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T2K

Advancements in Long Baseline Neutrino Oscillation Experiments: Precision Physics, CP Violation, and Hierarchy

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Outline

- Neutrino Oscillations in a nutshell
    - CP violation with neutrinos.
- T2K experiment
- Analysis procedure
- νA cross-section
- T2K recent results.
- Beyond T2K.

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Neutrino Oscillations in a nutshell

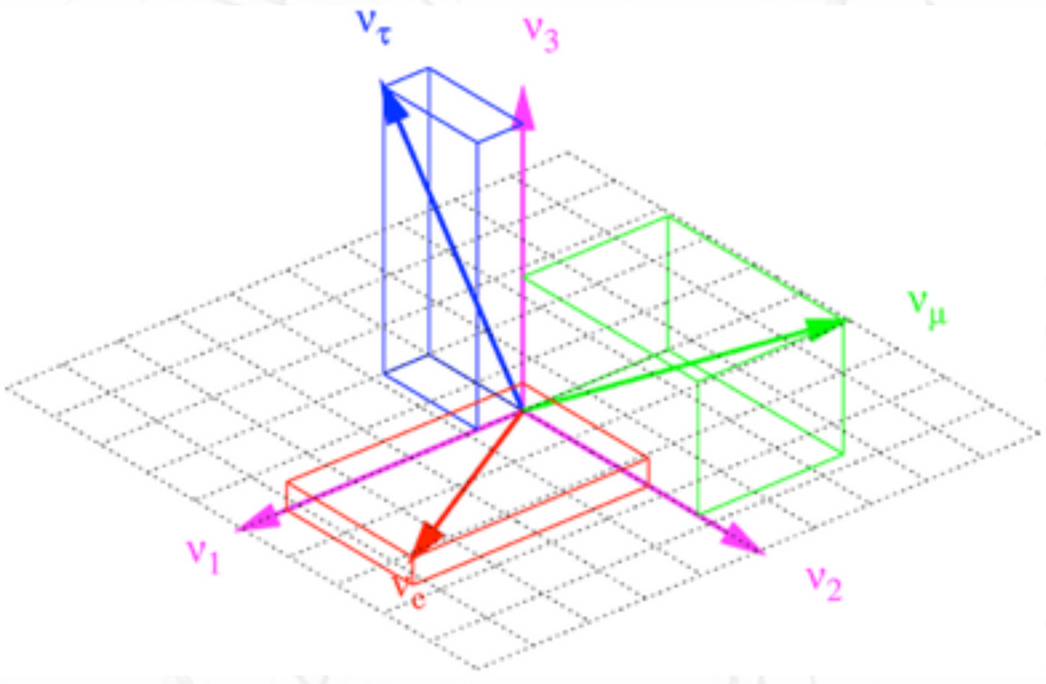
Neutrino oscillations

- Neutrino flavour eigenstates are not the same than the neutrino Lorentz eigenstates.
- Eigenstates are related through a rotation matrix.

Flavour eigenstates	Lorentz eigenstates
$(\nu_e, \nu_\mu, \nu_\tau)$	(ν_1, ν_2, ν_3)
state of the neutrino interactions	states of the neutrino propagation in space

Pontecorvo–Maki–Nakagawa–Sakata (PMNS) matrix

$$\begin{pmatrix} \nu_e & \nu_\mu & \nu_\tau \end{pmatrix} = U_{PNMS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



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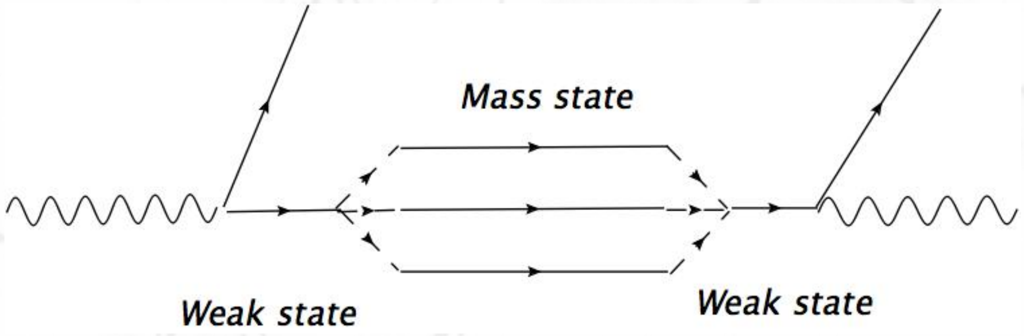
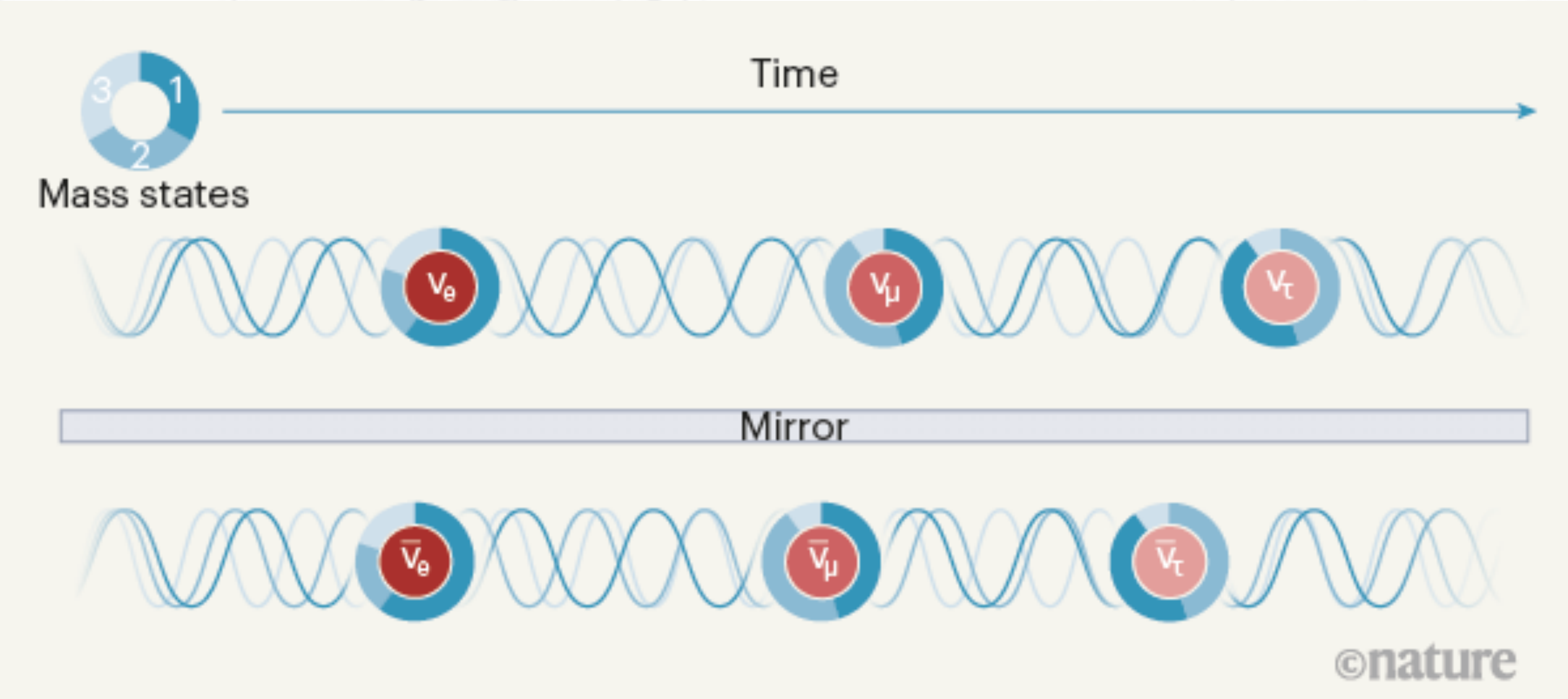
Neutrino oscillations

- Neutrinos are produced always as a flavour neutrino (electron, muon, tau) but they propagate in vacuum as mass states (they do no interact)





- Neutrinos propagate at different speeds (mass) keeping the coherence, at the interaction point the proportions change and other neutrino flavour might appear.

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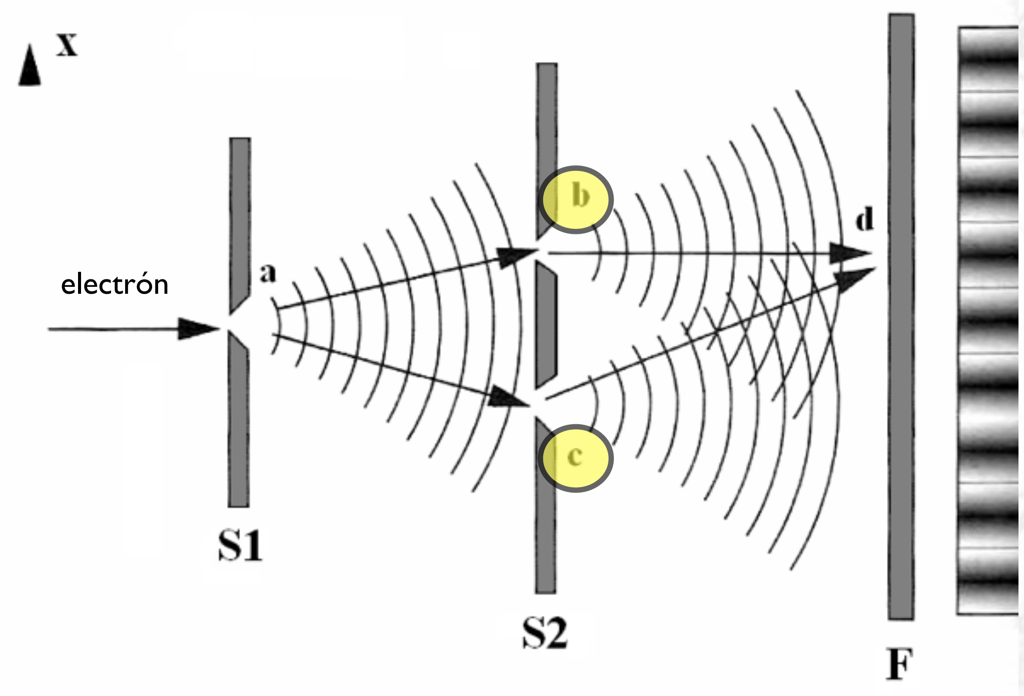
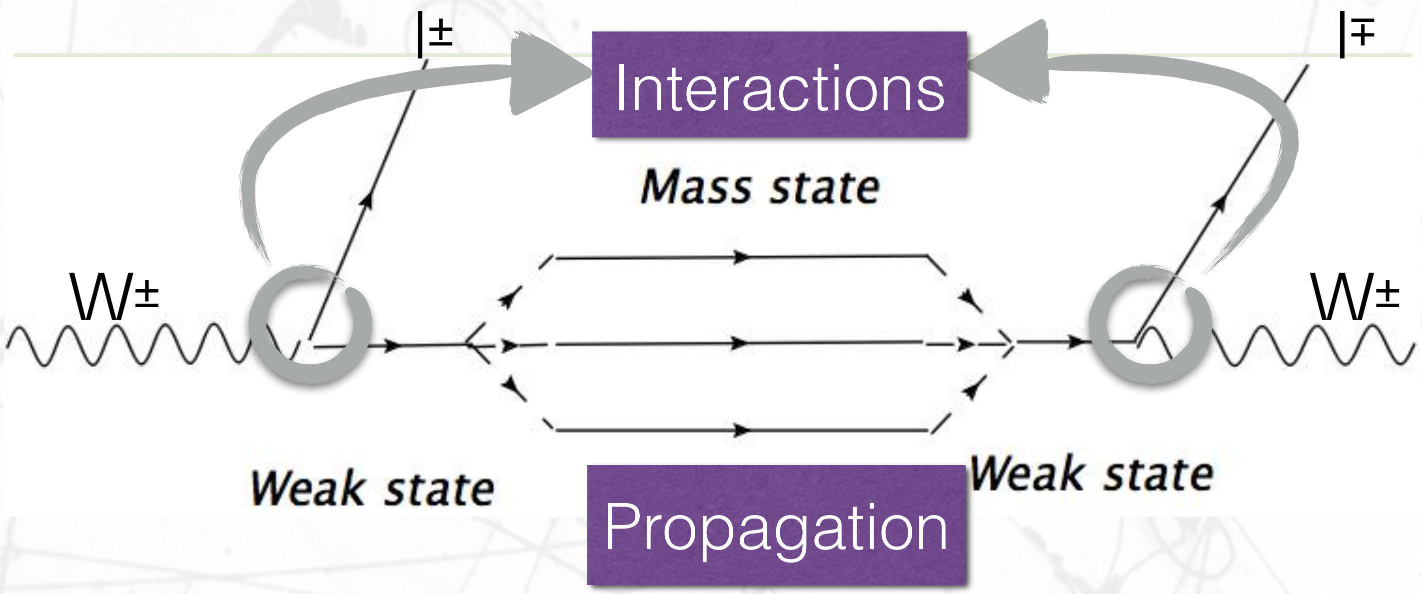
Neutrino oscillations

Neutrino oscillations is an interference phenomena similar to the one in the **double slit experiment**.

Analogy





Electrons go from source to detector through **both slits** at same time

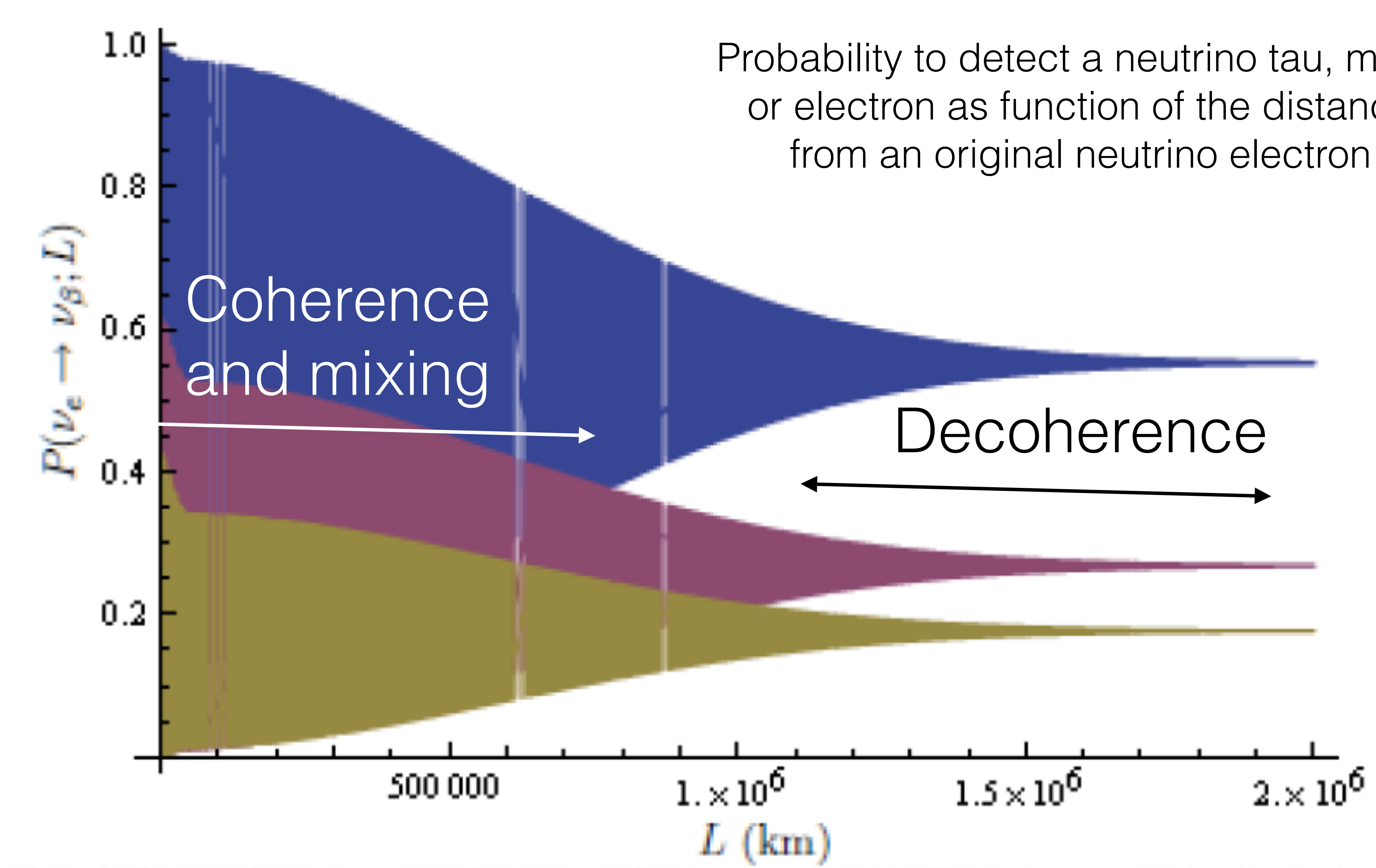
Neutrinos fly through **both mass** states at the same time.

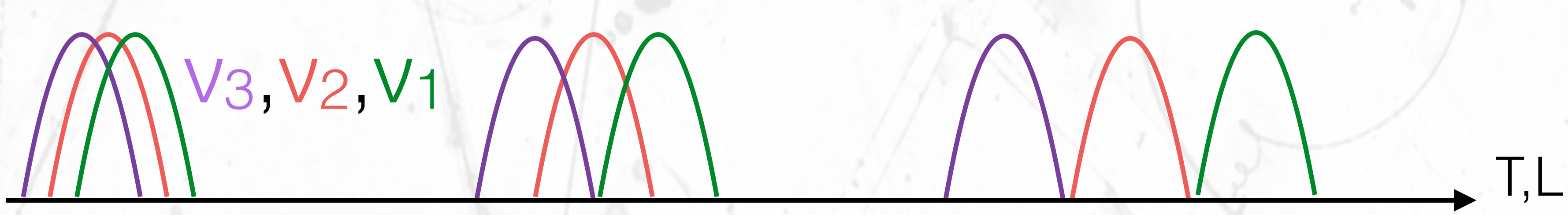
Every slit forces a different **path length**(**phase**) → **interference**

Every mass state forces a different frequency and **path length**(**phase**) → **interference**

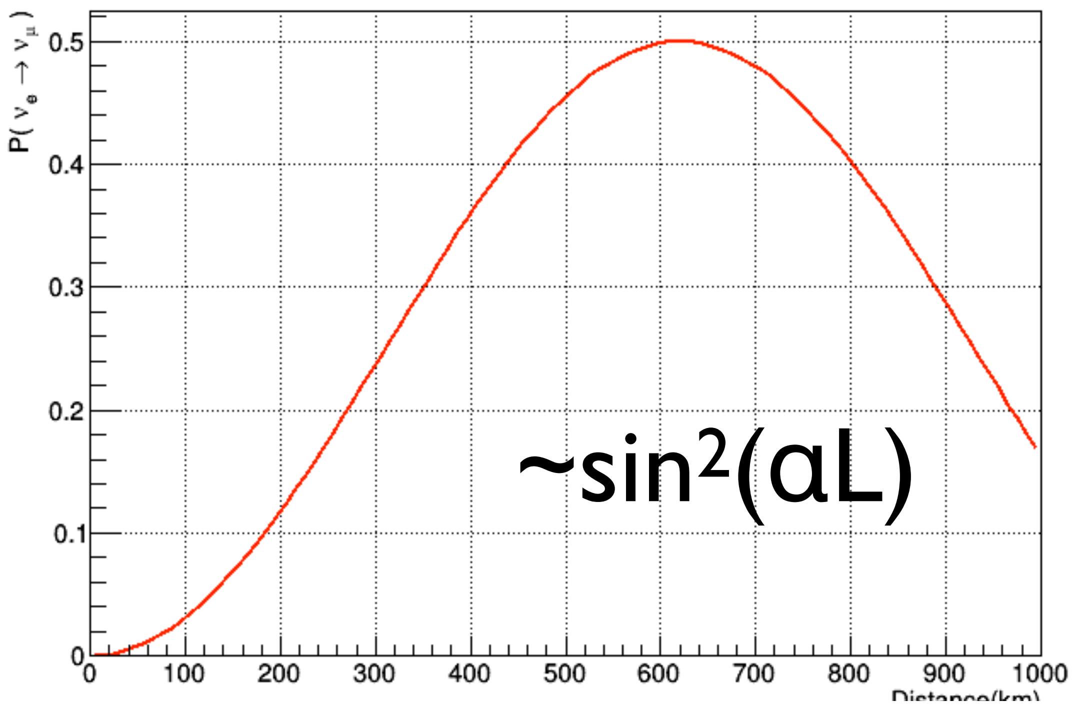
$$|\nu_{e,\mu,\tau}\rangle = A_{e,\mu,\tau;1}(t)|\nu_1\rangle + A_{e,\mu,\tau;2}(t)|\nu_2\rangle + A_{e,\mu,\tau;3}(t)|\nu_3\rangle$$

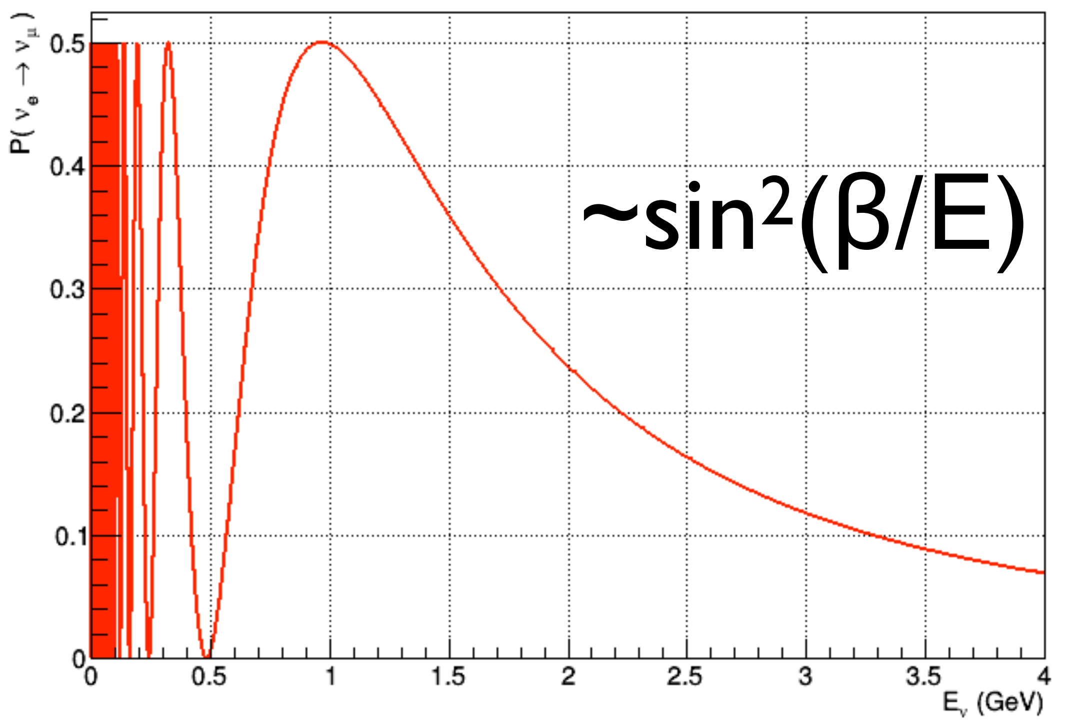
Quantum (de)coherence





Oscillations with 2ν





θ = π/2

$\Delta m^2 = 2.\text{x}10^{-3}\ eV^2$

Simplified 2ν formula

$$|<\nu_\mu|\nu_e;t>|^2 = \sin^2\frac{\theta}{2}\sin^2 1.267\frac{\Delta m^2 L}{E}\frac{GeV}{eV^2 km}$$

Oscillations are seen as change of ν flavour composition as function of: Energy & Distance

$$P(\nu_\alpha \rightarrow \nu_\beta)$$

Mass hierarchy

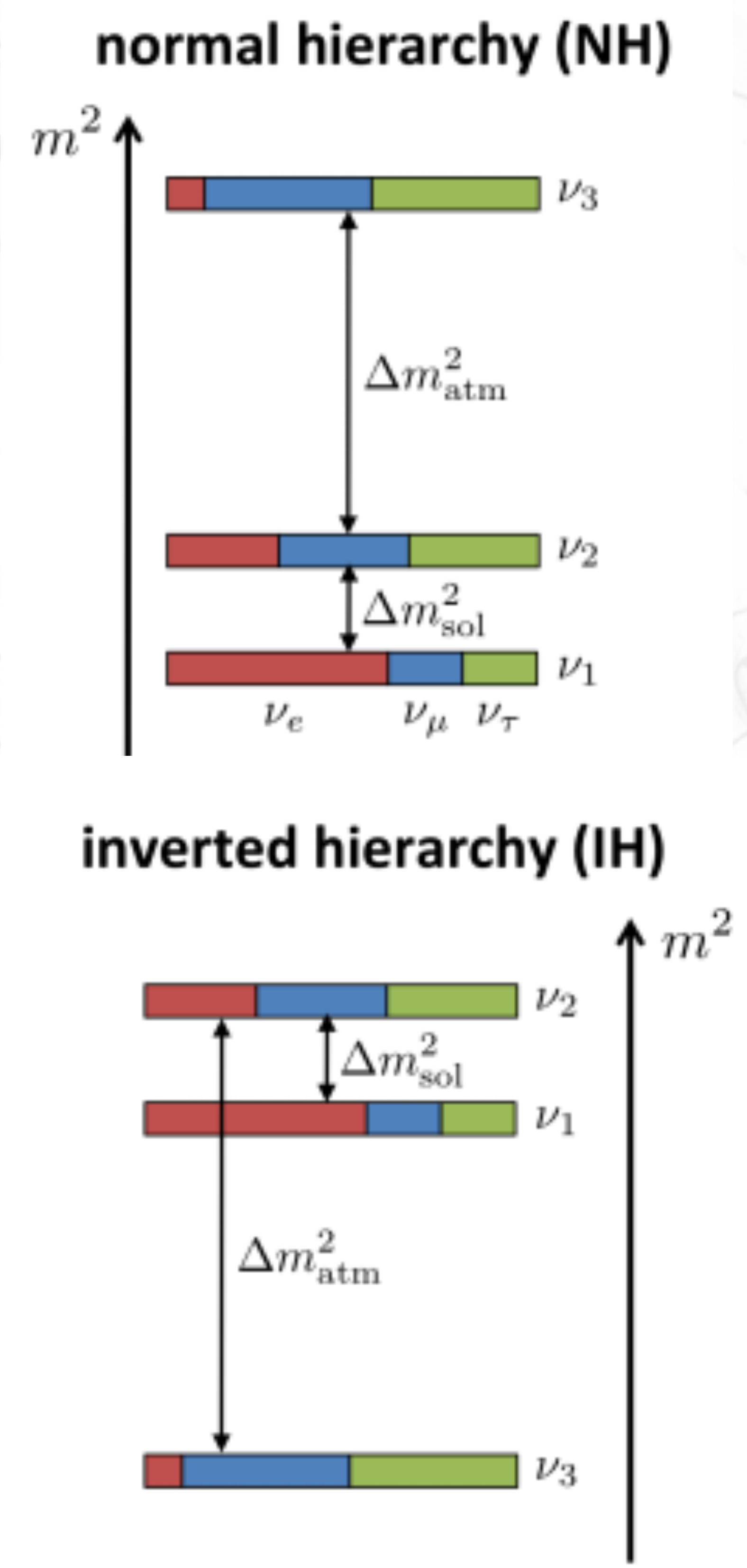
- Oscillations is a quantum interference phenomenon that depends on the (quadratic) mass difference:

$$\Delta m^2_{ij} = m^2_i - m^2_j$$

- Due to matter effects in solar neutrinos we know:

$$\Delta m^2_{12} > 0$$

- Hierarchy determines the ordering of the masses. Traditionally:
  - Normal: $m_1 < m_2 < m_3$
  - Inverted: $m_3 < m_1 < m_2$



~~CP~~ in ν

CPT conserved: CP violation —> T violation

- CP violation is only possible with more than 2 neutrino species (property of 3x3 imaginary matrices).

$$\begin{pmatrix}\nu_e & \nu_\mu & \nu_\tau\end{pmatrix} = U_{PNMS}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

$$U_{PNMS} = \begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\begin{pmatrix}\cos\theta_{13} & 0 & e^{-\delta_{CP}}\sin\theta_{13}\\ 0 & 1 & 0\\ -e^{\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13}\end{pmatrix}\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}$$

  - With less than 3 ν's, the imaginary phase can factorised (no CP violation).
  - With more than 3 ν's, there is more than 1 CP phase.
- To observe CP violation, it is required "explicit flavour transition":

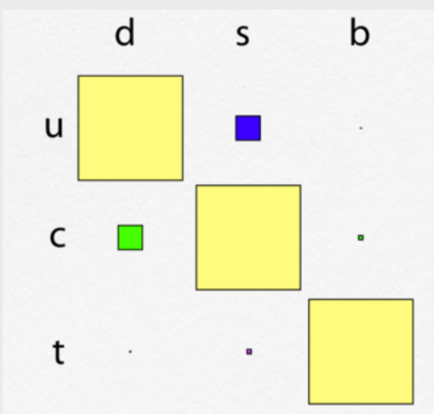
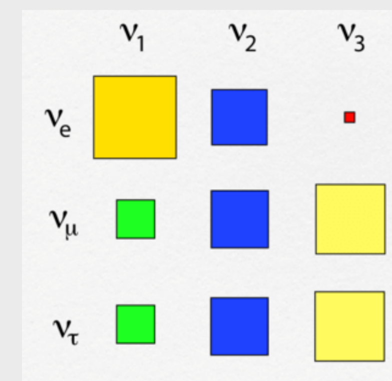
$$P(\nu_\alpha \to \nu_\beta) = P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)?$$

- Disappearance is like 2 neutrino oscillations (neutrino → all others) , no direct CP violation can be observed.

$$P(\nu_\alpha \to \nu_\alpha) = P(\bar{\nu}_\alpha \to \bar{\nu}_\alpha)$$

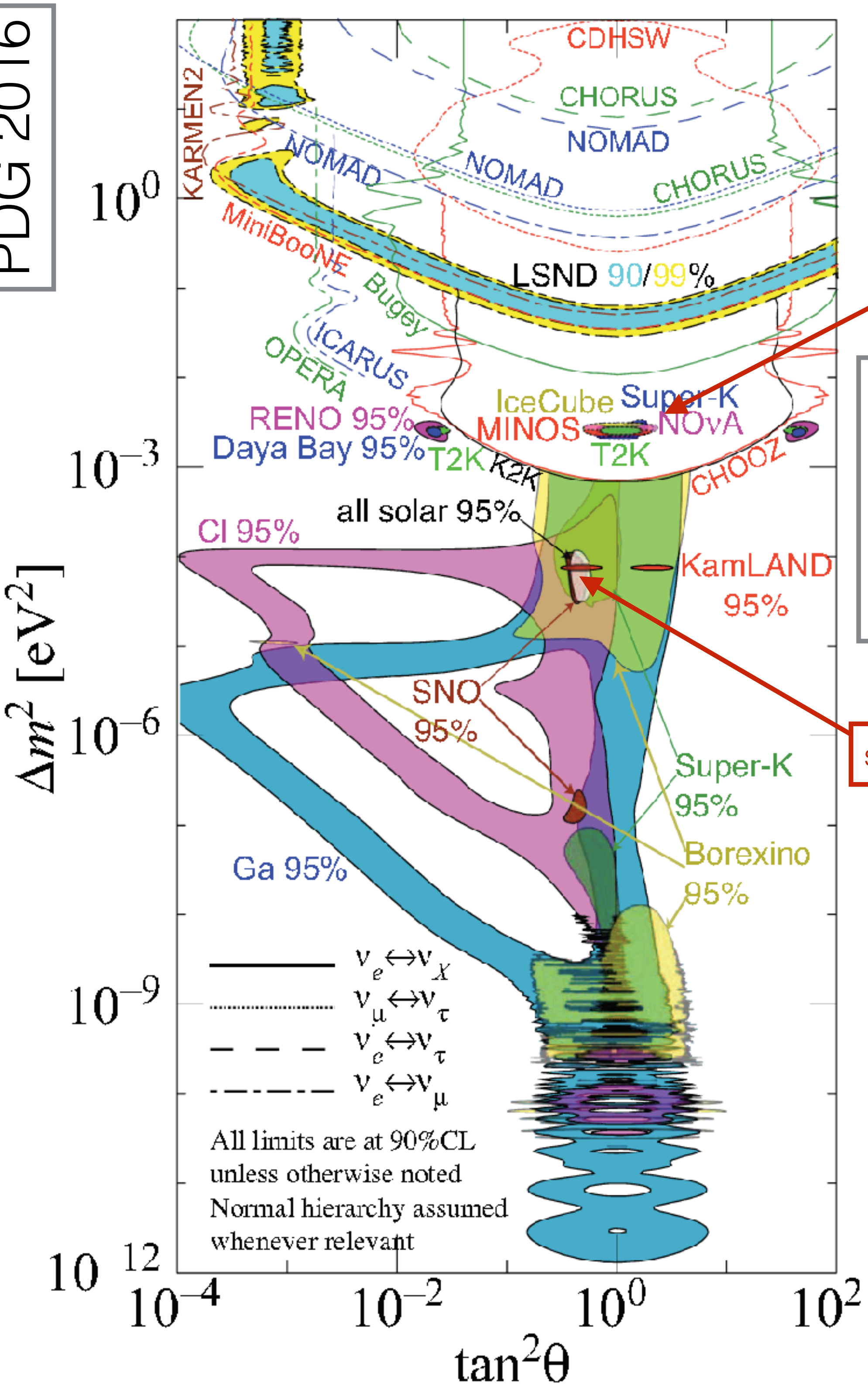
PNMS vs CKM

The mixing and CP violation phenomena was observed in 1964 in quarks trough weak interactions in neutral kaon decays.

Quarks (CKM)	Neutrinos (PNMS)
 Mostly diagonal	Flat"ish" 
$\begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$ Unitarity is not enforced by construction	$\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$ Unitarity enforced by construction following N_ν=3 from LEP

Oscillation parameters

PDG 2016



PNMS Matrix

$$U_{PNMS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

PDG 2018

	Parameter	best-fit	3σ
~4%	Δm^2_{21} $[10^{-5}$ eV$^2]$	7.37	6.93 – 7.96
~3%	$\Delta m^2_{31(23)}$ $[10^{-3}$ eV$^2]$	2.56 (2.54)	2.45 – 2.69 (2.42 – 2.66)
~11%	$\sin^2\theta_{12}$	0.297	0.250 – 0.354
~15%	$\sin^2\theta_{23}$, $\Delta m^2_{31(32)} > 0$	0.425	0.381 – 0.615
	$\sin^2\theta_{23}$, $\Delta m^2_{32(31)} < 0$	0.589	0.384 – 0.636
~7%	$\sin^2\theta_{13}$, $\Delta m^2_{31(32)} > 0$	0.0215	0.0190 – 0.0240
	$\sin^2\theta_{13}$, $\Delta m^2_{32(31)} < 0$	0.0216	0.0190 – 0.0242
~31%	δ/π	1.38 (1.31)	2σ: (1.0 - 1.9) (2σ: (0.92-1.88))

Most of the parameters measured with <10% precision

θ_{23} is known with 15% precision.

Remaining parameters are δ_{CP}, the hierarchy and the θ_{23} octant (>45°?)

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T2K experiment

"the Japanese way"

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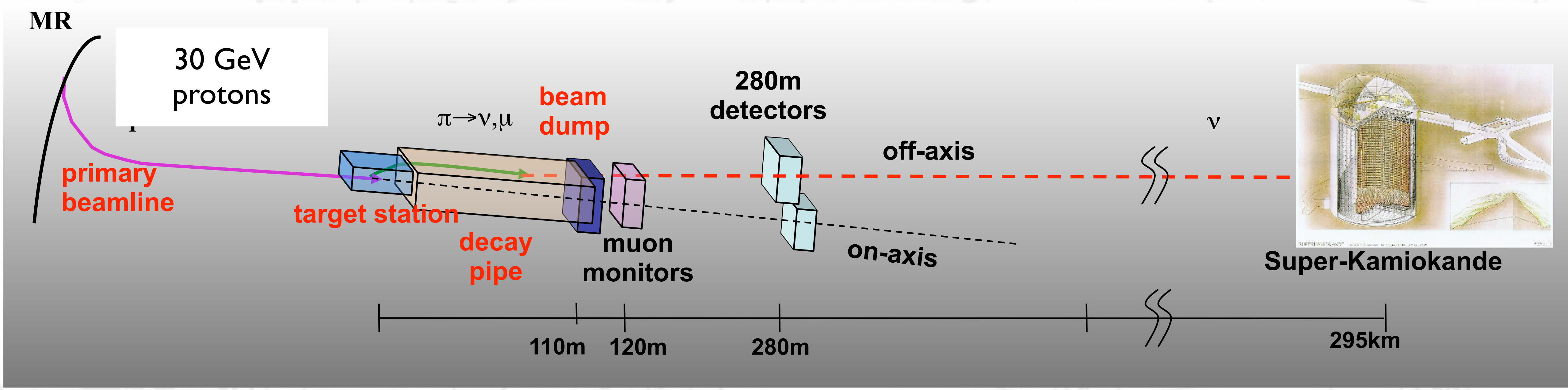
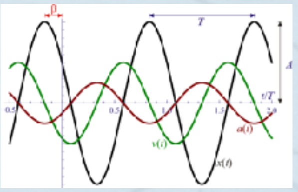
T2K experiment



Neutrinos produced in a particle accelerators or nuclear reactors.

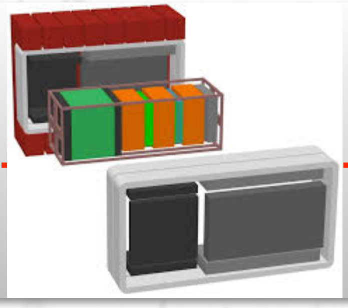
Neutrino flux properties

ν oscillations



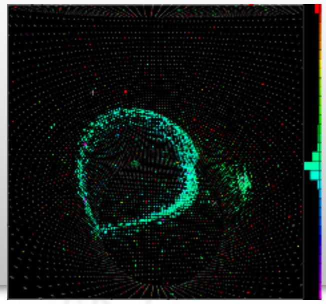
Neutrino flux & flavour

$\nu_\mu, \bar{\nu}_\mu$



$\nu_e \bar{\nu}_e$

$\nu_\mu \bar{\nu}_\mu$



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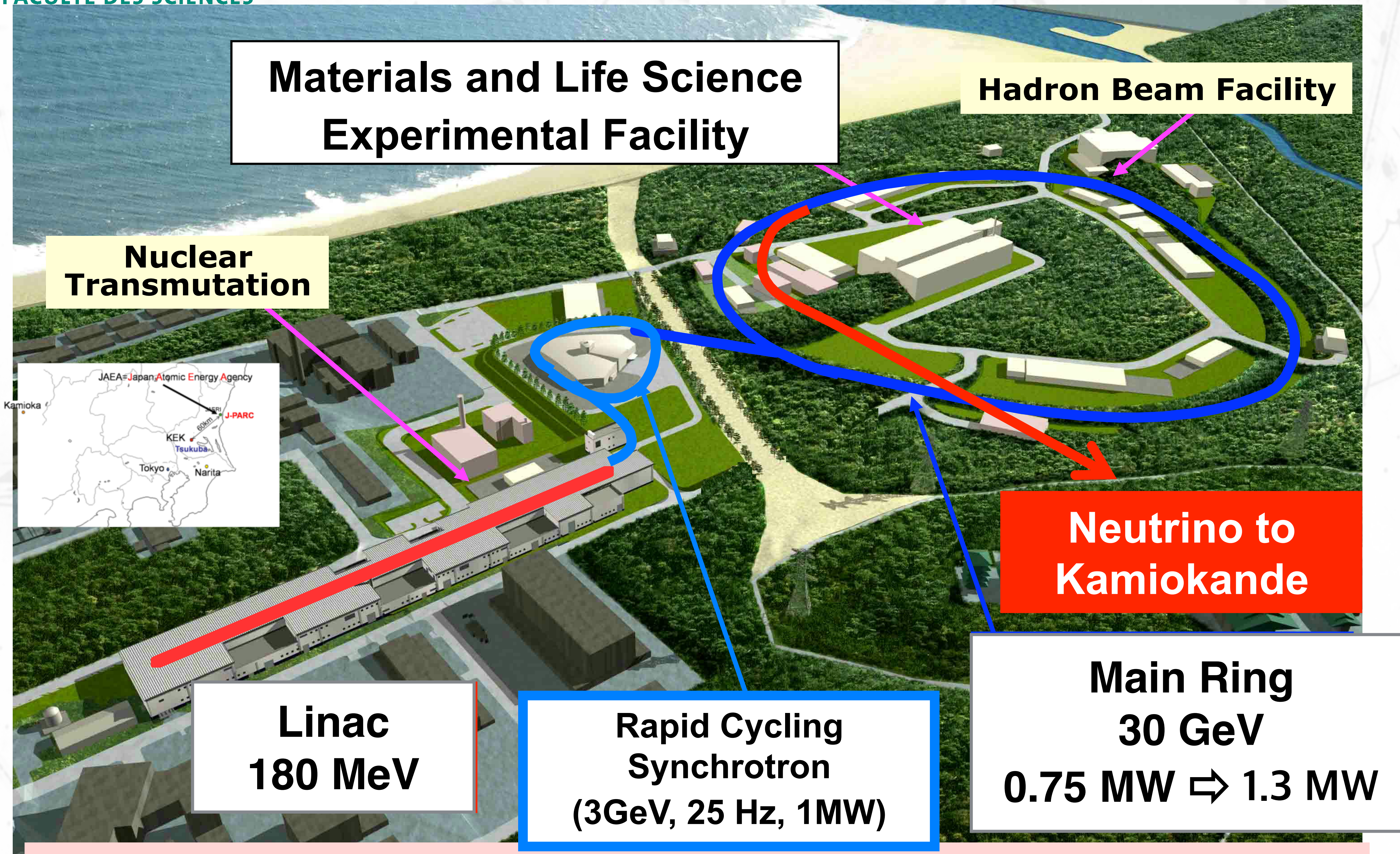
JPARC

T2K



J-PARC = Japan Proton Accelerator Research Complex

Joint Project between KEK and JAEA

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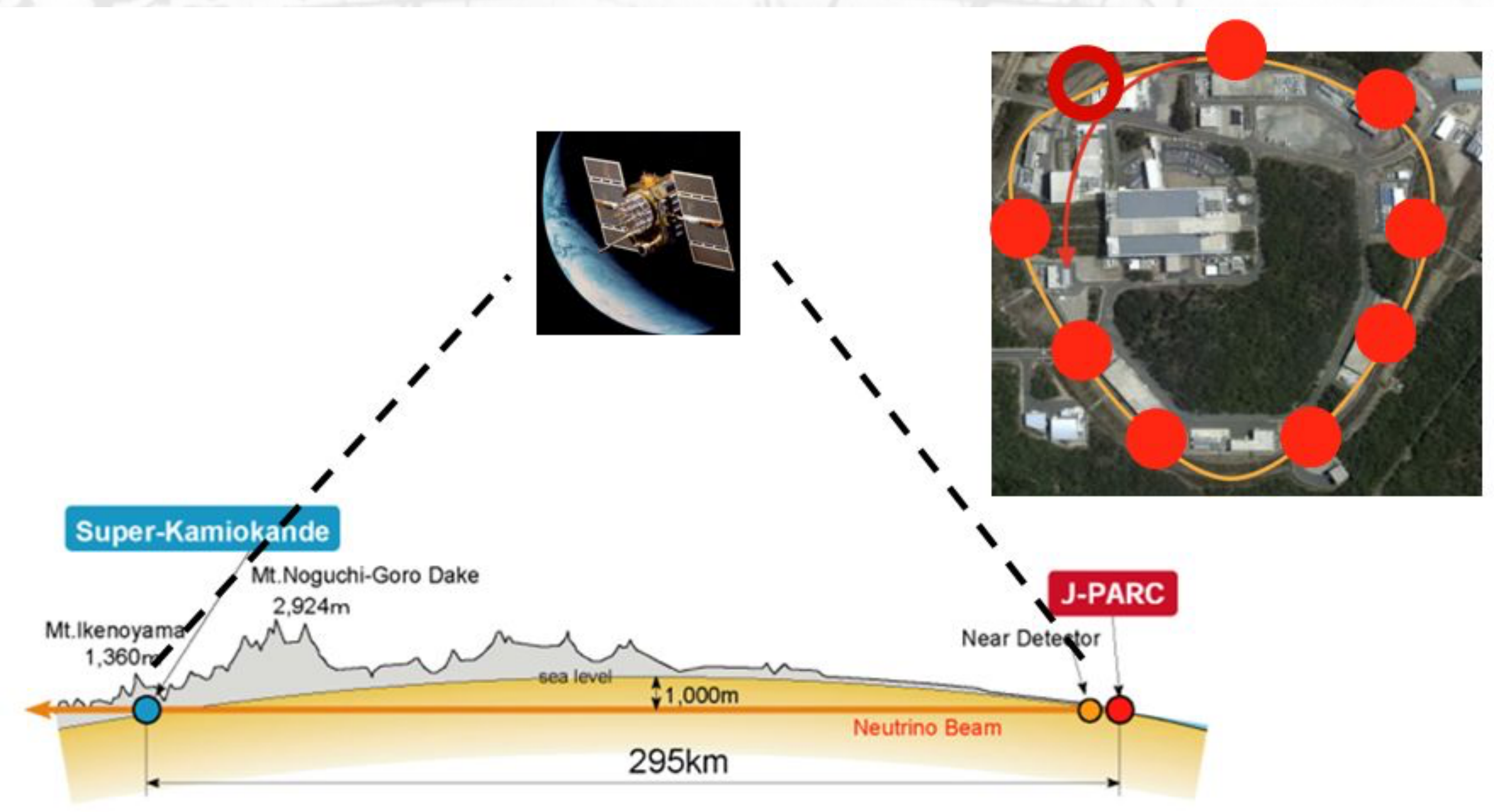
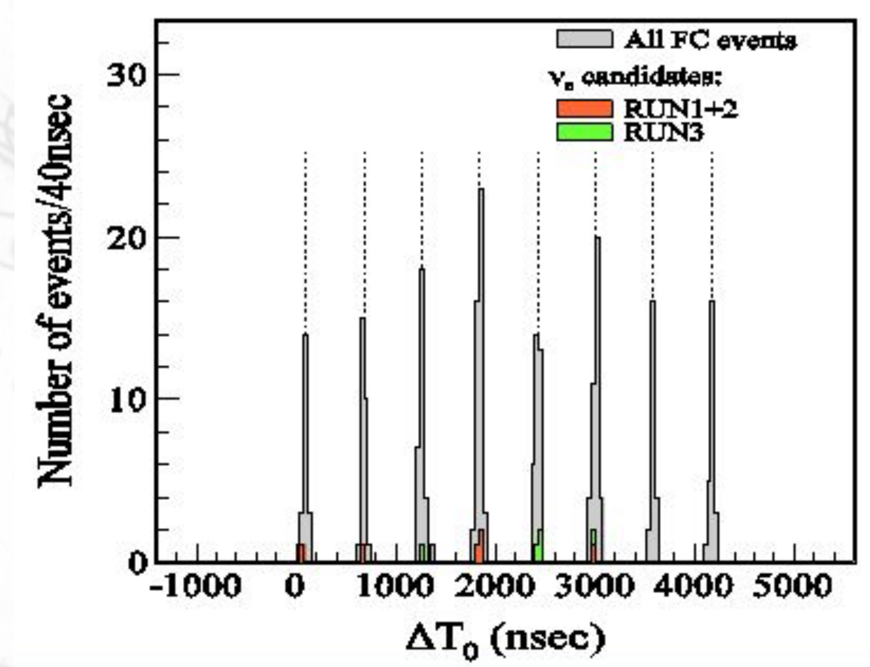
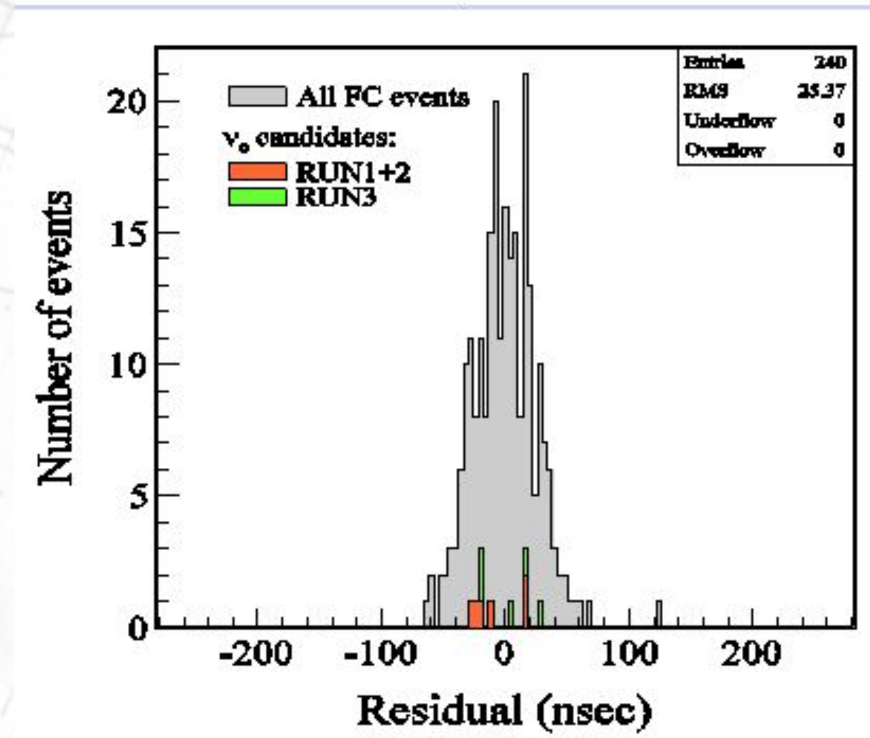
Time synchronisation

- GPS system used to synchronise the beam and the far detector.
- “Common view” GPS method is used.
- A second GPS and a Rubidium clock used in far detector to monitor stability.







50 ns resolution !!!

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Data Set

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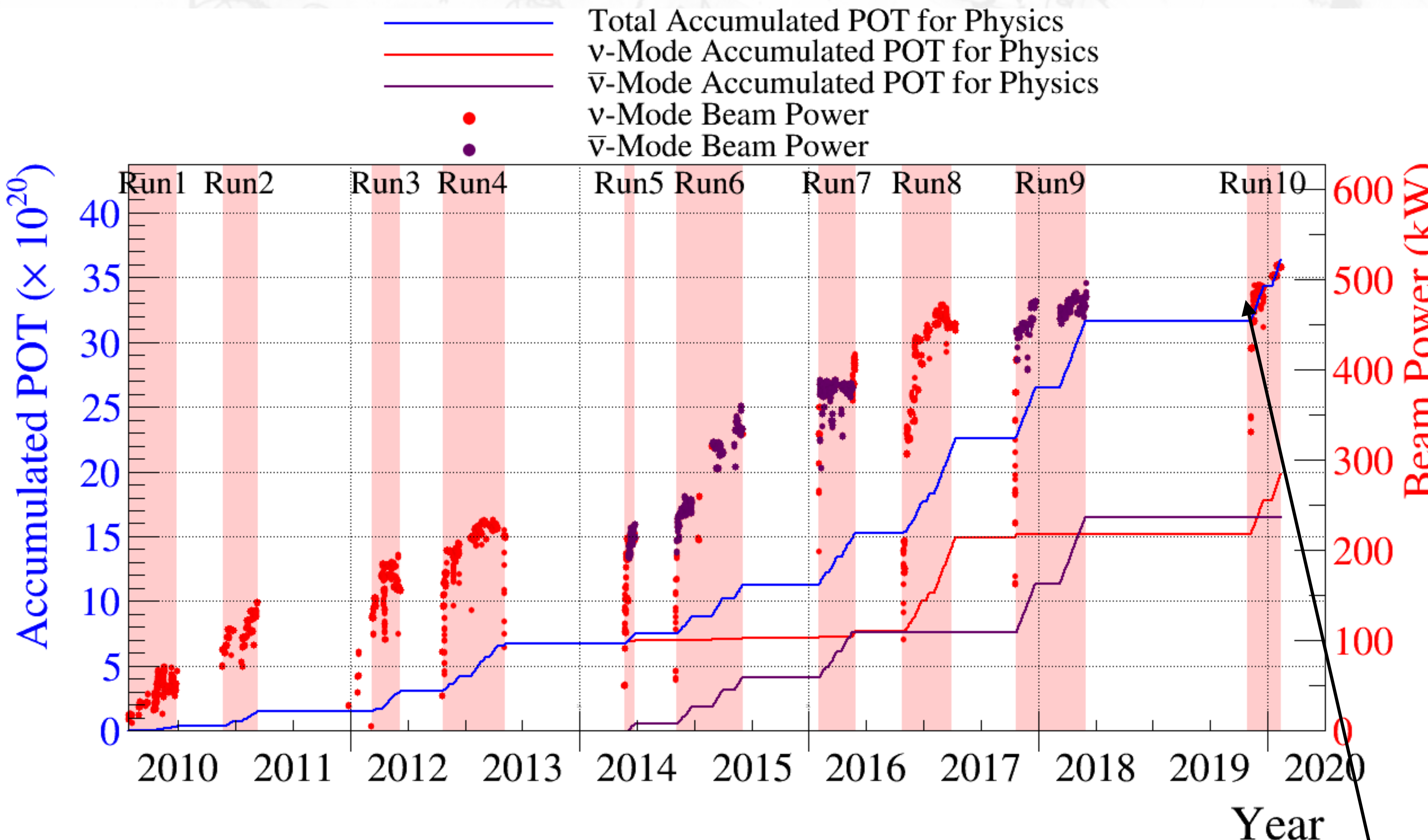

1.97 x 10^{21} POT in ν mode

1.63 x 10^{21} POT in anti-ν mode.

515 kW stable operation in 2019
+ 33% of ν-mode for next analysis

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Producing neutrinos

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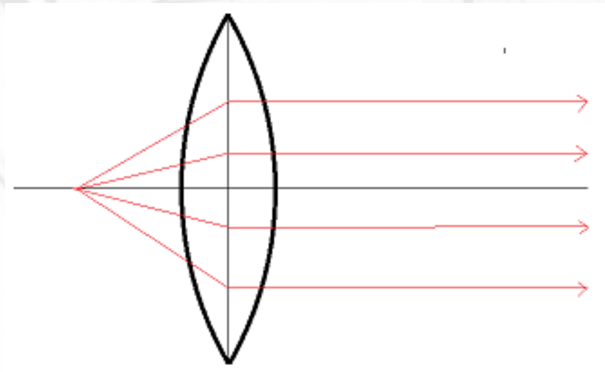
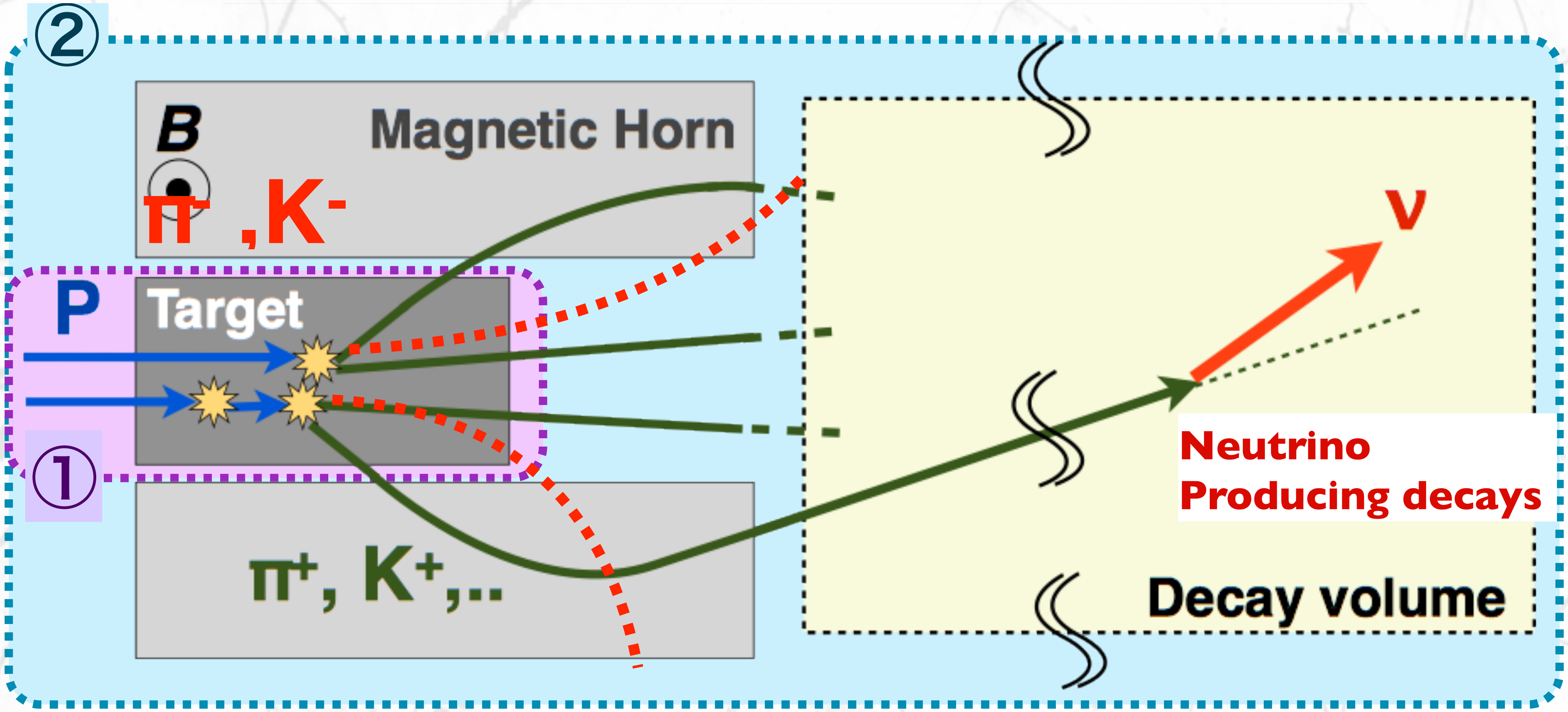
Horns are light convergent lenses: increases flux of ν's in certain directions.

Reversing the horn current we can select π^- over π^+ enhancing anti-neutrinos vs neutrinos.

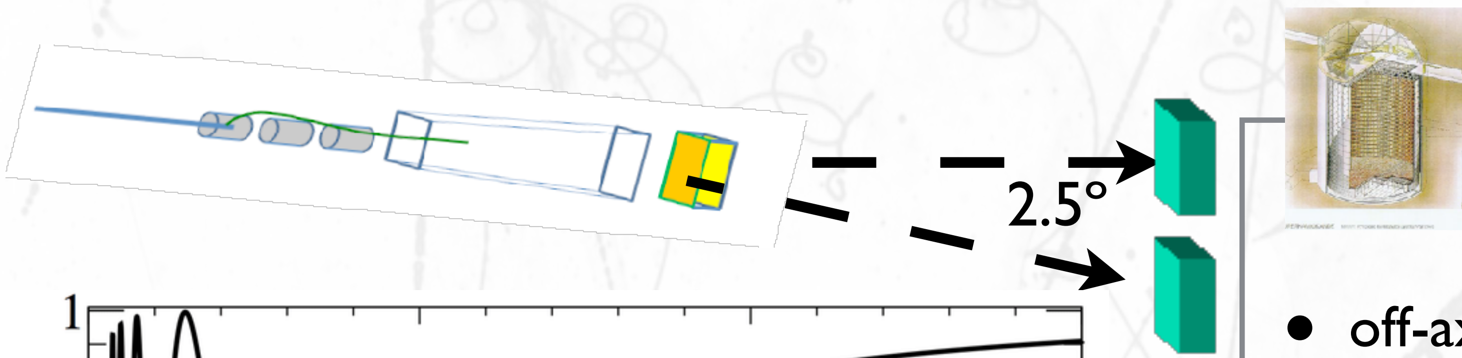
$$\pi^+ \rightarrow \mu^+ \nu_\mu$$
$$\pi^- \rightarrow \mu^- \bar{\nu}_\mu$$

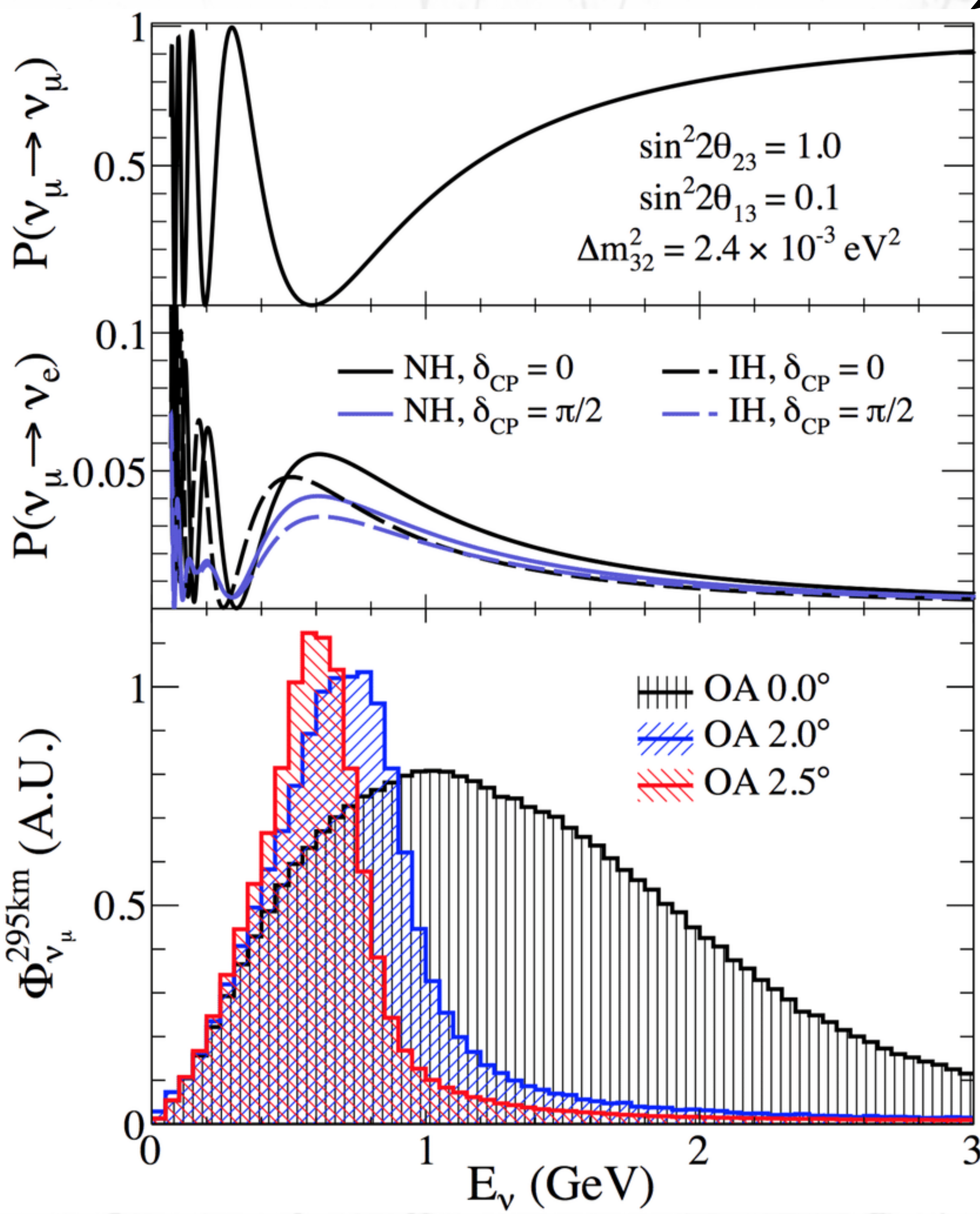




T2K runs a system of 3 consecutive horns to optimise ν's yield and correct "optical" aberrations.

Off(On)-axis beam





Off-axis

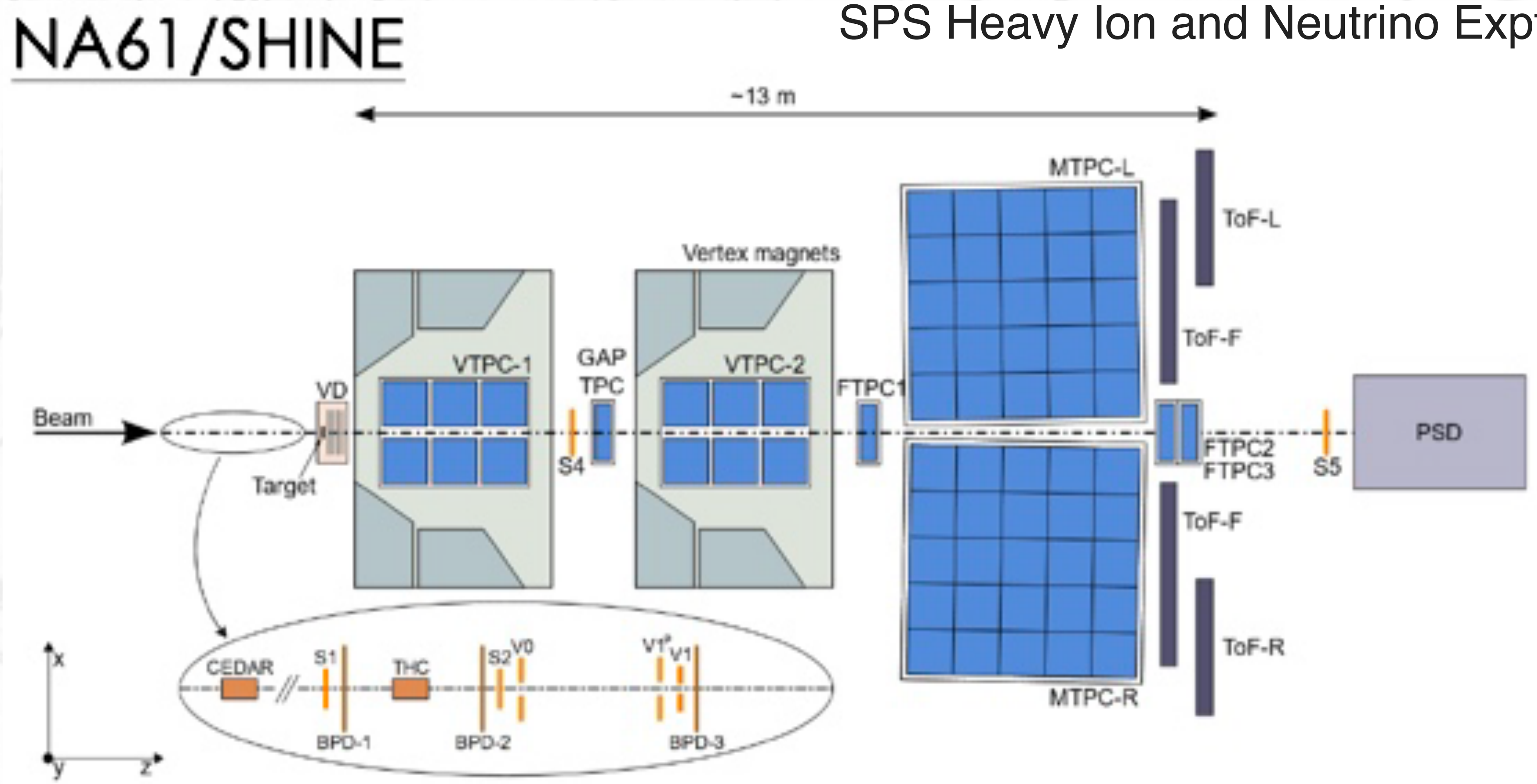
- off-axis optimises the flux at the maximum of the oscillation.
- Only one oscillation maximum can be measured at a fixed distance.
- Narrow beam less dependent on beam uncertainties but more on beam pointing.
- Lower energies achieved.

