Overview of Neutrino Cross-Section Results

and their importance for neutrino oscillation experiments

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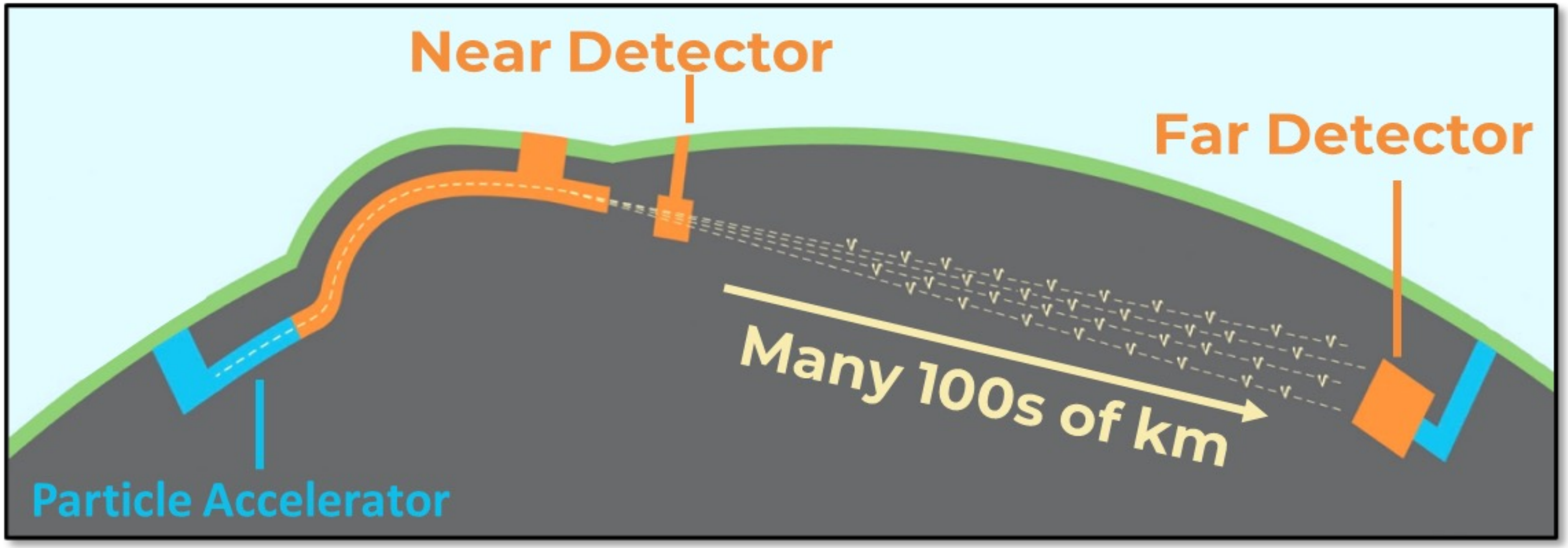
stephen.joseph.dolan@cern.ch

Heavily inspired by excellent talks at Neutrino 2024 from M. Buizza Avanzini, K. McFarland, A. Papadopoulou and J. Tena Vidal

Why do we care?



$$N_\ell(E_\nu) \propto P(\nu_\mu \rightarrow \nu_\ell)(E_\nu)\,\sigma(E_\nu)\,\Phi_\nu(E_\nu)\,\epsilon(E_\nu)$$

- $N_\ell(E_\nu)$: **Far detector event rate**
- $P(\nu_\mu \rightarrow \nu_\ell)(E_\nu)$: **Oscillation Probability**
- $\sigma(E_\nu)$: **Interaction Cross Section**
- $\Phi_\nu(E_\nu)$: **Incoming neutrino flux**
- $\epsilon(E_\nu)$: **Detector Efficiency**

Why do we care?

Current long-baseline experiments

	T2K	NOvA
Baseline	295 km	800 km
N_μ^{rec} (ν-mode)	318	384
N_e^{rec} (ν−mode)	94	181

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Current systematic uncertainties

Uncertainty on N_e^{rec}	T2K	NOvA
All Syst.	**~5%**	**~3.5%**

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Far detector event rate

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😱 Large contribution to syst. uncertainties from cross-section modelling

😅 Syst. uncertainties remains small compared to stat. uncertainties

Why do we care?

Future long-baseline experiments

	Hyper-K	DUNE
	arXiv:1805.04163	*arXiv:2002.03005*
Baseline	295 km	1300 km
N_{μ}^{rec} (ν-mode)	~10000	~7000
N_{e}^{rec} (ν−mode)	~2000	~1500

Current systematic uncertainties

Uncertainty on N_e^{rec}	T2K	NOvA
Cross Sections	**~4%**	**~3.5%**
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Why do we care?

Future long-baseline experiments

	Hyper-K (arXiv:1805.04163)	DUNE (arXiv:2002.03005)
Baseline	295 km	1300 km
N_{μ}^{rec} (ν-mode)	~10000	~7000
N_{e}^{rec} (ν–mode)	~2000	~1500

Current systematic uncertainties

Uncertainty on N_{e}^{rec}	T2K	NOvA
Cross Sections	**~4%**	**~3.5%**
All Syst.	**~5%**	**~3.5%**

😱 Large contribution to syst. uncertainties from cross-section modelling

😱 Current syst. uncertainties are larger than projected stat. uncertainties

➡ Improved understanding of neutrino interactions is necessary to avoid being prematurely limitation by syst. uncertainties

How to confront this?

✓ High-statistics, high-resolution near detector data for in-situ constraints

Examples:

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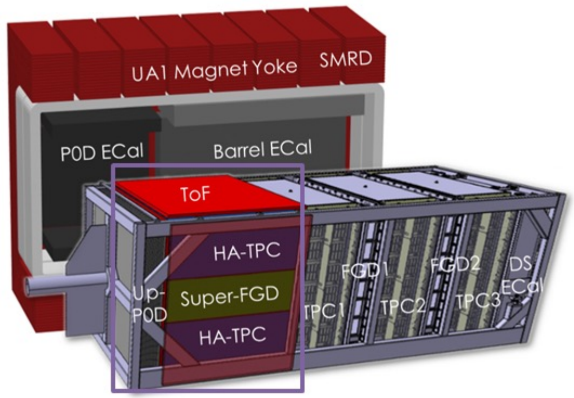
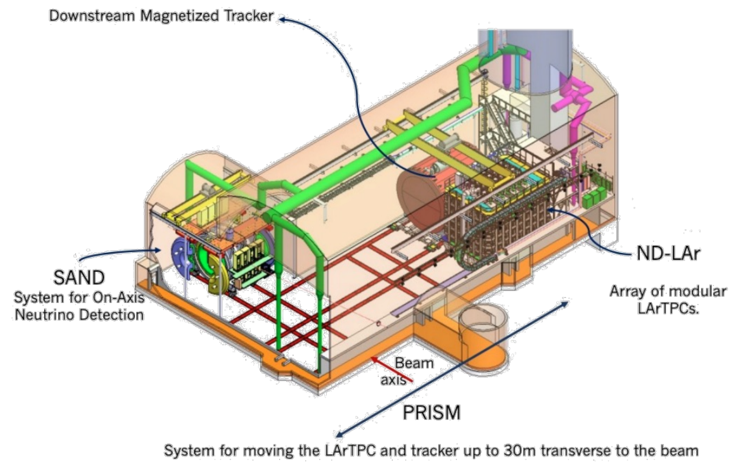
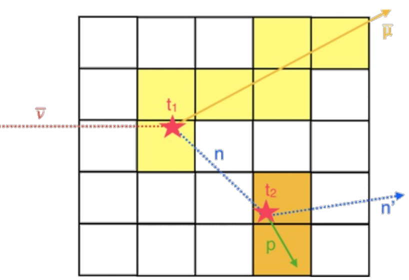
Examples:



T2K/HK ND-Upgrade

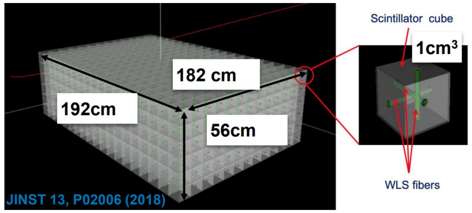


DUNE ND Complex



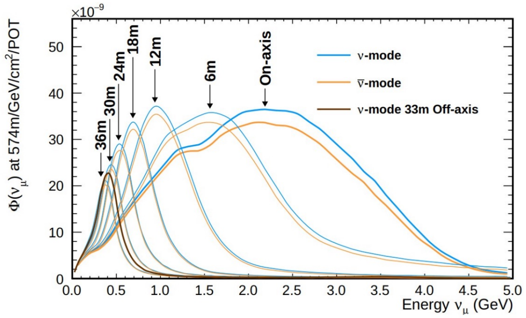
Neutron measurements

Phys. Rev. D **101**, 092003
Phys. Rev. D **110**, 032019

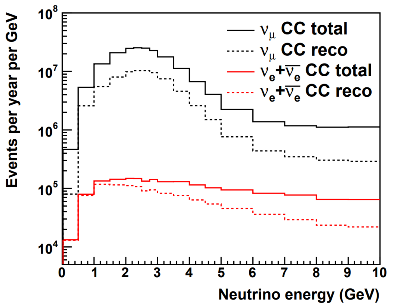


Super-fine granularity

JINST **13**, P02006



Movable detector: PRISM



More than 50M events/y

Instruments **2021**, *5*(4), 31

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~ A baseline model grounded in realistic nuclear theory

Examples:

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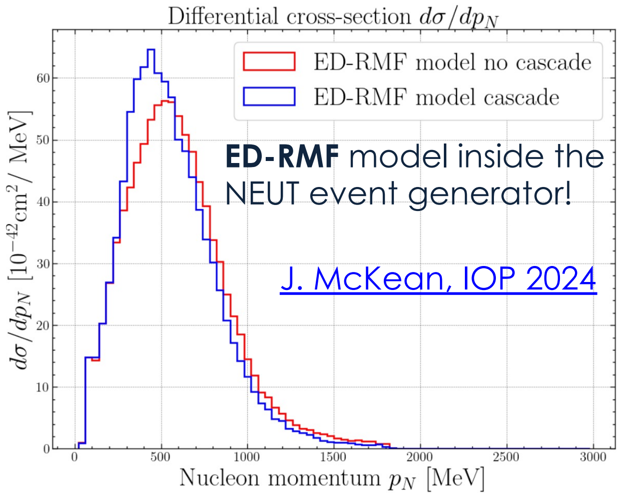

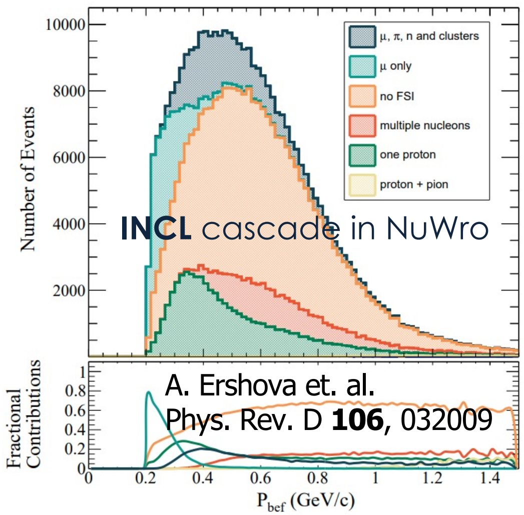

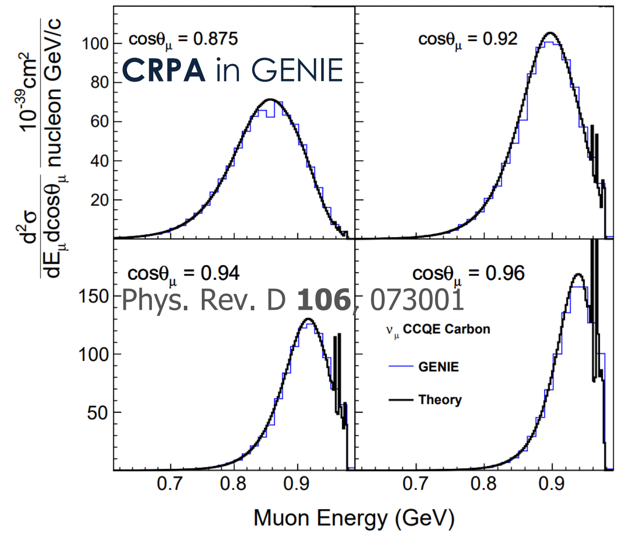

Real NEUT logo pending …

How to confront this?

✓ High-statistics, high-resolution near detector data for in-situ constraints

~ A baseline model grounded in realistic nuclear theory

✗ Comprehensive parametrisation of what we don't know

(i.e. a complete uncertainty model)

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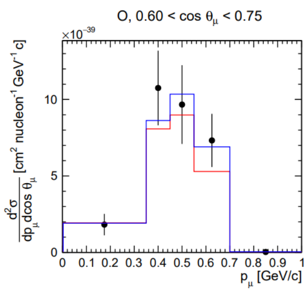
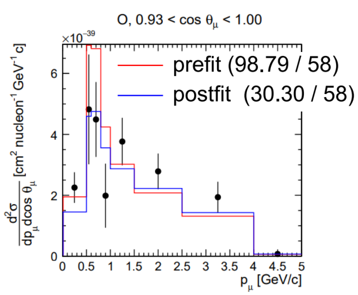
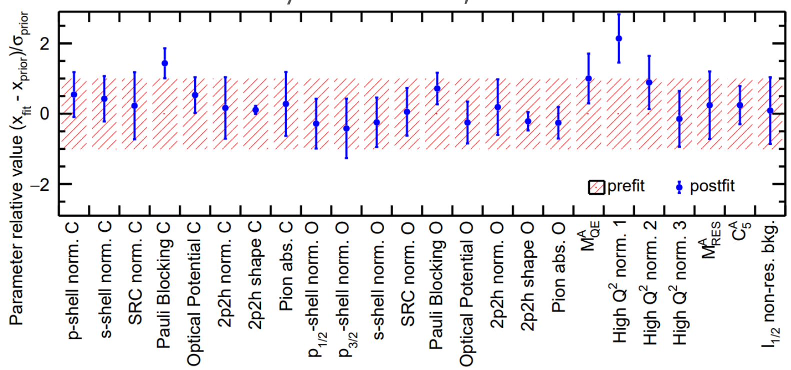
Example:

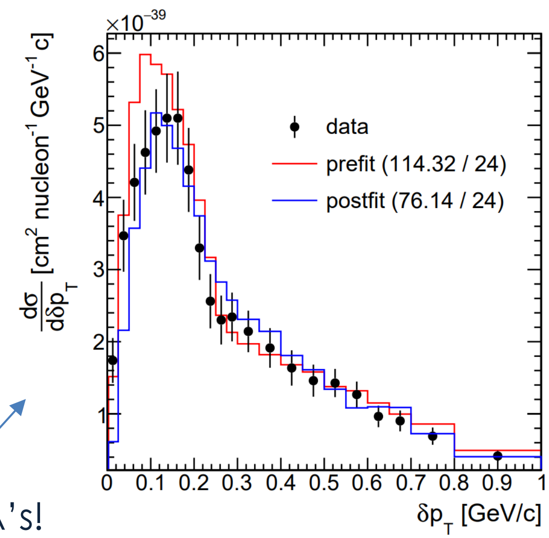




Phys. Rev. D **109**, 072006



T2K's uncertainty model successfully describes T2K's cross sections …



… but not MINERvA's!

How to confront this?

✓ High-statistics, high-resolution near detector data for in-situ constraints

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✗ Comprehensive parametrisation of what we don't know

(i.e. a complete uncertainty model)

Providing a means to get to *these* is the primary goal of cross-section measurements

An anonymous oscillation-focussed experimentalist

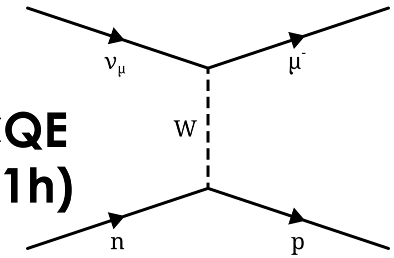
- **This takes time** and iteration with theorists / model builders
- We cannot wait for DUNE and Hyper-K to turn on, **we need to do this now**


KEEP CALM
AND
MEASURE dσ/dx

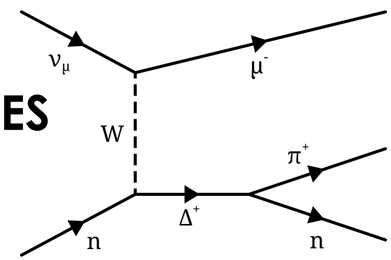
What we measure

Interaction Modes

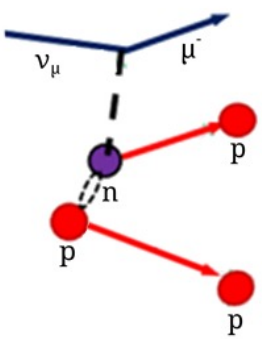
CCQE (1p1h)

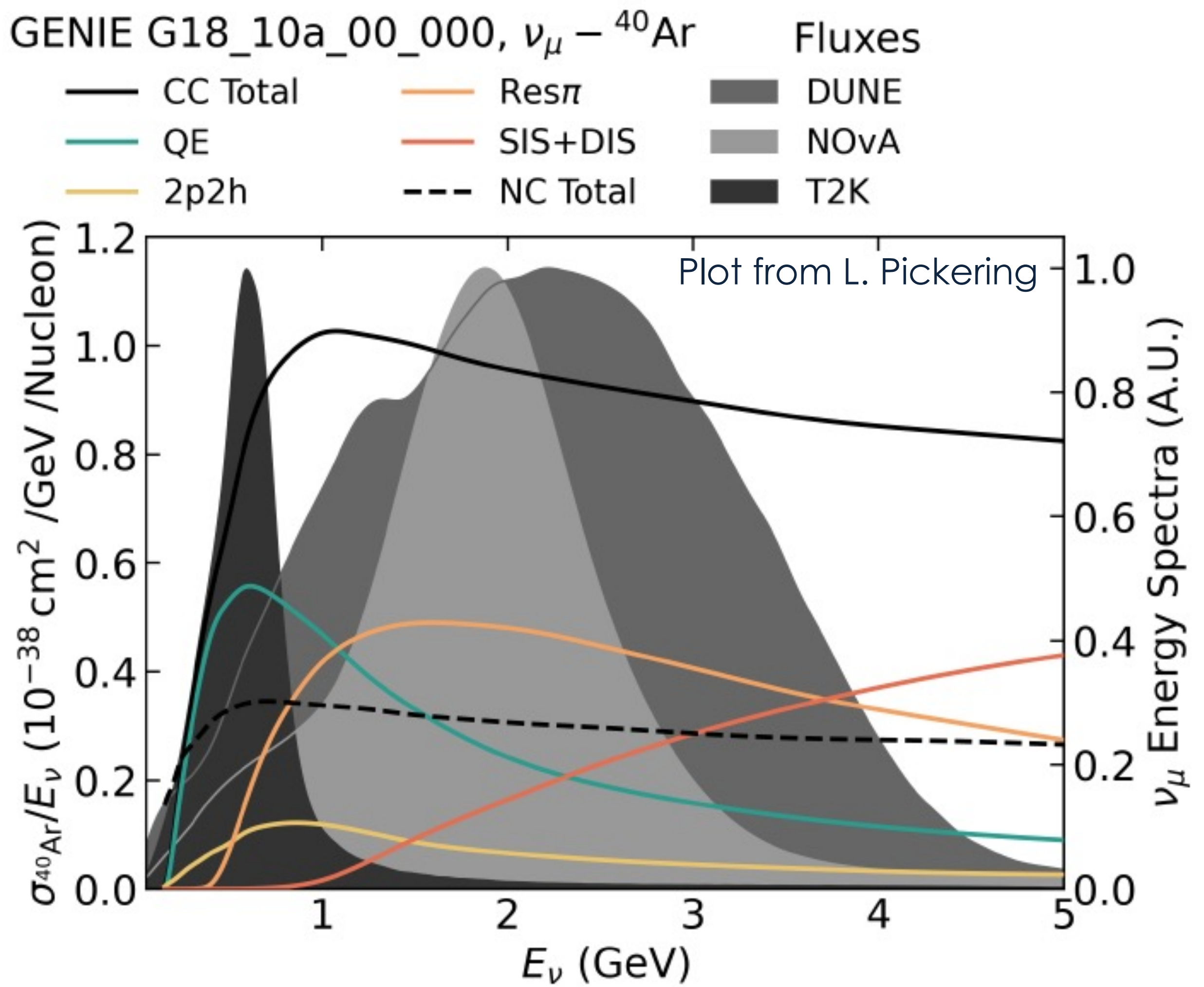


CCRES



2p2h



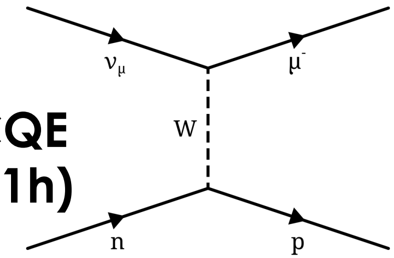


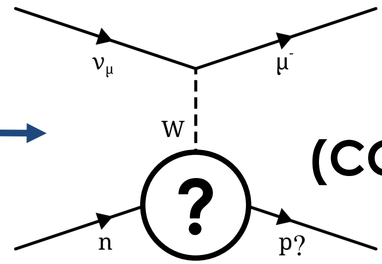
What we measure

Interaction Modes

Interaction Topologies

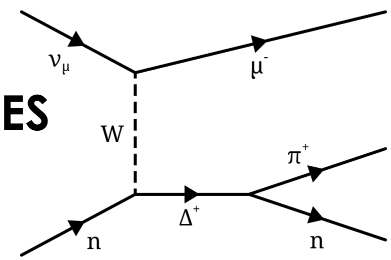
CCQE (1p1h)



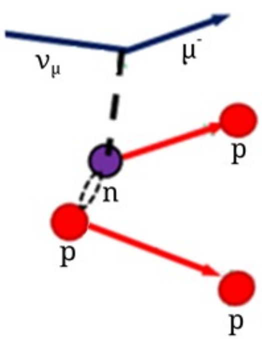


CC0π (CCQE-like)

CCRES



2p2h



What we measure

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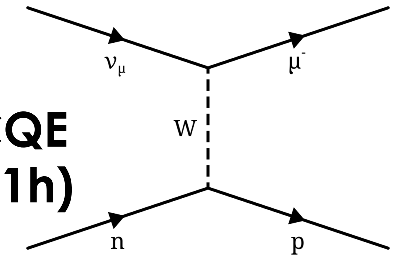

