The University of Manchester

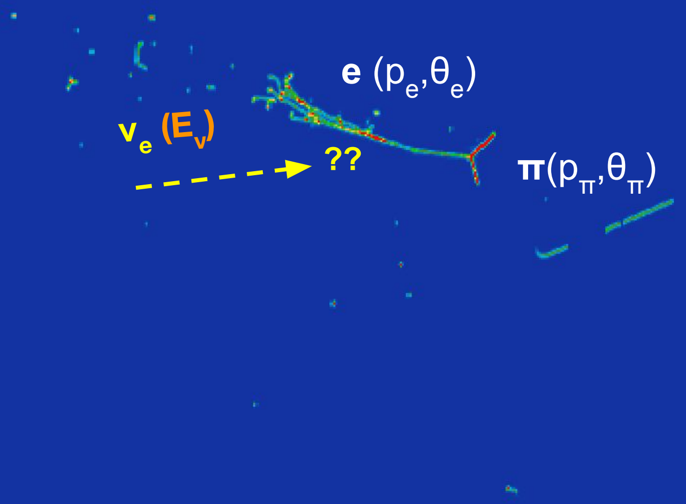
Neutrino scattering: WG 2 Summary

Christophe Bronner, Raúl González Jiménez, Elena Gramellini

NuFact 2024, September 21st , ANL

The importance of **neutrino cross sections**

This is all you see in your detector:
we never see the neutrino directly!



You identify the final state particles to
infer neutrino flavor:
count how many ν_e and ν_μ

From the reconstructed particles' momenta
you **infer neutrino energy:**

$$P(osc) \sim \sin^2(L / E_\nu)$$

Event display courtesy of μBooNE

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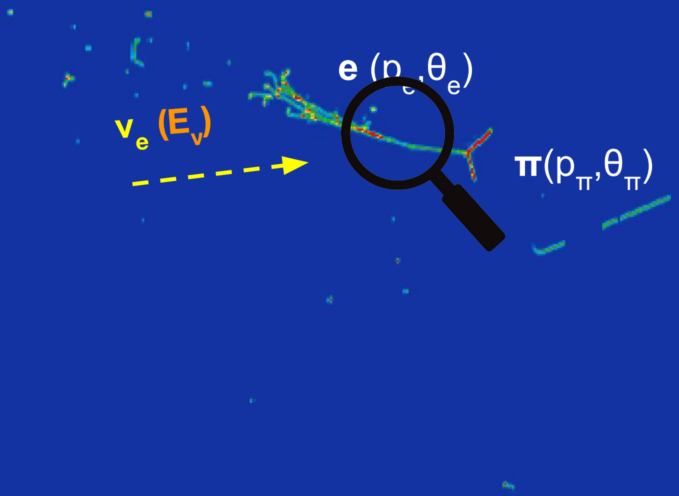
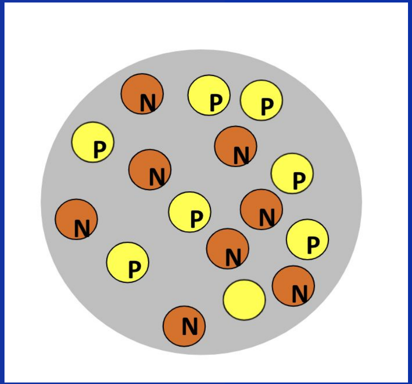


What gets in between



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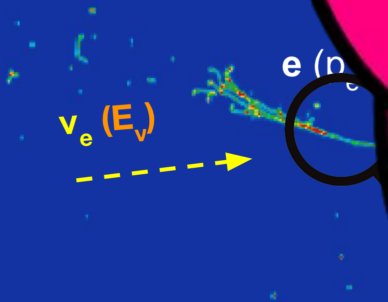
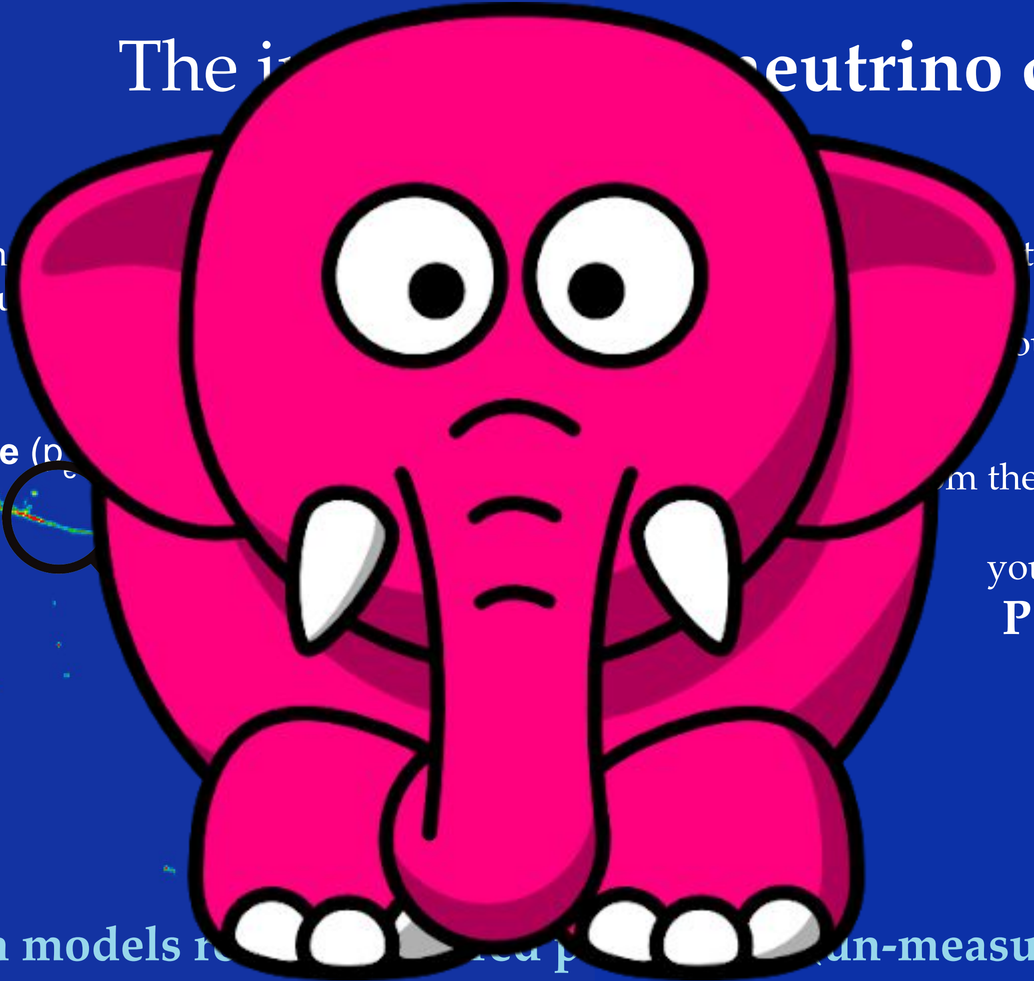
$$P(osc) \sim \sin^2(L / E_\nu)$$

Cross-section models relate measured particles to (un-measurable) neutrinos
we need to correctly predict the ν-N interaction as a function of energy

The i… neutrino cross sections

This is all you see in … we never see the neu…





…the final state particles to … **infer neutrino flavor:** …ount how many ν_e and ν_μ

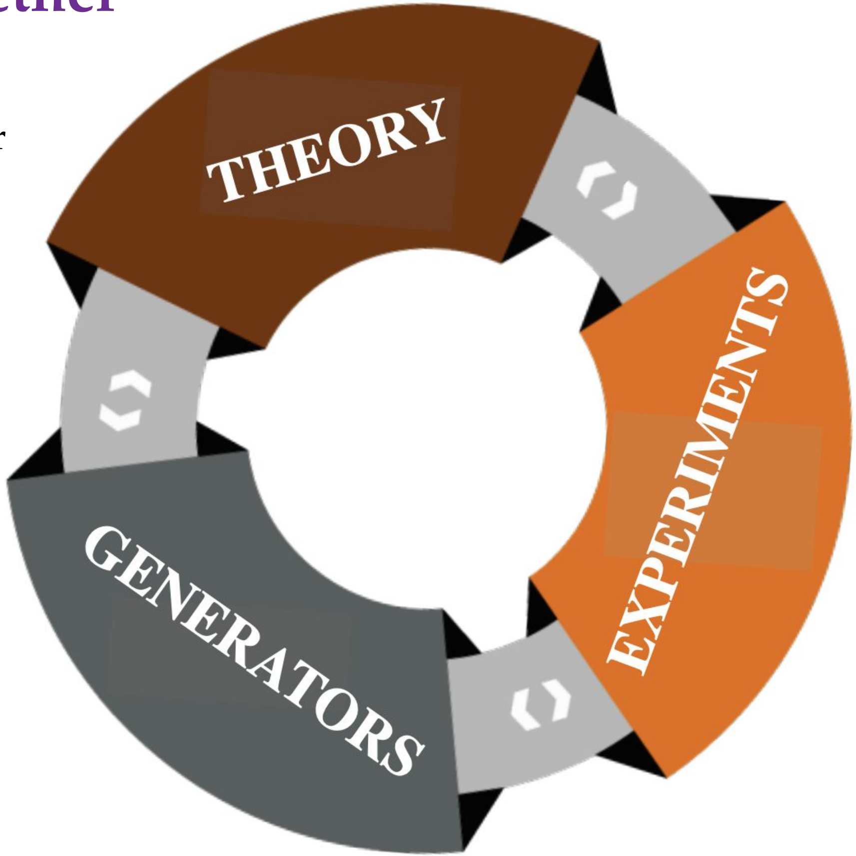
…m the reconstructed particles' momenta … you **infer neutrino energy:**

P(osc) ~ sin^2(L / E_ν)

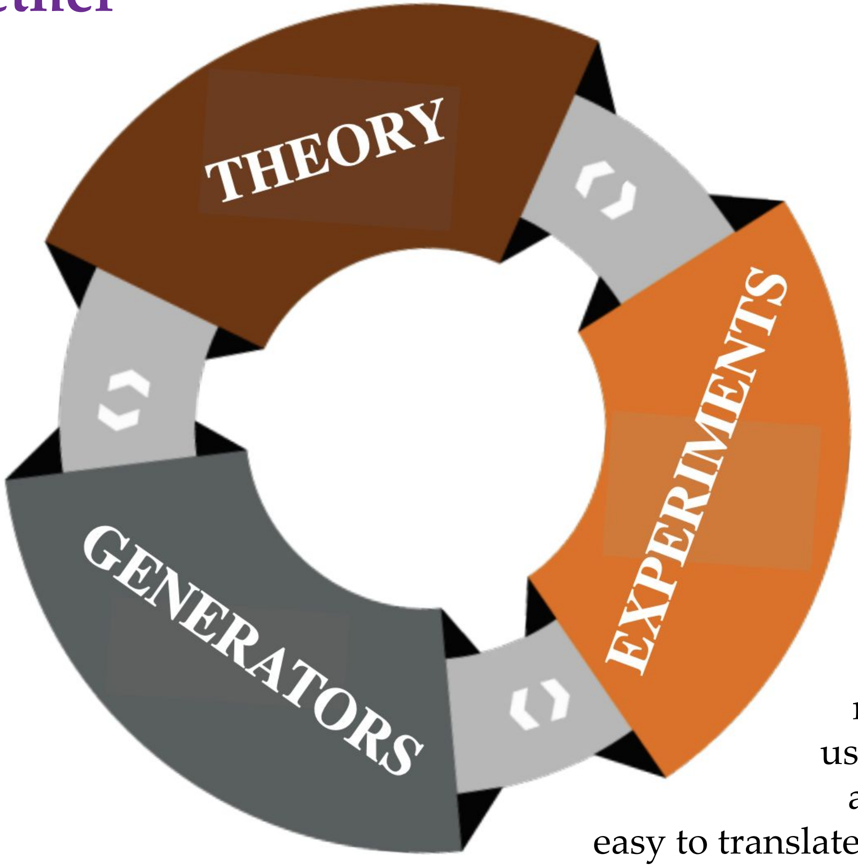
Cross-section models re… …ed p… (un-measurable) neutrinos we need to correctly predict the ν-N interaction as a function of energy

How WG2 plays together

Continuous improvement of our understanding neutrino interactions from the interplay between model development (theory & implementation) and cross section results.