On-axis

- on-axis optimises the total integrated flux.
- Spectrum with higher neutrino energy (longer oscillation distances)
- If broad enough, more than one oscillation maximum can be measured at a fixed distance.

NA61-SHINE

SPS Heavy Ion and Neutrino Expt (SHINE)



NA61/Shine measures the production of pions and kaons as function of the momentum and angle for protons interacting with carbon.

Hadroproduction experiments carried in equal conditions to ν beam experiments are critical!

Latest measurements made with exact T2K replica target

NA61-SHINE

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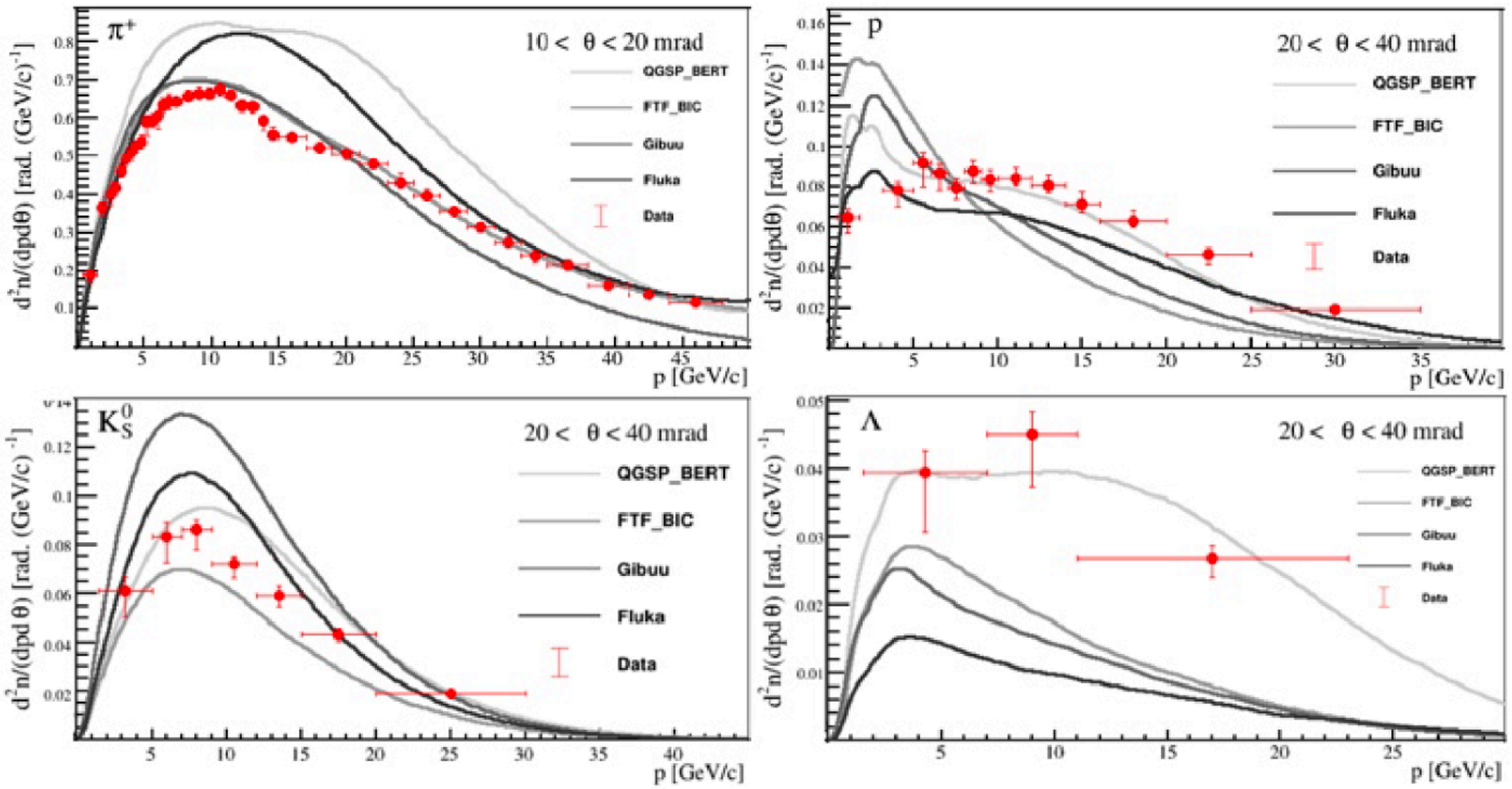
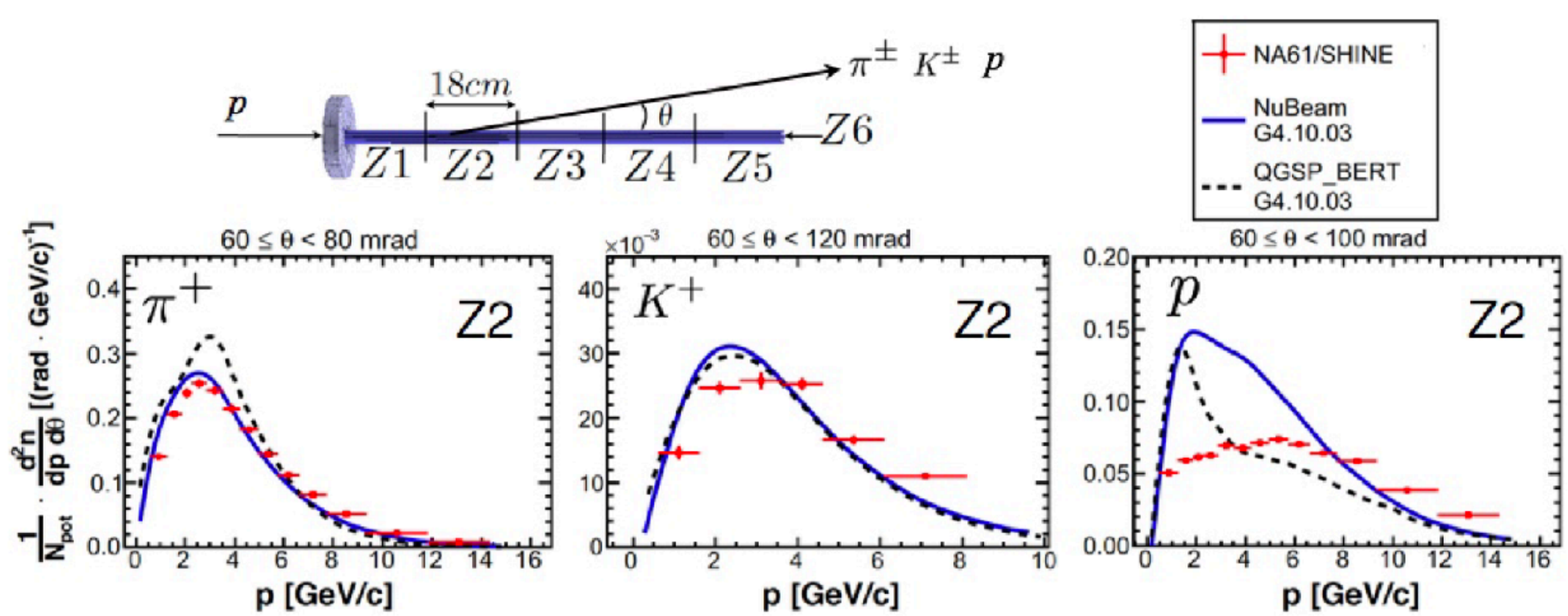
T2K

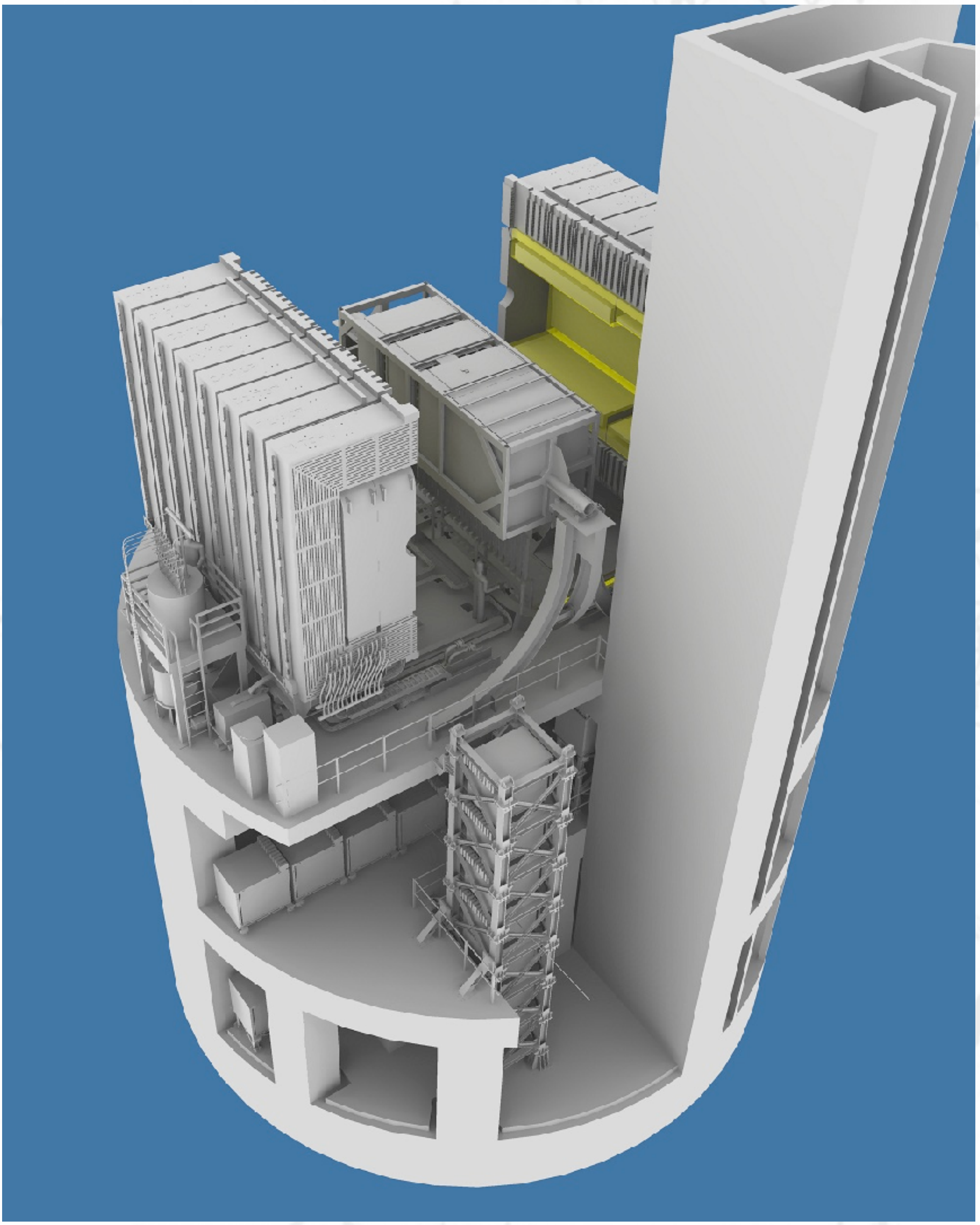


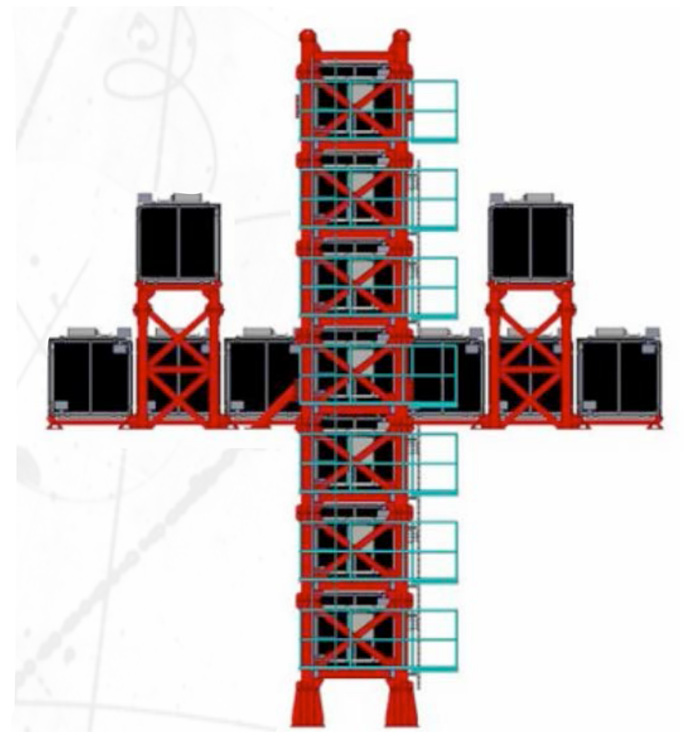
Measurement of pions, proton, K and Λ's in a 30 GeV proton-Carbon interactions

Measurement of production with exact replica of the target to account for re-interactions inside the target

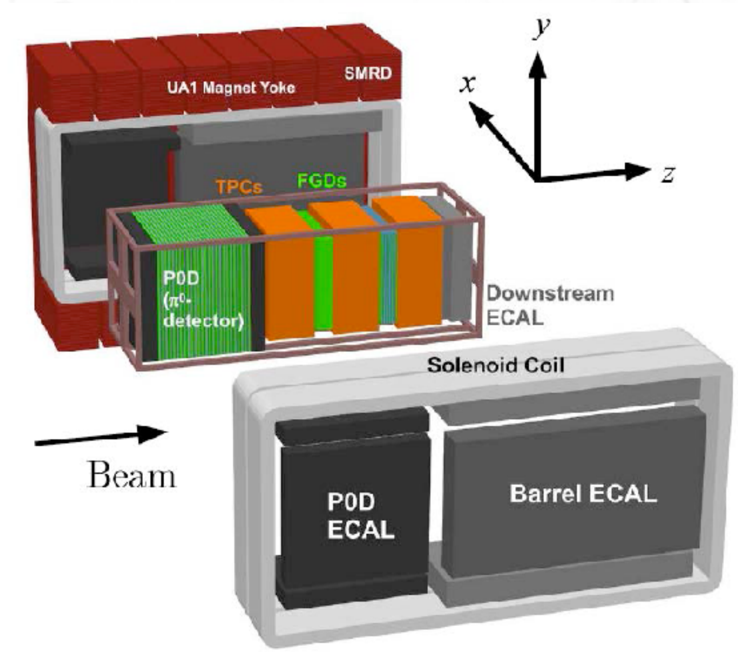


Near Detector Site

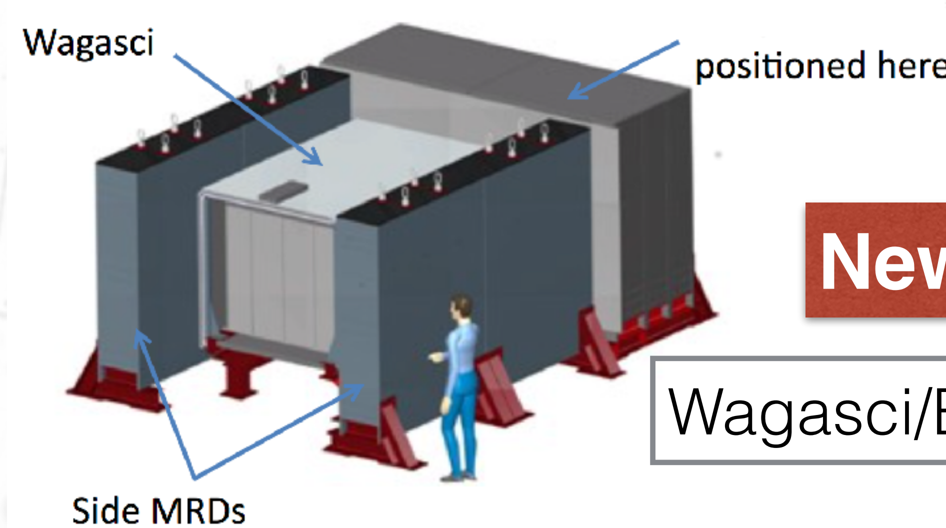




INGRID: On-axis



ND280: Off-axis



New in 2019!

Wagasci/BabyMind: Off-axis

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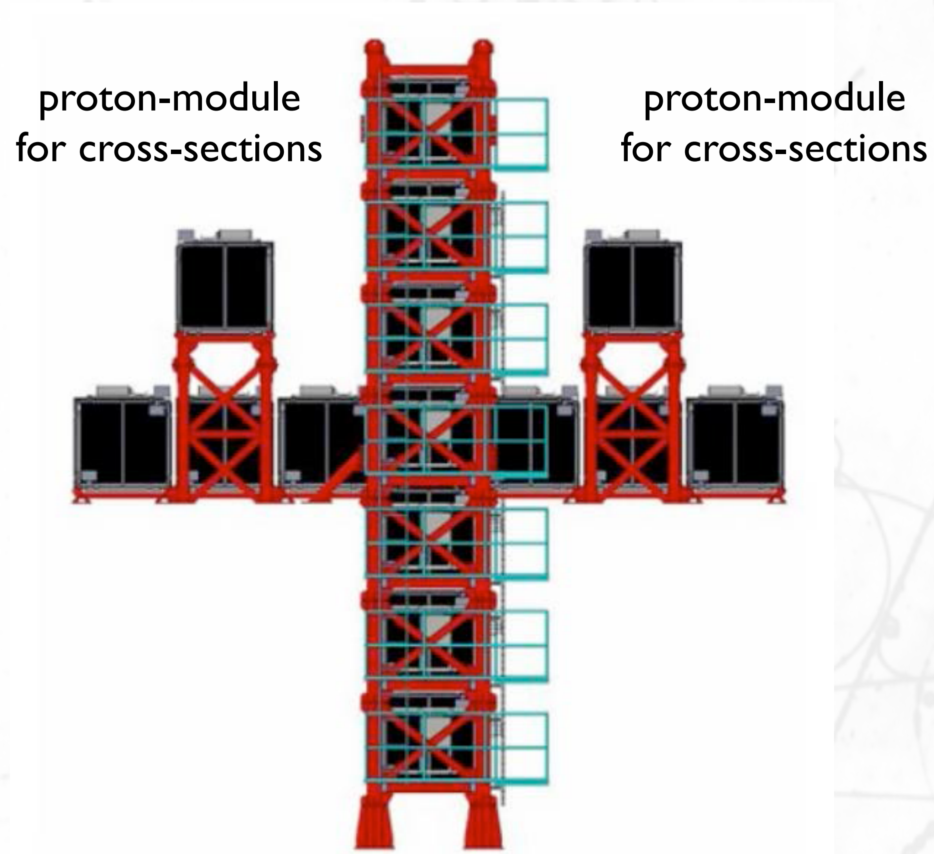
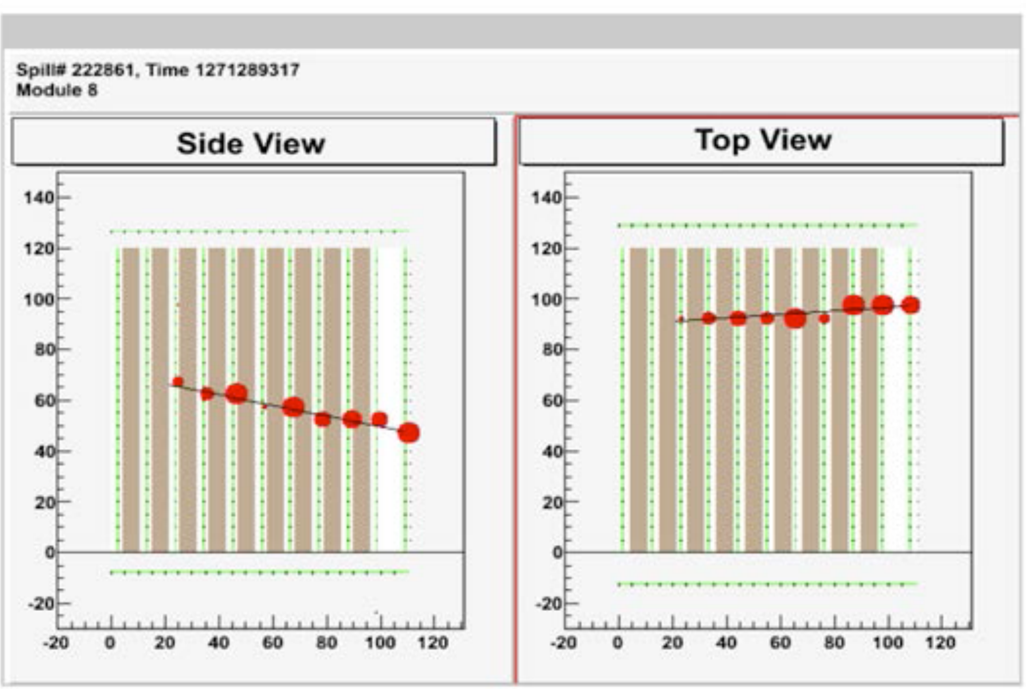
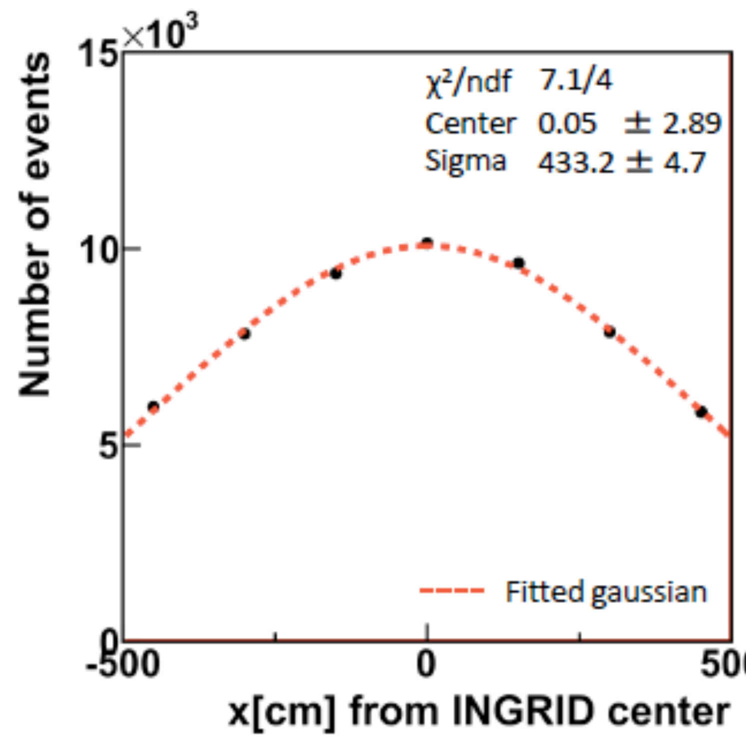
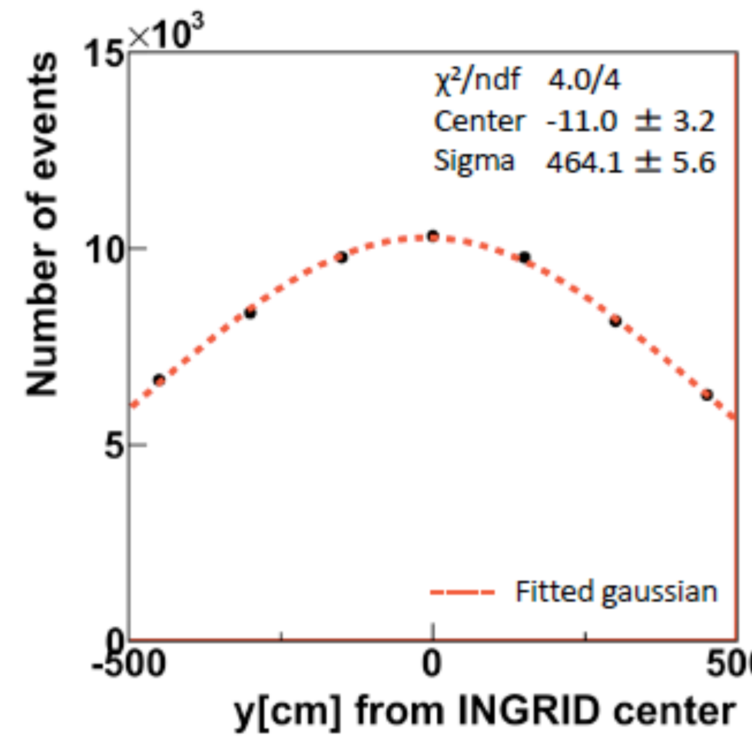
On-Axis ND



- INGRID counts ν($\bar{\nu}$) CC events in a cross of 13 identical detectors:
    - total rate monitors beam intensity stability with respect to proton on target counting.
    - The relative event counts between modules monitor the beam direction stability.







Off-Axis ND

- Same off-axis angle as SuperKamiokande (2.5 degrees)
- Measure ν_μ and ν_e spectrum before the oscillation → TPCs + FGDs
- Measure background processes to oscillation (NCπ^0, NC1π, CC1π…)
- Compare Carbon and Oxygen interactions (FGD2 and P0D)

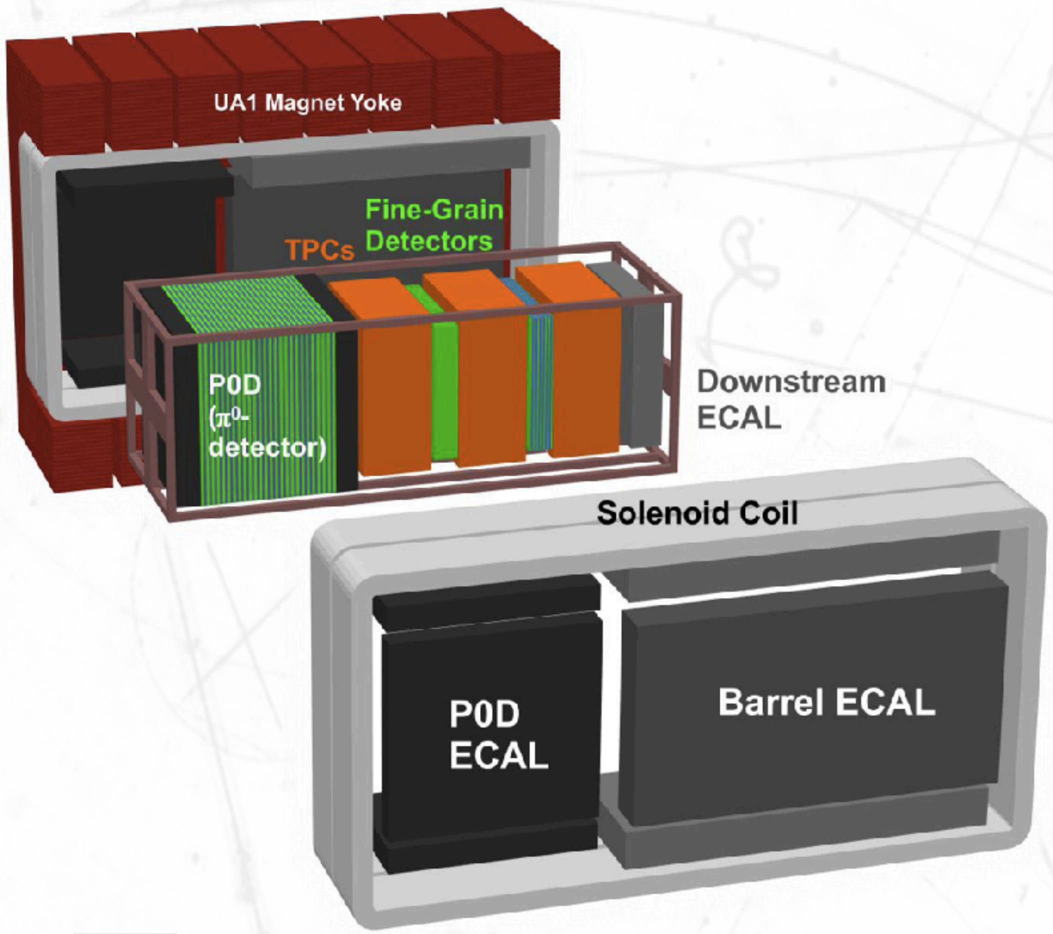
Magnet

Excellent neutrino-antineutrino selection

ND280 installed in ex-UA1 magnet (0.2 T) 3.5x3.6x7.3 m

2 FGDs (Fine Grained Detector):
active target mass for the tracker, optimized for p/π separation
Carbon+Water target in FGD2

SMRD (Side Muon Range Detector):
scintillator planes in magnet yokes.
Measure high angle muons



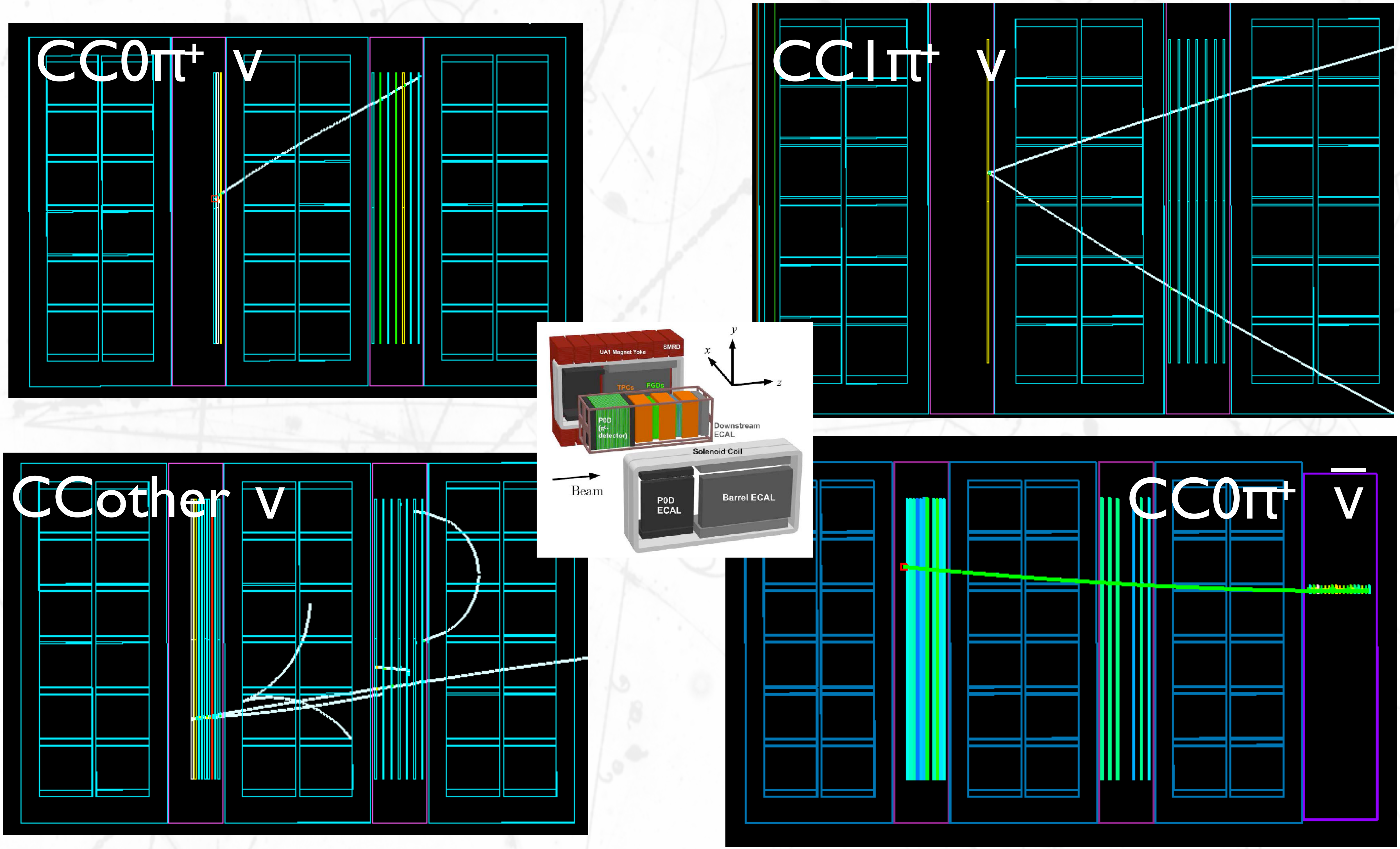
3 TPCs (Time Projection Chambers):
measure momentum and charge of particles from FGD and P0D, PID capabilities through dE/dx

P0D (π0 detector):
scintillator bars interleaved with fillable water target bags and lead and brass sheets.
Optimised for γ detection

P0D, Barrel and Downstream ECAL:
scintillator planes with radiator to measure EM showers

Magnet was granted by CERN

Off-Axis ND

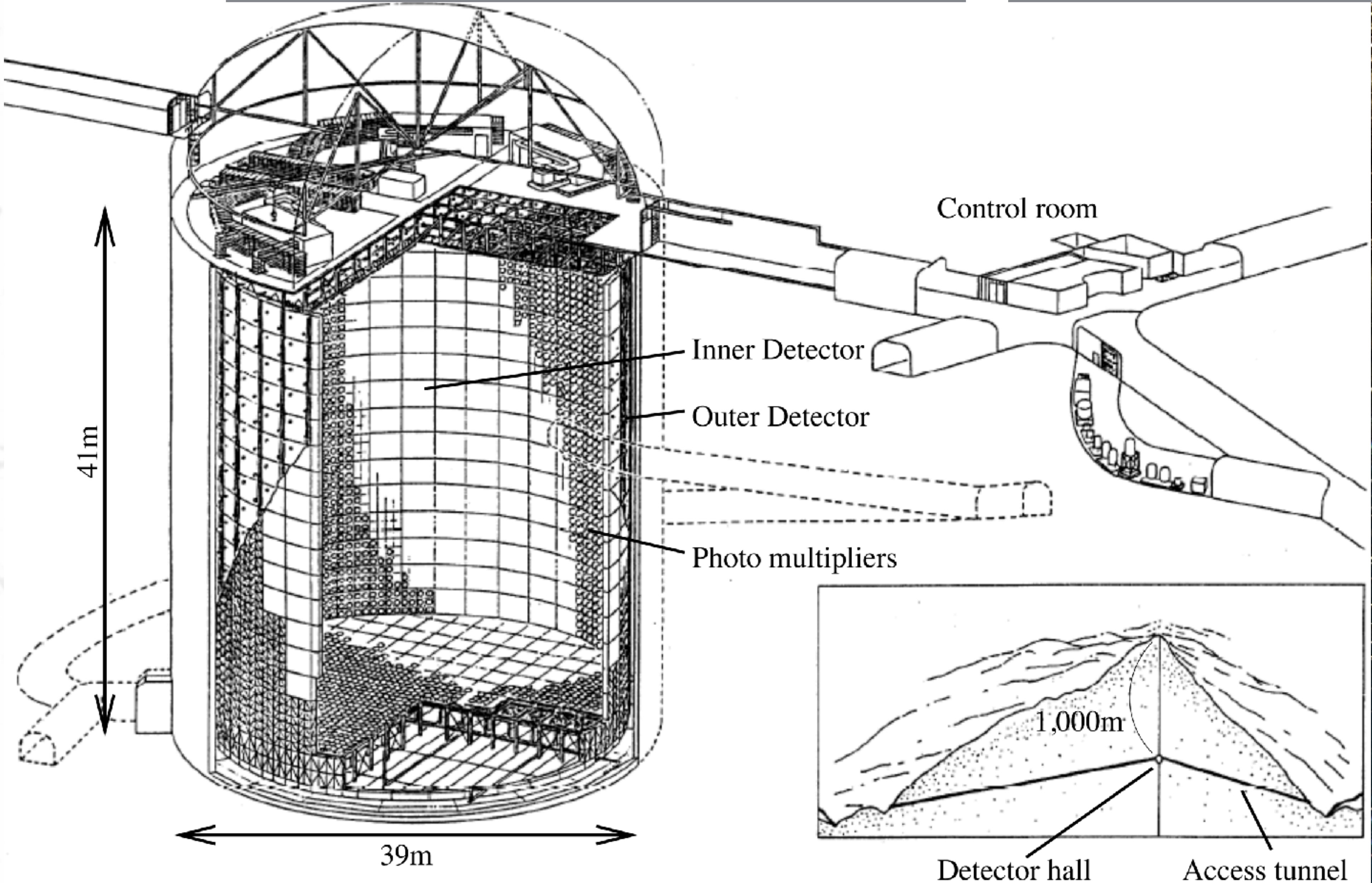


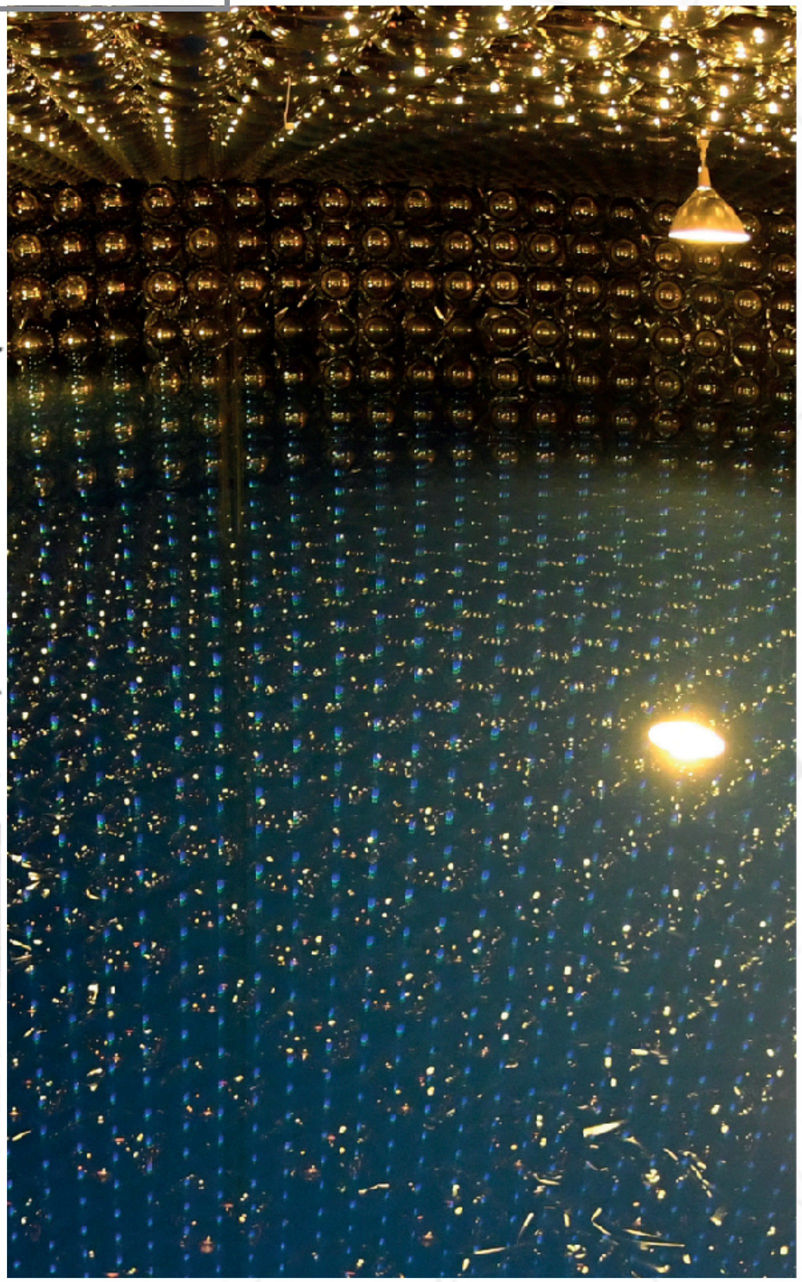
Off-axis ND280 analysis real events

Far detector: concept

50 kton of ultra-pure water

~11000 20” PMT’s





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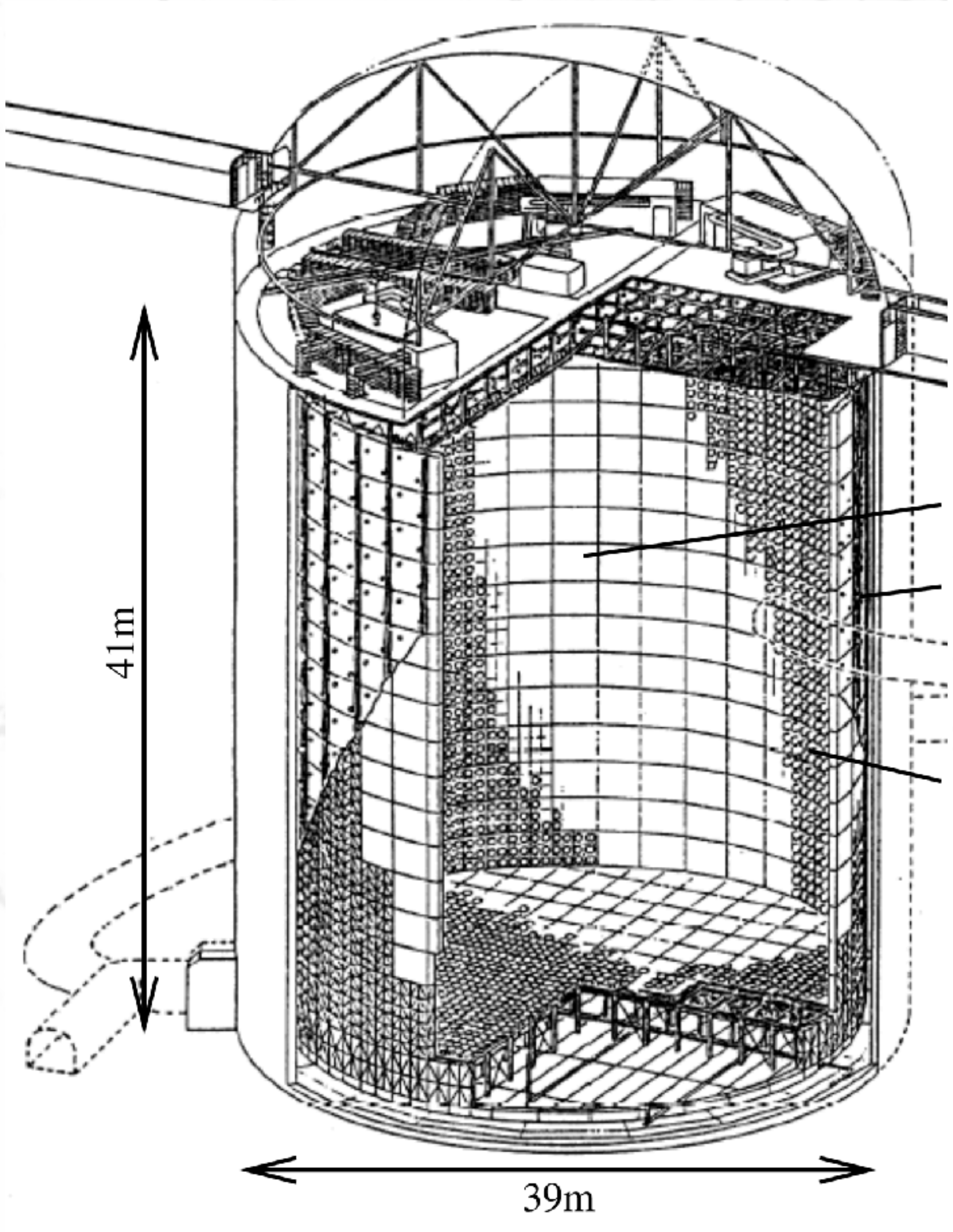
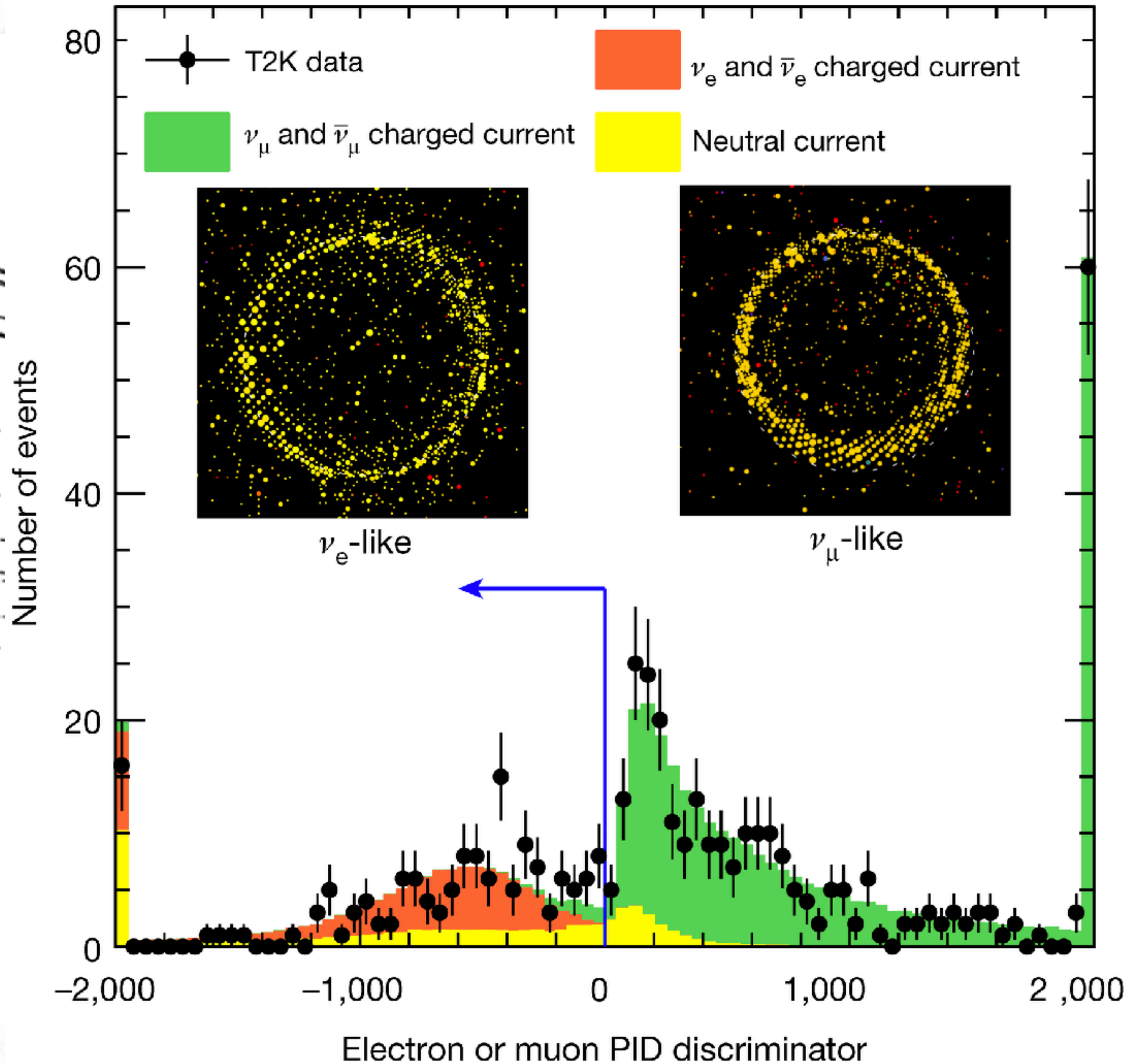
Far detector: capabilities

T2K





Particle identification

Interaction vertex reconstruction

Track Multiplicity

Particle range

Electromagnetic energy reconstruction

Hadronic interactions

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T2K

One basic ingredient:

νA cross-sections

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LBL analysis

T2K

- Since the neutrino energy is not monochromatic:
  - we need to determine event by event the energy of the neutrino.
- This estimation is not perfect and the cross-section does not cancels out in the ratio.

$$\frac{N^{far}_{evts}(\vec{\theta}^{reco}_{\nu})}{N^{near}_{evts}(\vec{\theta}^{reco}_{\nu})} = \frac{\int \sigma(E_\nu)\phi^{far}(E_\nu)P_{far}(\vec{\theta}^{reco}_{\nu}|E_\nu)P_{osc}(E_\nu)dE_\nu + Back_{far}(\vec{\theta}^{reco})}{\int \sigma(E_\nu)\phi^{near}(E_\nu)P_{near}(\vec{\theta}^{reco}_{\nu}|E_\nu)dE_\nu + Back_{near}(\vec{\theta}^{reco})}$$

- The neutrino oscillations introduce differences in the flux spectrum and the ratio does not cancel the cross-sections.

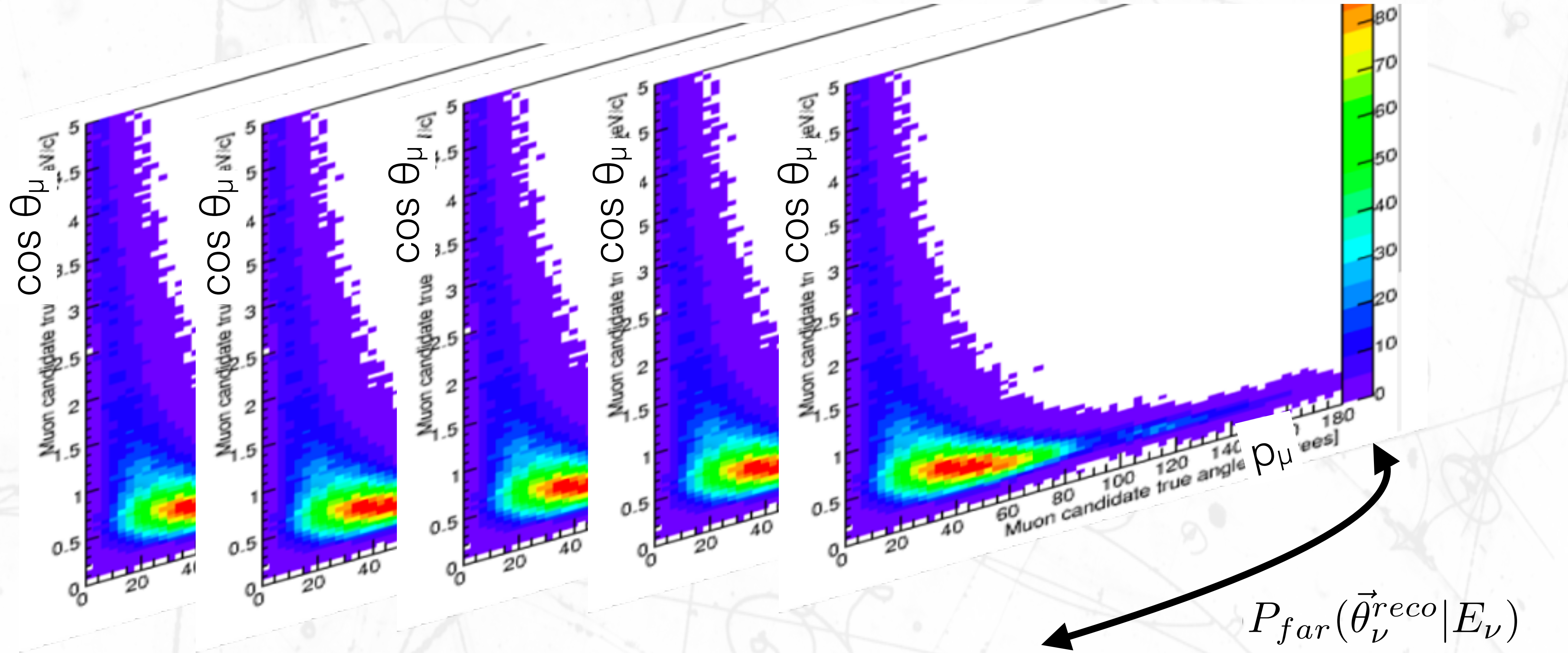
$\phi^{far}(E_\nu) \neq \phi^{near}(E_\nu)$ Near and far fluxes are different

$\sigma(E_\nu)$ Cross-section neutrino nucleus are not well known.

$P_{near,far}(\vec{\theta}^{reco}_{\nu}|E_\nu)$ Neutrino energy depended observables depend on cross-section models.

$Back_{near,far}(\vec{\theta}^{reco}_{\nu})$ Background prediction depends on cross-section models.

T2K approach



$$\frac{N_{evts}^{far}(\vec{\theta}_\nu^{reco})}{N_{evts}^{near}(\vec{\theta}_\nu^{reco})} = \frac{\int \sigma(E_\nu)\phi^{far}(E_\nu)P_{far}(\vec{\theta}_\nu^{reco}|E_\nu)P_{osc}(E_\nu)dE_\nu + Back_{far}(\vec{\theta}^{reco})}{\int \sigma(E_\nu)\phi^{near}(E_\nu)P_{near}(\vec{\theta}_\nu^{reco}|E_\nu)dE_\nu + Back_{near}(\vec{\theta}^{reco})}$$

$P_{far}(\vec{\theta}_\nu^{reco}|E_\nu)$ is given by νA models

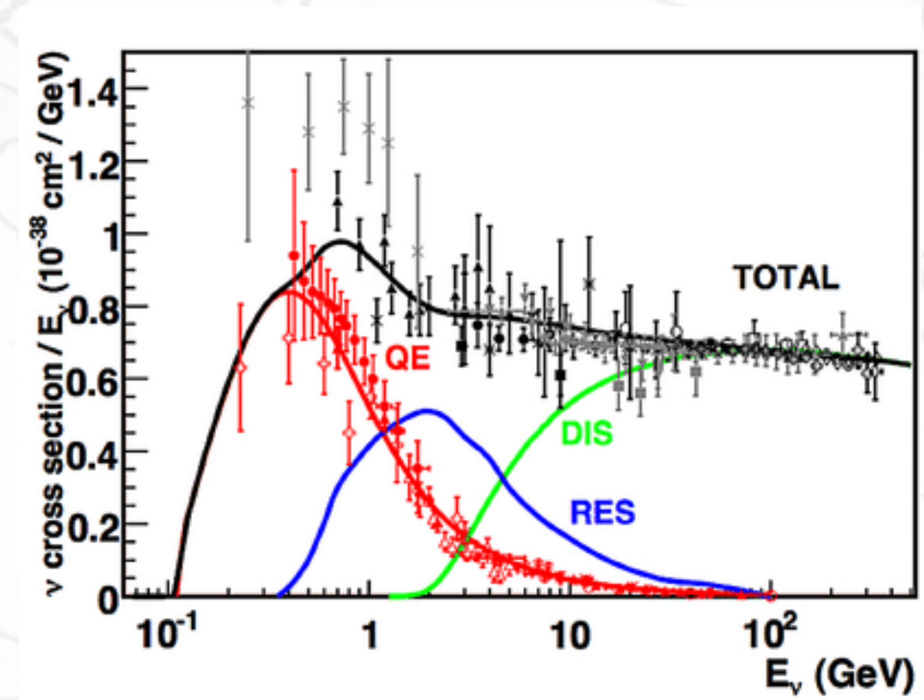
To some level all experiments do the same.

vA cross-sections

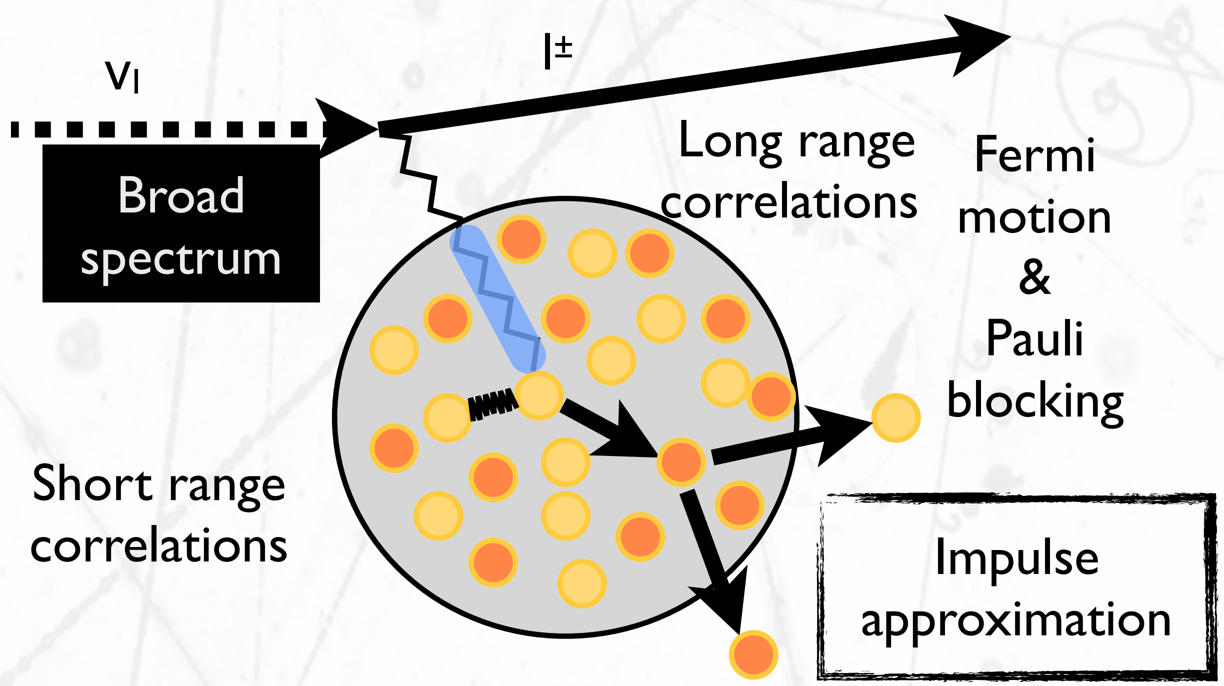
Describing $P_{far}(\vec{\theta}_{\nu}^{reco}|E_{\nu})$

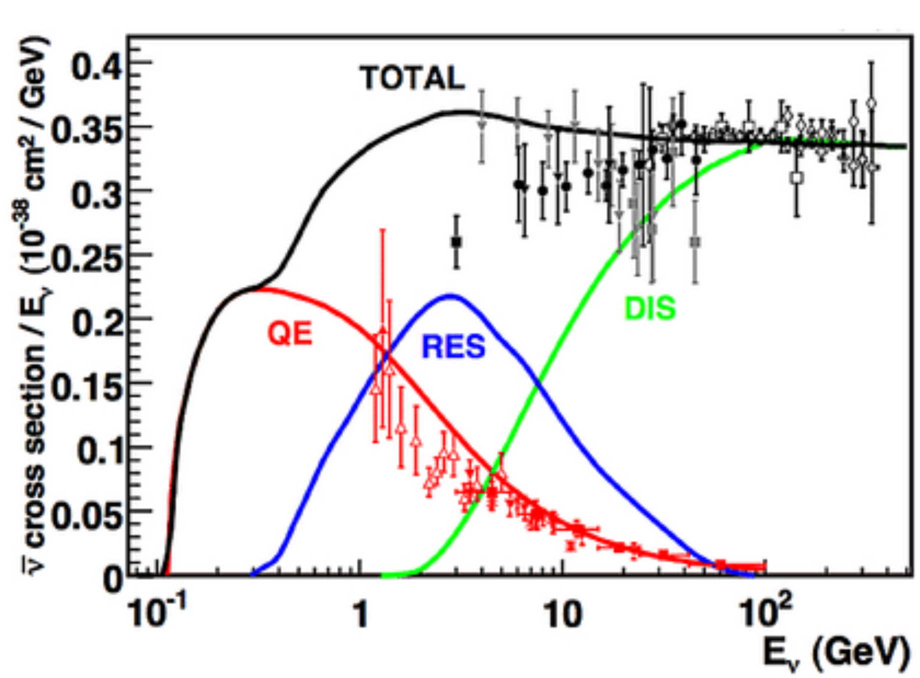
@ the nucleon level !

$CCQE$	$\nu_\mu n \to \mu^- p$
$CC1\pi$	$\nu_\mu p \to \mu^- \Delta^{++} \to \mu^- \pi^+ p$
	$\nu_\mu n \to \mu^- \Delta^{+} \to \mu^- \pi^+ n$
	$\nu_\mu n \to \mu^- \Delta^{+} \to \mu^- \pi^0 p$
$CCN\pi$	$\nu_\mu N \to \mu^- \Delta^{+,++} \to \mu^- N'\pi\pi...$
$CCDis$	$\nu_\mu N \to \mu^- N'\pi, \pi, ...$



@ the nucleus level !





