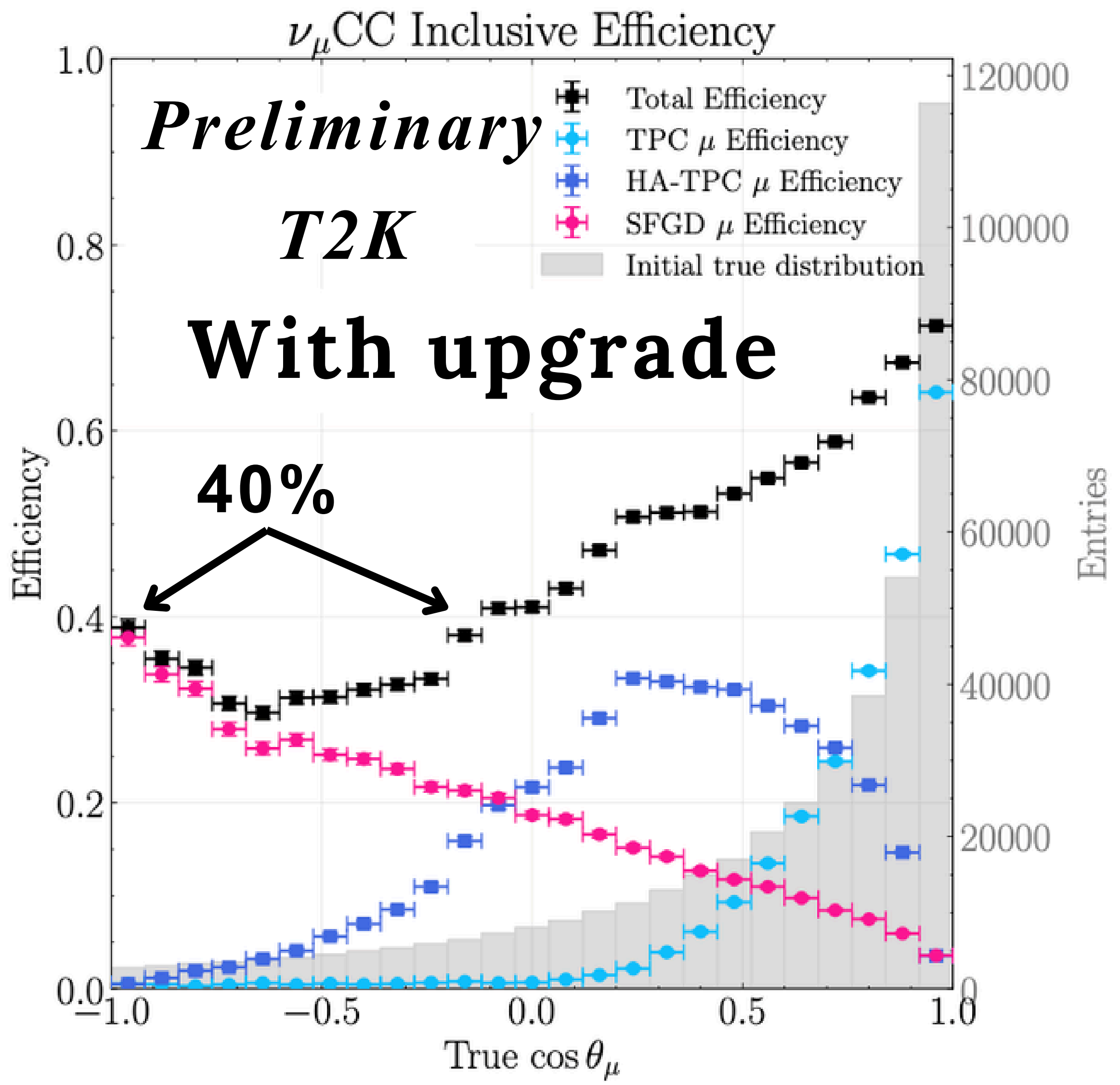


From OA side

- Implementing these 3 CCInclusive samples
- For next IRN :)

$$\epsilon = \frac{\text{Number of selected } \nu_\mu\text{CC events}}{\text{Initial number of } \nu_\mu\text{CC events}}$$

OA latest results
- Summary -

Pre ND280 upgrade

- Fake Data Studies ✔️ complementary to datafit to evaluate bias for assumptions in xsec model

Name	Applied to
SFtoLFG	1p1h
non-QE	pi-abs, 2p2h
1pi hadron kinematics	RES
CRPA	1p1h

- New results in oscillation parameters including more data at Far Detector! 🙂

Post ND280 upgrade

- Recently finished **CCInclusive selection! (First selection with upgrade!)**

From OA

Currently implementing these samples to run fits with upgrade!

In parallel

(very significant for OA)

Planned an even **better upgrade for ND280**

@Daniel Ferlewicz

Link to talk

Beam upgrade! 😁

@Jean-Baptiste Plançon

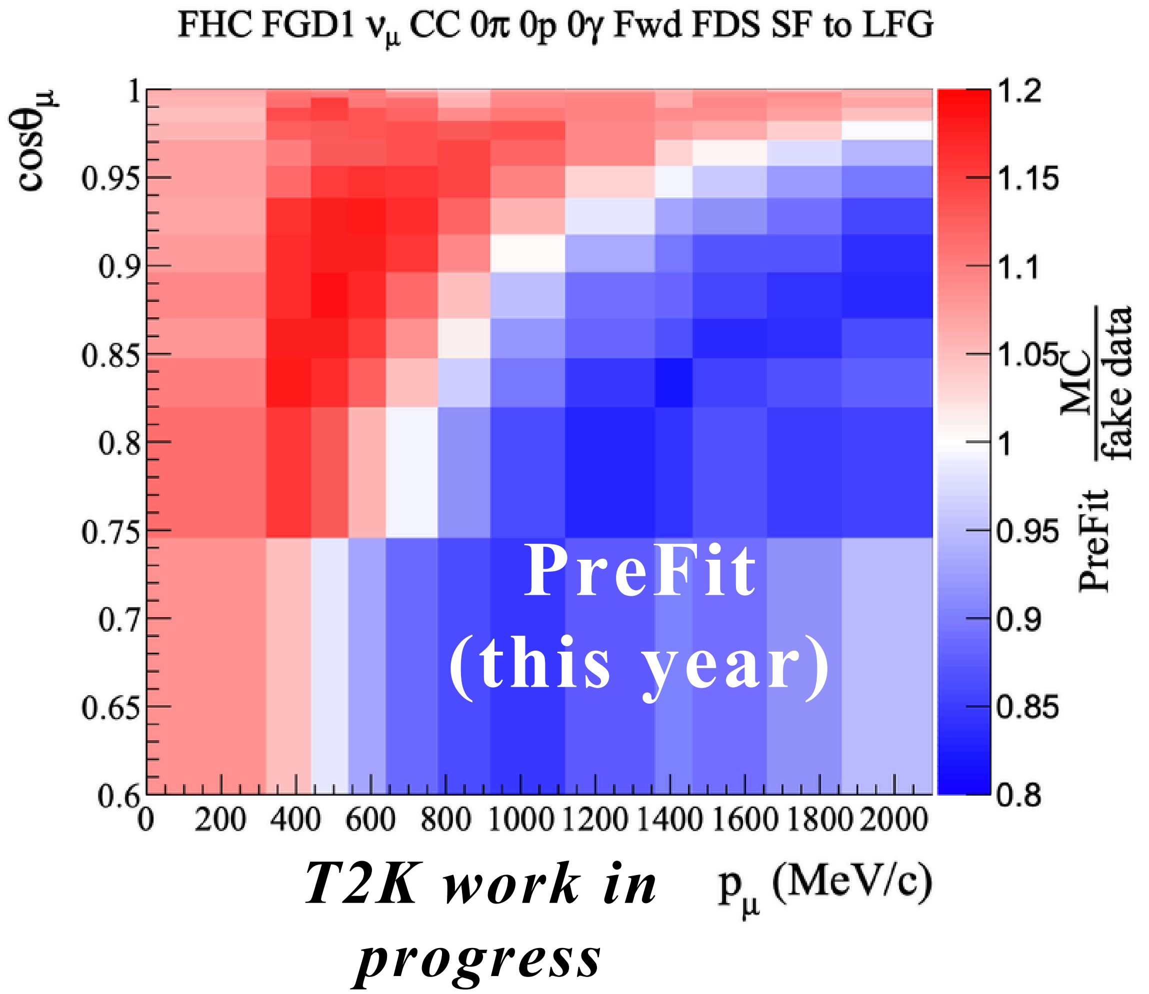
Link to talk

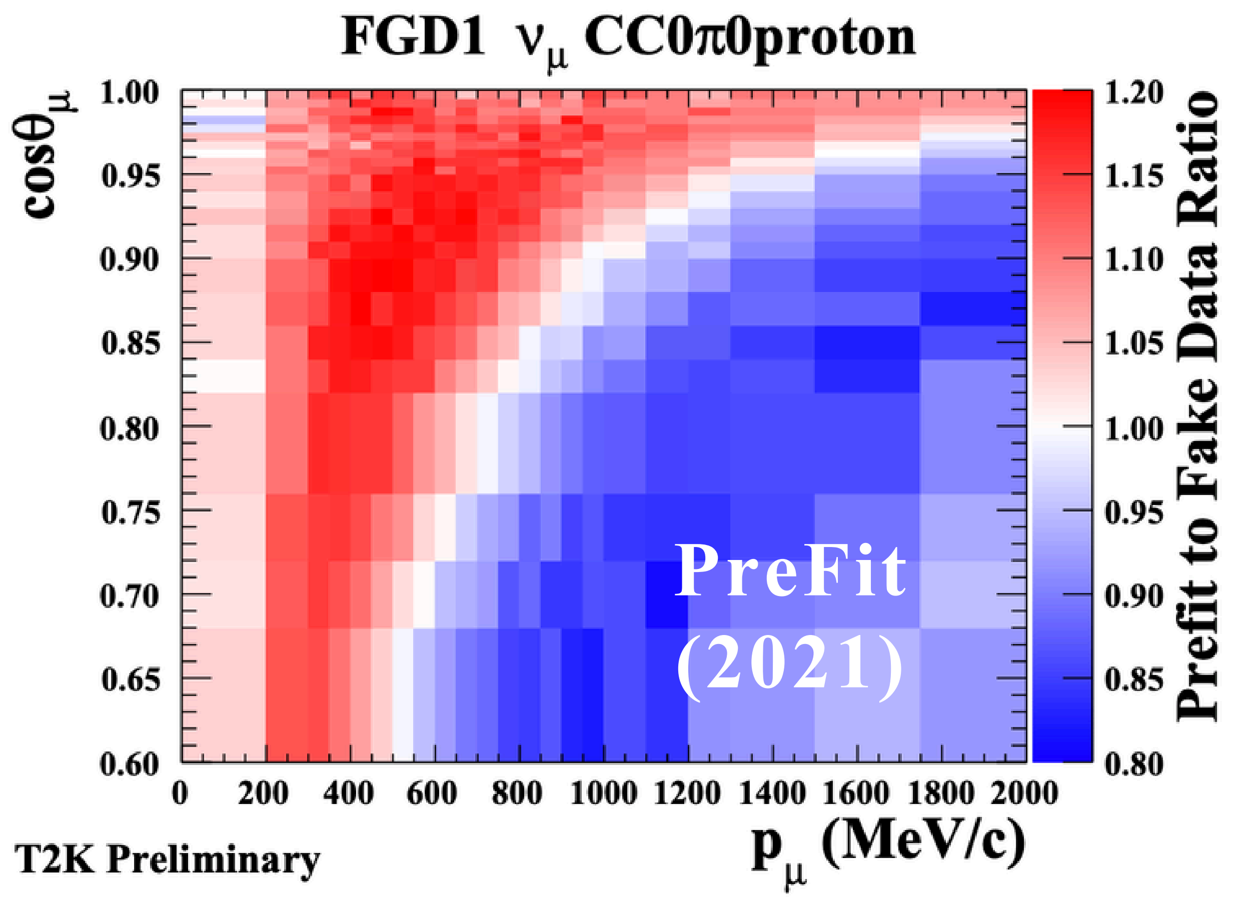
Thank mu for the attention!

