

Navigating the Nucleus

The path to precision measurements of neutrino oscillations



Laura Munteanu (CERN)

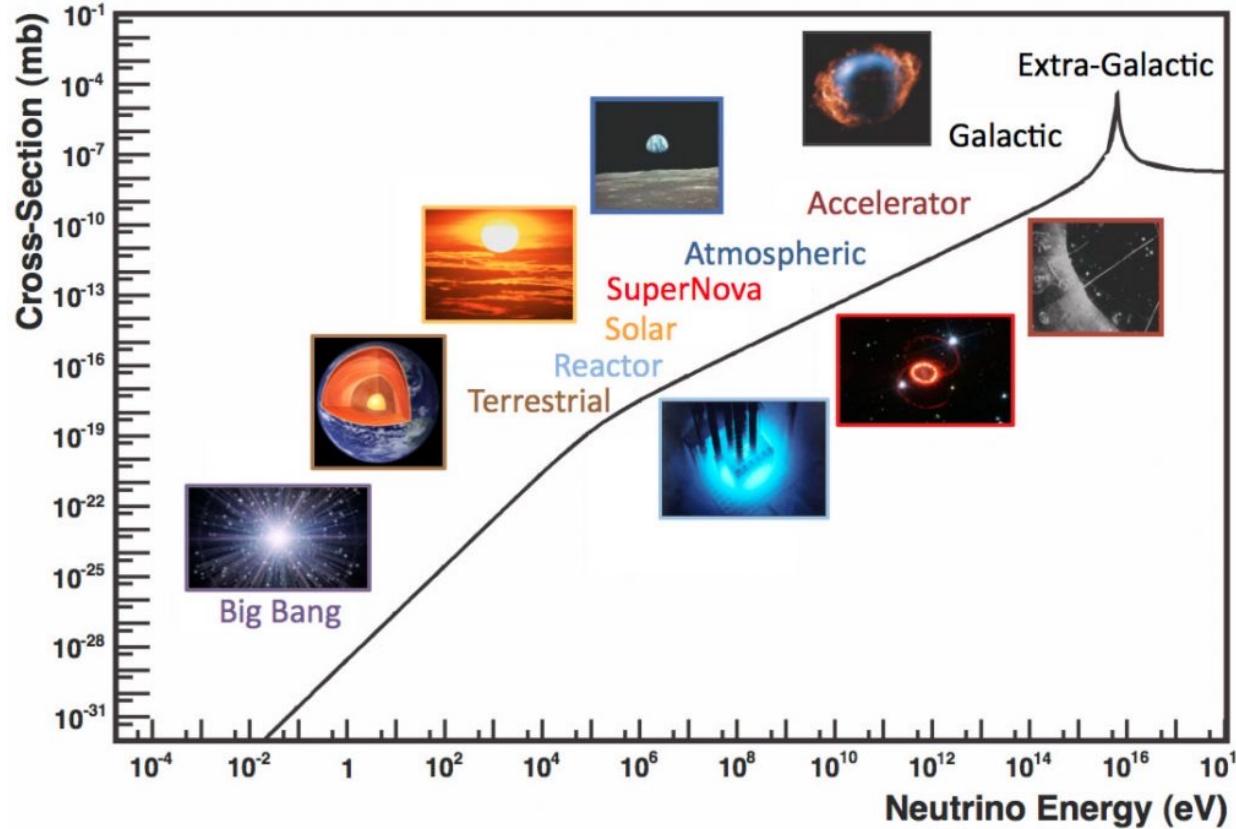
Séminaire LLR

13 March 2023



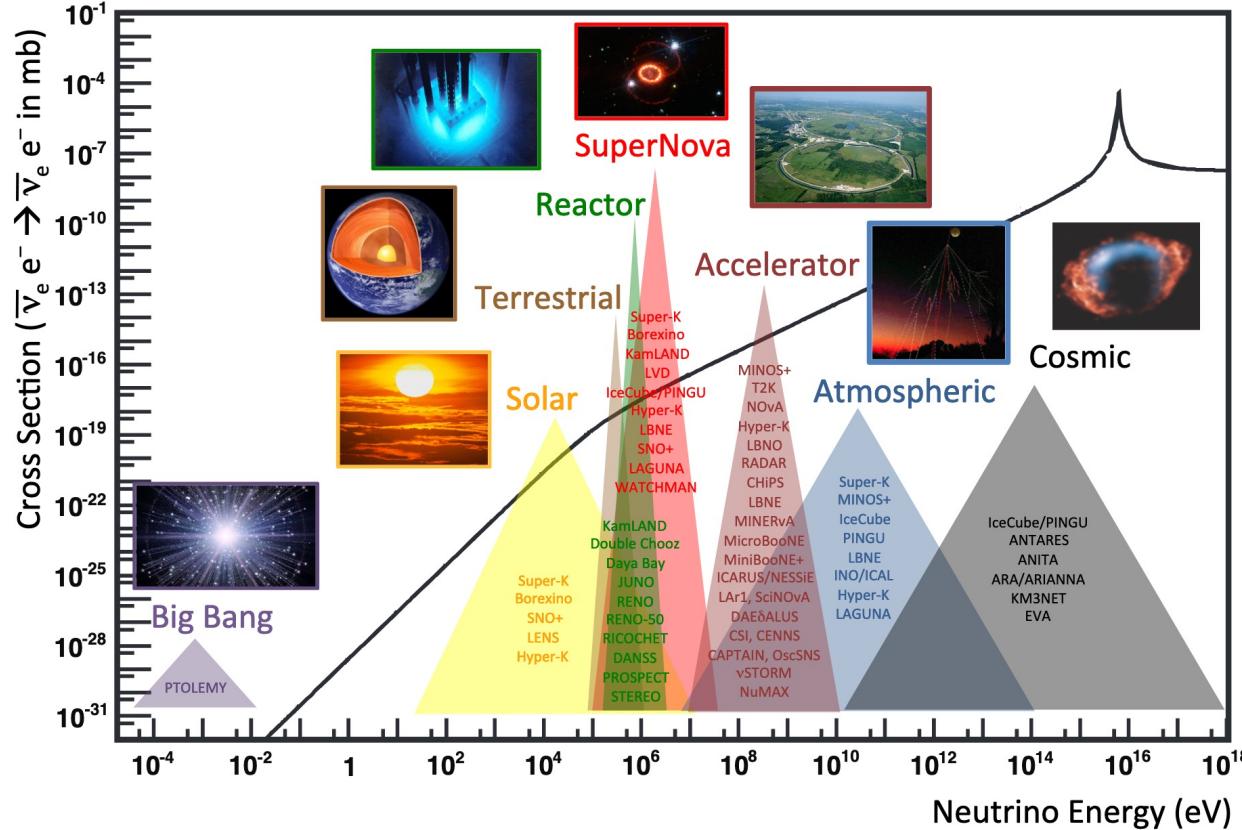
Neutrinos in the Universe

Rev. Mod. Phys. 84, 1307 (2012)



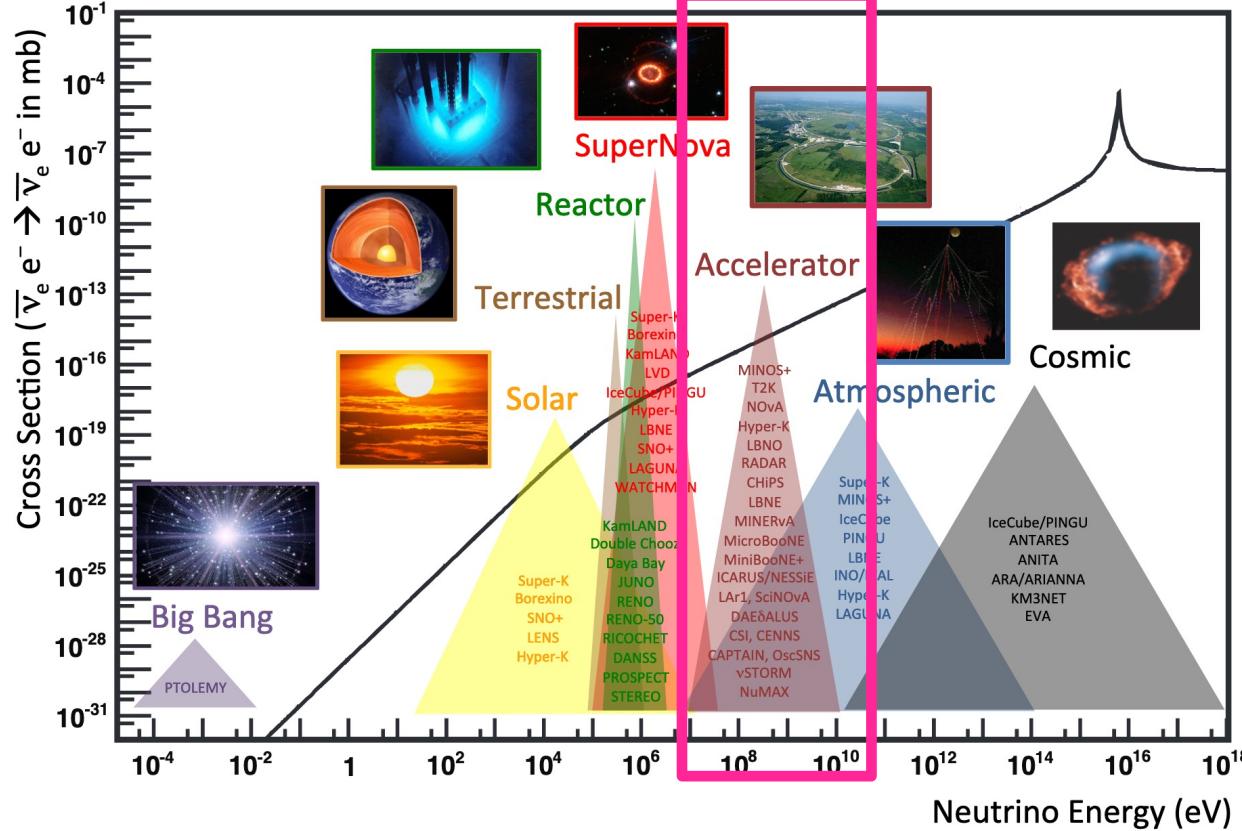
Neutrinos in the Universe

Modified for Snowmass 2013 Report, Chapter 2



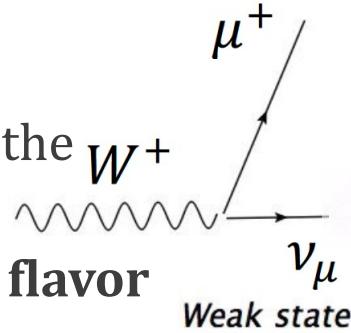
Neutrinos in the Universe

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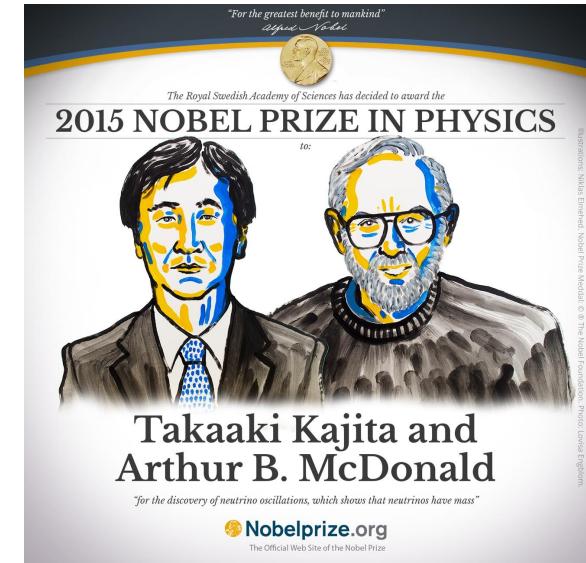
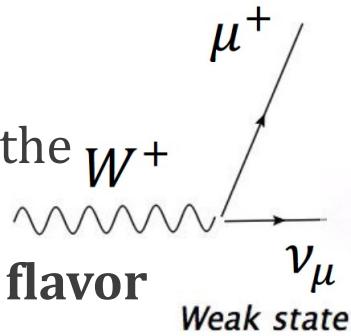
Neutrino Oscillations (I)

- Neutrinos interact exclusively via the **weak interaction**
- They are produced in a particular **flavor eigenstate**



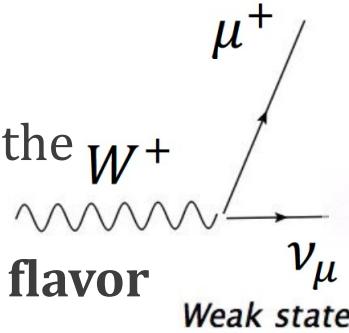
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- Neutrinos have **mass!**



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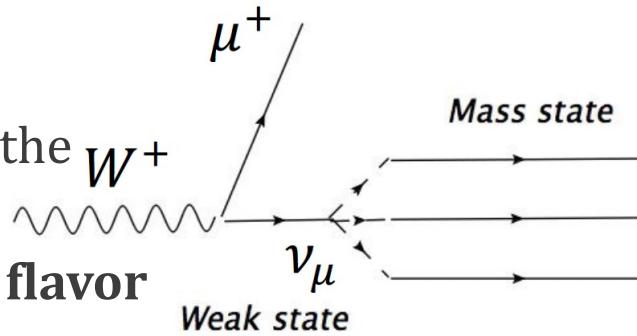


$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1}^* & U_{e2}^* & U_{e3}^* \\ U_{\mu 1}^* & U_{\mu 2}^* & U_{\mu 3}^* \\ U_{\tau 1}^* & U_{\tau 2}^* & U_{\tau 3}^* \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Pontecorvo-Maki-Nakagawa-Sakata (PMNS)

Neutrino Oscillations (I)

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- Neutrinos have **mass!**
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- They **propagate** in their mass eigenstates



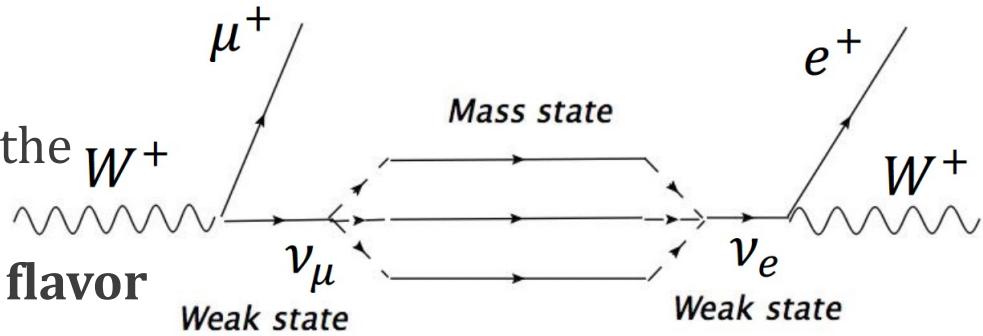
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$$\nu_\alpha = \sum_i U_{\alpha,i}^* |\nu_i\rangle$$

$$|\nu_i\rangle(t) = e^{-iE_i t} |\nu_i\rangle$$

Neutrino Oscillations (I)

- Neutrinos interact exclusively via the **weak interaction**
- They are produced in a particular **flavor eigenstate**
- Neutrinos have **mass!**
- Flavor eigenstates \neq **Mass eigenstates**
- They **propagate** in their mass eigenstates
- During interactions (detection) they **collapse** into a (different?) flavor eigenstate



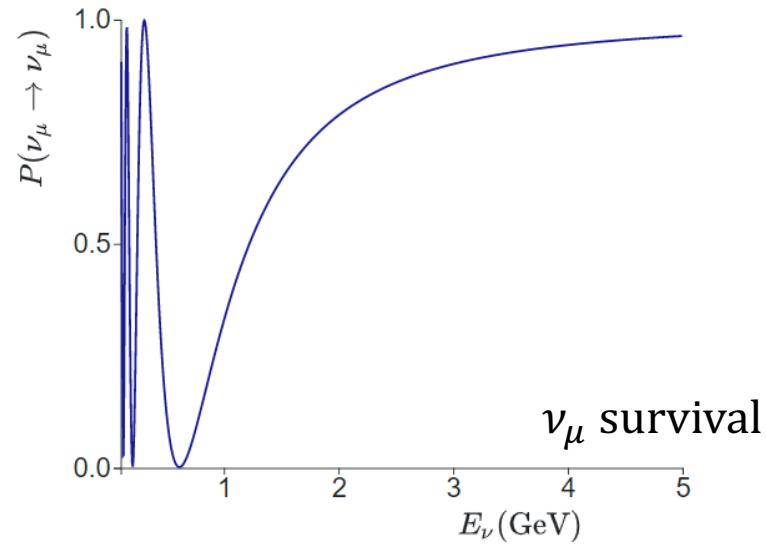
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$$\nu_\alpha = \sum_i U_{\alpha,i}^* |\nu_i\rangle \quad |\nu_i\rangle(t) = e^{-iE_i t} |\nu_i\rangle$$

$$P(\nu_\alpha \rightarrow \nu_\beta) = \left| \sum_i U_{\alpha i}^* U_{\beta i} e^{-i \frac{m_i^2}{2E}} \right|^2$$

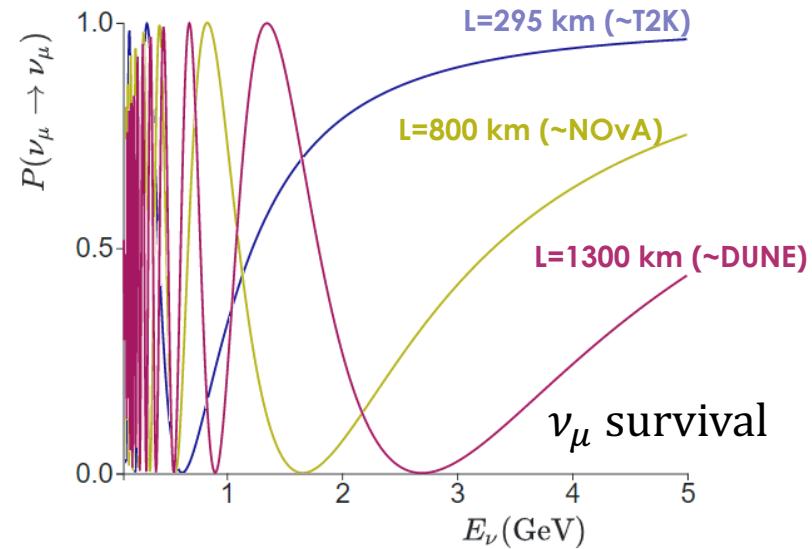
What can we learn from neutrino oscillations?

- The oscillation probability depends on:
 - The neutrino energy



What can we learn from neutrino oscillations?

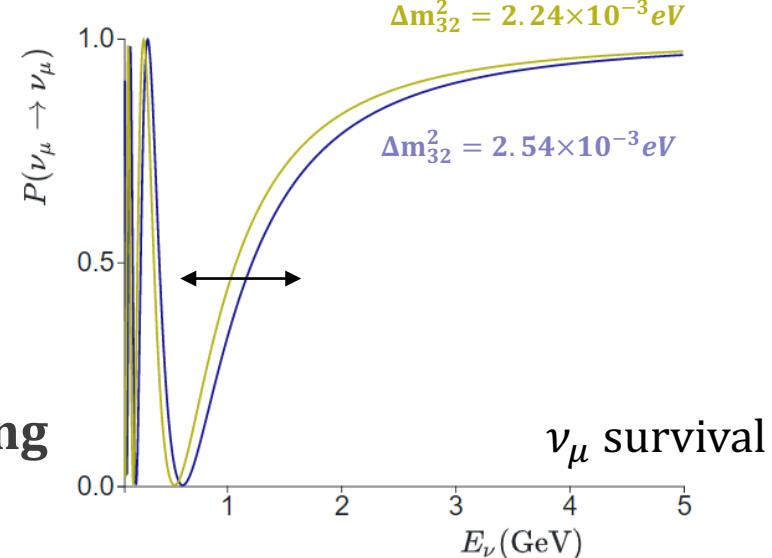
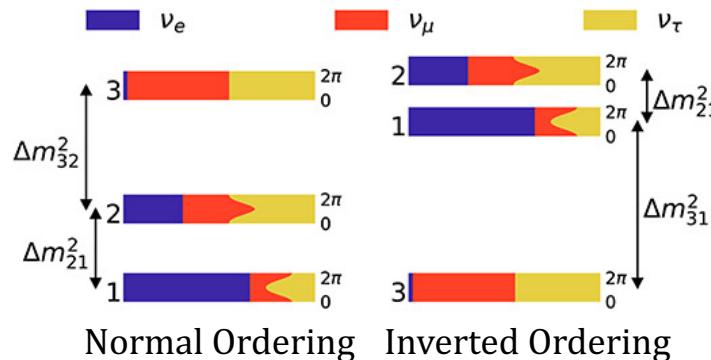
- The oscillation probability depends on:
 - The neutrino energy
 - The oscillation path length (the “baseline”)



What can we learn from neutrino oscillations?

- The oscillation probability depends on:
 - The neutrino energy
 - The oscillation path length (the “baseline”)
 - The neutrino mass difference

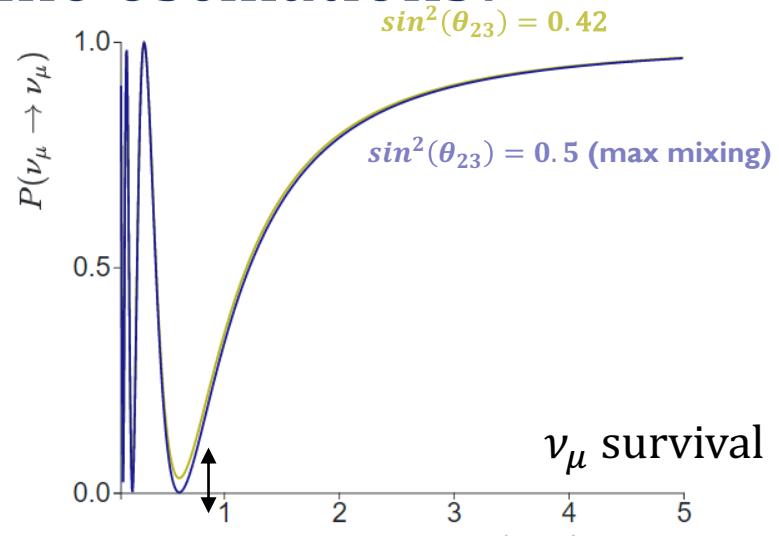
Can shed light on the **neutrino mass ordering**



One of the main unknowns in
neutrino physics

What can we learn from neutrino oscillations?

- The oscillation probability depends on:
 - The neutrino energy
 - The oscillation path length (the “baseline”)
 - The neutrino mass difference
 - The PMNS parameters

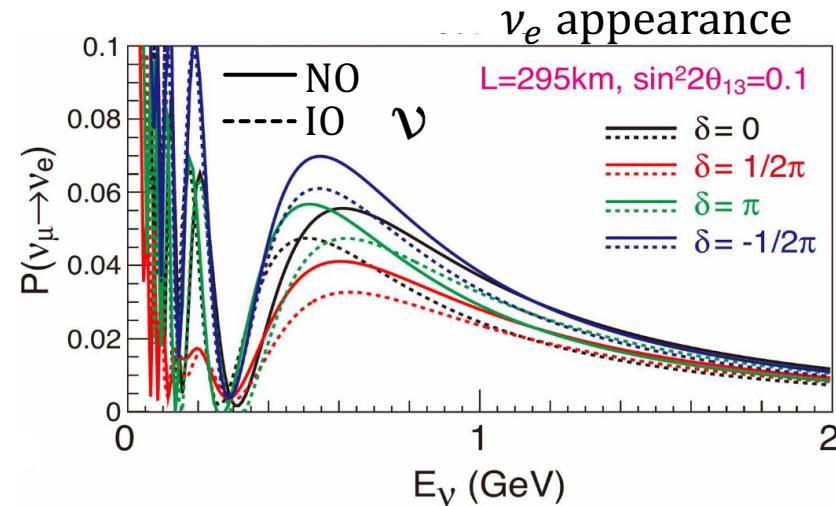


$$s_{ij} = \sin\theta_{ij}$$
$$c_{ij} = \cos\theta_{ij}$$

$$U = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{+i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}$$

What can we learn from neutrino oscillations?

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 - The neutrino energy
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 - The neutrino mass difference
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Is CP-symmetry violated in neutrino oscillations?

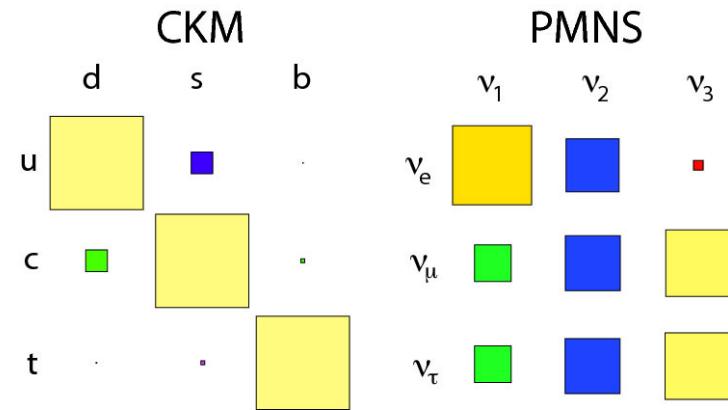
$$s_{ij} = \sin \theta_{ij}$$

$$c_{ij} = \cos \theta_{ij}$$

$$U = \begin{pmatrix} & \text{“Solar”} & \\ & c_{12} & s_{12} & 0 \\ & -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} & \text{“Reactor/Accelerator”} & \\ c_{13} & 0 & s_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13} e^{+i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} & \text{“Atmospheric”} & \\ 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}$$

What can we learn from neutrino oscillations?

- The oscillation probability depends on:
 - The neutrino energy
 - The oscillation path length (the “baseline”)
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Precise values of oscillation parameters → symmetries?

$$\begin{aligned}s_{ij} &= \sin\theta_{ij} \\c_{ij} &= \cos\theta_{ij}\end{aligned}$$

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How do we measure
neutrino oscillations?

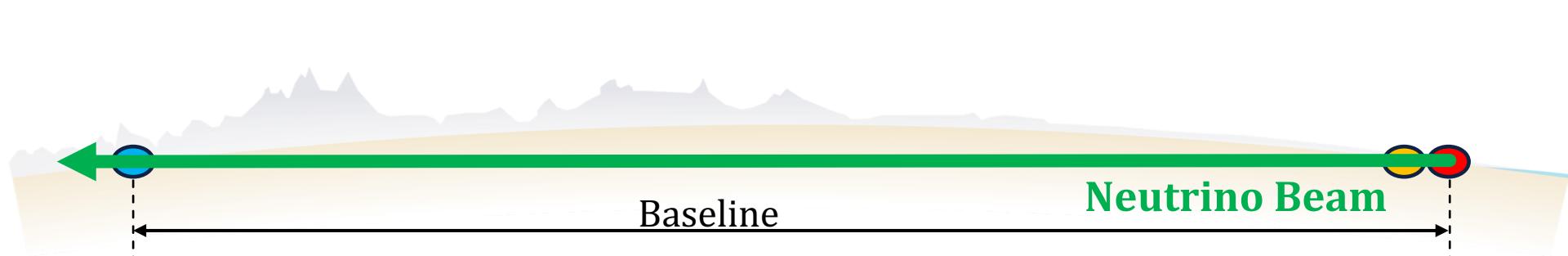
Long-baseline oscillation experiments

Far detector

Near detector

Neutrino beam

- High purity and high intensity ν_μ or $\bar{\nu}_\mu$ beam
- Produced by impinging protons on a target
- Neutrinos produced from meson decays



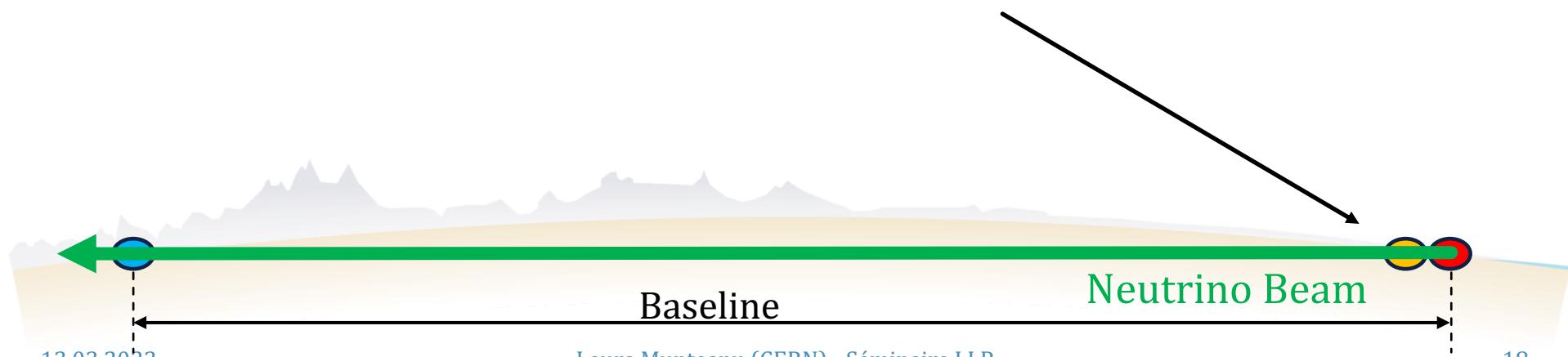
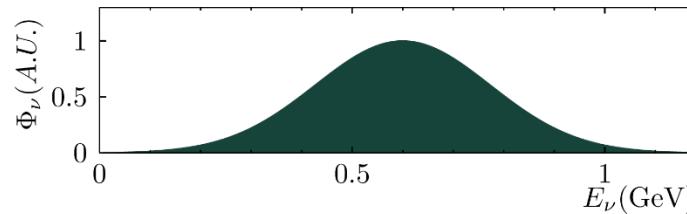
Long-baseline oscillation experiments

Far detector

Near detector

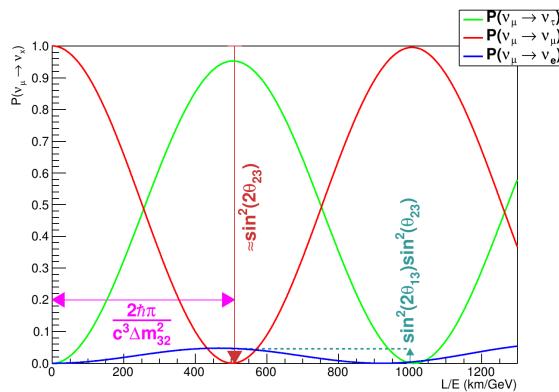
Neutrino beam

- Measure the spectrum before oscillations

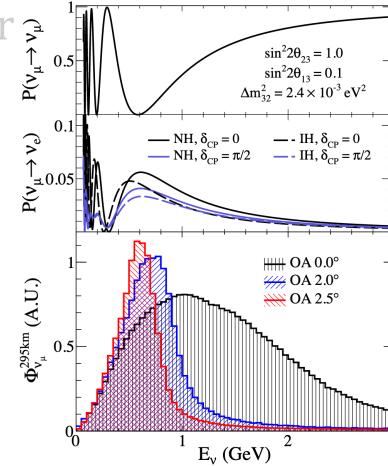


Long-baseline oscillation experiments

Far detector



Near detector



Neutrino beam

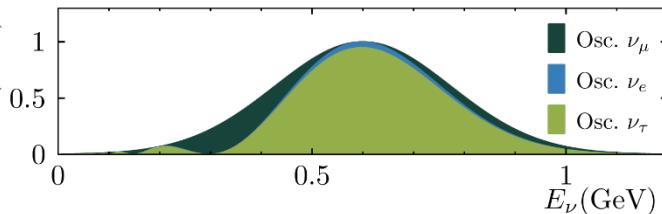
- The baseline and the neutrino energy are optimized to **maximize the oscillation probability**
- T2K uses the “**off-axis**” technique



