NEUT model improvements and external data fits

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NuFact 2015
Rio de Janeiro
Aug 13, 2015

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2. NEUT
   - Spectral Function
   - Nieves 2p2h
   - RPA
3. External Data Fits
   - CCQE fits
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4. Summary and Outlook

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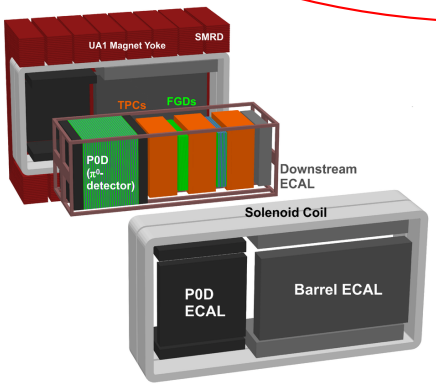
T2K Oscillation Analysis Overview

External Data
- MiniBooNE
- MinervA
- ANL
- BNL
- π-C scattering
- ...

NEUT
- CCQE
- pion production
- CC coherent
- FSI cascade model
- ...

model parameters priors & covariance matrix



ND280 Data

Neutrino
- CC0π
- CC1π
- CCother

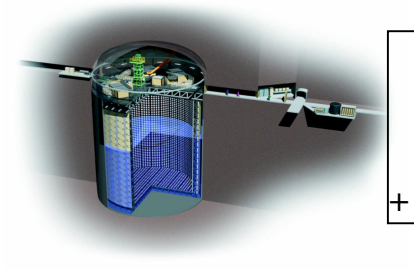
Anti-Neutrino
- CC1track
- CCNtrack

Near Detector Fit

With covariance matrix:
- Detector systematics
- Flux systematics

see Talk K. Mahn (Tue Aug 11)

extrapolation to Super-K



Super-K Data
- 1 Ring e-like
- 1 Ring mu-like

+ Super-K detector systematics

Oscillation Analysis

see Talk K. Duffy (Tue Aug 11)

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The NEUT Neutrino Generator

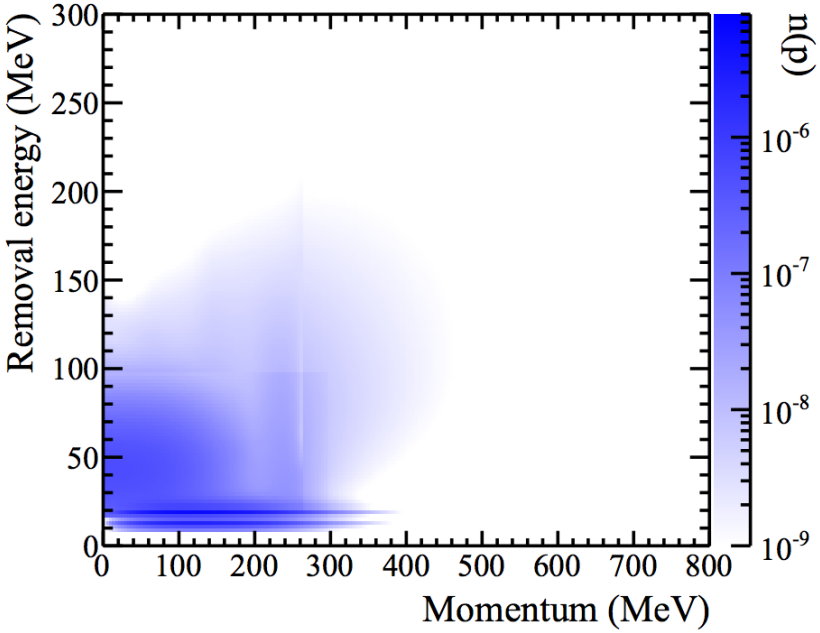
Default (NEUT $< 5.3.2$)

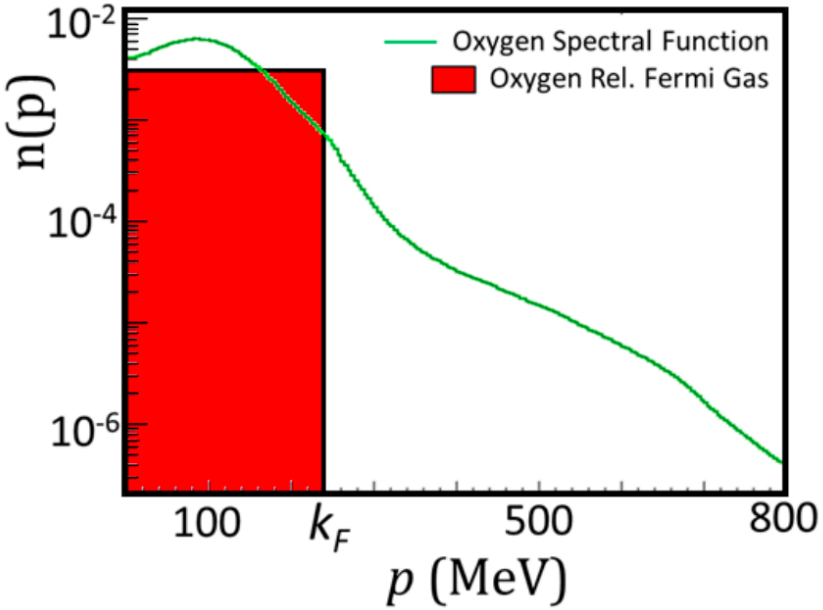
- Llewellyn-Smith model for 1p1h CCQE interactions.
- Rein-Sehgal model for resonant and coherent pion production.
- BBBA05 form factor with default M_A of 1.21 GeV/c^2 for CCQE and resonant production.
- GRV94/GRV98 pdfs with Bodek-Yang corrections for DIS.
- Relativistic Fermi Gas (RFG) from Smith-Moniz with Pauli-blocking as initial state nuclear model.

