Future uncertainties for oscillation experiments

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ECT*, Trento

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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 Neutrino 2024 talk	384	106	181	32	~5%

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

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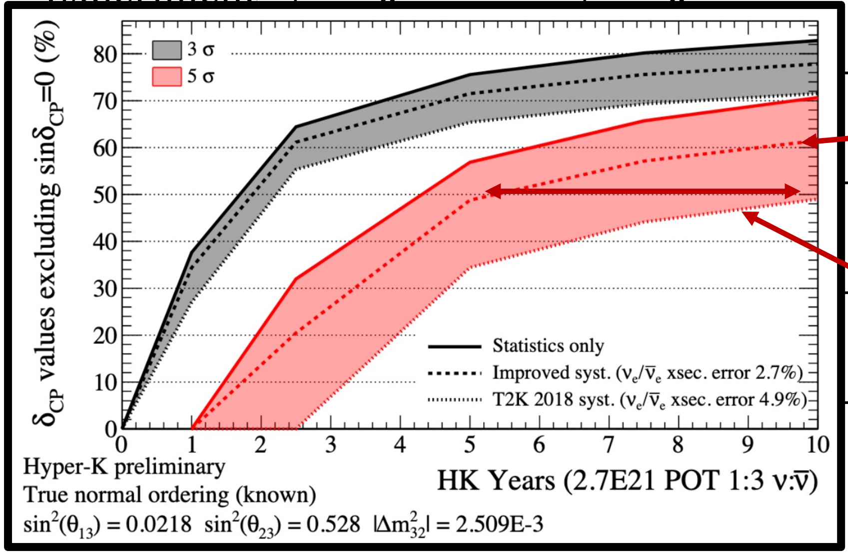
			9		~5%
			181	32	~5%
			~2(	**00**	**?**
			~150		



Sensitivity to exclude CP conserving values for δ_{CP}

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

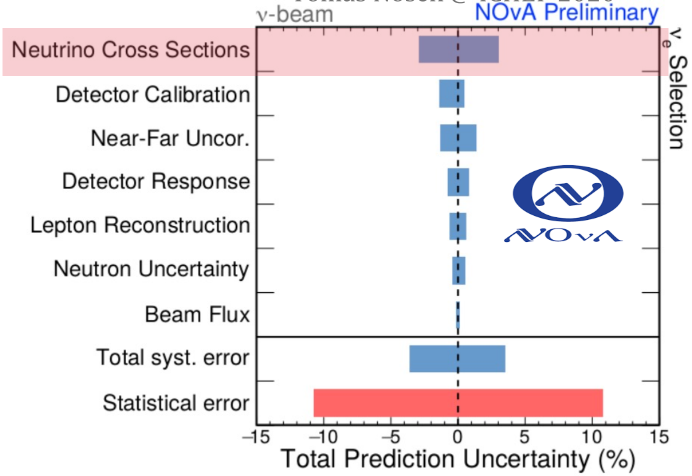
arXiv:2303.03222

Syst. uncertainty

Sample		Flux⊗Interaction (%)	Total (%)
1Rμ	ν	2.2 (12.7)	3.0 (13.0)
	$\bar{\nu}$	3.4 (11.8)	4.0 (12.0)
1Re	ν	3.6 (13.5)	4.7 (13.8)
	$\bar{\nu}$	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

Ok, we need 1-3%... but on *what*?

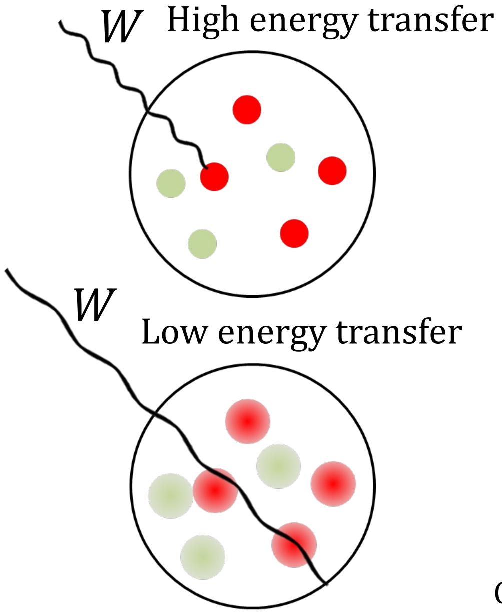
The **physics** of the largest sources of uncertainties:

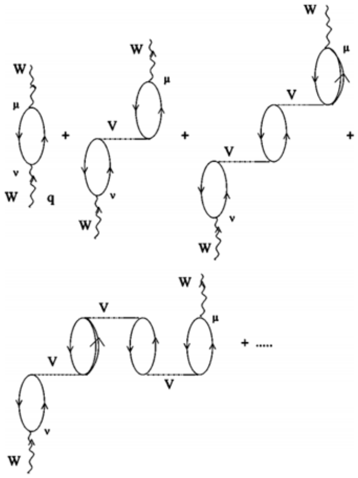
1. Beyond PWIA physics
2. FSI and impact on hadronic system
3. ν_e/ν_μ differences
4. SIS/hadronization

Physics beyond PWIA

Plane Wave Impulse Approximation

Interaction happens with a **single nucleon** which exits **without "feeling" the nucleus (no RPA or FSI)**





[*Phys. Rev. C* ***70****, 055503*]

Collective effects in the nucleus (~"RPA")

Graphics from S. Dolan

Physics beyond PWIA

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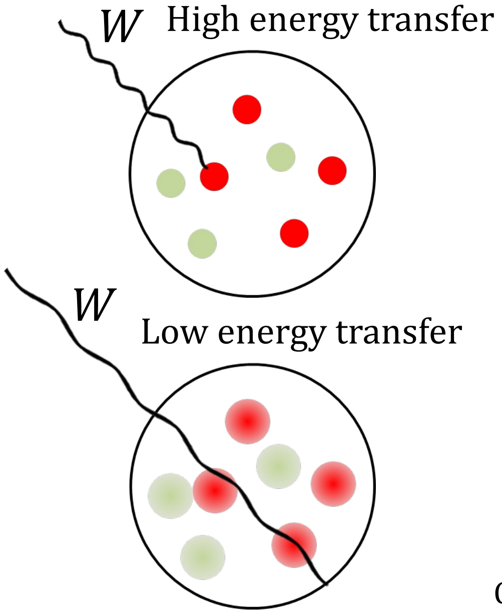

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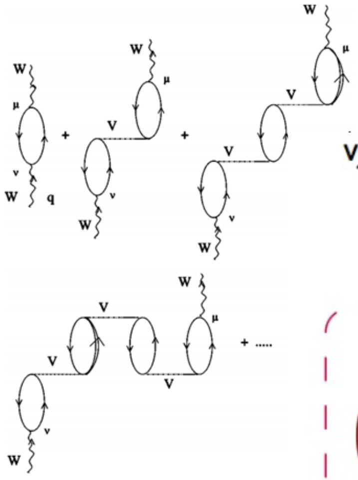
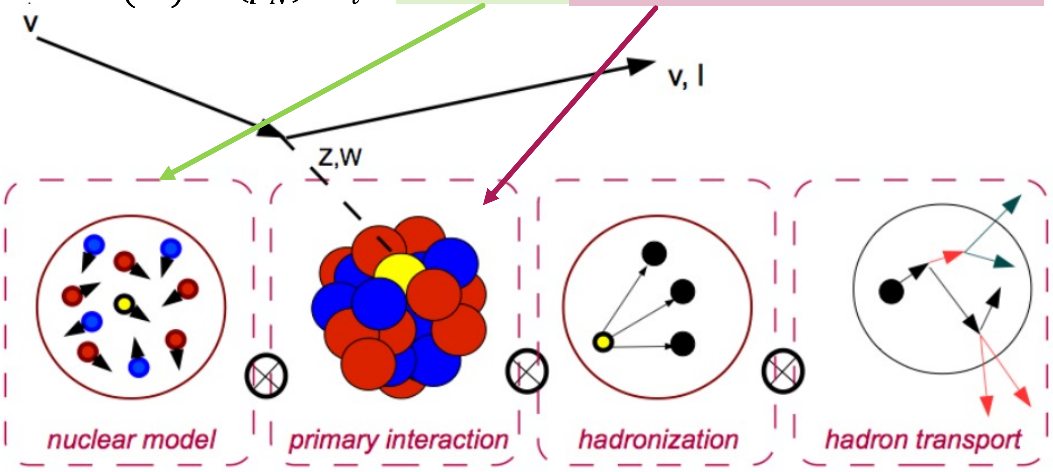


*Phys. Rev. C **70**, 055503*

Collective effects in the nucleus (~"RPA")

Built in to the way neutrino interaction generators work

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

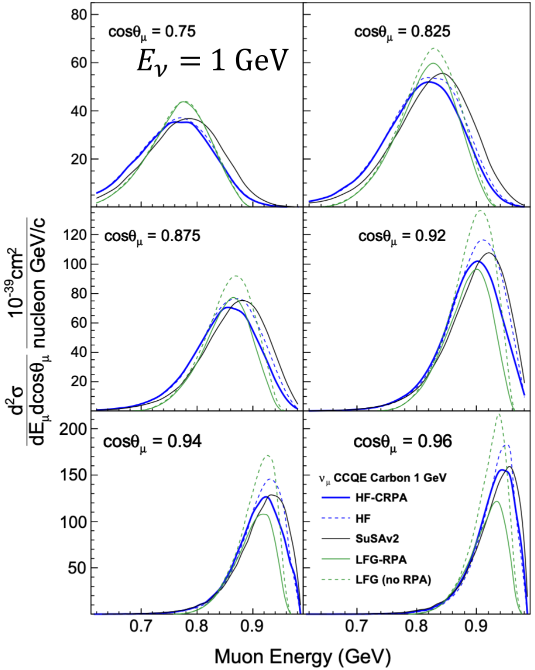


Credit C. Andreopoulous

Physics beyond PWIA

Models differ significantly in their predictions…

Different physics (ν_μ on C)



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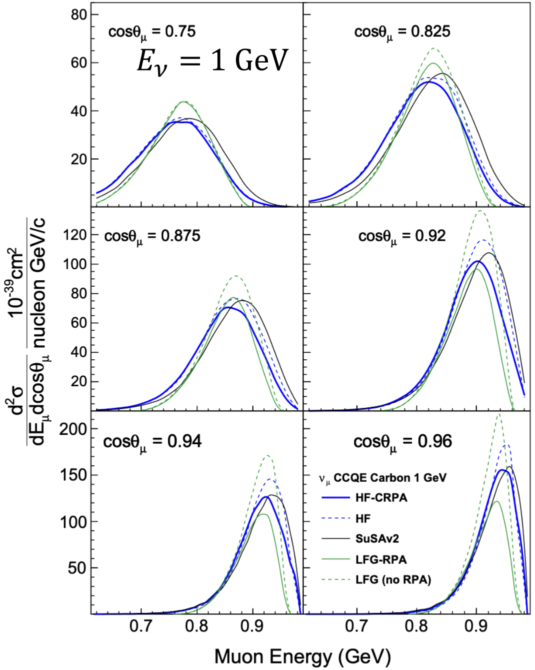
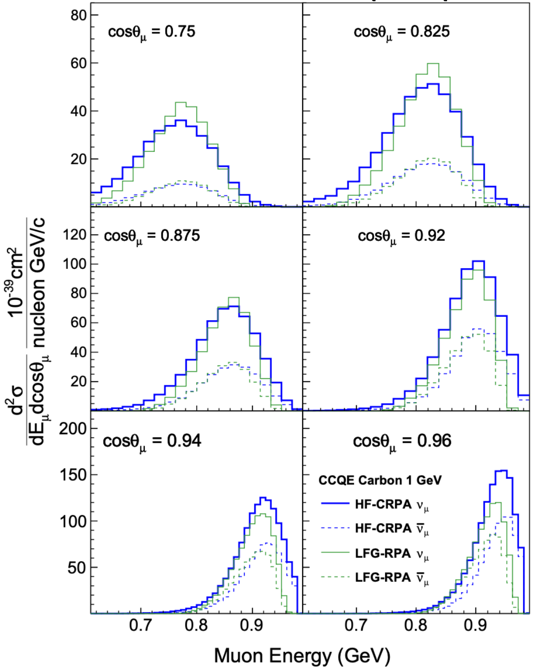


Impact on $\nu_\mu/\bar{\nu}_\mu$



Physics beyond PWIA

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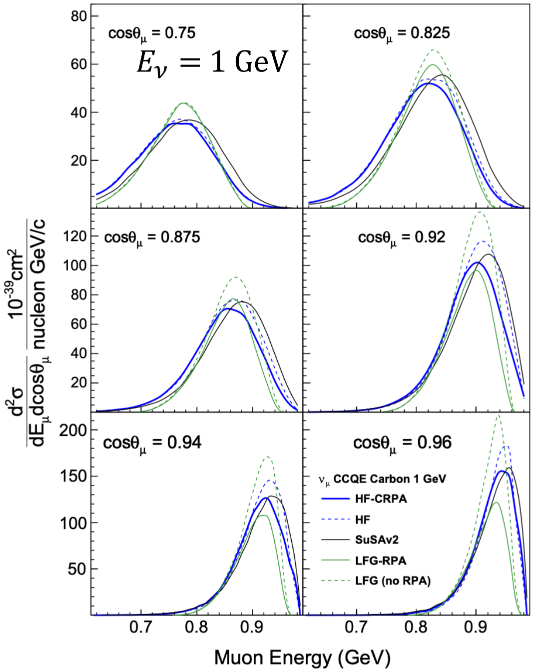

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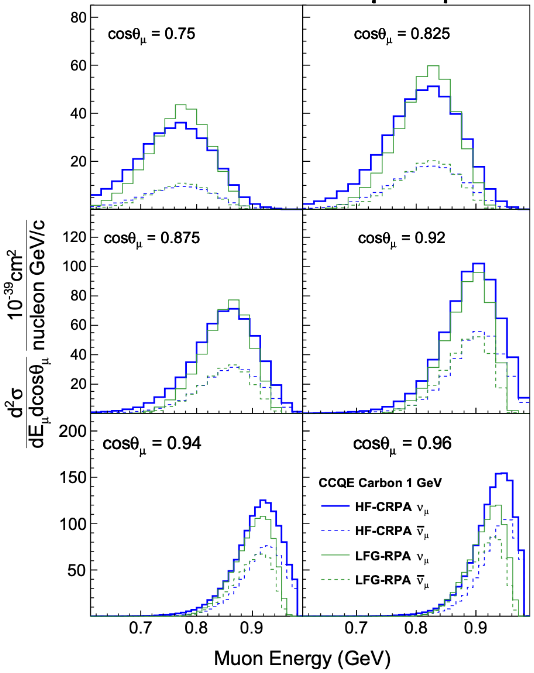
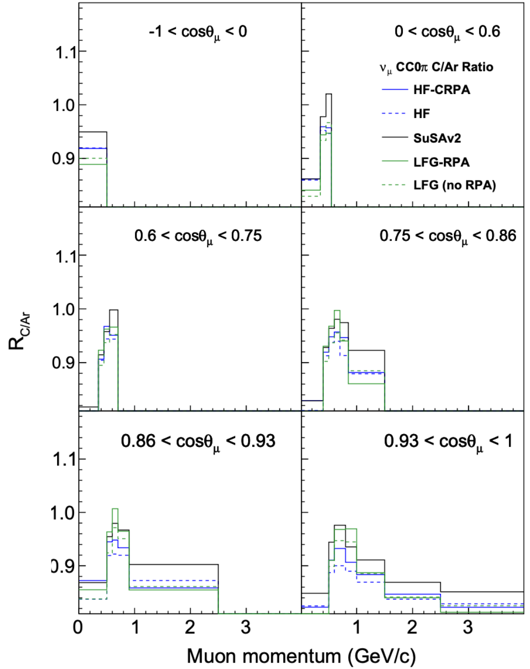