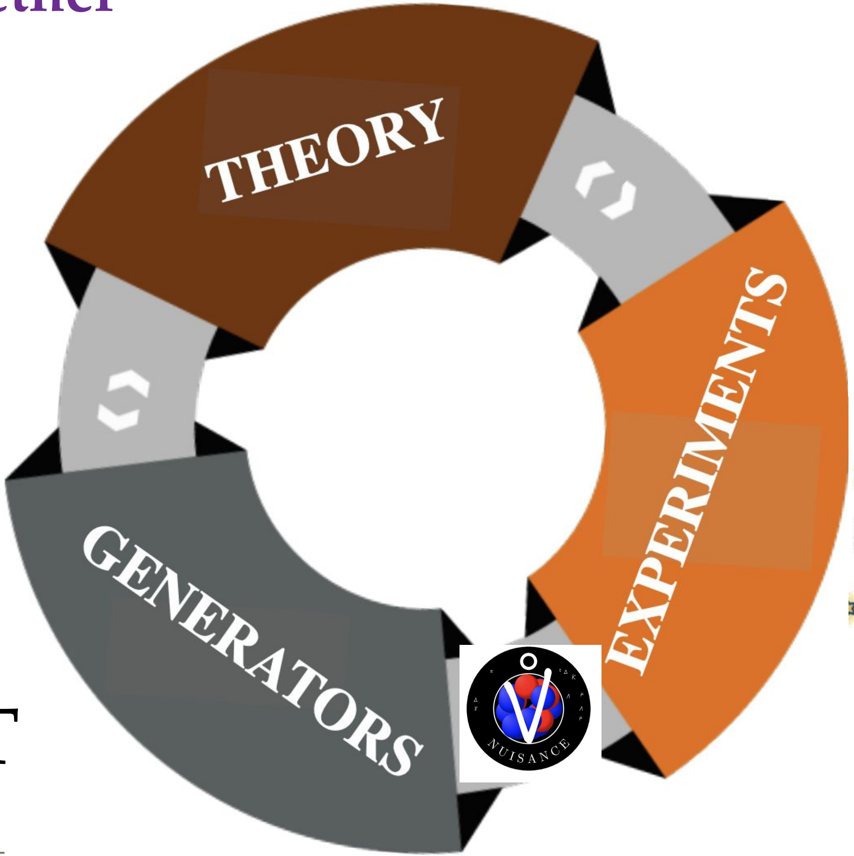
How WG2 plays together



Aim to perform measurements in a form useful for model building, and produce predictions easy to translate into usable observables

How WG2 plays together

28 talks,
o(15) posters



Achilles

Genie

NuWro
Wroclaw Neutrino Event Generator

NEUT

GiBUU
The Giessen Boltzma

NINJA

MINERvA

LHC
Scattering and Neutrino Detector at the LHC

SBN Program

NOvA

T2K

FASER

Elena Gramellini | elena.gramellini@manchester.ac.uk
MANCHESTER 1824
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Questions for our speakers

Questions for our speakers

1) How can we have more theory-based uncertainties, in particular for neutrino oscillation studies?

2) How can we incorporate state-of-the-art nuclear models, providing information on the hadrons, in generators?

3) How to use the wealth of experimental measurements already available and expected in the coming years to solve key issues in neutrino scatterings?

4) Which kind of experiments are needed to improve the modeling of neutrino-nucleus cross section?

5) What are the main reaction channels and, therefore, the main systematic uncertainties in oscillation experiments?

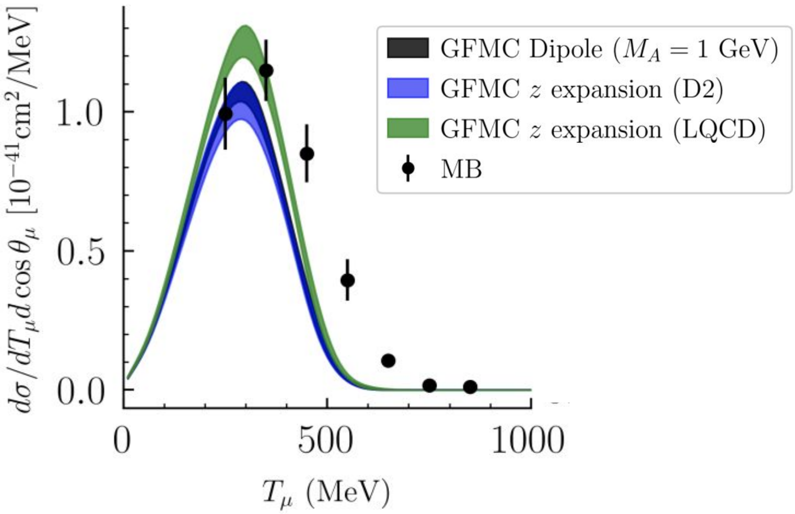
6) Can you highlight the unique experimental capabilities of your detector... and how that relates to important observables?

Q: How can we have more theory-based uncertainties?

Elena Gramellini | elena.gramellini@manchester.ac.uk

Uncertainties from theory…

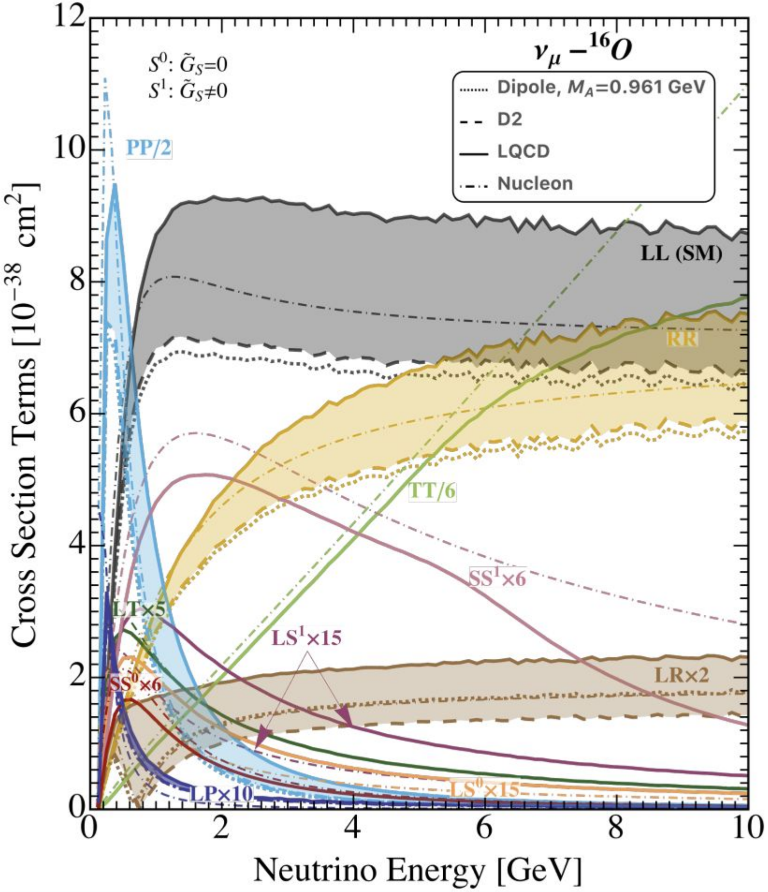
Noemi Rocco Uncertainties for ab-initio calculation with GFMC for MiniBooNE axial form factor



MiniBooNE	$0.2 < \cos\theta_\mu < 0.3$
GFMC Difference in $d\sigma_{\text{peak}}$ (%)	18.6

D.Simons, N. Steinberg, NR, et al arXiv:2210.02455

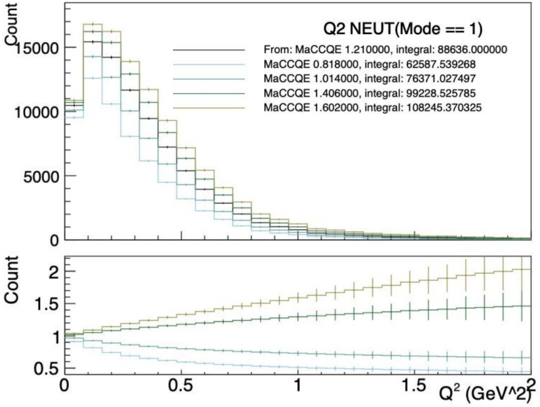
in the context of BSM



… to event generators (NEUT & GiBUU) …

NEUT
→ NEUT ReWeight: A critical tool for uncertainty propagation
→ for QE and Res1Pi form factors
→ for Pion and Nucleon cascade (w/ caveats)

→ NuHepMC early adopter



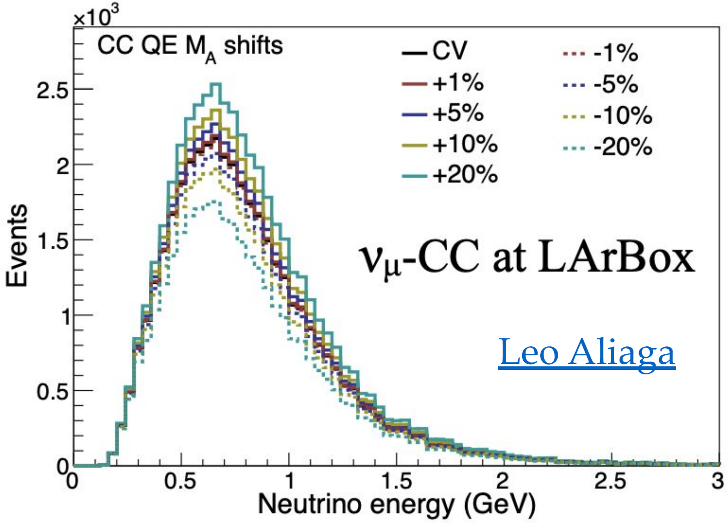
Luke Pickering

GiBUU event generator.

No tune to ν data →

can be used for refining systematics

Prof-of-principle: shift to M_A CC QE



… to experiments (ν-N interaction uncertainties in DUNE)

DUNE has completed a new (GENIE-based) baseline model → philosophy: introduce freedoms to cover all relevant wrongness, **prioritize flexibility**!

NuSystematics easy for DUNE and other experiments to use.

Big contributions from GENIE dev and MicroBooNE collab

Stephen Dolan: wish list of systematics to implement/already implemented

Ground state
Removal energy shape
SRC "tail" strength
Shell-like shape
q3 dependent shift

CCQE
Z-expansion parameters
RPA
Optical potential
Pauli blocking

2p2h
Normalisation
SuSAv2 to Valencia
Pair content
Energy dependence
Delta vs not delta
Nucleon ejection model

Resonant pion production
MA, Mv, Norm
Pauli blocking
RPA / Optical potential effects?
W shape
$\pi^{+/-}$ vs π^0 fraction tweaks
Resonance decay kinematics
Resonance broadening
…

SIS/DIS
Transition region strength
AGKY dials
Bodek-Yang parameters
Non-RES low W contrib.
Multiplicity modifications
Alternative model (AMU)
…

FSI
hA pion fate dials
hA nucleon fate dials
π abs. pair fractions
hA to hN, INCL, G4BC

Misc
NC norms
Coh shape+norm
nue/numu ratio
nue/nuebar ratio
Ad-hoc neutron ejection

… to experiments (ν-N interaction uncertainties in DUNE)

DU… …mplement/already implemented

…oduction

…ential effects?

… tweaks
…/ kinematics
…lening

…rength

…meters
…ntrib.
…cations
(AMU)

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Misc
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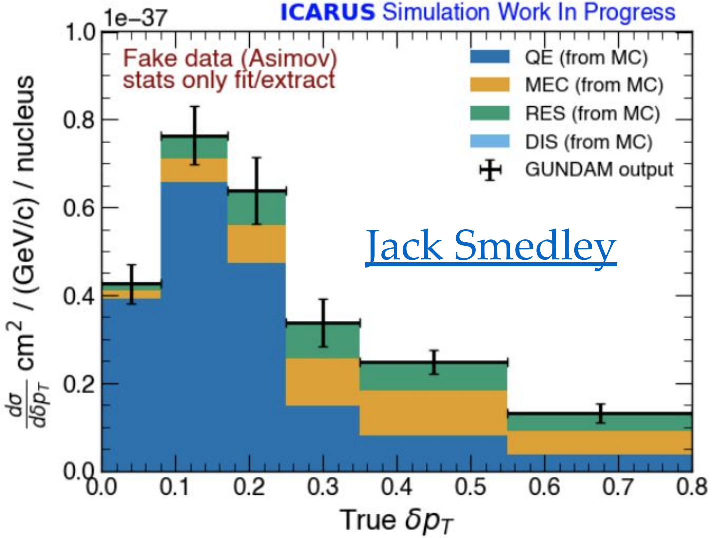
Ad-hoc neutron ejection

If you build (sharable systems), they will come

ICARUS → Unfolding and cross section extraction with GUNDAM, a binned maximum likelihood fitter developed within the T2K collaboration
→ **code is open-source**!

→ End-to-end extraction procedure validated on Asimov data, it works!



Jack Smedley

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Q: How can we incorporate state-of-the-art nuclear models in generators?

Q: How can we incorporate state-of-the-art nuclear models in generators?

