Latest oscillation results from T2K

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Neutrino oscillations

Neutrino can change flavour while propagating

- This mechanism can be described by 6 parameters :
  - 3 mixing angles, θ_{12} θ_{13} and θ_{23} and 2 Δm^2_{ij}
  - A CP violating phase : δ_{CP}

Two neutrino mixing probability

$$P(\nu_x \to \nu_y) = sin^2(2\theta) sin^2(1.27 \Delta m^2 \frac{L(km)}{E(GeV)})$$

Three neutrino mixing

(+ Majorana phases)

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

Flavour | **Solar and reactor** | **Reactor and accelerator** | **Atmospheric and accelerator** | **Mass**

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Flavour | **Solar and reactor** | **Reactor and accelerator** | **Atmospheric and accelerator** | **Mass**

Solar and reactor:

$\theta_{12} = (33.6 \pm 0.8)°$

$|\Delta m^2_{12}| = (7.50 \pm 0.18) \cdot 10^{-5}$ eV²

Atmospheric and accelerator:

$\theta_{23} = (45 \pm 3)°$

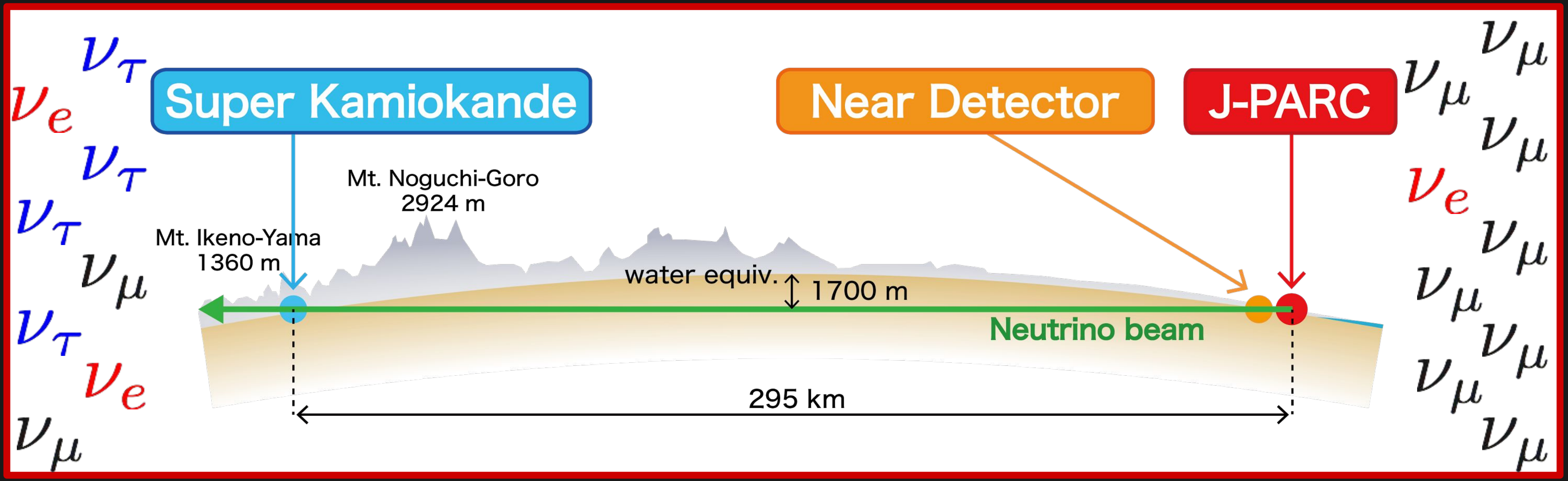
$|\Delta m^2_{32}| = (2.52 \pm 0.04) \cdot 10^{-3}$ eV²

Reactor and accelerator:

$\theta_{13} = (8.5 \pm 0.15)°$

$\delta_{CP} \approx -90°$ slightly favored

Tokai to Kamioka



T2K is a long-baseline neutrino oscillation experiment

- A ν_μ beam, peaked at ~600 MeV is produced at J-PARC (Tokai, Japan)
- The neutrinos are then detected in the near detector ND280, and in the far detector, 295 km away, Super-Kamiokande (Kamioka).

T2K physics goals

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

- ➤ Two main initial goals :
  - ➡ Precise measurement of ν_μ disappearance :
    - → Atmospheric sector, measurement of θ_{23} and Δm^2_{32} ✓
  - ➡ Observation of ν_e appearance in the ν_μ beam :
    - → Access to the interference parameter θ_{13} ✓
- ➤ Now taking data with anti-neutrino ⇒ combined ν_e and $\bar{\nu}_e$ appearance :
  - → First constraints of δ_{CP}
- ➤ T2K is also doing various cross-section measurements in several of its sub-detectors !

Oscillation probability

➤ ν_μ disappearance probability

➡ In T2K, given the energy of the neutrino, we can simplify the formula to :

$$P(\nu_\mu \to \nu_\mu) \sim 1 - \left(\underbrace{\cos^4\theta_{13}\cdot\sin^2 2\theta_{23}}_{\text{Leading term}} + \underbrace{\sin^2 2\theta_{13}\cdot\sin^2\theta_{23}}_{\text{Next-to-leading}}\right) \times \sin^2\frac{\Delta m^2_{31}\cdot L}{4E}$$

Can be used to resolve octant

➤ ν_e appearance probability

➡ Around T2K's oscillation maximum :

a = 2 √2 $G_F n_e$ E and becomes -a for anti-neutrino

$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{32}L}{4E_\nu}\right)\left(1+\frac{2a}{\Delta m^2_{31}}(1-2\sin^2\theta_{13})\right)$$

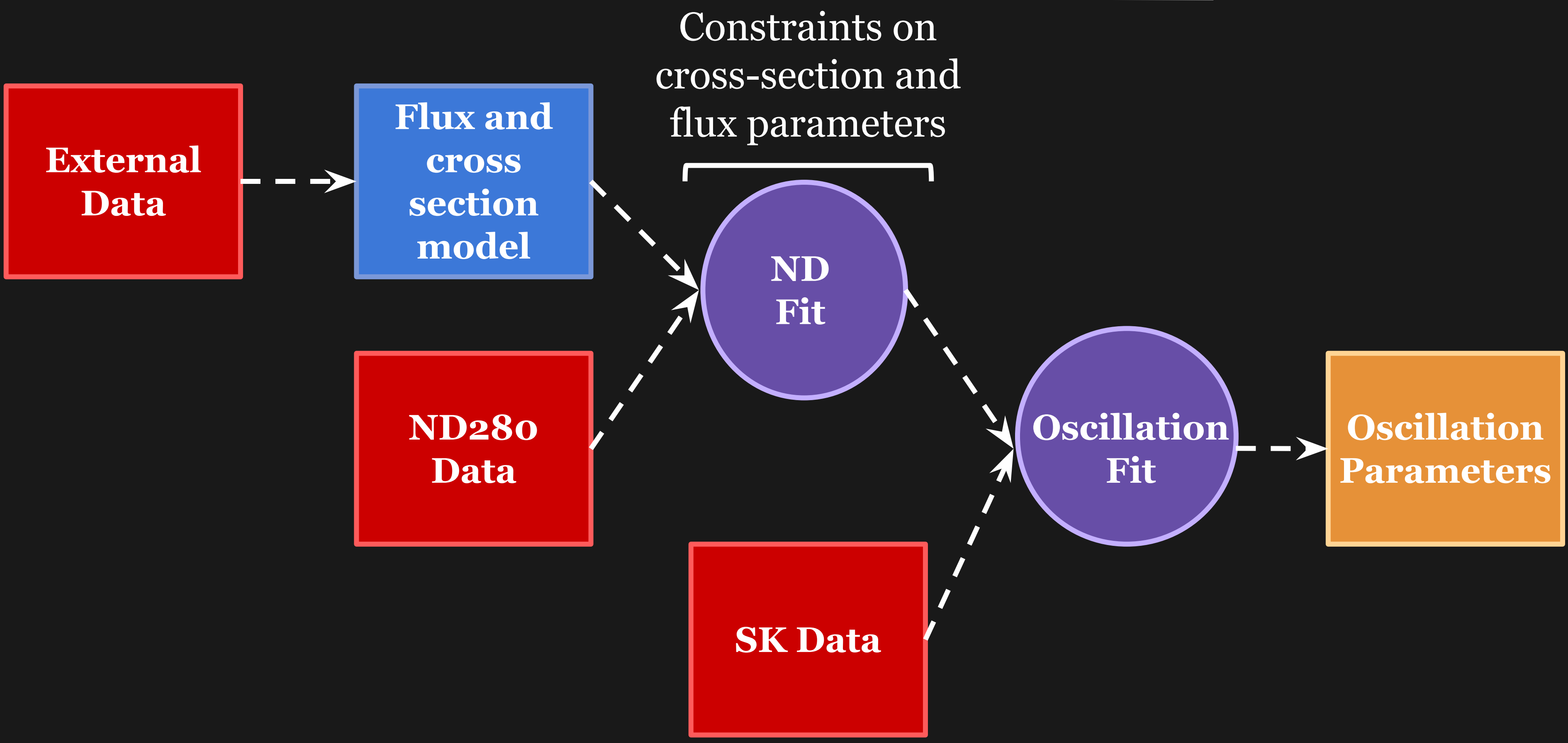
Leading including matter effect

$$-\sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13}\cos\theta_{13}\sin\delta\sin^2\left(\frac{\Delta m^2_{32}L}{4E_\nu}\right)\sin\left(\frac{\Delta m^2_{21}L}{4E_\nu}\right)$$

CP violating

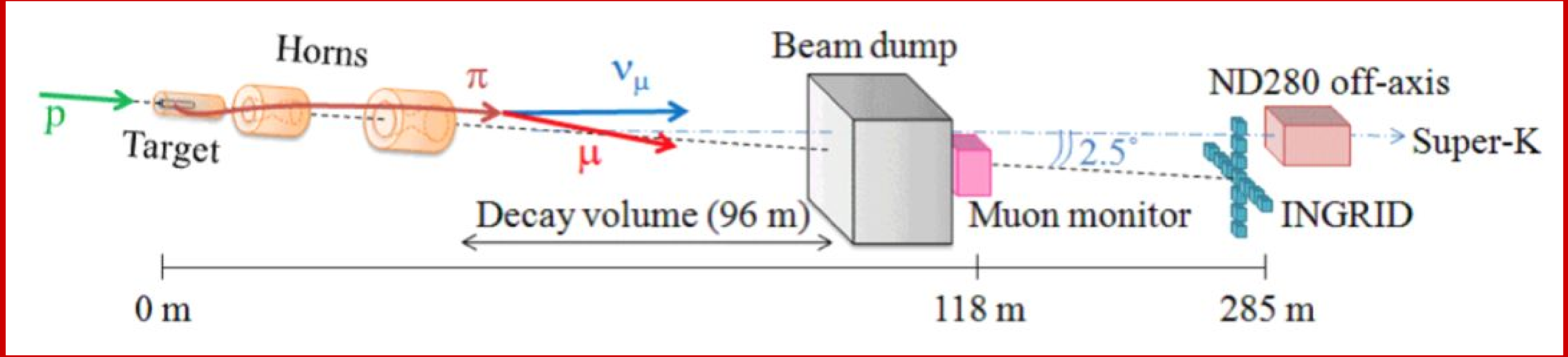
Replace by -δ for anti-neutrino

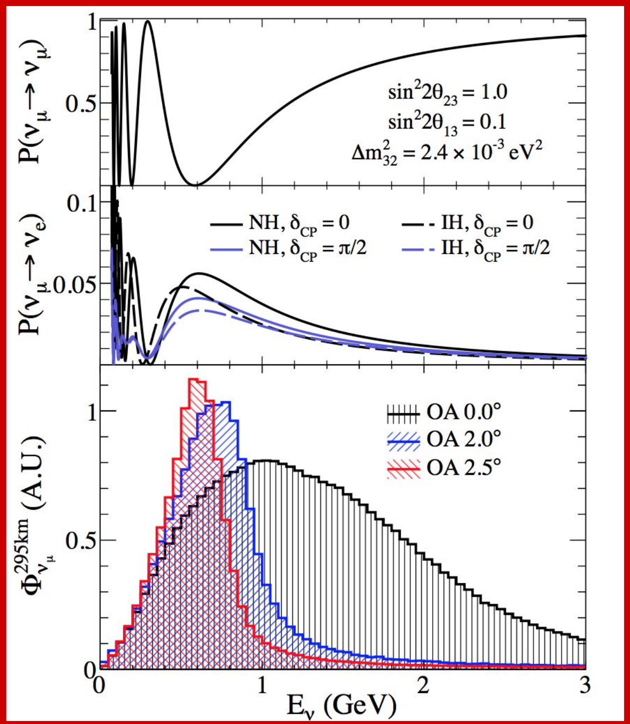
T2K oscillation analysis chain



We do a first fit with the near detector data in order to constrain our flux and cross-section models, to have a precise prediction of the number of events we expect at the far detector.

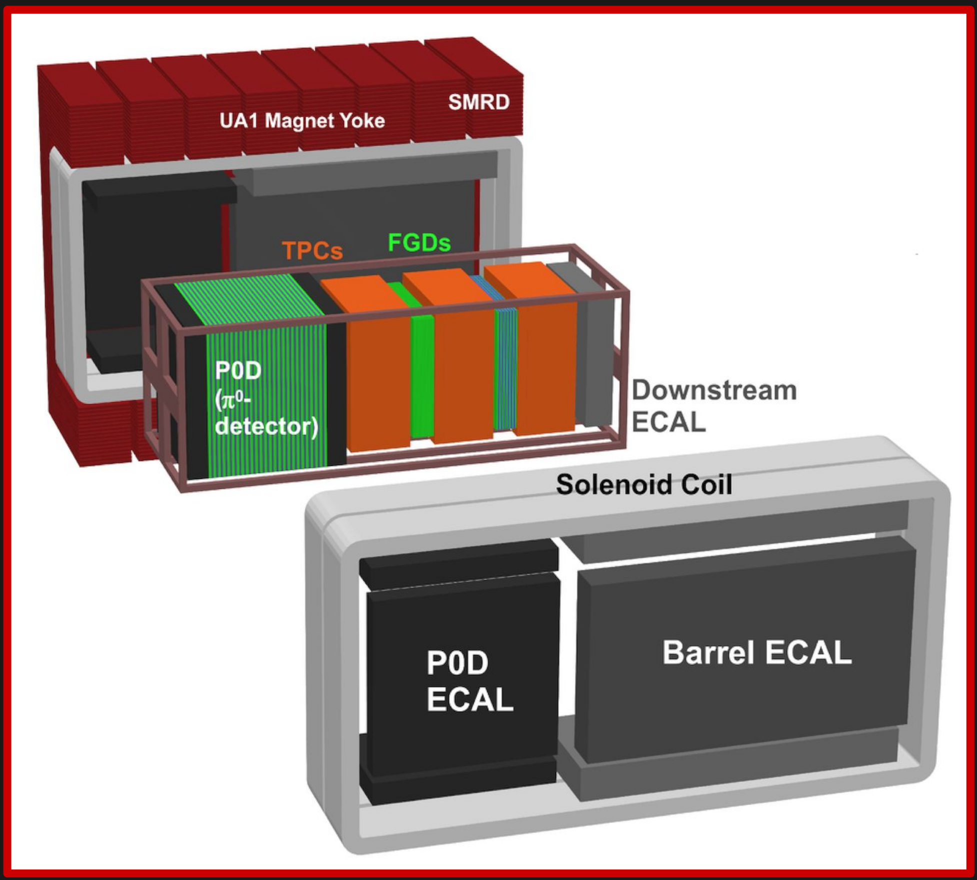
T2K beam





- First use of off-axis ν_μ beam to get a beam more peaked in energy.
  - ➡ The energy is peaked around oscillation maximum (0.6 GeV).
- The pion and kaon production at target is constrained by the NA61/SHINE experiment at CERN, allowing us to reduce systematic uncertainties on the flux of neutrino.
- An anti-neutrino beam can be obtained by reversing current in the magnetic horns.

