Neutrino-nucleus interaction uncertainties for future generation neutrino oscillation experiments

The road to precision measurements

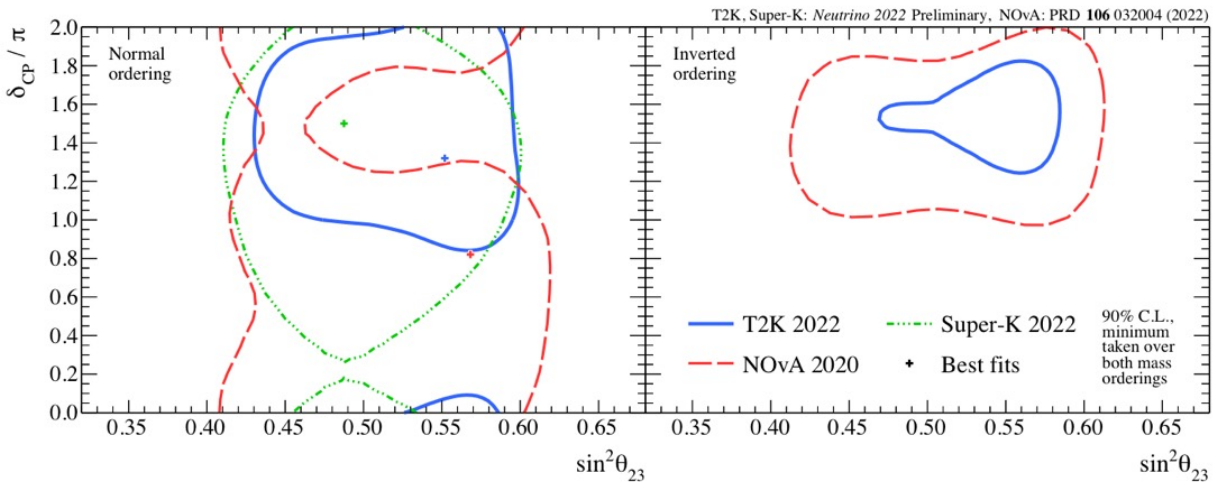
Laura Munteanu (CERN)

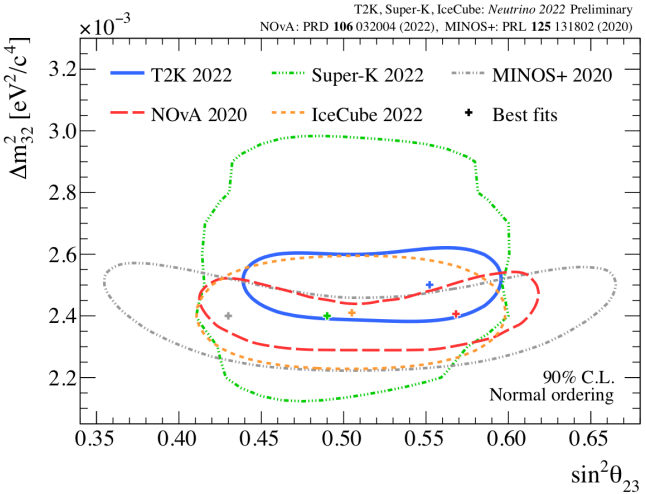
NuFACT 2023, Seoul, South Korea

21 August 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**

See also C. K. Jung's keynote talk

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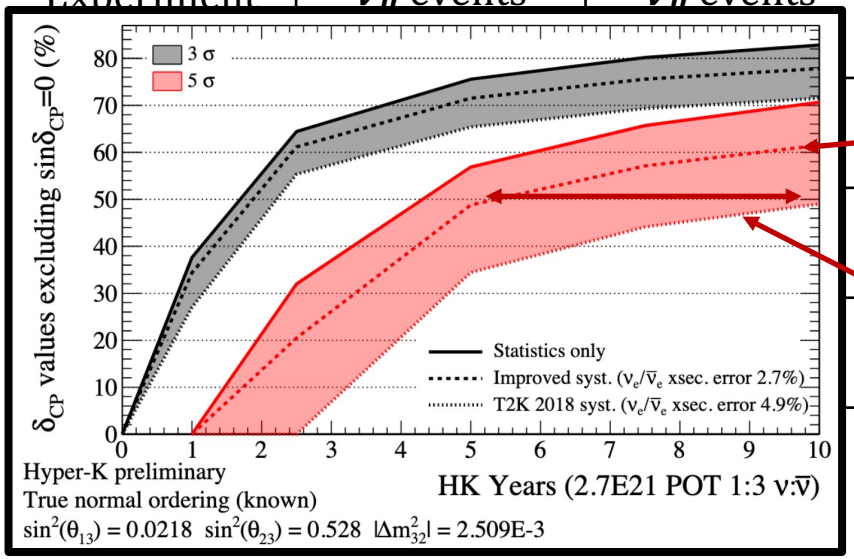
Hyper-K Kyper-K TDR	**~10000**	**~14000**	**~2000**	**~2000**	**?**
DUNE DUNE FD TDR	**~7000**	**~3500**	**~1500**	**~500**	**?**

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!

Are we prepared for future experiments?

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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

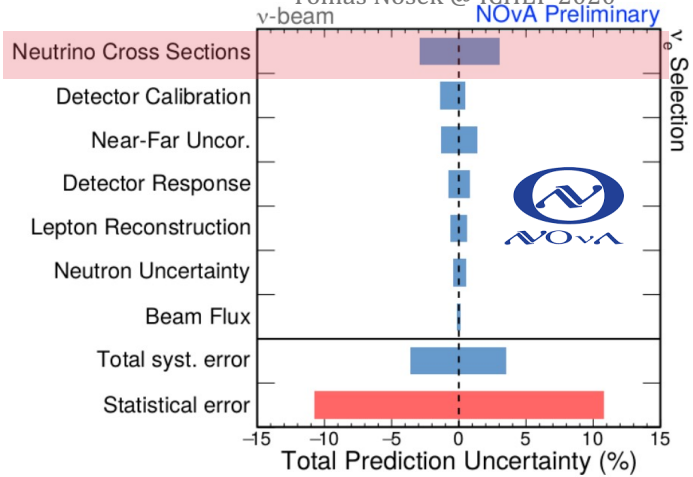
arXiv:2303.03222

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



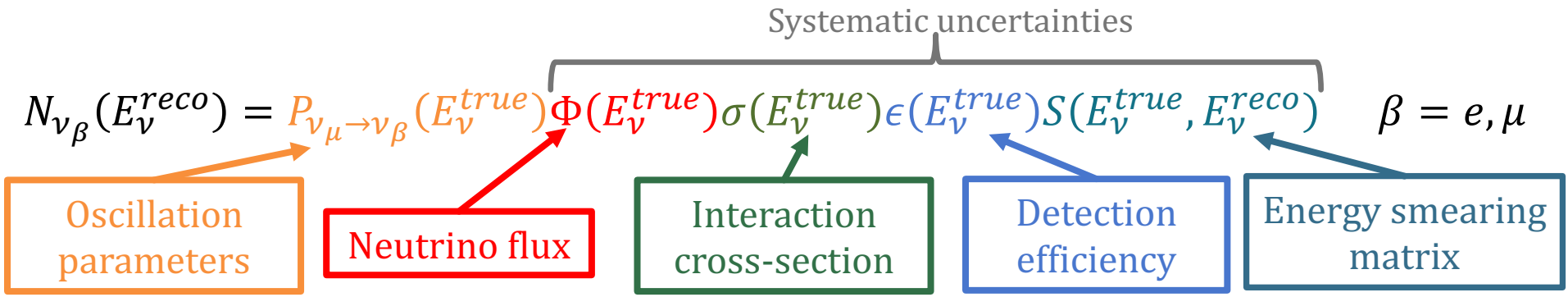
The description of **neutrino-nucleus interactions** is the **dominant source of systematic uncertainty** for oscillation measurements