- Clearly communicate what parts of the prediction are most important for your experiment/measurements
- Meet model-builders *at least* half way:
  - Well defined/documented interfaces
  - Generator developers need to *outreach* to model-builders groups
  - Push for state-of-the-art models to be used in data analysis once implemented
- **Make citing the models used by your generator easy!**

Luke Pickering

NuHepMC built-in tool

Elena Gramellini | elena.gramellini@manchester.ac.uk
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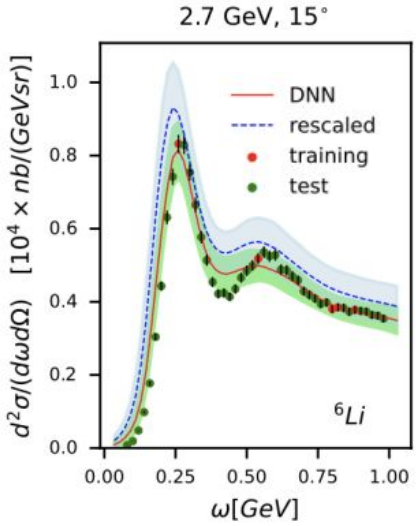
NuWro & GENIE

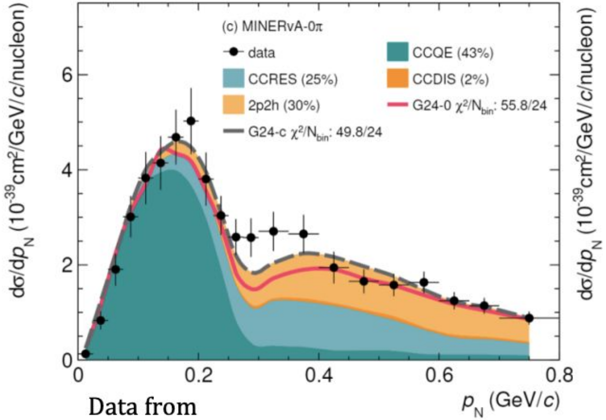
NuWro Highlight implementations:
→ Argon spectral function
→ Correction from nuclear effects affecting lepton
→ Exclusive MEC model
→ ML for reconstruction of model independent lepton-nucleus interaction



Hemant Prasad

GENIE Highlights:
→ New external FSI models
→ Upcoming MK single-pion model, and exotic long lived particles
→ Tuning: global fit to TKI data

John Plows

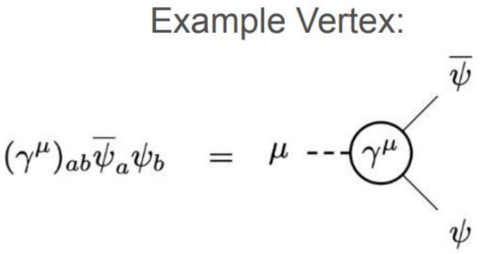


Data from
Phys Rev Lett 121 (2018) 022504
Phys Rev D 101 (2020) 092001

Achilles & Marley

Achilles Highlights:
→ Includes QE, Res, 1b2b interference
→ Novel intranuclear cascade
(w/ π interactions and absorption)
→ Automating BSM via Universal Feynman Output

→ NuHepMC early adopter



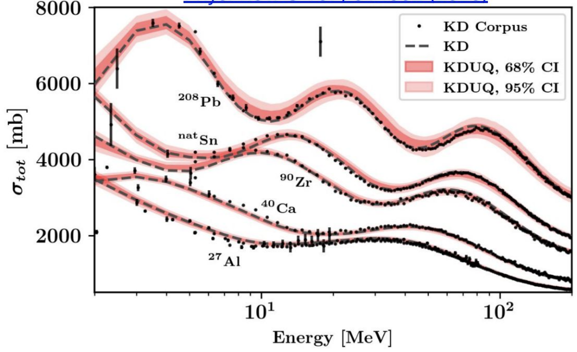
Joshua Isaacson

Marley (Focused on MeV scale)
Highlight implementations:

→ HF-CRPA model for energy continuum of high-lying nuclear states
→ Nuclear de-excitation model
→ Optical potential uncertainties

→ NuHepMC early adopter

Phys. Rev. C 107, 014602 (2023)



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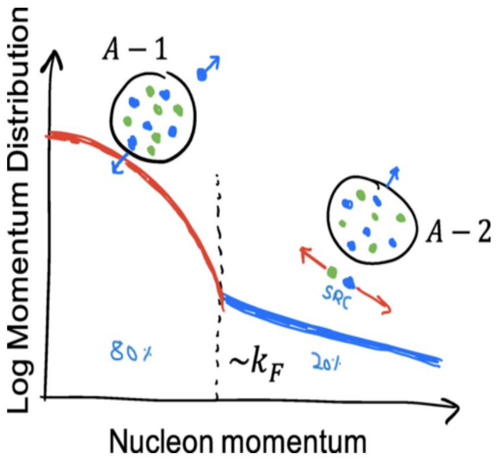
Q: Which kind of experiments/measurements are needed to improve the modeling of neutrino-nucleus cross section?

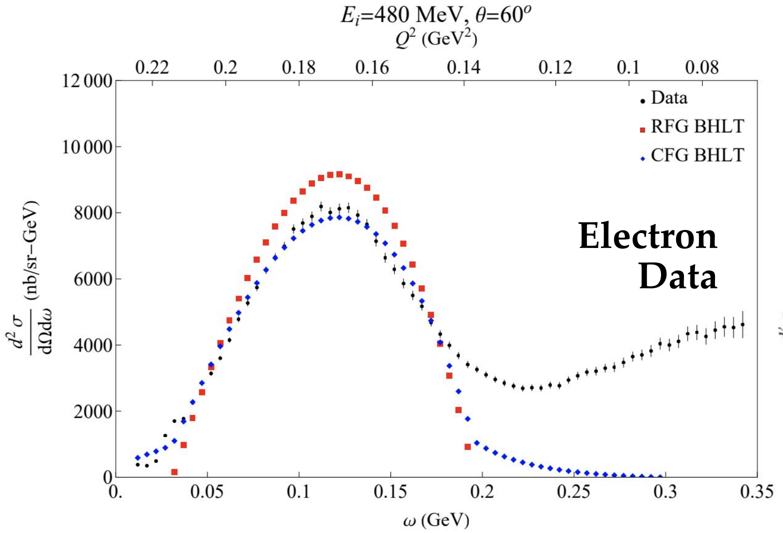
A: e-N scattering data complementing ν-N scattering: we gotta pin down the **V-** before we try to measure the **-A**

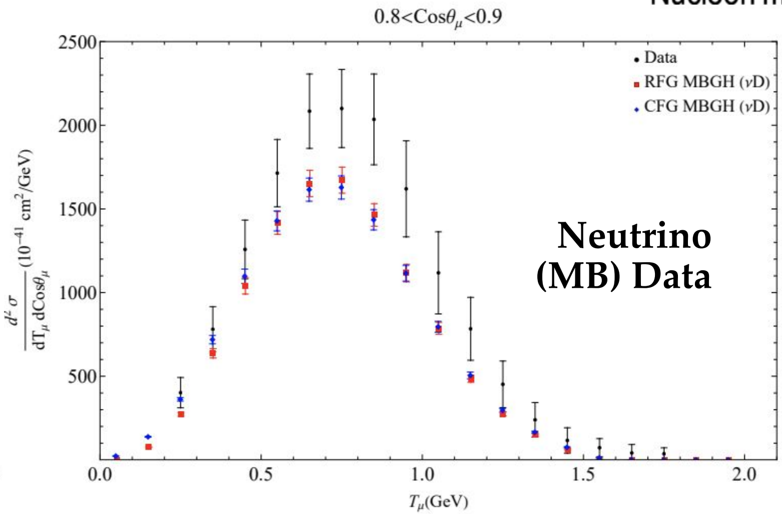
Improving nuclear models

Sam Carey **Correlated Fermi Gas Model:** a more realistic description of the dynamic of the target nucleus wrt **Relativistic Fermi Gas** model

Fully analytic implementation of CFG model for CCQE lepton (e, ν)-nucleus scattering. Appreciable difference in e-scattering.
In ν case, the difference between CFG and RFG predicted form factors is washed out.







Improving nuclear models

Tania Franco Munoz **Relativistic mean-field** based model with **one-** and **two-body current** contributions to the 1p-1h excitation represents a more realistic treatment of the nuclear structure.

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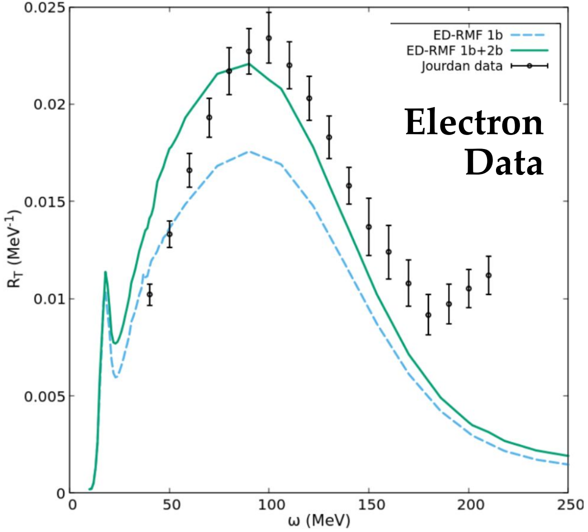
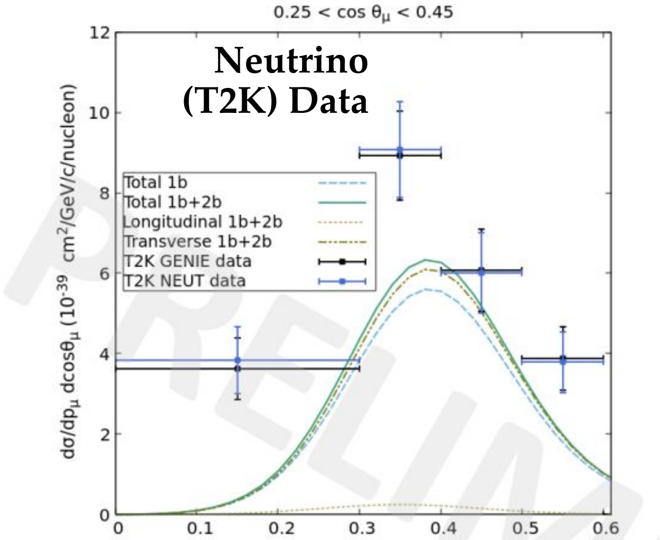
Electron-nucleus results → cross sections are, in general, well reproduced (better control of shell model occupations is still needed)

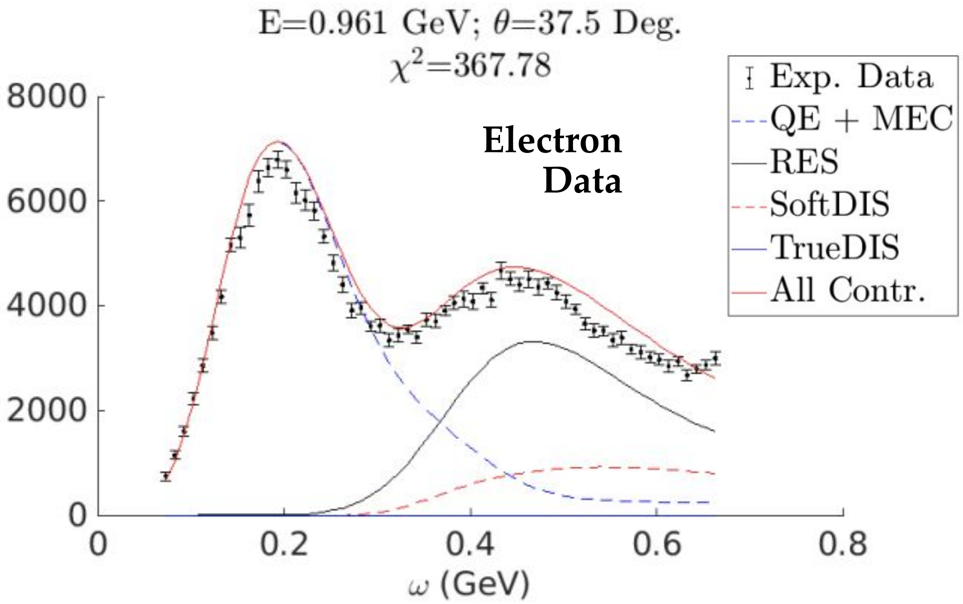
Neutrino-nucleus cross sections → are mostly transverse, the effect of two-body currents is significant.

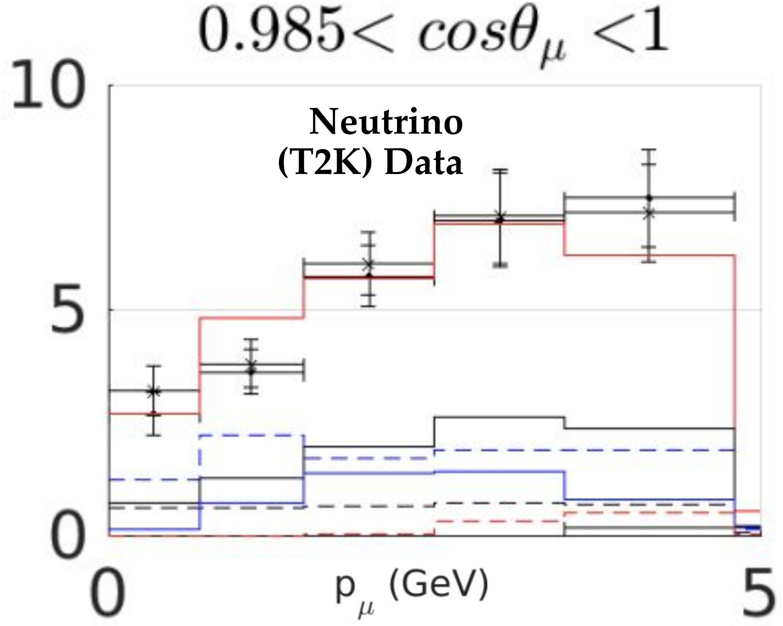




Improving nuclear models

Jesus Gonzales-Rosa The superscaling model (SuSAv2) model takes into account the complexities of nuclear structure, so far mainly used in QE. **SuSAv2-inelastic**: model expansion to describe the full inelastic spectrum (Δ, other res., DIS). At forward angles, the contributions of SoftDIS and TrueDIS get larger and become crucial to explain the experiment. The overestimation at lower momentum can be corrected using **Relativistic Mean Field**

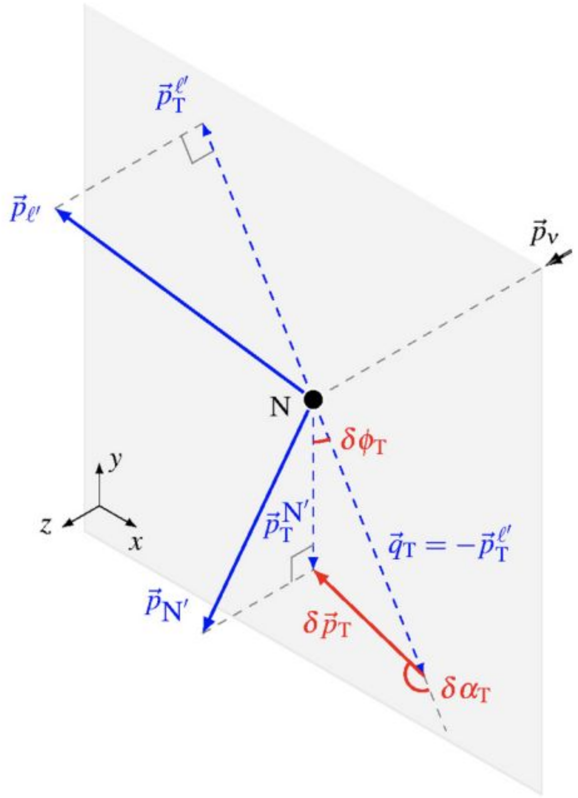




Q: Which kind of experiments/measurements are needed to improve the modeling of neutrino-nucleus cross section?