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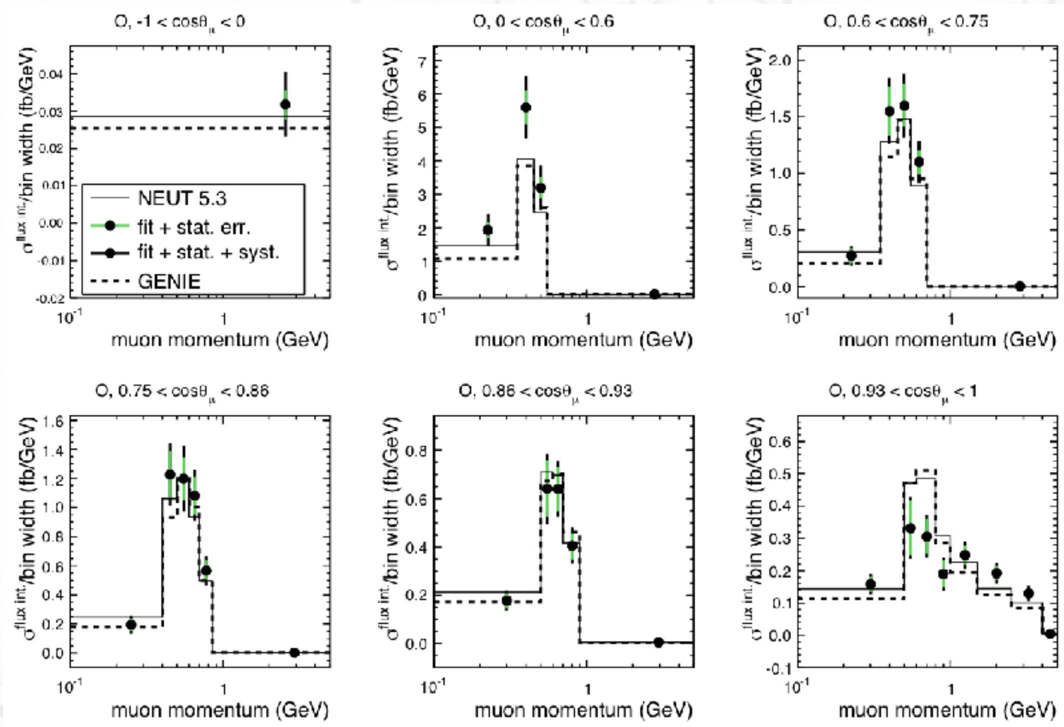
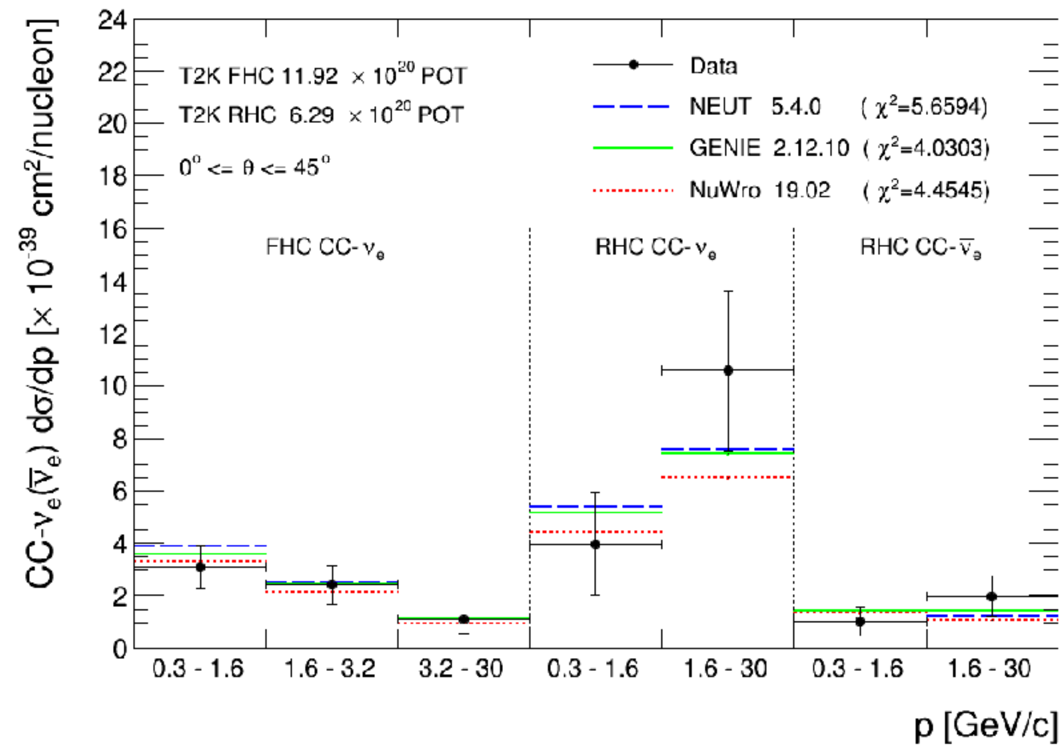
νA cross-sections

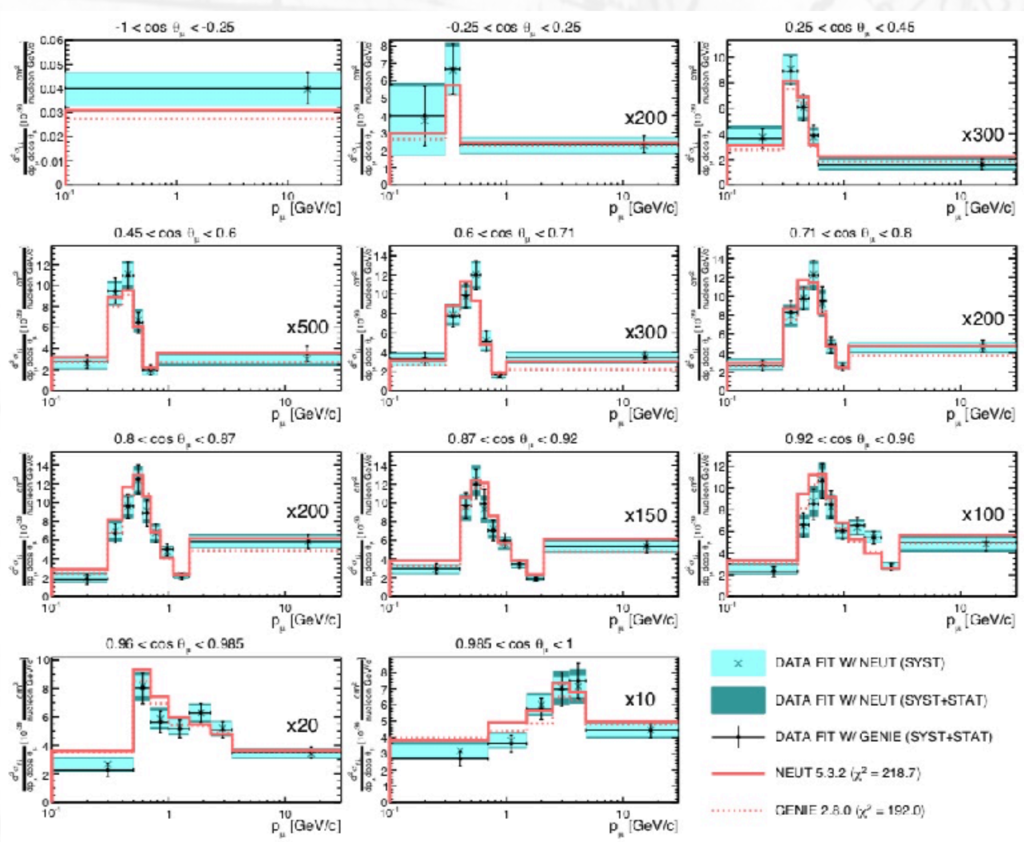
ν_μ CC0π on Oxygen



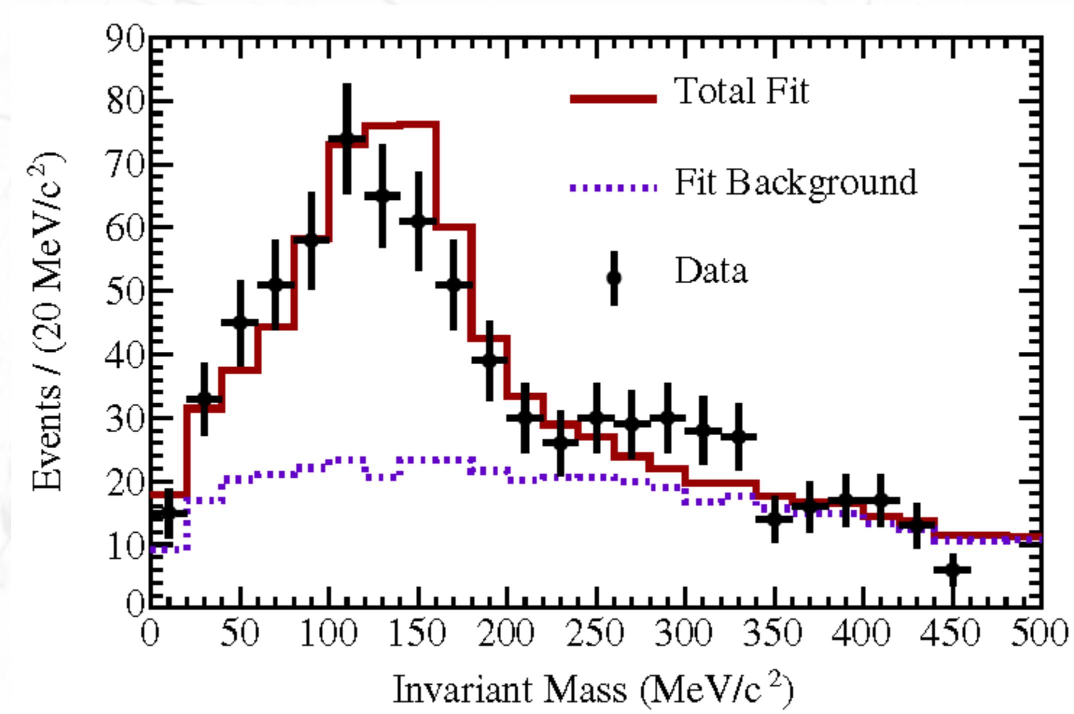
ν_e CC on Carbon



inclusive ν_μ CC on C

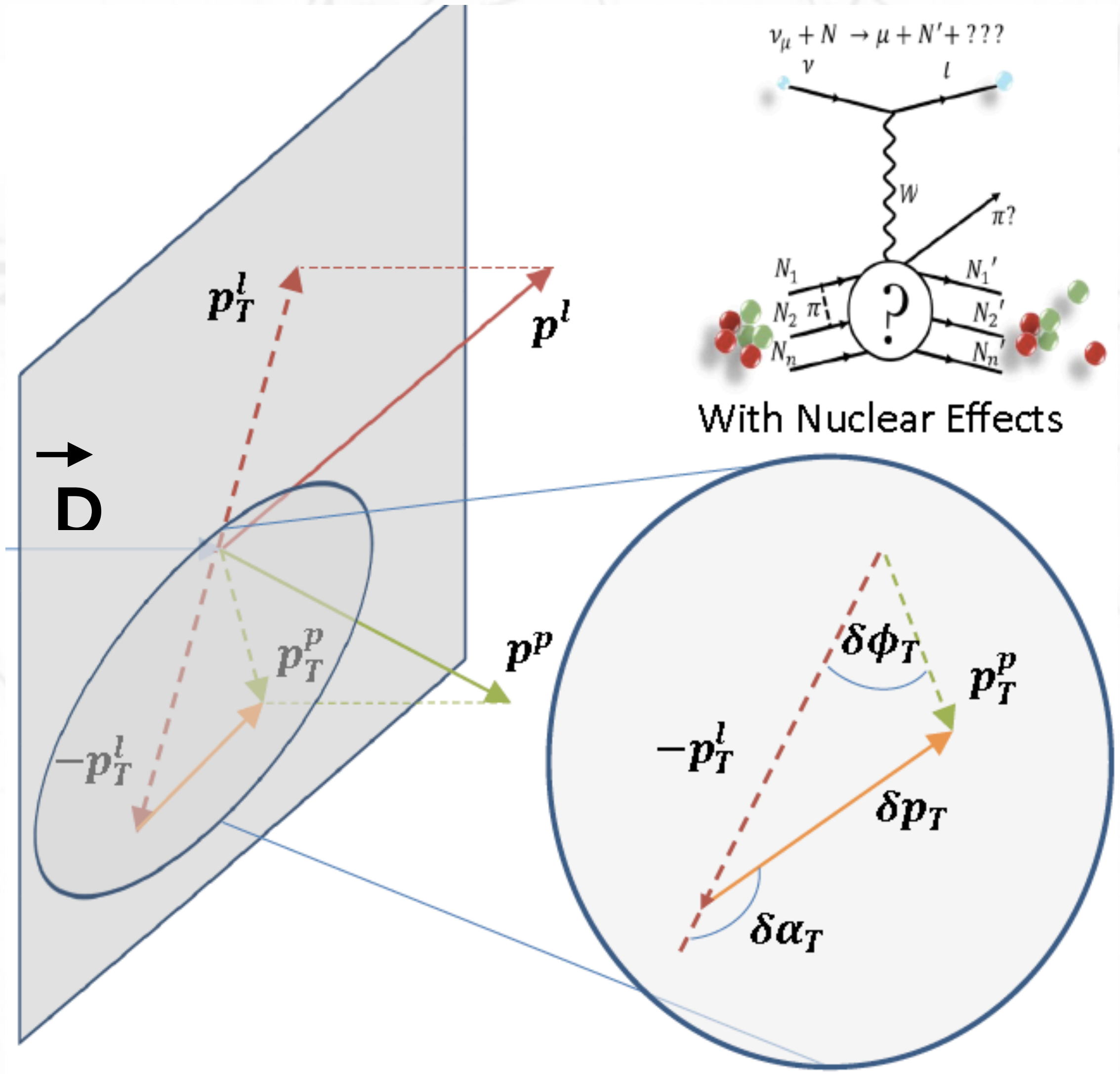


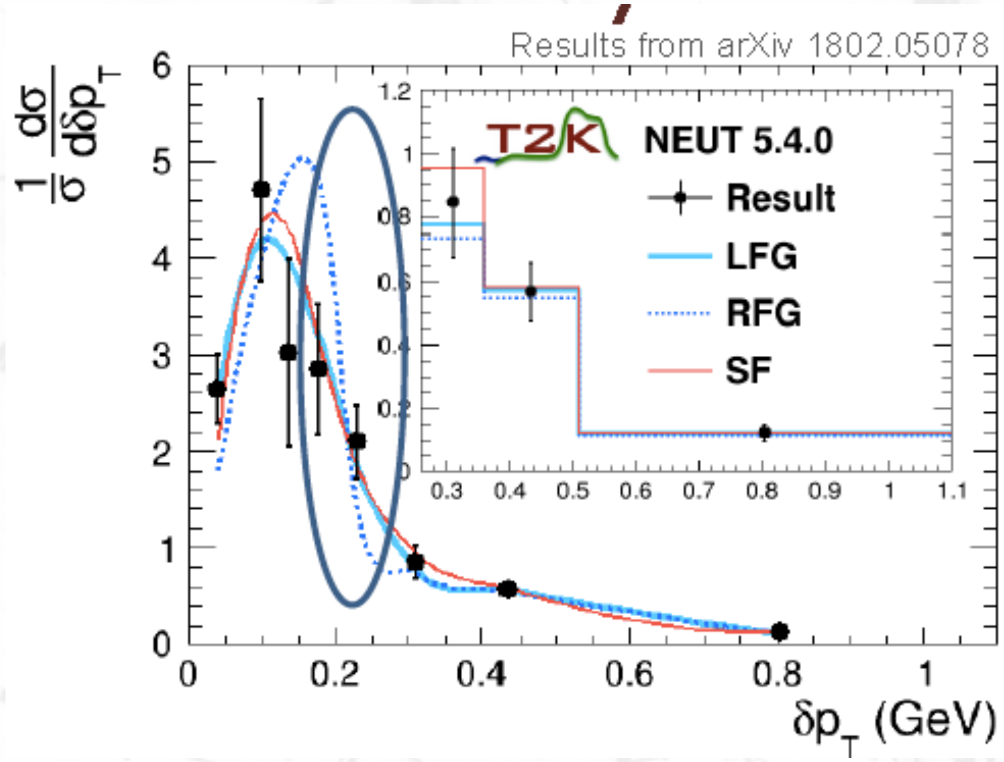
ν_μ NCπ^0 on Water

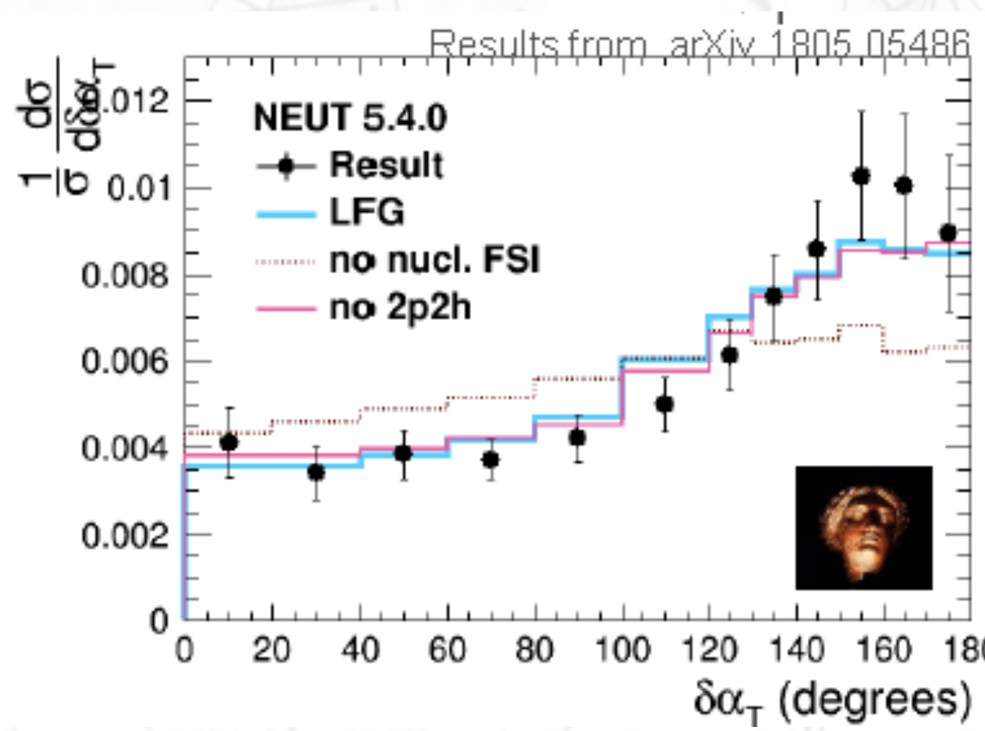


νA cross-sections

Low energy recoil proton allow us to measure transverse momentum imbalance to access nuclear effects: Fermi momentum and re-interactions.







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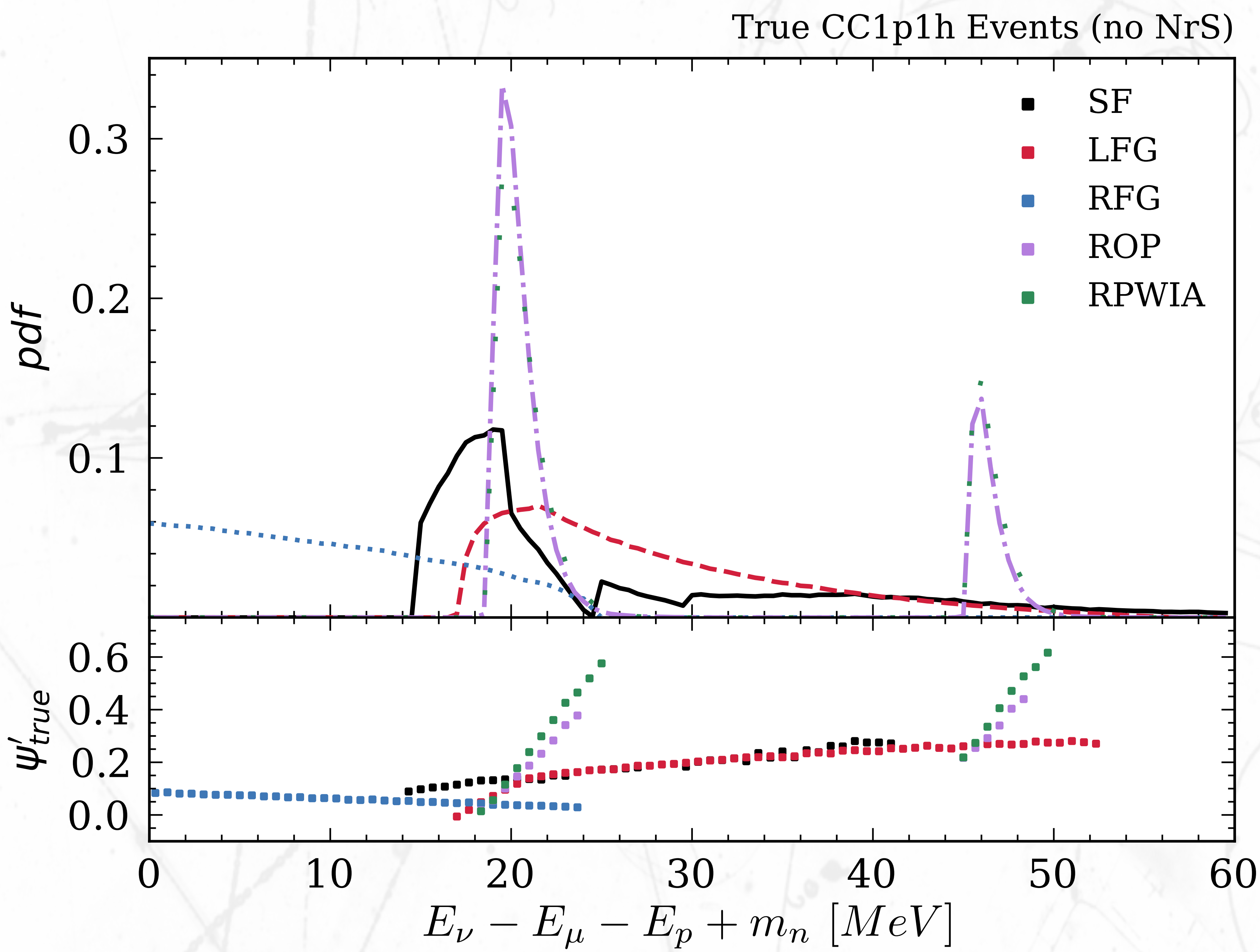
Example: removal energy

T2K



LFG and RFG are Fermi gas model

SF is a phenomenological model

ROP & RPWIA are Mean Field calculations

Energy required to allow for the reaction

$$\nu A \rightarrow \mu p A'$$

taking into account final state excitation levels

50 MeV is ~7% of the mean neutrino energy in T2K

νA cross-sections

Main issues

- Description of **the initial (and final) nuclear state**: energy reconstruction,…
- Determination of **vector and axial current form factors**: Q2 dependencies,…
- **Collective nuclear effects**: nuclear media polarisation, initial correlated pairs, 2 (and 3) body currents,…
- **Nuclear re-scattering:** nuclear transparency to pions and nucleons produced during the ν interactions.
- Also: nuclear mass dependencies, electron neutrinos, etc…

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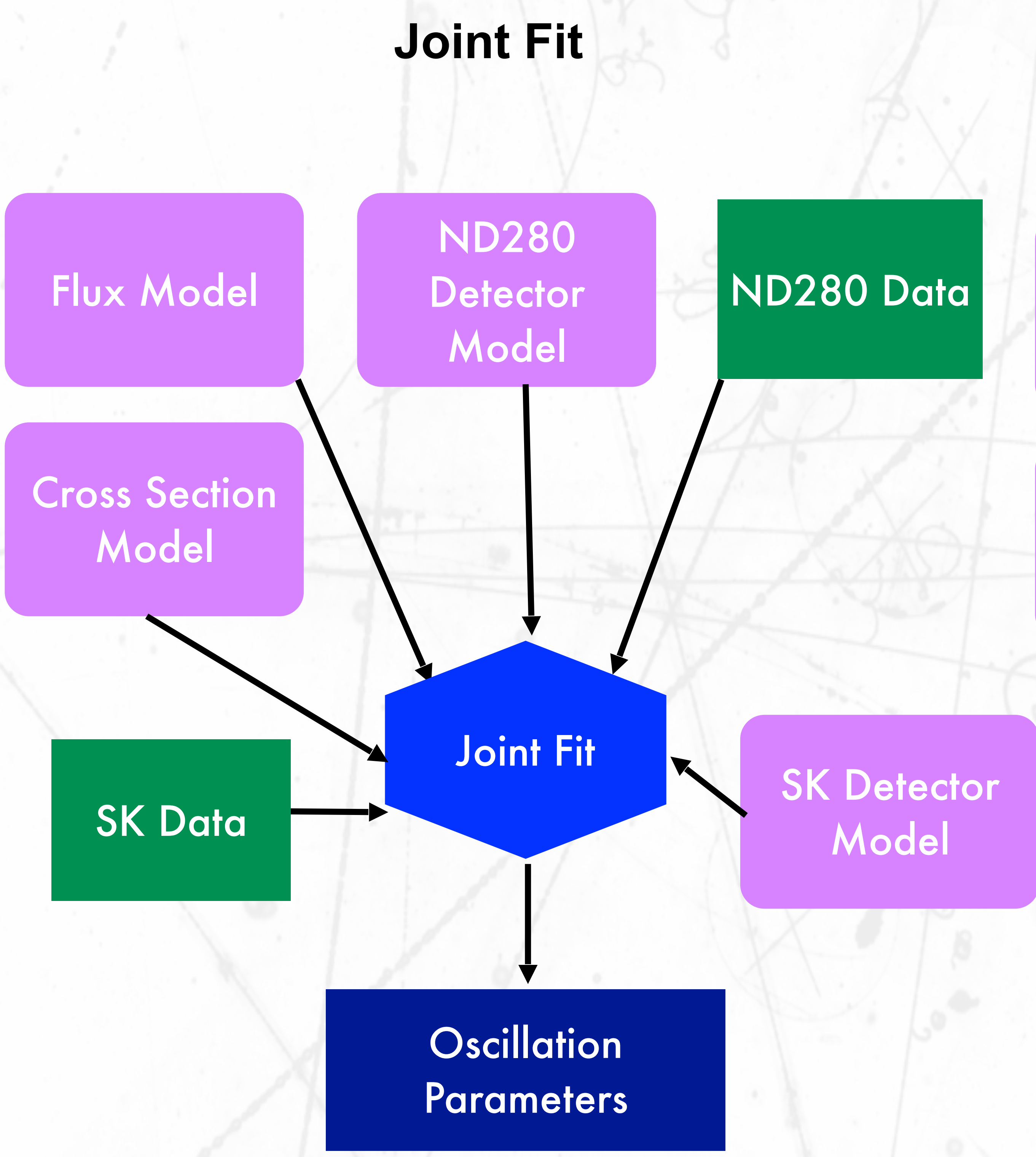
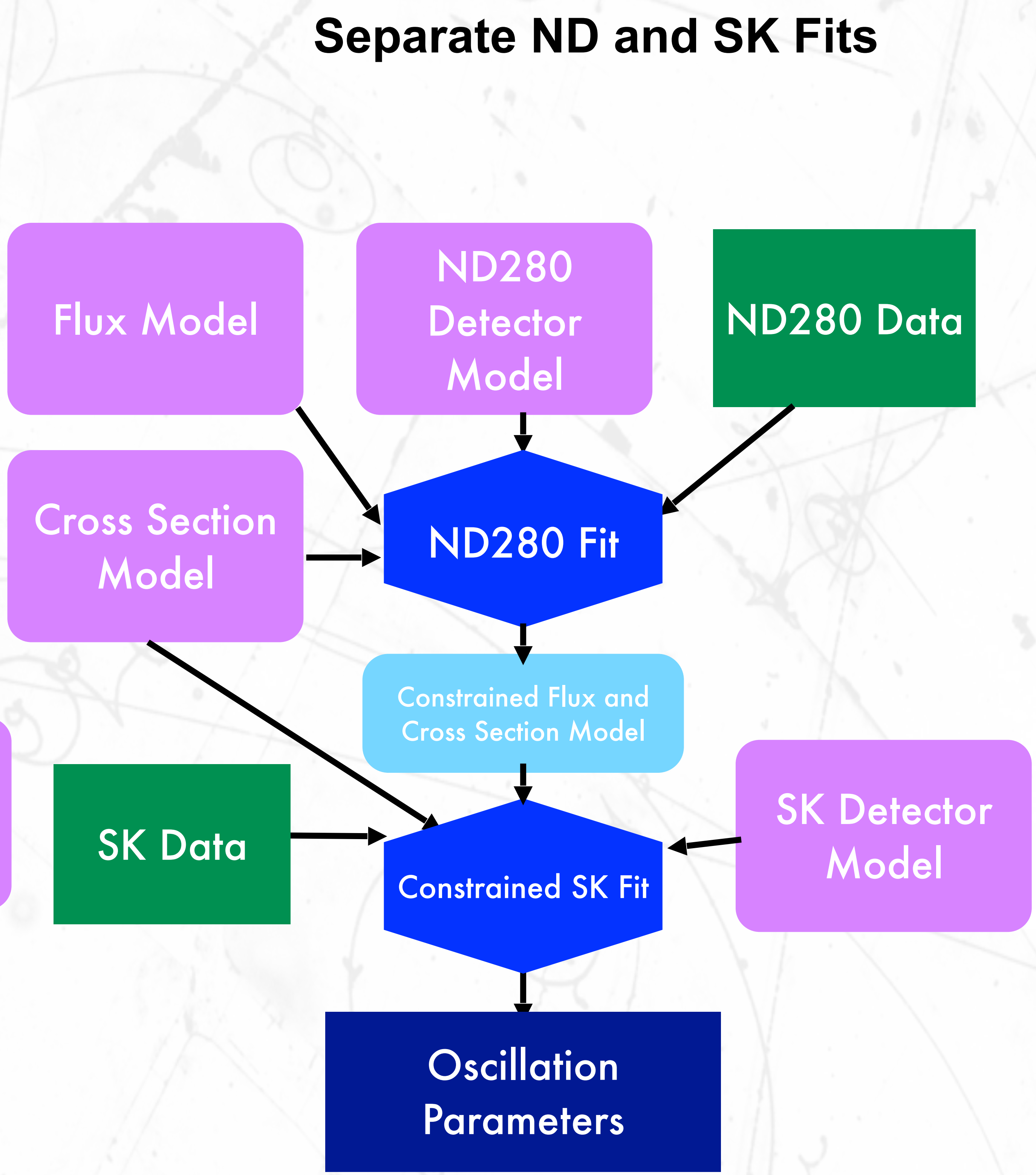
Analysis procedure

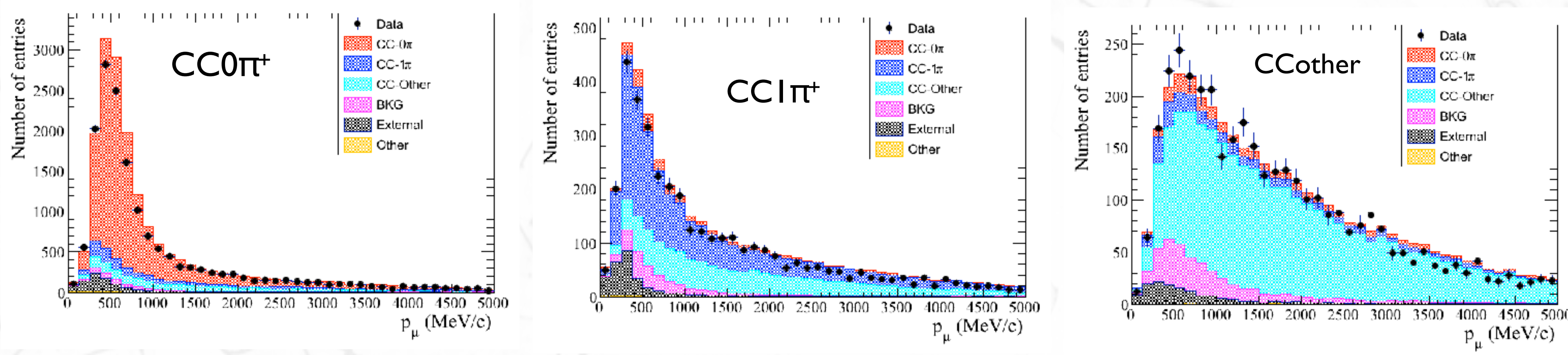
Statistical methods



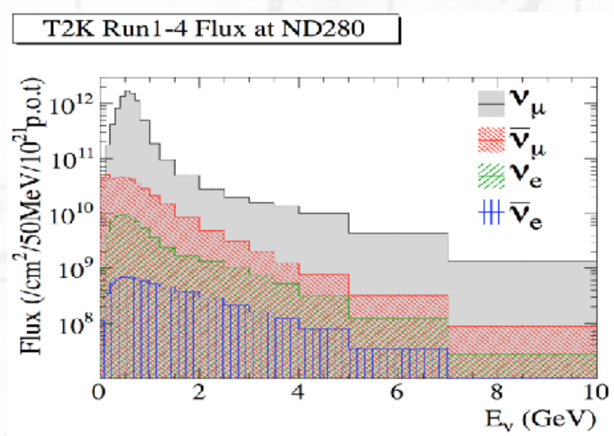


Less conceptually

Near detector data

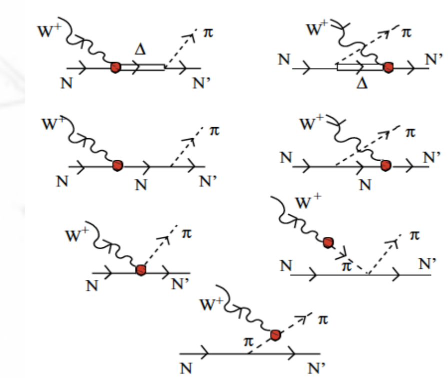


⊕ Hadron production flux prediction Shive + beam monitors

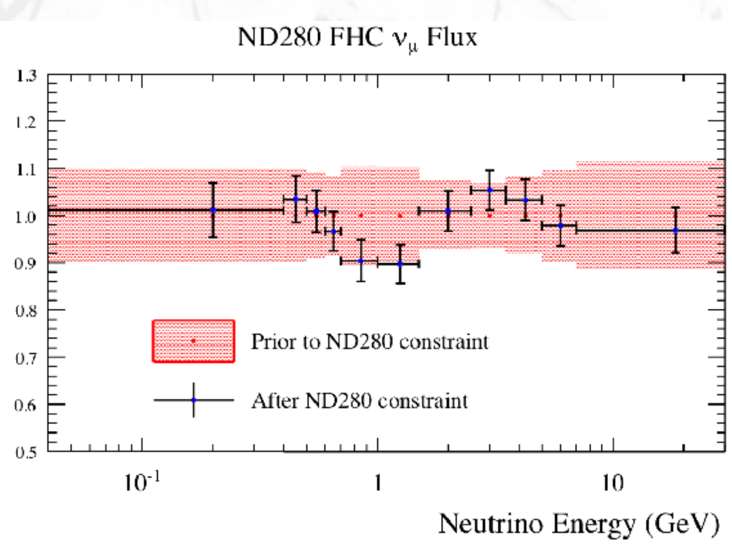


feed back

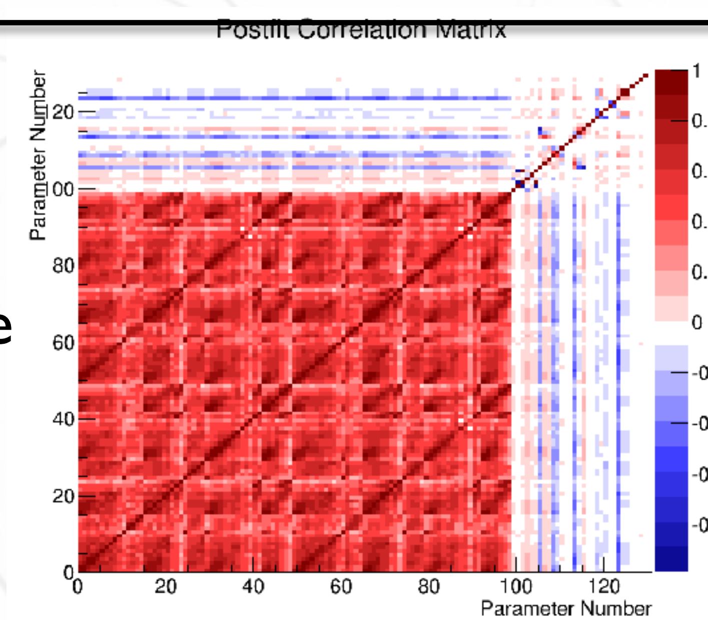
⊕ Cross-section model



= Corrected flux and cross-section model



& error covariance matrix



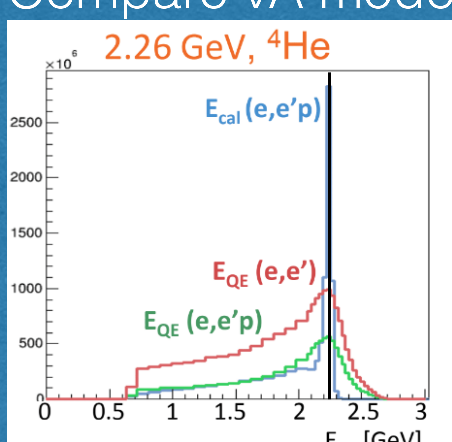
External support: We are not alone!

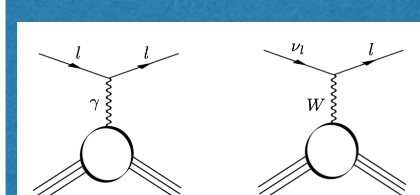
MINERvA

- Slightly higher energy.
- Independent neutrino flux.
- Large statistics.
- Similar target material.

e4V

- Use electron scattering data (electron energy is accurately known) to explore uncertainties in the neutrino energy reconstruction.
- Compare νA modela vs eA data.

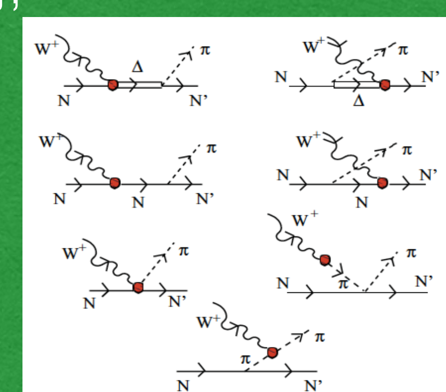


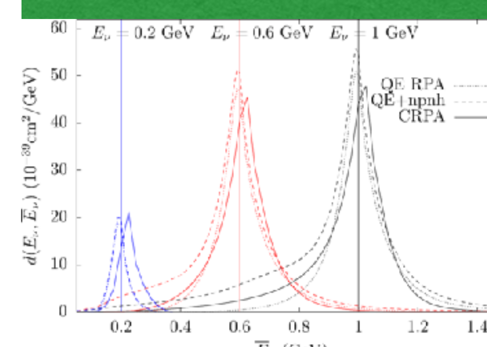


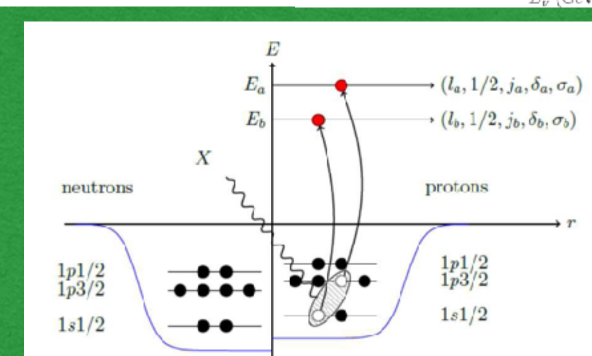
+ N61 !

Theory community (NUSTEC collab.)

- Local Fermi Gas models
- Spectral Functions.
- Mean Field Approximations.
- RPA, CRPA,…
- Pion production models.
- “ab initio” calculations.
- Microscopic 2p2h models.
- ν_μ vs ν_e
- Connection νA vs eA
- ,,,,





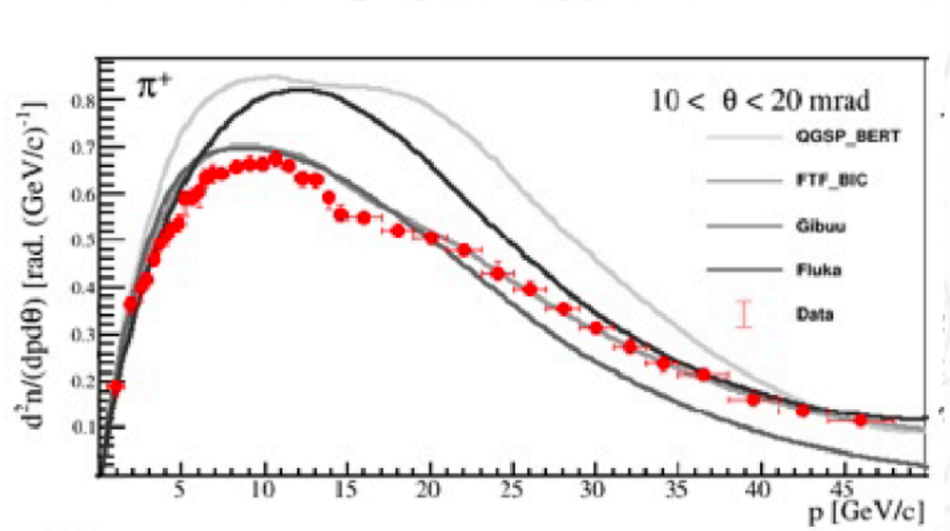


T2K results

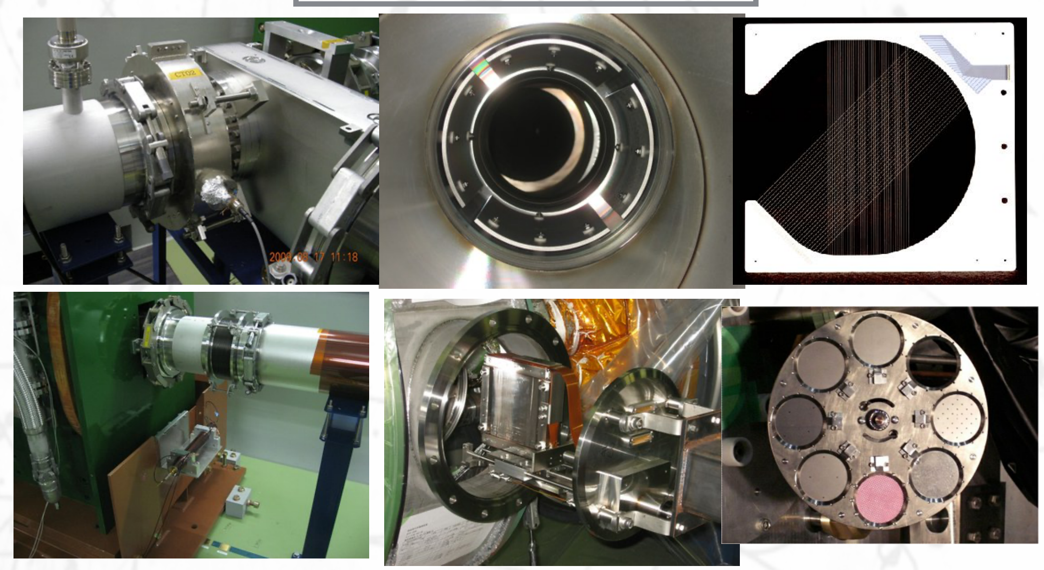
Beam model

Beam model is obtained from a full GEANT simulation of the particle transport reweighed by the NA61 results

Input

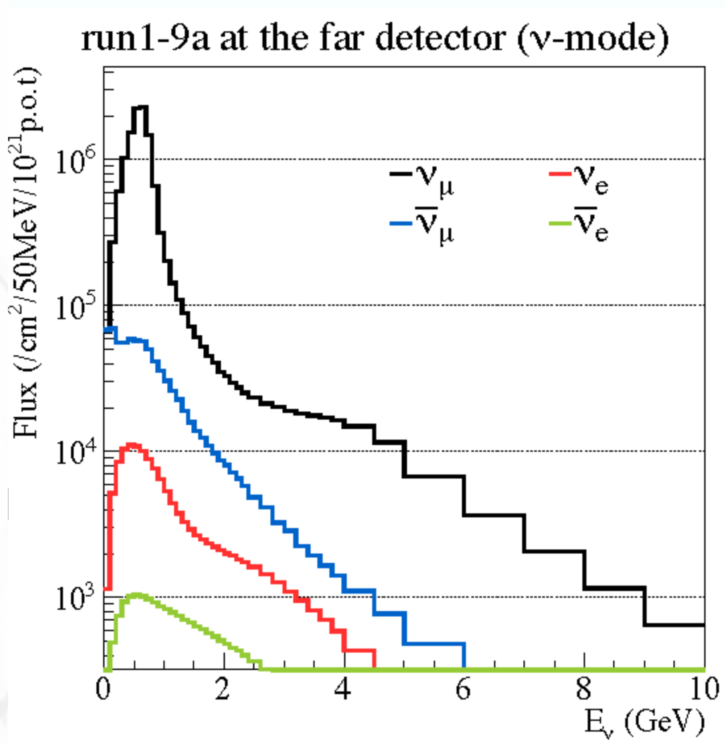


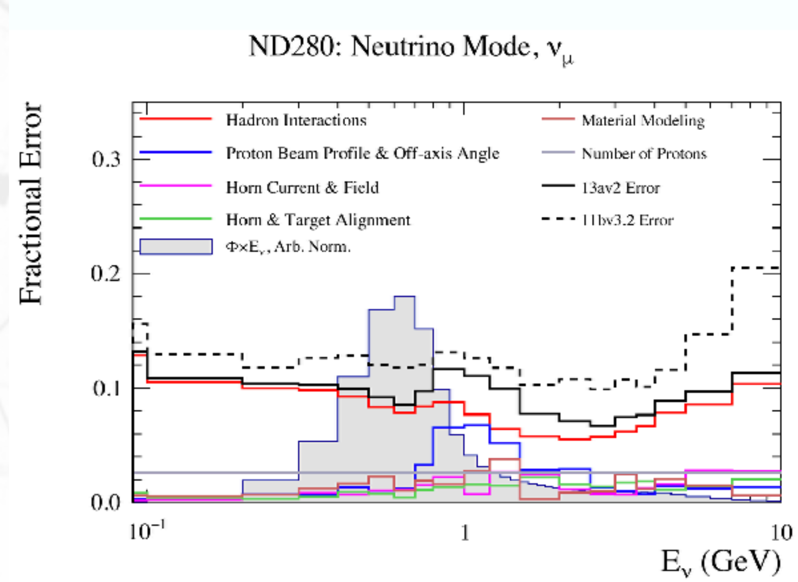
Beam monitors

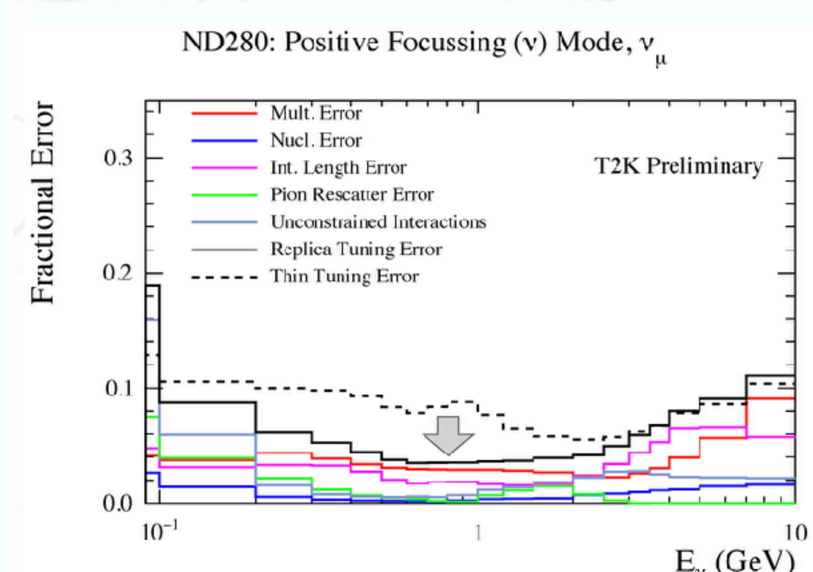


GEANT 3

Output

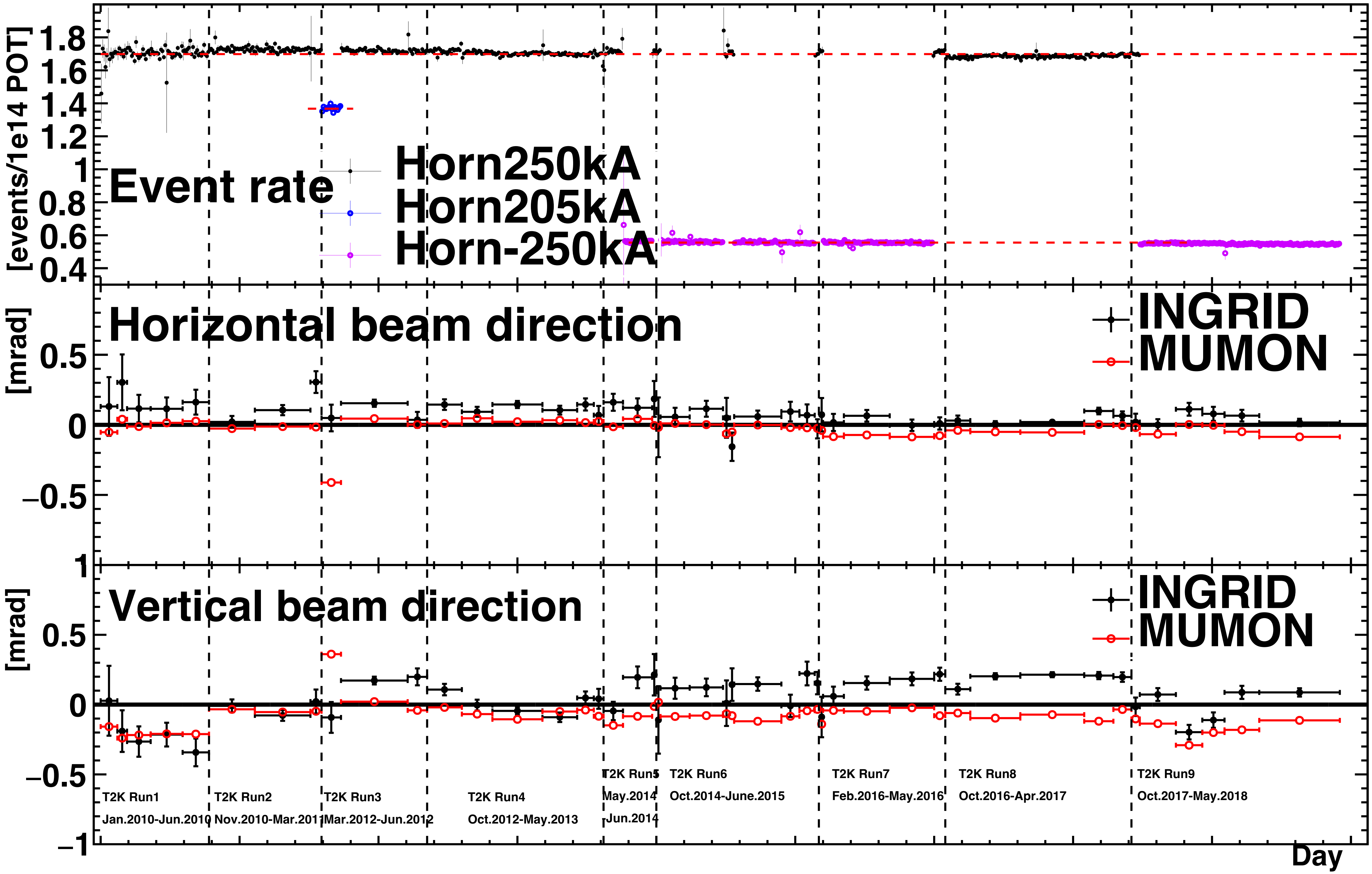






Including error covariance matrix

Beam stability



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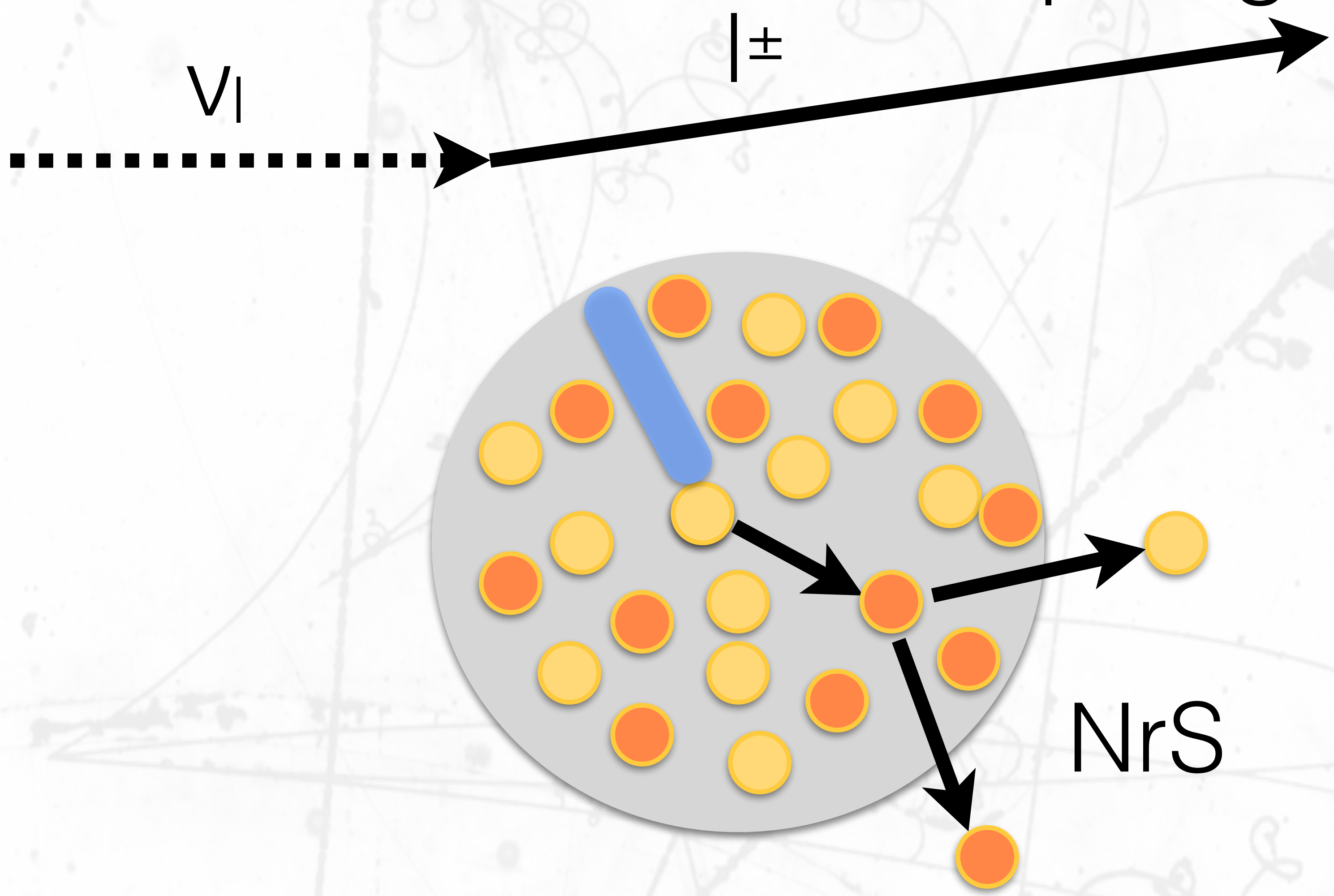
Near detector data: "topologies"



T2K categorise events based on the visible particles after Nuclear re-scattering.

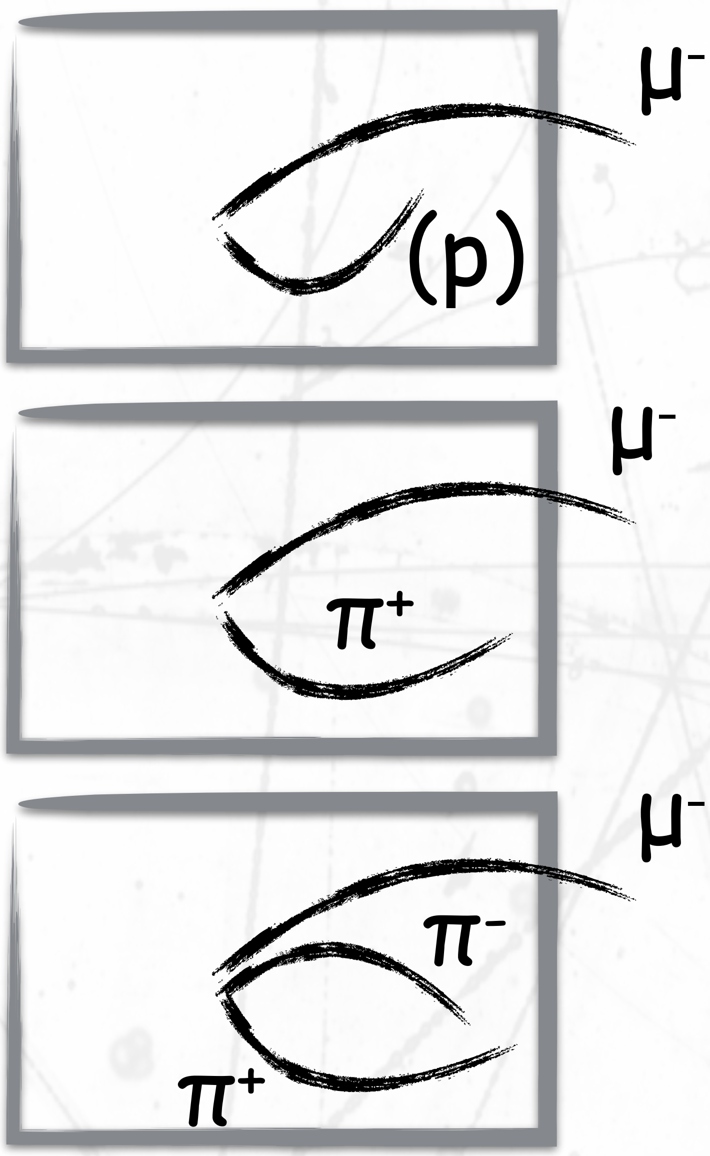
protons and neutrons are not visible and have little selection power.

Topology		ν-nucleon
No pions	→	CC1p1h+CC2p2h
One pion	→	CCResonant
Many pions & π^0	→	CCDIS

Strategy!
focus on pion detection

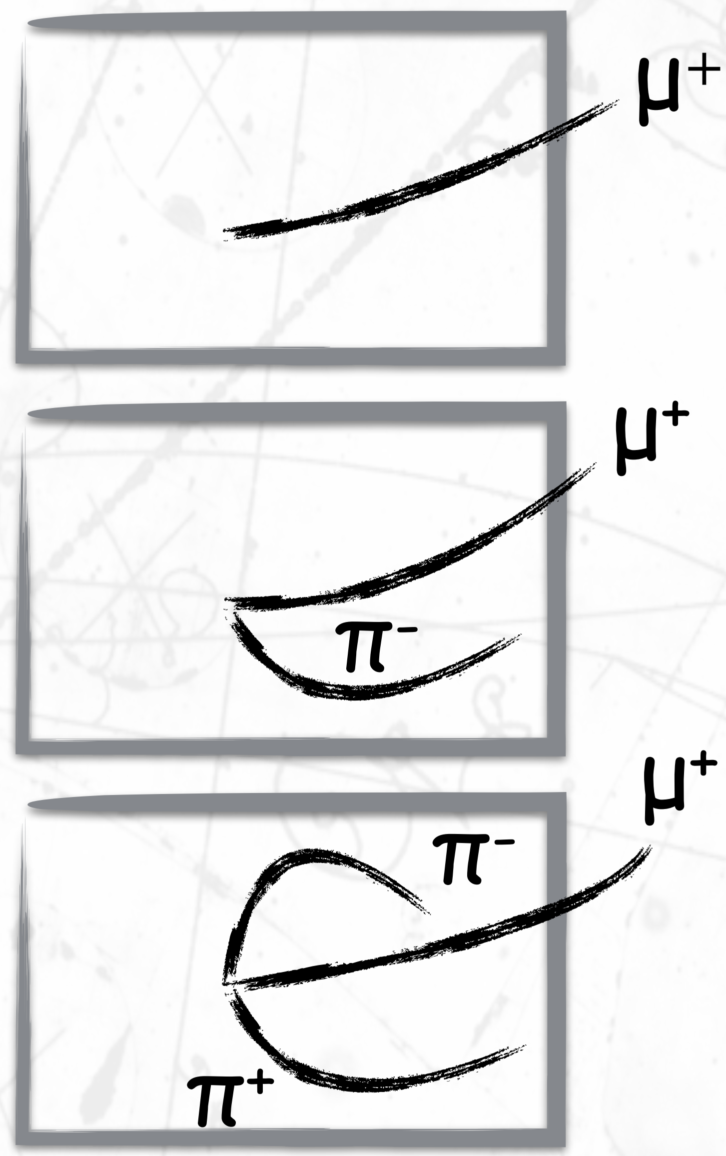
Near detector data

Forward Horn Current (FHC)

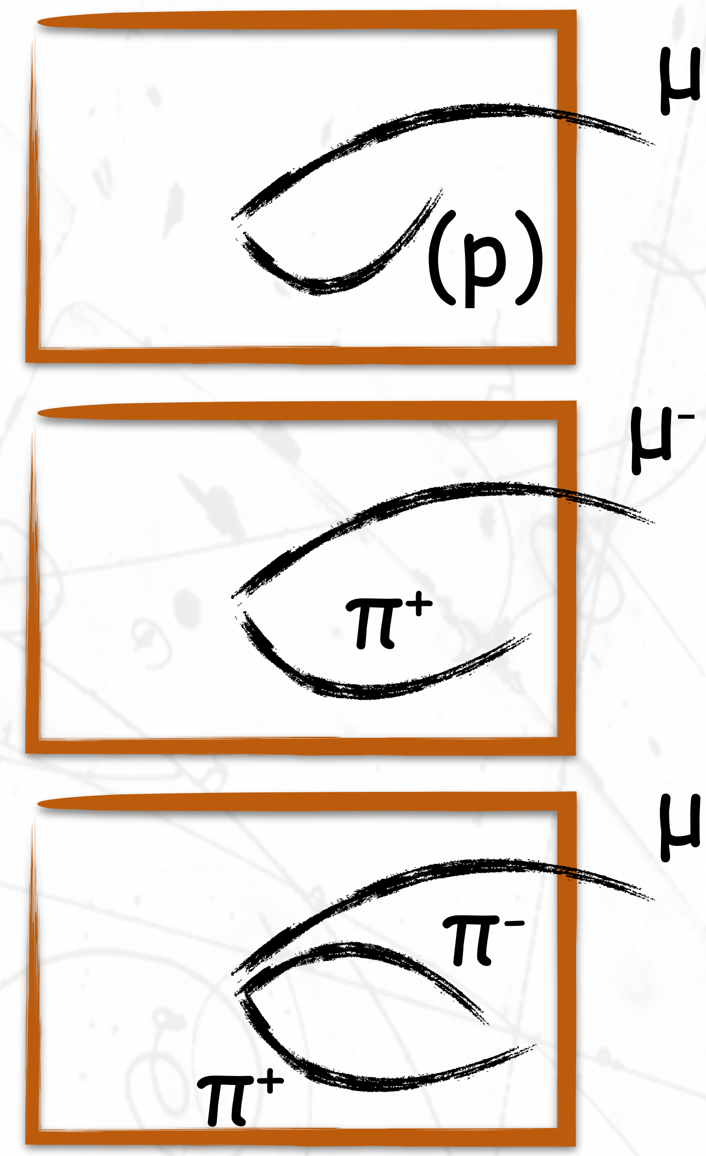


ν sample

Reversed Horn Current (FHC)



$\bar{\nu}$ sample



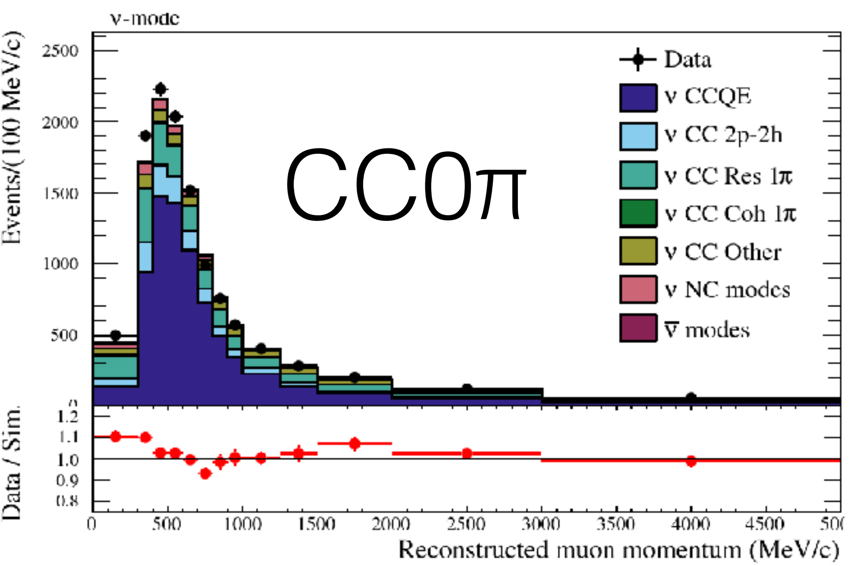
ν sample

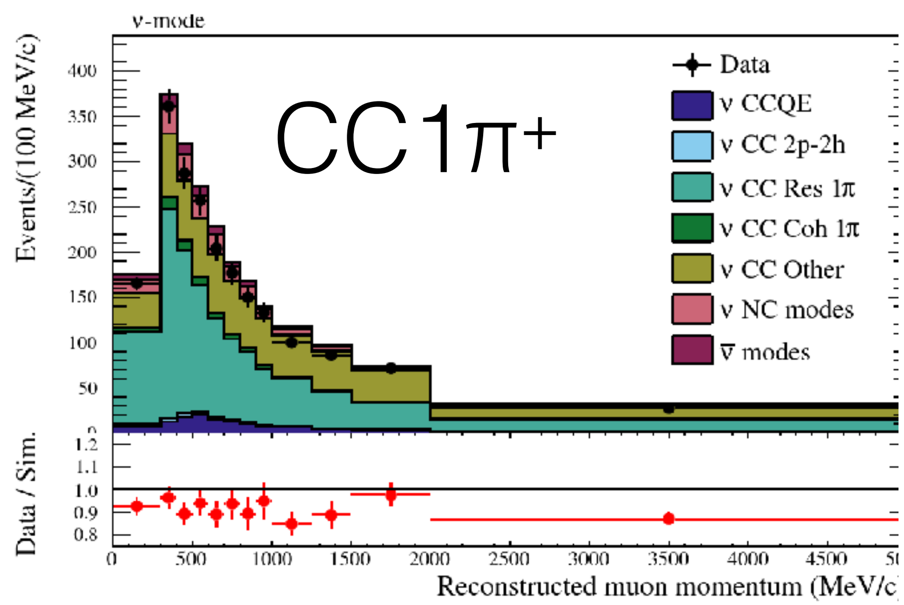
All are duplicated in FGD1 (pure CH) and FGD2 (CH+O)

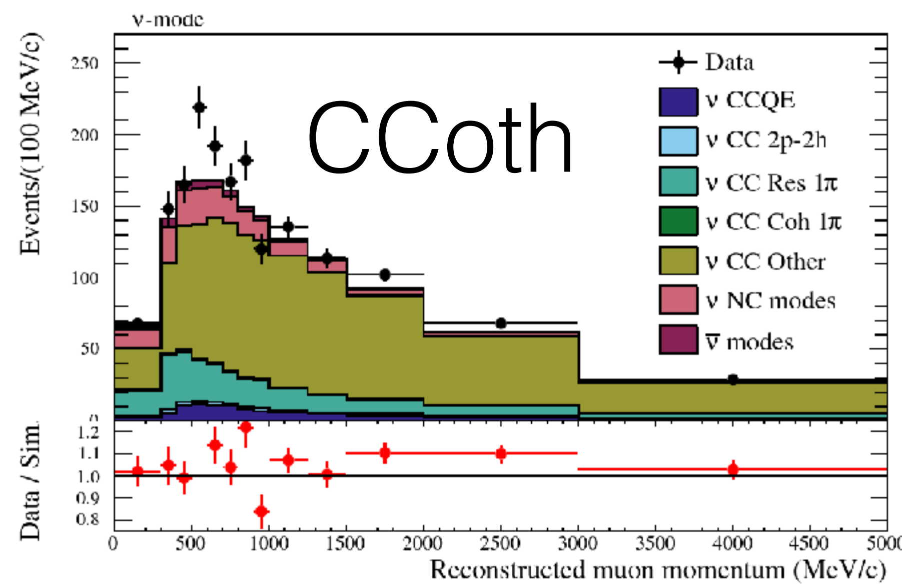
ND input samples

Forward Horn Current

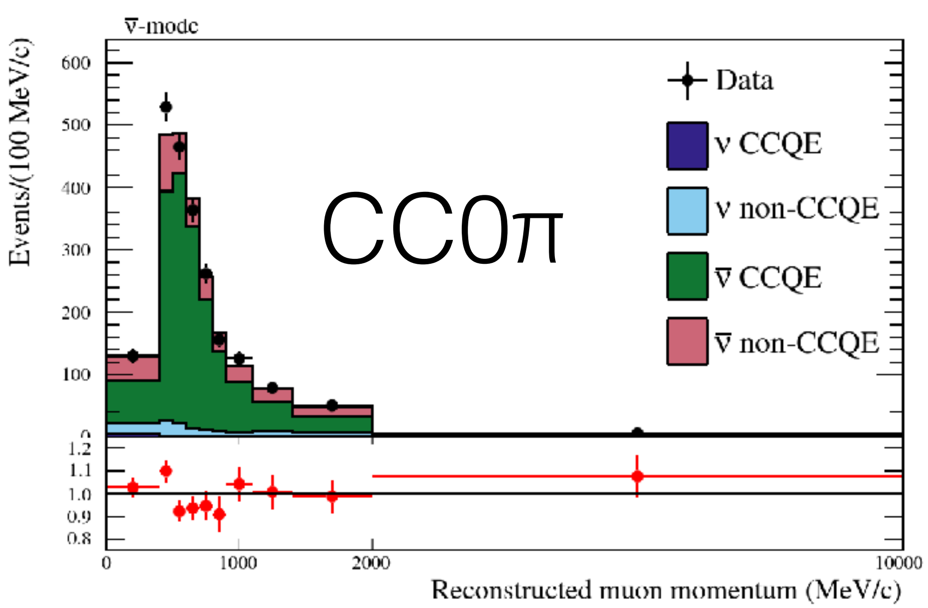
We use 18 different samples (based on topology) in (p_μ, cos θ_μ)



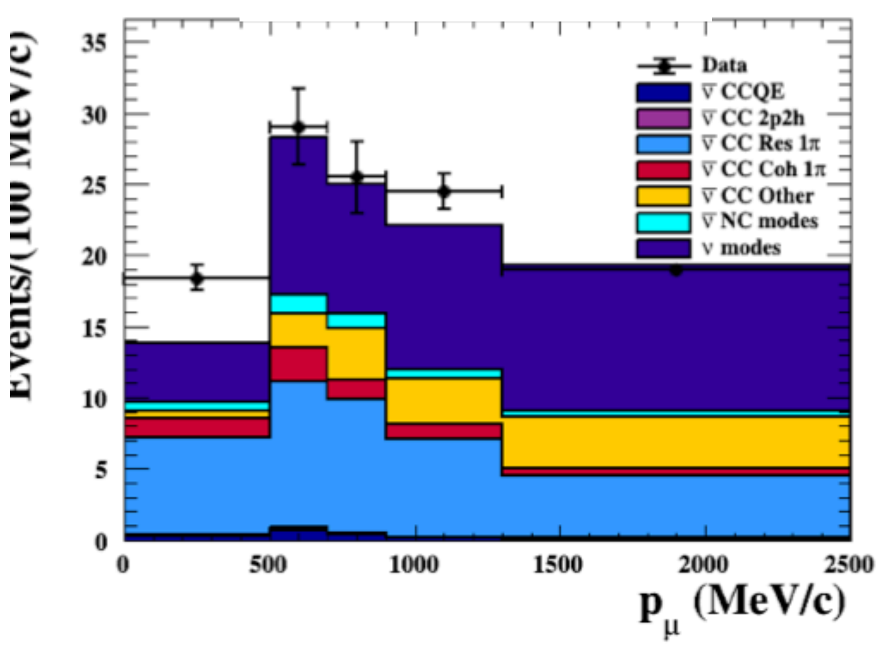




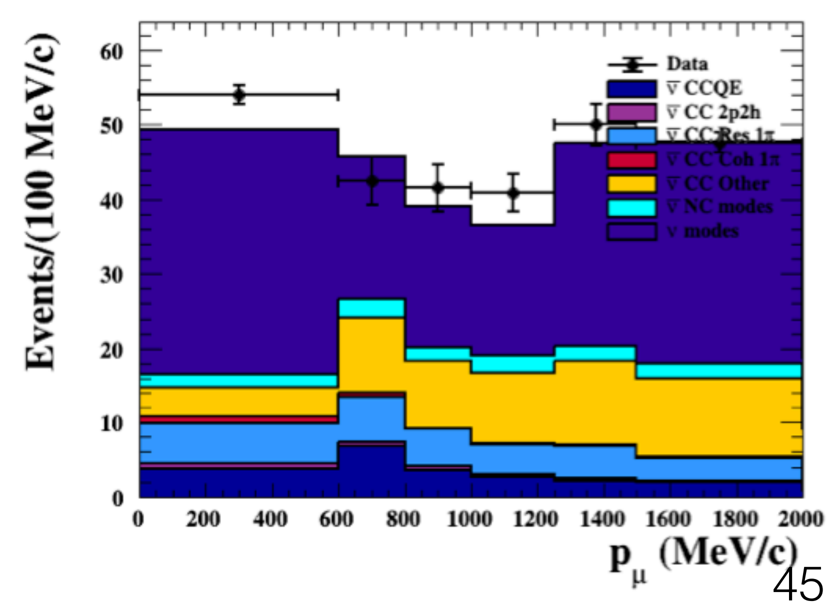
Reversed Horn Current



CC1π+



CCOth



Neutrino Interaction Working Group (NIWG)

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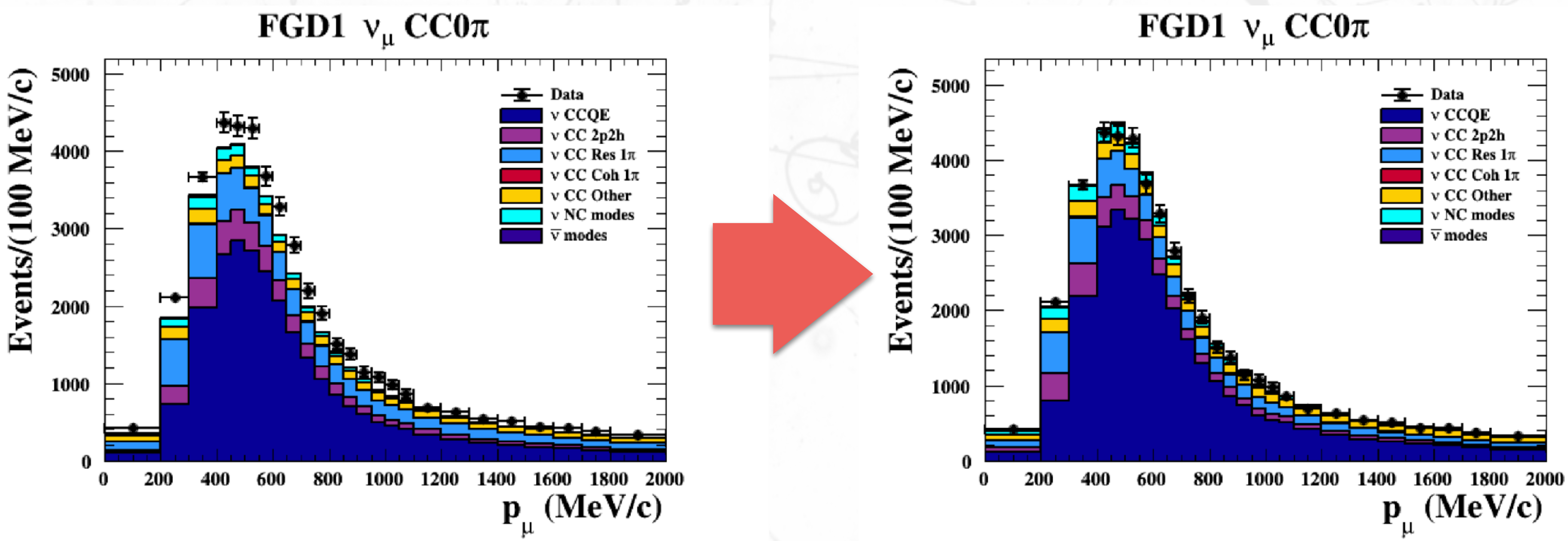
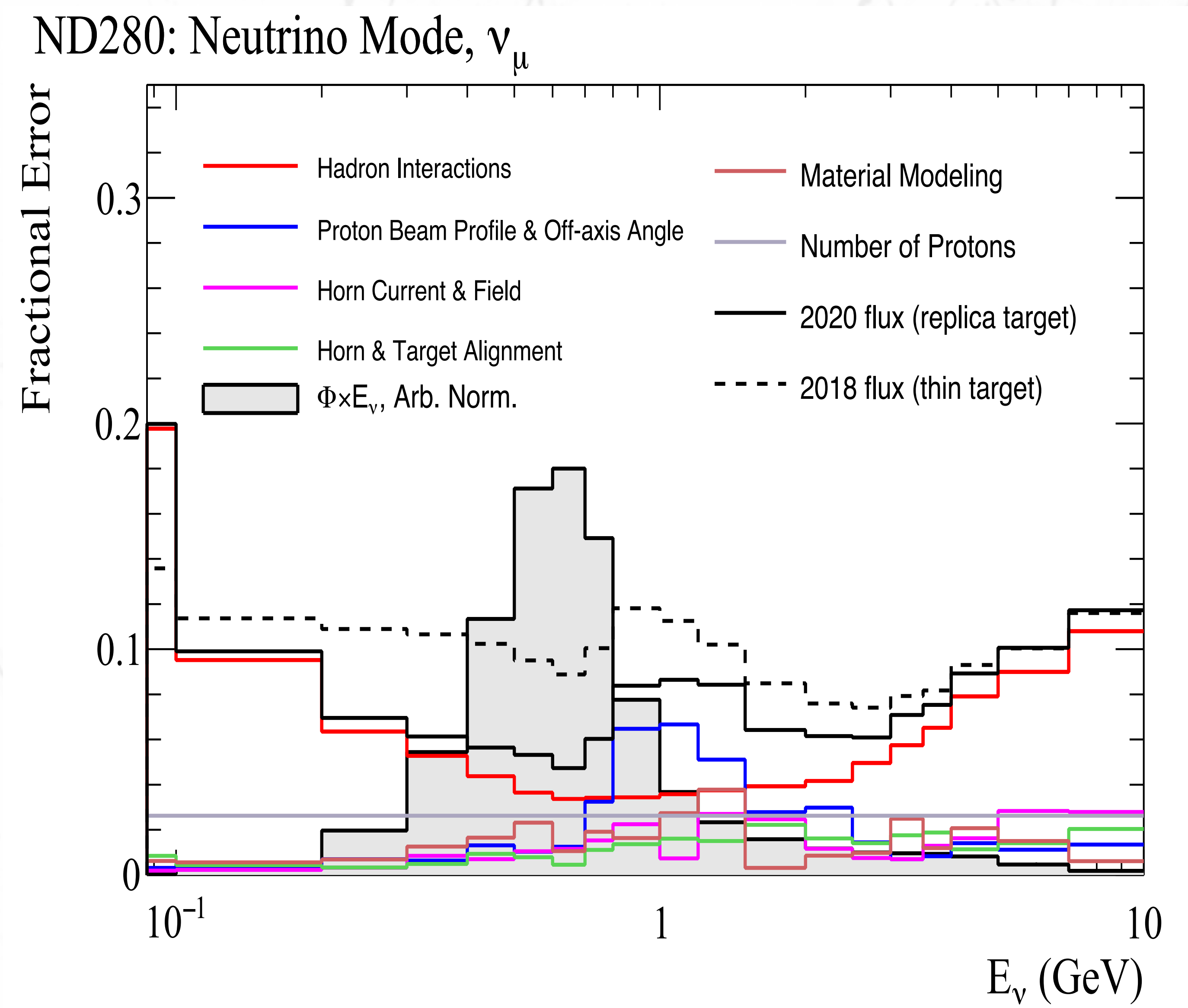
- Add physical degrees of freedom to the cross-section models.
- Be sure the degrees of freedom fits/agrees with available data.
- Be sure we provide enough freedom for the model to adapt to the experimental results.
- Check the physics validity and interpret them.