Long-baseline oscillation experiments

Far detector

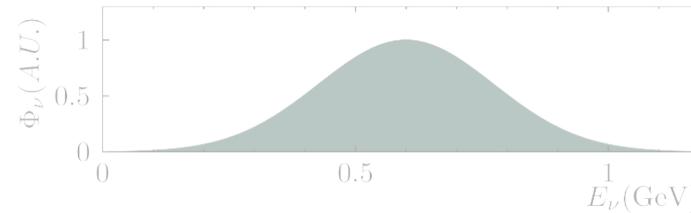
- Measure the **oscillated spectrum**



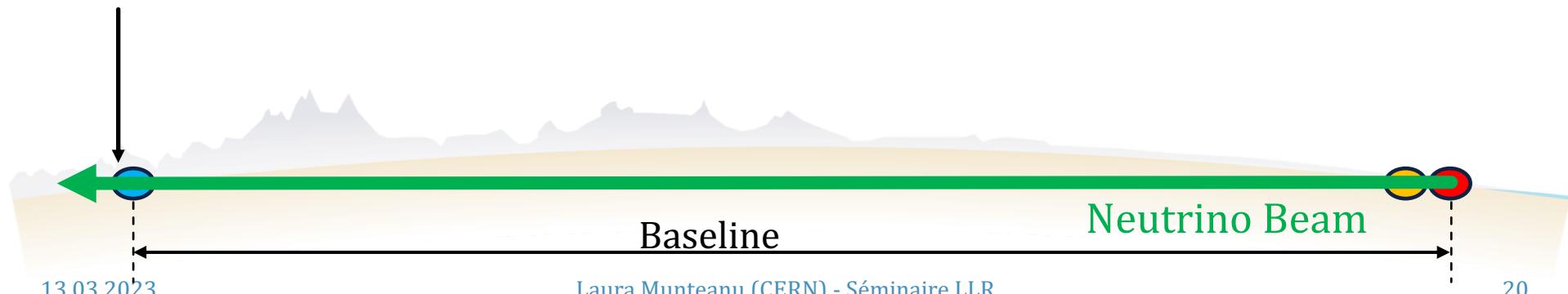
- Infer oscillation parameters

Near detector

- Measure the spectrum before oscillations

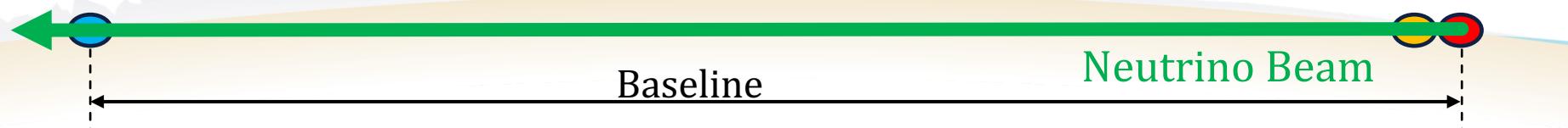


Neutrino beam

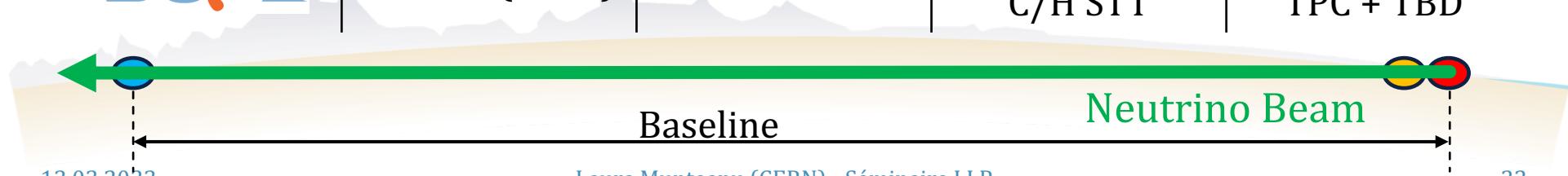


Long-baseline oscillation experiments

Experiment	Beam Energy	Baseline	Near detector	Far detector
 T2K	600 MeV (Narrow)	~300 km	Scintillator bars+water	Water Cherenkov
	1.2 GeV (Wide)	~800 km	Plastic scintillator	Plastic scintillator
 NOvA	600 MeV (Narrow)	~300 km	Scintillator cubes + TBD	Water Cherenkov
	2.5 GeV (Wide)	~1200 km	Argon TPC + C/H STT	Liquid Argon TPC + TBD



Long-baseline oscillation experiments

Experiment	Beam Energy	Baseline	Near detector	Far detector
Current	T2K 	600 MeV (Narrow)	~300 km	Scintillator bars+water
	NOvA 	1.2 GeV (Wide)	~800 km	Plastic scintillator
Future	HyperK 	600 MeV (Narrow)	~300 km	Scintillator cubes + TBD
	DUNE 	2.5 GeV (Wide)	~1200 km	Argon TPC + C/H STT
 <p>The diagram illustrates the long-baseline neutrino beam path. A horizontal green line represents the baseline, extending from a blue circle on the left to a red circle on the right. A yellow shaded area below the baseline represents the neutrino beam. A dashed arrow at the bottom indicates the direction of the neutrino beam along the baseline.</p>				

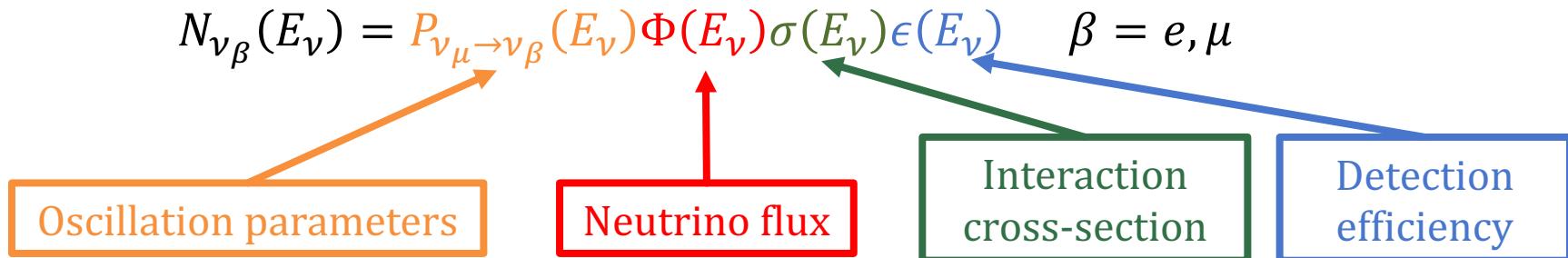
Example: the T2K oscillation analysis

- Oscillation parameters are measured by comparing the observed event rates at the near and the far detectors

$$N_{\nu_\beta}(E_\nu) = P_{\nu_\mu \rightarrow \nu_\beta}(E_\nu) \Phi(E_\nu) \sigma(E_\nu) \epsilon(E_\nu) \quad \beta = e, \mu$$

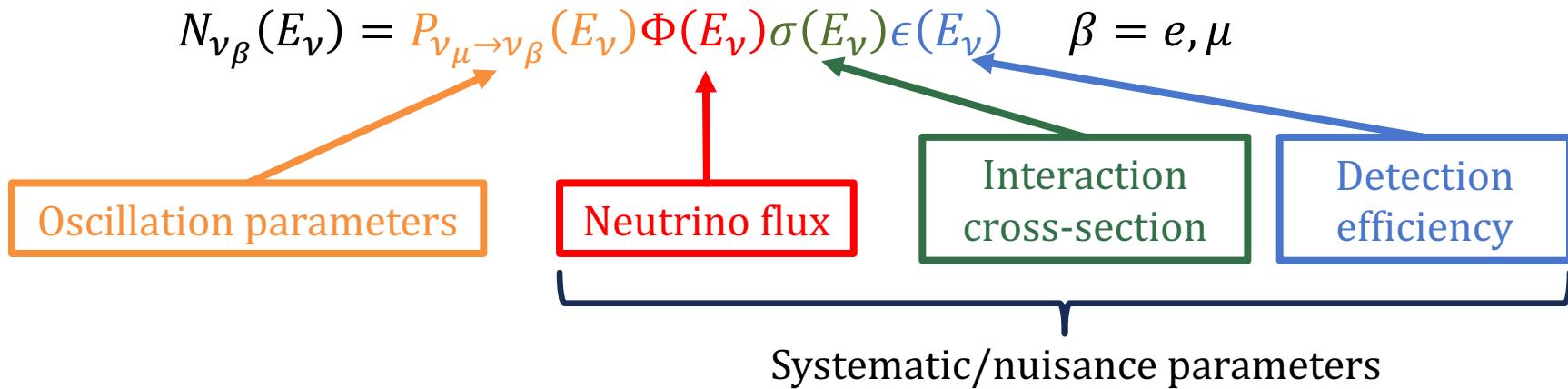
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$\beta = e, \mu$

Oscillation parameters

Neutrino flux

Interaction cross-section

Detection efficiency

- At the ND, oscillations are negligible + **much higher event rate**
 - Use ND data to **constrain systematic parameters**

Example: the T2K oscillation analysis

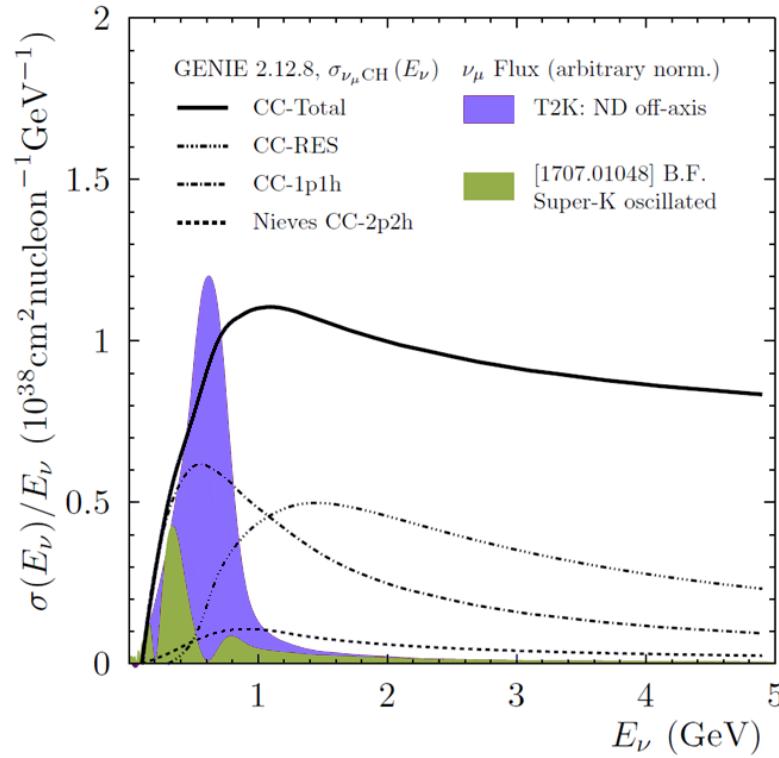
- Oscillation parameters are measured by comparing the observed event rates at the near and the far detectors

$$N_{\nu_\beta}(E_\nu^{reco}) = P_{\nu_\mu \rightarrow \nu_\beta}(E_\nu^{true}) \Phi(E_\nu^{true}) \sigma(E_\nu^{true}) \epsilon(E_\nu^{true}) S(E_\nu^{true}, E_\nu^{reco}) \quad \beta = e, \mu$$

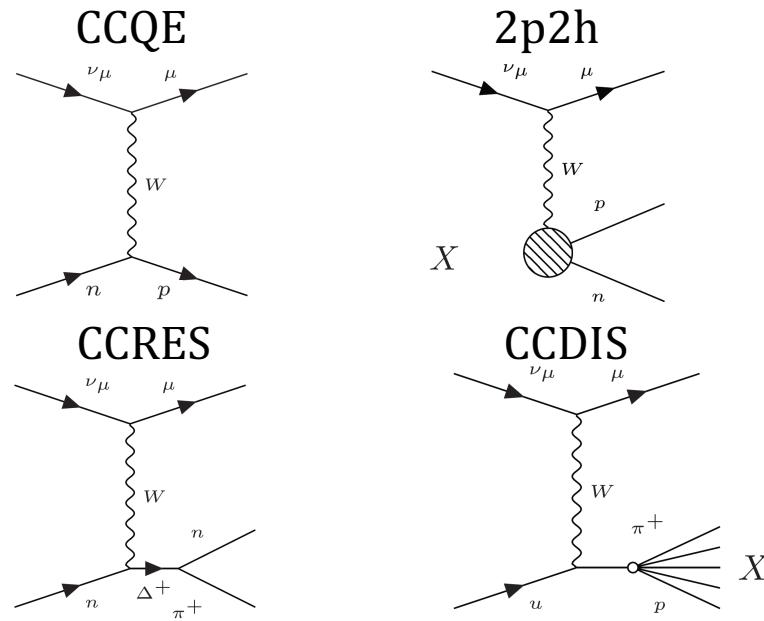
Energy smearing matrix

- At the ND, oscillations are negligible + **much higher event rate**
 - Use ND data to **constrain systematic parameters**
- Not a simple task!
 - Rely on a ND-to-FD **flux+cross-section extrapolation model**
 - Relies on **knowledge of true to reconstructed neutrino energy mapping**

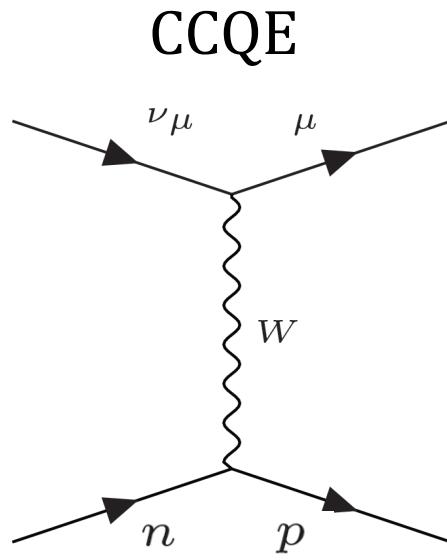
Neutrino interactions at T2K energies



- Dominant channel is charged-current quasi-elastic (**CCQE**)
- But also multinucleon interactions (**2p2h**) resonant interactions (**CCRES**) and deep inelastic scattering (**CCDIS**)



Neutrino interactions at T2K energies



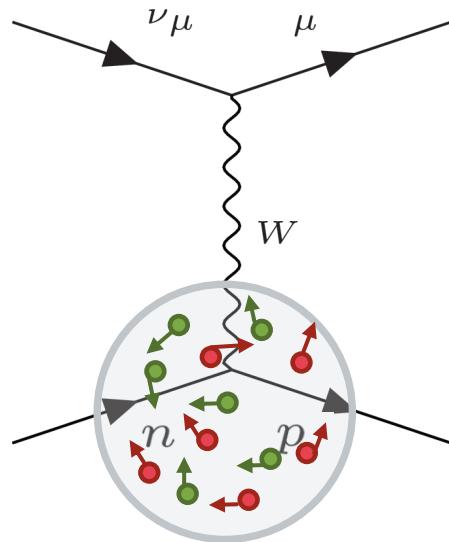
- If initial state nucleon is at rest: two body process → exact energy reconstruction

$$E_{QE} = \frac{m_p^2 - m_\mu^2 - (m_n - E_B)^2 + 2E_\mu(m_n - E_B)}{2(m_n - E_B - E_\mu + p_\mu^z)}$$

- Far detector can only detect charged leptons
 - Optimize near detector to do the same!

Aside - Nuclear effects

CCQE



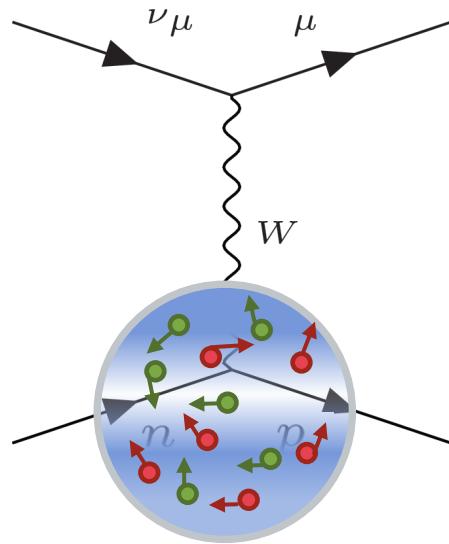
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- Nucleons are bound inside complex nuclei

Nuclear effects

- Fermi motion

Aside - Nuclear effects

CCQE



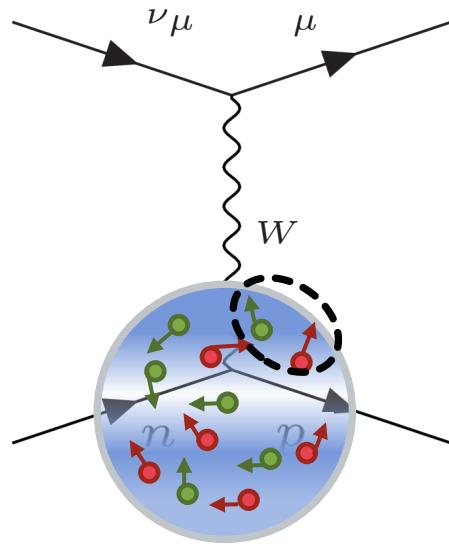
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Nuclear effects

- Fermi motion
- Nuclear/optical potential

Aside - Nuclear effects

CCQE



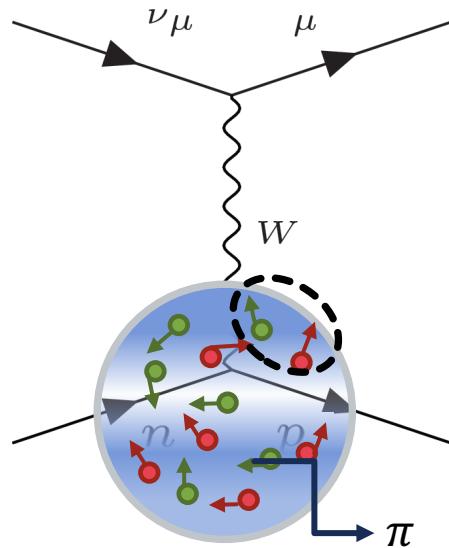
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Nuclear effects

- Fermi motion
- Nuclear/optical potential
- Correlations between nucleons

Aside - Nuclear effects

CCQE

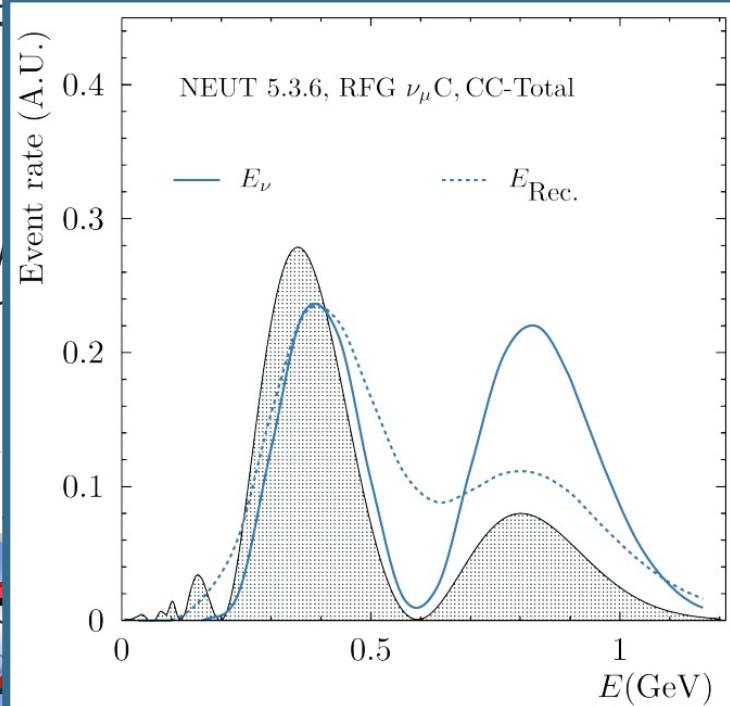
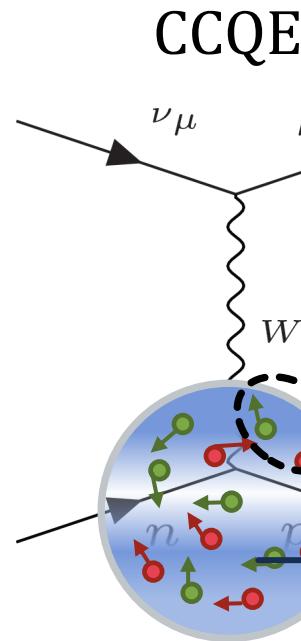


- In reality, the true process is not a simple 2-body scatter
- Nucleons are bound inside complex nuclei

Nuclear effects

- Fermi motion
- Nuclear/optical potential
- Correlations between nucleons
- Interactions with the nuclear medium (Final State Interactions or FSI)

Aside - Nuclear effects



Impact of nuclear effects on
reconstructed neutrino energy
(oscillated spectrum)

process is not a simple 2-

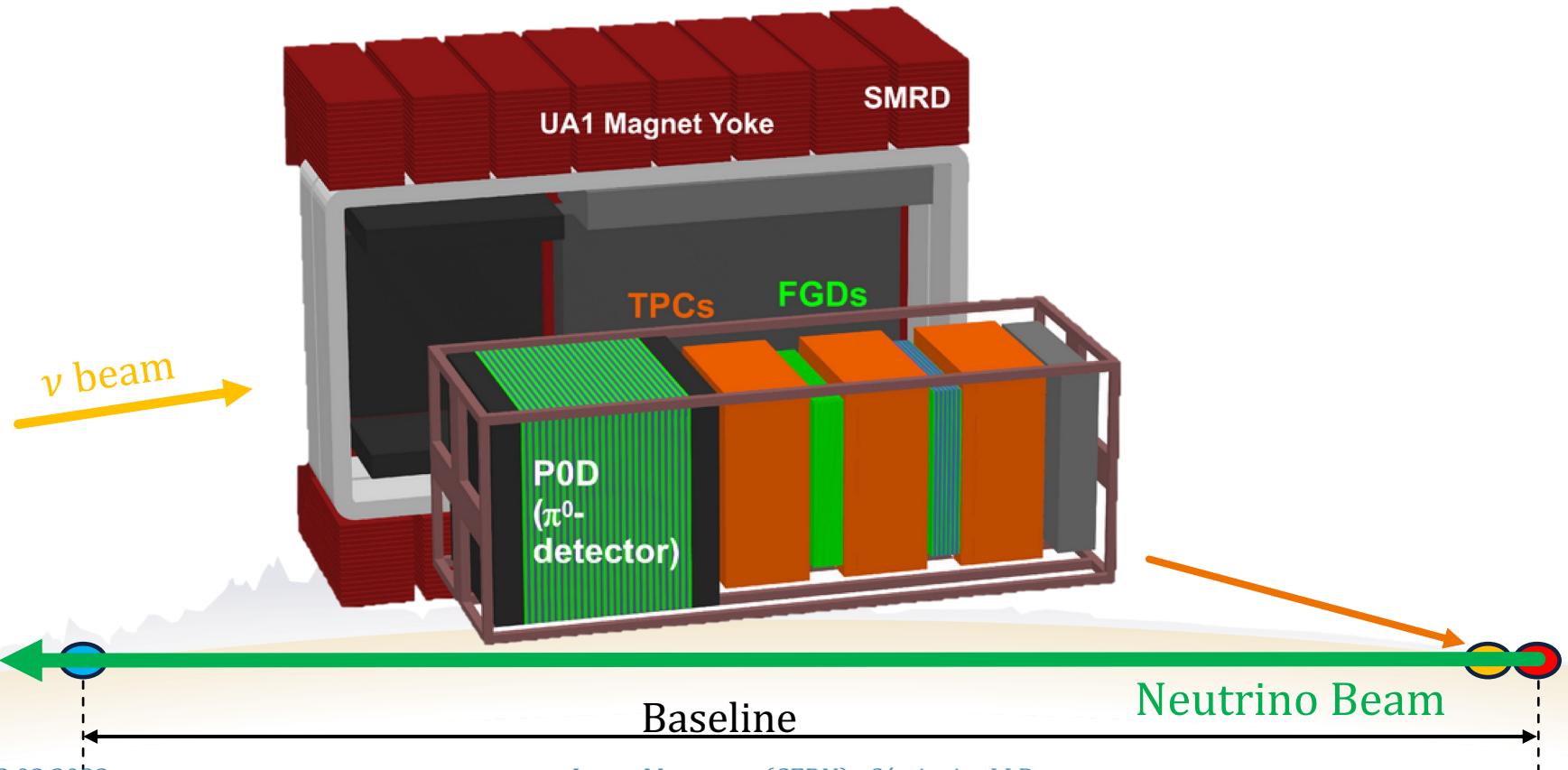
inside complex nuclei

ential

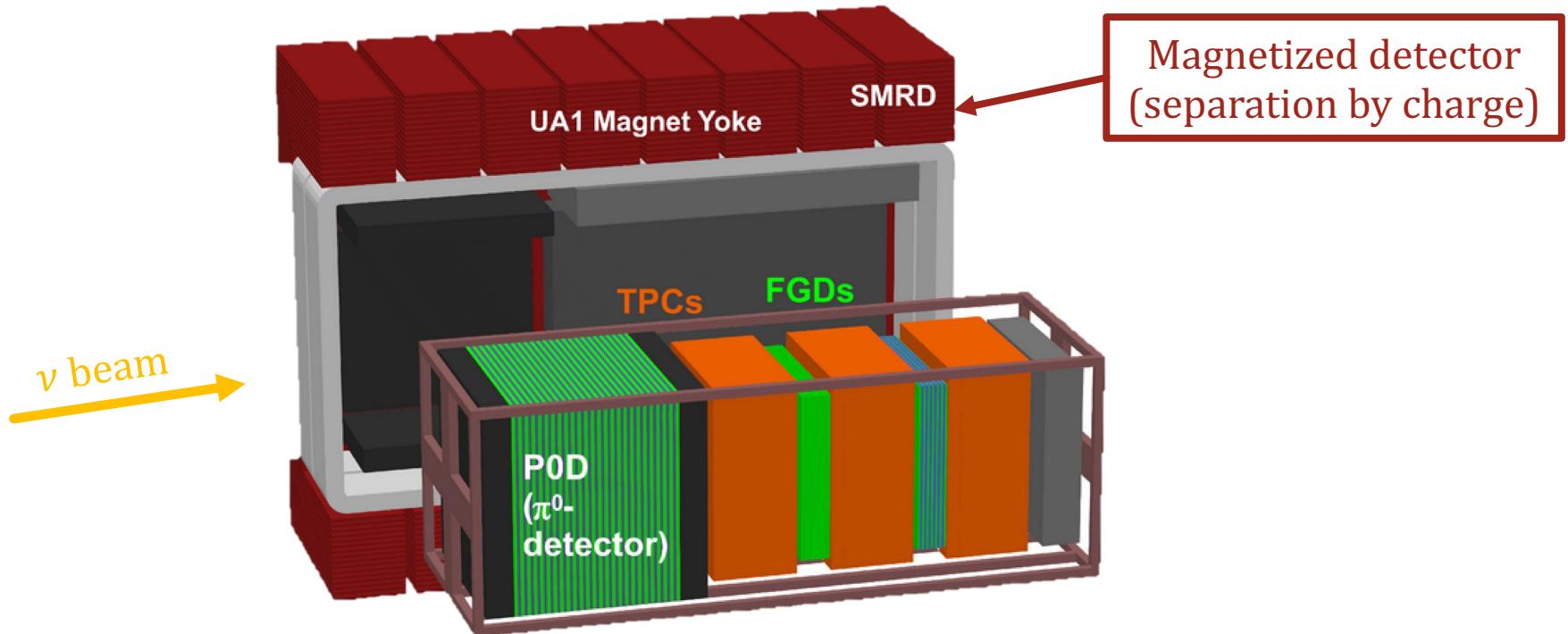
nucleons

the nuclear medium (Final
FSI)