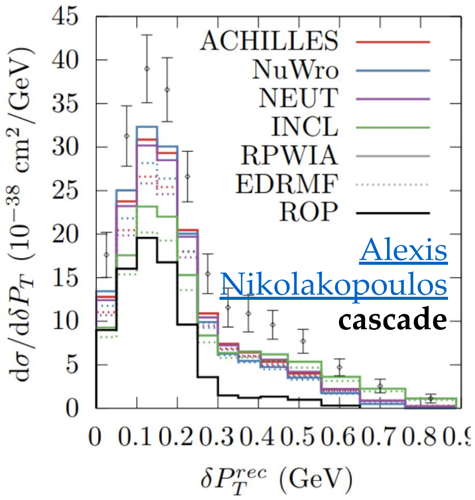
A: ν-XS focusing on specific portions of the model… & tension!

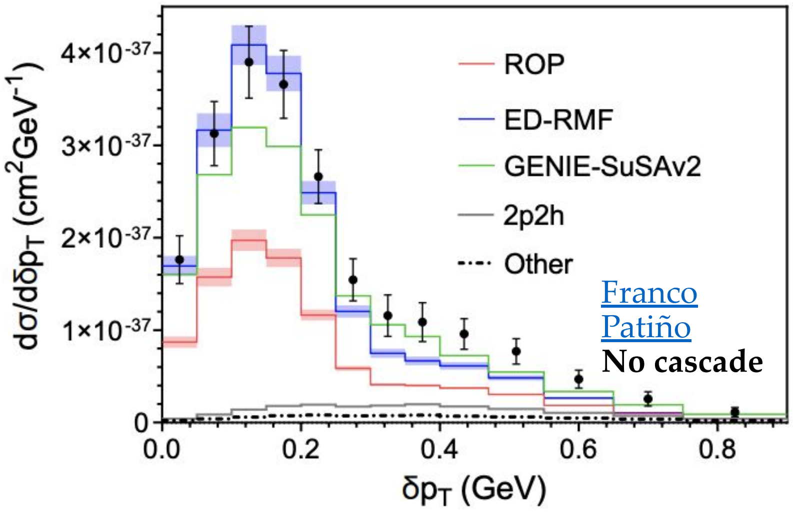
TKI : transverse kinematic imbalance variables



TKI have the potential to disentangle FSI vs non-FSI

1μ1p selections: variables that measure **correlations between both particles in the final state** allow us to discriminate between nuclear models and separate contributions from different channels.





Relativistic Distorted Wave Impulse Approximation (RDWIA) → cause unfactorized relativistic and fully quantum approach extensively applied in e-scattering.

FSI in our theoretical models improves general agreement with experimental data.
<u>**Smearing effects make comparisons difficult**</u>

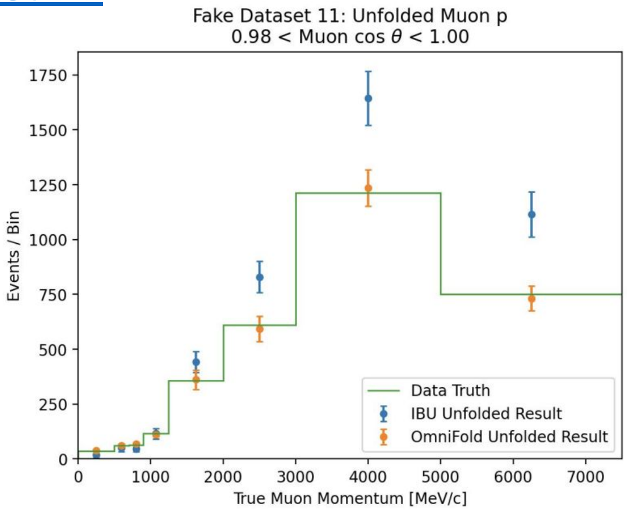
non-FSI

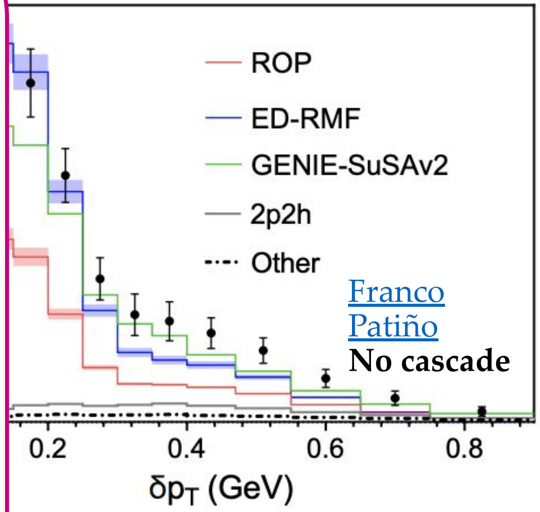
Omnifold is a new ML assisted idea for unfolding Andrew Cudd

Iterative unfolding procedure:

1. Reweight reconstructed MC distribution to (better) match data

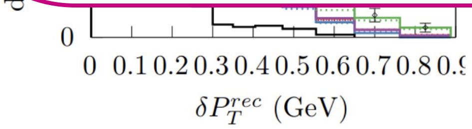
2. Reweight nominal truth MC distribution to incorporate information from step 1





Franco Patiño
No cascade

e Approximation (RDWIA)
d fully quantum approach

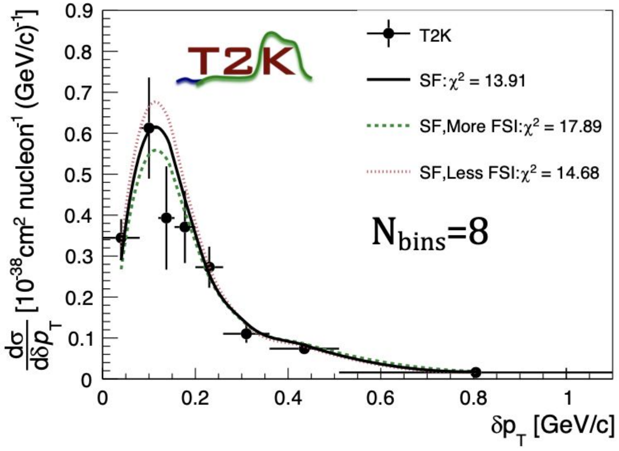


FSI in our theoretical models improves general agreement with experimental data.
Smearing effects make comparisons difficult

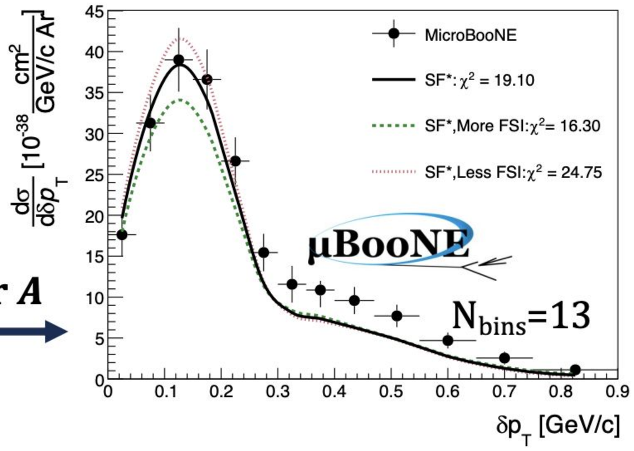
Comparative analysis of TKI variables for CC0π1p in T2K, MicroBooNE, Minerva

Same (w/ caveats) exclusive observables measured by **T2K, MicroBooNE, Minerva**
→ Exploiting complementarity to lift degeneracies!

Potential issues with: 2p2h A-scaling, nucleon FSI strength, physics beyond PWIA.
No single model or configuration is capable of describing
global neutrino scattering measurements



Higher *A* →



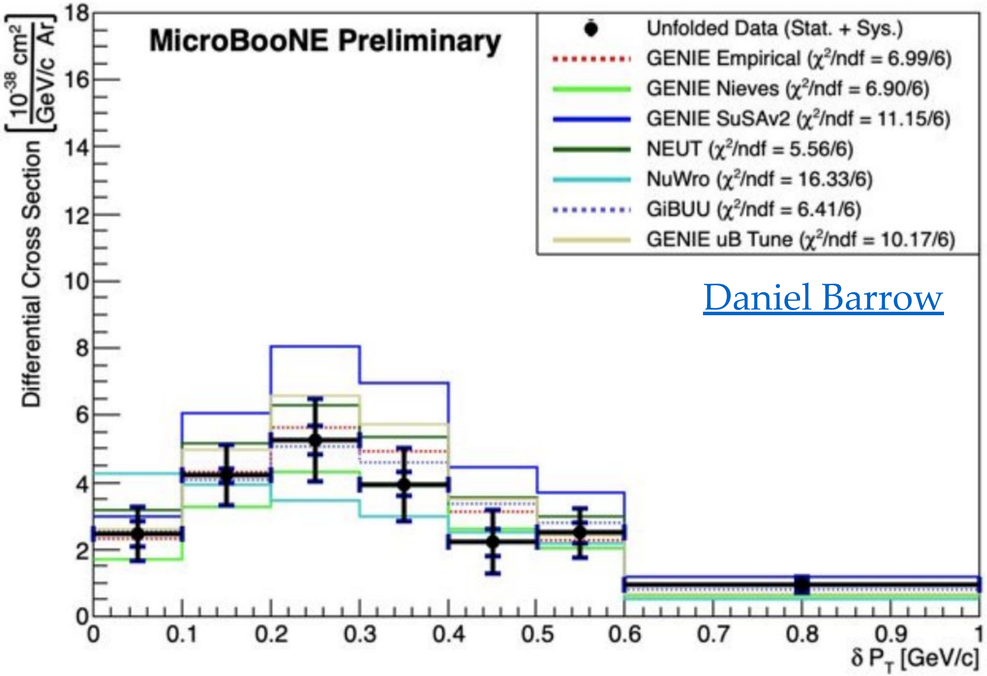
Laura Munteanu

More TKI: CC2p0π (MicroBooNE)

TKI variables calculated w/ sum of the two proton momentum

LArTPC: very low proton threshold (300 MeV/c)
→ proton kinematics particularly sensitive to modeling choices

Conclusions:
→ Observe model/data disagreements in shape and normalisation
→ SuSAv2 normalisation is over-predicted
→ NuWro peaks in lowest values of δPT



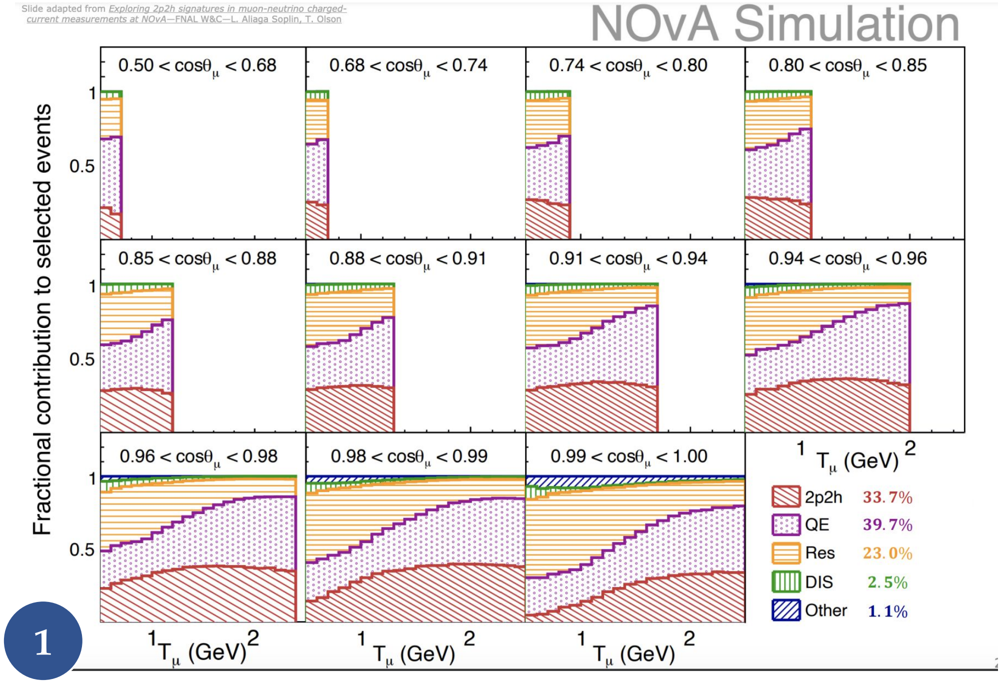
Daniel Barrow

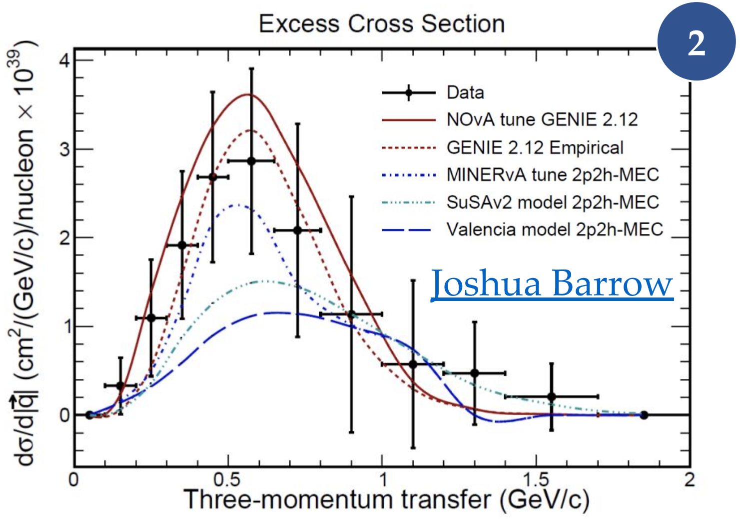
MICROBOONE-NOTE-1133

2p2h-Focused Cross Sections w/ inclusive ν_μ CC (NOvA)

