Neutrino-nucleus interaction event generators for neutrino oscillation experiments

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IRN Neutrino, Nantes

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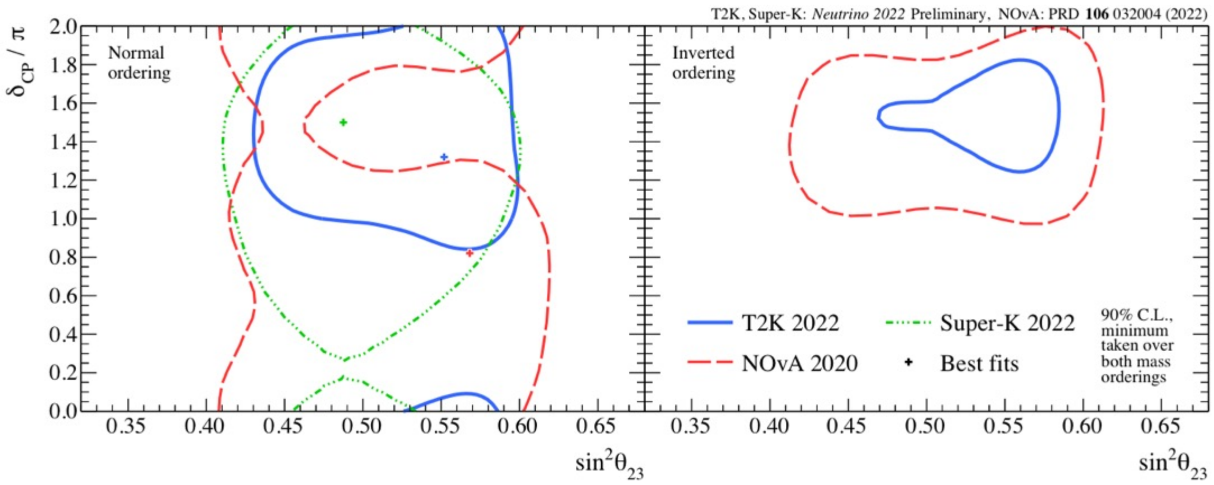
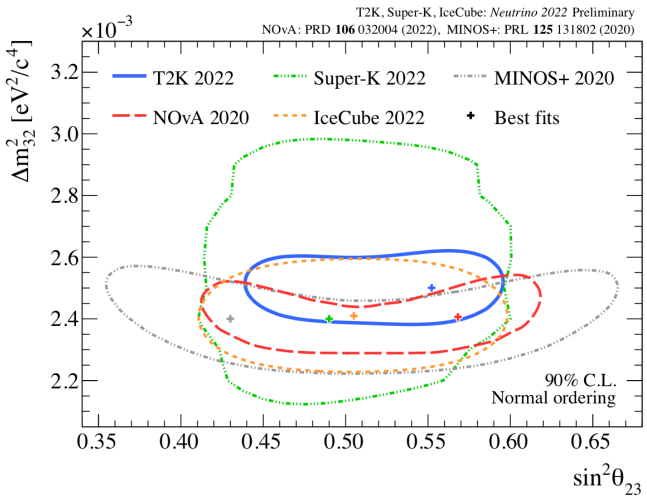
Outline

- Challenges for current and future long-baseline experiments
- Nuclear effects – what do we need to control?
- The role of neutrino event generators
- Success/limitations
- Solutions?

Current experiments – results and challenges

Long-baseline experiments are **uniquely suited to search for CP violation** in the lepton sector and study 3-flavor oscillations





- Measurements of CP violation are **severely limited by statistics** and knowledge of MO
- Now entering the **precision measurement era**

Are we prepared for future experiments?

Experiment	ν_μ events	$\bar{\nu}_\mu$ events	ν_e events	$\bar{\nu}_e$ events	Systematic error
T2K	318	137	94	16	~5%
NOvA	211	105	82	33	~10%

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

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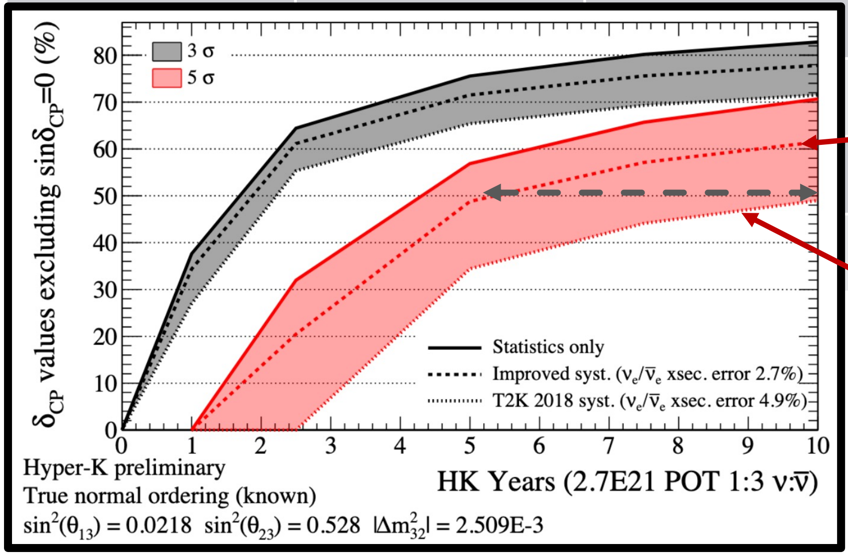
[illegible]	[illegible]	[illegible]	94	16	~5%
[illegible]	[illegible]	[illegible]	8	[illegible]	~10%
[illegible]	[illegible]	[illegible]	~2	0	?
[illegible]	[illegible]	[illegible]	~150	~500	?



Improved systematics

T2K-level systematics

*and similar situation for DUNE

Sensitivity to exclude CP conserving values for δ_{CP}

Can delay physics results by several **years.**

Or prevent them altogether!

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T2K	318	137	94	16	~5%
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Hyper-K	~10000	~14000	~2000	~2000	**Need ~1%-3%!**
DUNE	~7000	~3500	~150	~500	**Need ~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**

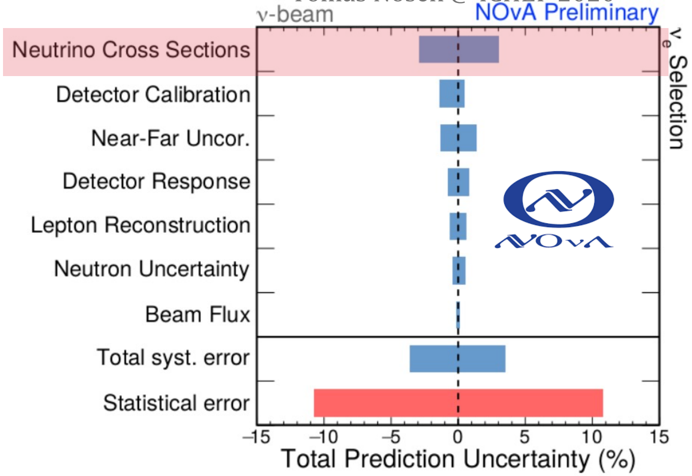
Finding the culprit

T2K

Error source (units: %)	1R FHC	1R RHC	MR FHC CC1π^+	1Re FHC	1Re RHC	1Re FHC CC1π^+	1Re 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

T2K Run 1-10, preliminary

Tomas Nosek @ ICHEP 2020



The description of **neutrino-nucleus interactions** is the **dominant source of systematic uncertainty** for oscillation measurements

Neutrino cross-sections and oscillations

- Oscillation parameters are inferred from event spectra as a function of neutrino energy

Systematic uncertainties

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

Oscillation parameters | Neutrino flux | Interaction cross-section | Detection efficiency | Energy smearing matrix

- Constrain flux + cross-section systematics with near detector
- But **heavily rely on models** to predict near-to-far detector extrapolation + neutrino energy smearing matrix

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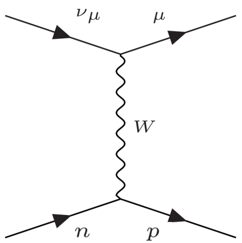
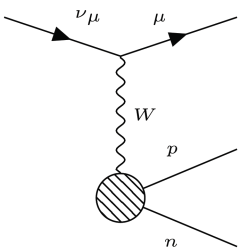
Same – but different!

Charged current channels essential for reliable flavor identification
Same for most experiments!

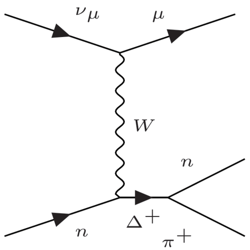
CCQE



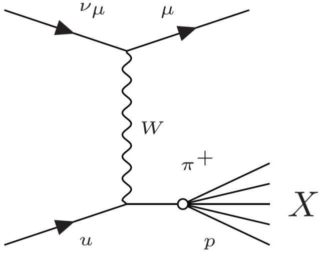
2p2h



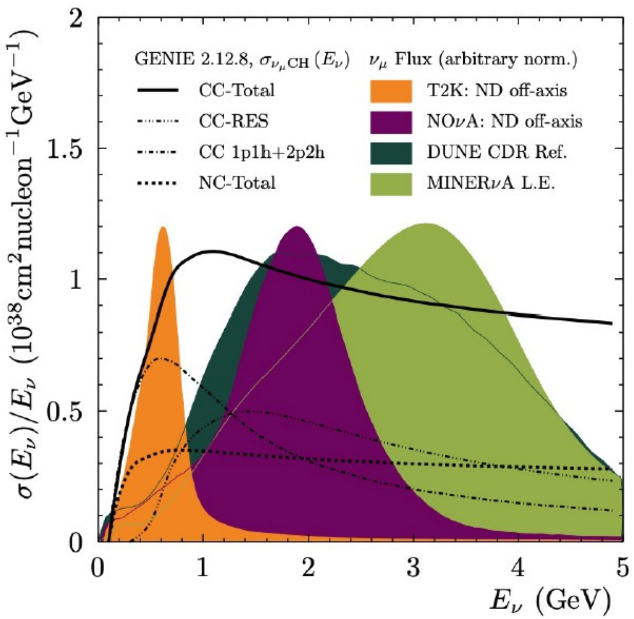
CCRES



CCDIS



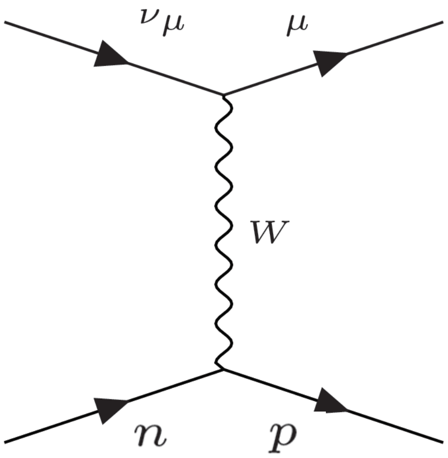
But…



- Their relative contribution varies across experiments (different **flux**)
- **Uncertainties** related to **nucleon-**level processes

From the nucleON to the nucleUS

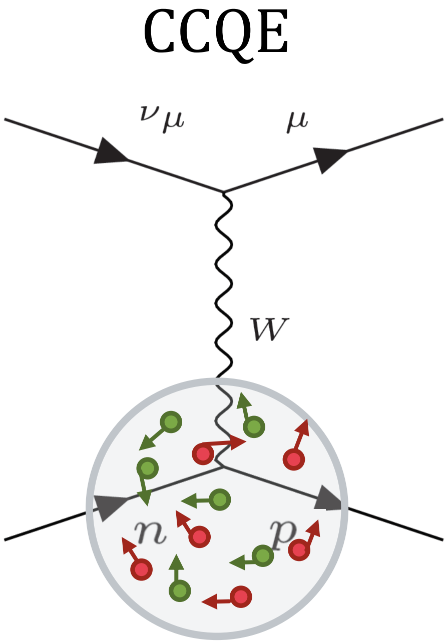
CCQE



"Simplest" CC interaction

- Nucleons are bound inside complex nuclei

From the nucleON to the nucleUS



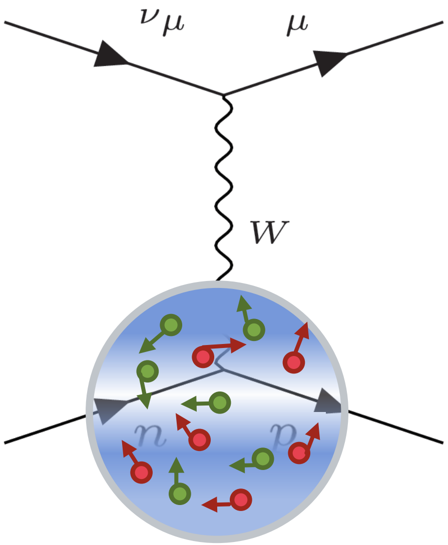
- Nucleons are bound inside complex nuclei

Nuclear effects

- Fermi motion

From the nucleON to the nucleUS

CCQE

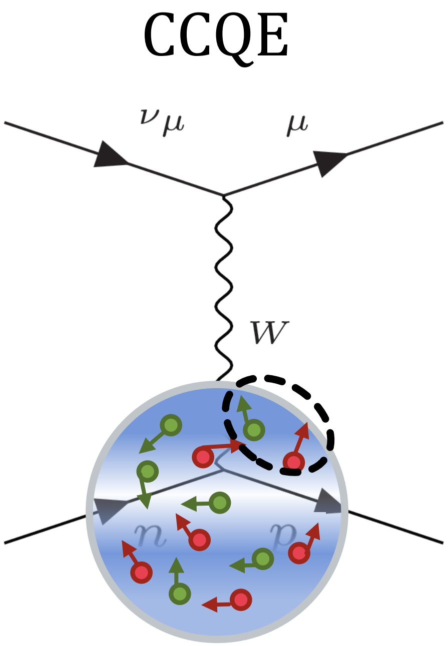


- Nucleons are bound inside complex nuclei

Nuclear effects

- Fermi motion
- Nuclear/optical potential

From the nucleON to the nucleUS



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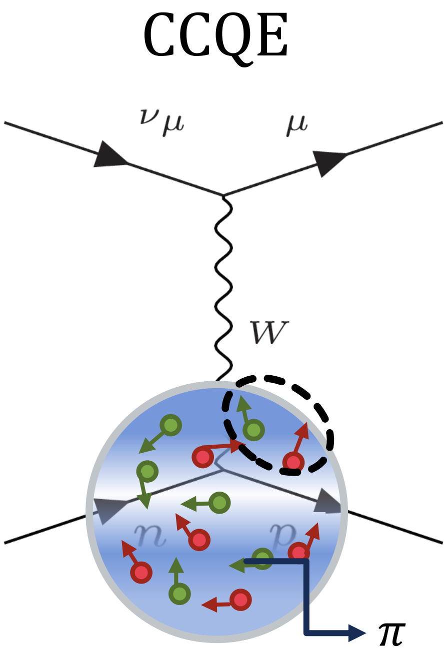
- Correlations between nucleons

From the nucleON to the nucleUS



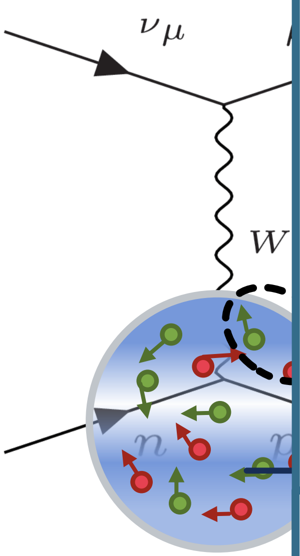
- Nucleons are bound inside complex nuclei

Nuclear effects

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

From the nucleON to the nucleUS

CCQE

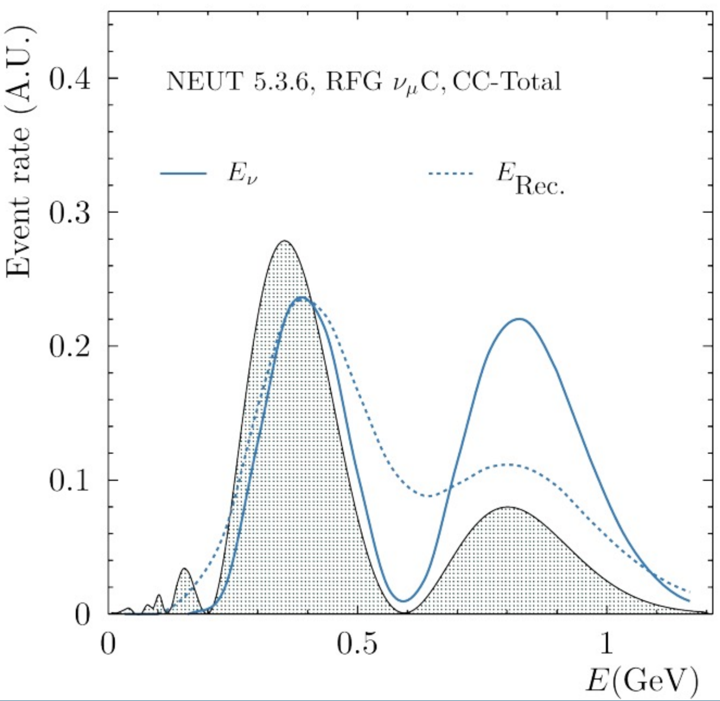


inside complex nuclei

ntial

n nucleons

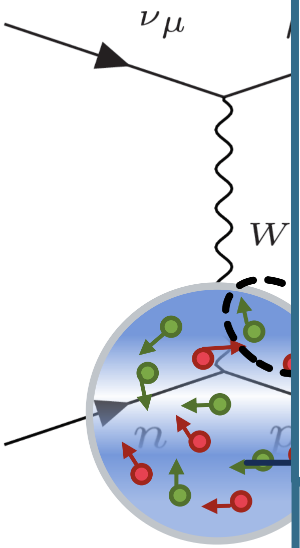
nuclear medium (Final
FSI)

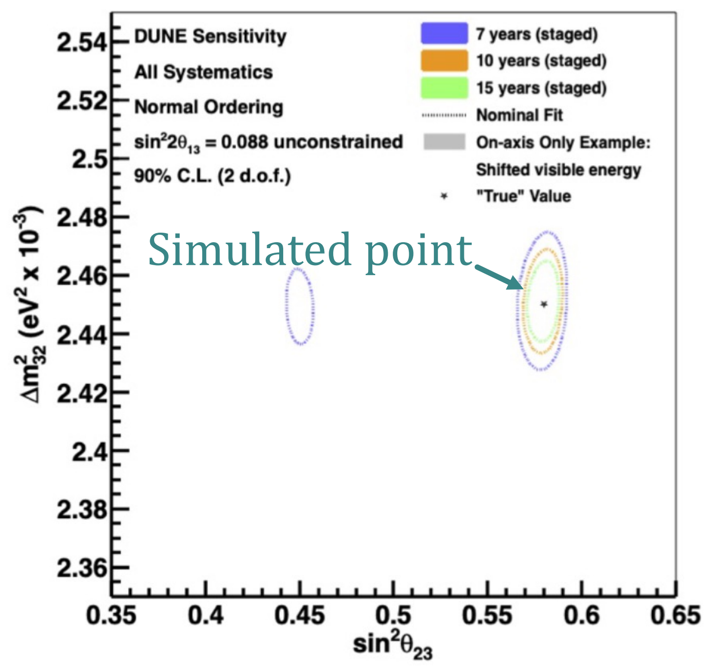


Impact of nuclear effects on reconstructed neutrino energy (oscillated spectrum)

From the nucleON to the nucleUS

CCQE





Impact of nuclear effects on **oscillation measurements**

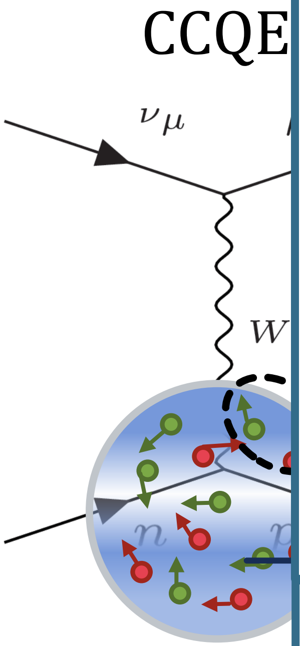
inside complex nuclei

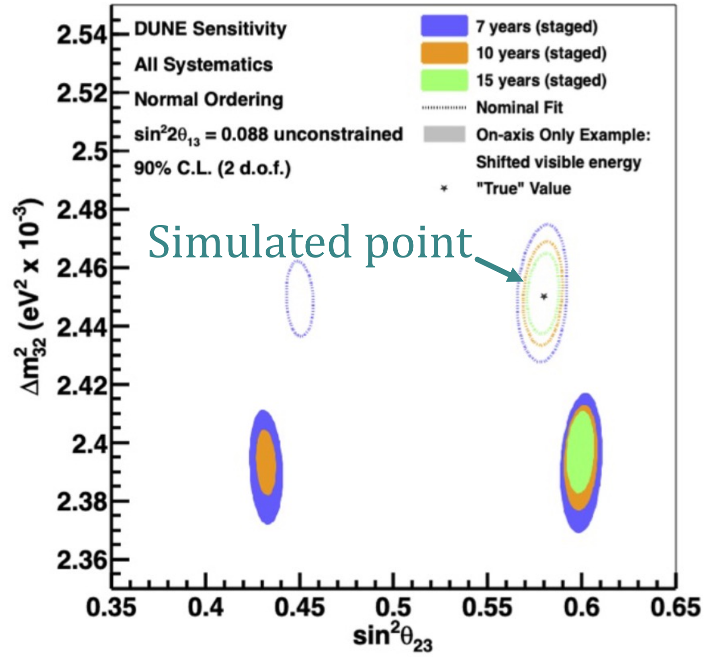
ntial

n nucleons

e nuclear medium (Final FSI)

From the nucleON to the nucleUS





Impact of nuclear effects on
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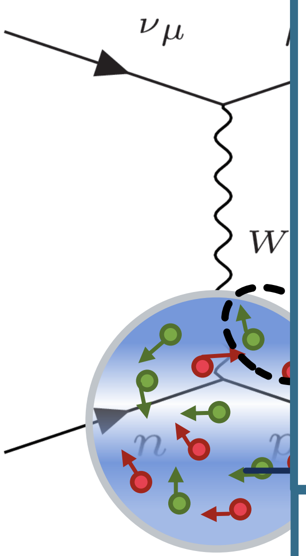
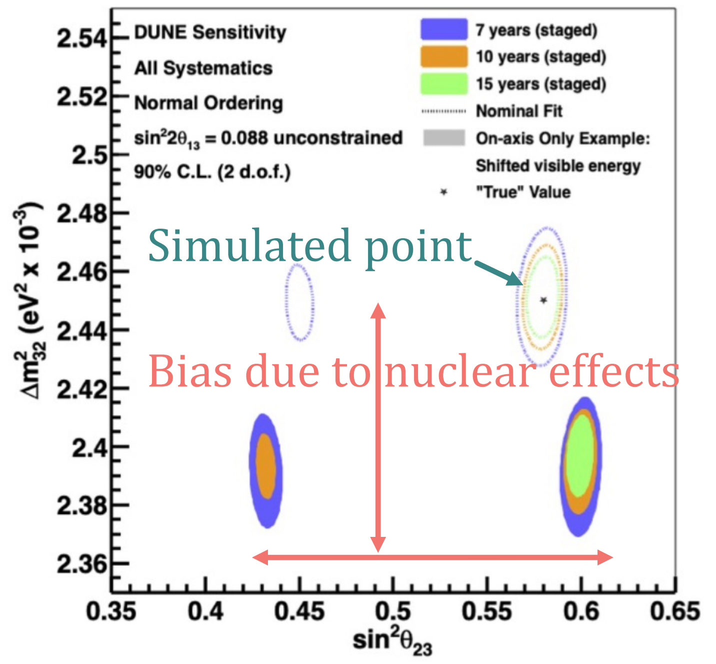
CCQE