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**



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

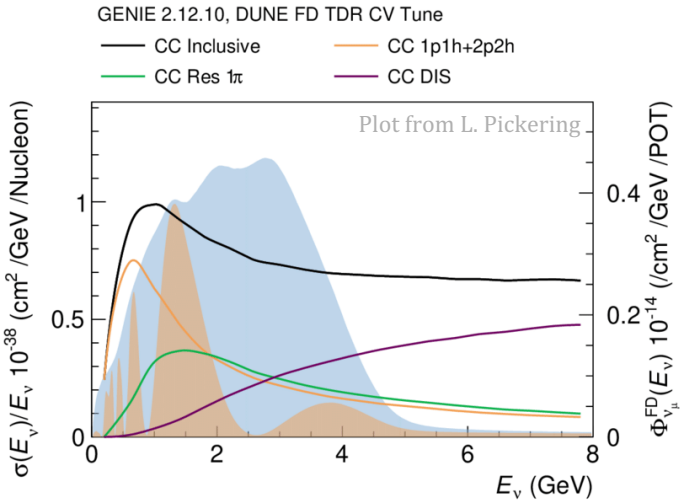
- Constrain systematics with **near detector**
- But **heavily rely on models** to predict near-to-far detector extrapolation

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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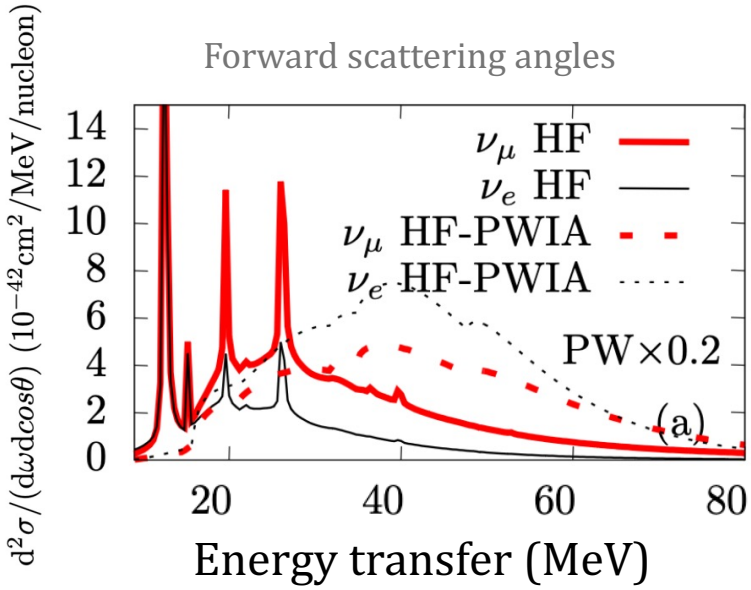
But we rely on models to predict:

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



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

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

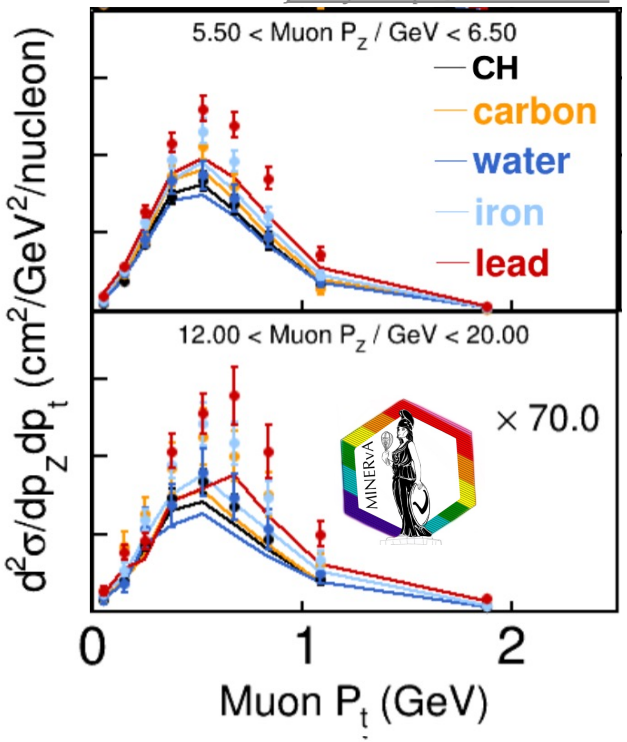
Oscillation analyses and model dependence

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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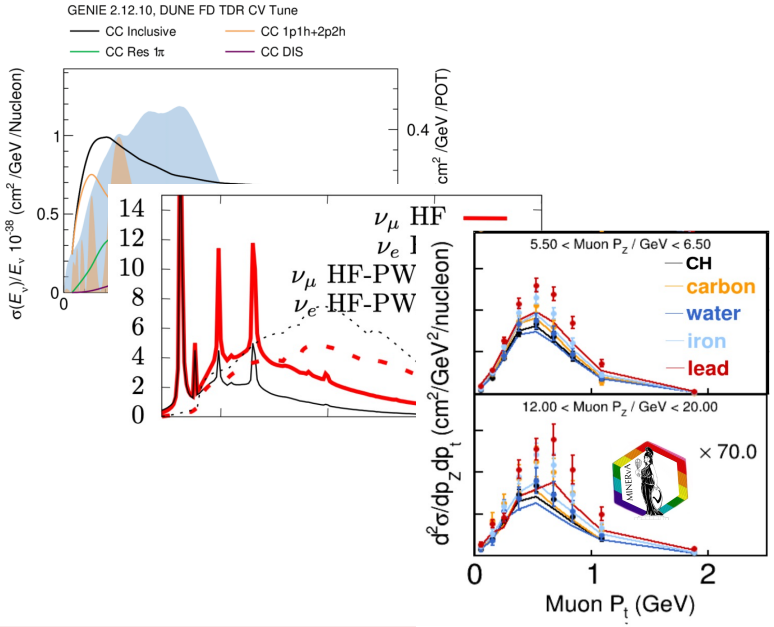
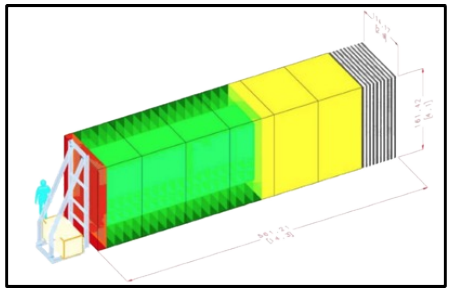
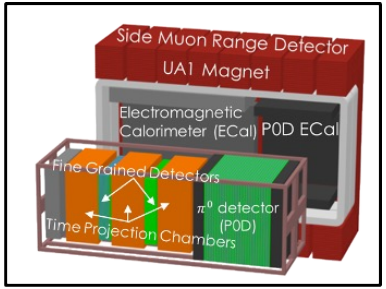


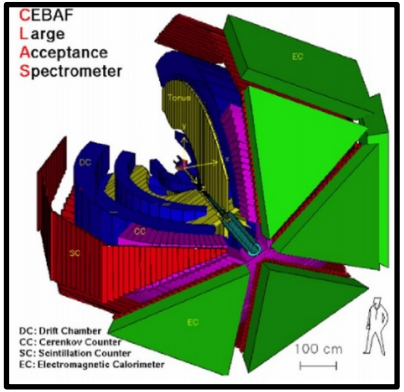
Model dependence <u>cannot</u> be escaped in neutrino oscillation experiments

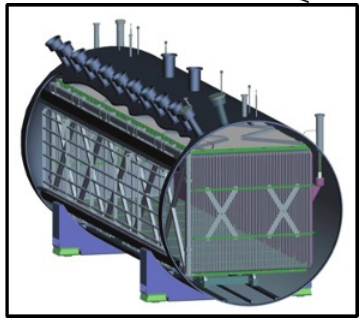
How do our models perform?

