Tuning generator-based cross-section models

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Outline

Goal:
Fit world data on relevant cross sections for T2K

In framework of a generator (NEUT)
Data-driven parametrization with errors and covariances

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- Technique, results, difficulties
- Future plans

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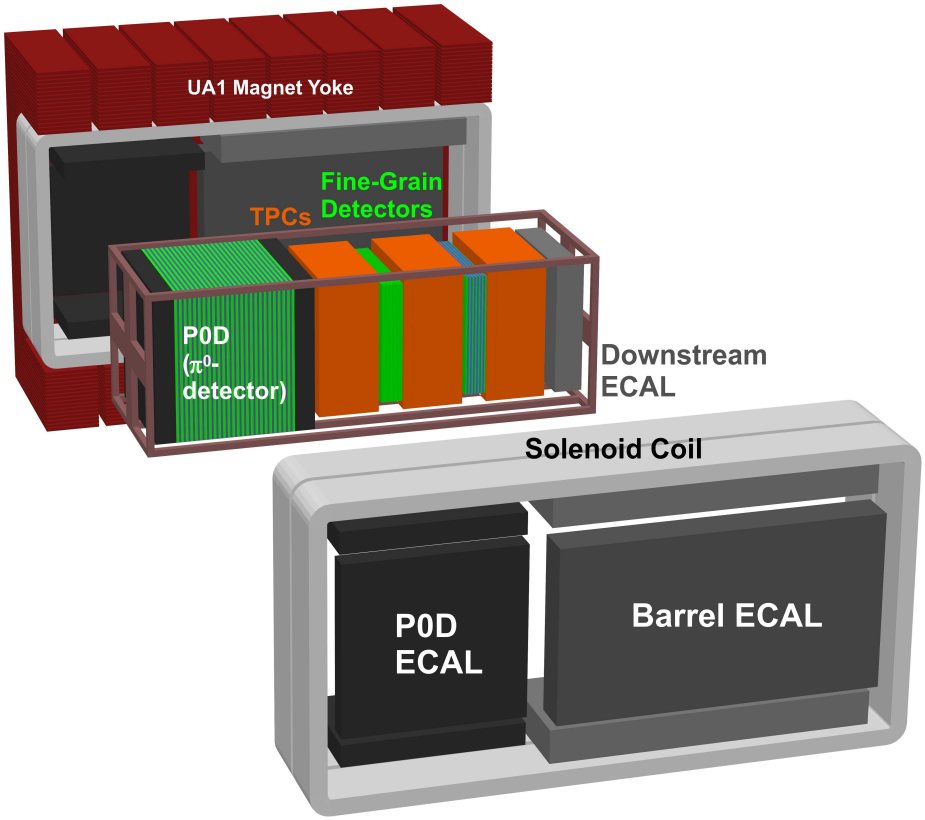
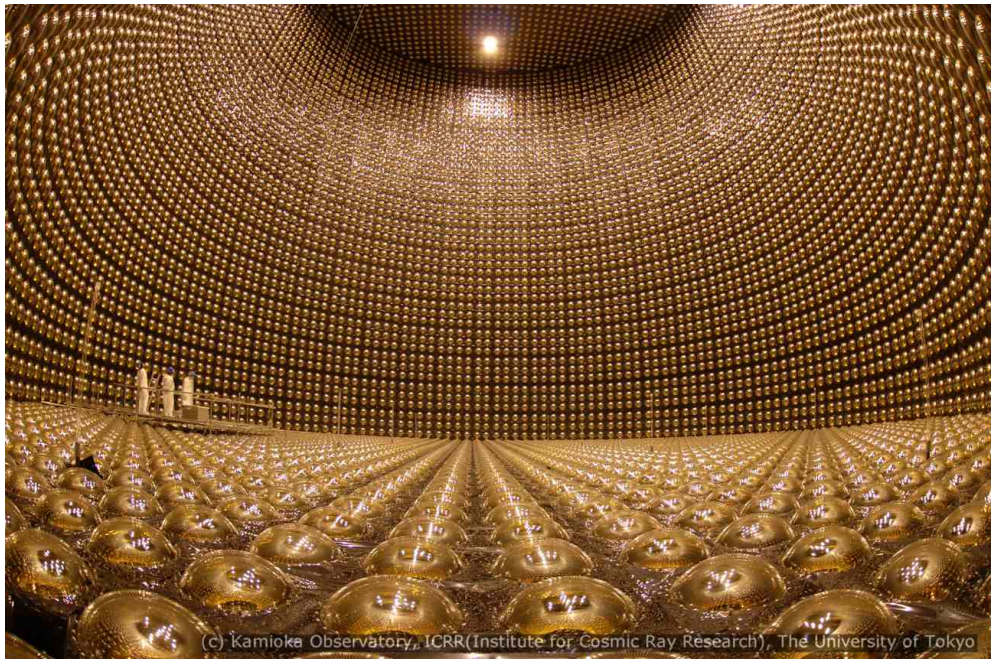
- So far only a first attempt
- Technique, results, difficulties
- Future plans
- Work from T2K ν interaction WG:
  - P. de Perio, M. Hartz, Y. Hayato, K. Mahn, K. McFarland, PR, P. Sinclair, R. Terri, M. Wascko

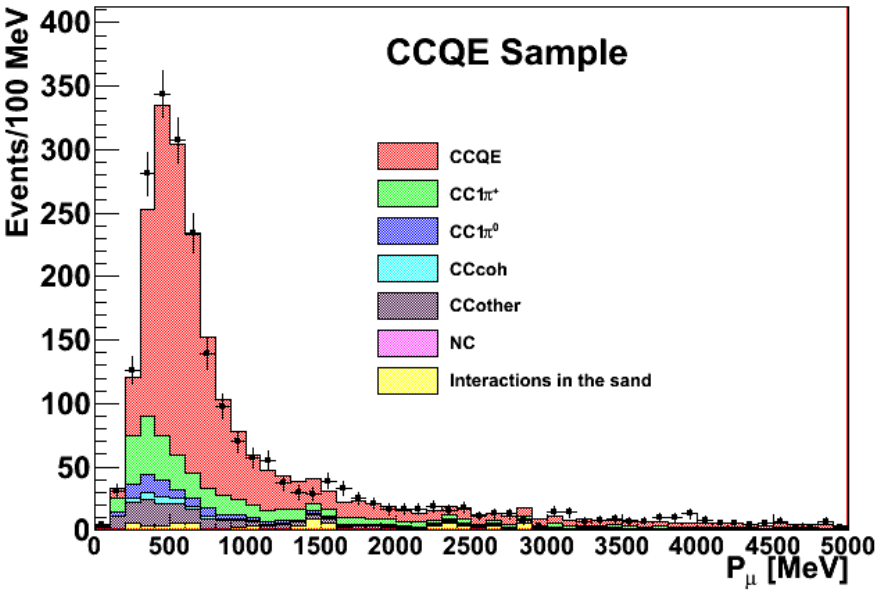
Motivation: T2K

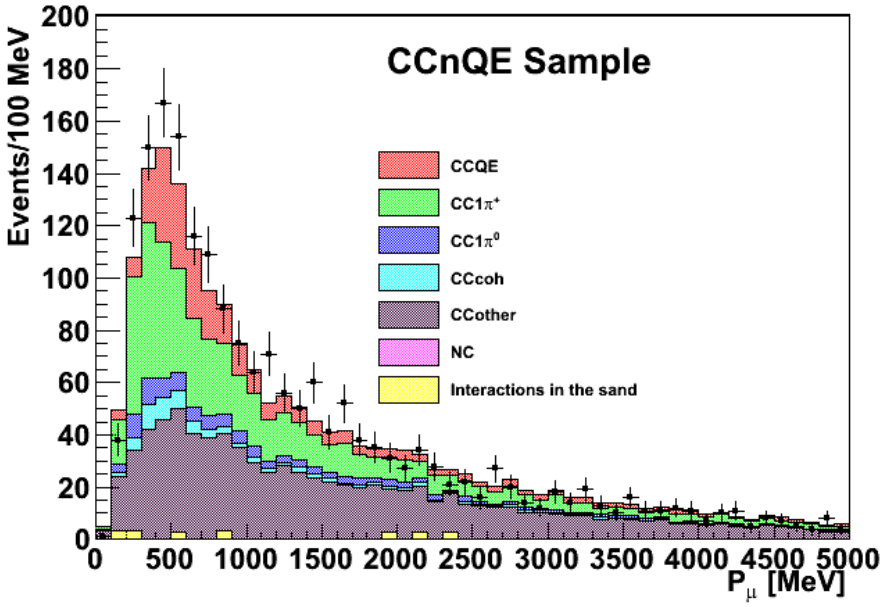




- ND280 $\neq$ SuperK $\Rightarrow$ parametrize ND constraint
  - Flux and cross section parameters