Latest improvements (NEUT 5.3.2):

- Initial state nuclear model: Spectral function model by Benhar et al. implemented.
- 2p2h model of Nieves implemented.
- Random Phase Approximation (RPA).
- More realistic pion form factors from Graczyk and Sobczyk (*Phys. Rev. D* **77**, 053001 (2008)).

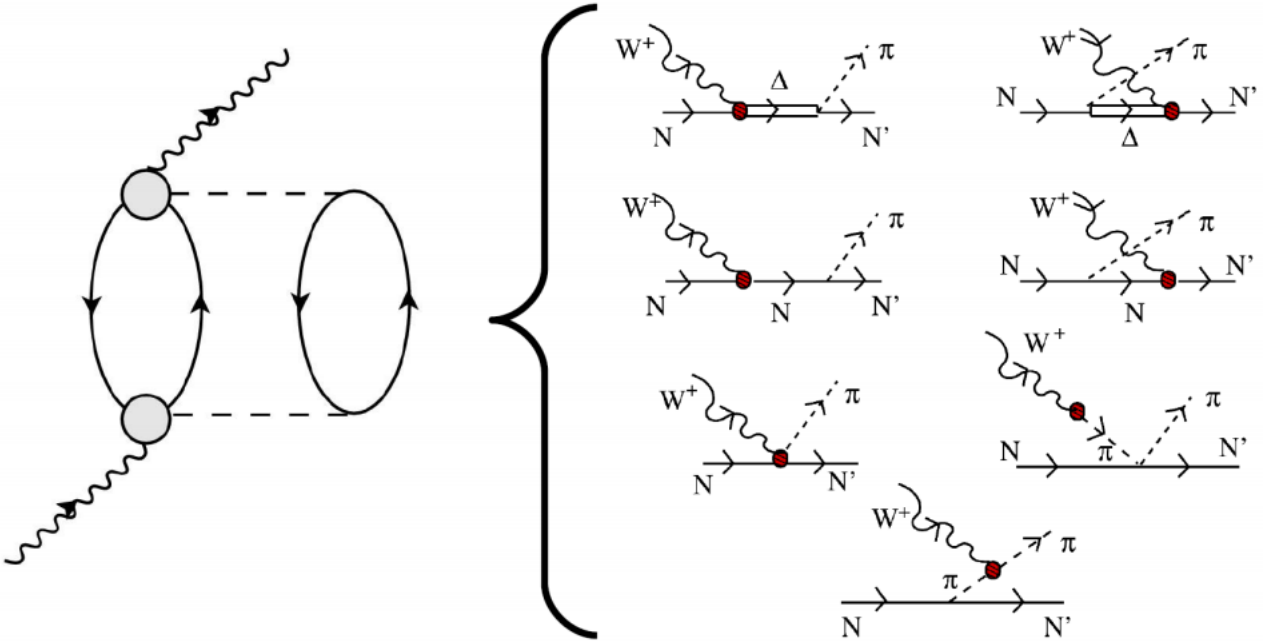
Spectral Function





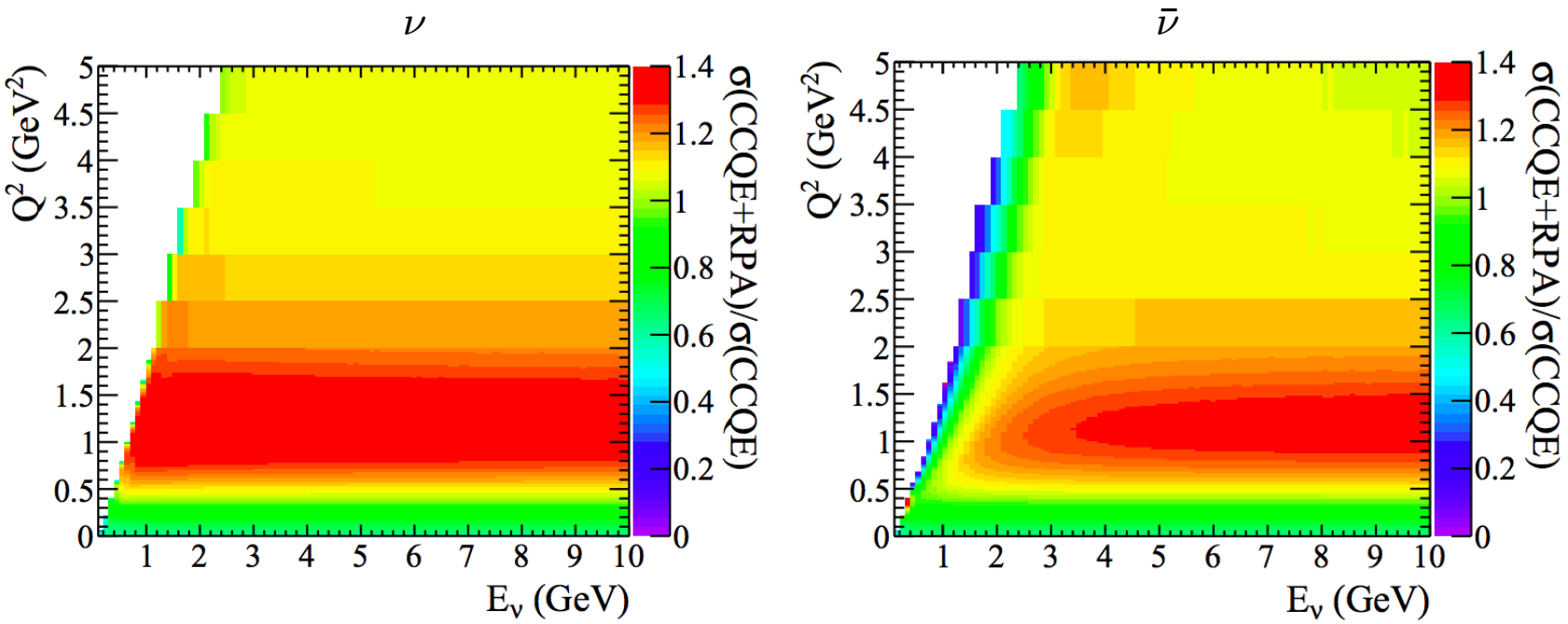
- Spectral Function in nucleon momentum and removal energy by Benhar et al. (*Phys. Rev. C* **62**, 034304 (2000)).
- Standard Impulse Approximation used.
- Available for C, O and Fe.
- Pauli-blocking with hard cut-off.
- Effective Spectral Function by Bodek et al. recently added to NEUT but not yet candidate model for T2K.

Nieves 2p2h model



- Interaction with pair of short range correlated nucleons.
- Use pre-calculated tables based on Nieves et al. (*Phys. Rev. C* **83**, 045501 (2011)).
- Only lepton kinematics predicted, hadronic part through Sobczyk model.
- High energy extension based on Gran et al. (*Phys. Rev. D* **88**, 113007 (2013)).