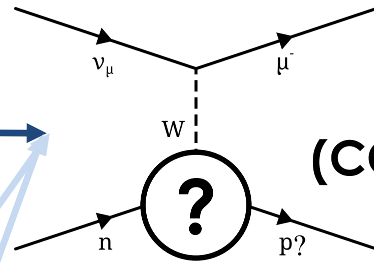

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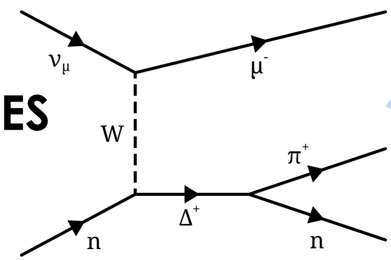
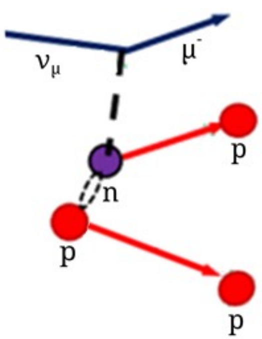
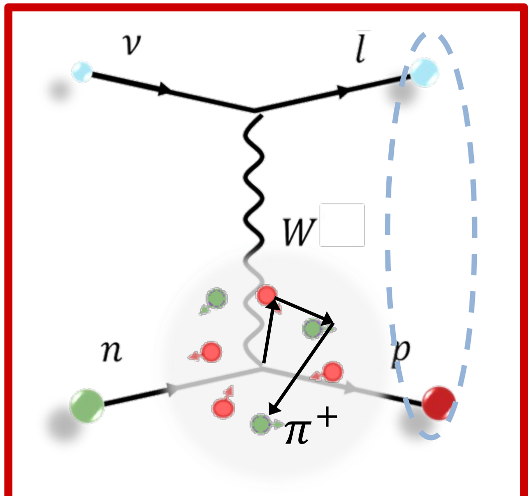


2p2h

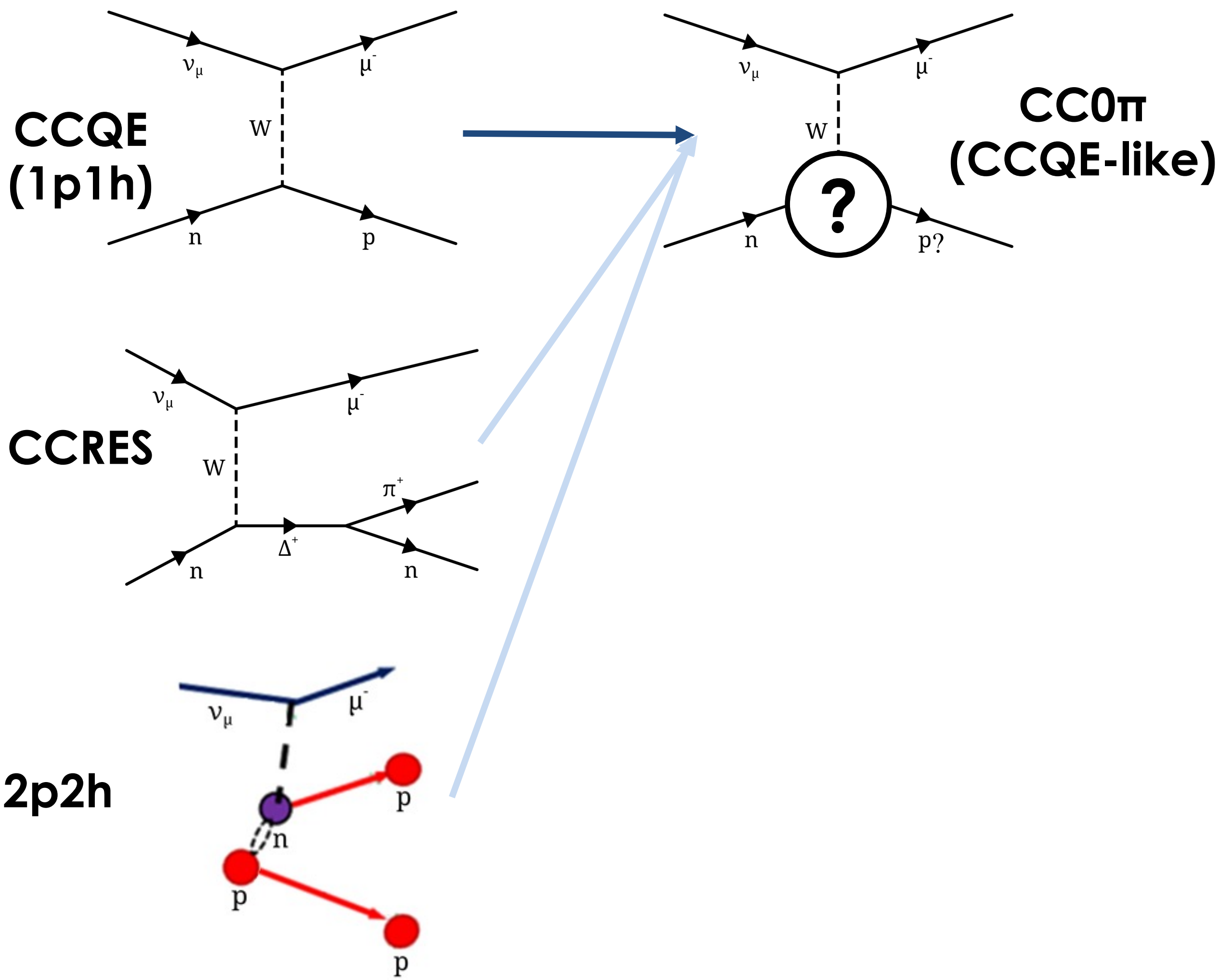


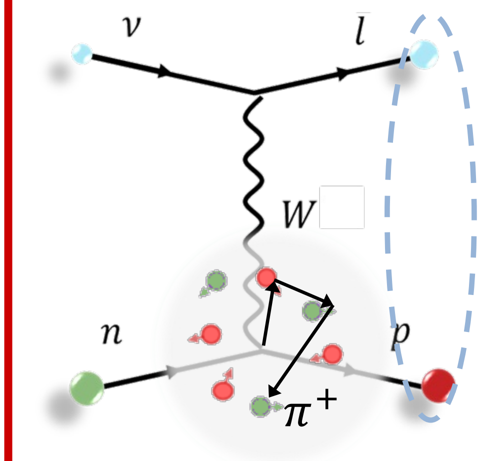


CCRES + πabs. → CC0π

What we measure

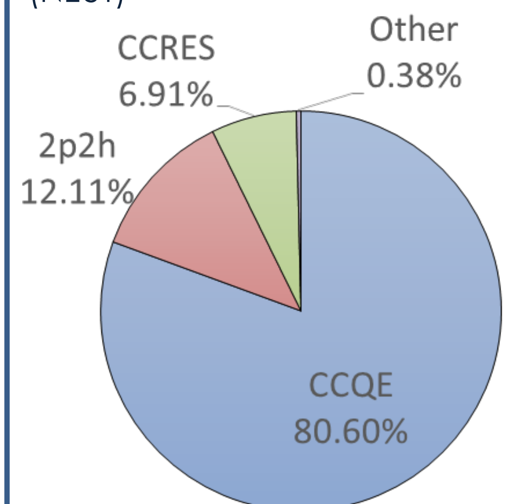
Interaction Modes | **Interaction Topologies**





CCRES + πabs. → CC0π

Interaction modes in
CC0π topology:
(NEUT)



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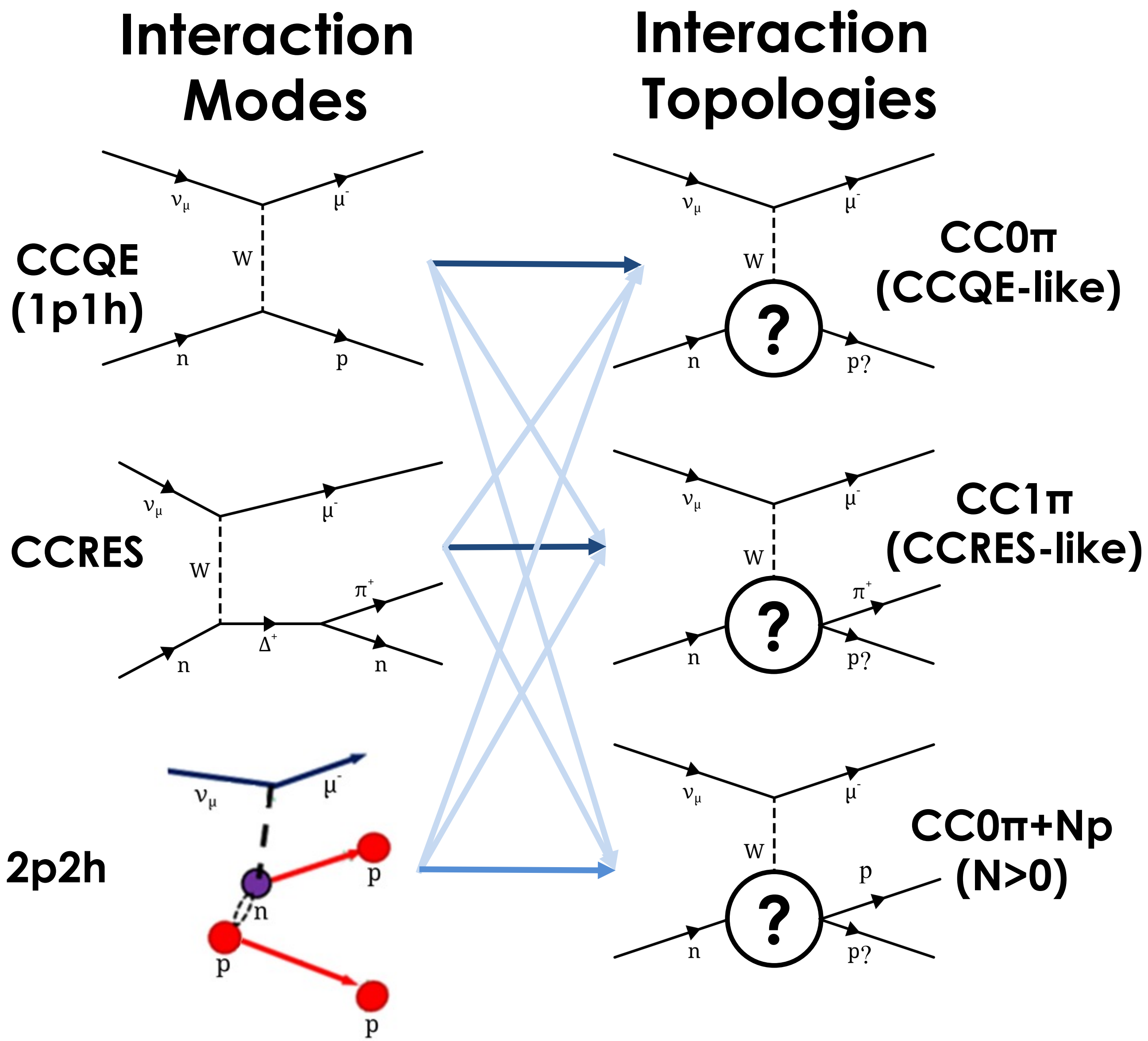
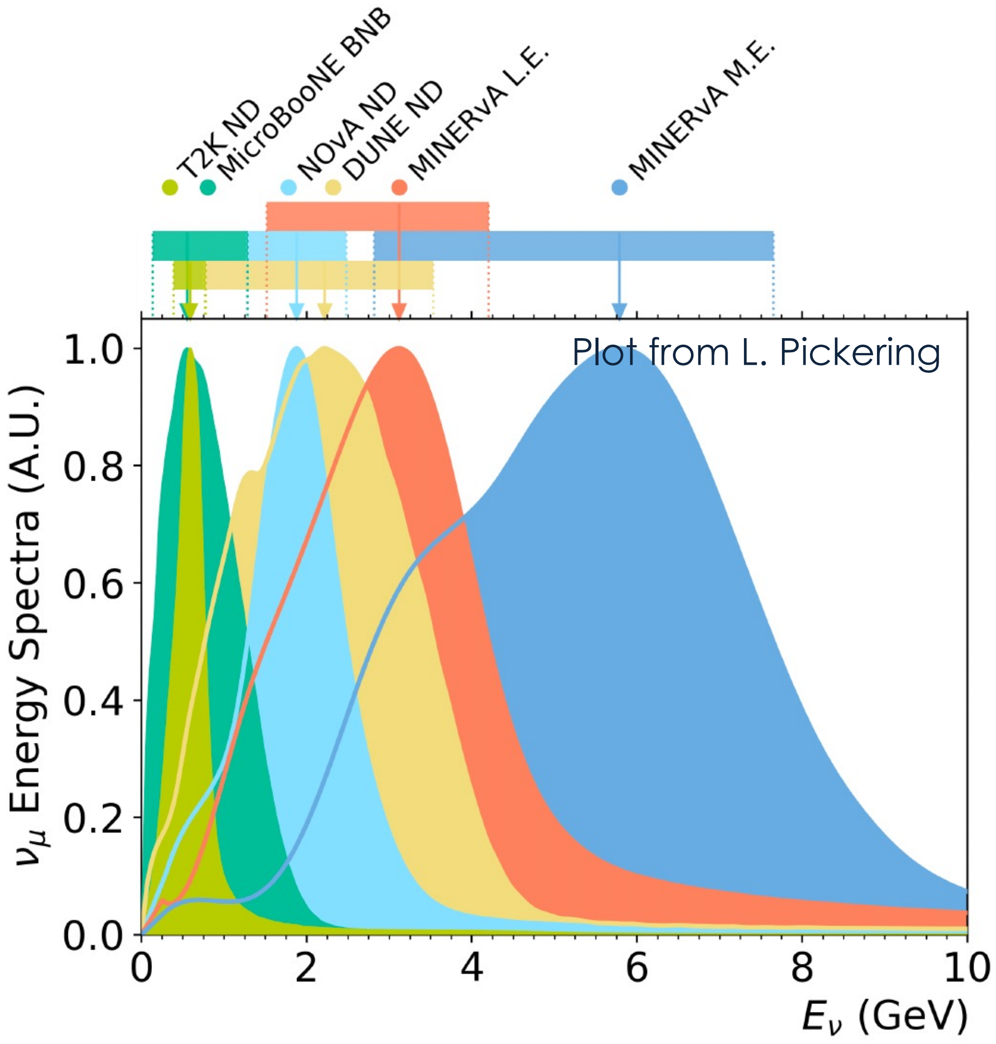


Cross-section collaborations



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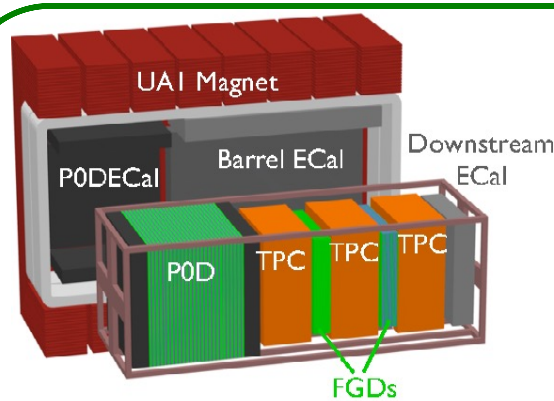
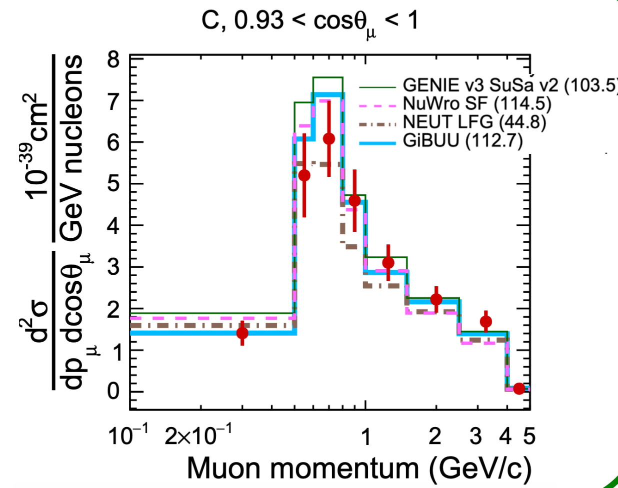
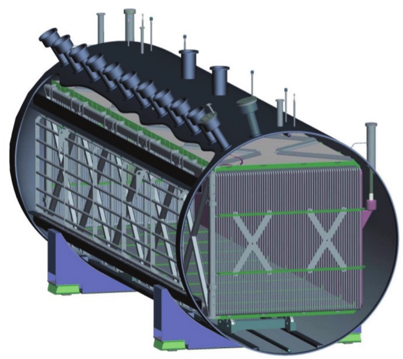
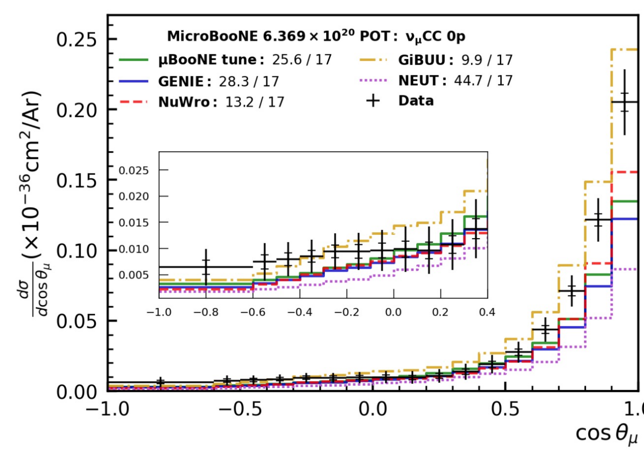


CH and H_2O targets
$E_\nu^{peak} \sim 0.6$ GeV





Ar target
$E_\nu^{peak} \sim 0.8$ GeV



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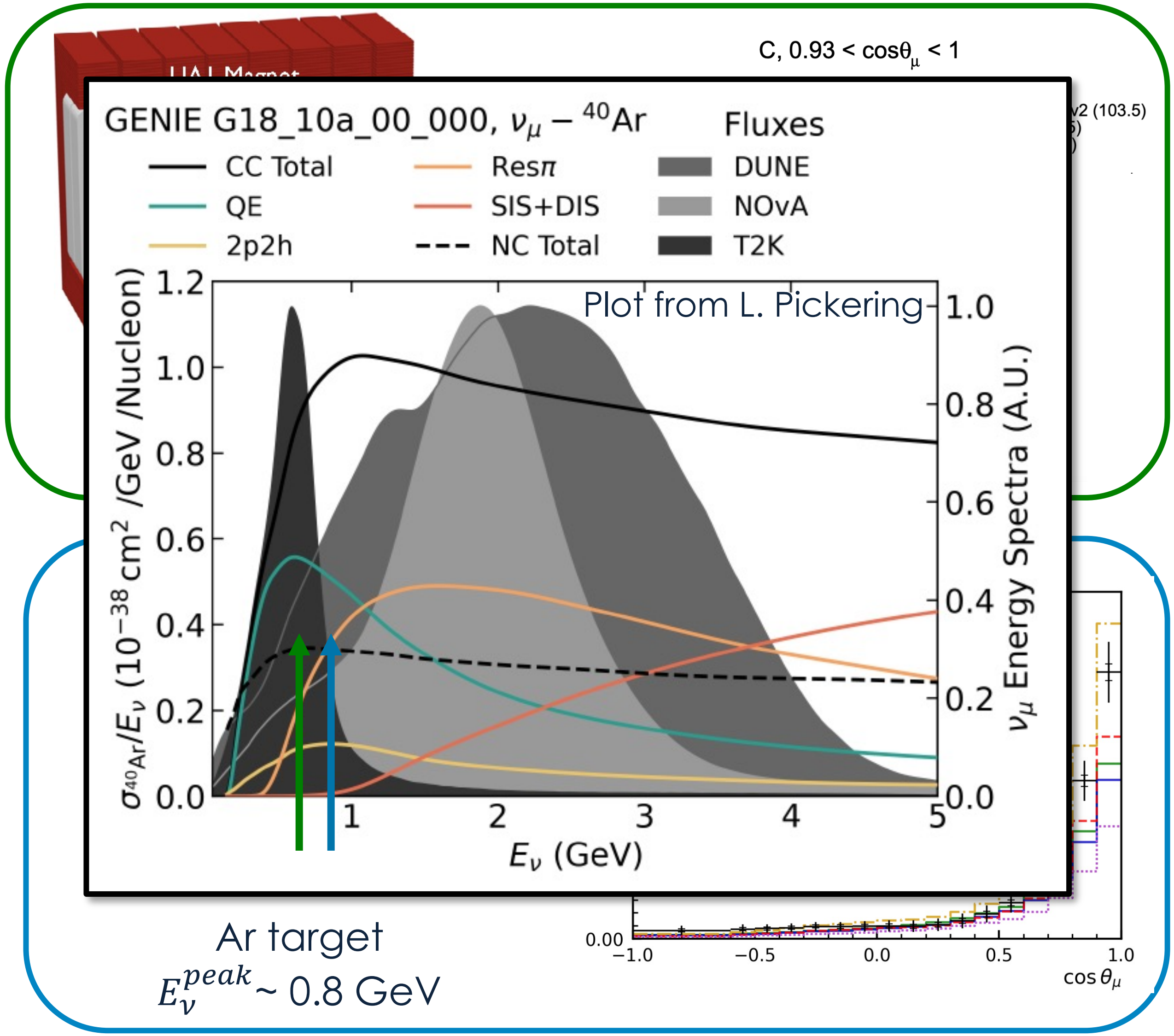

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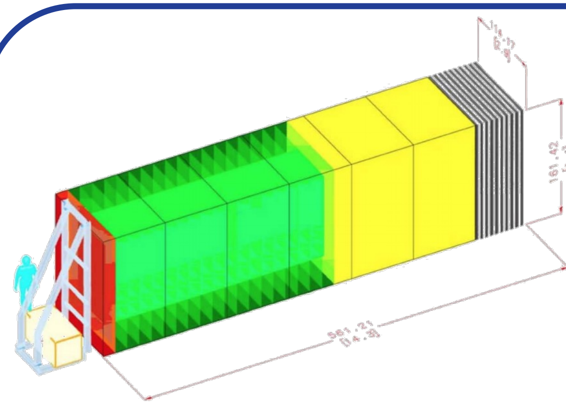
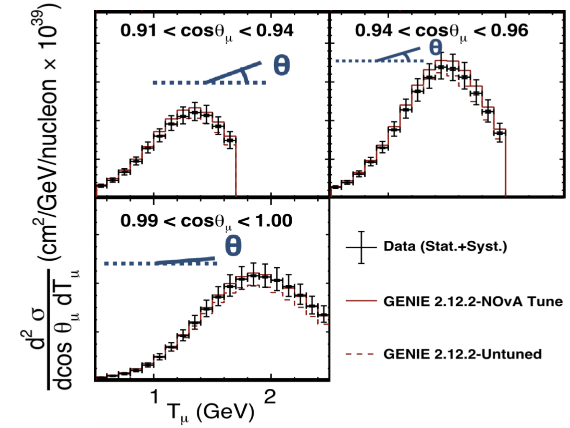
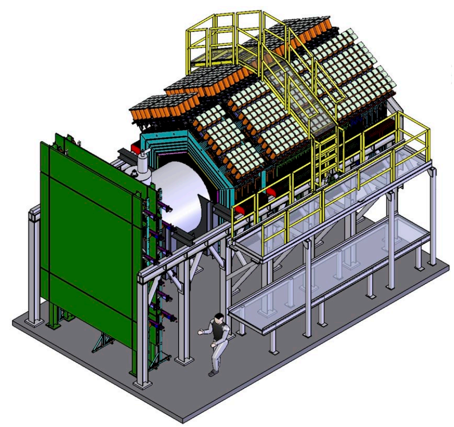
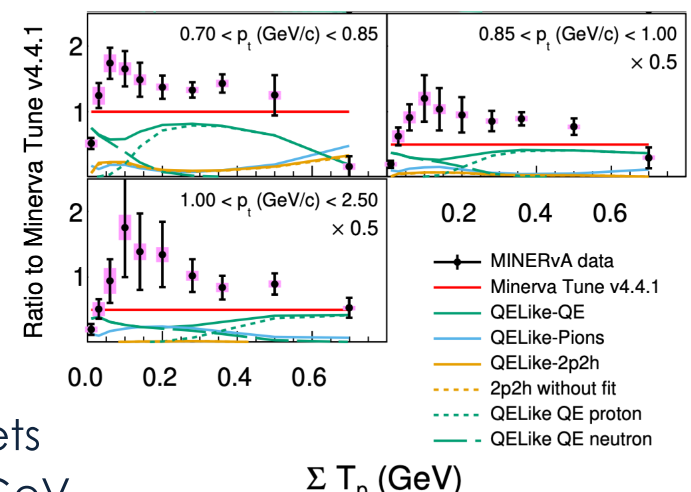