Two inclusive measurements with strong 2p2h contributions

Slide adapted from *Exploring 2p2h signatures in muon-neutrino charged-current measurements at NOvA—FNAL W&C—L. Aliaga Soplin, T. Olson*





Joshua Barrow

Tensions again observed wrt. to SuSAv2 & Valencia

Particularly true at low hadronic energy and medium momentum transfer

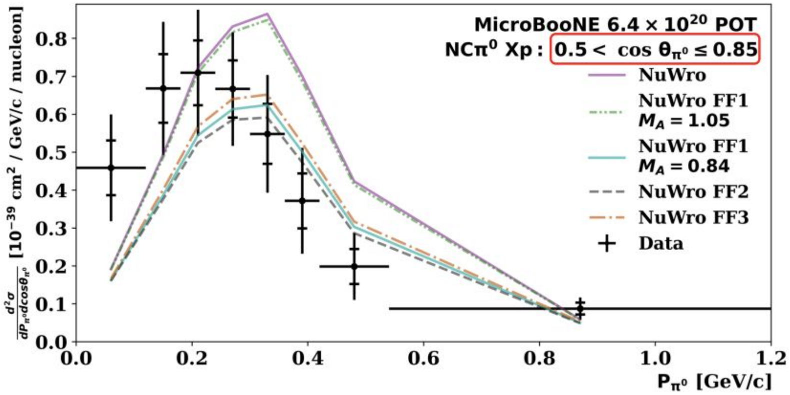
Speaks to needs for improved QE & 2p2h modeling

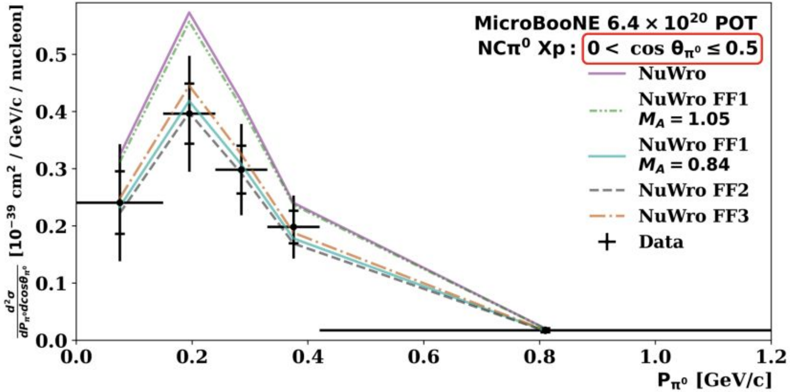
And let's not forget the pions…

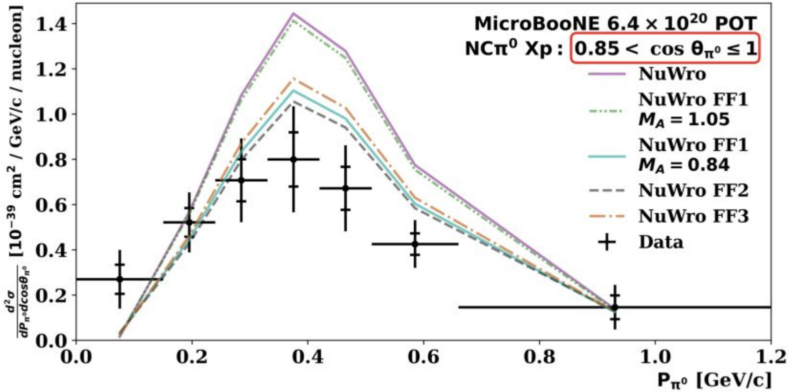
MicroBooNE Patrick Green **first double-differential cross-section measurement in π0 kinematics** (momentum, angle):

- systematic overprediction compared to data

- enhanced sensitivity to mis-modelling in different regions of phase space: sensitivity to form factor modeling & hadron re-interactions







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Q: Which kind of experiments/measurements are needed to improve the modeling of neutrino-nucleus cross section?

A: Disentangle XS & Flux effects

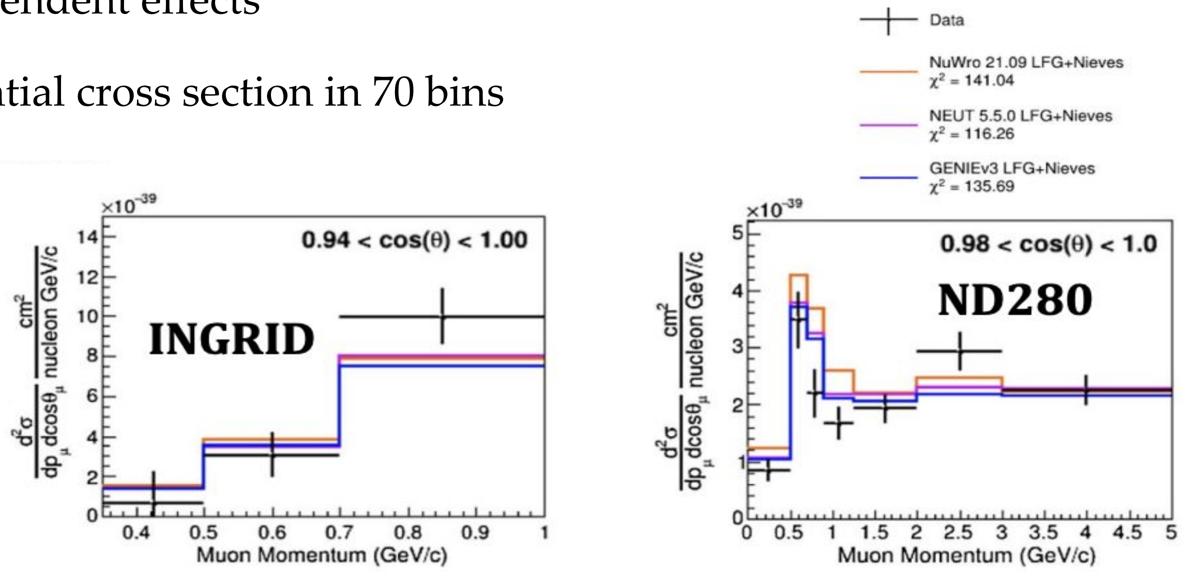
Prism-like measurement: Joint on-/off-axis $\nu\mu$ CC0π @T2K

Joint on-/off-axis ν_μ CC0π measurement w/ ND280 + INGRID.
→ the measurement aim at disentangling
XS and flux energy dependent effects

→ Results reported as 2D differential cross section in 70 bins
kinematics (p_{μ}, $\cos\theta_\mu$)

Future:
adding WAGASCI detector
(first CC0π measurement
on CH & H_2O performed!)

More detectors, more prism!



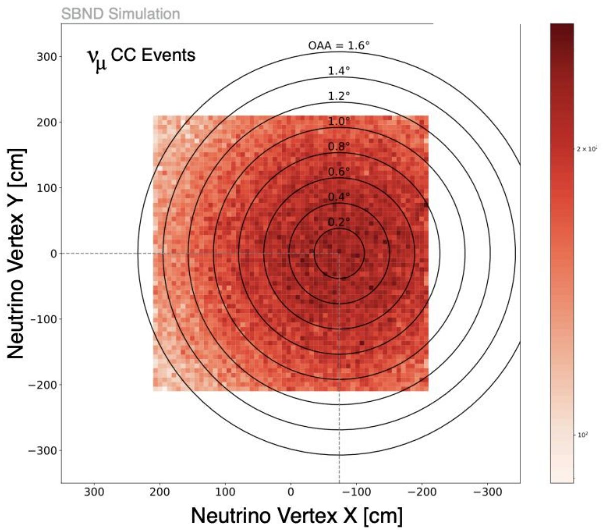
[Laura Munteanu]

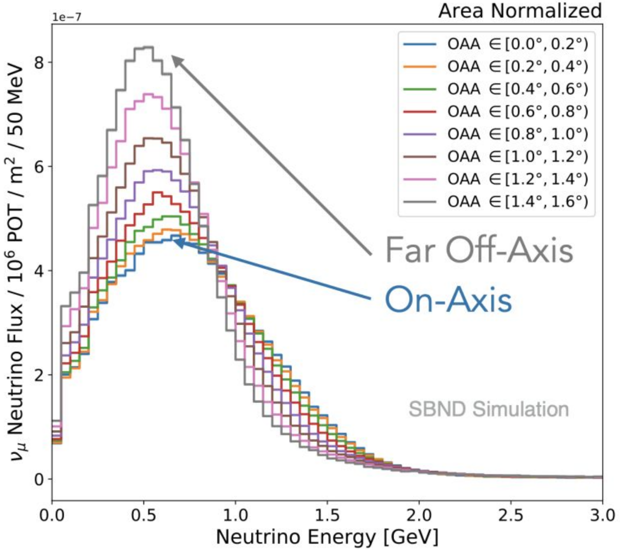
Prism-like measurement in single detector: SBND

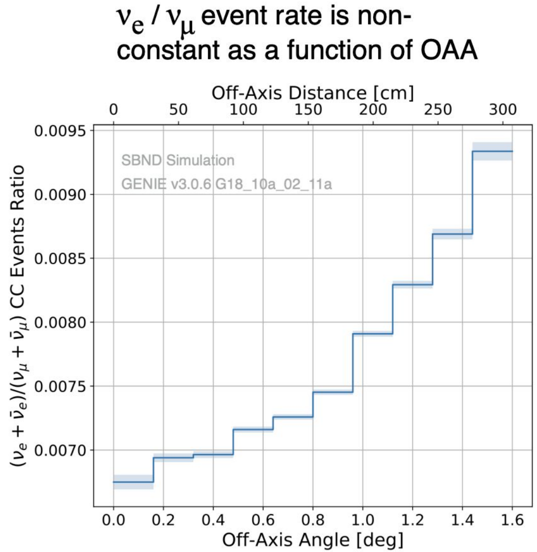
SBND detector @ 110 m from BNB source: on-axis and off-axis at the same time.

Use a fixed detector (same technology, same nucleus!) to samples multiple off-axis fluxes

[Leo Aliaga]





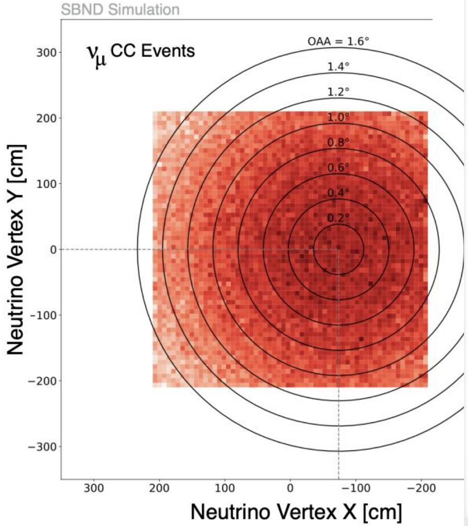


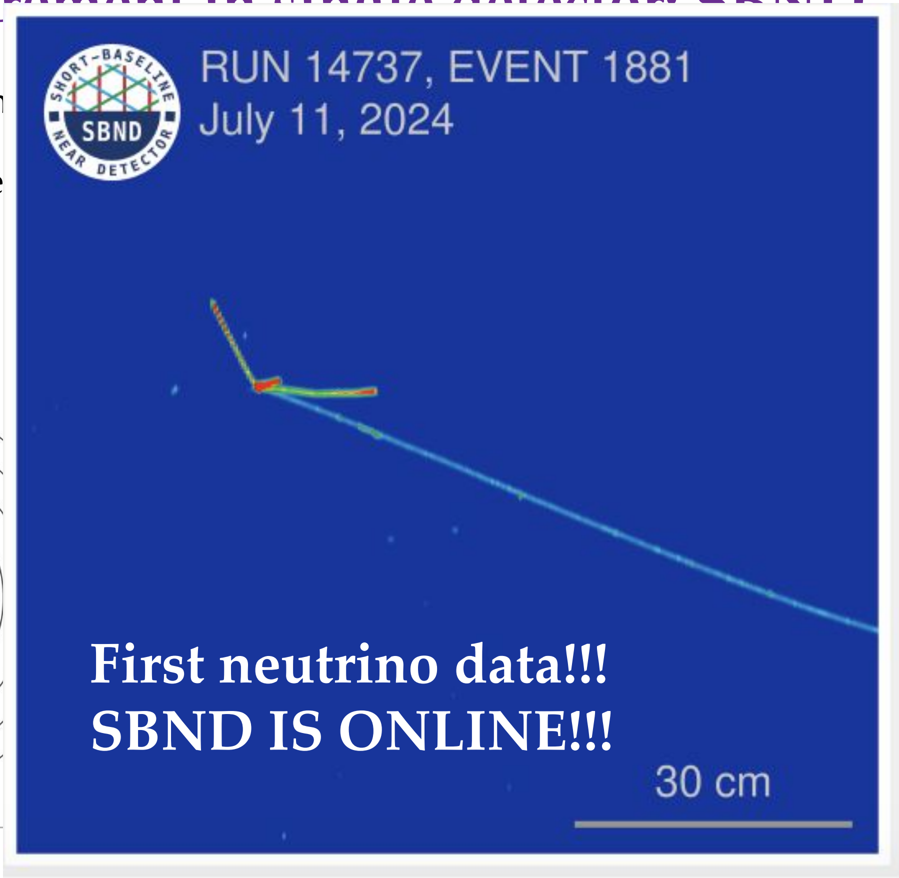
Prism-like measurement in single detector: SBND

SBND detector @ 110 m from

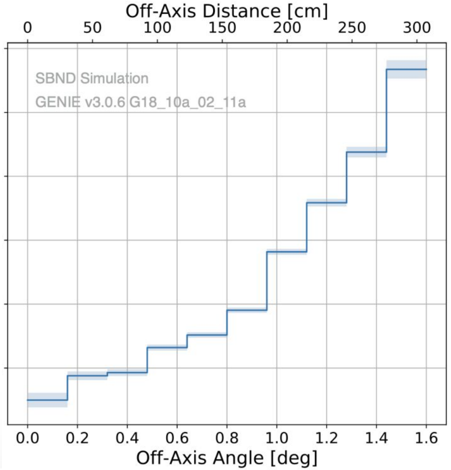
Use a fixed detector (same te ... luxes

[Leo Aliaga](#)





ν_e / ν_μ event rate is non-constant as a function of OAA



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Q: How can we use the wealth of experimental measurements already available and upcoming to solve key issues in neutrino scatterings?

