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Département de physique
nucléaire et corpusculaire

Neutrino-Nucleus cross-sections in neutrino oscillations

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Introduction

Cross-sections in oscillations

Oscillations in a nutshell

$$\frac{N^{far}_{events}(E_\nu)}{N_{events}(E_\nu)} = \frac{\int \sigma(E'_\nu)\Phi(E'_\nu)P(E_\nu|E'_\nu)P_{osc}(E'_\nu)dE'_\nu + \text{Back }(E_\nu)}{\int \sigma(E'_\nu)\Phi(E'_\nu)P(E_\nu|E'_\nu)dE'_\nu + \text{Back }(E_\nu)}$$

Correlation

🟦 Neutrino flux different for near and far

🟩 What we want !!!!

CROSS-SECTION RELATED

🟧 Total cross-section as function of energy

🟪 Wrong interaction channel (i.e. π's, NC-γ,…) different btw near and far

🟥 How the neutrino energy is reconstructed different at near and far

Much more than a simple dσ/dE

Cross-sections in oscillations

- Actually in experiments we do not measure the energy, we measure a set of parameters relates to the energy:

$$P(\vec{Q}_{\rm obs}|E_\nu)$$

This is our X-section problem!

- So, what we want is to measure a set of variable Q_{obs} as proxy of the E_ν, allowing us to obtain the oscillation parameters Ω_{osc}

$$P(\vec{Q}_{\rm obs}|\Omega_{\rm osc}) = \int P(\vec{Q}_{\rm obs}|E_\nu)\Phi(E_\nu)P_{\rm osc}(E_\nu|\Omega_{\rm osc})dE_\nu$$

- Q_{obs} varies from experiment to experiment: from leptonic kinematics (T2K|HK) to leptonics+hadronics variables (Nova|Dune).

- In both cases the conditional probability $P(\vec{Q}_{\rm obs}|E_\nu)$ is the key.

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And it is…

Last T2K oscillation analysis

Eur. Phys. J. C manuscript No.
(2023) 83:782

ND ~ FD

Sample		Uncertainty source (%)			Flux⊗Interaction (%)	Total (%)
		Flux	Interaction	FD + SI + PN		
1Rμ	ν	2.9 (5.0)	3.1 (11.7)	2.1 (2.7)	2.2 (12.7)	3.0 (13.0)
	$\bar{\nu}$	2.8 (4.7)	3.0 (10.8)	1.9 (2.3)	3.4 (11.8)	4.0 (12.0)
1Re	ν	2.8 (4.8)	3.2 (12.6)	3.1 (3.2)	3.6 (13.5)	4.7 (13.8)
	$\bar{\nu}$	2.9 (4.7)	3.1 (11.1)	3.9 (4.2)	4.3 (12.1)	5.9 (12.7)
1Re1de	ν	2.8 (4.9)	4.2 (12.1)	13.4 (13.4)	5.0 (13.1)	14.3 (18.7)
		Near		Far	Near	

X.X **(Y.Y)**
after ND fit
before ND fit

for electron larger than for muons

correlations Flux-interactions

Near detector is critical

Huge improvement : 13% —> 3%

… but not sufficient

we need of the order of 1% for HK

are we sure this is correct ?

Before we start: Water Cherenkov

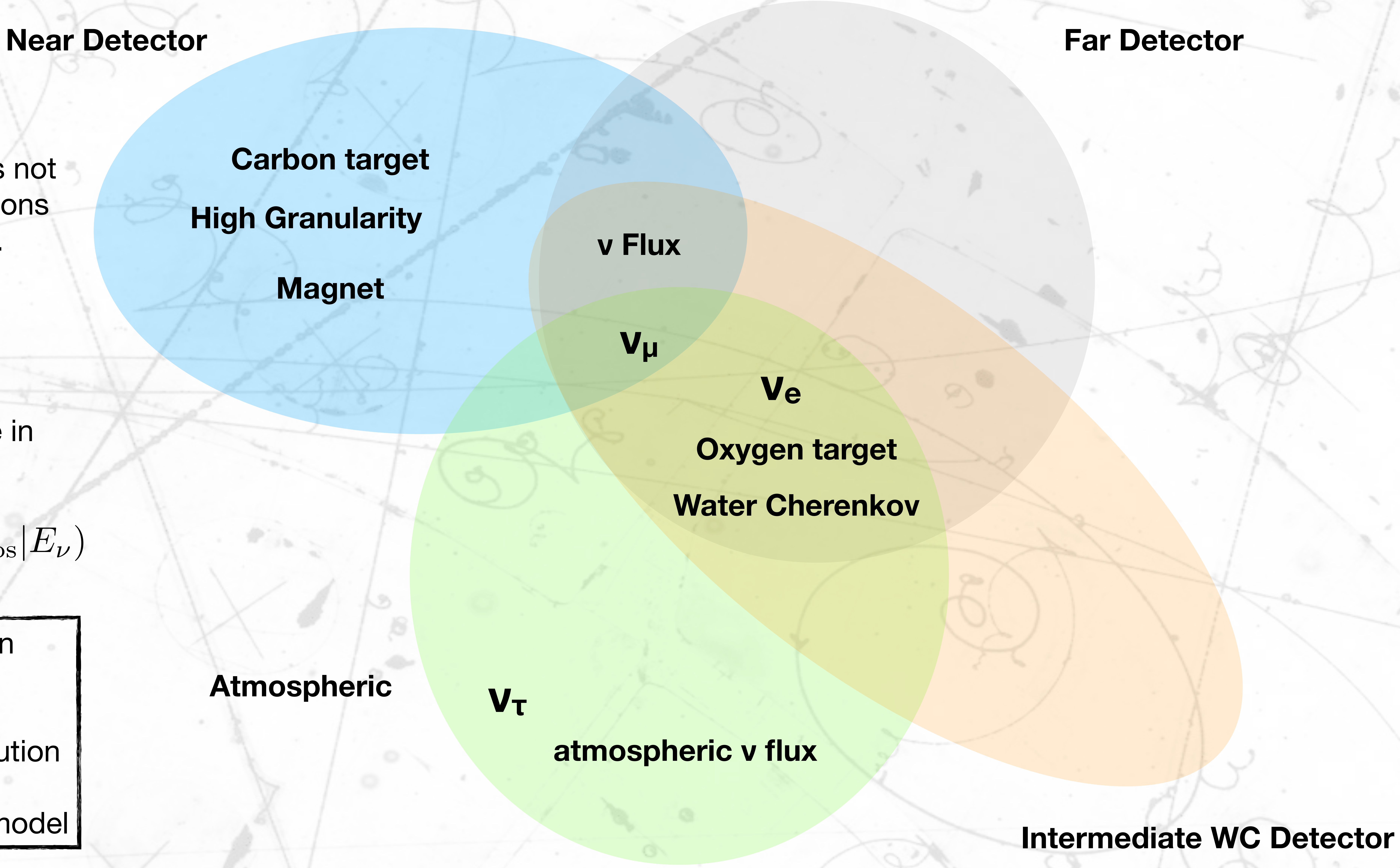
This complex connection map is not by chance, it has technical reasons and we have to leave with it.

In general, but particularly true in Hyper-Kamiokande

$$P_{\text{Near}}(\vec{Q}_{\text{obs}}|E_\nu) \neq P_{\text{Far}}(\vec{Q}_{\text{obs}}|E_\nu)$$

Q_{obs} are normally the muon momentum and angle :

clean but also limited in resolution
—>
it relies heavily on the theory model



Near Detector

Far Detector

Carbon target

High Granularity

Magnet

ν Flux

ν_μ

ν_e

Oxygen target

Water Cherenkov

Atmospheric

ν_τ

atmospheric ν flux

Intermediate WC Detector

Before we start: calorimetric case

Even in this case, there are issues:

ν_μ vs ν_e

Granularity

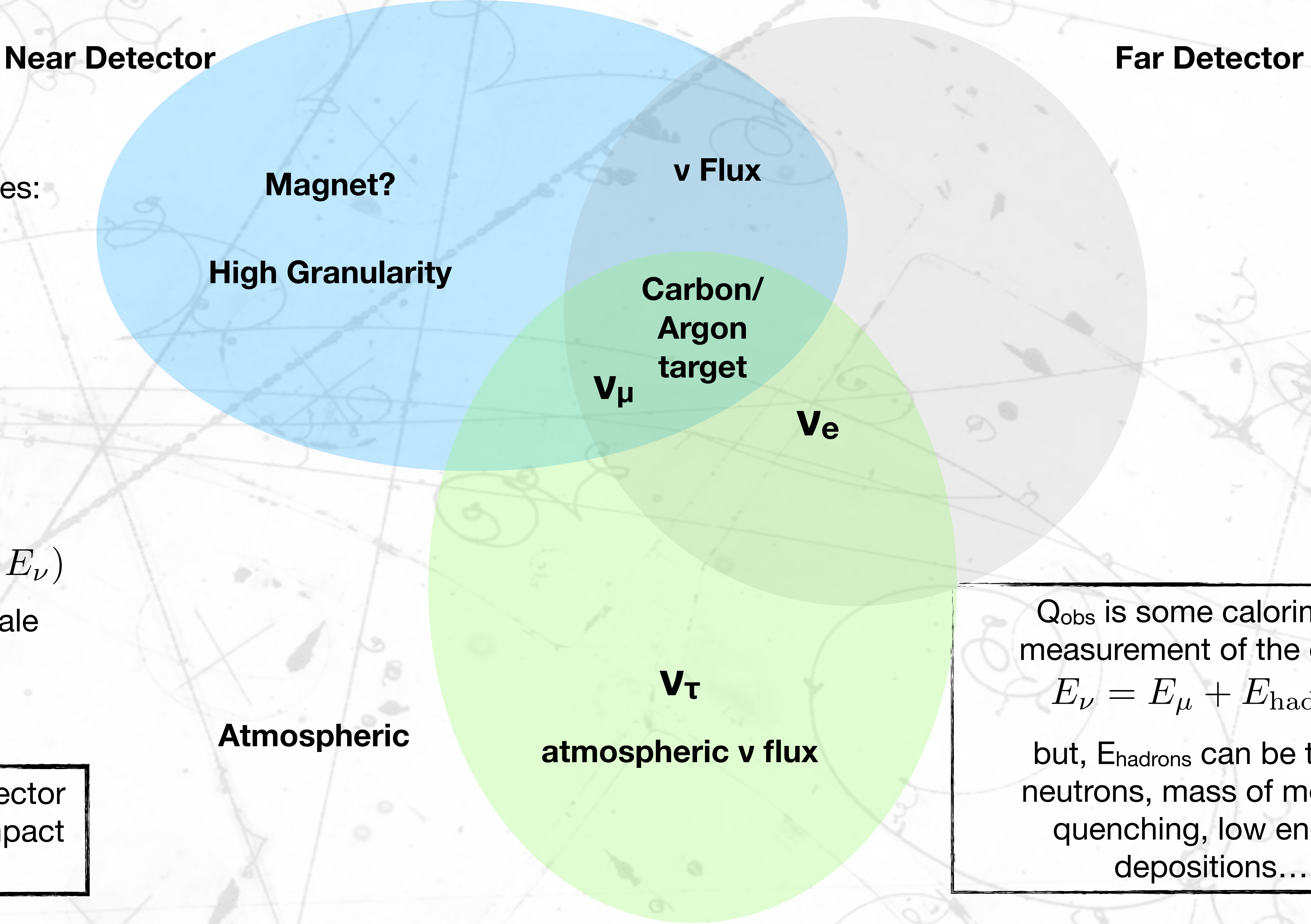
Detector acceptance

….

so

$$P_{\rm Near}(\vec{Q}_{\rm obs}|E_\nu) \neq P_{\rm Far}(\vec{Q}_{\rm obs}|E_\nu)$$

although probably in smaller scale and related to detector.



The only magnetised Far detector was Minos and it had little impact on electron neutrinos

$Q_{\rm obs}$ is some calorimetric measurement of the energy

$$E_\nu = E_\mu + E_{\rm hadrons}$$

but, $E_{\rm hadrons}$ can be tricky: neutrons, mass of mesons, quenching, low energy depositions…

Why is X-sect a problem ?

- Main issue : we do not have a proper model to **describe the cross-sections** in all its complexity, We have **Effective models** ! :
    - atoms of 12/16 (or 40) nucleons reduced to a single potential.
    - Inner proton/neutron structure unknown at these energies.
    - Non-trivial initial and final nuclear state description
    - Transition from relativistic to non-relativistic.
    - Quantum mechanical effects difficult to include: Pauli blocking, interferences…

- Experimental measurements are difficult:
    - high **target mass** and low number of interactions.
    - **low granularity** detectors (cost but not always).
    - Events with **two energy scales**: low momentum hadrons vs high momentum muons.
    - The **Nucleus is a hidden part of your experiment :** no way to know what happened inside.

- In addition
    - we do not know the neutrino flux with precision.

The only solution found (both WC and Calorimetry) is to try to model the cross-section with some d.o.f. and fix them in the experiment.

BUT!
Wrong model can bring wrong conclusions:

$$\sigma_{\text{true}}\ \Phi_{\text{true}} \sim \sigma_{\text{wrong}}\ \Phi_{\text{wrong}}$$

This is a condition that applies to Calorimetric and Water Cherenkov approaches —> near and far detector fluxes are different even before oscillations.

