Treatment of neutrino-interaction uncertainties in T2K analyses

Kamil Skwarczyński

ECT* workshop, measuring neutrino interactions for next-generation oscillation experiments

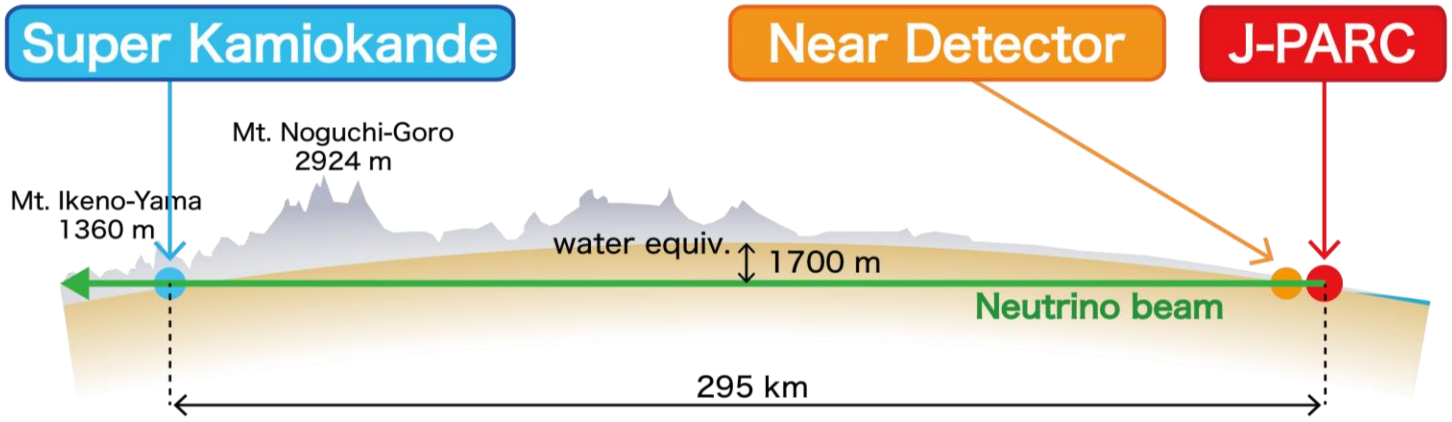
22.10.2024

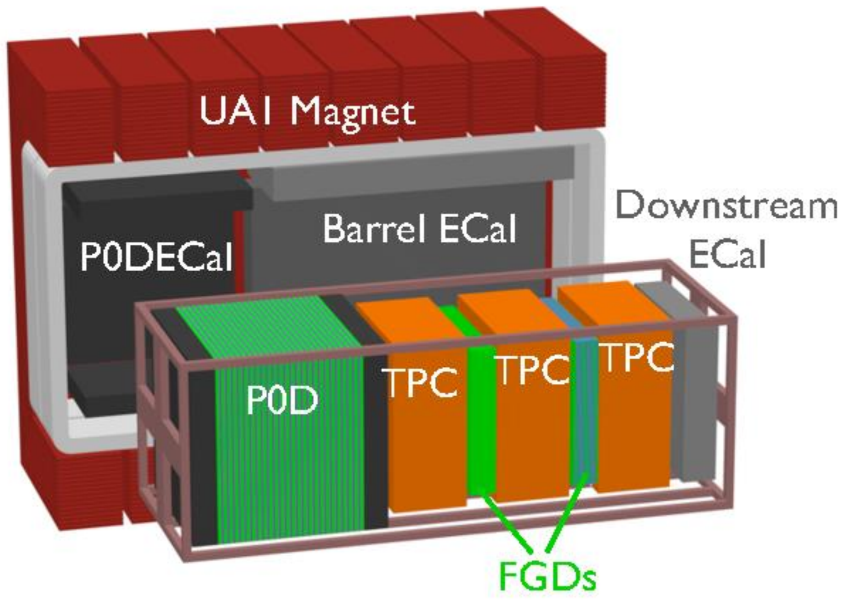
T2K is currently running long baseline experiment measuring neutrino oscillations and cross-section.

Near Detector ND280 is Hydro-Carbon based detector with water layers.

Far Detector Super-Kamiokande is water-based detector.

Upgrade of ND280 is finished this is important challenge for improving modelling.





Introduction

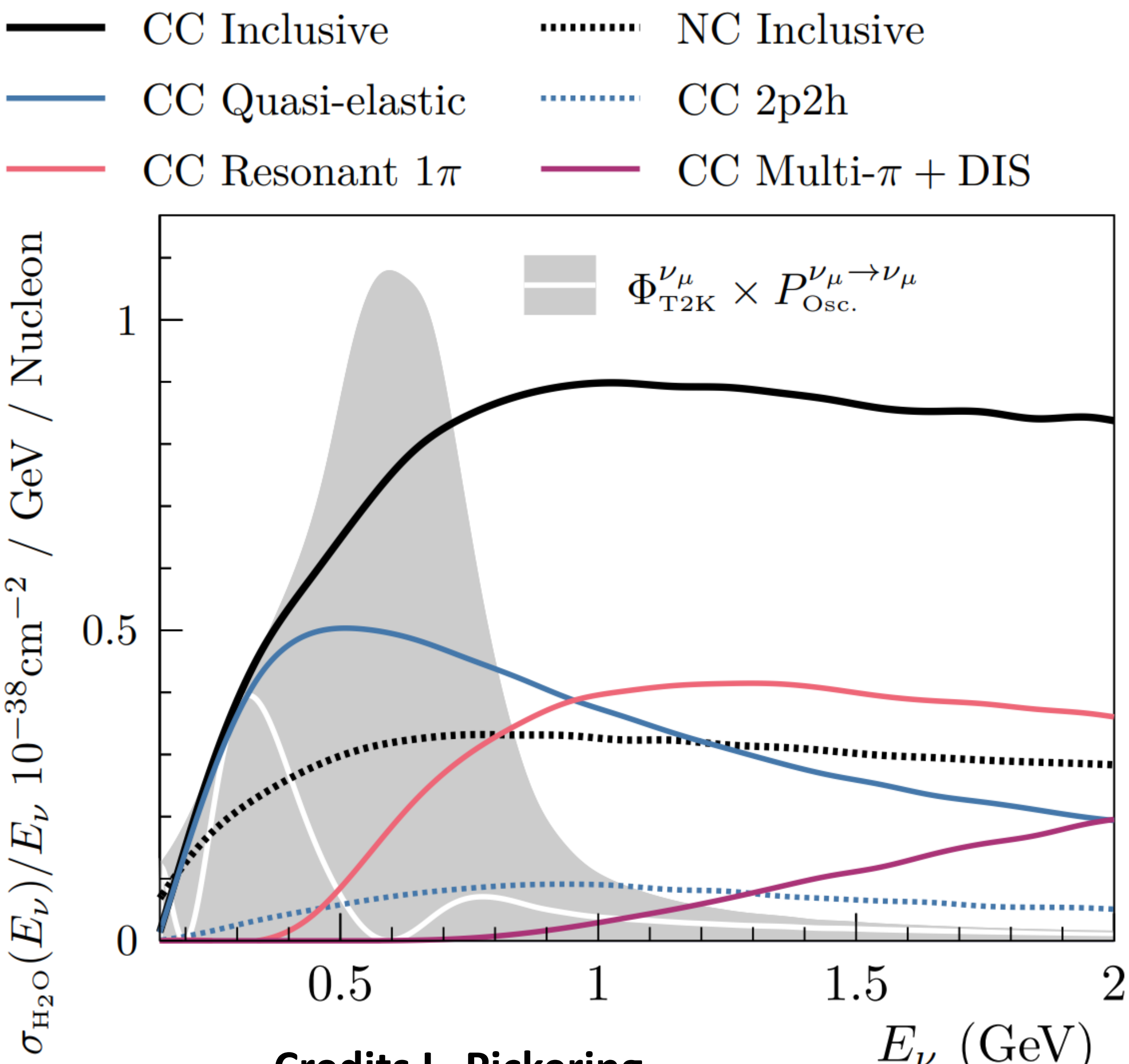
T2K Uses NEUT generator see [Patrick's talk]

For **T2K** flux most dominant channel is QE.

In NEUT each mode is simulated using different model.

Same **FSI** frameworks is used for each mode.

However nuclear model is tied interaction model, thus modes can have different nuclear model.



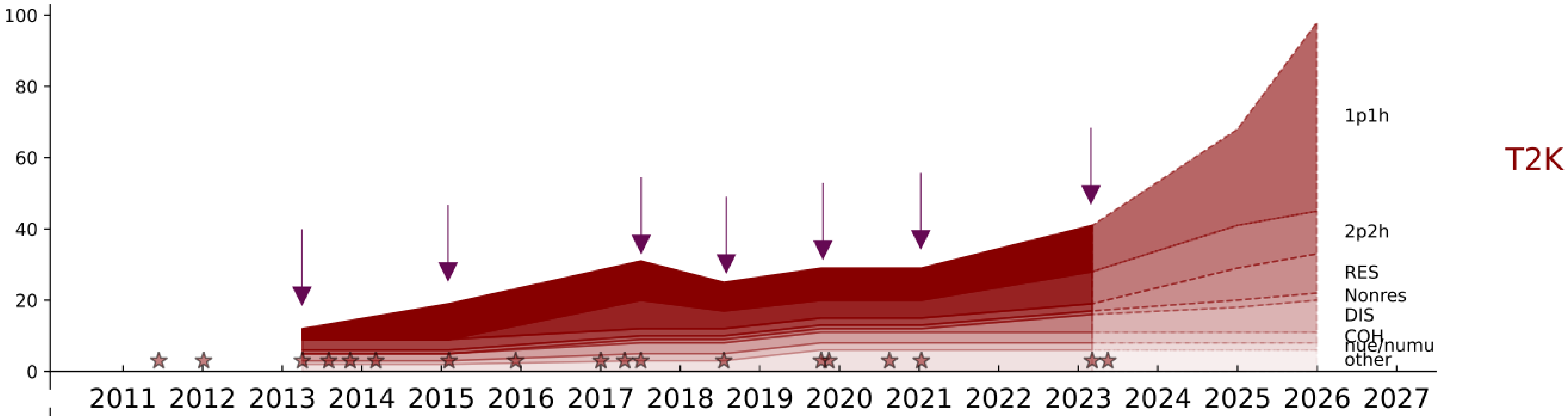
Credits L. Pickering

So Many Uncertainties

Number of T2K uncertainties is increasing

To better understand we have to take a look at samples at T2K

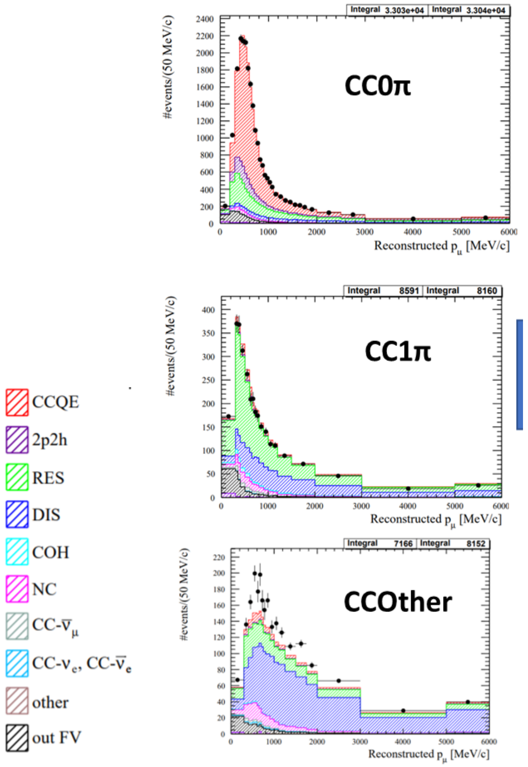
See [Jeremy's talk]



Sample Development ND280

ND280 in OA is using samples mostly based on π multiplicity

Separate CCQE and RES and DIS components



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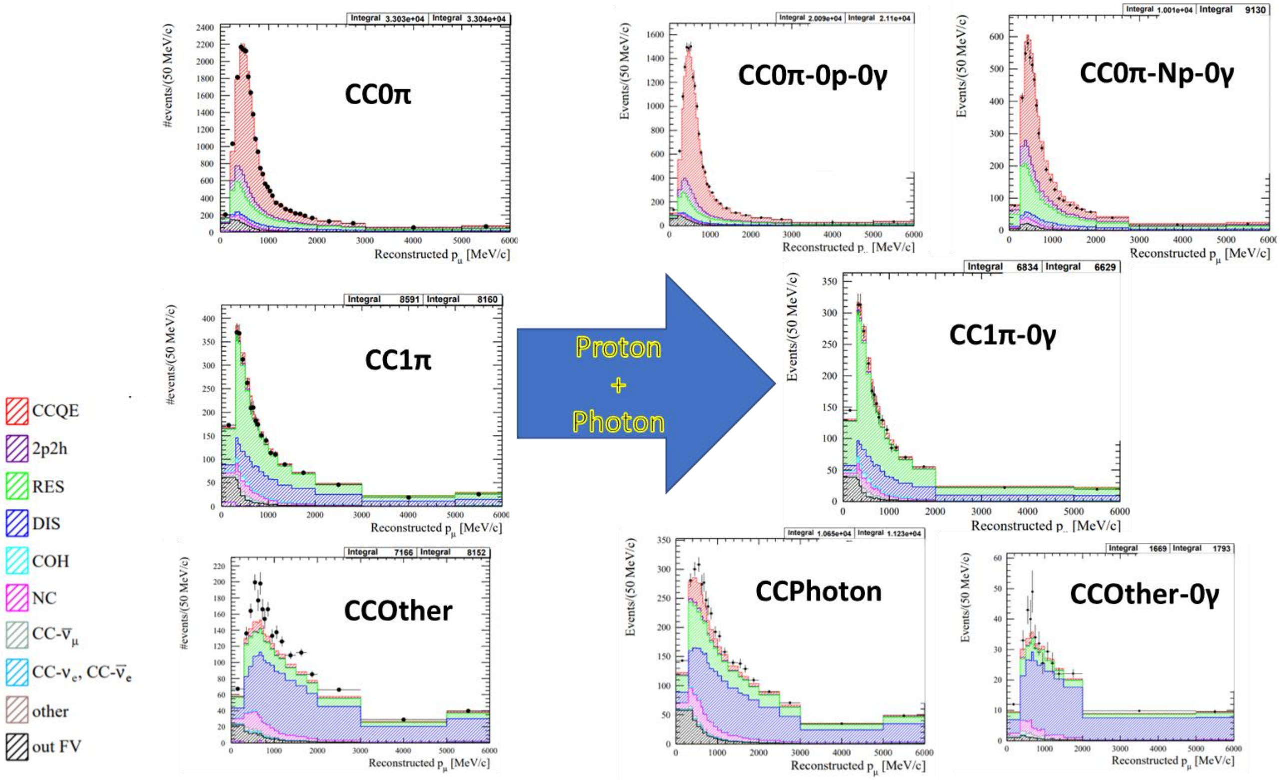
2022 -> proton and photon tagging



Sample Development ND280

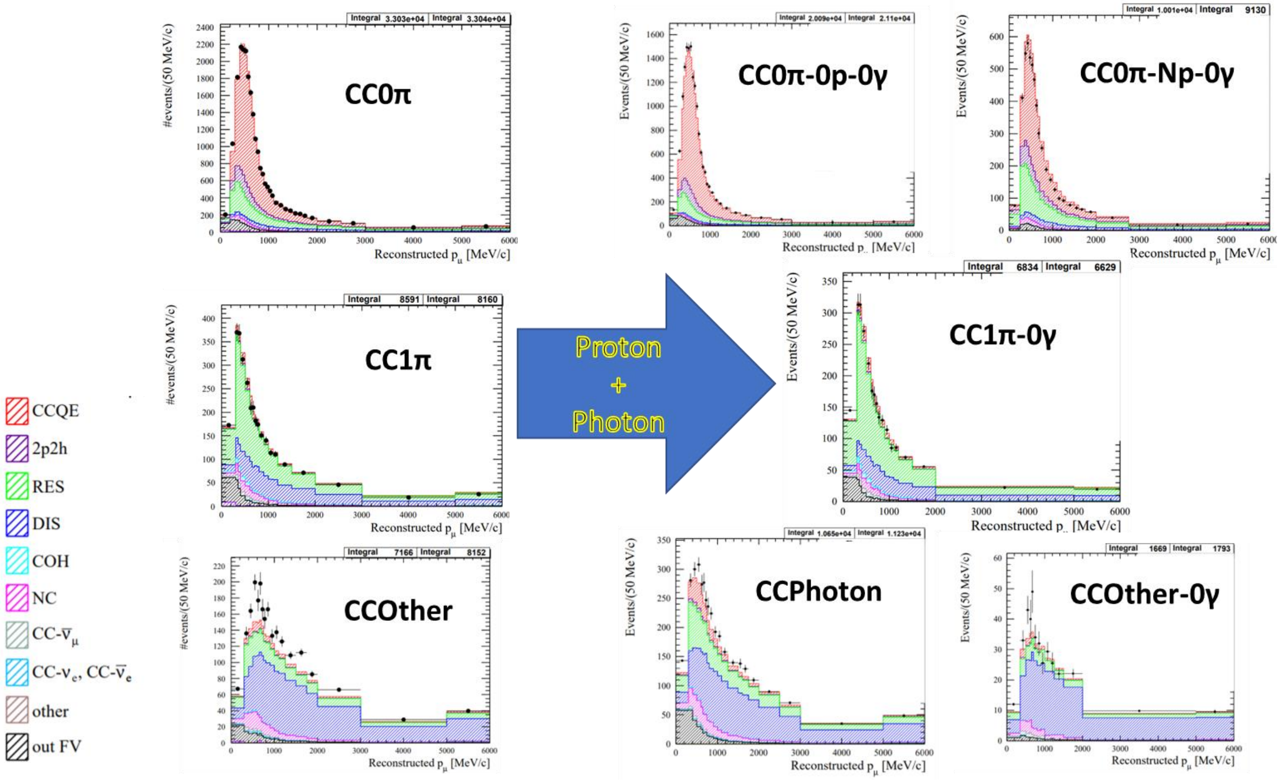
ND280 in OA is using samples mostly based on π multiplicity

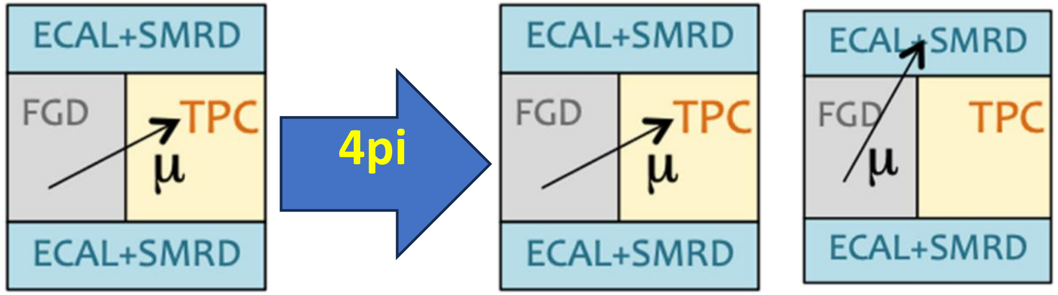
Separate CCQE and RES and DIS components