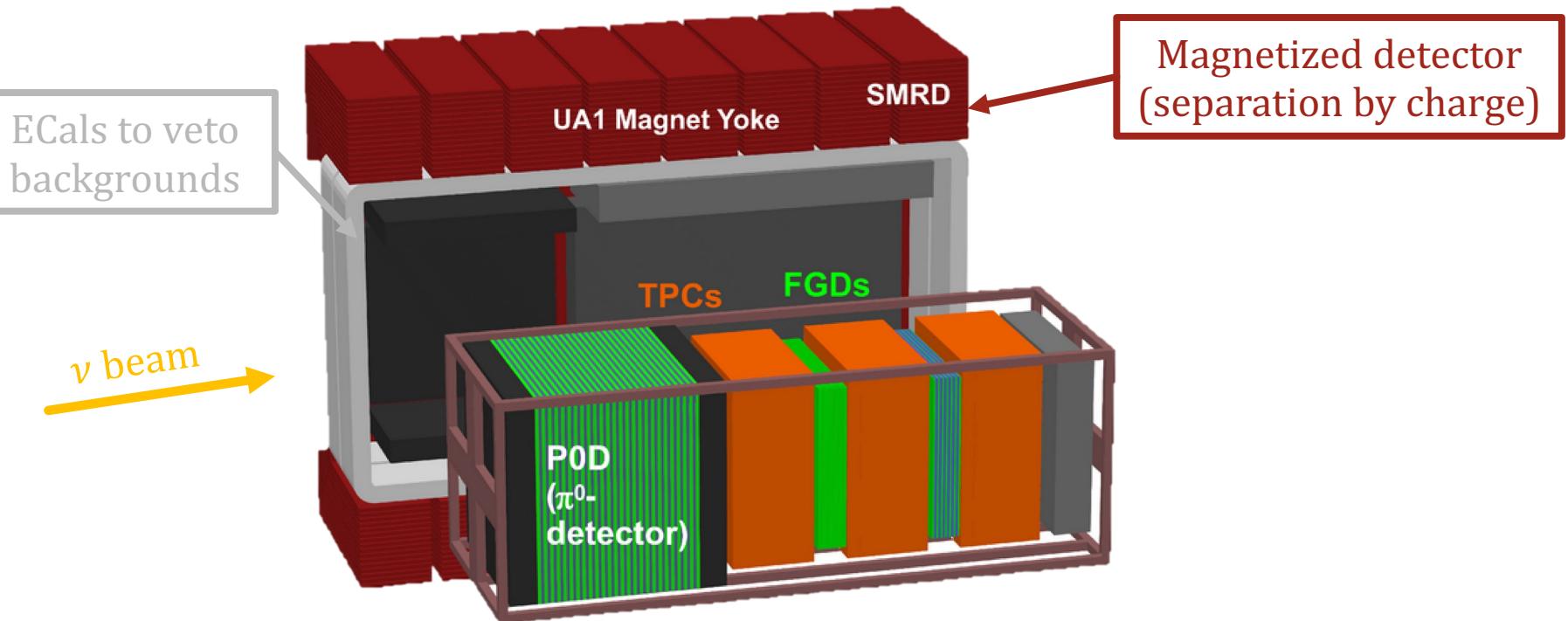
The T2K near detector at 280 m: ND280



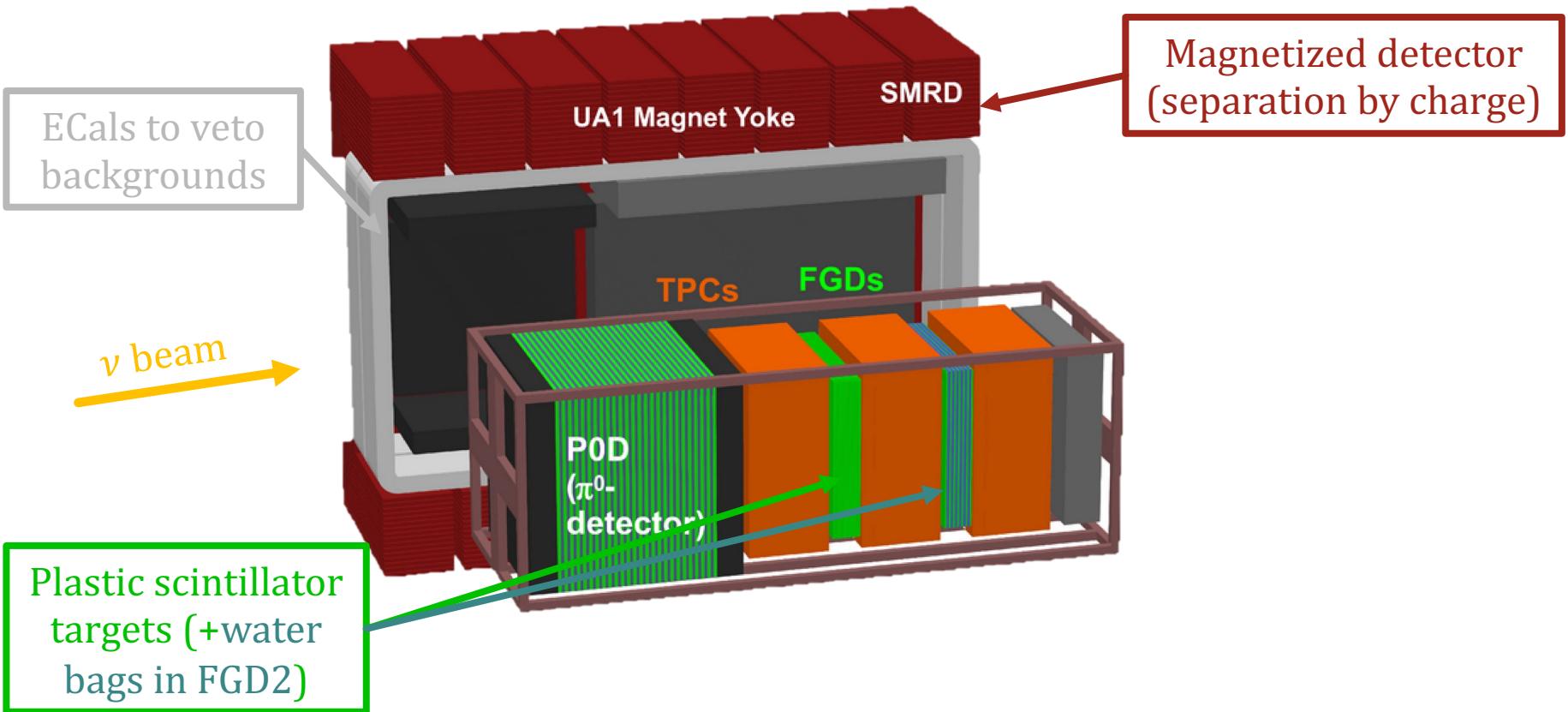
The T2K near detector at 280 m: ND280



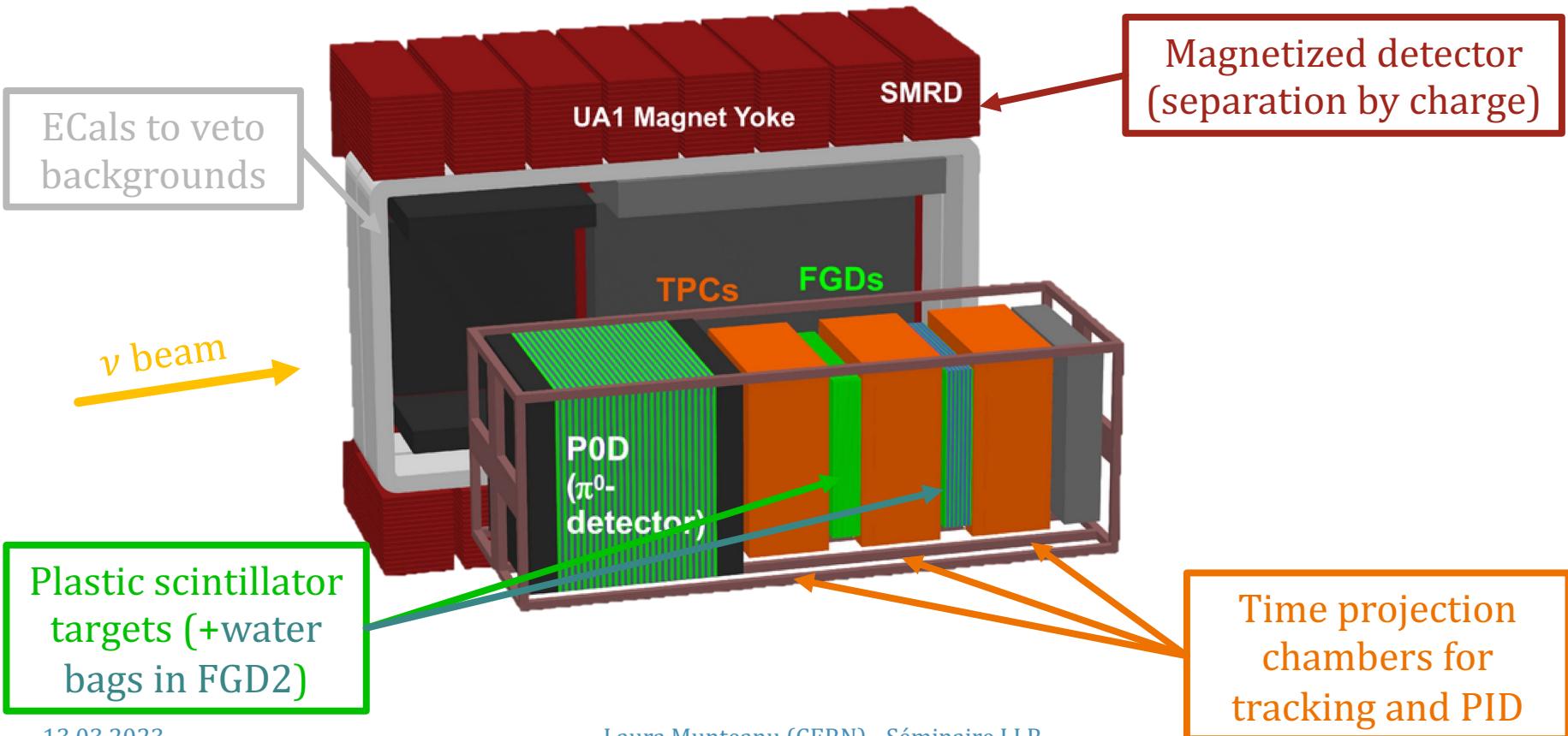
The T2K near detector at 280 m: ND280



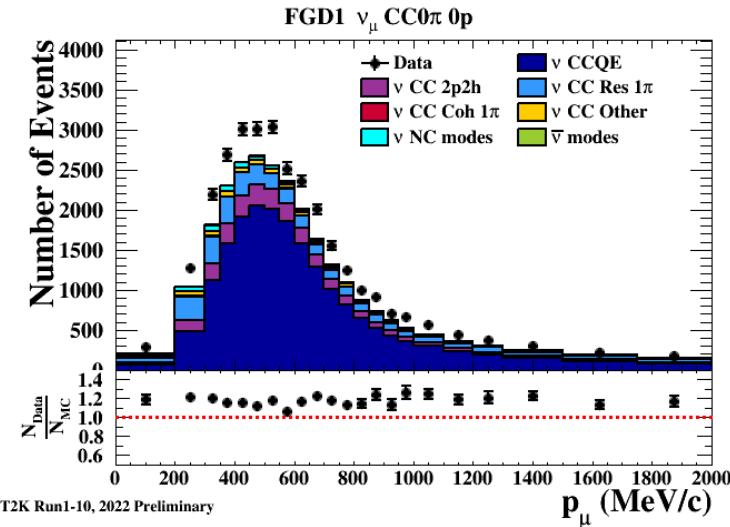
The T2K near detector at 280 m: ND280



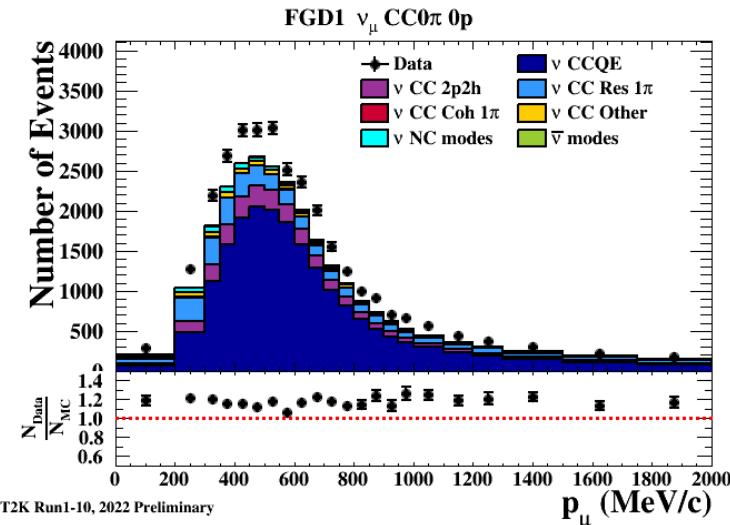
The T2K near detector at 280 m: ND280



Constraining systematics with ND280 data

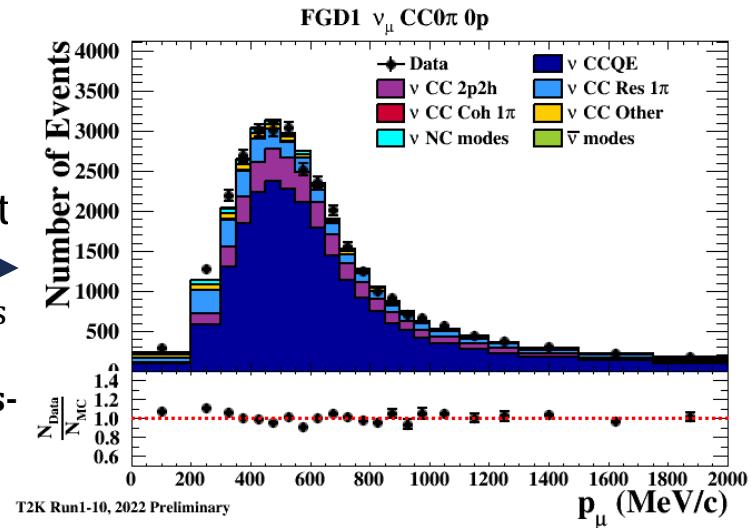


Constraining systematics with ND280 data



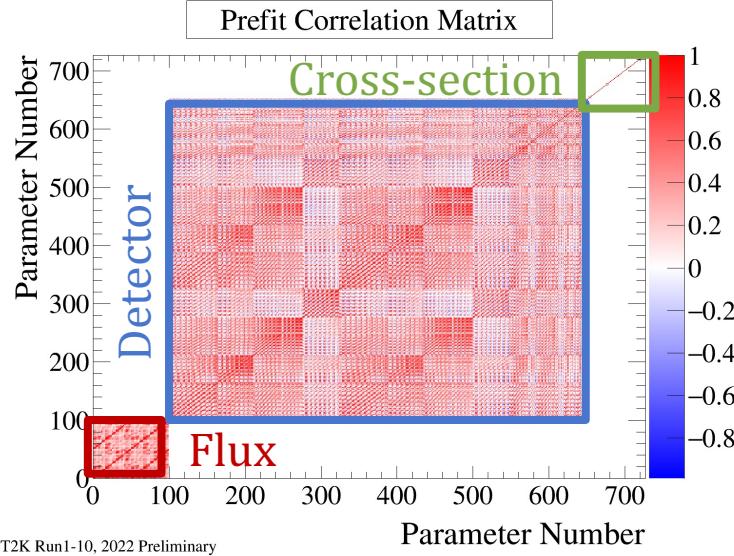
Frequentist fit

Varies parameters
related to flux,
detector and **cross-
section model**



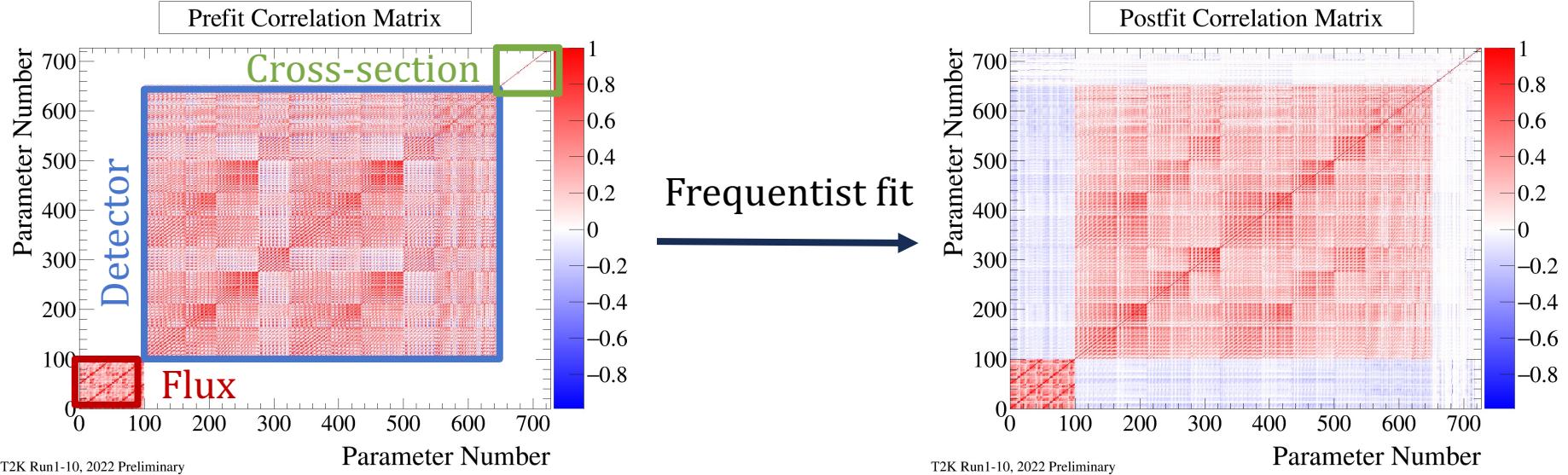
- Significant improvement in data-MC agreement

Constraining systematics with ND280 data



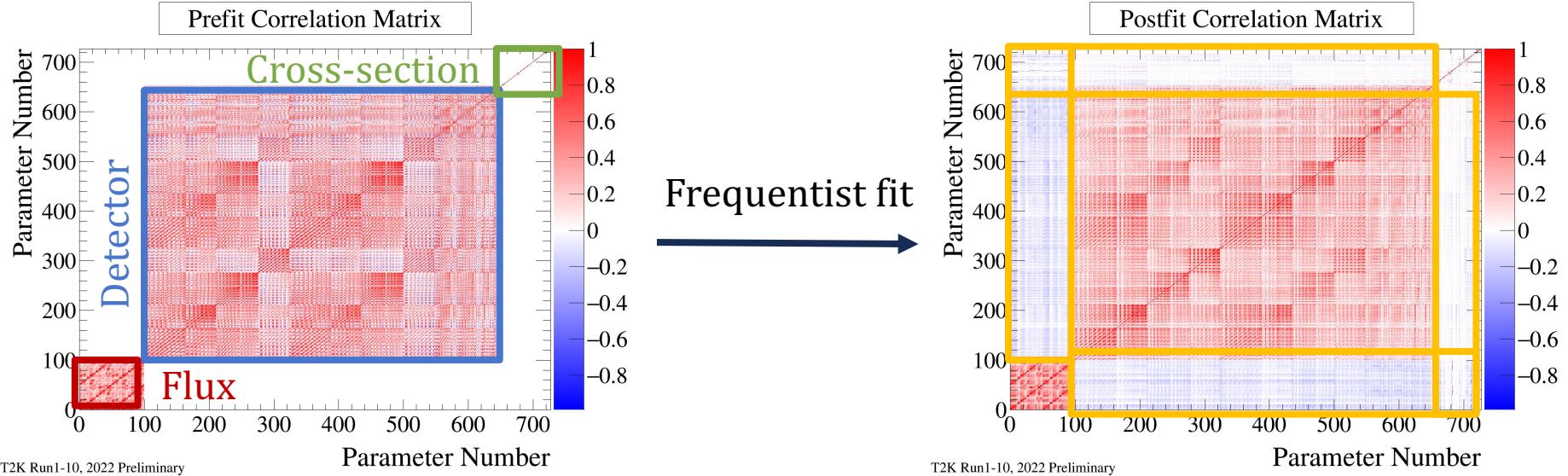
- Significant improvement in data-MC agreement
- Identifies **correlations** between parameter categories

Constraining systematics with ND280 data



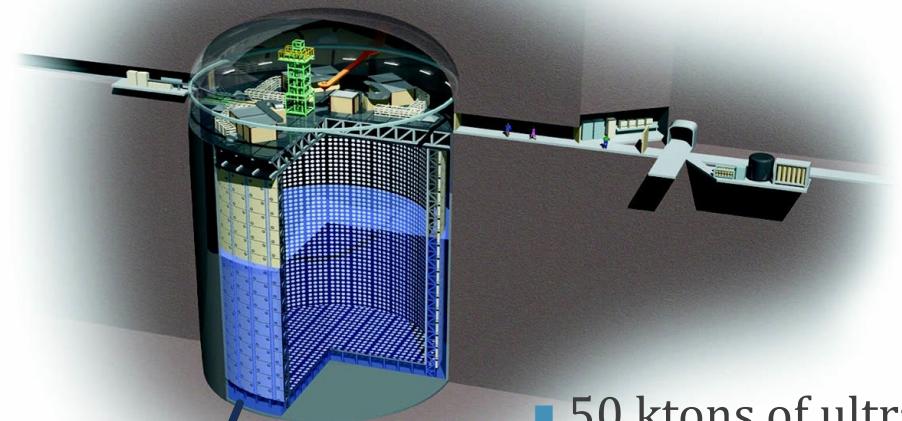
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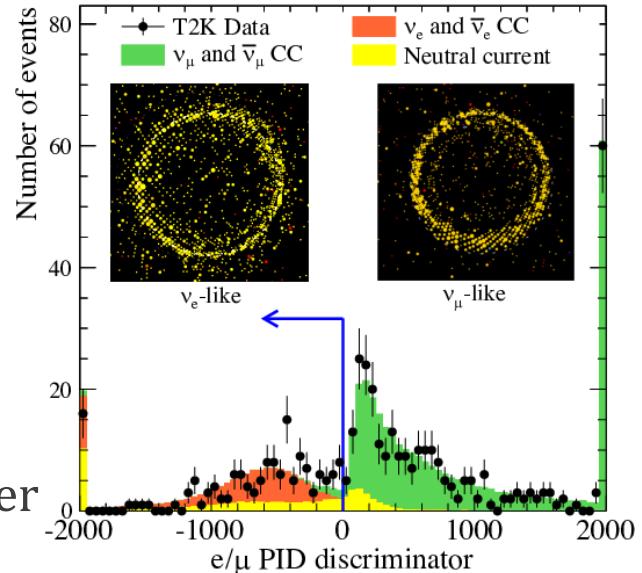


- Significant improvement in data-MC agreement
- Identifies **correlations** between parameter categories

The Far Detector: Super-Kamiokande



- 50 ktons of ultra-pure water
- ~11,000 PMTs
- Detects charged leptons through Cherenkov radiation

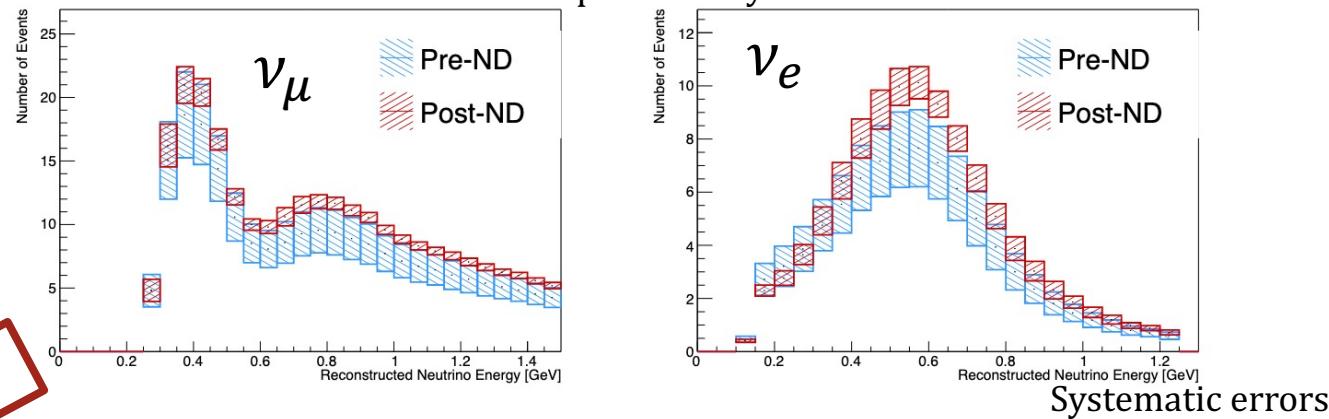


Baseline

Neutrino Beam

Impact of ND constraint on FD spectra and errors

T2K preliminary



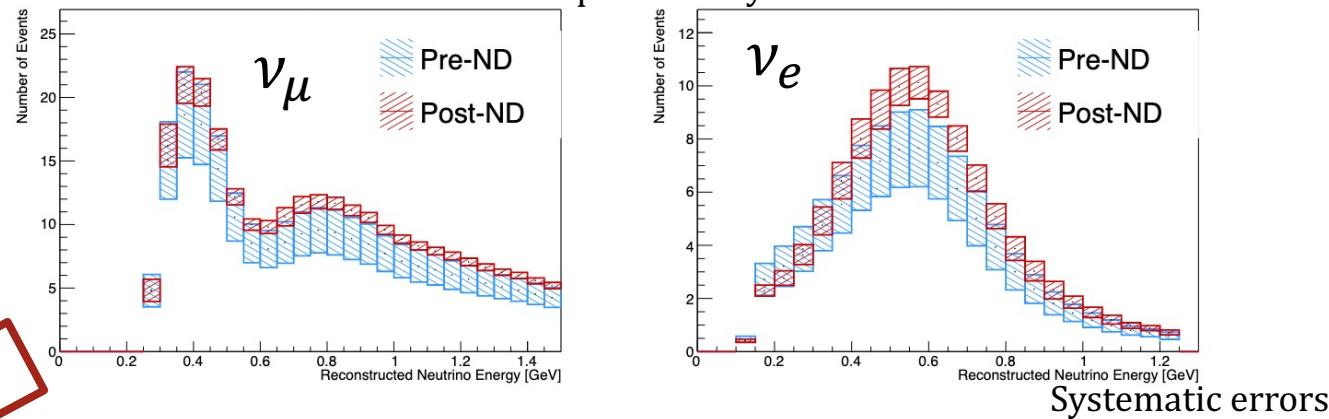
Before ND fit

Error source (units: %)	1R		MR		1Re		FHC/RHC	
	FHC	RHC	FHC	CC1 π^+	FHC	RHC		
Flux	5.0	4.6	5.2		4.9	4.6	5.1	4.5
Cross-section (all)	15.8	13.6	10.6		16.3	13.1	14.7	10.5
SK+SI+PN	2.6	2.2	4.0		3.1	3.9	13.6	1.3
Total All	16.7	14.6	12.5		17.3	14.4	20.9	11.6

T2K Run 1-10, preliminary

Impact of ND constraint on FD spectra and errors

T2K preliminary



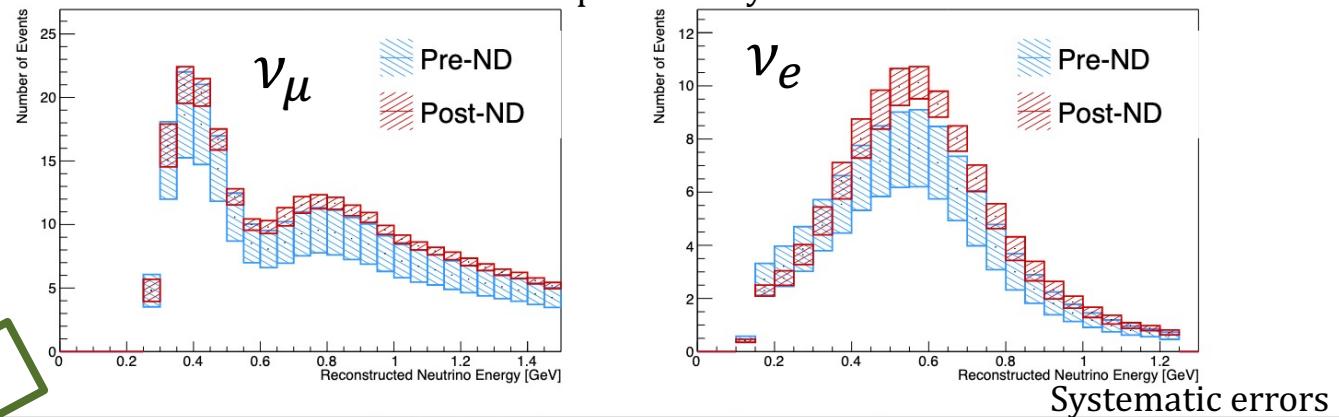
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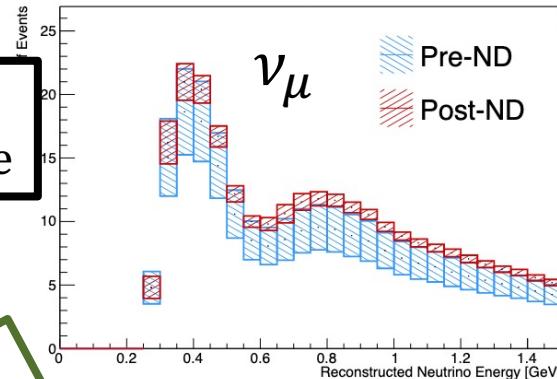


After ND fit

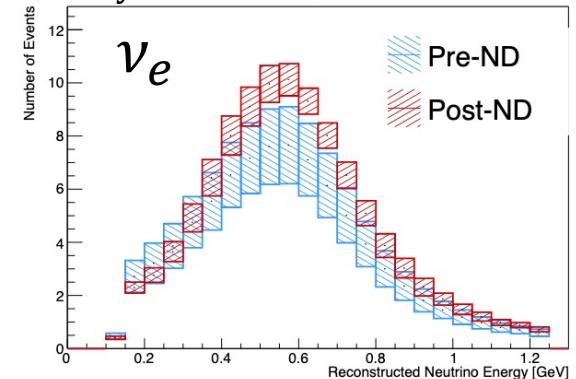
Error source (units: %)	1R		MR		1Re		FHC/RHC	
	FHC	RHC	FHC	CC1 π^+	FHC	RHC		
Flux	2.8	2.9	2.8		2.8	3.0	2.8	2.2
Xsec (ND constr)	3.7	3.5	3.0		3.8	3.5	4.1	2.4
Flux+Xsec (ND constr)	2.7	2.6	2.2		2.8	2.7	3.4	2.3
Xsec (ND unconstr)	0.7	2.4	1.4		2.9	3.3	2.8	3.7
SK+SI+PN	2.0	1.7	4.1		3.1	3.8	13.6	1.2
Total All	3.4	3.9	4.9		5.2	5.8	14.3	4.5

Impact of ND constraint on FD spectra and errors

T2K preliminary



But also tuned
spectrum shape

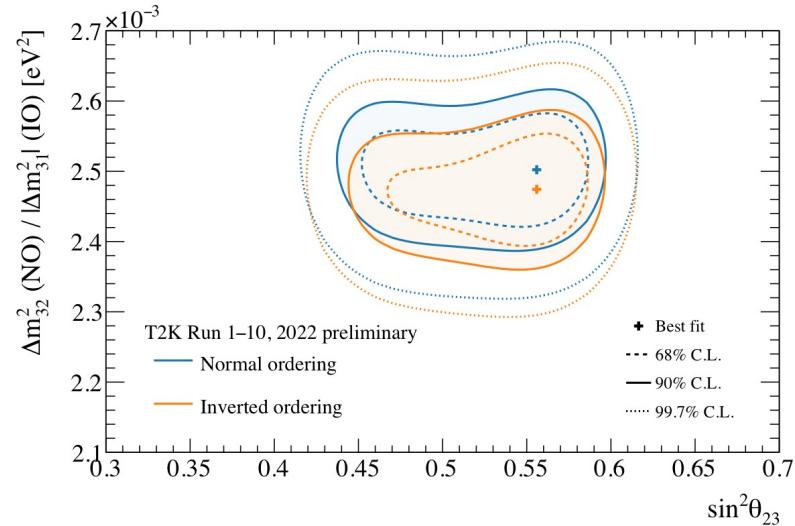


Systematic errors

After ND fit

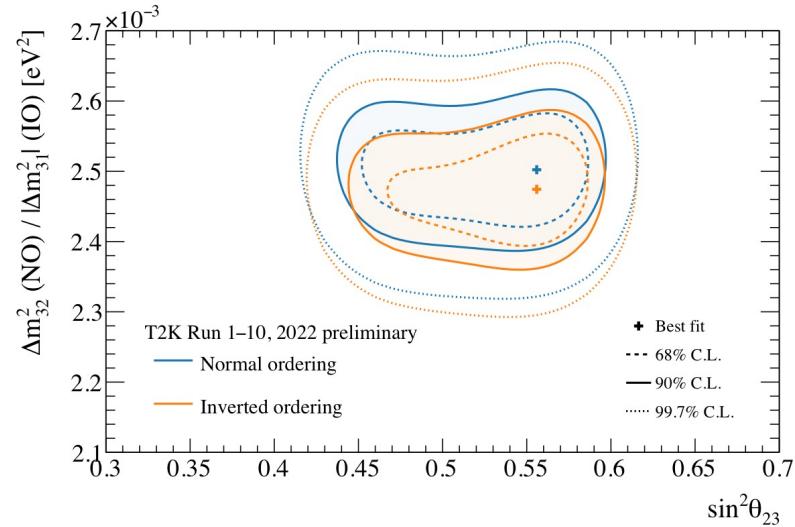
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ν_μ disappearance results

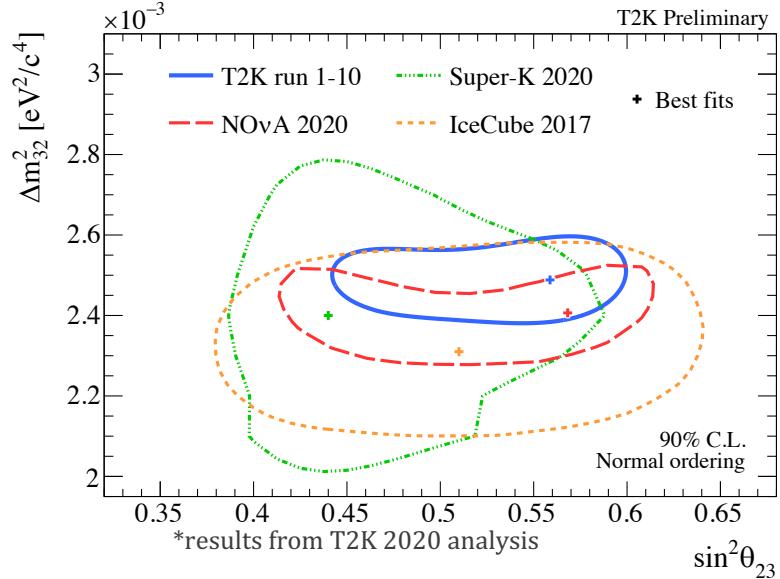


- Best-fit value for $\sin^2 \theta_{23}$ is in the upper octant
 - Though lower octant still allowed at 68% C.L.
- Weak preference for Normal Ordering

ν_μ disappearance results

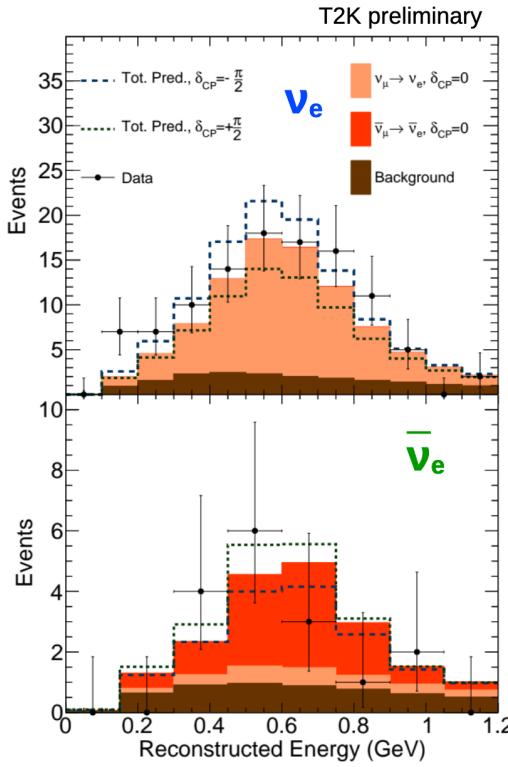


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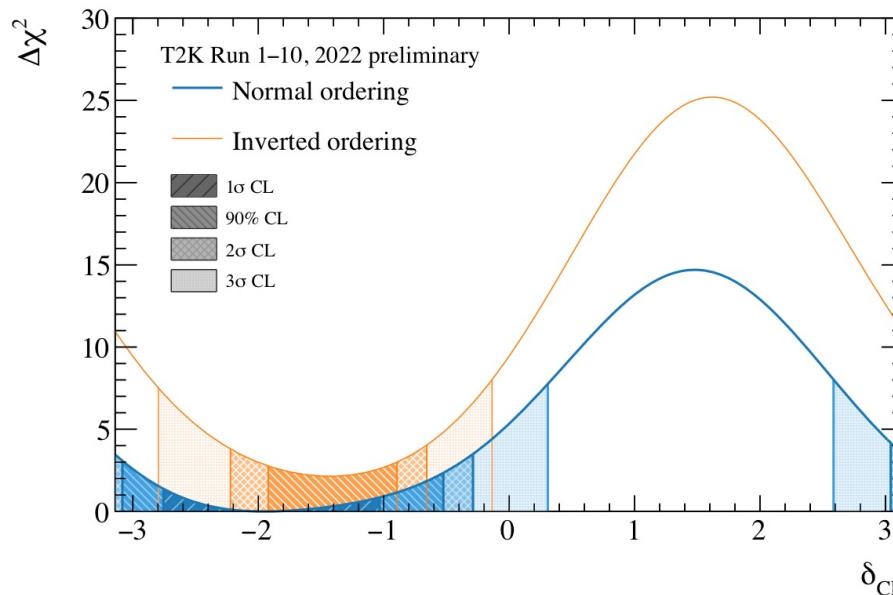


- World leading constraint on atmospheric oscillation parameters!

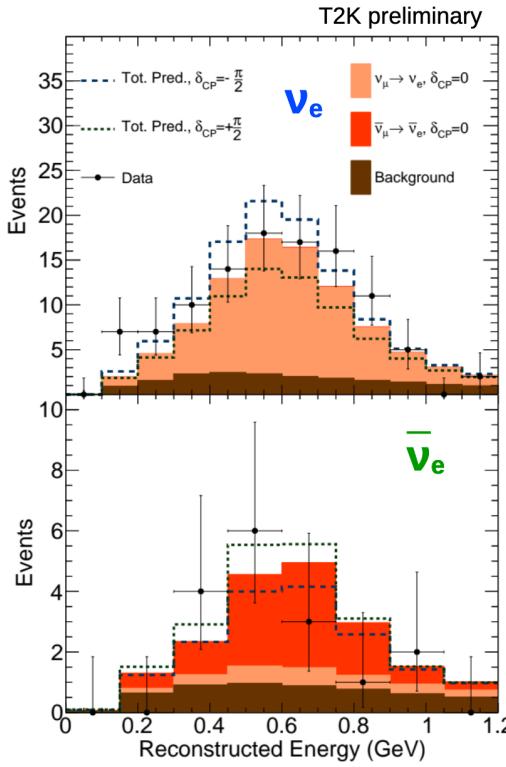
ν_e appearance results



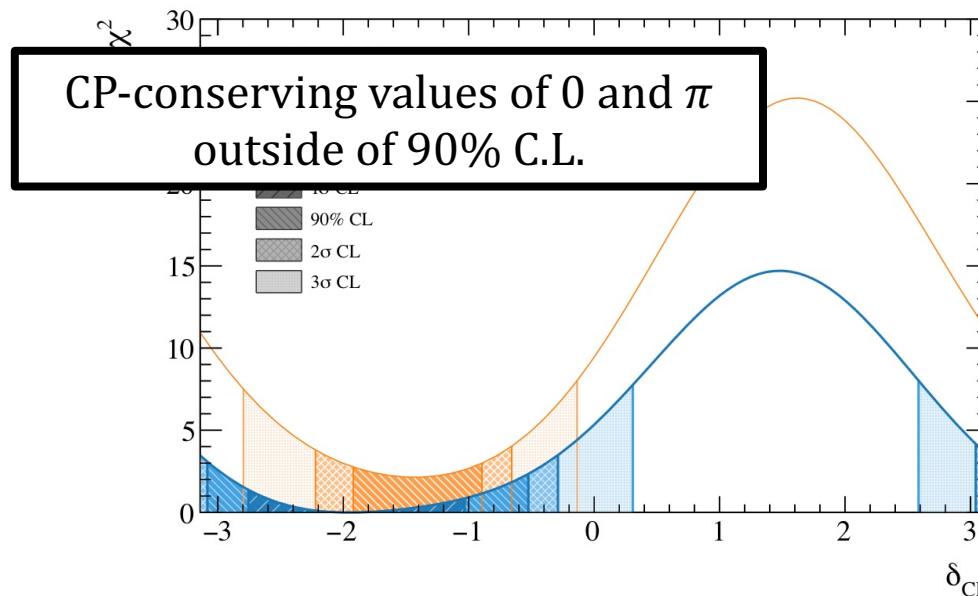
- Difference in the number of observed ν_e vs $\bar{\nu}_e$ candidates indicates a preference for $\sin \delta_{CP} < 0$



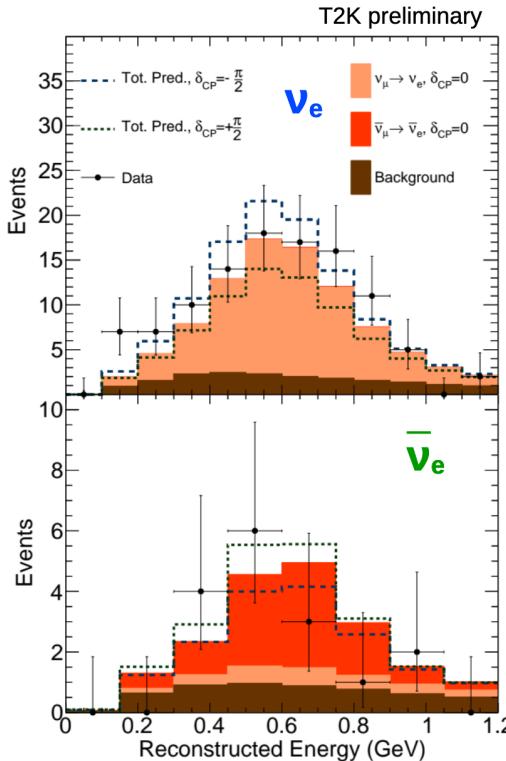
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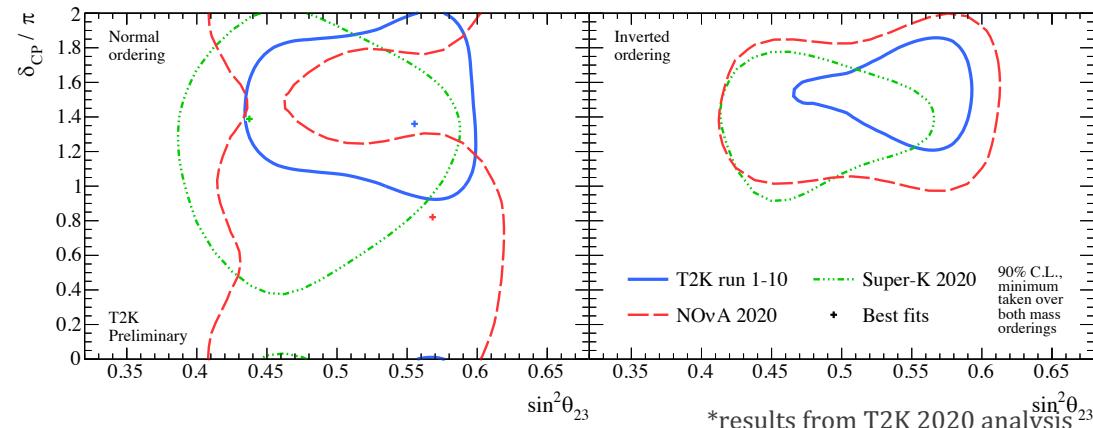
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ν_e appearance results



- Difference in the number of observed ν_e vs $\bar{\nu}_e$ candidates indicates a preference for $\sin\delta_{CP} < 0$
- NOvA results prefer $\sin\delta_{CP} > 0$ (assuming NO)
 - But no statistically significant tension
 - Both in good agreement assuming IO



How can we do better?