Impact of nuclear effects on
oscillation measurements

inside complex nuclei

ntial

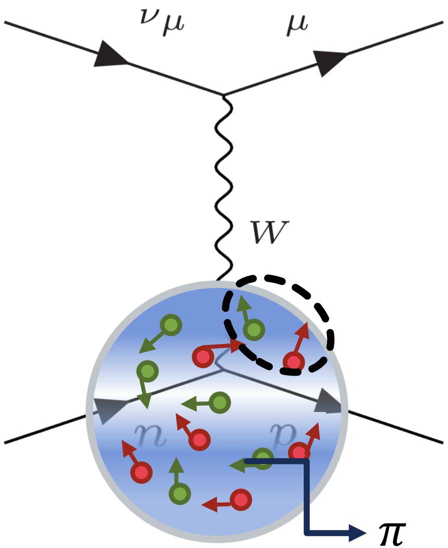
n nucleons

nuclear medium (Final

FSI)

From the nucleON to the nucleUS

CCQE



- 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)

+ so many targets (C, H, O, Ar), so little data…

+ different models for each type of interaction/effect/flavor

The role(s) of neutrino interaction generators

- Provide a (sufficiently) accurate **description** of neutrino-nucleus interactions
  - To be used as input model to oscillation analyses/model backgrounds
- **Compare** theoretical predictions to experimental measurements
  - To benchmark our models
- **Propagate uncertainties** related to the modelling of neutrino-nucleus cross-sections

Neutrino interaction generators*

*Most widely used by accelerator-based experiments

Nucl.Instrum.Meth.A 614 (2010) 87-104

Genie

UNIVERSAL NEUTRINO GENERATOR & GLOBAL FIT

Nucl.Phys.B Proc.Suppl. 159 (2006) 211-216

NuWro

Wroclaw Neutrino Event Generator

Phys.Rept. 512 (2012) 1-124

GiBUU

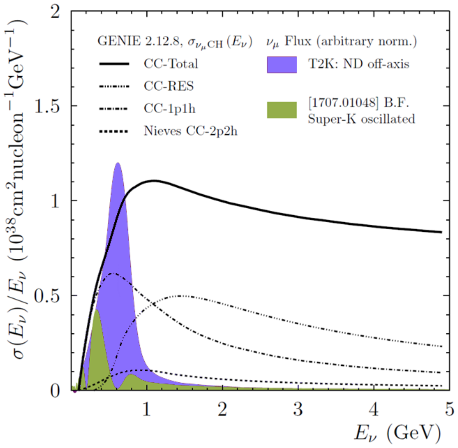
Eur.Phys.J.ST 230 (2021) 24, 4469-4481

NEUT

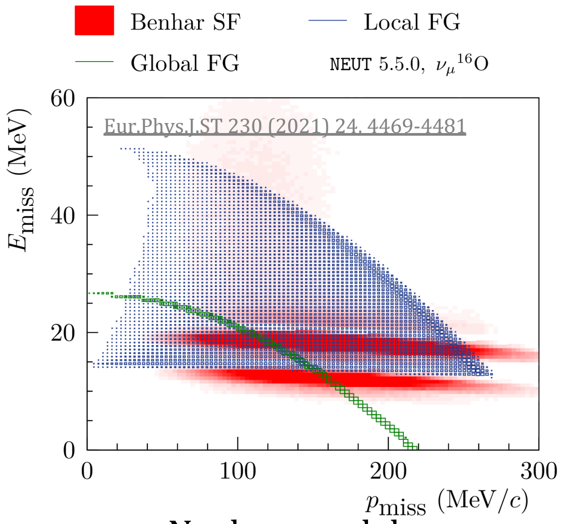
Phys.Rev.D 107 (2023) 3, 033007

How do generators work?

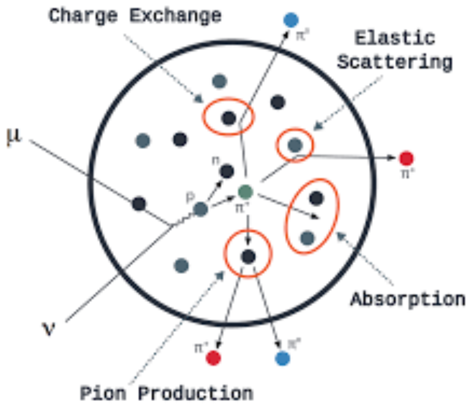
Sample neutrino $\Phi(E_\nu)\times\sigma_{tot}(E_\nu)$ → Determine interaction channel → Sample kinematics from model → Transport through nucleus



$\Phi(E_\nu)\times\sigma_{tot}(E_\nu)$

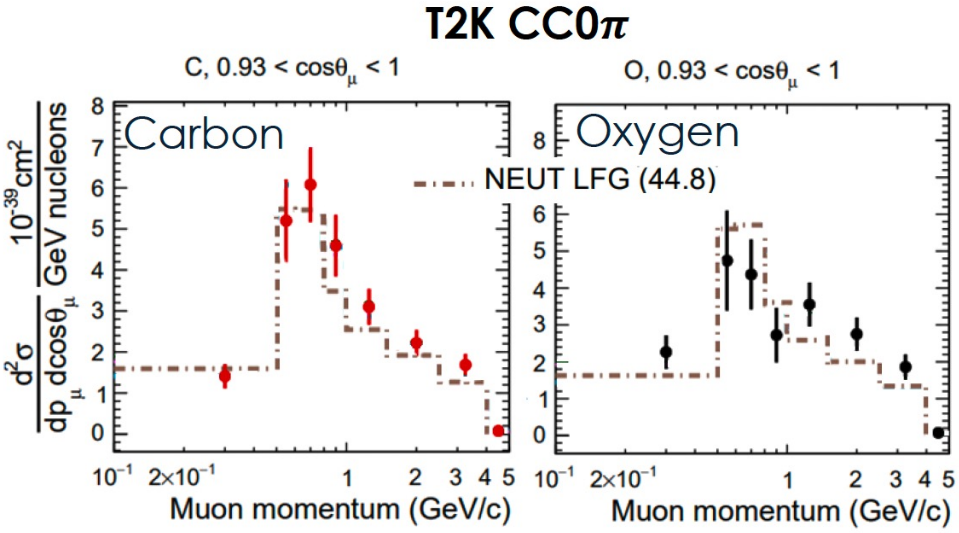


Nuclear models

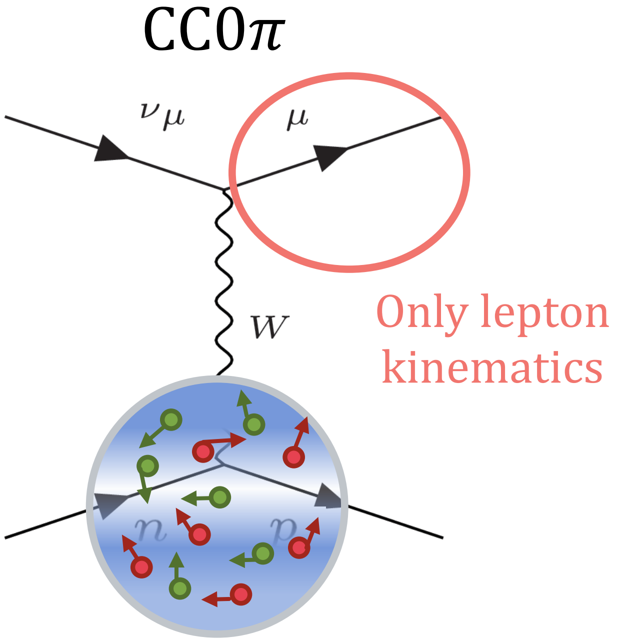


FSI

A success story

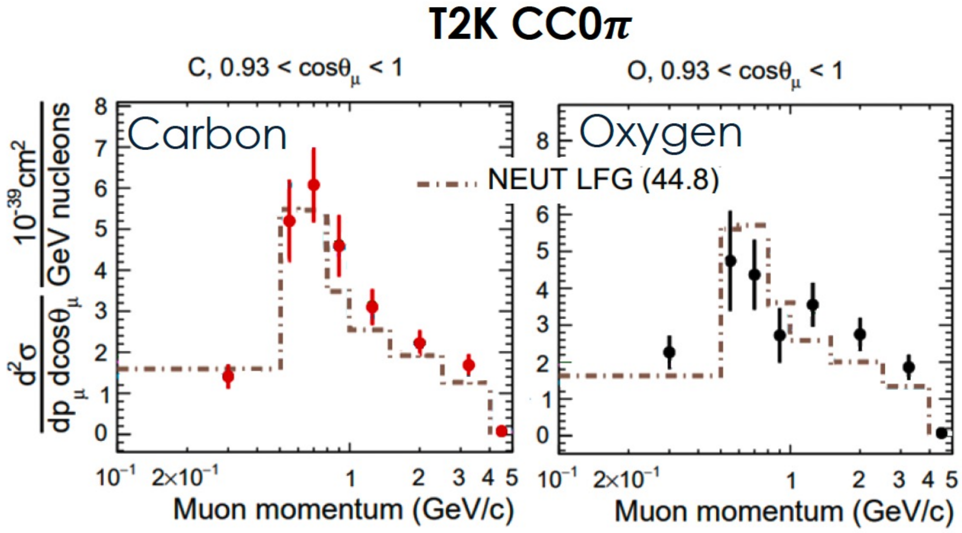


[Phys.Rev.D 101 (2020) 11, 112004]

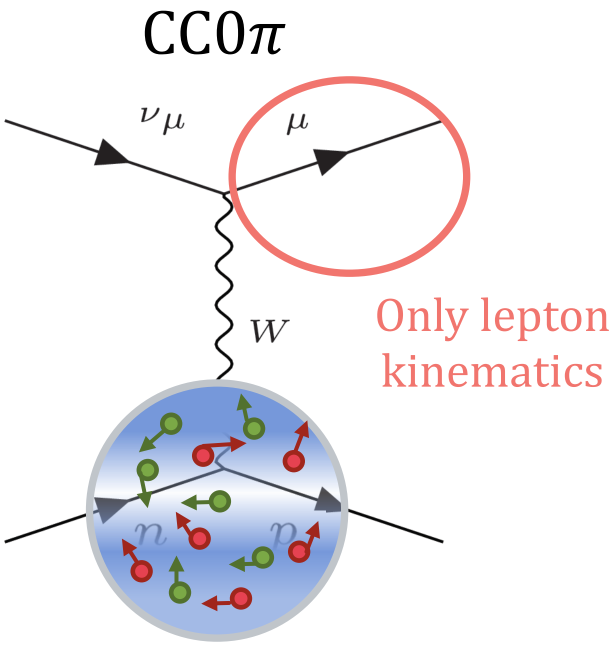


Generators do a (reasonably) good job at predicting the cross-section for **inclusive** measurements

A success story



Phys.Rev.D 101 (2020) 11, 112004

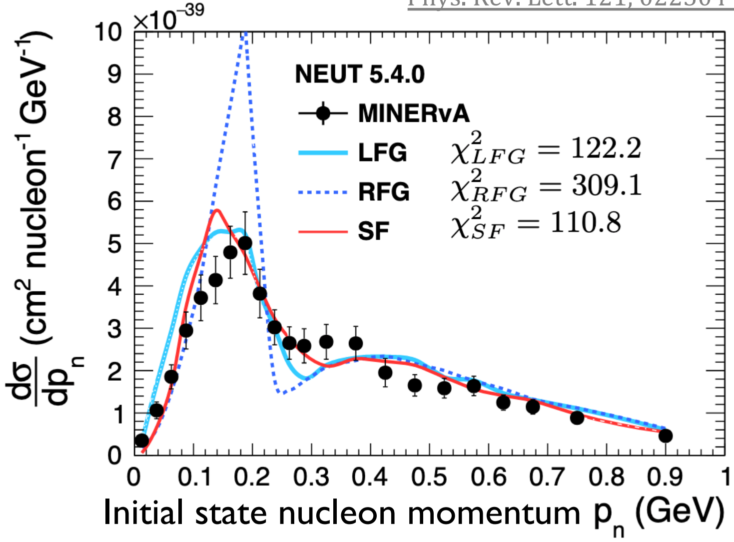


Generators do a (reasonably) good job at predicting the cross-section for **inclusive** measurements

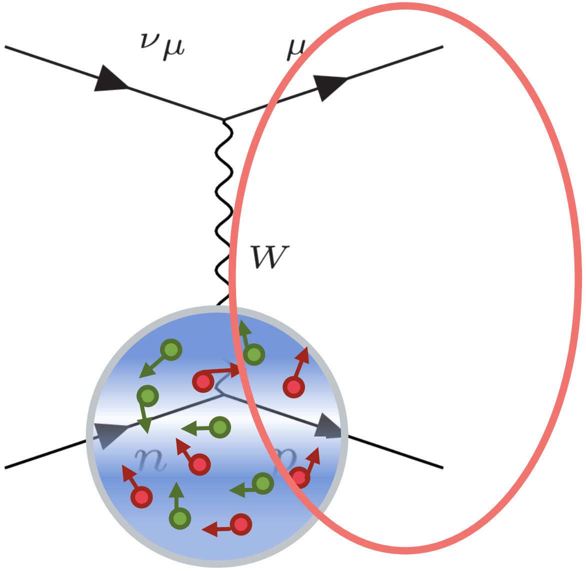
…except at low q_0 (~15% of events) – **more on that later!**

A success story?

arXiv:1810.0603
Phys. Rev. Lett. 121, 022504 (2018)



CC0π



But **none of them** offer a good quantitative prediction for (semi-)exclusive measurements

Lepton+hadron kinematics

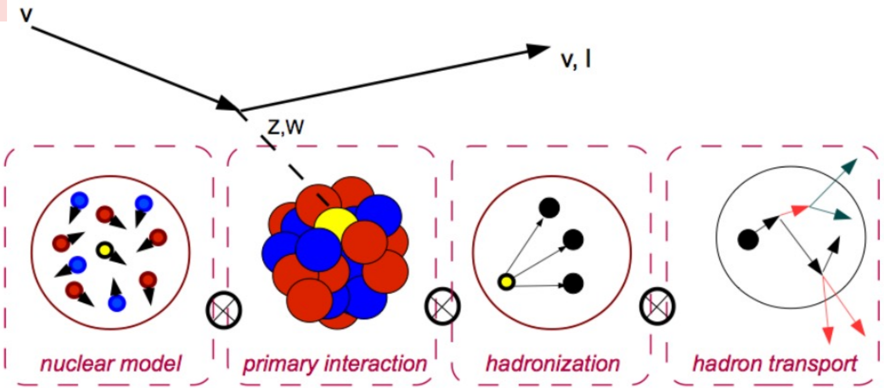
Reaching the limits of our approximations

- Generators (often) factorize the process based on the plane wave impulse approximation (PWIA)
  - IA – the neutrino interacts with an isolated nucleon.
  - PW – the final state nucleon exits the nucleus as a plane wave.

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

Nuclear spectral function

Single nucleon dynamics



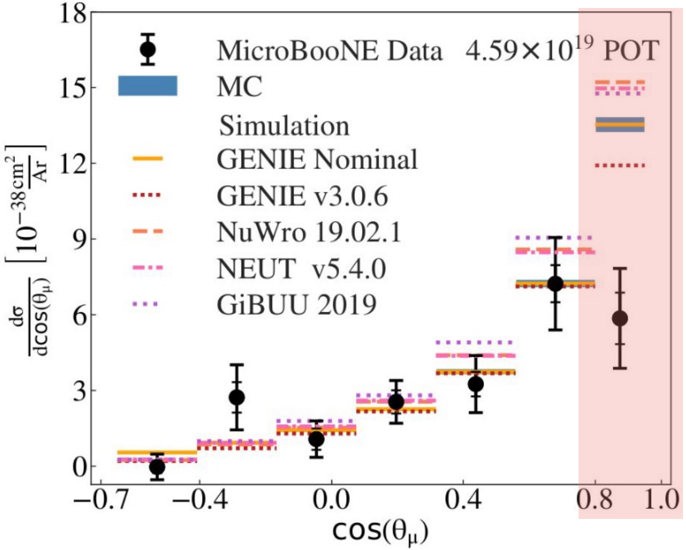
✗ Nucleon correlations added in an ad-hoc way

✗ FSI modelled through semi-classical cascades

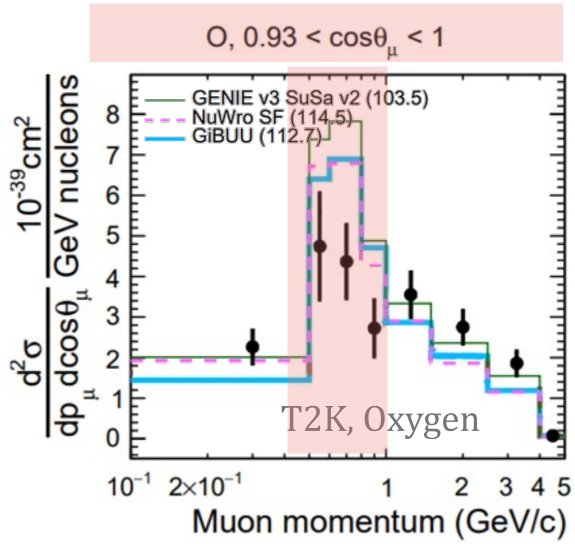
How bad is it?

Model disagreement

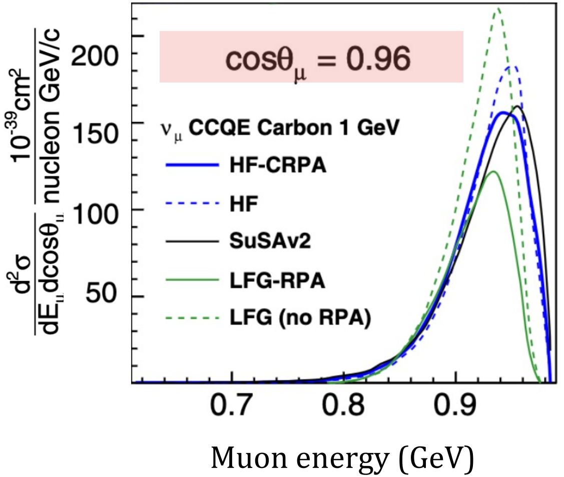
<u>*Phys.Rev.Lett.* 125 (2020) 20, 201803</u>



<u>*Phys.Rev.D* 101 (2020) 11, 112004</u>



<u>*Phys.Rev.D* 106 (2022) 7, 073001</u>



These effects show up at forward scattering angles (low energy transfer)

PWIA breaks down

Increasingly important for oscillation measurements

The curse of dimensionality

- We ask generators to give predictions for X dimensions
- But theory inputs are usually inclusive (Y dimensions)
- If X>Y – assign the kinematics for remaining X-Y dimensions using a best guess approach!

Channel	What we ask from the generators	What theorists give us
CCQE	$\frac{d^5\sigma}{dE_l dcos\theta_l dE_N dcos\theta_N dcos\theta_{lN}}$	$\frac{d^5\sigma}{dE_l dcos\theta_l dE_N dcos\theta_N dcos\theta_{lN}}$
2p2p	$\frac{d^8\sigma}{dq_0 dq_3 d\boldsymbol{p_1} d\boldsymbol{p_2}}$	$\frac{d^2\sigma}{dq_0 dq_3}$
Resonant single meson production	$\frac{d^8\sigma}{dq_0 dq_3 d\boldsymbol{p_N} d\boldsymbol{p_\pi}}$	$\frac{d^2\sigma}{dQ^2 dW}$
Deep inelastic scattering	$\frac{d^N\sigma}{dxdy \prod_i d\boldsymbol{p_i}}$	$\frac{d^2\sigma}{dxdy}$

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What can we do about it?

- Consolidate strong ties with the theory community
  - Essential to iterate with theory developments as we make new, more exclusive measurements
- Take more data – make more **exclusive** measurements!
- Continue improving our generators
  - More sophisticated models exist but are not implemented yet – **active effort!**
- In the meantime, include sufficient freedoms in our analyses
  - Flexibility is key!

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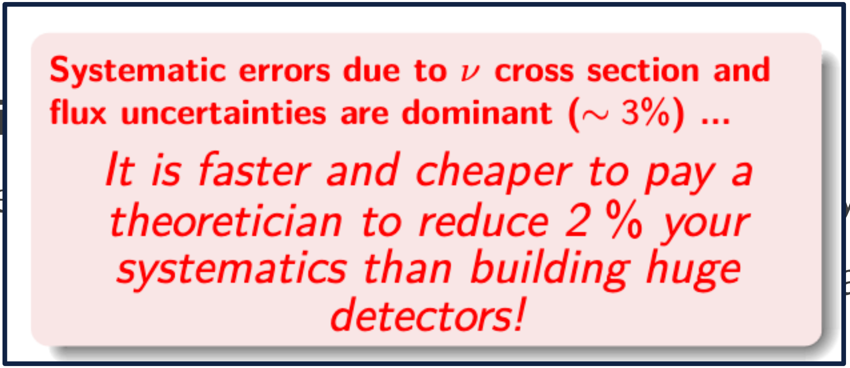
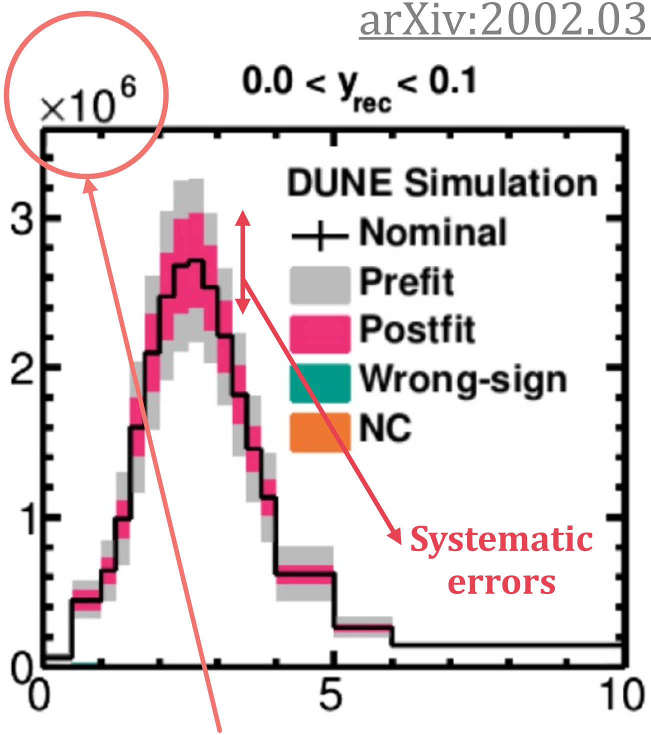


G. Megias @ NuInt 2018

Flexibility

arXiv:2002.03005

- Future experiments (DUNE/HK) will have unprecedented levels of statistics at the ND
  - Sensitive to the most minute details in our simulations
- To prepare for future analyses we need to include significantly more freedom than we do in current analyses



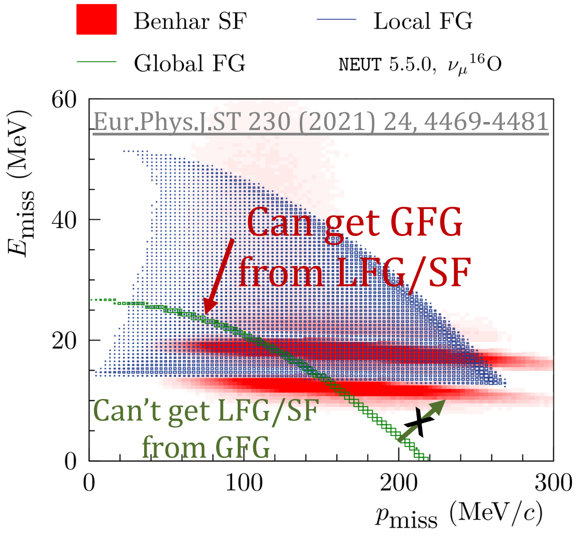
This plot **HAS** statistical error bars!

