Neutrino scattering (WG 2):

Christophe Bronner, Yokohama National University
Vishvas Pandey, Fermilab
Elena Gramellini, University of Manchester
NuFact 2025, Sept 1st , Liverpool

Neutrinos are difficult

Neutrinos are the most abundant massive particle in the universe, and one of the least understood.
They are neutral: we can't directly detect them. We can study them only if they interact, but…

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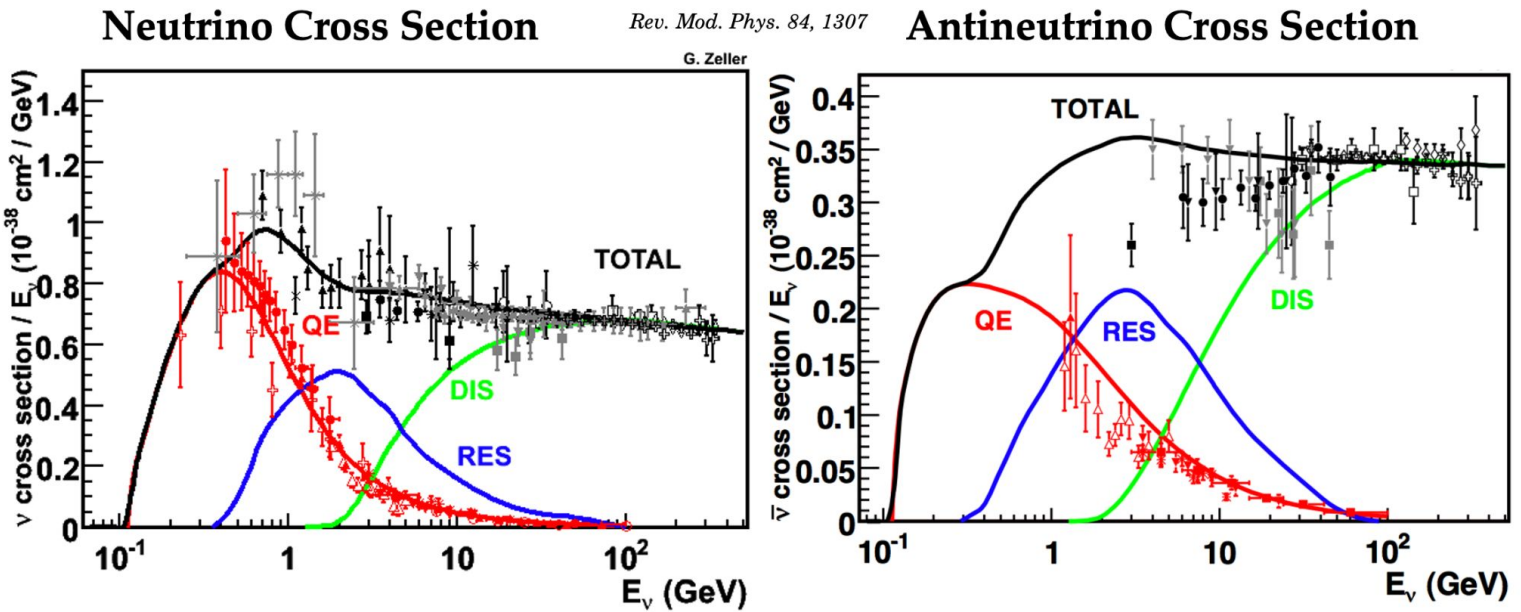
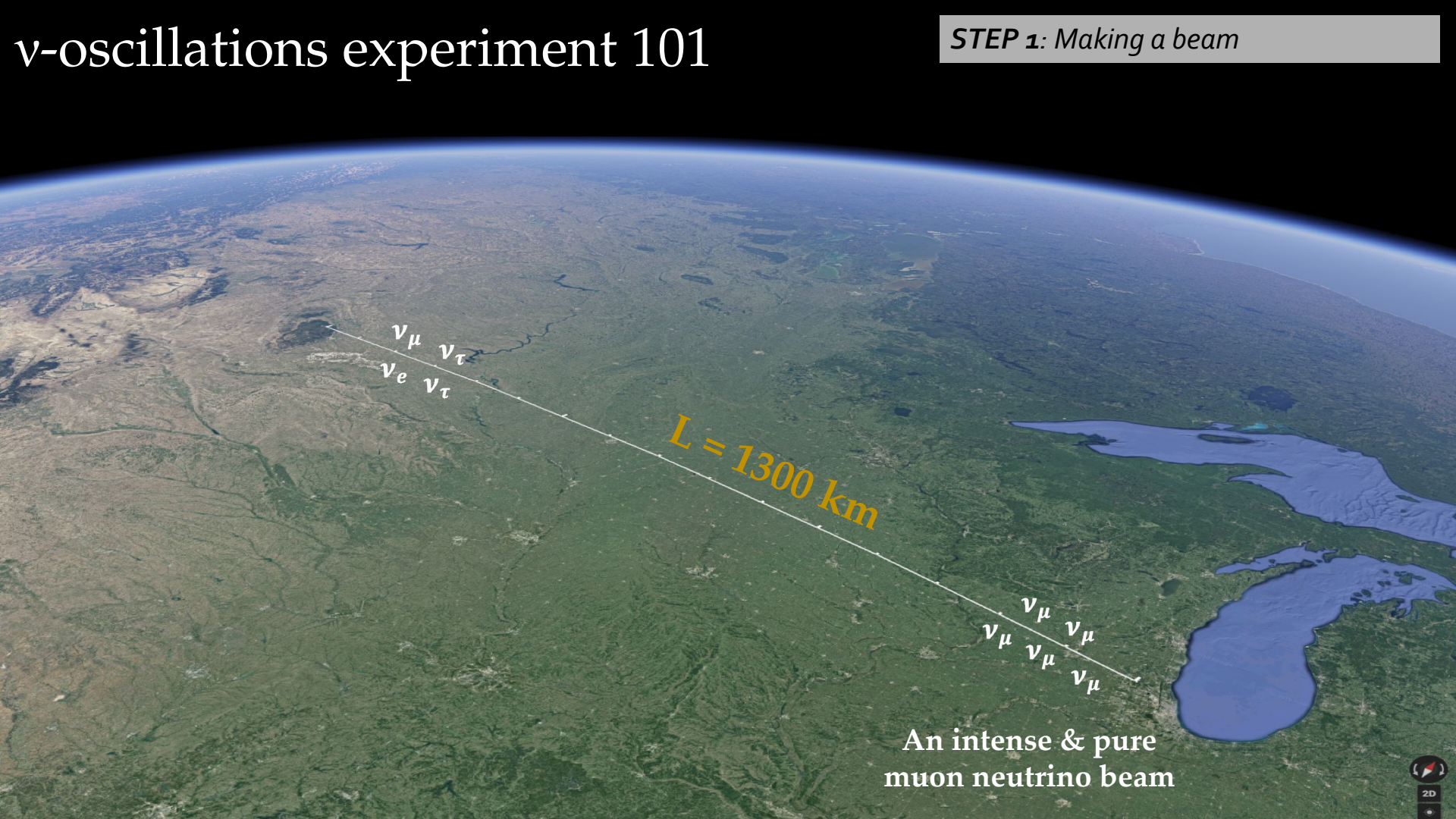


Neutrinos **don't really like to interact**!

ν-oscillations experiment 101

***STEP 1**: Making a beam*



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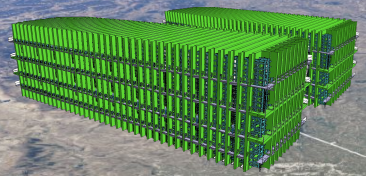
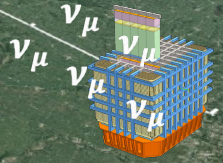


$N^{\mu \rightarrow e}_{FD}$(Er): Number of ν_e in reco energy

ν_μ ν_τ ν_e ν_τ

L = 1300 km

N^{μ}_{ND}(Er): Number of ν_μ in reco energy



ν_μ ν_μ ν_μ ν_μ ν_μ

An intense & pure muon neutrino beam

ν-oscillations experiment 101

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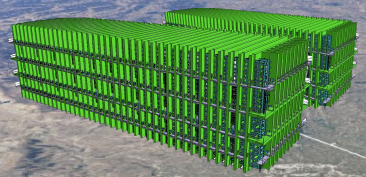

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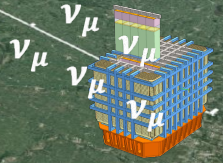

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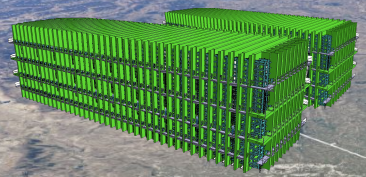

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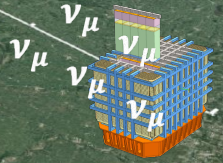

Your detectors (near and far) count number of neutrino interactions of as a function of reconstructed energy…

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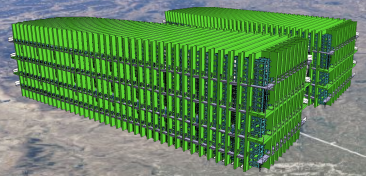
$$N^{\mu\rightarrow e}_{FD}(Er) = \int \phi^{\mu}_{FD}(Et)\, \mathbf{P_{\mu\rightarrow e}(Et)}\, \sigma_e(Et)\, \varepsilon_e(Et)\, U_{FD}(Et, Er)\, dEt$$

- $\phi^{\mu}_{FD}(Et)$: Neutrino Flux
- $P_{\mu\rightarrow e}(Et)$: Oscillation Probability
- $\sigma_e(Et)$: **ν_e Cross Section**
- $\varepsilon_e(Et)$: Signal efficiency
- $U_{FD}(Et, Er)$: Detector Response



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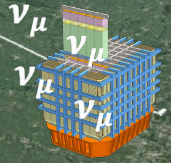