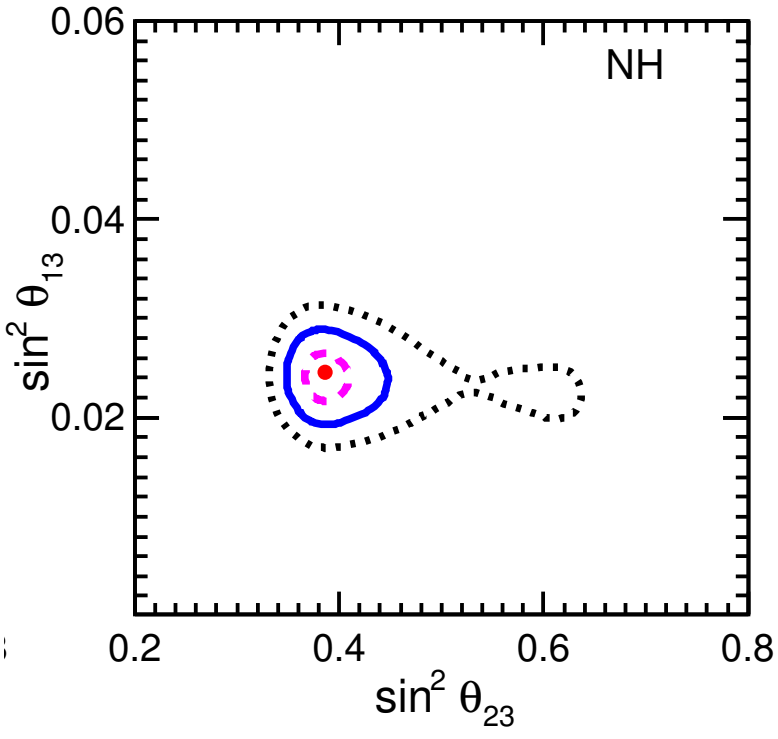
Motivation: T2K

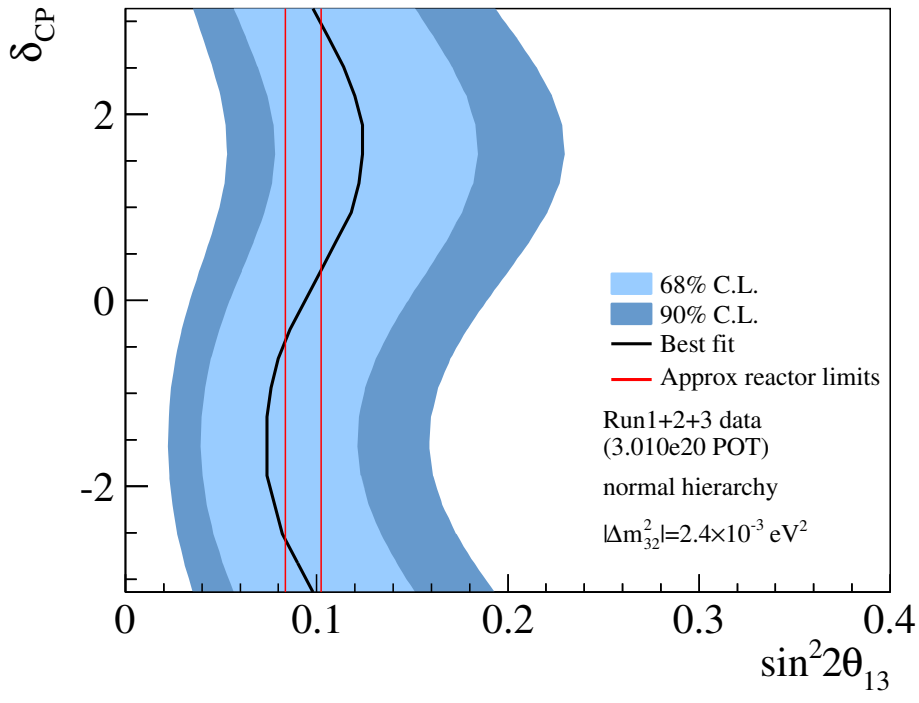




- Cross sections not yet measured in ND: need external data
- K. Mahn's talk for ND constraint
- G. Christodoulou's talk for ND cross section status

Motivation: General



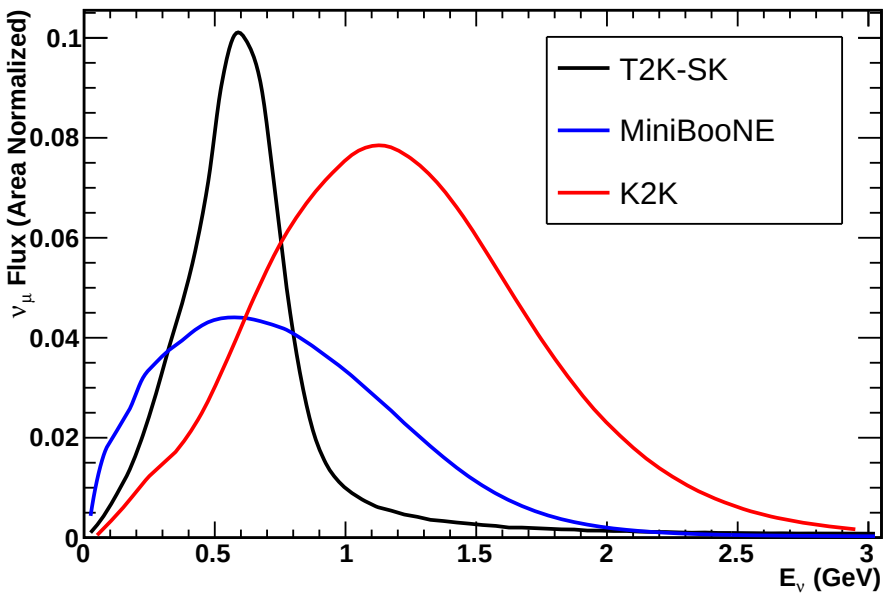


Fogli *et al.*, arXiv:1205.5254

- Precision goals for ν oscillations
- 1–few GeV E_ν, medium–heavy nuclear targets important

Fit technique

- Factorize fit into FSI, CCQE, Single π
- *Ad hoc* parameters if necessary for data/MC agreement
- Concentrate on MB this time (crosscheck with K2K)
  - Similar target, E_ν



Fit technique

- Factorize fit into FSI, CCQE, Single π
- *Ad hoc* parameters if necessary for data/MC agreement
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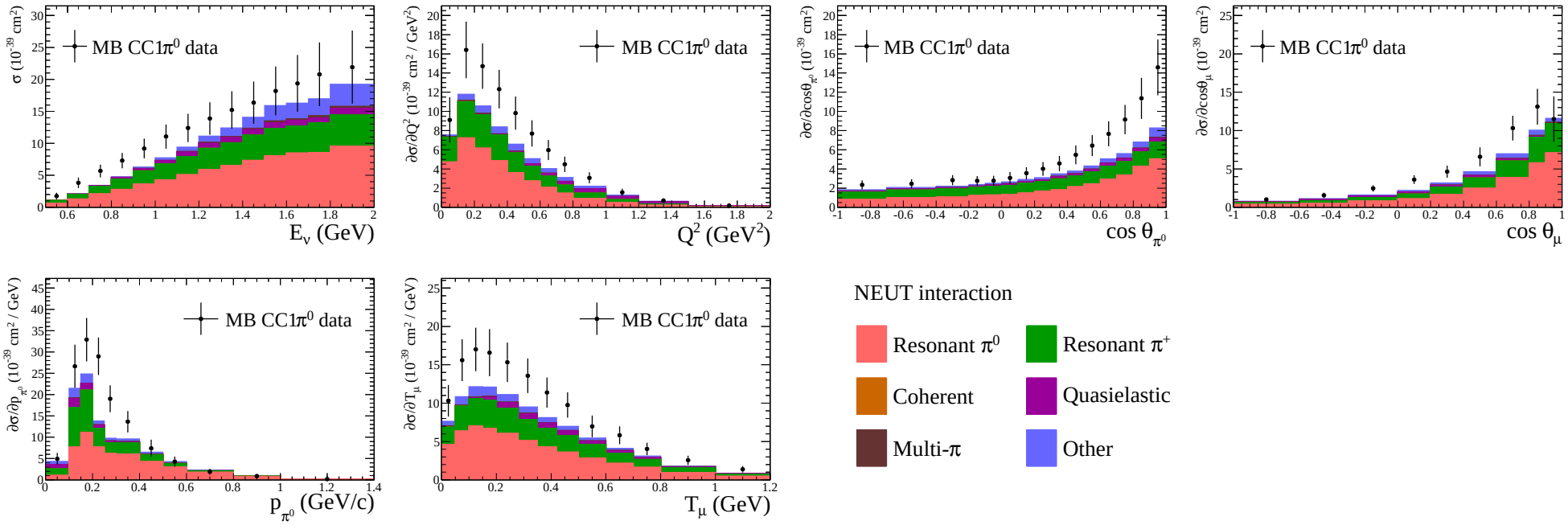
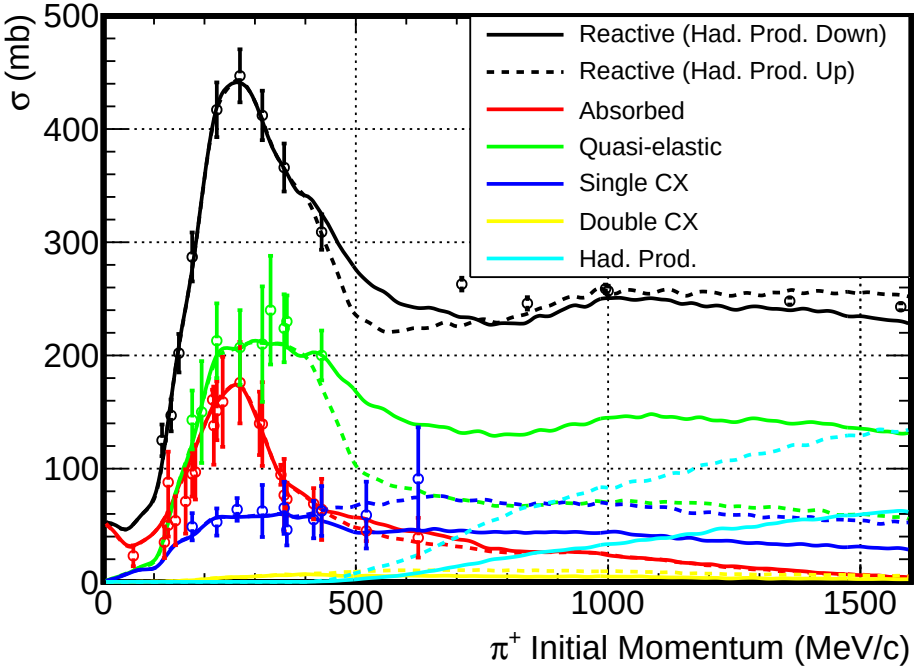
  - Similar target, E_ν
  - Multiple differential cross sections