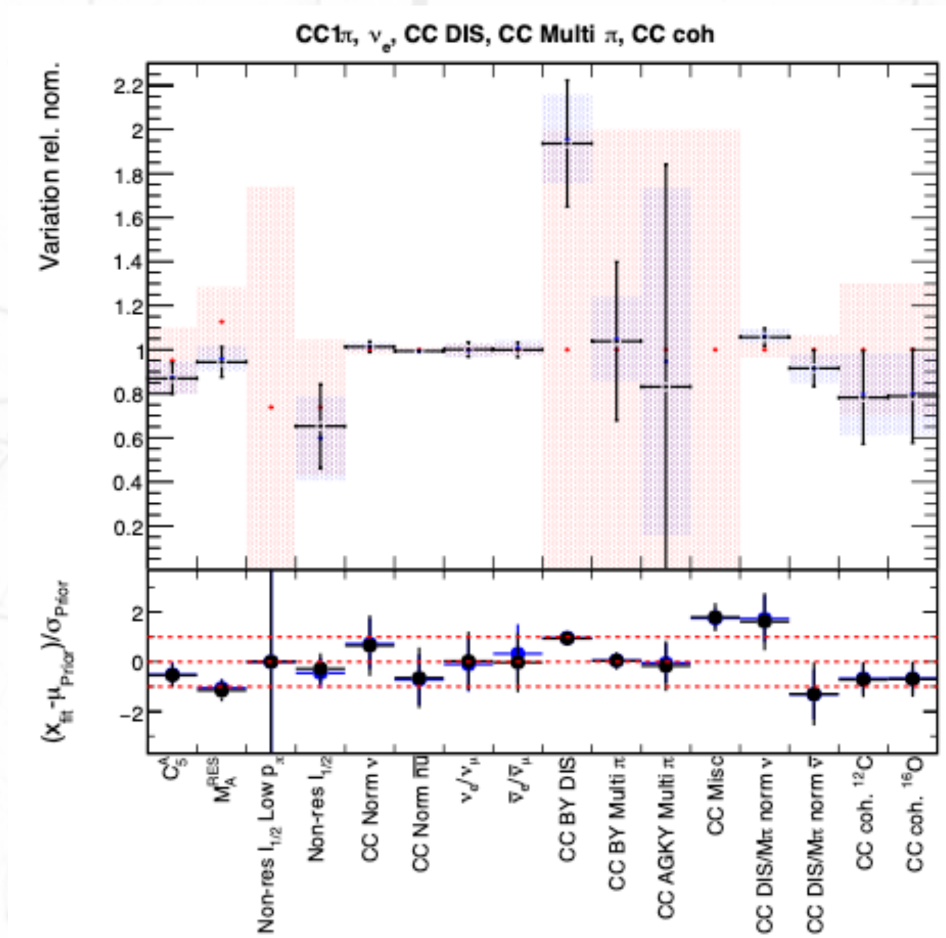
Global-fit p value = 74%

Examples of ND fits

Flux parameters

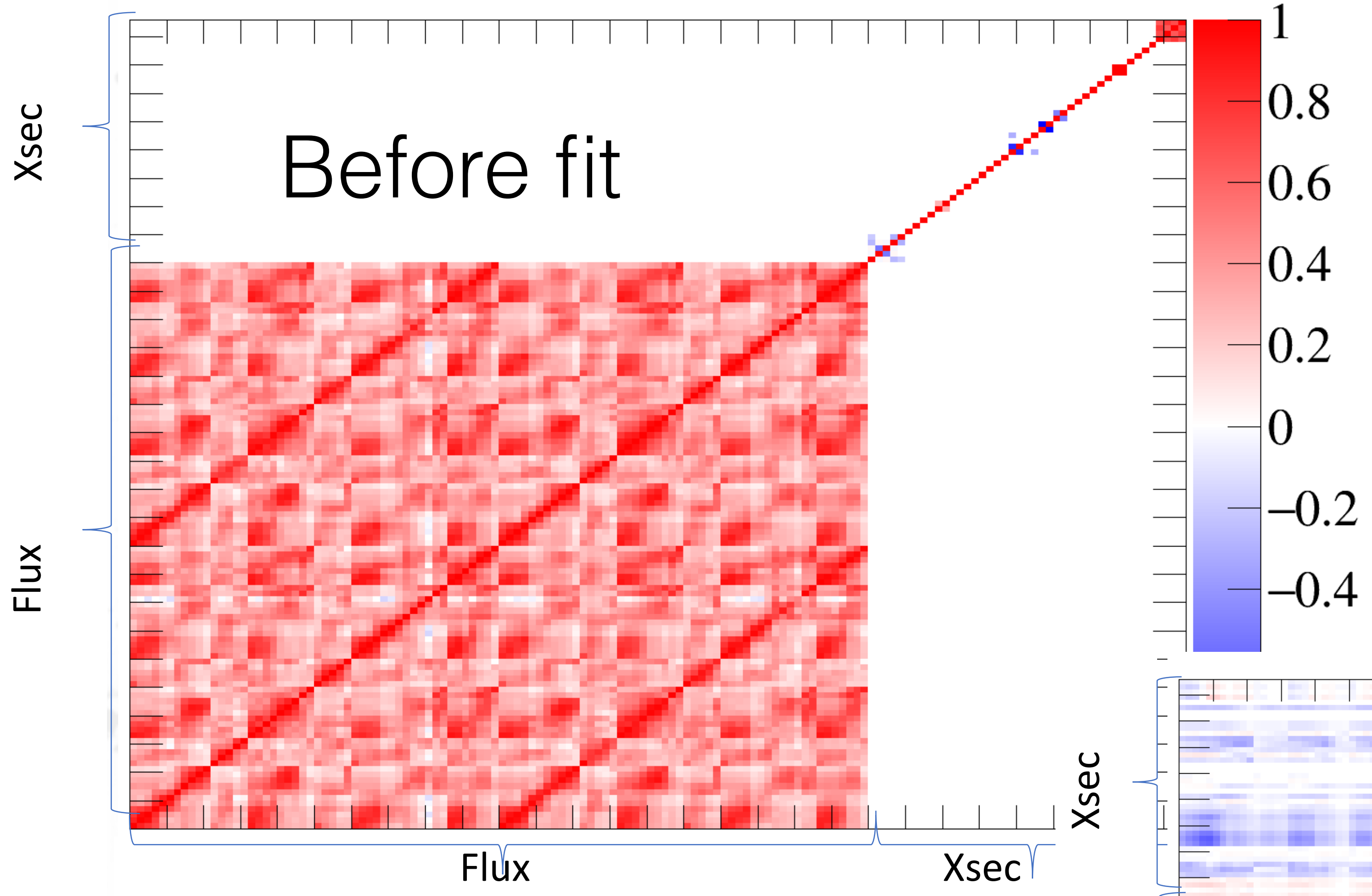


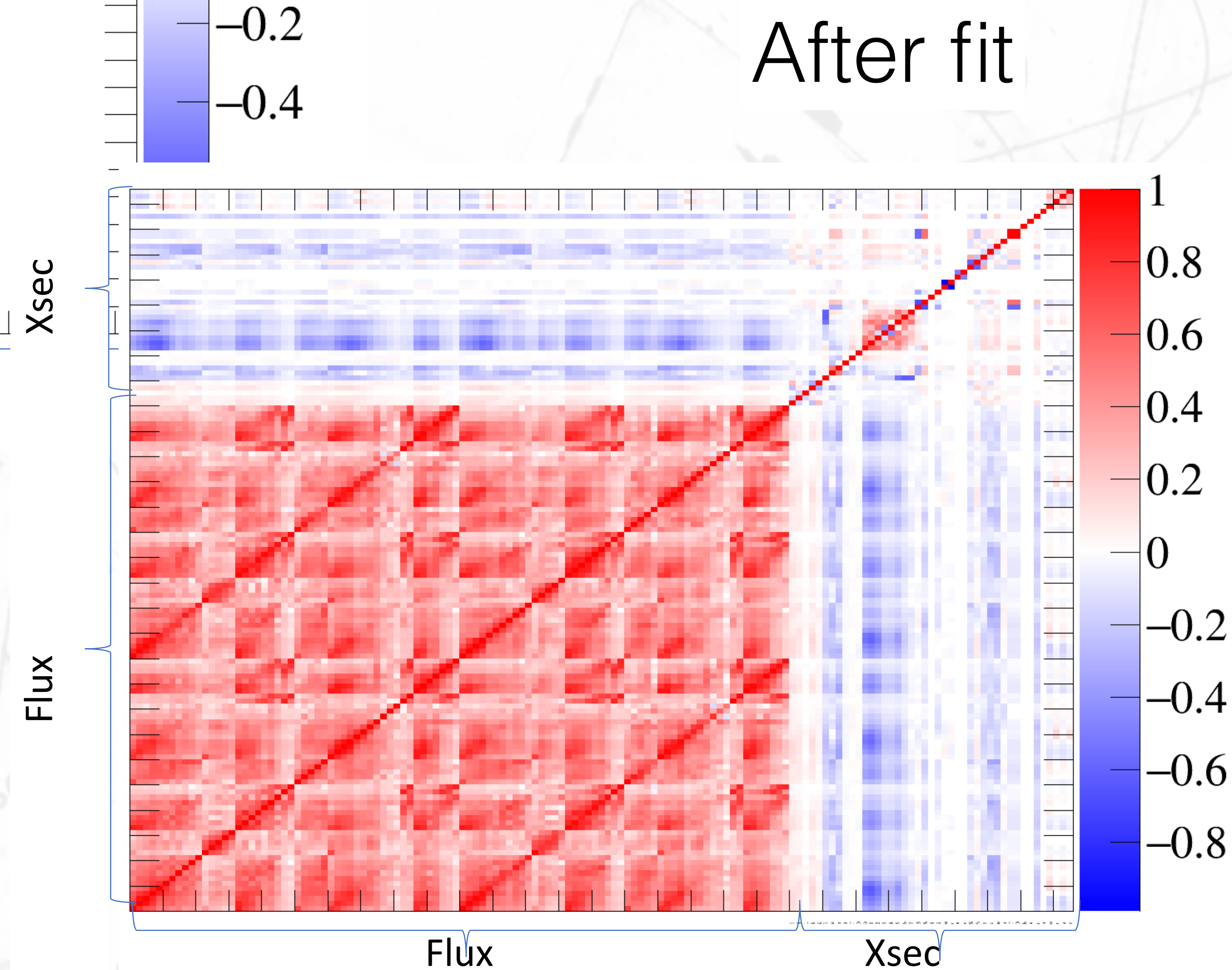
X-section parameters



Results do not deviate from priors.

Correlation matrix





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Before going on!

T2K

model dependent extraction

- To optimise available ν statistics**, T2K does not properly measure CP violation.**

  - **T2K takes the PNMS paradigm and adjust the CP phase** to the results (also CP conserving cos(δ) plays a role):

    - using a model helps to extract more accurate information from the data.

    - Most of the sensitivity comes from the comparison of the **ν_e appearance (θ_{13},δ_{CP})** with the reactor **$\bar{\nu}_e$ disappearance (θ_{13}).**

- In the future the **comparison ν_e and $\bar{\nu}_e$** will be used alone to **determine the CP.**

Caveat

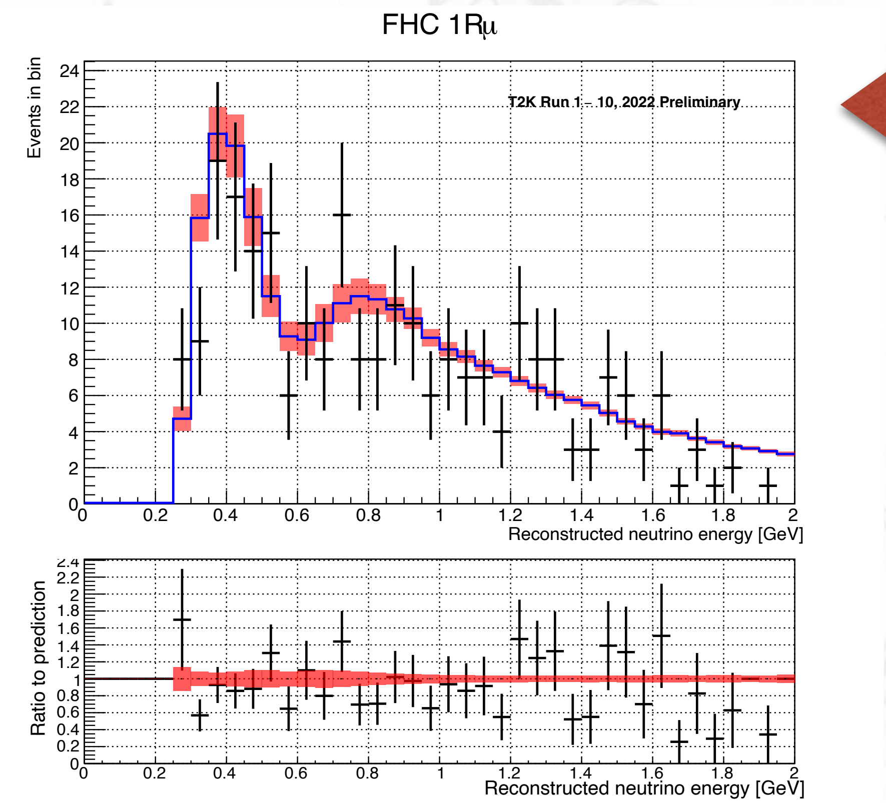
- Even if we use (p_μ,θ_μ) templates for the fit, the representation of the data is done using the reconstructed neutrino energy assuming:
  - 2-2 body reaction CCQE: ν n —> μ p reaction.
  - with target neutron (n) at rest.

$$E_\nu^{rec} = \frac{1}{2}\frac{m_\mu^2 + (m_n^{eff})^2 - m_p^2 - 2E_\mu m_n^{eff}}{E_\mu - |\vec{p_\mu}|\cos\theta_\mu - m_n^{eff}}$$

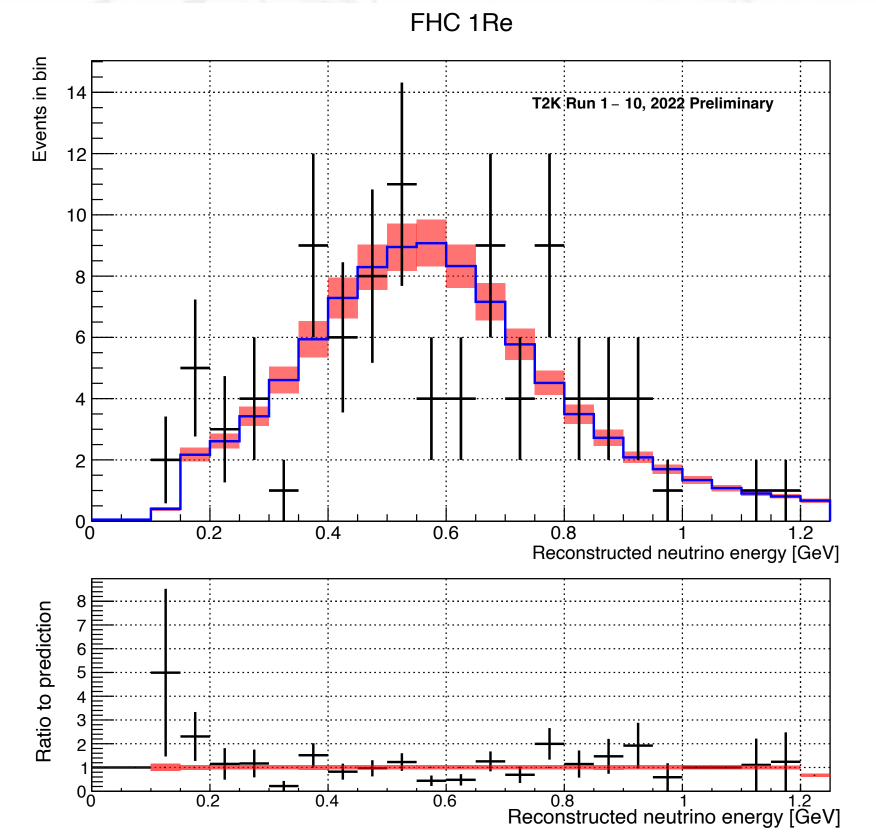
$$m_n^{eff} = m_n - E_b$$

Forward Horn Current SK data

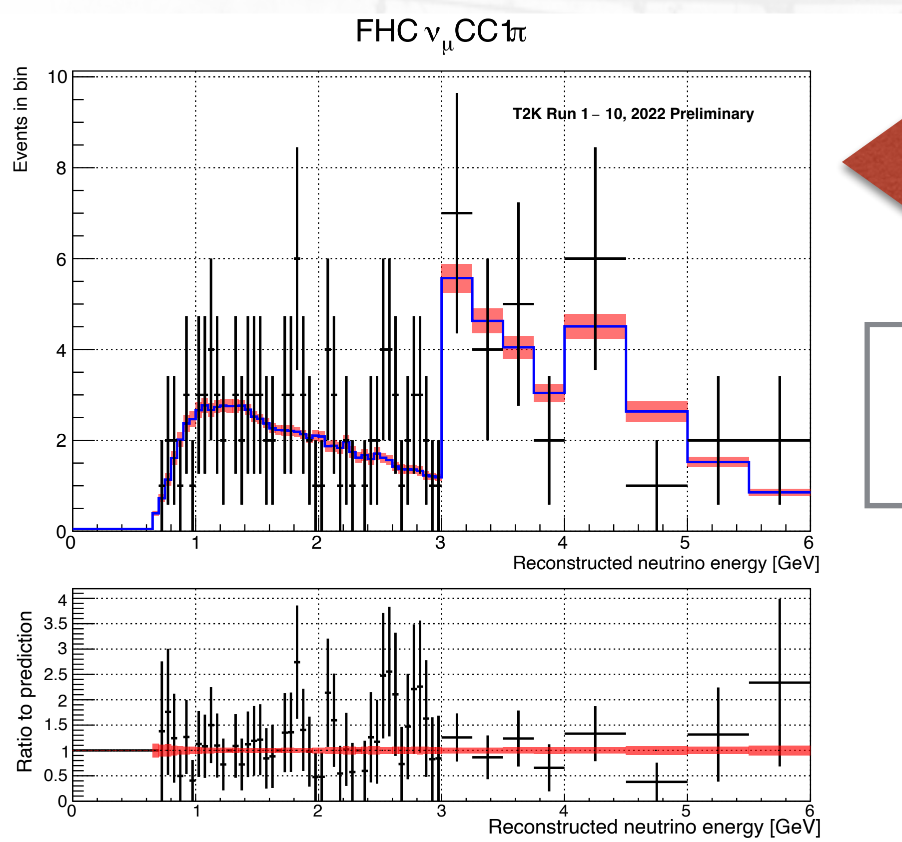
T2K



1μ0π sample

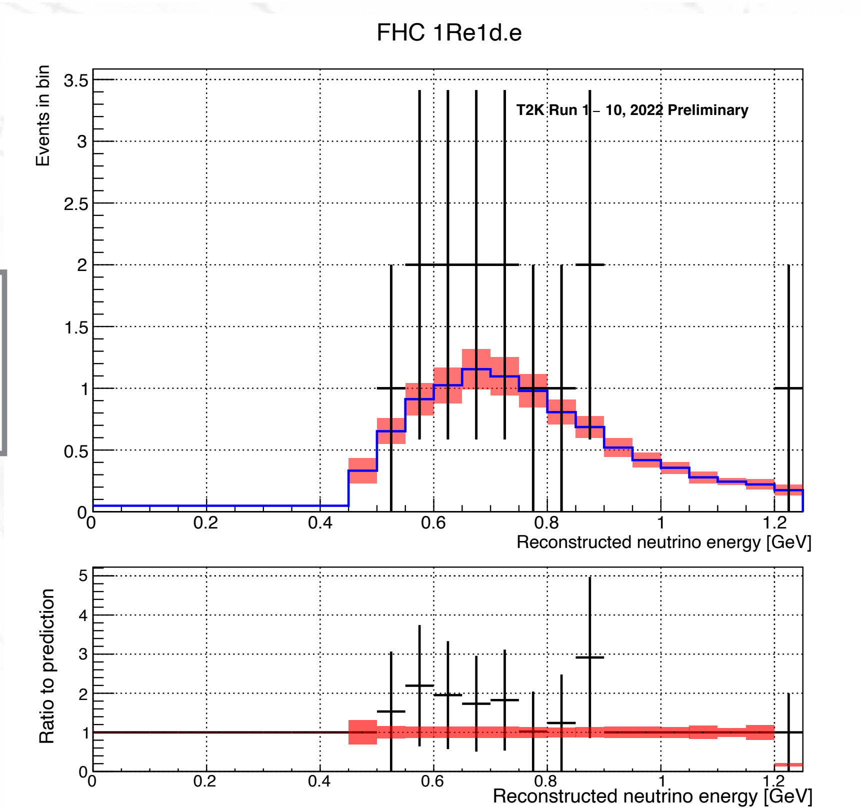


1e0π sample



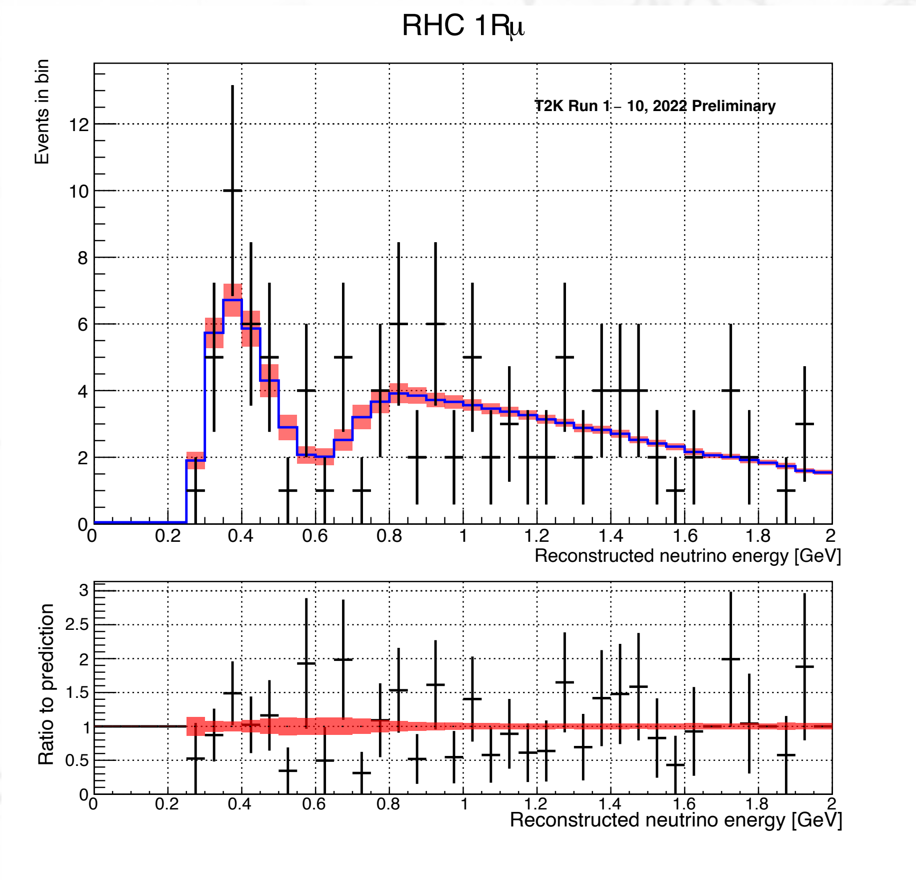
1μ1π sample

delayed electrons from $\pi^+ \rightarrow \mu^+ \rightarrow e^+$



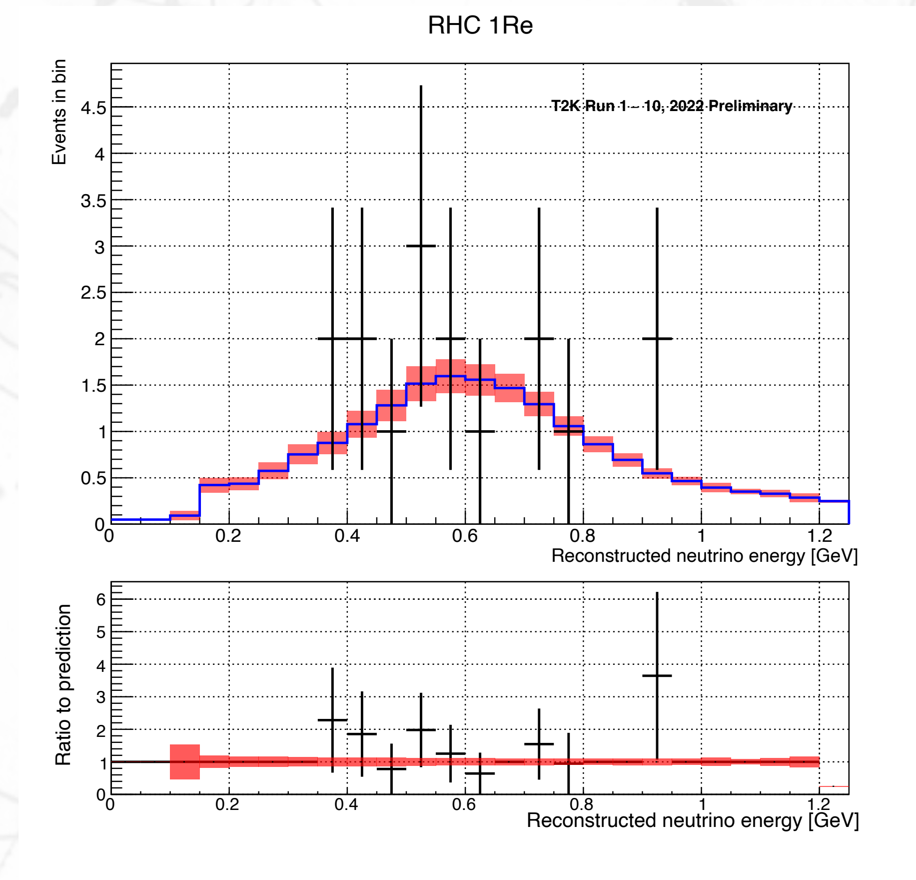
1e1π sample

Reversed Horn Current SK data



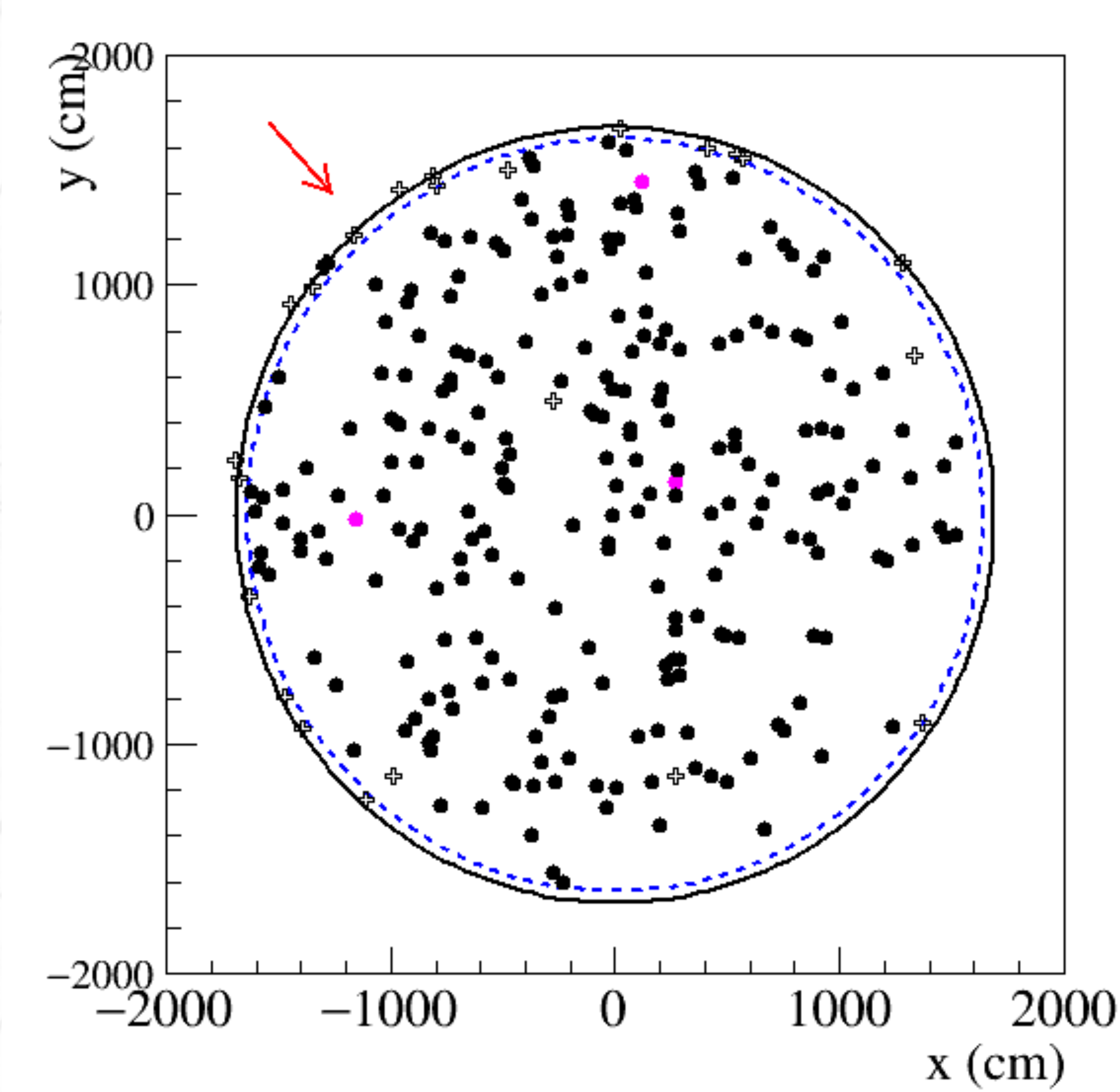
1μ0π sample

1e0π sample

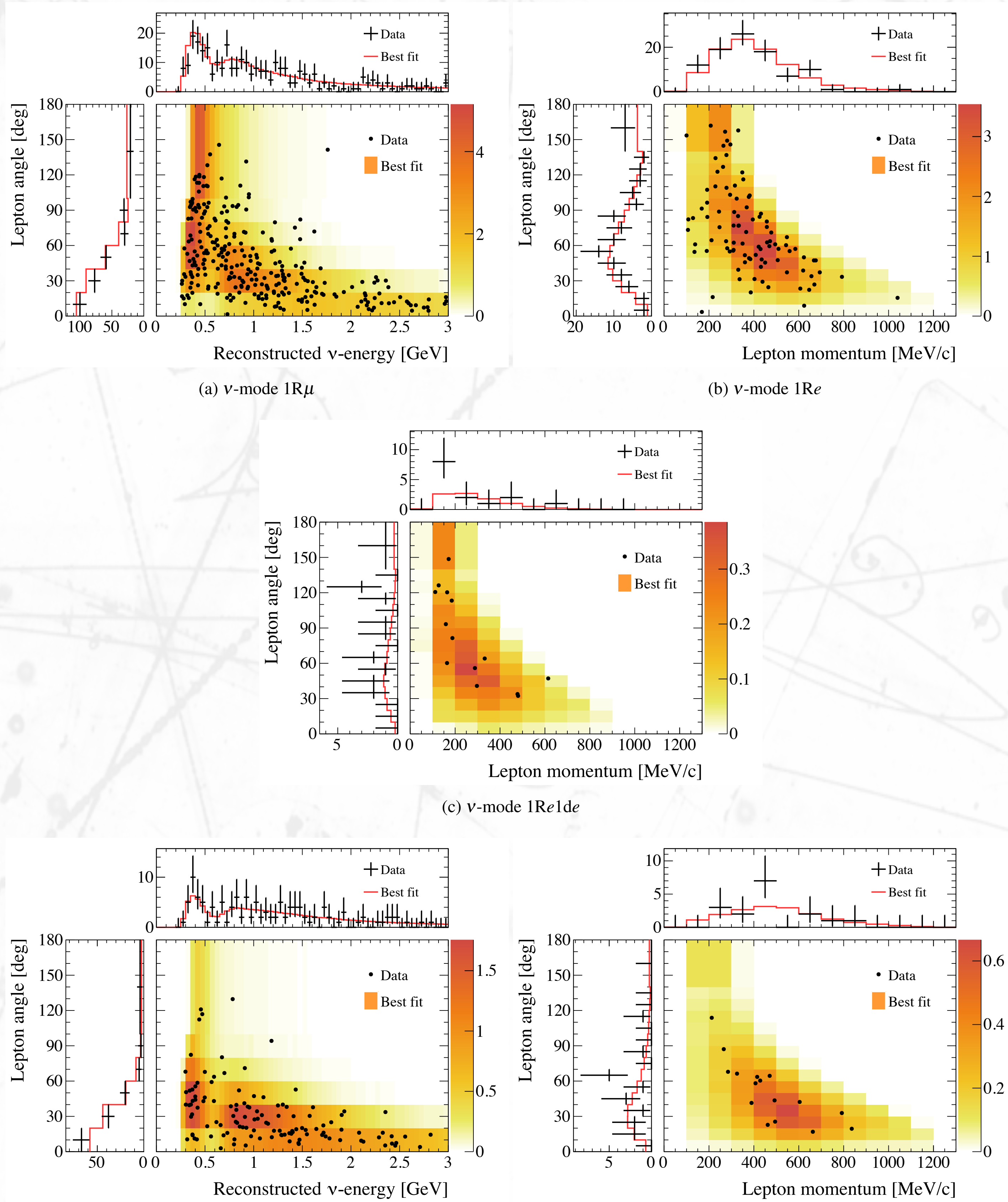


In RHC, the majority of delayed electrons are μ^+ which decay to electrons

Event vertex position in SK

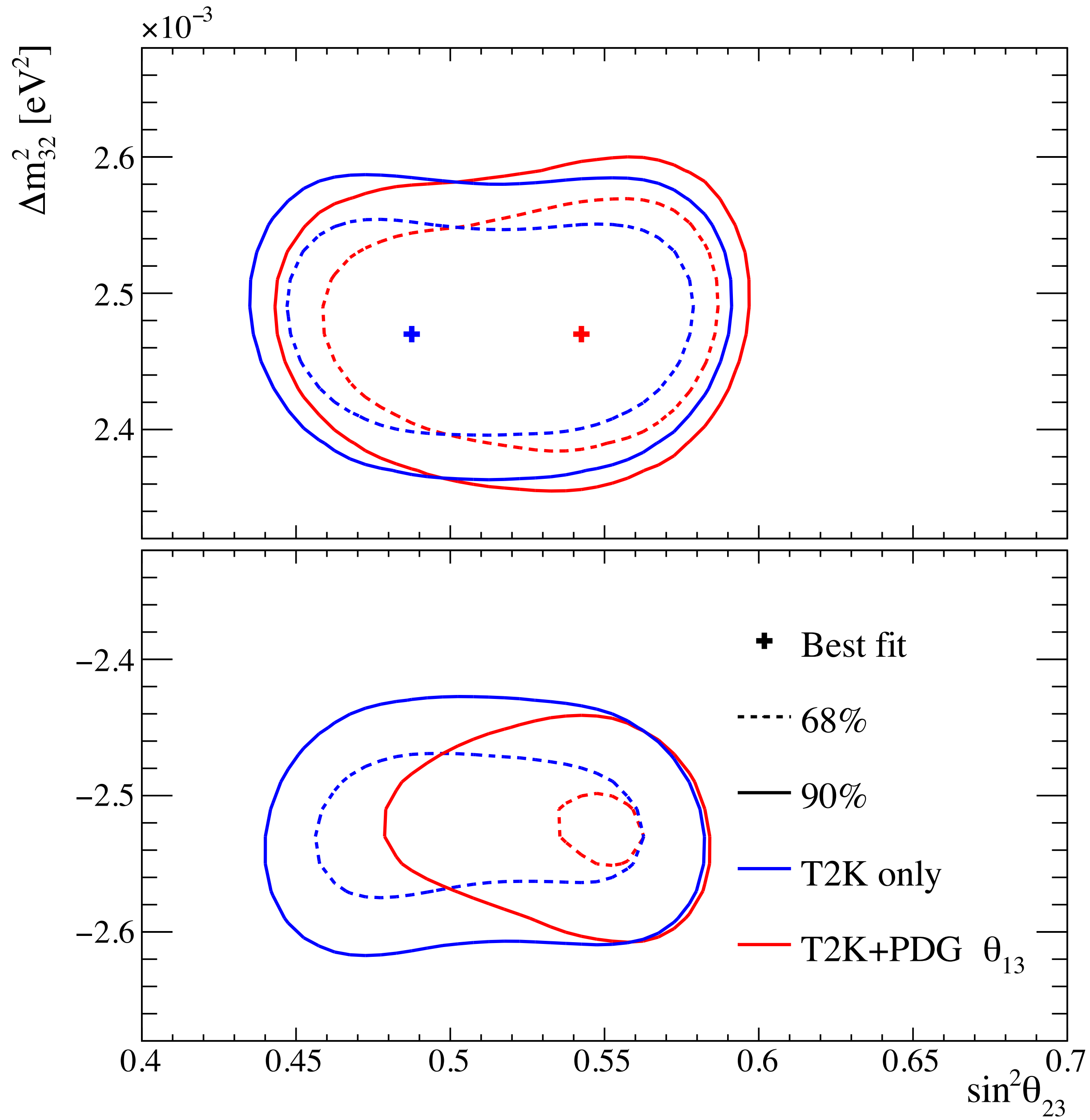


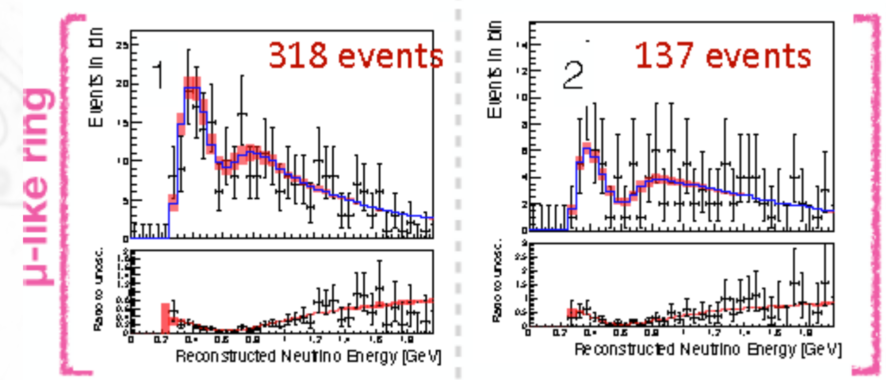
in 2D



(a) ν-mode 1Rμ
(b) ν-mode 1Re
(c) ν-mode 1Re1de
(d) $\overline{\nu}$-mode 1Rμ
(e) $\overline{\nu}$-mode 1Re

$\overset{(-)}{\nu}_{\mu}$ disappearance



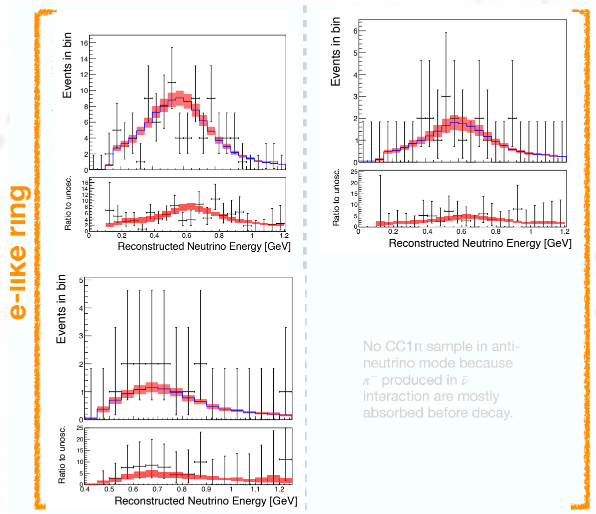


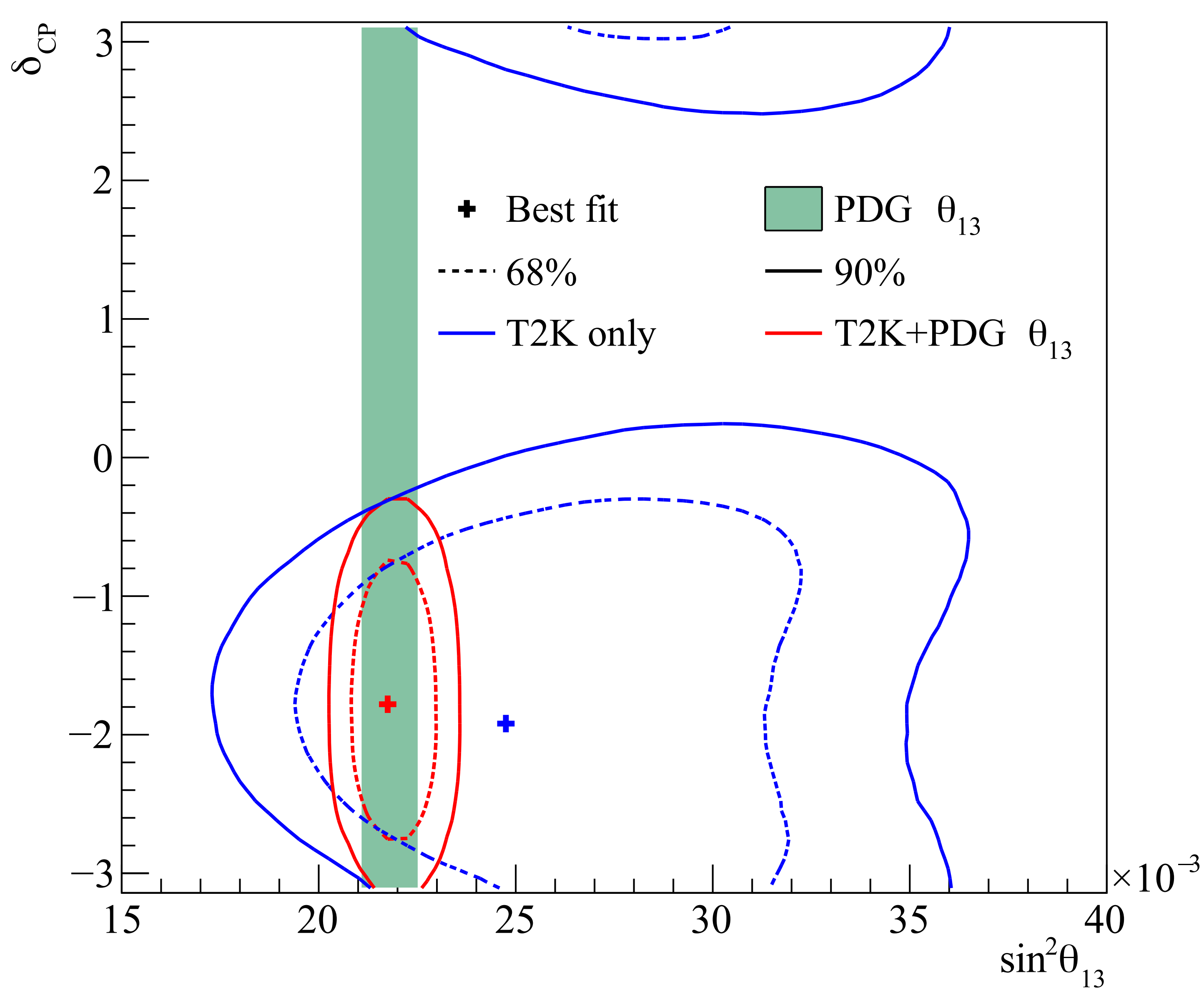
Slight preference for non-maximal θ_{23}

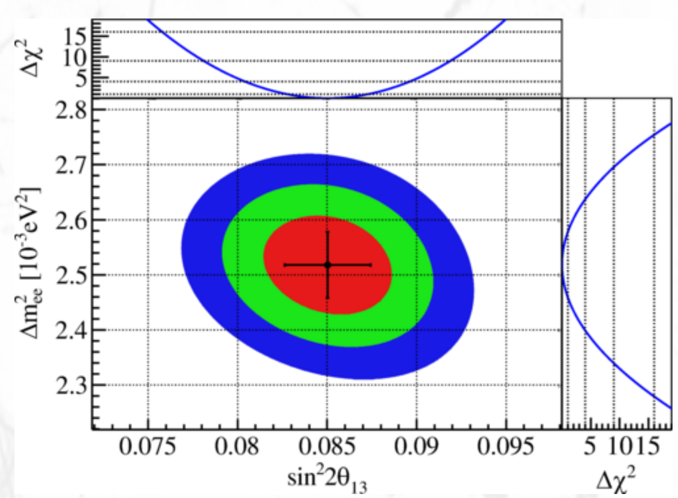
Slight preference for normal hierarchy

		$\sin^2\theta_{23}$ < 0.5	$\sin^2\theta_{23}$ > 0.5	Sum
Δm^2_{32}	> 0 (NO)	0.195 (0.260)	0.613 (0.387)	0.808 (0.647)
	< 0 (IO)	0.035 (0.152)	0.157 (0.201)	0.192 (0.353)
Sum		0.230 (0.412)	0.770 (0.588)	1.000

δ_{CP} measurement





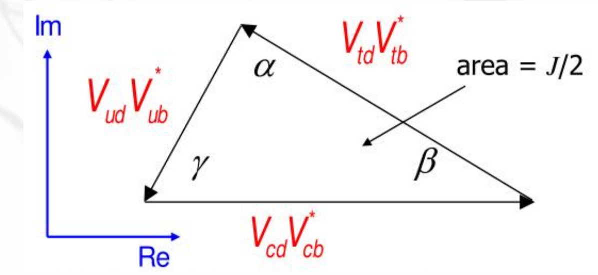


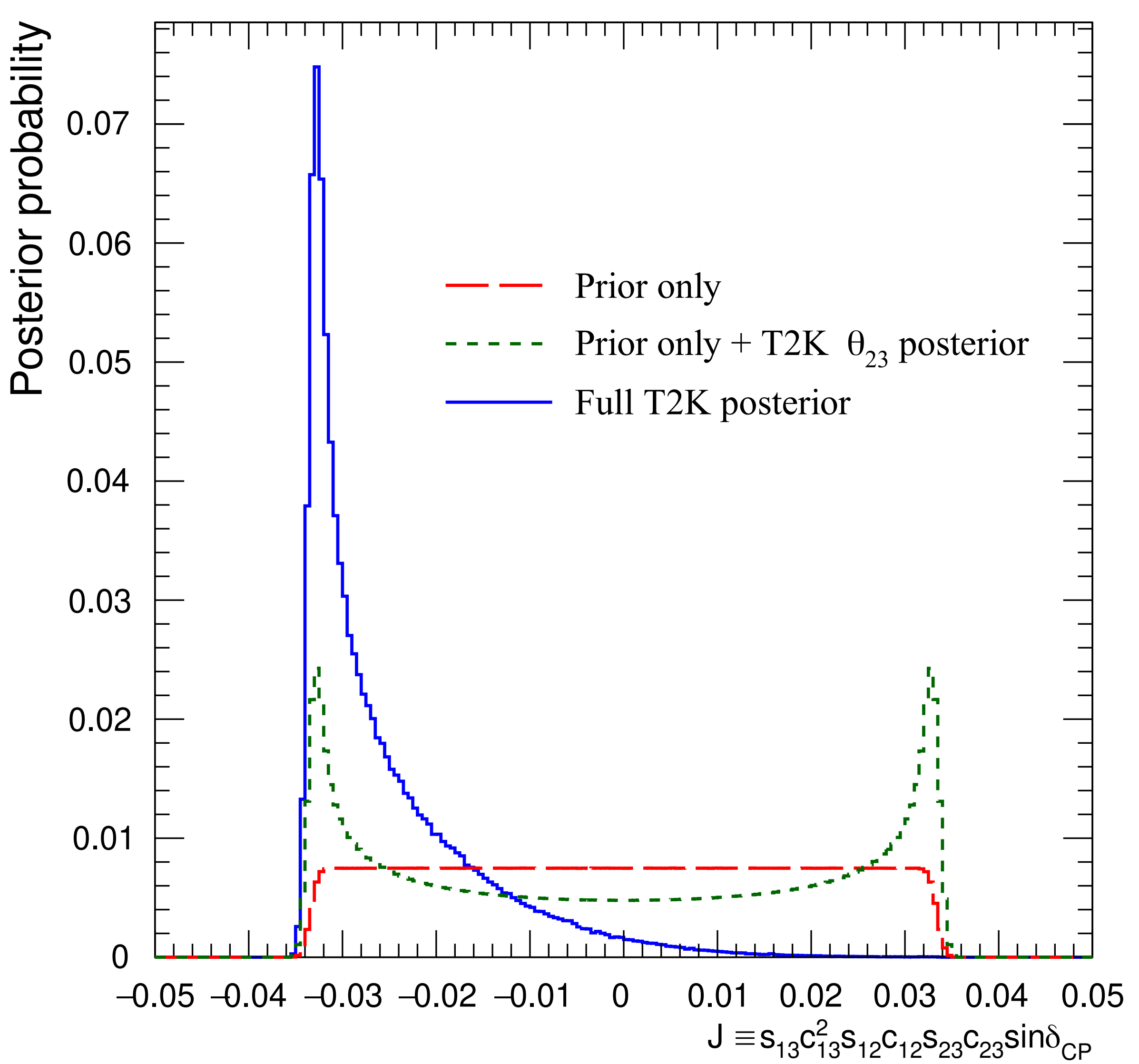
Reactor neutrino data on θ_{13}

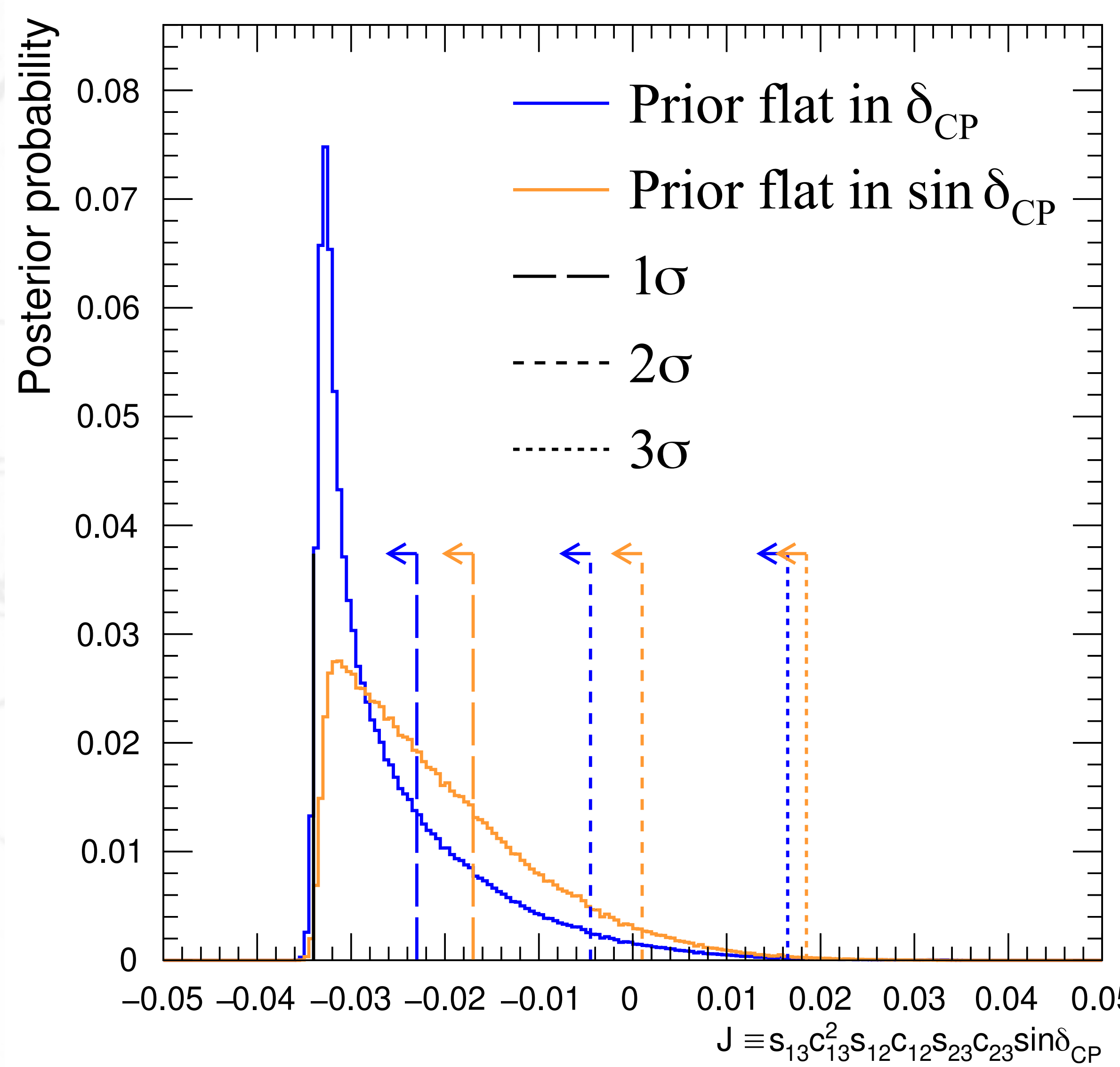
Phys. Rev. Lett. **130**, 161802

Jarlskog invariant

$$J = \sin\theta_{13}\cos^2\theta_{13}\sin\theta_{12}\cos\theta_{12}\sin\theta_{23}\cos\theta_{23}\sin\delta_{CP}$$







J^{max} ~ 0.033 for neutrinos

J^{max} ~ 0.000032 for quarks

Expected vs observed

T2K

Sample		True δ_{CP} (rad.) $-\pi/2$	0	$\pi/2$	π	Data
1Rμ	ν-mode	346.61	345.90	346.57	347.38	318
	$\bar{\nu}$-mode	135.80	135.45	135.81	136.19	137
1Re	ν-mode	96.55	81.59	66.89	81.85	94
	$\bar{\nu}$-mode	16.56	18.81	20.75	18.49	16
1Re1de	ν-mode	9.30	8.10	6.59	7.79	14

Uncertainties

after(before) ND fit

Sample		Uncertainty source (%) Flux	Interaction	FD + SI + PN	Flux⊗Interaction (%)	Total (%)
1Rμ	ν	2.9 (5.0)	3.1 (11.7)	2.1 (2.7)	2.2 (12.7)	3.0 (13.0)
	$\bar{\nu}$	2.8 (4.7)	3.0 (10.8)	1.9 (2.3)	3.4 (11.8)	4.0 (12.0)
1Re	ν	2.8 (4.8)	3.2 (12.6)	3.1 (3.2)	3.6 (13.5)	4.7 (13.8)
	$\bar{\nu}$	2.9 (4.7)	3.1 (11.1)	3.9 (4.2)	4.3 (12.1)	5.9 (12.7)
1Re1de	ν	2.8 (4.9)	4.2 (12.1)	13.4 (13.4)	5.0 (13.1)	14.3 (18.7)

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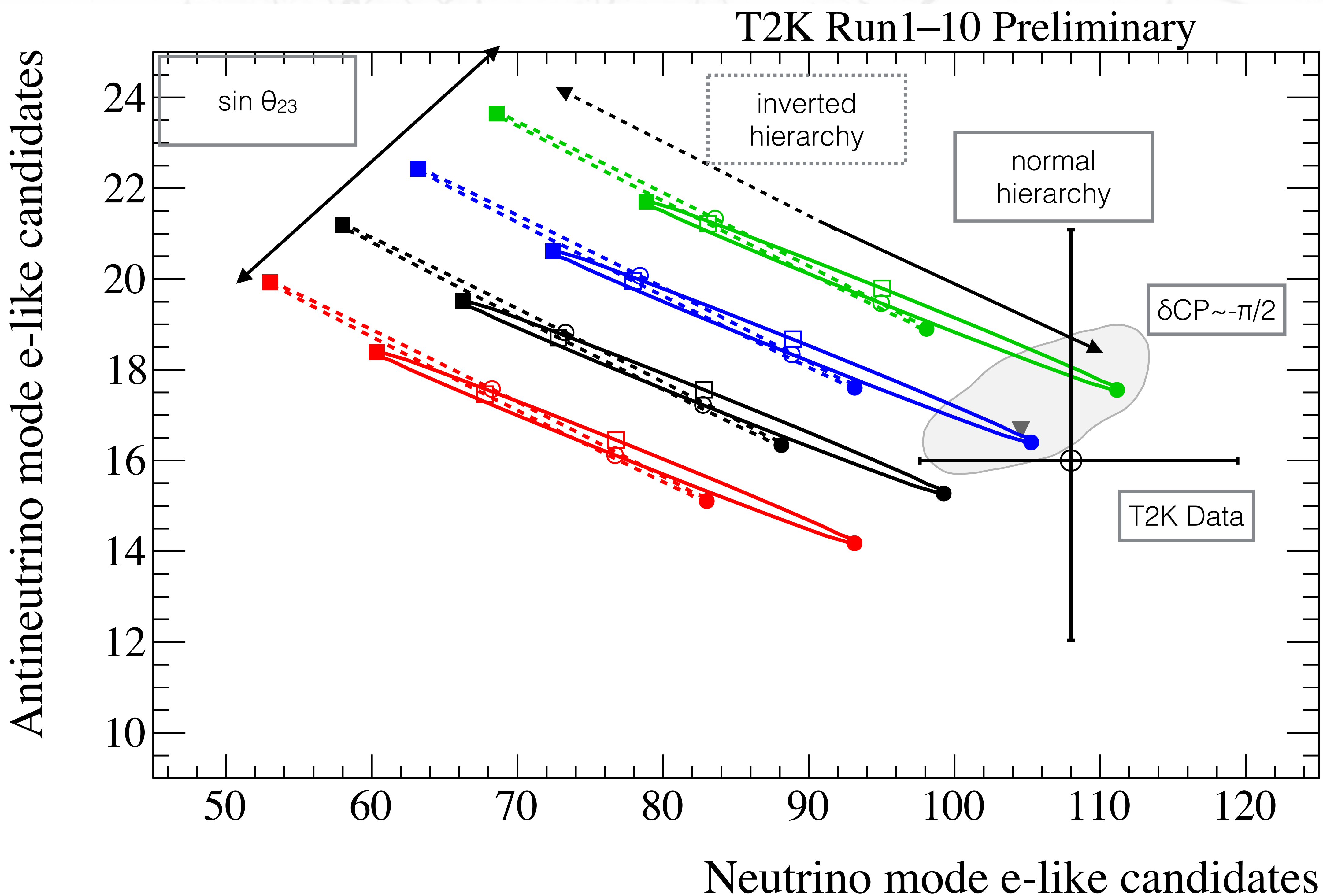
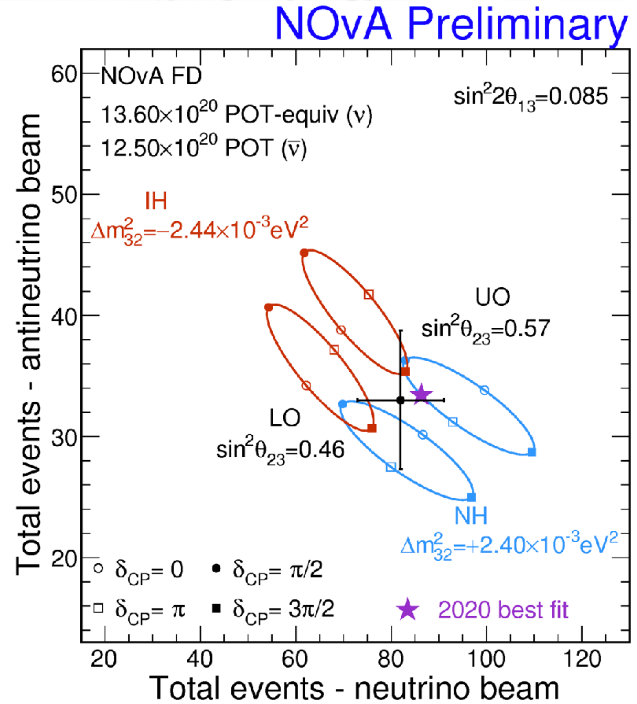
Events & CP violation phase

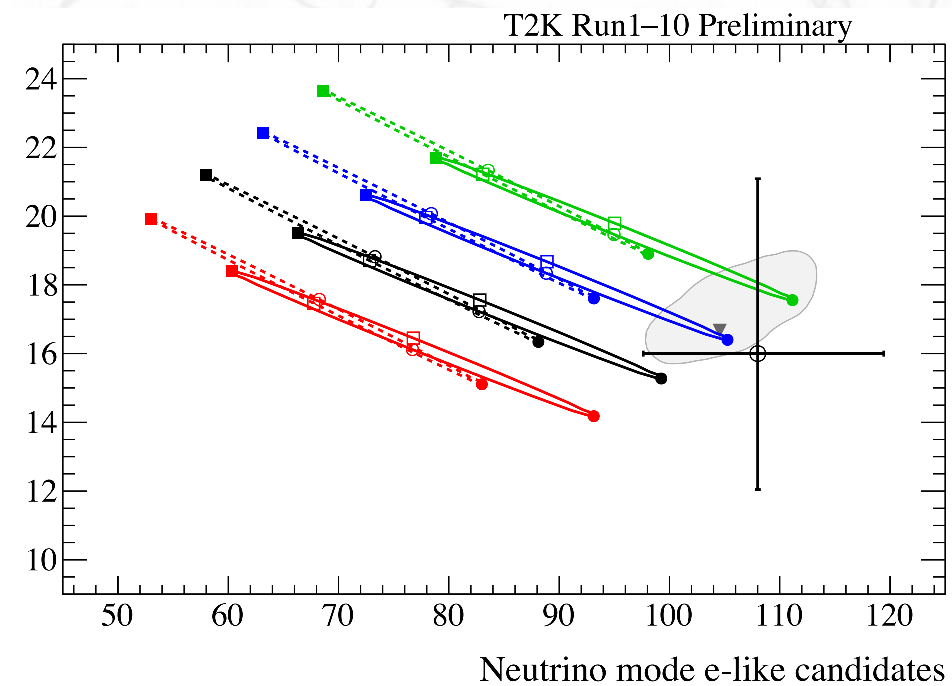


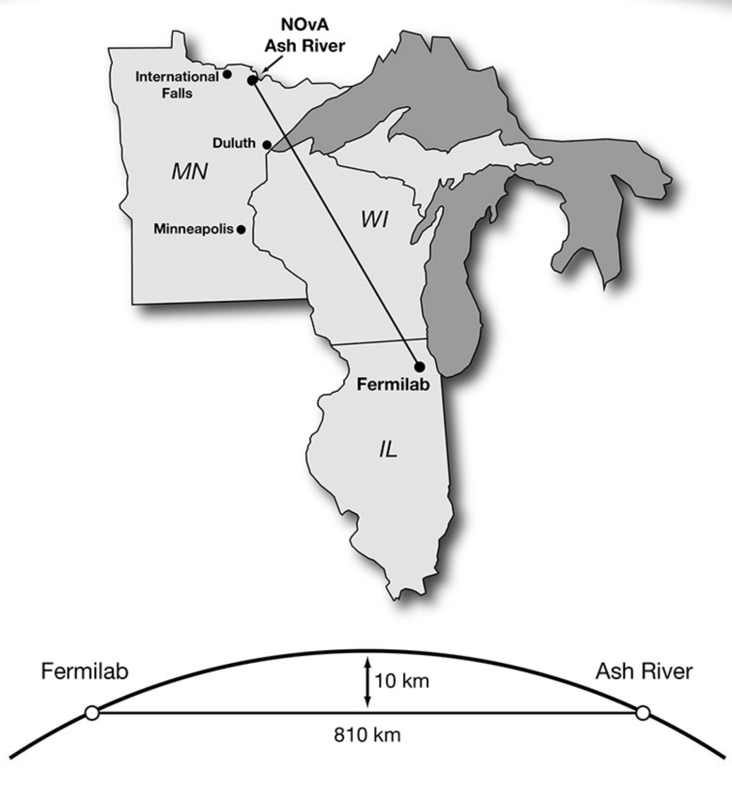
ν energy dependency is not reflected in this plot

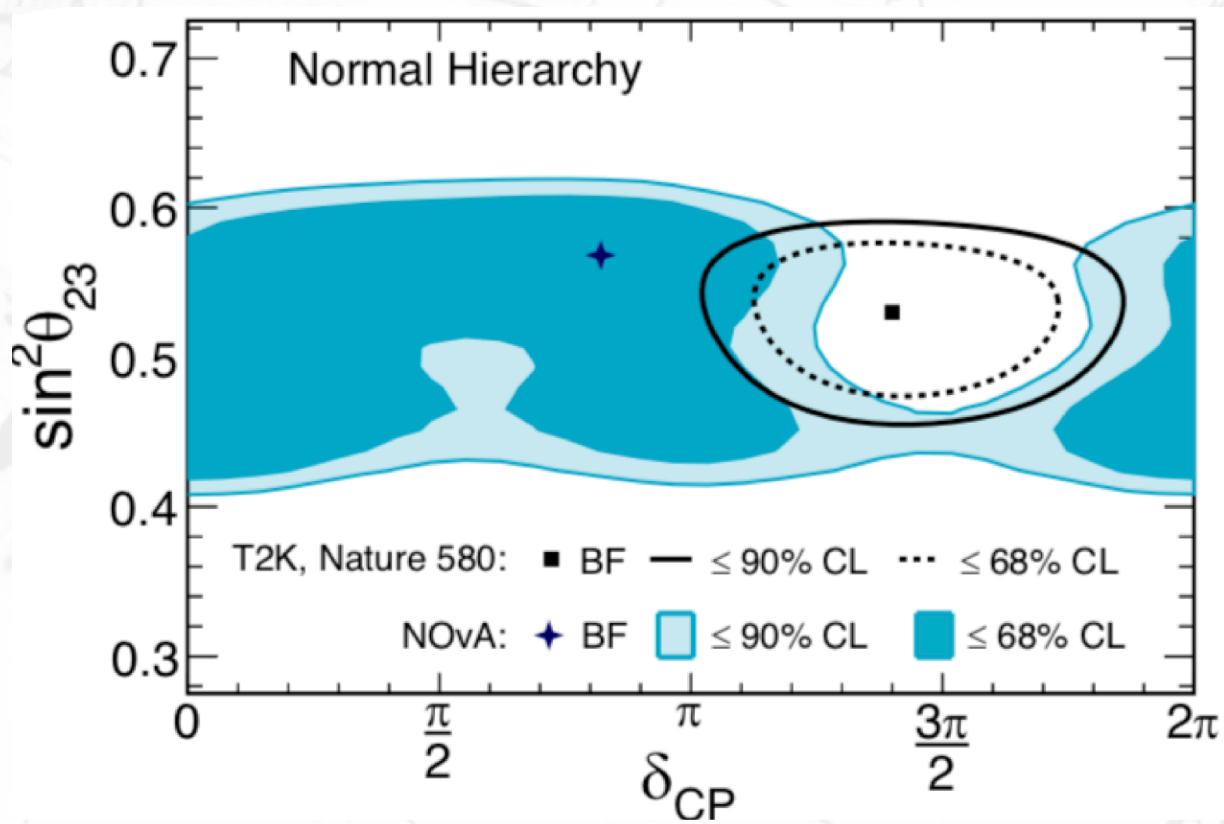
Nova vs T2K results

NOvA is a similar experiment in USA with oscillation over 800 km and different detector technology & neutrino energy.

