Overview of NIWG uncertainties

(S.Bolognesi CEA)

- Summary of (largest) xsec uncertainties for Neutrino 2020
- Interplay and connections with xsec measurements

Introduction

- **Fitting ND data for the Oscillation Analysis (OA) and measuring a xsec with ND** data are two very different analyses

- But they share some of the systematic uncertainties, notably regarding the nu-nucleus interaction model

  ⇨ **work on NIWG syst** is useful for both xsec measurements and ND data fit

- Final aim is the same: falsify / tune / guide the development of nu-nucleus xsec models:

  - for xsec measurement this should be (at least part of) the original motivation of the analysis

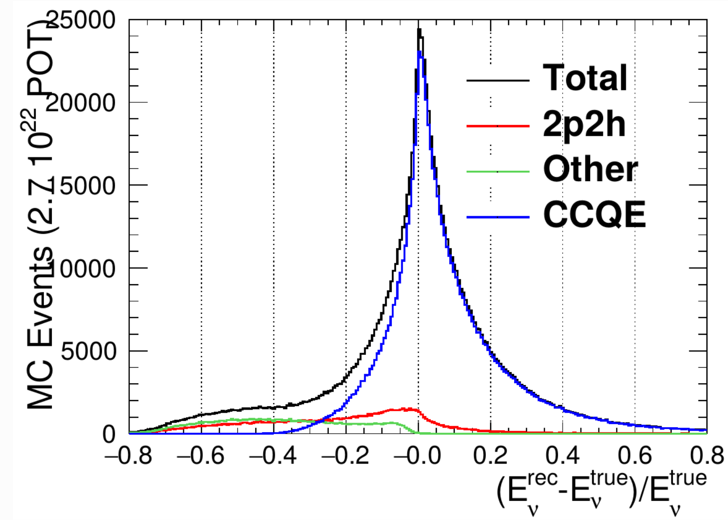
    ⇨ some xsec analyses can be particularly useful (see **xsec strategy document**)

  - for xsec measurement this happens 'after the fact' **(measurement-models comparisons)**

The ND data fit for the OA

- **Measurement at ND:**

$$N^{ND}_{\nu_\alpha}(E^{reco}_\nu) \approx \int \phi^{ND}_{\nu_\alpha}(E_\nu) \times \sigma^{ND}_{\nu_\alpha}(E_\nu) \times F_{theo}(E^{reco}_\nu - E_\nu)\, dE_\nu$$



$$\overline{E_\nu} = \frac{m_p^2 - (m_n - E_b)^2 - m_\mu^2 + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu cos\,\theta_\mu)}$$

Need a good xsec model in order to:

- disentangle flux and xsec (degenerate effects on data)
- move from your observables (p_μ, θ_μ -> E_ν^{reco}) to E_ν^{true}

- **Measurement of oscillation by ND → FD extrapolation:**

$$\frac{N^{FD}_{\nu_{\alpha'}}(E^{reco}_\nu)}{N^{ND}_{\nu_\alpha}(E^{reco}_\nu)} \approx \int \boxed{P_{\nu_\alpha \to \nu_{\alpha'}}(E_\nu)} \times \frac{\phi^{FD}_{\nu_{\alpha'}}(E_\nu)}{\phi^{ND}_{\nu_\alpha}(E_\nu)} \times \frac{\sigma^{FD}_{\nu_{\alpha'}}(E_\nu)}{\sigma^{ND}_{\nu_\alpha}(E_\nu)} \times \frac{F_{FD}(E^{reco}_\nu - E_\nu)}{F_{ND}(E^{reco}_\nu - E_\nu)}\, dE_\nu$$

$$\frac{\sigma^{FD}_{\nu_{\alpha'}}(E_\nu)}{\sigma^{ND}_{\nu_\alpha}(E_\nu)}$$

Xsec uncertainties do not cancel completely because of:

different neutrino flavour

different acceptance

$$\frac{F_{FD}(E^{reco}_\nu - E^{vis}_\nu)}{F_{ND}(E^{reco}_\nu - E_\nu)}$$

To maximise cancellation of uncertainties you may want to use same *F*, but **you can 'validate' it with more info available at ND** (eg protons, vertex activity, neutrons) → eg multidimensional ND fit

- **Background subtraction:** NC and intrinsic ν_e is the only 'real' background (all the rest oscillates)

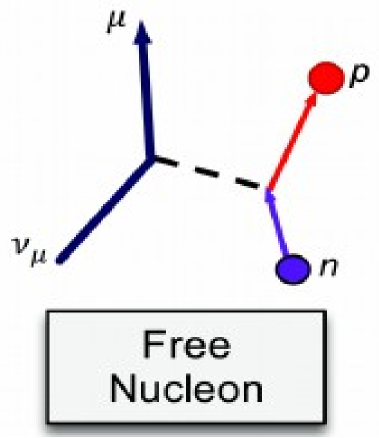
A cross-section measurement

Design the analysis in the most model-independent way:

$$\frac{d\sigma_{f.i.}}{dx_i} = \frac{N_i^{CC0\pi}}{\epsilon_i^{MC}\Phi N_{neutrons}^{FV}} \times \frac{1}{\Delta x_i}$$

- x_i are direct observables in the detector (eg p, θ of μ,π,p and their combinations) and not unfold to 'true' variables (as E_ν^{true})
  (similarly the signal is defined post-FSI: not CCQE but CC0p)
- Flux integrated xsec (i.e. same integrated flux for all bins of x_i) → do not disentangle flux and xsec in the differential measurement
- **Model uncertainties remains in the efficiency corrections and (to second order) in the 'unfolding' of detector effects**
  → define the phase space of your signal as a region of constant, well known and high(ish) efficiency
  → use a clever binning: not too large bins to avoid efficiency variations inside each of them (interesting strategies here have been proposed, notably for multidimensional measurements)
- Background subtraction: analysis-dependent → often a model-dependent fit to control regions (similar to ND fit for OA)

CCQE nucleon-level



Leptonic current $J_\mu = \bar{\nu}_l \gamma_\mu (1-\gamma_5)\, l$

Propagator

$$\approx \frac{1}{Q^2 - M_W^2}, \quad Q^2 \ll M_W^2$$

Where Q^2 is the transferred 4-momentum
$Q^2 = (p_l - p_\nu)^2$

Hadronic current

$$J^\mu = \bar{u}_N \left[\gamma^\mu F_1(Q^2) + \frac{i}{2M_N} \sigma^{\mu\nu} q_\nu F_2(Q^2) + \gamma^\mu \gamma_5 F_A(Q^2) + \frac{1}{2M_N} q^\mu \gamma_5 F_P(Q^2) \right] u_N$$

The cross-section depends on **form factors (F_i) = distribution of electroweak charge in the nucleon (a composite object)**

- F_1,F_2 electromagnetic form factors strongly constrained by electron-proton scattering
- F_P pseudoscalar form factor is connected to F_A by PCAC (Partially Conserved Axial Current)
- **F_A** constrained by electroweak CC bubble-chamber data (neutrino-deuterium scattering)

The functional form describes the 'internal structure' of the nucleon. Can be computed with Lattice QCD (on-going...). For now based on an ansatz: dipole = the simplest possible distribution

$$F_A^{\text{dipole}}(Q^2) = g_A \left(1 + \frac{Q^2}{M_A^2}\right)^{-2}$$

M_A = free parameter which describe the size of the nucleon $M_A = (1.026 \pm 0.021)$ GeV