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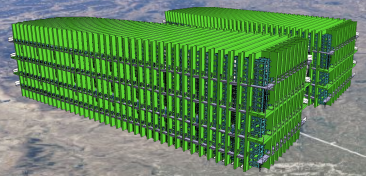

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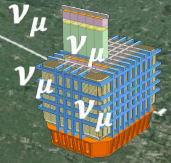

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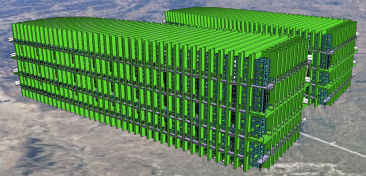

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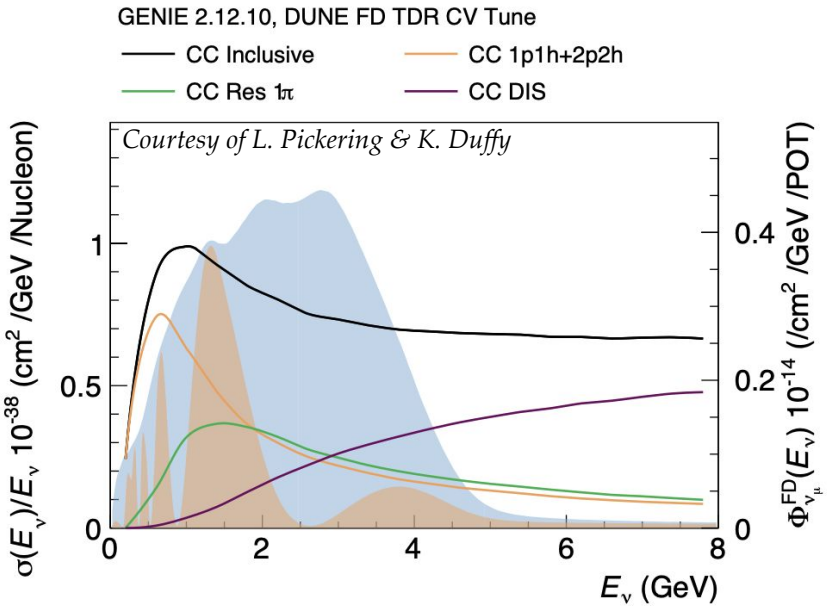
Joint WG1+WG2 session!

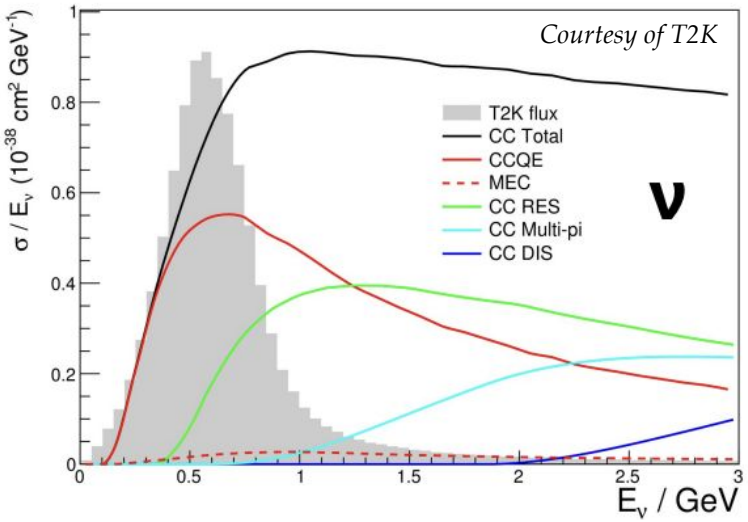
Tue afternoon

e4ν, MicroBooNE, T2K, theory

Why **Step 2** is hard

Both in broad energy beams and narrow energy beams with feed down events multiple interaction channels are accessible
→ different signatures at same energy





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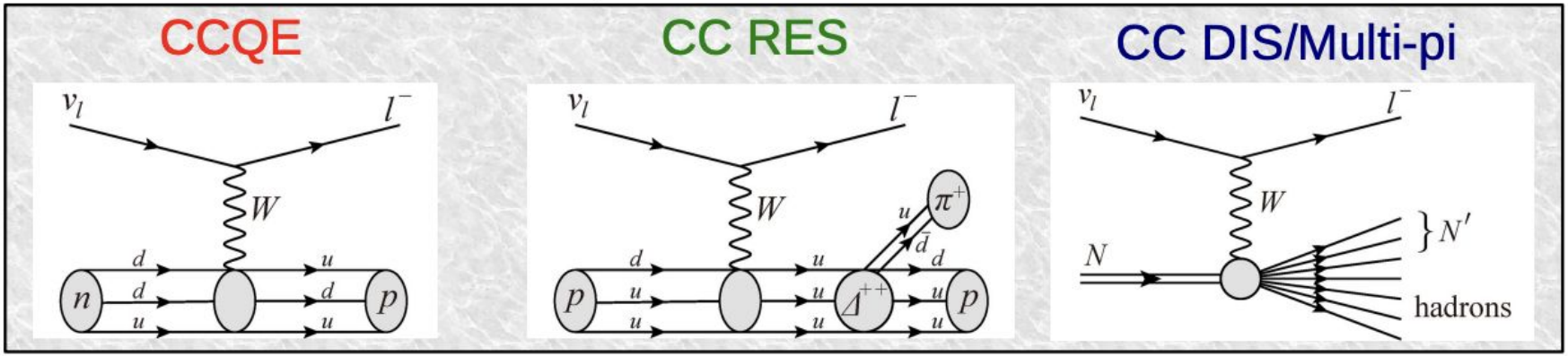

Courtesy of T2K

[Spectral function approach in NuWro: modelling of multinucleon final states in quasielastic scattering]

[Understanding neutrino π production with the GiBUU model]
[Optimizing the description of the delta region in the Ghent Hybrid model for pion production]

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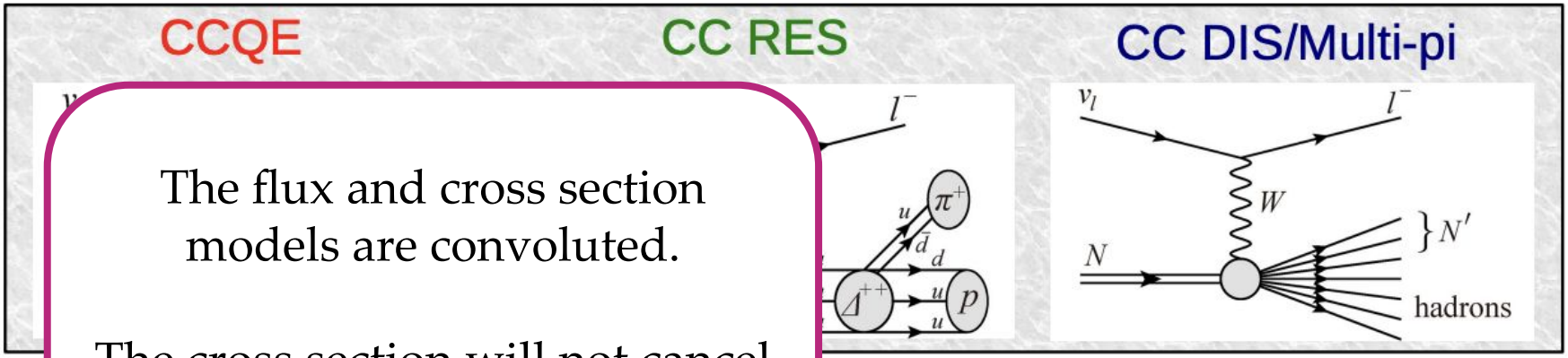

Courtesy of C. Bronne

The flux and cross section models are convoluted.

The cross section will not cancel out and is crucial for extraction of the oscillation parameters.