Random Phase Approximation (RPA)



- Nuclear screening effect due long range nucleon-nucleon correlations.
- NEUT implementation depends on Q^2 and E_ν, based on Nieves et al. (*Phys. Rev. C* **83**, 045501 (2011)).
- Assumes Local Fermi Gas, but also valid for Relativistic Fermi Gas.
- No Spectral Function RPA correction.

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CCQE Fit procedure and datasets

Procedure:

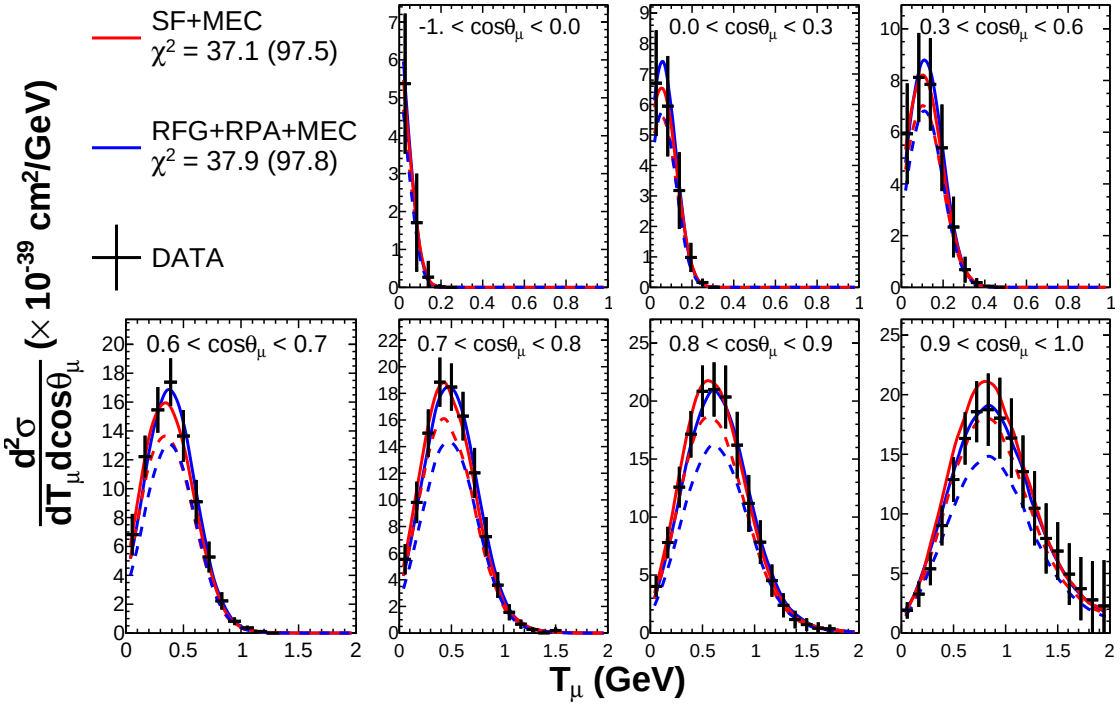
1. Float model parameters (M_A, 2p2h normalization, p_F) and MiniBooNE normalization in χ^2 fit within each model.
2. Test agreement of complete dataset with model through standard Pearson χ^2 Goodness of Fit test.
3. Use Parameter Goodness of Fit (PGoF) test for consistency between datasets within each model.
4. Rescale parameter errors to span differences between datasets according to PGoF test.
5. Apply PGoF procedure to an ND280 data fit and external data fits to ensure prior errors cover both the external fit results and ND280 data at 1σ.

