Overview of neutrino cross section measurements

(since last Neutrino conference & at long-baseline energy range)

Margherita Buizza Avanzini

with a big thanks to several colleagues: S. Dolan, L. Pickering, D. Cherdack, D. Hadley, D. Harris, D. Ruterbories, R. Gran, K. McFarland, A. Papadopoulou, K. Duffy, M. Wetstein,...

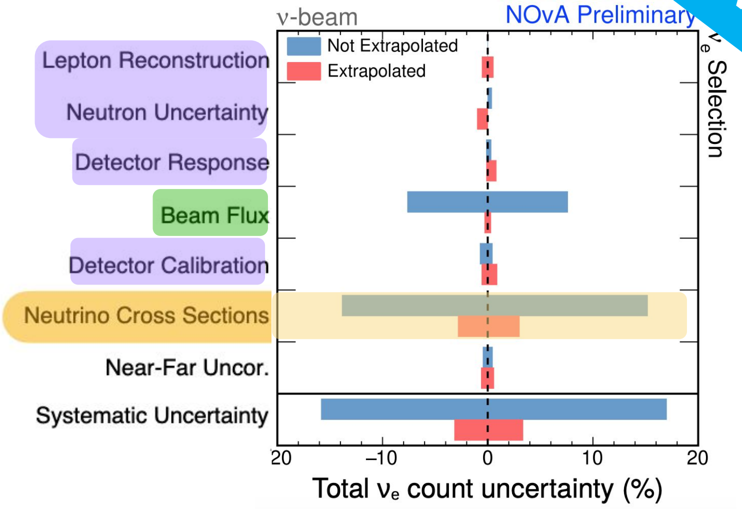
Why neutrino cross sections matter?

T2K

NOvA

This conference

Error source	ν_e appearance
Flux	2.8
ν cross section (ND tuned)	3.8
ν cross section untunable	2.9
SK detector	2.7
Total	4.9



J. Wolcott @Neutrino2024

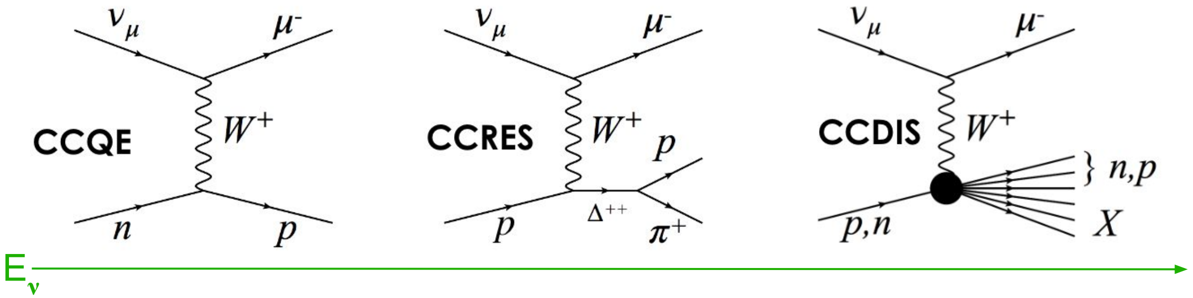
Neutrino interaction uncertainties are the ~ dominant source of systematics in current long-baseline experiments

Today not the major problem, we have ~100 ν_e appearance events... but this will become a problem soon (Hyper-Kamiokande, DUNE)

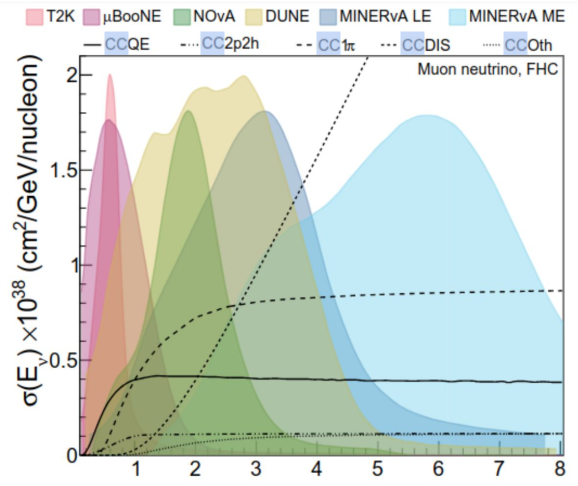
$$\frac{N^{far}_{events}(\vec{x})}{N^{near}_{events}(\vec{x})} = \frac{\sigma(E_\nu,\vec{x}) \otimes \Phi^{far}(E_\nu) \otimes D^{far}(\vec{x}) \otimes P_{osc}(E_\nu)}{\sigma(E_\nu,\vec{x}) \otimes \Phi^{near}(E_\nu) \otimes D^{near}(\vec{x})}$$

ν interaction predictions and uncertainties

Our current detectors are especially sensitive to Charged Current interactions. Depending on the incoming flux (E_ν), different interactions are the most probable:



Neutrino energy reconstruction methods rely on the final state particle kinematics (and on the detector technology).



from C. Wret

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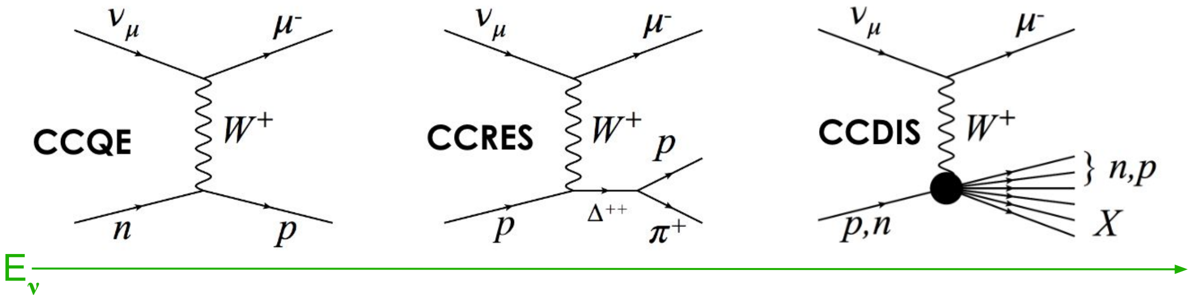

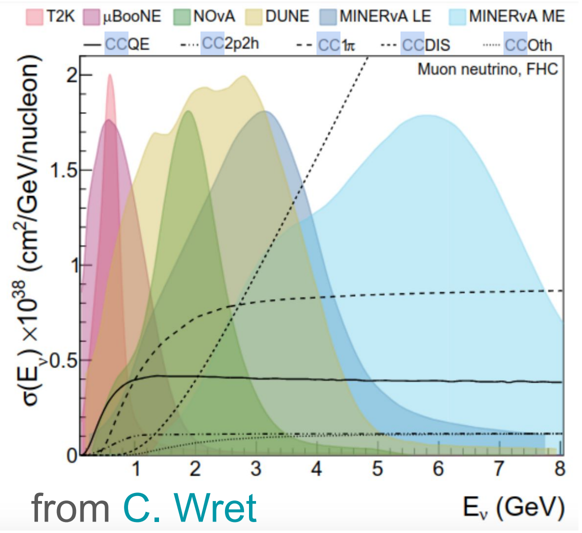

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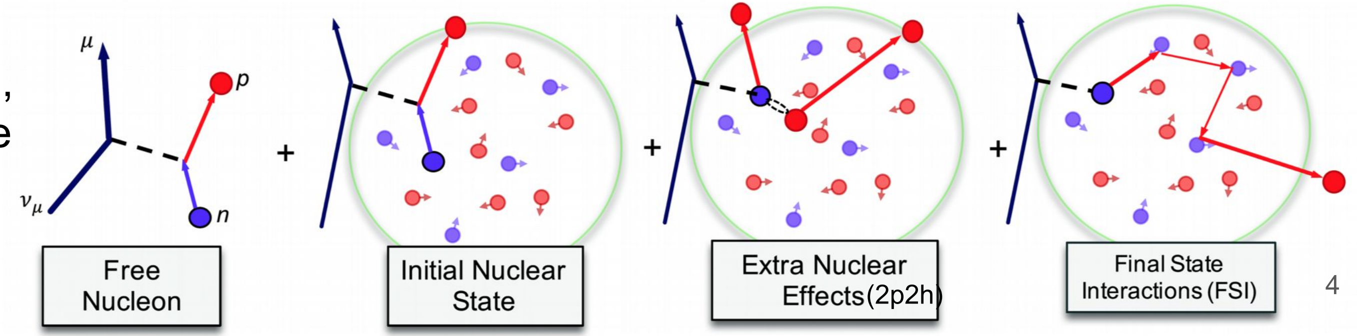
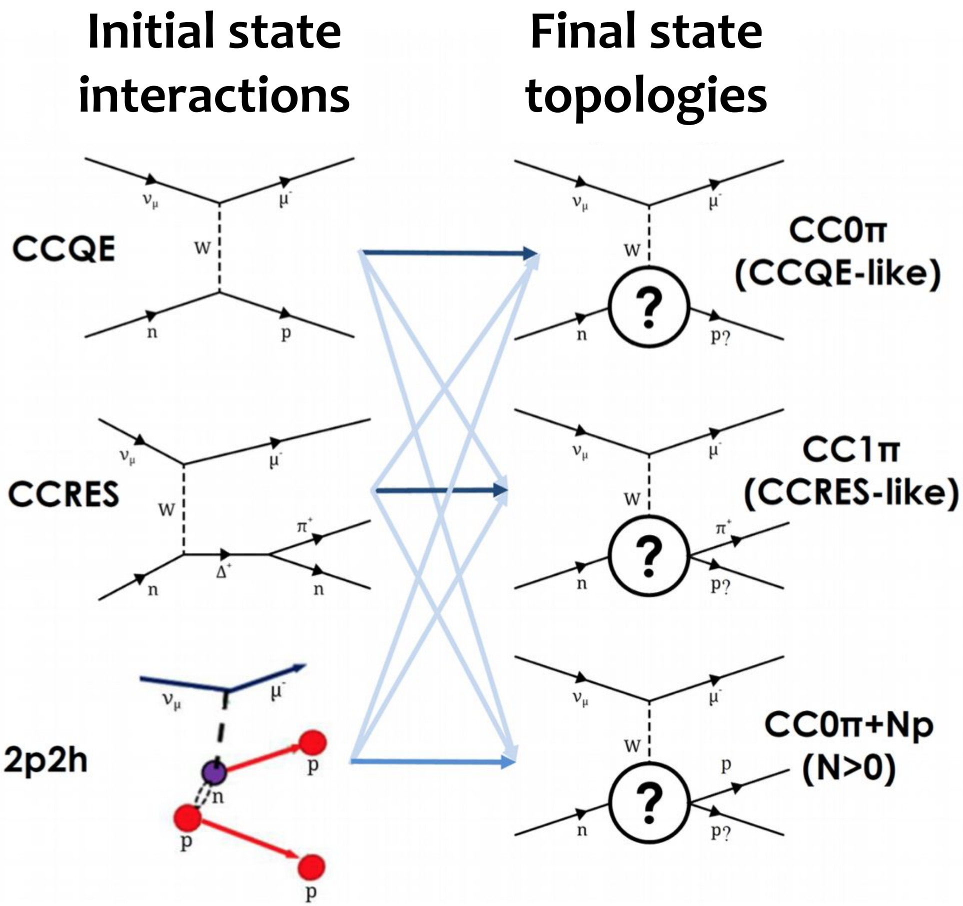
Neutrino energy reconstruction methods rely on the final state particle kinematics (and on the detector technology).

Ideally, from the final state, we want to access the true interaction, but **nuclear effects** play an important role



Final state topologies



Our detectors can only reconstruct final state particles after nuclear effect

- charged lepton (CC) or no lepton (NC)
- w. or w/o pions: $0\pi^{+-0}$, $1\pi^{+-0}$
- w. or w/o protons: 0p, 1p, Np

Final state topologies are the only categories we can access w/o referring to theoretical models, but they are **composed of a mixture of initial state interactions**

Difficult task for the xsec community is to try to characterize these initial state interactions to check/tune theoretical models

What is a cross section?

$$\frac{d\sigma}{dx_i dy_j} = \frac{N_{ij}^{signal}}{\epsilon_{ij} \Phi N_{nucleons}^{FV}} \times \frac{1}{\Delta x_i \Delta y_j}$$

What is a cross section?