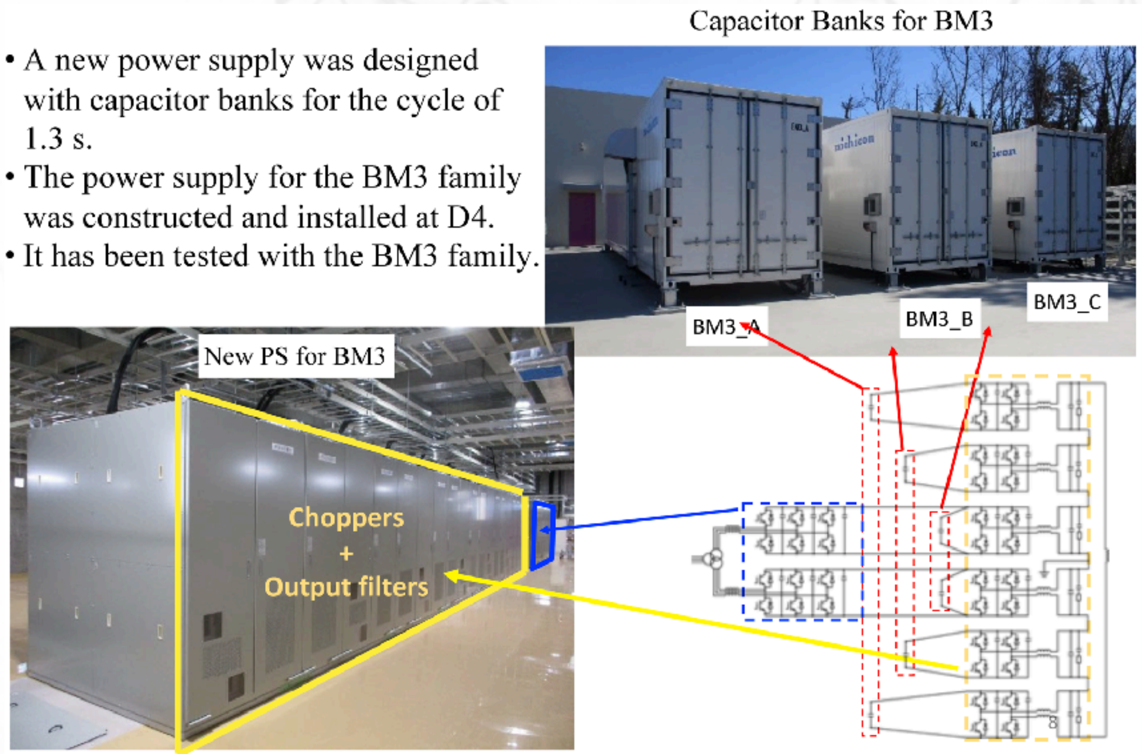


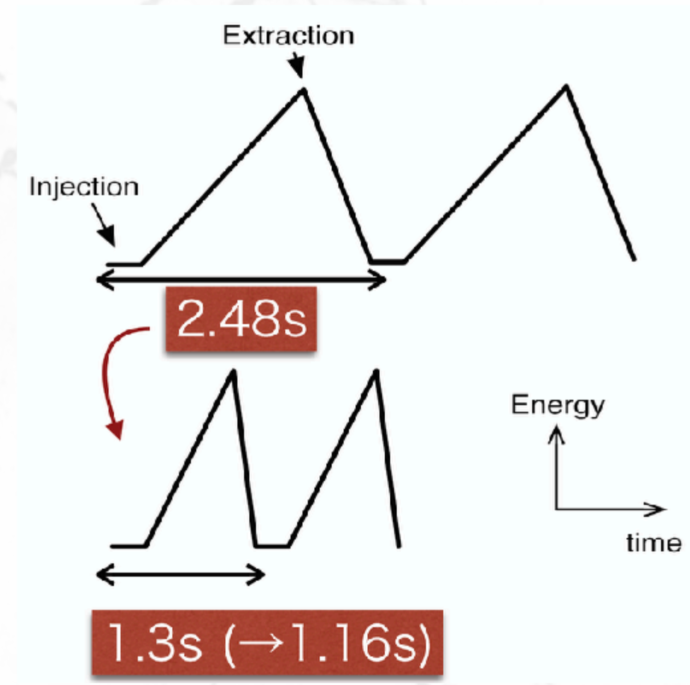






Beam upgrade





f_{rep}=0.4 Hz ⊕ PPP = 2.7×10^{14} ⊕ 30 GeV = 515 kW

515 kW stable operation in 2019

MR Power Supply approved

JFY 2020

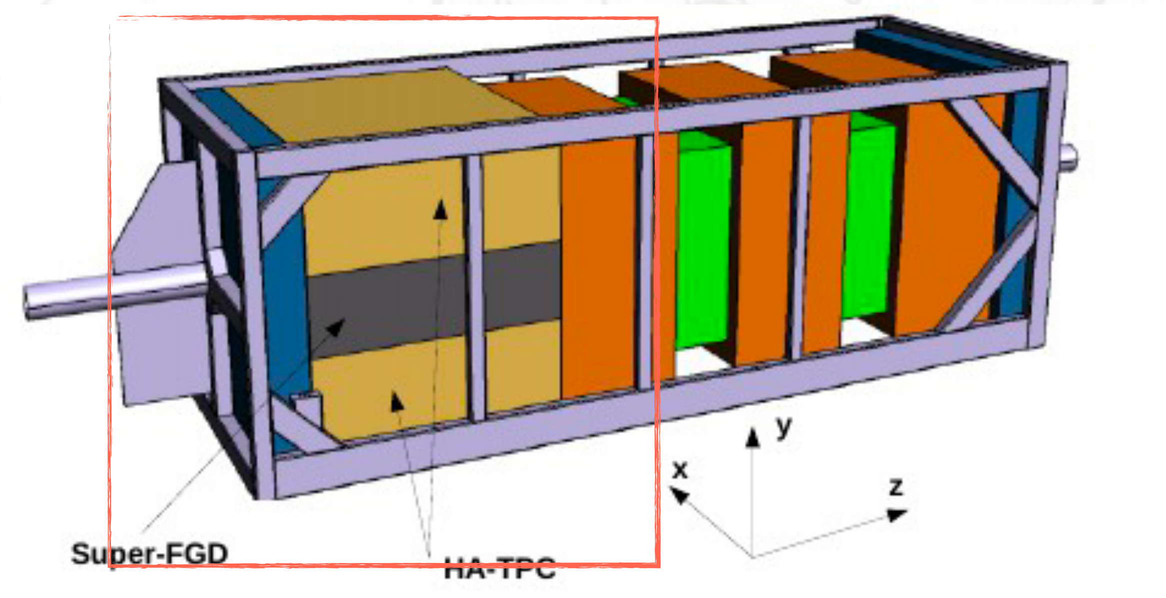
f_{rep}=0.77 Hz ⊕ PPP = 2.2×10^{14} ⊕ 30 GeV = 810 kW

exp. >800 kW by 2023

RF upgrade and Machine development

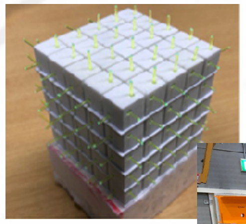
f_{rep}=0.86 Hz ⊕ PPP = 3.2×10^{14} ⊕ 30 GeV = 1.3 MW

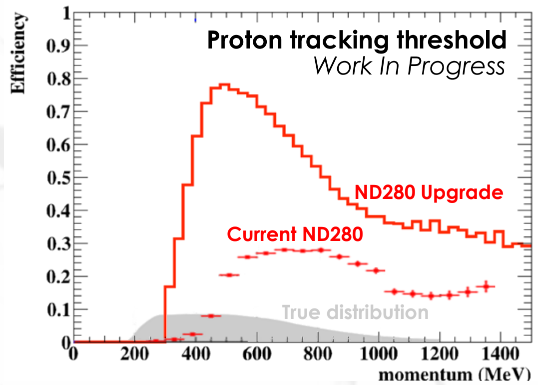
ND280 upgrade



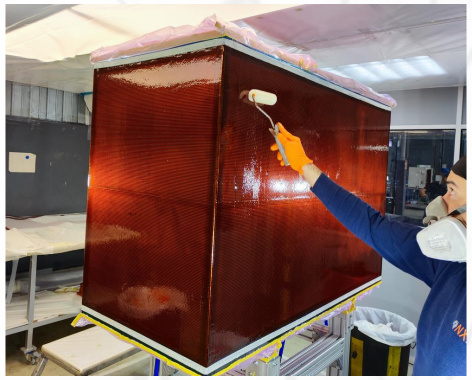
- **sFGD:** quasi-3D imaging.
  - Improved target tracking.
  - Improved proton detection threshold.
  - Neutron detection capabilities & kinematics reconstruction in final state

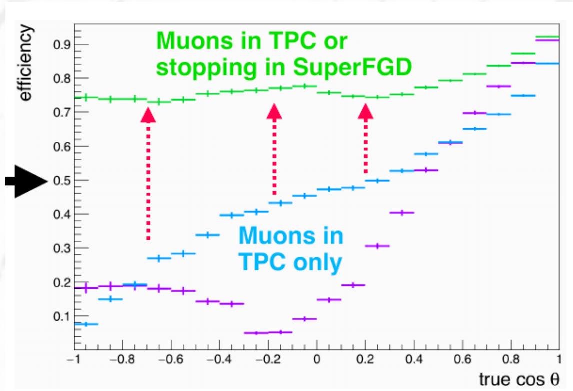
x2 in statistics for equal p.o.t.





- **High Angle TPC's:**
  - Improved high angle acceptance:





- **Time of Flight**
  - Reduction of background from magnet interactions.
  - σ ~ 130 ps

Beyond T2K

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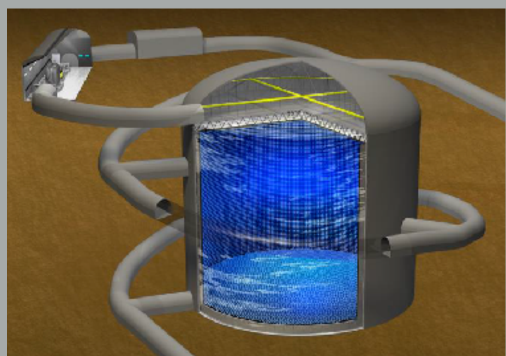
Next Generation Experiments

COMPLEMENTARY

Hyperkamiokande

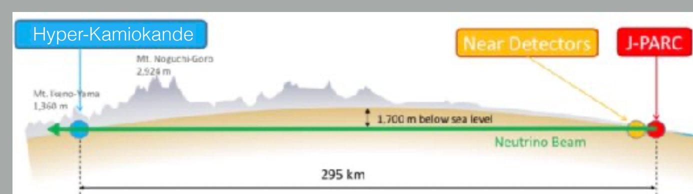
JAPAN

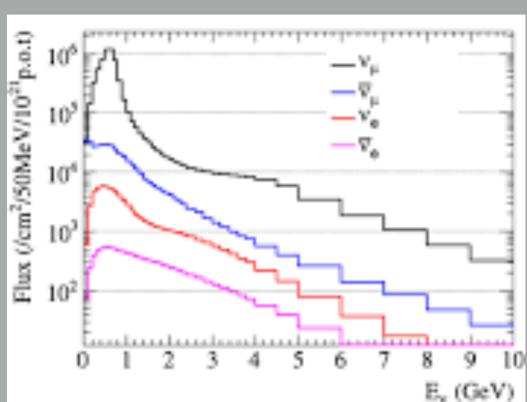


1 x 258 kTon
water Čerenkov

Oxygen and hydrogen targets

295 km
flight distance



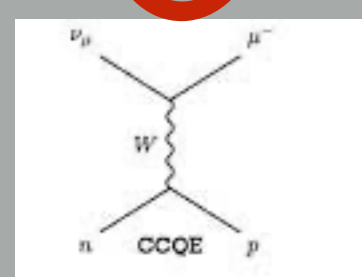


Narrow (off-axis) neutrino beam

E_ν ~ [0.5,1.] GeV

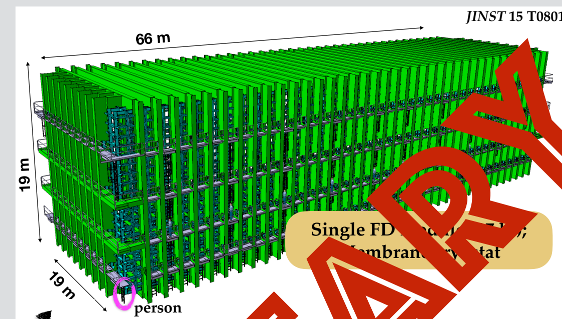
1 oscillation peak

Mainly CCQE
Kinematical
reconstruction



Dune

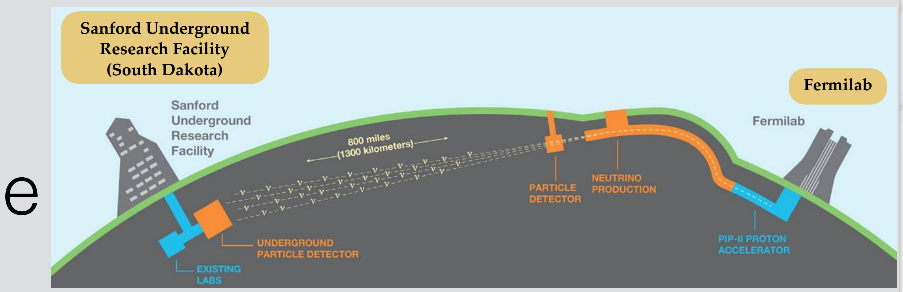
USA

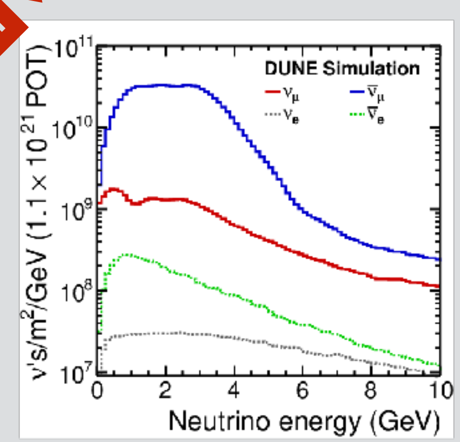


4 x 17 kTon
liquid Argon TPC

Argon target

1300 km
flight distance



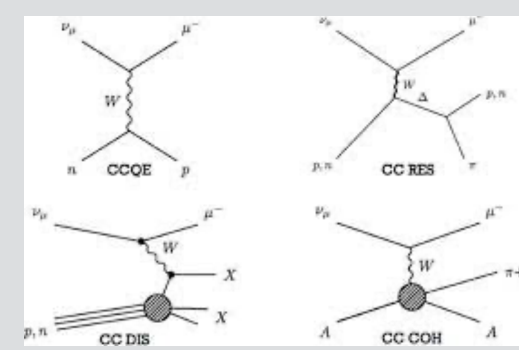


Broad (on-axis) neutrino beam.

E_ν ~ [1.,5.] GeV

2 oscillation peaks

CCQE, CCRes
CCDiS
Track-Calorimetric
reconstruction



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Conclusions & steps forward

- Long Base Line technology is **mature:**
  - research of years show the requirements for a **precision measurement using this technology.**
  - This includes **hadron production experiments, nuclear theory, beam monitor technology and advanced statistical methods.**
- Active **theoretical** developments on neutrino-nucleus interactions (systematic errors!)
- Closing the **measurement of the PMNS matrix** (no unitarity meas. possible).
  - Atmospheric angle close to maximal.
  - Rejected large fraction of $\delta_{CP} > 0$ with 99.7% C.L.
  - Mild preference for normal hierarchy.
- **Tension with NOvA** starts to be relevant.
- T2K measurements paves the road for the approved **HyperKamiokande** to be operated in **2027.**
  - **DUNE** provides a complementary methodology and it will be in operation in 203X.

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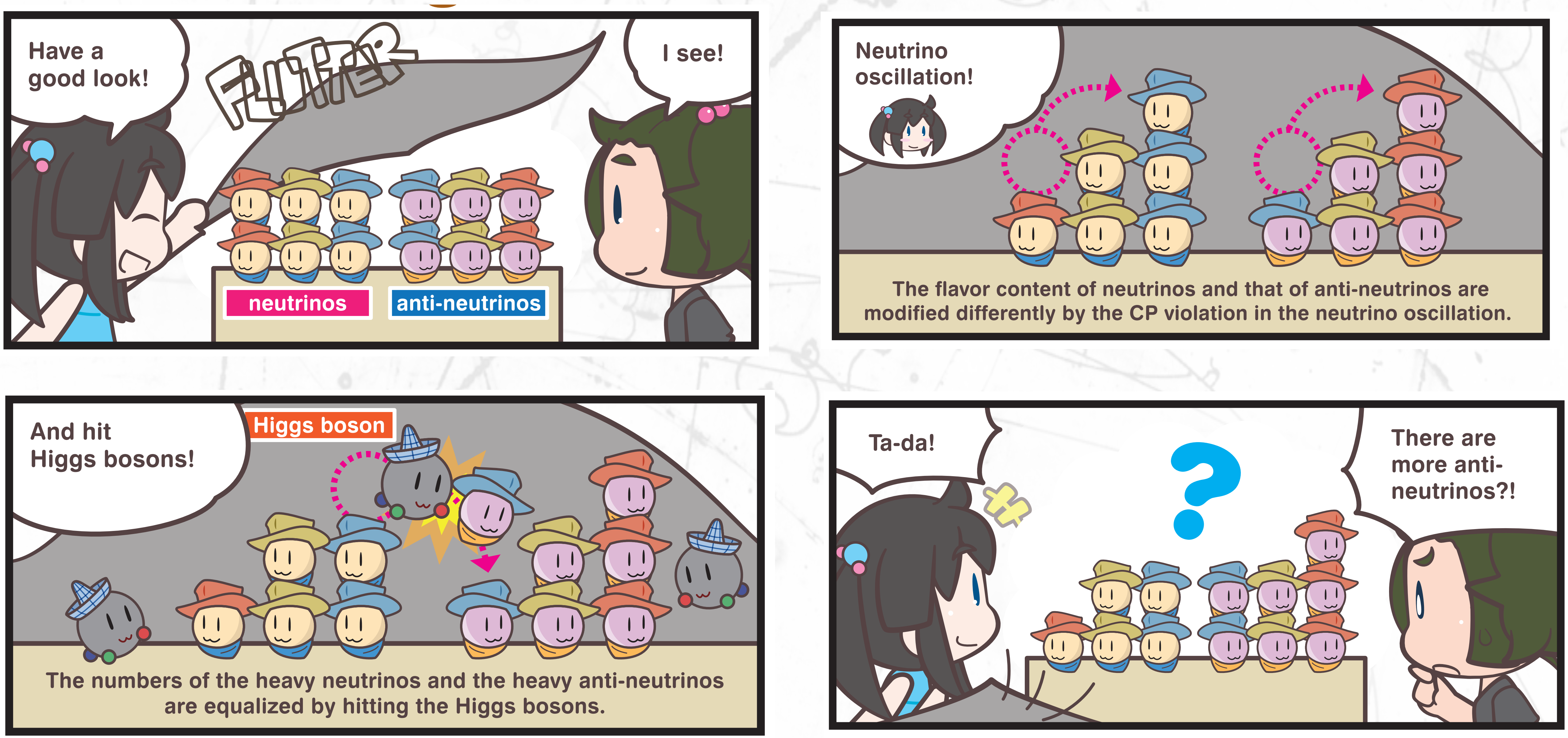
T2K

Neutrino Magic!



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Supporting slides

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What can be improved?

- More statistics and more interaction channels in SK (i.e. adding pions to ν_μ CC).
- What is the role of neutrons?
- Improve on cross-section models: more exclusive, more and better data,
- Can we constrain more interaction channels: NC, electron neutrinos, transverse variables…?
- How much can we gain by fitting NoVa and T2K or SK and T2K together?

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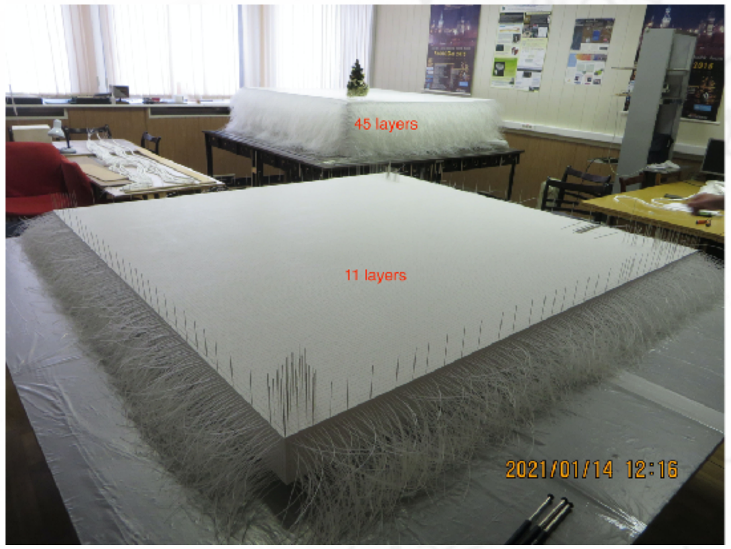
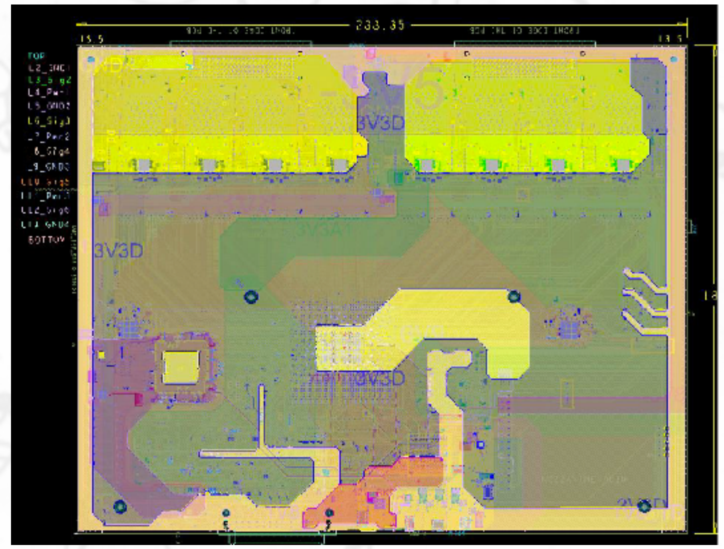
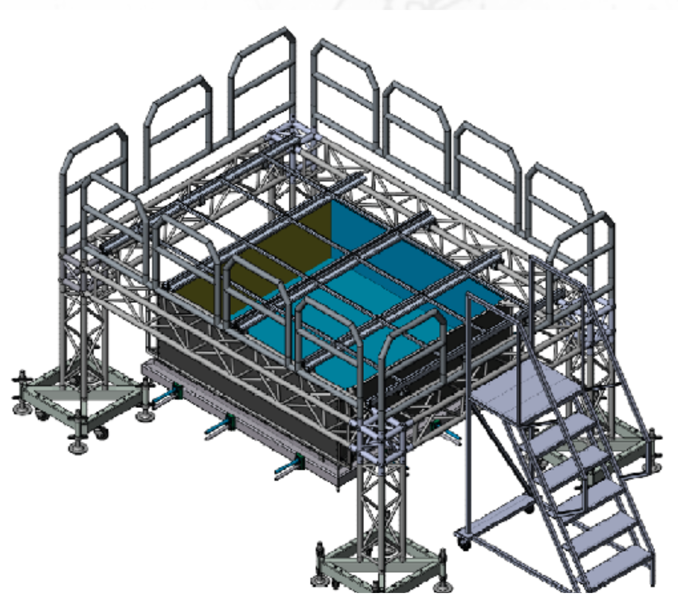
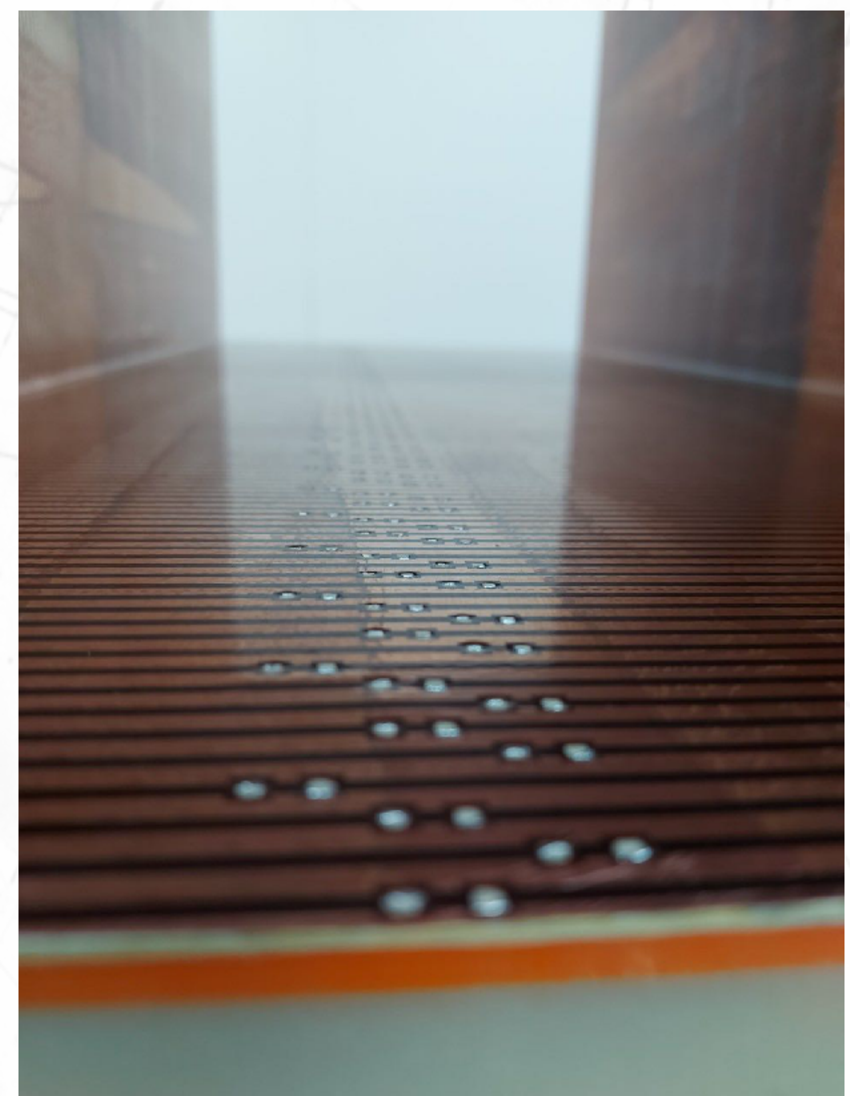
Progress in Upgrade

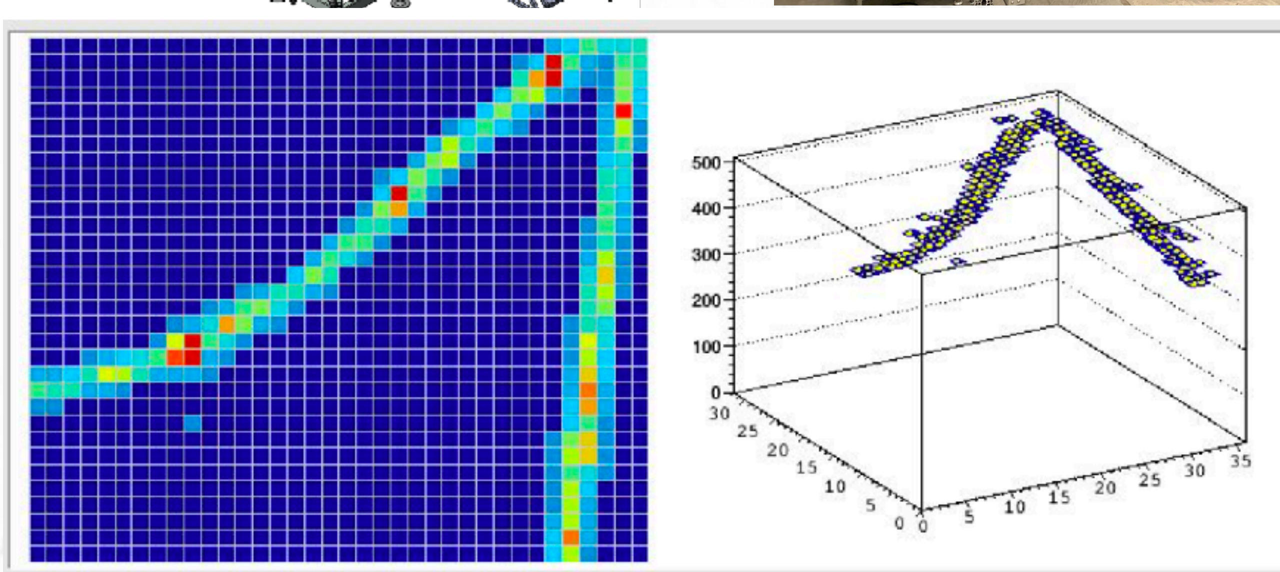
T2K



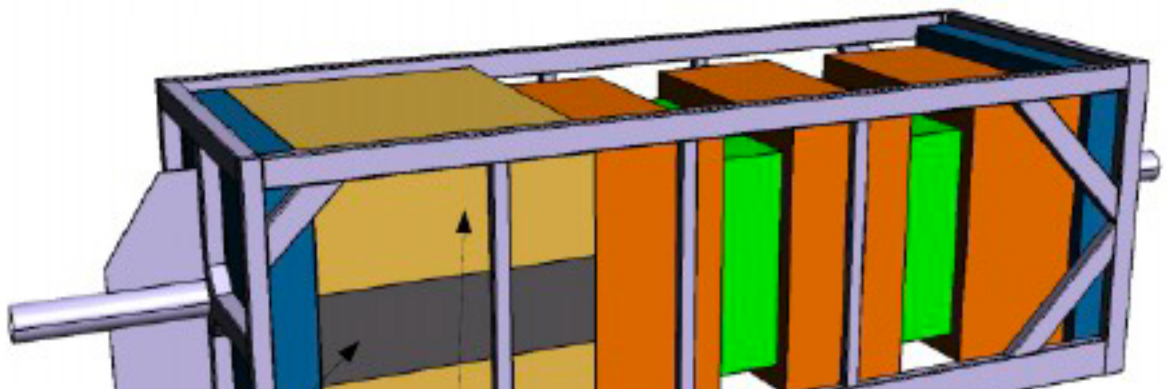


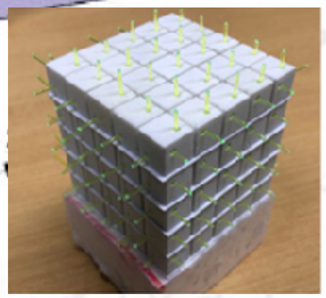


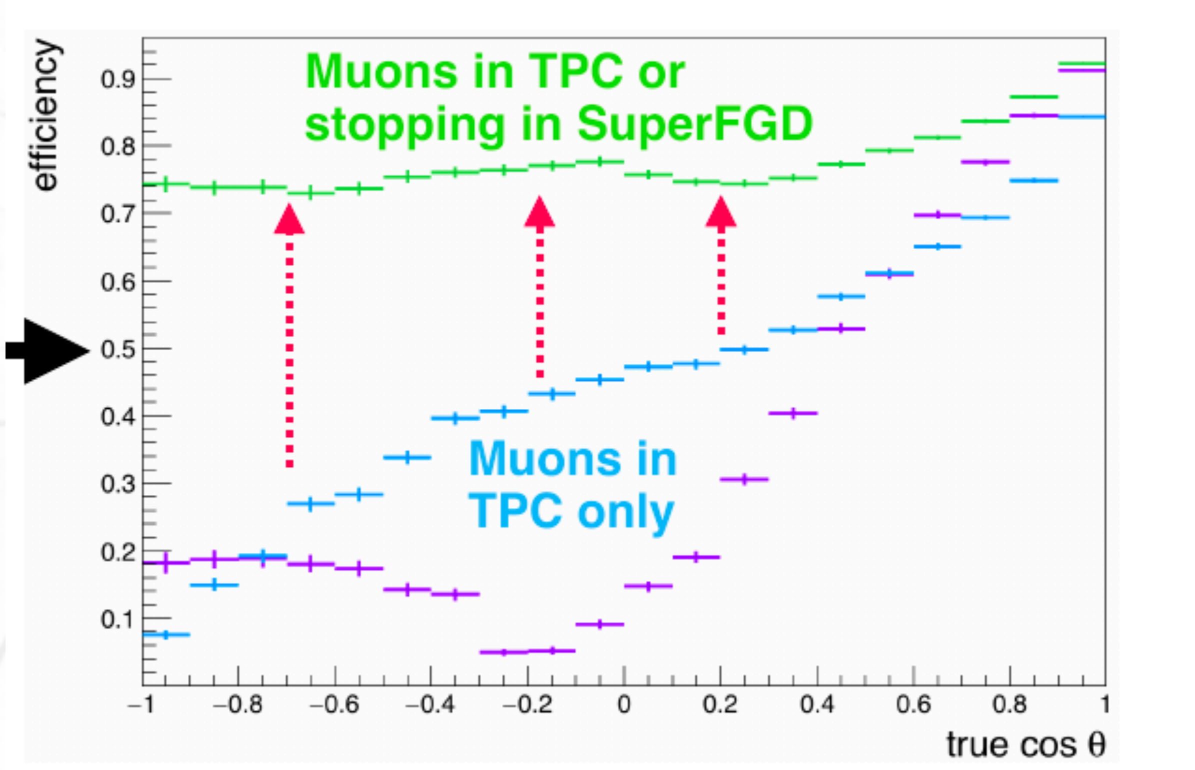




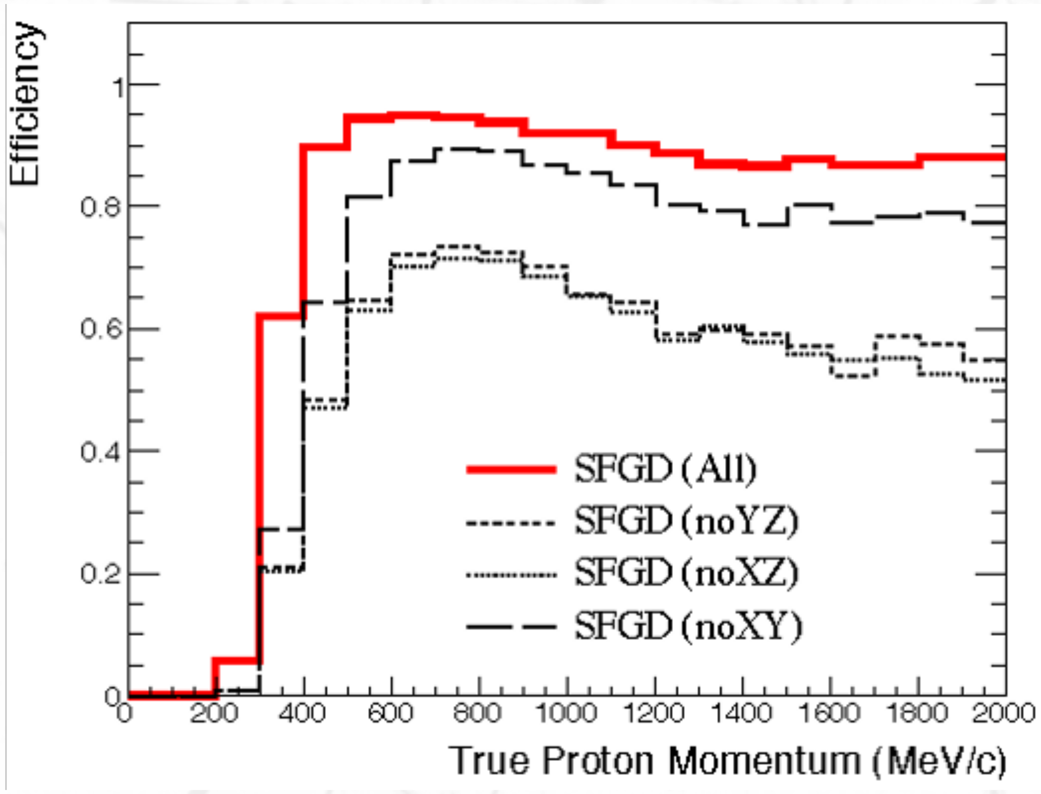
ND280 upgrade





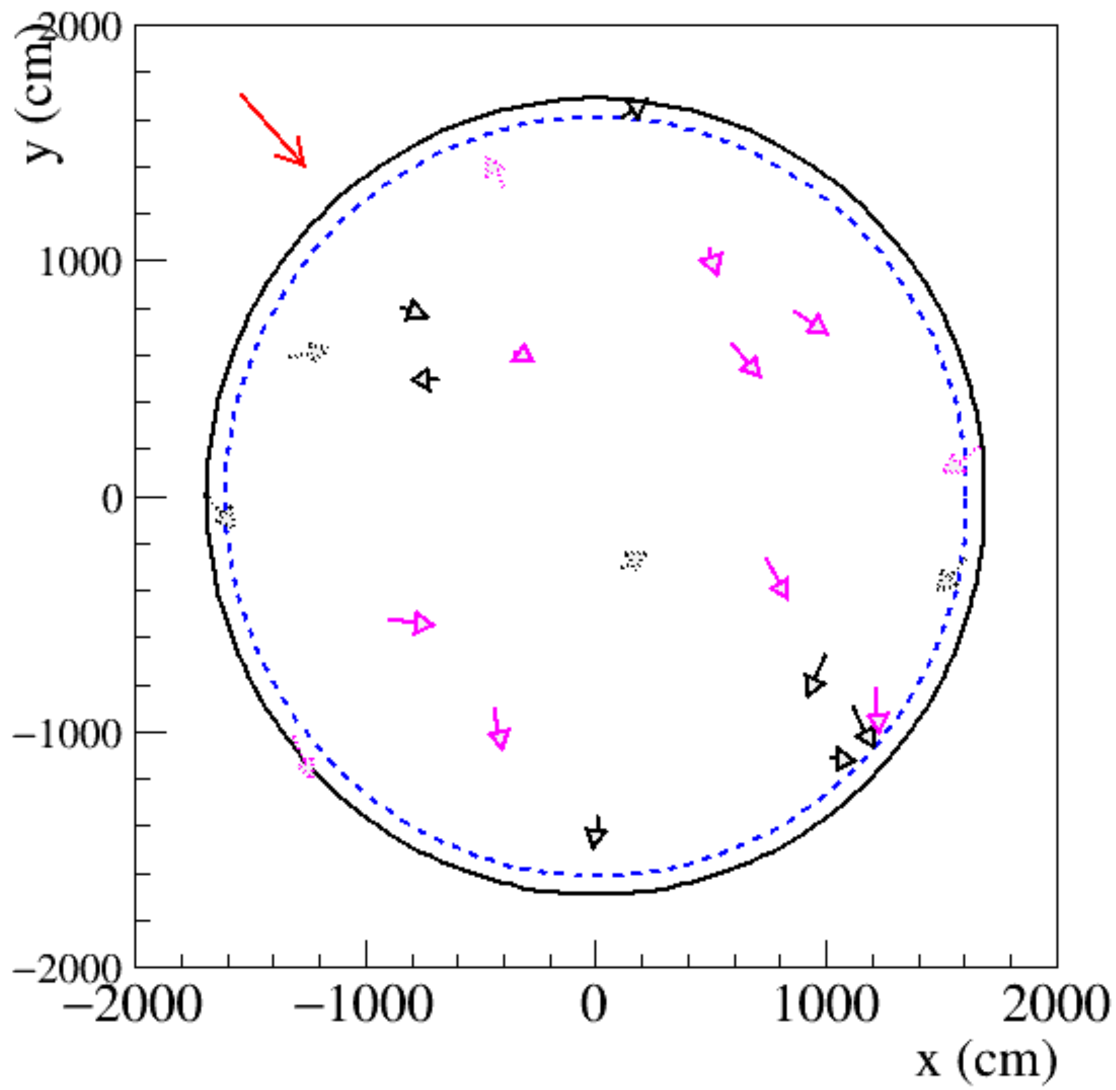


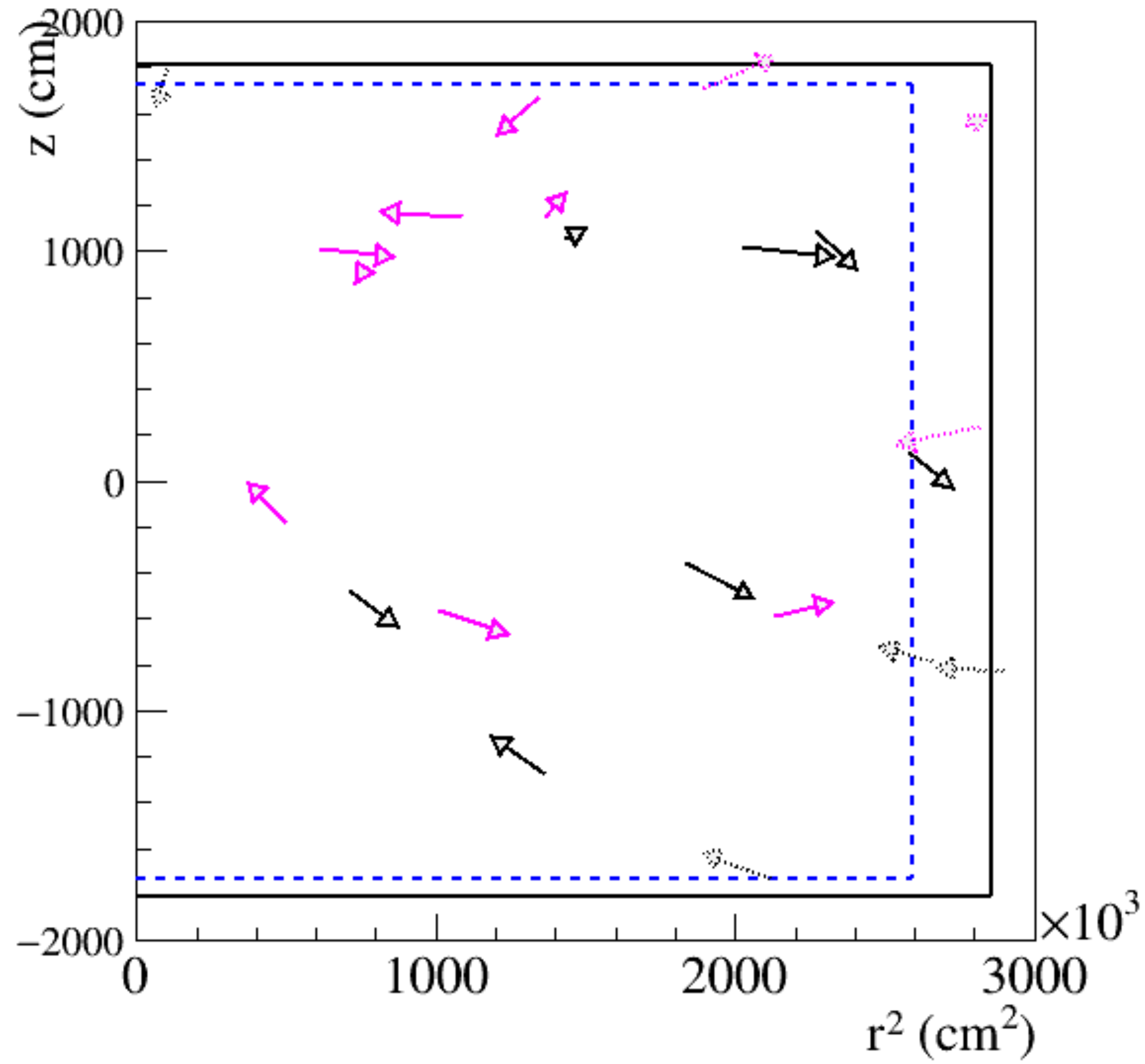
ND280 upgrade goals

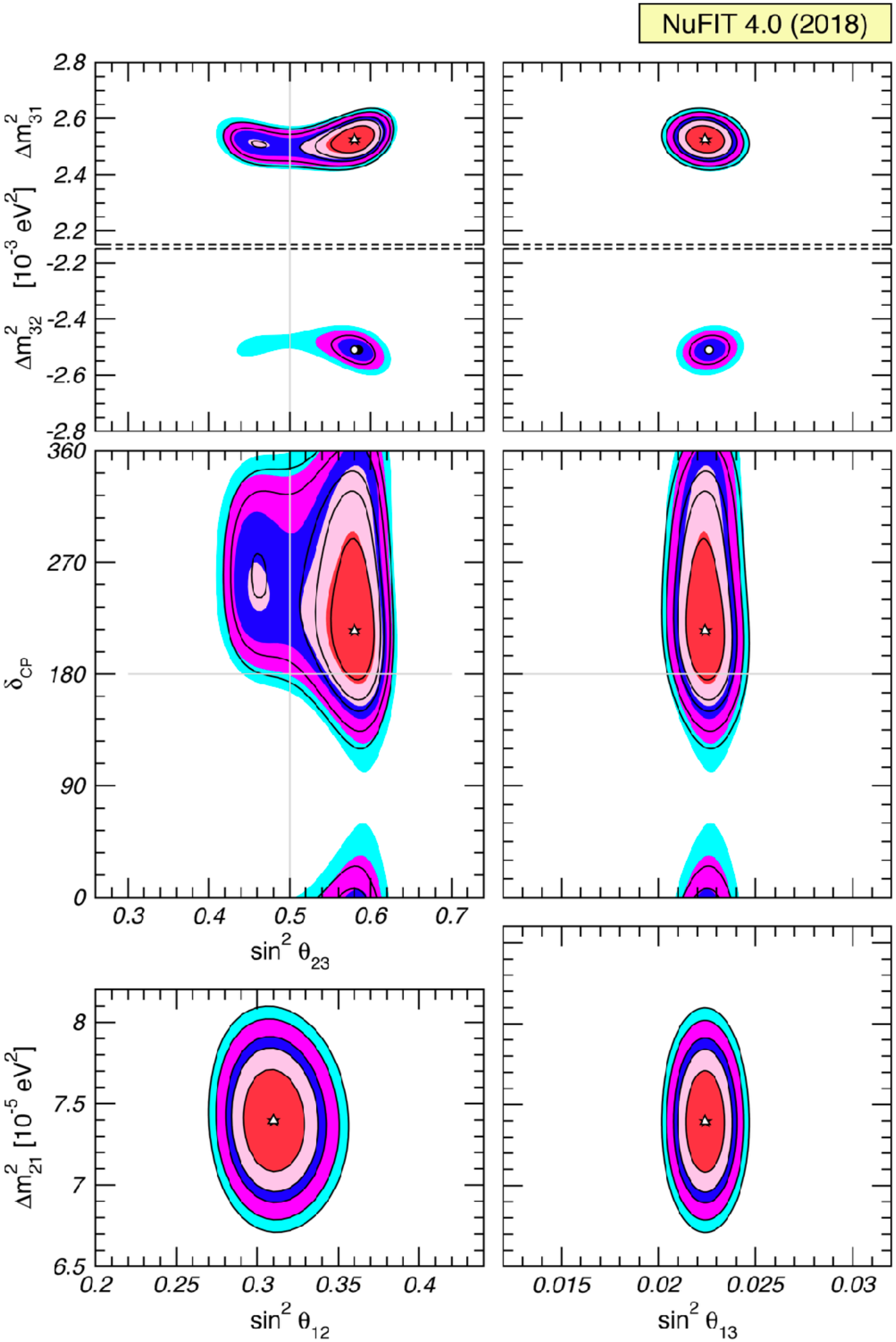


- quasi-3D imaging.
  - Improved target tracking.
  - Improved proton detection threshold.
  - neutron detection capabilities
- Improved high angle acceptance:
  - High Angle TPC's.
- x 2 in statistics for equal p.o.t.
- Time of Flight for background reduction.
- Access to neutrons in final state (LANL test beam).

ν_e vertex distribution





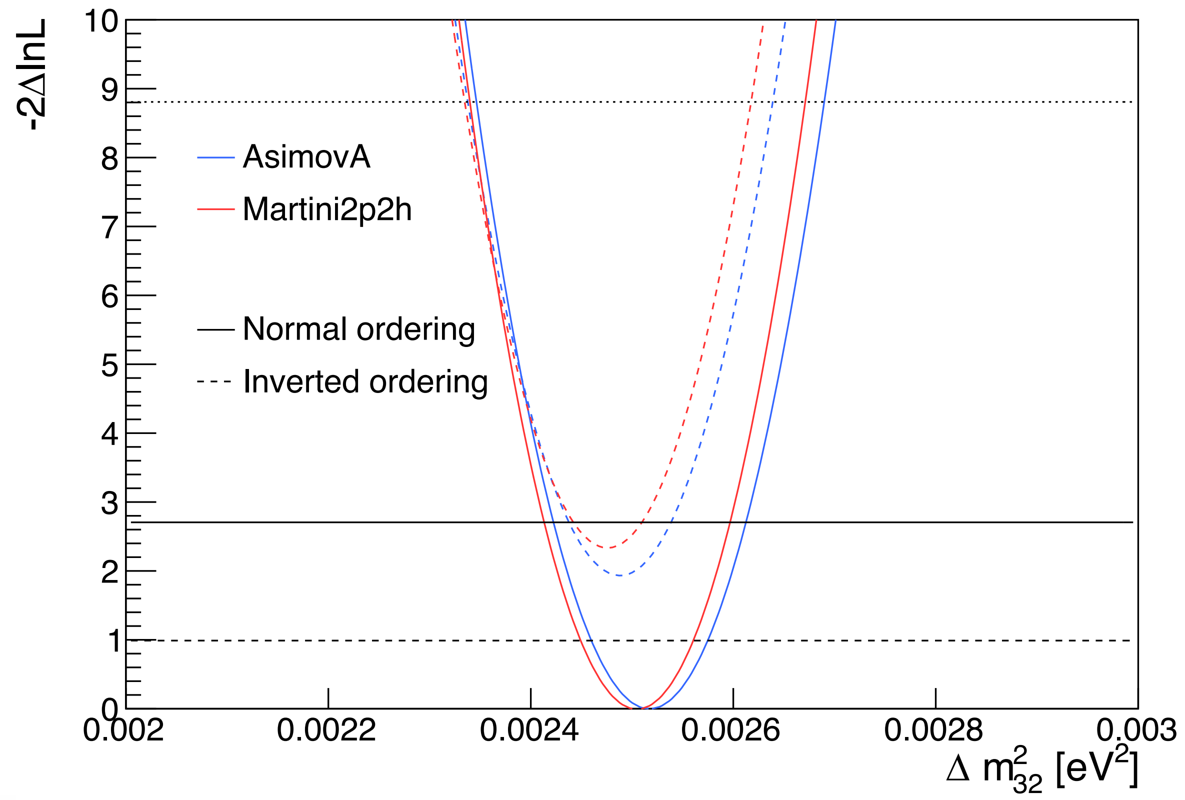


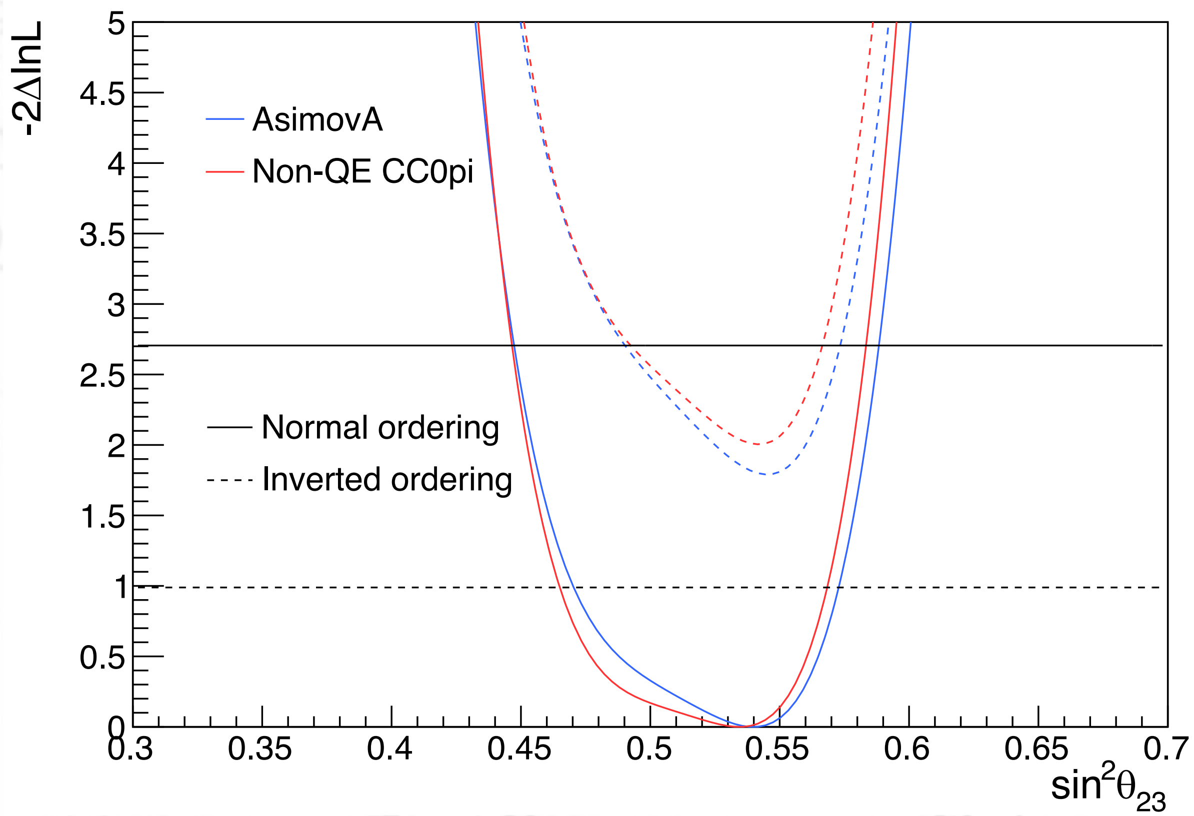
arXiv:1811.05487v1

Global Fits

Robustness tests

- Fit data simulated with alternate interaction models and check parameter bias
  - No significant biases seen on θ_{23}, θ_{13} or δ_{CP} from any of these alternate models
  - Small bias seen on Δm^2_{32}
    - an additional uncertainty of 1.4×10^{-5} was added to account for this
- Better treatment of nuclear removal energy systematic reduces the (old fake) large bias.





Oscillation fits

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T2K

$\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ combined analysis within the 3ν oscillation paradigm (PMNS).
Solar oscillation and θ_{13} parameters from 2018 PDG values.

Binned likelihood comparing data to MC predictions.

Bins of reconstructed energy from lepton kinematics assuming CCQE two body interactions.