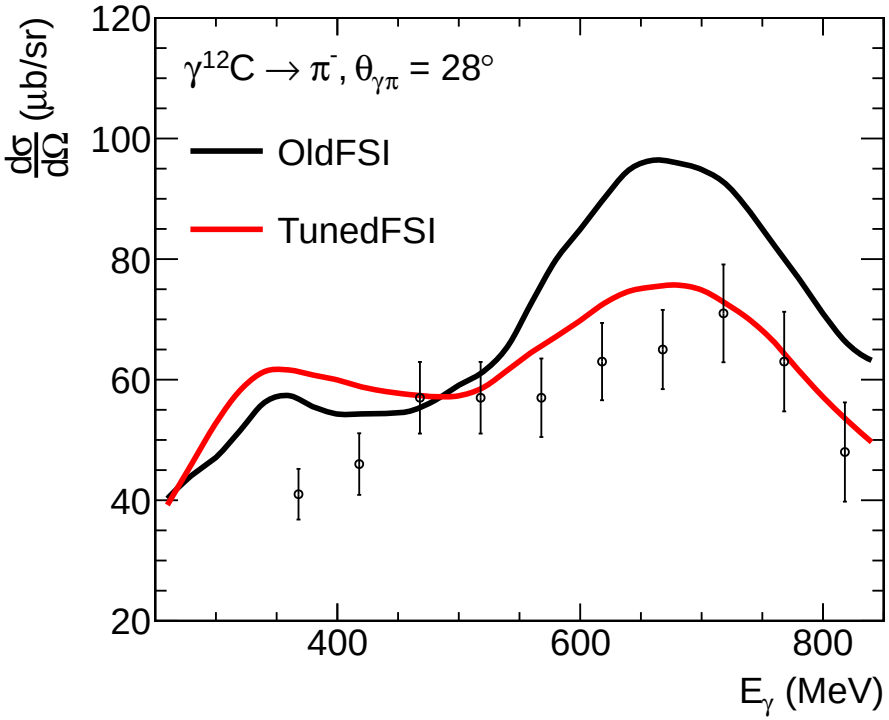
FSI

- Semi-classical cascade model
- Tune QE, π absorption, charge exchange, particle production[1]

π-nucleus



π photoproduction



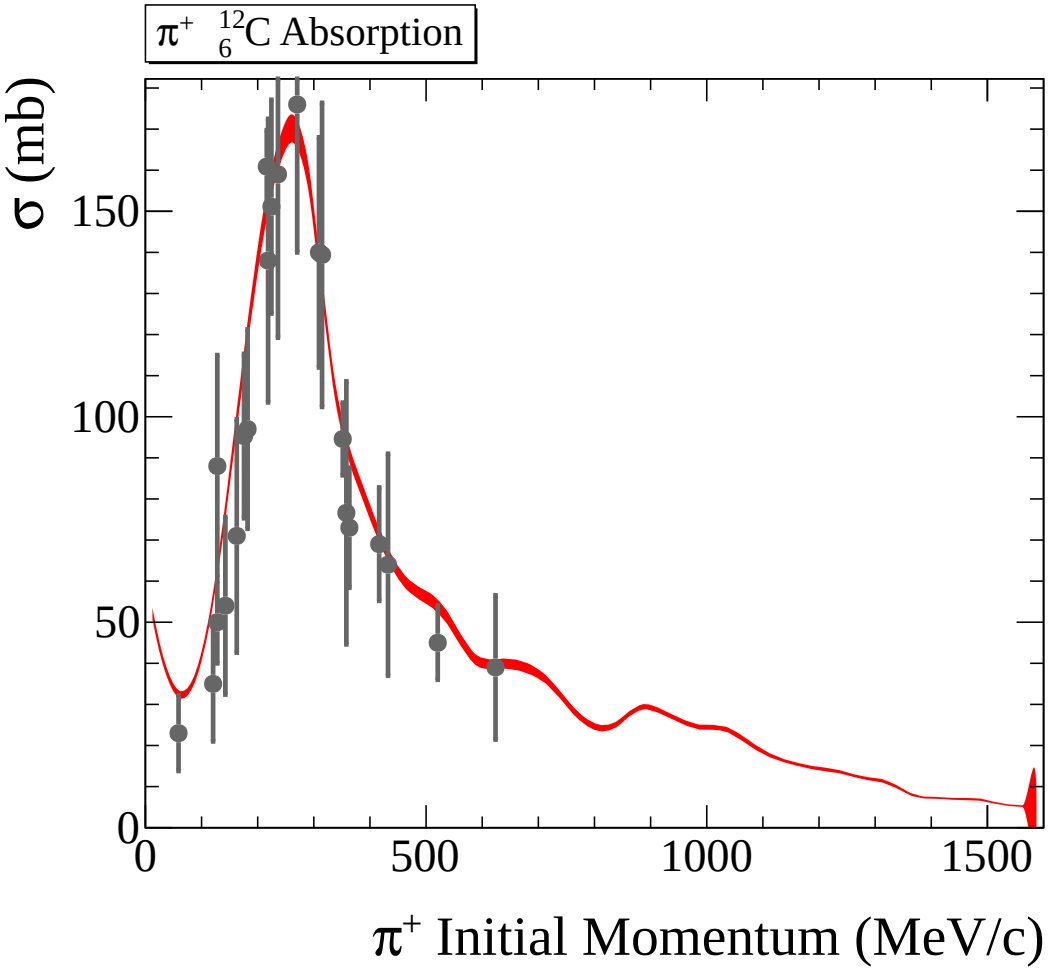
- Good best fit, but errors...

[1] Patrick de Perio, *NEUT Pion FSI*, NuInt11

FSI uncertainties

- Unknown data correlations
  - Uncorrelated χ^2 used

  $\Rightarrow$ Errors too small



FSI uncertainties

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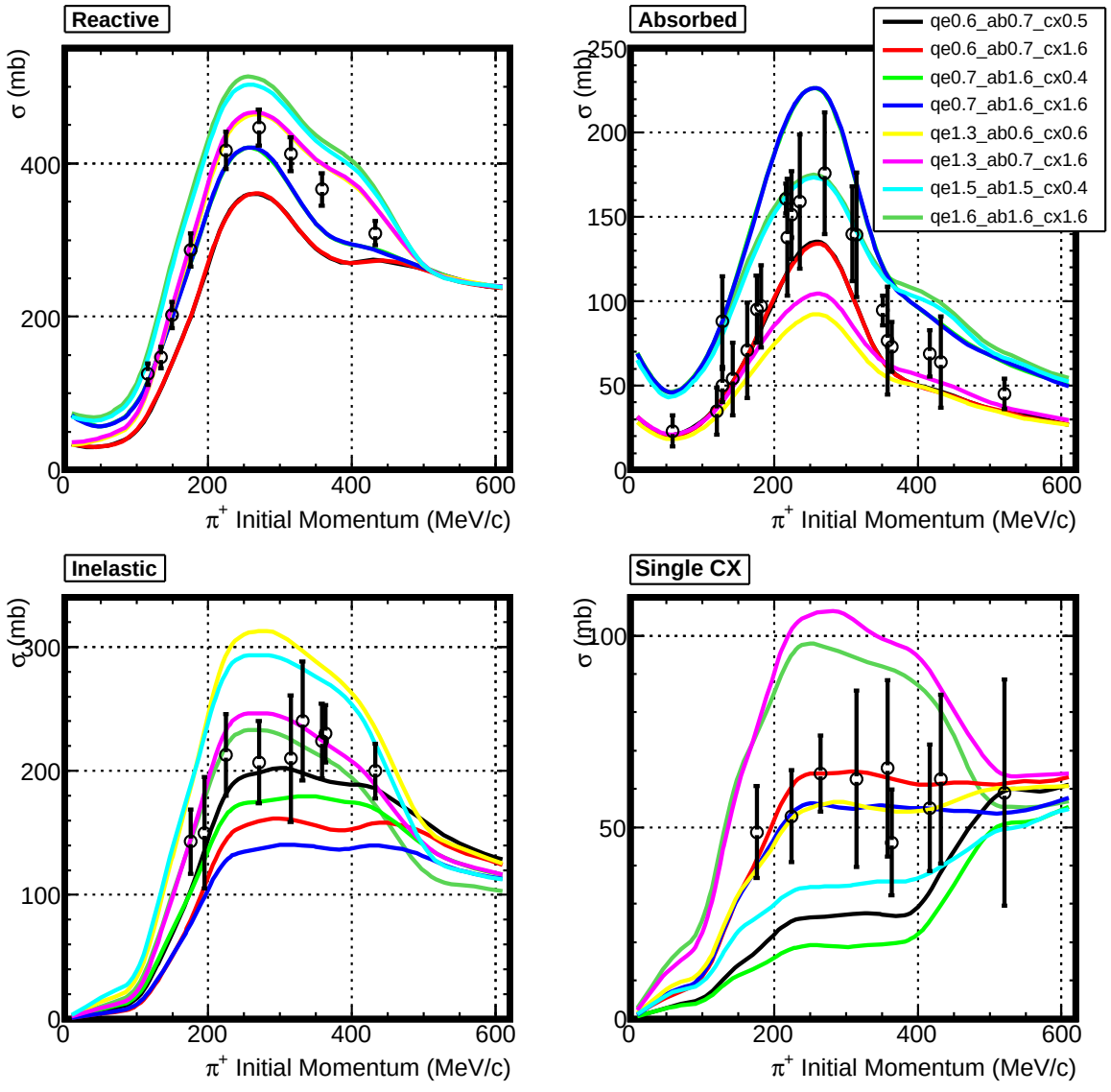
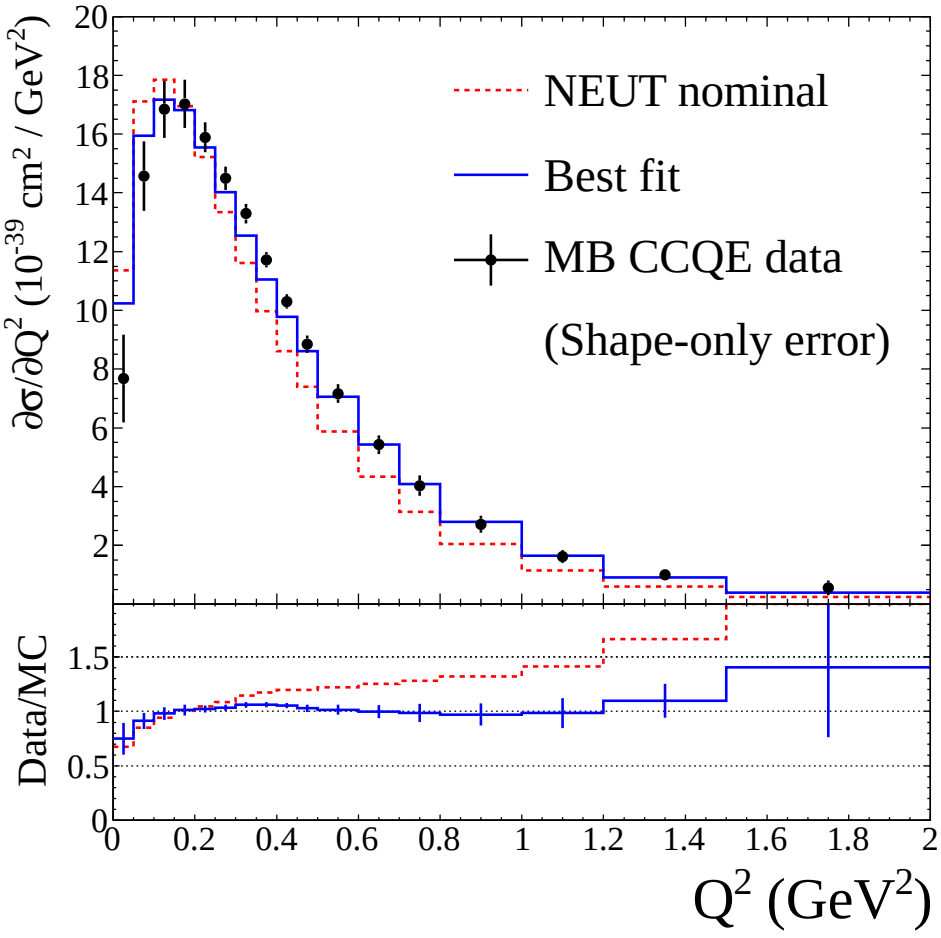
  - Uncorrelated χ^2 used