After background subtraction and unfolding of detector effects

$$\frac{d\sigma}{dx_i dy_j} = \frac{N^{signal}_{ij}}{\epsilon_{ij}\Phi N^{FV}_{nucleons}} \times \frac{1}{\Delta x_i \Delta y_j}$$

true variables

efficiency correction

double (or more?) differential

- Signal, to be defined considering the detector capabilities ⇒ **final state topology**
- Selected signal samples contain also some background ⇒ need of **background samples**
- Observables, to be chosen considering the detector capabilities ⇒ **usually lepton and/or hadron kinematics**
- Limit the model dependence of the efficiency correction ⇒ perform **2D (or more) differential measurements**, phase space restriction,...
- Cross section to be extracted as a function of the true observables ⇒ **unfolding of detector effects**

Typical night of a neutrino cross-section analyser

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But we also have fun…

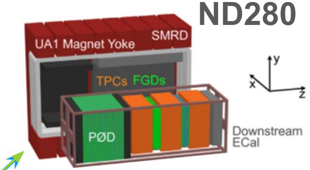
Main actors in the field

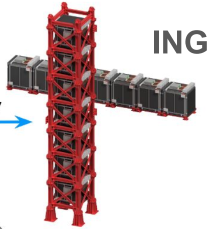
1. Near detectors
2. H_2O and plastic CH
3. different off-axis

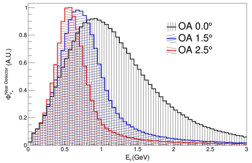
$\overline{E}_\nu$ = 0.6 GeV
2.5° off-axis

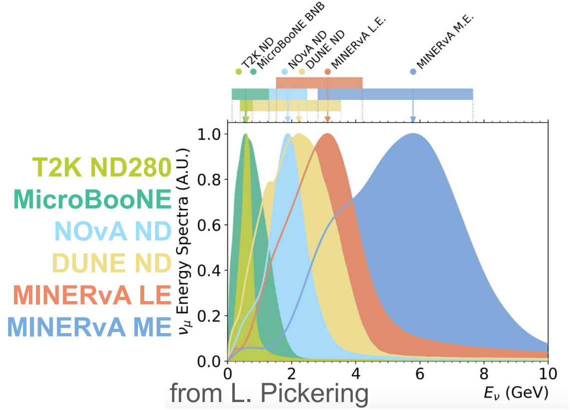
$\overline{E}_\nu$ = 1.1 GeV
on-axis

$\overline{E}_\nu$ = 0.9 GeV
1.5° off-axis





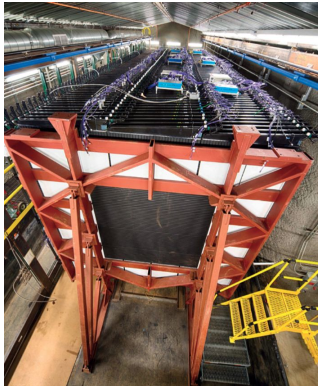




1. Liquid scintillator
2. off-axis

Fermilab
NuMI beam

$\overline{E}_\nu$ = 1.8 GeV
0.8° off-axis



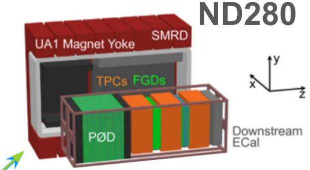
Main actors in the field

T2K

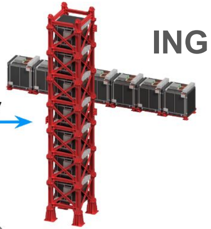
1. Near detectors
2. H_2O and plastic CH
3. different off-axis

J-PARC

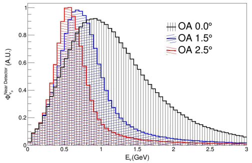
$\bar{E}_\nu$ = 0.6 GeV, 2.5° off-axis → ND280



$\bar{E}_\nu$ = 1.1 GeV, on-axis → INGRID



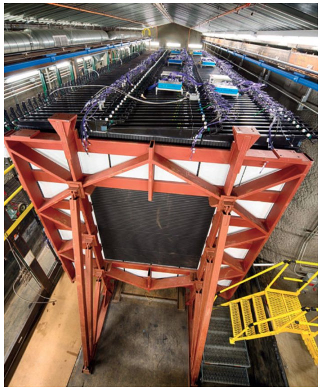
$\bar{E}_\nu$ = 0.9 GeV, 1.5° off-axis → WAGASCI



NOvA

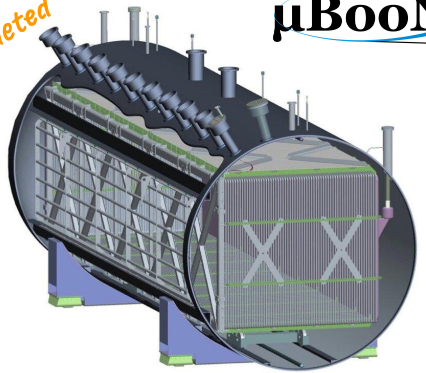
1. Liquid scintillator
2. off-axis

Fermilab NuMI beam → $\bar{E}_\nu$ = 1.8 GeV, 0.8° off-axis



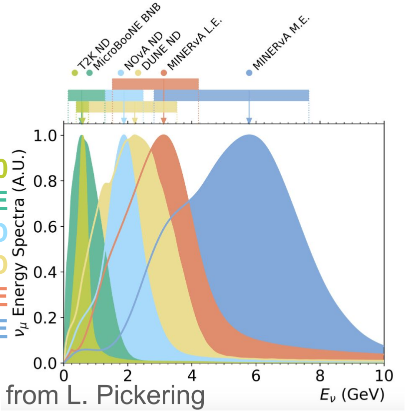
μBooNE

Data taking completed



1. LArTPC
2. BNB beam on-axis
3. NuMI beam off-axis

Fermilab: $\bar{E}_\nu$ = 0.8 GeV, BNB on-axis; $\bar{E}_\nu$ = 0.9 GeV, NuMI, 8° off-axis

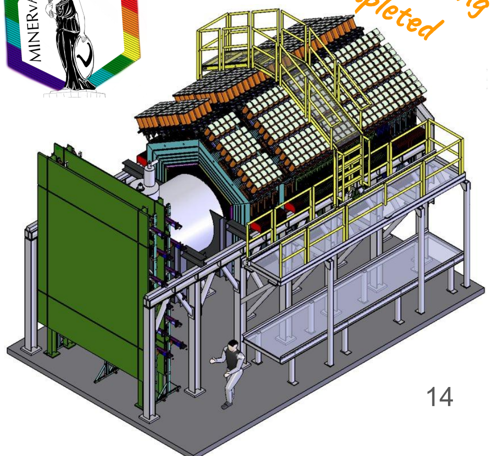


MINERvA

Data taking completed

1. Several targets: C, CH, Fe, Pb, H_2O, He
2. two beams ~3GeV and ~6GeV

Fermilab NuMI beam → E_ν ~3.5GeV (Low), ~6GeV (Mid.), on-axis



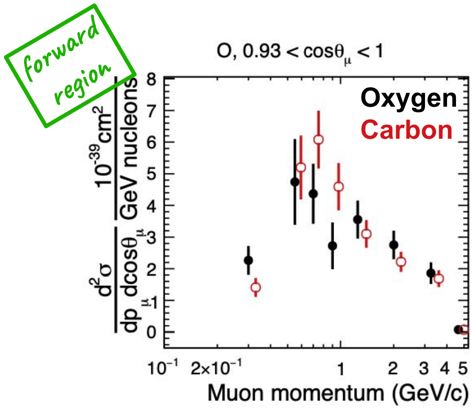
Priorities of neutrino cross-section community

- **Limit model dependence**, by defining the signal depending on the final state topology (instead of the true interaction), by carefully choosing the observables (detectable variables) and applying the efficiency corrections
- Characterise the **dominant channels CC0π and CC1π**, while also exploring subdominant or rare ones (characterise the background)
- **Promote combined measurements** (multi-flux, multi-target, multi-channel) that allow to provide correlations between measurements and explore E- and A- dependences
- **Explore nuclear effects**, that are the main responsible of systematics in the oscillation analysis
- Provide new measurements on **different targets**: CH, water, Argon (but also Pb and Fe)
- Provide **data release** allowing to preserve useful data results over the next decades and in the simplest format for theoreticians to be used
- Develop, maintain and share **sophisticated tools and careful procedures** for the cross section extraction (unfolding and error propagation) and diagnostic

How these measurements are used?

exemple from recent T2K developments

Simultaneous 2D CC0π measurement on O and C @ND280 in p_μ and $\cos\theta_\mu$



Phys. Rev. D 101, 112004 (2020)

Other previous tuning examples: MINERvA, MicroBooNE, NOvA

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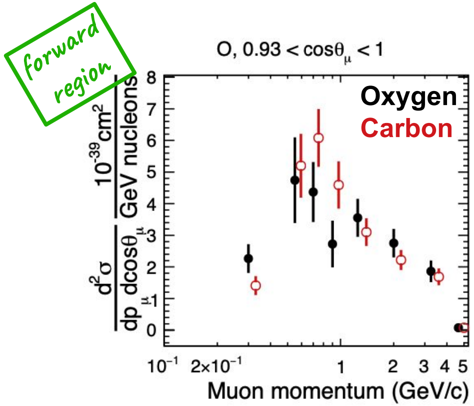

Phys. Rev. D 101, 112004 (2020)

comparison of data against different models (SuSav2, SF, LFG) and generators (NuWro, GENIE, NEUT, GiBUU)

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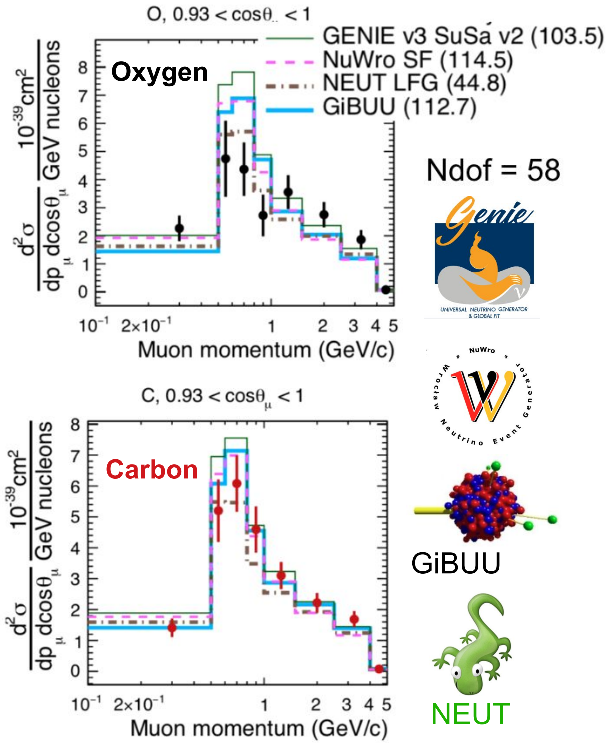

Ndof = 58

GiBUU

NEUT

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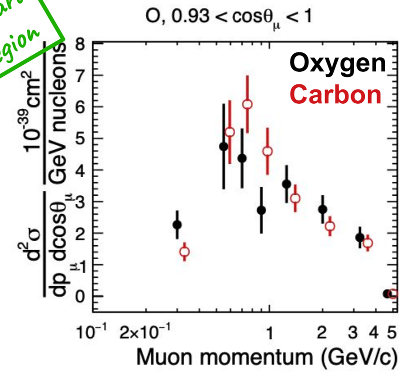
forward region



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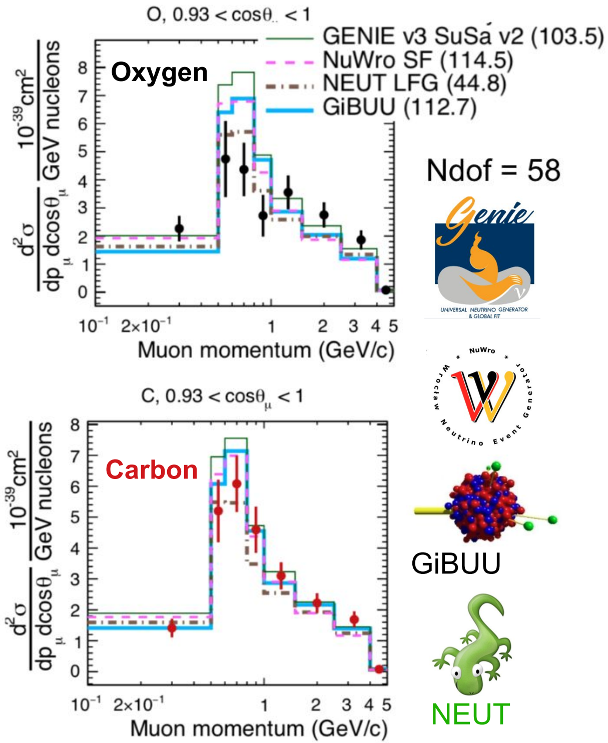

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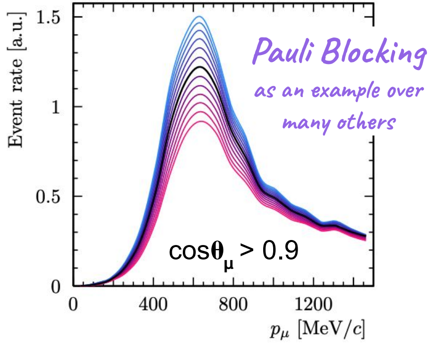
GiBUU

NEUT

clear disagreement with most sophisticated nuclear model in this region

Need to develop a **systematics parameterisation** of ν interaction models able to recover enough freedom

Phys. Rev. D 109, 072006 (2024)



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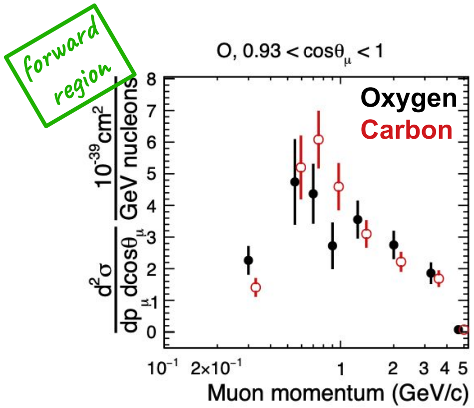

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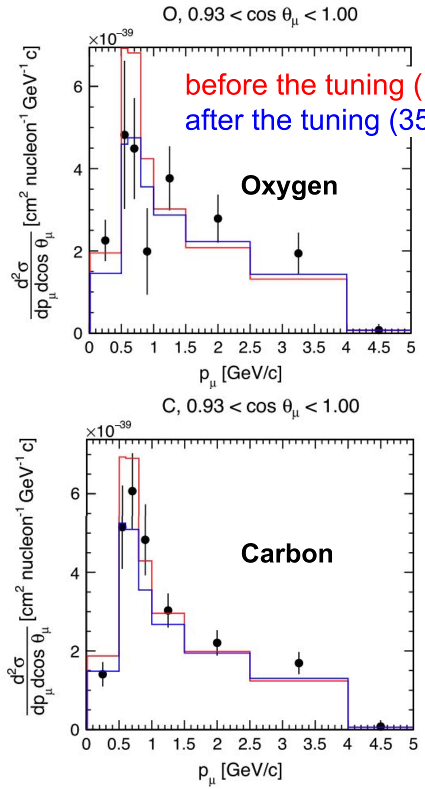

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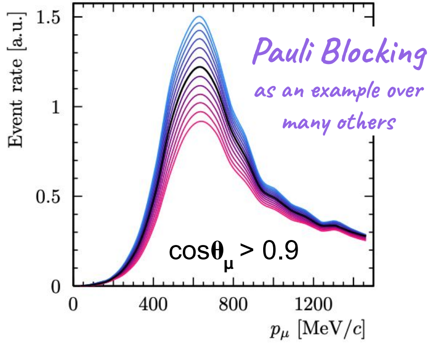


is the parameterisation allowing a good tuning? Check on O&C xsec results

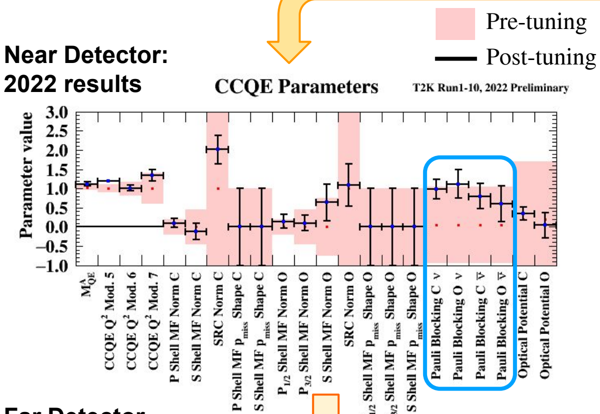
Other previous tuning examples: MINERvA, MicroBooNE, NOvA

How these measurements are used?

