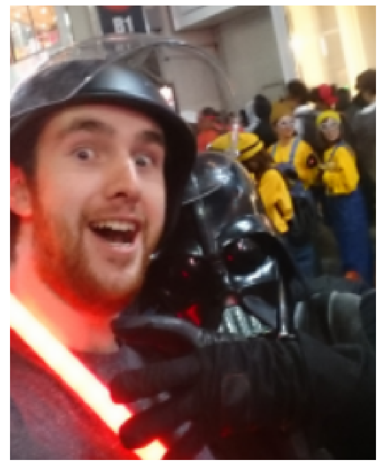
Tuning the GENIE interaction model to MINERvA data

90+% Patrick Stowell's work

https://arxiv.org/abs/1903.01558



Link to thesis

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9 July 2019

nuisance.hepforge.org
NUISANCE

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MELIORA 1850

T2K

Introduction

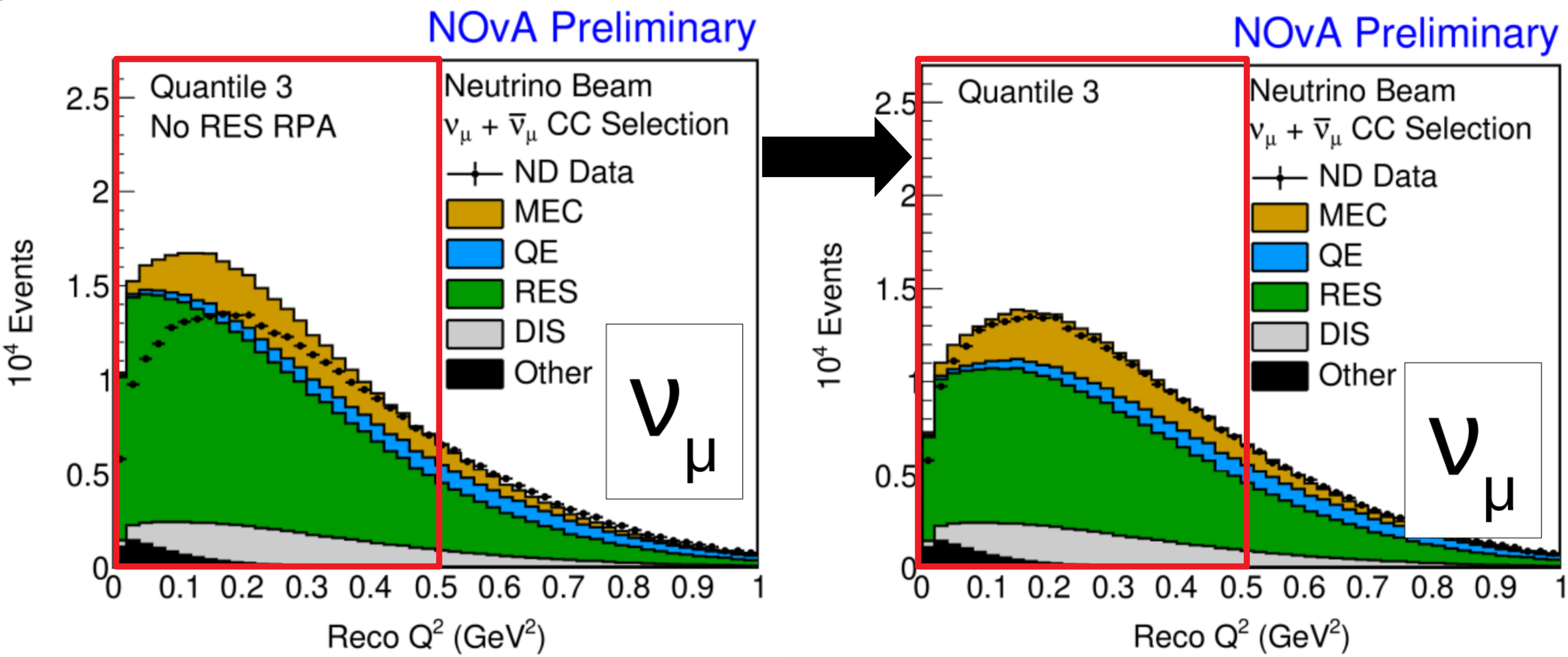
- Patrick Stowell's (Sheffield) work during his NPC at FNAL with MINERvA, summer 2017
- Used NUISANCE with GENIE and published MINERvA data to tune and develop an empirical single pion production model
- GENIE 2.12.6 with default settings* to match current experiments' simulations
  - Wanted to provide experiments with usable model and uncertainties
  - Did not want to run with "latest and greatest" models: harder to apply for experiments
  - Can be reproduced in GENIE vX.Y.Z with model Å, Ä, Ö, by push of a button

*A coherent tuning was also applied from MINERvA data

Justification

Jeremy Wolcott

- We never quiet get single pion modelling right
- NOvA currently applies 1p1h Nieves RPA correction to resonant events

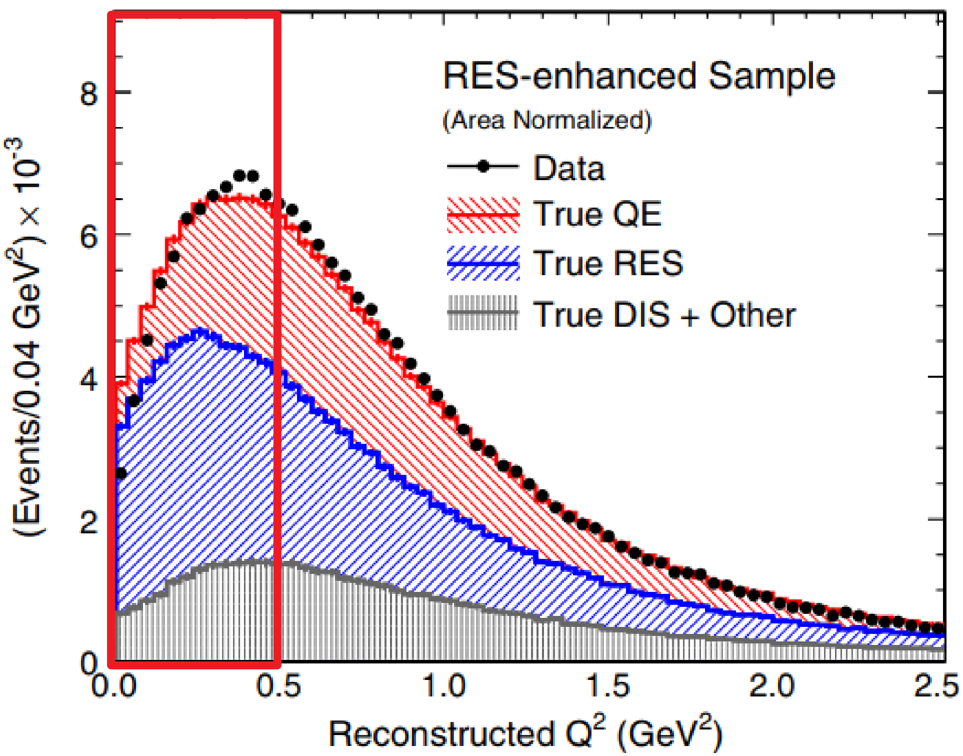


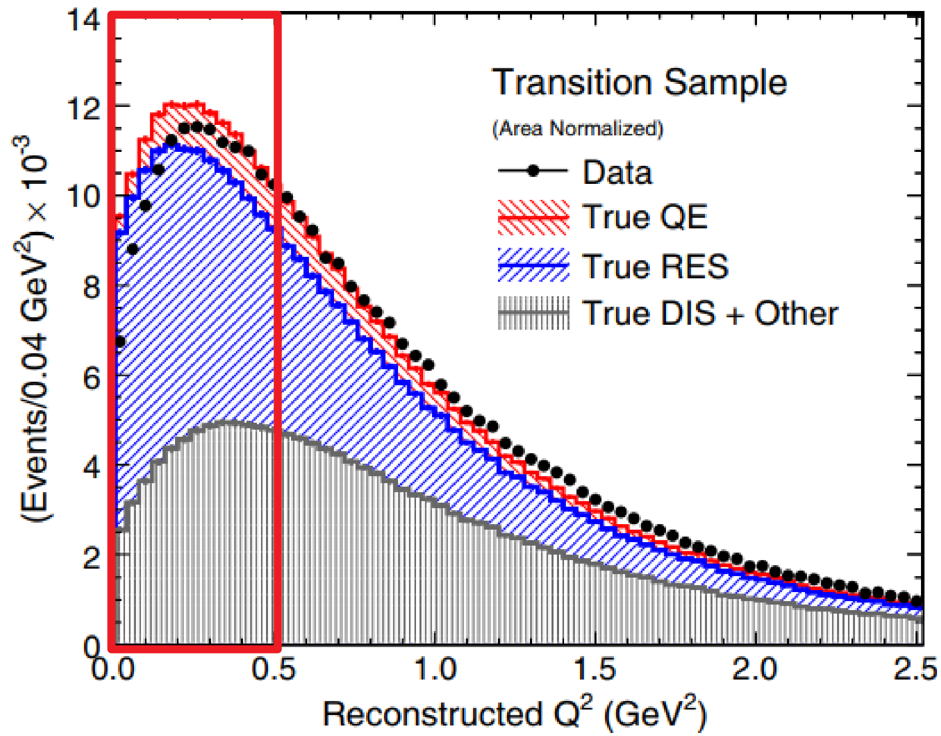
- Quartiles are in E_{had}/E_ν

Justification

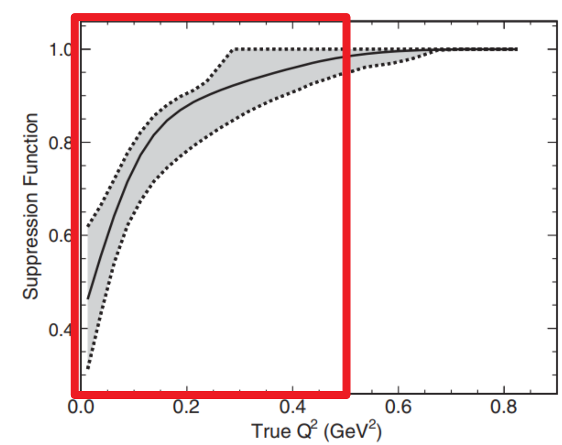
PRD 91 012005

- MINOS CCQE analysis saw consistent low-Q^2 mismodelling in resonant-enhanced sidebands