- The obvious answer: **more data!**
 - T2K and NOvA are both statistically limited
 - But joint fits (T2K+NOvA & T2K+SK atmospherics) are under way!

Complementary experiments with different systematics
Increased combined sensitivity

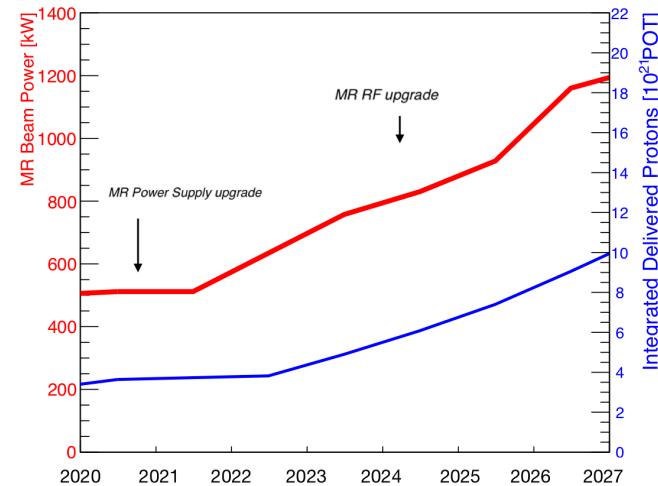
Experiment	Beam Energy	Baseline	Near detector	Far detector	Enhanced sensitivity to
	600 MeV (Narrow)	~300 km	Scintillator bars	Water Cherenkov	δ_{CP}
	1.2 GeV (Wide)	~800 km	Plastic scintillator	Plastic scintillator	Mass ordering

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- T2K-II phase: increased beam intensity

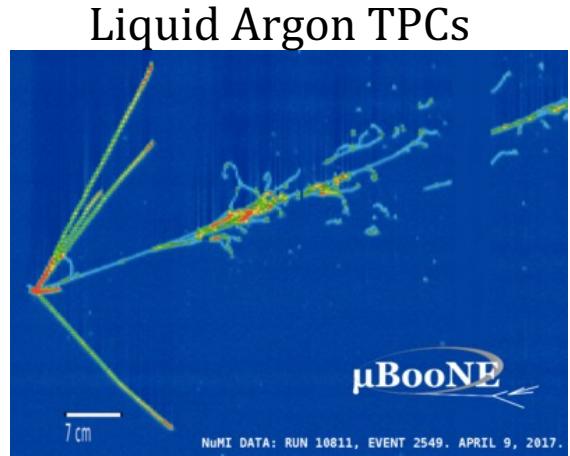
Increase beam power
from 500 kW
to 700 kW
to 1.3 MW!

T2K Projected POT (Protons-On-Target)

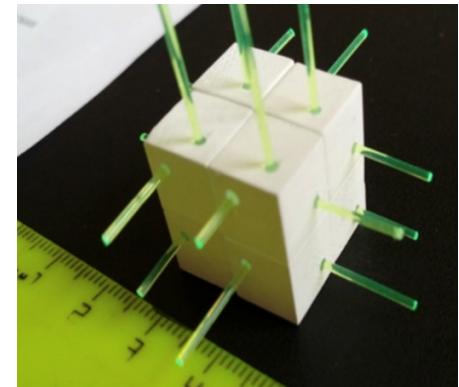


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- **Better detectors**
 - To resolve the new data in finer detail

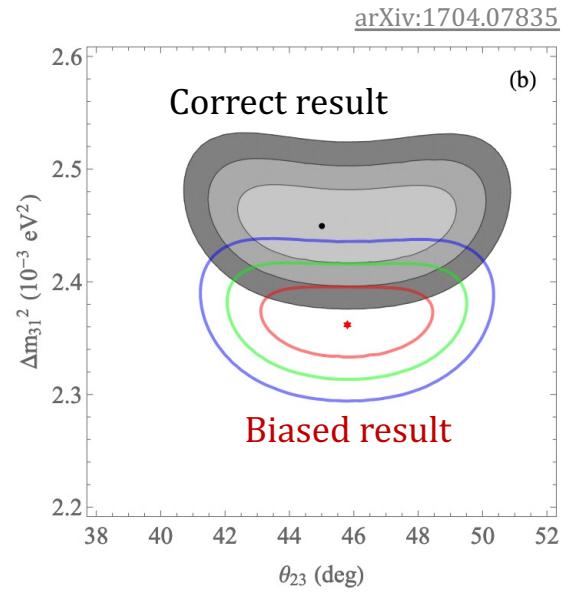


Scintillator cubes



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 - But joint fits (T2K+NOvA & T2K+SK atmospherics) are under way!
 - T2K-II phase: increased beam intensity
- **Better detectors**
 - To resolve the new data in finer detail
- Improved treatment of **systematic errors**
 - To build **robust** analyses

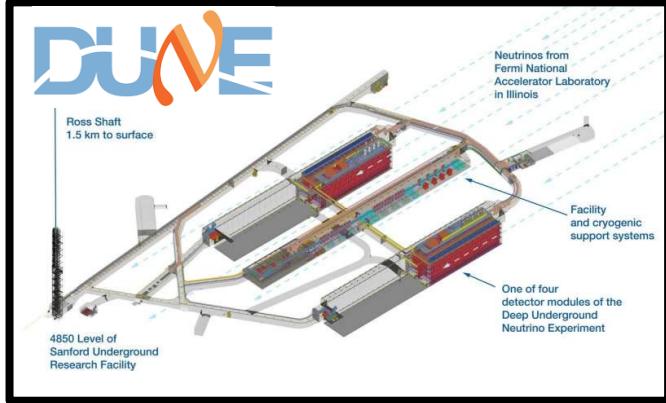


Bias in oscillation parameter measurement due to nuclear effects

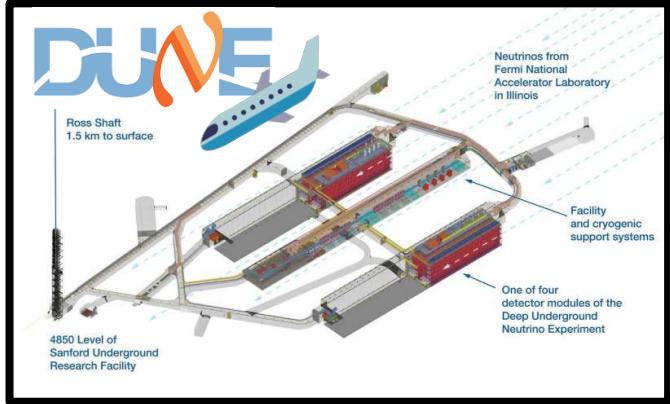


What does the future look like?

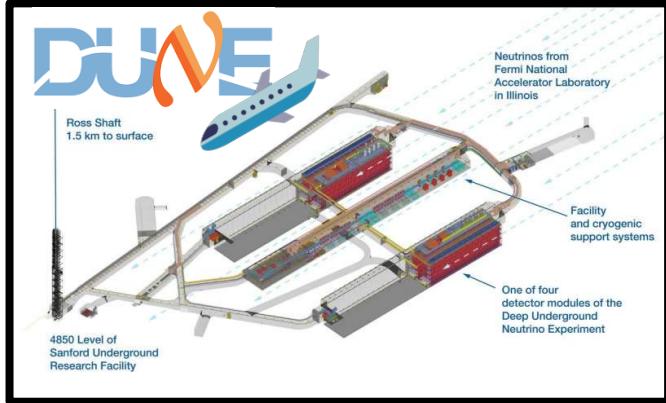
Future experiments and goals



Future experiments and goals



Future experiments and goals



- Ambitious and comprehensive physics programs
 - Neutrino oscillations, BSM physics, SuperNova neutrinos
- First short-term goals include determining whether CP symmetry is violated in neutrino oscillations
- Mid- to long-term goals include **precision measurements** of oscillation parameters
- **Complementary!**

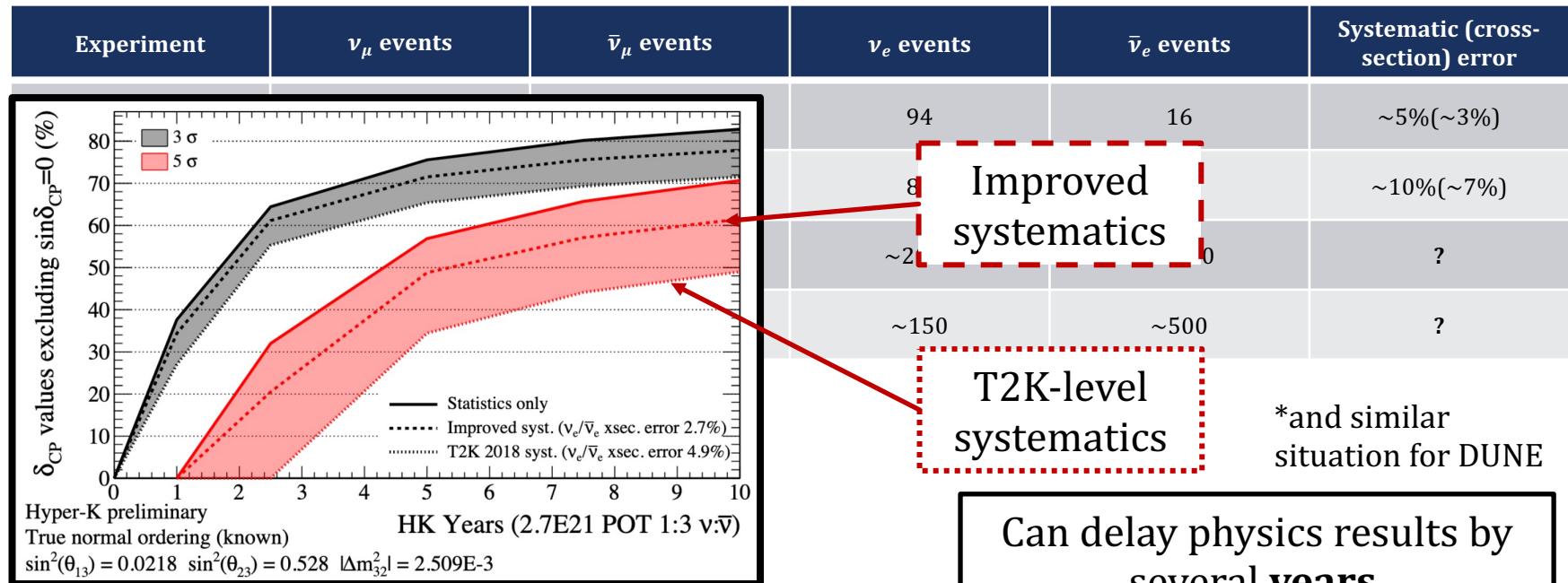
Are we prepared for future experiments?

Experiment	ν_μ events	$\bar{\nu}_\mu$ events	ν_e events	$\bar{\nu}_e$ events	Systematic (cross-section) error
T2K	318	137	94	16	$\sim 5\%(\sim 3\%)$
NOvA	211	105	82	33	$\sim 10\%(\sim 7\%)$

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Hyper-K	~ 10000	~ 14000	~ 2000	~ 2000	?
DUNE	~ 7000	~ 3500	~ 150	~ 500	?

Are we prepared for future experiments?



Sensitivity to exclude CP conserving values for δ_{CP}

Can delay physics results by several years.

Or prevent them altogether!

Are we prepared for future experiments?

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Hyper-K	~ 10000	~ 14000	~ 2000	~ 2000	Need $\sim 1\%-3\%$!
DUNE	~ 7000	~ 3500	~ 150	~ 500	Need $\sim 1\%-3\%$!

- **Woefully unprepared** at current level of systematics!
- Need dedicated, focused effort in order for future experiments not to be **pre-maturely limited by systematics**



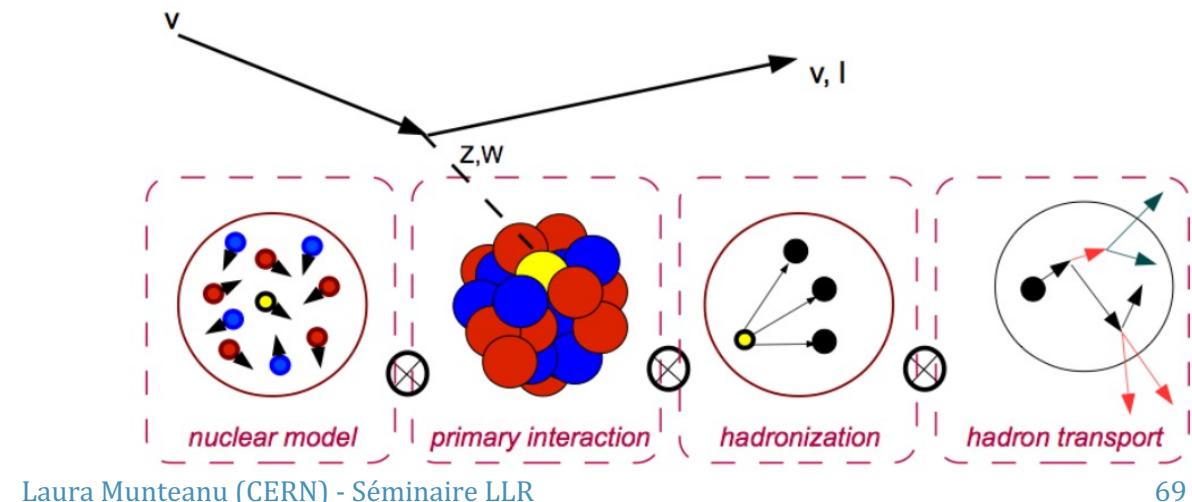
So where do we begin improving our
systematic uncertainties?



Step-by-step: the generator way

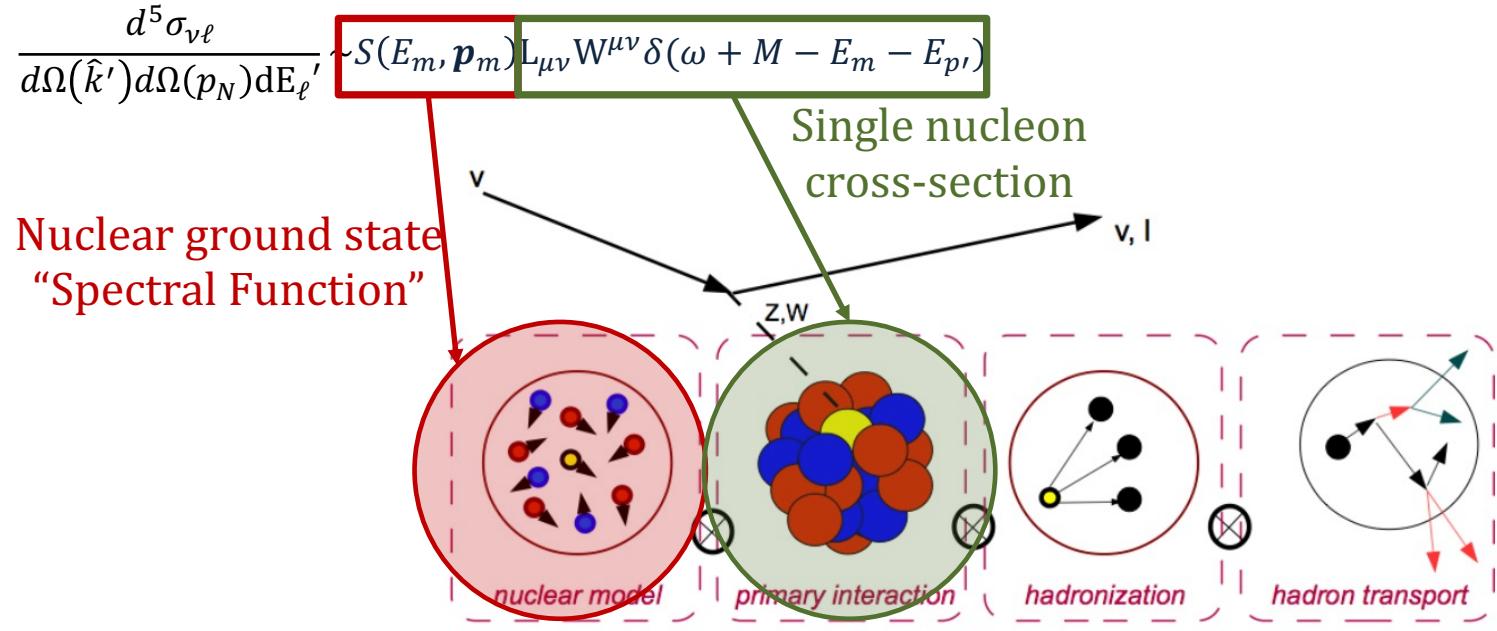
- Modern **neutrino-nucleus event generators** (NEUT, GENIE, NuWro) factorize the steps of the interaction
- This is an **approximation** but offers modularity in the improvements we can make

$$\frac{d^5\sigma_{\nu\ell}}{d\Omega(\hat{k}')d\Omega(p_N)dE_{\ell}'} \sim S(E_m, \mathbf{p}_m)L_{\mu\nu}W^{\mu\nu}\delta(\omega + M - E_m - E_{p'})$$



Step-by-step: the generator way

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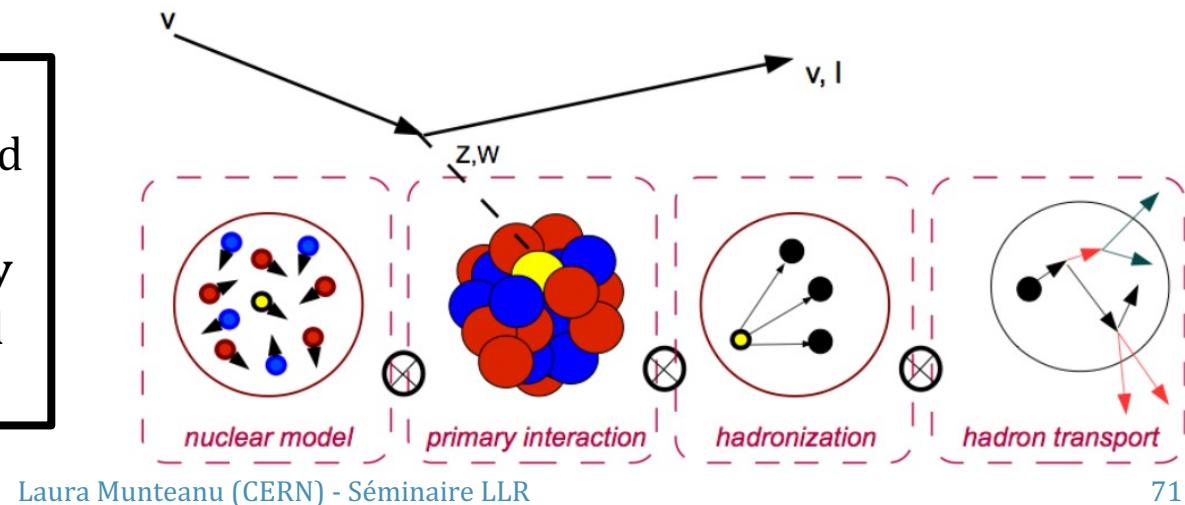
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- And in our comparisons

Our knowledge of neutrino-nucleus interactions is limited

Need to preserve flexibility to explore different model predictions



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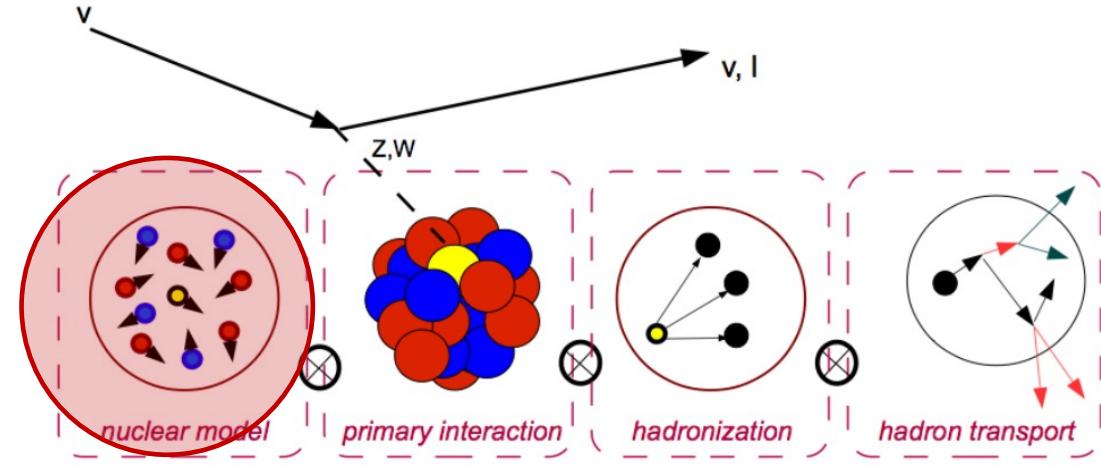
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The nuclear ground state

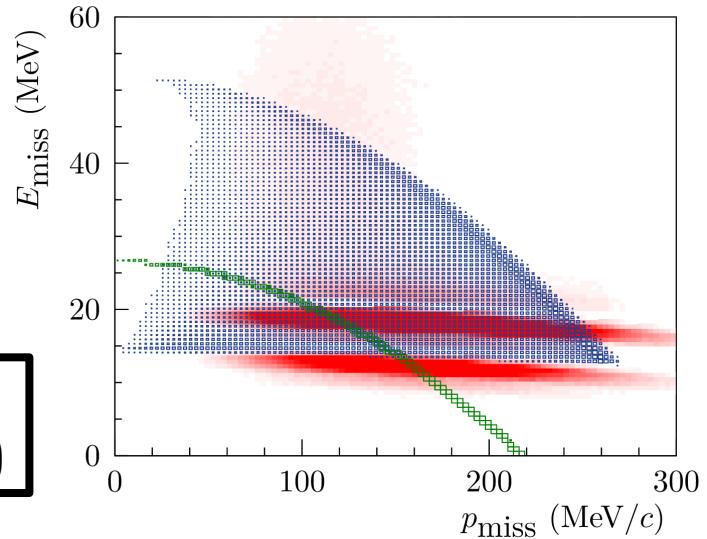
$$\frac{d^5\sigma_{\nu\ell}}{d\Omega(\hat{k}')d\Omega(p_N)dE_{\ell}'} \sim S(E_m, \mathbf{p}_m) \epsilon_{\mu\nu} W^{\mu\nu} \delta(\omega + M - E_m - E_{p'})$$

E_{miss}
(~nucleon removal energy)

p_{miss}
(~nucleon momentum)

[Eur.Phys.J.ST 230 \(2021\) 24, 4469-4481](#)

Benhar SF Local FG
Global FG NEUT 5.5.0, $\nu_\mu {}^{16}\text{O}$



$$\vec{p}_{\text{miss}} = \vec{p}_\nu - \vec{p}_\mu - \vec{p}_p$$

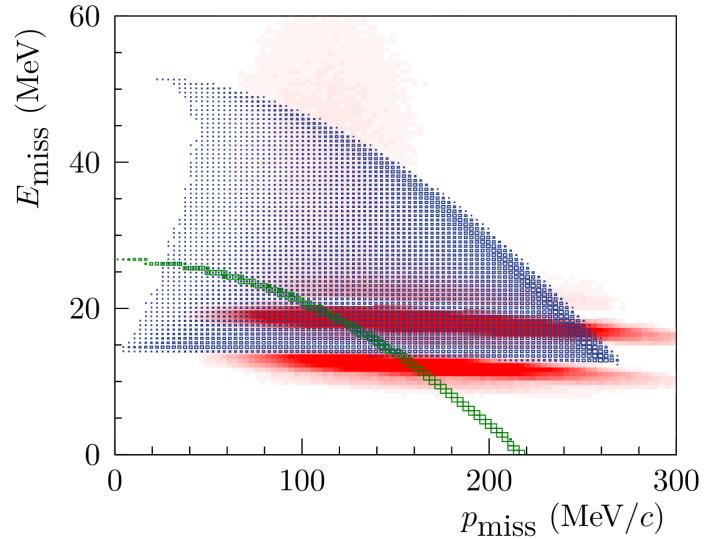
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- Multiple ground state models are available in neutrino interaction generators

Eur.Phys.J.ST 230 (2021) 24, 4469-4481

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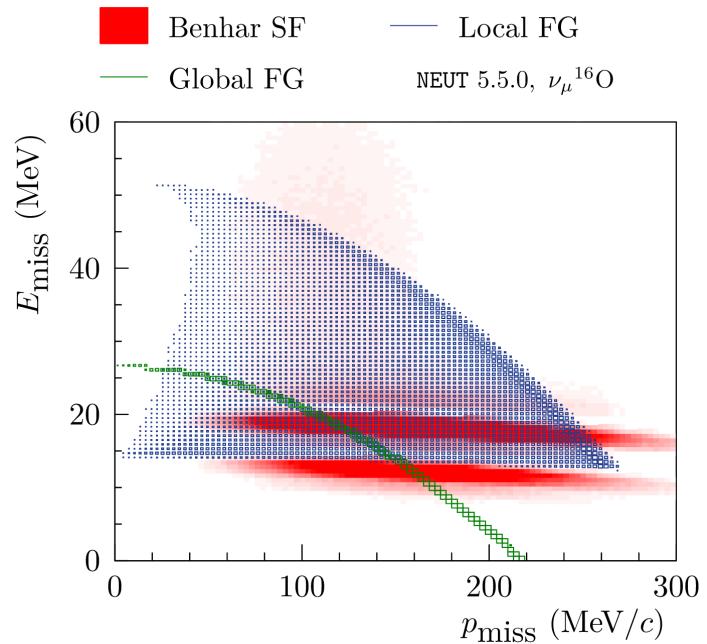
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- Multiple ground state models are available in neutrino interaction generators
- RFG assumes the nucleus is a “box”-like potential and nucleons behave like a Fermi gas
 - Simplistic, widely used in the early days of neutrino oscillations, low predictive power

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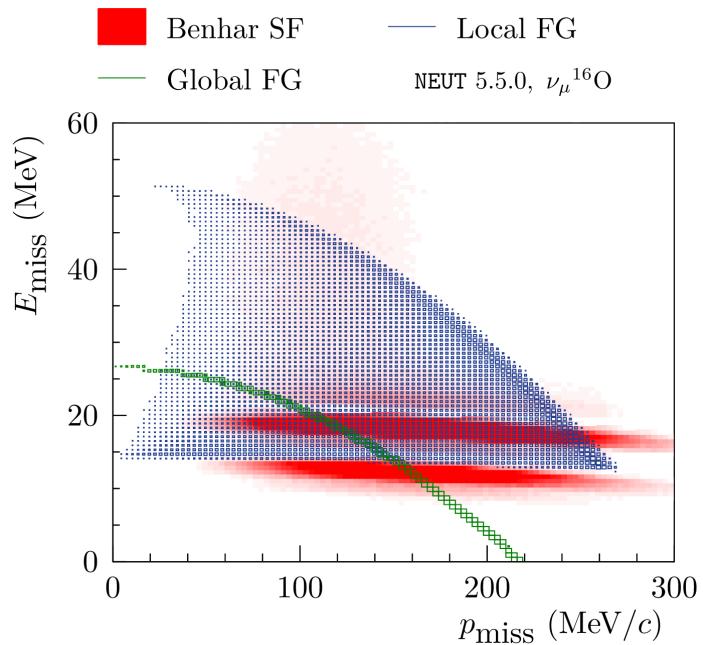
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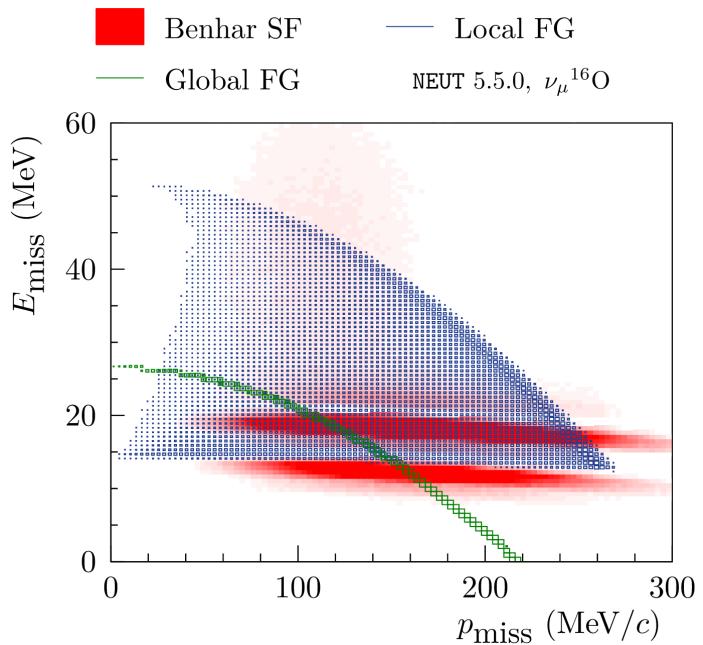
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 - Tuned to electron scattering data
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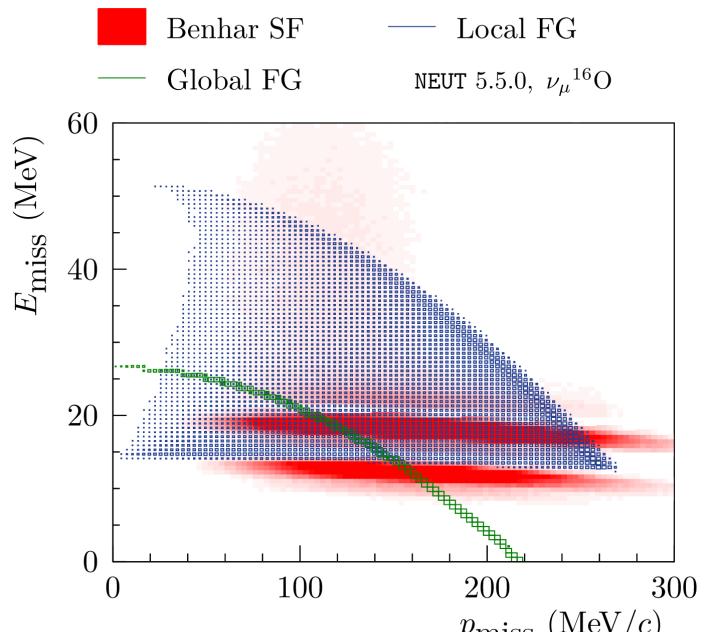
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- More sophisticated models exist but are not yet implemented in generators (**ongoing work**)

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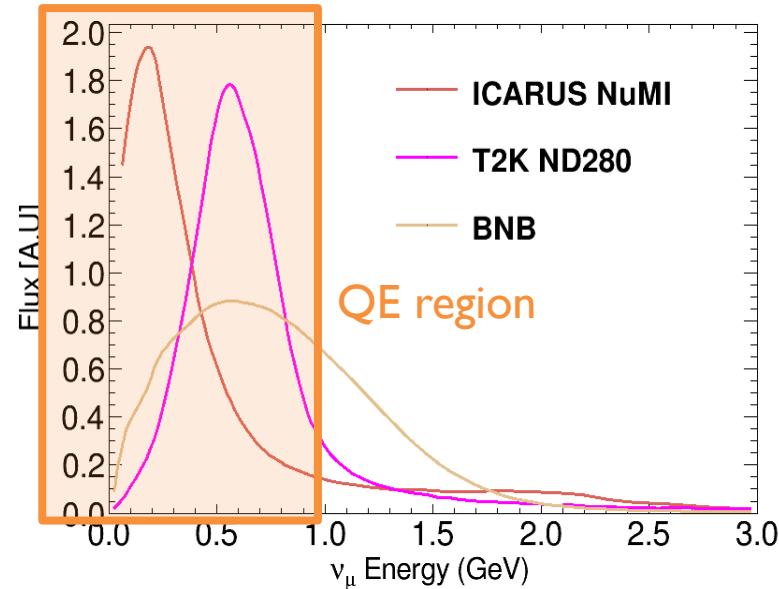


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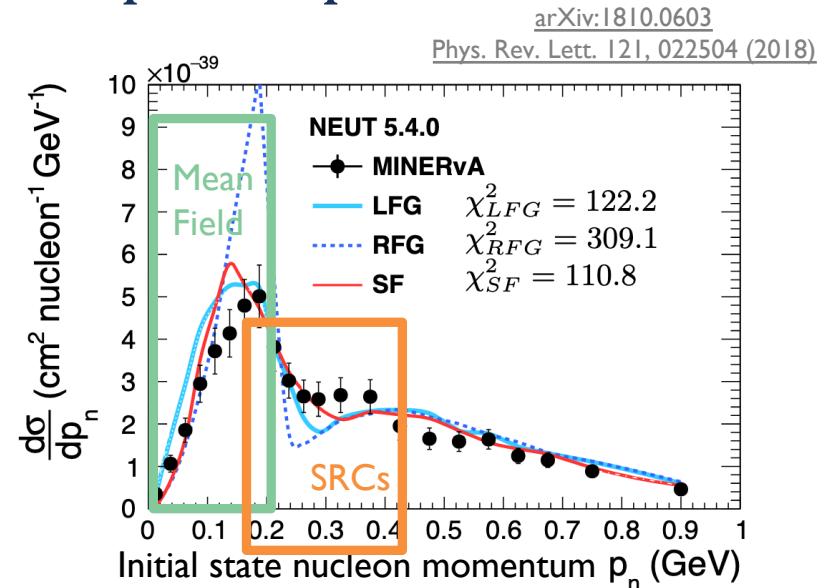
How does the nuclear ground state impact experiments?

