Neutrino-nucleus cross-section measurements

Towards the next generation of oscillation experiments

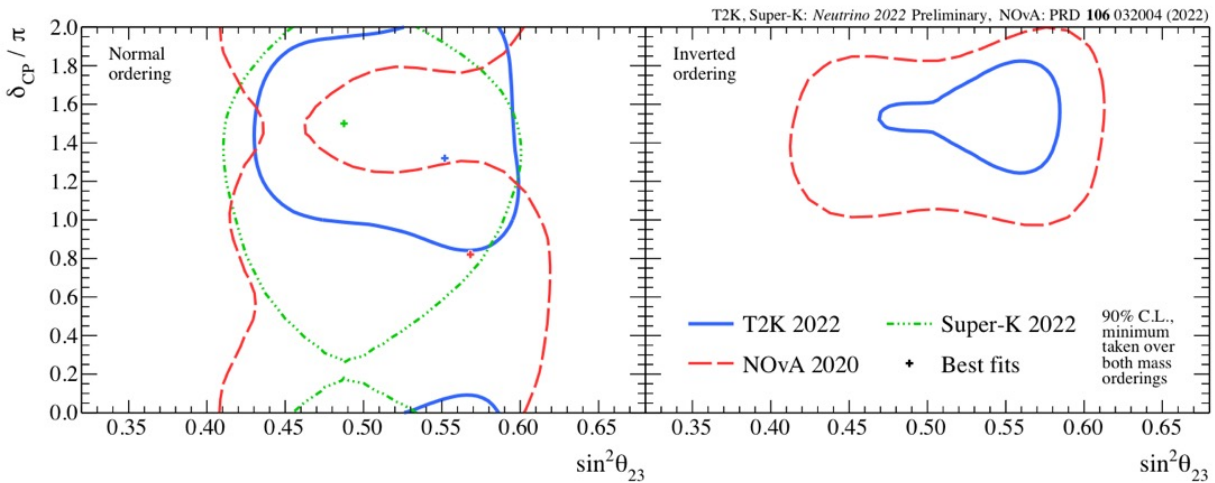
Laura Munteanu (CERN)

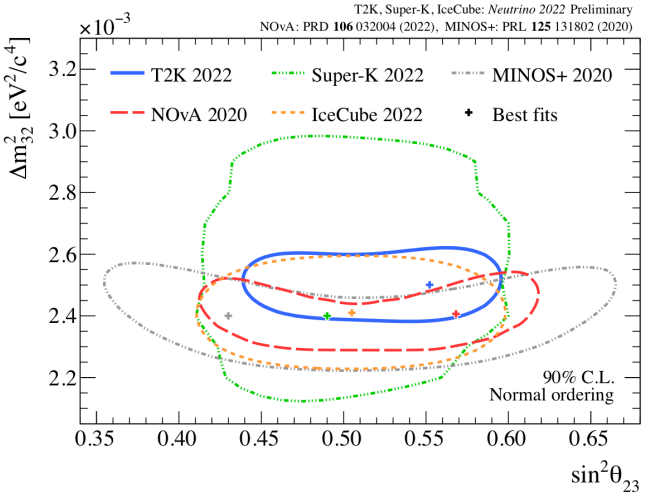
NuPhys 2023, London, UK

19 December 2023

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 mass ordering
- 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 arXiv:2303.03222	318	137	94	16	~5%
NOvA PRD106,032004 (2022)	211	105	82	33	~5%

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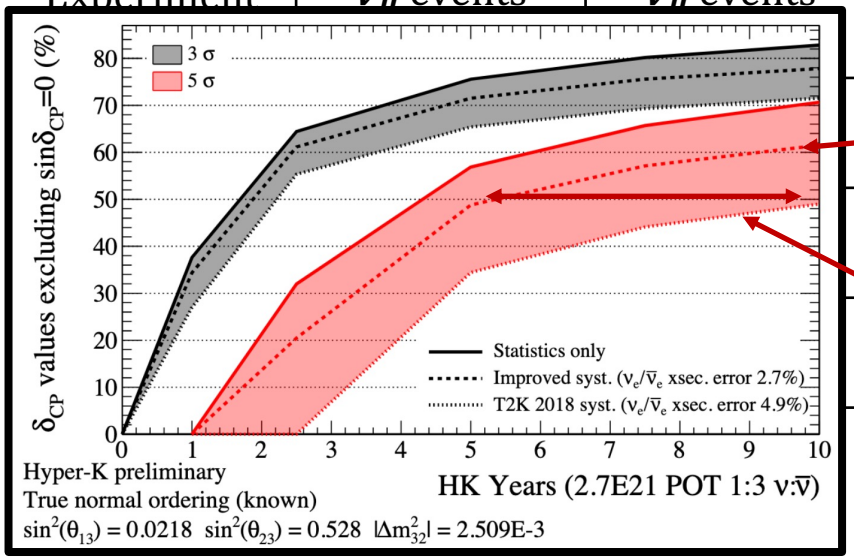
Hyper-K Kyper-K TDR	**~10000**	**~14000**	**~2000**	**~2000**	**?**
DUNE DUNE FD TDR	**~7000**	**~3500**	**~1500**	**~500**	**?**

Are we prepared for future experiments?



Sensitivity to exclude CP conserving values for δ_{CP}

Experiment	ν_μ events	$\bar{\nu}_\mu$ events	ν_e events	$\bar{\nu}_e$ events	Systematic error
			9		~5%
			82	33	~5%
			~2(	)0	?
			~150		

Improved systematics

T2K-level systematics

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

Or prevent them altogether!

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Need dedicated, focused effort in order for future experiments not to be **pre-maturely limited by systematics**

Finding the culprit

T2K

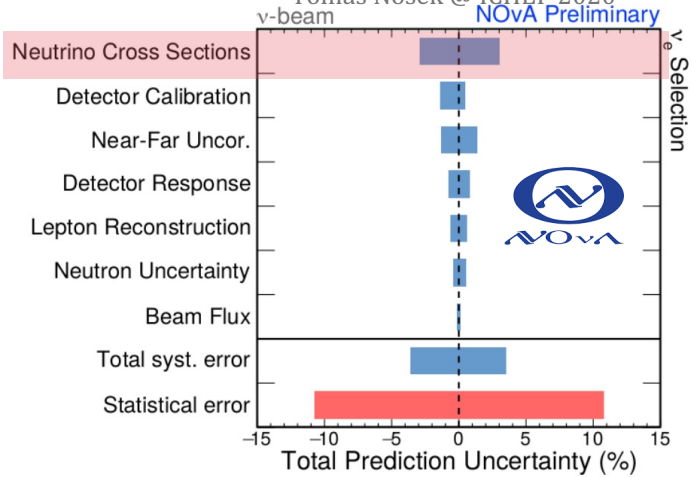
arXiv:2303.03222

Syst. uncertainty

Sample		Flux⊗Interaction (%)	Total (%)
1Rμ	ν	2.2 (12.7)	3.0 (13.0)
	$\overline{\nu}$	3.4 (11.8)	4.0 (12.0)
1Re	ν	3.6 (13.5)	4.7 (13.8)
	$\overline{\nu}$	4.3 (12.1)	5.9 (12.7)
1Re1de	ν	5.0 (13.1)	14.3 (18.7)

After (before)
near detector constraint

Tomas Nosek @ ICHEP 2020



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

What do we need

to successfully control cross-section systematics?

Neutrino cross-sections and oscillations

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

Systematic uncertainties

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

Oscillation parameters

Neutrino flux

Interaction cross-section

Detection efficiency

Energy smearing matrix

Neutrino cross-sections and oscillations

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Oscillation parameters

Neutrino flux

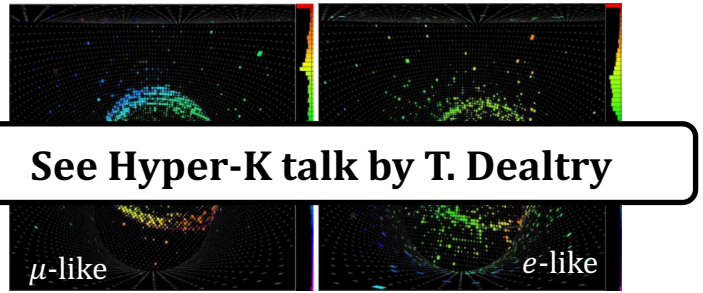
Interaction cross-section

Detection efficiency

Energy smearing matrix

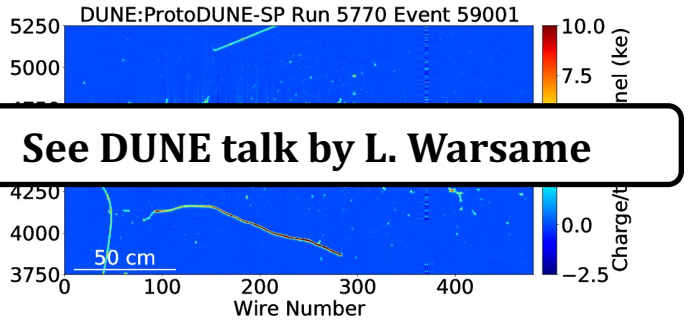
- Constrain systematics with **near detector**
- But **heavily rely on models** to predict near-to-far detector **extrapolation and neutrino energy smearing**

Neutrino energy reconstruction



See Hyper-K talk by T. Dealtry

Water Cherenkov – measure kinematics of particles above threshold

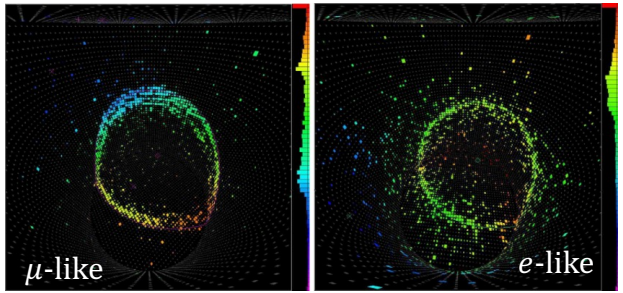


See DUNE talk by L. Warsame

LArTPC – measure particles' energy deposits

Different detectors – different methods – different priorities

Neutrino energy reconstruction



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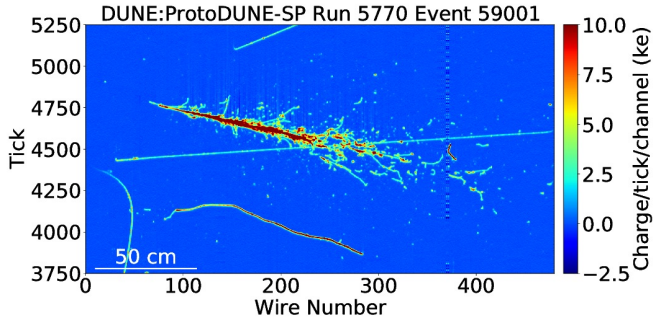
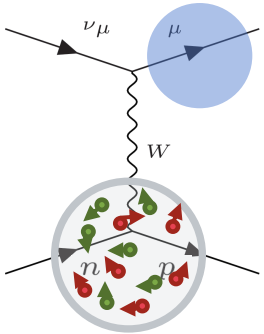


LArTPC – measure particles' energy deposits

Different detectors – different methods – different priorities

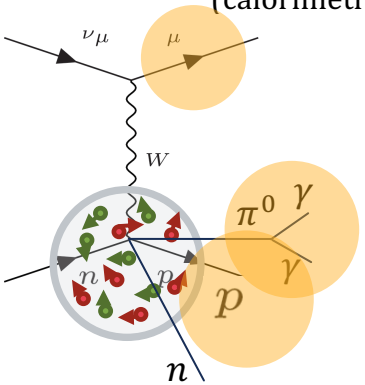
Neutrino energy reconstruction

("kinematic" energy reconstruction)



Infer neutrino energy **from lepton kinematics** under 2-body reaction assumption

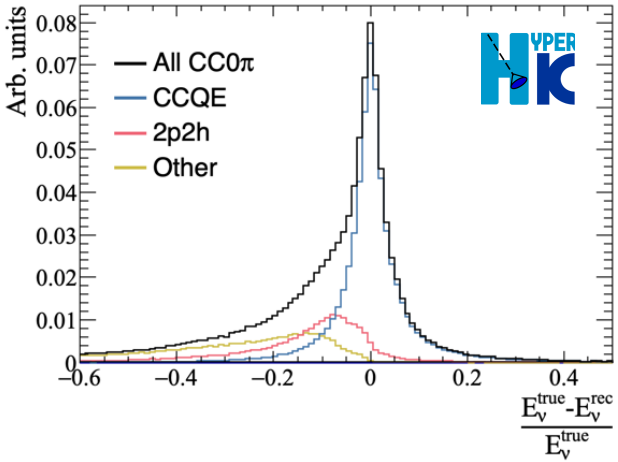
(calorimetric energy reconstruction)



Add up all **visible energy** from final state particles

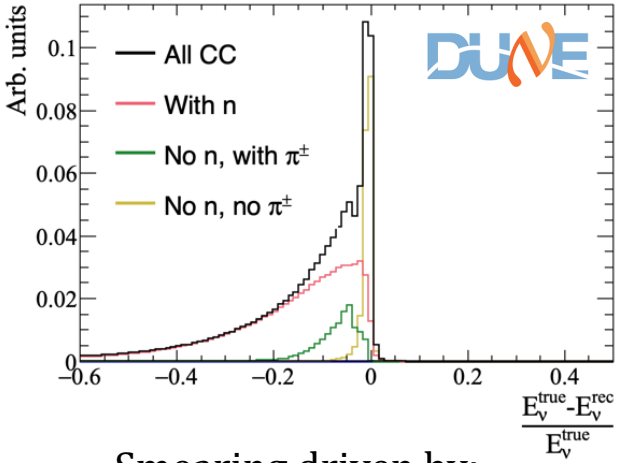
Different detectors – **different methods** – different priorities

Neutrino energy reconstruction



Smearing driven by:

- **Nuclear ground state**
- **Pion transport** through nucleus

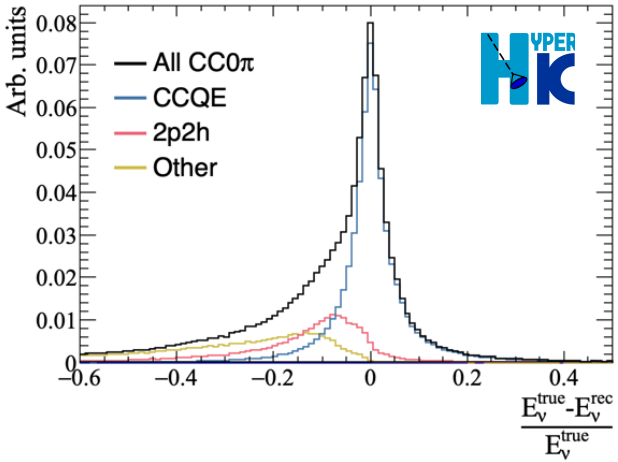


Smearing driven by:

- Fraction of **energy carried by neutrons**
- **Pion production** processes

Different detectors – different methods – **different priorities**

Neutrino energy reconstruction



Smearing driven by:
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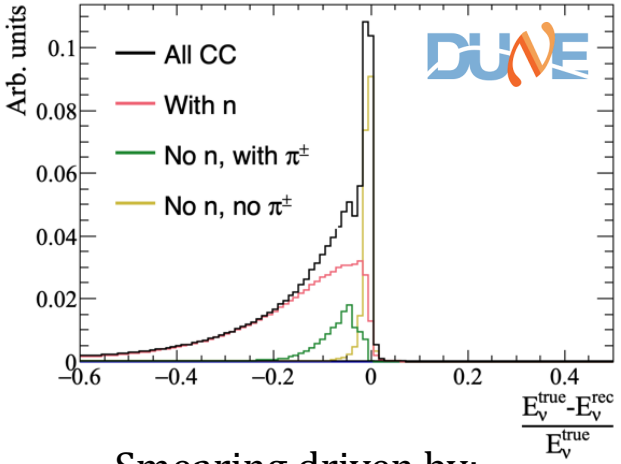
Wider intrinsic smearing but easier to control



Smearing driven by:
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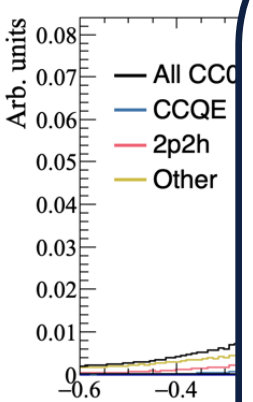
- **Pion production** processes

Smaller intrinsic smearing but **harder to control**

Different detectors – different methods – **different priorities**

Neutrino en



Smearing driv

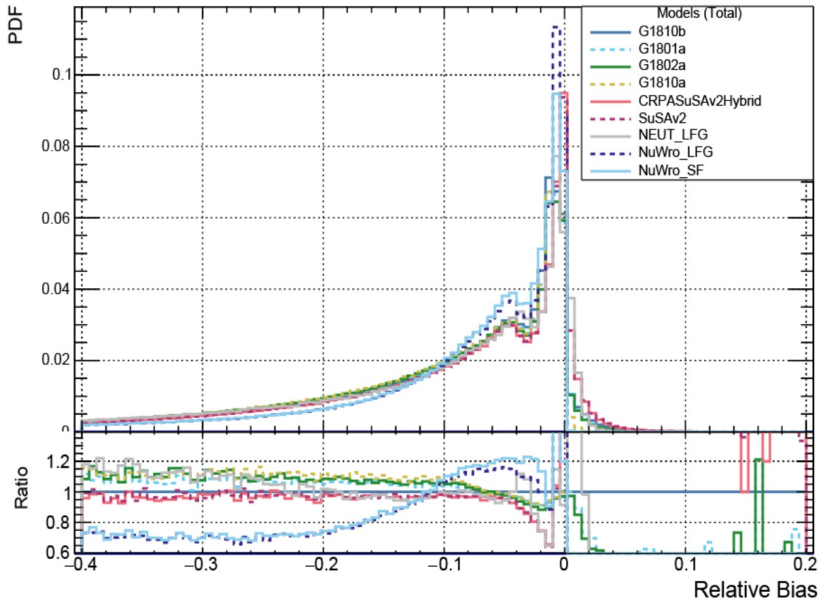
- **Nuclear gr**
- **Pion trans**

Wider intrinsic sm

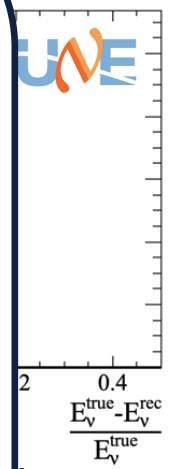
Differe

Relative bias on the reconstructed neutrino energy for DUNE from multiple models

Plot by A. Wong Wei Ren



High model disagreement



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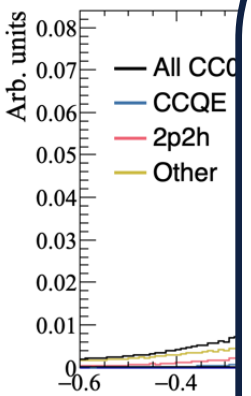

Smearing driv

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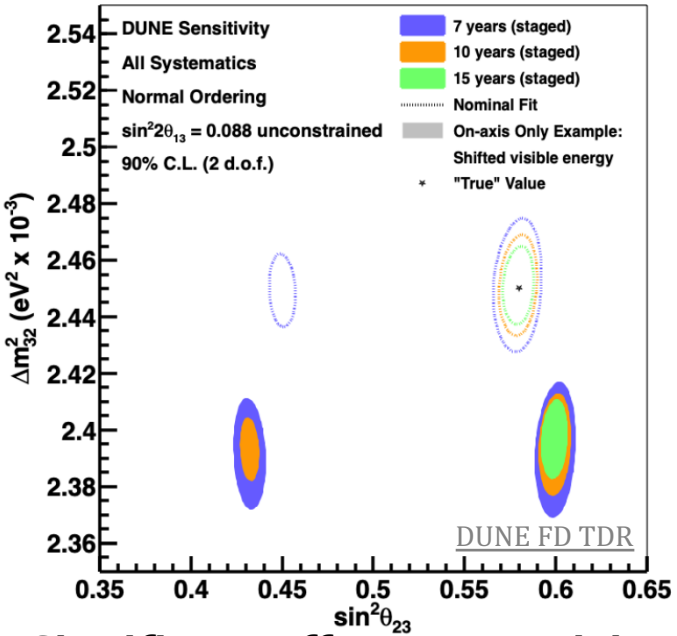
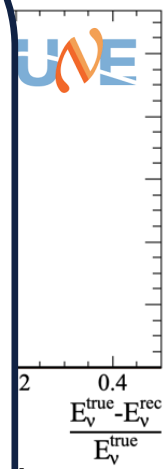
Wider intrinsic sm

Differe

Impact of invisible energy mis-modelling on oscillation parameters



Significant effect on precision measurements



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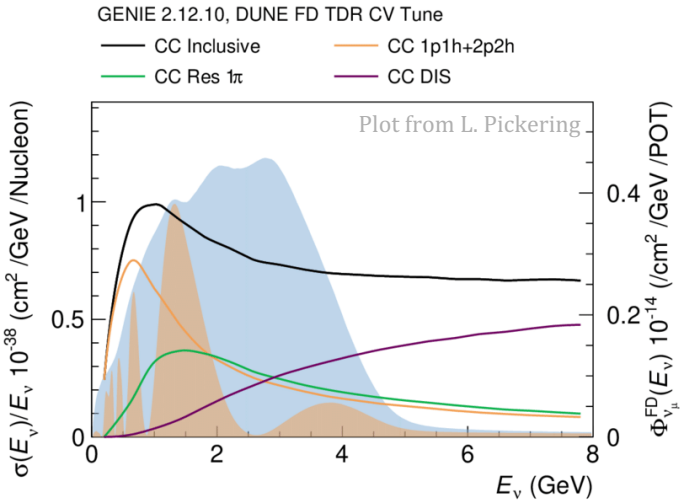
Oscillation analyses and model dependence

Near detectors are an **essential part** of any oscillation experiment

But we rely on models to predict:

- **The energy dependence of neutrino cross sections**



The near and far detectors see different neutrino fluxes due to

- Oscillations
- Acceptance
- Beam geometry

Different models predict different evolutions of $\sigma(E_\nu)$

Oscillation analyses and model dependence

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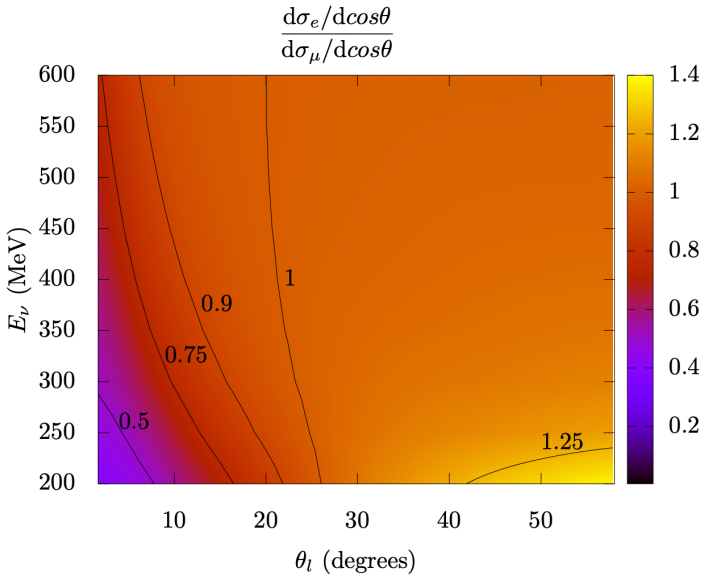
- **How cross sections change for different neutrino species (ν_μ/ν_e)**



Phys.Rev.Lett. 123 (2019) 5, 052501

Near detectors predominantly measure ν_μ
Rely on theory predictions to extrapolate to ν_e

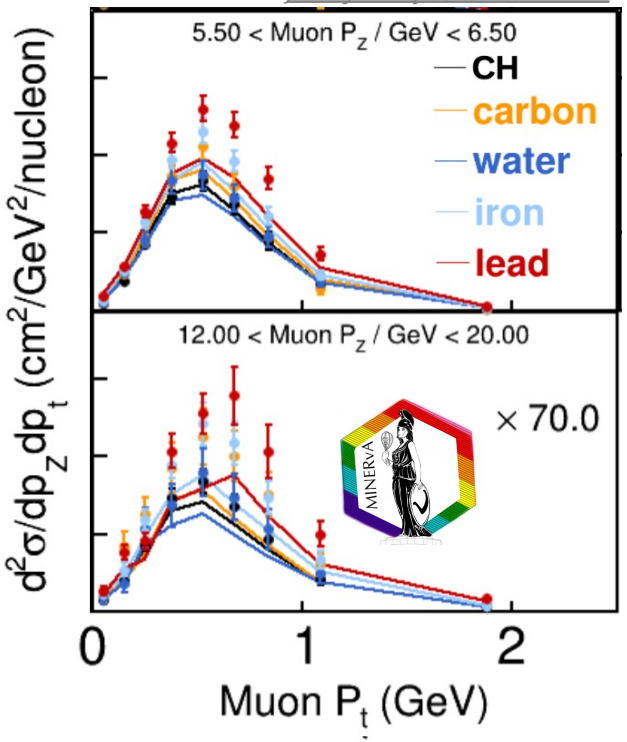
Oscillation analyses and model dependence

Near detectors are an **essential part** of any oscillation experiment

But we rely on models to predict:

- The energy dependence of neutrino cross sections
- How cross sections change for different neutrino species (ν_μ/ν_e)
- **How cross sections change for different targets**

J. Kleykamp @ NuINT2022



Ar, CH

CH, H_2O

Oscillation analyses and model dependence

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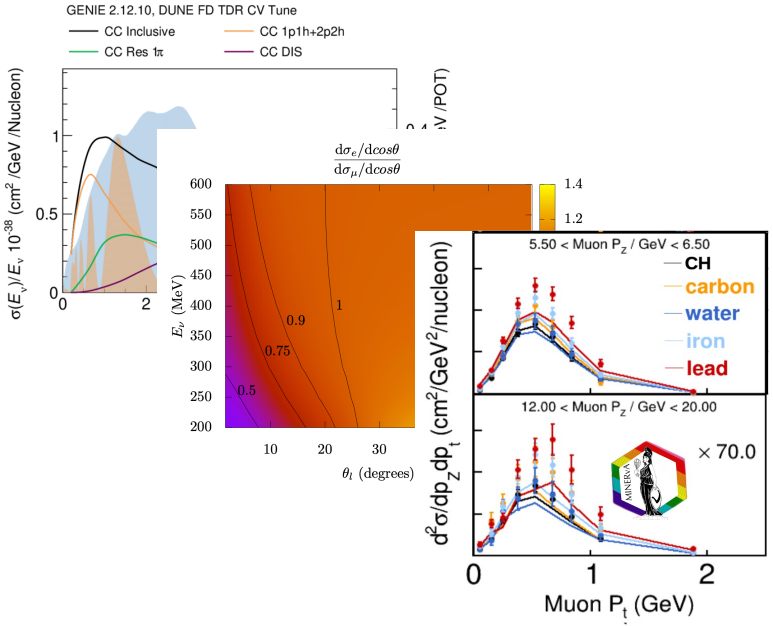
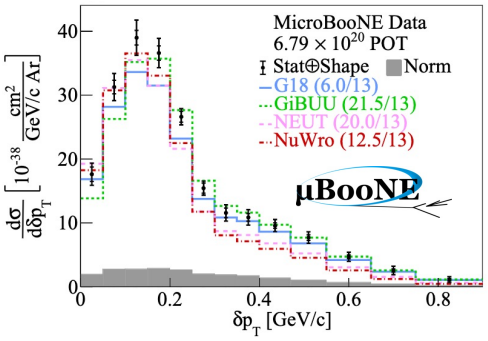


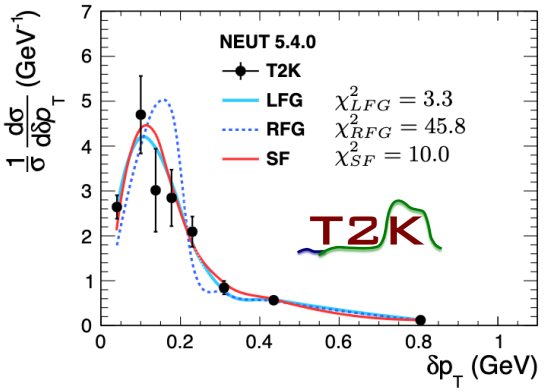
Model dependence cannot be escaped in neutrino oscillation experiments

How do our models perform?

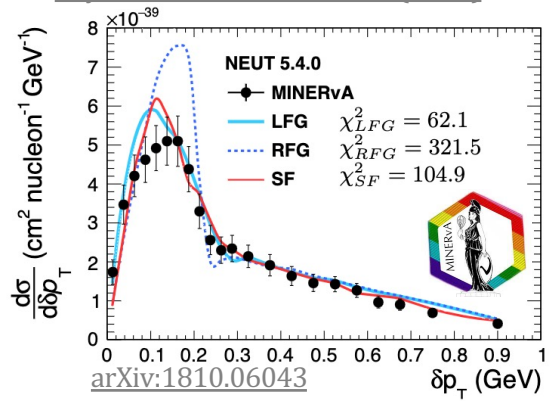
arXiv:2301.03700



arXiv:1810.06043
Phys. Rev. D 98, 032003 (2018)



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



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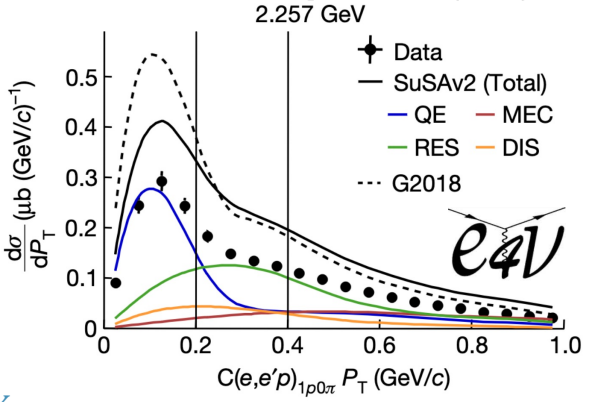

How do our models perform?