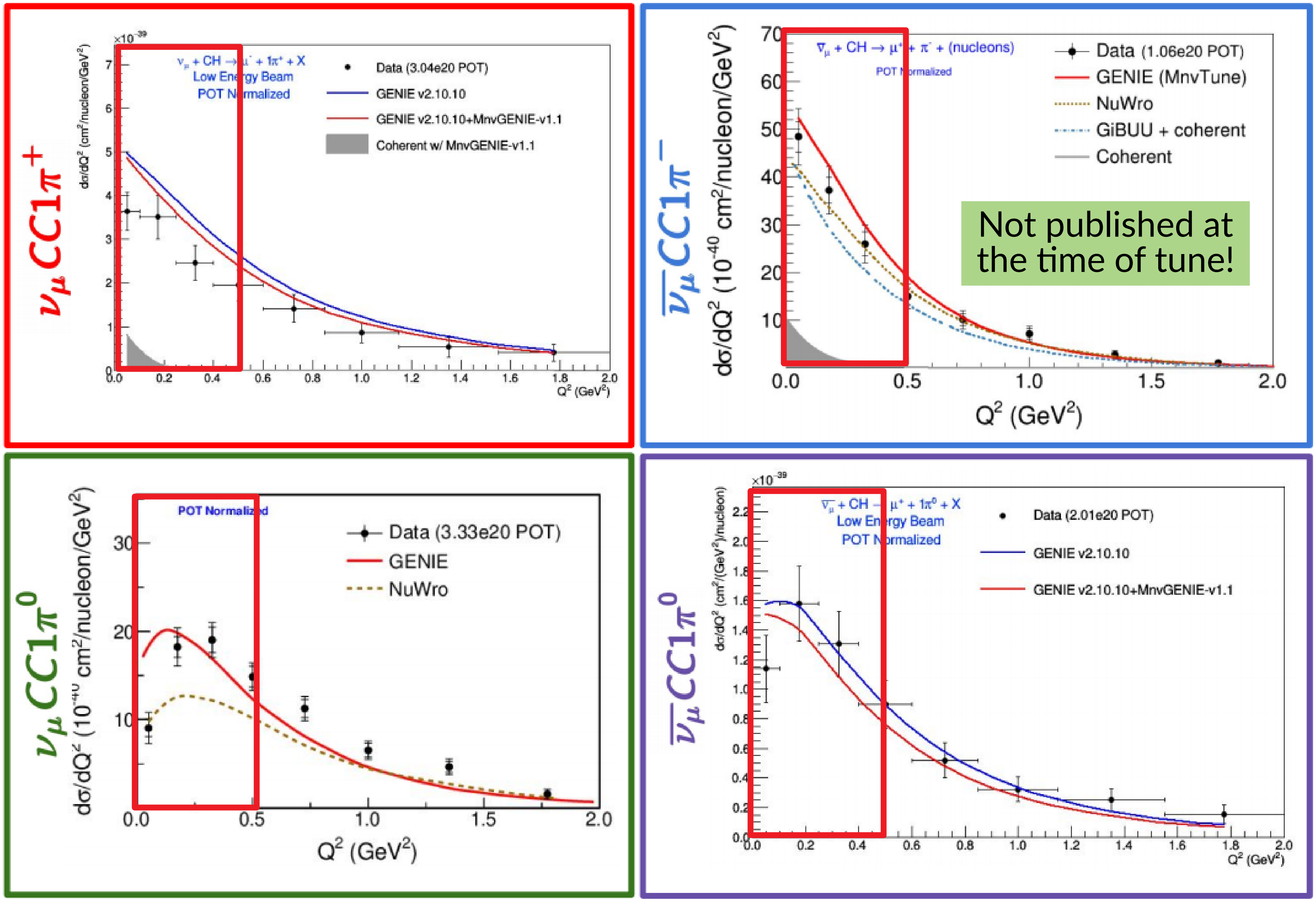
- Developed Q^2 dependent suppression for that analysis



A. Bercellie

Justification

- MINERvA sees indications in most channels



Justification

- The source of this mismodelling is (probably) a complex combination of missing known effects
  - e.g. lepton mass effects, non-resonant background modelling, resonance in-medium propagation, poor nucleon model, multi-pion/DIS transition model, FSI
- And unknown effects!

- We are not trying to assess where the effect comes from, we're just providing a tune to data
  - Provides experiments with data driven model and uncertainties
  - Much better than ignoring the problem
  - But certainly not a complete solution!

Method

- Didn't want to use measurements in "theory variables", e.g. Q^2_{True}
  - Possible interaction model dependence in data
- Use observed kinematic distributions
  - Straight-forward smearing
  - Less reliant on correct theory systematics in expt.

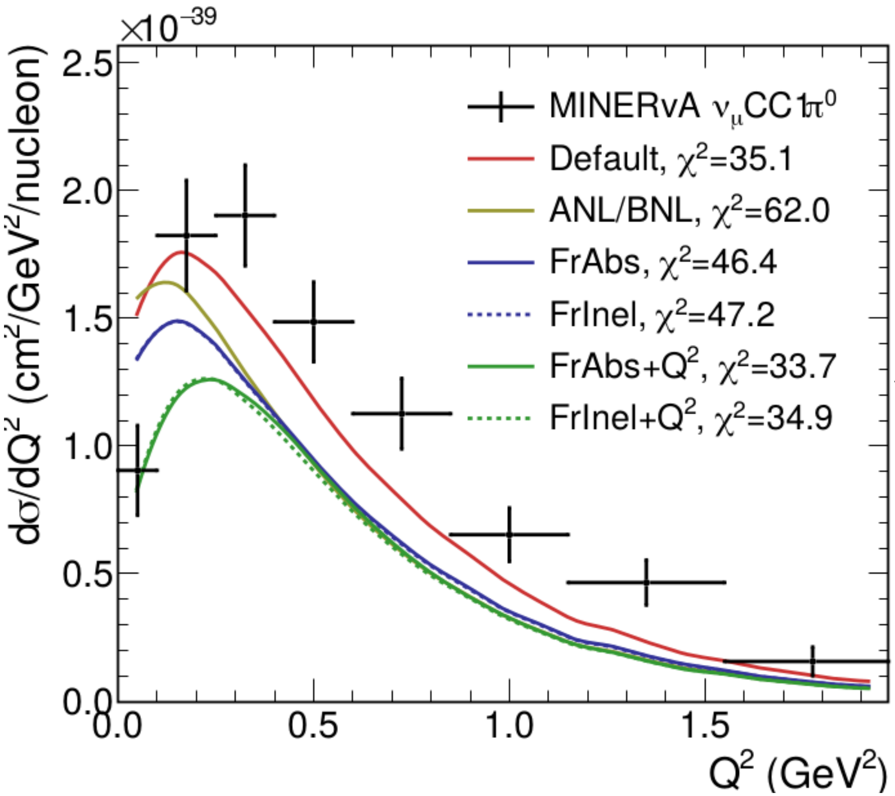
Channel	ν_μCC1$\pi^\pm$ [19]	ν_μCC$N\pi^\pm$ [20]	ν_μCC1π^0 [21]	$\bar{\nu}_\mu$CC1π^0 [20]
$\mathrm{N_{bins}}$ p_μ	8	9	8	9
$\mathrm{N_{bins}}$ θ_μ	9	9	9	9
$\mathrm{N_{bins}}$ T_π	7	7	7	7
$\mathrm{N_{bins}}$ θ_π	14	14	11	11
$\mathrm{N_{bins}}$ total	38	39	35	36
Signal definition	$1\pi^\pm, \geq 0\pi^0$	$> 0\pi^\pm, \geq 0\pi^0$	$1\pi^0, 0\pi^\pm$	$1\pi^0, 0\pi^\pm$
	$1\mu^-$	$1\mu^-$	$1\mu^-$	$1\mu^+$
	$W_{\mathrm{rec}} < 1.4$ GeV	$W_{\mathrm{rec}} < 1.8$ GeV	$W_{\mathrm{rec}} < 1.8$ GeV	$W_{\mathrm{rec}} < 1.8$ GeV
	—	—	$\theta_\mu < 25^\circ$	—

