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Neutrino cross sections
and their impact on oscillation measurements

Margherita Buizza Avanzini

Summer School on Neutrino Physics Beyond the Standard Model

Strasbourg, July 7th 2025

Layout

1. Neutrino cross section in neutrino oscillation (accelerator) experiments
2. Neutrino interactions and nuclear effects
3. Neutrino cross-section measurements
4. Neutrino cross-section extraction
5. How cross-section measurements are used in LBL experiments
6. Future perspectives

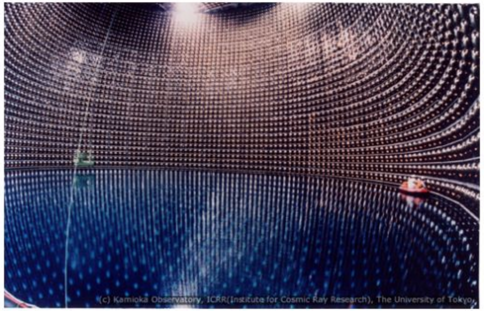
Caveat 1: personal choice on treated subjects

Caveat 2: most of materials taken from my personal activity in T2K

Caveat 3: impossible to cover everything in 90min ;-)

Neutrino cross sections in LBL experiments

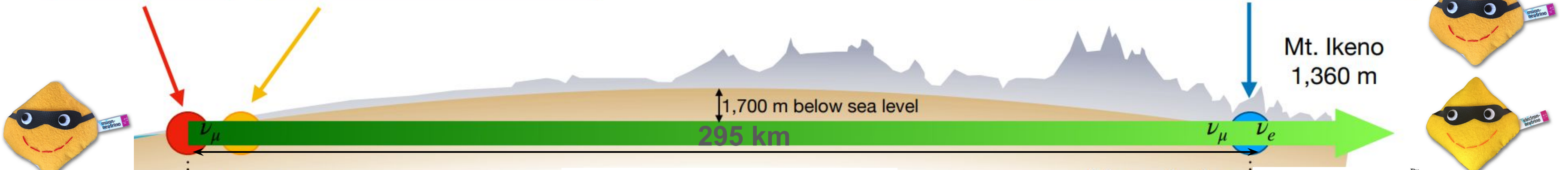
Long baseline experiment principle



J-PARC

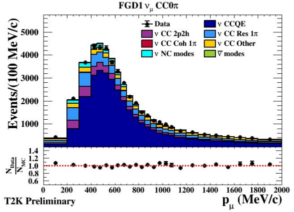
Near Detectors

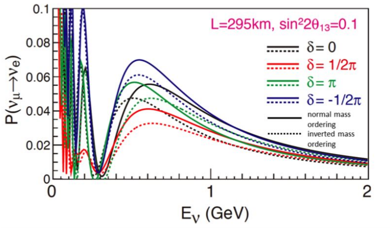
Super-Kamiokande



Tokai

ν_μ beam

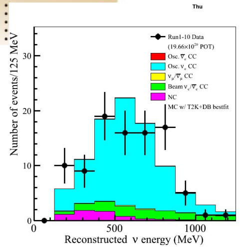




Kamioka

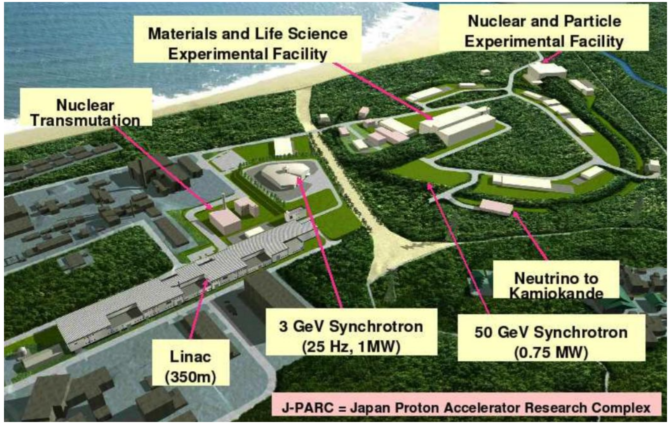
ν_e appearance

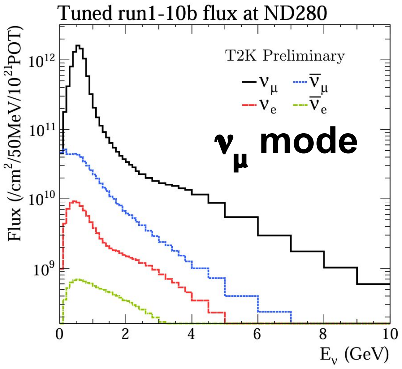
ν_μ disappearance

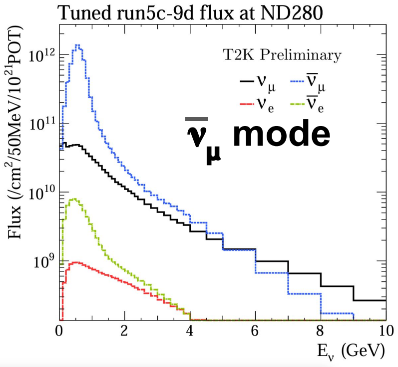


A typical ν LBL oscillation experiment

(exemple from T2K)







ν_μ
$\bar{\nu}_\mu$
ν_e
$\bar{\nu}_e$

We start by producing a muon (anti-)neutrino beam at the accelerator

A typical ν LBL oscillation experiment

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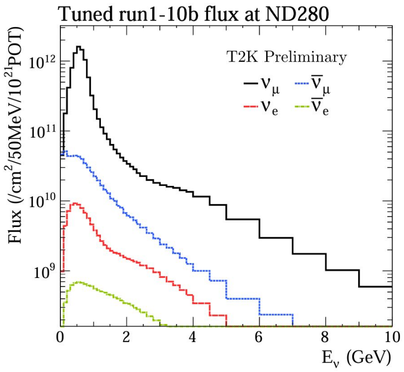

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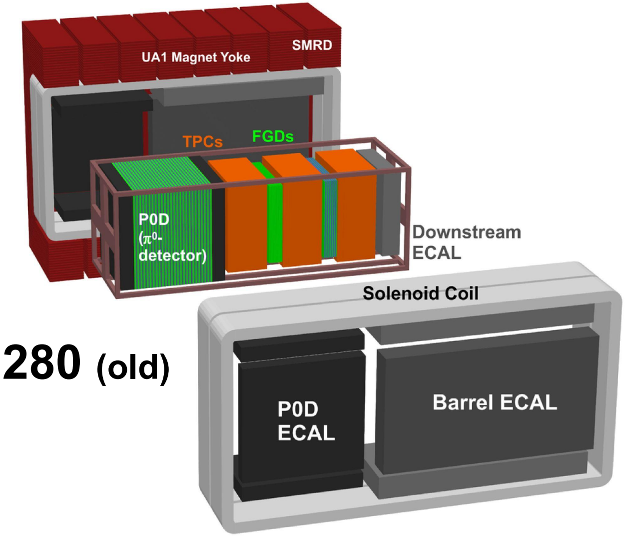
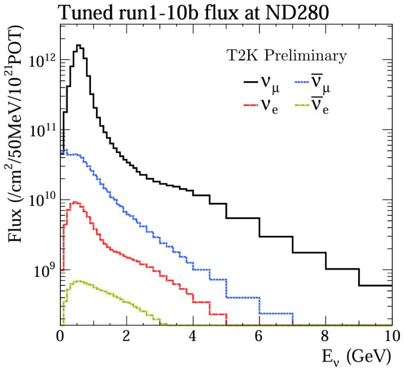


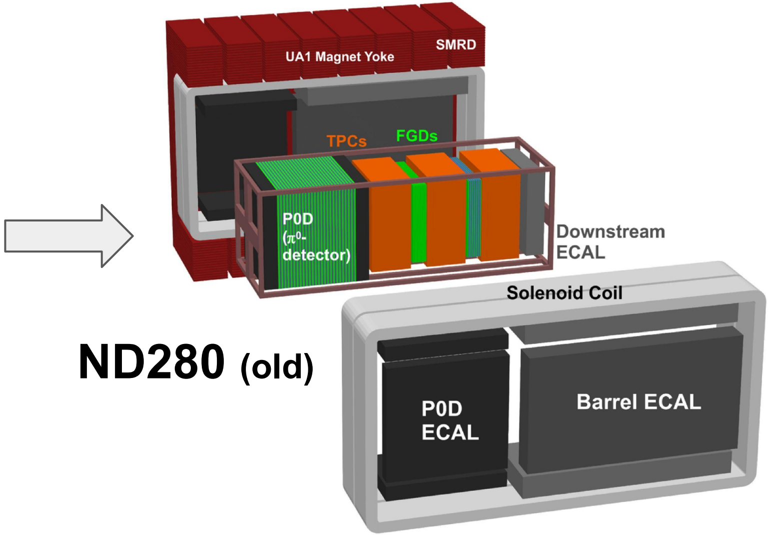
ND280 (old)

The target material is essentially made of plastic scintillator

A typical ν LBL oscillation experiment

(exemple from T2K)





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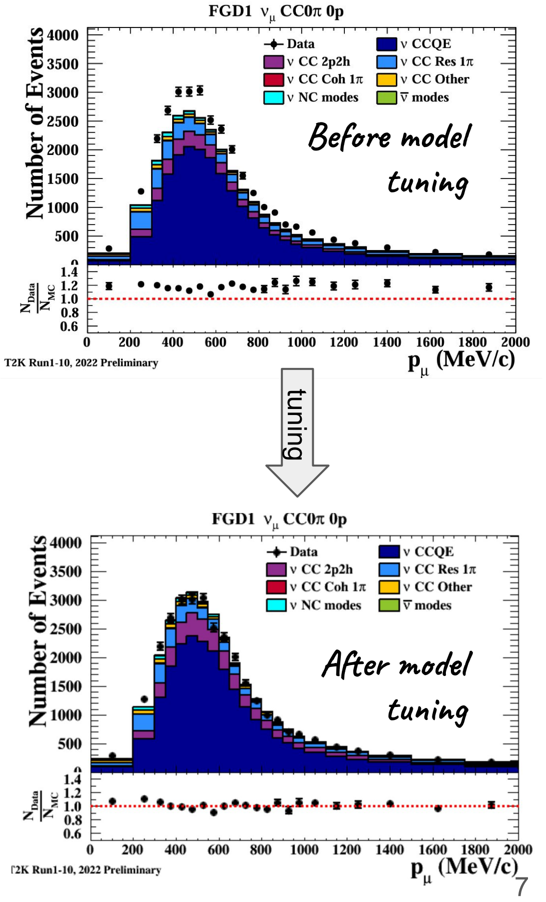

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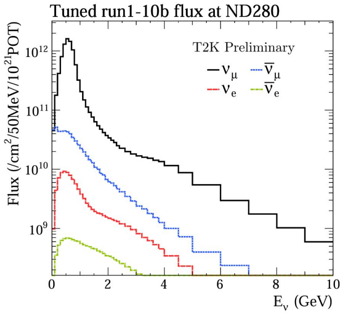
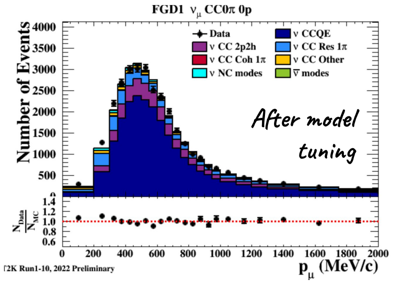
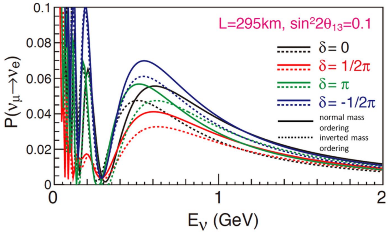
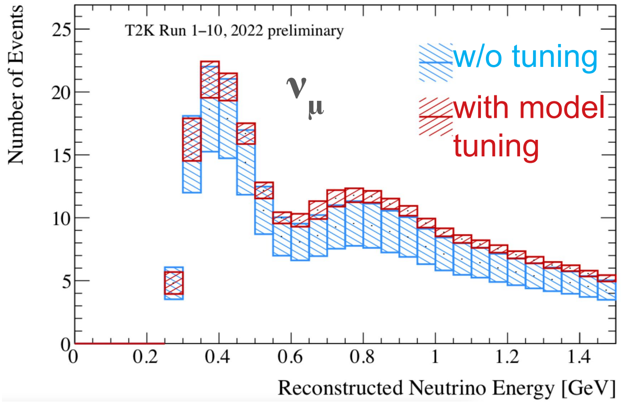






& after oscillations



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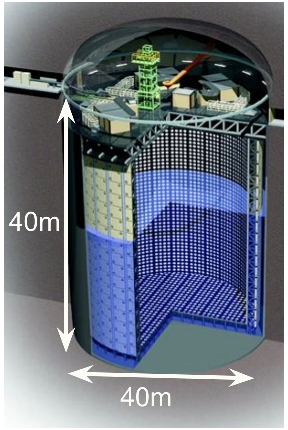
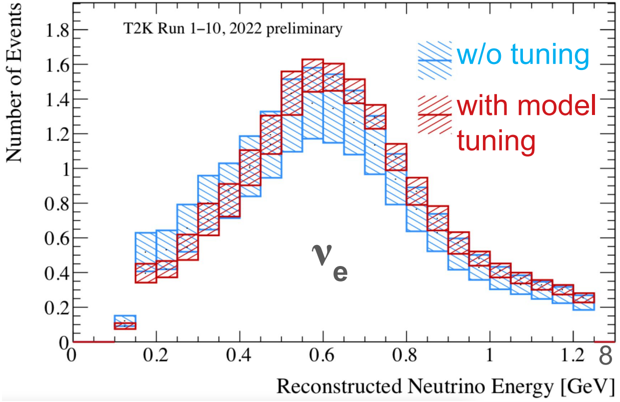
Super-Kamiokande, water cherenkov detector





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A typical ν LBL oscillation experiment

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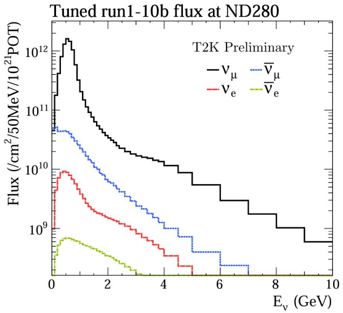

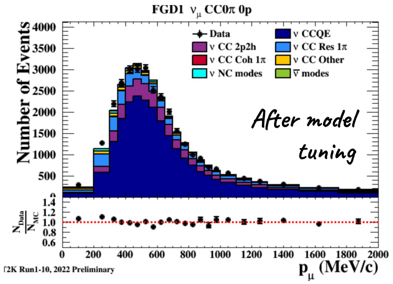

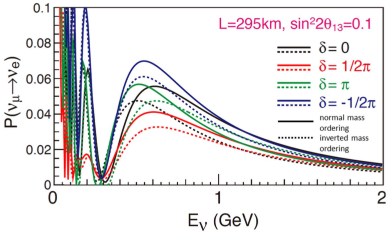

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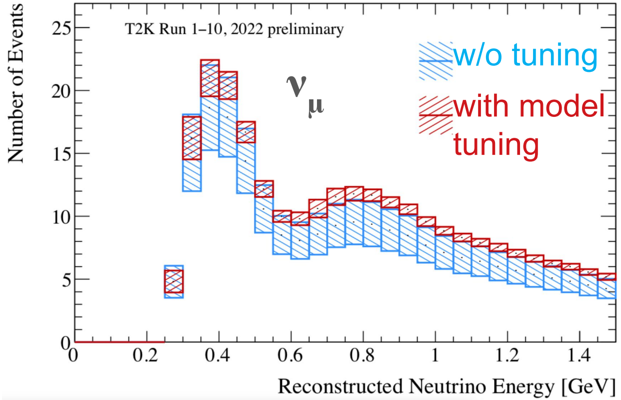

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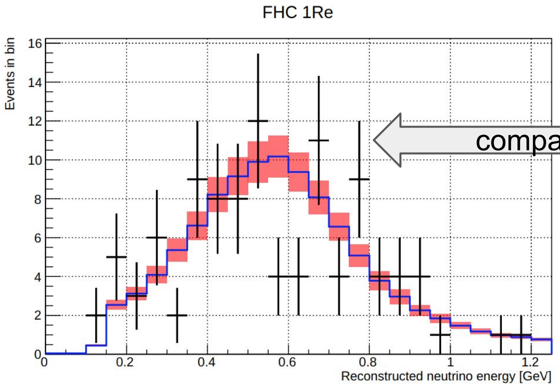
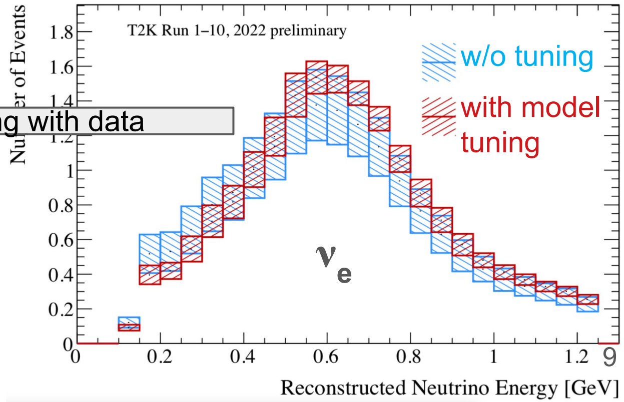


comparing with data



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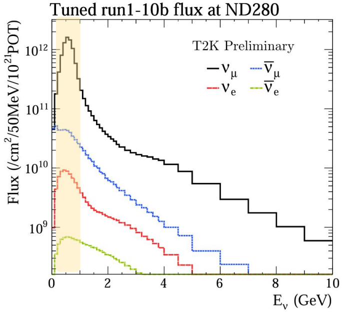

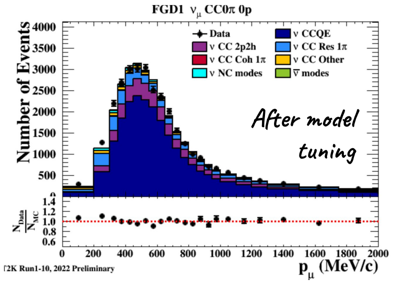

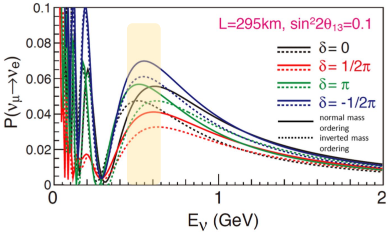

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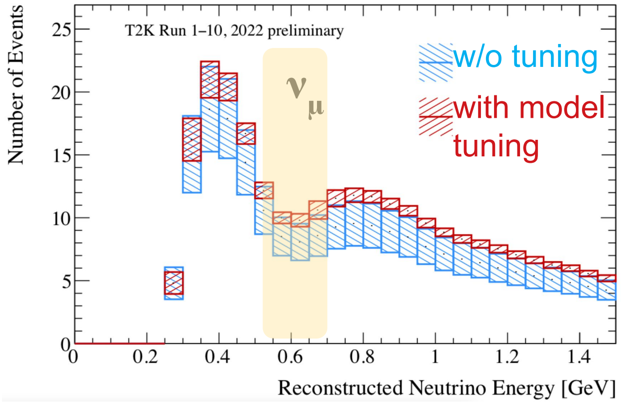

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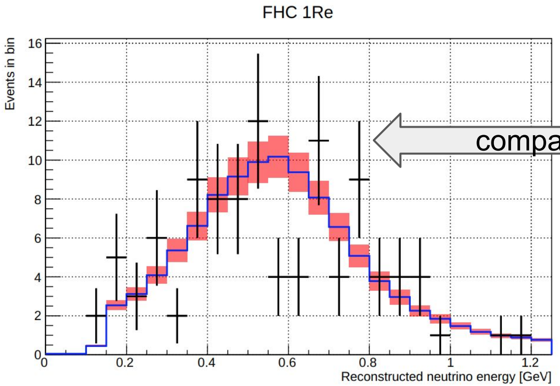

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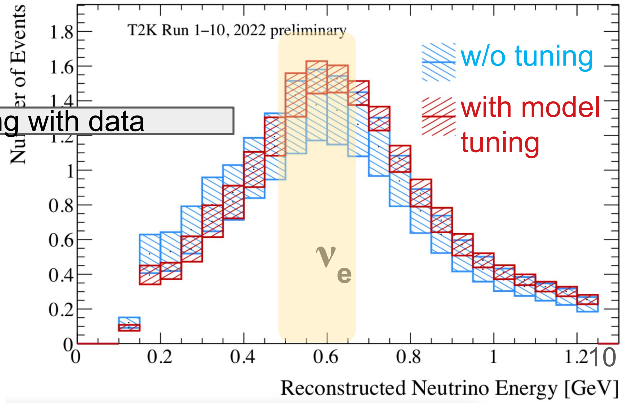

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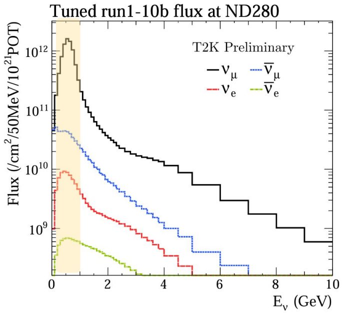

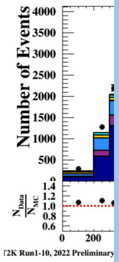

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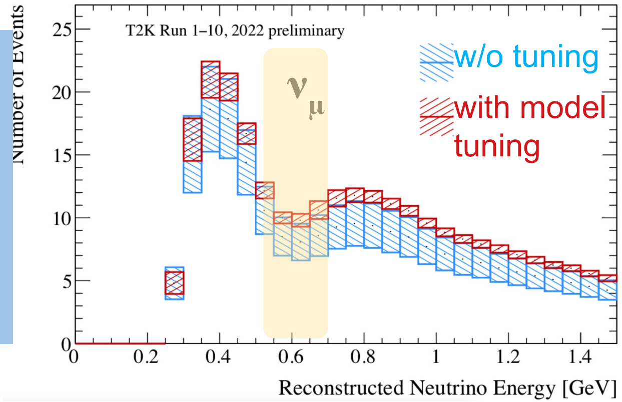

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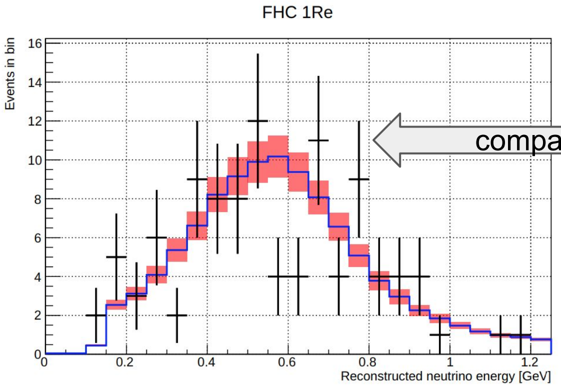

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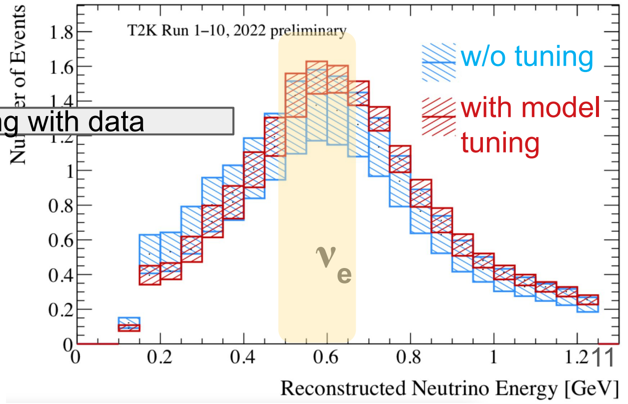

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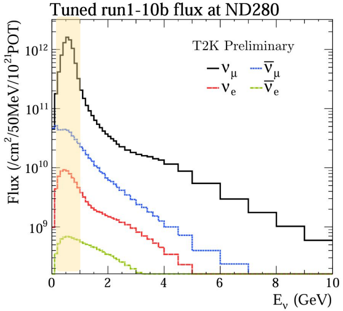

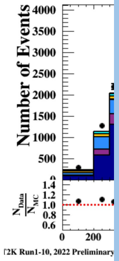

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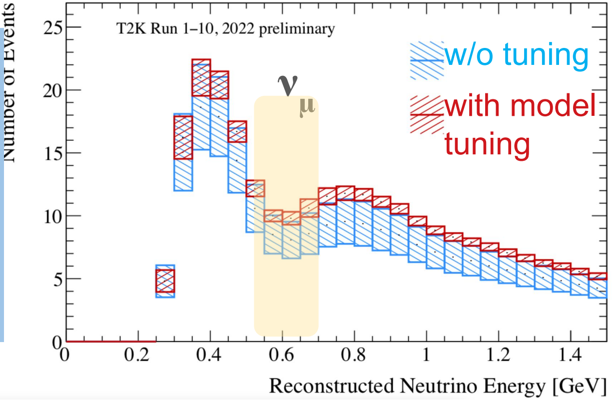
Well nothing strange here?



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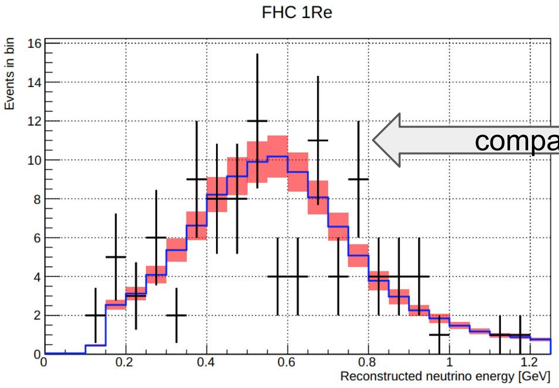

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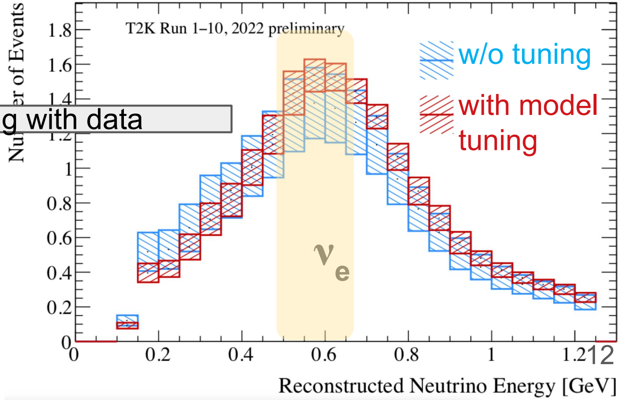
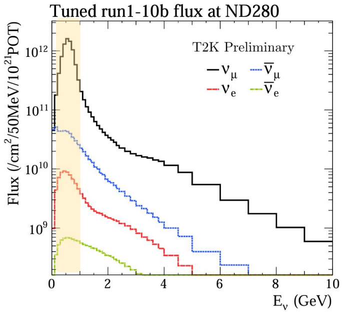


A typical ν LBL oscillation experiment

(exemple from T2K)



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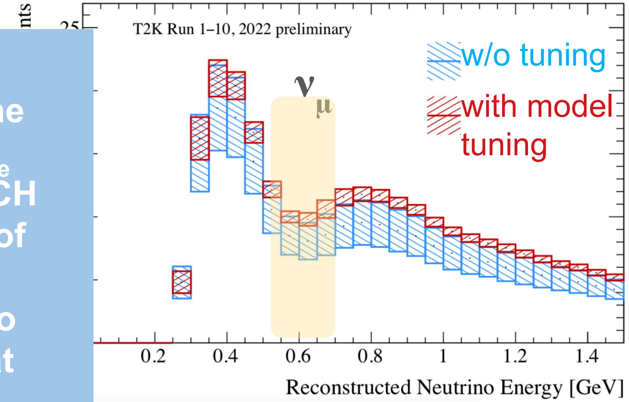
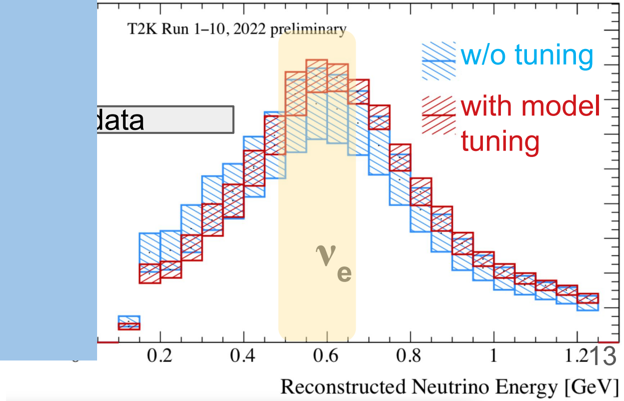
Non-exhaustive list of challenges:

1. at the near detector we caracterise ν_μ but at the far detector we are particularly interested to ν_e
2. at the near detector we have a dominance of CH target, while the far detector is entirely made of water
3. at the near detector we characterise a neutrino beam before the oscillation, while the shape at the far detector is definitely different





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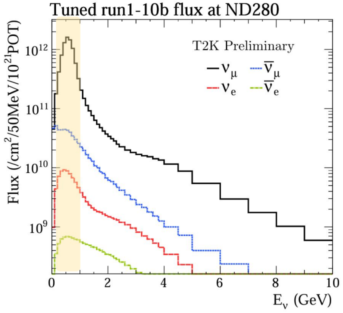

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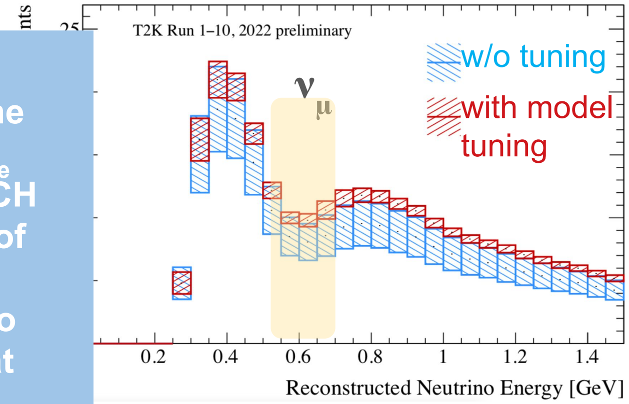
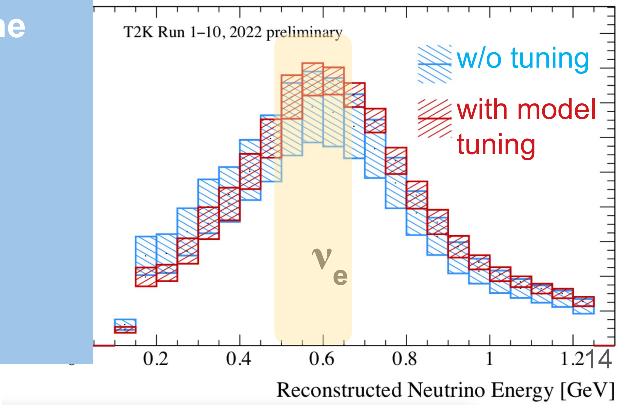
⇒ all these aspects require an extrapolation from the near to the far detector
⇒ this extrapolation is usually based on theoretical models for neutrino interactions
⇒ we need very solid neutrino interaction models

Are we ready?





