Parameterising CCQE interactions in the Spectral Function model for neutrino oscillation analyses

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ÉCOLE POLYTECHNIQUE | INSTITUT POLYTECHNIQUE DE PARIS

IN2P3 Les deux infinis

P2IO Physique des 2 Infinis et des Origines

Outline

1. Introduction

Neutrino oscillations: the precision era

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

Current systematic uncertainties in T2K

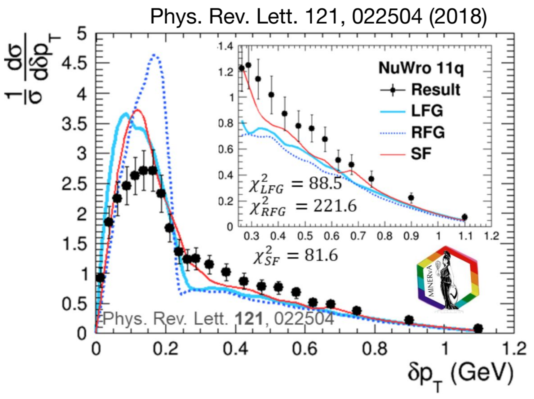
Nature 580, 339-344

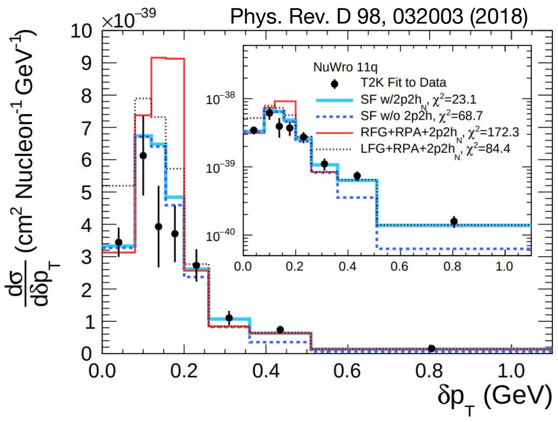
Source	$N(\nu_e)$
Binding energy	7.1%
Total	8.8%

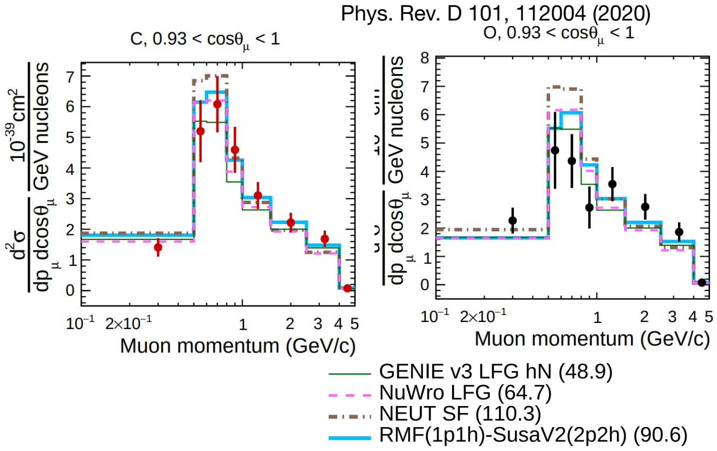
Neutrino interaction uncertainties must be reduced!

Cross section measurements

- Cross section measurements allow to test our neutrino interaction models
- Current models struggle to describe (semi-)inclusive measurements
- In this talk we introduce new theory-driven freedoms to robustly improve agreement

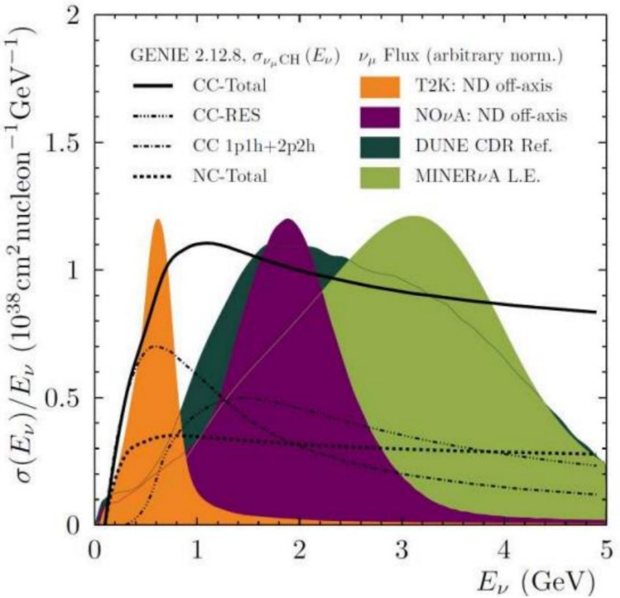




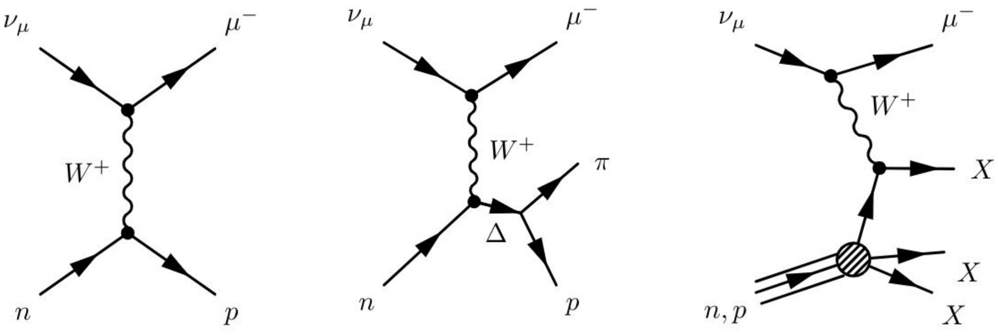


2. Neutrino-nucleus interaction models

Neutrino interactions

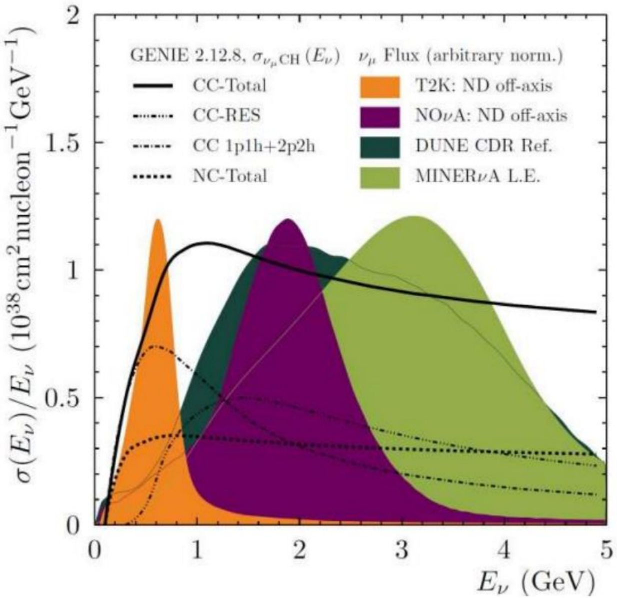


Quasi-elastic (CCQE) | Resonant (CCRES) | Deep Inelastic Scattering (CCDIS)



- In order to estimate neutrino energy, a good understanding of neutrino-nucleus interactions is necessary
- CCQE is the dominant interaction in T2K/HK, and is a significant mode in NOvA, MINERvA and DUNE

Neutrino interactions



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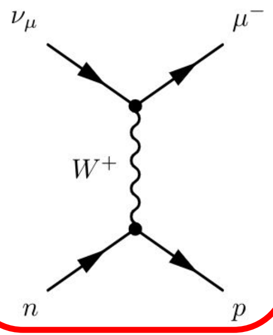
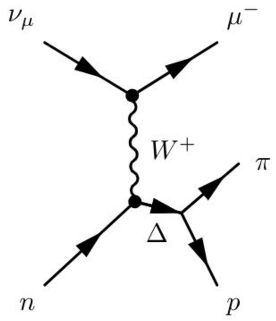
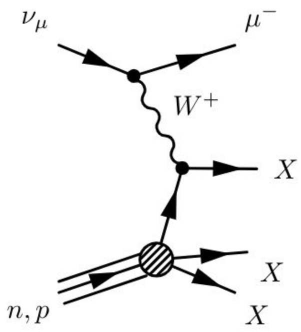


This talk

Resonant (CCRES)



Deep Inelastic Scattering (CCDIS)



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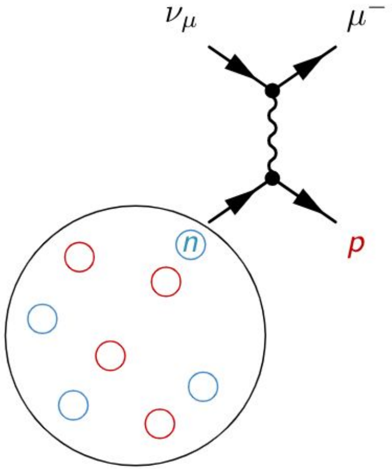
Initial state nucleons

- 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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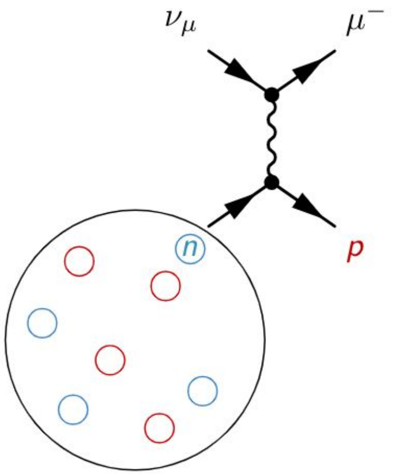


Fermi gas

Relativistic Fermi Gas (RFG)

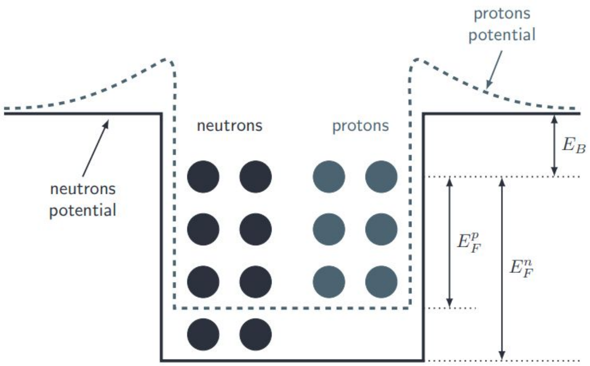
Nucleons move freely in a constant binding energy within the nuclear volume

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

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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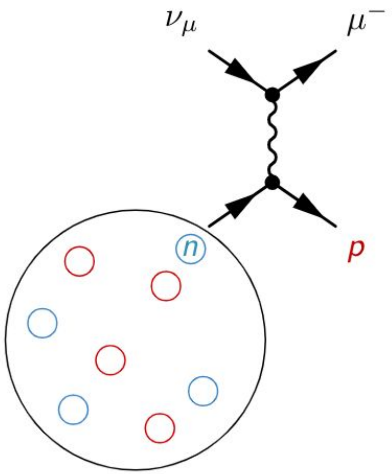

Spectral Function (SF)

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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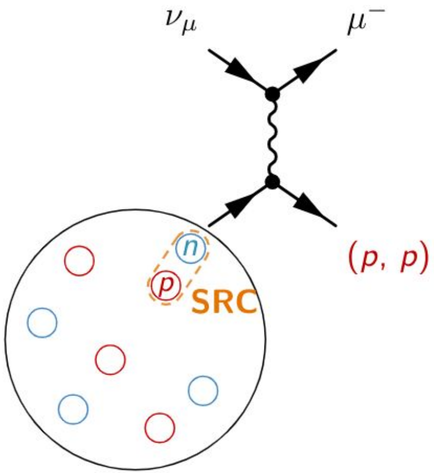

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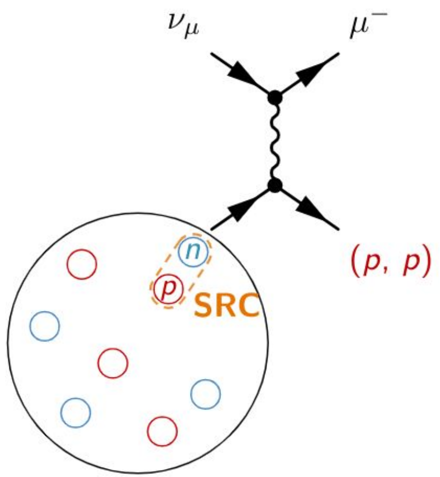