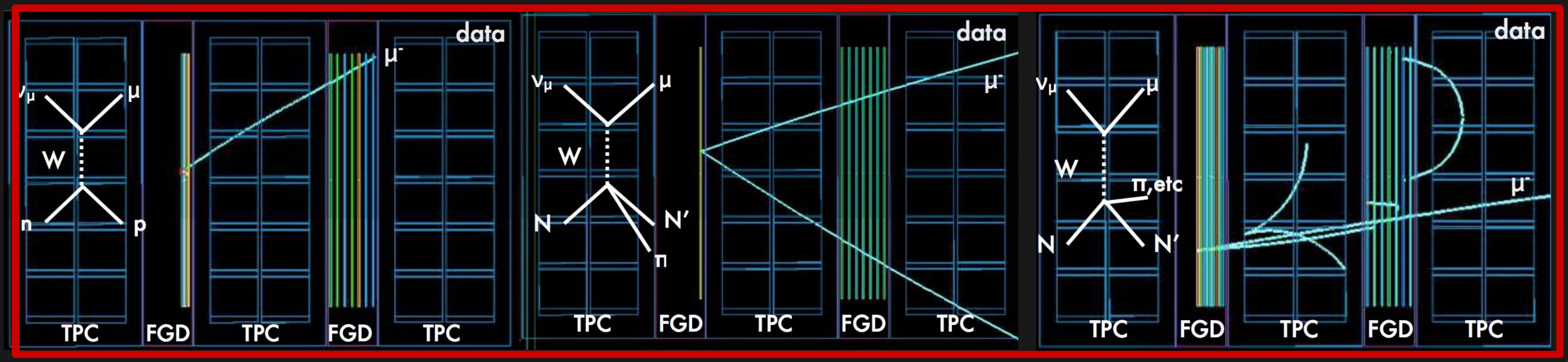
T2K near detector : ND280



- ND280 is located 2.5° off-axis (same as Super-K).
- Several sub-detectors inside the magnet :
  - ➡ Fine Grained Detector (FGD), plastic scintillator bars for FGD1 and scintillator/water for FGD2 as target.
  - ➡ Time Projection Chamber (TPC) to reconstruct momentum and charge.
  - ➡ Pi0 detector (P0D) and Electromagnetic calorimeter (ECal).
- **Measure neutrino spectrum and composition before oscillations.**

T2K near detector in the oscillation analysis

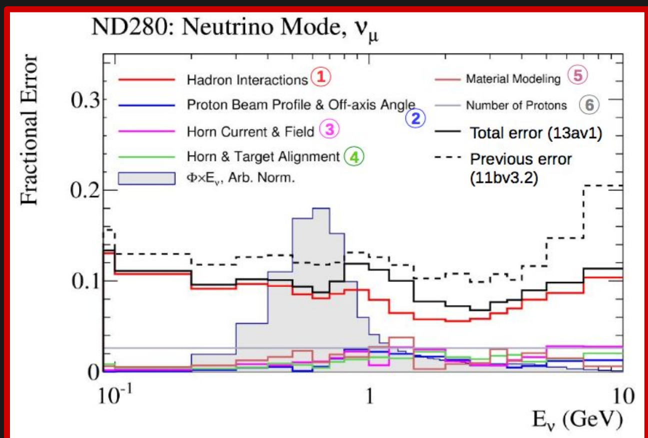
- ➤ Select charged-current (CC) muon neutrino interactions in the tracker.
  - ➡ The FGDs are used as targets.
  - ➡ With the TPCs, retrieve the momentum and charge of the tracks produced.
- ➤ We break the CC inclusive into 3 samples, depending on the number of pions reconstructed.
- ➤ We have 14 samples : 6 in neutrino mode (3 per FGD), 4 in anti-neutrino mode with anti-neutrino selection and 4 in anti-neutrino mode with neutrino contamination.



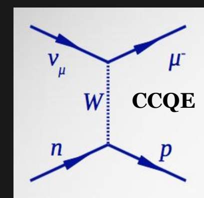
Quasi-elastic candidate   Single pion candidate   DIS candidate

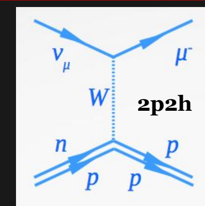
T2K near detector in the oscillation analysis

Flux

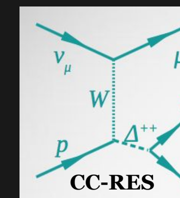


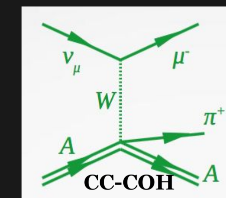
Cross-section



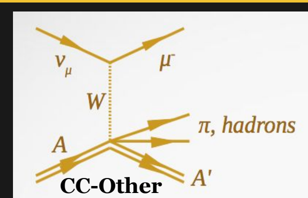


CC0π : 13 parameters

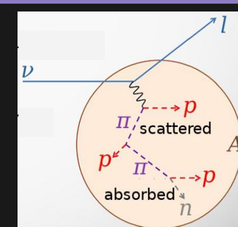




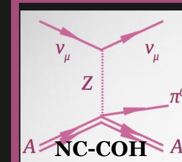
CC1π : 4 parameters

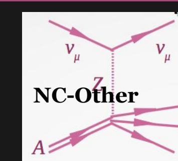


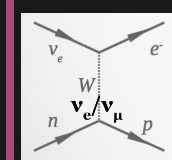
CCOther : 1 parameter



Final state interaction : 6 parameters





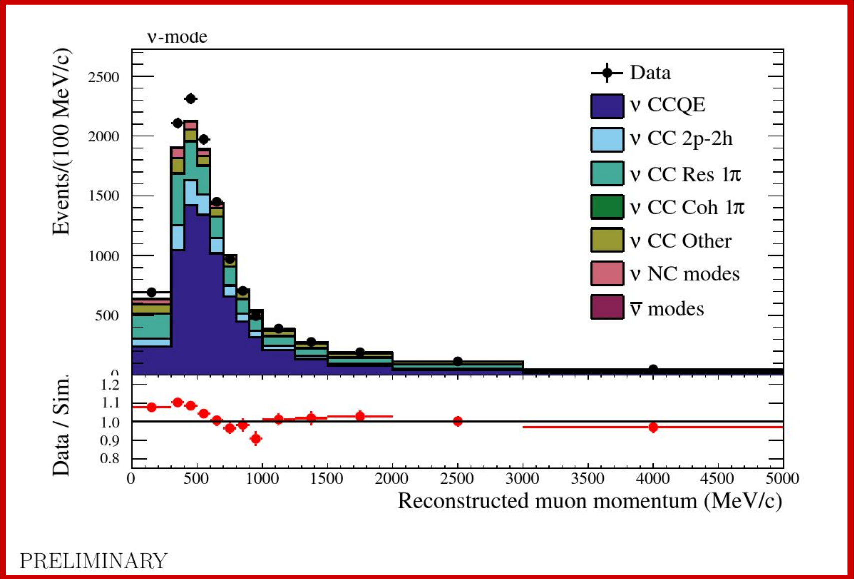


Other : 3 parameters

- Even constrained with external data, the flux and cross-section uncertainties are still quite large and don’t represent perfectly the data.
- We fit the models to the ND data to constrain further the flux and cross-section, helping to improve the prediction in the far detector.

T2K near detector in the oscillation analysis

FGD2 CC0π sample prefit



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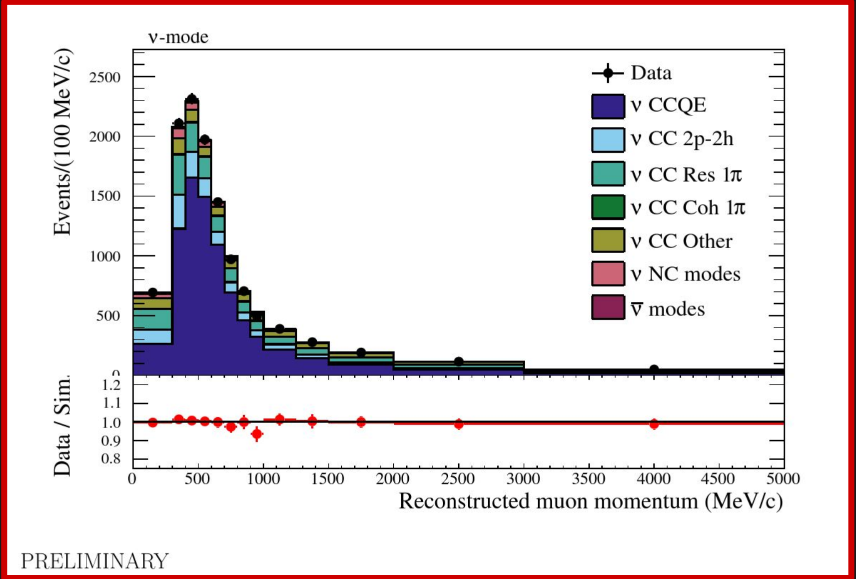

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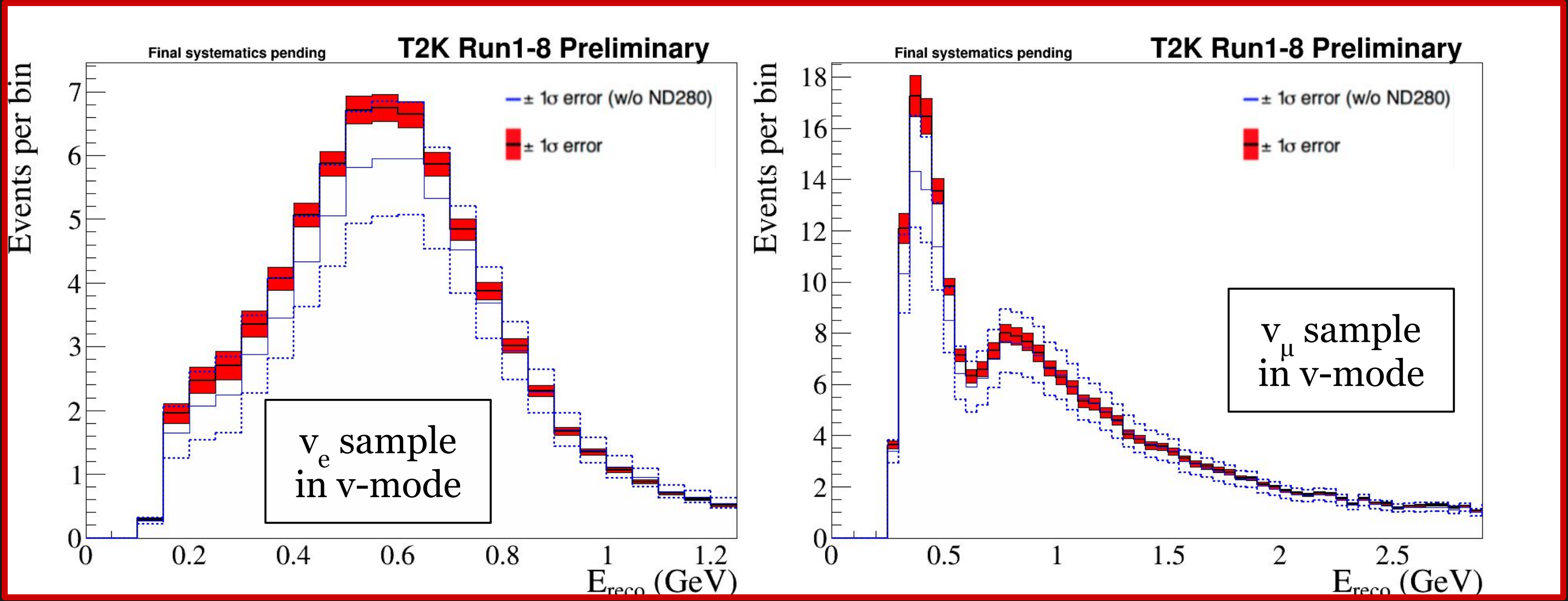
T2K near detector in the oscillation analysis

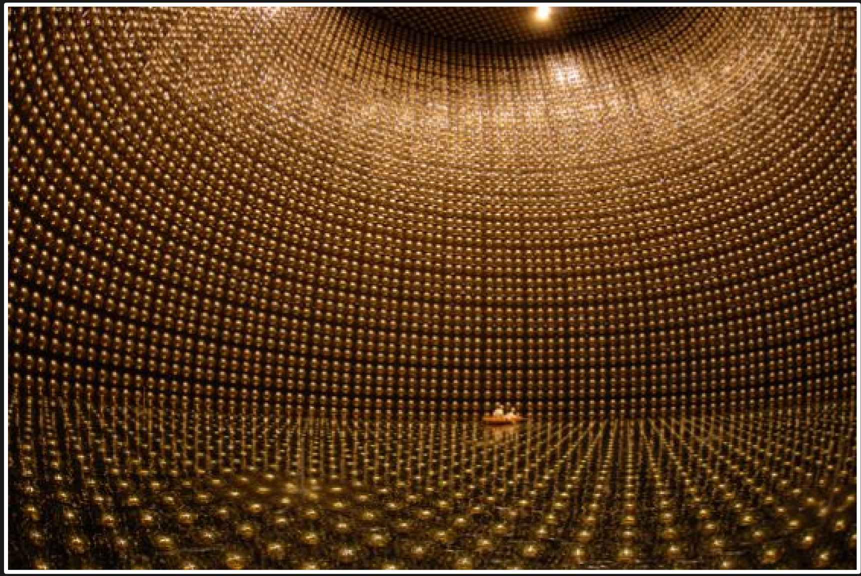
ND280 helps to reduce the systematic uncertainties in the oscillation analysis from ~14% to ~5%

Spectrum of events at SK for ν-mode samples



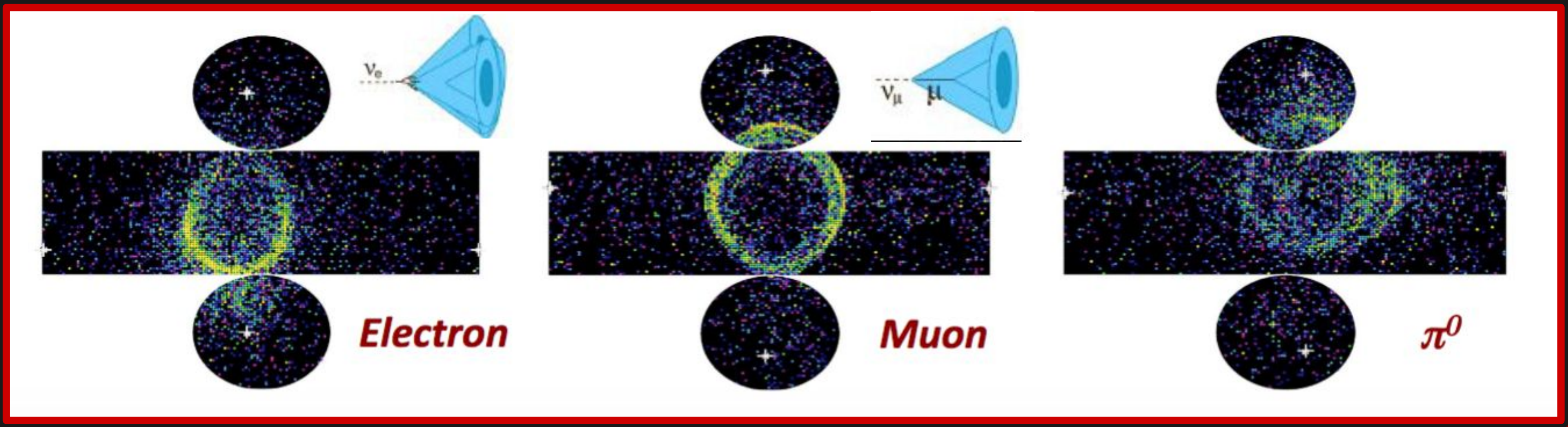
	ν_μ sample ν mode	ν_e sample ν mode	$\bar{\nu}_\mu$ sample $\bar{\nu}$ mode	$\bar{\nu}_e$ sample $\bar{\nu}$ mode
Total w/o ND280	**13.9%**	**15.9%**	**11.7%**	**13.7%**
Total with ND280	**4.3%**	**7.3%**	**3.8%**	**7.7%**

The far detector : Super-Kamiokande



Cherenkov detector with 50 kT of water.