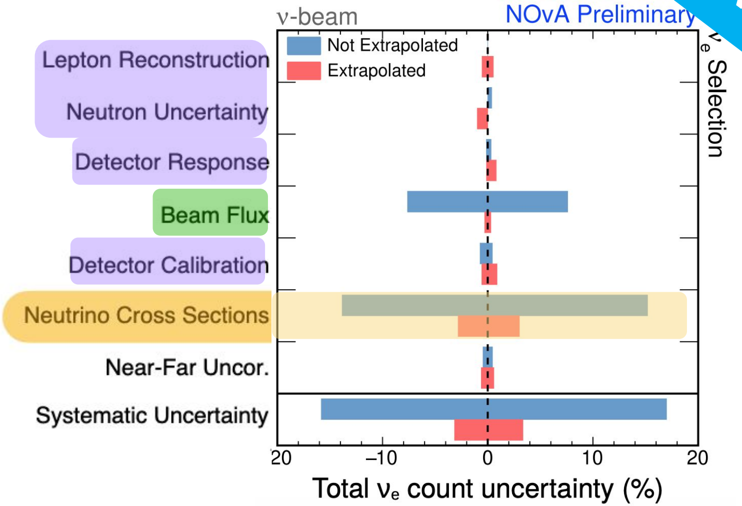
T2K

Why neutrino cross sections matter?

Neutrino 2024 conference

NOvA

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

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

Today not the major problem, we have ~150 ν_e appearance events... but this will become a problem soon (Hyper-Kamiokande, DUNE)

Concrete exemple from T2K

The international journal of science / 16 April 2020

nature

Nature, vol. 580, p. 339–344 (2020)

THE MIRROR CRACK'D

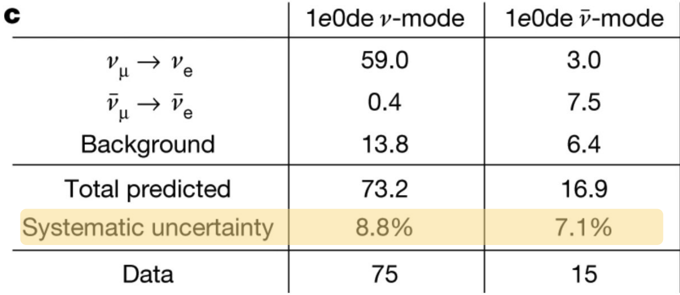
An indication of matter–antimatter symmetry violation in neutrinos

Coronavirus The models driving the global response to the pandemic

Hot source Remnants of primordial nitrogen in Earth's mantle

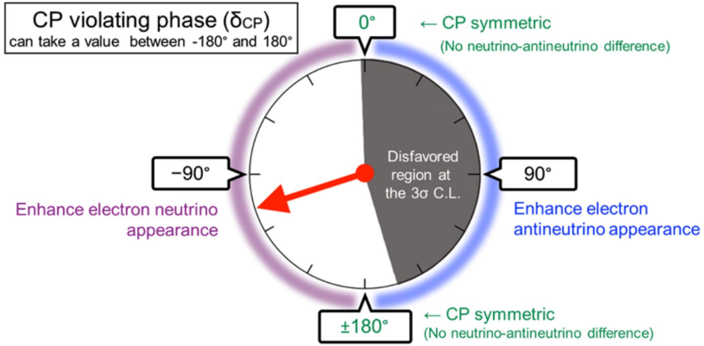
Origin of a species Revised age for Broken Hill skull adds twist to human evolution

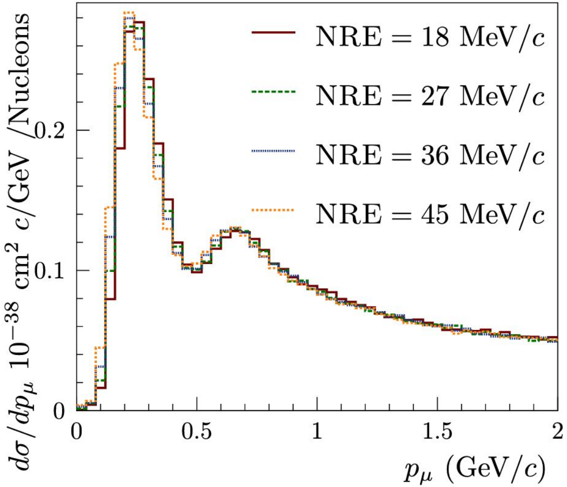
Publishing on Nature (in 2020) the first hints toward a CP violation



c

	1e0de ν-mode	1e0de $\bar{\nu}$-mode
$\nu_\mu \rightarrow \nu_e$	59.0	3.0
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	0.4	7.5
Background	13.8	6.4
Total predicted	73.2	16.9
Systematic uncertainty	8.8%	7.1%
Data	75	15





Phys. Rev. D 103, 112008 (2021)

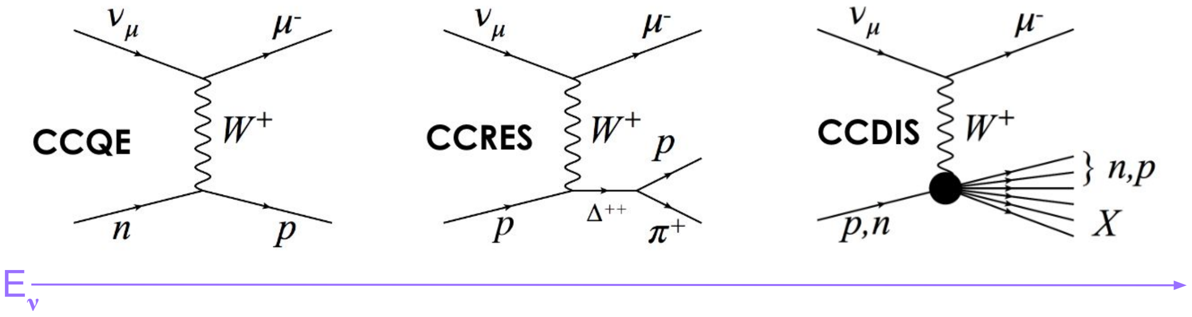
For that analysis, over a total 9% systematics in the appearance channel, 8% effect came by the uncertainties on the Nucleon Removal Energy (NRE)

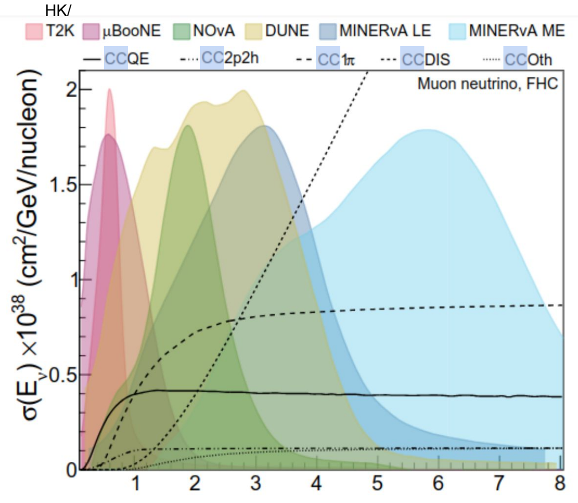
Lot of work has been done since then, but neutrino interactions remain the main reason of systematics uncertainties in LBL experiments

Neutrino interactions

Neutrino-nucleon interactions

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

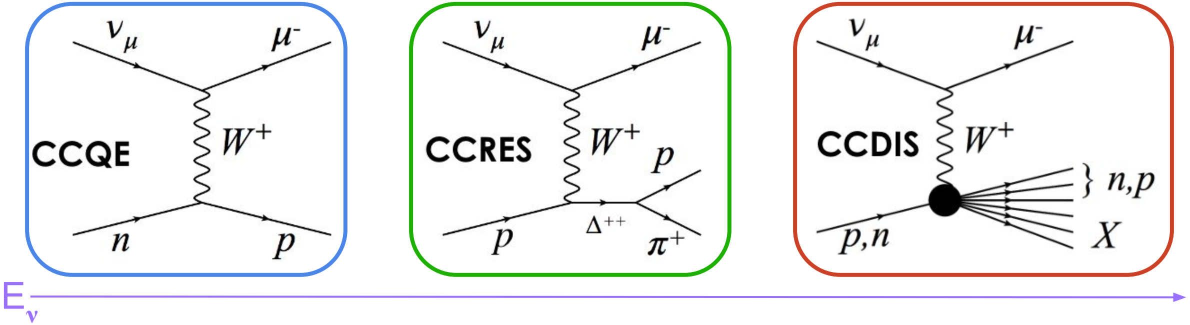


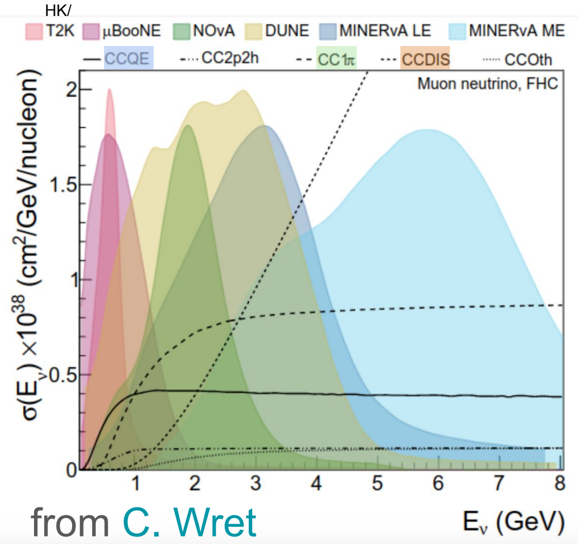


from C. Wret

Neutrino-nucleon interactions

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





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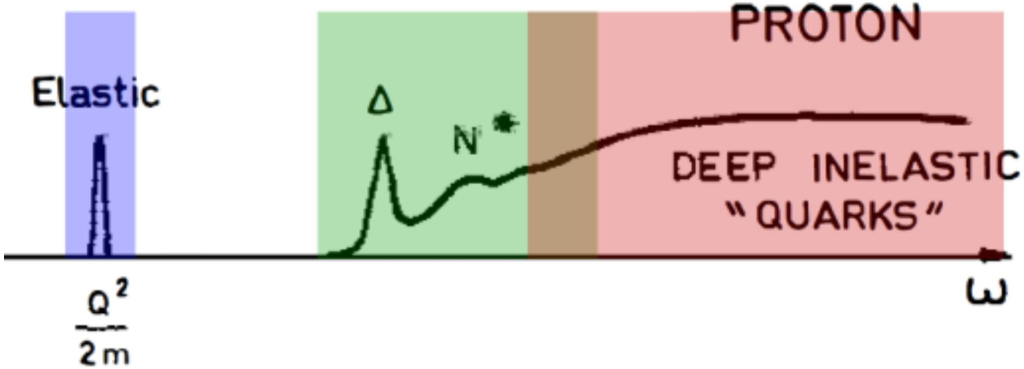
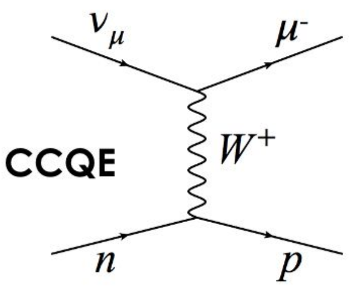


(Energy transfer)

Charged Current Quasi Elastic (CCQE)



Let’s start with the “easiest” **neutrino-nucleon** interaction: the so-called CCQE. This is an interaction widely used in accelerator experiments

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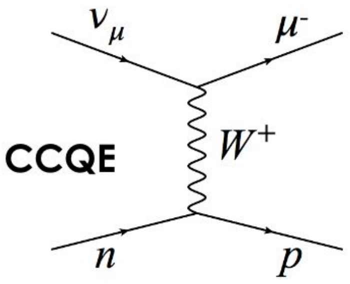

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General cross-section formula

$$\frac{d\sigma}{dQ^2} = \frac{1}{64\pi M^2 E_\nu^2} |\mathcal{M}|^2$$

Interaction amplitude

nucleon mass

ν energy

$Q^2 = (p_\nu - p_\mu)^2$ = momentum transfer
(to the nucleon)

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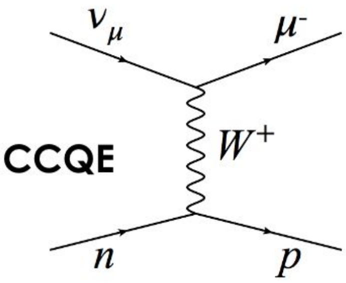

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$$|\mathcal{M}|^2 = \frac{G_F^2 \cos^2\theta_C}{2} L^{\mu\nu} H_{\mu\nu}$$

$Q^2 = (p_\nu - p_\mu)^2$ = momentum transfer
(to the nucleon)

Specifically for CCQE:

$$\mathcal{M} = \frac{G_F \cos\theta_C}{\sqrt{2}} \left[\bar{u}_\mu \gamma^\mu (1 - \gamma^5) u_\nu\right] \cdot \langle p | J_\mu^{\text{had}} | n \rangle$$

$G_F = 1.1803 \times 10^{-5}\ \text{GeV}^{-2}$, $\cos\theta_c = 0.97425$

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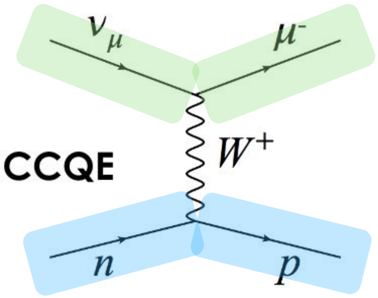

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Interaction amplitude

nucleon mass

ν energy

Fermi constant

Cabibbo angle

Hadronic part (4x4 tensor)

$$|\mathcal{M}|^2 = \frac{G_F^2 \cos^2 \theta_C}{2} L^{\mu\nu} H_{\mu\nu}$$

Leptonic part (4x4 tensor)

$Q^2 = (p_\nu - p_\mu)^2$ = momentum transfer (to the nucleon)

Leptonic current (4-vector)

Hadronic current (4-vector)

Specifically for CCQE:

$$\mathcal{M} = \frac{G_F \cos\theta_C}{\sqrt{2}} \left[\bar{u}_\mu \gamma^\mu (1-\gamma^5) u_\nu\right] \cdot \langle p | J_\mu^{\text{had}} | n \rangle$$

Remember: only for left handed ν ;-) (or right-handed $\bar{\nu}$)

$G_F = 1.1803 \times 10^{-5}\ \text{GeV}^{-2}\ ,\ \cos\theta_c = 0.97425$

Charged Current Quasi Elastic (CCQE)

Hadronic current

$$\langle p|J_\mu^{\text{had}}|n\rangle = \bar{u}_p\left[F_1(Q^2)\gamma_\mu + F_2(Q^2)i\sigma_{\mu\nu}\frac{q^\nu}{2M} + F_A(Q^2)\gamma_\mu\gamma_5 + F_P(Q^2)q_\mu\gamma_5\right]u_n$$

Various nucleon form factors to take into account that nucleons have a structure (they are not point like)

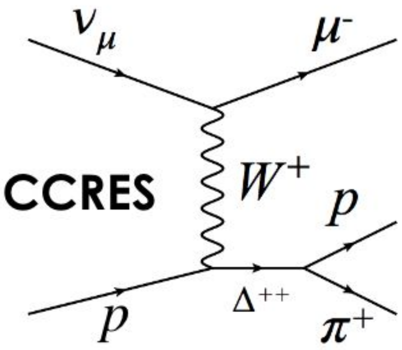
F_1 and F_2 are related to the vector part of the interaction (as in the electromagnetic interaction, similar between electrons and neutrinos). F_1 is related to the nucleon electric charge distribution, F_2 to the magnetic moment

F_A and F_P are related to the axial part of the interaction (specific to neutrinos). In particular F_A, the most relevant for us, describes how the axial component of the interactions “distributes” within the nucleon

Dipole description

$$F_A(Q^2) = \frac{F_A(0)}{\left(1 + \frac{Q^2}{(M_A^{QE})^2}\right)^2}$$

Charged Current Resonant (CCRES)



CCRES happens at higher energy (and higher energy transfer) than CCQE

In this case, a resonance (often a Δ) is produced, with a subsequent decay in pions and nucleons

$$\nu_\mu\, p \to \mu^-\, p\, \pi^+, \qquad \overline{\nu}_\mu\, p \to \mu^+\, p\, \pi^-$$
$$\nu_\mu\, n \to \mu^-\, p\, \pi^0, \qquad \overline{\nu}_\mu\, p \to \mu^+\, n\, \pi^0$$
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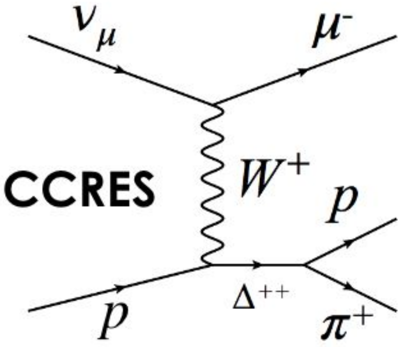

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$$\begin{aligned} \nu_\mu\, p &\rightarrow \mu^-\, p\, \pi^+, & \overline{\nu}_\mu\, p &\rightarrow \mu^+\, p\, \pi^- \\ \nu_\mu\, n &\rightarrow \mu^-\, p\, \pi^0, & \overline{\nu}_\mu\, p &\rightarrow \mu^+\, n\, \pi^0 \\ \nu_\mu\, n &\rightarrow \mu^-\, n\, \pi^+, & \overline{\nu}_\mu\, n &\rightarrow \mu^+\, n\, \pi^- \end{aligned}$$

Describe the interaction now is more complex (several possible resonances, interferences terms…)

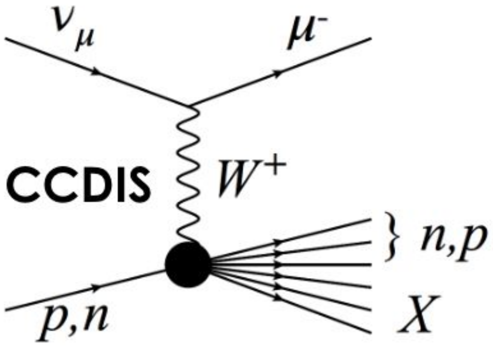
The reference model is pretty old (>50y ago)

Clear need to better understand this process, very relevant for instance for DUNE

Axial form factor for CCRES (?)
Described in the same way as for CCQE

$$C_5^A(Q^2) = \frac{C_5^A(0)}{\left(1 + \frac{Q^2}{(M_A^{\mathrm{RES}})^2}\right)^2}$$

Charged Current Deep Inelastic Scattering (CCDIS)



CCDIS happens at higher energy (and higher energy transfer) than CCRES

At very high energy, the interactions happens with the nucleon quarks → pretty well understood mechanism (via the so called perturbative QCD ~ parton model)

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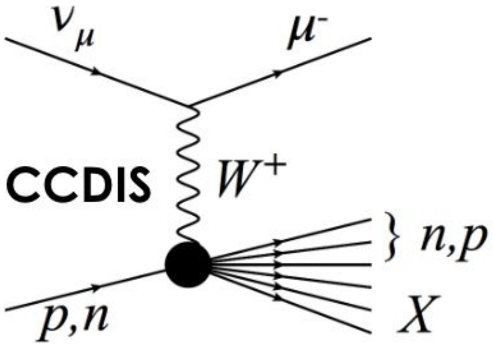

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At very high energy, the interactions happens with the nucleon quarks → pretty well understood mechanism (via the so called perturbative QCD ~ parton model)

The cross section can be written as a function of the Bjorken variables x and y

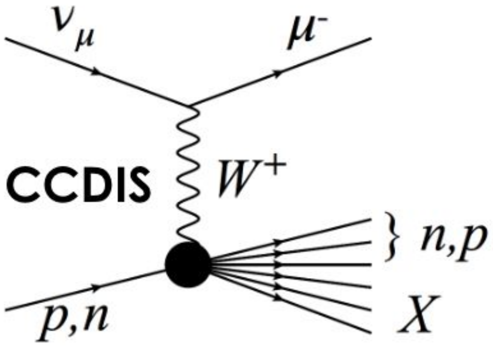
$$x = \frac{Q^2}{2M\omega} \qquad y = \frac{\omega}{E_\nu}$$

$\omega = E_\nu - E_l$ energy transfer to the nucleon

$$\frac{d^2\sigma^{\nu(\bar{\nu})}}{dx\,dy} = \frac{G_F^2 M E_\nu}{\pi}\left(\frac{M_W^2}{Q^2+M_W^2}\right)^2\left[xy^2F_1(x,Q^2)+\left(1-y-\frac{Mxy}{2E_\nu}\right)F_2(x,Q^2)\pm xy\left(1-\frac{y}{2}\right)F_3(x,Q^2)\right]$$

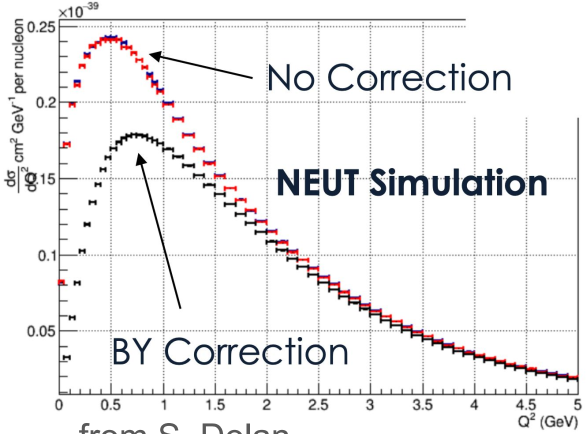
F_1, F_2 and F_3 are the nuclear structure functions and describe how quarks and gluons "react" to the neutrino interaction. F_1 and F_2 are for the vectorial part, while F_3 for the axial part (only for **ν**!)

Charged Current Deep Inelastic Scattering (CCDIS)



CCDIS happens at higher energy (and higher energy transfer) than CCRES
But for $Q^2 < 2$GeV, describing the CCDIS process become complex → QCD is not anymore perturbative and we need approximation
Bodek-Yang model allows to extrapolate the QCD at lower Q^2. It also covers the so called RES to DIS transition region

Parameters are introduced to correct the various structure function, based on comparisons with available data (empirical model)

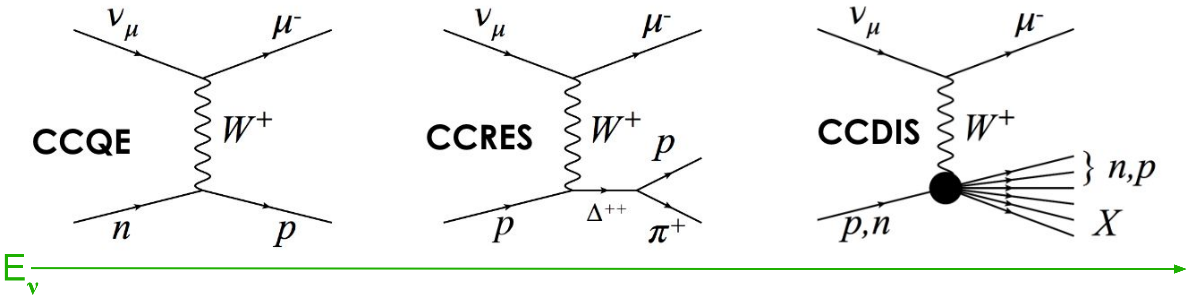


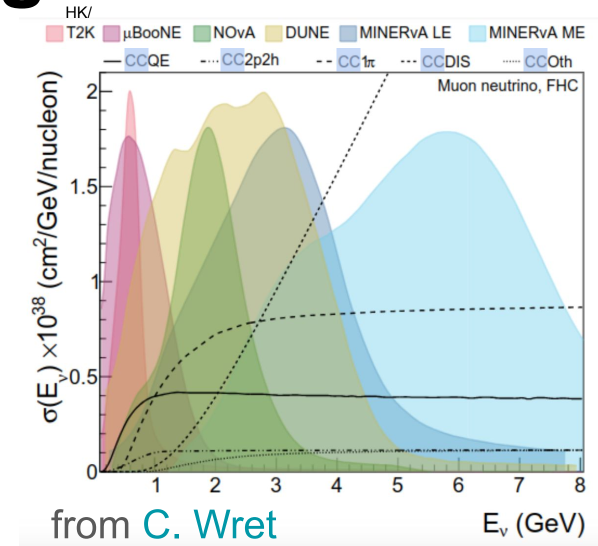
from S. Dolan

https://arxiv.org/abs/2108.09240

Let’s start measuring

Although complex and difficult to test, we have models, so let’s start measuring neutrino cross sections and validate those models!



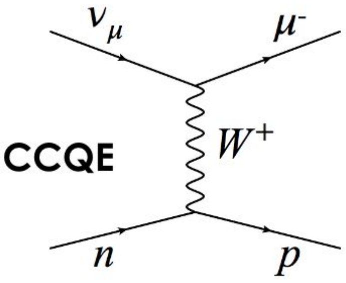


from C. Wret

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

What we can detect are the products of the neutrino interactions.
For the charged current interactions we look for a lepton in the final state and eventually (some) hadrons (proton and pions)

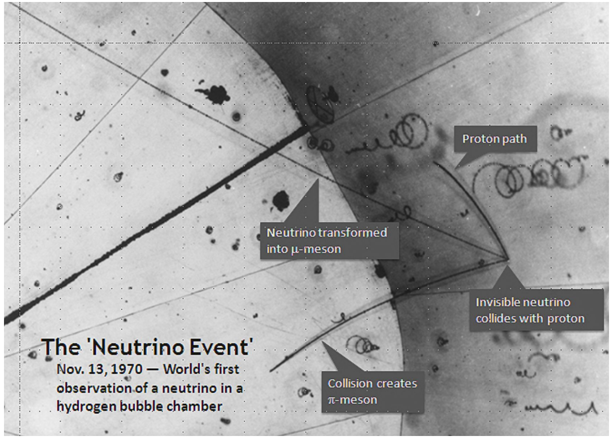
Measuring the axial mass in neutrino-nucleon scattering



axial-vector coupling constant

$$F_A(Q^2) = \frac{F_A(0)}{\left(1 + \frac{Q^2}{(M_A^{QE})^2}\right)^2}$$

axial mass



Experiment $\nu_\mu d \rightarrow \mu^-\ p\ p_s$	QE events	Q^2 range GeV/c^2	M_A (published)
$Mann_{73}$	166	.05 – 1.6	0.95 ± .12
$Barish_{77}$	500	.05 – 1.6	0.95 ± .09
$Miller_{82,77,73}$	1737	.05 – 2.5	1.00 ± .05
$Baker_{81}$	1138	.06 – 3.0	1.07 ± .06
$Kitagaki_{83}$	362	.11 – 3.0	$1.05^{+.12}_{-.16}$
$Kitagaki_{90}$	2544	.10 – 3.0	$1.070^{+.040}_{-.045}$
$Allasia_{90}$	552	.1-3.75	1.080 ± .08

Bubble chamber experiments measure M_A^{QE} close to 1 GeV.

Here the target is essentially made of deuterium (ie 1p and 1n)

J.Phys.Conf.Ser.110:082004,2008

What changes when we move to a neutrino-nucleus interaction?

Current neutrino detectors use more complex nuclei (CH, H_2O, Ar,...), thus neutrino interactions happen with nucleons bound in nuclei

Need to take into account that initial state nucleons are not static → how can we model the nucleus ?