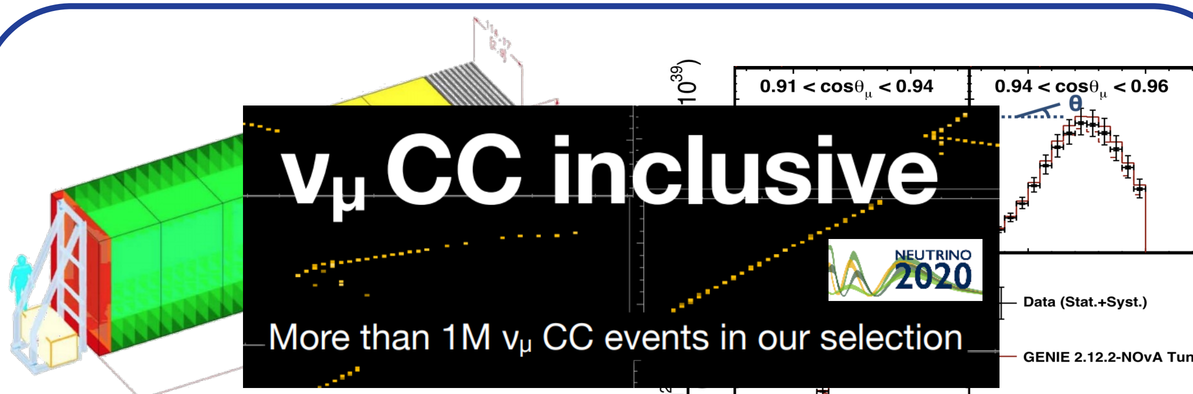
~CH "NoVA Soup" target
E_ν^{peak}~ 1.8 GeV





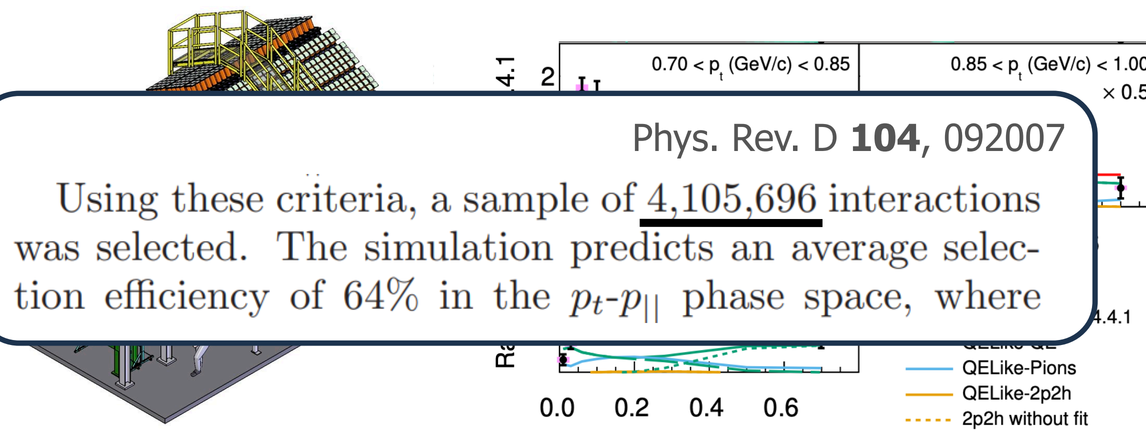
C, CH, Pb, Fe, H_2O, He targets
$E_\nu^{peak,LE}$~ 3 GeV, $E_\nu^{peak,ME}$~ 6 GeV

Cross-section collaborations



~CH "NoVA Soup" target

$E_\nu^{peak} \sim 1.8$ GeV



Phys. Rev. D **104**, 092007

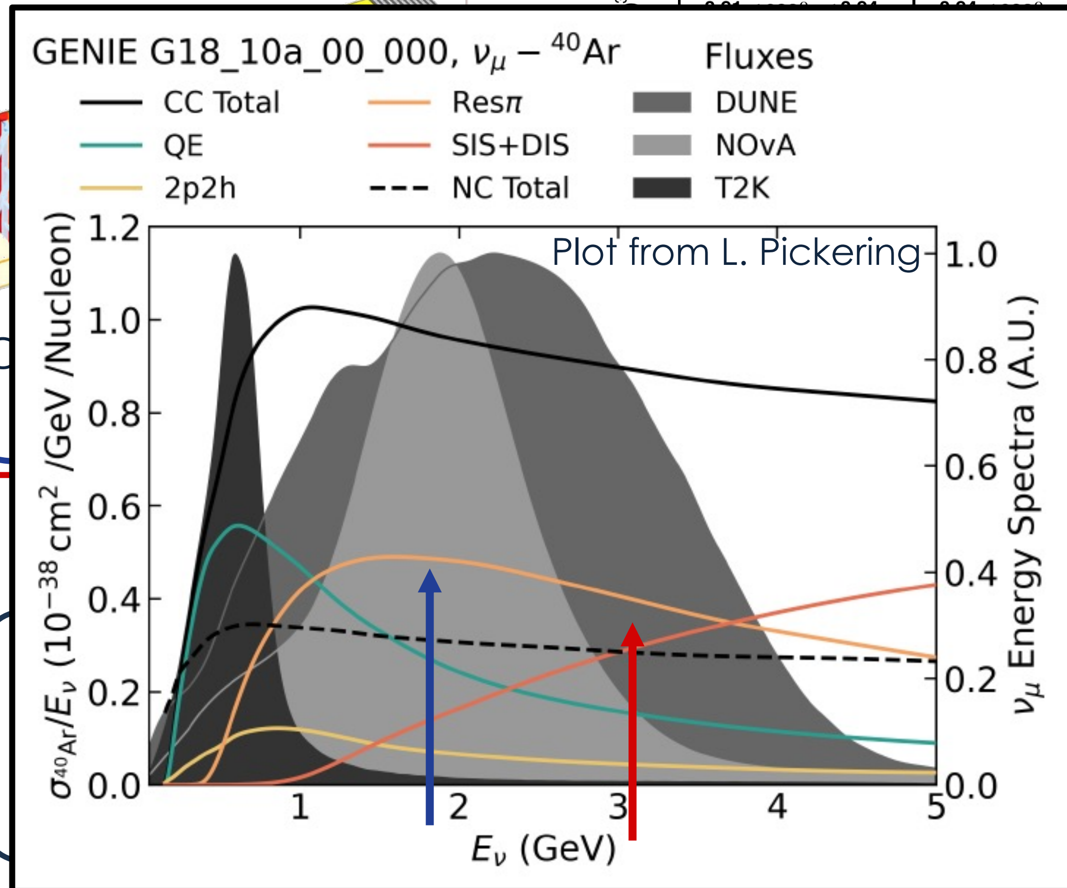
Using these criteria, a sample of 4,105,696 interactions was selected. The simulation predicts an average selection efficiency of 64% in the p_t-$p_{||}$ phase space, where

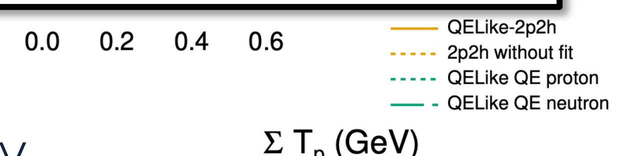
C, CH, Pb, Fe, H_2O, He targets

$E_\nu^{peak,LE} \sim 3$ GeV, $E_\nu^{peak,ME} \sim 6$ GeV

Cross-section collaborations

~C





C, CH, Pb, Fe, H_2O, He targets

$E_\nu^{peak,LE}$~ 3 GeV, $E_\nu^{peak,ME}$~ 6 GeV

Cross-section collaborations

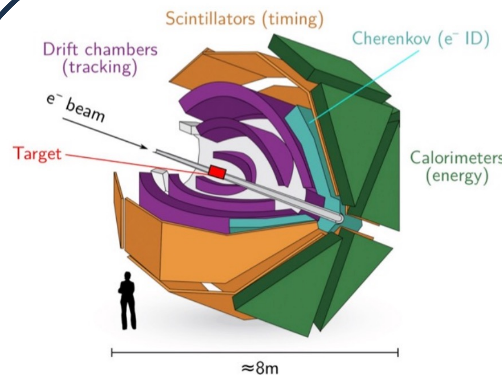
T2K

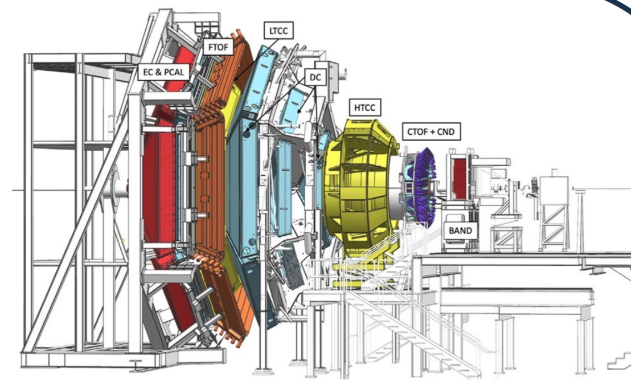
μBooNE

NOvA

MINERvA

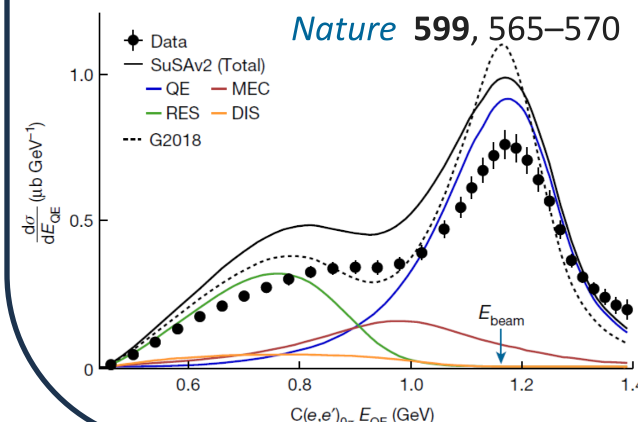
e4ν

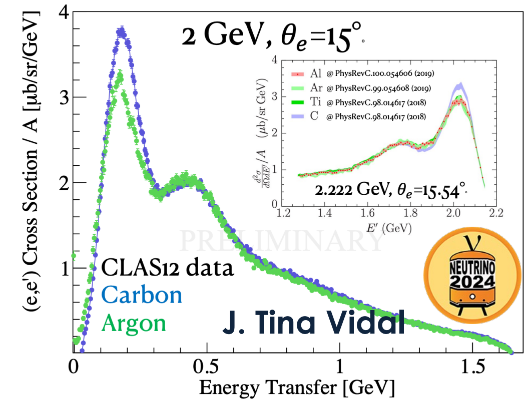




	CLAS6	CLAS12
Targets	^{4}He, C & Fe	H, D, ^{4}He, C, (O), ^{40}Ar and more
Beam Energy	1.1, 2.2, 4.4 GeV	(1), 2, 4, 6 GeV

Nature **599**, 565–570





Latest measurements

Since last NuFact …

T2K

$\nu_e CC1\pi^+$ on CH

WAGASCI CC0π on CH + H_2O

NCπ^+ on CH

(NuINT 2024)

NOvA

$\bar{\nu}_\mu$CC-INC (NuINT 2024)

Low hadronic energy CC0π0p

Inference of 2p2h cross section

(FNAL W&C seminar)

µBooNE

Neutrons on Ar (arXiv:2406.10583)

NCπ^0 (arXiv:2404.10948)

CC0π w/correlated observables (arXiv:2403.19574)

Joint CC0p, CCNp (arXiv:2402.19281)

CC0π generalised imbalance (arXiv:2310.06082)

MINERvA

Low hadronic energy at ~6 GeV

Multi-differential transverse imbalance at ~6 GeV

Inference of ν_e / ν_μ ratio (NuINT 2024)

Inference of SIS cross section

Low hadronic energy $\nu_e + \bar{\nu}_e$ (arXiv:2312.16631)

Low hadronic energy $\bar{\nu}_\mu$ w/neutrons (arXiv:2310.17014)

Latest measurements

Since last NuFact …

T2K

ν_eCC1π^+ o…

WAGASCI CC0π …

NCπ^+ on CH

(NuINT 2024)

NOvA

$\bar{\nu}_\mu$CC-INC (NuINT 2024)

Low hadronic energy CC0π0p

Inference of 2p2h cross section

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Joint CC0p, CCNp (arXiv:2402.19281)

…0π generalised imbalance (arXiv:2310.06082)

See all this (and more) in WG2 talks

Low hadronic e… GeV

Multi-differential trans… …ce at ~6 GeV

Inference of ν_e / ν_μ ratio …NT 2024)

Inference of SIS cross section

Low hadronic energy ν_e+ $\bar{\nu}_e$ (arXiv:2312.166…)

Low hadronic energy $\bar{\nu}_\mu$ w/neutrons (arXiv:2310.17014)

How to confront this?

✓ High-statistics, high-resolution near detector data for in-situ constraints

~ A baseline model grounded in realistic nuclear theory

✗ Comprehensive parametrisation of what we don't know

(i.e. a complete uncertainty model)

Providing a means to get to *these* is the primary goal of cross-section measurements

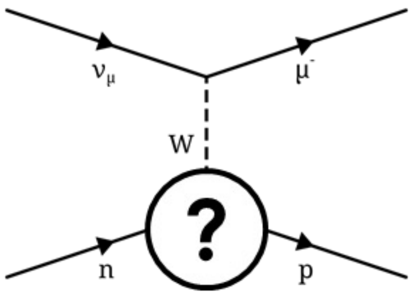
An anonymous oscillation-focussed experimentalist

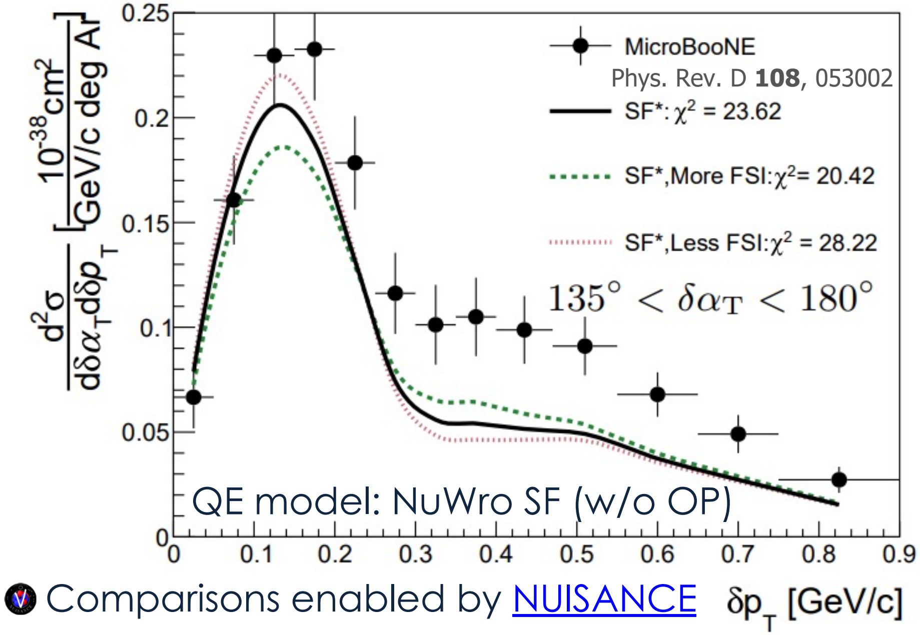
How cross sections help

arXiv:2407.10962
See talk by L. Munteanu

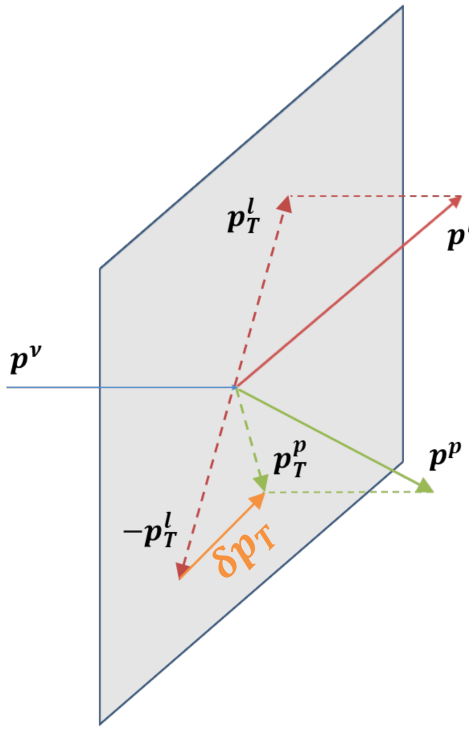
Example

- MicroBooNE measure missing transverse momentum (δp_T) in CC0π interactions





Comparisons enabled by NUISANCE



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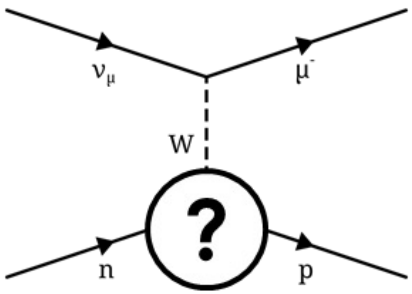

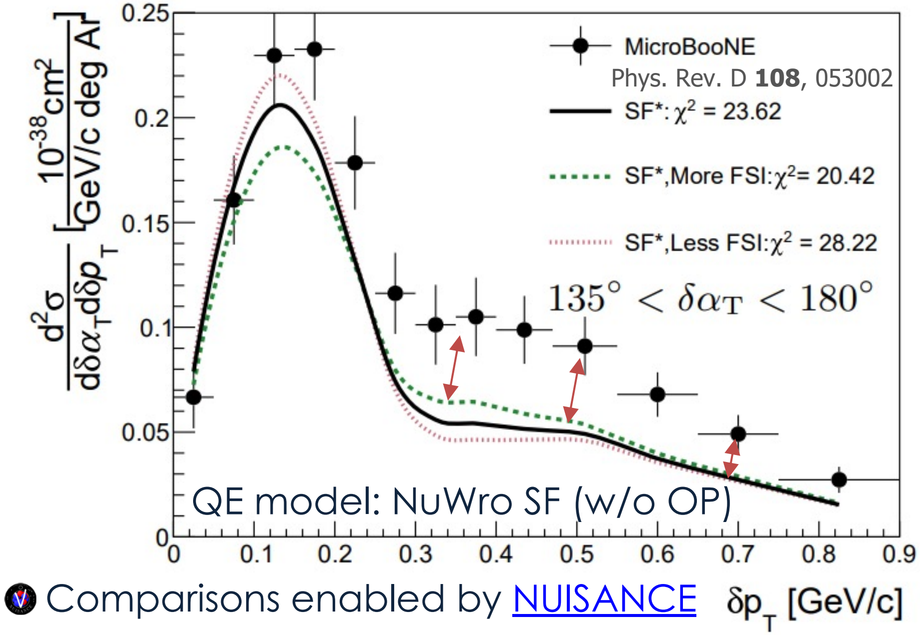

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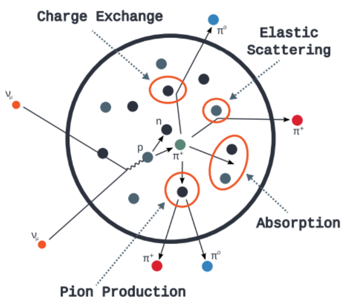
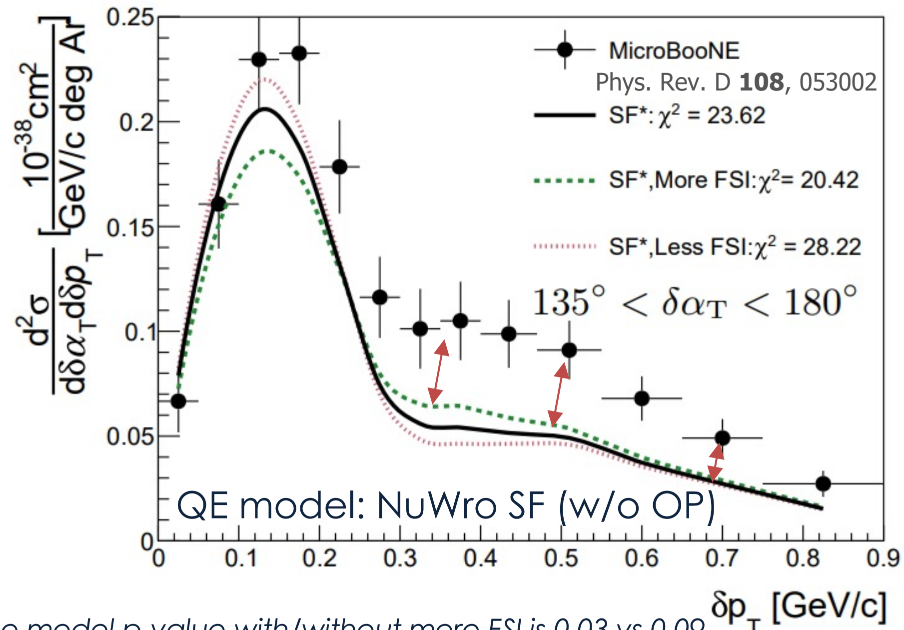
Final State Interactions (FSI)





* *the model p-value with/without more FSI is 0.03 vs 0.09*

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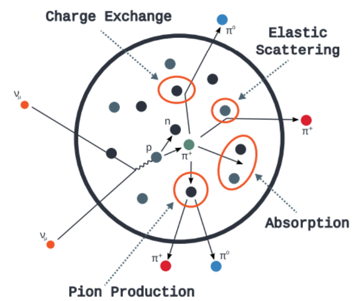
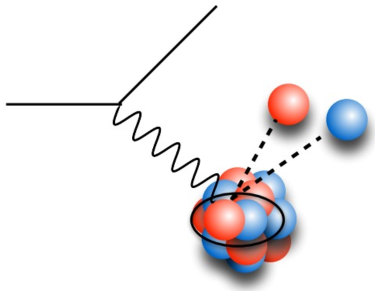
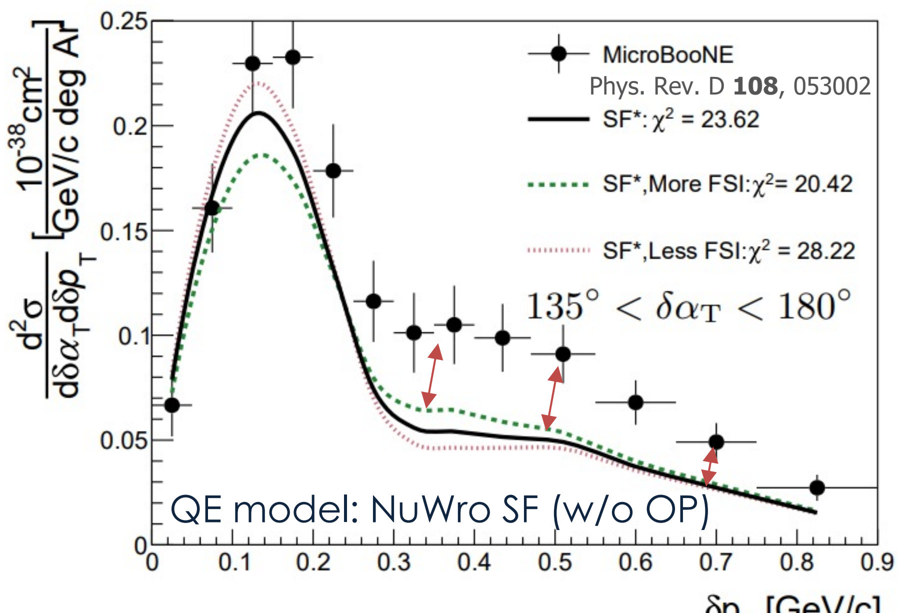