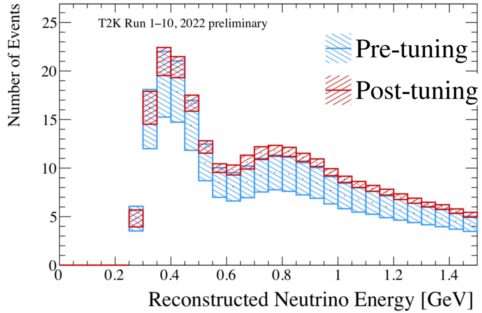
exemple from recent T2K developments

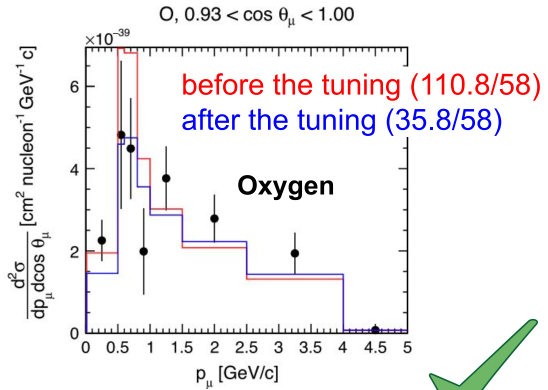
New parameterisation applied in **the official model tuning for the oscillation analysis**

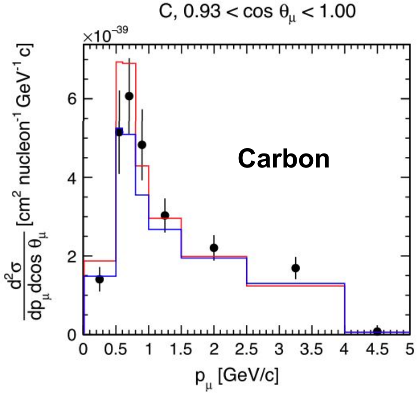
Near Detector: 2022 results



Far Detector predictions







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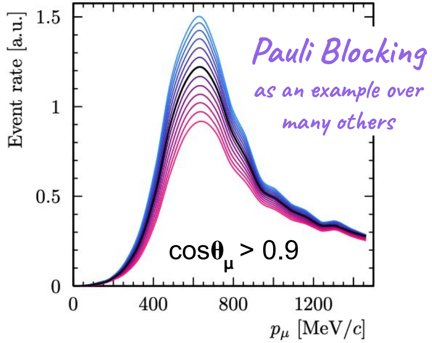

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What's new since last Neutrino conference?

T2K

ν_e CC1π+ on CH, poster #54

Joint CC0π on CH and H_2O with WAGASCI

NCπ^+ on CH, NuInt 2024

ν_μ and anti-ν_μ CC-Coherent π prod, Phys. Rev. D **108**, 092009 (2023)

Joint CC0π on CH on- and off-axis, Phys. Rev. D **108**, 112009 (2023)

NOvA

Anti-ν_μ CC Inclusive, NuInt2024

Low hadronic energy CC0π, Wine&Cheese seminar

ν_μ CC π^0, Phys. Rev. D **107**, 112008 (2023)

μBooNE

See Afroditi's talk tomorrow

NCπ^0 : BNB, arXiv:2404.10948

CCπ^0: BNB, arXiv:2404.09949

Joint CC0p/CCNp, BNB (0.8 GeV), arxiv:2402.19281 (short), arxiv:2402.19216 (long)

CC0π1p generalized kinematic imbalance variables, BNB, Phys. Rev. D 109, 092007

3D CC Inclusive, BNB, arxiv:2307.06413

η production in Argon, BNB, Phys. Rev. Lett. 132, 151801 (2024)

Multi-Differential CC0π1p TKI, BNB, Phys. Rev. Lett. 131, 101802 (2023), Phys. Rev. D 108, 053002 (2023)

Quasi-elastic Λ baryon production, NuMI beam, Phys. Rev. Lett. 130, 231802 (2023)

CC0π2p, BNB, arXiv:2211.03734

ν_e CC0π, Phys. Rev. D 106, L051102 (2022)

NuInt2024

MINERvA

$\bar{\nu}_e$ and ν_e CC Inclusive at low Q2 on CH, ME, Phys. Rev. D 109, 092008 (2024)

Neutrons in anti-ν_μ CC on CH, Phys. Rev. D 108, (2023) 112010

Axial vector form factor from antineutrino-proton scattering, Nature, 614, 48-53 (2023)

Joint ν_μ CC0π on CH, C, water, Fe, and Pb, Phys. Rev. Lett. 130, 161801 (2023)

High-Stat. anti-ν_μ CC0π on CH at E_ν~ 6GeV, Phys. Rev. D 108, (2023) 032018 (2023)

Coherent π+ production in C, CH, Fe and Pb at $\langle E_\nu \rangle$~6 GeV, Phys. Rev. Lett. 131, 051801 (2023)

CC1π+ on CH, C, H2O, Fe, and Pb, Phys. Rev. Lett. 131, 011801 (2023)

ME flux contraint using anti-ν, Phys. Rev. D 107, 012001 (2023)

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Testing xsec A-dependence for several channels!
Can we rely on CH measurements to extrapolate to H_2O or Ar?

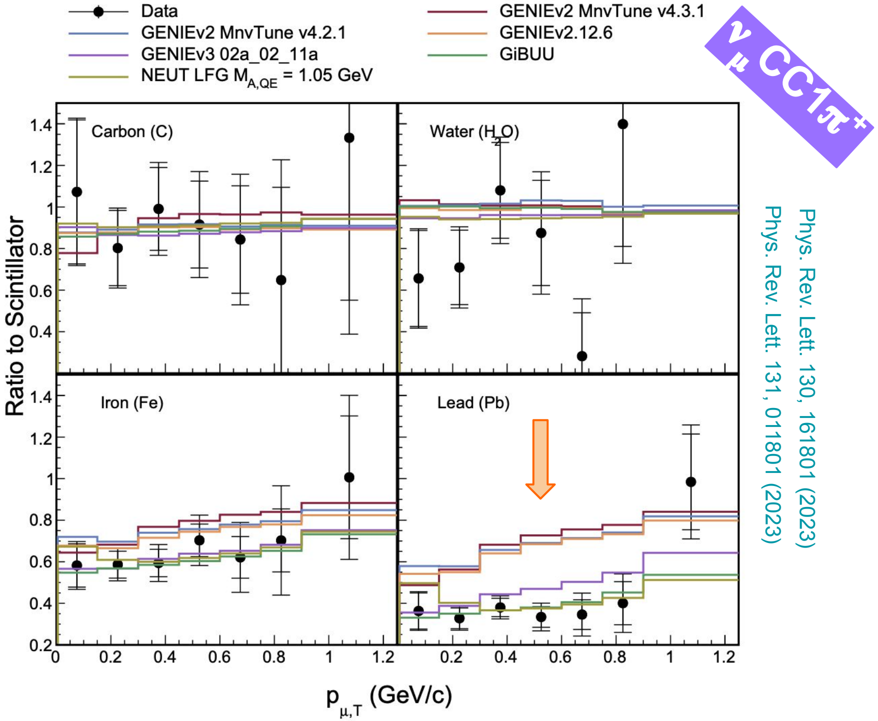
Multi-target @MINERvA

$\langle E_\nu \rangle \sim 6$ GeV

Simultaneous measurement on **several targets,** 8 variables explored. None of the 6 models tested reproduce the data well

A-dependence is different in different model/generators

Considering also CC0π channel, seems to point on a **higher π absorption than what could be imagined by looking at CH**



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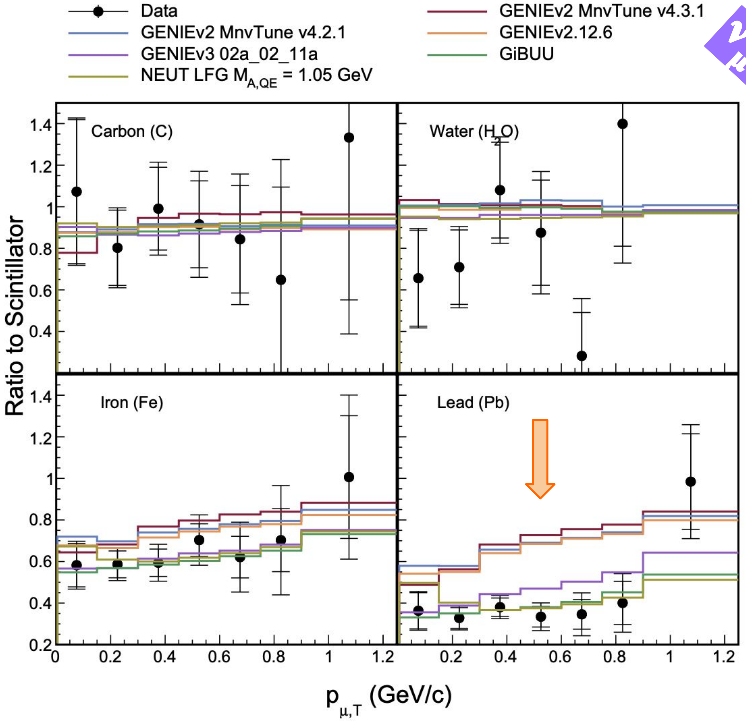

ν_μ CC1π^+

Phys. Rev. Lett. 130, 161801 (2023)
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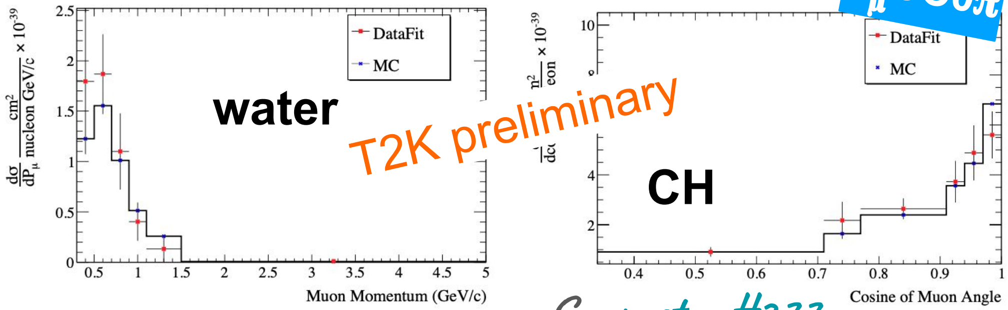
and @T2K

$<E_\nu> \sim 0.9$ GeV

First measurement using the WAGASCI/ BabyMind detector

Plastic and water (+plastic) modules → allow simultaneous measurements on CH and H_2O
Two water/CH simultaneous 1D measurements: p_μ ans $\cos\theta_\mu$

ν_μ CC0π



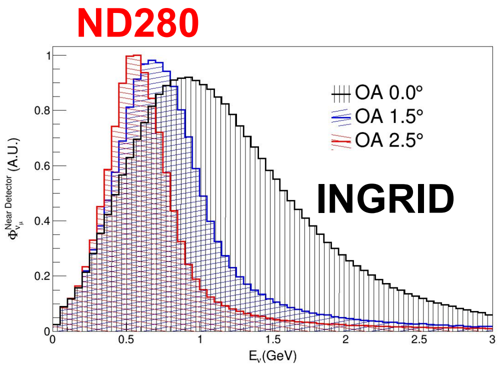
See poster #277

Future plans include joint measurements with ND280

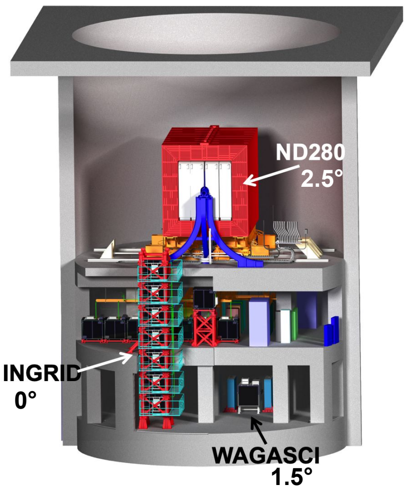
Multi-flux @T2K

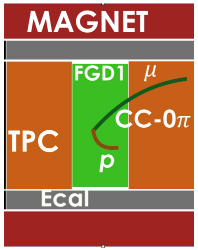
Try to study the energy dependence of neutrino interactions. Can we extrapolate xsec at different E_ν?