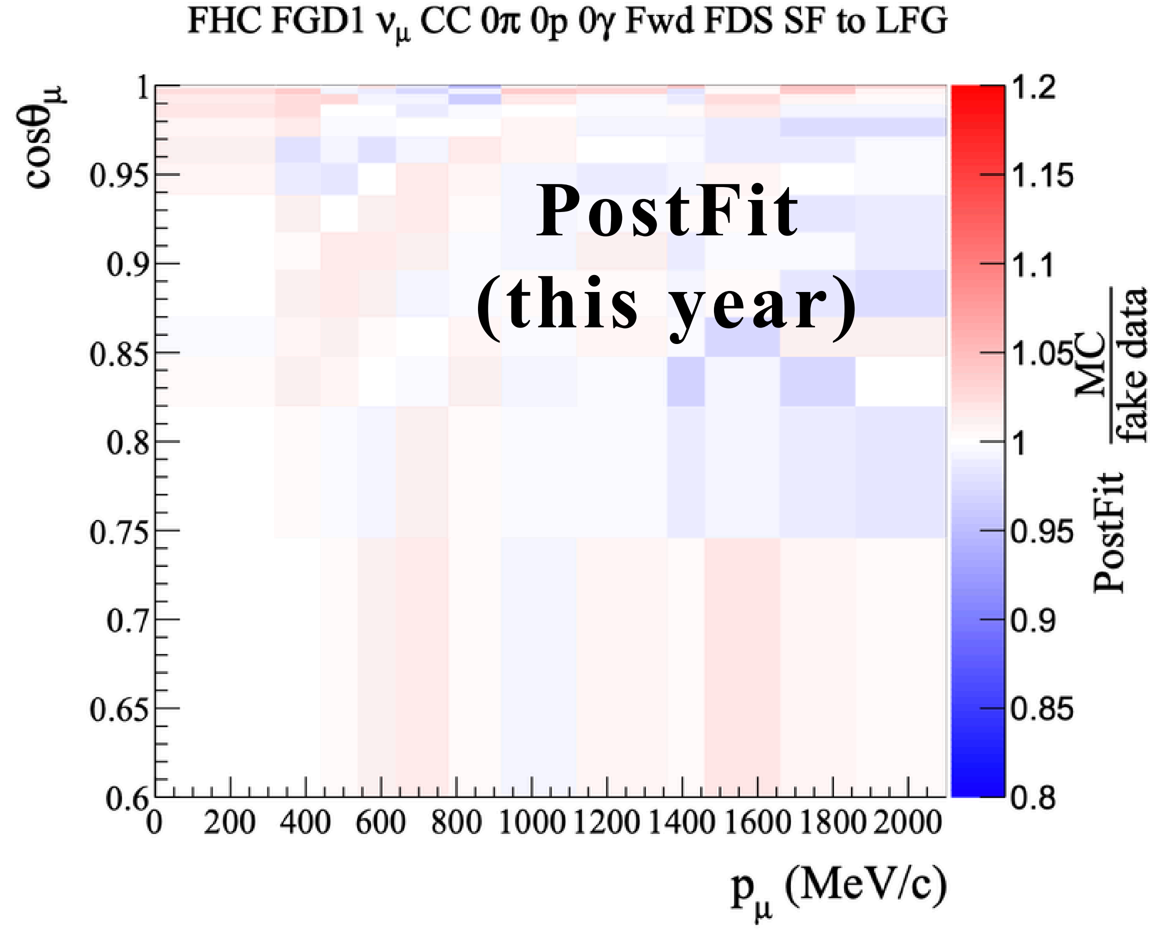
Spare

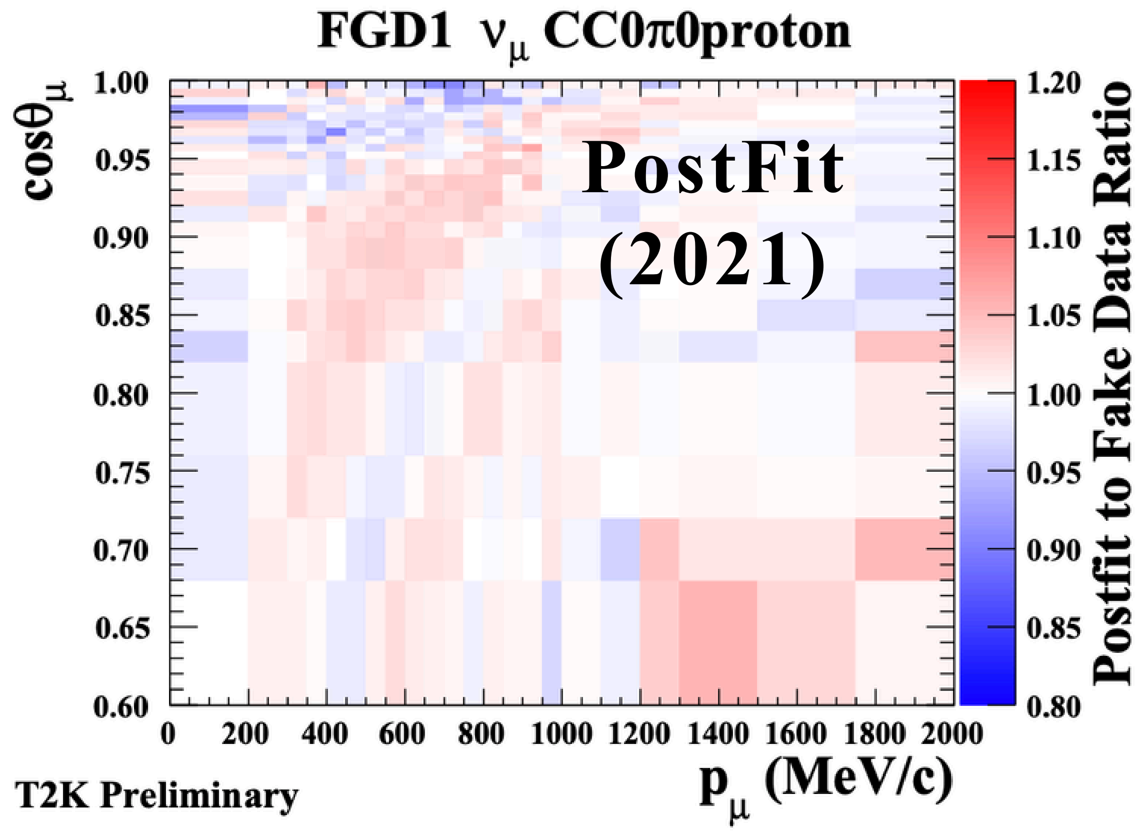
FDS SF to LFG Event rates comparison

- Our postFit better reproduces the fake data with respect to 2021 studies → Smoother behaviour



