Characterising the role of final state interactions on neutrino energy estimation in the DUNE and Hyper-K era

Based on arXiv:2511.03964 and arXiv:2605.28696

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In collaboration with Stephen Dolan (CERN), Yinrui Liu (Columbia U.) and Jake McKean (U. Kyoto)

NSTAR 2026, Seville, Spain

9 September 2026

See NuSTEC 19 Aug 2026 CEWG seminar for more details

How precise is “precise”?

	Current	**Future: goal**
Stat.	5-10%	1-3%
Syst.	5%	<1-3%
X-sec.	4%	???

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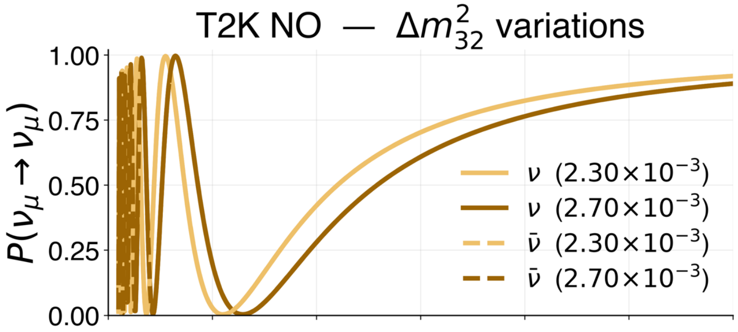
Uncertainty on total *normalization*

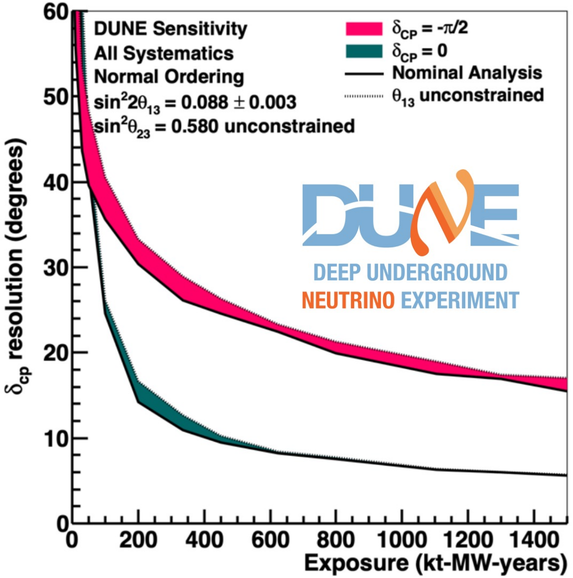


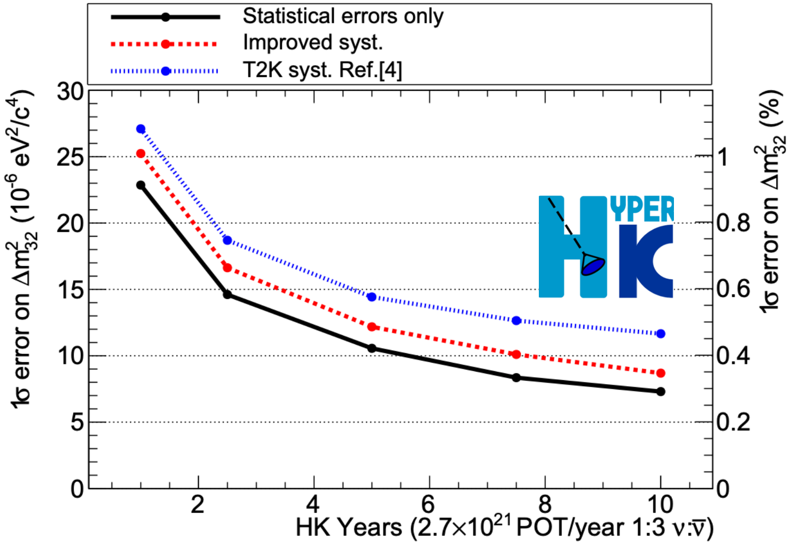
Shape information is crucial for oscillation measurements

See arXiv:2605.28696 for more details

How precise is "precise"?

Possible definition: to reach precision measurement goals





$\sim 20^o$ if $\delta_{CP} = -\pi/2$

$\sim 0.5\%$ on Δm^2_{32}

See arXiv:2605.28696 for more details

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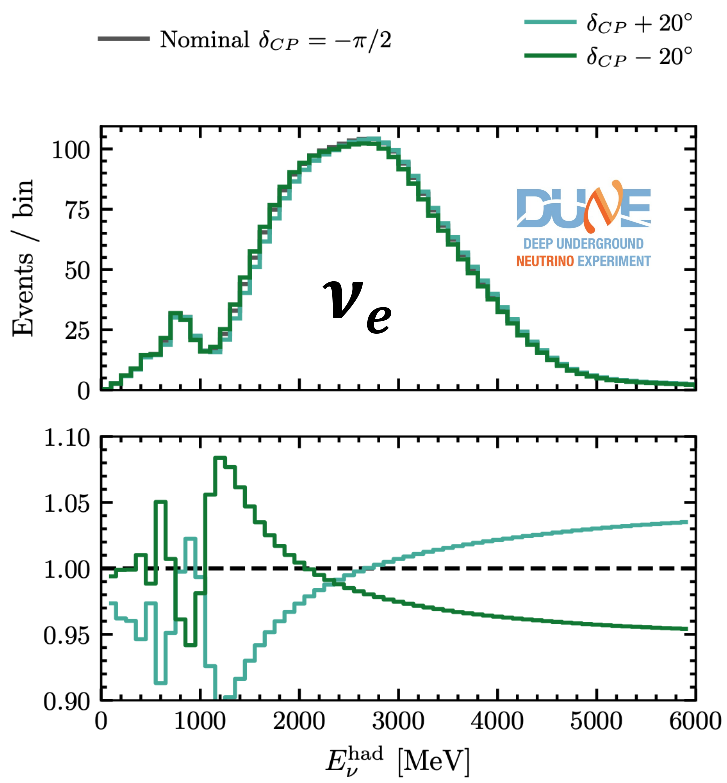

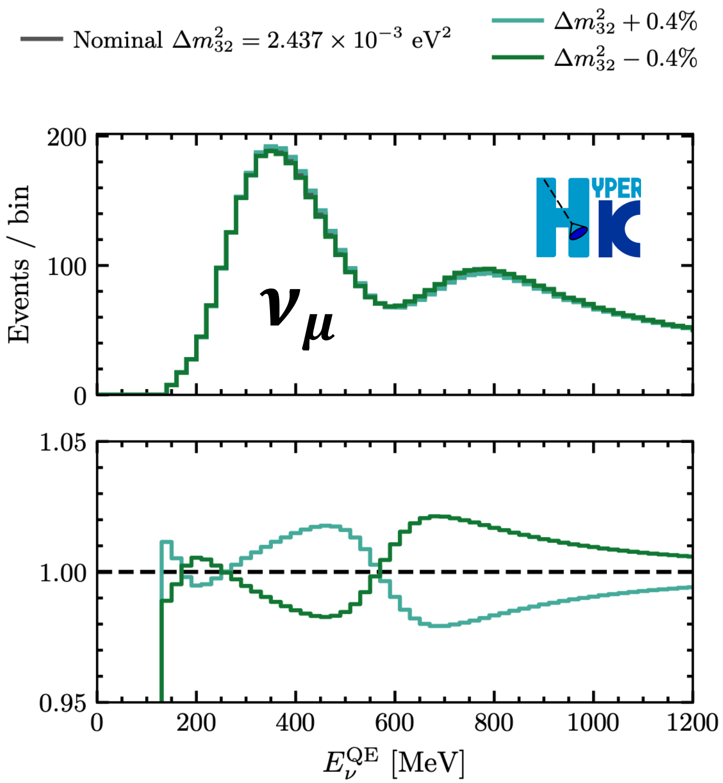

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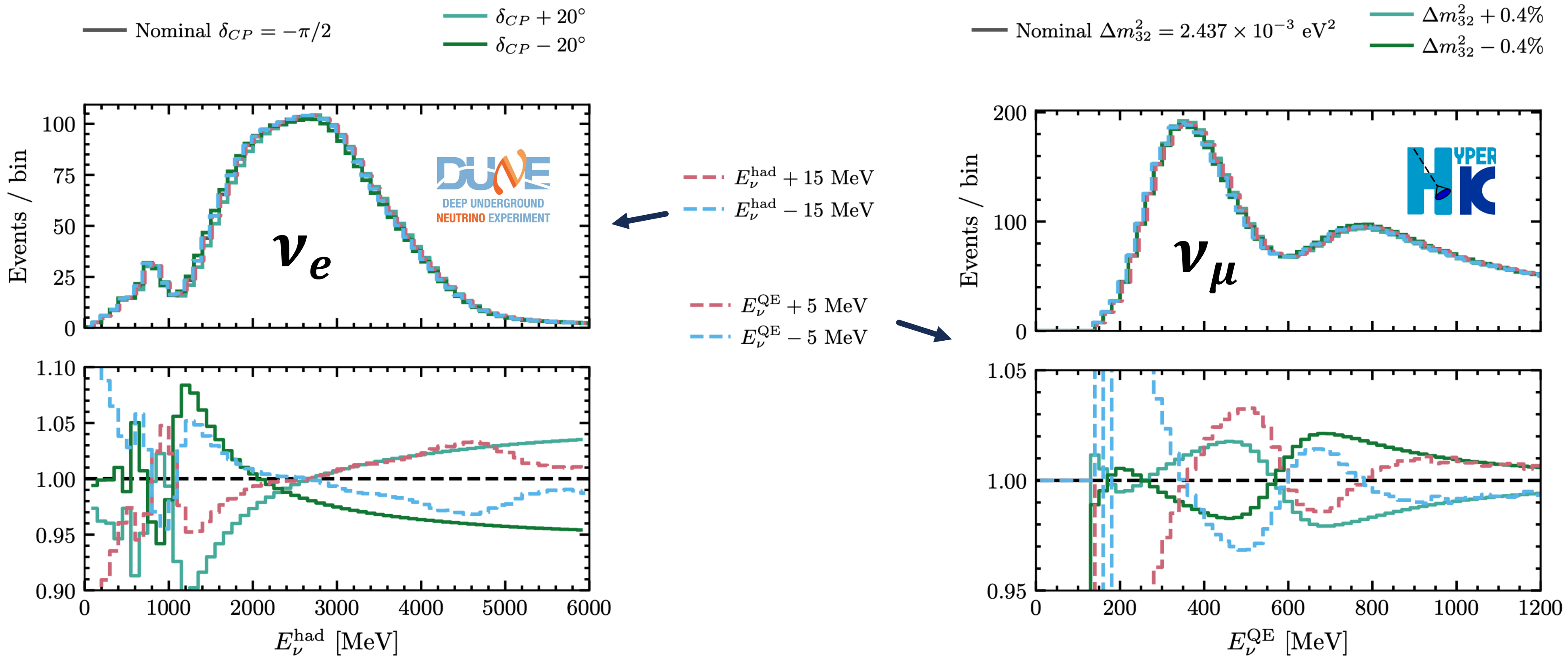

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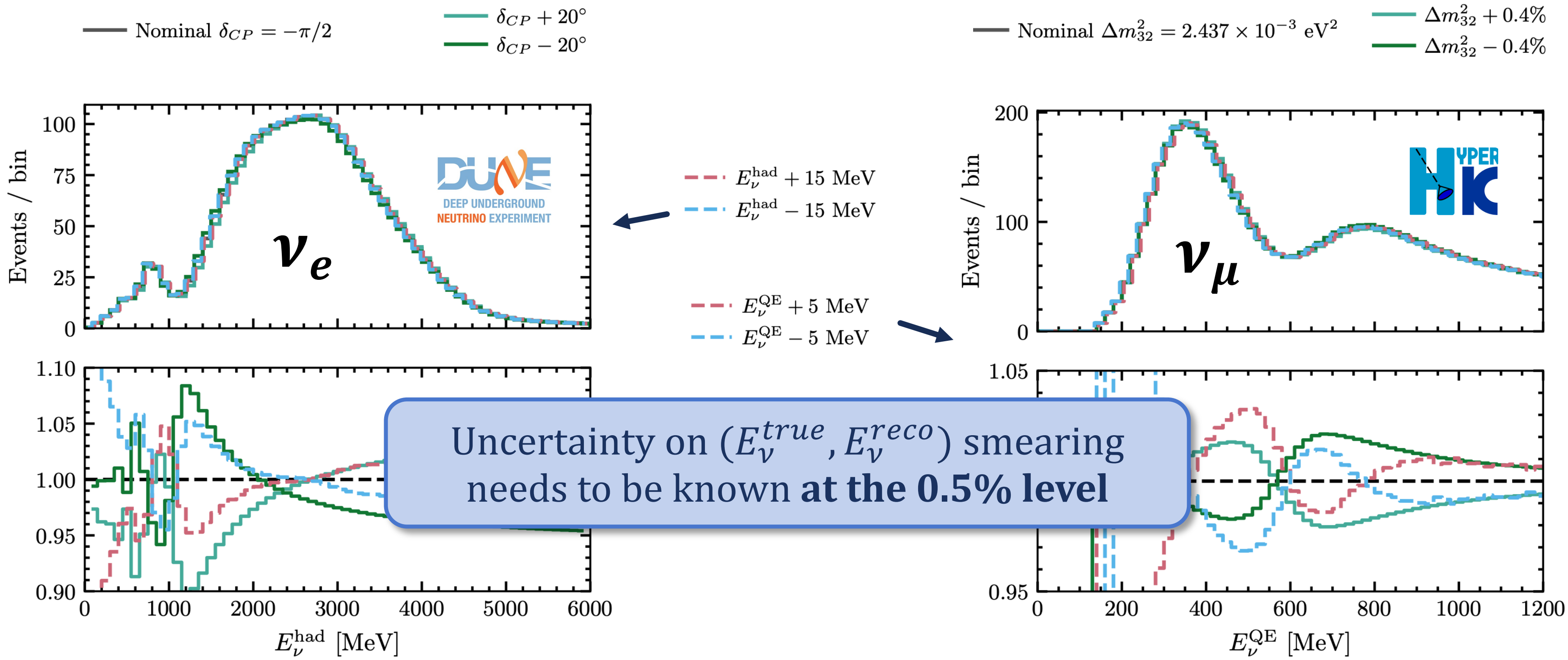
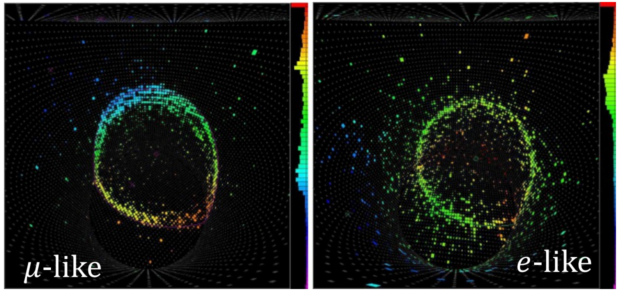
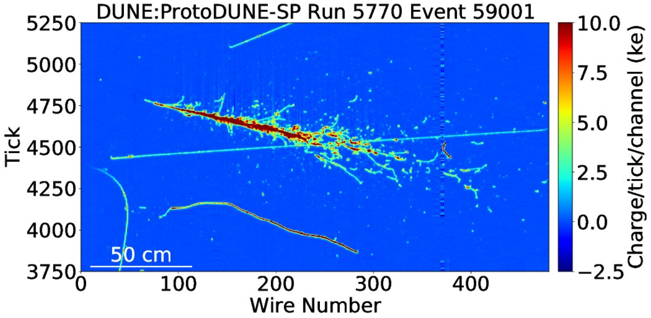


