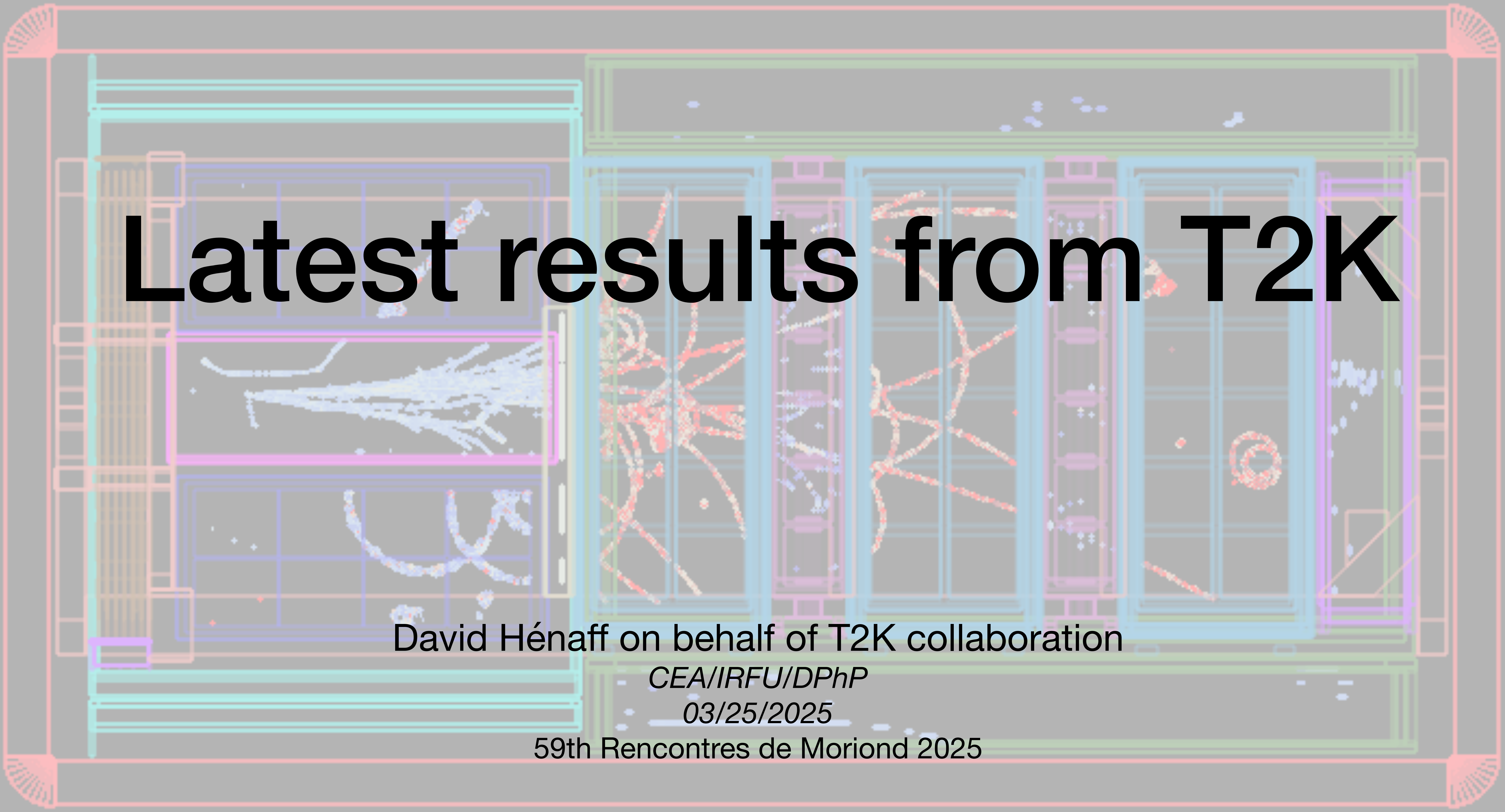

Latest results from T2K

David Hénaff on behalf of T2K collaboration
CEA/IRFU/DPhP
03/25/2025
59th Rencontres de Moriond 2025

Outline

- ν oscillation for accelerator long baseline
- T2K Oscillation analysis
- Joint oscillation analyses
- T2K Cross-section results
- T2K upgrades

Long baseline accelerator

ν oscillation:

Atmospheric — Reactor — Solar

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

$\theta_{23} \approx 45°$ — $\theta_{13} \approx 10°$ — $\theta_{12} \approx 35°$

Atmospheric exp. — *Reactor* — *Solar exp.*

Reactor LBL

Accelerator LBL

- Oscillation is parametrized by: $sin^2\theta_{ij}$, Δm^2_{ij}, δ_{CP}
  - Depends also on experimental condition: L/E, medium crossed (Matter effect => Mass ordering)

Long baseline accelerator

ν oscillation:

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \underbrace{\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}}_{\text{Atmospheric}} \underbrace{\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{pmatrix}}_{\text{Reactor}} \underbrace{\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}}_{\text{Solar}} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}.$$

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$\theta_{13} \approx 10°$ — *Reactor*

$\theta_{12} \approx 35°$ — *Solar exp.*

Accelerator LBL

Reactor LBL

- Oscillation is parametrized by: $sin^2\theta_{ij}$, Δm^2_{ij}, δ_{CP}
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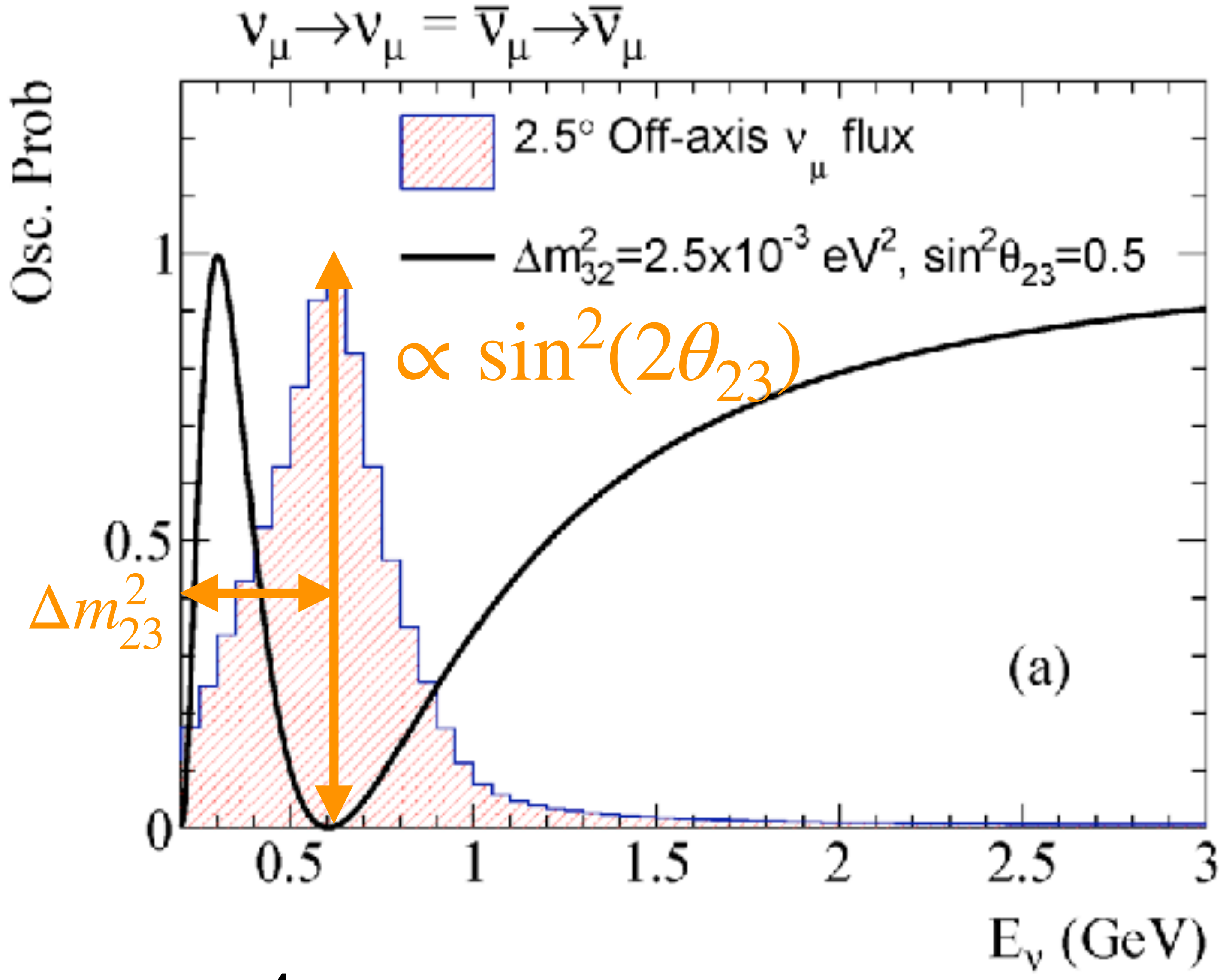
Oscillation at long baseline:

- Produce $\nu_\mu/\overline{\nu_\mu}$ beam and perform the measurement of rate, energy and flavor before and after oscillation

<u>*Disappearance channel*</u>

$$P(\nu_\mu \to \nu_\mu) = P(\frac{L}{E}; \theta_{23}, \Delta m^2_{32})$$



Long baseline accelerator

ν oscillation:

Atmospheric | Reactor | Solar

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

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Atmospheric exp. | *Reactor* | *Solar exp.*

Accelerator LBL | *Reactor LBL*

- Oscillation is parametrized by: $sin^2\theta_{ij}$, Δm^2_{ij}, δ_{CP}
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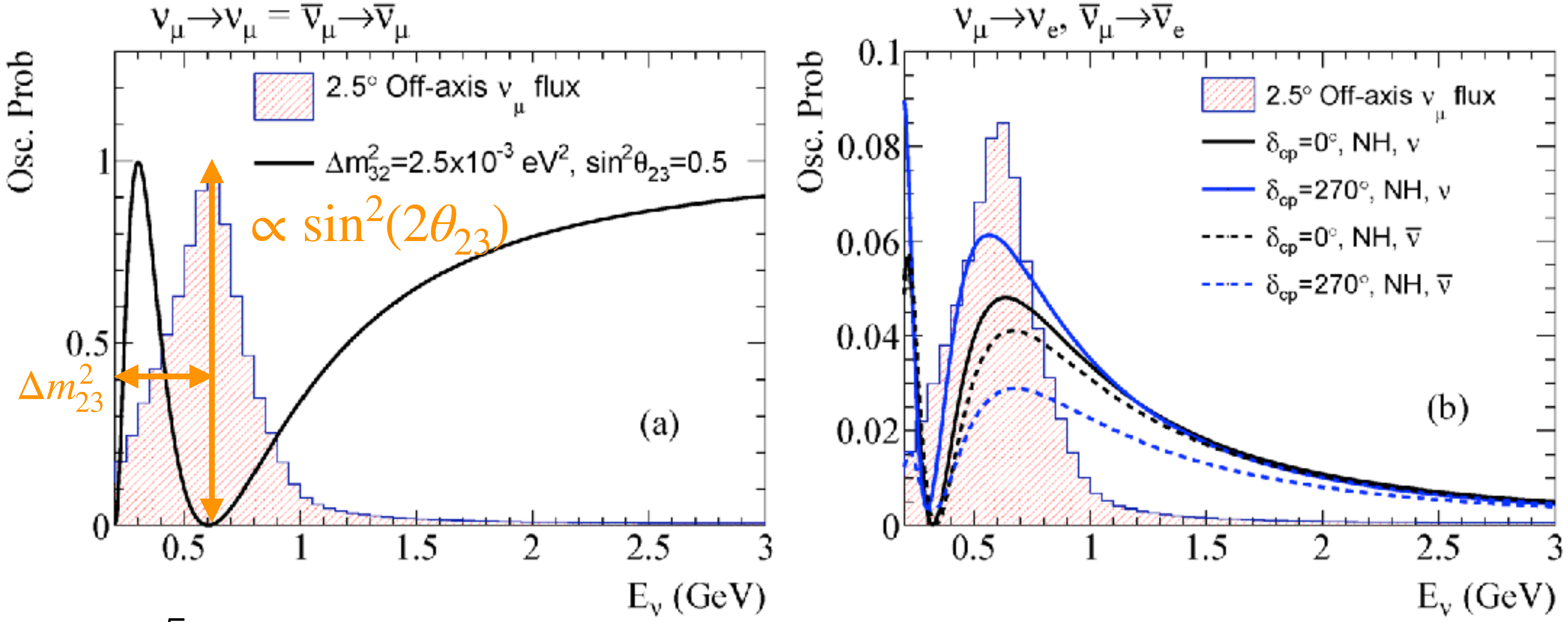
$$P(\nu_\mu \rightarrow \nu_\mu) = P(\frac{L}{E}; \theta_{23}, \Delta m^2_{32})$$

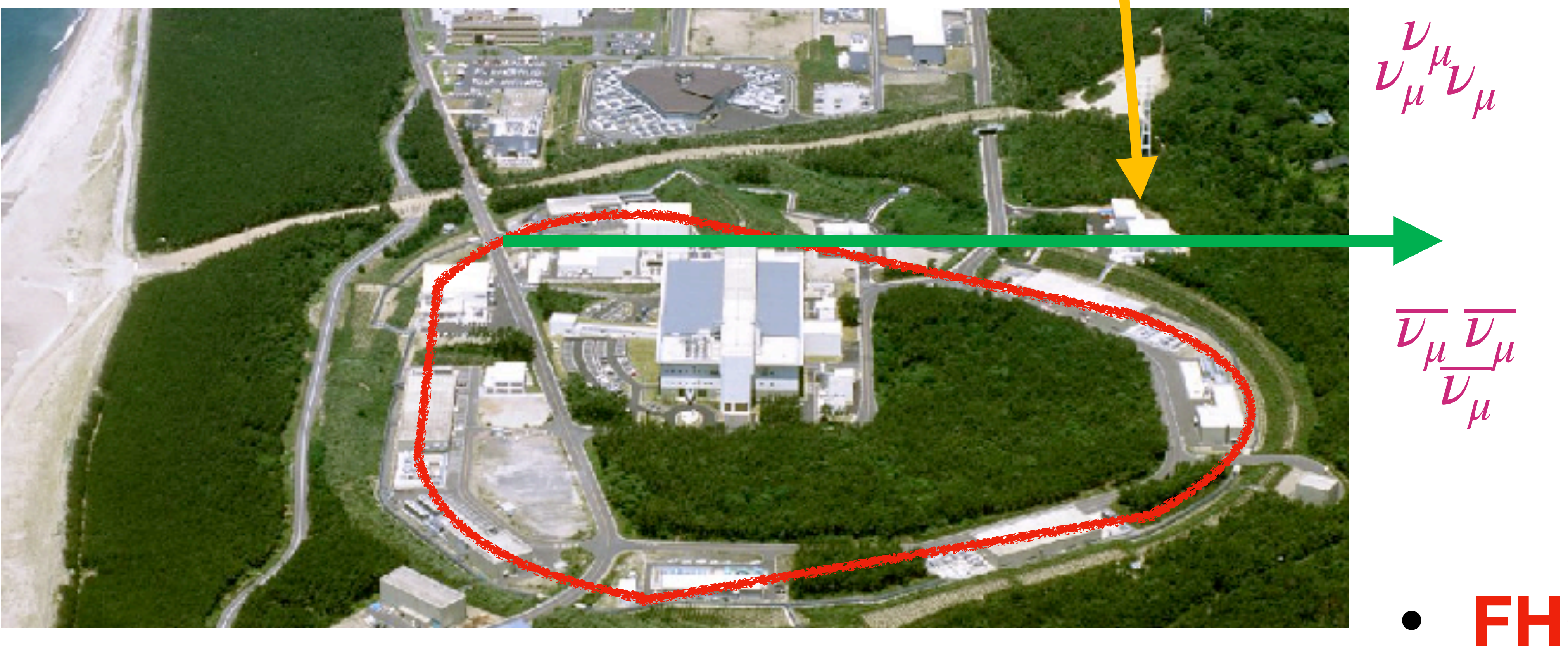
<u>*Appearance channel*</u>

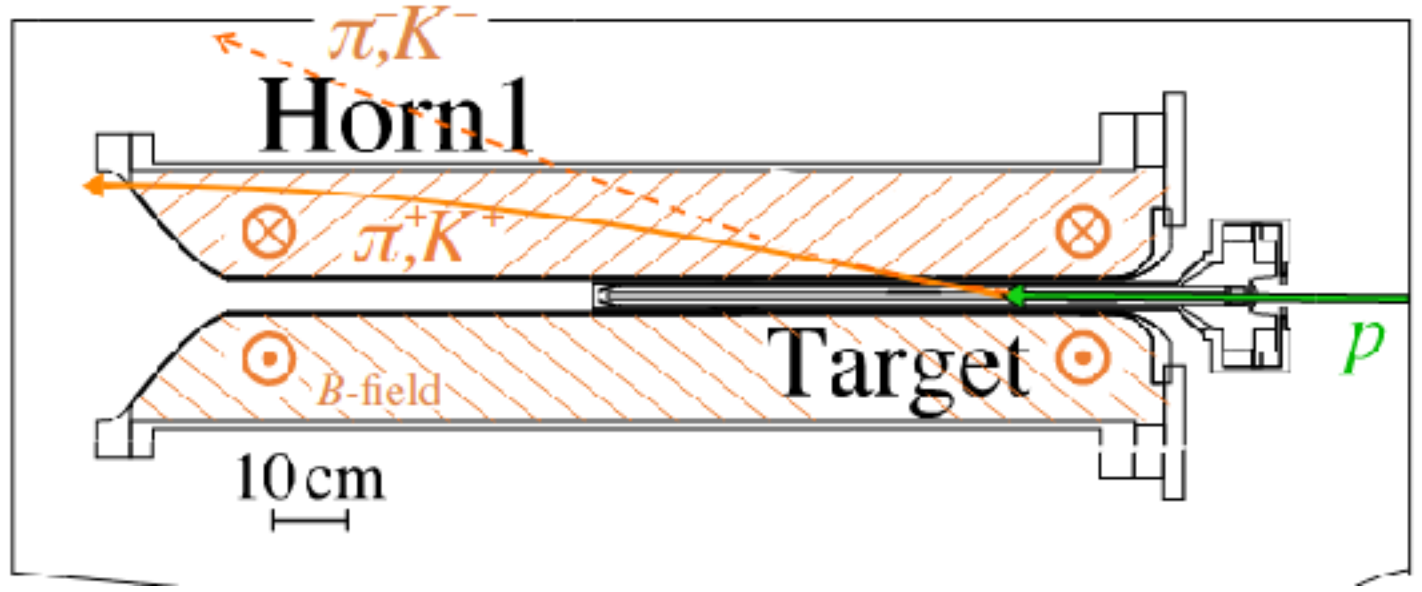
$$P(\overset{(-)}{\nu_\mu} \rightarrow \overset{(-)}{\nu_e}) = P(\frac{L}{E}; \theta_{23}, \theta_{13}, \Delta m^2_{21}, \Delta m^2_{23}, \pm \sin\delta_{CP})$$



- Exclusion of $\delta_{CP} = 0, \pi$? ; **Value of δ_{CP}?**
- Mass ordering (**sign of Δm^2_{32}?**)
- Octant of θ_{23} -> (<0.5, >0.5, maximal)?