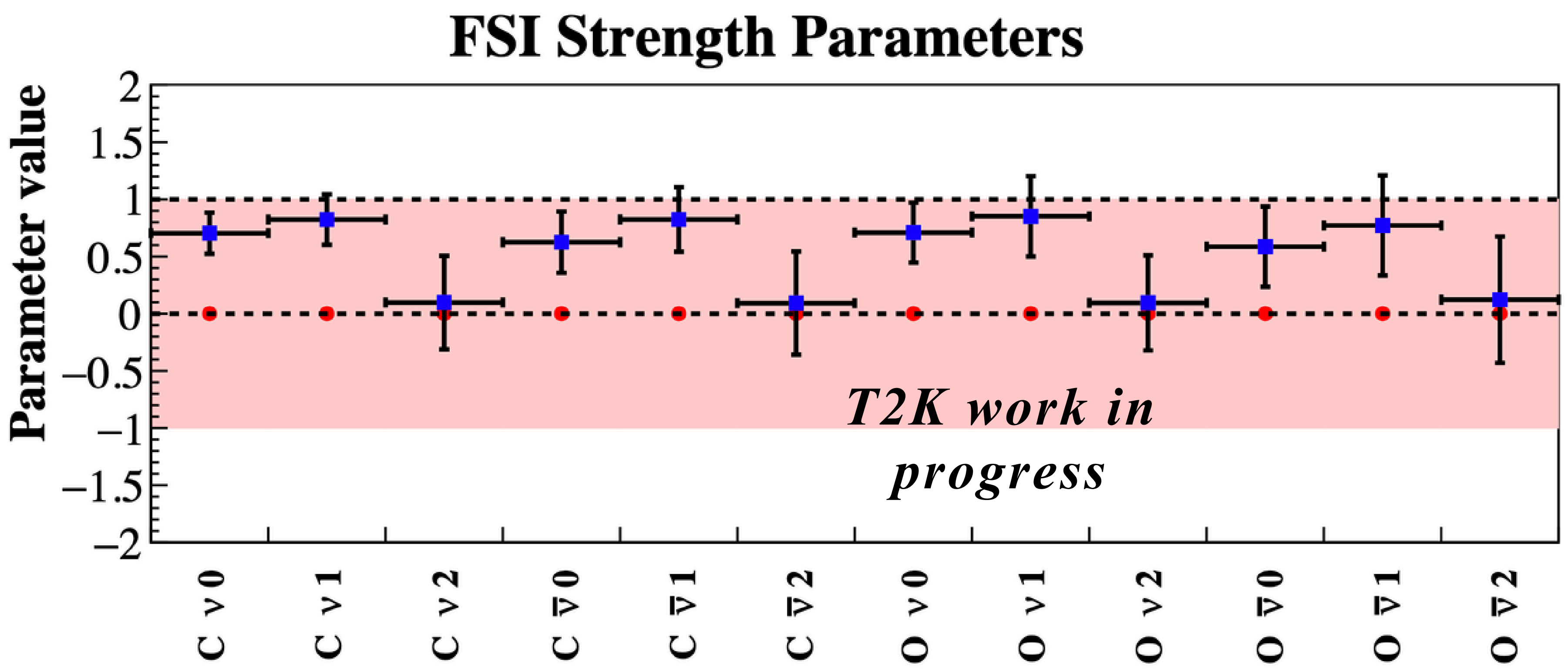


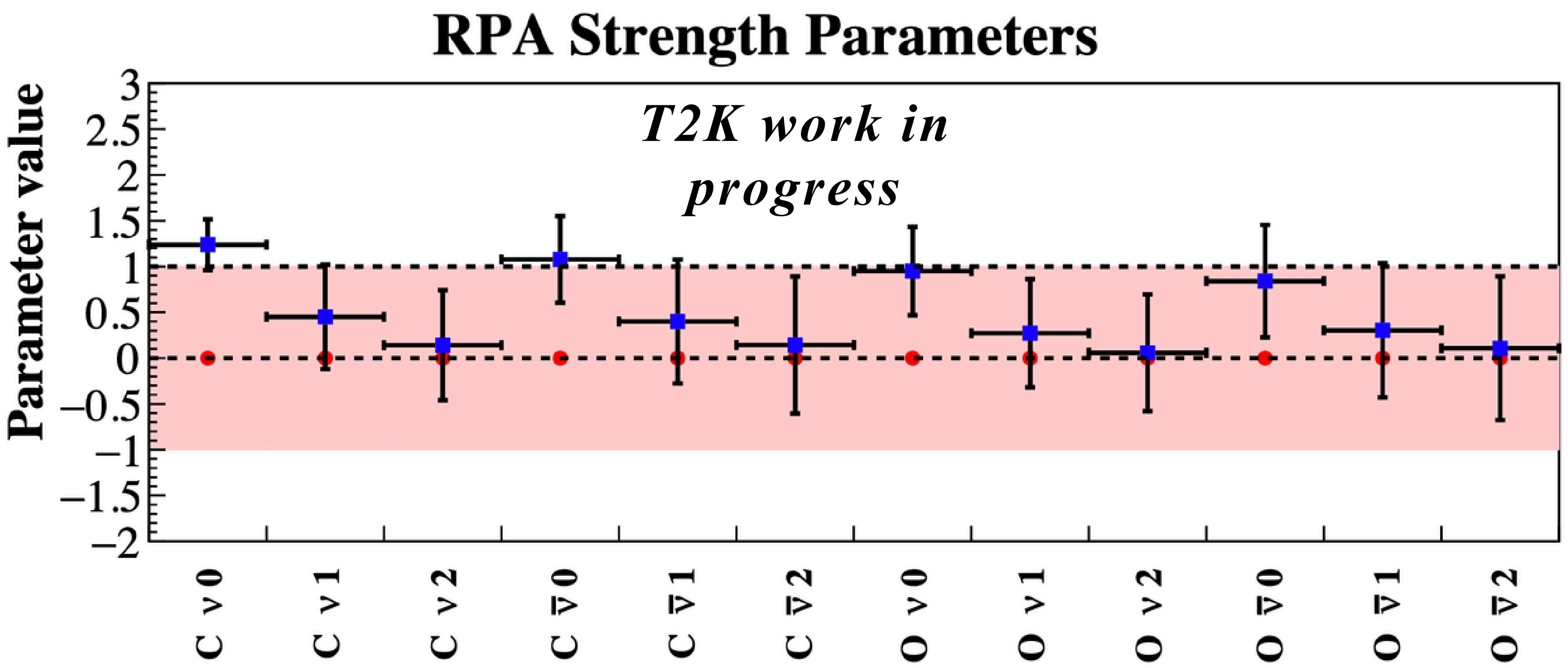




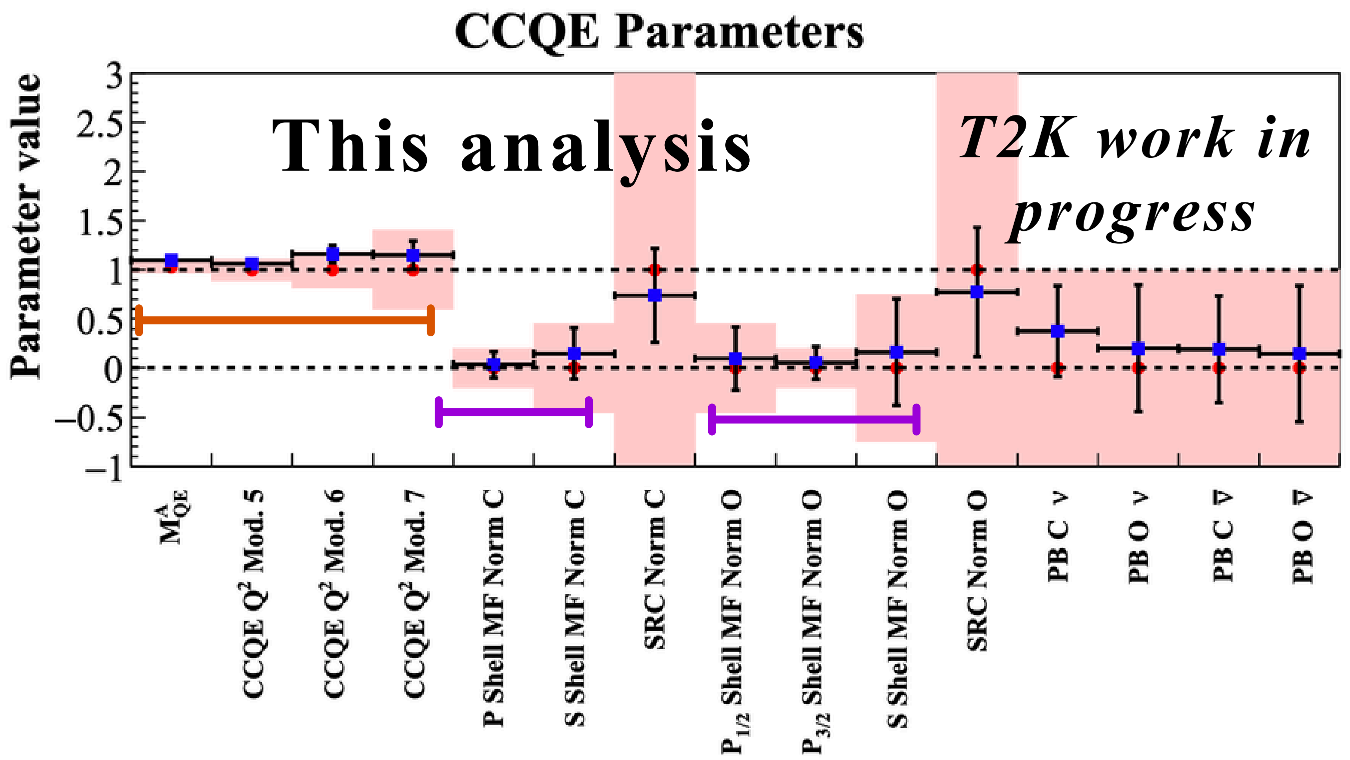
FDS SF to LFG - other remarks

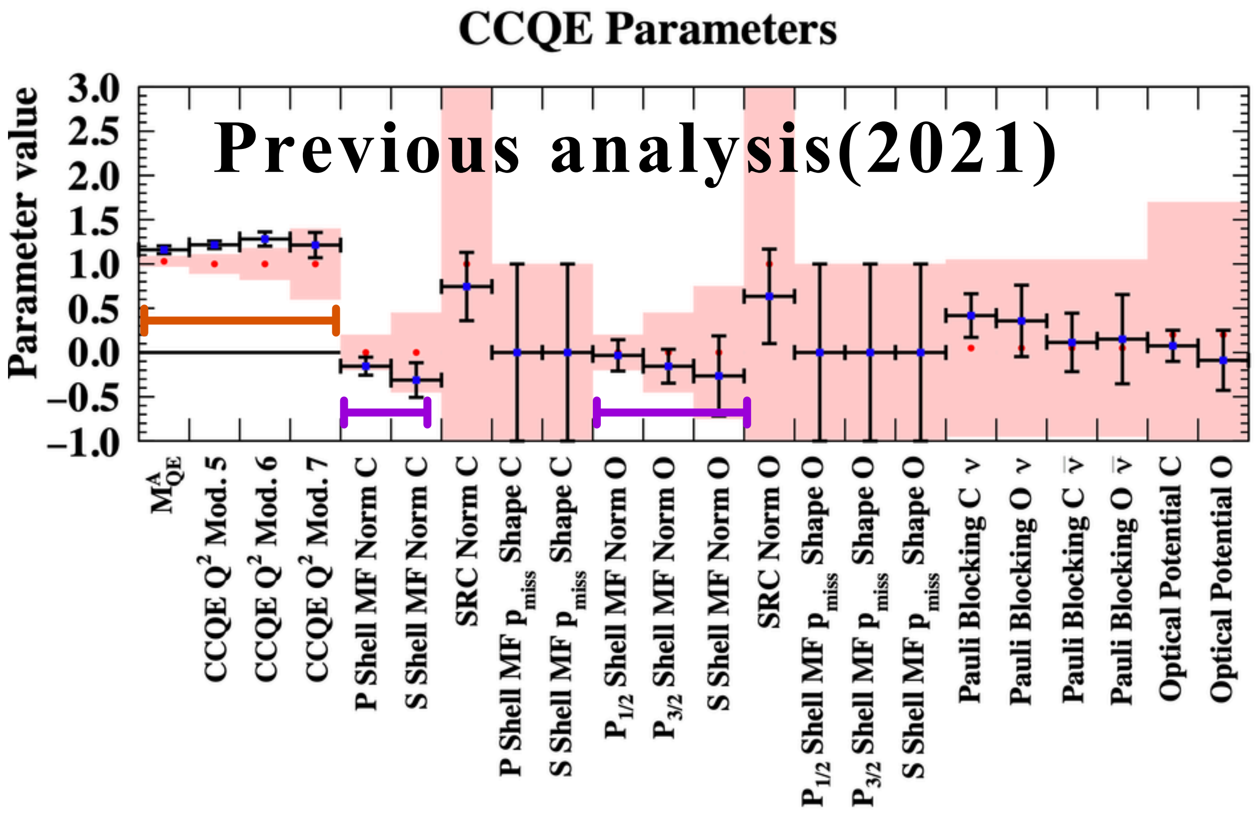
- Indeed, FSI/RPA parameters (new in this analysis) absorbs part of the model