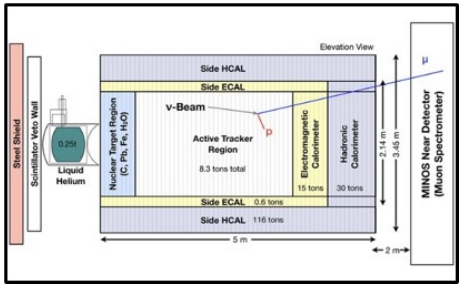
Experiments are providing us with large amounts of novel cross-section measurements





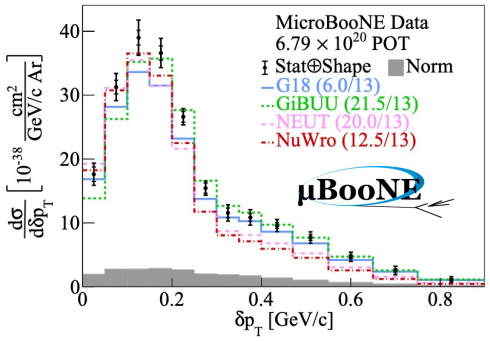




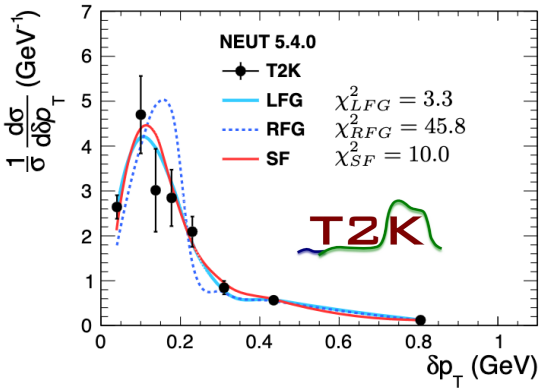


How do our models perform?

arXiv:2301.03700



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



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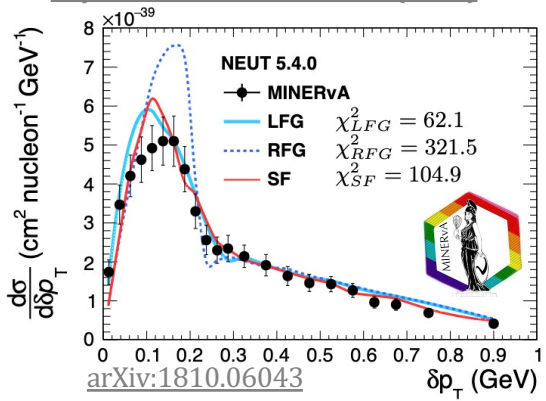

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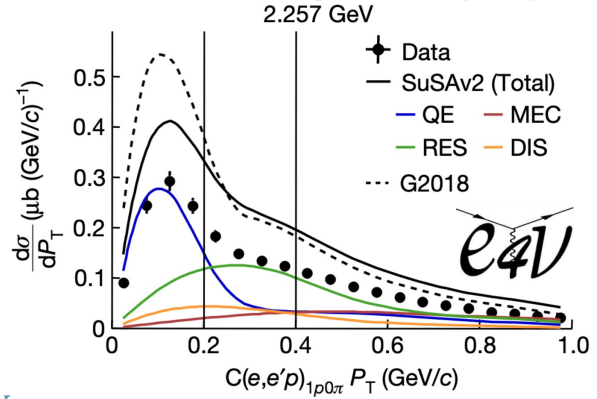
Nature 599, p. 565–570 (2021)



How do our models perform?

No model is able to describe global neutrino scattering measurements

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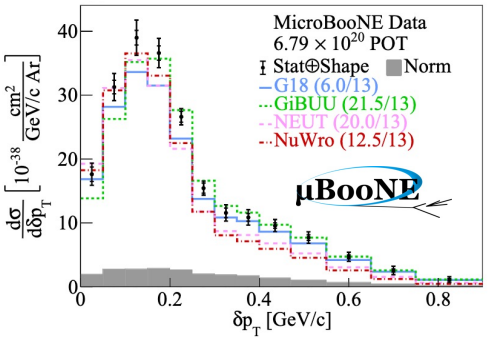

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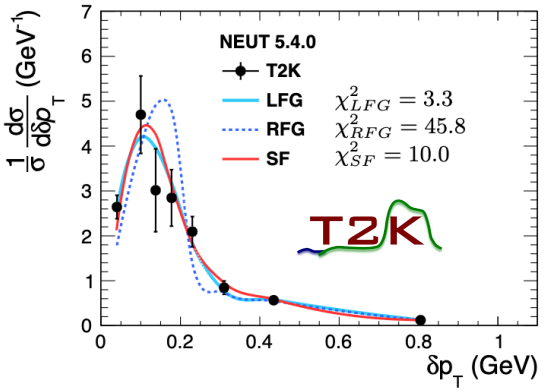

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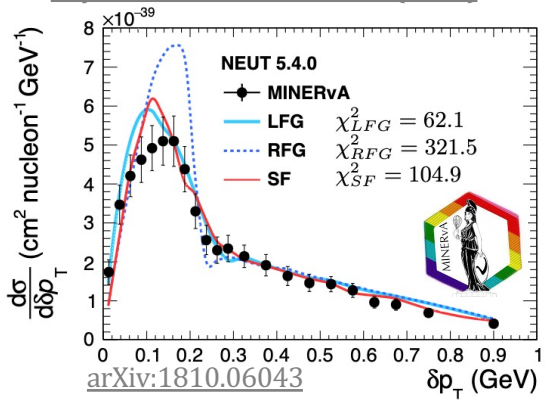

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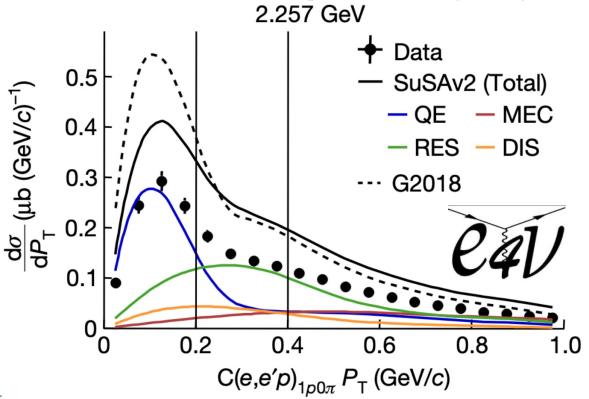

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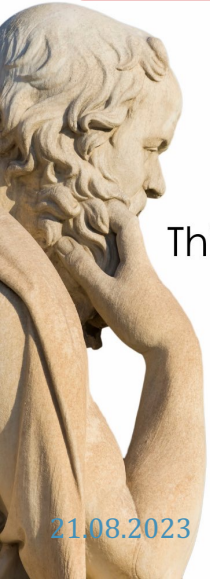
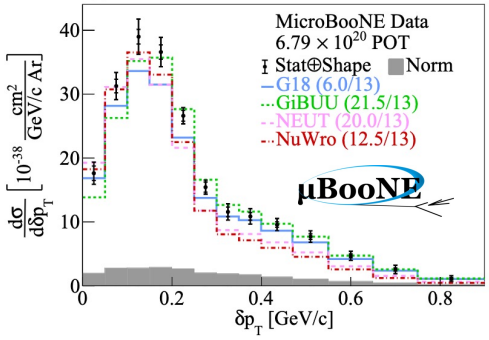


"One thing I know, that I know nothing. This is the source of my wisdom."