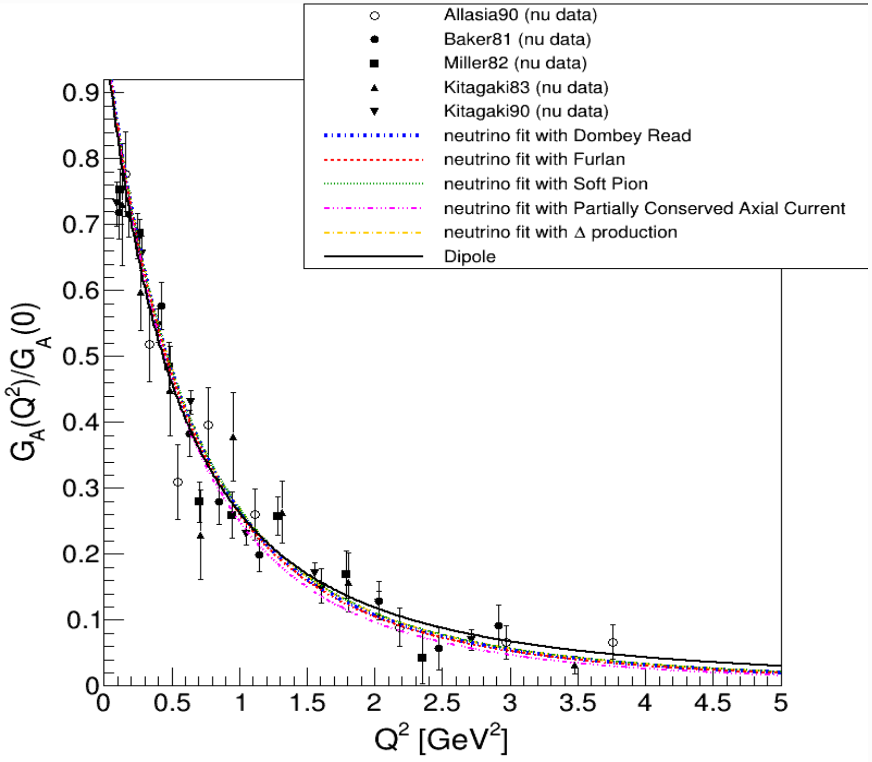
$G_A = F_A(0)$ strongly constrained by neutron b-decay (same diagram but at Q^2~0)

$g_A = 1.2723 \pm 0.0023$

Nucleon-level uncertainty

- More sophisticated functional forms for the axial form factors has been proposed (see TN315): z expansion, 2-component model ...

- Fundamental problem: **low statistics of bubble chamber data at high Q^2 → uncertainty in that region depends on the assumed functional form**

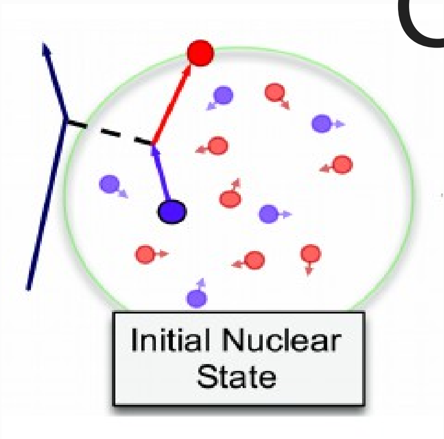


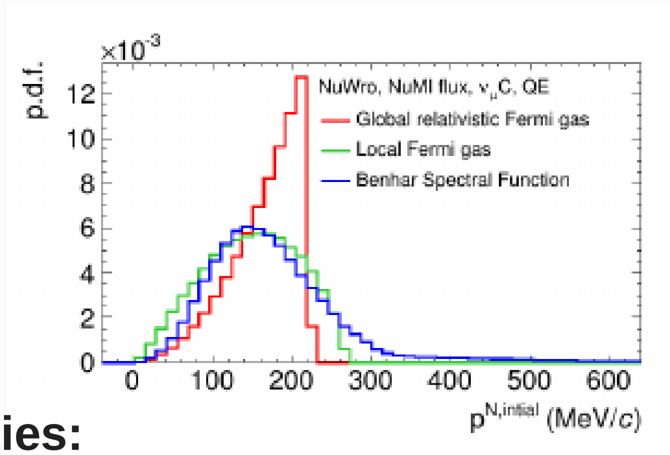
- Effect of this uncertainty tested in OA and it is small enough to be negligible (as of today)

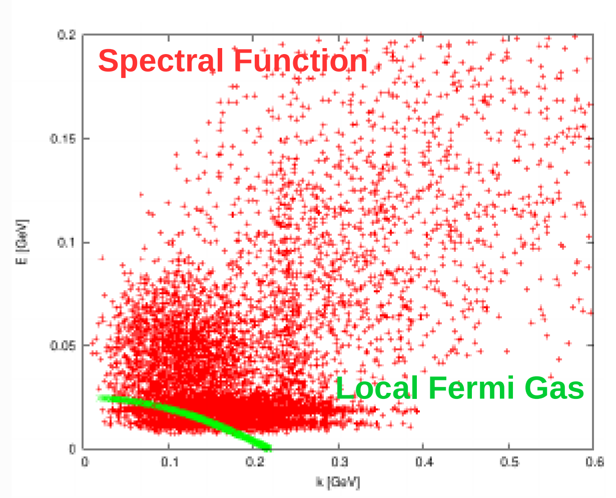
- In future: different proposals for **measurements on H** with Single and Double Transverse Variables

→ need to assess impact of such unceartinty

CCQE: nuclear model



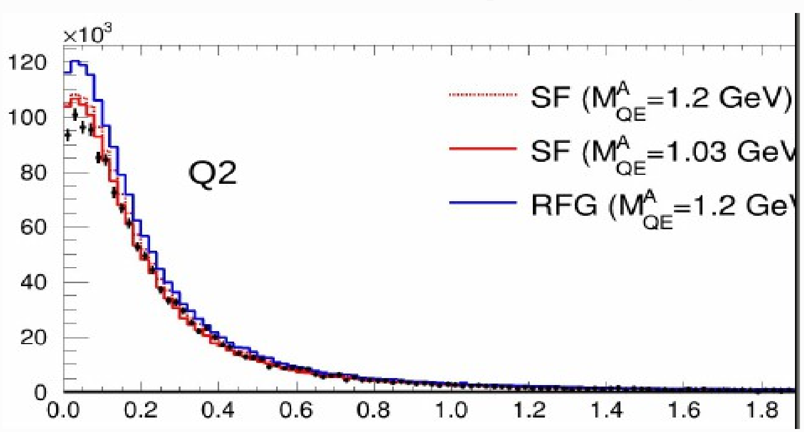




- **Fundamental uncertainties:**
  - distribution in energy and momentum of the initial nucleon (E_b, p_F)
  - (+ 2nd order effects due to non-factorization eg "FSI" on lepton)
  - … anything else we are missing … ?

