Updates on the T2K oscillation analysis (OA)

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JENNIFER2
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Outline

- Current results
- Recall on the analysis
- Perspectives in the near and longer term

Oscillation analysis with T2K

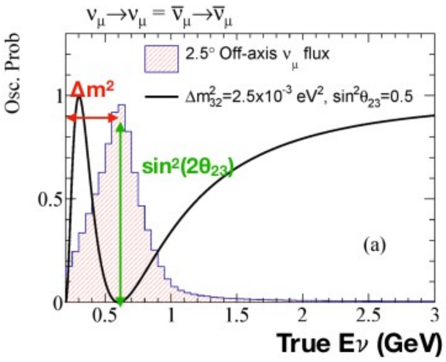
C. Giganti, Neutrino 2024

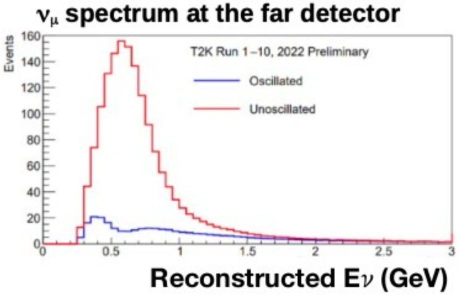
ν_μ and $\bar{\nu}_\mu$ disappearance

$$P(\nu_\mu \to \nu_\mu) = P(\bar{\nu}_\mu \to \bar{\nu}_\mu) = 1 - \sin^2(2\theta_{23})\sin^2\left(1.27\frac{\Delta m^2 L}{E}\right)$$

Same oscillation probability for ν and $\bar{\nu}$

Sensitive to $|\Delta m^2_{32}|$ and to $\sin^2(2\theta_{23})$ → no sensitivity to mass ordering and δ_{CP}





ν_e and $\bar{\nu}_e$ appearance

$$P(\overline{\nu}_\mu \to \overline{\nu}_e) \simeq \sin^2\theta_{23}\frac{\sin^2 2\theta_{13}}{(A-1)^2}\sin^2[(A-1)\Delta_{31}]$$

$$(\mp)\alpha\frac{J_0\sin\delta_{CP}}{A(1-A)}\sin\Delta_{31}\sin(A\Delta_{31})sin[(1-A)\Delta_{31}]$$

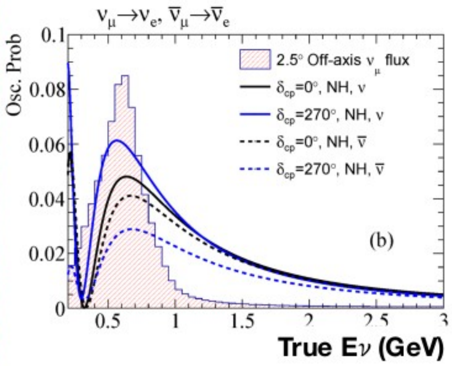
$$+\alpha\frac{J_0\cos\delta_{CP}}{A(1-A)}\cos\Delta_{31}\sin(A\Delta_{31})sin[(1-A)\Delta_{31}] + O(\alpha^2)$$

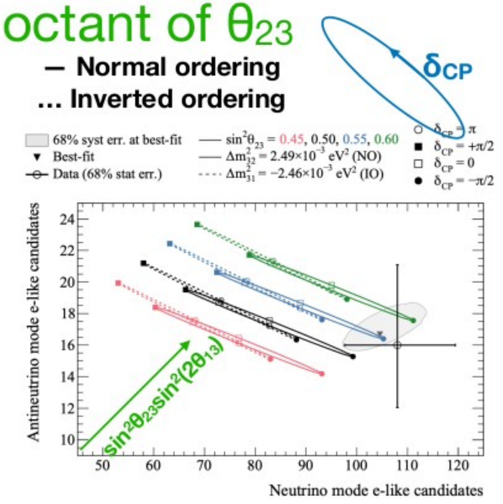
$$\alpha = \Delta m^2_{21}/\Delta m^2_{31} \sim 1/30$$

$$J_0 = \sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}\cos\theta_{13}$$

$$A = (\mp)2\sqrt{2}G_F n_e E/\Delta m^2_{31}$$

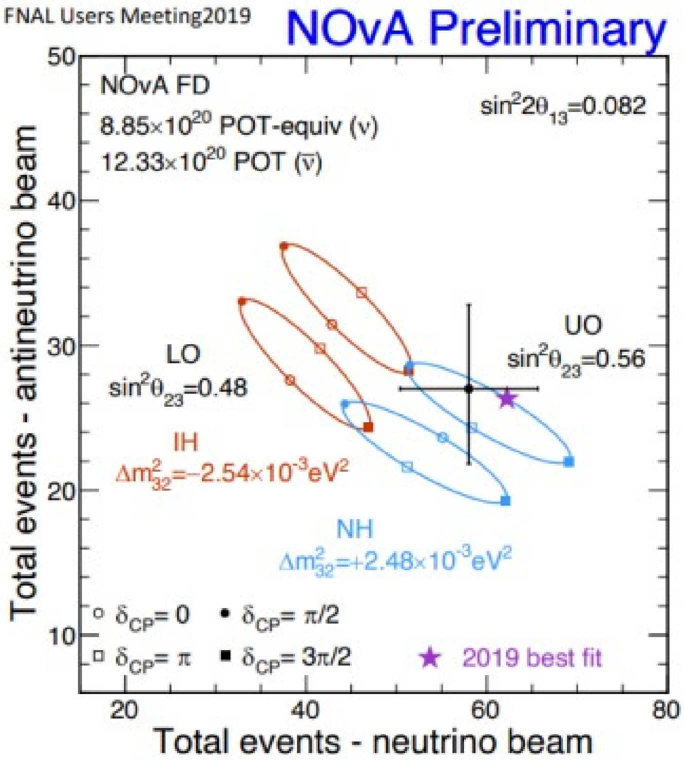
Sensitivity to δ_{CP}, to the mass ordering and to the octant of θ_{23}

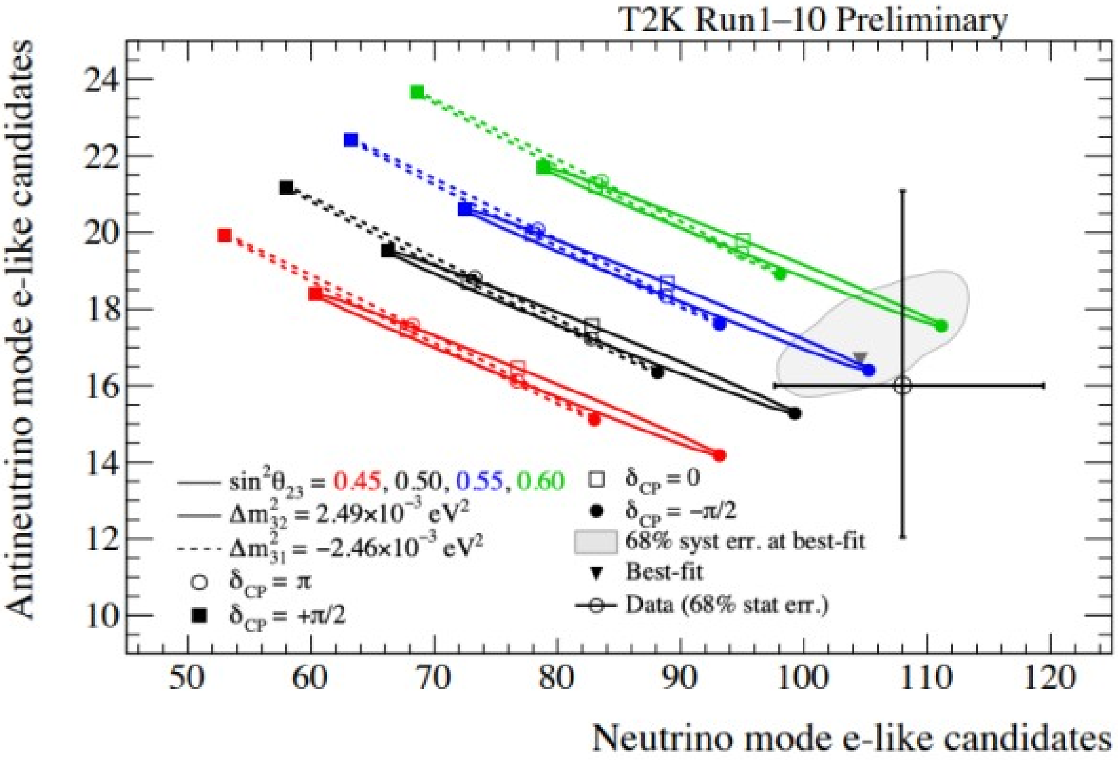




T2K-NOvA bi-probability plots

T2K prefers the same phase irrespectively of the hierarchy while NOvA does not (opposite phases)



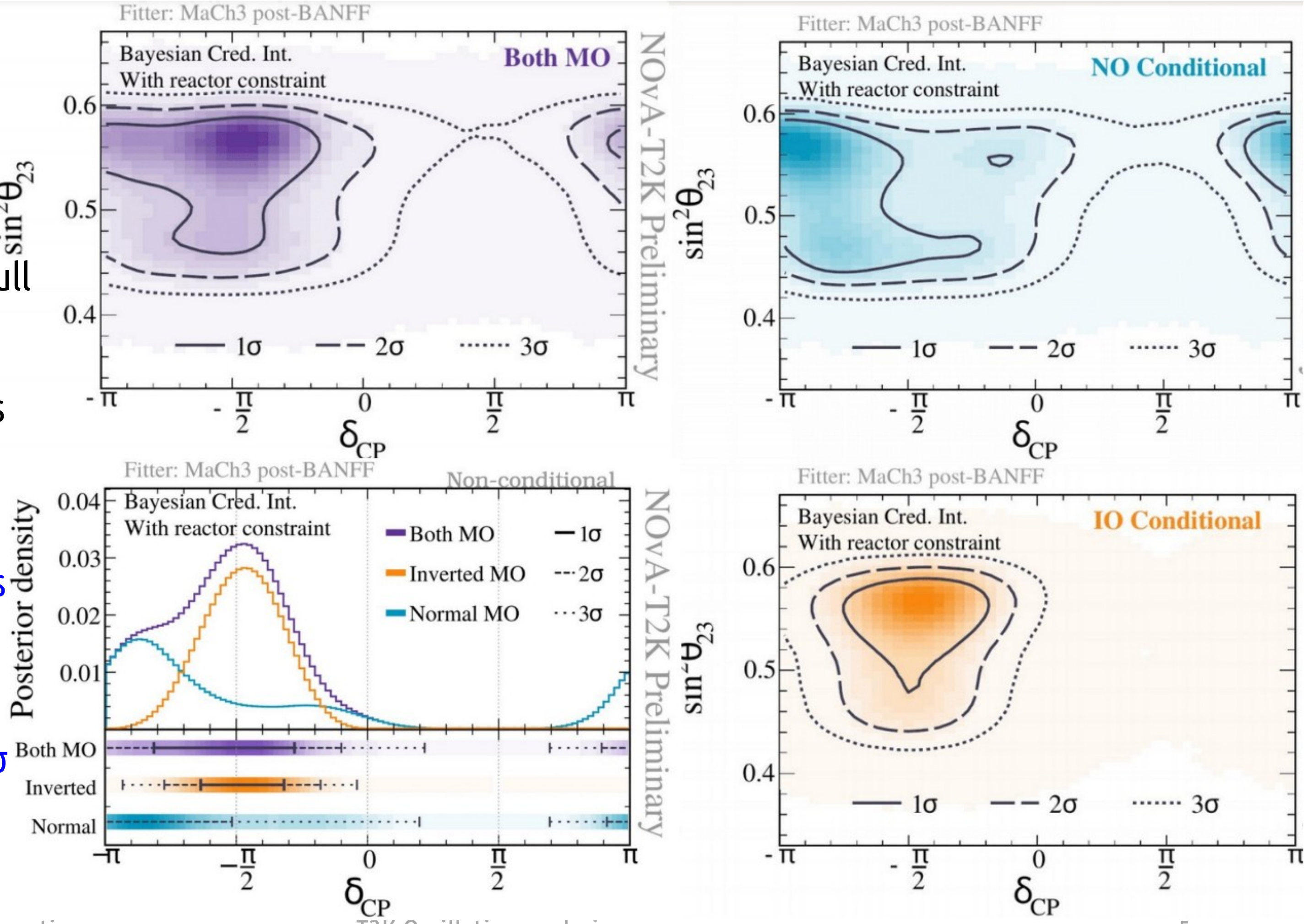


NB: these plots are a bit outdated but they are for illustration purpose here

T2K-NOvA combination

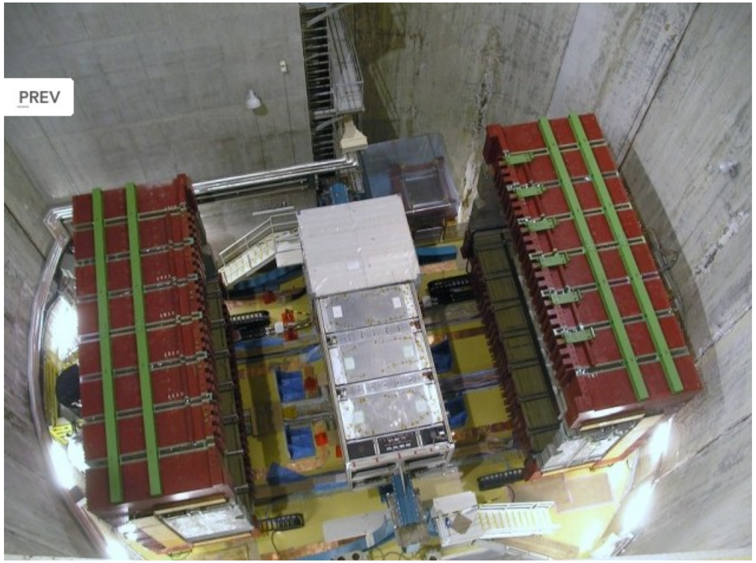
- Different L (295 vs 810 km) and E lift degeneracies
- After several years of work a proper combination of full likelihood with coherent statistical inference across full phase space
- Implementation of detectors effects, models and systematic uncertainticies

- Leading world result on Δm^2_{32}
    - err 1.5% (2% T2K only)
- Best combined fit is for IO but there is no strong MO preference
- $\delta_{CP} \sim +\pi/2$ outside 3σ interval for both MO
- For IO, CP conservation excluded at 3σ
- Wider δ_{CP} range allowed NO



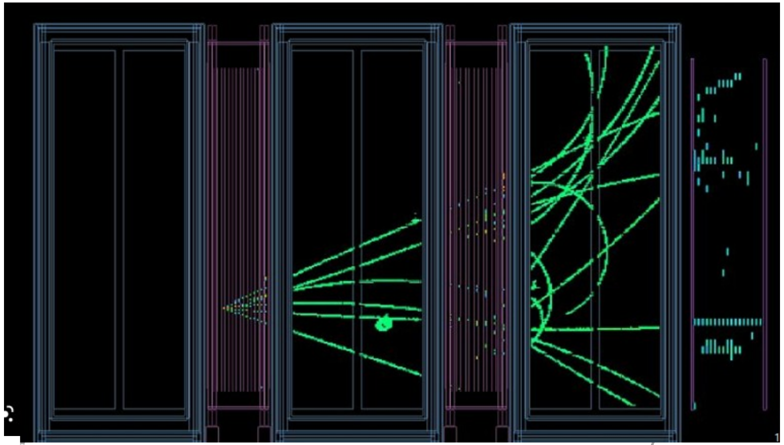
OA with T2K: near detector fit

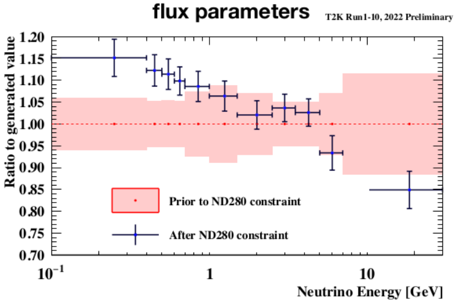
Several unknowns:
- the neutrino **flux** (different between near and far)
- the neutrino **interaction parameters** (that depend on nuclear models, from the target composition)
- There are **several different final states each with a different efficiency** in the detectors.

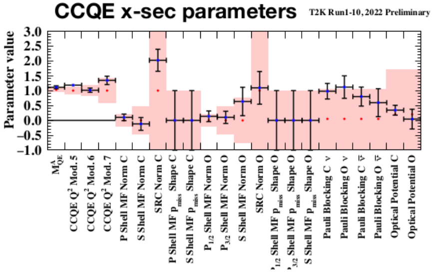


The goal is to **predict as precisely as possible the number of neutrinos that we expect at the far detector** → the difference is due to oscillations (appearance of electron neutrinos, disappearance of muon neutrinos)

→ Use the high stat **near detector** data (at only 280 m) to get a constraint on unknown quantities ("nuisance parameters").

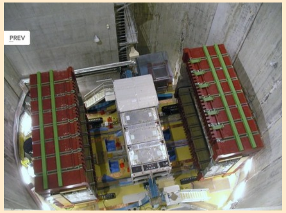


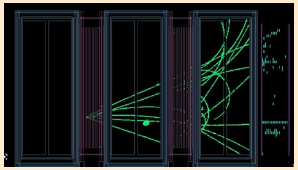




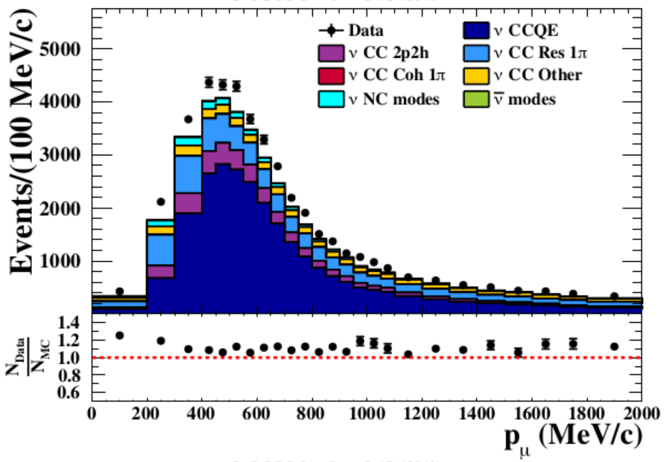
OA with T2K: near detector fit

The "Near detector fit"

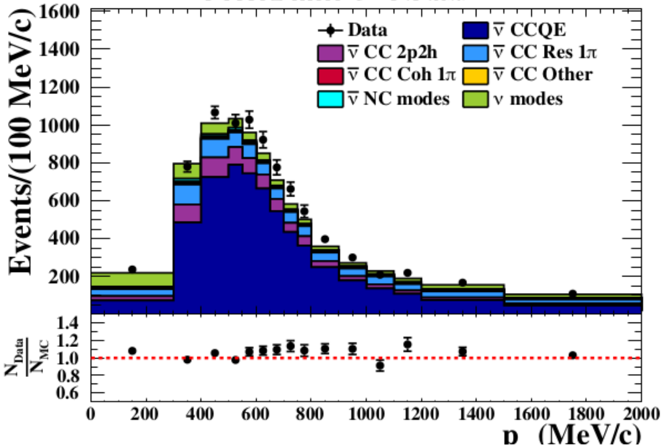


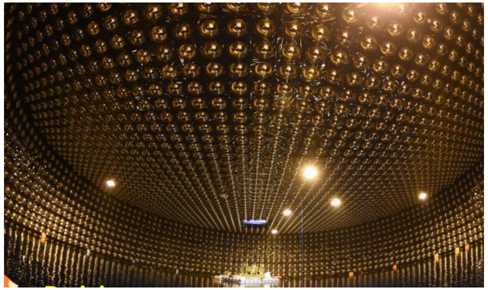


Near detector data BEFORE fit

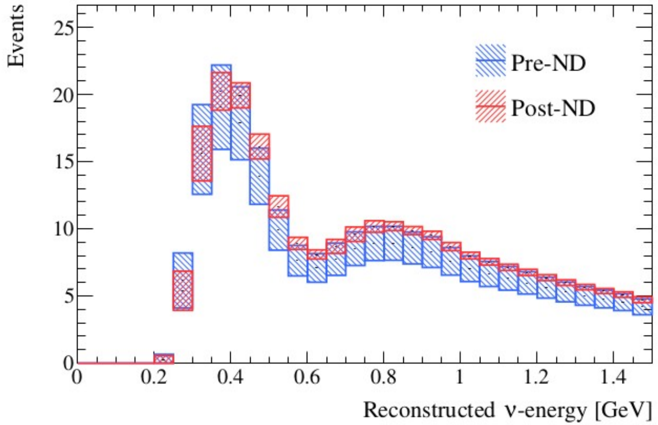


Near detector data AFTER fit



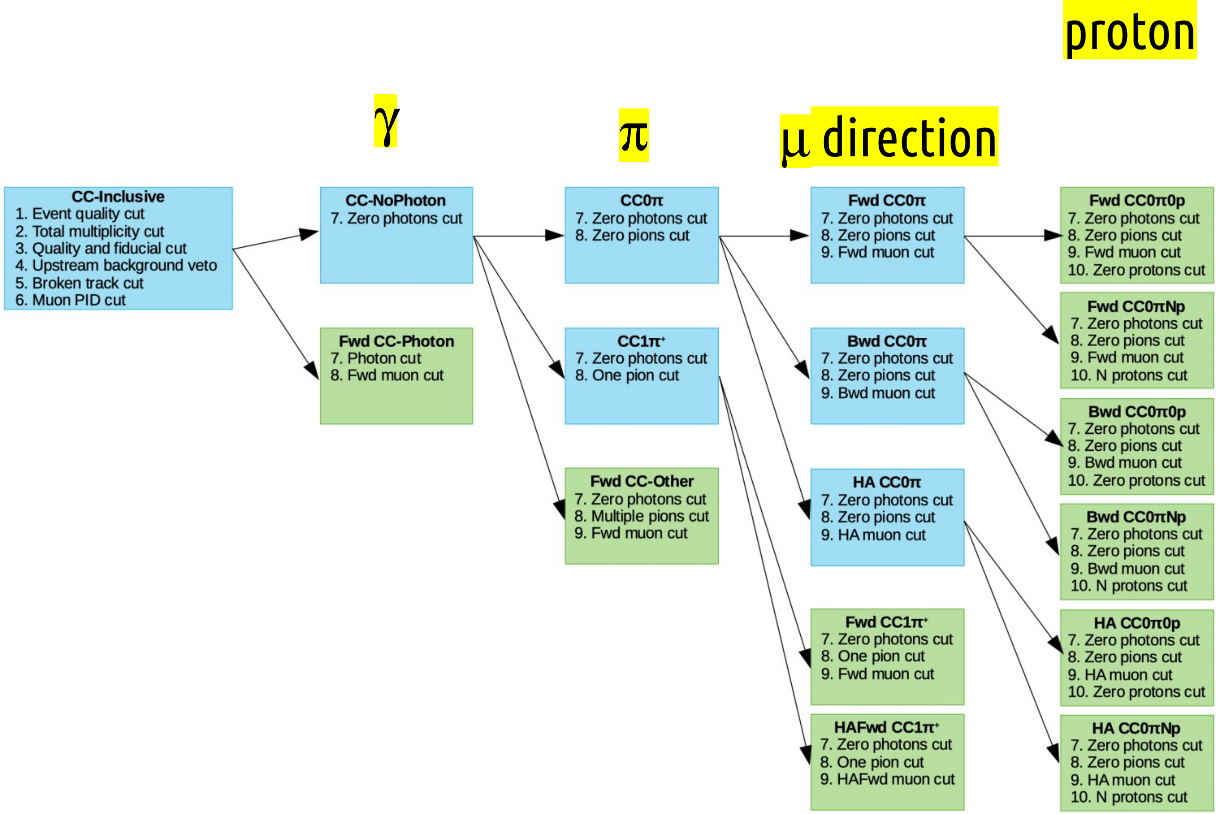


Uncertainty on the prediction at far BEFORE ad AFTER the near detector fit:

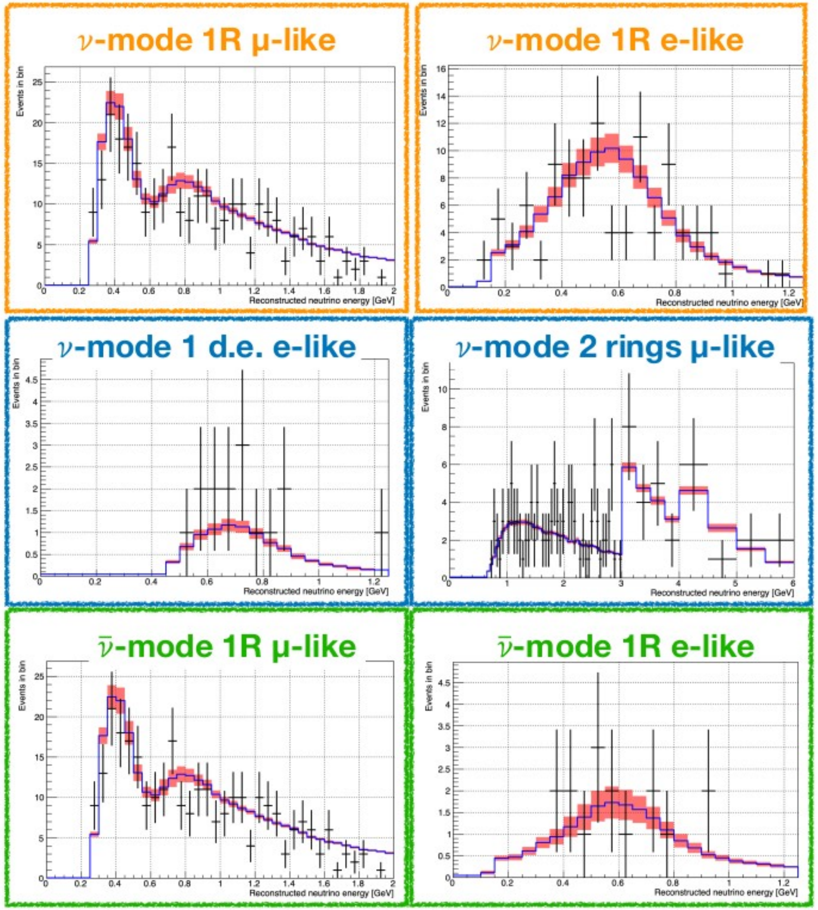


Current ND samples ("OAR11B")

- In reality the fitted samples are the result of a very detailed selection
  - FHC ("neutrino") samples separated based on # of reco γ, p and π
  - RHC ("antineutrino" split depending on # π only
  - Currently this results into 32 subsamples.
  - The event rates of each samples are binned and fitted in the 2D plane: (momentum, angle) of the mu+ (or mu-) candidate
  - No electron data used so far nor pion or proton kinematics



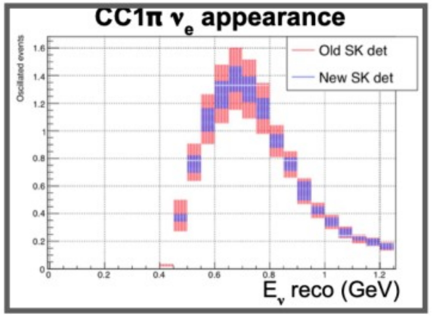
Super-K samples (OAR11A)



- 6 samples are selected at SK
  - 2 samples 1R μ-like/e-like in ν-mode → CCQE enhanced
  - 2 samples CC1π enhanced (2 rings or with an additional decay electrons)
  - 2 samples 1R μ-like/e-like in $\bar{\nu}$-mode → CCQE enhanced
- New detector covariance matrix at SK → significantly reduce systematics in the 1 Re+d.e. sample

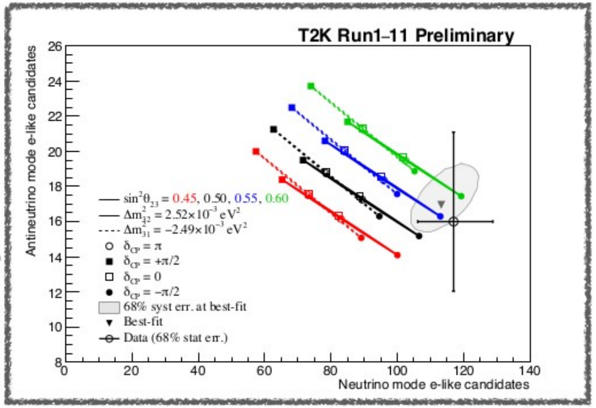
Sample	OA22	New results
ν-mode 1Rμ	3.4%	3.2%
ν-mode 1Re	5.2%	4.9%
ν-mode MR	4.9%	3.9%
ν-mode 1Re+d.e.	14.3%	6.3%
$\bar{\nu}$-mode 1Rμ	3.9%	5.0%
$\bar{\nu}$-mode 1Re	5.8%	6.7%

17

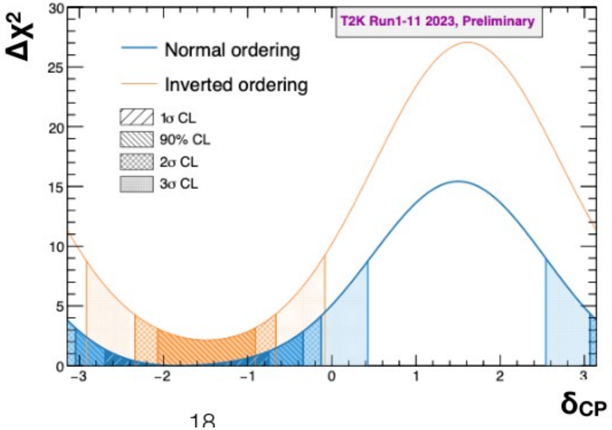


Results OAR11A (Neutrino 2024)

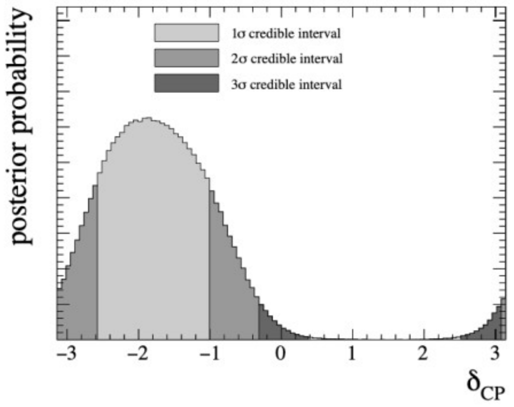
Sample	δ_{CP}=-π/2	δ_{CP}=0	δ_{CP}=π/2	δ_{CP}=π	Data
ν-mode 1Rμ	417.2	416.3	417.1	418.2	357
ν-mode MR	123.9	123.3	123.9	124.4	140
$\bar{\nu}$-mode 1Rμ	146.6	146.3	146.6	147.0	137
ν-mode 1Re	113.2	95.5	78.3	96.0	102
$\bar{\nu}$-mode 1Re+d.e.	10.0	8.8	7.2	8.4	15
$\bar{\nu}$-mode 1Re	17.6	20.0	22.2	19.7	16



- Preference for δ_{CP}~-π/2 but CP conserving values are within the 2σ interval



Credible intervals marginalized over both hierarchies



D. Carabadjac poster

Bayesian fitter (MaCh3)

Bayesian (MaCh3) → posterior probabilities on physical quantities.

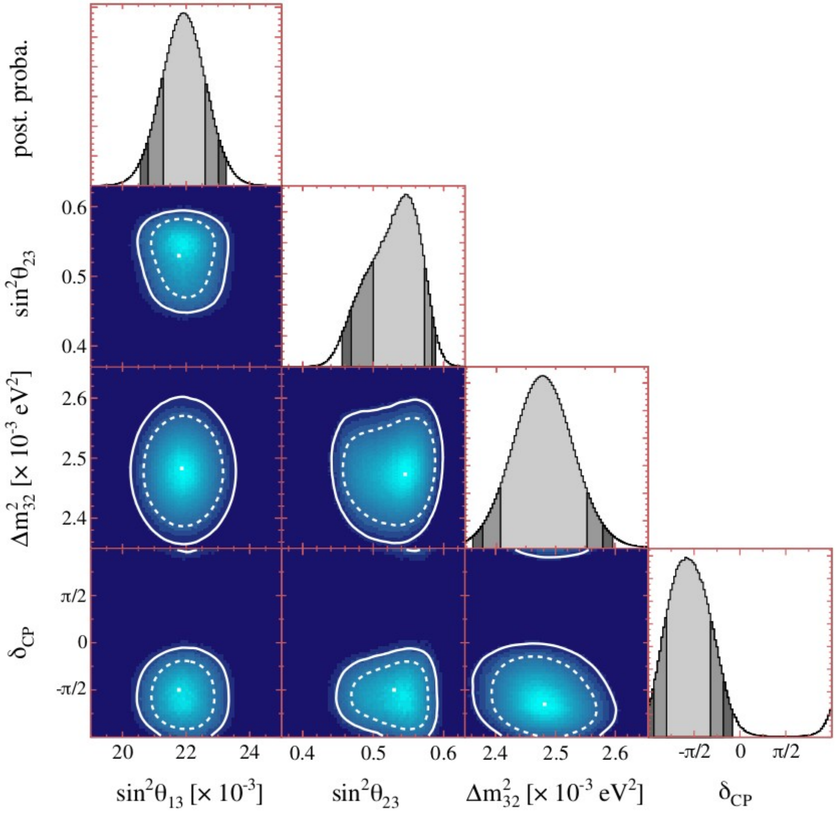
Can fit the near detector and far detector data simultaneously

Metropolis-Hastings Markov-chain Monte Carlo.

Nuisance parameters are marginalized

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}\left\{U_{\beta i}U^*_{\alpha i}U^*_{\beta j}U_{\alpha j}\right\}\sin^2\left(\frac{\Delta m^2_{ij}L}{4E}\right) + 2\sum_{i>j}\mathrm{Im}\left\{U_{\beta i}U^*_{\alpha i}U^*_{\beta j}U_{\alpha j}\right\}\sin\left(\frac{\Delta m^2_{ij}L}{2E}\right)$$

$$\begin{aligned}
-\ln(L) = & \sum_i^{ND280bins} N_i^p(\vec{b},\vec{x},\vec{f},\vec{d}) - N_i^d + N_i^d ln[N_i^d/N_i^p(\vec{b},\vec{x},\vec{f},\vec{d})] \\
& + \sum_i^{SK1R_\mu bins} N_i^p(\vec{b},\vec{x},\vec{skd}) - N_i^d + N_i^d ln[N_i^d/N_i^p(\vec{b},\vec{x},\vec{skd})] \\
& + \sum_i^{SK1R_e bins} N_i^p(\vec{b},\vec{x},\vec{skd}) - N_i^d + N_i^d ln[N_i^d/N_i^p(\vec{b},\vec{x},\vec{skd})] \\
& + \frac{1}{2}\sum_i^{E_\nu bins}\sum_j^{E_\nu bins} \Delta b_i (V_b^{-1})_{i,j}\Delta b_j \\
& + \frac{1}{2}\sum_i^{xsecpars}\sum_j^{xsecpars} \Delta x_i (V_x^{-1})_{i,j}\Delta x_j \\
& + \frac{1}{2}\sum_i^{fsipars}\sum_j^{fsipars} \Delta f_i (V_f^{-1})_{i,j}\Delta f_j \\
& + \frac{1}{2}\sum_i^{nd280det}\sum_j^{nd280det} \Delta d_i (V_d^{-1})_{i,j}\Delta d_j \\
& + \frac{1}{2}\sum_i^{skdet}\sum_j^{skdet} \Delta skd_i (V_{skd}^{-1})_{i,j}\Delta skd_j
\end{aligned}$$

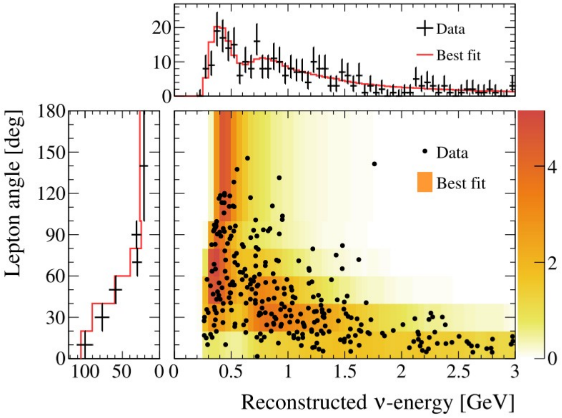


Gradient descent fitters (GUNDAM, Ptheta)

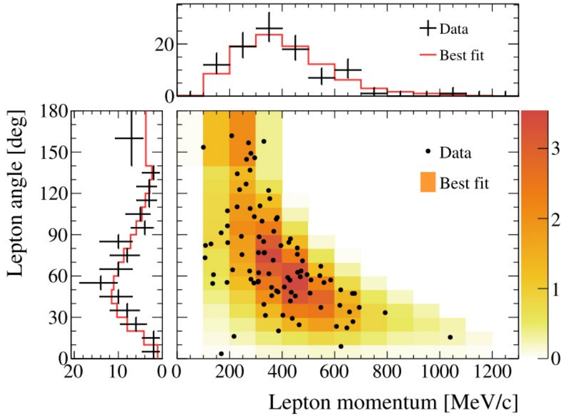
We also have **“MINUIT” based minimizers** (gradient descent) that fit the ND data (**GUNDAM**, formerly BANFF) or the FD data (**PTheta**).

Nuisance parameters are profiled.

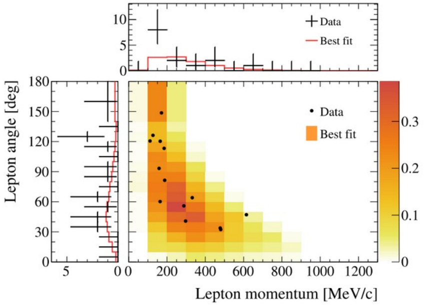
PTheta fits the angular and momentum distributions of leptons and in some cases the reconstructed energy assuming the Quasi-elastic kinematics



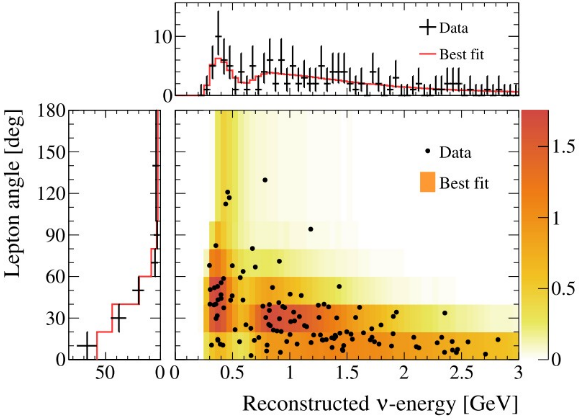
(a) ν-mode 1Rμ



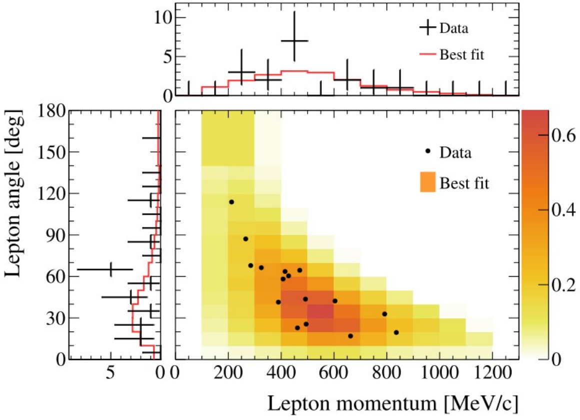
(b) ν-mode 1Re



(c) ν-mode 1Re1de



(d) $\overline{\nu}$-mode 1Rμ



(e) $\overline{\nu}$-mode 1Re

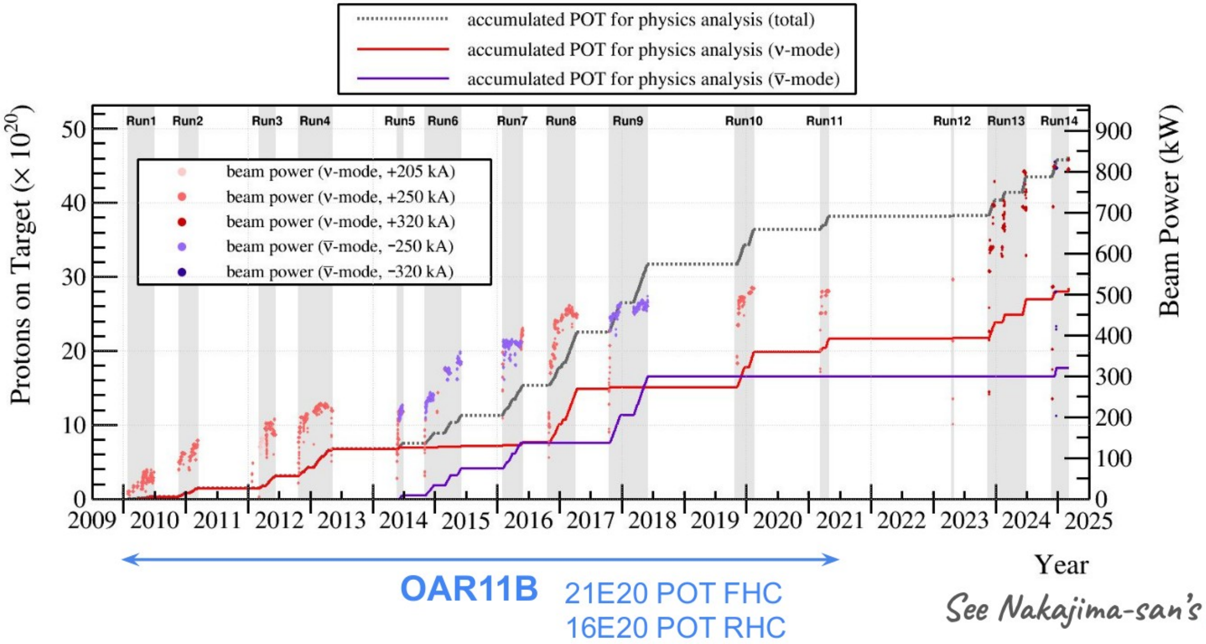
OAR11B

The current analysis is called OAR11B.

It is expected to converge about half 2025

no new POT at SK for this release but new sample will be introduced

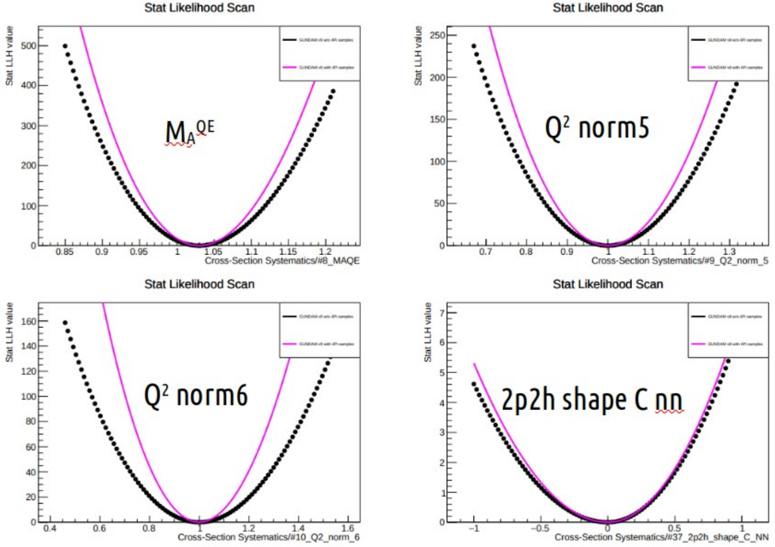
+ several improvements →

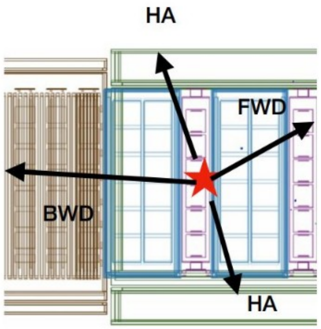


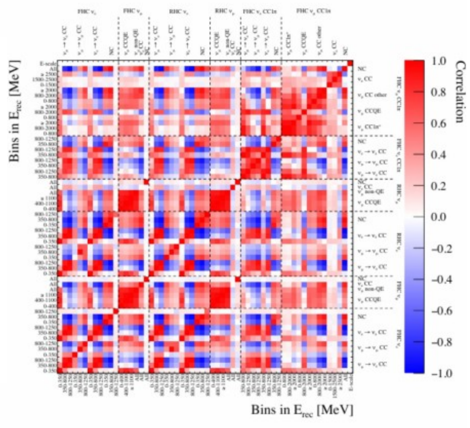
See Nakajima-san's talk

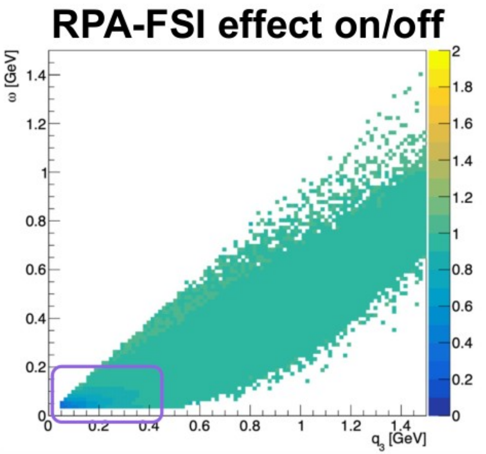
Improvements of OAR11B

- Better ND constrain thanks to new high angle samples and new reconstruction
- Also introduced a new parametrization with more freedom for uncertainties at low Q^2 (forward region)
- Technical improvements in the ND fit (event by event splines for detector systematics)
- Improved SK detector errors
- Addition of a Multi-ring e-like sample at SK: expect 6 additional electron neutrino candidates (CC1π mode)









OAR14

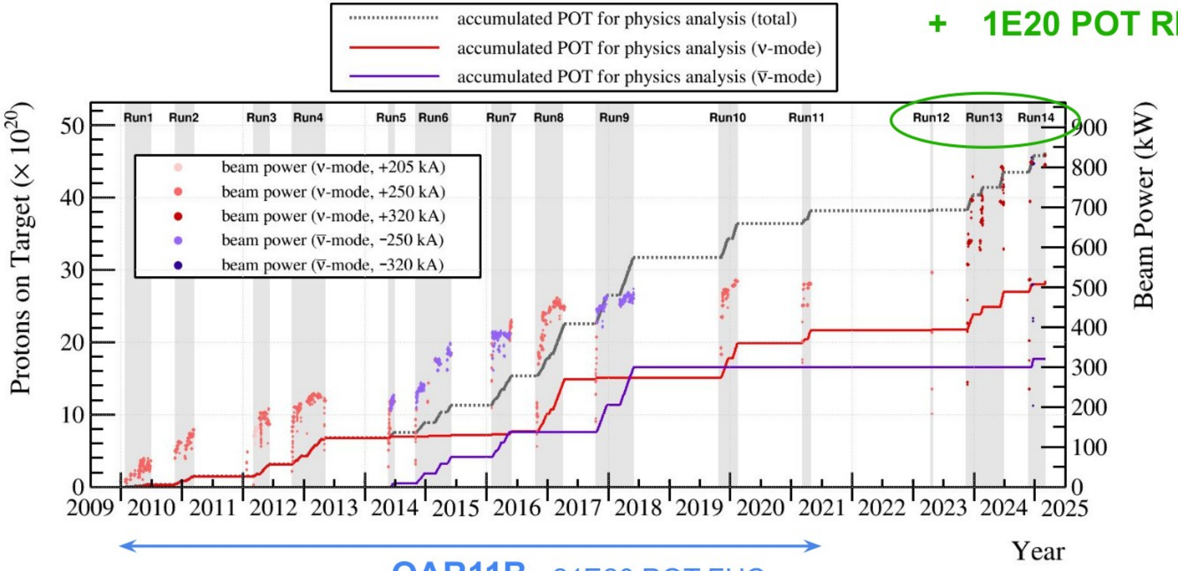
Includes significantly more statistics at the far detector (+0.8e20 i.e. a +17% increase in POT reaching 5.5e20)

Work is in progress to update the SK detector systematics as the compensation of the Earth magnetic field was not working perfectly due to a failure of some coils (now partially repaired)

These new data also have higher Gd concentration (0.01→ 0.03%) and higher horn current (250 kA → 320 kA).

Data taken with the upgraded ND280. The plan is to keep the near detector constraint of the “old near detector” for this release and to postpone the exploitation of the post-upgrade samples to 2026. But we want to use the new ND data to have a consistency check of +320 kA data.