Flexibility

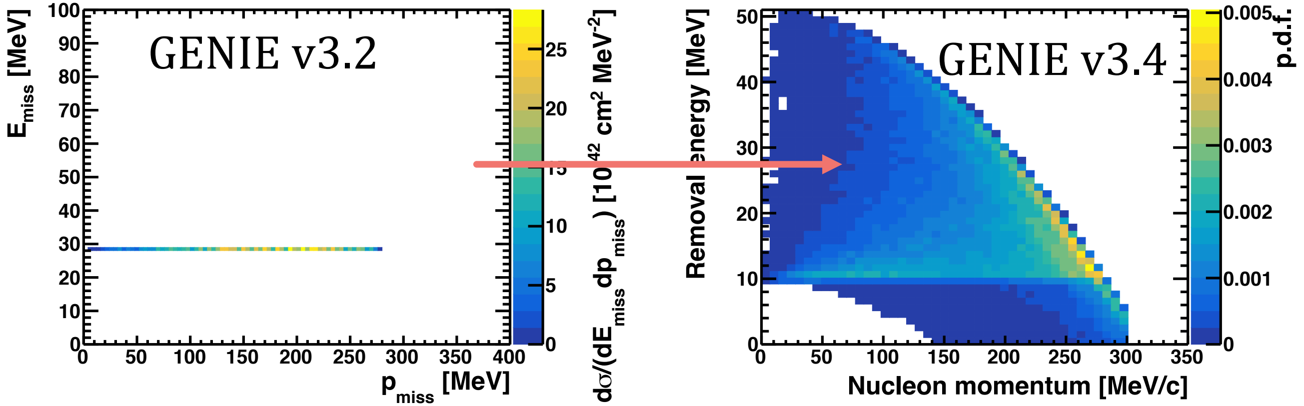
Example for nuclear model

Examples:

- Generating with an increased (but still motivated) phase space



Recent development:



Will be used for DUNE with new freedoms

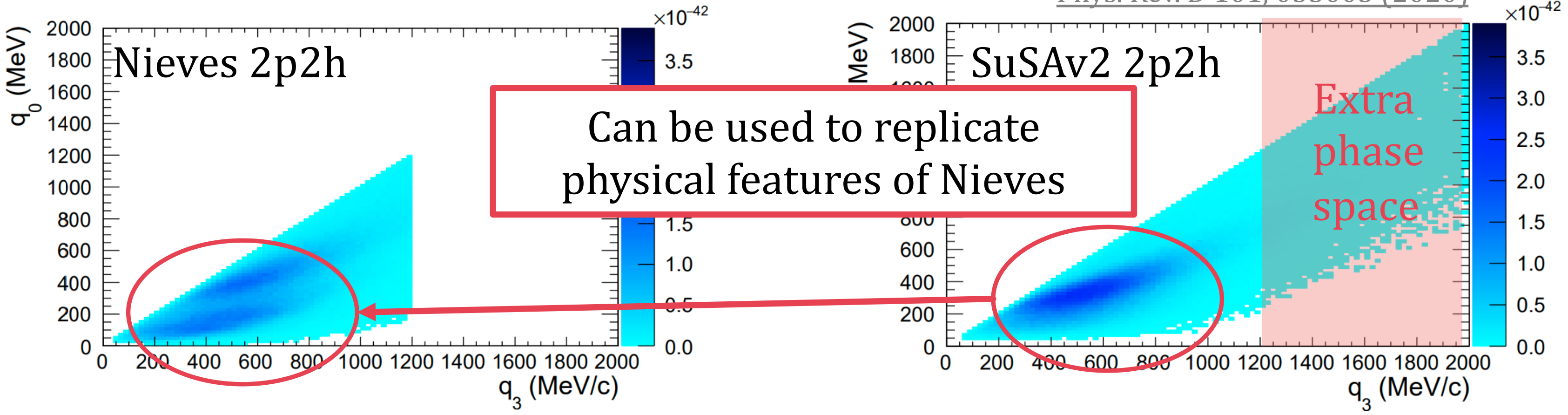
Flexibility

Example for 2p2h

Examples:

- Generating with an increased (but still motivated) phase space

Phys. Rev. D 101, 033003 (2020)



SuSA v2 has better agreement with electron scattering data

Sharing the tools

- Generators use different file formats and often different internal conventions
  - Experimental tools are usually built around one generator
  - Swapping generators is difficult
- Several efforts to mitigate this problem:

JINST **12** P01016
NUISANCE

  - Downstream: **NUISANCE** – widely used tool to sythesize output from all generators and confront them to cross-section measurements
    - But loses interfacing with internal generator flux drivers/detector geometry packages
  - Upstream: Ongoing effort to develop a common format (**NuHEPMC**) which all generators would use

Sharing the tools

- Increasingly important as oscillation experiments are starting to perform **joint fits**
  - T2K+SK atmospherics – easy to combine systematics since both use NEUT
  - T2K+NOvA – **extremely hard to combine systematics** because T2K uses NEUT and NOvA uses GENIE (but some of the physics is the same!)
- First step towards sharing tools: recent agreement reached between **DUNE+SBN experiment** (ICARUS and SBND) to use the **same** base model and systematic error tools
  - Easier since all are GENIE-based
  - Work is shared among all collaborations

Towards better communication

- NuInt workshops
  - Essential role in interfacing between theory and experimental/generator community
  - Next one in spring 2024 in Brazil
- NuSTEC
  - Collaboration between theorists and experimentalists – non exhaustive!
- Dedicated generator workshops:
  - TENSIONS, ECT*, Generators Workshop @ Fermilab…
- Communication with nuclear physics community
  - In particular, use of electron scattering data to benchmark models

Summary

- Neutrino-nucleus interaction uncertainties will be the dominant (limiting) source of systematic uncertainties for oscillation experiments
- The physics of these processes is complex and relies on neutrino interaction generator to provide a bridge between theory and experiments
- Current generators have come a long way, but are reaching the limits of their approximations
- Generators should be used to prepare for future experiments by including appropriate degrees of freedom in analyses
- Ongoing efforts to facilitate the communication between generators and their communities
- Imperative to ensure communication with theory community in this process

Thank you for your attention!

Supplementary slides

Neutrino interaction generators*

*Most widely used by accelerator-based experiments

GENIE
- Arguably most widely-used
- Large active development team (collaboration)
- Support for experiment integration
- Primarily used by Fermilab-based experiments
- Has its own reweighting framework

NuWro
- Wide range of available models
- Developed and maintained mostly by theorists
- Lack of reweighting framework
- Primarily used for comparisons to data

NEUT
- Originally developed for cosmic neutrino backgrounds for proton decay
- Primarily used by T2K, SK, HK
- Closed-source (may change soon!)
- Small development team
- Has its own reweighting framework

GiBUU
- Sophisticated quantum mechanical treatment of particle transport
- Very small development team
- Difficult to integrate with experimental suites

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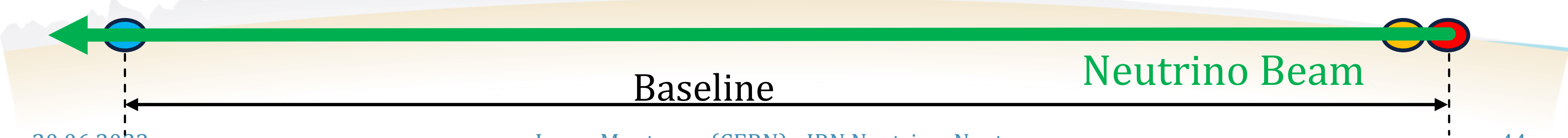
ACHILLES
- Developed mostly by theorists
- Takes inspiration from collider community experiments (FeynRules)
- Good agreement with electron scattering data

GiBUU

Long-baseline oscillation experiments

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

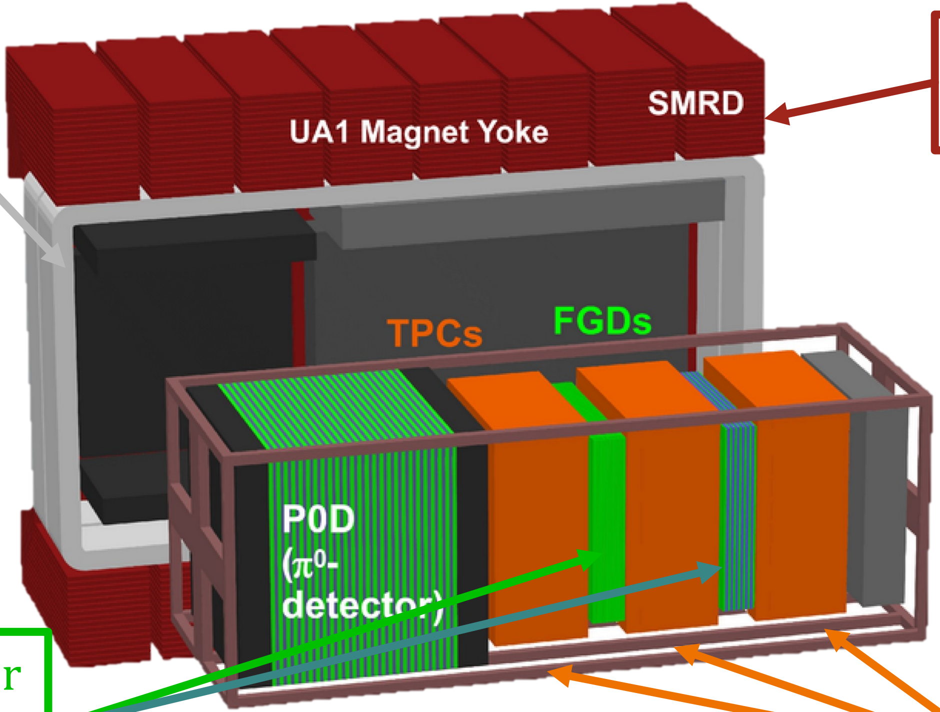


The T2K near detector at 280 m: ND280

ECals to veto backgrounds

Magnetized detector (separation by charge)

ν beam

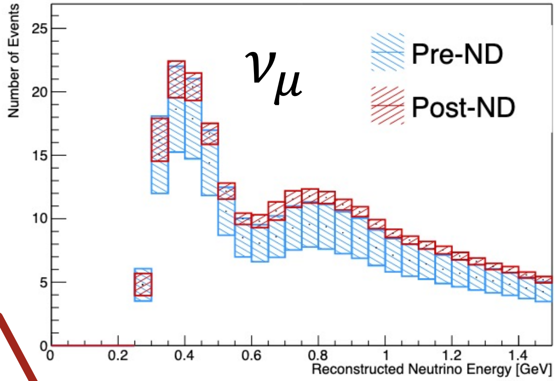


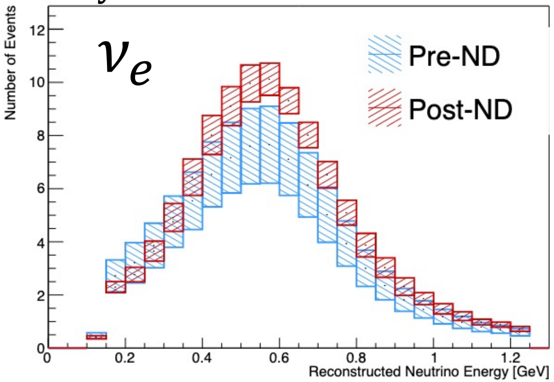
Plastic scintillator targets (+water bags in FGD2)

Time projection chambers for tracking and PID

Impact of ND constraint on FD spectra and errors

T2K preliminary





Systematic errors

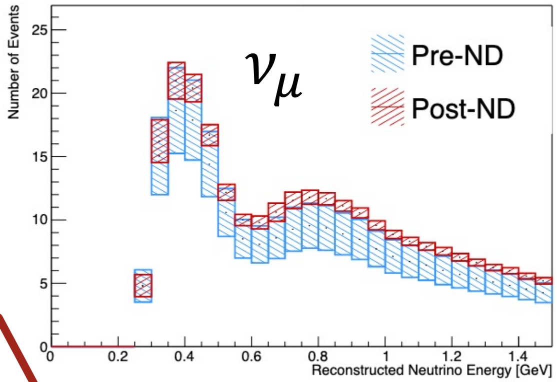
Before ND fit

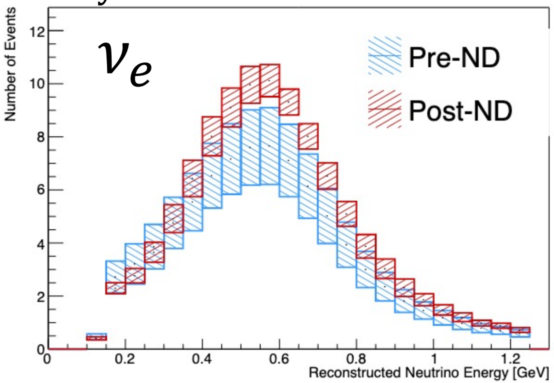
Error source (units: %)	1R FHC	1R RHC	MR FHC CC1π^+	1Re FHC	1Re RHC	1Re FHC CC1π^+	FHC/RHC
Flux	5.0	4.6	5.2	4.9	4.6	5.1	4.5
Cross-section (all)	15.8	13.6	10.6	16.3	13.1	14.7	10.5
SK+SI+PN	2.6	2.2	4.0	3.1	3.9	13.6	1.3
Total All	16.7	14.6	12.5	17.3	14.4	20.9	11.6

T2K Run 1-10, preliminary

Impact of ND constraint on FD spectra and errors

T2K preliminary





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	1R		MR	1R*e*			
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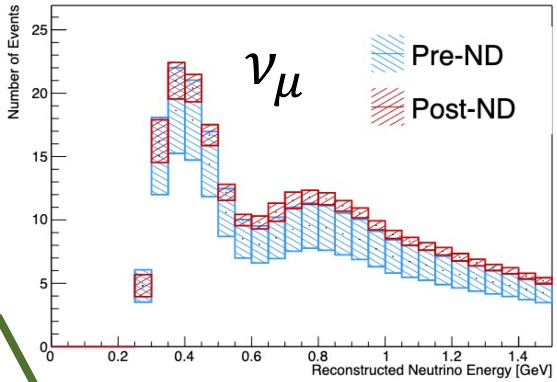

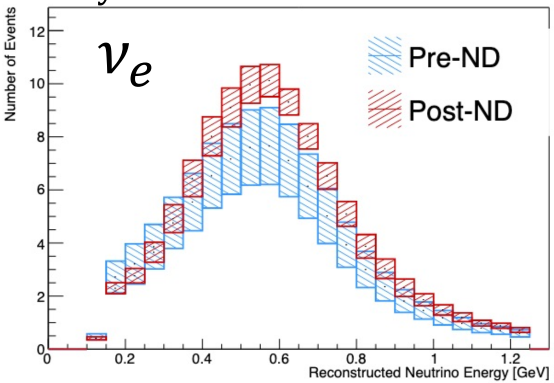

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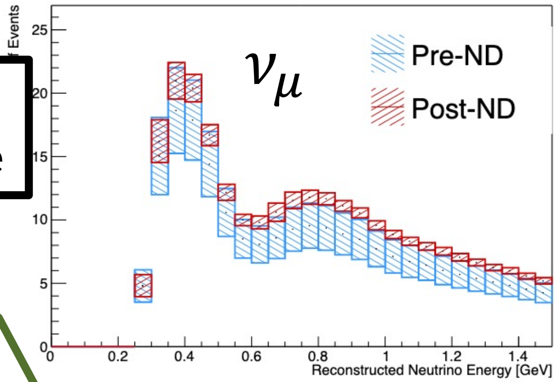
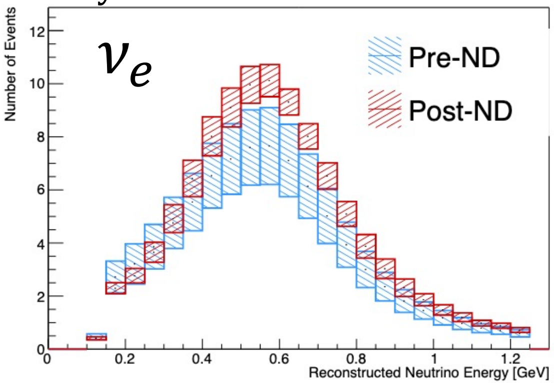
T2K Run 1-10, preliminary

Impact of ND constraint on FD spectra and errors

T2K preliminary

But also tuned spectrum shape





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T2K Run 1-10, preliminary

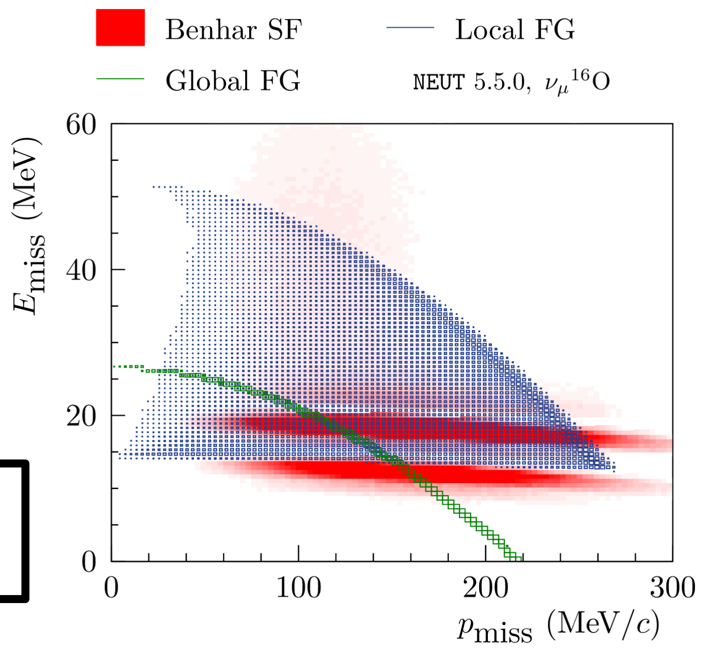
The nuclear ground state

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

E_{miss}
(~nucleon removal energy)

p_{miss}
(~nucleon momentum)

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



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

$$E_{miss} = \omega - T_p^{pre-FSI} - \Delta m_{n\to p} - T_{nucl.remnant}$$

The nuclear ground state

- Multiple ground state models are available in neutrino interaction generators

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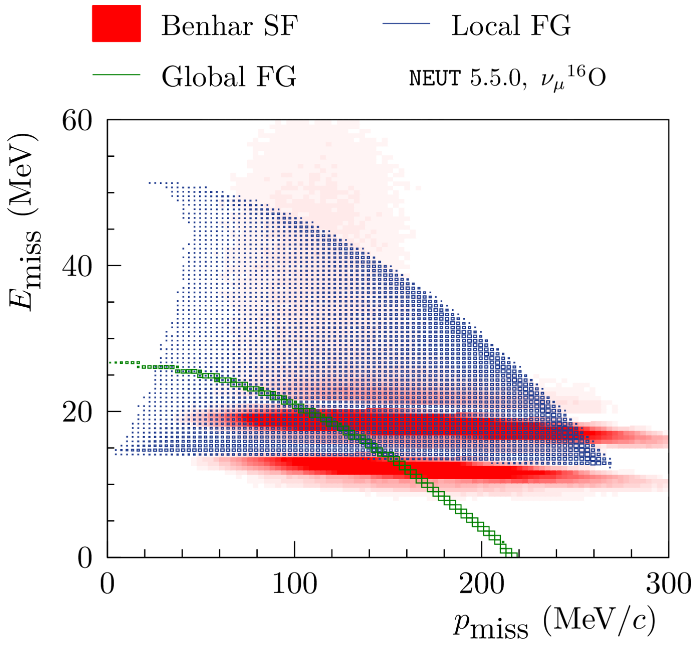

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The nuclear ground state

- 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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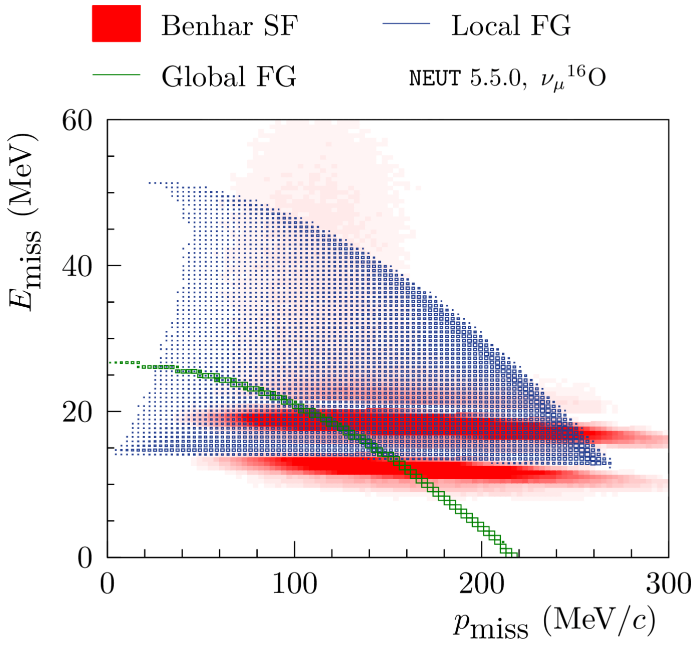