No model is able to describe global neutrino scattering measurements

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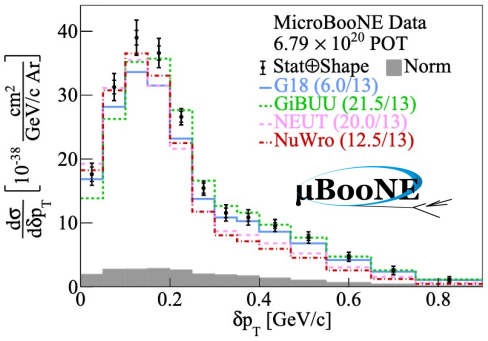

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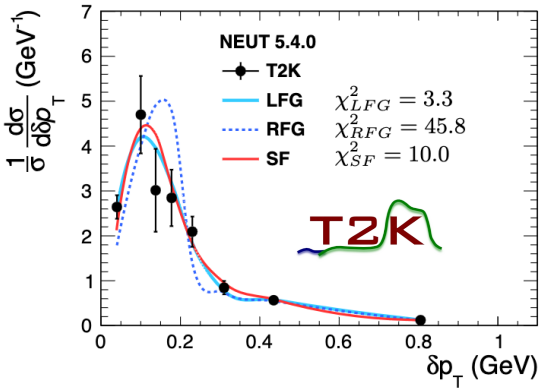

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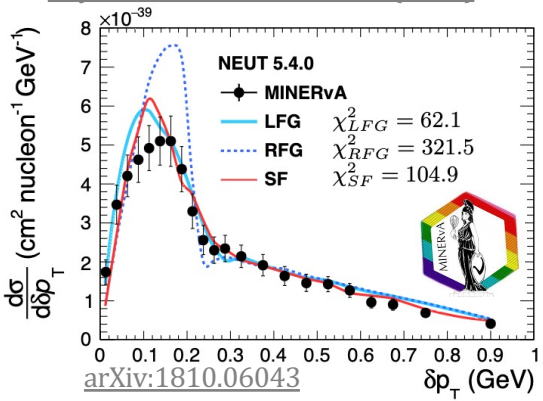

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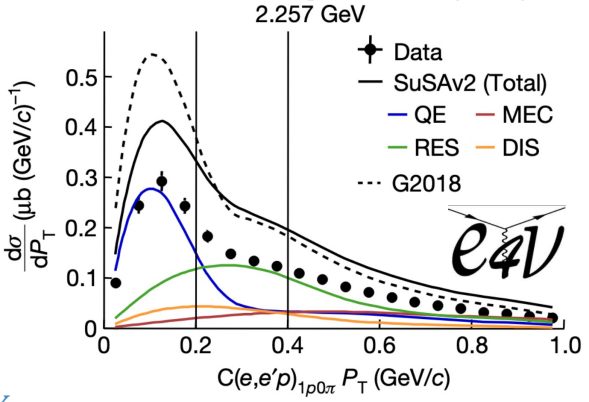

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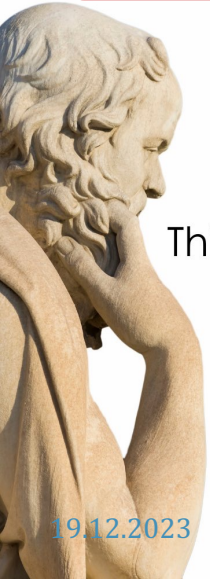
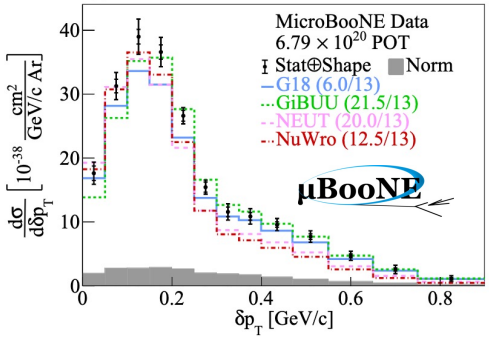


"One thing I know, that I know nothing. This is the source of my wisdom."

Socrates, as he analyzes neutrino cross-section measurements

arXiv:2301.03700



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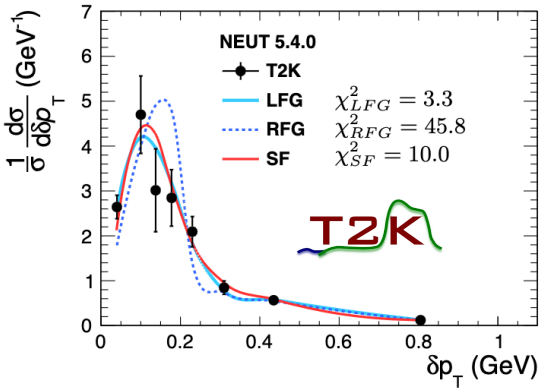

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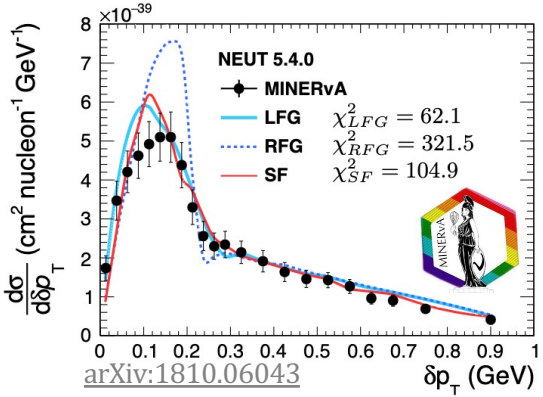

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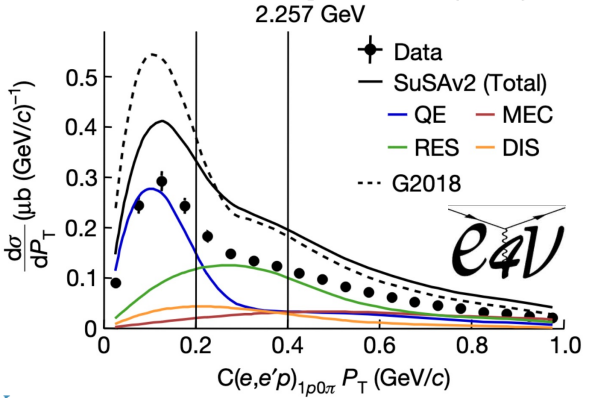
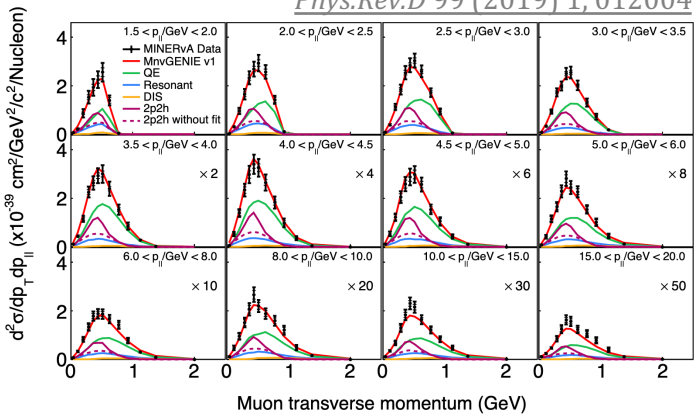


Where are we today?

We've come a long way since NuPhys 2019!

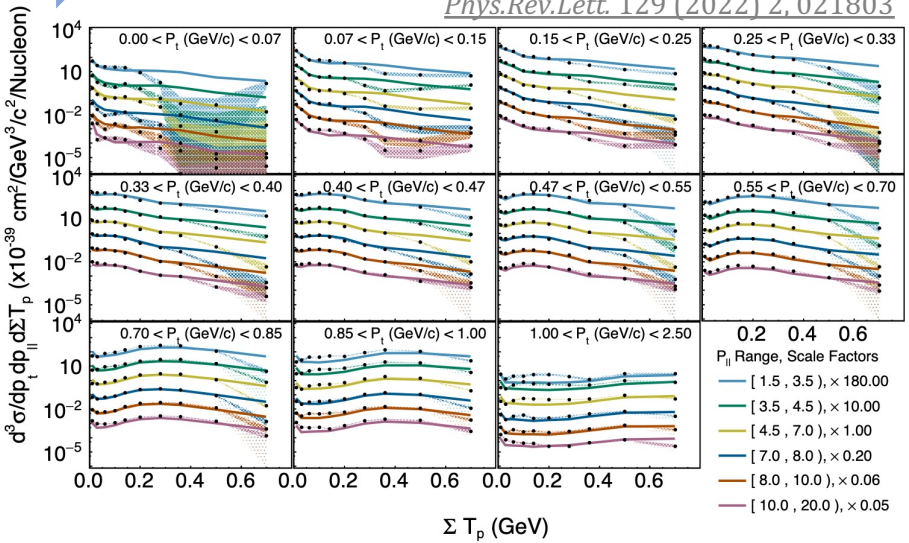
100k evts 2D muon kinematics

Phys.Rev.D 99 (2019) 1, 012004



~2M evts 3D muon kinematics +$\sum T_p$

Phys.Rev.Lett. 129 (2022) 2, 021803



+many new measurements (different targets, π-prod…)

We've come a long way since NuPhys 2019!

100k evts 2D muon kinematics

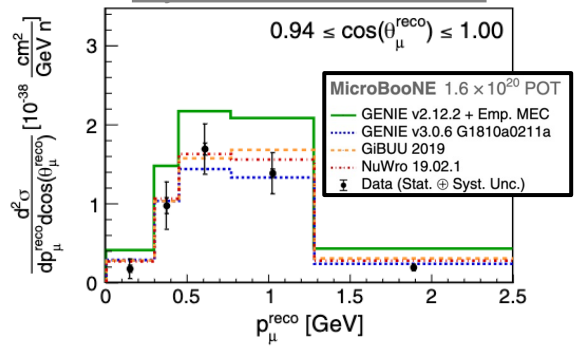
First inclusive measurements on LAr (**~27k evts**)

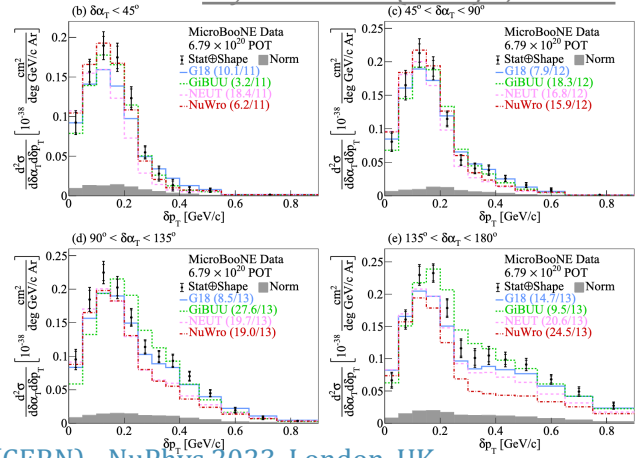
~2M evts 3D muon kinematics +$\sum T_p$

>500k $\nu - Ar$ events
>10 publications
1D, 2D, 3D, multiple topologies

Phys.Rev.D 108 (2023) 5, 053002

Phys. Rev. Lett. 123, 131801





2D TKI measurements, 3D differential cross section, pion production, rare channels (Λ, η)…

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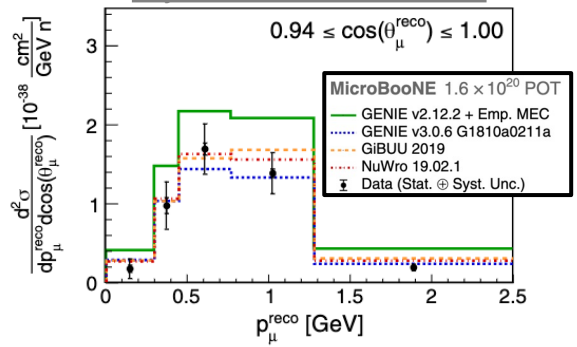
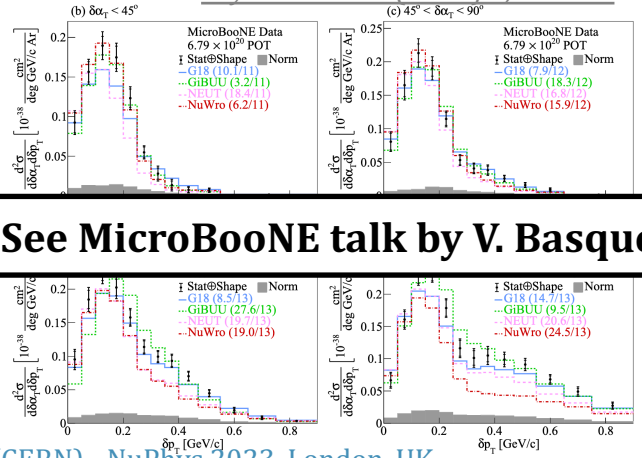
Phys.Rev.D 108 (2023) 5, 053002

Phys. Rev. Lett. 123, 131801





See MicroBooNE talk by V. Basque

2D TKI measurements, 3D differential cross section, pion production, rare channels (Λ, η)…

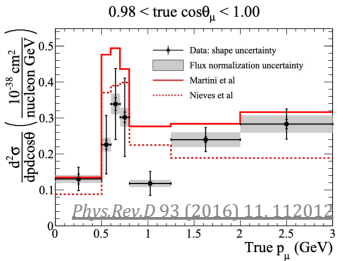
We've come a long way since NuPhys 2019!