T2K experiment

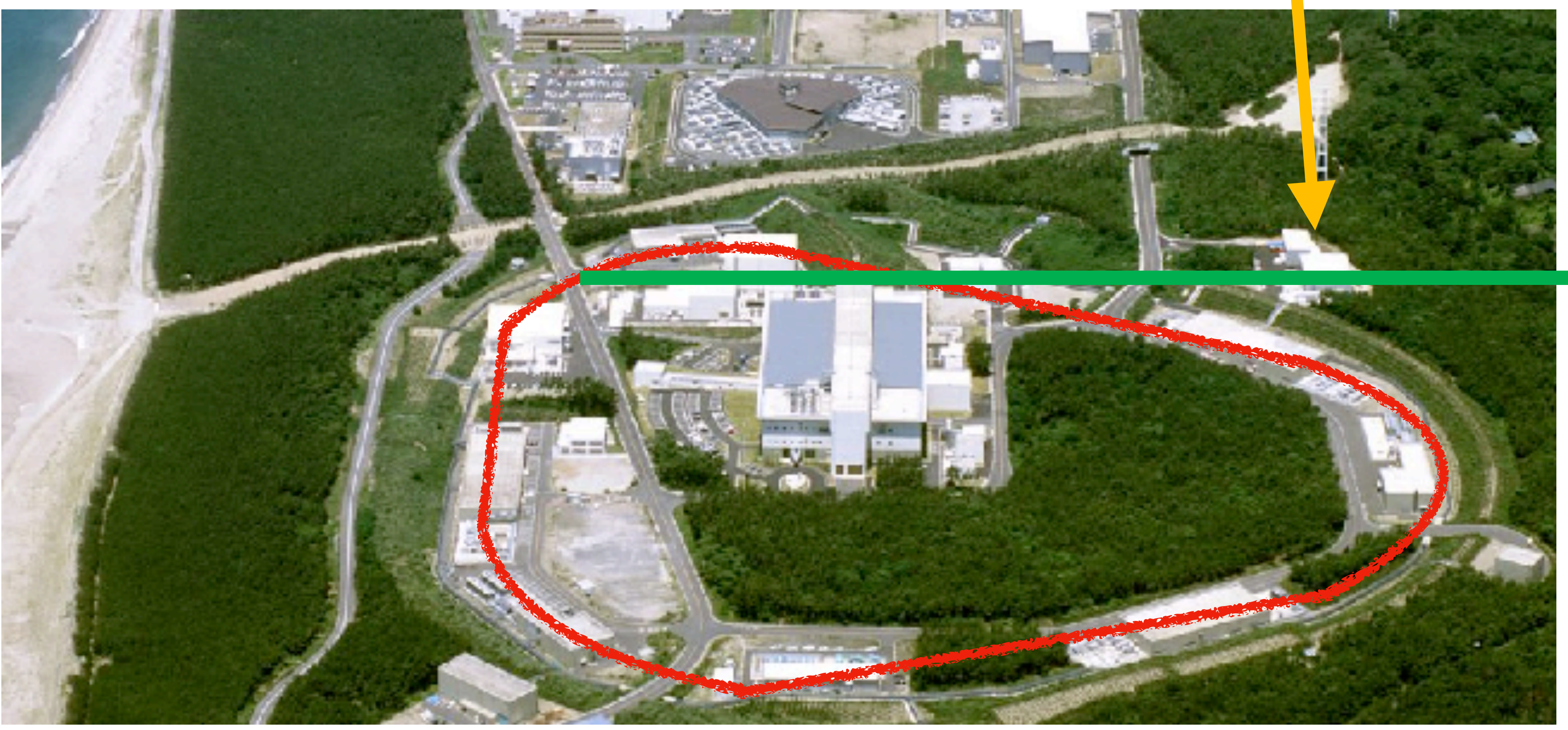


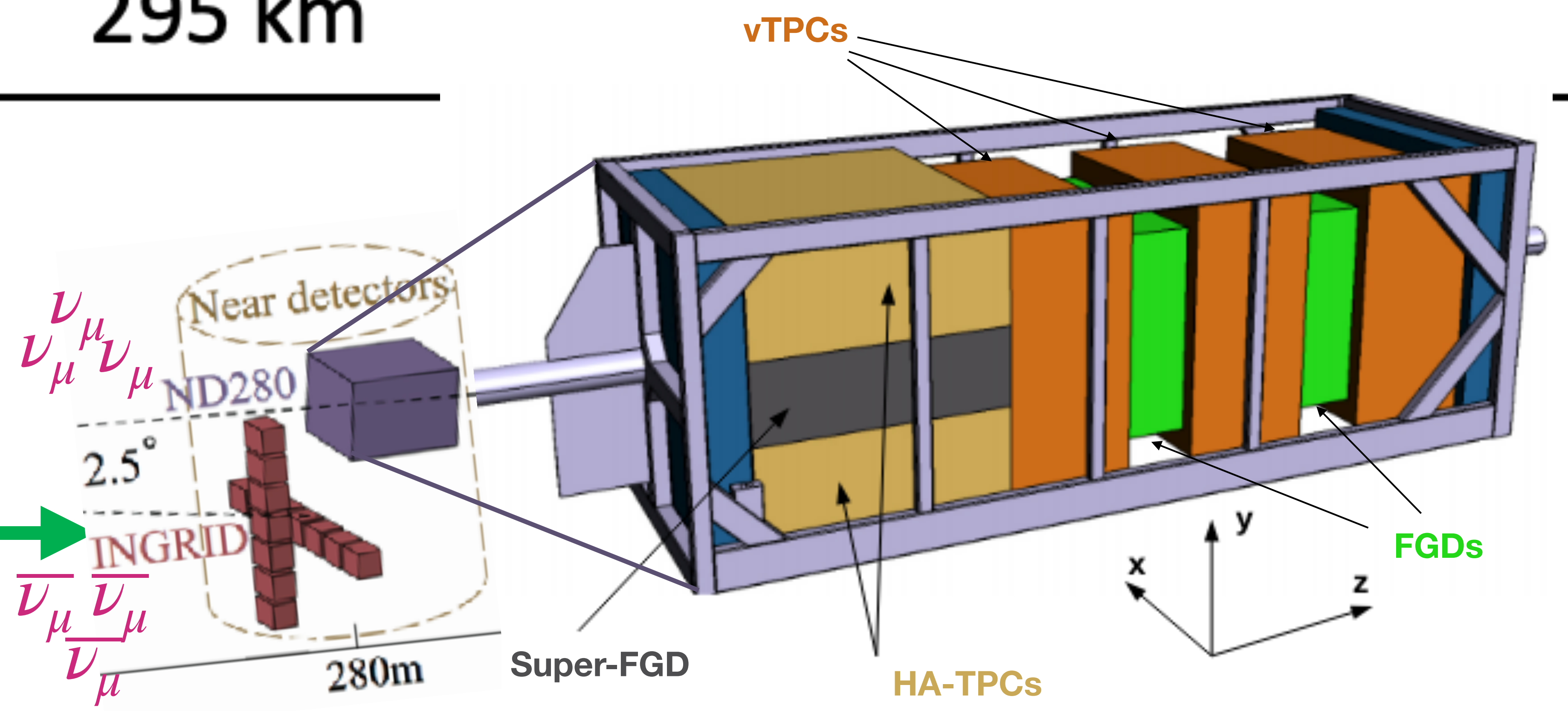


- **FHC, RHC precise**

- **Beam:** 30 GeV protons on a graphite target, producing Kaons and Pions

T2K experiment

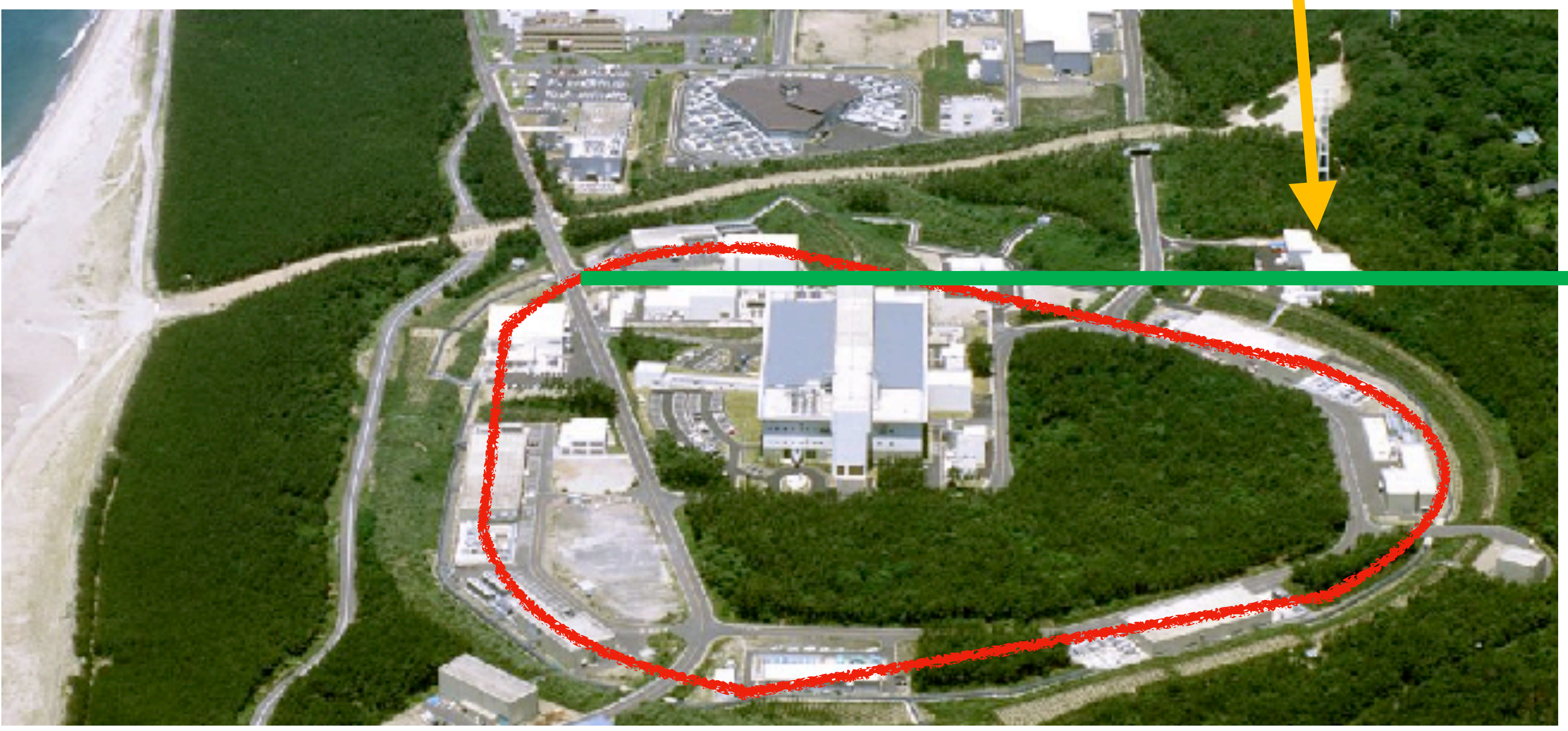


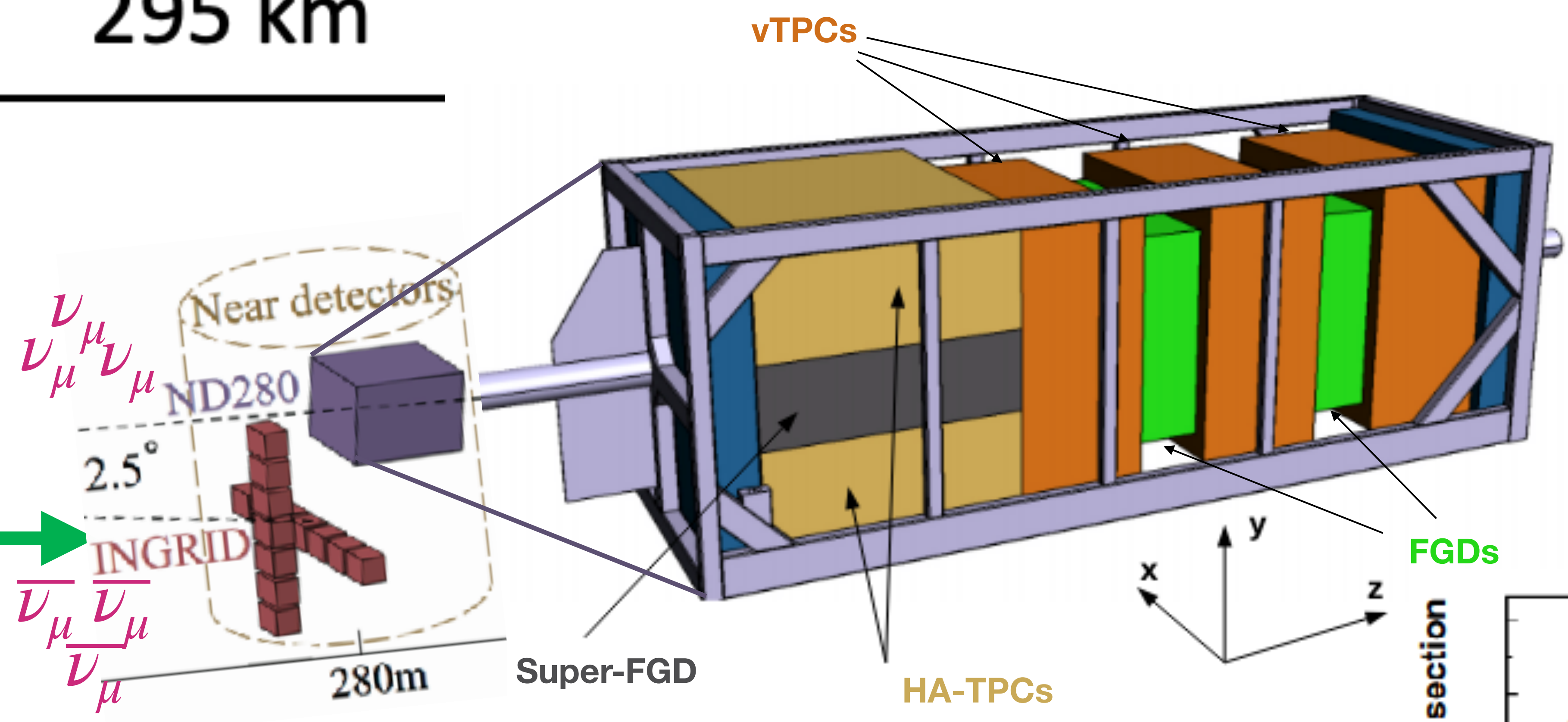


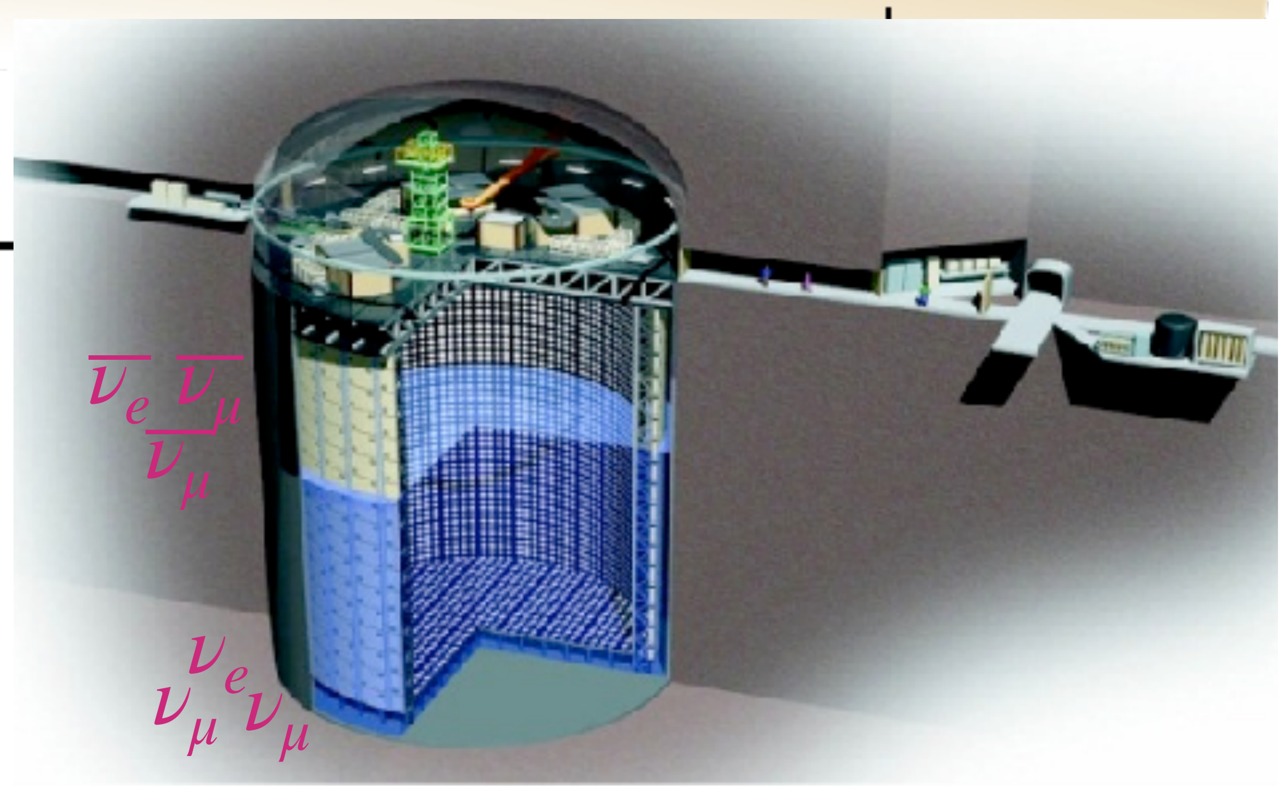
- **Beam:** 30 GeV protons on a graphite target, producing Kaons and Pions

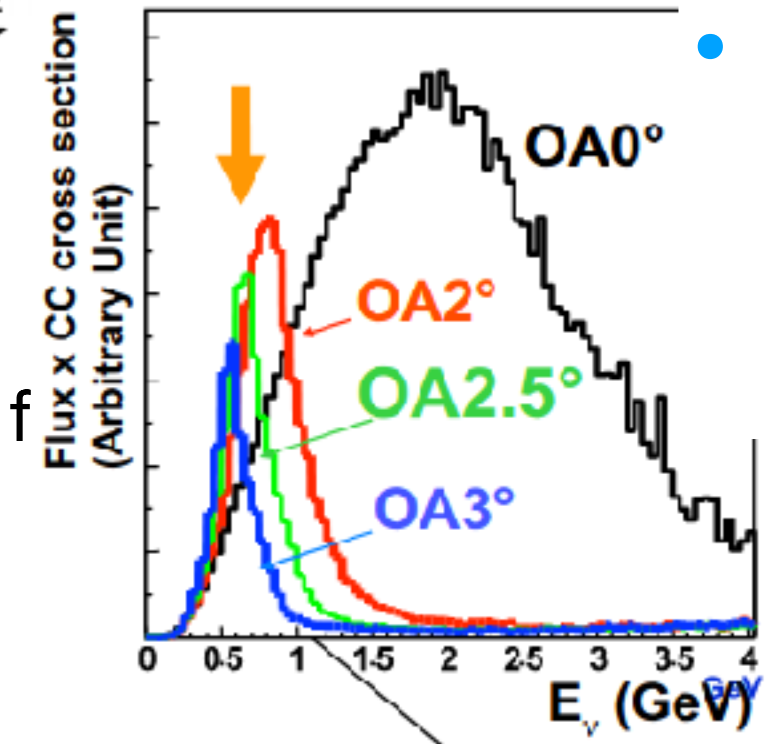
- **ND site:** *on and off axis detectors:*
    - Beam monitoring
    - Tune flux & interaction models predictions for OA
    - ν cross-sections
    - Magnetized 0.2T
    - Upgraded ND280 completed

T2K experiment









- **Beam:** 30 GeV protons on a graphite target, producing Kaons and Pions

- **ND site:** *on and off axis detectors:*
  - Beam monitoring
  - Tune flux & interaction models predictions f
  - ν cross-sections
  - Magnetized 0.2T
  - Upgraded ND280 completed

- **FD site:**
  - Super-Kamiokande
  - 50kton water Cherenkov detector

T2K oscillation analysis

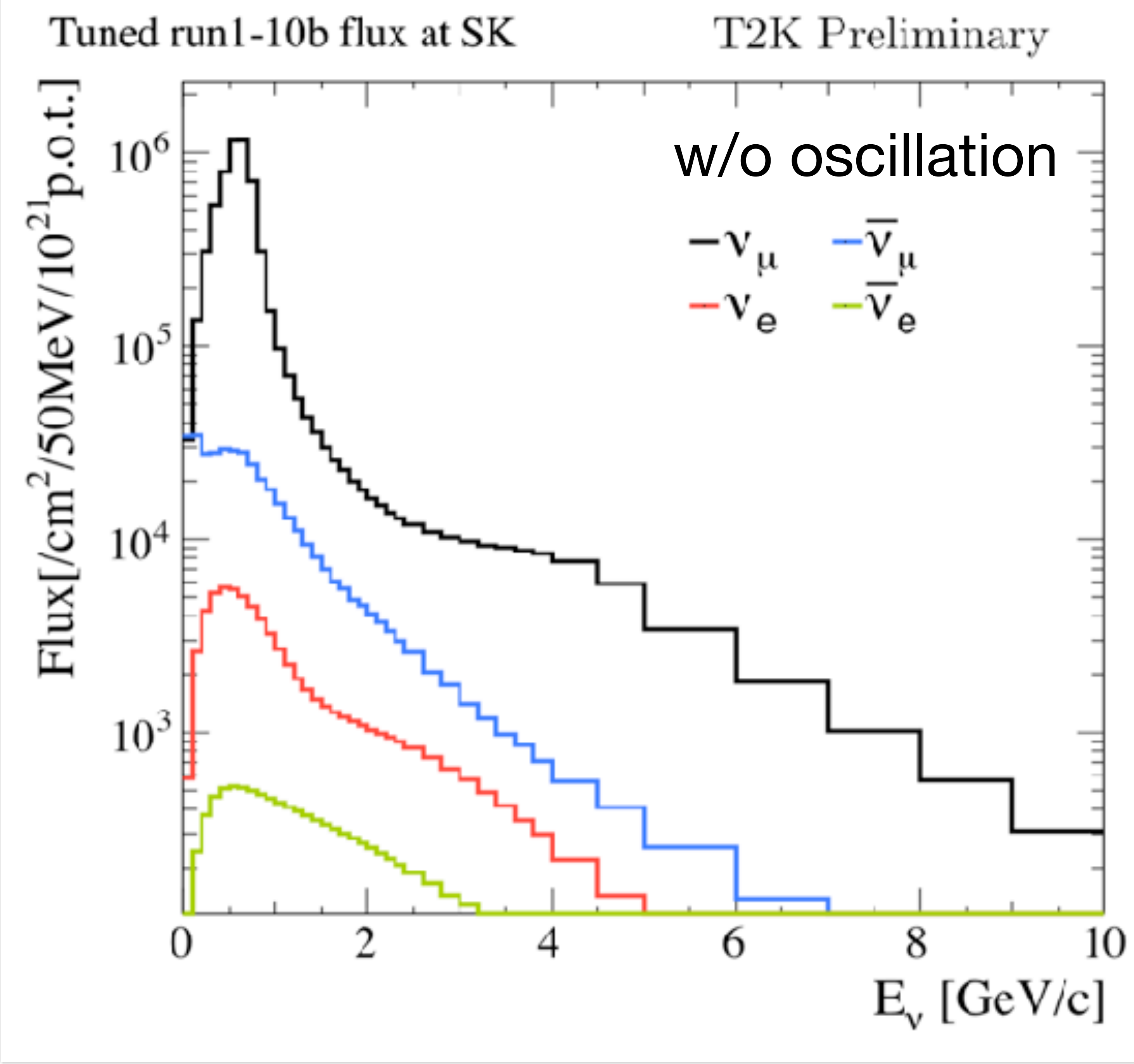
Frequentist approach (Bayesian also available)

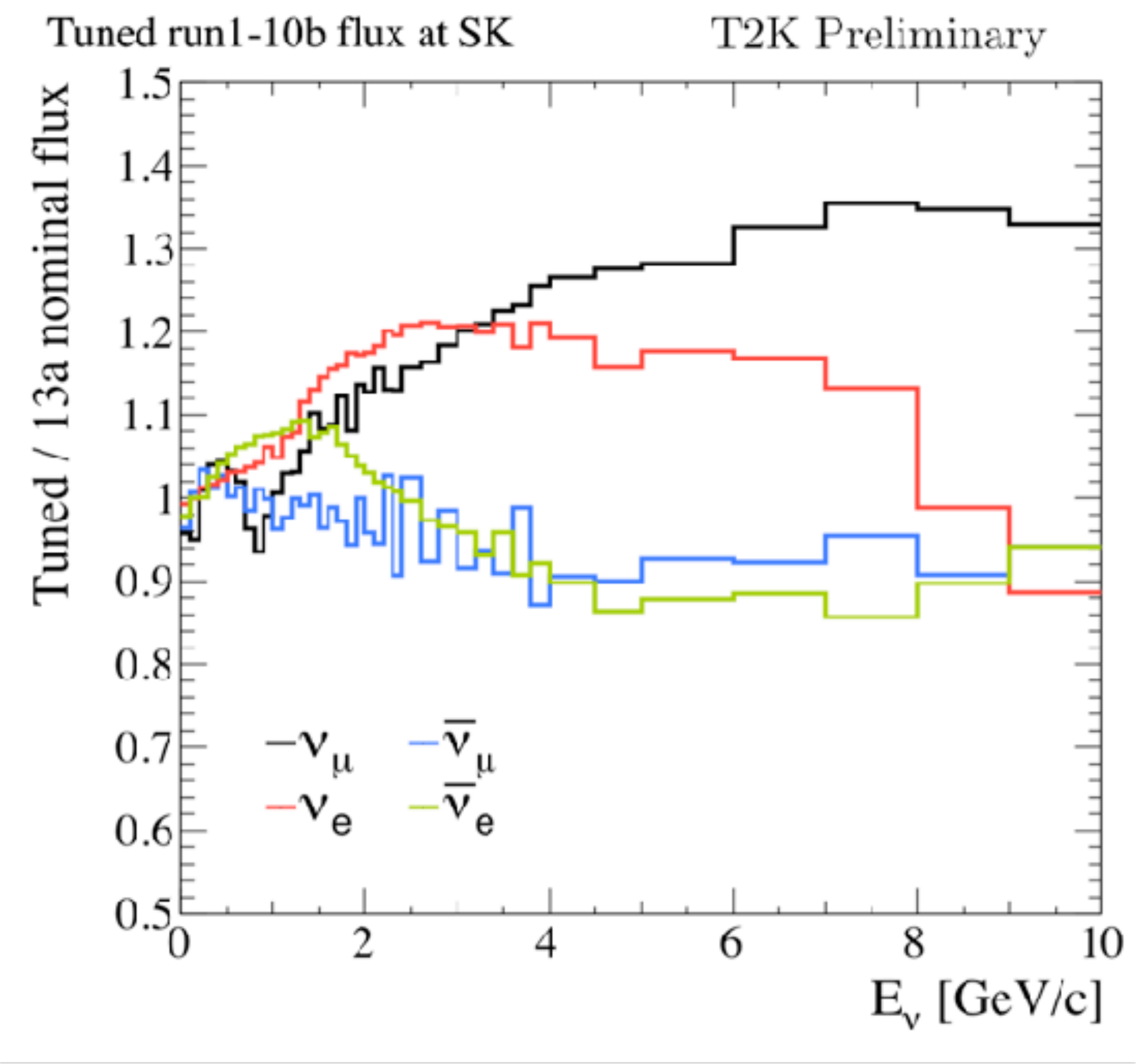
Sequential fit of ND and then FD data

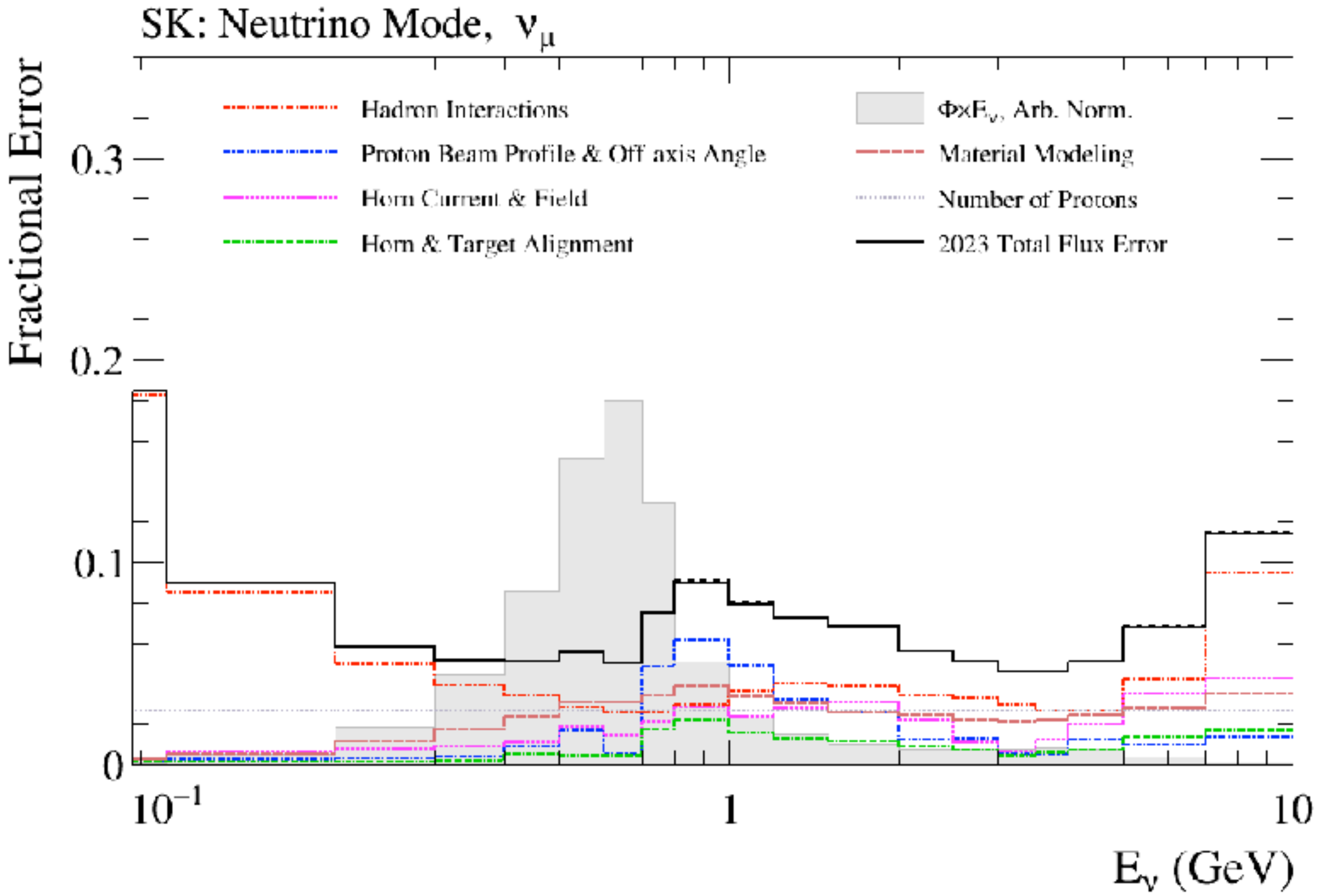
Flux Prediction
Proton beam measurement with NA61/SHINE inputs

Flux:

- Clear impact of tuning
- Error below 10% at T2K energies







T2K oscillation analysis

Frequentist approach (Bayesian also available)