Impact on C/Ar ratio



Physics beyond PWIA

Not shown here, but also different in ν_e/ν_μ ratio (see Phys. Rev. D **108**, L031301)

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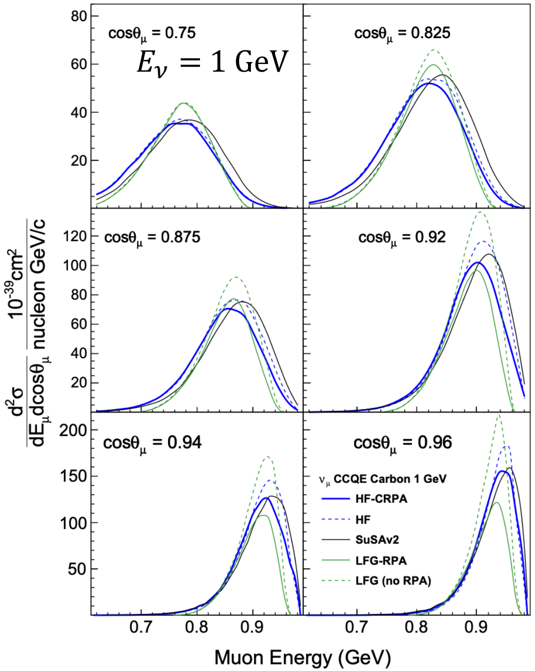
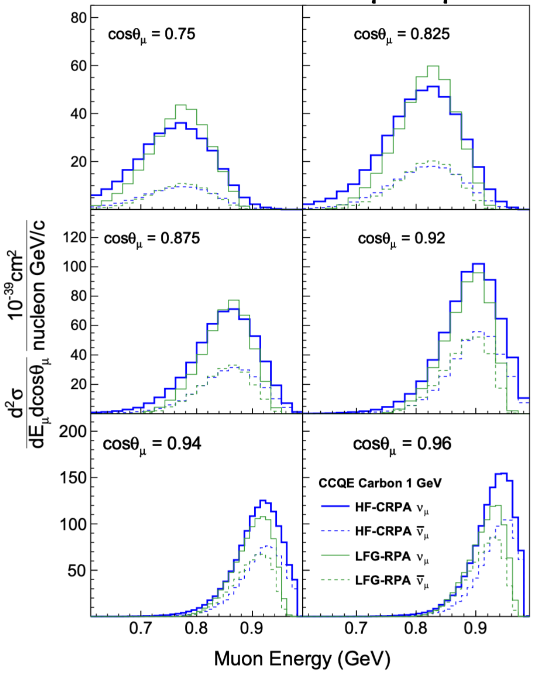


Impact on $\nu_\mu/\bar{\nu}_\mu$



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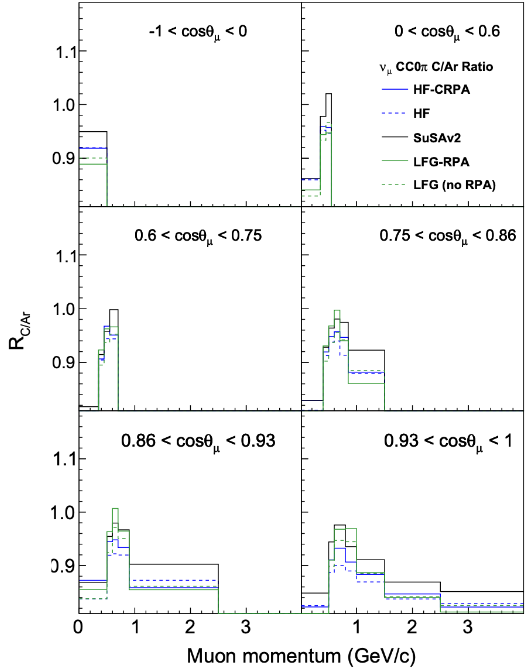

Phys. Rev. D **106**, 073001

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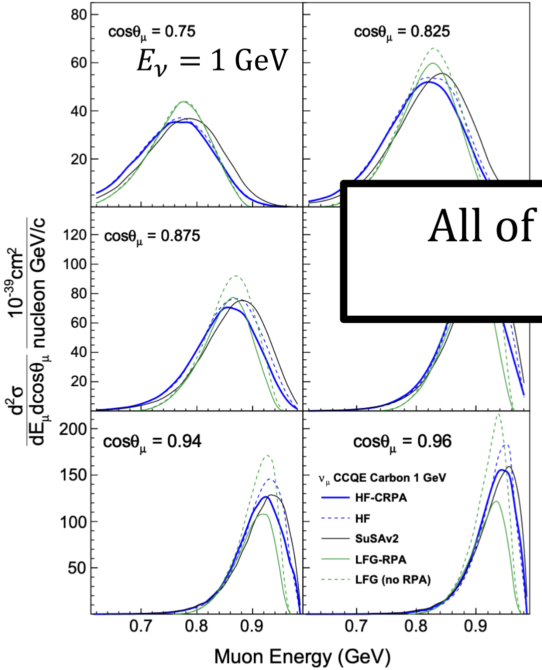

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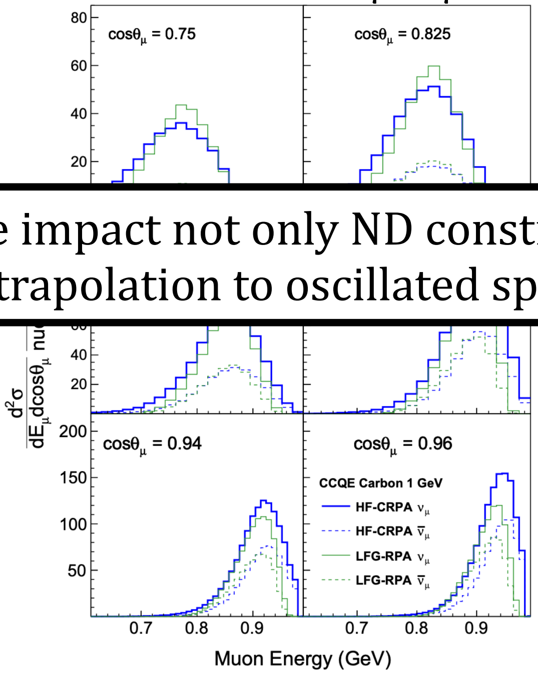

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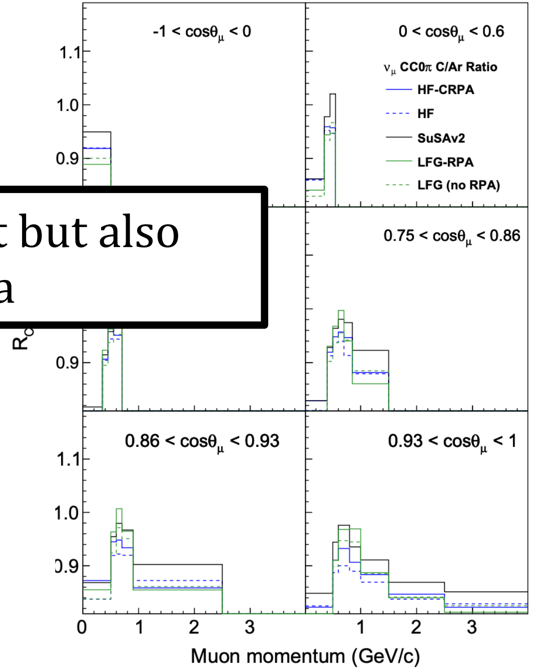
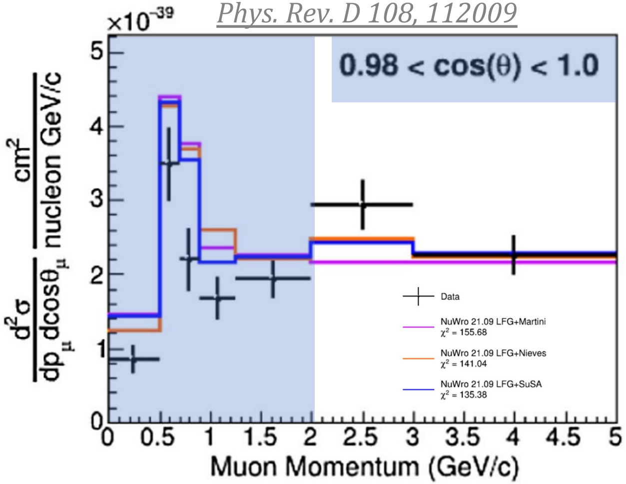


All of these impact not only ND constraint but also extrapolation to oscillated spectra

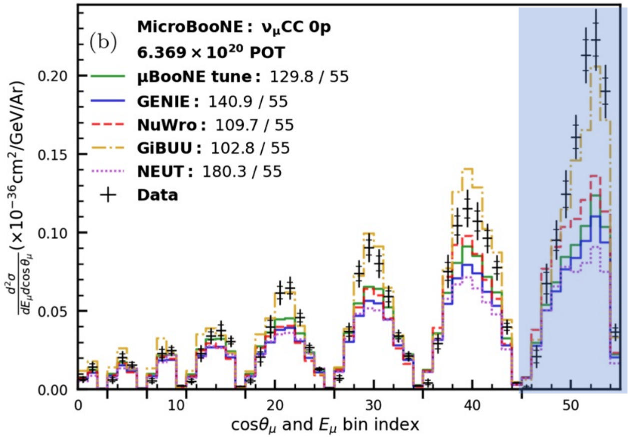
Physics beyond PWIA

Do we see it in our measurements? Yes! **And it can cause problems…**

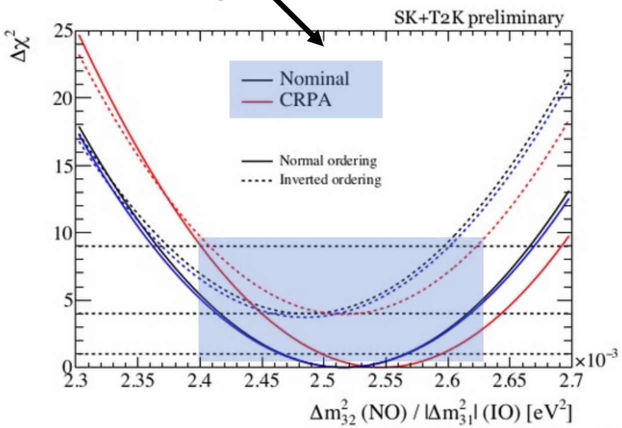
Phys. Rev. D 108, 112009



Phys.Rev.D 110, 013006



From C. Wret's talk



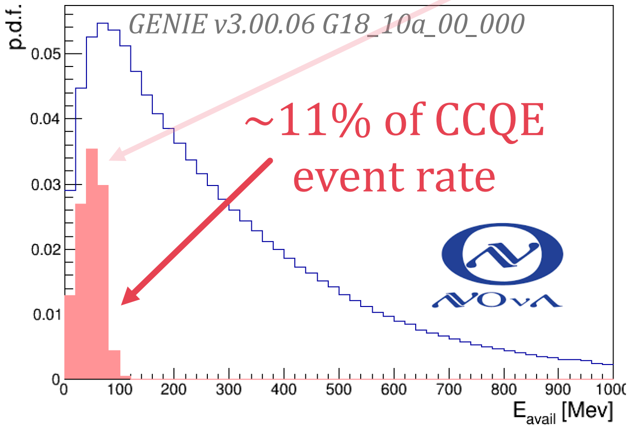
Shows up in experimental measurements in regions sensitive to low energy transfer
(e.g. high $cos\theta_{\mu}$, low proton momentum/E_{avail}, p_{μ} close to flux peak etc.)

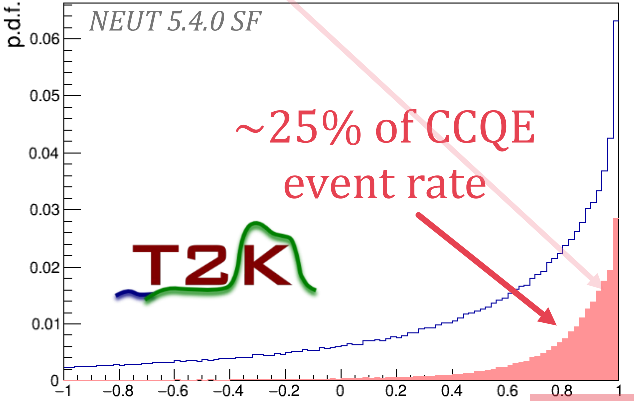
Has large impact (~100% of syst. error size) for oscillation measurements (T2K/T2K+SK atmo.)

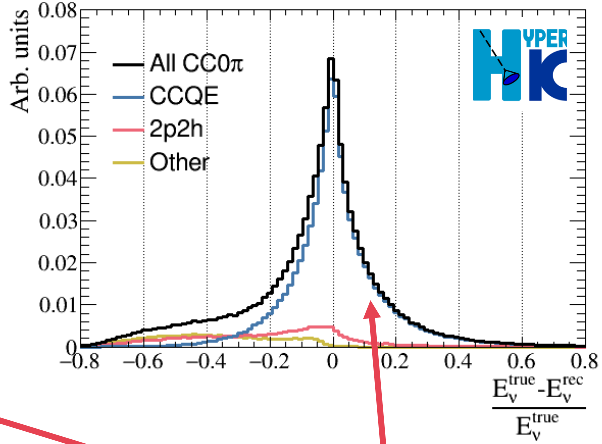
Who needs to care about this?

In principle, everyone, but **mostly if regions of low energy transfer impact your physics of interest**

ω < 100 MeV







Will result in shape differences visible impacting oscillation measurements

$$E_\nu^{rec} = \frac{2(M_n - E_B)E_\mu - (E_B^2 - 2M_nE_B + m_\mu^2 + \Delta M^2)}{2\left[M_n - E_B - E_\mu + |\vec{k}_\mu| \cos\theta_\mu\right]}$$

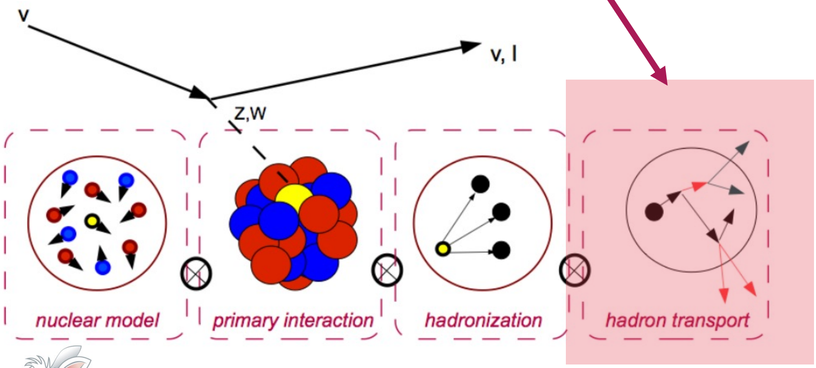
FSI* and the hadronic system

Referring to the effect of intra-nuclear cascades (INC)

How does FSI impact oscillation measurements?