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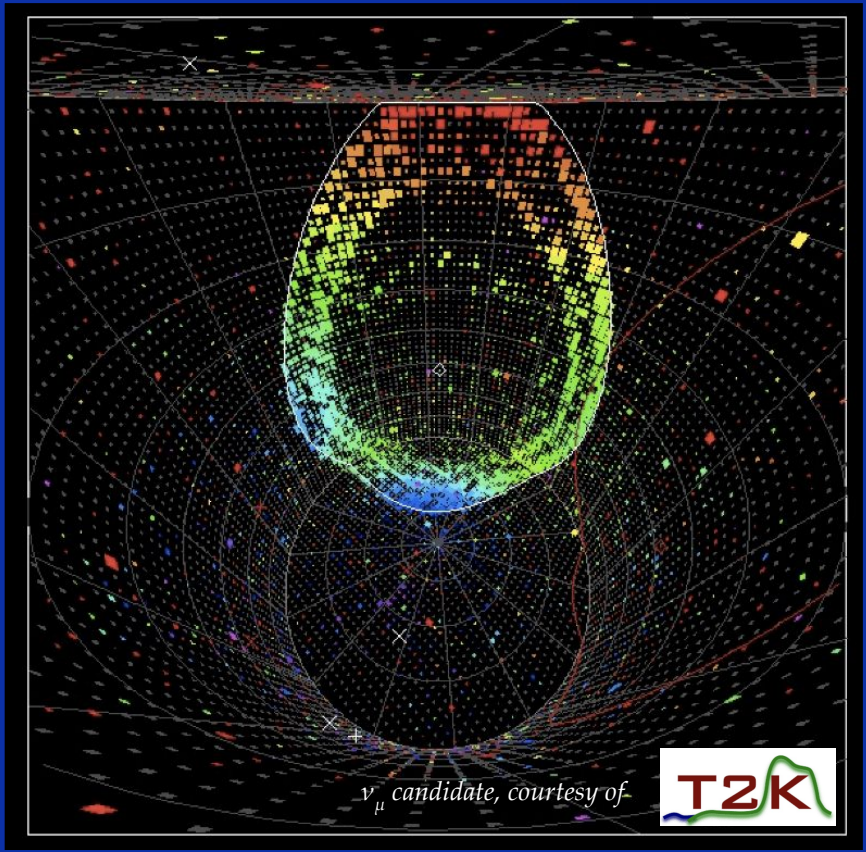
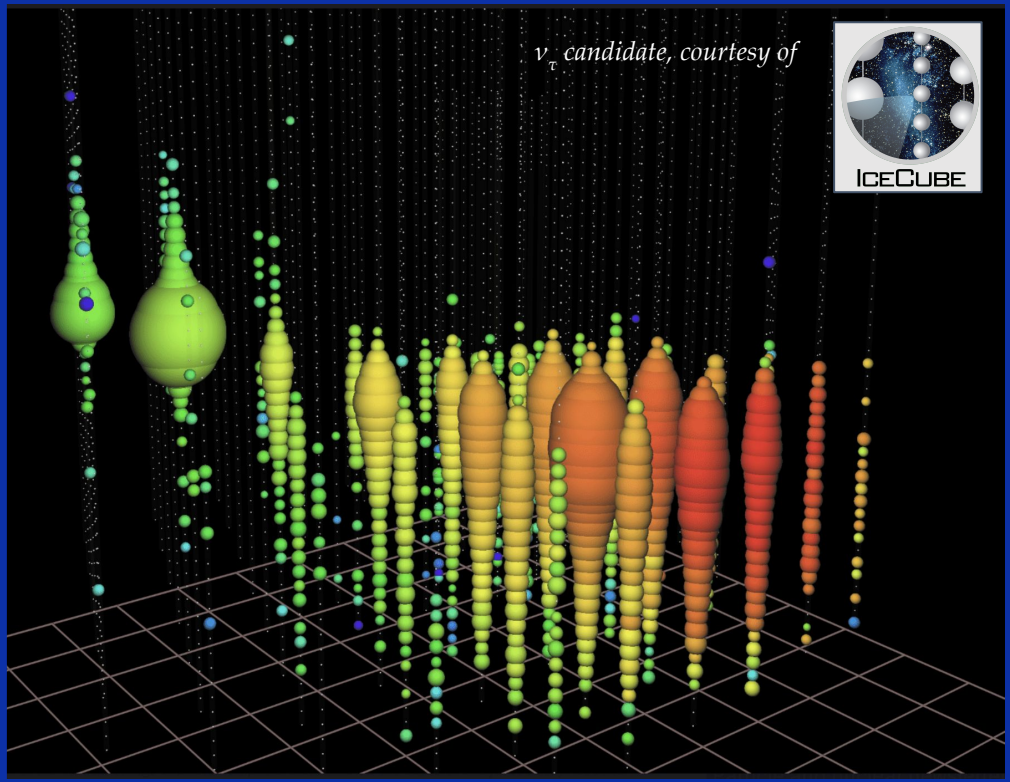
we never see the neutrino directly!





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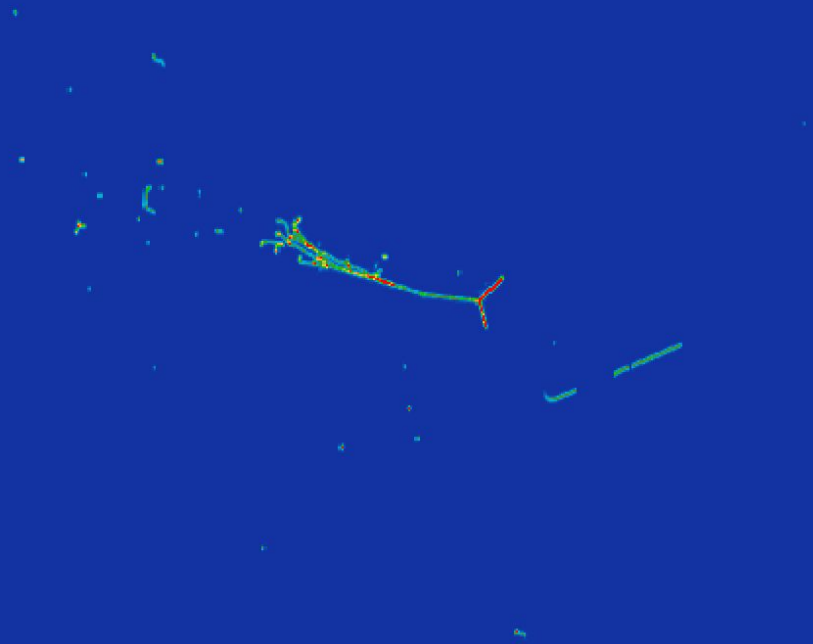

ν_e candidate, courtesy of μBooNE

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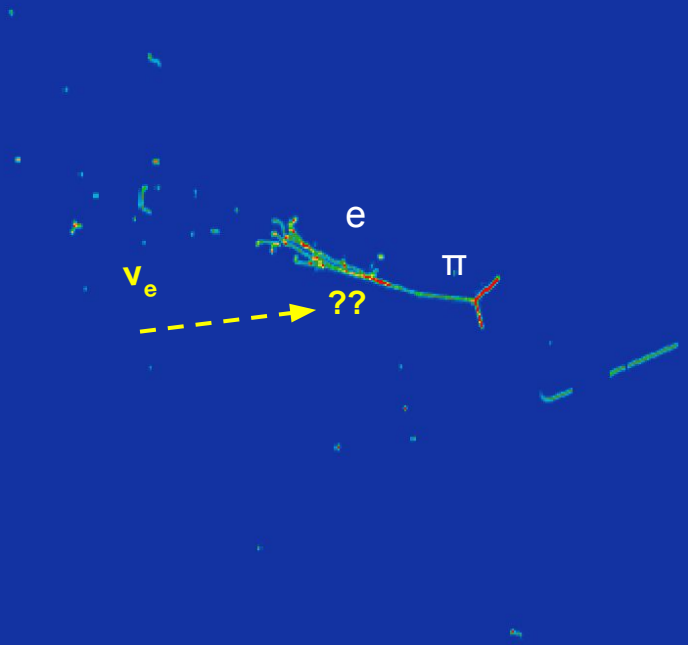

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You identify the final state particles to
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count how many ν_e and ν_μ

Tue Morning:
new XS measurements from
SBND, MicroBooNE,
ICARUS, DUNE

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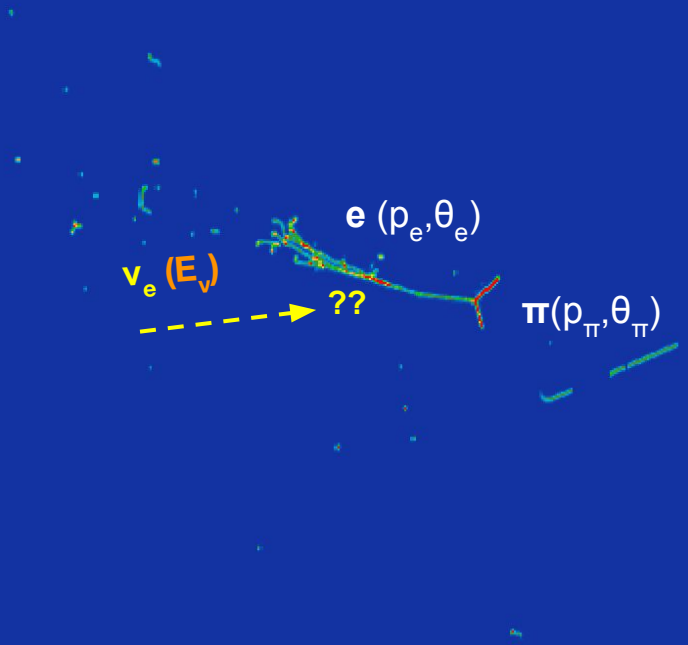

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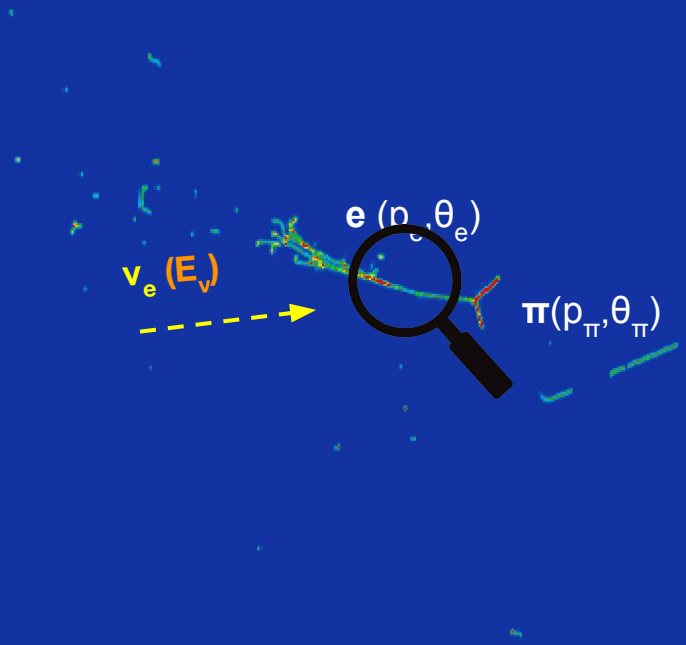
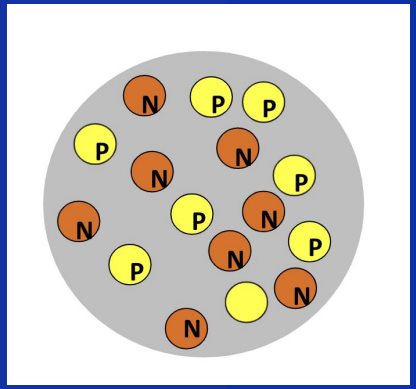