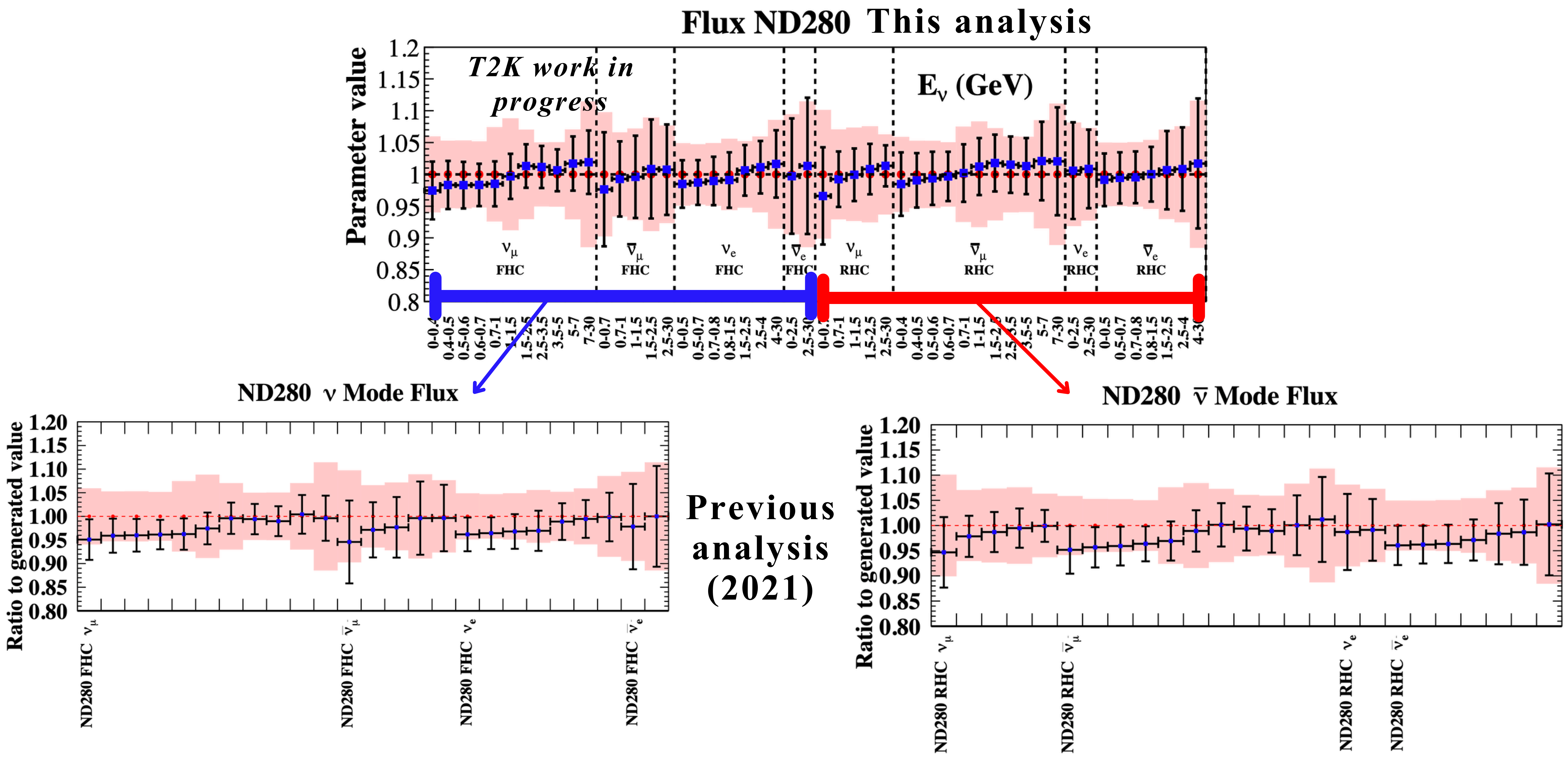
- Thus reducing strong impact on other parameters, like **axial mass, Q2 normalizations**, **Mean Field effects**, …





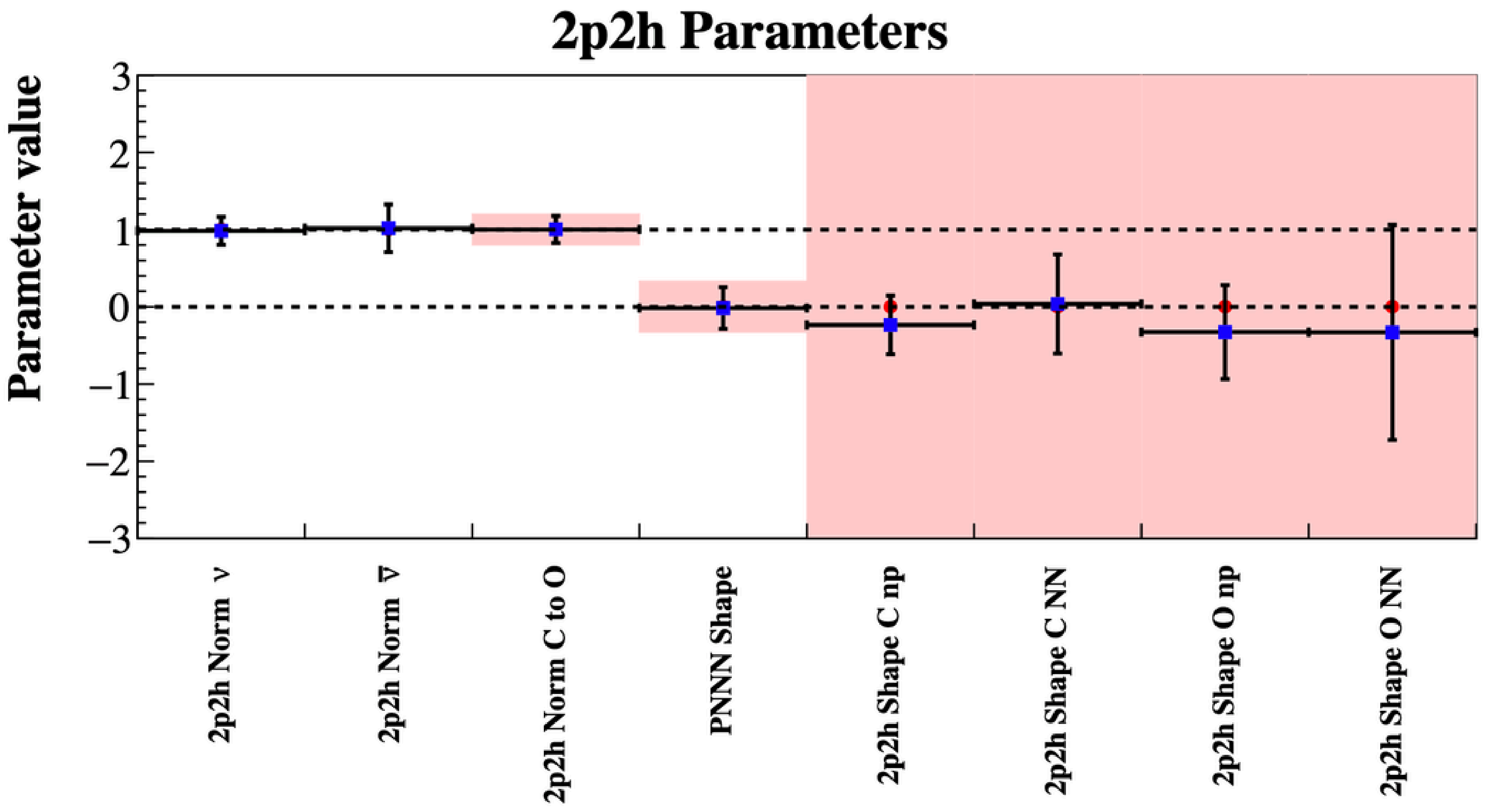
FDS SF to LFG - other remarks

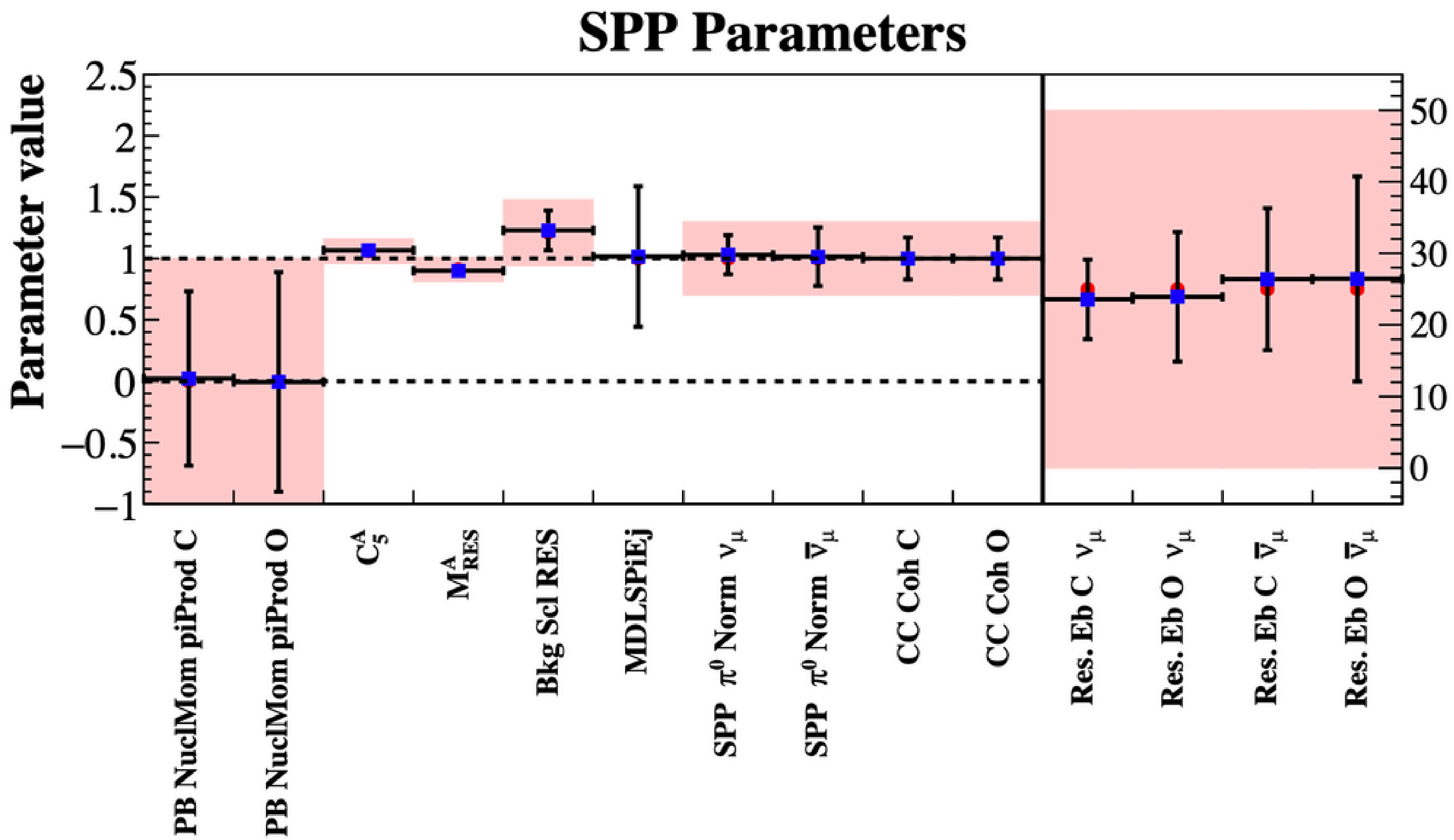
- Flux parameters closer to prior (good news)