Two-particle two-hole (2p2h) interactions





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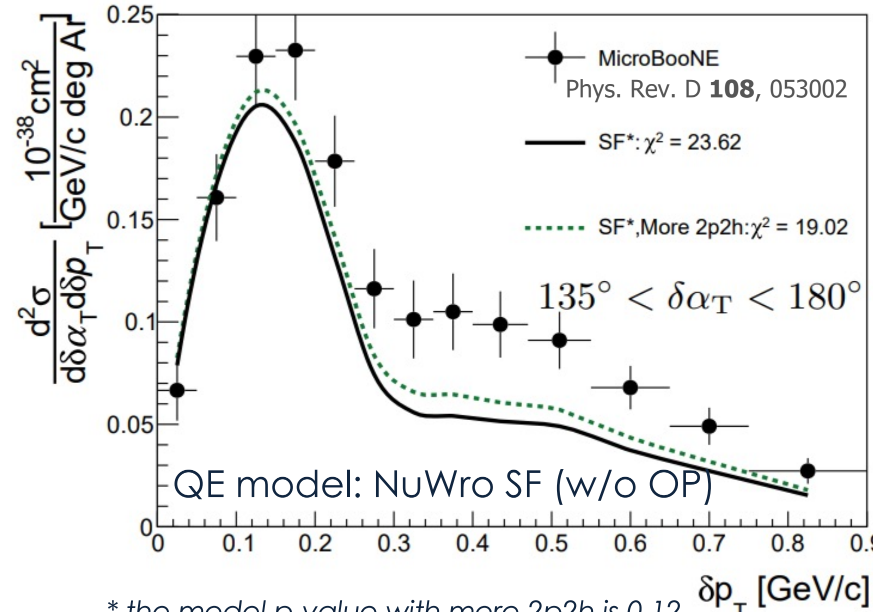

* *the model p-value with more 2p2h is 0.12*

How cross sections help

arXiv:2407.10962
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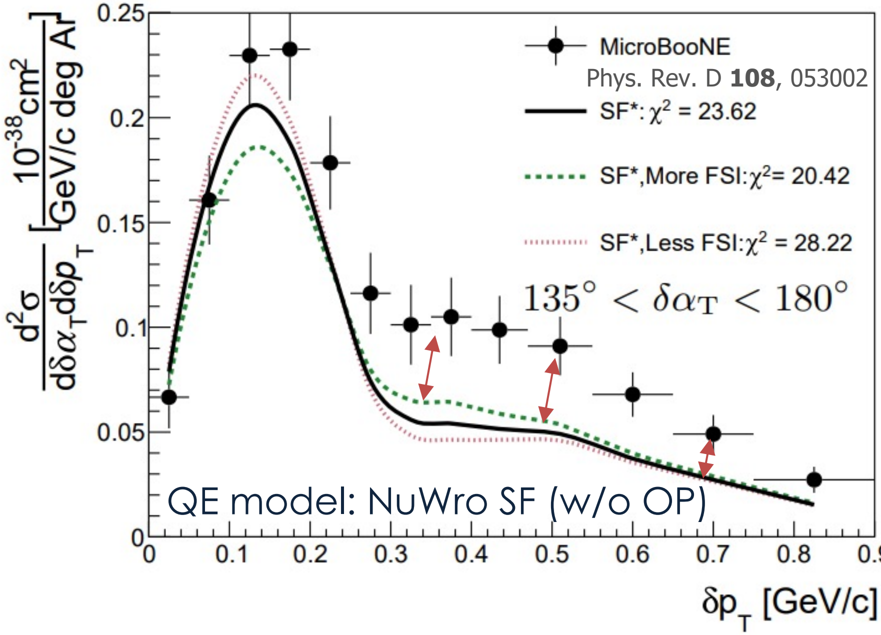
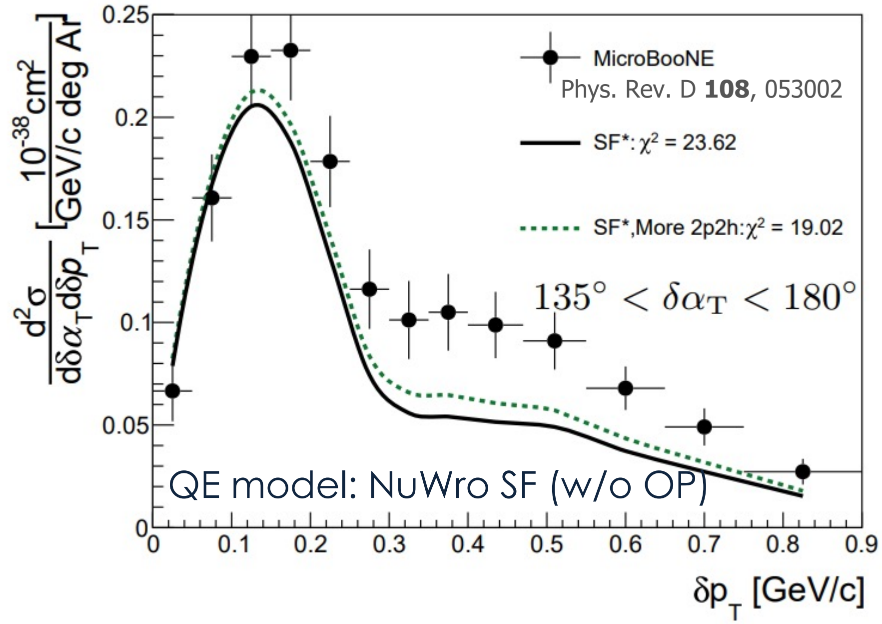
The measurements suggest **insufficient modelling of nuclear effects** motivating:

- **Development of better models**
- **New uncertainties to cover this**

But, alone, they don't tell us exactly what is wrong …





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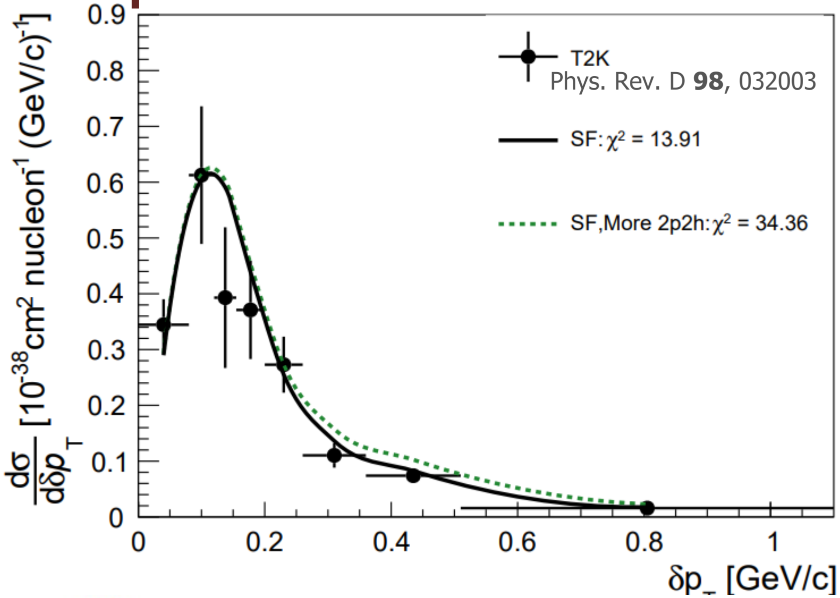

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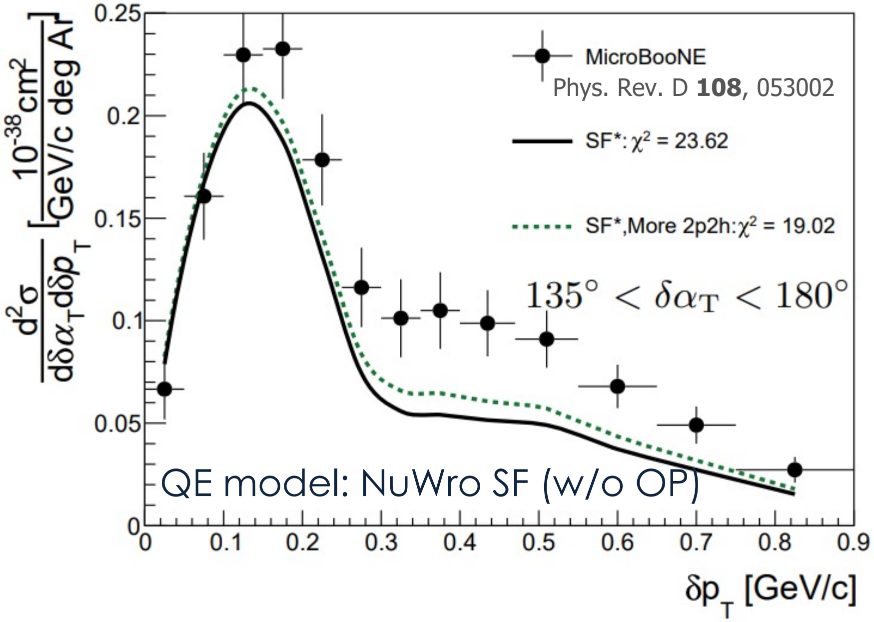

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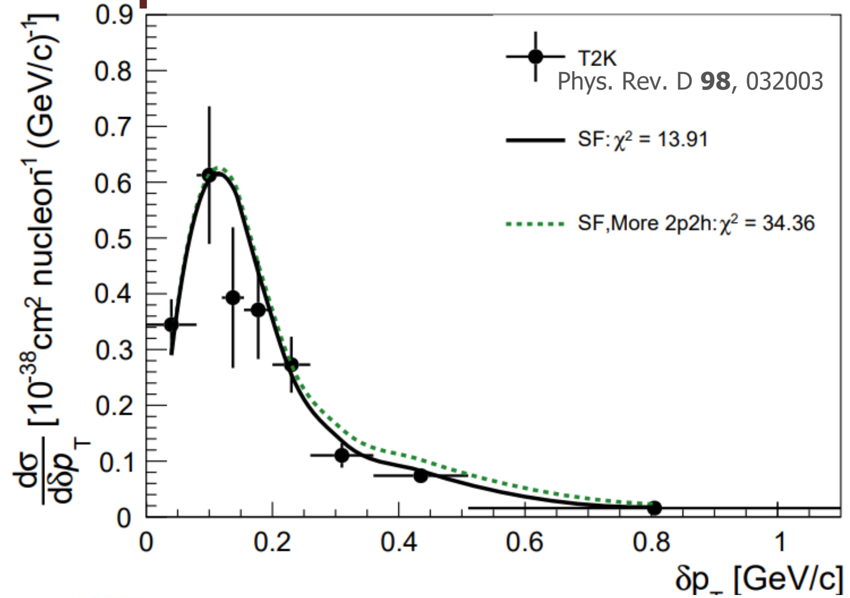

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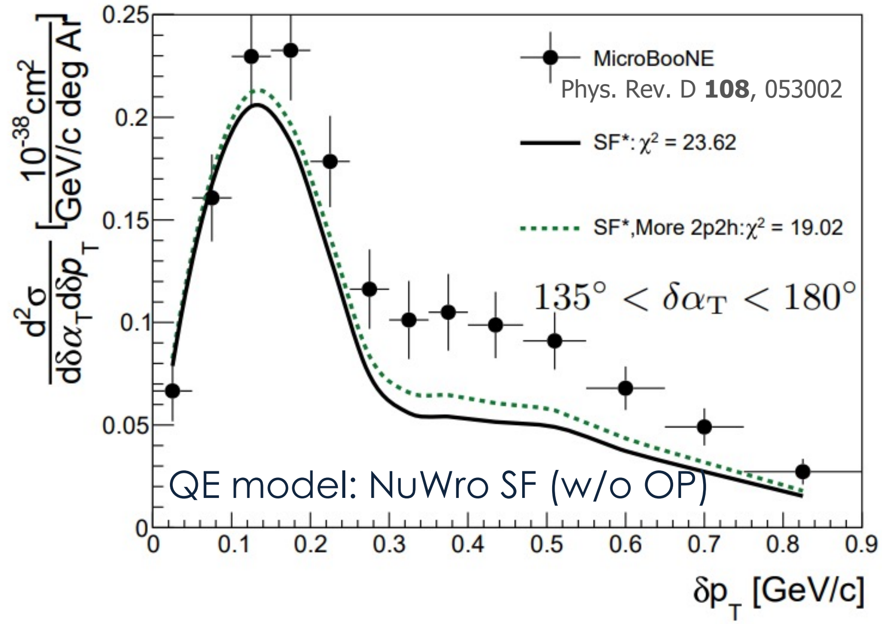

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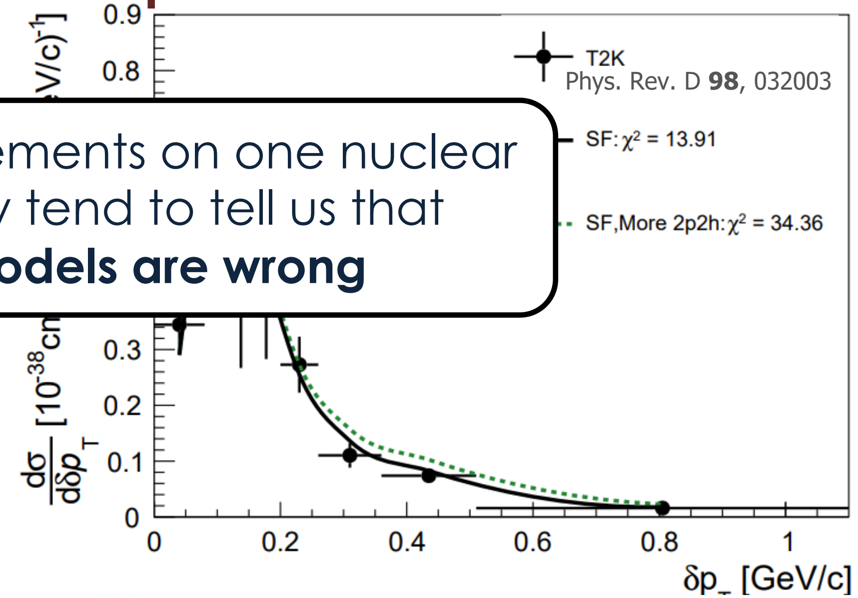
High resolution measurements on one nuclear target at one energy tend to tell us that **most/all of our models are wrong**



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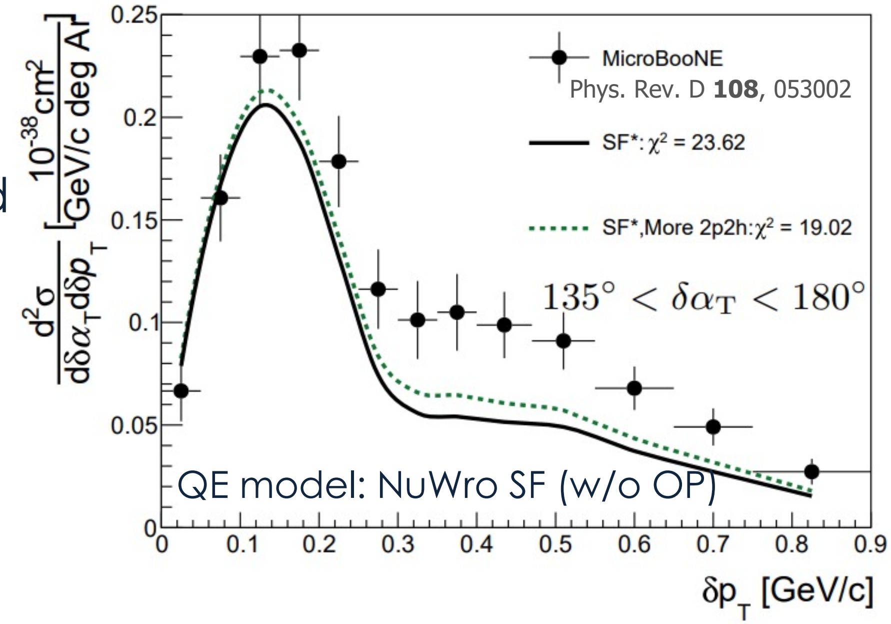

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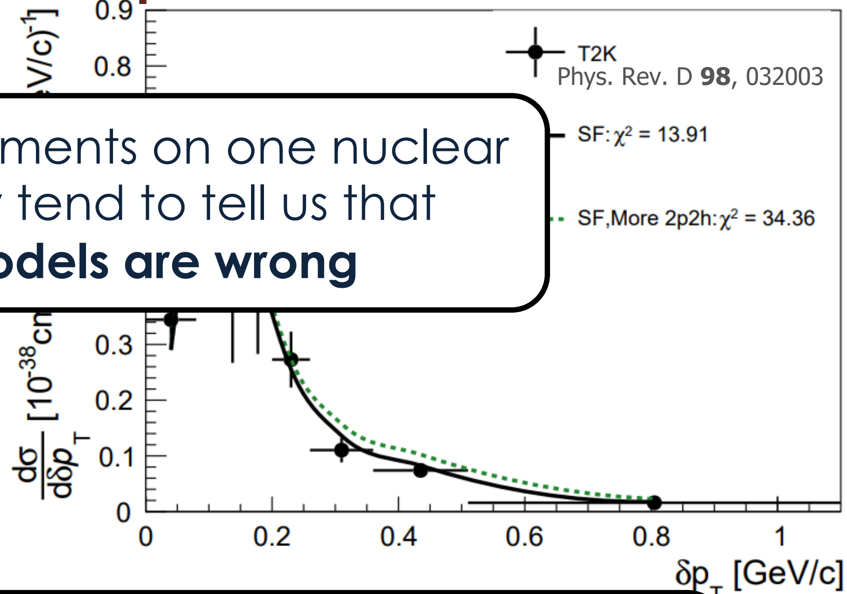

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- Measure… disagree…
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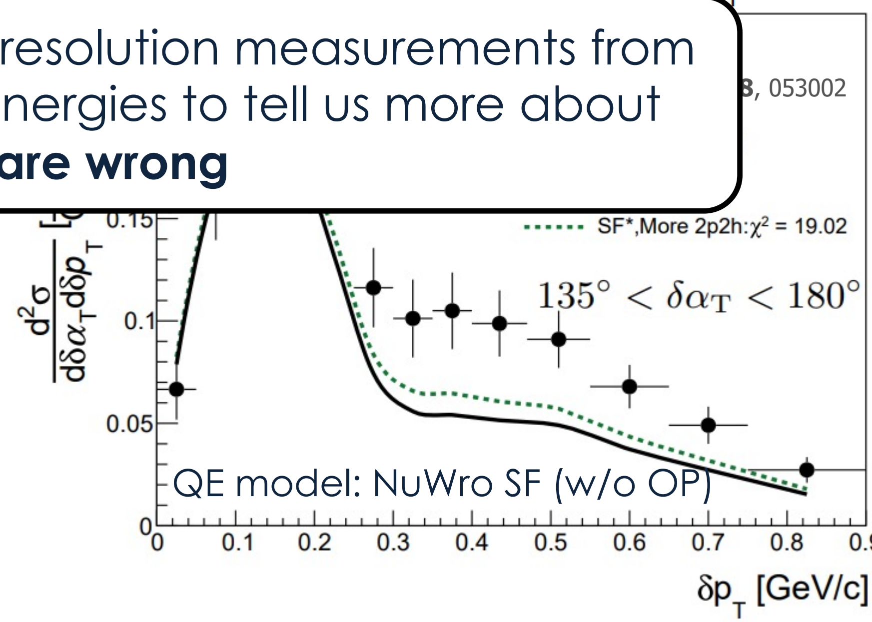


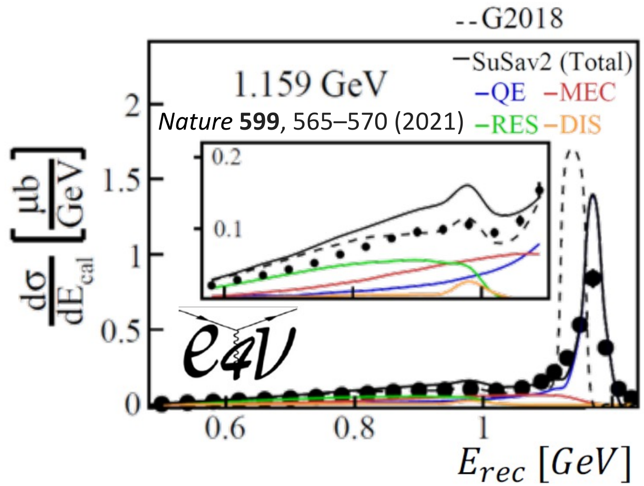
Combining experiments: high resolution measurements from multiple targets at multiple energies to tell us more about **why they are wrong**

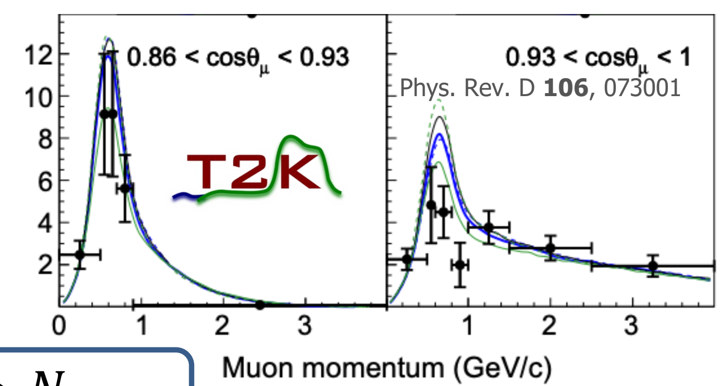
What else have we leant?