2022 -> proton and photon tagging

2024 -> 4pi angular coverage

More alike with SK-samples





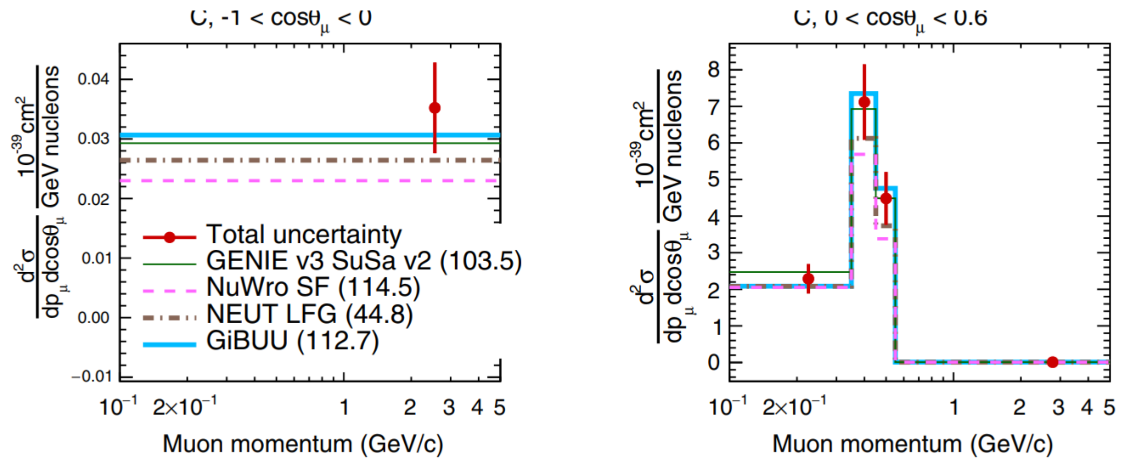
Most common channel for cross-section is **0pi**

1pi is second most popular channel

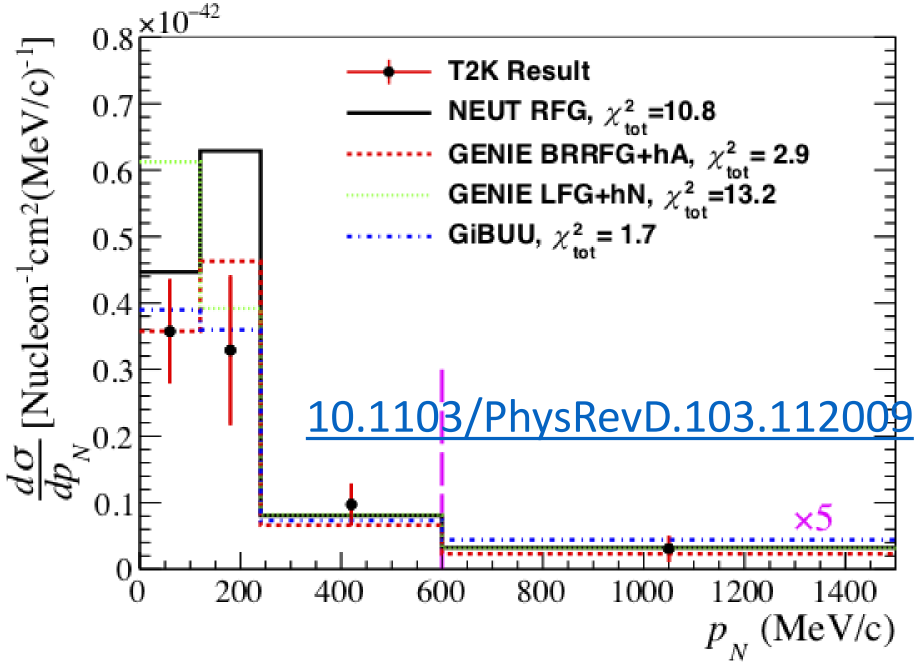
Different variables for example transverse kinematic imbalance

Multiple subdetectors different targets and off-axis angel correlations.

More exotic measurements focus on Coherent, NC Pi0 or nue



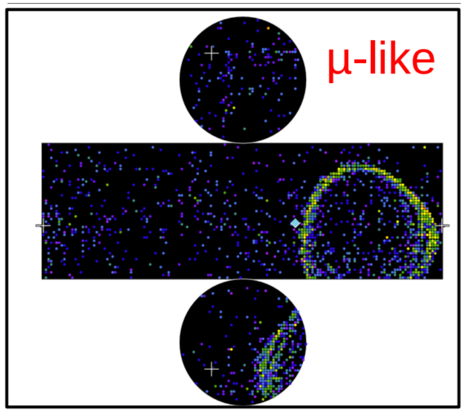
Phys. Rev. D 101, 112004

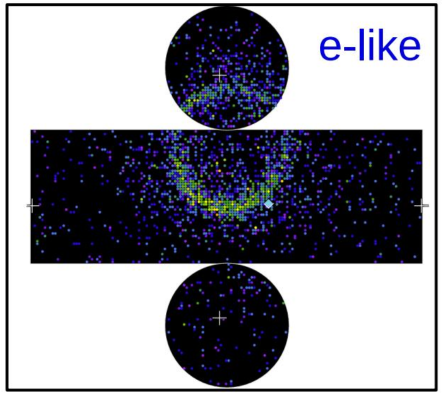


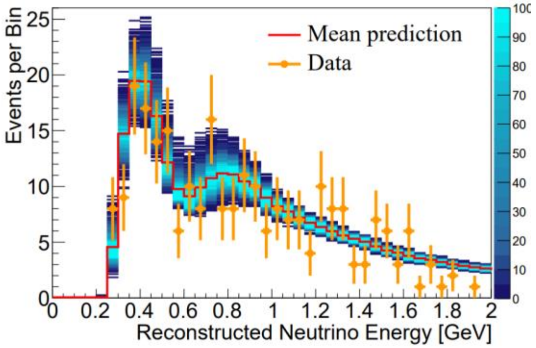
10.1103/PhysRevD.103.112009

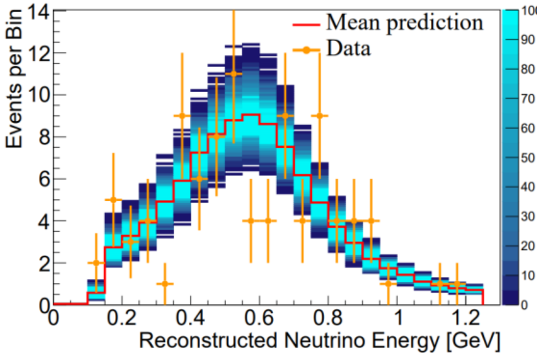
Sample Development SK

SK mostly using sample with one μ-like or e-like rings.
Targeting **CCQE**





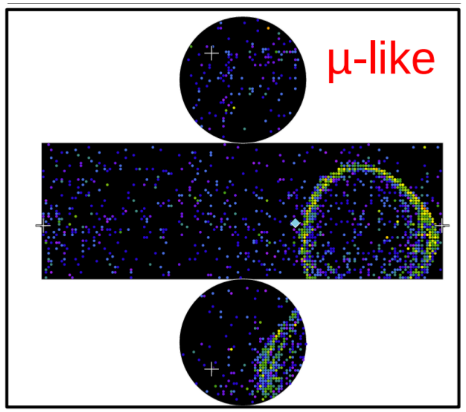


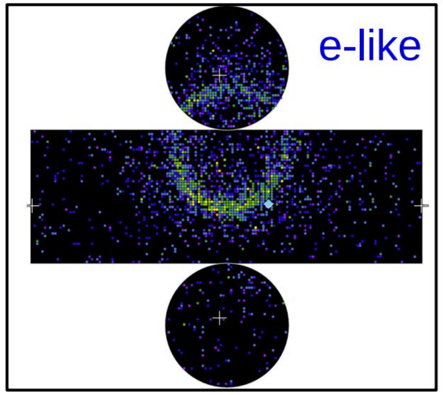


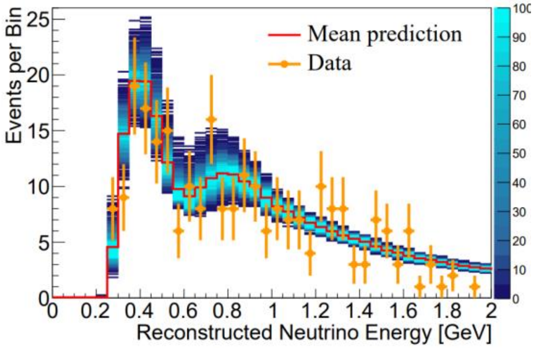
https://doi.org/10.48550/arXiv.2303.03222

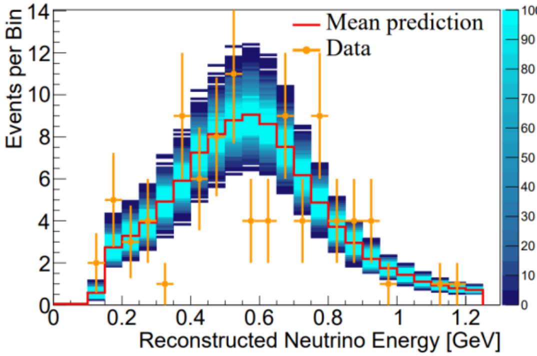
SK mostly using sample with one μ-like or e-like rings.
Targeting **CCQE**

In recent years more samples with more than one ring (targeting **CC RES**) have been included









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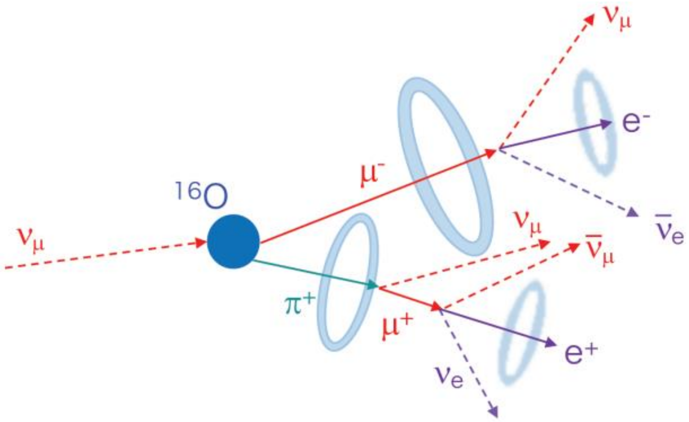
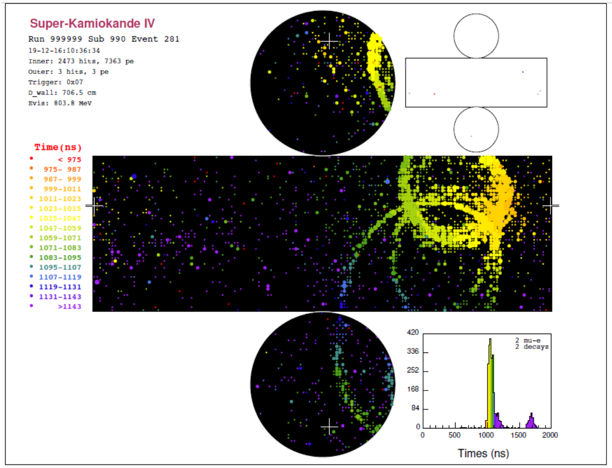




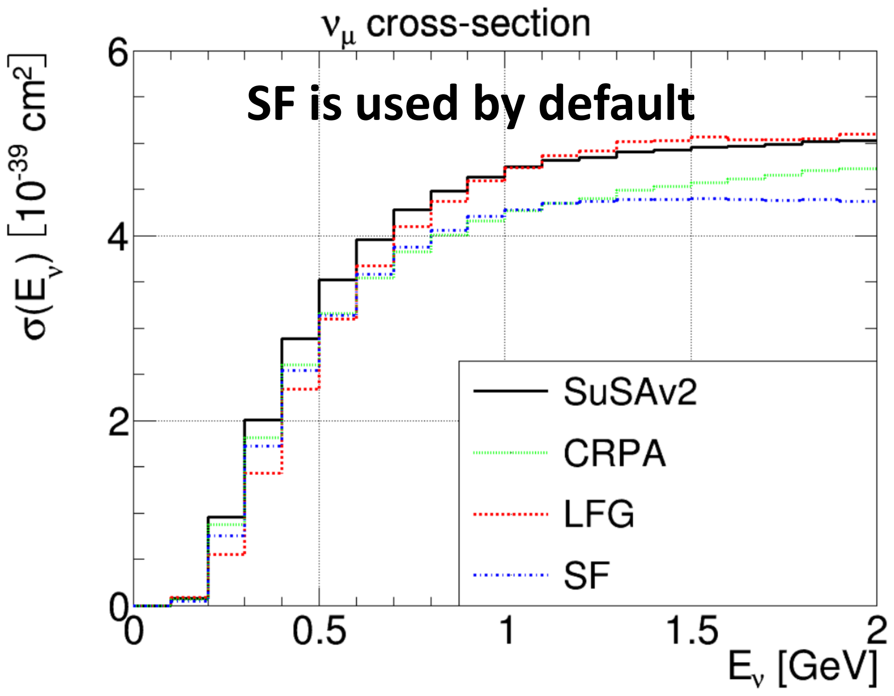
Fake Data Studies

In **T2K** we generate MC with particular set of models.
For example, Spectral Function as nuclear model for QE.

We don't know which model is correct. Production is time consuming.

Fake Data Study (FDS) :

1. Reweight MC to new model (SF to LFG), treat it as (fake) data
2. Fit you prior model to (fake) data
3. Assess impact of model change



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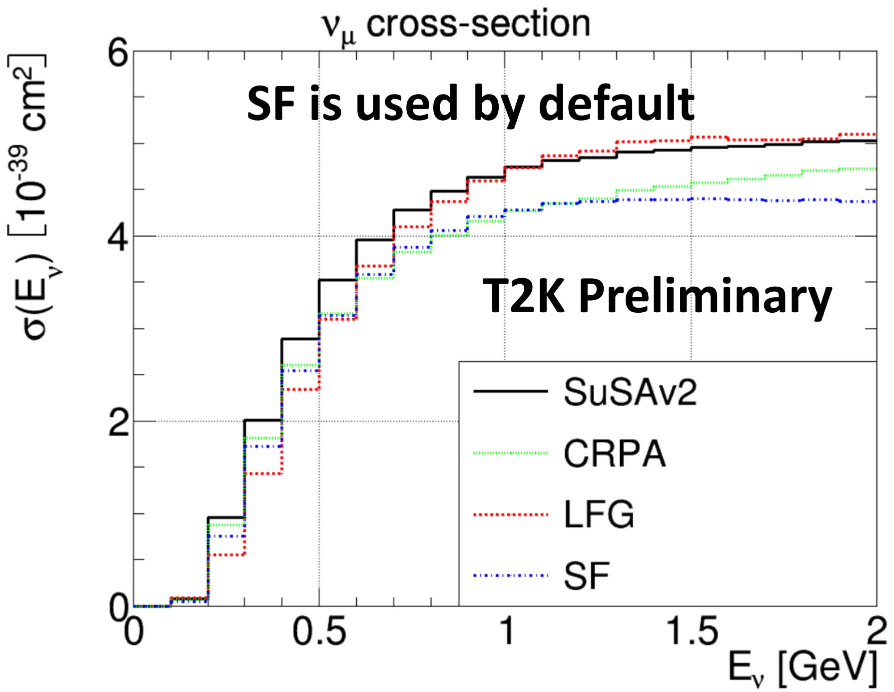
FDS help motivate model changes.
In 2022 CRPA FDS had largers impact -> improvement to systematic modelling



Example of bias

Simulated data set	Relative to	$\sin\theta_{23}$	Δm^2_{32}
CCQE z-exp high	Total	-0.5%	-9.5%
	Syst.	-1.0%	-24.1%
	Size	-1.8%	-5.4%
HF CRPA	Total	-11.7%	33.8%
	Syst.	-25.1%	84.9%
	Size	2.0%	-5.4%
Martini 1π	Total	-1.5%	-7.3%
	Syst.	-3.2%	-18.5%
	Size	-0.2%	-1.0%

I will go through each interaction mode

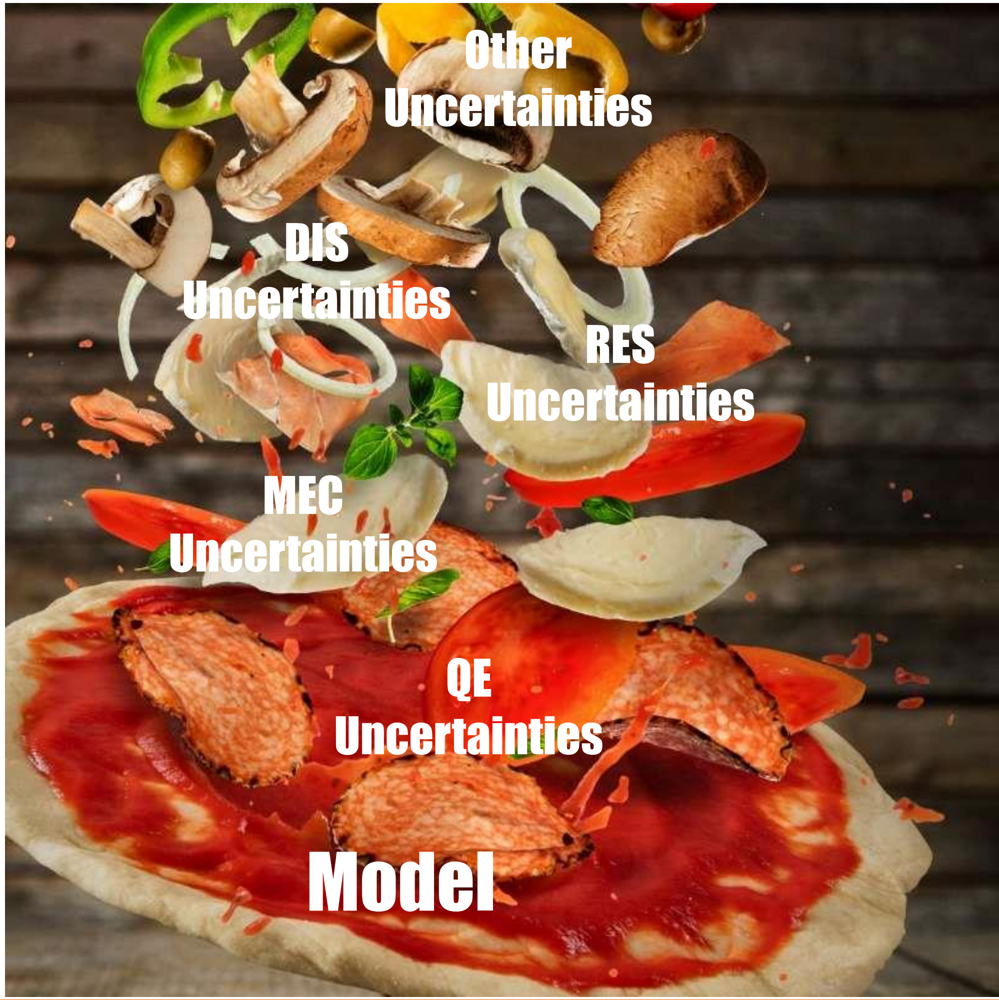
Will describe how each being modelled described.