Procedure

- Default GENIE + MINERvA coherent tune
  - $E_\pi < 0.45$ GeV → 0.5 norm, $E_\pi > 0.45$ GeV → 1.0 norm
- Apply ANL/BNL tune from paper

K. Eur. Phys. J. C (2016)

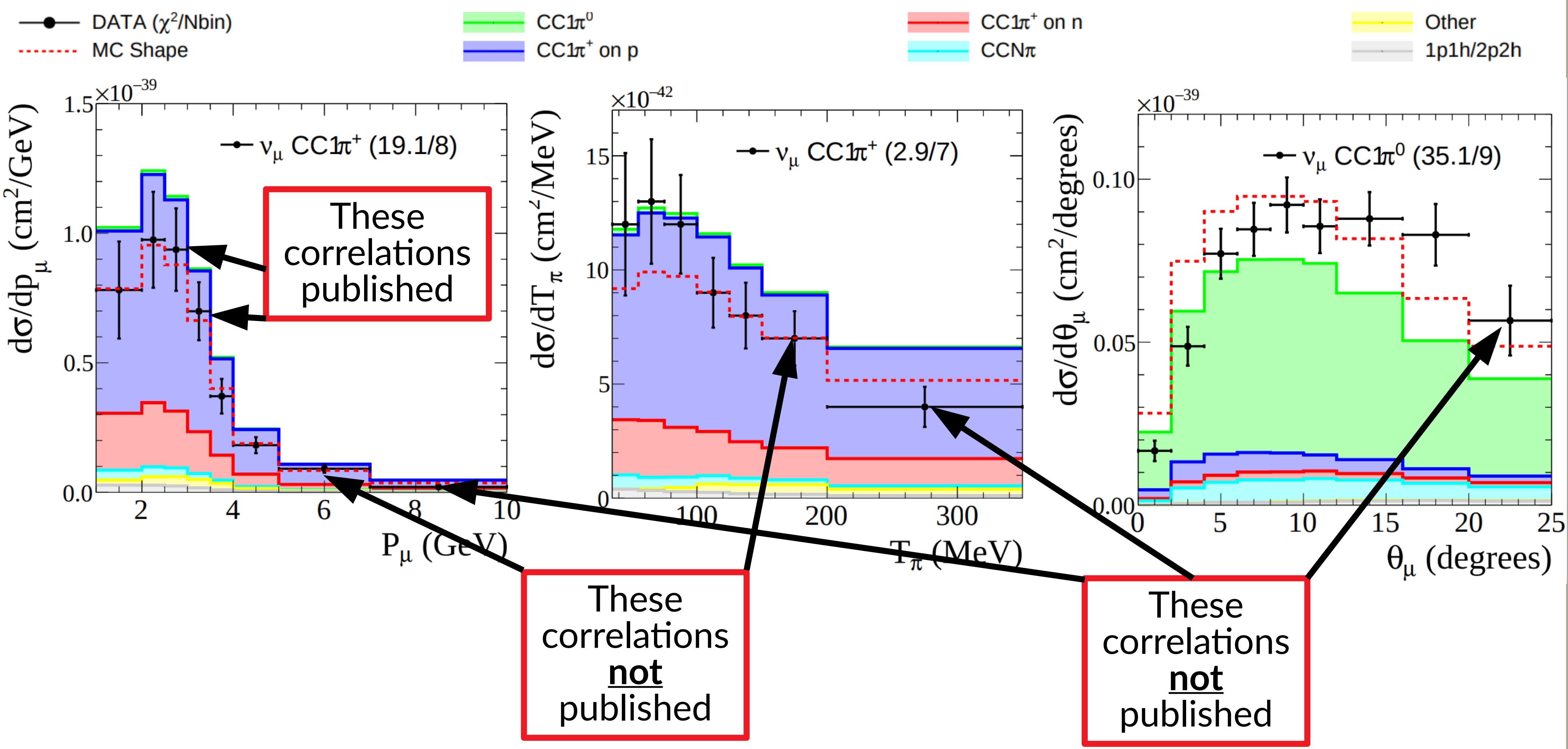
- Identify and tune theory parameters
- Introduce empirical tune



Different tunes

Correlations

- All data (so far) are single dimension cross-sections



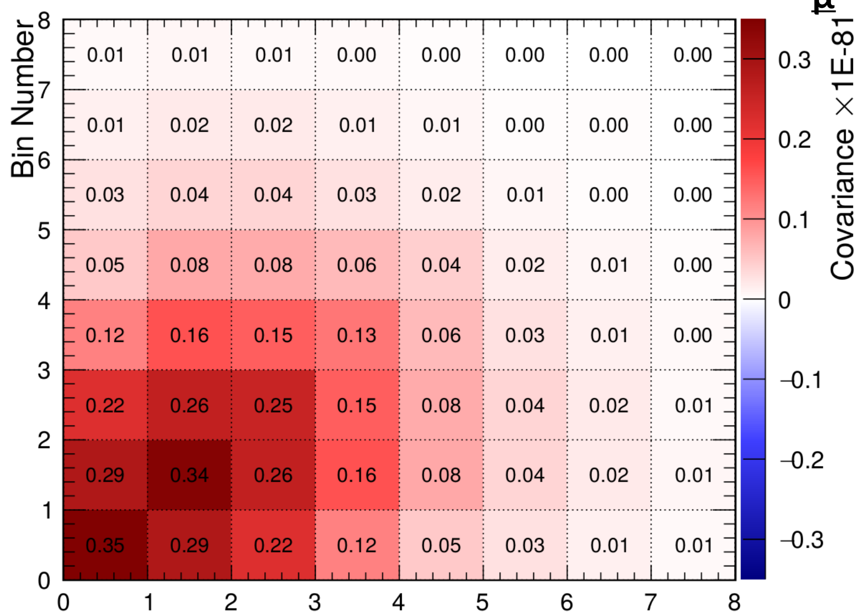
- Have correlations for each individual distribution
- No cross-correlations between distributions

Correlations

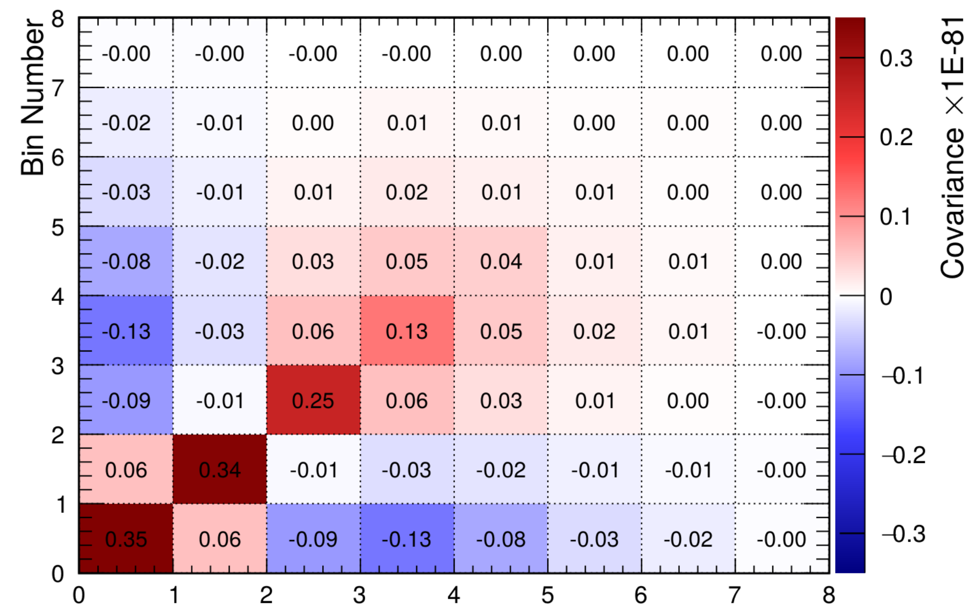
- Fine, some correlations are missing; do we care?
- Yes! CC1π^0 is CC1π^+ background and vice versa
  - Side-band sample in one is signal sample in the other
- CC1π^+ is sub-sample of CCNπ^+
- Flux uncertainties largely the same
- Detector/reconstruction largely the same