“Simplest” models used a Fermi gas assumption

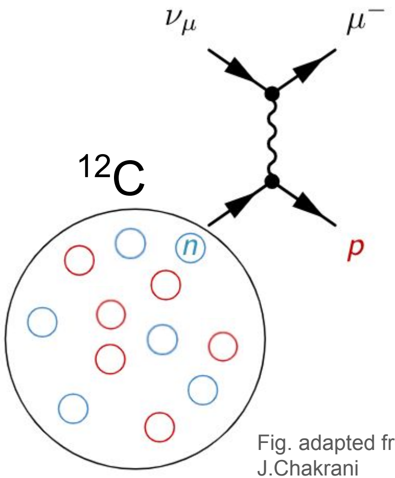


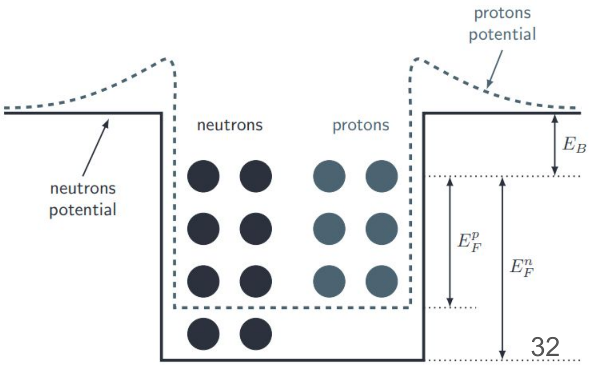
Fig. adapted from J.Chakrani

Relativistic Fermi Gas (RFG)

Nucleons move freely in a constant binding energy within the nuclear volume

Local Fermi Gas (LFG)

The nucleus is described with the local density approximation



T. Golan

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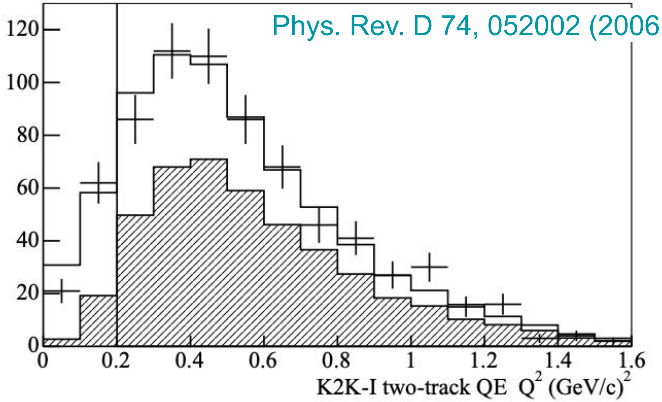
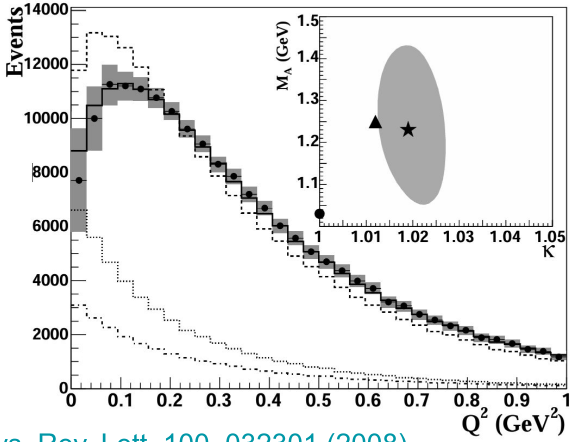


Phys. Rev. D 74, 052002 (2006)

K2K measures M_A^{QE} from neutrino-H_2O interactions

"We use a relativistic Fermi gas model for oxygen and assume the form factor is approximately a dipole with one parameter, the axial vector mass M_A, and fit to the shape of the distribution of the square of the momentum transfer from the nucleon to the nucleus. Our best fit result for ***M_A = 1.20 ± 0.12 GeV.****"*



Phys. Rev. Lett. 100, 032301 (2008)

MiniBooNE measures M_A^{QE} from neutrino-CH interactions

"Using a high-statistics sample of ν_μ CCQE events, MiniBooNE finds that a simple Fermi gas model, with appropriate adjustments, accurately characterizes the CCQE events observed in a carbon-based detector. The extracted parameters include an effective axial mass, ***M_A^{eff}=1.23 ± 0.20 GeV****"*

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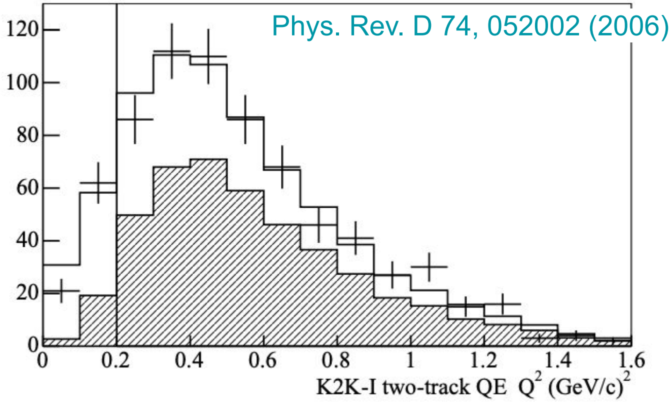

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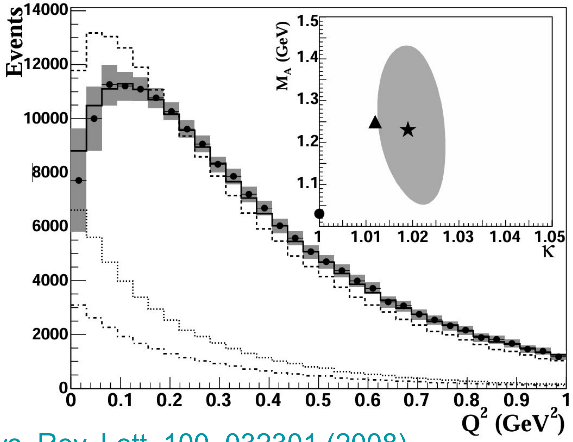

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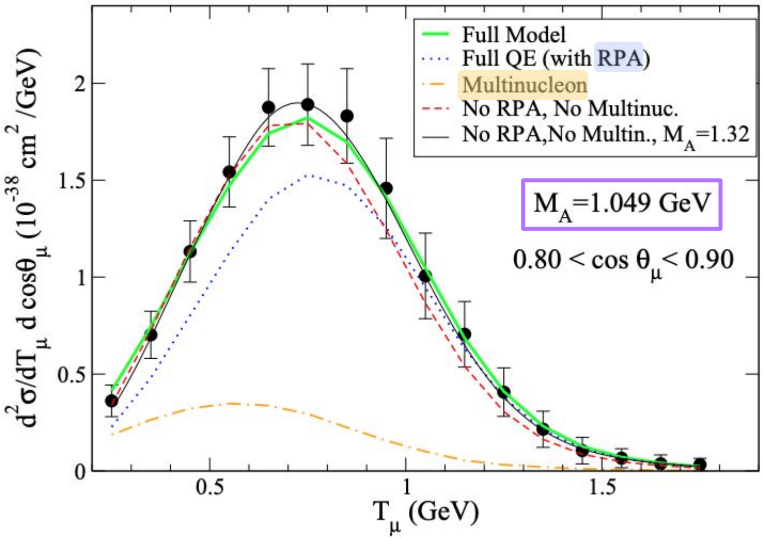
The axial mass shouldn't depend on the nucleus, right?

Solving the M_A^{QE} puzzle



https://doi.org/10.1016/j.physletb.2011.11.061

By accounting for additional nuclear effects (here named RPA and multinucleon) it is possible to explain MiniBooNE “CCQE” results with a more reasonable value of M_A^{QE}, close to the one obtained by bubble chamber experiments

RPA (Random Phase Approximation) is a correction added to take into account correlations between nucleons that affect the nuclear response. They generally suppress the cross section for low momentum transfer interactions

Multinucleon effects (often known as 2p2h) account for neutrino interactions that happen with a pair of correlated nucleons (np, nn, pp)

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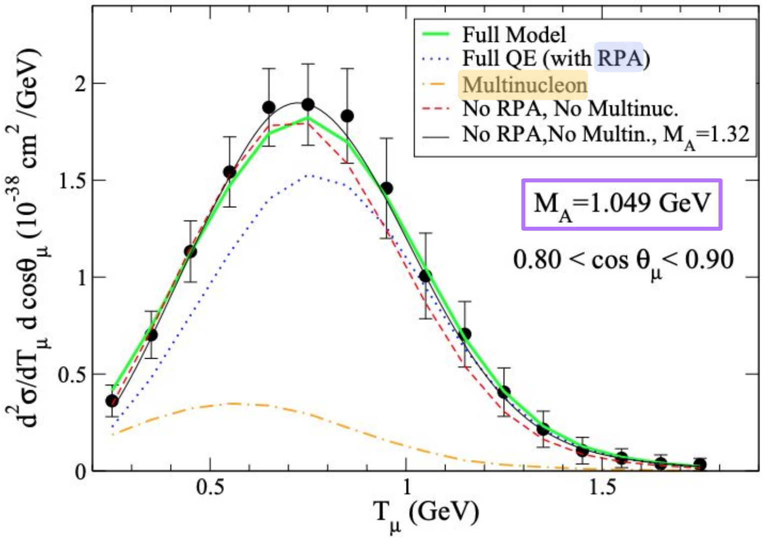

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Nuclear effects!!!!

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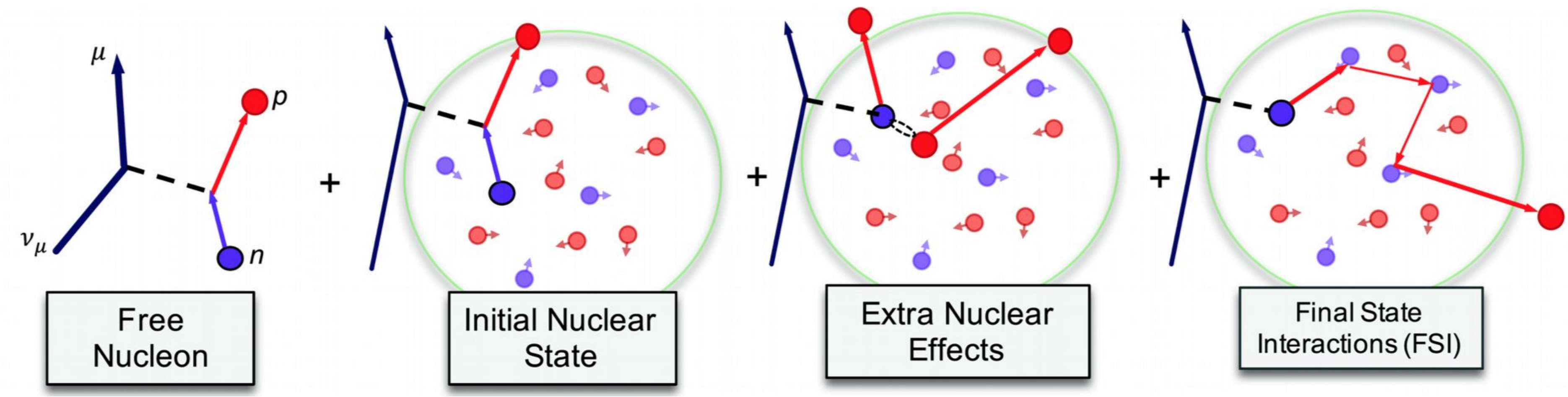
The role of nuclear effects



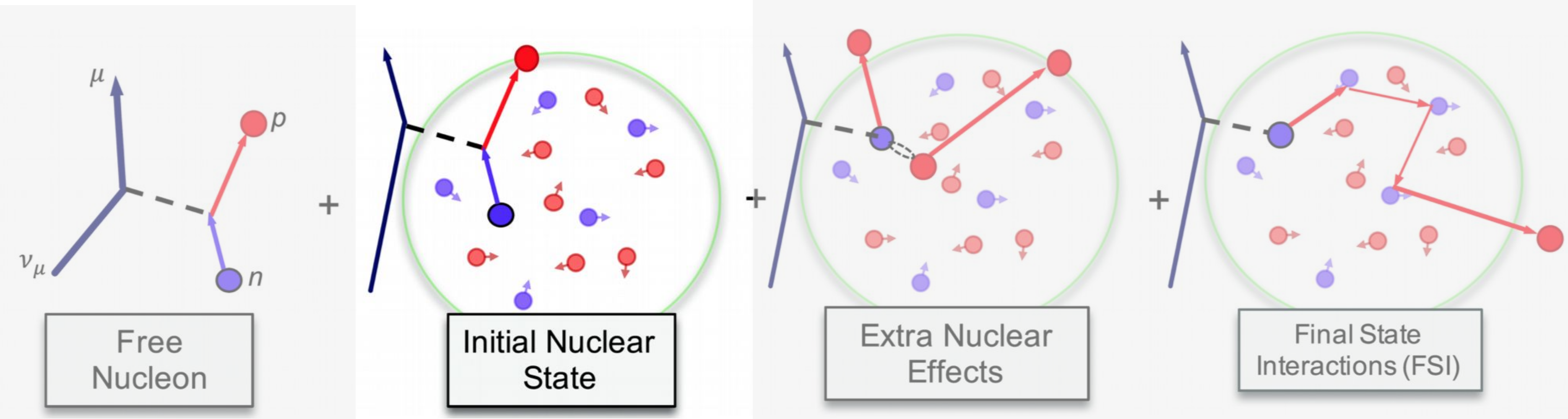
Nucleons are bounded in nuclei

Neutrinos interact with nucleons that have an initial (Fermi) momentum

They can interact with a pair of correlated nucleons (2p2h) since nucleon can be affected by short and long range correlation

The resulting nucleon can reinteract within the nucleus before exiting it

The role of nuclear effects



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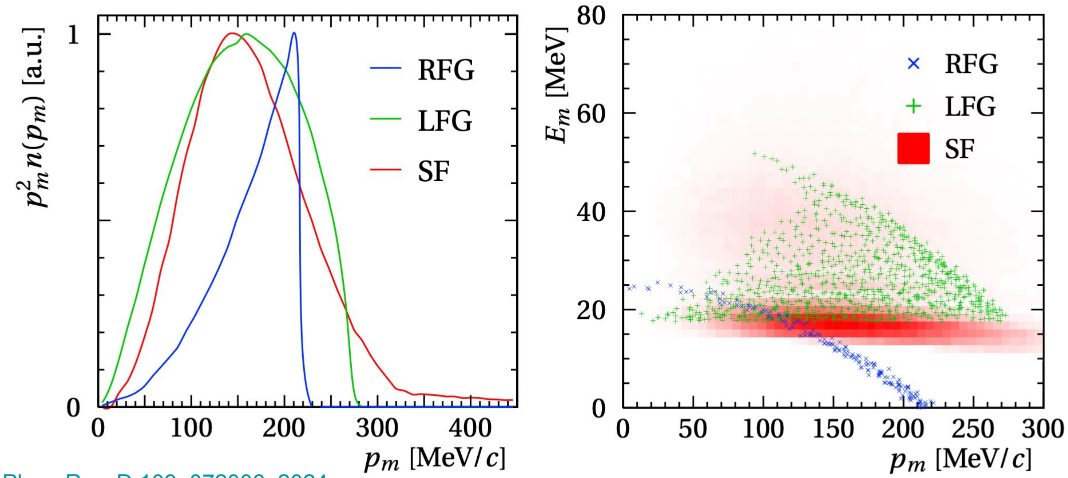
Nuclear models

~ initial nucleon momentum and energy

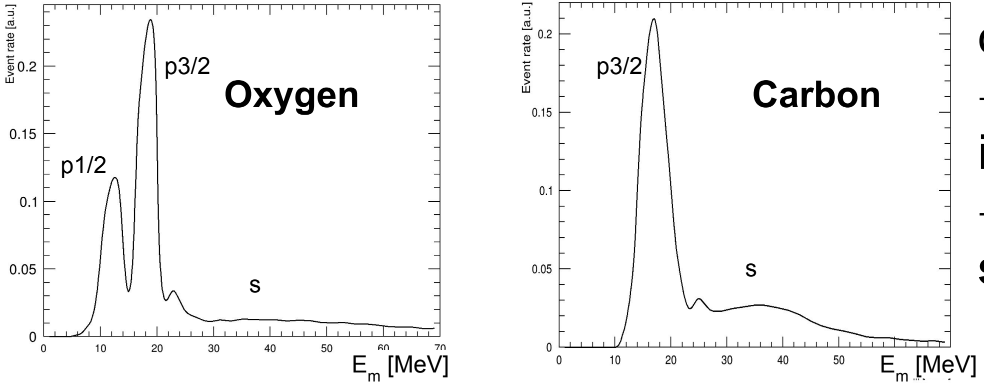


Phys. Rev. D 109, 072006, 2024

More sophisticated (wrt Fermi gas) **nuclear models as Spectral Function (SF)**

try to reproduce the nuclear shell structure

Shell occupancy in SF model

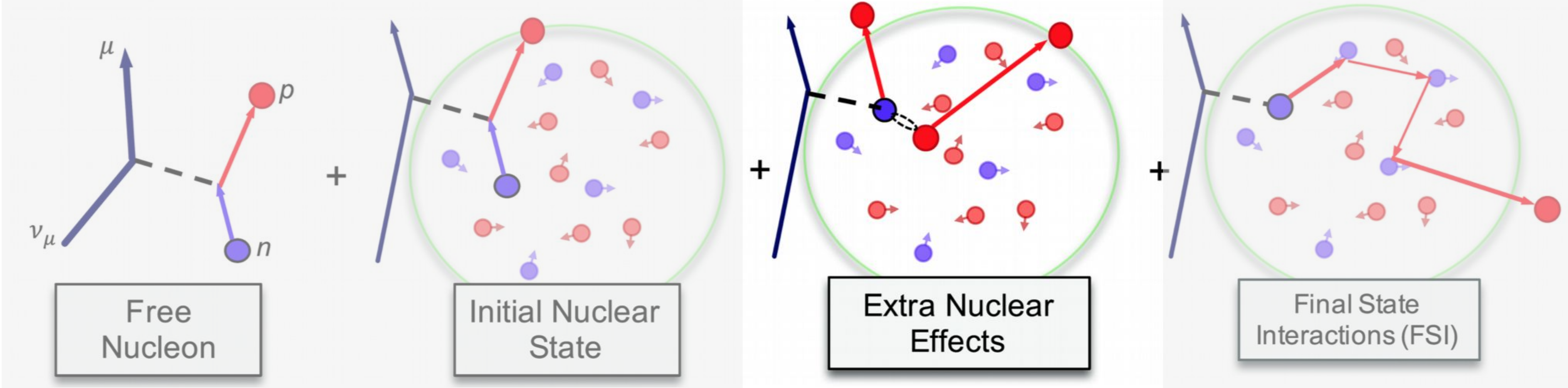


The final state particle kinematics depend on the initial state kinematics

→ need to precisely model the initial state if we want to interpret the final state

→ we thus now tend to **use more sophisticated available nuclear models**

The role of nuclear effects



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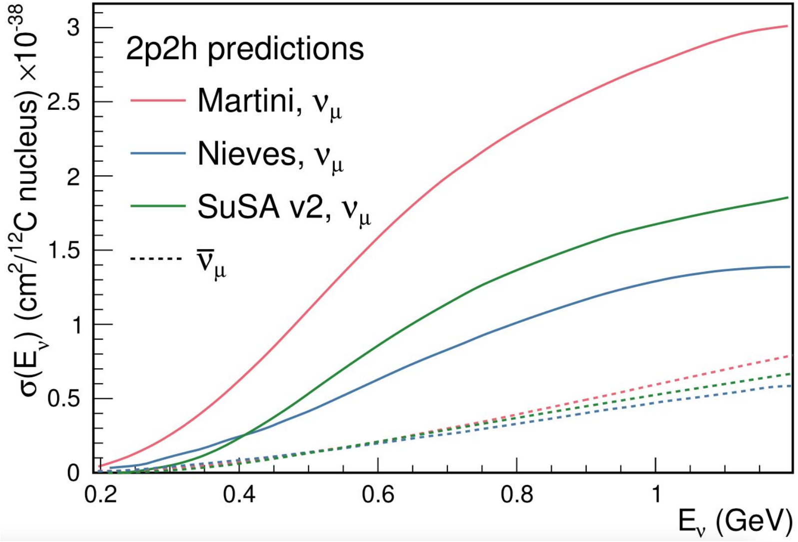
2p2h models

Eur. Phys. J. C (2023) 83:782



Now we know that we need to describe 2p2h interactions.

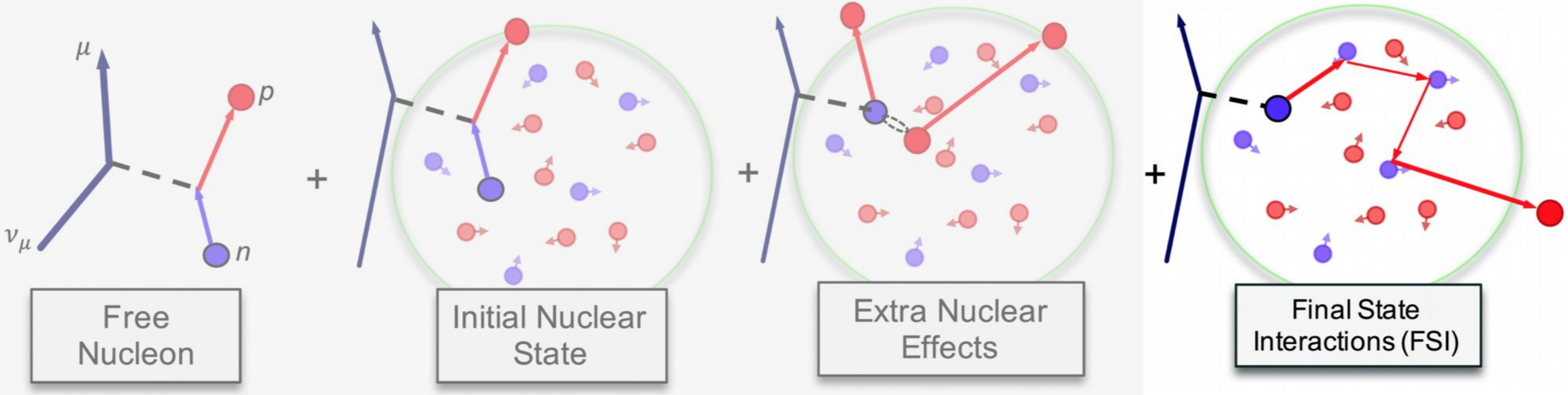
Several models describing 2p2h are also available and they predict pretty different cross section values → this is source of systematics uncertainties

How many 2p2h interactions do we have?

Which kind of final state kinematics they give?

If you have 2 protons in the final state and one is under threshold?

The role of nuclear effects



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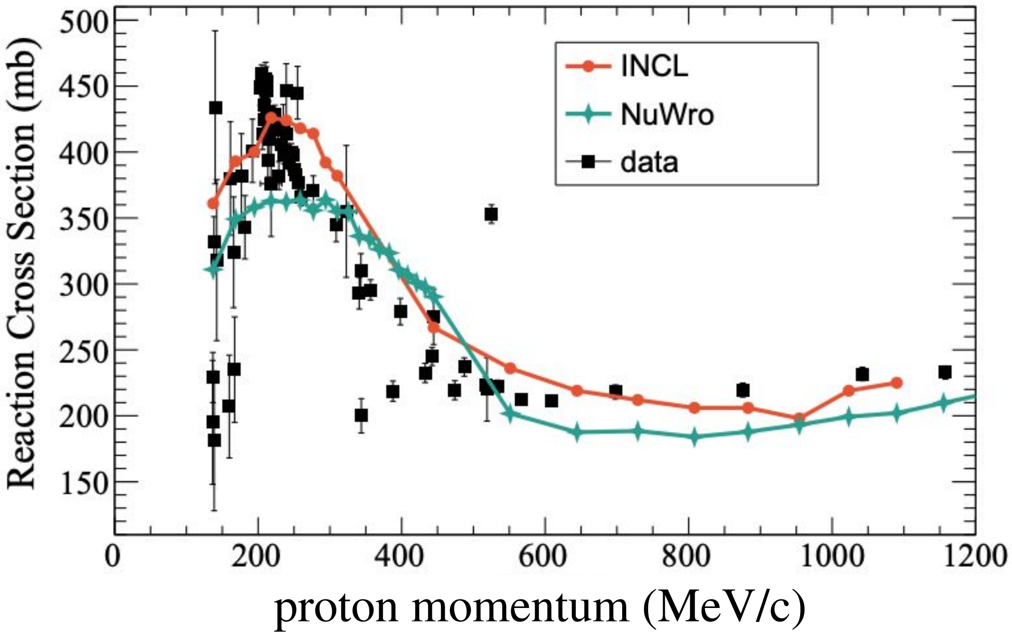
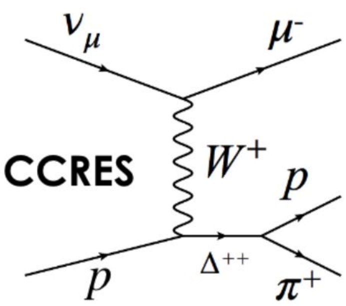
FSI models

Finally FSI can drastically change the aspect of the final state kinematics and even the nature of the final state particles: deviate hadrons, re-absorb hadrons (pions or protons), create new ones, nucleus excited state to de-excitate



Once more, different models predict different things



Phys. Rev. D 106, 032009 (2022)

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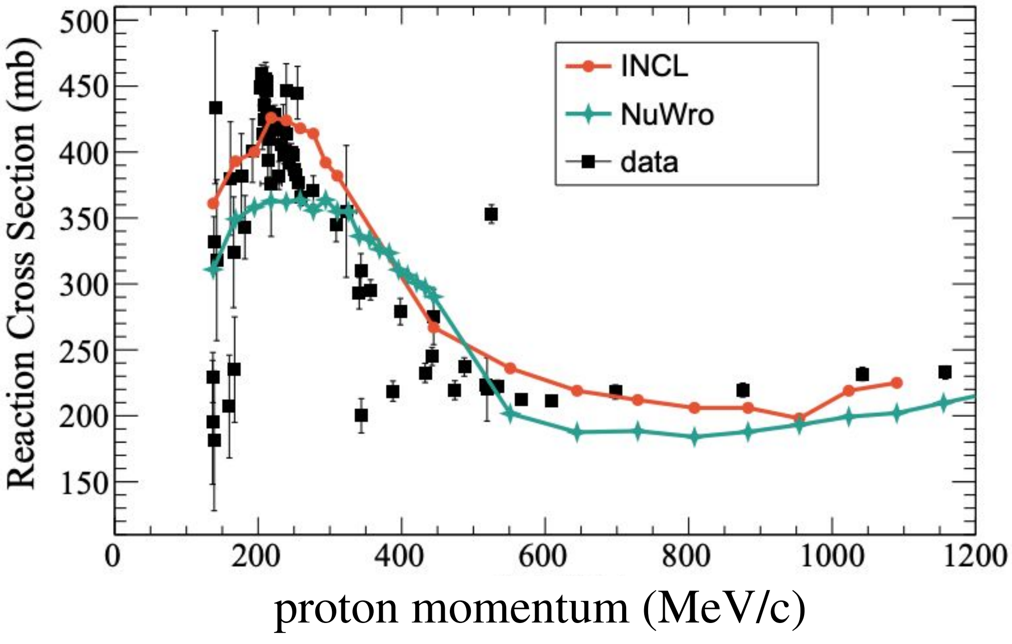

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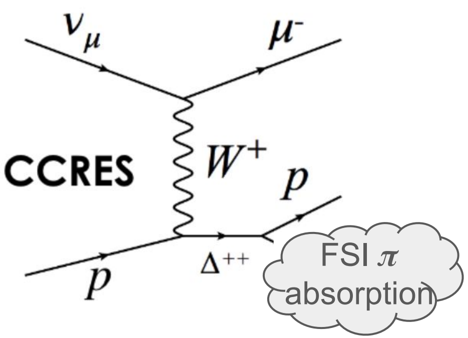


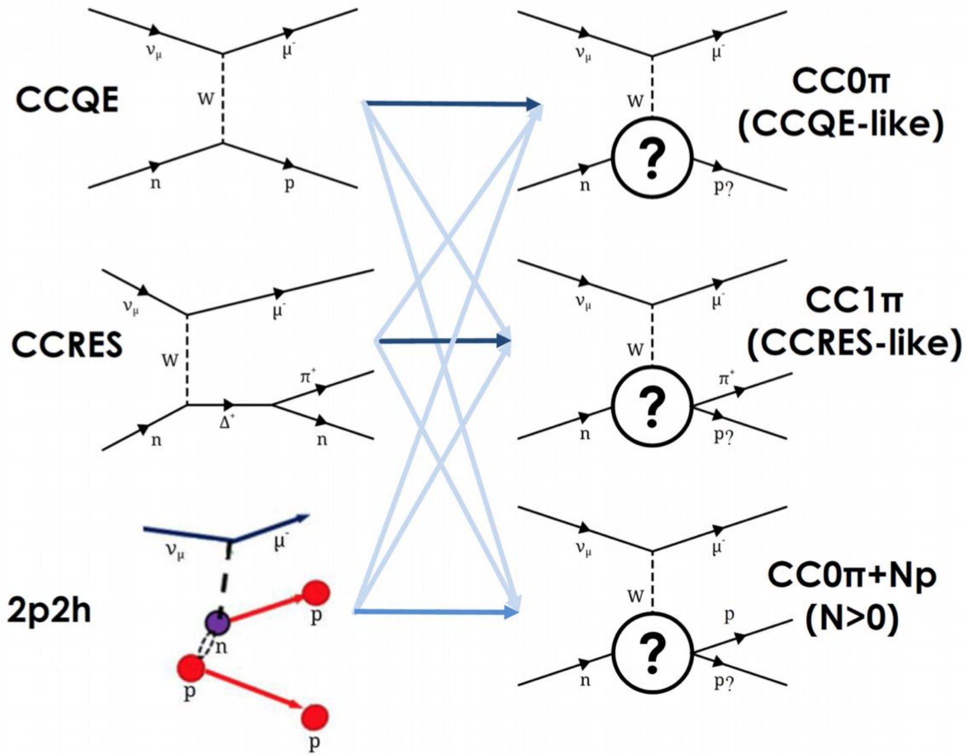
This final state look like a CCQE one 😬

⇒ when looking for a muon and a proton in the final state, what were K2K and MiniBooNE selecting?