Will try to mention briefly what is done correctly and what is missing.

Focus on uncertainties used in Oscillation Analysis T2K.
Will try to mention also Cross-section and Joint-Fits.

Outline

- QE
- MEC
- RES
- DIS
- FSI
- Other



QE

QE Model

Artur Ankowski **QE** model [Phys. Rev. Lett., 108:052505]

Assuming Dipole Approximation -> Single parameter MAQE

and 3 ad-hoc high Q2 normalisations.

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

QE Model

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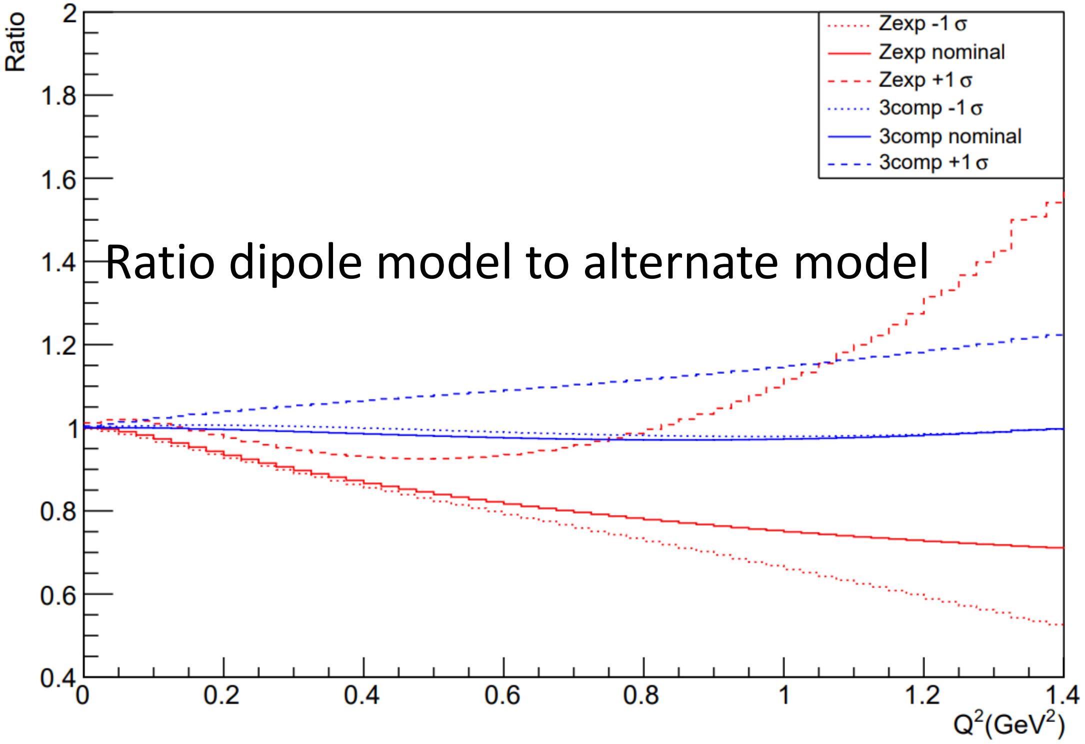


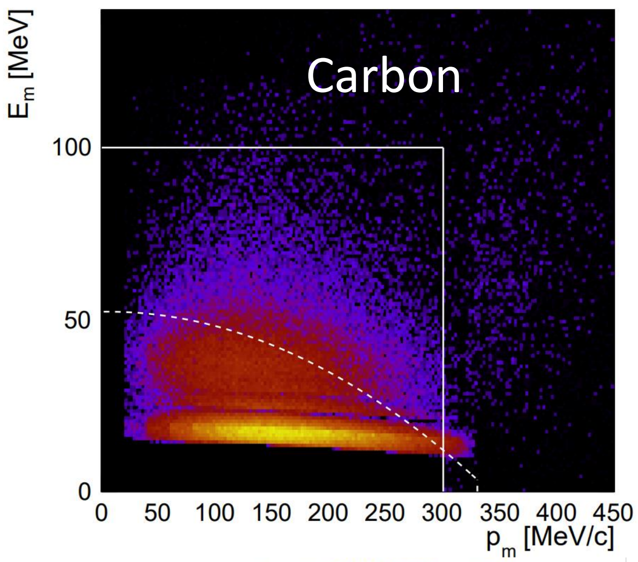
We account for Z-expansion/3 component via Fake Data Studies.

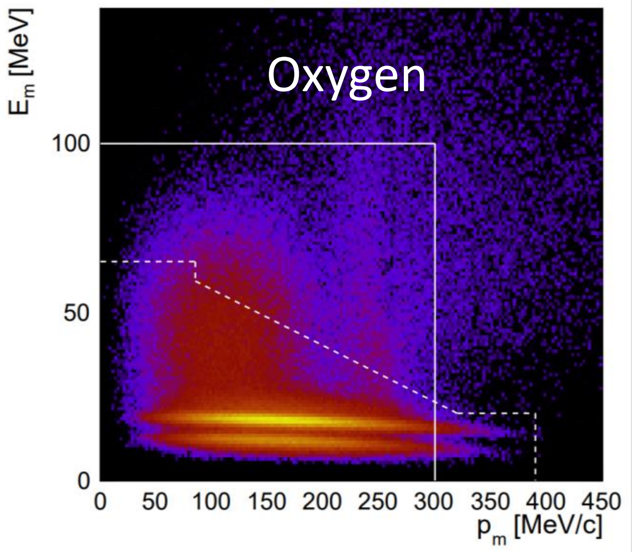
Impact on oscillation contours ins negligible thus we think current dipole is sufficient.

https://doi.org/10.48550/arXiv.2303.03222

Simulated data set	Relative to	δ_{CP}
CCQE z-exp high	Total	0.4%
	Syst.	1.7%
MINERvA pion tune	Total	0.9%
	Syst.	3.5%
Data-driven pion	Total	1.0%
	Syst.	3.9%
Pion SI	Total	1.0%
	Syst.	4.6%

Spectral Function (QE)



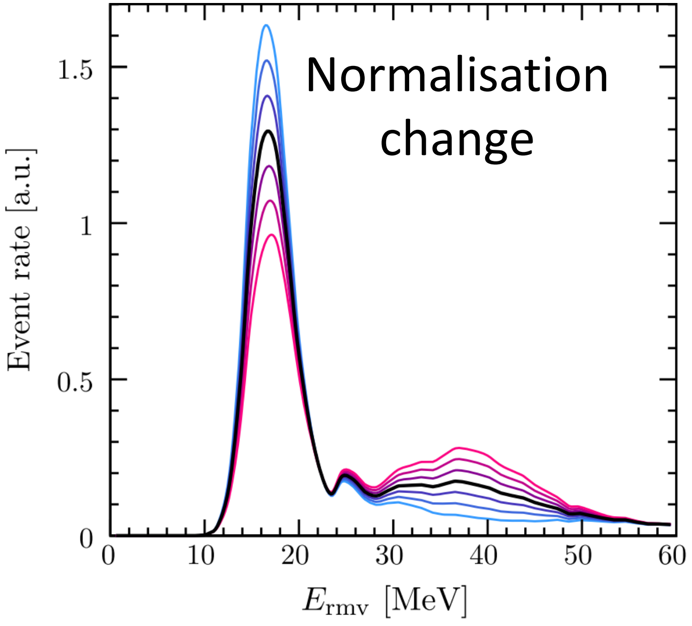


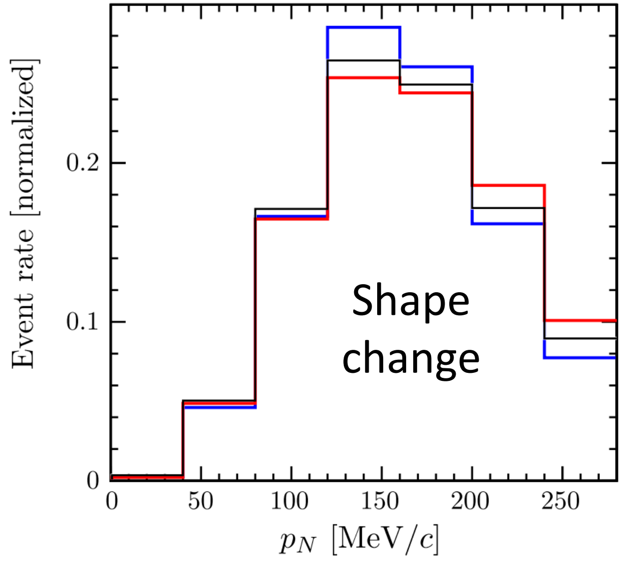
10.1103/PhysRevD.109.072006

We use Benhar SF for QE model.

In the analysis we allow to change:

- Normalisation of each shell and separate for SRC
- Shape freedom for each shell and separate of SRC
- Probability whether correlated nucleon is proton on neutron in SRC
- Totally uncorrelated between Carbon and Oxygen



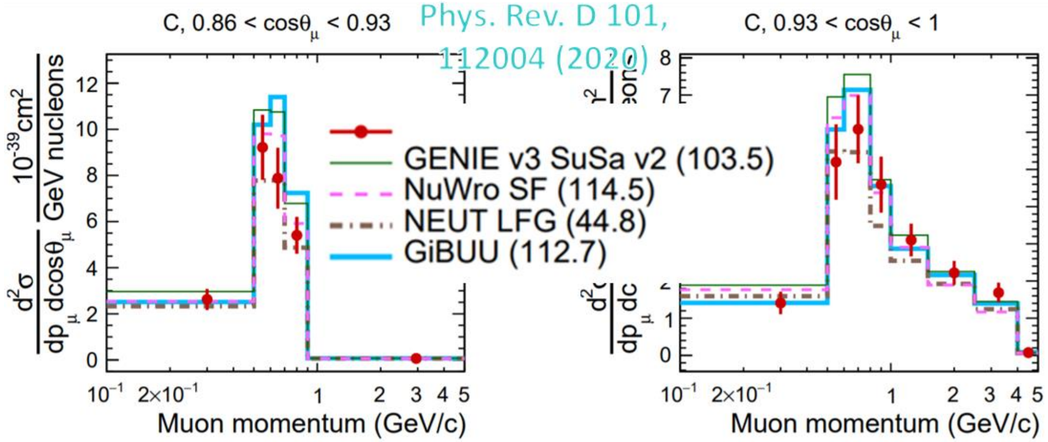


CRPA (QE)

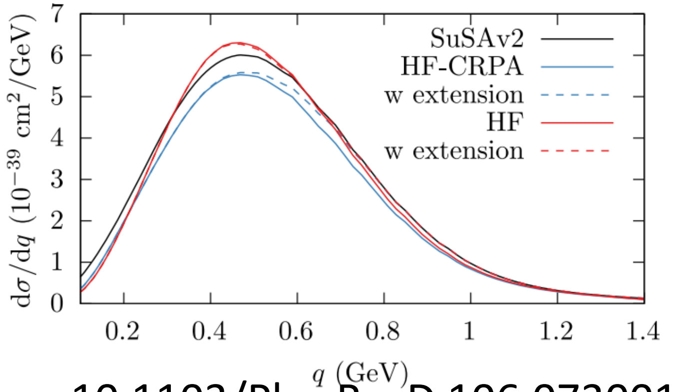
SF model is built on top of the PWIA -> FSI are not included

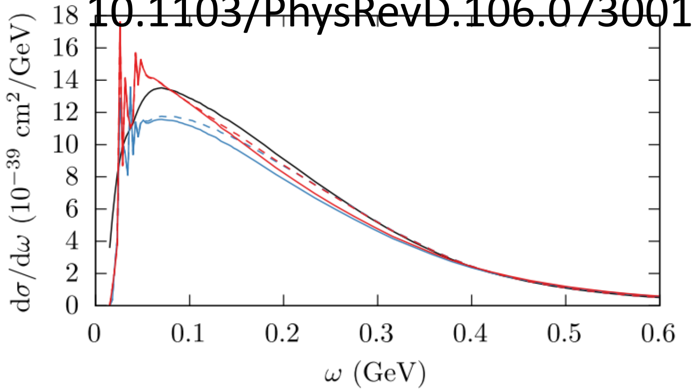
We account for CRPA and FSI by having reweighting based on
- CRPA-PW/HF-PW -> CRPA
- HF/HF-PW -> FSI

HF = Hartree Fock
PW = Plane Wave
CRPA = Continuum-Random Phase Approximation



Phys. Rev. D 101, 112004 (2020)



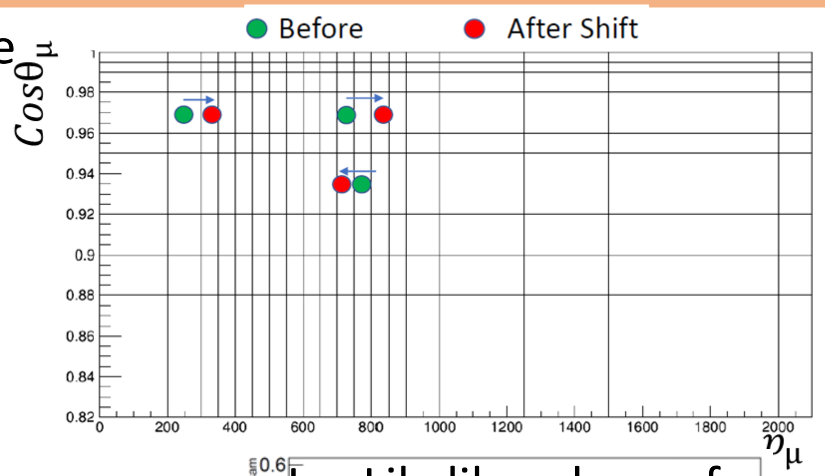


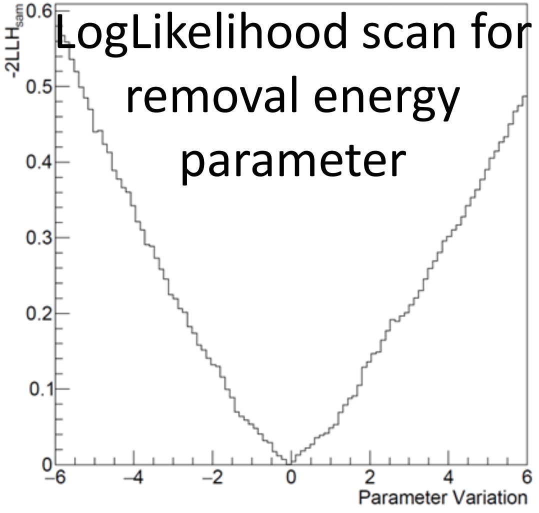
10.1103/PhysRevD.106.073001

Removal Energy (QE)

Removal Energy is implemented as Migration systematics – events can change bins

Result in discontinuous likelihood -> problematic





LogLikelihood scan for removal energy parameter

Removal Energy (QE)

Removal Energy is implemented as Migration systematics – events can change bins

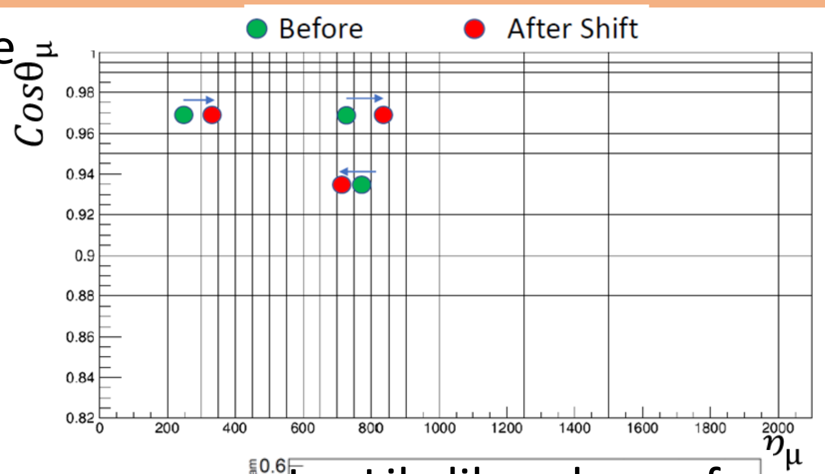
Result in discontinuous likelihood -> problematic

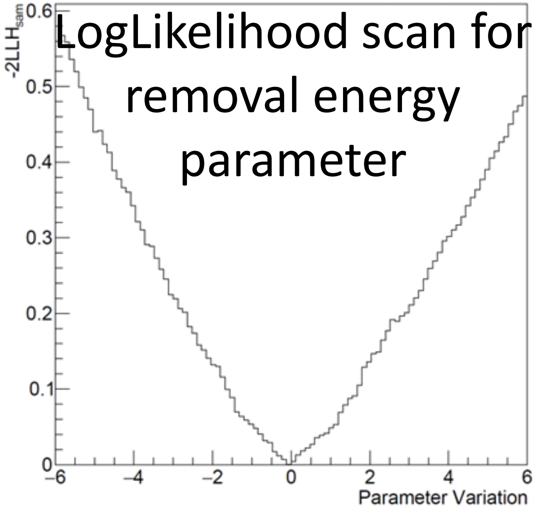
Two parameters affecting momentum shift

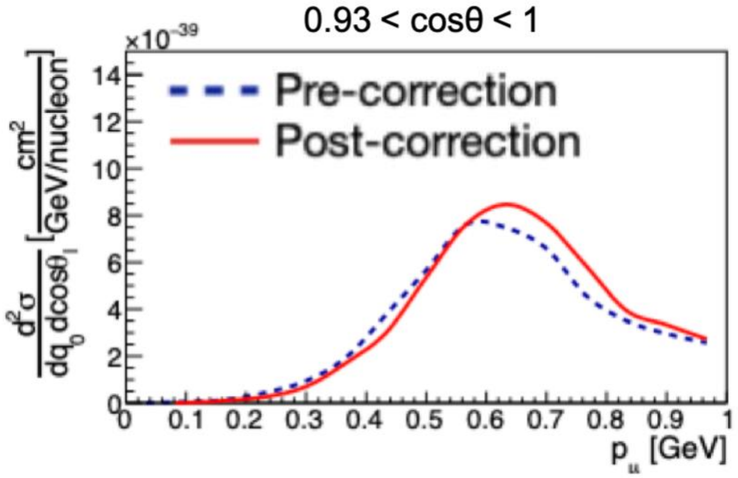
Delta actual removal Energy value

Alpha – correction based on electron scattering data based on arXiv:2301.09195v1

Feel like a fool after Raul's talk…







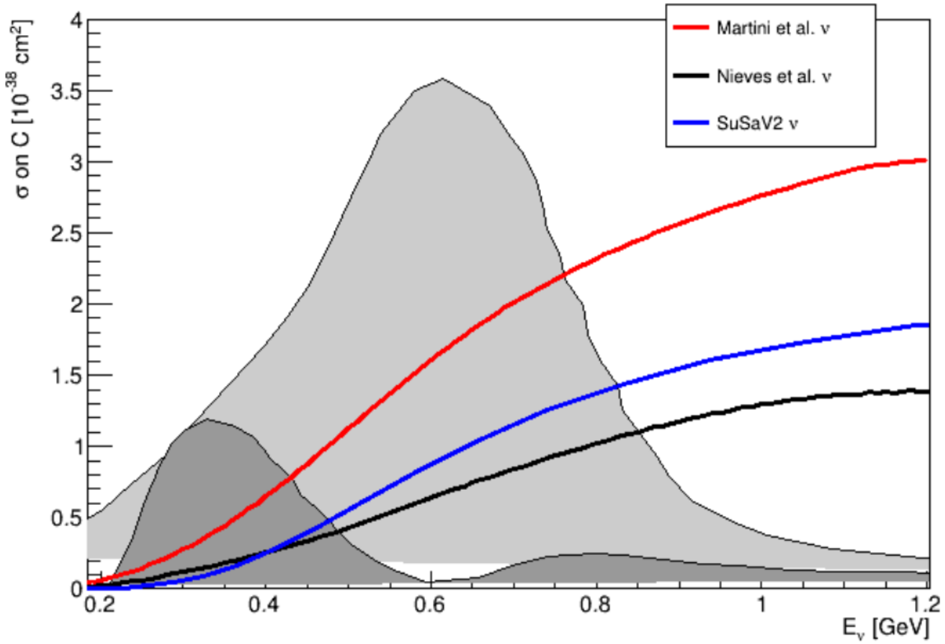
$$(\Delta E_{rmv})_{\nu,T} = \delta_{\nu,T} + \alpha(mq_3 + c)$$

MEC/2p2h

T2K Uses Hadron Tensor 2p2h Nieves model

The nuclear ground state is a local Fermi gas.