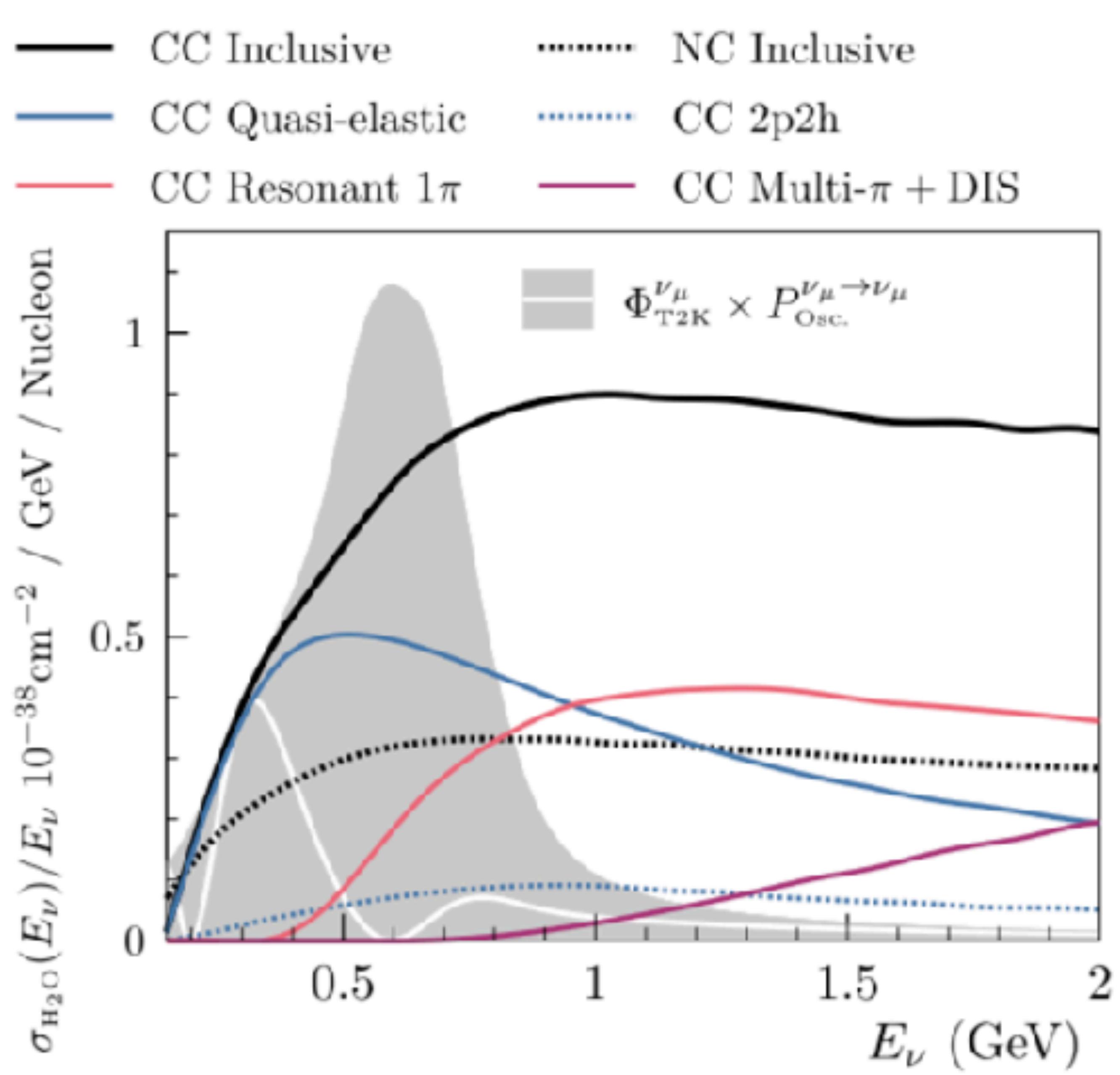
Sequential fit of ND and then FD data

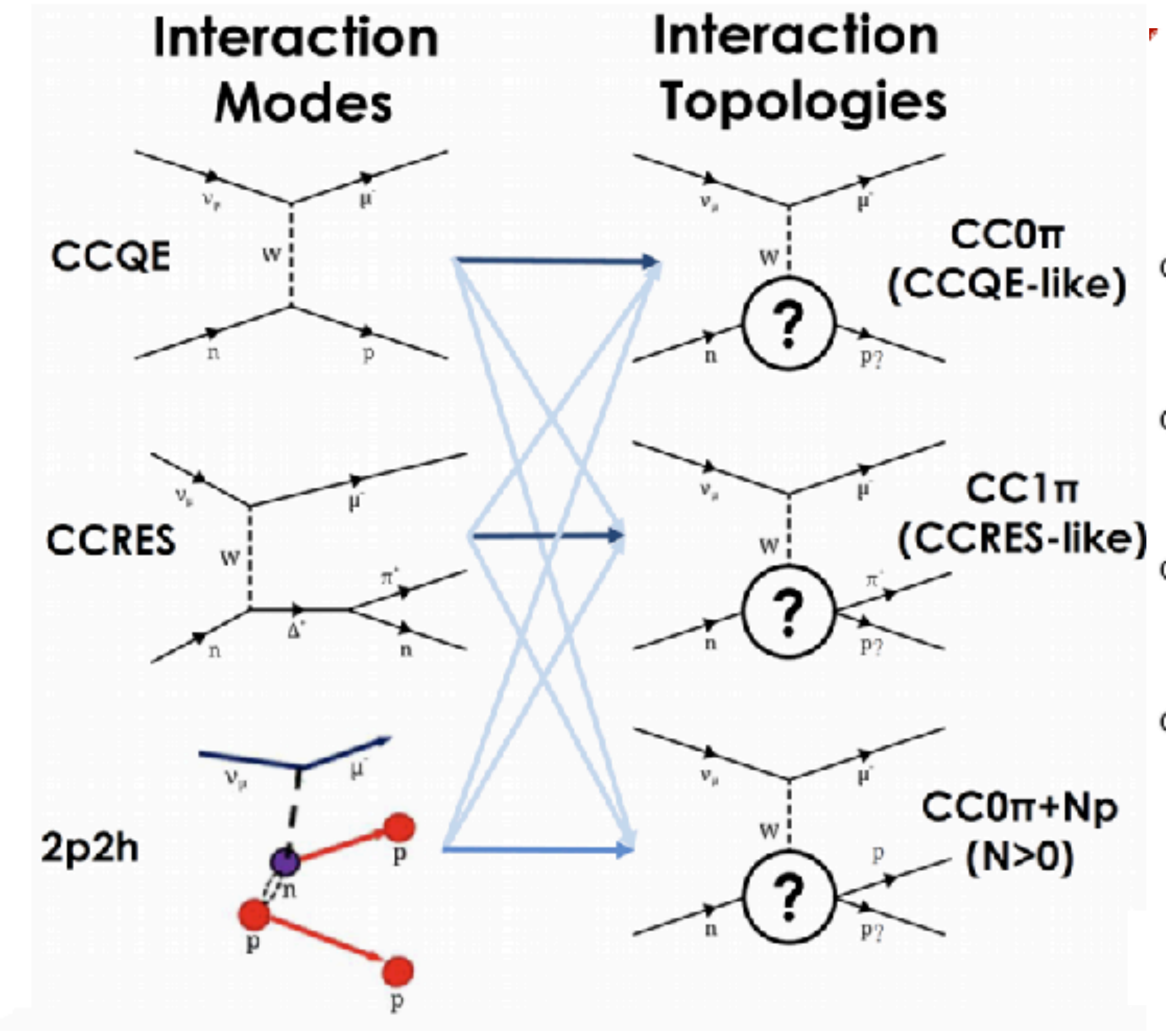
Flux Prediction
Proton beam measurement with NA61/SHINE inputs

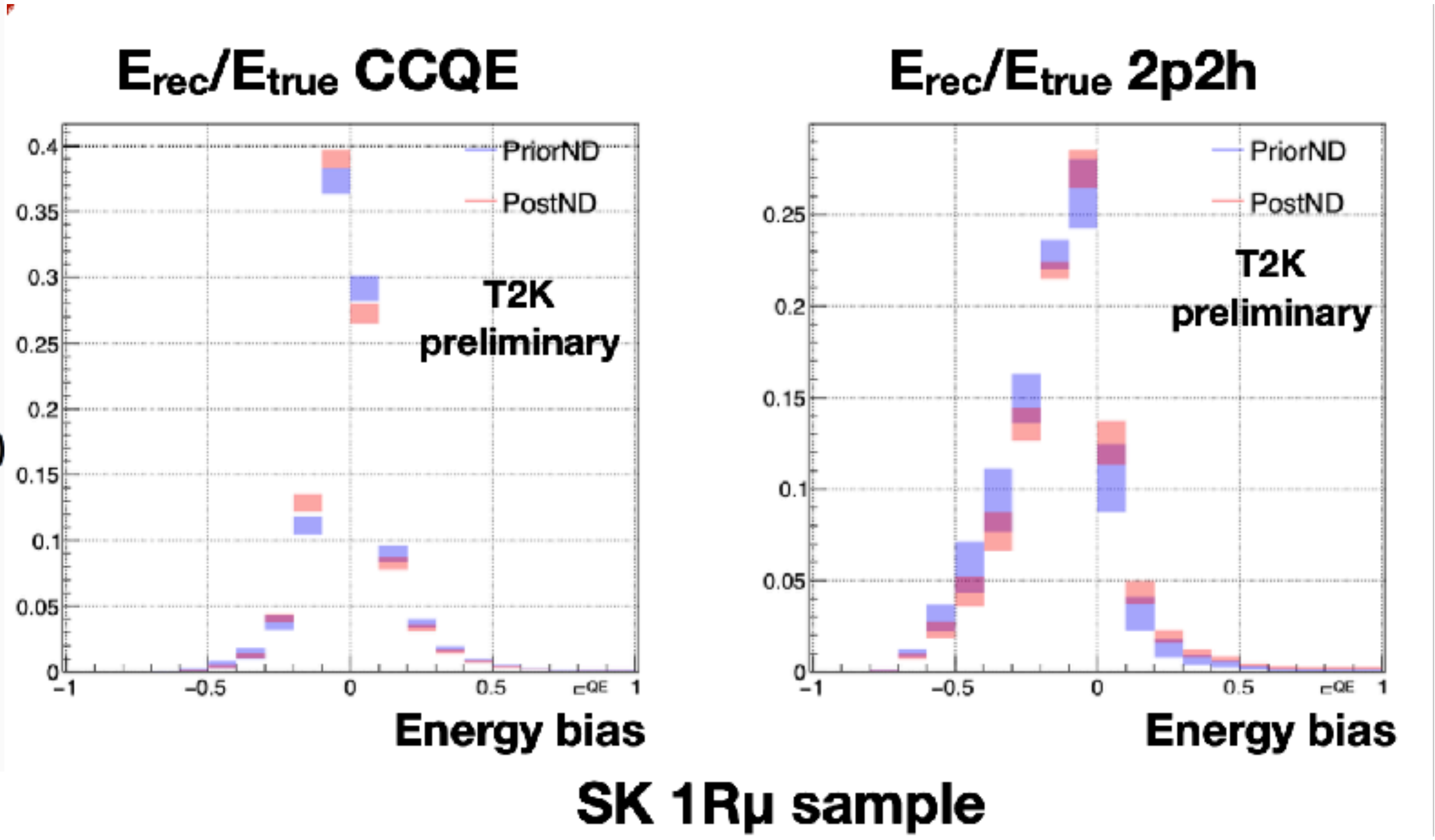
Neutrino interaction
Cross-section models

Interaction models:

- For T2K dominant channel in CCQE
- Contribution from CC resonant and 2p2h not negligible
- Mis-modeling may bias reconstructed neutrino energy







T2K oscillation analysis

Frequentist approach (Bayesian also available)

Sequential fit of ND and then FD data

Flux Prediction
Proton beam measurement with NA61/SHINE inputs

ND280 Measurement
Selections of $\nu_\mu, \overline{\nu_\mu}$, constrain flux and cross-section

Neutrino interaction
Cross-section models

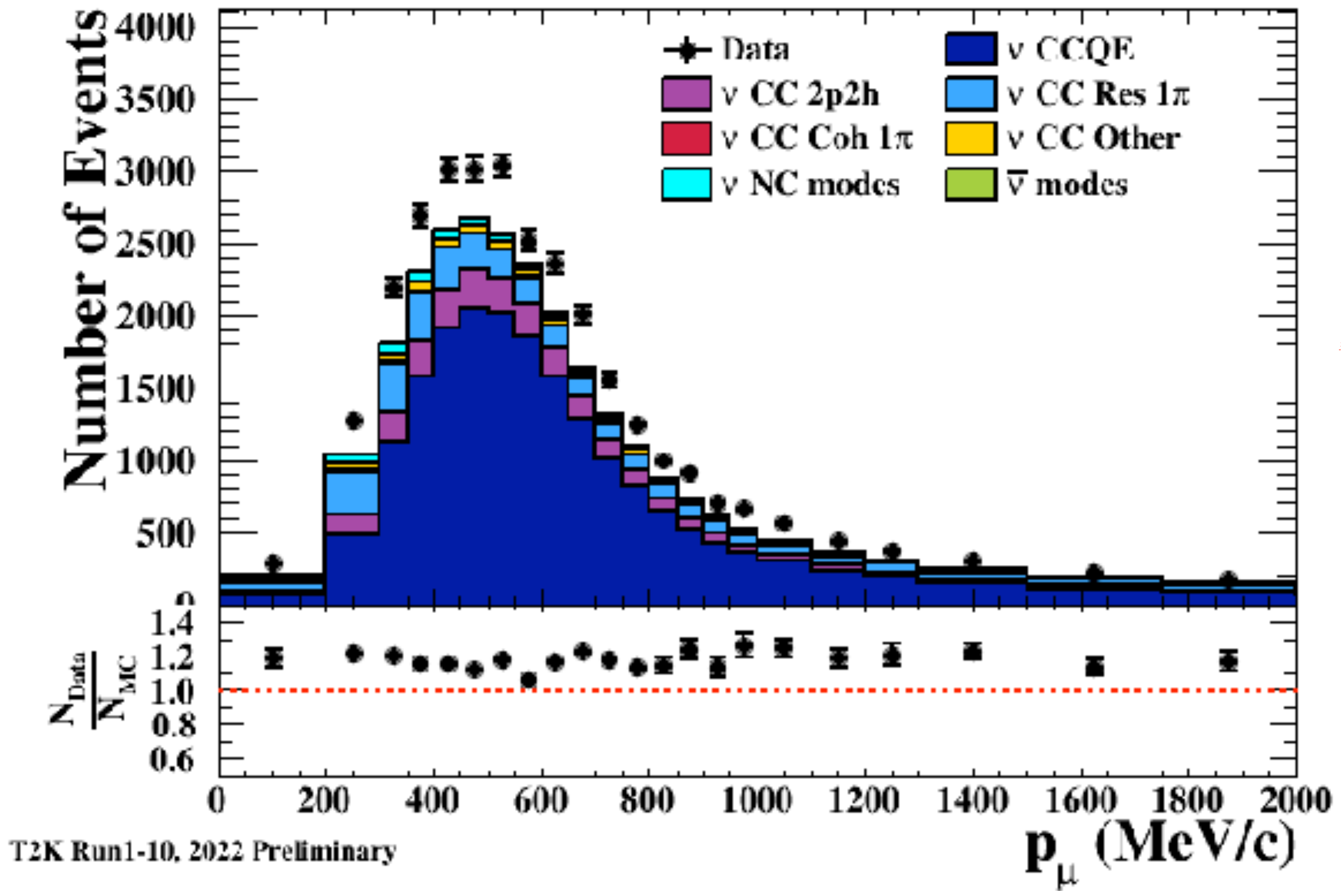
Fitter

SK prediction
Covariance matrix w/ flux, x-section and ND280 systematics

ND Fit:

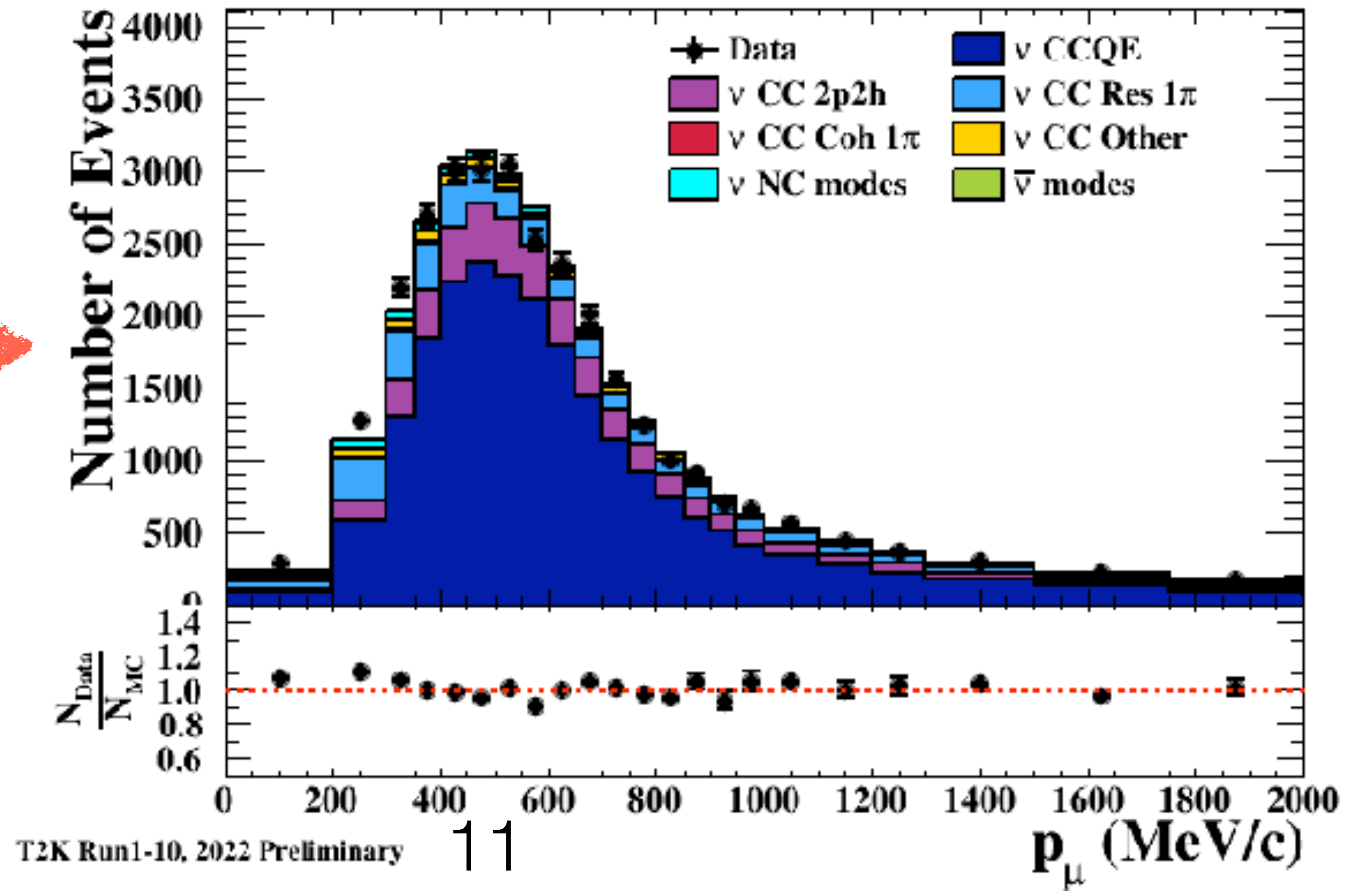
- Same analysis as Neutrino-2022
- Flux and cross-section model is fitted on ND data
  - 12 samples in p_u and $\cos(\theta_\mu)$
- Predictions at FD are then made based on this tuning

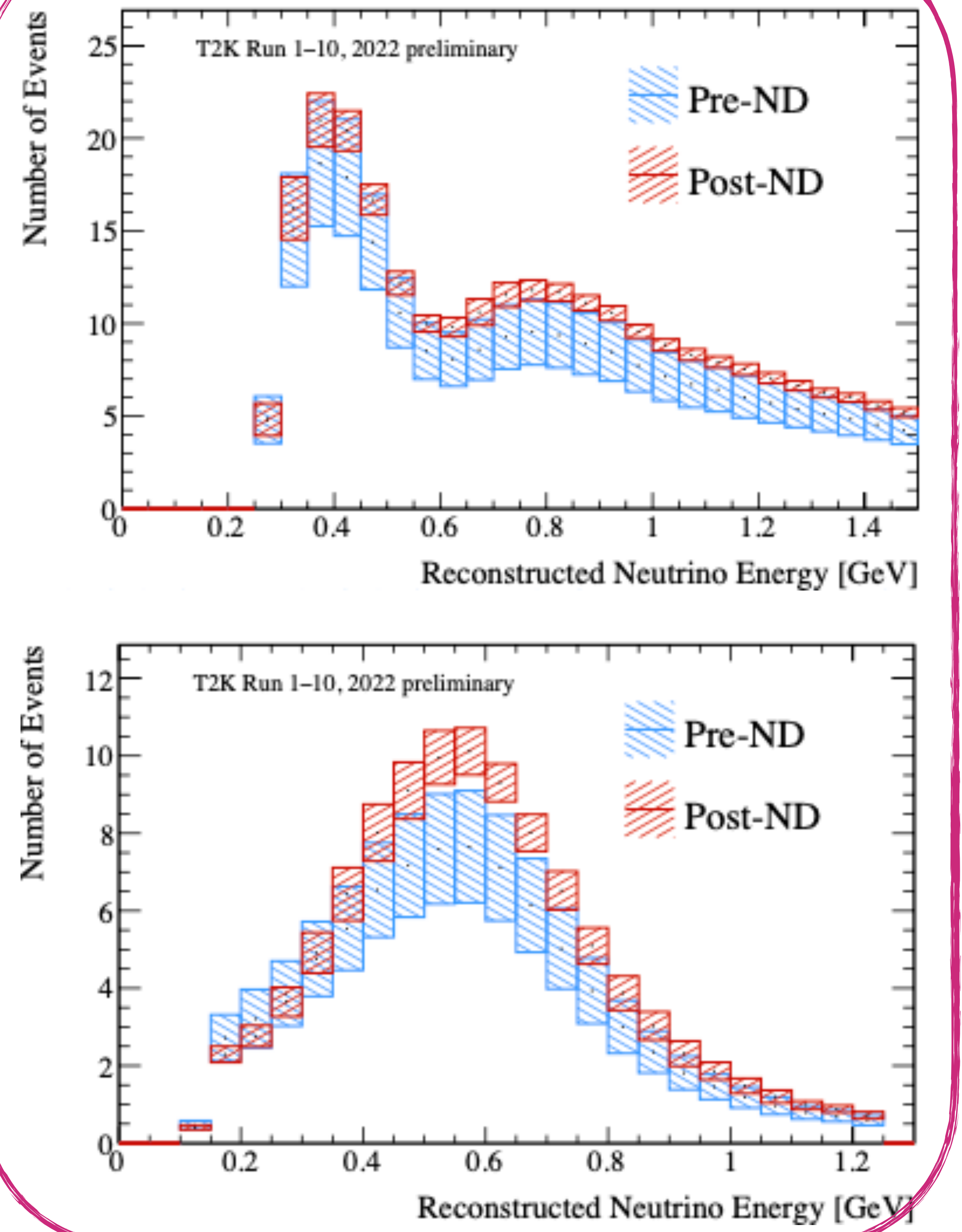
Example: FGD1 ν_μ CC0π 0p



ND fit

Example: FGD1 ν_μ CC0π 0p

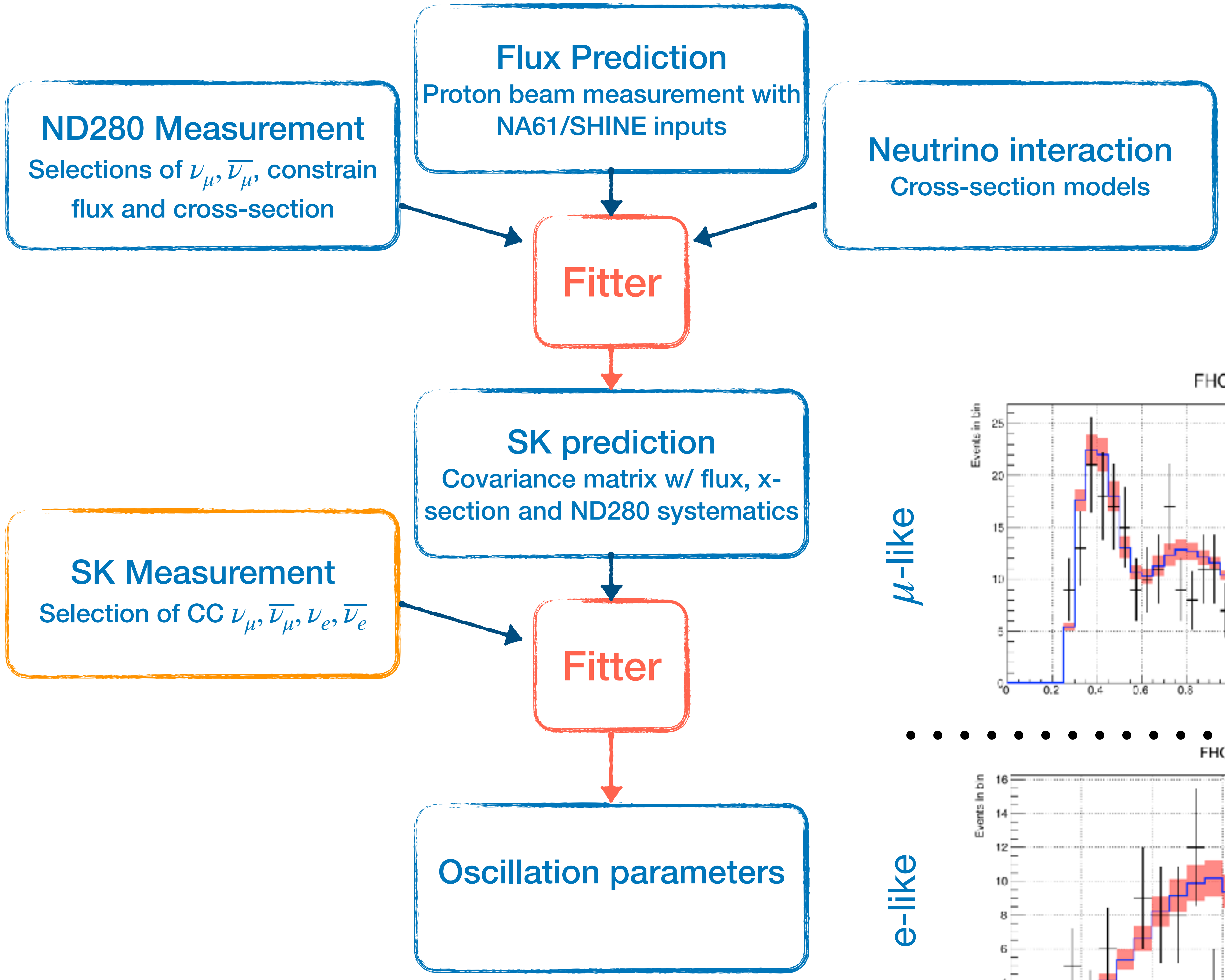




T2K oscillation analysis

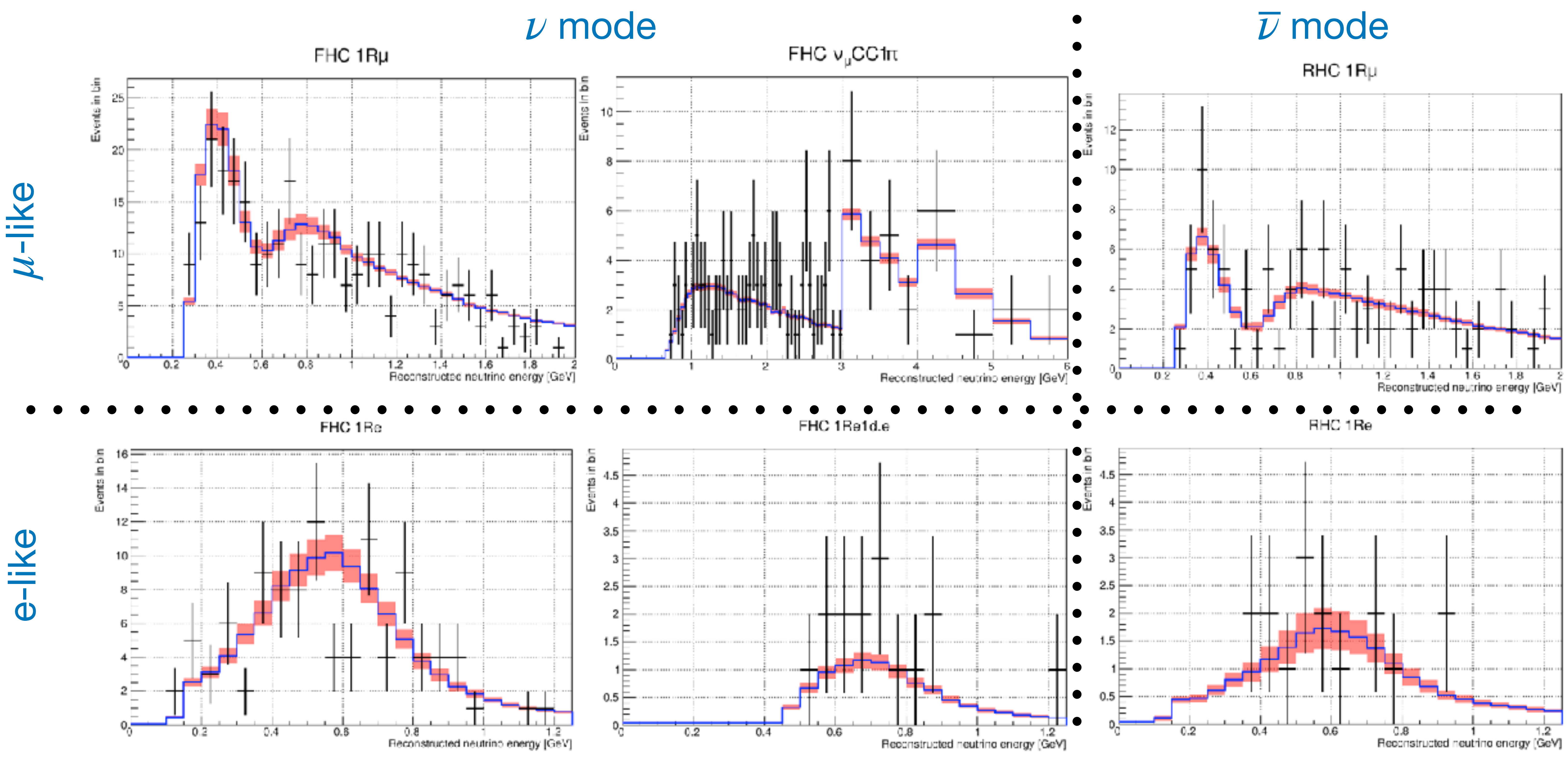
Frequentist approach (Bayesian also available)