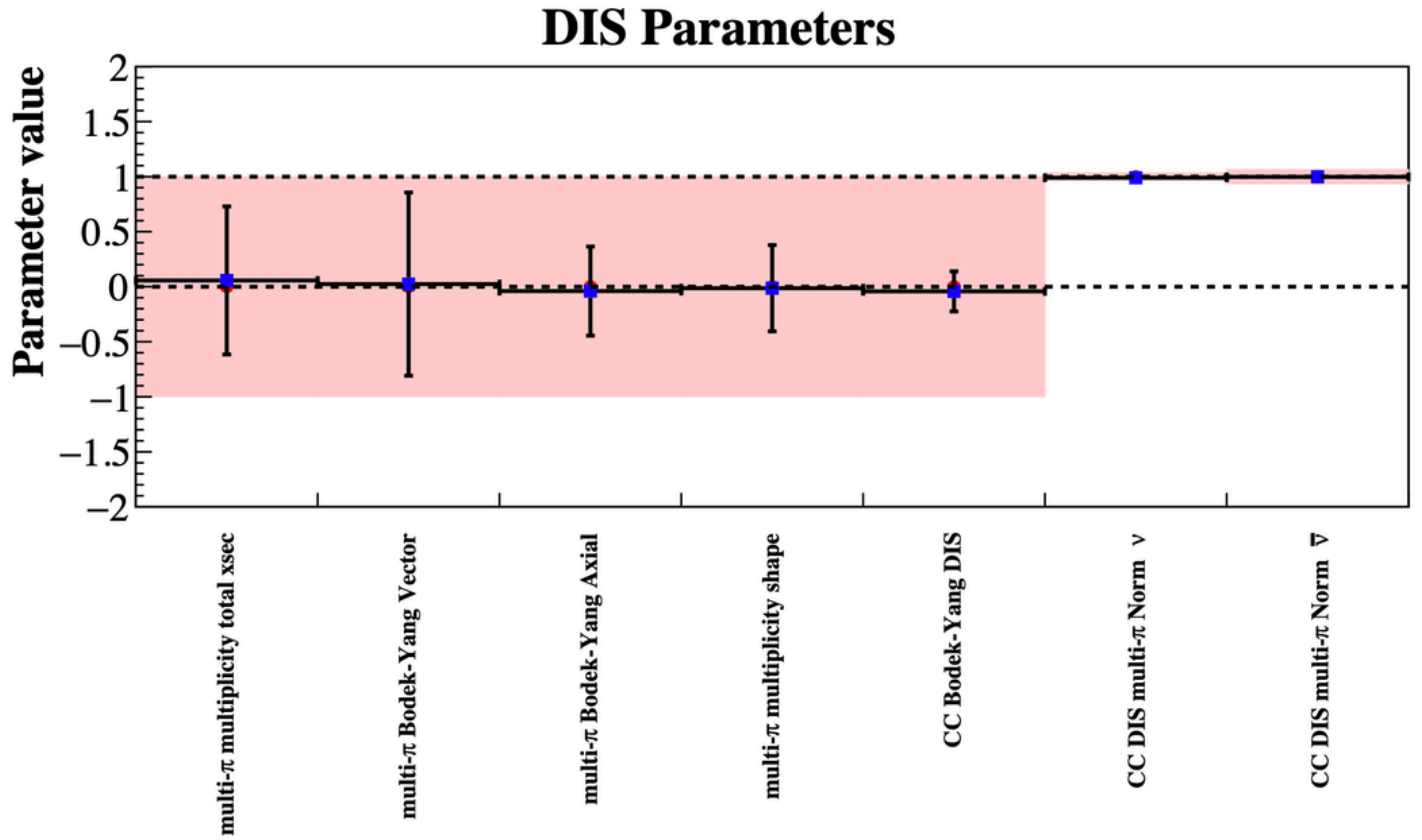


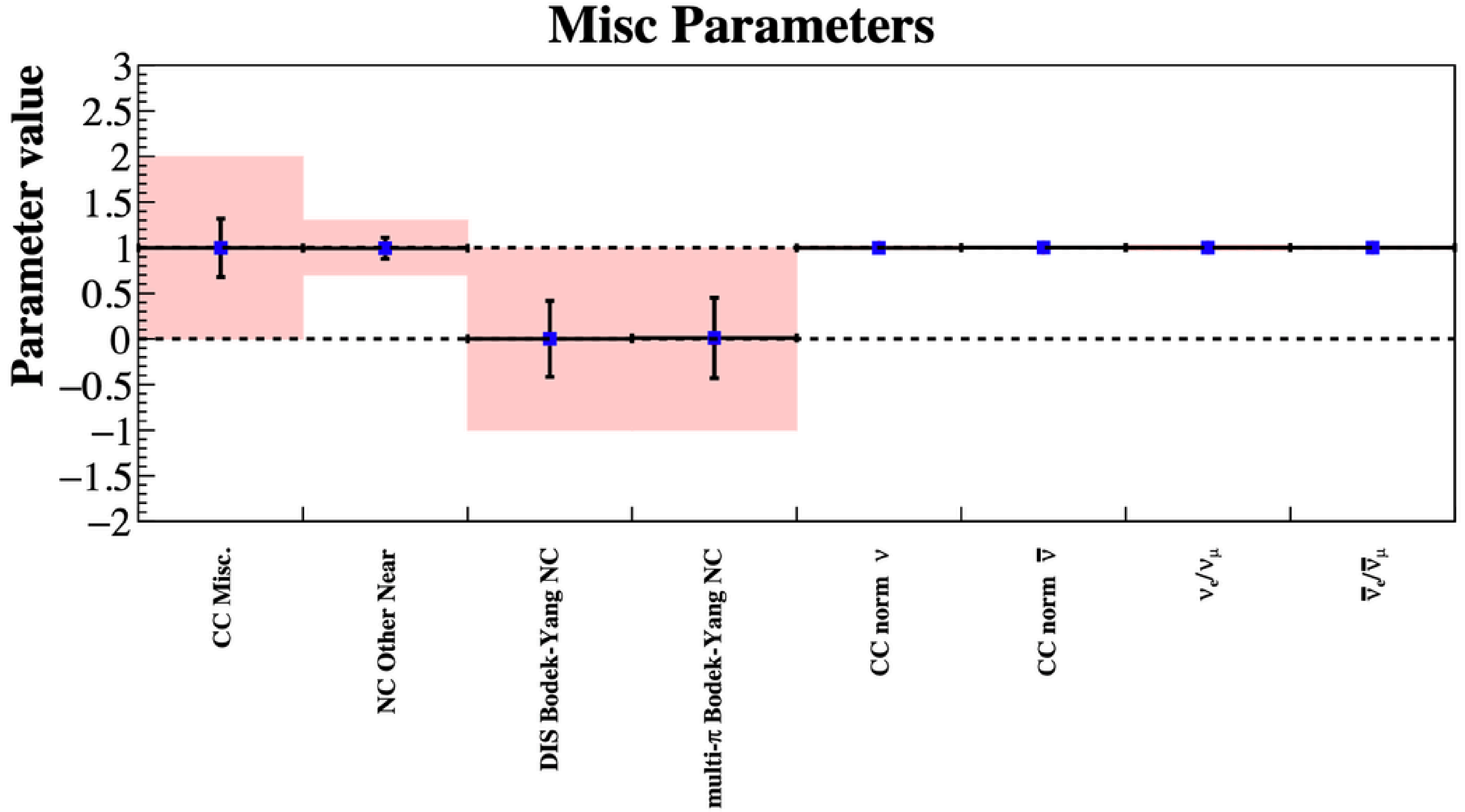
FDS SF to LFG - other systematics

T2K work in progress



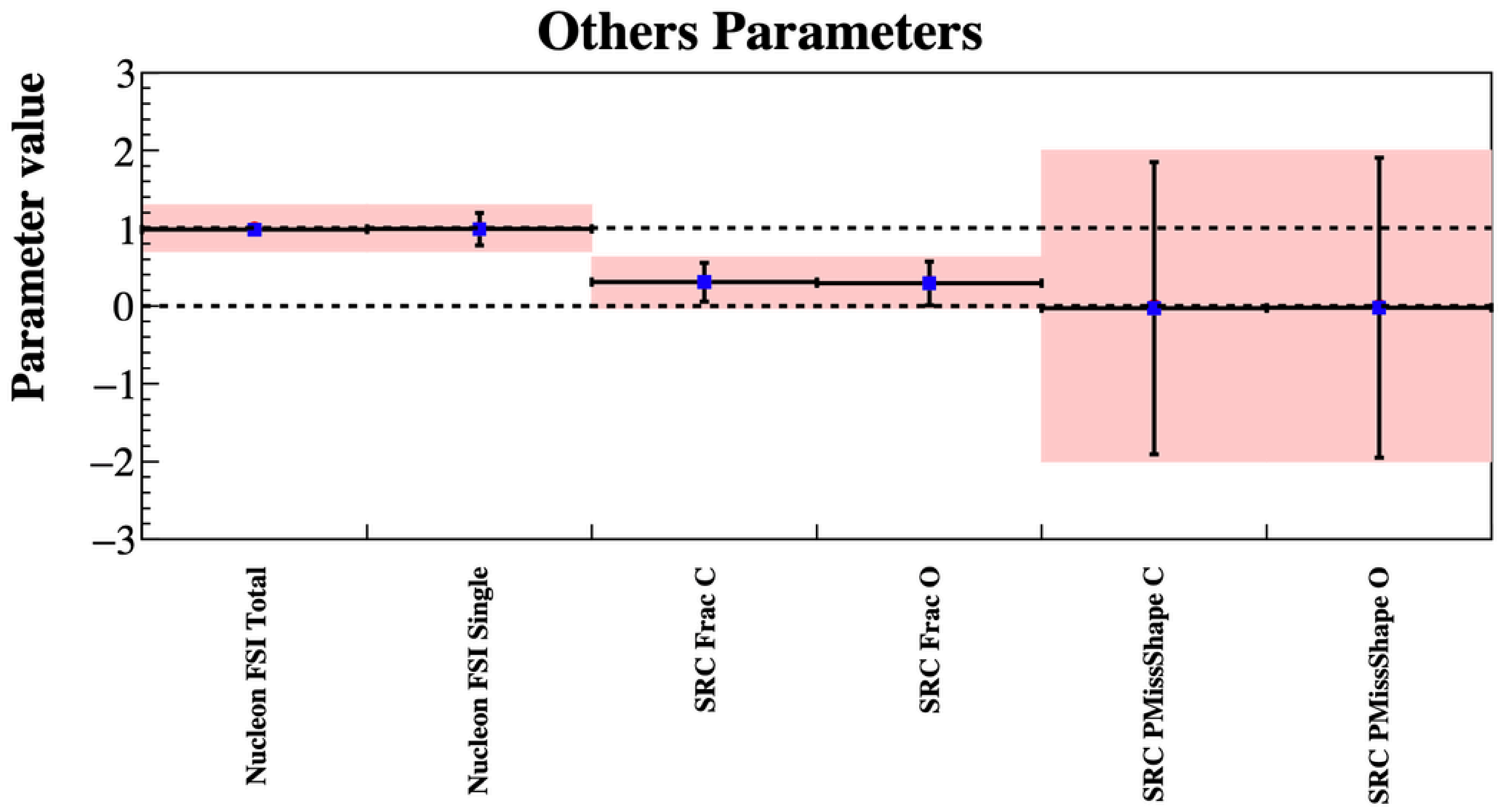


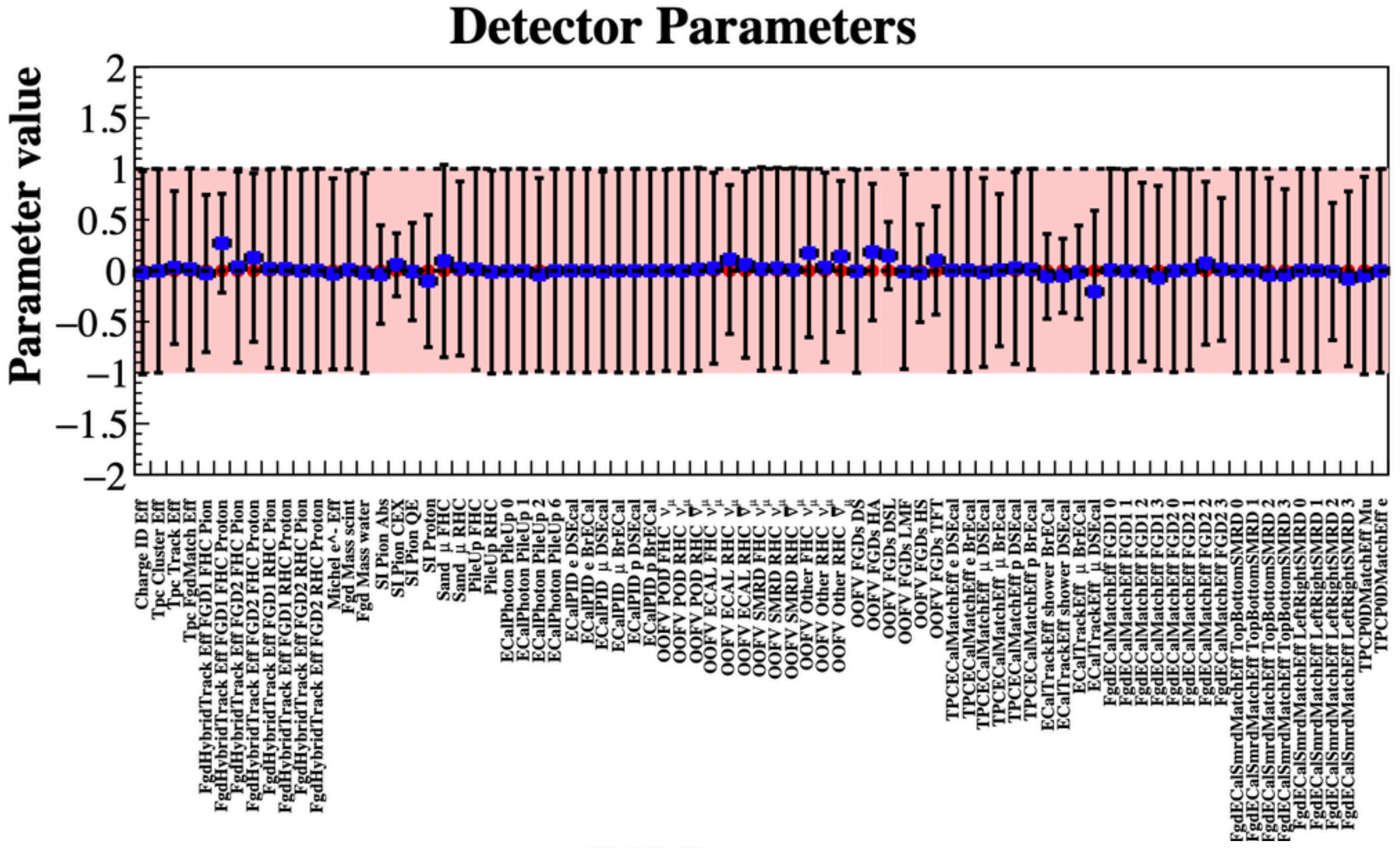


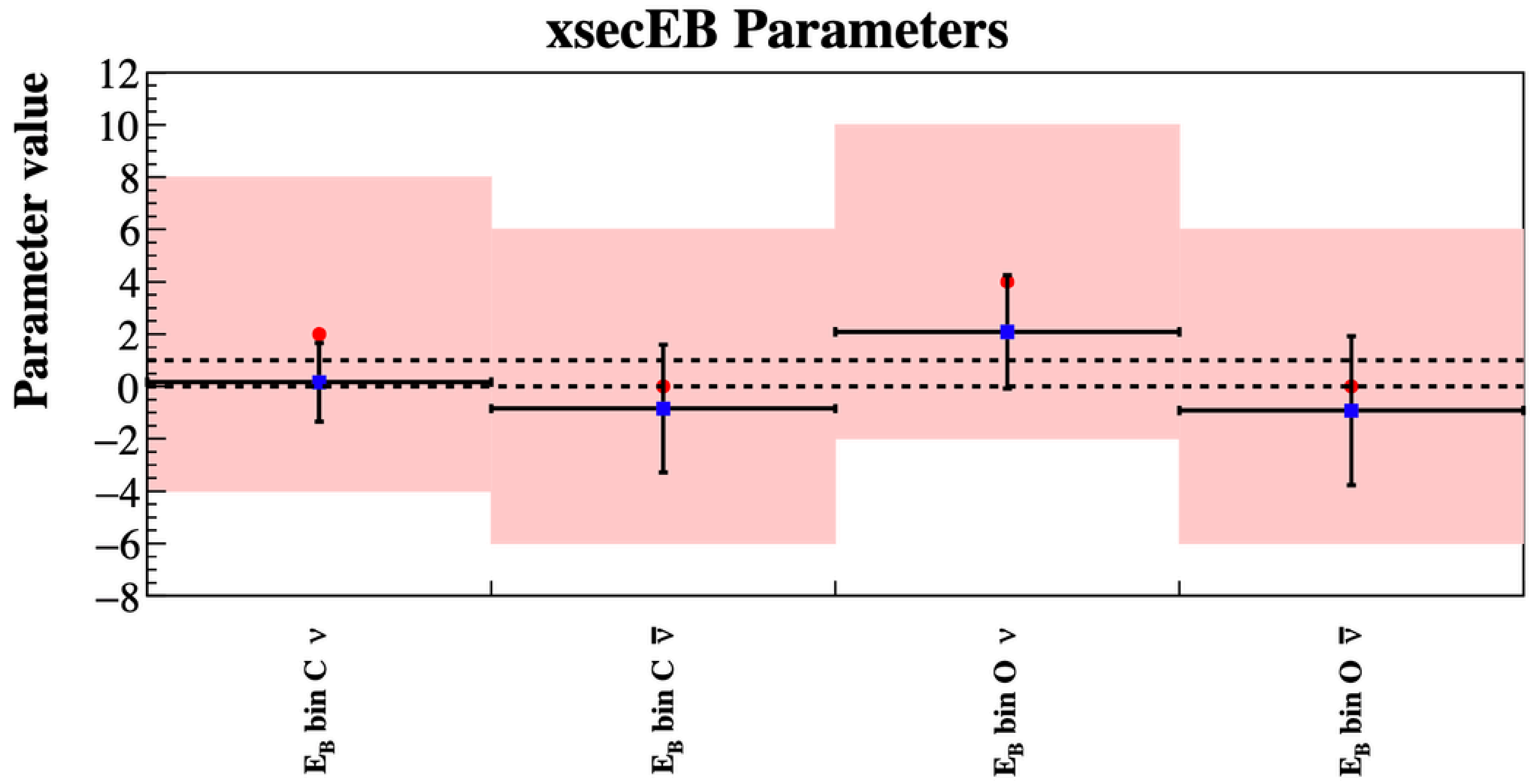


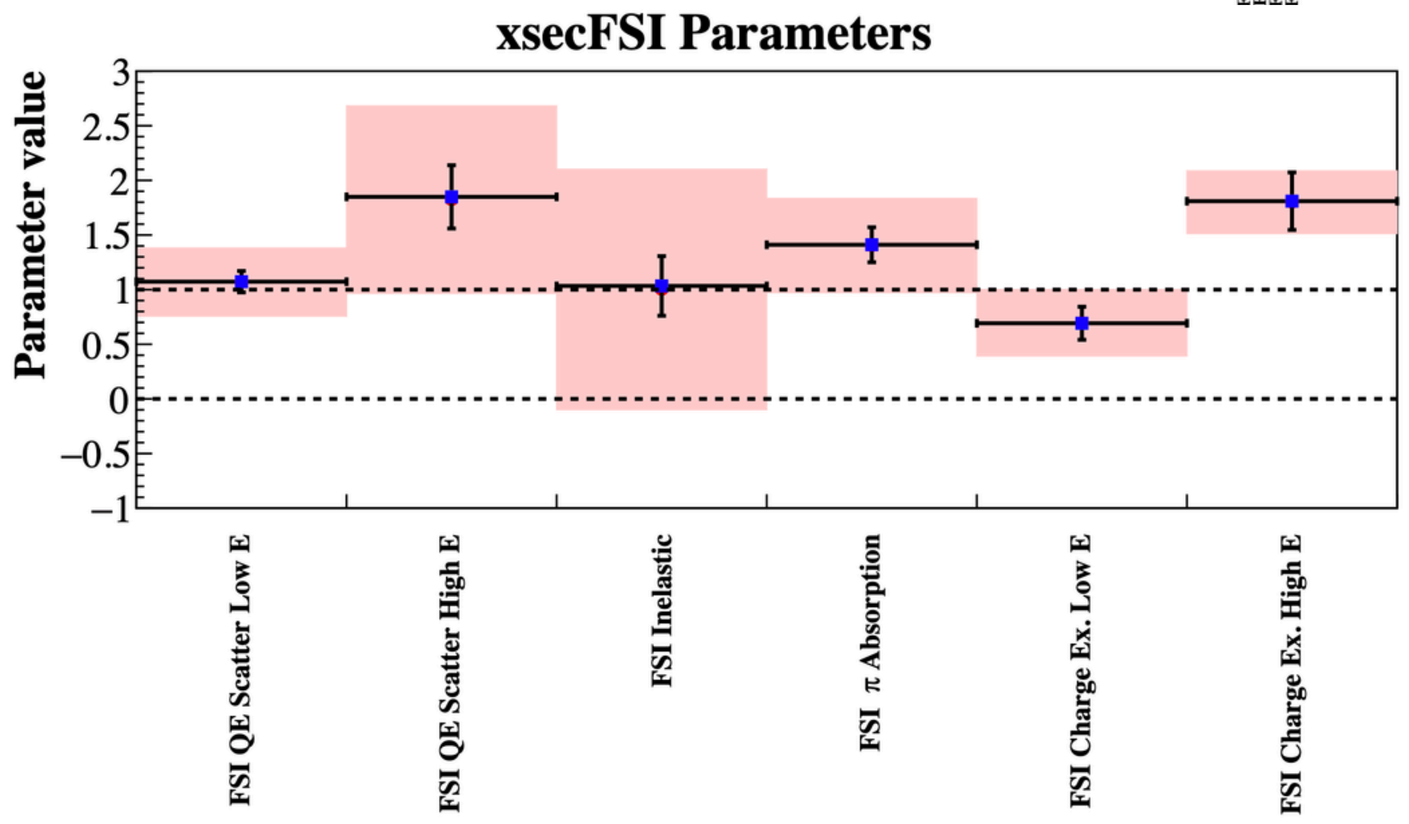
FDS SF to LFG - other systematics