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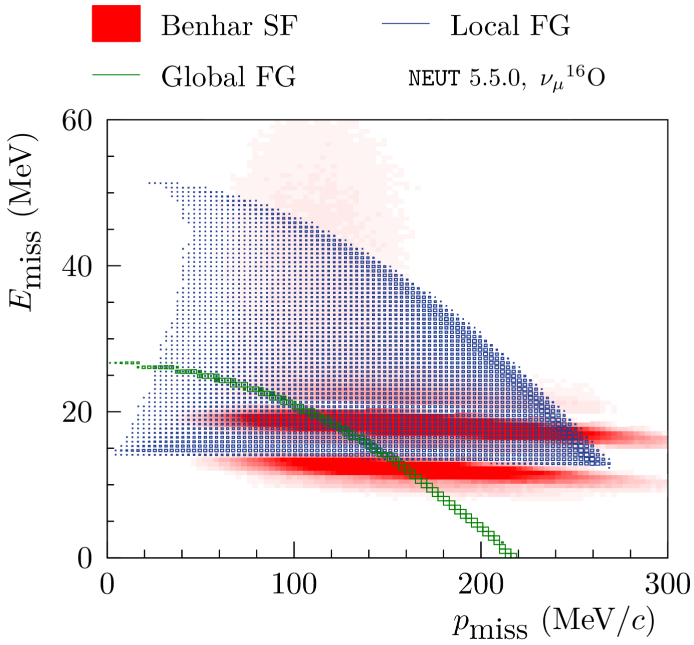

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  - Accounts for nuclear shell structure
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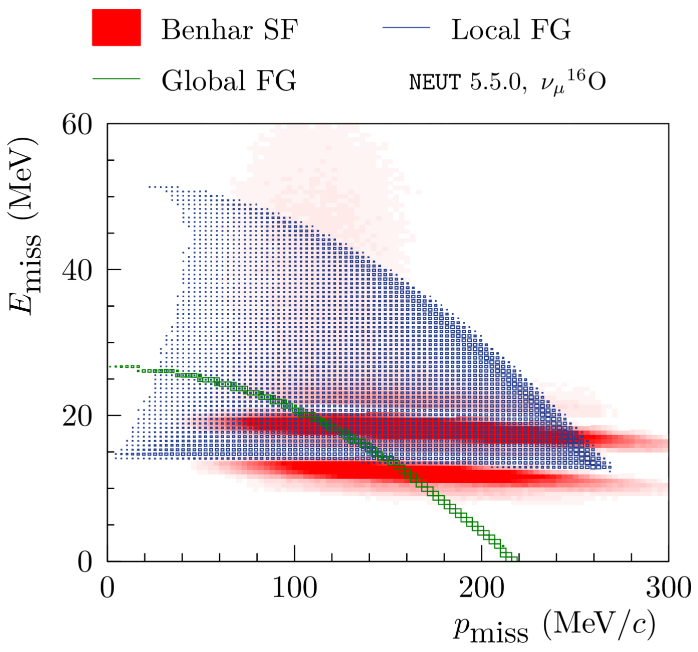

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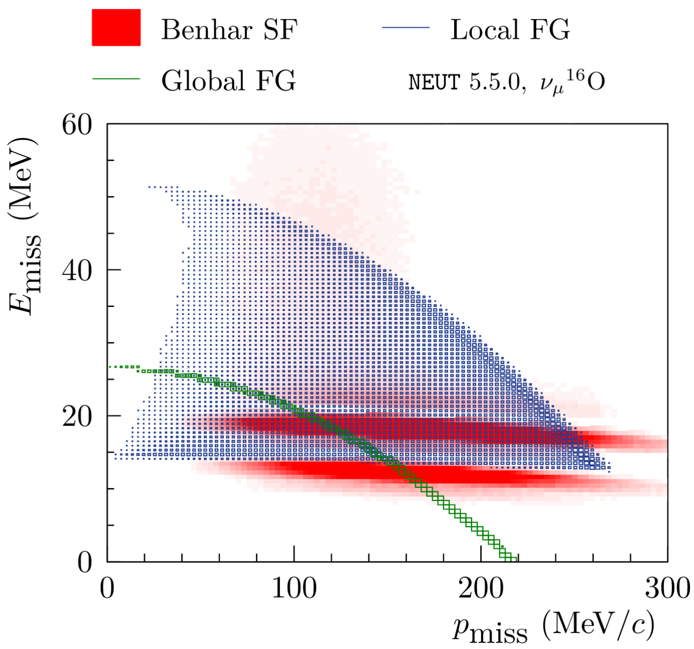
  - Good predictive power for final state particles (but not perfect!)
- More sophisticated models exist but are not yet implemented in generators (**ongoing work**)

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



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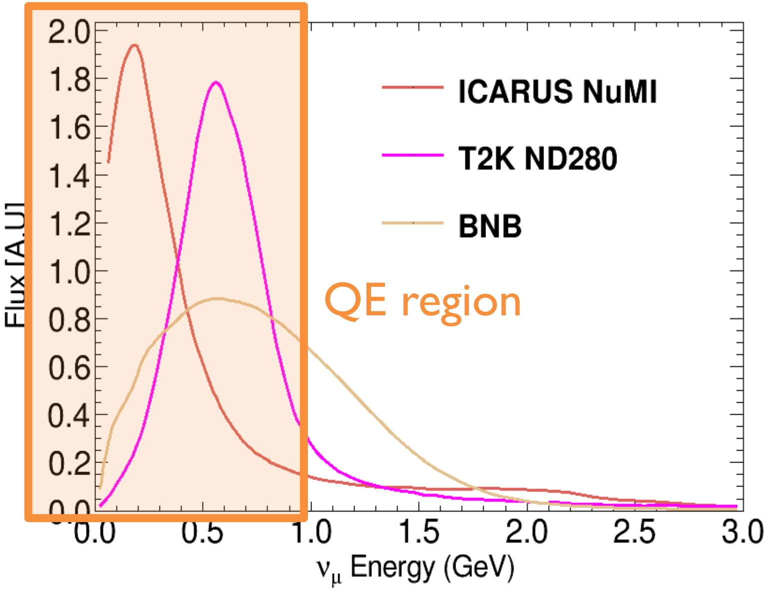
How does the nuclear ground state impact experiments?

- 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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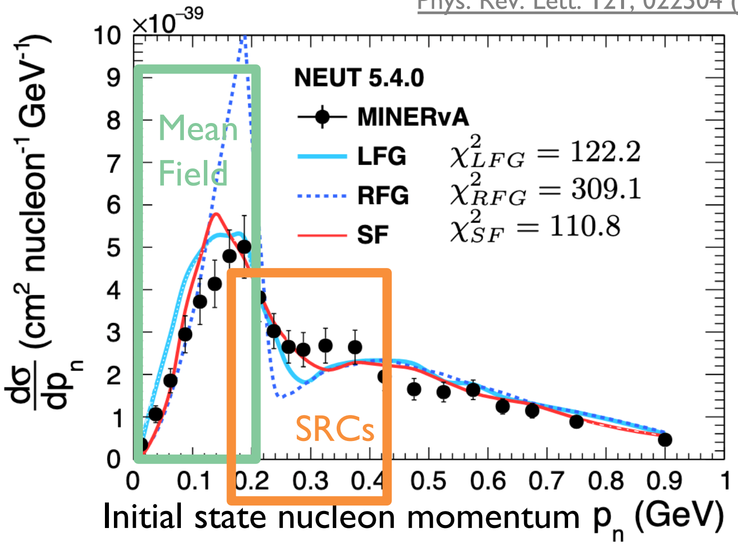
- Mismodelling the nucleon momentum alters **predictions on hadron kinematics**
  - Will be crucial for experiments sensitive to the hadronic side of the final state

arXiv:1810.0603

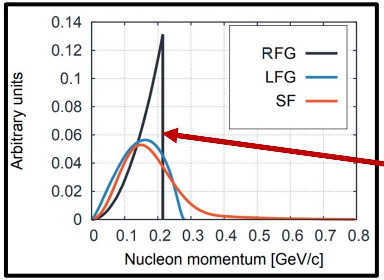
Phys. Rev. Lett. 121, 022504 (2018)



SRCs 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
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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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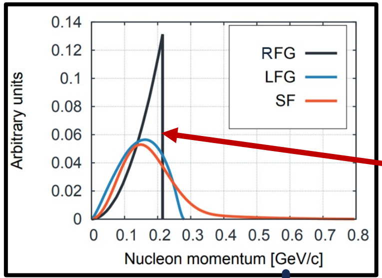

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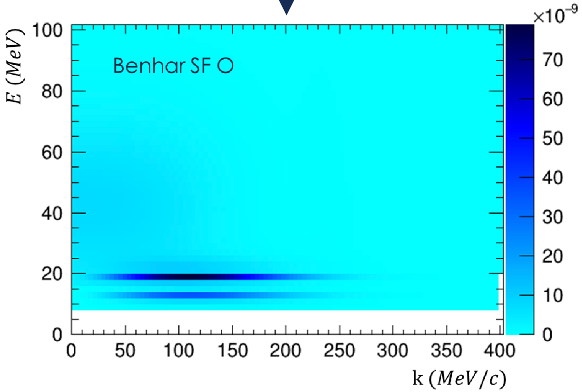
Change in nuclear model



Now incorporated here

The 50th Anniversary NEUTRINO 2022 Virtual Seoul May 30 (Mon) - June 4 (Sat), 2022

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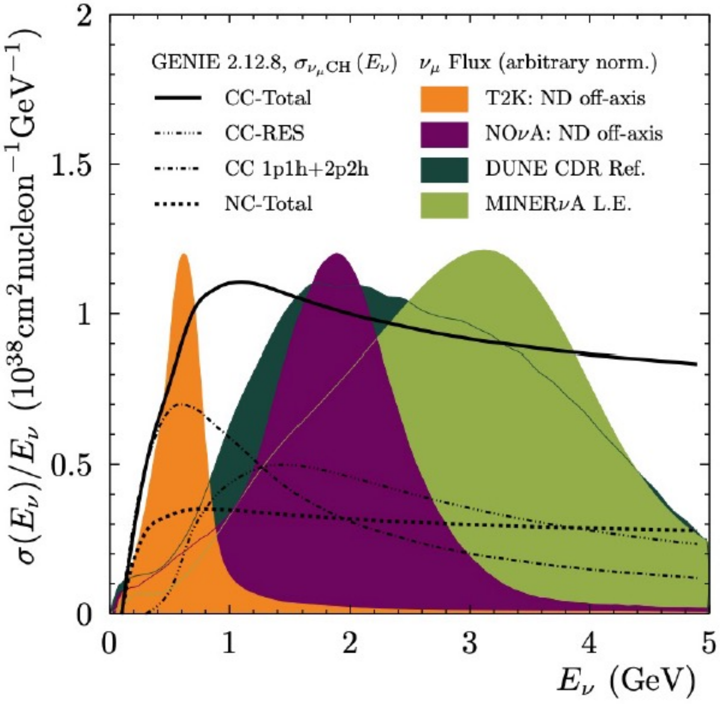
T2K Run 1-10, preliminary

Ongoing work on DUNE

- 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



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

Ongoing work on DUNE

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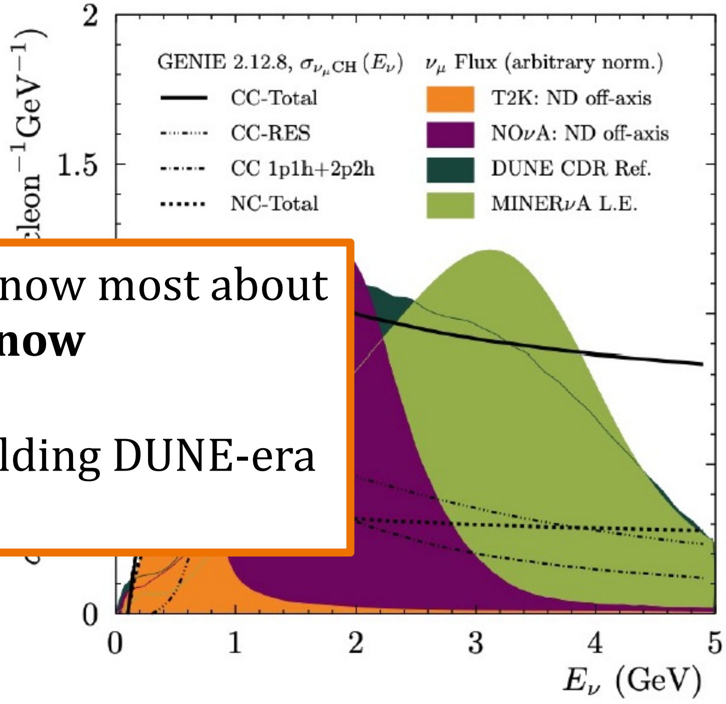
- At DUNE statis… to some of **the** … **differences** in…
- DUNE doesn't …
  - Need a **flexible model** which allows us to cover the variations suggested by other models and measurements
- Need a model which is adapted for both oscillation studies and BSM physics

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

Perfect starting point for building DUNE-era analyses



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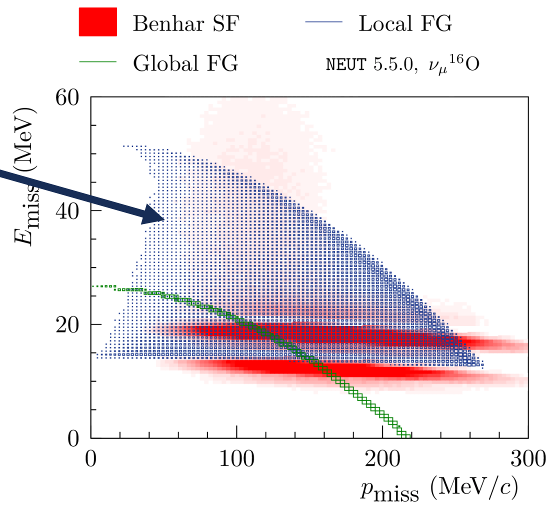
But QE interactions are **those which we can measure best**
Remain important for **precision measurements**

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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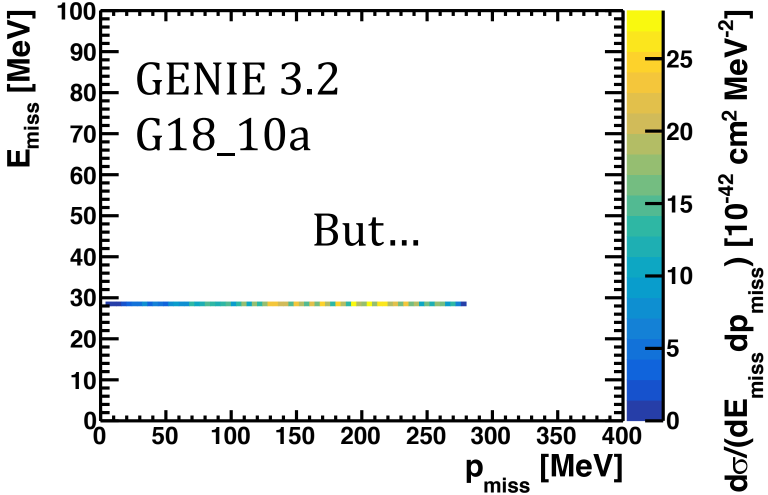
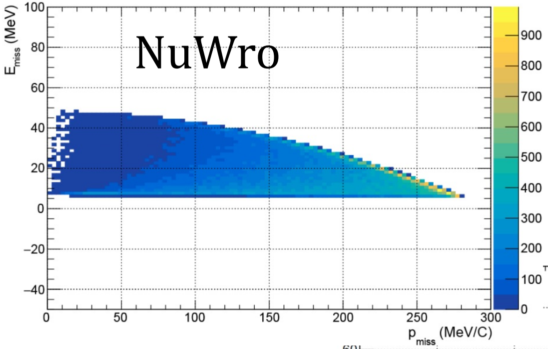
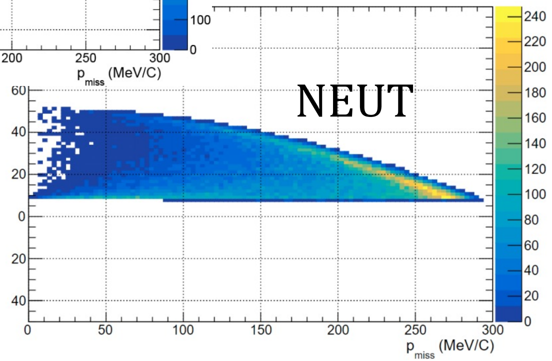
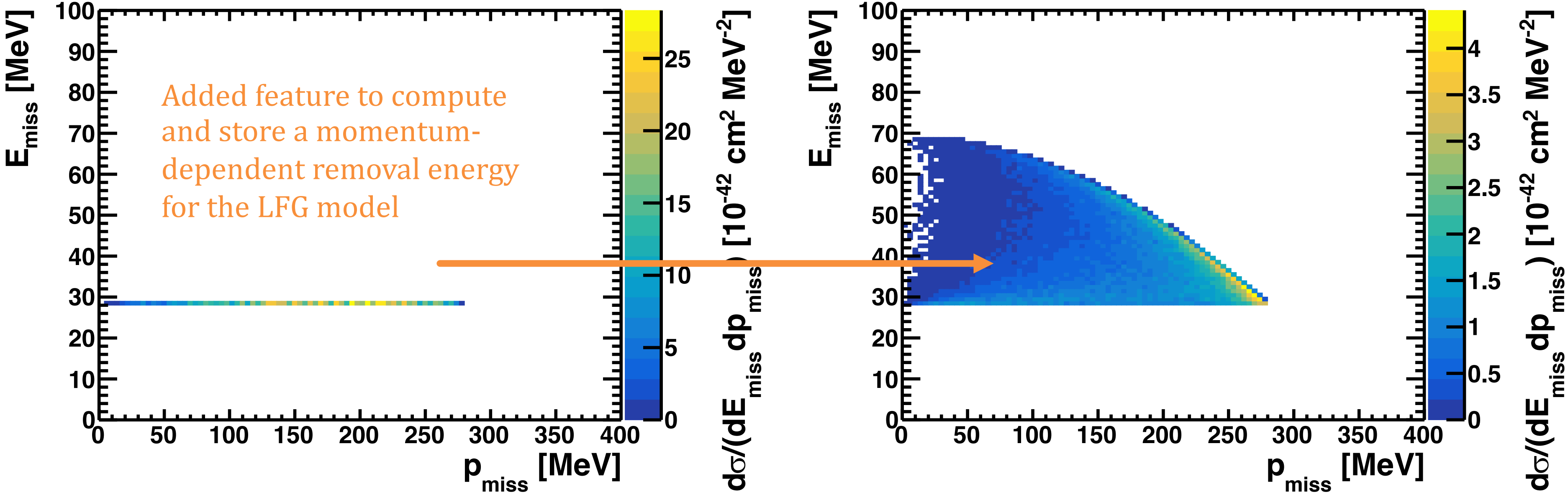






Expanding the ground state phase space

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



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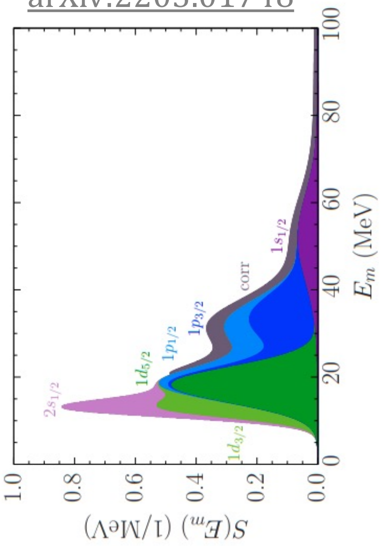
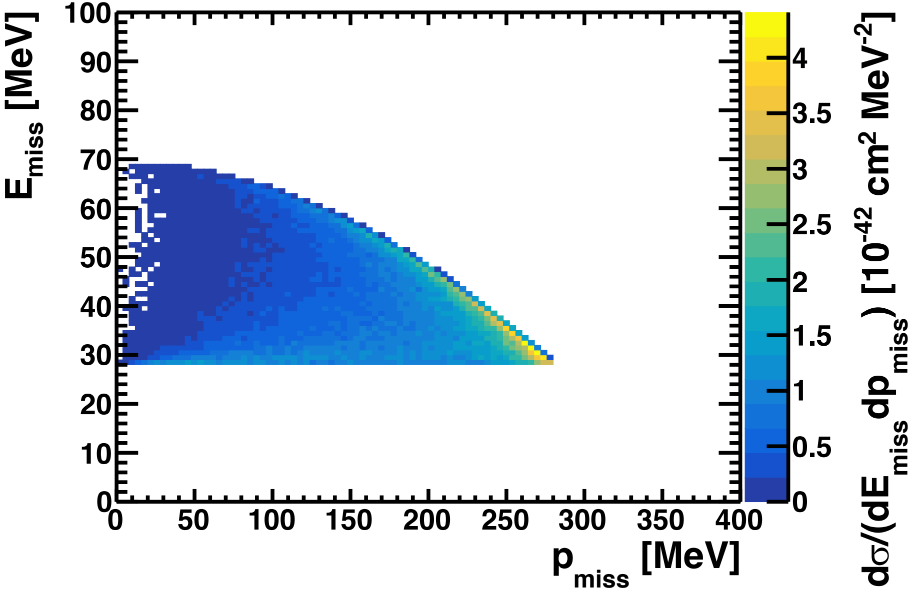
Covers relevant energies for Argon nuclear shells!