- Most nuclear models predict removal energies which vary in a range of **10-50 MeV**
- Nucleon momenta span ranges of up to **hundreds of MeV**
- Mismodelling the removal energy causes a **direct bias** in reconstructed neutrino energy
 - Particularly important for oscillation measurements which evolve as a function of neutrino energy
 - But also for lower-energy physics (e.g. BSM physics)



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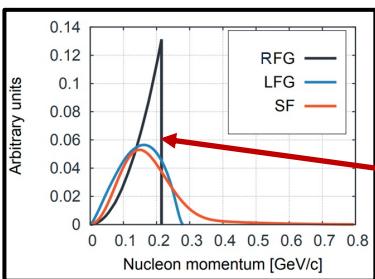
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 - But also for lower-energy physics (e.g. BSM physics)
- Mismodelling the nucleon momentum alters **predictions on hadron kinematics**
 - Will be crucial for experiments sensitive to the hadronic side of the final state



SRGs or “correlated tail” effects become important at nucleon momenta of O(200-700 MeV)

Example from T2K

2018



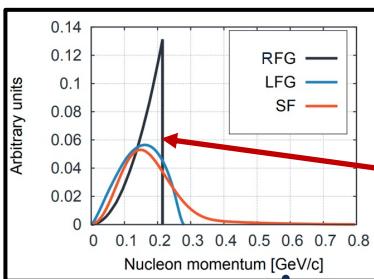
Type of Uncertainty	$\nu_e/\bar{\nu}_e$ Candidate Relative Uncertainty (%)
Super-K Detector Model	1.5
Pion Final State Interaction and Rescattering Model	1.6
Neutrino Production and Interaction Model Constrained by ND280 Data	2.7
Electron Neutrino and Antineutrino Interaction Model	3.0
Nucleon Removal Energy in Interaction Model	3.7
Modeling of Neutral Current Interactions with Single γ Production	1.5
Modeling of Other Neutral Current Interactions	0.2
Total Systematic Uncertainty	6.0

The systematic uncertainty on the predicted relative number of electron neutrino and electron antineutrino candidates in the SK samples with no decay electrons.

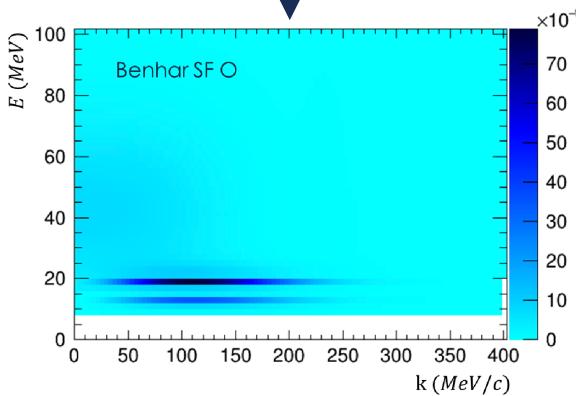
[Nature](#) volume 580, pages 339–344 (2020)

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2018



Change in
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Neutrino Production and Interaction Model Constrained by ND280 Data	2.7
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Nucleon Removal Energy in Interaction Model	3.7
Modeling of Neutral Current Interactions with Single γ Production	1.5
Modeling of Other Neutral Current Interactions	0.2
Total Systematic Uncertainty	6.0

The systematic uncertainty on the predicted relative number of electron neutrino and electron antineutrino candidates in the SK samples with no decay electrons.

Nature volume 580, pages 339–344 (2020) The 50th Anniversary



Now incorporated here

Error source (units: %)	1R		MR		1Re		FHC/RHC
	FHC	RHC	FHC	CC1 π^+	FHC	RHC	
Flux	2.8	2.9	2.8		2.8	3.0	2.8
Xsec (ND constr)	3.7	3.5	3.0		3.8	3.5	4.1
Flux+Xsec (ND constr)	2.7	2.6	2.2		2.8	2.7	3.4
Xsec (ND unconstr)	0.7	2.4	1.4		2.9	3.3	2.8
SK+SI+PN	2.0	1.7	4.1		3.1	3.8	13.6
Total All	3.4	3.9	4.9		5.2	5.8	14.3

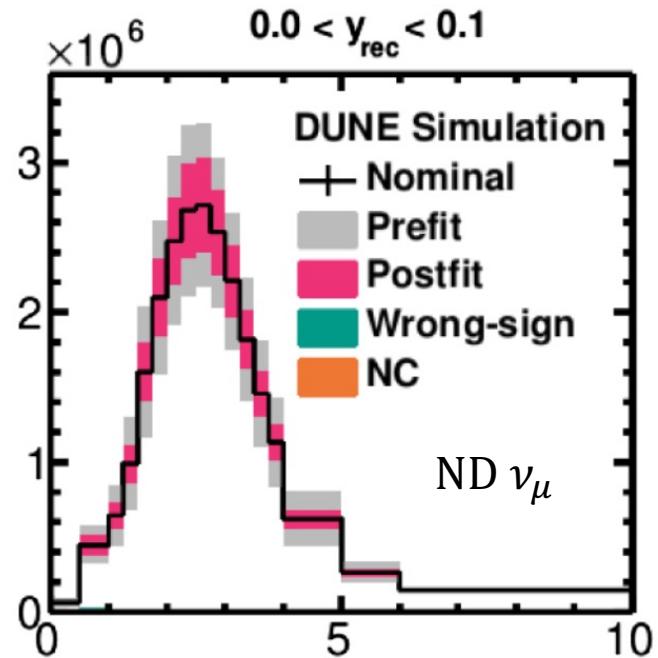
T2K Run 1-10, preliminary

82

Ongoing work on DUNE

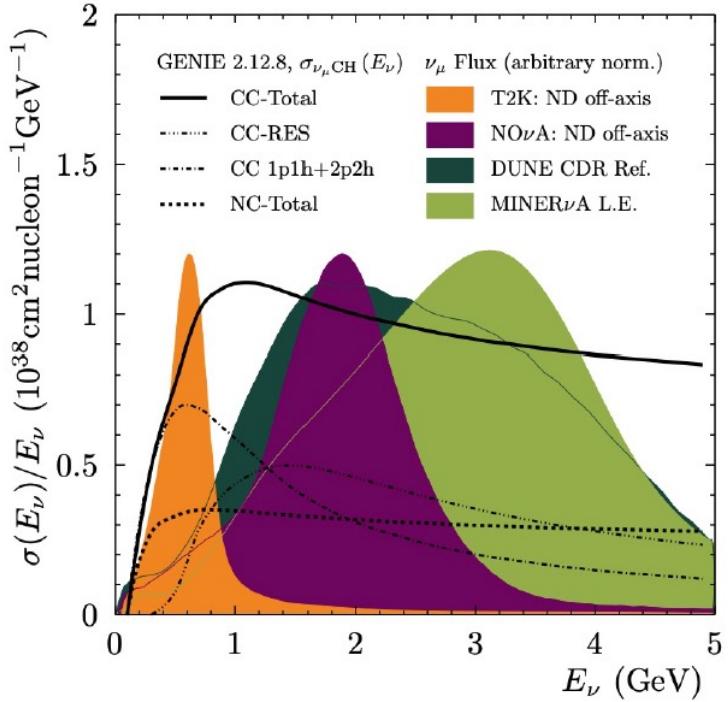
arXiv:2002.03005

- DUNE is preparing oscillation sensitivity studies focused on its **near detectors**
- At DUNE statistics, we will be sensitive to some of **the most minute differences** in nuclear models
- DUNE doesn't have data yet
 - Need a **flexible model** which allows us to cover the variations suggested by other models and measurements
- Need a model which is adapted for both oscillation studies and BSM physics



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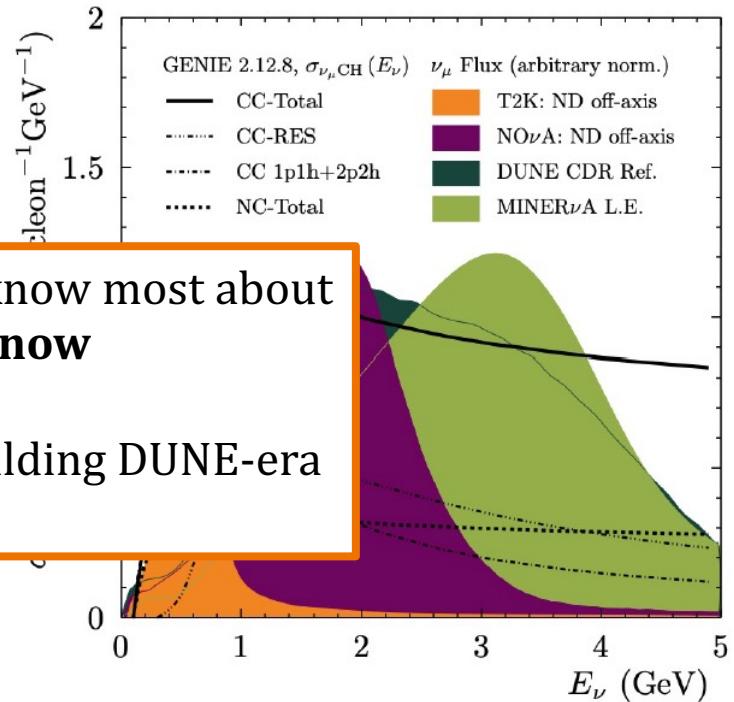
DUNE is not QE dominated
But QE interactions are **those which we can measure best**
Remain important for **precision measurements**

Ongoing work on DUNE

- DUNE is preparing oscillation sensitivity studies focused on its **near detectors**
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- DUNE doesn't
 - Need a **flexible model** which allows us to cover the variations suggested by other models and measurements
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The QE regime is where we know most about
what we don't know

Perfect starting point for building DUNE-era
analyses

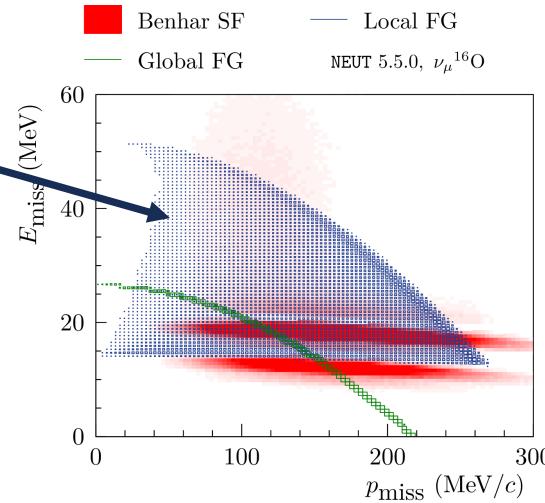


DUNE is not QE dominated
But QE interactions are **those which we can measure best**
Remain important for **precision measurements**

The base model

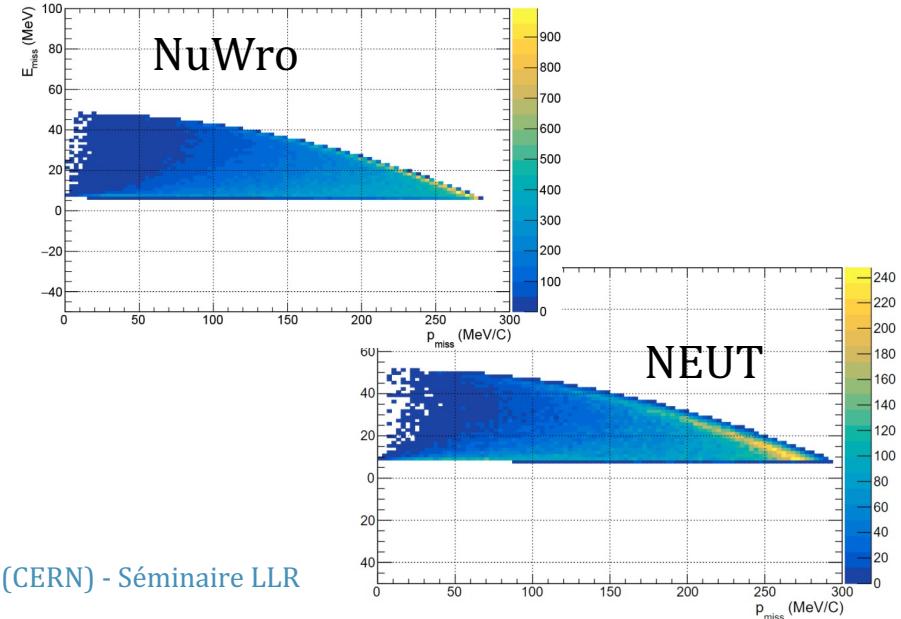
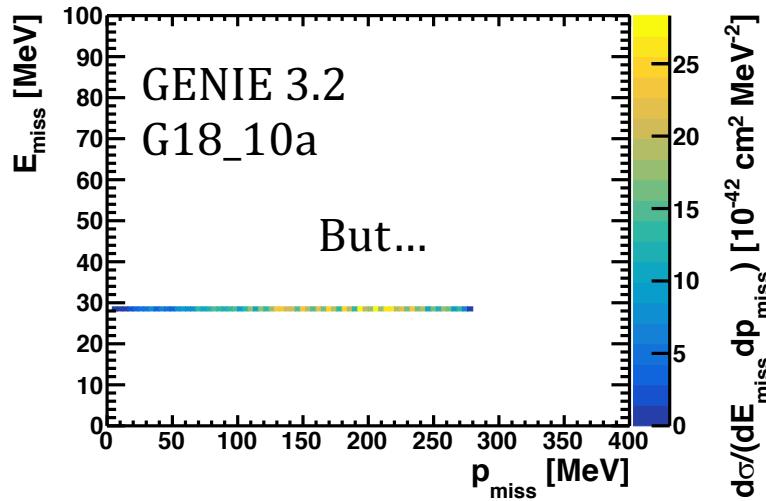
- The DUNE production framework is optimized to use the GENIE event generator
- GENIE does not have a 2D spectral function model yet
- But want to take inspiration from what we've learned from T2K
 - Choose an LFG model!

Can be reweighted to a
spectral function!



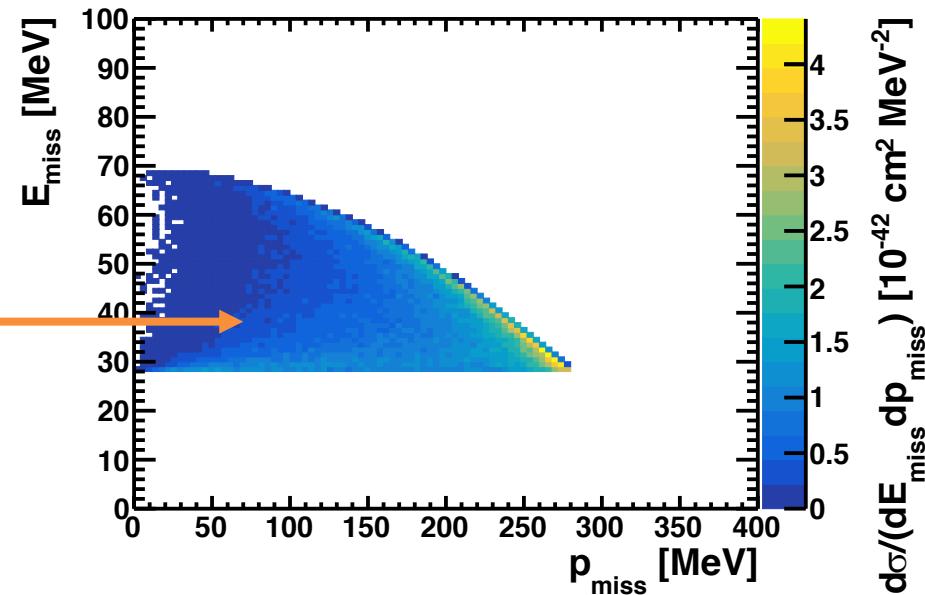
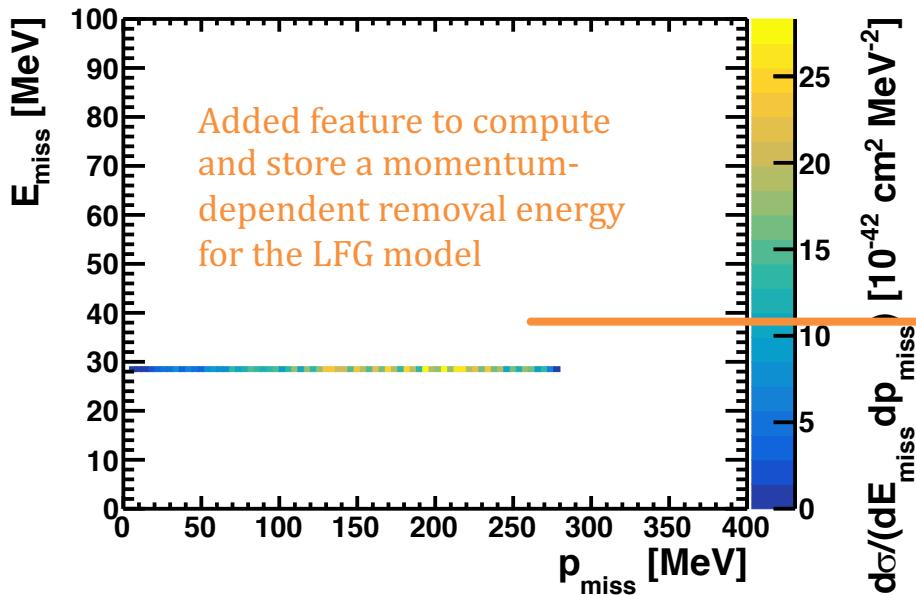
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Expanding the ground state phase space

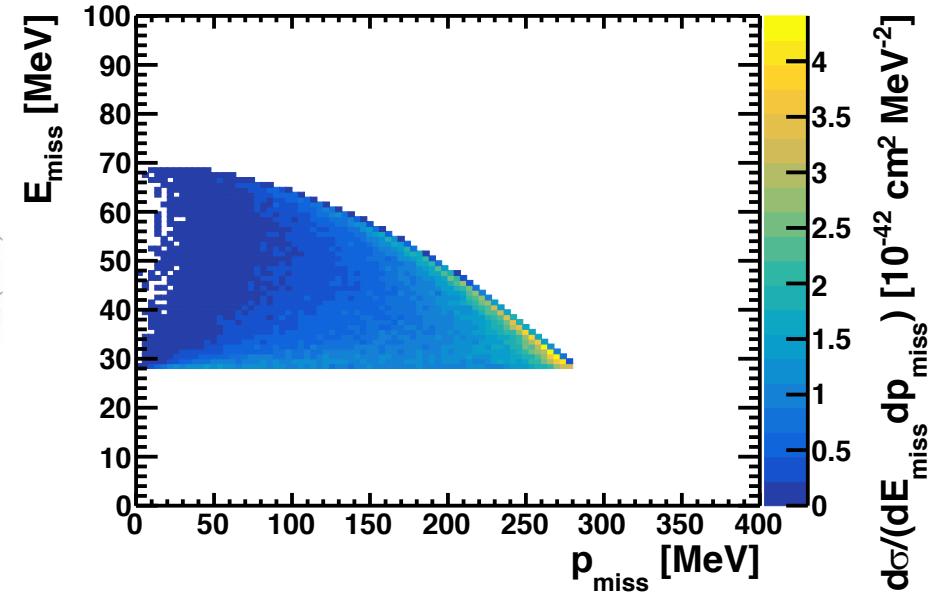
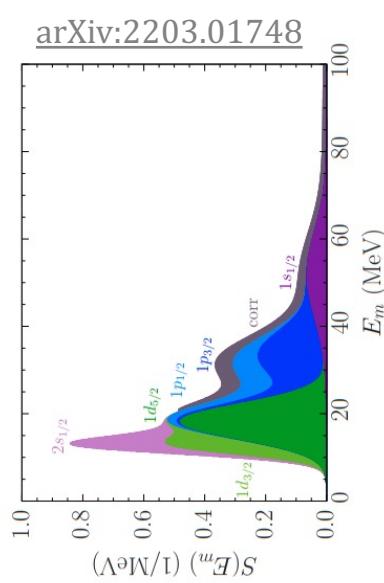
- For an LFG model, the dependence between the removal energy and the nucleon momentum is well-understood (Fermi gas approach)



Expanding the ground state phase space

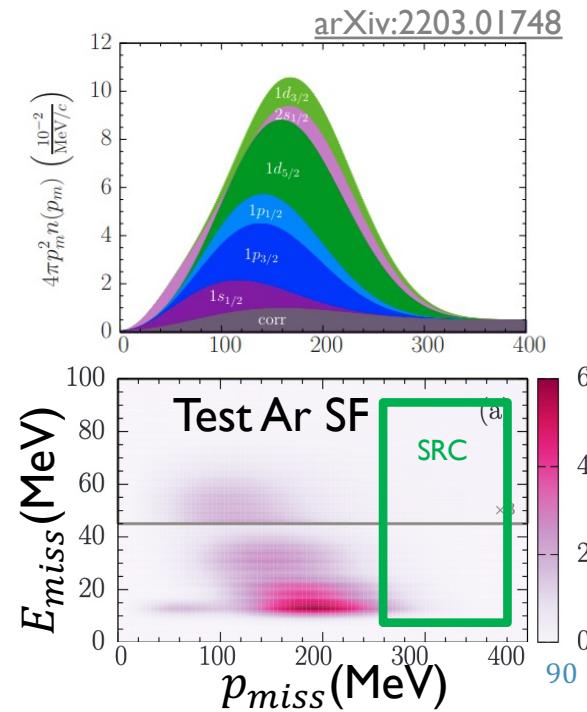
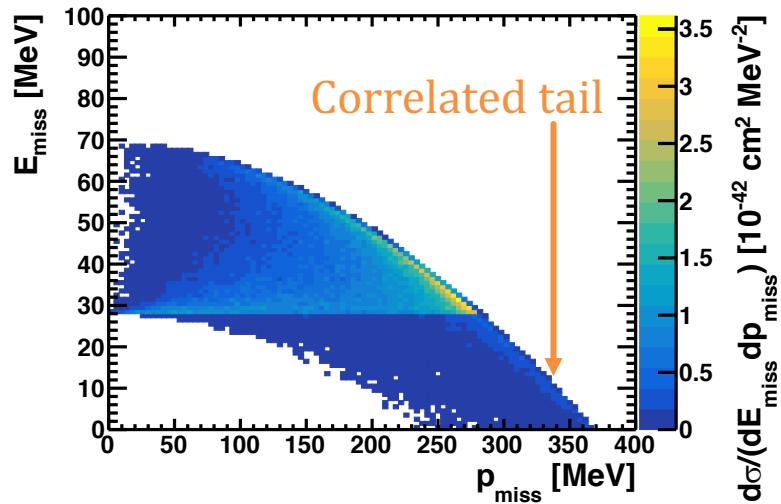
- For an LFG model, the dependence between the removal energy and the nucleon momentum is well-understood (Fermi gas approach)

Covers relevant energies
for Argon nuclear shells!



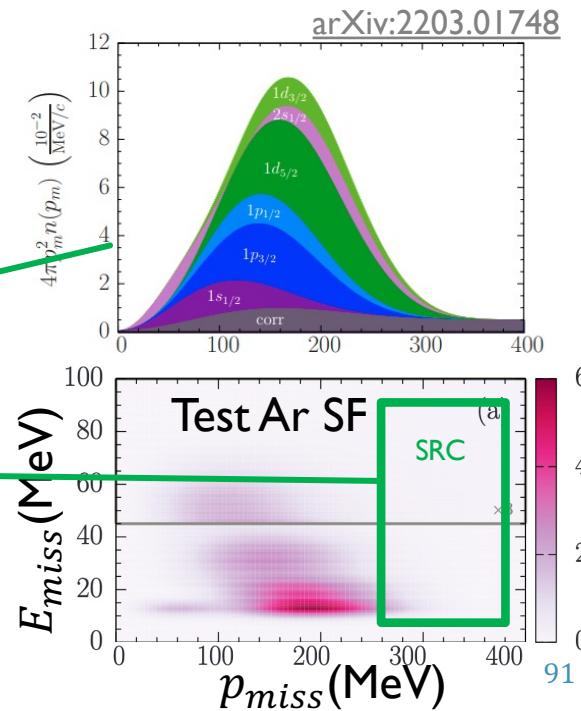
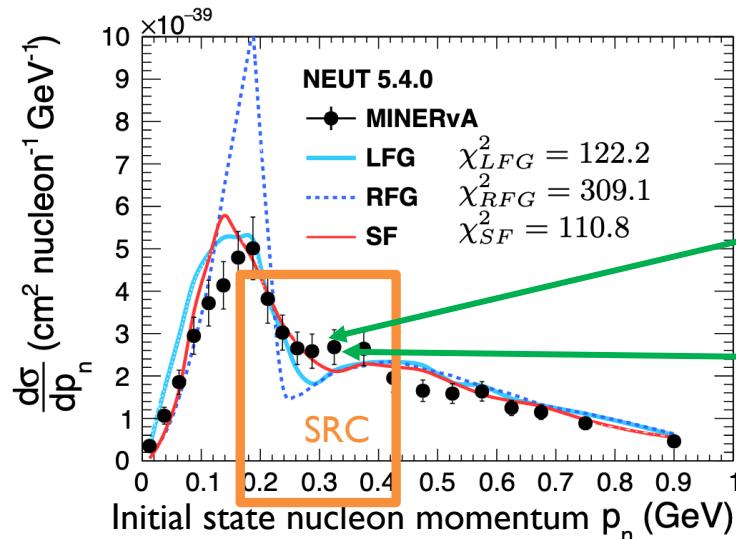
Expanding the ground state phase space

- Will be used in conjunction with “correlated tail” feature



Expanding the ground state phase space

- Will be used in conjunction with “correlated tail” feature
- Probes nucleon correlations – high model disagreement



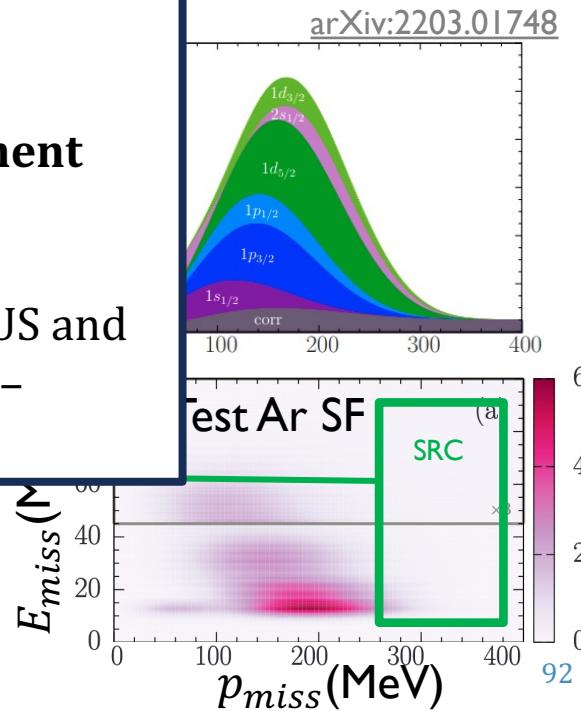
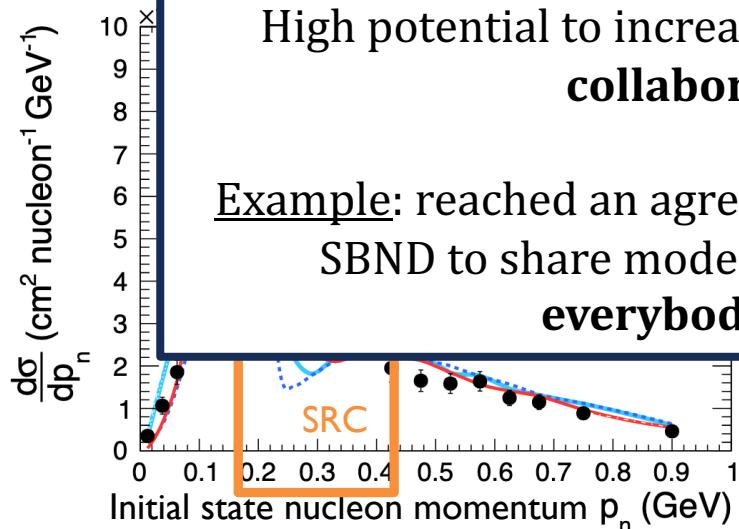
Expanding the ground state phase space

- Will be used in conjunction with “correlated tail” feature
- Probes nu

This work is as relevant for DUNE as it is for
Hyper-K and SBN experiments

High potential to increase **cross-experiment collaboration!**

Example: reached an agreement with ICARUS and SBND to share model and systematics – **everybody wins!**



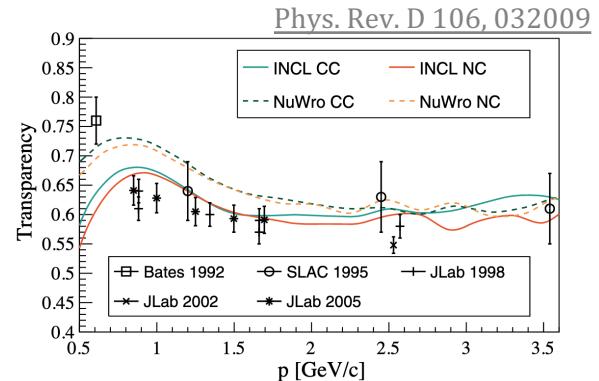
Beyond the nuclear ground state

- CCQE(-like) interactions are easiest to study experimentally
 - Main channel for Hyper-K and future SBN experiments (ICARUS, SBND)
 - And provide a gateway towards understanding more complex processes relevant at DUNE energies
- But the work is just getting started! We need to understand:

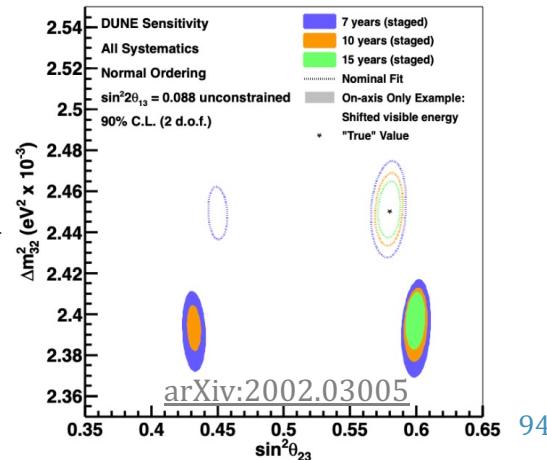
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Bias in oscillation parameters if
20% of proton energy were
carried away by neutrons
FSI-like effect