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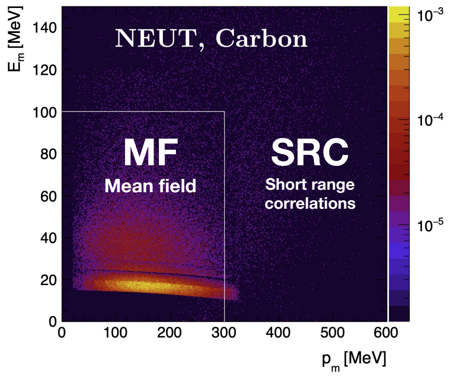

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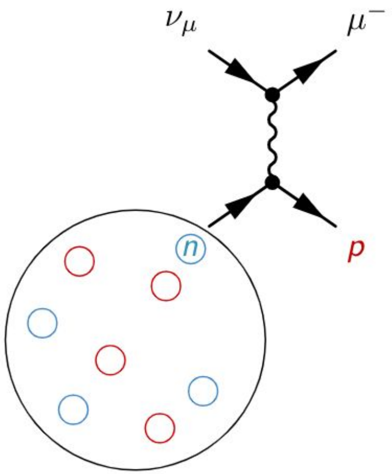

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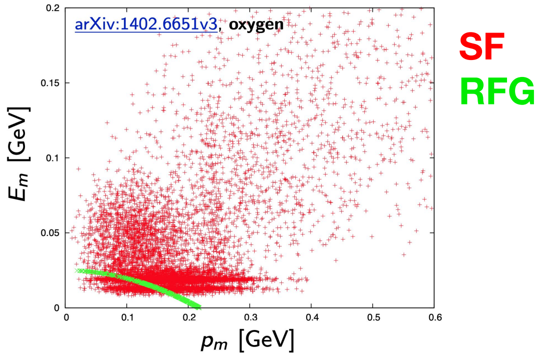

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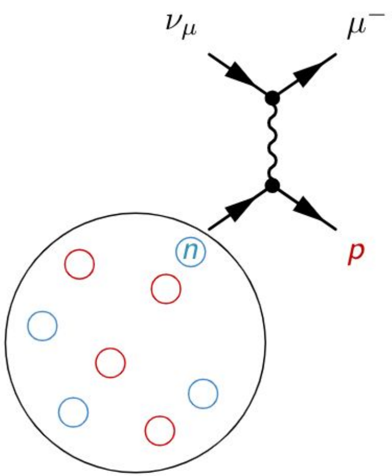

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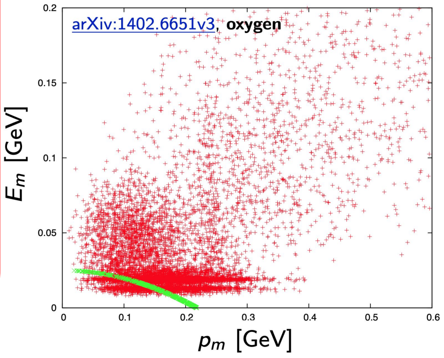
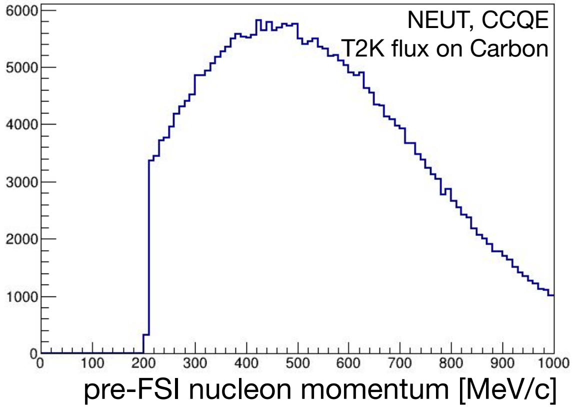


SF
RFG

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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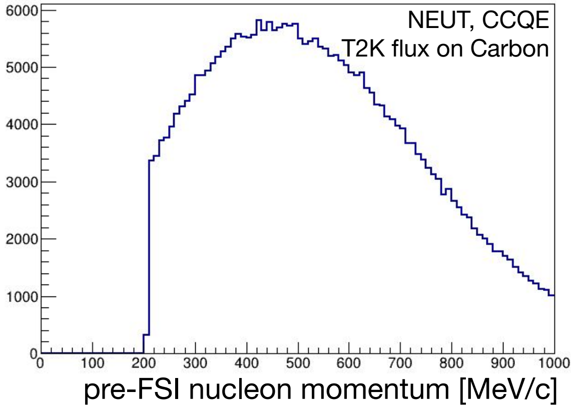

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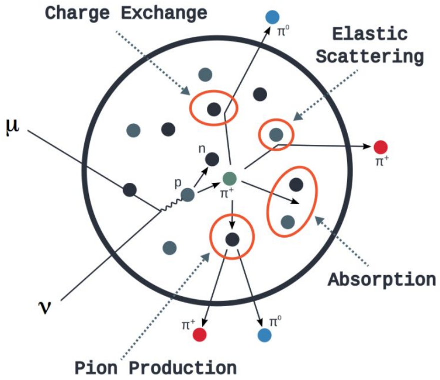
  - Outgoing particles may re-interact with the nuclear matter



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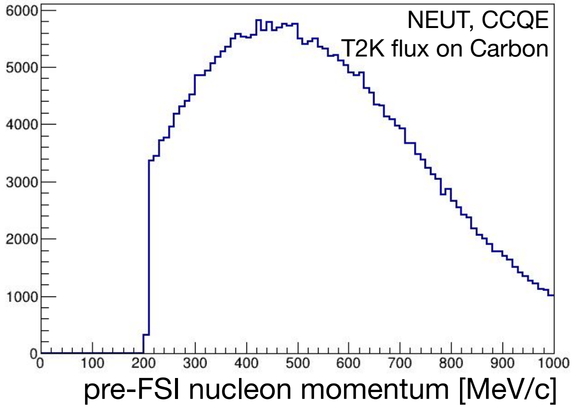

- Final state interactions (FSI):
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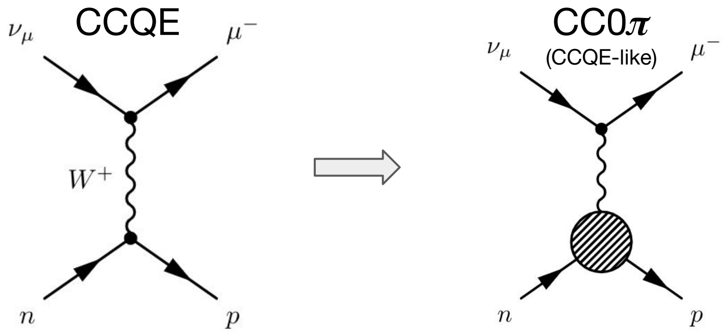
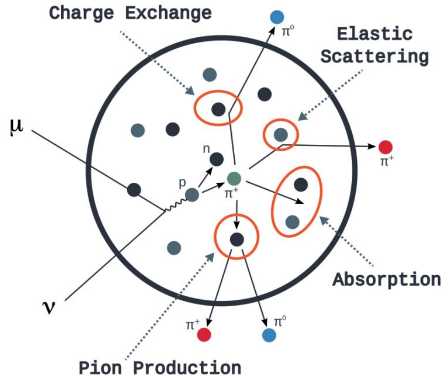
  - Can cause different interactions to have the same final state



Interaction mode

Interaction topology



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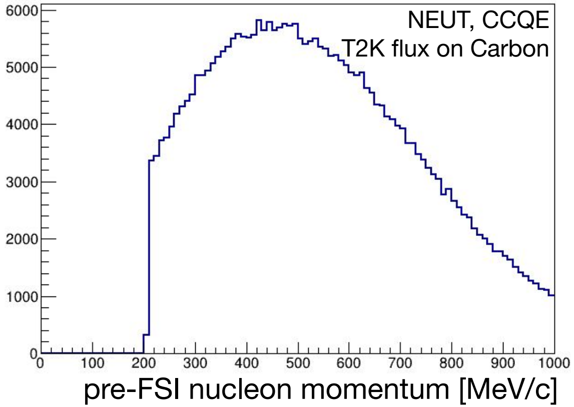

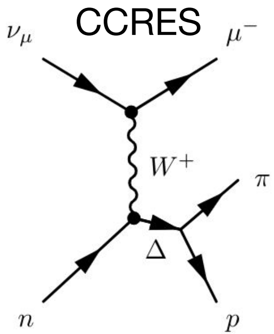

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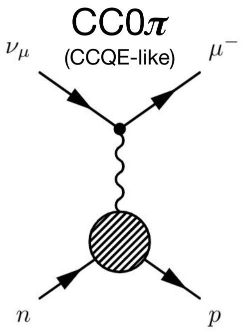

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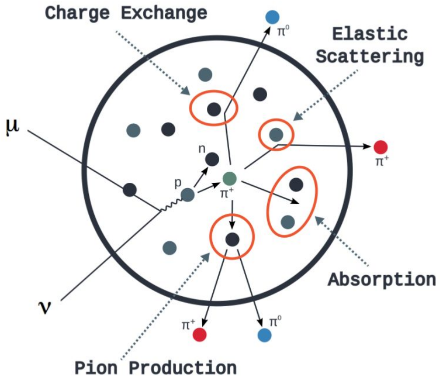

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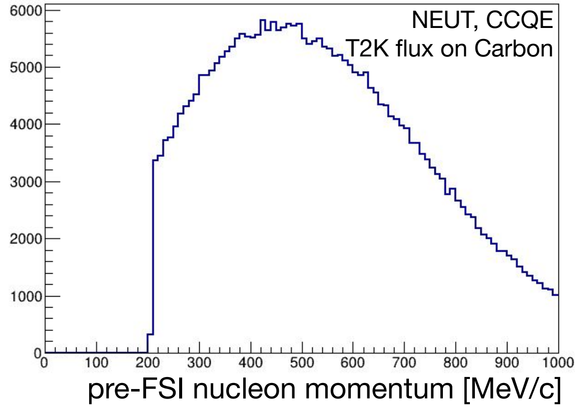

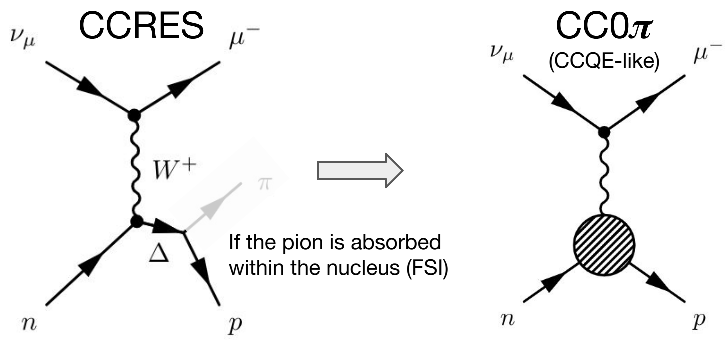

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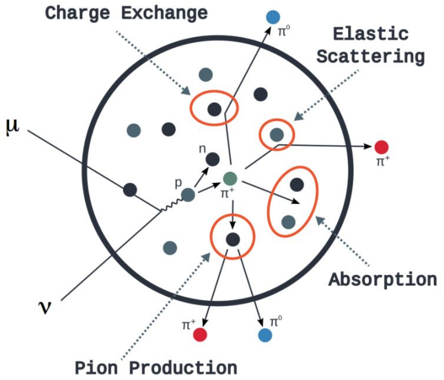
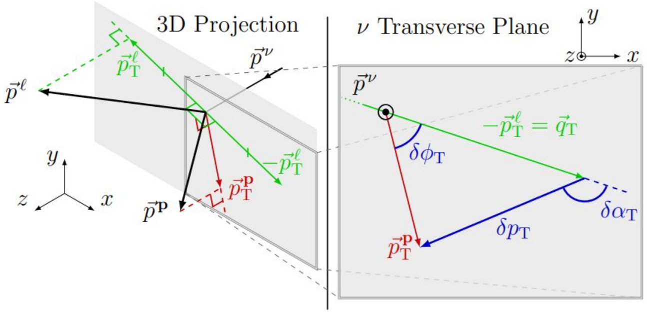
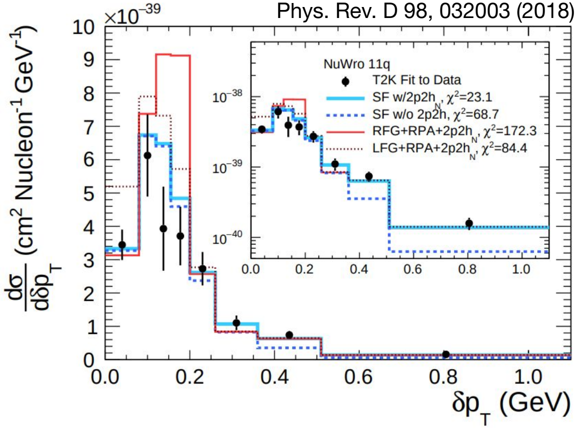