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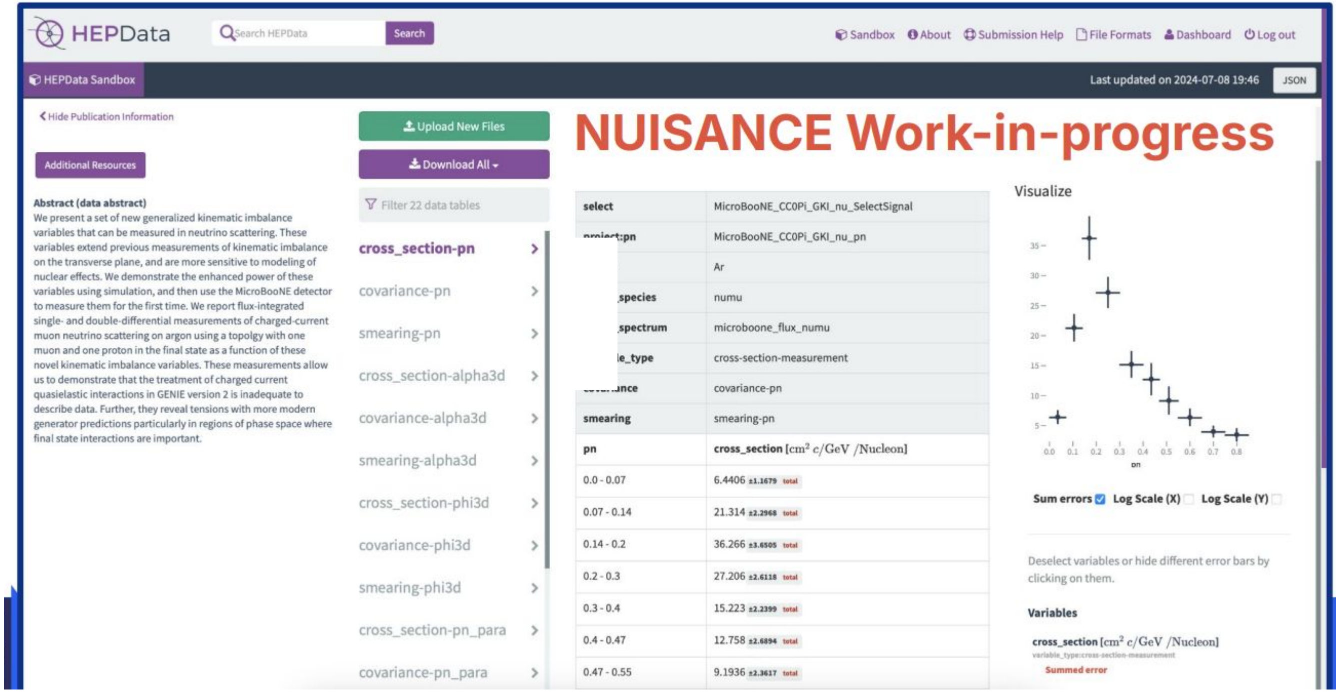
Common XS frameworks

Luke Pickering

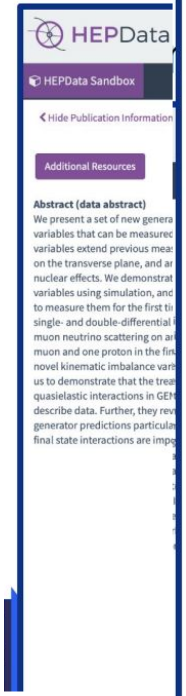
NUISANCE aims to provide a coherent framework for comparing neutrino generators to external data. NUISANCE can also tune cross-section parameters to available data.

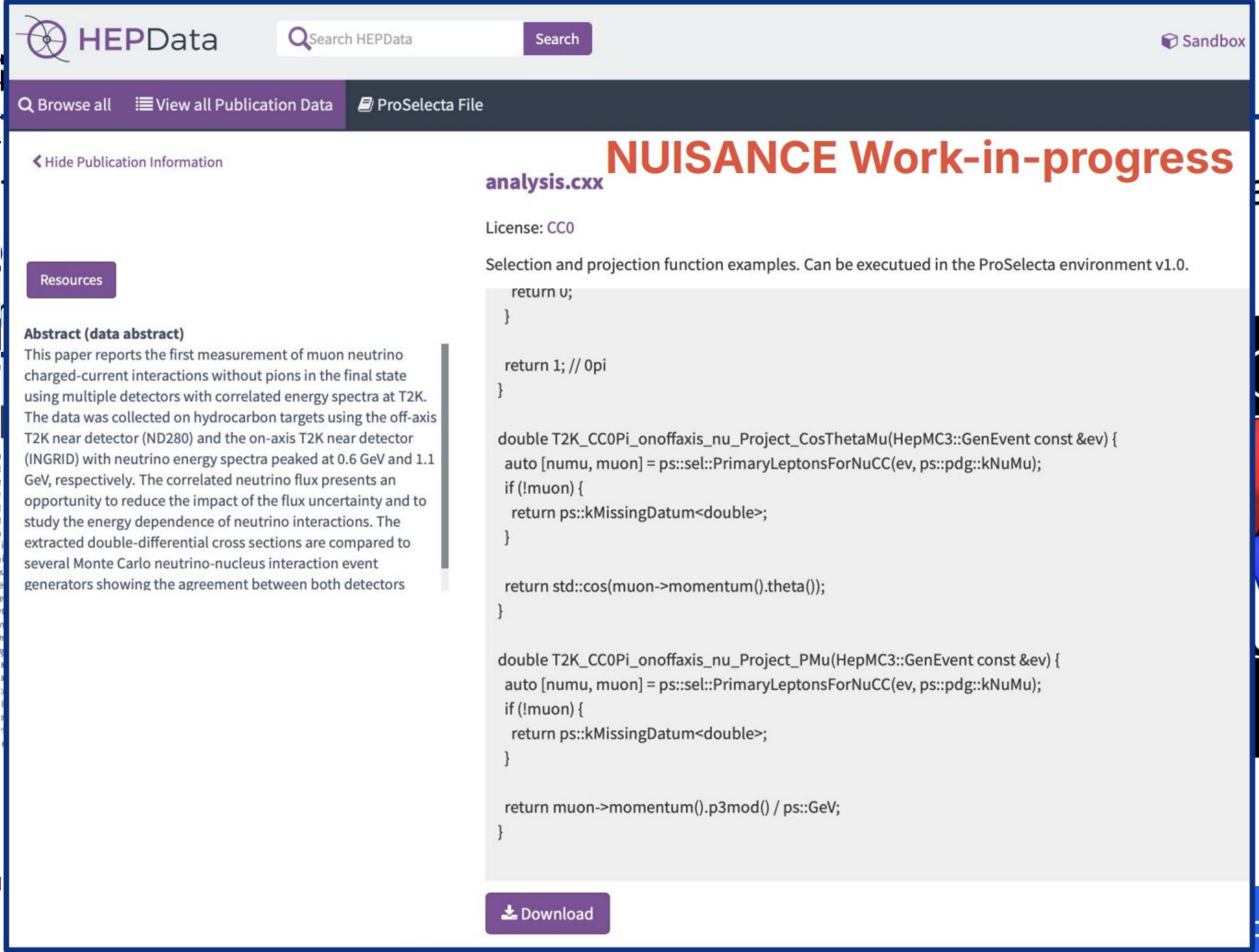


Comm… …ering

NUISANC… …s to

external d…





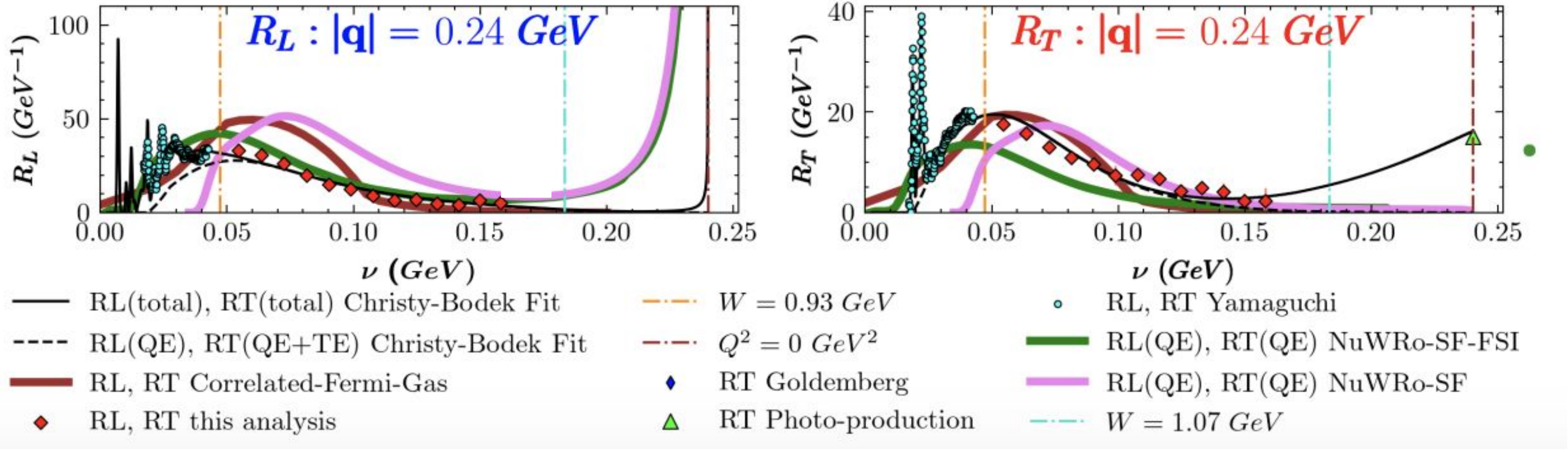
Christy-Bodek Universal Fit to e-scattering data

Zihao Lin

Fit large data set electron nucleus scattering (even more now, including H,D, nuclear targets)

Vast kinematic range, both longitudinal and transverse contributions

⇒ fine grain validation and tune MC generators + test first-principle nuclear theories.



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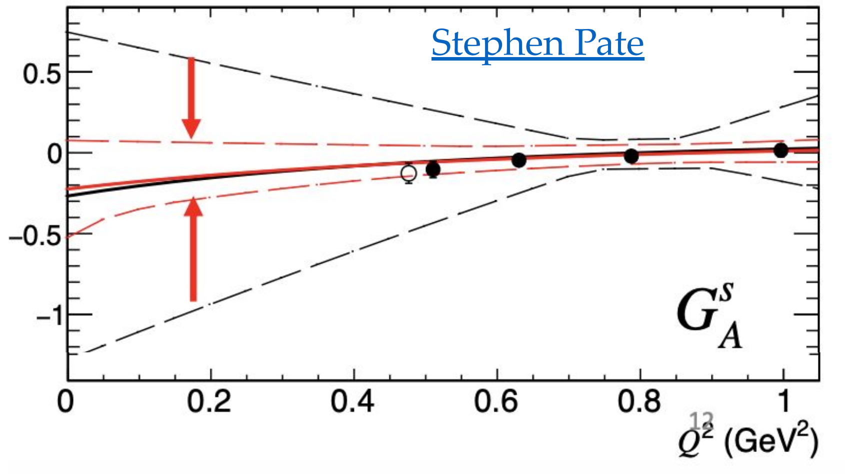
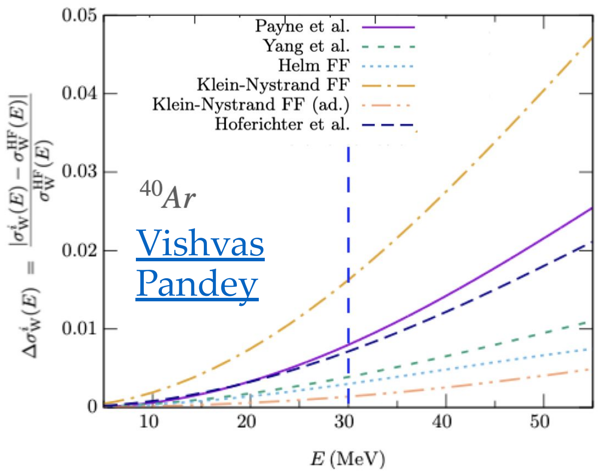
Axial form factors



Goal: determine the Q^2-dependence of the strange axial form factor and s-quark content from elastic electron and neutrino scattering data globally available. (accessible only from neutral current)

Inclusion of MiniBooNE data in the analysis (red dashed fit)
→ huge reduction of uncertainties in G_A^s measurement

Microscopic calculations + future precise measurements of CEvNS XS and PVES asymmetry will enable precise determination of weak form factor and neutron distributions.