To remember!

- Recent T2K/NOvA/SK experience of **joined analysis** called for a **common treatment of cross-sections**
  - both in the modelling and the degrees of freedom definition.
- Cross-sections is the **common language of all the oscillation experiments** and we need a coherent (and solid?) treatment.
- Same issue for **neutrino fluxes,** but this is another battle…

ν_μ & ν_e

Different goals for ν_μ and ν_e

ν_μ

- Precision disappearance oscillation :
  - atmospheric parameters also critical for CP violation.
  - added sensitivity to hierarchy.
- Laboratory for cross-section measurements and model constrains
  - impact on ν_e x-section modelling.
- P(Q|E) is critical for muon neutrinos.
- Large amount of muon neutrinos at Near Detector.

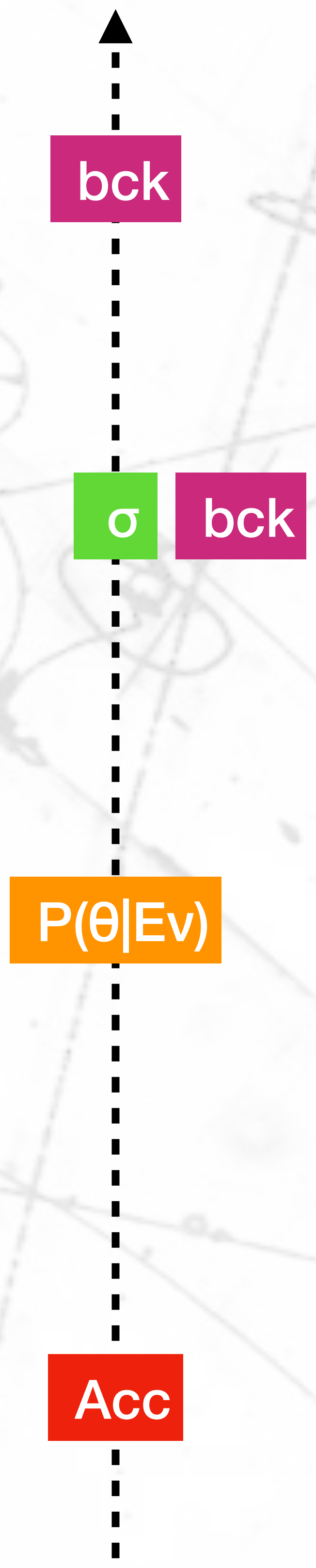
Model Connection?

ν_e

- Appearance measurements —> CP violation.
- Not really a must now but critical in next generation.
- The P(Q|E) less relevant.
  - more important in DUNE but mainly counting in Off-axis configurations.
  - $\sigma(E_{\nu e})$ is critical, actually $\sigma(E_{\nu e})/\sigma(E_{\nu\mu})$
- Very few neutrino electrons at Near Detector:
  - low statistics and high (π^0) background

X-sections: we need to know

- The backgrounds (conceptually can be related to reaction channel migration)
- The interaction probably, but also the relation between the different interaction channels.
- E reconstruction: what are the experimental observable in our model?
- Acceptance: which are the events we detect in the near, the far detector and in our “selection” sample.



I will mark with these labels the expected effect of the modelling on our experiment.

Modelling X-sections

Why modelling is so difficult?

- Traditionally cross-section has been split into :
    - Initial conditions
    - Nucleon interactions
    - final states interactions
- This is a (gross?) simplification,

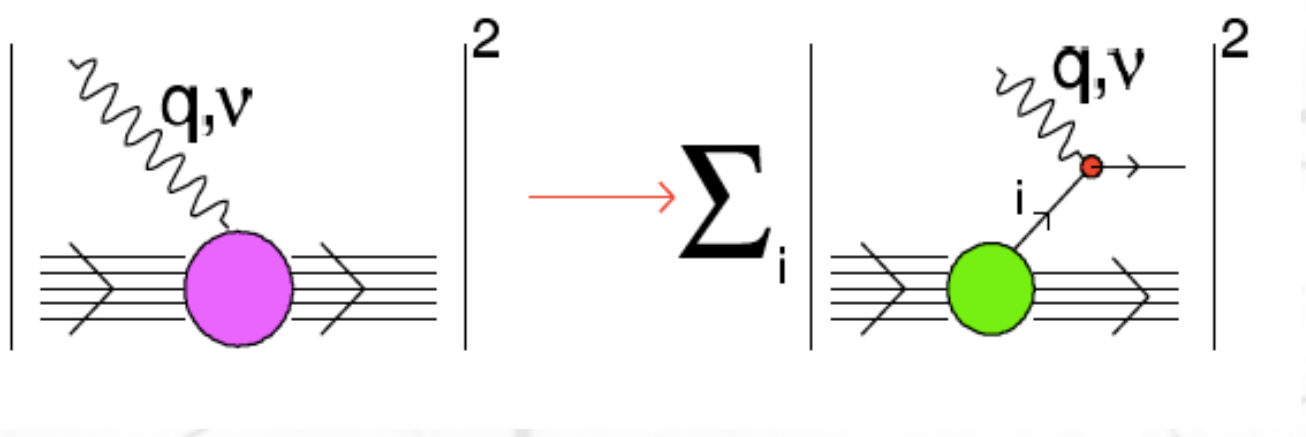
In reality the neutrino interacts with a nucleus and produces particles it does not interact with a nucleon in a nucleus producing particles that interact subsequently with the remaining nucleus.

I will use the same subdivision to describe the issues we are facing
But!! pay attention : some of them are interconnected leading to potential double-counting.

Why modelling is so difficult?

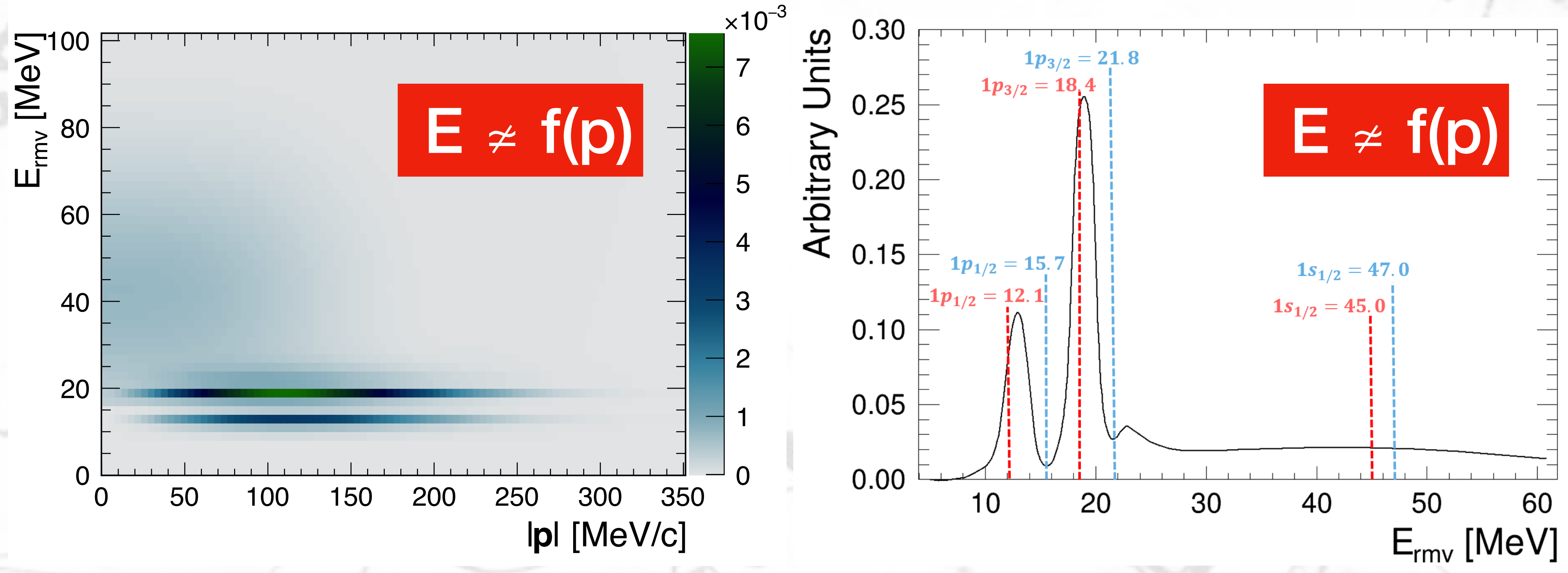
Initial conditions

- The nucleus is a set of A strongly interacting particles.
- The usual description is given by the Impulse Approximation: nucleon in a potential.

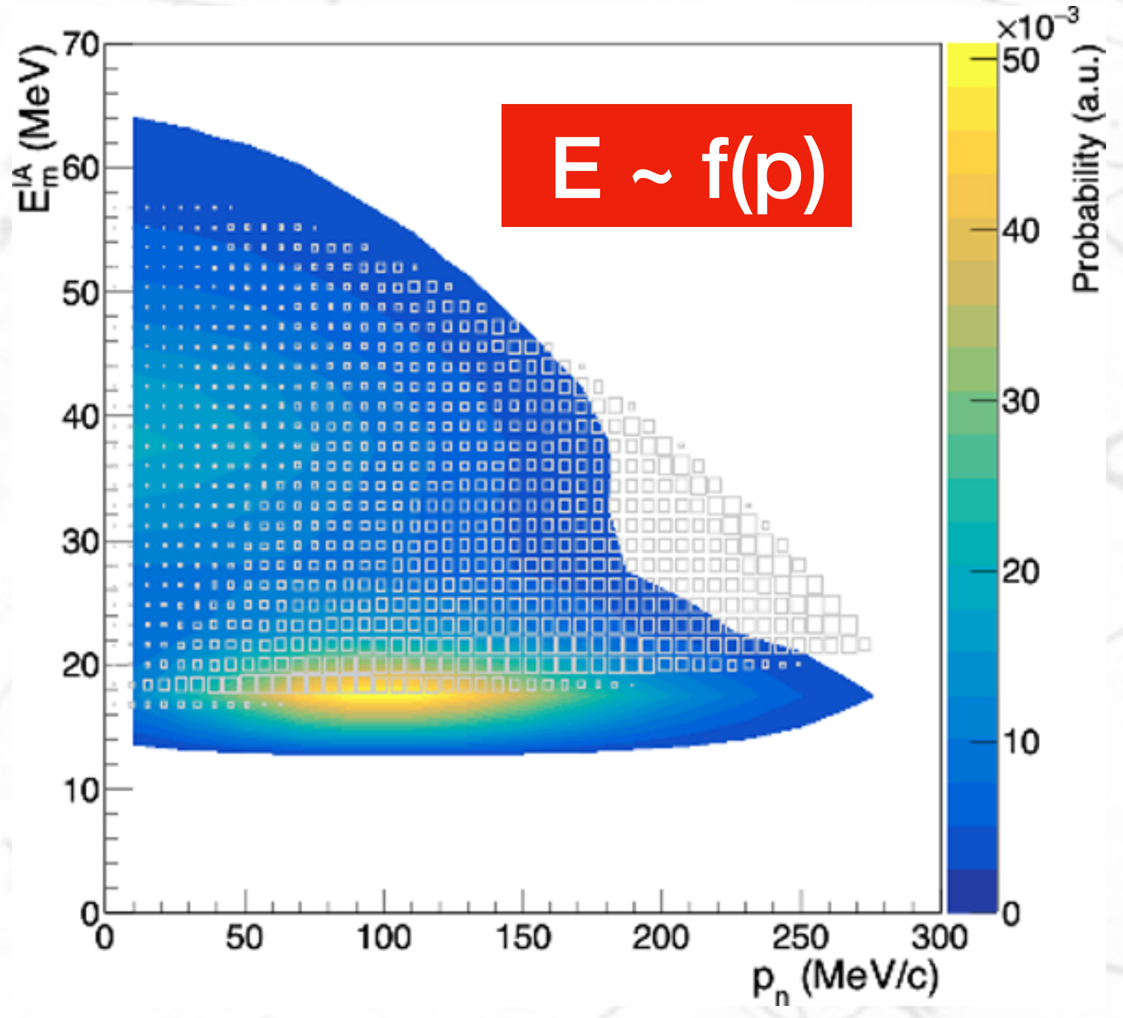


  - But this is not completely correct: we ignore correlations (2 body states) and interferences in Final states. P(θ|Eν) Acc σ
- In this description we normally describe target nucleons in potentials through its dispersion relation : P(θ|Eν) Acc σ
  - classically one single potential and no QM solution : continuous Fermi levels.
  - modern methods do shell model, either phenomenological (Spectral Functions) or calculations (mean field or ab-initio).
    - More advance models also take into account the quantum numbers of particles in a shell.
    - Both approaches has pro's and con's.