Uncertainty on $(E_\nu^{true}, E_\nu^{reco})$ smearing needs to be known **at the 0.5% level**

Neutrino energy reconstruction



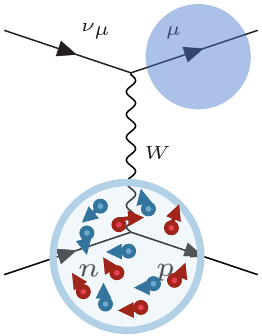
Water Cherenkov – measure kinematics of particles above threshold



LArTPC – measure particles' energy deposits

Neutrino energy reconstruction

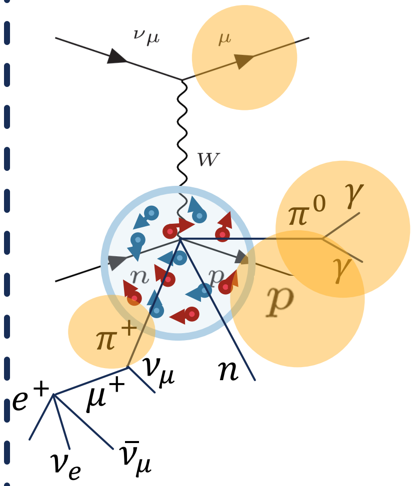
(kinematic energy reconstruction)



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

$$E_\nu^{QE} = \frac{m_p^2 - m_\ell^2 - (m_n - E_b)^2 + 2E_\ell(m_n - E_b)}{2(m_n - E_b - E_\ell + p_\ell^z)}$$

(calorimetric energy reconstruction)



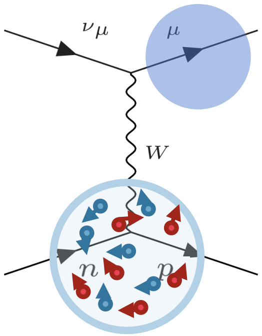
Add up all **visible energy** from final state particles

$$E_\nu^{avail} = E_\ell + \sum_{i=p,\pi^\pm} T_i + \sum_{i=\pi^0,\gamma} E_i$$

Inspired by S. Dolan's INSS 2023 lecture

Neutrino energy reconstruction

(kinematic energy reconstruction)



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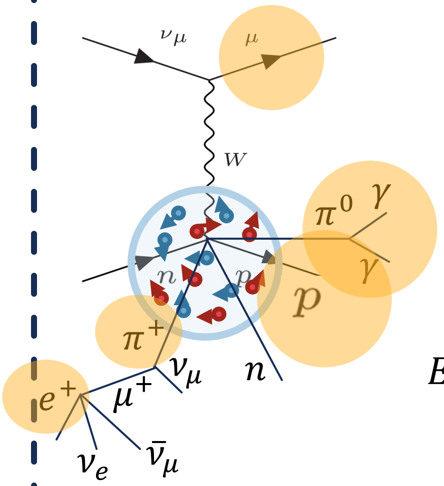

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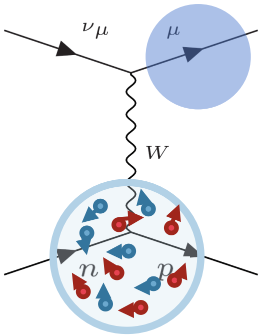

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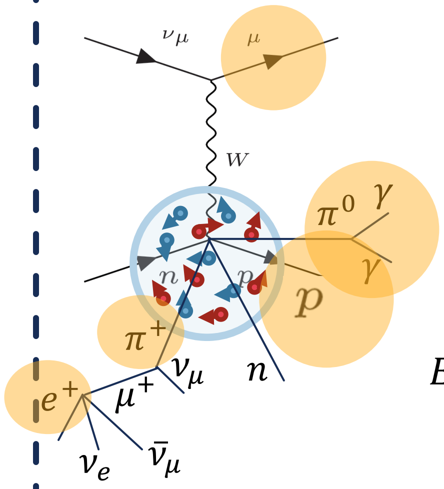


Add up all **visible energy** from final state particles

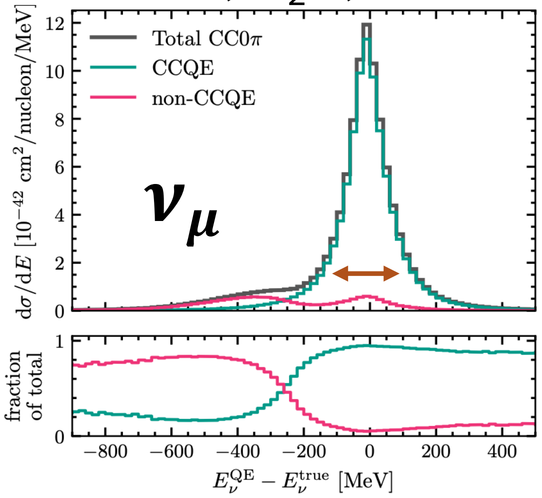
Reality is somewhere in between the two

$$E_\nu^{had} = E_\ell + \sum_{i=p} T_i + \sum_{i=\pi^{0,\pm},\gamma} E_i$$

$$E_\nu^{avail} = E_\ell + \sum_{i=p,\pi^\pm} T_i + \sum_{i=\pi^0,\gamma} E_i$$

What makes E_{rec} different from E_{true} ?

HK flux, H_2O, CC0π

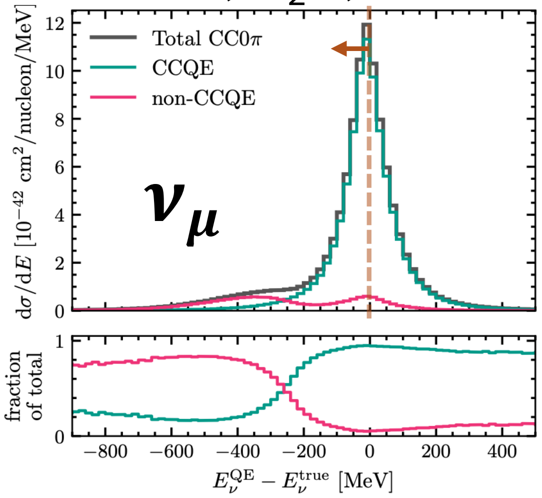


For the majority of the talk, we use NuWro 25.03.1 with SF, 2016 Valencia 2p2h and Rein Sehgal model

Fermi motion

What makes E_{rec} different from E_{true} ?

HK flux, H_2O, CC0π



Fermi motion

Binding energy

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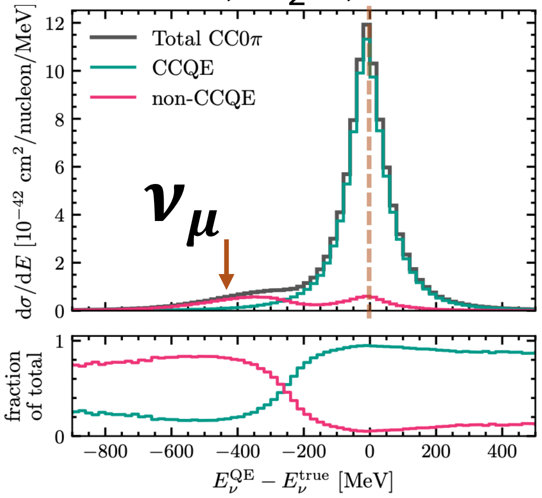

Fermi motion

Binding energy

Non-QE processes

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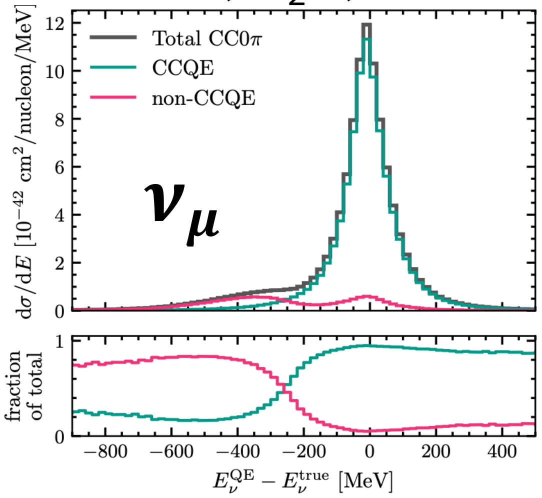
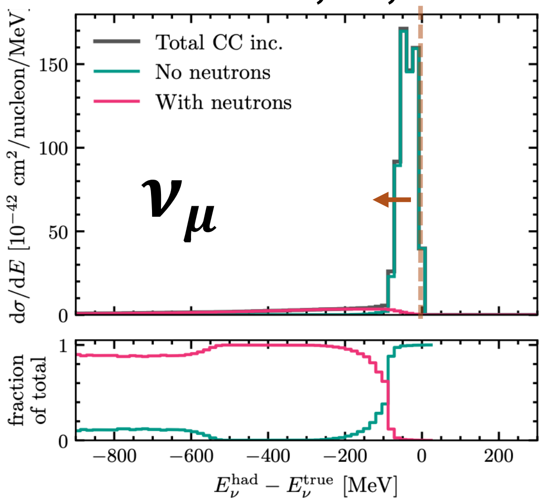


DUNE flux, Ar, CCInc.



Fermi motion
Binding energy
Non-QE processes

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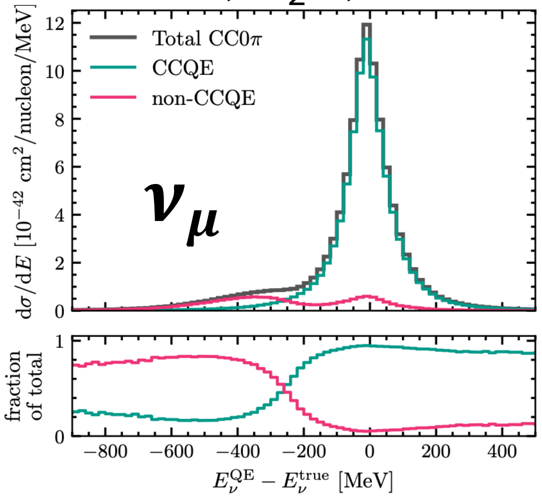

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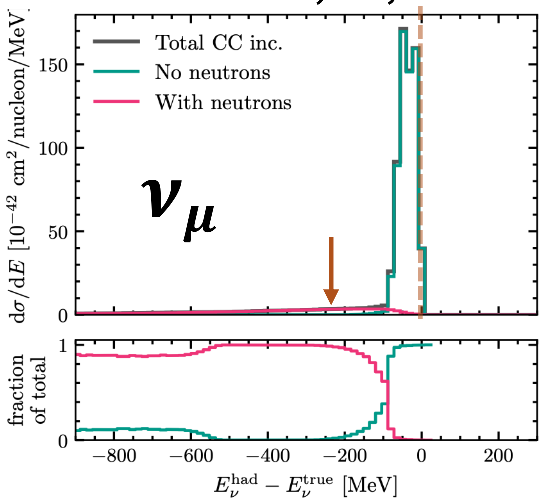
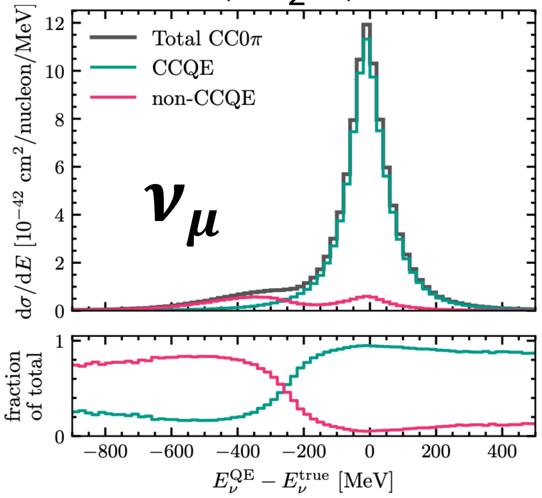


Fermi motion
Binding energy
Non-QE processes

Binding energy
Neutrons

What makes E_{rec} different from E_{true} ?

HK flux, H_2O, CC0π



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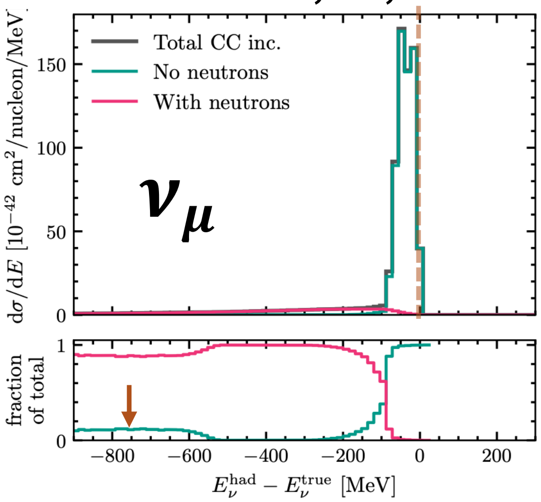
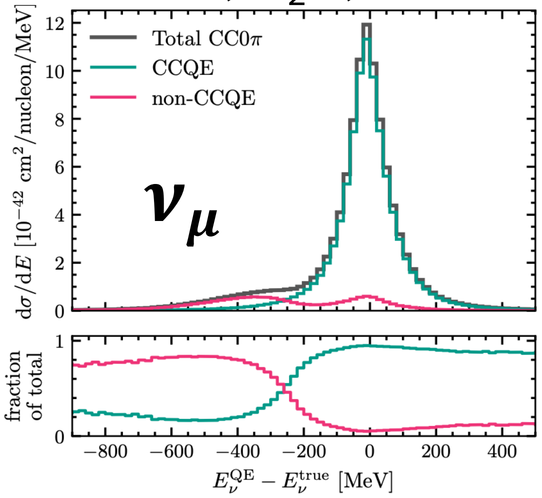


Fermi motion
Binding energy
Non-QE processes

Binding energy
Neutrons
+ some other particles not included here (nuclear clusters, Λs, etc)

What makes E_{rec} different from E_{true} ?