  $\Rightarrow$ Errors too small
- Choose 8 parameter sets
- Cover data uncertainties
- Propagate in analysis



CCQE



Fits to MiniBooNE data:

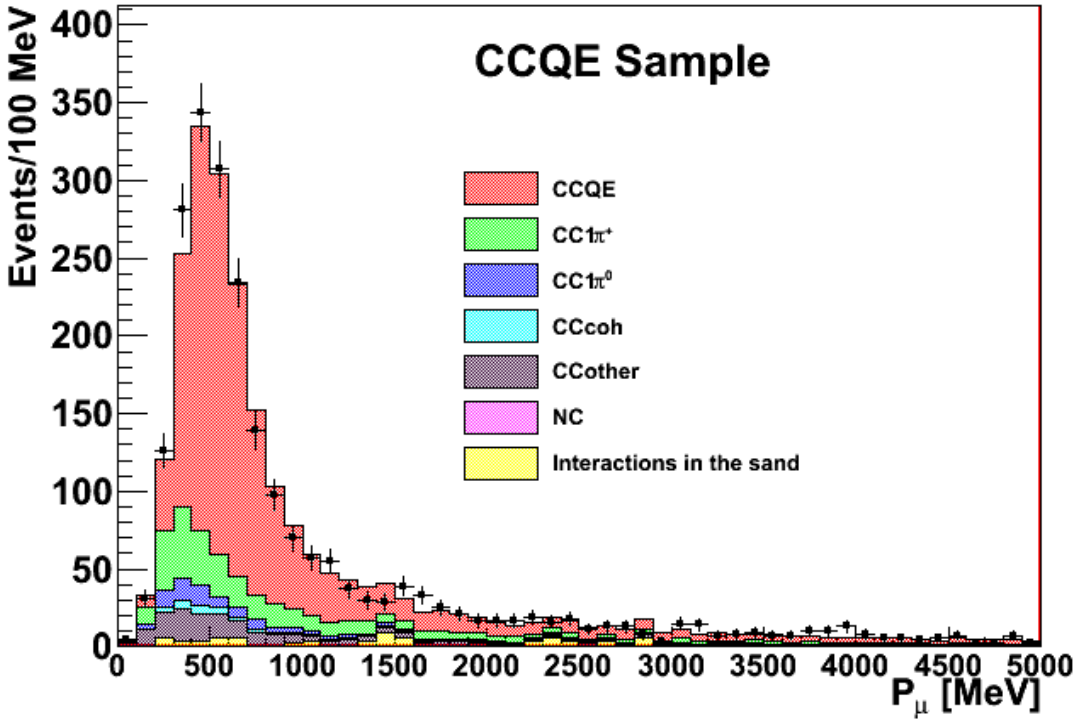
NEUT	M_A	$= 1.64 \pm 0.04$ GeV
	Norm	$= 0.88 \pm 0.02$
NUANCE[a]	M_A	$= 1.3 \pm 0.17$ GeV
	κ	$= 1.01 \pm 0.01$
NuWro FG[b]	M_A	$= 1.35 \pm 0.07$ GeV

[a] PRD **81**, 092005 (2010)
[b] C. Juszczak *et al.*, PRC **82**, 045502 (2010)

- Fit to 2D $(T_\mu, \cos\theta_\mu)$ MiniBooNE data
- Shape errors plus 11% normalization

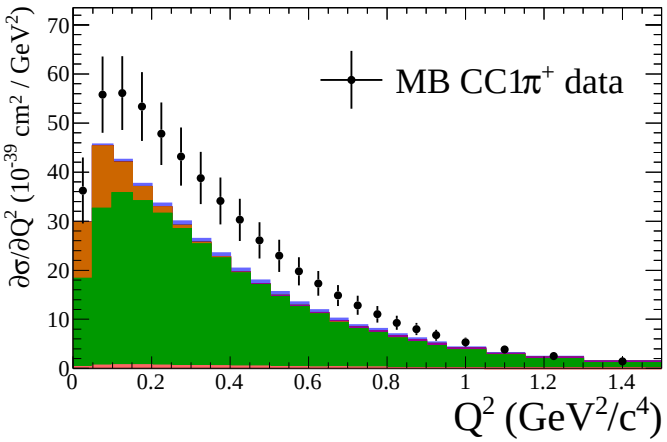
CCQE

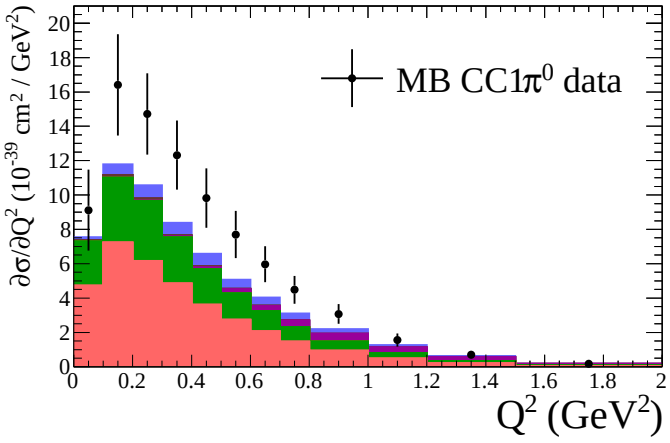
- Inflate error to "best − nominal", use ND constraint

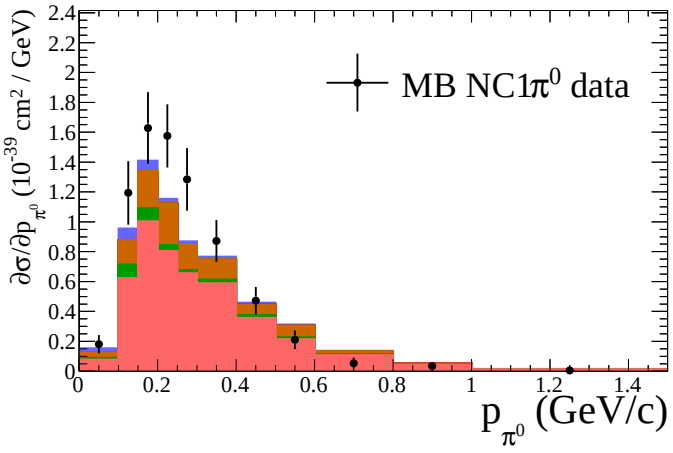


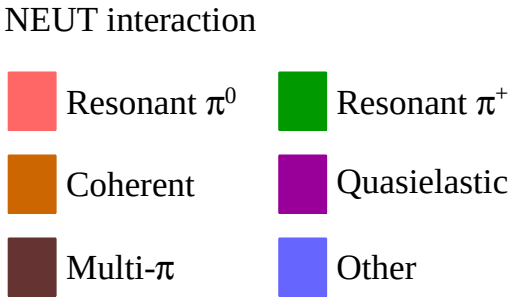
- Nuclear model
  - 13% error on p_F for low Q^2 variation (electron scattering)
  - Difference between spectral function (NuWro) and Fermi gas as error