Spectral Function
Hartree-Fock Mean Field



Local Fermi gas vs SF



In short:

Similar phase-space with different dispersion relations of target nucleons

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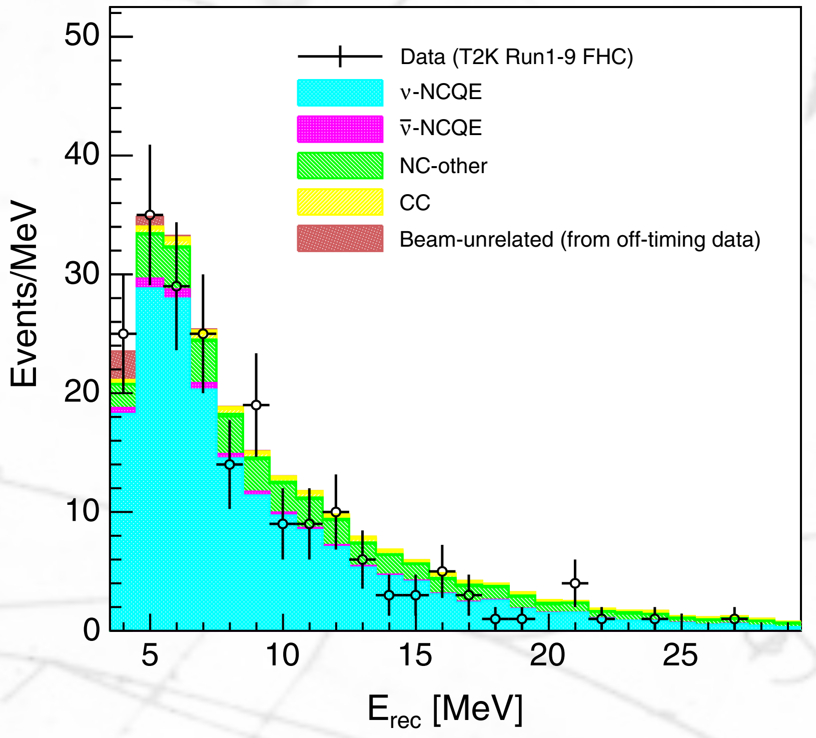
Why modelling is so difficult?

Initial conditions

- We are also displacing a nuclear state by removing one particle to another nuclear state.
- There is energy consumed in this process **(removal energy):** P(θ|Eν) σ
  - Minimal removal energy is the difference between the two nuclear ground states.
- Most probably the final state is not at ground level : P(θ|Eν) σ
  - The **excitation levels** of the final nucleus are important.
    - nucleus can even break, **the fission energy comes from the neutrino.**
  - Difficult to calculate since the final nucleus is different from the initial and probably not “stable” —> many final states and lack of theoretical models.
- Intrinsically **related to the initial and final conditions** in a non-trivial manner :
  - it affects the momentum of the outgoing part. P(θ|Eν) Acceptance σ
  - Related to final conditions since not all transitions are possible due to quantum number conservations. P(θ|Eν) Acceptance σ
  - final state when nucleus is broken is difficult to evaluate. P(θ|Eν)

Final state nucleus can be excited

T2K has measured the de-excitation of Oxygen to evaluate the NC interactions.



$$\nu(\bar{\nu}) + {}^{16}\mathrm{O} \rightarrow \nu(\bar{\nu}) + n + {}^{15}\mathrm{O}^{*},$$

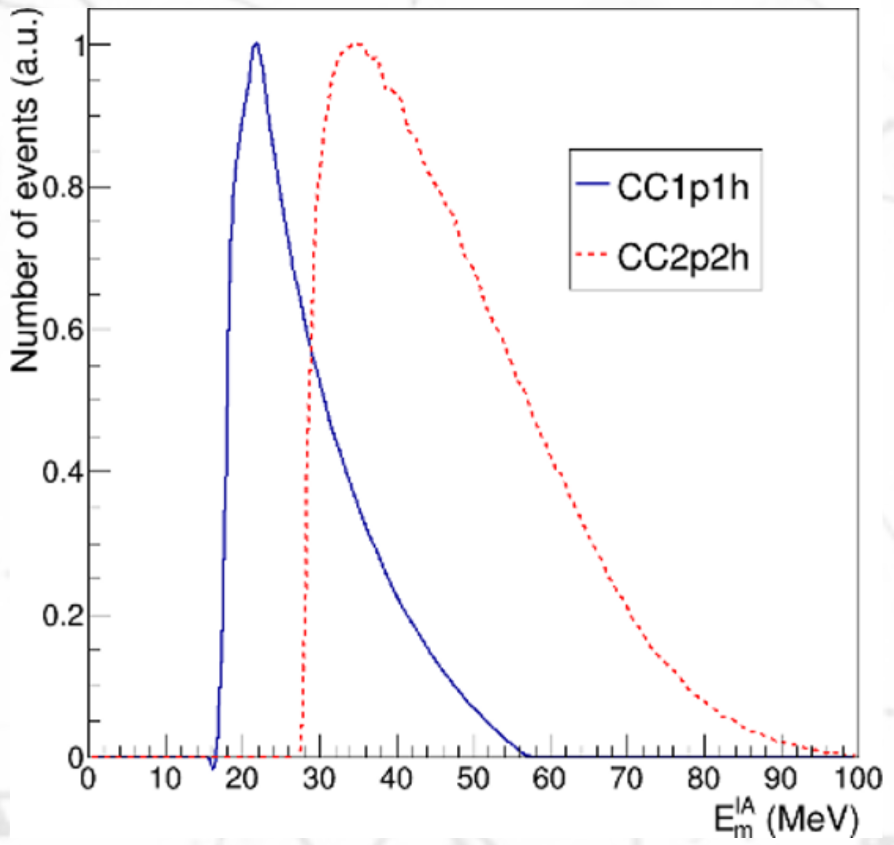
$$\nu(\bar{\nu}) + {}^{16}\mathrm{O} \rightarrow \nu(\bar{\nu}) + p + {}^{15}\mathrm{N}^{*},$$

Excitation energy related to removal energy

Removal energy in the (wrong) Local Fermi Gas model.

25 MeV is large (~4%) compare to neutrino energy (650 MeV)

This model considers (like the SF) the energy removed from the nucleus (binding energy of the nucleon). Is this sufficient?

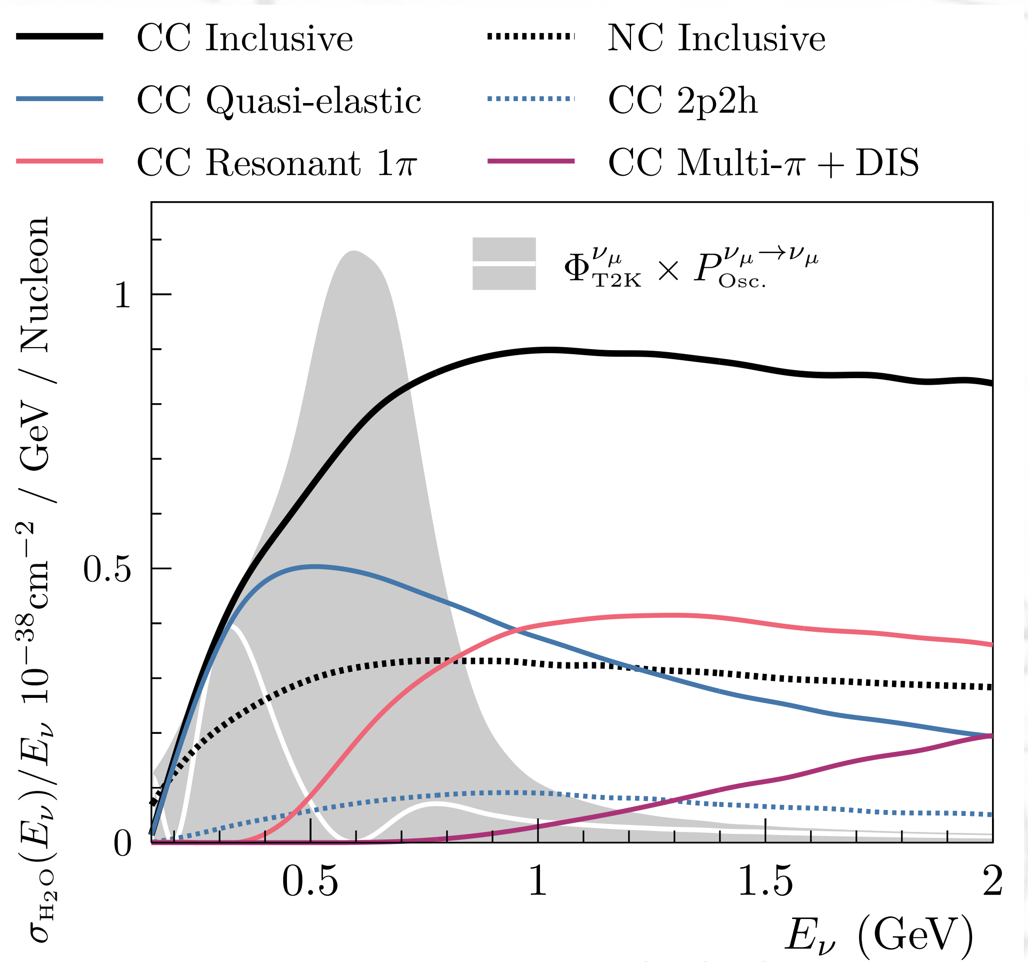


Why modelling is so difficult?

Nucleon interactions

- The nucleon is not a point-like particle —> Cross-sections are modelled using form factors.
  - **Vector form-factors** from electron scattering. P(θ|Eν) Acc σ
  - Some **theory cooking** PCAC,… P(θ|Eν) σ Acc
  - The **Axial form factors** are unknown. P(θ|Eν) Acc σ
- The **pion case** is even more complex : P(θ|Eν) σ bck Acc
  - many partial amplitudes with interference with resonant and non-resonant contributions.
- **Experimentally** the neutrino-nucleon interaction is poorly known.
  - **Lack of statistics: old experiments.**
  - Experimental issues : no **free neutrons in nature**. Most of the experiments are done on large (A>10) nuclei and corrected by nuclear effects.
  - We **assume Vector form factors** from electron scattering.
    - unfolding - folding issues might rise.

Many different cross-sections



The simple CCQE

$$|M|^2 = \frac{G_F^2}{2} L_{\alpha\beta} W^{\alpha\beta}$$

$$L_{\alpha\beta} = 8(k'_\alpha k_\beta + k_\alpha k'_\beta - g_{\alpha\beta} Q^2 + \epsilon_{\alpha\beta\rho\sigma} k^\rho k'^\sigma)$$

$$W_{\alpha\beta} = -g_{\alpha\beta} W_1 + \frac{p^\alpha p^\beta}{M^2} W_2 + \frac{i\epsilon^{\alpha\beta\rho\sigma} p_\rho q_\sigma}{2M^2} W_3 + \frac{q^\alpha a^\beta}{M^2} W_4 + \frac{p^\alpha q^\beta + q^\alpha p^\beta}{2M^2} W_5 + \frac{i(p^\alpha q^\beta - q^\alpha p^\beta)}{2M^2} W_6$$

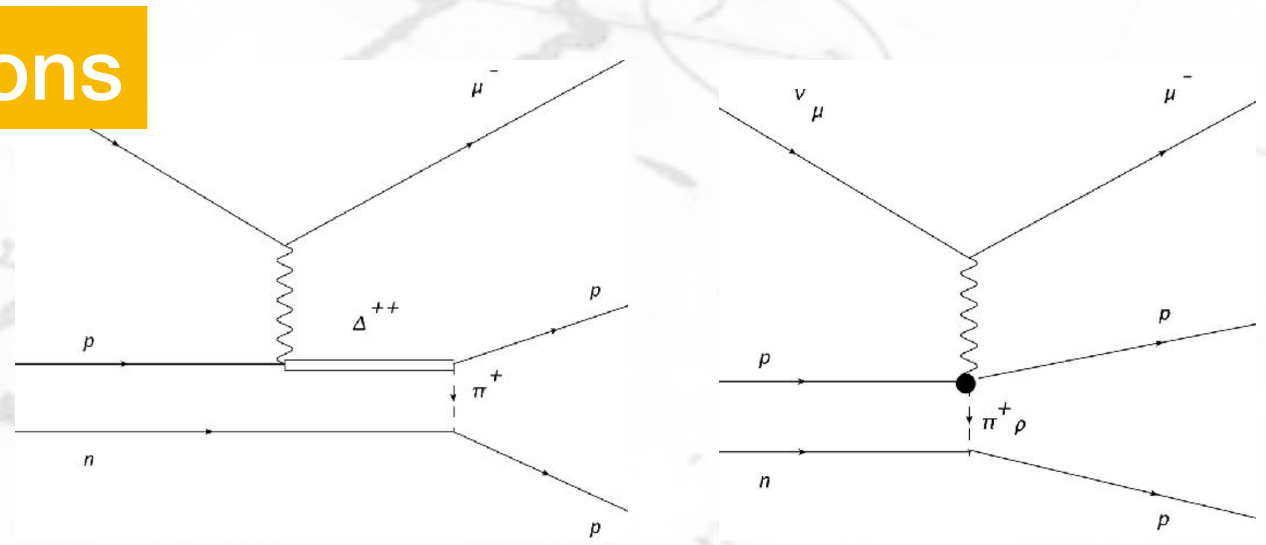
$W_{\alpha\beta}(q^2)$ are form factors derived from experiments (when possible)

Beyond CCQE we need to consider helicities, multiparticle states, several reaction sub-channels (resonant vs non-resonant) …

Why modelling is so difficult?