100k evts 2D muon kinematics

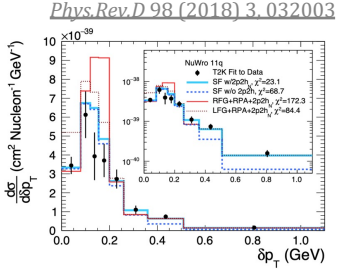
~2M evts 3D muon kinematics $+\sum T_p$

First inclusive measurements on LAr (**~27k evts**)

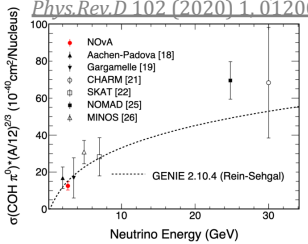
>500k $\nu - Ar$ events
>10 publications
1D, 2D, 3D, multiple topologies



Phys.Rev.D 93 (2016) 11, 112012



Phys.Rev.D 98 (2018) 3, 032003

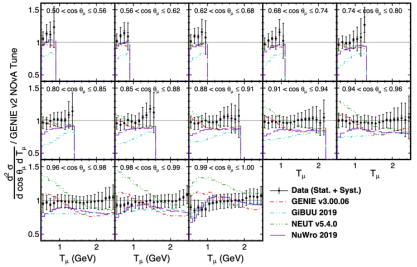


Phys.Rev.D 102 (2020) 1, 012004

arXiv:2303.14228

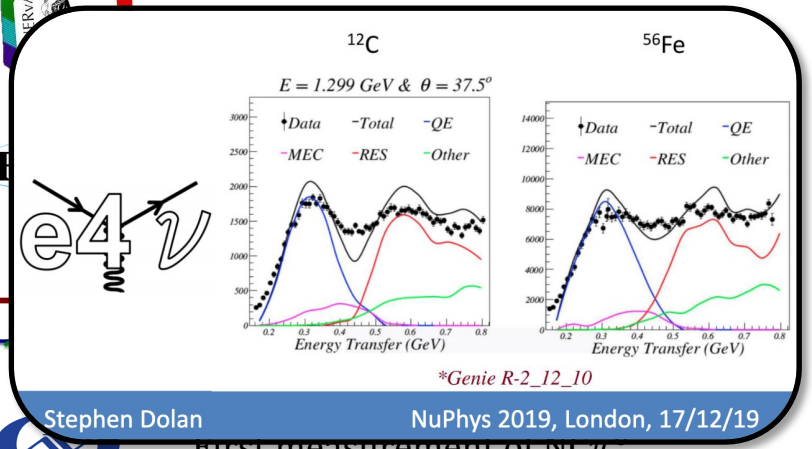
Wealth of joint measurements:
C/O, $\nu_\mu/\bar{\nu}_\mu$, on/off-axis detectors

Phys.Rev.D 107 (2023) 5, 052011



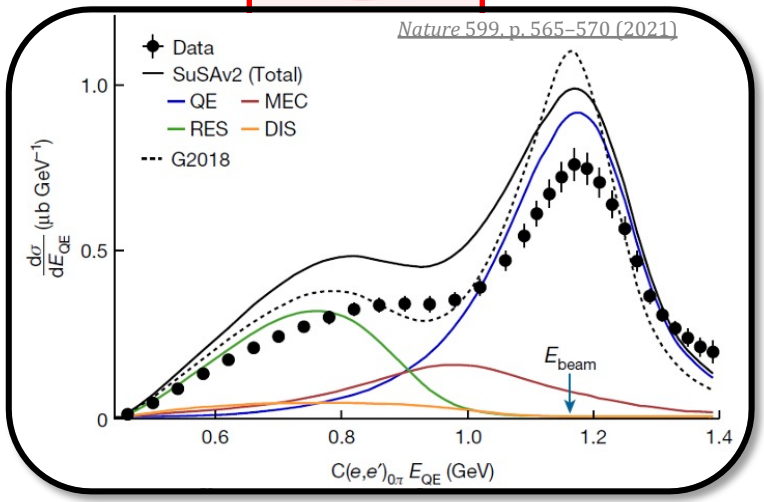
2D ν_μ CC inclusive, ν_e CC inclusive, CCπ^0 & more in the pipeline!

We've come a long way since NuPhys 2019!



First measurement of NCπ^{0} cross section

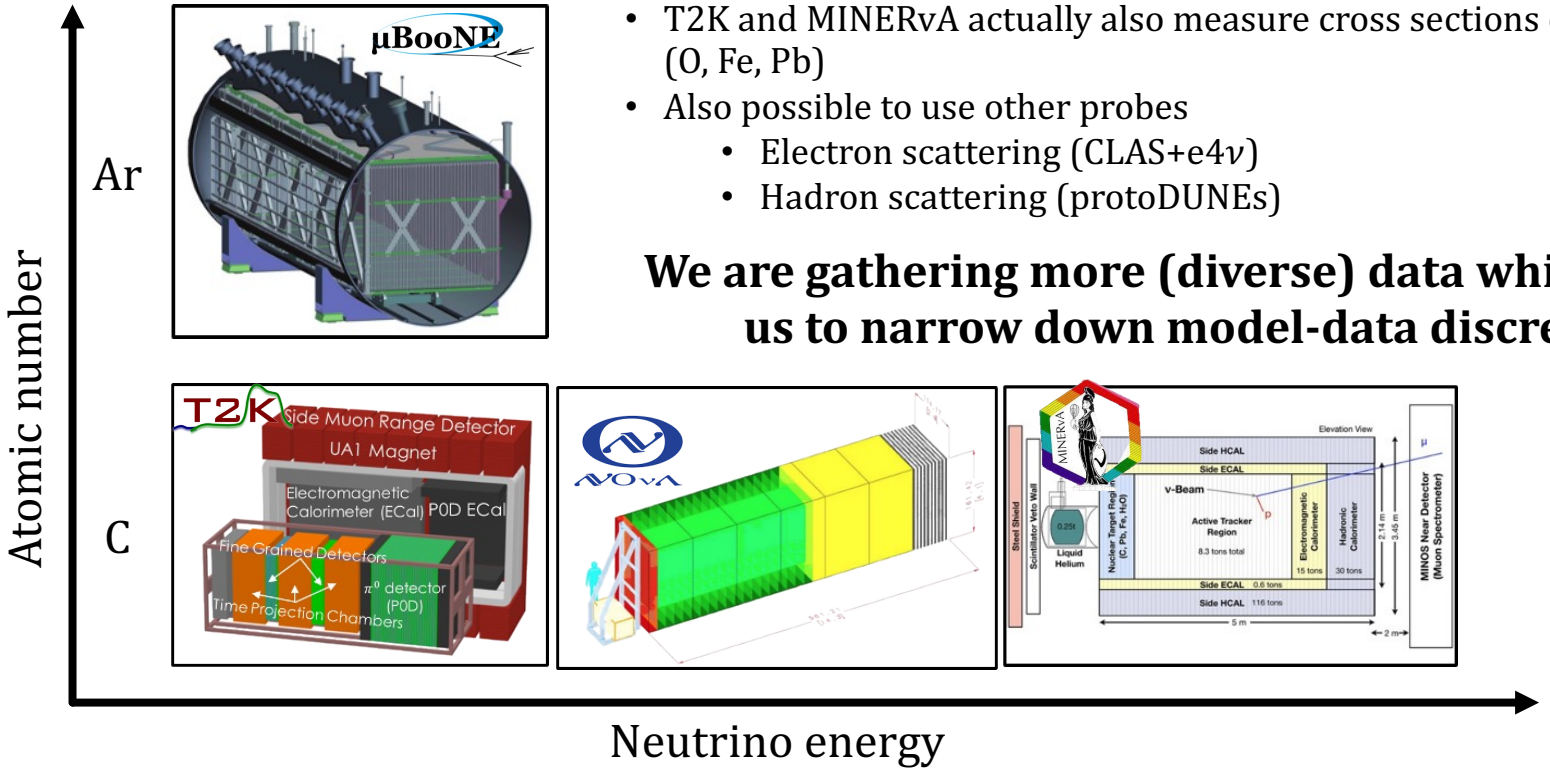
Just beginning to probe CLAS $ee'p$ data



& more in the pipeline!

Nature publication confronting generator predictions with $ee'p$ data and more to come!

Probing the full phase space



- T2K and MINERvA actually also measure cross sections on other targets (O, Fe, Pb)
- Also possible to use other probes
  - Electron scattering (CLAS+e4ν)
  - Hadron scattering (protoDUNEs)

We are gathering more (diverse) data which will allow us to narrow down model-data discrepancies

Some recent highlights

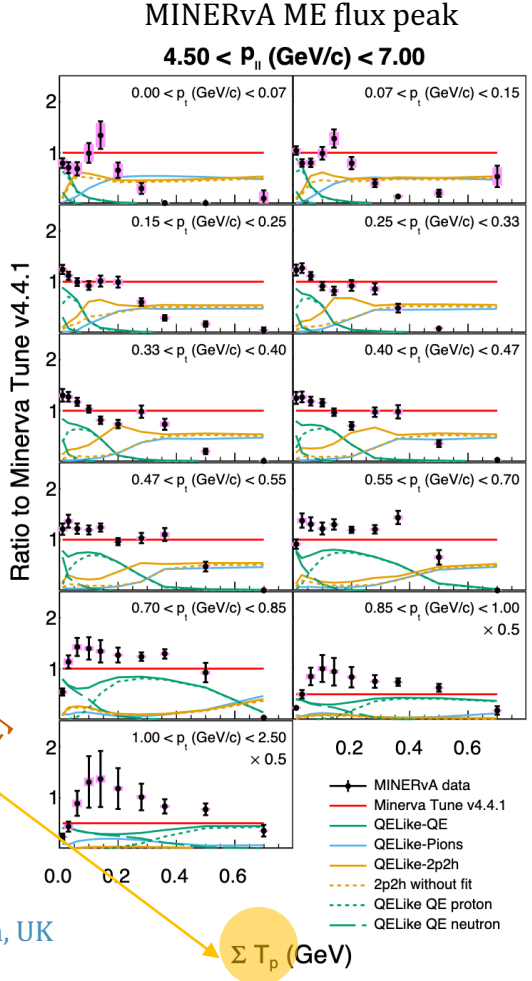
(sorry, I cannot cover all new measurements in 30 mins!)

Calorimetric measurements

NOvA and DUNE (will) use calorimetric energy estimators

$$E_\nu = E_{lep} + \sum T_p + \sum T_{\pi^\pm} + E_{\gamma/\pi^0}$$

Proxy for energy transfer in QE



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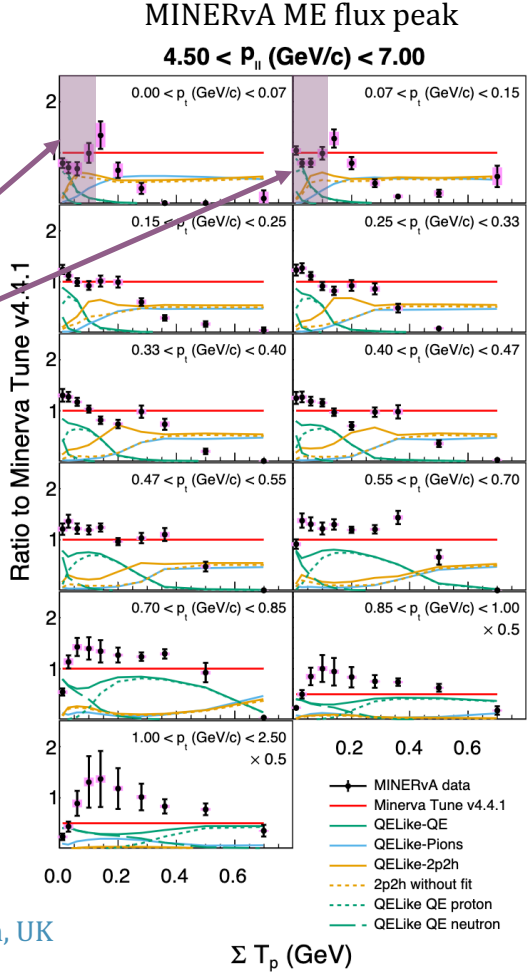
- Low energy transfer suppression needed (consistent with inclusive measurements)



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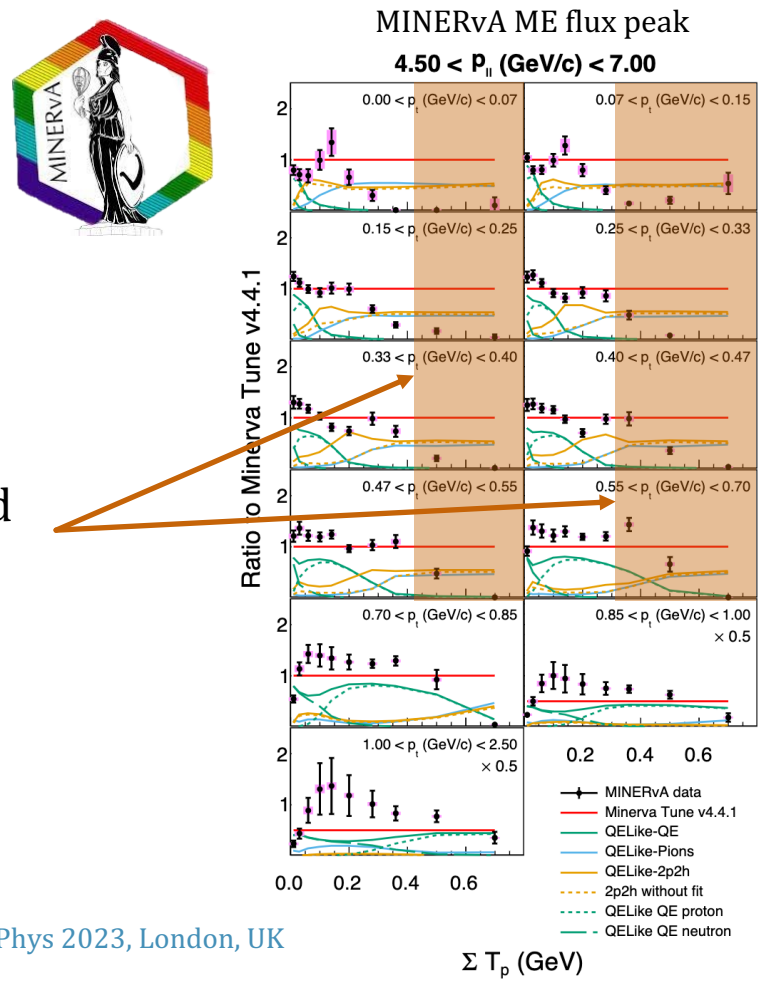
- Significant overestimation of 0π background processes (2p2h, π-absorption…)



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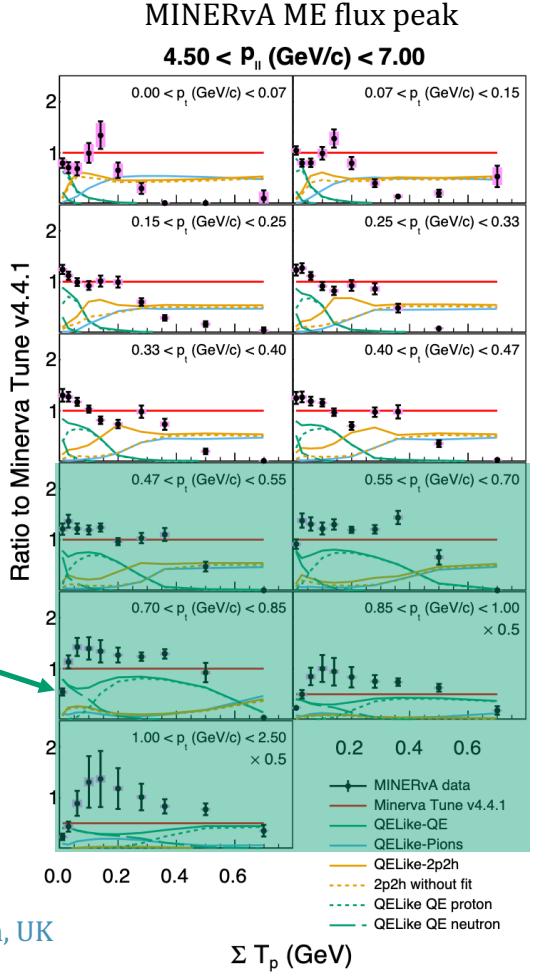