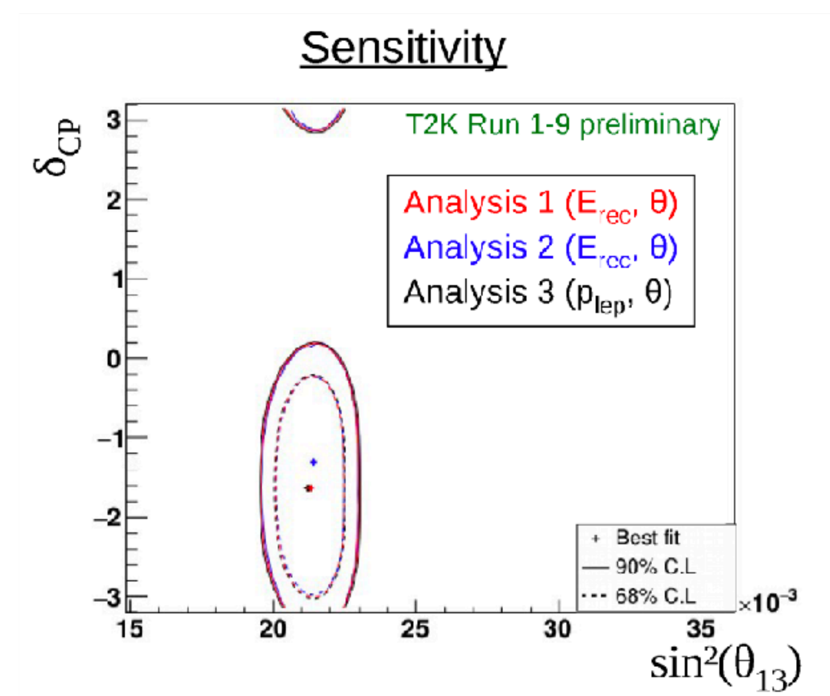
ν_e sample also bins in θ_e

$$-2\ln\lambda(\overline{\delta_{CP}};\boldsymbol{a}) = 2\sum_{i=1}^{N}\left[n_i^{\mathrm{obs}}\ln\left(\frac{n_i^{\mathrm{obs}}}{n_i^{\mathrm{exp}}}\right)+n_i^{\mathrm{exp}}-n_i^{\mathrm{obs}}\right] + (\boldsymbol{a}-\boldsymbol{a}_0)^T\mathbf{C}^{-1}(\boldsymbol{a}-\boldsymbol{a}_0)$$

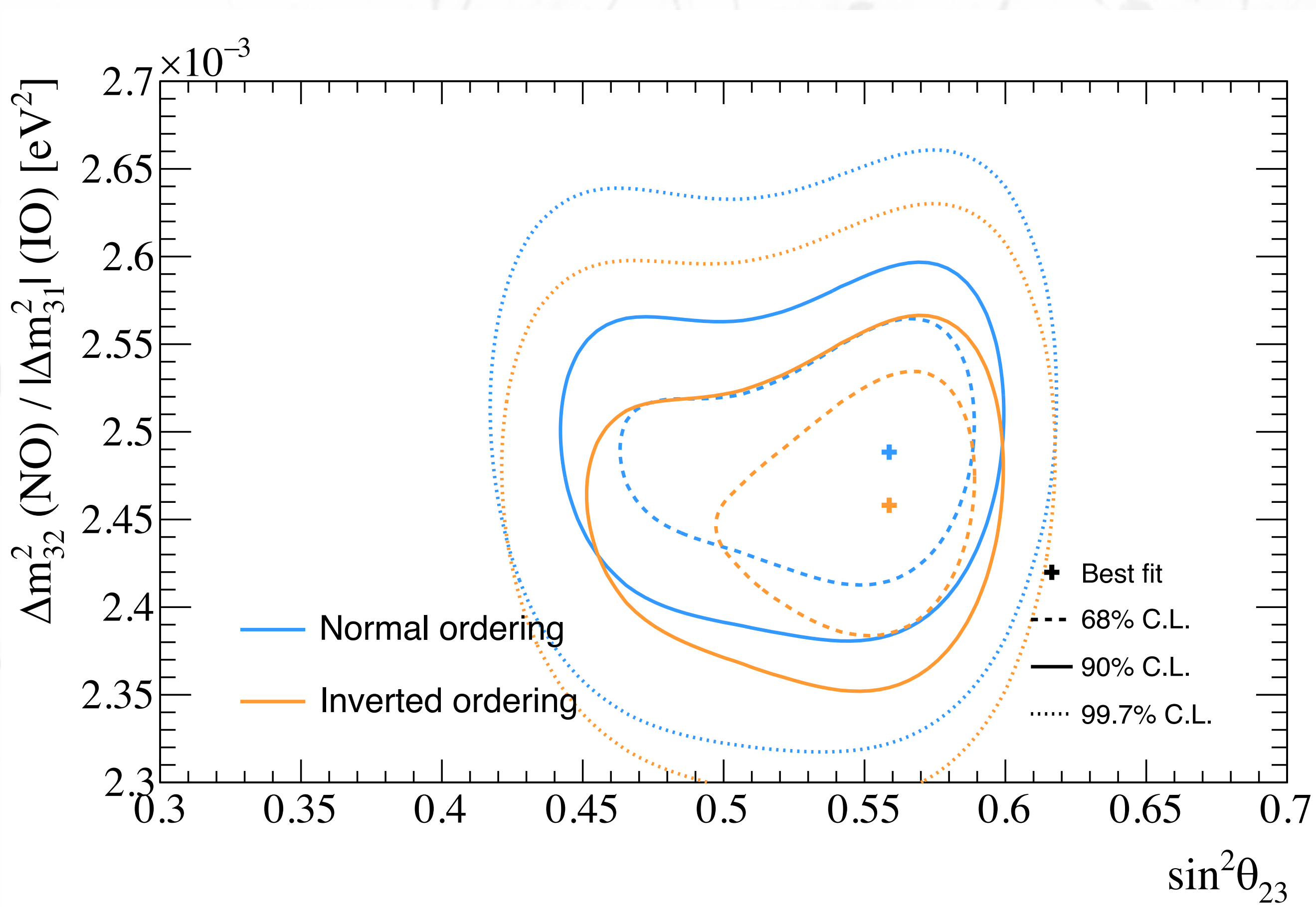
$$E_{rec} = \frac{ME_\mu - m_\mu^2/2}{M - E_\mu + |\vec{p}_\mu|\cos\theta_\mu}$$

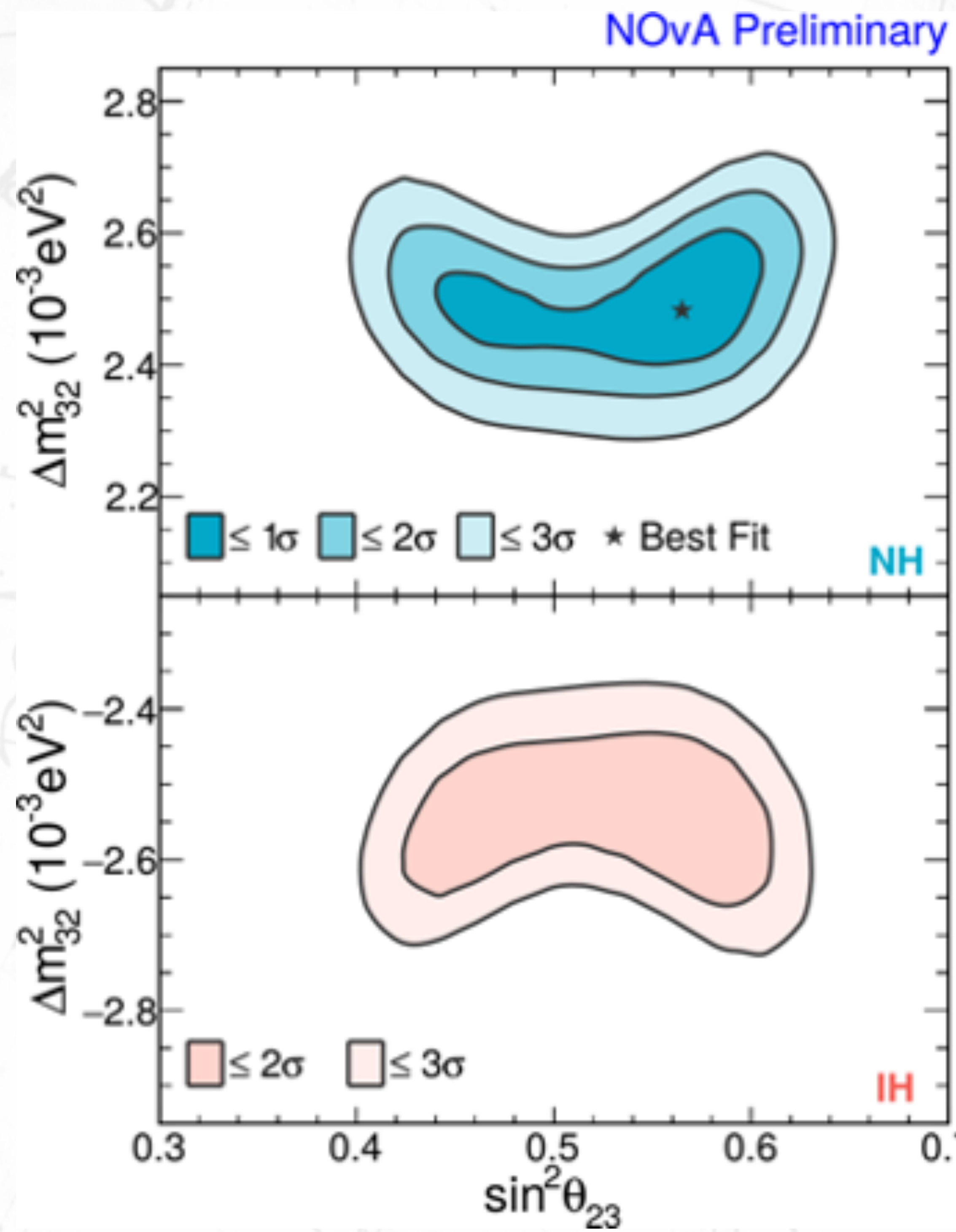
Three statistical methods
Bayesian Markov Chain MonteCarlo and two frequentist approach.

Frequentists confidence intervals (grid search) agree with the Bayesian factors and credible intervals.

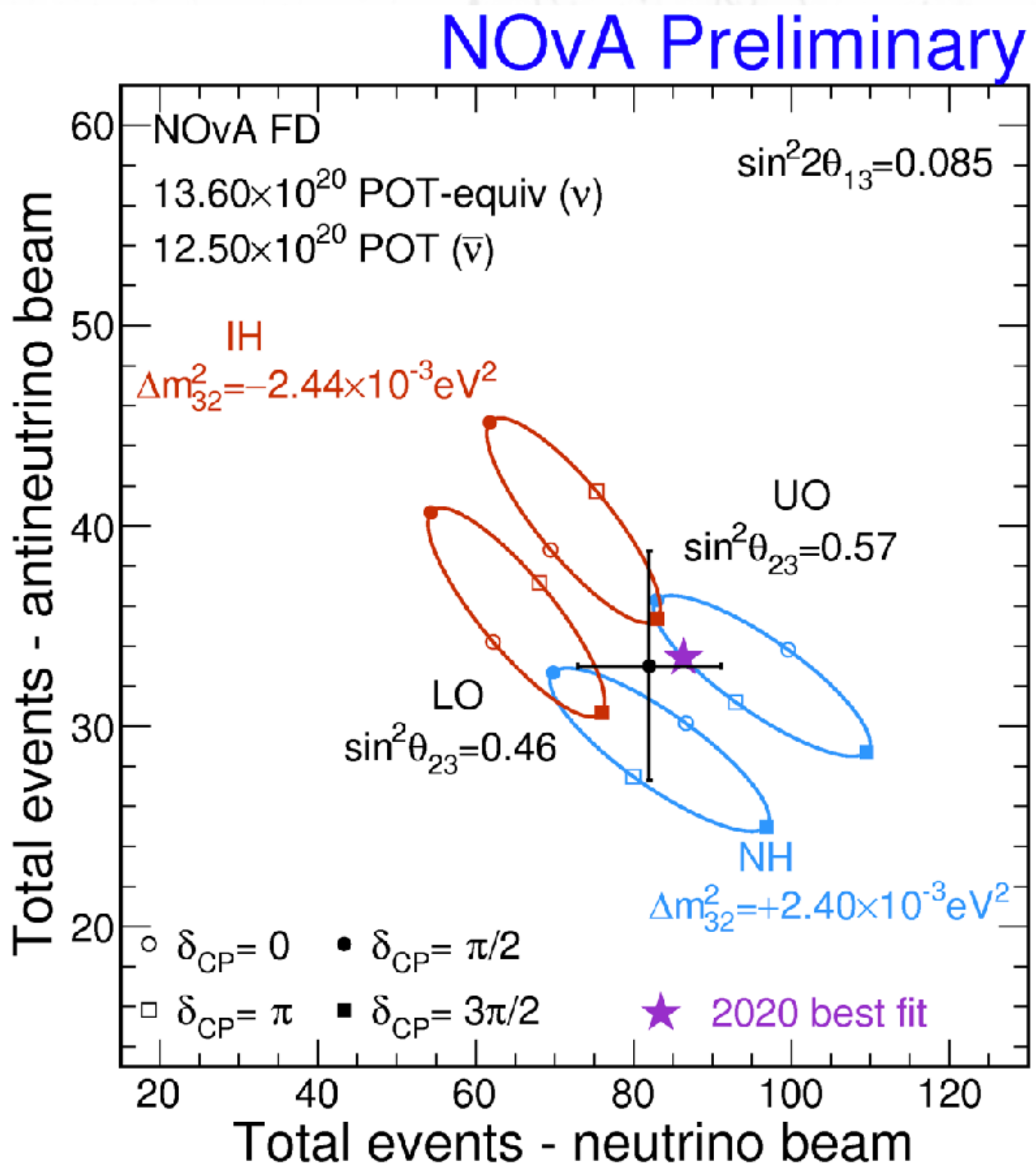


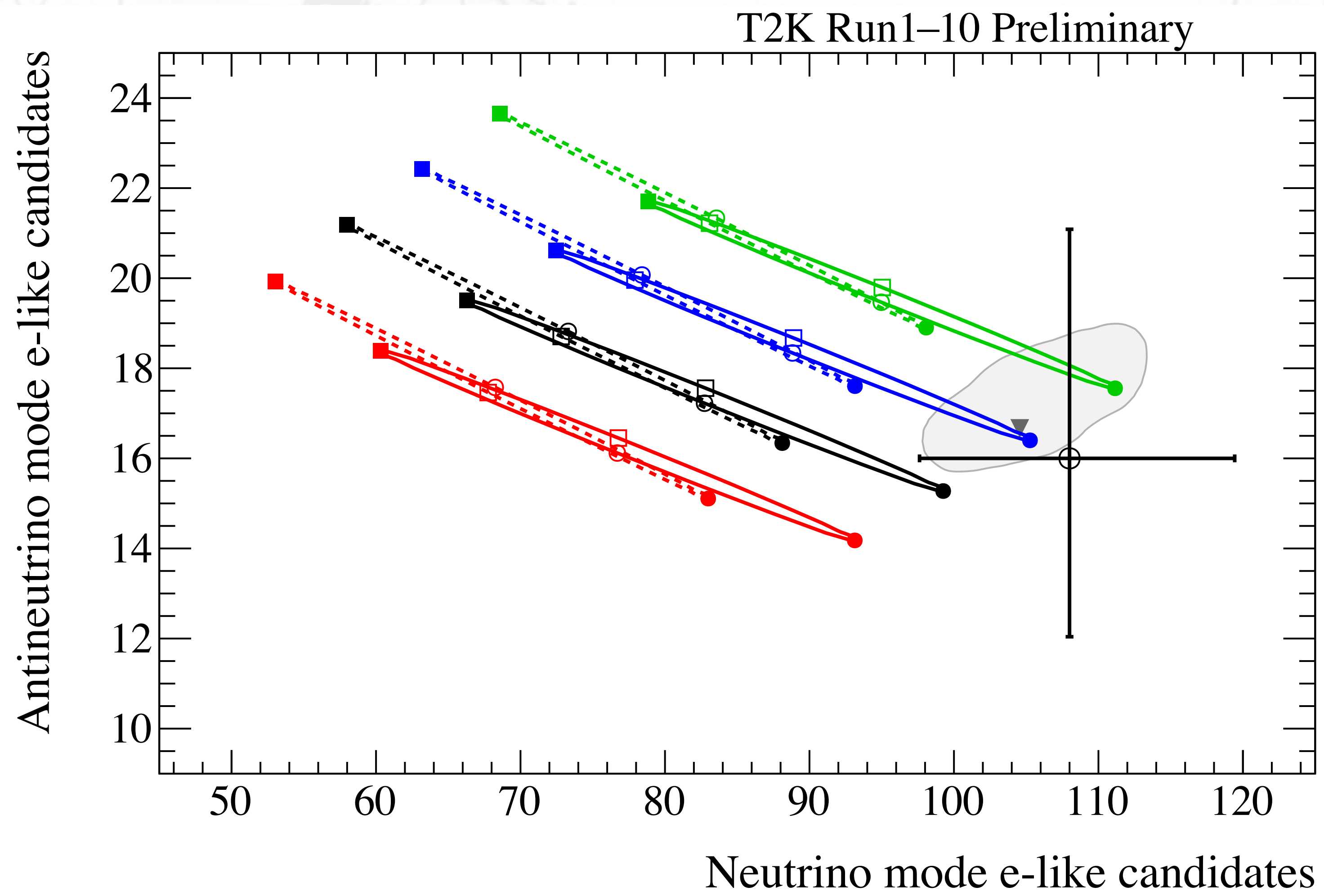
Nova vs T2K results





Nova results





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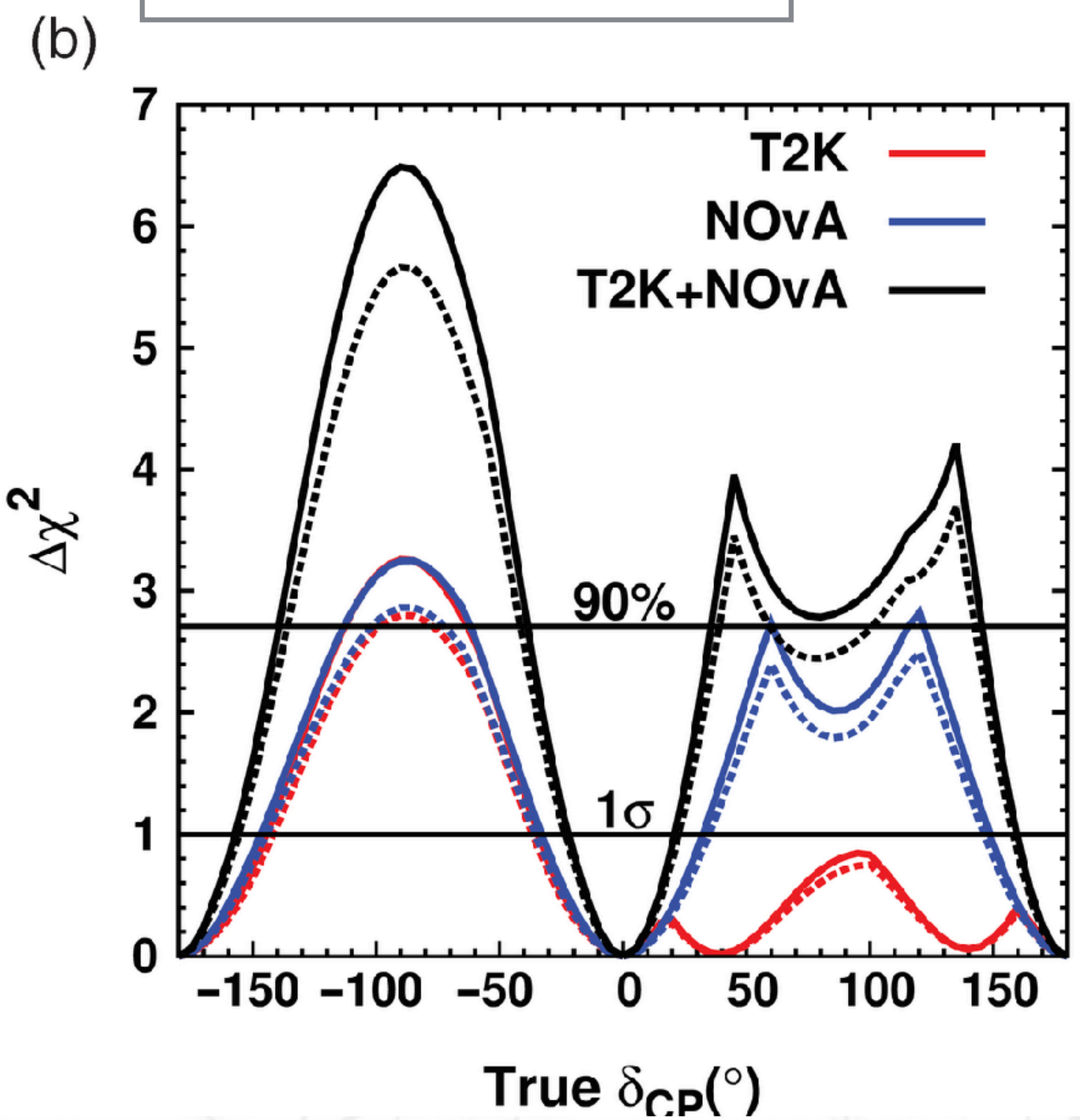
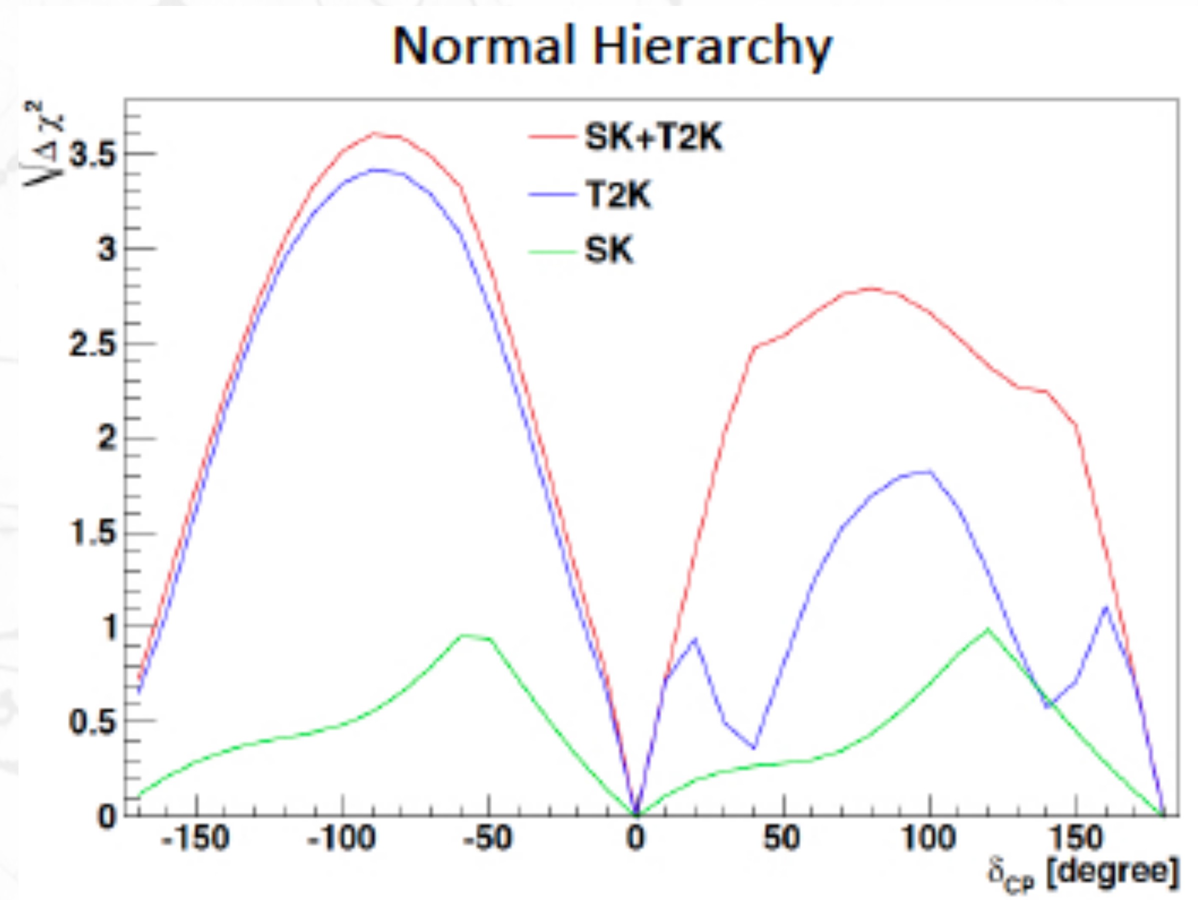
Combined analysis T2K

Sensitivity T2K+Nova

Progress of Theoretical and Experimental Physics,
Volume 2015, Issue 4,
April 2015, 043C01



Sensitivity T2K+SK



T2K formed working groups with Nova and SK to provide combined oscillation analyses

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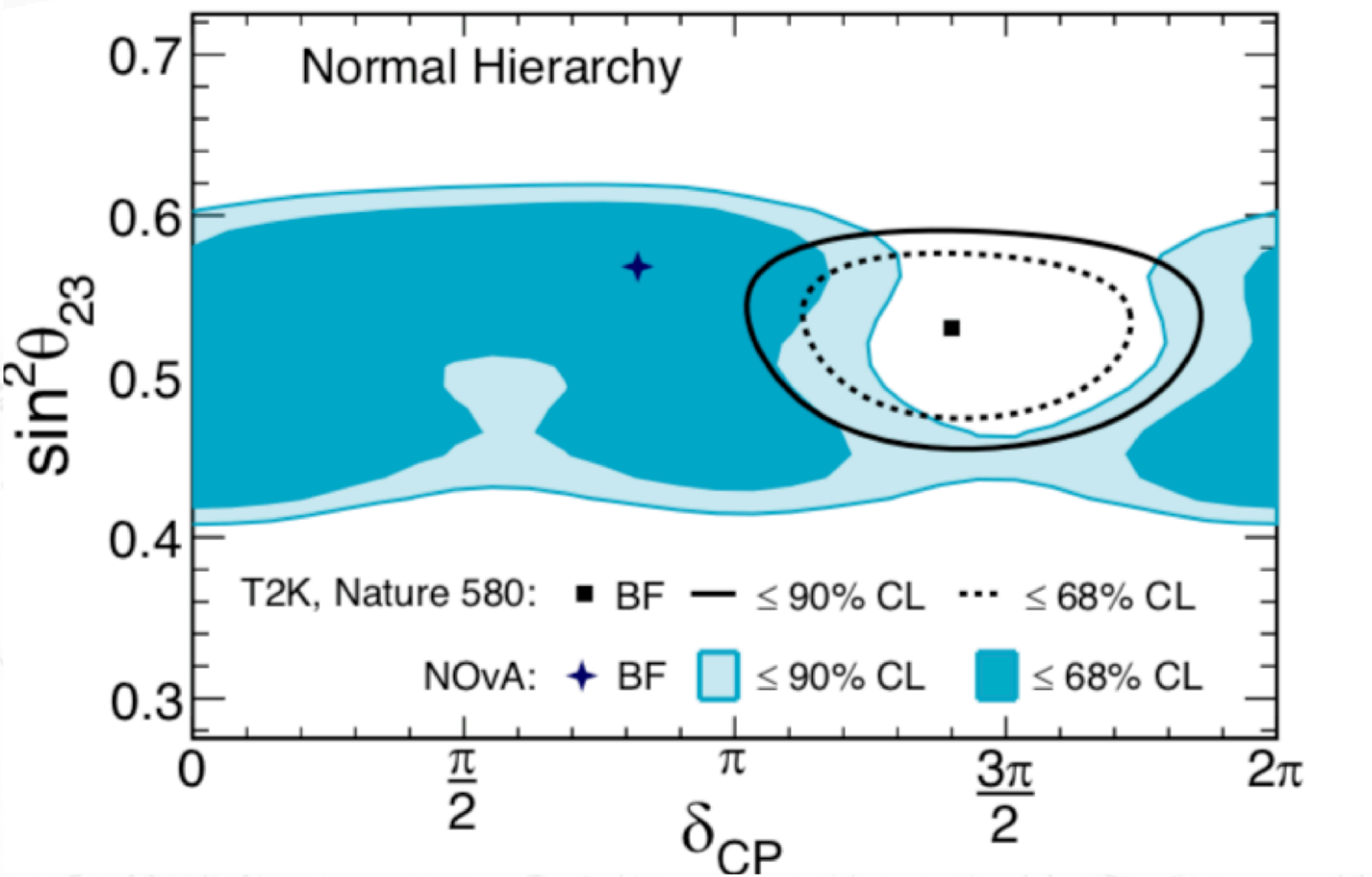
T2K vs Nova



Approx oscillation formulae

Appearance

$$P(\nu_\mu \rightarrow \nu_e) = 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2\Delta_{31} \times \left(1 \pm \frac{2a}{\Delta m_{31}^2}(1-s_{13}^2)\right)$$ Leading term

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

$$\mp 8c_{13}^2 s_{13}^2 s_{23}^2 \cos\Delta_{32}\sin\Delta_{31}\frac{aL}{4E}(1-2s_{13}^2)$$ Matter effect

$$\mp 8c_{13}^2 c_{12}c_{23}s_{12}s_{13}s_{23}\sin\delta\sin\Delta_{32}\sin\Delta_{31}\sin\Delta_{21}$$ CP Violating

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

ν vs. $\bar{\nu}$ sign change

$c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$ $\Delta_{ij} = \Delta m_{ij}^2 \frac{L}{4E_\nu}$ $a = 2\sqrt{2}G_F n_e E$

Disappearance

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - (\cos^4\theta_{13}\cdot\sin^2 2\theta_{23} + \sin^2 2\theta_{13}\cdot\sin^2\theta_{23})\cdot\sin^2\frac{\Delta m_{32}^2 \cdot L}{4E_\nu}$$

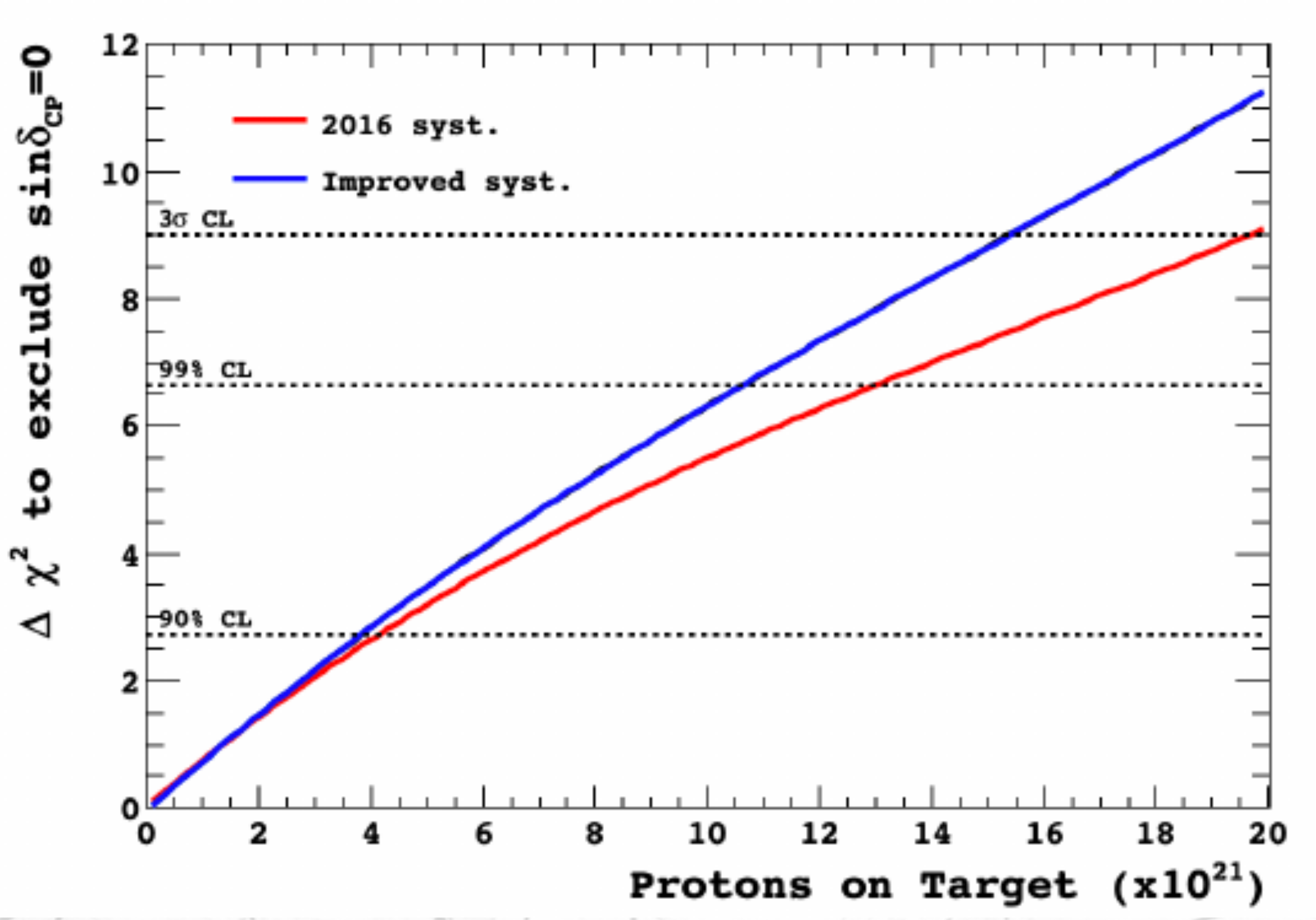
Statistical methods

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

Expected vs Data

	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = \pi/2$	$\delta_{CP} = \pi$	Data
FHC 1Rμ	346.61	345.90	346.57	347.38	318
RHC 1Rμ	135.80	135.45	135.81	136.19	137
FHC 1Re	96.55	81.59	66.89	81.85	94
RHC 1Re	16.56	18.81	20.75	18.49	16
FHC 1R ν_e CC1π^+	9.30	8.10	6.59	7.79	14
FHC 1Rμ ($E_{rec} < 1.2$ GeV)	209.14	208.80	209.11	209.57	191
RHC 1Rμ ($E_{rec} < 1.2$ GeV)	68.09	67.90	68.09	68.30	71

T2K: impact of ND



- T2K has still **significant x-section** systematic errors.
- T2K measurements are important for **HK**, **Dune**, **Nova** and **atmospheric neutrino oscillations.**

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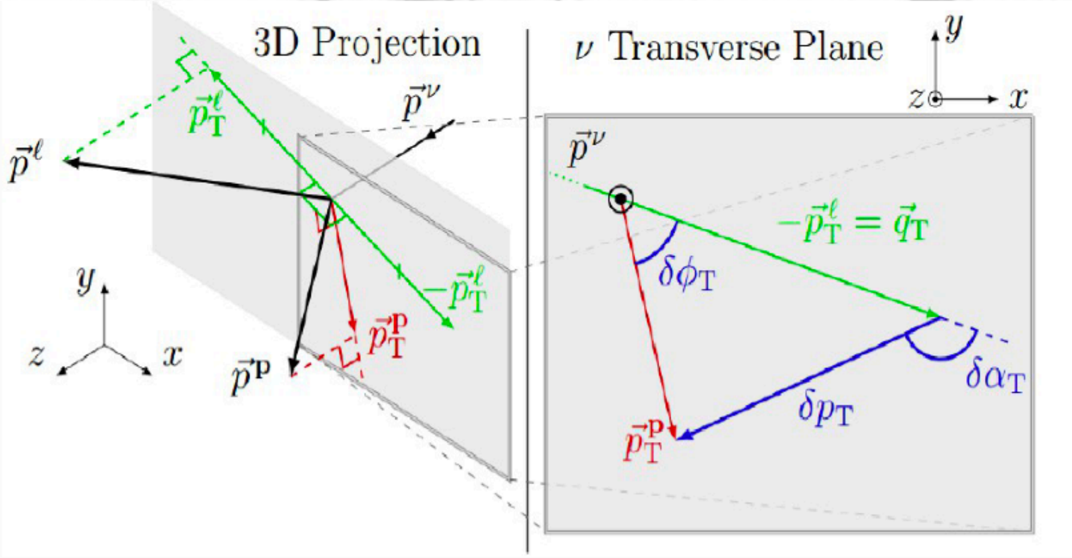
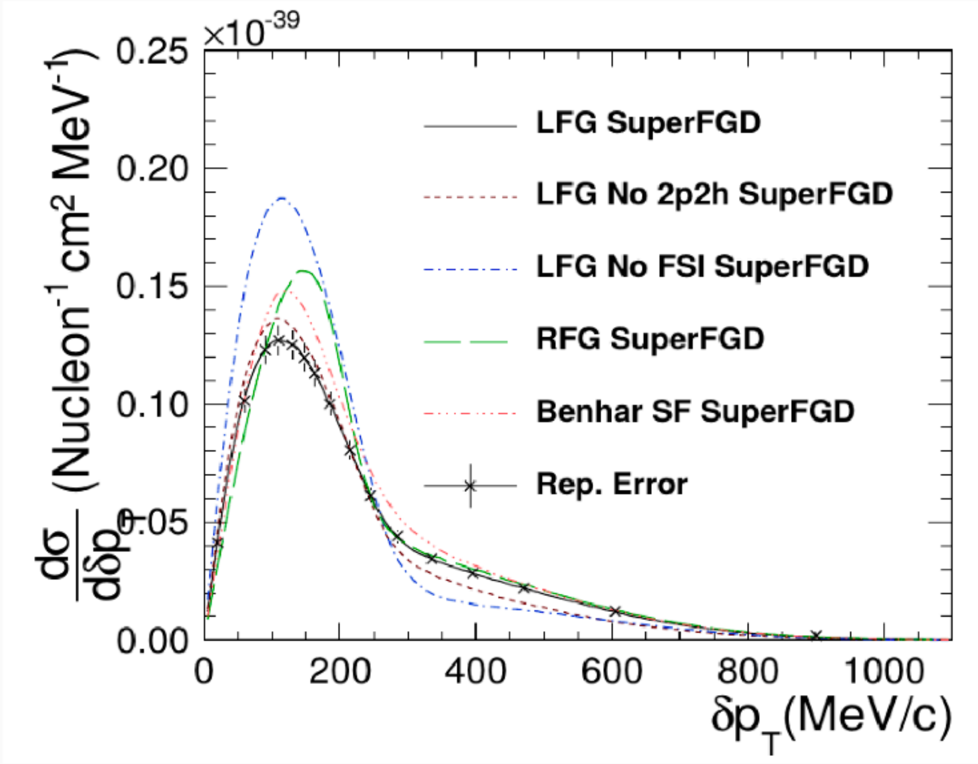
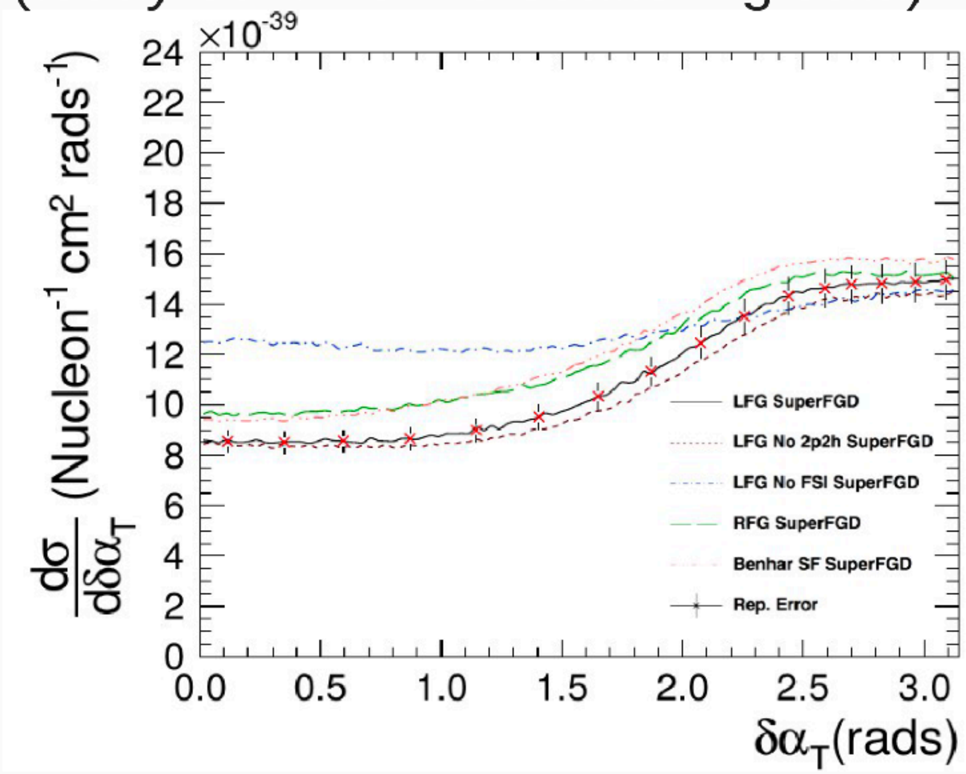
How to use this proton information:
“Single Transverse Variables” and beyond!
→ measurements of Fermi momentum, binding energy, 2p2h...



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



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

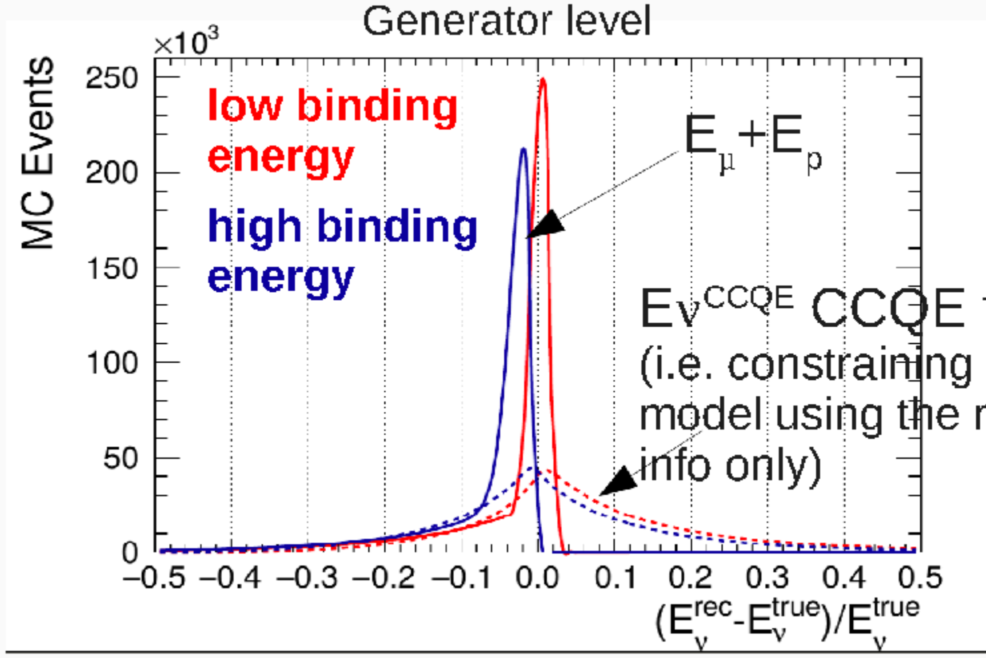


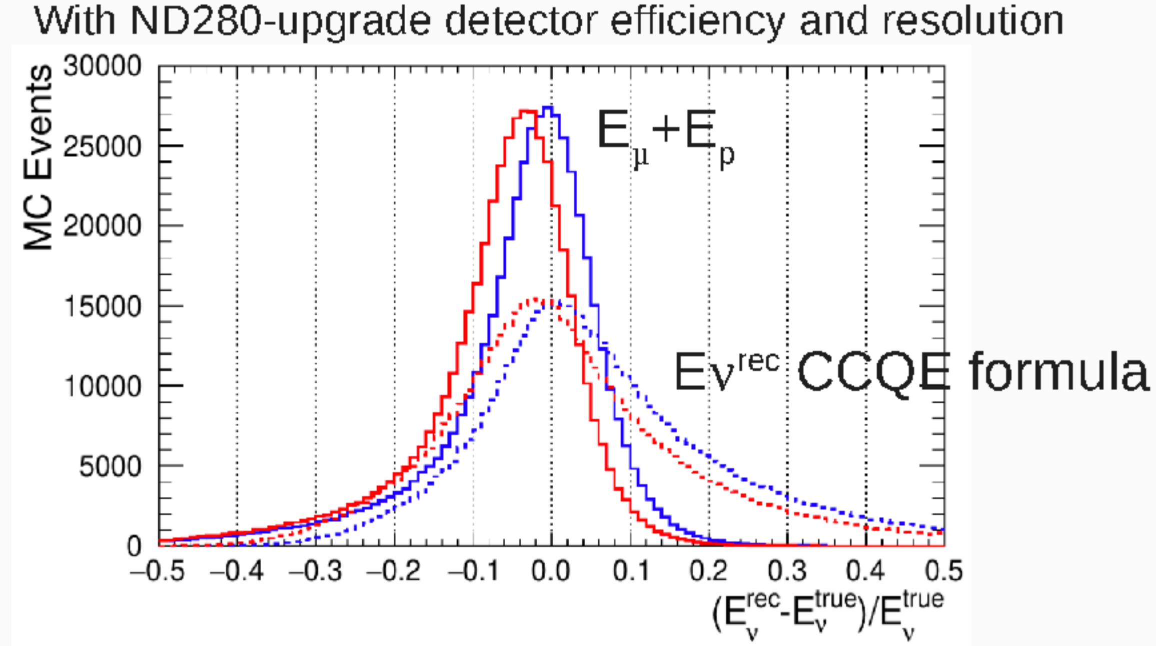
ND280 upgrade

T2K

Another variable: total energy

- The Eν^rec CCQE formula does not include information on the outgoing proton → Eμ+Ep is a much better estimator of the true neutrino energy





Smearing of Eν^rec is dominated by Fermi momentum,

smearing of Eμ+Ep is dominated by flux (and detector effects)

→ **Eμ+Ep is a much more robust estimator of true Eν and of binding energy**

- **This is just the appetizer! We are starting investigating possible other variables and combinations → a lot of new sensitivity**

A good example of the 'iterative' process: new detector + *DATA* → new ways of doing analysis / looking at our systematics → improvements of oscillation analysis!

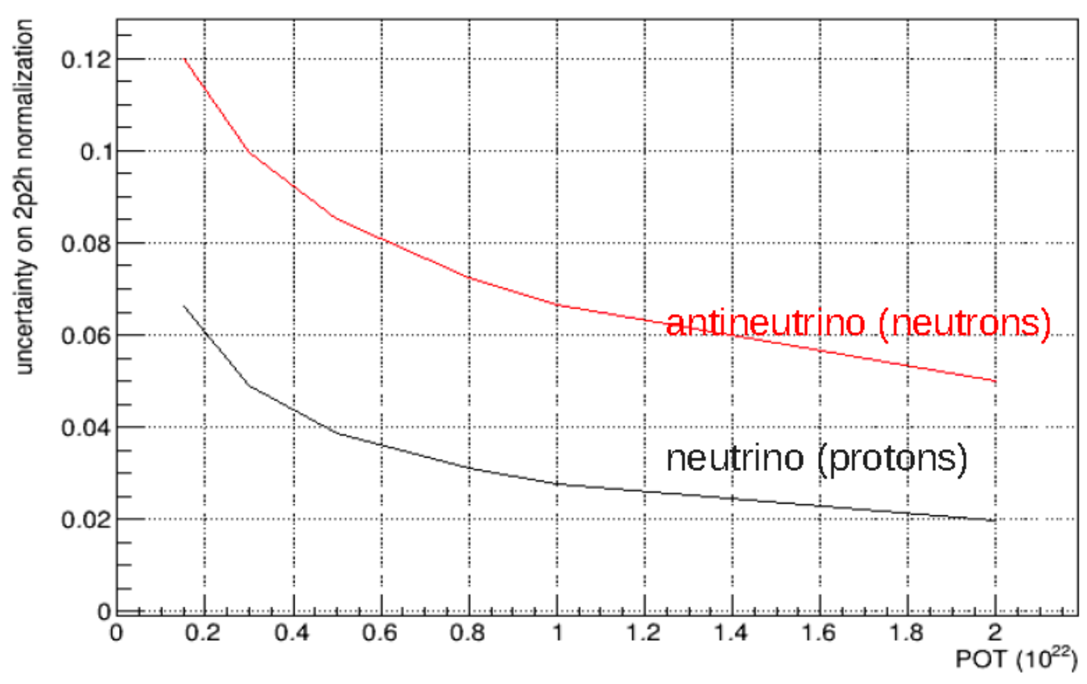
SuperFGD: neutrons

- The superFGD can detect neutrons with ~60% efficiency

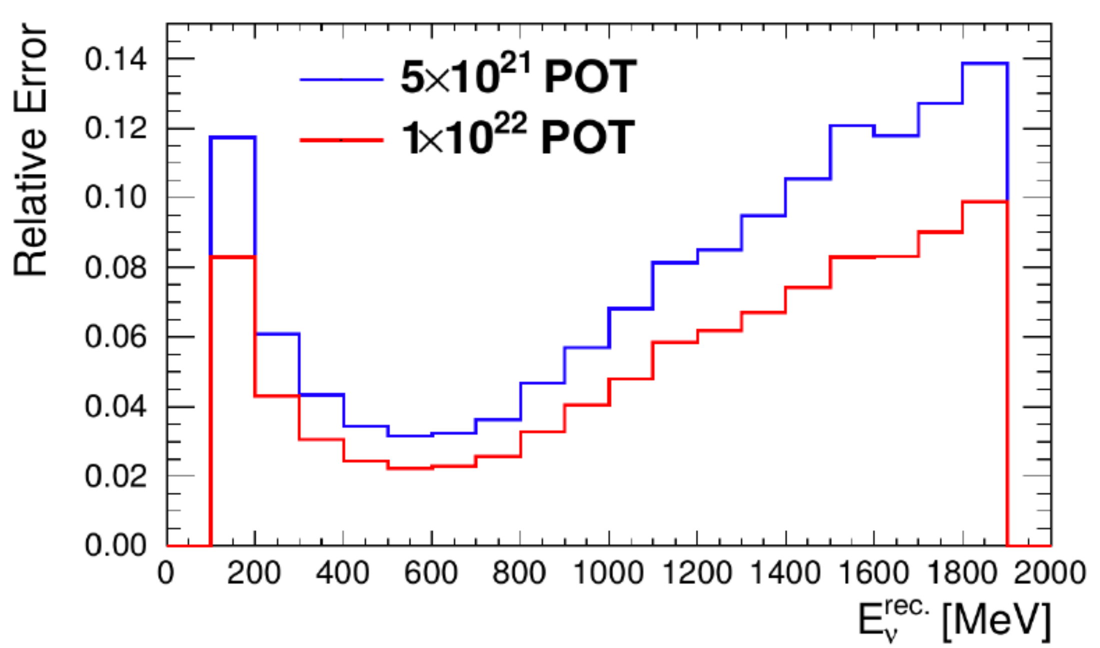
- If the path is long enough (>50 cm) also neutron energy is measured with resolution 15-30%
(to be calibrated with neutron test-beam at LosAlamos)

- The background can be rejected by reducing the fiducial volume (no reliable simulation available yet)

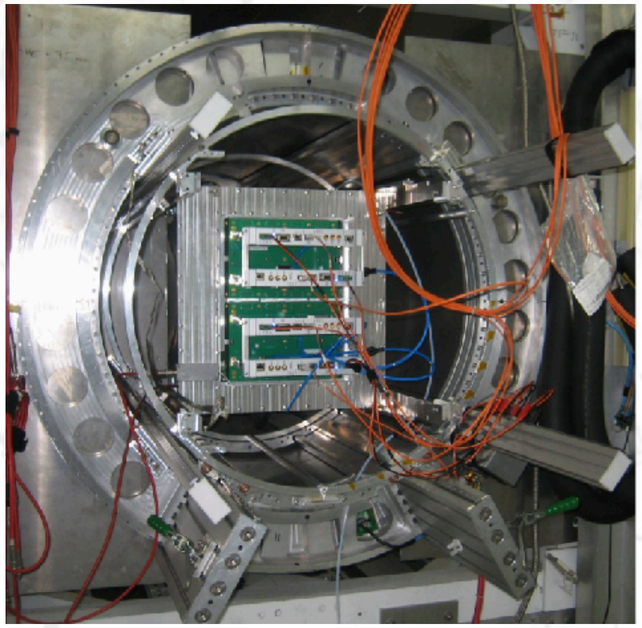
The same analyses shown for protons can be repeated for neutrons.
Example of fitting single transverse variables



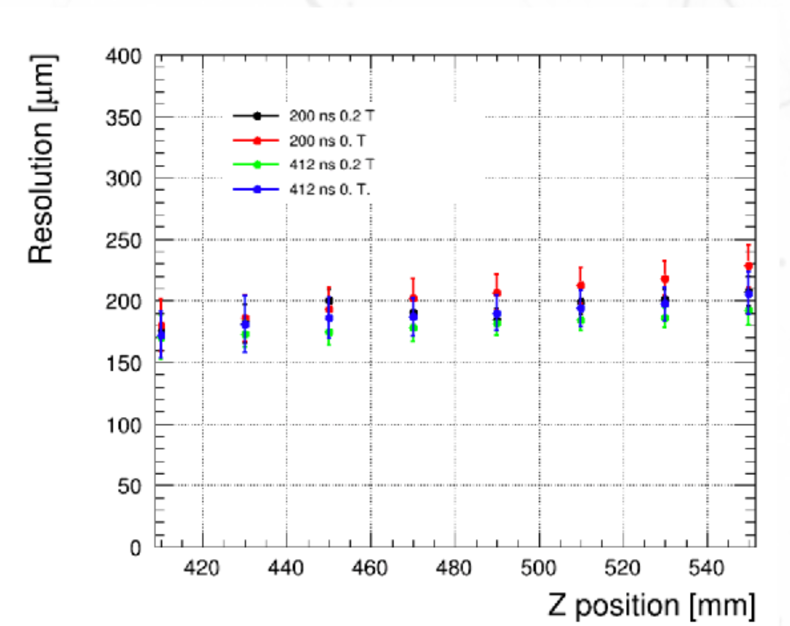
A lot of interesting physics with neutron tagging (e.g. DSNB, increased atm MH sensitivity)
→ e.g. neutron multiplicity as a function of neutrino energy



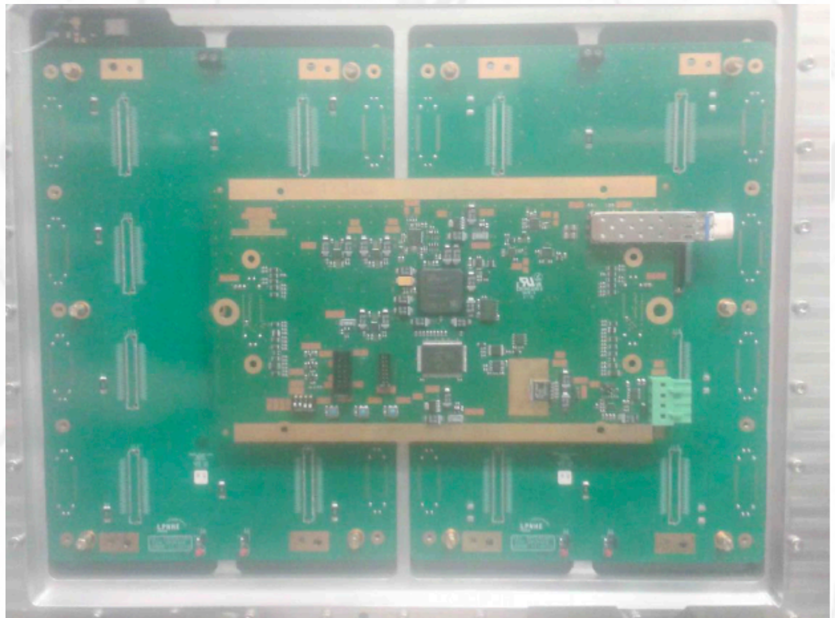
HA-TPC @DESY

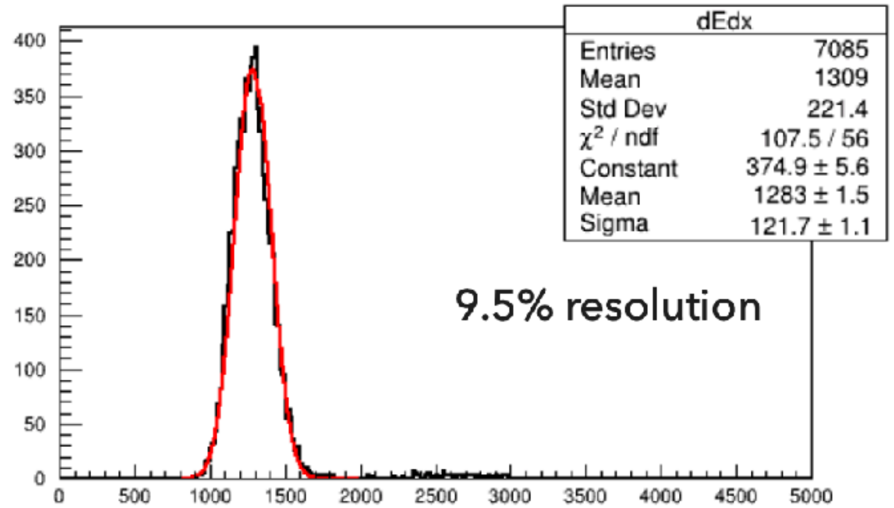


- Test Beam with Resistive MicroMegas at DESY in June 2019
  - 4 GeV electrons, analysis on-going
  - Excellent spatial resolution (~200 µm for horizontal tracks) and dE/dx resolution

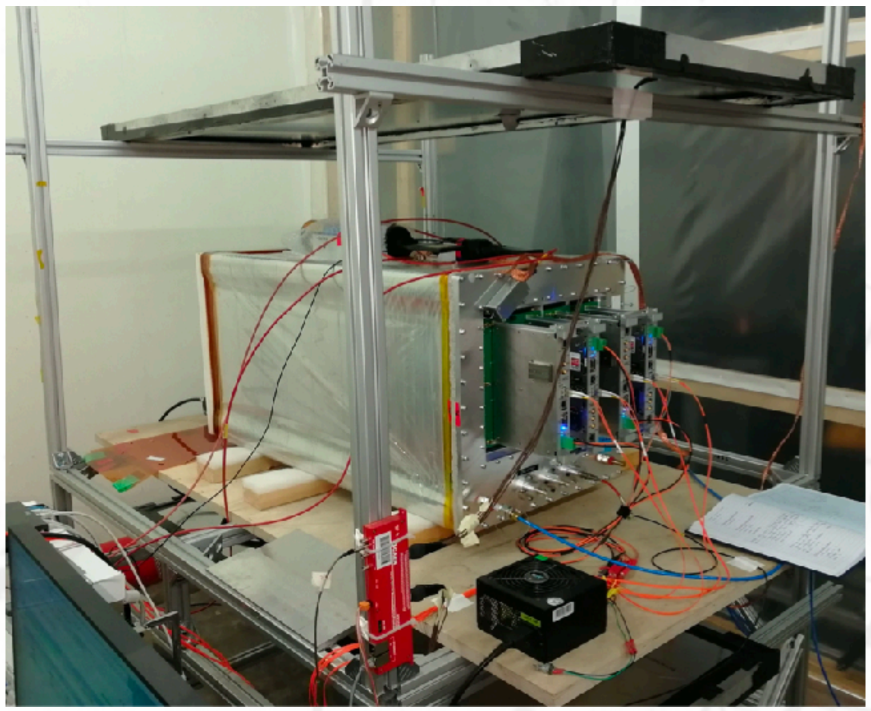


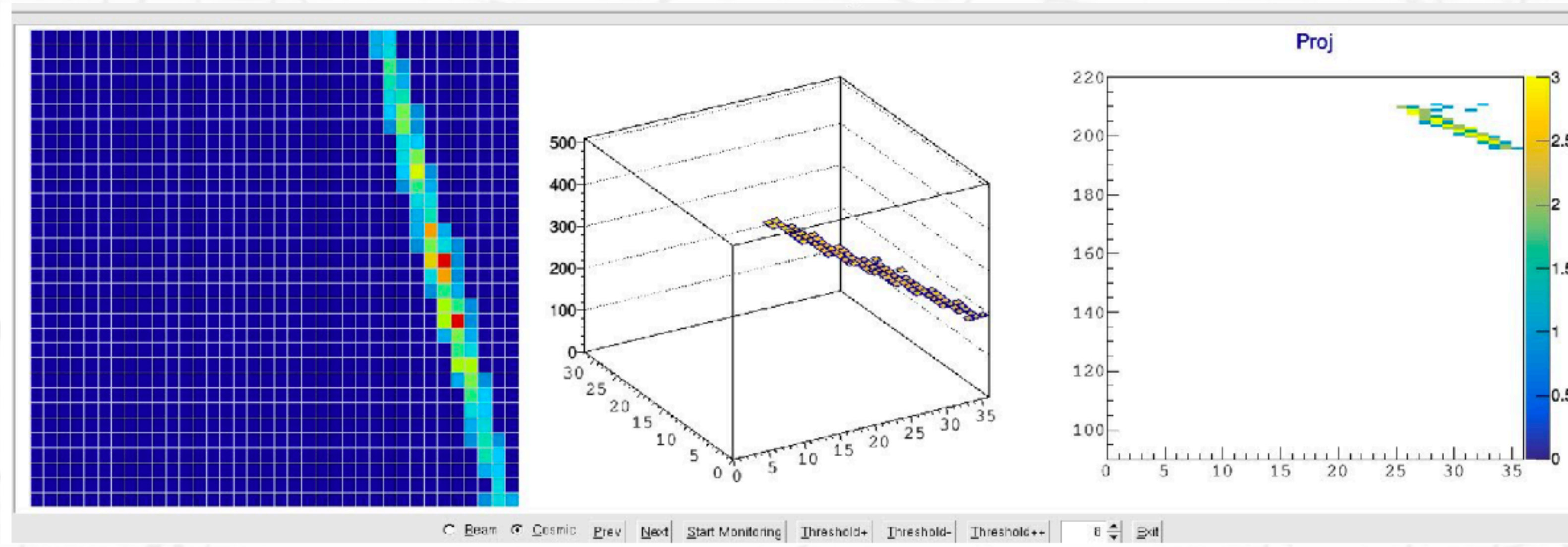
- HA-TPC electronics:
  - First Front-End mezzanine (FEM) prototype has been tested
  - First Front-End-Card (FEC) will be delivered in Jan 2020

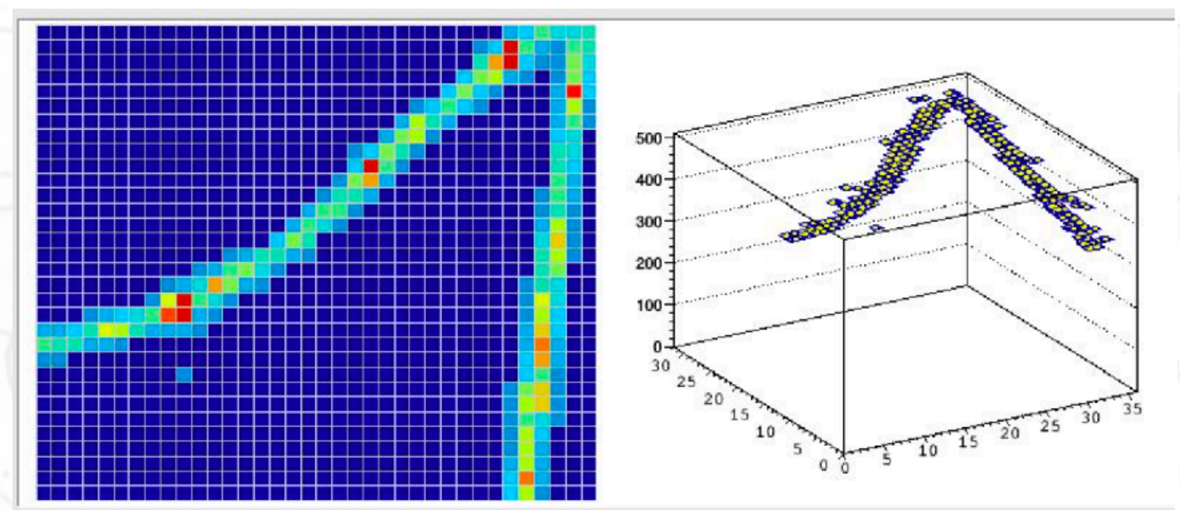




HA-TPC prototype @ CERN





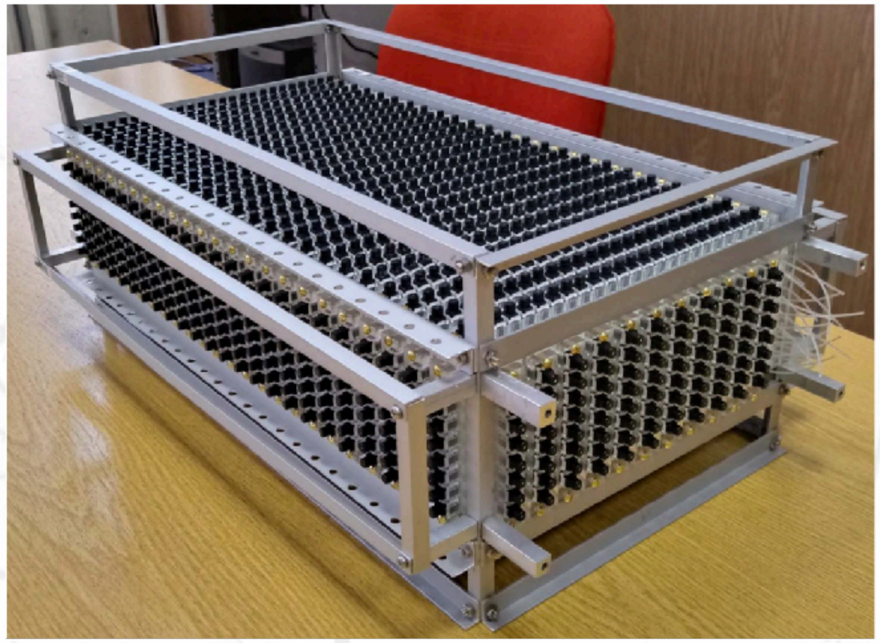


- Stable operation at 18 kV
- 2nd prototype to improve gas leak rate expected in Feb 2020
- First TPC field cage expected in June
    - External review committee for the TPC field cage design has been formed → expect 1st meeting in January

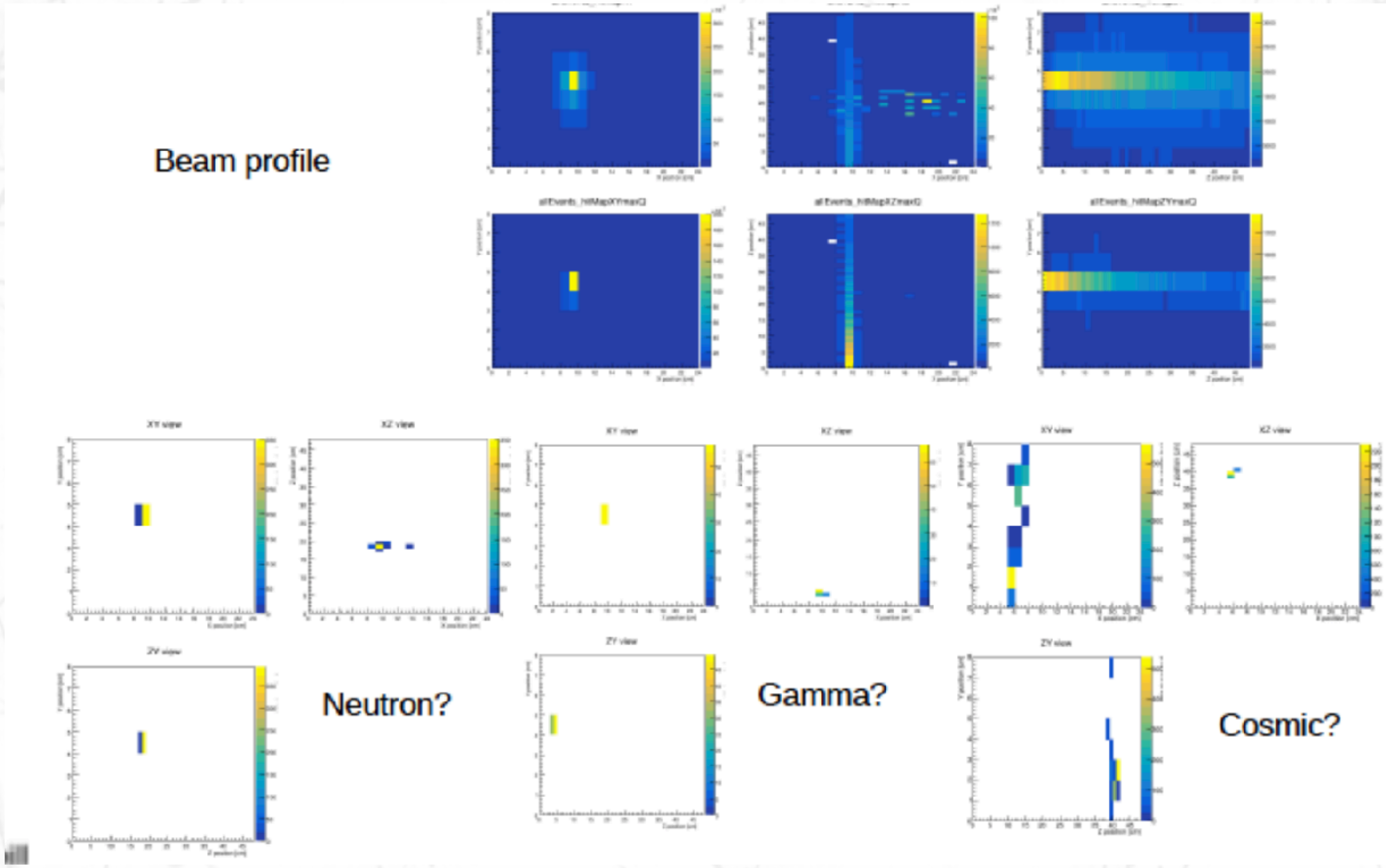
Super-FGD

- Assembly with Fishing Line at INR ➞
  - 27 full size (192 x 184 cubes) x-y layers assembled
  - 56 z layers (15 x 192 cubes) ➞ corresponding to the full height of the Super-FGD
  - All cubes will be produced by Jan 2021
  - Review to discuss feasibility of assembly method organized by T2K ➞ Fishing-Line method has been chosen as primary option for the assembly
  - Design of the Super-FGD electronics is on-going ➞ all CITIROC chips have been bought

Super-FGD prototype neutron tests at LANL

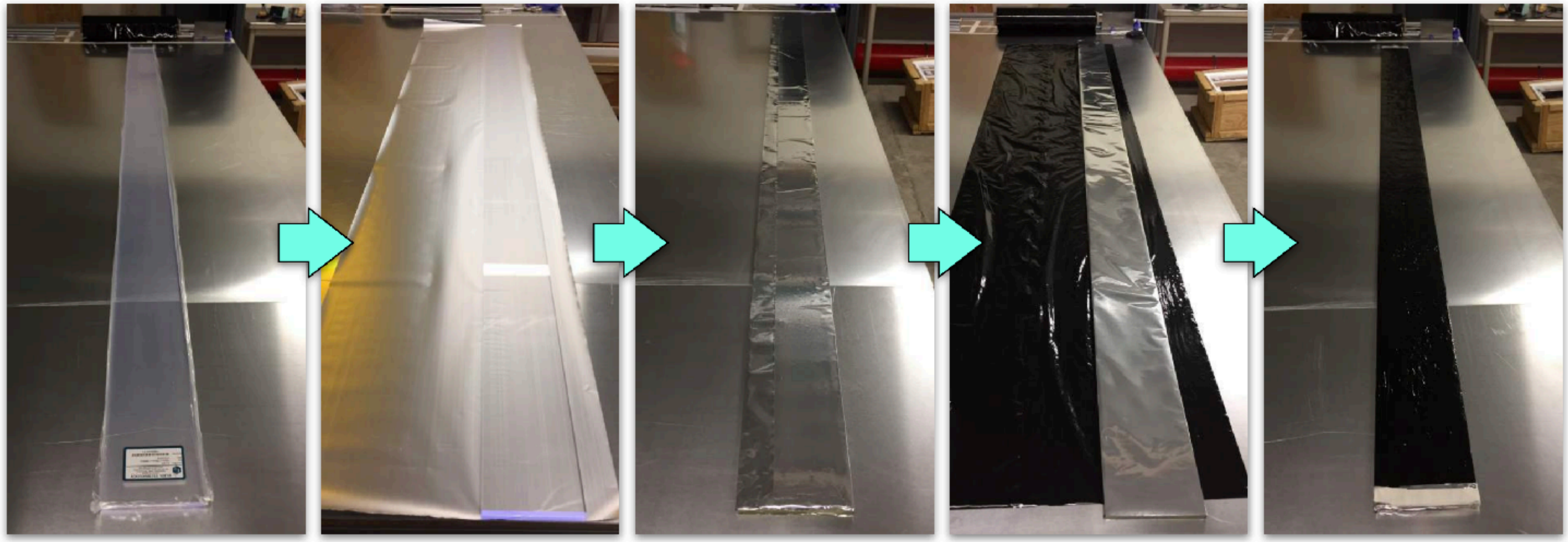


- Data taking in December
- Neutron beam profile clearly visible
- Analysis of the data is on-going



Time Of Flight

- Start assemblying scintillator bars
- Most of the components already received
- First ToF module assembled



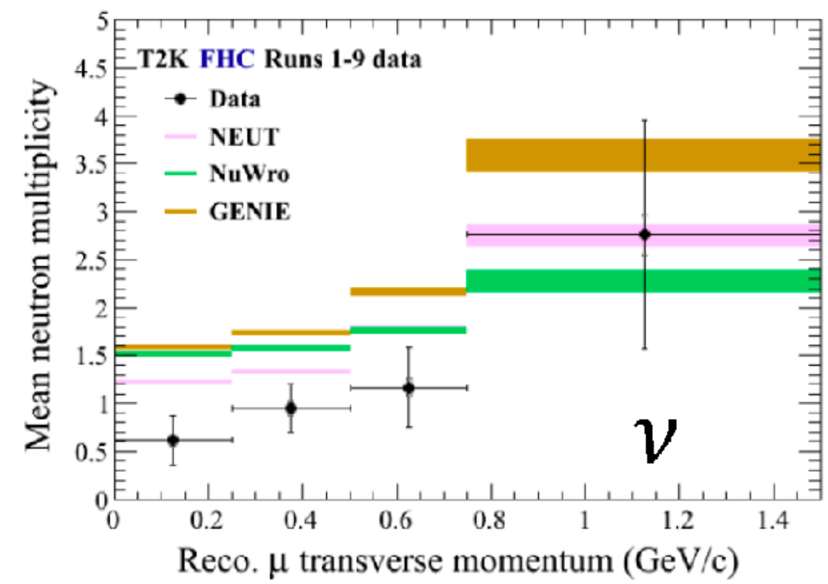
3 layers of Al foil + 6 layers of black stretch film

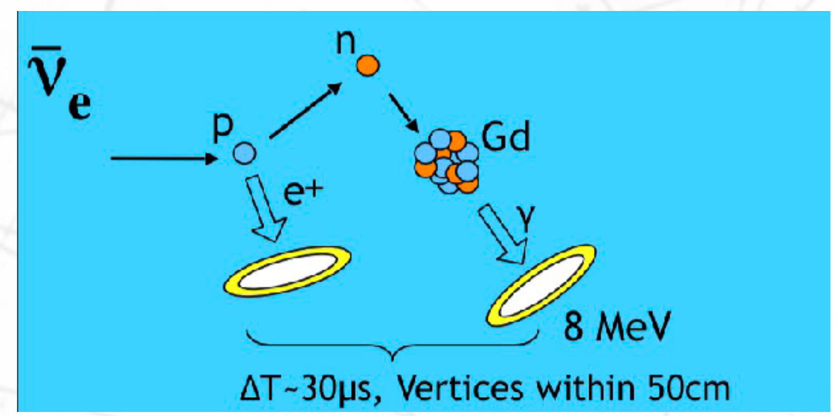
- Mock-up basket

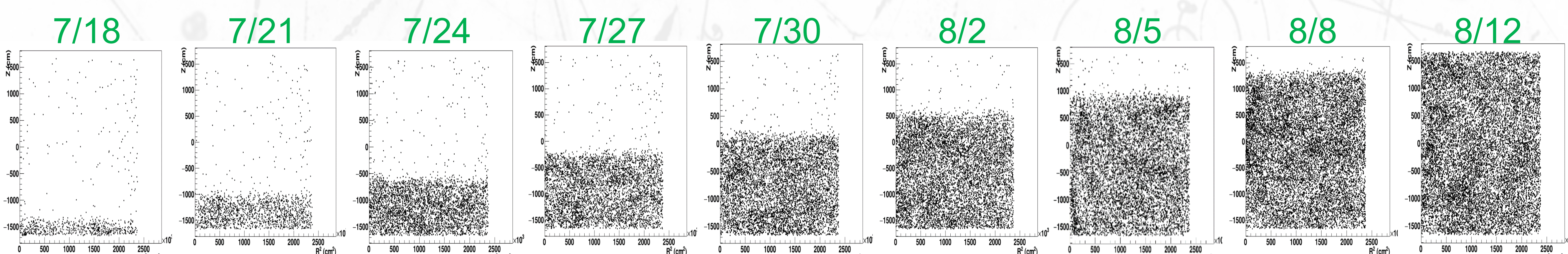
- The 6 ToF modules will be installed into the “mini basket” that has been delivered to CERN
    - Mock-up of the upstream part of the real ND280 basket
    - It will be used to test integration of the different sub-detectors

SK Gadolinium

- SK Gadolinium project
  - enhance neutron detection to improve low-energy ν_e detection (non-T2K goal).
  - may provide wrong-sign background constraint in $\bar{\nu}_e$
    - more exclusive data samples.
- Leak repairs to SK tank finished in 2019.
- Load $Gd_2(SO_4)_3$ in stages up to 0.2%.
- Loading completed in 2020.