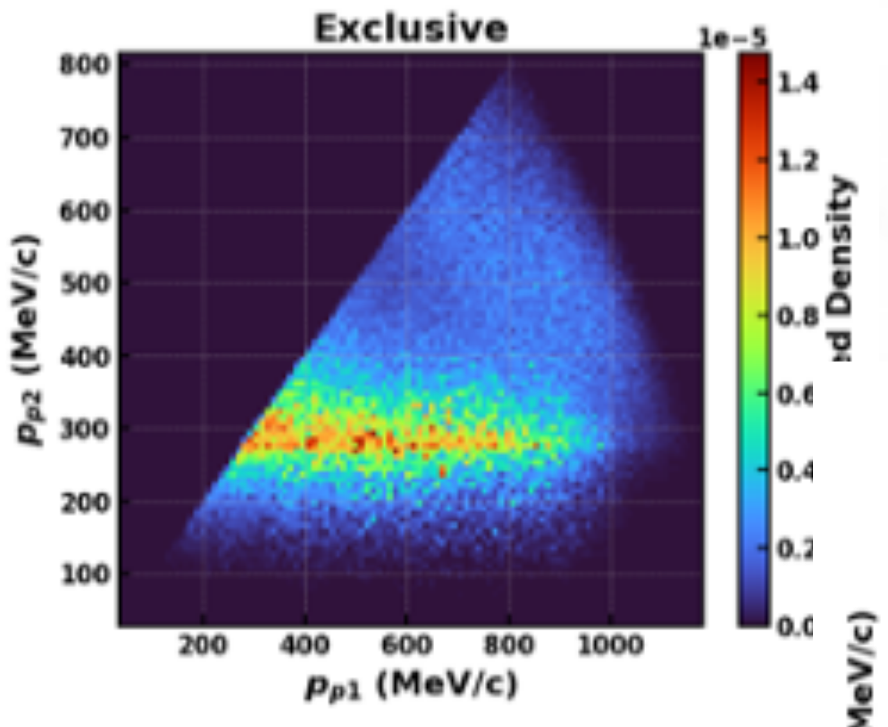
Nucleon interactions

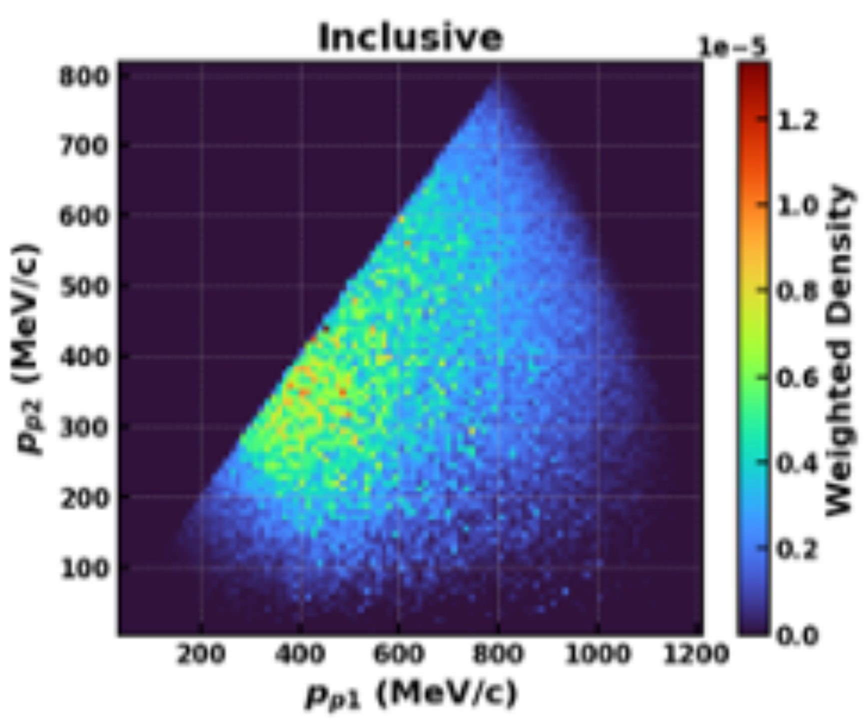
- Not only it is difficult, it is messy:
  - There are possible interactions with **2 bodies** in the nucleus (2p2h).
  - This is very **similar to CCQE** but with a totally different P(E'ν|Eν). P(θ|Eν)
  - It has **more than one channel** (resonant and non-resonant) that interfere cons(des)tructively. P(θ|Eν) Acc σ
- It is also difficult to separate from :
  - **initial state nucleon pairs** (something like a deuterium atom inside the nucleus) : double counting and interference P(θ|Eν) σ
  - **nucleon absorption by the nucleus** : interference with some 1p1h and resonant. P(θ|Eν)
- Different models assume differently, they can be consistent but not across models —> **Frankenstein models.**
- **Experimentally difficult to measure:**
  - only one nucleon is visible, the lepton energies overlap with 1p1h and pion production, …

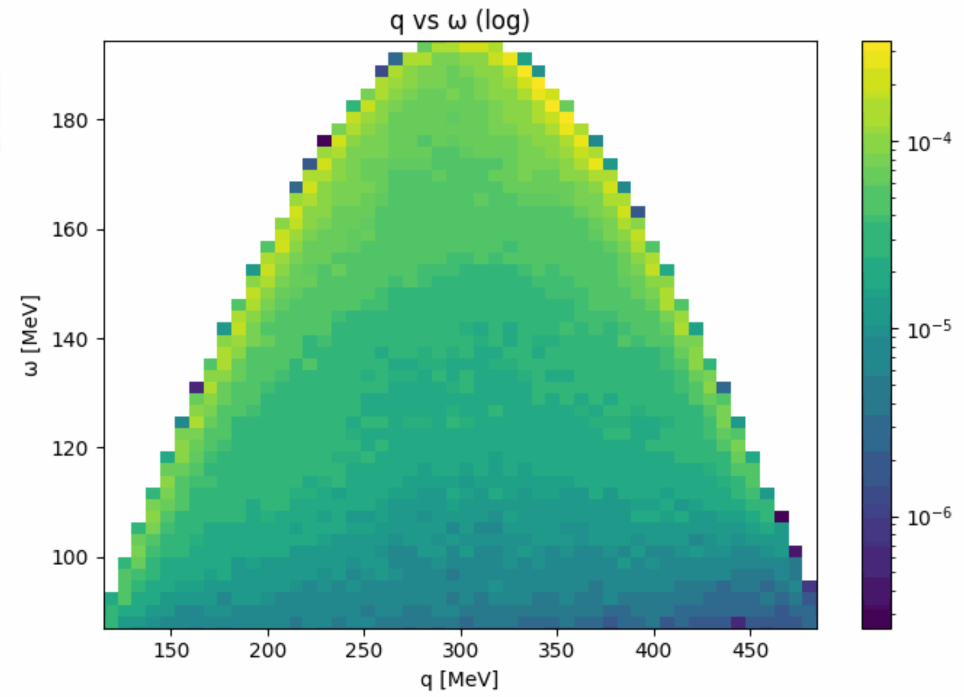


Diagrams for 2p2h in Valencia Model

Complex calculations, fully exclusive models start to be available now





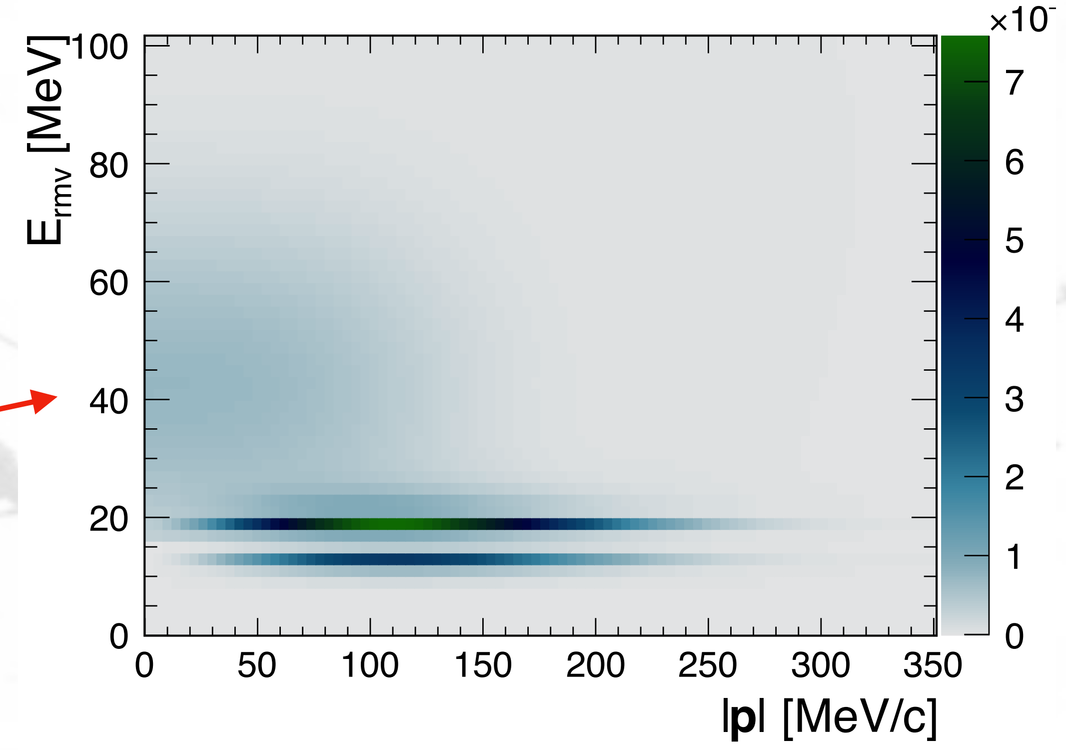


Models have different predictions : Ghent model.

Model ingredients and assumptions are important

2p2h and double counting

- Nuclei is a complex Quantum Mechanics system that we model basically as a nucleon in a potential. But this is not a reality:
  - nucleons can be (with a probability) found in pairs (some sort of virtual deuterium nuclei). These states normally provide high momentum targets beyond Fermi momentum as in Spectral functions.
- The 2p2h (interactions with 2 nucleons) overlap to the “pre-existing” nucleon pairs:
  - how to distinguish them?
  - Energy tails in SF are not double counting 2p2h events?
  - Initial and final states are the same: different channels can interfere.



Similar issues with 3p3h

Difficulties in asymmetric nuclei :

A >> 2 Z

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Why modelling is so difficult?

Final states Interactions

- This part has been neglected in all its complexity until recently. There are several aspects:
  - **Pauli blocking :**
    - normally **implemented as a “cut”** in the possible outgoing nucleon momentum.
    - In reality we need to **antisymmetrize** the waveform —> Need full QM treatment only possible in Mean Field calculations (or “ab-inition”)

P(θ|Eν) σ Acc

  - **Final state interactions:**
    - normally **only scattering with other nucleons** was considered but :
      - The outgoing **lepton and mesons are in a deep potential** that alters the dispersion relation: Energy-momentum balance of the reaction.

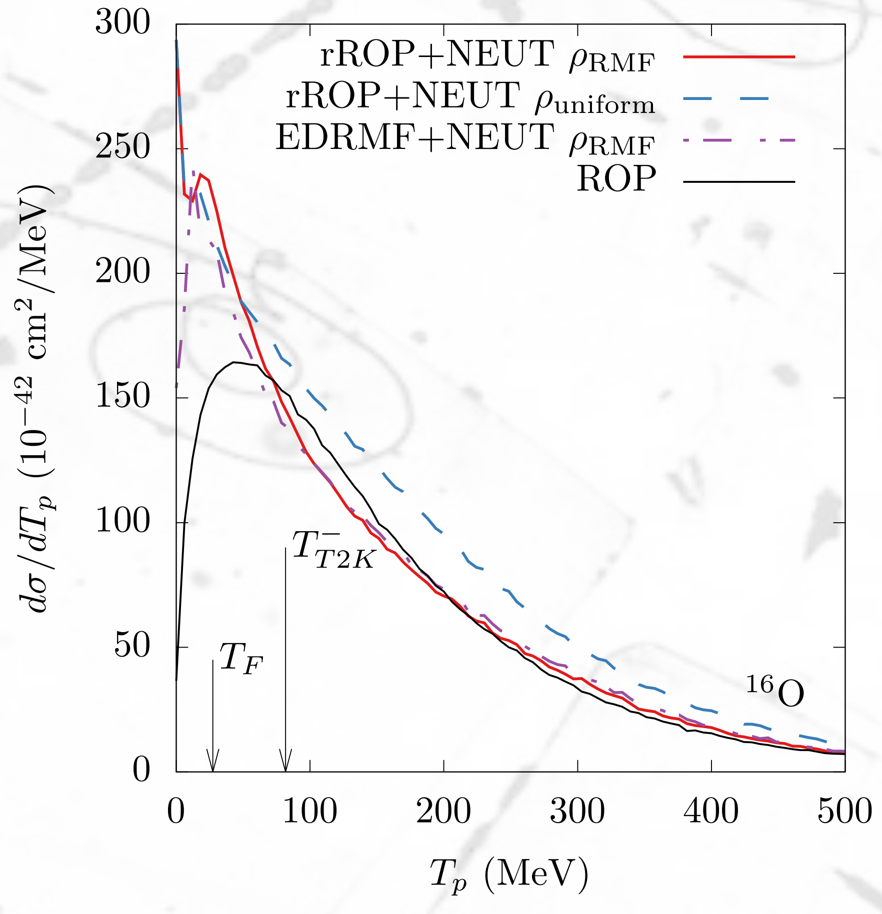
σ P(θ|Eν) Acc bck

      - The same model can also predict **inelastic potential through imaginary components: consistecy**
      - How to reconcile/unite both?
  - **Also, there might be interferences:**
    - **How to distinguish from a nucleon in a nucleus followed by the scattering and the nucleon after the nucleus?** Double counting and interferences are possible in a consistent treatment.