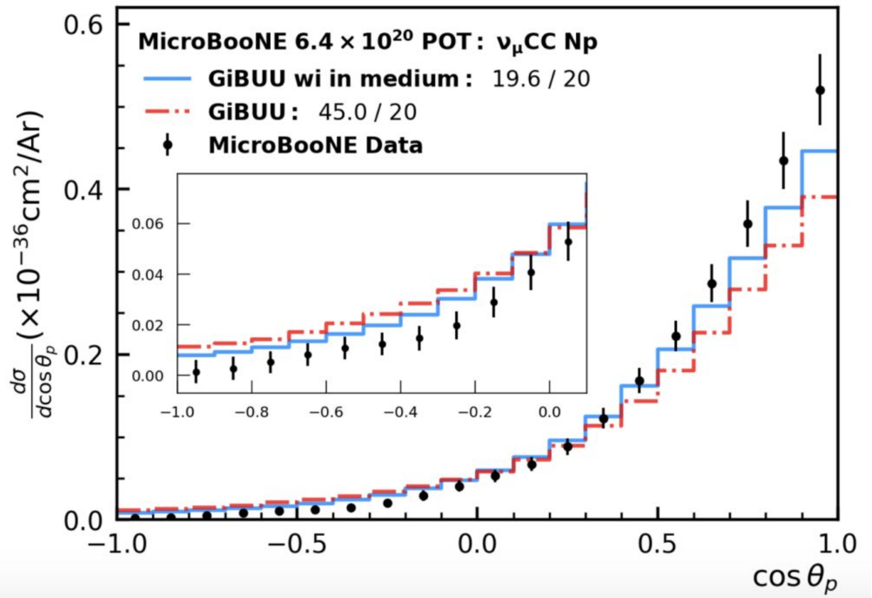
Constraining 10s of MeV elastic ν-N scattering (CEvNS) cross sections are important for probing new physics in CEvNS experiments.

A new look at FSI

In **medium effects** account for the **change in the N-N interaction cross section** when computed **within** the nuclear medium → modify FSI description
Can be tested in existing data!

ν_μ CC inclusive

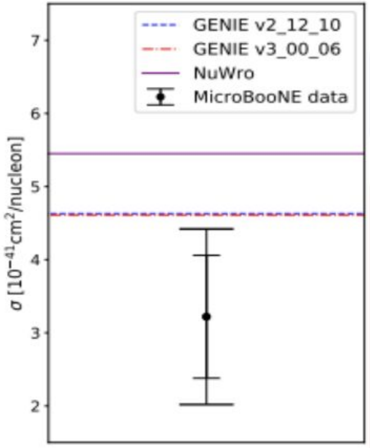
Ben Bogart



Eta production modeled inside the nuclear medium,

$\langle\sigma\rangle = (3.22 \pm 0.84 \pm 0.86) \times 10^{-41}$ cm²/nucleon

Atika Fatima



- $\langle\sigma\rangle_{\mathrm{free}} = 1.87 \times 10^{-41}$ cm²/nucleon
- $\langle\sigma\rangle_{^{40}\mathrm{Ar}} = 1.78 \times 10^{-41}$ cm²/nucleon

- GENIE *v*2_12_10: 4.63×10^{-41} cm²/nucleon
- GENIE *v*3_00_06*G*18_10*a*_02_11*a*: 4.61×10^{-41} cm²/nucleon
- NuWro 19.02.1: 5.45×10^{-41} cm²/nucleon
- NEUT v5.4.0: 11.9×10^{-41} cm²/nucleon

Phys. Rev. Lett. 132, 151801 (2024)

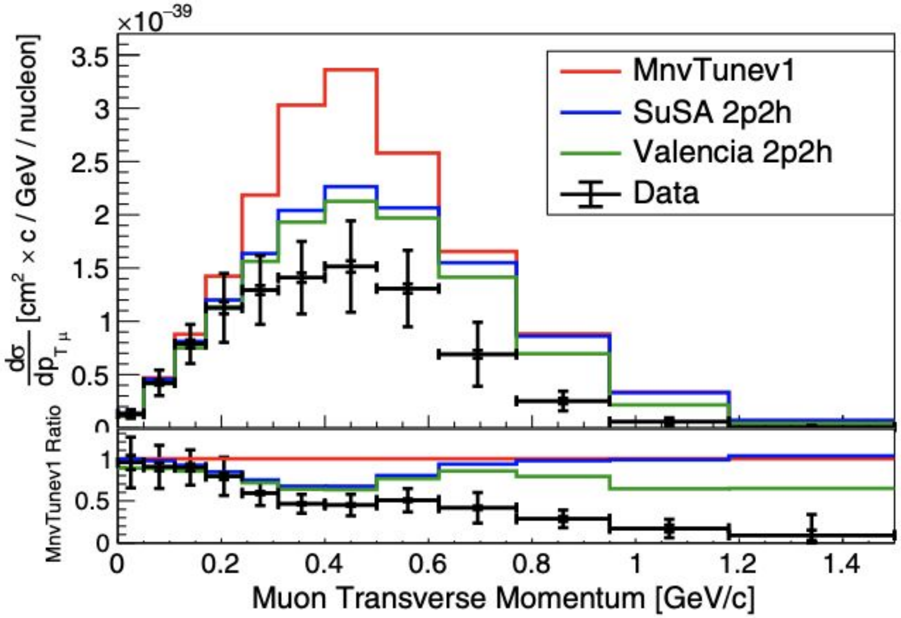
Q: Highlight the unique experimental capabilities of your detector…

… what new information can you bring?

When the detector can "see" neutrons: Multi-neutron cross section in Minerva

Neutrons are an important source of energy reconstruction bias for oscillation experiments

Minerba Betancourt



→ MINERvA can detect neutrons efficiently: cross section for an antineutrino to produce multiple neutrons in the final state and no more than 100 MeV of available energy

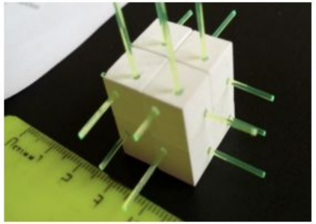
→ Multi-neutron cross section for a sample dominated by 2p2h and FSI-rich

→ Many leading models do not agree with data!

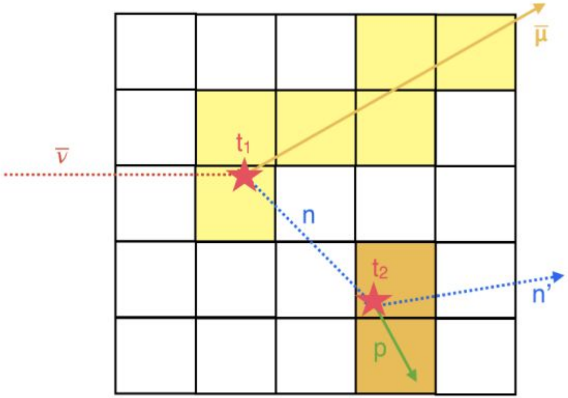
Elena Gramellini | elena.gramellini@manchester.ac.uk

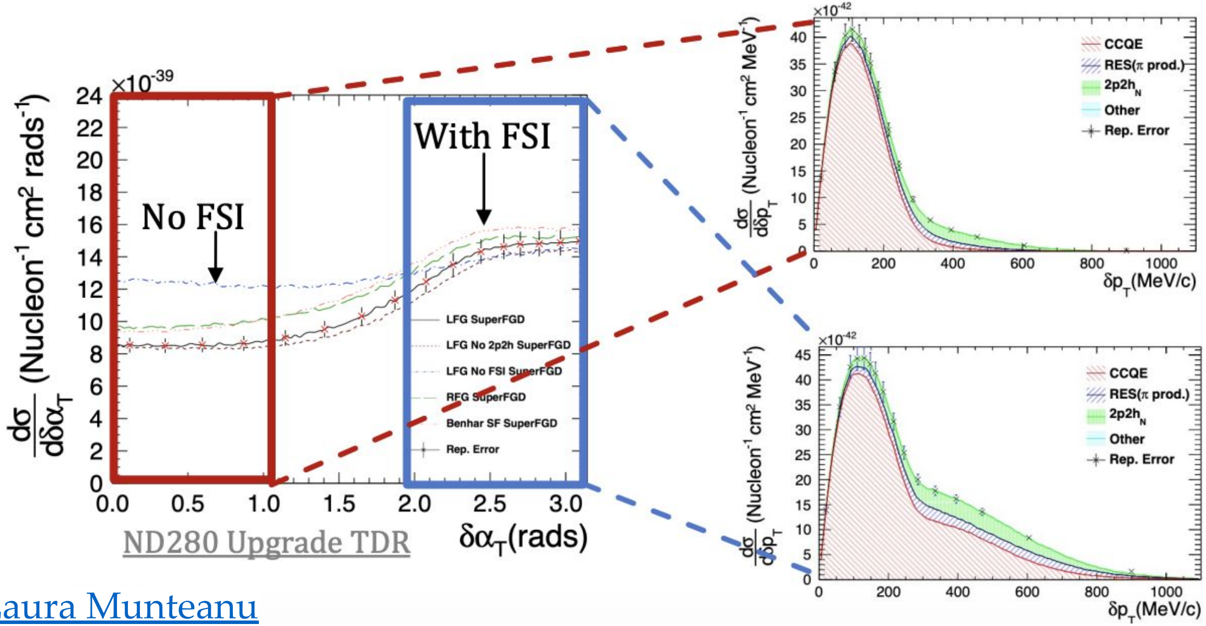
When the detector can "see" neutrons: T2K ND upgrade

ND280 Upgrade TDR



T2K ND280 upgrade with SuperFGD:
protons with ~30 MeV (~300 MeV/c) threshold and **neutrons!**
→ Measuring E_{miss} via neutrons & scattering off free protons



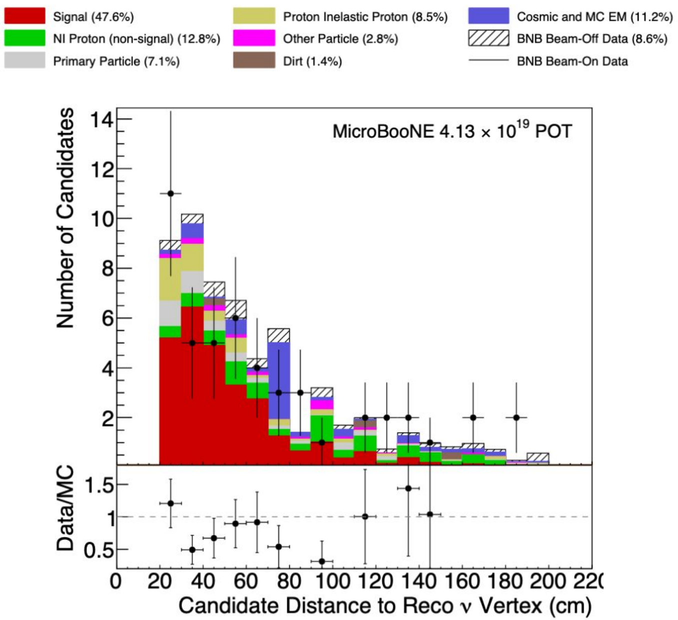


Laura Munteanu

When the detector can "see" neutrons: LArTPCs

MicroBooNE Patrick Green

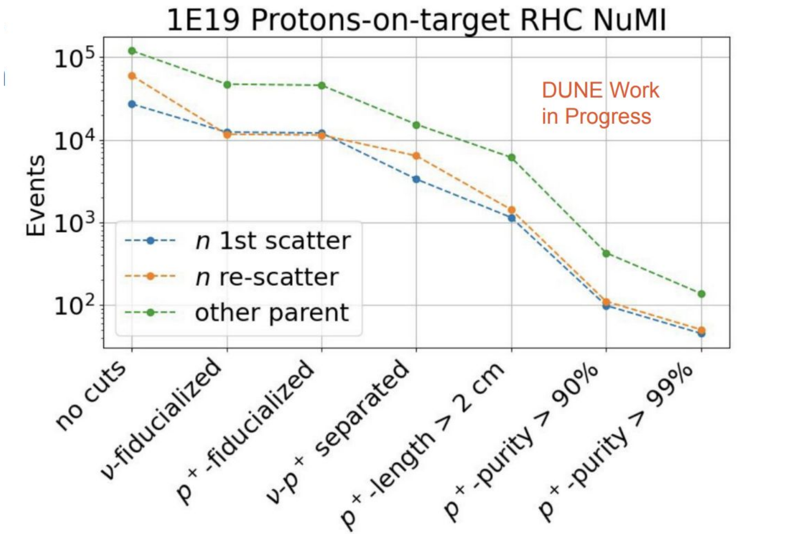
ID method: detection of secondary protons (**charge**)
→ 48% purity for primary neutrons



