New constraints on nuclear models from T2K Near Detector Upgrade

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P2IO BSM-Nu Second Workshop
IJCLab, Orsay
April 11th, 2022

ÉCOLE POLYTECHNIQUE
INSTITUT POLYTECHNIQUE DE PARIS
IN2P3 Les deux infinis
Physique des 2 Infinis et des Origines

Outline

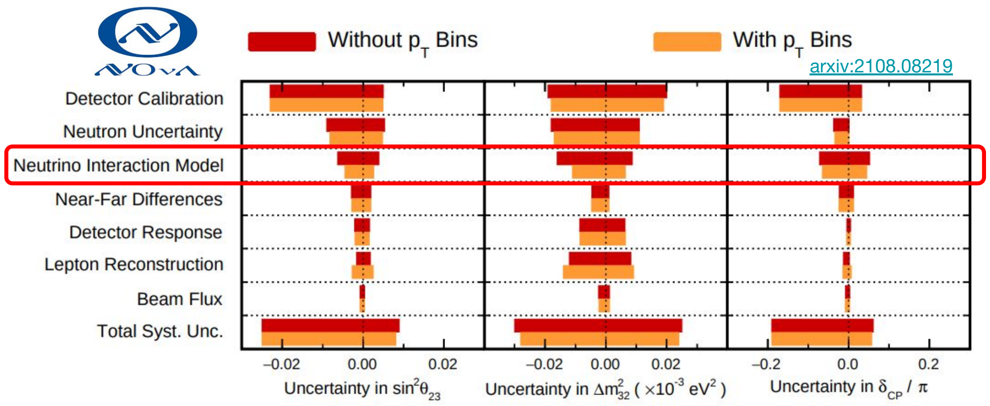
1. Introduction
2. Neutrino-nucleus interaction models
3. Systematic uncertainties and fits to cross section measurements
4. Projected constraints with T2K ND Upgrade
5. Summary and prospects

1. Introduction

Neutrino oscillations: the precision era *(See Ciro's presentation)*

- First hints of CP violation
- Currently: NOνA, T2K (w/ ND upgrade)
- Future: DUNE, Hyper-Kamiokande
- Still limited by statistics, but not for long!

DEEP UNDERGROUND NEUTRINO EXPERIMENT

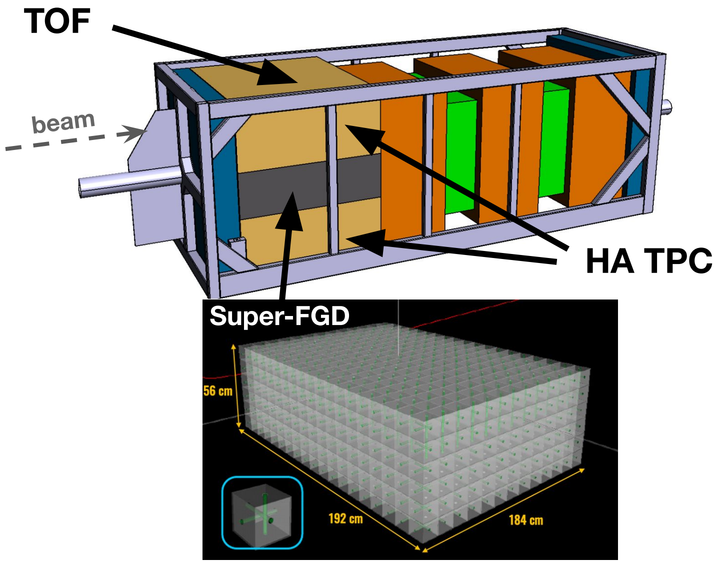


Phys.Rev.D 103, 112008 (2021)

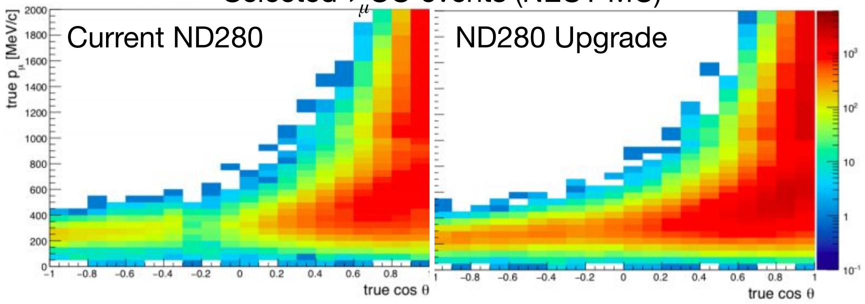
	1-Ring μ		1-Ring e			
Error source	FHC	RHC	FHC	RHC	FHC 1 d.e.	FHC/RHC
SK Detector	2.4	2.0	2.8	3.8	13.2	1.5
SK FSI+SI+PN	2.2	2.0	3.0	2.3	11.4	1.6
Flux + Xsec (ND constrained)	3.3	2.9	3.2	3.1	4.1	2.7
Nucleon Removal Energy	2.4	1.7	7.1	3.7	3.0	3.6
$\sigma(\nu_e)/\sigma(\bar{\nu}_e)$	0.0	0.0	2.6	1.5	2.6	3.0
NC1γ	0.0	0.0	1.1	2.6	0.3	1.5
NC Other	0.3	0.3	0.2	0.3	1.0	0.2
$\sin^2\theta_{23} + \Delta m^2_{21}$	0.0	0.0	0.5	0.3	0.5	2.0
$\sin^2\theta_{13}$ PDG2018	0.0	0.0	2.6	2.4	2.6	1.1
All Systematics	5.1	4.5	8.8	7.1	18.4	6.0

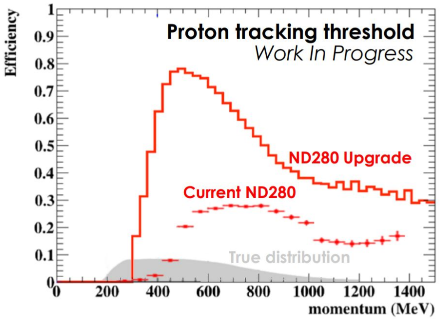
⟹ Neutrino interaction uncertainties must be reduced!

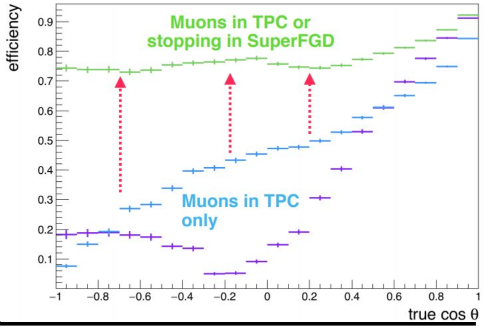
- Improved reconstruction at high and backward angles → better constraints on the neutrino interaction model
- Increased target mass (x2 current ND280) → more statistics
- Better reconstruction of outgoing nucleons → access to new observables



Selected ν_μ CC events (NEUT MC)



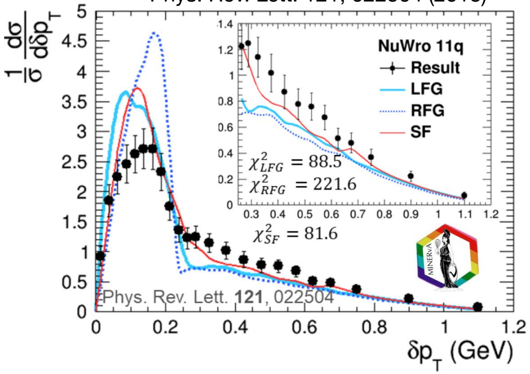




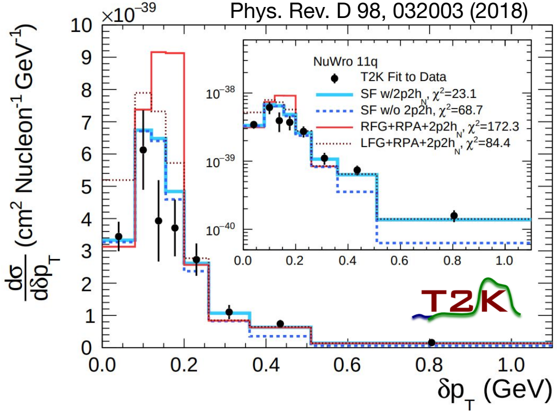
Cross section measurements *(See Ciro's presentation)*

- Cross section measurements allow to test our neutrino interaction models
- Current models struggle to describe cross section data
- In this talk we explore the uncertainties on the models to see if they can accommodate these discrepancies, and also use the ND data to constrain them

Phys. Rev. Lett. 121, 022504 (2018)



Phys. Rev. D 98, 032003 (2018)



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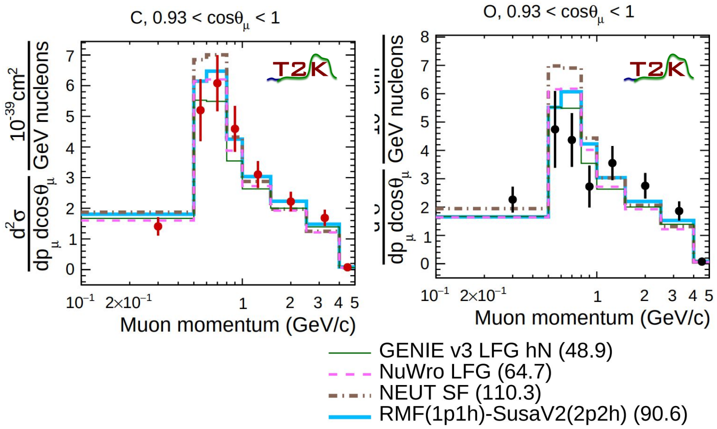
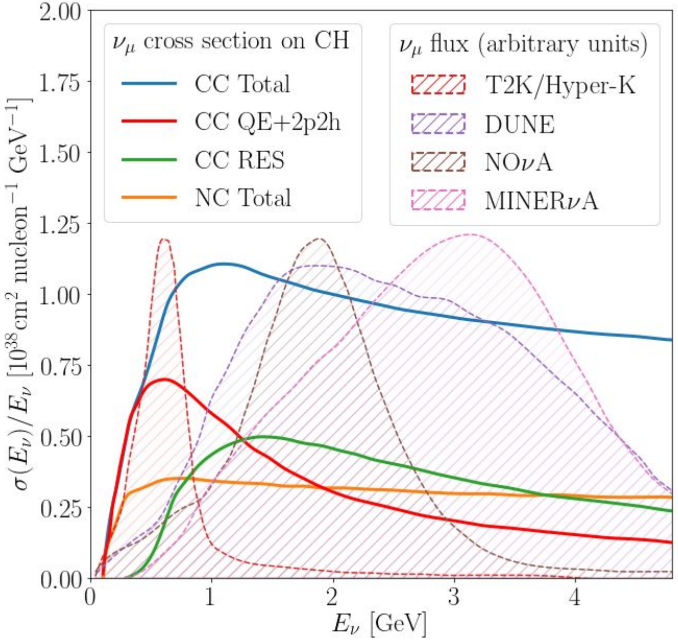
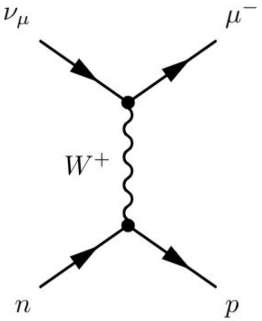