P(θ|Eν) σ

  - Pions can be absorbed given a **CC1p1h signature:** what is the difference with C1p1h at nuclear level? bck

How to come with a consistent model ?



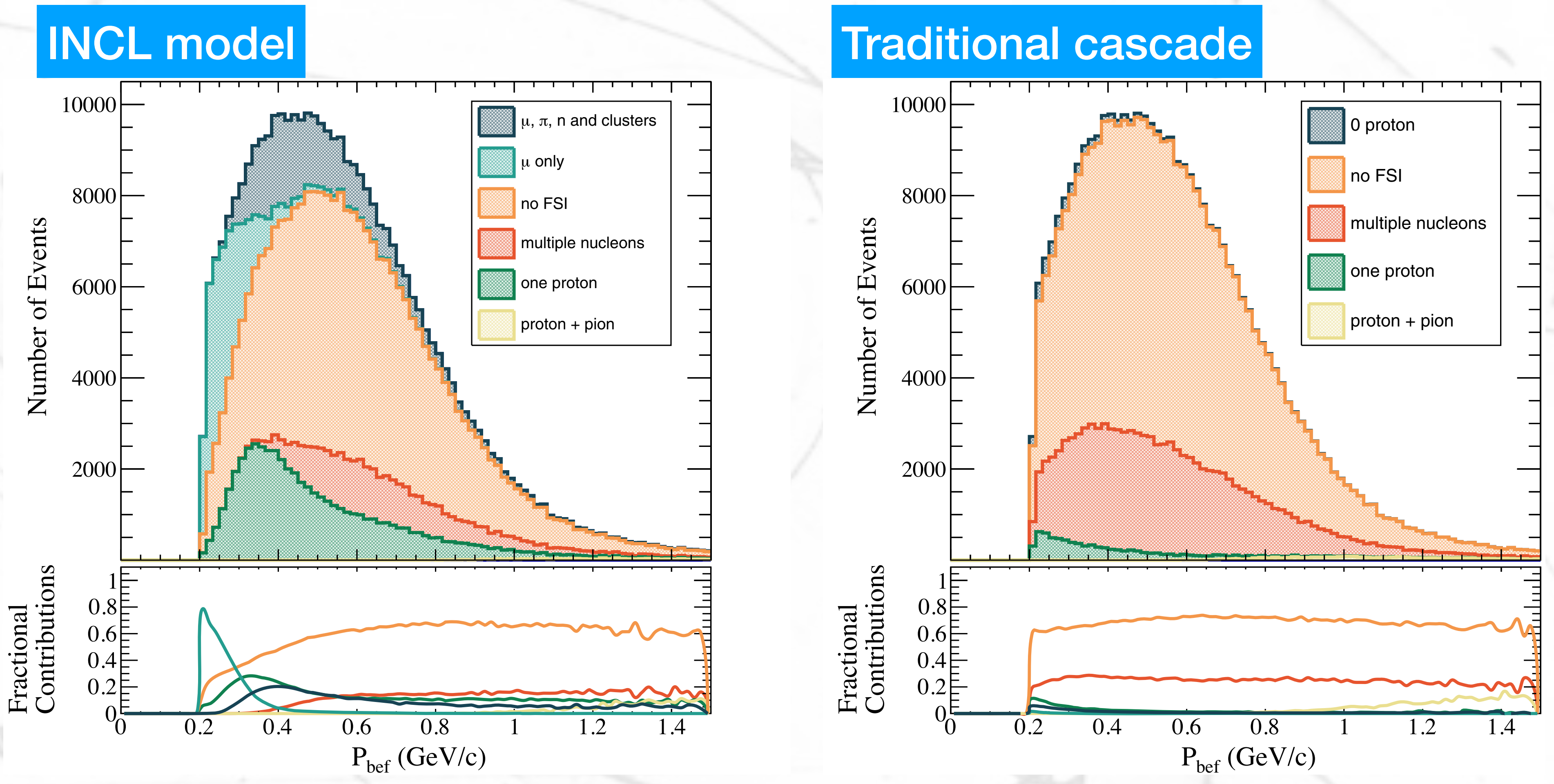
New studies to explore complementarity between cascade and interaction potential implementations :

strong relation with double counting and model integration.

PHYSICAL REVIEW C **105**, 054603 (2022)

Some models include optical potentials in a consistent manner but they cannot predict final states.

Richer physics is needed to describe the interactions : INCL model



PHYSICAL REVIEW D **106**, 032009 (2022)

More … (relativistic vs non)

- We are in a low energy interaction region (400 - 1000 GeV) with even smaller transverse momentum and energy:
  - this is a r**egion where the relativistic and non-relativistic models merge.**
  - normally **a consistent relativistic description of the nucleus in Mean Field is computationally difficult.**
  - The relativistic description might not be perfect for low momentum transfer.
- We need a model that transit from one to the other. Tools are getting in place to do this (i.e. Normalising flow algorithms).
- Luckily in HK/T2K we care mainly about low energy, high energy is a background for us, but! :
  - combination with other experiments or atmospheric neutrinos will require a self consistent large energy range model.

Carbon vs Oxygen

- Our **near detector is normally based on carbon**: good balance between mass, segmentation and cost.
  - active water is a challenge and more for high precision.
  - some models break for C or O due to assumptions and nuclear configurations.
- The **transport of C model to O cross-sections** is not so easy :
  - nuclear energy levels (2 in carbon and 3 in Oxygen) —> even with a proper C measurement there is an “extrapolation” to make.
  - How to evaluate the uncertainty ?
    - model predicts small deviations from C to O of ~% per nucleon. But, we are far from testing it.
- Good complex models can help, but…. can we really be sure ? to which level?
  - A detailed data-model comparison in C can help to gain confidence to certain level.
  - Experimental data will be always needed, at which level ?

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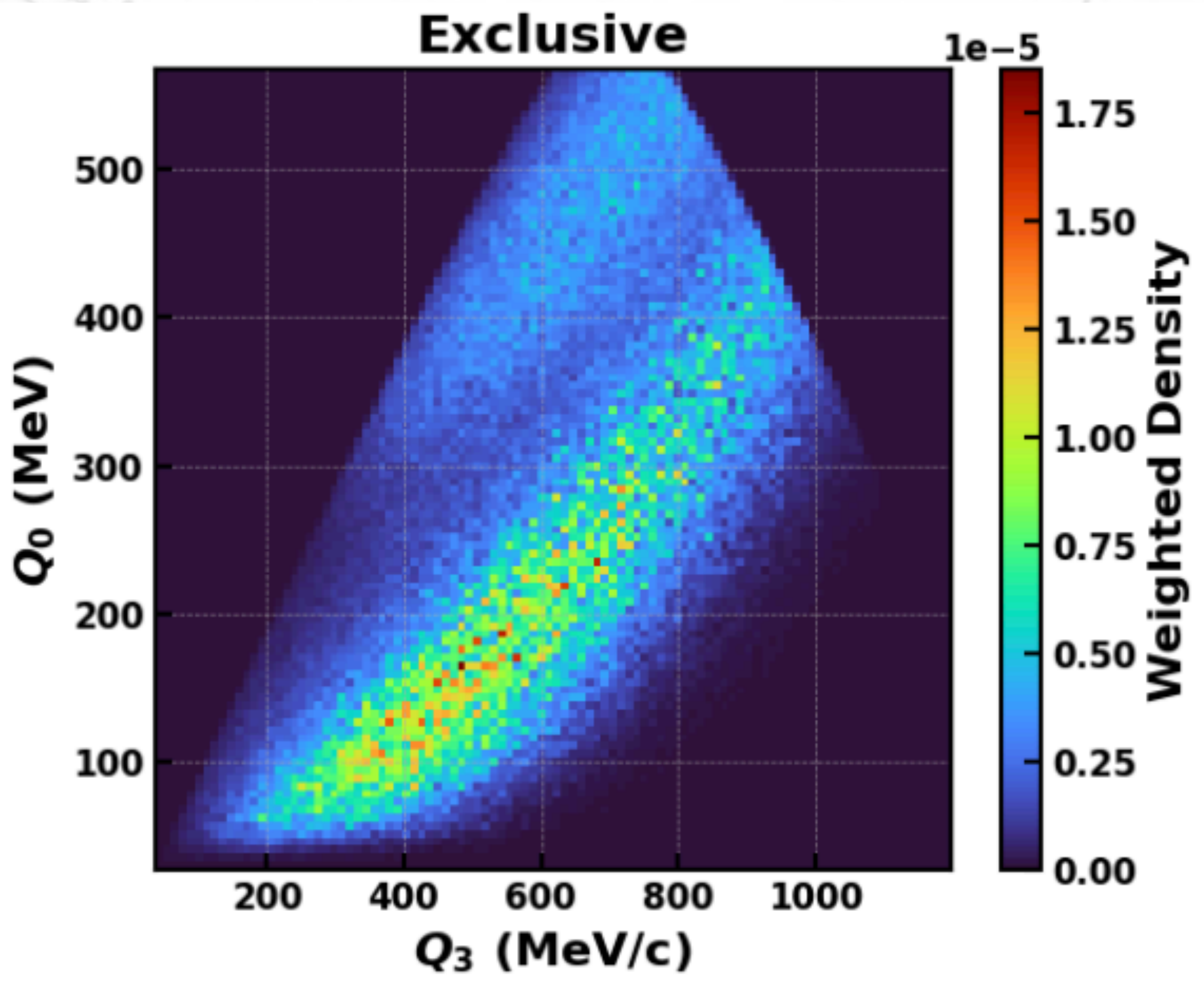
neutrinos vs antineutrinos

- “a priori” different target —> different initial state.
- **different final state** (i.e. proton vs neutron) —> experimental challenges
- at **nucleon level V vs A have different signs** —> destructive for antineutrinos —> more delicate in calculations.
- we have no way to separate them in the fast detector —> ND magnet immense asset.
- experimentally electron neutrinos have lower statistic and larger backgrounds
  - **anti-neutrino electrons** more challenging, close to impossible? **both needed for CP violation.**
- The effect of asymmetric nuclei (^{40}Ar) might be large.

ν_{μ} VS ν_{e}

- **A priory only the mass of the lepton** is important but :
  - **different mass changes the q_0,q_3 mapping of the nucleus for a fixed energy** —> Not the same strength give a neutrino energy
  - electrons emit **breemstrahlung** :
    - available estimates claiming for small effect.
    - complex interplay with experimental measurements (photon merged in electron showers or not).
- For a precision measurement we will need to measure it. But :
  - low statistics.
  - very different experimental techniques (tracking vs cherenkov) call for a solid model behind (breemstrahlung for example)

Example :
(q0,q3) nuclear strength for the Valencia 2p2h model



It is not impossible that a very precise knowledge of muon neutrino interactions provide sufficient information for the electron neutrino… but, How to prove this?