Largest source of strong rate correlation is the flux

CC1$\pi^\pm$ p_μ covariance



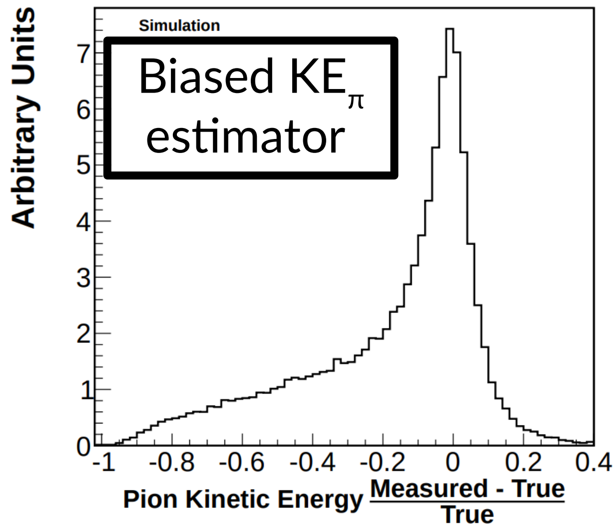
Rate



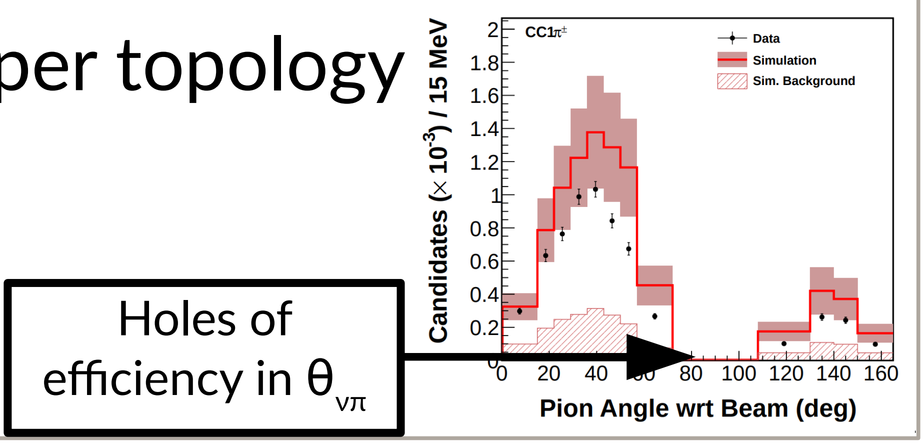
Shape

Correlations

- Only correct way is to re-run analyses simultaneously, keeping track of the correlated universes
  - No volunteers in MINERvA, so wasn't done
- Pick a distribution which controls the normalisation (rate), use the others as shape
  - We chose p_μ because
    - Clean in MINERvA
    - Pretty flat efficiency
    - Pretty good smearing
    - Largely insensitive to shape variations of fitting parameters



- Chose to use one p_μ distribution per topology
  - Could've done one p_μ in total
- Doesn't fully mitigate problem



Pause for air

- If you're keen on keeping your data fresh

Release cross-correlations in your measurement

- People will misinterpret your data and make wrong conclusions about modelling if you don't
- Everyone agrees it needs to be done, but no one does it

Applying ANL/BNL tune

- Chose a decent set of GENIE systematics to weight in
  - M_A^{res}, CC_{RES}^{Norm}, Non-Res Norm, 2π norm, (non)isotropic RS
- Apply tuning from ANL/BNL paper

CC1π^0 gets uniformly worse

All θ_μ shape distributions are worse

Distribution	Channel	N_{bins}	Default	ANL/BNL
p_μ (Rate)	$\nu_\mu CC1\pi^+$	8	19.1	13.8
	$\nu_\mu CCN\pi^+$	9	35.4	19.5
	$\nu_\mu CC1\pi^0$	8	11.1	19.6
	$\bar{\nu}_\mu CC1\pi^0$	9	7.4	6.4
θ_μ (Shape)	$\nu_\mu CC1\pi^+$	9	7.1	12.4
	$\nu_\mu CCN\pi^+$	9	4.5	10.4
	$\nu_\mu CC1\pi^0$	9	35.1	71.5
	$\bar{\nu}_\mu CC1\pi^0$	9	9.3	14.0
T_π (Shape)	$\nu_\mu CC1\pi^+$	7	2.9	2.6
	$\nu_\mu CCN\pi^+$	7	39.8	34.7
	$\nu_\mu CC1\pi^0$	7	28.3	31.4
	$\bar{\nu}_\mu CC1\pi^0$	7	19.3	17.9
θ_π (Shape)	$\nu_\mu CC1\pi^+$	14	25.4	26.5
	$\nu_\mu CCN\pi^+$	14	11.7	11.1
	$\nu_\mu CC1\pi^0$	11	13.5	15.0
	$\bar{\nu}_\mu CC1\pi^0$	11	5.7	5.9
Total χ^2		148	275.6	312.7

Rate χ^2 improves?

Pretty much everything else gets worse

Total χ^2 is bad with and without

<u>Tensions in applying nucleon fits to nuclear data</u>

Not very surprising

We've seen this numerous times before (e.g. initial state, RPA, 2p2h, FSI…)

Oftentimes, un-modelled nuclear effects to blame

How do we "fix" it?

Fitting, part I

- Maybe it's all in FSI parameters?
- Apply a penalty on nucleon parameters from ANL/BNL tuning, no penalty on remaining parameters

Parameter	Default Value	GENIE-RW Name
CC Resonant Axial Mass (M_A^{res})	1.12 ± 0.22 GeV	MaCCRES
CC Resonant Normalization (NormRes)	100 ± 20 %	NormCCRES
CC1π Nonresonant Normalization (NonRes1π)	100 ± 50 %	NonRESBGvnCC1pi NonRESBGvpCC1pi NonRESBGvbarnCC1pi NonRESBGvbarpCC1pi
CC2π Nonresonant Normalization (NonRes2π)	100 ± 50 %	NonRESBGvnCC2pi NonRESBGvpCC1pi NonRESBGvbarnCC1pi NonRESBGvbarpCC1pi
Pion Angular Emission (π-iso)	0 (RS)	Theta_Delta2Npi
Pion Absorption FSI Fraction (FrAbs)	100 ± 30 %	FrAbs_pi
Pion Inelastic FSI Fraction (FrInel)	100 ± 40 %	FrInel_pi

Nucleon parameters from ANL/BNL

Freely fitted parameters

Fitting, part I

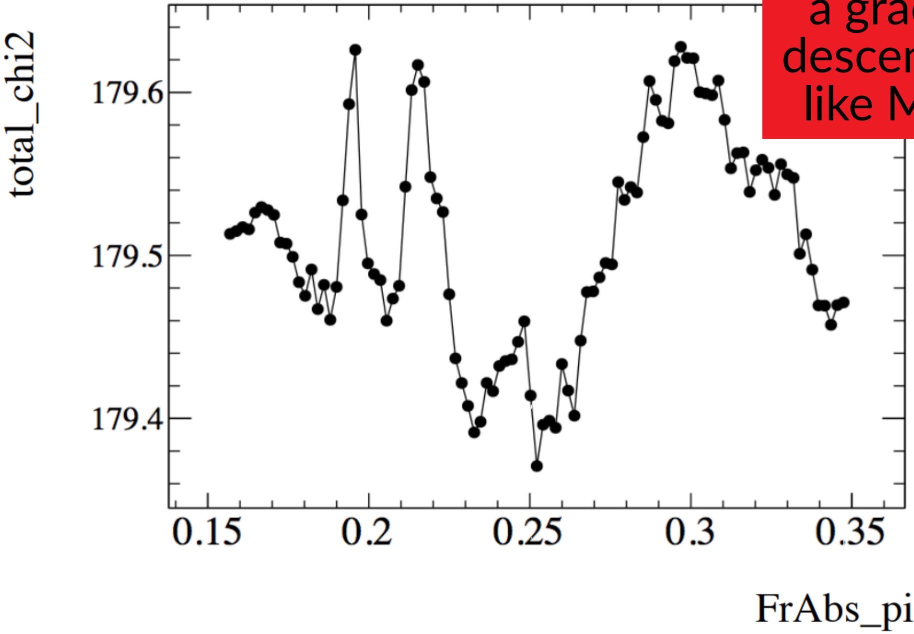
- Hold on, two FSI parameters?! Well spotted!

Pion Absorption FSI Fraction (FrAbs)	100 ± 30 %	FrAbs_pi
Pion Inelastic FSI Fraction (FrInel)	100 ± 40 %	FrInel_pi

- Initially tried fitting all FSI parameters simultaneously
- Tiny errors from strange behaviour in the test-statistic
  - Not present when varying one FSI parameter at a time
  - Or any other parameter simultaneously

jointPION-kinematic-fit
M_A^{RES} : 0.93 ± 0.02 (GeV)
NormRES : 114.0 ± 3.0 %
NormDIS : 46.2 ± 3.7 %
Theta_Delta2Npi : 1.0 ± 0.0 σ
MINERvARW_MINOSRPA_Apply : 1.0 ± 0.0 σ
FrCEx_pi : 1.332 ± 0.0061 σ
FrInel_pi : 0.9481 ± 0.0047 σ
FrAbs_pi : 0.2522 ± 0.0192 σ
FrPiProd_pi : 0.1226 ± 0.005 σ
NormDIS2PI : 93.8 ± 31.9 %
CHI2 : 182.686
NDOF : 115.0
CHI2/NDOF : 1.589

Tiny errors



Very very difficult for a gradient descent algo like Minuit

Fitting, part I

- GENIE authors contacted, and this is intended
- Tries to maintain pion-nucleus scattering cross-section by varying cushion terms up to hard-coded precision
  - Simultaneous fit not possible with this FSI model
- Decided to evaluate which parameters had largest effect on total χ^2 and use it as only FSI parameter being fit
  - Limitation of this paper
- Inelastic scattering and pion absorption were largest effects
  - The other fits had the pion parameters move to +300%; the test-statistic had poor sensitivity
  - The non-FSI parameters always converged to similar values, unlikely to be cherry-picking