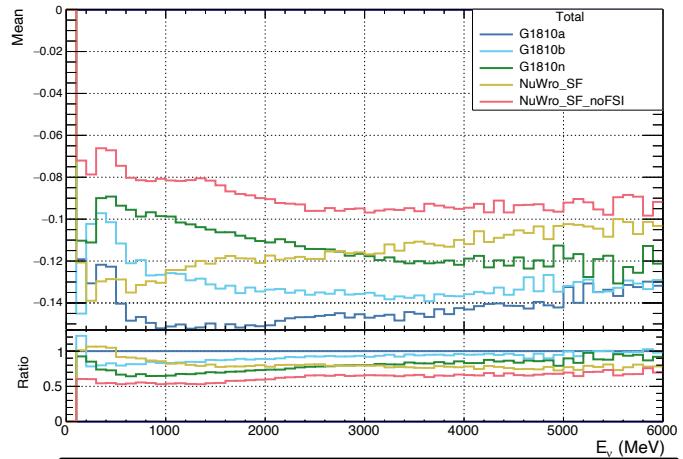


For Carbon: 40% of protons
re-interact inside the nucleus



Beyond the nuclear ground state

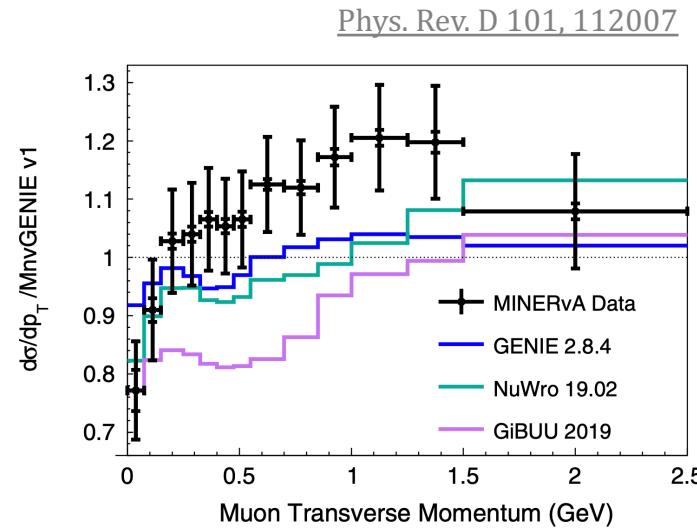
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 - Cross-section energy dependence



Mean of neutrino energy bias as a
function of neutrino energy for DUNE flux
High model disagreement

Beyond the nuclear ground state

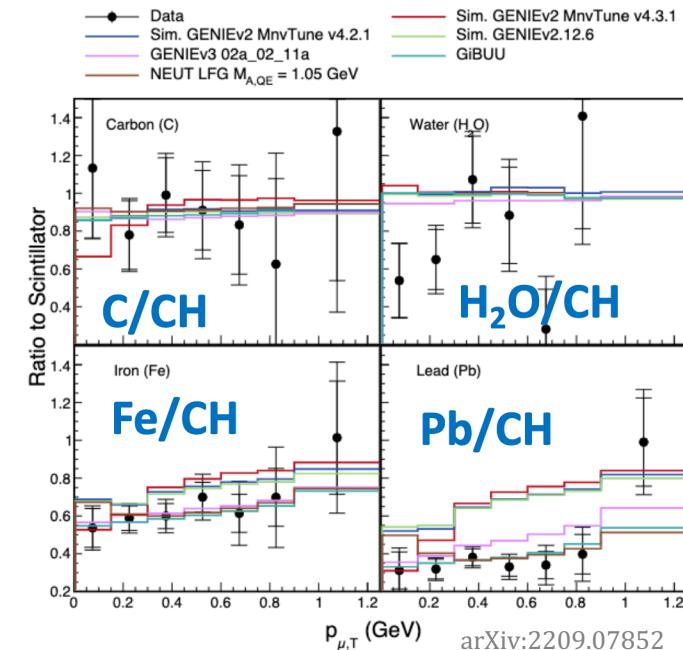
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DIS-enriched measurement from MINERvA
High model disagreement

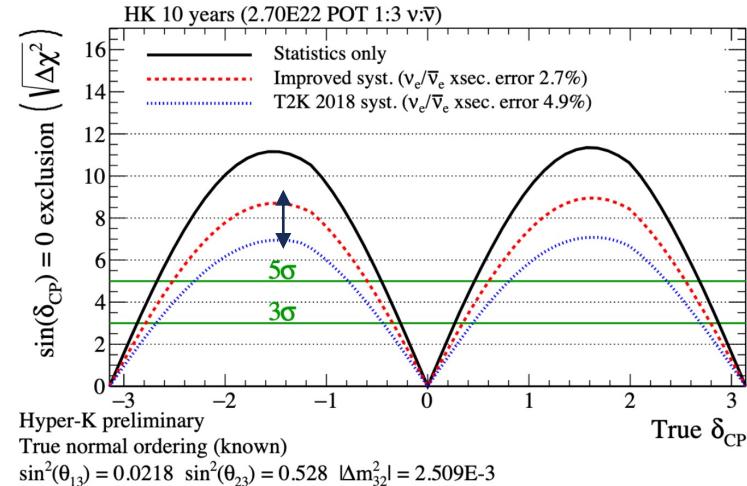
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 - How nuclear effects vary with atomic number



Beyond the nuclear ground state

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- But the work is just getting started! We need to understand:
 - Final state interactions (hadron transport inside the nucleus)
 - Cross-section energy dependence
 - Resonant interactions and the deep inelastic regime
 - How nuclear effects vary with atomic number
 - Differences in ν_e vs ν_μ cross-sections (**crucial for δ_{CP} !**)*



Majority of the systematic error contribution

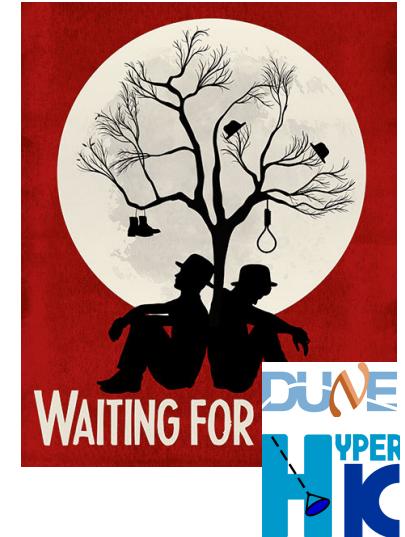
*Leading uncertainties from nuclear ground state model!



What do we do in the meantime?

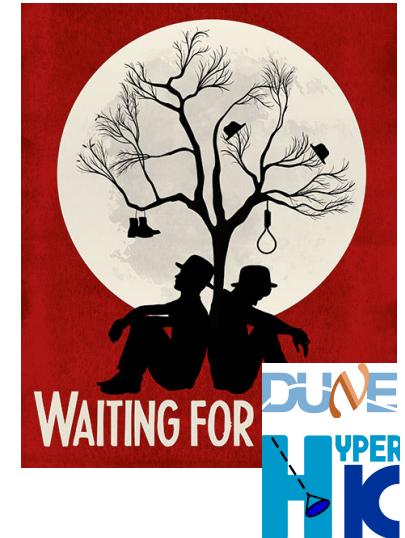
What do we do in the meantime?

- Hyper-K and DUNE will begin taking data in ~2027 and ~2030s
- We must use this time to **make the best possible measurements** of neutrino interactions we can
- And **reduce model uncertainties**
- Plenty of opportunities:
 - Dedicated test-beam facilities: **protoDUNEs** (Ar@CERN), **ArgonCube** (Ar@Fermilab), **WCTE** (water@CERN)
 - Fermilab Short-Baseline program: ICARUS+SBND
 - The T2K Near Detector Upgrade



What do we do in the meantime?

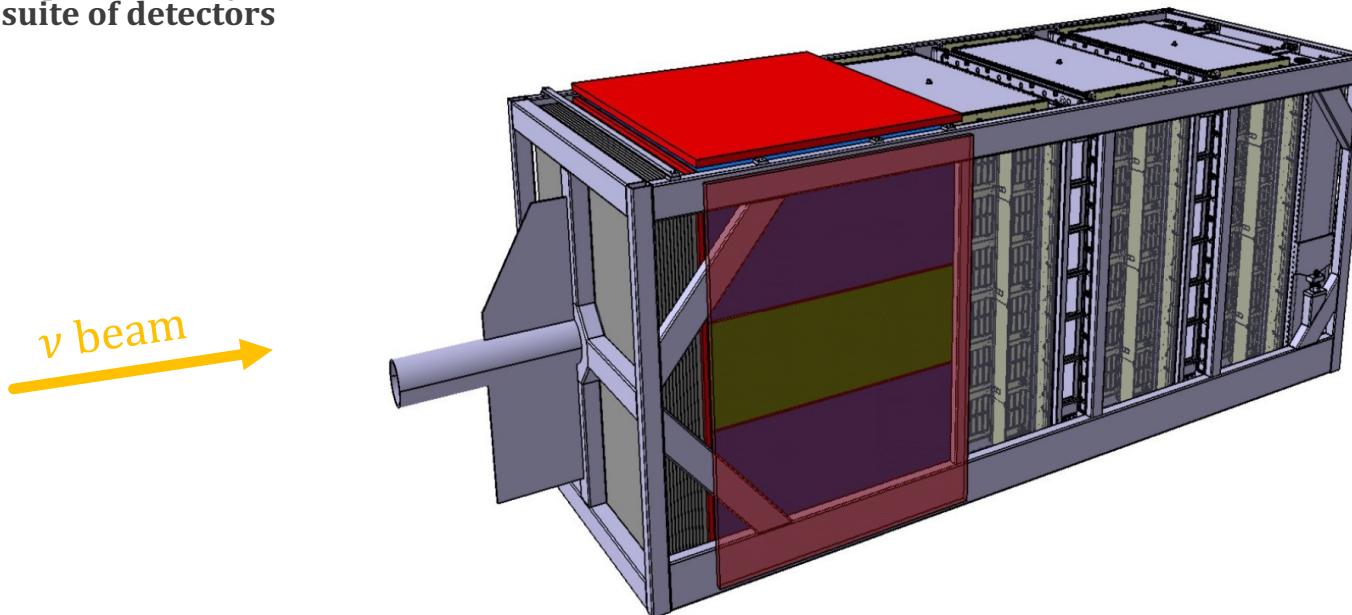
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The T2K ND280 Upgrade project

ND280 Upgrade TDR

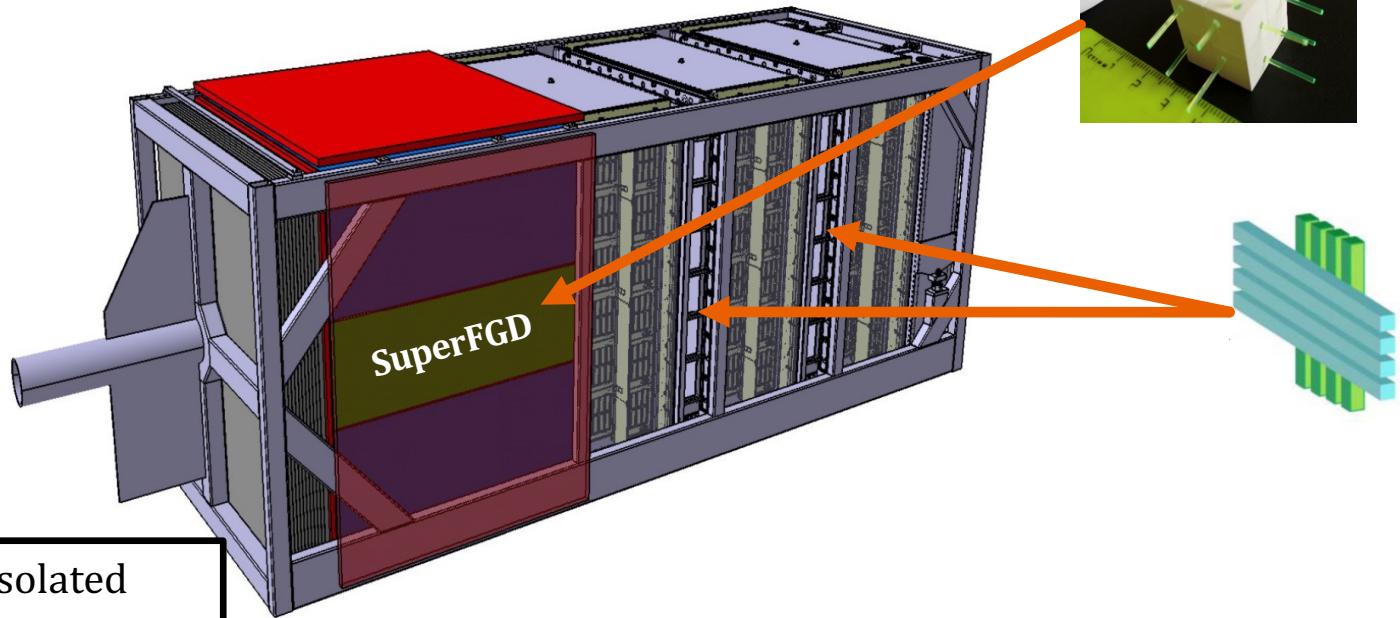
Replace P0D by new suite of detectors



The T2K ND280 Upgrade project

ND280 Upgrade TDR

Replace P0D by new suite of detectors



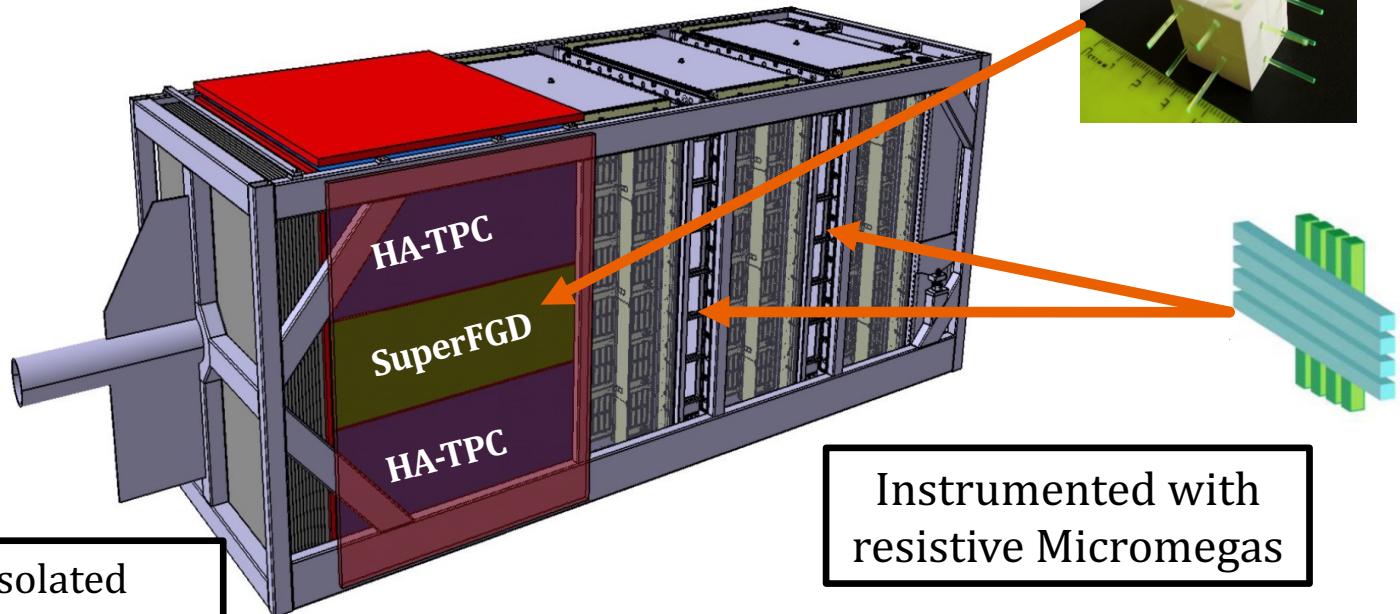
2M 1cm³ optically isolated scintillator cubes

2x fiducial mass of current FGDs

The T2K ND280 Upgrade project

ND280 Upgrade TDR

Replace P0D by new suite of detectors



2M 1cm³ optically isolated scintillator cubes

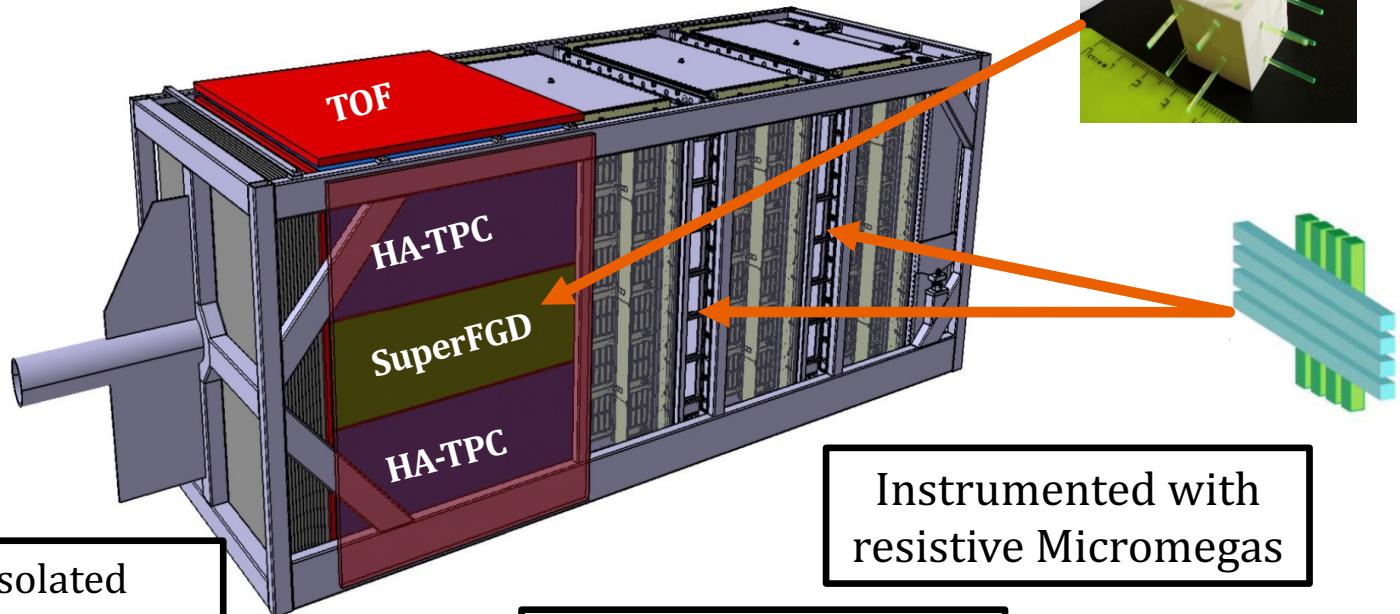
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Instrumented with resistive Micromegas

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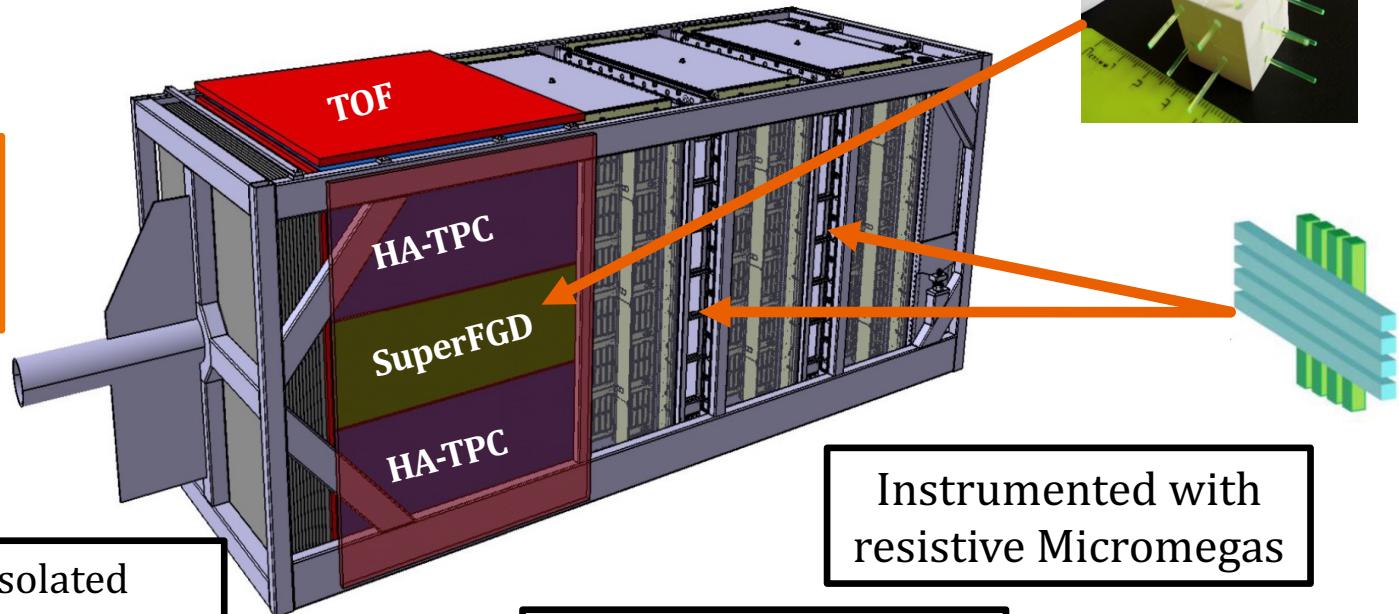
150 ps timing resolution for PID

The T2K ND280 Upgrade project

[ND280 Upgrade TDR](#)

Replace P0D by new suite of detectors

>100 researchers
22 institutes
7 countries



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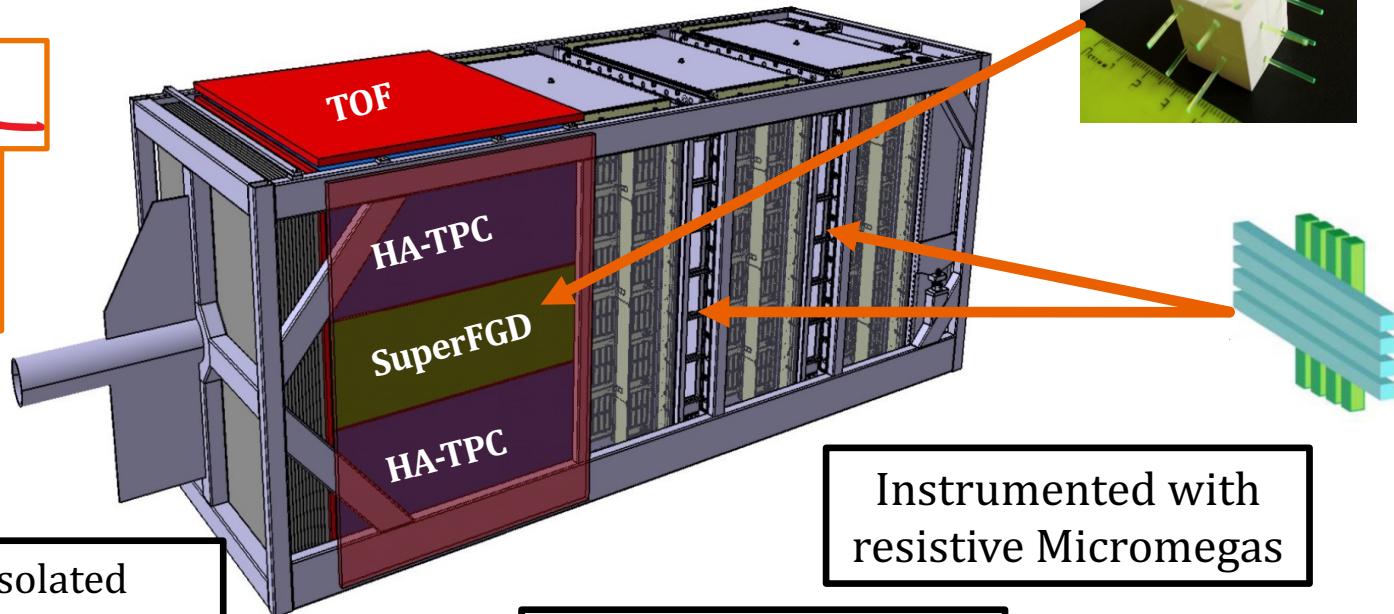


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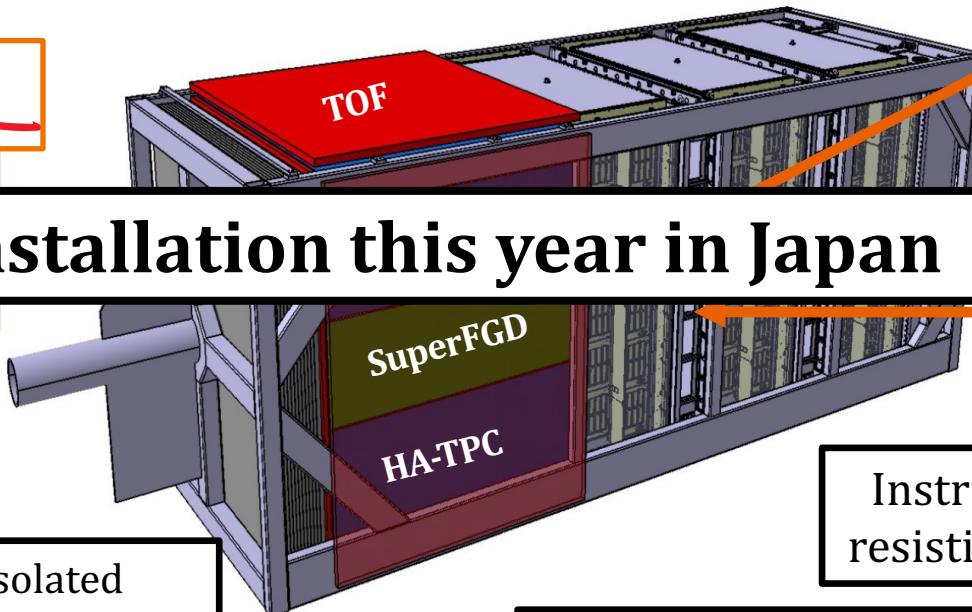
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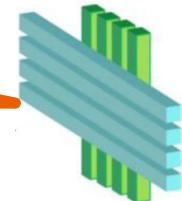
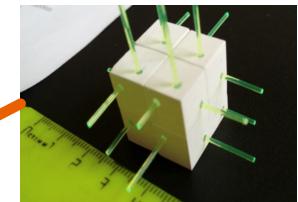


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13.03.2023

Laura Munteanu (CERN) - Séminaire LLR



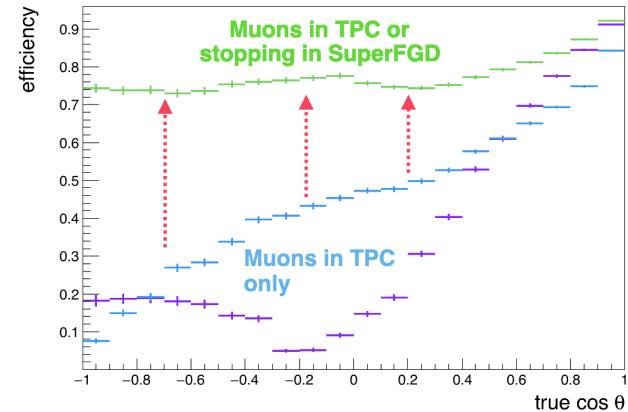
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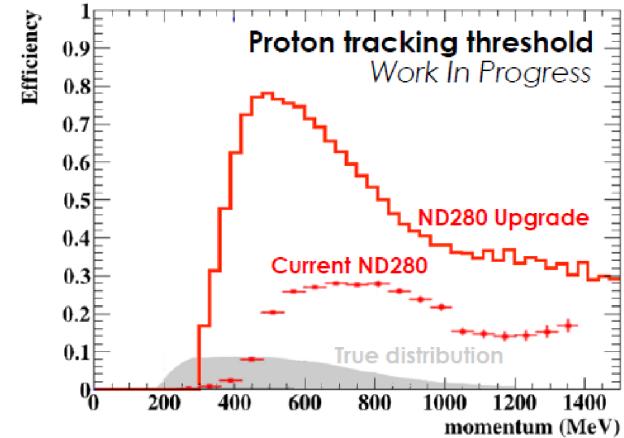
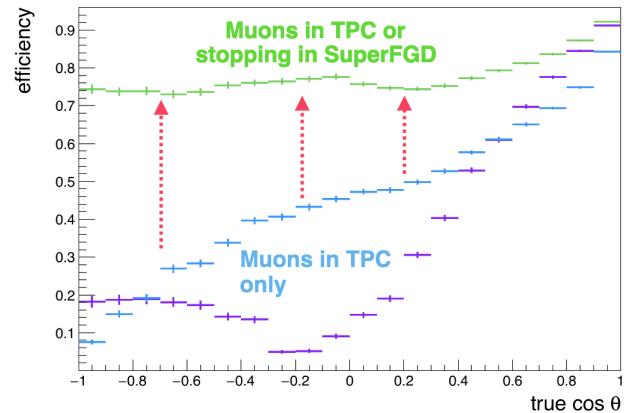
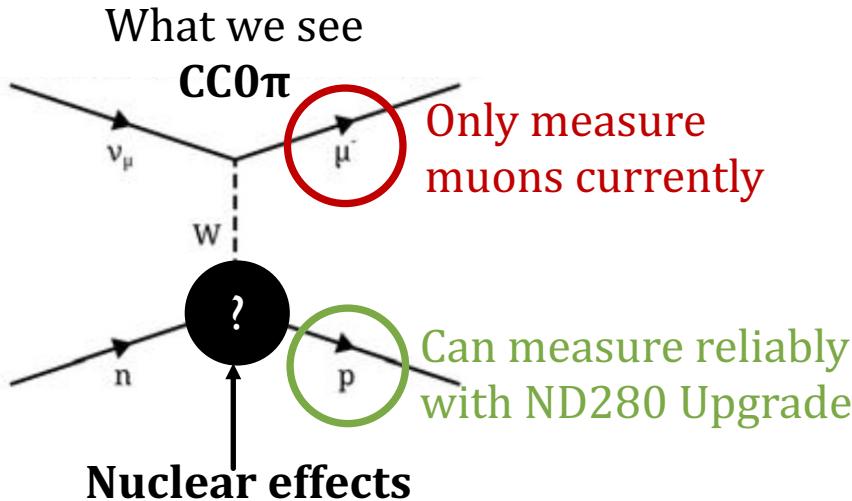
Capabilities of the ND280 Upgrade

- Full 4π angular coverage (same as SK)



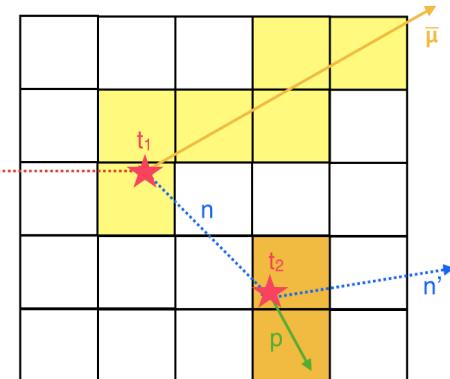
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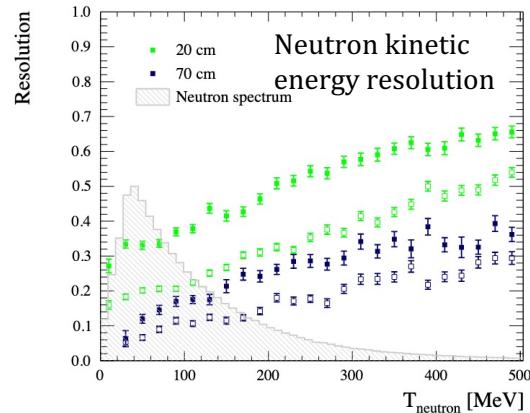
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- Capability to measure (not just tag!) **neutrons**
 - Unmatched by Liquid Argon TPCs

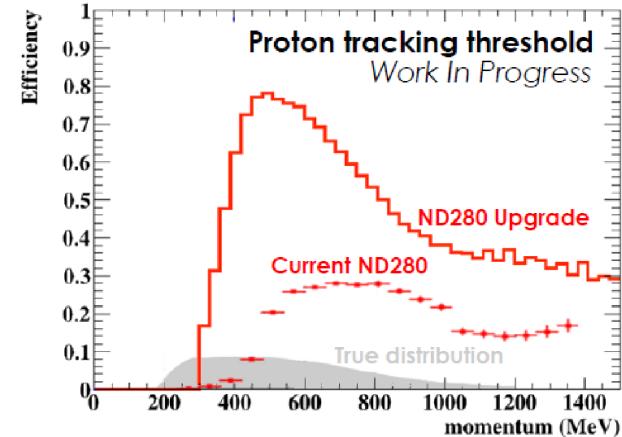
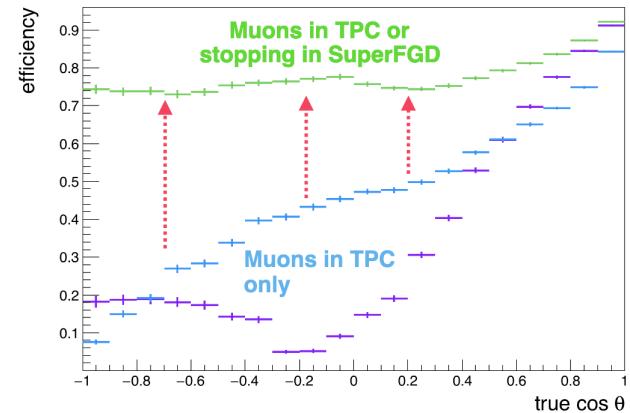


Phys. Rev. D 101, 092003

13.03.2023



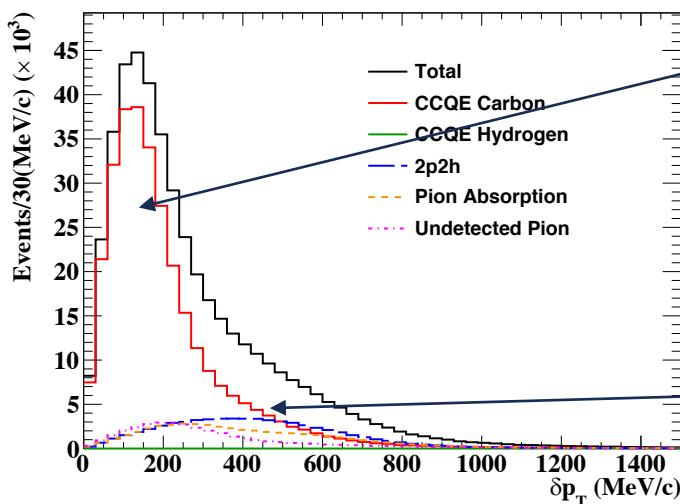
Laura Munteanu (CERN) - Séminaire LLR



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What can the ND280 Upgrade do for us?