Single Transverse Variables: δp_T Phys. Rev. C 94, 015503 (2016)



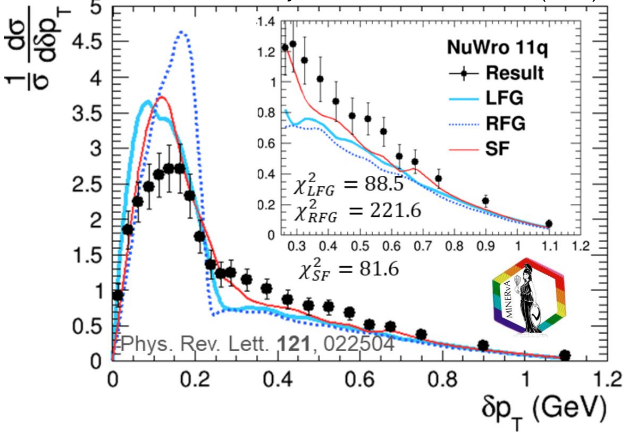
T2K

Phys. Rev. D 98, 032003 (2018)



MINERvA

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



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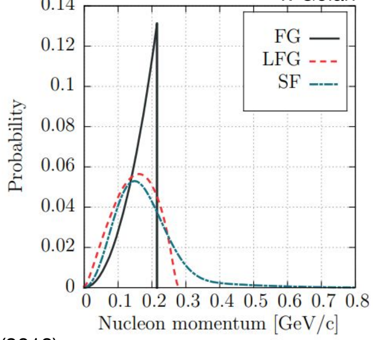

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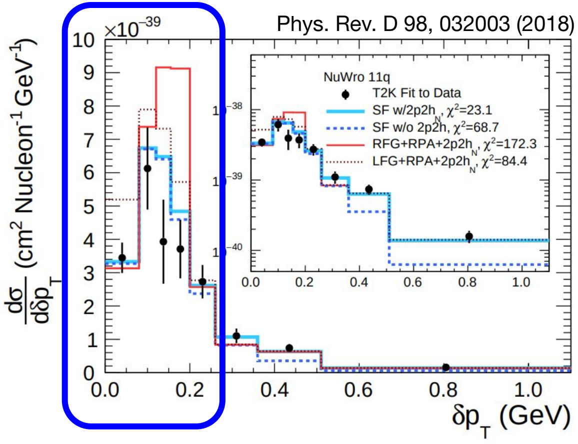

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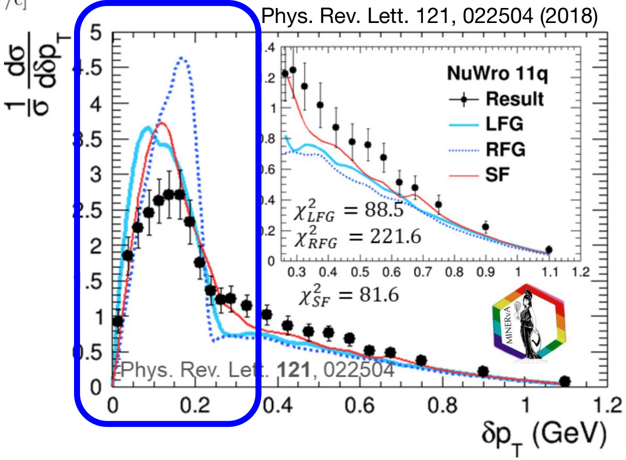

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T2K

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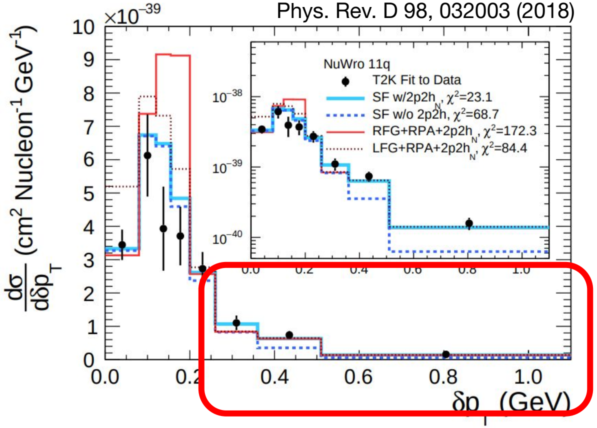

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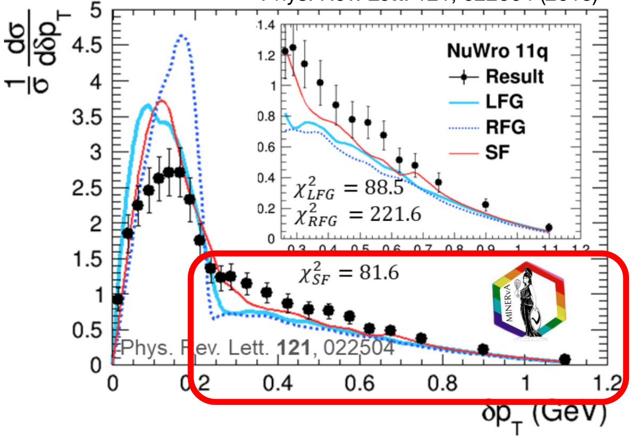

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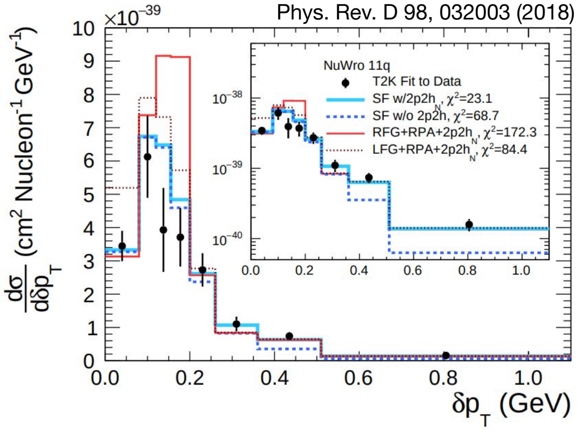
- None of the models describe well the data…

T2K



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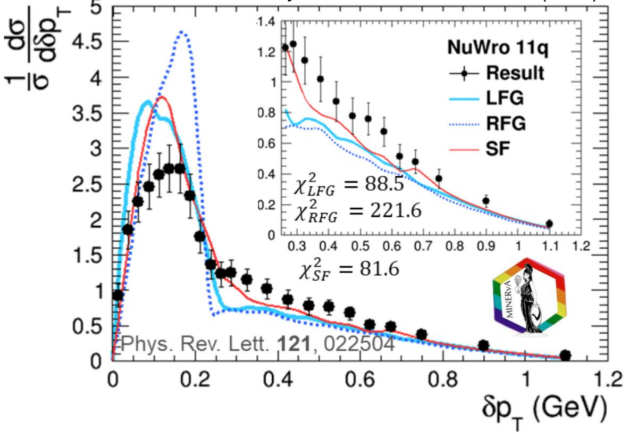


3. Systematic uncertainties in CCQE interactions

New freedoms in the model

- The models do not describe well semi-inclusive data
- A new parameterisation of the CCQE SF model is implemented in NUISANCE to take into account systematic uncertainties
- Applied on NEUT 5.4.0 model (arxiv:2106.15809)

SF model: systematic uncertainties

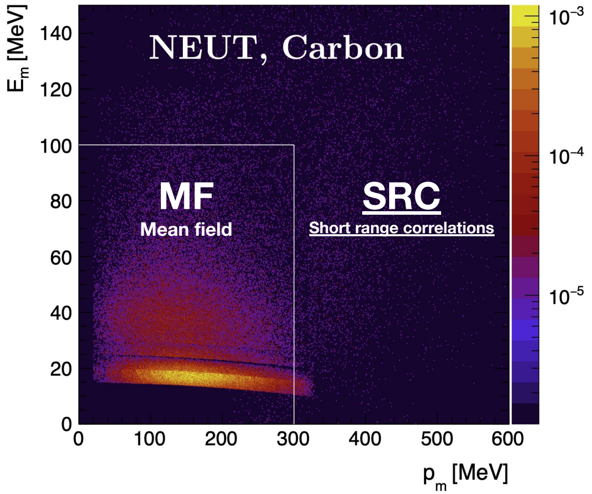
- SF model: $P(p_m, E_m) = P_{MF}(p_m, E_m) + P_{corr}(p_m, E_m)$

  pairs of strongly-correlated nucleons (~20%)

  - SRC contribution : 5% of CCQE in NEUT vs. 15% in NuWro

  ➤ **Systematic:** SRC normalization

=> Two outgoing nucleons are produced (before FSI)



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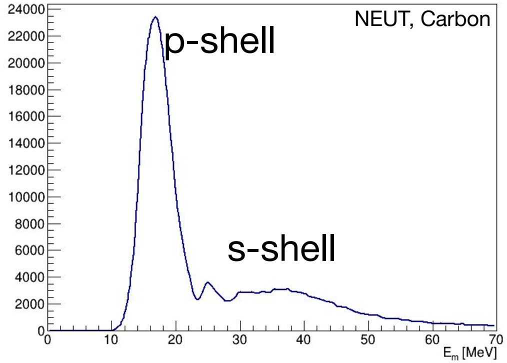

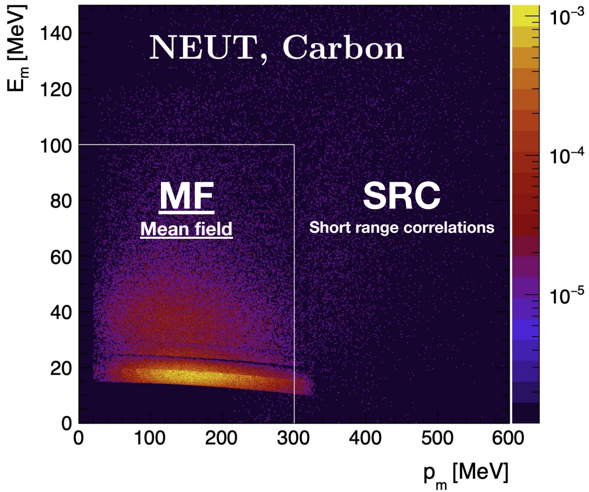

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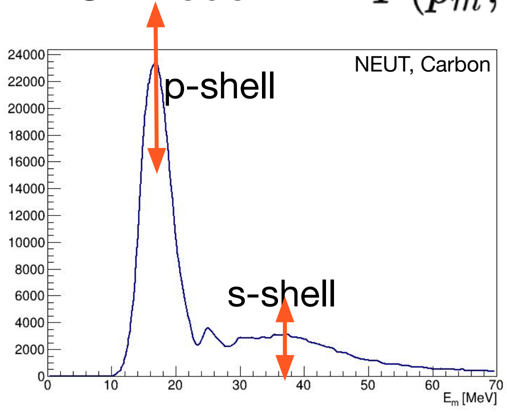


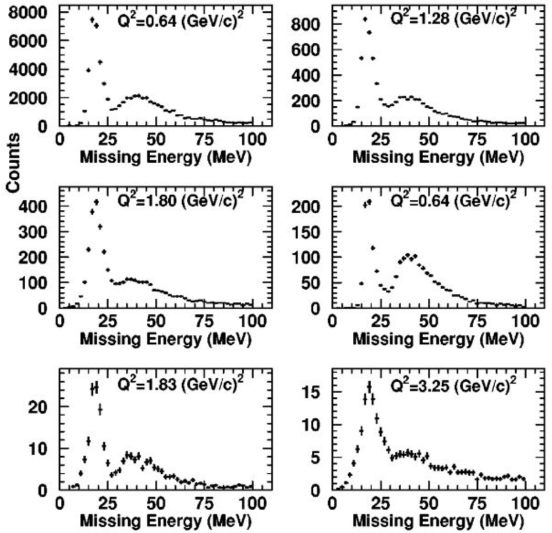
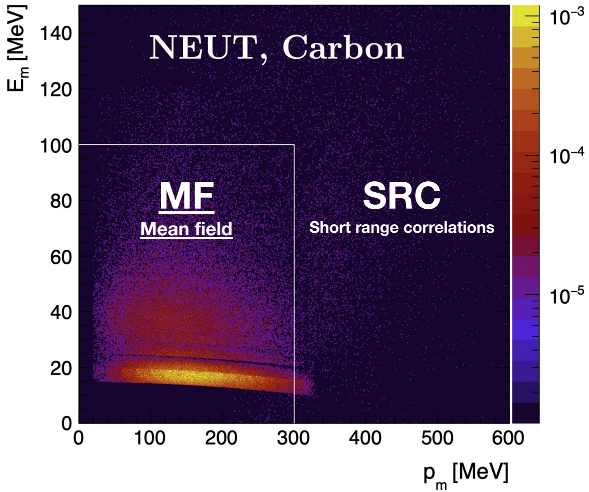


FIG. 3. Measured missing energy spectra for carbon at the different Q^2. The top left and middle right panels refer to the forward and backward electron angle kinematics, respectively, at Q^2 =0.64 (GeV/c)^2 and the middle left and bottom left panels refer to the forward and backward electron angle kinematics, respectively, at Q^2=1.80 (GeV/c)^2. These are the L-T separation kinematics.