Fitting, part I

- Both FrAbs and FrInel fits converge to similar parameter values and test-statistics, with clear improvements in χ^2

Parameter	Default Value	ANL/BNL Value	FrAbs Fit Result	FrInel Result
M_A^{res} (GeV)	1.12 ± 0.22	0.94 ± 0.05	1.07 ± 0.04	1.08 ± 0.04
NormRes (%)	100 ± 30	115 ± 7	94 ± 6	92 ± 6
NonRes1π (%)	100 ± 50	43 ± 4	44 ± 4	44 ± 4
NonRes2π (%)	100 ± 50	-	166 ± 32	161 ± 33
π-iso	$0 =$ RS	-	$1 =$ Iso (limit)	$1 =$ Iso (limit)
FrAbs (%)	100 ± 30	-	109 ± 16	-
FrInel (%)	100 ± 40	-	-	109 ± 24
MINERνA χ^2	275.6	312.7	242.3	240.7
χ^2_{pen}	299.3	0.0	9.3	11.1
Total χ^2	574.8	312.7	251.6	251.8
N_{DoF}	148	148	145	145

- As expected, ANL/BNL parameters are contended in the fit
- The fit moves closer to the GENIE nominal, except for the non-resonant background

Fitting, part I

- Fit individual cross-section topologies to gauge which is pulling

Parameter	ν_μCC1π^+	ν_μCC$N\pi^+$	ν_μCC1π^0	$\bar{\nu}_\mu$CC1π^0
M_A^{res} (GeV)	0.97 ± 0.05	0.97 ± 0.05	1.02 ± 0.05	0.96 ± 0.05
NormRes (%)	110 ± 7	110 ± 7	104 ± 7	111 ± 7
NonRes1π (%)	43 ± 4	42 ± 4	44 ± 4	43 ± 4
NonRes2π (%)	300 (limit)	99 ± 30	300 (limit)	300 (limit)
π-iso	1 = Iso (limit)	1 = Iso (limit)	1 = Iso (limit)	1 = Iso (limit)
FrAbs (%)	156 ± 53	128 ± 34	126 ± 17	82 ± 31
MINERνA χ^2	36.6	64.1	92.3	34.6
χ^2_{pen}	0.5	0.7	3.2	0.3
Total χ^2	37.1	64.8	95.5	34.9
N_{DoF}	35	36	32	33

- CC1π^0 channel does not agree well with prior
  - Anti-neutrino pulls to different FSI parameter value
- Parameters largely agree for the fits, no huge pulls
  - NonRes2π barely has an effect, which is why +300%

Have we learnt anything?

Arguably, yes.

ANL/BNL prior does not agree with data

Largest pull from $CC1\pi^0$

Be careful with your priors and uncertainties

Fitting, part II

- MINOS and MiniBooNE have both seen this before
  - MINOS imposed an empirical Q^2 dependent tuning
- NOvA currently see this
  - Apply the RPA correction from CCQE
- Empirical Q^2 dependent tuning could absorb missing nuclear effect, but difficult to diagnose where it is from
  - There's so much missing in single pion production models
- Develop our own form for the Q^2 dependent suppression

$$w(Q^2) = 1 - (1 - R_1)(1 - R(Q^2))^2$$

Lagrange interpolating function in Q^2

$$R(Q^2 < x_3) = \frac{R_2(Q^2 - x_1)(Q^2 - x_3)}{(x_2 - x_1)(x_2 - x_3)} + \frac{(Q^2 - x_1)(Q^2 - x_2)}{(x_3 - x_1)(x_3 - x_2)}.$$

Cut-offs at x_1, x_2, x_3; **tune R_1 and R_2**

Fitting, part II

- Including the Q2-dependent suppression alleviates the tension with the ANL and BNL tuning

Parameter	FrAbs Tune	FrAbs + low-Q^2 Tune	FrInel Tune	FrInel + low-Q^2 Tune
M_A^{res} (GeV)	1.07 ± 0.04	0.92 ± 0.02	1.08 ± 0.04	0.93 ± 0.05
NormRes (%)	94 ± 6	116 ± 3	92 ± 6	116 ± 7
NonRes1π (%)	43 ± 4	46 ± 4	44 ± 4	46 ± 4
NonRes2π (%)	166 ± 32	99 ± 31	161 ± 33	120 ± 32
π-iso	1.0 (limit)	1.0 (limit)	1.0 (limit)	1.0 (limit)
FrAbs (%)	109 ± 16	48 ± 21	-	-
FrInel (%)	-	-	109 ± 24	132 ± 27
Lag. R_1	-	0.32 ± 0.06	-	0.37 ± 0.09
Lag. R_2	-	0.5 (limit)	-	0.60 ± 0.16
MINERνA χ^2	242.3	212.2	240.7	215.7
χ^2_{pen}	9.3	0.7	11.1	0.5
Totalχ^2	251.6	212.9	251.8	216.2
N_{DoF}	145	143	145	143

- And improves the χ2 from the MINERvA data-sets
- Absorption and inelastic tune ~agree, although R_2 sits at the limit
  - Still not a great χ2, and tension may be artificially relieved

Fitting, part II

- Looking at individual distributions' χ^2
  - Sometimes $1\pi^+$ improves with Q^2 tune, whereas $1\pi^0$ worsens

Distribution	Channel	N_{bins}	FrAbs Tune	FrAbs + low-Q^2 Tune	FrInel Tune	FrInel + low-Q^2 Tune
p_μ (Rate)	ν_μCC1$\pi^\pm$	8	12.0	10.8	12.3	10.9
	ν_μCC$N\pi^\pm$	9	26.1	16.2	26.8	17.9
	ν_μCC1π^0	8	19.0	26.2	19.3	26.9
	$\bar{\nu}_\mu$CC1π^0	9	6.2	7.1	6.3	7.2
θ_μ (Shape)	ν_μCC1$\pi^\pm$	9	7.5	7.4	7.4	7.1
	ν_μCC$N\pi^\pm$	9	4.0	6.3	4.1	5.6
	ν_μCC1π^0	9	44.5	20.0	45.6	20.5
	$\bar{\nu}_\mu$CC1π^0	9	10.2	7.0	10.3	6.9
T_π (Shape)	ν_μCC1$\pi^\pm$	7	2.5	2.5	2.3	2.4
	ν_μCC$N\pi^\pm$	7	31.2	28.9	29.4	27.7
	ν_μCC1π^0	7	30.9	27.1	29.9	32.0
	$\bar{\nu}_\mu$CC1π^0	7	16.6	15.7	16.0	18.7
θ_π (Shape)	ν_μCC1$\pi^\pm$	14	13.0	13.4	12.6	12.6
	ν_μCC$N\pi^\pm$	14	6.9	7.0	6.2	6.3
	ν_μCC1π^0	11	8.3	12.2	8.9	9.4
	$\bar{\nu}_\mu$CC1π^0	11	3.4	4.4	3.5	3.7
Total χ^2		148	242.3	212.2	240.7	215.7

Fitting, part II

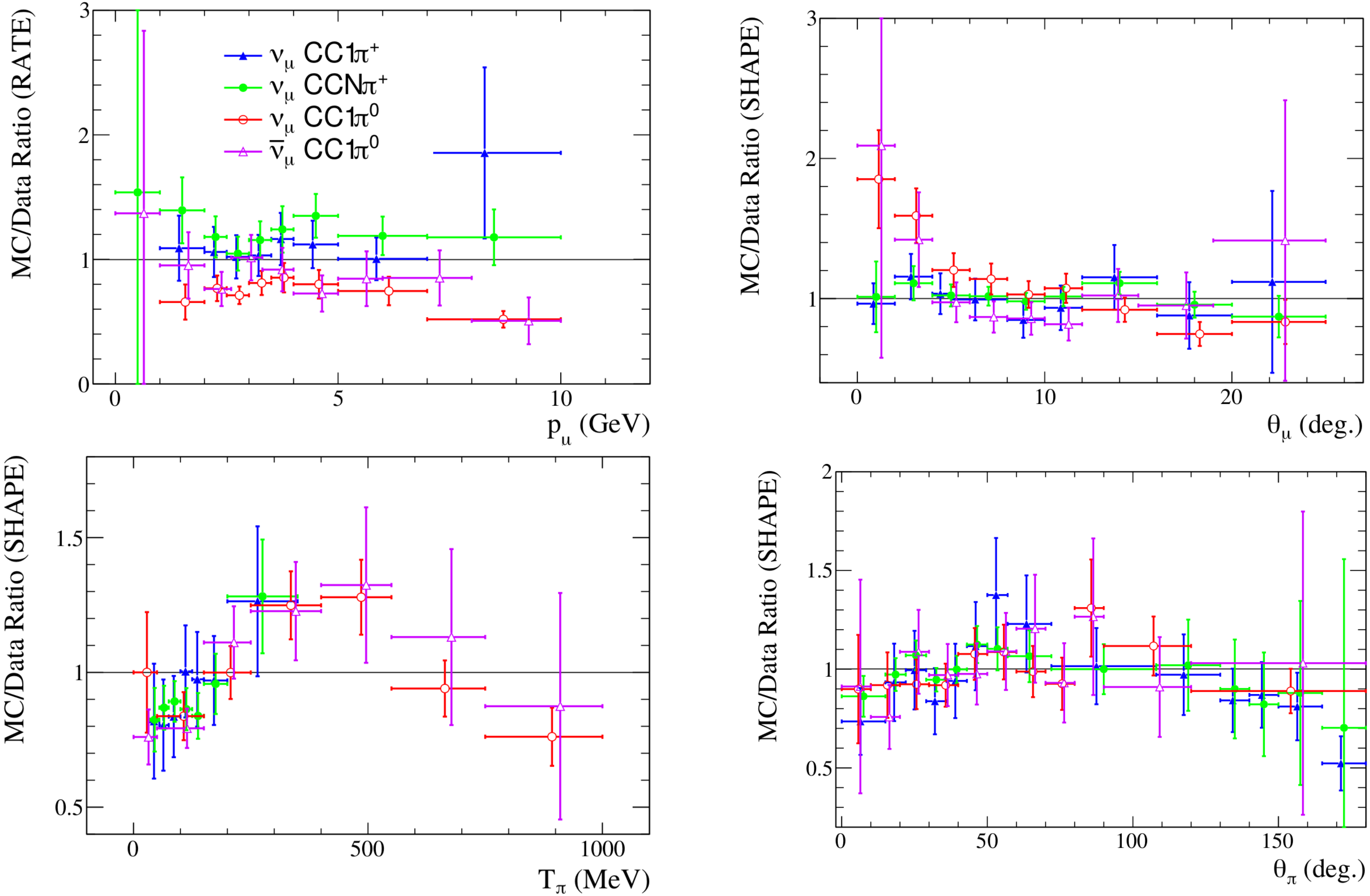
- ANL/BNL penalty term steers the nucleon parameters
  - Mismodelling absorbed in very different R_1 and R_2