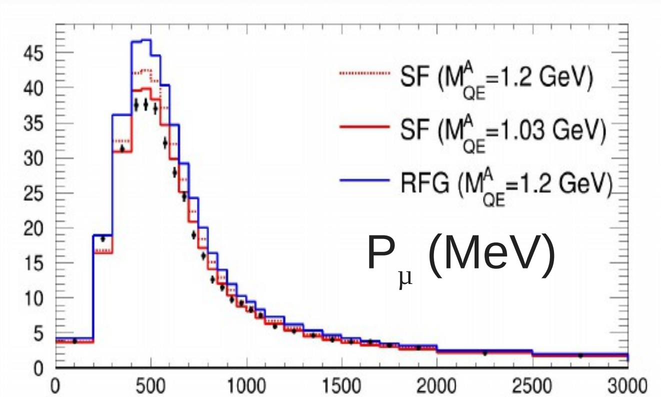
- We are moving to **SF as baseline model:** fully tuned to electron scattering data (NIWG is performing its own comparison to such data to establish uncertainties on Eb. What to do with pF?)

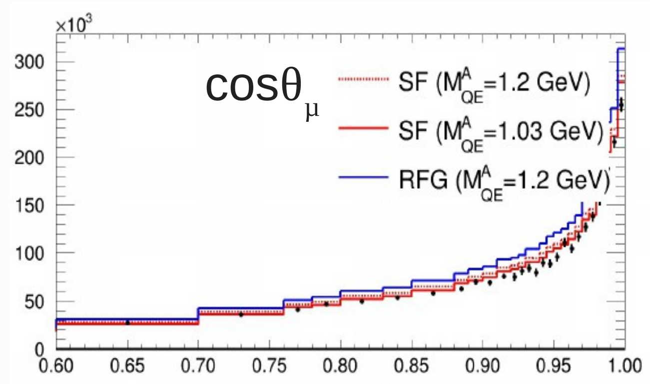
- **Still data-MC discrepancies** (xsec? flux? detector?): effective Q^2 corrections



Similar observations in CC0pi xsec analyses

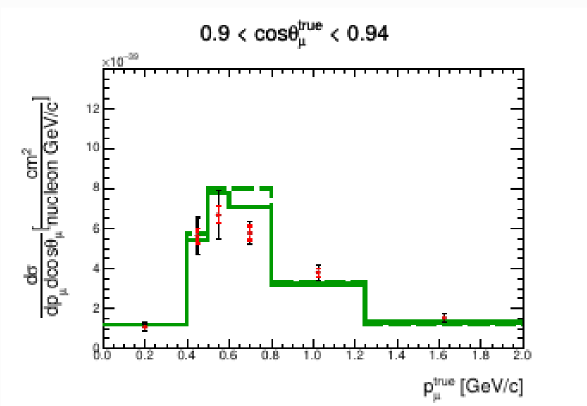
CCQE: ND prefit vs xsec measurements

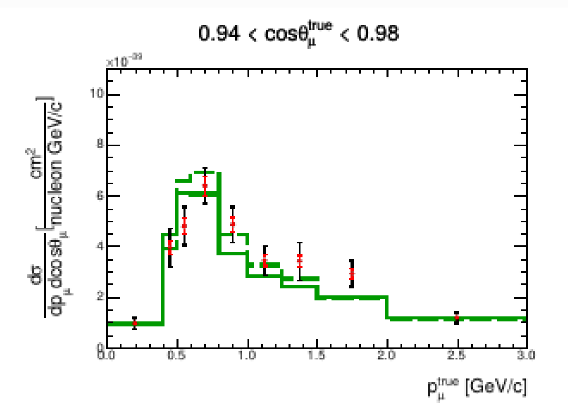


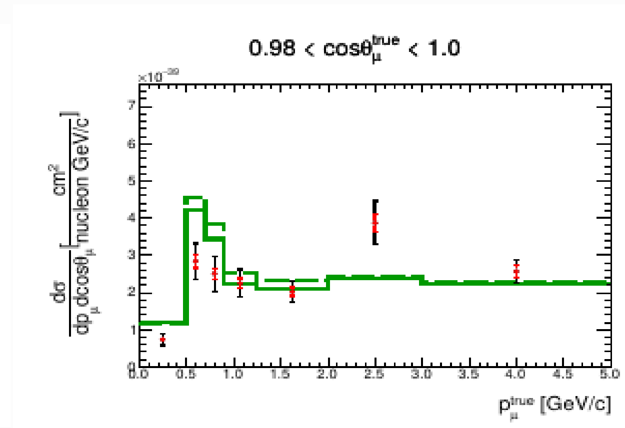


CC0pi ND prefit plot at reco level (Laura)

CC0pi xsec measurement (Ciro, Margherita)

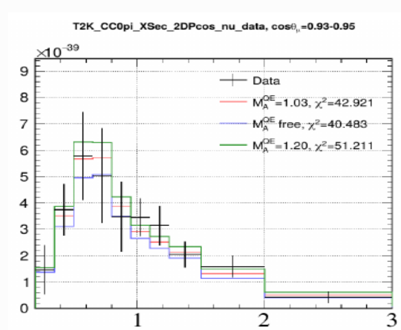


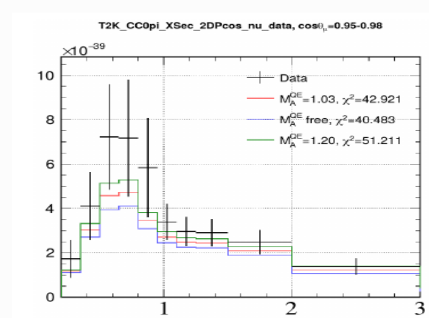


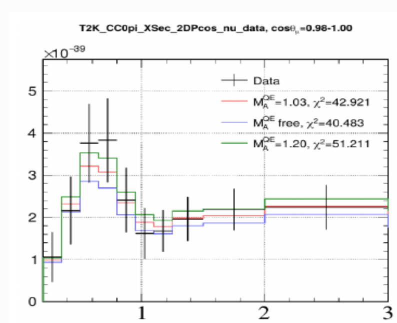


Is there a way to make such comparisons of xsec measurements vs model more quantitative/useful? Especially now that xsec is exercising more advanced selections then ND fit (eg using protons)

E.g. in NIWG we are fitting Q^2 dependence corrections to old xsec measurements







Useful measurements

Putting together **reconstructed tracks (muon, proton) and low energy deposits from unreconstructed tracks (vertex activity):**

- CC0pi xsec as a function of E_ν^{rec} (from p_μ, θ_μ) and/vs E_{had} → as a validation of E_ν^{rec} kinematics formula
- CC0pi xsec as a function of reconstructed q_3, ω

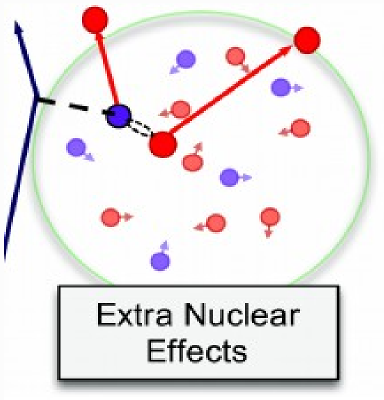
→ useful to understand Q^2-dependent discrepancy