Datasets:

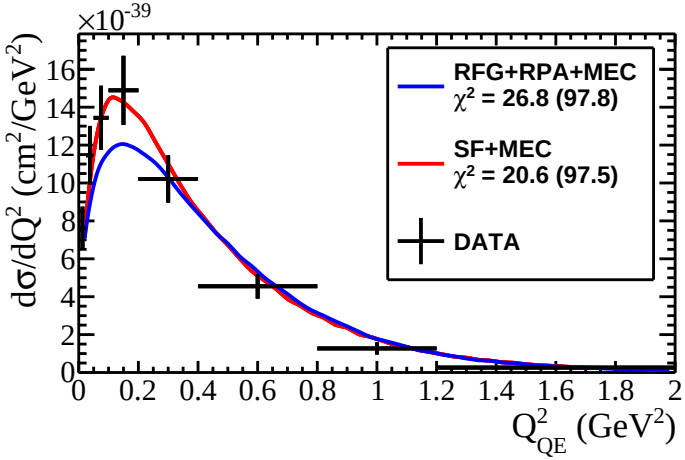
- MiniBooNE: $\frac{d^2\sigma}{dT_\mu\, d\cos\theta_\mu}$ for ν and $\bar{\nu}$ (CCQE-corrected data from *Phys. Rev. D* **81**, 092005 (2010) and *Phys. Rev. D* **88**, 032001 (2013))
- MINERνA: $\frac{d\sigma}{dQ^2_{\mathrm{QE}}}$ for ν and $\bar{\nu}$ with restricted phase space $\theta_\mu \leq 20^\circ$, including cross-correlations (*Phys. Rev. Lett.* **111**, 022502 (2013) and *Phys. Rev. Lett.* **111**, 022501 (2013))

Models: **RFG + RPA + MEC** vs **SF + MEC**.