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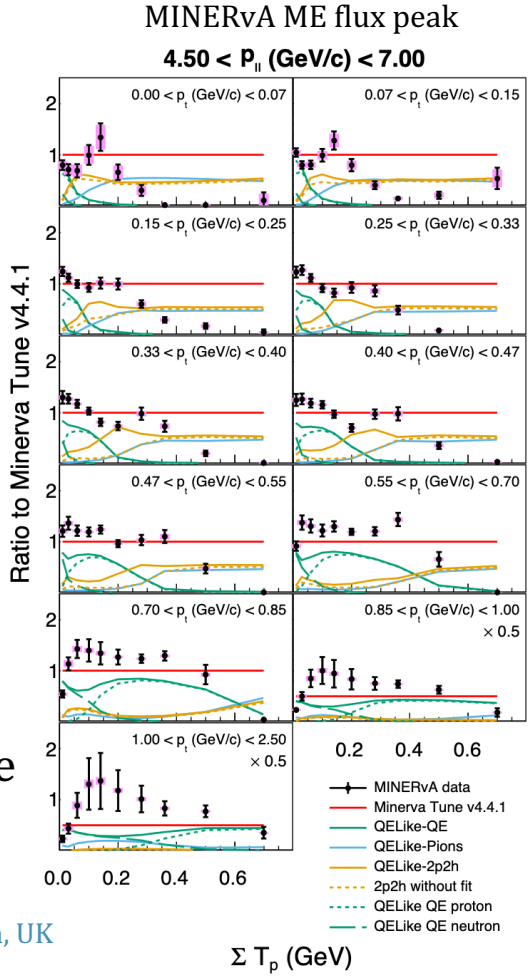
- Neutron producing FSI effects underpredicted

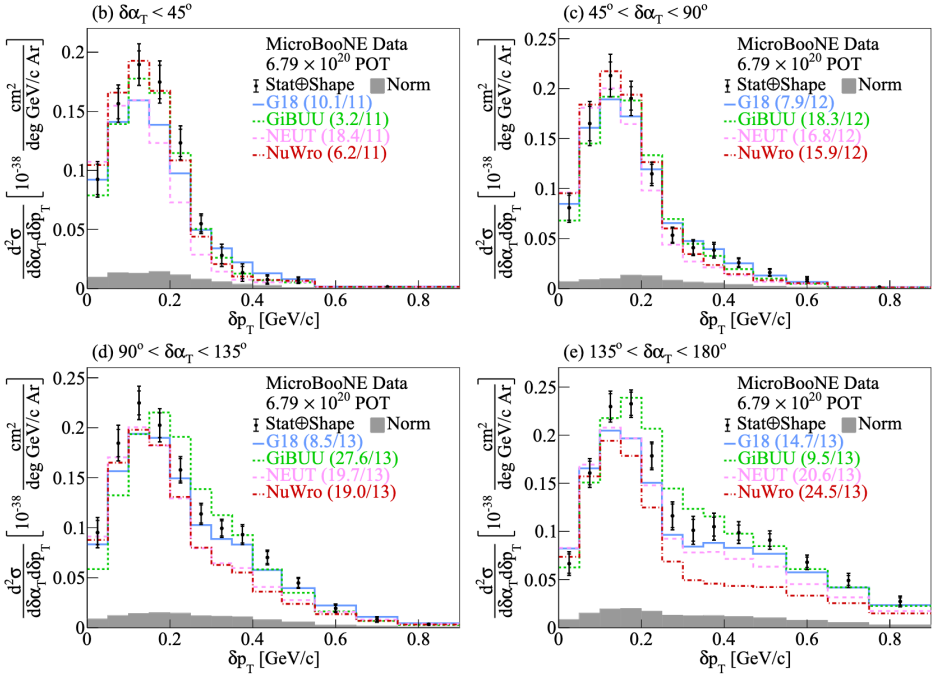
Wealth of information (incl. energy dependence) to analyze

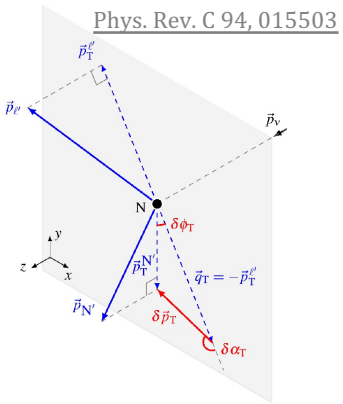
Highlights critical model issues relevant for DUNE



Kinematic imbalance

First 2D measurement of Transverse Kinematic Imbalance (TKI) on Ar





Phys.Rev.D 108 (2023) 5, 053002

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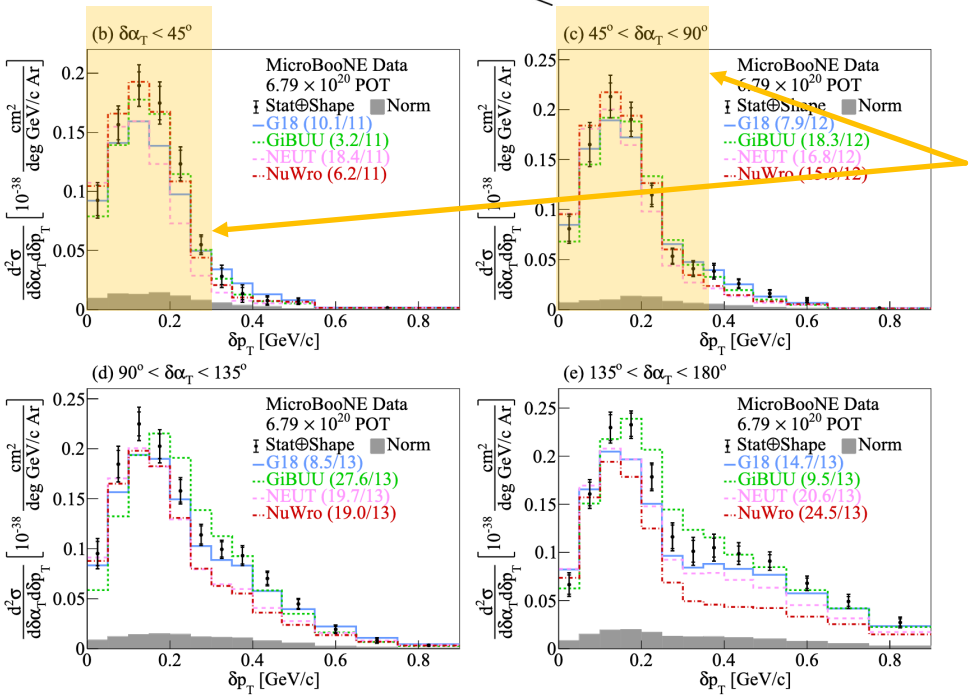
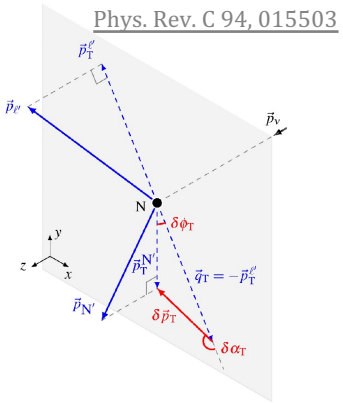


Bulk @ low $\delta\alpha_T$ is sensitive to **Fermi motion**

Phys. Rev. C 94, 015503



Phys.Rev.D 108 (2023) 5, 053002

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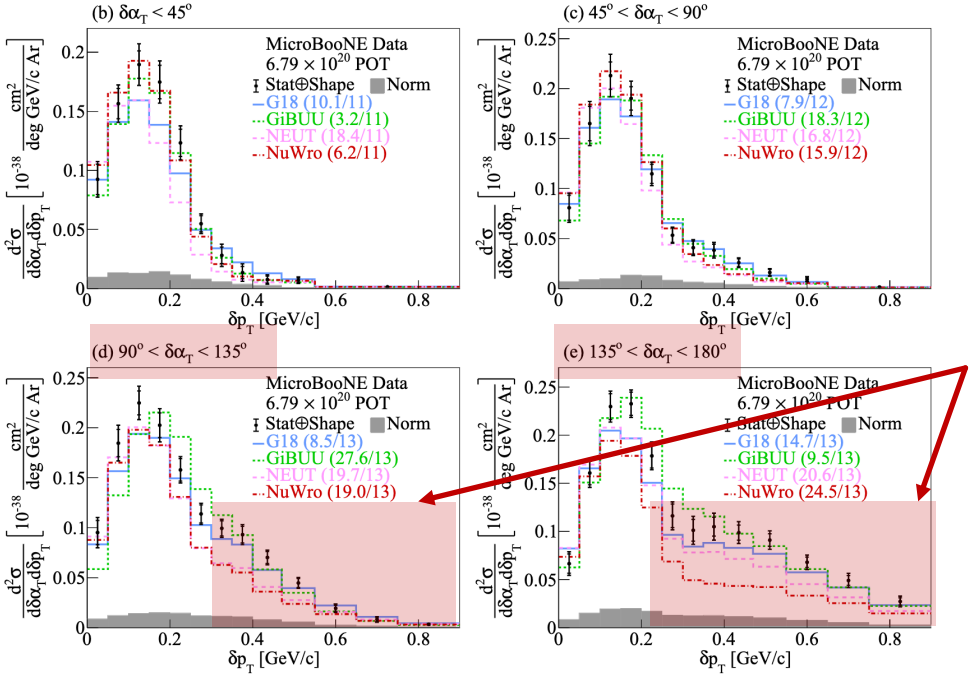

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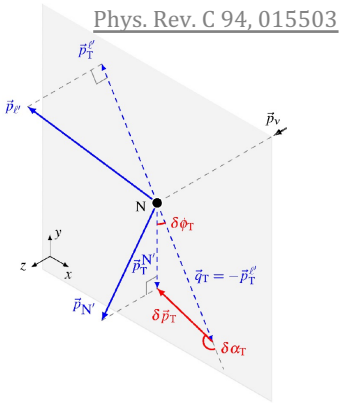
Phys. Rev. C 94, 015503



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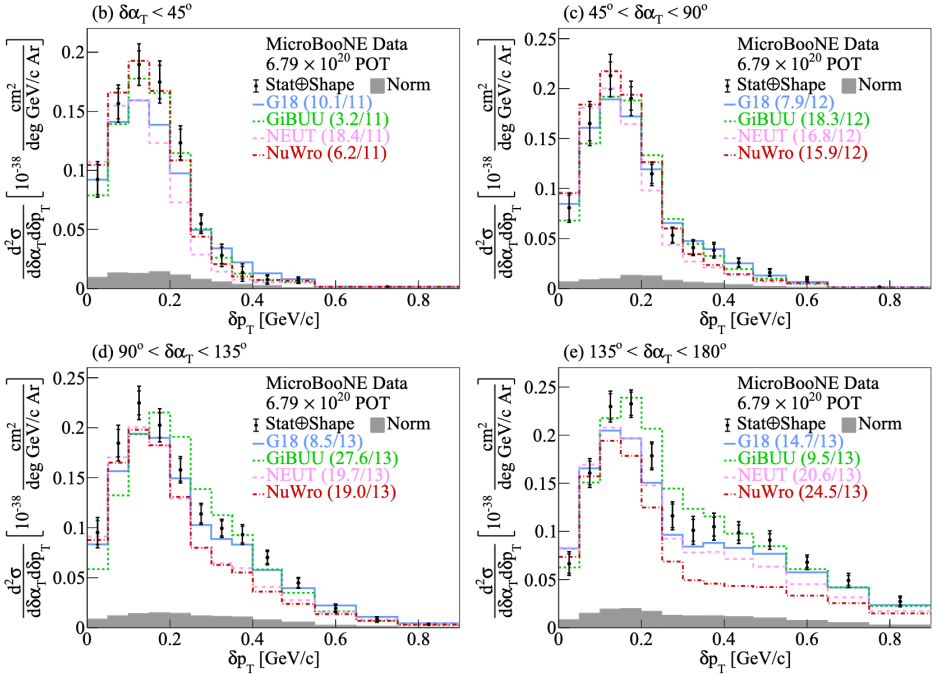

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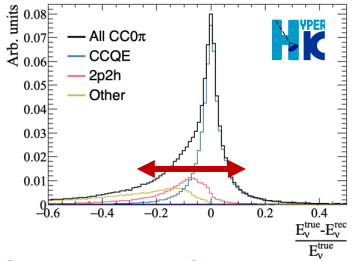
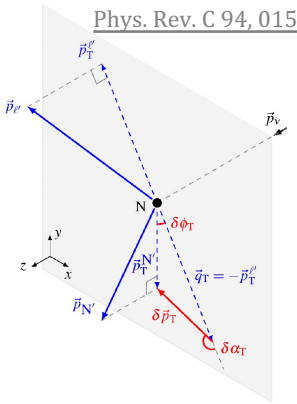


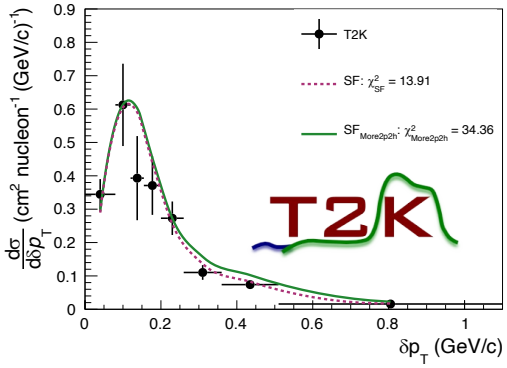
Dominant source of bias for T2K/HK and for ~1/3 of DUNE interactions

Phys. Rev. C 94, 015503



Phys.Rev.D 108 (2023) 5, 053002

Completing the puzzle



Benhar SF model

+20% 2p2h strength

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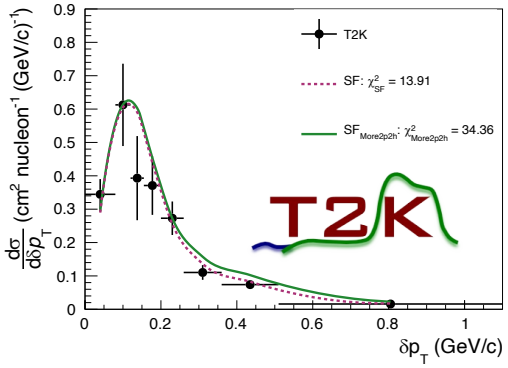
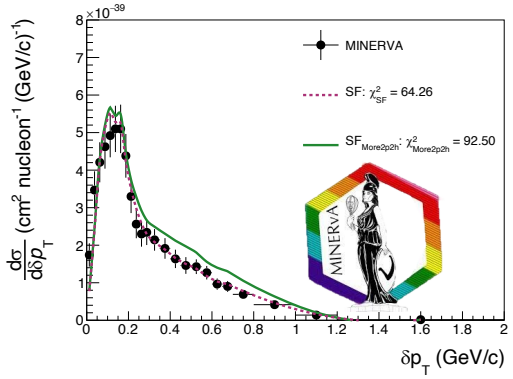