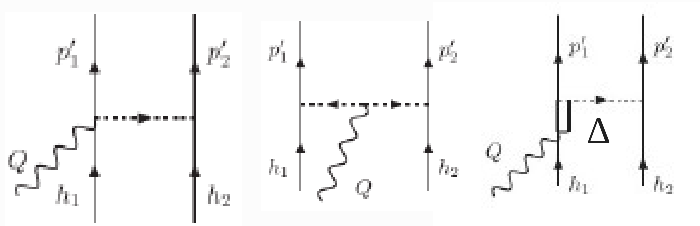
- CC0pi xsec as a function of variables related with initial nucleon momentum and energy (eg single tranverse variables, p_n) → useful to tune/falsify nuclear models

“By product”:

You will need to develop/improve uncertainties on proton FSI, pF and Eb reweighting where NIWG miss manpower
Developing NIWG uncertainties for hadronic final state is a crucial input for the future OA with data from ND280 upgrade

Multinucleon: aka 2p2h





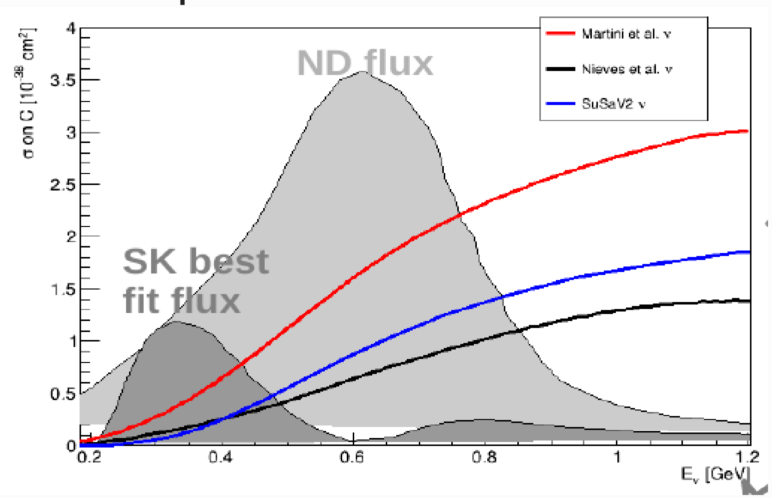
+ others ...

We do not know much about it: into the core of nuclear physics → various different approaches/models
Our baseline (Nieves) is a microscopic model (supposed to consider all diagrams, still various choices/approximations to be made in the calculation)

A lot of uncorrelated uncertainties with flat priors (completely agnostic and effective)

- free overall normalization separately for nu and nubar
- E_ν dependence of 2p2h

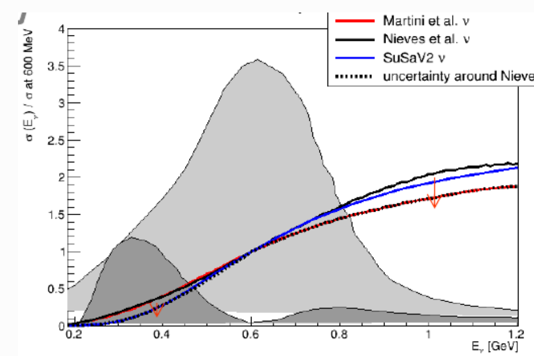
Comparison between 3 models



→ all shifted to the same fixed value at 600 MeV (considering that we already have a free normalization fitted at ND)

→ r = ratio between the highest/lowest model at each En

→ parameter *a*, *b* spanning between the different models



$$\sigma(E_\nu) = \sigma^{model}(E_\nu)*2p2hNorm * [a + (1-a)/r(E_\nu)] \quad (E_\nu<600 \text{ MeV})$$

$$\sigma(E_\nu) = \sigma^{model}(E_\nu)*2p2hNorm * [b + (1-b)/r(E_\nu)] \quad (E_\nu>600 \text{ MeV})$$

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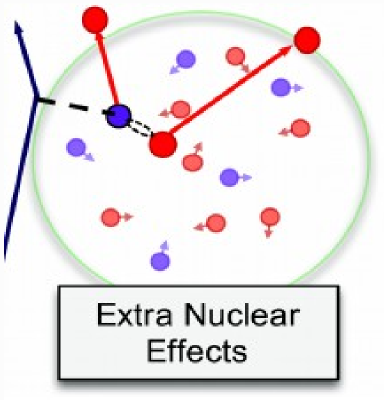

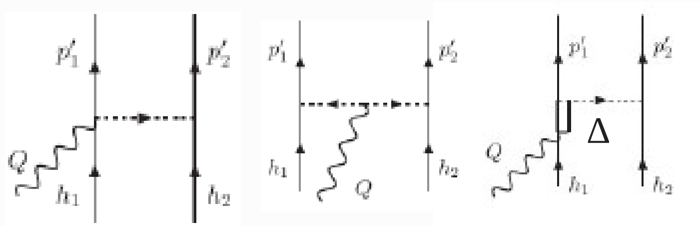

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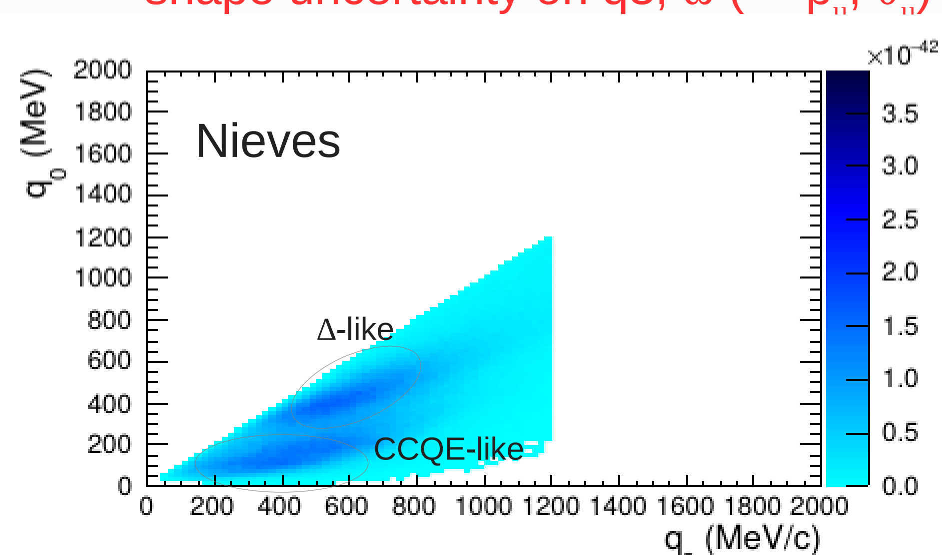