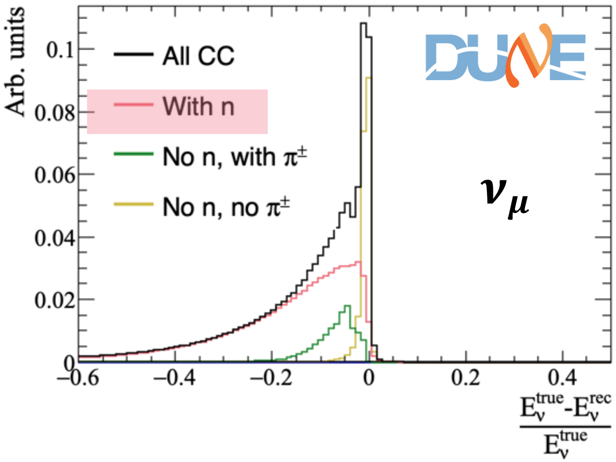
Will discuss impact on:

- Neutrons
- Pions
- Clusters/de-excitation



FSI also has a significant impact on **proton** kinematics/multiplicities but I don't have time to cover it

FSI and neutrons

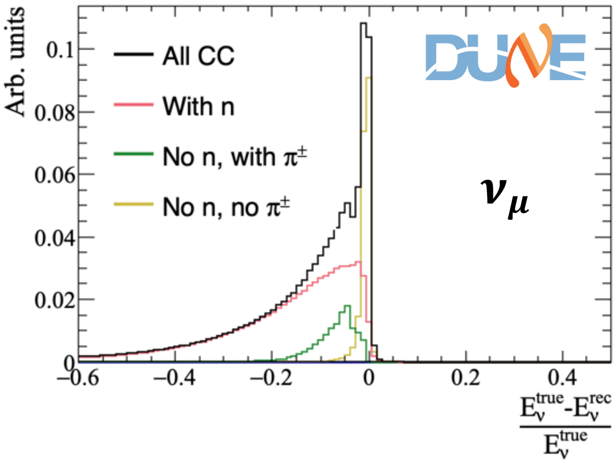


Neutrons are the largest source of neutrino energy bias for DUNE

$$E_{\text{avail}} = \Big(\sum_{i=p,\pi^\pm} E^i_{\text{kin}} \Big) + \Big(\sum_{i=,\pi^0,\gamma,K^0,K^\pm} E^i_{\text{total}} \Big)$$

$$E_\nu^{rec} = E_\mu + E_{avail}$$

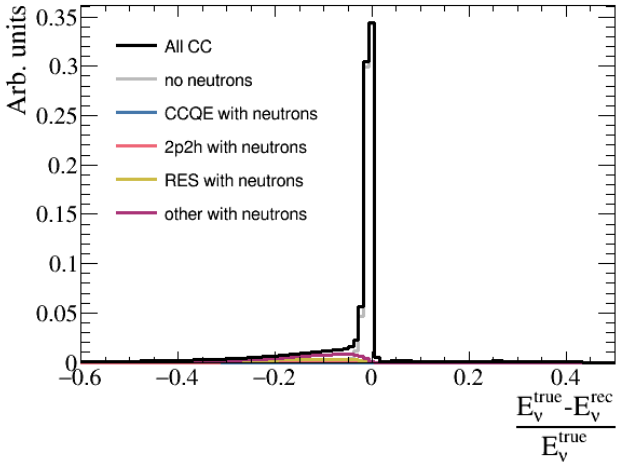
FSI and neutrons



Neutrons are the largest source of neutrino energy bias for DUNE

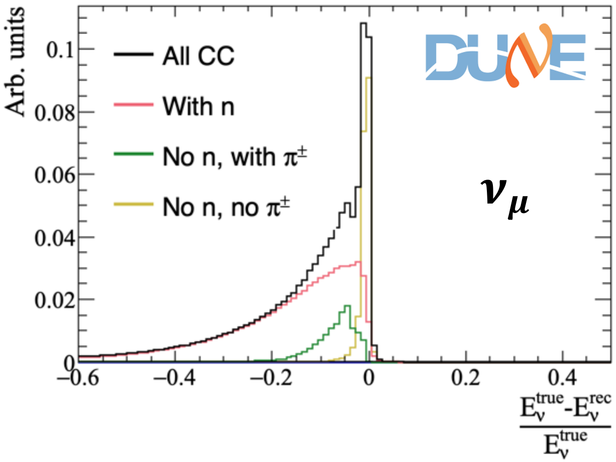
Where do they come from?

In these plots, we neglect the impact of pions by assuming we can reconstruct them individually



Before FSI: mostly from **a fraction of DIS/SIS interactions**

FSI and neutrons



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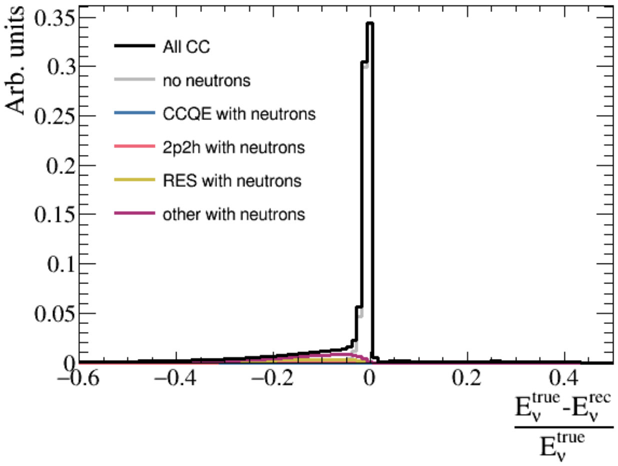

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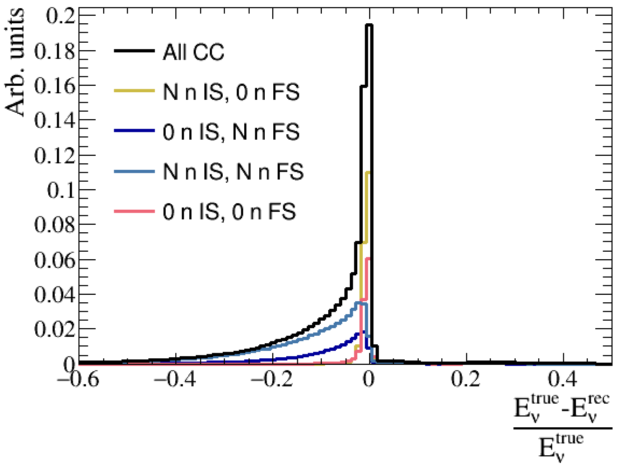
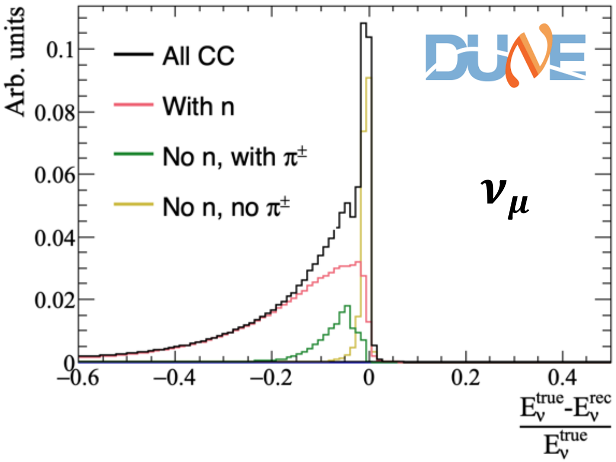


After FSI: mostly **all modes producing neutrons** (and some charge exchange FSI)

FSI and neutrons



Neutrons are the largest source of neutrino energy bias for DUNE

FSI and its alteration to neutron kinematics is the main source of neutrons at DUNE energies (for neutrinos)

Where do they come from?

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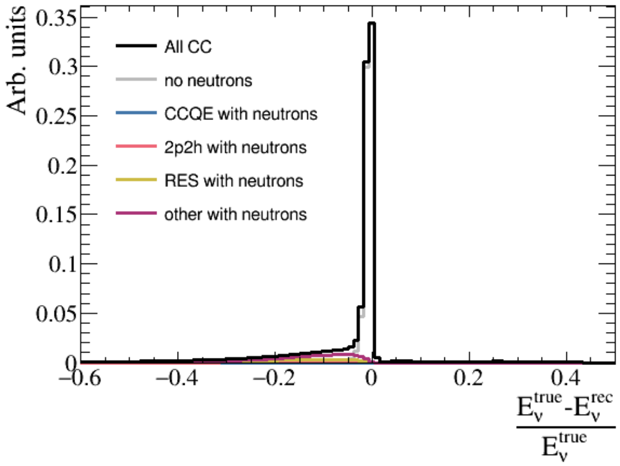

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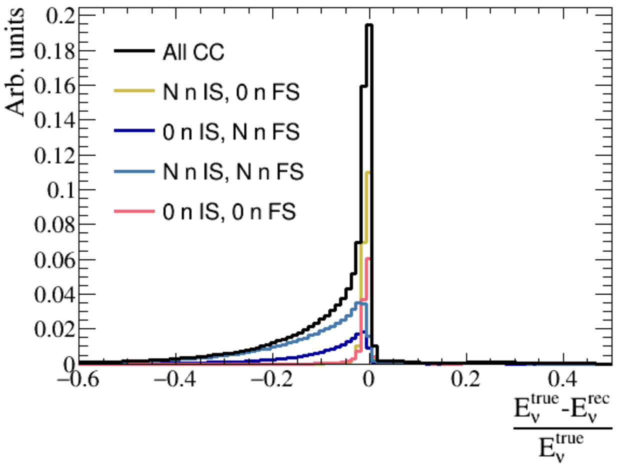
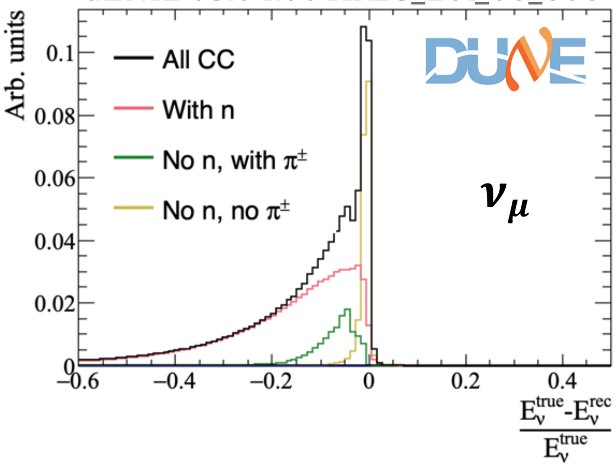


After FSI: mostly **all modes producing neutrons** (and some charge exchange FSI)

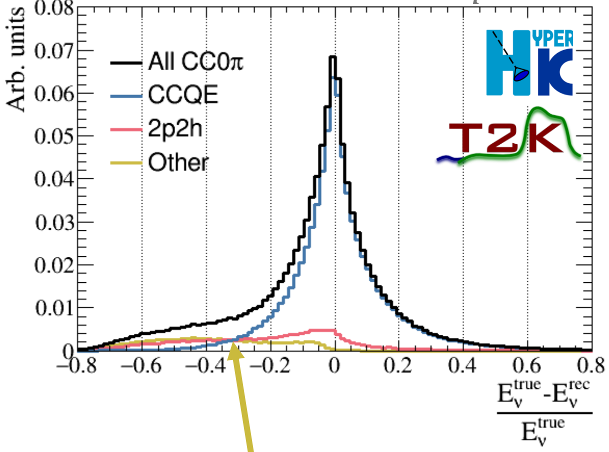
FSI and pions

GENIE v3.04.00 AR23_20i_00_000



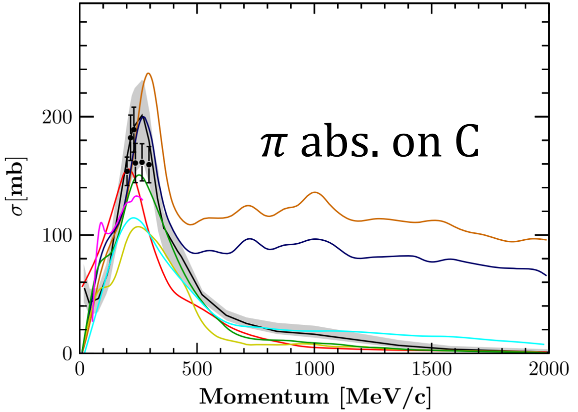
Pions are the second largest source of neutrino energy bias for DUNE

NEUT 5.4.0 SF+Valencia 2p2h



They also have a significant impact at T2K/HK energies via **pion absorption**

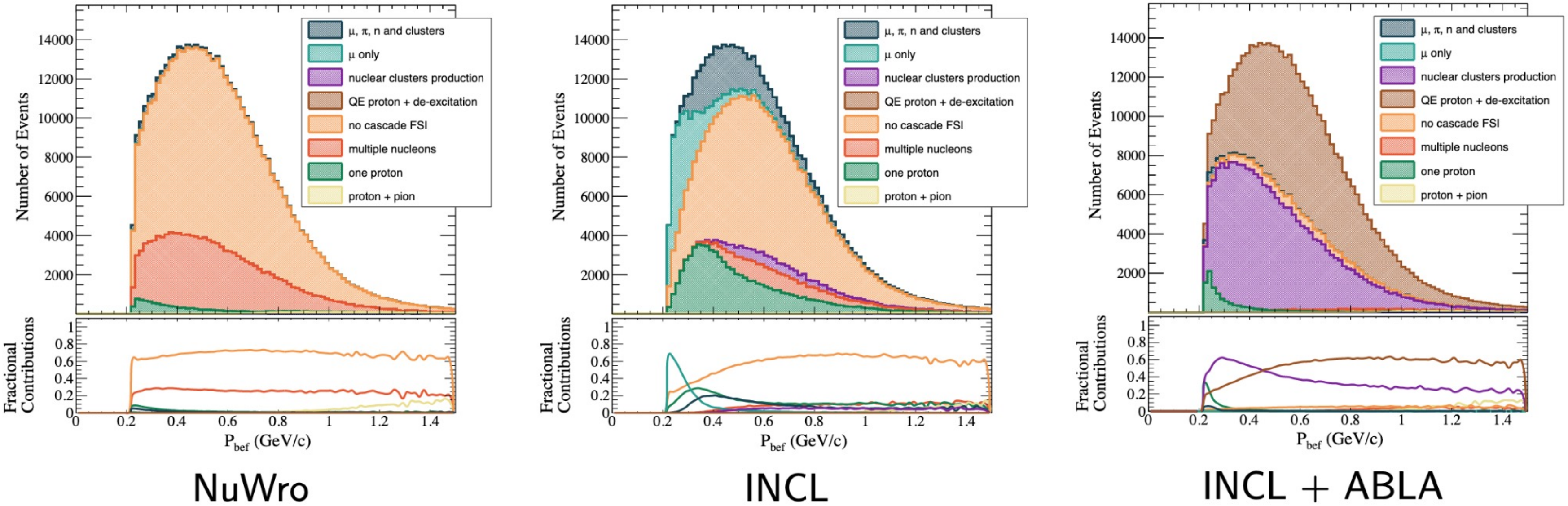
*Phys. Rev. D **99**, 052007*



Uncertainties of O(40%)