Sequential fit of ND and then FD data



Update of the analysis:

- Add run 11 (10% statistics in ν-mode), first data including SK-Gd
- 6 samples in total
- New SK covariance matrix
  - Reduction of systematic uncertainties



T2K-only oscillation results

First presented at Neutrino 2024 : https://doi.org/10.5281/zenodo.12704703

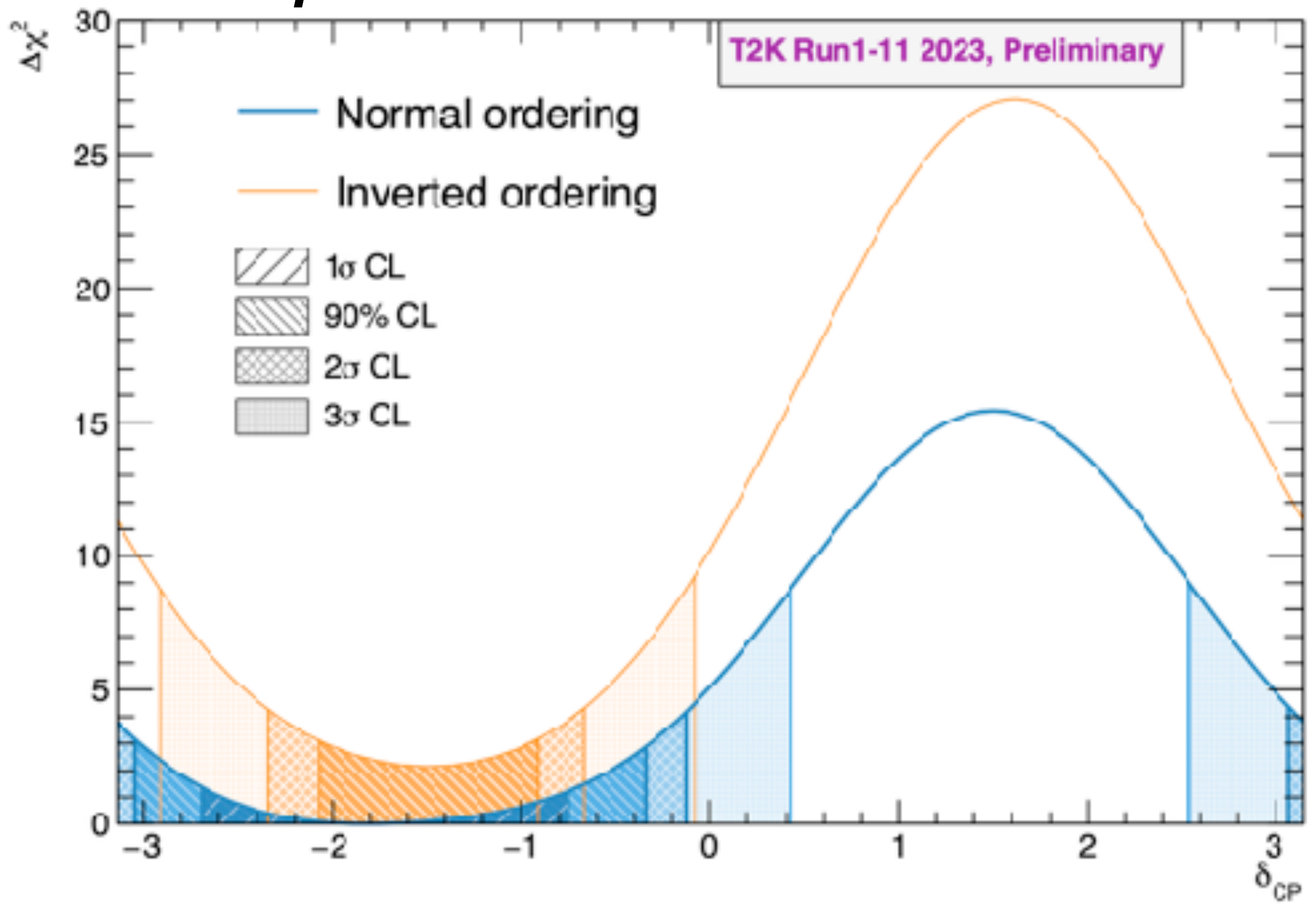
δ_{CP}:

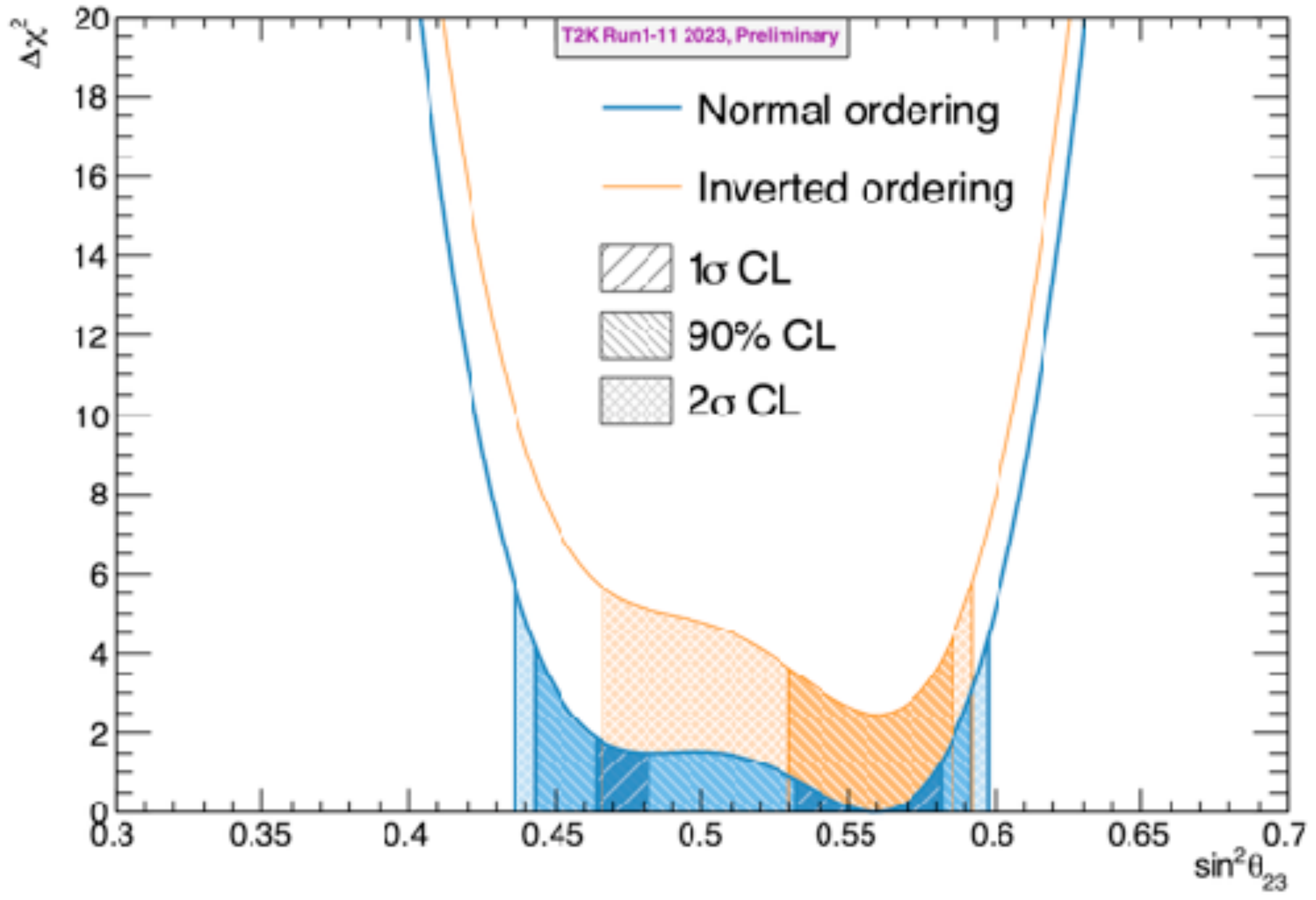
- Preference for $\delta_{CP} \approx -\frac{\pi}{2}$
- Jarlskog-invariant gives a parametrized independent way to measure CP violation
- CP conservation excluded at >2σ in case of IO and <2σ for NO

θ_{23} **and mass ordering:**

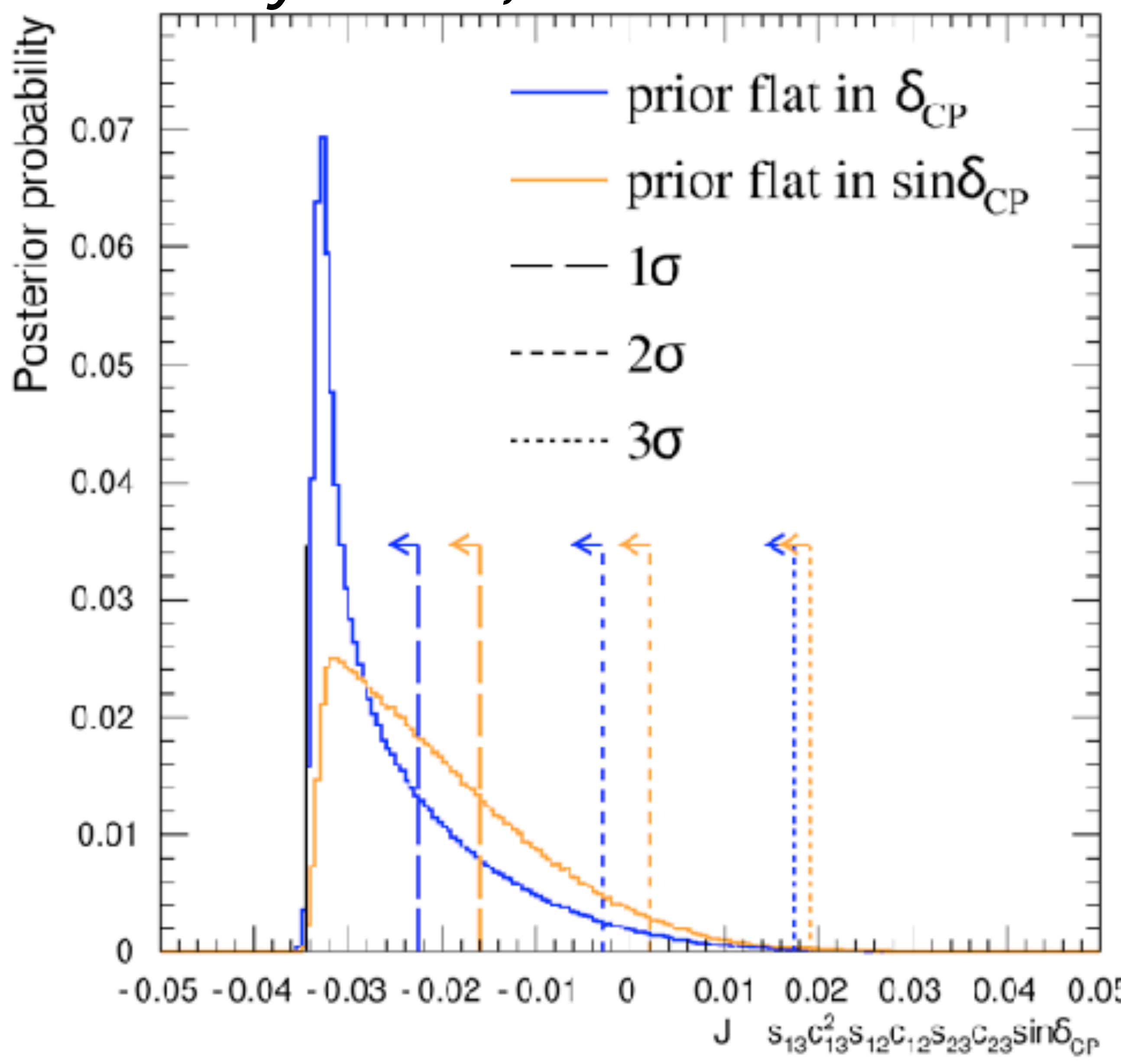
- Preference for NO and upper octant but not significant

Frequentist





Bayesian, both MO



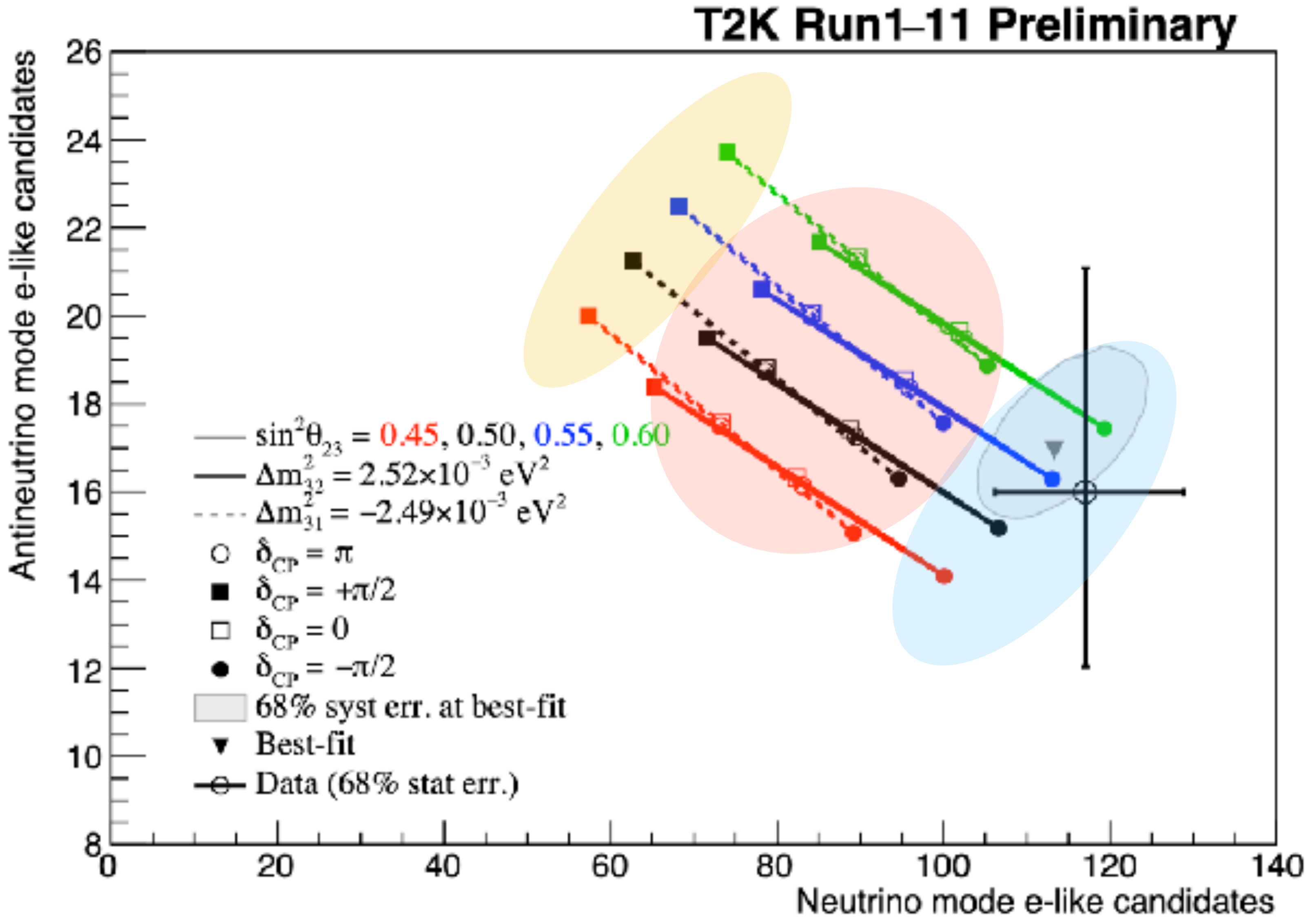
Best fit:

	Normal ordering	Inverted ordering
$\sin^2(\theta_{13})/10^{-3}$	$(21.9^{+0.9}_{-0.5})$	$(22.0^{+1.0}_{-0.4})$
δ_{CP}	$-2.08^{+1.33}_{-0.61}$	$-1.41^{+0.64}_{-0.82}$
Δm^2_{32} (NO)/Δm^2_{31} (IO)	$(2.521^{+0.037}_{-0.050})10^{-3}\mathrm{eV}^2/\mathrm{c}^4$	$(-2.486^{+0.043}_{-0.044})10^{-3}\mathrm{eV}^2/\mathrm{c}^4$
$\sin^2(\theta_{23})$	$0.568^{+0.024}_{-0.125}$ (90%)	$0.567^{+0.021}_{-0.048}$ (90%)

Combining results

T2K-only limitations:

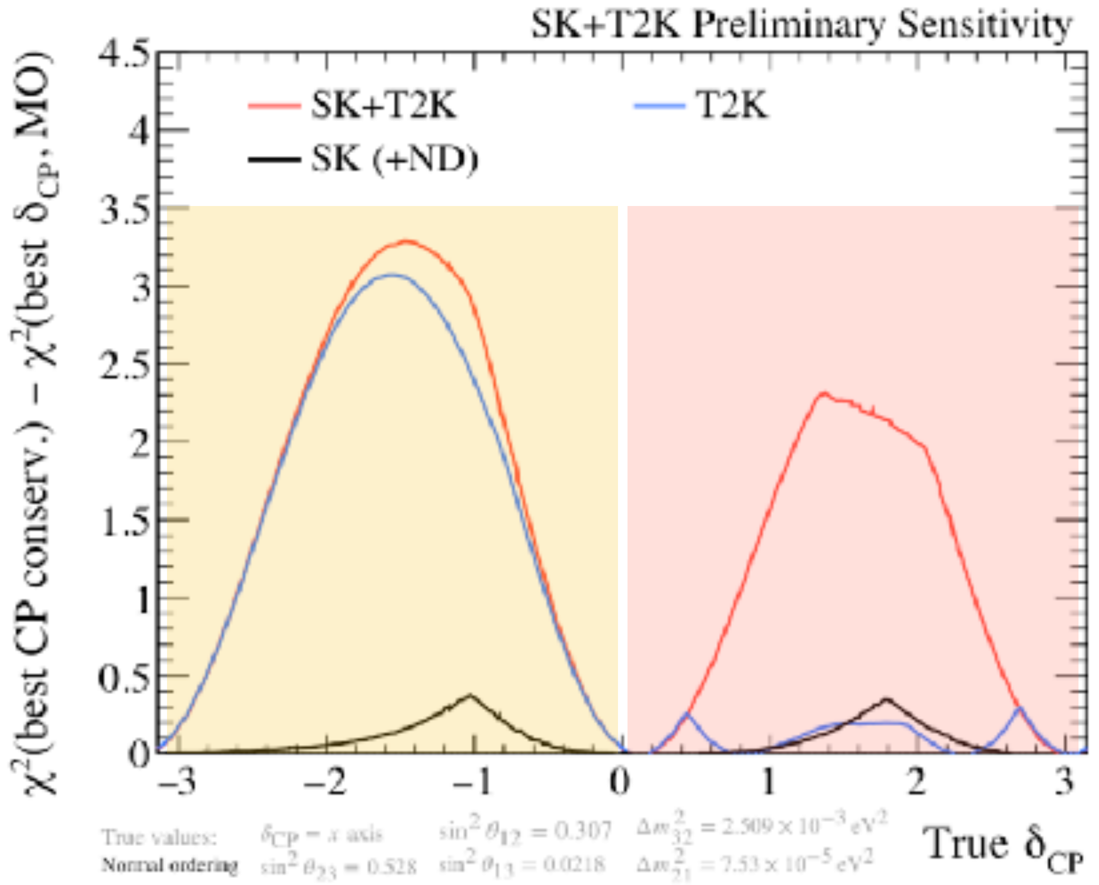
- If $\delta_{CP} = \frac{\pi}{2}$ and IO, $-\frac{\pi}{2}$ and NO T2K could be sensitive to mass ordering
- Otherwise: Sensitivity decreases



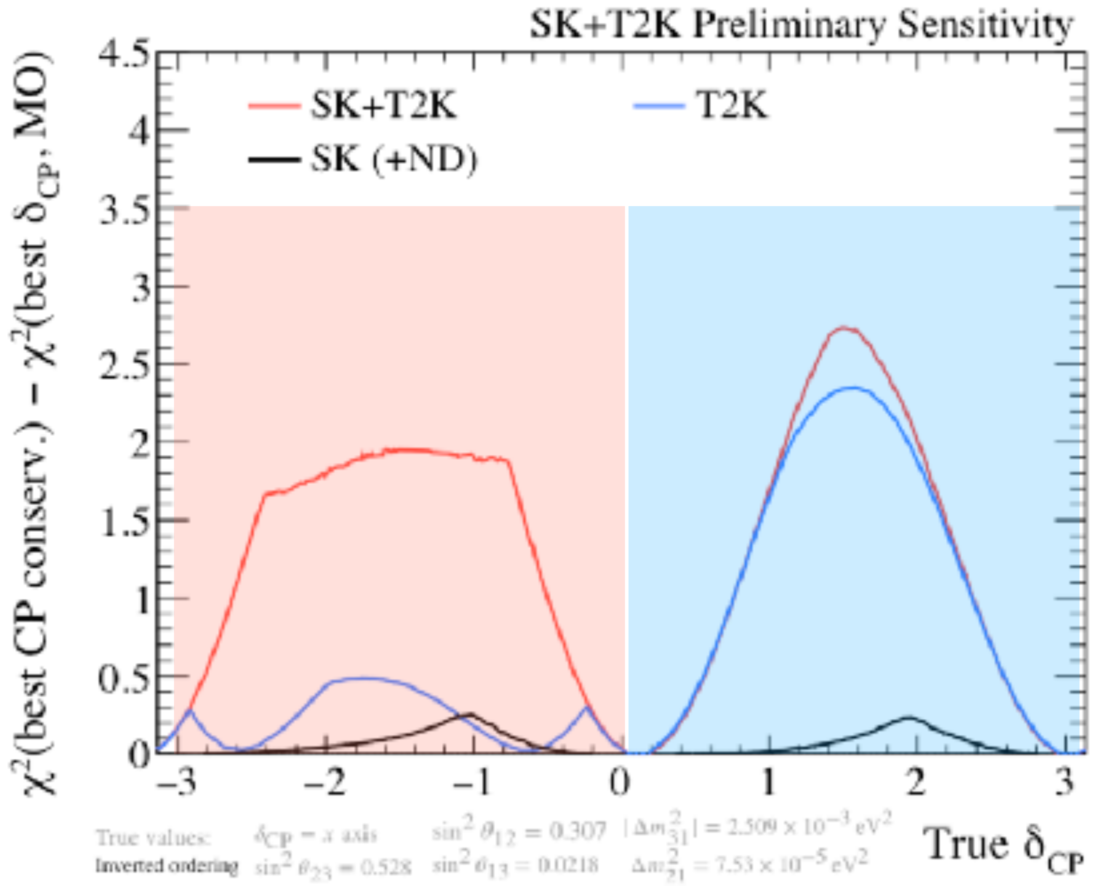
Break degeneracy:
Perform joint-fit with other experiments
(Different baseline, energy)