What gets in between



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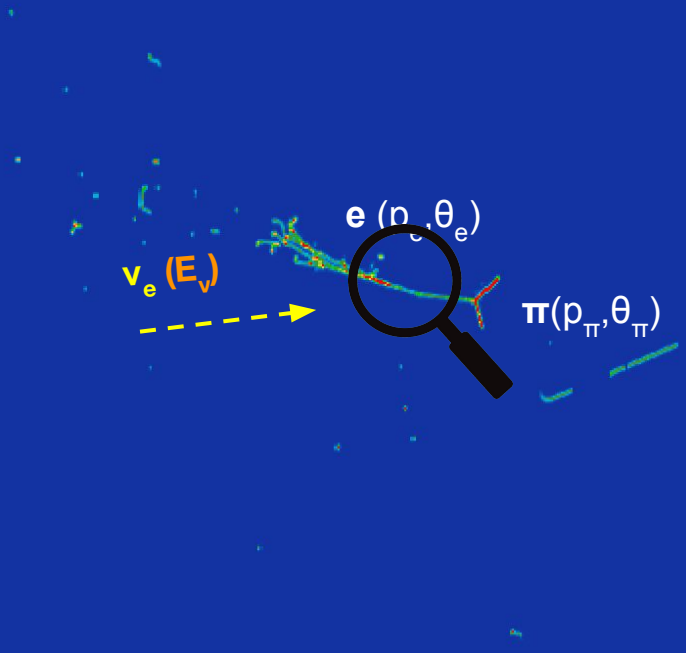

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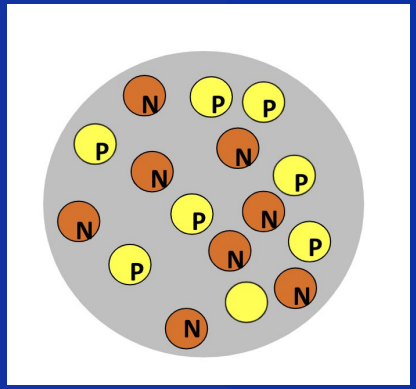

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Cross-section models relate measured particles to (un-measurable) neutrinos, need to correctly predict the ν-N interaction make-up as a function of energy

How does this feeds back into neutrino "new" physics? CP Violation @ long baseline

Type of Uncertainty	$\nu_e/\bar{\nu}_e$ Candidate Relative Uncertainty (%)
Super-K Detector Model	1.5
Pion Final State Interaction and Rescattering Model	1.6
Neutrino Production and Interaction Model Constrained by ND280 Data	2.7
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Modeling of Neutral Current Interactions with Single γ Production	1.5
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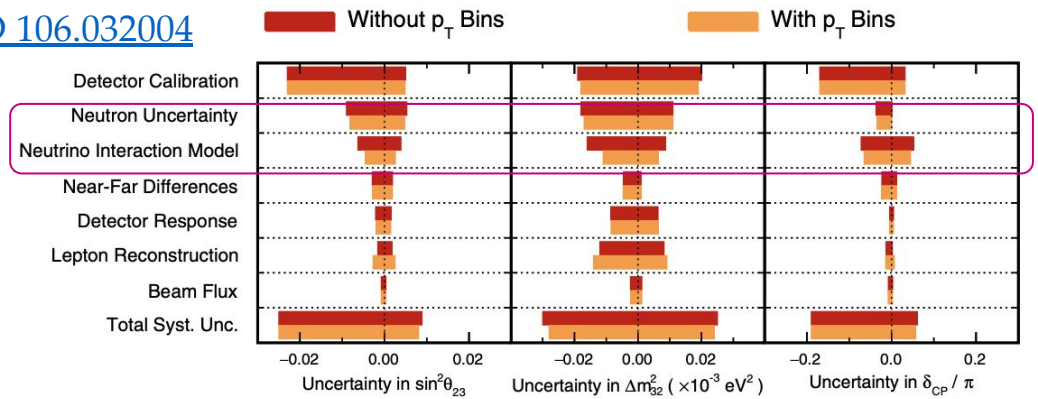
Total Systematic Uncertainty	6.0

T2K, Nature 2020

"uncertainty on the ν_e and $\bar{\nu}_e$ cross-sections... [is] the 2nd largest single source of systematic uncertainty in the CP asymmetry measurement."

NOνA PRD 106.032004



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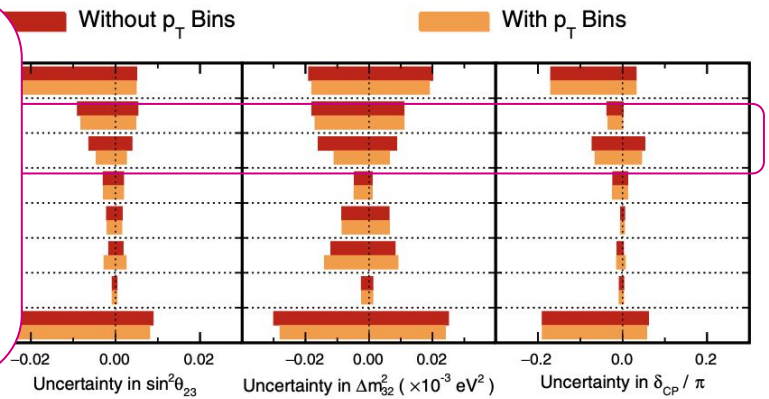
DUNE/HyperK/JUNO
CP violation uncertainty budget
is extremely stringent.
We need to do better than this!



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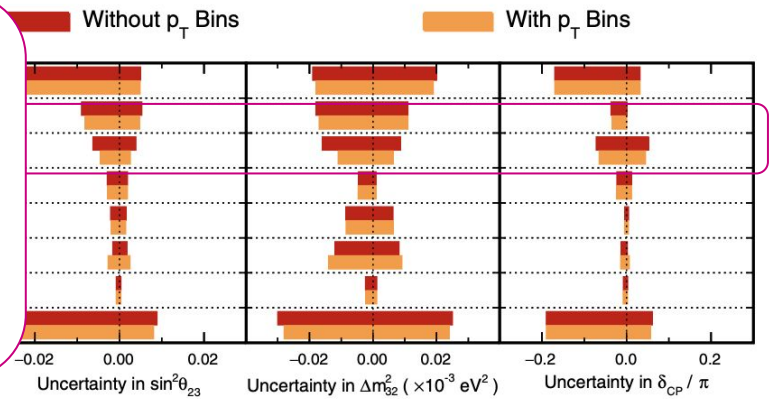
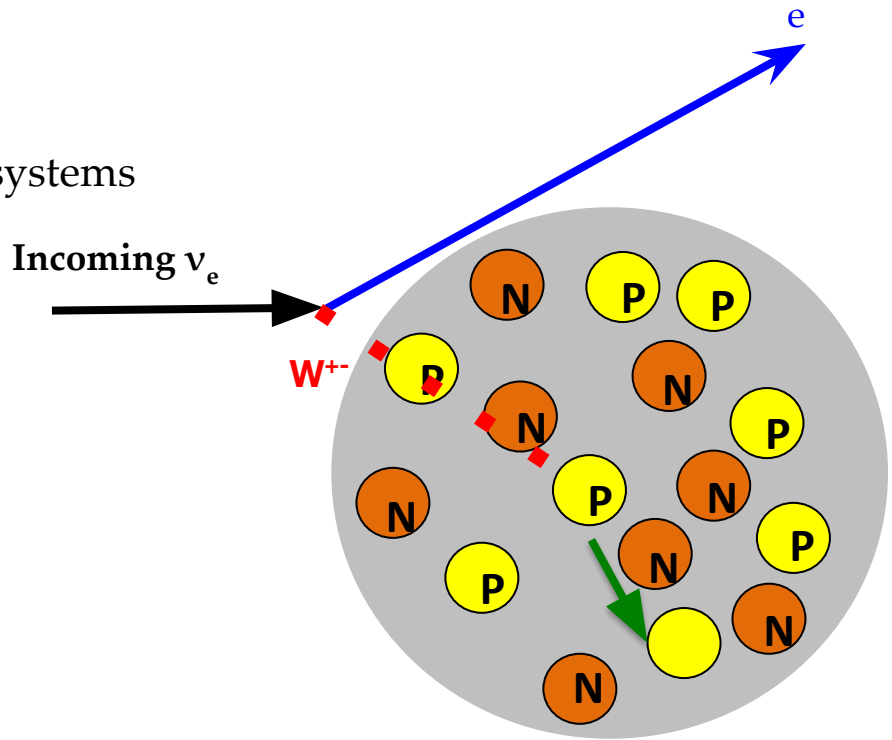
New XS measurements from T2K, Wagasci-BABYMind, NINJA, MINERνA (Thu afternoon)
New Ideas: nuSCOPE (Thu morning)



The Nucleus is a Complex System

Neutrinos do not interact in a vacuum:
they scattering off complex nuclear and atomic systems



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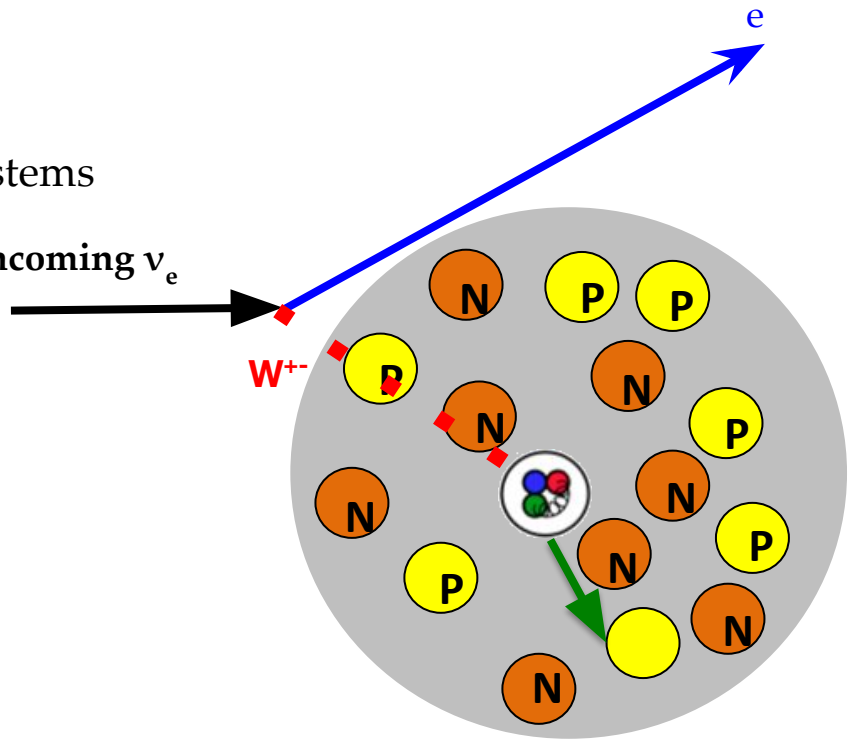
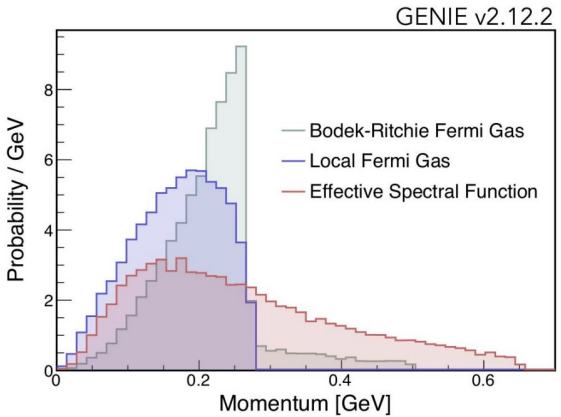