Final state topologies

Initial state interactions

Final state topologies



Our detectors can only reconstruct final state particles after nuclear effect

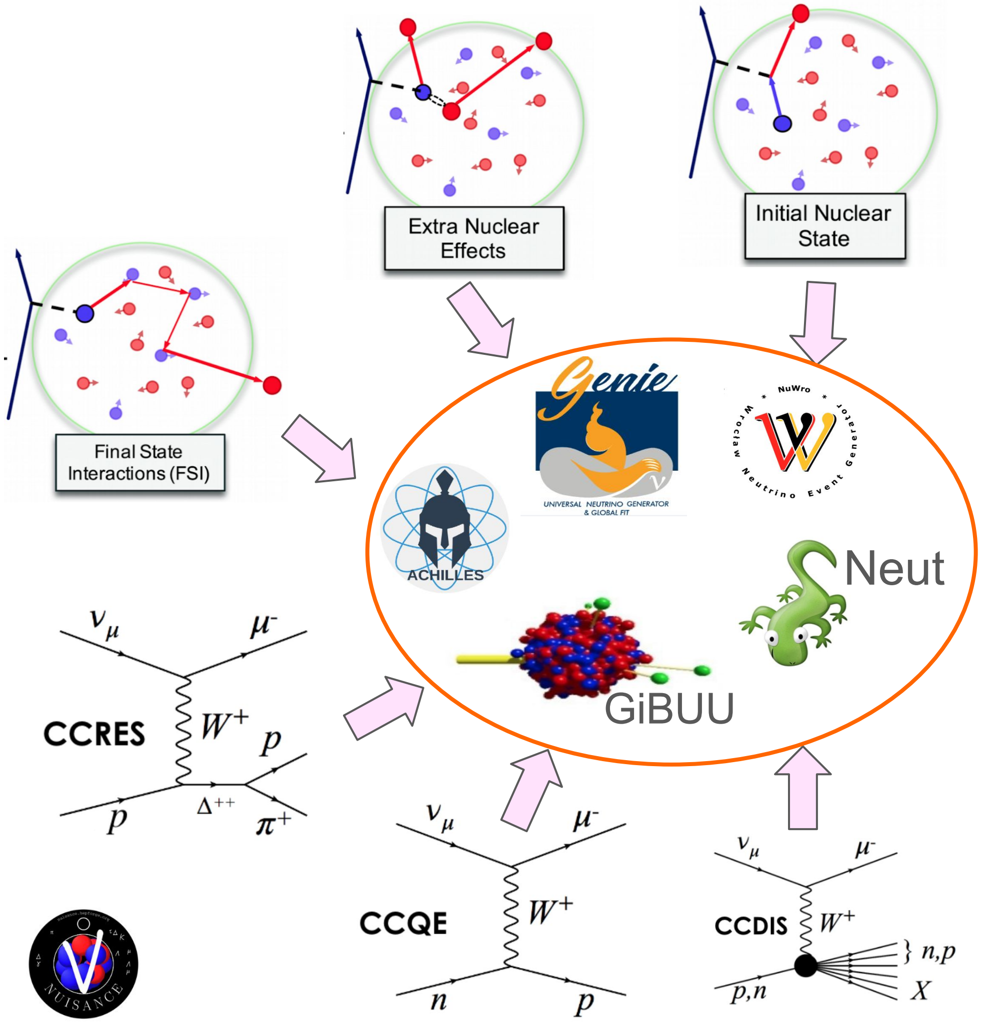
- charged lepton (CC) or no lepton (NC)
- w. or w/o pions: $0\pi^{+-0}$, $1\pi^{+-0}$
- w. or w/o protons: 0p, 1p, Np

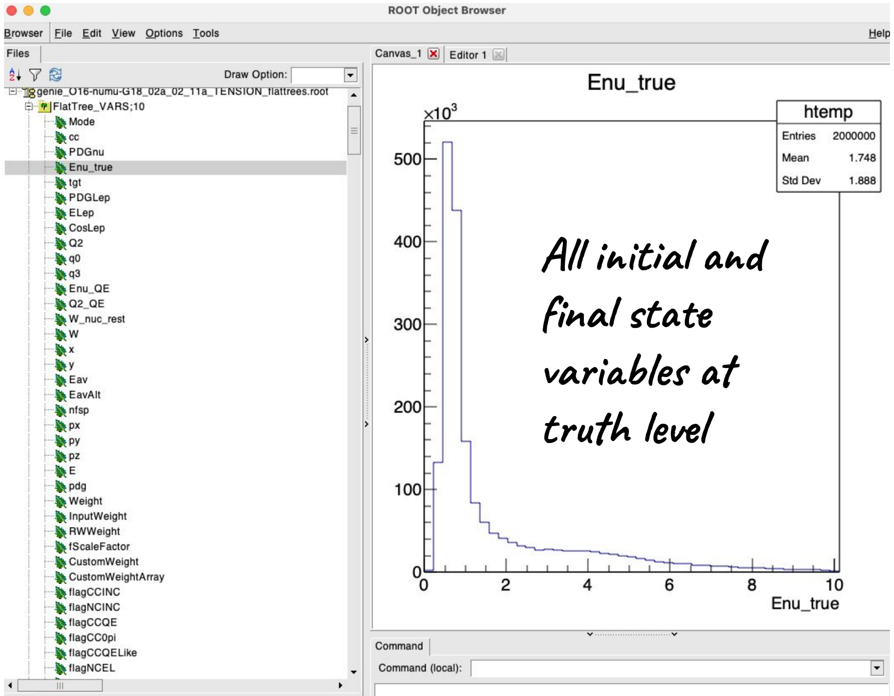
Final state topologies are the only categories we can access w/o referring to theoretical models, but they are **composed of a mixture of initial state interactions**

Difficult task for the xsec community is to try to characterize these initial state interactions to check/tune theoretical models (and for the theory community to try to predict our final state topologies starting from the initial state interactions)

Neutrino Generators

They usually contain several models for each kind of interaction and of nuclear effect.
You need to provide the incoming neutrino flux, the desired target and can chose the models

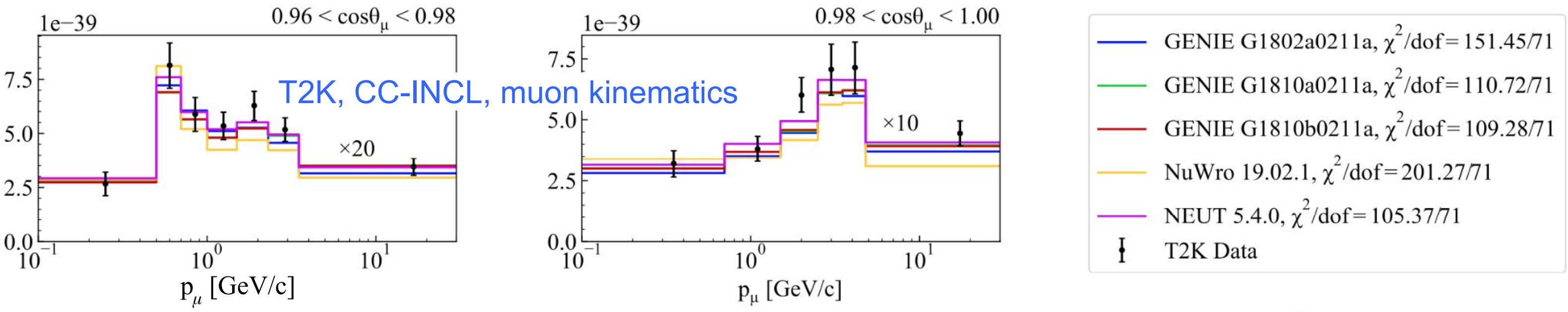




All initial and
final state
variables at
truth level

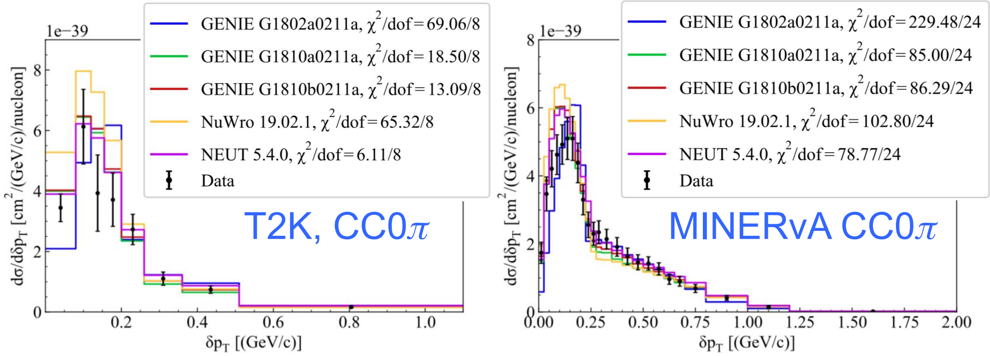
XSEC experiments: Comparisons and challenges as from TENSION 2019

M.B.A. et al., Phys. Rev. D 105, 092004 (2022)



T2K, CC-INCL, muon kinematics

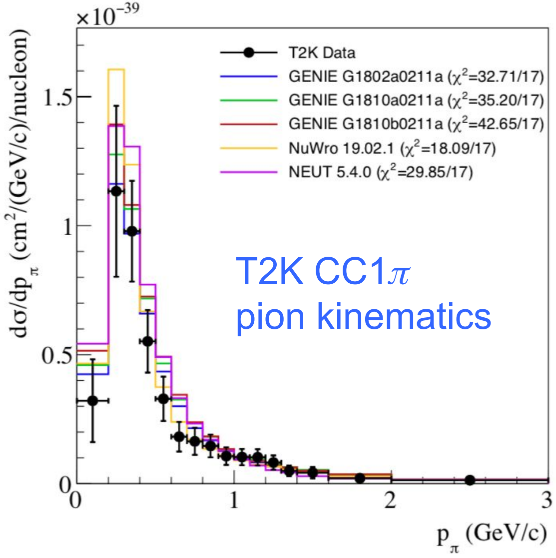
Despite the increasing availability and quality of cross-section data and extraction techniques, as well as of the available interaction models, TENSION is still the right word to use…



T2K, CC0π

MINERvA CC0π

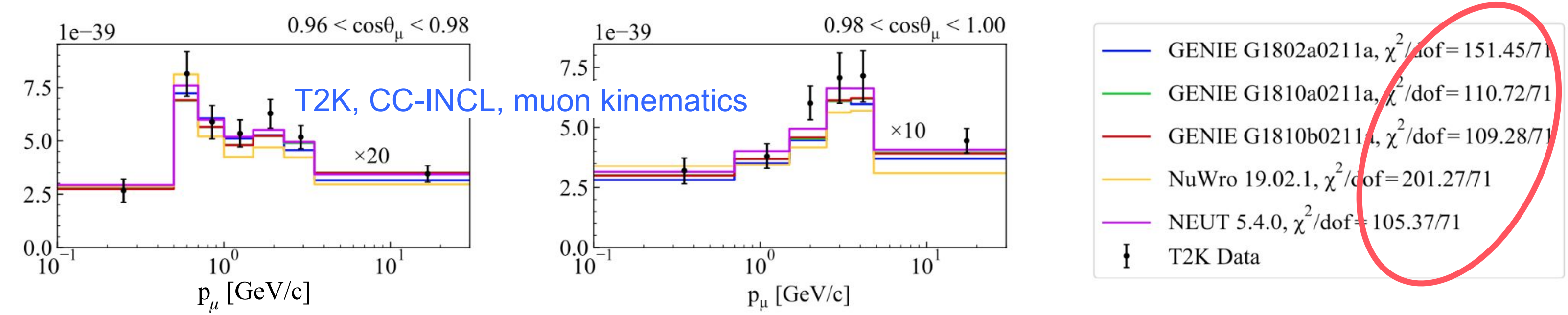
Transverse Kinematic Imbalance Variables

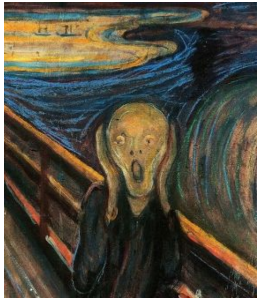


T2K CC1π
pion kinematics

XSEC experiments: Comparisons and challenges as from TENSION 2019

M.B.A. et al., Phys. Rev. D 105, 092004 (2022)





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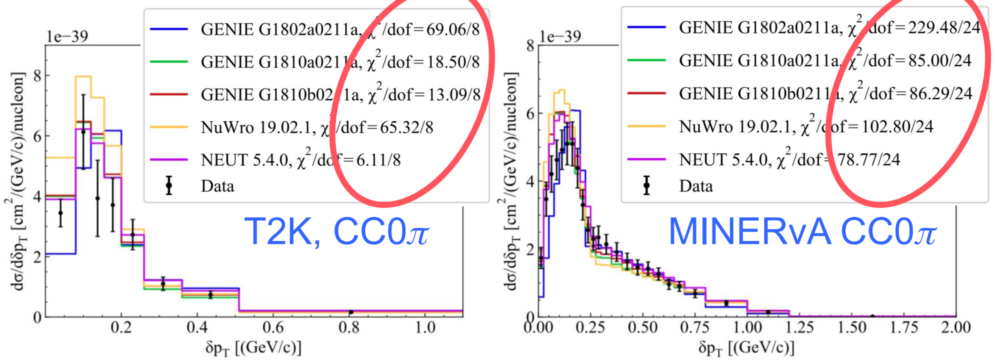
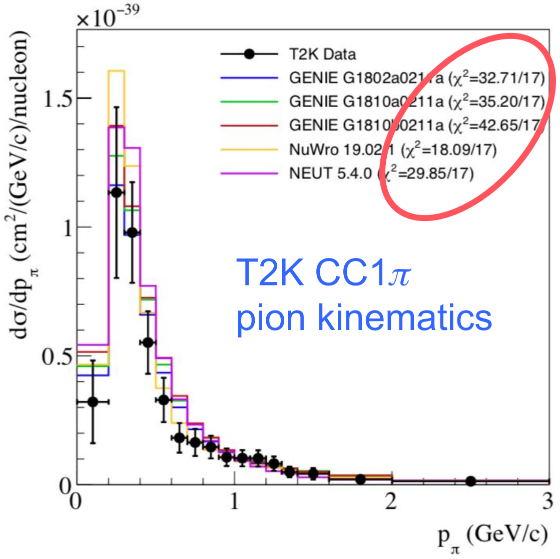


Transverse Kinematic Imbalance Variables

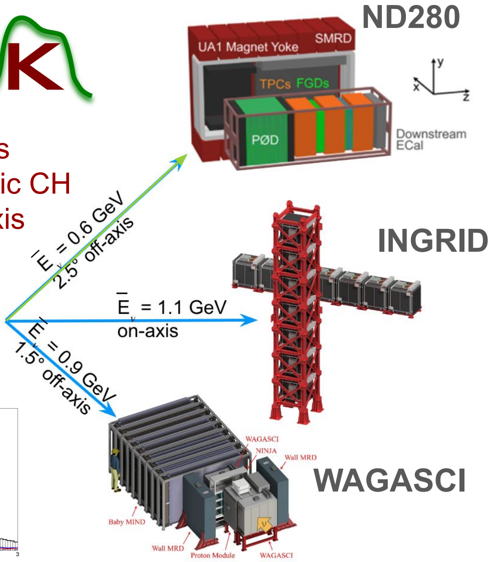


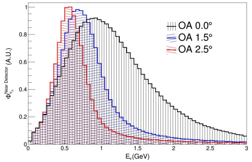
KEEP
CALM
AND
MEASURE
ν XSEC

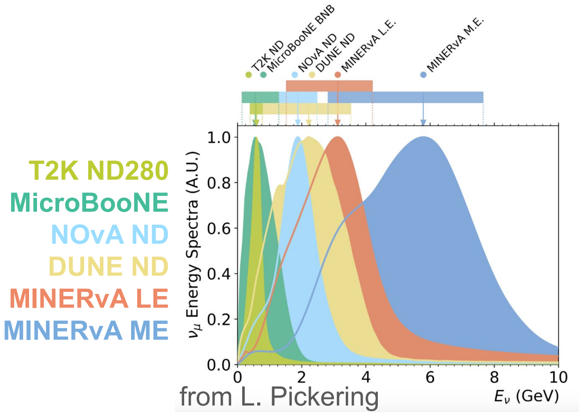
Neutrino cross section measurements

Main actors in the field

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





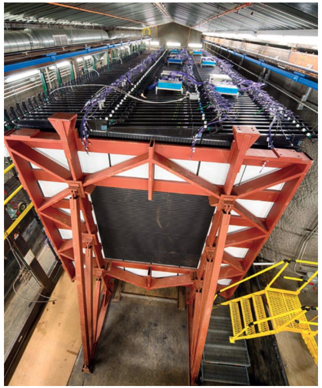


from L. Pickering

1. Liquid scintillator
2. off-axis

Fermilab
NuMI beam

$\bar{E}_\nu$ = 1.8 GeV
0.8° off-axis

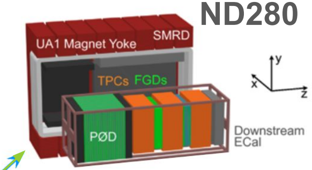


Main actors in the field

T2K

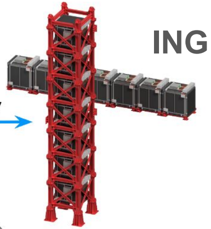
1. Near detectors
2. H_2O and plastic CH
3. different off-axis

ND280



$\bar{E}_\nu$ = 0.6 GeV
2.5° off-axis

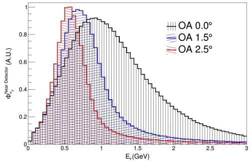
INGRID



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

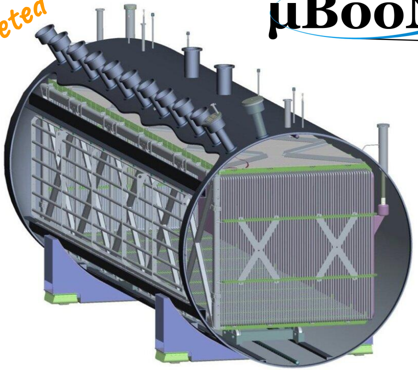
$\bar{E}_\nu$ = 0.9 GeV
1.5° off-axis

WAGASCI



Data taking completed

µBooNE

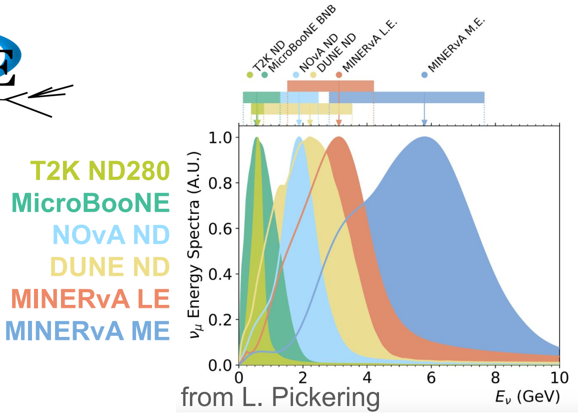


1. LArTPC
2. BNB beam on-axis
3. NuMI beam off-axis

$\bar{E}_\nu$ = 0.8 GeV
BNB on-axis

$\bar{E}_\nu$ = 0.9 GeV
NuMI, 8° off-axis

Fermilab



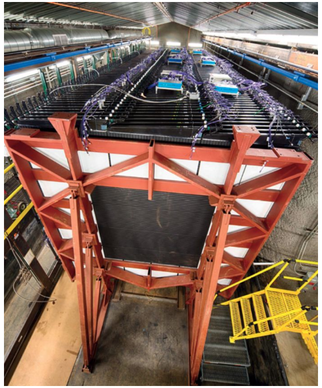
from L. Pickering

NOvA

1. Liquid scintillator
2. off-axis

Fermilab
NuMI beam

$\bar{E}_\nu$ = 1.8 GeV
0.8° off-axis



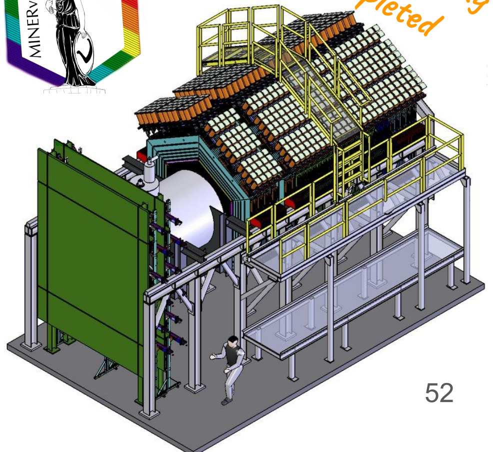
Data taking completed

MINERvA

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 and maintain **sophisticated tools and careful procedures** for the cross section extraction (unfolding and error propagation) and diagnostic

What is a cross section?

x, y = generic observables

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

What is a cross section?

After background subtraction and unfolding of detector effects

x, y = generic observables

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

true variables

efficiency correction

double (or more?) differential

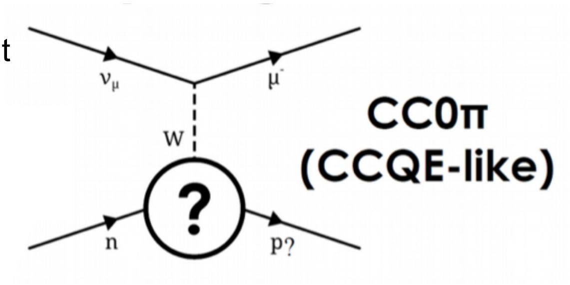
- Signal, to be defined considering the detector capabilities ⇒ **final state topology**
- Selected signal samples contain also some background ⇒ need of **background samples**
- Observables, to be chosen considering the detector capabilities ⇒ **usually lepton and/or hadron kinematics**
- Limit the 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**

What do we need to measure a cross section?

(taking as an example the [Oxygen and Carbon CC0pi measurement from T2K]())

A signal definition, for instance CC0π, that lives in the truth space

CC0π: we look for a reconstructed μ, potentially a reco p and NO pions



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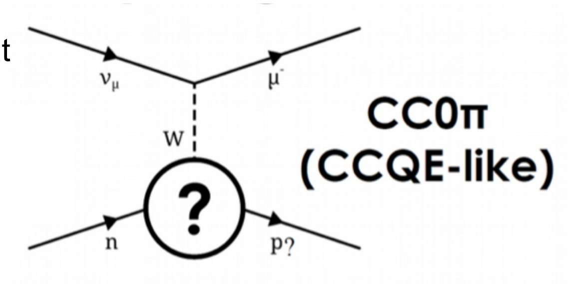
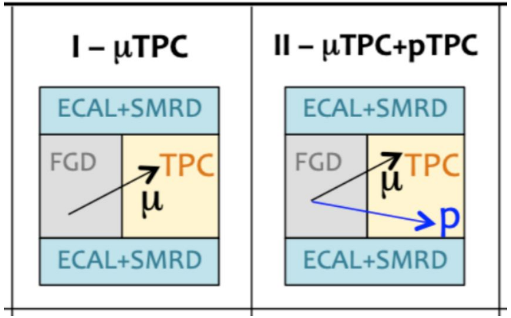


A signal selection, that applies on the reconstructed events with an adequate choice of **observables**, for instance lepton kinematics



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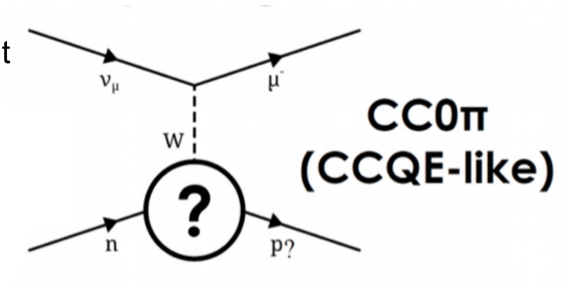

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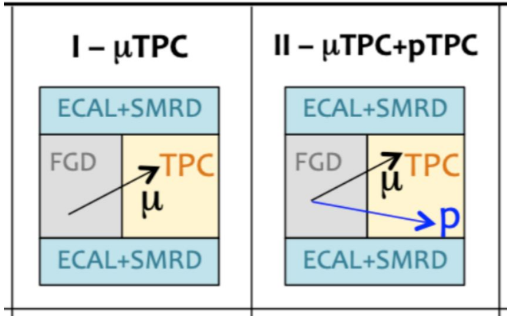
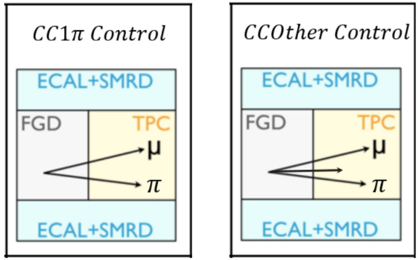


A background selections



to constrain the background remaining in the signal samples

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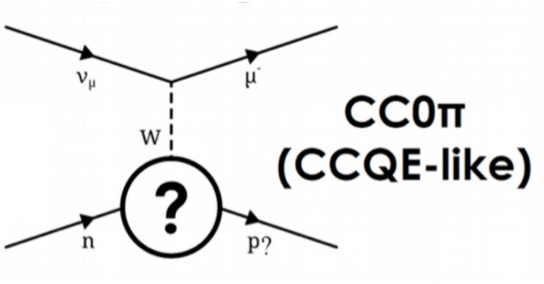

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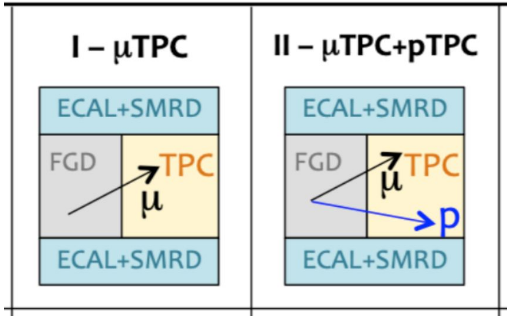
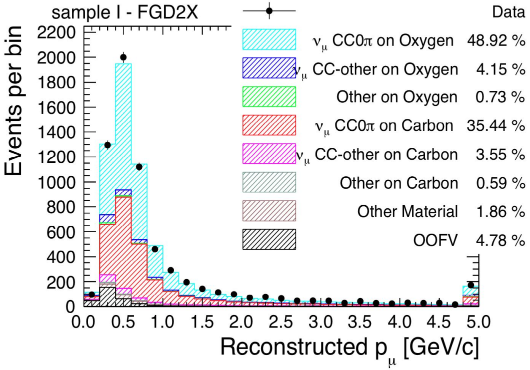


A Montecarlo prediction, that is the fundamental tool to:

1. have an idea of the background contamination and sample purity
2. move from the reco to the truth space (detector unfolding matrix and efficiency correction)
3. find the needed MC adjustments when compared to data



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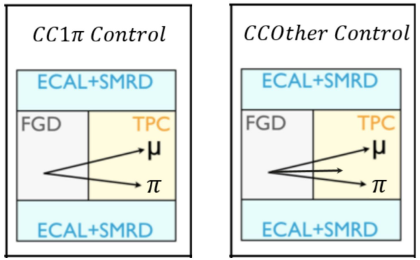
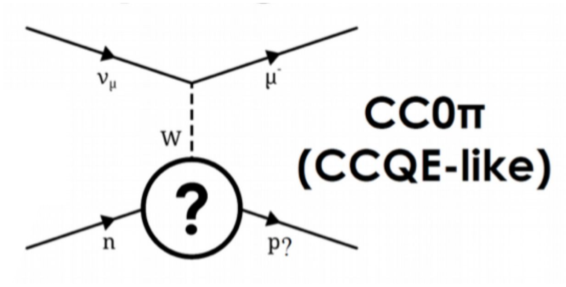


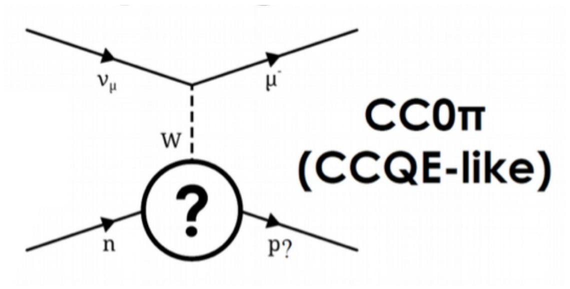
to constrain the background remaining in the signal samples

What are the best observables to exploit?



We select a muon and eventually a proton. We can be tempted to try to extract the cross section as a function of the neutrino energy, the observable really needed for the oscillation analysis

What are the best observables to exploit?



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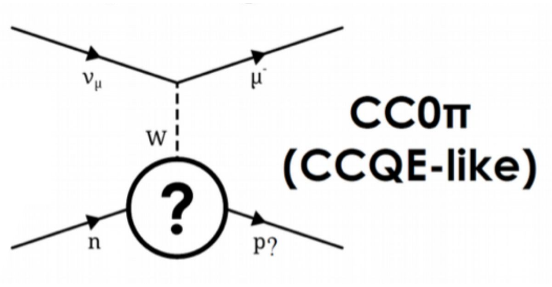
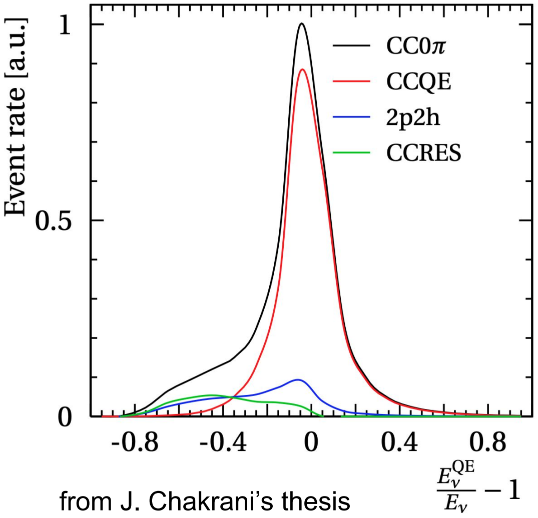


We select a muon and eventually a proton. We can be tempted to try to extract the cross section as a function of the neutrino energy, the observable really needed for the oscillation analysis

How can we reconstruct the neutrino energy from the final state w/o knowing the occurred interaction and exploiting essentially the muon information?



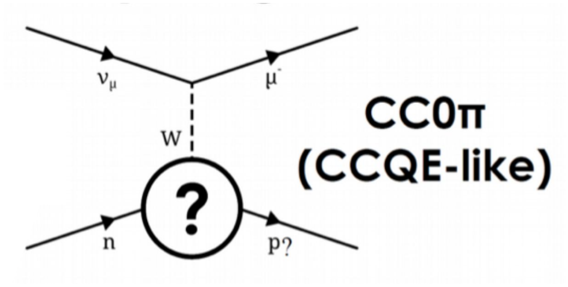
from J. Chakrani's thesis

Essentially… we can't!

And a cross section extracted as a function of the true neutrino energy will be by definition model dependent

(using conventional neutrino beams)

What are the best observables to exploit?

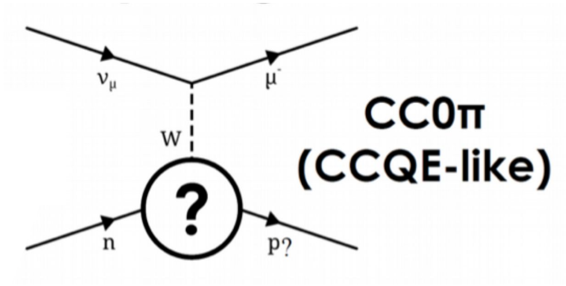


$\cancel{E}_\nu$

p_μ and/or $\cos\theta_\mu$

We usually consider the muon kinematics (direction and momentum), that are in general well reconstructed by the detector

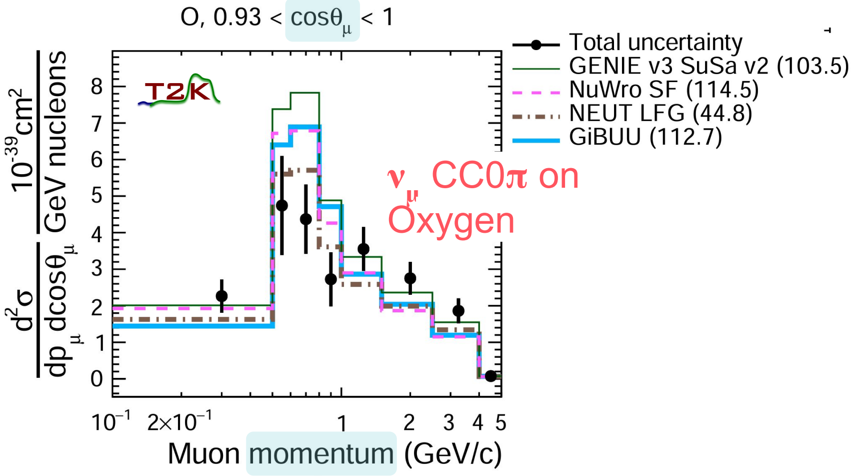
What are the best observables to exploit?