Single pion fits





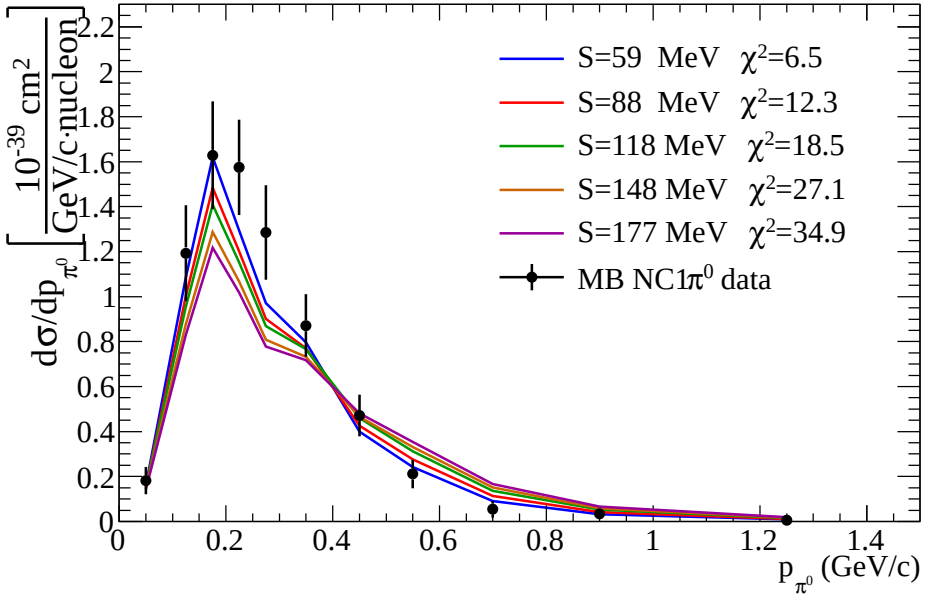


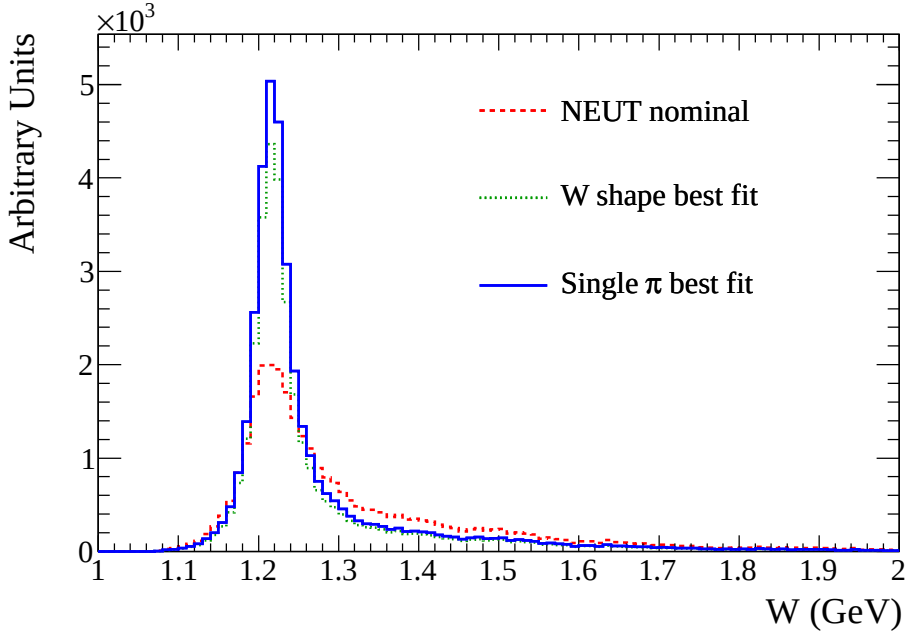


- Defined by particles exiting nucleus
- Predicted by Rein-Sehgal + FSI $\Rightarrow$ joint fit
- Fit parameters: M_A^{res}, "W shape", normalizations (NC/CC tension?)

CC1π, CC coherent, NC1π^0. penalized: NC1$\pi^\pm$, NC coherent, NC other

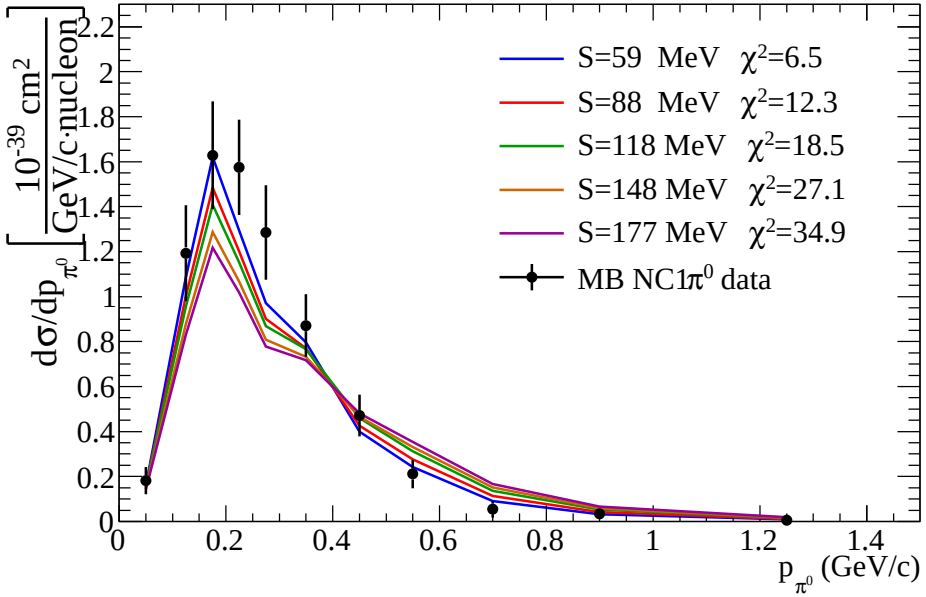
W shape

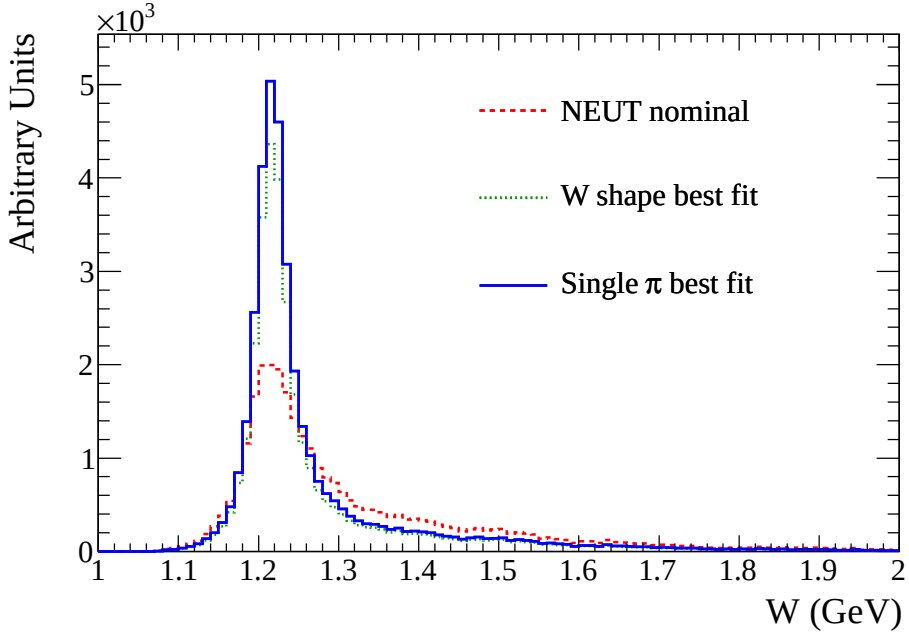




- Need to vary NC1π^0 p_{π^0} shape
  - Used in SK ν_e appearance fit
- Idea: Make Δ width a free parameter
- Reweight as function of πN invariant mass W
- Best fit unphysical: use "best − nominal" as error

W shape





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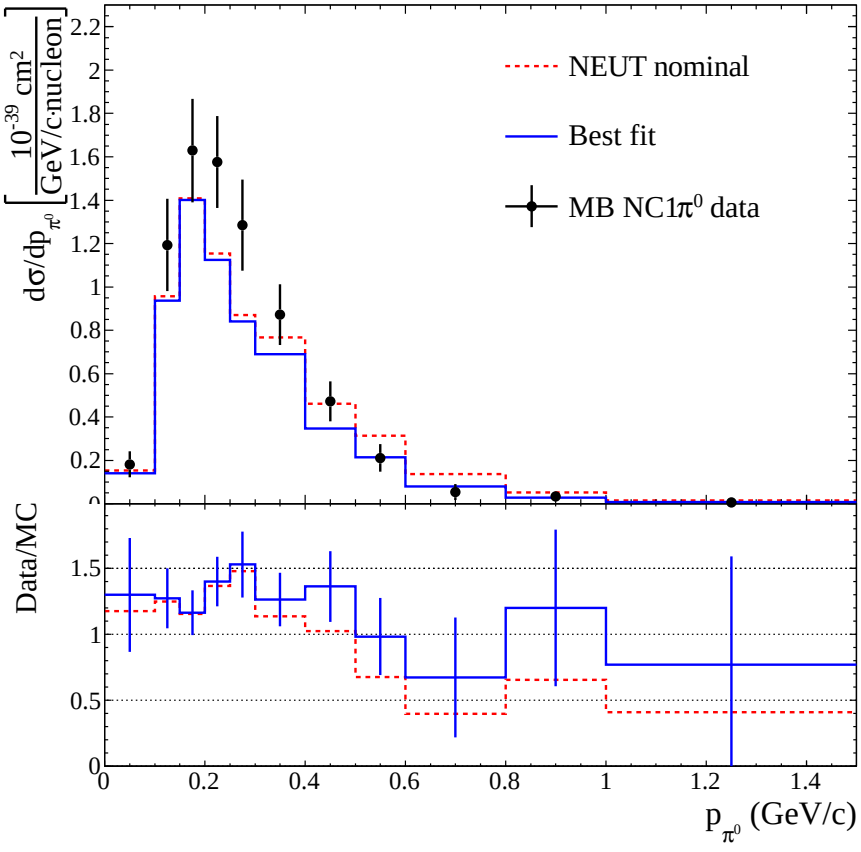
Not easy to find physically-motivated parameters to cover data/MC discrepancies

Correlations and "Peelle's Pertinent Puzzle"

$$\chi^2 = (\mathbf{D} - \mathbf{M})^{\mathsf{T}} \mathbf{V}^{-1} (\mathbf{D} - \mathbf{M})$$



- Bin-bin correlations make fit undershoot
  - "Peelle's Pertinent Puzzle"[2]