The nucleon is not at rest!
Fermi Motion must be modeled



Credit: M. Del Tutto

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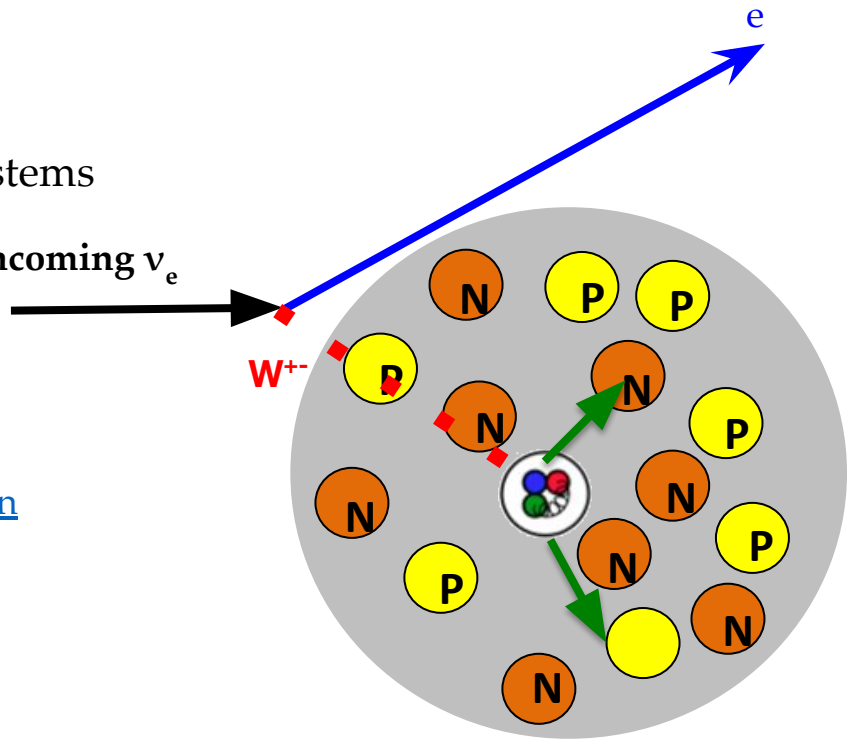

Strongly interacting nucleons
→ alteration of electroweak couplings modeled w/ RPA or more complex models.
[Implementation of the Martini–Ericson–Chanfray–Marteau RPA-based (anti)neutrino cross section model in the GENIE neutrino event generator]
→ rich physics effects for forward-going charged lepton

Interactions with correlated pair of nucleons:
→ Meson Exchange Current
→ Short Range Correlations
[Short-Range Correlations and Meson-Exchange Currents in neutrino and electron scattering)]

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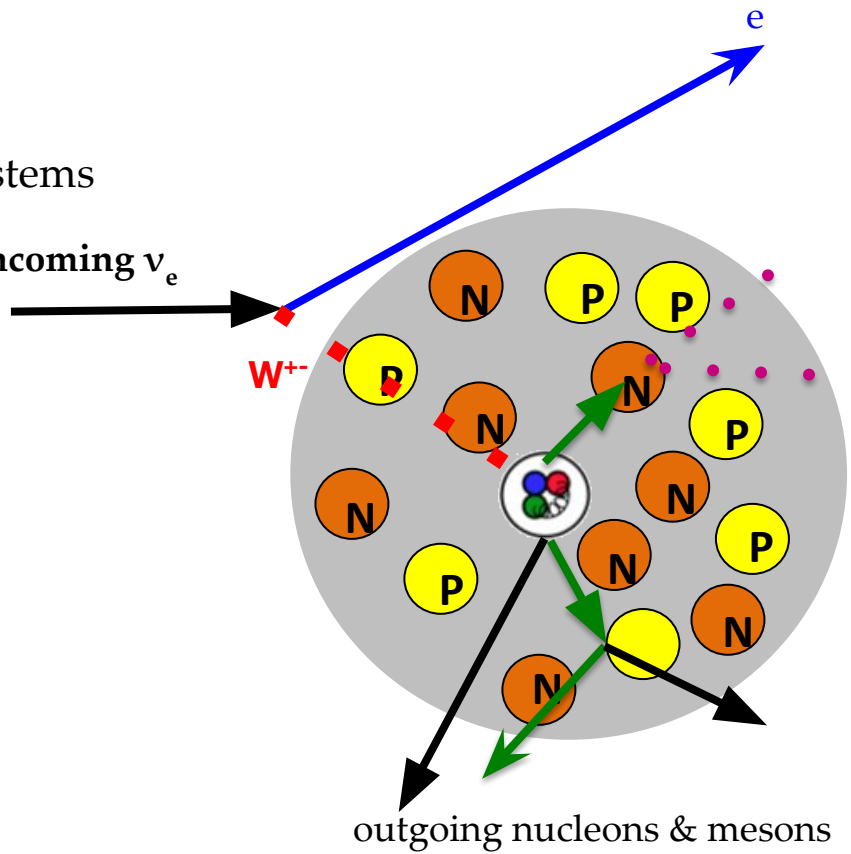
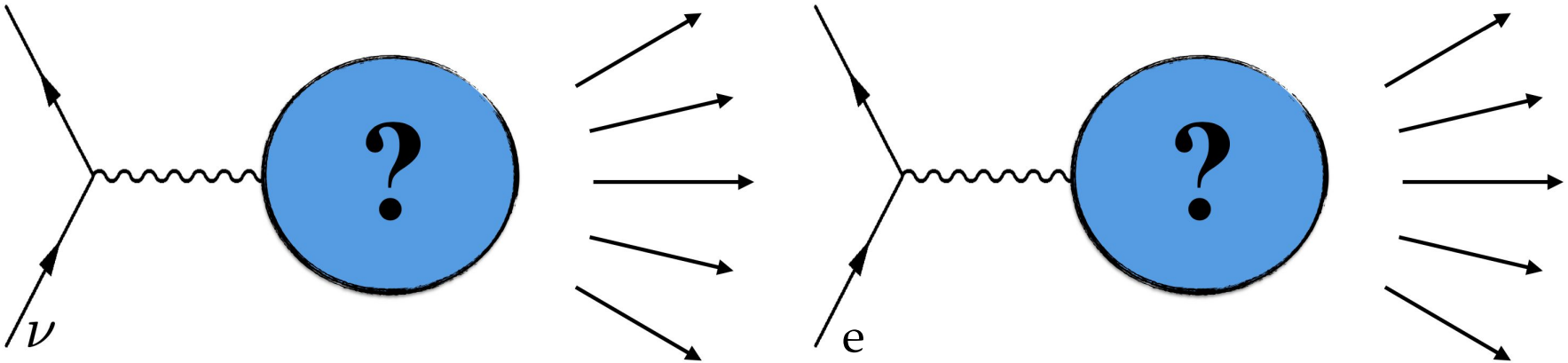
Final State Interactions
→ charged and neutral mesons & nucleons

2+ outgoing protons possible even for "true" CCQE events



A word on charge lepton scattering



Electron scattering experiments enormous advantage: the energy of the incoming lepton is KNOWN. Data from these experiments helps us constrain "the vector" portion of the V-A interaction common to neutrinos! Many contributions from both theory and experiment

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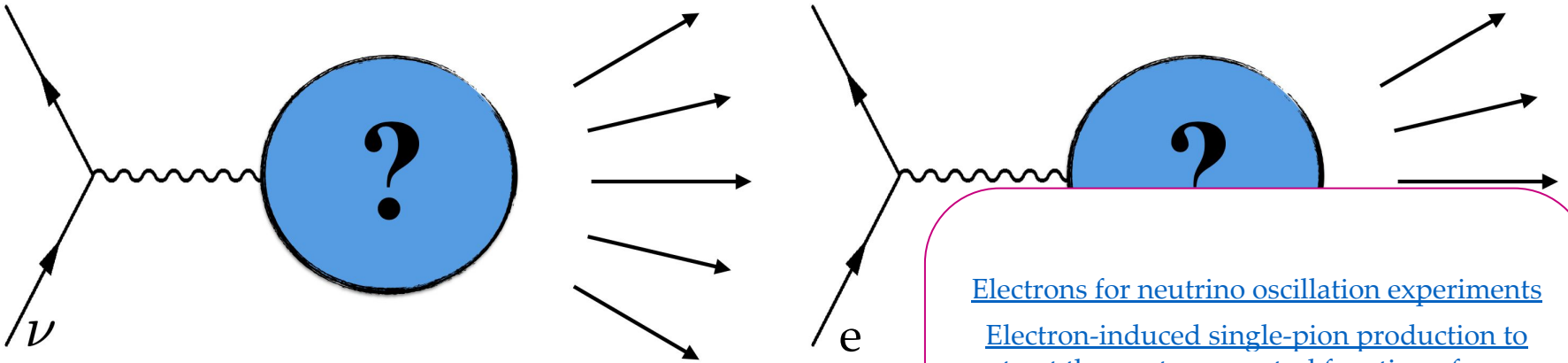