Neutrino CCQE fits: MiniBooNE and MINERνA



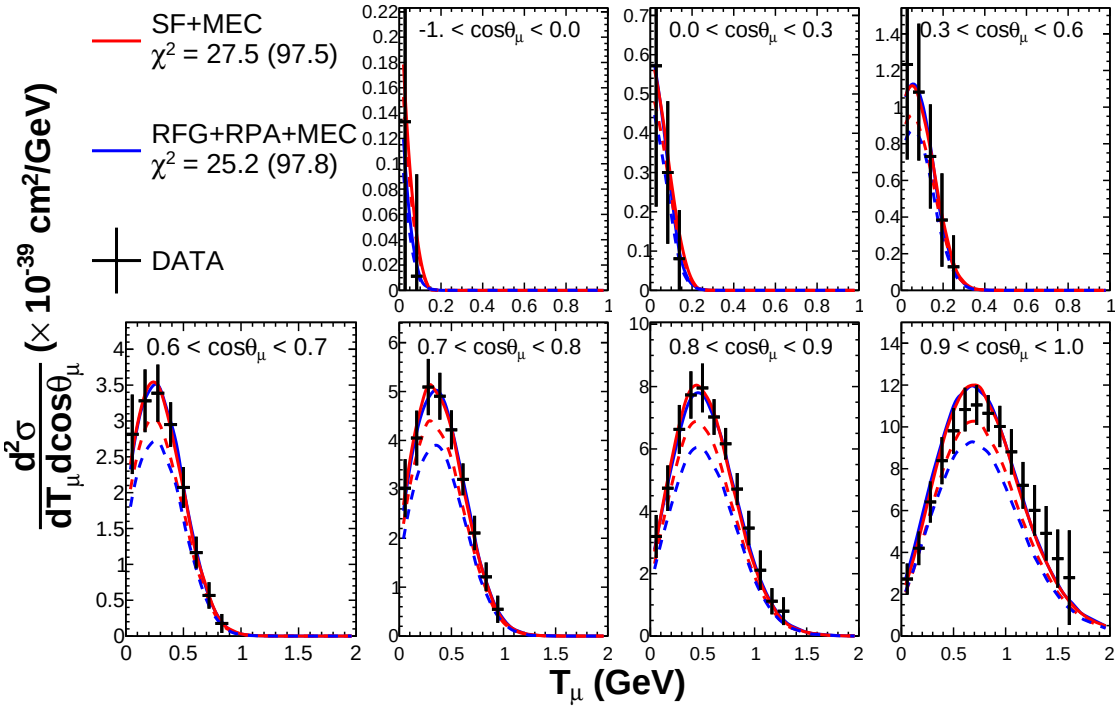
MiniBooNE



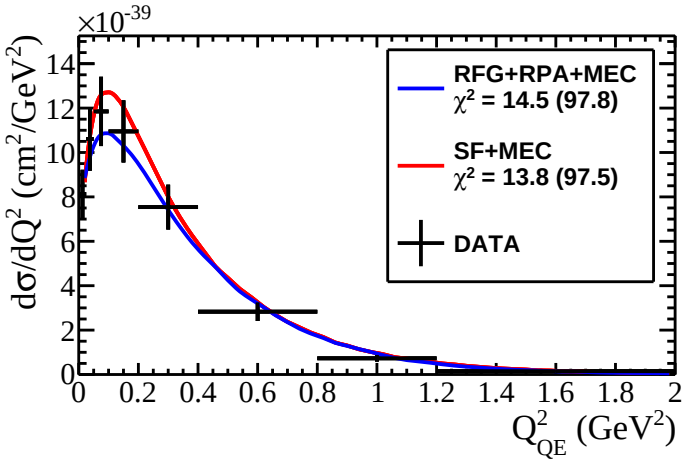
MINERνA

- χ^2 is from each dataset while total χ^2 in brackets.
- Dashed line: without MiniBooNE normalization terms.
- Even though much more bins for MiniBooNE, fit not dominated by MiniBooNE data.

Anti-Neutrino CCQE fits: MiniBooNE and MINERνA



MiniBooNE



MINERνA

- χ^2 is from each dataset while total χ^2 in brackets.
- Dashed line: without MiniBooNE normalization terms.
- Even though much more bins for MiniBooNE, fit not dominated by MiniBooNE data.

Fit results

Fit type	χ^2/DOF	M_A (GeV)	MEC (%)	p_F (MeV)
Rel. RPA	**97.8/195**	1.15 ± 0.03	27 ± 12	223 ± 5
Non-rel. RPA	117.9/195	1.07 ± 0.03	34 ± 12	225 ± 5
SF + MEC	**97.5/196**	1.33 ± 0.03	0 (at limit)	234 ± 4

- Best fit χ^2 good for both **RFG + Rel. RPA + MEC** and **SF + MEC**, but no MB correlations so Gaussian statistics invalid.
- Parameter Goodness of Fit: $\bar{\chi}^2 := \chi^2_{\rm tot} - \sum_{i=1}^{D} \chi^2_i$, where χ^2_i is the result of an individual fit to Dataset i.
- Number of degrees of freedom: $P_{PGoF} := \sum_{i=1}^{D} P_i - P_{\rm tot}$.
- Test compatibility between datasets in framework of model (*Phys. Rev. D* **65**, 014011 (2001))
- If different datasets favour different parameter values, model cannot describe all the data consistently.

PGoF tests: RFG + RPA + MEC

Datasets	χ^2/DOF	Goodness of Fit(%)	χ^2/DOF	PGoF (%)
All	97.8/195	100.00	**17.9/6**	**0.66**
MINERνA (ν vs $\bar{\nu}$)	23.4/13	3.74	1.0/3	79.03
MiniBooNE (ν vs $\bar{\nu}$)	58.3/179	100.00	2.0/3	58.69
ν **(MB vs MIN)**	62.6/127	100.00	**16.1/3**	**0.11**
$\bar{\nu}$ (MB vs MIN)	38.5/65	99.64	6.1/3	10.75
MINERνA vs MiniBooNE	97.8/195	100.00	15.9/3	0.12
ν vs $\bar{\nu}$	97.8/195	100.00	-3.3/3	100.0

- Largest tension between MINERνA and MiniBooNE neutrino results.
- Note: PGoF test requires uncorrelated datasets, so result for MINERνA's PGoF for ν vs $\bar{\nu}$ is too good.

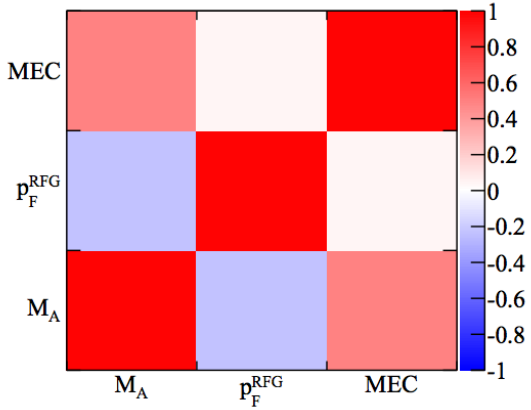
PGoF tests: SF + MEC

Datasets	χ^2/DOF	Goodness of Fit(%)	χ^2/DOF	PGoF (%)
All	97.5/196	100.00	**41.1/4**	**0.0**
MINERνA (ν vs $\bar{\nu}$)	12.6/13	47.75	1.0/2	59.87
MiniBooNE (ν vs $\bar{\nu}$)	50.2/180	100.00	6.5/2	3.85
ν **(MB vs MIN)**	54.8/128	100.00	**25.1/3**	**0.0**
$\bar{\nu}$ (MB vs MIN)	34.1/65	99.64	8.5/2	1.40
MINERνA vs MiniBooNE	97.5/196	100.00	34.6/2	0.12
ν vs $\bar{\nu}$	97.5/196	100.00	8.5/2	1.39

- Largest tension between MINERνA and MiniBooNE neutrino results.
- SF + MEC model finds much worse agreement between datasets.