Socrates,
as he analyzes neutrino cross-section measurements

arXiv:2301.03700



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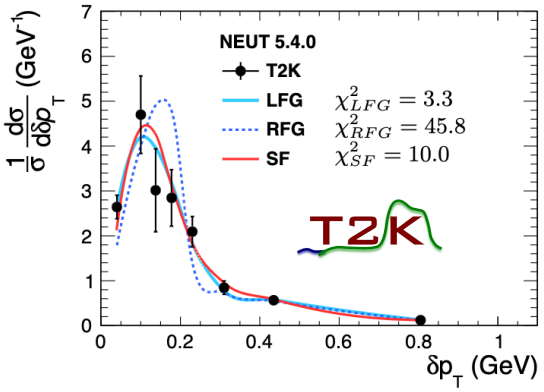

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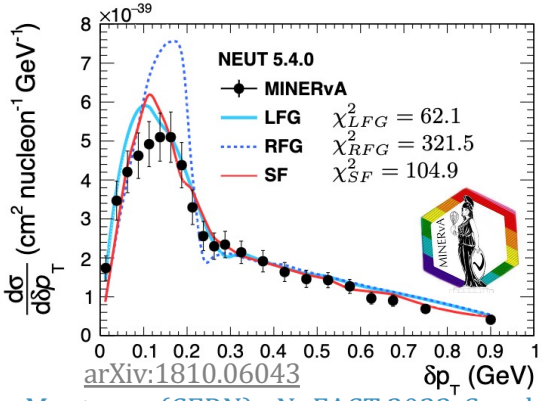

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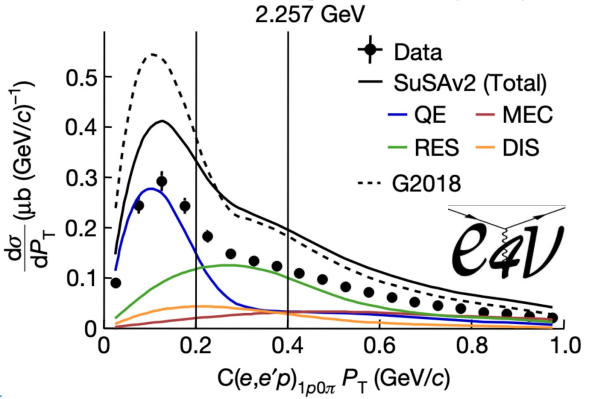

What do we (not) know about neutrino interactions?

Known unknowns
(non-exhaustive)

Hadron transport inside the nucleus
$\nu/\bar{\nu}$ differences
Impact of nuclear potential
C/O/Ar/Fe/etc. differences
Relative contributions of different channels
Hadronization
…
…
…

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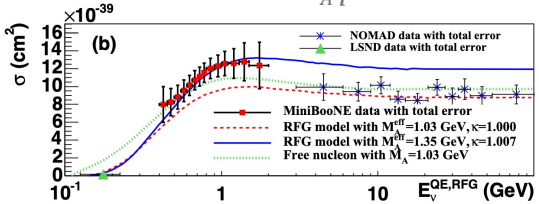
Unknown unknowns

MiniBooNE M_A puzzle



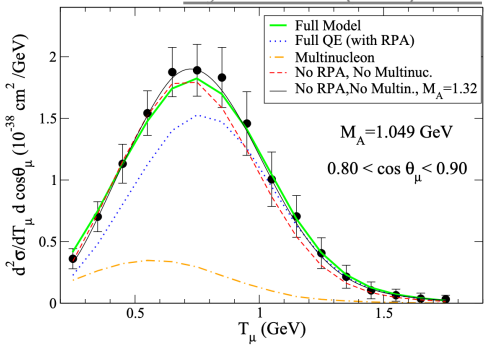
Phys.Rev.D 81 (2010) 092005

Multinucleon interactions (2p2h)

+

nuclear screening (RPA)

Phys.Lett.B 707 (2012) 72-75



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Hadron transport inside the nucleus

$\nu/\bar{\nu}$ differences

Impact of nuclear potential

C/O/Ar/Fe/etc. differences

Relative contributions of different channels

Hadronization

…

…

…

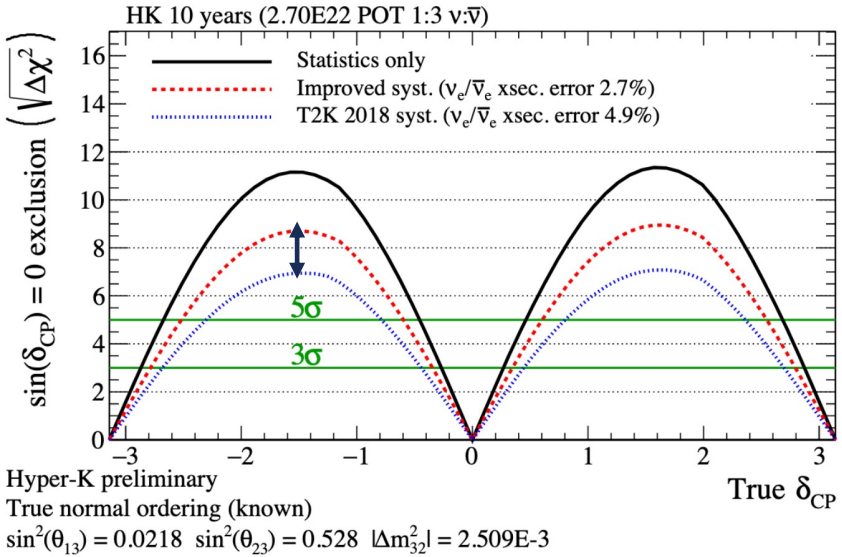
Previous unknown unknowns become known unknowns!

Why do we care?

For measuring $\sin\delta_{CP}$

For precision measurements

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

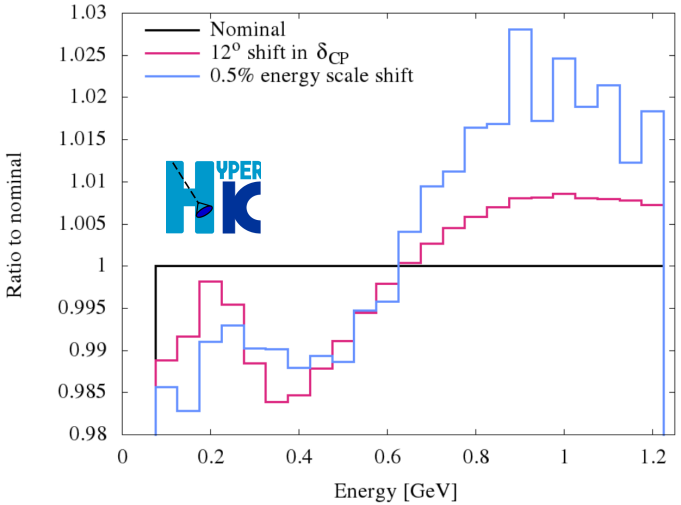


Dominant systematics related to the uncertainty on $\boldsymbol{\sigma(\nu_e)}$ **and** $\boldsymbol{\sigma(\nu_\mu)}$ **differences**

Current constraints mainly driven by theory

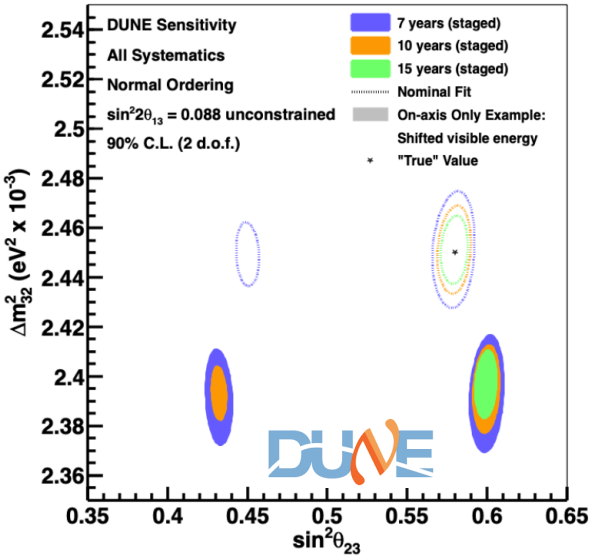
See talk by S. Dolan (Tuesday, WG2)