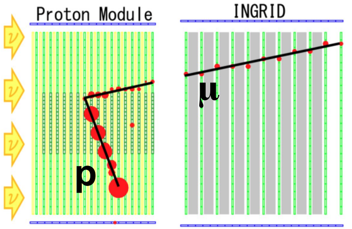
Phys. Rev. D **108**, 112009 (2023)



First joint on/off-axis ν_μ CC0π analysis on CH, using two T2K near detectors at different angles wrt the beam direction → different (correlated) fluxes





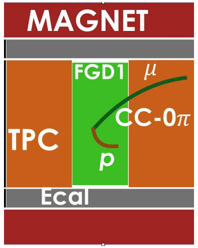


ν_μ CC0π on CH

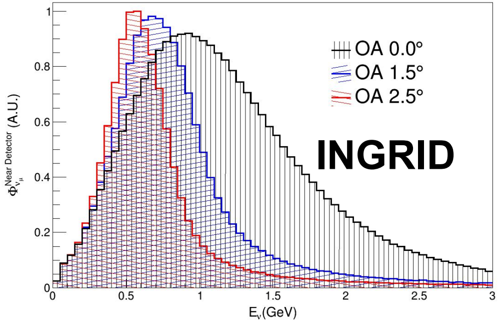
Multi-flux @T2K

Try to study the energy dependence of neutrino interactions. Can we extrapolate xsec at different E_ν?

Phys. Rev. D **108**, 112009 (2023)



ND280



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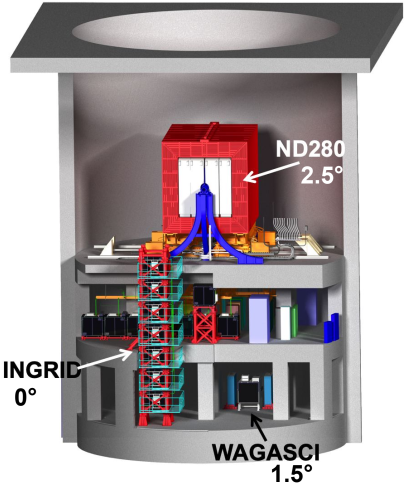

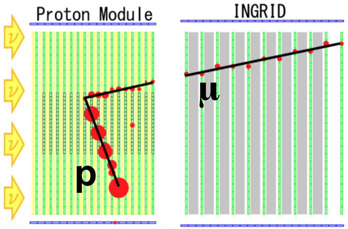

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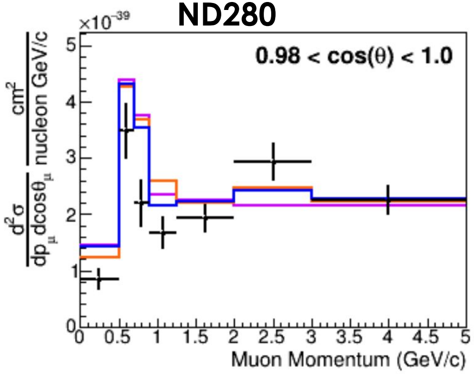
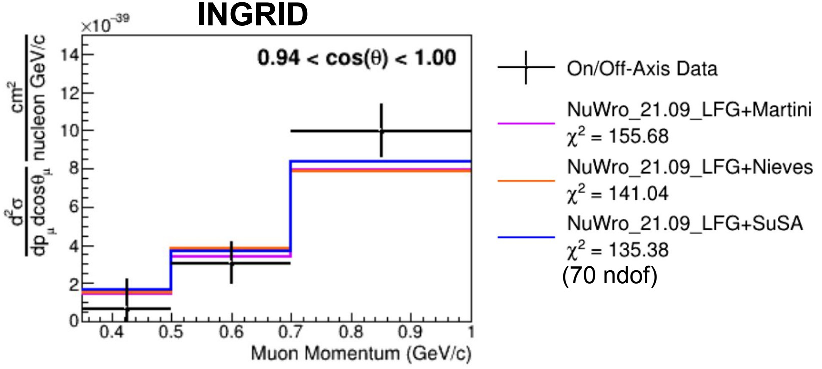




Allows to study the **energy dependence of ν interactions** (same beam but different spectra) especially 2p2h or CCRES

For the first time, **possible to test models simultaneously at two different angles/fluxes**

Models struggle in reproducing data

Protons @µBooNE: T&G KI

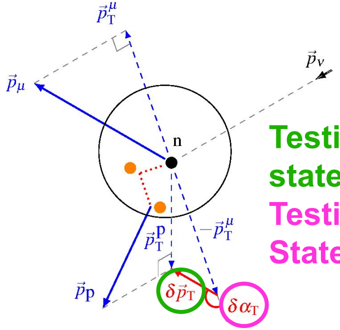
µBooNE

$\langle E_\nu \rangle \sim 0.8$ GeV

Transverse Kinematics Imbalance

ν_μ CC0π 1p on Ar

When the p is reconstructed in addition to the µ, we can access variables combining µ and p, that allow to test nuclear effects (2p2h, FSI, Fermi motion): imbalance in the f.s. ⇔ some nuclear effects



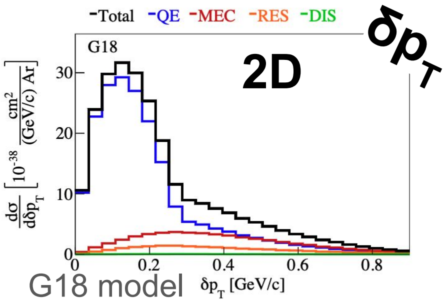
Testing the initial state nucleon

Testing Final State Interactions

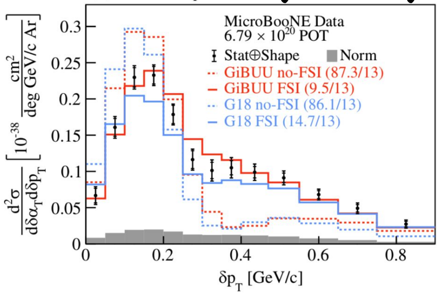
First TKI measurement on Ar!

Phys. Rev. Lett. 131, 101802 (2023),

Phys. Rev. D 108, 053002 (2023)



G18 model



See poster #626

Protons @µBooNE: T&G KI

µBooNE

<E$_\nu$> ~ 0.8 GeV

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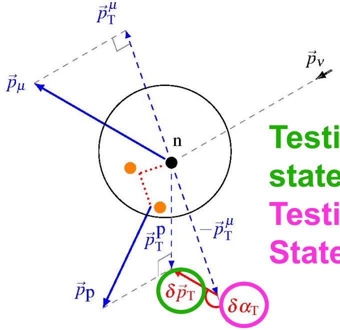

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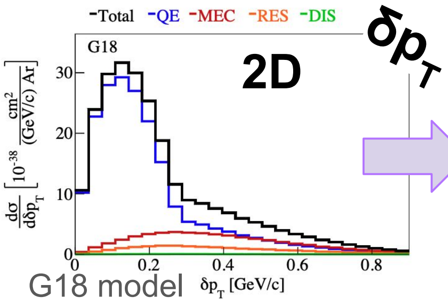

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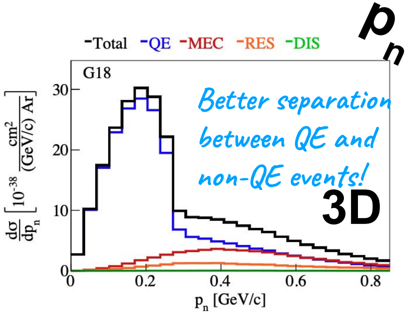


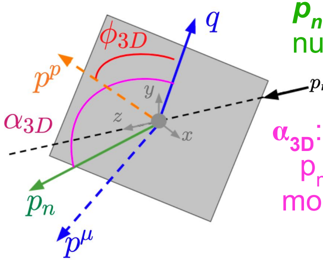
Using a series of variables combining µ and p kinematics: δp_T, δp_{Tx}, δp_{Ty}, $\delta\alpha_T$, $\delta\varphi_T$, $\cos\vartheta_\mu$, $\cos\vartheta_p$, $E^{cal} = E_\mu + K_p + E_b$, p_n, α_{3D}

First TKI measurement on Ar!

Phys. Rev. Lett. 131, 101802 (2023),

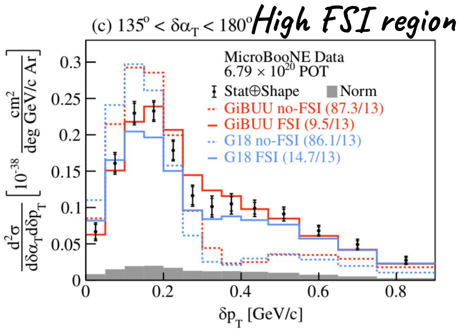
Phys. Rev. D 108, 053002 (2023)

Generalized Kinematics Imbalance



p_n ~ initial struck nucleon mom. ~ δp_T in 3D

α_{3D}: angle between p_n and the total mom. transfer q ~ $\delta\alpha_T$, in 3D



First GKI measurement!

Phys. Rev. D 109, 092007

See poster #626

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µBooNE

$<E_\nu> \sim 0.8$ GeV

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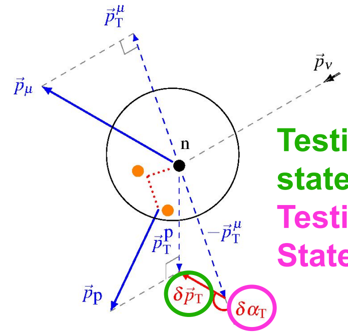

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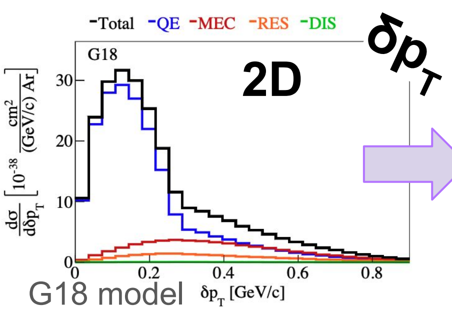

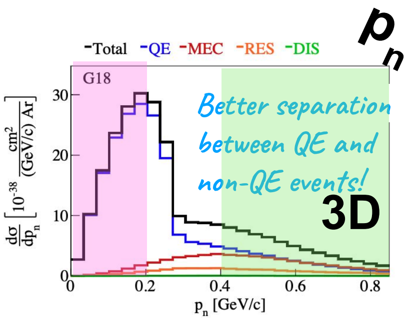

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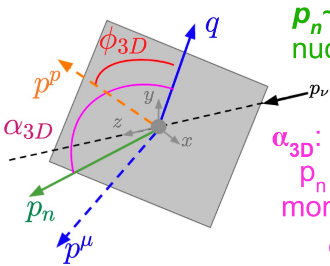

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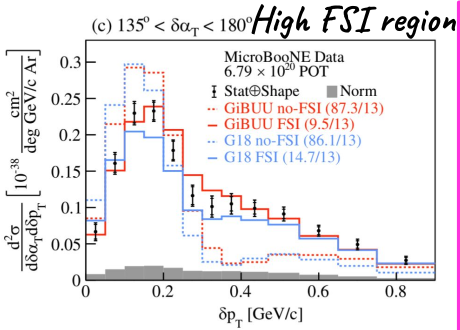
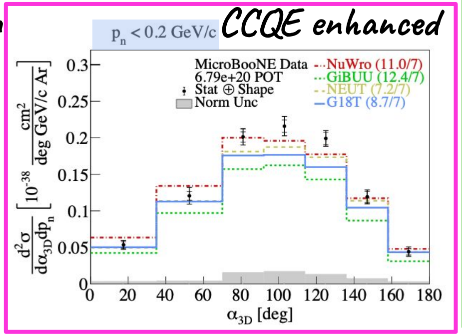
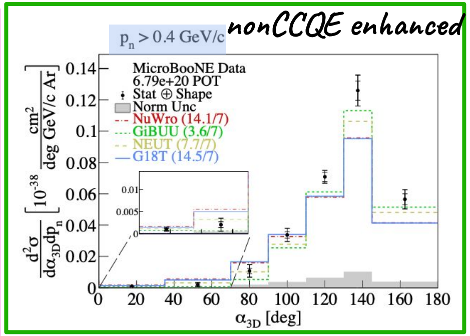






First GKI measurement!