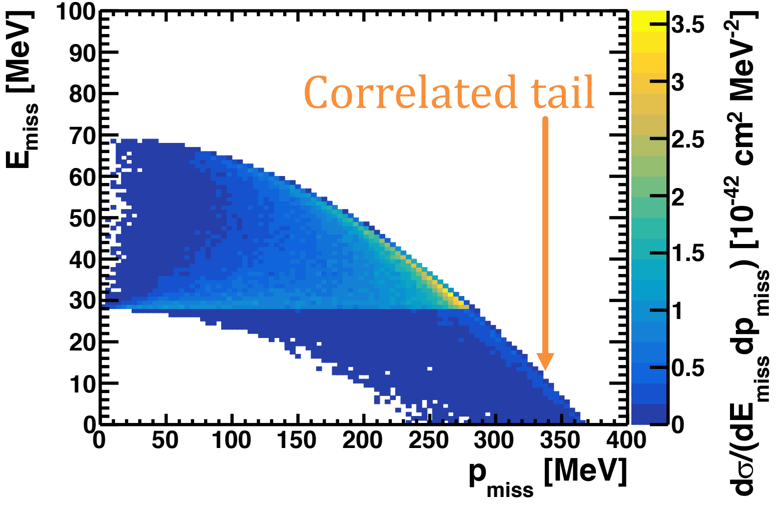
arXiv:2203.01748



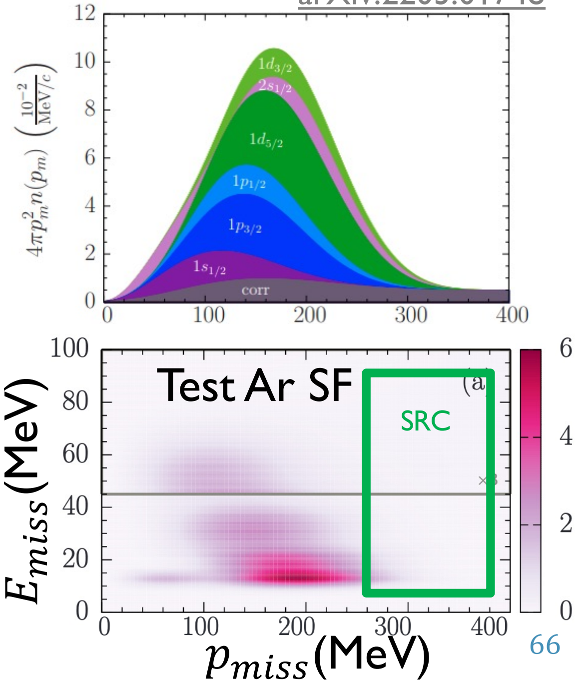


Expanding the ground state phase space

- Will be used in conjunction with "correlated tail" feature

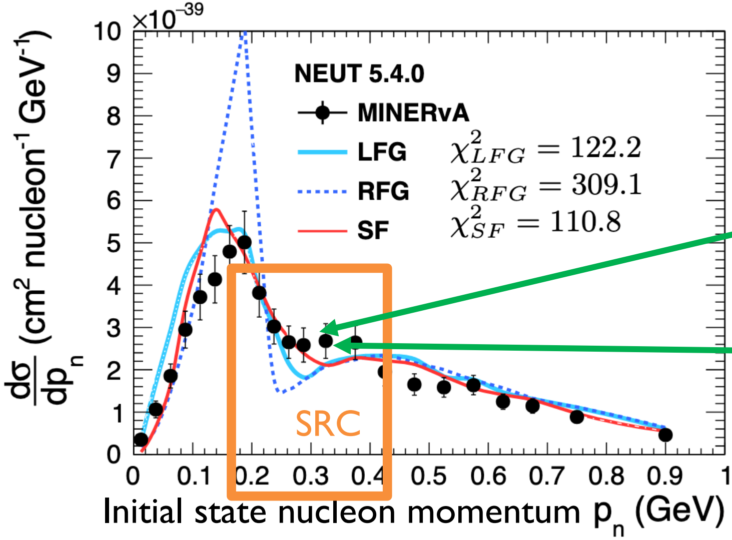


arXiv:2203.01748



Expanding the ground state phase space

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



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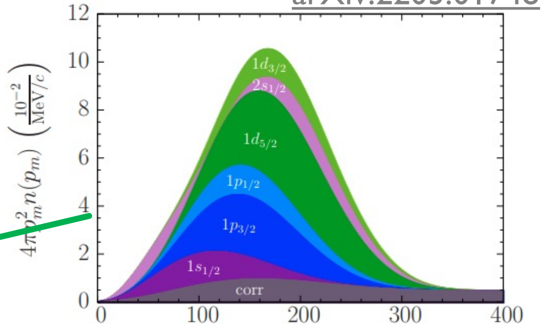
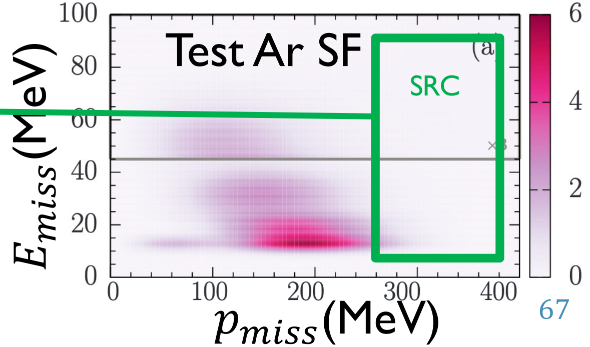




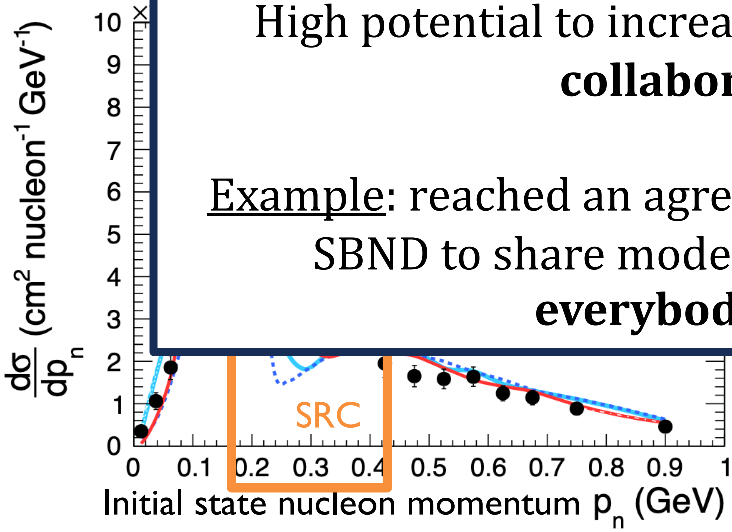
Expanding the ground state phase space

- 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**!

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



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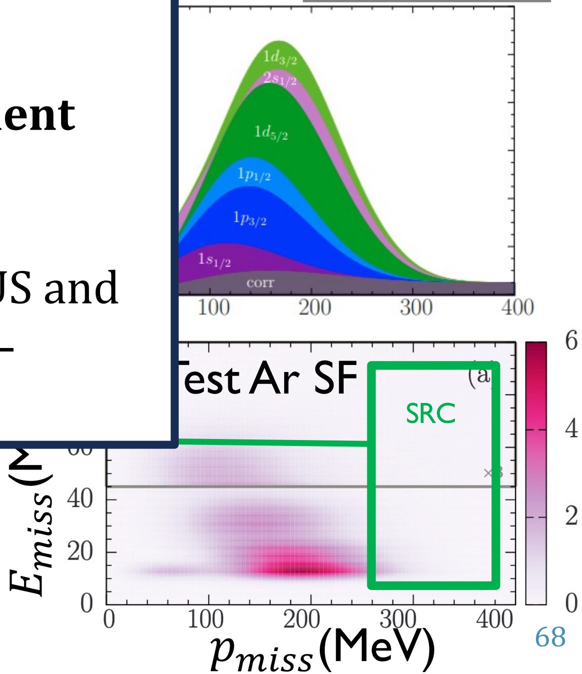

Beyond the nuclear ground state

- 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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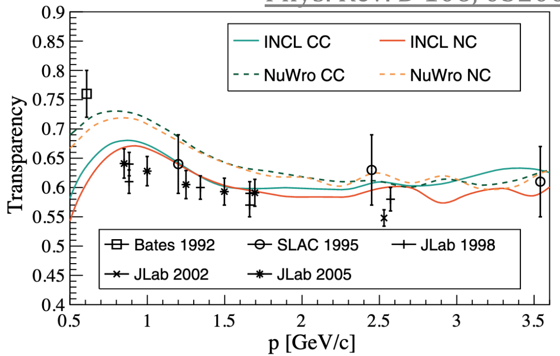
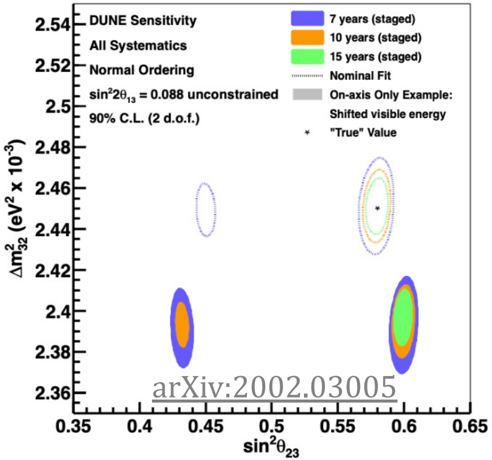
Phys. Rev. D 106, 032009



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

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



arXiv:2002.03005

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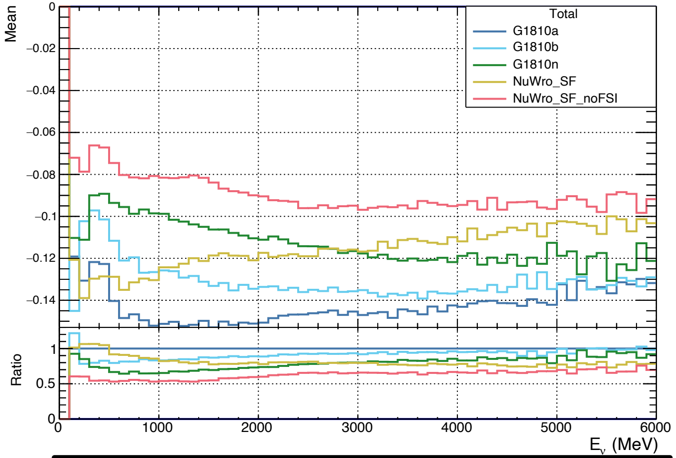

Mean of neutrino energy bias as a function of neutrino energy for DUNE flux
High model disagreement

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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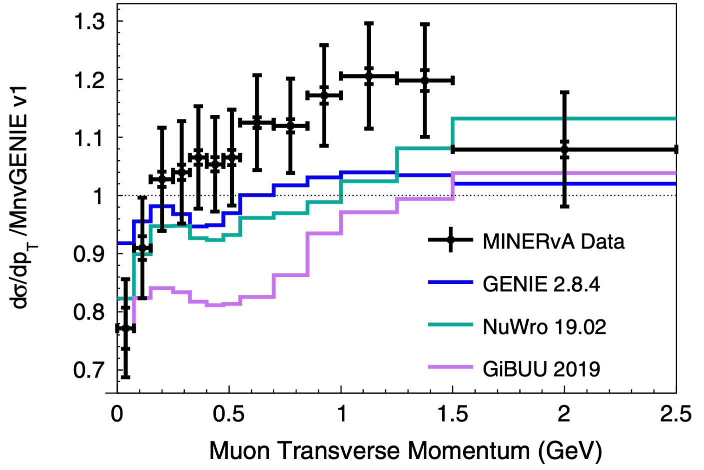
  - Cross-section energy dependence
  - Resonant interactions and the deep inelastic regime

Phys. Rev. D 101, 112007



DIS-enriched measurement from MINERvA
High model disagreement

Beyond the nuclear ground state

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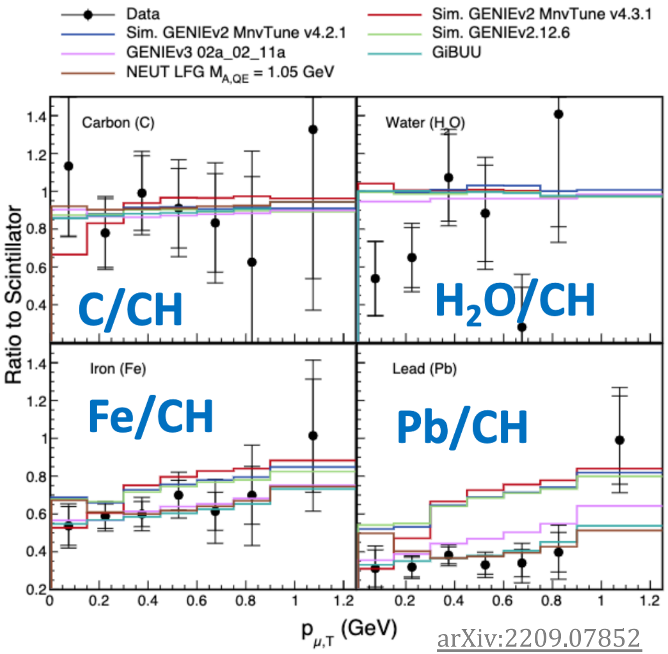
  - How nuclear effects vary with atomic number



arXiv:2209.07852

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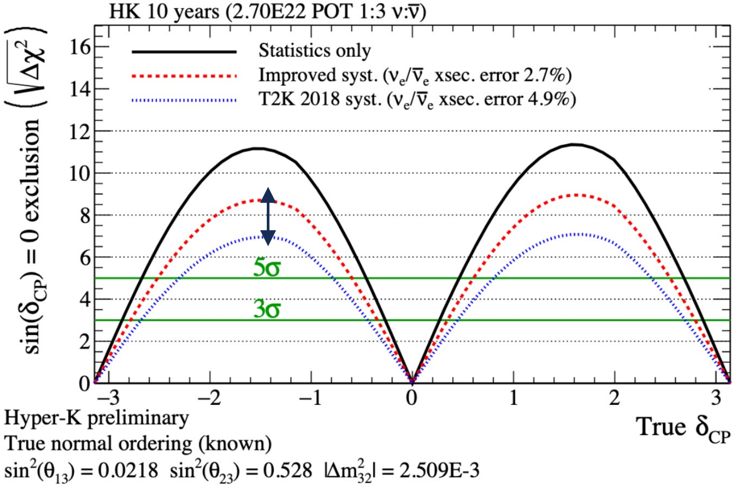
- But the work is just getting started! We need to understand:
  - Final state interactions (hadron transport inside the nucleus)
  - Cross-section energy dependence
  - Resonant interactions and the deep inelastic regime
  - How nuclear effects vary with atomic number
  - Differences in ν_e vs ν_μ cross-sections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



Majority of the systematic error contribution

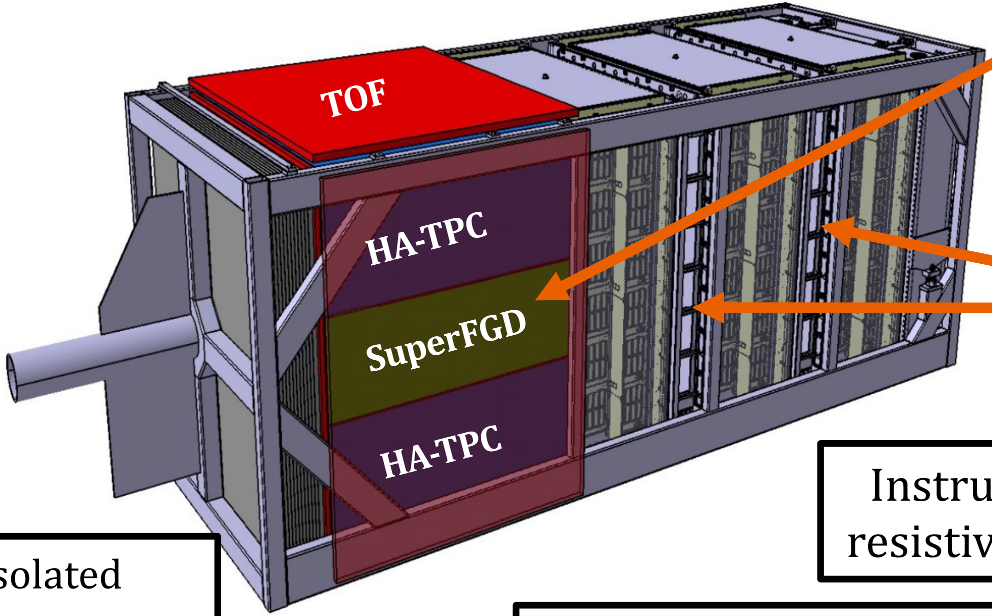
*Leading uncertainties from nuclear ground state model!

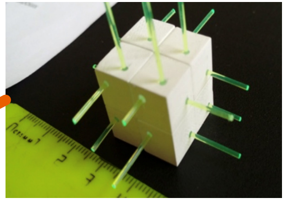
The T2K ND280 Upgrade project

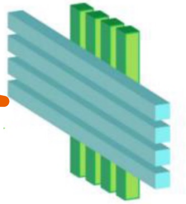
ND280 Upgrade TDR

Replace P0D by new suite of detectors

>100 researchers
22 institutes
7 countries







2M 1cm^3 optically isolated scintillator cubes

2x fiducial massof current FGDs

Instrumented with resistive Micromegas

150 ps timing resolution for PID

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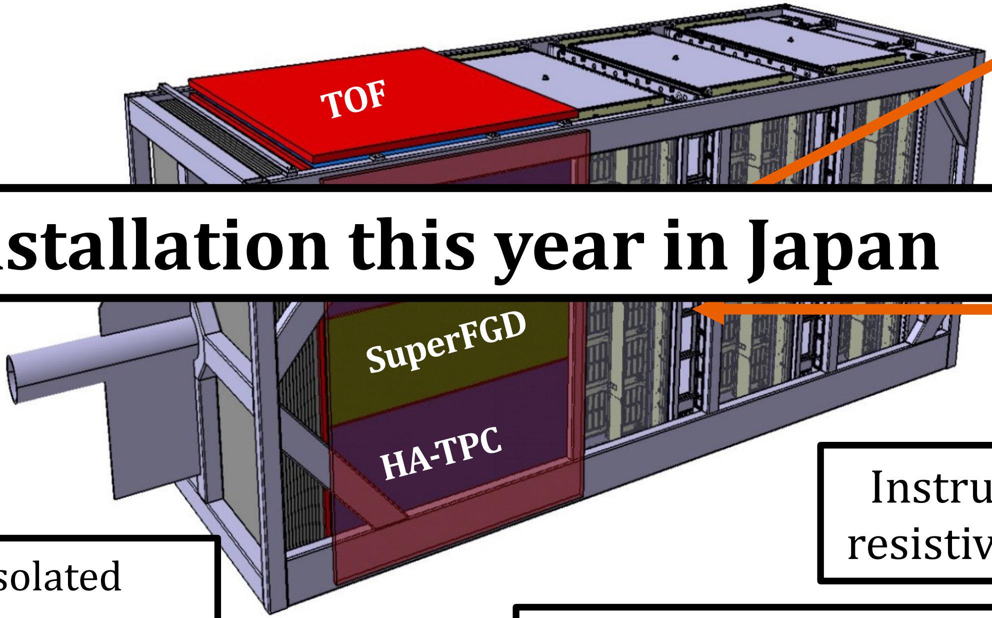
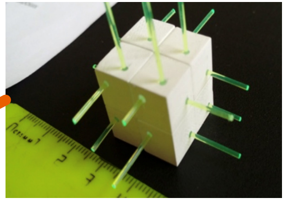
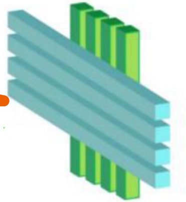






Installation this year in Japan

2M 1cm^3 optically isolated scintillator cubes

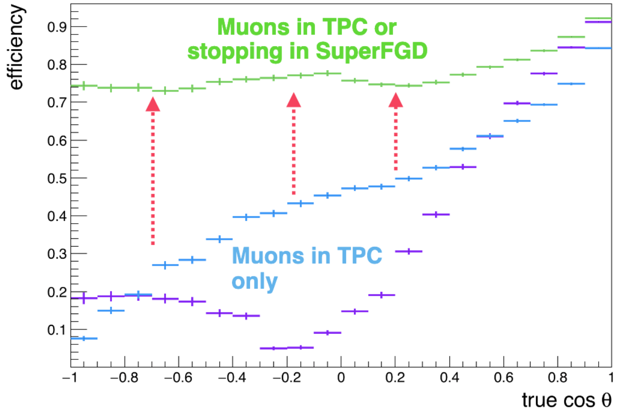
2x fiducial massof current FGDs

Instrumented with resistive Micromegas

150 ps timing resolution for PID

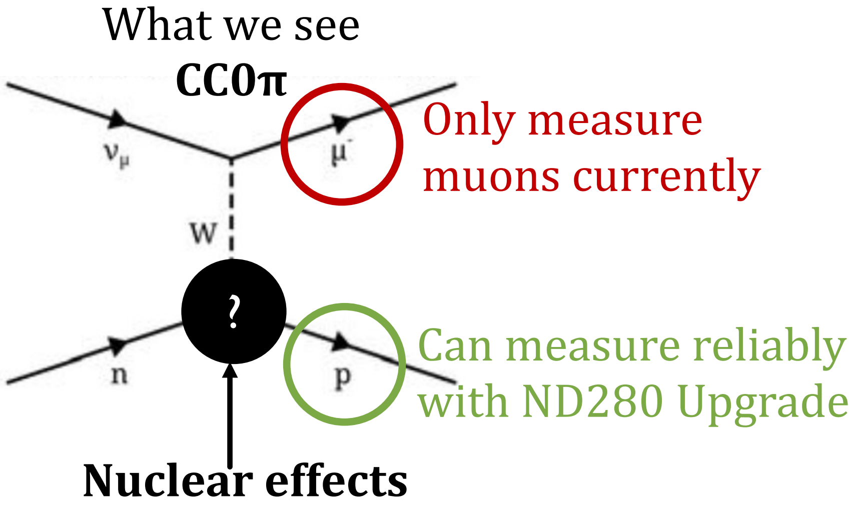
Capabilities of the ND280 Upgrade

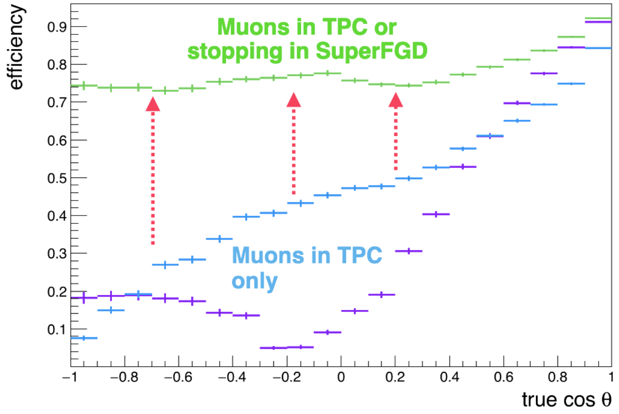
- Full 4π angular coverage (same as SK)

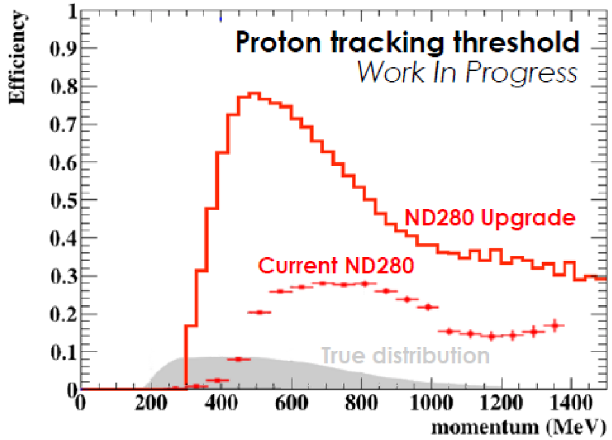


Capabilities of the ND280 Upgrade

- Full 4π angular coverage (same as SK)
- Low momentum thresholds for detecting **protons**
  - Can realiably measure full final state in neutrino interactions!