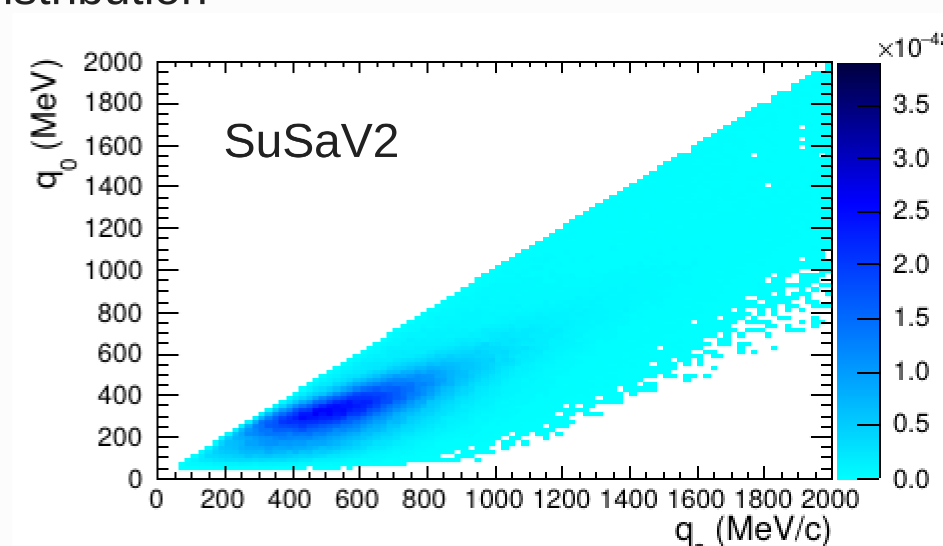

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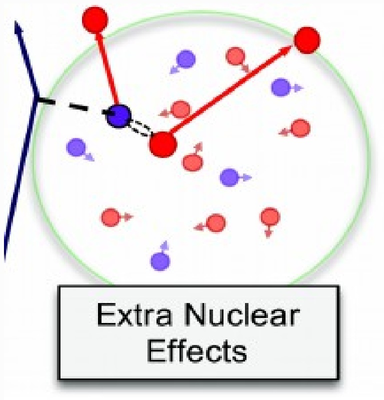

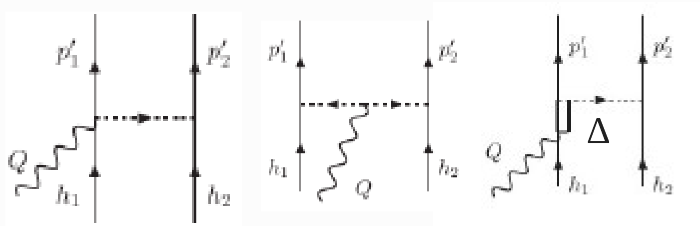

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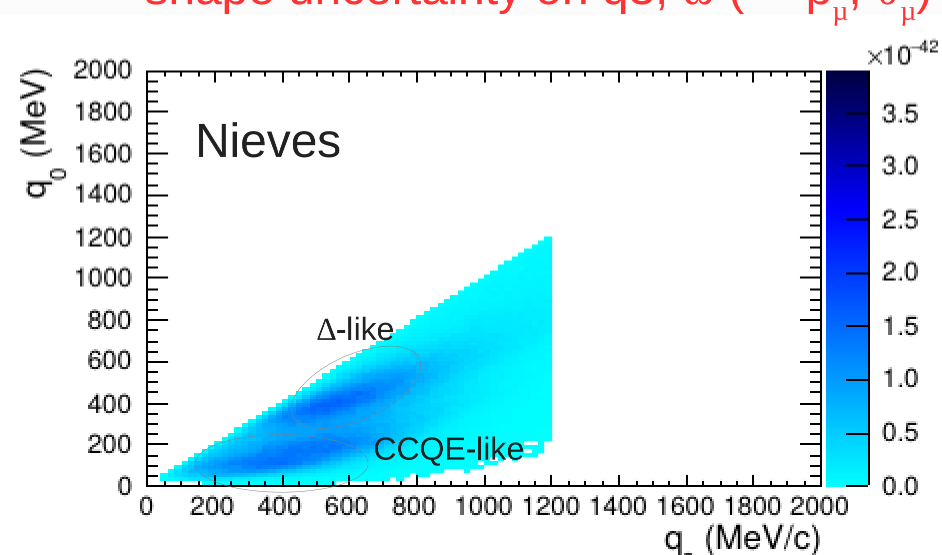

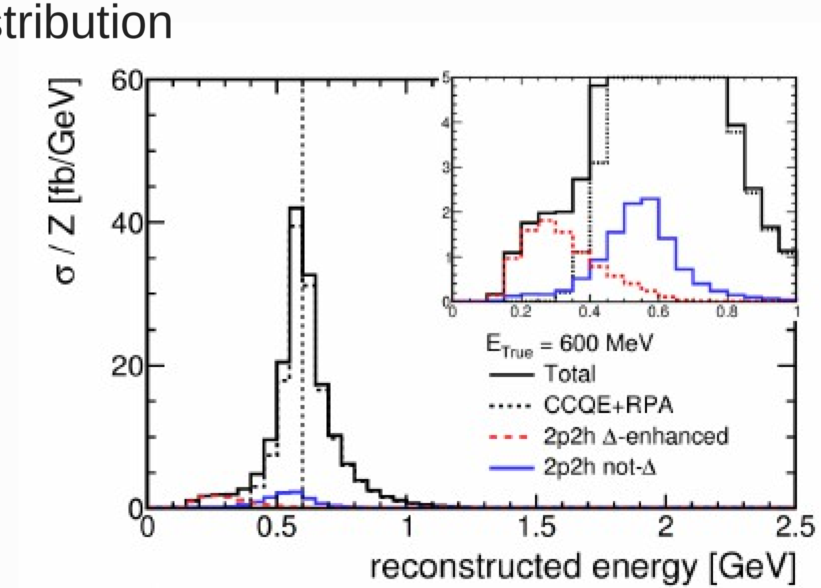

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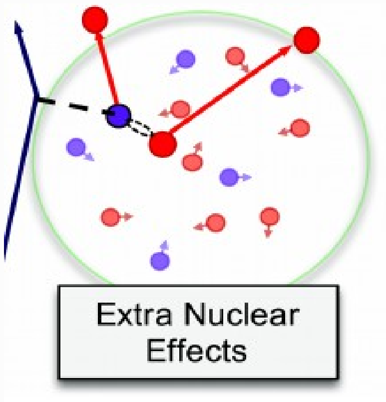