FSI and nuclear clusters and de-excitation routines

See talk from A. Ershova on Wednesday for in-depth discussion



Essentially: more complex cascade models (e.g. INCL) and de-excitation routines (e.g. ABLA, THALYS) predict different compositions of final state products and momentum sharing

ν_e/ν_μ differences

If we trust lepton flavor universality, ν_e and ν_μ cross sections only differ due to the lepton mass O(~100 MeV)

This impacts:

1. Size and uncertainty of radiative corrections
2. Regions of phase space where these differences matters (mostly at low ω)

ν_e/ν_μ differences

Nat Commun **13**, 5286 (2022)

If we trust lepton flavor universality, ν_e and ν_μ cross sections only differ due to the lepton mass O(~100 MeV)

	E_ν, GeV		$\left(\frac{\sigma_e}{\sigma_\mu}-1\right)_{LO}$, %	$\frac{\sigma_e}{\sigma_\mu}-1$, %
T2K/HyperK	0.6	ν	2.47 ± 0.06	2.84 ± 0.06 ± 0.37
		$\bar{\nu}$	2.04 ± 0.08	1.84 ± 0.08 ± 0.20
NOvA/ DUNE	2.0	ν	0.322 ± 0.006	0.54 ± 0.01 ± 0.22
		$\bar{\nu}$	0.394 ± 0.003	0.20 ± 0.01 ± 0.19

This impacts:

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2. Regions of phase space where these differences matters (mostly at low ω)

Current experiments assume ~5% for these differences

Thanks to improved theoretical calculations, this should be the least of our worries for now

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Nat Commun **13**, 5286 (2022)

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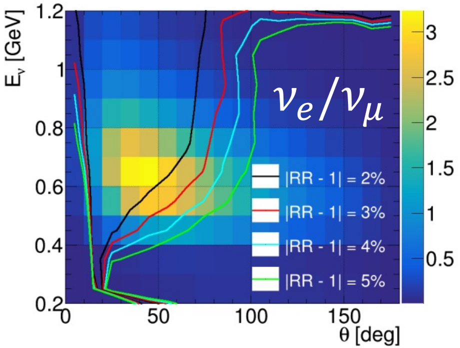
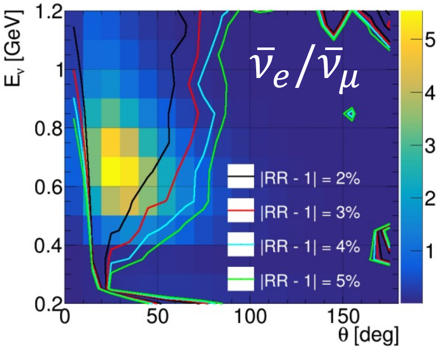
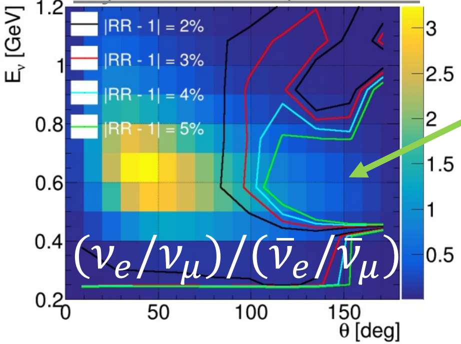




Phys. Rev. D **108**, L031301



Would have a large impact on **CPV discovery**
→but models constrain it to <2% and will be measured in-situ

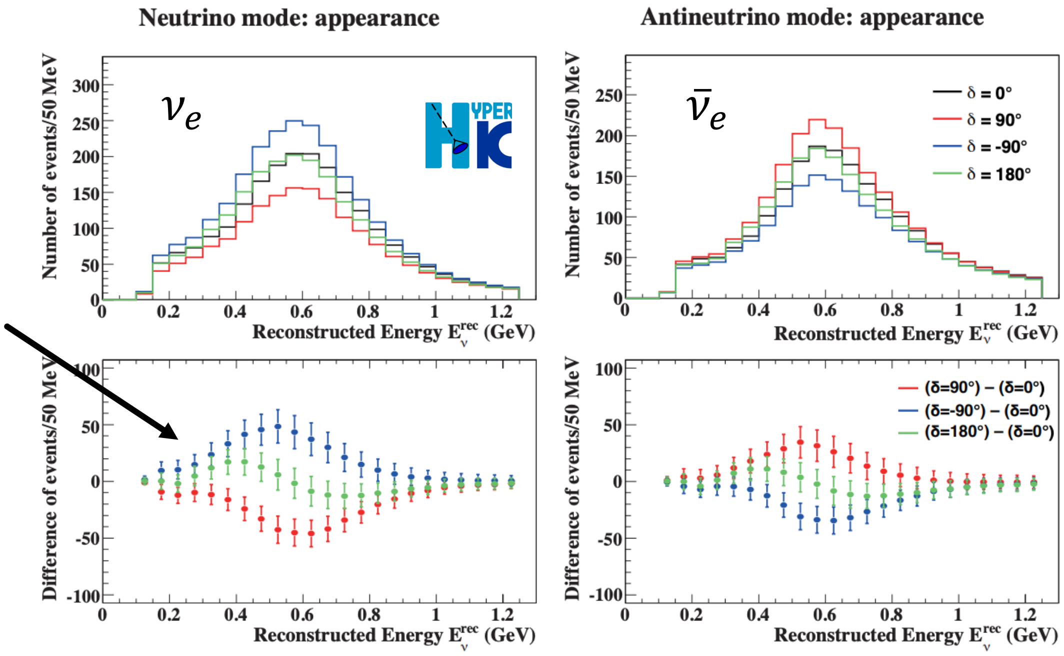
ν_e/ν_μ differences

Current experiments parametrize radiative corrections and model differences only in terms of **normalization**

Particularly important for HK

- Significant part of ν_e spectrum in region where ν_e/ν_μ differences are important
- High ν_e statistics are **sensitive to shape information**
  - Need a finer parametrization of ν_e uncertainties

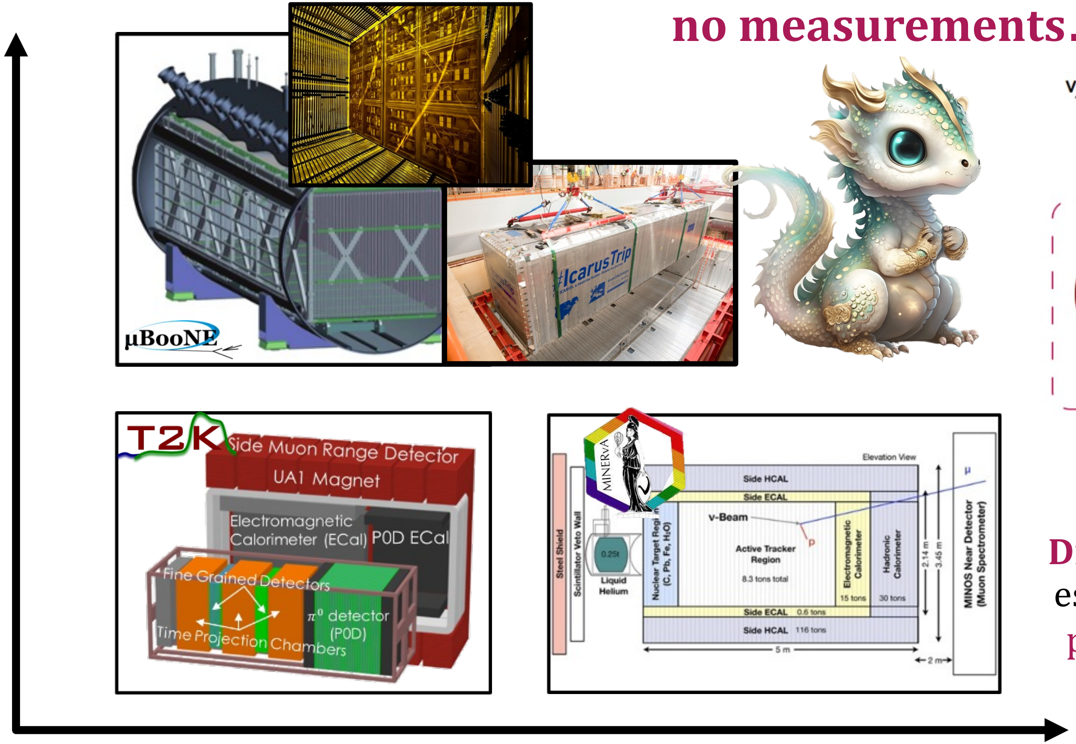
Also important for DUNE 2nd osc. maximum analyses



These effects will have a large impact on $\sin^2\theta_{23}$ octant determination

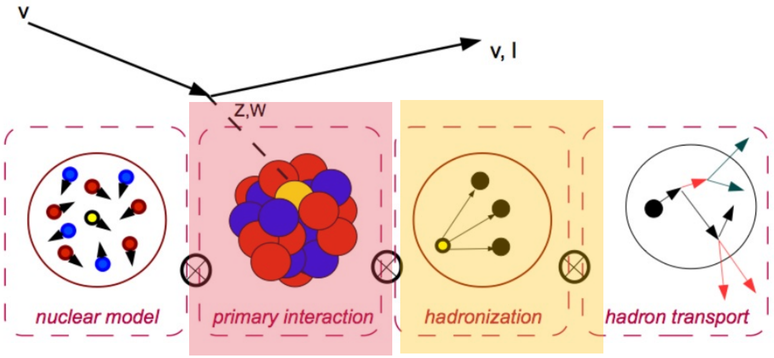
SIS/DIS

SISy/DISy dragons and no measurements…



Atomic number

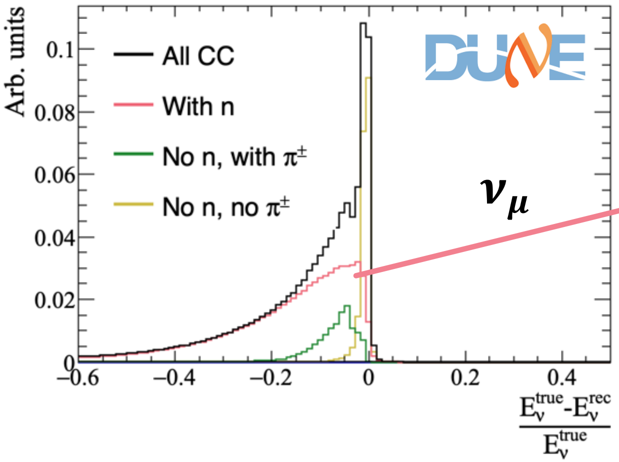
Neutrino energy



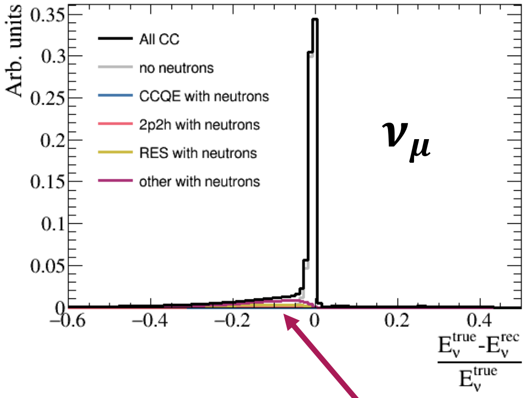
Difficult to calculate esp. at low Q^2 (non-perturbative QCD)

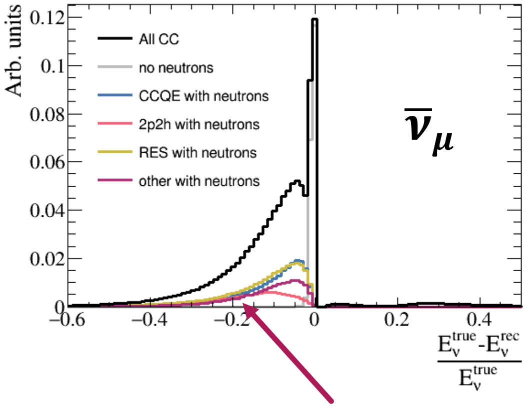
~Impossible to calculate theoretically
Non-reweightable from first principles

SIS/DIS



Sources of **neutrons** before FSI
(and neglecting impact of pions)

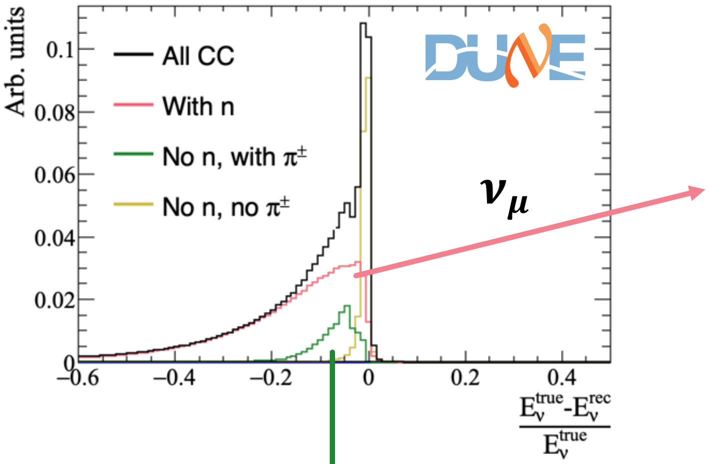




SIS/DIS is the largest source of invisible energy pre-FSI for neutrinos

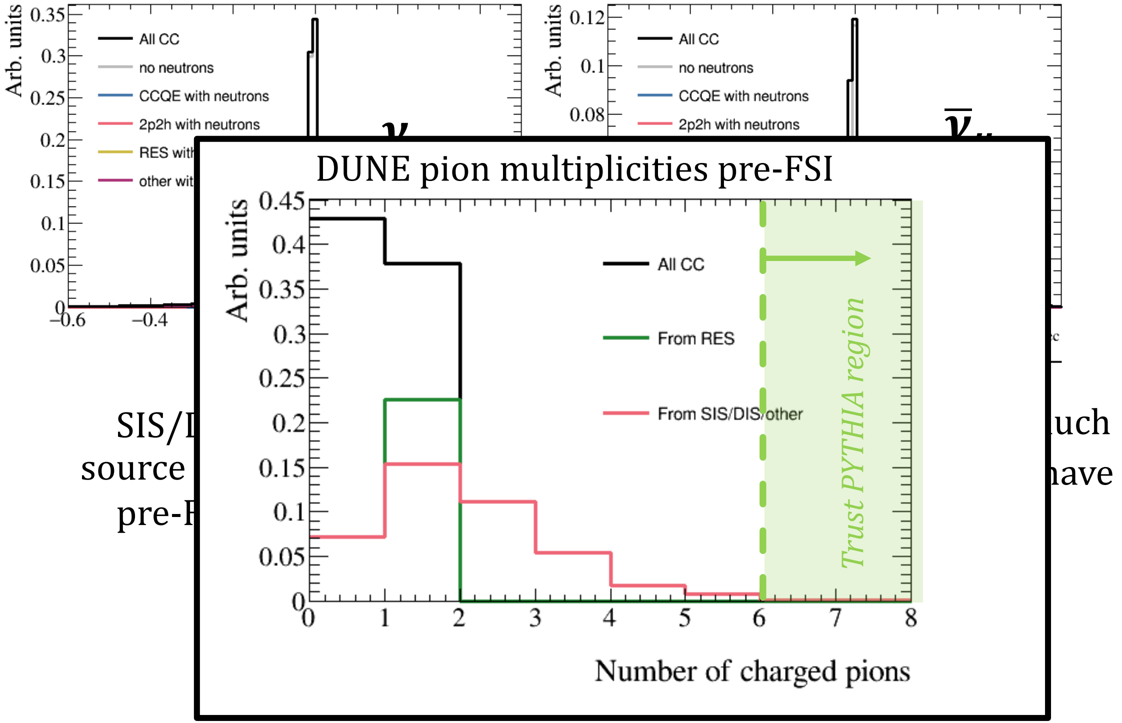
For $\bar{\nu}_\mu$ SIS/DIS produce ~as much neutrons as other modes but have the **highest uncertainty**

SIS/DIS



Many of these pions come from **hadronization routines** (typically PYTHIA) but…

Sources of **neutrons** before FSI
(and neglecting impact of pions)



"I would not trust PYTHIA for anything with less than 6 pions"

S. Prestel (a PYTHIA author)

How do we implement such uncertainties?