Phys Rev C 68, 064603 (2003)



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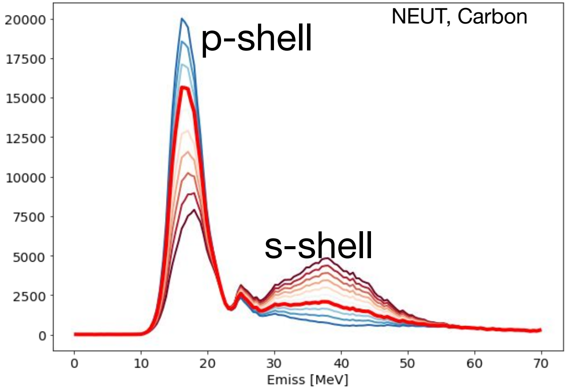
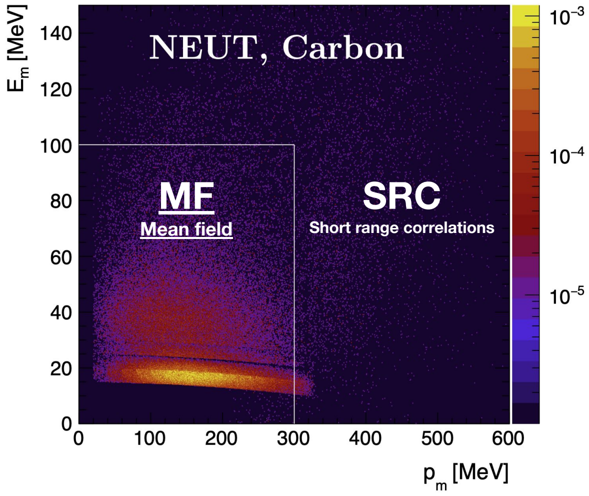
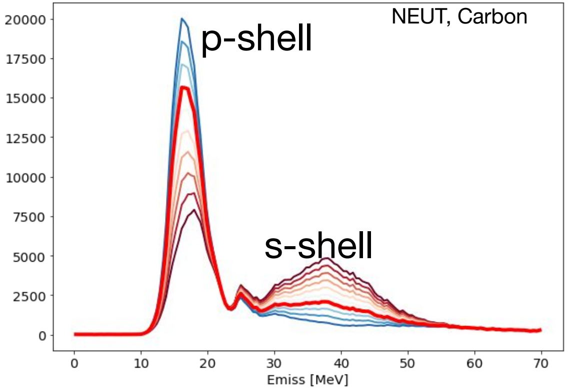


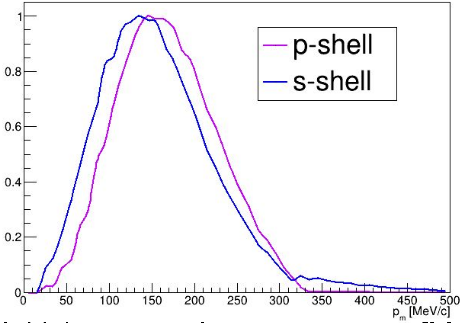
➤ **Systematics:** shell occupancies



SF model: systematic uncertainties

- SF model: $P(p_m, E_m) = P_{MF}(p_m, E_m) + P_{corr}(p_m, E_m)$

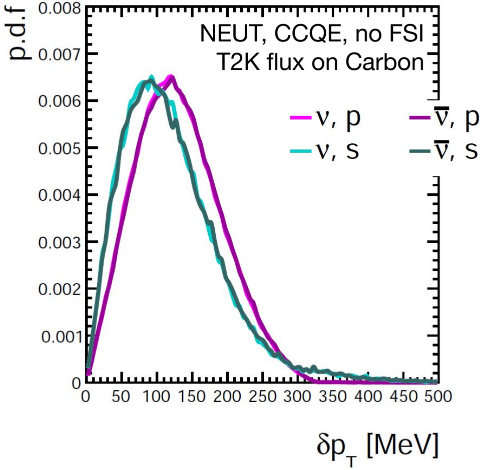


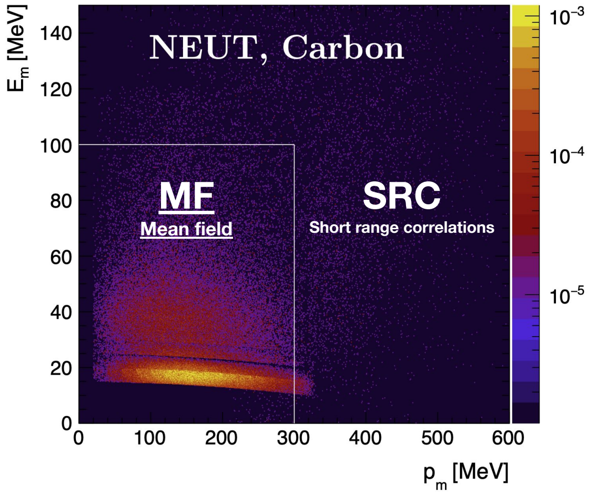


Initial state nucleon momentum [MeV/c]

➤ **Systematics:** shell occupancies

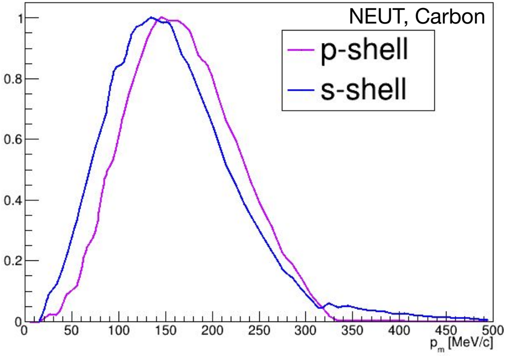
- Impacts the outgoing nucleon kinematics



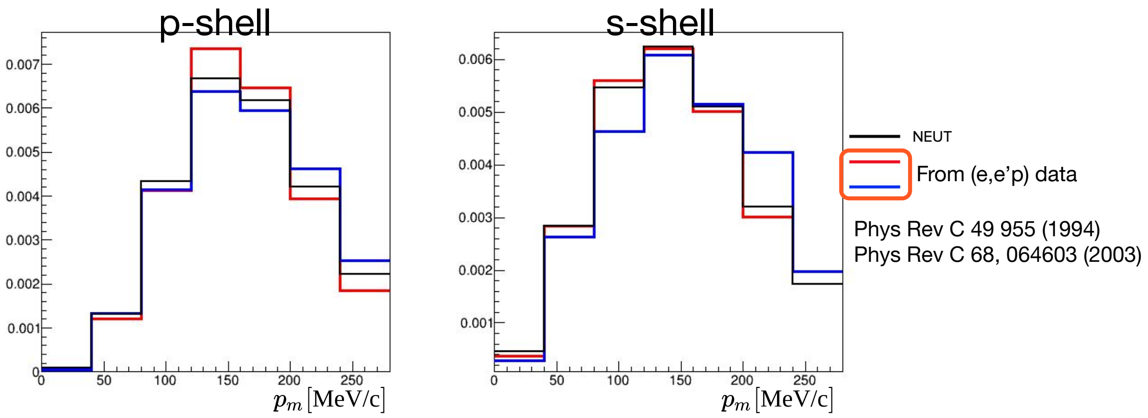


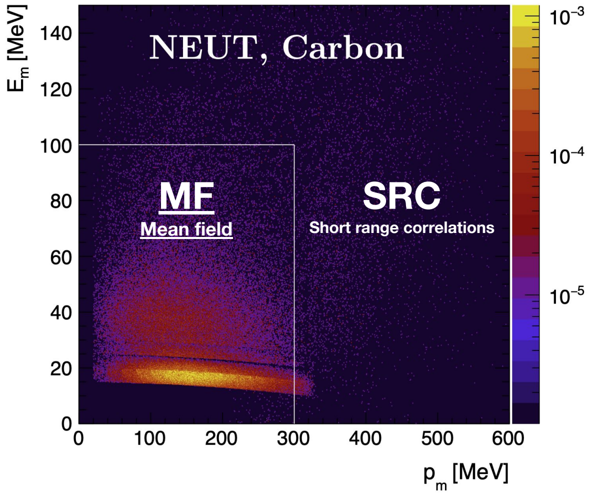
SF model: systematic uncertainties

- SF model: $$P(p_m, E_m) = P_{MF}(p_m, E_m) + P_{corr}(p_m, E_m)$$



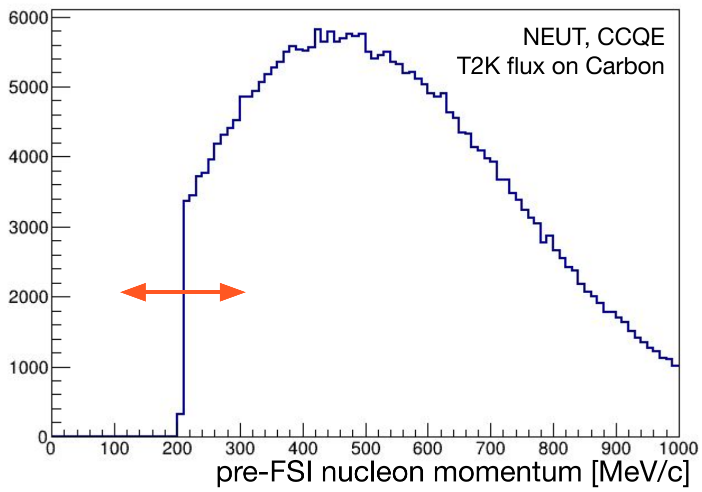
➤ **Systematics:** shape variations of the initial state momentum in each shell

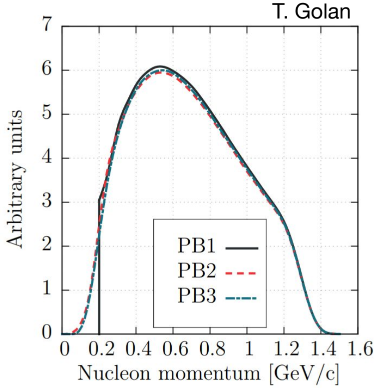




Nuclear effects: Pauli Blocking

- By Pauli principle, an interaction cannot occur if it leads to the creation of a nucleon in a state that is already occupied





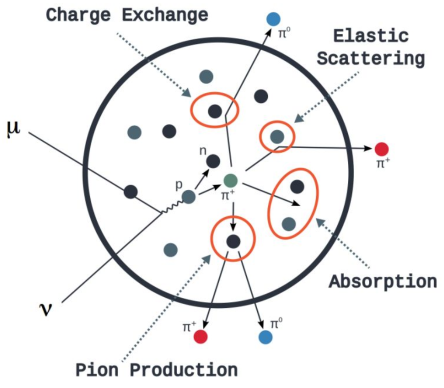
➤ **Systematic:** Pauli Blocking threshold

- Since this affects very low momentum protons, this parameter may not be well constrained by samples like CC0pi+Np (proton momentum threshold in detectors)

Final State Interactions

- Outgoing nucleon:

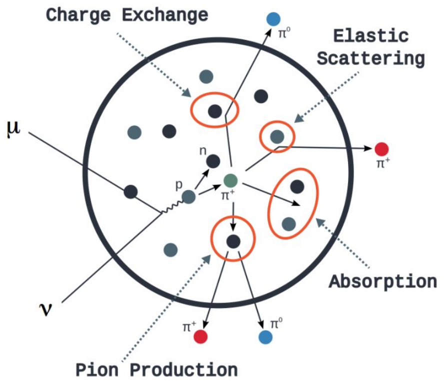
➤ **Systematic:** Nucleon FSI: simple parameter to change the amount of events undergoing FSI w.r.t. no FSI



Final State Interactions

- Outgoing nucleon:

➤ **Systematic:** Nucleon FSI: simple parameter to change the amount of events undergoing FSI w.r.t. no FSI



- Outgoing lepton:
  - The SF model does not include the impact of FSI on the differential cross section in lepton kinematics
  - This can be accounted by altering the lepton kinematics with an optical nuclear potential (Phys. Rev. D 91, 033005 (2015))
  - Available in NuWro (used to generate reweight templates for NEUT)