Some more general lessons

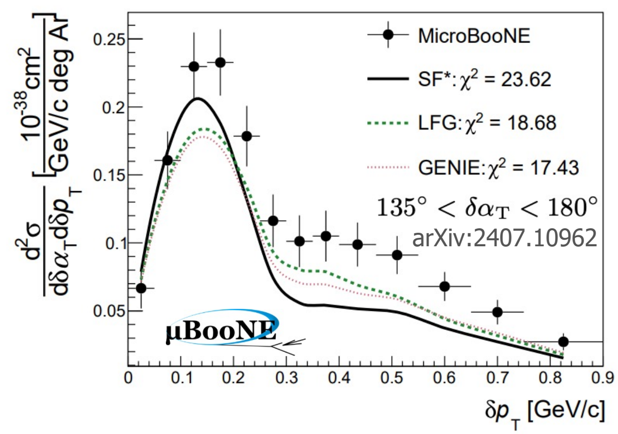
All models are wrong …

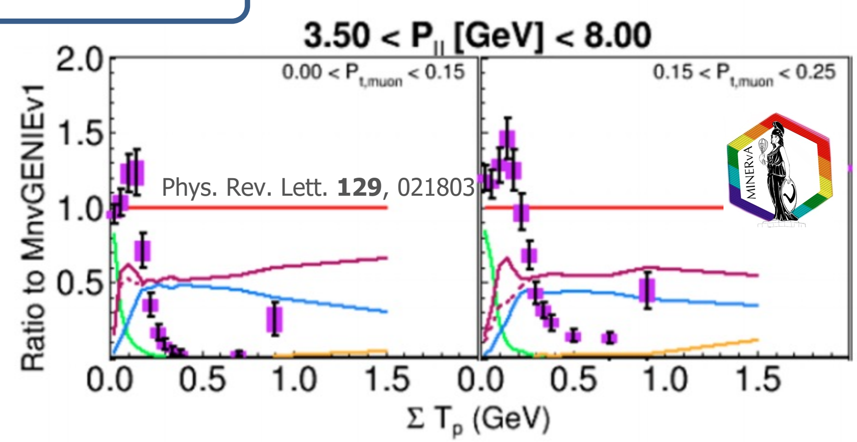
- Neutrino interaction cross sections are hard to model. Our current generator predictions are all ruled out by existing measurements.





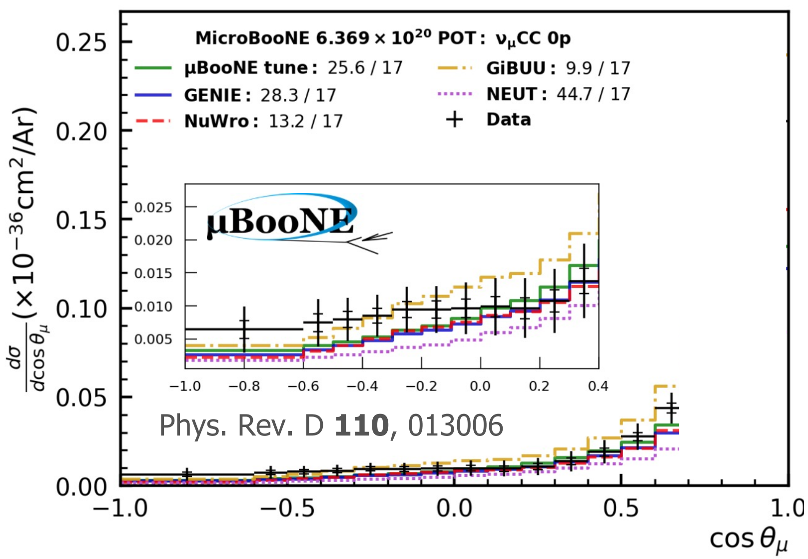
$$\chi^2_{models} \gg N_{bins}$$



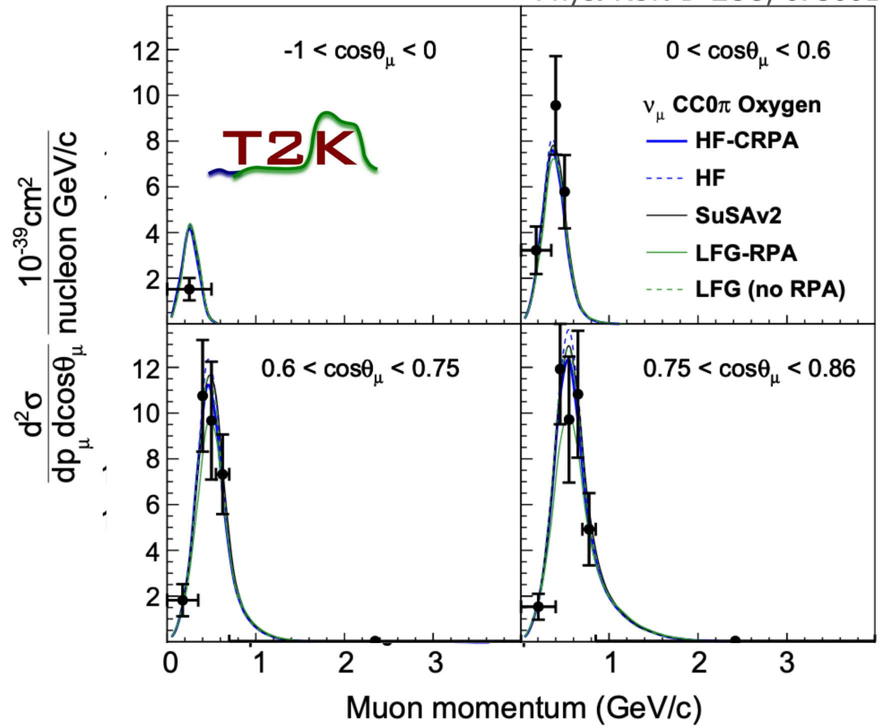


Not all the time …

Some models do **a good job of describing lepton kinematics** …

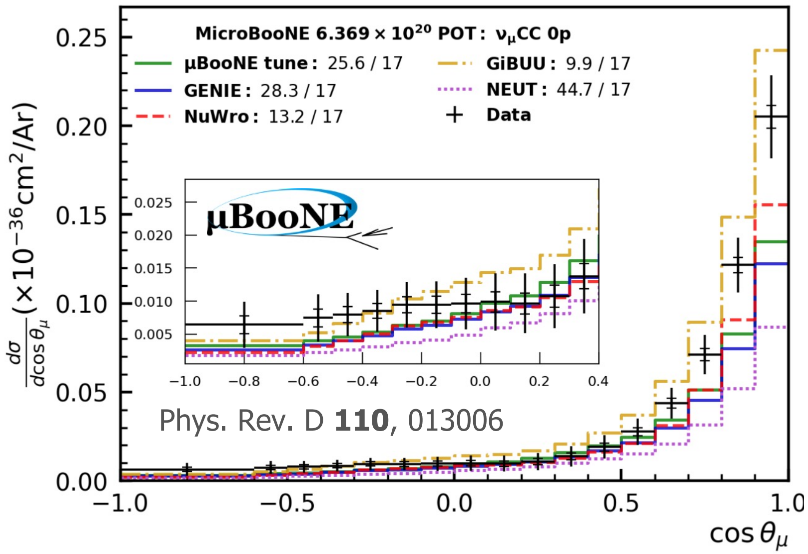


Phys. Rev. D **106**, 073001



… but definitely sometimes!

But **not at very forward angles** (= low energy transfer = more nuclear effects)



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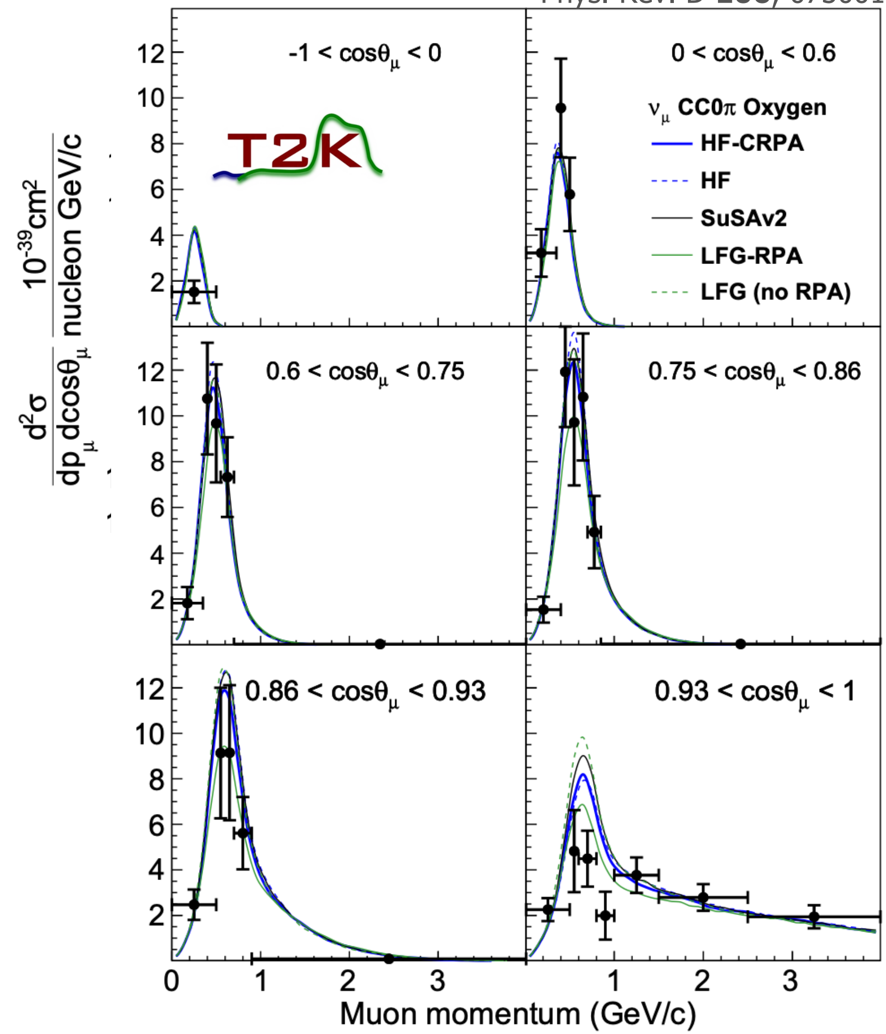
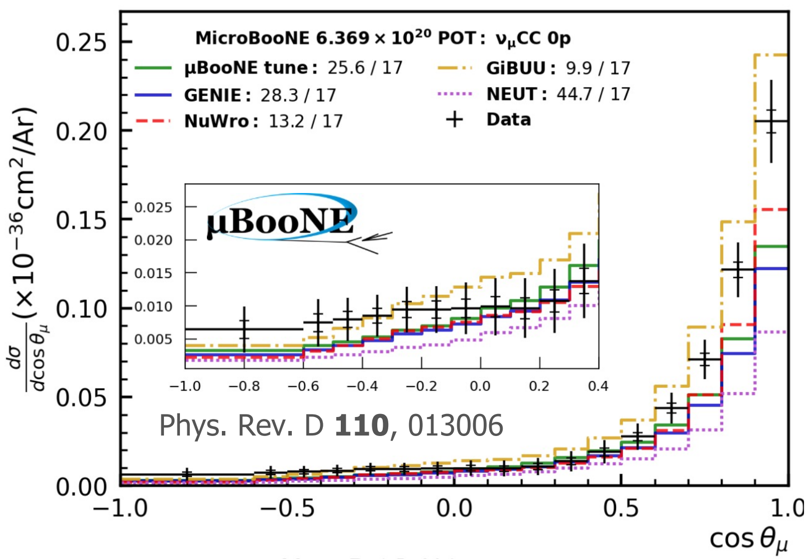


… but definitely sometimes!

And **not simultaneously at different energies or on different targets**



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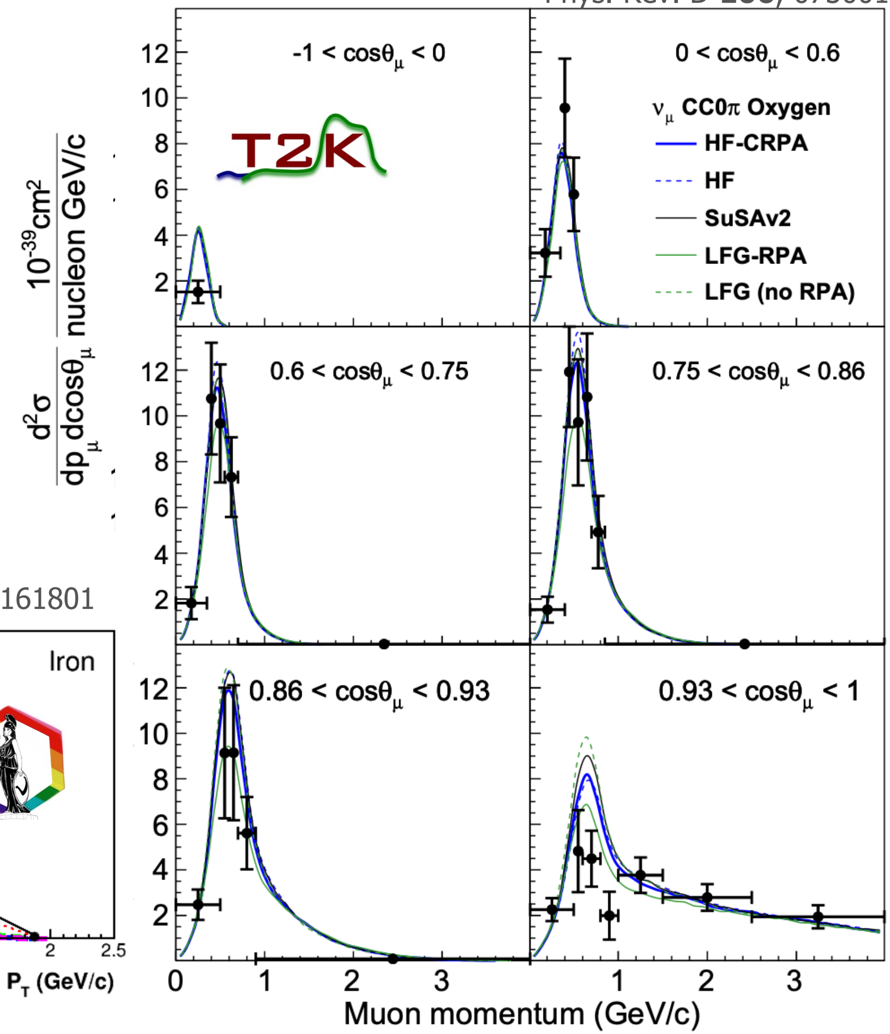
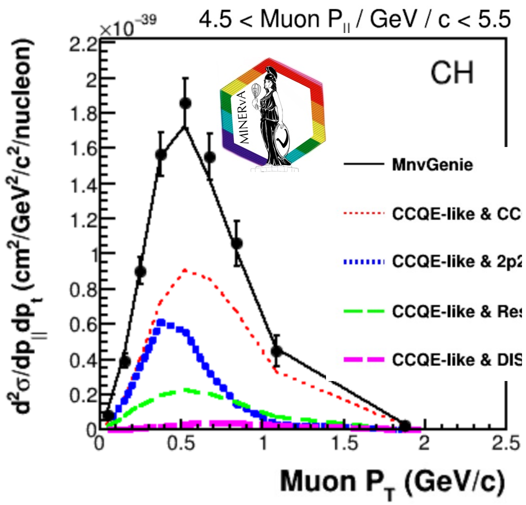
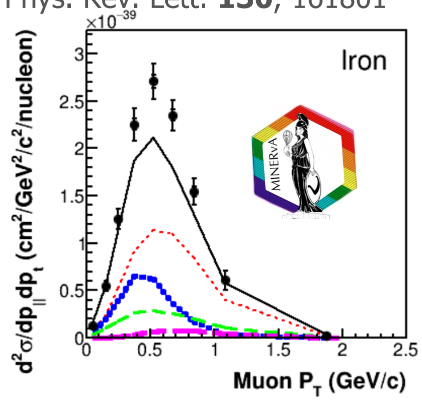




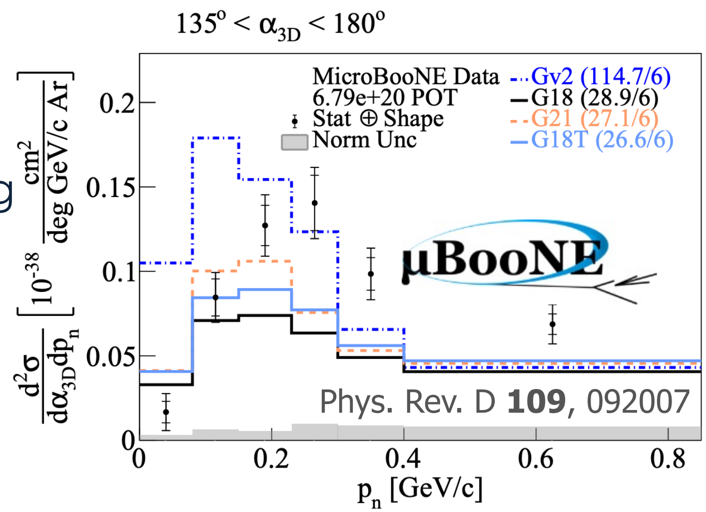
Phys. Rev. Lett. **130**, 161801

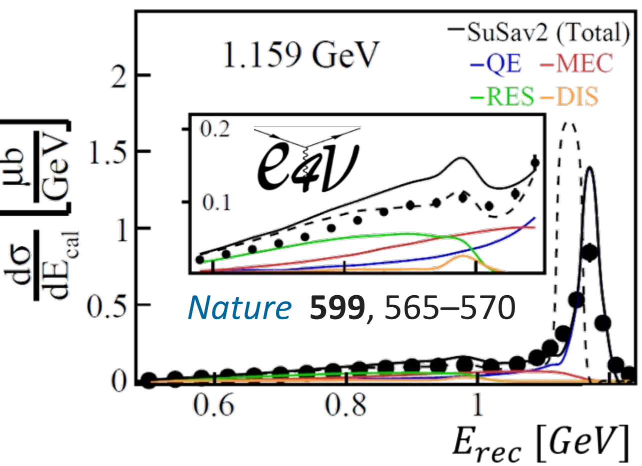


Hadron kinematics:😱

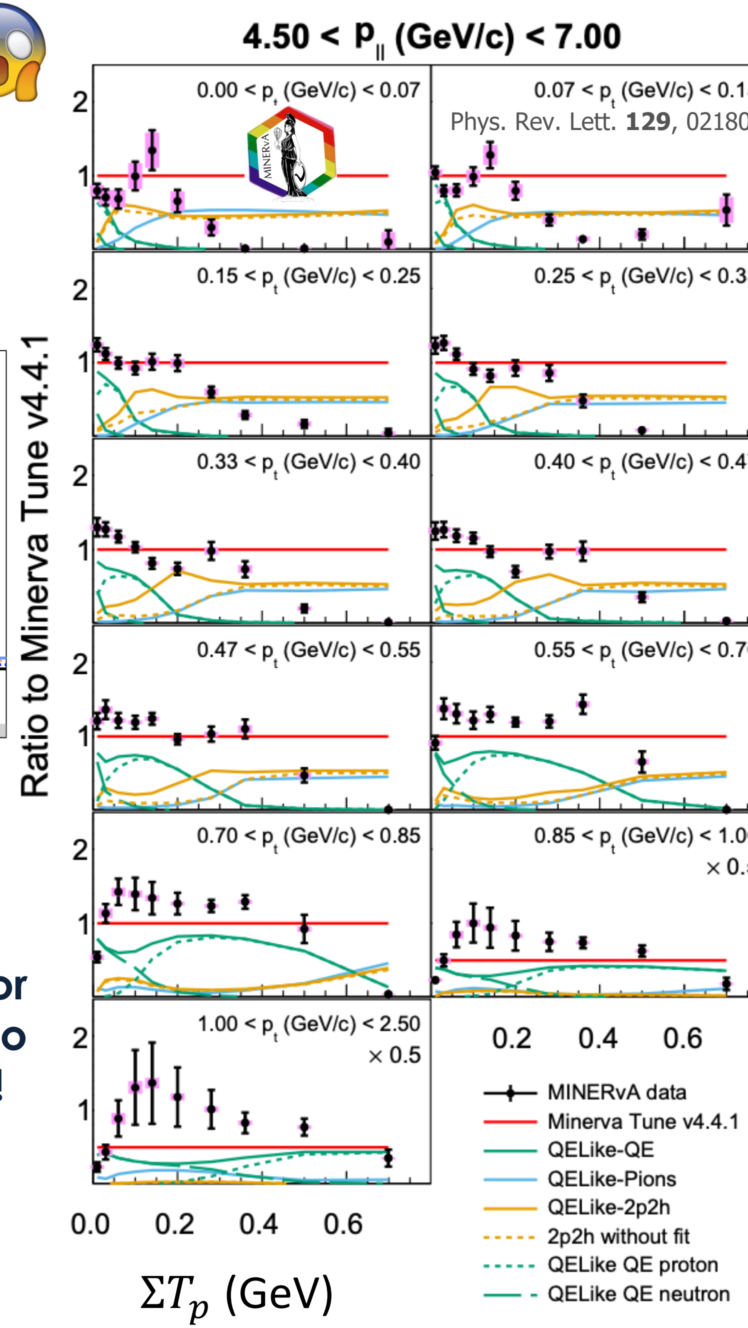
Hadron kinematics are consistently found to be poorly modelled

Poor agreement with measurements probing the **visible energy** we expect oscillation experiments to see





Crucial to understand for modelling DUNE neutrino energy reconstruction!