$\cancel{E}_\nu$ ⏮ **p_μ and/or $\cos\theta_\mu$**

We usually consider the muon kinematics (direction and momentum), that are in general well reconstructed by the detector

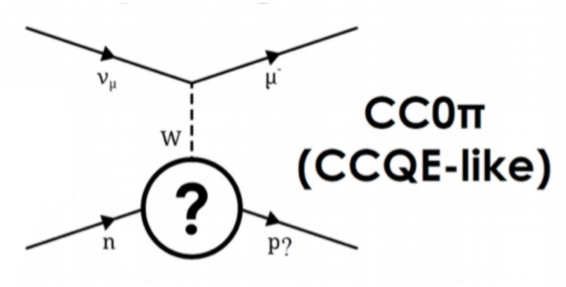
In addition, providing multi dimensional measurements is encouraged, since this allows a better mapping of the phase space


O, $0.93 < \cos\theta_\mu < 1$

ν_μ CC0π on Oxygen

Phys. Rev. D 101, 112004 (2020)

What are the best observables to exploit?



~~E_ν~~

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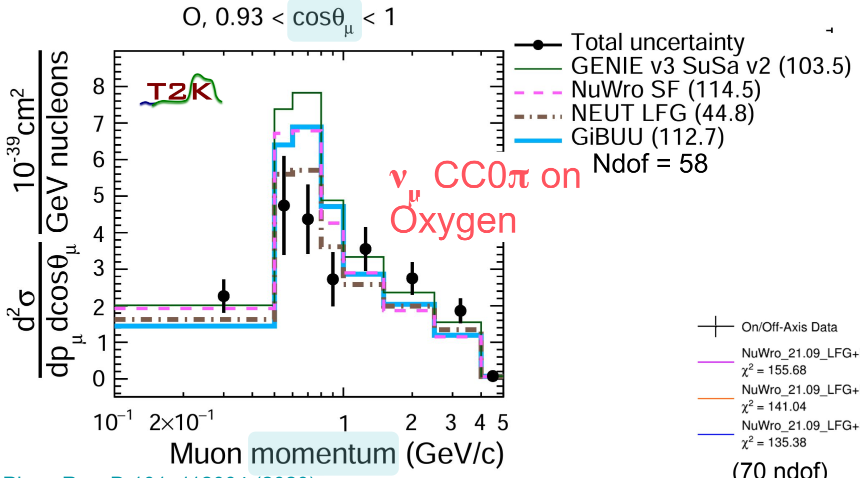


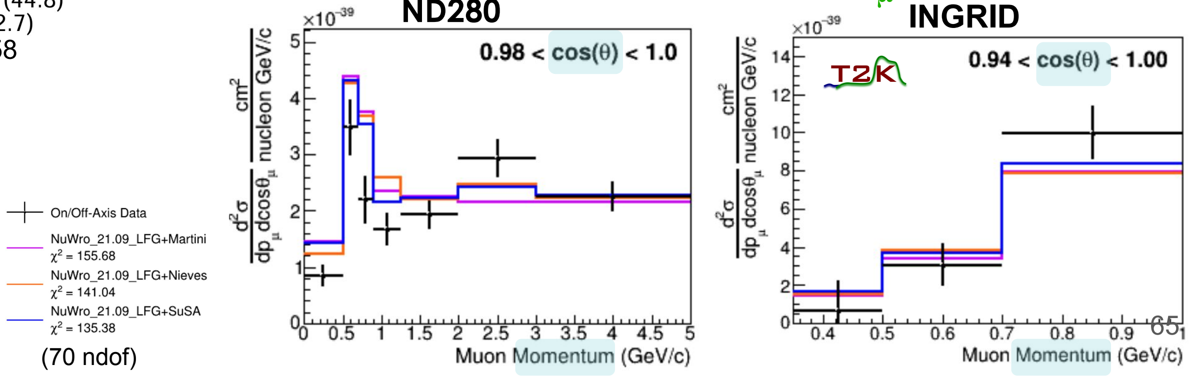
ν_μ CC0π on Oxygen

Phys. Rev. D 101, 112004 (2020)

At T2K we can also study the same interaction at different energy spectra by combining different near detectors

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

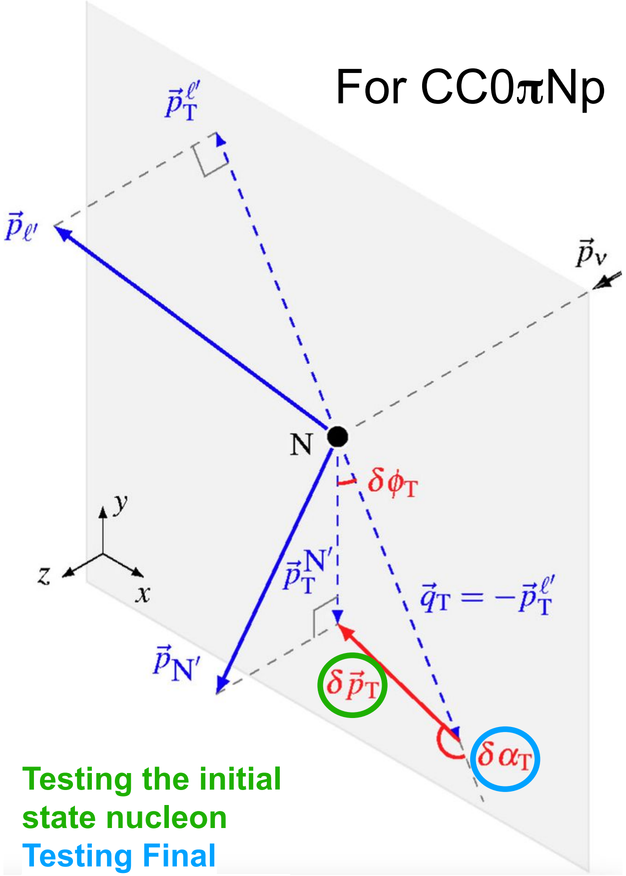
ν_μCC0π on CH



(70 ndof)

Transverse kinematic imbalance variables (TKI)

For CC0πNp



Testing the initial state nucleon

Testing Final State Interactions

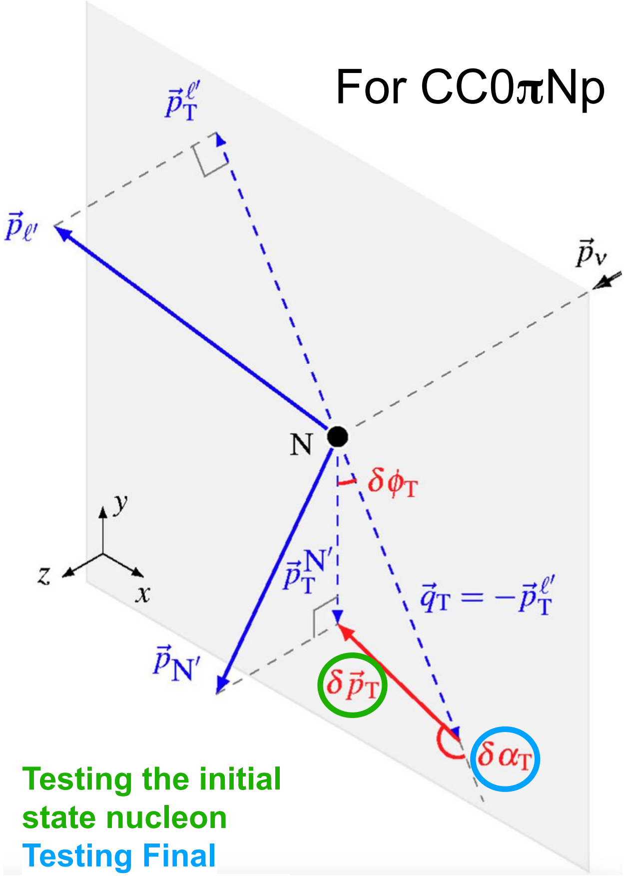
On free nucleon, there is no final state transverse imbalance.

If TKI exist, this means that there is a transverse kinematic imbalance, i.e. some nuclear effects

Using TKI variables is a way to study nuclear effects

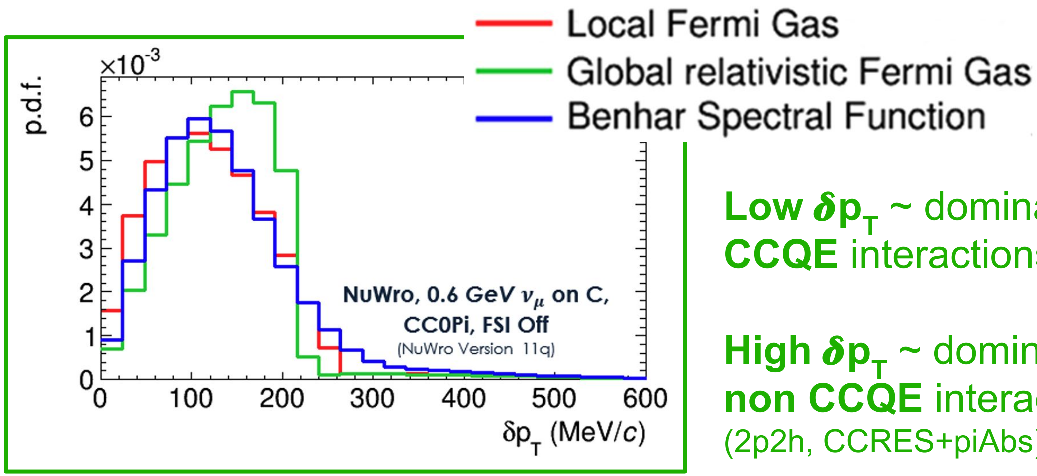
Transverse kinematic imbalance variables (TKI)

For CC0πNp



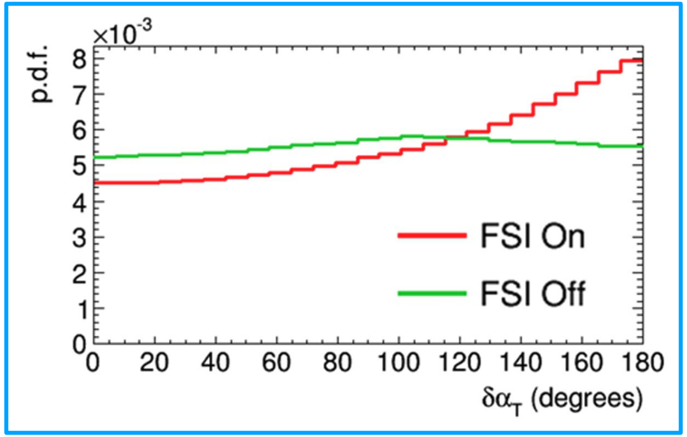
Testing the initial state nucleon

Testing Final State Interactions



Low δp_{T} ~ dominance of **CCQE** interactions

High δp_{T} ~ dominance of **non CCQE** interactions (2p2h, CCRES+piAbs)



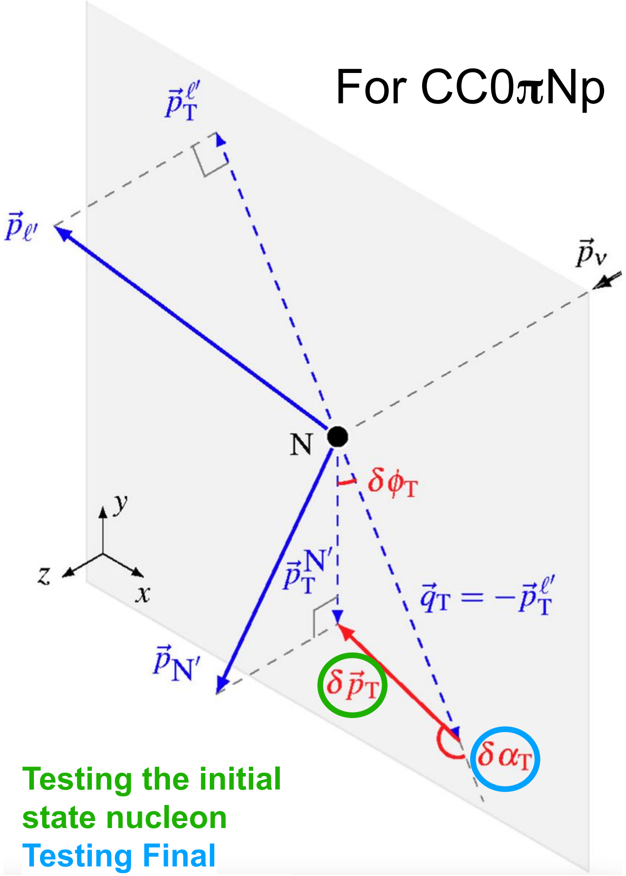
Low $\delta\alpha_{\mathrm{T}}$ ~ low FSI effects

High $\delta\alpha_{\mathrm{T}}$ ~ high FSI effects

from S.Dolan PhD thesis

Transverse kinematic imbalance variables (TKI)

For CC0πNp



Testing the initial state nucleon

Testing Final State Interactions

Again, even better discrimination power when using simultaneously 2 variables → deeper tests of nuclear effect models

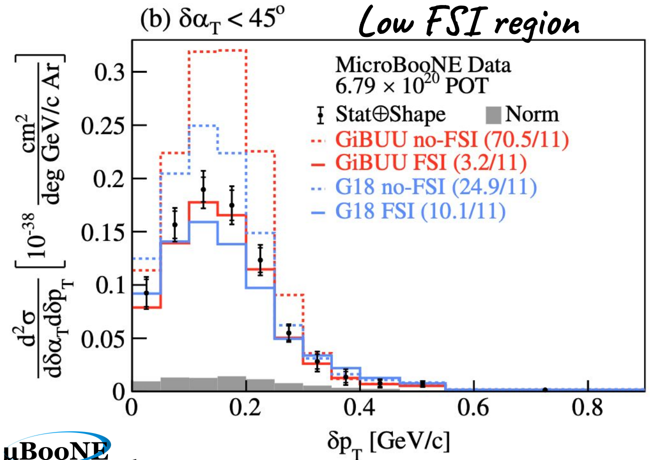
δp_T distribution is definitely not the same at high and low $\delta\alpha_T$ regions

First TKI measurement on Ar!

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

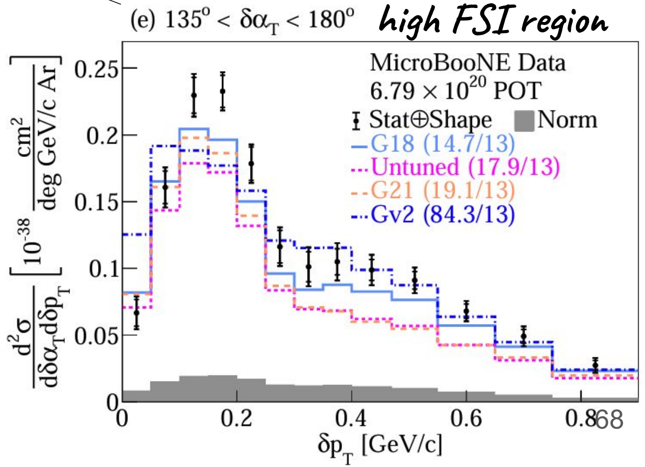
Phys. Rev. D 108, 053002 (2023)

Low FSI region

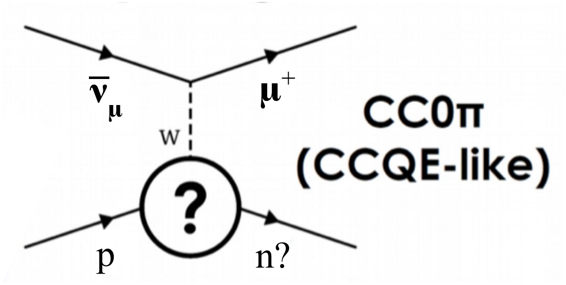


µBooNE

high FSI region



TKI and anti-neutrinos



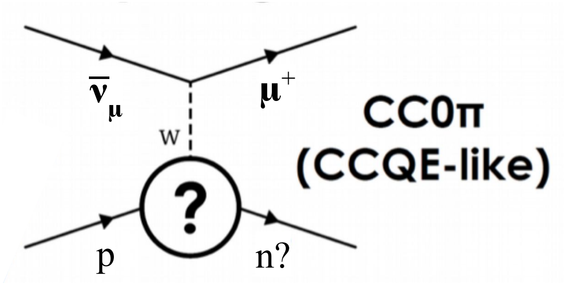
Nature, 614, 48-53 (2023)

Antineutrinos interact with the protons in the detector.

Let’s consider plastic scintillator target, essentially made of CH. C contains 6 protons and Hydrogen?? Only 1!!

That means that antineutrino interactions with H are essentially interaction on a free proton → no nuclear effects!!!

TKI and anti-neutrinos



Nature, 614, 48-53 (2023)

Antineutrinos interact with the protons in the detector.

Let's consider plastic scintillator target, essentially made of CH. C contains 6 protons and Hydrogen?? Only 1!!

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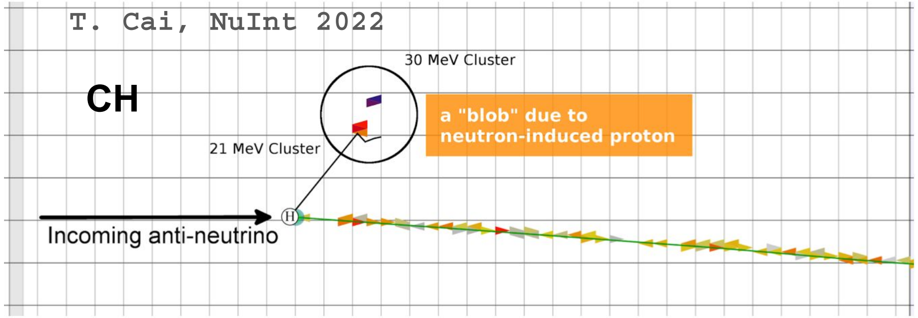
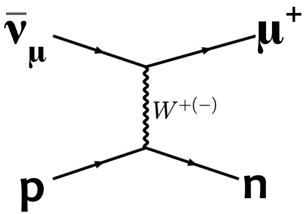
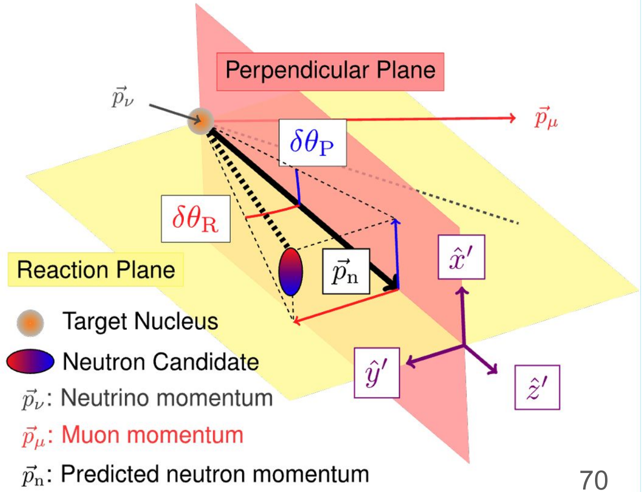
Only need the neutron direction!

Neutrons by definition are difficult to detect → look at n Secondary Interactions that produce visible p





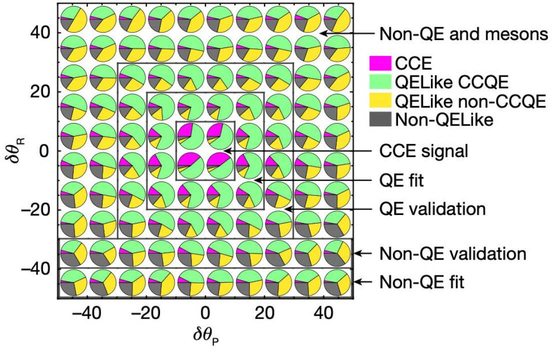


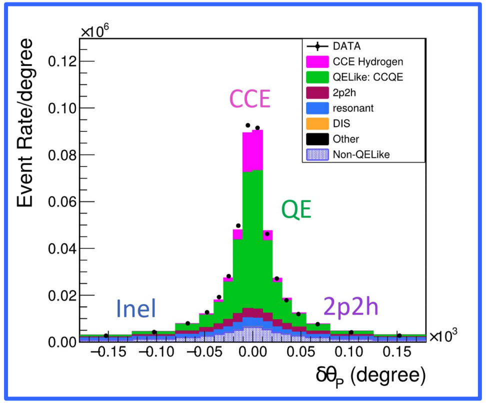
Neutrons @MINERvA

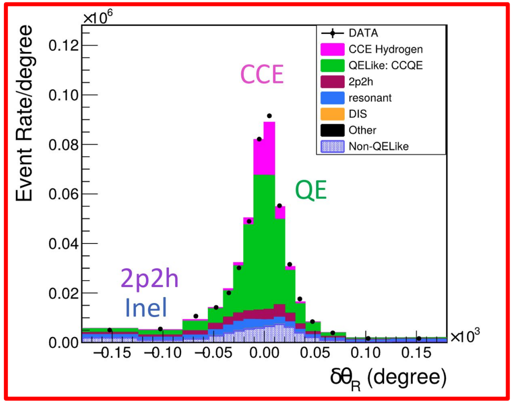
Only need the neutron direction!

Cuts on TKI angular variables

Nature, 614, 48-53 (2023)







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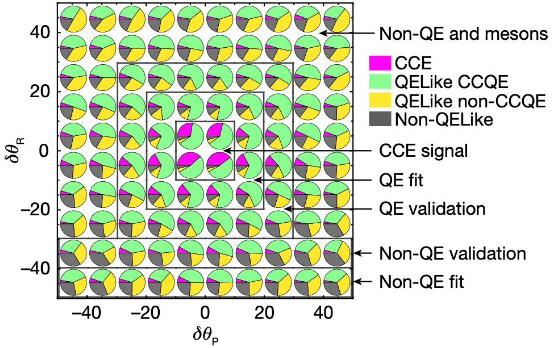
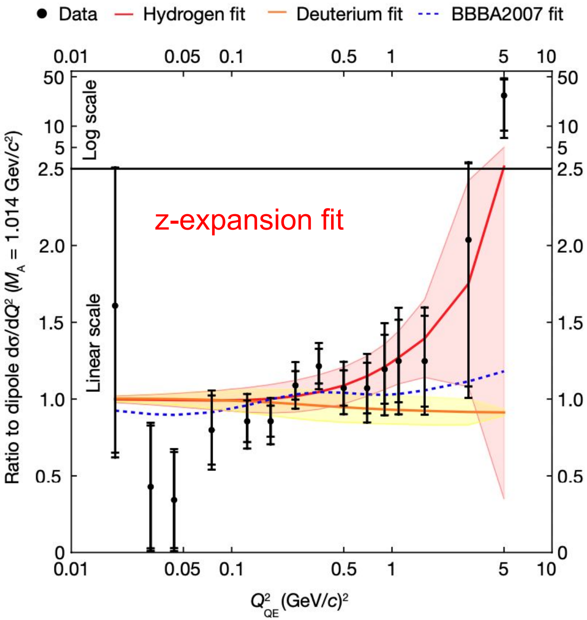
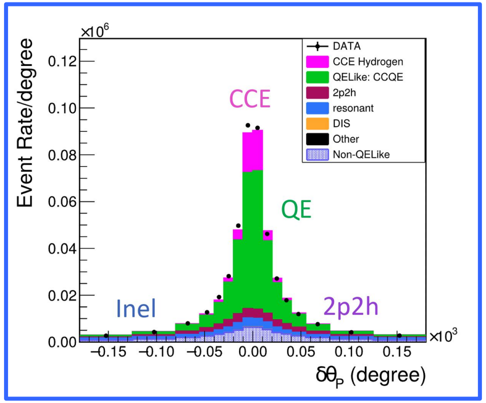
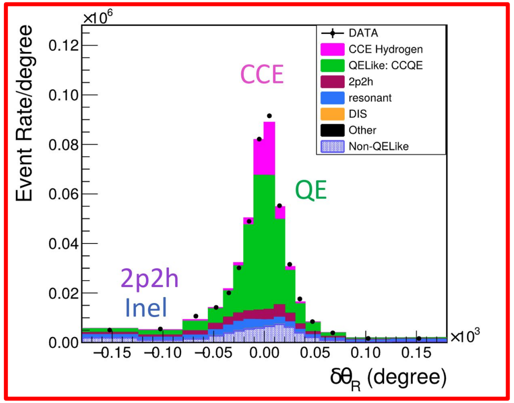








CCE xsec measured vs Q^2_{QE}: **first statistically significant measurement of the anti-ν CCE scattering on the free p!**

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**

Dipole

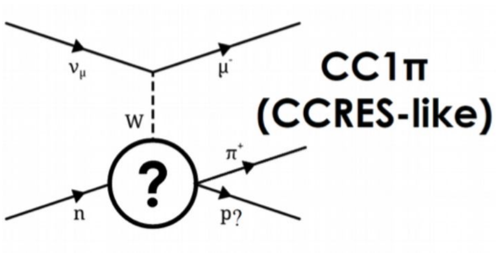
$$F_A(Q^2) = \frac{F_A(0)}{\left(1 + \frac{Q^2}{(M_A^{QE})^2}\right)^2}$$

?

z-expansion

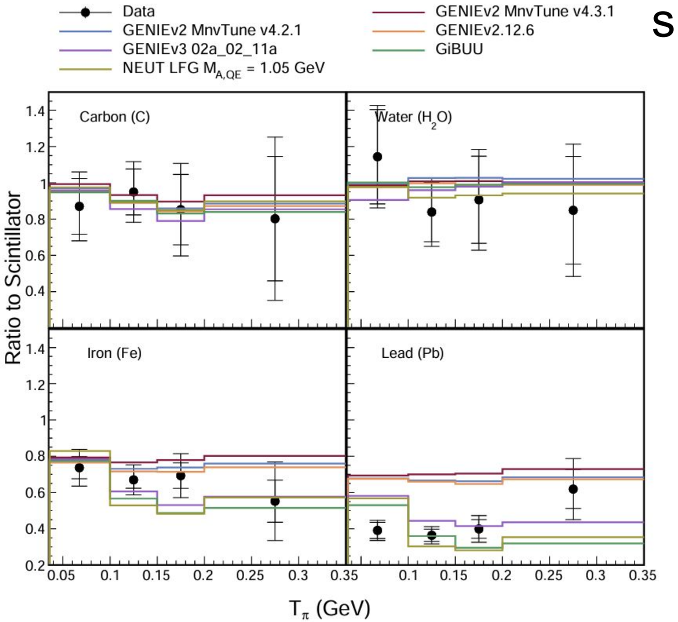
$$F_A(Q^2) = \sum_{k=0}^{k_{\max}} a_k \, z(Q^2)^k$$

Pion kinematics

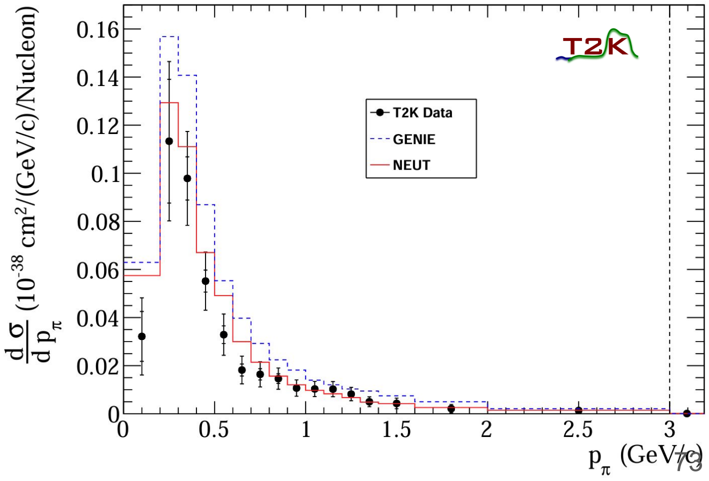


Studying the pion kinematics is also fundamental and help characterizing the CCRES interactions.

As well as studying xsec on different targets simultaneously



Phys. Rev. D 101, 012007 (2020)



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! ($m_\mu \neq m_e$)

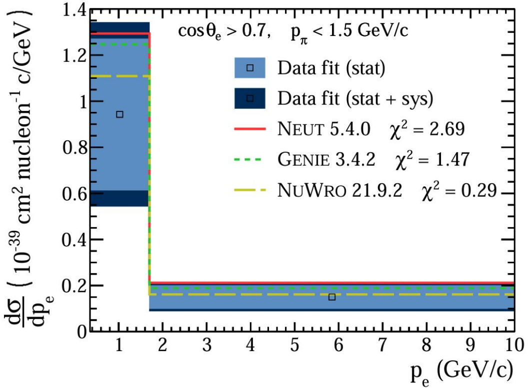
Electron neutrinos

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

T2K

First ν_e CC1π^+ measurement!

Important $\boldsymbol{\nu}_e$ 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

arXiv:2505.00516

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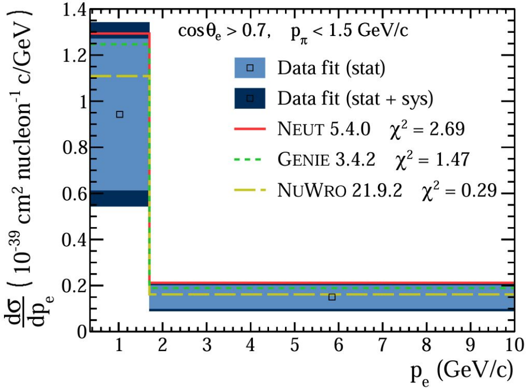

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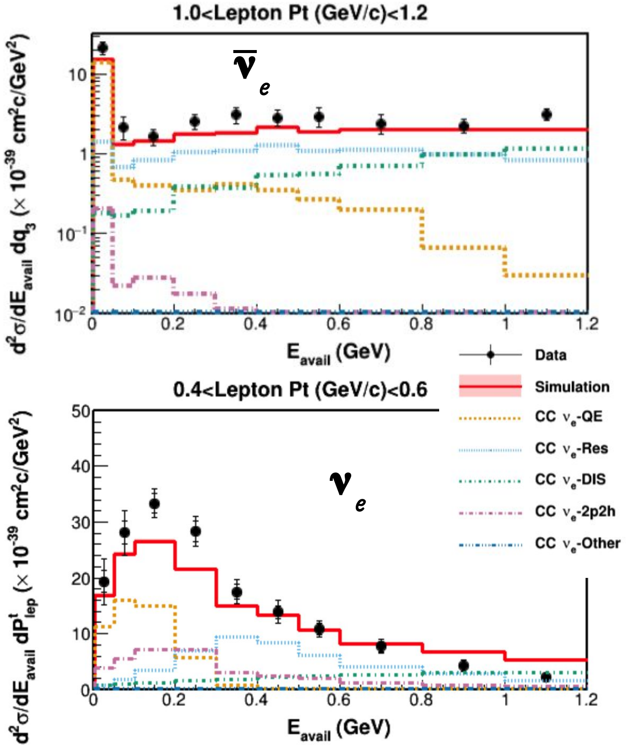
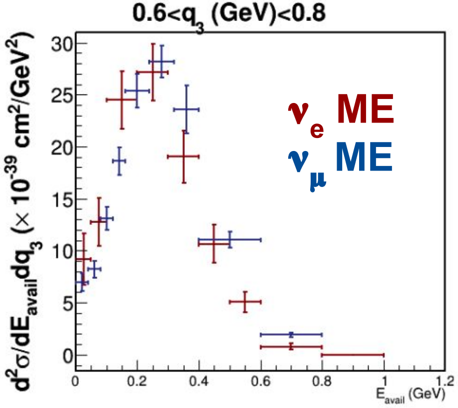
High statistics **(~10^4 events)**, **CC-Inclusive**, low E_{avail} (bkg limit), E_e> 2.5 GeV, ME beam, **CH target**

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



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

Phys. Rev. D 109, 092008 (2024)



Comparison with equivalent ν_μ measurement

How we concretely extract a cross section

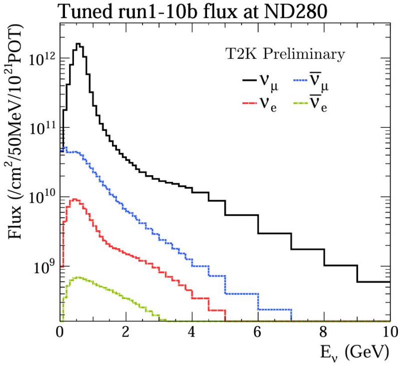
What are the main systematic sources in a cross-section measurement?