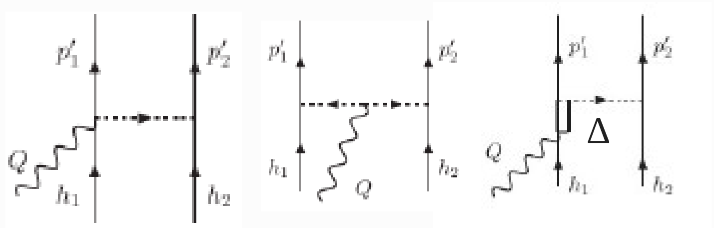

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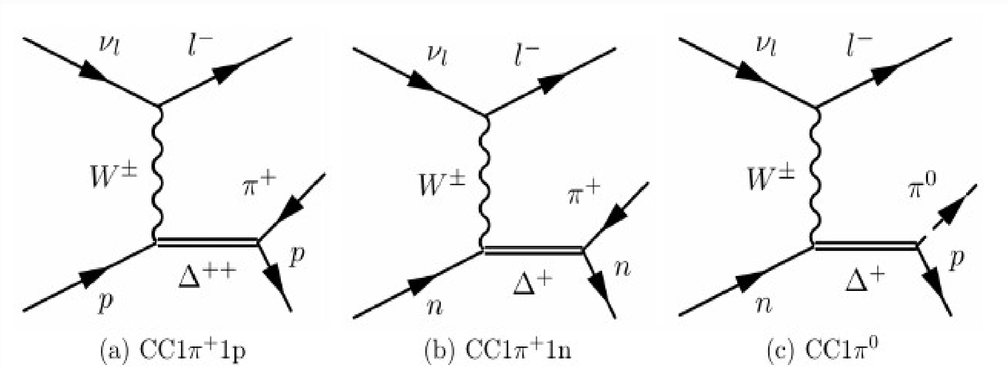
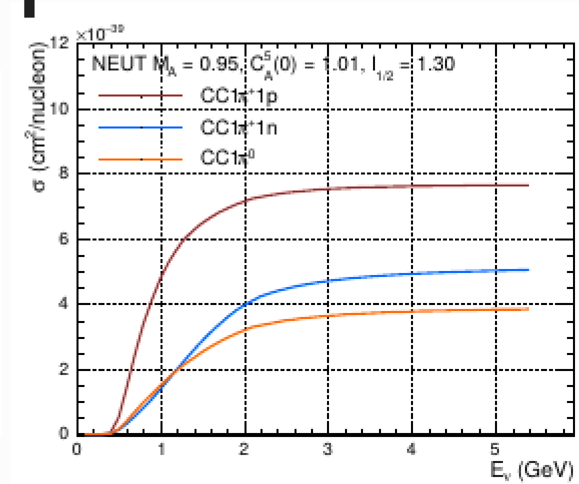
- free overall normalization separately for nu and nubar
- E_ν dependence of 2p2h
- shape uncertainty on q3, ω ($\rightarrow p_\mu, \theta_\mu$) distribution
- normalization and shape partially correlated between C and O (20-30%)

Help us! This correlation is based on a very preliminary analysis of electron scattering data → **systematical assessement of 2p2h in electron-scattering for different targets** can be done (eg in SuSa framework) and would help us setting more meangiful uncertainties

Single pion production





- CC Resonant single pion production: **dominated by Δ++ at T2K energies**

  Actually, more resonances and continuum should also be considered (see Minoo talk):

  continuum considered for isospin = 1/2 channel with free normalization (I1/2)

- **Form factor** defined (similarly to CCQE): M_A^{res}, $C_A^5(0)$

  Mares, CA5(0), I1/2 are nucleon-level uncertainties constrained by bubble chamber data

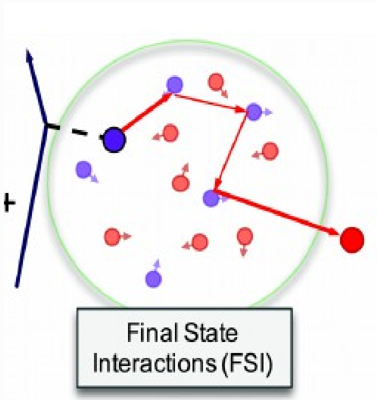
- Nucleon model is Local Fermi Gas.

Additional nuclear effects (eg modification of D width in nuclear medium) are known but not included neither in the model neither in the uncertainty

→ nucleon-level parameters (MARES,CA5(0), I1/2) are inflated to include in an effective way the nuclear uncertainties. Prior uncertainties from external fit to MiniBoone and Minerva fit

Help NIWG for the next step: include *real* nuclear level uncertainties in CCRes: if CCRes is a large background for your analsysis then you should care about this

Pion FSI and SI



FSI: semi-classical cascade = simulation of π propagation inside the nucleus by little steps → at each step a given probability of pion interaction

Secondary Interactions are the same of FSI but it happens on another nucleus (not the one where the main interactions was) somewhere in the detector along the pion track

The next OA will have for the first time the same nuclear model for FSI and SI (from NEUT) and coherent uncertainties:

FSI:

Parameter	Best fit $\pm 1\sigma$
f_{QE}	1.07 ± 0.31
f_{ABS}	1.40 ± 0.43
f_{CX}	0.70 ± 0.30
f_{INEL}	1.00 ± 1.10
f_{QEH}	1.82 ± 0.86

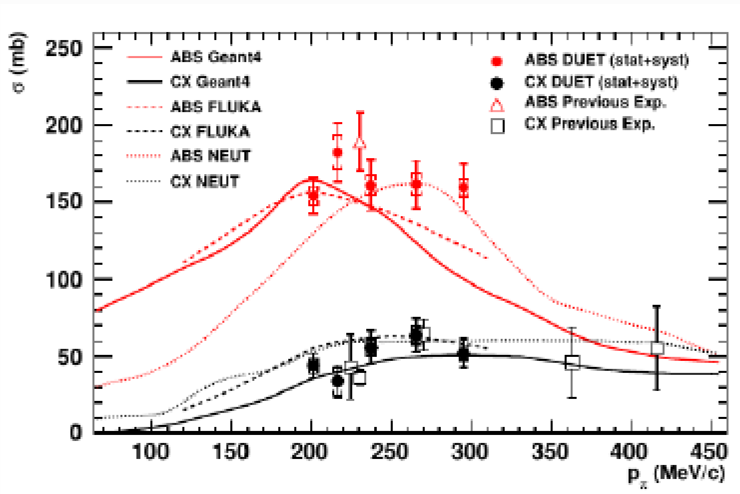
5 (correlated) dials = uncertainty on the probability of pion re-interaction at each step of the cascade
(QE scattering at high and low energy,pion absorption, charge exchange, inelastic scattering ie hadron production)
Constrained by fit to external p-N data
[note: CX at high energy removed because redundant]

SI: One **single parameters** which represent the probability of SI → now fully tuned **in a coherent way with respect to FSI** (Thanks Mitchell!)

Manpower needed for next step: **expose SI parameter for a joint fit at ND of SI and FSI → first example of a new treatment of 'detector' systematics.** Very good topic for a new CC1pi xsec student!