HK flux, H_2O, CC0π



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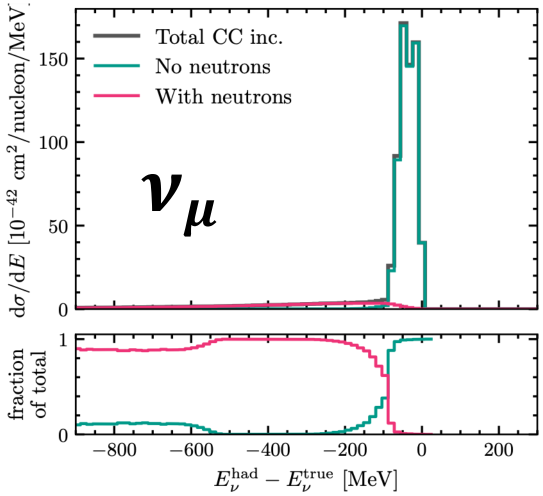

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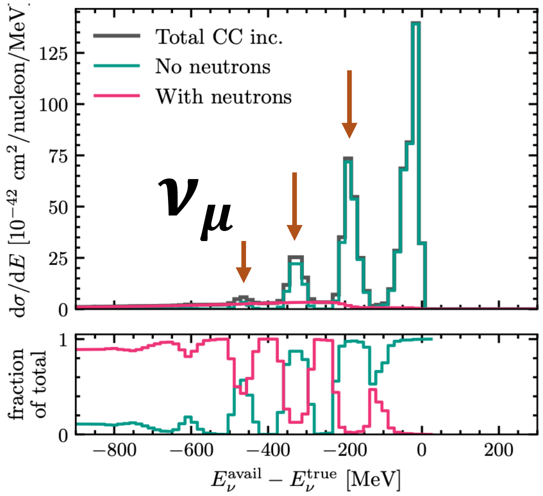


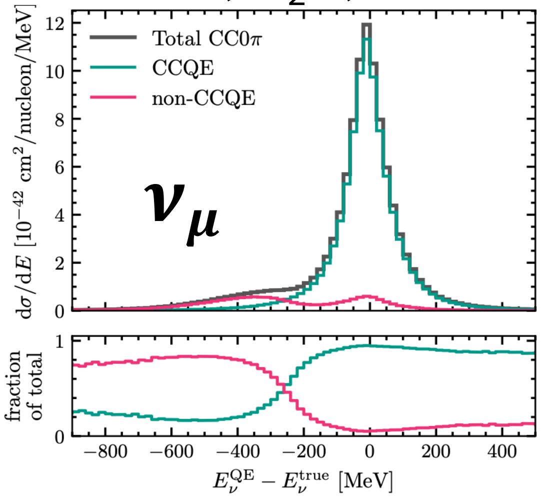
Fermi motion
Binding energy
Non-QE processes

Binding energy
Neutrons

Binding energy
Neutrons
Charged pions

How does FSI change this?

HK flux, H_2O, CC0π



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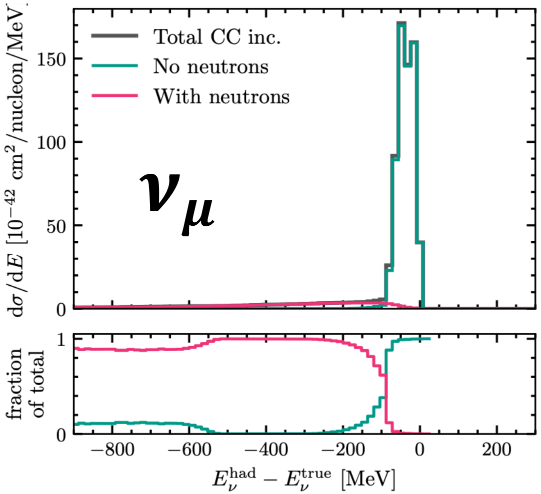

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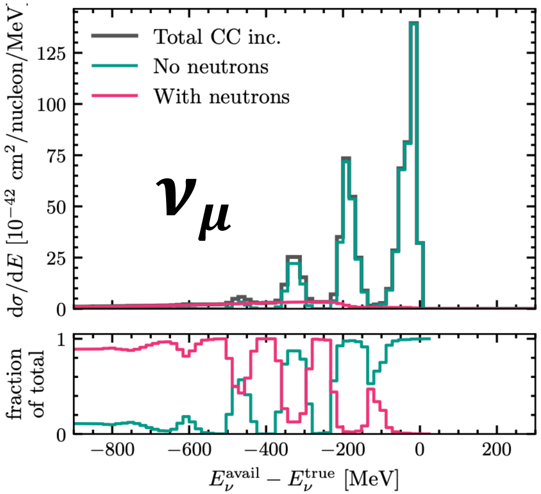

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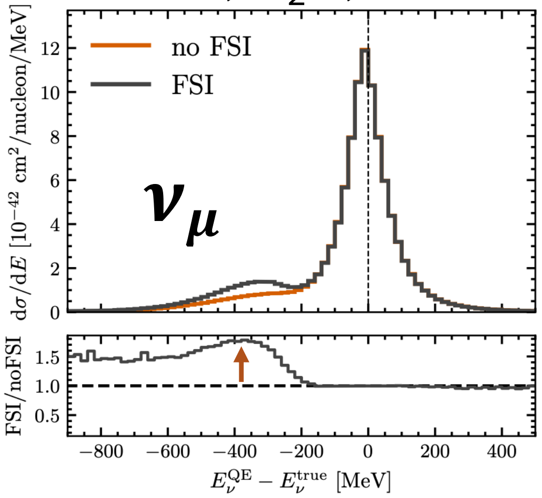

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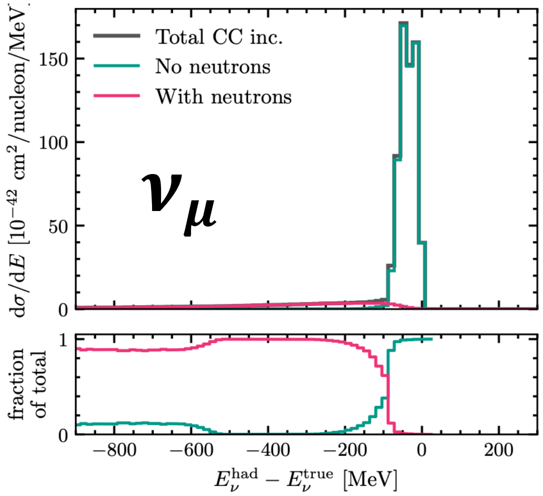

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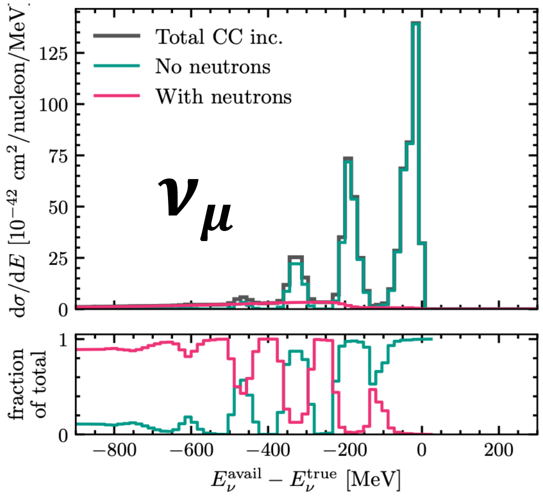
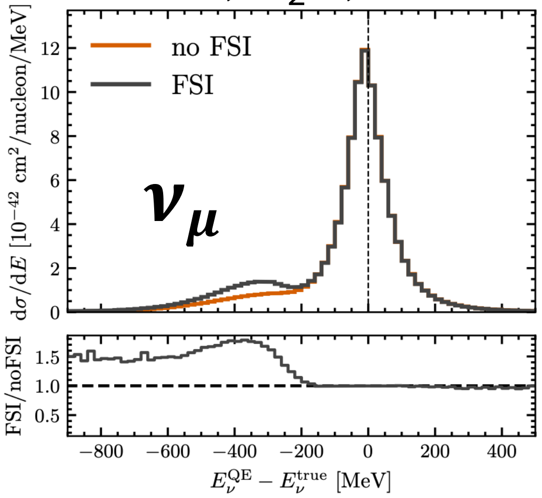


Changes non-QE contribution via pion absorption

**Also changes QE slightly via pion production FSI but it is a very small effect*

How does FSI change this?

HK flux, H_2O, CC0π



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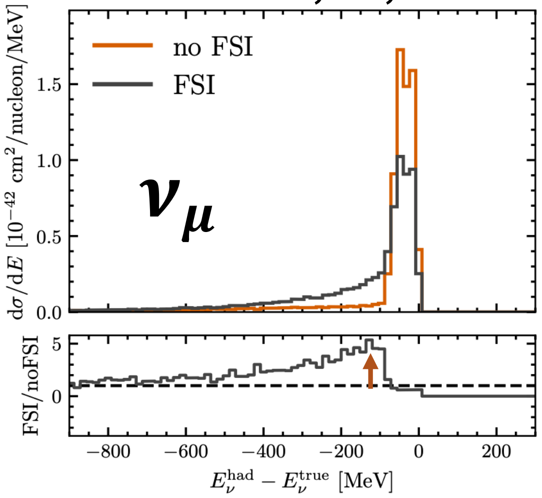

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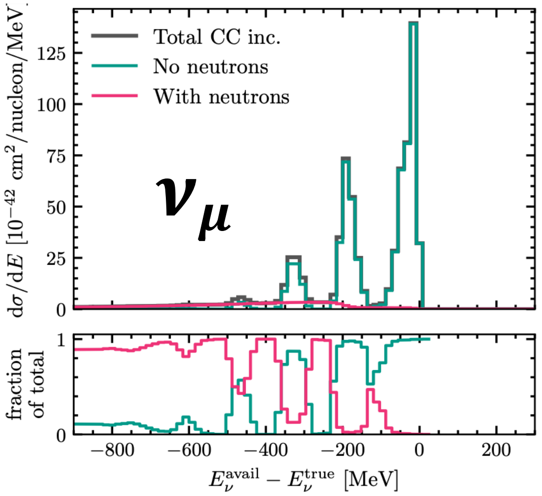

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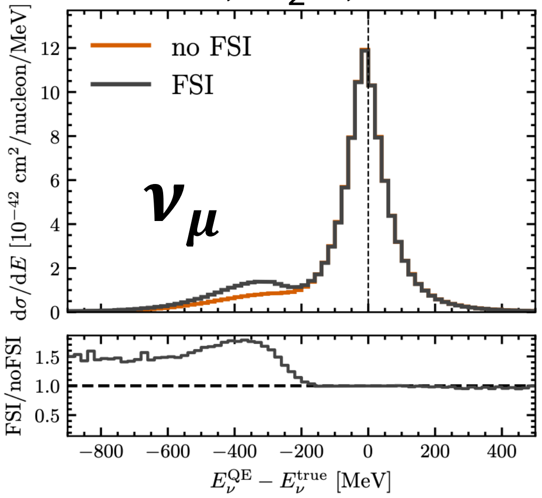
Creates neutrons

How does FSI change this?

HK flux, H_2O, CC0π



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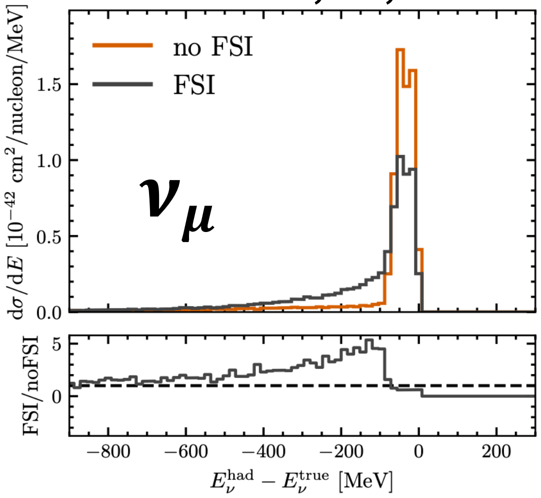

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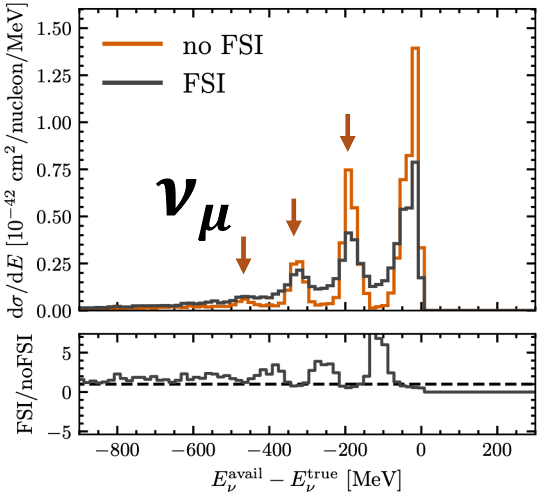

Changes non-QE contribution via pion absorption

Also changes QE slightly via pion production FSI but it is a very small effect

Creates neutrons

Creates neutrons
Changes pion multiplicity

Recap so far

- DUNE and Hyper-K neutrino-energy estimators are sensitive to FSI effects
- Particularly important are pion absorption and processes involving neutrons

Bias vs *uncertainty* on bias

- The fact that there is a difference between E_{reco} and E_{true} is not a problem
    - ...as long as the difference is *under control*

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- First principle uncertainties are hard/impossible to assign
  - The physics is really hard: many-body low-Q^2 QCD
  - FSI/nuclear model/SI processes should be described by consistent physics, but they are not
  - Different implementations/models use different sets of ingredients
  - No clear preference from experimental measurements on which model is preferred
  - Different sub-processes matter for different experiments

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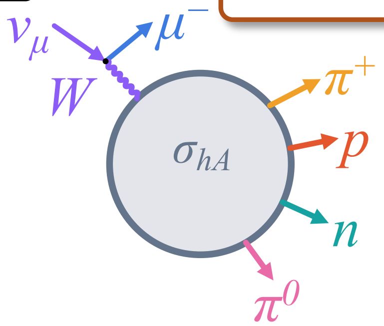
- Some approaches to estimate uncertainty:
  - FSI model spread
  - Including quantum mechanical effects