Atmospheric

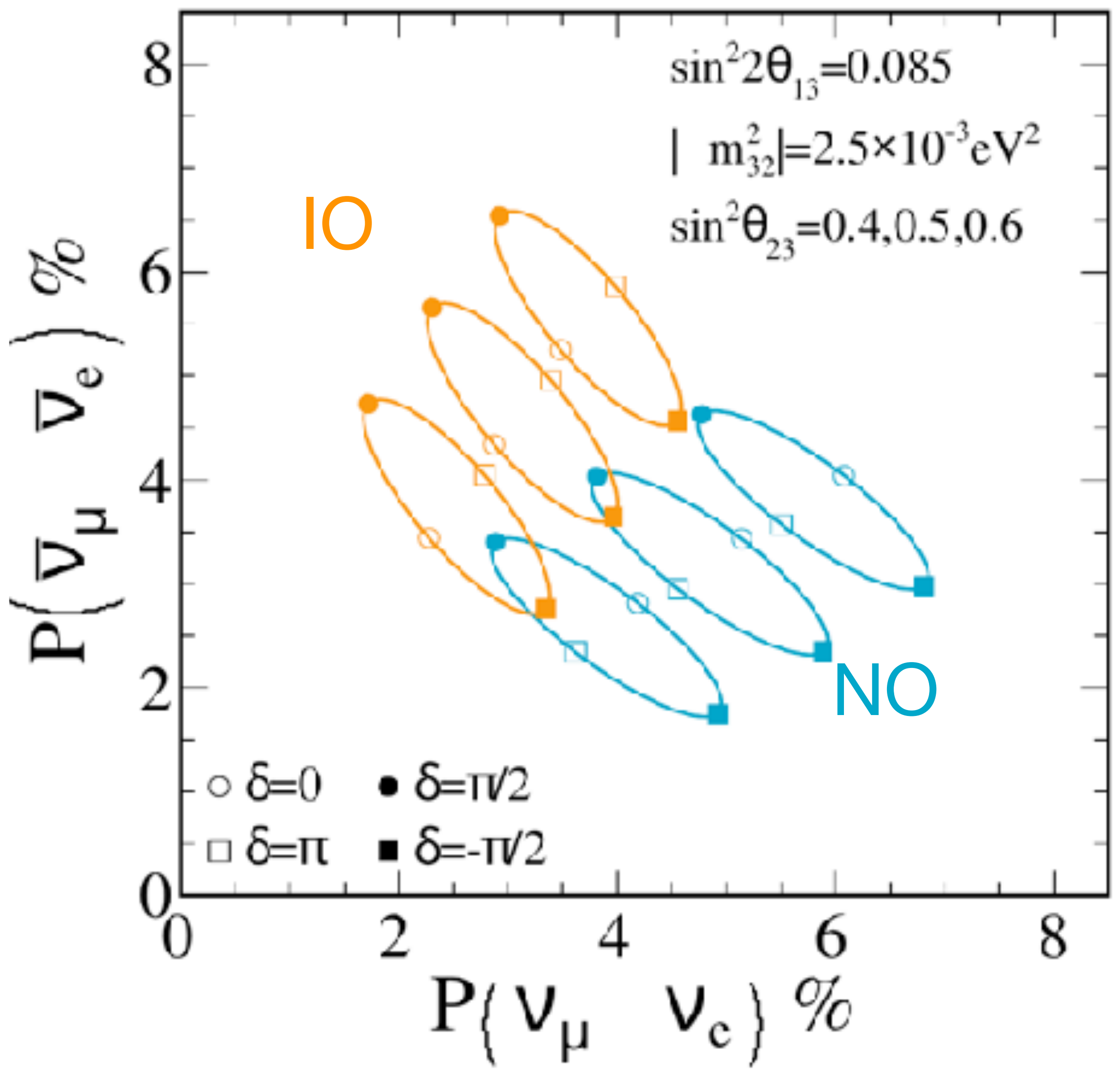
True NO



True IO



NOvA: L=810 km, E=2.0 GeV



T2K-SK joint fit

First Joint Oscillation Analysis of Super-Kamiokande Atmospheric and T2K Accelerator Neutrino Data, T2K and SK collaborations, 2025
10.1103/PhysRevLett.134.011801

Challenges :

- Huge work was made to unify model and systematic uncertainties
- Correlations were evaluated between T2K beam and SK atmospheric samples

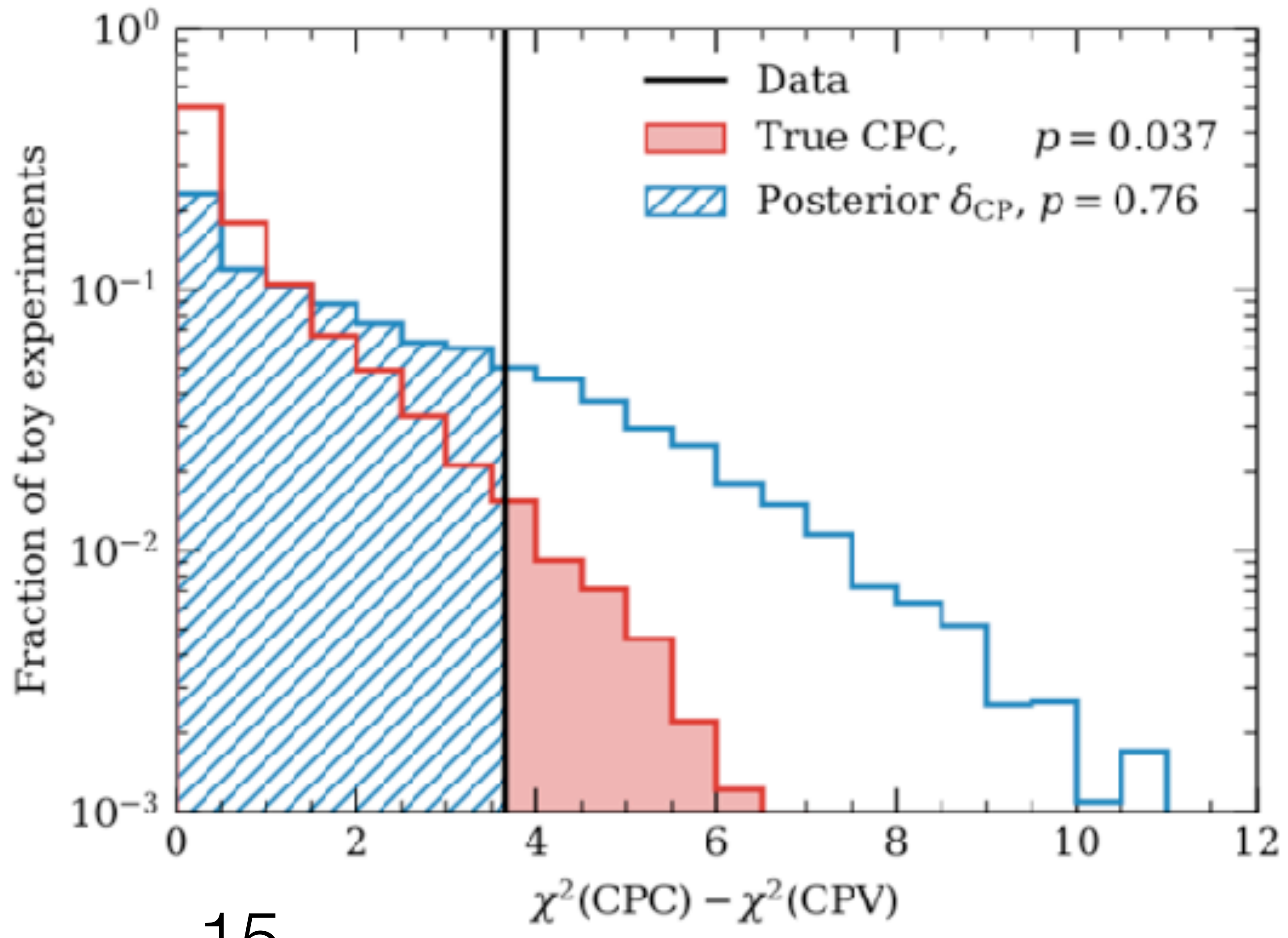
Results :

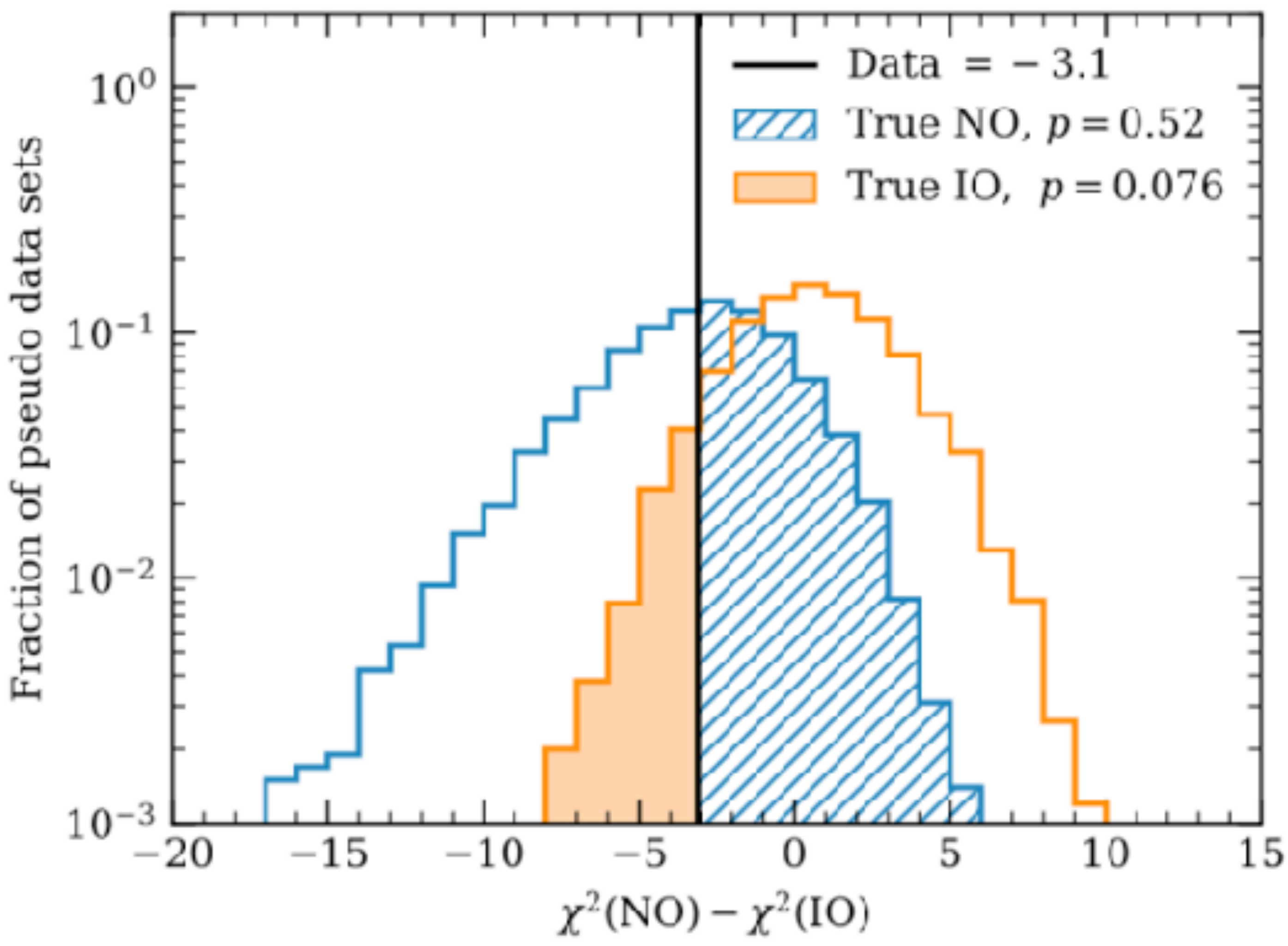
- δ_{CP}:
    - The bayesian approach is excluding the CP-conserving values of the Jarlskog invariant with a significance between 1.9-2σ
    - Frequentist approach is getting p(CPC)=0.037 corresponding to a 2σ level
- Mass ordering:
    - Normal ordering is preferred with a p-value for IO of 0.08

	$\sin^2\theta_{13}$	$\delta_{\rm CP}$	Δm^2_{32} [10^{-3} eV^2]	$\sin^2\theta_{23}$
Normal ordering	0.0220	$-1.76^{+0.60}_{-0.74}$	$2.514^{+0.057}_{-0.060}$	$0.471^{+0.104}_{-0.017}$
Inverted ordering	0.0219	$-1.49^{+0.50}_{-0.52}$	$2.485^{+0.056}_{-0.061}$	$0.556^{+0.021}_{-0.033}$

Interaction Model Summary

	"Low-energy" samples SK FC sub-GeV and T2K	"High-energy" samples SK FC multi-GeV, PC, Upmu
Charged Current Quasi-Elastic (CCQE)	T2K model with ND280 constraint, correlated in low-E/highE (except for high-Q^2 parameters)	
	high-Q^2 params w/ND280	high-Q^2 params w/o ND
	+ extra ν_e/ν_μ xsec diff. error	
Two particles two holes (CC2p2h)	T2K model w/ND280	SK model (100% error) + T2K-style shape error
Resonant Interactions	T2K model w/ND280 + new p_π shape uncertainty + extra NC1π^0 uncertainties	SK model for 3 dials also in T2K model, use more recent, larger T2K priors
Deep inelastic	T2K model w/ND280	SK model
Tau neutrino interactions	SK model (25% normalization error) correlated in low-E/highE	
Final State Interactions	T2K model w/ND280	T2K model w/o ND280 (mostly same as SK model)
Secondary Interactions	T2K model, correlated in low-E/high-E not applied to SK Upmu samples	





T2K-NOvA joint fit

Challenges :

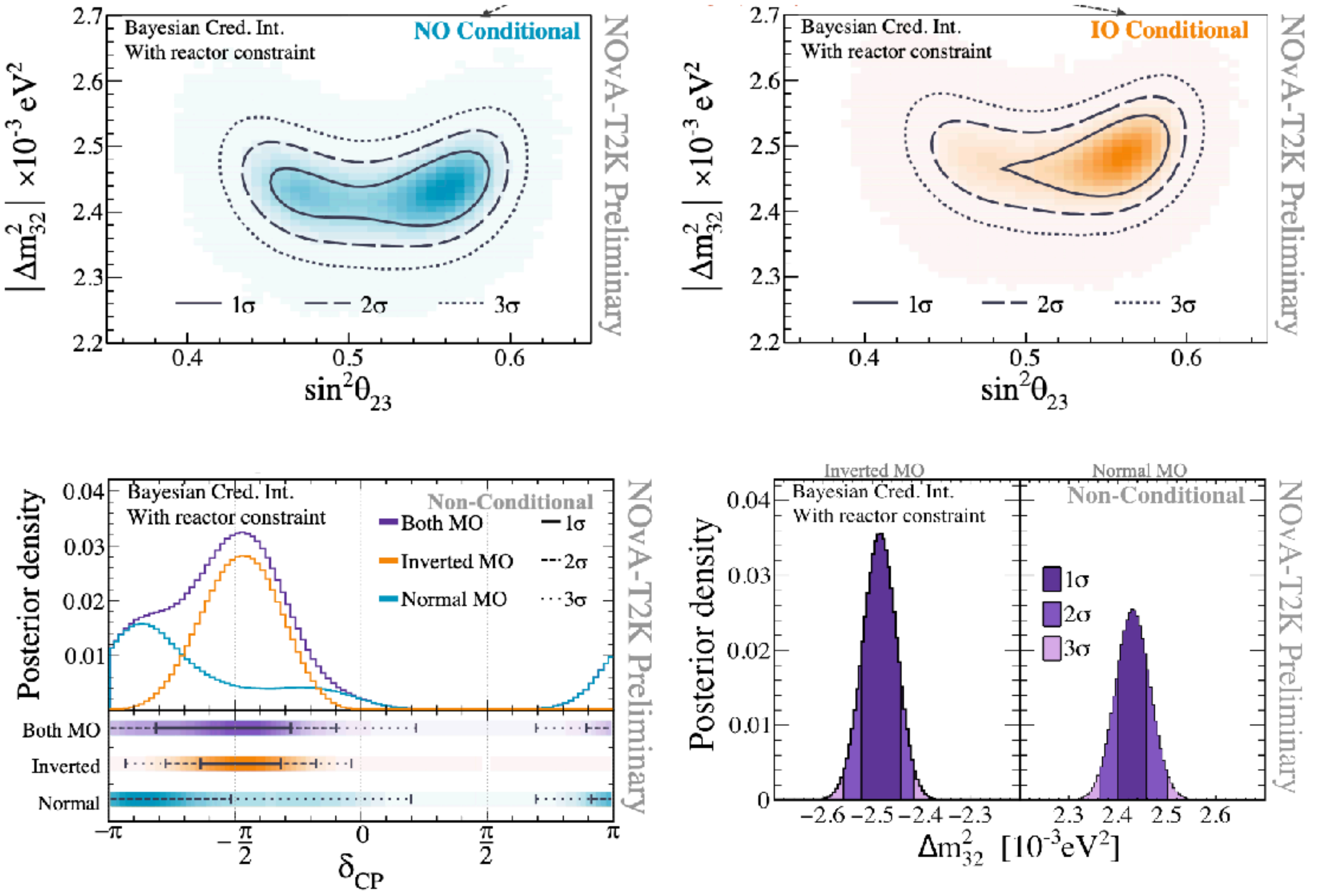
- Main source of correlations: Cross-section model
  - Studied artificial scenarios to see possible correlations
  - Evaluate the robustness of the fit against various models
  - Cross-experiment models after ND constraint

θ_{23} and $\left|\Delta m^2_{32}\right|$:

- Results still consistent with maximal mixing of θ_{23}

δ_{CP}:

- $\delta_{CP} = \frac{\pi}{2}$ excluded at 3σ for both mass ordering
- In case of IO, CP-conservation is excluded at 3σ

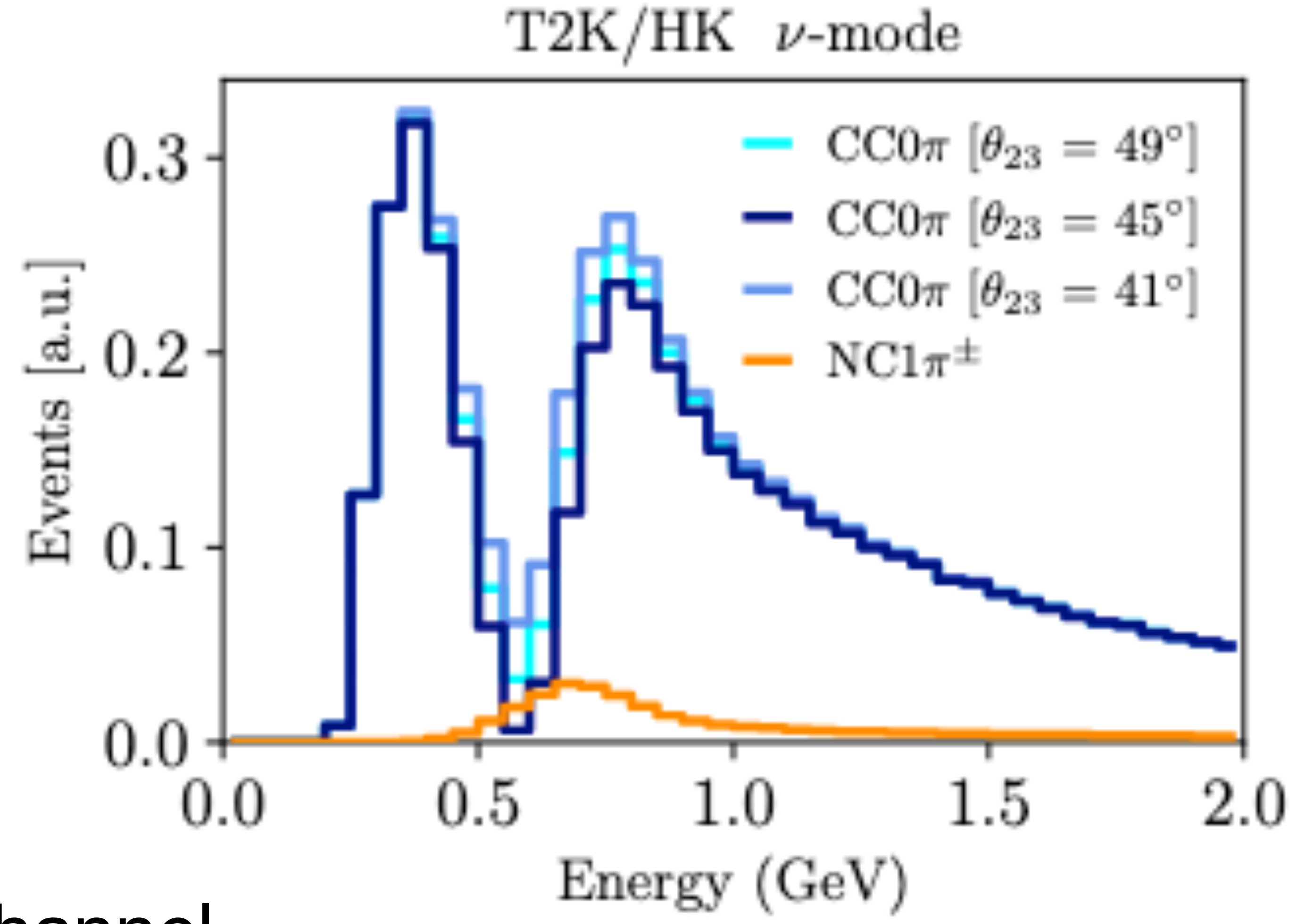


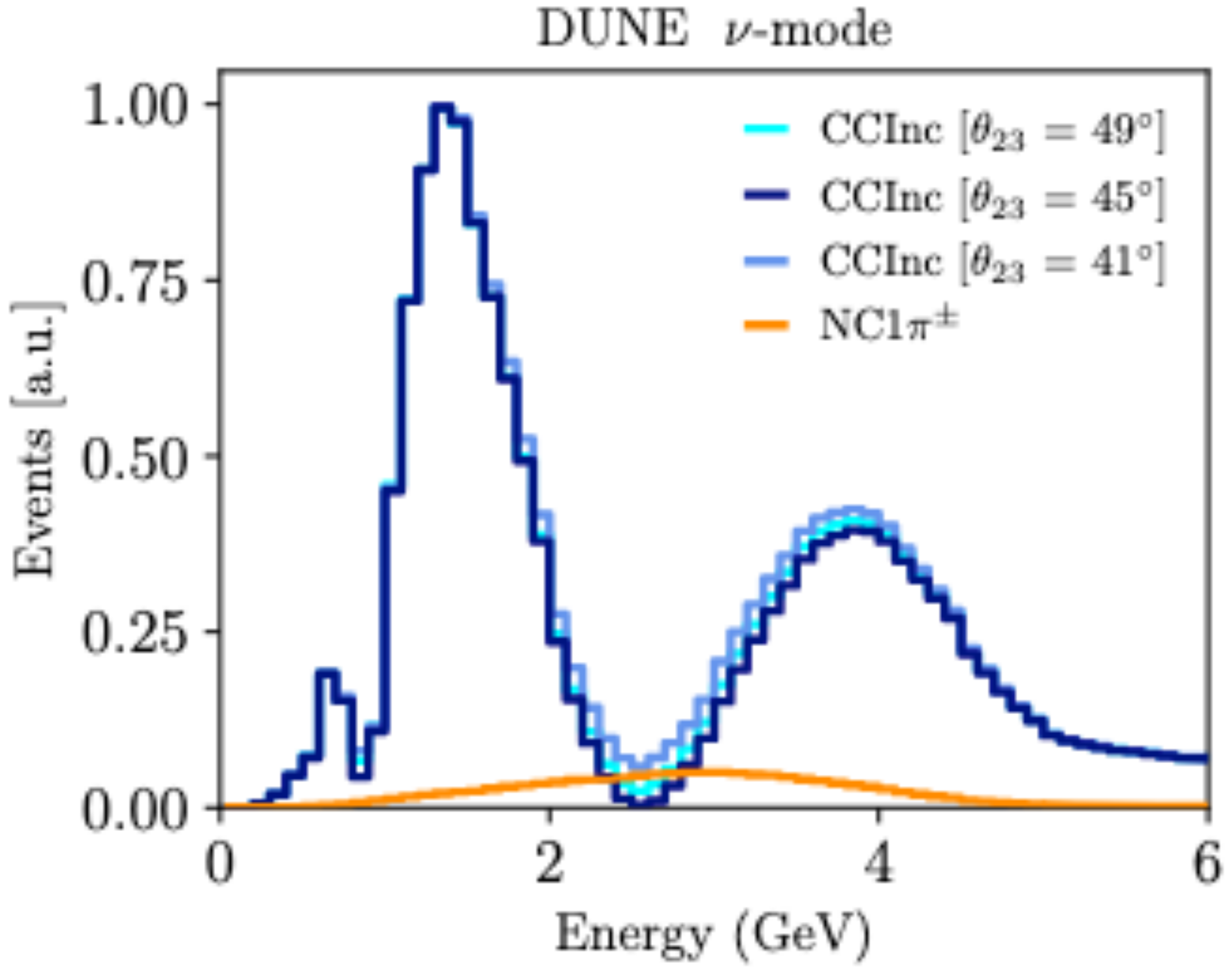
First presented at Fermilab on February, 16th, 2024 : https://indico.fnal.gov/event/62062/contributions/279004/attachments/175258/237774/021624_NOvAT2K_JointFitResults_ZV.pdf