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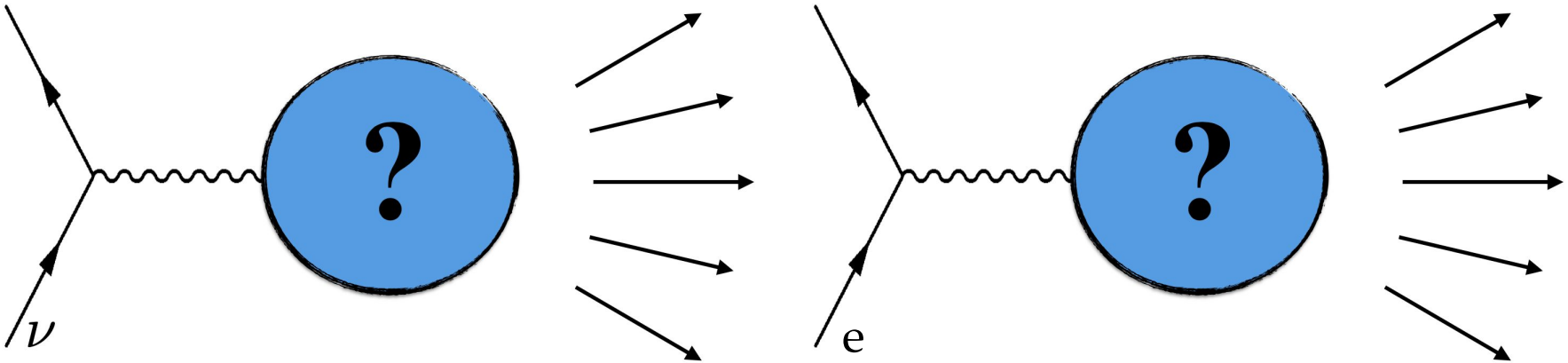
Electrons for neutrino oscillation experiments

Electron-induced single-pion production to extract the neutron spectral function of argon 40.

Global Extraction of the C-12, Ca-40, and Fe-56 Nuclear Electromagnetic Response Functions and Comparisons to Nuclear Theory and Neutrino/Electron Monte Carlo Generators

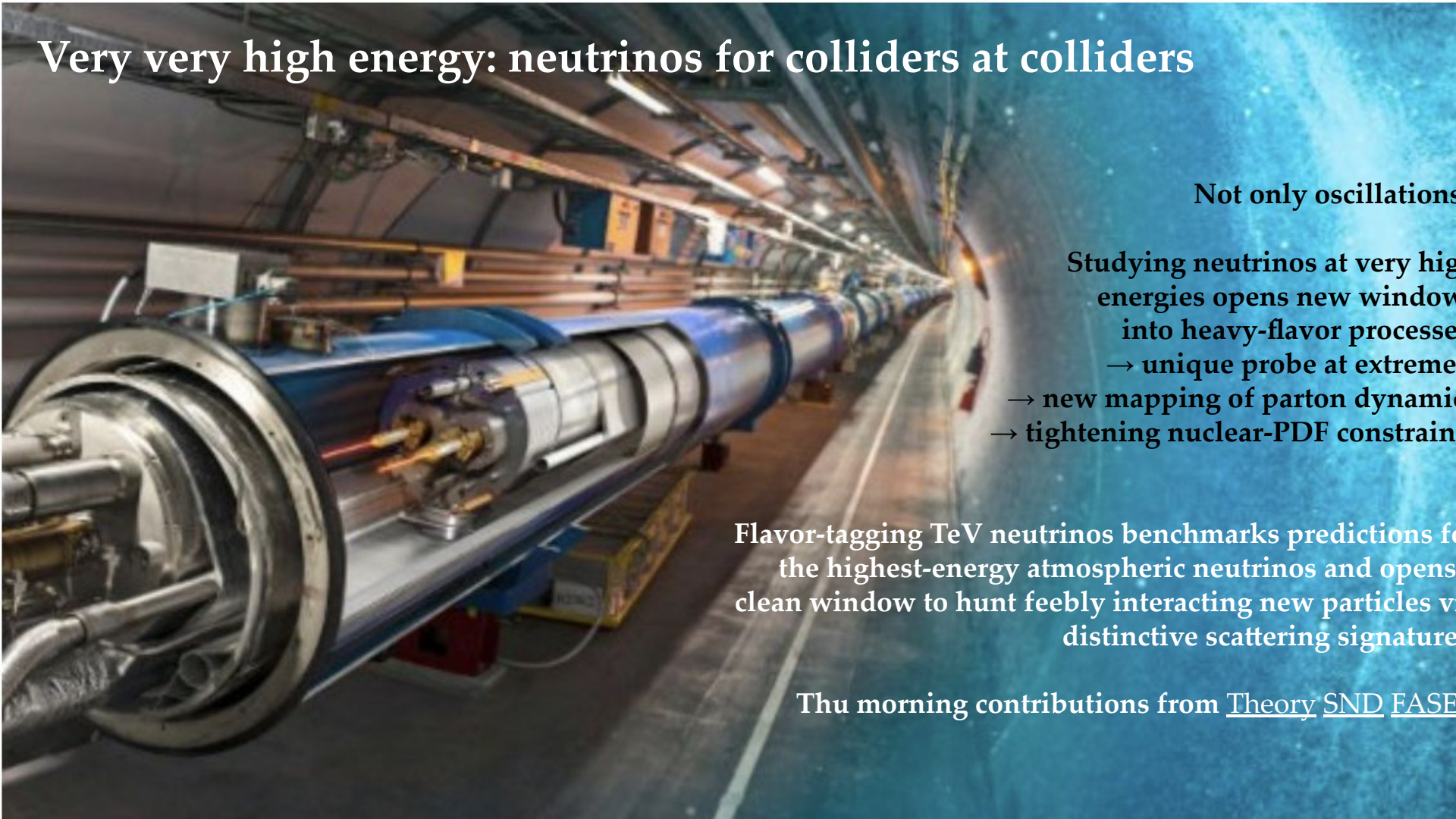
A word on charge lepton scattering



Electron scattering experiments enormous advantage: the energy of the incoming lepton is KNOWN. Data from these experiments helps us constrain "the vector" portion of the V-A interaction common to neutrinos! To probe the axial nucleon form factor we can only use neutrinos…

The Axial Form Factor Extracted from Elementary Targets

Very very high energy: neutrinos for colliders at colliders



Not only oscillations

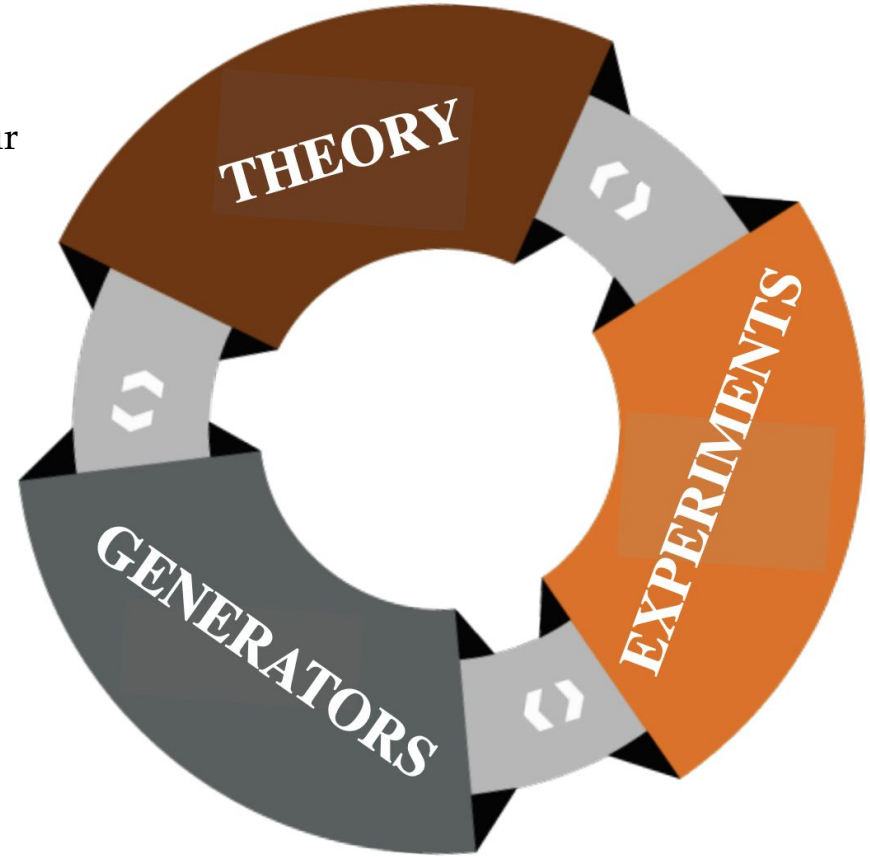
Studying neutrinos at very hig
energies opens new window
into heavy-flavor processe
→ unique probe at extreme
→ new mapping of parton dynami
→ tightening nuclear-PDF constrain

Flavor-tagging TeV neutrinos benchmarks predictions f
the highest-energy atmospheric neutrinos and opens
clean window to hunt feebly interacting new particles v
distinctive scattering signature