Main challenges for precision measurements



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

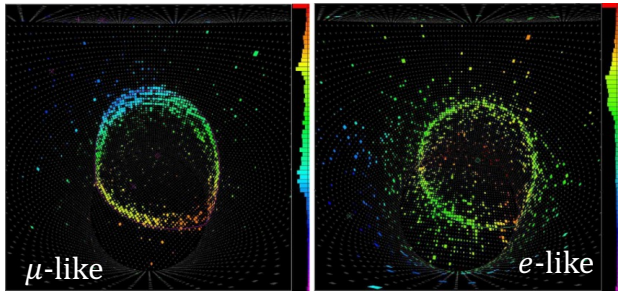
DUNE FD TDR



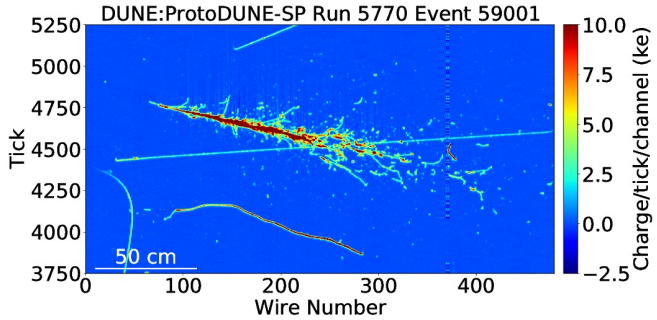
Bias in osc. parameter measurements due to shift in visible energy

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

Neutrino energy reconstruction



Water Cherenkov – measure kinematics of particles above threshold

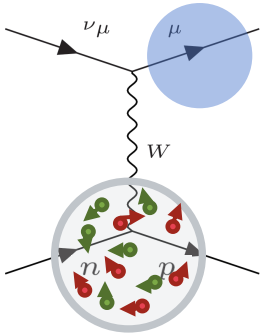


LArTPC – measure particles' energy deposits

Different detectors – different methods – different priorities

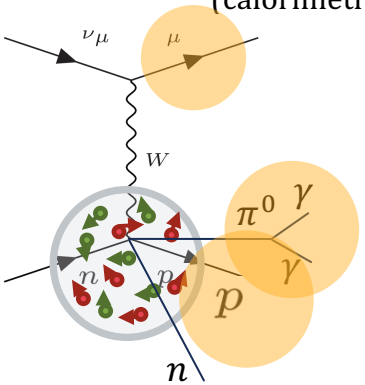
Neutrino energy reconstruction

("kinematic" energy reconstruction)



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

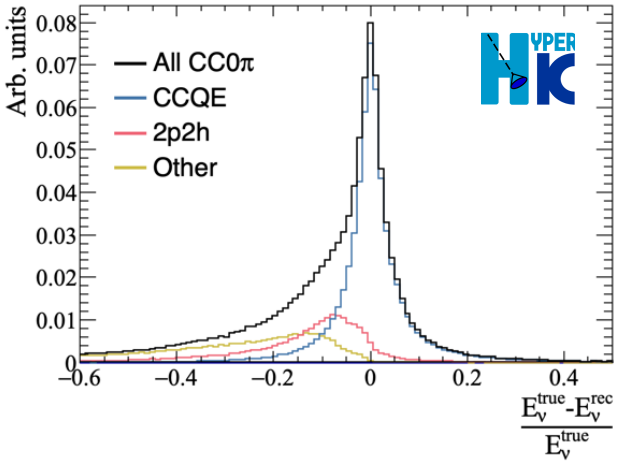
(calorimetric energy reconstruction)



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

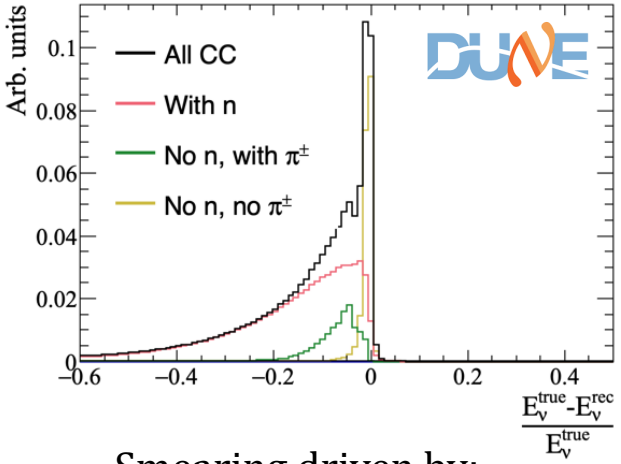
Different detectors – **different methods** – different priorities

Neutrino energy reconstruction



Smearing driven by:

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

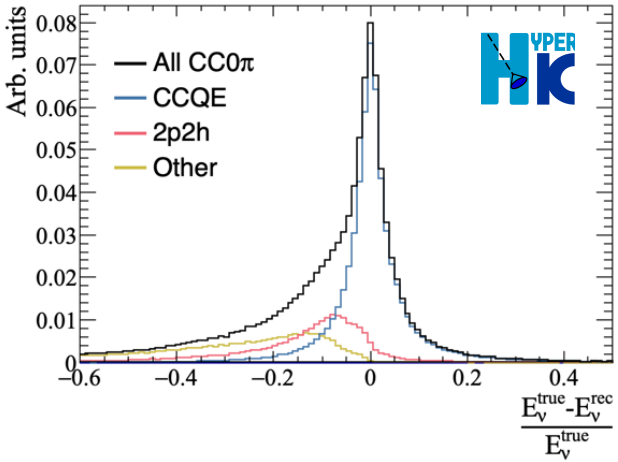


Smearing driven by:

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

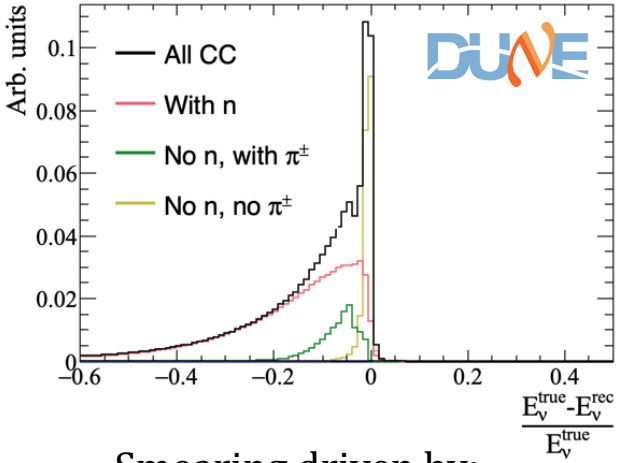
Different detectors – different methods – **different priorities**

Neutrino energy reconstruction



Smearing driven by:
- **Nuclear ground state**
- **Pion transport** through nucleus

Wider intrinsic smearing but easier to control

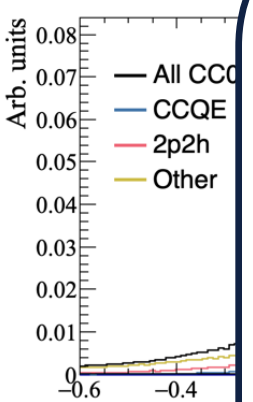


Smearing driven by:
- Fraction of **energy carried by neutrons**
- **Pion production** processes