Toward a better model

T2K cross-section analyses:

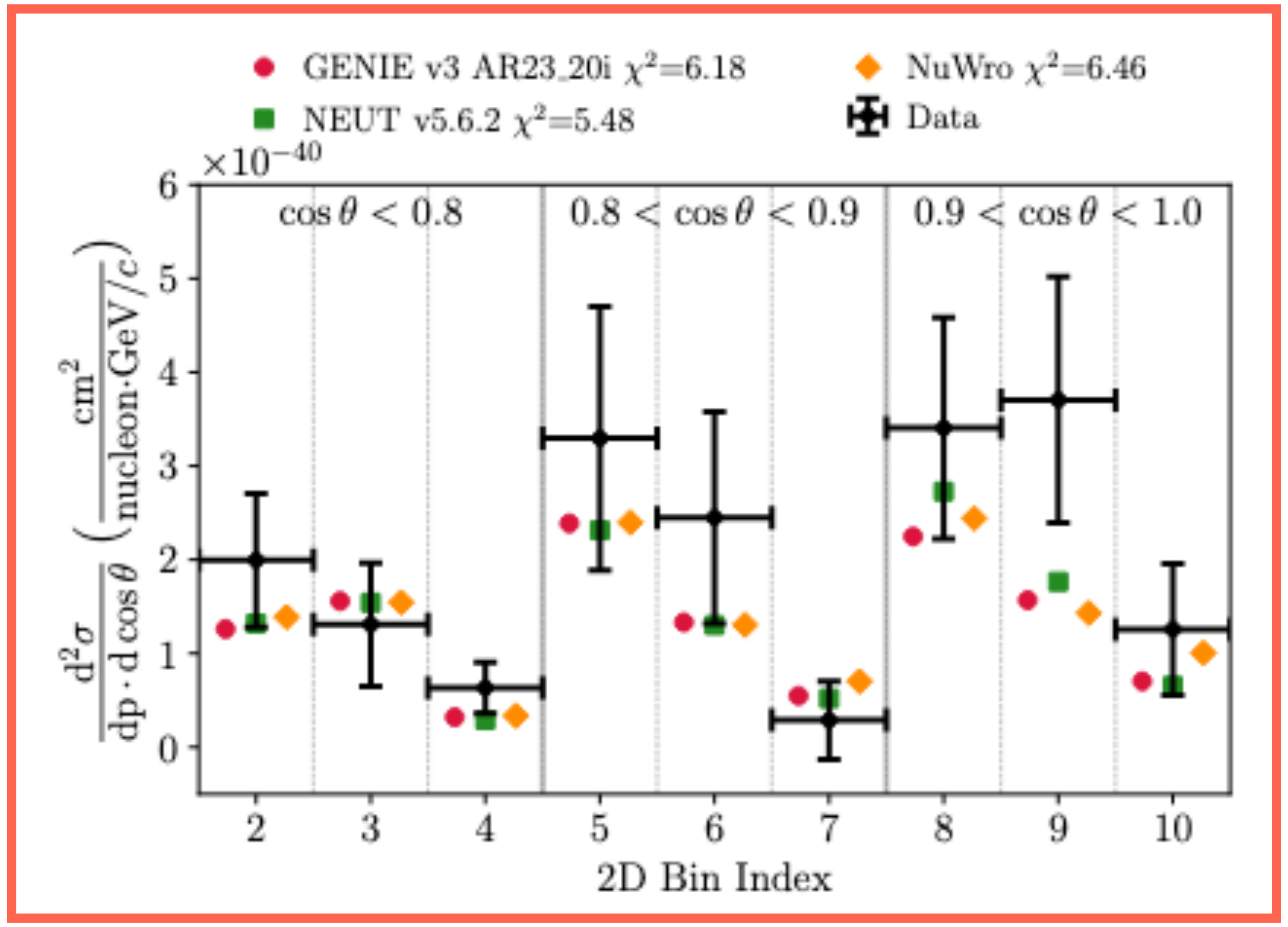
- T2K is also doing ν cross-section analysis
  - This is fundamental for OA since it helps to understand neutrino interactions model

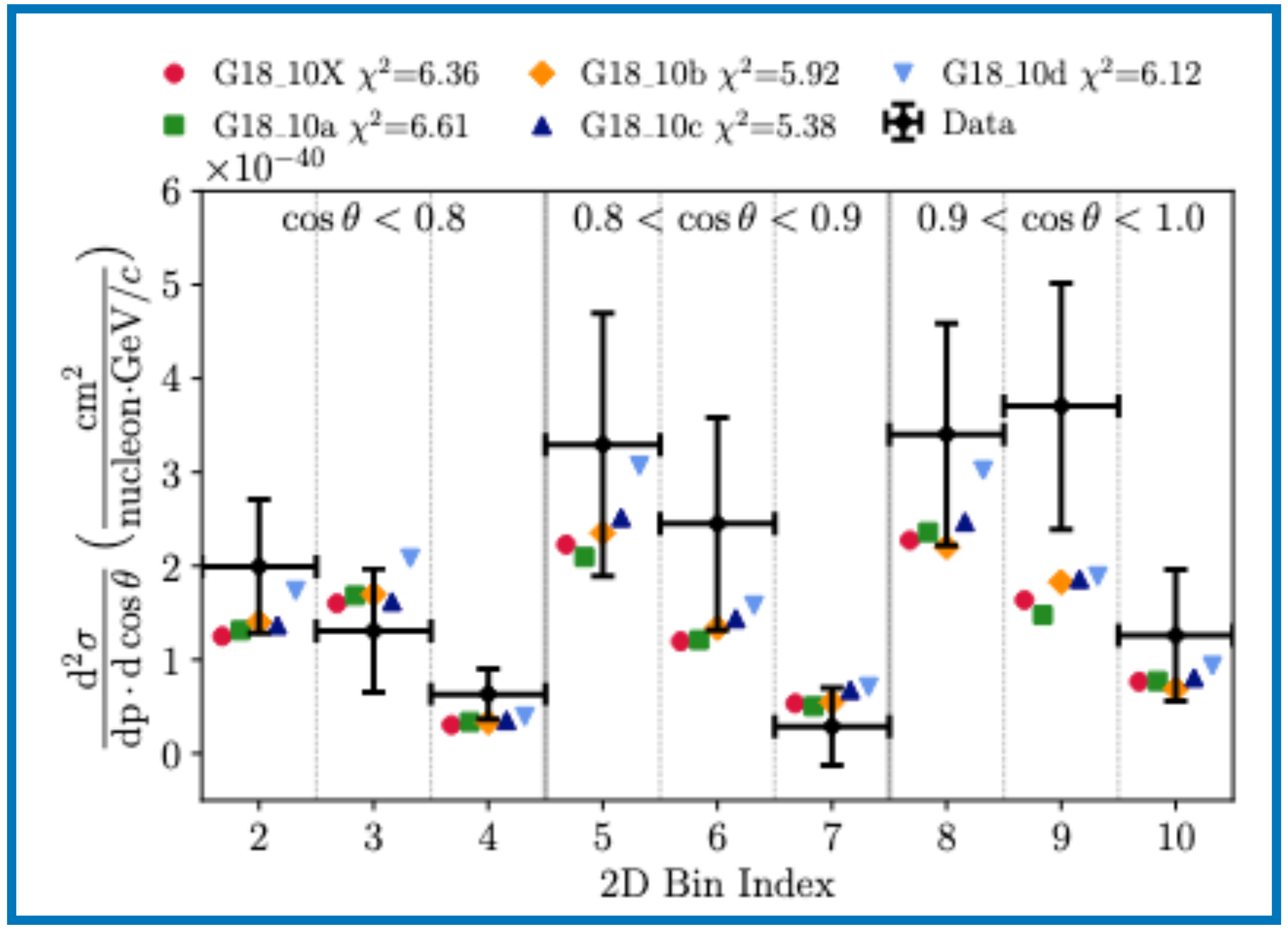




NC1π^+ cross-section measurement:

- **arXiv:2503.06849v2 and arXiv:2503.06843v2**
- First double-differential cross-section measurement of this channel
- Comparison with various ν interactions generators and FSI (Final State Interaction) model
  - Overall agreement is observed with tested model predictions
  - Observed a higher variation due to FSI than generators
    => Stress the importance of studying in details FSI

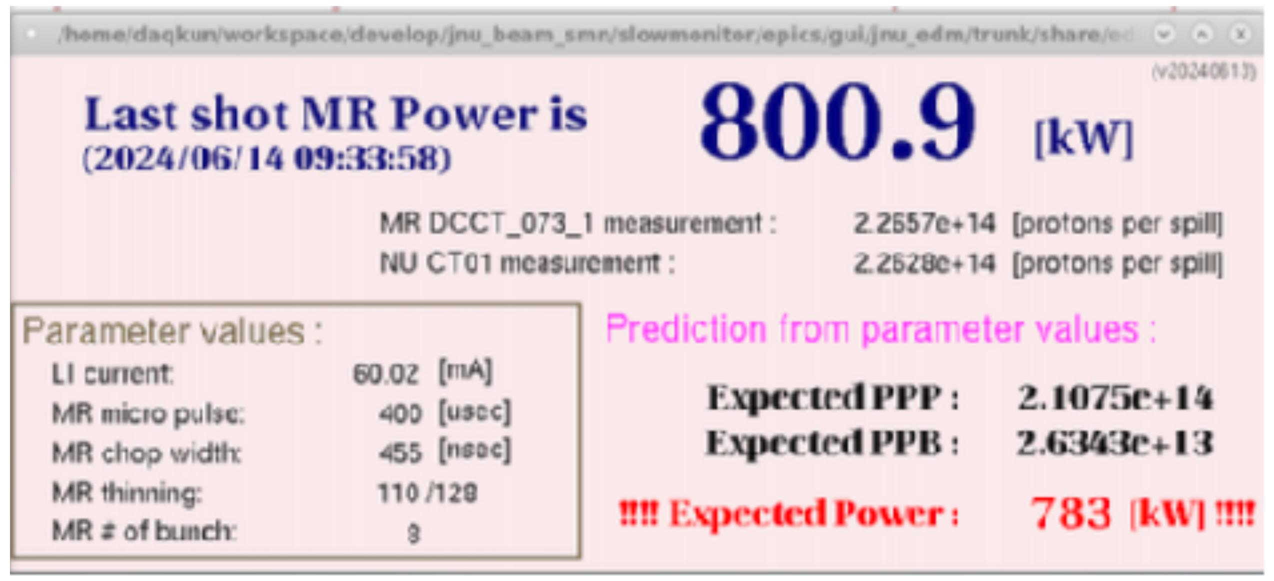


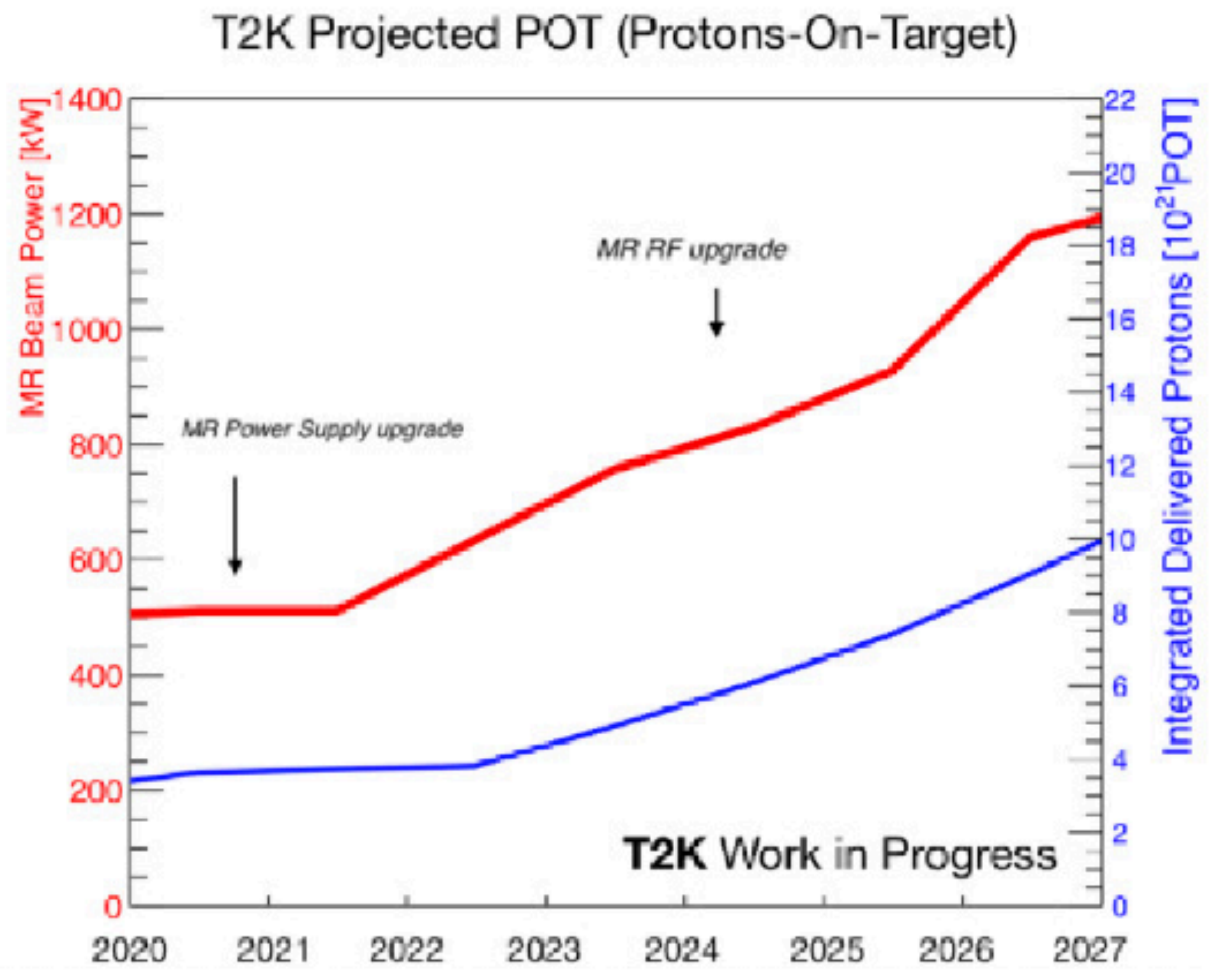


Future improvements

Beam upgrade:

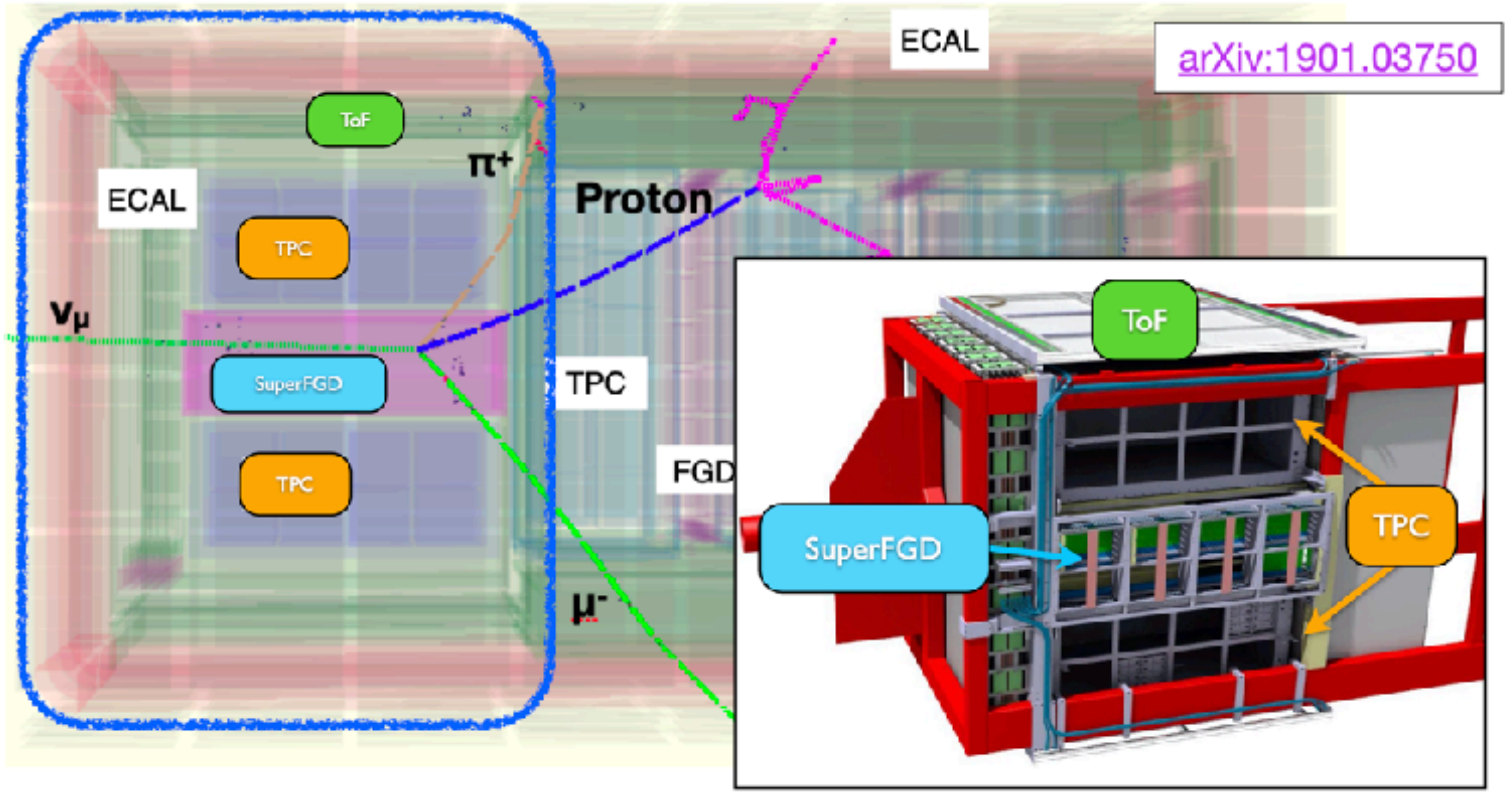
- T2K is upgrading its beam line to increase power
    - Higher repetition rate (factor 2)
    - **Reached 800kW in June 2024** (500kW before)
- Expect to reach 1.2MW by 2027
- Important increases in statistics in the next years
    - Which is the dominant error right now in OA results

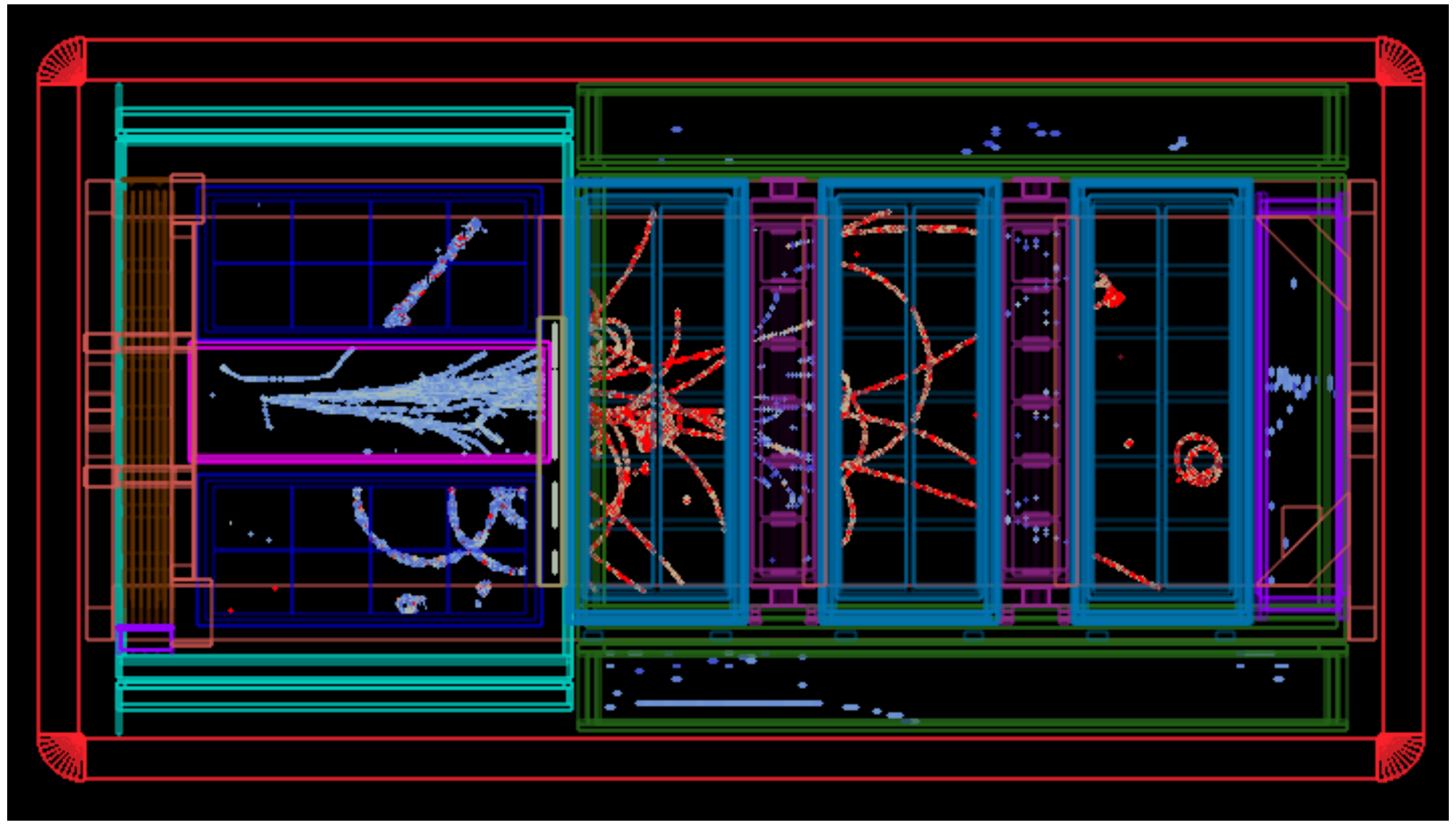




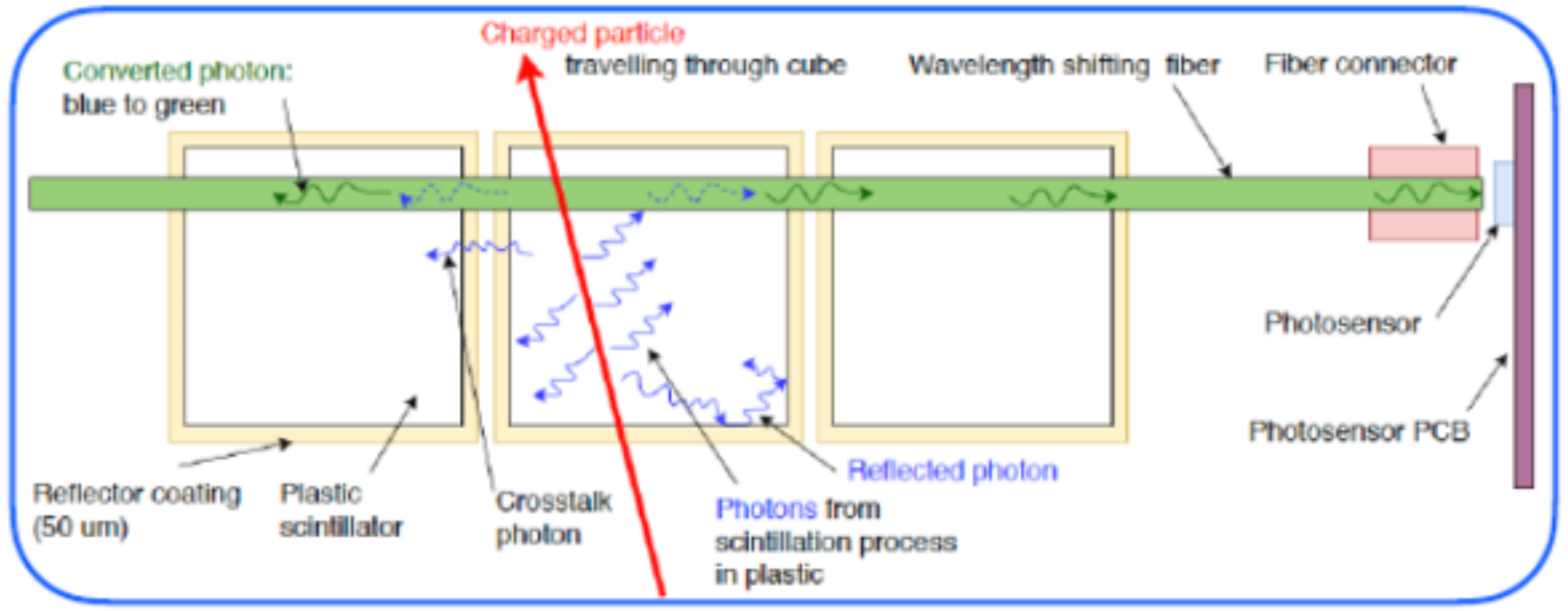
ND280 upgrade:

- T2K has completed the upgrade of its ND
    - One highly segmented target, two additional TPCs at high angle, all surrounded by TOF scintillator panels