Meet the (cascade) models

Space-like



hA2018 Intranuke

INCL(++)

hN2018 Intranuke

G4BC

Meet the (cascade) models

Space-like

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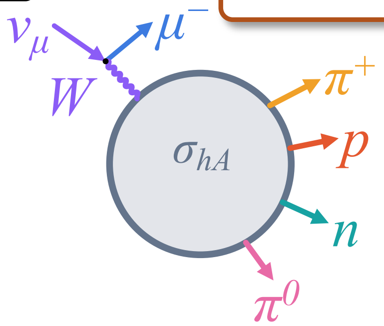

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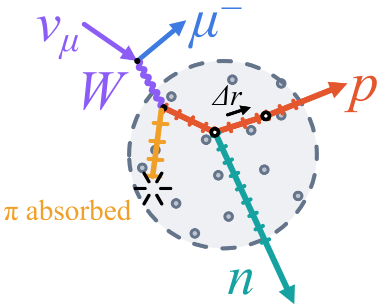
Space-like

hN2018 Intranuke

Same sort of cascade with different unerlying choices used in NEUT and NuWro



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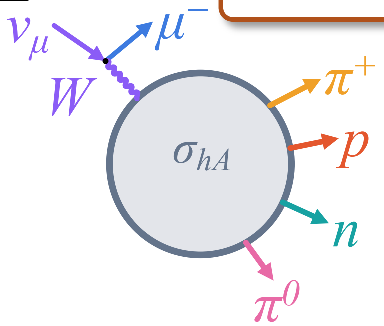
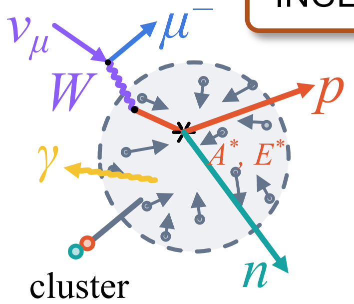


INCL(++)

Time-like



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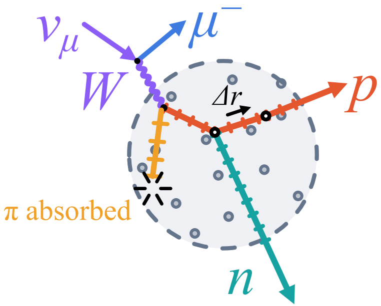

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Space-like

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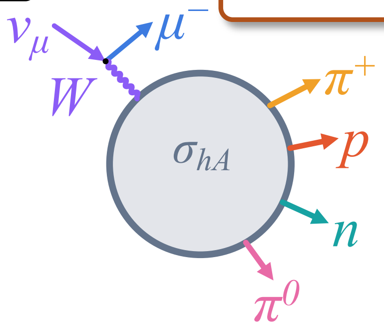

INCL(++)

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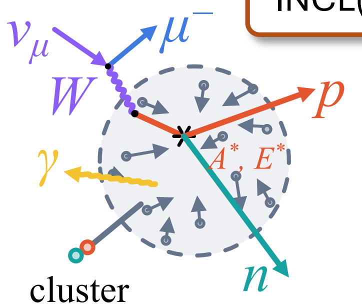

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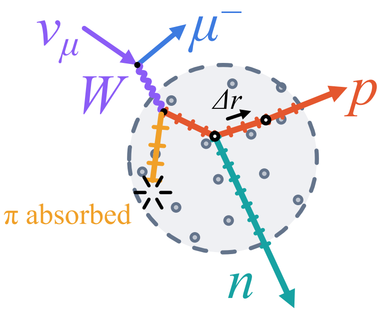

G4BC

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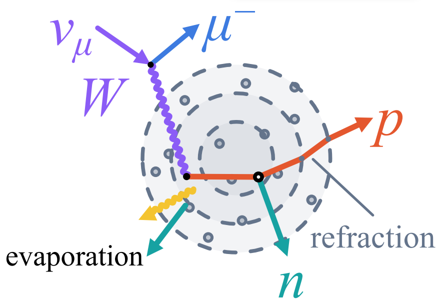
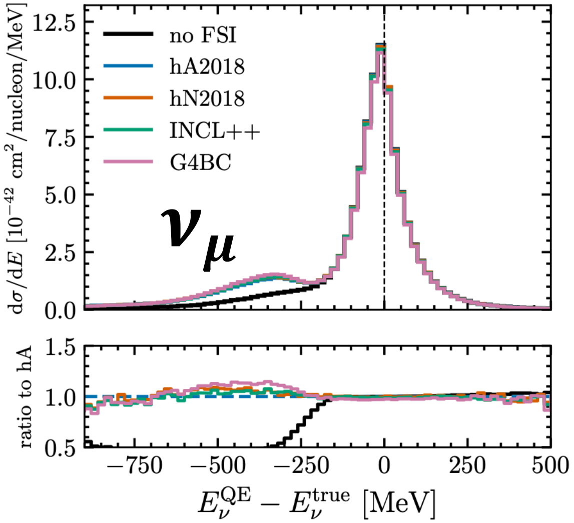


Entire cascade model variations

HK flux, H_2O, CC0π



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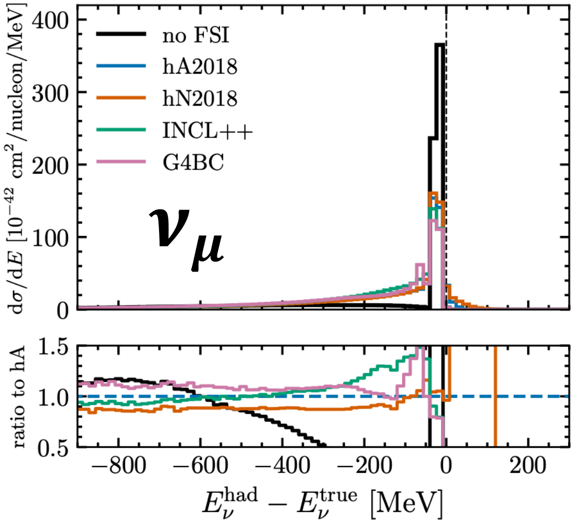

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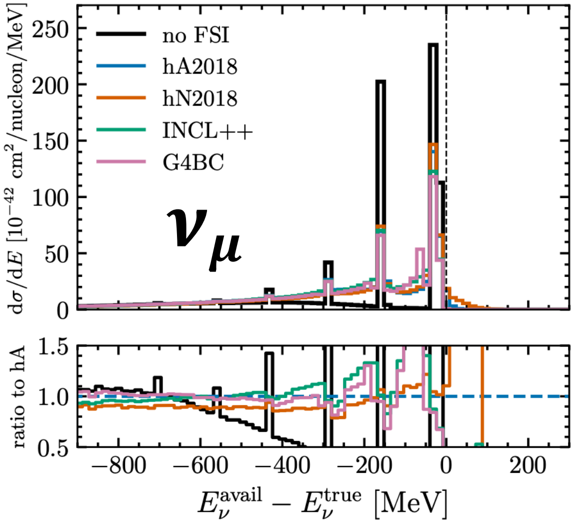
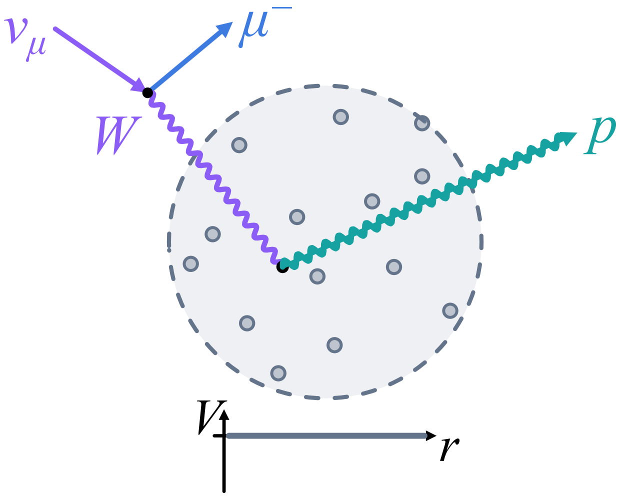


> 10% impact across most energy range

Bringing quantum mechanics back into it

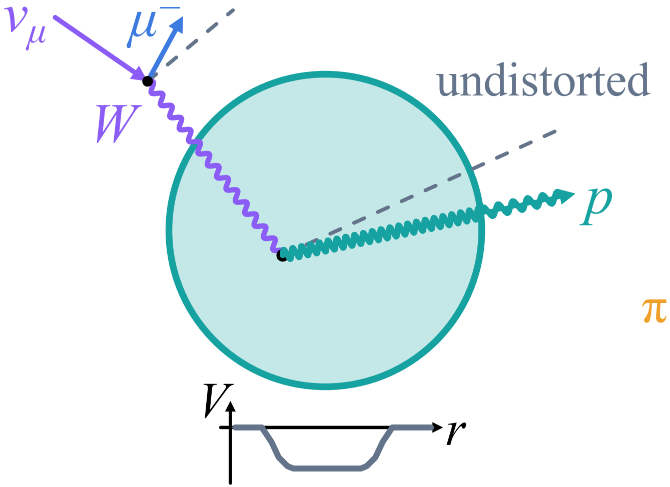
Microscopic approaches take into account the effect of FSI on the final wavefunctions which can also affect the lepton kinematics

RPWIA



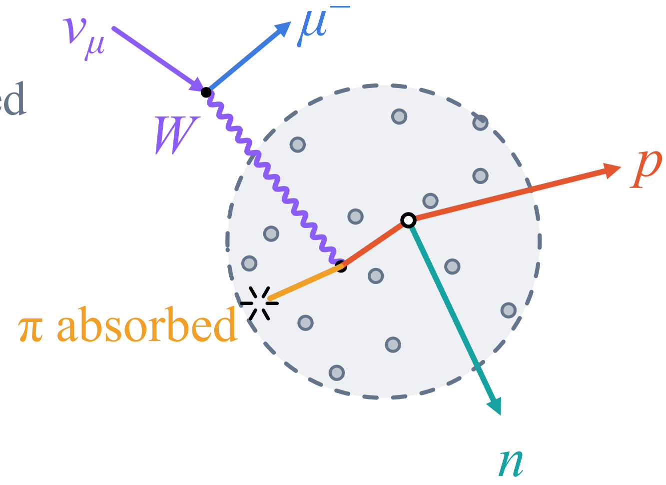
no potential

EDRMF



energy-dependent potential

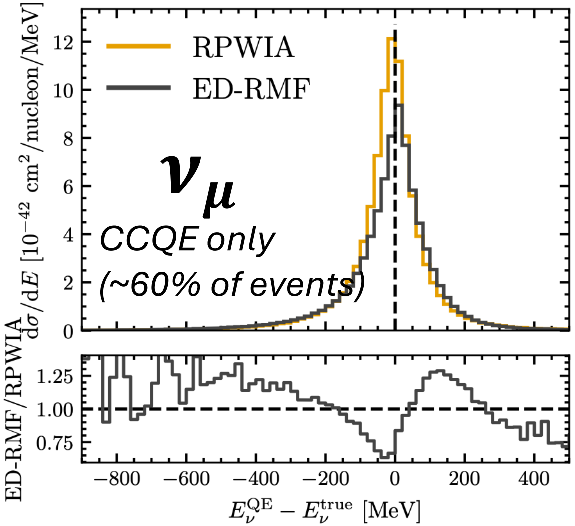
cascade



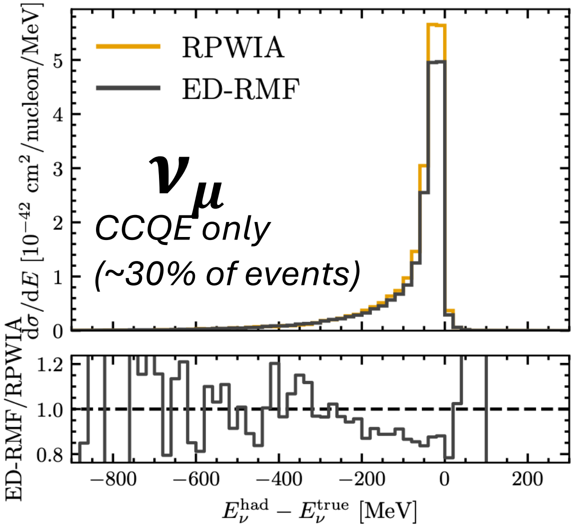
no wave equation: classical trajectories