Same target,
higher energy



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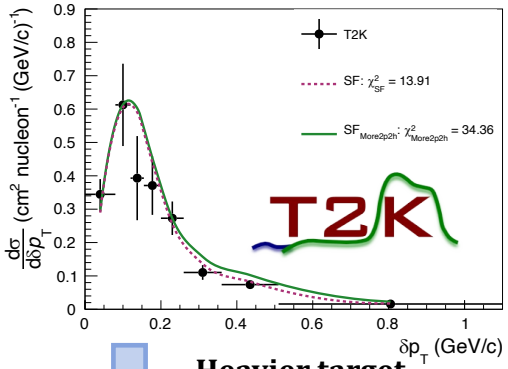

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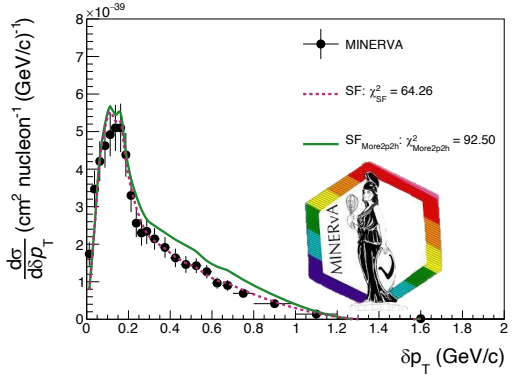

Benhar SF model
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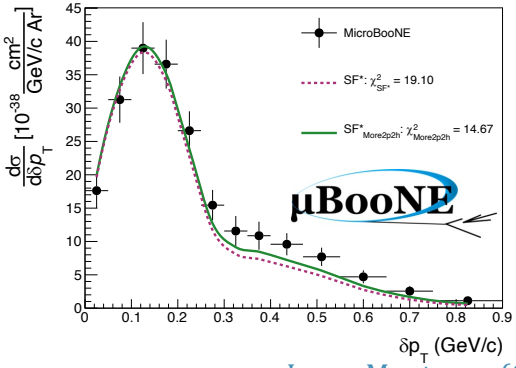
Heavier target,
similar energy



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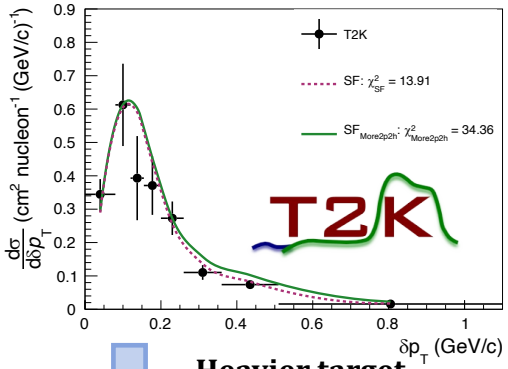

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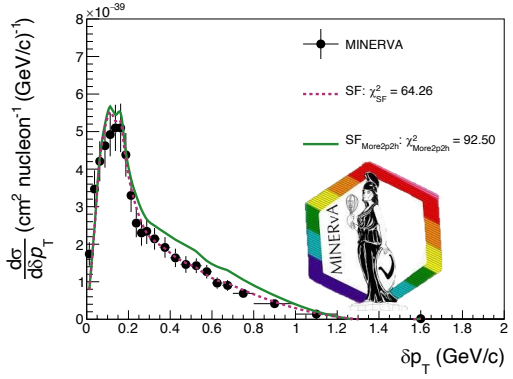

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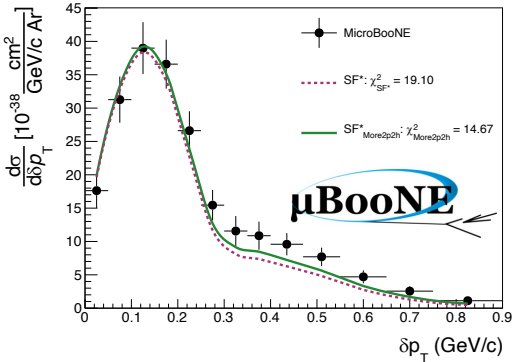
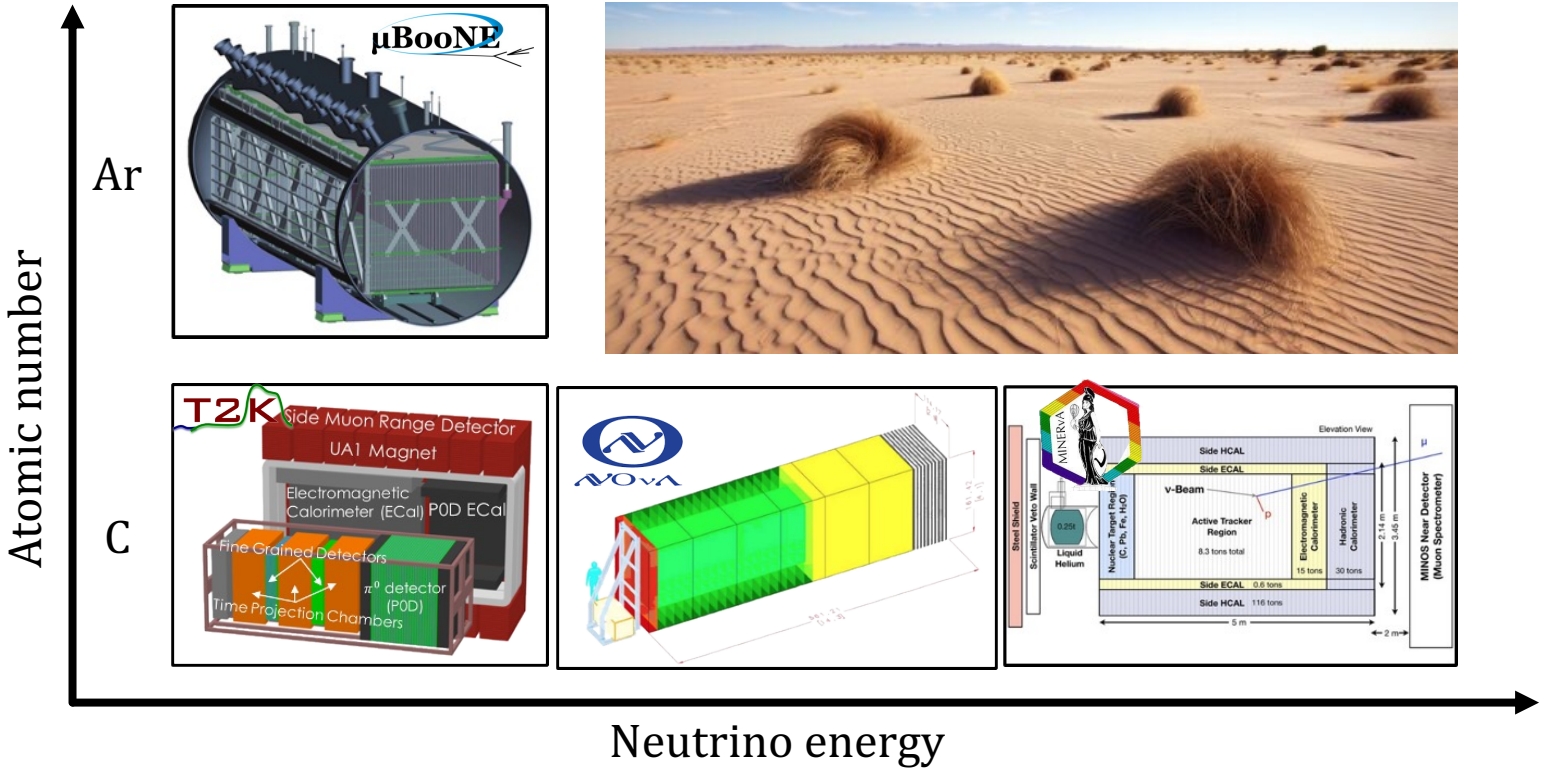


Same variable, different experiments:

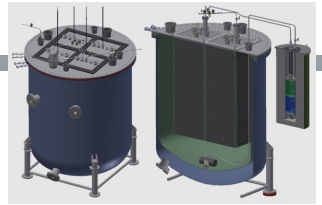
- T2K & MINERvA don't require 2p2h enhancement (consistent with 3D measurement overprediction!)
- MicroBooNE seems to require an even larger enhancement
- Issue with A-scaling for non-QE?

Recipes for success

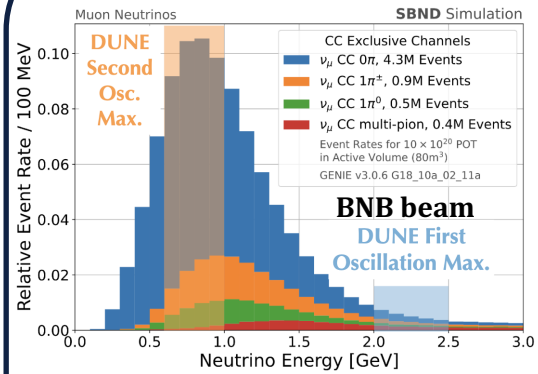
Probing the full phase space



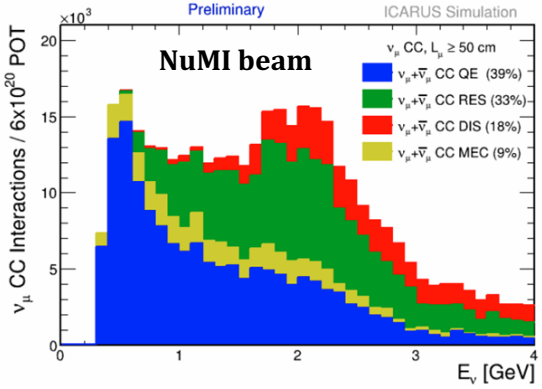
New measurements on Ar



L.Yates @ NuINT2022

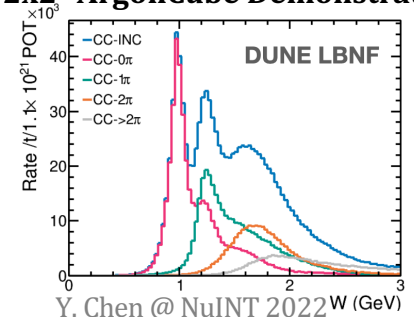


S. Dolan @ NuINT2022

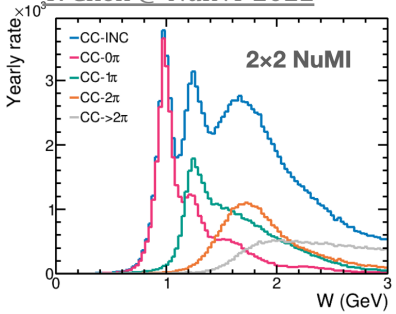


Imminent high statistics measurements on LAr

"2x2" ArgonCube Demonstrator

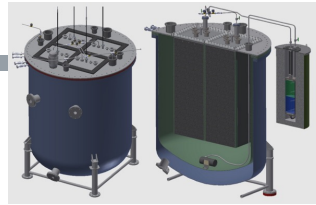


Y. Chen @ NuINT 2022

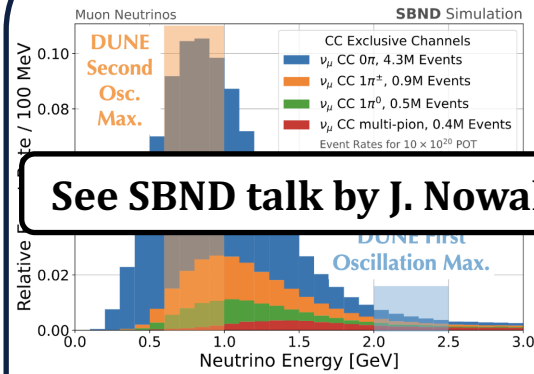


New measurements targeting π-production region

New measurements on Ar

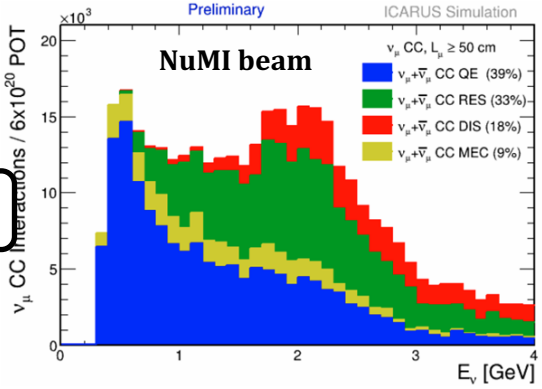


L.Yates @ NuINT2022



See SBND talk by J. Nowak

S. Dolan @ NuINT2022



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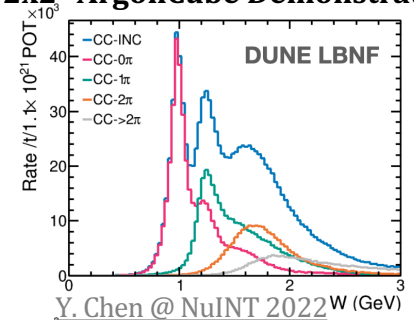
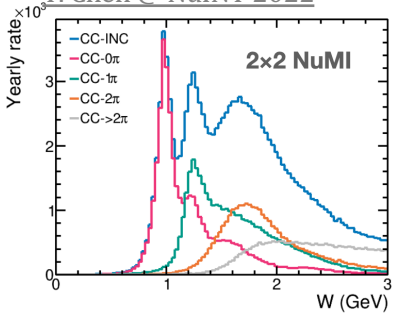
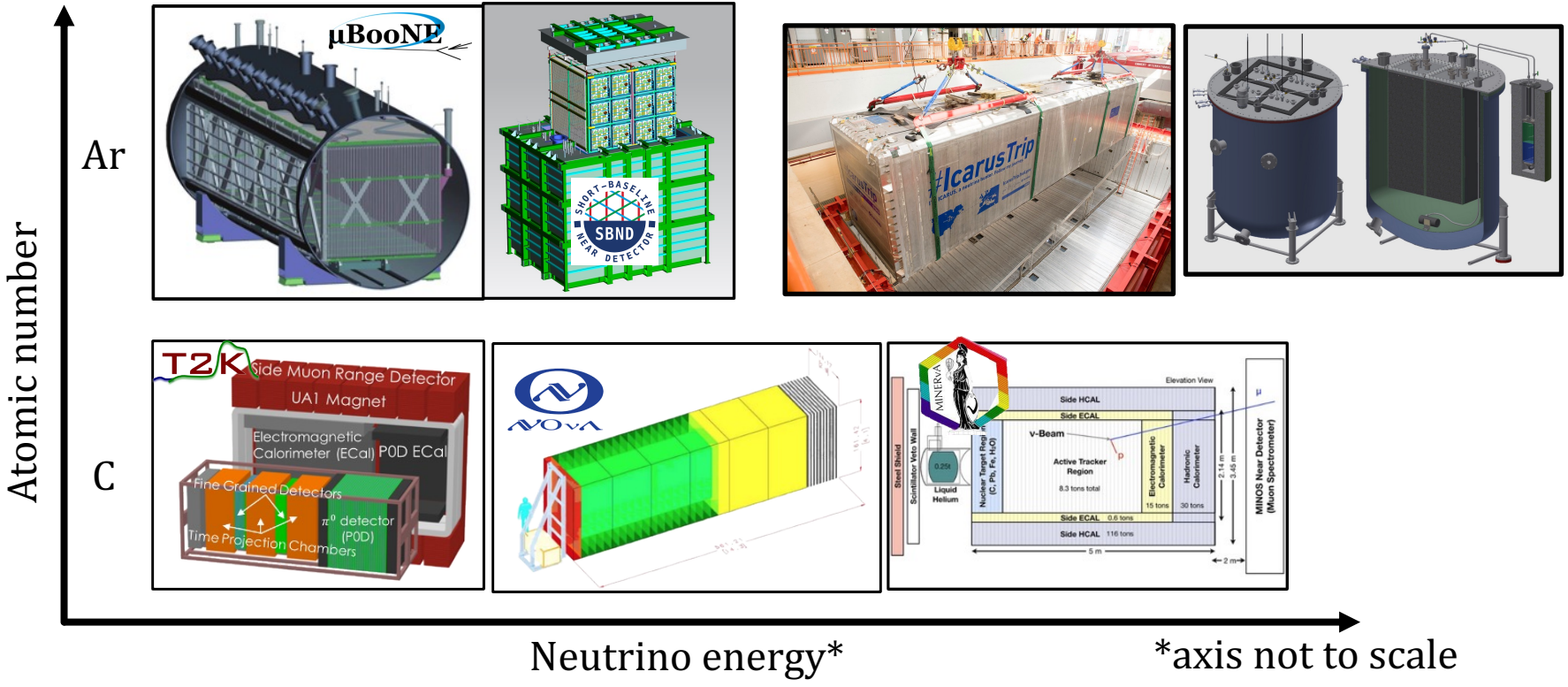