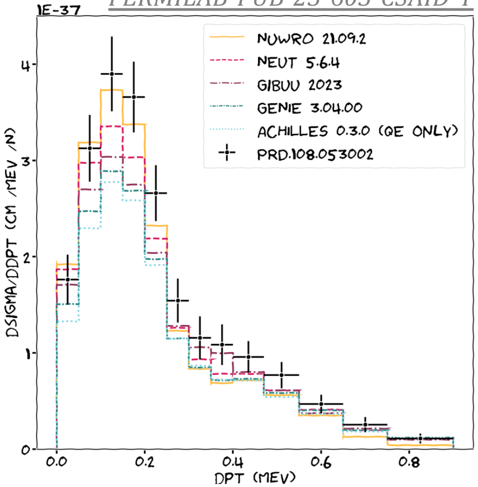
- Standardizing generator outputs
- Granulating uncertainties
- Improved analysis tools

Complex "engineering" project so we need to work together!

Standardizing generator outputs

- NuHepMC
  - Standardized format for generator output inspired by HepMC3
  - Already in the process of being adopted by GENIE, NEUT, Achilles & others

FERMILAB-PUB-23-603-CSAID-T



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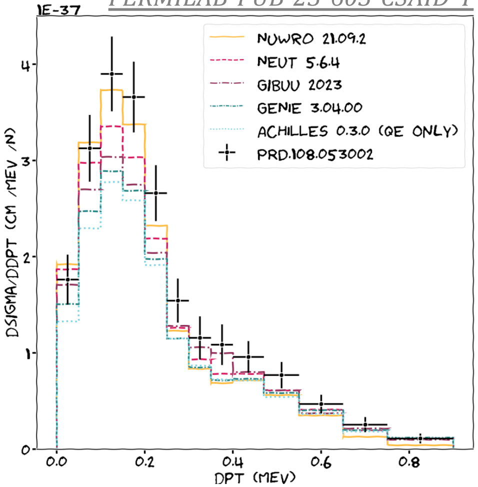
FERMILAB-PUB-23-603-CSAID-T



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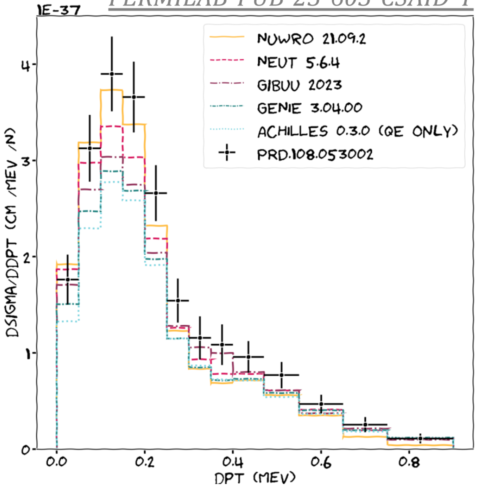
- NuSystematics
  - Common systematics framework for multiple experiments
  - Share development of common systematics

FERMILAB-PUB-23-603-CSAID-T



NuSystematics / nusystematics Public

Standardizing generator outputs

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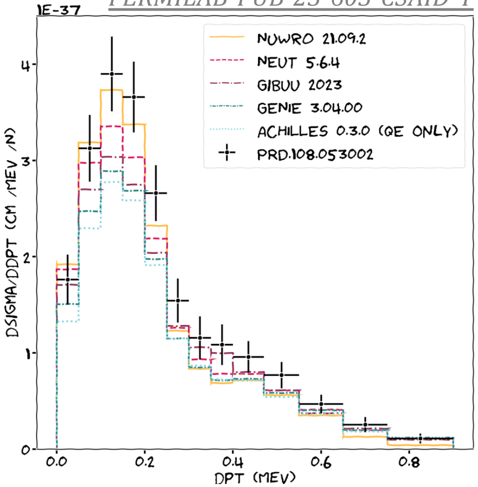
  - Allows us to extract parametrizations of uncertainties!
- NuSystematics
  - Common systematics framework for multiple experiments
  - Share development of common systematics
- Others? Let's discuss your ideas after this talk!

FERMILAB-PUB-23-603-CSAID-T

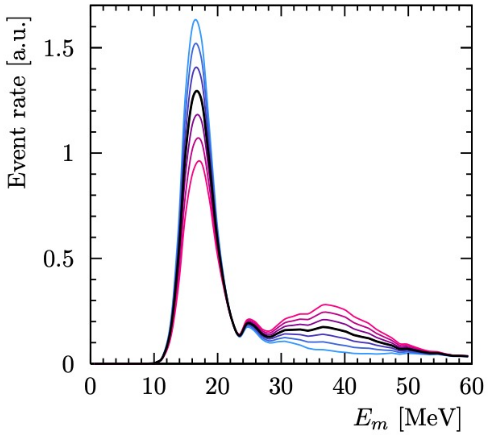


NuSystematics / nusystematics Public

Granulating uncertainties

Get to the **physics of interest**
with as much **detail** as possible

Example:
CCQE uncertainties from T2K



Modify directly the **shell occupancies** in SF model

O(50) d.o.f. for CCQE processes covering wide range of physics:

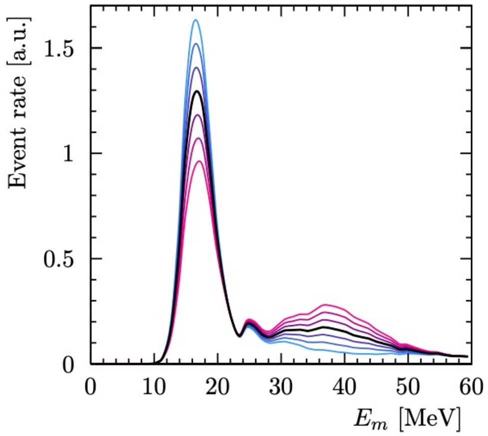
- Removal energies
- Fermi motion
- SRCs
- Optical potential
- Pauli Blocking
- Etc…

Granulating uncertainties

Get to the **physics of interest** with as much **detail** as possible

Encode **near/far detector differences** (flavor, target, energy)

Example:
CCQE uncertainties from T2K



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- Removal energies
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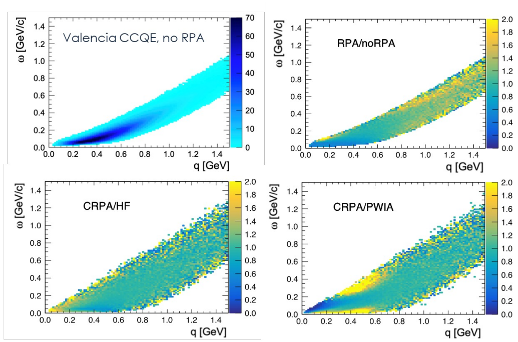
- Optical potential
- Pauli Blocking
- Etc…

Example:
SF→CRPA reweight from T2K



Take ratios of hadron tensors as a function of ω and q…

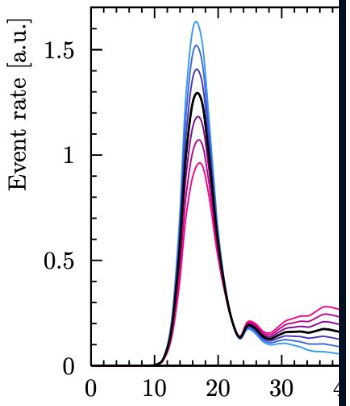
But also as a function of E_ν
Repeat for $(\nu_\mu, \nu_e, \bar{\nu}_\mu, \bar{\nu}_e)\times$(C,O)

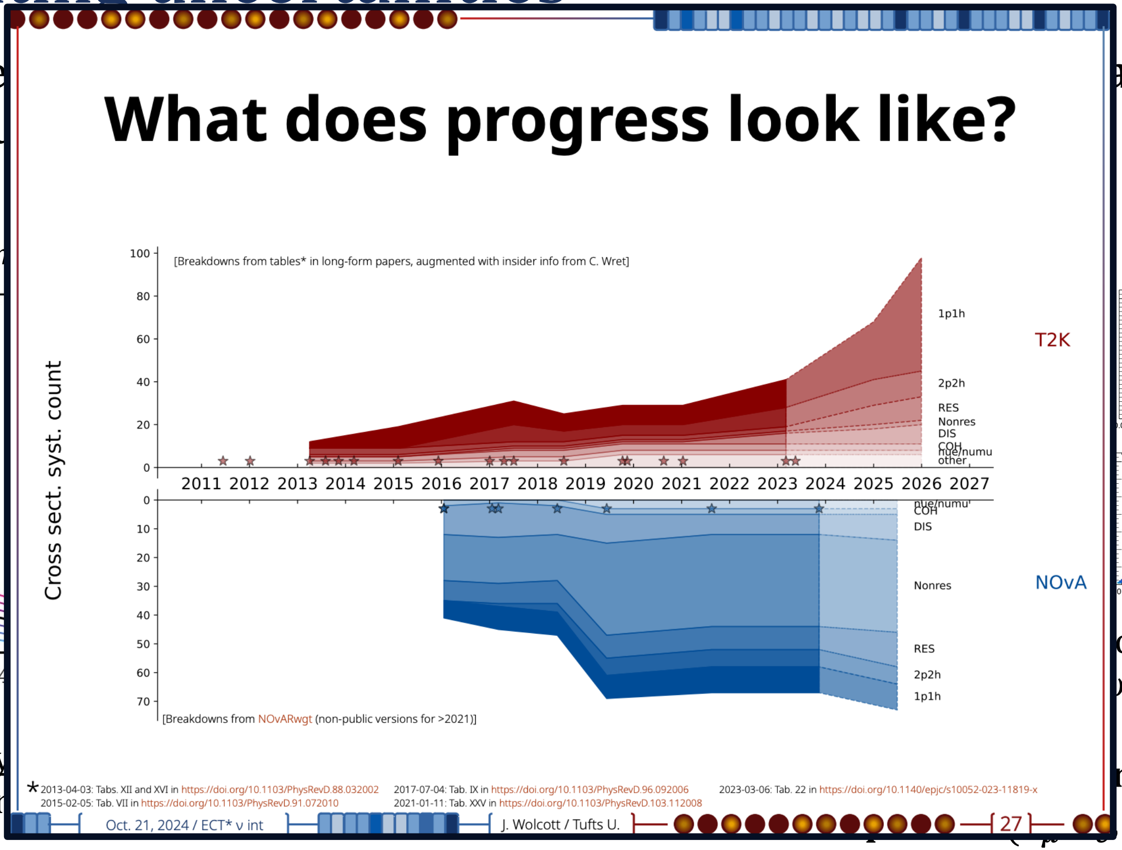
Phys. Rev. D 109, 072006

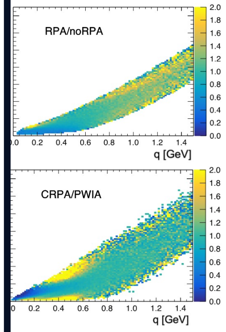
Granulating uncertainties

Get to the … ar detector
with as mu … target, energy)

Example:
CCQE uncertainties fron







… on tensors as a
… and q…

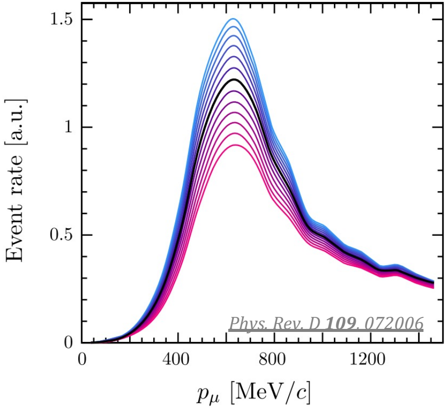
Modify directly …
occupancies i…

…nction of E_ν
… $\bar{\nu}_\mu, \bar{\nu}_e)\times$(C,O)

Granulating uncertainties

But our generators/models often don't allow us to design uncertainties from first principles…

Example 1:



Effect of Pauli Blocking from different simulations on observable p_μ

Granulating uncertainties

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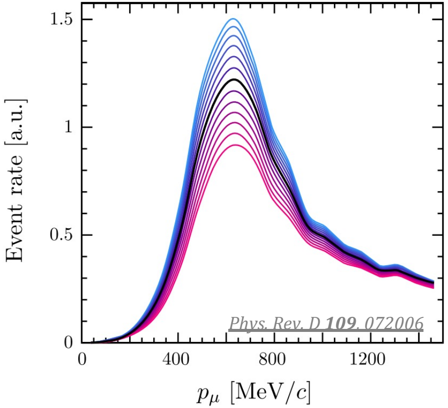
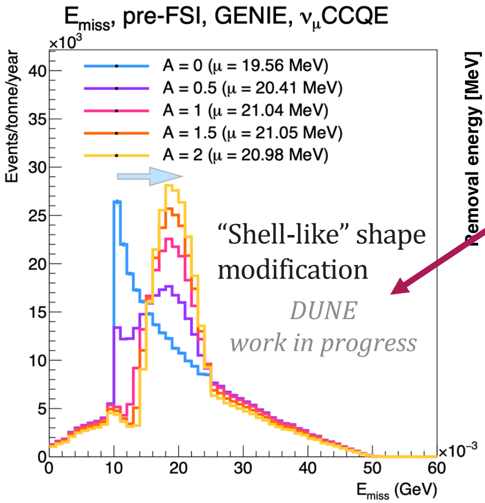
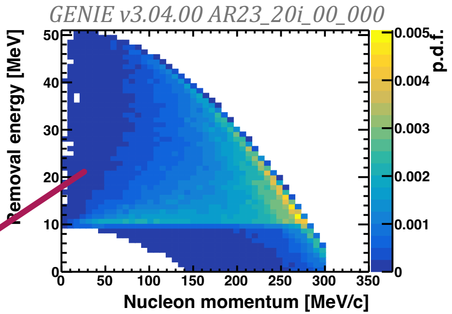