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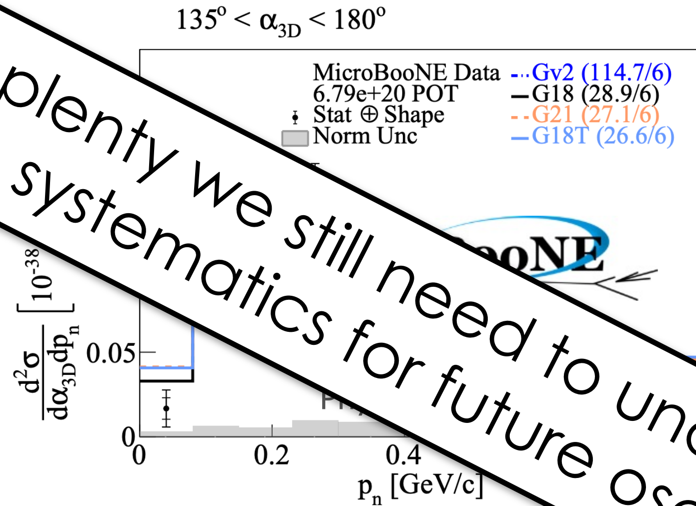
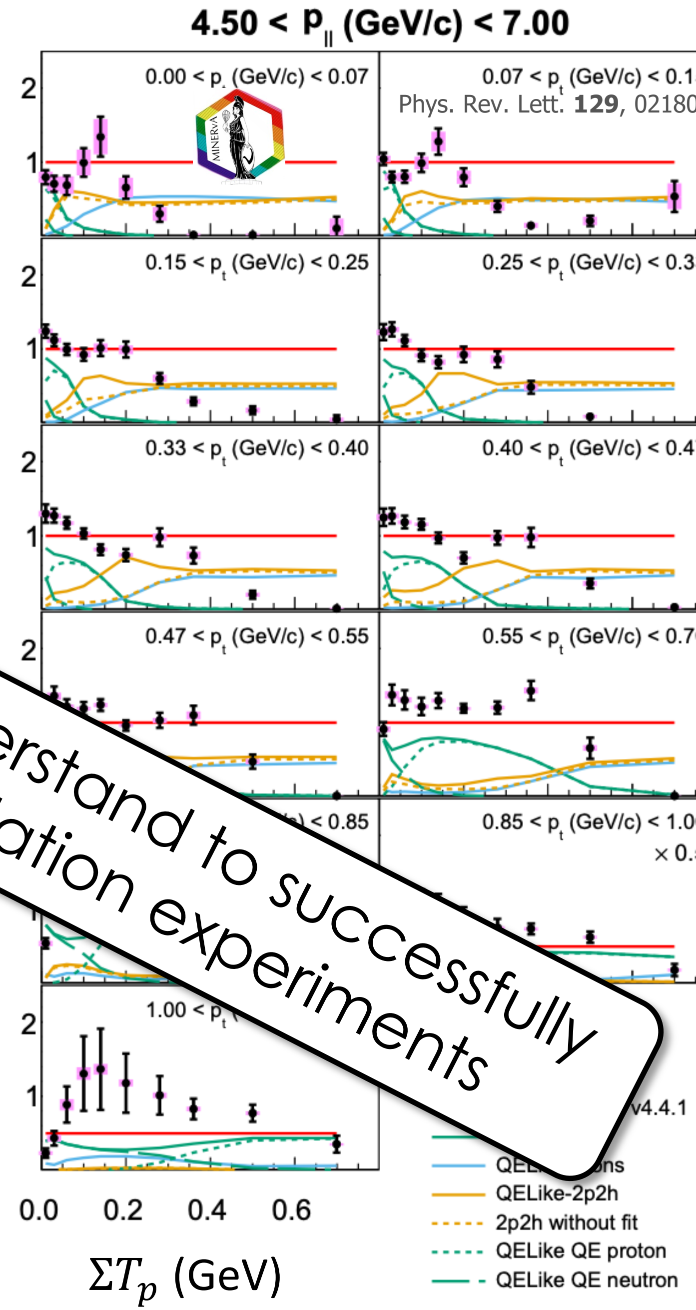
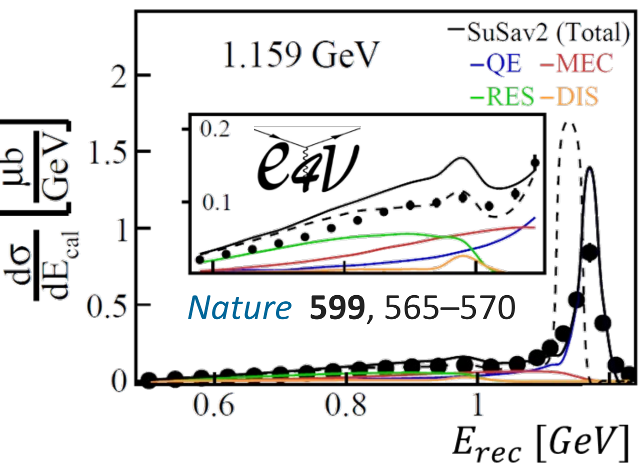


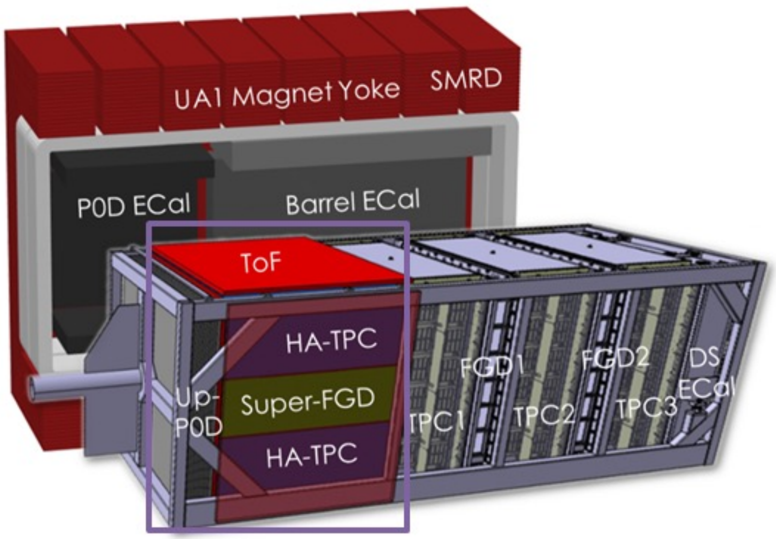


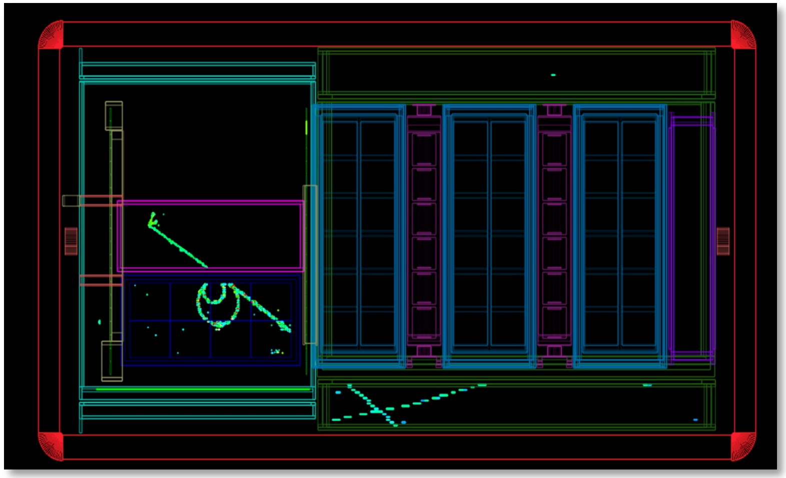


Crucial to understand for modelling DUNE neutrino energy reconstruction!

We have plenty we still need to understand to successfully mitigate systematics for future oscillation experiments

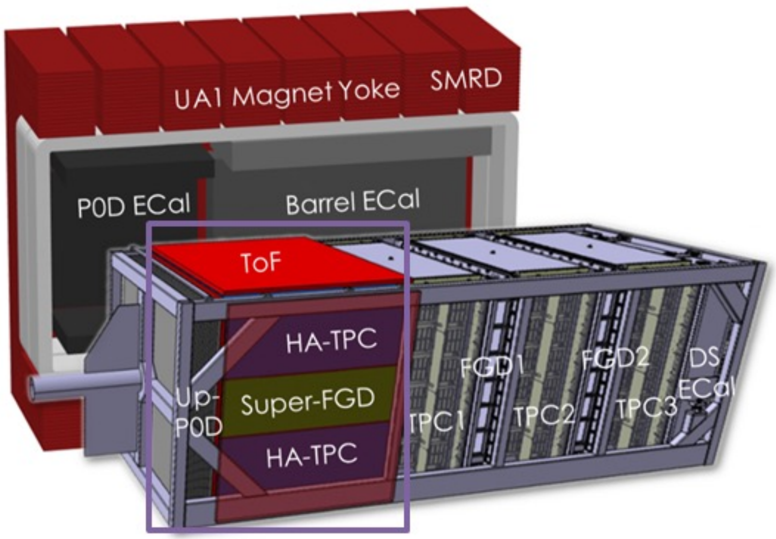
A bright future for cross sections

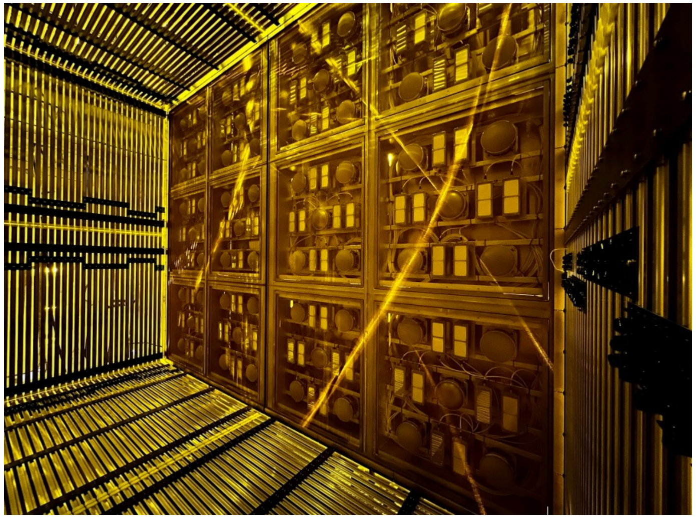


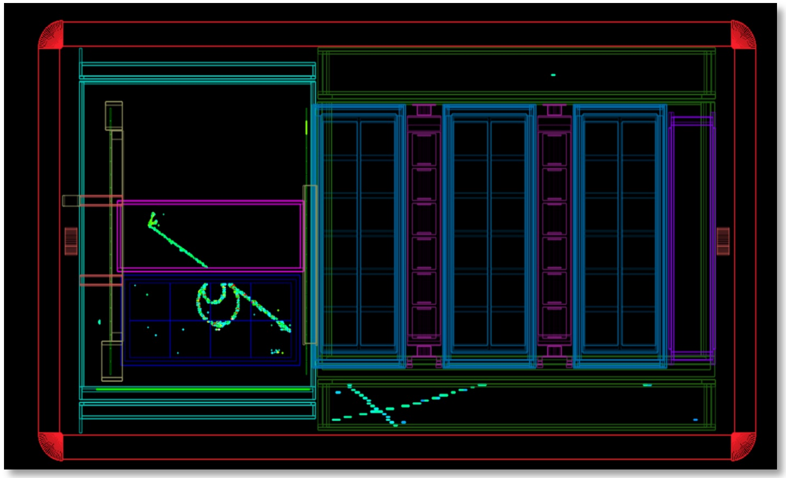


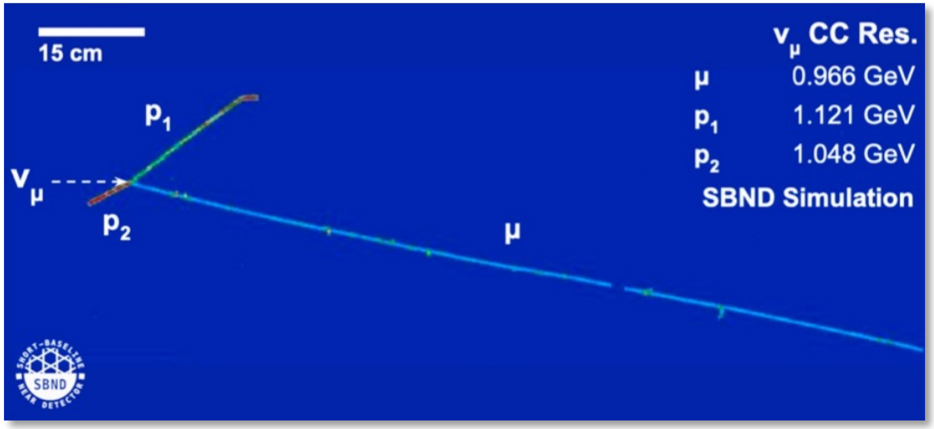
T2K ND280-Upgrade:
now taking data!

A bright future for cross sections





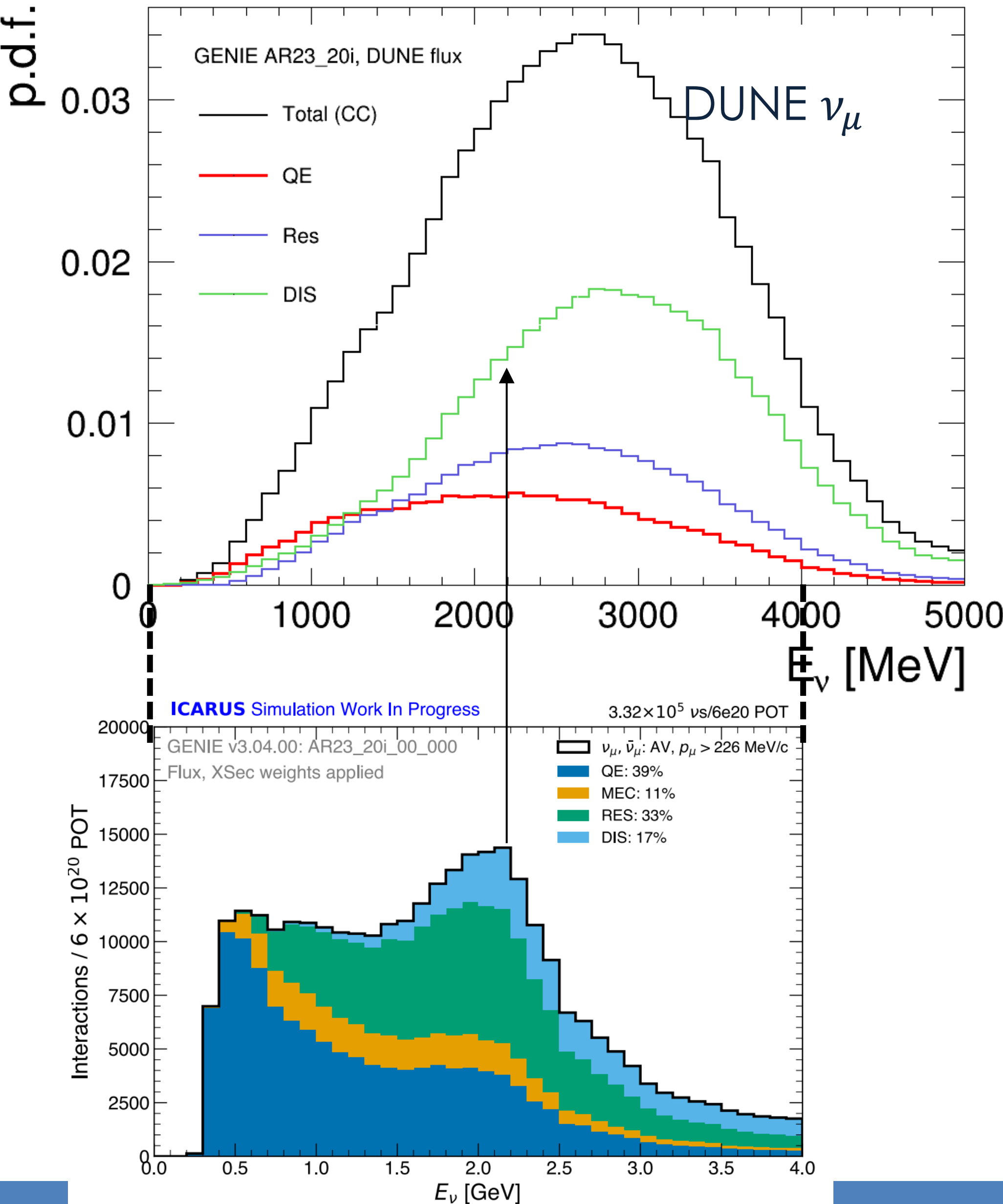


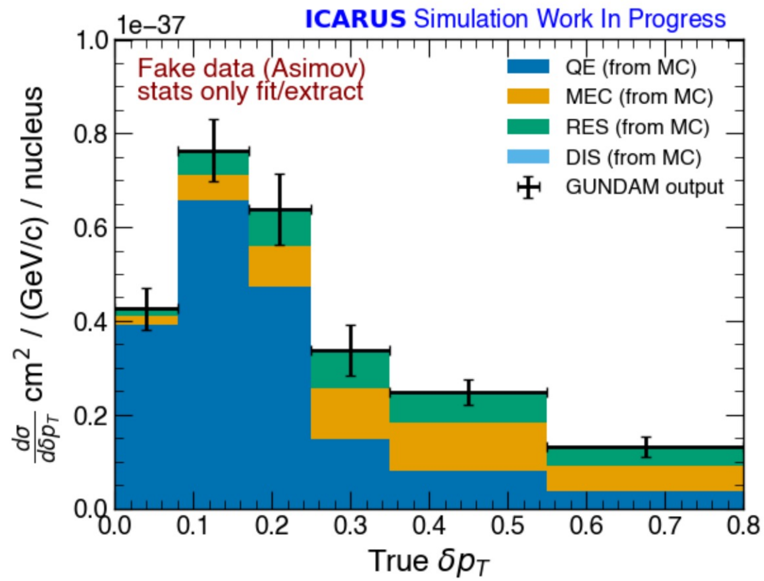


T2K ND280-Upgrade: now taking data!

SBND: now taking data!

A bright future for cross sections





ICARUS in NuMI: completing it's first measurements

New detectors, new capabilities

- Higher statistics
- Lower thresholds
- Better resolutions
- New accessible topologies
- Simultanious measurements at different E_ν (PRISM)

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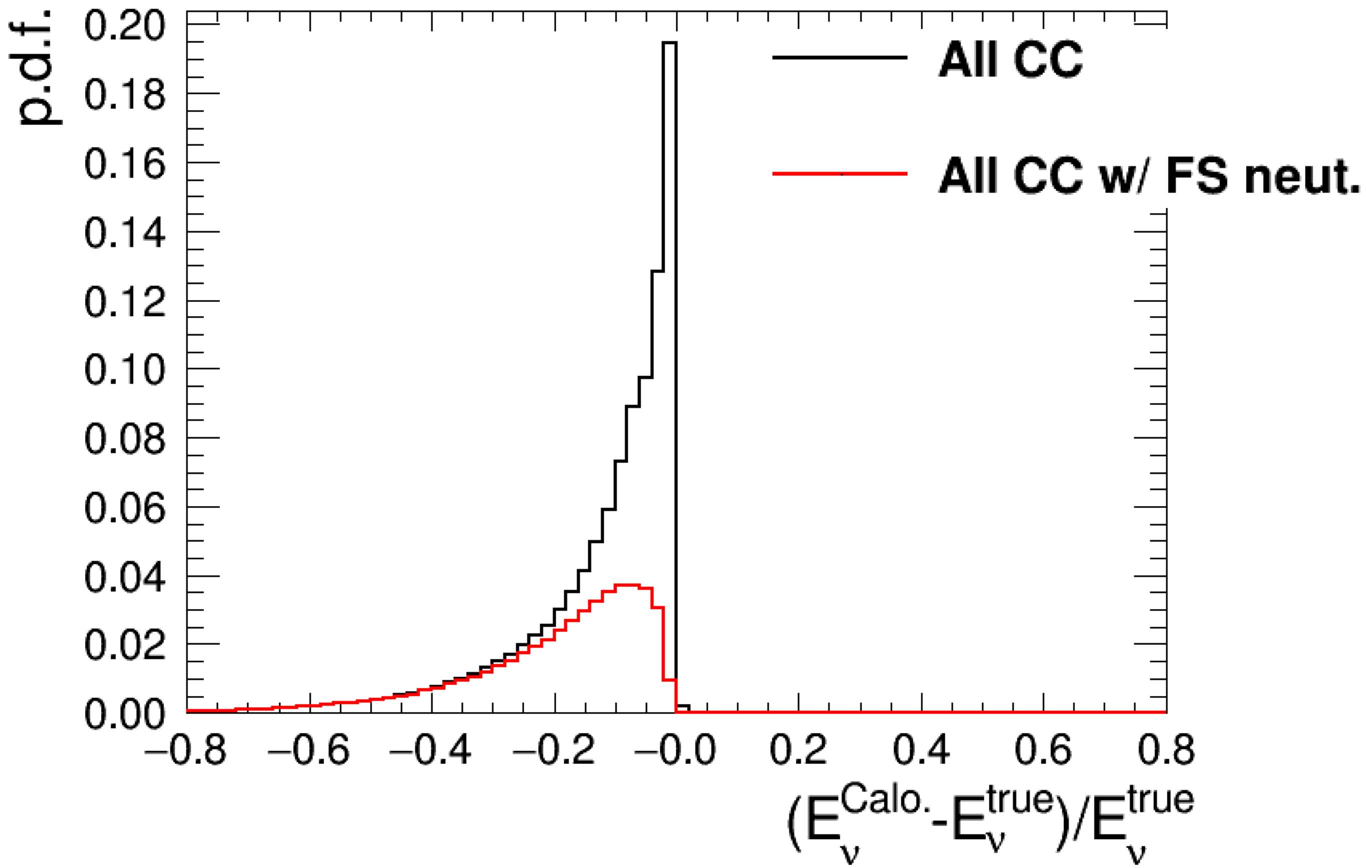
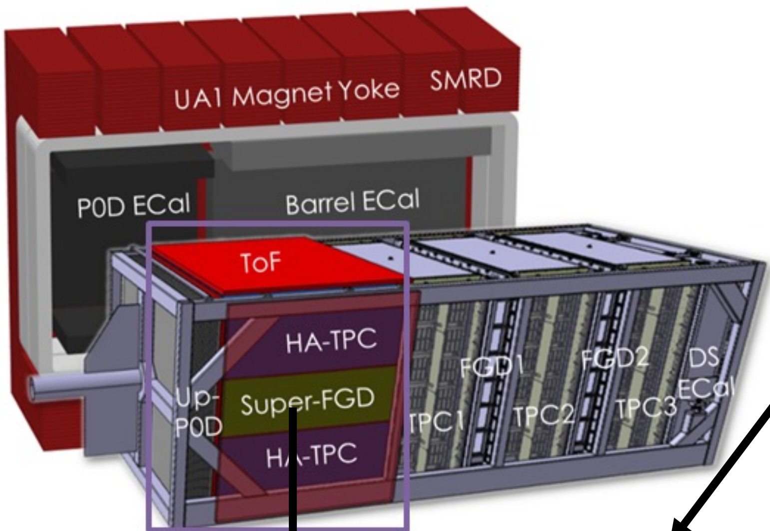
Neutrons neutrons neutrons



Neutrons are most of the energy we miss in calorimetric neutrino energy reconstruction.

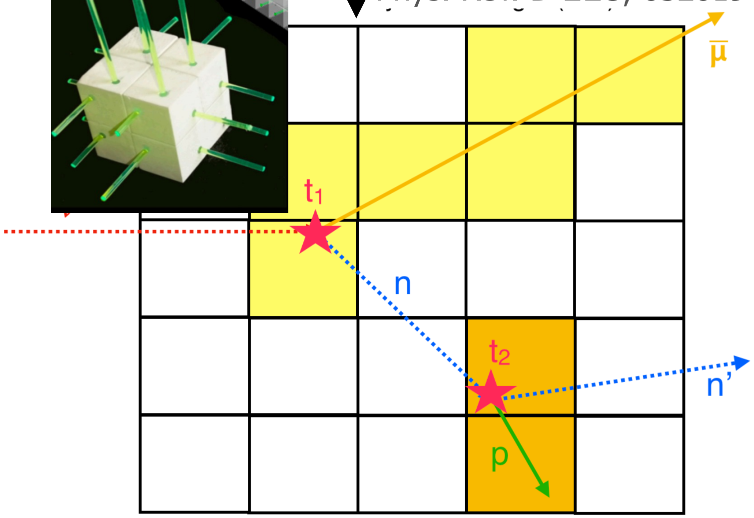
Wouldn't it be great if we could measure them …

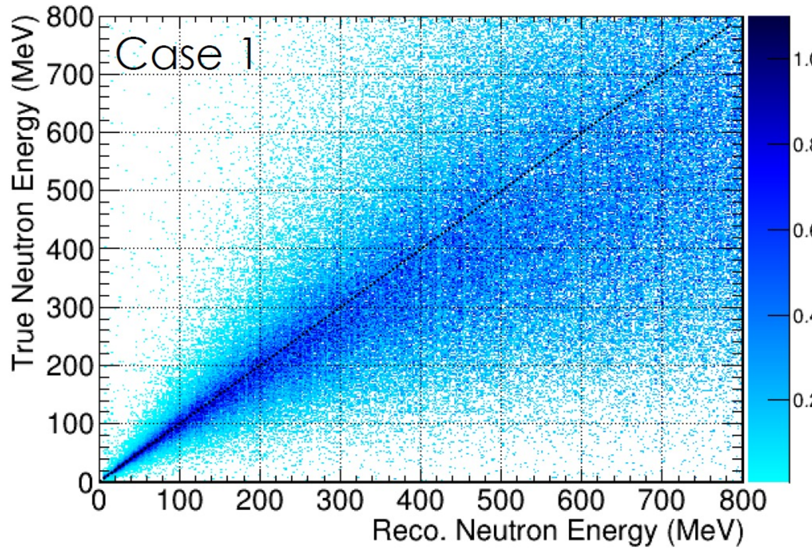
Neutrons neutrons neutrons



- Detect neutrons through their secondary interactions
- Measure their position and their time of arrival: determine neutron energy!
- Super-FGD position and timing resolution enables neutron energy measurements!