We have separate normalisation for ν and $\bar{\nu}$ with flat prior

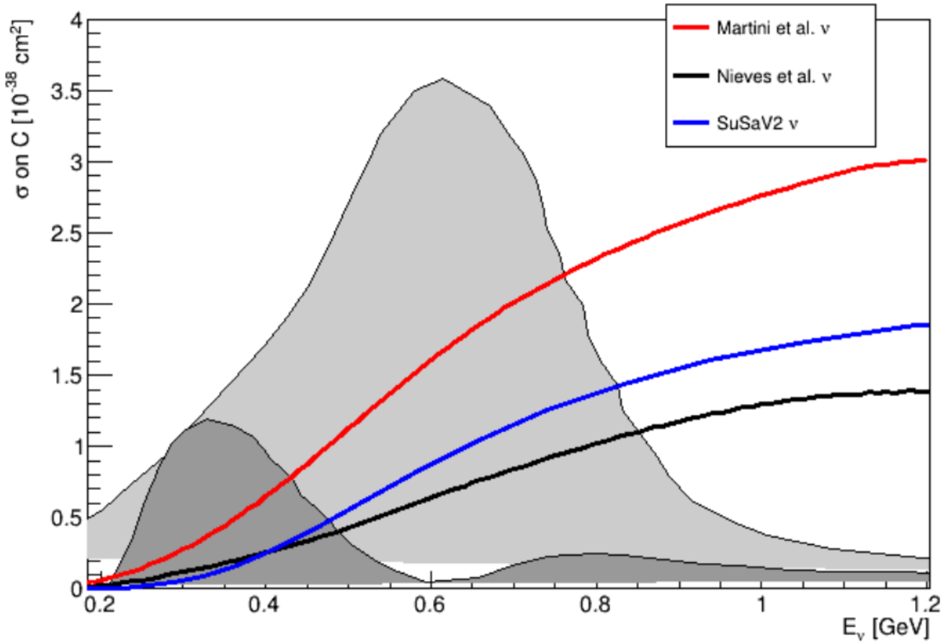


T2K Uses Hadron Tensor 2p2h Nieves model

The nuclear ground state is a local Fermi gas.

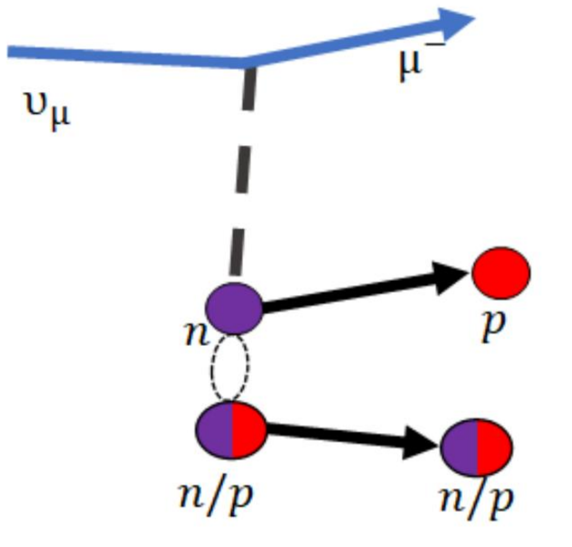
We have separate normalisation for ν and ν̅ with flat prior

Each generator has different shape of Enu -> freedom as function of Enu from Nieves to alternative models.



We have uncertainty allowing us to change fraction of pN to NN in 2p2h.

Nieves model provides cross-sections for both:
pN and NN initial states.

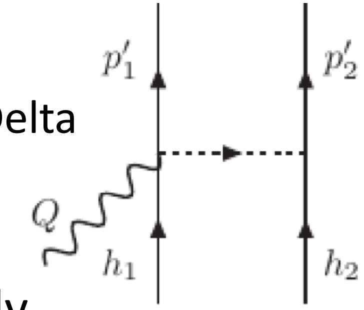


2p2h

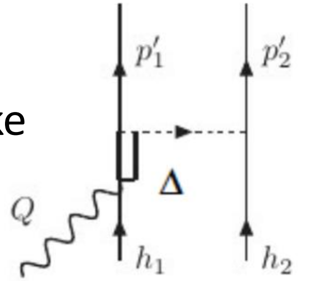
2p2h can be happen w or w/o delta propagator

Different predictions of q0/q3

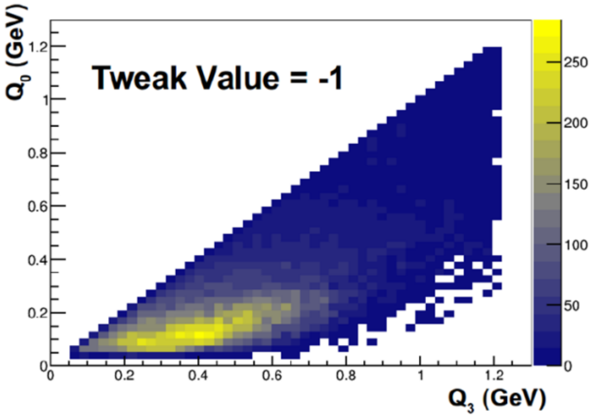
Non-Delta



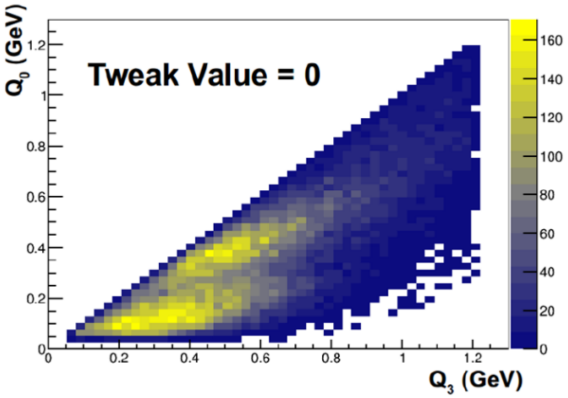
Delta-like



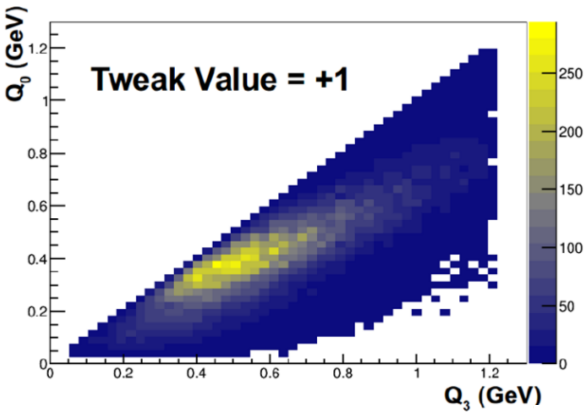
Non-Delta like only



Default

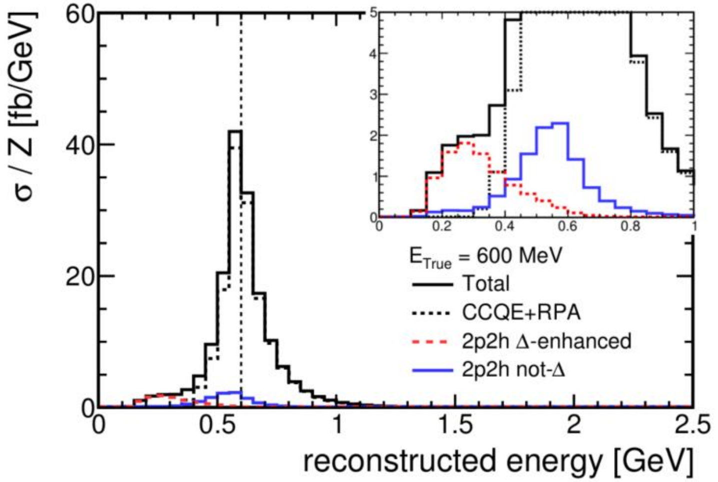


Delta-like only



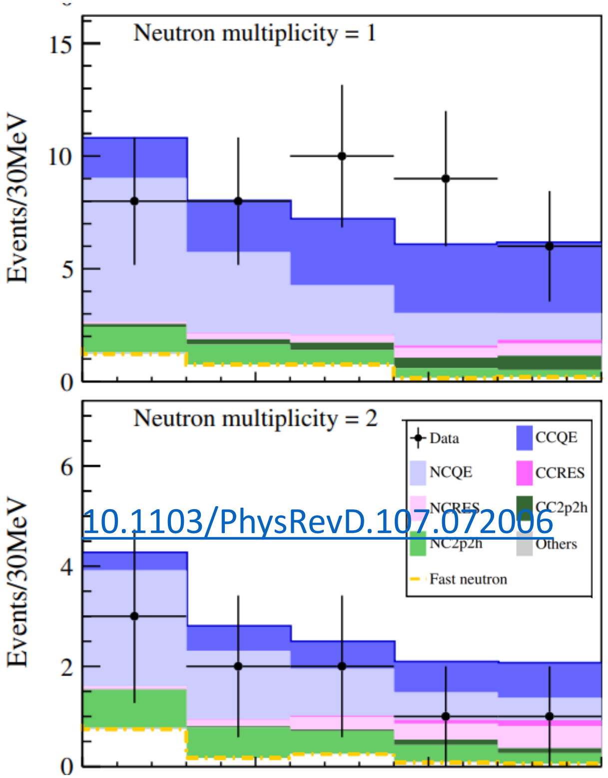
Can move separately each pair between Delta-like to Non-Delta like.

SK for 1 Ring sample -> assumes ν Energy with QE-like assumption -> systematic introduces bias

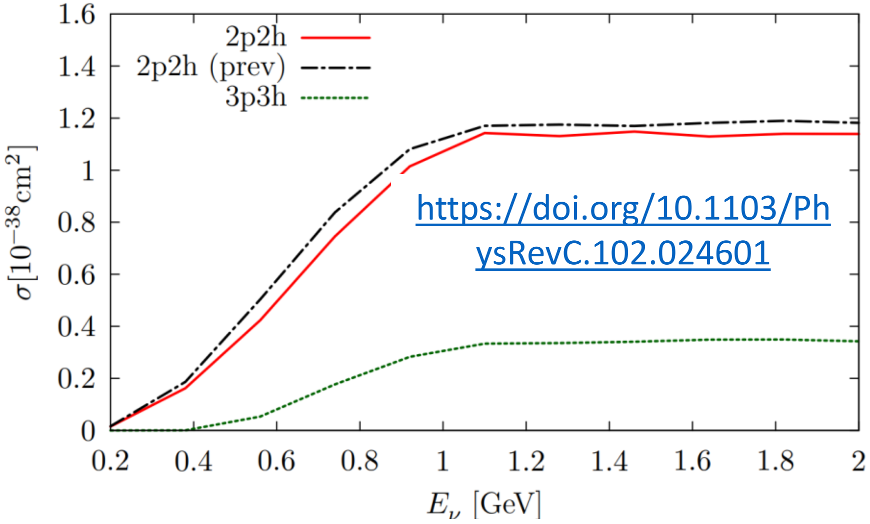


Missing bits

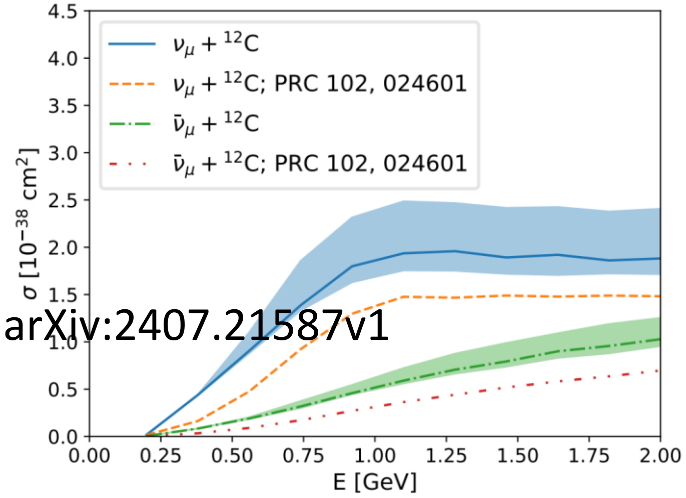
- 3p3h are missing in NEUT.
- NC 2p2h are missing. Alternative TEM model do have NC2p2h (available in NuWro)
- New prediction being 20-40% larger than before
- MEC and SRC (From SF QE) are fully uncorrelated



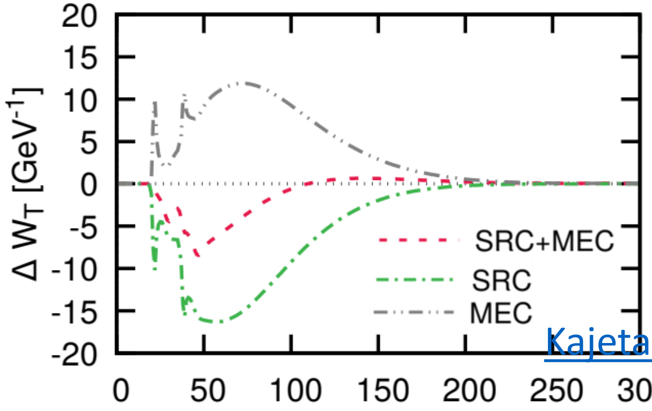
10.1103/PhysRevD.107.072006



https://doi.org/10.1103/PhysRevC.102.024601



arXiv:2407.21587v1



Kajetan Niewczas PhD Thesis

RES

CC Res

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

T2K uses Rein-Seghal model with Sobczyk and Graczyk parametrisation

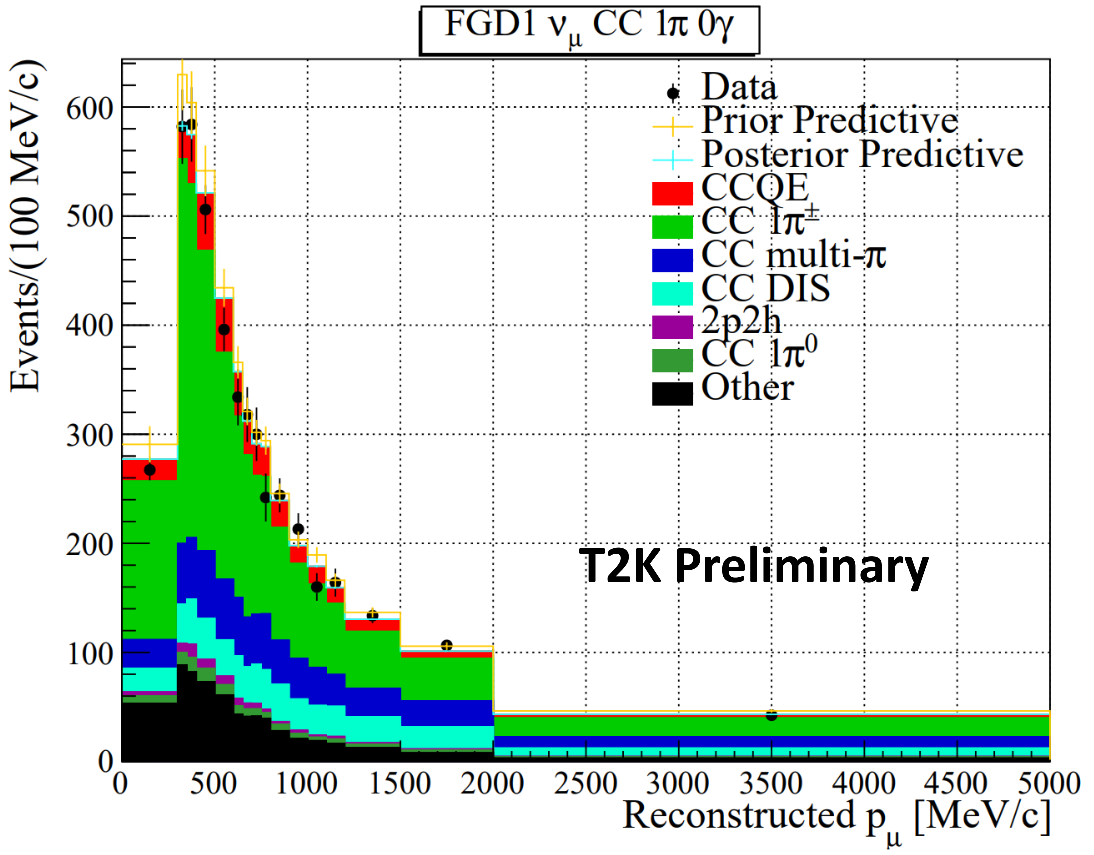
NEUT simulate non resonant BKG for spin ½. We have uncertainty accounting for size of this BKG

Use BNL and ANL data to tune these parameters

However not for spin 3/2, see Natalie's talk

Overall agreement for 1pi sample are good

For hadron agreement is quite poor several uncertainties related to it.