2. Neutrino-nucleus interaction models

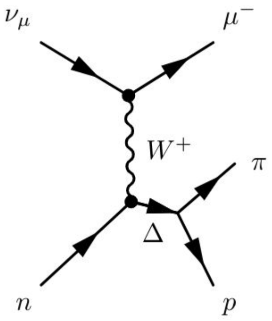
Neutrino interactions



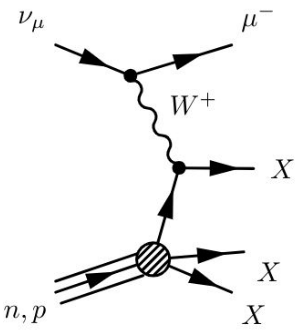
Quasi-elastic (CCQE)



Resonant (CCRES)

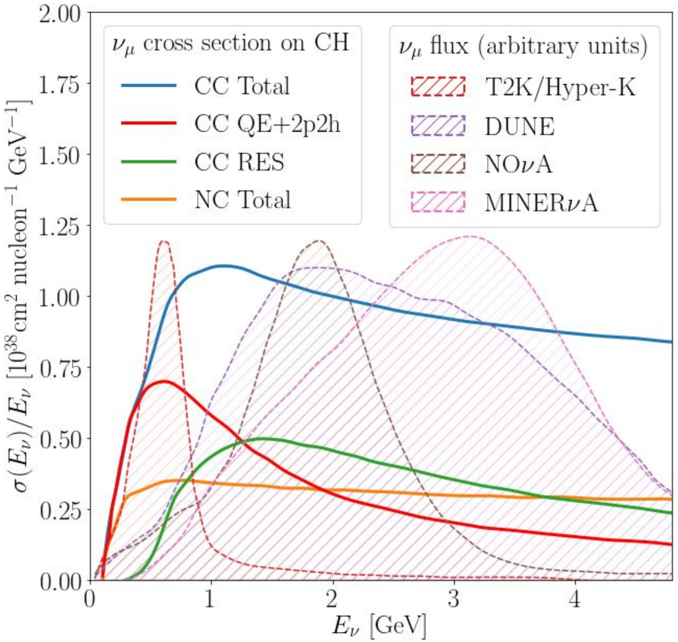


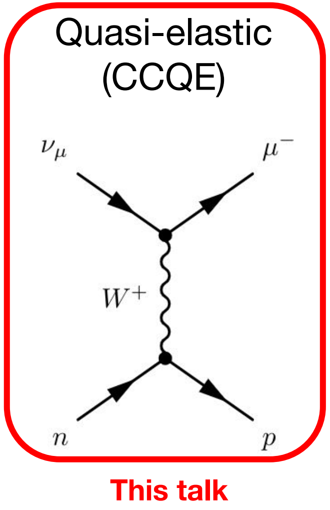
Deep Inelastic Scattering (CCDIS)

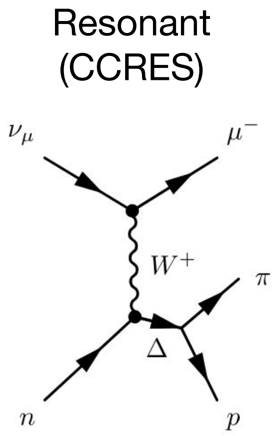


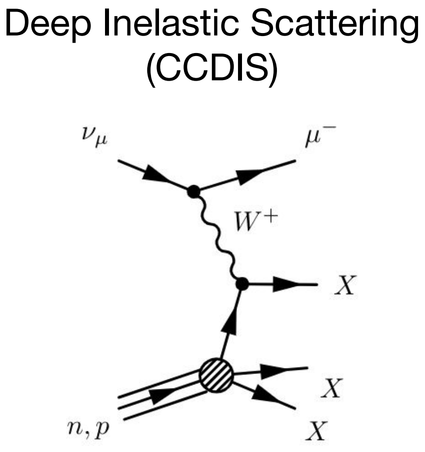
- In order to estimate neutrino energy, a good understanding of neutrino-nucleus interactions is necessary
- CCQE is the dominant interaction in T2K/Hyper-Kamiokande, and is a significant mode in NOνA, MINERνA and DUNE

Neutrino interactions









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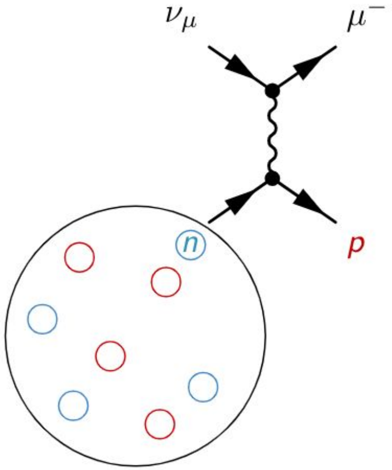
Initial state nucleons

- Neutrinos can interact with nucleons bound within nuclei (Carbon, Oxygen, Argon...)
- Initial state nucleons are non-static: Fermi motion
- How to model this?



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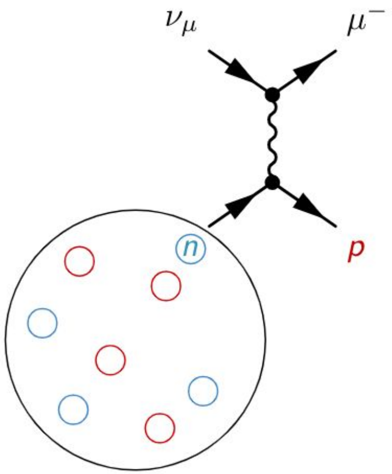


Fermi gas

Relativistic Fermi Gas (RFG)

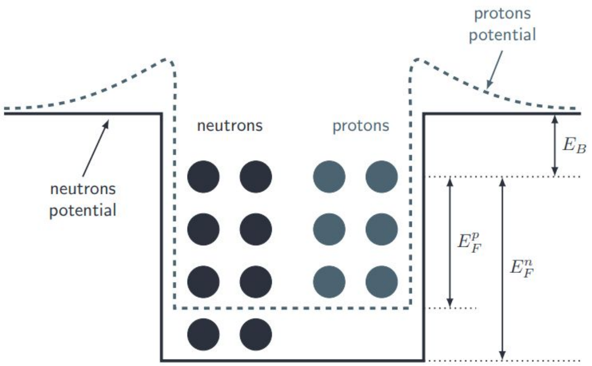
Nucleons move freely in a constant binding energy within the nuclear volume

$$p_F = \left(3\pi^2 \rho \frac{Z}{A}\right)^{1/3}$$

Local Fermi Gas (LFG)

The nucleus is described with the local density approximation

$$p_F(r) = \left(3\pi^2 \rho(r) \frac{Z}{A}\right)^{1/3}$$



T. Golan

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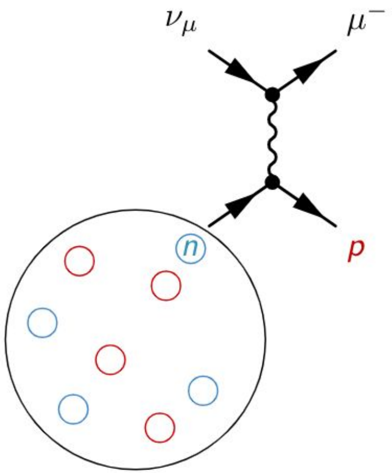


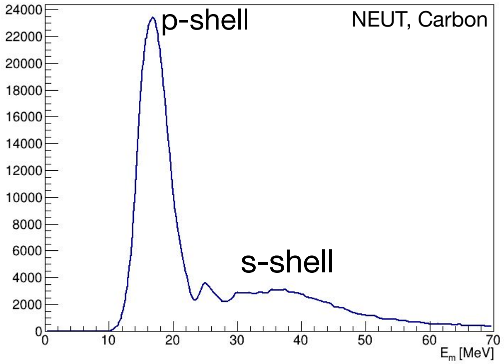
Spectral Function (SF)

The probability of removing of a nucleon with momentum p_m and leaving residual nucleus with excitation energy E_m

$$P(p_m, E_m) = \boxed{P_{MF}(p_m, E_m)} + P_{corr}(p_m, E_m)$$

Independent nucleons, moving in a mean-field potential within the shell-model picture → built from (e,e'p) data (~80%)

→ One outgoing nucleon is produced



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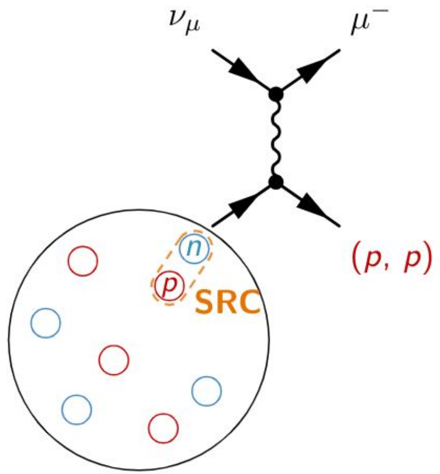

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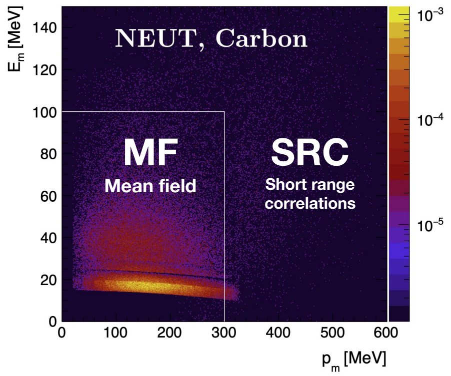

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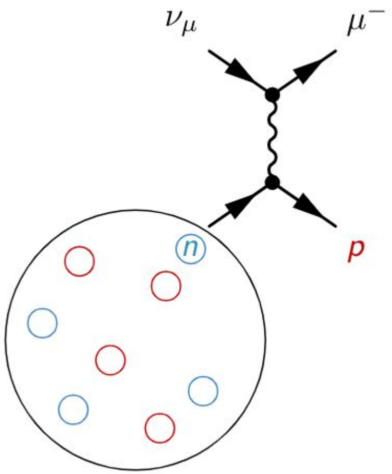

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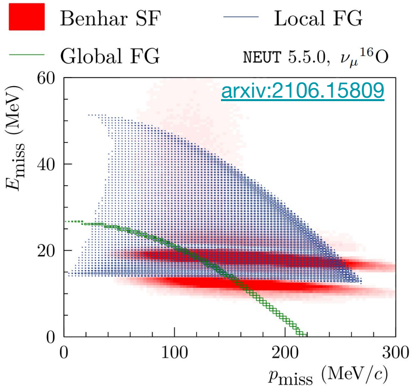