➤ **Systematic:** strength of the optical potential correction

4. Fits to published data

Fits to published data

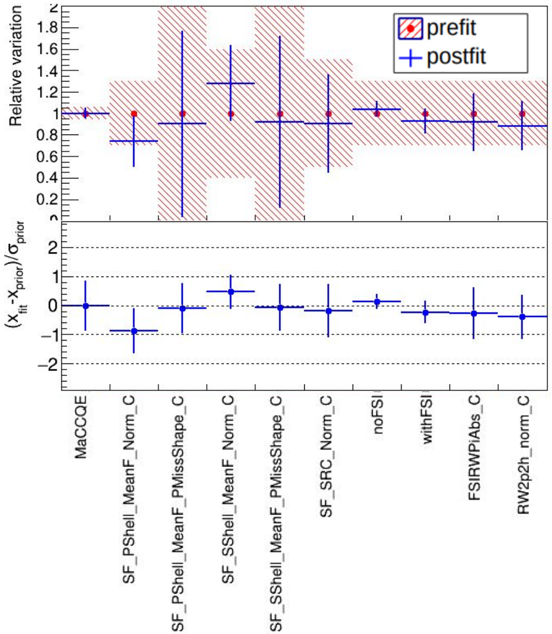
- Ingredients:
    - Model: NEUT with SF model (for Oxygen and Carbon)
    - Parameters: SF model parameters (+ normalisation parameters for other interactions)
    - Data: cross section measurements from T2K and MINERvA
- Chi-square(*): $\chi^2_{\text{data}} = \sum_{1\leq i,j\leq n} \left(B_i - B_i^{MC}\right)\left(M^{-1}\right)_{ij}\left(B_j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

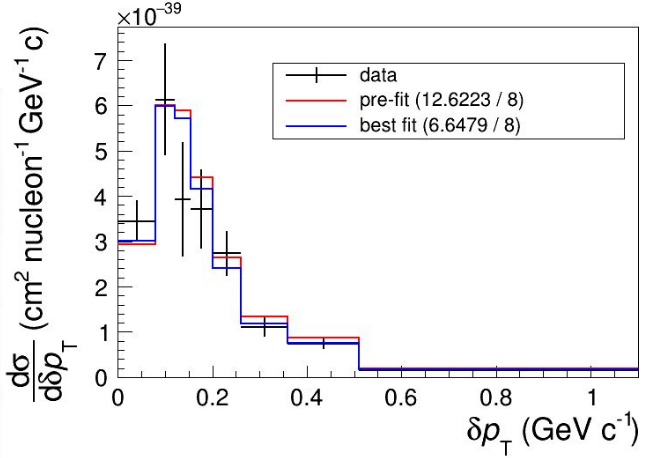
(*) Peelle's Pertinent Puzzle was avoided using a different decomposition of the data histogram and covariance matrix, see back-up

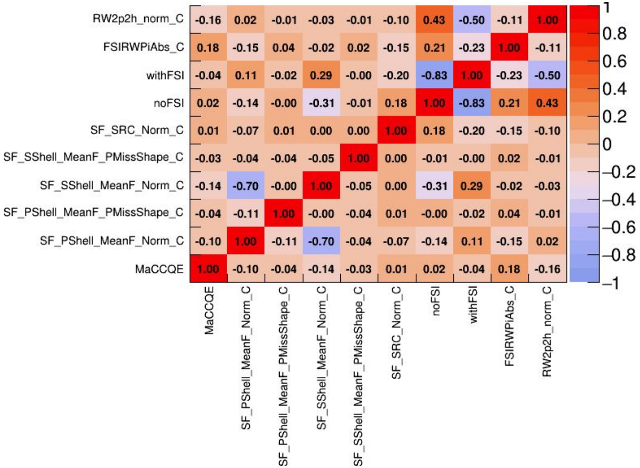
T2K CC0pi δp_T Phys. Rev. D 98, 032003 (2018)

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 δp_T Phys. Rev. D 98, 032003 (2018)

Parameters used in this fit:

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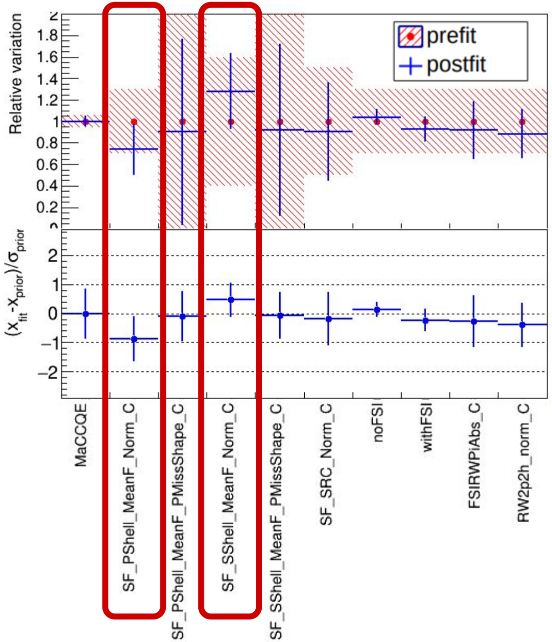

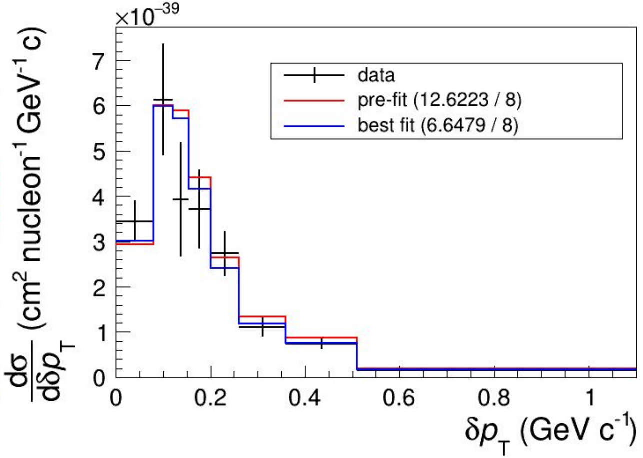

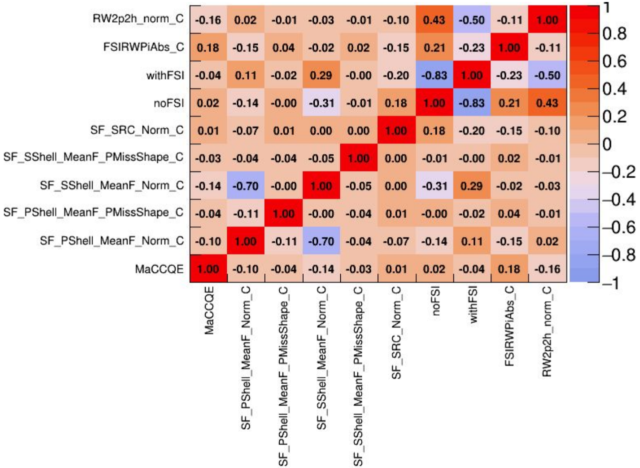

T2K CC0pi δp_T Phys. Rev. D 98, 032003 (2018)

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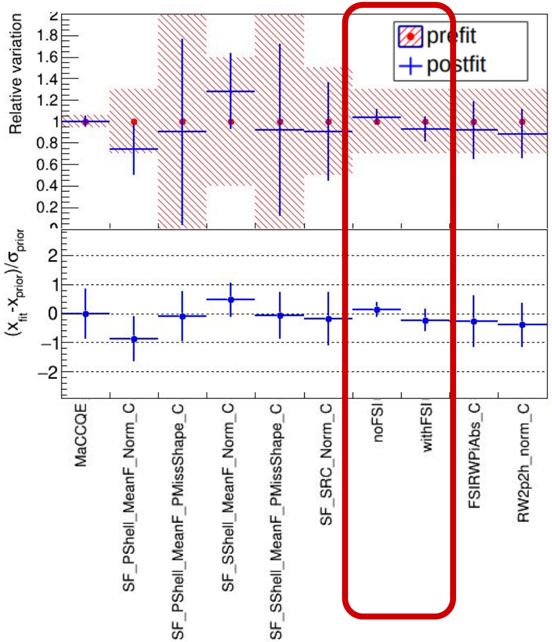
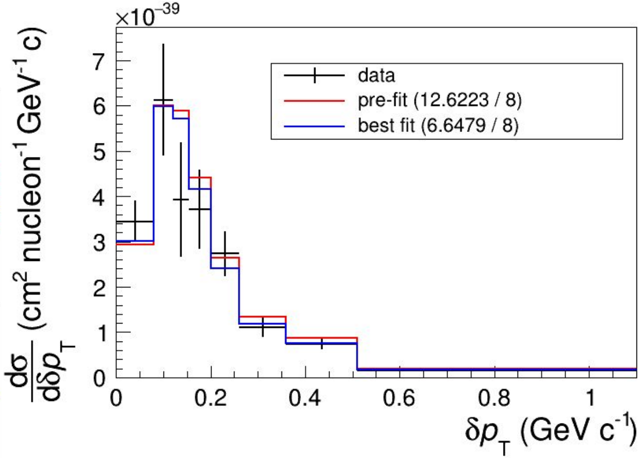


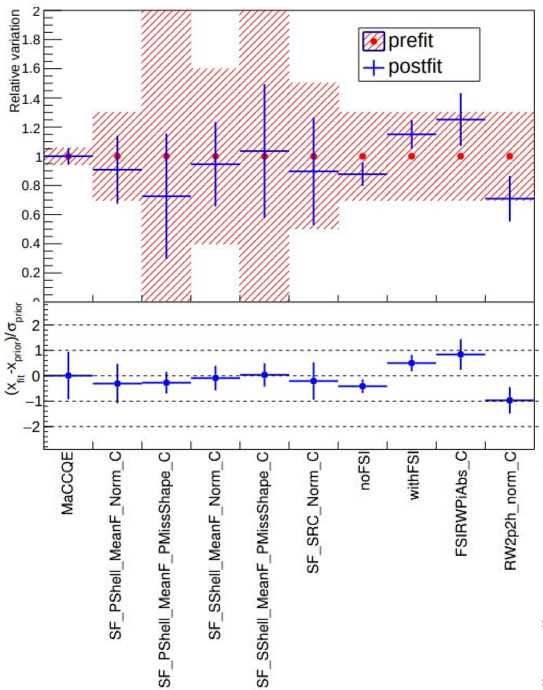


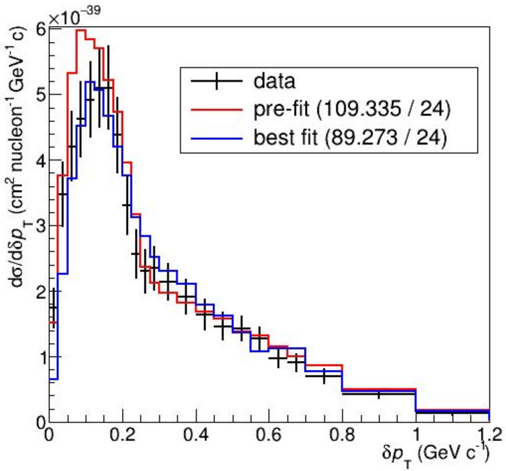
	MaCCQE	SF_PShell_MeanF_Norm_C	SF_PShell_MeanF_PMissShape_C	SF_SShell_MeanF_Norm_C	SF_SShell_MeanF_PMissShape_C	SF_SRC_Norm_C	noFSI	withFSI	FSIRWPiAbs_C	RW2p2h_norm_C
RW2p2h_norm_C	-0.16	0.02	-0.01	-0.03	-0.01	-0.10	0.43	-0.50	-0.11	1.00
FSIRWPiAbs_C	0.18	-0.15	0.04	-0.02	0.02	-0.15	0.21	-0.23	1.00	-0.11
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

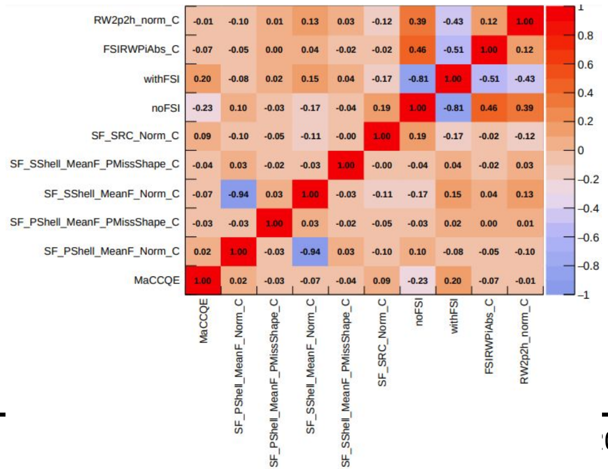
MINERvA CC0pi δp_T Phys. Rev. Lett. 121, 022504 (2018)