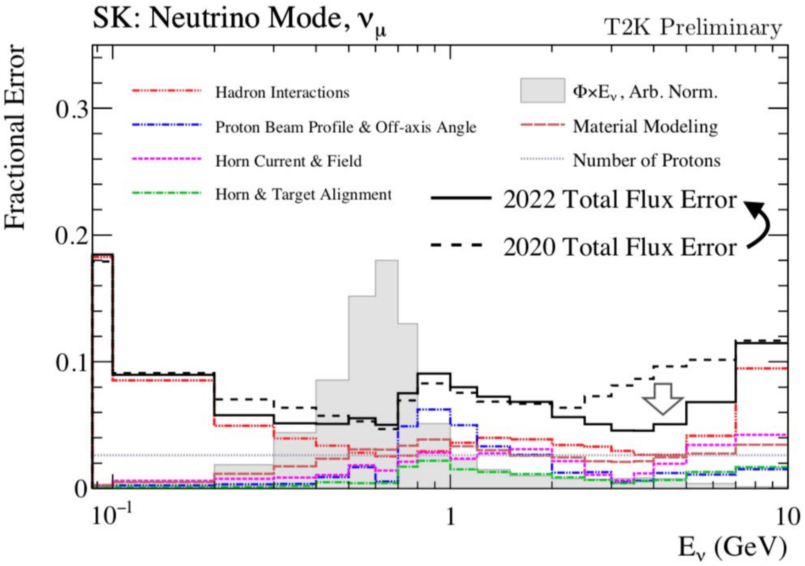
Examples from T2K

Since your starting point is a Montecarlo prediction, you should take into account three main systematics sources that will affect it:

The neutrino flux prediction

Thanks to simulations and external experiments, we are able to quote the uncertainty on our flux predictions in bins of true neutrino energy





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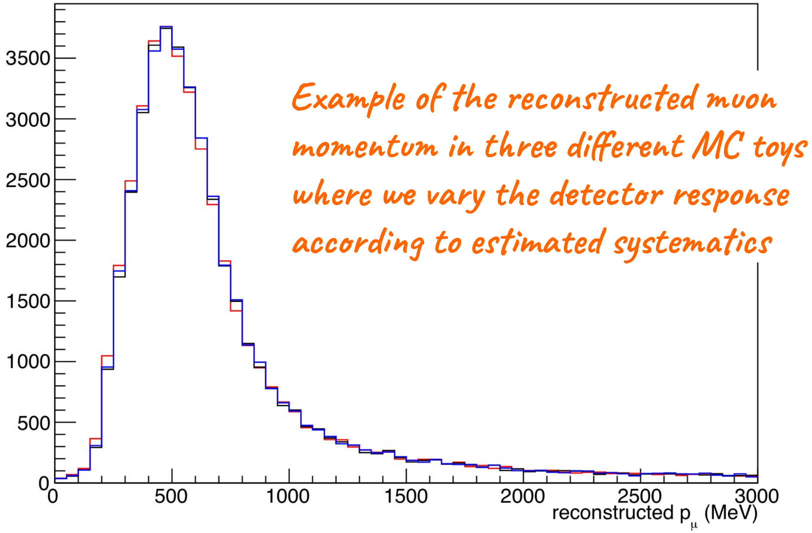
The detector effects

A series of detector systematics are estimated by comparing reconstruction results between the MC and data. Uncertainties can be propagated to the MC predictions



Example of the reconstructed muon momentum in three different MC toys where we vary the detector response according to estimated systematics

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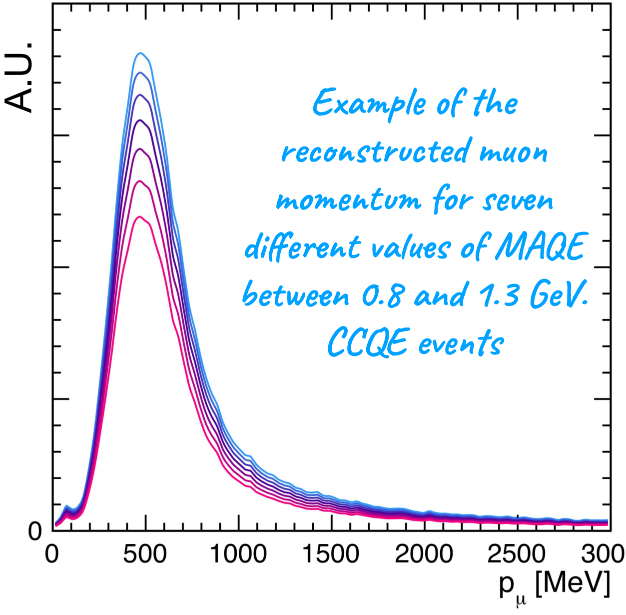
The interaction model uncertainties

We have a tool that allows to estimate the reweight to be applied to each event when we vary the value of specific parameters affecting the neutrino interaction predictions



Example of the reconstructed muon momentum for seven different values of MAQE between 0.8 and 1.3 GeV. CCQE events

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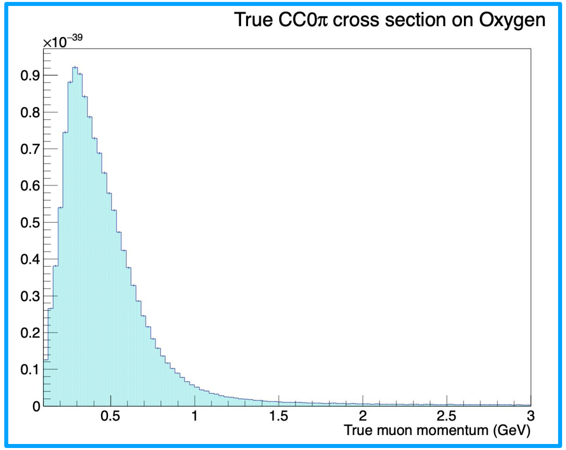
$$\frac{d\sigma}{dx_i dy_j} = \frac{N_{ij}^{signal}}{\epsilon_{ij} \Phi N_{nucleons}^{FV}} \times \frac{1}{\Delta x_i \Delta y_j}$$

The effect of these uncertainties will propagate on several elements of the cross-section calculation.

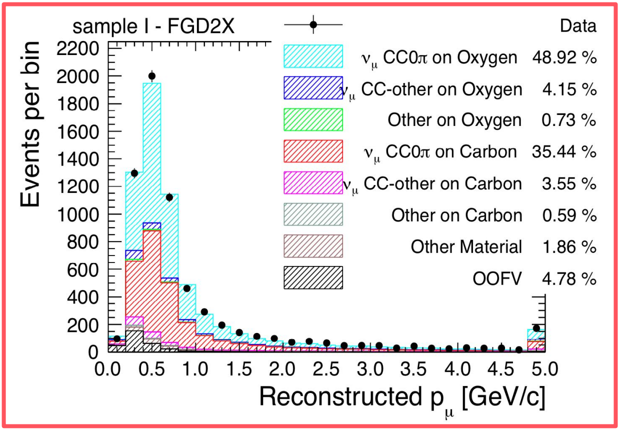
However we have a prior knowledge of these systematics

The unfolding problem



Detector effects: selection efficiency, detector acceptance, observable resolution

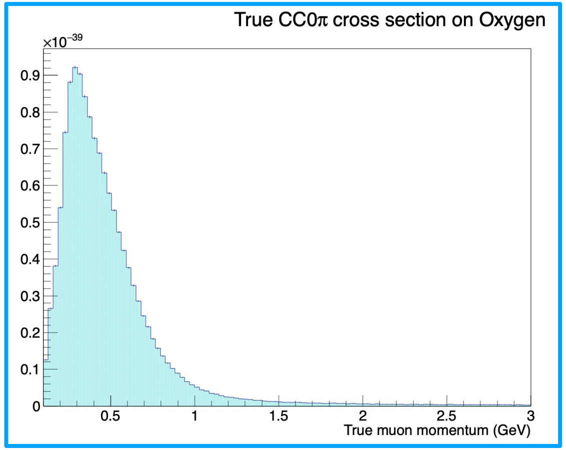
All these in principle simulated with the detector simulation



to compare with theoretical models we need to provide our measurements in the truth space

Reconstructed space (the one accessible with the detector).

The unfolding problem



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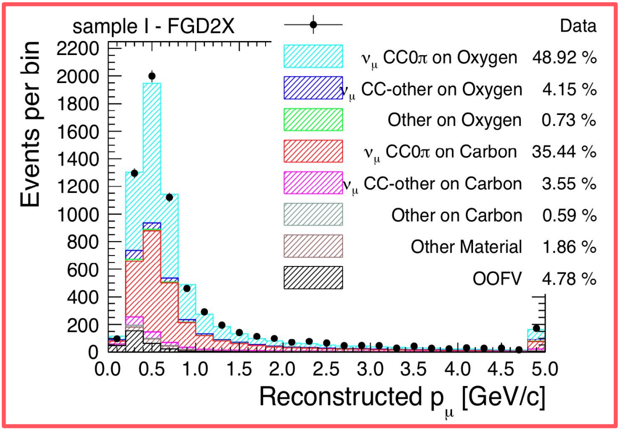

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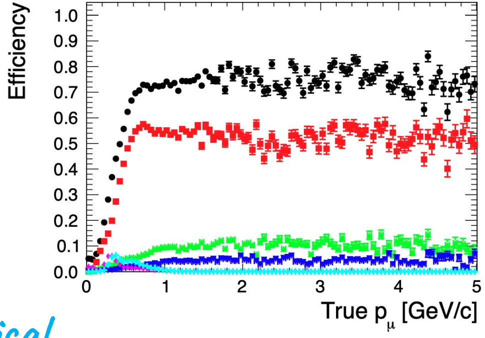

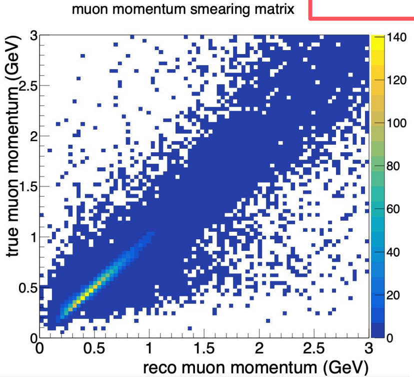

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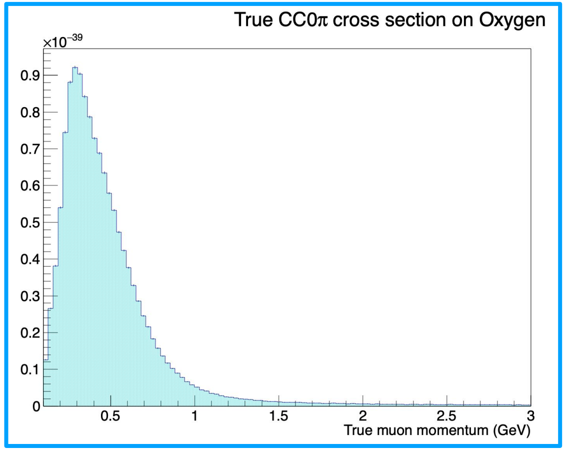

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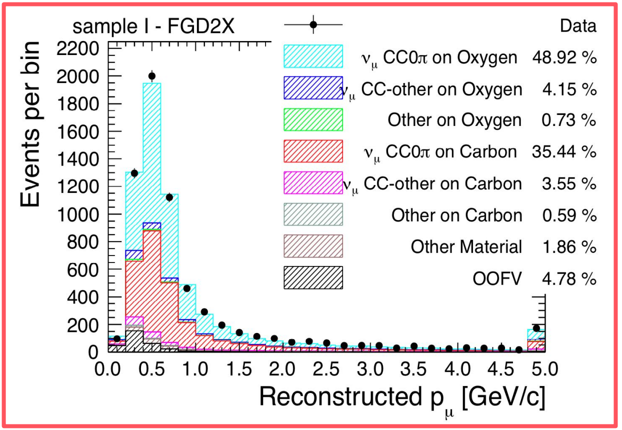

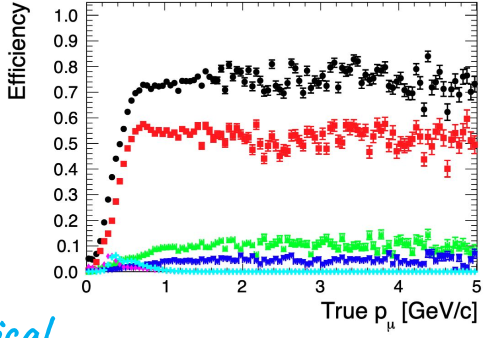

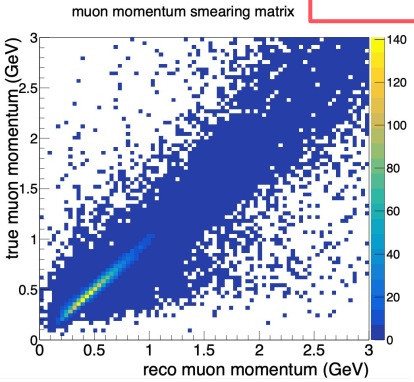

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UNFOLDING

the detector effects

Reconstructed space (the one accessible with the detector).

Several unfolding methods exist

1. Iterative D’Agostini unfolding (favorite method by MINERVA collab)
   https://arxiv.org/abs/1010.0632

2. Wiener Singular Value Decomposition (favorite one by MicroBooNE collab)
   https://doi.org/10.1088/1748-0221/12/10/P10002

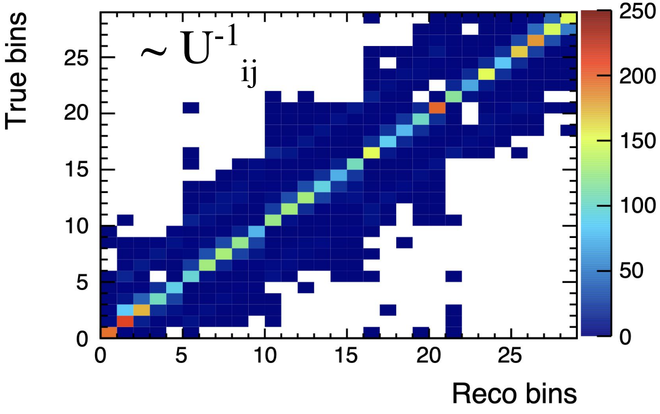
3. Likelihood fitting (favorite one by T2K collab)
   Phys. Rev. D 101, 112004 (2020)

All facing the same (ill-posed) problems

no time to cover here,
see L. Koch for a recap

Also new methods under development based on Machine Learning techniques :
Omnifold Phys. Rev. Lett. 124, 182001 (2020)

Unfolding via likelihood fitting (in a nutshell)



Essentially you want to export you measurement from the reco to the truth space: you need to unfold the detector effects

Num. of background events in the true bin i according to the MC

Smearing matrix to move from the truth to the reco bins

$$N_j^{\mathrm{reco}} = \sum_i^{\text{true bins}} \left[c_i N_i^{\mathrm{sig}} + N_i^{\mathrm{bkg}} \right] U_{ij}^{-1}$$

Num. of reco events in the reco bin j

$\boxed{N_i^{\mathrm{signal}}}$ = what we want to extract

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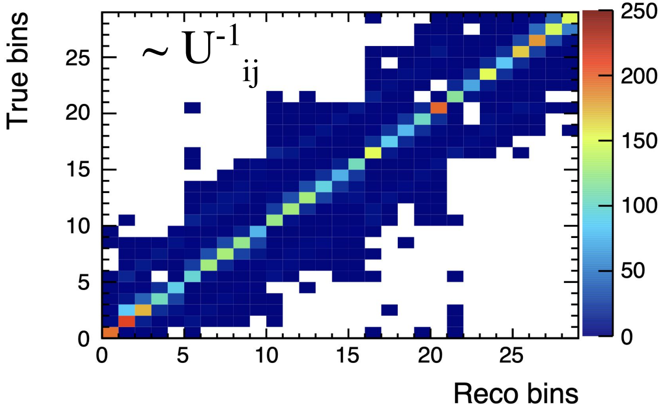

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Standard iterative unfolding requires to know the smearing matrix and essentially invert them to do the unfolding. In the likelihood fitting we don't concretely use a matrix, we leave the fitter to tell us what is the value of c_i

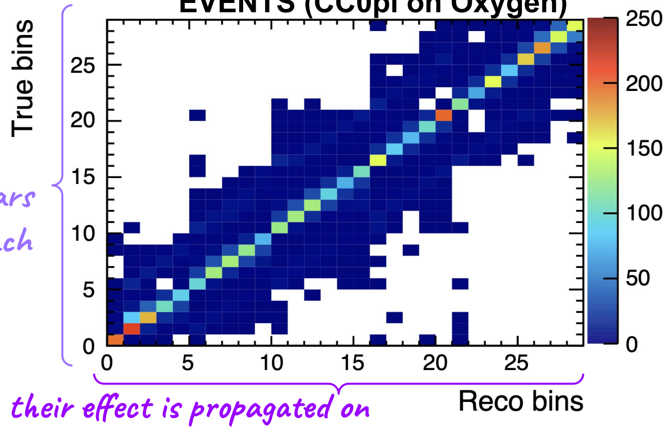
Zoom on the template parameters

Template parameters are **FREE** parameters that rescale the MC signal events (eventually corrected by some systematics) and thus they have the dominant effect (wrt the systematics parameters)

There is **one** template parameter **per truth signal bin** (in which you want to extract your cross section)

They thus **apply on the MC truth space and on MC truth bins of signal events** but they try **to adjust the data/MC agreement in the reco space** (the one that we really measure) ⇒ we don't explicitly use a matrix

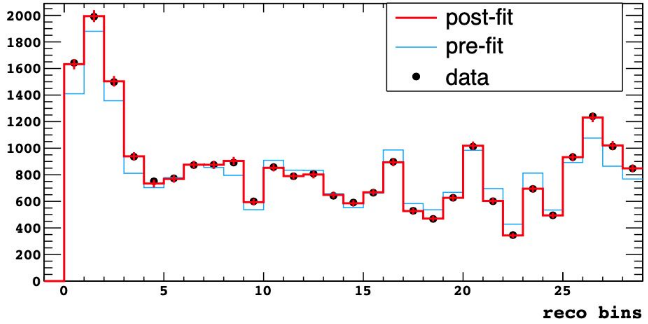
Condensed true vs reco bins matrix for SIGNAL EVENTS (CC0pi on Oxygen)



template pars apply on each true bin

their effect is propagated on relevant reco bin(s)

RECO SPACE



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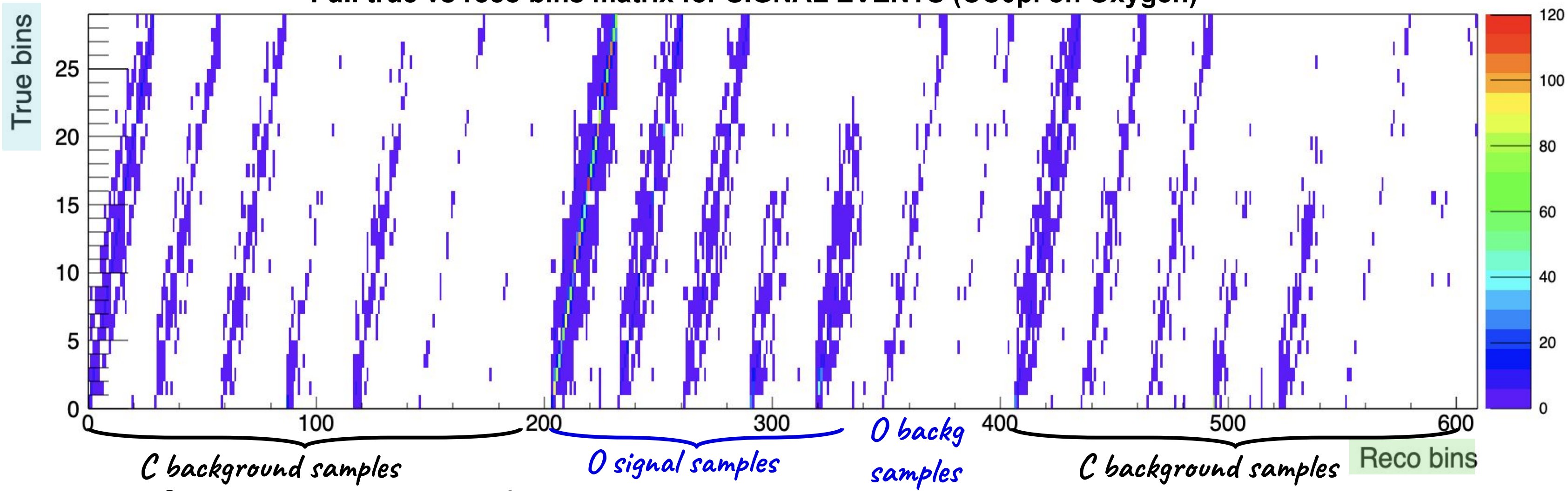
Data/MC correction, aka template parameters

Smearing matrix to move from the truth to the reco bins

Zoom on the template parameters

from O and C CC0pi analysis

Full true vs reco bins matrix for SIGNAL EVENTS (CC0pi on Oxygen)

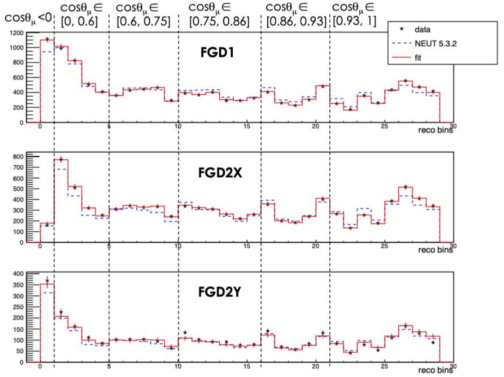


C background samples

O signal samples

O backg samples

C background samples



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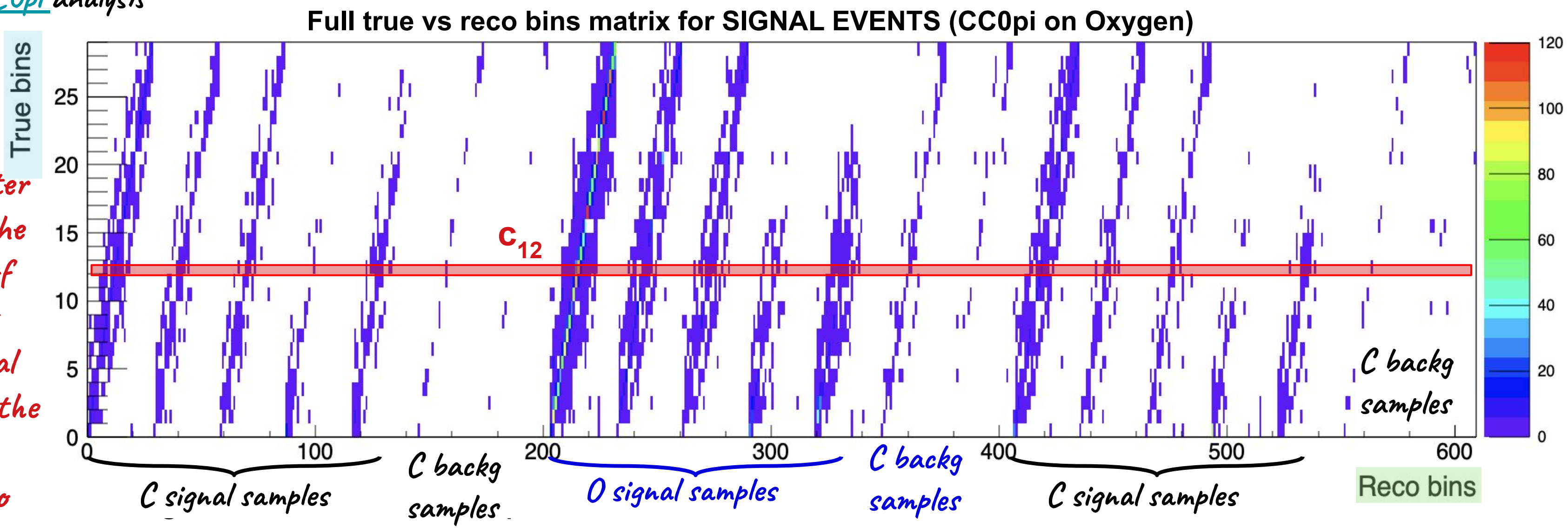
from O and C CC0pi analysis

Moving parameter c_{12} ⇔ moving the signal content of truth bin 12 ⇔ moving the signal content of ALL the reco bins corresponding to true bin 12 ⇔ agreement with data is checked in the reco space over all the reco bins depending on true bin 12



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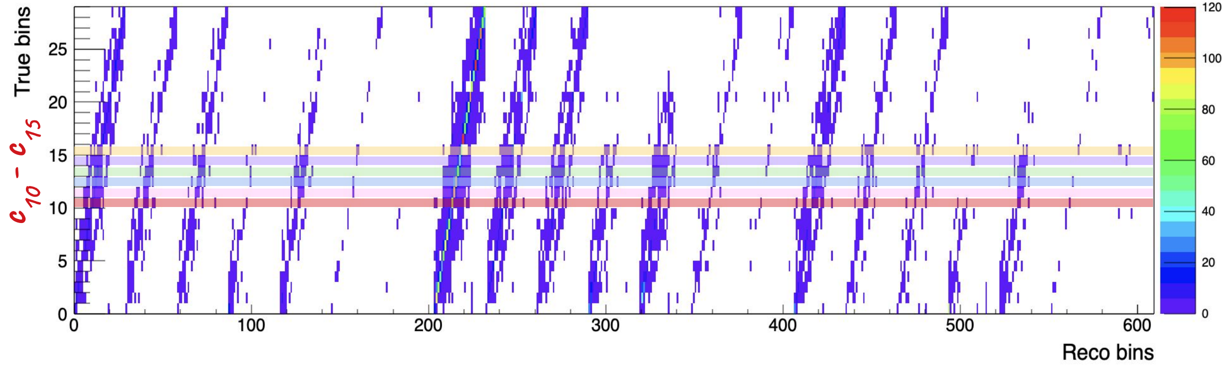
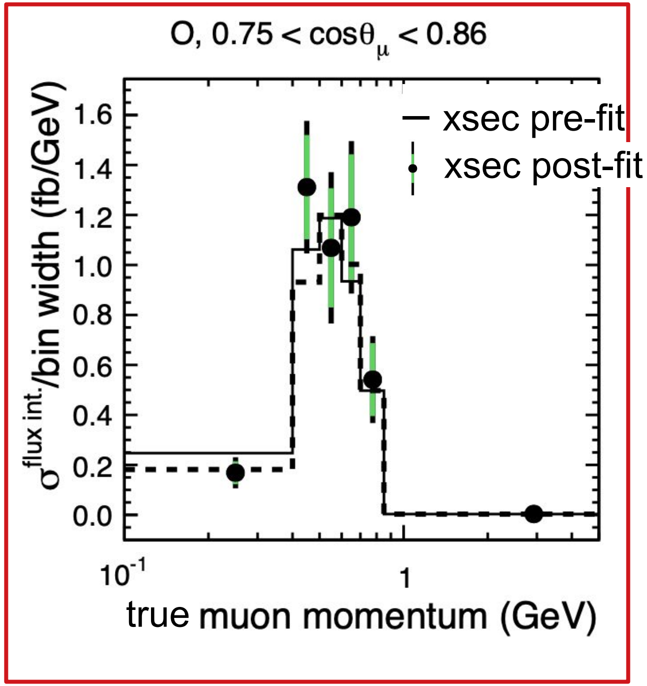


TRUE SPACE



xsec post-fit ~ c_i * (xsec pre-fit)

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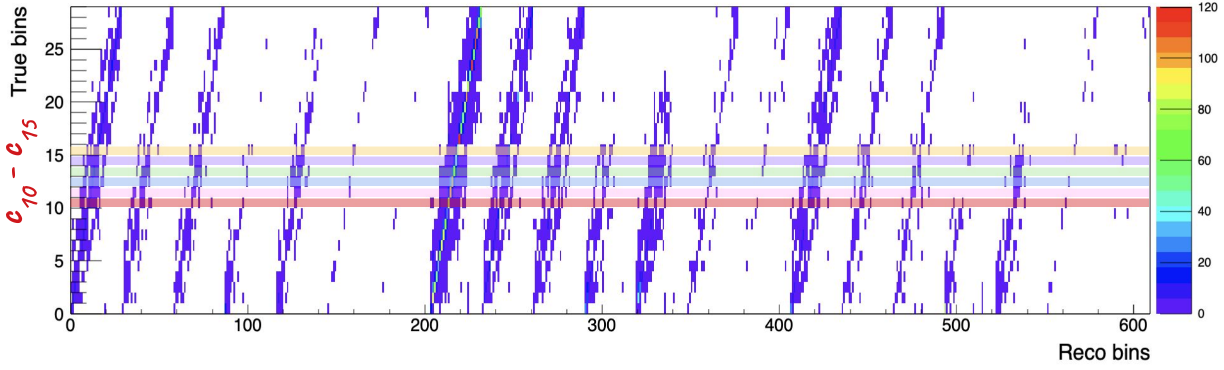

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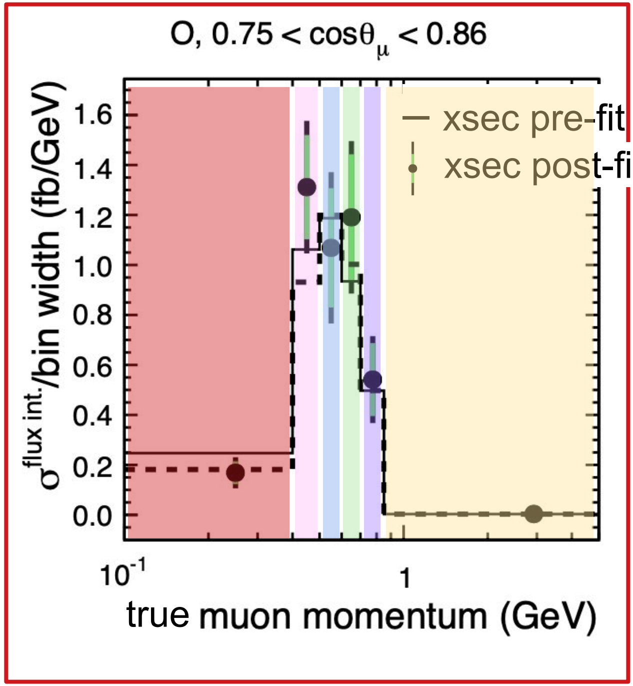

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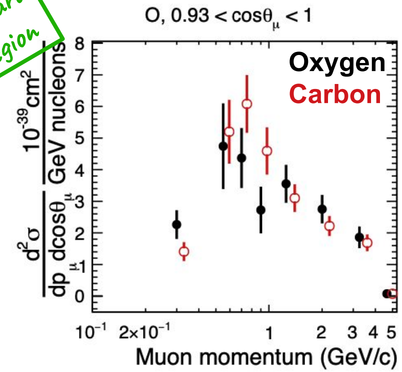
How neutrino cross section measurements help reducing cross section systematics in neutrino oscillation experiments?