Y. Chen @ NuINT 2022



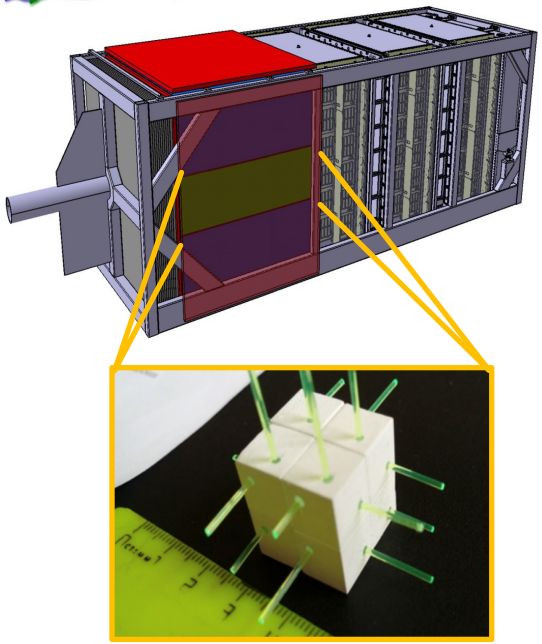
New measurements targeting π-production region

Really probing the full phase space



Detailed measurements

ND280 Upgrade

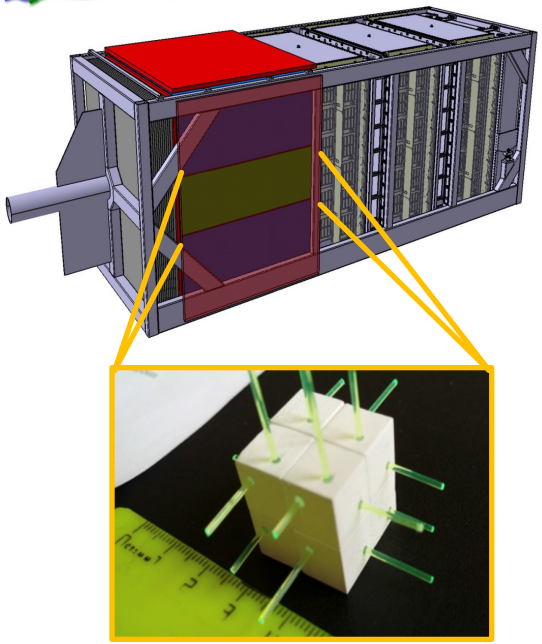


Super Fine-Grained detector
2M 1cm^3 scintillator cubes

Detailed measurements

See T2K talk by S. Dolan

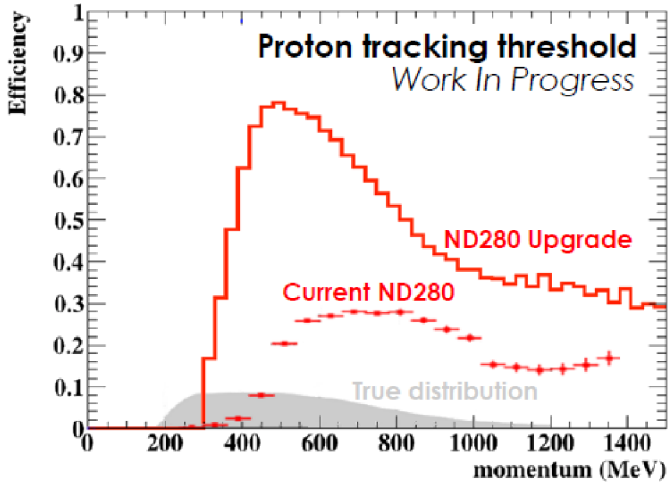
ND280 Upgrade



Super Fine-Grained detector
2M 1cm^3 scintillator cubes

High-precision CC0π-focused measurements

- **Well understood detector** technology
- **Low** particle detection **thresholds**



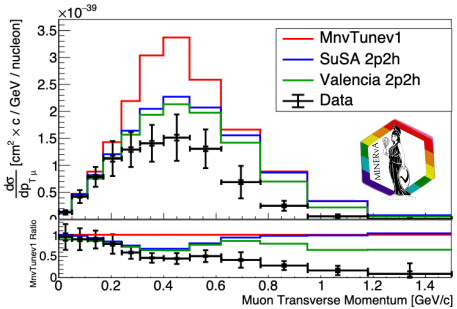
Phys.Rev.D 105 (2022) 3, 032010

Neutrons! Neutrons! Neutrons!

Critical to measure neutrons for DUNE precision goals

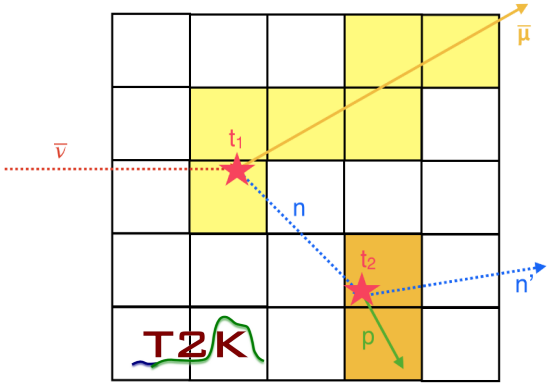
- Fraction of invisible energy carried by neutrons
- Using neutrons to measure nucleon-level effects + neutrino flux?

Cross section of events with final state neutrons



arXiv:2310.17014

Neutron **detection** and **energy measurement** in T2K ND280 Upgrade



Phys.Rev.D 101 (2020) 9, 092003

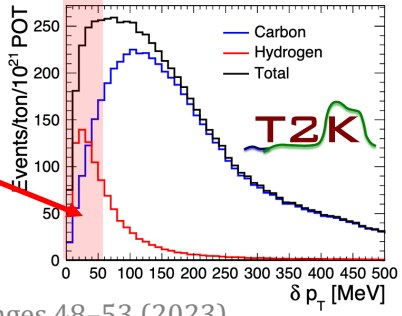
Hydrogen tagging

arXiv 2310.15633

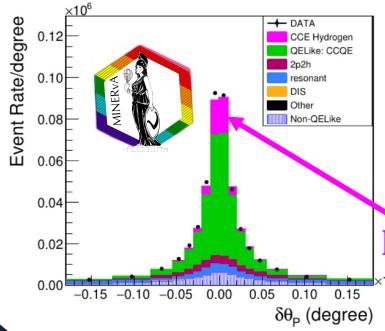
Phys.Rev.D 101 (2020) 9, 092003

Proposed method

~60% H purity



Nature 614, pages 48–53 (2023)

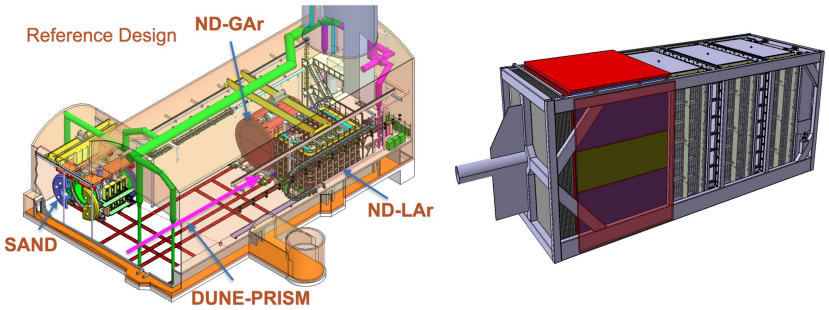


First measurement

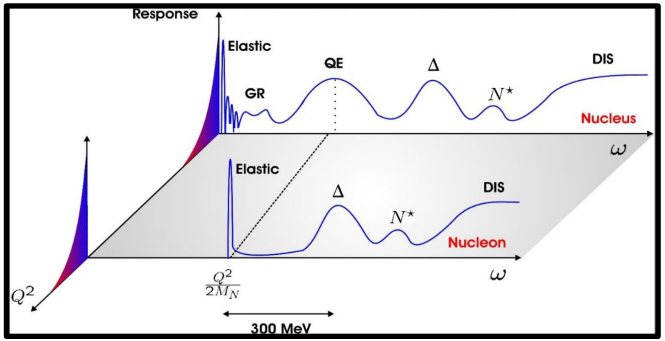
H contribution

Beyond dedicated cross-section measurements

Capable near detectors



Strong ties with theory community



Plot from N. Jachowicz

Essential to constrain neutrino flux+cross-section effects *in situ*

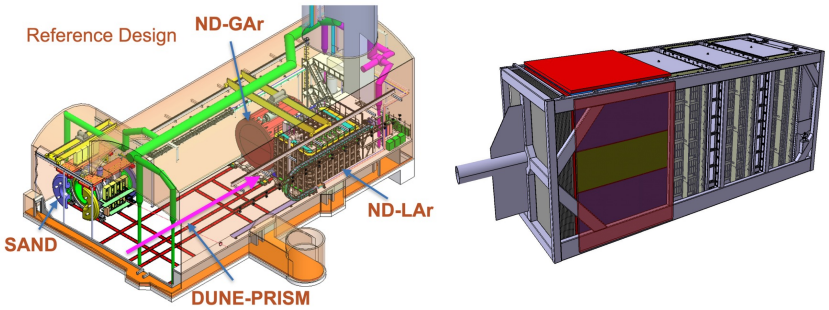
New models (SF, SuSAv2, CRPA, etc..) → **Implement in generators & compare with data!**

Identify **unknown unknowns**

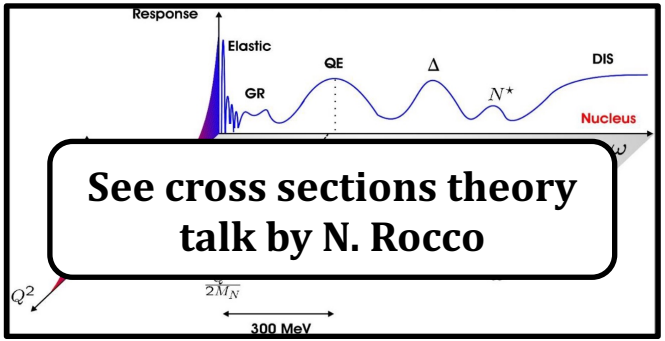
Tune **known unknowns**

Beyond dedicated cross-section measurements

Capable near detectors



Strong ties with theory community



See cross sections theory talk by N. Rocco

Plot from N. Jachowicz

Essential to constrain neutrino flux+cross-section effects *in situ*

New models (SF, SuSAv2, CRPA, etc..) → **Implement in generators & compare with data!**

Identify **unknown unknowns**

Tune **known unknowns**

Summary and outlook

- Neutrino oscillation physics is entering the precision measurement era
- Future-generation experiments will be dominated by systematic uncertainties
- A precise control of neutrino cross-section uncertainties is imperative to achieve their goals
- Lots of progress in measuring neutrino cross sections since 2019
- But we still have a long way to go
- Need high statistics, highly-differential and robust measurements in the next few years
- Rely on strong collaboration with theory community and capable near detectors

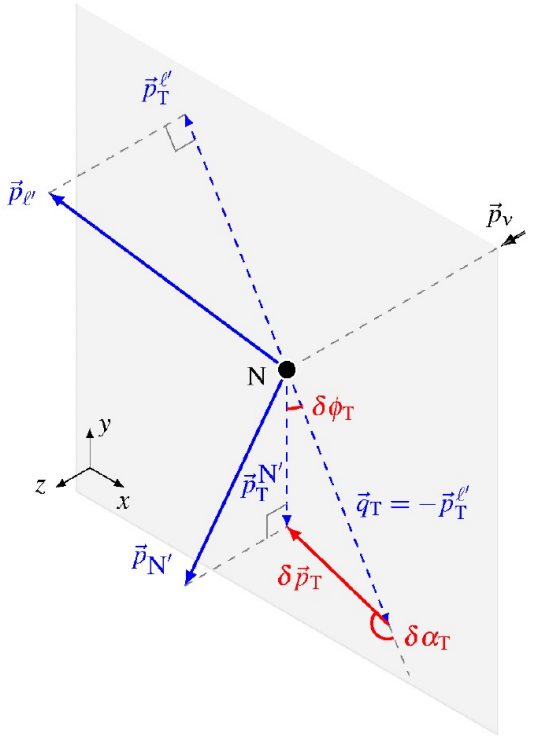
Thank you for your attention!