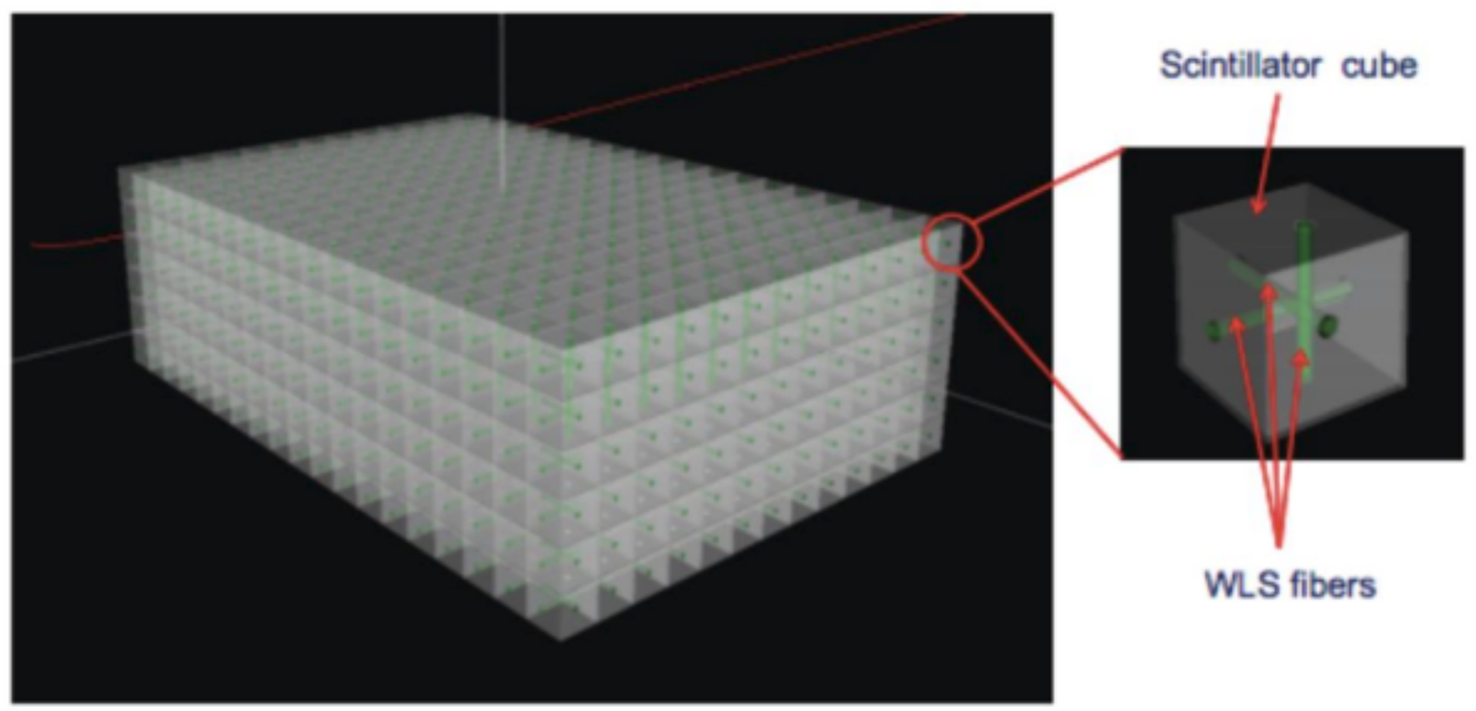
SuperFGD

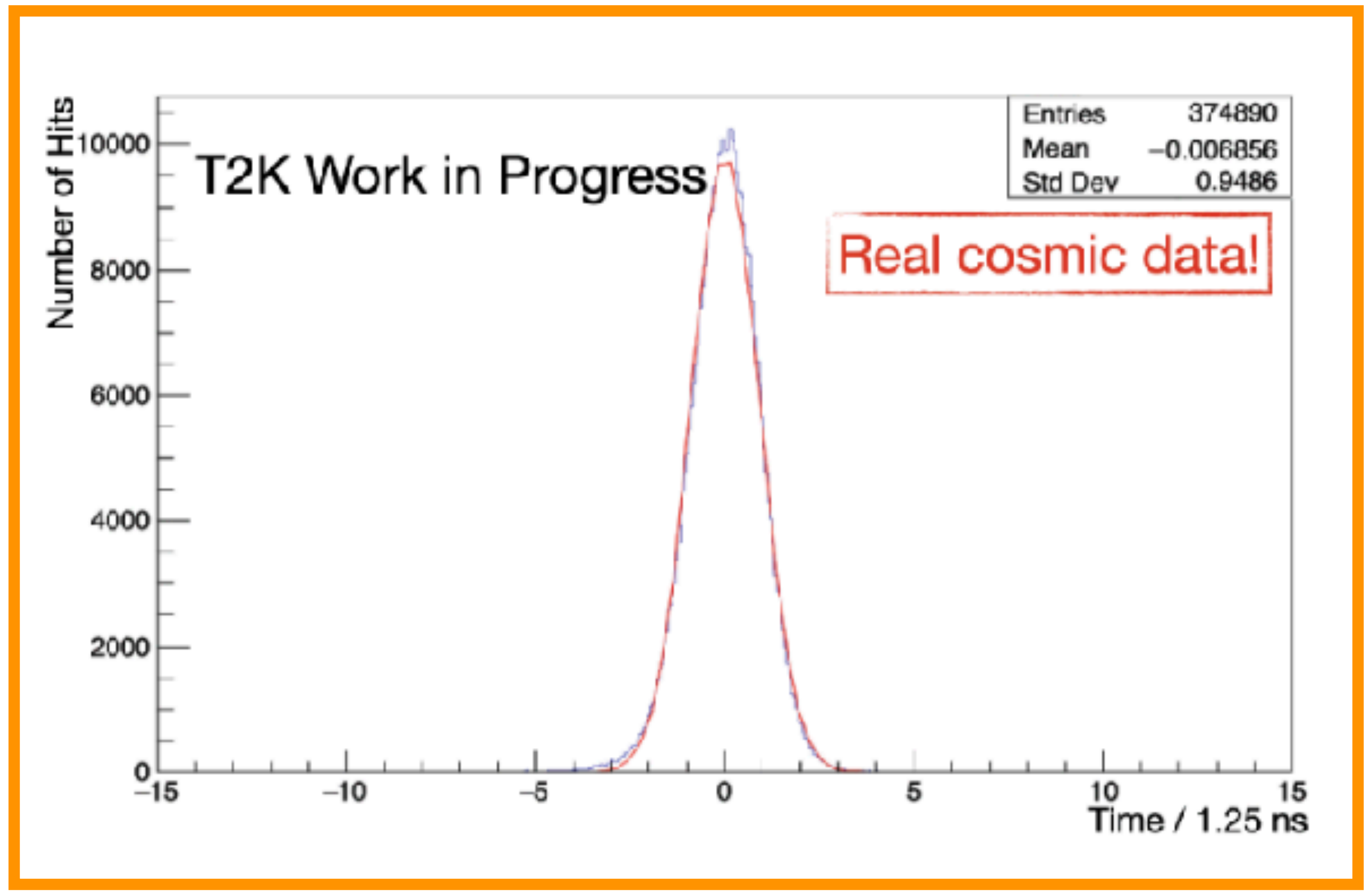


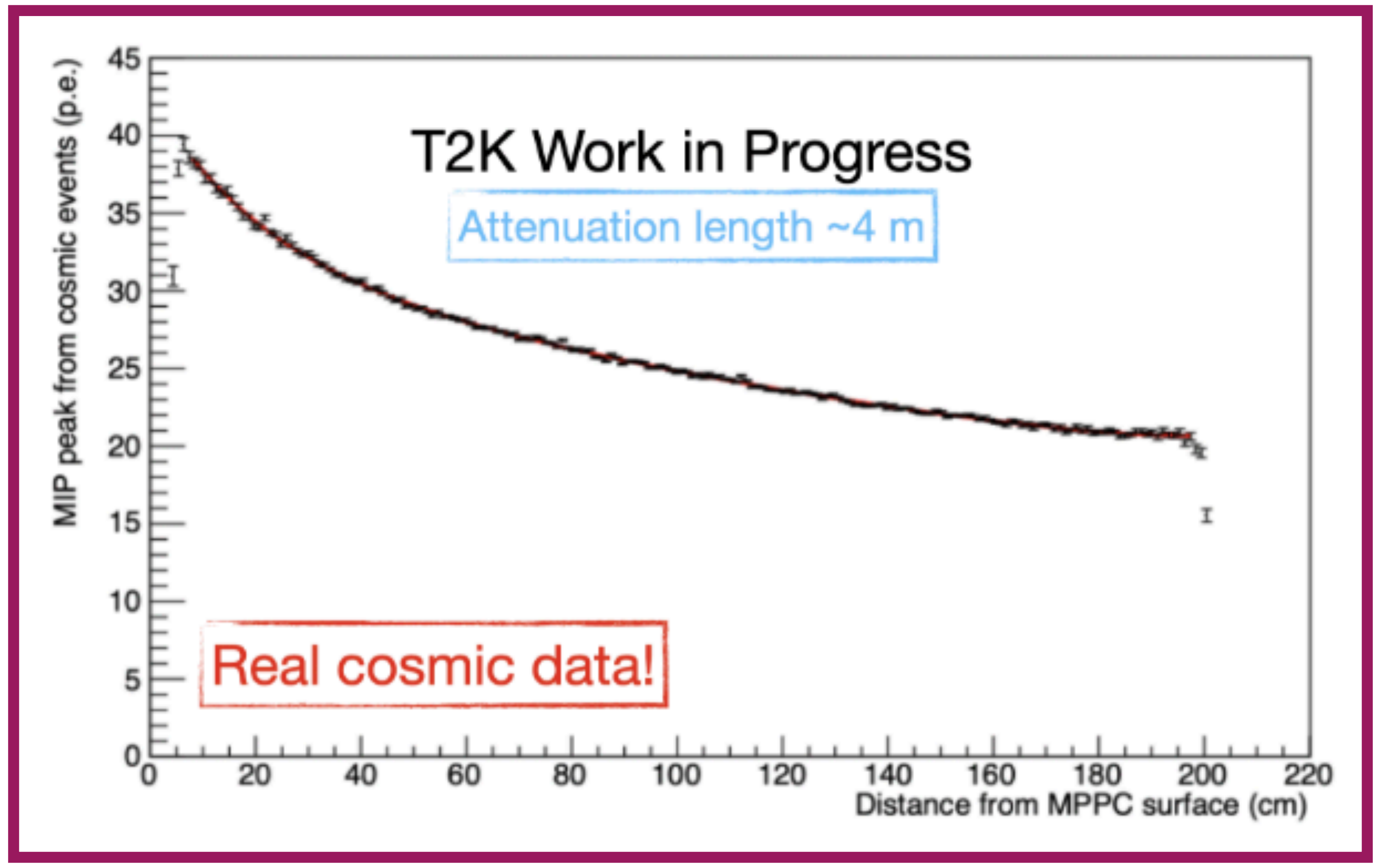
1x1x1 cm³ cubes
Polystyrene scintillator
1.5% paraterphenyl
0.01% POPOP
Chemical etched reflector
WLS fiber Kuraray Y11
2-clad (⌀=1mm)

Main characteristics

- Highly segmented target made of 2 millions cubes of plastic scintillators
- Readout by a 3D array of fibres
  - Precise location of primary vertex
  - Lower threshold for protons and neutrons







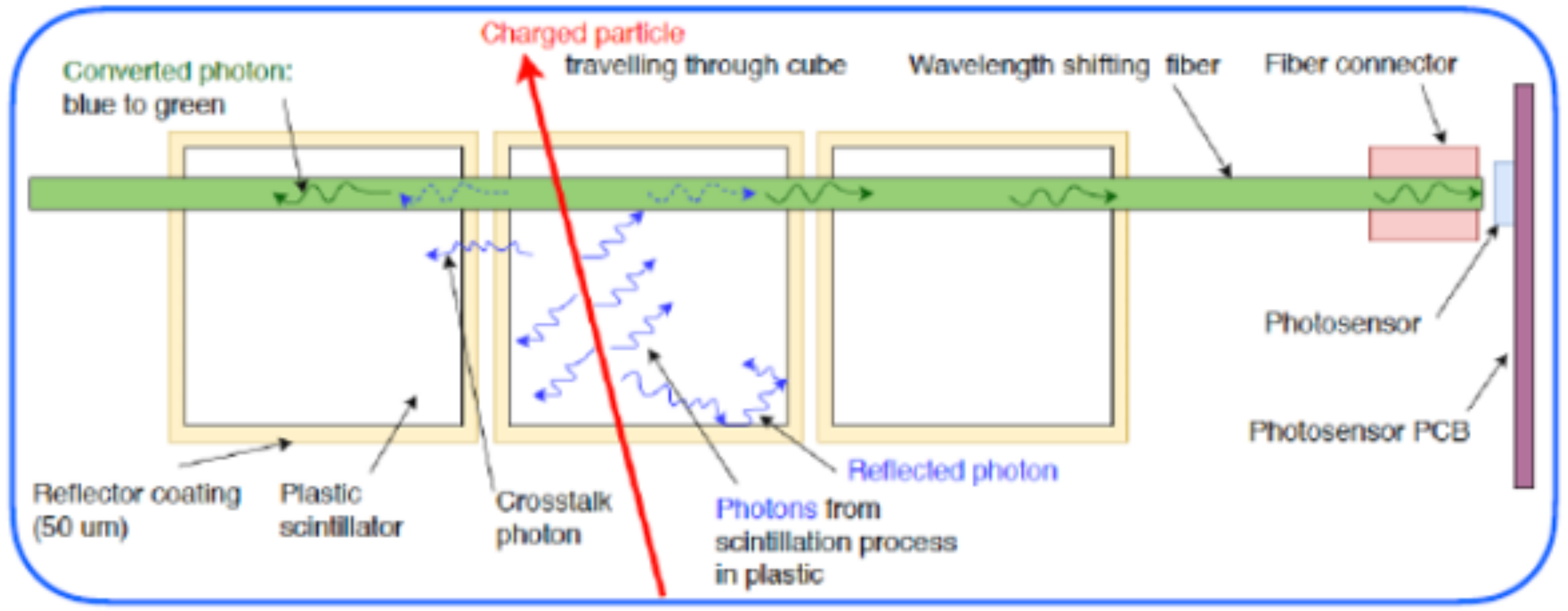
Performances

- **Time**: Time shift between (x,y,z) channels crossed by same tracks
  - **~1.2 ns time resolution** per channel
- **Light Yield**: Measurement of the ~55k attenuation length with cosmic
  - Consistent with expectations

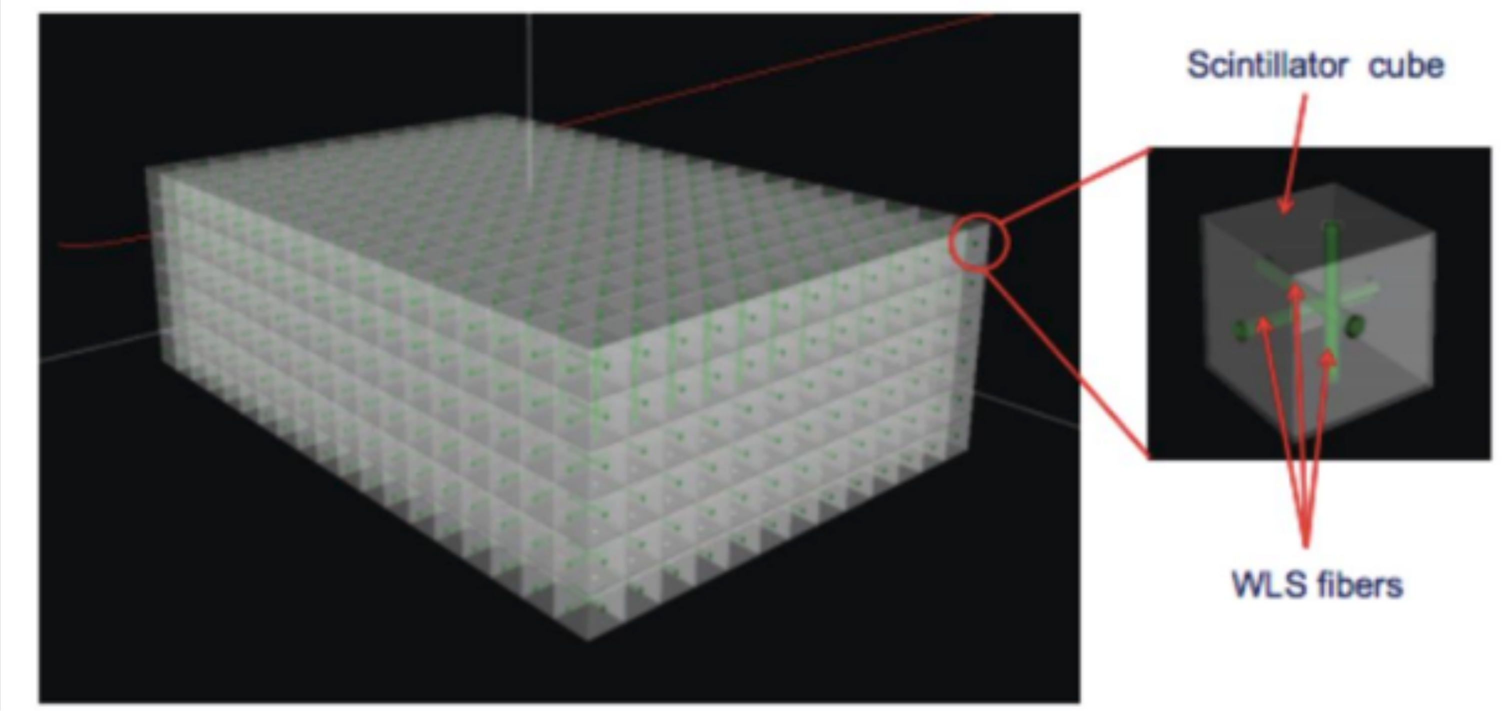
SuperFGD

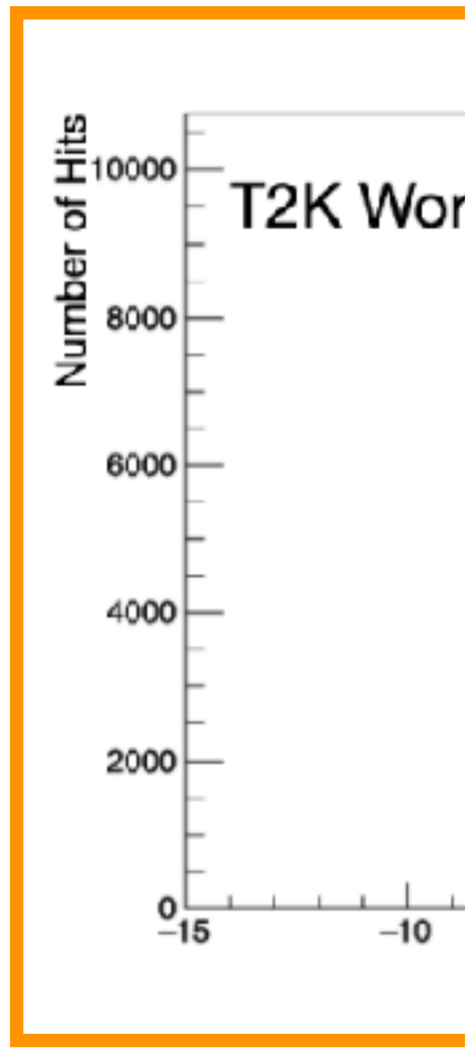
Main characteristics

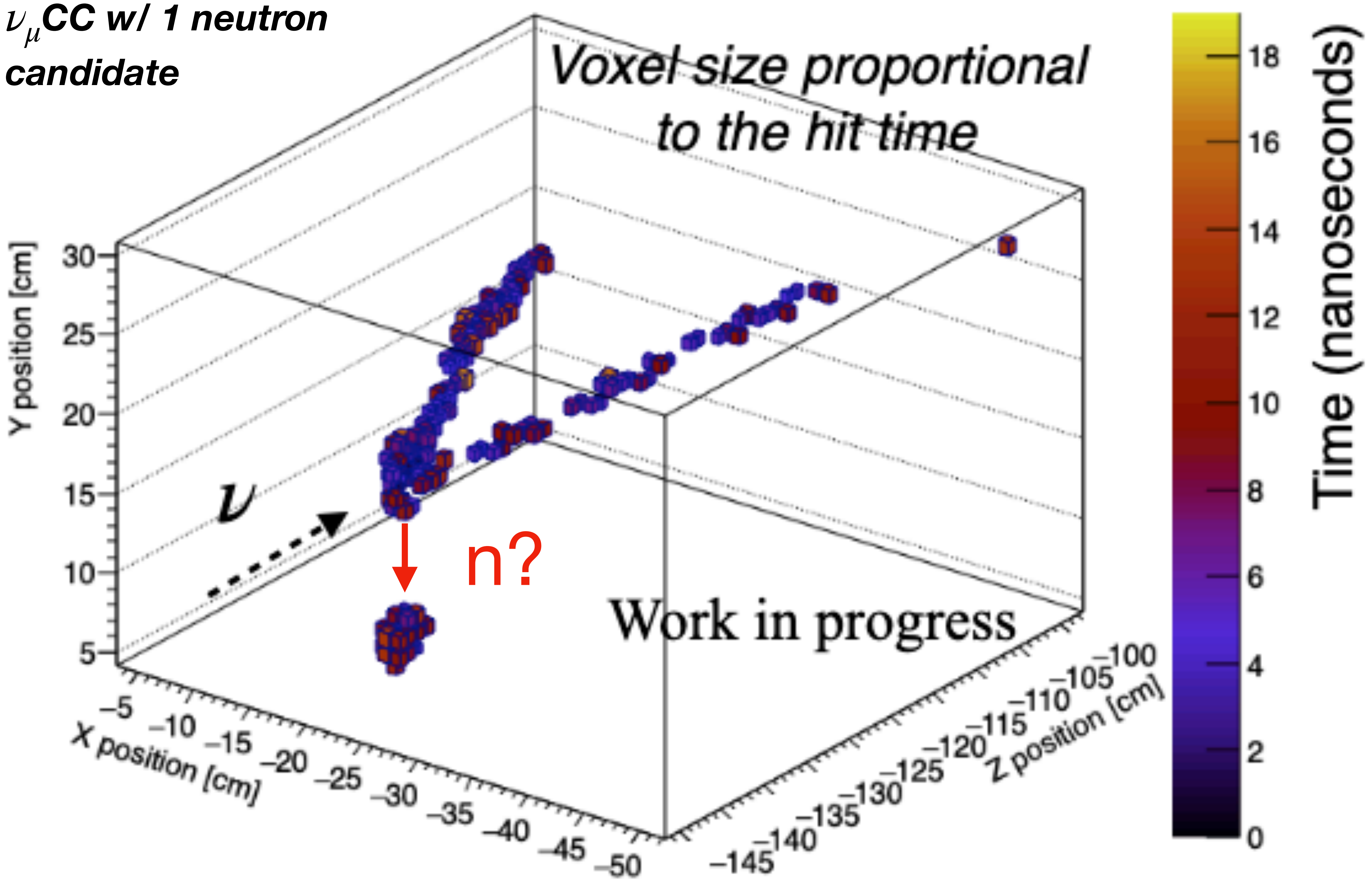
- Highly segmented target made of 2 millions cubes of plastic scintillators
- Readout by a 3D array of fibres
    - Precise location of primary vertex
    - Lower threshold for protons and neutrons

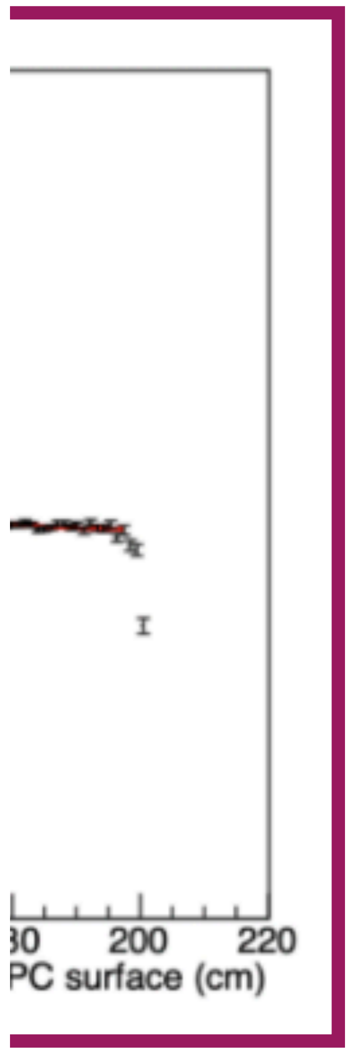


1x1x1 cm³ cubes
Polystyrene scintillator
1.5% paraterphenyl
0.01% POPOP
Chemical etched reflector
WLS fiber Kuraray Y11
2-clad (⌀=1mm)







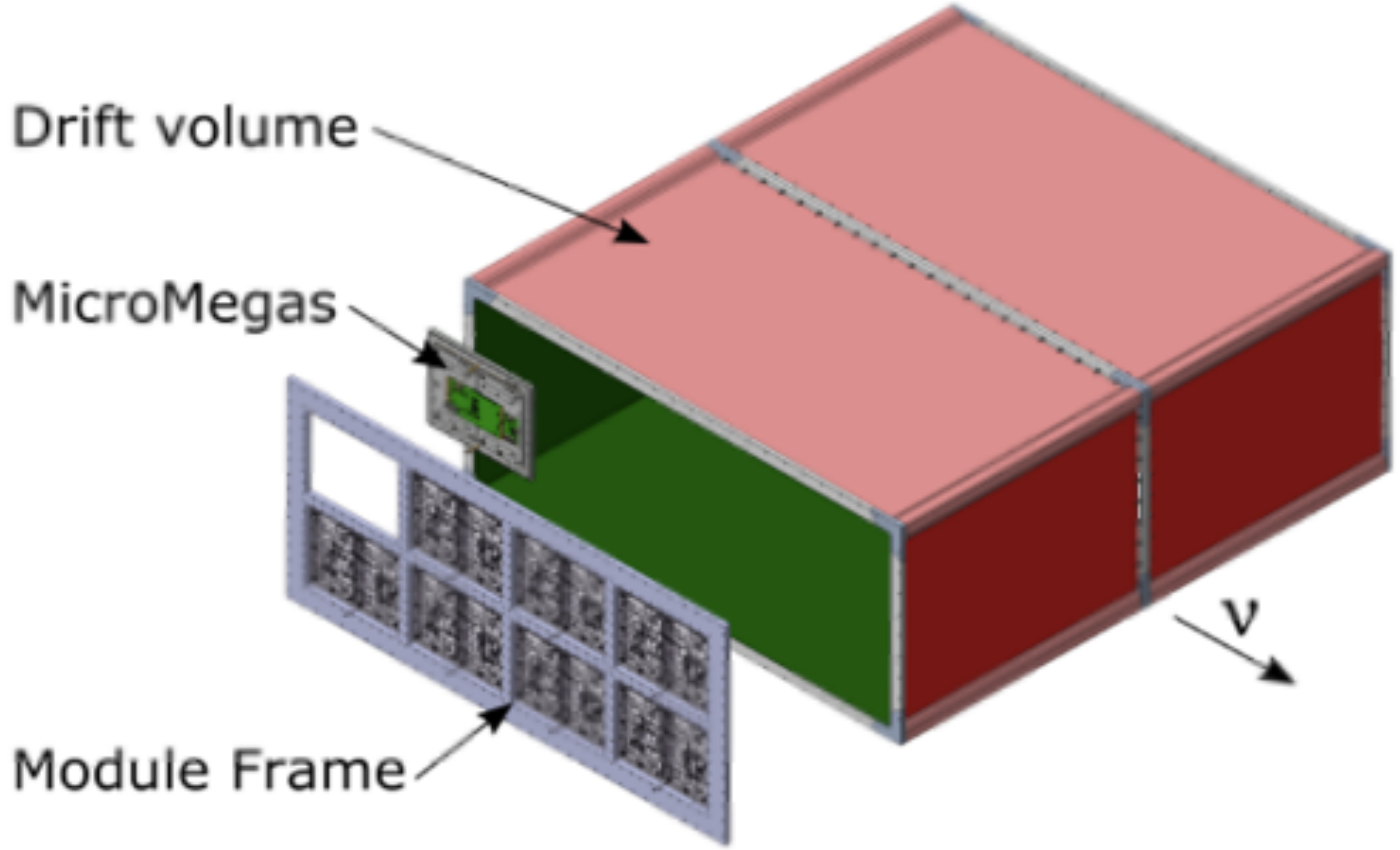


Performances

- **Time**: Time shift between (x,y,z) channels crossed by same tracks
    - **~1.2 ns time resolution** per channel
- **Light Yield**: Measurement of the ~55k attenuation length with cosmic
    - Consistent with expectations

=> Allow to see hadrons!