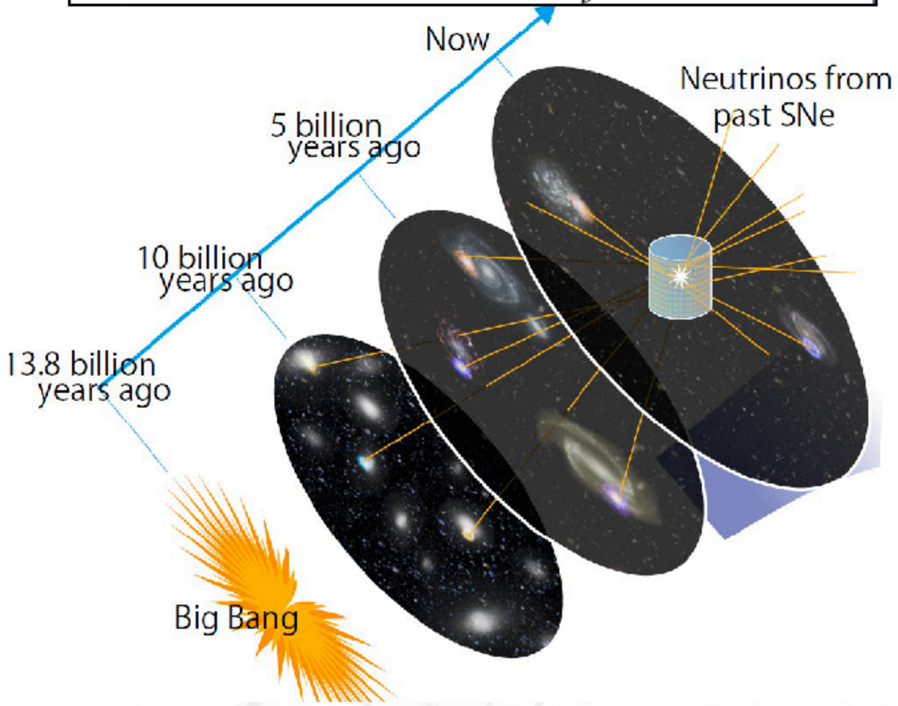


SK-Gd

Diffused Supernova Neutrino Backgrounds

- Neutrinos produced from the past SN bursts and diffused in the current universe.
  - ~ a few SN explosions every second → $O(10^{18})$ SNe so far in this universe
  - Can study history of SN bursts with neutrinos

$$\frac{dF_\nu}{dE_\nu} = c\int_0^{z_{\max}} R_{\rm SN}(z)\frac{dN_\nu(E'_\nu)}{dE'_\nu}(1+z)\frac{dt}{dz}dz$$

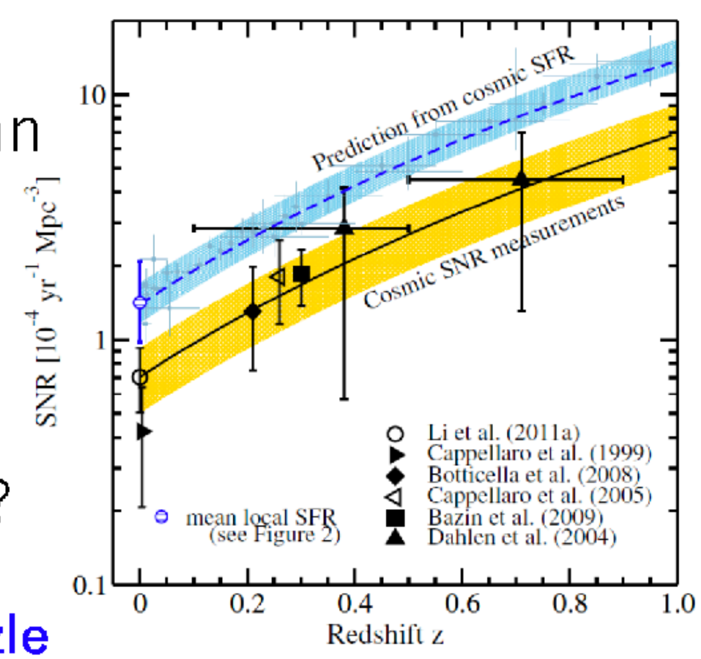


SN rate problem

- Observed SN burst rate lower than prediction from cosmic star formation rate
  - Invisible dim supernova?
  - Black-hole formation?
  - Something blocking optical light?

DSNB signal could resolve the puzzle

H. Horiuchi et al, Astrophys. J. **738**, 154 (2011)

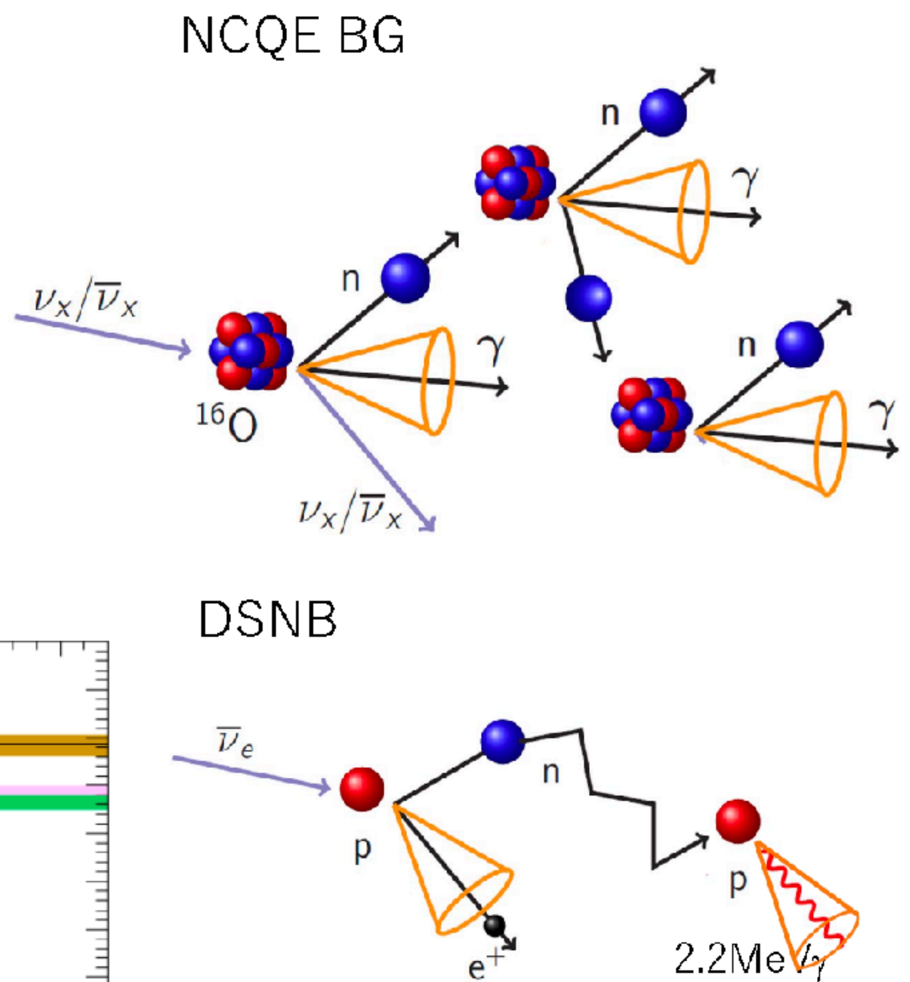


SK-Gd

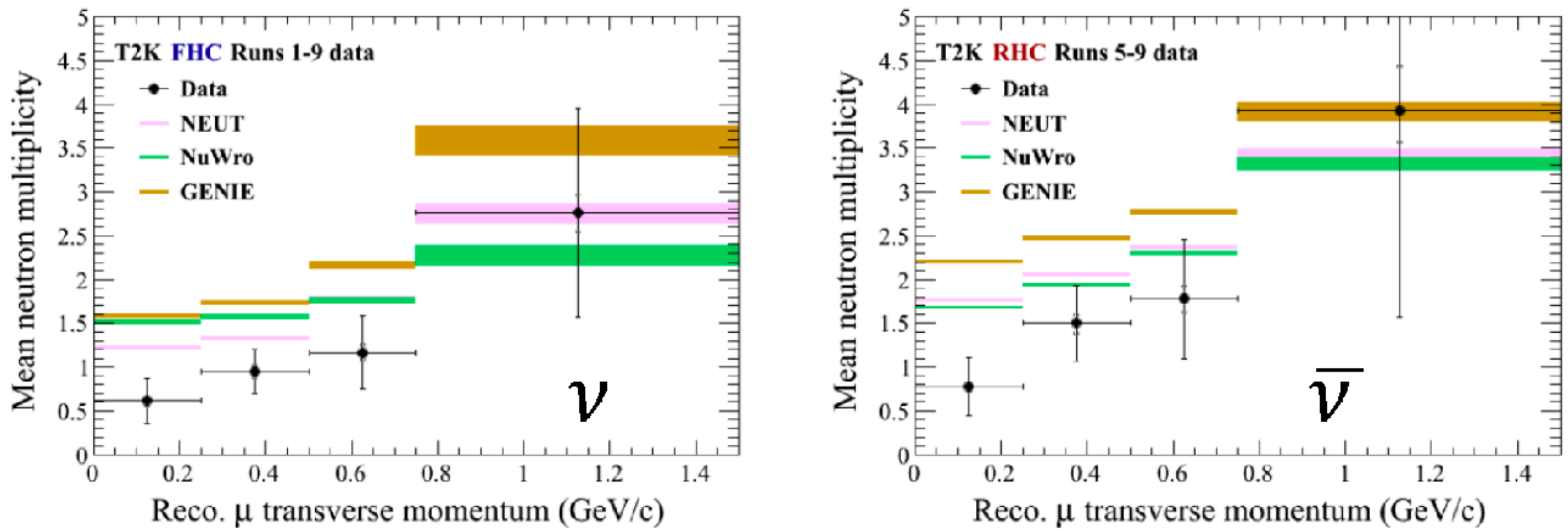
NCQE measurements with T2K

- Another important data: Neutron multiplicity

Multiple neutrons produced through hadronic final-state interactions (FSI) in nuclei, and secondary interactions (SI) in the detector medium ➡ Key to reduce NCQE BG



Measured mean neutron multiplicity (CC) and MC predictions

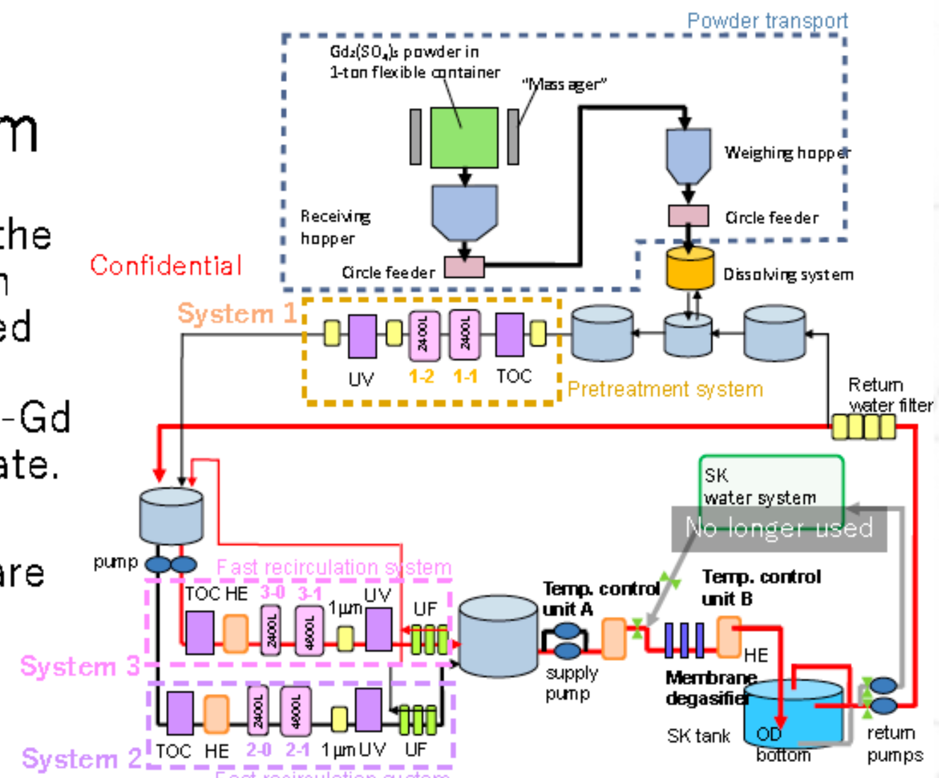


Large discrepancy causes ~44% systematic error for NCQE BG estimation

SK-Gd

Migration of the water system

- Since Dec. 24, 2019, the SK pure water system has been disconnected from the recirculation loop and the new SK-Gd is in use with 60t/h rate.
- Specially developed resins for $Gd_2(SO_4)_3$ are under final test.
- Full 120t/h power is under preparation



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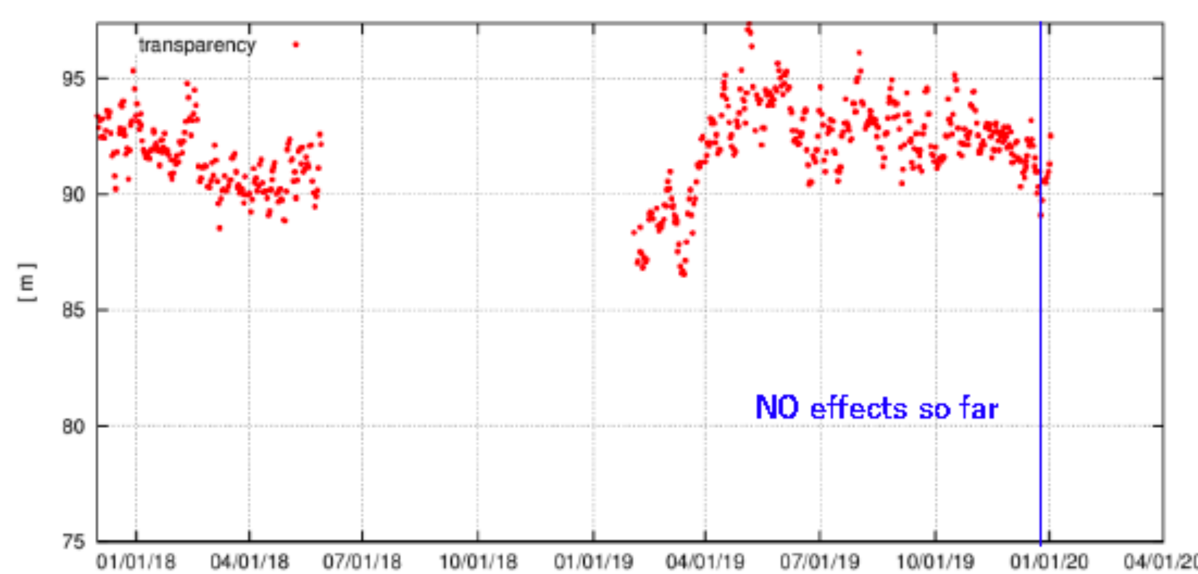
The water transparency

- After 2 weeks of SK-Gd water system operation



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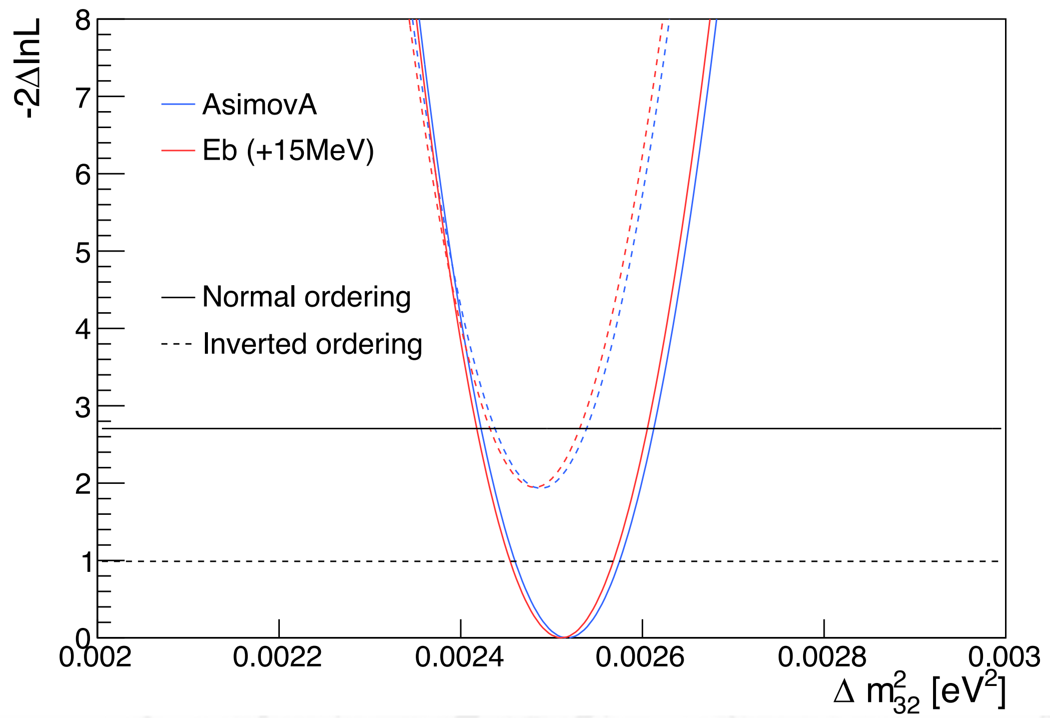
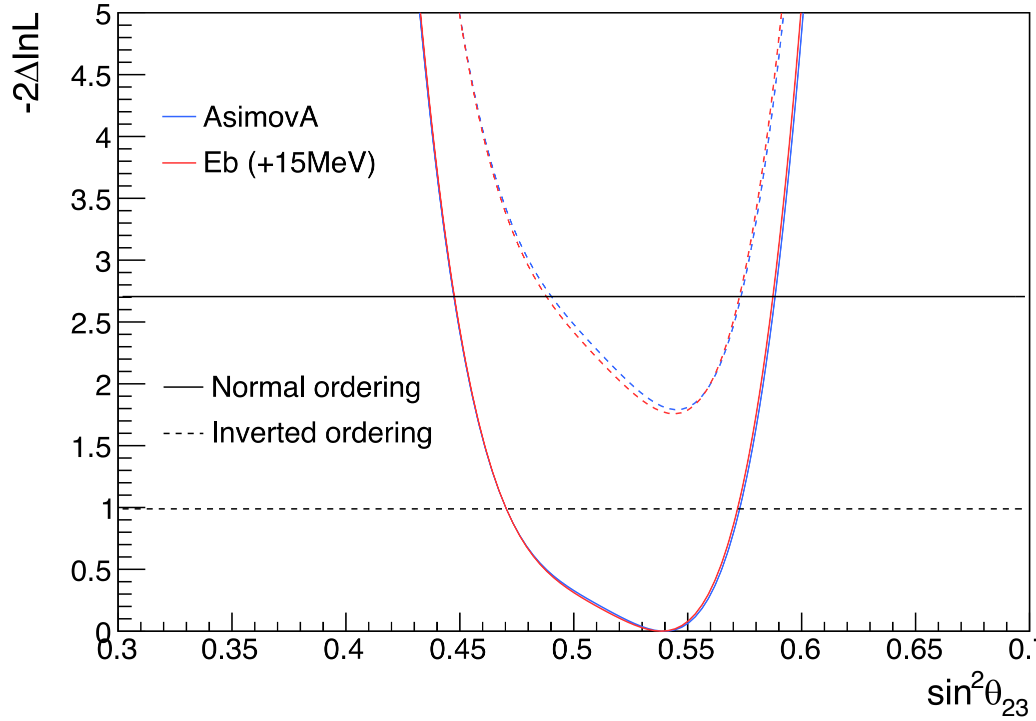
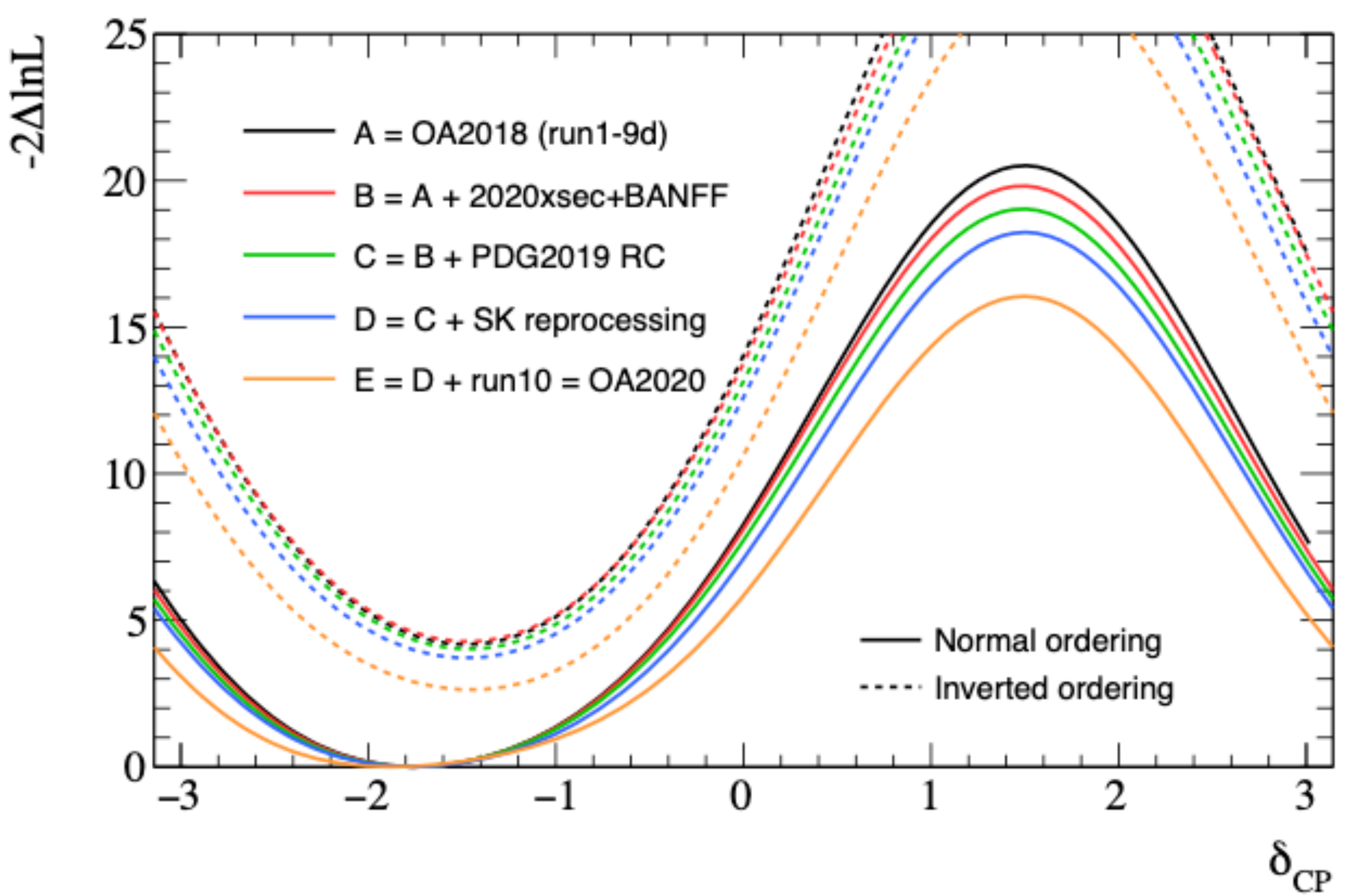
Removal Energy robustness





Changes from 2009 and 2010

Main change is coming from data fluctuations in 2010

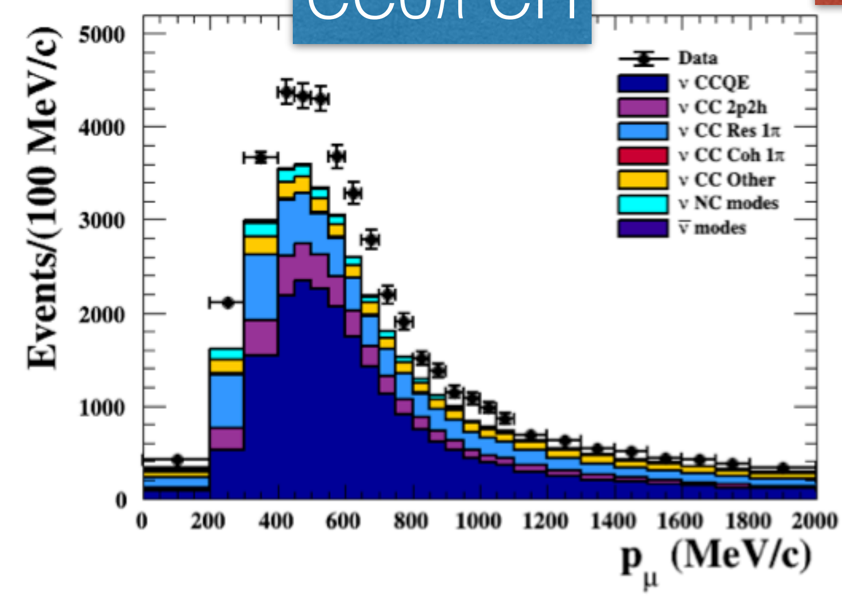


FHC is ν-mode
RHC is $\bar{\nu}$-mode

FHC

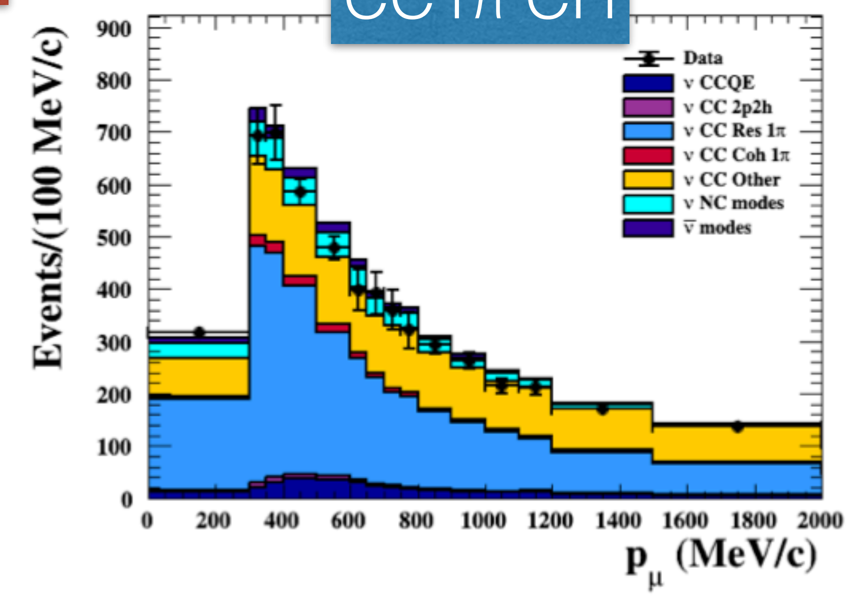
Pre-fit

CC0π CH



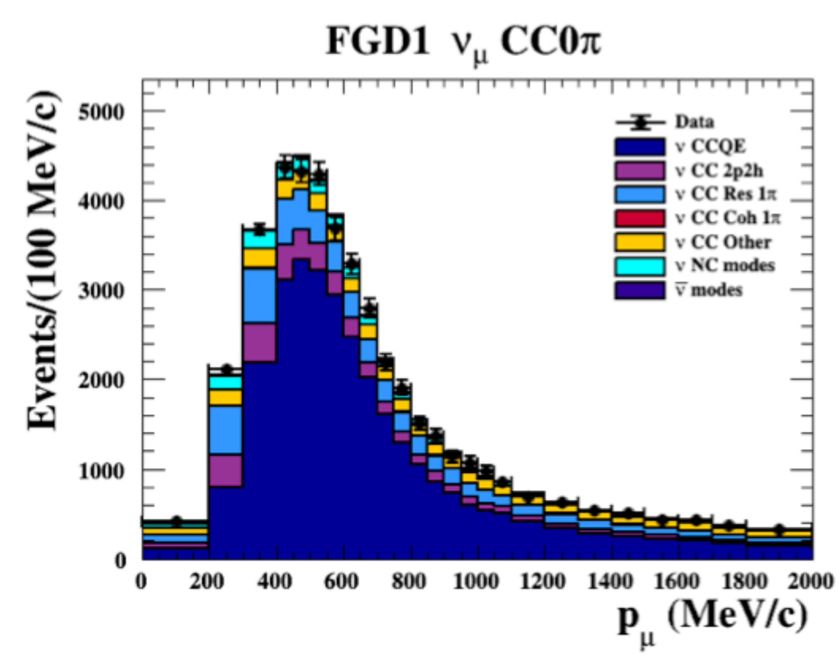
(a) FGD1 FHC ν_μ 0π

CC1π CH

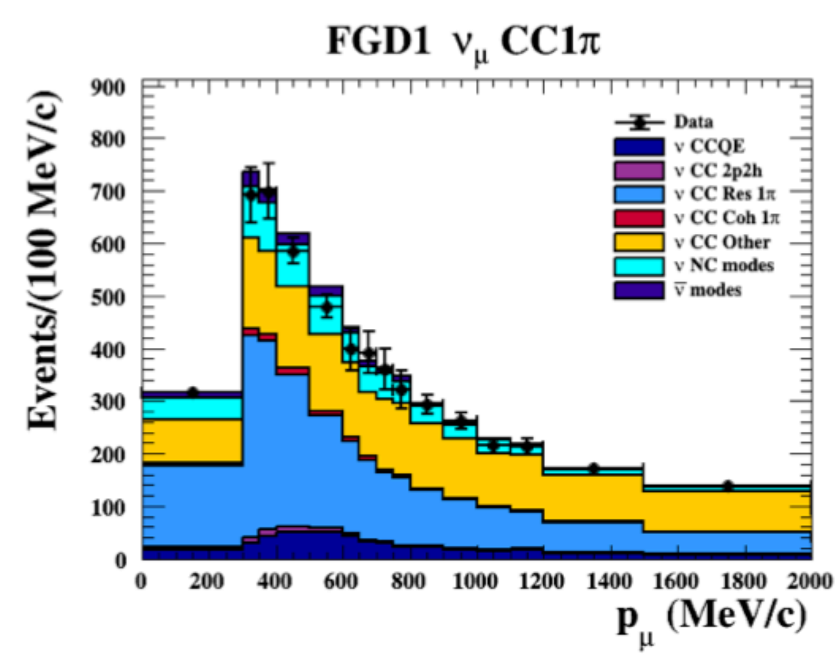


(b) FGD1 FHC ν_μ 1π

Post-fit



(a) FGD1 FHC ν_μ 0π



(b) FGD1 FHC ν_μ 1π

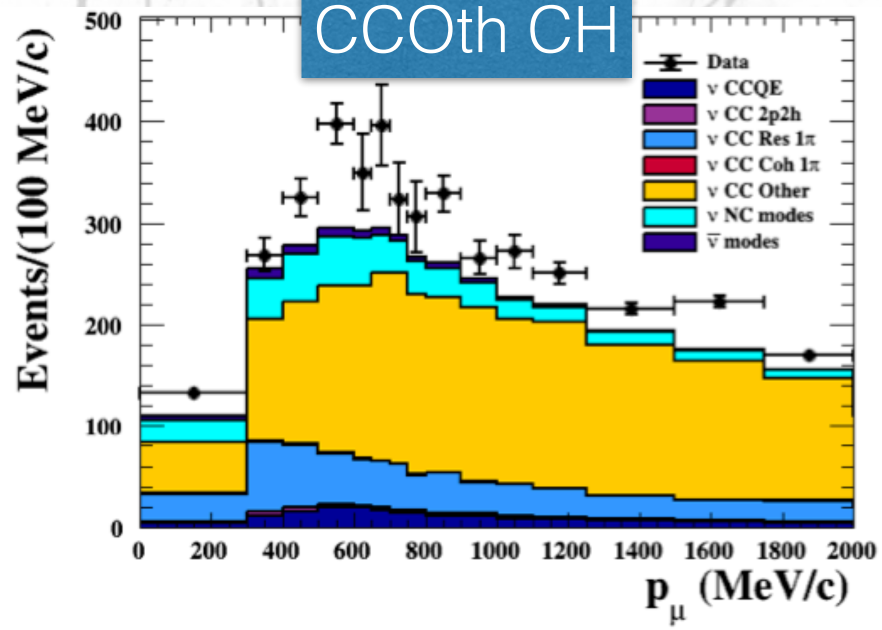
FHC is ν-mode
RHC is $\bar{\nu}$-mode

Pre-fit

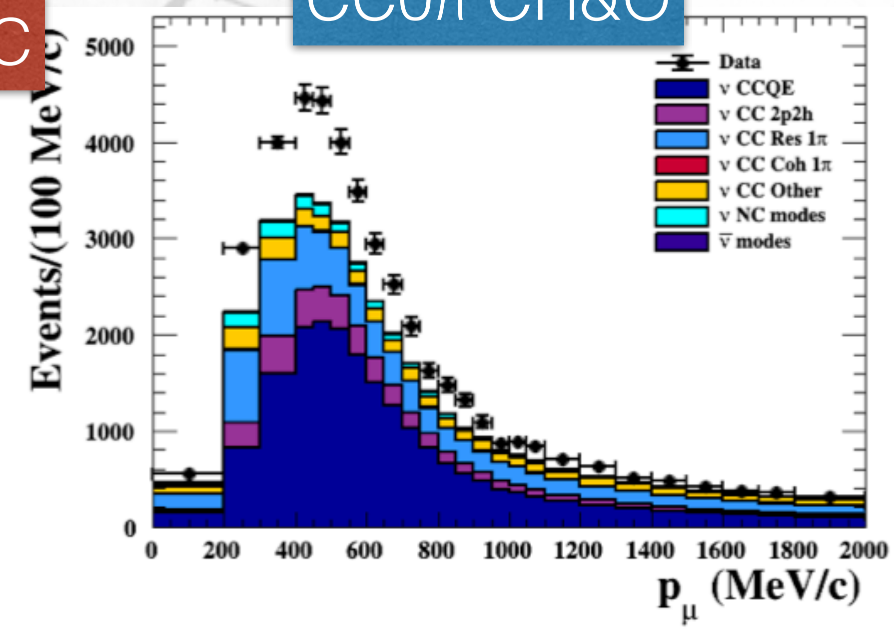
CCOth CH

FHC

CC0π CH&O

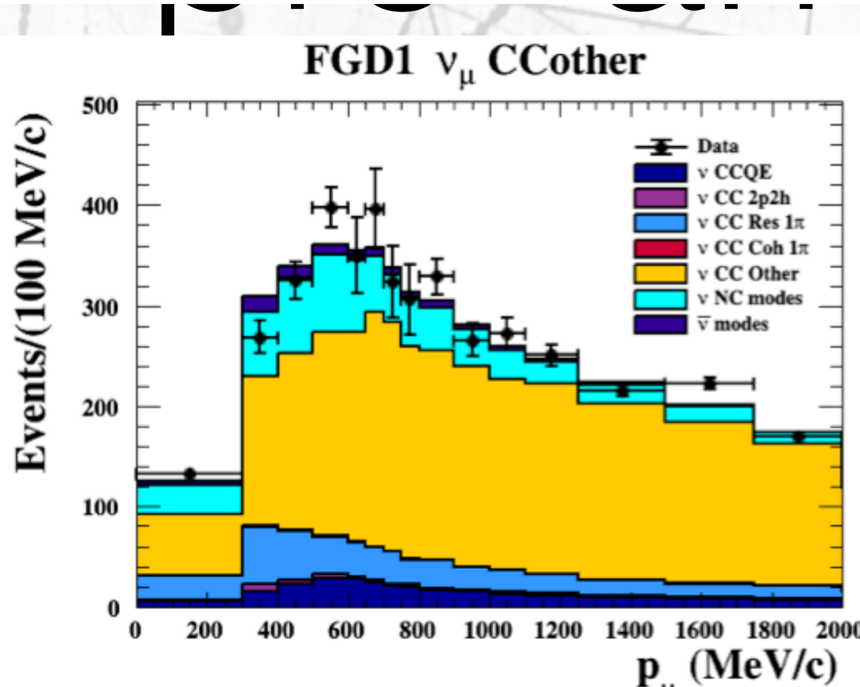


(c) FGD1 FHC ν_μ Other

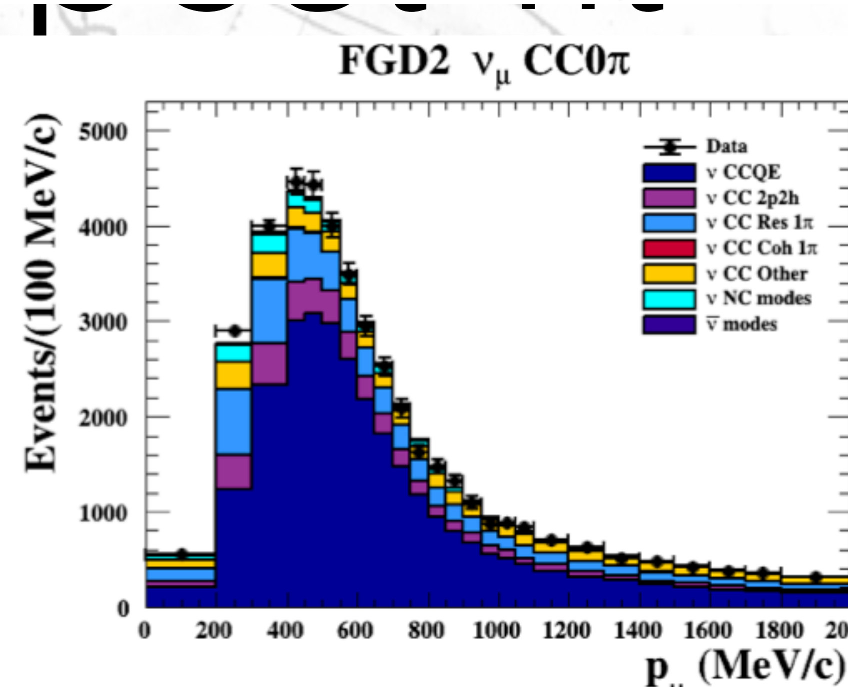


(d) FGD2 FHC ν_μ 0π

Post-fit



(c) FGD1 FHC ν_μ Other



(d) FGD2 FHC ν_μ 0π

FHC is ν-mode
RHC is $\bar{\nu}$-mode

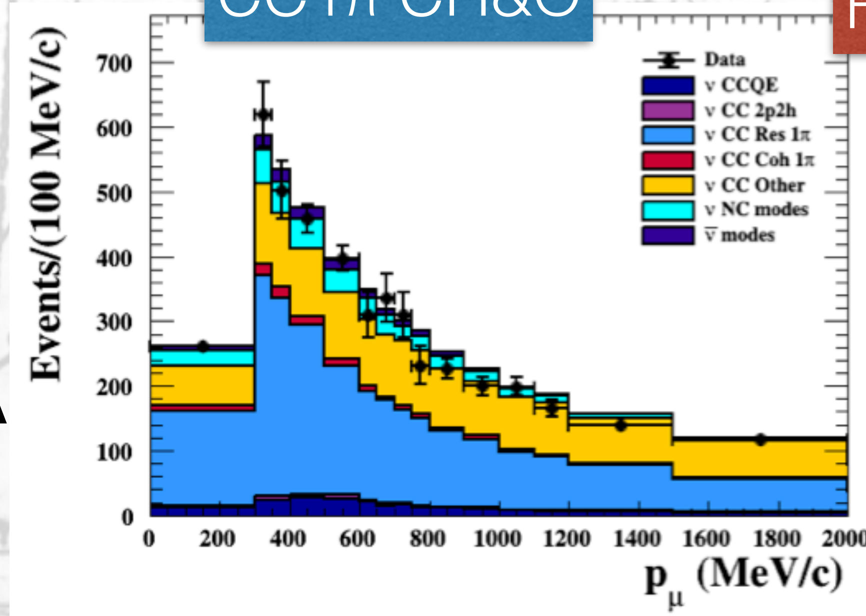
CC1π CH&O

FHC

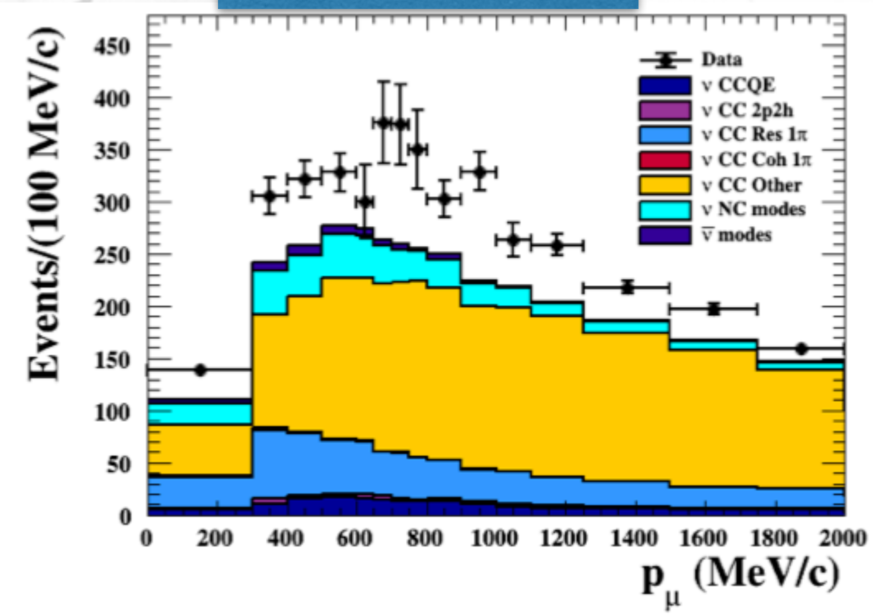
CCOth CH&O

Pre-fit

A

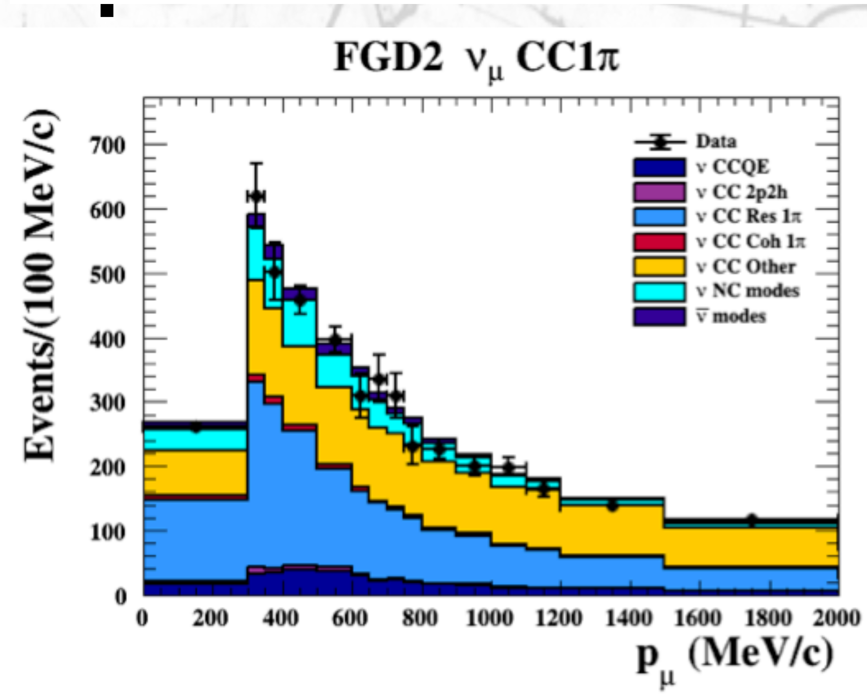


(e) FGD2 FHC ν_μ 1π

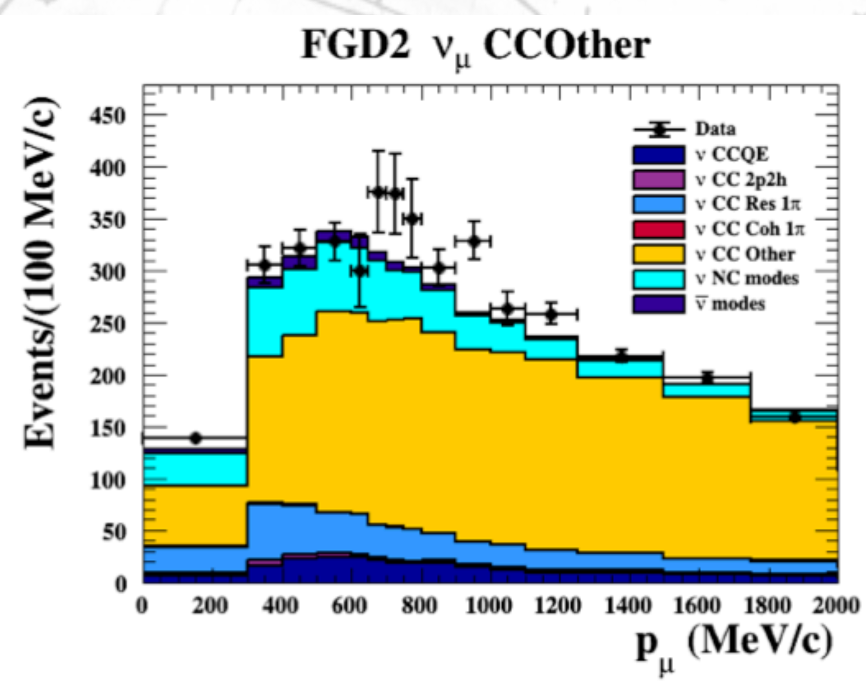


(f) FGD2 FHC ν_μ Other

Post-fit



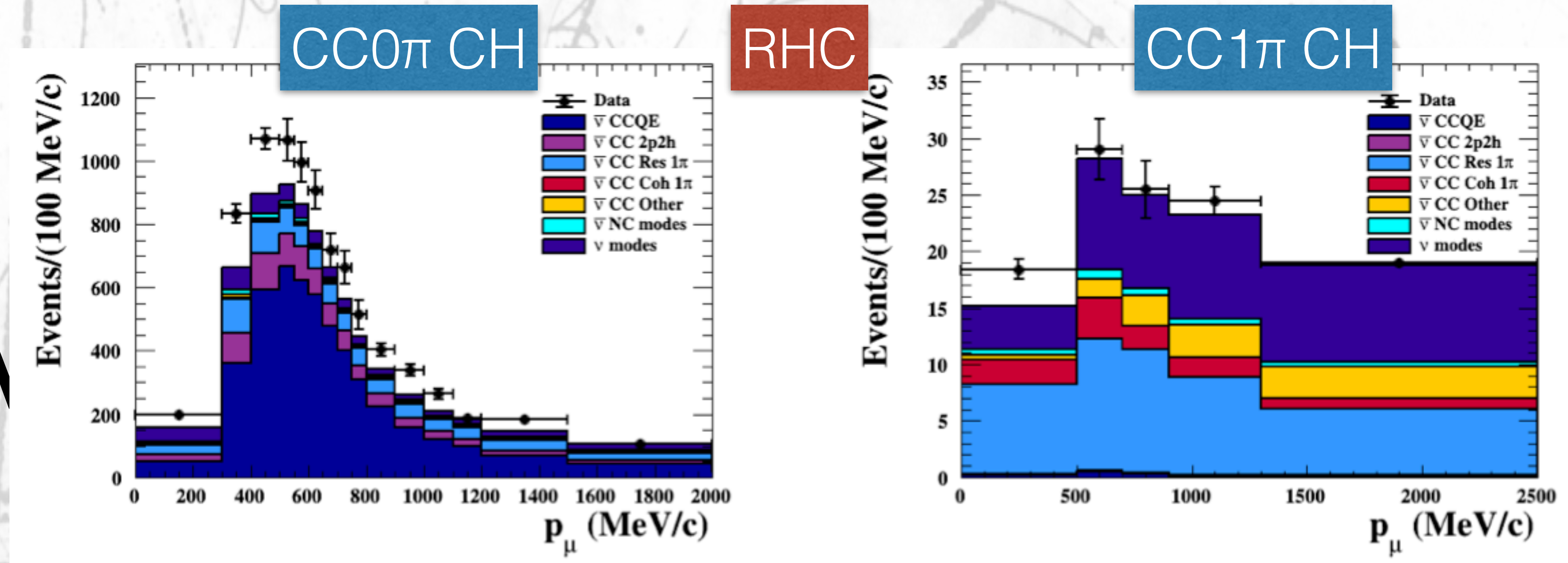
(e) FGD2 FHC ν_μ 1π



(f) FGD2 FHC ν_μ Other

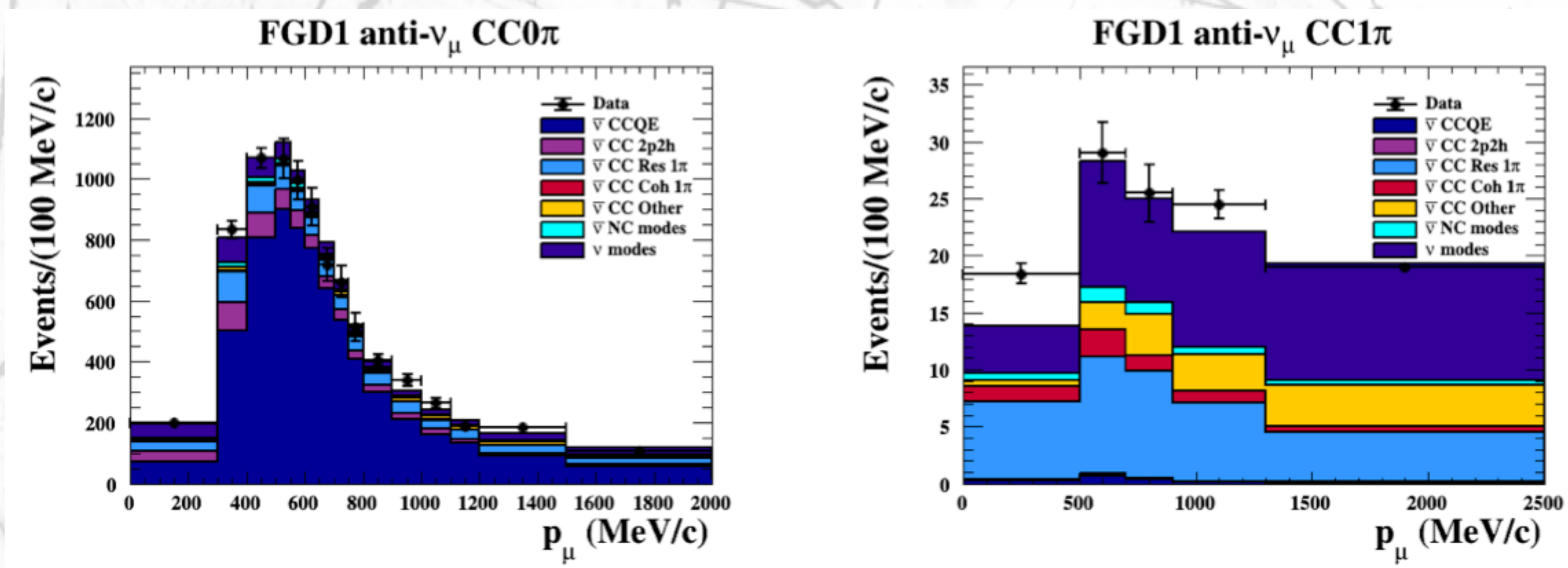
FHC is ν-mode
RHC is $\bar{\nu}$-mode

Pre-fit



(a) FGD1 RHC $\bar{\nu_\mu}$ 0π (b) FGD1 RHC $\bar{\nu_\mu}$ 1π

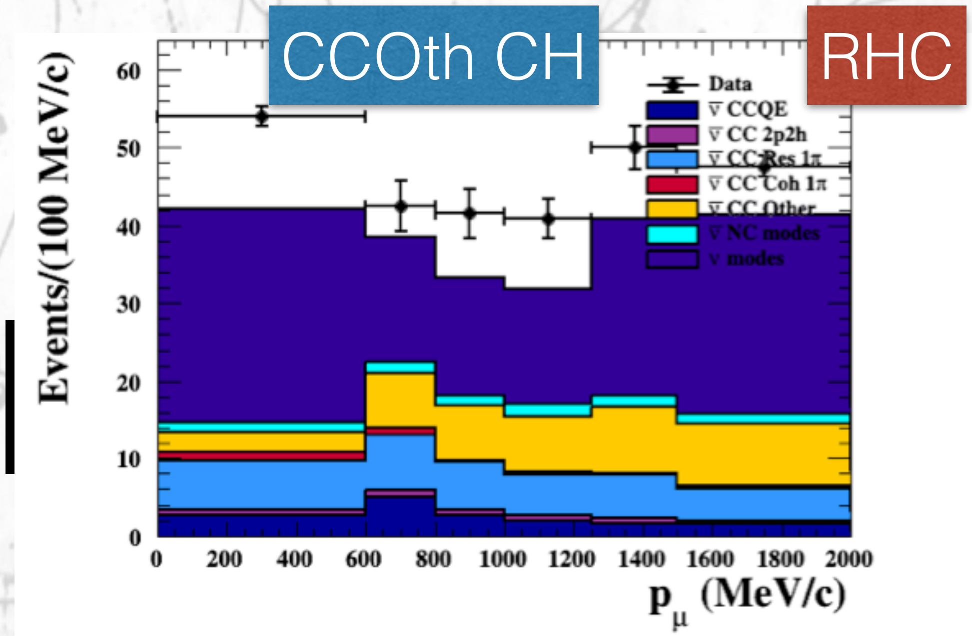
Post-fit



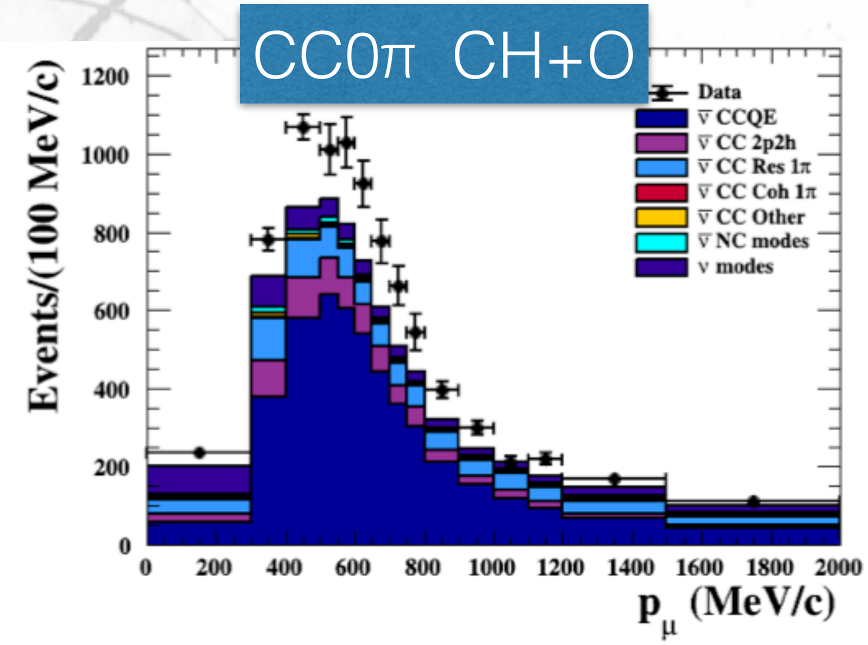
(a) FGD1 RHC $\bar{\nu_\mu}$ 0π (b) FGD1 RHC $\bar{\nu_\mu}$ 1π