Smaller intrinsic smearing but **harder to control**

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

Neutrino en



Smearing driv

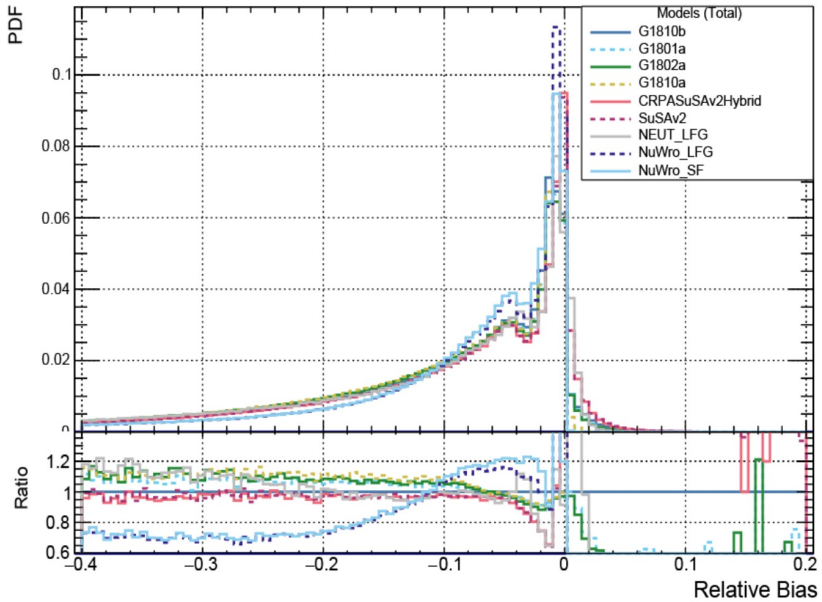
- **Nuclear gr**
- **Pion trans**

Wider intrinsic sm

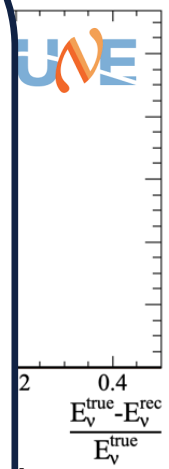
Differe

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

Plot by A. Wong Wei Ren



High model disagreement



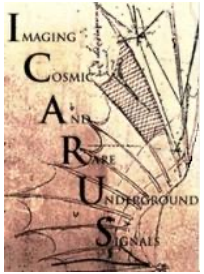
y carried by

processes

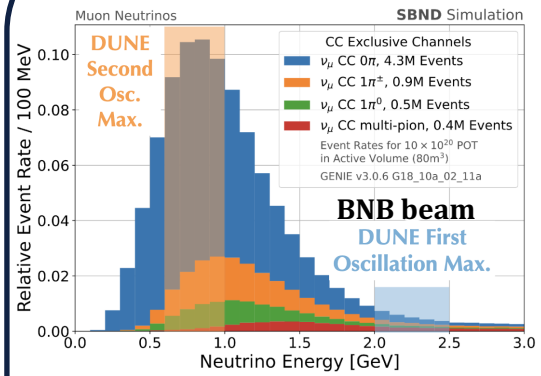
but harder to control

iorities

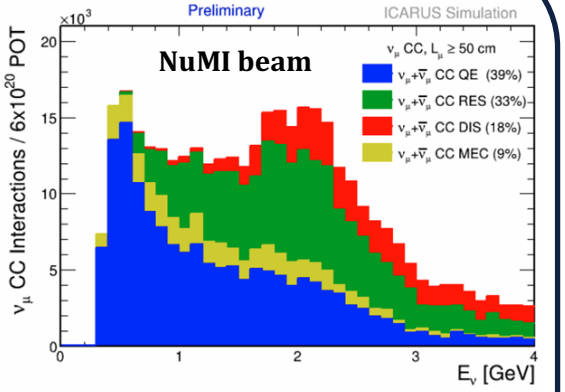
The future of neutrino cross-sections is bright!



L.Yates @ NuINT2022

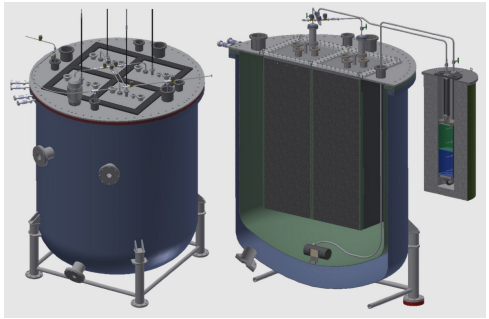


S. Dolan @ NuINT2022



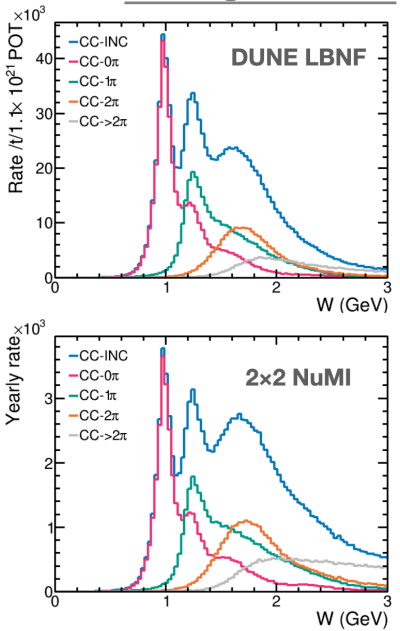
High statistics measurements on LAr

The future of neutrino cross-sections is bright!



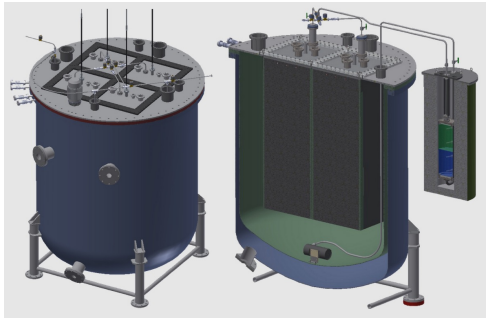
“2x2” ArgonCube Demonstrator

Y. Chen @ NuINT 2022



New measurements targeting π-production region

The future of neutrino cross-sections is bright!



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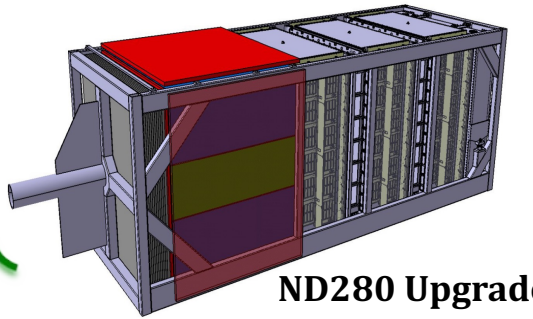
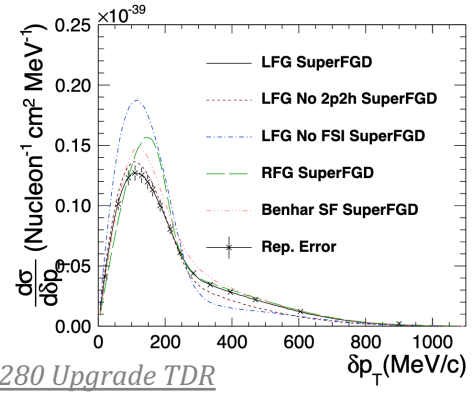


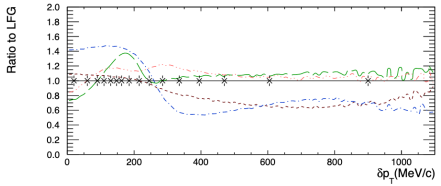
ND280 Upgrade

High-precision CC0π-focused measurements

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

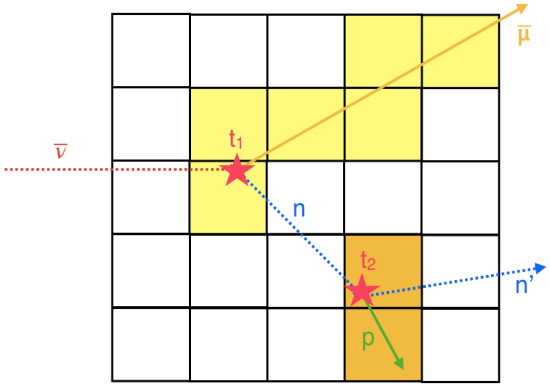


ND280 Upgrade TDR

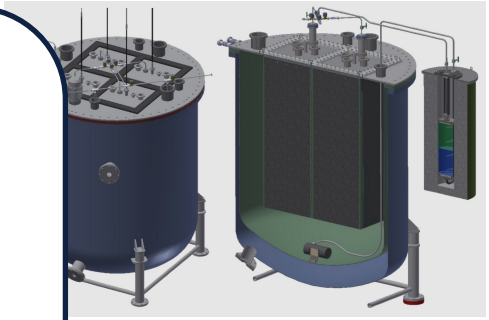


The future of neutrino cross-sections is bright!