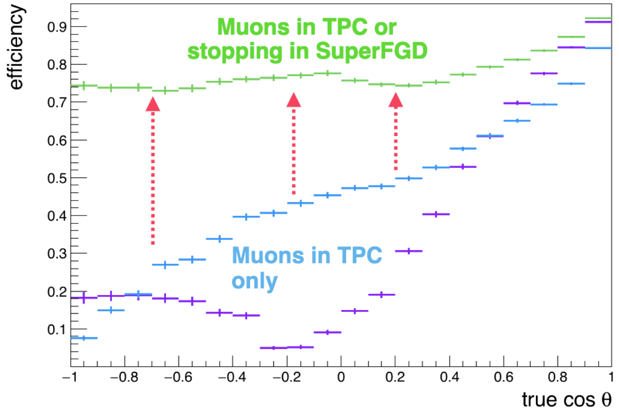


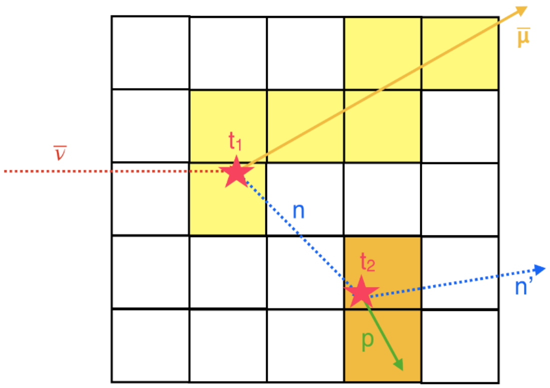




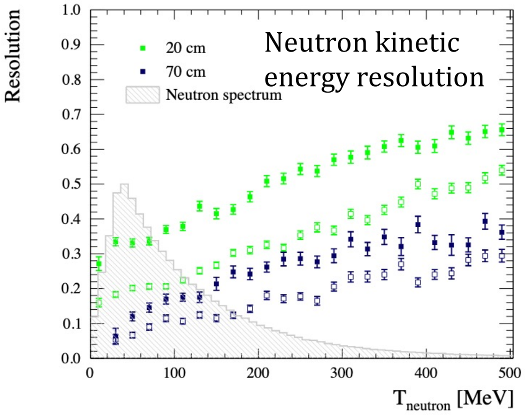
Capabilities of the ND280 Upgrade

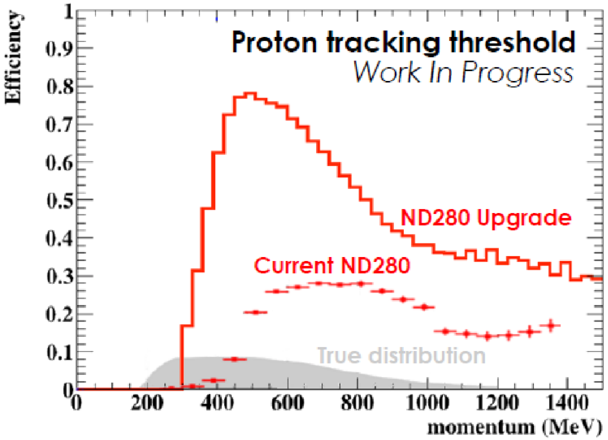
- Full 4π angular coverage (same as SK)
- Low momentum thresholds for detecting **protons**
  - Can realiably measure full final state in neutrino interactions!
- Capability to measure (not just tag!) **neutrons**
  - Unmatched by Liquid Argon TPCs





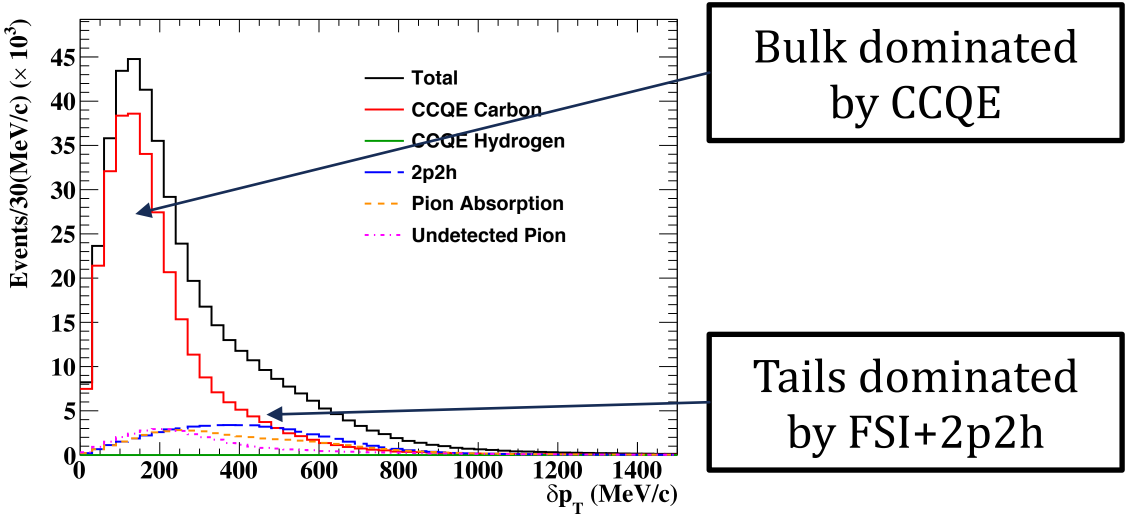
Phys. Rev. D 101, 092003



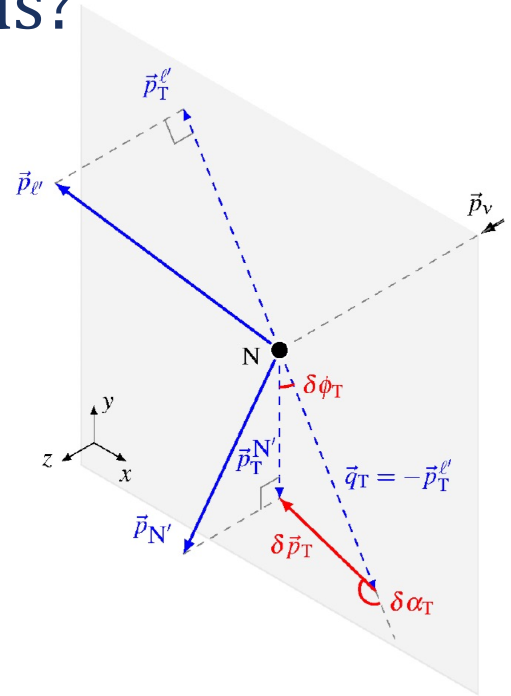


What can the ND280 Upgrade do for us?

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



Phys. Rev. D 105, 032010



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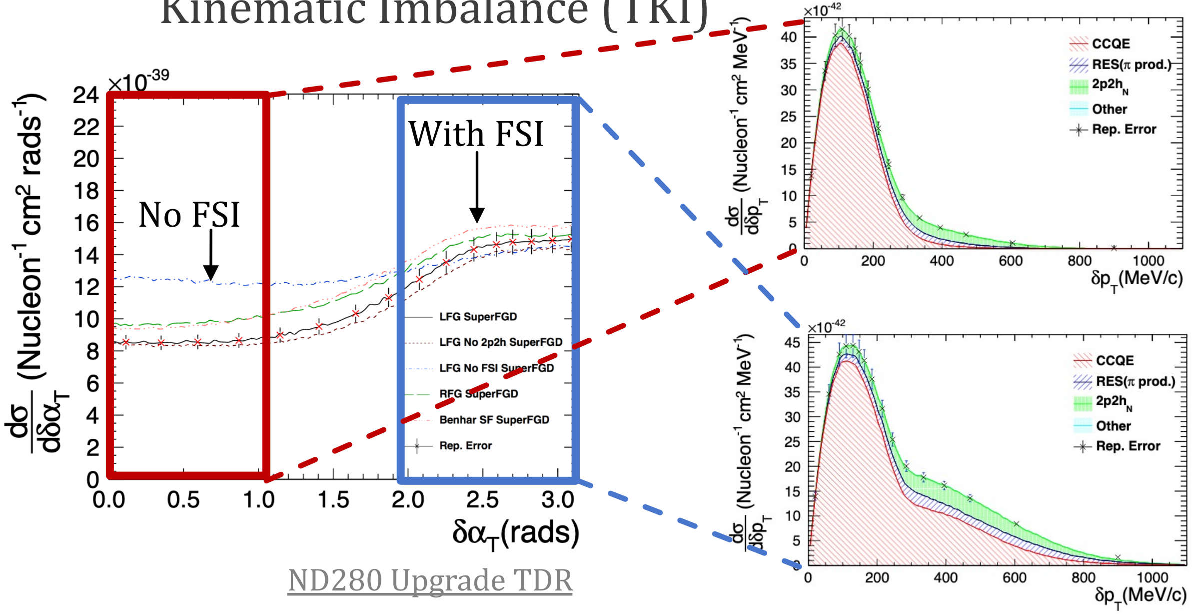
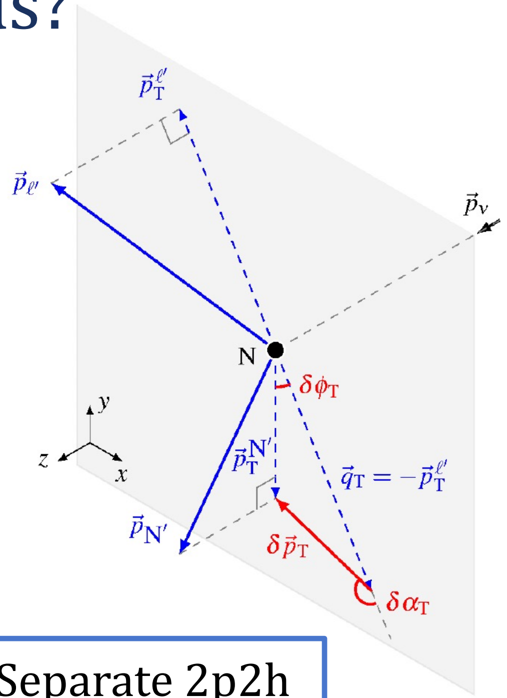


ND280 Upgrade TDR



Separate 2p2h and FSI effects!

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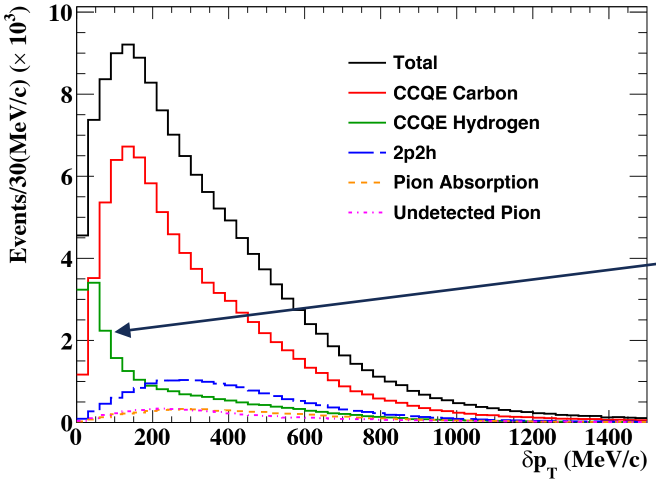
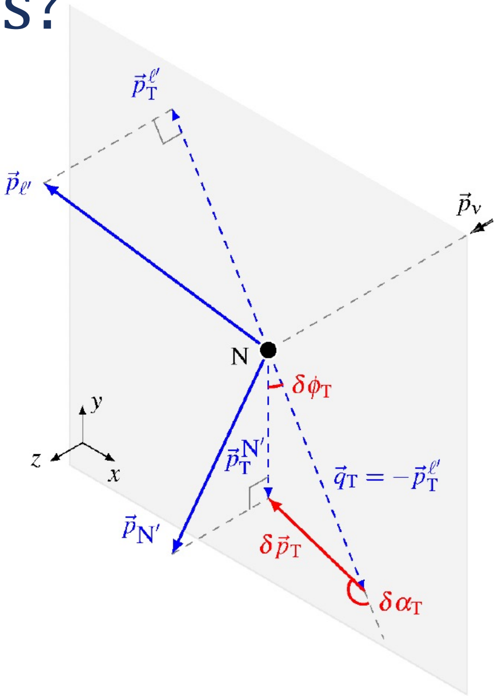


Phys. Rev. D 105, 032010
Phys. Rev. D 101, 092003

Antineutrinos:
Peak from interactions on hydrogen

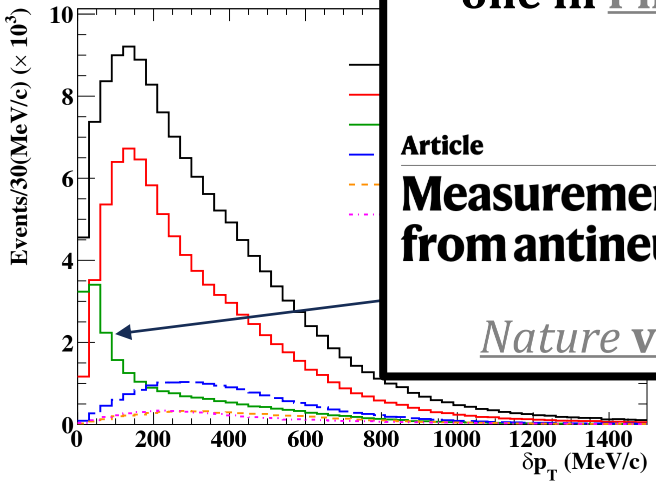
No nuclear effects

Possible thanks to **neutron detection**!



What can the ND280 Upgrade do for us?

- Access to **exclusive** variables
  - E.g. probe nu… Kinematic I…



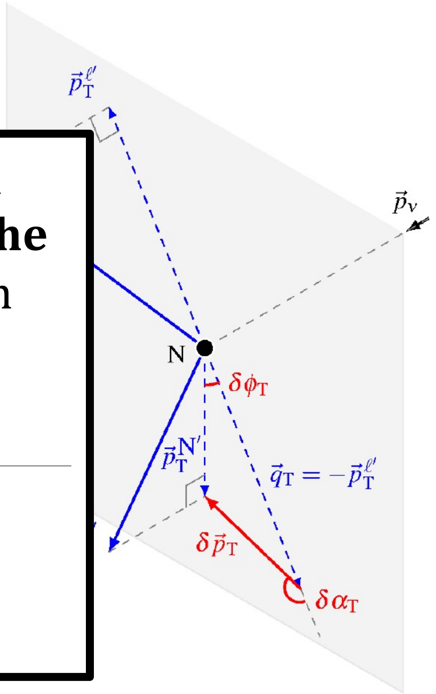
A recent measurement from the MINERvA collaboration using **a method inspired by the one in Phys. Rev. D 101, 092003** has been published in Nature

Article

Measurement of the axial vector form factor from antineutrino–proton scattering

Nature **volume 614**, pages 48–53 (2023)

Possible thanks to **neutron detection**!



Phys. Rev. D 105, 032010

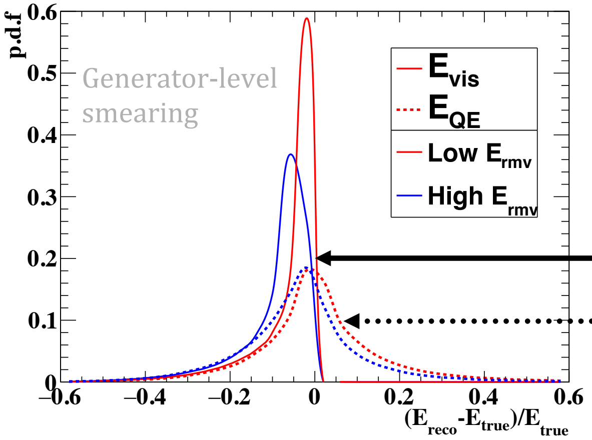
Phys. Rev. D 101, 092003

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



Phys. Rev. D 105, 032010

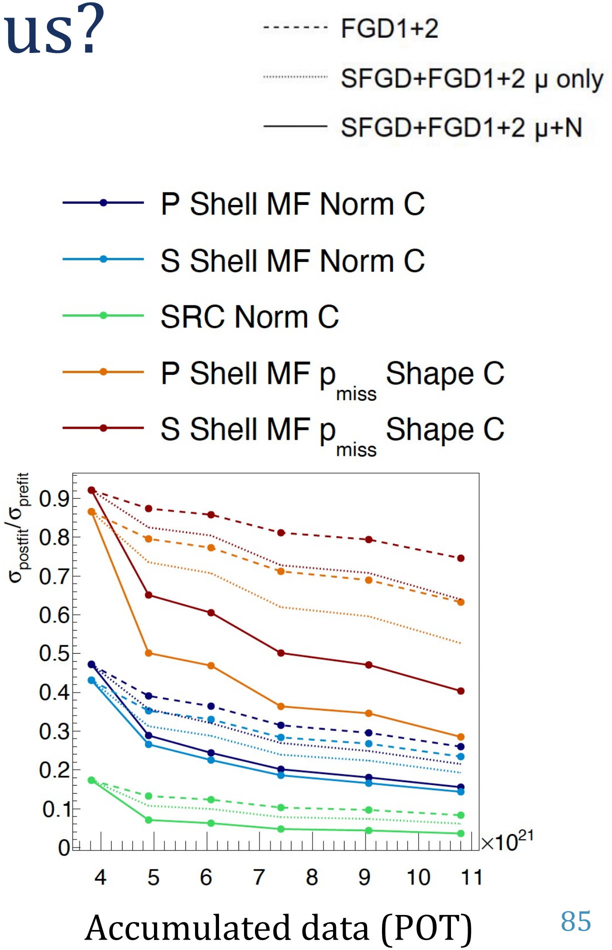
Reduced bias in neutrino energy reconstruction

E_{vis} bias dominated by **detector resolution**

E_{QE} dominated by **nuclear effects**

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
- Significantly **improve constraints** on systematic error parameters for oscillation analyses
- Help build more **robust** analyses
- Give us **novel measurements**!

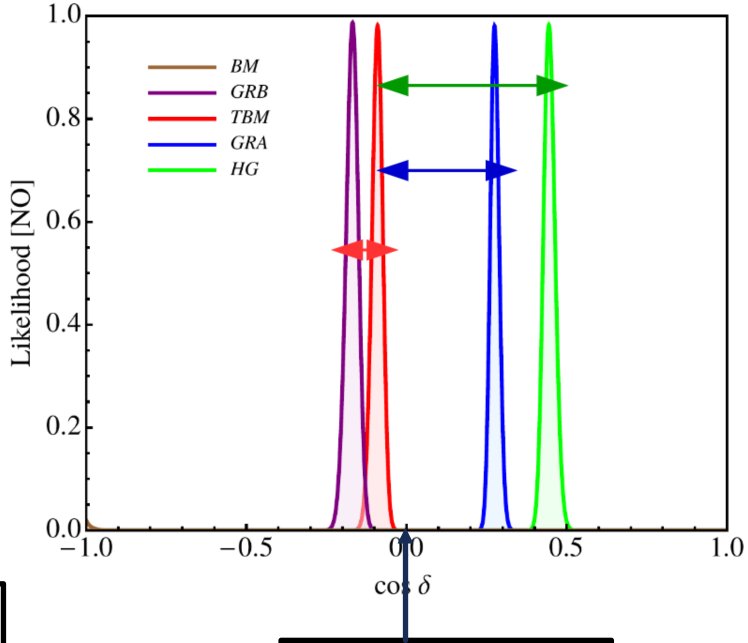


Precision measurements of δ_{CP}

- 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: $\sigma(\delta_{CP}) < 30°$
  - Good: $\sigma(\delta_{CP}) < 23°$
  - Excellent: $\sigma(\delta_{CP}) < 5°$