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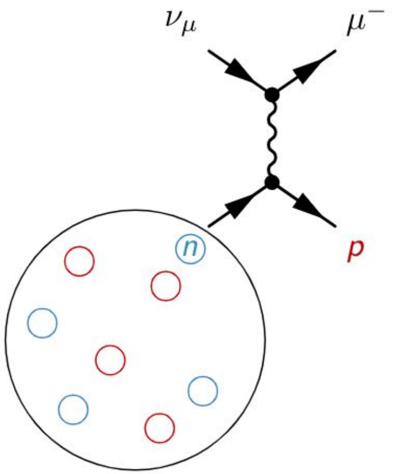

This talk

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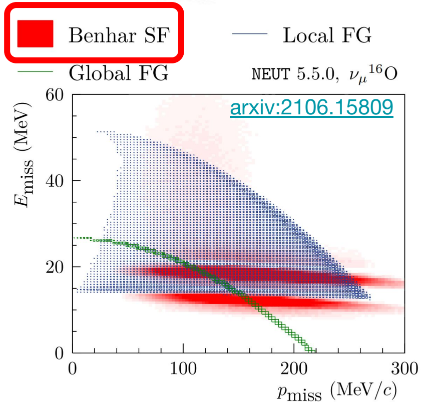
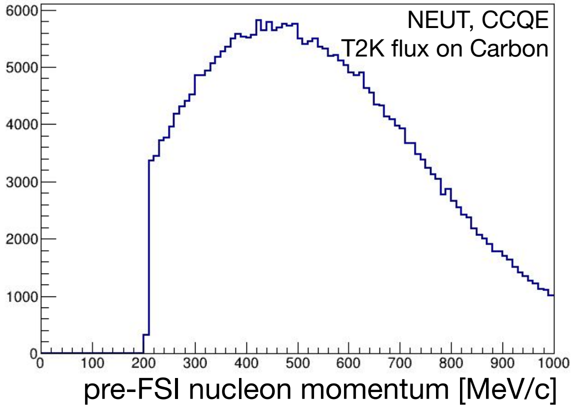


Additional nuclear effects

- Pauli blocking (PB):
  - By Pauli principle, an interaction cannot occur if it leads to the creation of a nucleon in a state that is already occupied
  - Simple model: reject events with outgoing nucleon momentum below Fermi level



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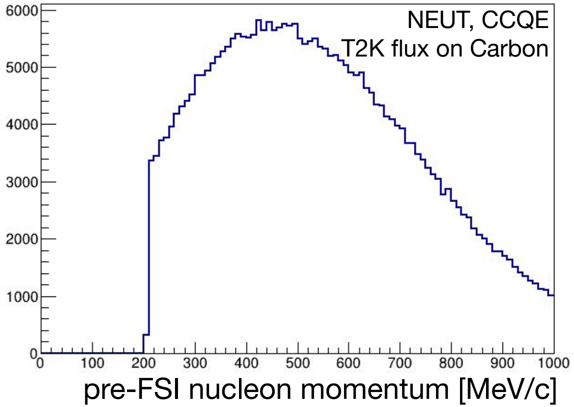
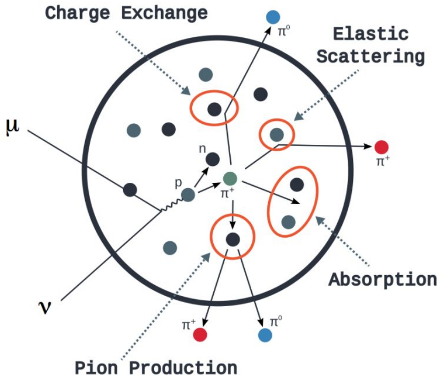


- Final state interactions (FSI):
  - Outgoing particles may re-interact with the nuclear matter



See Anna's presentation

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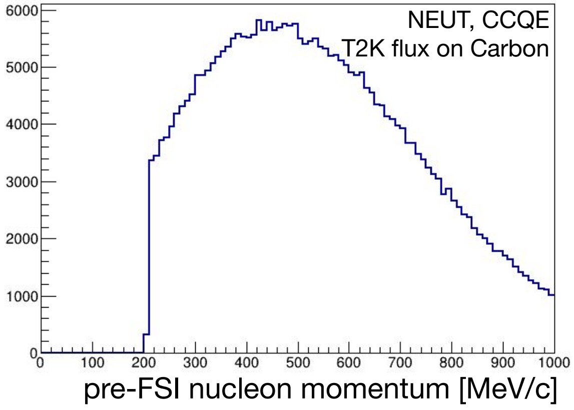
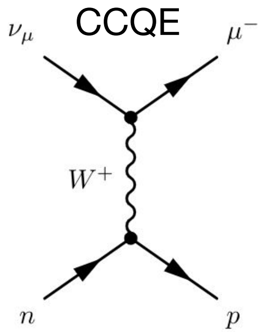
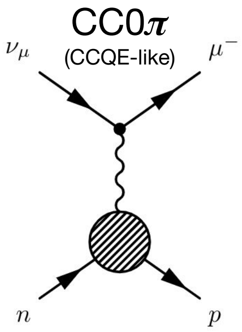


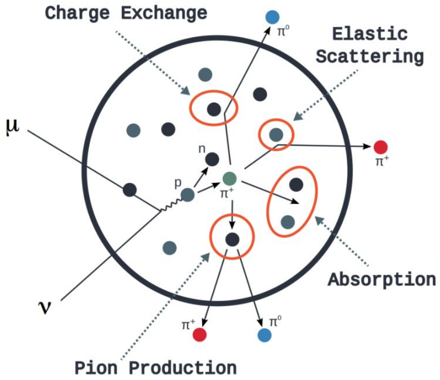
- Final state interactions (FSI):
  - Outgoing particles may re-interact with the nuclear matter
  - Can cause different interactions to have the same final state



Interaction mode



Interaction topology



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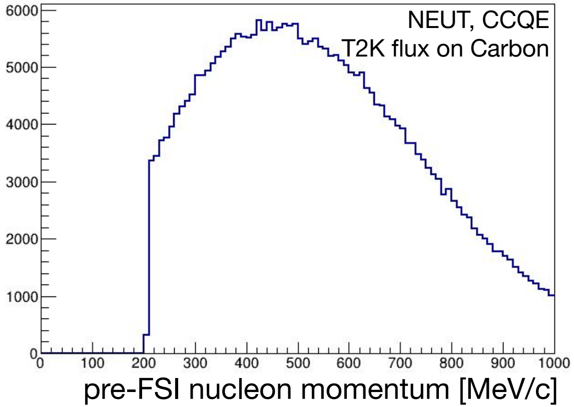

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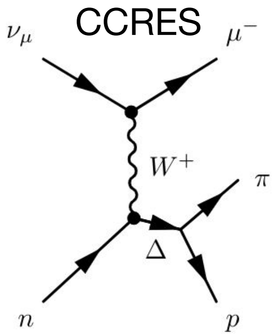

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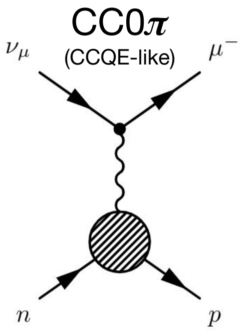

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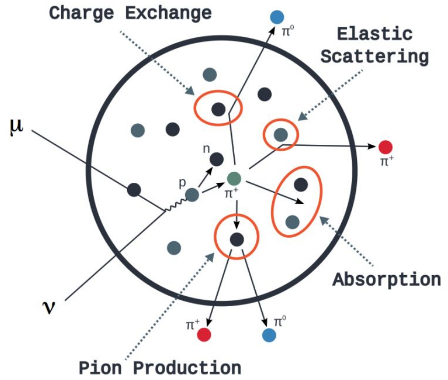

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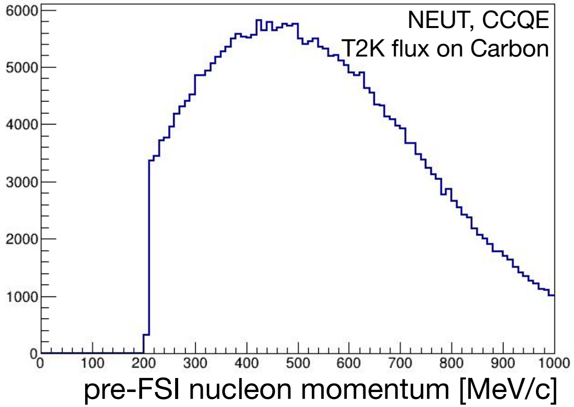

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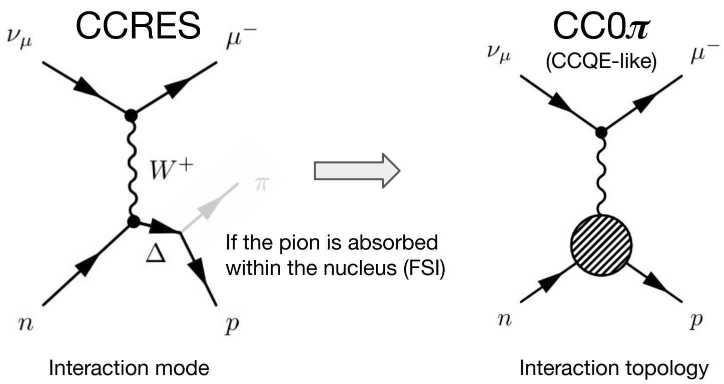
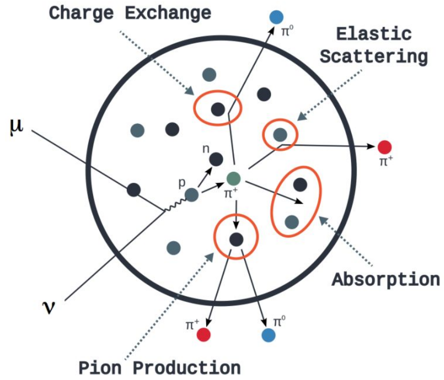
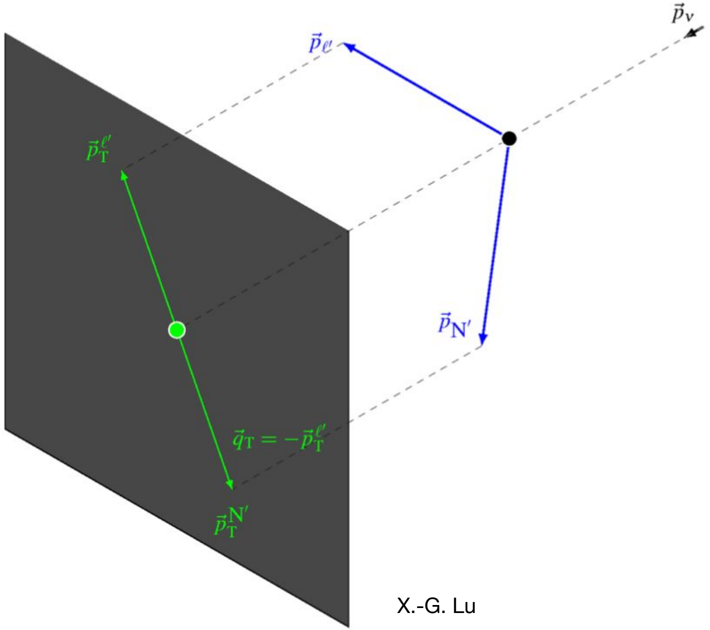




See Anna's presentation

Single Transverse Variables Phys. Rev. C 94, 015503 (2016)