Phys. Rev. D 109, 092007

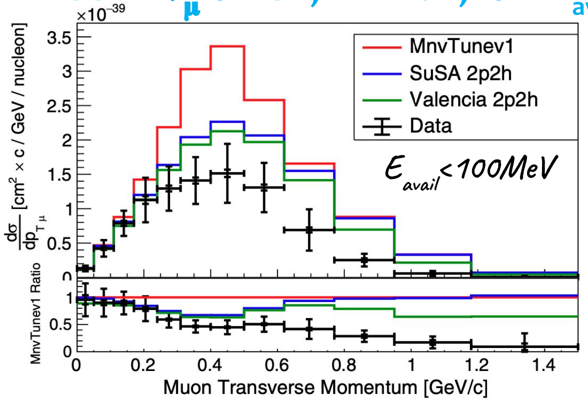
See poster #626

Some old models clearly disfavoured. More recent models agree in certain regions and are worse in others. **Simultaneous use of 2 variables enhance the discrimination power among different nuclear effects!**

Neutrons @MINERvA

Calorimetric reconstruction of E_ν (NOvA, DUNE) can be biased if presence of neutrons is not taken into account. But neutrons by definition are difficult to detect → look at n SI that produce visible p

CCNn $\bar{\nu}_\mu$ on CH, ME flux, low E_{avail}



Phys. Rev. D 108, (2023) 112010

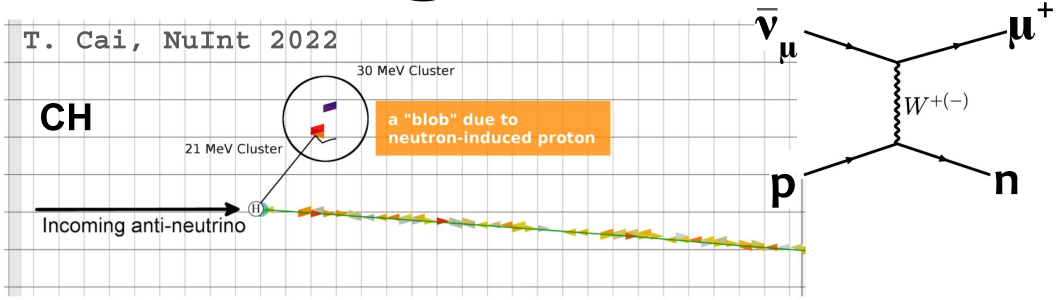
See poster #88

Multi-neutrons measurements at low E_{avail} (=non E_μ and non n activity) → ++ 2p2h

Models overpredicts the number of neutrons

Theoretical xsec overestimated wrt data

→ **pointing to a 2p2h or FSI mismodelling?**



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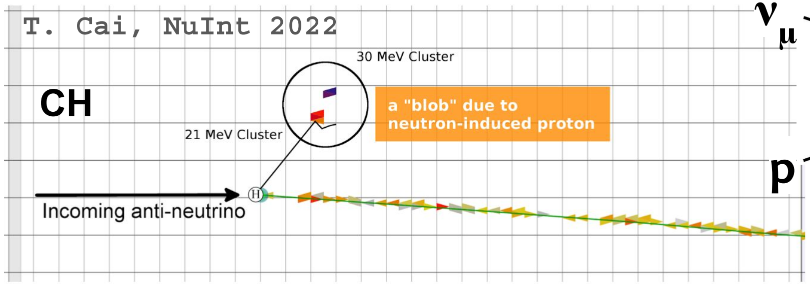
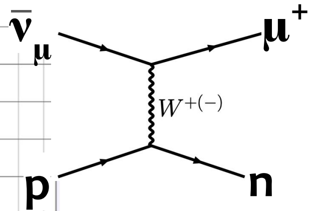
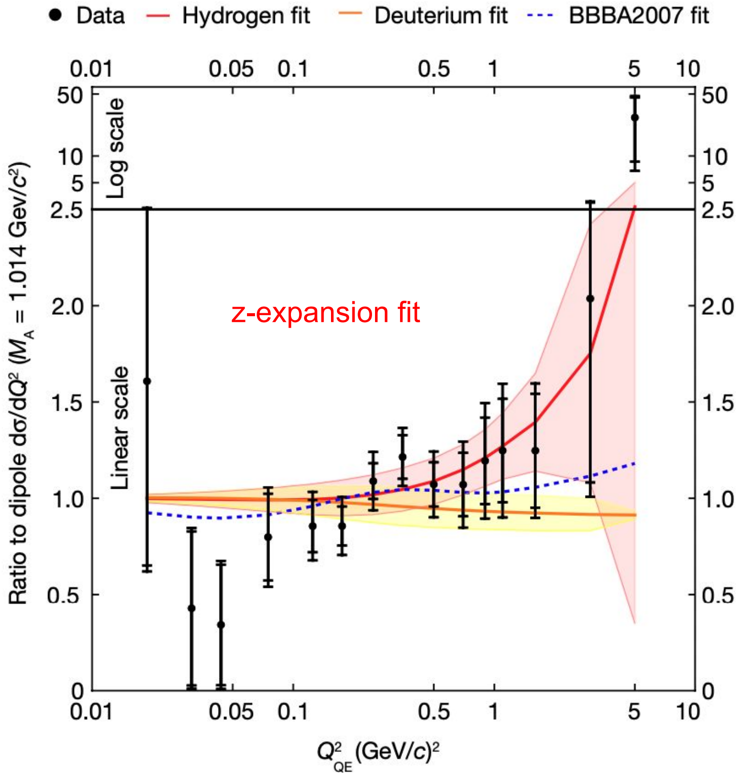
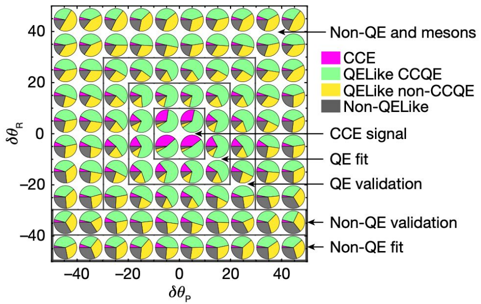


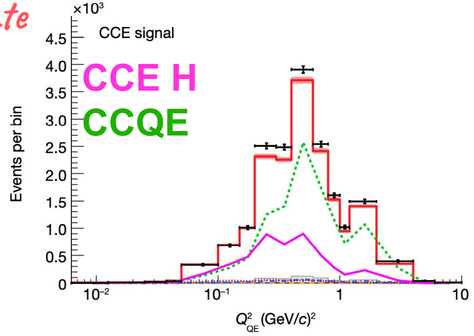




And if we get rid of nuclear effects? Try to isolate $\bar{\nu}_\mu$ CC elastic interactions on H, i.e. on free p!

Cuts on TKI angular variables





Nature, 614, 48-53 (2023)

CCE xsec measured vs Q^2_{QE}: **first statistically significant measurement of the anti-ν CCE scattering on the free p!**

Results used to **measure the axial vector form factor** → first measurements on free p!

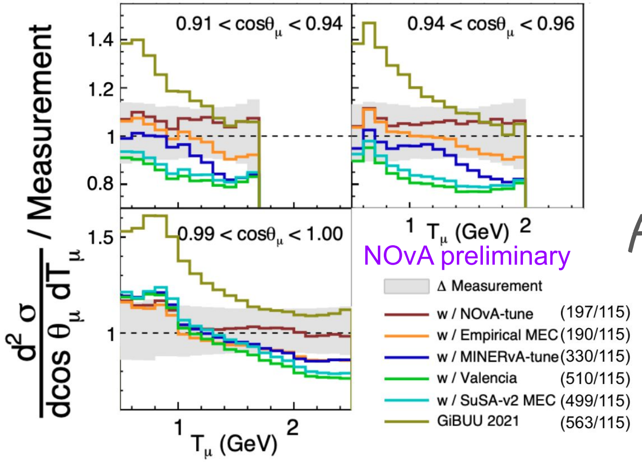
Favors larger F_A at higher Q^2 → **deviation from dipole F_A**

Exploiting E_{avail} @NOvA

Try to use the Σ of all hadrons
Available energy (E_{avail}): total energy of all observable final state hadrons (well established variable since Phys. Rev. Lett. 116, 071802 (2016))
$<E_\nu>$ ~ 1.8 GeV

ν_μ **CC 1 track** → limit CCRES and CCDIS

Analysis in 3D (T_μ, $\cos\theta_\mu$, E_{avail}) and then projected to muon kinematics



High stat!

Testing several 2p2h models
→ none of them correctly reproduce data

Several other model comparisons available in:
NOvA CC0π @NuInt2024, W&C seminar
NOvA CC1π @NuInt2024, W&C seminar

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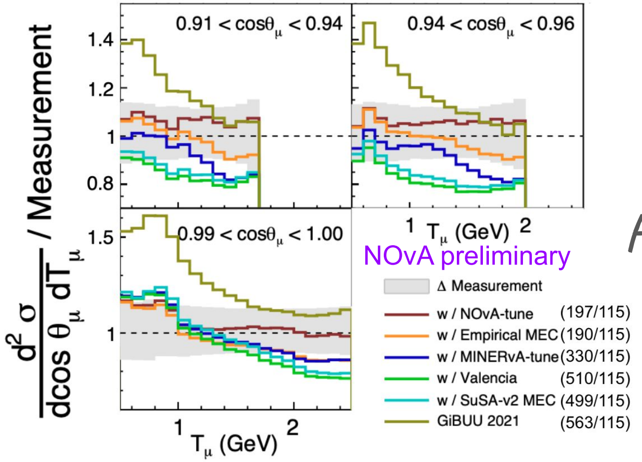

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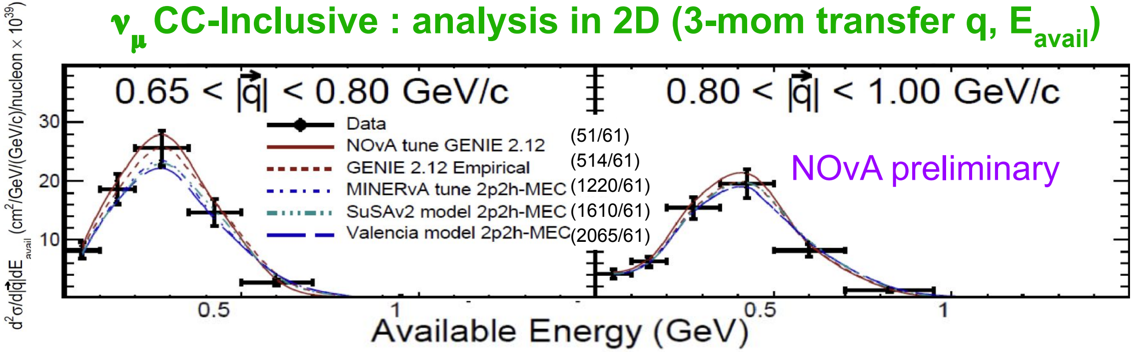
High stat!

ν_μ CC-Inclusive : analysis in 2D (3-mom transfer q, E_{avail})



Xsec evolves with increasing q → similar pattern already seen in MINERvA

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NOvA CC1π @NuInt2024, W&C seminar

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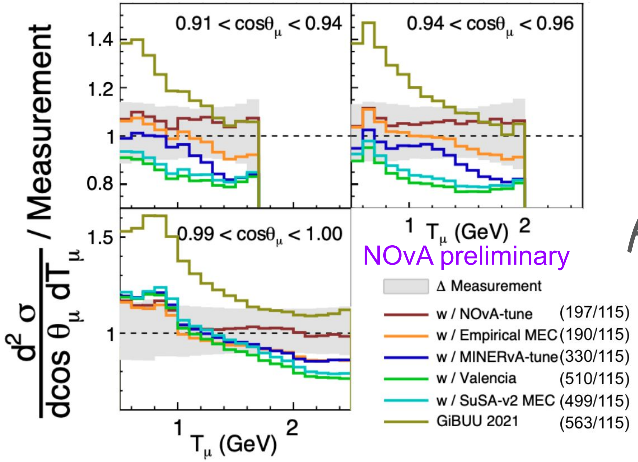

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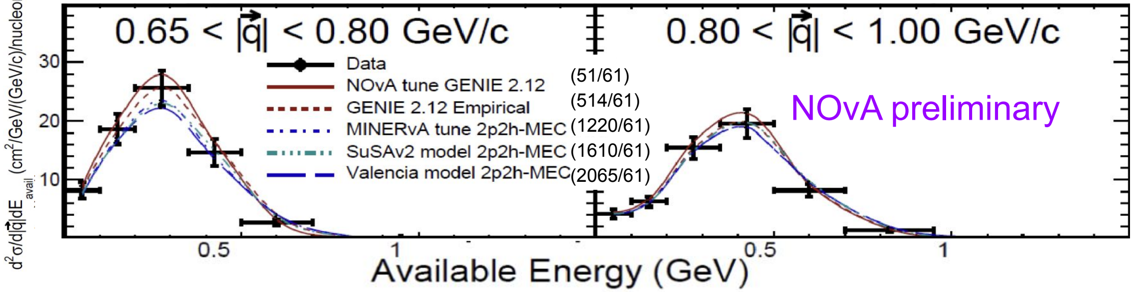


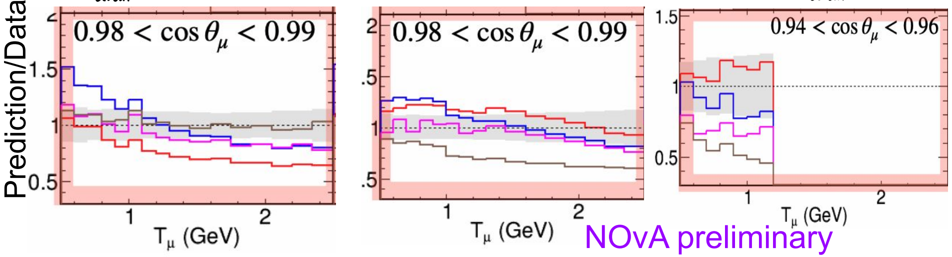
Xsec evolves with increasing q → similar pattern already seen in MINERvA
Testing several 2p2h models

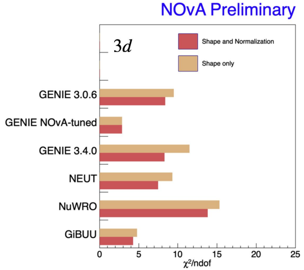
High stat!