- Detect neutrino CC interactions
- Excellent muon/electron separation thanks to the shape of the Cherenkov ring.
- Only 1% of muons are misidentified as electrons.



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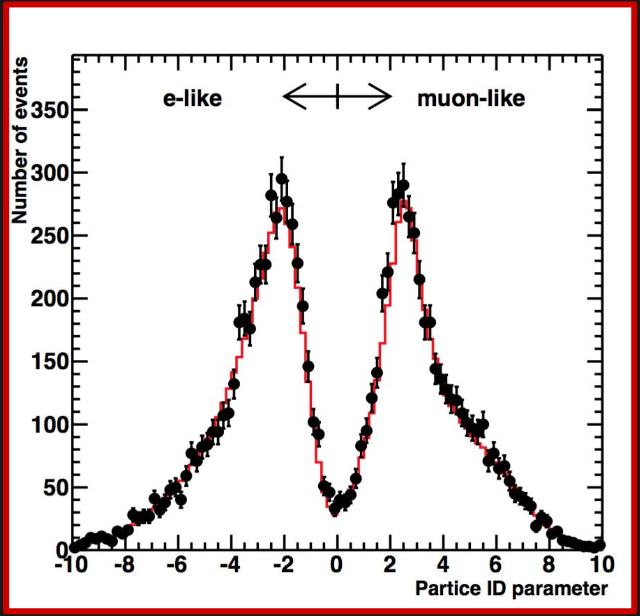

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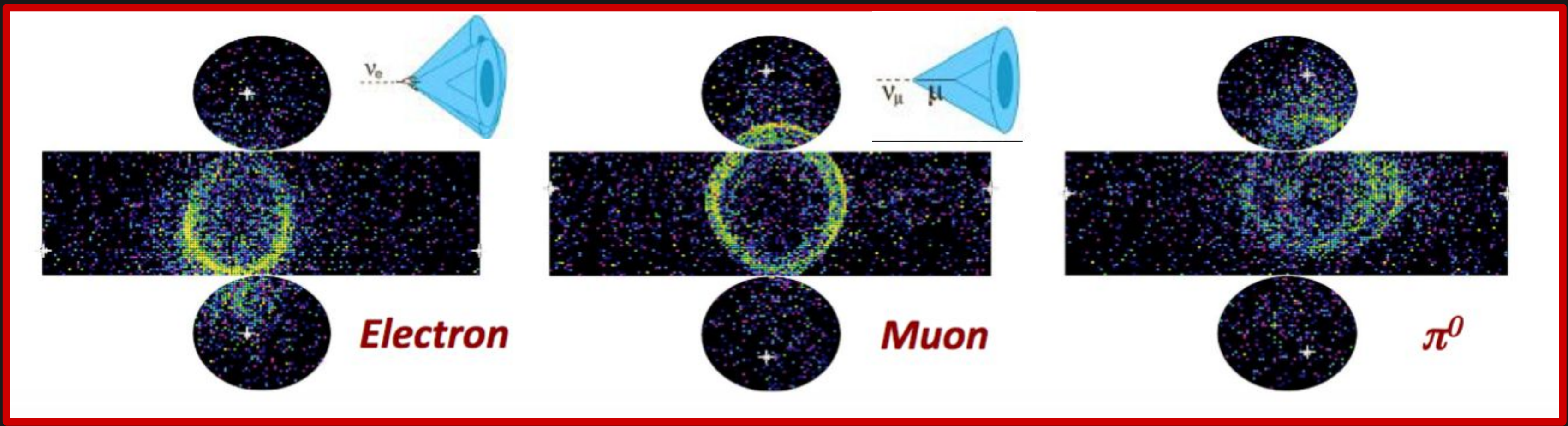
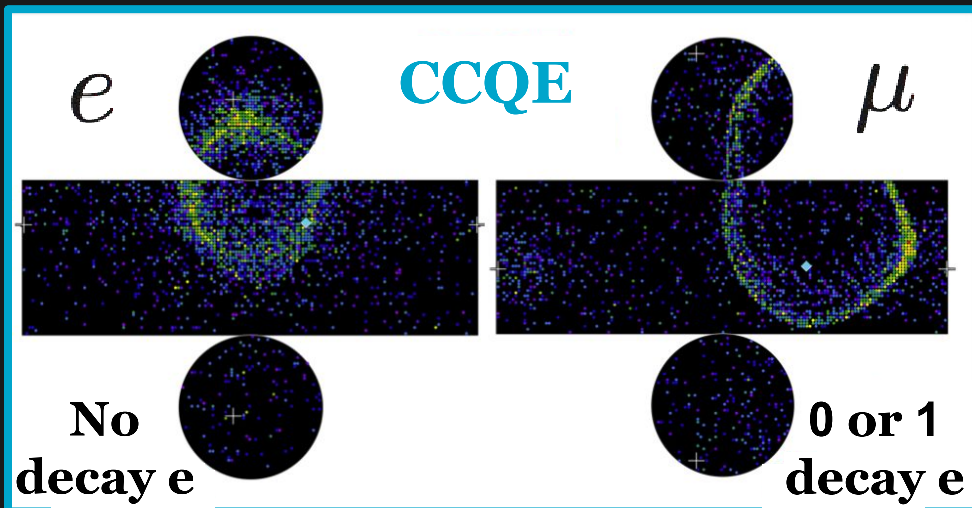
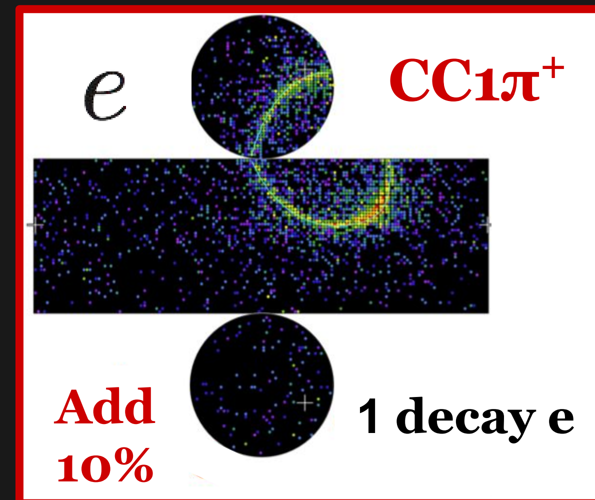
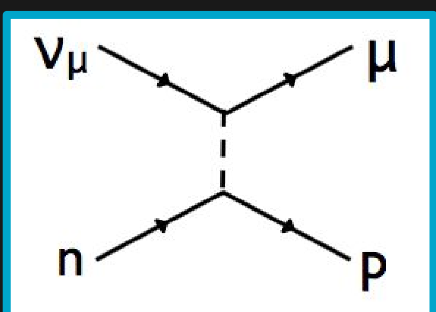


Five far detector samples

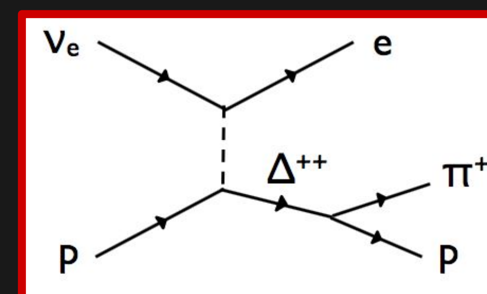




New Sample



- One reconstructed ring electron and muon samples for both neutrino and anti-neutrino.
  - ➡ Mainly CC quasi-elastic events.
- Added during winter 2016 a new sample with 1 electron ring and 1 decay electron which add ~10% of events.
  - ➡ Mainly single pion production from electron neutrino.



T2K oscillation analysis

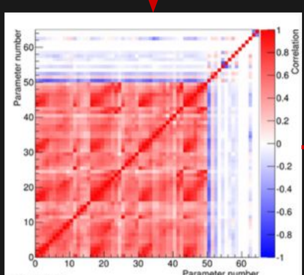
Flux model constrained by NA61/SHINE

Cross-section model constrained by other experiments (Minerva, Miniboone…)

Systematic error source	$\Delta N_{SK}/N_{SK}$ before ND fit	$\Delta N_{SK}/N_{SK}$ after ND fit
Flux	7.90%	3.94%
Cross section	10.66%	4.85%
Flux and cross section	12.40%	3.19%
Final state/secondary interactions at SK	1.93%	
SK detector	2.22%	
Total	13.92%	4.25%

ND Fit

lepton p-θ



Constrained covariance matrix

SK Fit

Oscillation Parameters

$$N_{SK} = \int dE\ \Phi(E) \times \sigma(E) \times \epsilon_{SK}(E) \times P(\nu_\alpha \to \nu_\beta, E, \theta_{ij}, \Delta m^2_{ij}, \delta_{CP})$$

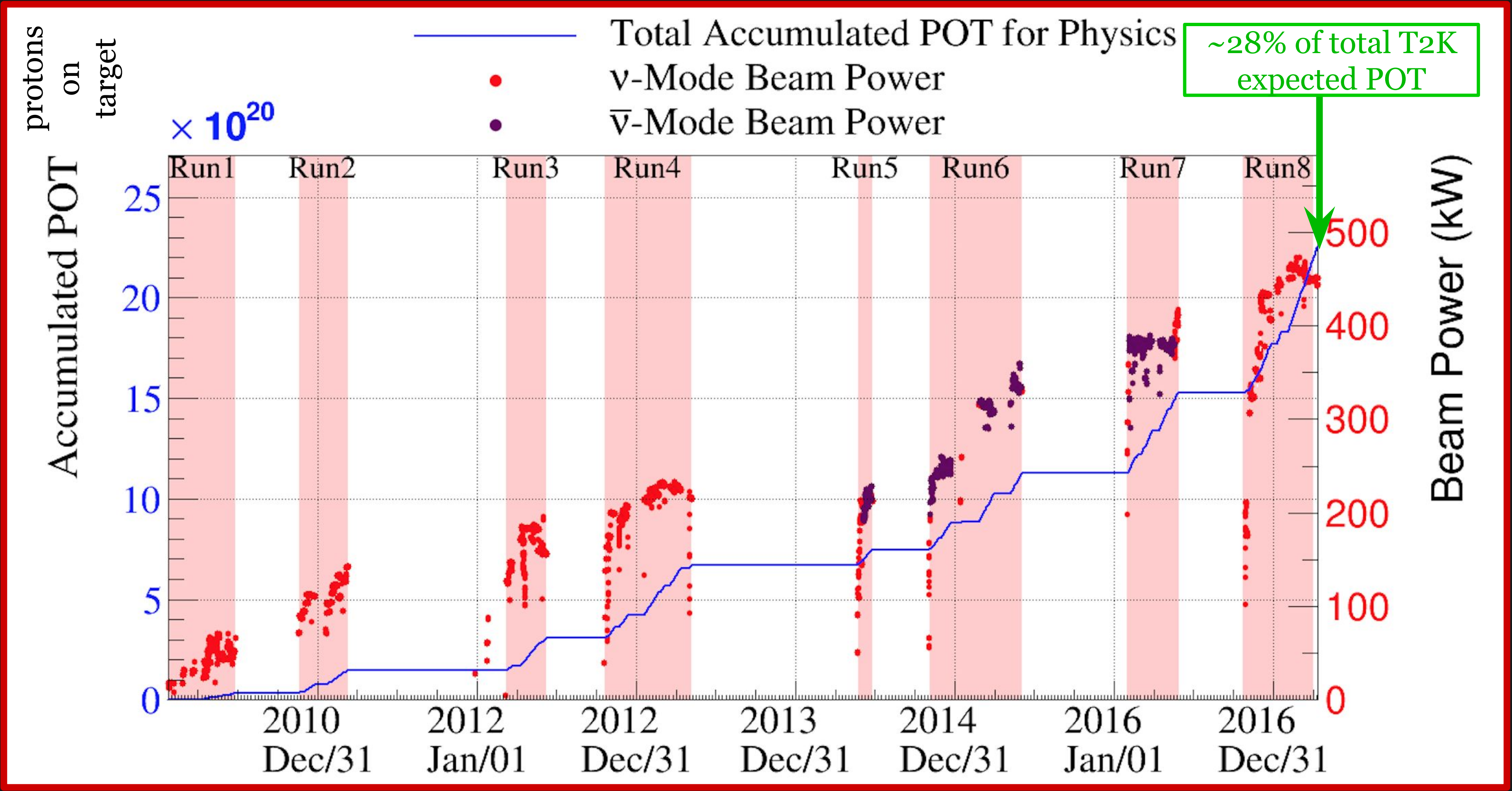
# of events

Flux and Cross section : constrained by ND

Detector efficiency

Oscillation probability

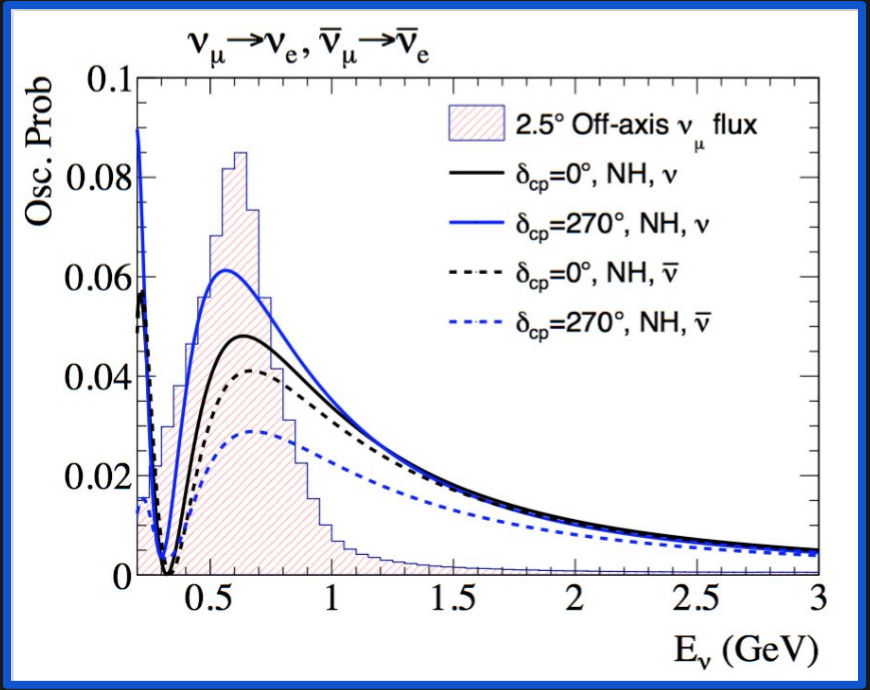
Data taking



Now running at an impressive 470 kW !