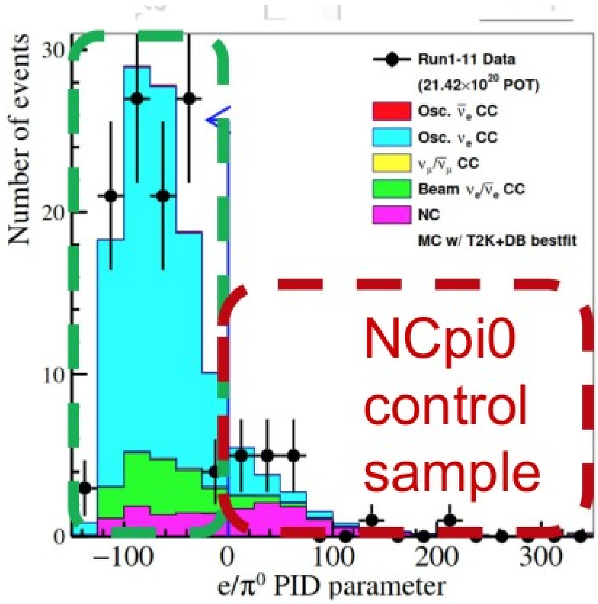
+ 7E20 POT FHC
+ 1E20 POT RHC



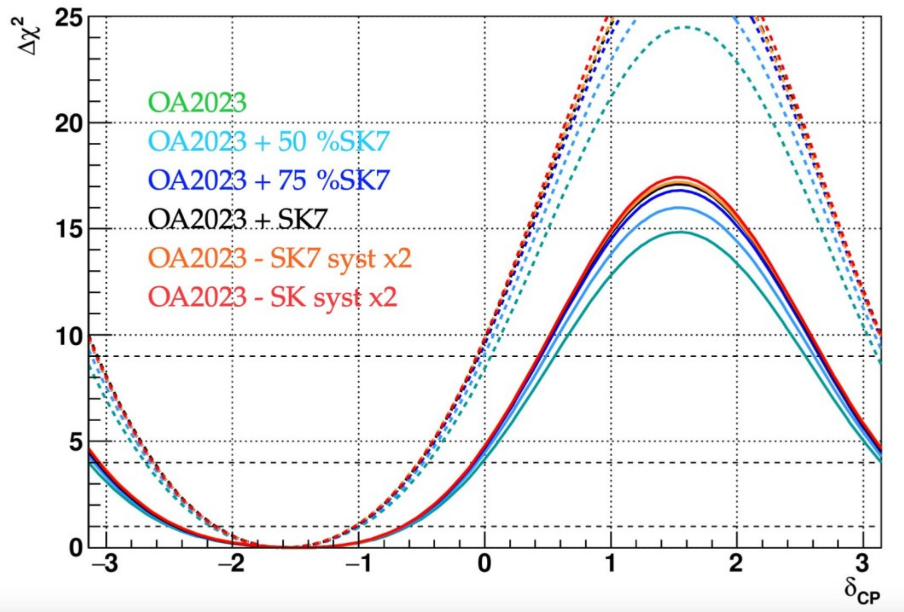
OAR11B 21E20 POT FHC
16E20 POT RHC

See Nakajima-san’s talk

OAR14



Adding new statistics even assuming higher systematics at SK will result in a predicted significant improvement on delta_CP



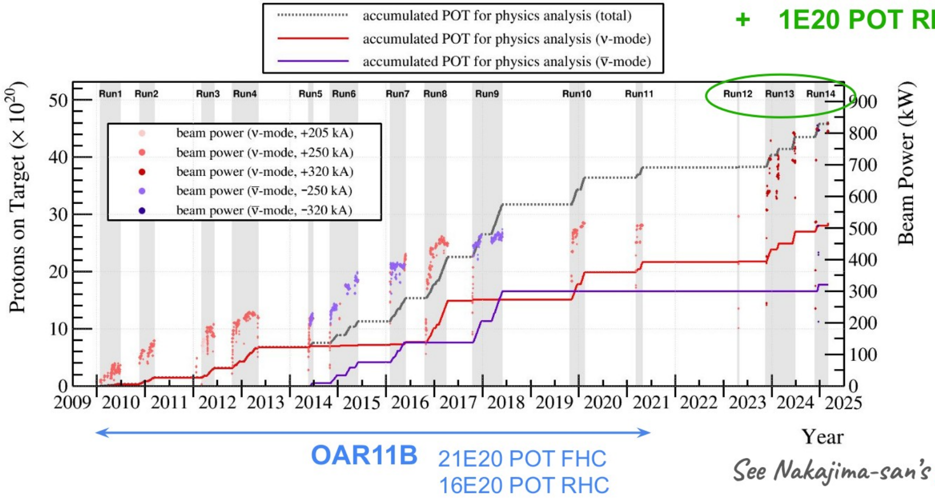
We are also planning to include a new control sample at SK (NCpi0). Constrain background and recover some signal. The activity is focused mainly on parametrizing well the interaction level systematics related to this sample.

Before HK

Aim is to reach 8e21 POT before the start of HK
(fingers crossed for the beam to behave well!)

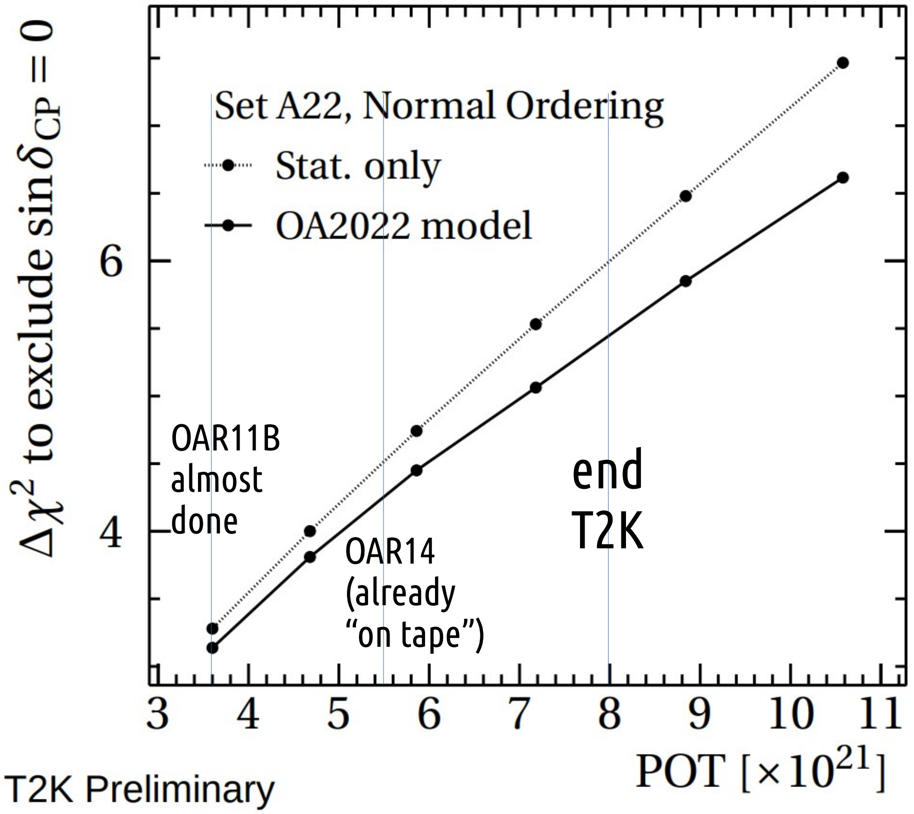
Perform the analysis including the upgraded samples.

+ 7E20 POT FHC
+ 1E20 POT RHC

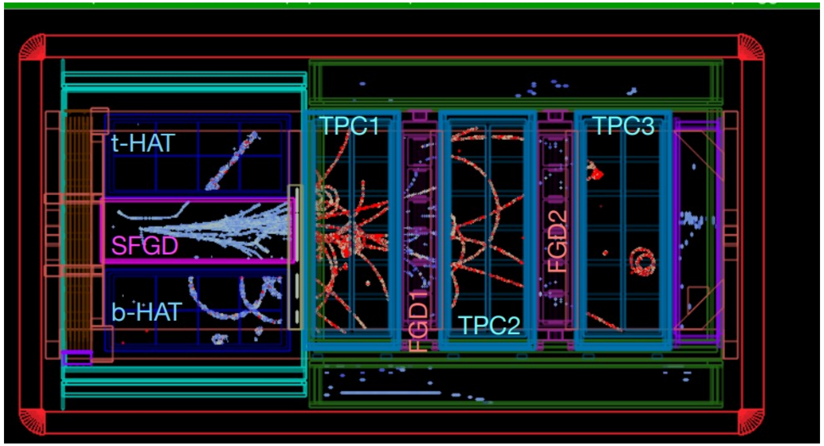


See Nakajima-san's talk

Exp. sensitivity ~ for present T2K best fit



Potential of the new near detector



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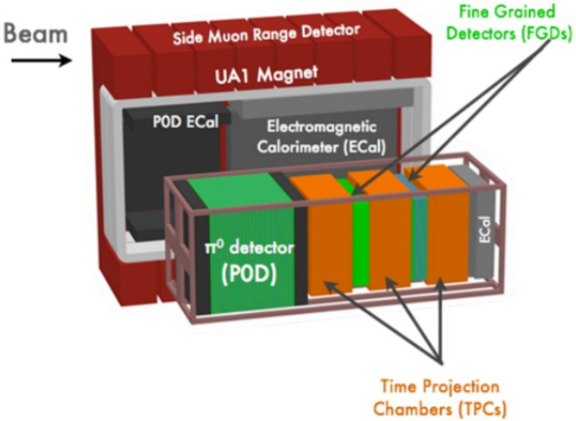
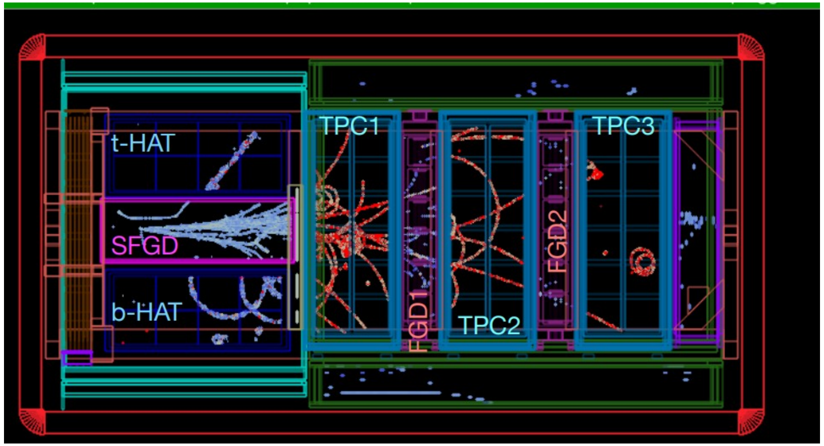


Potential of the new near detector



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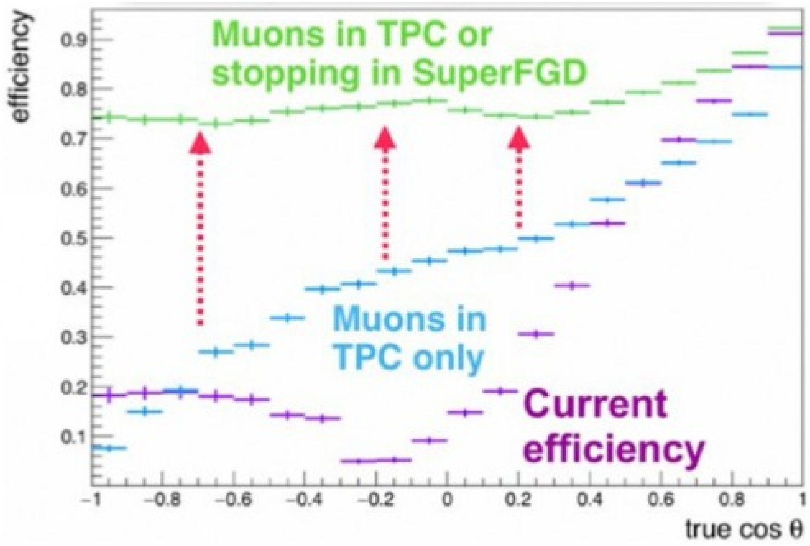
We are relearning to drive

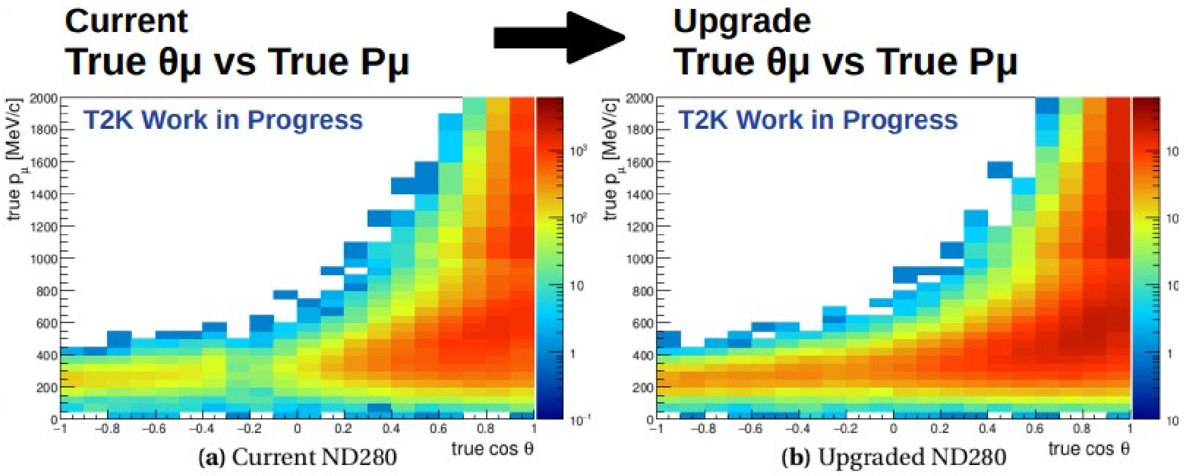
Chambers (TPCs)

"4π" acceptance

Horizontal TPCs!

θμ efficiency (current vs upgrade)





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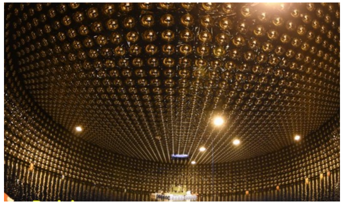
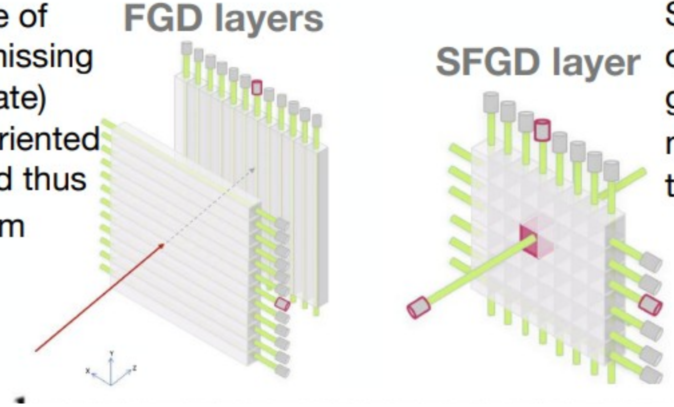


Constrain a similar phase-space. Rely less on models to extrapolate from ND to FD.

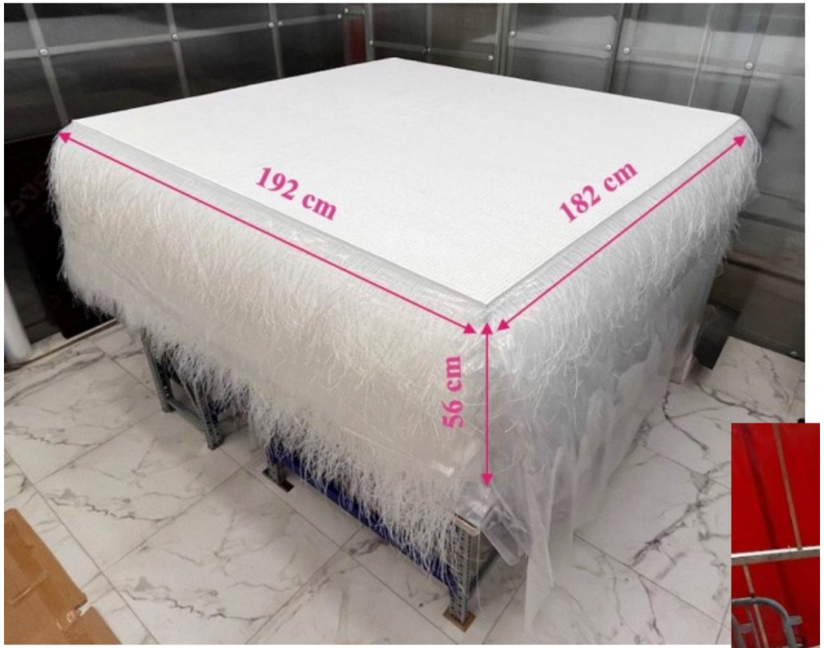
Excellent granularity/redundancy

FGD is made of bars (each missing one coordinate) alternately oriented in planes and thus needs ≥ 4 cm tracks

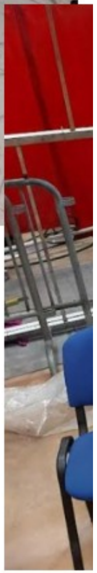


SuperFGD is made of cubes (each gives 3D info) and needs ≥ 2 cm tracks

- Around 2 million 1cm^3 plastic cubes
- Readout on 3 orthogonal planes
  - not just XY
- Doubles the previous FGD mass

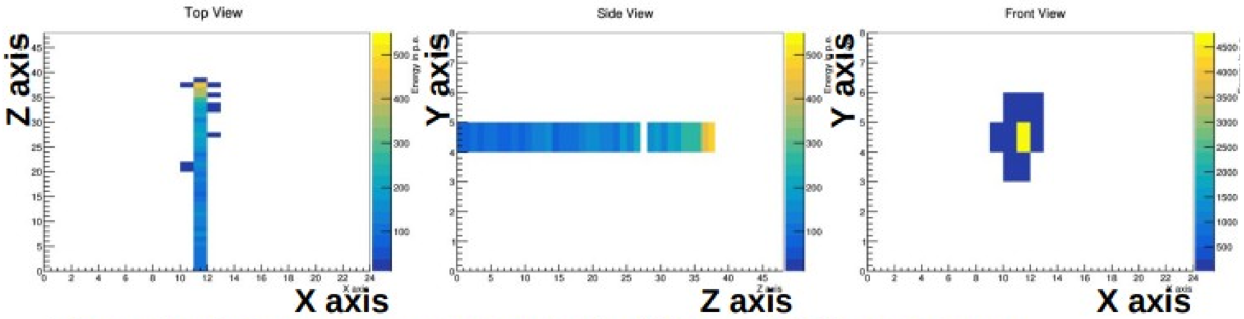


Cube planes joined with Fishing lines



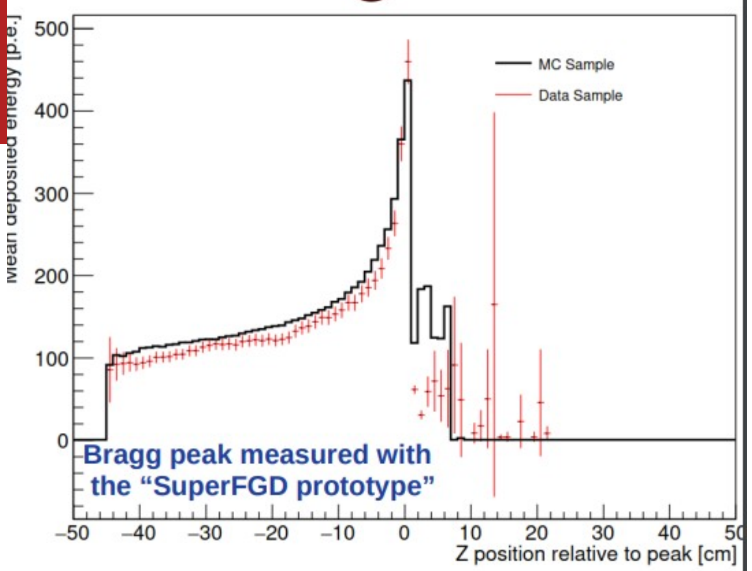
Proton reconstruction

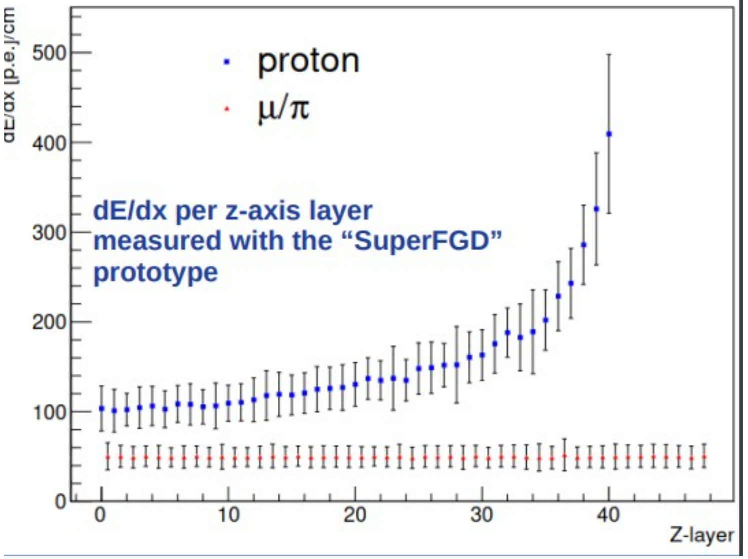
- **Stopping Protons**
  - Due to its particle containment, particle ID is possible through dE/dx, using SuperFGD only!



Example of an stopping proton in the "SuperFGD" prototype.

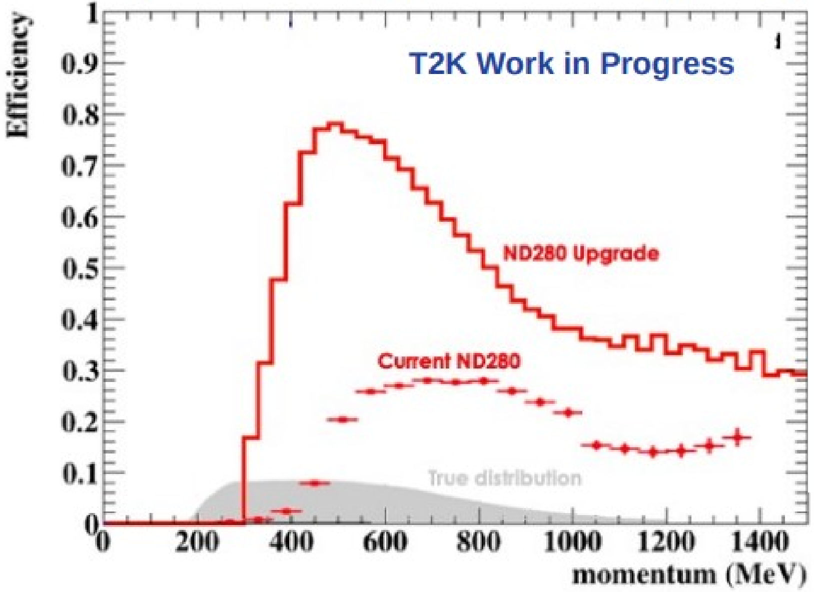
For exiting protons an even better tagging with dE/dx



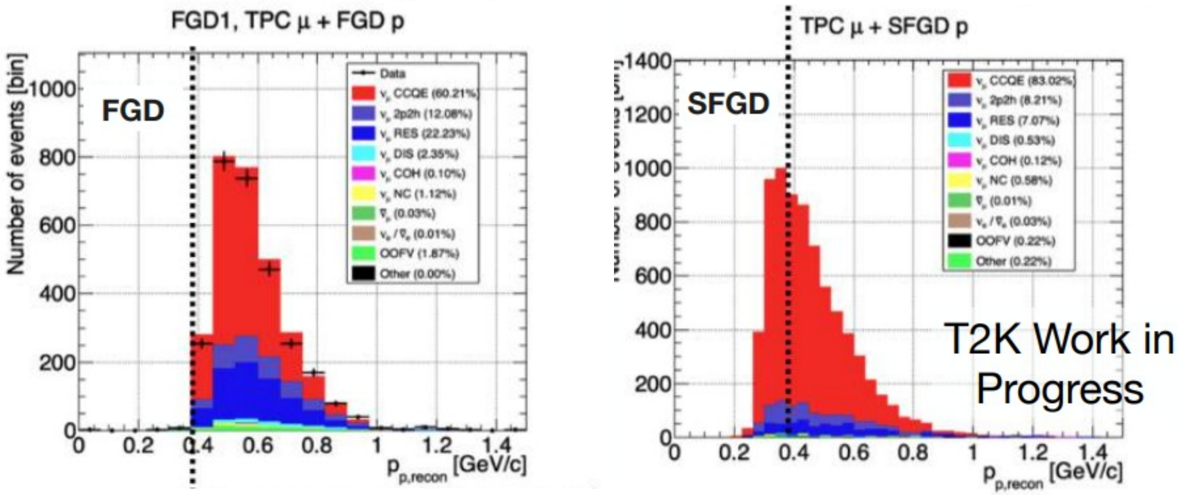


Proton reconstruction

Pp efficiency (current vs upgrade)



Proton threshold + purity



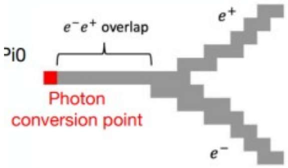
From >400 down to ~300 MeV protons

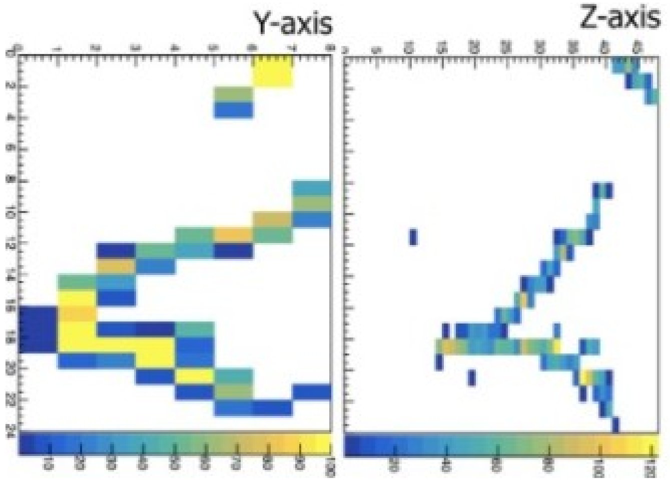
Much better CCQE purity (contamination from 2p2h and CC1π greatly reduced): 2p2h topologies become less degenerate with CCQE if you can “zoom in” the vertex at low thresholds + better proton/pion misid.