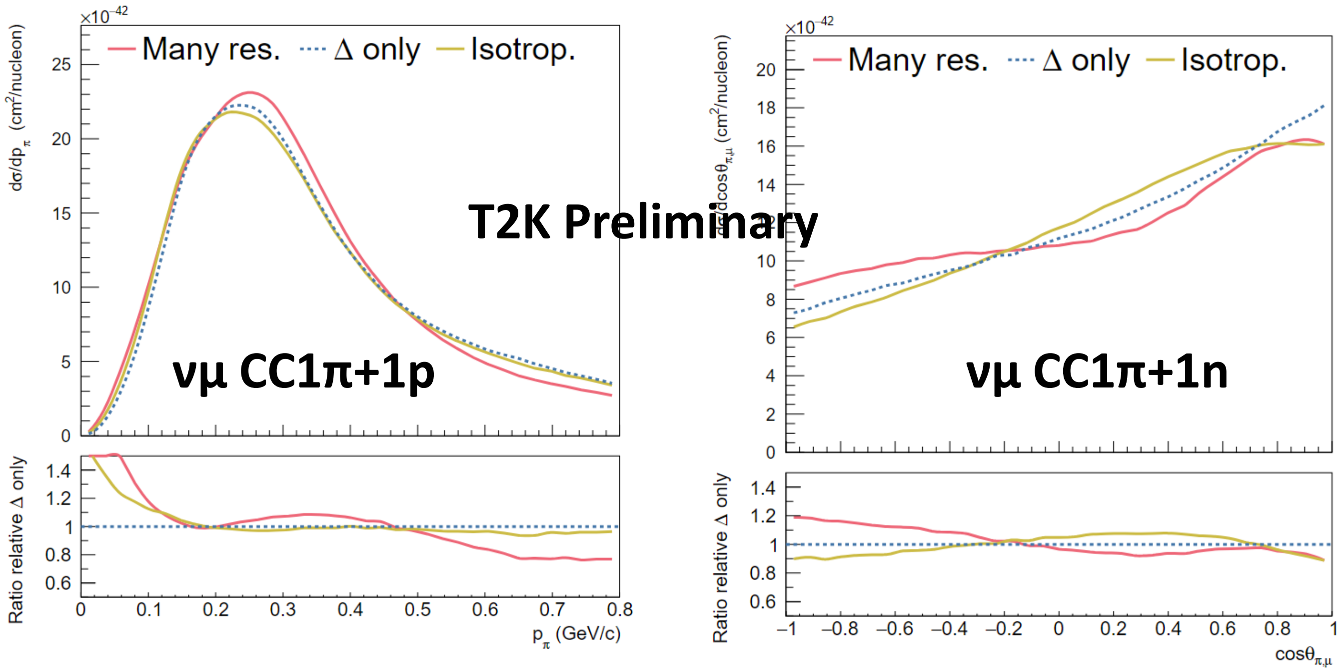


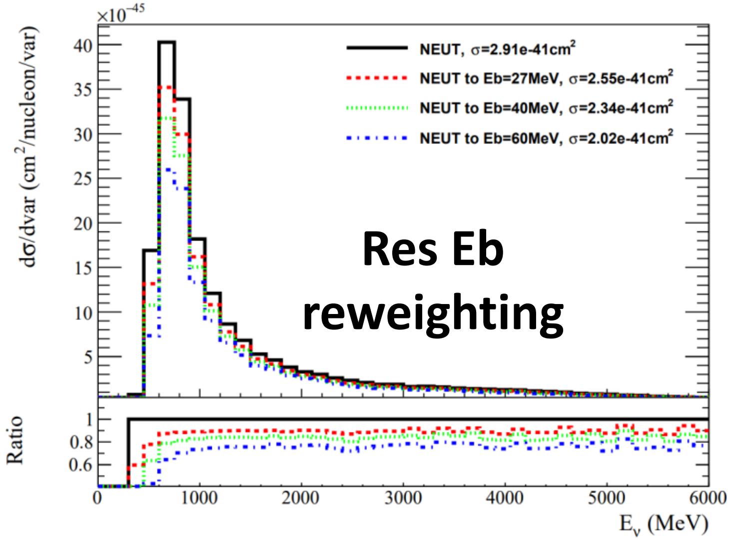
In T2K we account

Change type of delta resonance Decay.

Account for Res Eb via reweighting (based on NuWro response). NEUT doesn't have Eb for RES.

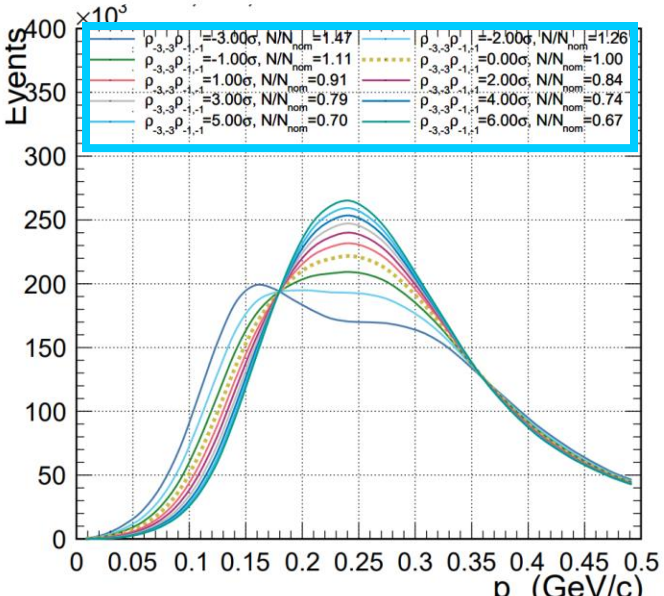
Apply Pi0 normalisation based on
- MINERvA CC1π+ and CC1π0
- MiniBooNE CC1π+ and CC1π0



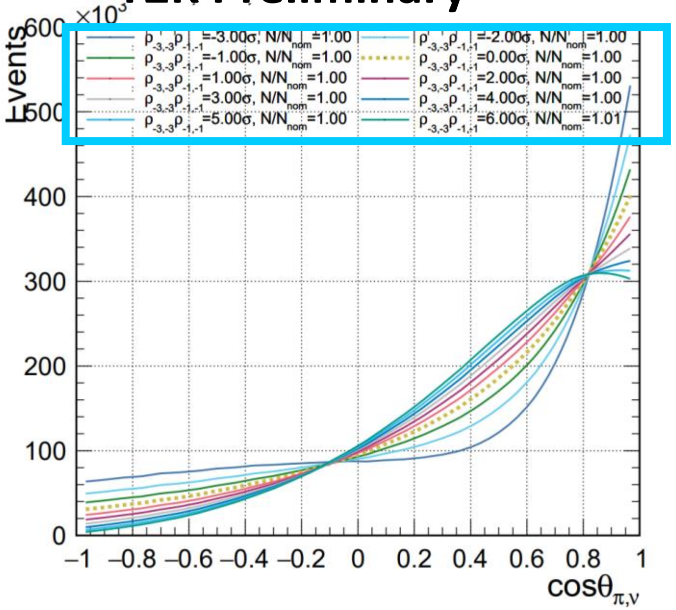


We have possibility to modify W by changing matrix elements (rho): [10.1016/0550-3213(86)90106-9]

This has visible impact on hadron kinematics.



T2K Preliminary



$$W^{\Delta}(\theta,\phi)=\frac{1}{\sqrt{4\pi}}\frac{1}{\tilde{\rho}}\left\{Y_0^0\tilde{\rho}-\frac{2}{\sqrt{5}}Y_0^2\left(\tilde{\rho}_{33}-\frac{1}{2}\rho\right)+\frac{4}{\sqrt{10}}\left(\mathrm{Re}Y_1^2\mathrm{Re}\tilde{\rho}_{31}-\mathrm{Re}Y_2^2\mathrm{Re}\tilde{\rho}_{3,-1}\right)\right\}$$

$$\tilde{\rho}=\sum_{m=-l}^{m=+l}\rho_{m,m}=\rho_{+3,+3}+\rho_{+1,+1}+\rho_{-1,-1}+\rho_{-3,-3}$$

$$\tilde{\rho}_{+3,+3}=\rho_{+3,+3}+\rho_{-3,-3}$$

$$\tilde{\rho}_{+3,+1}=\rho_{+3,+1}-\rho_{-1,-3}$$

$$\tilde{\rho}_{+3,-1}=\rho_{+3,-1}+\rho_{+1,-3}$$

Multiplicative

In T2K analyses we use 1D response functions.

Assumes that we can factorise weights

w(x,y) ?= w(x)*w(y)

$$W^{\Delta}(\theta, \phi) = \frac{1}{\sqrt{4\pi}} \frac{1}{\tilde{\rho}} \left\{ Y_0^0 \tilde{\rho} - \frac{2}{\sqrt{5}} Y_0^2 \left(\tilde{\rho}_{33} - \frac{1}{2}\rho \right) + \frac{4}{\sqrt{10}} \left(\mathrm{Re} Y_1^2 \mathrm{Re} \tilde{\rho}_{31} - \mathrm{Re} Y_2^2 \mathrm{Re} \tilde{\rho}_{3,-1} \right) \right.$$

$$\tilde{\rho} = \sum_{m=-l}^{m=+l} \rho_{m,m} = \rho_{+3,+3} + \rho_{+1,+1} + \rho_{-1,-1} + \rho_{-3,-3}$$

$$\tilde{\rho}_{+3,+3} = \rho_{+3,+3} + \rho_{-3,-3}$$

$$\tilde{\rho}_{+3,+1} = \rho_{+3,+1} - \rho_{-1,-3}$$

$$\tilde{\rho}_{+3,-1} = \rho_{+3,-1} + \rho_{+1,-3}$$

Non-Multiplicative

In T2K analyses we use 1D response functions.

Assumes that we can factorise weights

$$w(x,y) \;!\!= \; w(x)*w(y)$$

Matrix elements uncertainties are not used as nuisance parameters but as fake data study

In Fake Data Study we apply single weight which is combination of multiple variations avoiding problem

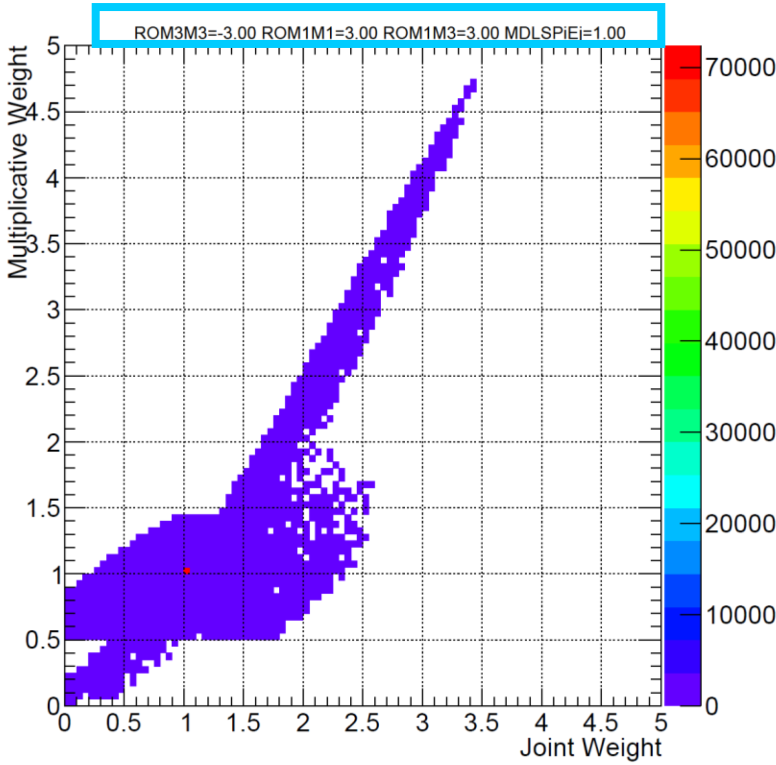
$$W^{\Delta}(\theta,\phi) = \frac{1}{\sqrt{4\pi}}\frac{1}{\tilde{\rho}}\left\{Y_0^0\tilde{\rho} - \frac{2}{\sqrt{5}}Y_0^2\left(\tilde{\rho}_{33} - \frac{1}{2}\rho\right) + \frac{4}{\sqrt{10}}\left(\mathrm{Re}Y_1^2\mathrm{Re}\tilde{\rho}_{31} - \mathrm{Re}Y_2^2\mathrm{Re}\tilde{\rho}_{3,-1}\right)\right.$$

$$\tilde{\rho} = \sum_{m=-l}^{m=+l}\rho_{m,m} = \rho_{+3,+3} + \rho_{+1,+1} + \rho_{-1,-1} + \rho_{-3,-3}$$

$$\tilde{\rho}_{+3,+3} = \rho_{+3,+3} + \rho_{-3,-3}$$

$$\tilde{\rho}_{+3,+1} = \rho_{+3,+1} - \rho_{-1,-3}$$

$$\tilde{\rho}_{+3,-1} = \rho_{+3,-1} + \rho_{+1,-3}$$



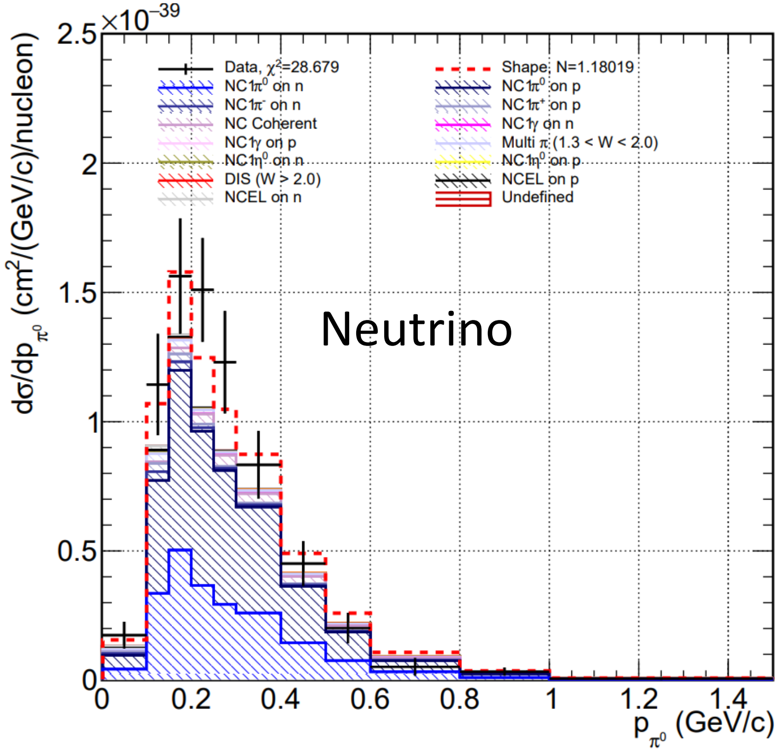
Missing NCPi0

NEUT underestimates NCPi0 predictions.

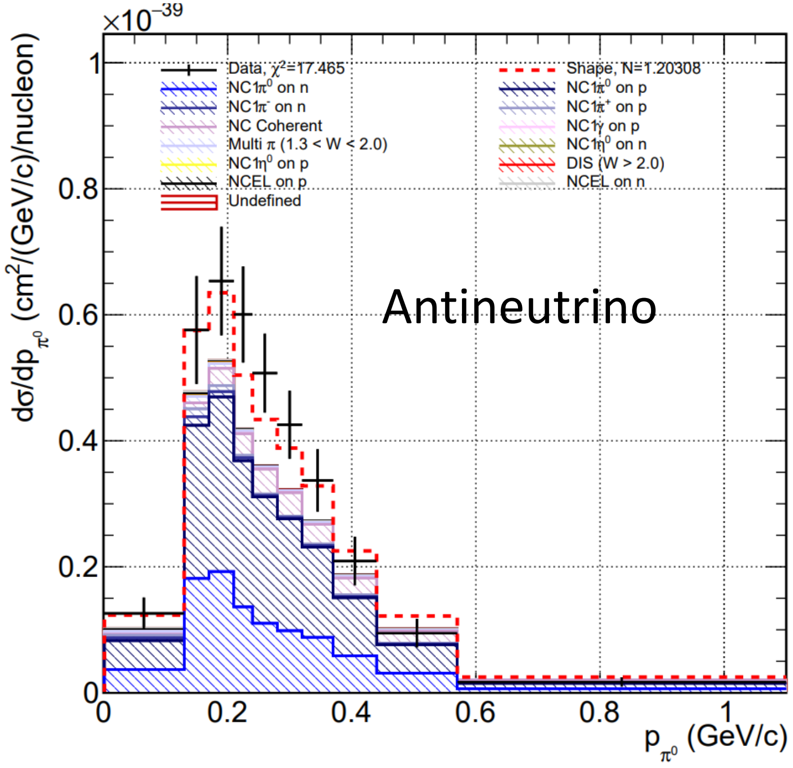
This usually isn't a problem for mainstream T2K analysis.