How these measurements are used?

exemple from recent T2K developments

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

forward region



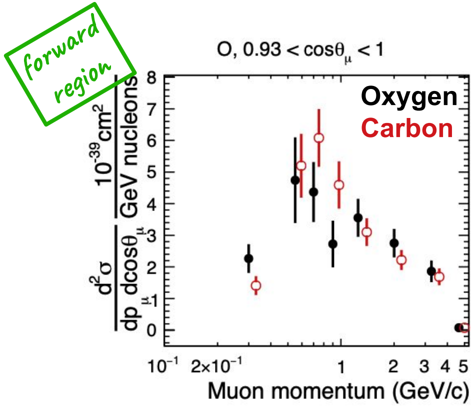
Phys. Rev. D 101, 112004 (2020)

Other previous tuning examples: MINERvA, MicroBooNE, NOvA

How these measurements are used?

exemple from recent T2K developments

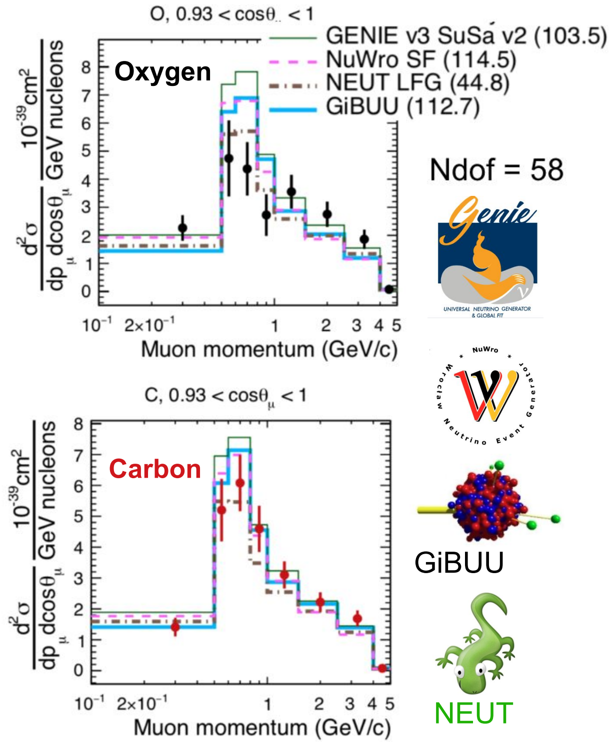
Simultaneous 2D CC0π measurement on O and C @ND280 in p_μ and $\cos\theta_\mu$



Phys. Rev. D 101, 112004 (2020)

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

Phys. Rev. D 101, 112004 (2020)



Ndof = 58

GiBUU

NEUT

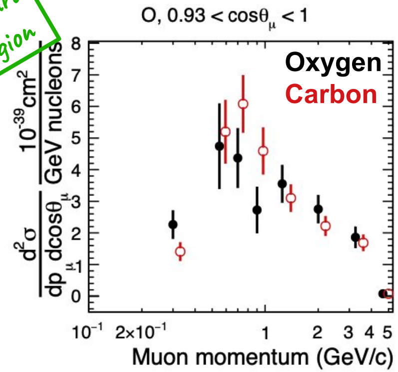
Other previous tuning examples: MINERvA, MicroBooNE, NOvA

How these measurements are used?

exemple from recent T2K developments

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

forward region



Phys. Rev. D 101, 112004 (2020)

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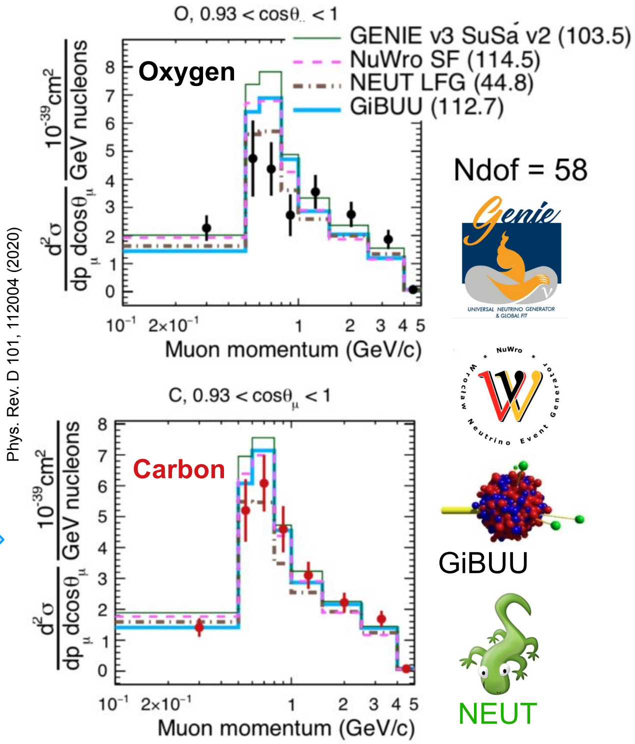
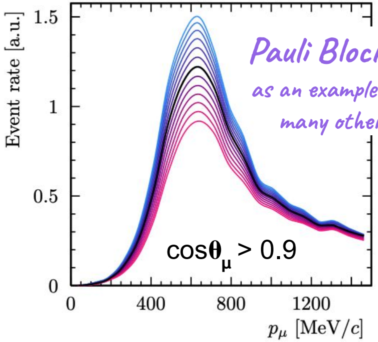


clear disagreement with most sophisticated nuclear model in this region

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

Phys. Rev. D 109, 072006 (2024)



Example: Pauli blocking is simply modeled in our MC, but more complex models exist → introduce freedom to our PB model

Other previous tuning examples: MINERvA, MicroBooNE, NOvA

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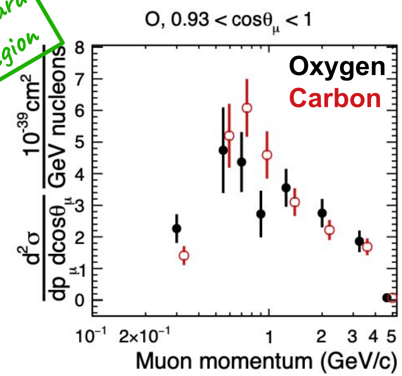
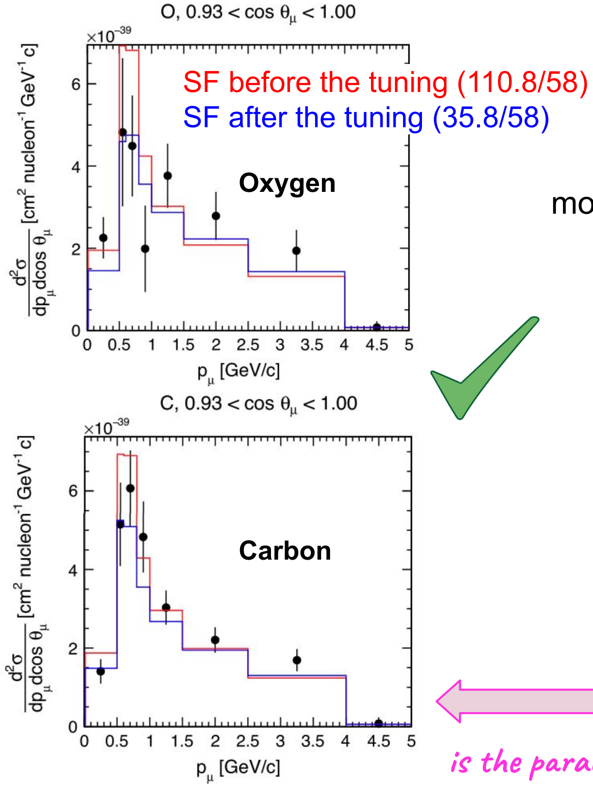


Phys. Rev. D 101, 112004 (2020)



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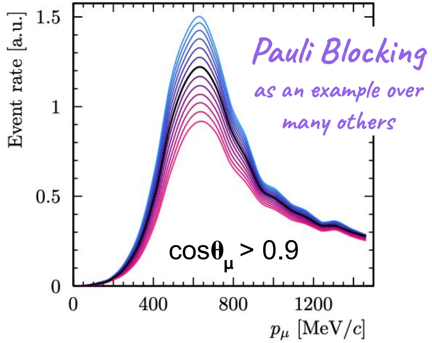
Phys. Rev. D 109, 072006 (2024)



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

Other previous tuning examples: MINERvA, MicroBooNE, NOvA

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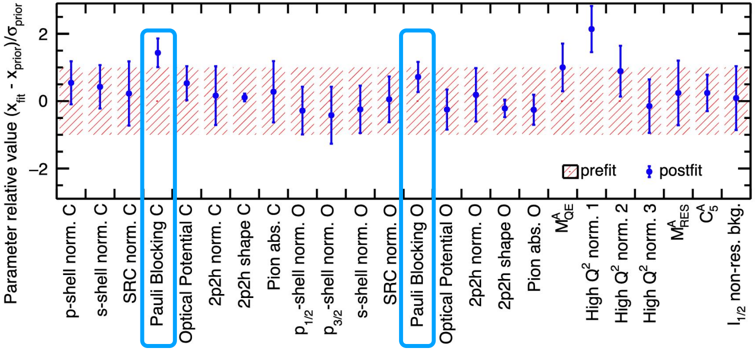
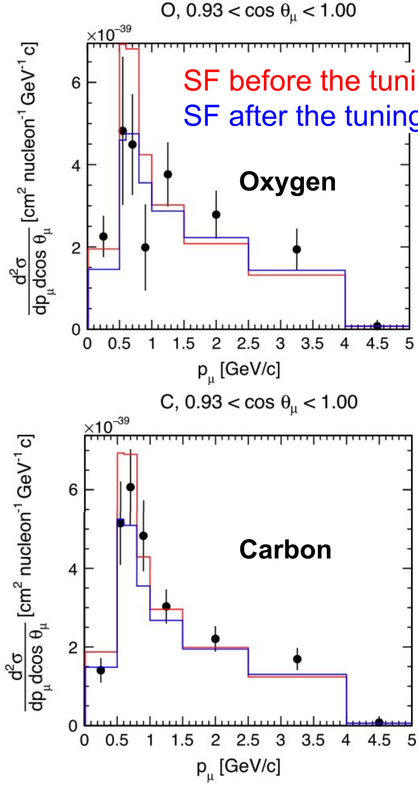
exemple from recent T2K developments

The post tuning agreement is obtained thanks to a fit where we make the SF models to move according to a series of systematics parameters, including PB



Pauli Blocking has significantly moved, in order to recover the data/MC agreement in the forward region

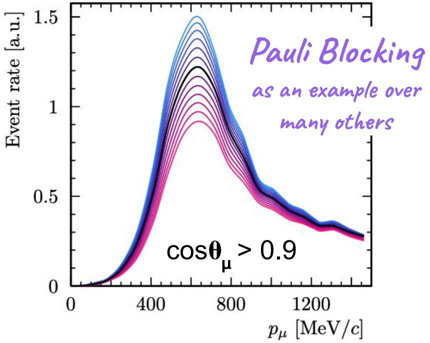


SF before the tuning (110.8/58)

SF after the tuning (35.8/58)

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

Phys. Rev. D 109, 072006 (2024)



Pauli Blocking
as an example over many others

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

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

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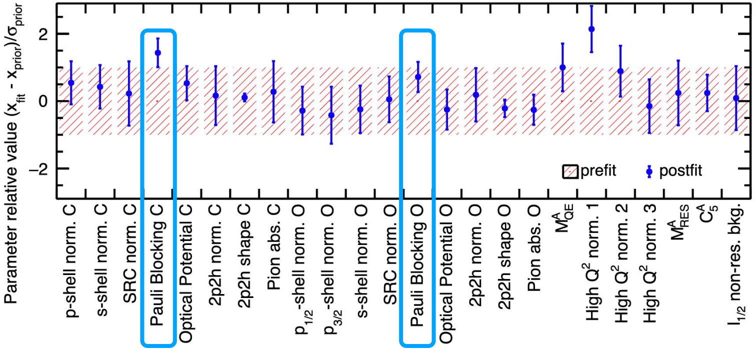

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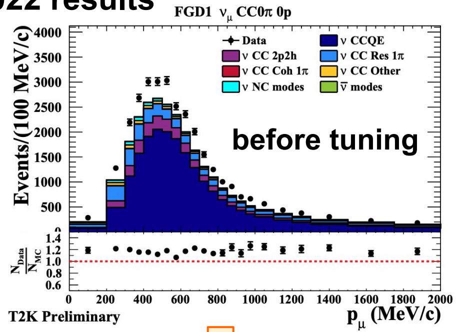
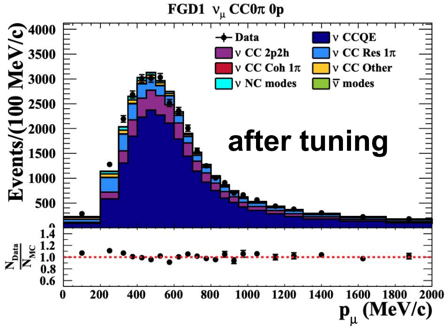
Near Detector: 2022 results





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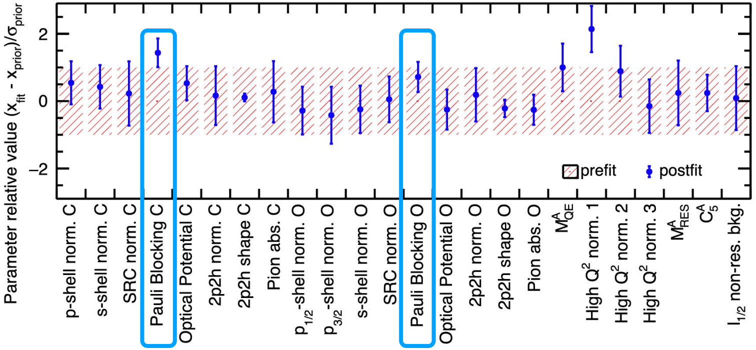

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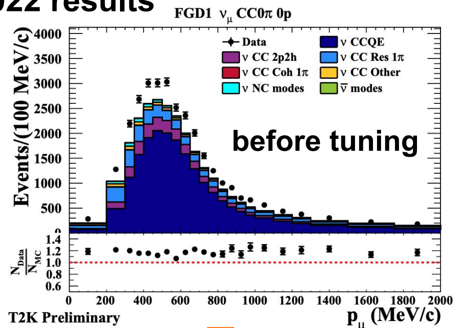
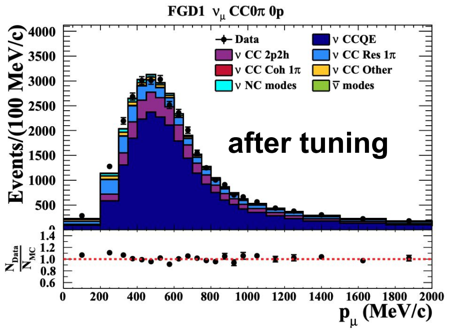
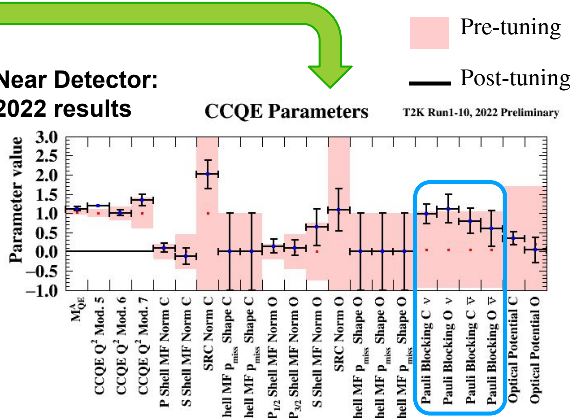


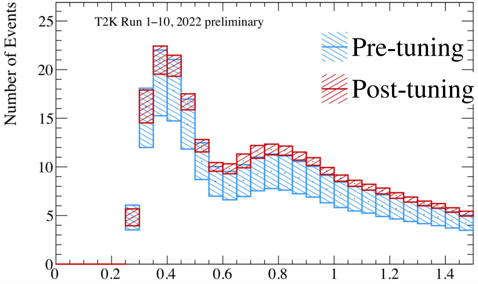


The **tuned model is used to predict the spectra at the far detector SK:** reduced error bars and modified shape/norm

Near Detector: 2022 results



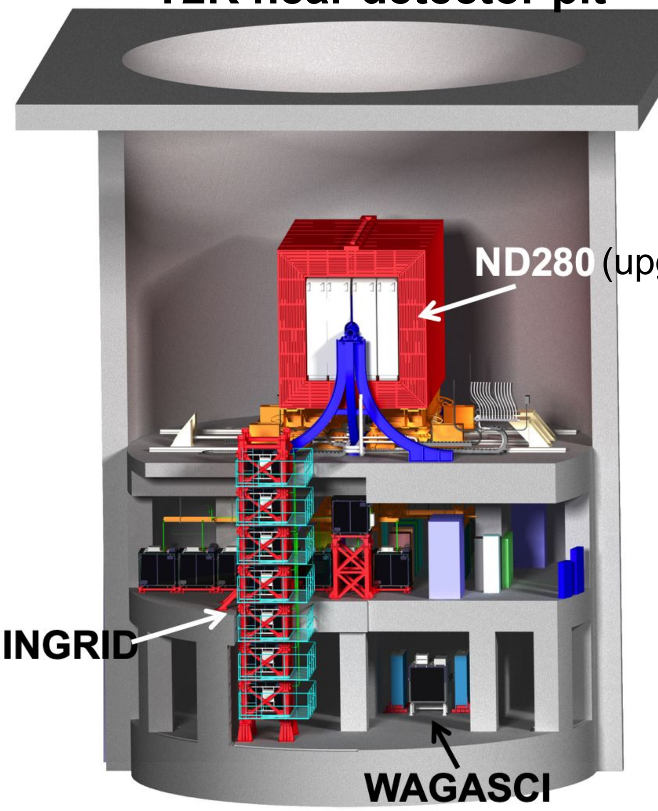
Far Detector predictions

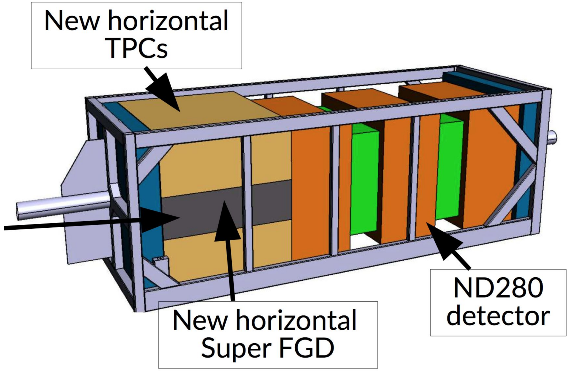


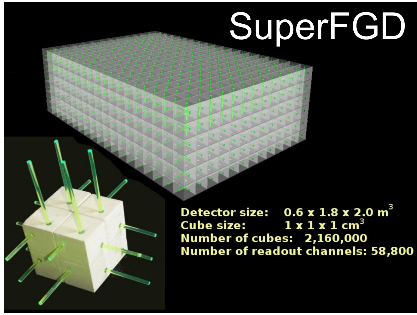
Future perspectives

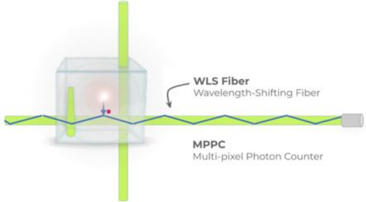
ND280-Upgrade and the Super-FGD

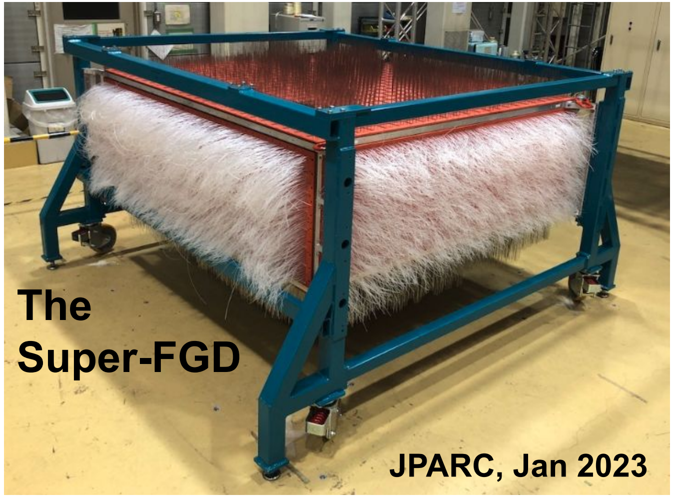
T2K near detector pit





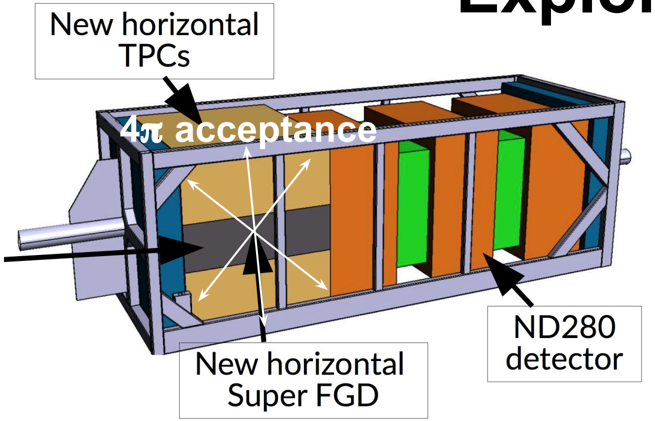


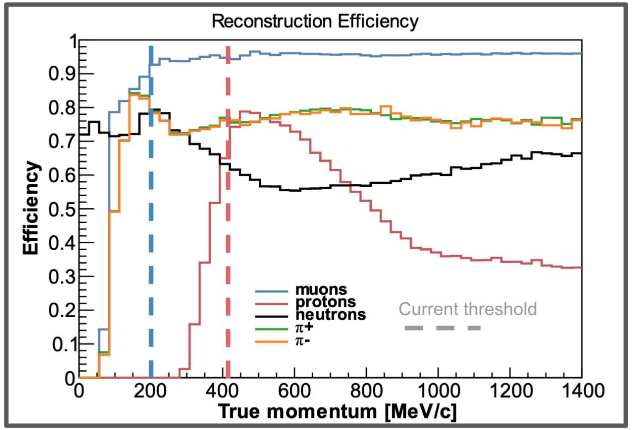




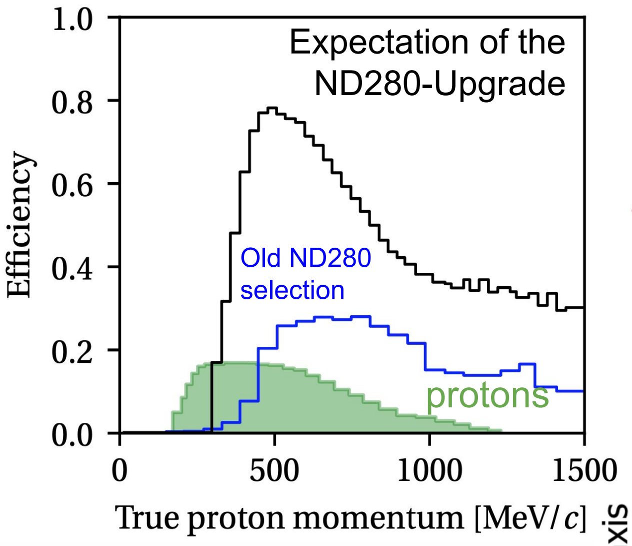
Super-FGD: 192 × 192 × 56 scintillator cubes (2 million) with 3D readout => 2 tons of fully active target

Exploiting the ND280-Upgrade capabilities

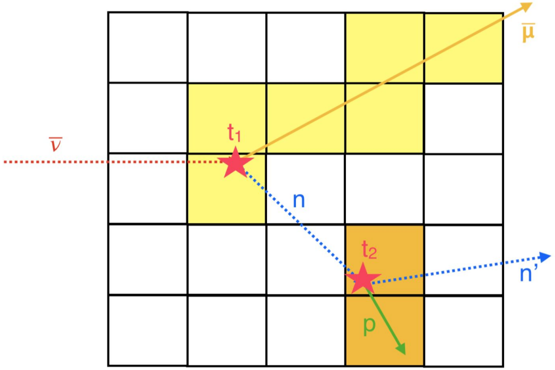




Updated version of plot from [Phys. Rev. D 105, 032010](#) (by **Noë Roy**)

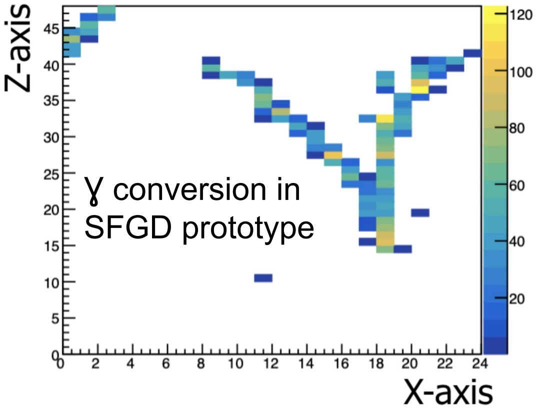


Neutron detection concept



Phys. Rev. D 101, 092003 (2020)

- \+ **Acceptance!**
- \+ **Protons!**
- \+ **Pions!**
- \+ **Neutrons!**
- \+ **better ν_e reco!**



ɣ conversion in SFGD prototype

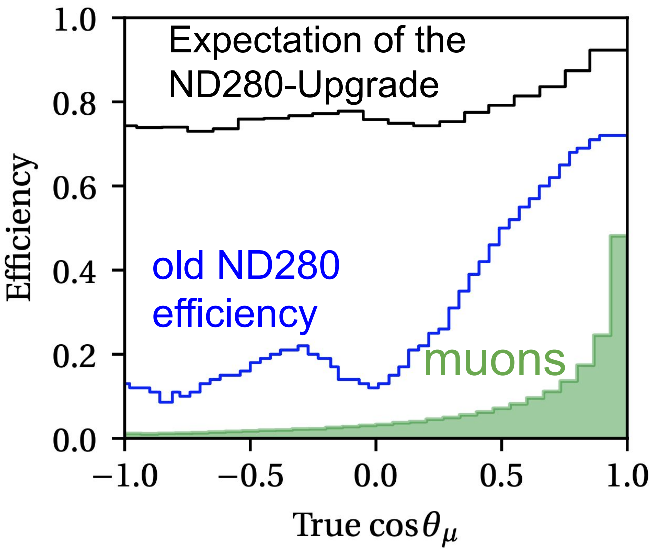
Measuring high angle muons

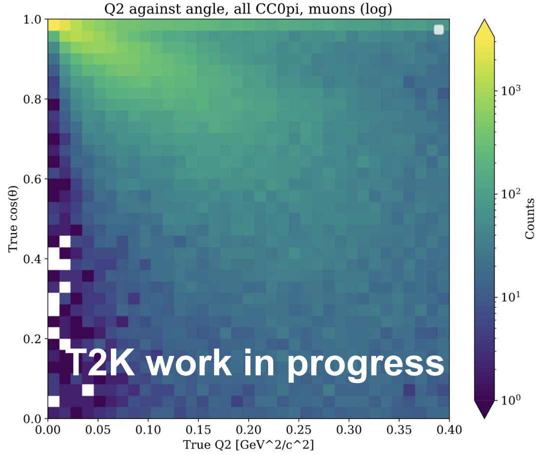
Expected almost flat efficiency in cosθ from -1 to 1 with the ND280 Upgrade

detecting higher angle muons

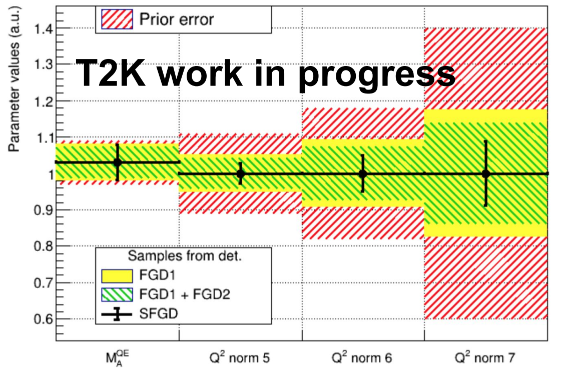
~ exploring higher Q^2 regions

~ better characterize the form factor models (as a function of Q^2)





From JB Plancon

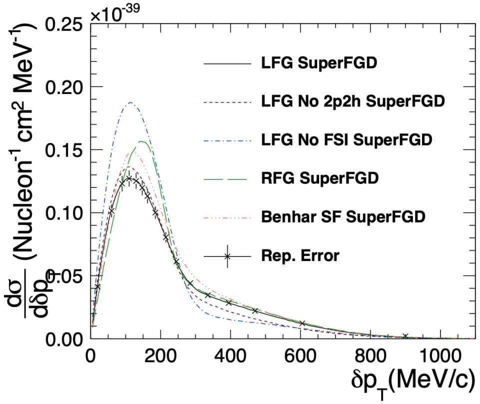


From S. Joshi

CC0pi selection

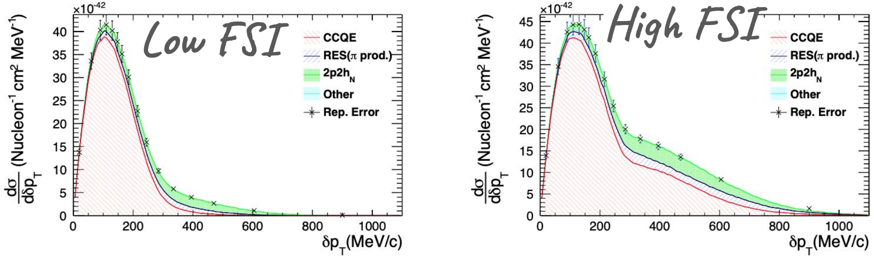
Upgrade TDR

Measuring low momentum protons



Discrimination of nuclear models on CH!