Improved PID (e/γ/n)

So far we could get a limiting purity level due to large contamination from low-energy photon conversions (mainly coming from the dense, and close volume of the magnet).

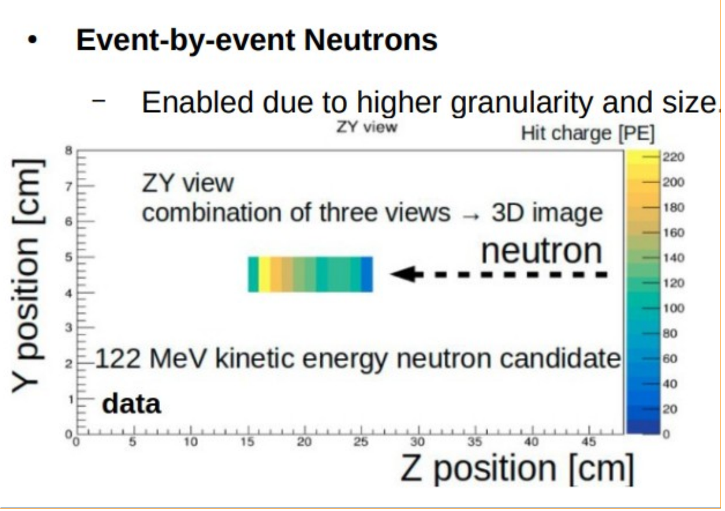
In this also the new TOF systems plays a significant role.

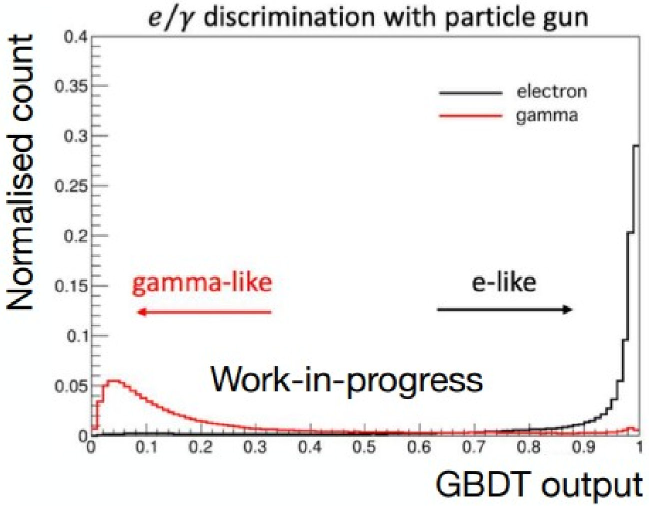




Maybe opens the way to include nue samples in the ND fit?

Neutrons:





Event-by-event neutron reconstruction

Neutron reconstruction available for the first time at ND (tagging available at SK thanks to recent addition of Gadolinium)

Search for an isolated deposit. Measure time of flight between the (anti-)neutrino vertex and the neutron interaction.

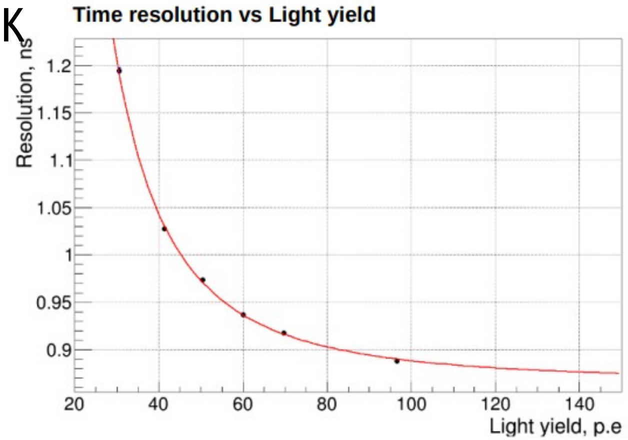
50% tagging efficiency.

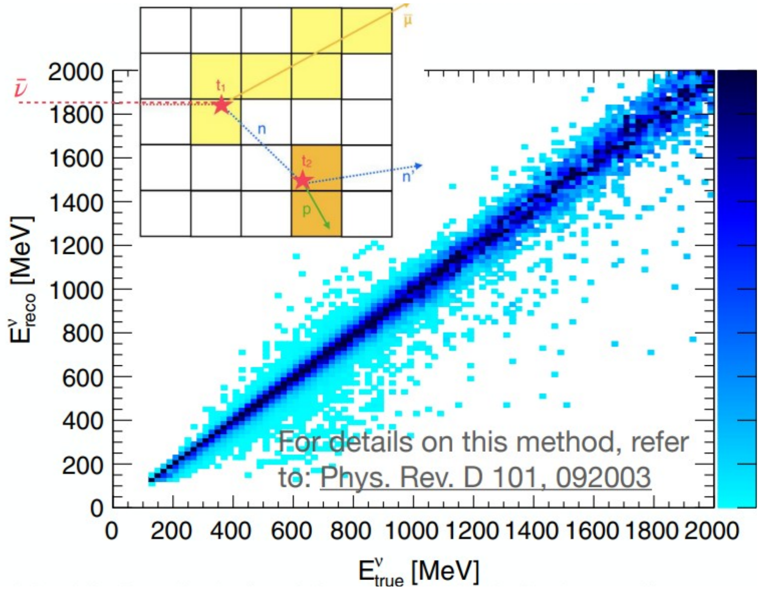
Great for antineutrino runs:

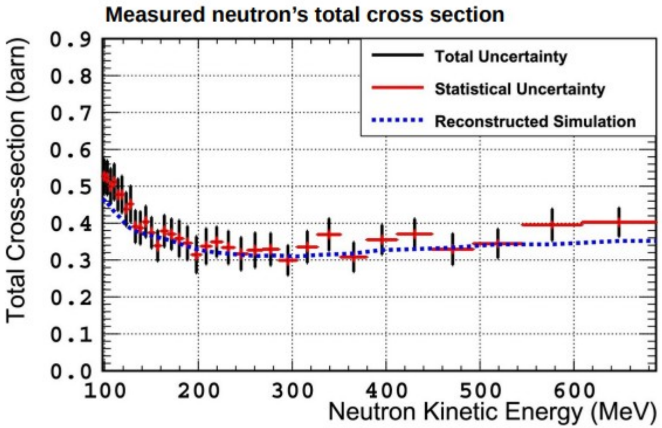
$\bar{\nu}_\mu\, p \rightarrow$ **n** μ^+ (CCQE)

Antineutrino energy resolution might improve from 15 to 7%.

Also useful to disentangle pure CCQE from 2p2h, FSI …







Plans for exploiting the new samples - I

Including the samples in the fit is the last step of a series of studies that are in progress. We need to:

- **understand the new data** (calibrations, response, simulation parameters)
- Extend our model for **detector systematics** and validate it with several ad-hoc control samples
- Make sure that the **parametrization of interaction model uncertainties** is flexible enough to cover our lack of knowledge about the new phase space corresponding to the upgrade selections

First step involves making **consistency-checks**.
Is the fit output "stable" with "simple" post-upgrade samples similar as the previous ones (CC0pi, CC1pi, CCother) i.e. only using the kinematics of the muon?

NB: also the flux has recently been changed by using a 320 kA horn current in place of 250 kA (backup).

The OA group is also getting "technically" ready to incorporate new inputs using templates while the real ones will become mature enough.

Plans for exploiting the new samples - II

beyond muons → **use proton, pion kinematics?**

Proton momentum is a proxy for energy transfer. Dominant systematic uncertainty in OA2022 is the treatment of low-ω effects →

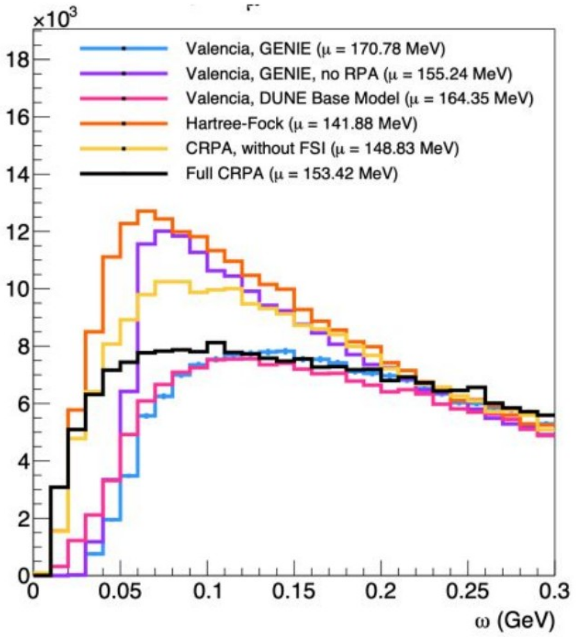
protons+muons: **extract information from their correlations using (Transverse Kinematic Variables, δp_T)**:

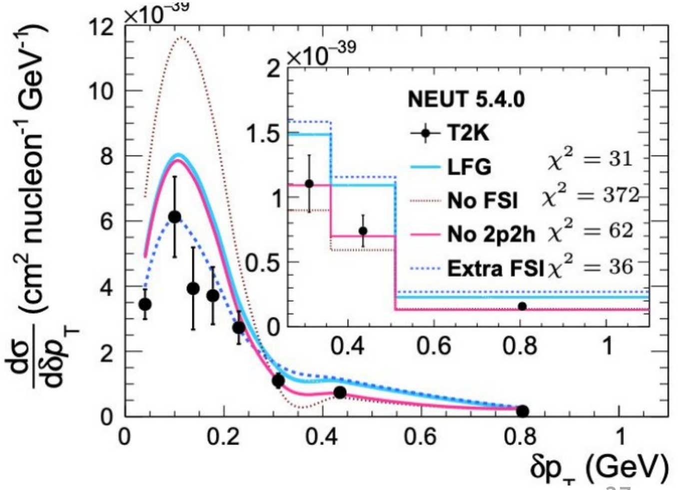
→ good sensitivity to FSI, Fermi motion and removal energy
→ improved separation of QE and non-QE in 0π samples giving a better control over **neutrino energy reconstruction bias**:
1st order importance on systematics for OA

What about **pions**? Multiring samples enriched in 1π interactions. Background to signal samples. Systematics might become relevant with more statistics.

Current post fit ND does not reproduce proton angle well also also the pion spectrum.

Work ongoing on the definition of the samples + associated systematics.





Conclusions

- During **JENNIFER2** the OA analysis has improved significantly
- Lots of activity ongoing for including the data of last year
- Including the upgrade data in the OA brings a lot of opportunities for improving the precision of the T2K results → aiming for first samples in 2026
    - And a real "investment" also for the HK era!
- POT increase is still the main driver in improving the constrains: use the next two years to accumulate more POT and fully exploit what we already took.

Conclusions

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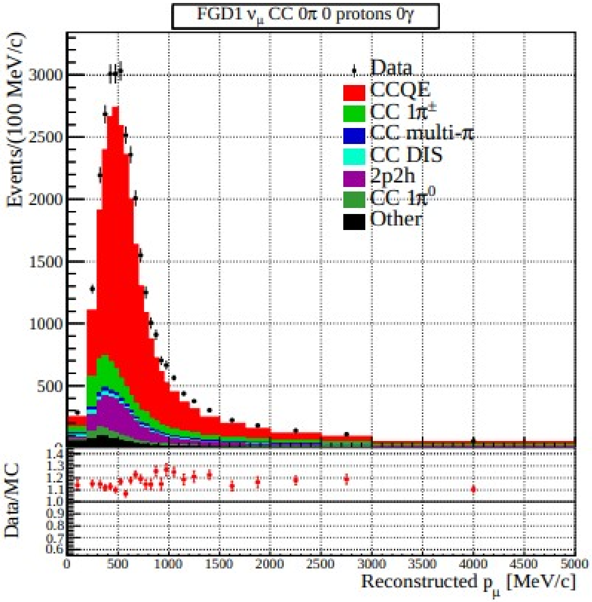
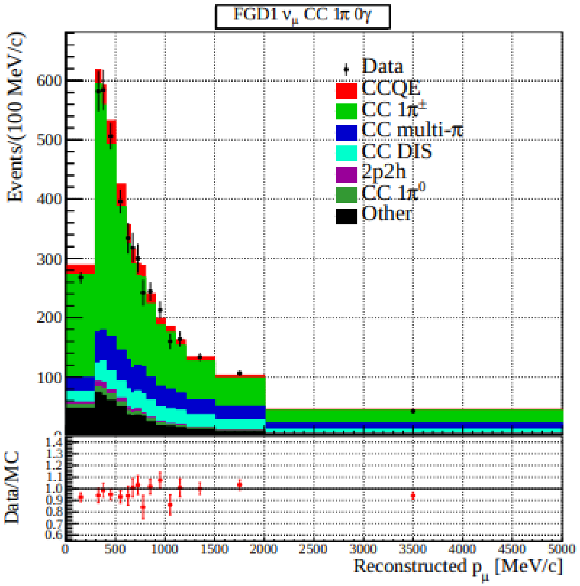
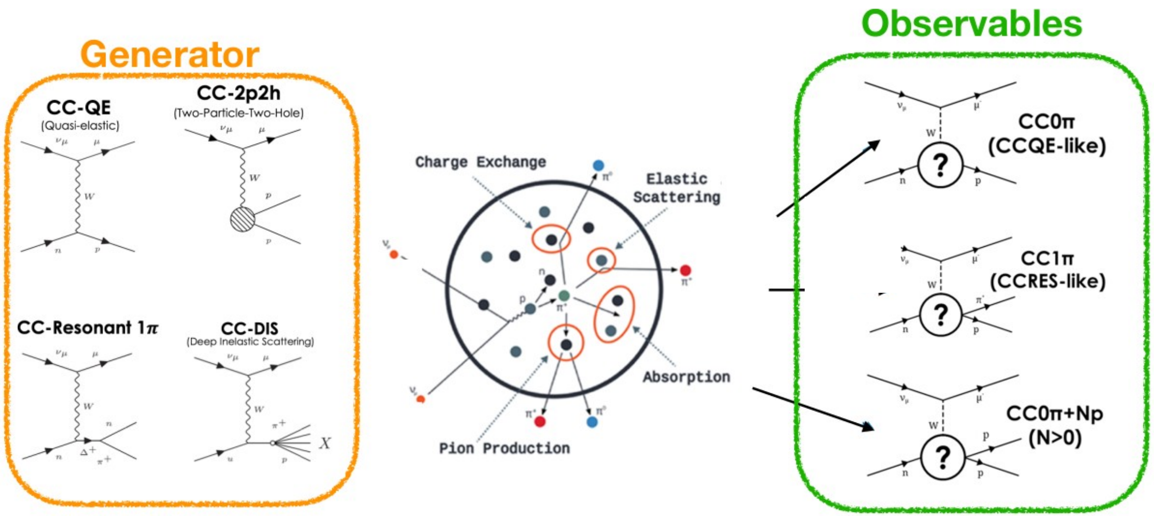
- Lots of activity ongoing for including the data of last year
- Including the upgrade data in the OA brings a lot of opportunities for improving the precision of the T2K results → aiming for first samples in 2026
  - And a real “investment” also for the HK era!
- POT increase is still the main driver in improving the constrains: use the next two years to accumulate more POT and fully exploit what we already took.
- Lots to be done for **JENNIFER3**!

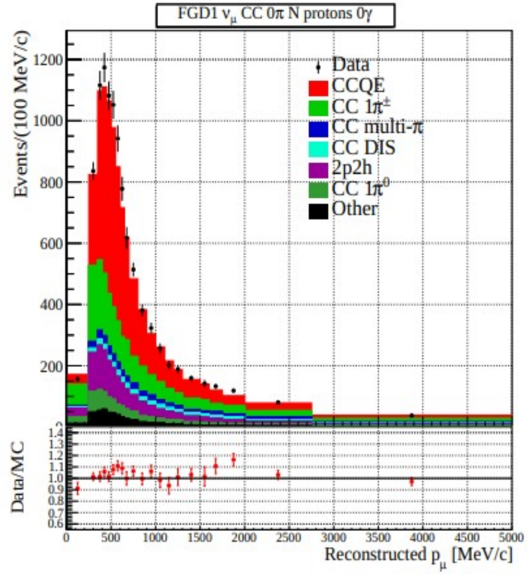
Mapping reco-truth

The current ND samples (“topologies” CC0π, CC1π, CCother) are designed to map as accurately as possible to the interaction processes. But detector effects create significant cross-feeding → some of this are “unavoidable” (nuclear effects): a pion could be absorbed in the nucleus and appear as a CCQE.



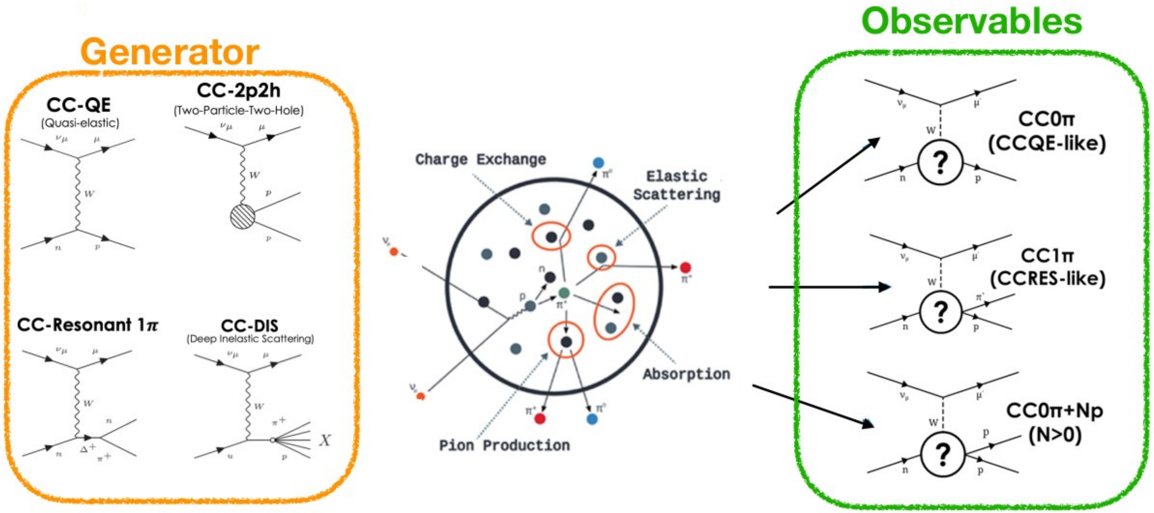




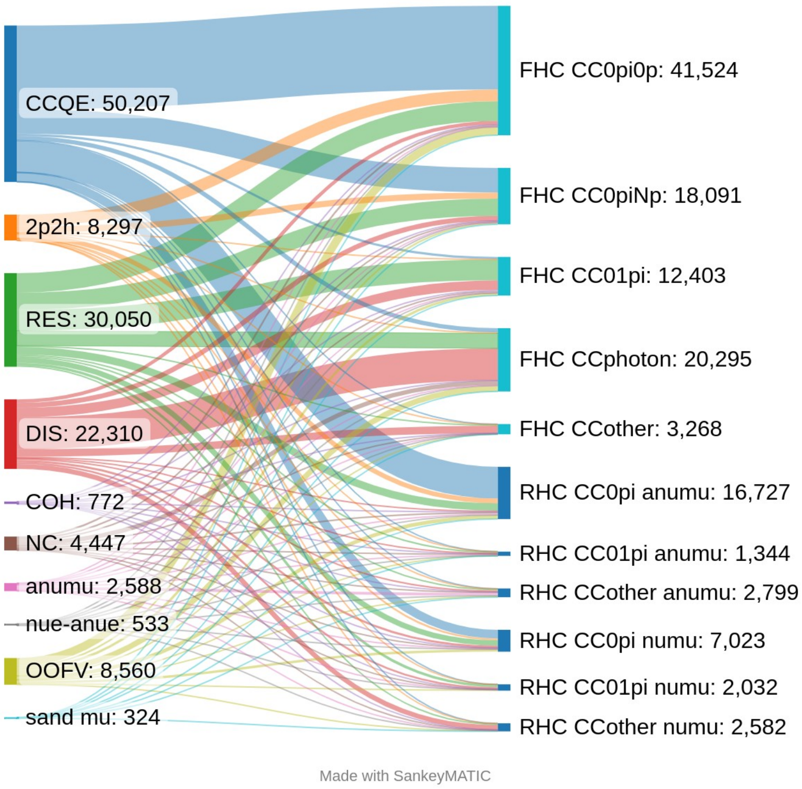


Mapping reco-truth

But in general improvements in angular and energy acceptance with the upgraded ND will allow to define much more targeted and accurate samples addressing the interaction contributions



presently



Improvements in the recent analyses

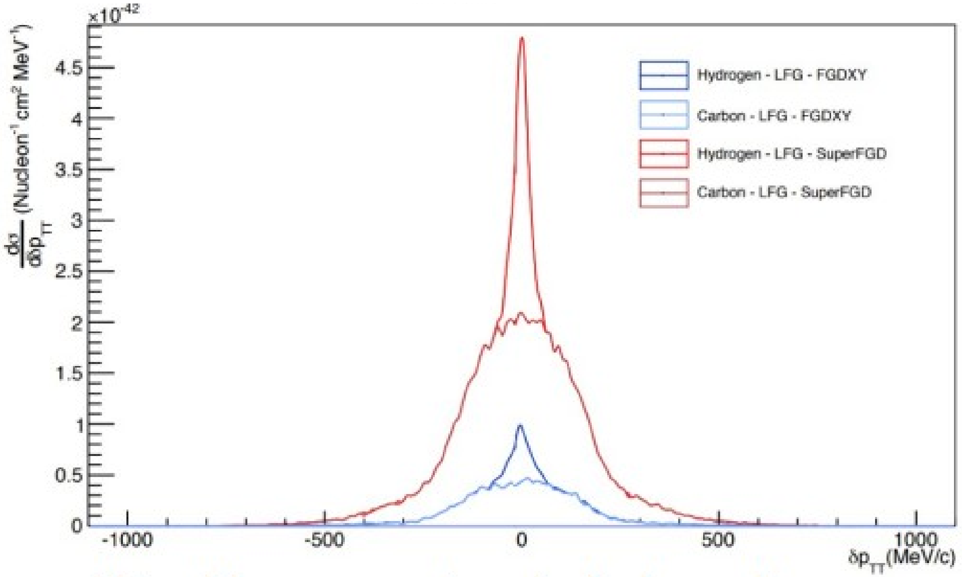
release	Improvements	@ ND	@ FD
2022	**FLUX** & ν **interaction** model	• New p-tagged & γ tagged samples	• μ-like CC1π • multi-ring samples
2023			• + Run 11 +9% FHC • Gd 0.01 % in SK • New selection (decay e) • New SK systematic detector matrix
2024		• 4π samples • New reconstruction ("Prod. 7") • "Splinification" of ND280 systematics	• New multi-ring e-like sample

Probing nuclear effects better

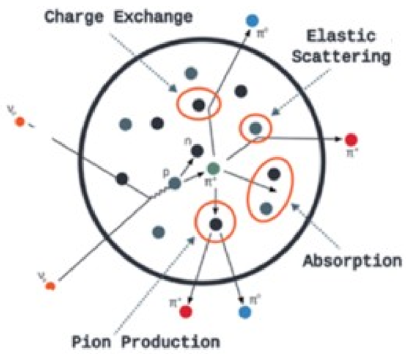
High angle and low momentum acceptance allow measuring "transverse kinematic variables" crucial to measure nuclear effects like **"final state interactions"** or scattering on correlated nucleon pairs (**2p-2h**).

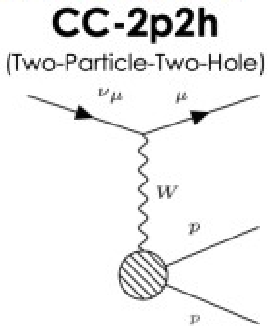
Target is CH → can single out interactions on H (Z=1, N=0 → no nuclear effects!)