Effect of Pauli Blocking from different simulations on observable p_μ

Example 2:





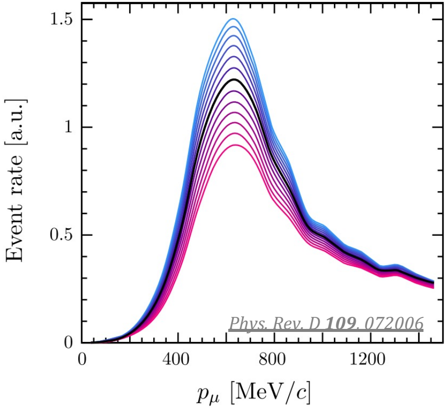
…even though we're using an LFG model

Granulating uncertainties

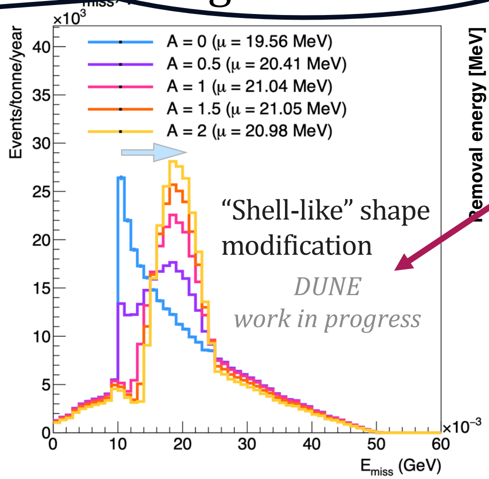
But our generators/models often don't allow us to design uncertainties from first principles…

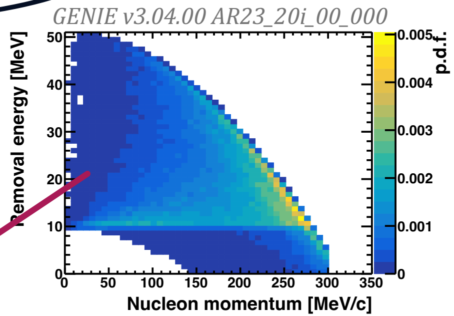
"Parametrized ignorance"

Example 1:



Effect of Pauli Blocking from different simulations on observable p_μ





…even though we're using an LFG model

An ad-hoc solution is better than no solution!

Improving our tools for future needs

Multi-dimensional reweighting:
Can all response functions be factorized?

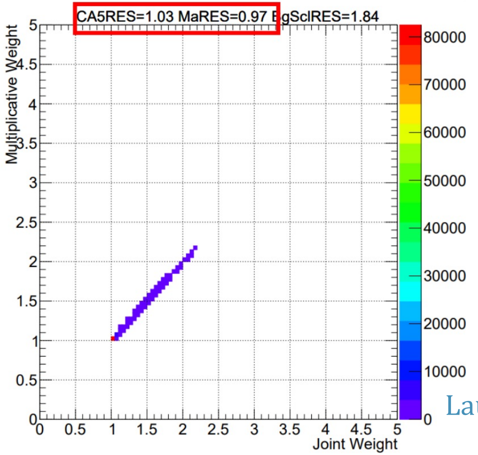
From a T2K masterclass by K. Skwarczynski

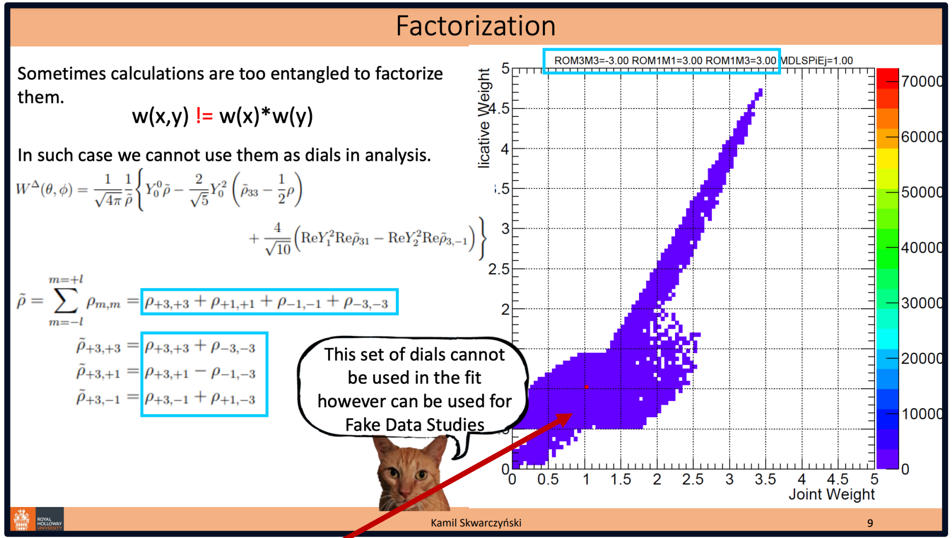
Example: RES form factors

$$F_A^{RES}(Q^2) = \frac{C_5^A(0)}{\left(1 + \frac{Q^2}{(M_A^{RES})^2}\right)^2}$$

$w(C^A_5, M_A^{RES})$?= $w(C^A_5)*w(M_A^{RES})$

Not too bad!





But this doesn't always work…

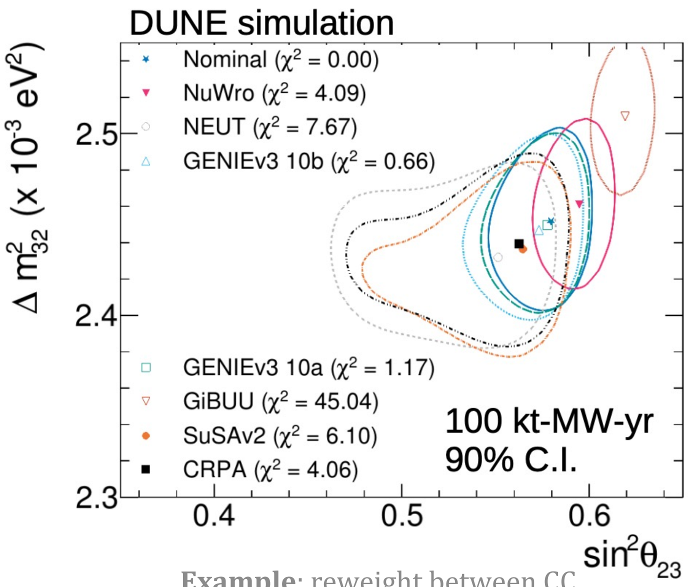
Solutions exist (e.g. PCA for z-expansion) but
no universal solution

Improving our tools for future needs

Using Machine Learning tools

Synthesizing complex effects to get at impact on observables

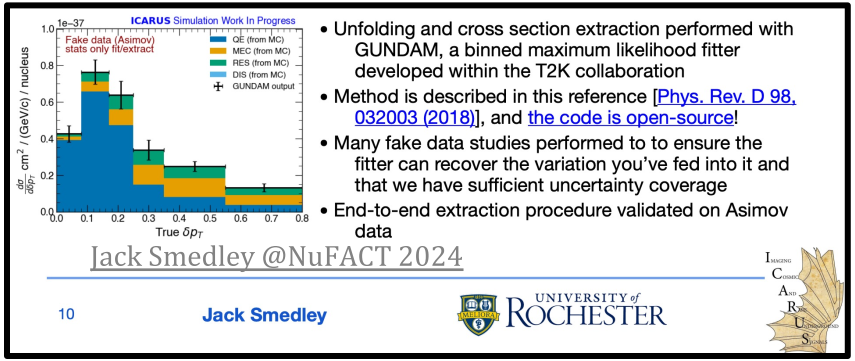
From C. Wilkinson's talk yesterday

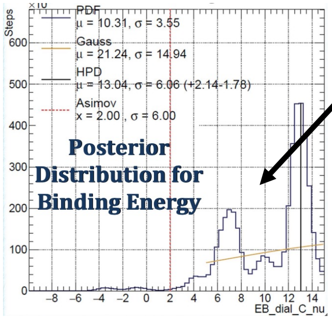


Example: reweight between CC Inclusive predictions from generators

Improved analysis tools

Cope with complex parameters & large stats





We pretend this is Gaussian…

But MaCh3 helps us see it's not!

Improving our tools for future needs

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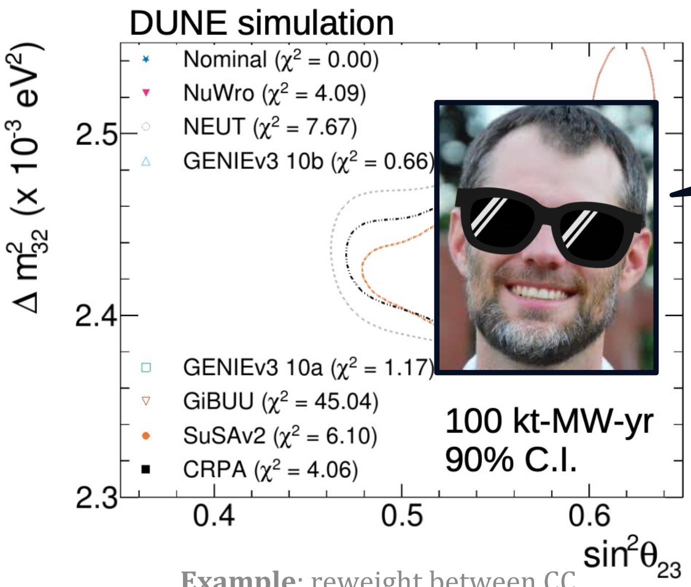

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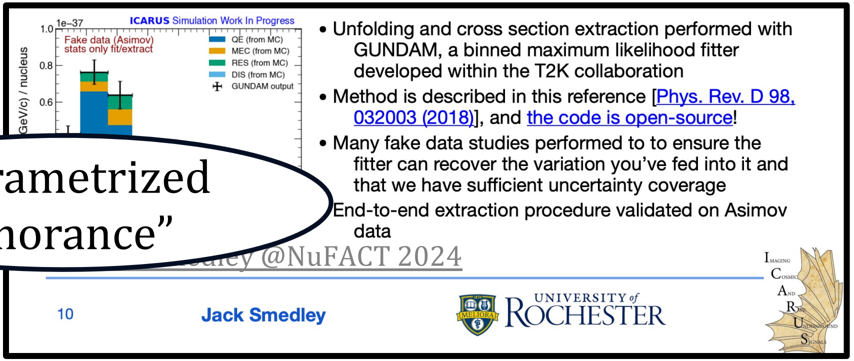
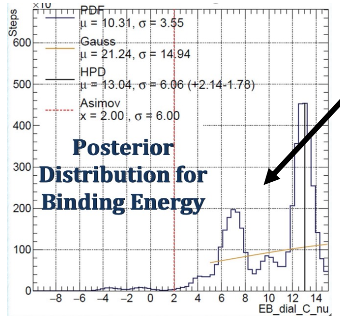




We pretend this is Gaussian…

But MaCh3 helps us see it's not!

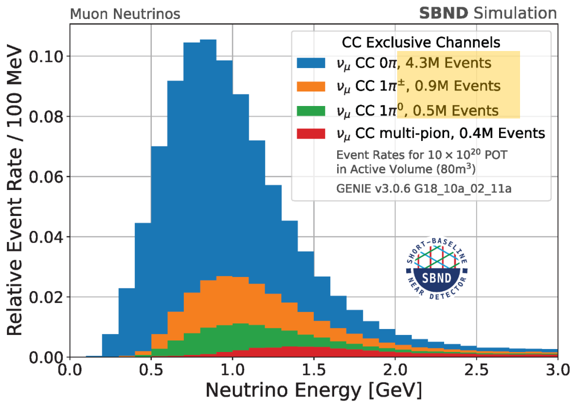
Reducing uncertainties in the meantime

Systematic uncertainties encode what we don’t know…

- It is important to have **robust parametrizations** so that we don’t misatribute effects
- But also to keep making measurements to **better understand all processes**

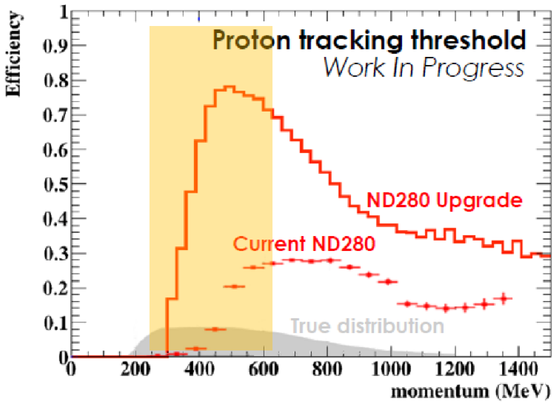
With neutrino scattering experiments… (non-exhaustive list)

Higher statistics



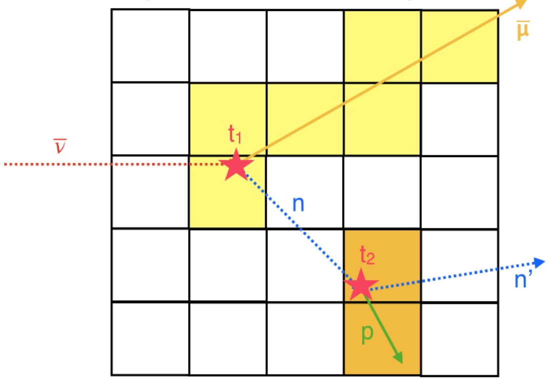
Low hadron thresholds

(access to low ω region!)



Neutrons!