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







MINERvA CC0pi δp_T Phys. Rev. Lett. 121, 022504 (2018)

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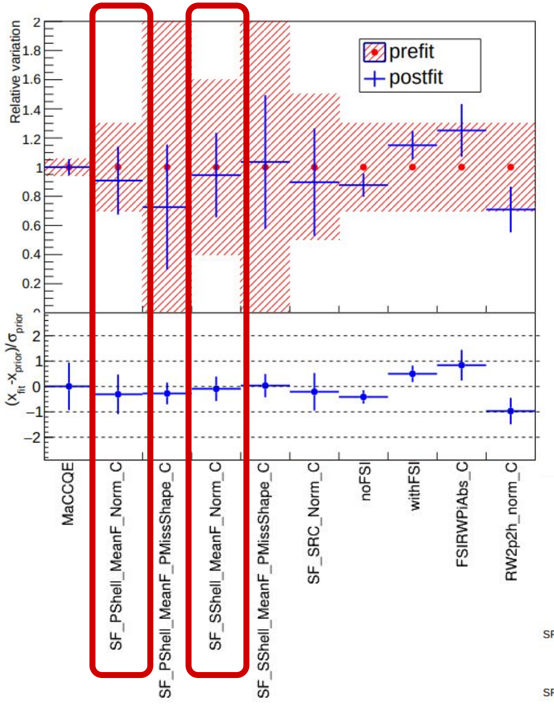

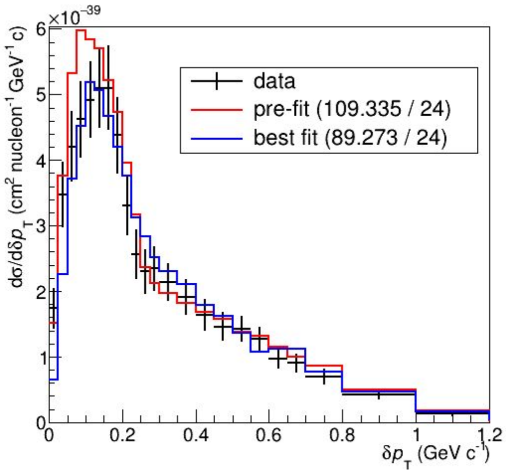

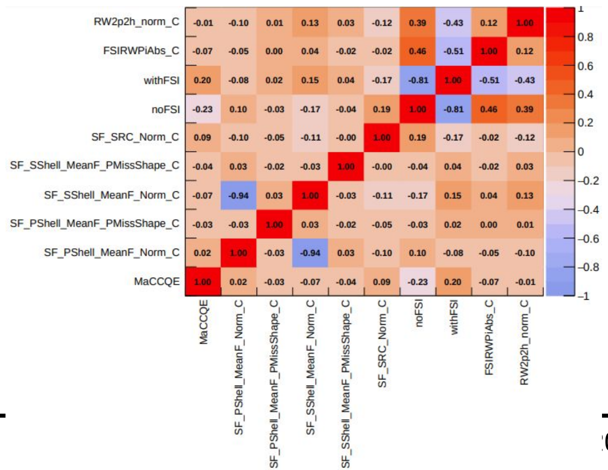

Parameters used in this fit:

- M_A^{QE}
- Shell occupancies
- p_m **shape**
- SRC norm
- No FSI / with FSI (correlated)
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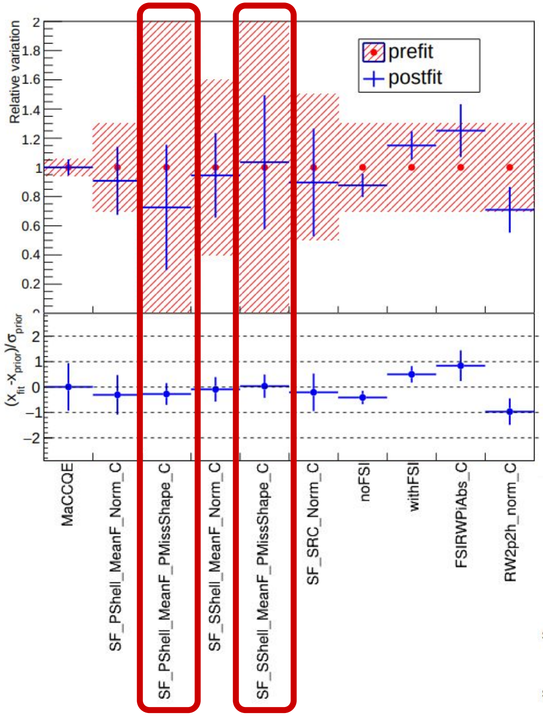

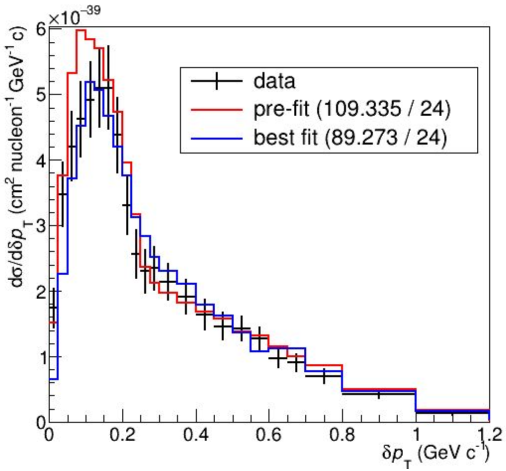

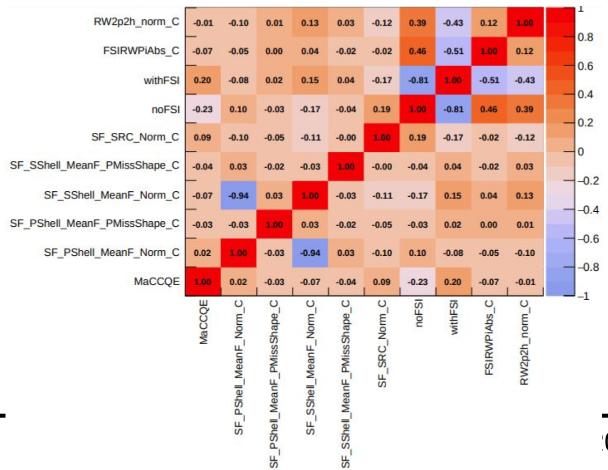

MINERvA CC0pi δp_T Phys. Rev. Lett. 121, 022504 (2018)

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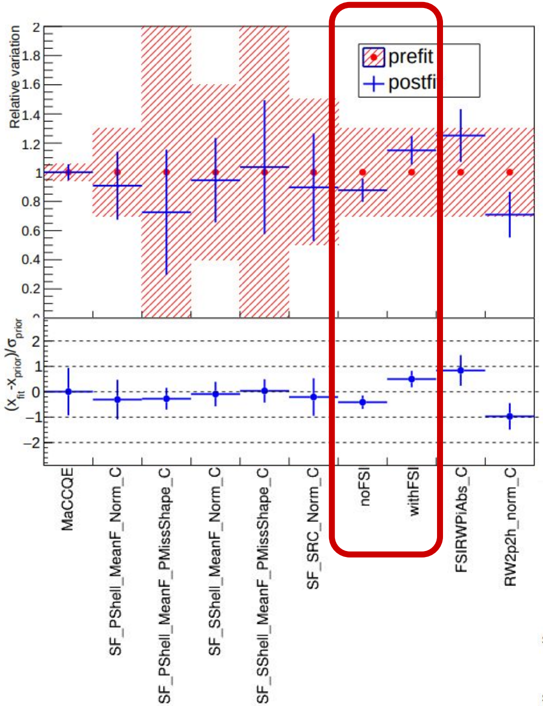
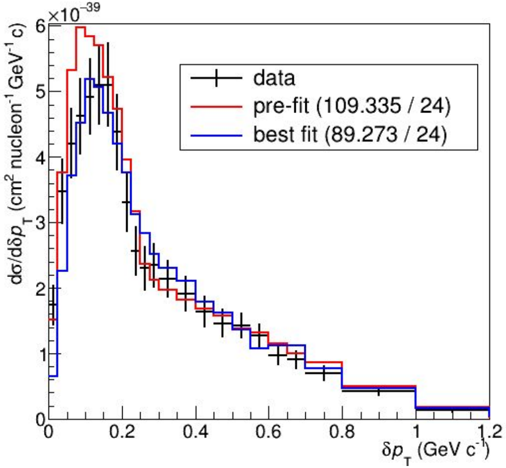
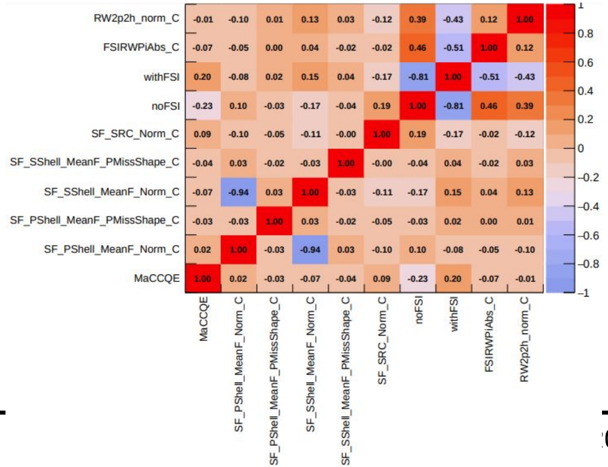
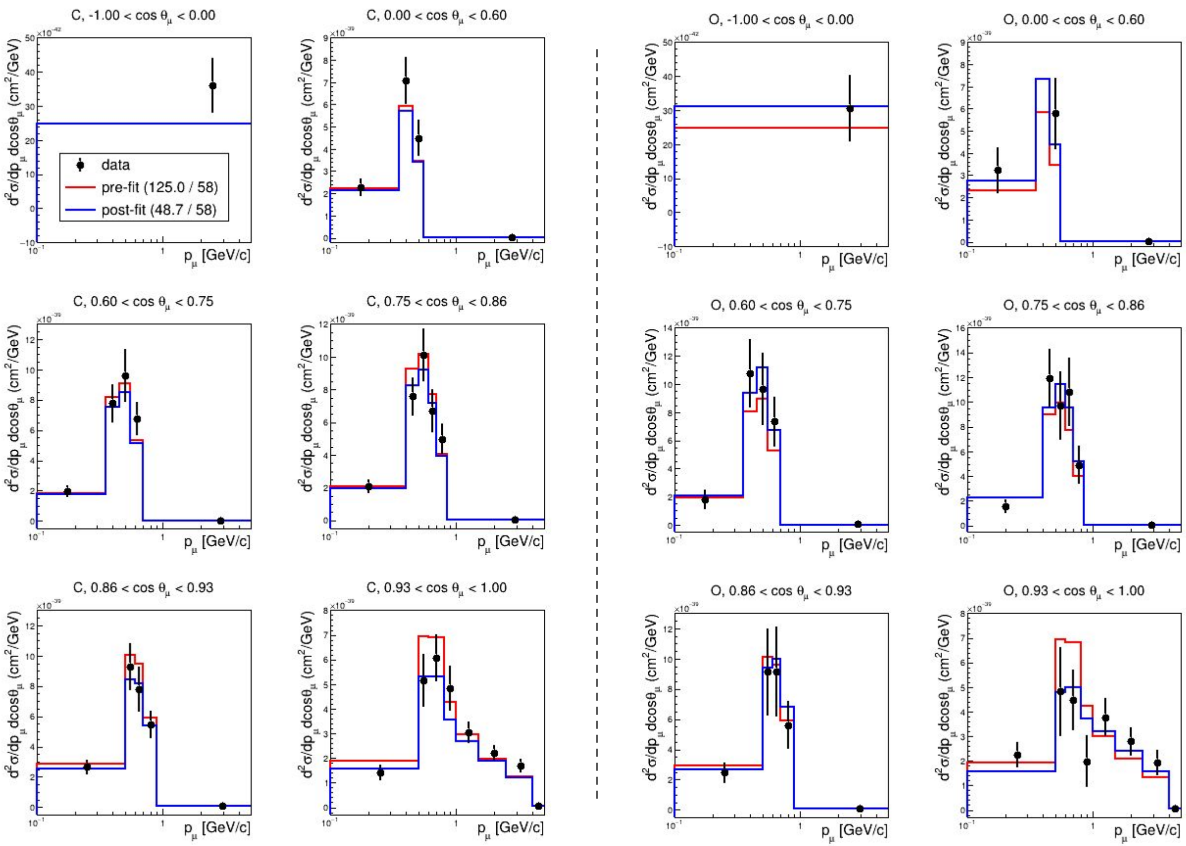