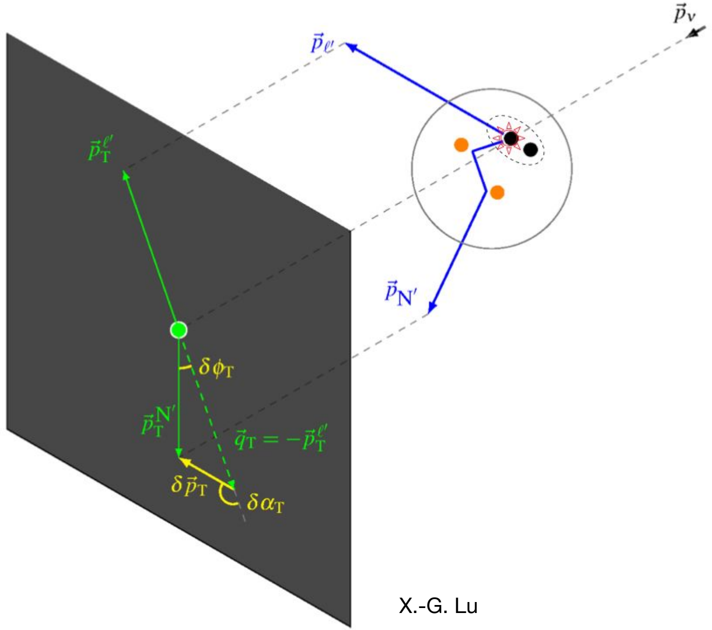
Static nucleon target



X.-G. Lu

Single Transverse Variables Phys. Rev. C 94, 015503 (2016)

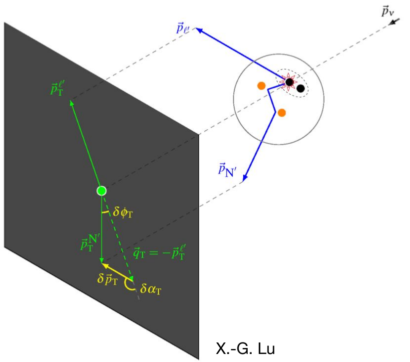
Nucleon bound within nuclear target



X.-G. Lu

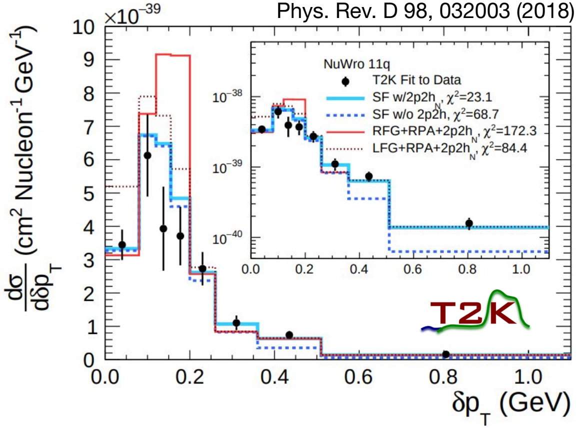
- Need the reconstruction of both muons and nucleons
- Probe nuclear effects (Fermi motion, FSI, ...)

Single Transverse Variables: δp_T Phys. Rev. C 94, 015503 (2016)



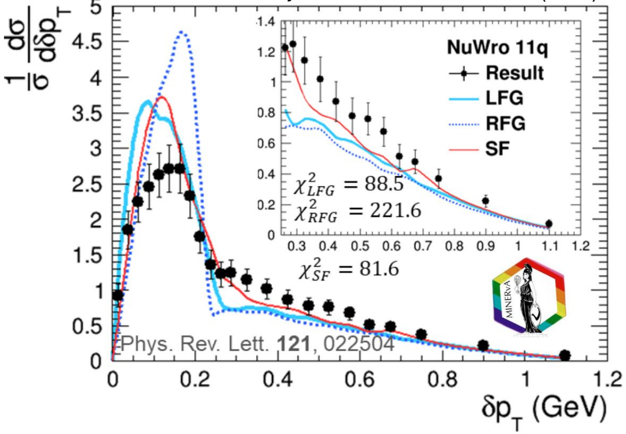
T2K

Phys. Rev. D 98, 032003 (2018)



MINERνA

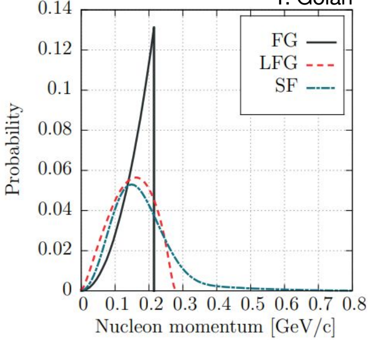
Phys. Rev. Lett. 121, 022504 (2018)



Single Transverse Variables: δp_T Phys. Rev. C 94, 015503 (2016)

- The bulk of the distribution is sensitive to the initial state nucleon momentum

T. Golan



T2K

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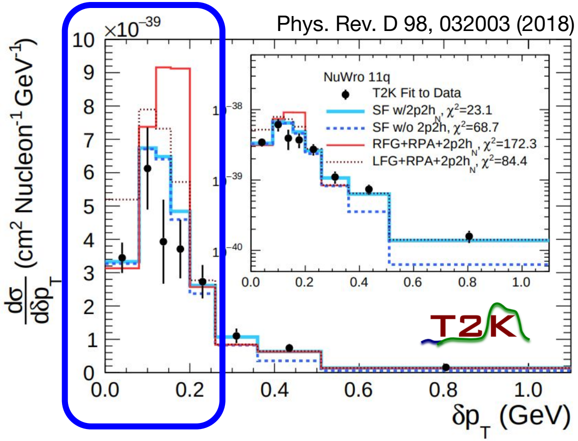

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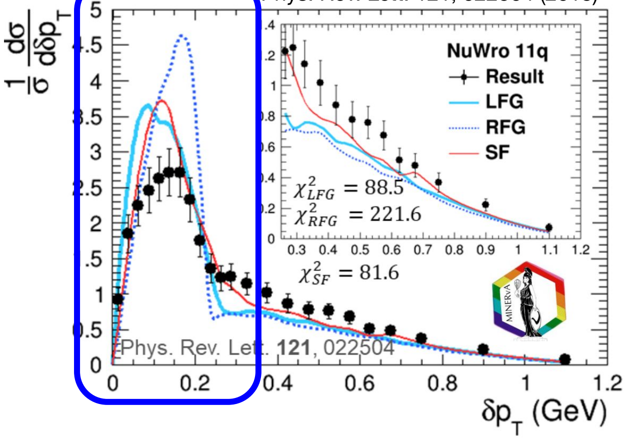

Single Transverse Variables: δp_T Phys. Rev. C 94, 015503 (2016)

- The bulk of the distribution is sensitive to the initial state nucleon momentum
- The tail of the distribution is sensitive to FSI, SRC, 2p2h

T2K

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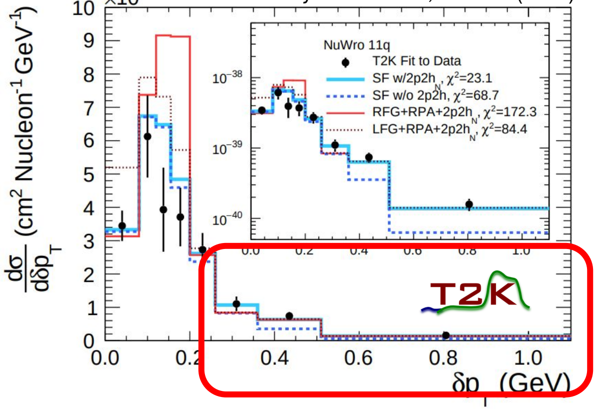

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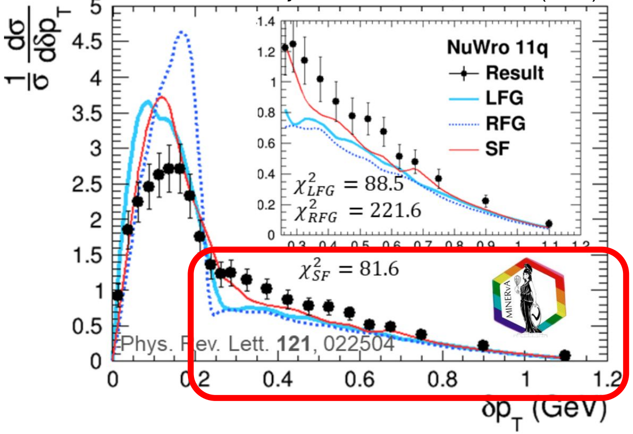
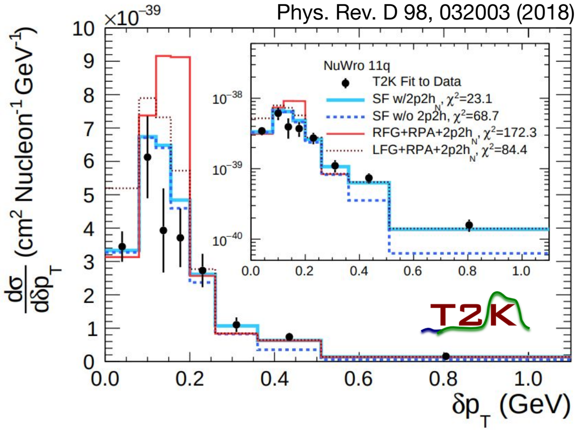
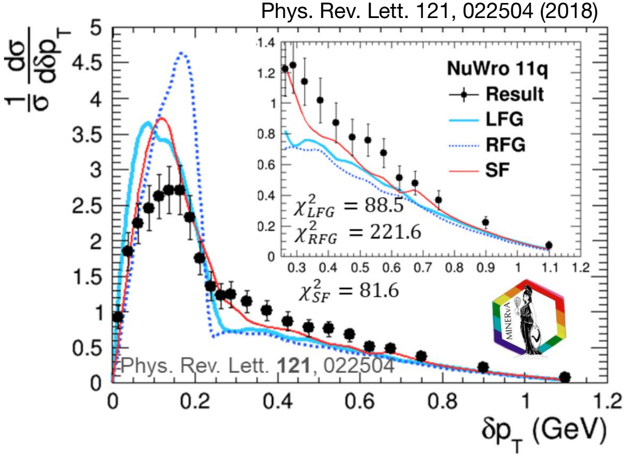


- The bulk of the distribution is sensitive to the initial state nucleon momentum
- The tail of the distribution is sensitive to FSI, SRC, 2p2h
- None of the models describe well the data...