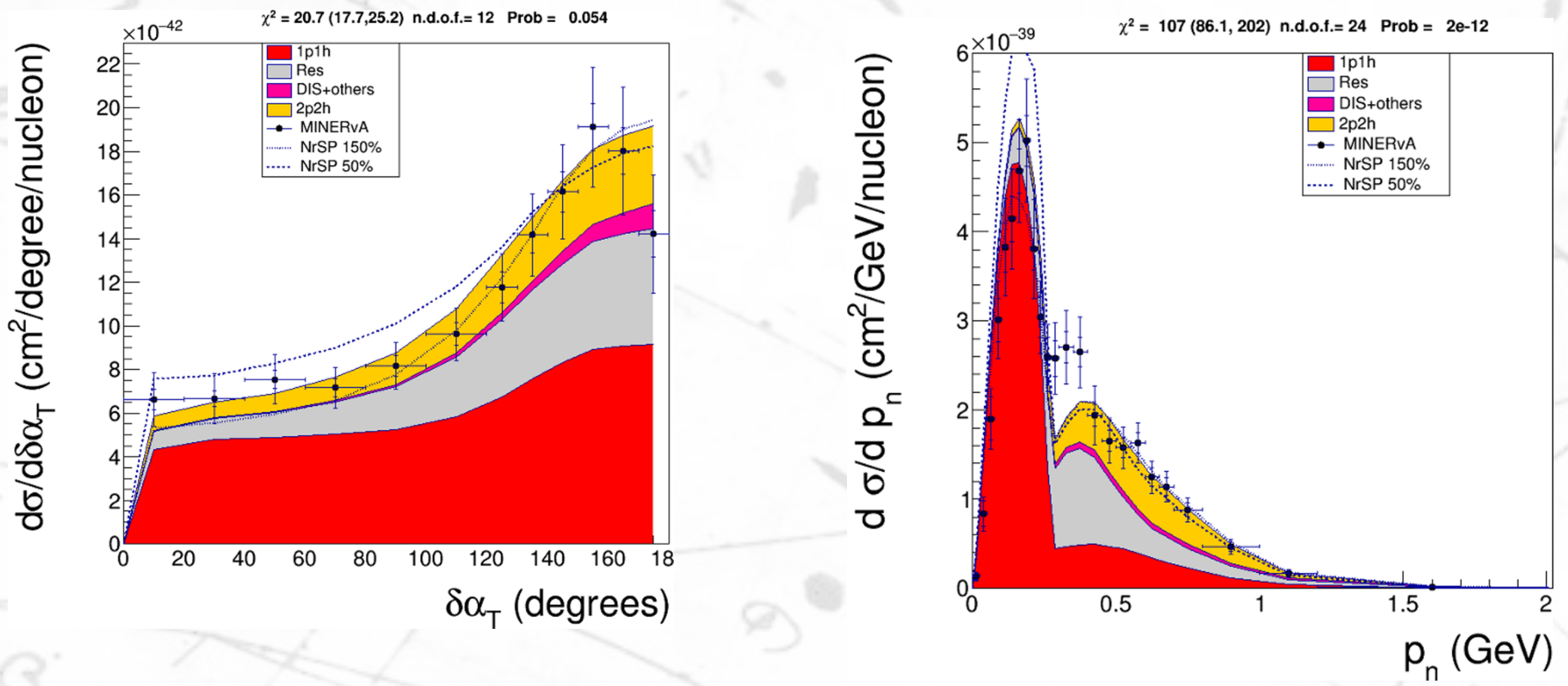
To evolve on the understanding we need more precise experimental measurements :

better detectors, different nuclei, but also ingenuity to analyse the data

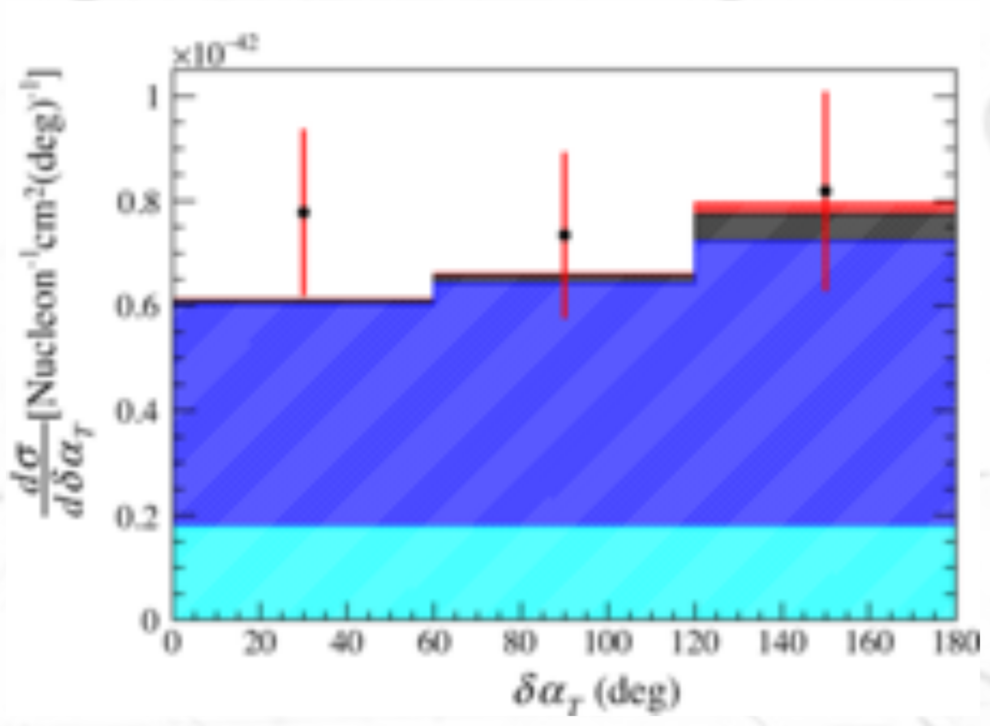
TKI observables

- Experiments moved into new observables where the neutrino energy plays reduced role : Transverse kinematic (TKI) variables. P(θ|Eν)
- New variables are able to singularise contributions :
  - Fermi momentum
  - Nuclear re-scattering, …
- But they need the reconstruction of **hadron observables** with precision:
  - **low threshold and high tracking performance.**
- These observables have been **used by Minerva to isolate interaction with hydrogen** to explore ν-nucleon interactions.
- This is a very **promising field not fully investigated.**
  - High statistics high granularity (like new T2K sFGD) :
    - multidimensional analysis
    - adding neutrons to the equation.

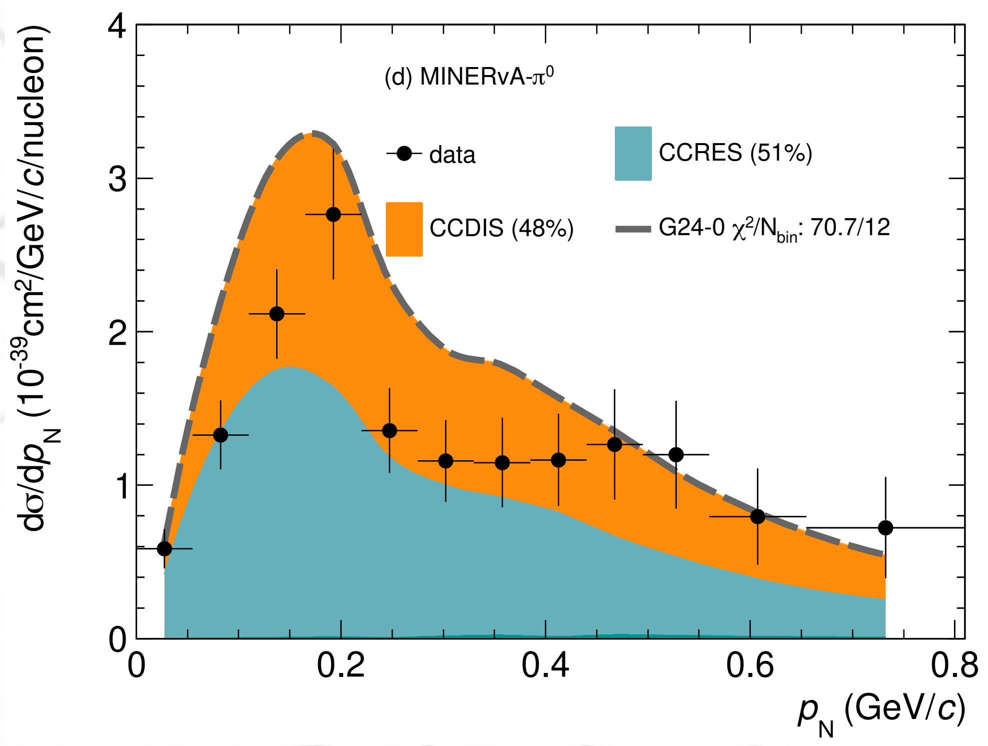
MINERVA results CC0π



T2K result CCπ⁺



MINERvA CCπ⁰

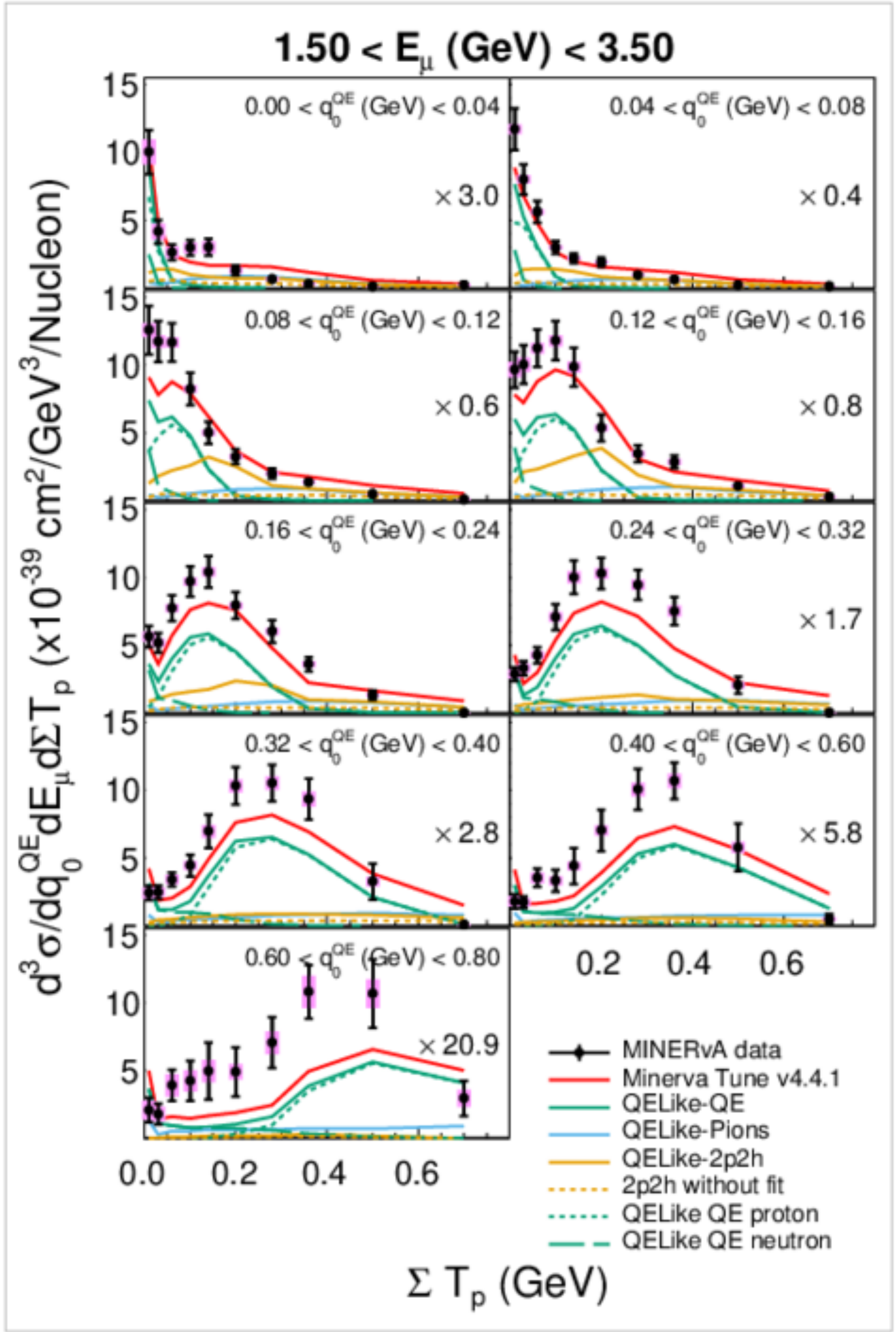


Energy flow measurements

- Minerva explores beyond the usual events with tracks to reduce the hadronic threshold.
- The use of hadronic deposited energy opens new possibilities.

$$\sum_i T_p^i = E_\nu - E_\mu - E_{\text{removal}}$$

- Bridge between the calorimetric and the Cherenkov approaches. P(θ|Eν)



Energy sensitive observables

P(θ|Eν)