Parameter	ν_μCC1π^+	ν_μCCNπ^+	ν_μCC1π^0	$\bar{\nu}_\mu$CC1π^0
M_A^{res} (GeV)	0.93 ± 0.02	0.92 ± 0.02	0.96 ± 0.05	0.94 ± 0.05
NormRes (%)	115 ± 3	117 ± 3	114 ± 7	115 ± 7
NonRes1π (%)	43 ± 4	43 ± 4	45 ± 4	43 ± 4
NonRes2π (%)	300 (limit)	70 ± 28	300 (limit)	300 (limit)
π-iso	1 = Iso (limit)	1 = Iso (limit)	1 = Iso (limit)	1 = Iso (limit)
FrAbs (%)	92 ± 65	79 ± 40	74 ± 22	34 ± 35
Lag. R_1	0.53 ± 0.16	0.43 ± 0.13	0.21 ± 0.14	0.14 ± 0.22
Lag. R_2	0.50 (limit)	0.50 (limit)	0.63 ± 0.31	1.00 (limit)
MINERνA χ^2	32.2	55.7	71.2	27.7
χ^2_{pen}	0.1	0.4	0.5	0.0
Total χ^2	32.3	56.1	71.7	27.7
N_{DoF}	33	34	30	31

- At times at the limit for R_2
- Not enough power in data? Insufficient model freedom?