FHC is ν-mode
RHC is $\bar{\nu}$-mode

Pre-fit

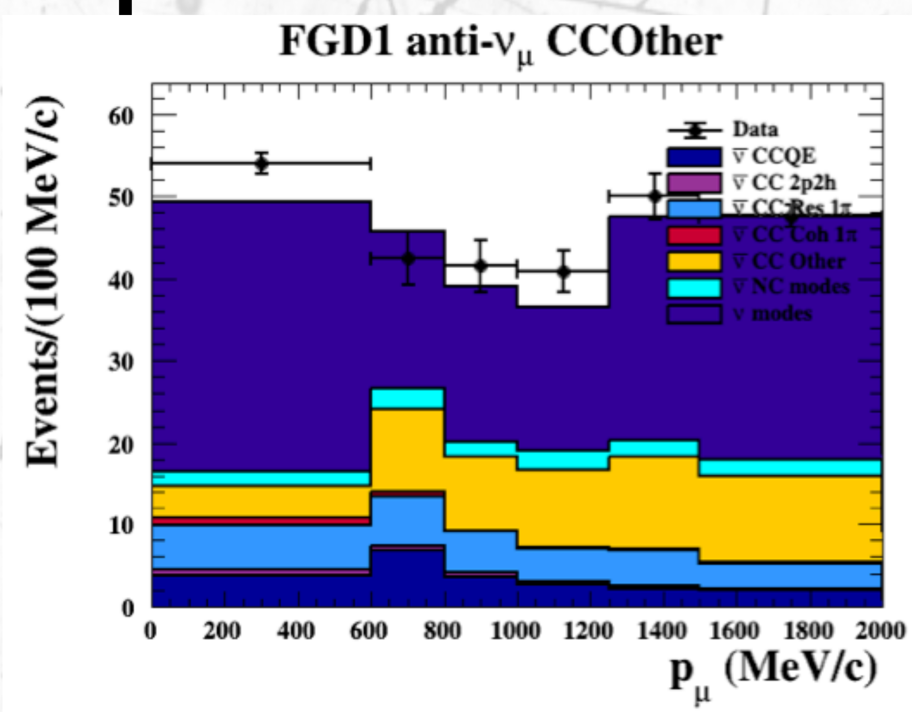


(c) FGD1 RHC $\bar{\nu_\mu}$ Other

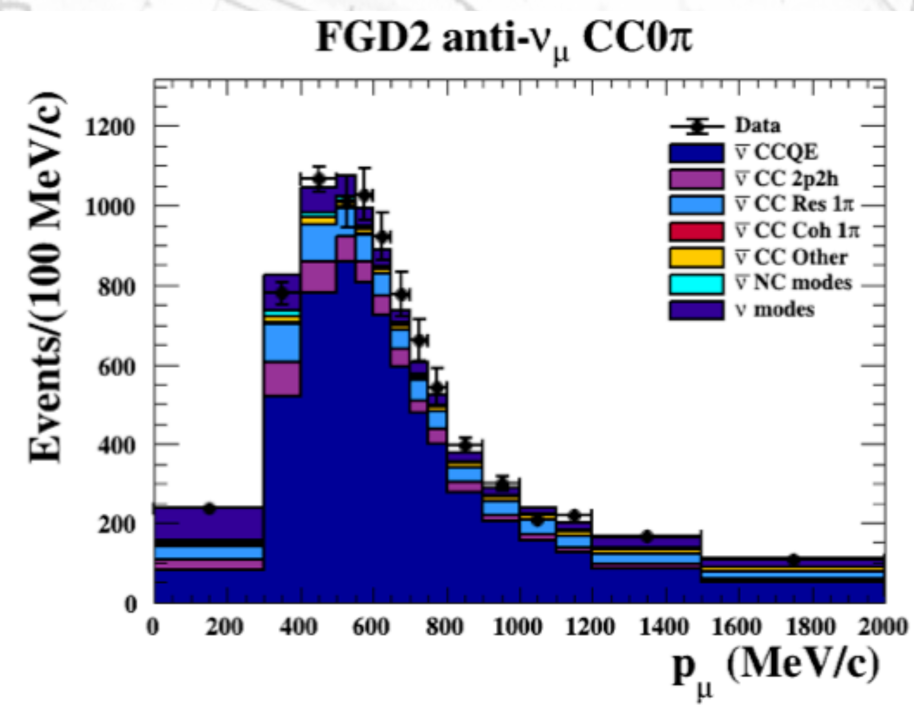


(d) FGD2 RHC $\bar{\nu_\mu}$ 0π

Post-fit



(c) FGD1 RHC $\bar{\nu_\mu}$ Other



(d) FGD2 RHC $\bar{\nu_\mu}$ 0π

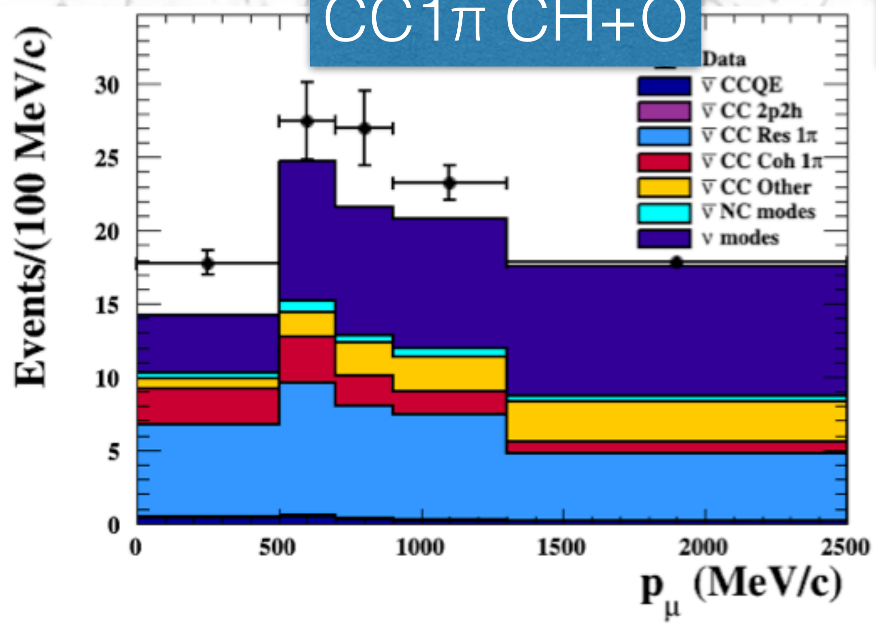
FHC is ν-mode
RHC is $\bar{\nu}$-mode

CC1π CH+O

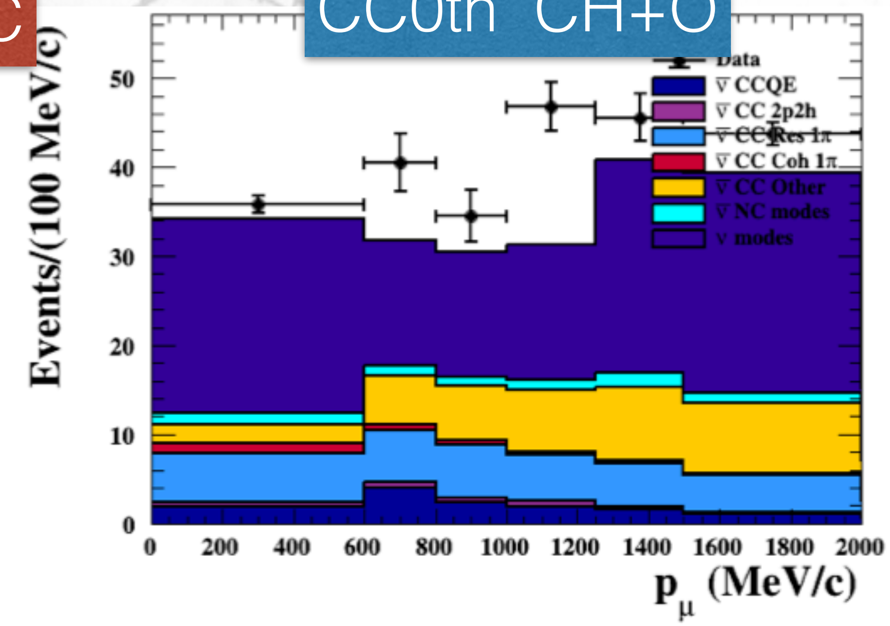
RHC

CC0th CH+O

Pre-fit

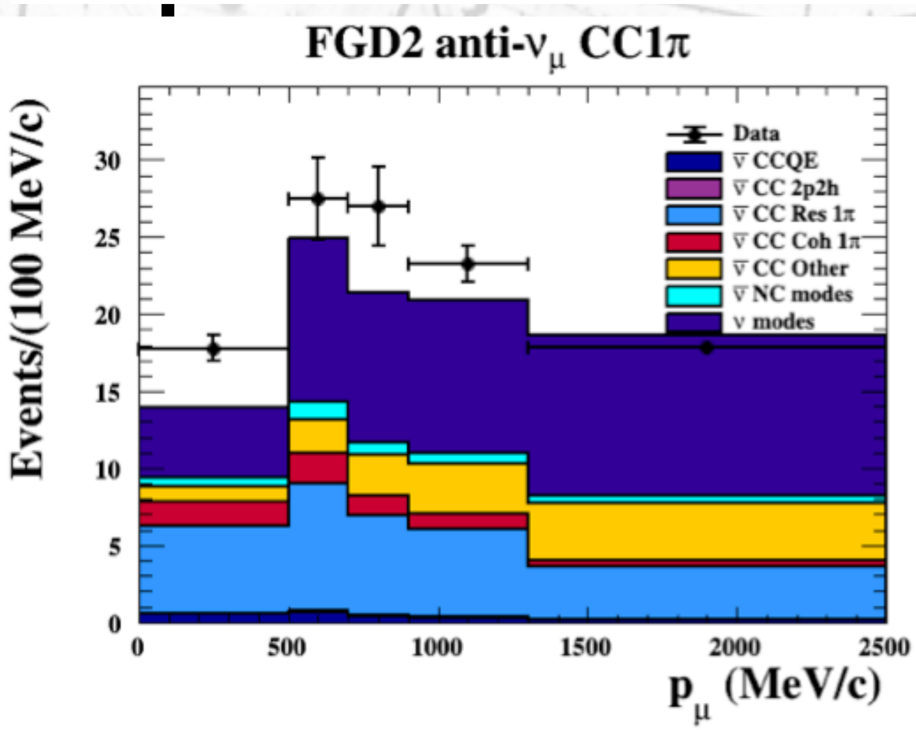


(e) FGD2 RHC $\bar{\nu_\mu}$ 1π

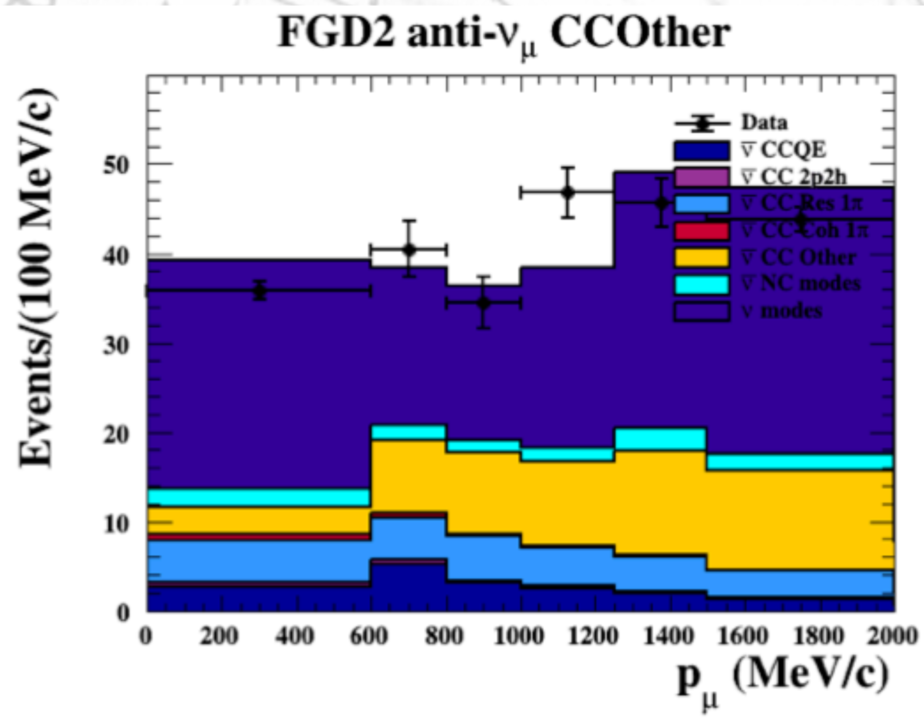


(f) FGD2 RHC $\bar{\nu_\mu}$ Other

Post-fit



(e) FGD2 RHC $\bar{\nu_\mu}$ 1π



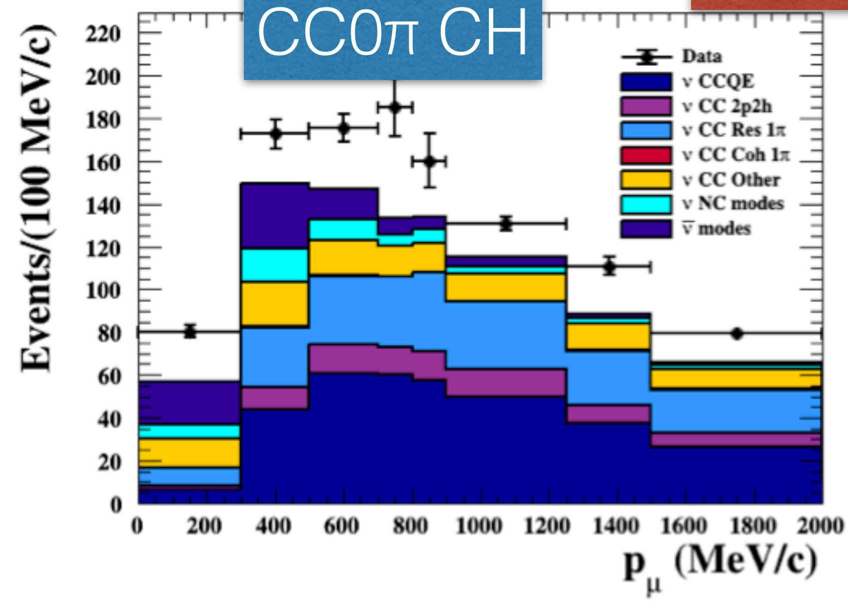
(f) FGD2 RHC $\bar{\nu_\mu}$ Other

FHC is ν-mode
RHC is $\bar{\nu}$-mode

neutrinos in RHC

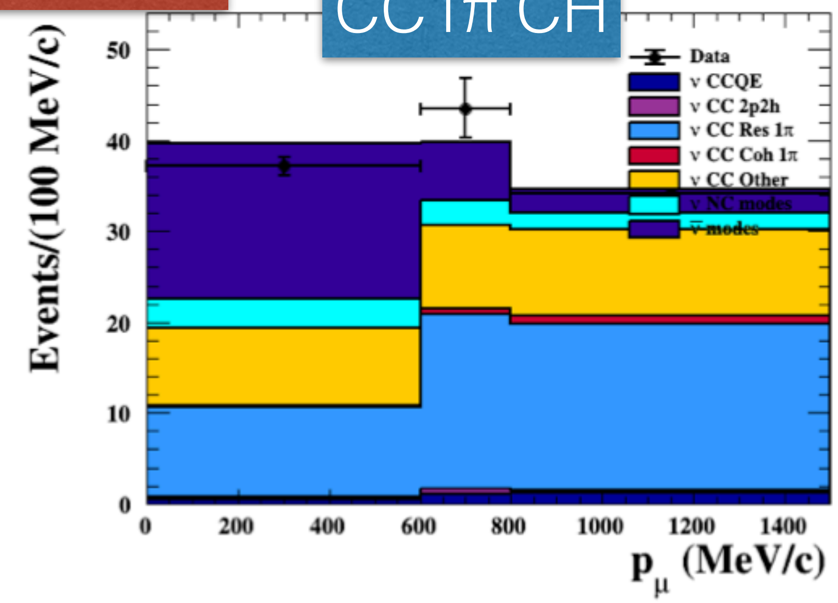
Pre-fit

CC0π CH



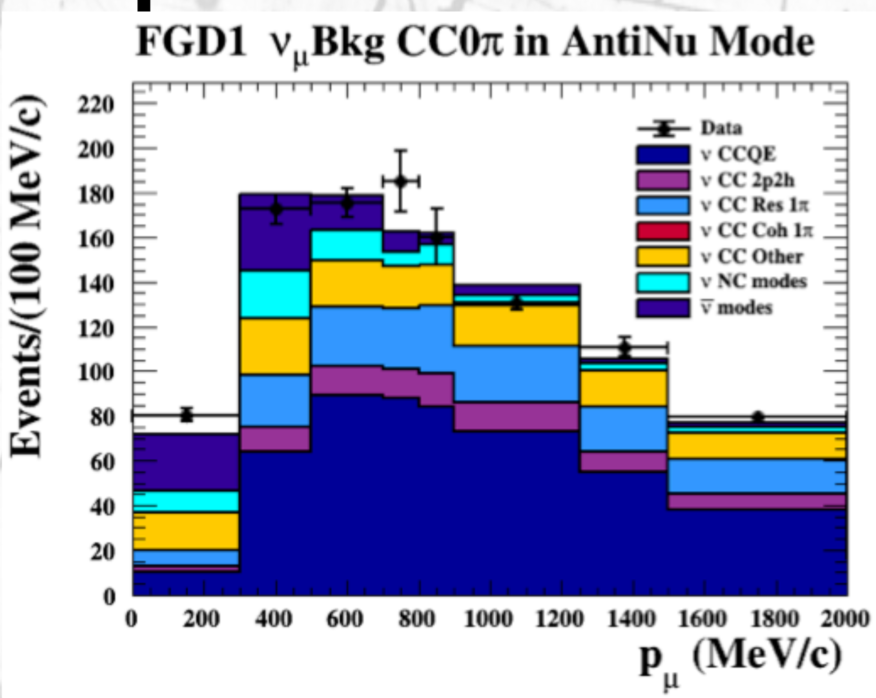
(a) FGD1 RHC ν_μ 0π

CC1π CH

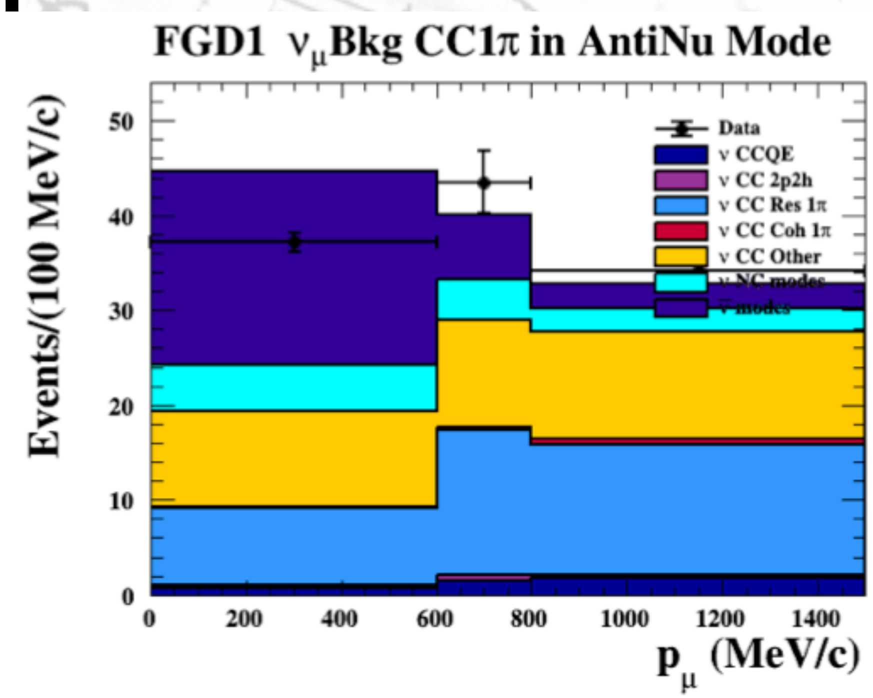


(b) FGD1 RHC ν_μ 1π

Post-fit



(a) FGD1 RHC ν_μ 0π



(b) FGD1 RHC ν_μ 1π

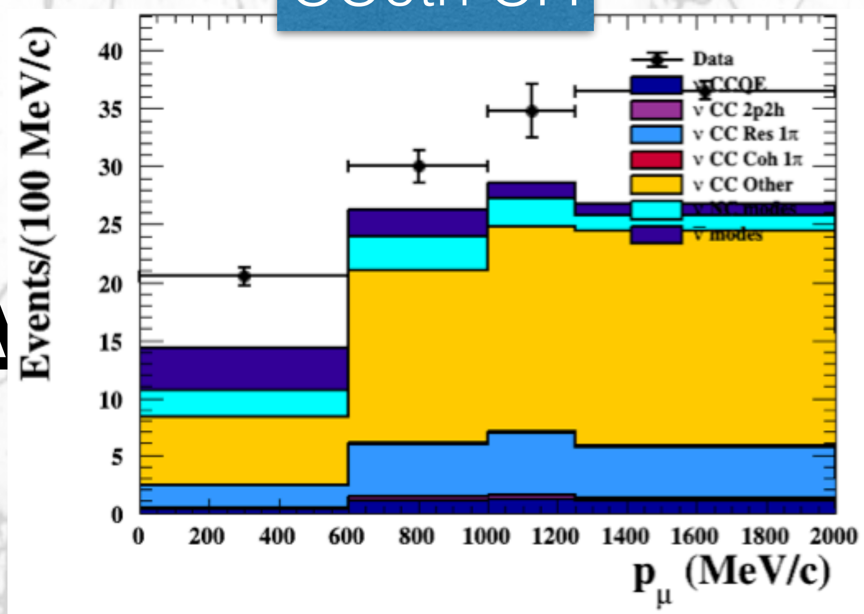
FHC is ν-mode
RHC is $\bar{\nu}$-mode

neutrinos in RHC

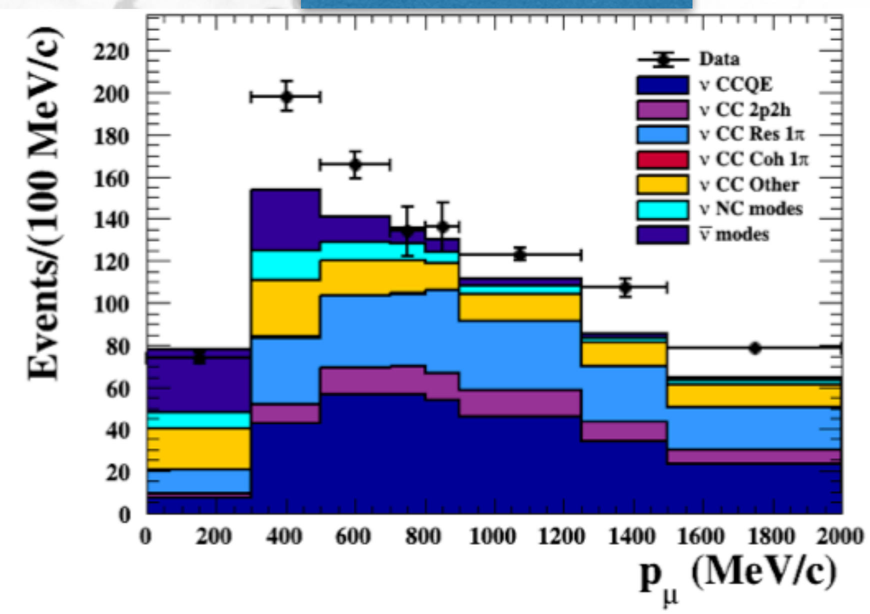
CC0th CH

CC0π CH&O

Pre-fit

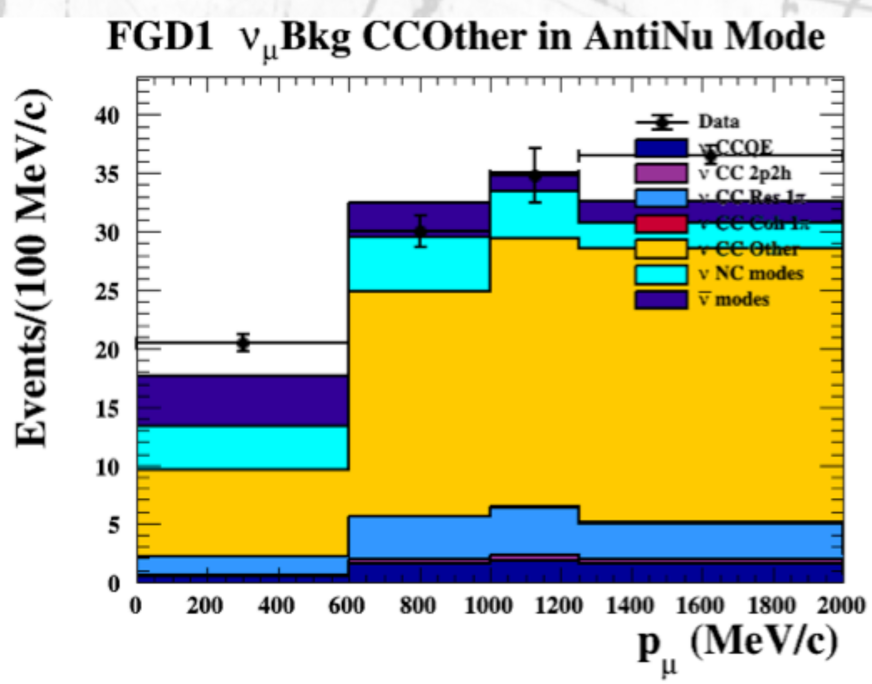


(c) FGD1 RHC ν_μ Other

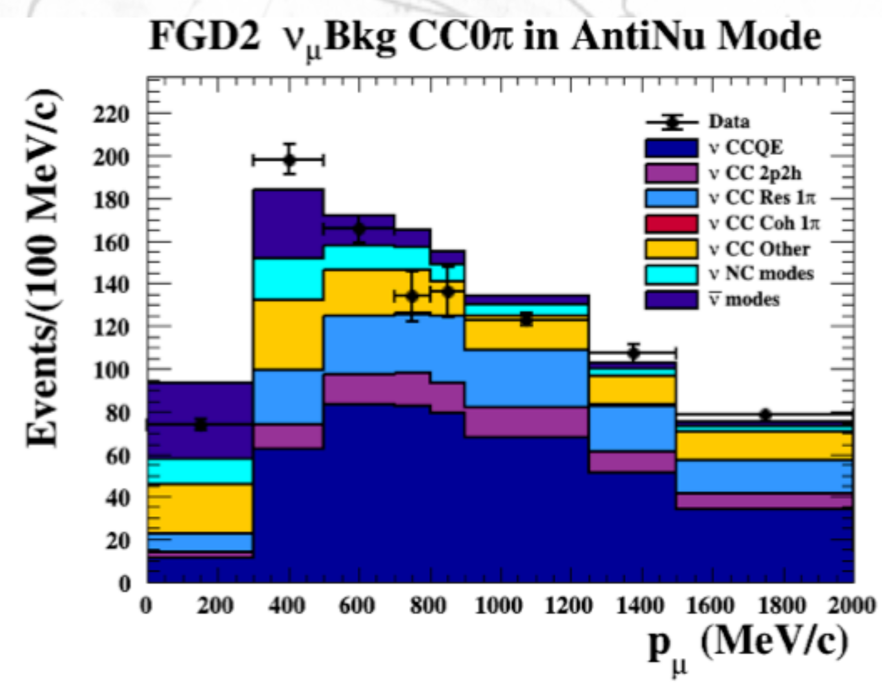


(d) FGD2 RHC ν_μ 0π

Post-fit



(c) FGD1 RHC ν_μ Other



(d) FGD2 RHC ν_μ 0π

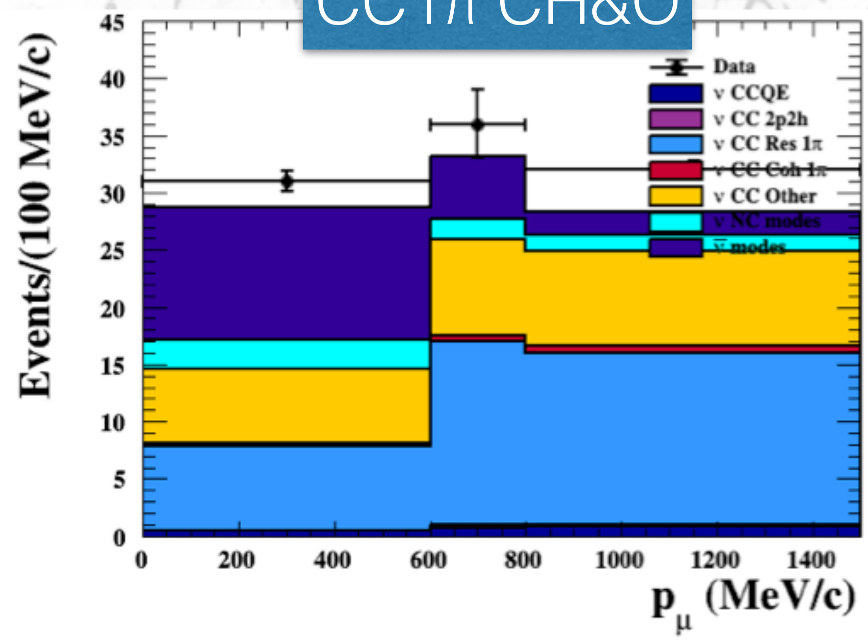
FHC is ν-mode
RHC is $\bar{\nu}$-mode

neutrinos in RHC

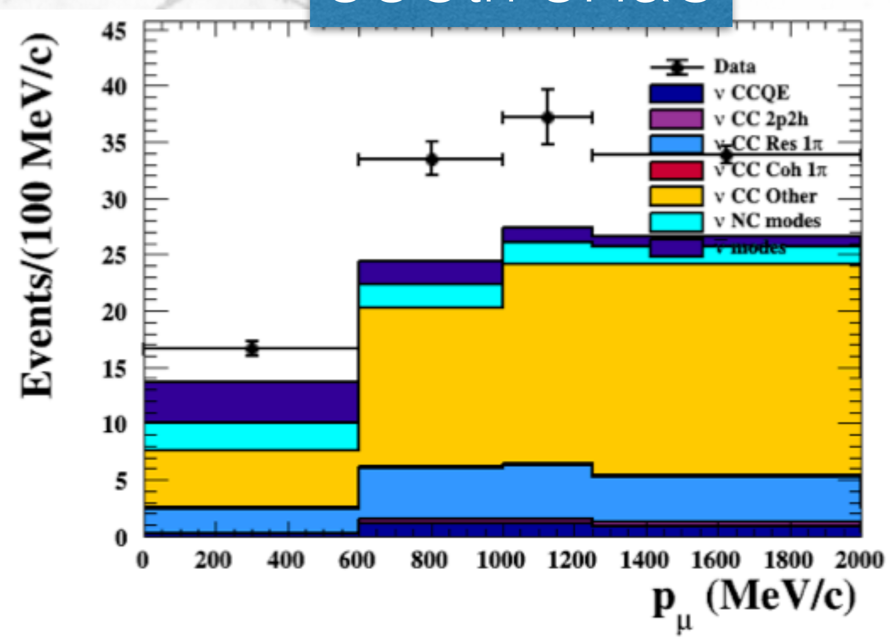
CC1π CH&O

CCOth CH&O

Pre-fit

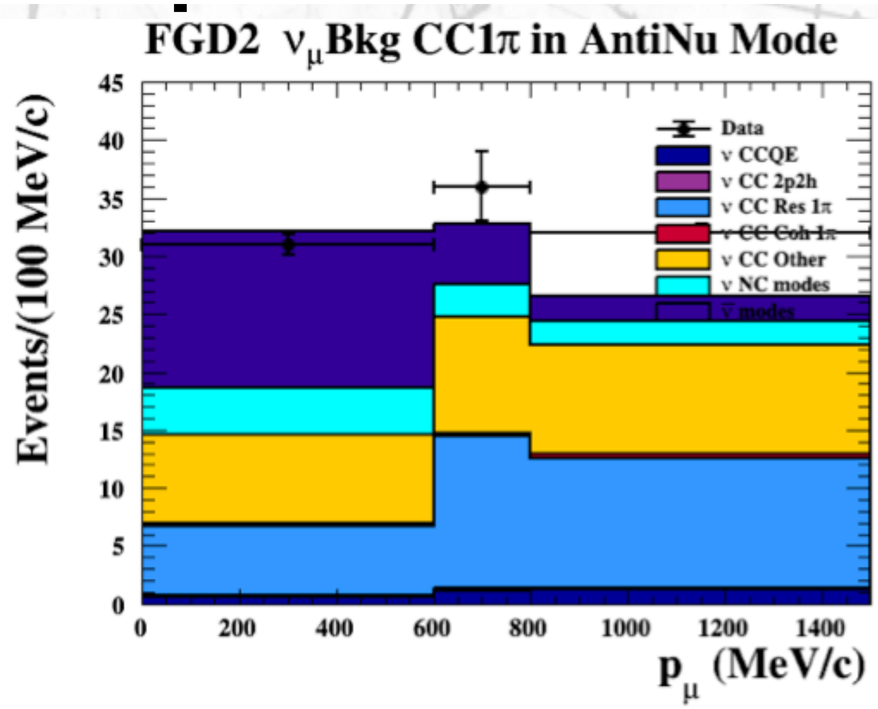


(e) FGD2 RHC ν_μ 1π

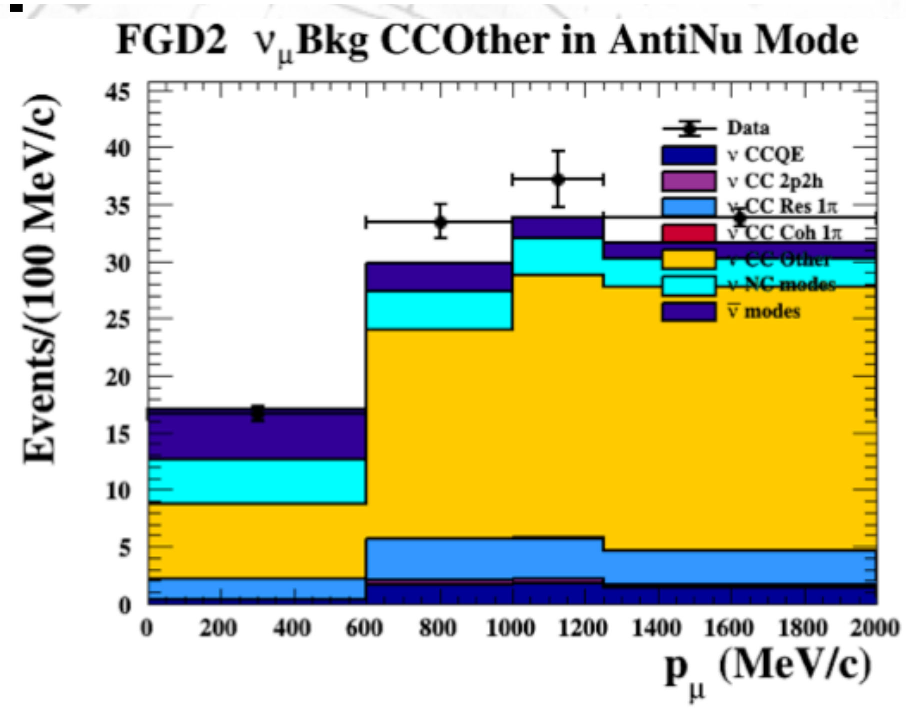


(f) FGD2 RHC ν_μ Other

Post-fit



(e) FGD2 RHC ν_μ 1π



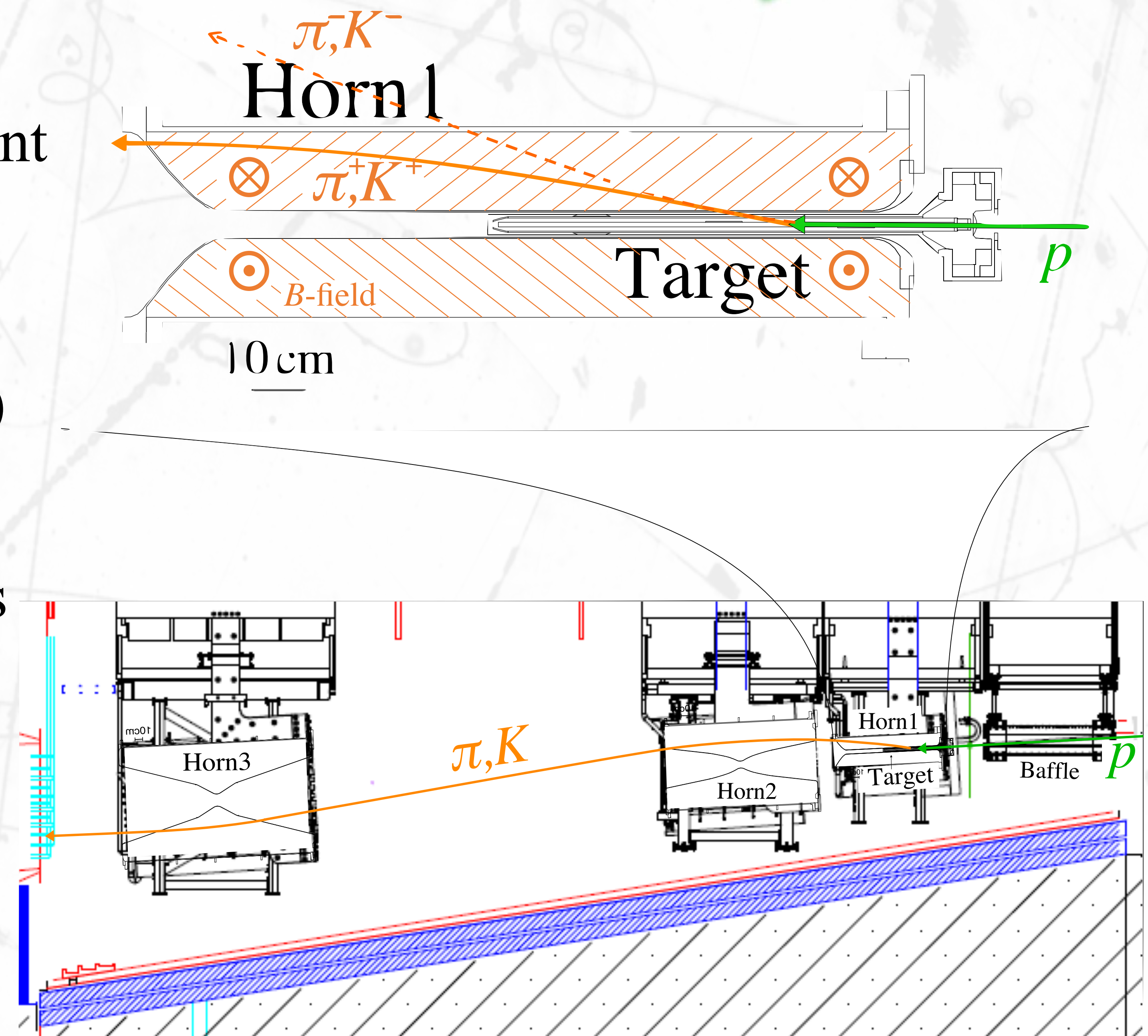
(f) FGD2 RHC ν_μ Other

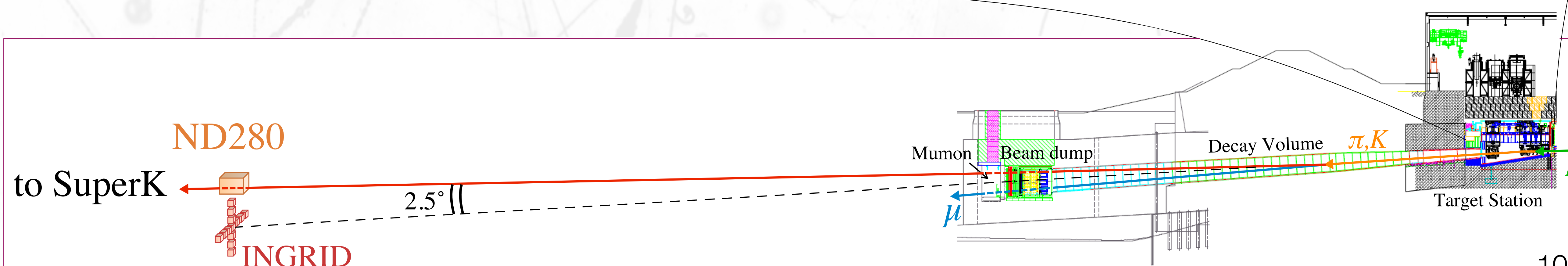
Neutrino beam

- 3 Horns system with 250 kA current sinusoidal ~3ms pulse.
- Forward (neutrino enhanced) and Reversed (anti-neutrino enhanced) modes.
- The beam is slightly tilted towards the earth.

planned upgrade to reach 320kA

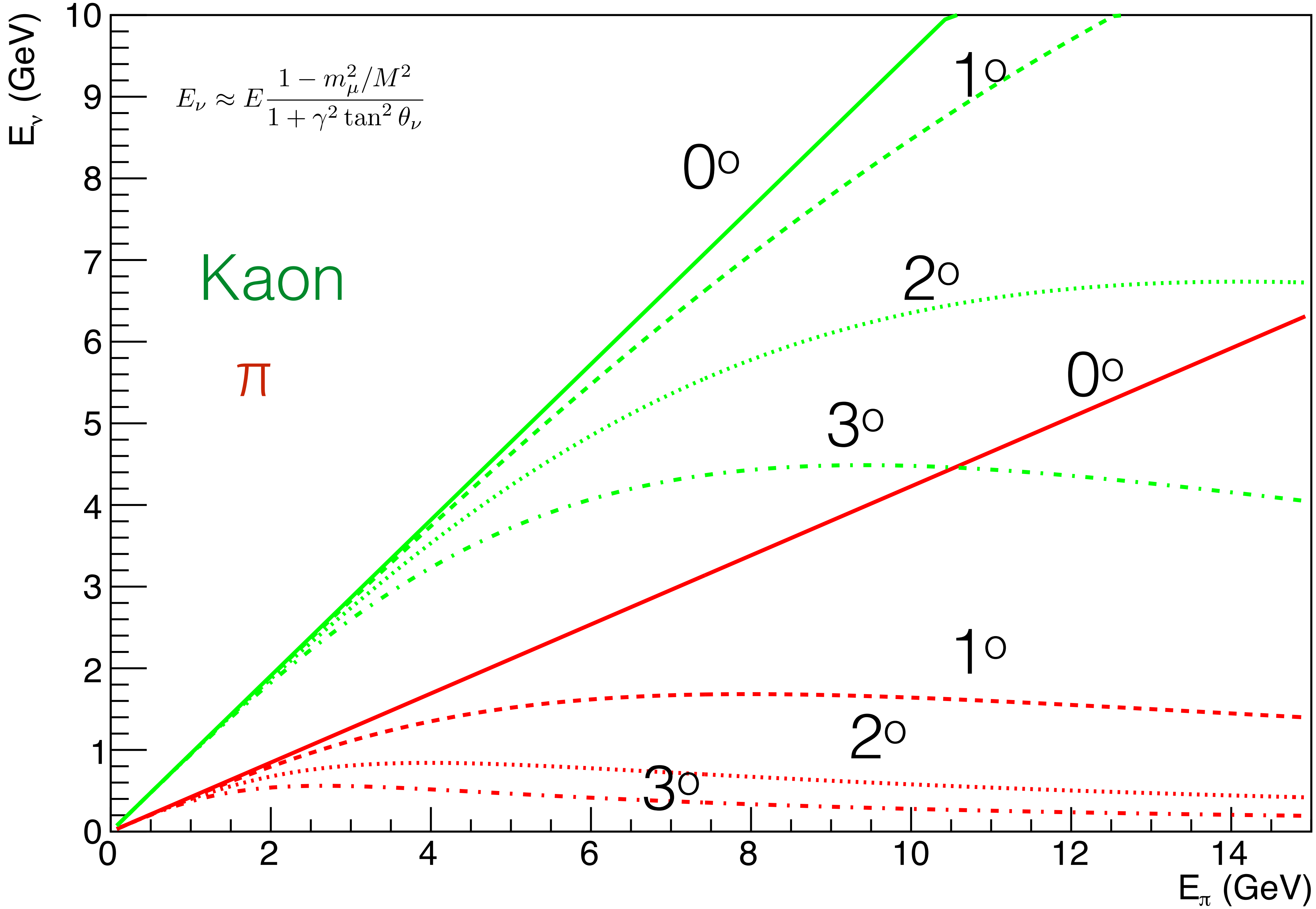
⟶ +~20% ν flux





on vs off Axis

T2K

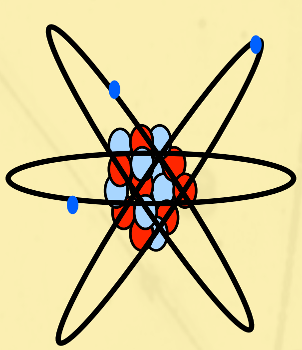


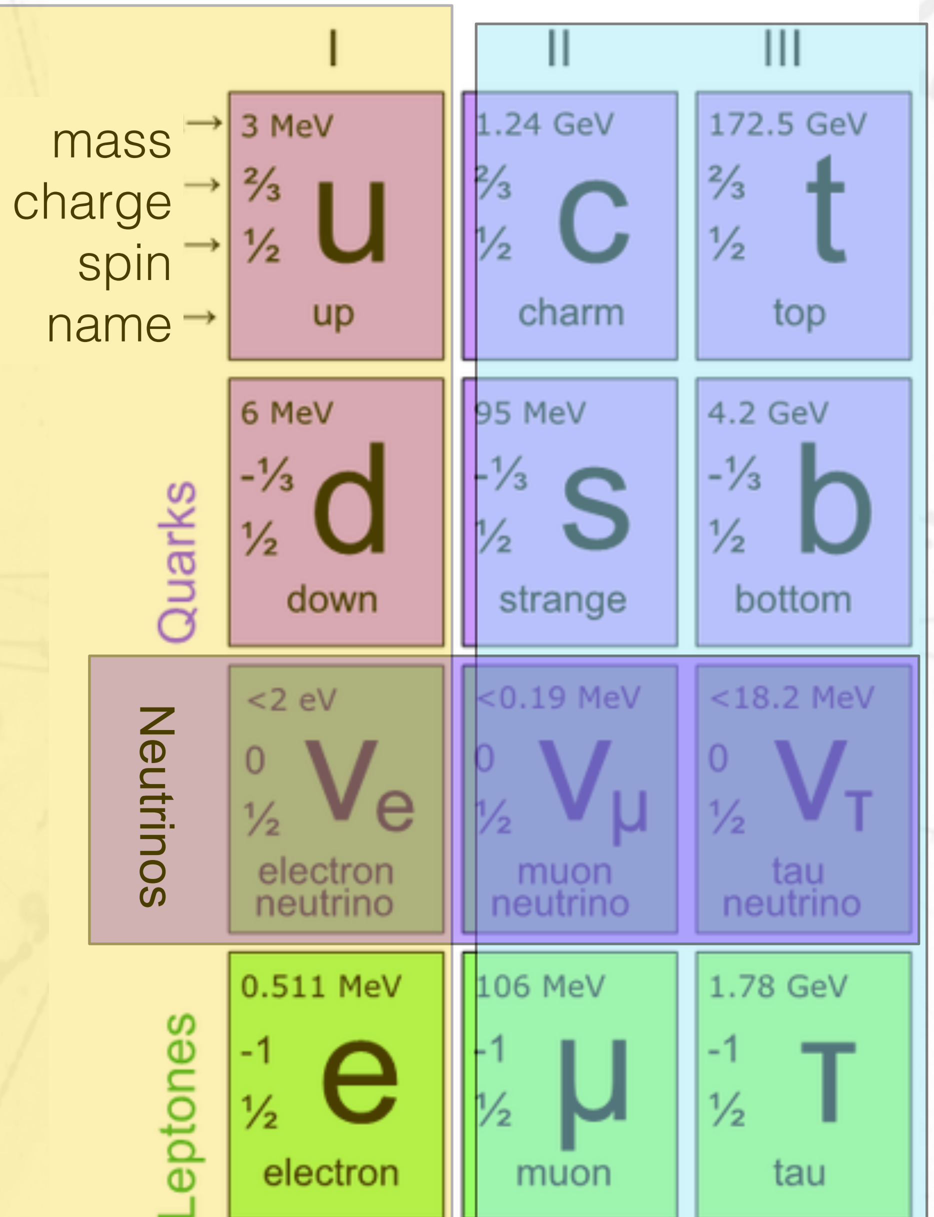
Standard Model

Fermions are grouped in three families with similar properties but larger masses

Matter around us is made of the lightest particles.

quark Up/down
lepton electron

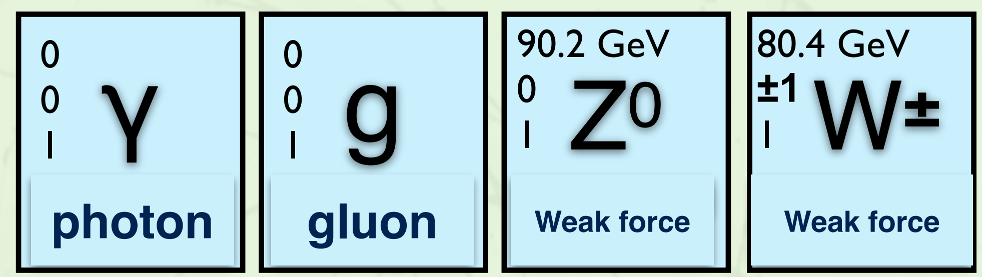




Produced in accelerators and cosmic rays

Forces and bosons.

Photon Electromagnetic
gluon Strong (Nuclear)
Z^0 $W^\pm$ Weak (radioactivity)



All these particles are indivisible, they are the smallest components in nature.

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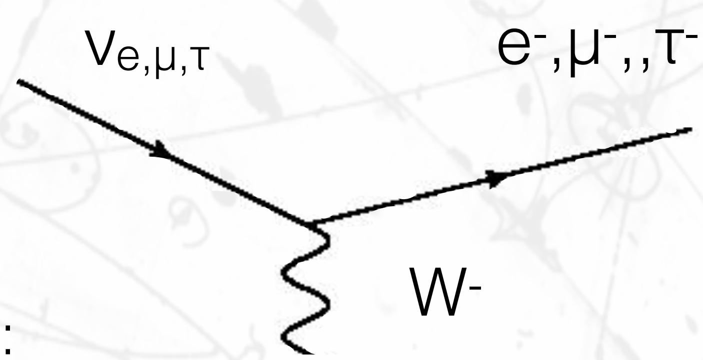
What are neutrinos?

"When you ask what are electrons and protons I ought to answer that this question is not a profitable one to ask and does not really have a meaning. The important thing about electrons and protons is not what they are but how they behave - how they move."

P.M. Dirac, Indian Science Congress Badora (1955)

Neutrinos are:



- indivisible fermions with Spin 1/2.
- with no electric charge.
- interacting only through weak interactions (and gravitation):
  - cross-section is very small. A 1 GeV neutrino can cross 10^6 earth diameters with no interactions.
- with very small mass (~ 10^{-6} times the electron mass)
- neutrino flavour (3 families) is defined by the charged partner in weak interactions:
  - $\nu_{e,\mu,,\tau}$ are produced/consumed associated to e,μ,,τ

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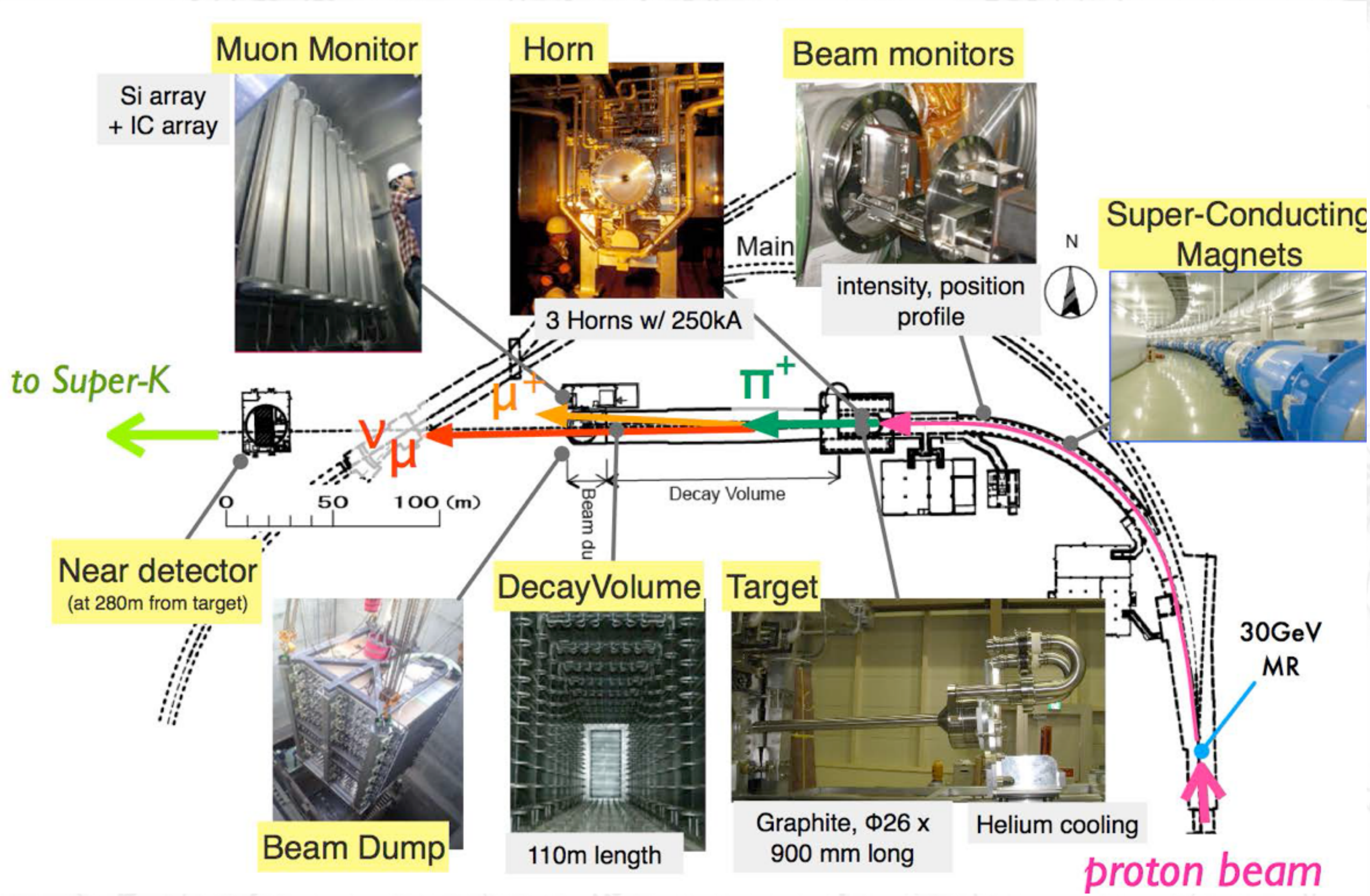
ν beam @ JPARC

T2K



Fast extraction with beam pulse every 2 sec.

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Beam monitors

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Proton beam monitors are essential for protecting beam-line equipment, as well as for understanding and predicting the **neutrino flux**

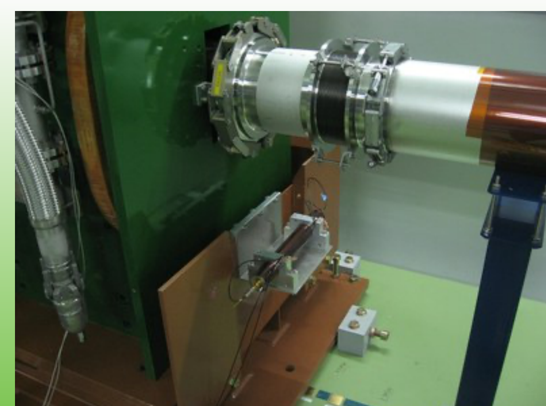
Beam intensity

Current transformers

<2.7% precision

Beam Loss

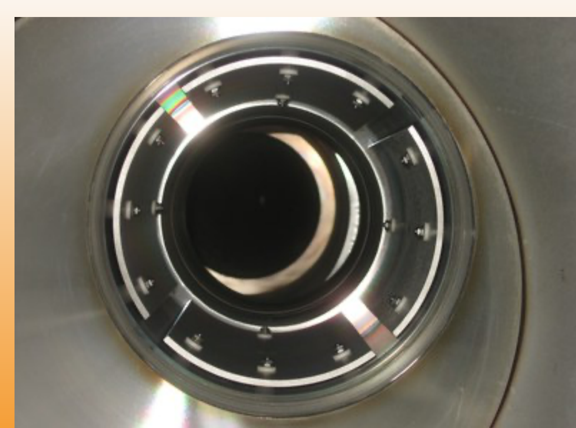
Sensitive down to 16mW loss



Beam position

Electro Static monitors

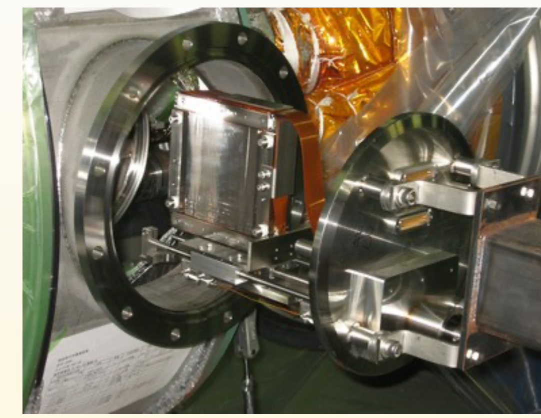
450μm precision



Beam position and profile

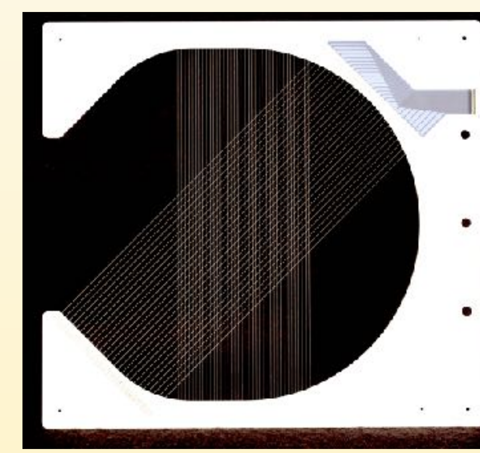
Segmented Secondary Emission Monitors

100μm position
200μm width



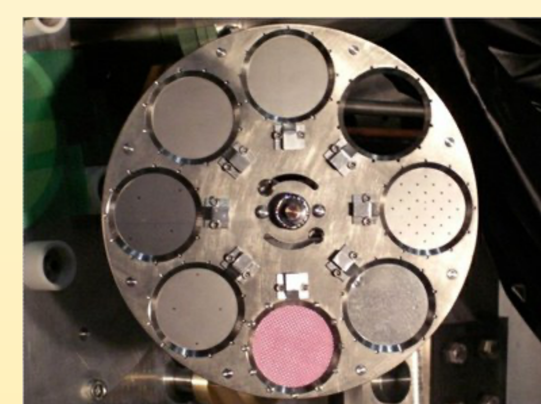
Wire Secondary Emission Monitors

100μm position
200μm width

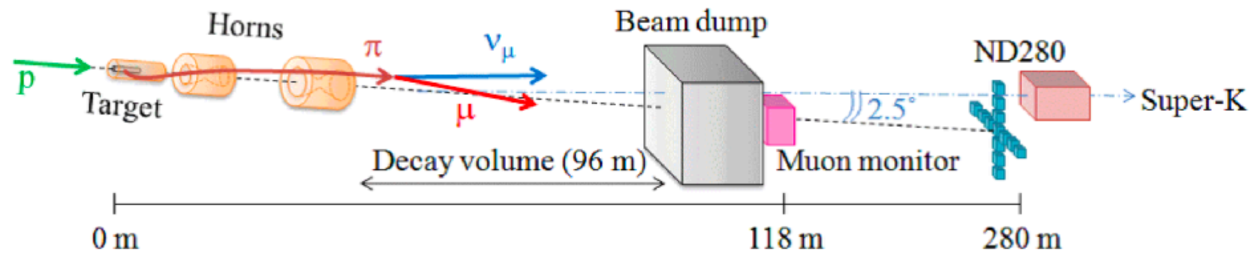


Optical transition radiation

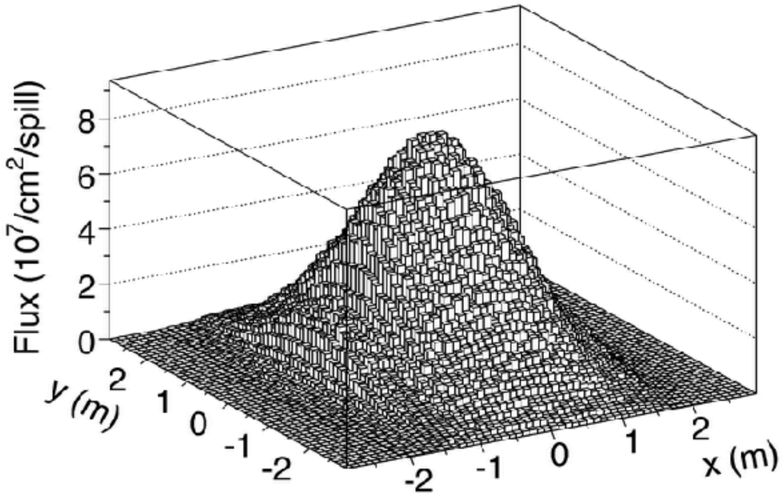
<500μm precision



Beam control: Muon monitors



- Monitors the beam direction from the μ produced in π decays.
- Embedded in the beam dump samples the high energy muons.
- ionisation chambers and silicon PIN diodes.
- High irradiation area: ~10^{14} electrons/cm/month at 750 KW.



Simulation of μ fluency

PNMS and CP violation

Leptonic CP violation will manifest as a difference of the vacuum oscillation probabilities for neutrinos and anti-neutrinos

Cabibbo, 1977; Bilenky, Hosek, Petcov, 1980, Barger, Whisnant, Phillips, 1980

$$P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) = -16 J_{\alpha\beta} \sin\frac{\Delta m^2_{21} L}{4E} \sin\frac{\Delta m^2_{32} L}{4E} \sin\frac{\Delta m^2_{31} L}{4E}$$

- Jarlskog invariant $J_{\alpha\beta}$ gives an idea of the amplitud of CP violation:

Jarlskog, 1985

$$J_{\alpha\beta} = Im(U_{\alpha 1} U^*_{\alpha 2} U^*_{\beta 1} U_{\beta 2}) = \pm J$$

sign depends on the permutation of αβ

$$J = s_{12} c_{12} s_{23} c_{23} s_{13} c^2_{13} \sin\delta = J^{max} \sin\delta$$

J^{max} ~ 0.033 for neutrinos

J^{max} ~ 0.000032 for quarks

J^{max} ~ 0.09 for maximal mixing

The expected effect is larger in neutrinos than in quarks

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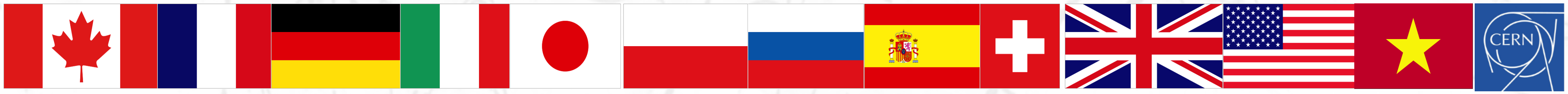
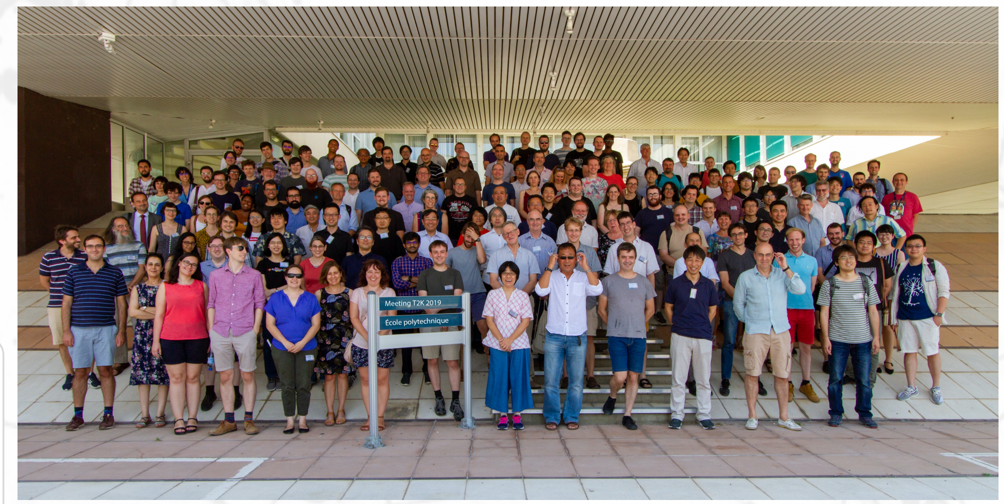
T2K Collaboration



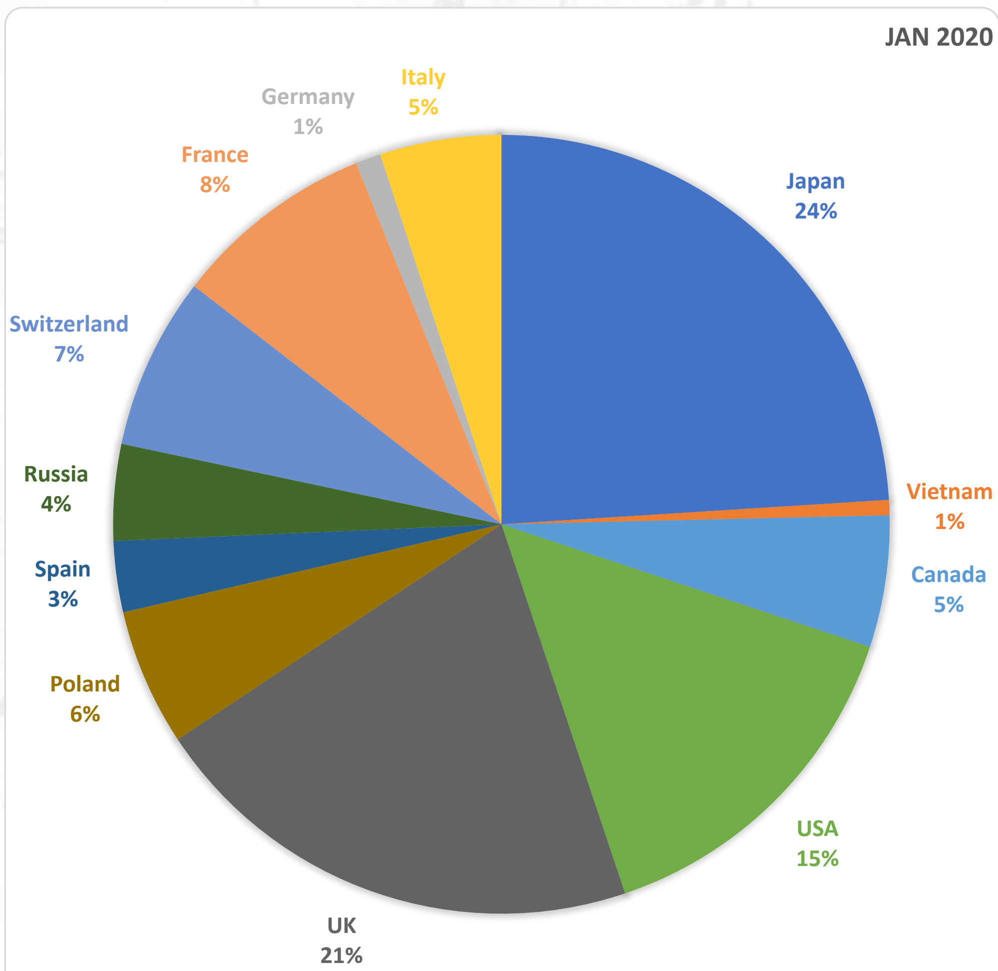
~500 members, 69 Institutes, 12 countries

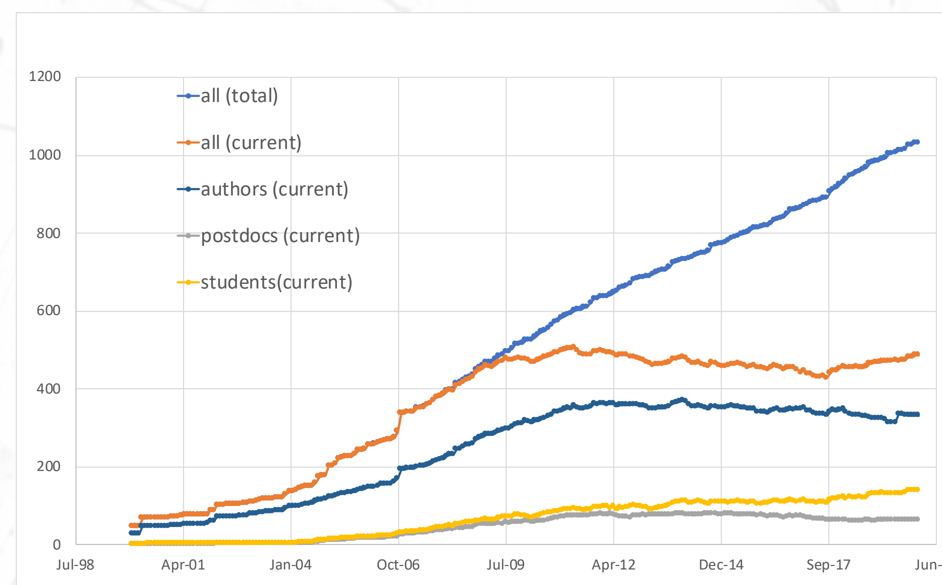
Asia	117
Japan	114
Vietnam	3

Americas	96
Canada	26
USA	70



Europe	262
France	40
Germany	5
Italy	24
Poland	27
Russia	19
Spain	14
Switzerland	34
UK	99





Very strong European contribution including CERN

Operated since 2009