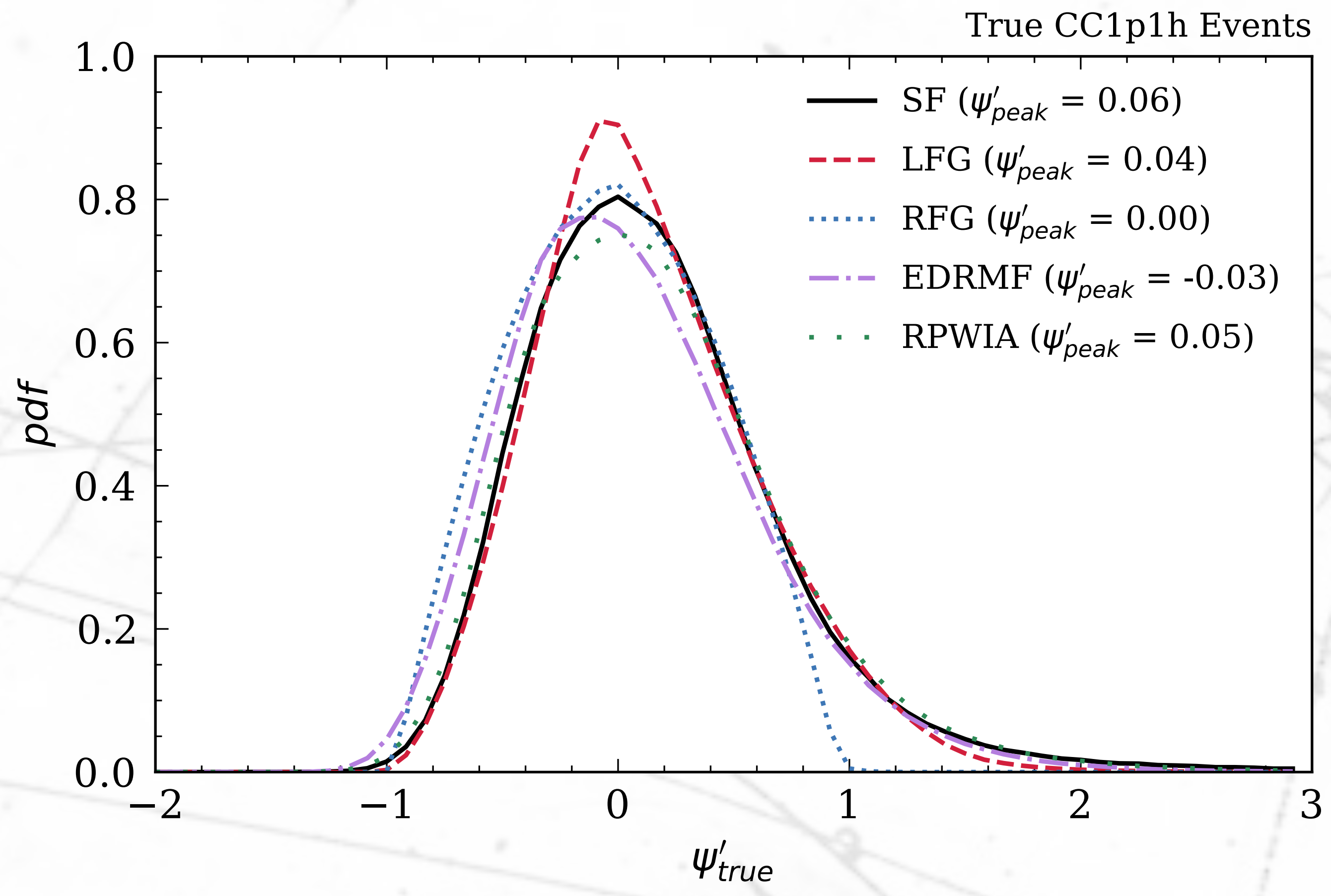
- With all the developments during the last year we still do not have a energy measurement that we can test with data.
- The energy flow from Minerva is a good variable but we miss a reference energy to calibrate.
  - this is easy in electron scattering.
- But, there are variables that can help in CCQE: the superscaling ψ'
  - ψ' is validated/calibrated in ee'A scattering —> good reference.
- This variable is approximately a gaussian centred at 0 with with ~1/3 for any neutrino energy and nuclei.

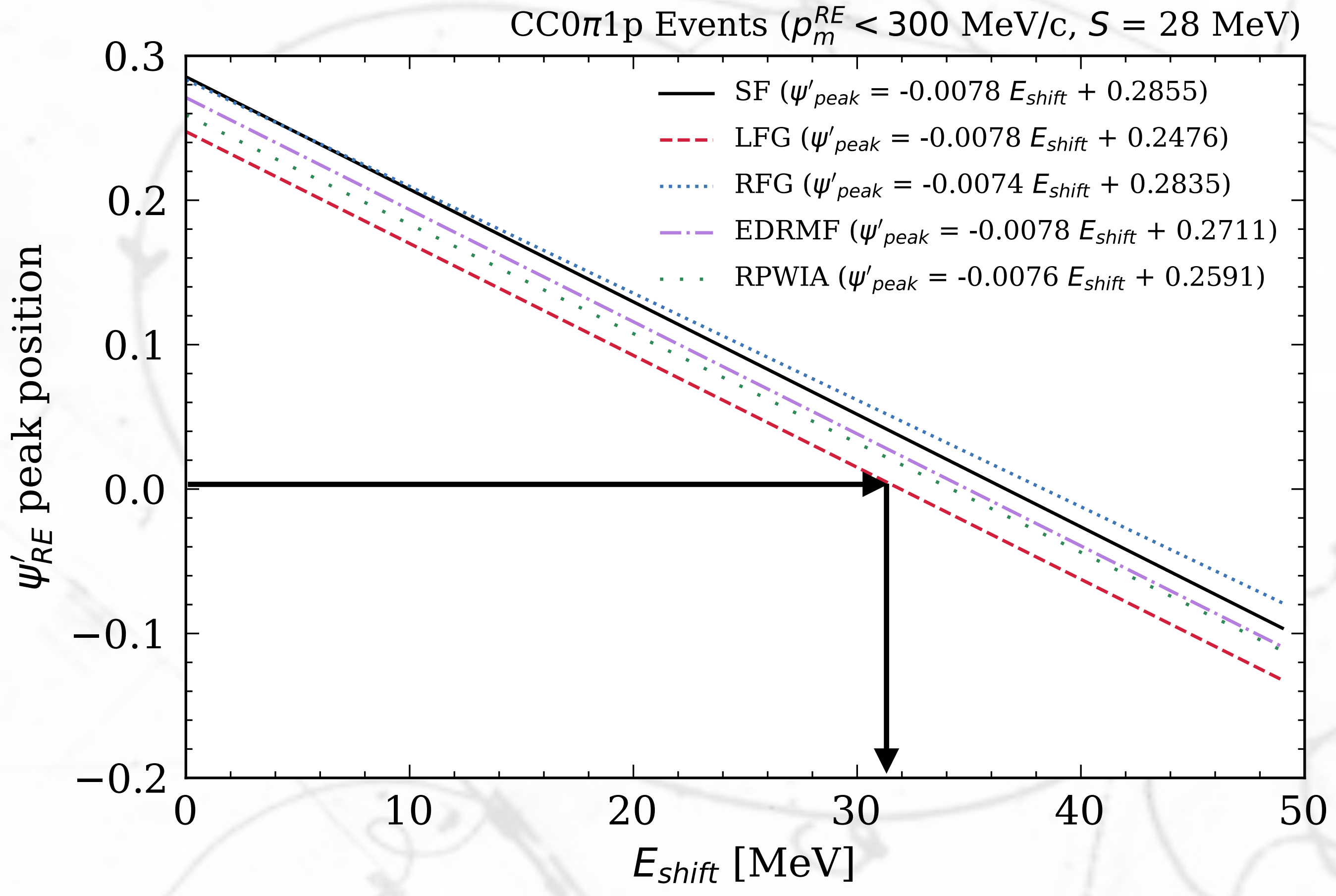
$$\psi'(\omega,\vec{q}) = \frac{1}{\sqrt{\sqrt{1+\eta_F^2}-1}}\frac{\lambda-\tau}{\sqrt{(1+\lambda)\tau+\kappa\sqrt{\tau(1+\tau)}}}$$

with

$$\begin{aligned}\eta_F &= \frac{k_F}{M_N}\\ \kappa &= \frac{|\vec{q}|}{2M_N}\\ \lambda &= \frac{\omega - E_{\text{shift}}}{2M_N}\\ \tau &= \kappa^2-\lambda^2\end{aligned}$$

ψ is not energy but it validates its model
$\omega = E_\nu - E_\mu$





D.Douga et al, Phys. Rev. D 109, 073001

Interplay flux-cross-sections

- Unfortunately we do not measure cross-sections but : “flux-folded cross-sections”:
    - $\sigma_{true}\ \phi_{true} \sim \sigma_{wrong}\ \phi_{wrong}$
- This is unavoidable (until Enubet is there) and one of the reasons we need strong neutrino-nucleus cross-section models.
- But also we need flux models.
    - The better we know the model the more restrictive will be on our cross-section models.
- We should also try to look for alternative ways to measure the flux such as the one of Minerva.

and beyond…the absolute flux

- There is a way to obtain “at least” the absolute integrated flux.

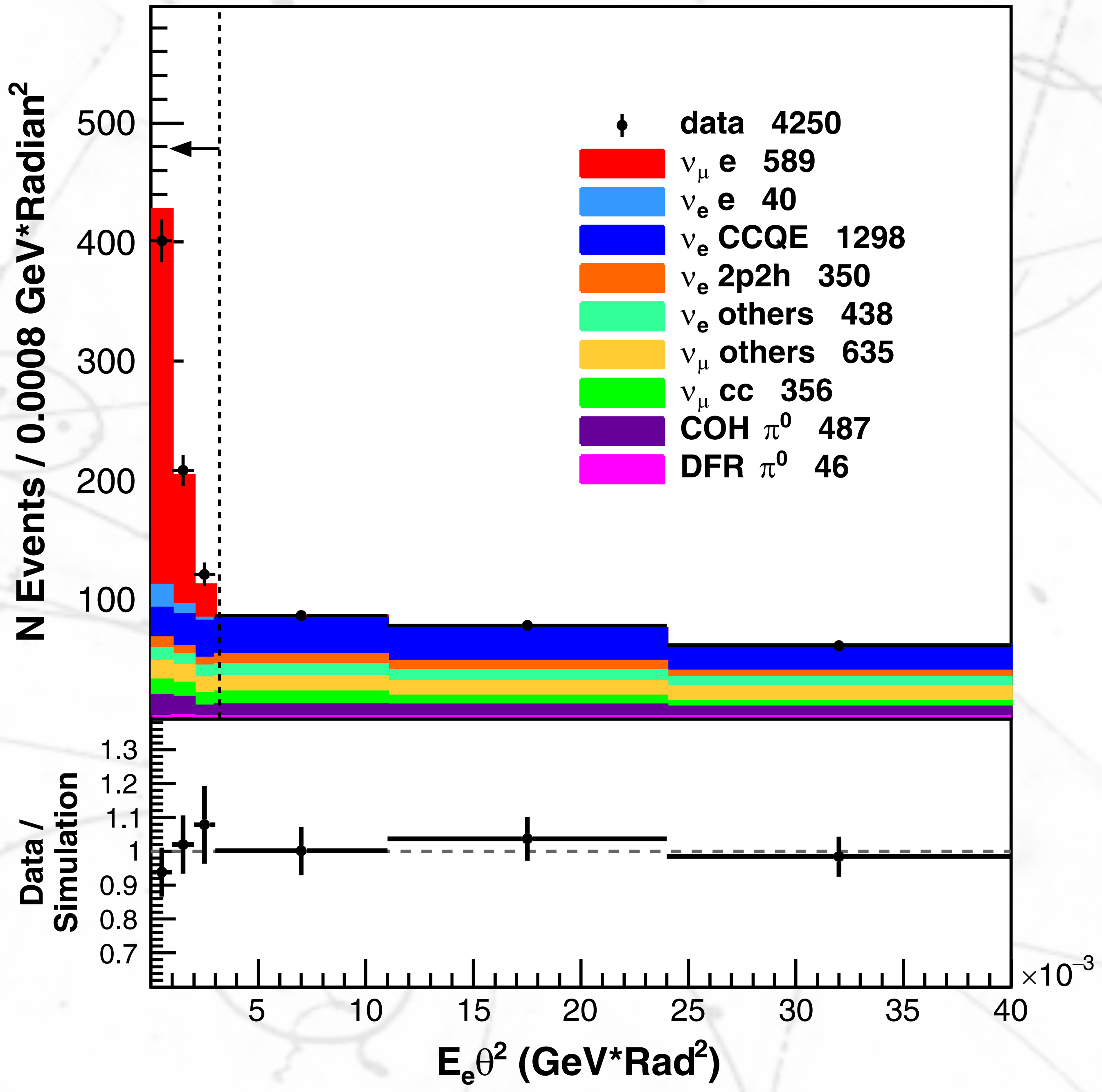
$\nu_e e^- \to \nu_e e^-$

- $\bar{\nu}_e e^- \to \bar{\nu}_e e^-$

- This was used by Minerva to gain control on the flux (3.3 %!)

Phys. Rev. D 107, 012001

- But:
  - Very low cross-section and high backgrounds.
  - It has little dependency with the neutrino energy (NC) and very small theoretical uncertainties.
- With a massive detector this is a must to control further the flux uncertainties.