Wave distortions

HK flux, H_2O, CCQE



DUNE flux, Ar, CCQE



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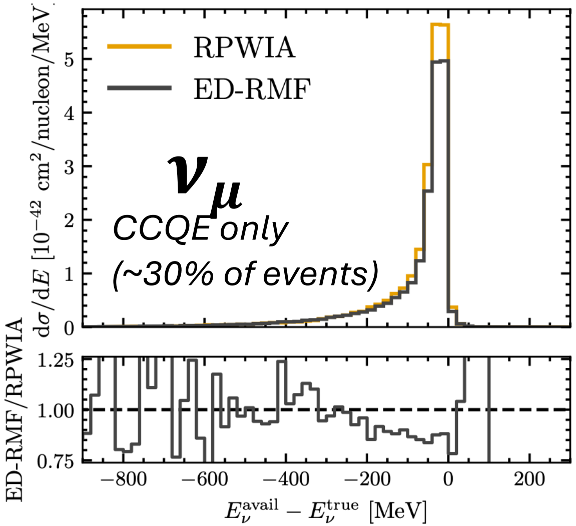
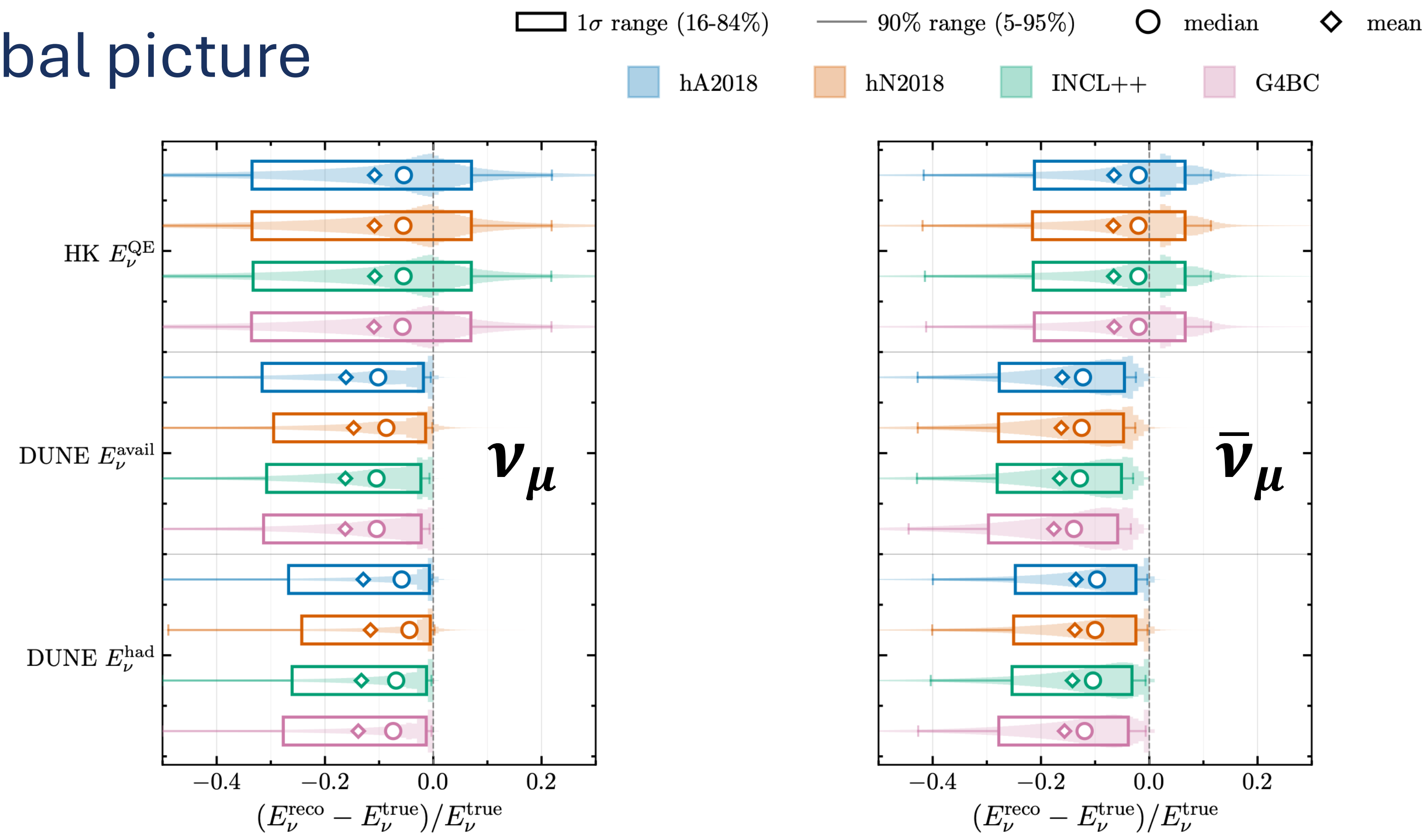


Up to ~25% effect for CCQE interactions

Global picture



Global picture

Flavour	Observable	FSI / no FSI		$\pi_{abs}\pm 31\%$		NN MFP $\pm 30\%$		INC model var.		Nuc. Pot. on/off	
		median	mean	median	mean	median	mean	median	mean	median	mean
		Absolute bias [MeV]									
ν_μ	Hyper-K E_ν^{QE}	7.8	30.6	4.2	15.0	0.3	2.0	1.7	9.9	8.8	0.1
	DUNE E_ν^{avail}	22.3	55.0	0.7	2.2	12.8	15.0	44.4	28.4	0.5	5.4
	DUNE E_ν^{had}	36.3	63.4	4.9	8.3	25.0	13.2	53.5	32.5	0.5	5.0
$\bar{\nu}_\mu$	Hyper-K E_ν^{QE}	5.6	22.9	2.8	11.1	0.3	1.4	0.4	3.1		
	DUNE E_ν^{avail}	30.0	21.4	7.1	6.4	11.8	14.6	40.9	28.2		
	DUNE E_ν^{had}	38.5	31.3	15.1	12.5	14.4	16.4	61.1	43.1		
		Relative bias [%]									
ν_μ	Hyper-K E_ν^{QE}	1.2	2.4	0.6	1.2	0.1	0.1	0.2	0.1	1.1	1.3
	DUNE E_ν^{avail}	3.1	2.7	0.0	0.0	1.2	0.9	1.8	1.5	0.0	0.3
	DUNE E_ν^{had}	2.2	3.2	0.2	0.3	1.0	0.8	3.0	2.3	0.0	0.3
$\bar{\nu}_\mu$	Hyper-K E_ν^{QE}	0.7	1.8	0.4	0.9	0.0	0.1	0.0	0.2		
	DUNE E_ν^{avail}	0.6	0.8	0.2	0.2	0.5	0.6	1.7	1.5		
	DUNE E_ν^{had}	1.2	1.3	0.5	0.5	0.6	0.7	2.3	2.1		

>5 MeV (Hyper-K), >15 MeV (DUNE)
>0.5%

Global picture

See paper for details

Flavour	Observable	FSI / no FSI		$\pi_{abs} \pm 31\%$		NN MFP $\pm 30\%$		INC model var.		Nuc. Pot. on/off	
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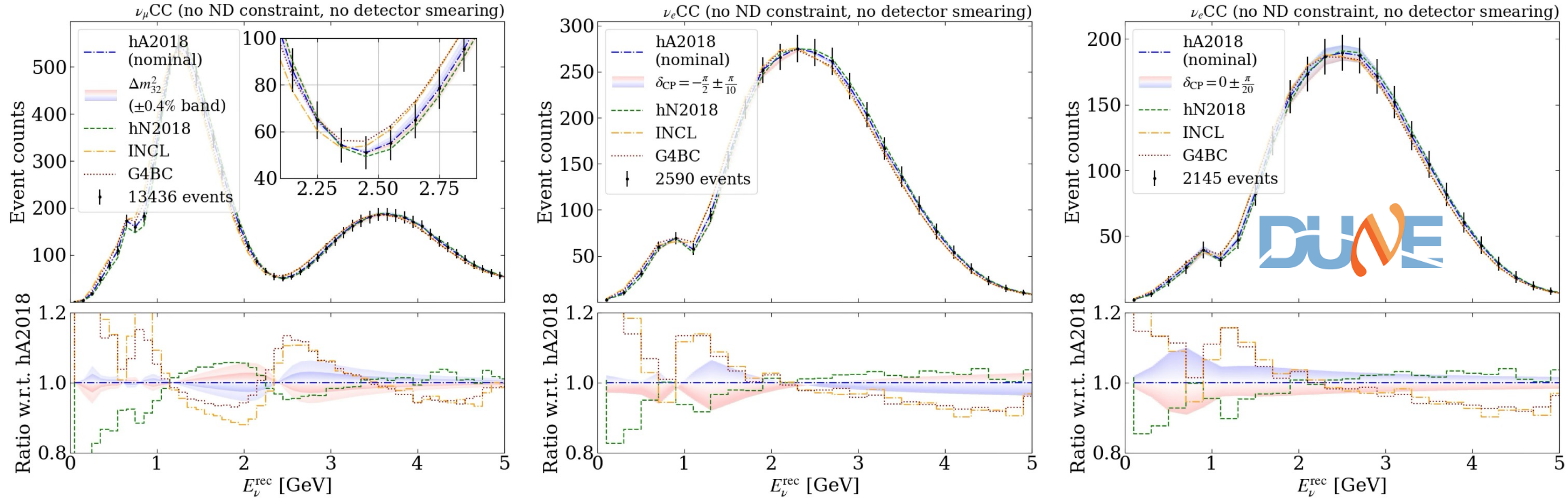
>5 MeV (Hyper-K), >15 MeV (DUNE)
>0.5%

DUNE flux, Ar, CCInc.

arXiv:2511.03964

Impact on oscillated spectra: DUNE

$\nu_\mu \to \nu_\mu$ $\nu_\mu \to \nu_e$ $\nu_\mu \to \nu_e$

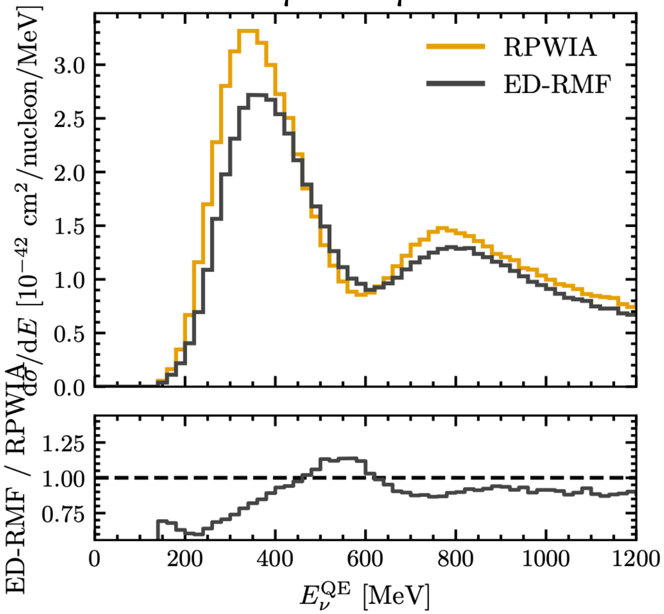


Cascade FSI changes are compatible with an energy scale shift of the size of the target precision for oscillation parameter measurements

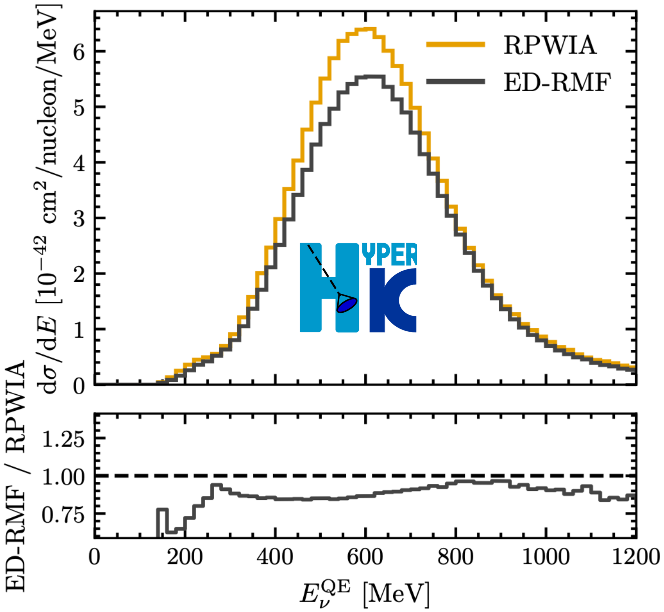
HK flux, H_2O, CC0π

Impact on oscillated spectra: Hyper-K

$\nu_\mu \rightarrow \nu_\mu$



$\nu_\mu \rightarrow \nu_e$



Microscopic FSI changes affect both the normalization and the shape of the spectra - can mimic the behavior of several osc. parameters

Summary

What have we shown?

- Neutrino energy reconstruction is sensitive to the details of FSI modelling
- FSI modeling is really hard
- Plausible variations of FSI modeling impacts reconstructed neutrino energy spectra with a size and shape that is degenerate with oscillation parameter variations that DUNE and Hyper-K hope to be sensitive to

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What does this mean?

- It is essential that we are able to reliably constrain FSI for the success of next generation experiments
- This relies on flexible uncertainty parametrizations which can capture all the relevant FSI features (energy dependece, interplay between cascade and microsropic features, different processes…)

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- Theory models of FSI/SI benchmarked against available data
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- Direct constraints on invisible/missing energy in neutrino scatters (e.g. from e4ν or nuSCOPE)

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Thank you for your attention!

Supplementary material

Relationship between E_ν^{true} and proxies

Proxy: (kinematic energy reconstruction)

$$E_\nu^{QE} = \frac{m_p^2 - m_\ell^2 - (m_n - E_b)^2 + 2E_\ell(m_n - E_b)}{2(m_n - E_b - E_\ell + p_\ell^z)}$$

What we really measure:

$$\boldsymbol{E_\nu^{QE,rec}} = \frac{m_p^2 - m_\ell^2 - (m_n - E_b)^2 + 2\boldsymbol{E_\ell^{rec}}(m_n - E_b)}{2(m_n - E_b - \boldsymbol{E_\ell^{rec}} + \boldsymbol{p_\ell^{z,rec}})}$$

+Cherenkov threshold, transparency, reconstruction efficiency…

$E_\nu^{QE} - E_\nu^{QE,rec}$ → detector energy scale (ref: 2.4% for SK)

Proxy: (calorimetric energy reconstruction)

$$E_\nu^{avail} = E_\ell + \sum_{i=p,\pi^\pm} T_i + \sum_{i=\pi^0,\gamma} E_i$$

What we really measure:

$$\boldsymbol{E_\nu^{avail,rec}} = \boldsymbol{E_\ell^{rec}} + \sum_{i=p,\pi^\pm} \boldsymbol{T_i^{rec}} + \sum_{i=\pi^0,\gamma} \boldsymbol{E_i^{rec}}$$

+recombination, quenching, space-charge…

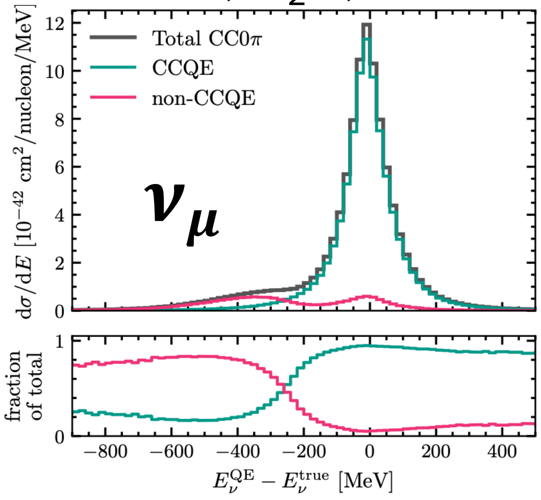
$E_\nu^{avail} - E_\nu^{avail,rec}$ →detector energy scale

$E_\nu^{proxy,true} - E_\nu^{proxy,rec}$ is constrained through **detector calibration**

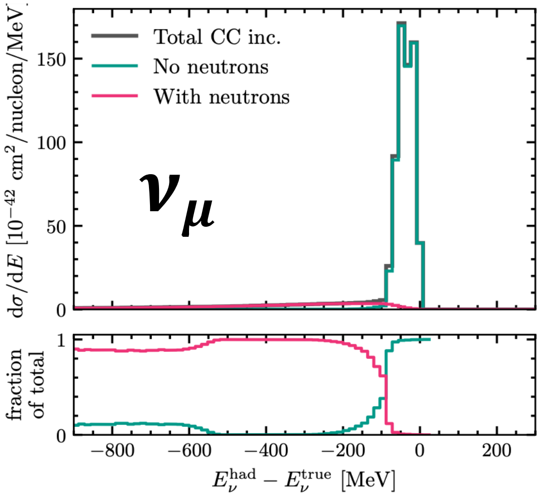
But what about $E_\nu^{true} - E_\nu^{proxy}$?