Very important to reduce the systematics in the measurement of the neutrino energy at SK that spoils the resolution on Δm^2



"Double momentum imbalance" SIMULATION on FGDs and SuperFGD,

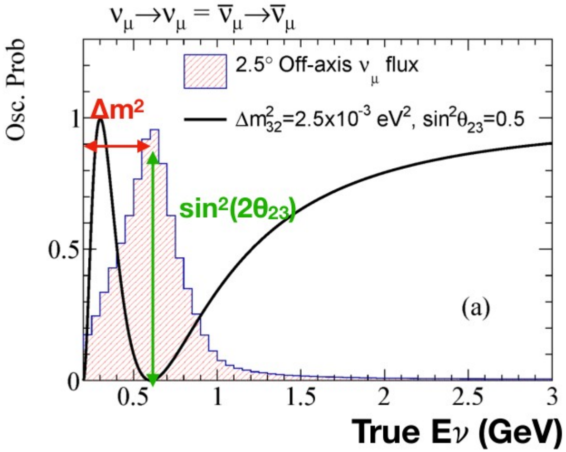


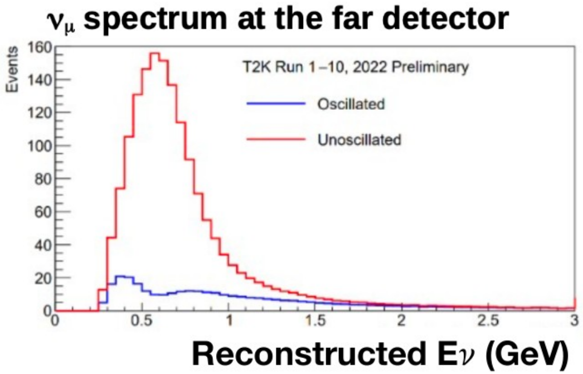


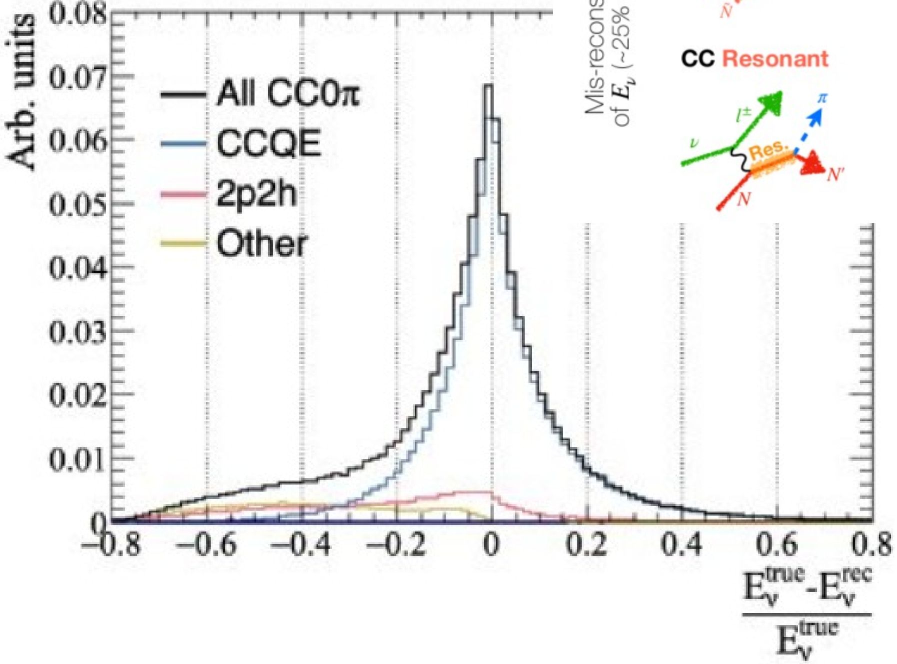
Systematics on neutrino energy

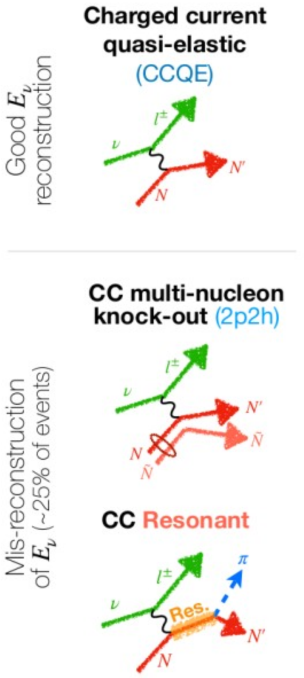
The 2-body quasi-elastic formula used to reconstruct the neutrino energy from the muon kinematics has large tails due to non CCQE components (i.e. 2p2h). Smearing is instead mainly related to the Fermi motion of nucleons in Oxygen nuclei.

It is important to have a well constrained model by the near detector data to reduce systematics (which are already today above stat errors for Δm^2).







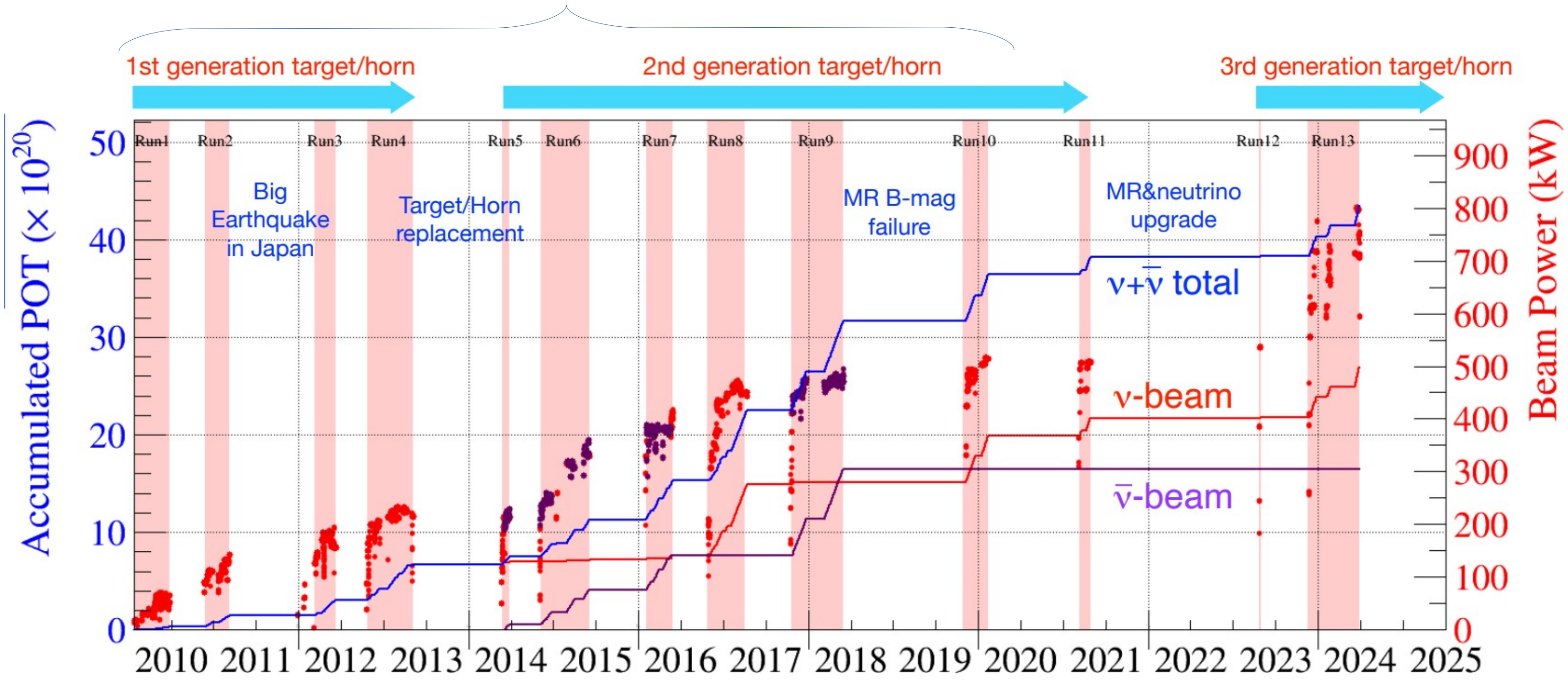


OA2022

release	Improvements	@ ND	@ FD
2022	**FLUX** & ν **interaction** model	• New p-tagged & γ tagged samples	• μ-like CC1π • multi-ring samples

OA2022

Publication close

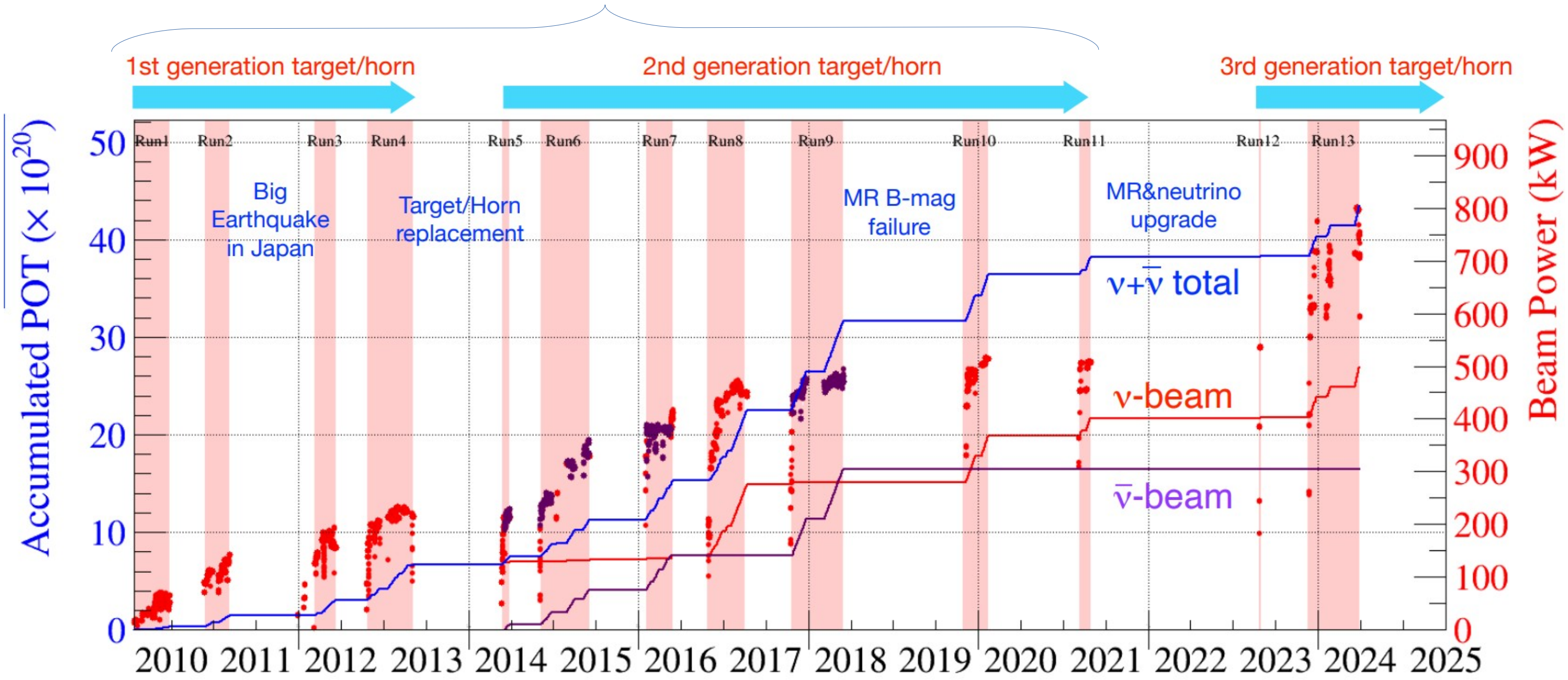


OA2023

2023			• + Run 11 +9% FHC • Gd 0.01 % in SK • New selection (decay e) • New SK systematic detector matrix

OA2023

Publication close

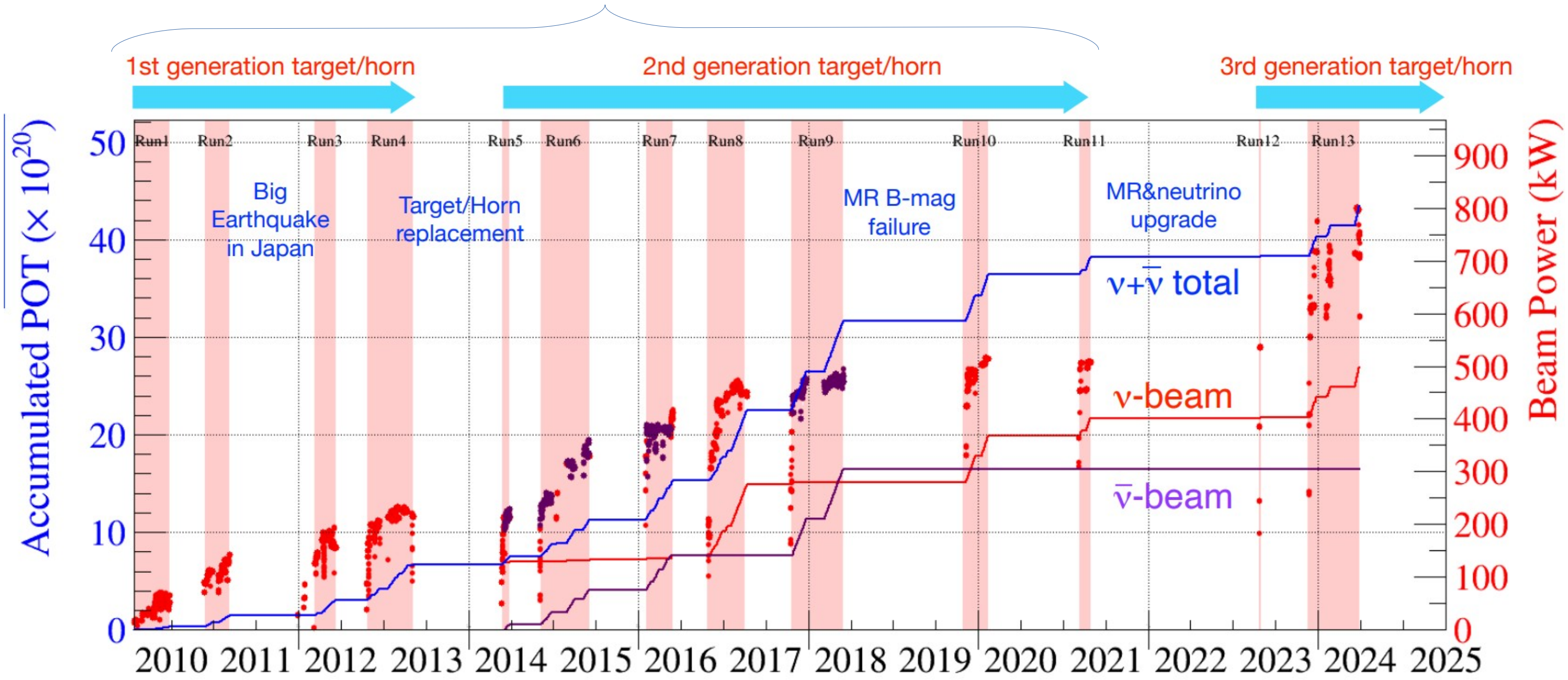


OA2024

2024		• 4π samples • New reconstruction ("Prod. 7") • "Splinification" of ND280 systematics	• New multi-ring e-like sample

OA2024

Being finalized

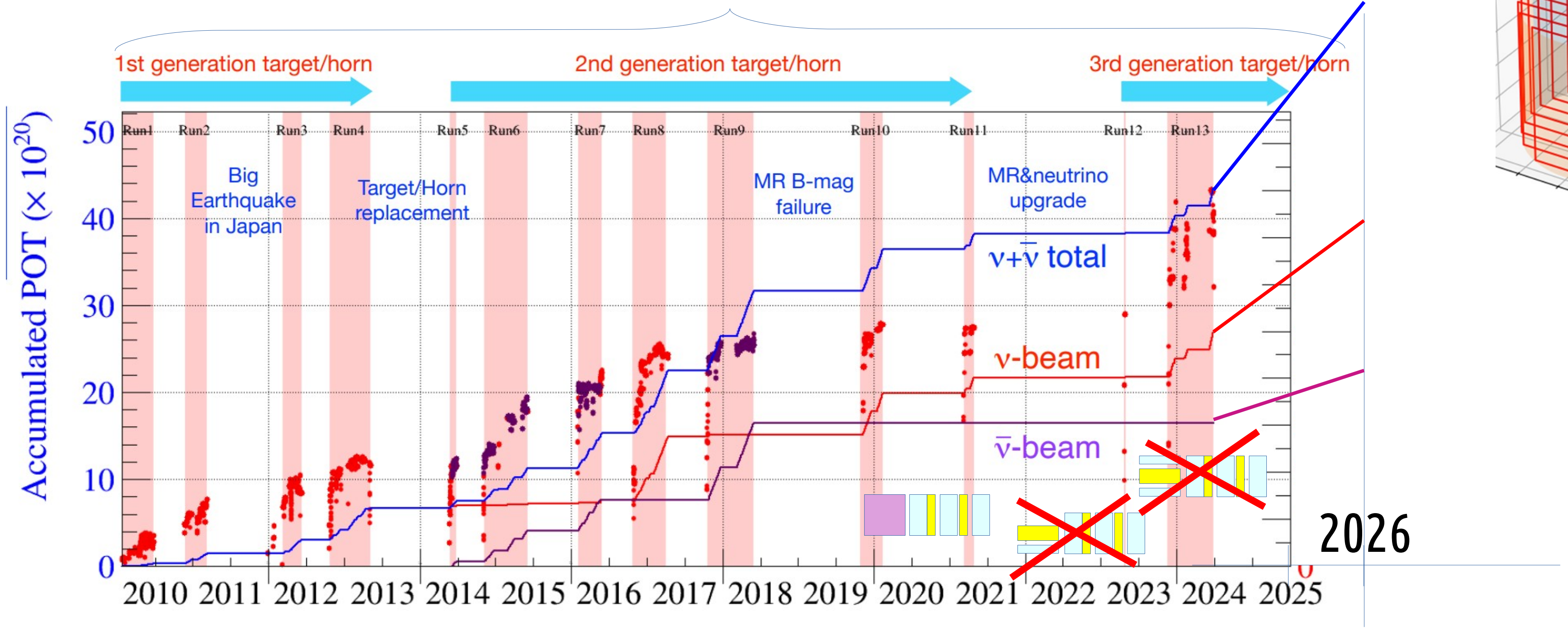


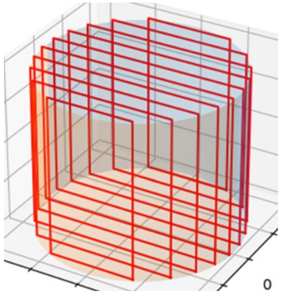
Plans for this year

- FD runs 12-13 FHC (+1.4E21 PoT), RHC (+0.6E21 PoT)
- Add **NCπ^0 sample** + use data with **SK coils problem**
- No new ND inputs used in OA2025

OA2025

https://www.t2k.org/asg/members/2024-11-13/acintro





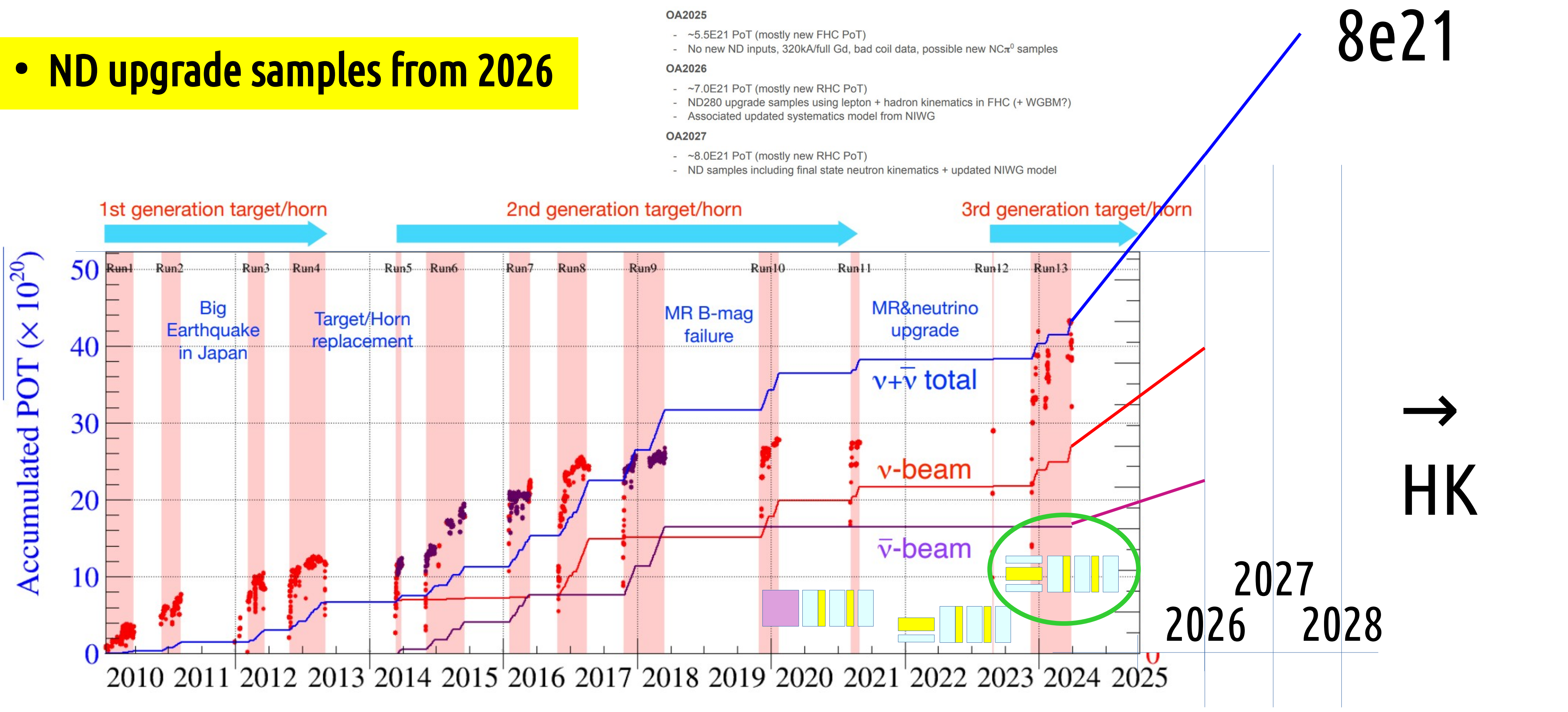
Longer term > OA 2025

- **ND upgrade samples from 2026**

OA2025
- ~5.5E21 PoT (mostly new FHC PoT)
- No new ND inputs, 320kA/full Gd, bad coil data, possible new NCπ^0 samples

OA2026
- ~7.0E21 PoT (mostly new RHC PoT)
- ND280 upgrade samples using lepton + hadron kinematics in FHC (+ WGBM?)
- Associated updated systematics model from NIWG