$\Rightarrow$ Choose RFG+RPA+MEC as default T2K model.

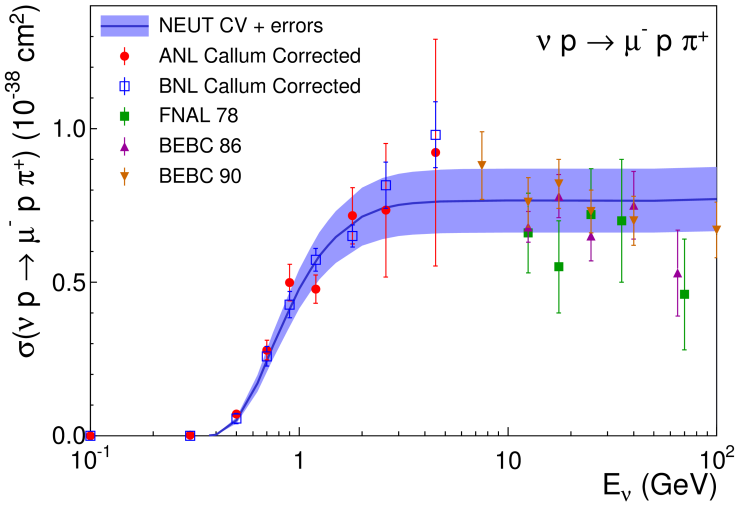
Parameter errors and covariance matrix for **RFG+RPA+MEC**

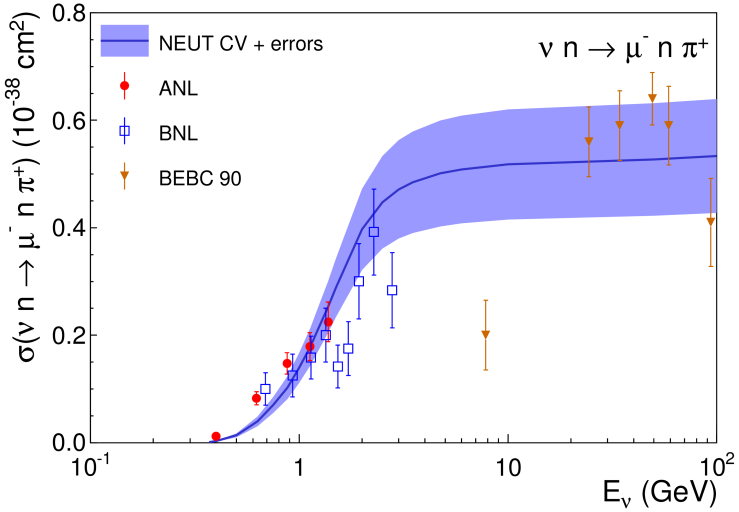


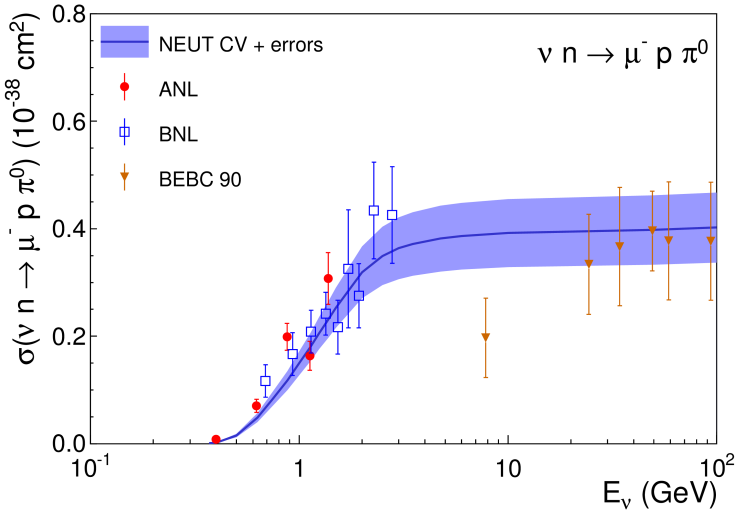
- $\Delta\chi^2 \neq 1$ for 1σ errors.
- Scale parameter errors to cover all datasets with PGoF test, ie. scale errors to make sure $\Delta\chi^2 = \chi^2_{PGoF}/DOF$.
- Most tension between MiniBooNE and MINERνA PGoF value, hence scale by $\sqrt{15.9/3} \approx 2.3$.
- Additional inflation of errors when compared to ND280 data, based on PGoF between ND280 vs MiniBooNE vs MINERνA by a factor of $\sqrt{38.0/6} \approx 2.5$ wrt initial MINUIT errors.