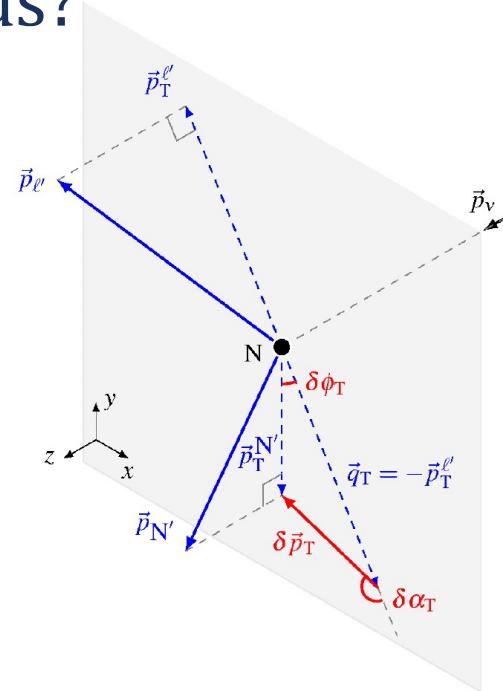
- Access to **exclusive** variables
 - E.g. probe nuclear effects by looking at Transverse Kinematic Imbalance (TKI)



Bulk dominated
by CCQE

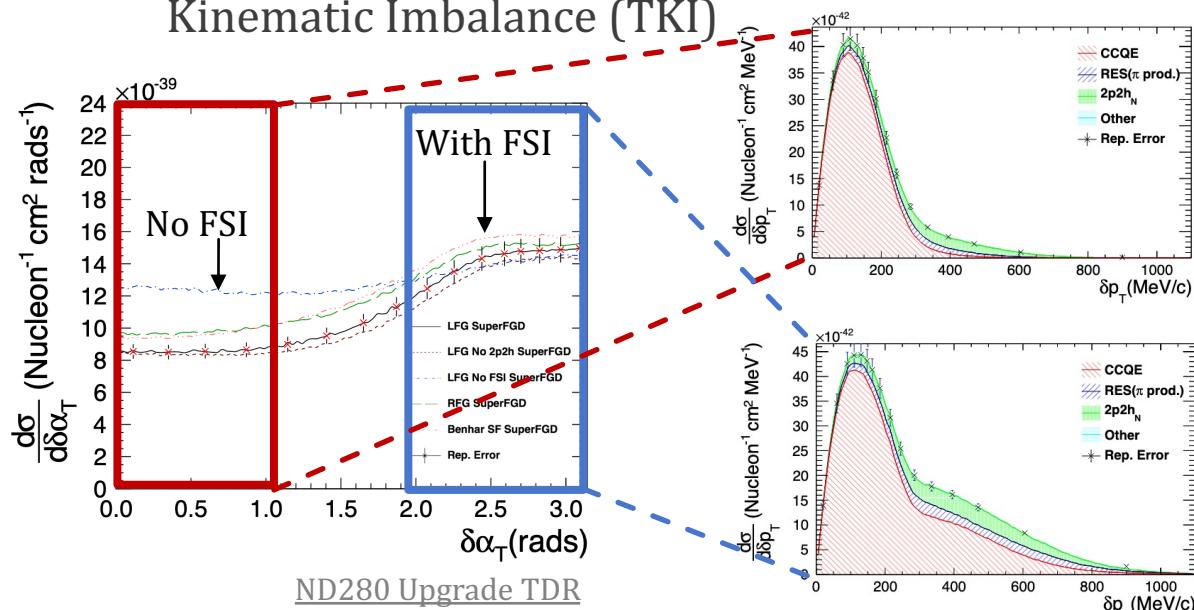
Tails dominated
by FSI+2p2h

Phys. Rev. D 105, 032010



What can the ND280 Upgrade do for us?

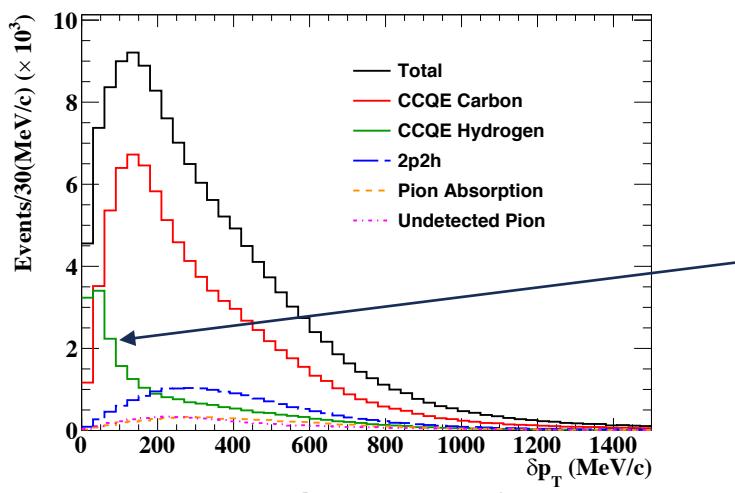
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Separate 2p2h
and FSI effects!

What can the ND280 Upgrade do for us?

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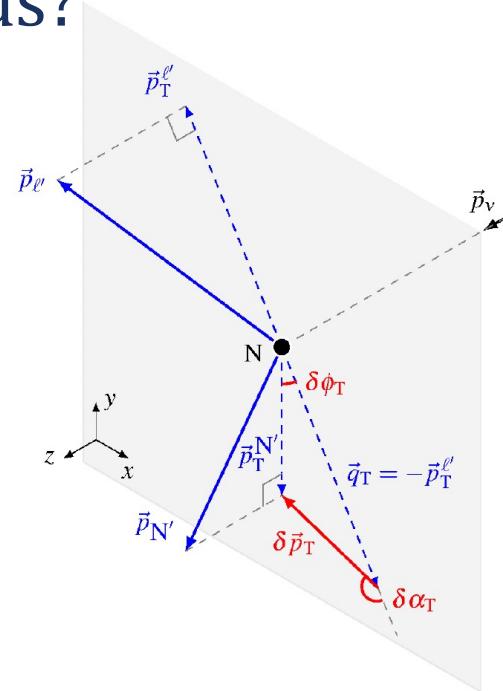
Phys. Rev. D 105, 032010

Phys. Rev. D 101, 092003

Antineutrinos:
Peak from interactions
on hydrogen

No nuclear effects

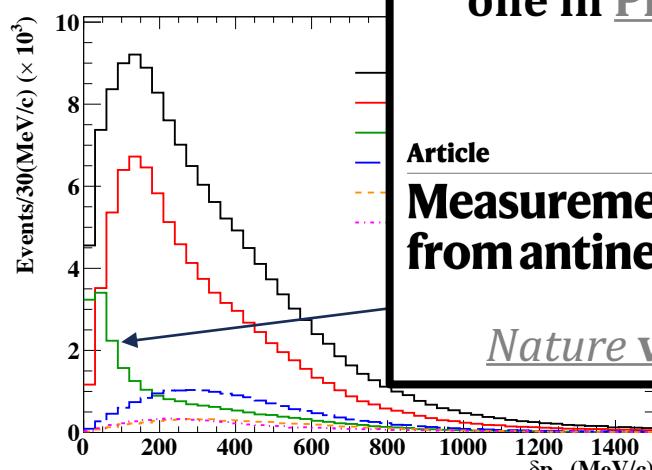
Possible thanks to
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What can the ND280 Upgrade do for us?

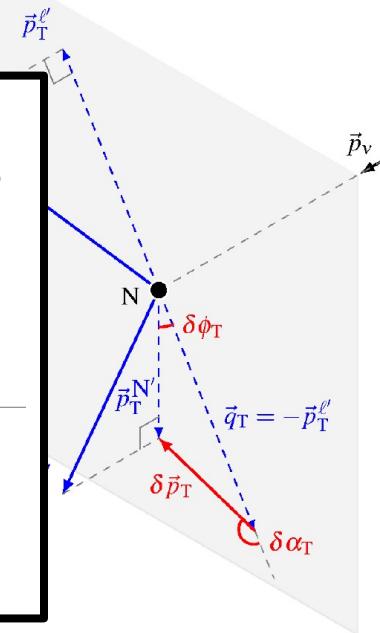
- Access to **exclusive** variables

- E.g. probe neutrino Kinematic Invariance



A recent measurement from the MINERVA collaboration using **a method inspired by the one in Phys. Rev. D 101, 092003** has been published in Nature

Possible thanks to
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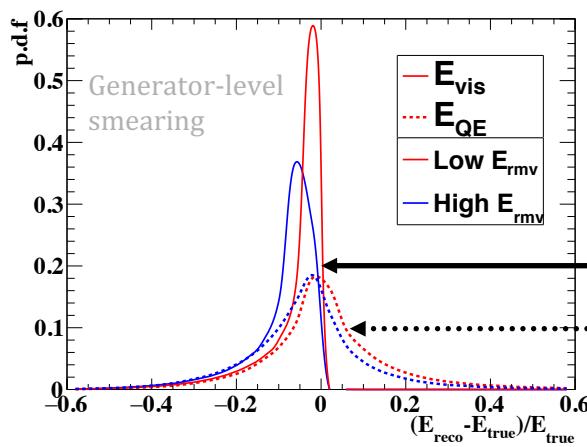


What can the ND280 Upgrade do for us?

- Access to **exclusive** variables
 - E.g. probe nuclear effects by looking at Transverse Kinematic Imbalance (TKI)
 - Using calorimetric estimators for neutrino energy

$$E_{vis} = E_\mu + T_N$$

Method used by NOvA & DUNE

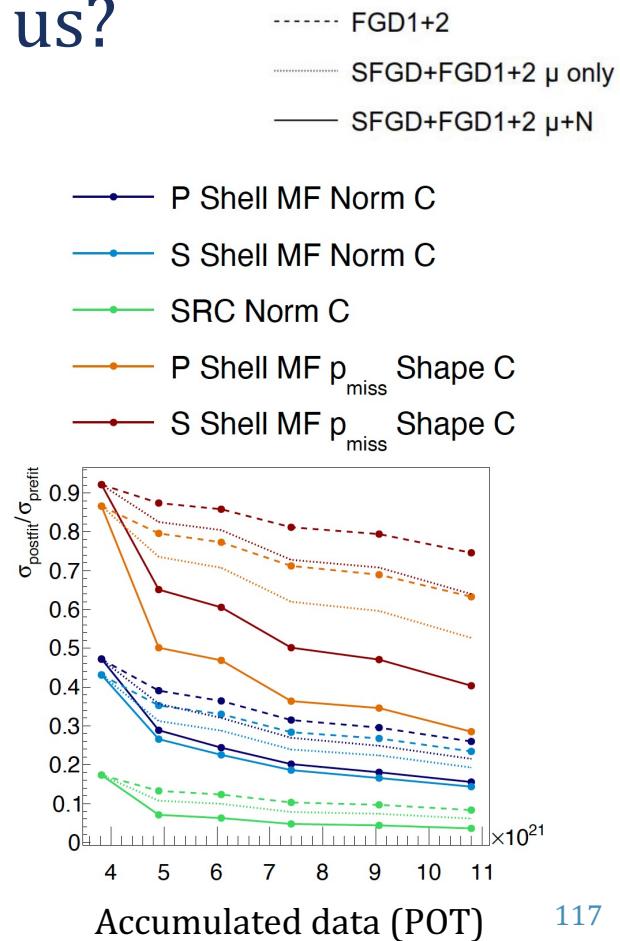


Reduced bias in neutrino energy reconstruction

E_{vis} bias dominated by **detector resolution**
 E_{QE} dominated by **nuclear effects**

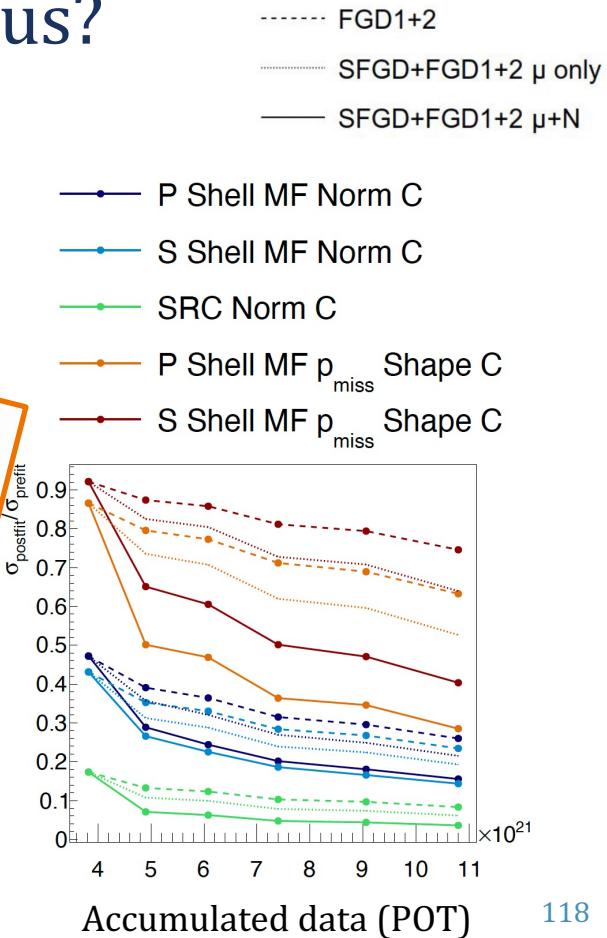
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- Access to **exclusive** variables
 - E.g. probe nuclear effects by looking at Transverse Kinematic Imbalance (TKI)
 - Using calorimetric estimators for neutrino energy
- Significantly **improve constraints** on systematic error parameters for oscillation analyses
- Help build more **robust** analyses
- Give us **novel measurements!**



What can the ND280 Upgrade do for us?

- Access to **exclusive** variables
 - E.g. probe nuclear effect by looking at Kinematic Imbalance (TKD)
 - Using calorimetric energy
- Significantly **improve** systematic error parameter analyses
- Help build more **robust** analyses
- Give us **novel measurements!**



Summary

- Neutrino oscillation experiments are entering the **precision measurement era**
- **Dominant source** of systematic uncertainties related to **neutrino-nucleus cross-sections**
- Current results **hint at CP-violation in the lepton sector**, but more data is needed
- Future experiments **Hyper-K and DUNE** have ambitious programs which will determine the values of oscillation parameters precisely
- But will rapidly be **hindered by systematic uncertainties** related to neutrino-nucleus interactions
- **Dedicated effort needed** to improve our understanding of neutrino-nucleus interactions
- Exciting new measurements ahead!

Thank you for your attention!

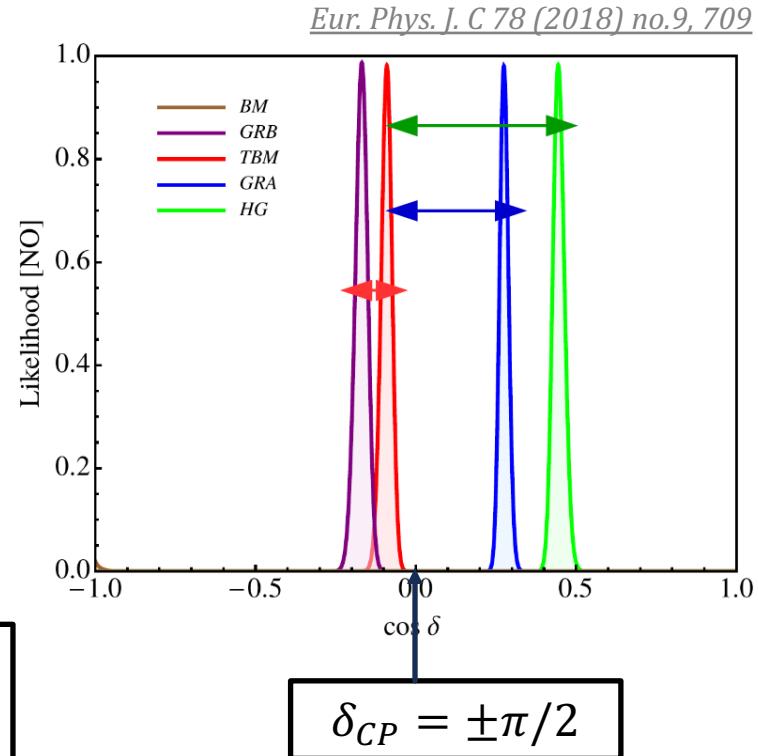


Supplementary material

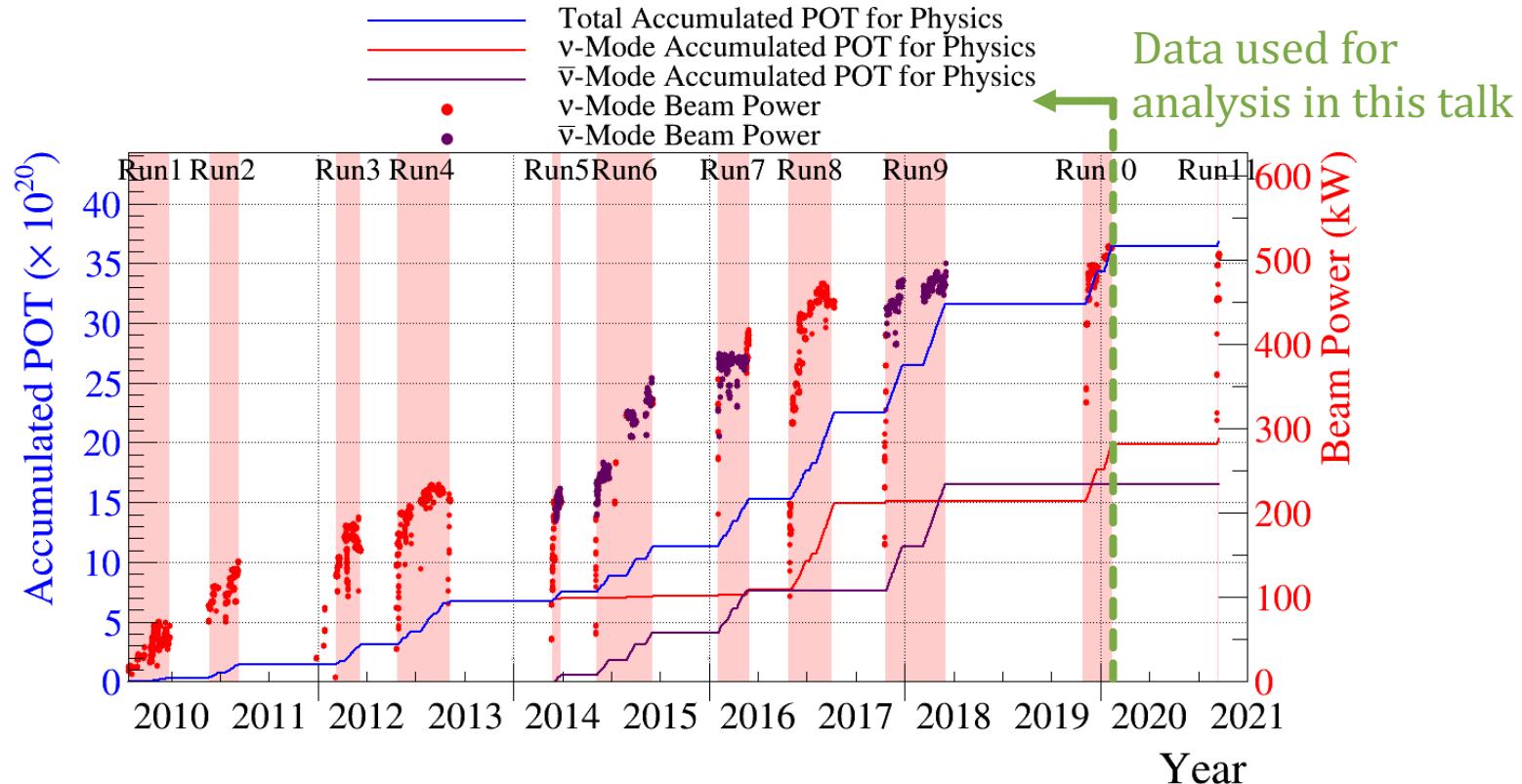
Precision measurements of δ_{CP}

- Measuring CP violation (CPV) \neq measuring δ_{CP}
- If no CPV in neutrino oscillations: exclude matter-antimatter asymmetry explanation through lepton sector CPV
- If CPV is observed: we can **constrain leptogenesis models**
 - But need **precise** measurement of δ_{CP} !
- Model separation power vs δ_{CP} resolution:
 - **Satisfactory:** $\sigma(\delta_{CP}) < 30^\circ$
 - **Good:** $\sigma(\delta_{CP}) < 23^\circ$
 - **Excellent:** $\sigma(\delta_{CP}) < 5^\circ$

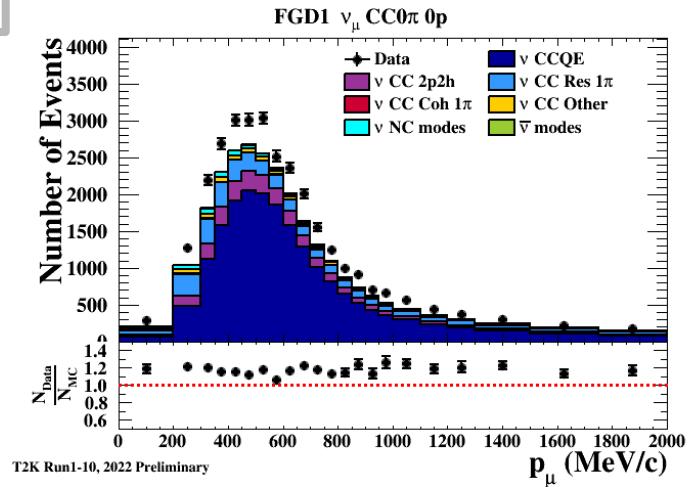
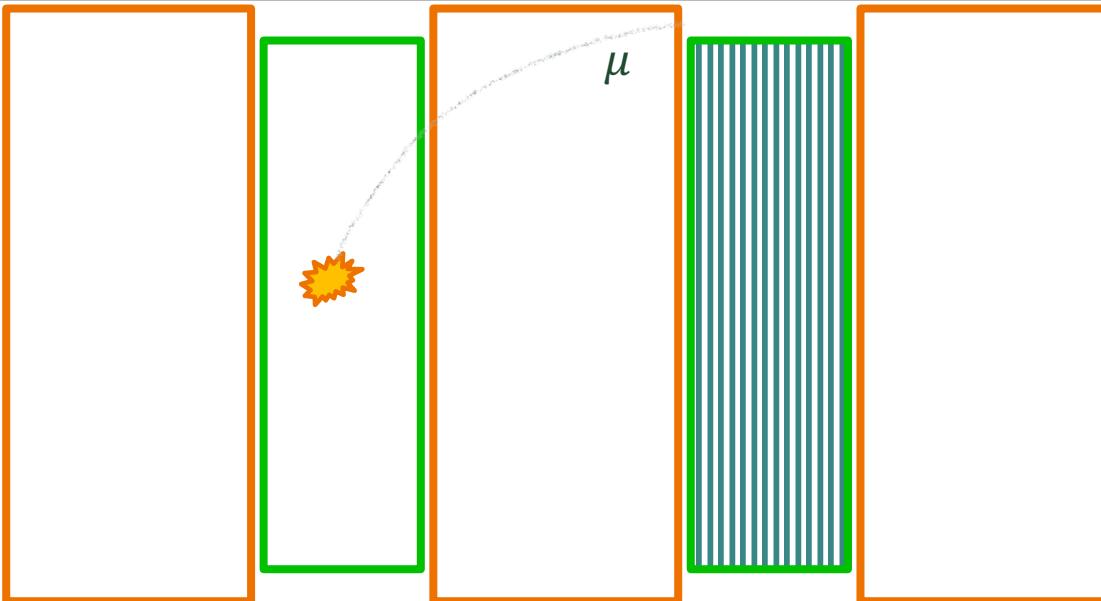
Hyper-K and
DUNE target



Collected T2K data

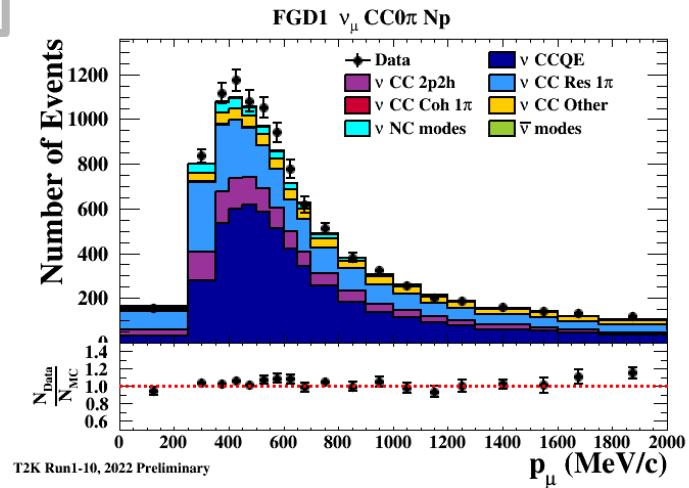
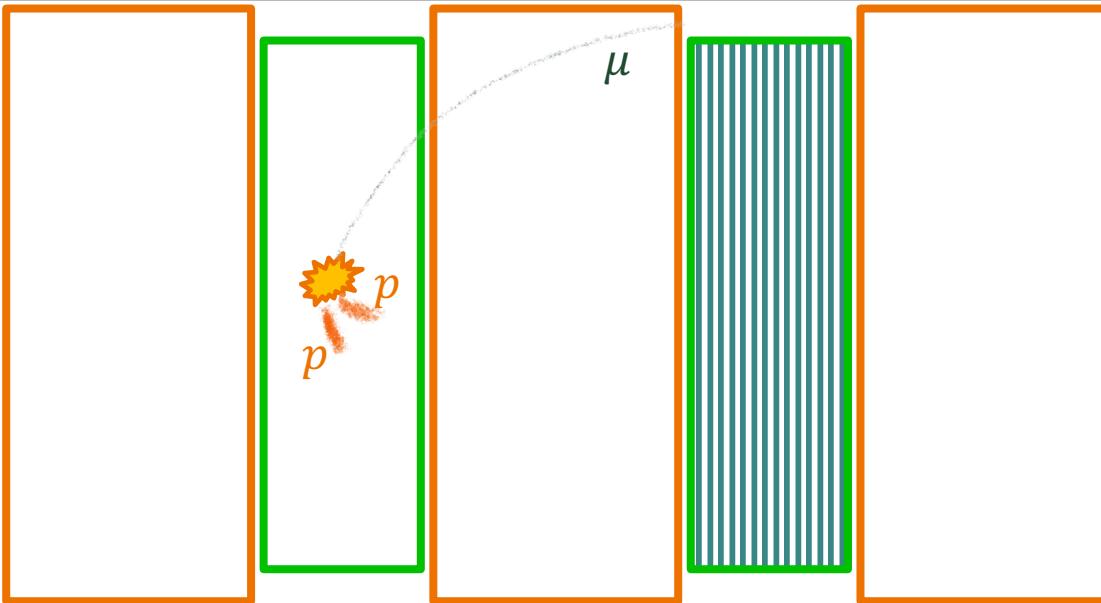


Samples: CC0 π 0p



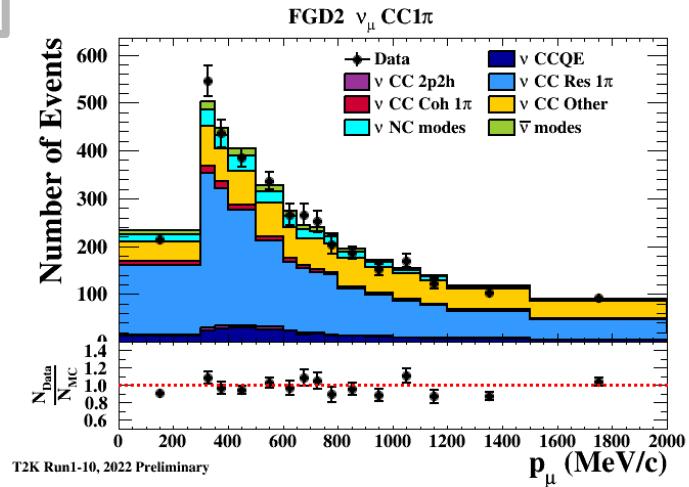
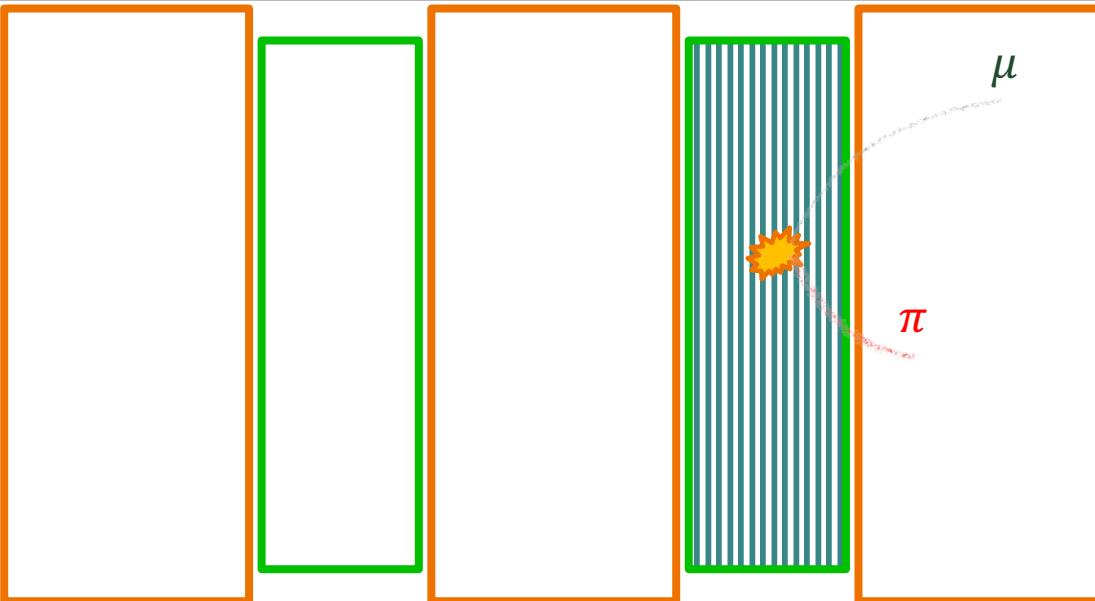
$1\mu, 0\pi, 0p$
Enriched in CCQE interactions

Samples: CC0 π Np



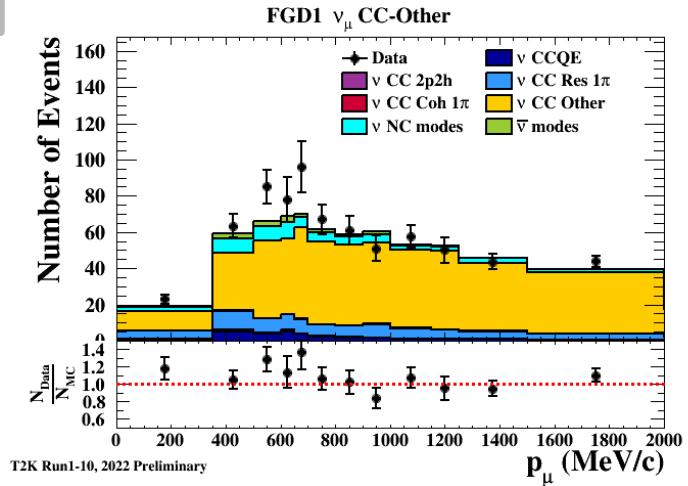
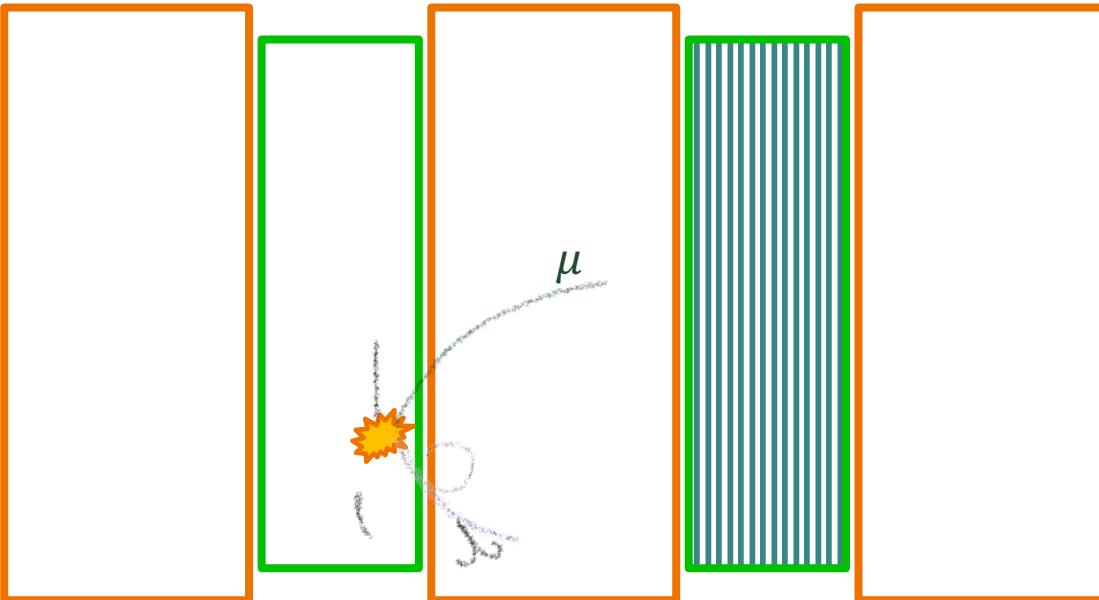
$1\mu, 0\pi, Np$
Constrains FSI-related
background