See poster #390

$\bar{\nu}_\mu$ CC-Inclusive : analysis in 3D (T_μ, $\cos\theta_\mu$, E_{avail})

E_{avail} < 100MeV *300MeV < E_{avail} < 600MeV* *1GeV < E_{avail} < 2GeV*





Testing several models. **Low E_{avail} region is the dominant one** (~50% of events, ++CCQE, 2p2h). Need a tuned model for a ~better agreement with data

Several other model comparisons available in:
NOvA CC0π @NuInt2024, W&C seminar
NOvA CC1π @NuInt2024, W&C seminar

Most of xsec measurements done with ν_μ beam at near detectors, but far detectors particularly interested to ν_e. Can we extrapolate from ν_μ to ν_e → need to study them also at the ND! ($m_\mu \neq m_e$)

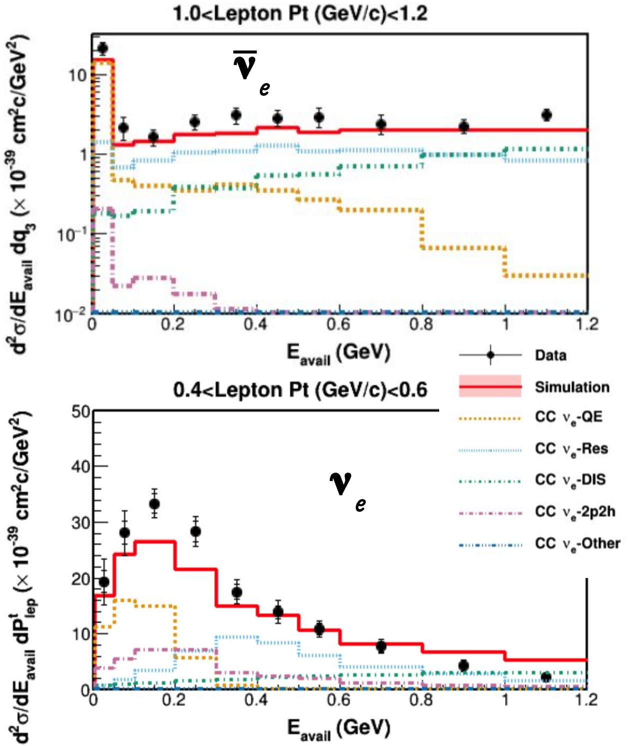
Electron neutrinos

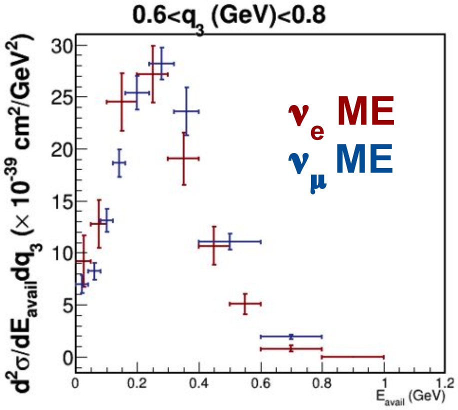
High statistics (**~10^4 events**), **CC-Inclusive**, low E_{avail} (bkg limit), E_e> 2.5 GeV, ME beam, **CH target**

Two 2D cross section measurements (E_{avail}, q_3), (E_{avail}, p_T)

$<E_\nu> \sim 6$ GeV

Phys. Rev. D 109, 092008 (2024)





Comparison with equivalent ν_μ measurement

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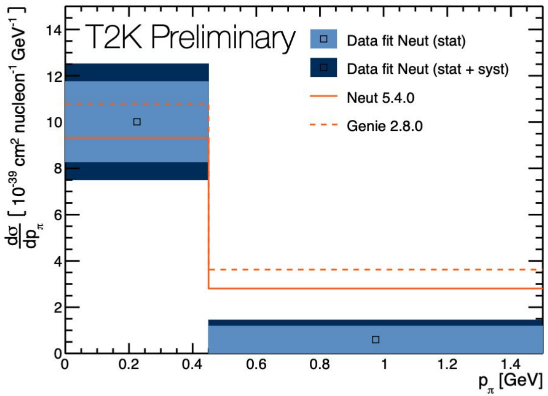
Most of xsec measurements done with ν_μ beam at near detectors, but far detectors particularly interested to ν_e. Can we extrapolate from ν_μ to ν_e → need to study them also at the ND! ($m_\mu \neq m_e$)

E_ν^{peak} ~ 0.6 GeV

T2K

First ν_e CC1π^+ measurement!

Important ν_e appearance channel
3D measurement (p_e, θ_e, p_π) projected in 1D



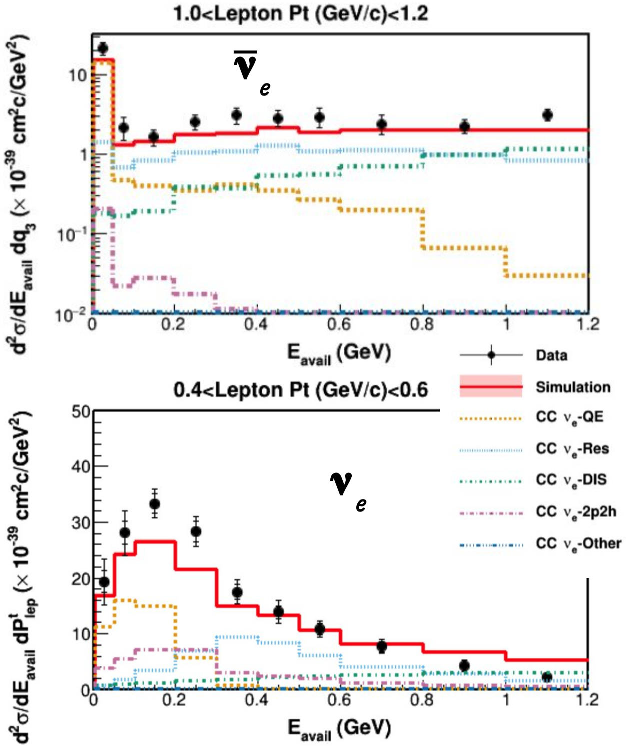
Still low statistics (~100 events), but models seems to overpredict the data

See poster #54

High statistics (~10^4 events), **CC-Inclusive**, low E_{avail} (bkg limit), E_e> 2.5 GeV, ME beam, **CH target**

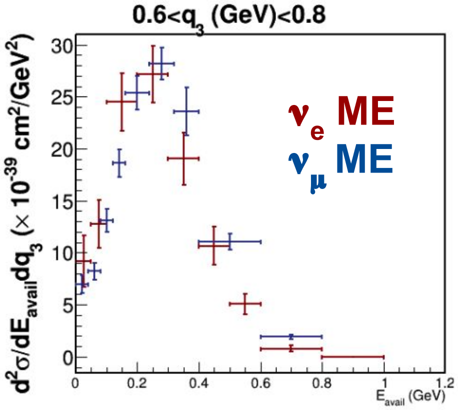
Two 2D cross section measurements (E_{avail}, q_3), (E_{avail}, p_T)

MINERvA



<E_ν> ~ 6 GeV

Phys. Rev. D 109, 092008 (2024)



Comparison with equivalent ν_μ measurement

Need to characterise also NC interactions, often background for oscillation analyses!

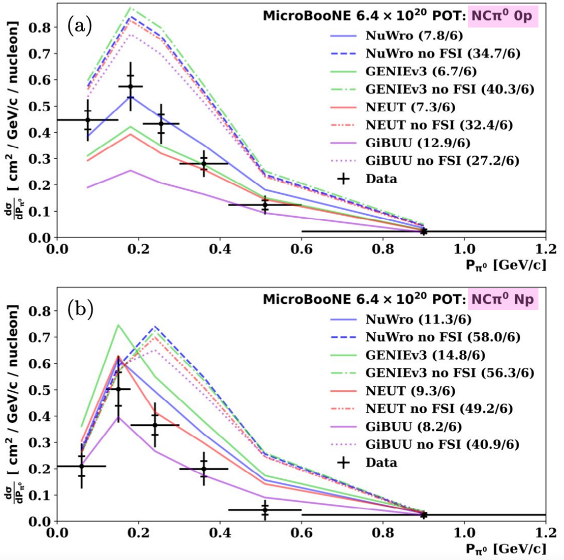
And Neutral Currents?

$<E_\nu> \sim 0.8$ GeV

μBooNE

π^0 production represents a major background for EM shower selection (e.g. **ν_e appearance**), but poorly studied process

First 2D NCπ^0 measurement on Ar!
2D measurement in $p_{\pi 0}$ and $\cos\theta_{\pi 0}$



Simultaneous measurement of 0p and Np channels → important to understand the difference between 0p/Np topologies

Clearly favouring models containing FSI, better agreement with 0p channel

Also provide test of different form factor predictions (see the paper)

~ 5000 sel. events arXiv:2404.10948

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And Neutral Currents?

$<E_\nu>$ ~ 0.8 GeV MicroBooNE

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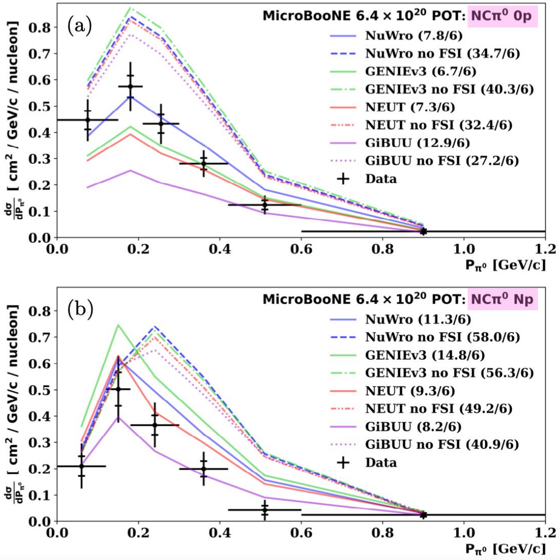

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Also provide test of different form factor predictions (see the paper)

~ 5000 sel. events arXiv:2404.10948

T2K *E^{peak}_ν ~ 0.6 GeV*

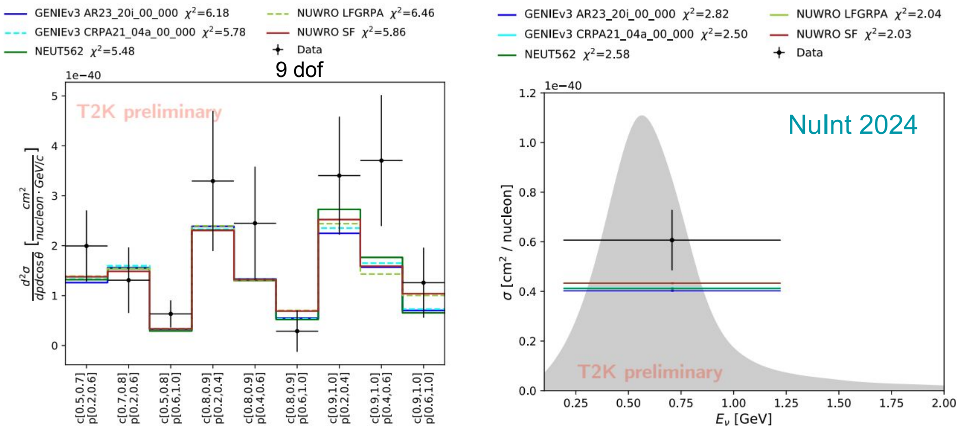
NCπ^+ production represents a major background for **ν_μ disappearance channel** → poorly studies process

First NCπ^+ measurement on CH below 2 GeV

2D measurement in $p_{\pi+}$ and $\cos\theta_{\pi+}$

0p channel is signal, Np channel is background

~ 500 sel. events



Comparisons with several nuclear and FSI models. No particular preference shown

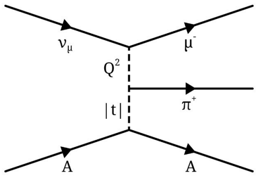
Still statistically limited → need to collect more data

When neutrinos interact coherently with the nucleus

CC-Coherent π production

Poorly studied interactions (so far), where the ν_μ **interacts with the nucleus as a whole**

Selection: low 4-mom transfer events where a charged π is produced



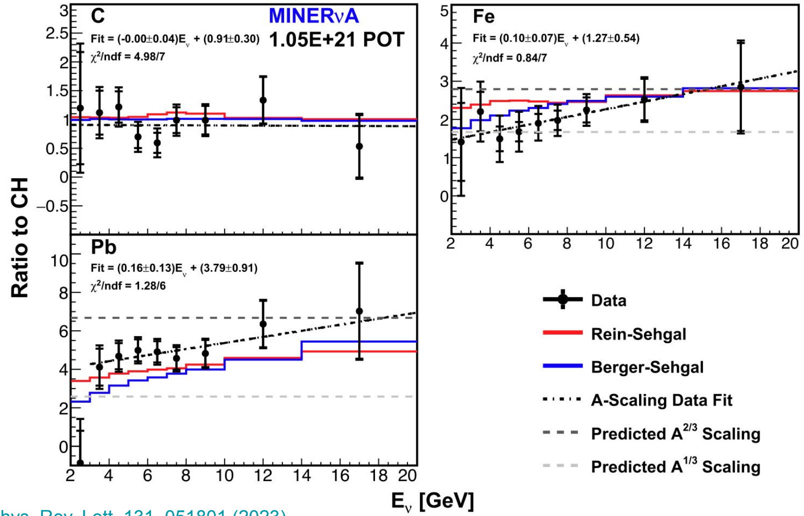
$\langle E_\nu \rangle$ ~ 6 GeV

Multi-targets

First ν_μ CC-Coh measurement on A>40 nuclei

First simultaneous measurements on several targets

Several A-scaling models tested: $A^{1/3}$, $A^{2/3}$, Belkov-Kopeliovich. Data seems to prefer this last, A-scaling important for DUNE