Parameters used in this fit:

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

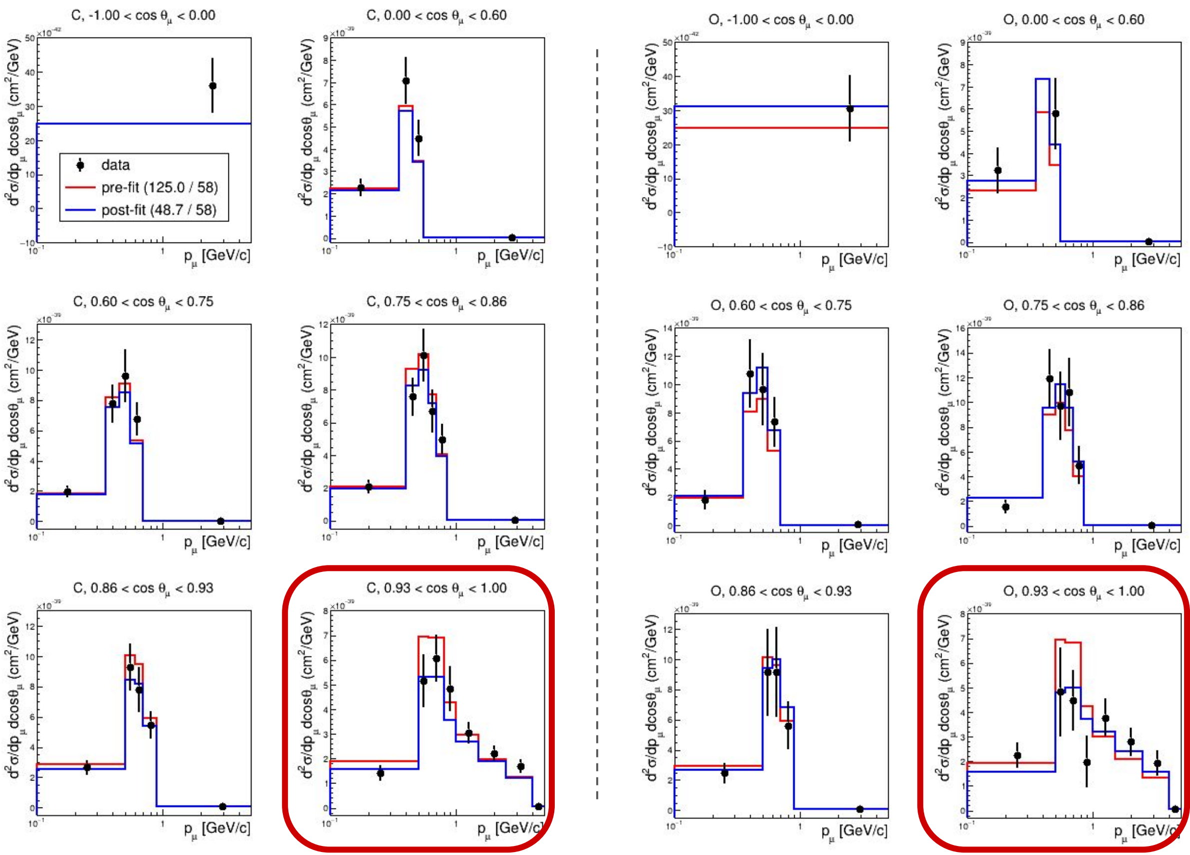


T2K CC0pi O & C measurement

Phys. Rev. D 101, 112004 (2020)

Parameters used in this fit:

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



Correlation matrix in the back-up

Parameters used in this fit:

- M_A^{QE}
- Shell occupancies
- p_m shape
- SRC norm
- Pauli blocking
- Optical potential correction
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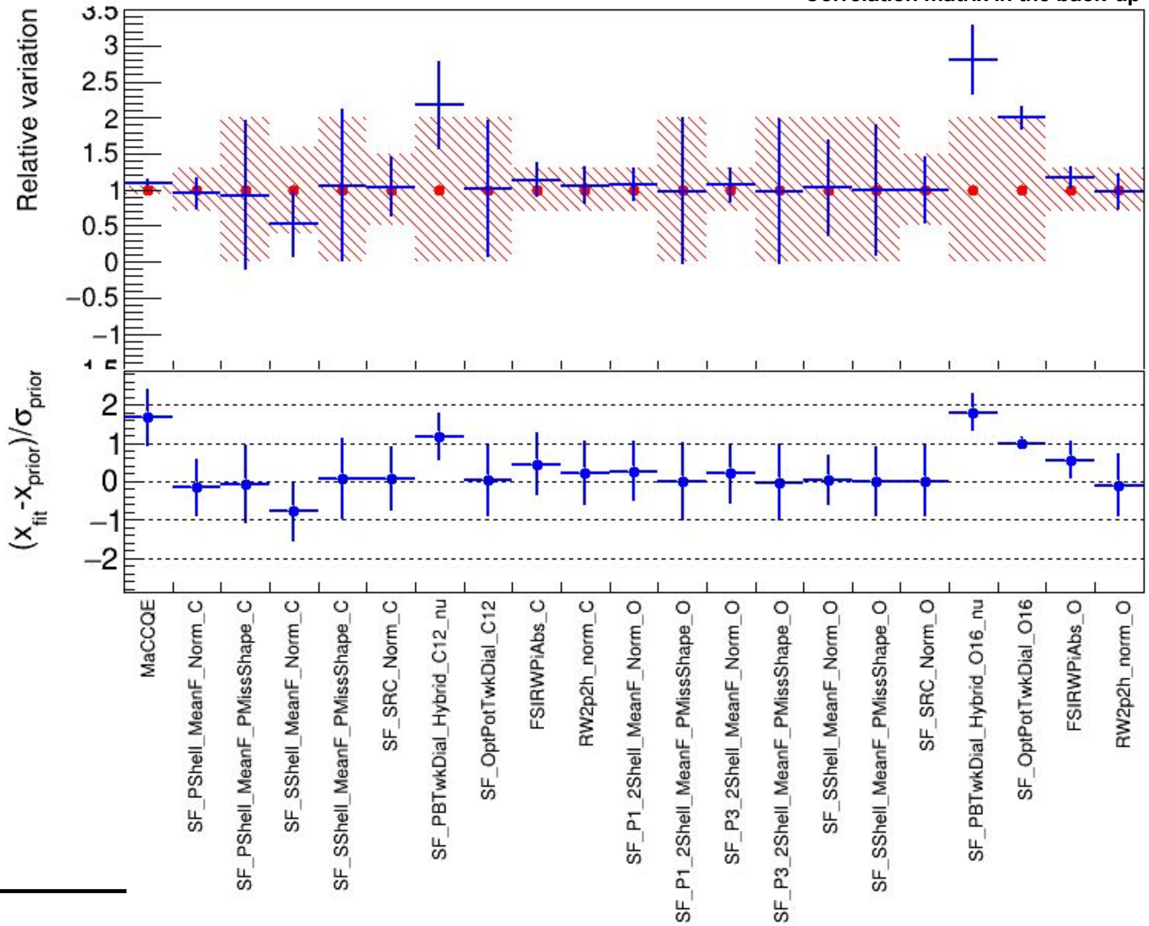


T2K CC0pi O & C measurement

Phys. Rev. D 101, 112004 (2020)

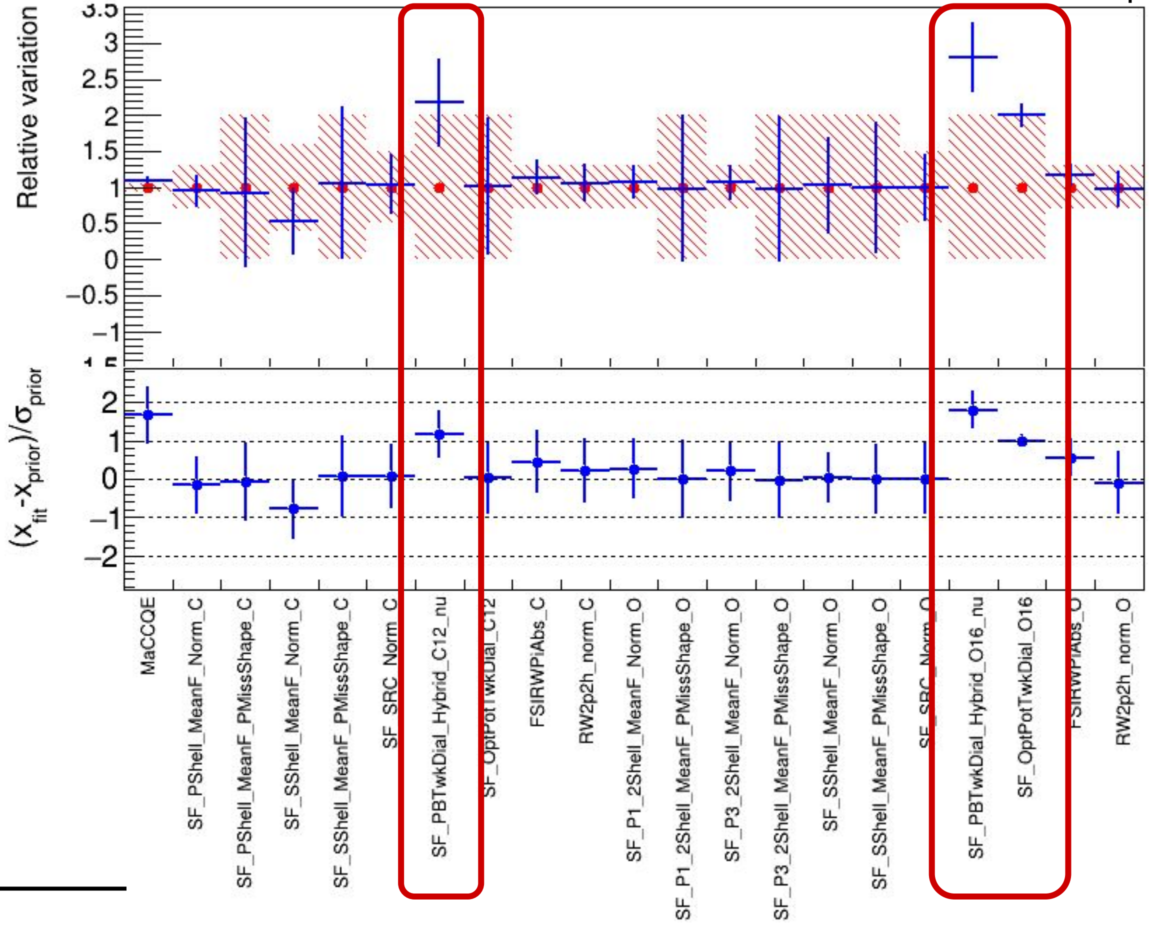
Parameters used in this fit:

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

Nominal PB threshold → 209 MeV/c

1σ shift in PB → 30 MeV/c

Correlation matrix in the back-up



T2K CC0pi O & C measurement

Phys. Rev. D 101, 112004 (2020)

Parameters used in this fit:

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- p_m shape
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- Pauli blocking
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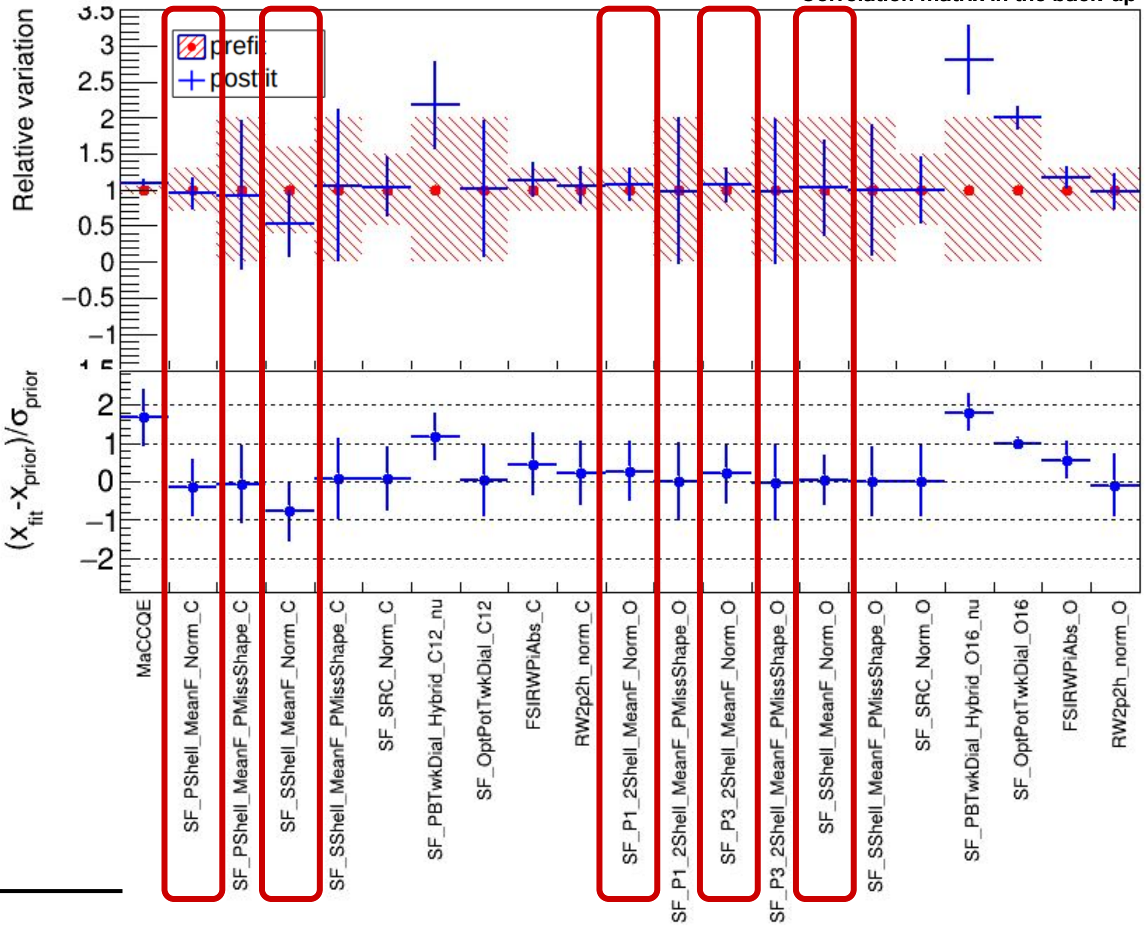
Correlation matrix in the back-up



5. Summary and prospects

Summary and prospects

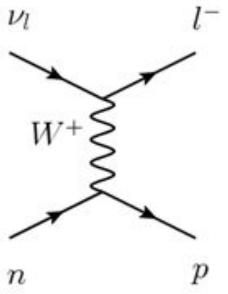
- A new set of physically-motivated uncertainties on the (semi-)inclusive predictions of the CCQE Spectral Function model were introduced
- Fitting to external data shows great improvement for T2K
- MINERvA data is sensitive to this parameterisation but shows little improvement in the data/MC agreement

- This parameterisation may still need further improvement especially for FSI and low energy transfer effects (e.g. see Jordan's talk next)
- New data and an appropriate choice of observables may help to better constrain and improve the model
- Some of this work has been used in a recent sensitivity study of T2K's ND upgrade (see arXiv:2108.11779)
- A complete set of uncertainties on semi-inclusive models will be crucial for upcoming oscillation measurements

Back-up

Pauli Blocking

- By Pauli principle, an interaction cannot occur if it leads to the creation of a nucleon in a state that is already occupied



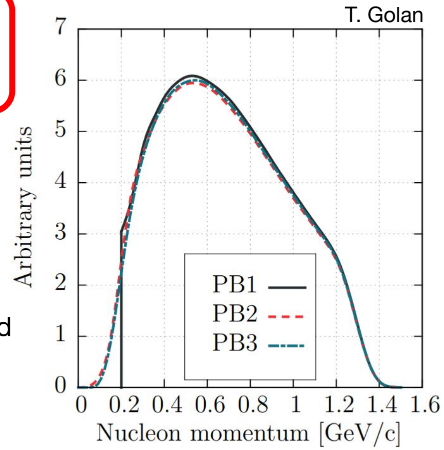
- Different possible models for SF:

This talk

$$P(p_m, E_m) \rightarrow \Theta(p_F - p_{final})P(p_m, E_m) \quad \text{(PB1) RFG-like}$$

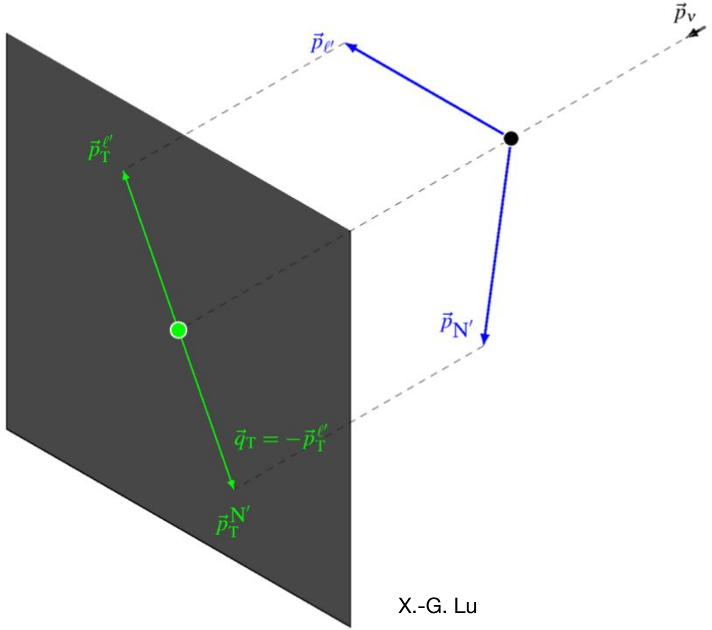
$$P(p_m, E_m) \rightarrow \Theta(p_F(r) - p_{final})P(p_m, E_m) \quad \text{(PB2) LFG-like}$$

$$P(p_m, E_m) \rightarrow \Theta(n(p_{final}) - \text{rand}[0,1])P(p_m, E_m) \quad \text{(PB3) MC method}$$



Single Transverse Variables

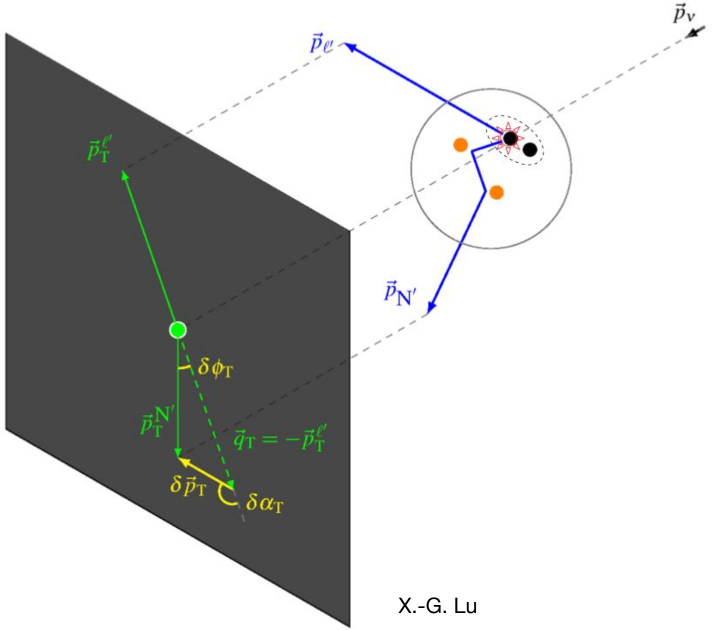
Static nucleon target



X.-G. Lu

Single Transverse Variables

Nucleon bound within nuclear target



X.-G. Lu

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

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

$$H_1 : \{B_1, ..., B_n\} \to H_2 : \{C_1, ..., C_n\}$$

$$C_i = \begin{cases} \frac{B_i}{\sum_k B_k} & , i < n \\ \sum_k B_k & , i = n \end{cases}$$

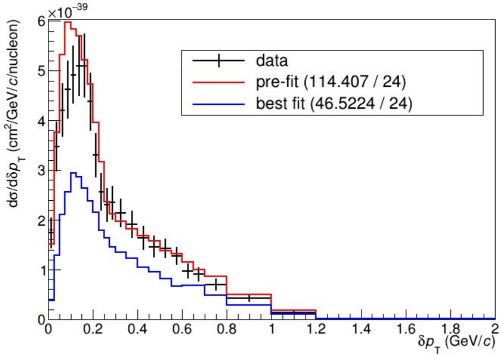
- We can obtain $\mathrm{Cov}\left[\{C_i\}\right]$ (norm-shape covariance) directly from the data covariance given by experiments $\mathrm{Cov}\left[\{B_i\}\right]$
- Perform the fit in this new basis using $N = \mathrm{Cov}[\{C_i\}]$

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

Avoiding Peelle's Pertinent Puzzle

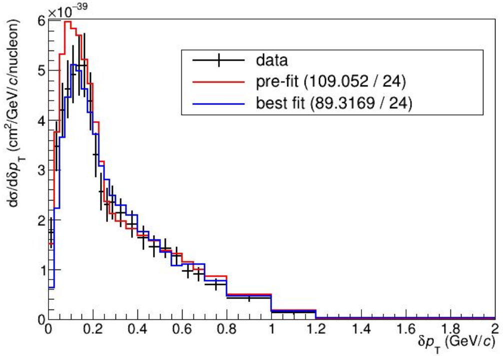
- Example of MINERvA dpt fit with the same parameterisation of slide 41:

Fit using minimizing the usual chi2



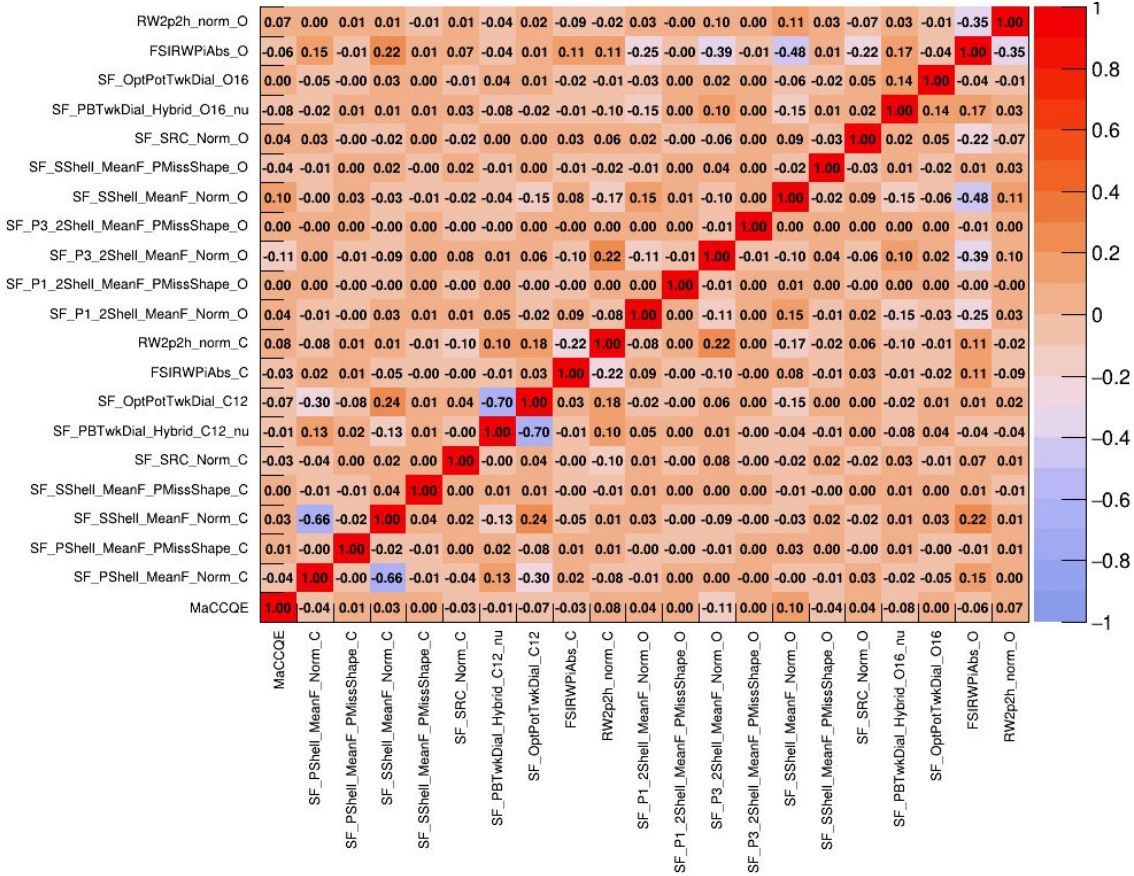
	Normal chi2	NS chi2
prefit	**114.407**	109.052
postfit	**46.5224**	108.201

Fit using minimizing the new chi2



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

T2K CC0pi O & C measurement (arxiv:2004.05434)



MINERvA CC0pi p_n Phys. Rev. Lett. 121, 022504 (2018)

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