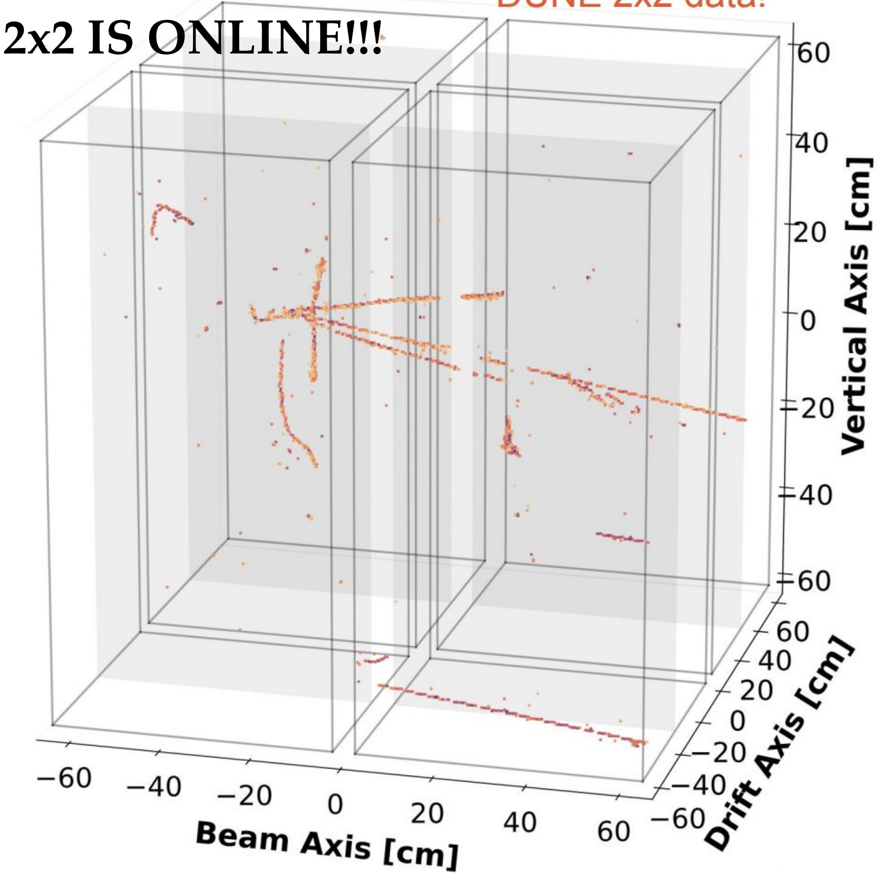
2x2 Demonstrator Andrew Cudd

Pixel-based LArTPC w/ optically separated modules optimized to DUNE ND high event rate

Light signal used to identify neutron scattering kinetic energy from neutron time-of-flight



First neutrino data!!!
2x2 IS ONLINE!!!



...ns: LArTPCs

2x2 Demonstrator [Andrew Cudd]

Pixel-based LArTPC w/ optically separated modules optimized to DUNE ND high event rate

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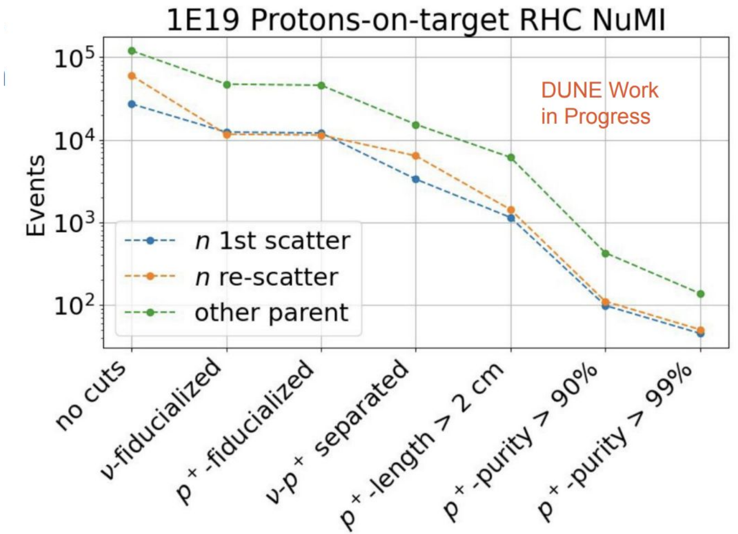
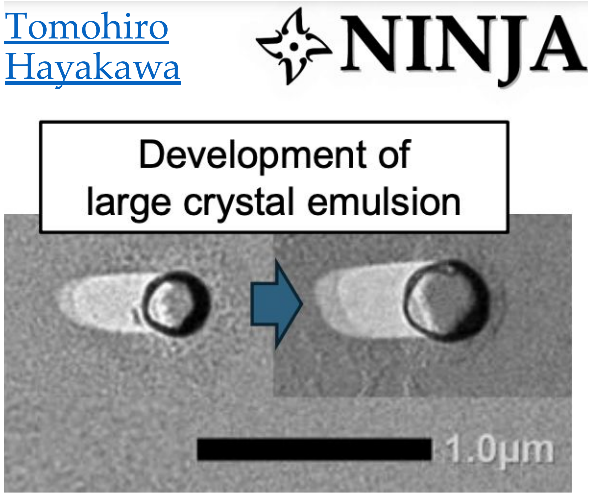


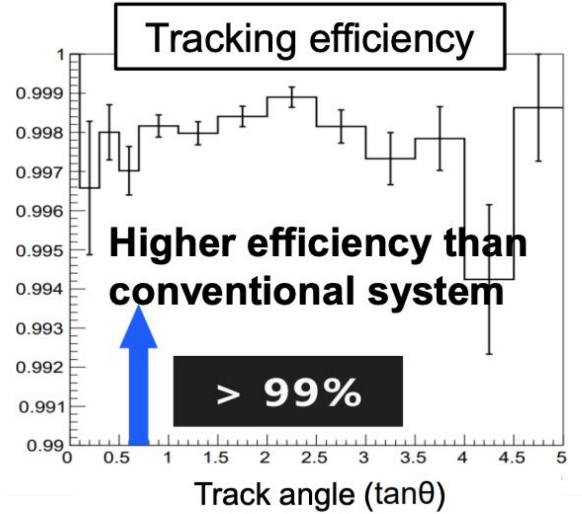
Elena Gramellini | elena.gramellini@manchester.ac.uk

NINJA: the power of fine tracking emulsions

Tomohiro Hayakawa



200 MeV/c proton momentum threshold



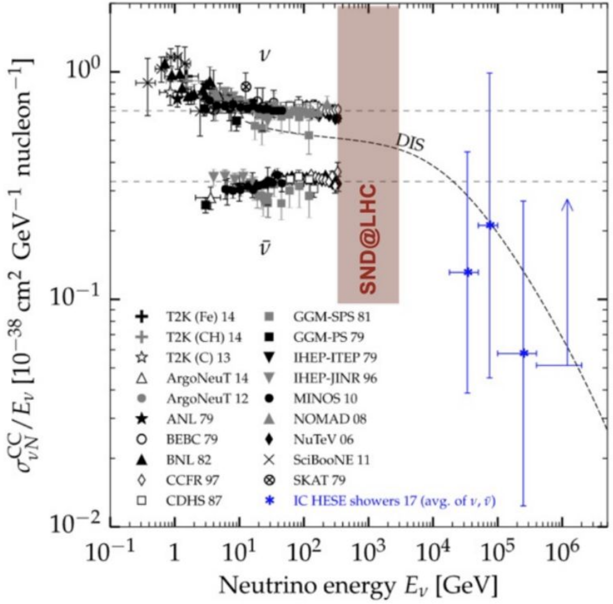
next-to-the-vertex interaction physics

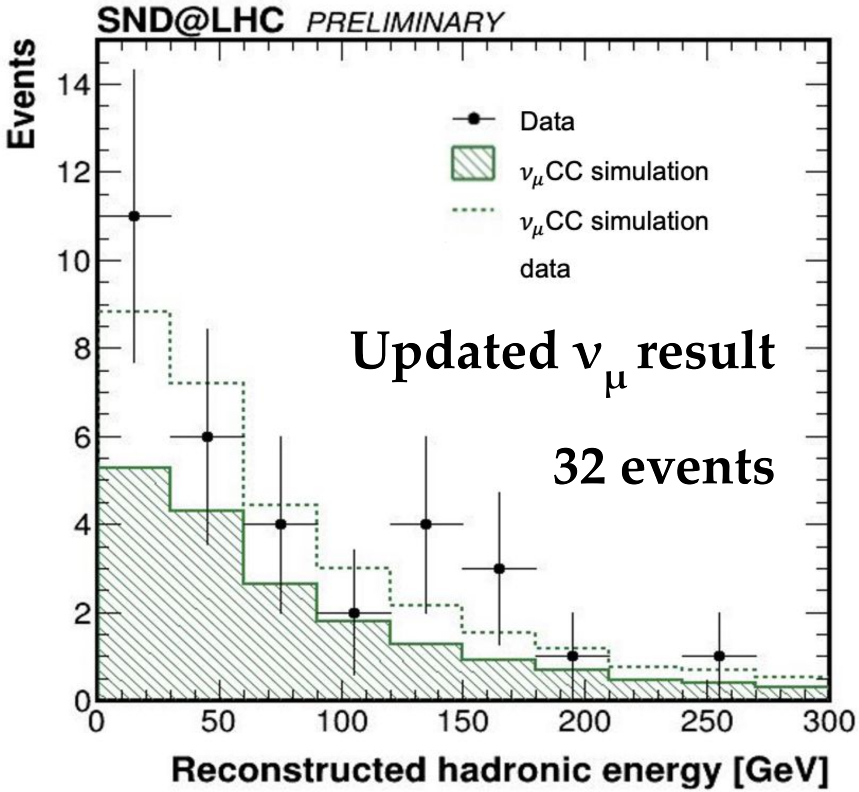
E71b Development: x2 faster than conventional system (x5 in a future upgrade)

Neutrinos in the GeV-TeV range: SND@LHC

Riddhi Biswas Particular capability:
energy range unexplored ~TeV energy range → all DIS
large yield of ν_τ will likely double existing data

PRL 122 (2019) 041101





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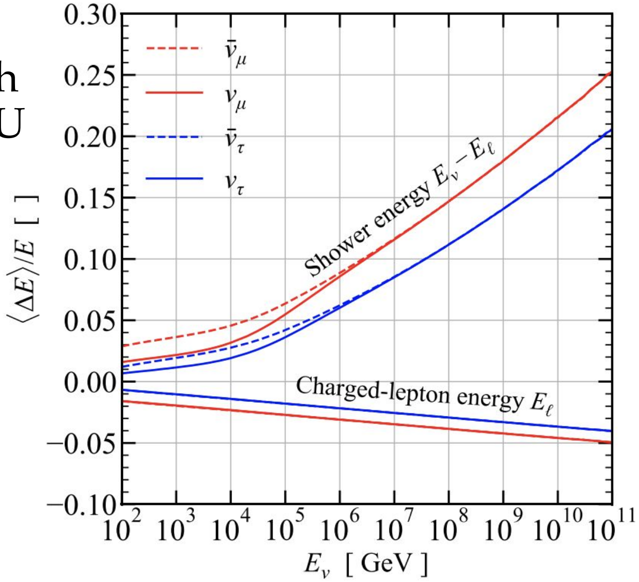
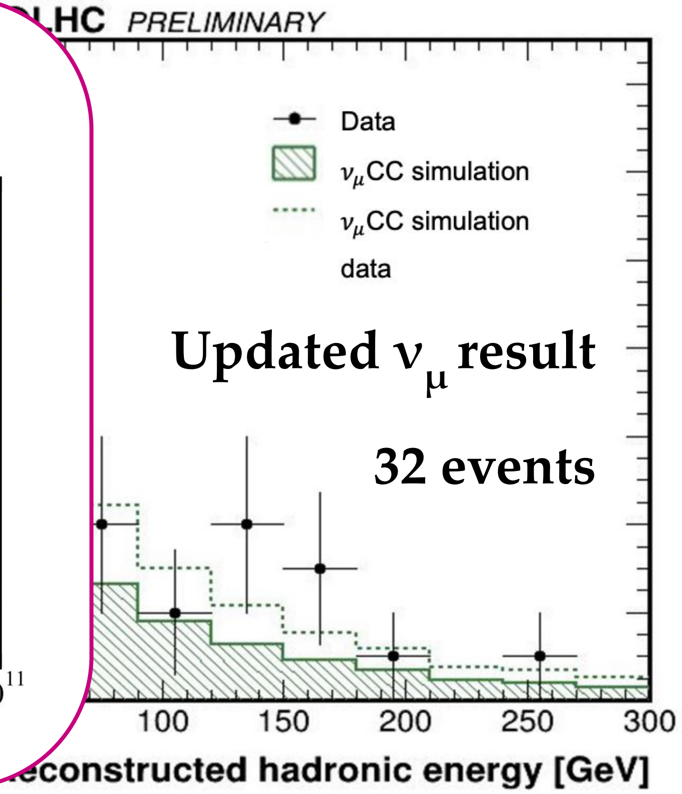
Neutrinos in the GeV-TeV range: SND@LHC

A cautionary word from the theory side

Ulrich Mosel FSI are essential even at very high energies of FASER. GiBUU can be used to study hadronization at HE

Bei Zhou Radiative correction of as large as 25% to be studied overlooked by current experiments on HE and UHE neutrinos.





Updated ν_μ result

32 events

Conclusions

Amazing progress in a exploding field!

The road ahead to deliver percent level interaction uncertainty for oscillation experiments is still long…

… but we know where to go!

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(to NuFact 2025 -- for location see Maury's talk)

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THANKS!!!