See talks by S. Dolan & S. Manly on Thursday



Phys. Rev. D 101, 092003

Reducing uncertainties in the meantime

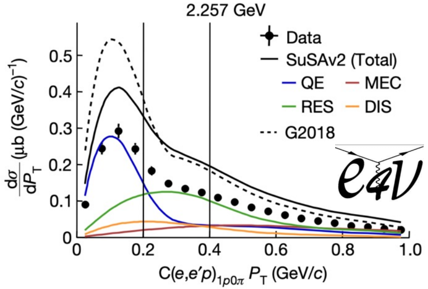
Systematic uncertainties encode what we don't know…

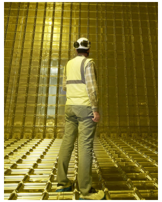
- It is important to have **robust parametrizations** so that we don't misatribute effects
- But also to keep making measurements to **better understand all processes**

…but not only! (non-exhaustive list)

Electron and hadron scattering

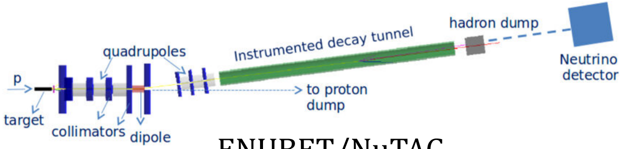
Nature 599, p. 565–570 (2021)



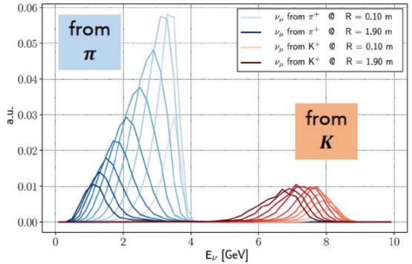


protoDUNE

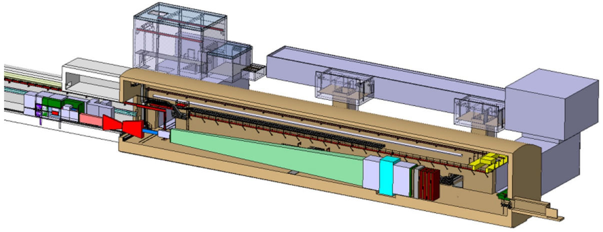
Monitored/tagged neutrino beams



ENUBET/NuTAG



Maybe even SHiP?



Potential to expect $O(10^5 - 10^6)\ \nu_\mu$ interactions around ~5-6 GeV

→SIS region relevant for DUNE!

Summary

- Future generation experiments need 1-3% level uncertainties in order not be prematurely limited by systematics
- Their needs in terms of physics are beyond what we are sensitive with current experiments and need **special attention**
- We need inputs from the theory community and new measurements to reduce the size of our uncertainties
- But also **robust** parametrizations of effects and sophisticated tools for high stats analyses
- **Hopefully some of the outcomes of this workshop!**

Thank you for your attention!

Back-Up

Neutrino cross-sections and oscillations

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

Systematic uncertainties

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

Oscillation parameters

Neutrino flux

Interaction cross-section

Detection efficiency

Energy smearing matrix

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Oscillation parameters

Neutrino flux

Interaction cross-section

Detection efficiency

Energy smearing matrix

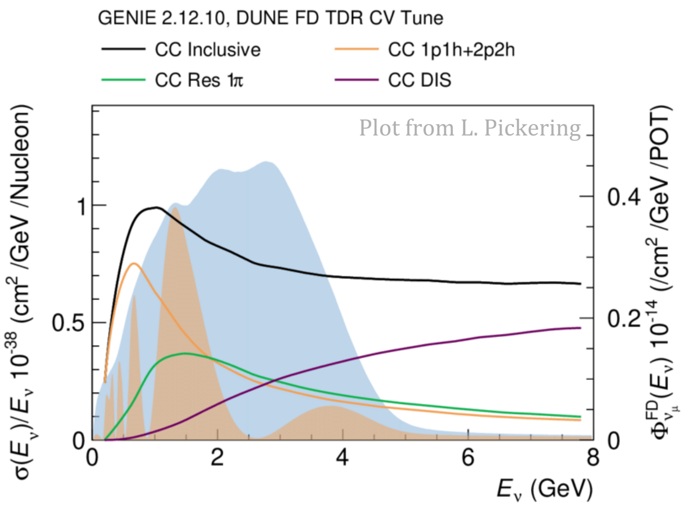
- Constrain systematics with **near detector**
- But **heavily rely on models** to predict near-to-far detector extrapolation

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

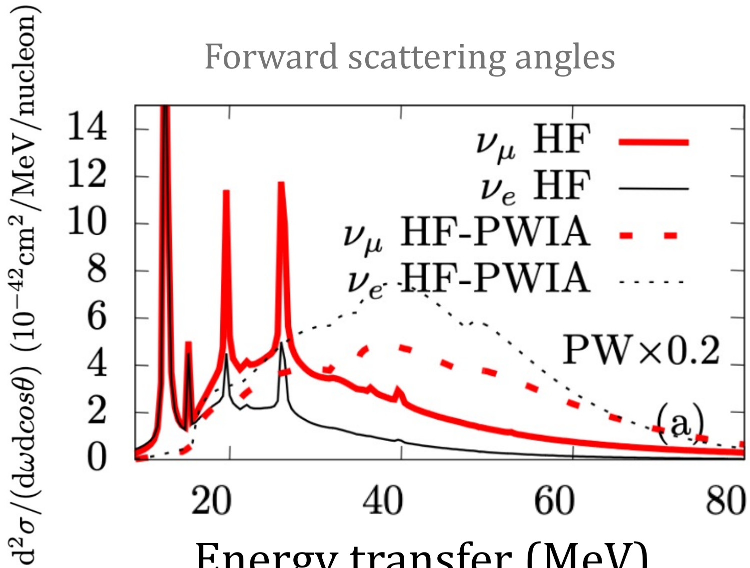
Near detectors are an **essential part** of any oscillation experiment

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)**

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

Forward scattering angles



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

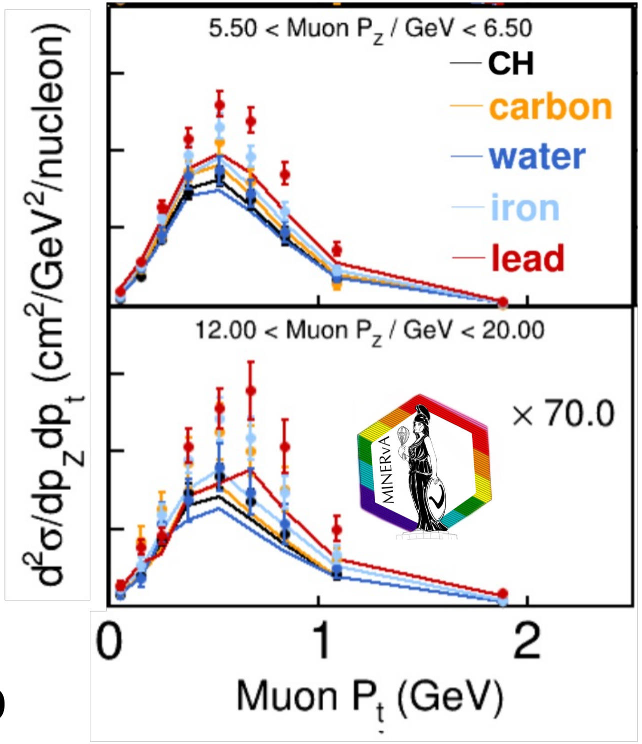
Oscillation analyses and model dependence

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

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)
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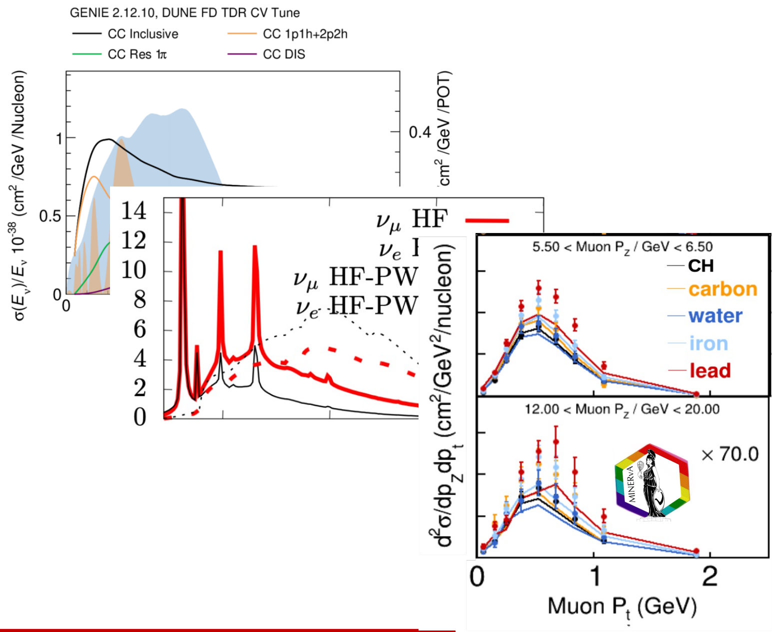
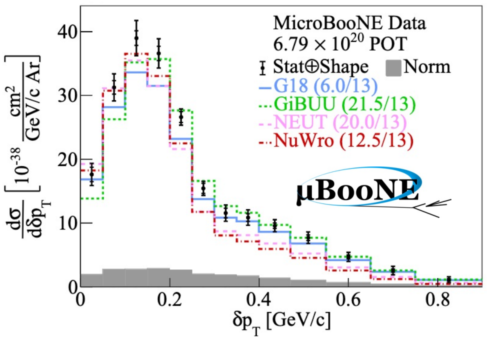


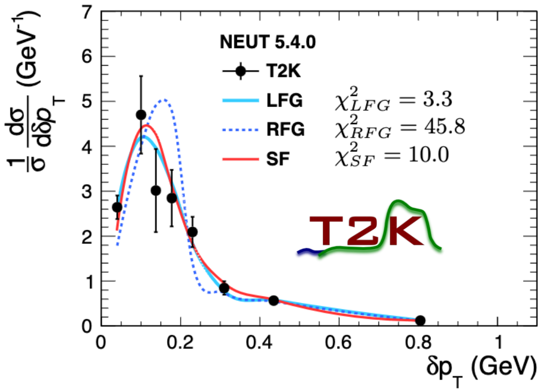
Model dependence <u>cannot</u> be escaped in neutrino oscillation experiments

How do our models perform?

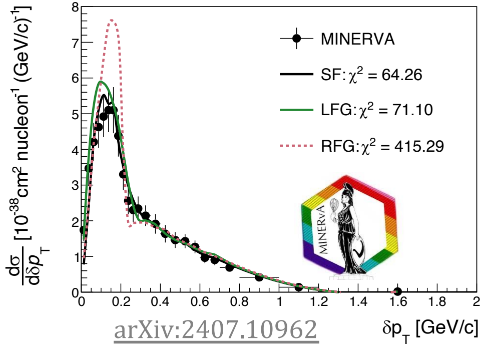
arXiv:2301.03700



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

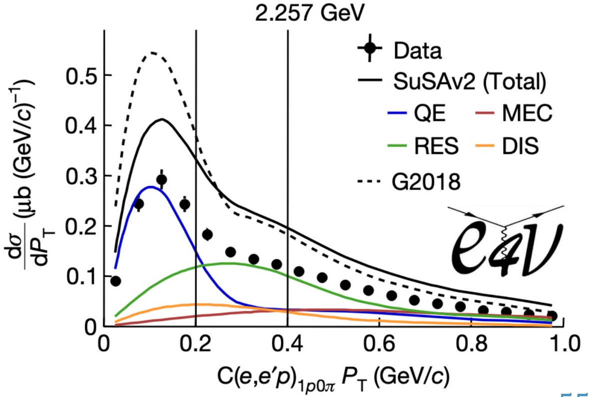


Phys. Rev. Lett. 121, 022504 (2018)



arXiv:2407.10962

Nature 599, p. 565–570 (2021)



How do our models perform?

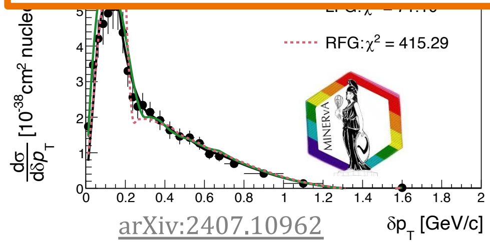
arXiv:1810.06043
Phys. Rev. D 98, 032003 (2018)

arXiv:2301.03700

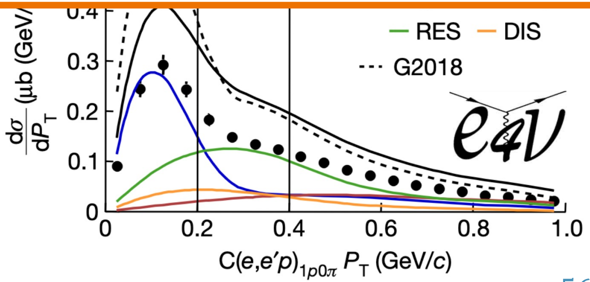
p-values of model comparisons to measurements
(red if excluded at <0.05)

arXiv:2407.10962

Measurement	N_{bins}	SF/SF*	LFG	RFG	More 2p2h	More FSI	Less FSI	More π abs.	Less π abs.
T2K $\delta\alpha_T$	8	0.01	0.00	0.00	0.00	0.00	0.02	0.06	0.02
T2K δp_T	8	0.08	0.69	0.00	0.00	0.02	0.07	0.00	0.18
MINERvA $\delta\alpha_T$	12	0.00	0.00	0.00	0.00	0.00	0.06	0.00	0.00
MINERvA δp_T	24	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MINERvA p_N	24	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MicroBooNE $\delta\alpha_T$	7	0.02	0.45	0.62	0.07	0.18	0.00	0.02	0.01
MicroBooNE δp_T	13	0.12	0.42	0.00	0.33	0.23	0.02	0.13	0.10
MicroBooNE δp_T low $\delta\alpha_T$	11	0.26	0.23	0.14	0.37	0.44	0.10	0.28	0.24
MicroBooNE δp_T mid-low $\delta\alpha_T$	12	0.07	0.40	0.19	0.23	0.38	0.00	0.08	0.06
MicroBooNE δp_T mid-high $\delta\alpha_T$	13	0.04	0.23	0.02	0.16	0.22	0.01	0.05	0.04
MicroBooNE δp_T high $\delta\alpha_T$	13	0.03	0.13	0.08	0.12	0.09	0.01	0.04	0.03



arXiv:2407.10962



How do our models perform?

arXiv:2301.03700

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

No model is able to describe global neutrino scattering measurements

p-values of model comparisons to measurements
(red if excluded at <0.05)

arXiv:2407.10962

Measurement	N_{bins}	SF/SF*	LFG	RFG	More 2p2h	More FSI	Less FSI	More π abs.	Less π abs.
T2K $\delta\alpha_T$	8	0.01	0.00	0.00	0.00	0.00	0.02	0.06	0.02
T2K δp_T	8	0.08	0.69	0.00	0.00	0.02	0.07	0.00	0.18
MINERvA $\delta\alpha_T$	12	0.00	0.00	0.00	0.00	0.00	0.06	0.00	0.00
MINERvA δp_T	24	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MINERvA p_N	24	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MicroBooNE $\delta\alpha_T$	7	0.02	0.45	0.62	0.07	0.18	0.00	0.02	0.01
MicroBooNE δp_T	13	0.12	0.42	0.00	0.33	0.23	0.02	0.13	0.10
MicroBooNE δp_T low $\delta\alpha_T$	11	0.26	0.23	0.14	0.37	0.44	0.10	0.28	0.24
MicroBooNE δp_T mid-low $\delta\alpha_T$	12	0.07	0.40	0.19	0.23	0.38	0.00	0.08	0.06
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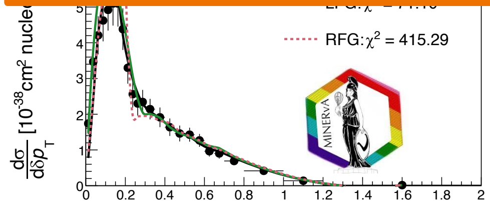

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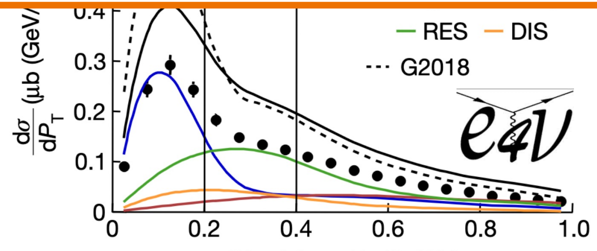

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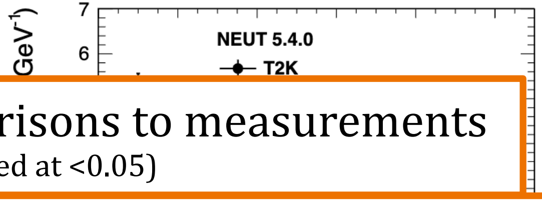

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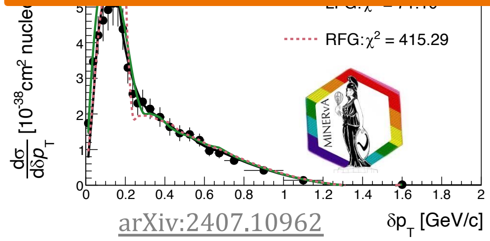
"One thing I know, that I know nothing. This is the source of my wisdom."