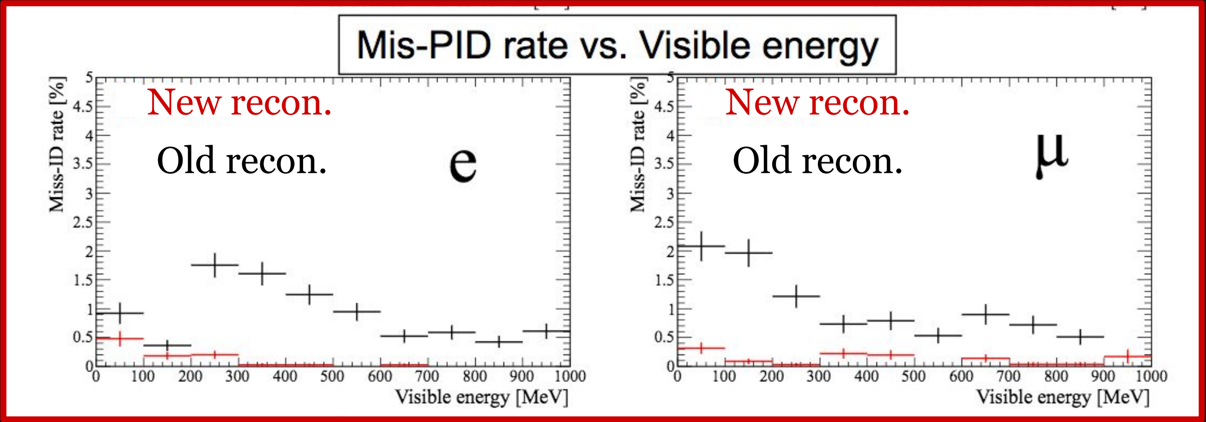
Joint neutrino and anti-neutrino mode analysis

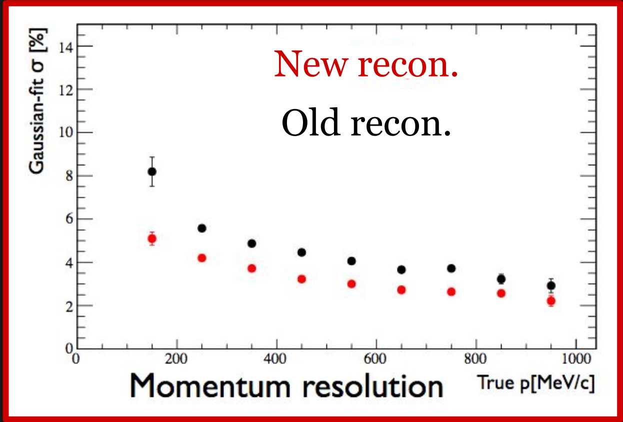
- The five SK samples presented earlier are used in the analysis, allowing simultaneous study of the ν_e / $\bar{\nu}_e$ appearance channels, and ν_μ / $\bar{\nu}_\mu$ disappearance channels.
- Why is anti-neutrino mode data important ?
  - ➡ The difference between ν_e and $\bar{\nu}_e$ appearance is directly related to δ_{CP}



Changes for this year

- New SK reconstruction algorithm has been used on SK selections.
  - Improved momentum resolution and misId tagging.
  - Allowing for almost 20% larger fiducial volume.





	ν_μ sample ν mode		ν_e sample ν mode		ν_e CC1π ν mode		ν_μ sample $\bar{\nu}$ mode		ν_e sample $\bar{\nu}$ mode	
	New	Old	New	Old	New	Old	New	Old	New	Old
# Signal Events	110.0	97.3	28.7	23.4	2.7	2.1	49.9	43.4	4.7	3.9
Purity	83%	71%	81%	81%	79%	72%	80%	68%	62%	63%

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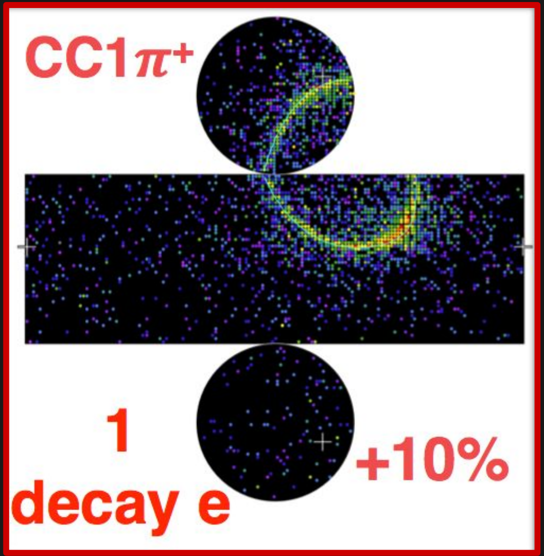
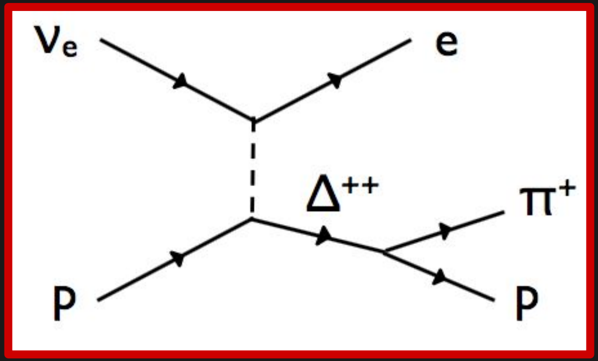
  - ➡ Add ~10% of new events for ν_e.





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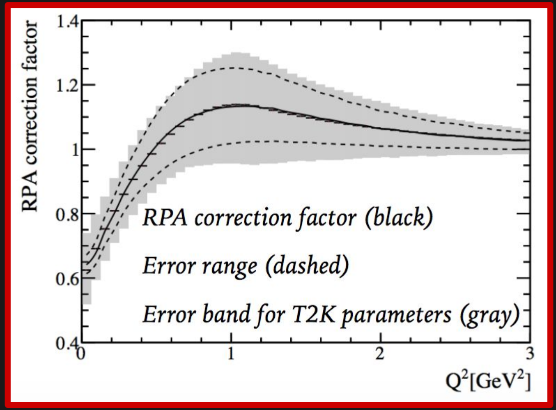
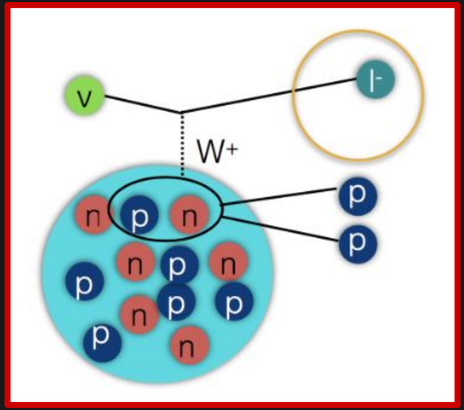
  - All the four other samples target CC quasi-elastic events (CCQE).
  - Add ~10% of new events for ν_e.
- Updated cross-section model :
  - Improved uncertainties to multi-nucleon interactions (2p2h).
  - And to long range nuclear interactions (RPA).



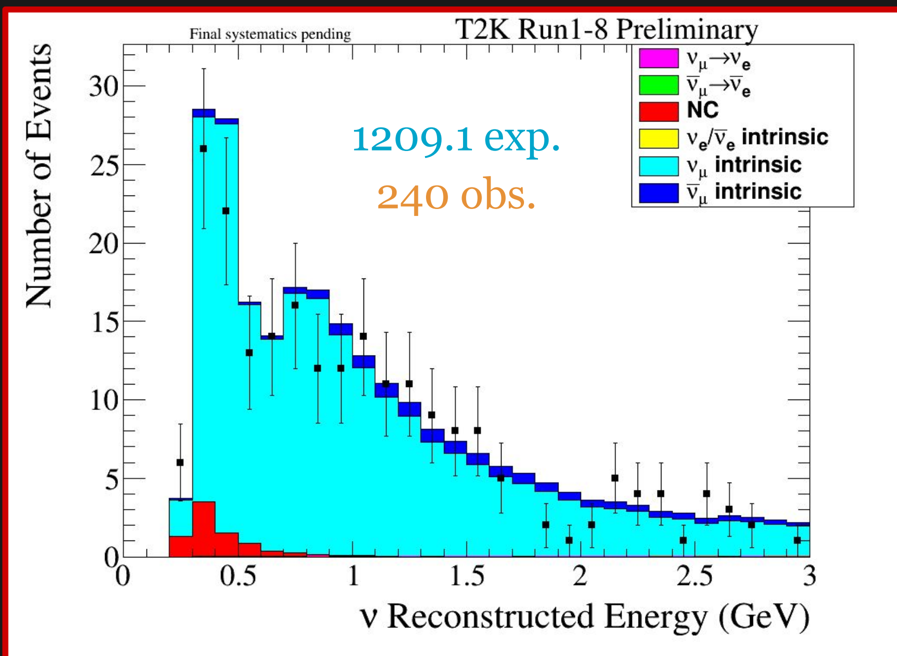


ν_μ and $\bar{\nu}_\mu$ disappearance

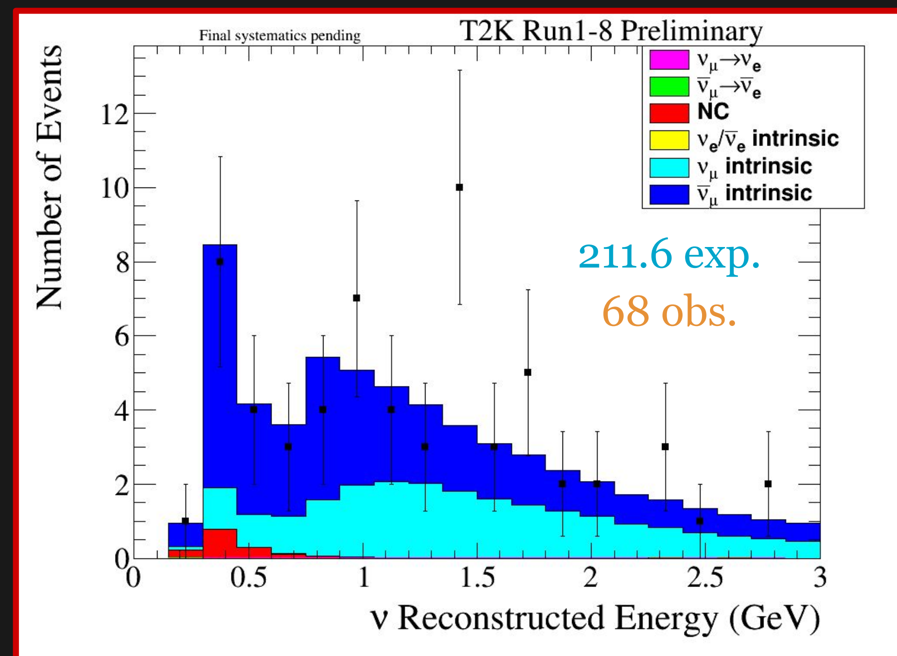
Expected without oscillations

Data

ν_μ



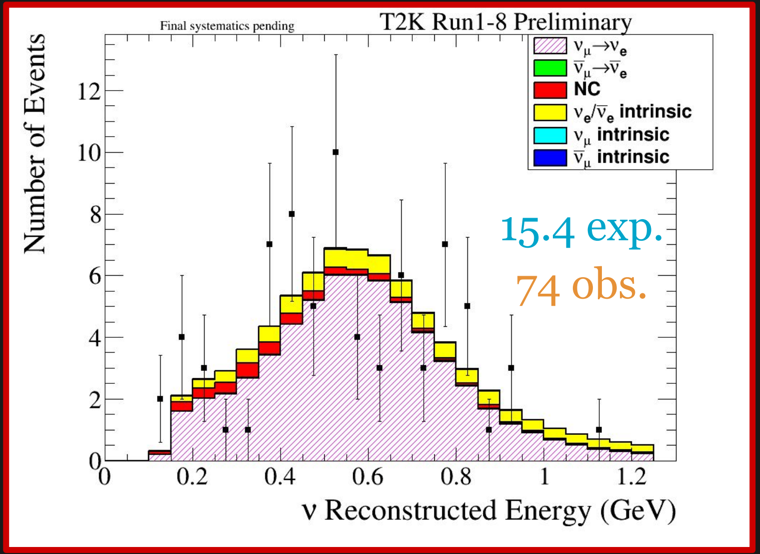
$\bar{\nu}_\mu$

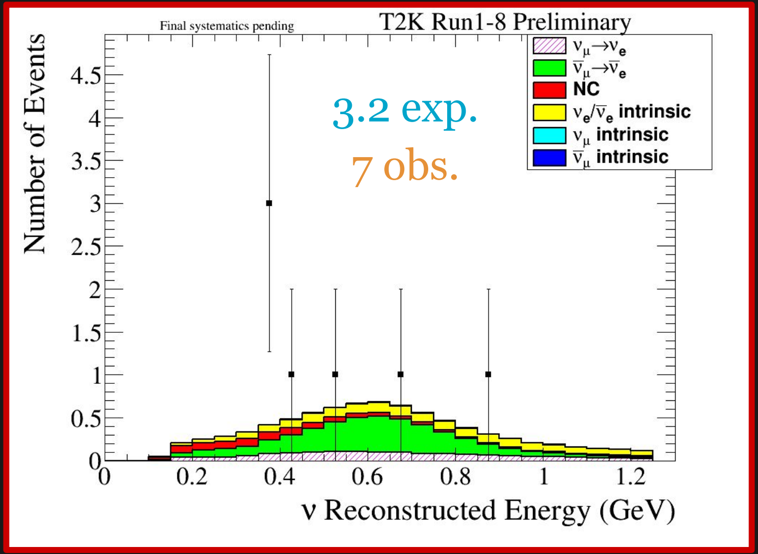


Reconstructed neutrino energy at the far detector for ν_μ and $\bar{\nu}_\mu$ candidate samples with the expected distribution in the no-oscillations hypothesis (blue) and the best-fit (orange).