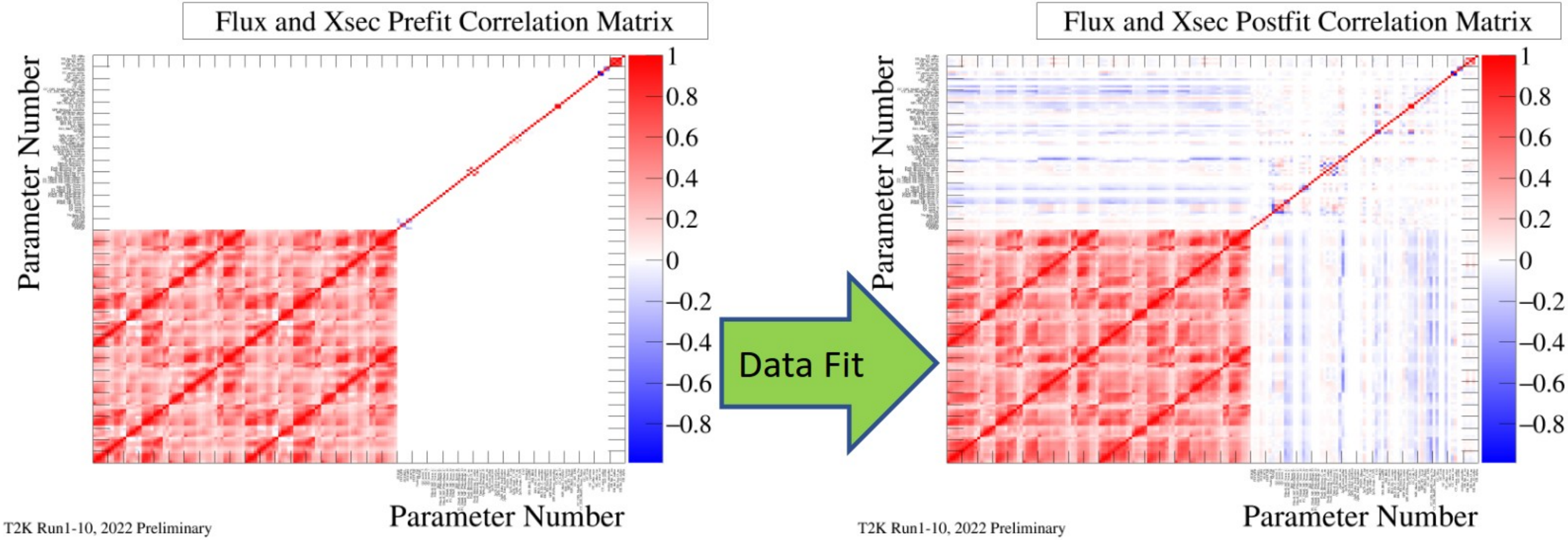
OA2027
- ~8.0E21 PoT (mostly new RHC PoT)
- ND samples including final state neutron kinematics + updated NIWG model



https://www.t2k.org/asg/members/2024-11-13/acintro

Diving deeper into the analysis

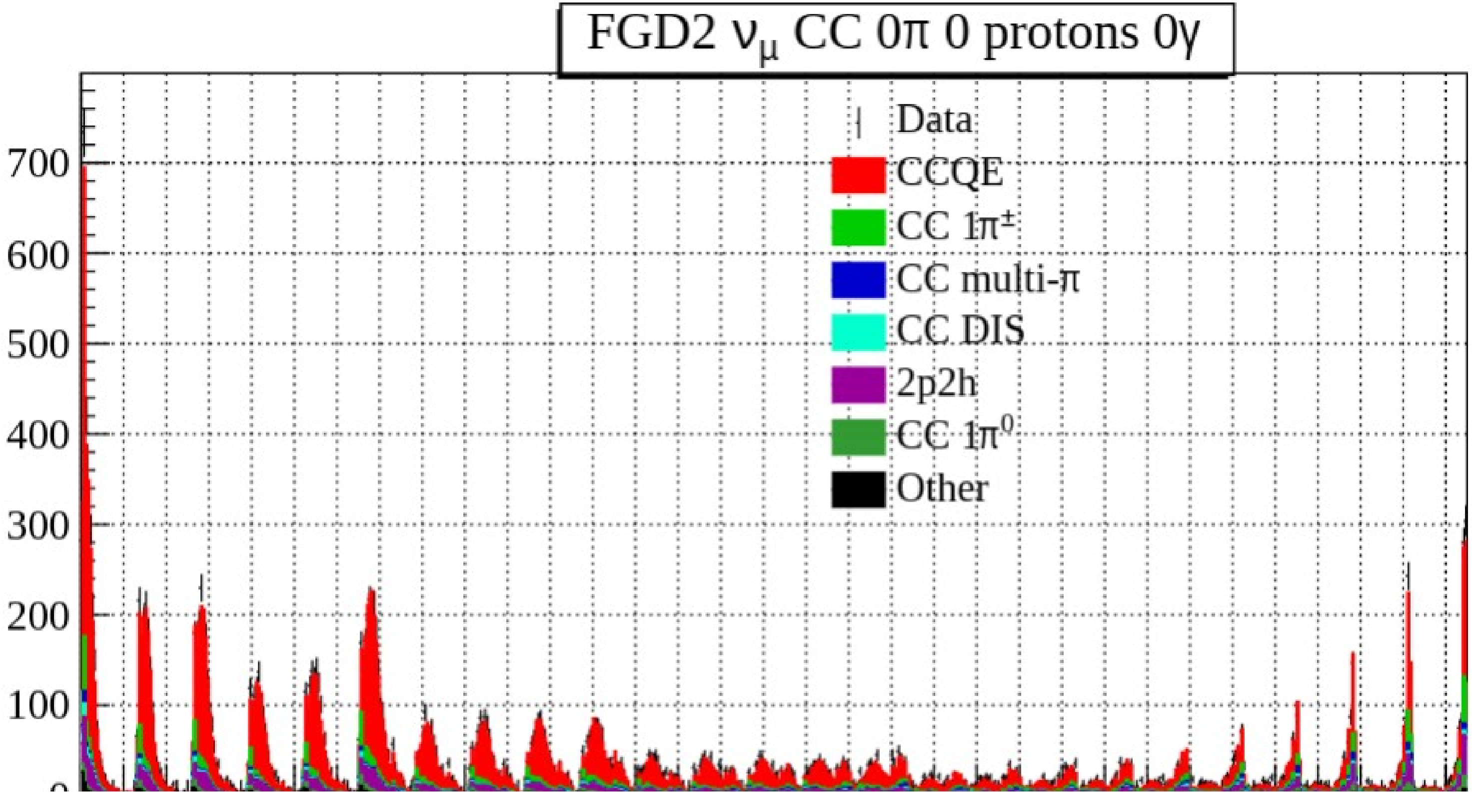
The fit is very complex. Besides the oscillation parameters it involves **hundreds of unknown parameters** ("nuisance") from **uncertainties in interaction models**, **final state interactions**, **flux uncertainty**, **detector parameters**. These are "fitted out" to finally access the interesting oscillation parameters (3).



ND inputs: binning

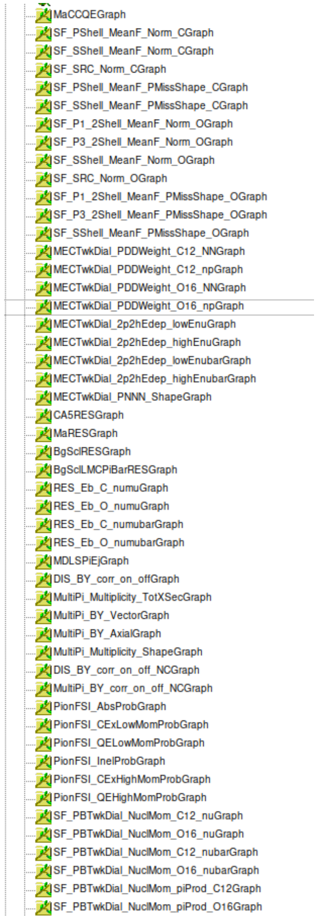
The ND fit acts on binned data using a 2D dimensional binning in the momentum and angle of the muon (no nu_e sample)

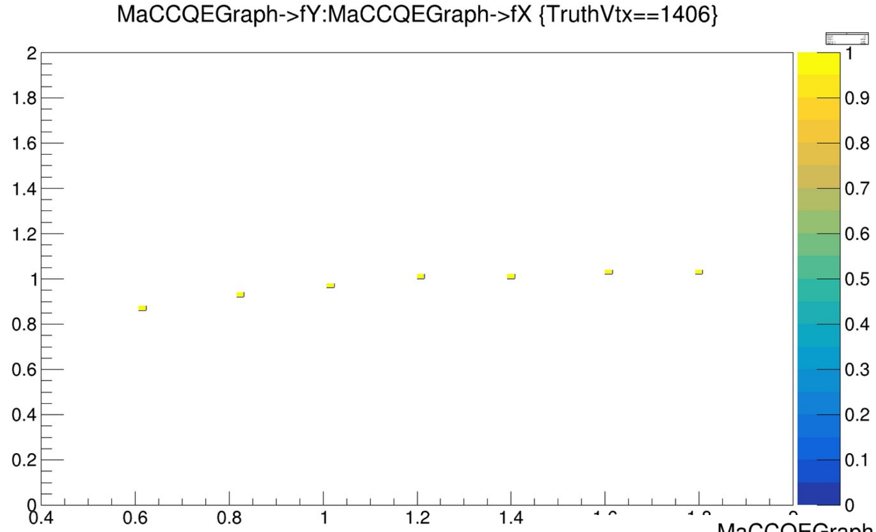
The binning has been recently improved by ensuring that it is larger than angular and momentum resolutions.

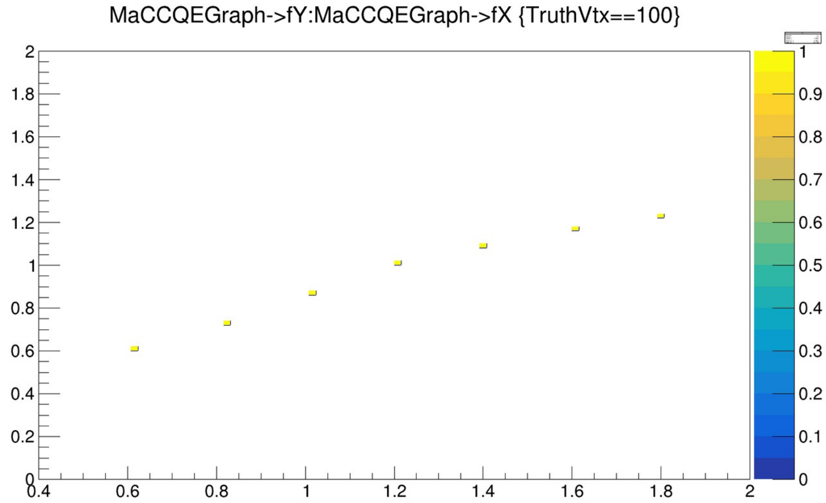


p-θ bins in sequential order

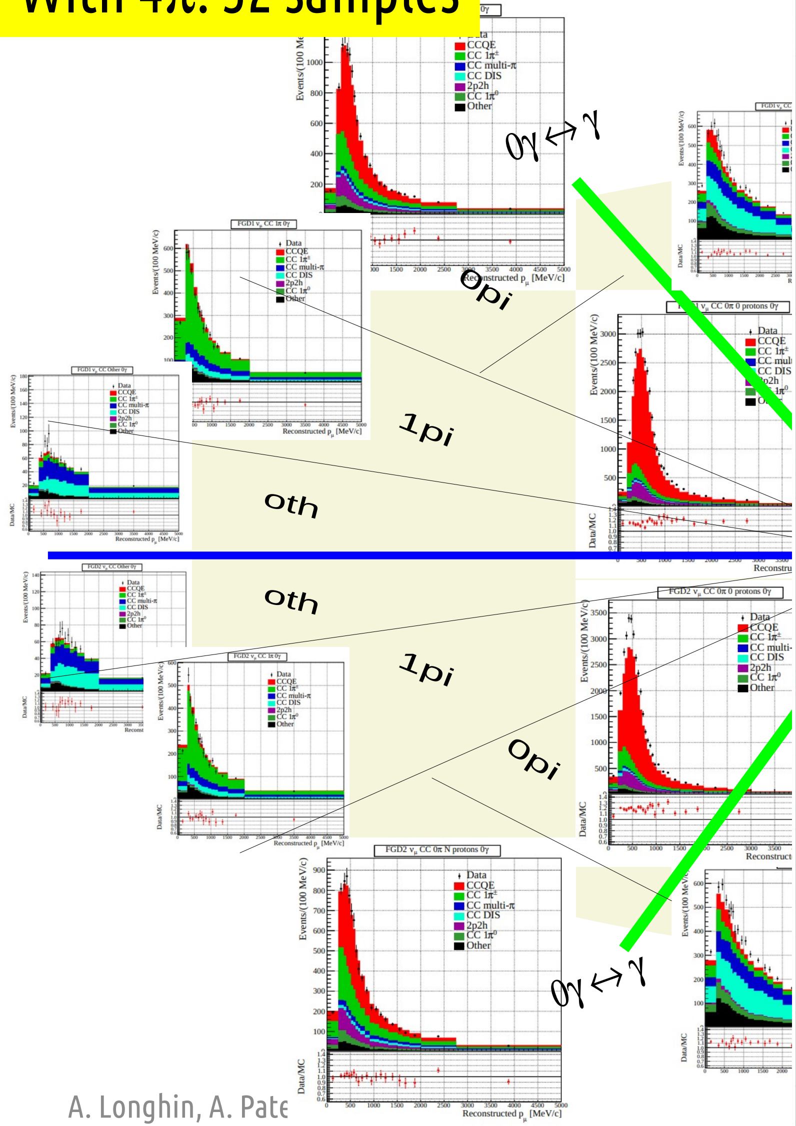
Event-by-event splines







With 4π: 32 samples



FGD1 numuCC 0pi Fwd 0 protons no photon:
FGD1 numuCC 0pi Fwd N protons no photon:
FGD1 numuCC 0pi Bwd NoPhoton No Protons
FGD1 numuCC 0pi Bwd NoPhoton N Protons
FGD1 numuCC 0pi HA NoPhoton No Protons
FGD1 numuCC 0pi HA NoPhoton N Protons
FGD1 numuCC 1Pi HAFwd NoPhoton
FGD1 numuCC 1pi Fwd no photon:
FGD1 numuCC other Fwd no photon:
FGD1 numuCC photon Fwd:
FGD2 numuCC 0pi Fwd 0 protons no photon:
FGD2 numuCC 0pi Fwd N protons no photon:
FGD2 numuCC 0pi Bwd NoPhoton No Protons
FGD2 numuCC 0pi Bwd NoPhoton N Protons
FGD2 numuCC 0pi HA NoPhoton No Protons
FGD2 numuCC 0pi HA NoPhoton N Protons
FGD2 numuCC 1Pi HAFwd NoPhoton
FGD2 numuCC 1pi Fwd no photon:
FGD2 numuCC other Fwd no photon:
FGD2 numuCC photon Fwd:
FGD1 anti-numuCC 0pi:
FGD1 anti-numuCC 1pi:
FGD1 anti-numuCC other:
FGD2 anti-numuCC 0pi:
FGD2 anti-numuCC 1pi:
FGD2 anti-numuCC other:
FGD1 NuMuBkg CC0pi in AntiNu Mode:
FGD1 NuMuBkg CC1pi in AntiNu Mode:
FGD1 NuMuBkg CCother in AntiNu Mode:
FGD2 NuMuBkg CC0pi in AntiNu Mode:
FGD2 NuMuBkg CC1pi in AntiNu Mode:
FGD2 NuMuBkg CCother in AntiNu Mode:

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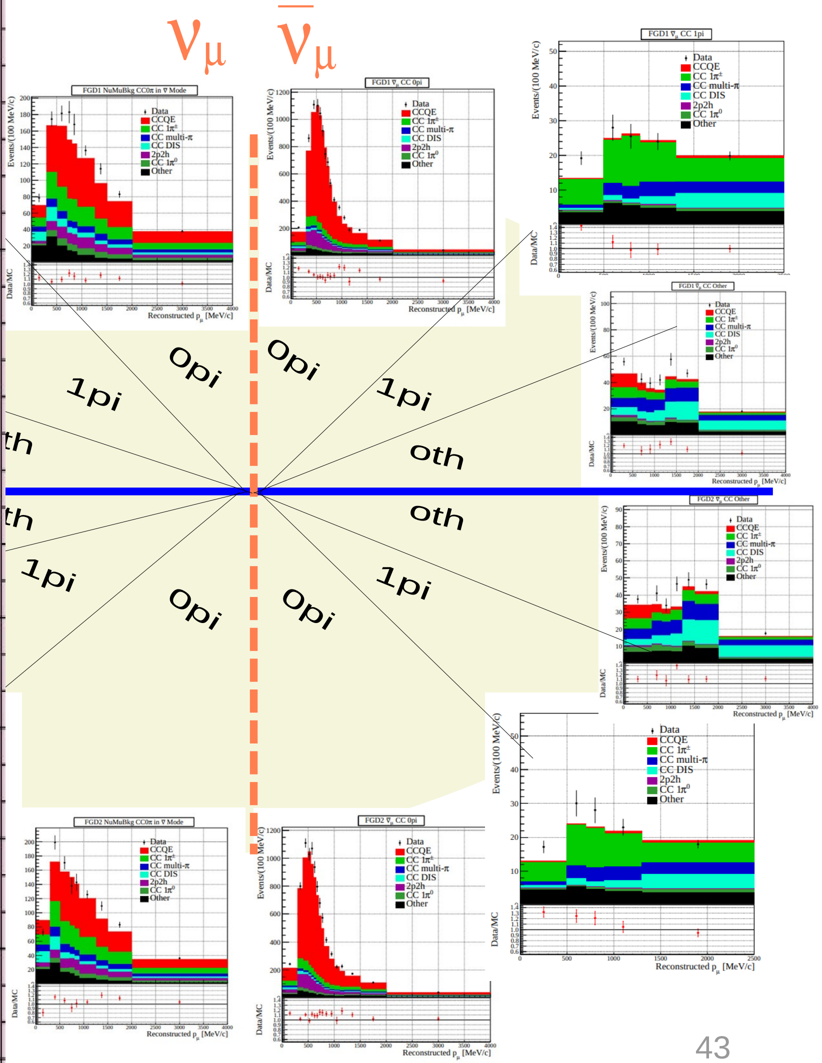
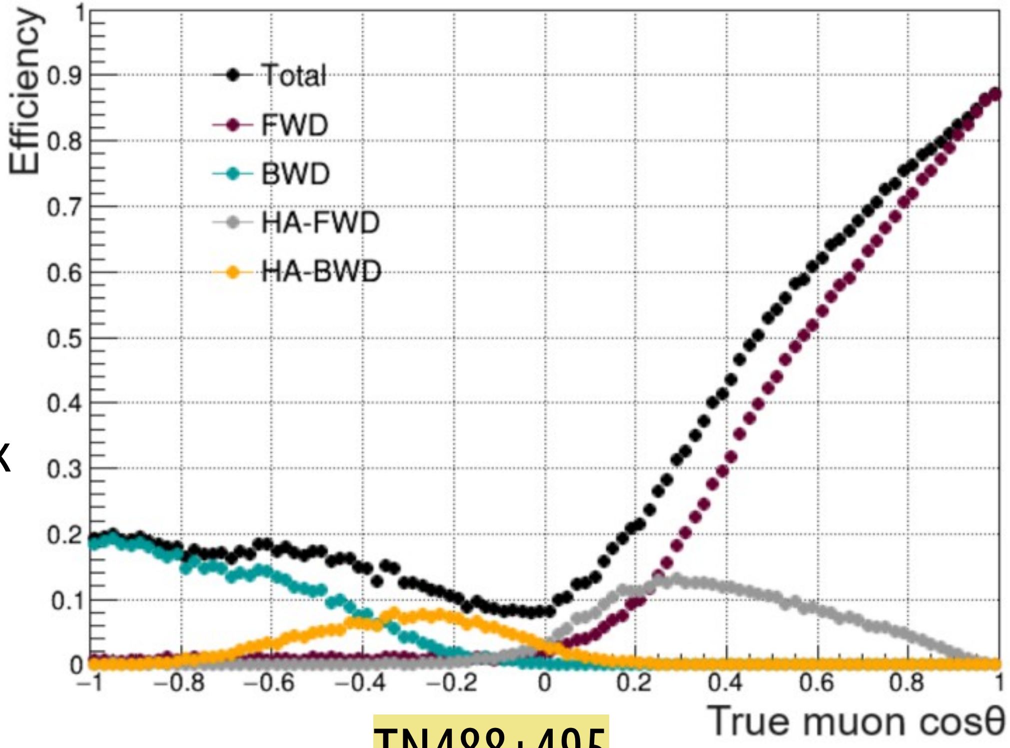


Improved acceptance in the FHC samples

T. Doyle[1], D. Fedorova[2], A. Finch[3], D. Hadley[4], A. Izmaylov[*2], S. King[†5], V. Kiseeva[6], L. Kneale[7], M. Lamers James[4], N. Latham[4], A. Lopez Moreno[5], V. Nguyen[8], K. Skwarczynski[9], A. Speers[3], I. Suslov[6], T. Wachala[10], and G. Zarnecki[10]

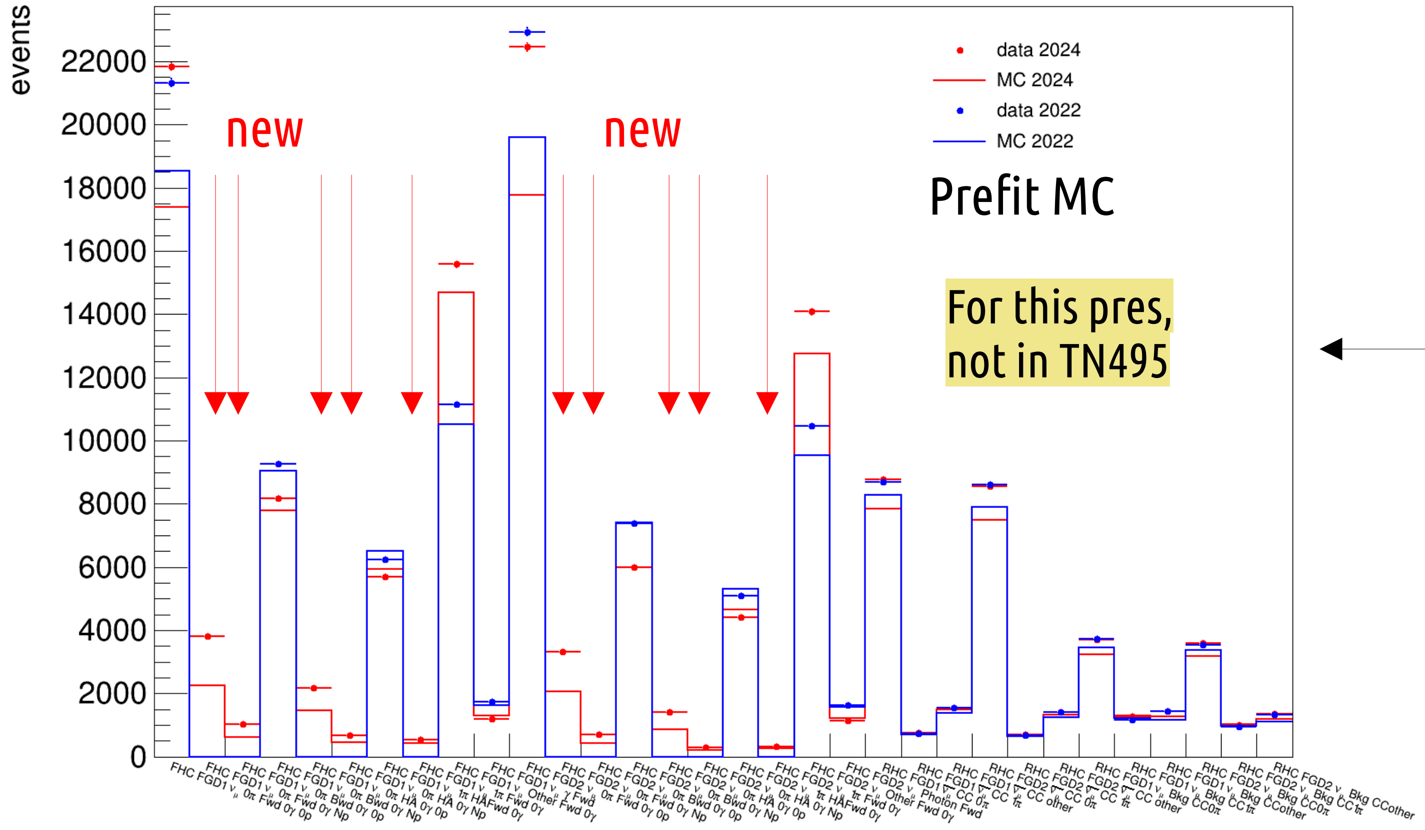
- FHC ToF for selecting backward going tracks
- Muon candidate that satisfies the TPC track quality and the μ TPC PID requirement
  - **Forward**: $Z_{start} < Z_{end}$. An FGD1-TPC2 (FGD2-TPC3) .
  - **Backward**: $Z_{start} > Z_{end}$. An FGD1-TPC1 (FGD2-TPC2)
- **High-Angle (HA)**: candidate fails TPC track quality but stops inside ECal or SMRD. Muon PID is based on ECal information or an SMRD segment. No check on the charge sign.
  - **High-Angle Forward (HA-Fwd)**: $Z_{start} < Z_{end}$
  - **High-Angle Backward (HA-Bwd)**: $Z_{start} > Z_{end}$



TN488+495

Comparison of ND samples (2022-24)

- Effect of new selections + prod7 reconstruction
- events increased by 13.7% in data (148813 vs 130894) and by 6.8% in MC (129290.34 vs 121093.868)