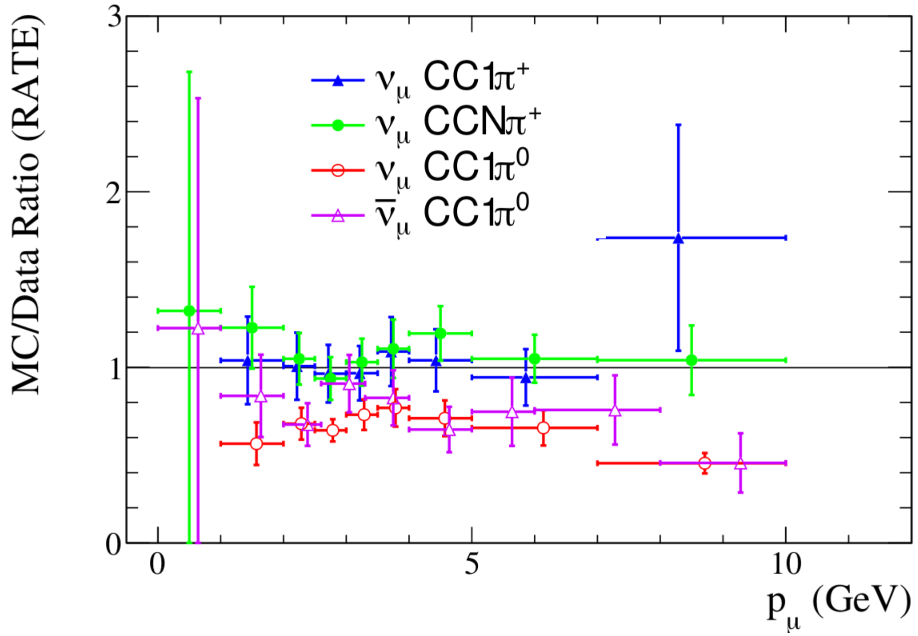
Fitting, part II

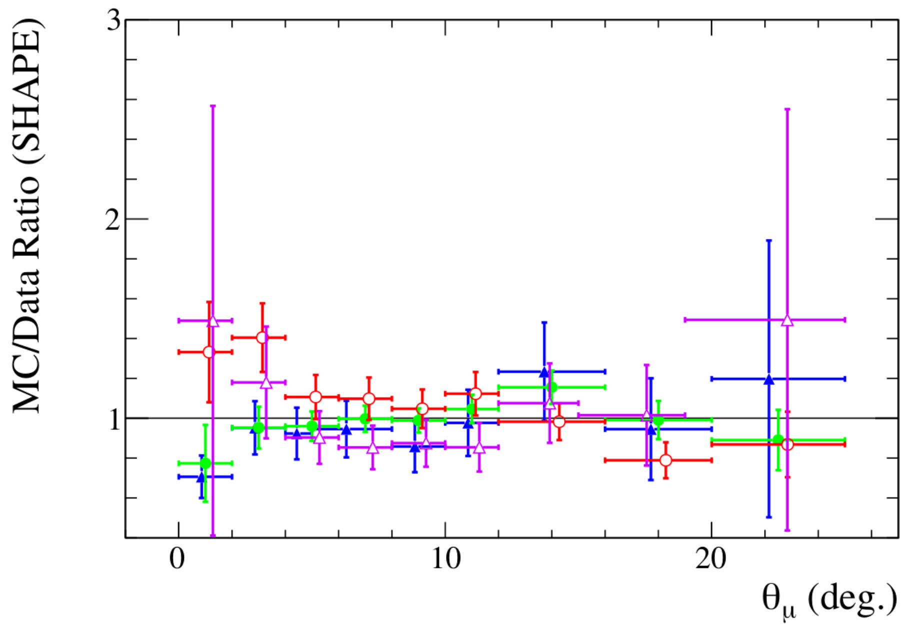
- FrAbs without Q^2 tuning

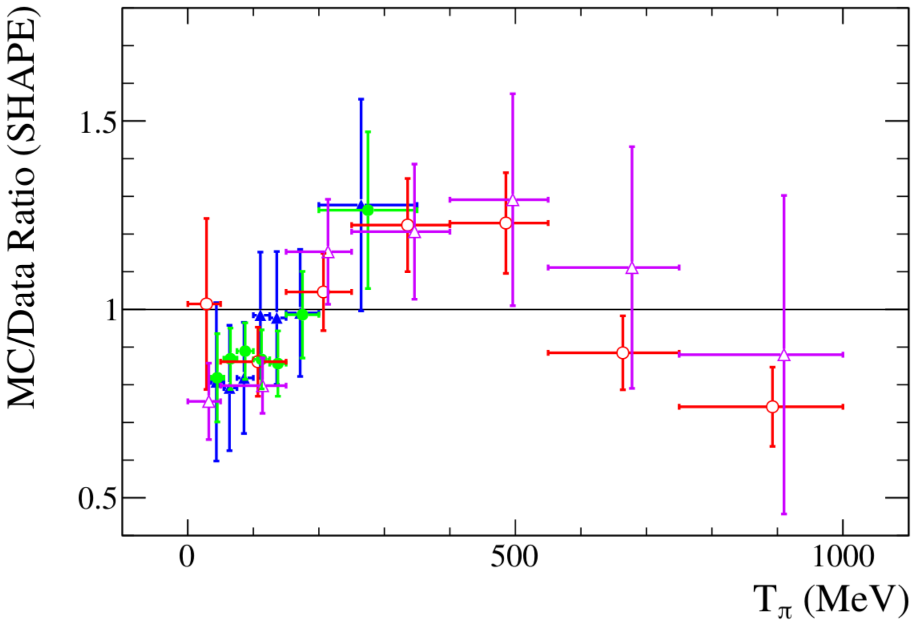


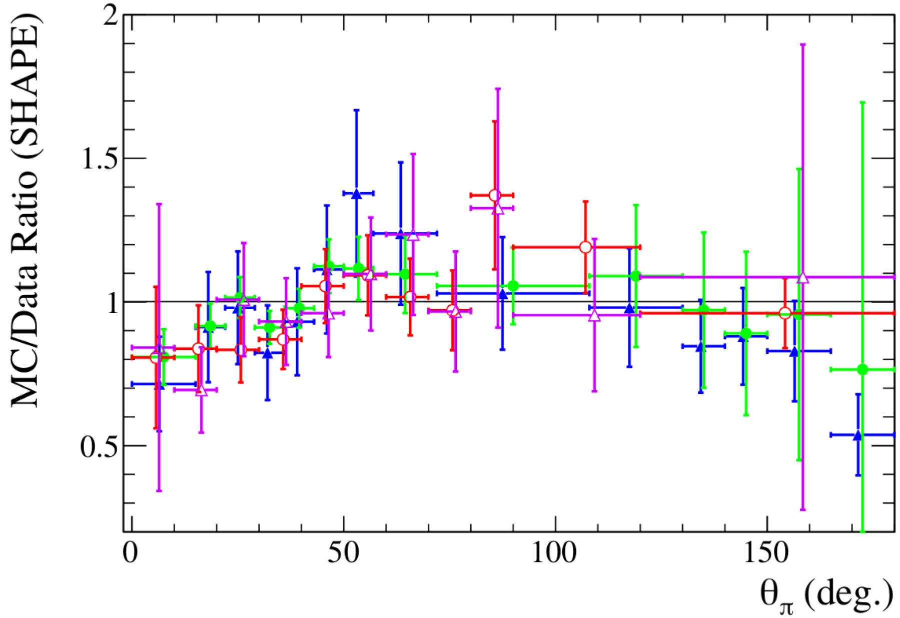
Fitting, part II

- FrAbs with Q^2 tuning



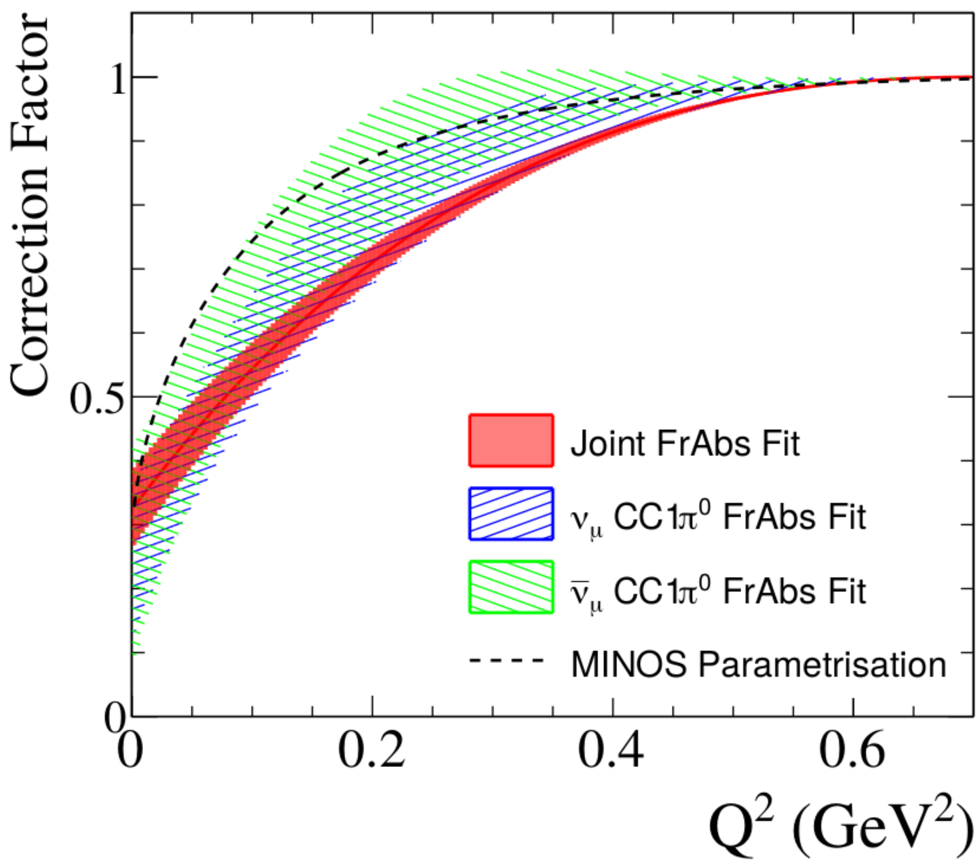


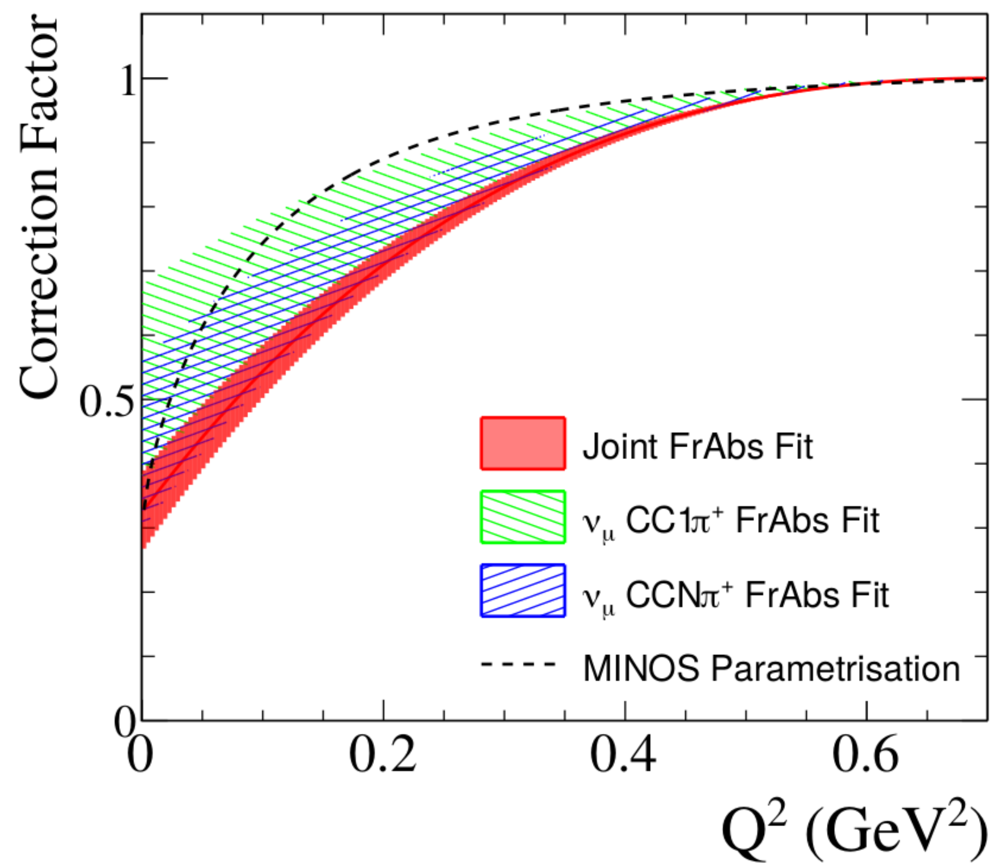




Fitting, part II

- Extracted Q^2 correction similar to MINOS'