Phys. Rev. D **101**, 092003
Phys. Rev. D **110**, 032019





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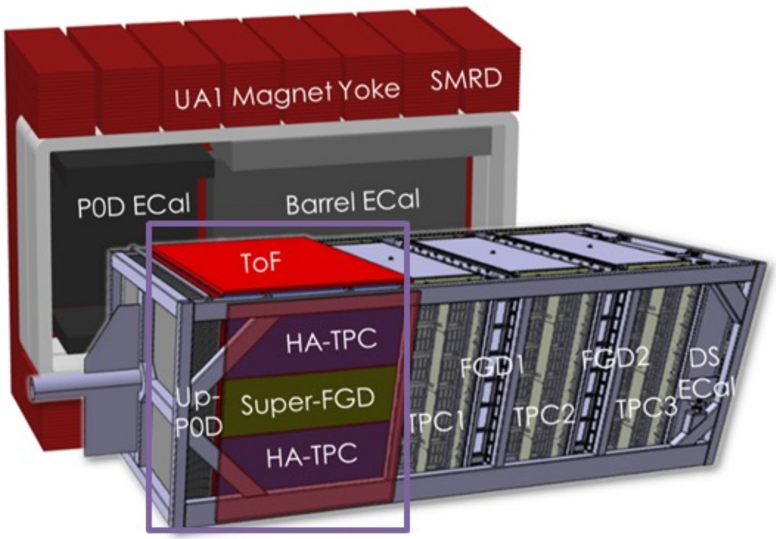

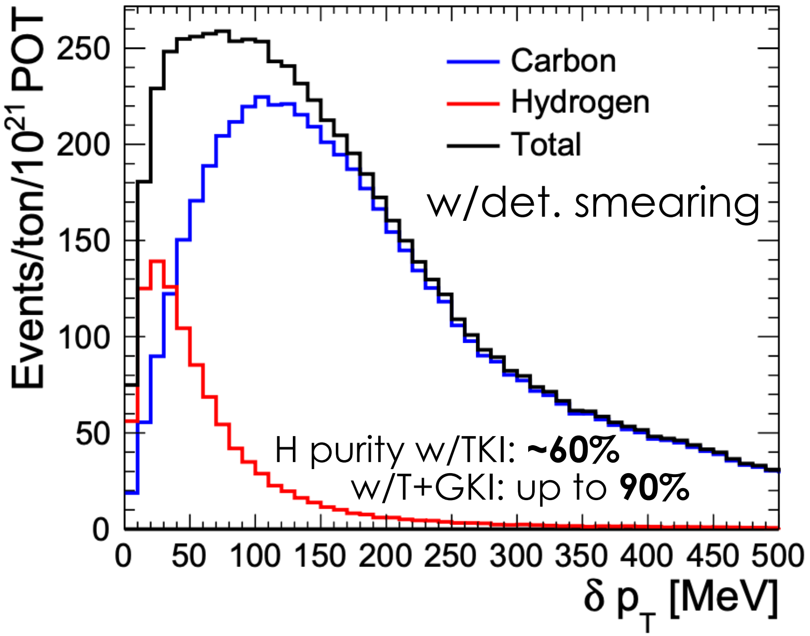

Phys. Rev. D **101**, 092003
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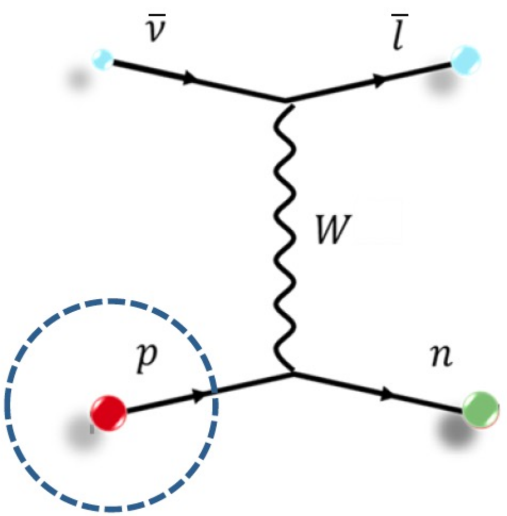
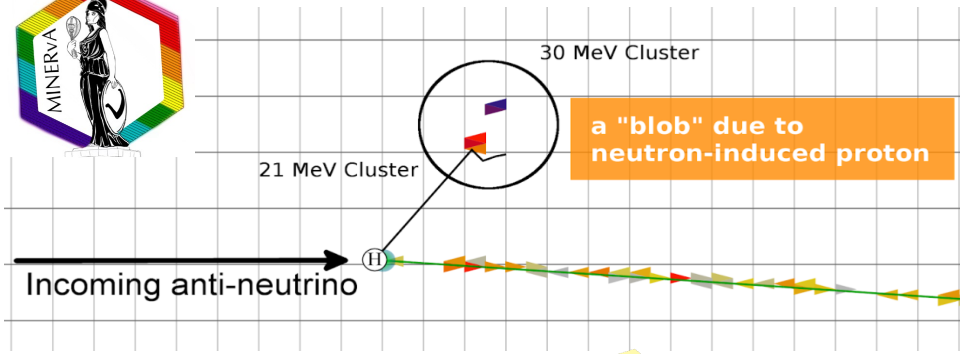
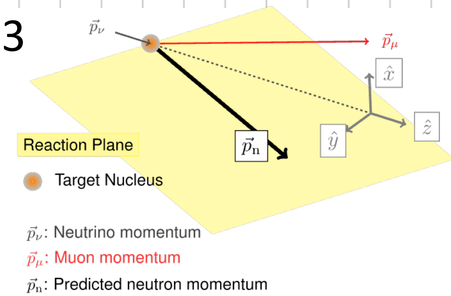


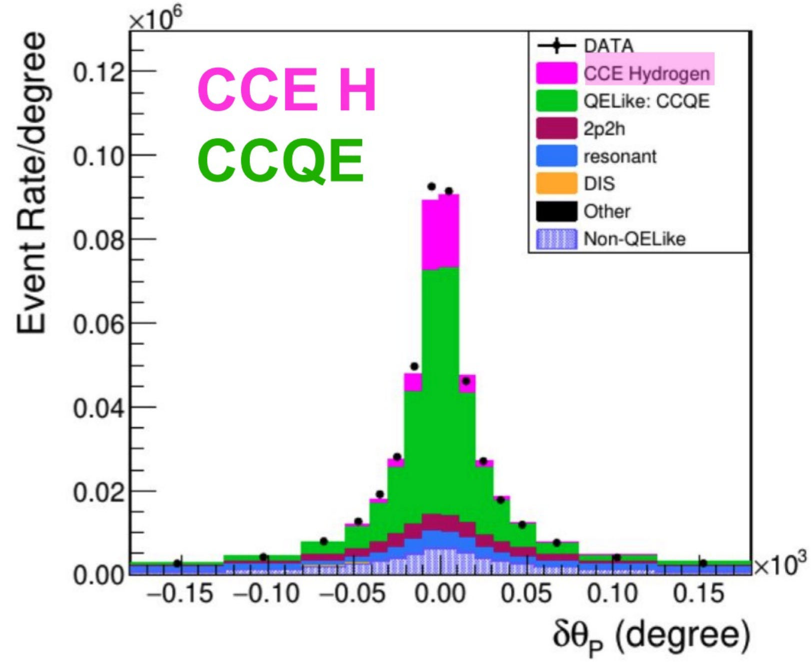
- Measurement of neutrons can allow a **kinematic separation of C and H** for antineutrino interactions on CH scintillator
  - No nuclear effects!
  - Golden sample for E_ν reconstruction?
  - Access to nucleon form factor physics!

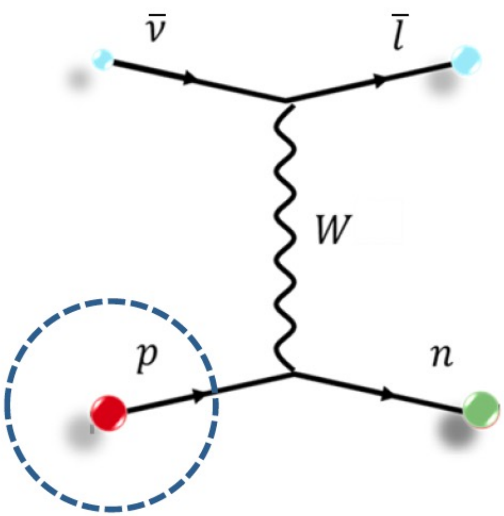
Neutrons neutrons neutrons



Nature, 614, 48-53







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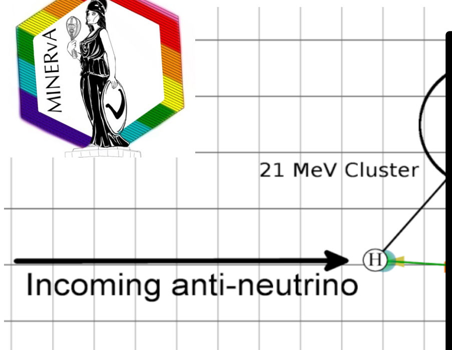
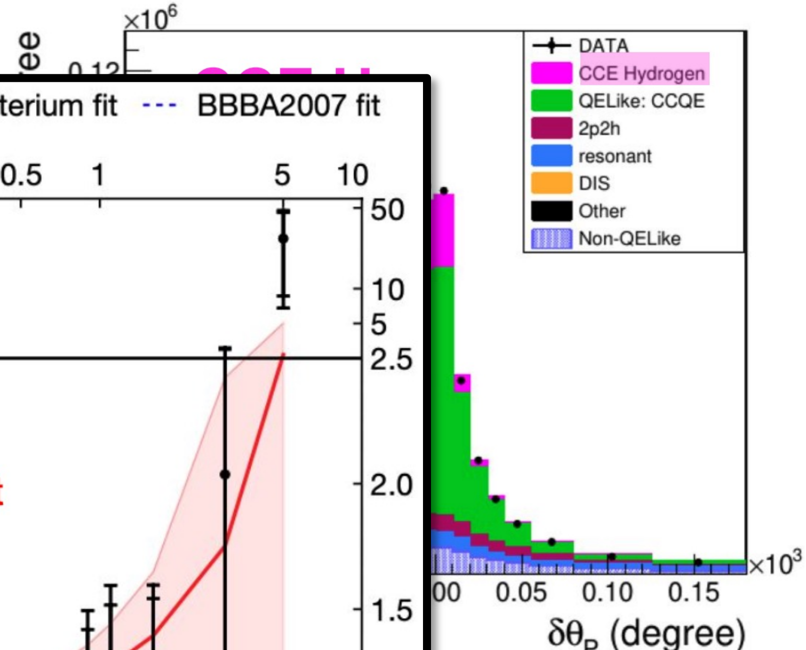
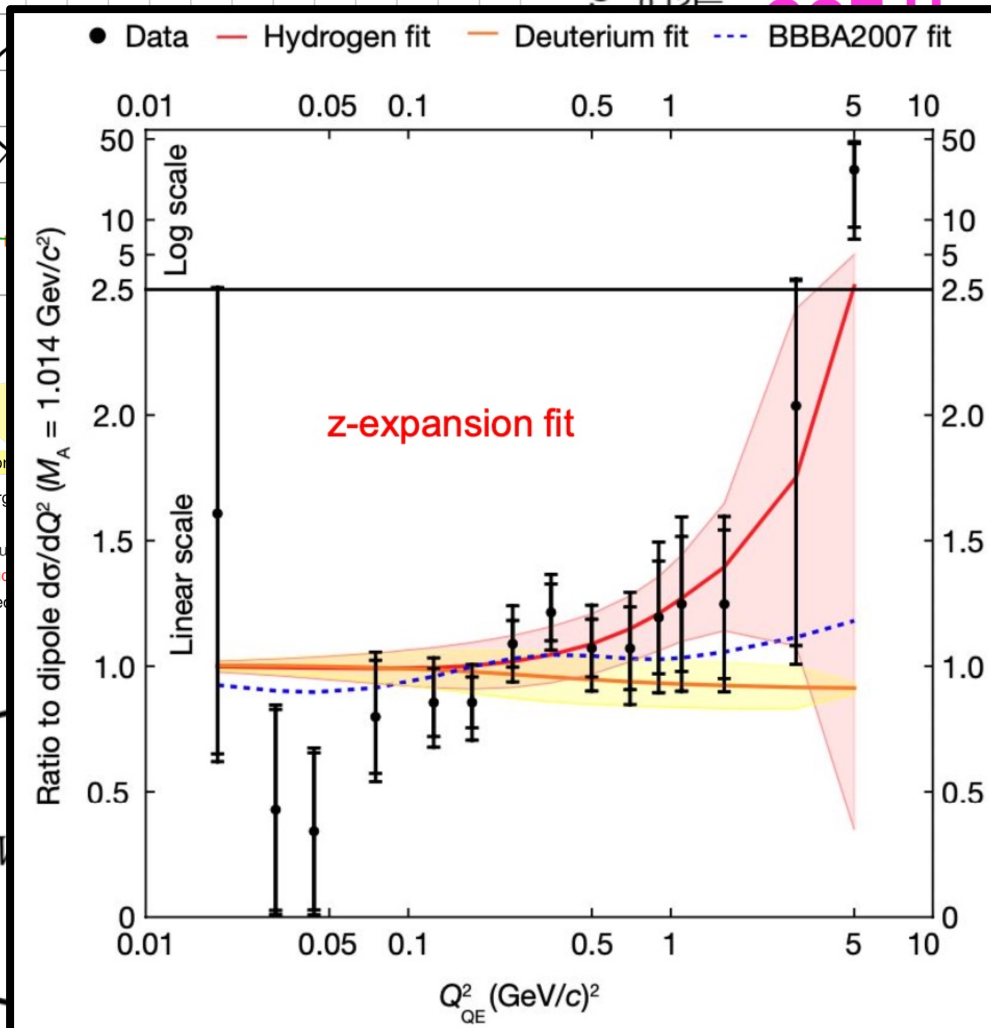
- MINERvA gave this a go!
  - No access to neutron momentum, but can use neutron direction

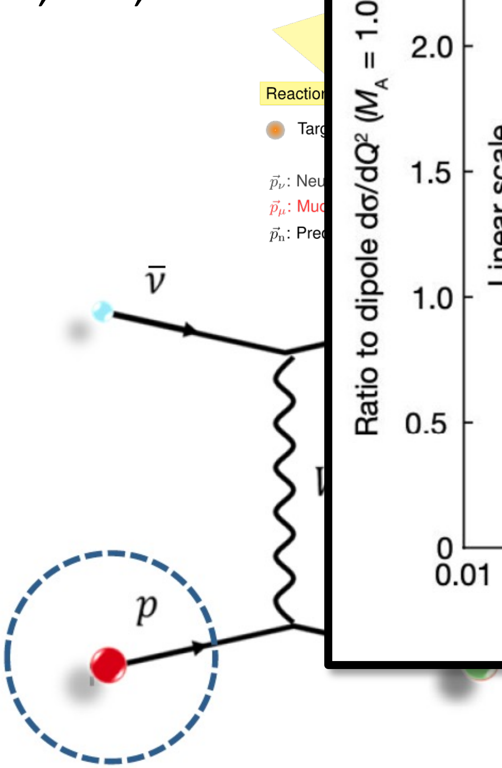
Neutrons neutrons neutrons



Nature, 614, 48-53







can allow a
and H for
n CH scintillator

reconstruction?
m factor physics!

- No access to neutron momentum, but can use neutron direction

Neutrons neutrons neutrons

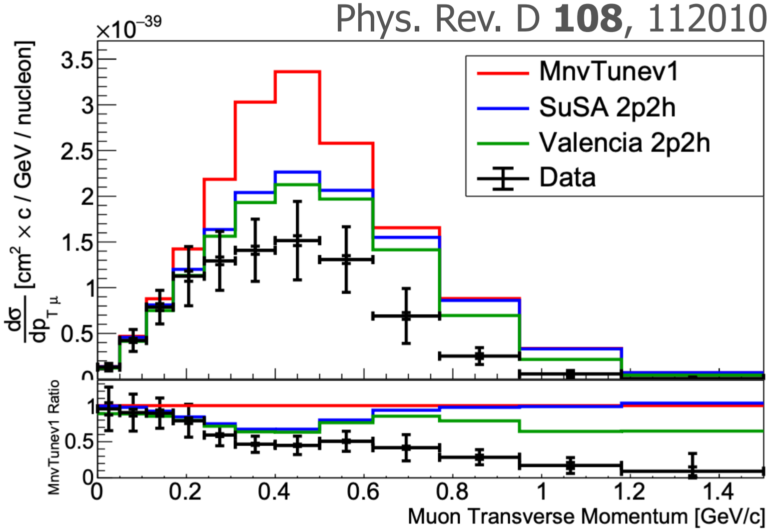
Plenty of interesting physics beyond hydrogen measurements

Example:

- Neutrons in neutrino CC0π → clean probe of FSI and 2p2h
- Multi-neutron production in anti-neutrino CC0π → clean probe of FSI and 2p2h

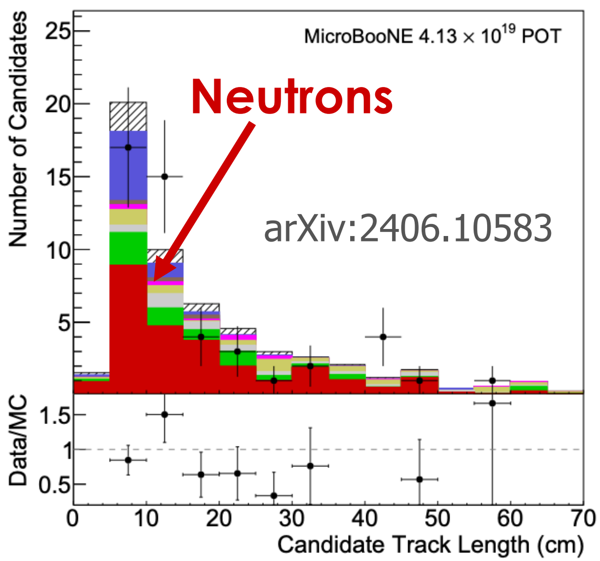
Multi-neutron production

Phys. Rev. D **108**, 112010



Neutron tagging in LAr

arXiv:2406.10583



New detectors, new capabilities

- Higher statistics
- Lower thresholds
- Better resolutions
- New accessible topologies
- Simultanious measurements at different E_{ν} (PRISM)

Here be dragons …

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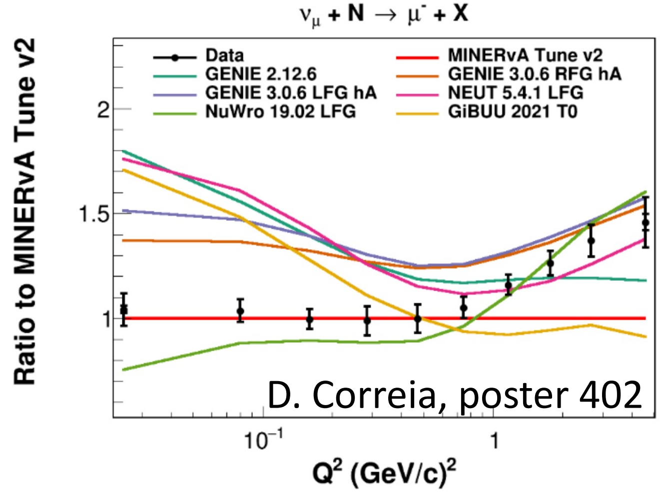
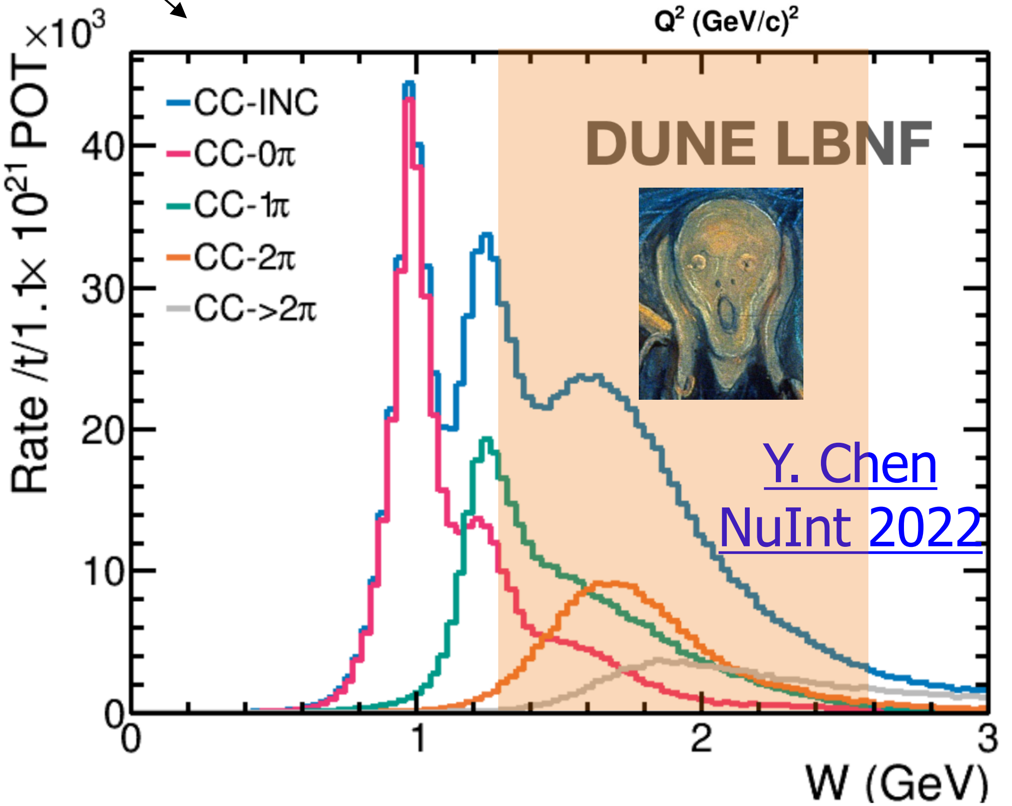
Shallow inelastic scattering

- SIS (low Q^2 DIS) is very challenging to model
  - Especially hadron multiplicities + energies
- Poor agreement with MINERvA's data
  - Especially for heavier nuclear targets
- Makes up ~30% of DUNE interactions