T2K

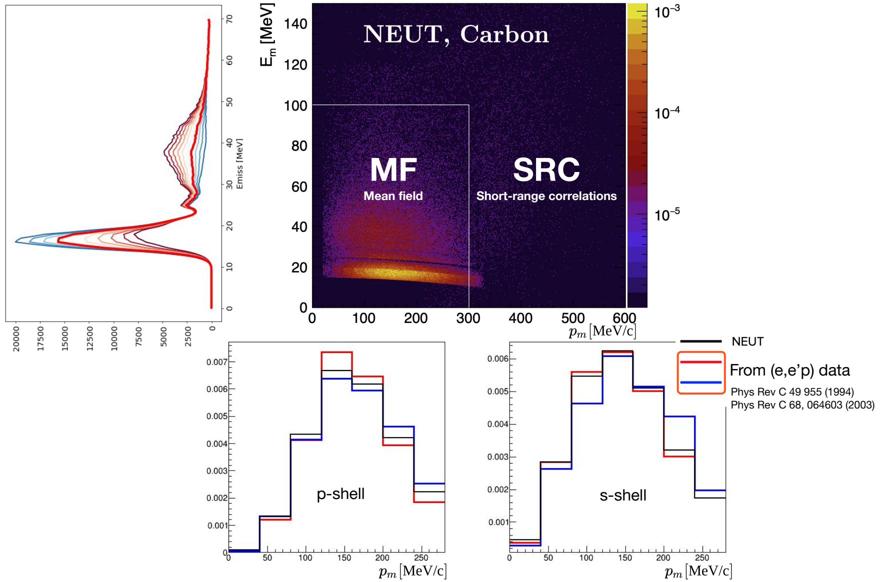


MINERνA



3. Systematic uncertainties and fits to cross section measurements

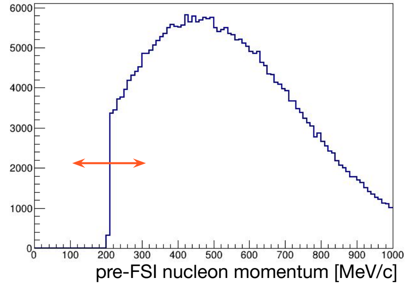
Initial state parameters



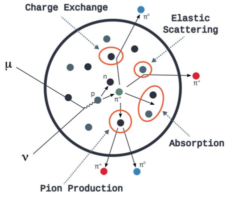
- Change the shape of the missing energy distribution by altering the shell occupancies
- Change the missing momentum distribution shape
- Change the contribution of SRC

Pauli Blocking parameter

- Change Pauli Blocking threshold on the pre-FSI nucleon momentum



FSI parameters



- Outgoing nucleon: Change the amount of events undergoing FSI w.r.t. no FSI *(see Anna's presentation for ways to improve)*
- Outgoing lepton: Change the lepton kinematics with an optical nuclear potential (Phys. Rev. D 91, 033005 (2015))

This parameterisation was implemented in NUISANCE and applied on NEUT 5.4.0 neutrino event generator (arxiv:2106.15809)

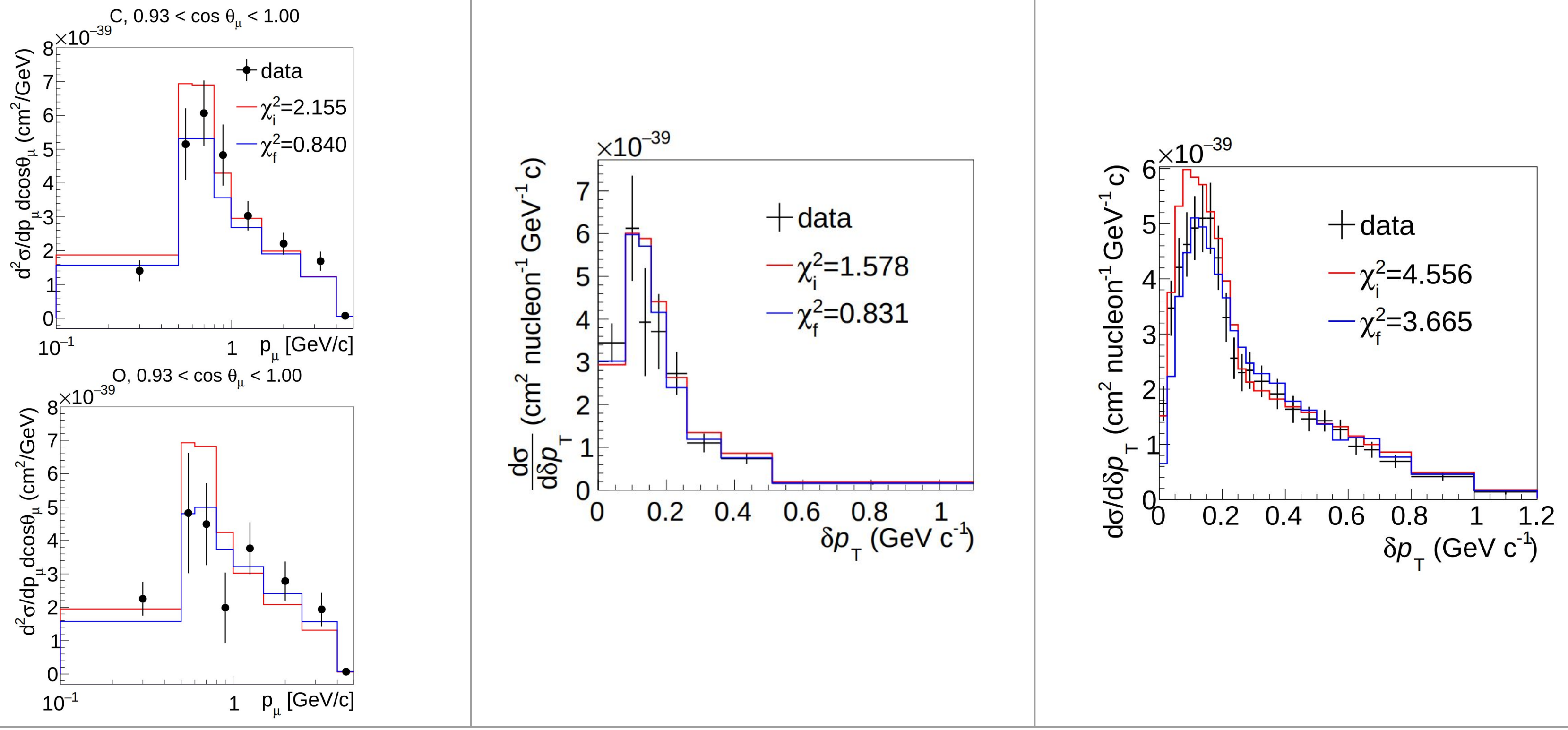
Fits to published data

- Ingredients:
  - Model: NEUT with SF model (for Oxygen and Carbon)
  - Parameters: SF model parameters (+ normalisation parameters for other interactions)
  - Data: cross section measurements from T2K and MINERvA
- Chi-square(*): $\chi^2_{\text{data}} = \sum_{1 \leq i,j \leq n} \left(B_i - B_i^{MC}\right) \left(M^{-1}\right)_{ij} \left(B_j - B_j^{MC}\right)$
- How is this parameterisation able to improve agreement with the data?

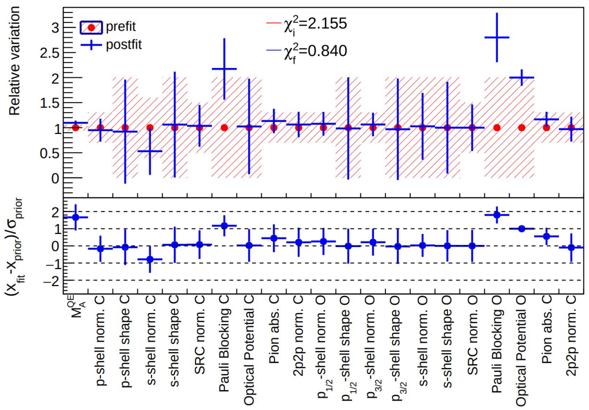
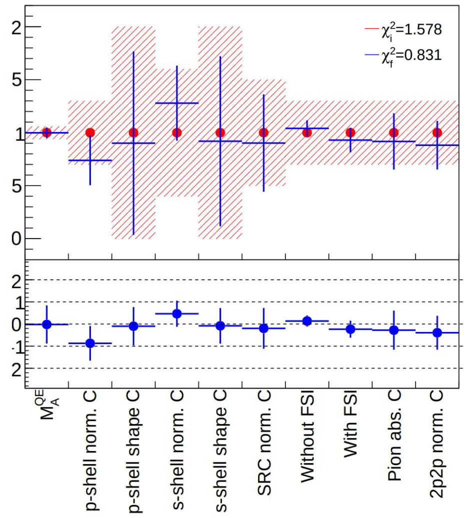
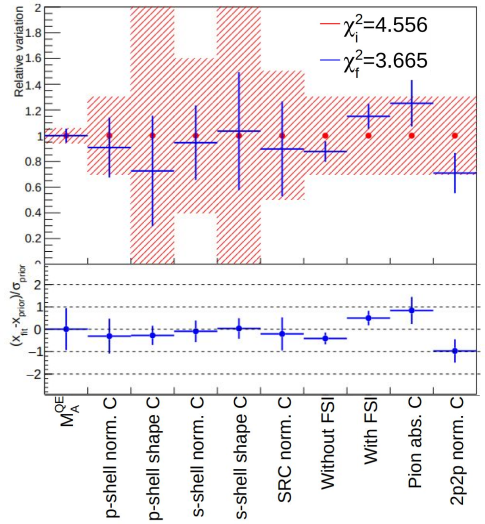
(*) Peelle's Pertinent Puzzle was avoided using a different decomposition of the data histogram and covariance matrix, see back-up

Fits to cross section measurements

T2K lepton kinematics on O & C (CC0π)	T2K δp_T on C (CC0π+Np)	MINERνA δp_T on C (CC0π+Np)

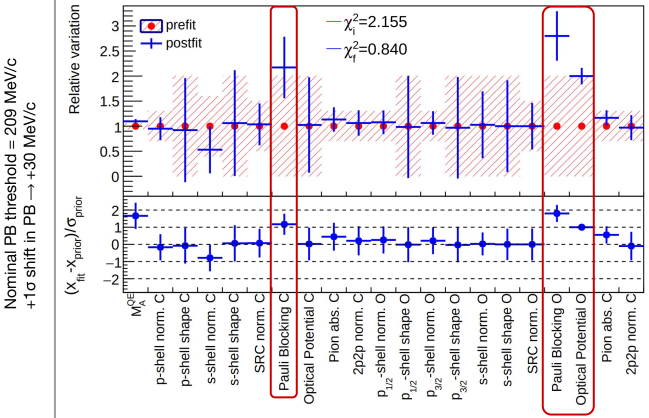


Fits to cross section measurements

T2K lepton kinematics on O & C (CC0π)	T2K δp_T on C (CC0π+Np)	MINERνA δp_T on C (CC0π+Np)
		

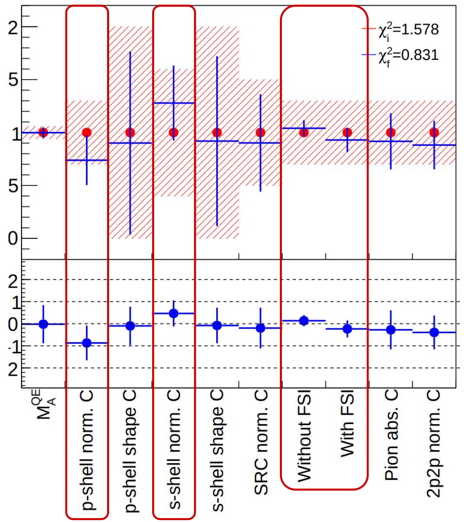
Fits to cross section measurements

T2K lepton kinematics on O & C (CC0π)