Pion FSI priors

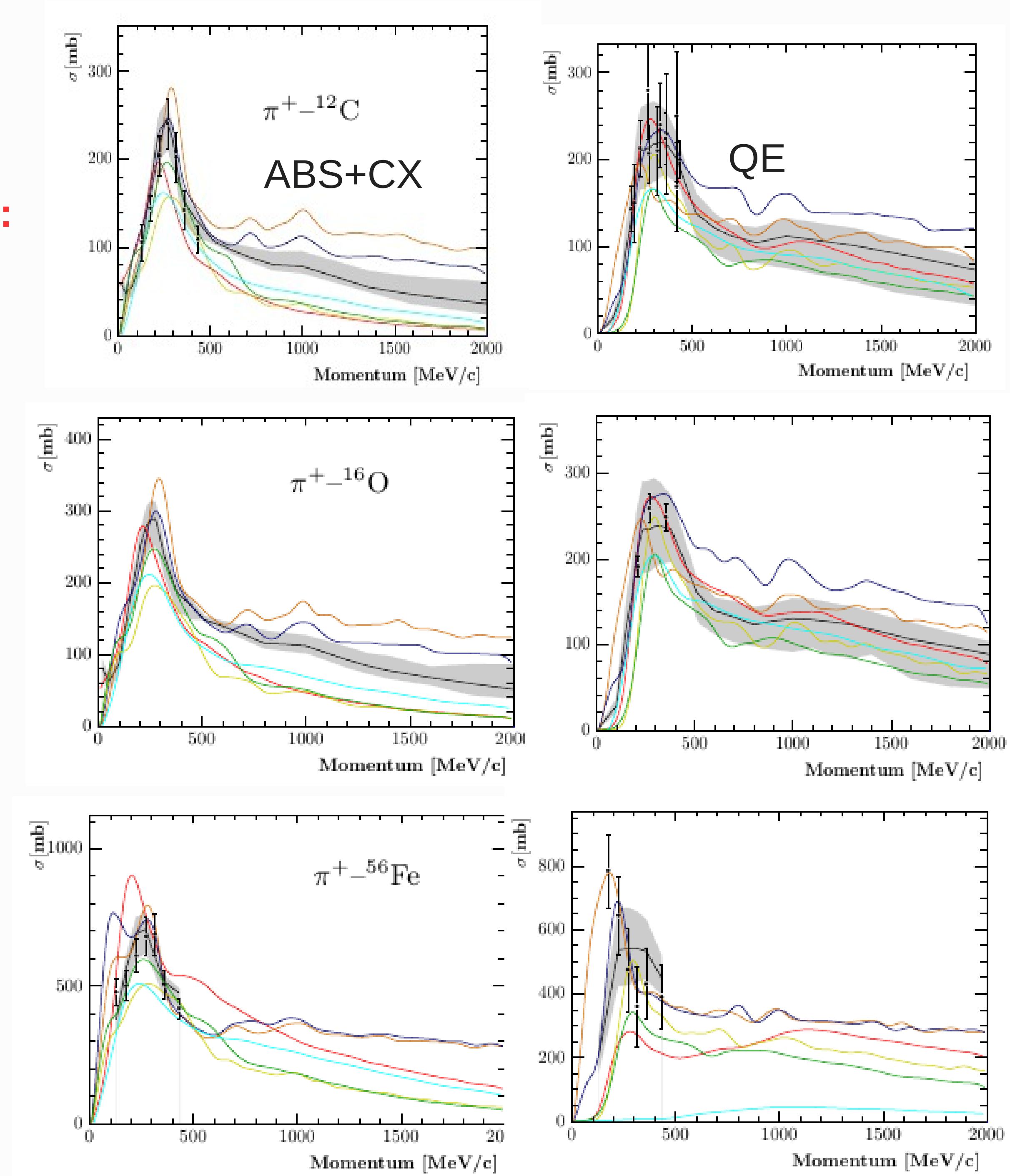
- **Constrains from pion-nucleus data:**



Xsec as a function of momentum of the incoming pion. Almost no measurement available on the kinematic of the outgoing pion.

FSI dials: only change the pion-nucleus integrated xsec for different channels.

- Need new dials to change the kinematics of rescattered pions. Constrain based on different data: pion photo-production

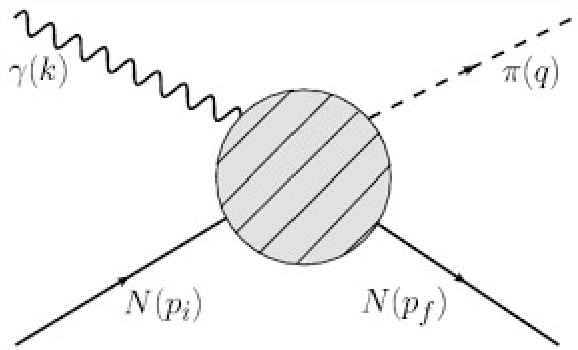


(e) ABS+CX

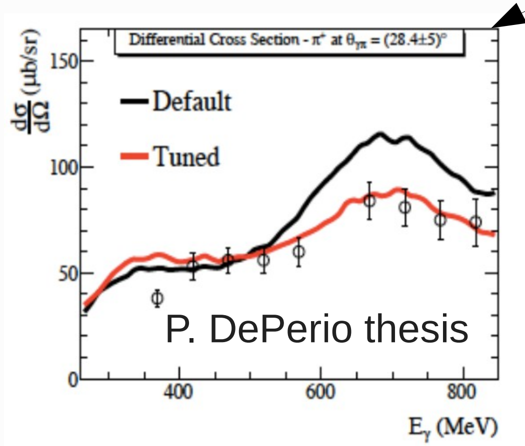
(much less data available for π-)

How to improve FSI uncertainty

- **Pion photo-production data** (pion production inside nucleus)

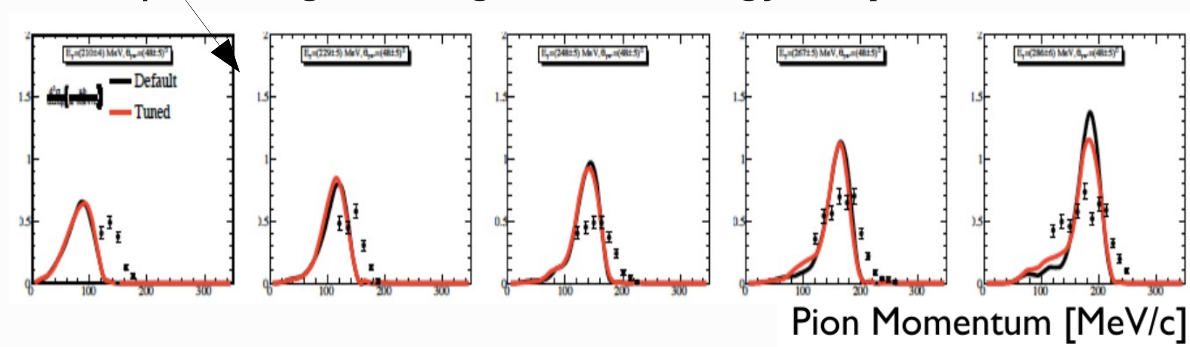


NEUT is able to model this process
– γn → π0 n, γn → π- p, γp → π0 p, γp → π + n
– Need to improve the model
– Current parameters are not enough to reproduce the photo-nuclear data



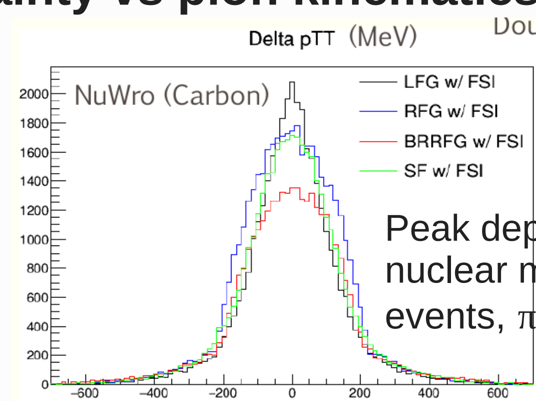
Fixed pion angle, integrated over pion momentum

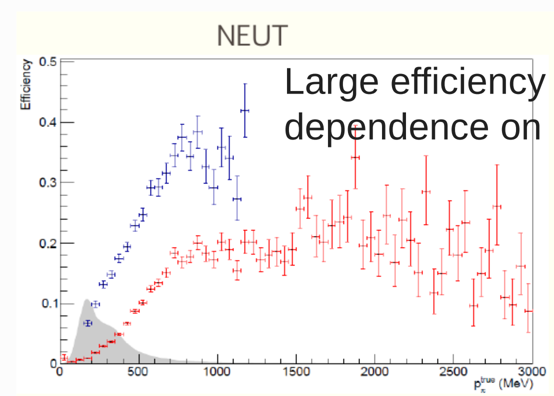
Fixed pion angle and gamma energy **vs pion momentum**