It was problem for T2K Beam+SK ATM Joint Fit analysis arXiv:2405.12488

There additional normalisation uncertainty has been used



MiniBooNE NCPi0 measurement



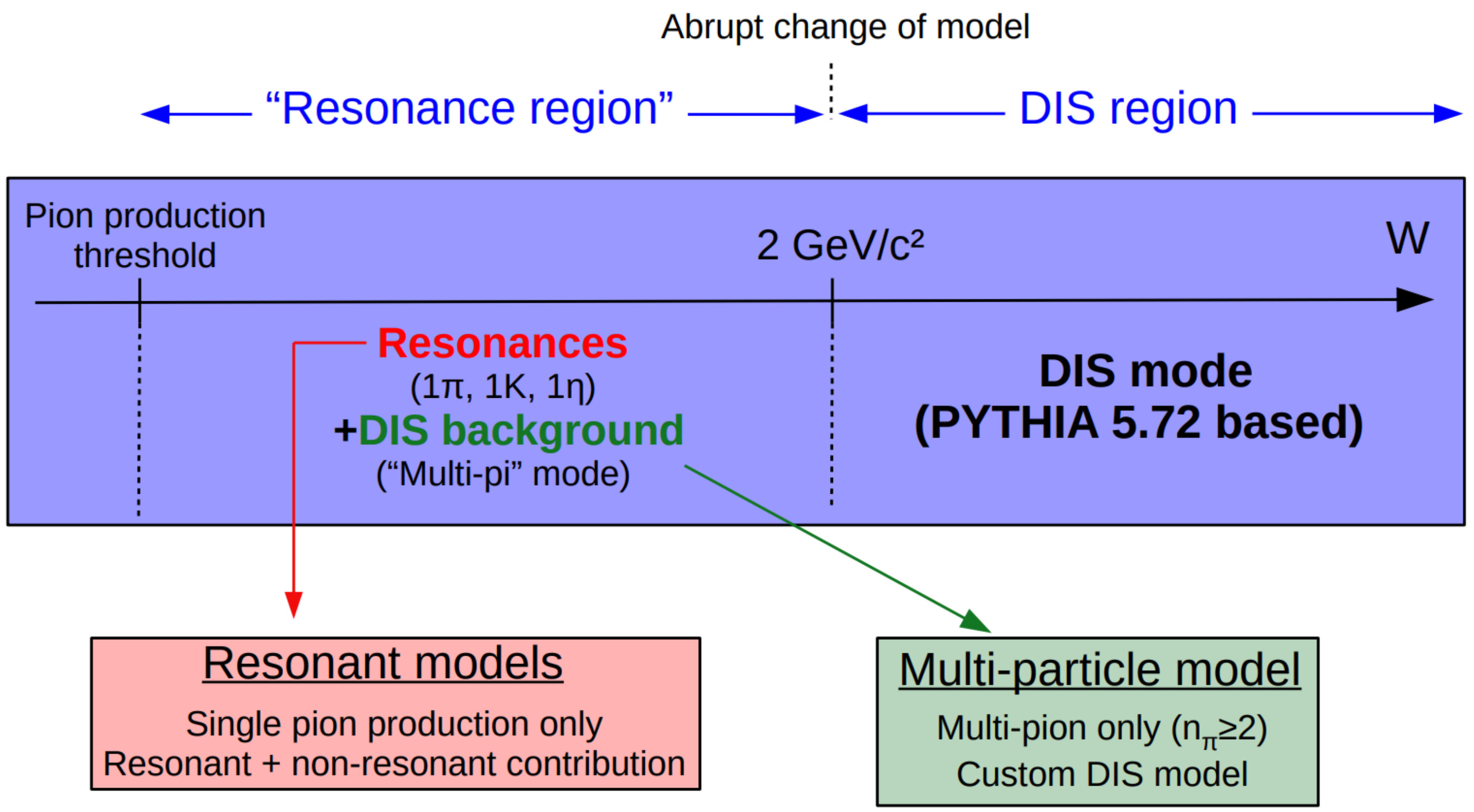
DIS

DIS

- Custom NEUT dis for low W.
- Pythia for high W

General normalisation for DIS (nu/nubar)

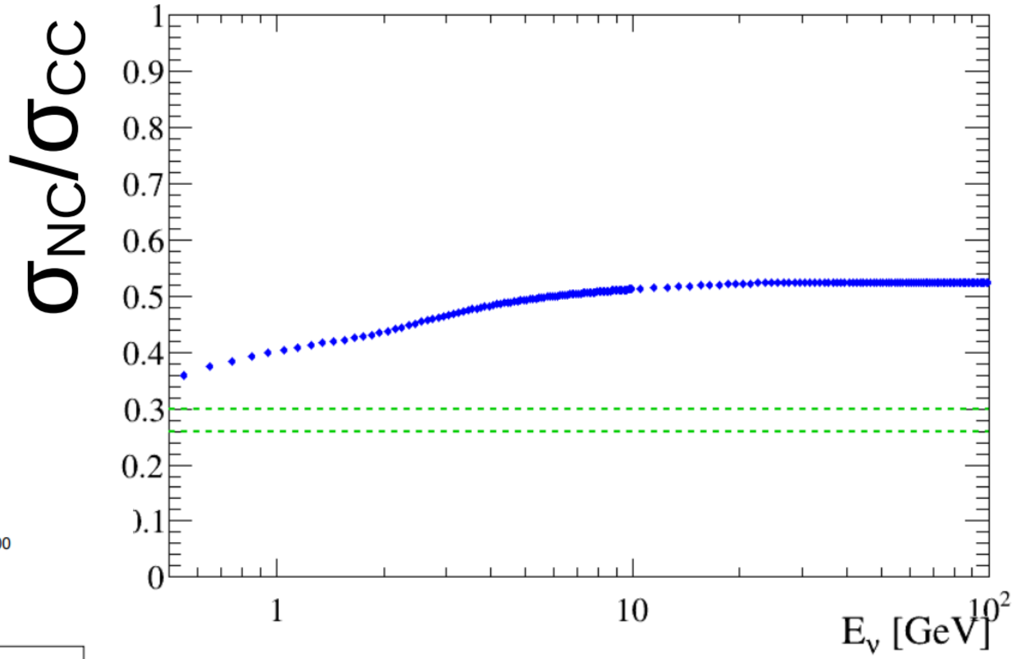
Several Bodek-Yang (BY) dials, affecting separately Low W and high W region and separately CC and NC.

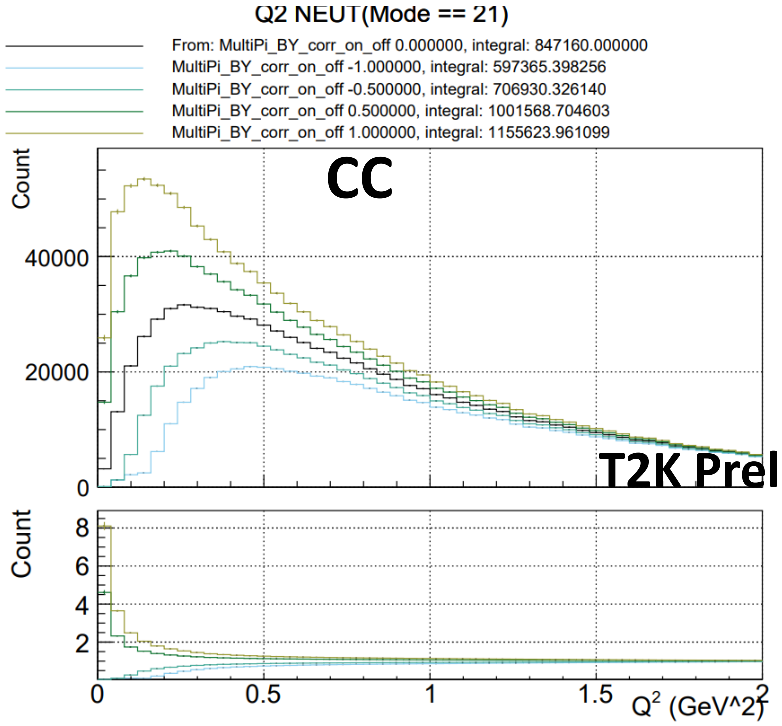


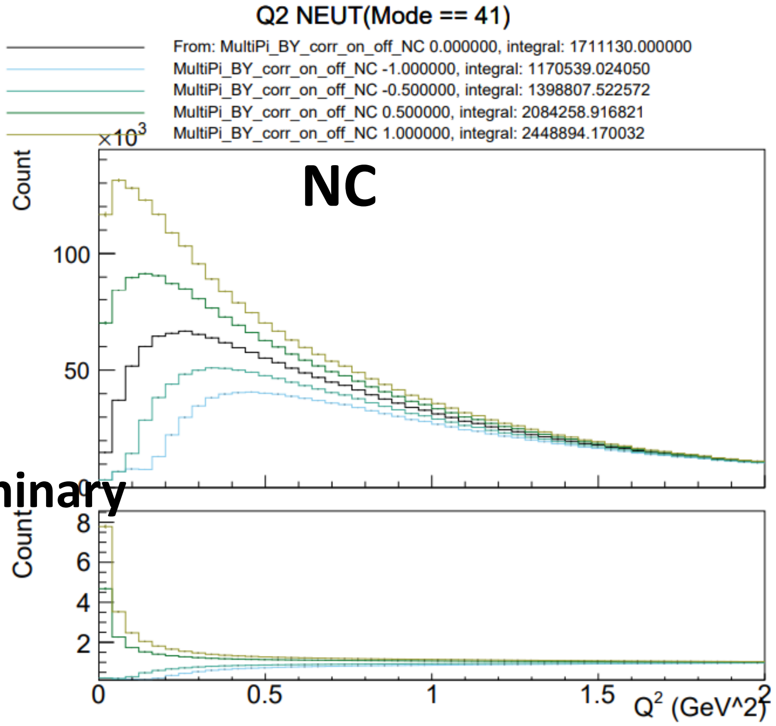
https://indico.cern.ch/event/881216/contributions/5073439/attachments/2533875/4360413/NEUT_DIS_NuINT2022.pdf

CC vs NC DIS

Since recently NEUT have proper calculation of NC DIS
- use Z0 propagator instead of W for NC
- use proper structure functions (eq 16.18 of PDG2011)







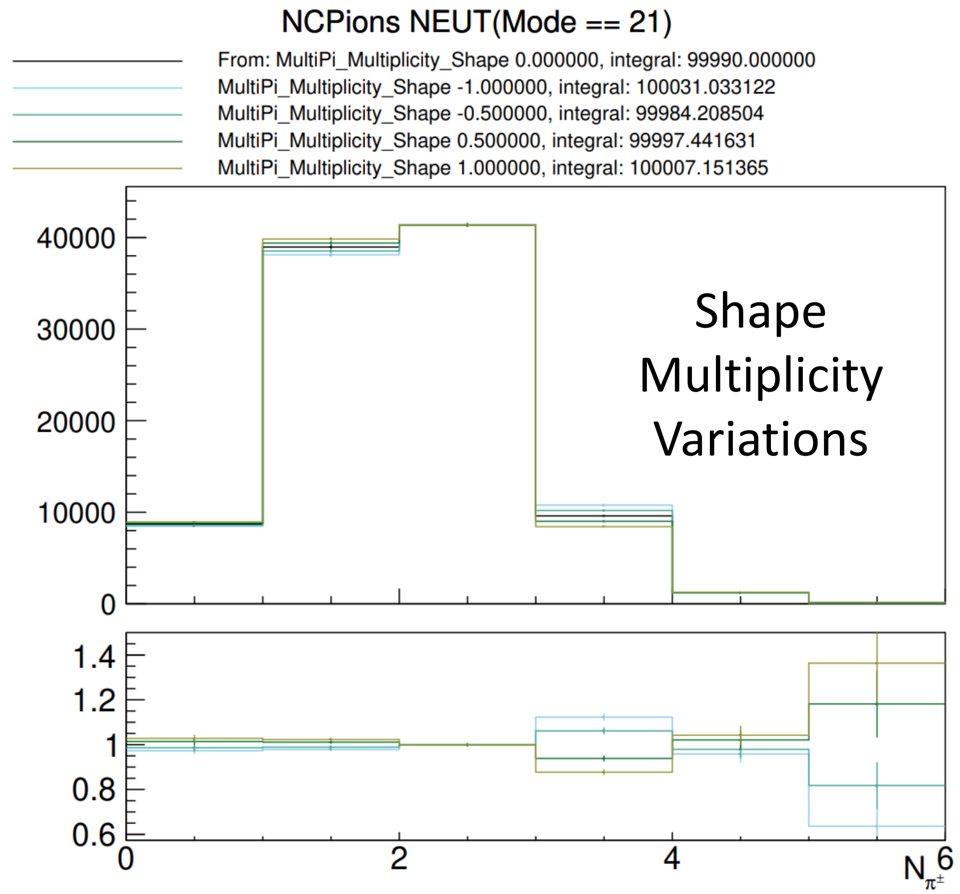
T2K Preliminary

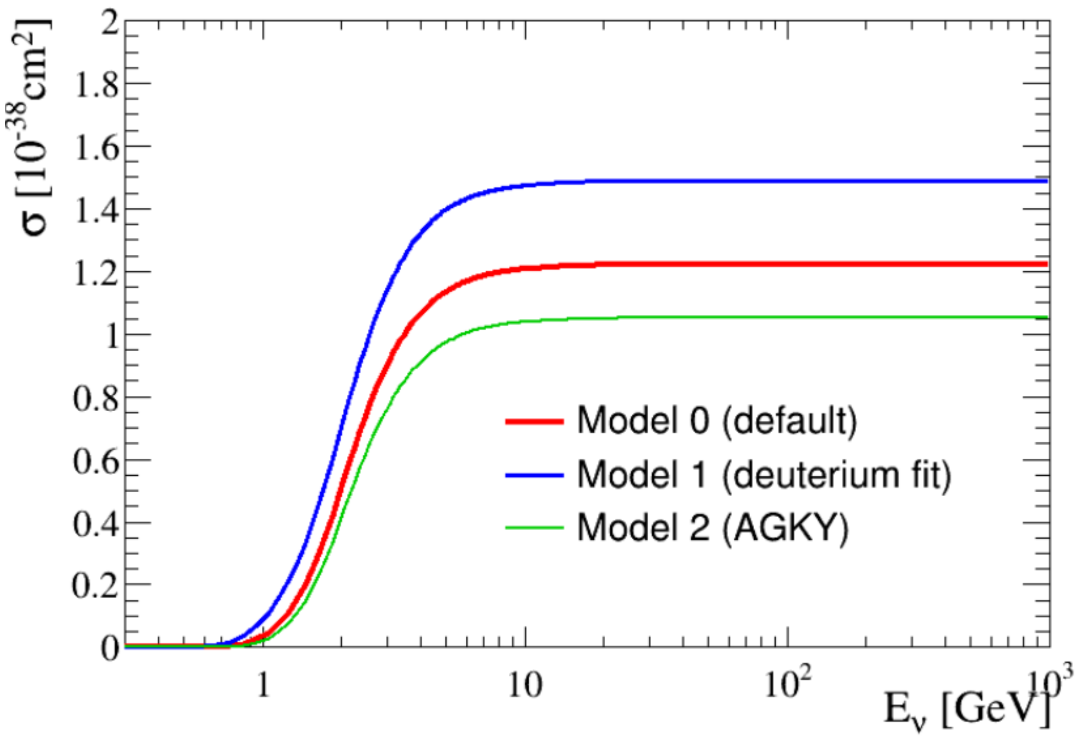
We have separate BY uncertainties for CC and NN

Multiplicity models

Account for different multiplicity models.

Reweighting from default to AGKY separately total cross-section and shape (W, pion multiplicity)



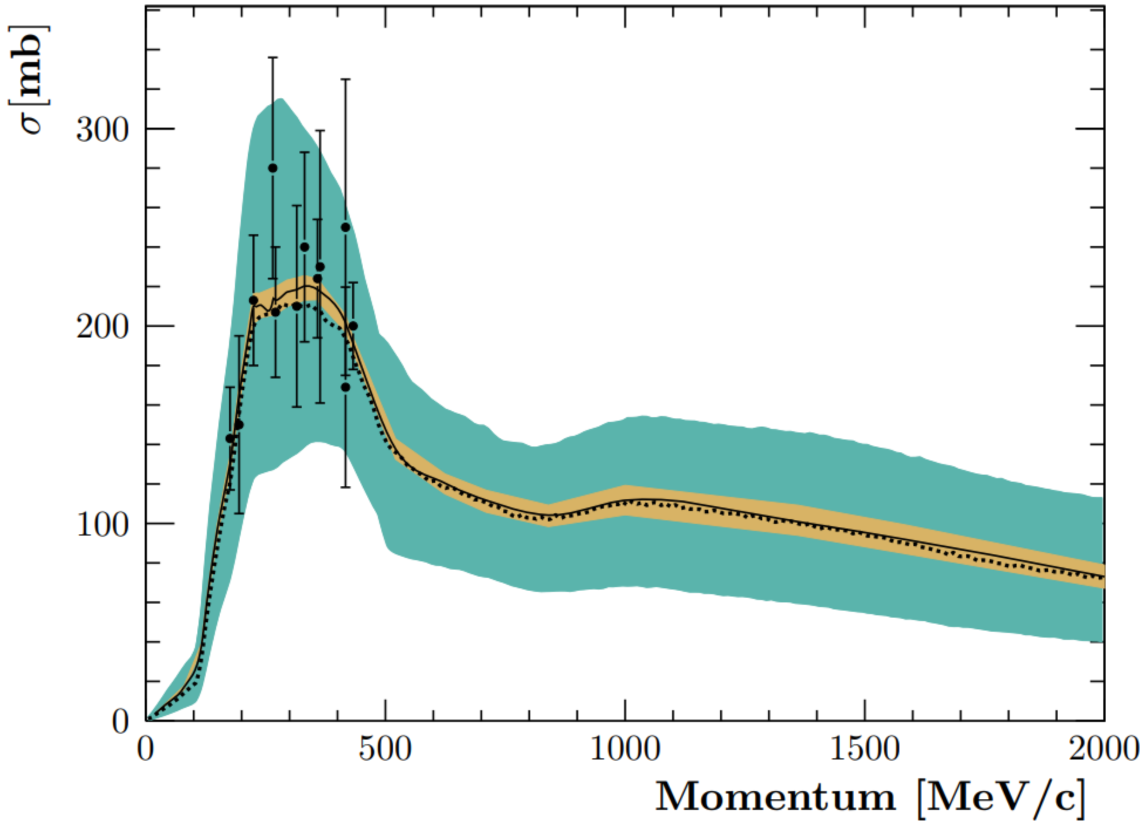


FSI

Pion FSI are simulated in NEUT using a semiclassical intranuclear cascade model

Cascade has been tuned based on DUET data with so called Elder-fit

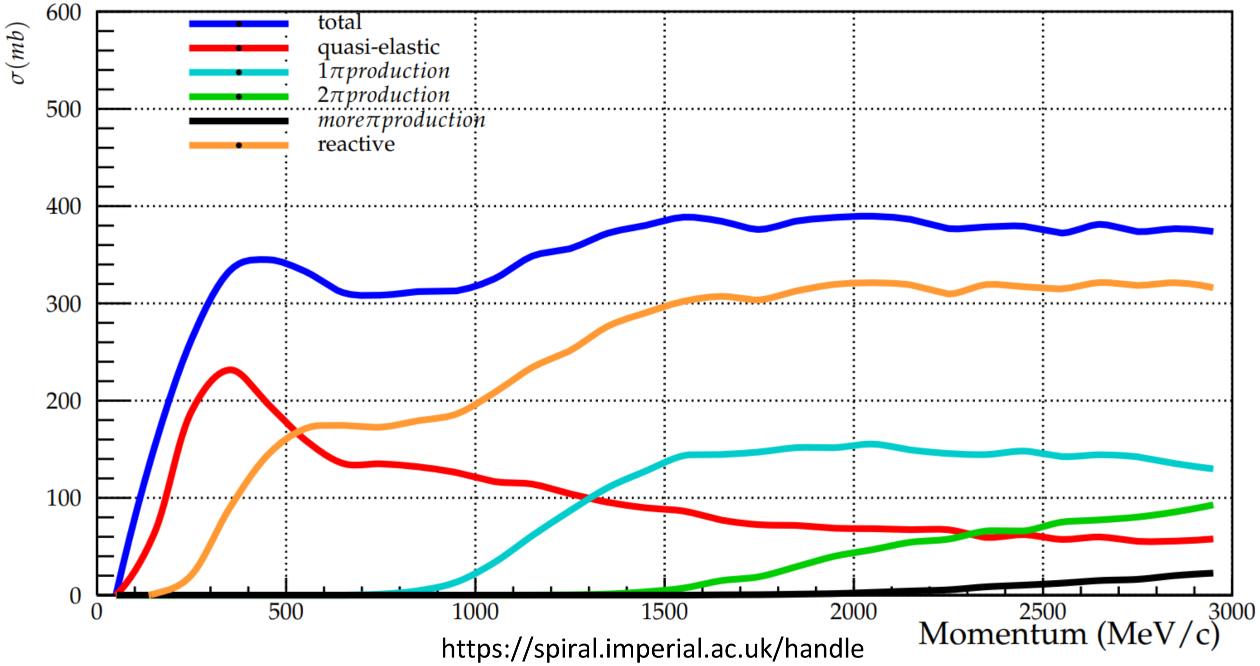
Parameter	Description	Momentum region [MeV/c]
f_{ABS}	Absorption	< 500
f_{QE}	Quasielastic scatter	< 500
f_{CX}	Single charge exchange	< 500
f_{QEH}	Quasielastic scatter	> 400
f_{CXH}	Single charge exchange	> 400
f_{INEL}	Hadron (N + $n\pi$) production	> 400