Supplementary material

Long-baseline oscillation experiments

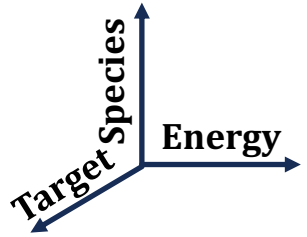
	Experiment	Beam Energy	Baseline	Near detector	Far detector
Current	T2K	600 MeV (Narrow)	~300 km	Scintillator bars+water	Water Cherenkov
	NOvA	1.2 GeV (Wide)	~800 km	Plastic scintillator	Plastic scintillator
Future	HYPER HK	600 MeV (Narrow)	~300 km	Scintillator cubes + TBD	Water Cherenkov
	DUNE	2.5 GeV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

Transverse Kinematic Imbalance

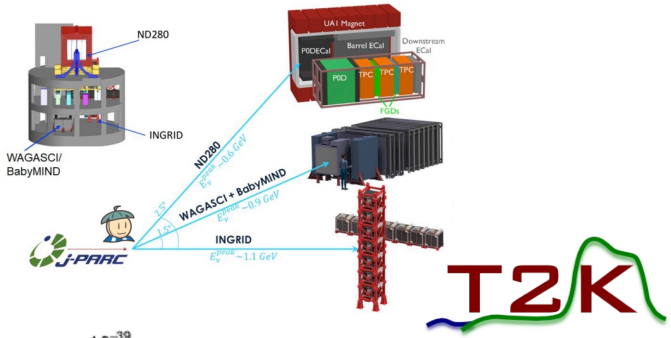


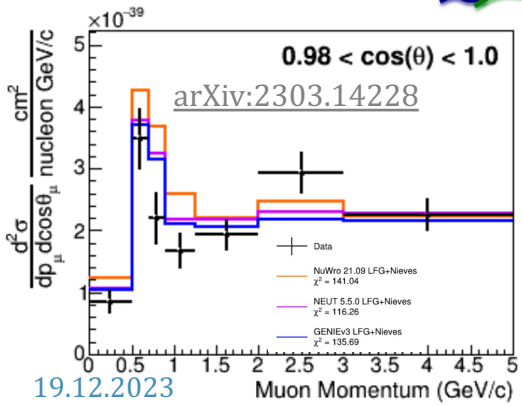
Phys. Rev. C 94, 015503

The era of joint measurements



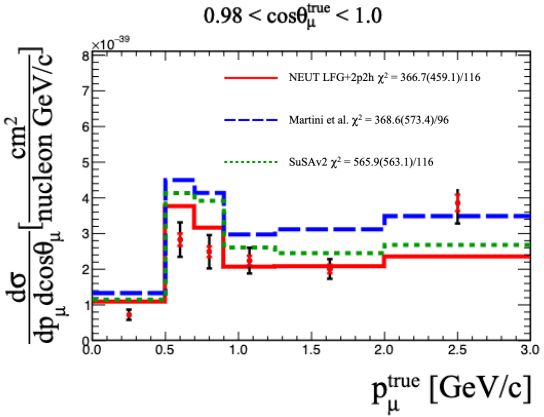
Joint on/off axis detectors
(probes energy dependence)



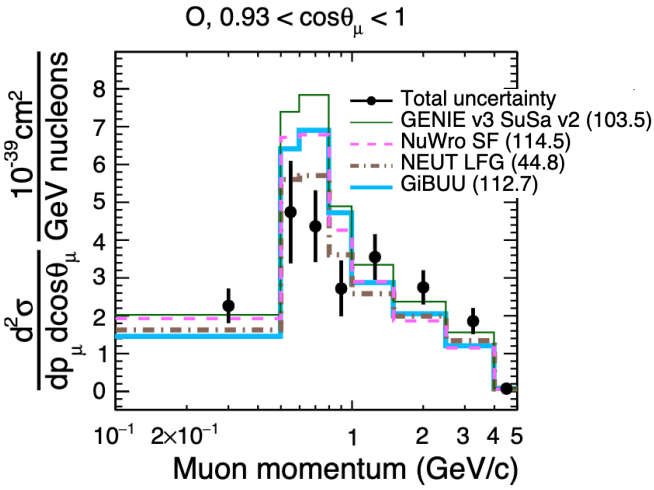


Joint $\nu_\mu/\bar{\nu}_\mu$ fluxes
(sensitivity to nuclear effects)

Phys.Rev.D 101 (2020) 11, 112001

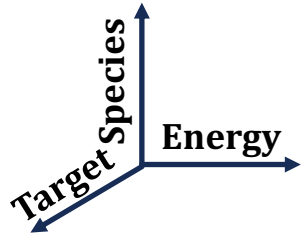


Joint C/O targets
(sensitivity to A-scaling)

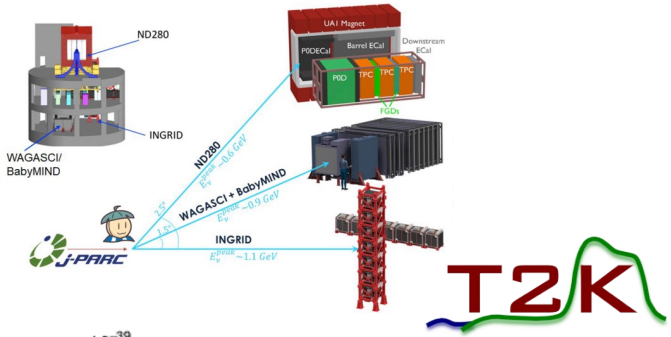


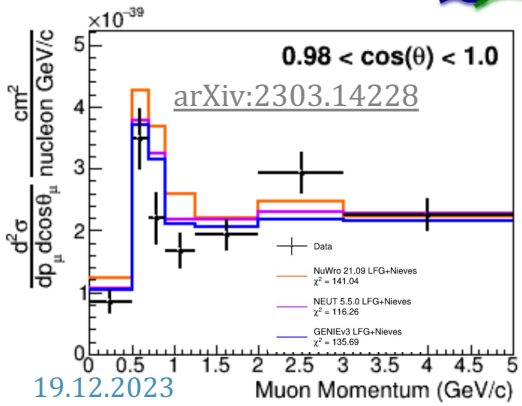
Phys.Rev.D 101 (2020) 11, 112004

The era of joint measurements



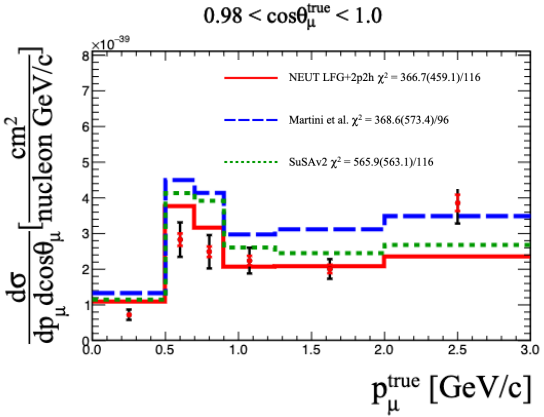
Joint on/off axis detectors
(probes energy dependence)





Joint $\nu_\mu/\bar{\nu}_\mu$ fluxes
(sensitivity to nuclear effects)

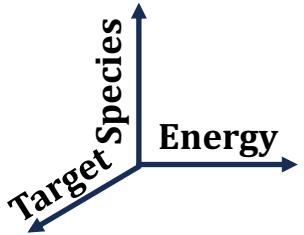
Phys.Rev.D 101 (2020) 11, 112001



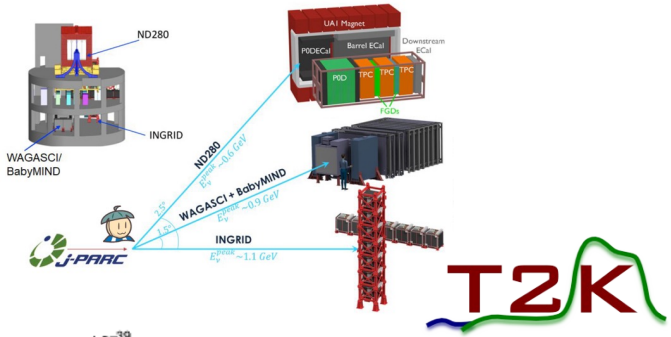
Agreement is not too bad with models **except at forward angles (low energy transfer region)**

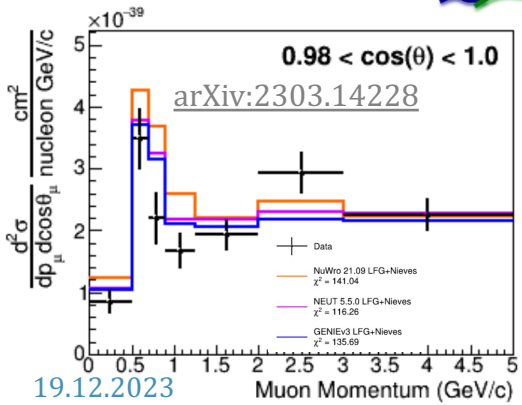
Dominant source of systematic uncertainty in current T2K and T2K+SK atmo. analyses
(equivalent to ~100% of syst error budget on Δm^2_{32})

The era of joint measurements



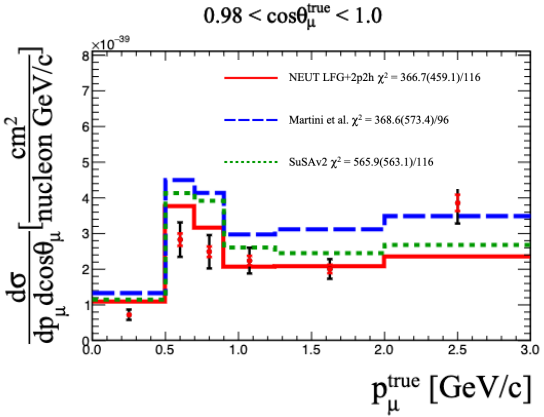
Joint on/off axis detectors
(probes energy dependence)





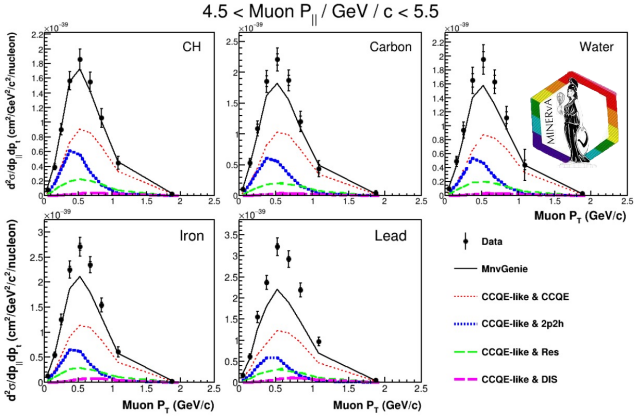
Joint $\nu_\mu/\bar{\nu}_\mu$ fluxes
(sensitivity to nuclear effects)

Phys.Rev.D 101 (2020) 11, 112001



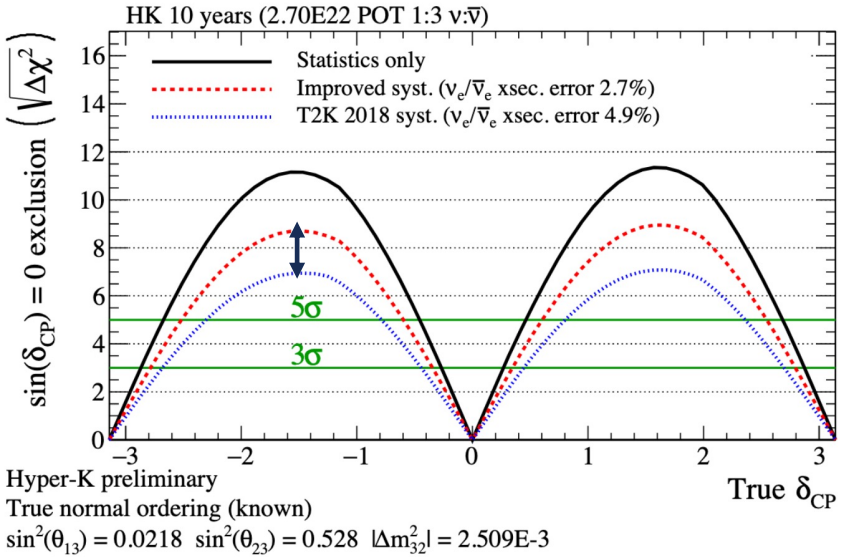
Joint target measurement
(A-scaling)

Phys.Rev.Lett. 130 (2023) 16, 161801



Agreement worsens as A increases…

Main challenge(s) for $\sin\delta_{CP} = 0$ exclusion



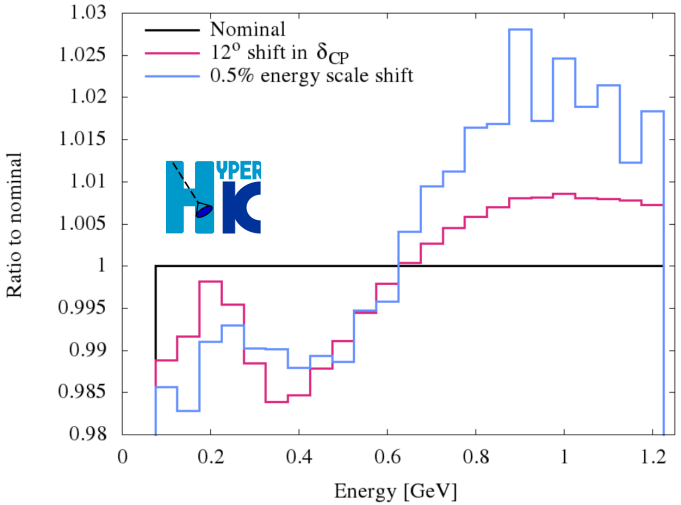
Dominant systematics related to the uncertainty on $\boldsymbol{\sigma(\nu_e)}$ **and** $\boldsymbol{\sigma(\nu_\mu)}$ **differences**

Current constraints mainly driven by theory

Prospects to significantly reduce theoretical uncertainties

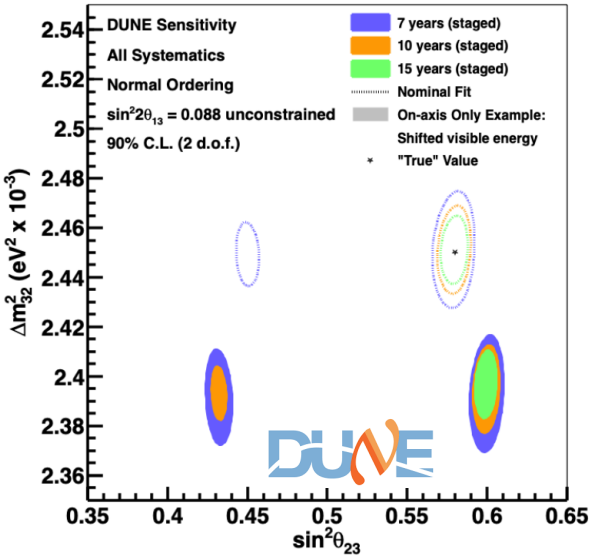
Nature Communications 13, 5286 (2022)
Phys.Rev.D 108 (2023) L031301

Main challenges for precision measurements



Energy scale like shift vs target precision on δ_{CP}

DUNE FD TDR



Bias in osc. parameter measurements due to shift in visible energy

Dominant systematics are those which affect the **shape** of the oscillated spectrum as a function of **reconstructed neutrino energy**