Neutron detection



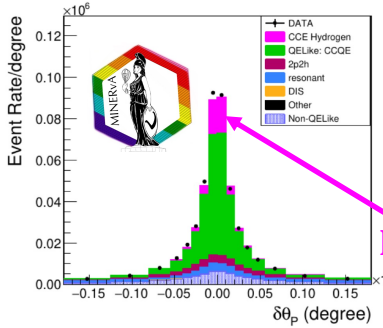
Phys.Rev.D 101 (2020) 9, 092003



2" ArgonCube Demonstrator

Hydrogen tagging

Nature 614, pages 48–53 (2023)

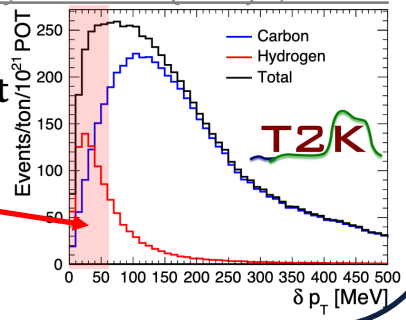


First measurement

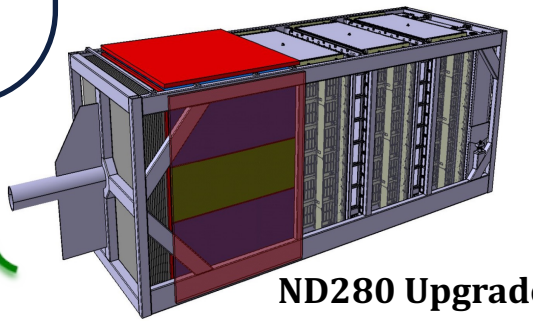
H contribution

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

Planned measurement



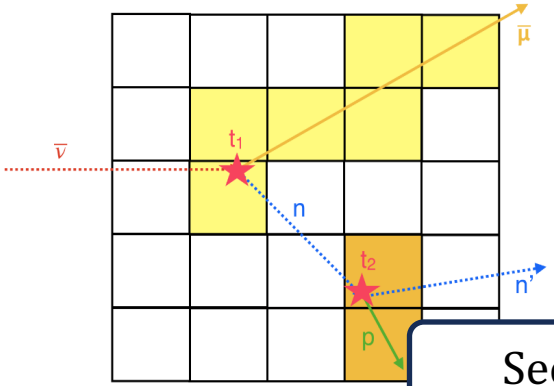
Improved H purity



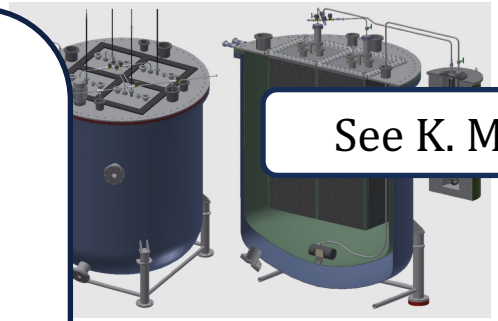
ND280 Upgrade

The future of neutrino cross-sections is bright!

Neutron detection



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

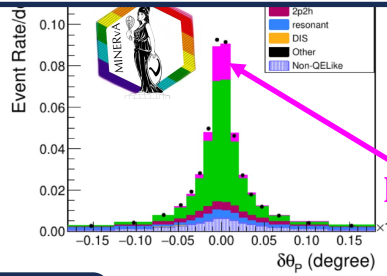


2" ArgonCube Demonstrator

See K. McFarland's talk on Tuesday!

See T. Doyle's talk on Wednesday!

Hydrogen tagging



First measurement

H contribution

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

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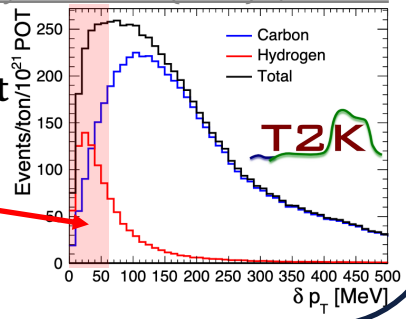

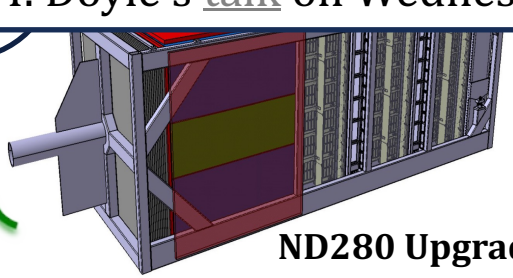

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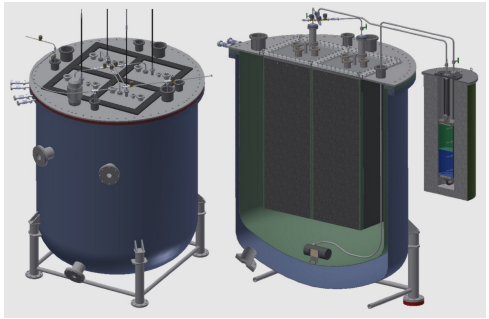
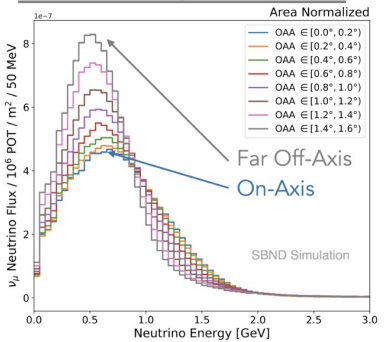


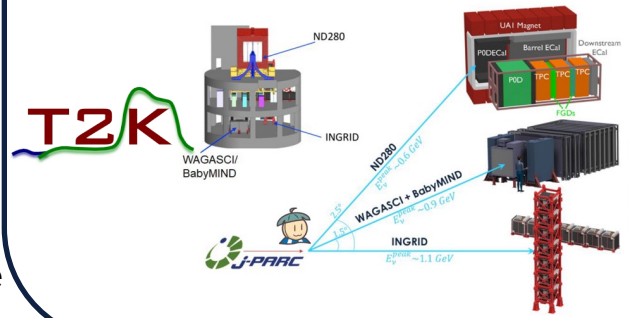
"2x2" ArgonCube Demonstrator

PRISM-style measurements

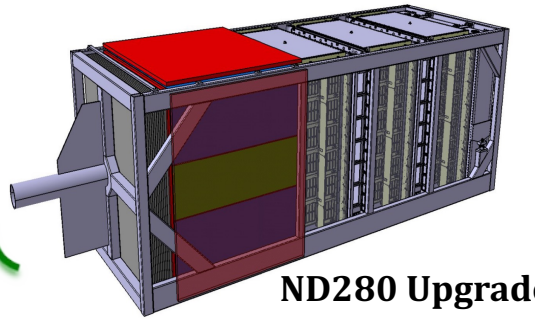
M. Del Tutto @ ICHEP 2022



A. Cudd @ NuFACT 2022 [arXiv:2303.14228]



New analysis techniques



ND280 Upgrade

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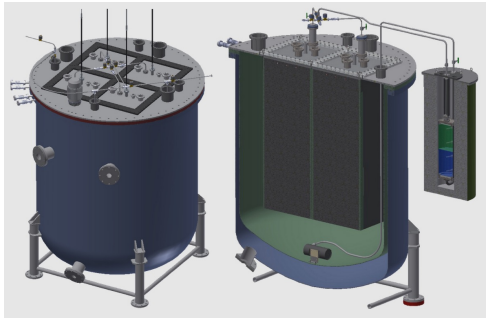

"2x2" ArgonCube Dem

PRISM-style measurements

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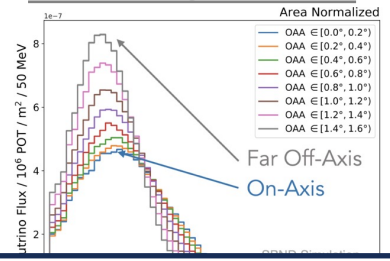
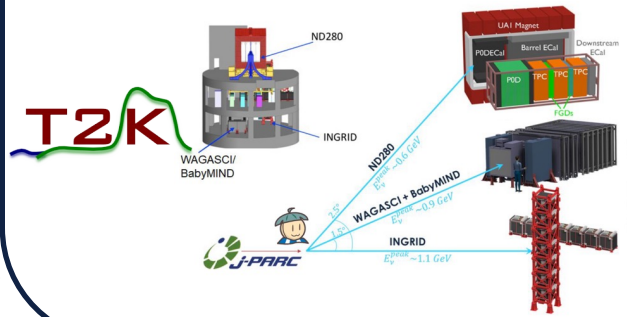


See M. Wilking's talk on Wednesday!