ν_e and $\bar{\nu}_e$ appearance

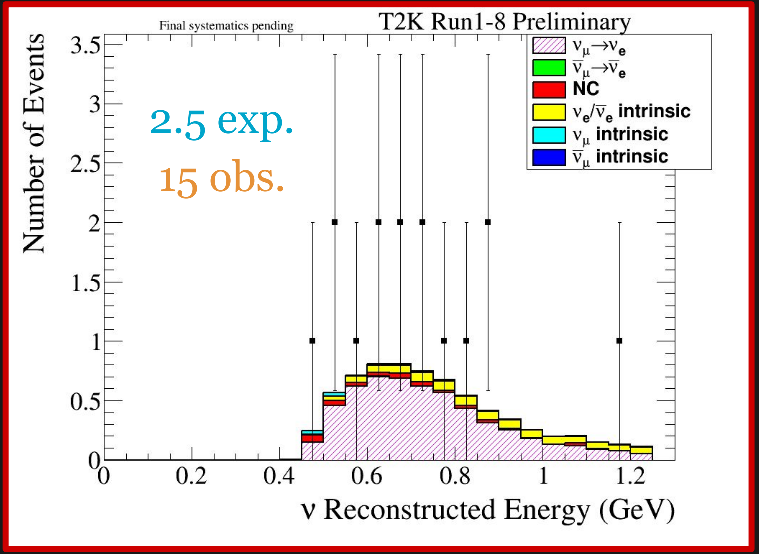
ν_e





$\bar{\nu}_e$

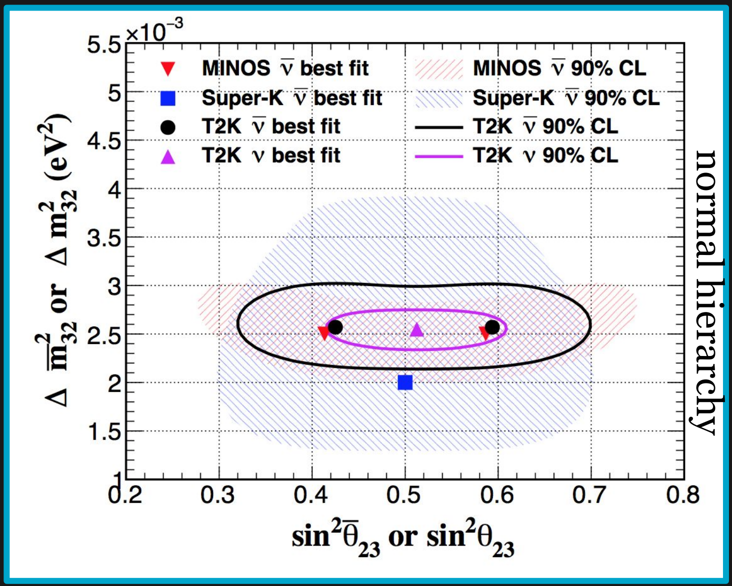
ν_e CC1π^+

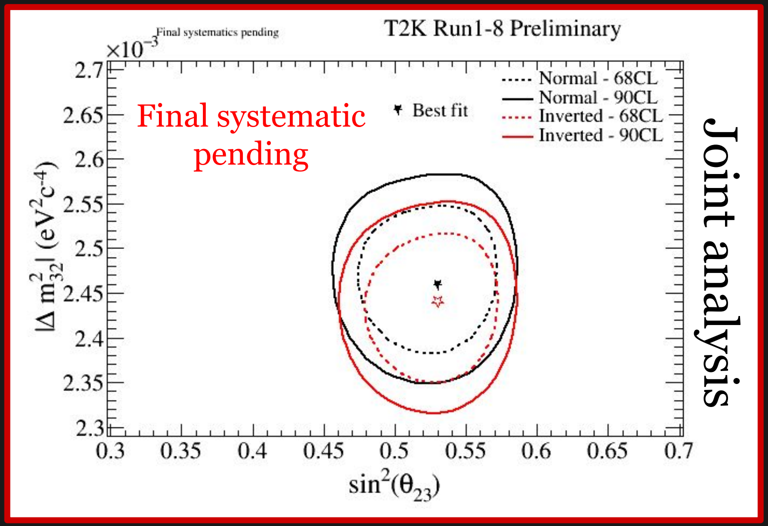


Expected without oscillations

Data

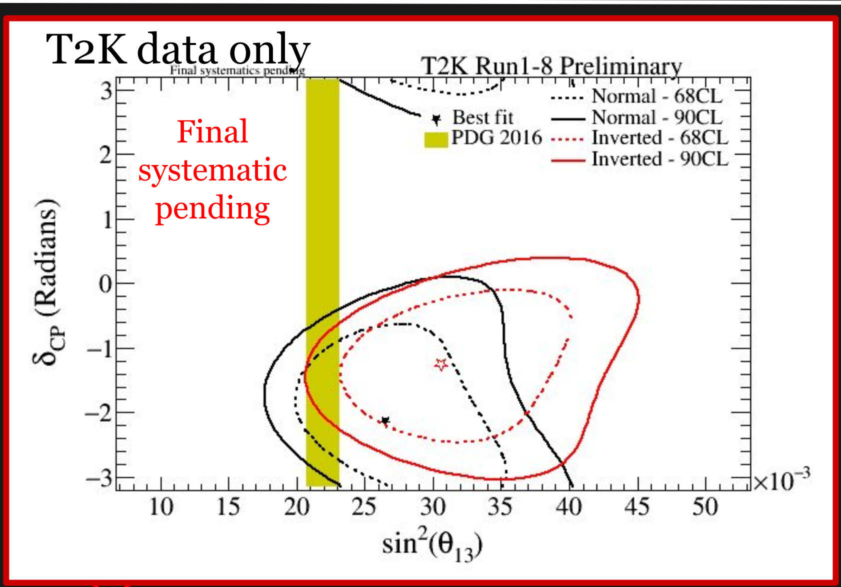
Confidence region in the $\sin^2\theta_{23}$ $|\Delta m^2_{32}|$ plane

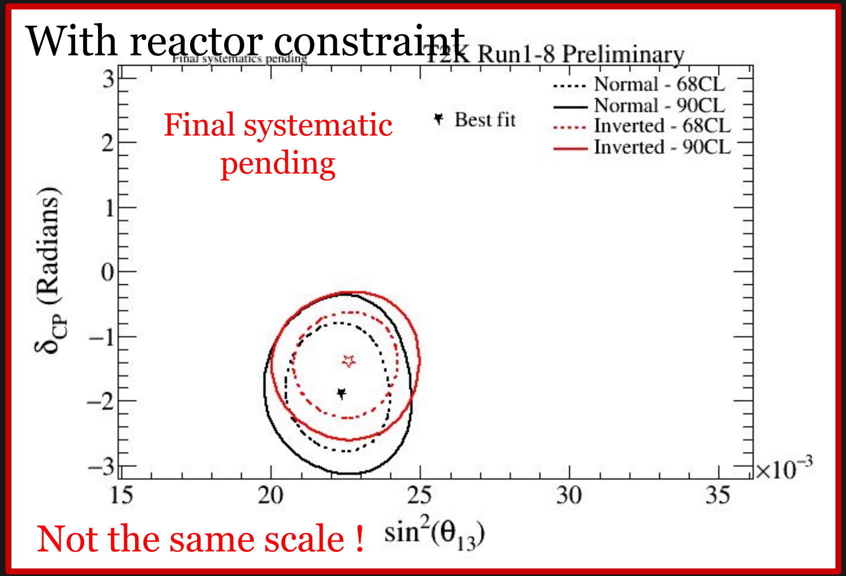




- Final systematic pending : finalizing the result now for publication.
- T2K results are consistent with past analysis results, maximal mixing (45°).
- Weakly prefers second octant.
- From separated ν and $\bar{\nu}$ analysis comparison, no hint of CPT violation.

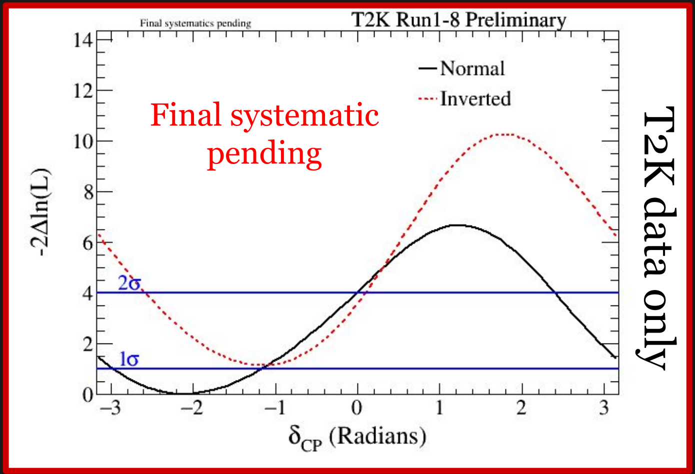
Confidence region in the $\sin^2\theta_{13}$ / δ_{CP} plane

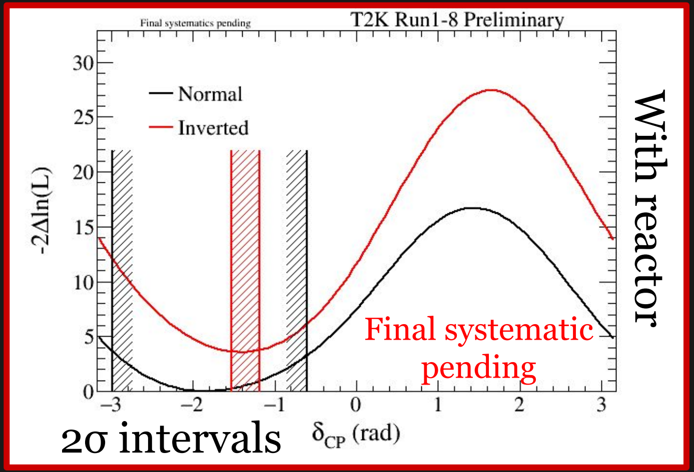




- With the anti-neutrino samples, T2K data by itself has already some sensitivity to δ_{CP} !
  - Disfavor region around $\delta_{CP} = +\pi/2$.
  - Preference for the $\delta_{CP} = -\pi/2$ region for both normal and inverted hierarchy.
- Good agreement between the reactor measurement of θ_{13} and T2K results.
- When adding the reactor constraint (PDG2015 : $\theta_{13} = 0.085 \pm 0.005$) the contour is further reduced.

First hints about δ_{CP}



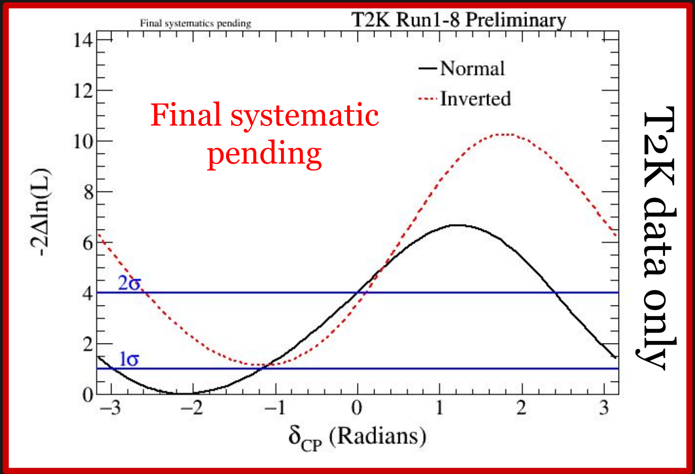


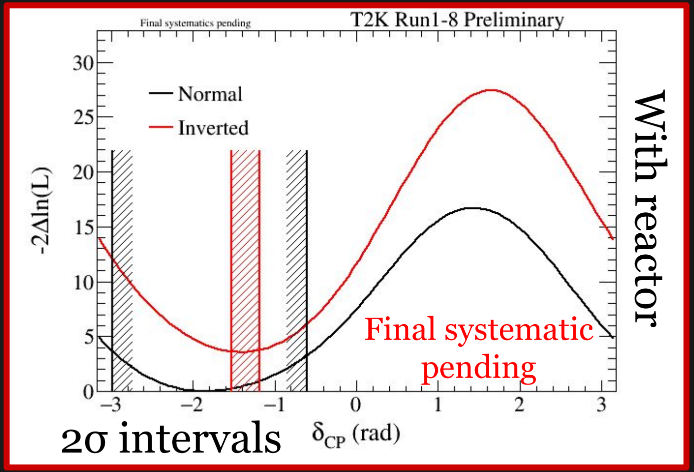
- Confidence intervals are obtained through the Feldman-Cousins method. All the parameters are marginalized and θ_{13} is marginalized using reactor value.

Parameter	Reactor	CL	Normal hierarchy	Inverted hierarchy
δ_{CP}	Yes	90%	$[-2.805, -0.830]$	-
δ_{CP}	Yes	2σ	$[-2.981, -0.600]$	$[-1.531, -1.184]$

- CP conservation excluded at 2σ confidence level ($\delta_{CP} \neq 0, \pi$).

First hints about δ_{CP}





Beam mode	Sample	δ_{CP} = -π/2	δ_{CP} = 0	Exp. w/o Osc.	Observed
Neutrino	*e*-like	73.5	61.5	15.4	74
Antineutrino	*e*-like	7.9	9.0	3.2	7

- We observe :
  - Less $\bar{\nu}_e$ candidates than expected
  - More ν_e candidates
- δ_{CP} = - π/2 is the most asymmetric value, and is therefore favored.
- CP conservation excluded at 2σ confidence level ($\delta_{CP} \neq 0, \pi$).

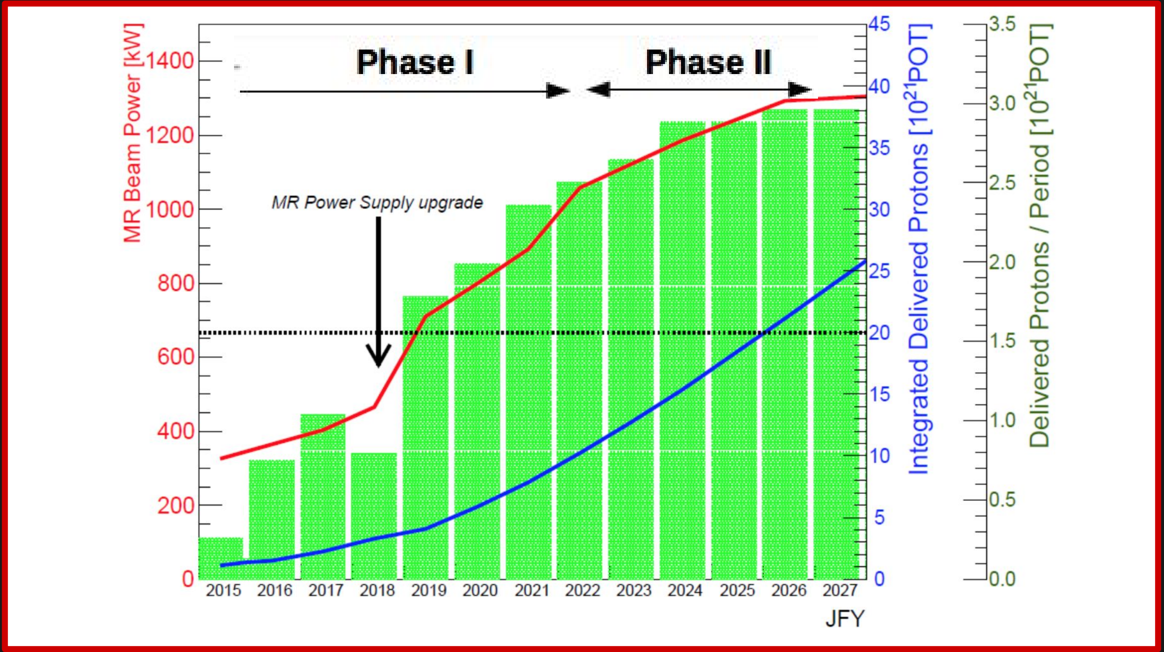
Future improvements

- Working on different longer term improvements :
  - Reduced flux uncertainties thanks to new NA61/SHINE analysis.
  - Improved selections in the Near Detector (anti-neutrino and improved angular acceptance).
  - SK 2-rings samples.

- Also working tightly with other experiment to get combined analysis :
  - Latest SK paper shows that combined analysis can get some sensitivity to mass ordering (https://arxiv.org/abs/1710.09126)
  - Just had a workshop with NOνA, now aiming for combined analysis in 2020/2021.

T2K II

- T2K approved statistics (7.8 x 10^{21} POT) is expected to be reached in ~2021.
- 1st phase of J-PARC Main Ring improvement should begin in 2018.
  - ➡ T2K II would extend T2K run to 20 x 10^{21} POT in ~ 2026 (expected start of Hyper-K).
  - ➡ This requires both an accelerator and beamline upgrade to reach 1.3 MW and analysis improvements.