T2K work in progress





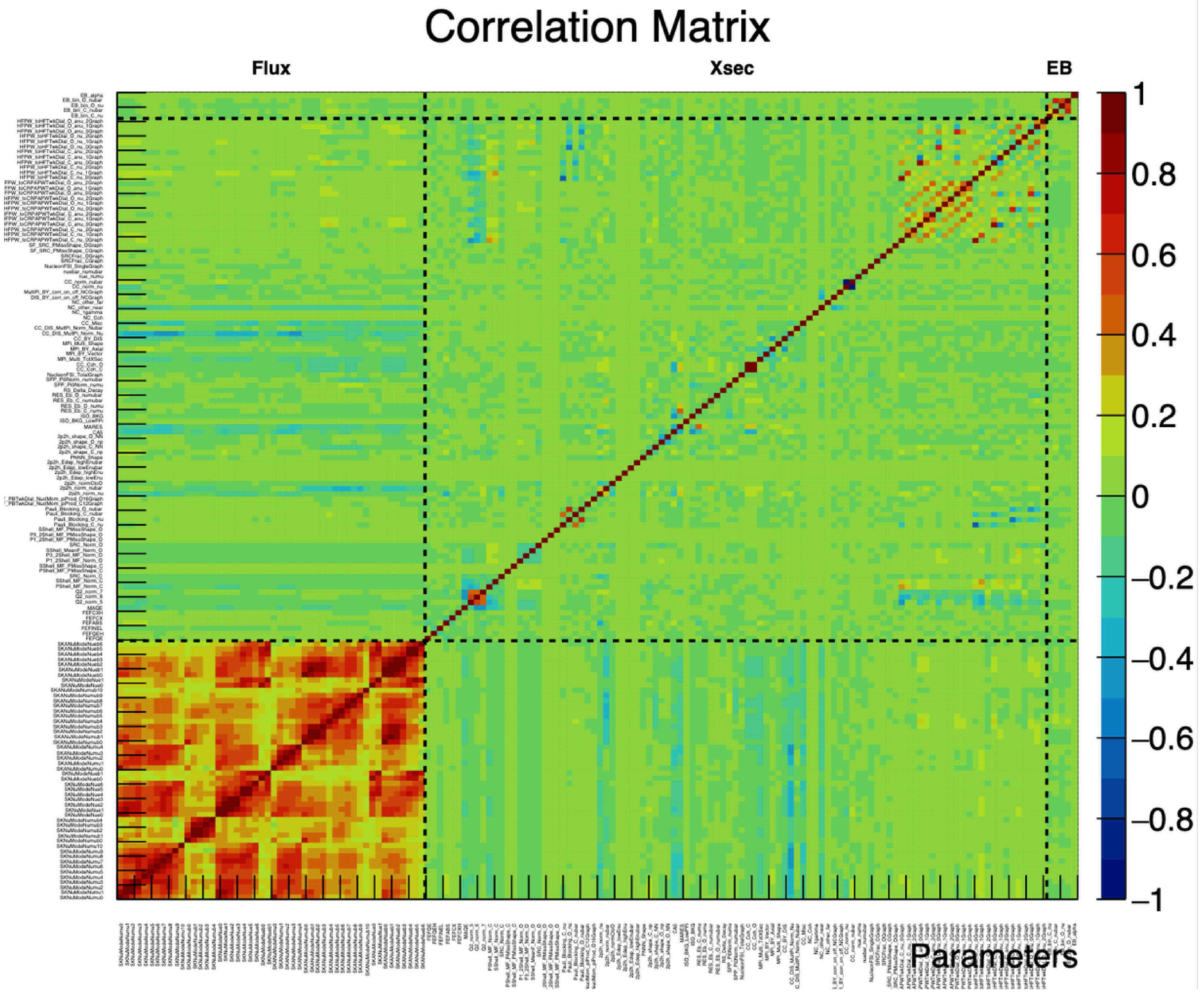




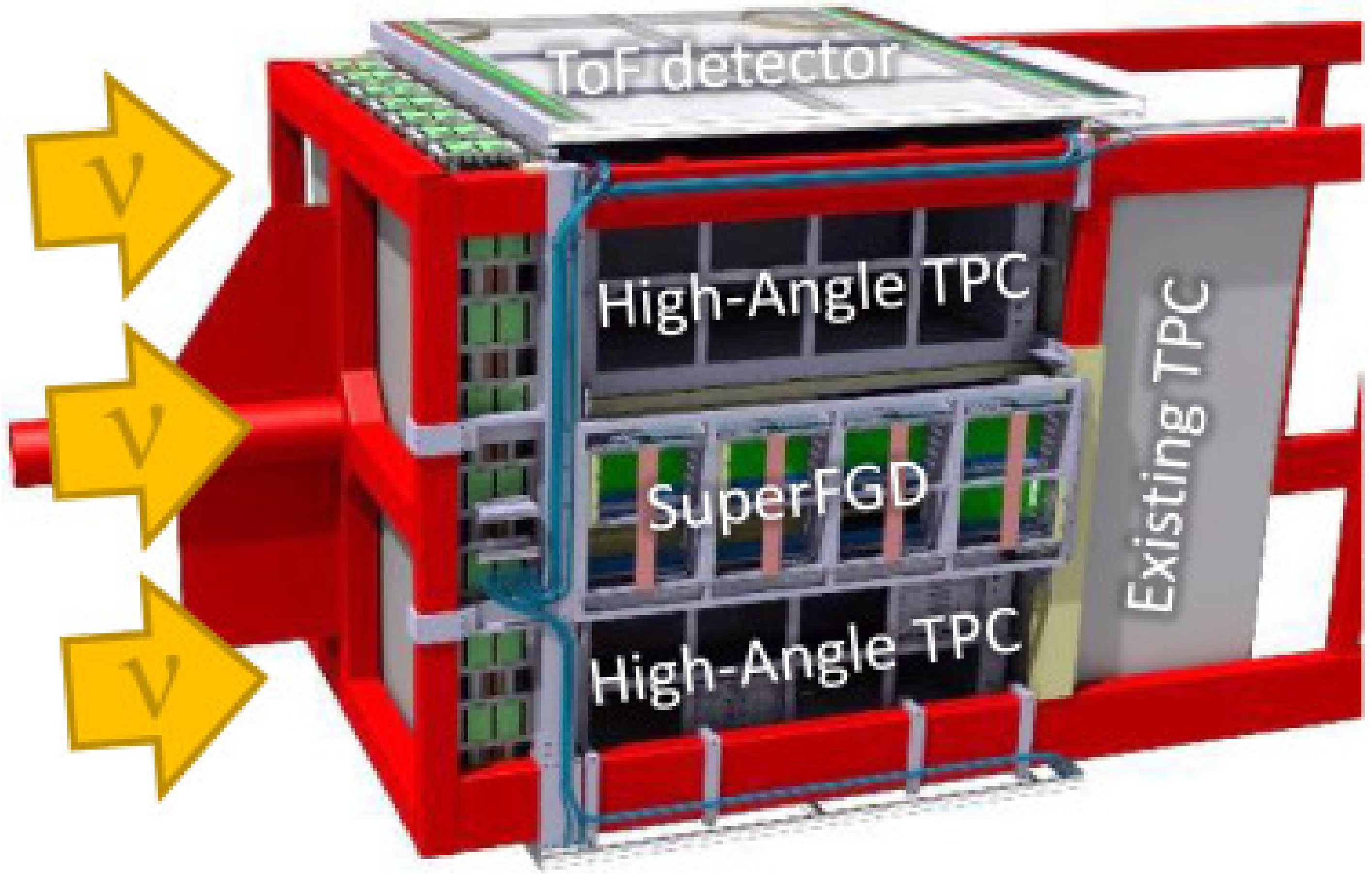
FDS SF to LFG - correlations

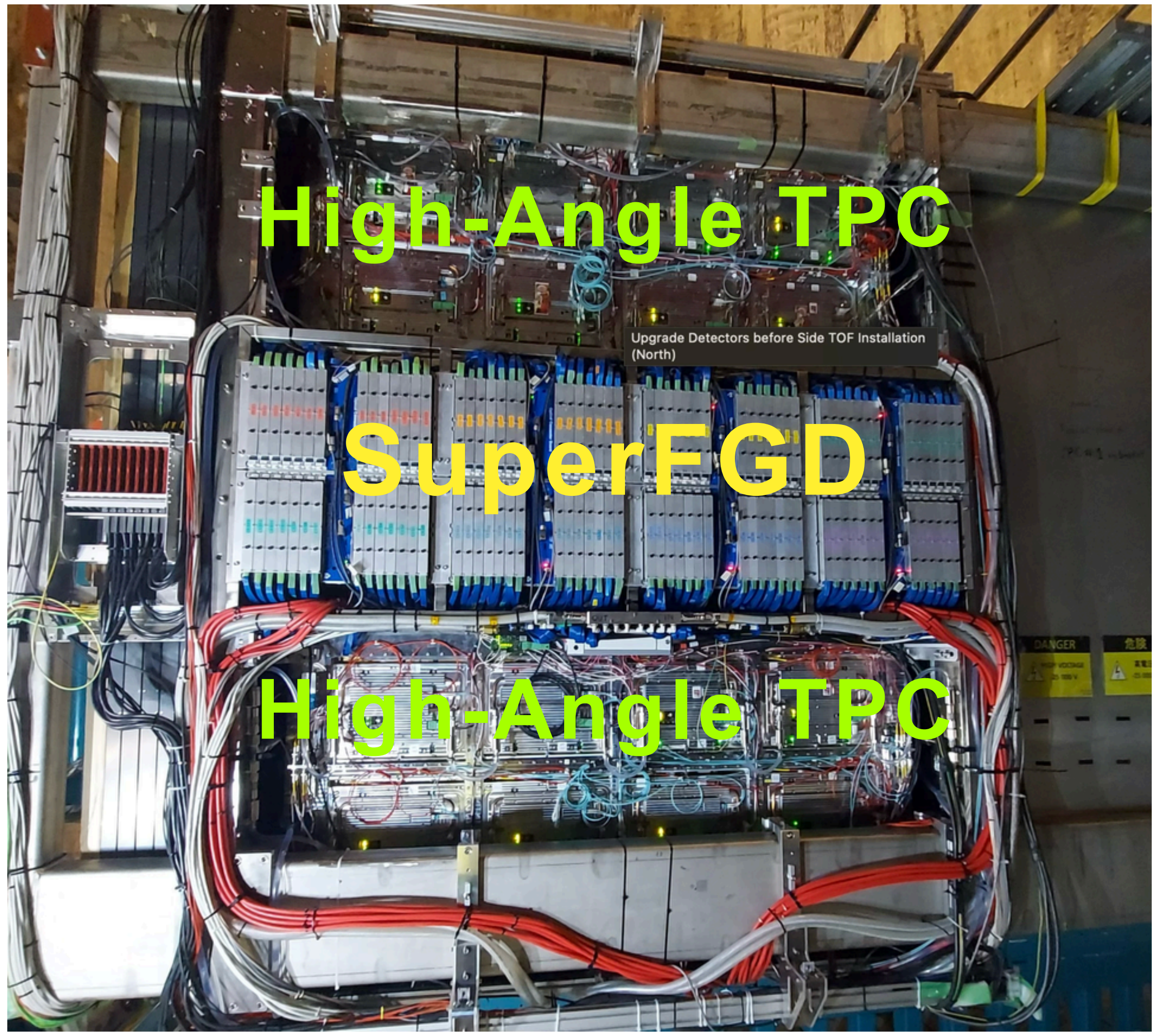
Computed from **Covariance matrix** propagated to Far Detector (= preFit correlations)

T2K work in progress



T2K Near Detector (ND280) Upgrade