What about anti-neutrinos?

HK flux, H_2O, CC0π



DUNE flux, Ar, CCInc.



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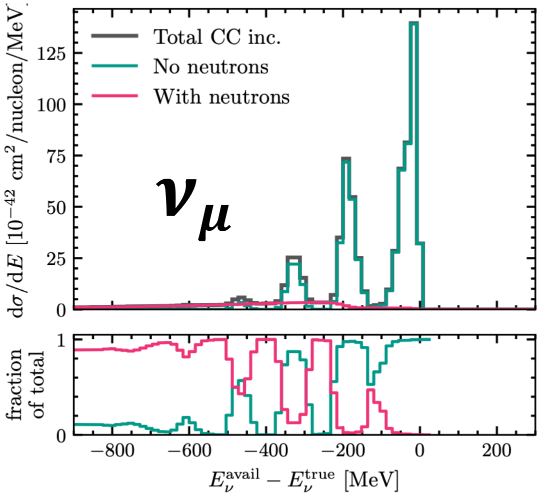

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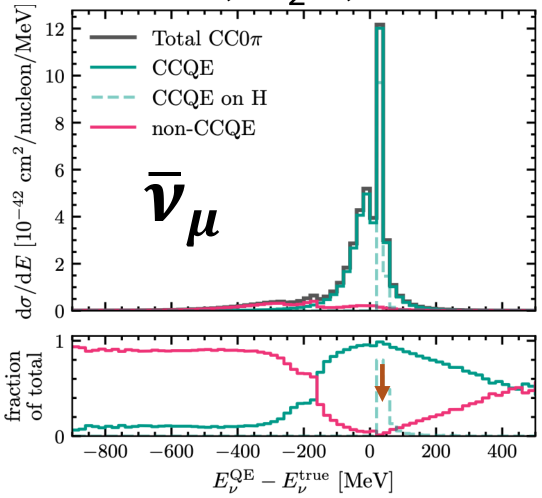

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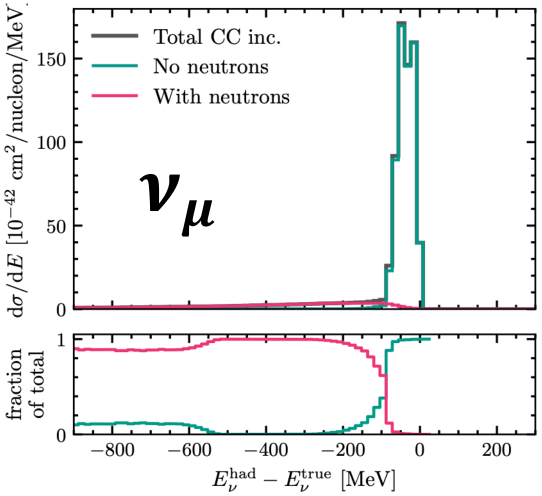

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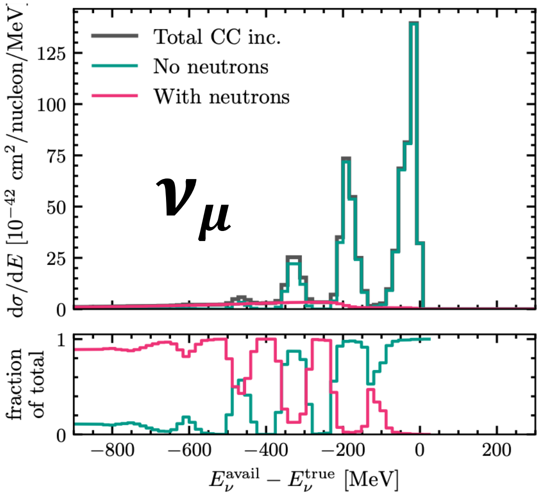
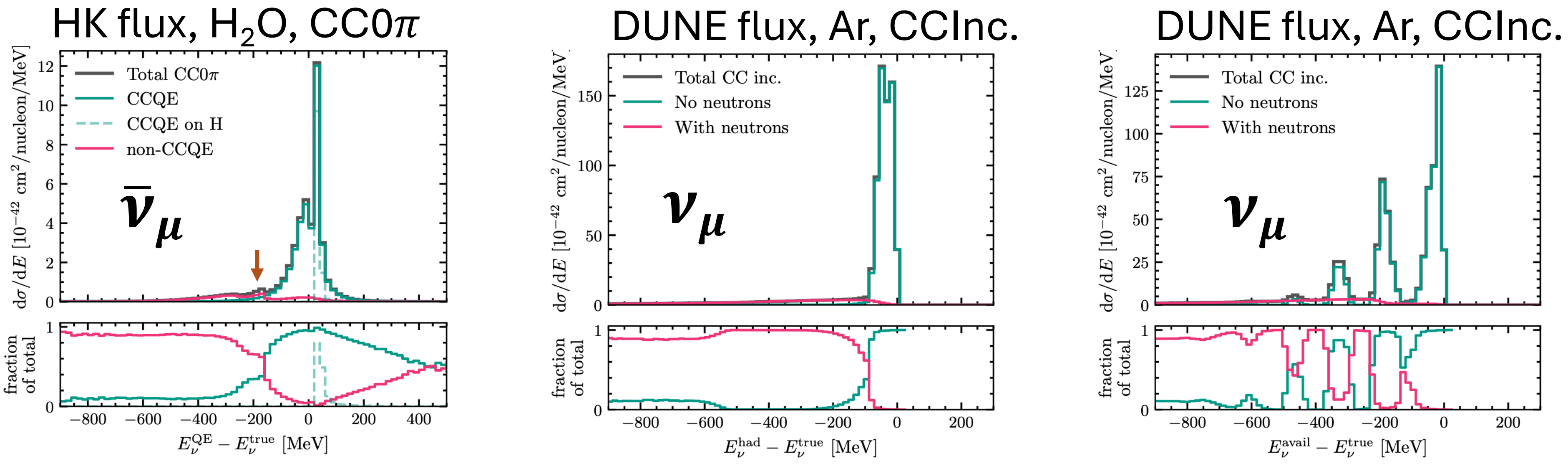


Hydrogen contribution

What about anti-neutrinos?



Hydrogen contribution

Λ baryons

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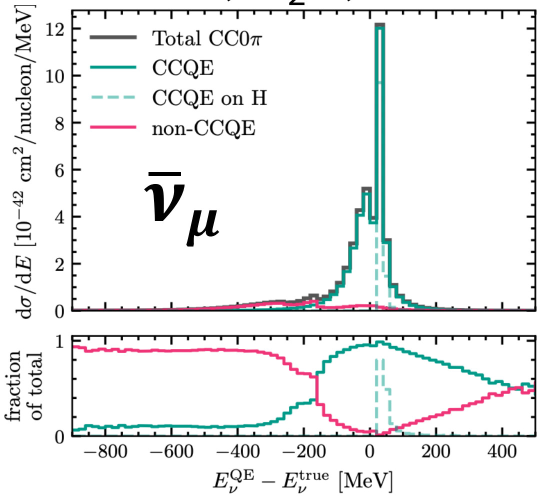
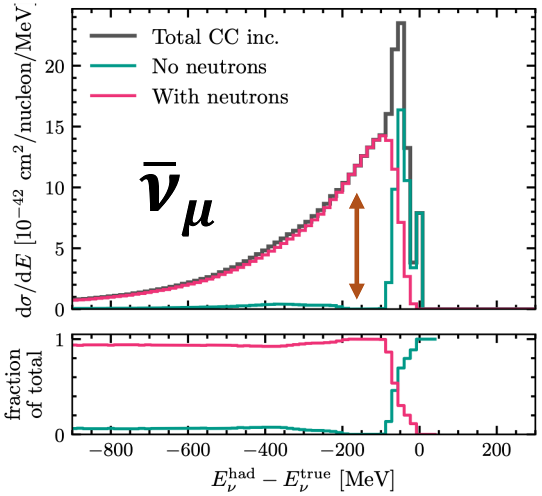
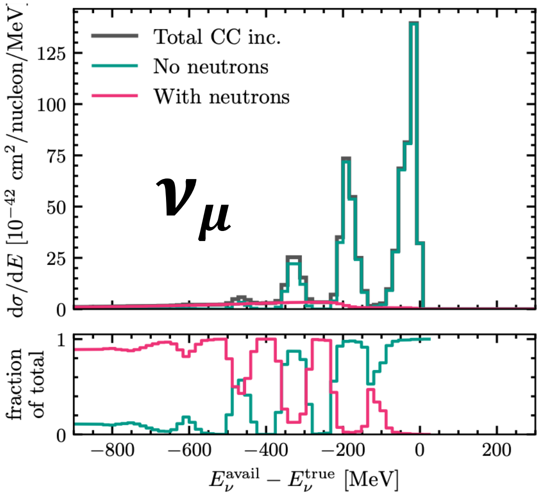
HK flux, H_2O, CC0π



DUNE flux, Ar, CCInc.



DUNE flux, Ar, CCInc.



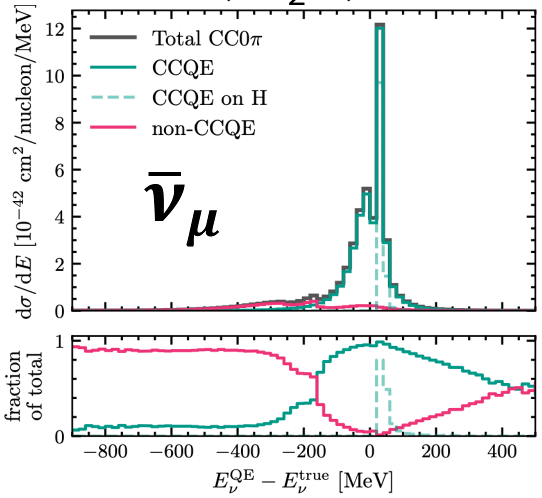
Hydrogen contribution

Λ baryons

Primary vertex neutrons

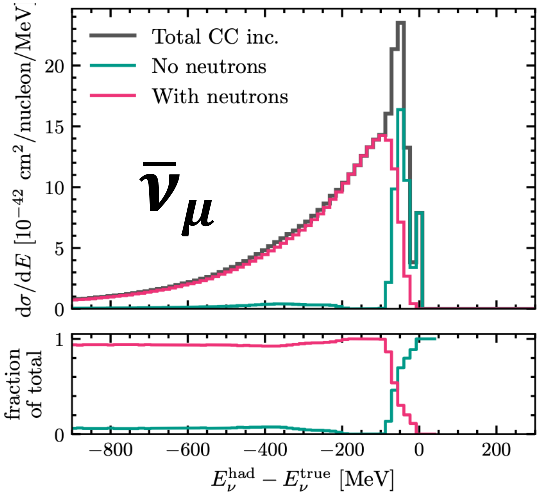
What about anti-neutrinos?

HK flux, H_2O, CC0π



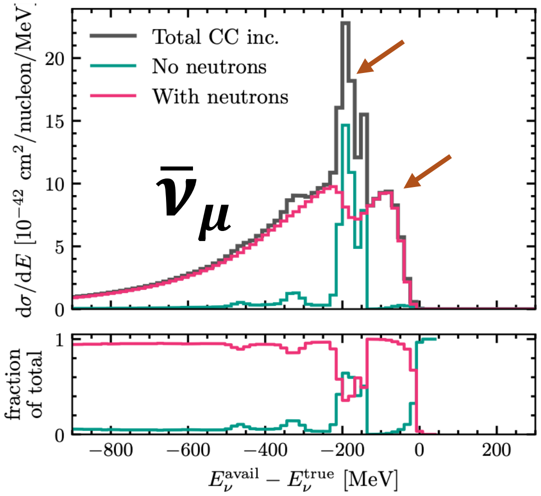
Hydrogen contribution
Λ baryons

DUNE flux, Ar, CCInc.



Primary vertex neutrons

DUNE flux, Ar, CCInc.



Primary vertex neutrons
Charged pions

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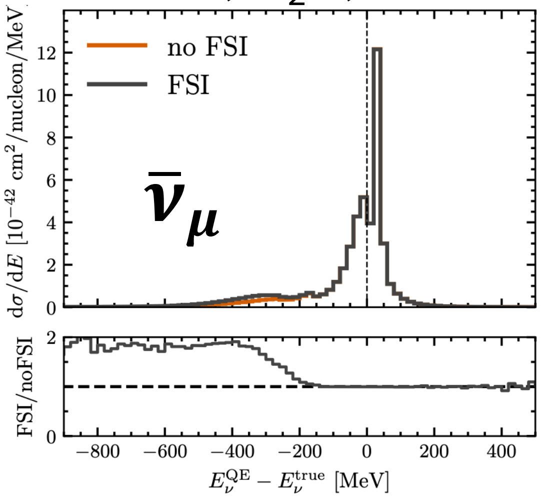

Hydrogen contribution
Λ baryons

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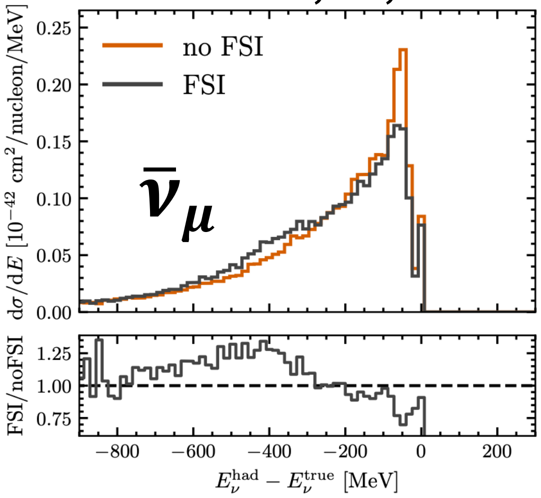
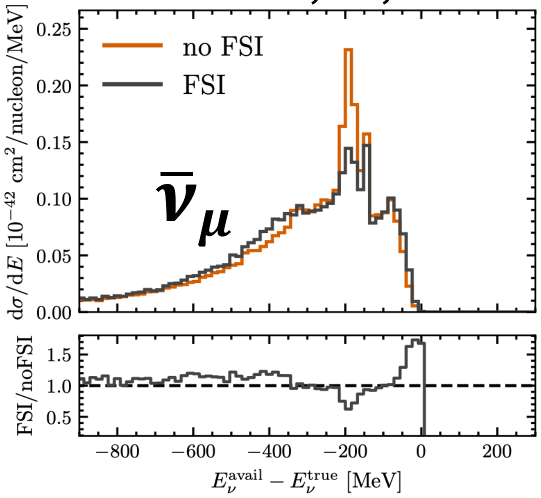


Primary vertex neutrons

DUNE flux, Ar, CCInc.