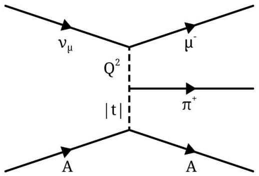
Phys. Rev. Lett. 131, 051801 (2023)

When neutrinos interact coherently with the nucleus

CC-Coherent π production

Poorly studied interactions (so far), where the ν_μ **interacts with the nucleus as a whole**

Selection: low 4-mom transfer events where a charged π is produced



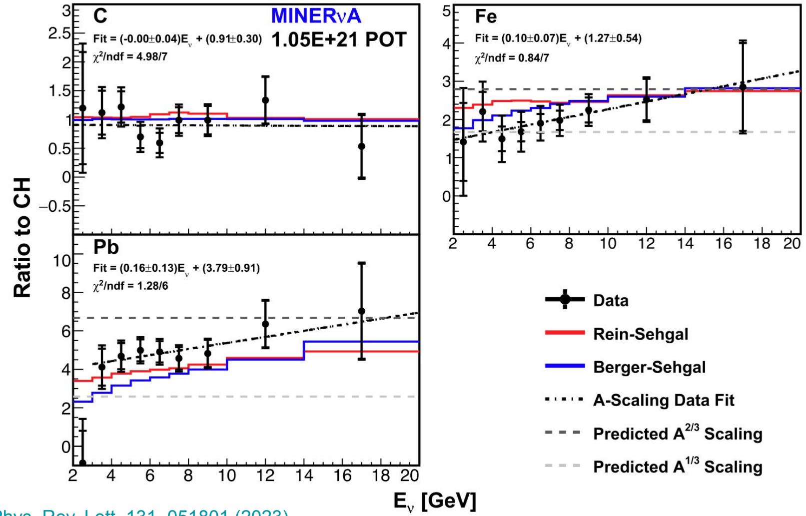
$<E_\nu> \sim 6$ GeV

Multi-targets

First ν_μ CC-Coh measurement on A>40 nuclei

First simultaneous measurements on several targets

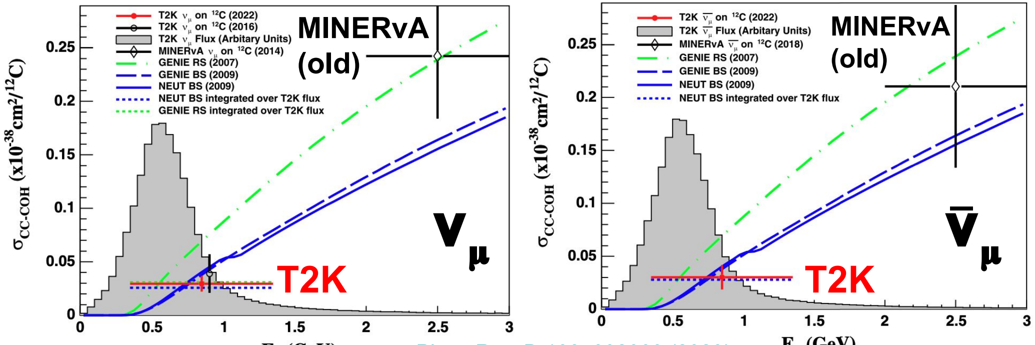
Several A-scaling models tested: $A^{1/3}$, $A^{2/3}$, Belkov-Kopeliovich. Data seems to prefer this last, A-scaling important for DUNE



Phys. Rev. Lett. 131, 051801 (2023)

$E_\nu^{peak} \sim 0.6$ GeV

Multi-beam modes



Phys. Rev. D 108, 092009 (2023)

First measurements of CC-Coh for $\bar{\nu}$ below 1GeV

Lower energy (and lower stat) wrt MINERvA: single bin

But same **CH target**!

Summary and prospect

See Kevin's talk in a moment
See Afroditi's talk tomorrow

- Neutrino cross sections are a **very active and pretty fundamental field** to ensure neutrino oscillation experiment success
- A **variety of experiments** involved in the quest for the neutrino interaction understanding → complementarity of the measurement and sharing of best practice
- I had a very limited time to treat the vastity of new results since Neutrino 2022: please enjoy NuInt2024 talks and other talks from the sessions today and tomorrow → **so many progresses in only 2y!**
- An additional amount of new results are already in the pipeline from the mentioned experiments
- Also, new measurements from other experiments will come soon: ICARUS, SBND, ArgonCube (Argon), the ND280-Upgrade (CH), NINJA (water et al), Annie (water)
- Need to **act as a community together with theoreticians and generator developers**, (like NuStec)
- Amount of available data is increasing and complexifying: towards a standardised Data Release format for **data preservation** ~HepData

Cross-section posters

- A. Furmanski: Measuring neutrino-induced neutrons in the MicroBooNE LArTPC, #636
- C. Thorpe: Rare neutrino interaction and pi0 production cross sections with MicroBooNE, #627
- L. Hagaman: Inclusive and exclusive pionless cross section measurements with MicroBooNE, #626

- K. Lachner, ν_μ CC0π cross-section measurement with calorimetric information at the upgraded T2K near detector, #278
- C. Jesus-Valls, The WAGASCI-BabyMIND detector of the upgraded T2K experiment, #277
- N. Latham, First Measurement of the Charged Current Electron Neutrino Pion Production Cross Section on a Carbon Target at T2K, #54
- K. Kowalik, Measurement of K+ production in the charged-current neutrino interactions in the T2K experiment, #555

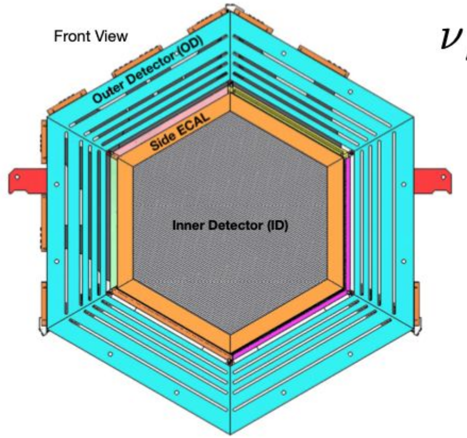
- Measuring the Multi-Neutron Antineutrino Cross Section at Low Charged Hadron Energy in MINERvA, Andrew Olivier, #88

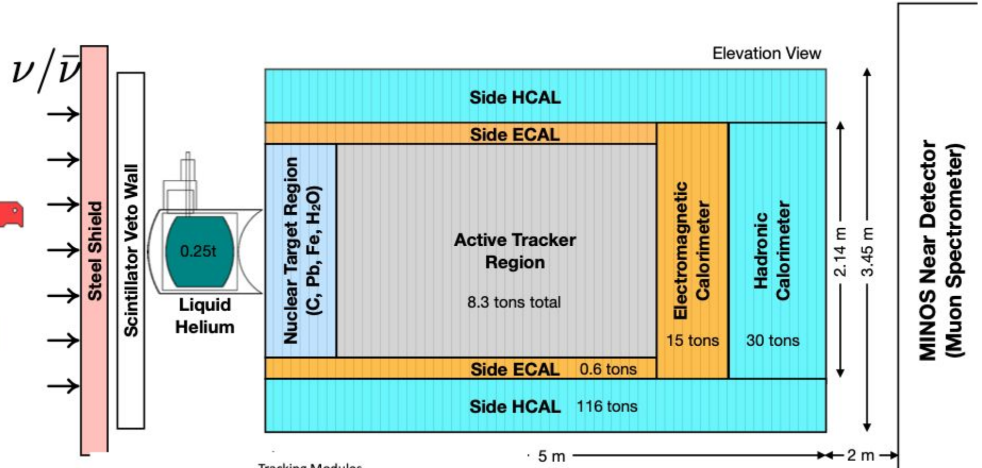
- T. Lackey, A double-differential electron antineutrino charged-current inclusive cross section in the NOvA near detector, #621
- M. Muether, Charged-pion Cross-section Measurements in the NOvA Near Detector, #574
- P. Singh, Muon Antineutrino Charge Current Inclusive Cross Section Measurement in NOvA,#390
- S. Sanchez-Falero, Status of the muon neutrino charged-current mesonless cross section measurement in the NOvA near detector, #411

MINERVA DETECTOR

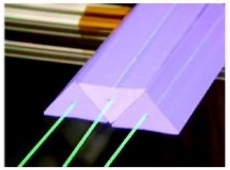
NuInt2022

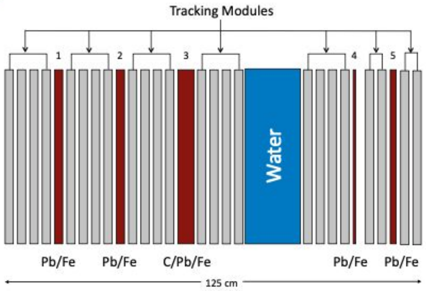
High Resolution Scintillator(CH) Detector





Nucl. Inst. and Meth. A743 (2014) 130.



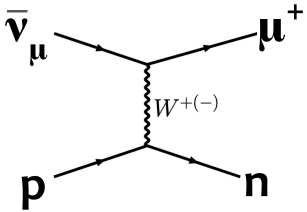


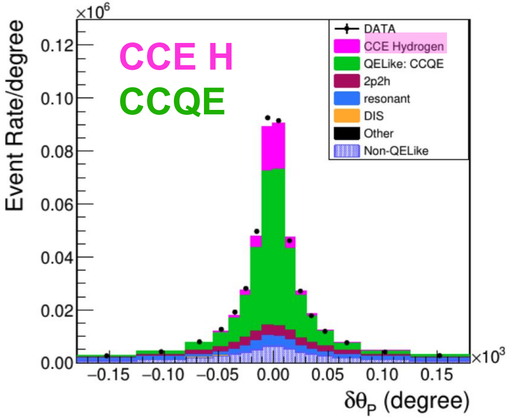
CH in tracker
Pb, Fe, C and water in target region
3.1 mm tracking resolution

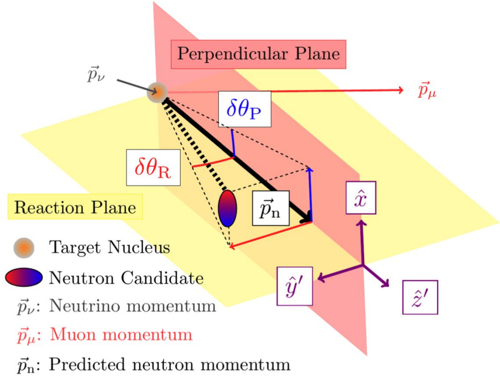
Neutrons & H @MINERvA

And if we get rid of nuclear effects? Try to isolate ν_μ CC elastic interactions on H, i.e. on free p!

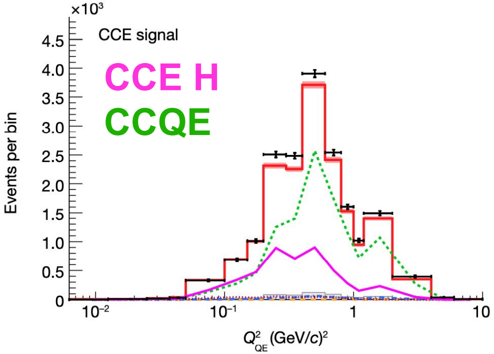
Nature, 614, 48-53 (2023)







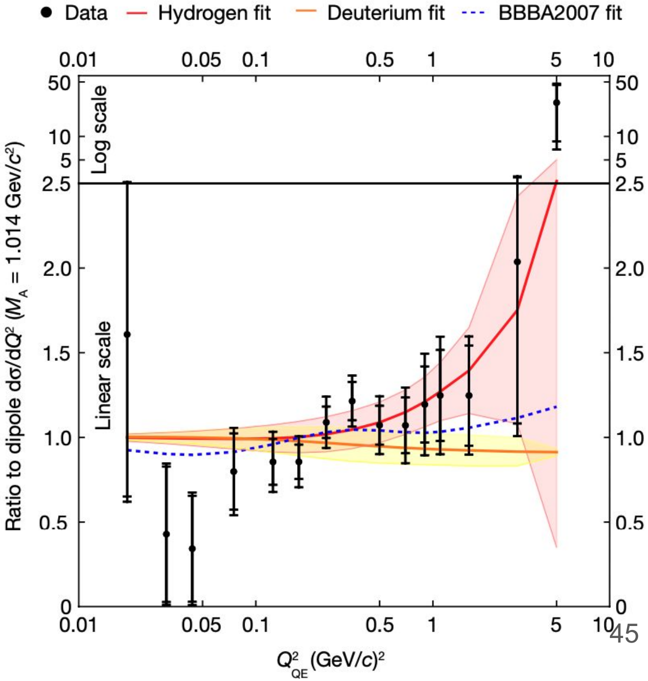
Cuts on angular variables



CCE xsec measured vs Q^2_{QE}: **first statistically significant measurement of the anti-ν CCE scattering on free p!**

Results used to **measure the axial vector from factor** → first measurements on free p!

Favors larger F_A at higher Q^2 → **deviation from dipole F_A**



Multi-target @MINERvA

Testing xsec A-dependence for several channels! Can we rely on CH measurements to extrapolate to H_2O or Ar?