A. Cudd @ NuFACT 2022 [arXiv:2303.14228]



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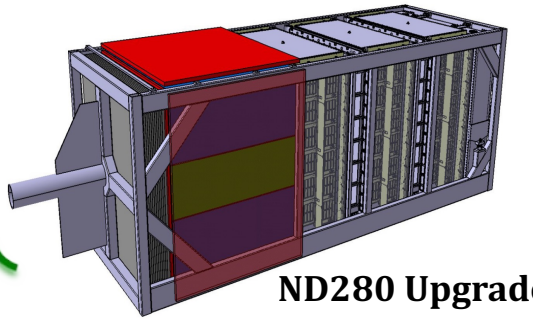

ND280 Upgrade

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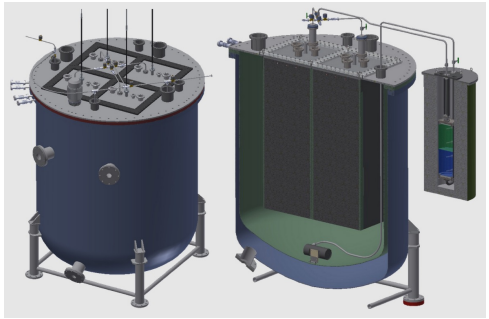
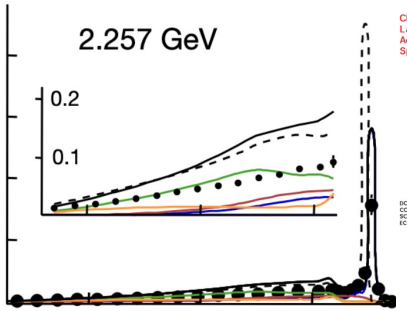
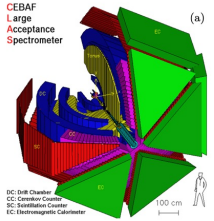


“2x2” ArgonCube Demonstrator

Electron scattering

Nature 599, p. 565–570 (2021)





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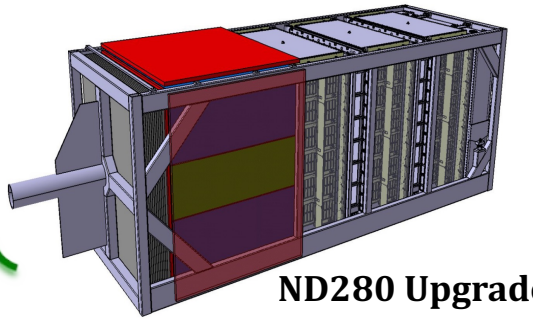


ND280 Upgrade

Beyond dedicated cross-section measurements

Cross-section measurements are
essential for future experiments

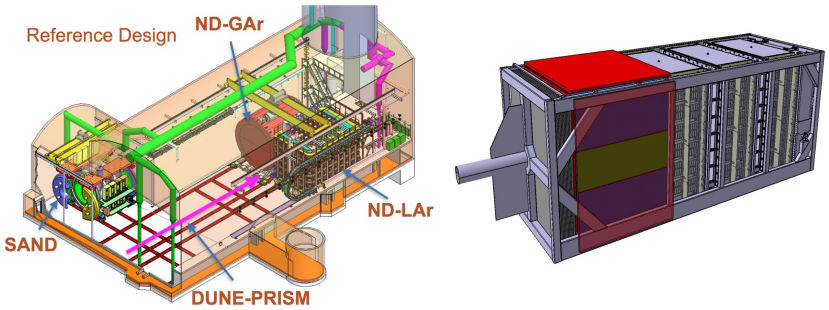
But we cannot rely solely on them

- Morals of this story:
  - Every measurement has backgrounds
  - No detector is perfect
  - No cross section model is perfect

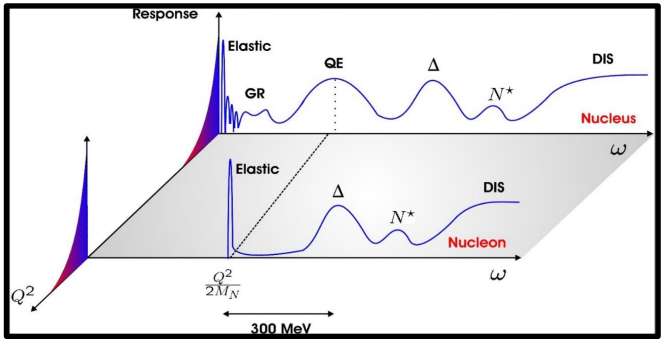
D. Harris @ INSS 2023

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**

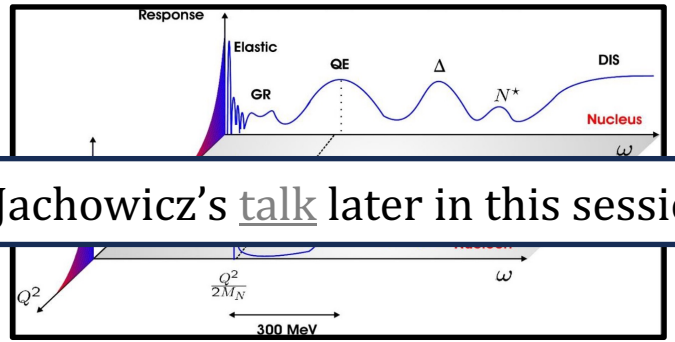
Tune **known unknowns**

Beyond dedicated cross-section measurements

Capable near detectors

See M. Hartz's talk later in this session!

Strong ties with theory community



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Identify **unknown unknowns**

Tune **known unknowns**

Summary and outlook

- Neutrino oscillation physics is entering the precision measurement era
- Future-generation experiments have ambitious goals, will gather huge statistics and will use powerful detectors
- Systematic uncertainties will become dominant
- A precise control of neutrino cross-section uncertainties is imperative to achieve their goals
- Exciting cross-section measurement programs planned
- Rely on strong collaboration with theory community and capable near detectors

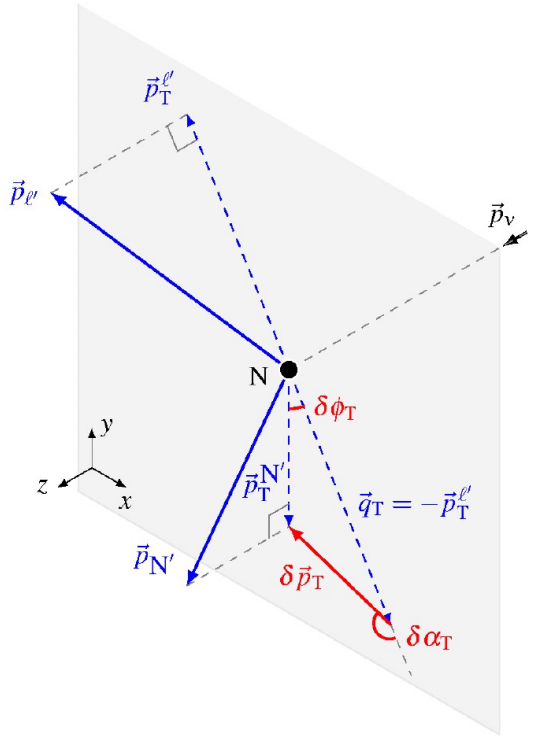
Thank you for your attention!

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 K	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