[2] "International evaluation of neutron cross-section standards", IAEA (2007)

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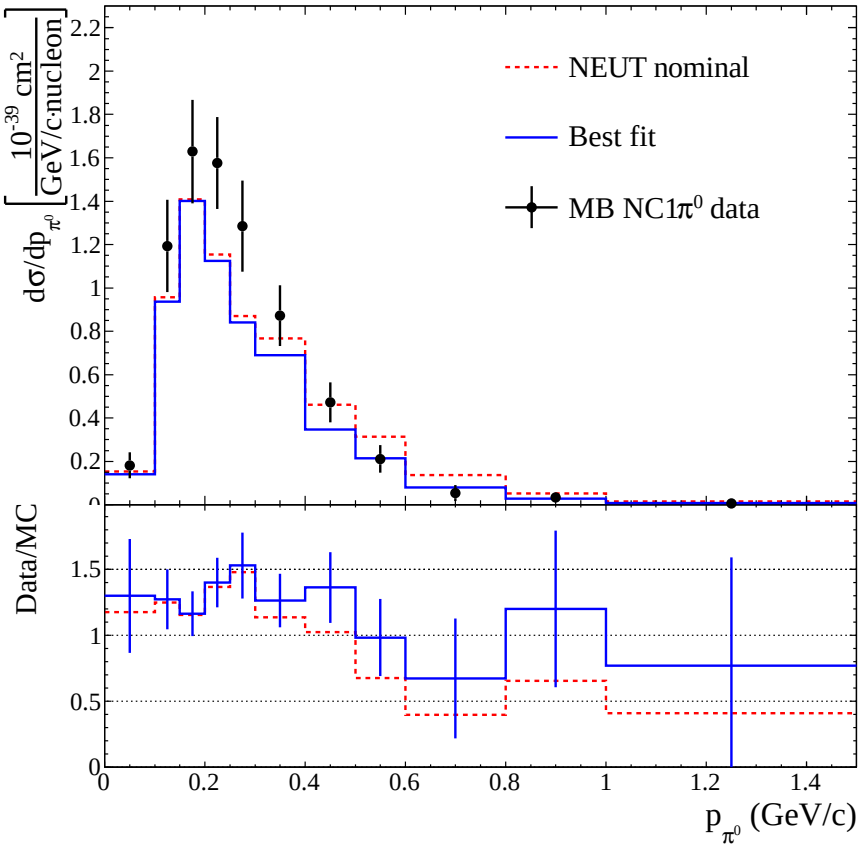

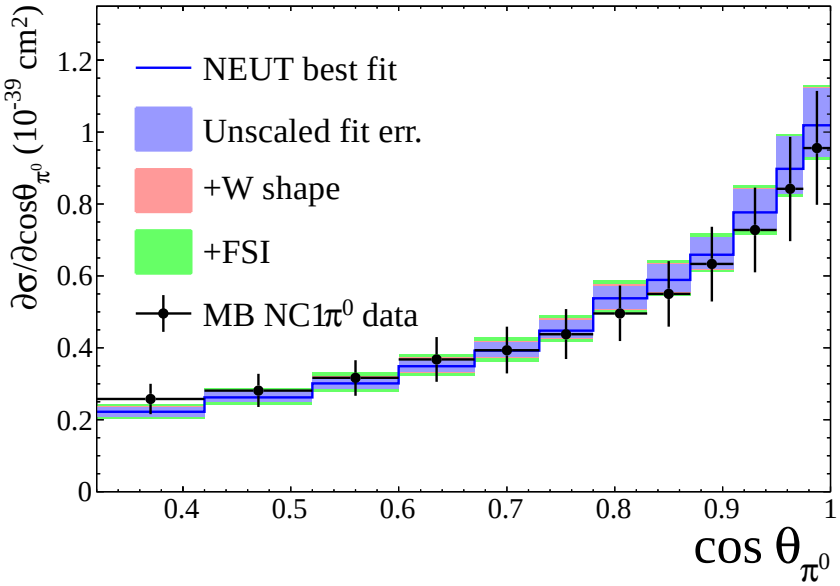

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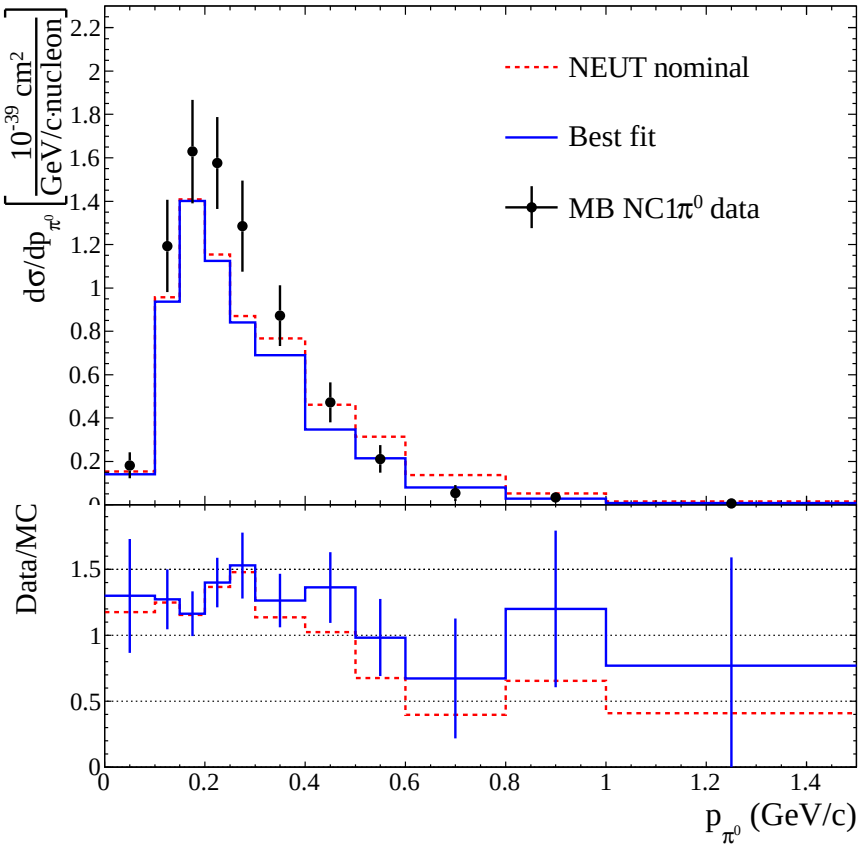

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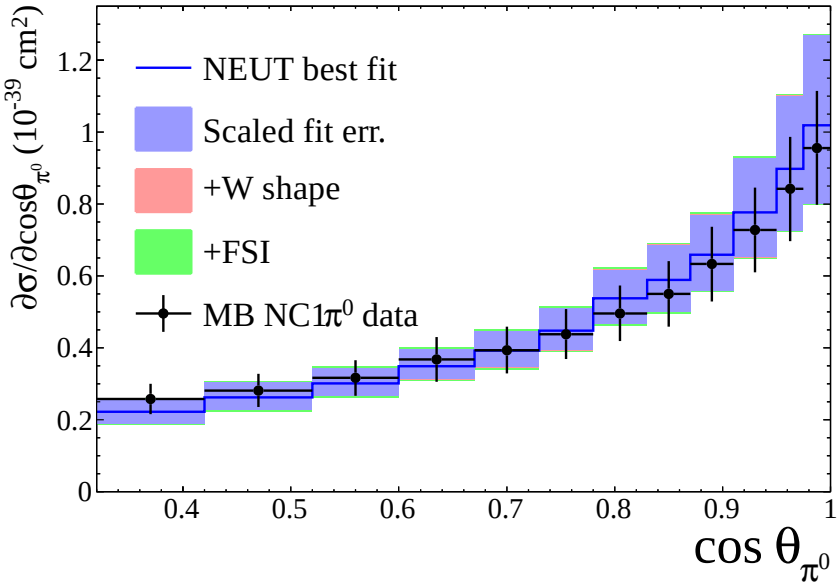
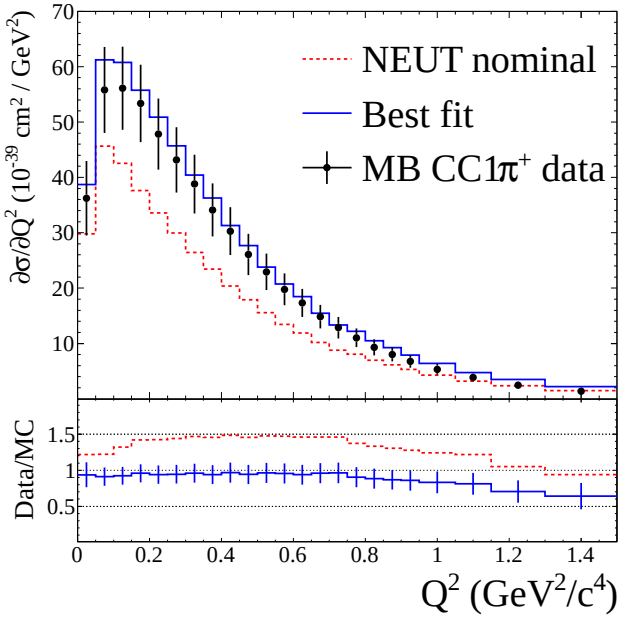
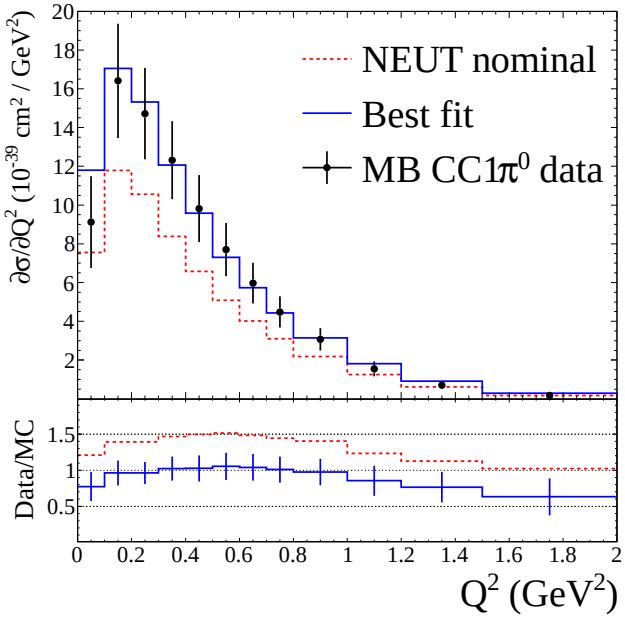
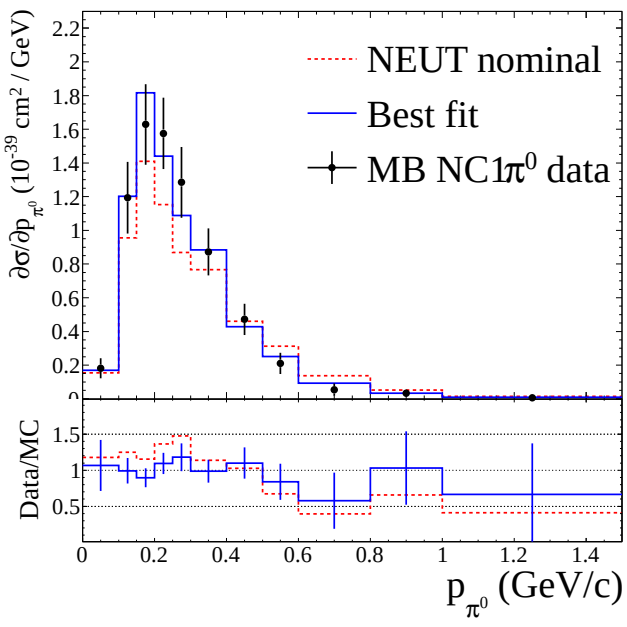