TN495

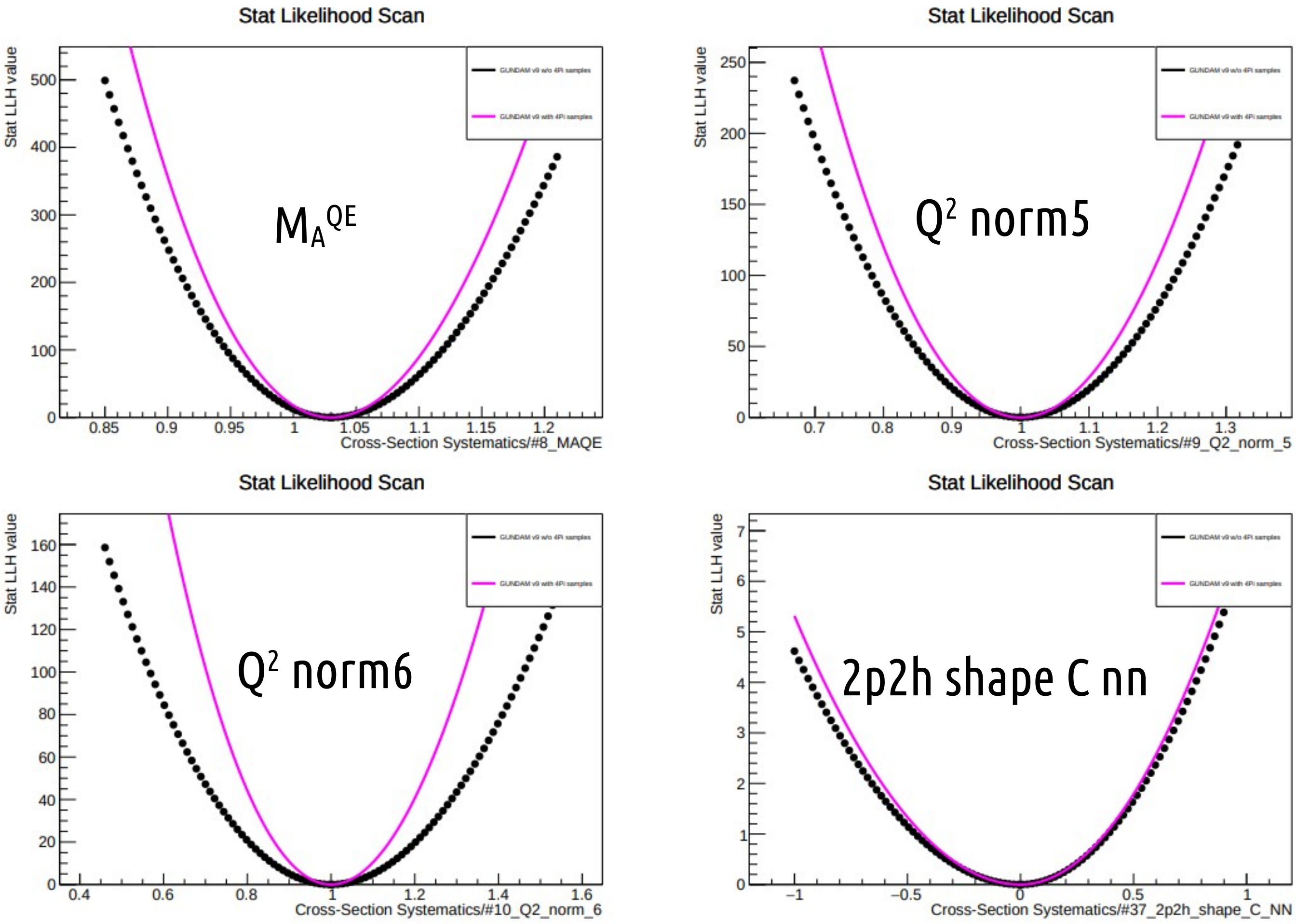
		OA2022	MC	Data	OA2024	MC	Data
FHC ν_μ	FGD1	CC0π0p0γ	18525.3	21329	CC0π0p0γ Fwd	17387.04	21843
					CC0π0p0γ HA	2253.74	3802
					CC0π0p0γ Bwd	615.10	1016
		CC0πNp0γ	9055.73	9257	CC0πNp0γ Fwd	7793.41	8181
					CC0πNp0γ HA	1471.68	2172
					CC0πNp0γ Bwd	439.29	672
		CC1π0γ	6493.55	6224	CC1π0γ Fwd	5934.16	5677
					CC1π0γ HA-Fwd	422.92	544
		CCNγ	10530	11156	CCNγ Fwd	14683.19	15578
		CCOther0γ	1621.28	1737	CCOther0γ Fwd	1305.53	1180
		Total	46225.86	49703		52306.06	60665
	FGD2	CC0π0p0γ	19600.1	22935	CC0π0p0γ Fwd	17762.64	22459
					CC0π0p0γ HA	2071.01	3323
					CC0π0p0γ Bwd	432.75	705
		CC0πNp0γ	7411.24	7373	CC0πNp0γ Fwd	5981.11	5999
					CC0πNp0γ HA	869.59	1399
					CC0πNp0γ Bwd	202.78	288
		CC1π0γ	5312.37	5099	CC1π0γ Fwd	4644.29	4393
					CC1π0γ HA-Fwd	253.61	307
		CCNγ	9542.79	10460	CCNγ Fwd	12757.46	14078
		CCOther0γ	1560.59	1620	CCOther0γ Fwd	1215.52	1130
		Total	43427.09	47487		46190.76	54081
RHC $\bar{\nu}_\mu$	FGD1	CC0π	8283.27	8676	CC0π	7843.47	8758
		CC1π	699.859	719	CC1π	760.61	748
		CCOther	1372.25	1533	CCOther	1493.52	1553
		Total	10355.379	10928		10097.60	11059
	FGD2	CC0π	7910.25	8608	CC0π	7487.96	8564
		CC1π	654.335	660	CC1π	676.52	693
		CCOther	1231.45	1396	CCOther	1336.53	1408
		Total	9796.035	10664		9501.01	10665
RHC ν_μ-bkg	FGD1	CC0π	3460.41	3714	CC0π	3232.69	3699
		CC1π	1212.69	1147	CC1π	1284.57	1260
		CC Other	1164.39	1425	CC Other	1274.21	1446
		Total	5837.49	6286		5791.47	6405
	FGD2	CC0π	3375.29	3537	CC0π	3184.23	3601
		CC1π	974.874	955	CC1π	1030.61	998
		CC Other	1101.85	1334	CC Other	1188.60	1339
		Total	5452.014	5826		5403.44	5938
Total			121093.868	130894		129290.34	148813

Effect of the new ND samples on the fit

TN495

- The fit is more constraining (log likelihood scans narrow)
- Some examples:
  - 2022
  - 2024

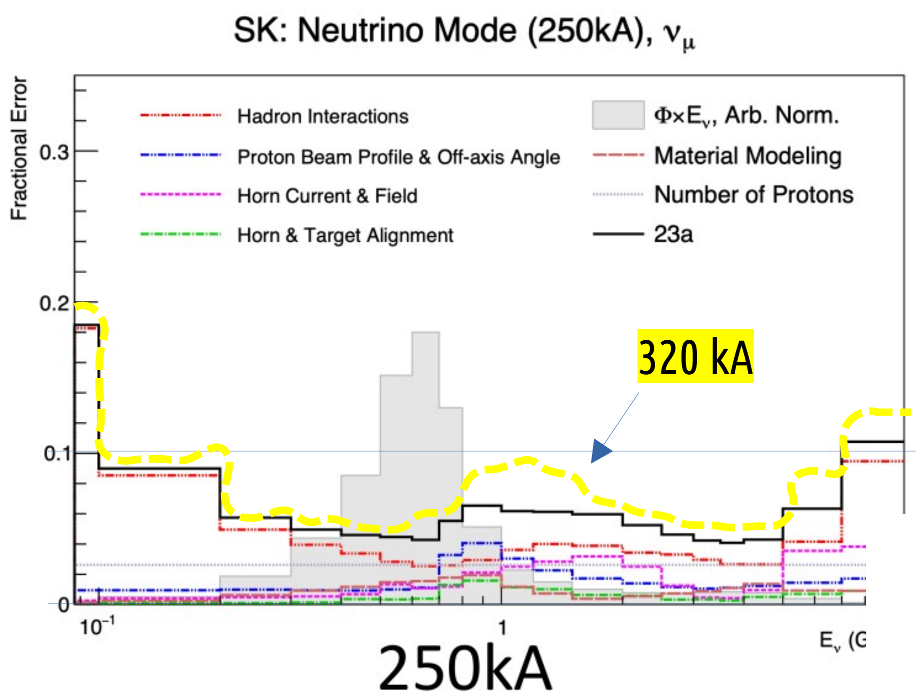
GUNDAM

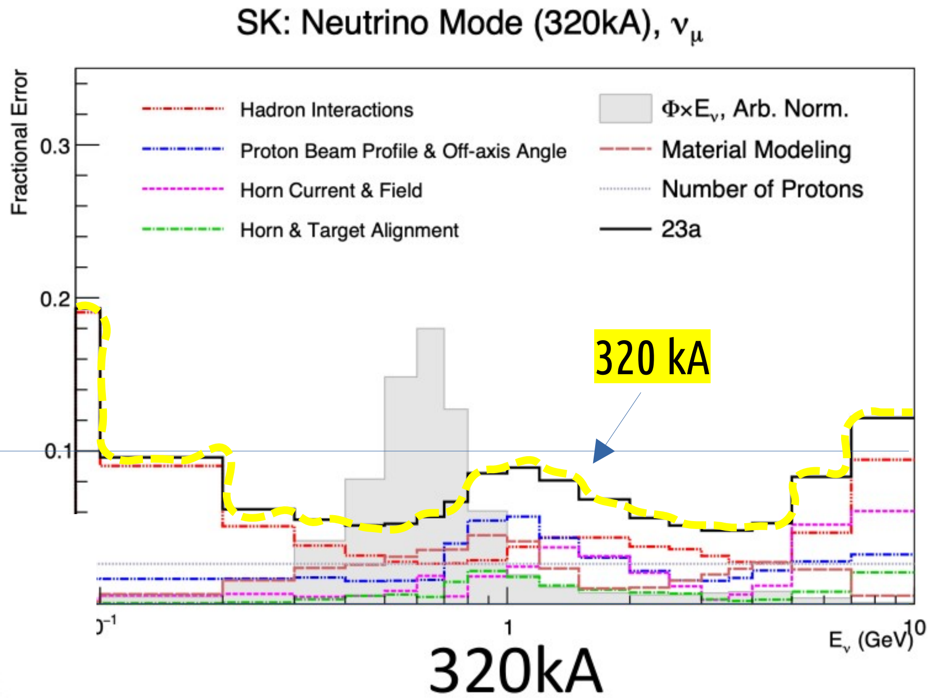


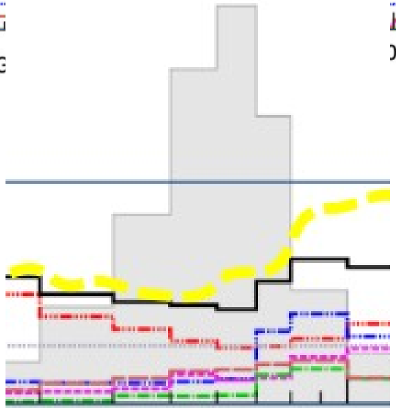
- addition in statistics and the fact that high-angle samples are ~ high-Q^2

Ewan Miller, Lena Iosu

Flux covariance matrix change







Uncertainty of 320 kA a little bit bigger especially in the high-energy tail but not dramatically.

Det. sys. splinificaction

4952

552

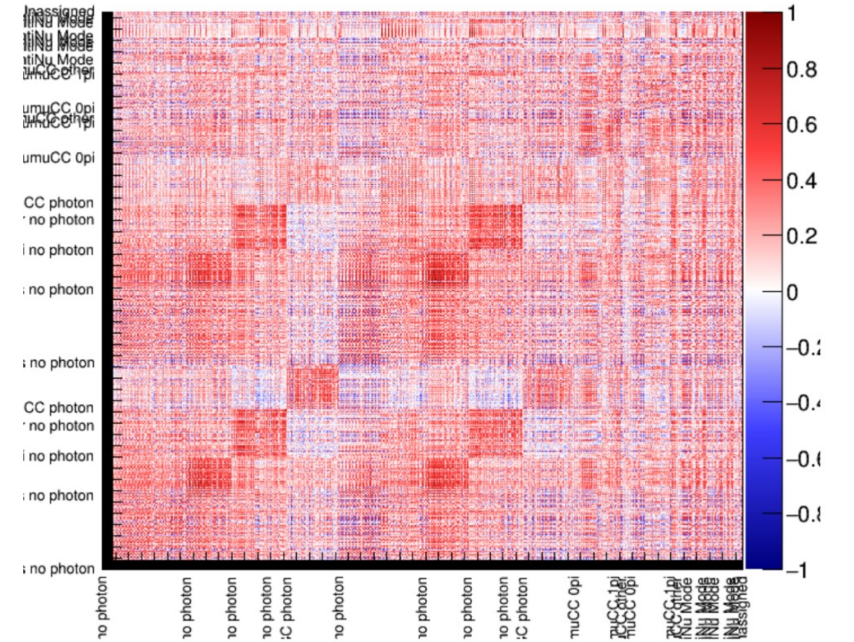


Figure 3: Matrix of correlations between bin contents calculated using 1,000 toy parameter throws

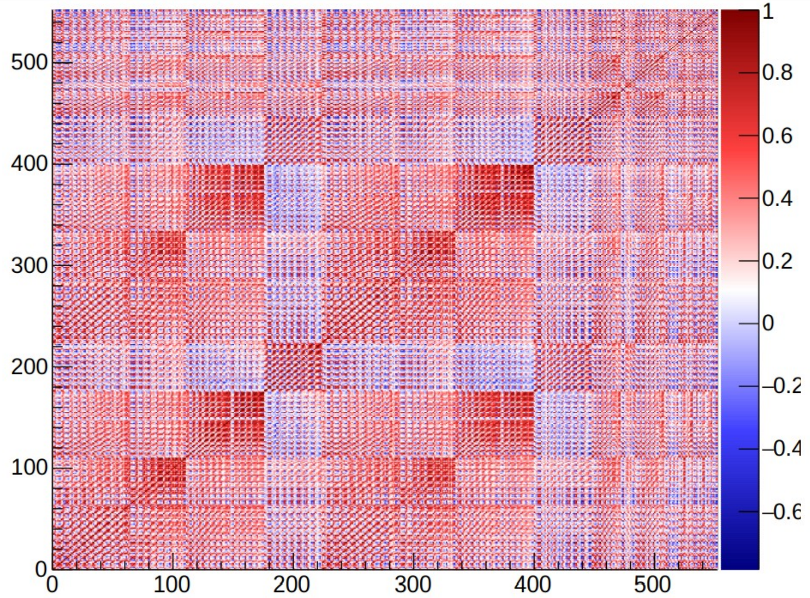


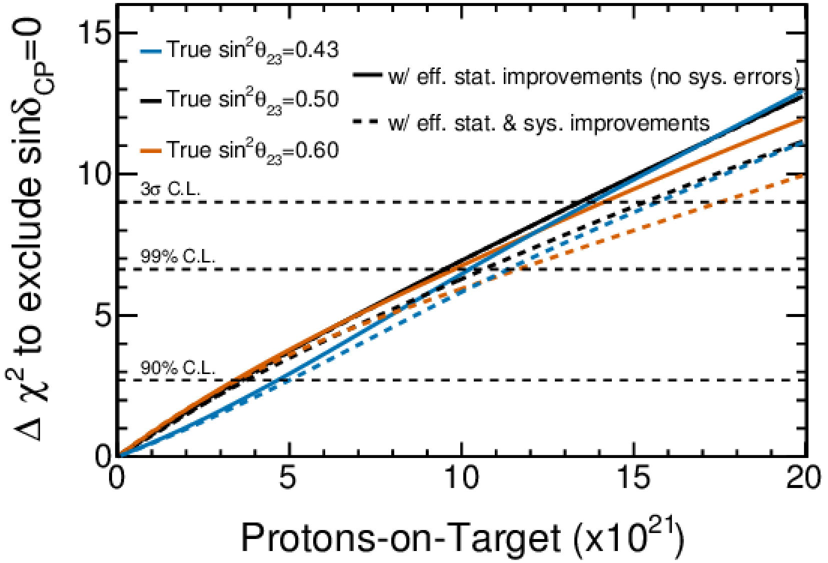
Figure 4: Matrix of correlations between merged bin normalisation parameters. The indices no longer correspond to individual bins but rather groups of bins.

Bin merging

E. Miller TN 464

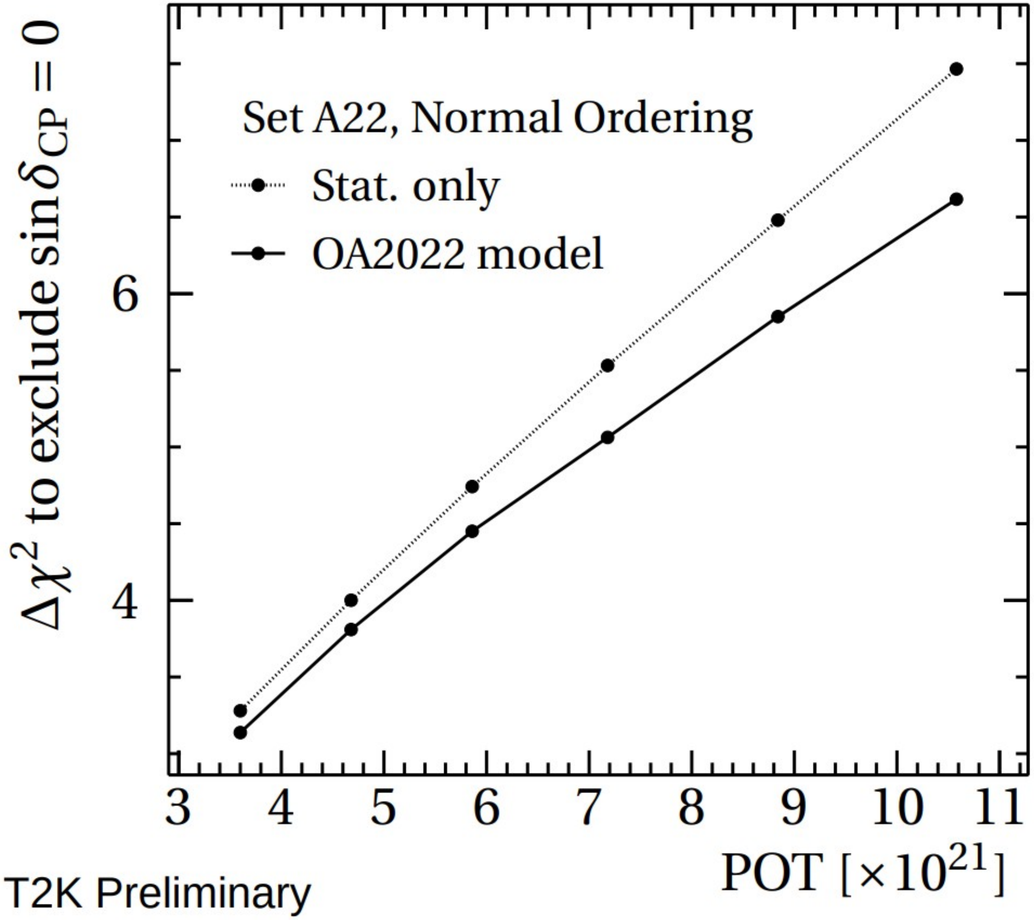
CP sensitivity updated plot

Based on Jaafar's studies
Use the new one for presentations!



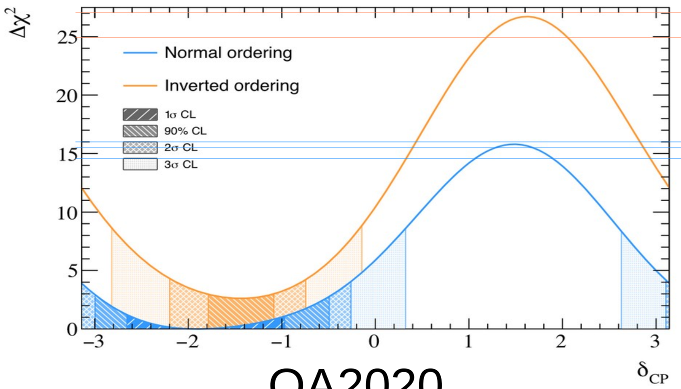
https://t2k.org/docs/plots/079

https://t2k.org/docs/plots/079/osc/images/sensitivities_1d_5.pdf

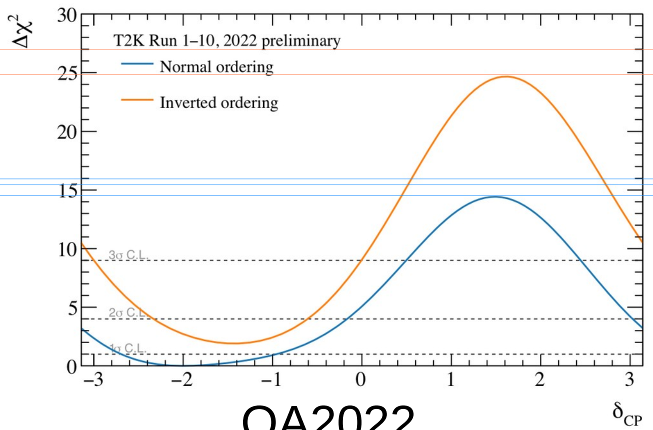


OA recent analyses at a glance

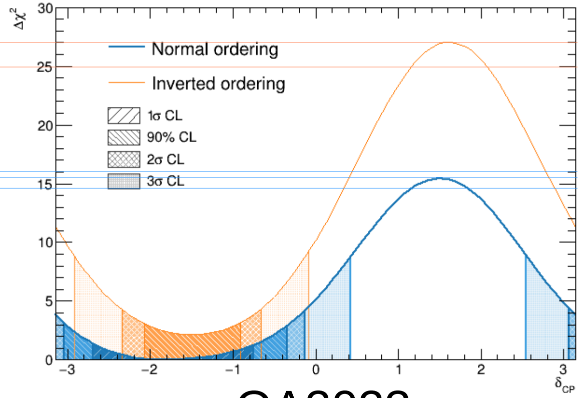
data



OA2020



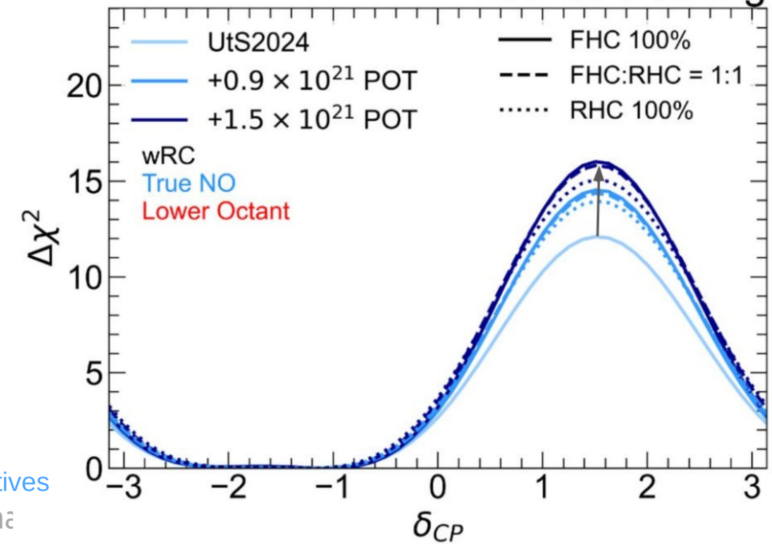
OA2022



OA2023

Link OA2020 https://t2k.org/docs/plots/063
Link OA2022 https://t2k.org/docs/plots/070
Link OA2023 https://t2k.org/docs/plots/077