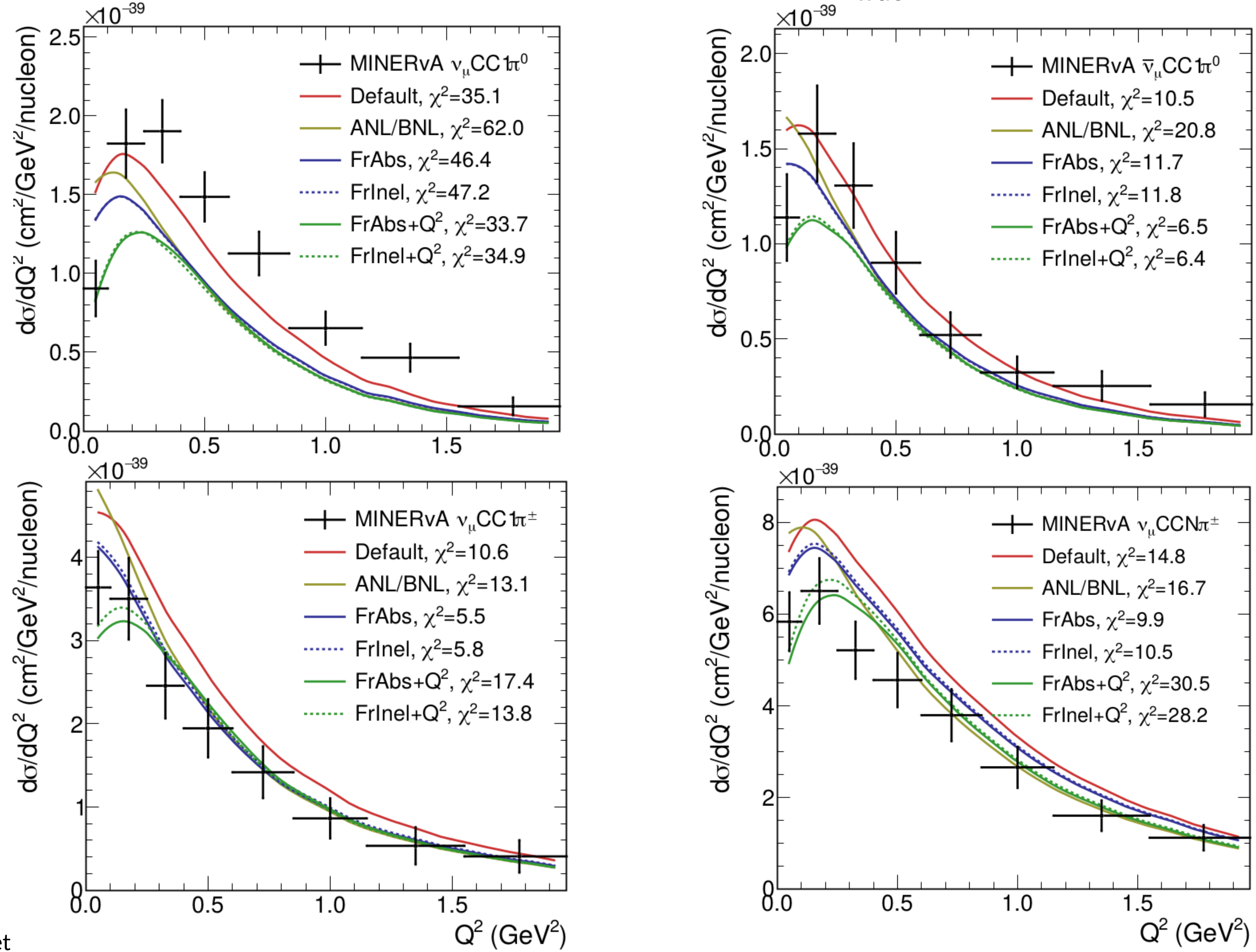




- Charged pion and neutral pion channels are similar to each other and the joint fit error band
- Doesn't do a perfect job

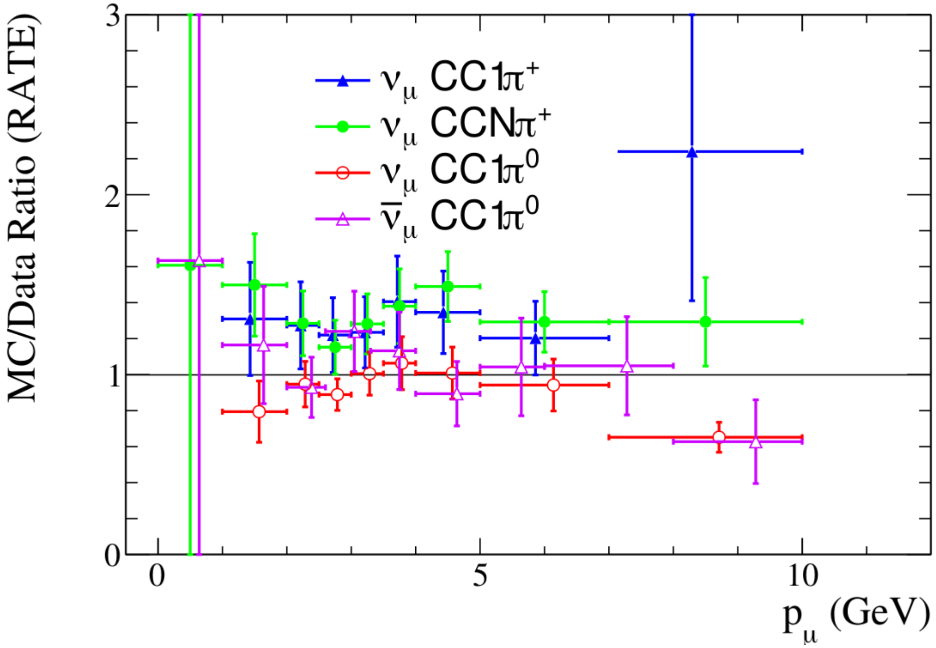
Fitting, part II

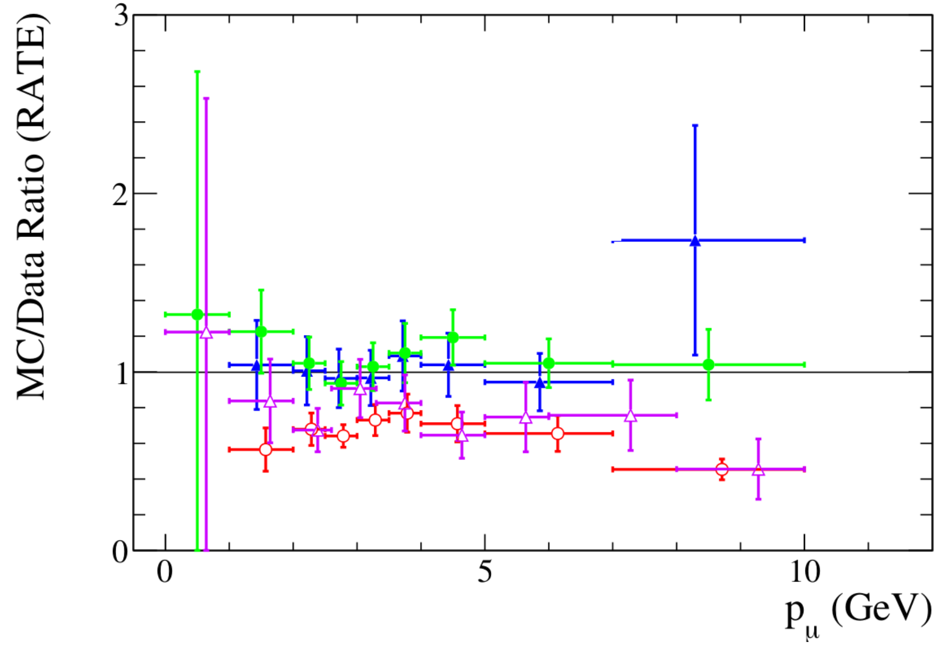
- Compare against MINERvA cross-section in Q^2_{True}



Fitting, part II

- The pion distributions are largely invariant to the tune
- We've changed nucleon physics and made a Q^2 tuning
  - Nothing explicitly working on the pions other than FSI and (non-)isotropic parameter





Fitting, part II

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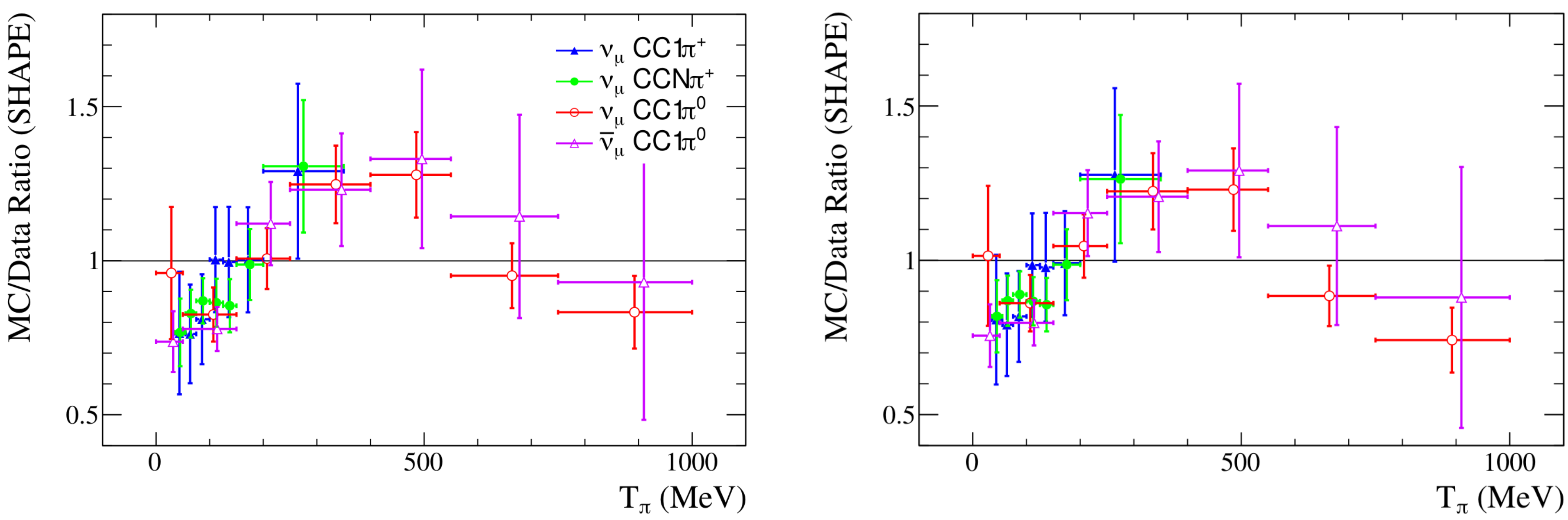

Conclusions

- Used MINERvA data to tune GENIE single pion production
- Tuning to nucleon level data worsens the prediction
- Tuning the nucleon level parameters with pion FSI added pulls the nucleon closer to GENIE nominal: clear tension
- CC1π^0 data in tension with other distributions
- Introduce Q^2 dependent correction, looking for a nuclear effect
- Alleviates tension with nucleon tune, but far from perfect

- Pion variables still aren't well described

Thanks!