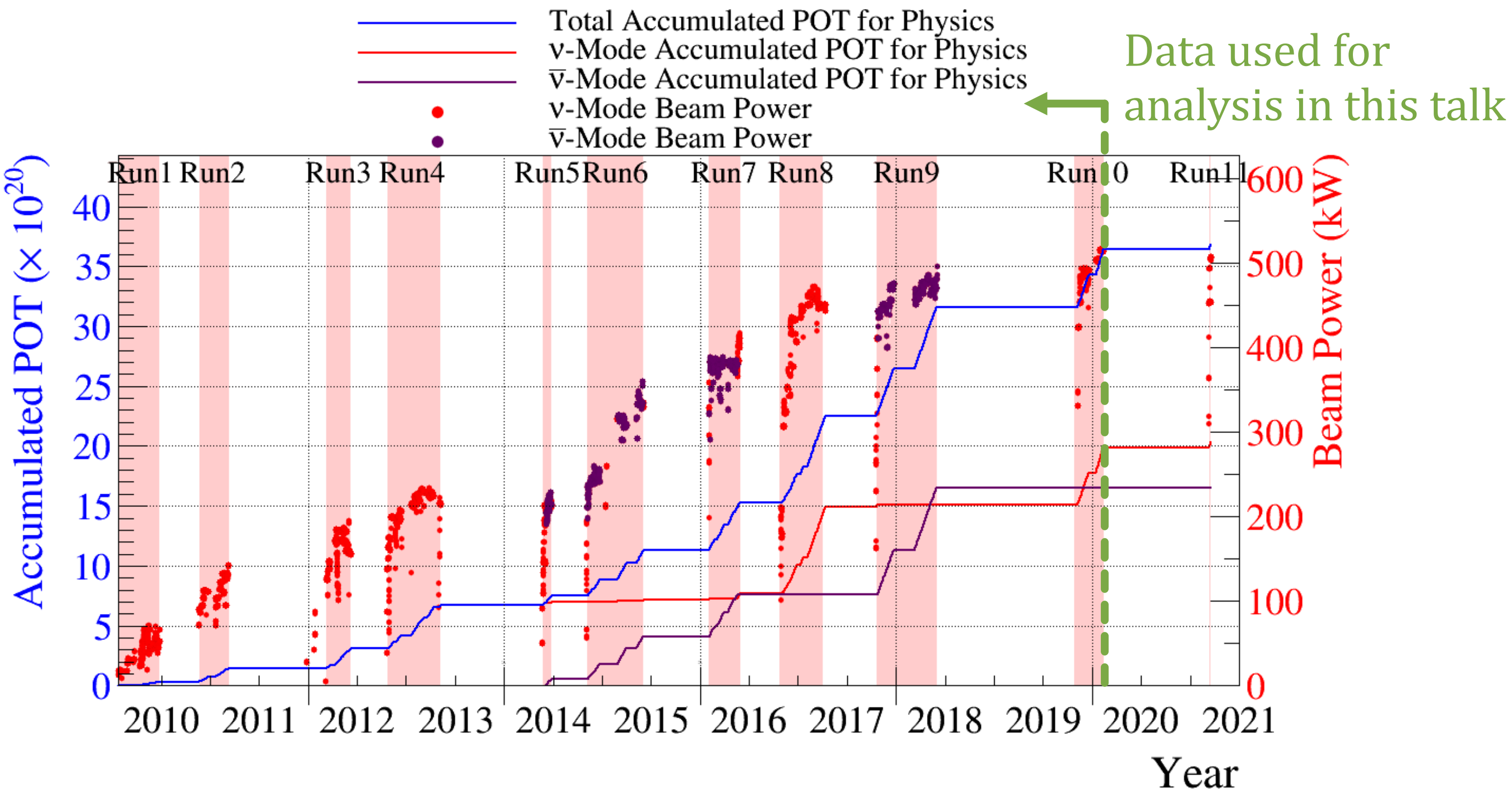
Hyper-K and DUNE target

Eur. Phys. J. C 78 (2018) no.9, 709

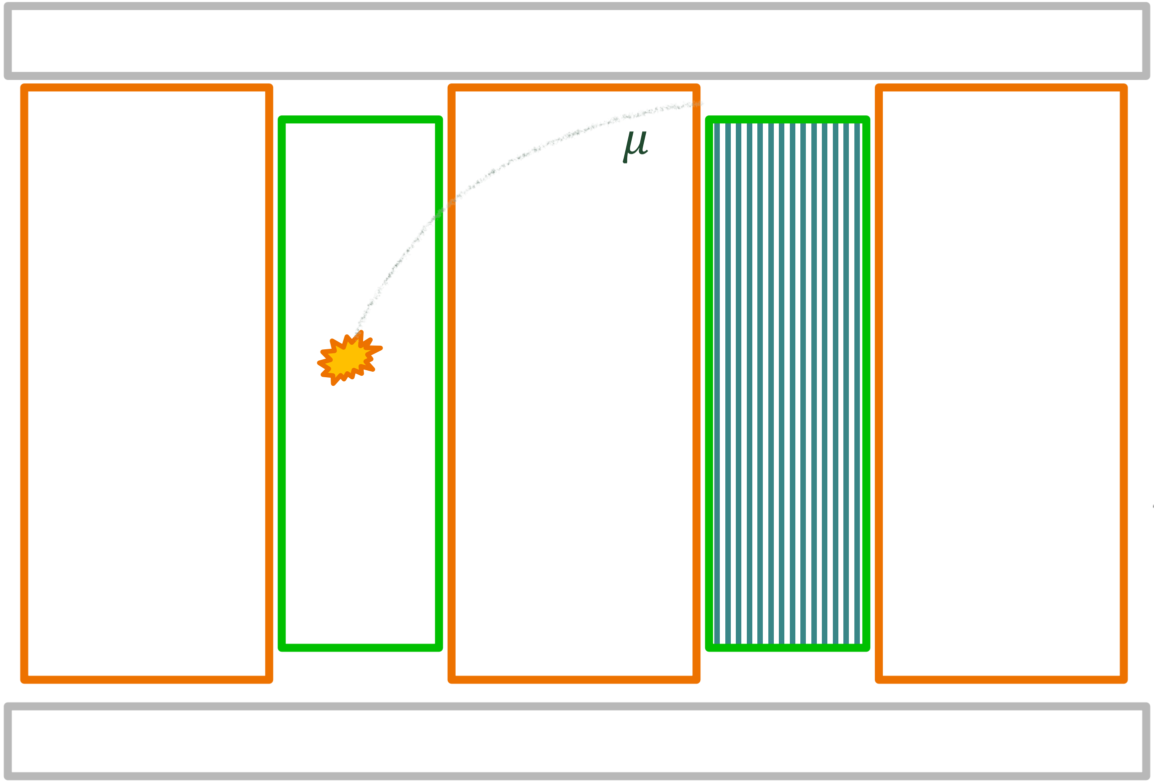


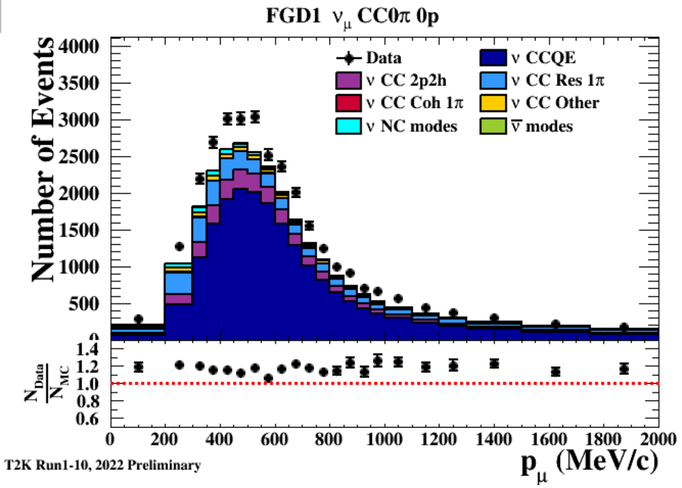
$\delta_{CP} = \pm\pi/2$

Collected T2K data



Samples: $CC0\pi0p$

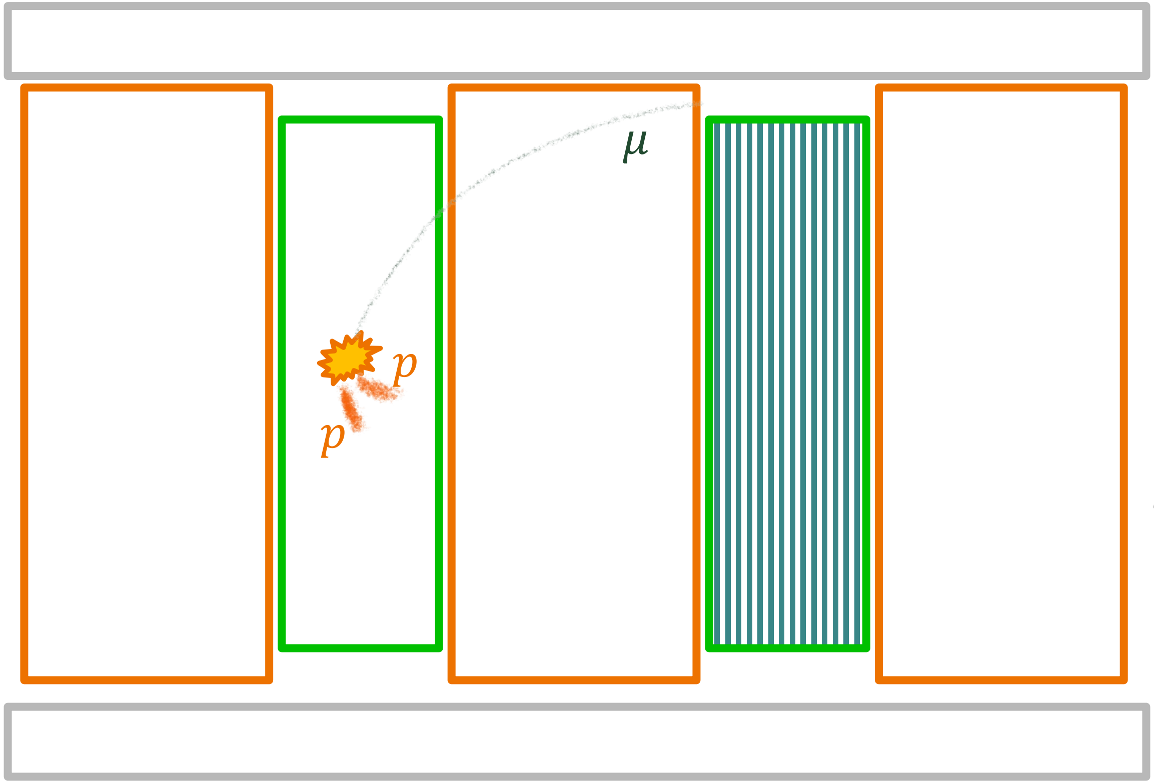


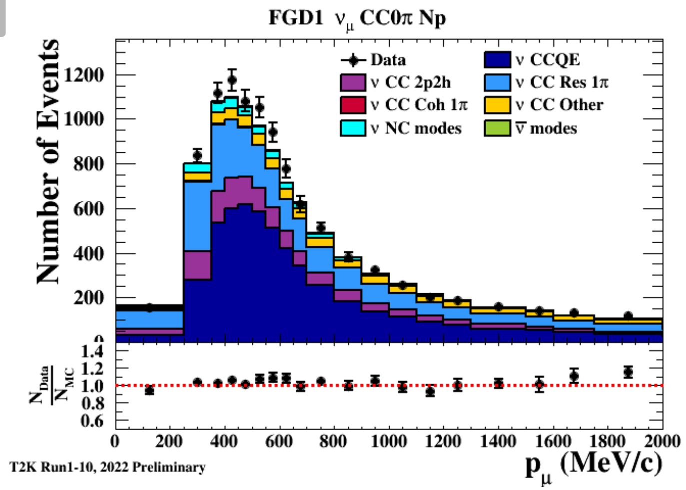


$1\mu, 0\pi, 0p$

Enriched in CCQE interactions

Samples: CC0πNp

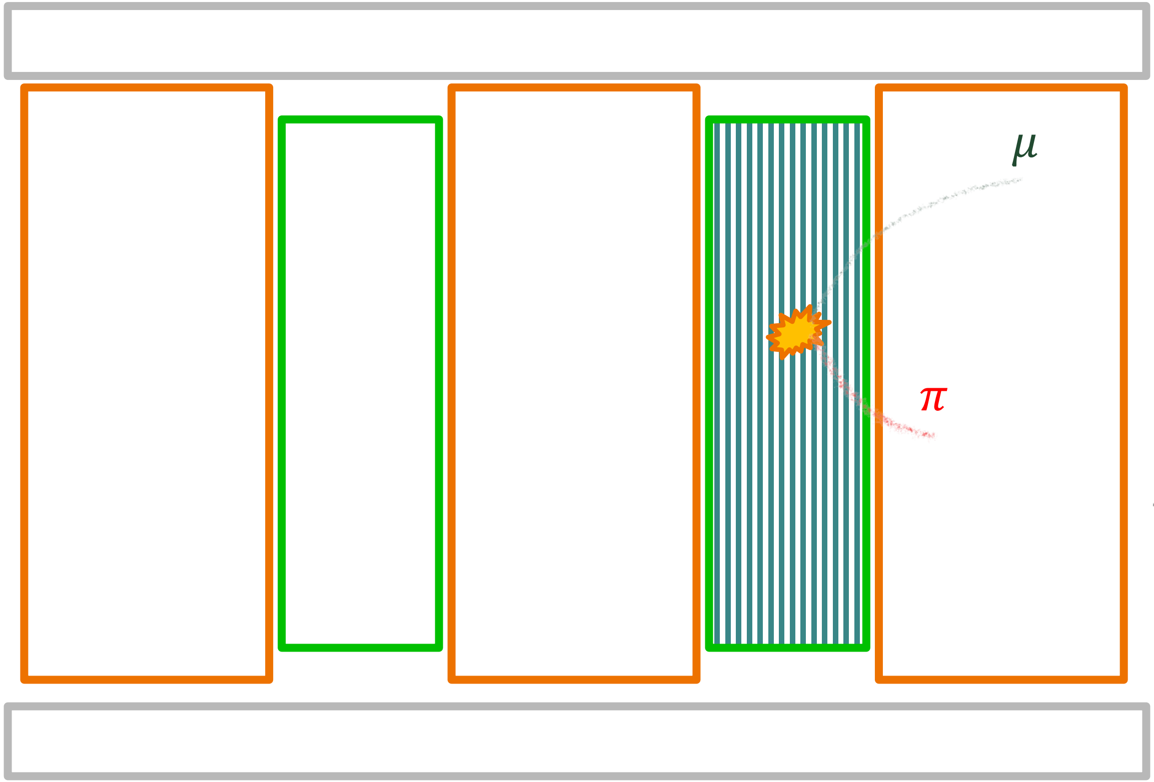


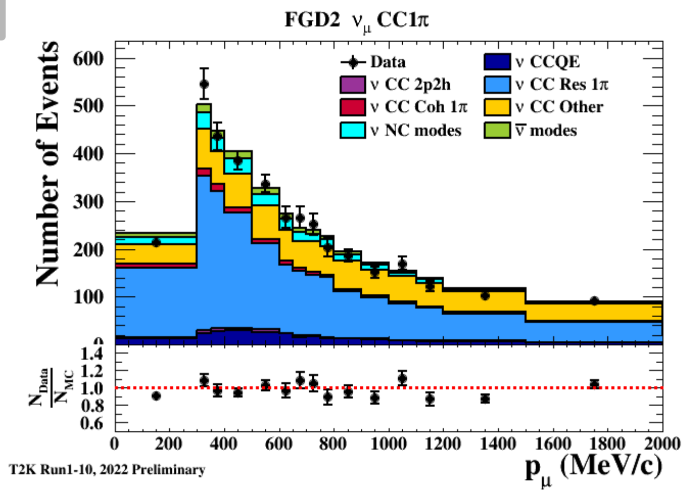


$1\mu, 0\pi, Np$

Constrains FSI-related background

Samples: CC1π

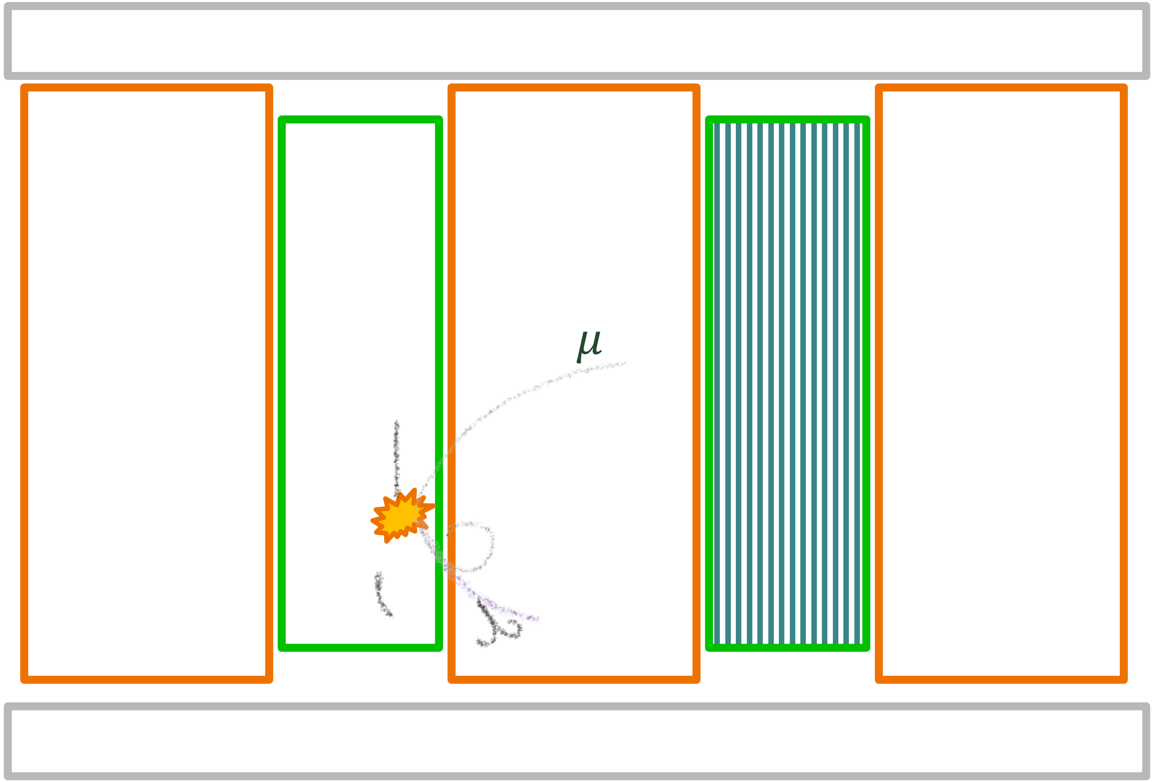


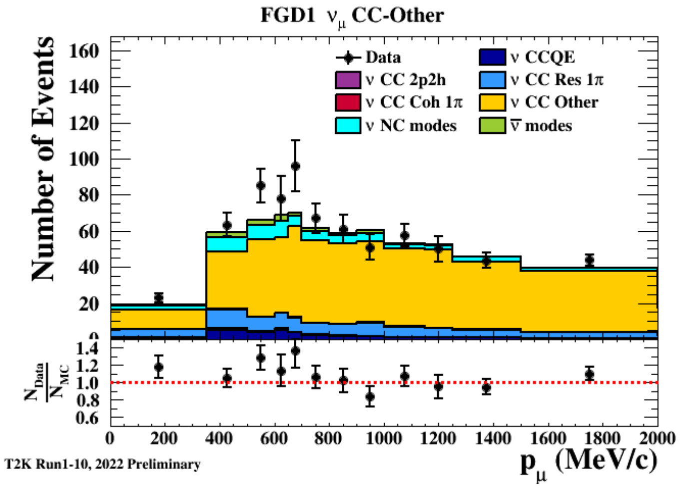


$1\mu, 1\pi$

Enriched in resonant interactions

Samples: CCOther

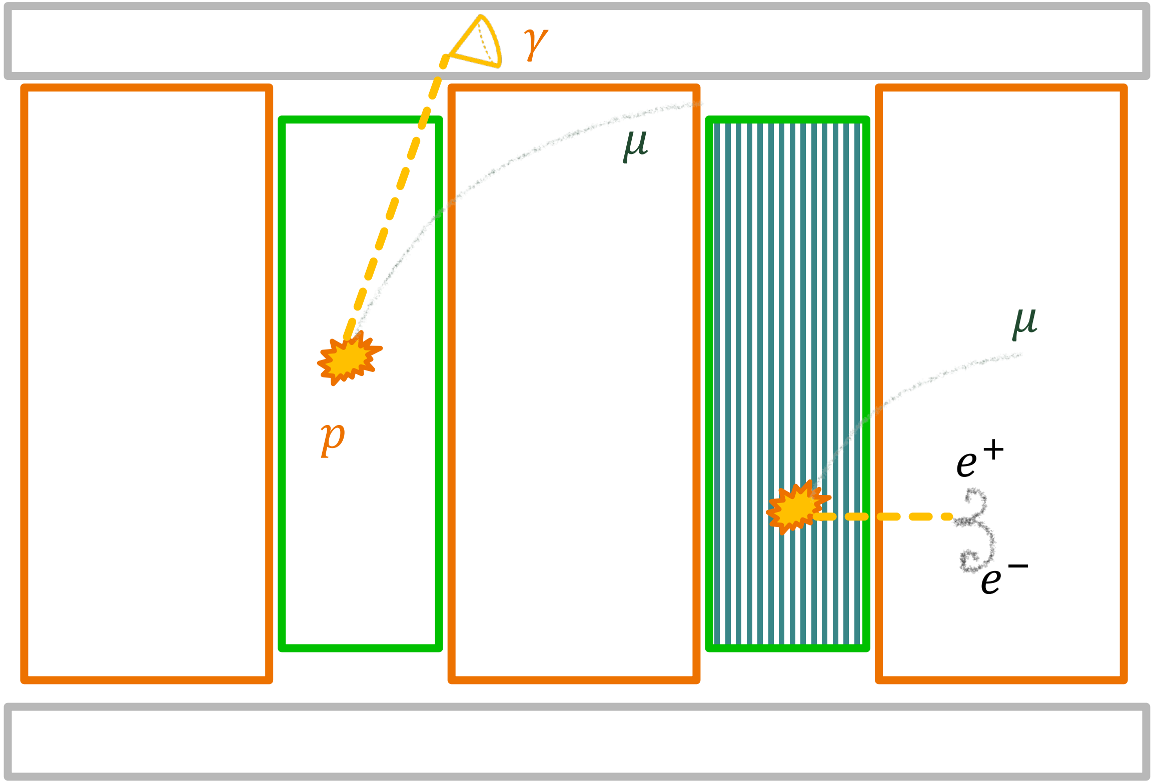


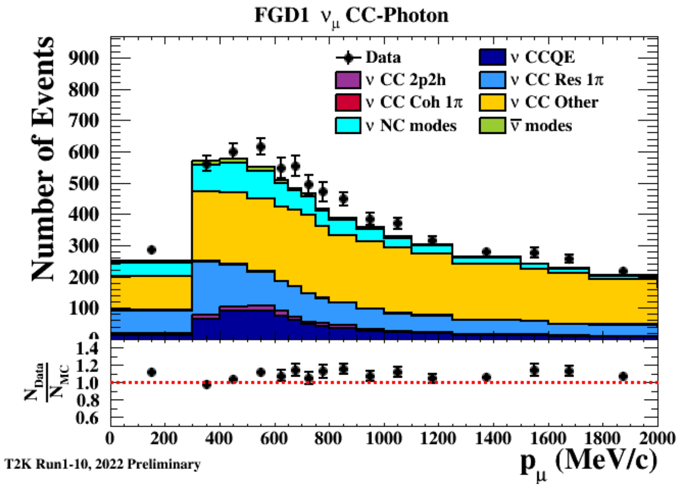


1μ + any other tracks

Enriched in DIS interactions

Samples: CCγ

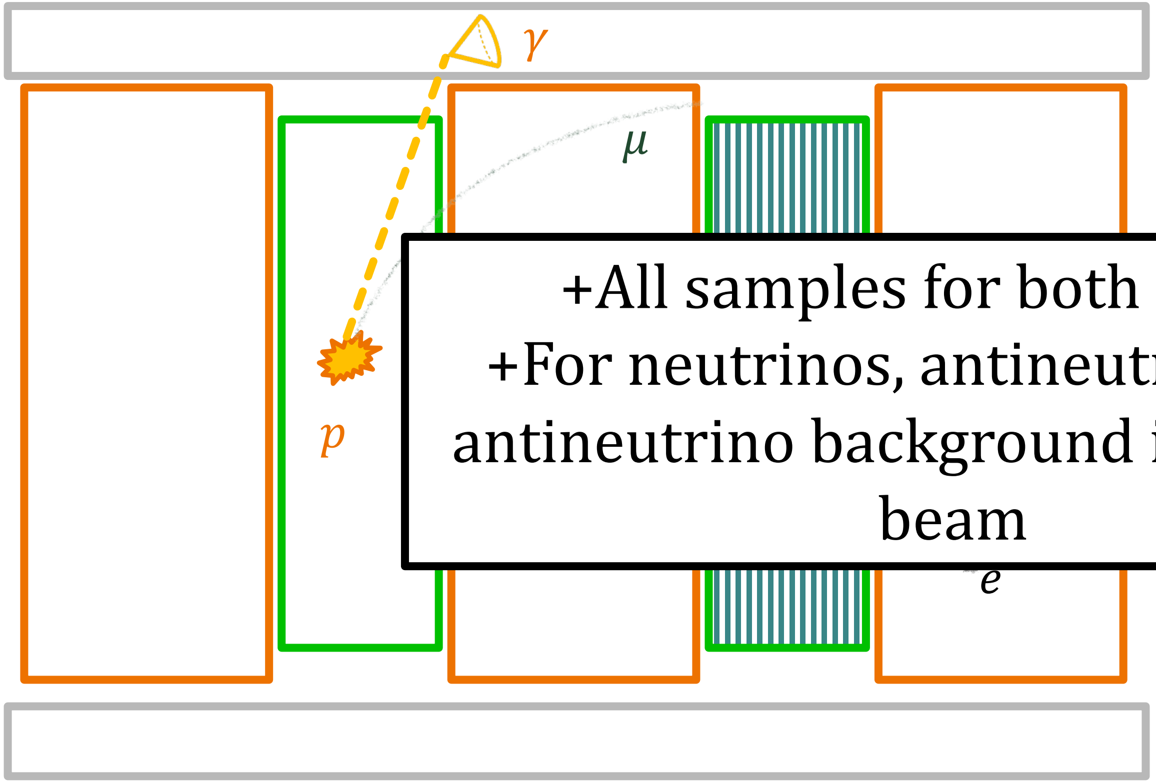