Fit type	χ^2/DOF	M_A (GeV)	MEC (%)	p_F (MeV)
Unscaled		1.15 ± 0.03	27 ± 12	223 ± 5
PGoF scaling	**97.8/195**	1.15 ± 0.06	27 ± 27	223 ± 11
Rescaled		$\mathbf{1.15 \pm 0.07}$	$\mathbf{27 \pm 29}$	$\mathbf{223 \pm 12}$

Procedure for pion production tuning



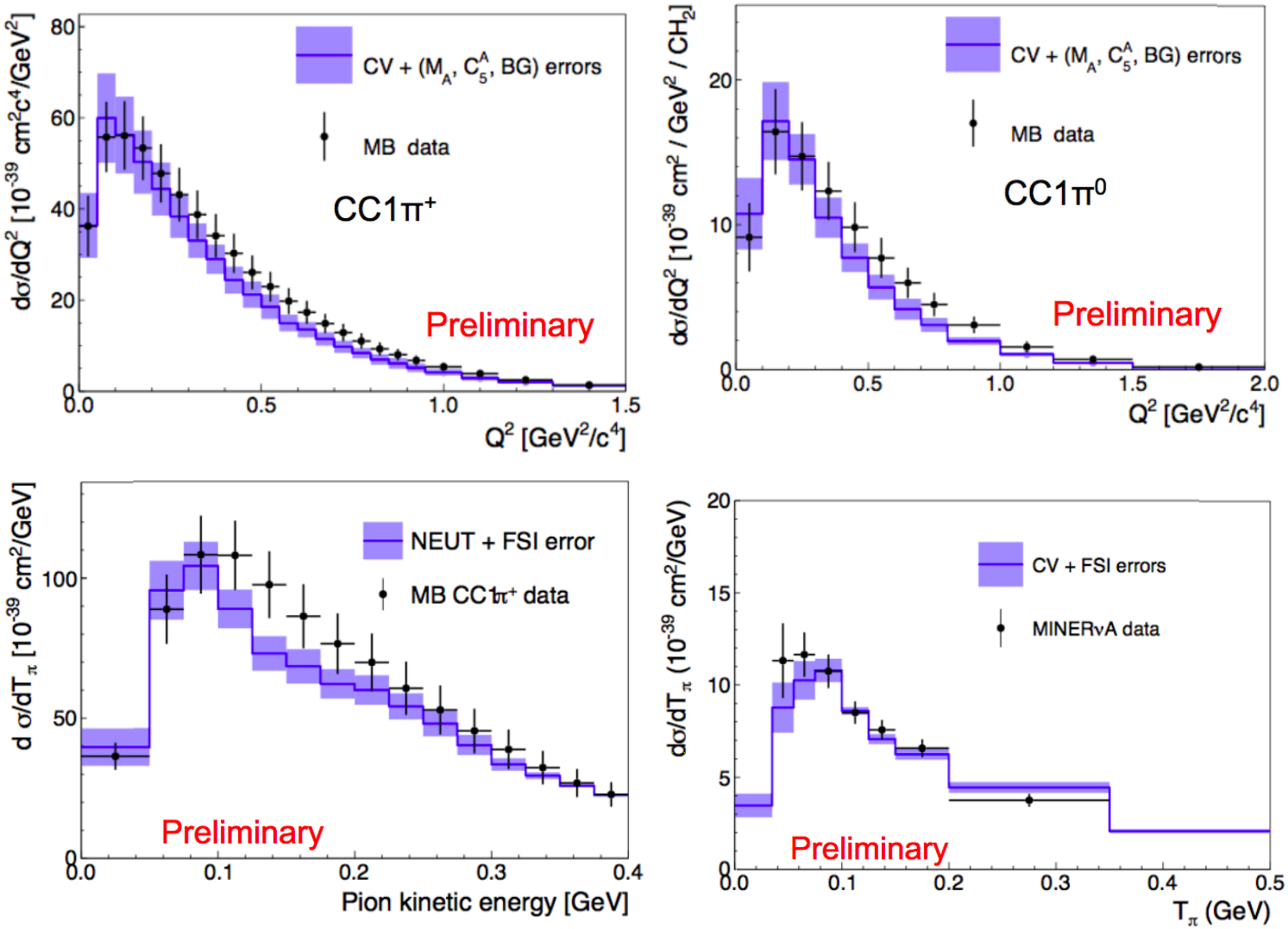




1. Update vector and axial form factors to those obtained by Graczyk and Sobczyk.
2. Tune model parameters (M_A^{RES}, $C_5^A(0)$ and non-resonant background scale) to available pion production data on deuterium (proxy for free nucleons) and hydrogen to avoid convoluted FSI effects.
3. Compare NEUT predictions with MiniBooNE and MINERνA data without fitting.
4. Choose errors to cover discrepancies between datasets.