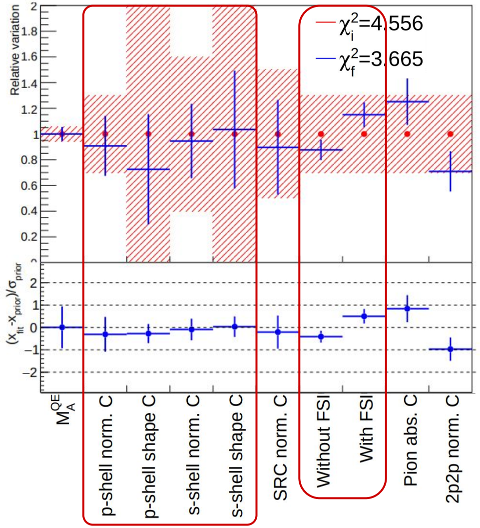


- The agreement with the data is driven by the Pauli Blocking and Optical Potential parameters
- Some sensitivity to the shell parameters can be noticed
- No sensitivity to the missing momentum shape parameters

T2K δp_T on C (CC0π+Np)



MINERνA δp_T on C (CC0π+Np)

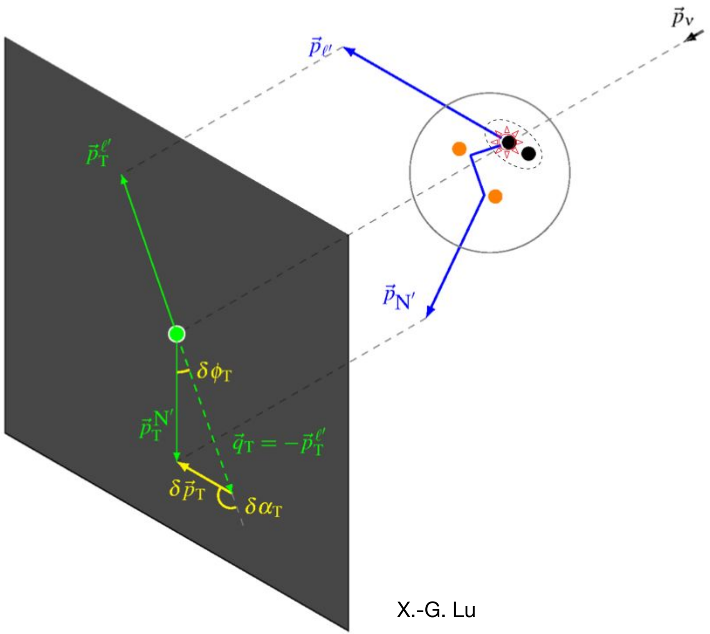


- The transverse momentum imbalance fits show more sensitivity to the initial state parameters as well as the FSI parameters
- The high postfit chi-square in MINERνA data may suggest that the FSI model is insufficient

4. Projected constraints with T2K ND Upgrade

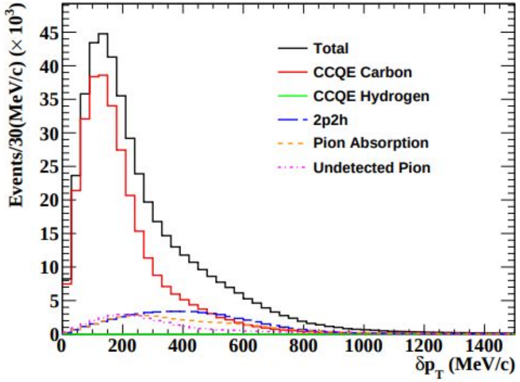
Single Transverse Variables

Nucleon bound within nuclear target

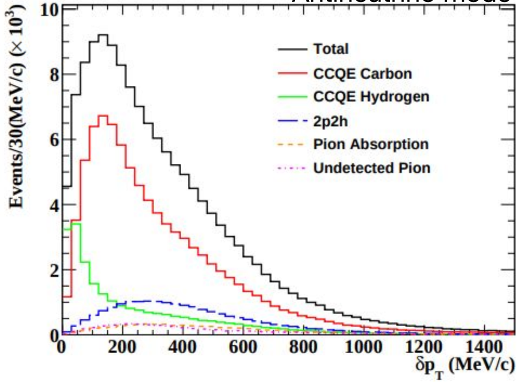


X.-G. Lu

Neutrino mode



Antineutrino mode



Transverse momentum imbalance δp_T

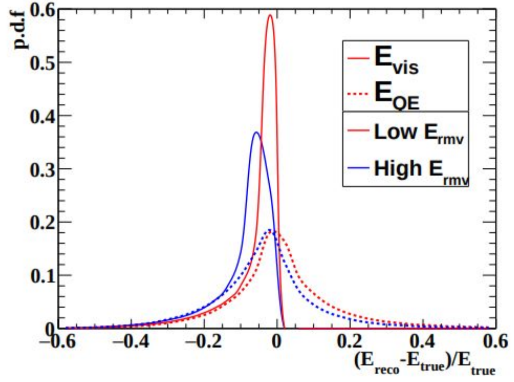
- Need the reconstruction of both muons and nucleons
- Probe nuclear effects (Fermi motion, FSI, ...)

Visible energy: Evis

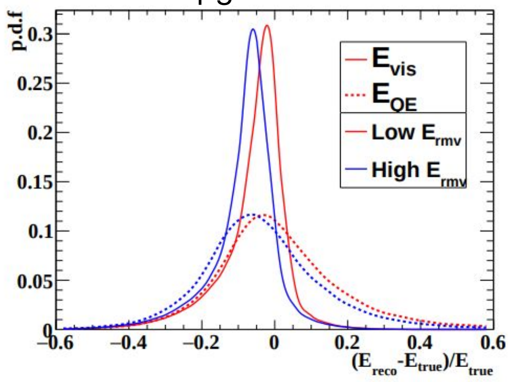
- The visible energy is defined as follows:
  - $E_{\text{vis}} = E_\mu + T_p$ for neutrino interactions
  - $E_{\text{vis}} = E_\mu + T_n$ for antineutrino interactions

- Evis is a good estimator of the neutrino energy

Generator level

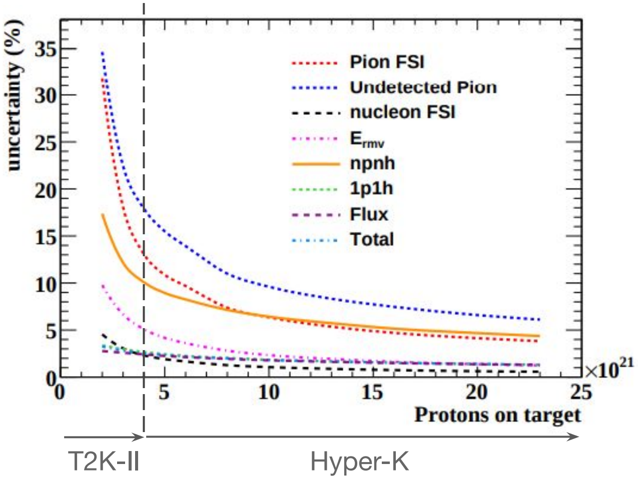


w/ ND Upgrade efficiencies

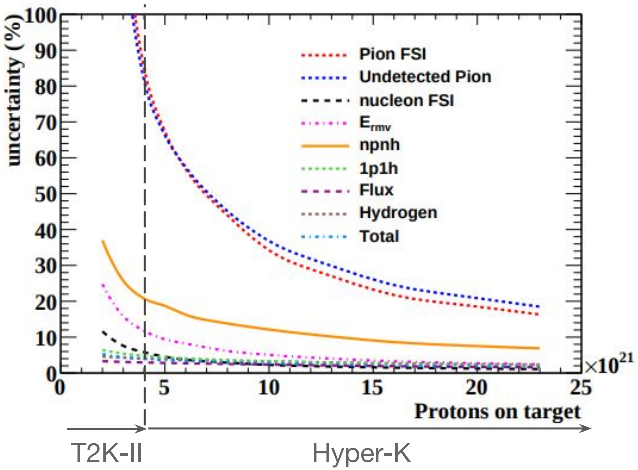


Sensitivity to the parameters

Neutrino



Antineutrino

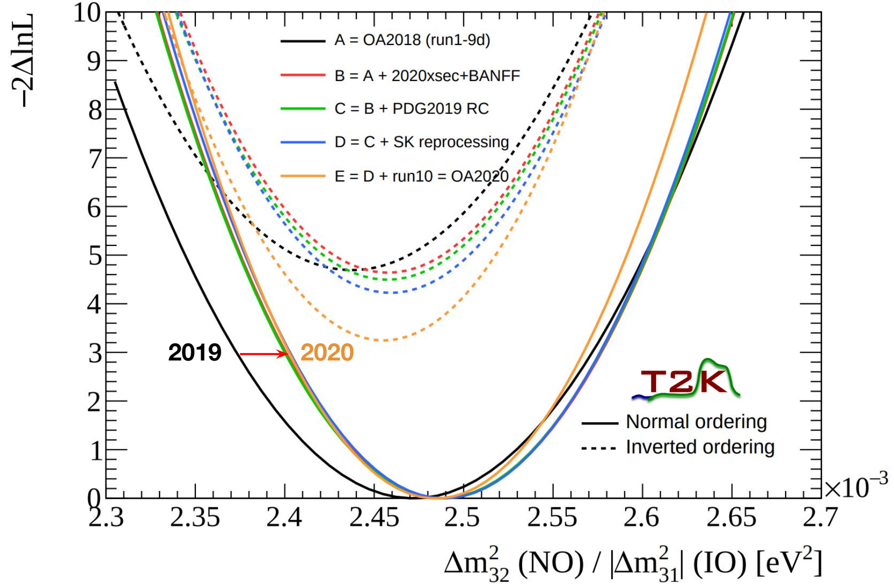


NOTE: neutrino and antineutrino samples fit separately

- Using the outgoing proton information (*eg. visible energy & transverse momentum imbalance*) allows a better reconstruction of the neutrino energy and constraint on systematic uncertainties
- The dominant systematic uncertainties can be constrained down to the few-% level as required by future oscillation analyses of T2K-II and next generation experiments

What will the impact be on the T2K oscillation analysis?