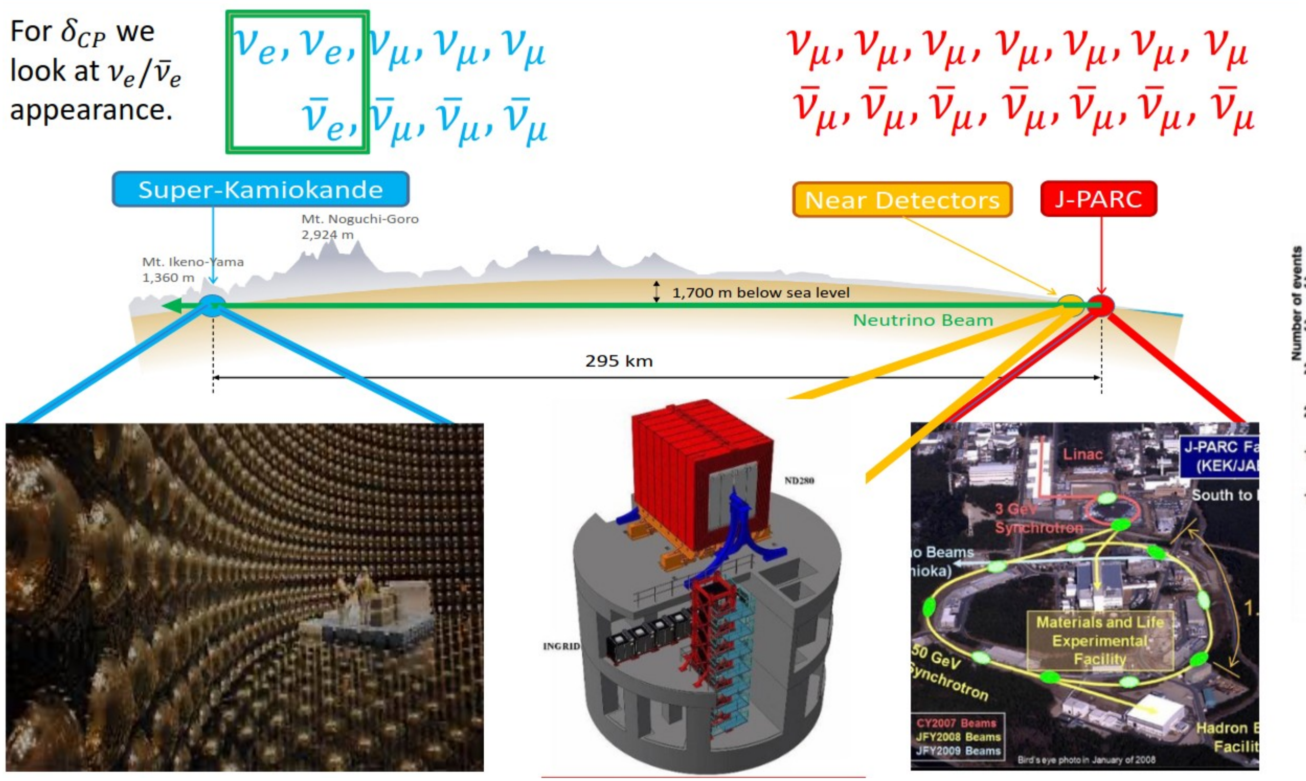
Eagerly "waiting" to transition to more "POT-driven" OA improvements! :)



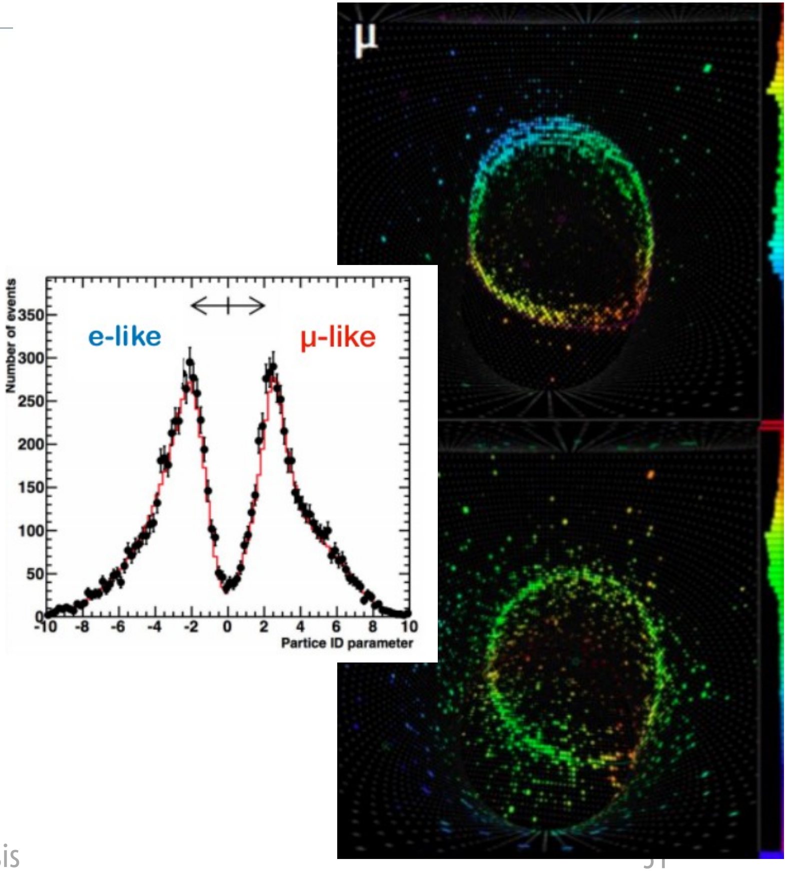
https://www.t2k.org/asg/meeting/2024/2024-07-18/post-summer-2024-sensitivity-studies-fhc-rhc-perspectives

Oscillation analysis with T2K

T2K uses difference in the process $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ to study the matter-antimatter asymmetry over a 295 km "travel".

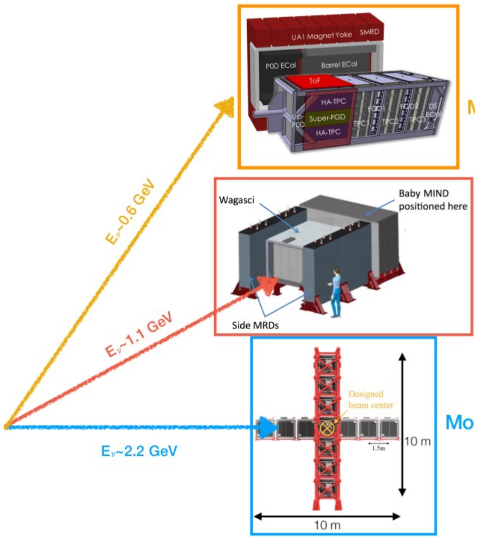


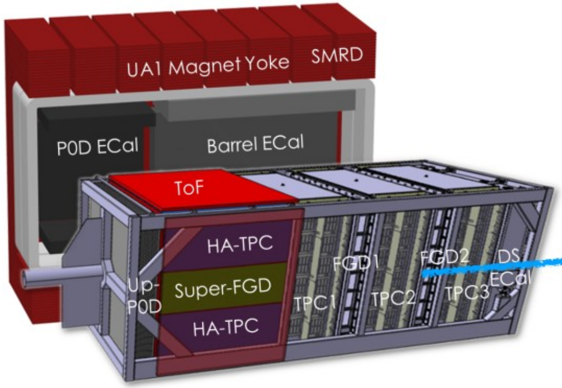
Super-Kamiokande can separate ν_μ from ν_e

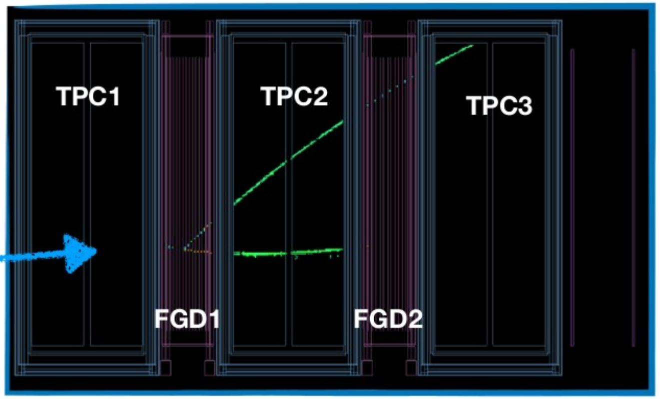


Near detectors → ND280

C. Giganti, Neutrino 2024







- Measure beam spectrum and flavor composition before the oscillations
- Detector installed inside the UA1/NOMAD magnet (0.2 T)
- An electromagnetic calorimeter to distinguish tracks from showers
- Upgraded in 2023 but for the analyses shown here the original tracker system is used:
  - 2 Fine Grained Detectors (target for ν interactions). FGD1 is pure scintillator, FGD2 has water layers interleaved with scintillator
  - 3 Time Projection Chambers: reconstruct momentum and charge of particles, PID based on measurement of ionization

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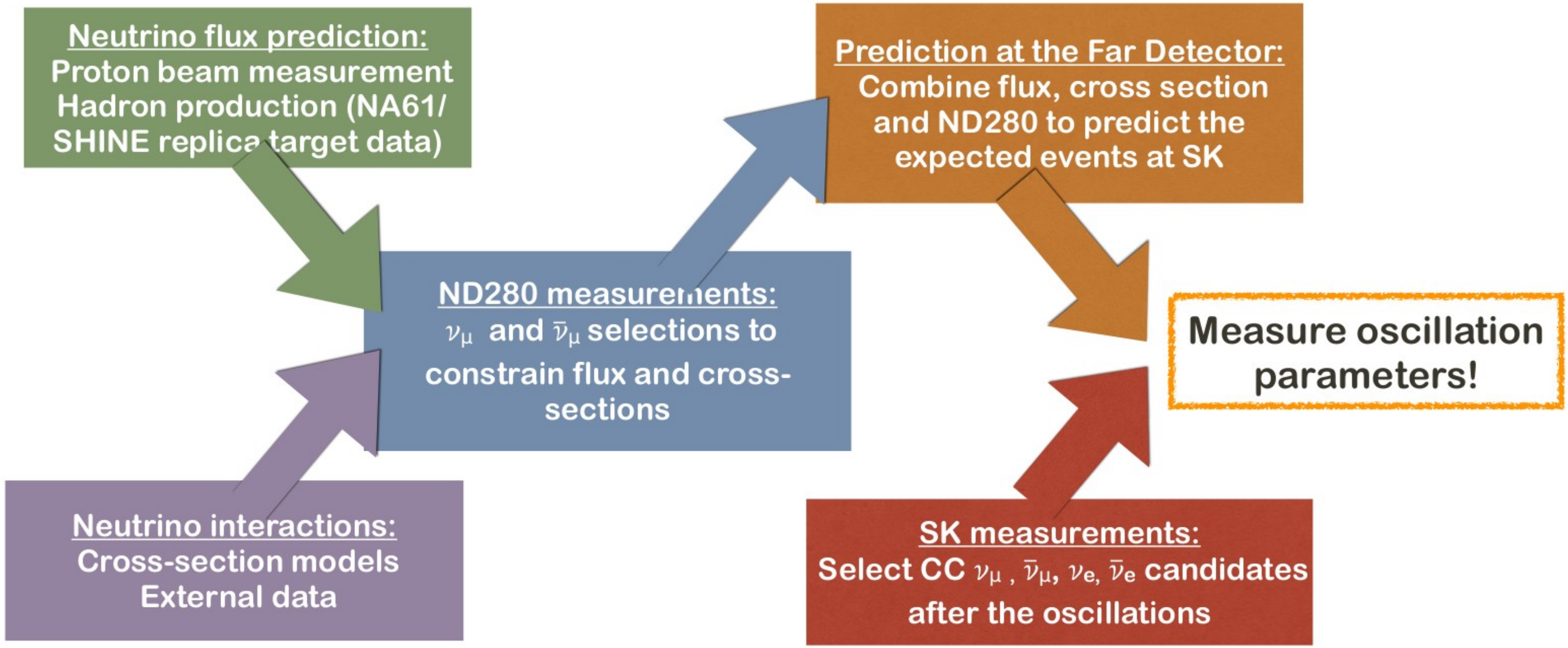
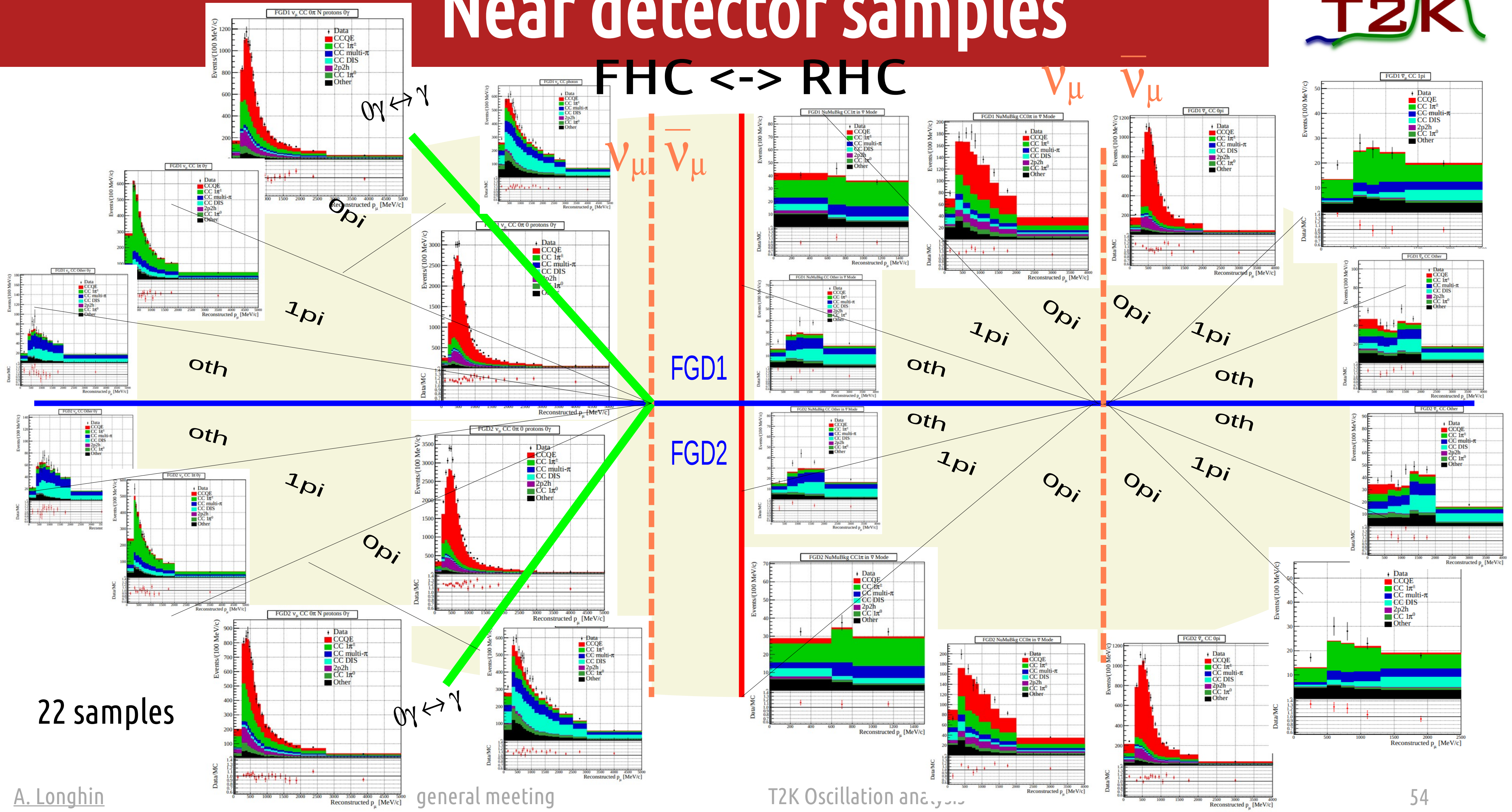
Oscillation analysis



Near and Far detector data are fitted either sequentially or simultaneously depending on the analysis considered

Near detector samples

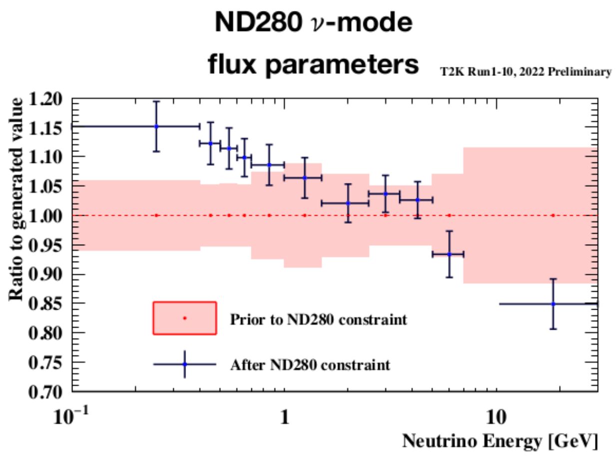
FHC <-> RHC

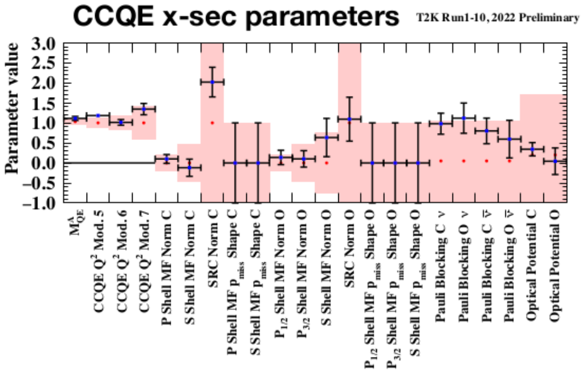


22 samples

ND fit

C. Giganti, Neutrino 2024

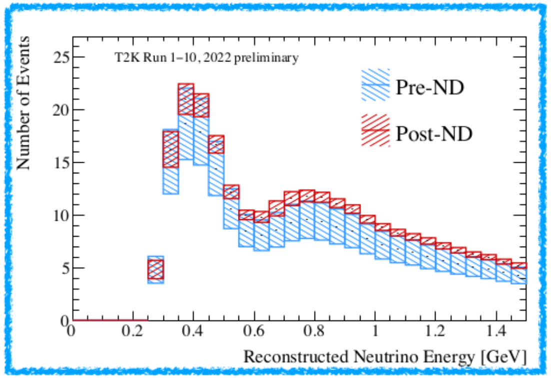




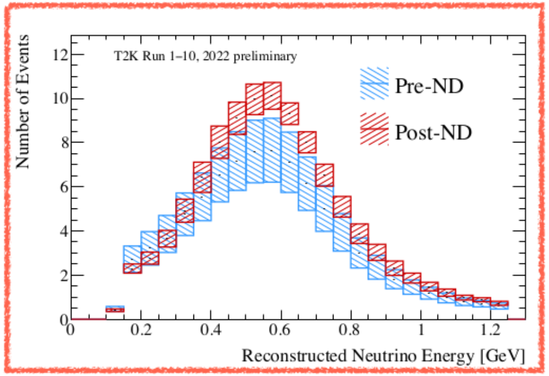
- Tune and reduce uncertainties from flux and cross-section systematics
- Correlate flux and cross-section to predict expected spectra at the Far Detector

Sample	Pre-ND fit	Post-ND fit
ν-mode 1Rμ	16.7%	3.4%
ν-mode 1Re	17.3%	5.2%
ν-mode MR	12.5%	4.9%
ν-mode 1Re+d.e.	20.9%	14.3%
$\bar{\nu}$-mode 1Rμ	14.6%	3.9%
$\bar{\nu}$-mode 1Re	14.4%	5.8%

SK Single ring μ-like sample



SK single ring e-like sample



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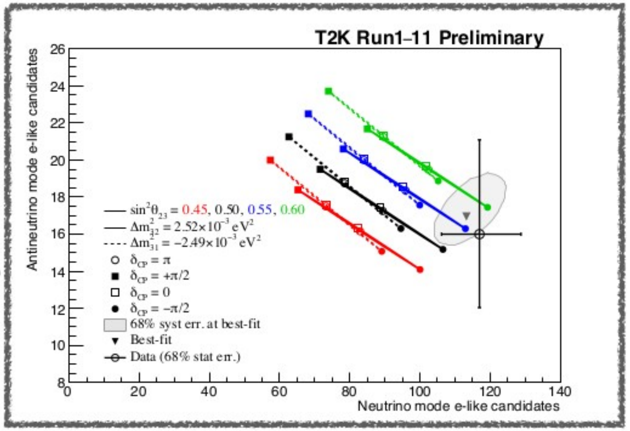
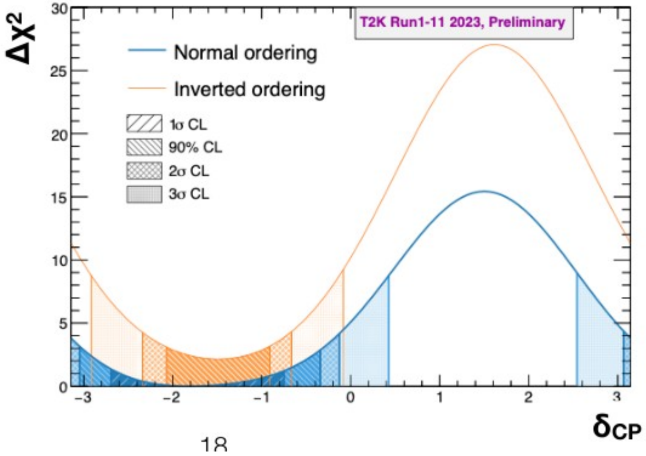
Results on δ_{CP}

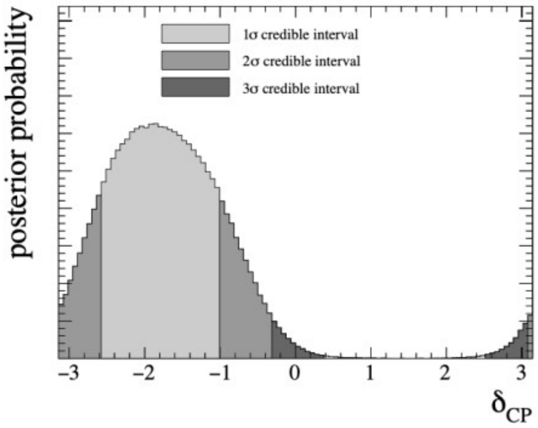
Sample	δ_{CP}=-π/2	δ_{CP}=0	δ_{CP}=π/2	δ_{CP}=π	Data
ν-mode 1Rμ	417.2	416.3	417.1	418.2	357
ν-mode MR	123.9	123.3	123.9	124.4	140
$\bar{\nu}$-mode 1Rμ	146.6	146.3	146.6	147.0	137
ν-mode 1Re	113.2	95.5	78.3	96.0	102
$\bar{\nu}$-mode 1Re+d.e.	10.0	8.8	7.2	8.4	15
$\bar{\nu}$-mode 1Re	17.6	20.0	22.2	19.7	16



- Preference for δ_{CP}~-π/2 but CP conserving values are within the 2σ interval



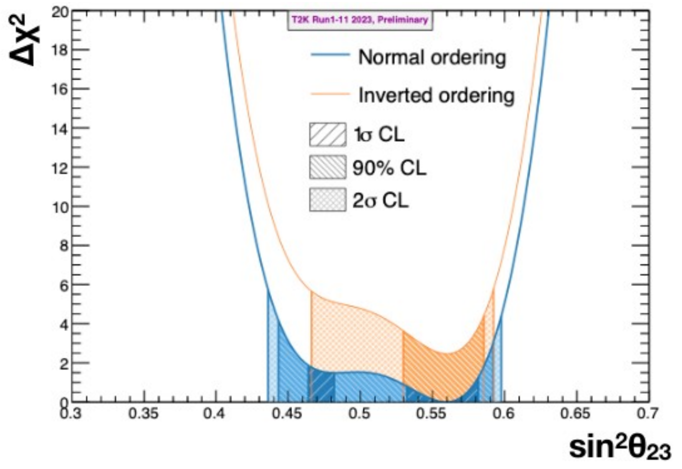
Credible intervals marginalized over both hierarchies

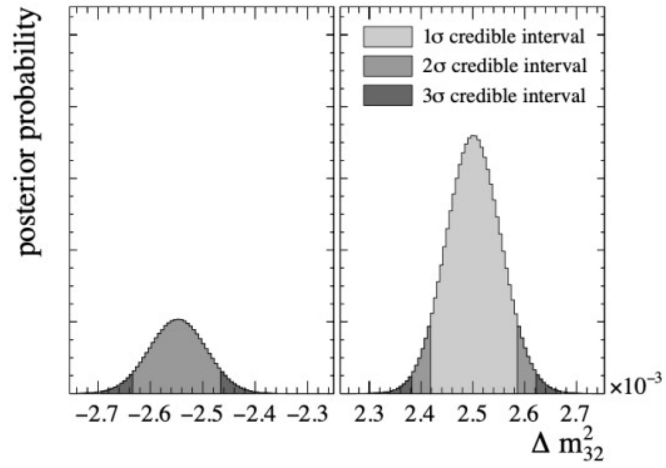


Mass ordering and θ_{23} octant

- Slight preference for normal ordering and upper octant but none of them is significant
  - Bayes factor NO/IO = 3.3
  - Bayes factor $(\theta_{23}>0.5)/(\theta_{23}<0.5) = 2.6$

	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Sum
NH $(\Delta m^2_{32} > 0)$	0.23	0.54	0.77
IH $(\Delta m^2_{32} < 0)$	0.05	0.18	0.23
Sum	0.28	0.72	1.00





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Z. Xie, L. Berns poster

arXiv:2405.12488

Results

- Both experiments individually prefer normal ordering and $\delta_{CP}\sim-\pi/2$, T2K prefers upper octant, SK prefer lower octant
- We performed Bayesian and Frequentist analyses → frequentist analyses shown today
- The CP-conserving value of the Jarlskog invariant is excluded with a significance between 1.9 and 2 σ
- In the frequentist analysis, p-value for CPC is 0.037 but increase to 0.05 when potential biases due to cross-section mis-modeling are included
- Normal ordering is preferred, p-value for IO 0.08