Primary vertex neutrons
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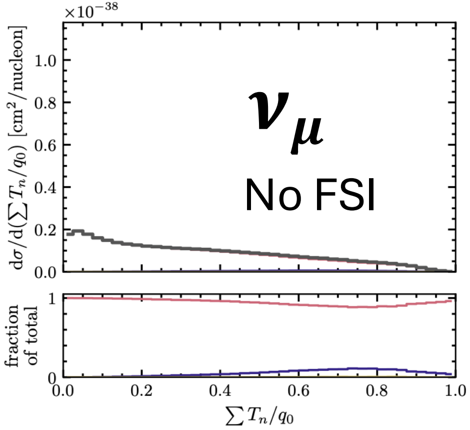
DUNE flux, Ar, CCInc.

Are these neutrons problematic at DUNE energies?



- In ν interactions, few neutrons are produced at the primary vertex and carry low fraction of energy transfer

DUNE flux, Ar, CCInc.

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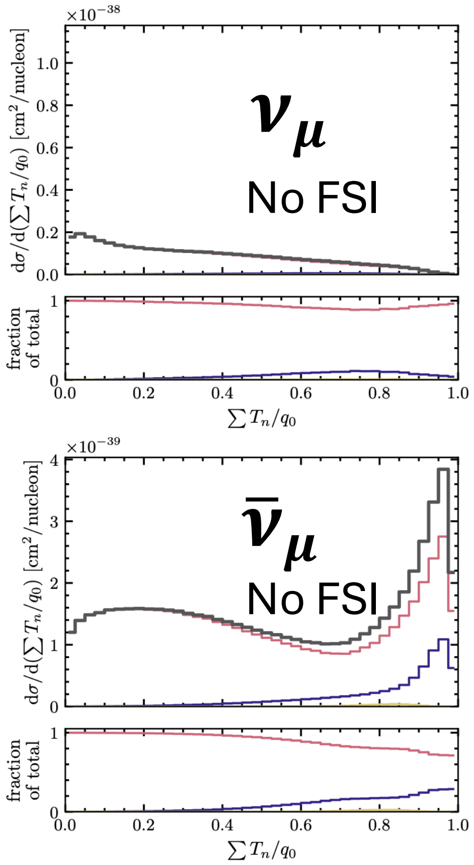

- In ν interactions, few neutrons are produced at the primary vertex and carry low fraction of energy transfer
- In $\bar{\nu}$ interactions, neutrons carry large fractions of the energy transfer

DUNE flux, Ar, CCInc.

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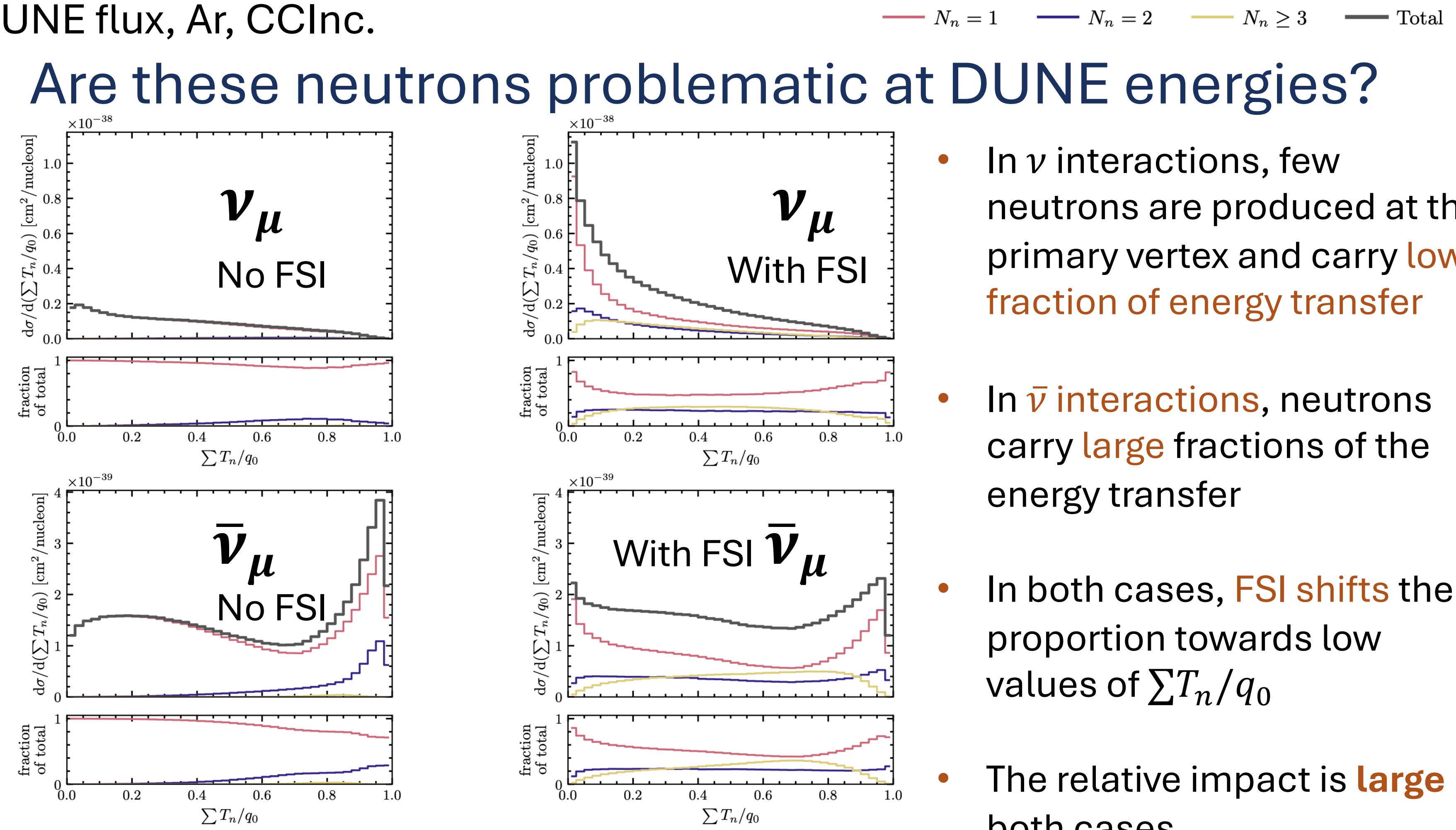
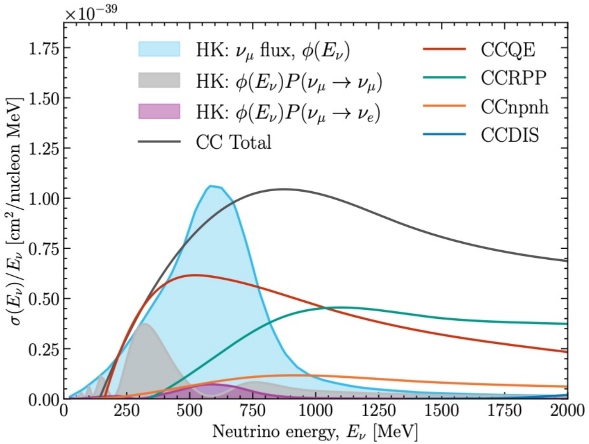
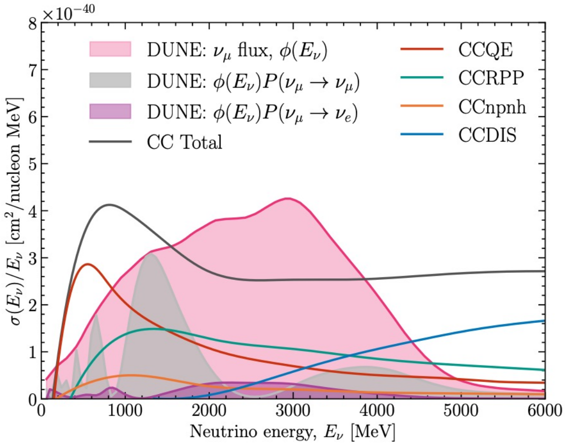


- In ν interactions, few neutrons are produced at the primary vertex and carry low fraction of energy transfer
- In $\bar{\nu}$ interactions, neutrons carry large fractions of the energy transfer
- In both cases, FSI shifts the proportion towards low values of $\sum T_n/q_0$
- The relative impact is **large** in both cases

Recap so far

- DUNE and Hyper-K neutrino-energy estimators are sensitive to FSI effects
- Particularly important are pion absorption and processes involving neutrons
- All examples so far are flux-averaged over oscillated experiment fluxes
- But oscillations distort the flux itself

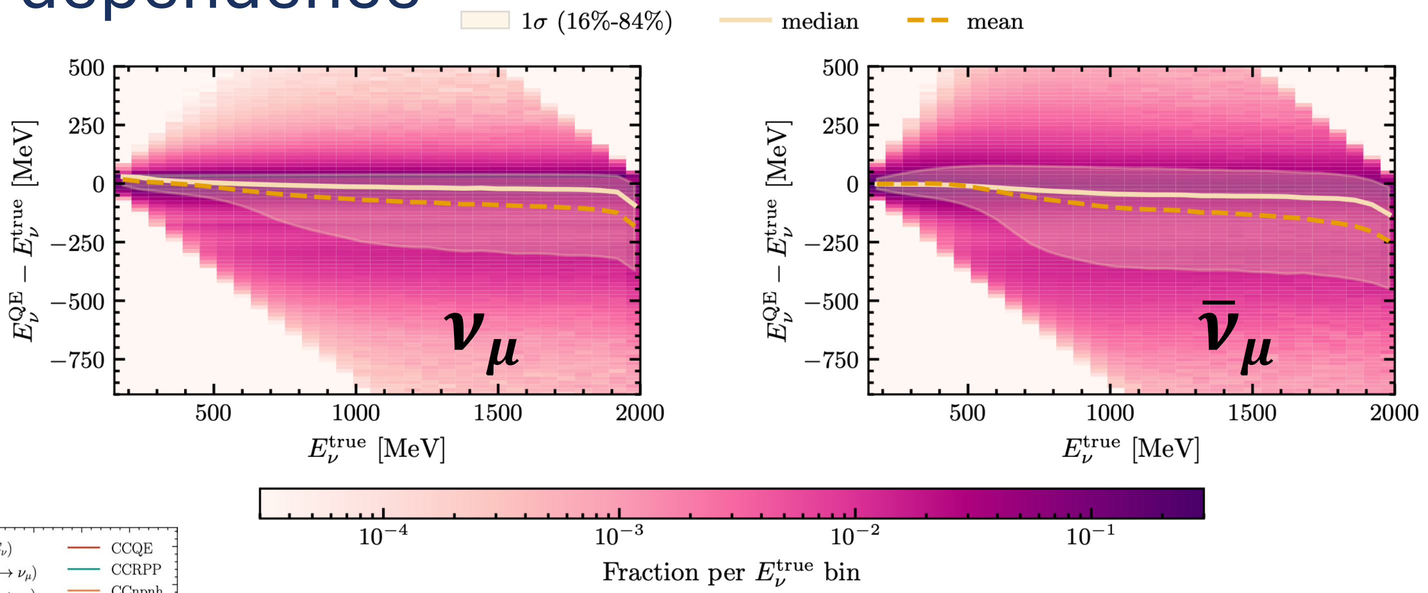


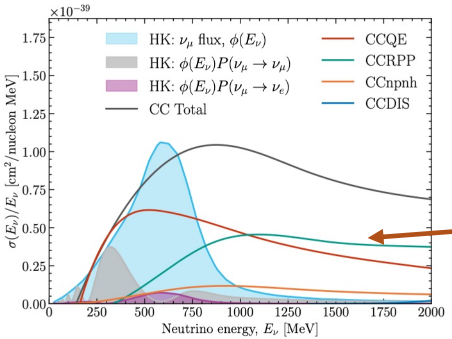


How does the neutrino energy bias depend on the neutrino energy itself?