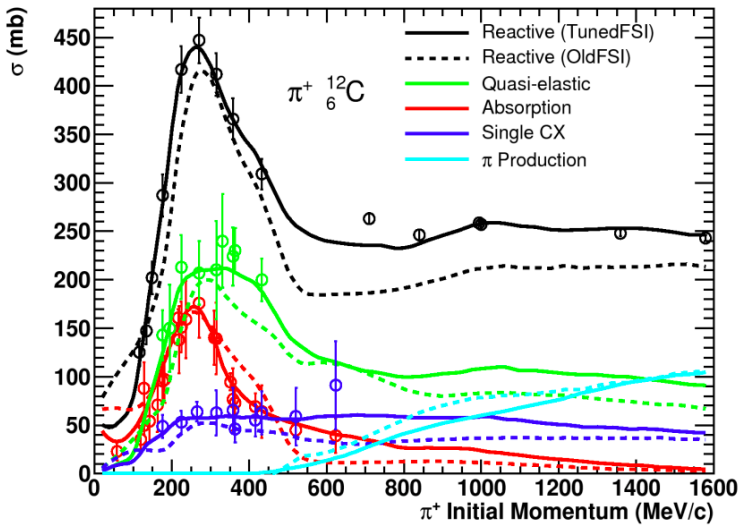
CV: $M_A^{\mathrm{RES}} = 0.95$ GeV/c^2, $C_5^A = 1.01$, nonresonant (I = 1/2) BG scale = 1.3, χ^2 =2.1

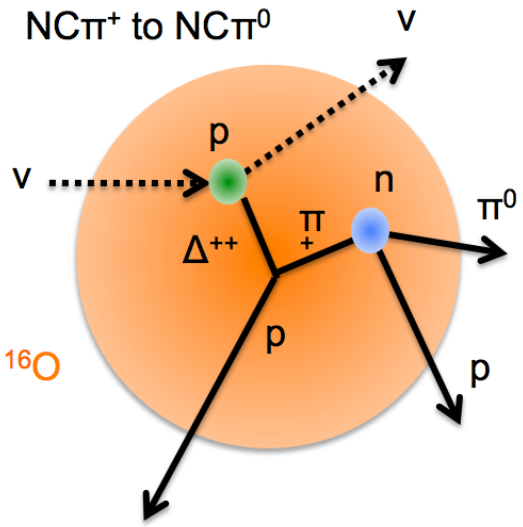
Results of tuning in Q^2 and pion kinematics



- Reasonable description of MiniBooNE normalization and MINERνA shape.
- Tension between normalizations of MiniBooNE and MINERνA.

FSI tuning





- NEUT Intra-nuclear cascade model tuned absorption, charge exchange and quasi-elastic pion-nucleus cross sections to external pion-carbon data.
- Currently revisiting FSI tuning, eg. adding recent DUET pion scattering data (pion charge exchange and absorption cross sections).

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Summary

Outlook

- Use MiniBooNE covariance matrix to properly account for correlations.
- Add more samples: MINERνA proton sample, K2K single pion data, SciBoone,...
- Include FSI parameters (absorption, charge exchange and pion production cross sections) in pion data fitting.
- Fit CC0pi data instead of CCQE(-corrected) data.
- Joint CC0pi + CC1pi fits
- Revisit FSI external data fits.

Summary

- RFG + RPA + MEC is current default T2K model for oscillation analysis.
- Poor agreement between MiniBooNE and MINERνA CCQE datasets.
- Good agreement between neutrino and antineutrino datasets.
- Best fit parameters still "effective", errors inflated to cover all external datasets.
- Tuned pion production model provides reasonable description of MiniBooNE and MINERνA data.

Backup

NEUT: future plans

- np/nn/pp fractions and its uncertainties for 2p2h models for proper C/O extrapolation.
- SF model: leptonic FSI (Ankowski et al.)
- Local Fermi Gas for CCQE
- Update Bodek-Yang correction for DIS.
- Martini 2p2h model and hadronic tensor.
- Radiative CCQE.

NEUT model defaults: RFG + RPA + MEC

Model parameter	NEUT default value
M_A^{QE}	1.21 GeV/c^2
Fermi momentum p_F^{RFG}	217 MeV/c
RPA	Nieves model
MEC normalization	100% Nieves model
Axial Form Factor	Dipole
Vector Form Factor	BBBA05

NEUT model defaults: SF + MEC

Model parameter	NEUT default value
M_A^{QE}	1.21 GeV/c^2
Fermi momentum p_F^{SF}	209 MeV/c
Mean-field width	200 MeV (Benhar SF nominal)
Normalization of correlated term	correlated term ∼20% of total
	CCQE cross-section (Benhar SF nominal)
MEC normalization	100% Nieves model
Axial Form Factor	Dipole
Vector Form Factor	BBBA05

Fit results with MB normalization

Fit type	χ^2/DOF	M_A (GeV)	MEC (%)	p_F (MeV)	$\lambda_\nu^{\mathrm{MB}}$	$\lambda_{\bar{\nu}}^{\mathrm{MB}}$
Rel. RPA	97.8/195	1.15±0.03	27 ±12	223±5	0.79±0.03	0.78±0.03
Non-rel. RPA	117.9/195	1.07±0.03	34 ±12	225±5	0.80±0.03	0.75±0.03
SF + MEC	97.5/195	1.33±0.03	0 (at limit)	234±4	0.81±0.03	0.86±0.03