HATPC concept

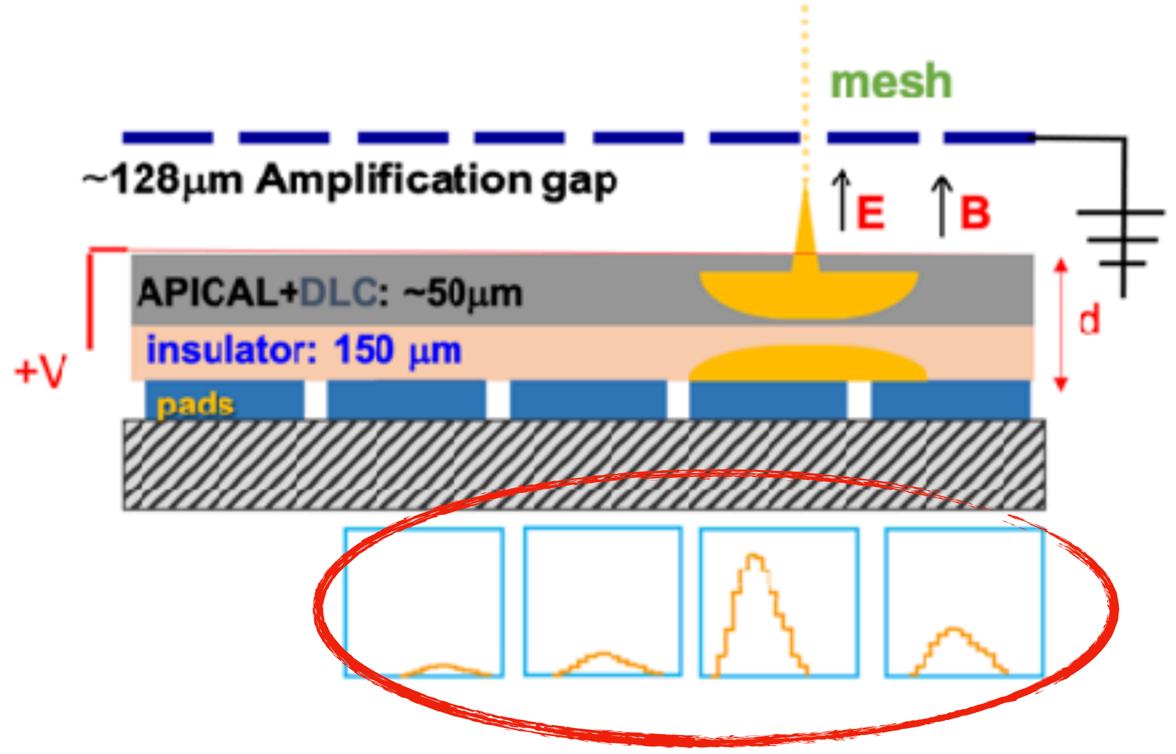


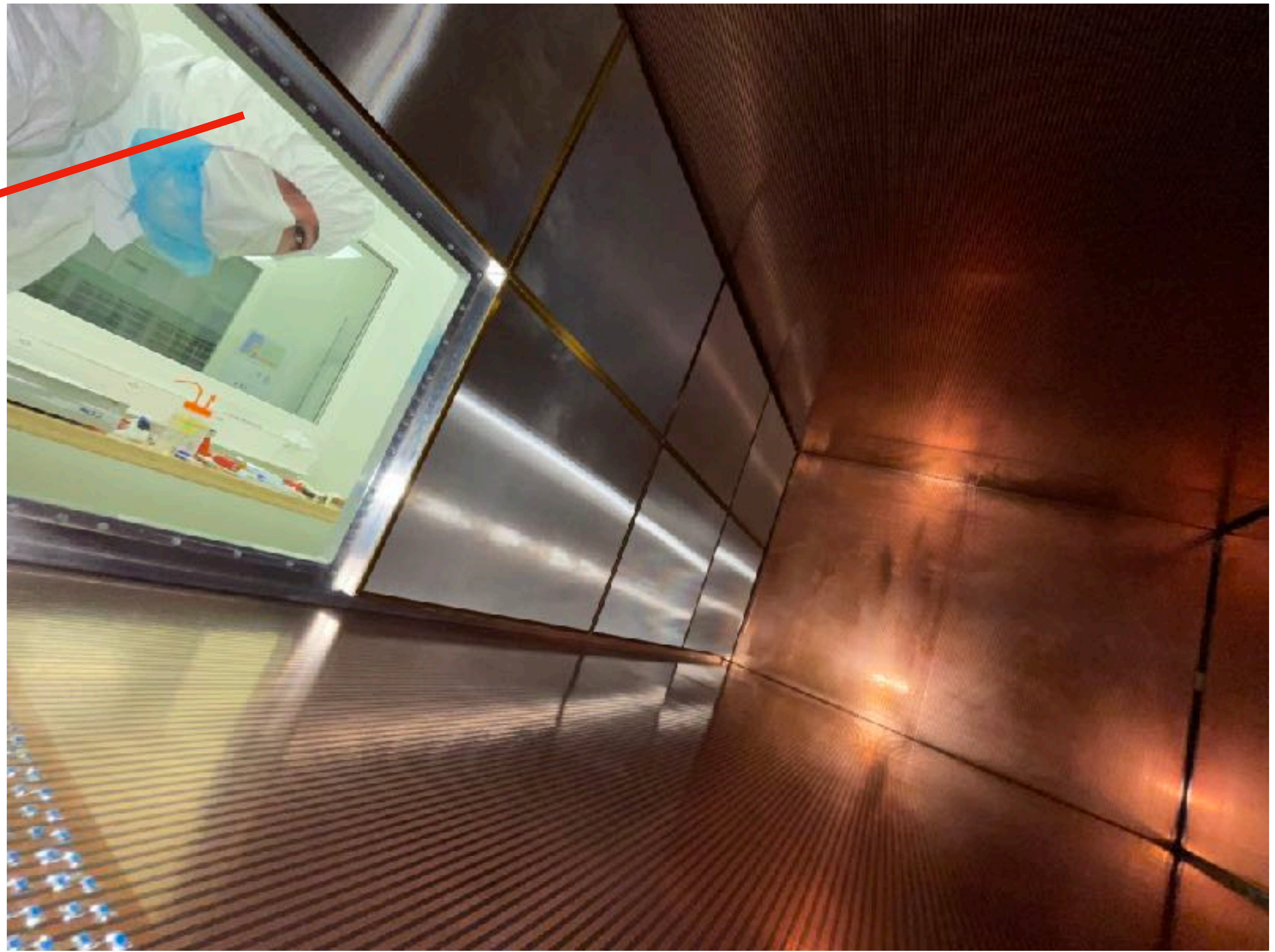
Atmospheric pressure TPC

- Gas: T2K mixture (95 Ar - 3 CF4 - 2 isoC4H10)
- New gas system -> contaminants better than 10ppm
- Drift length 1m
    - Central cathode @ 27kV
- Low material budget
    - Thin wall thanks to composite materials

Encapsulated Resistive Anode Micromegas (ERAM)

- Benefits from ILC TPC & RD51 (now DRD1)
- Bulk micromegas with a resistive layer (DLC) for **charge spreading**
    - Improves spatial resolution for same pads density
    - Reduce sparks rate -> Electronic protection
- Mesh at ground -> Improves E field homogeneity





From S. Levorato CERN Seminar: here

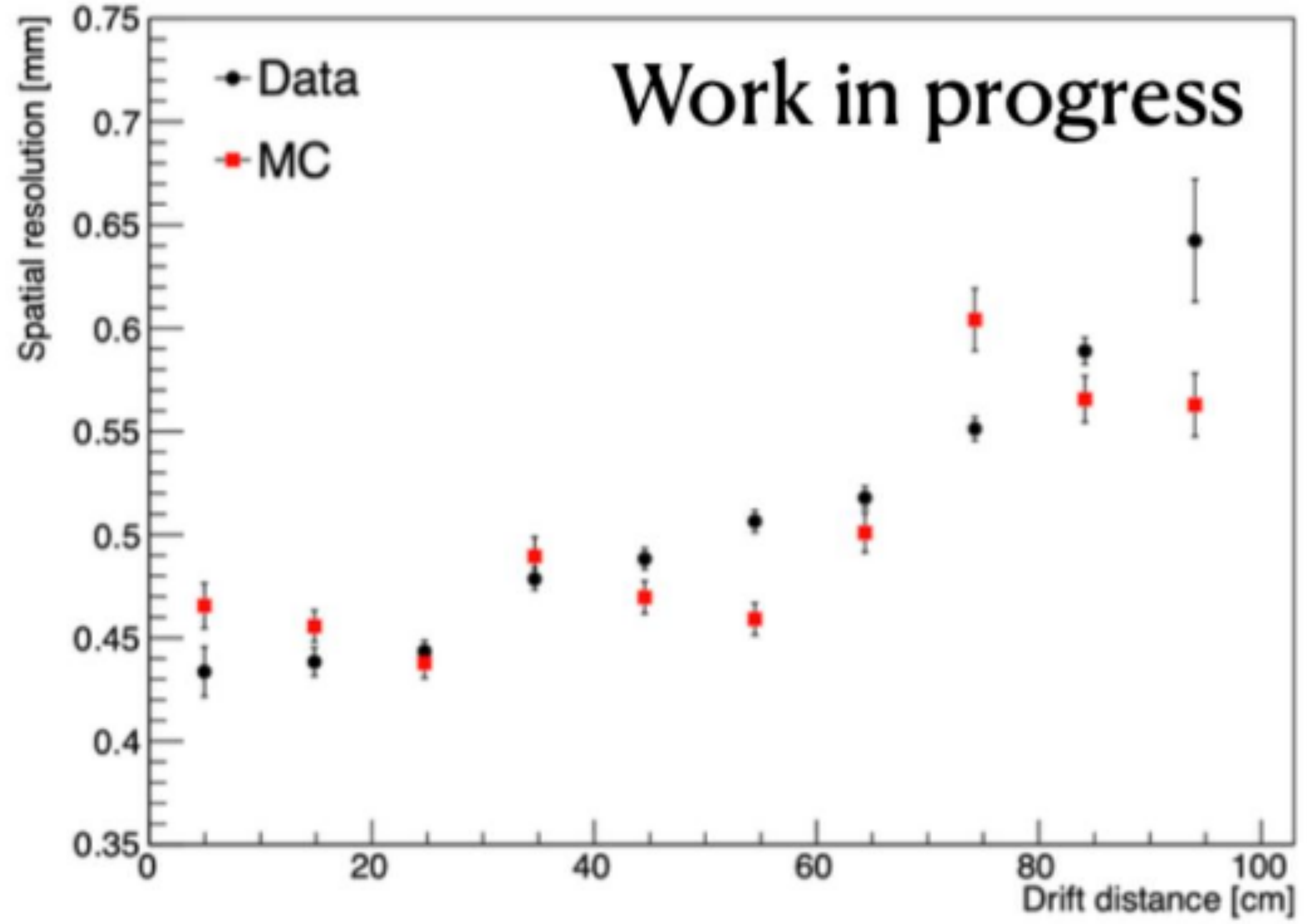
HATPC performances

Momentum resolution $\sigma_p/p < 9\%$ at 1GeV/c
(neutrino energy)

Energy resolution $\sigma_{dE/dx} < 10\%$
(PID muons and electrons)

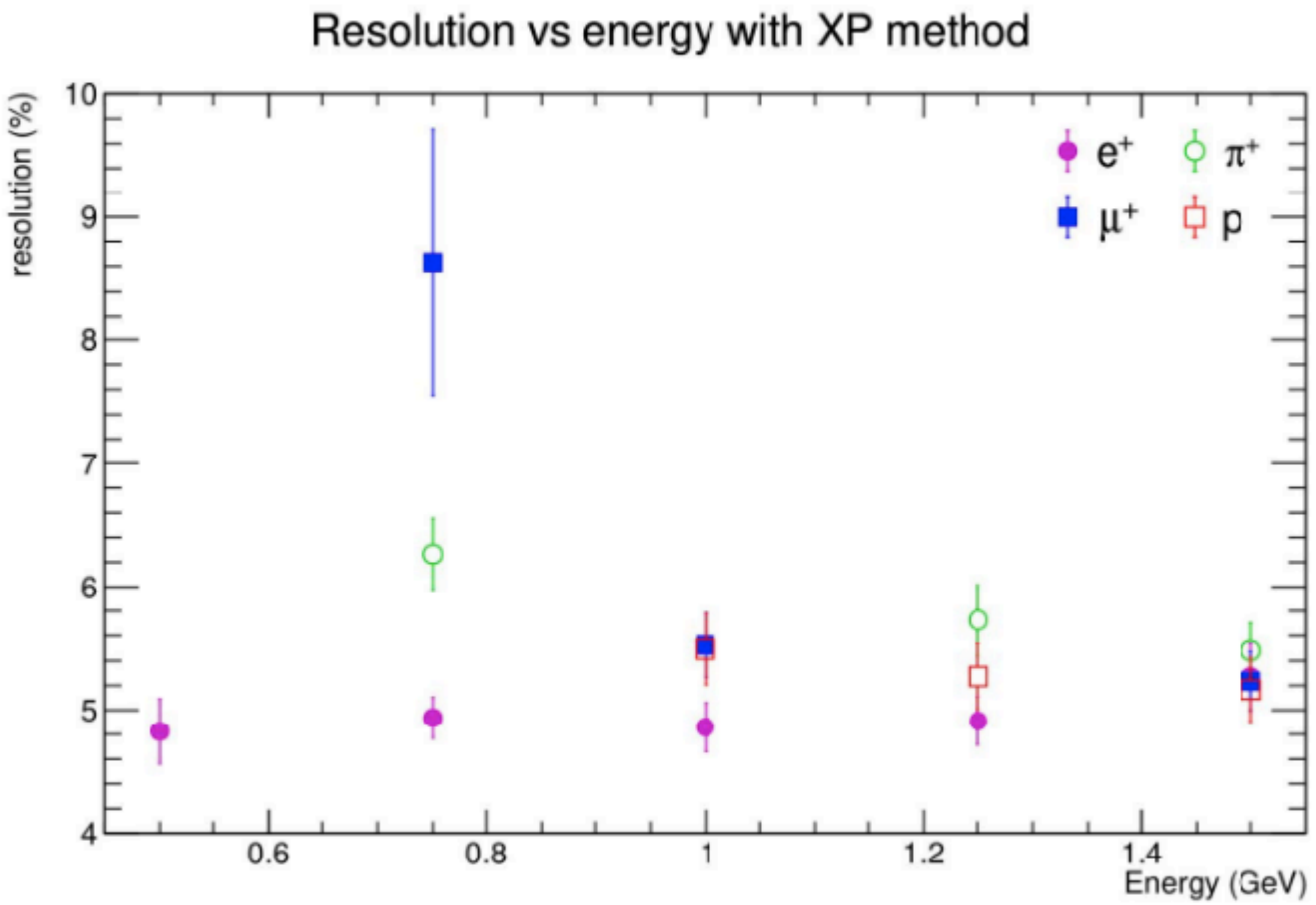
Space resolution $O(500\ \mu m)$
(3D tracking & pattern recognition)

Low material budget walls $\sim 3\%\ X_0$
(matching tracks from neutrino active target)



Commissioning cosmic data

From S. Levorato VCI2025: here



CERN:Test beam PS T10

TOF concept and installation

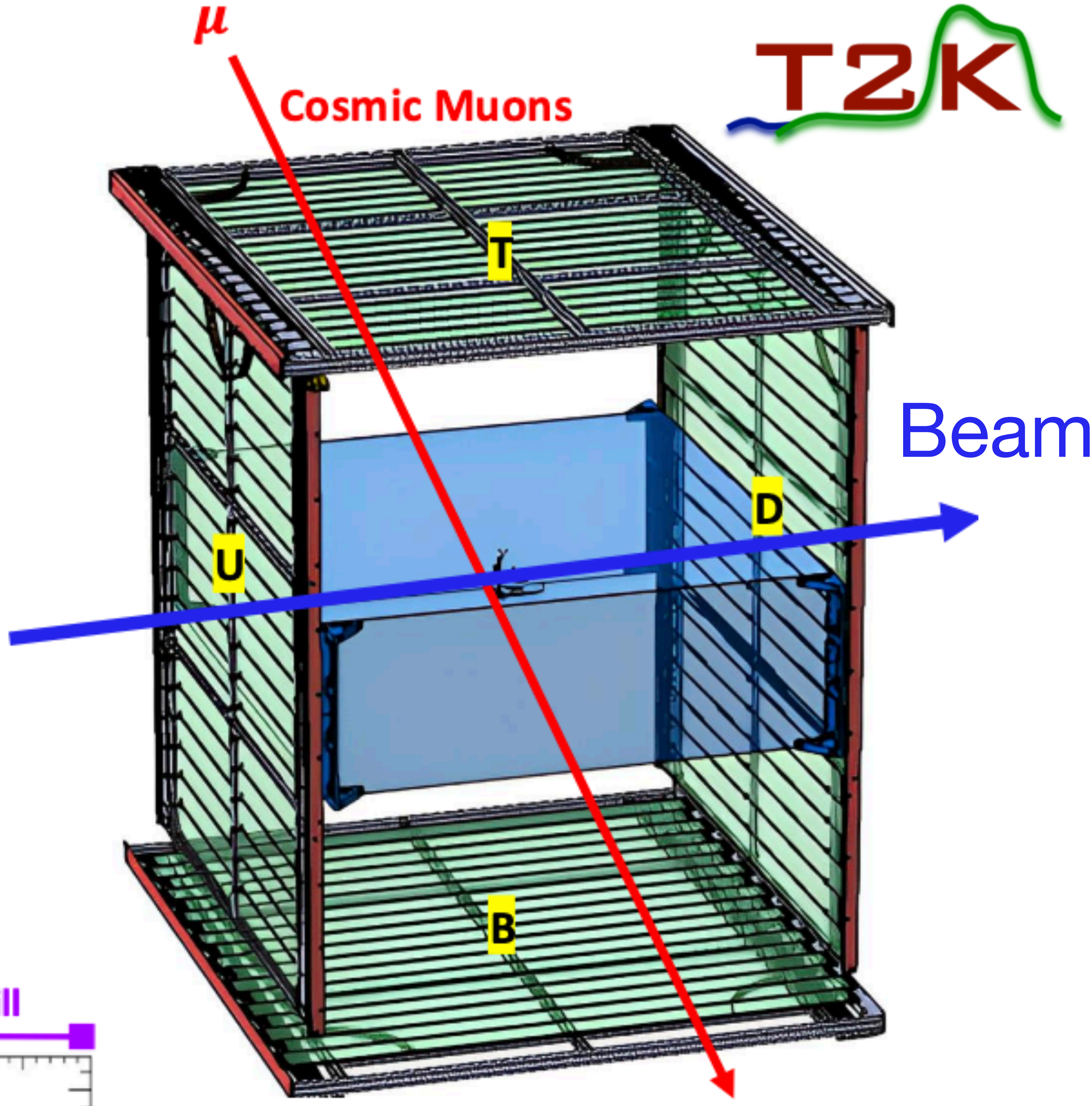
TOF modules

- Composed of 20 plastic scintillator bars arranged in a plane with a total active area of 5.4 m^2
- Readout on both ends by SiPM arrays
- Reach time resolution of ~ 150ps at CERN

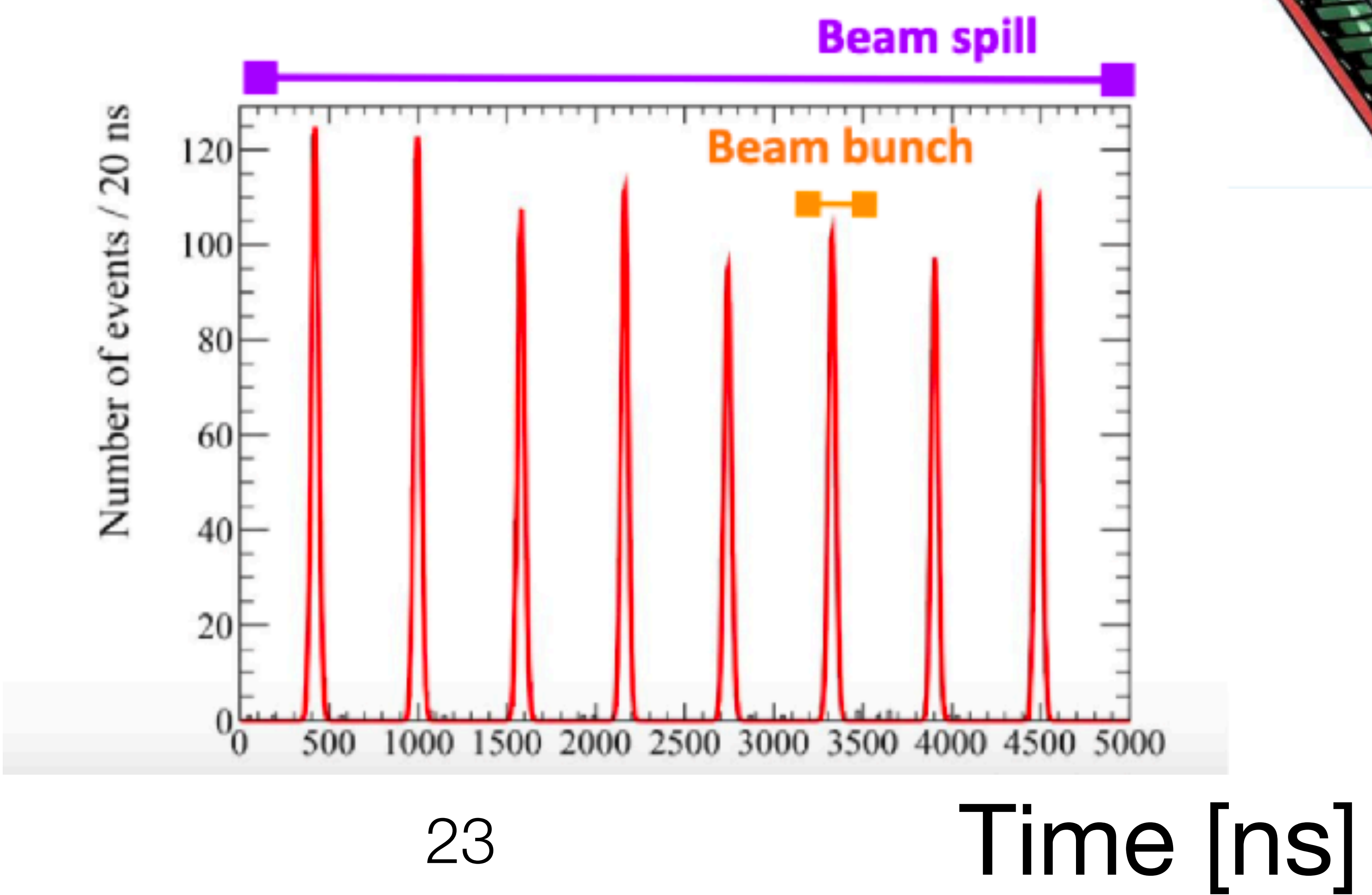
TOF goals

- PID using time-of-flight
- Tags background from out-of-fiducial volume
- Provide T0 to HATPCs
- Improve SFGD neutron time-of-light measurement
- Beam and horizontal muons monitoring

In addition has provided cosmic triggers to upgrade detectors



Plus 2 hidden side panels for a 4pi coverage of detectors



Conclusion

- T2K is aiming at precise measurement of LBL oscillation parameters $\theta_{23}, \Delta m^2_{23}, \delta_{CP}$ and mass ordering and cross-section analyses which are fundamental for future LBL (HK, DUNE)

- Oscillation analysis:
  - CP symmetry is excluded at 90% CL (T2K)
  - Mild preference for normal ordering and upper octant for θ_{23}

- Three main limitations of such measurement have been shown:

  - Degeneracy: Performing joint-fits with other experiments
  - Interaction models: Study ν cross-section for a better interaction model w/ ND upgrade
  - Statistics: T2K is upgrading its beam line and upgraded its near detector increasing the statistics

- Stay tuned for future T2K results!

Backup

Bayesian approach

- T2K is aiming at precise measurement of LBL oscillation parameters $\theta_{23}, \Delta m^2_{23}, \delta_{CP}$ and mass ordering and cross-section analyses which are fundamental for future LBL (HK, DUNE)