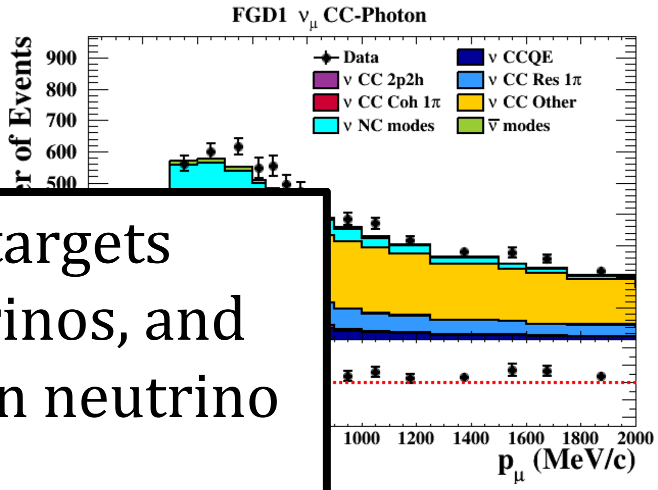
1μ + photon

Enriched in DIS interactions

Samples: CCγ

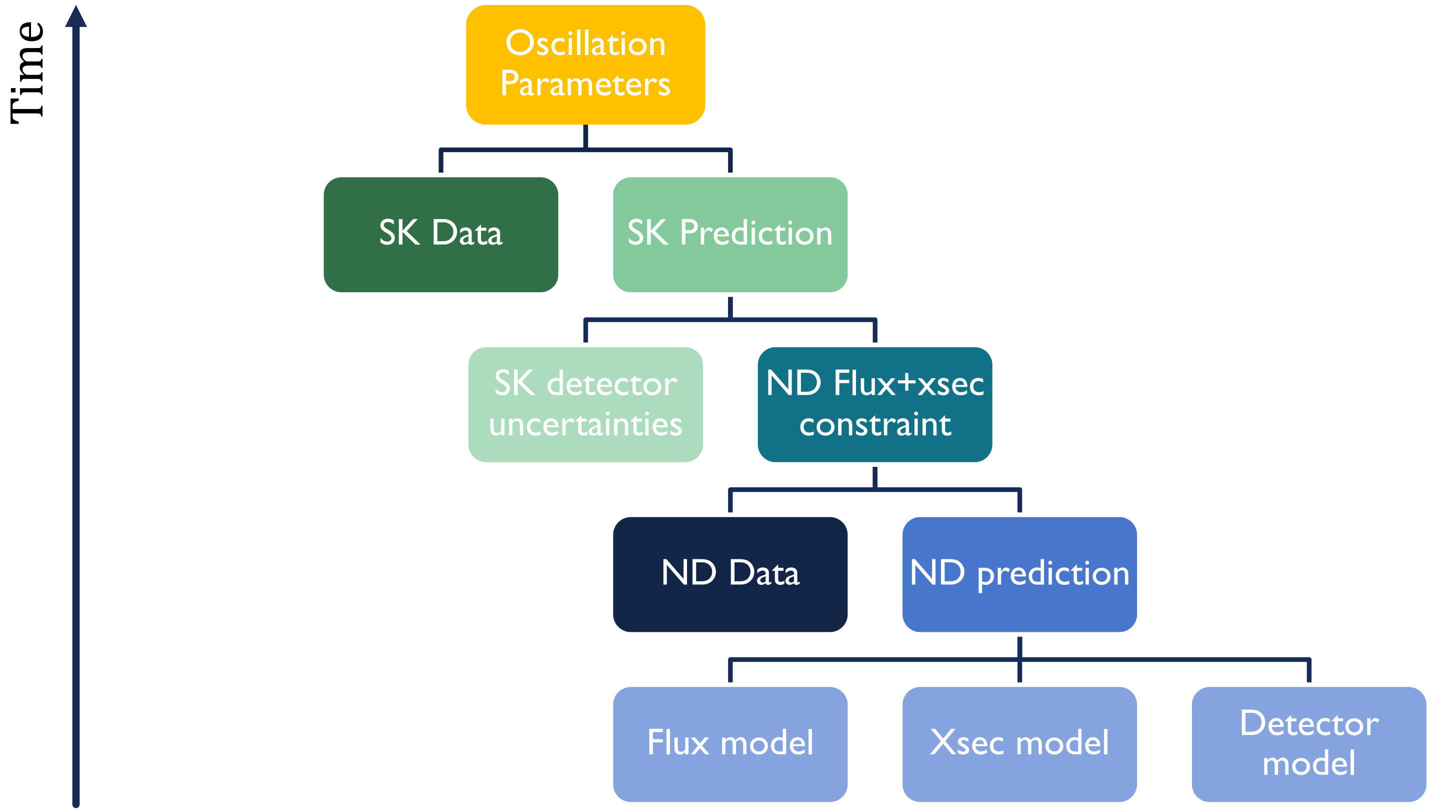


+All samples for both targets
+For neutrinos, antineutrinos, and antineutrino background in neutrino beam

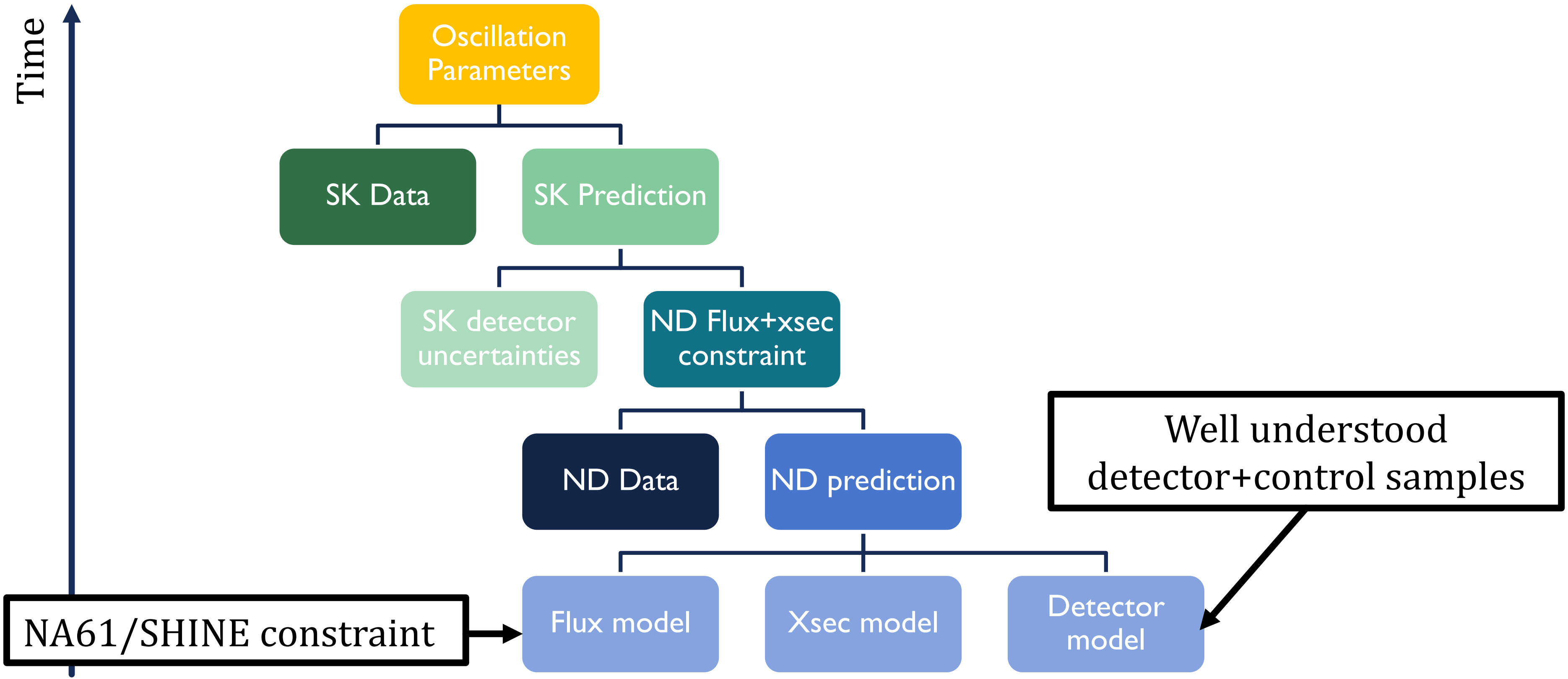


1μ + photon
Enriched in DIS interactions

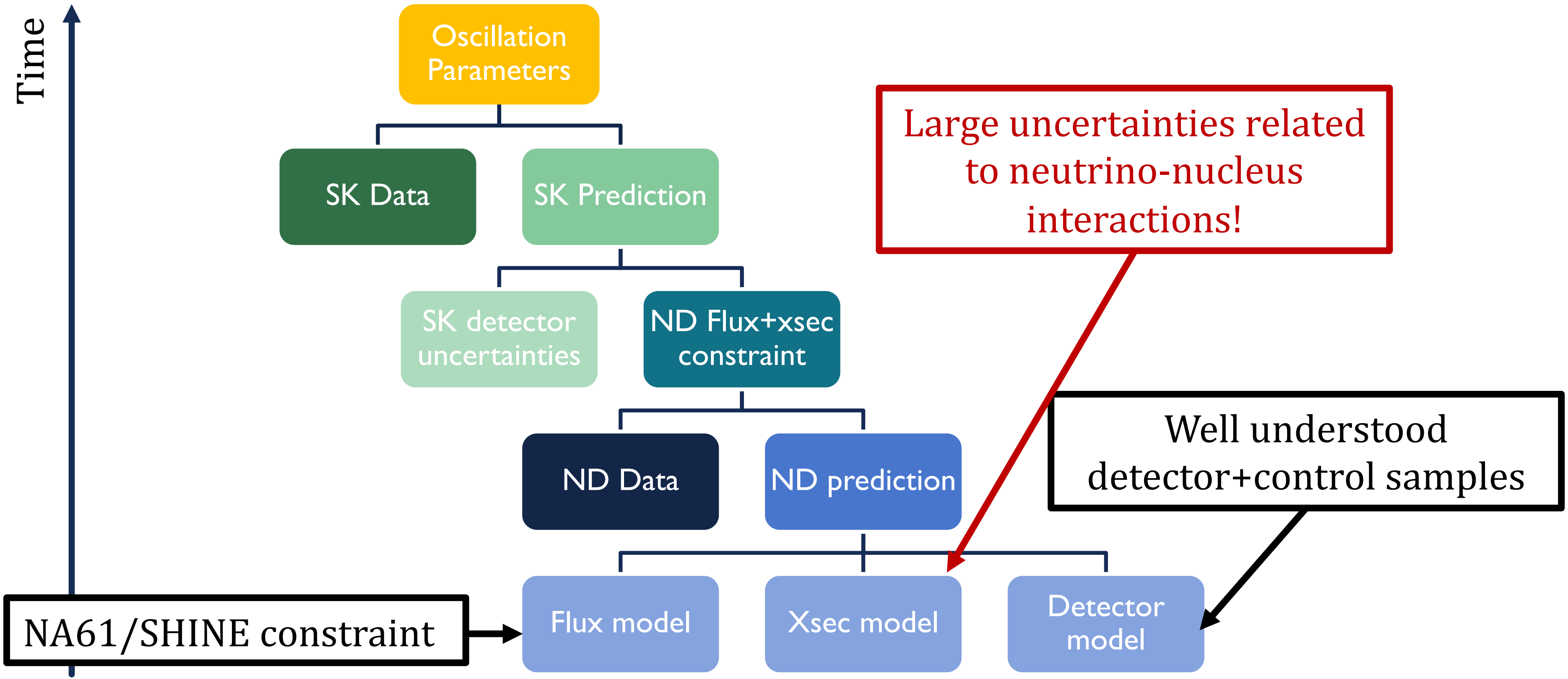
Analysis strategy



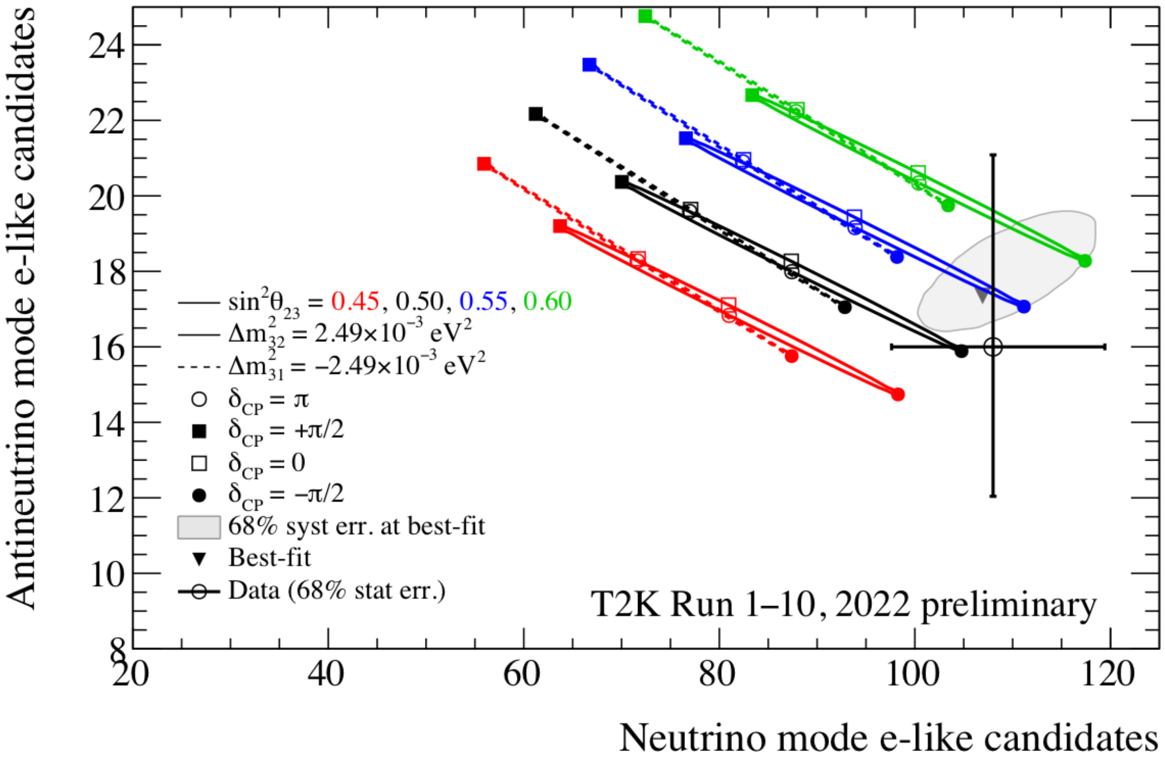
Analysis strategy



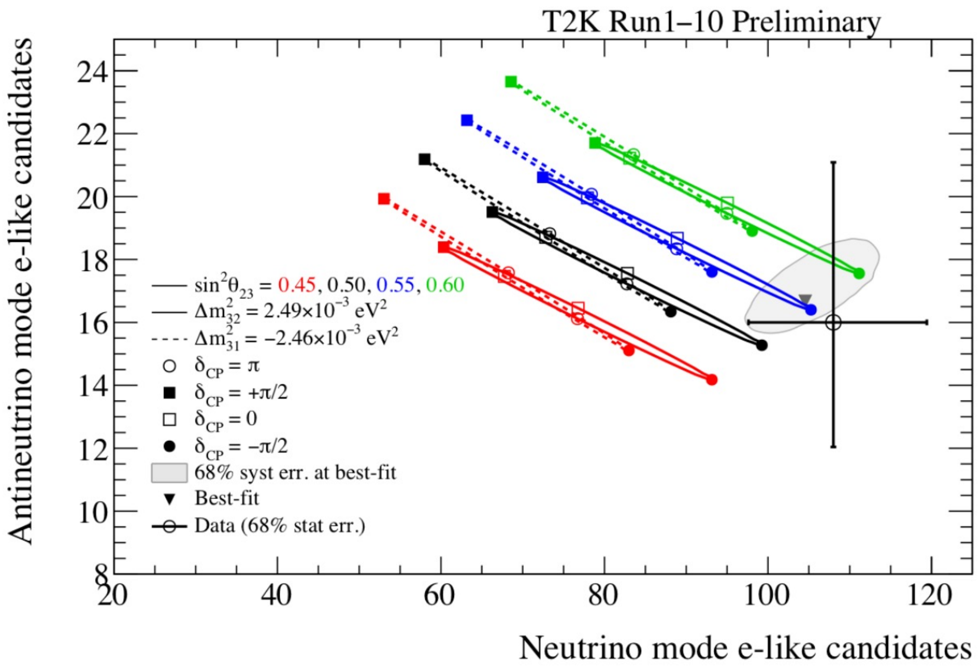
Analysis strategy

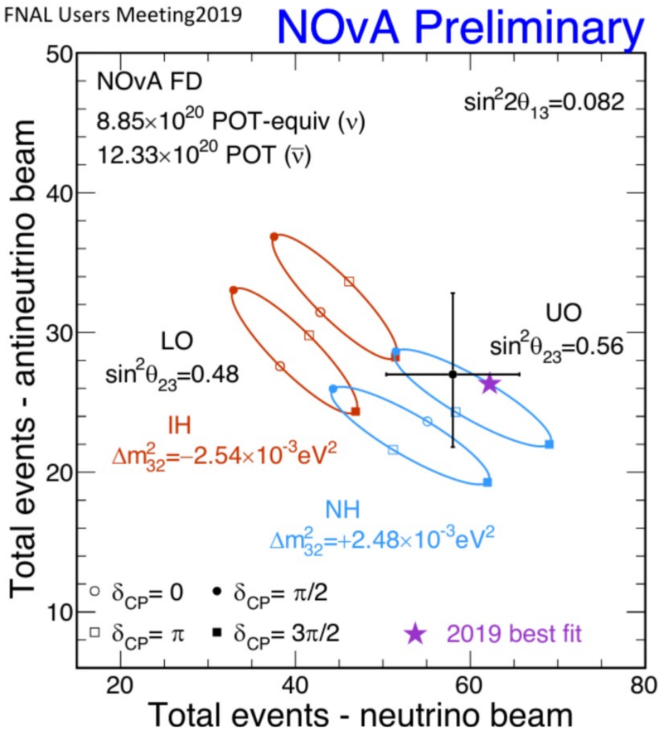


T2K Bi-probability plot

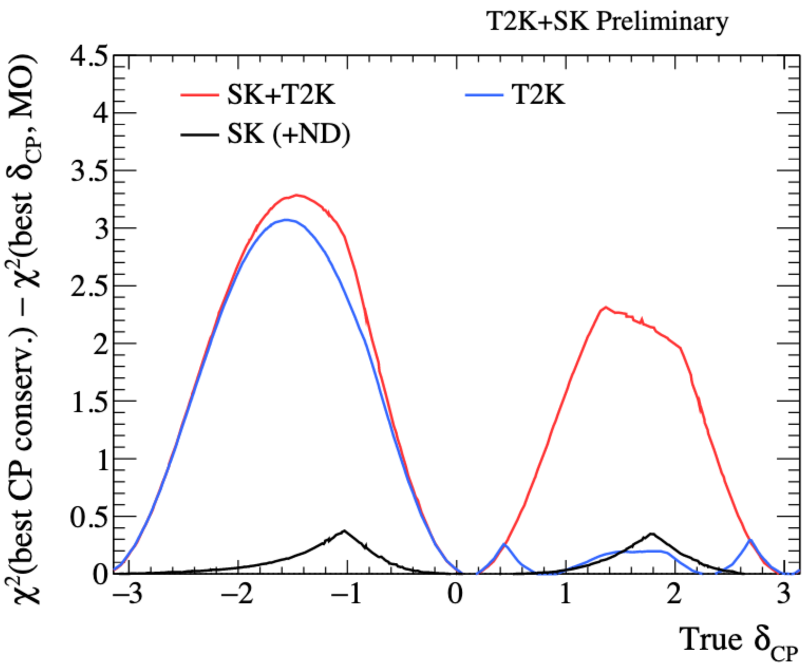


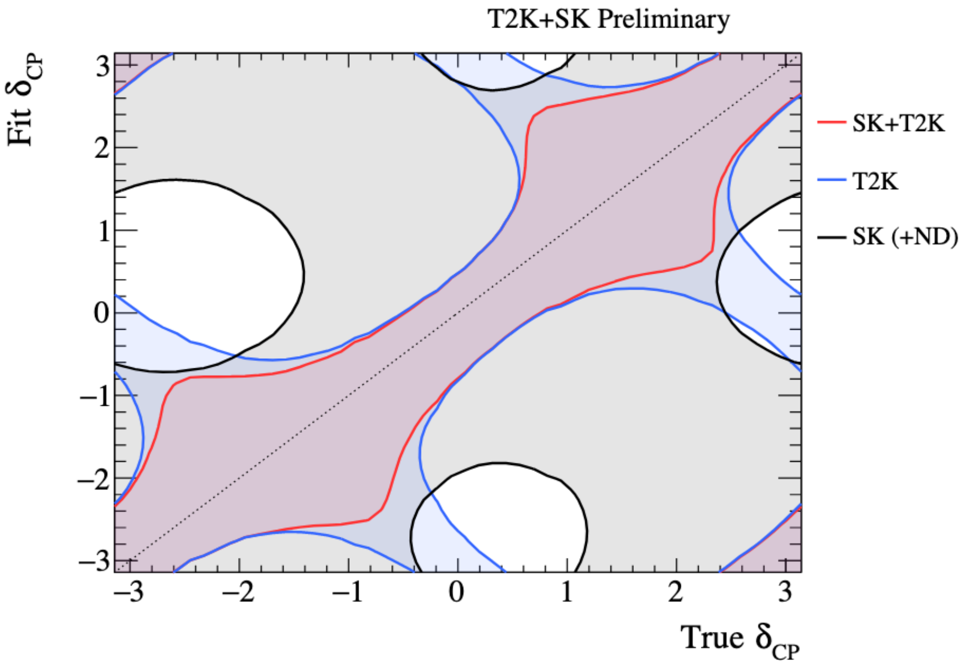
T2K-NOvA joint fit





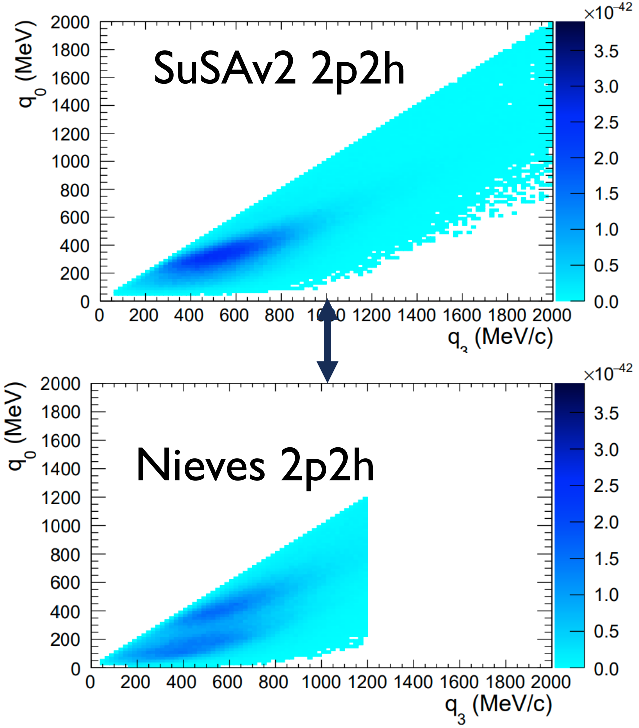
T2K+SK Atospherics Joint Fit





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



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