HK flux, H_2O, CC0π

Energy dependence

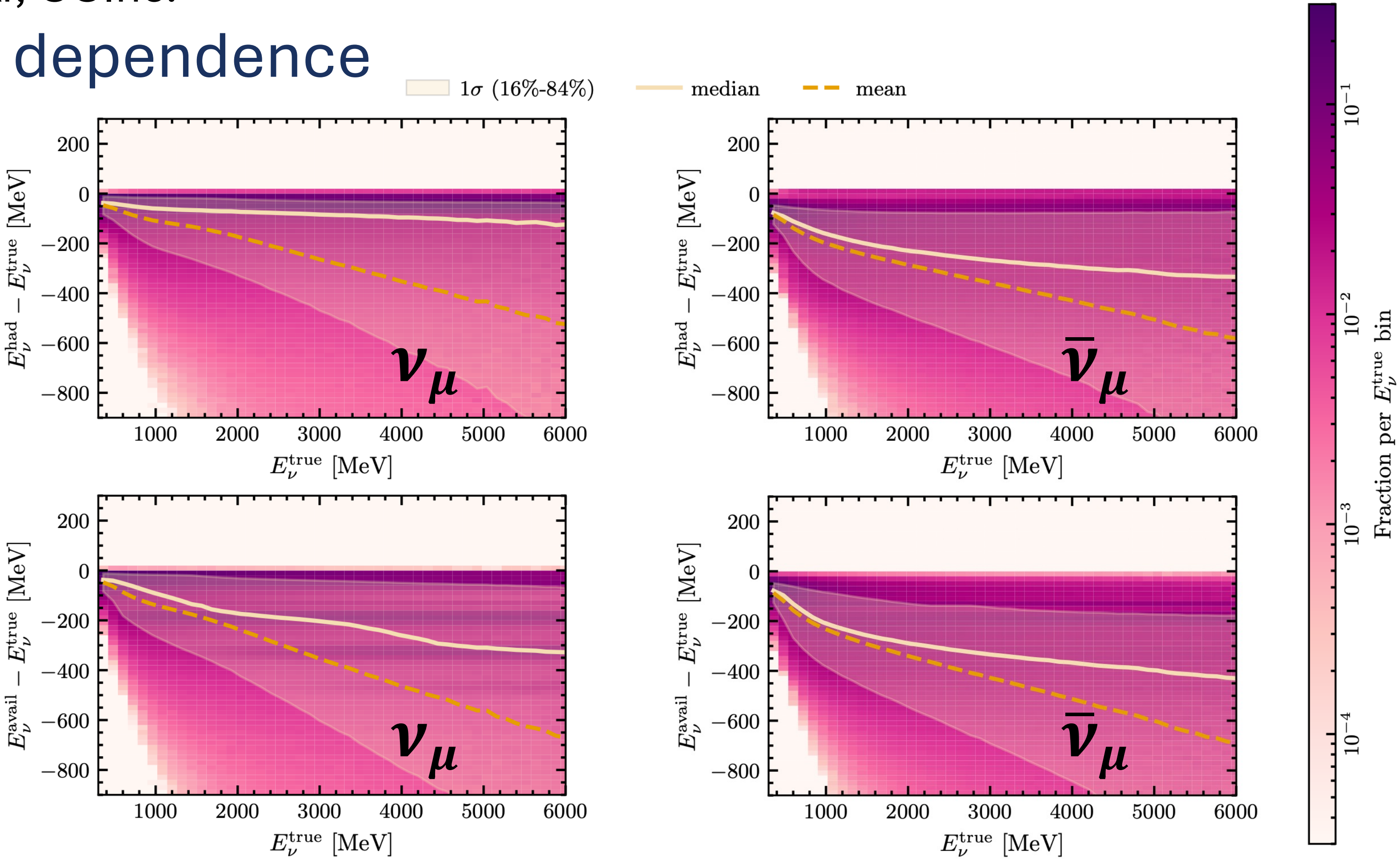




More pion production interactions → larger bias

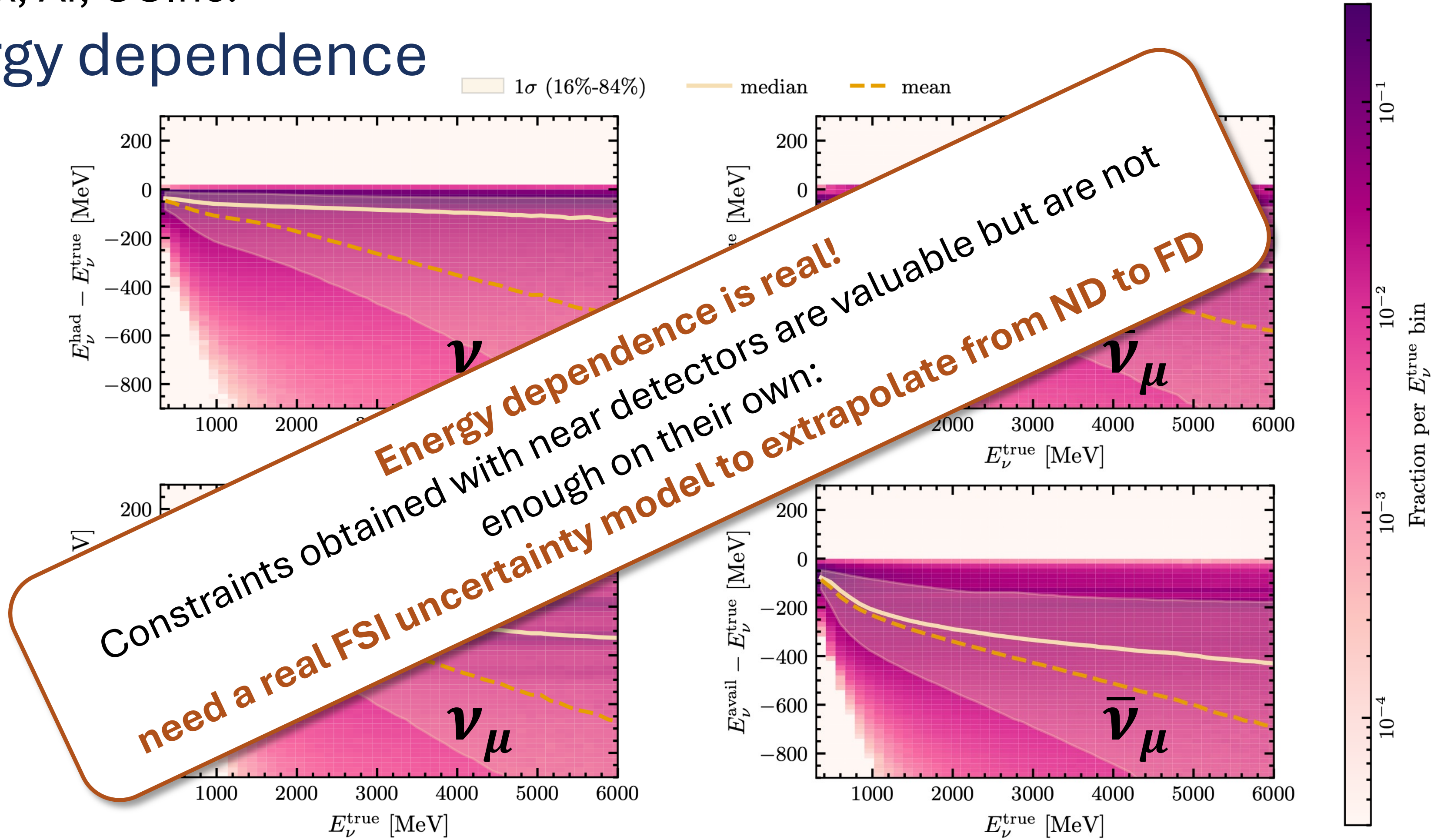
DUNE flux, Ar, CCInc.

Energy dependence



DUNE flux, Ar, CCInc.

Energy dependence



Data-driven variations

Pion scattering data

Phys.Rev.D 99 (2019) 5, 052007

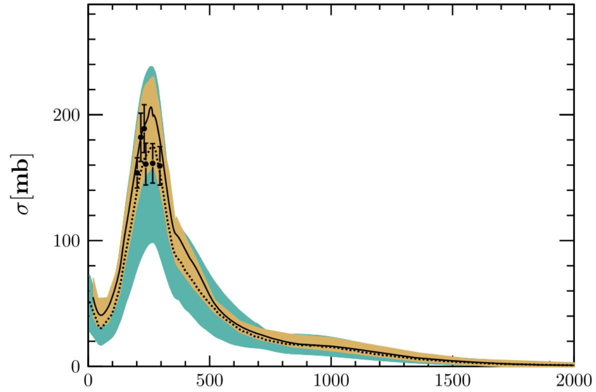


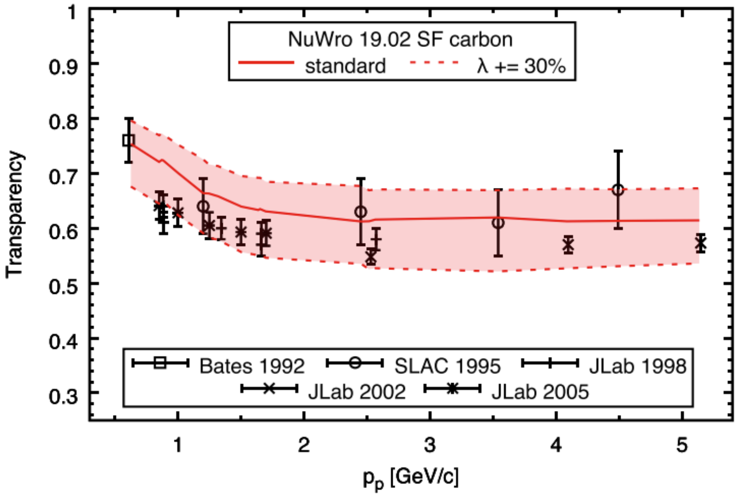
TABLE VIII. Postfit FSI parameters after error scaling.

Parameter	Best fit $\pm 1\sigma$
f_{QE}	1.07 ± 0.31
f_{ABS}	1.40 ± 0.43
f_{CX}	0.70 ± 0.30
f_{INEL}	1.00 ± 1.10
f_{QEH}	1.82 ± 0.86

Alter $\sigma_{\pi Abs}$ by $\pm 31\%$

Nuclear transparency data

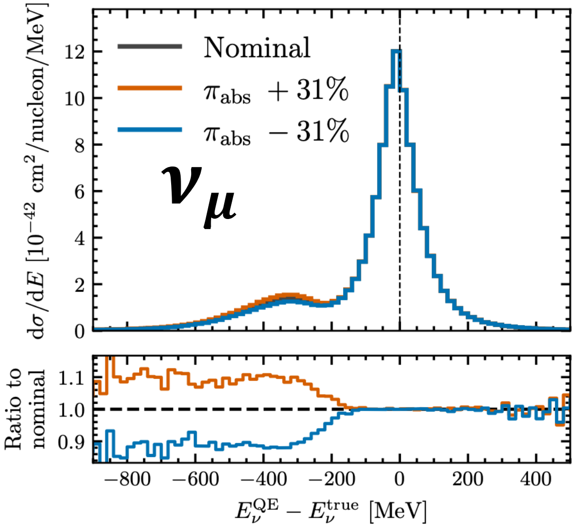
Phys.Rev.C 100 (2019) 1, 015505



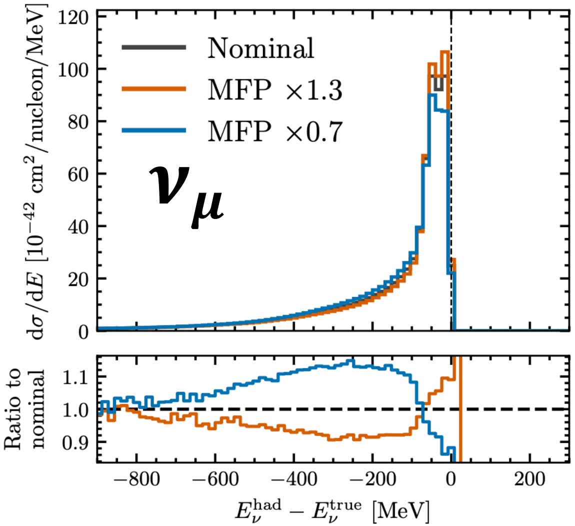
Alter nucleon mean free path (MFP) by $\pm 30\%$

Cascade FSI parameter variations

HK flux, H_2O, $CC0\pi$



DUNE flux, Ar, CCInc.



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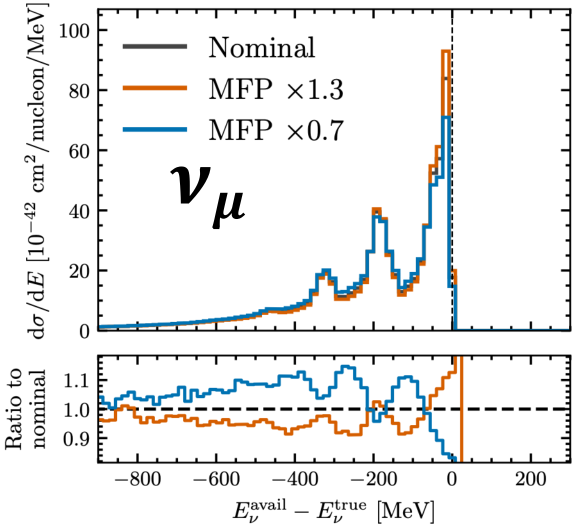
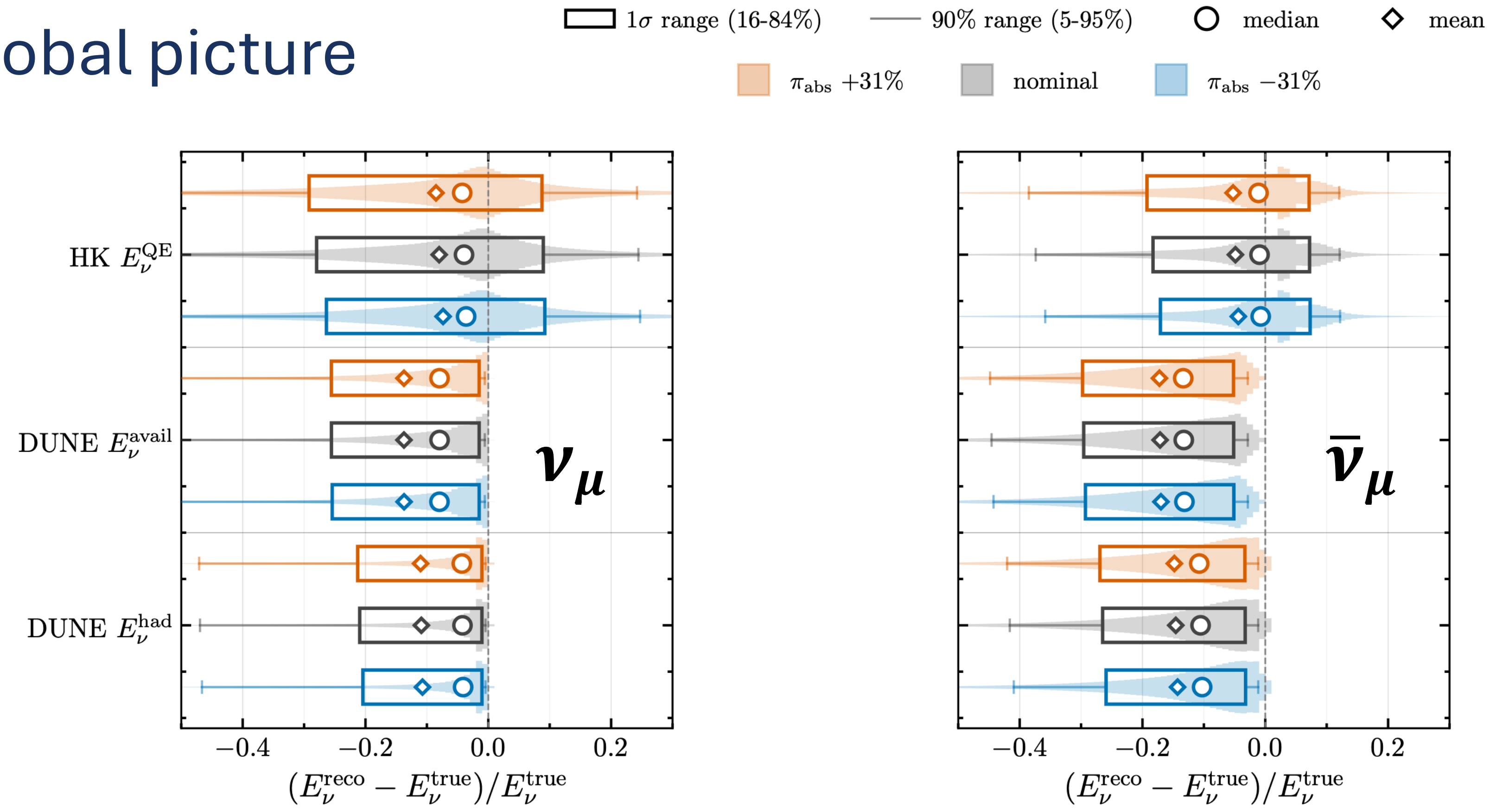


~10% impact in pion-dominated regions

Global picture



Global picture