- **First step: extract uncertainty vs pion kinematics**

Need manpower!
→ relevant for many xsec measurements: eg **crucial for the systematic and the interpretation of dpTT measurements**





Deep Inelastic Scattering

- Neutrino interaction on single quark through W(Z) exchange times **Parton Density Functions (PDF) = probability to find a quark in the nucleon with a given kinematics:**

  - PDF are modeled as a functions of x (= quark momentum / nucleon momentum) and y (energy trasferred to the hadronic system / neutrino energy) → W,Q^2 are calculated from E_ν, x, y

    PDF are well under control in perturbative QCD region (high Q^2) → at low Q^2 Bodek-Yang corrections

  - For W<2GeV (aka multi-pion mode) only events with >1 pion are kept (to avoid double counting with CCRes) and the multiplicity is chosen on the basis of a custom model tuned (different options available and tuning to bubble chamber data possible)

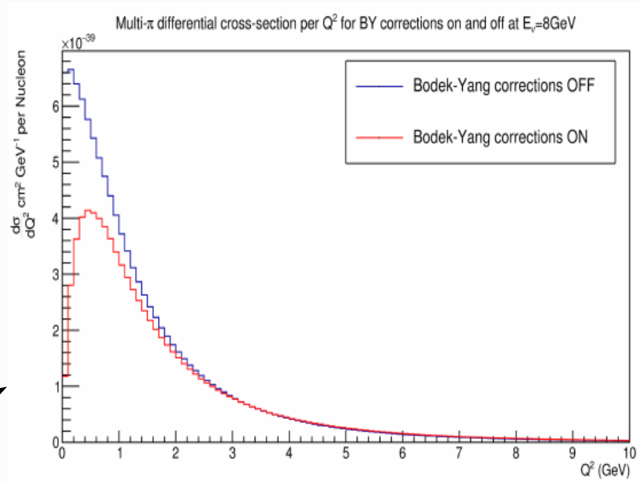
  - For W>2 GeV (DIS) the Pythia generator is used

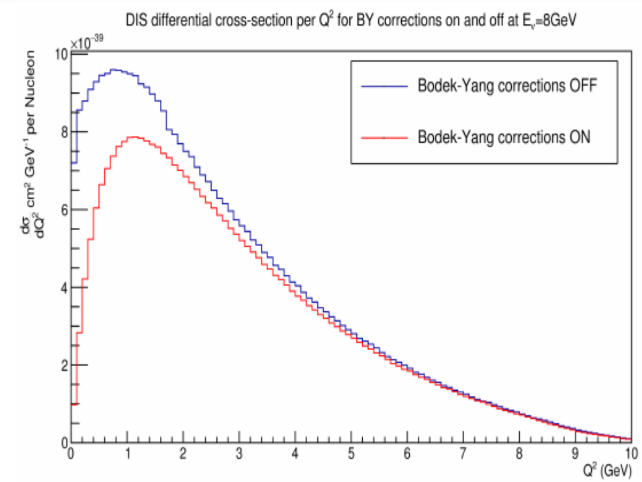
- Old systematic uncertainty $\sigma = \frac{0.4}{E_\nu}$

is being replaced by a more sophisticated treatment
(important for SK-atmospheric analysis and thus for T2K-SK joint fit)

DIS systematics

- **Bodek-Yang corrections on/off:**
  dial as a function of E_ν, Q^2

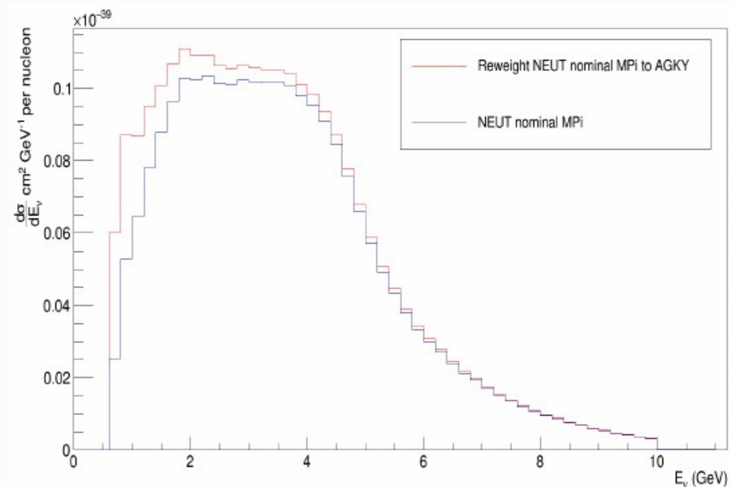




- **Difference between NEUT and GENIE multiplicity model for multi-pion mode** :

for now only a dial as a function of E_ν →

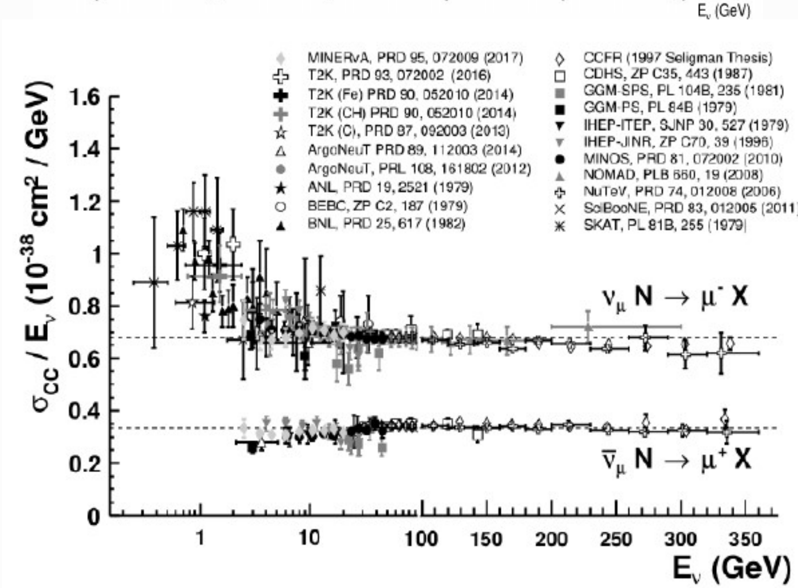
plans for p_π,W reweighting dial



- **Difference between average PDG value and NEUT integrated xsec:**

  3.5% for nu

  6.5% for nubar



Suggestions for the future

The “obvious” xsec analyses (CC0pi nu, nubar, C,O and CC1pi nu C,O) have been done
→ New analyses should be innovative in terms of new variables and more advanced selection wiuth respect to OA (transverse variables, VA, q3-ω, on/off-axis, …)

Typically this implies **new NIWG systematic** with respect to the OA (eg better proton and pion FSI) which, once implemented, are very useful for future OA as well

Once the measurement is done, is there a way to **go beyond the simple data-MC comparison:** can we envisage a model-dependent fit of new variables using (old and new) NIWG uncertaitinties?

Look at the list of NIWG topics where we need help (in blue in previous slides) and pick your favorite one!
CCRes is a very good candidate...