https://doi.org/10.1103/PhysRevD.99.052007

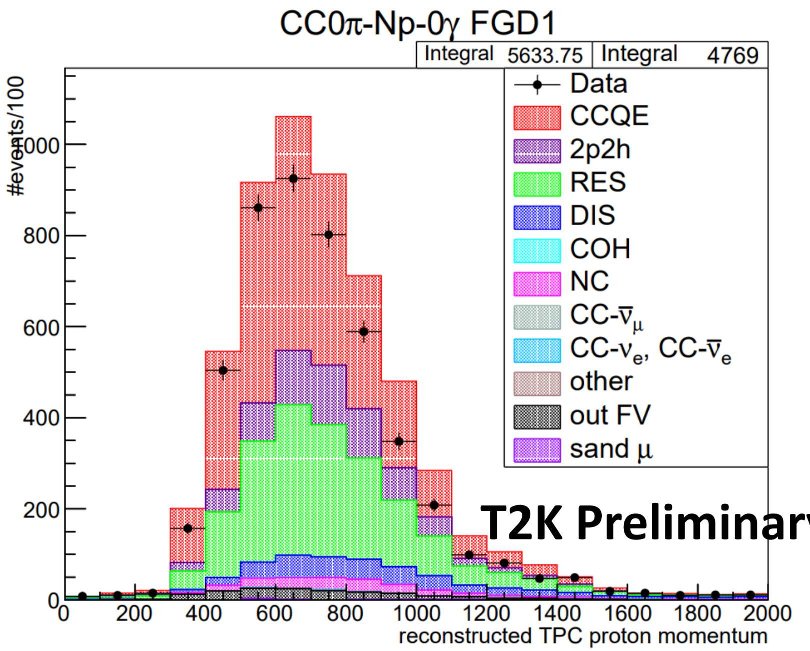
Final State Interactions Nucleons

Nucleon FSI are simulated in NEUT using a semiclassical intranuclear cascade model



https://spiral.imperial.ac.uk/handle/10044/1/85985

In T2K analysis we only use
total cross-section
1 pi production



T2K Preliminary

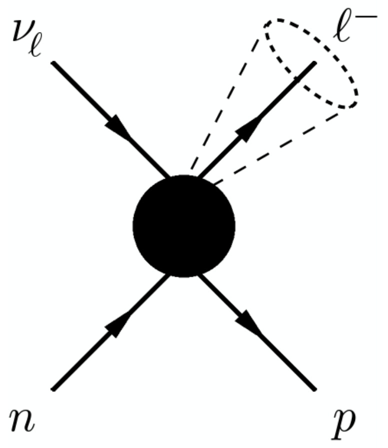
We don't use much protons with momentum higher than 1200 MeV

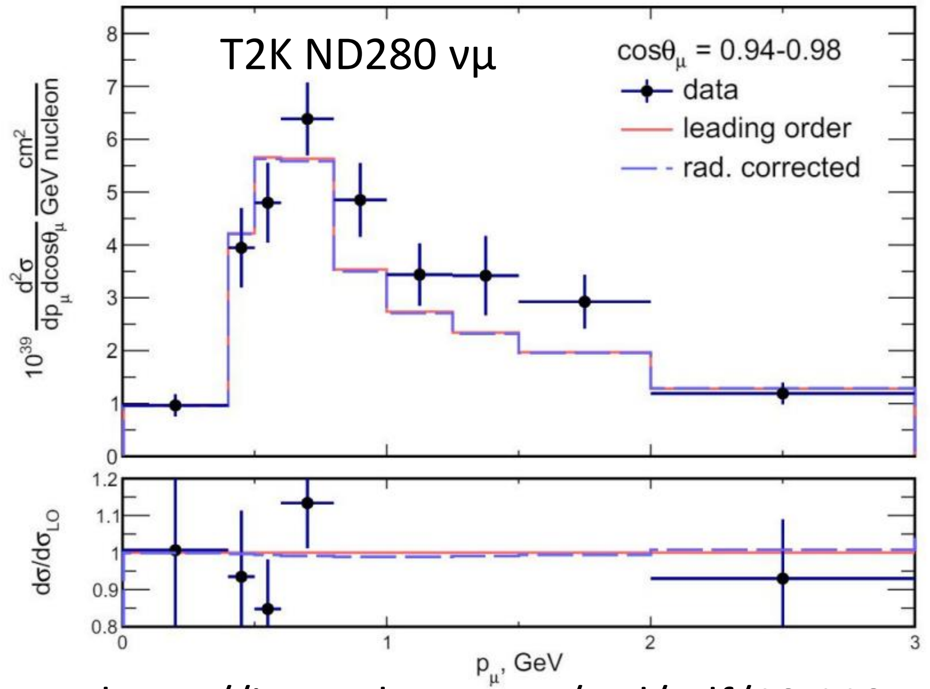
2π production is negligible for T2K

Radiative Correction

Collinear Photons can slightly distort observable properties in detector

It has minor impact on our predictions

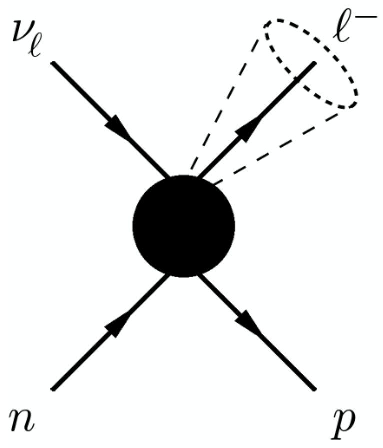


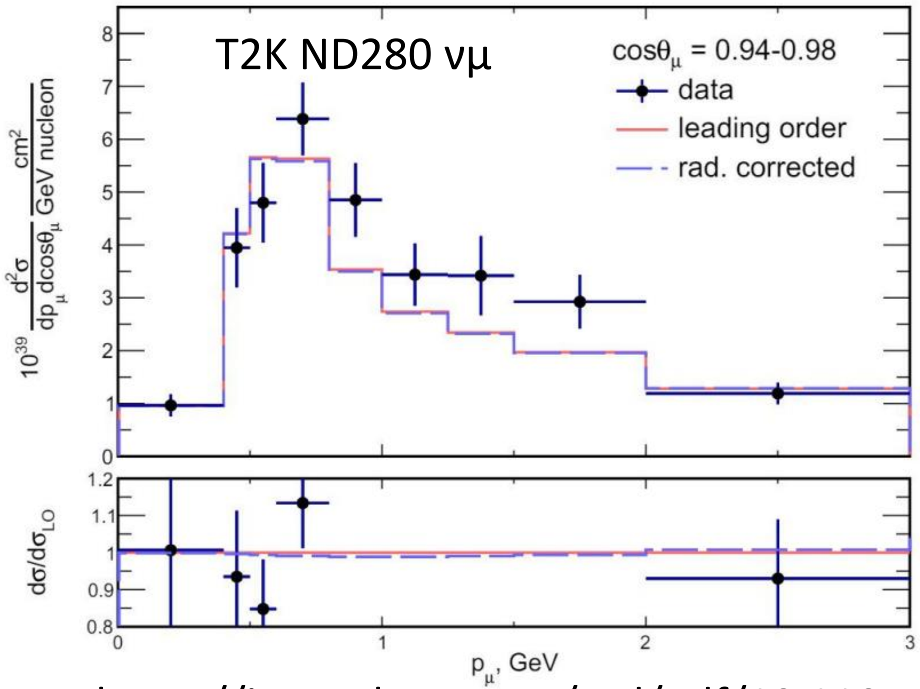


https://journals.aps.org/prd/pdf/10.1103/PhysRevD.106.093006

Collinear Photons can slightly distort observable properties in detector

It has minor impact on our predictions





https://journals.aps.org/prd/pdf/10.1103/PhysRevD.106.093006

Hard photons coming from radiative correction are energetic enough to be reconstructed. -> This can modify selection

Tested impact with Fake Data -> small

Missing proper simulation.

Other

Other

Normalisation parameters:

- Nue/NuMu normalisation ratio based on cross-section model differences: Phys. Rev. D 108, L031301
- Misc: CC RES K, η, γ and CC diffractive pion production
- NC1γ
- CC Coh
- NC Coh

Hyperion production and other rare channels are missing -> isn't a problem for main analysis but is a problem for more exotic cross-section measurements like Kaon production

Summary

Modelling of neutrino interactions in T2K is very robust.

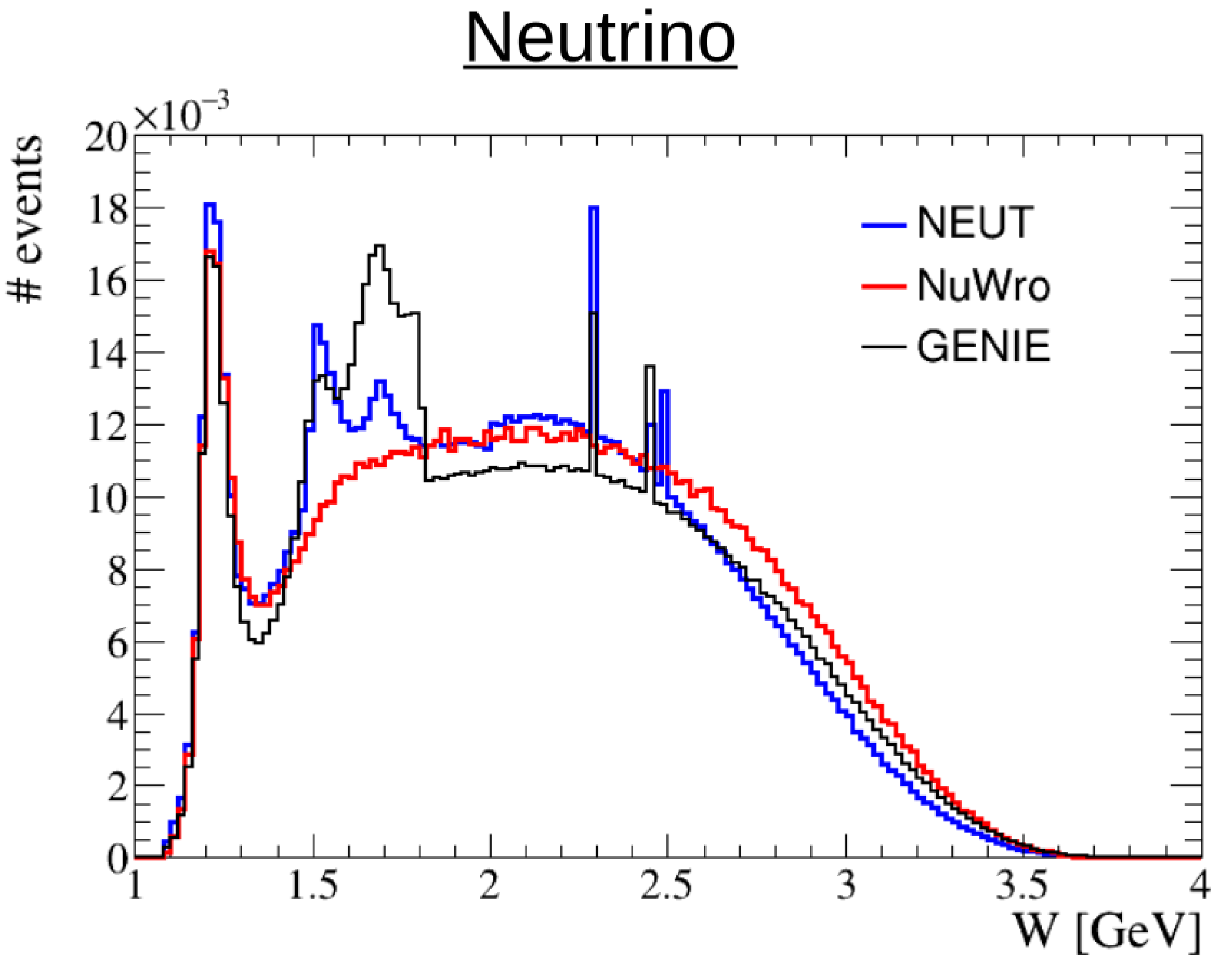
Some model unknowns are handled via Fake Data Studies.

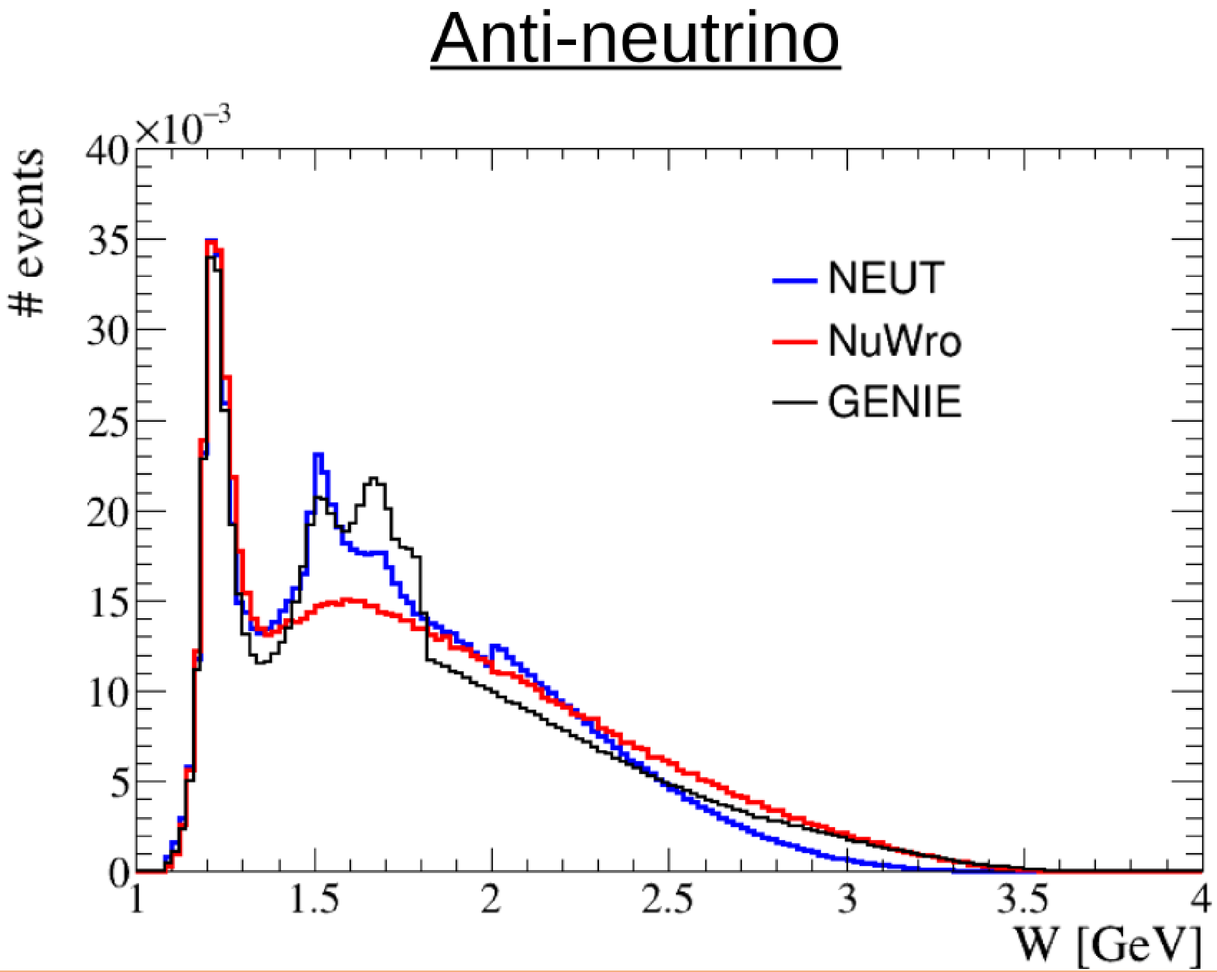
Still there is plenty to be improved.

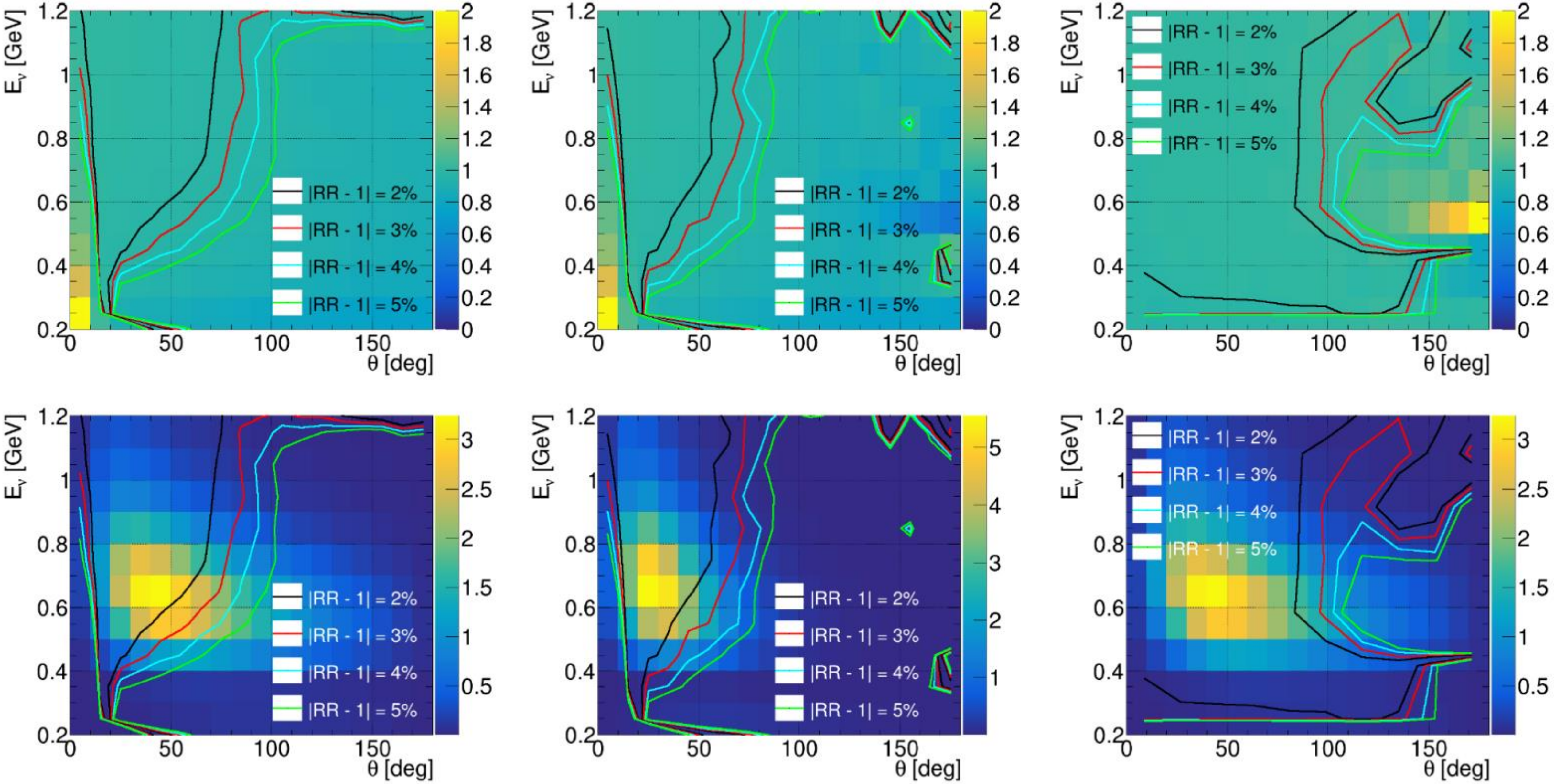
Hope this workshop will help improve treatment of uncertainties for current and future experiments.