- Exclude correlations ⇒ too-small errors
- For now: drop correlations, scale errors after fit
  - Match MB flux-averaged cross section error
- Next time: parametrize systs to add as penalty terms to fit

Best fits





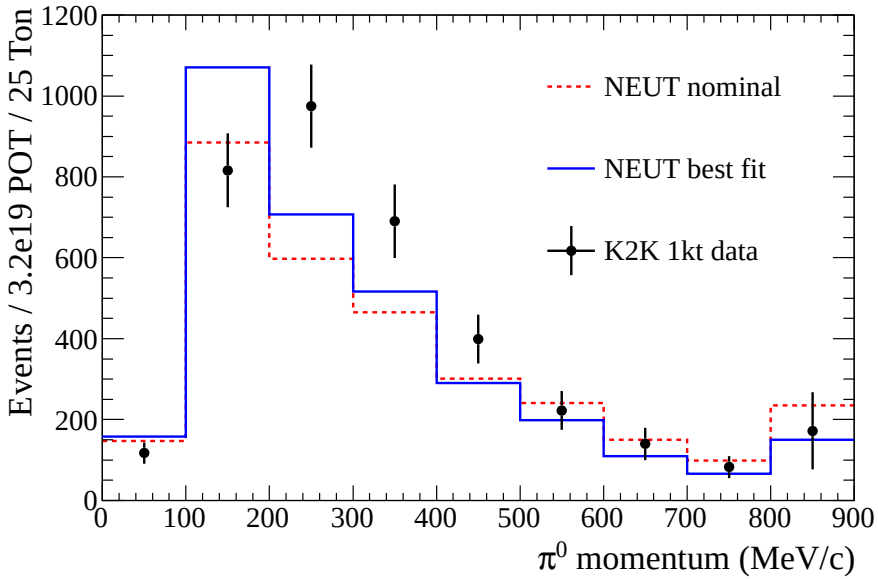


	Nominal	Best fit	Error	Penalized?
M_A^{res}	1.21 GeV	1.16	0.05	
W shape	1	0.48	–	
CC coherent norm.	1	0.66	0.35	
CC 1π norm.	1	1.63	0.16	
CC other shape	0	0.36	0.39	✓
NC coherent norm.	1	0.96	0.29	✓
NC $1\pi^0$ norm.	1	1.19	0.14	
NC $1\pi^{\pm}$ norm.	1	0.98	0.30	✓
NC other norm.	1	1.00	0.30	✓

$\chi^2/\text{dof} = 36.8/41$

K2K crosschecks

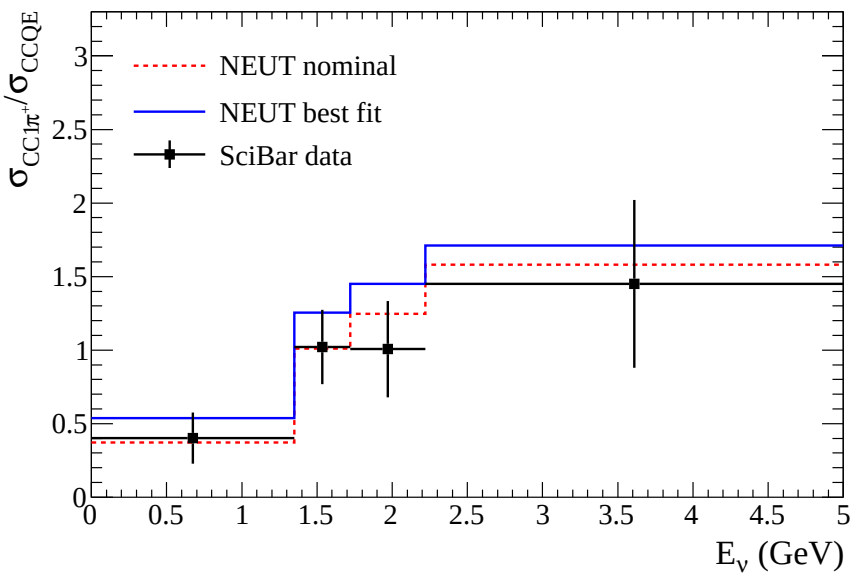
1kt NC1π^0



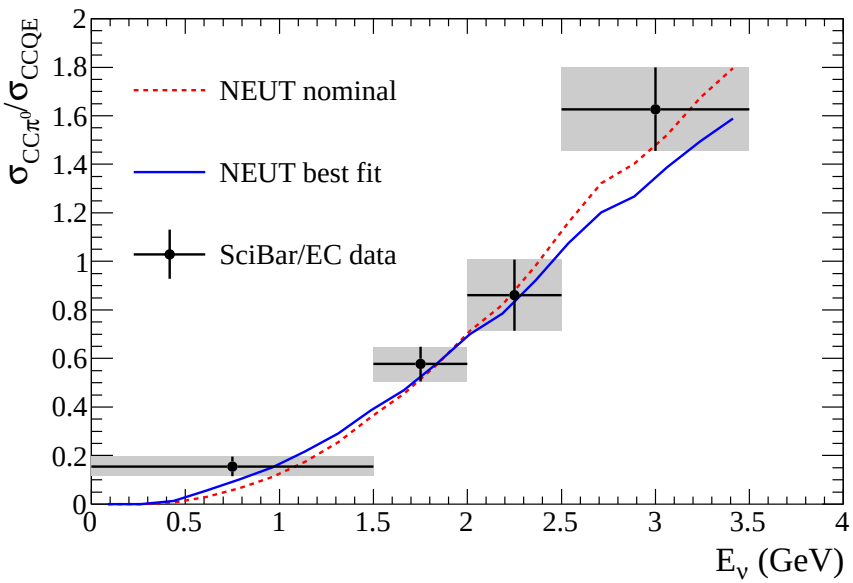
Data points are reco p_π, MC points are true p_π

- Defined by interaction at vertex
- (Differs from MB definition)

CC1π^+/CCQE



CCπ^0/CCQE



Other fit issues

- No correlations between samples.
  - Flux, detector systematics, . . . ?

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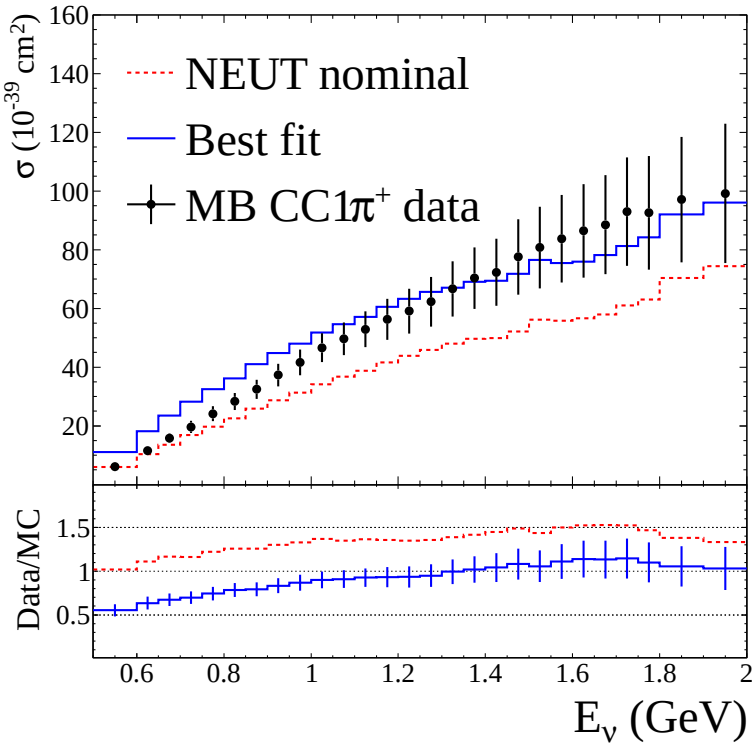
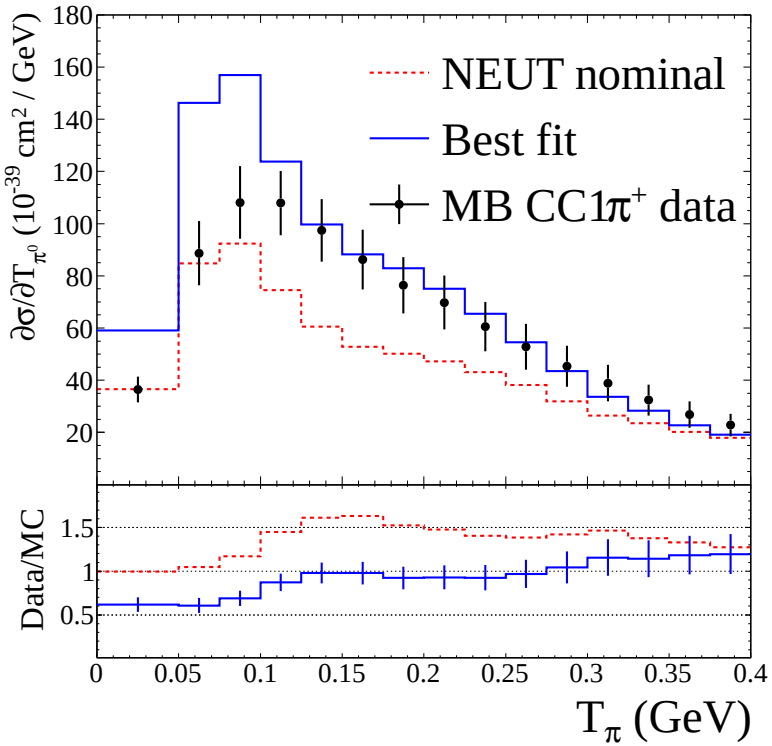
- No correlations between samples.
  - Flux, detector systematics, . . . ?
- Non-fit distributions not guaranteed to agree