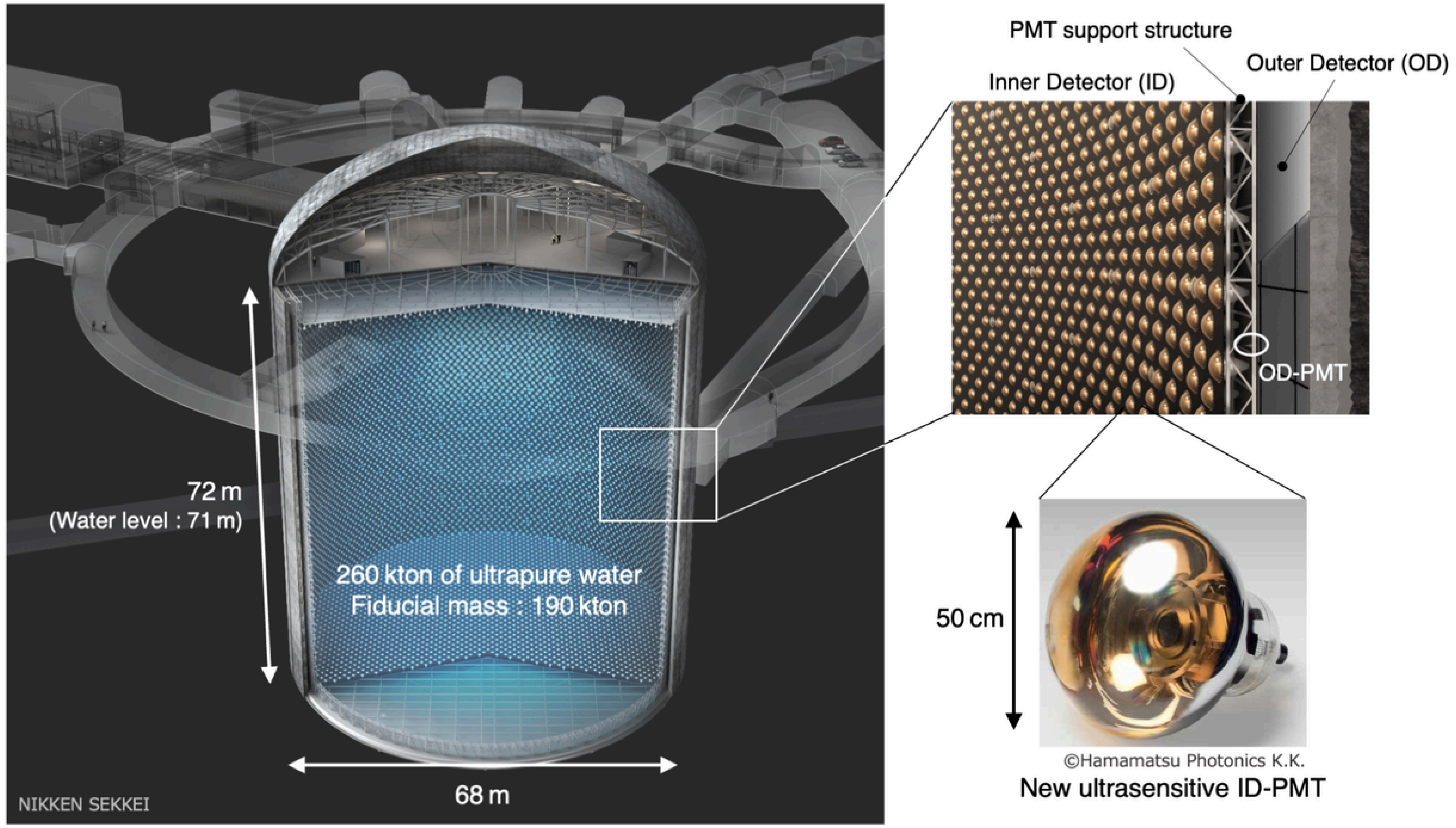


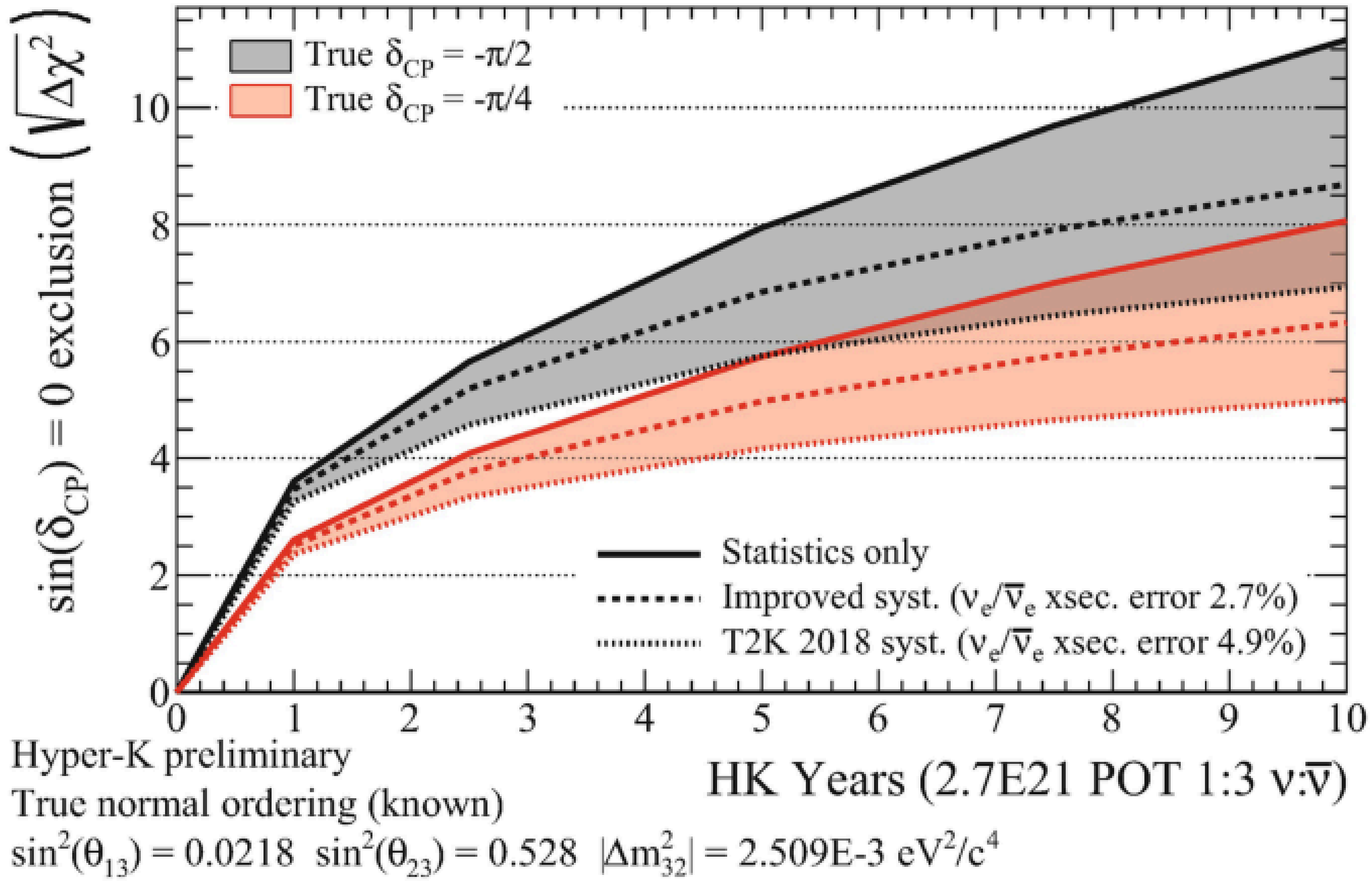


- **Time-of-flight (TOF)**: six scintillator panels around sFGD and HATPCs
- **Super Fine Grained Detector (sFGD)**: active target with 2.2 tons of plastic scintillator cubes
- **2 High-Angle Time Projection Chambers (TPCs)**: field cage with single gas box and Encapsulated Resistive Anode bulk Micromegas (ERAMs) as readout

Hyper-K construction!

New Far Detector!
~x8 bigger than SK
Planned to finish
contruction by 2028
🤞 🤞





Super-K PoT

New results with
PoT=~4.3E21

Previous year studies reported
PoT=~3.7E21

Enhancement of **~15%** data, in particular
- ~19% FHC (neutrino mode)
- ~9% RHC (antineutrino mode)