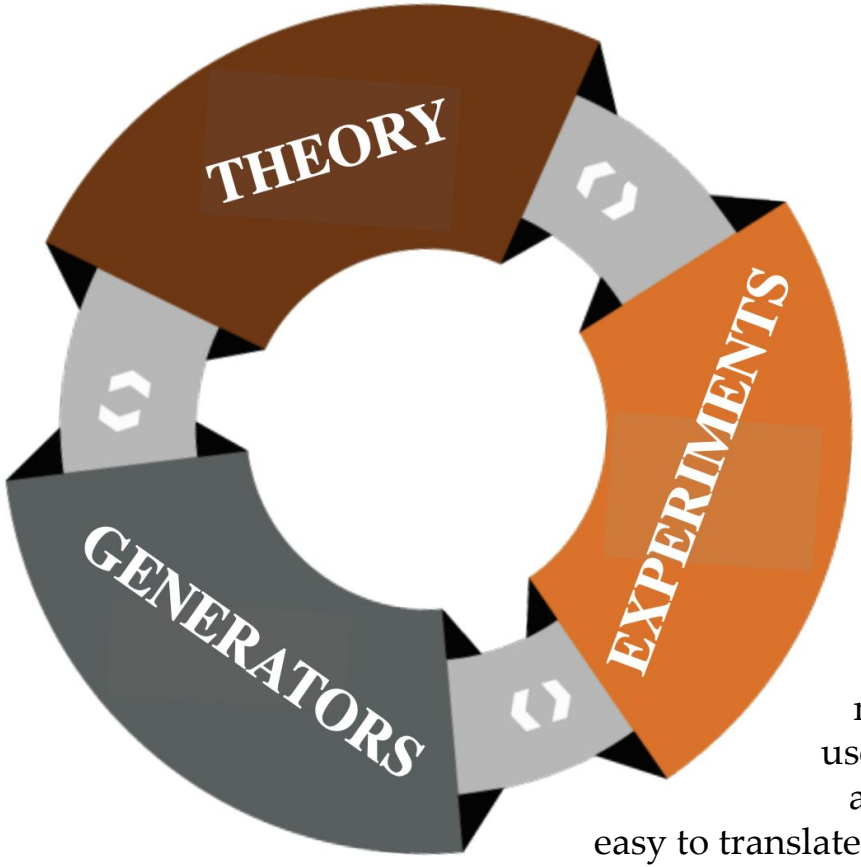
Thu morning contributions from Theory SND FASE

It all plays together

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

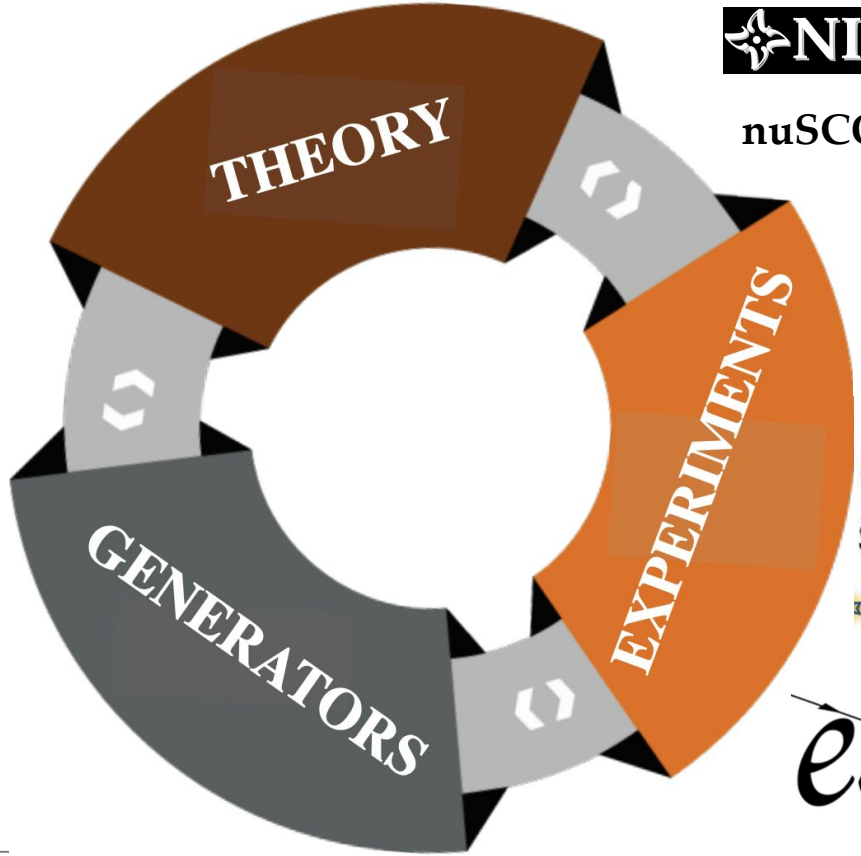


It all plays together



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

It all plays together



NINJA

nuSCOPE

DUNE

MINERvA

LHC
Scattering and Neutrino Detector
at the LHC

SBN
Program

NOvA

T2K

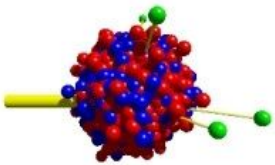
e4v

FASER

Gen Session
Tue Afternoon

Genie

NuWro
Wrocław Neutrino Event Generator



GiBUU
The Giessen Boltzma

MANCHESTER 1824
The University of Manchester

This week for WG2: Contributions

PLENARIES
This Afternoon:
A Theoretical Overview of Neutrino Interaction XSs
-- Raul Jimenez

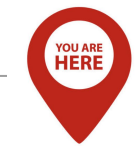
An Experimental Overview of Neutrino Interactions
-- Afroditi Papadopoulou

Friday afternoon:
Neutrino cross-sections at the BSM boundary
-- Zahra Khajeh Tabrizi

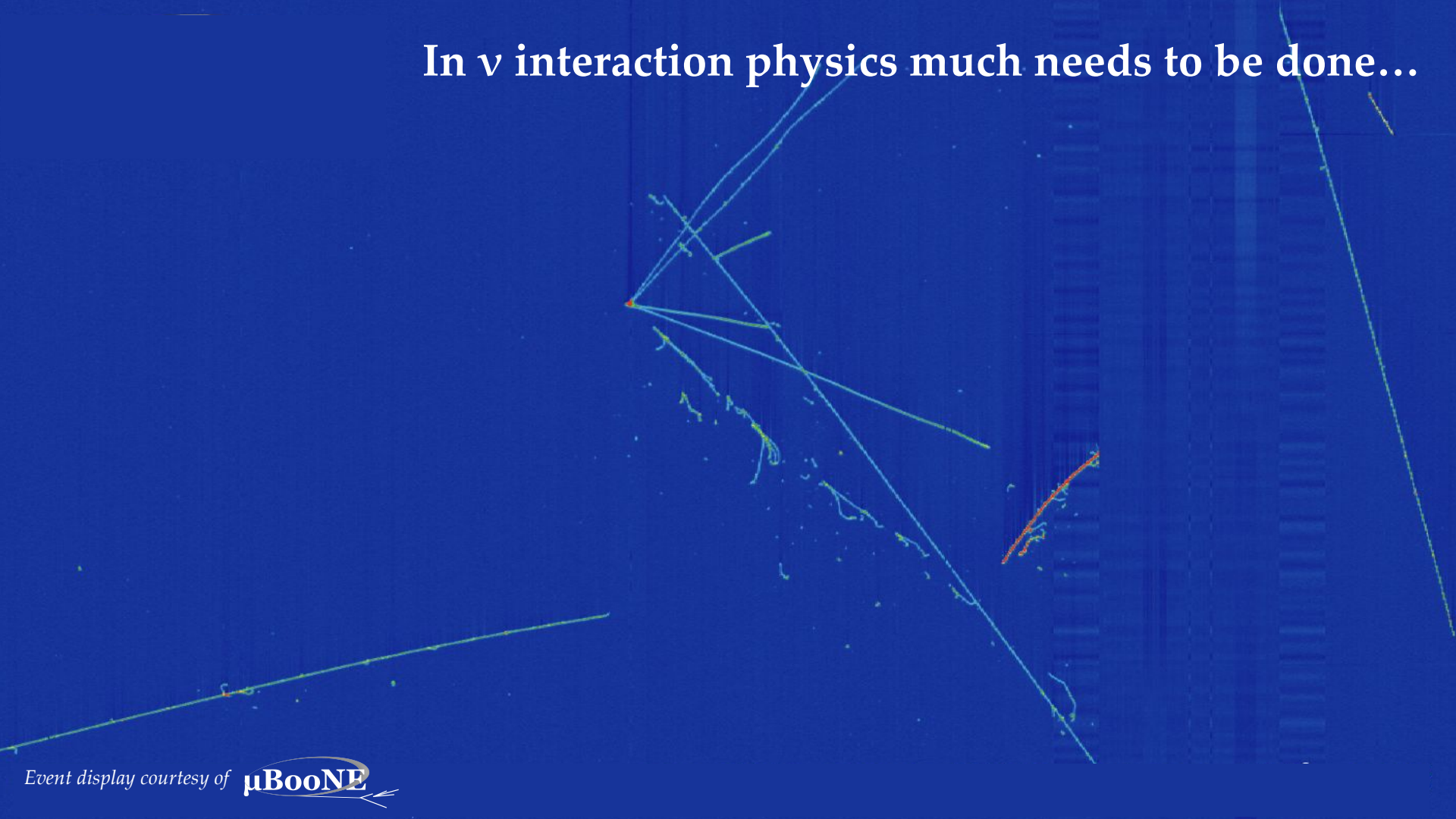
An overview of cross-section generators
-- Jan Sobczyk

PARALLELS:
Talks:
→ 11 experimental efforts,
→ 5 theory,
→ 4 generator,
→ 4 joint with WG1
→ 6 posters