Even better when 2D approach is used



Low FSI

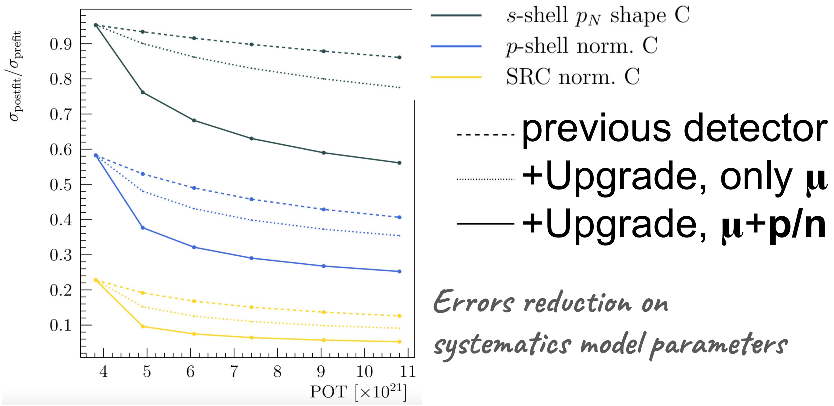
High FSI

(a) LFG - Low $\delta\alpha_T$

(b) LFG - High $\delta\alpha_T$

`Phys. Rev. D 101, 092003 (2020)`

TKI like variables (including Evis) are also good candidates for the model tuning



previous detector

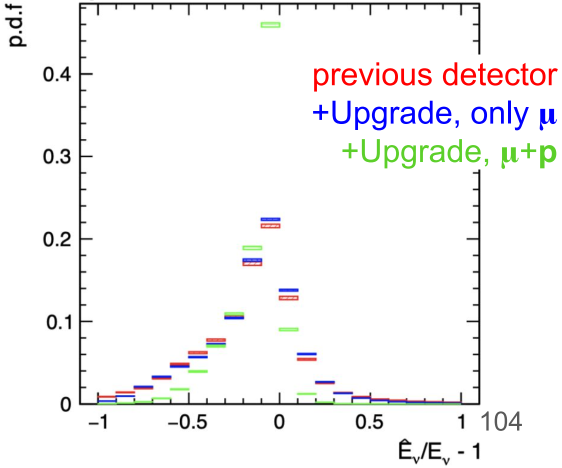
+Upgrade, only μ

+Upgrade, μ+p/n

Errors reduction on systematics model parameters

Better reconstruction of the final state = expected improvements in characterising CCQE and 2p2h interactions

@ ~ 11x10^{21} POT

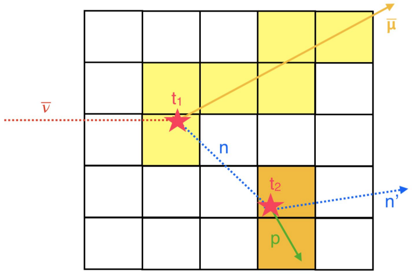


previous detector

+Upgrade, only μ

+Upgrade, μ+p

Measuring neutrons

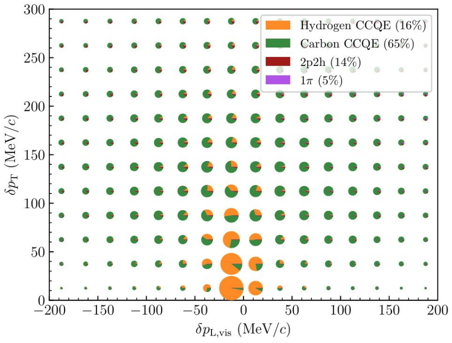


Phys. Rev. D 101, 092003 (2020)

With time of flight techniques it is possible to reconstruct also the **neutron momentum** → better characterisation of the final state. But also possible to measure **δ**p_T

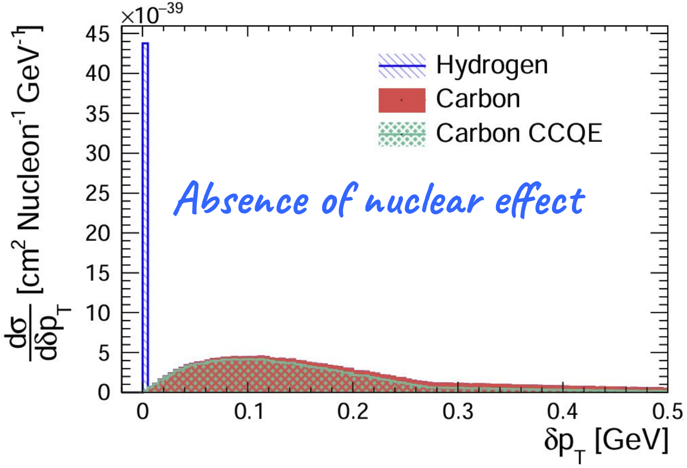
Possible to isolate interactions on free protons applying cuts on **δ**p_T

$$\delta p_{\mathrm{T}} = |\overrightarrow{p}^{l}_{T} + \overrightarrow{p}^{n}_{T}|$$



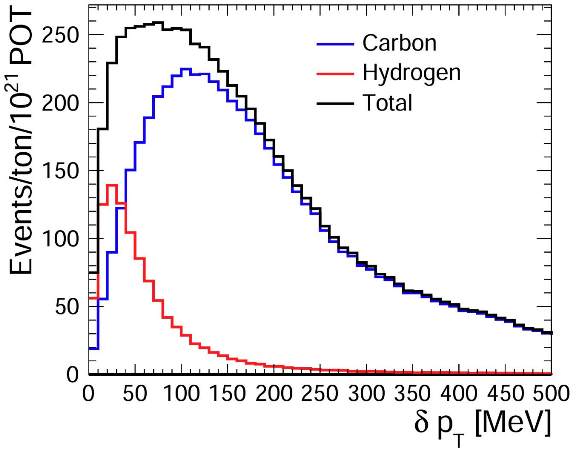
Phys. Rev. D 110, 032019 (2024)

True CCQE (T2K simulation)



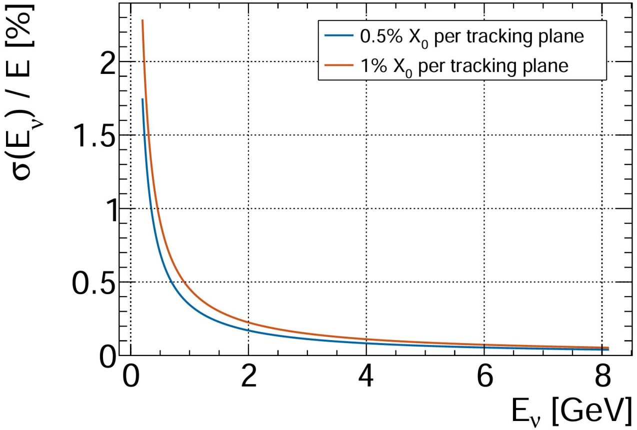
Absence of nuclear effect

Reco CC0π (T2K simulation)

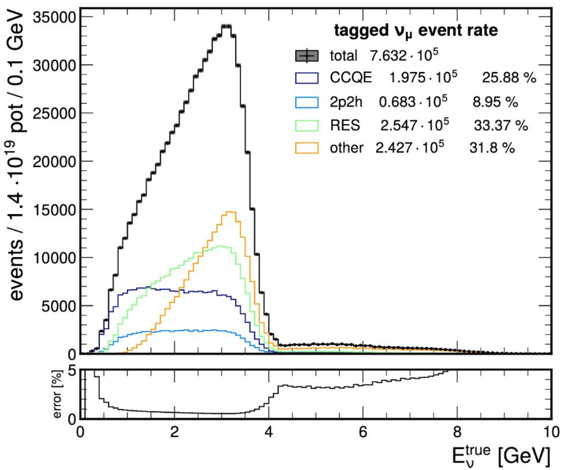


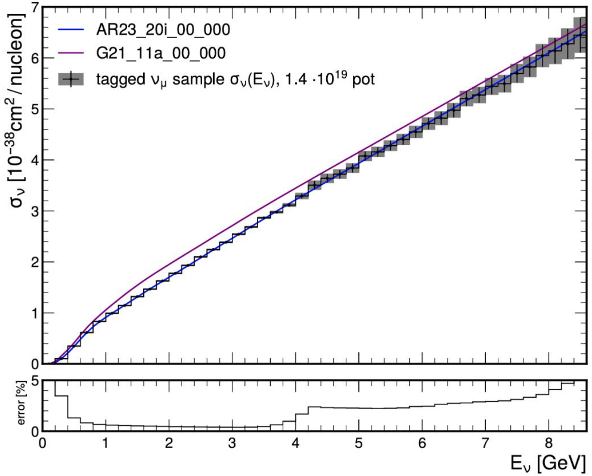
Possible better measurement of $F_A(Q^2)$

Prospect with a tagged neutrino beam @CERN (NuSCOPE)



With a tagged neutrino beam we should be able to know the neutrino energy BEFORE the interaction → major breakthrough since for **the first time we could be able to measure neutrino xsec as a function of E_ν !!**





See back Mathieu's lecture

arXiv:2503.21589

Final thoughts

- 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
- Impressive progresses in recent years, the community has grown and learned a lot of things
- Also, new measurements from other experiments will come soon: ICARUS, SBND, ArgonCube (Argon), the ND280-Upgrade (CH), NINJA (water et al), Annie (water), nuSCOPE (?)
- Still many things to do from both the experimental and the theoretical point of view
- 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

A typical ν oscillation experiment

Oscillation experiments require to know $\boxed{\Phi(E_\nu)}$, $\boxed{\sigma(E_\nu,\overline{x})}$ & $\boxed{D(\overline{x})}$…
simplified version:

$$\frac{N^{far}_{events}(\vec{x})}{N^{near}_{events}(\vec{x})} =$$

A typical ν oscillation experiment

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simplified version:

Oscillation probability depends on true E_ν

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

A typical ν oscillation experiment

Oscillation experiments require to know $\boxed{\Phi(E_\nu)}$, $\boxed{\sigma(E_\nu,\overline{x})}$ & $\boxed{D(\overline{x})}$… simplified version:

Cross-sections relate E_ν and observables; do not cancel in the ratio

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ν beam is not monochromatic

A typical ν oscillation experiment

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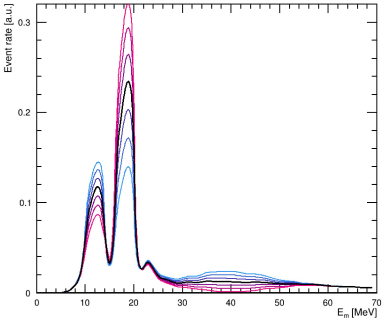
ν beam is not monochromatic

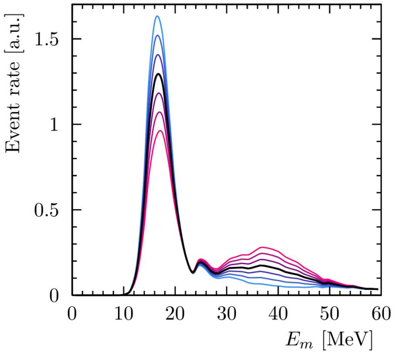
Detector effects
(efficiency, acceptance, target, resolution)

Near/far ratios don't fully cancel systematics:

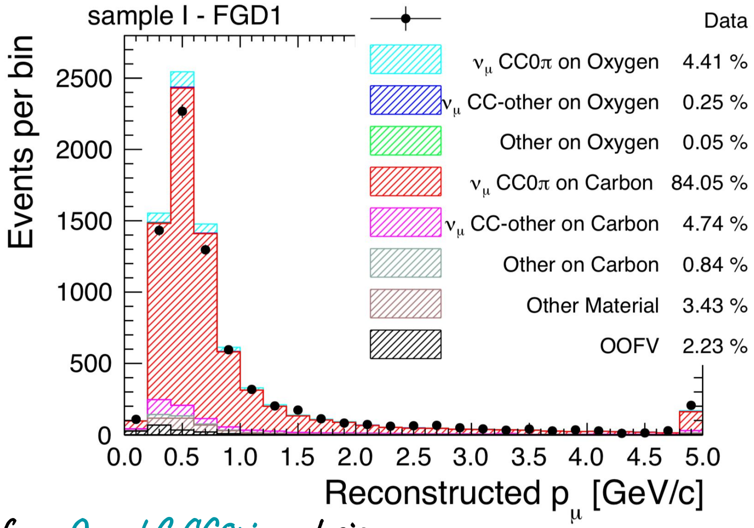
- $\Phi(E_\nu)$ change due to geometry and oscillation
- Acceptance, efficiency and targets different in the 2 detectors (near and far)
- ND is ν_μ dominated, but used to infer (via model) ν_e

Delicate analysis!


Event rate [a.u.]
0.3
0.2
0.1
0
0
10
20
30
40
50
60
70
E$_m$ [MeV]


Event rate [a.u.]
1.5
1
0.5
0
0
10
20
30
40
50
60
E_m [MeV]

What are the info contained in the reco bins?



from O and C CC0pi analysis

We usually have several reconstructed signal samples as well as several reconstructed background samples

We usually bin reconstructed events in well reconstructable observables (like $\cos\theta_\mu$ and/or p_μ), that are also the variable we could use to extract the cross section

In a reconstructed CC0π ($\cos\theta_\mu$, p_μ) bin (j) we have N_j reco events:

Num. of background events in the true bin i according to the MC

$$N_j^{\text{reco}} = \sum_i^{\text{true bins}} \left[\underbrace{c_i w_i^{\text{signal}} N_i^{\text{signal}}}_{\boxed{N_i^{\text{signal}}}} + w_i^{\text{bkg}} N_i^{\text{bkg}} \right] U_{ij}^{-1}$$

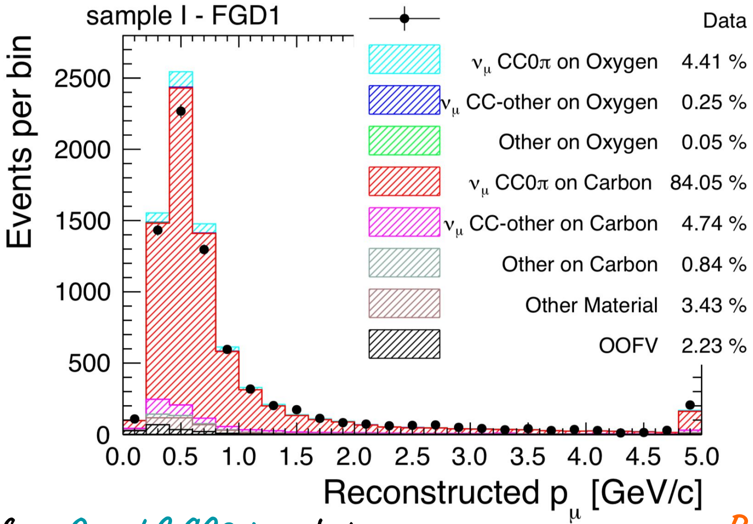
Num. of reco events in the reco bin j and sample s

= what we want to extract

Reweight due to the systematics effect

Smearing matrix to move from the truth to the reco bins

What are the info contained in the reco bins?



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Num. of signal events in the true bin i according to the MC

Num. of background events in the true bin i according to the MC

$$N_j^{\text{reco}} = \sum_i^{\text{true bins}} \left[\underbrace{c_i w_i^{\text{signal}} N_i^{\text{signal}}} + w_i^{\text{bkg}} N_i^{\text{bkg}} \right] U_{ij}^{-1}$$

Num. of reco events in the reco bin j and sample s

$\boxed{\mathrm{N}_{\mathrm{i}}^{\text{signal}}}$ = what we want to extract

Reweight due to the systematics effect

Smearing matrix to move from the truth to the reco bins

Zoom on the template parameters

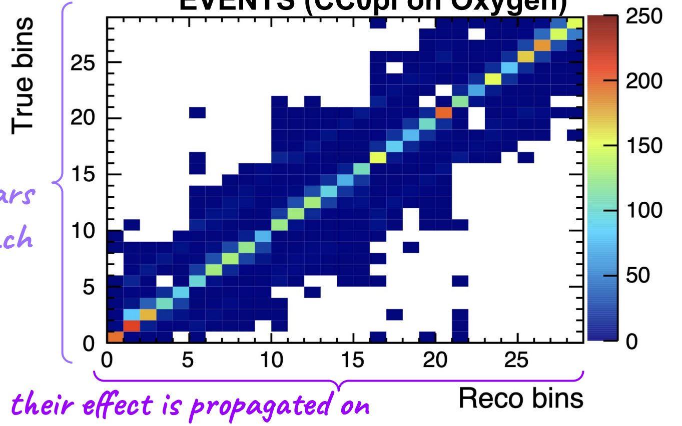
Template parameters ARE the **parameters of interest** in our xsec analyses

They are **FREE** parameters that rescale the MC signal events (eventually corrected by some systematics) and thus they have the dominant effect (wrt the systematics parameters)

There is **one** template parameter **per truth signal bin** (in which you want to extract your cross section)

They thus **apply on the MC truth space and on MC truth bins of signal events** but they try **to adjust the data/MC agreement in the reco space** (the one that we really measure)

Condensed true vs reco bins matrix for SIGNAL EVENTS (CC0pi on Oxygen)



template pars apply on each true bin

their effect is propagated on relevant reco bin(s)

$$N_j^{\text{reco}} = \sum_i^{\text{true bins}} \left[c_i w_i^{\text{signal}} N_i^{\text{signal}} + w_i^{\text{bkg}} N_i^{\text{bkg}} \right] U_{ij}^{-1}$$

Num. of reco events in the reco bin j and sample s

Data/MC correction, aka template parameters

Reweight due to the systematics effect

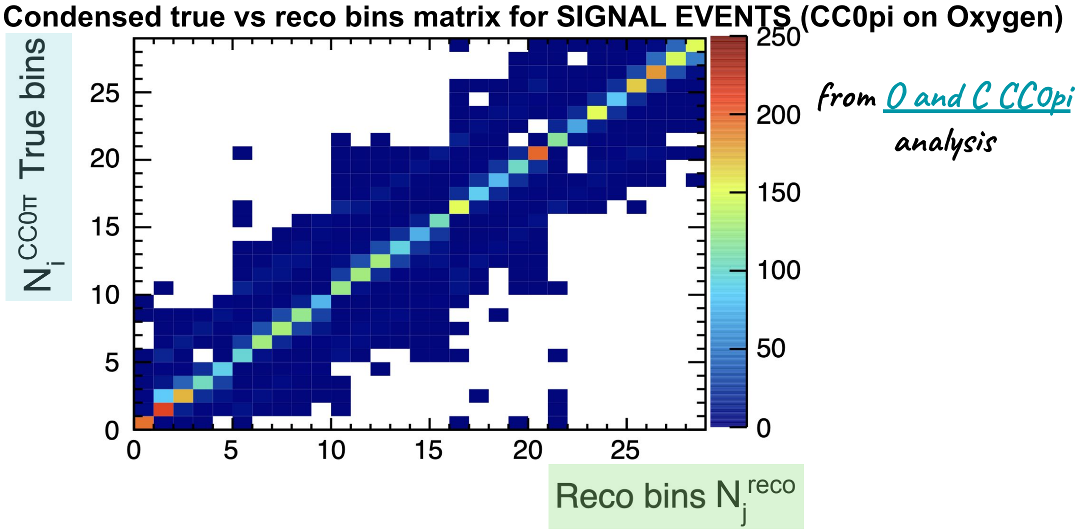
Num. of signal events in the true bin i according to the MC

Reweight due to the systematics effect

Num. of background events in the true bin i according to the MC

Smearing matrix to move from the truth to the reco bins

Zoom on the template parameters



from O and C CC0pi analysis

$$N_j^{\mathrm{reco}} = \sum_{i}^{\text{true bins}} \left[c_i w_i^{\mathrm{signal}} N_i^{\mathrm{signal}} + w_i^{\mathrm{bkg}} N_i^{\mathrm{bkg}} \right] U_{ij}^{-1}$$

Num. of reco events in the reco bin j and sample s

Reweight due to the systematics effect

Num. of signal events in the true bin i according to the MC

Num. of background events in the true bin i according to the MC

Data/MC correction, aka template parameters

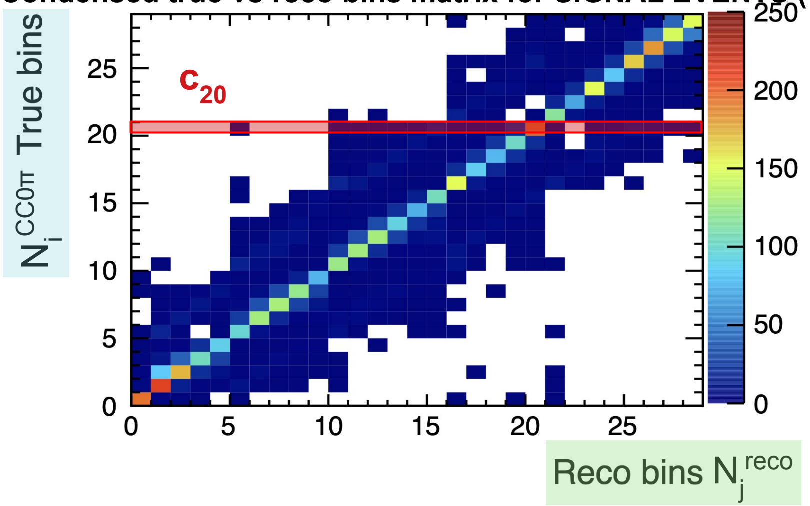
Reweight due to the systematics effect

Smearing matrix to move from the truth to the reco bins

Zoom on the template parameters

Moving parameter c_{20} ⇔ moving the signal content of truth bin 20 ⇔ moving the signal content of ALL the reco bins corresponding to true bin 20 ⇔ agreement with data is checked in the reco space

Condensed true vs reco bins matrix for SIGNAL EVENTS (CC0pi on Oxygen)



from O and C CC0pi analysis

Reweight due to the systematics effect

Num. of signal events in the true bin i according to the MC

Num. of background events in the true bin i according to the MC

$$N_j^{\text{reco}} = \sum_i^{\text{true bins}} \left[c_i w_i^{\text{signal}} N_i^{\text{signal}} + w_i^{\text{bkg}} N_i^{\text{bkg}} \right] U_{ij}^{-1}$$

Num. of reco events in the reco bin j and sample s

Data/MC correction, aka template parameters

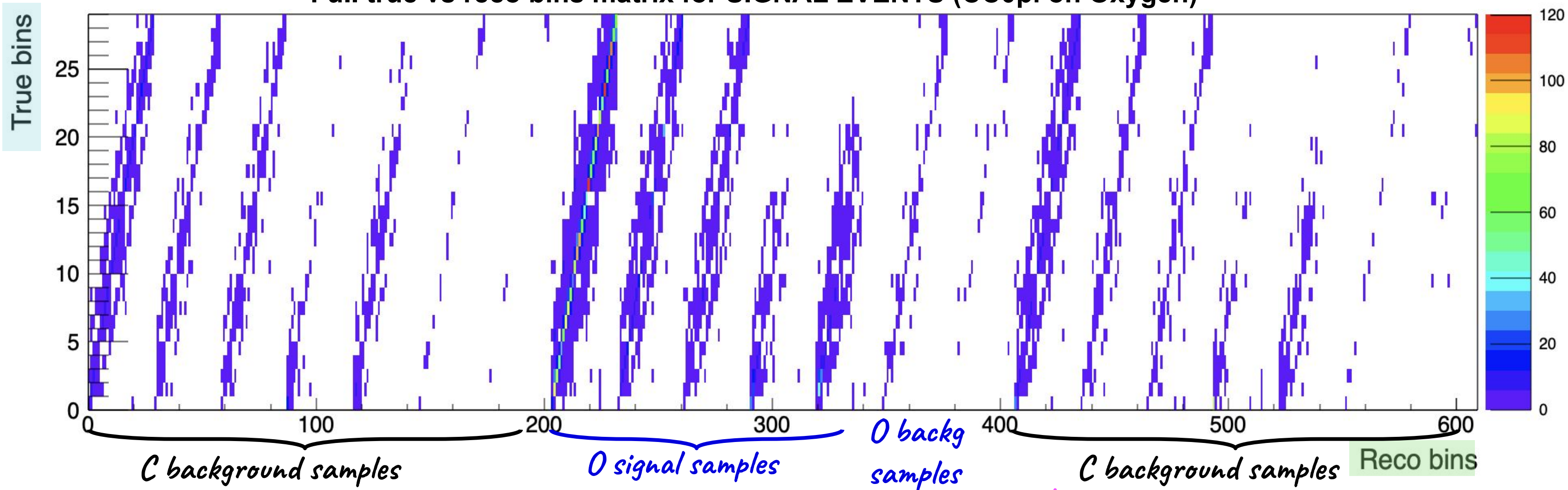
Reweight due to the systematics effect

Smearing matrix to move from the truth to the reco bins

Zoom on the template parameters

from O and C CC0pi analysis

Full true vs reco bins matrix for SIGNAL EVENTS (CC0pi on Oxygen)



$$N_j^{\mathrm{reco}} = \sum_i^{\text{true bins}} \left[c_i w_i^{\mathrm{signal}} N_i^{\mathrm{signal}} + w_i^{\mathrm{bkg}} N_i^{\mathrm{bkg}} \right] U_{ij}^{-1}$$

Num. of reco events in the reco bin j and sample s

Reweight due to the systematics effect

Num. of signal events in the true bin i according to the MC

Num. of background events in the true bin i according to the MC

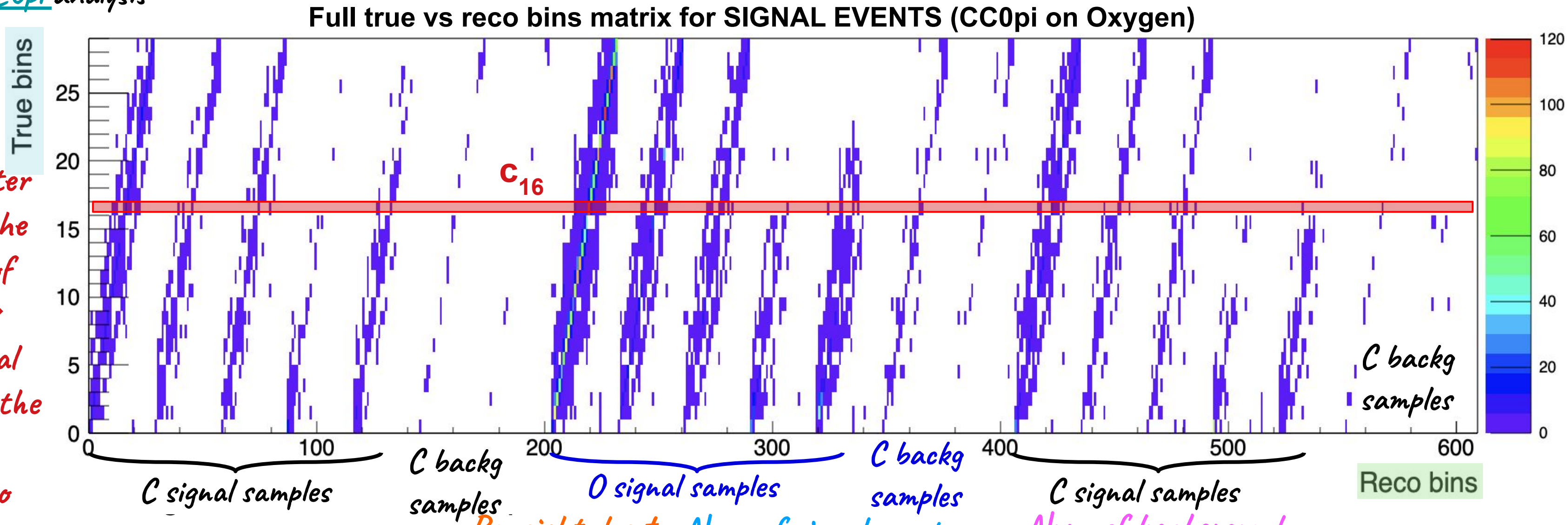
Data/MC correction, aka template parameters

Reweight due to the systematics effect

Smearing matrix to move from the truth to the reco bins

Zoom on the template parameters

from O and C CC0pi analysis


Full true vs reco bins matrix for SIGNAL EVENTS (CC0pi on Oxygen)

Moving parameter c_{16} ⇔ moving the signal content of truth bin 16 ⇔ moving the signal content of ALL the reco bins corresponding to true bin 16 ⇔ agreement with data is checked i the reco space

Reweight due to the systematics effect

Num. of signal events in the true bin i according to the MC

Num. of background events in the true bin i according to the MC

$$N_j^{\text{reco}} = \sum_i^{\text{true bins}} \left[c_i w_i^{\text{signal}} N_i^{\text{signal}} + w_i^{\text{bkg}} N_i^{\text{bkg}} \right] U_{ij}^{-1}$$

Num. of reco events in the reco bin j and sample s

Data/MC correction, aka template parameters

Reweight due to the systematics effect

Smearing matrix to move from the truth to the reco bins