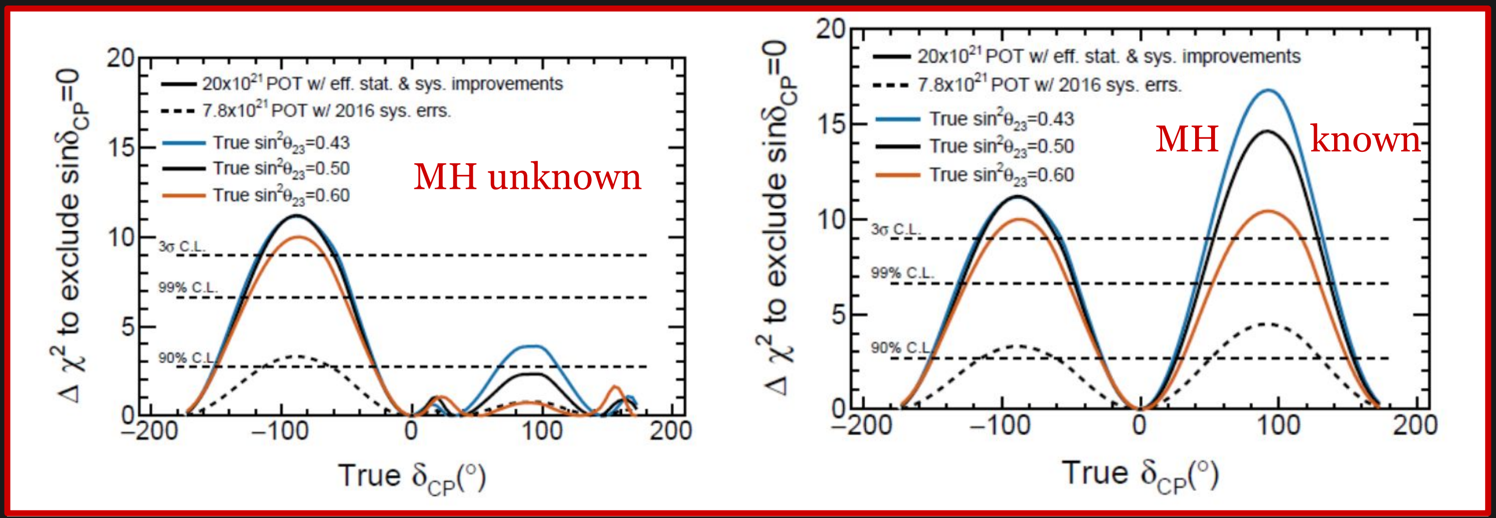


arxiv : 1609.04111

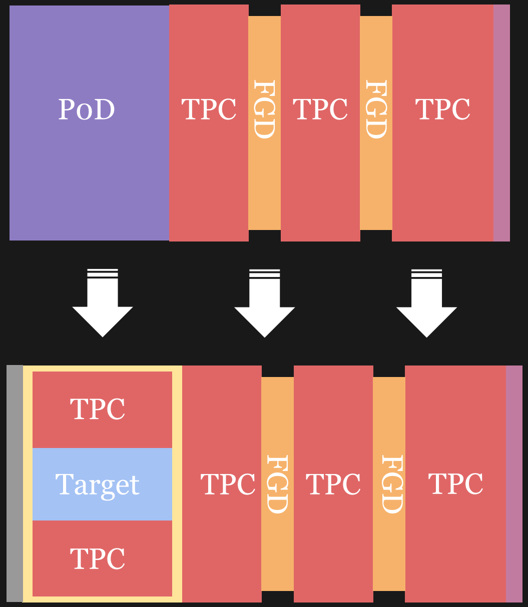
T2K II sensitivity and near detector upgrade

arXiv:1607.08004

based on the EOI submitted at J-PARC PAC



Presented by Sara during last GDR



Current ND

Possible upgrade

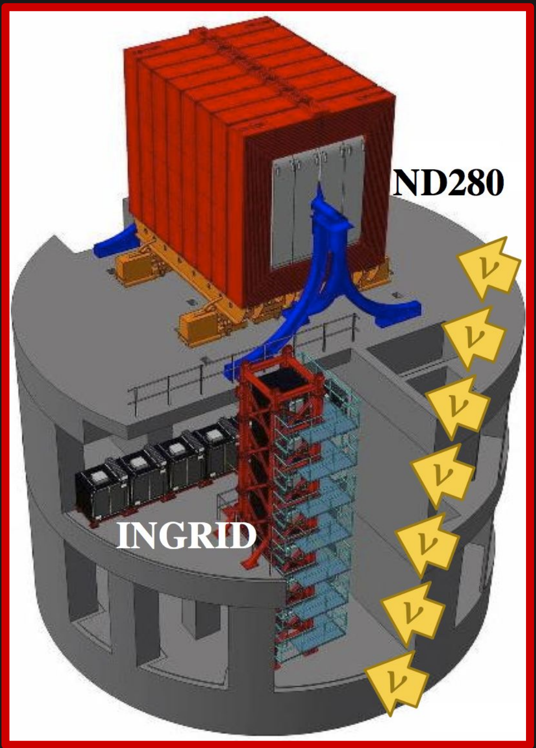
- T2K II could reach ~3σ sensitivity to δ_{CP} for the parameter values currently favoured.
- This requires significantly lower systematics uncertainties
- An upgrade of the near detector is under study to see if we can achieve ~3% systematic uncertainties.

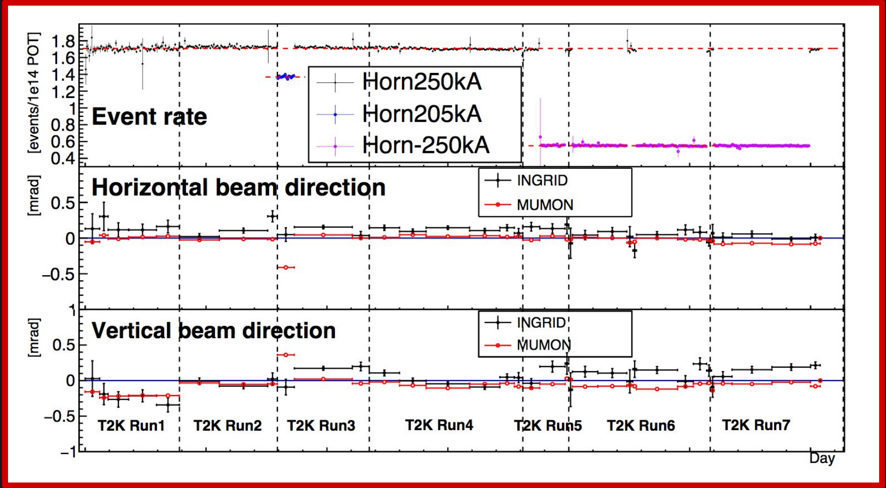
Summary

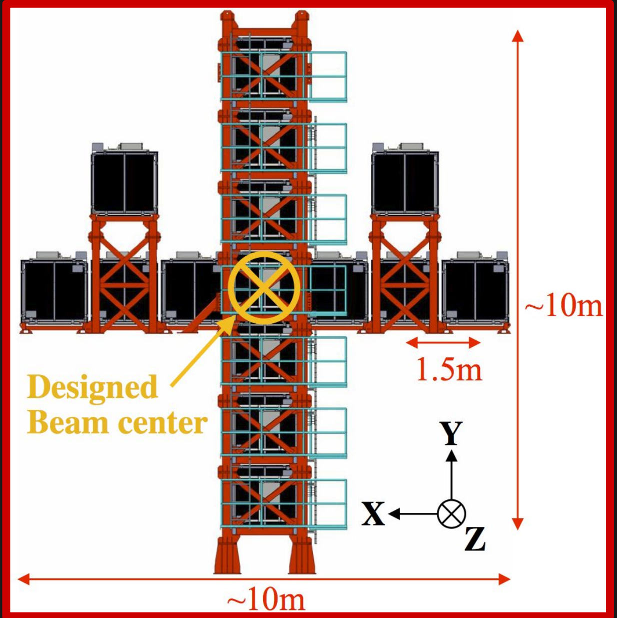
- Presented an overview of the latest T2K oscillation results :
  - ➡ Finalizing the analysis for publication.
  - ➡ Precise contour in the $\sin^2\theta_{23}$ / Δm^2_{23} plane, favoring maximal mixing (45°).
  - ➡ First hints of CP violation with neutrino and anti-neutrino data are getting stronger !
    - Good agreement between T2K and the reactor measurements for $\sin^2\theta_{13}$.
    - CP conservation hypothesis excluded at 2σ CL.
    - The new SK sample and the doubled statistics gives stronger δ_{CP} constraint
      - δ_{CP} (rad) = [-2.981, -0.6] for NH , [-1.531, -1.184] for IH at 2σ CL.
- 7.8 x 10^{21} POT expected to be reached in ~2021.
  - ➡ Proposal for extending T2K data-taking period to 2026 and accumulate up to 20 x 10^{21} POT to continue doing nice physics !
  - ➡ Planning an upgrade of the near detector around 2020 to further reduce the systematic uncertainties.
  - ➡ If interested, come and join the T2K II effort !

Thank you !

T2K near detector : INGRID

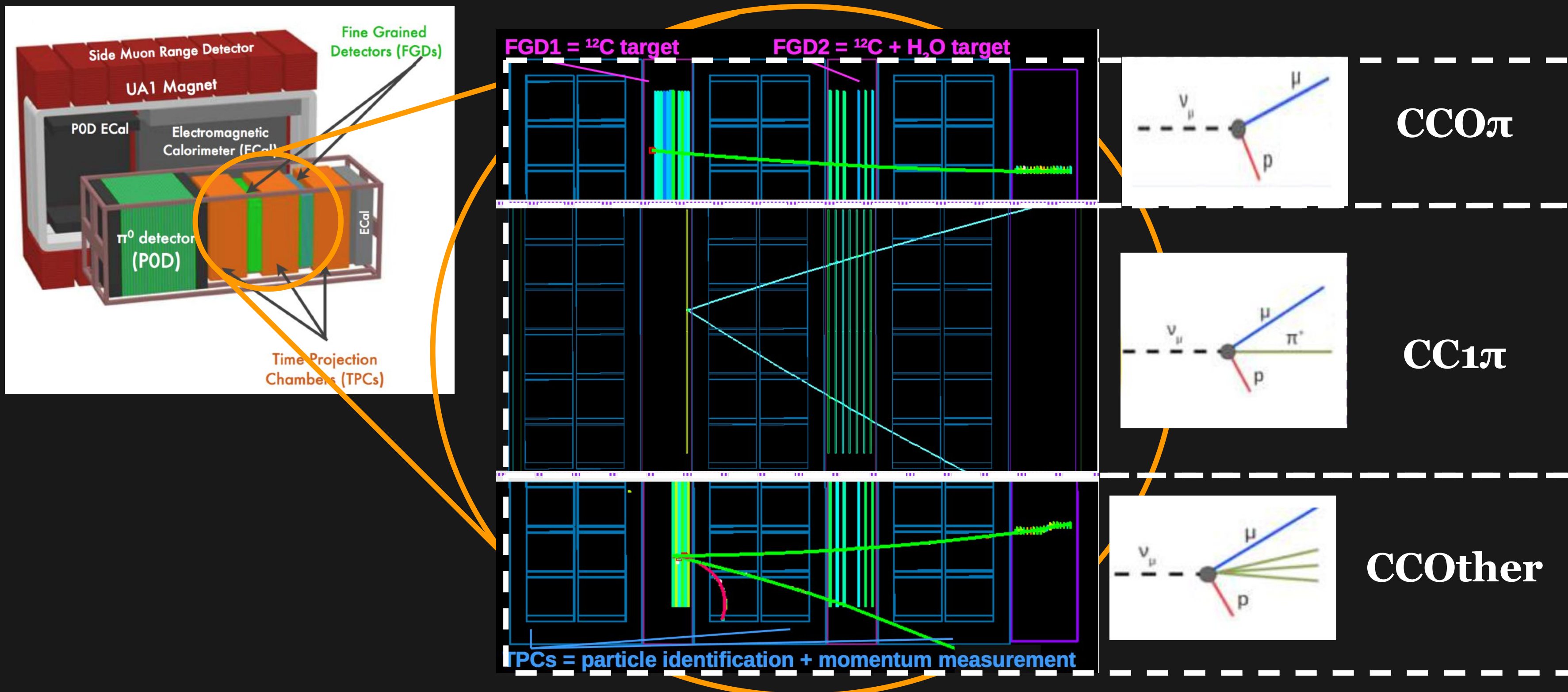






- Near detector pit at 280 m from the target
- INGRID is located on-axis.
  - iron/scintillator tracking calorimeters (16 modules)
  - Monitor beam, direction, stability.
  - Used to constrain flux systematic errors.

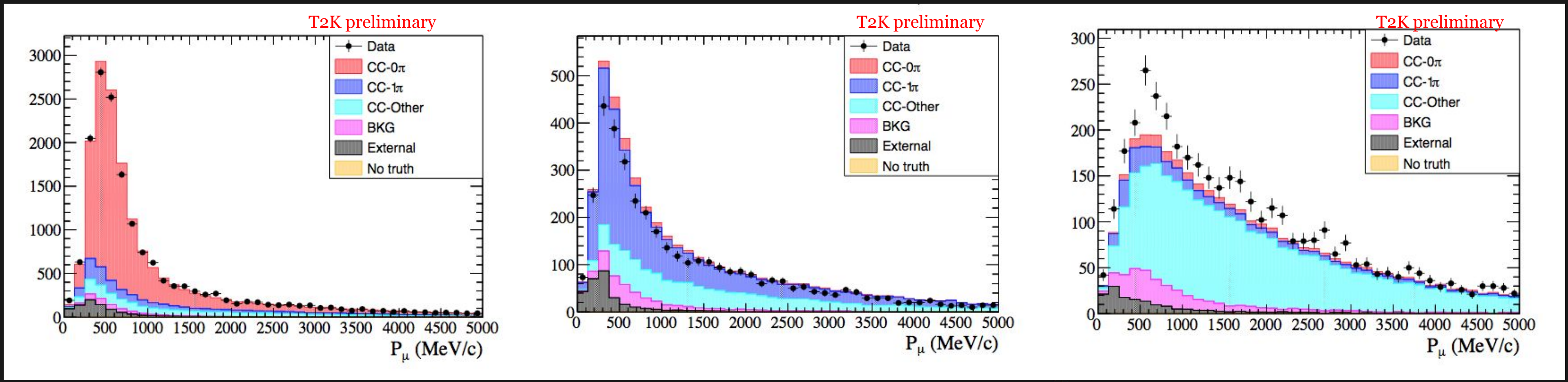
ND280 event selection



- ➤ We currently use a selection of ν_μ CC events in the tracker, using the FGD as target and the TPC to reconstruct charge and momentum.
- ➤ We separate the CC inclusive events in three topologies depending on the number of pions reconstructed (0, 1 and ≥2)