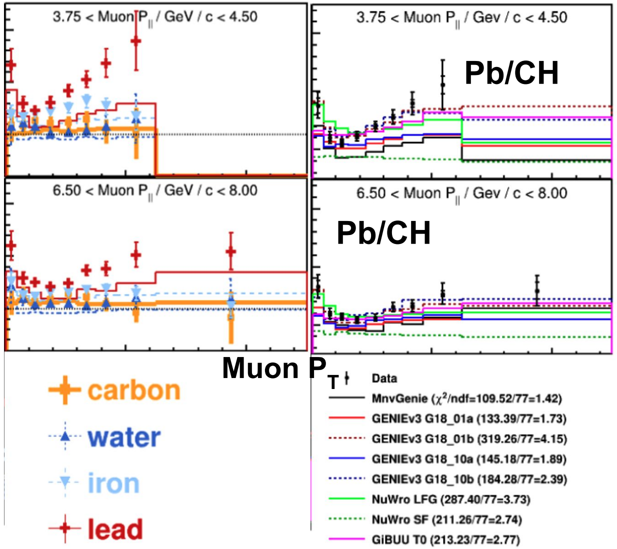
$<E_\nu> \sim 6$ GeV

CC0π

Excess above the prediction that grows with A and P_T but seems stable across $P_{||}$ → for growing A **nuclear effects depend more on the Q^2 than on the E_ν**

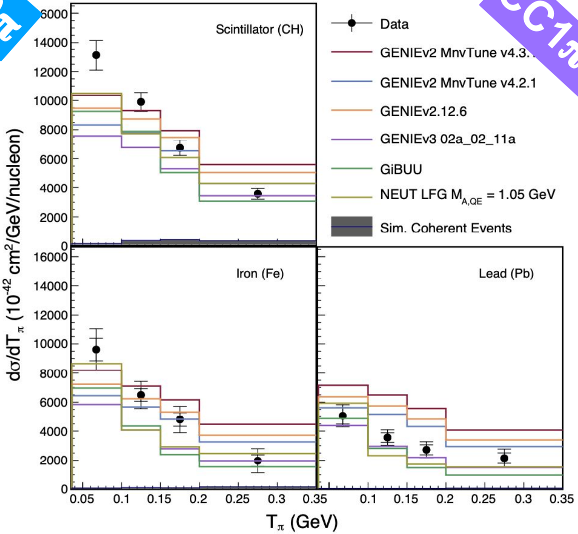
Different FSI models in GENIE have effects especially at high P_T

Considering also CC1π channel, seems to point on a **higher π absorption than what could be imagined by looking at CH**



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

CC1π+



Phys. Rev. Lett. 131, 011801 (2023)

Simultaneous measurement on **several targets,** 8 variables explored

None of the 6 models tested seems to reproduce the data well

A-dependence is different in different model/generators

GENIEv2 overpredict the A-scaling for Fe and Pb

CC-Coh

Poorly studied interactions, where the ν_μ **interacts with the nucleus as a whole**

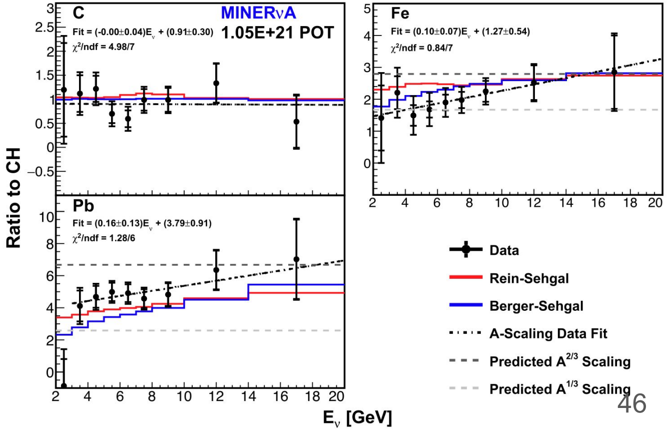
Selection of low 4-mom transfer events and a π+ is produced

First CC-Coh measurement on A>40 nuclei

First simultaneous measurements on several targets

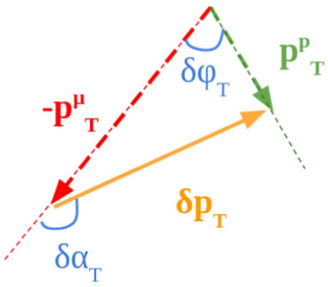
Several A-scaling models tested: $A^{1/3}$, $A^{2/3}$, Belkov-Kopeliovich

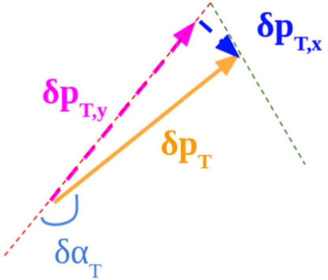
Seems to prefer this last, A-scaling important for DUNE

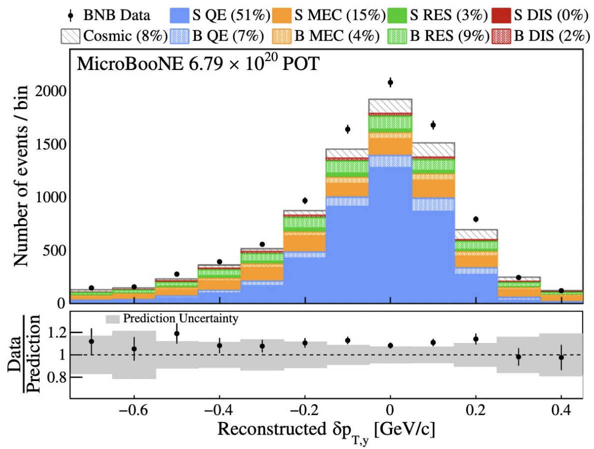


Phys. Rev. Lett. 131, 051801 (2023)

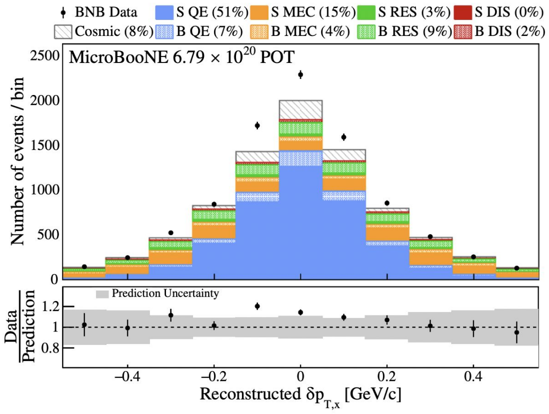
Transverse Kinematics Imbalance variables





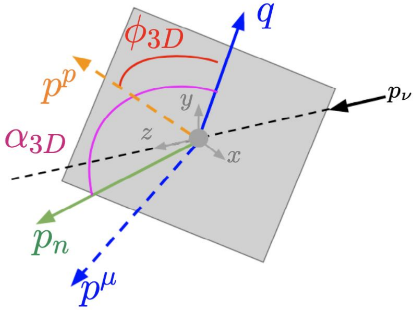


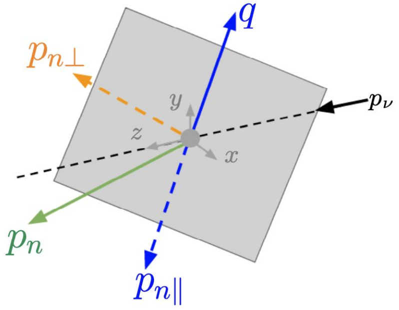
deltapTx asymmetric around zero (depends on cosdaT) → sensitive to FSI strenght

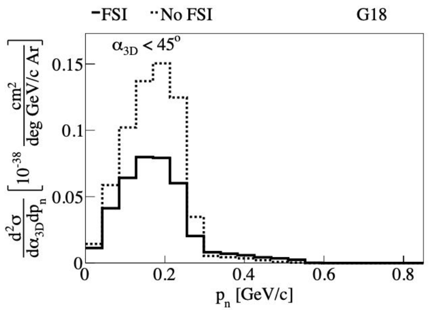


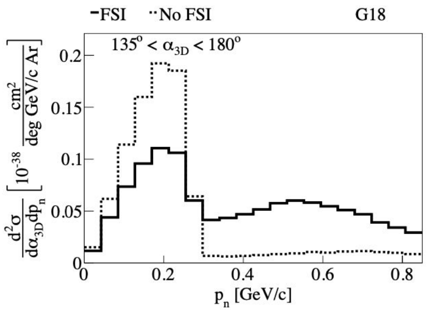
deltapTx symmetric around zero (depends on sindaT) → driven by Fermi momentum

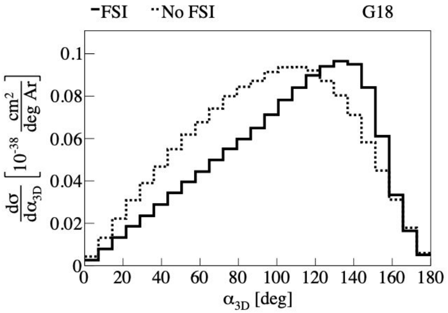
Generalised Kinematics Imbalance variables

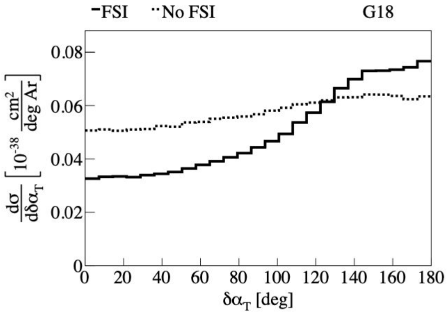




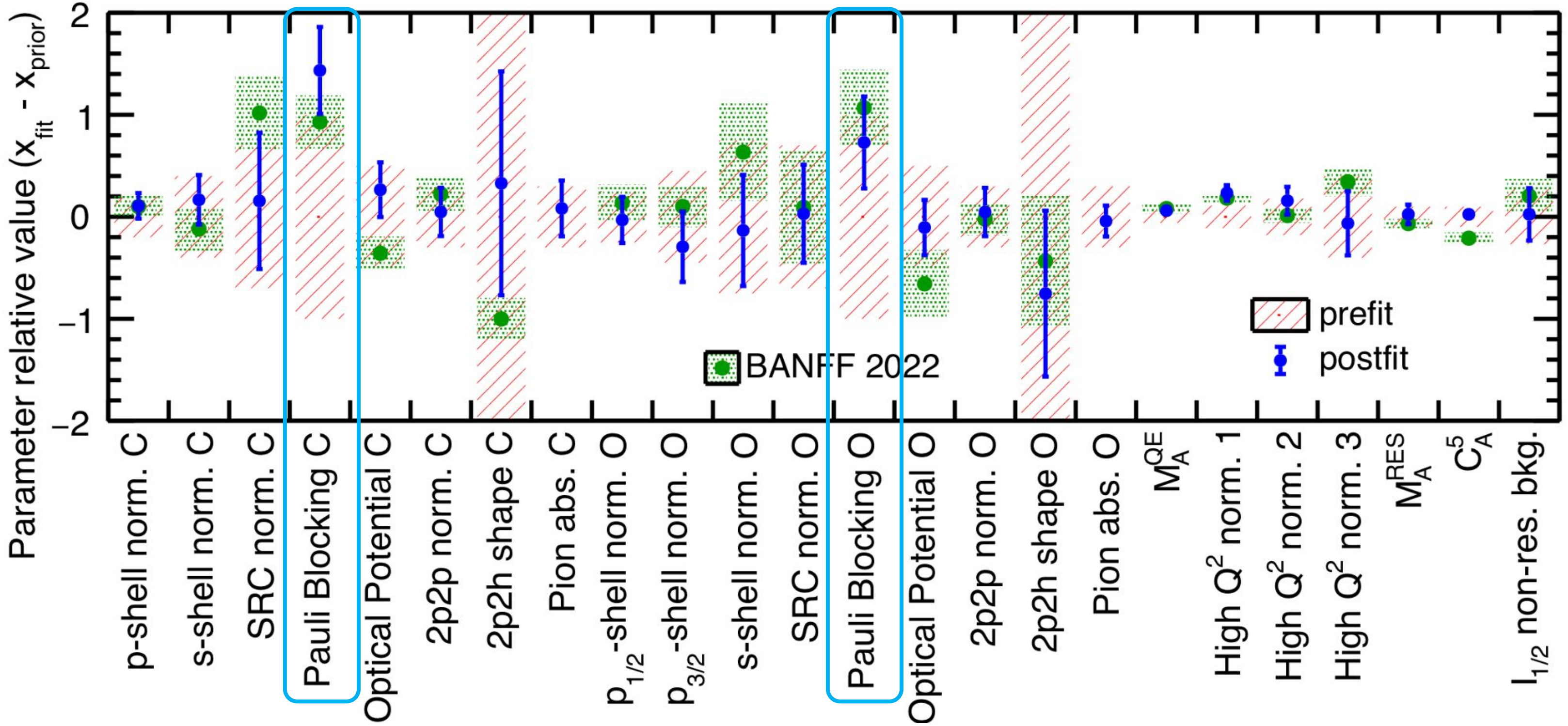








T2K Tuning



Parameter relative value (x_{fit} - x_{prior})
2
1
0
−1
−2
BANFF 2022
prefit
postfit
p-shell norm. C
s-shell norm. C
SRC norm. C
Pauli Blocking C
Optical Potential C
2p2p norm. C
2p2h shape C
Pion abs. C
$p_{1/2}$-shell norm. O
$p_{3/2}$-shell norm. O
s-shell norm. O
SRC norm. O
Pauli Blocking O
Optical Potential O
2p2p norm. O
2p2h shape O
Pion abs. O
M_A^{QE}
High Q^2 norm. 1
High Q^2 norm. 2
High Q^2 norm. 3
M_A^{RES}
C_A^5
$I_{1/2}$ non-res. bkg.