- We are currently implementing this parameterisation for the T2K oscillation analysis and evaluating the impact of the improved sensitivity with the ND Upgrade on the oscillation parameters
- The 2020 results, which improved the cross section model, showed better constraints on Δm^2
- The <u>precise</u> measurement of Δm^2 is very crucial for the determination of the mass hierarchy in combination with other experiments *(see Anatael's talk this afternoon)*

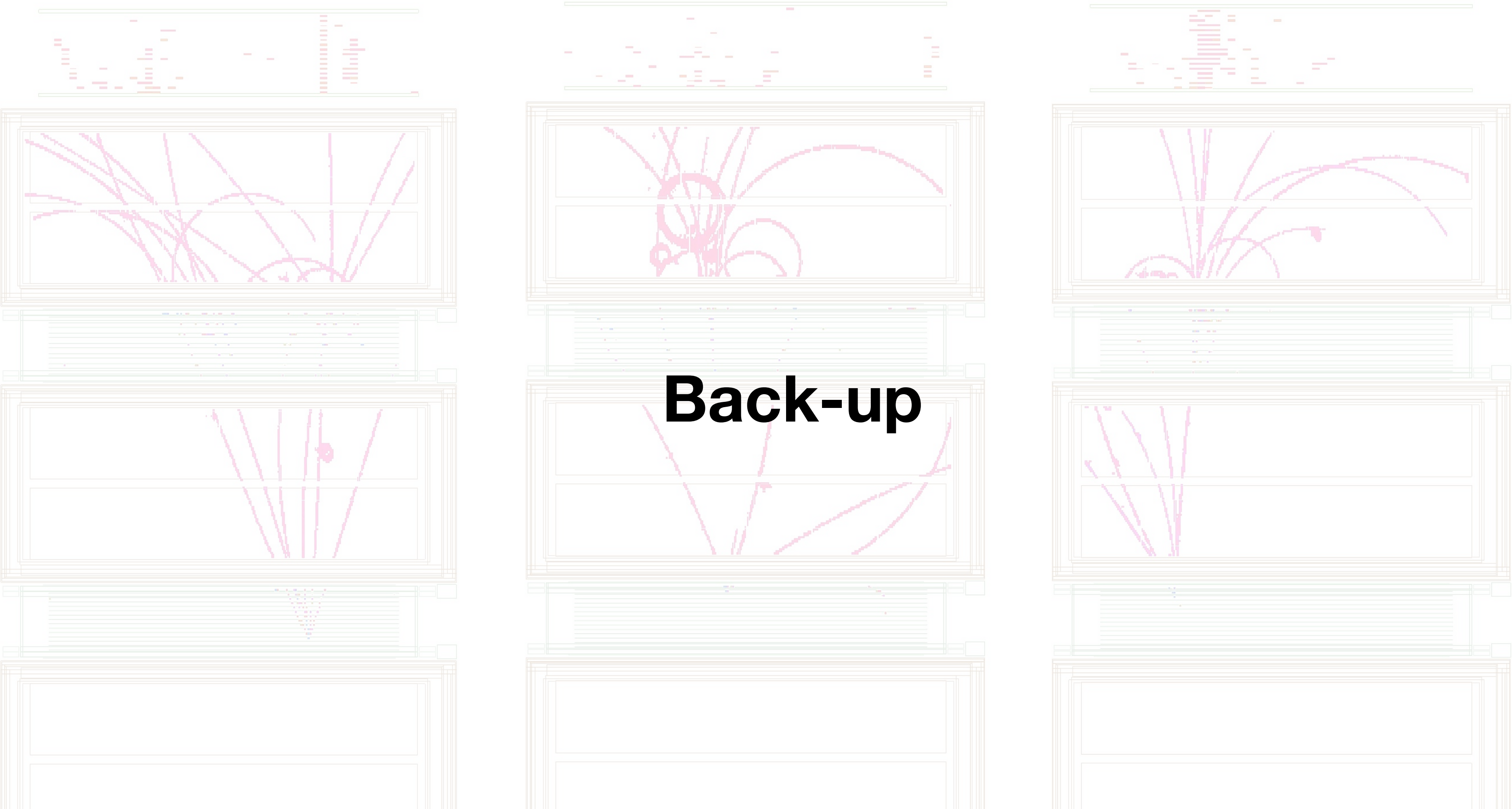


5. Summary and outlook

Summary and outlook

- A new set of physically-motivated uncertainties on the predictions of the CCQE Spectral Function model were introduced
- Fitting to external data shows great improvement for T2K cross section measurements, whereas MINERνA data is sensitive to this parameterisation but shows little improvement in the data/MC agreement
- The impact of the of the ND Upgrade's improved performance on constraining the systematic uncertainties has been estimated
- New data and an appropriate choice of observables may help to better constrain and improve the model for precise measurements of the oscillation parameters

- This parameterisation may still need further improvement especially for FSI *(see Anna's talk)*
- Ongoing effort to further quantify the impact of the T2K ND Upgrade on the sensitivity to the oscillation parameters



Back-up

Avoiding Peelle's Pertinent Puzzle (PPP)

- Attempts to fit neutrino cross-section data with a parameterisation of the interaction model gives us seemingly unphysically low normalisations PPP
- The reason this happens is subtle, but is related to the strong correlations in published covariance matrices and the corresponding "type" of Gaussian errors approximation
- In our standard approach we assume the absolute uncertainty on the cross section is independent of its normalisation
    - i.e. our uncertainties state that a 10 fb / GeV uncertainty on some bin remains at 10 fb / GeV even if we had underestimated our flux by 10% (and so the cross section is lower than measured)
    - This implies the relative uncertainty is larger if fitting to models that predict lower normalisations. This is what give us PPP
- We could alternatively suggest that it should be the relative uncertainty that is independent of its normalisation (D'Agostini does)
    - i.e. our uncertainties would state that a 10% uncertainty on some bin remains at 10% even if we had underestimated our flux by 10%
    - This implies the absolute uncertainty is larger if fitting to models that predict lower normalisations

Avoiding Peelle's Pertinent Puzzle (PPP)

- We can construct a covariance matrix that keeps the relative uncertainties constant when the normalization changes: a "Norm-Shape" covariance where one row contains the normalization of the data and the rest contains the shape

$$H_1 : \{B_1, ..., B_n\} \rightarrow H_2 : \{C_1, ..., C_n\} \qquad C_i = \begin{cases} \frac{B_i}{\sum_k B_k} & , i < n \\ \sum_k B_k & , i = n \end{cases}$$

- We can obtain $\mathrm{Cov}\left[\{C_i\}\right]$ (norm-shape covariance) directly from the data covariance given by experiments $\mathrm{Cov}\left[\{B_i\}\right]$

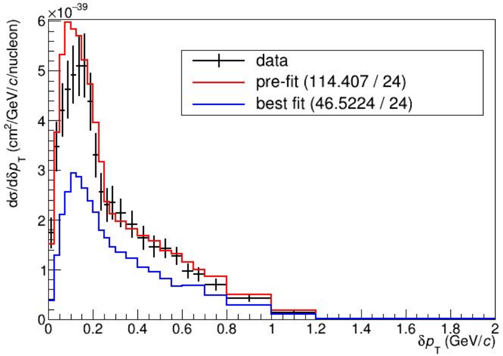
- Perform the fit in this new basis using $N = \mathrm{Cov}[\{C_i\}]$

$$\chi^2_{\mathrm{NS}} = \sum_{1 \leq i,j \leq n} \left(C_i - C_i^{MC}\right) \left(N^{-1}\right)_{ij} \left(C_j - C_j^{MC}\right)$$

Avoiding Peelle's Pertinent Puzzle

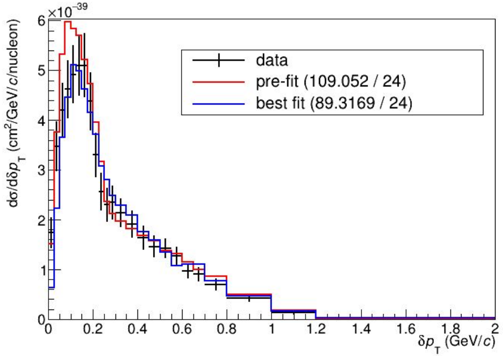
- Example of MINERvA dpt fit with the same parameterisation of slide 41:

Fit minimizing the usual chi2



	Normal chi2	NS chi2
prefit	**114.407**	109.052
postfit	**46.5224**	108.201

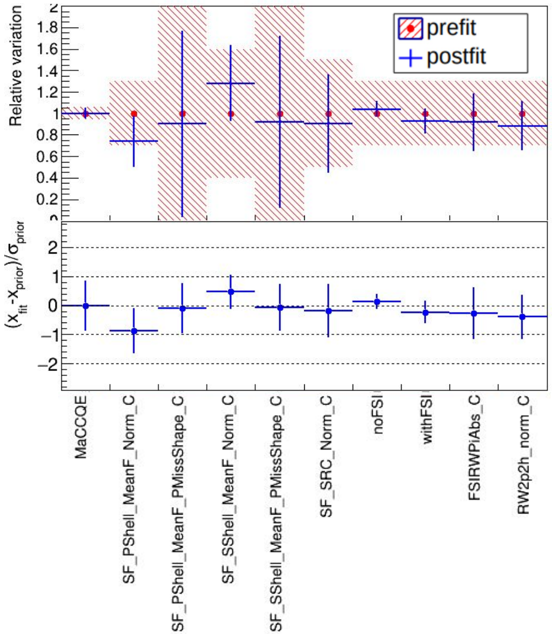
Fit minimizing the new chi2

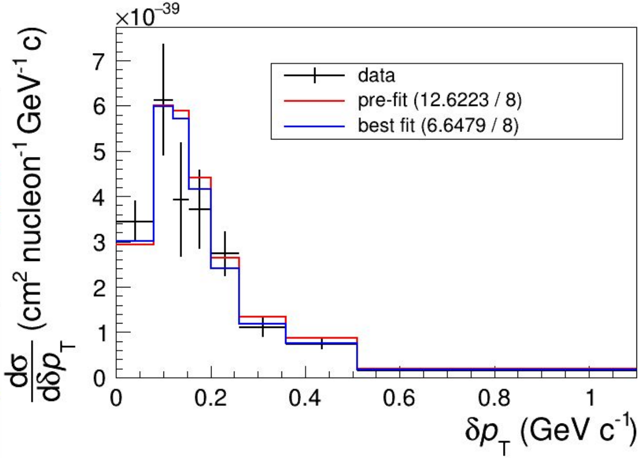


	Normal chi2	**NS chi2**
prefit	114.407	**109.052**
postfit	85.2858	**89.3169**

Parameters used in this fit:

- M_A^{QE}
- Shell occupancies
- p_m shape
- SRC norm
- No FSI / with FSI (correlated)
- Pion absorption normalization
- 2p2h normalization