Socrates, as he analyzes neutrino cross-section measurements



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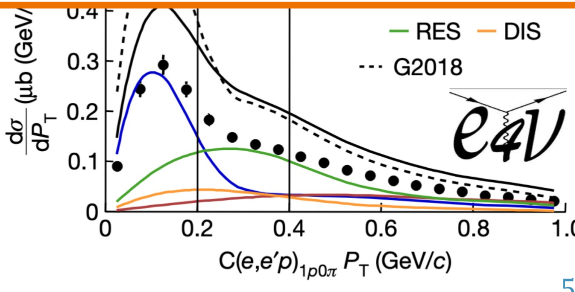
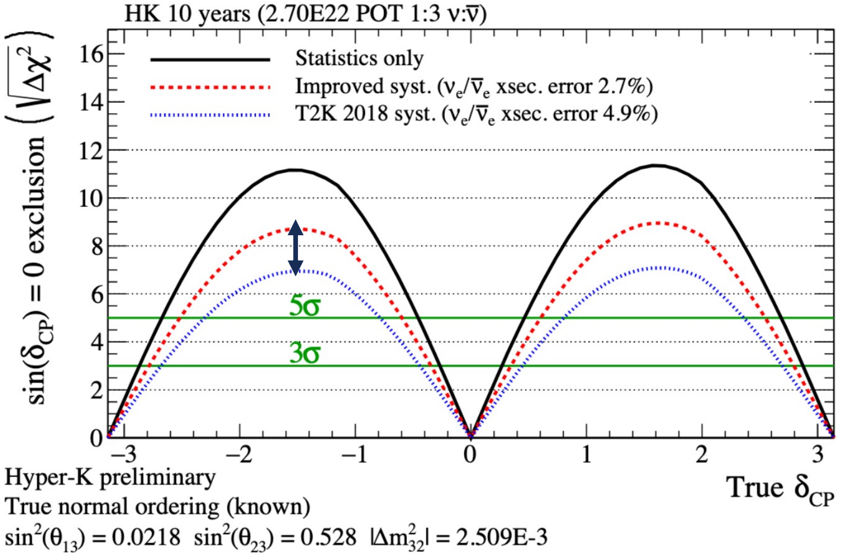


Main challenge(s) for $\sin\delta_{CP} = 0$ exclusion

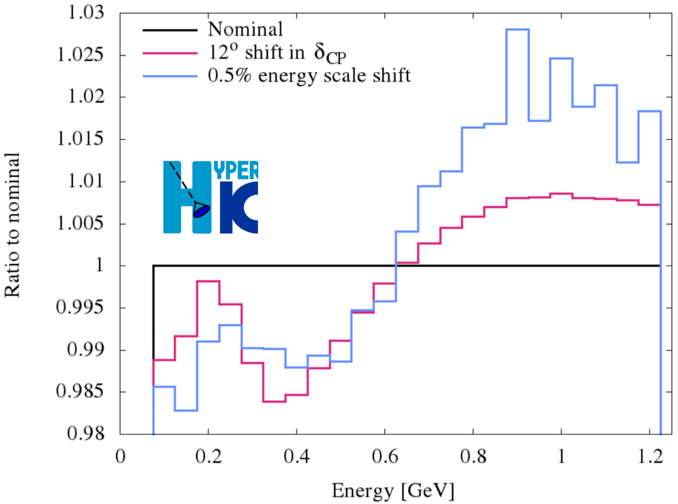


Dominant systematics related to the uncertainty on $\boldsymbol{\sigma(\nu_e)}$ **and** $\boldsymbol{\sigma(\nu_\mu)}$ **differences**

Current constraints mainly driven by theory

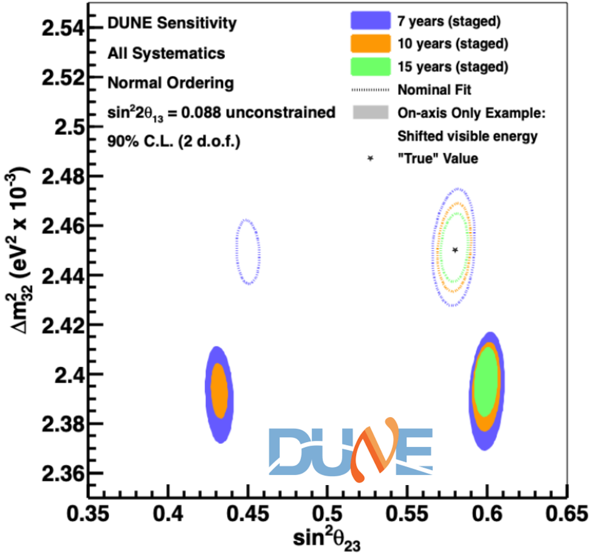
See talk by S. Dolan (Tuesday, WG2)

Main challenges for precision measurements



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

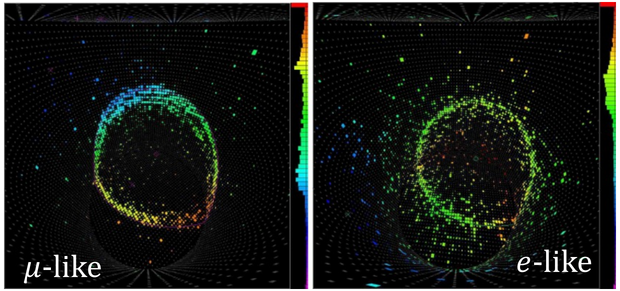
DUNE FD TDR



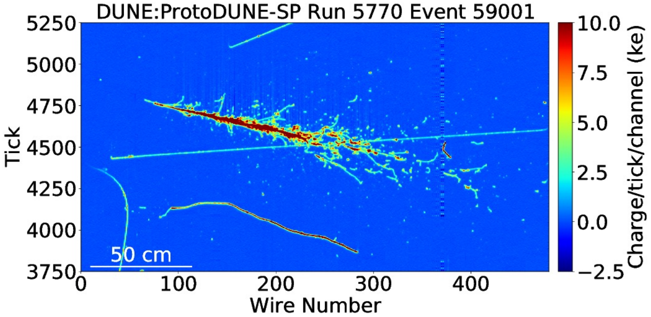
Bias in osc. parameter measurements due to shift in visible energy

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

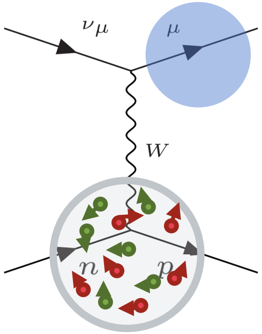


LArTPC – measure particles' energy deposits

Different detectors – different methods – different priorities

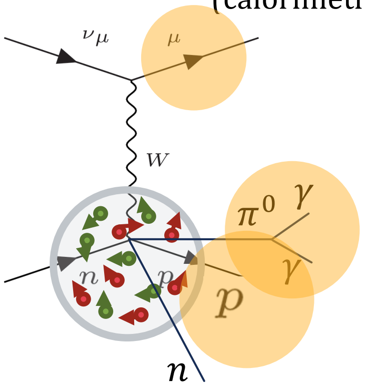
Neutrino energy reconstruction

("kinematic" energy reconstruction)



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

(calorimetric energy reconstruction)

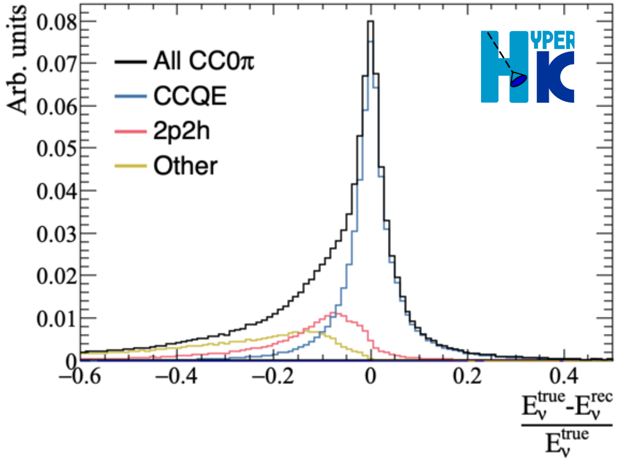


Add up all **visible energy** from final state particles

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

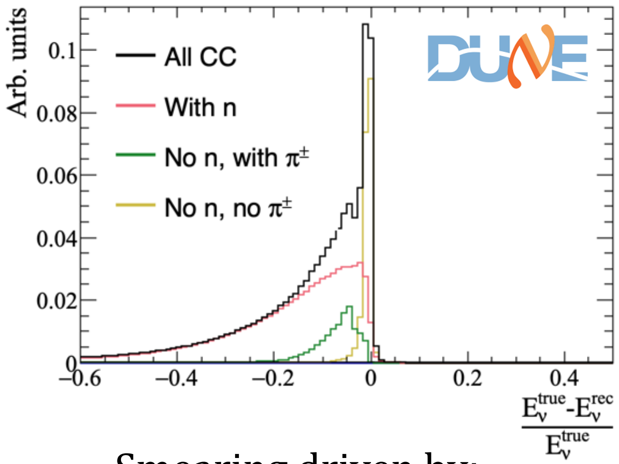
Inspired by S. Dolan's INSS 2023 lecture

Neutrino energy reconstruction



Smearing driven by:

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

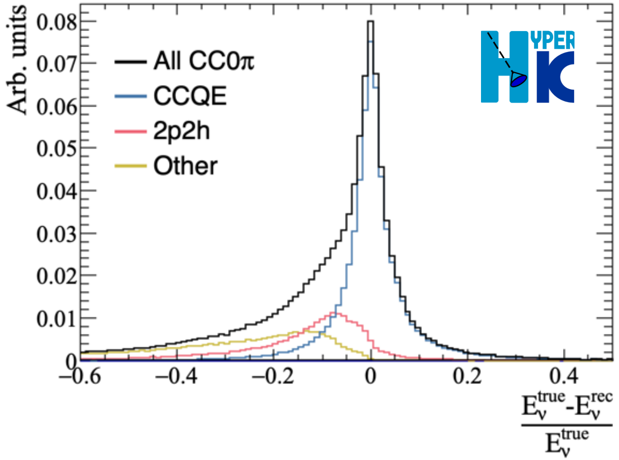


Smearing driven by:

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

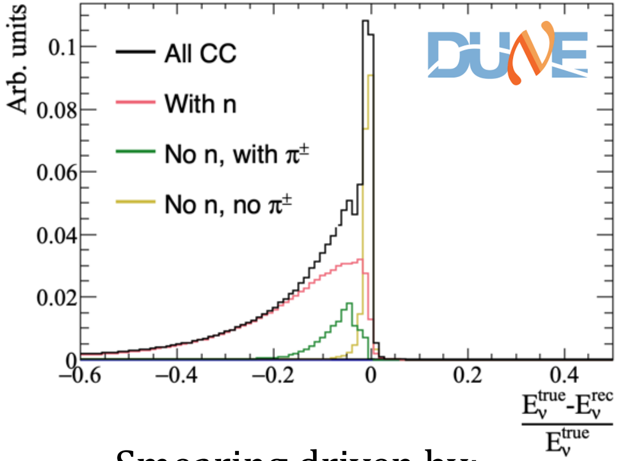
Different detectors – different methods – **different priorities**

Neutrino energy reconstruction



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

Wider intrinsic smearing but easier to control

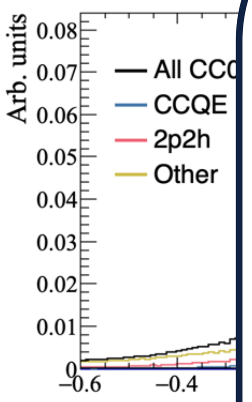


Smearing driven by:
- Fraction of **energy carried by neutrons**
- **Pion production** processes

Smaller intrinsic smearing but **harder to control**

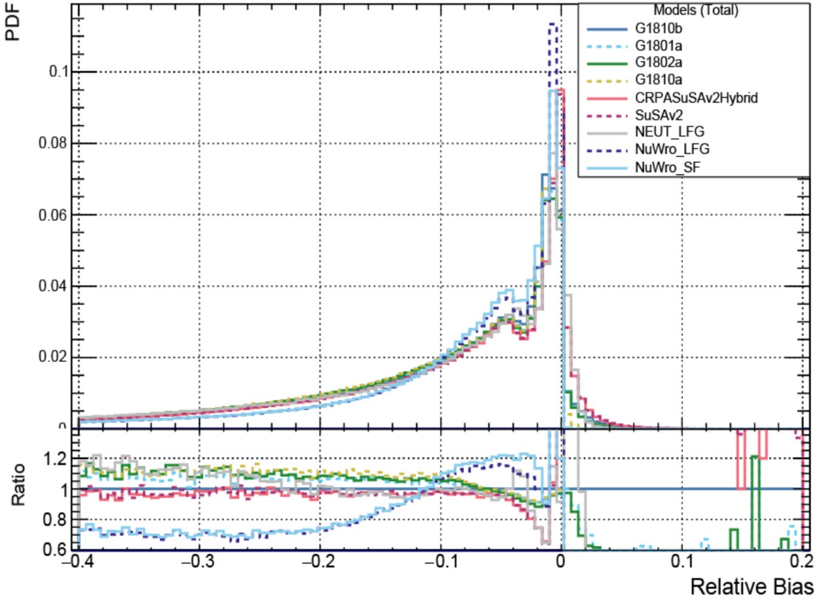
Different detectors – different methods – **different priorities**

Neutrino en

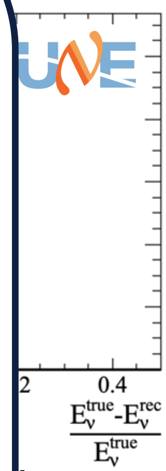


Relative bias on the reconstructed neutrino energy for DUNE from multiple models

Plot by A. Wong Wei Ren



High model disagreement



Smearing driv

- **Nuclear gr**
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