Generators

Event generators & new generation models

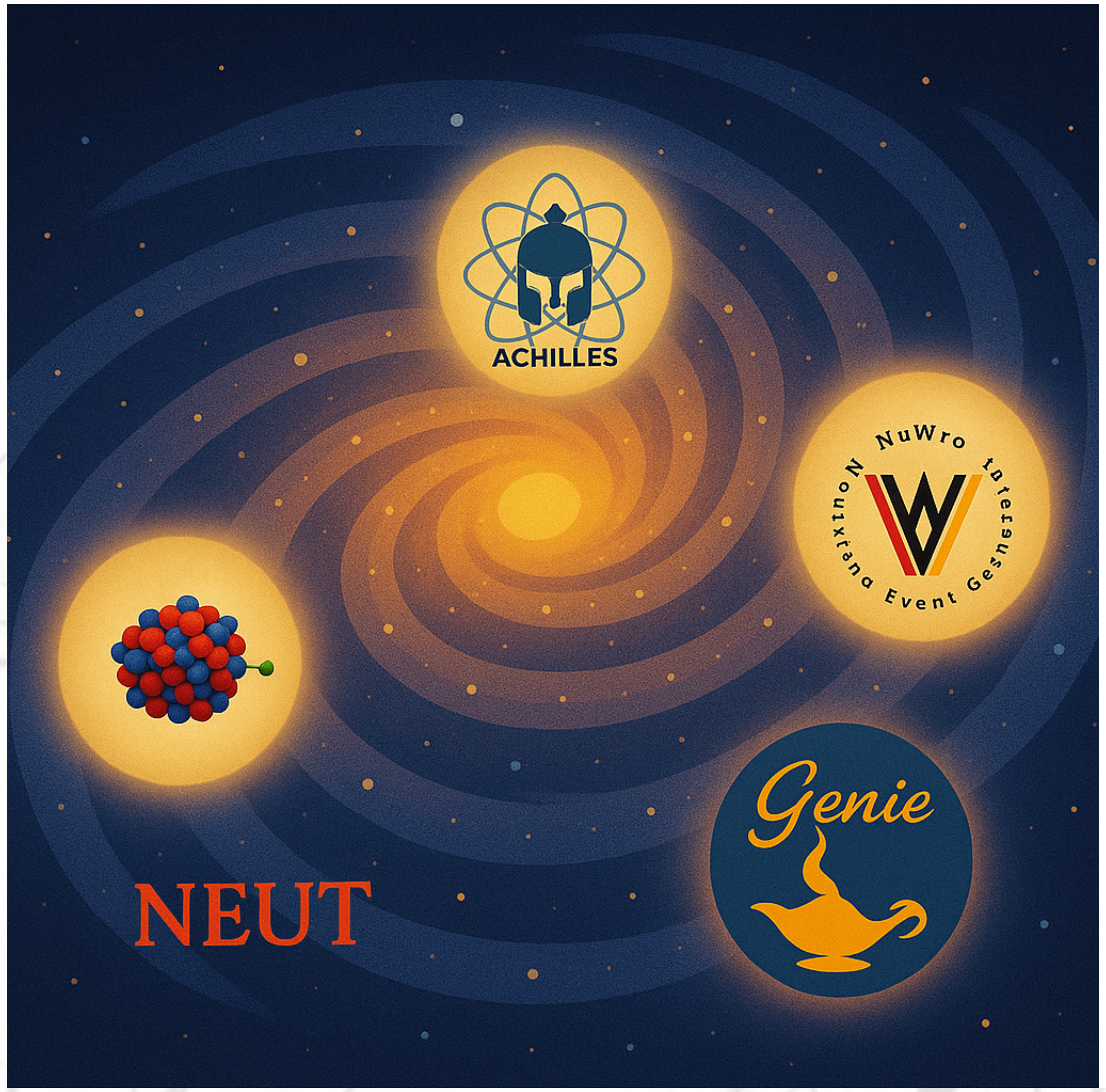
- More complex models imply also new mathematical methods to generate the events:
  - models are **slow** (some we know can generate handful number per day per CPU) —> modern methods investigated.
  - models are based in the splitting I mentioned at the beginning : can we integrate new models?
  - generators allow for several models to be combined —> how to ensure **coherence** ?
  - same generators should (ideally) be **adopted by all experiments : how to agree in the community ?**
  - models should integrate realistic parametrisations to be obtained from data.
  - ….

Using models across different nuclei

- This is (to me) an opened question.
- Critical for T2K (0 vs. C) but also a relevant experimental one:
  - can we use the expected high precision Ar events in MicroBoone, or Pb/Ti events in Ninja to tune the C model ? or viceversa.
- And, even more relevant when we try to compare or to join oscillation results.
- We expect plenty of data in Ar and C in the future, but those are too apart to be able to search for agreement,
  - we need intermediate nuclei.

Generator models

J.Sobczyk NUFACT 2025



There are several available and actively developed MC generators applicable for ~1 GeV neutrinos.

- **NEUT** - the main MC in Japanese experiments T2K, HK.
- **GENIE** - the main MC in US experiments NOvA, MicroBooNE, MINERvA, DUNE.
- **GiBUU** - developed by theorists in Giessen with the most sophisticated FSI model; used in many comparisons and studies.
- **NuWro** - developed by theorists in Wrocław; used in many comparisons and studies.
- **Achilles** - a relatively new project with important new additions.

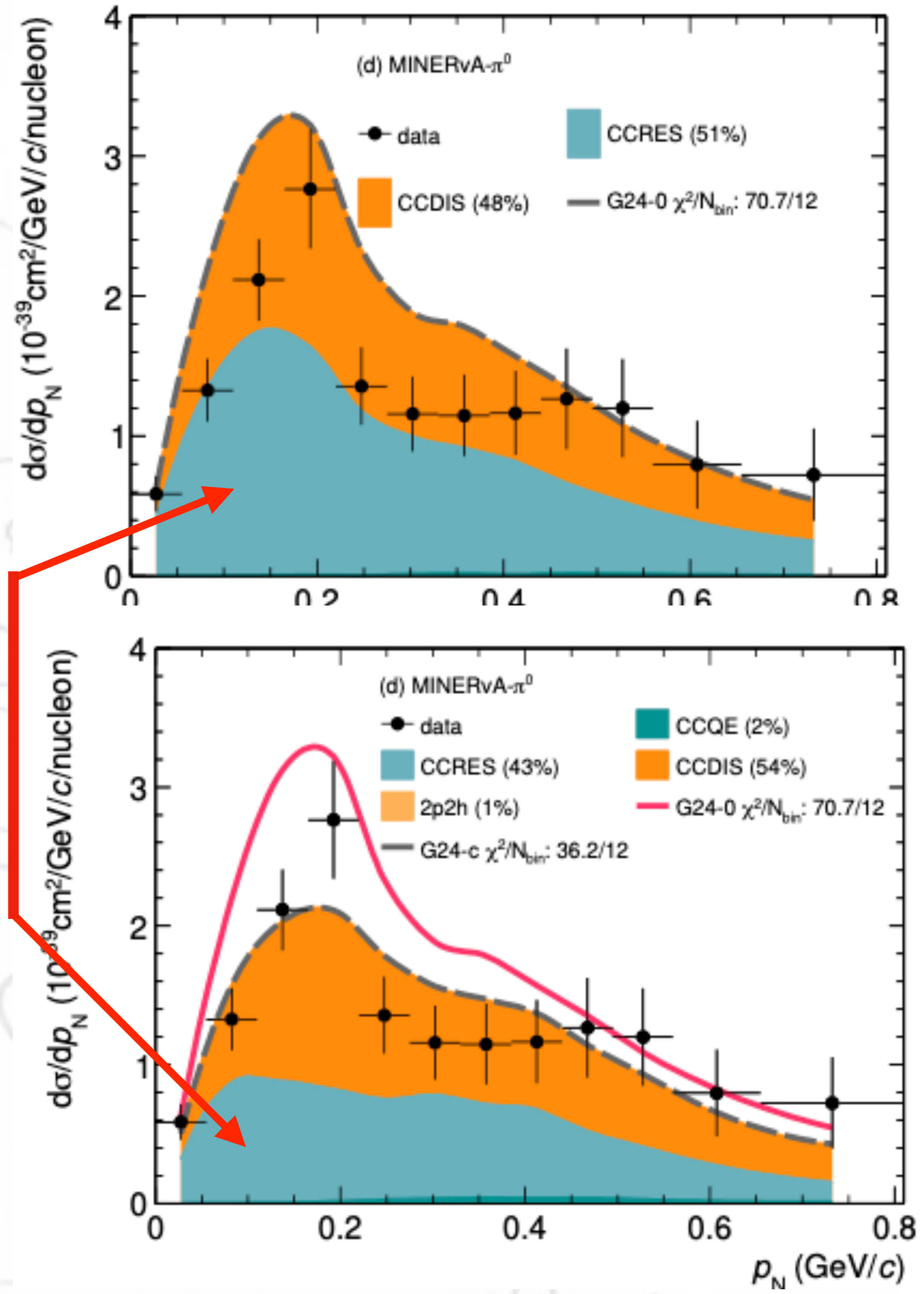
NEUT, GENIE, NuWro share plenty of physics concepts with several models included

GiBUU treats FSI in a more QM correct approach.

Achilles is a new concept.

Model Reweight

- In the past models were rigid or with little modelling degrees of freedom.
- Oscillation experiment requirements forced the development of reweighing tools, but the first ones were breaking the model.
    - Parametrisation of the X-sections based on physical parameters is important.
- Monte-Carlos are starting to introduce these tools by reweighing methods, but this is tricky (reweighing out of phase space,…) :
    - AI tools
    - Professor …

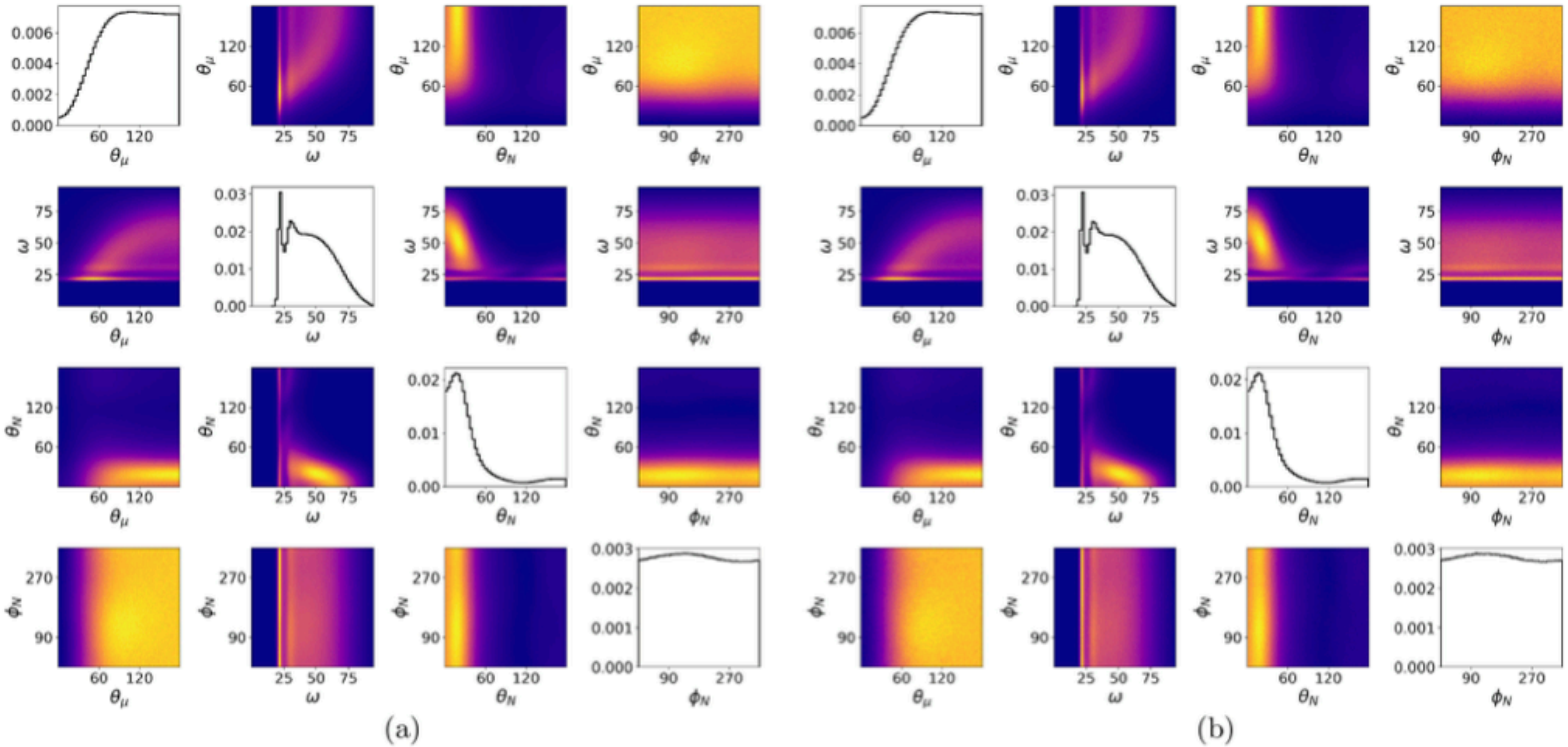


Genie reweight of TKI π^0 data.

UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES
Département de physique nucléaire et corpusculaire

Inserting complex models in MC

AI tools might help us to introduce complex nuclear calculations into MC by learning PDF distributions and help in reweighing models.



(a) true cross section
(b) normalizing flow besed model

$E_\nu = 200 MeV$

Target nucleon occupies $1p_{\frac{3}{2}}$ shell

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Mathias El Bas et al Phys. Rev D111 113001 (2025)

A spectacular agreement!

Many useful tools being developed including reweights

Conclusions

- Complex problem both theoretical and experimental.
- Huge development during last years but not quite there :
  - from free moving particles with altered masses to proper Hartree-Fock calculations.
- X-section is the cheapest way to improve the oscillation results.
- requires advances in several areas in parallel:

1. Theory (with parameters, please!)
2. Generator implementation of those models.
3. Experiments
4. Neutrino fluxes predictions

So far, T2K has shown consistent results regardless the X-model used (off-axis peak?)

is the oscillation less sensitive to x-section as we think (off-axis peak helps).

Although,
there will be no convincing CP violation claim without a convincing cross-section model