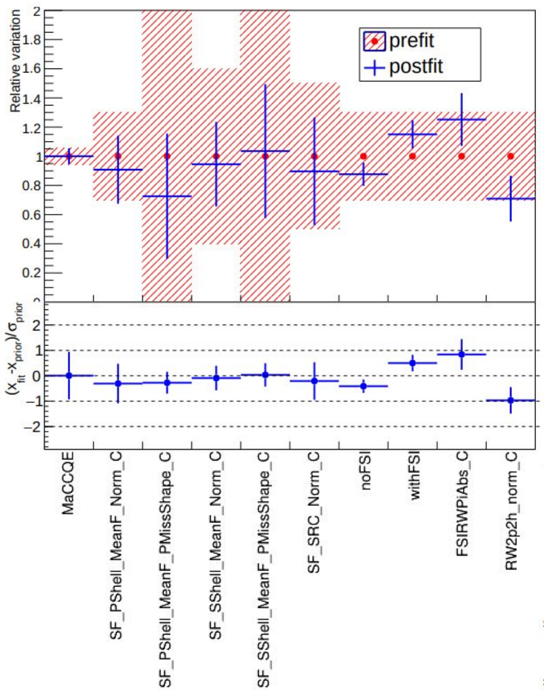


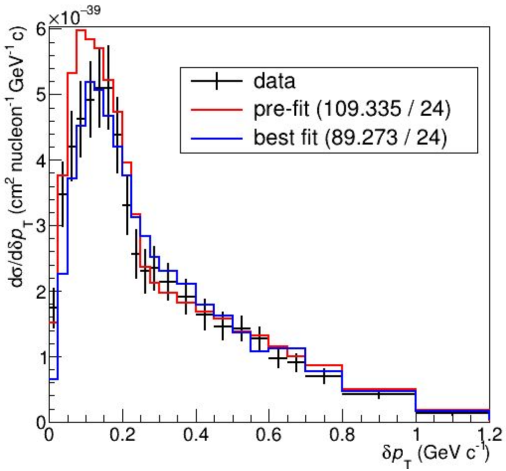


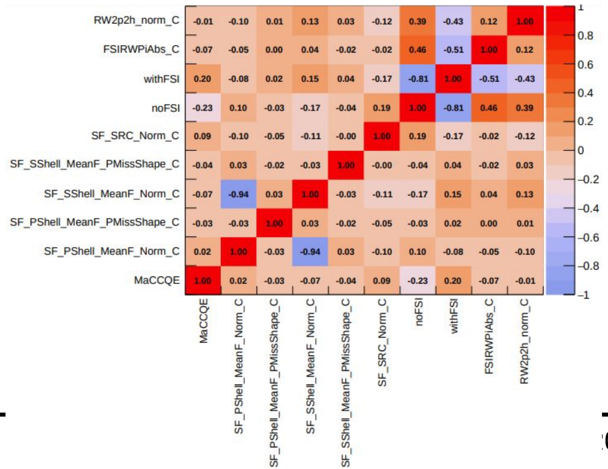
	MaCCQE	SF_PShell_MeanF_Norm_C	SF_PShell_MeanF_PMissShape_C	SF_SShell_MeanF_Norm_C	SF_SShell_MeanF_PMissShape_C	SF_SRC_Norm_C	noFSI	withFSI	FSIRWPiAbs_C	RW2p2h_norm_C
RW2p2h_norm_C	-0.16	0.02	-0.01	-0.03	-0.01	-0.10	0.43	-0.50	-0.11	1.00
FSIRWPiAbs_C	0.18	-0.15	0.04	-0.02	0.02	-0.15	0.21	-0.23	1.00	-0.11
withFSI	-0.04	0.11	-0.02	0.29	-0.00	-0.20	-0.83	1.00	-0.23	-0.50
noFSI	0.02	-0.14	-0.00	-0.31	-0.01	0.18	1.00	-0.83	0.21	0.43
SF_SRC_Norm_C	0.01	-0.07	0.01	0.00	0.00	1.00	0.18	-0.20	-0.15	-0.10
SF_SShell_MeanF_PMissShape_C	-0.03	-0.04	-0.04	-0.05	1.00	0.00	-0.01	-0.00	0.02	-0.01
SF_SShell_MeanF_Norm_C	-0.14	-0.70	-0.00	1.00	-0.05	0.00	-0.31	0.29	-0.02	-0.03
SF_PShell_MeanF_PMissShape_C	-0.04	-0.11	1.00	-0.00	-0.04	0.01	-0.00	-0.02	0.04	-0.01
SF_PShell_MeanF_Norm_C	-0.10	1.00	-0.11	-0.70	-0.04	-0.07	-0.14	0.11	-0.15	0.02
MaCCQE	1.00	-0.10	-0.04	-0.14	-0.03	0.01	0.02	-0.04	0.18	-0.16

Parameters used in this fit:

- M_A^{QE}
- Shell occupancies
- p_m shape
- SRC norm
- No FSI / with FSI (correlated)
- Pion absorption normalization
- 2p2h normalization





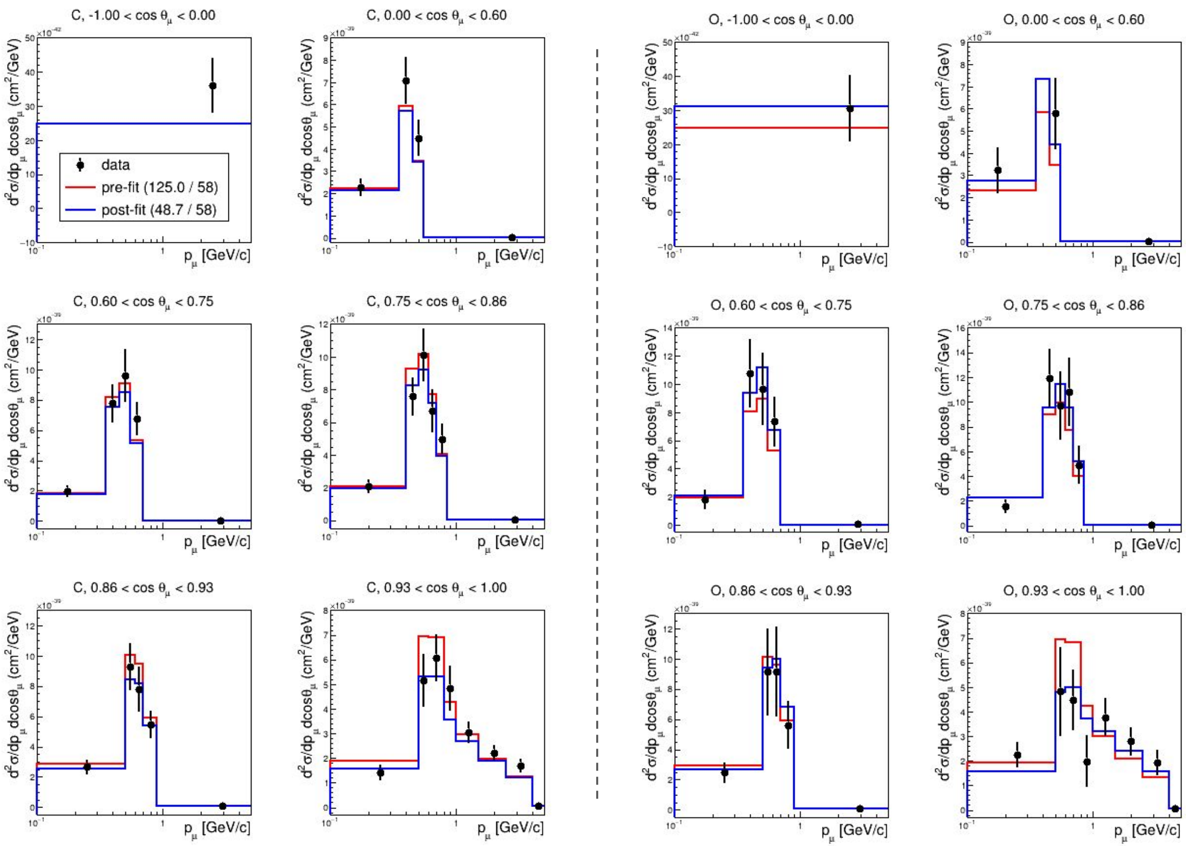


T2K CC0pi O & C measurement

Phys. Rev. D 101, 112004 (2020)

Parameters used in this fit:

- M_A^{QE}
- Shell occupancies
- p_m shape
- SRC norm
- Pauli blocking
- Optical potential correction
- Pion absorption normalization
- 2p2h normalization



T2K CC0pi O & C measurement

Phys. Rev. D 101, 112004 (2020)

Parameters used in this fit:

- M_A^{QE}
- Shell occupancies
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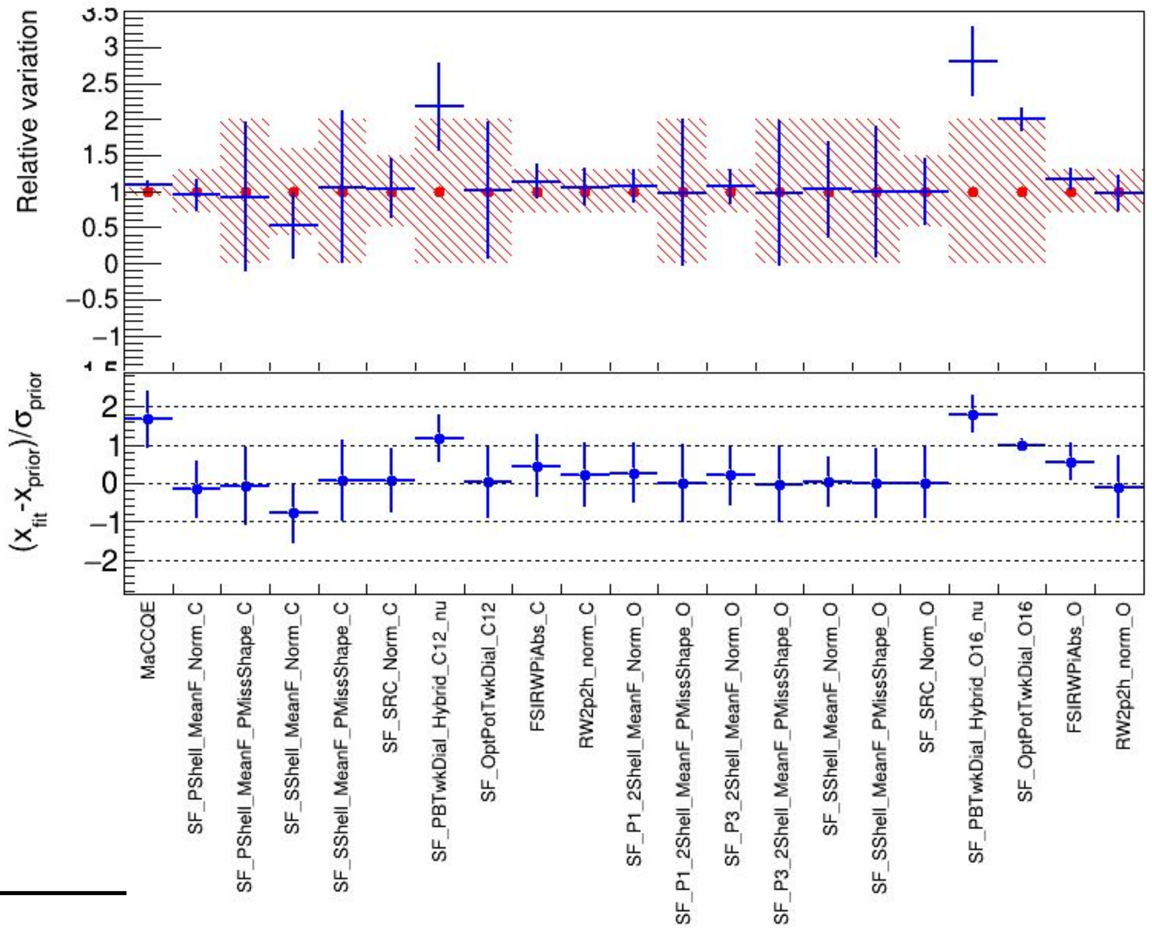
- 2p2h normalization



T2K CC0pi O & C measurement Phys. Rev. D 101, 112004 (2020)