Samples: CC1 π



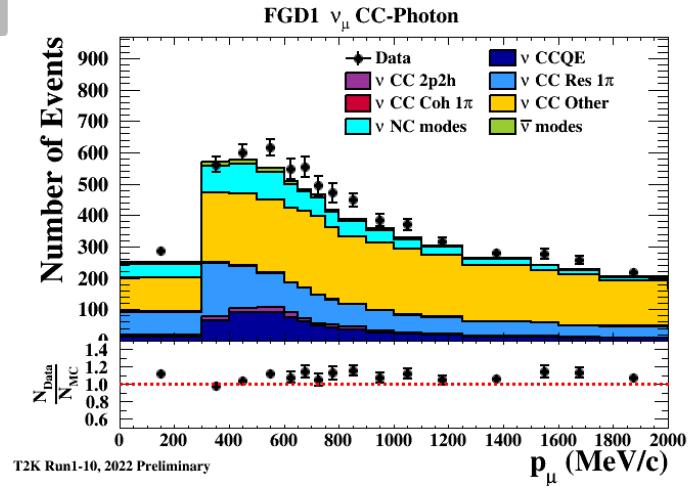
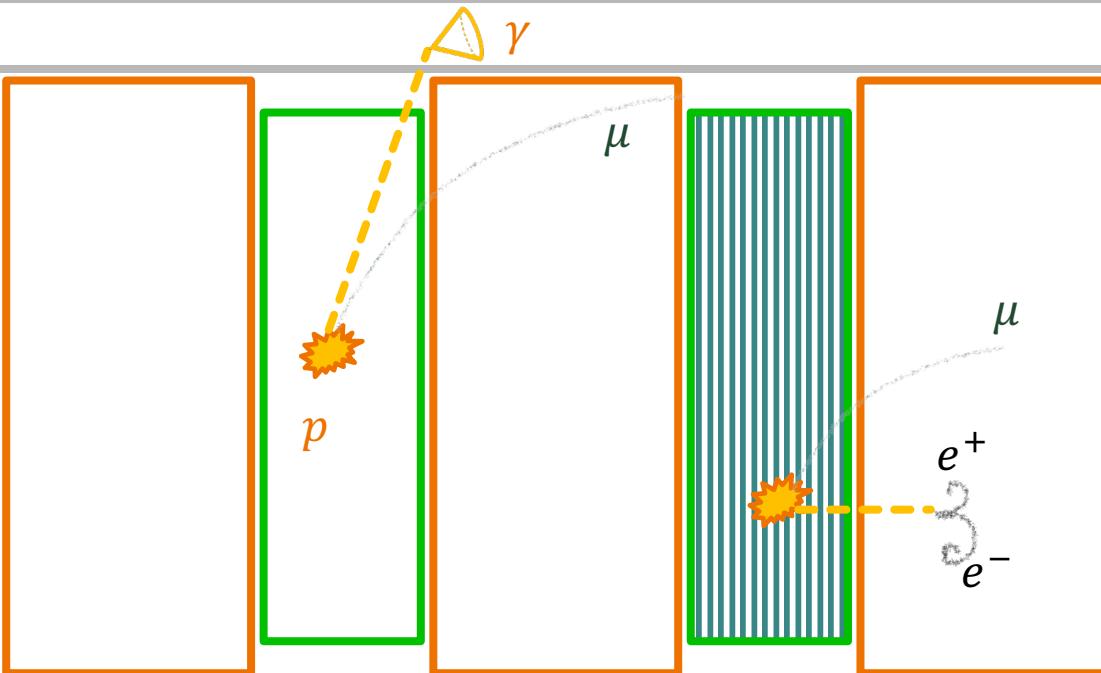
$1\mu, 1\pi$
Enriched in resonant
interactions

Samples: CCOther



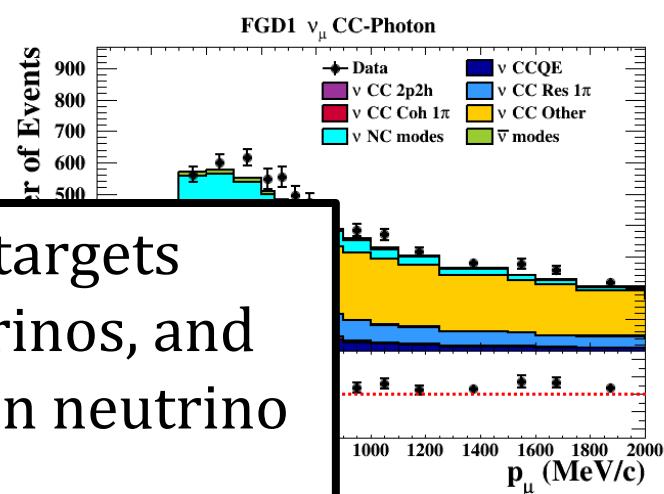
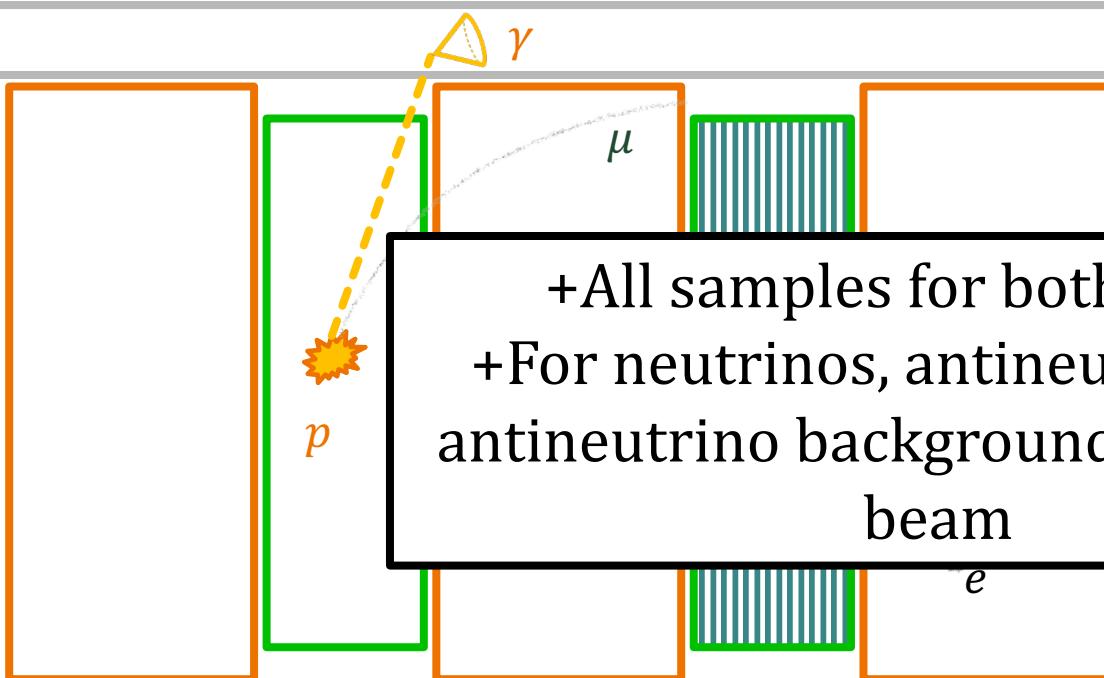
$1\mu + \text{any other tracks}$
Enriched in DIS interactions

Samples: CC γ



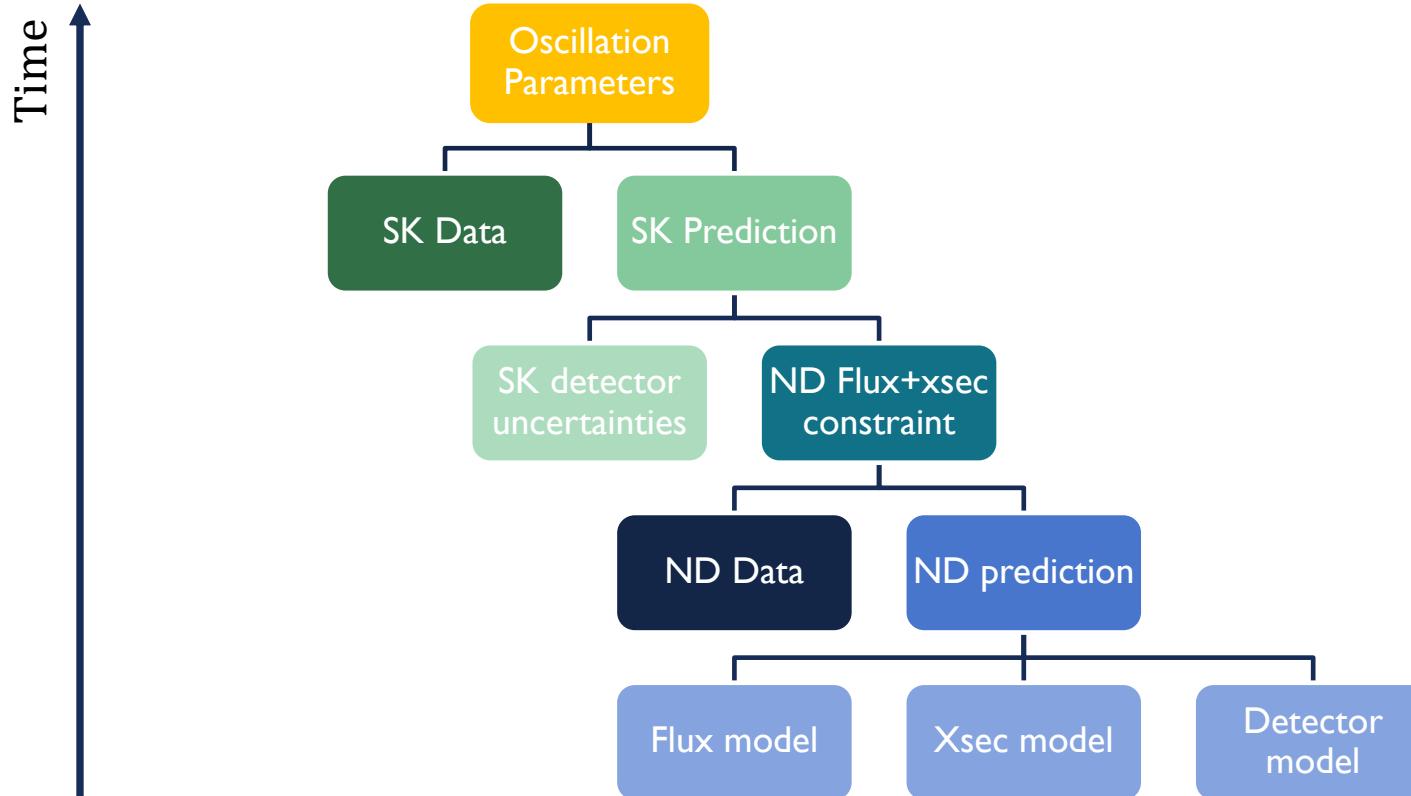
$1\mu + \text{photon}$
Enriched in DIS interactions

Samples: CC γ

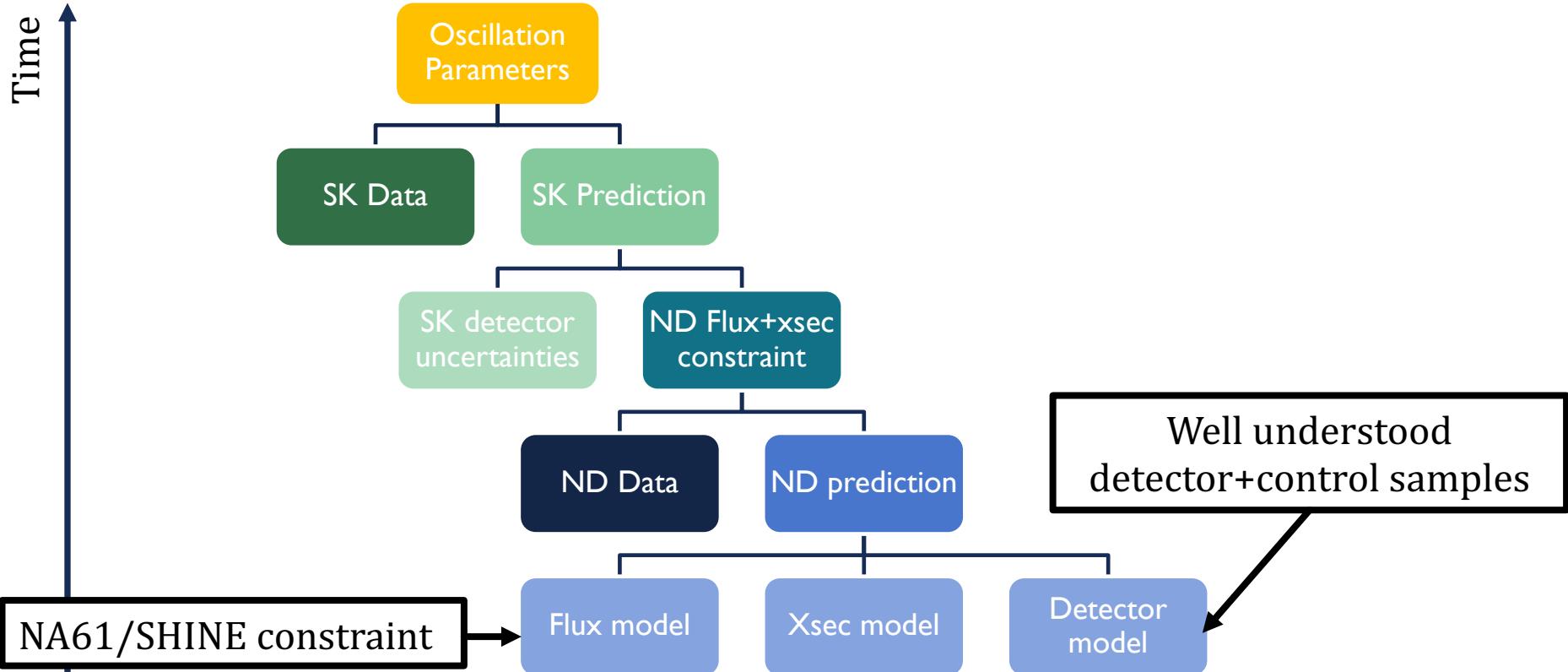


$\tau\mu + \text{photon}$
Enriched in DIS interactions

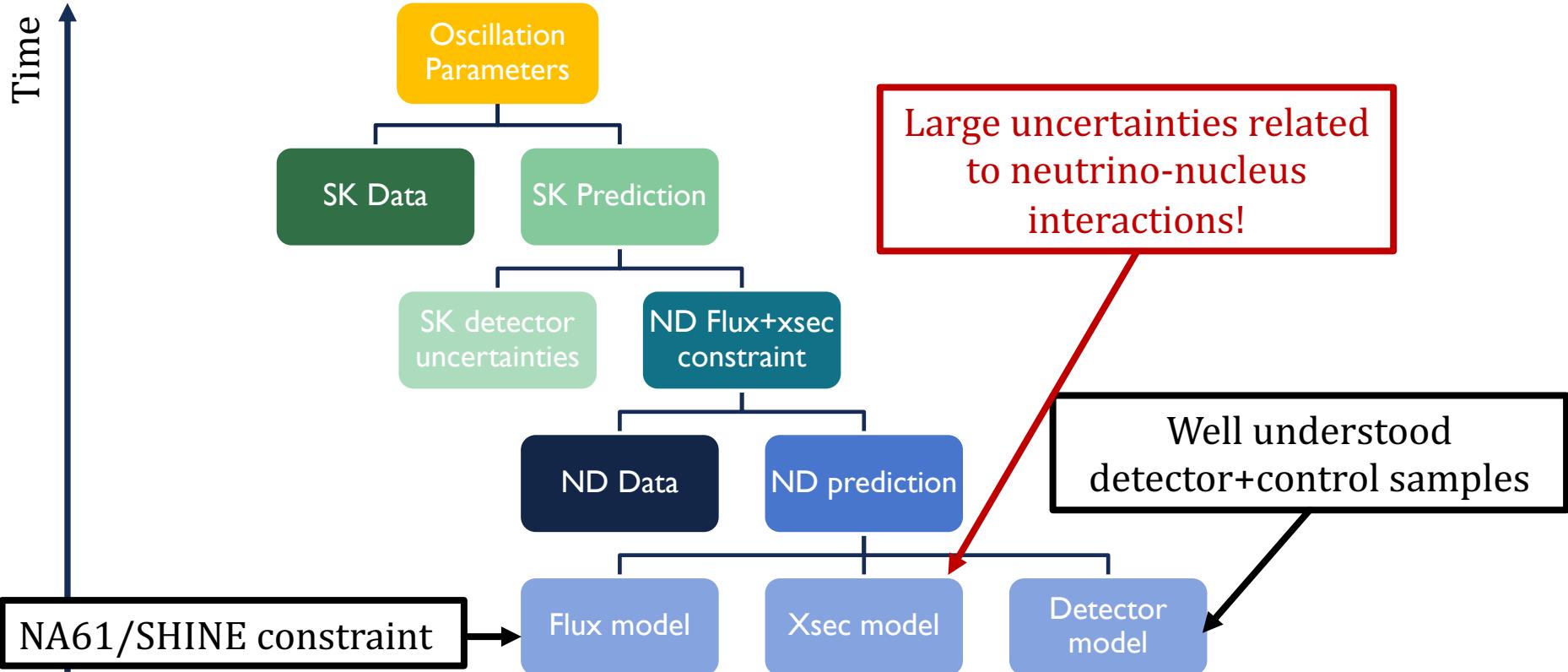
Analysis strategy



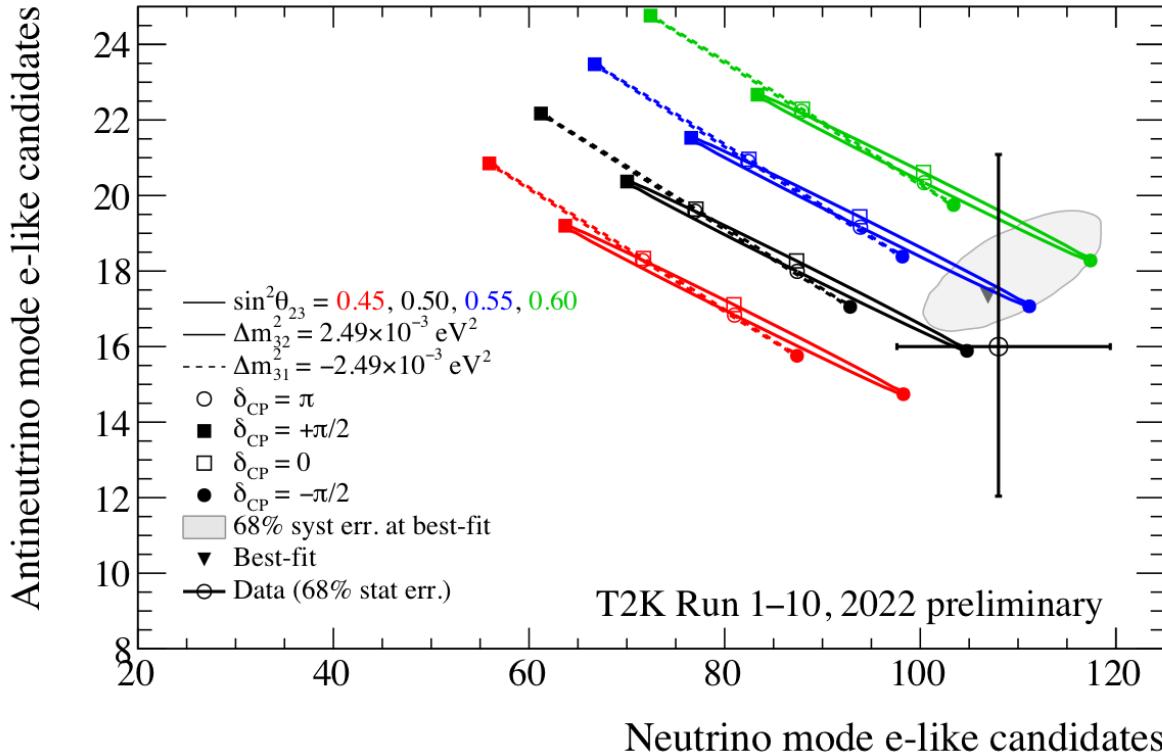
Analysis strategy



Analysis strategy

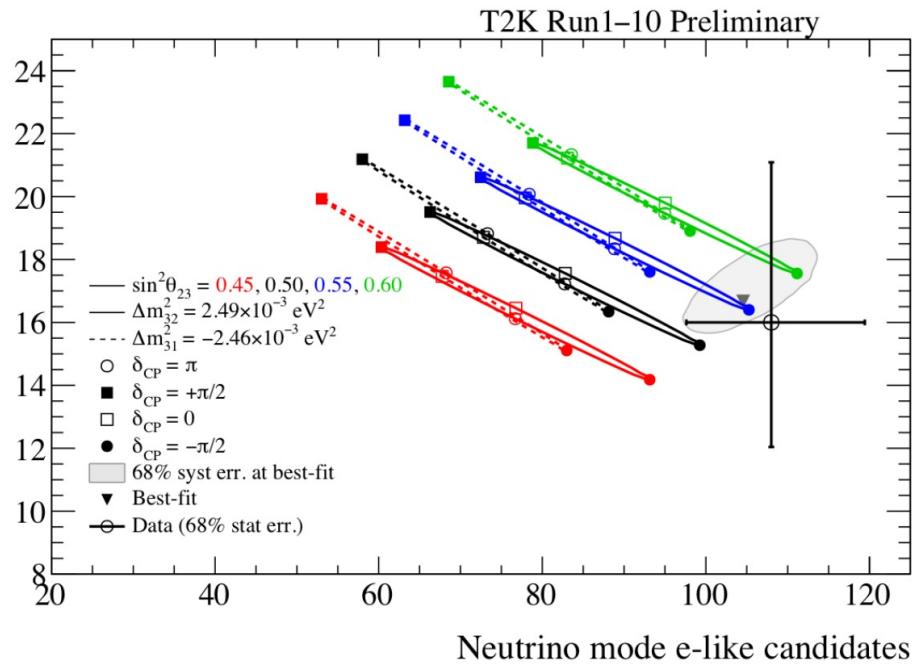


T2K Bi-probability plot



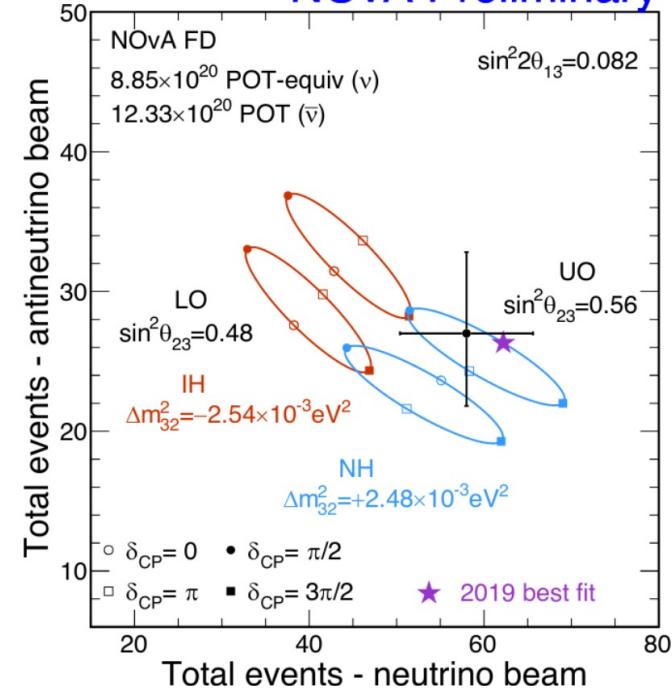
T2K-NOvA joint fit

Antineutrino mode e-like candidates

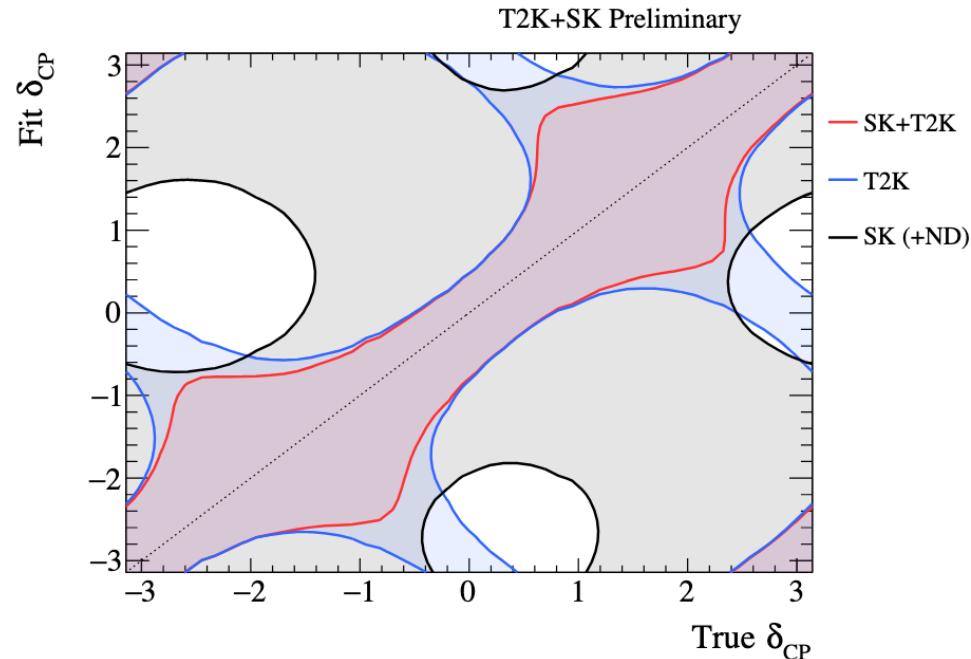
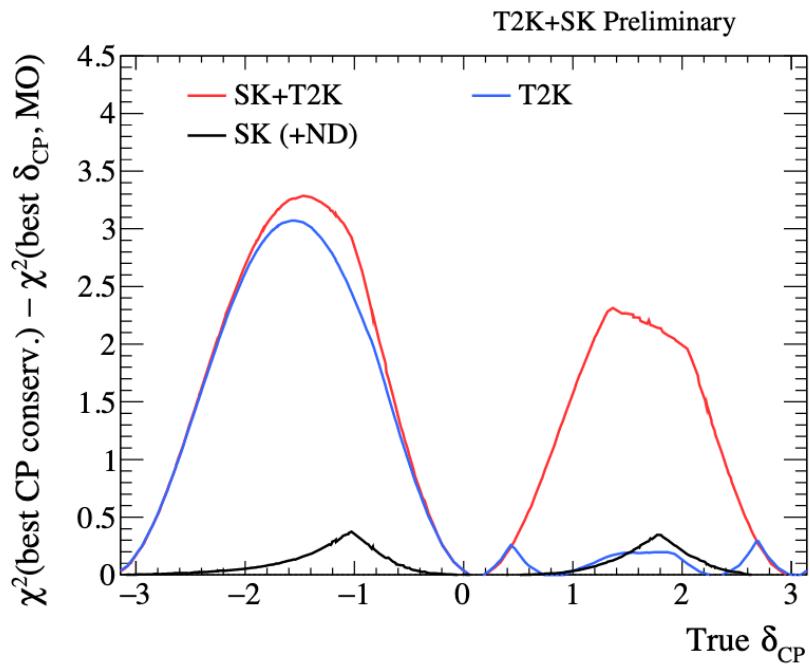


FNAL Users Meeting 2019

NOvA Preliminary

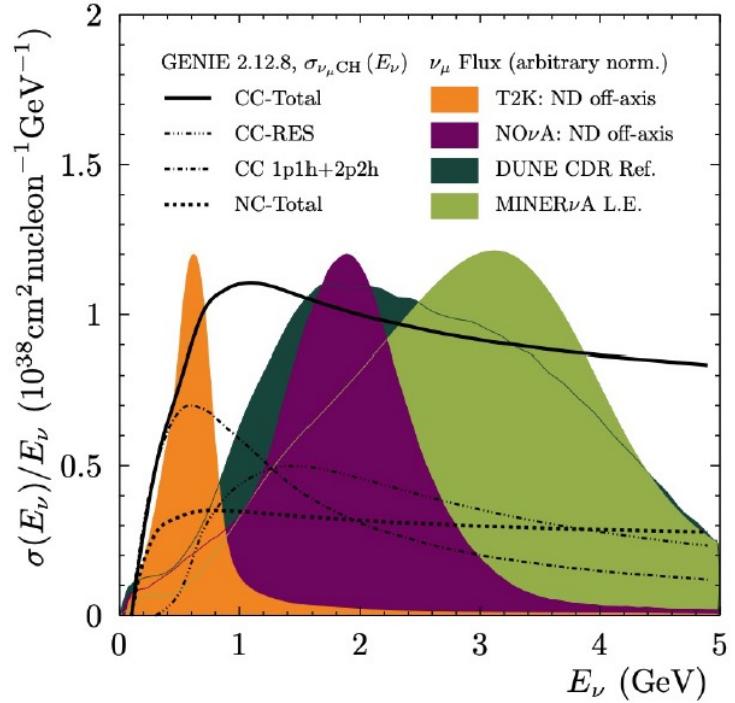


T2K+SK Atospheric Joint Fit



Ongoing work on DUNE

- DUNE is preparing a new set of sensitivity studies focused on the role of its **near detectors**
 - Complete overhaul of systematics model used in Physics TDR ([arXiv:2002.03005](https://arxiv.org/abs/2002.03005))
- At DUNE statistics, we will be able to resolve some of **the most minute details** in the way we model neutrino-nucleus interactions
- But no model is capable of comprehensively describing neutrino cross-section data
 - For DUNE, **we need a flexible model** which can cover the variations suggested by relevant neutrino cross-section measurements
- We also will need to pay particular attention to FSI
- Beyond oscillation measurements: we need a model that can be used for BSM physics and can model well the backgrounds that can affect these processes



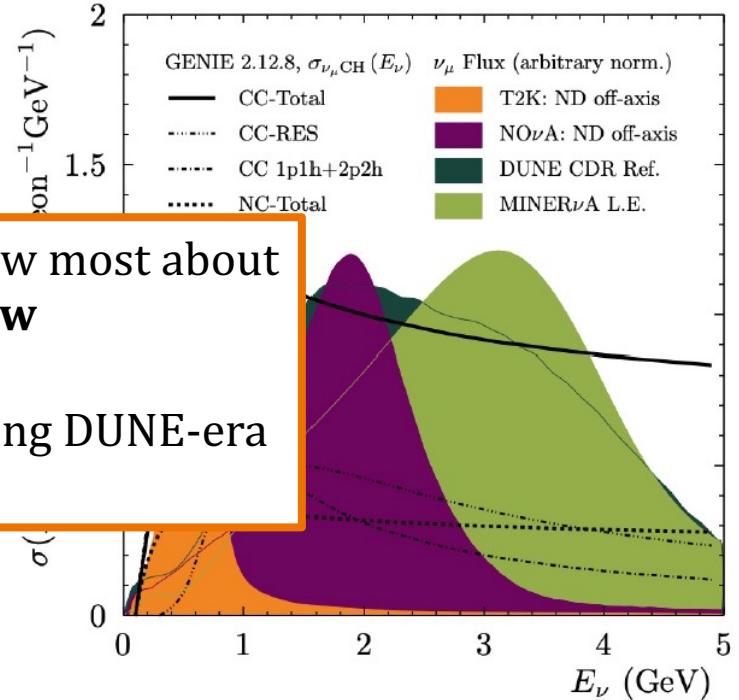
DUNE is not QE dominated
But QE interactions are **those which we can measure best**
Remain important for **precision measurements**

Ongoing work on DUNE

- DUNE is preparing a new set of sensitivity studies focused on the role of its **near detectors**
 - Complete overhaul of *systematics model used in Physics TDR* ([arXiv](#))
- At DUNE statistics **of the most minute neutrino-nucleus**
- But no model is currently available for describing neutrino interactions
 - For DUNE, **we need a flexible model** which can cover the variations suggested by relevant neutrino cross-section measurements
- We also will need to pay particular attention to FSI
- Beyond oscillation measurements: we need a model that can be used for BSM physics and can model well the backgrounds that can affect these processes

The QE regime is where we know most about
what we don't know

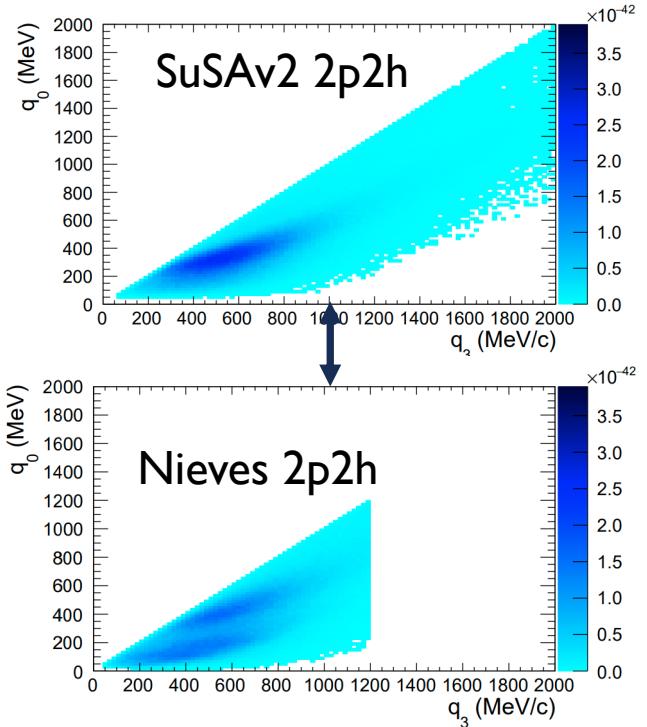
Perfect starting point for building DUNE-era analyses



DUNE is not QE dominated
But QE interactions are **those which we can measure best**
Remain important for **precision measurements**

DUNE interaction model

- The expansion of the ground state model is part of a broader effort to increase the flexibility of our analyses
- Interaction model choices:
 - Valencia 1p1h model for CCQE interactions
 - Z-expansion form factor
 - SuSAv2 2p2h
 - Berger-Sehgal for Resonant interactions
 - Bodek-Yang DIS
 - hA2018 for hadronization
- Each of these parts of the model requires the development of systematic uncertainties tailored to DUNE-era statistics



[Phys. Rev. D 101, 033003 \(2020\)](#)