Channel	Models	Uncertainties	Missing
QE	Ankowski, Benhar SF	Dipole form factor, robust SF description and CRPA/FSI implementation, Removal Energy,	Z-expansion etc
MEC	Nieves	HT prediction for each pair, general normalisations delta-like to non-delta like shape freedom	3p3h, NC 2p2h
SPP	Rein-Seghal, Graczyk-Sobczyk	Form factor and Res Eb for Reweighting and delta Decay shape type freedom. CC Pi0 normalisation	Spin 3/2 iso-scalar, NCpi0 norm issue
DIS	GRV98 PDF, BY correction, Pythia	Accounting for different multiplicity models and BY correction. Separate for CC and NC	Not understood W difference between generators
Final State Interactions	NEUT Cascade, Pinzon and Bertini	Reweighting for both nucleon and pion FSI	Doesn't account for alpha production as INCL model for example
Radiative Correction	Tomolak	Account for collinear photons	Missing robust simulation of hard photons

https://indico.cern.ch/event/881216/contributions/5073439/attachments/2533875/4360413/NEUT_DIS_NuINT2022.pdf





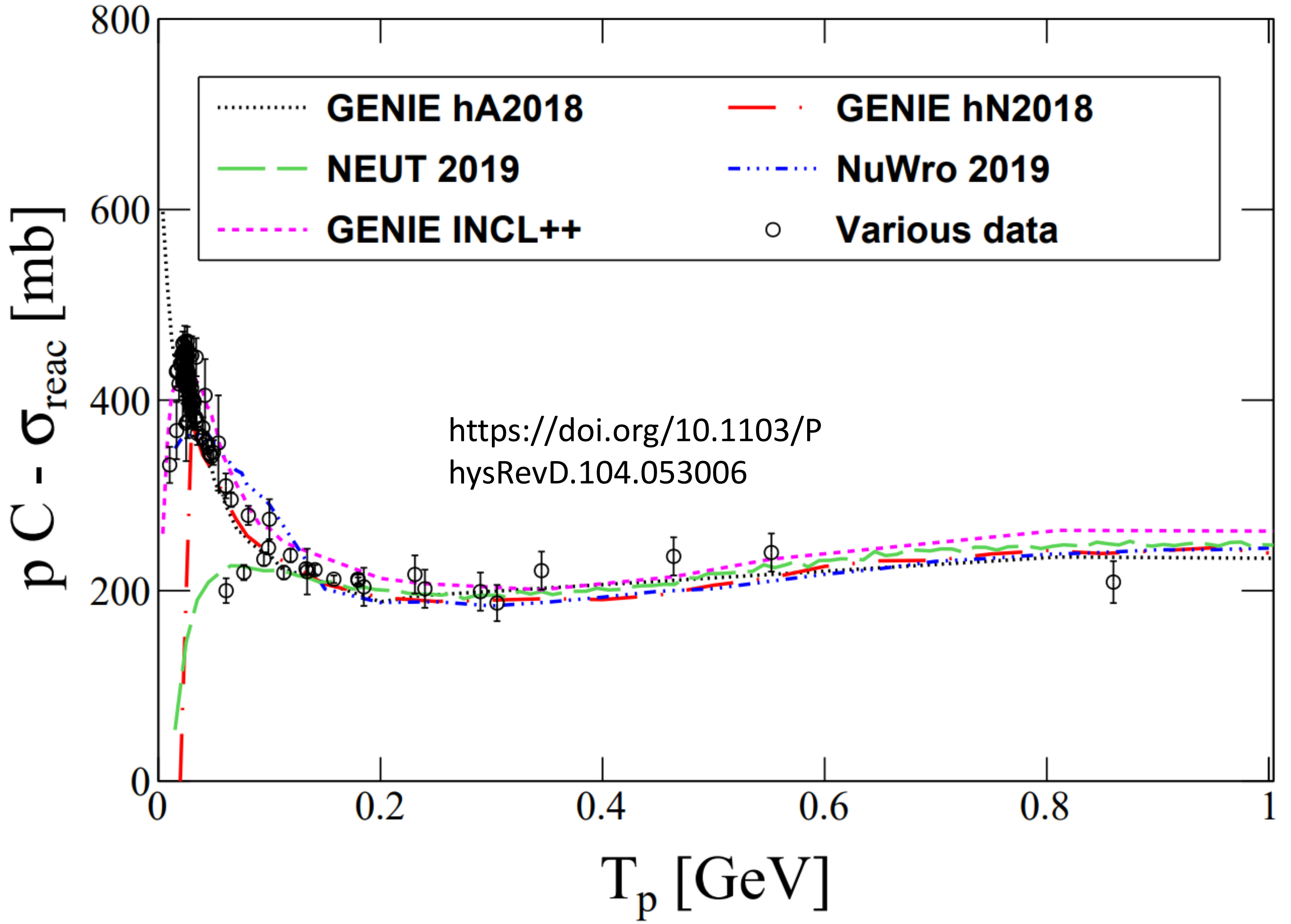


E_ν [GeV]
θ [deg]
|RR - 1| = 2%
|RR - 1| = 3%
|RR - 1| = 4%
|RR - 1| = 5%

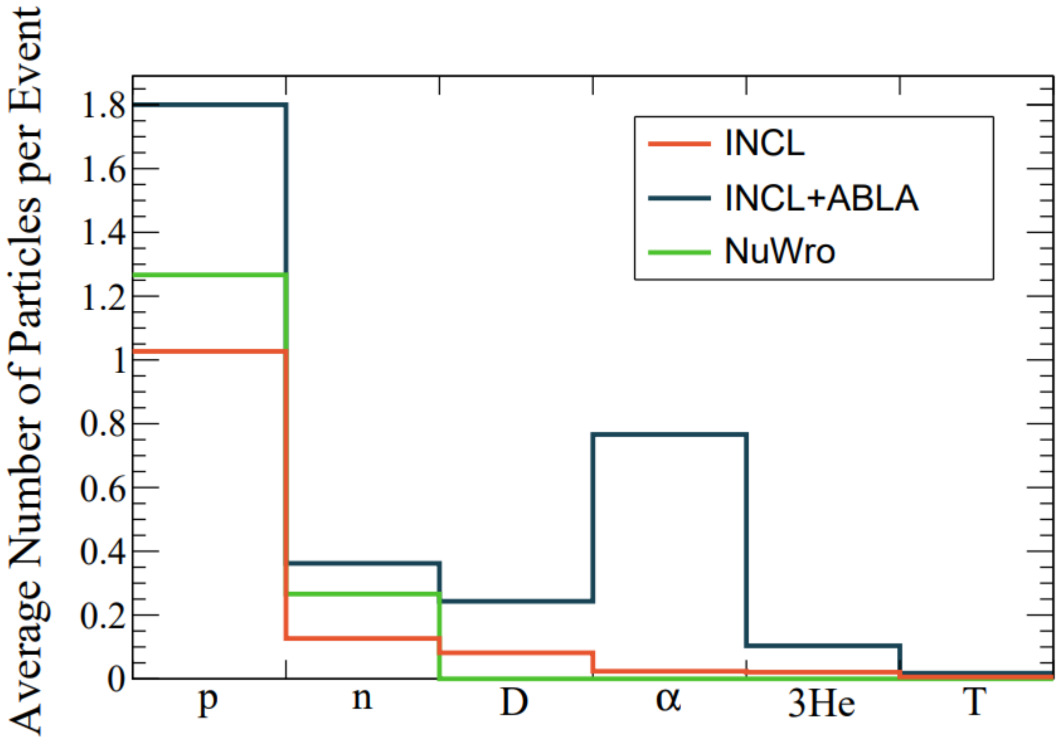
Final State Interactions Nucleons

NEUT compared with other generators is doing poor job at low kinetic energy

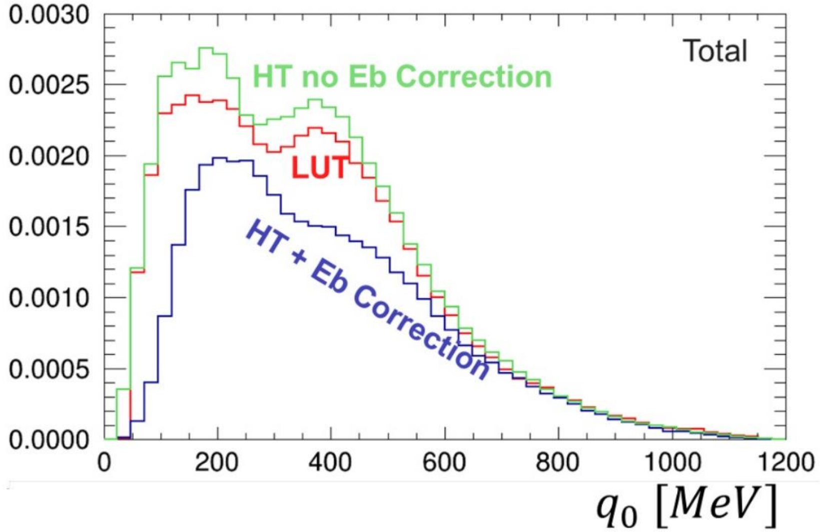
Xsec of nucleon scattering in nucleus by Bertini



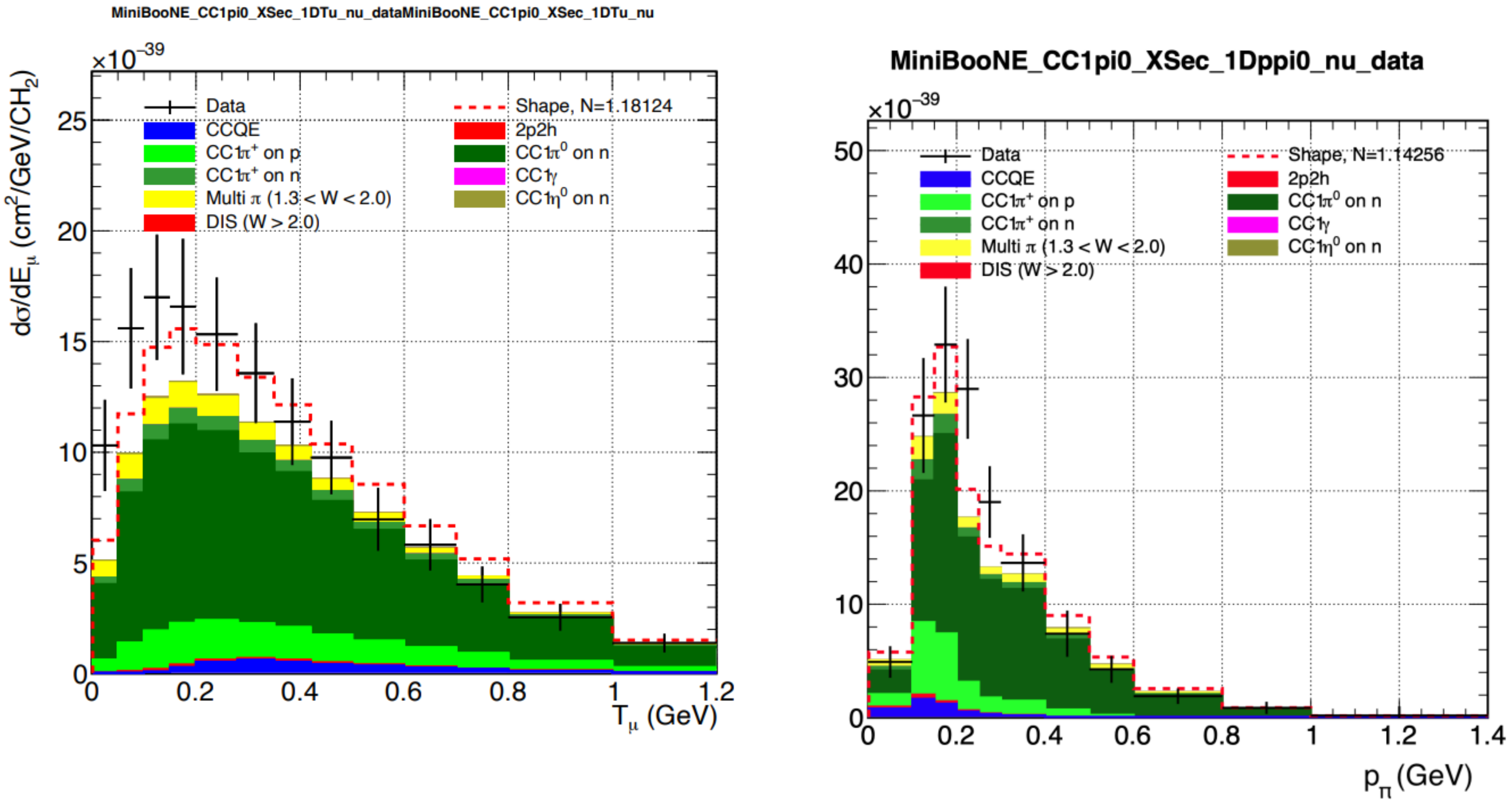
FSI Limitations



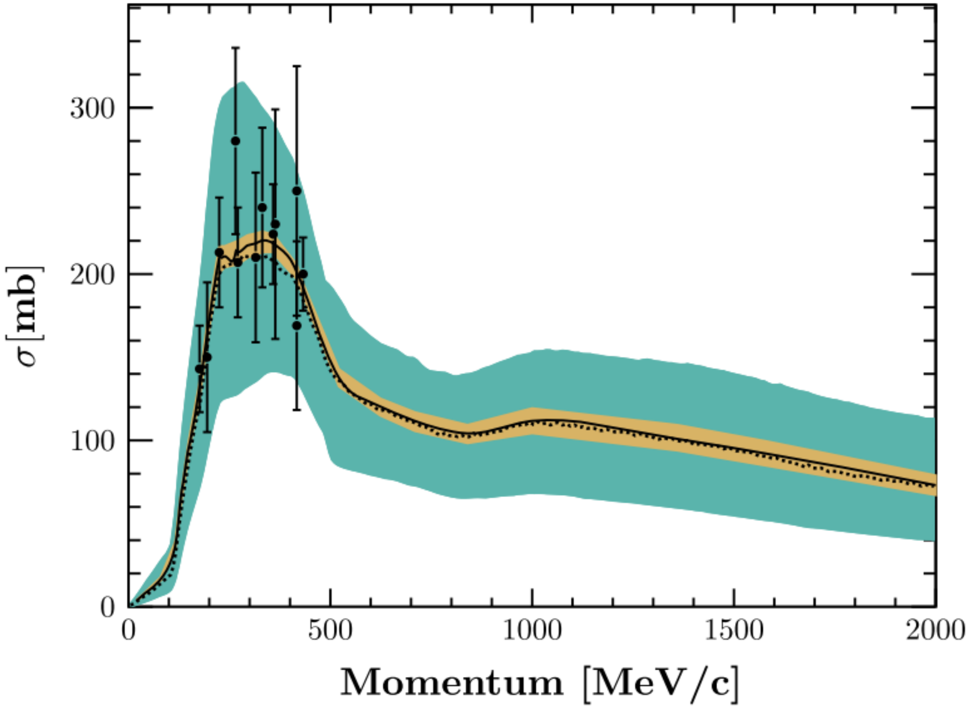
https://arxiv.org/pdf/2309.05410



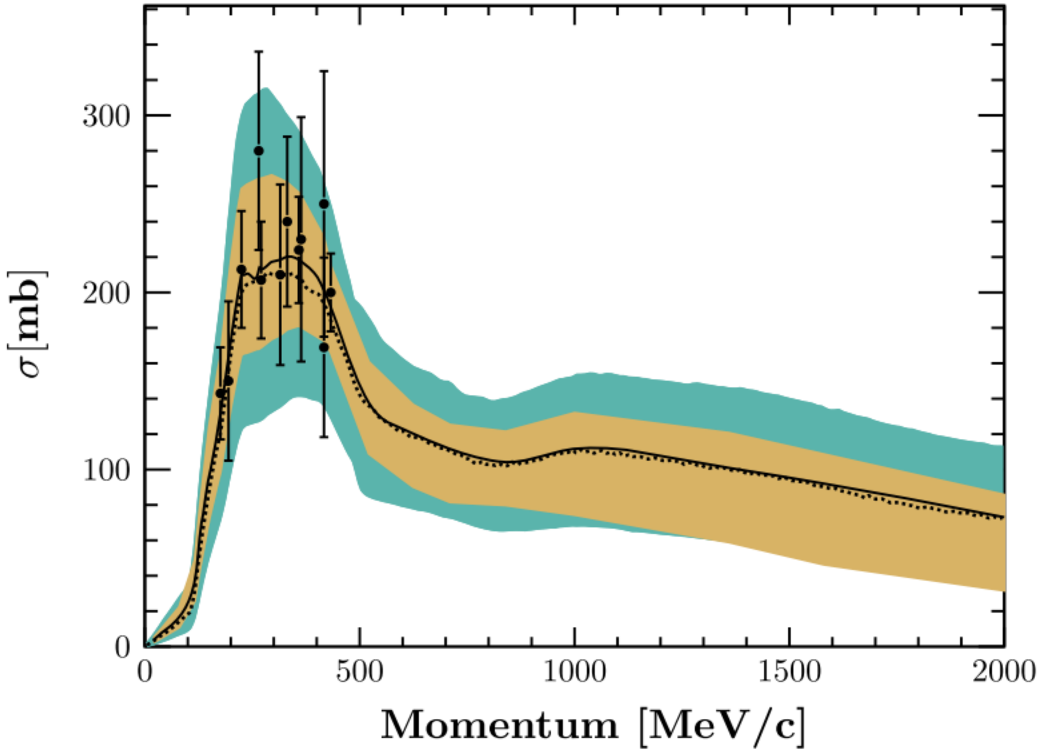
We account for Federico's correction to Eb via Fake Data Study [10.1007/JHEP04(2021)004]



(b) MiniBooNE CC1π^0



(b) Quasi-elastic



(b) Quasi-elastic