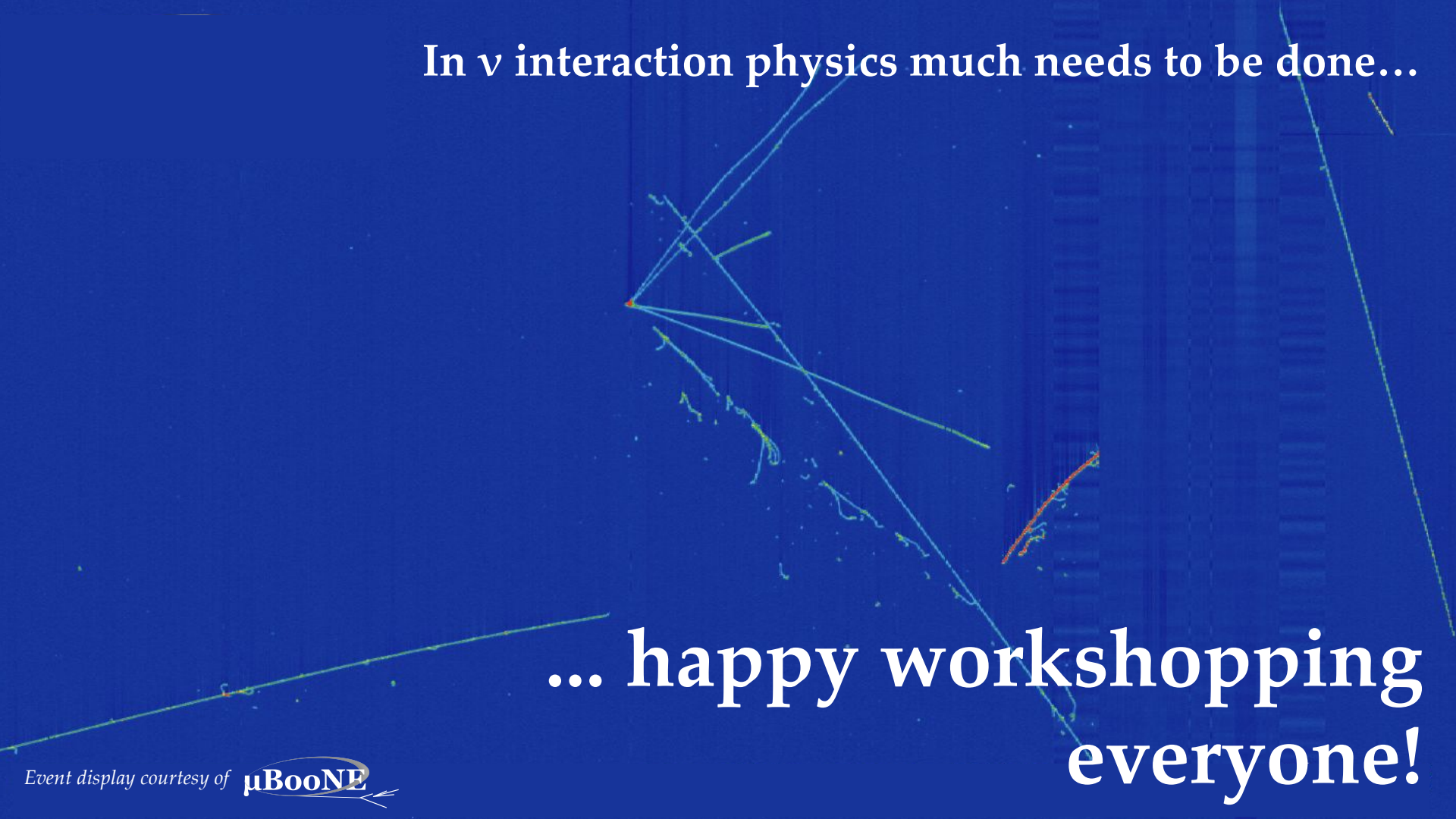
This week for WG2: Schedule (please check the indico here)

	Mon	Tue	Wed	Thu	Fri	Sat
Early Morning						Closeout
Late Morning		Experiment Argon		Experiment ν in Colliders		
Early Afternoon	Plenary XS theory overview XS exp overview	WG1-WG2 joint		Experiment JParc & Minerva		
Late Afternoon	Poster session	Gen		Theory	Plenary XS in BSM results XS Gen overview	

In ν interaction physics much needs to be done…



Event display courtesy of μBooNE

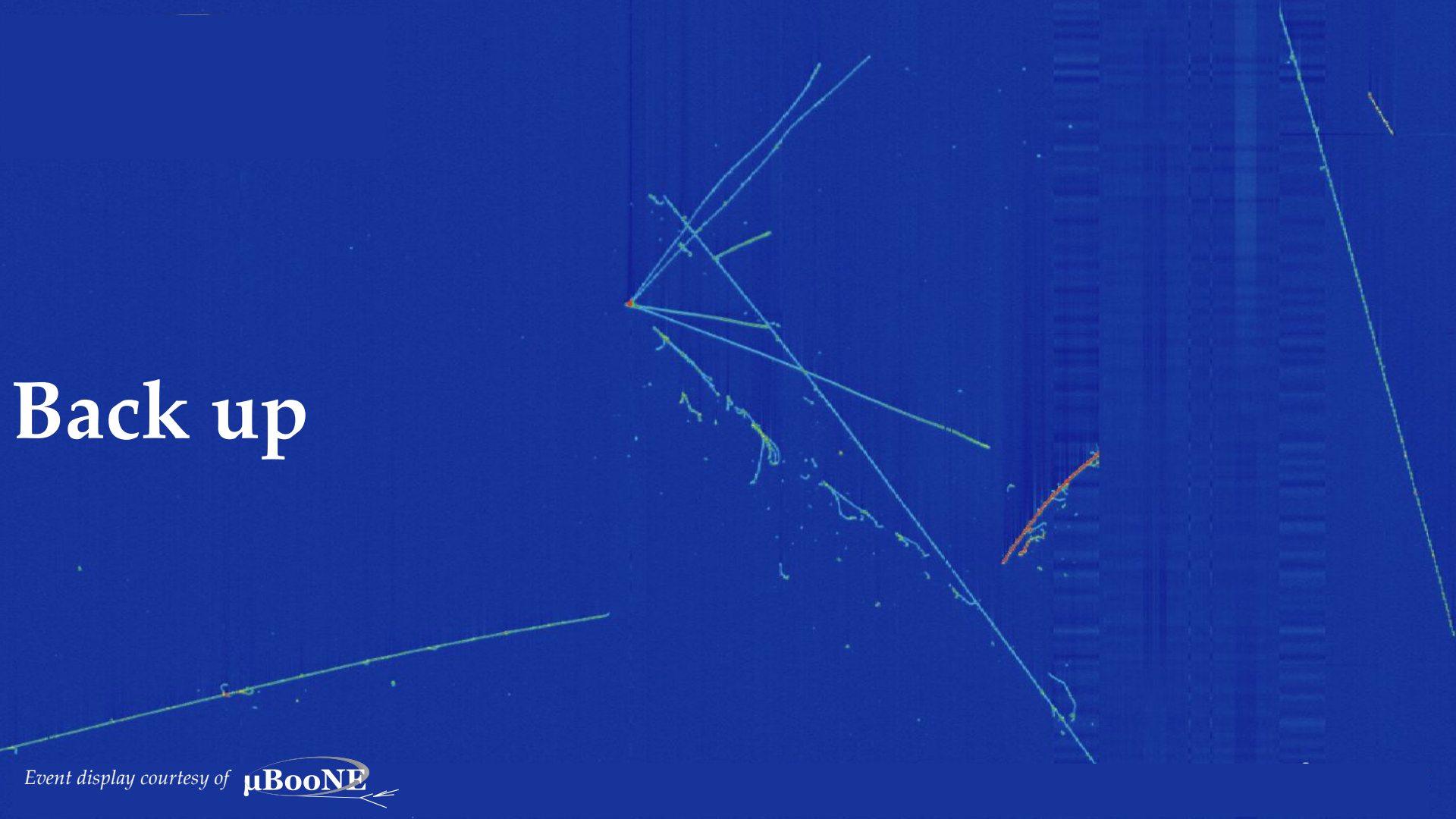

In ν interaction physics much needs to be done…
… happy workshopping everyone!
Event display courtesy of μBooNE

Thank you!

Special thanks for your help in preparing this talk:
Adi Ashkenazi

Event display courtesy of μBooNE

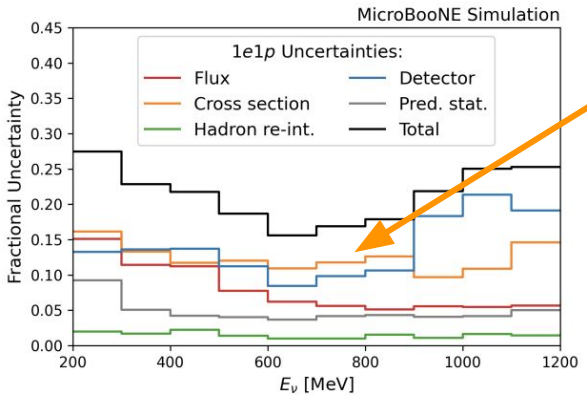
Back up



Event display courtesy of μBooNE

How does this feeds back into neutrino “new” physics? Anomaly hunting @ short baseline

ν_e Cross Section Systematics



CC-QE like

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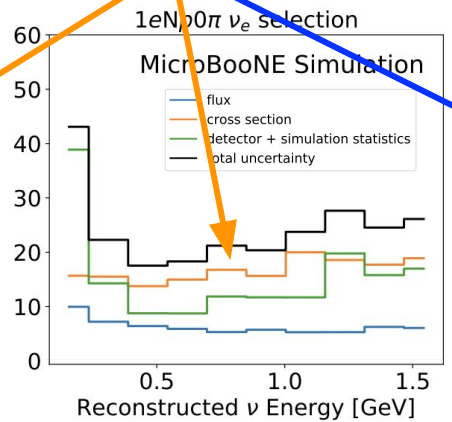
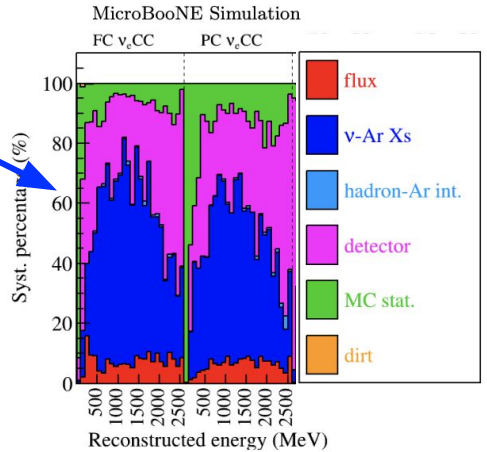


Pionless

Phys. Rev. D105, 112004 (2022)



Inclusive

Phys. Rev. D105, 112005 (2022)