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  - Especially hadron multiplicities + energies
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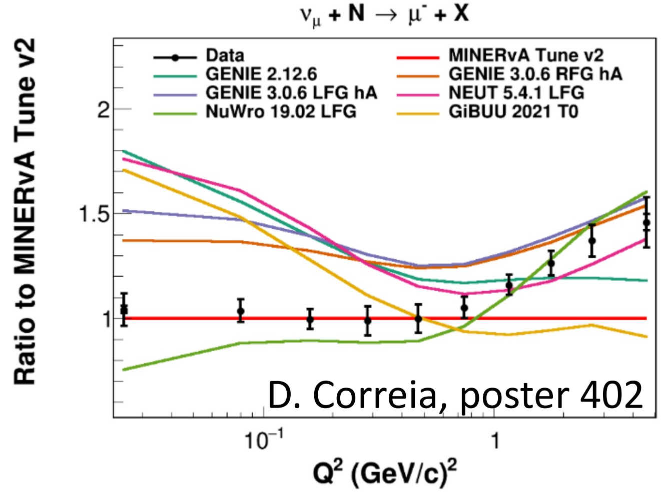
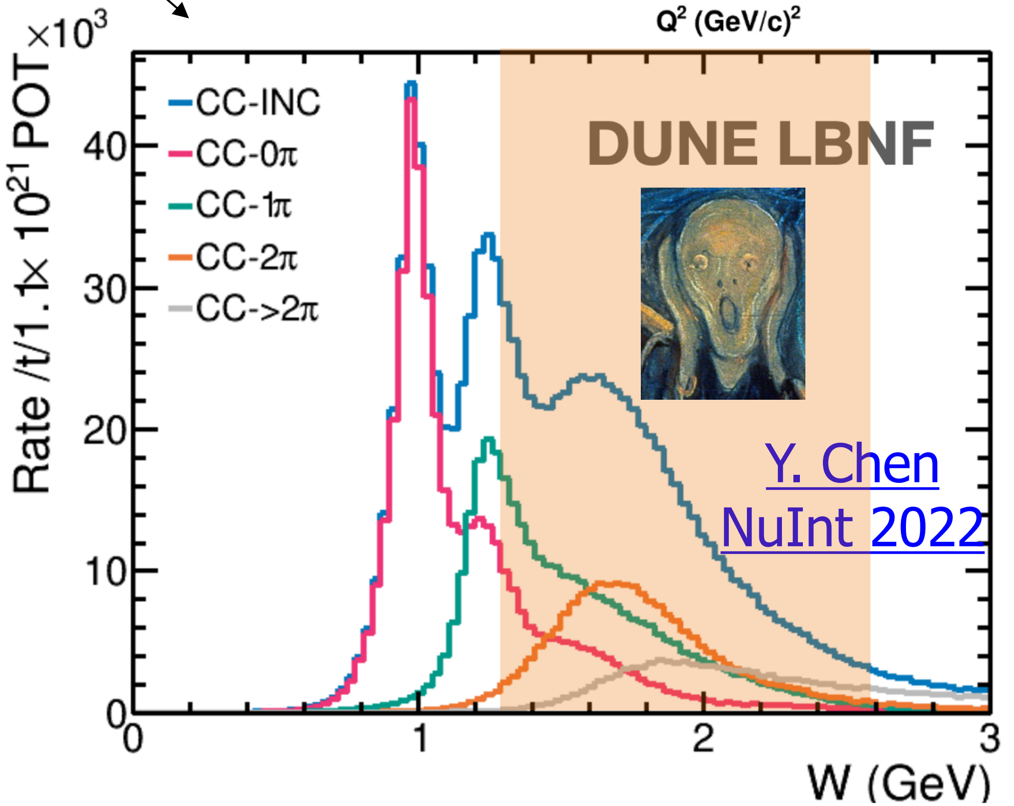
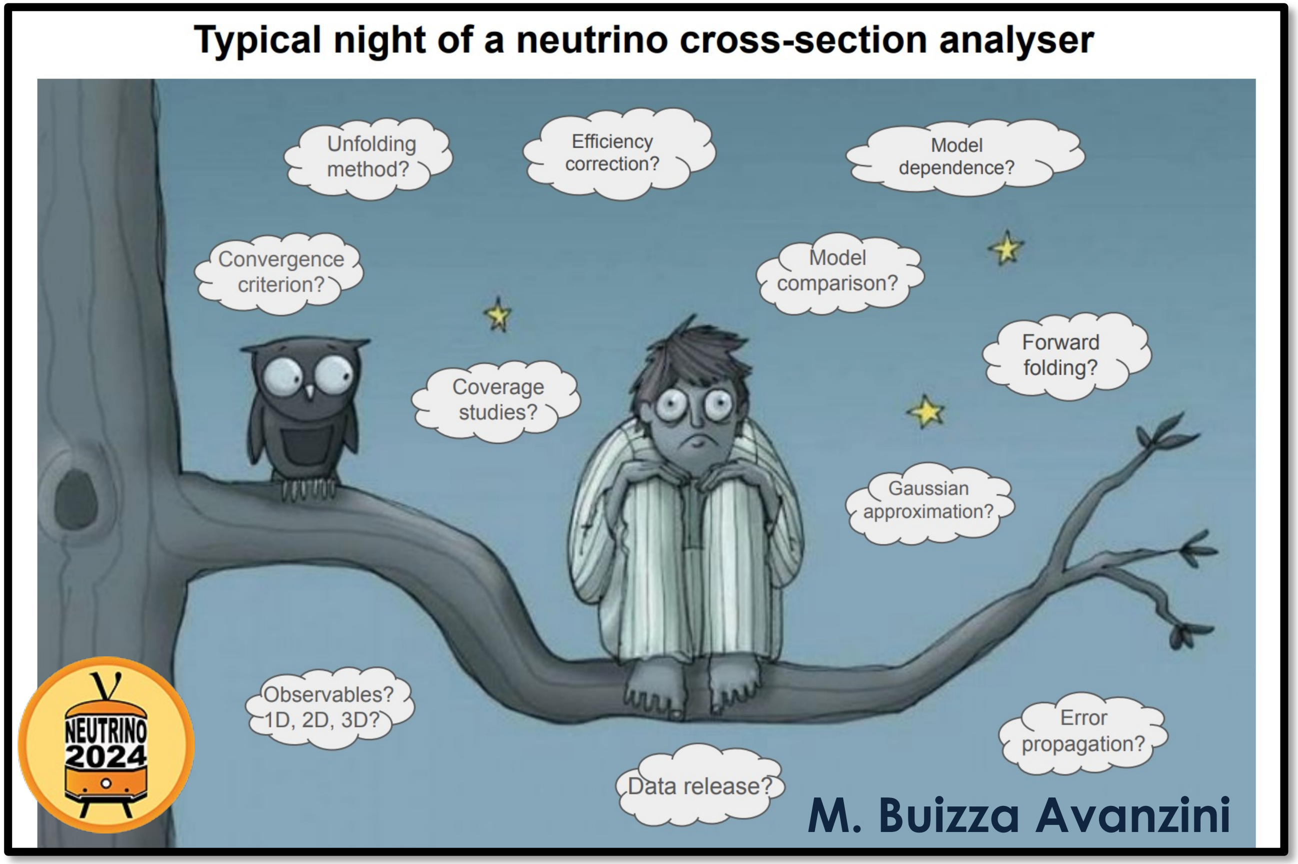
- Need to ground our models with more measurements
- But we expect very limited data on Argon before DUNE turns on!





Result longevity

- All cross-section measurements are model dependent
  - Sometimes in the unfolding
  - Usually in the efficiency correction
  - Always in the background subtraction



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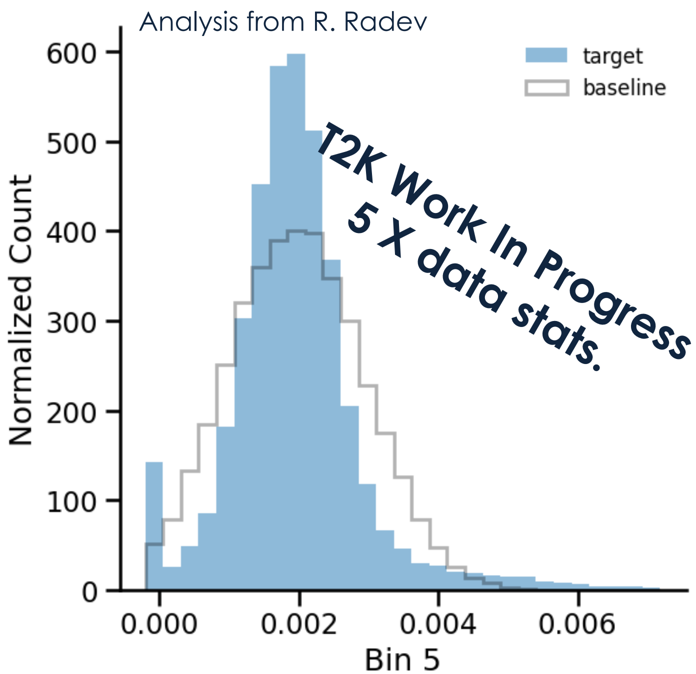

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- In the longer term:
  - Data preservation efforts (see MINERvA's work: arXiv:2009.04548)
  - Move towards more complete common-format data releases

E.g. in NUISANCE or hepdata

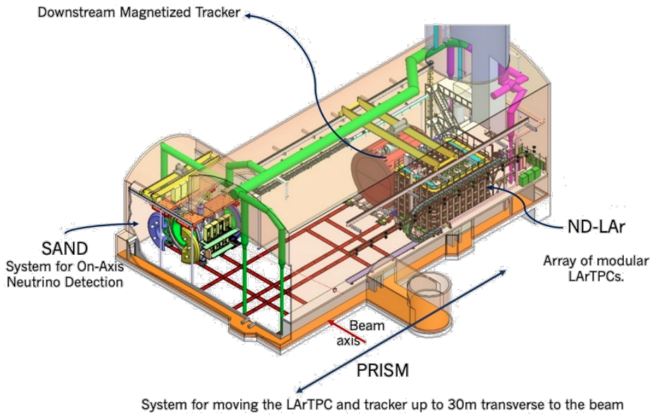
Summary

- A detailed understanding of neutrino-nucleus interactions is **crucial for current and future experiments** to realise their extraordinary goals
- Cross-section measurements are **an invaluable means to benchmark our models** or inspire new theory developments
- The latest results have allowed us to make **enormous progress** understanding neutrino interaction physics over the last 10 years, but **still have some way to go**
- The **upcoming generation** of experiments (just started data collection) **open the door to whole new types of measurements**
- How we deal with the **SIS region** for DUNE and **ensure the longevity of our measurements** remains a challenge
- Expect plenty of **exciting new results** and a continued exponential growth of the field in the run up to DUNE & Hyper-K.

Backups

Path to Precision Measurements

Improved near detector capabilities



Engagement with the nuclear theory community

GiBUU

Genie
UNIVERSAL NEUTRINO GENERATOR & GLOBAL FIT

NuWro
Wroclaw Neutrino Event Generator

Dedicated lepton-nucleus cross-section measurement programs

SBN Program

MINERvA

e4v

Three things we need to model

(a non exhaustive list)

1. The energy dependence of neutrino cross sections
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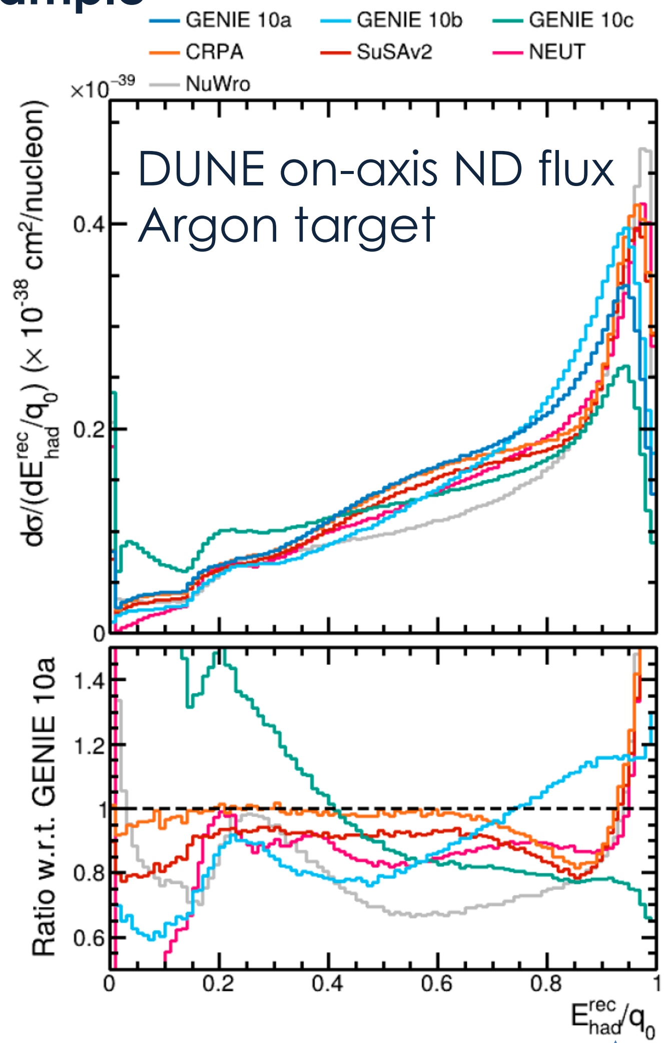
2. The smearing of our neutrino energy reconstruction
   - *So we can infer the shape of the oscillated spectrum*

3. Differences in the cross section for ν_e/ν_μ (and $\nu/\bar{\nu}$)
   - *So we can use ν_e appearance to probe CP-violation*

How generator development helps

Example



Fraction of energy transferred to the hadronic system that's expected to be visible

How generator development helps

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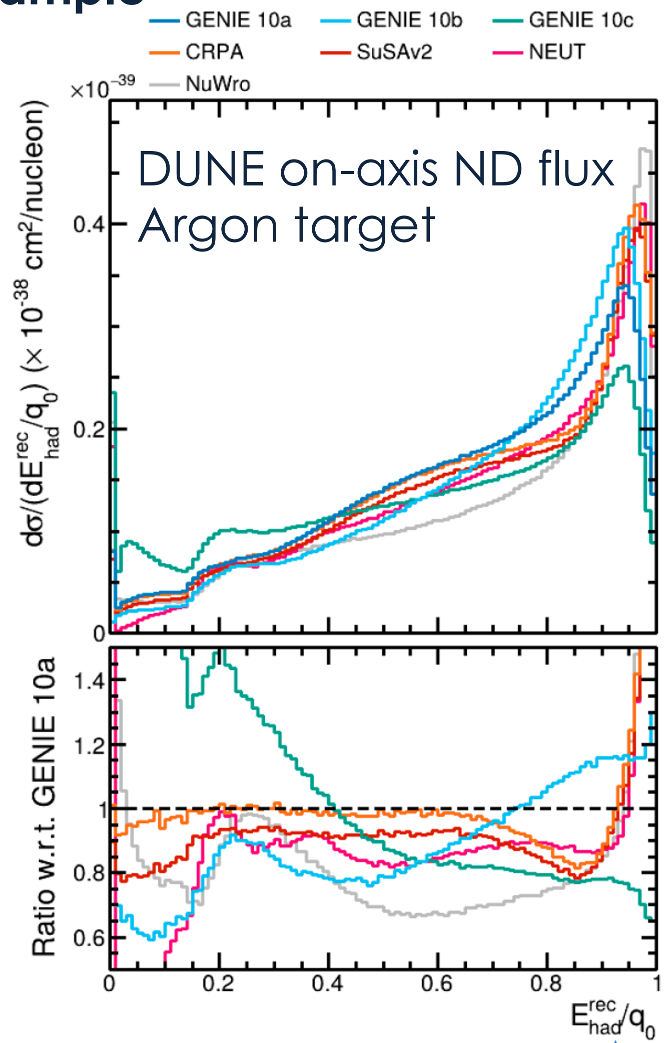
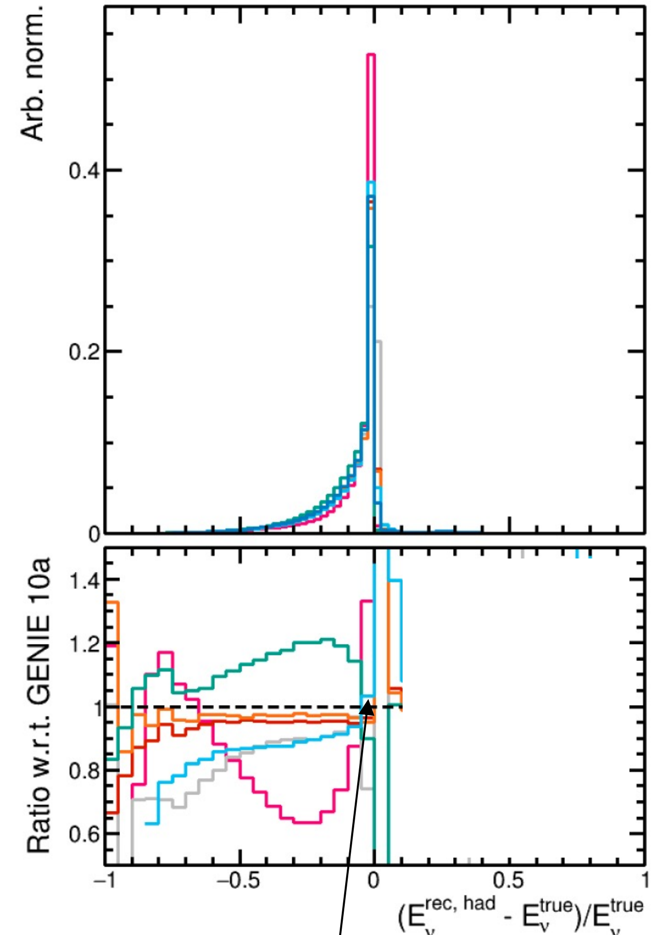


Fraction of energy transferred to the hadronic system that's expected to be visible

Thanks to having a variety of models in generators, we know about the potential differences:

- Can use this to bracket uncertainties!



Models are 50% different in predicting the fraction of interactions where we expect to get the neutrino energy within 10% of its true value

Digging deeper w/ MINERvA

- Q. Is disagreement in poorly modelled regions of lepton kinematics at:
  - Low energy transfer (~QE like)?
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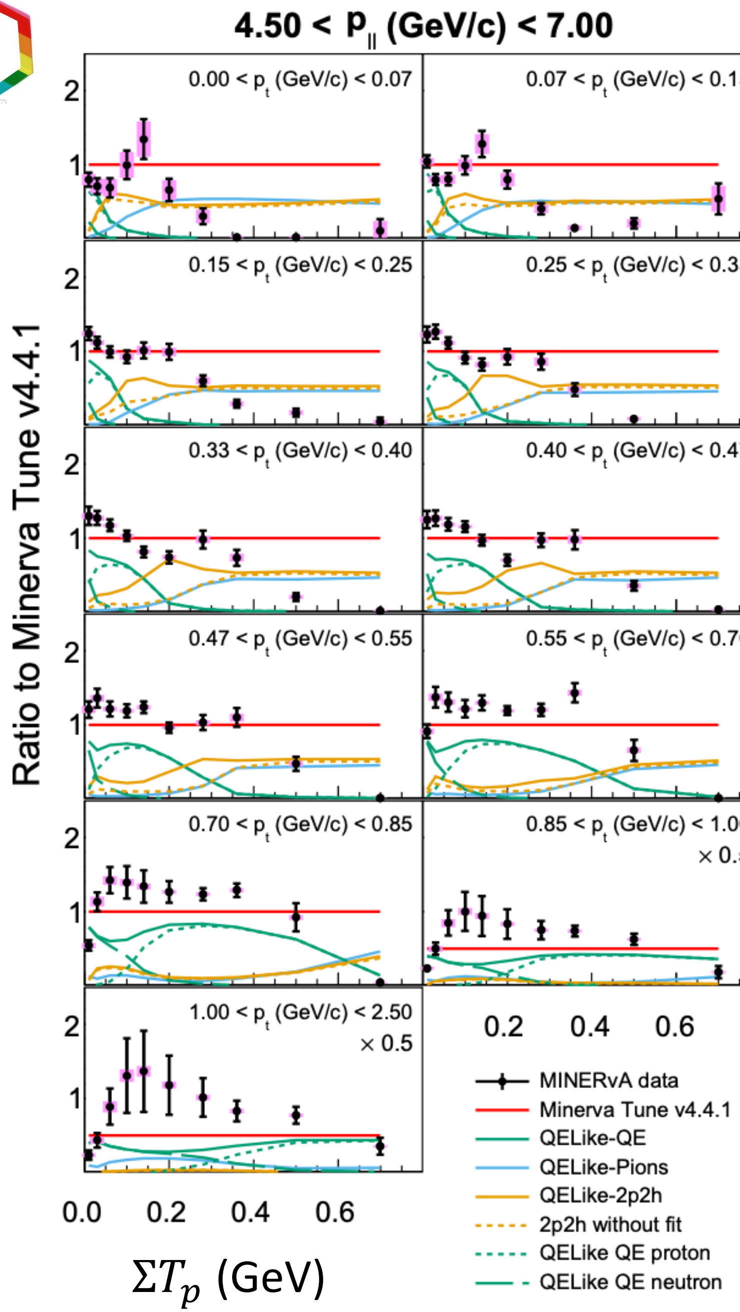

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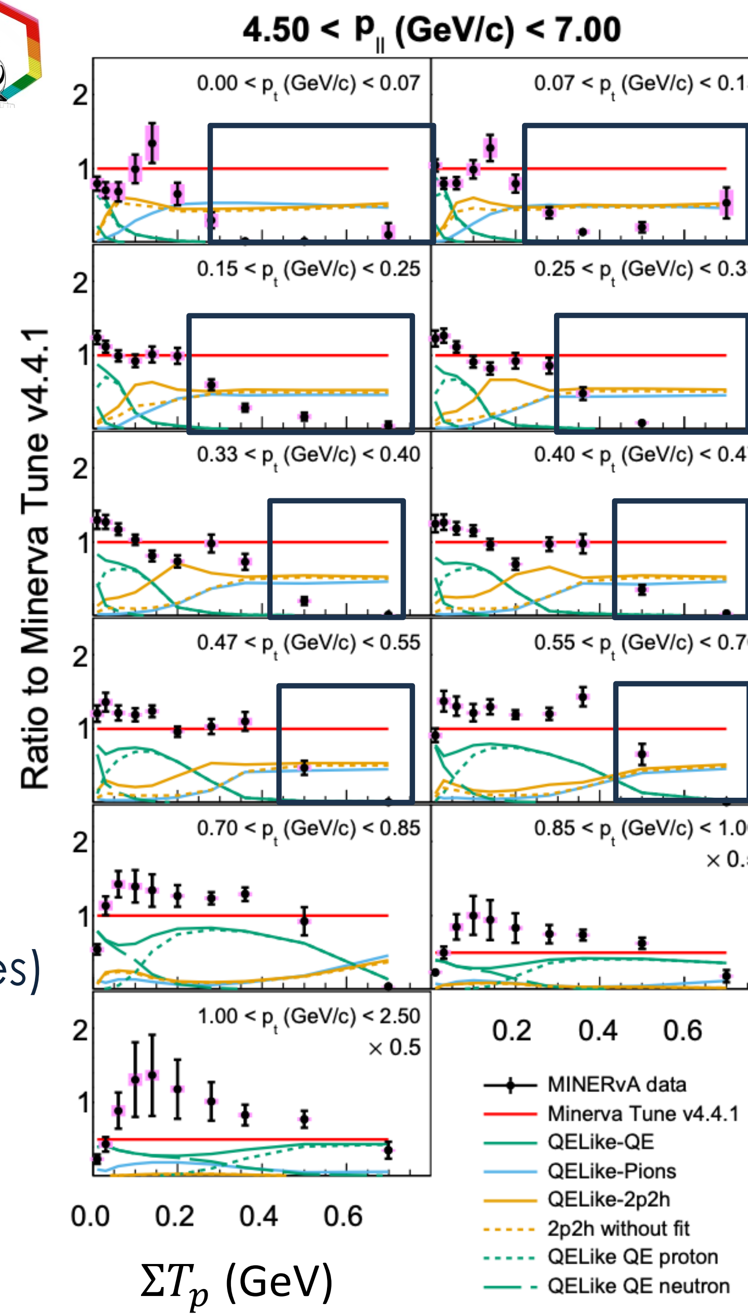

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- A. a bit of both …
  - Clear overestimation of nonQE (especially at forward angles)
  - But also disagreement in QE region (sometimes in the opposite direction)
    - Issues with FSI modelling?