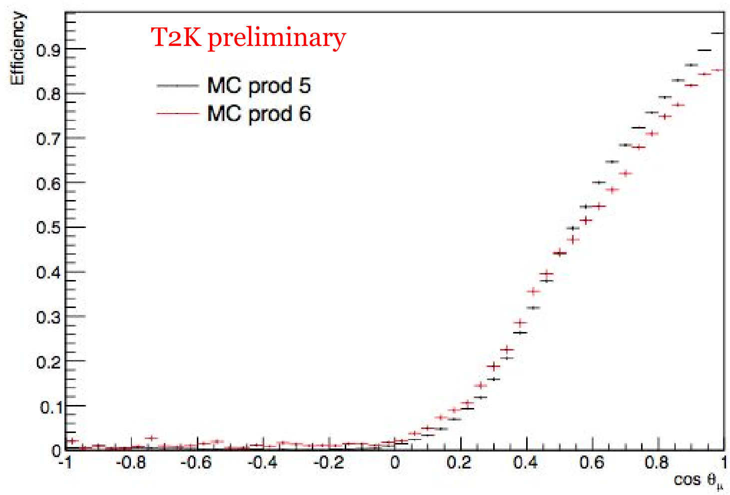
ND280 event selection

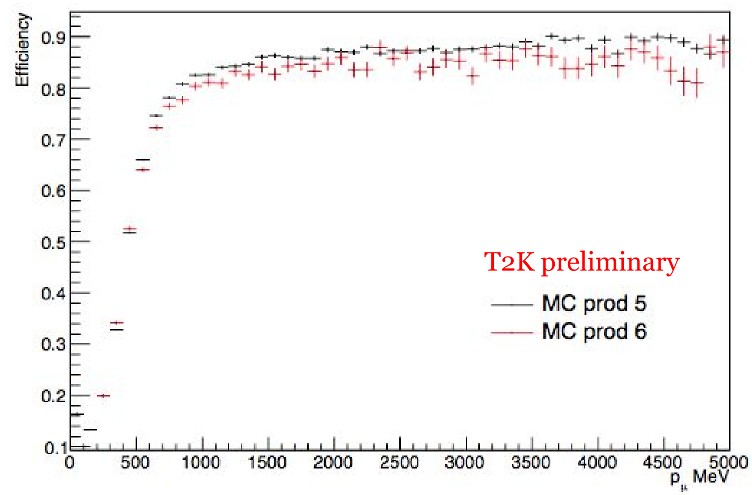
CC0pi CC1pi CCOther

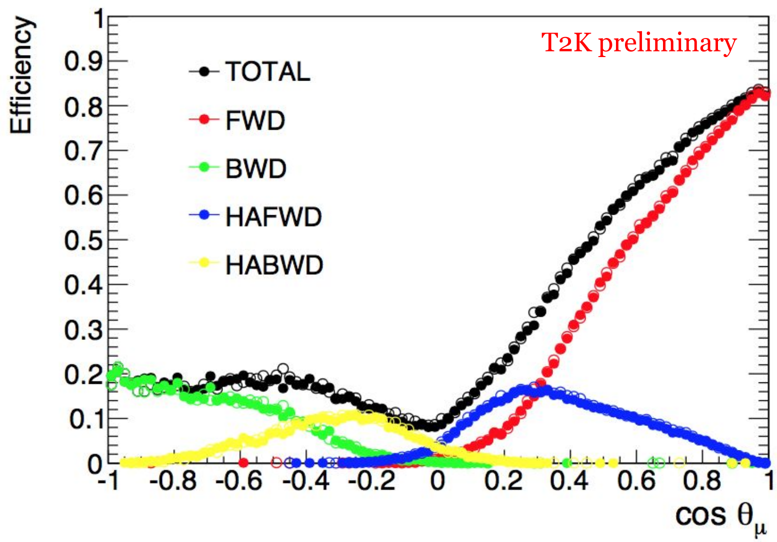


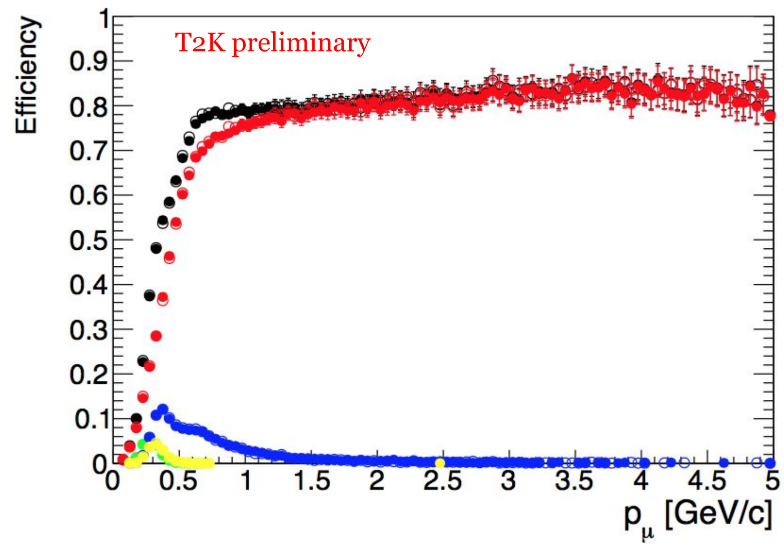
- We currently use a selection of ν_μ CC events in the tracker, using the FGD as target and the TPC to reconstruct charge and momentum.
- We separate the CC inclusive events in three topologies depending on the number of pions reconstructed (0, 1 and ≥2)

Current ND280 selection efficiency









Near detector fit : the BANFF

- This is a huge framework, with around 700 parameters !
- We use a Likelihood as :

$$\mathcal{L} = \mathcal{L}_{Poisson} \times \mathcal{L}_{Syst}$$

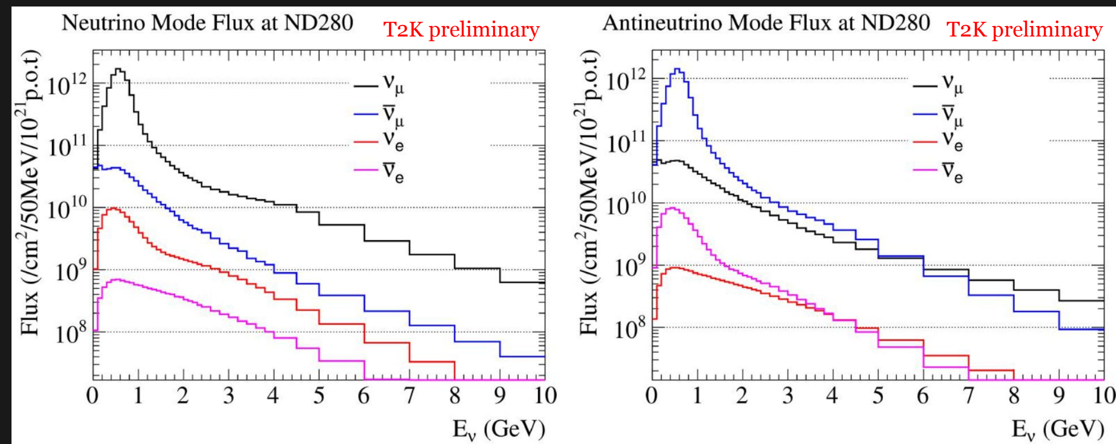
$$\ln\left(\mathcal{L}\right) = \sum_i N_i^{pred}(\mathbf{x}) - N_i^{data} + N_i^{data} \ln\left(\frac{N_i^{data}}{N_i^{pred}(\mathbf{x})}\right)$$

$$+\frac{1}{2}\sum_i\sum_j \Delta\mathbf{x}_i \left(V_{\mathbf{x}}^{-1}\right)_{i,j} \Delta\mathbf{x}_j$$

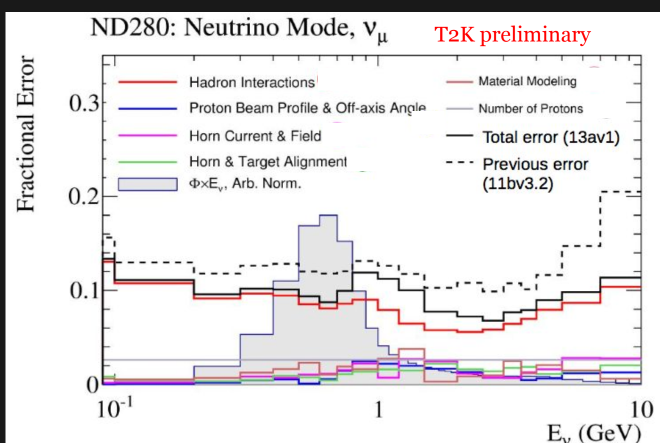
- Where the vector x of systematics can be decomposed in three parts :
  - ➡ **Detector**
  - ➡ **Flux**
  - ➡ **Cross-section**

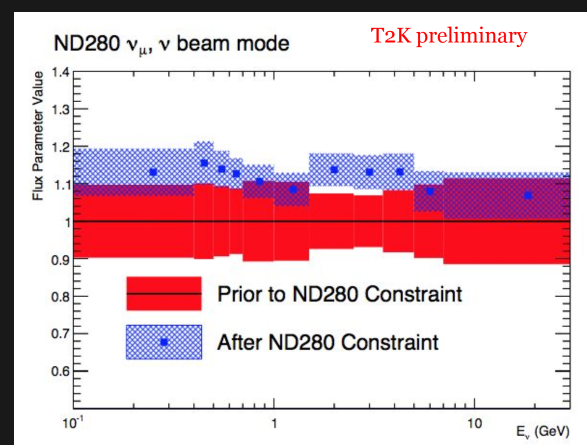
Flux uncertainties

The flux model is produced from generator tuned with NA61/SHINE data



Flux uncertainties from NA61





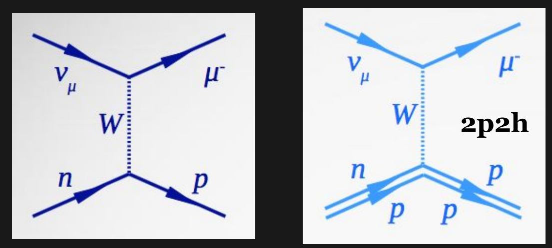
8.8% to 3.2% on $\Delta N_{SK}/N_{SK}$

Still ~10% uncertainty around flux peak on the normalisation

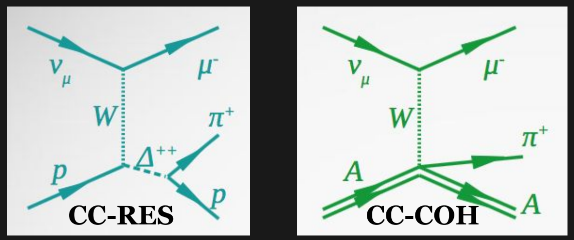
Need the BANFF fit to further reduce the error on the flux

Cross section model

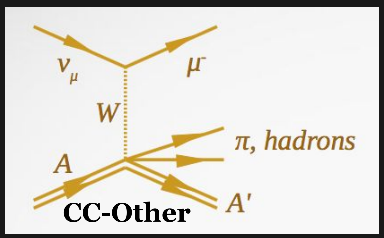
➤ For each interaction, we have a model with several parameters



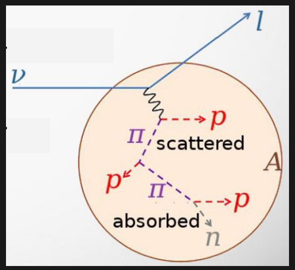
CC0π : 13 parameters



CC1π : 4 parameters

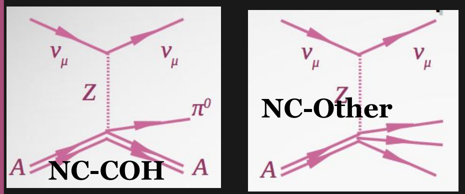


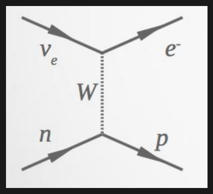
CCOther : 1 parameter



Final state interaction : 6 parameters

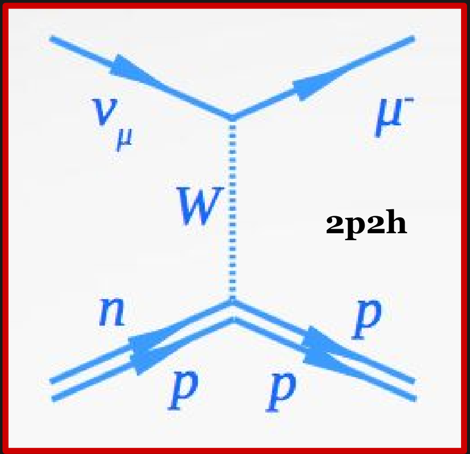
ν_e/ν_μ



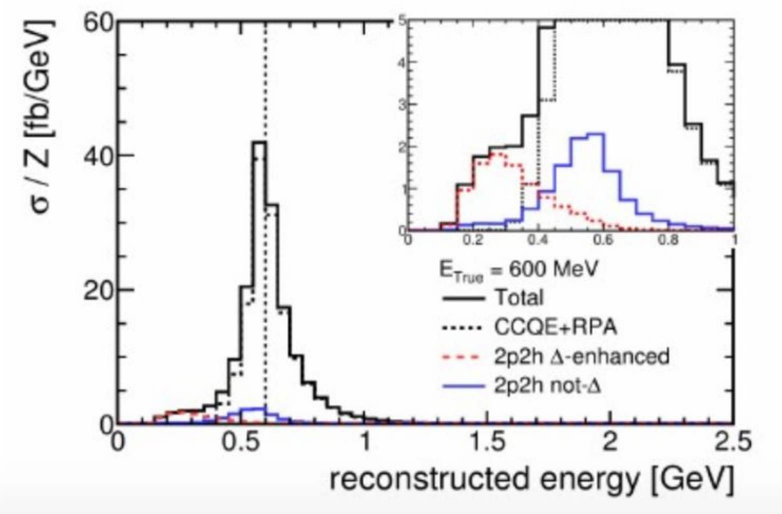


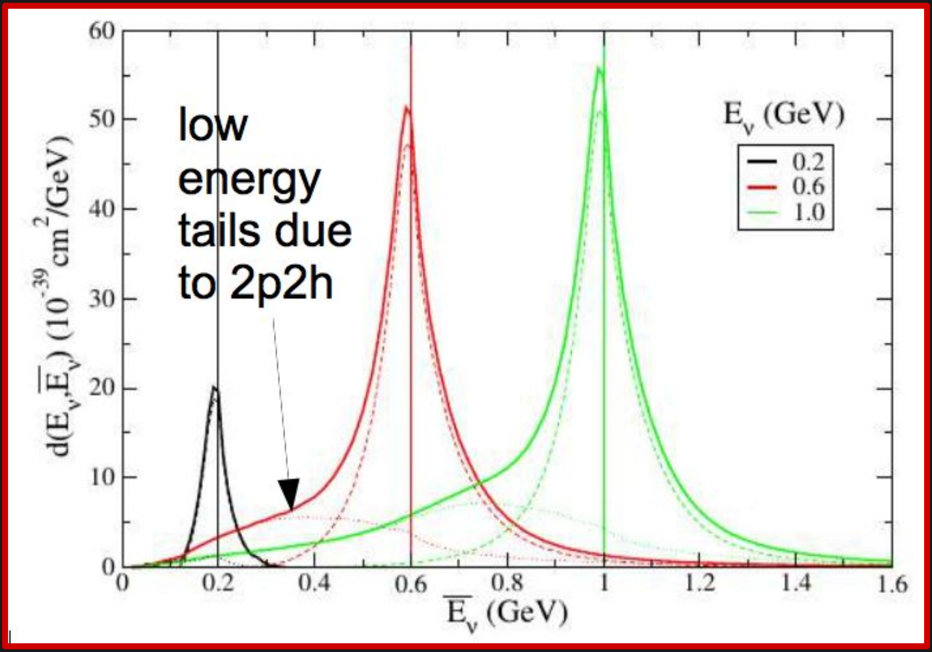
Other : 3 parameters

2p2h



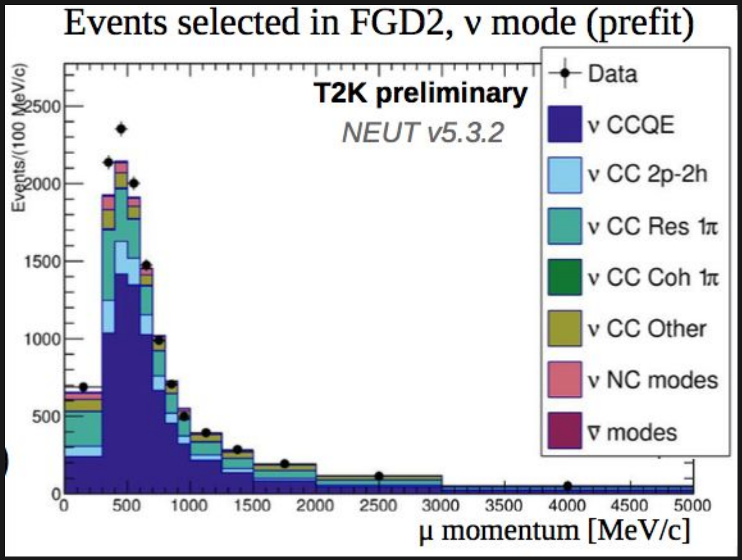
- Effect on recontructed energy:

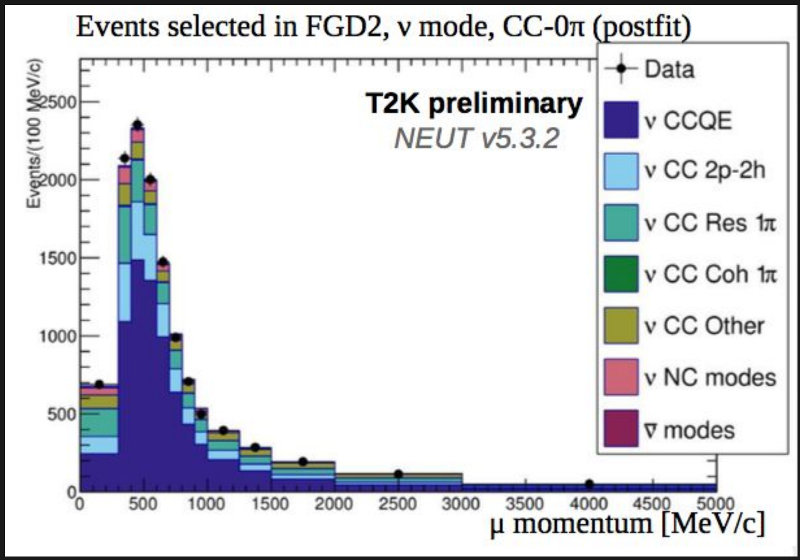




Cross section uncertainties

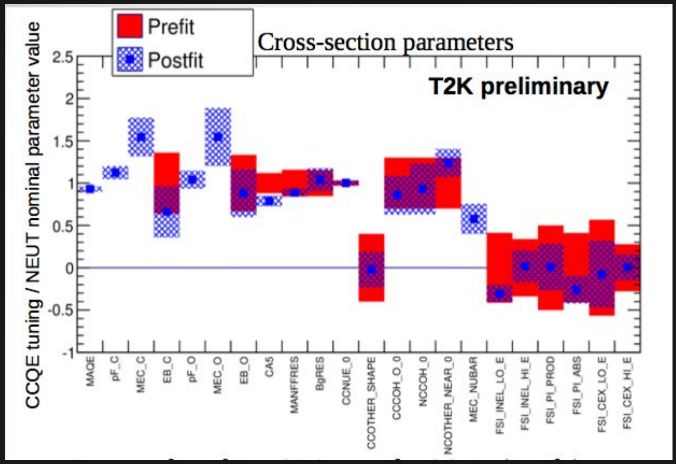
➤ We fit all those parameters with ND data to constrain them





Prefit

$\Delta N_{SK}/N_{SK} = 7.1\%$

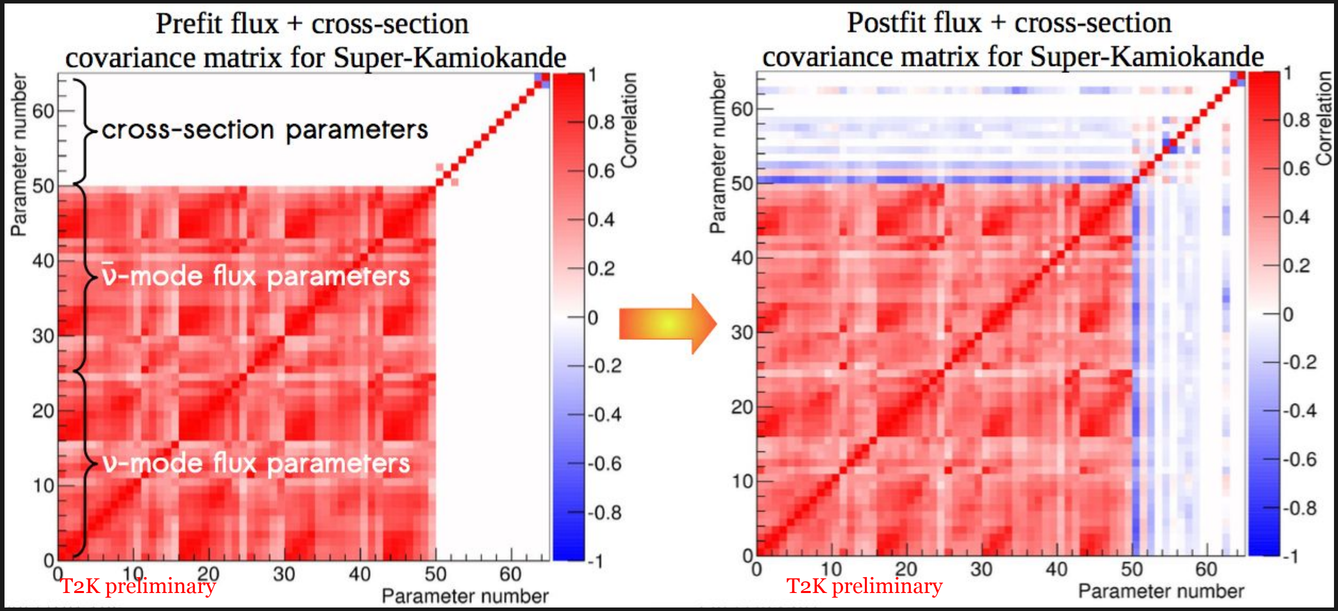


Postfit

$\Delta N_{SK}/N_{SK} = 4.7\%$

BANFF results

- The fitter itself is quite robust, it is tested with a bunch of fake data studies to verify we don’t get any biases from the cross-section model we use, and if we do, to add it as a systematic.
- All those biases are taken into account in the ND280 covariance matrix
- Matrix that is the final output of the BANFF and is given to the oscillation group as an input to the SK data fit.



Source of uncertainty at SK

Source of Uncertainties			SK event sample: $\Delta N_{SK}/N_{SK}$ (1σ error)				
			ν-beam			$\bar{\nu}$-beam	
			1-ring μ-like	1-ring e-like	CC-1π^+ e-like	1-ring μ-like	1-ring e-like
SK: Detector + Final State Int. + 2ndary int.			4.2%	3.5%	14.0%	11.1%	4.0%
Beam + Near detectors	Neutrino Beam flux		3.6%	3.7%	3.6%	3.8%	3.8%
	ν-interaction cross-section	*MEC (corr)*	*3.5%*	*3.9%*	*0.5%*	*3.0%*	*3.0%*
		MEC bar (corr)	*0.2%*	*0.1%*	*0.0%*	*1.8%*	*2.3%*
		NC 1γ (uncorr)	*0.0%*	*1.5%*	*0.4%*	*0.0%*	*3.0%*
		$\sigma(\nu_e) / \sigma(\nu_\mu)$	*0.0%*	*2.6%*	*2.4%*	*0.0%*	*1.5%*
		(Cross-section: sub total)	4.0%	5.1%	4.8%	4.2%	5.5%
	(Flux + Cross-section Sub total)		2.9%	4.2%	5.0%	3.5%	4.7%
Oscillation parameters: $\sin^2\theta_{13}$, $\sin^2\theta_{12}$, Δm^2_{21}			0.0%	4.2%	3.8%	0.0%	4.0%
Total			5.1%	6.8%	15.3%	11.7%	7.4%

The far detector fit

$$N_{SK} = \int dE\ \Phi(E) \times \sigma(E) \times \epsilon_{SK}(E) \times P(\nu_\alpha \rightarrow \nu_\beta, E, \theta_{ij}, \Delta m^2_{ij}, \delta_{CP})$$

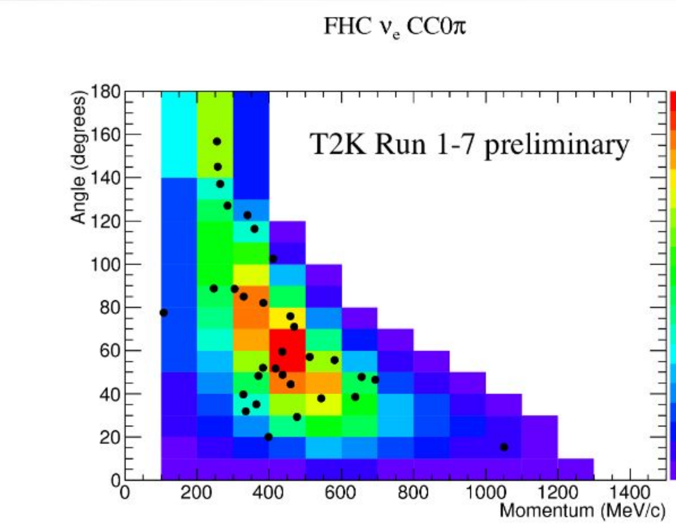
# of events — Flux — Cross section — Detector efficiency — Oscillation probability

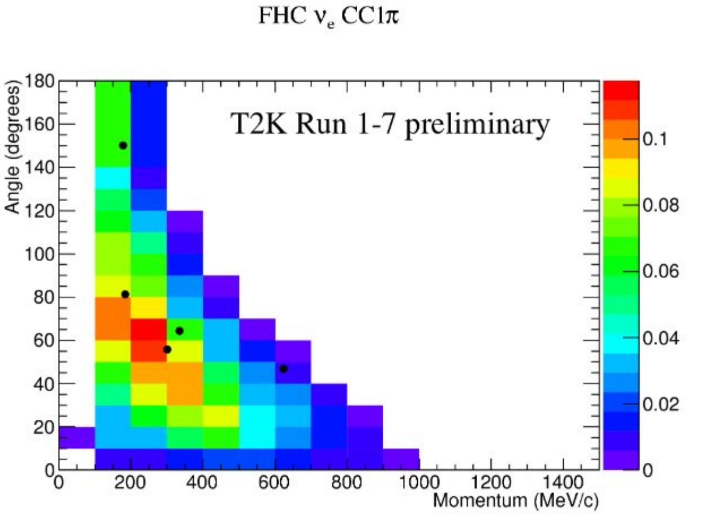
Flux and Cross section: Constrained with the near detector

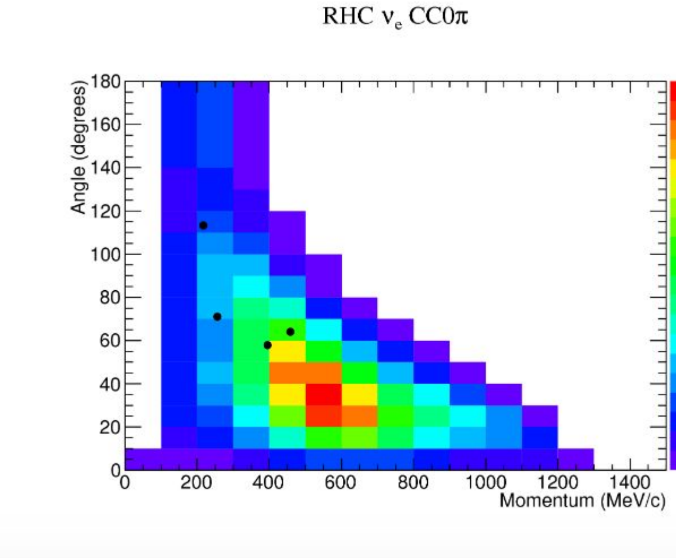
Three different analyses performed to extract the oscillation parameters :

- A frequentist analysis with a $\Delta\chi^2$ fit to
  - ➡ E_{rec} / θ_{lep} for electron neutrino and anti-neutrino.
  - ➡ E_{rec} for muon neutrino and anti-neutrino.
- A Bayesian analysis with a likelihood fit to
  - ➡ p_{lep} / θ_{lep} for electron neutrino and anti-neutrino.
  - ➡ E_{rec} for muon neutrino and anti-neutrino.
- A Bayesian with a Markov-Chain MC
  - ➡ E_{rec} for all samples.
  - ➡ Simultaneously fitting the near detector data.

2D distributions for electron neutrino samples

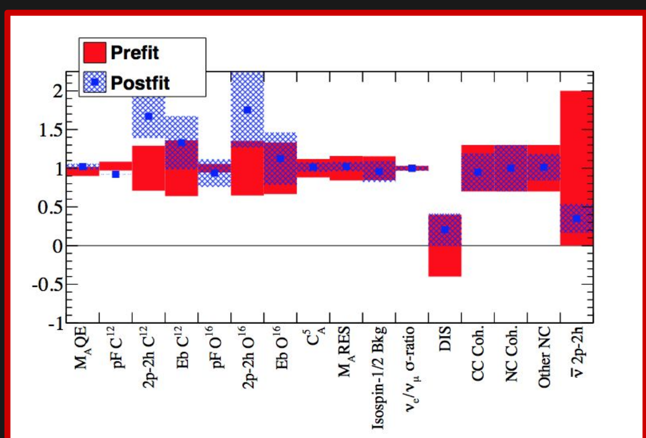


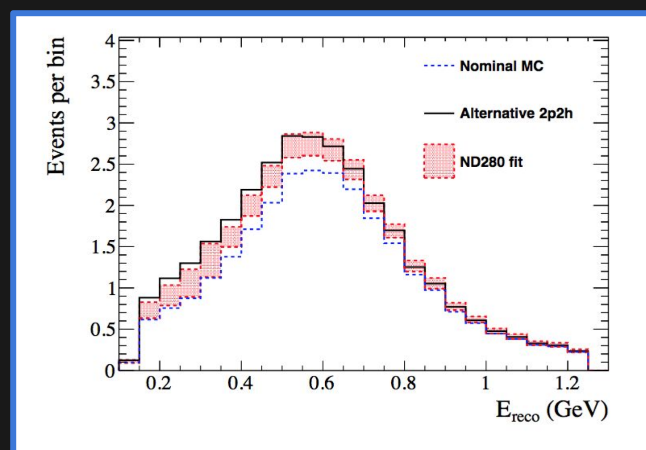


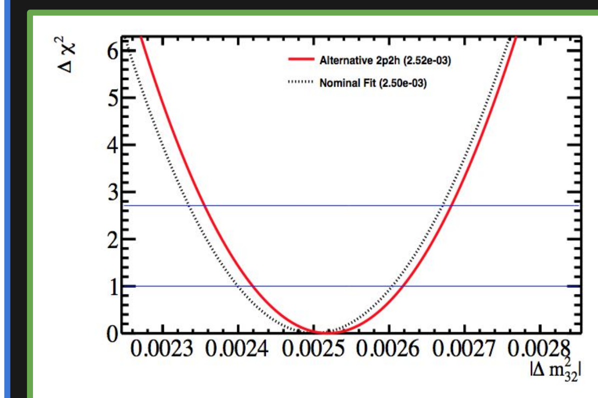


Fake data studies

- We produce some fake data set (example here alternative 2p2h model) that we fit to ND280 data.
- This fit results is used to adjust SK predicted spectra.
- We produce and fit SK fake data set, with the fit to ND280 data as input, to obtain the bias on the oscillation parameters.







Alternative model	Maximum bias on parameter (σ)		
	Δm^2_{23}	$sin^2\theta_{23}$	$sin^2\theta_{13}$
Alternative *2p–2h*	0.20	0.21	0.18