Future plans

- Fix existing issues
- Include more datasets
  - Especially H/D: separate nuclear effects
  - T2K near detector measurements!
- Repeat with GENIE
- *Ad hoc* parameters $\longrightarrow$ model improvements
  - Nuclear spectral function
  - Internucleon correlations
  - Updated single π form factors[3]
  - Rein-Sehgal nonresonant contribution

[3] Graczyk and Sobczyk, PRD **77** 053001 (2008); Lalakulich *et al.*, PRD **74** 014009 (2006); Hernandez *et al.*, PRD **76**, 033005 (2007)

Conclusions

- First attempt at parametrizing world data with uncertainties
  - Good Enough™ for current T2K analysis
- Much still to do!
- Will need input from theory/phenomenology as well as experiment

T2K ν_e appearance:

Error source	SK uncertainty (%)
Flux × cross section	
ND constrained	6
ND non-constrained	13
SK+FSI	10

11 candidate events

Backup slides

Bibliography: datasets

- MiniBooNE:
  - CCQE Phys. Rev. D81, 092005 (2010)
  - $CC1\pi^+$ Phys. Rev. D83, 052007 (2011)
  - $CC1\pi^0$ Phys. Rev. D83, 052009 (2011)
  - $NC1\pi^0$ Phys. Rev. D81, 013005 (2010)
- K2K
  - $NC1\pi^0$ Phys. Lett. B619 (2005) 255-262
  - $CC1\pi^+/CCQE$ Phys. Rev. D78, 032003 (2008)
  - $CC\pi^0/CCQE$ Phys. Rev. D83, 054023 (2011)

NEUT

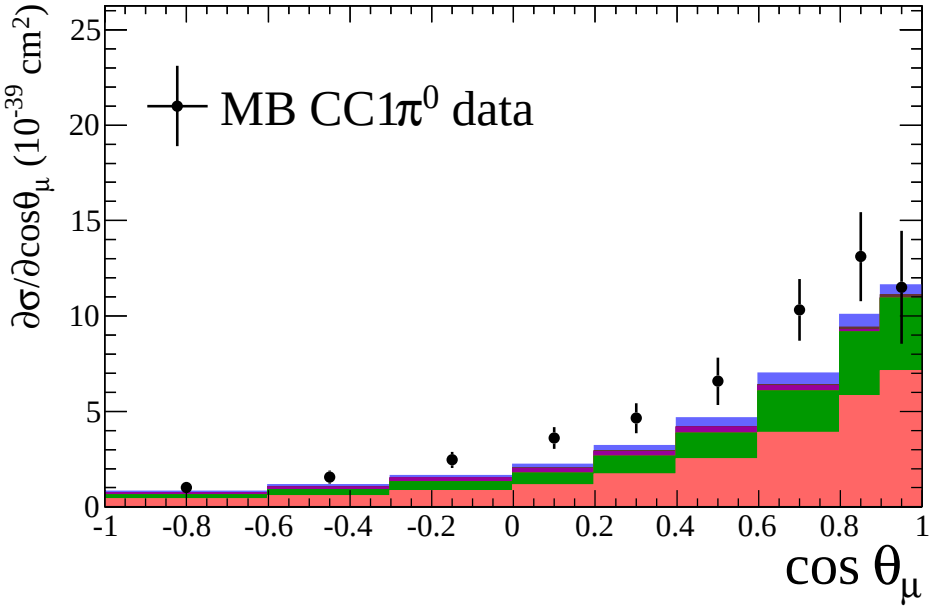
- Originally developed for Kamiokande
- Updated for SuperK, K2K, SciBooNE, T2K
- $100\,\mathrm{MeV} \lesssim E_\nu \lesssim \mathrm{TeV}$

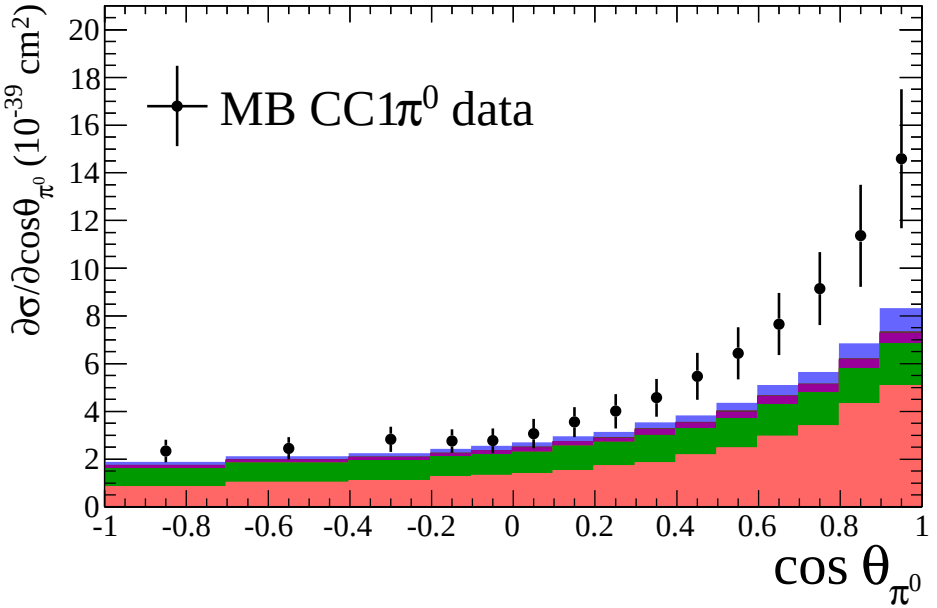
CCQE	Llewellyn-Smith model. Dipole form factors
Single π	Rein-Sehgal model
	▸ Also coherent π
Nucl. effects	Relativistic Fermi gas (Smith & Moniz)
FSI	Cascade model (Salcedo *et al.* Δh)

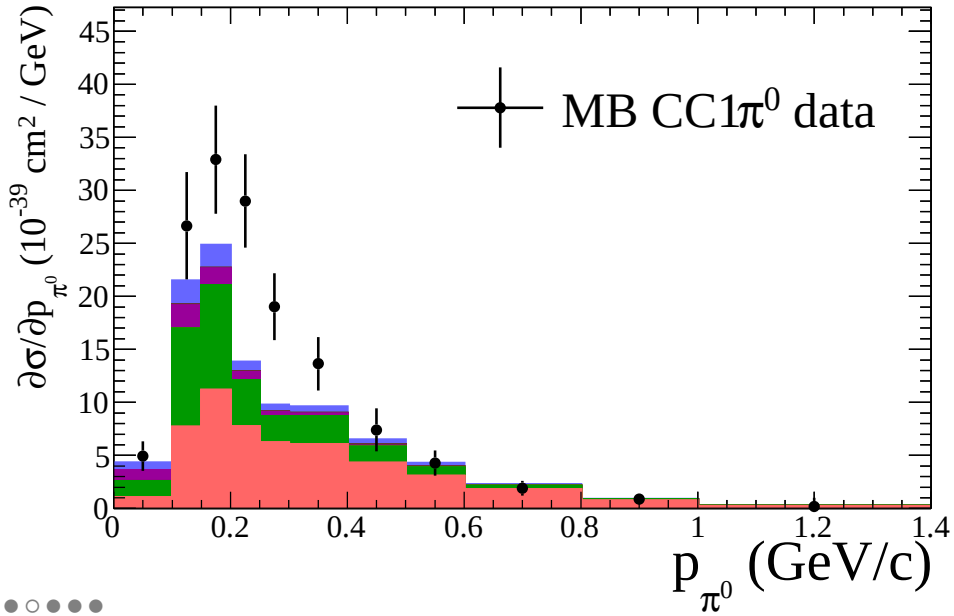
Peelle's Pertinent Puzzle

- Robert Peelle (1987):
  - Measure $x_1 = 1.5 \pm 0.15(\text{stat.}), \qquad x_2 = 1.0 \pm 0.10(\text{stat.})$
  - Plus fully-correlated 20% uncertainty
  - $\chi^2 = (\mathbf{x} - \mu)^T \mathbf{C}^{-1} (\mathbf{x} - \mu)$
  - $\hat{\mu} = 0.88 \pm 0.22$!
- Right answer if model correct, correlated uncertainty additive
- Our model imperfect, uncertainty additive+multiplicative
- Wide literature, not clear how to apply here:
  - Several perspectives: "International evaluation of neutron cross-section standards", IAEA (2007)
  - We have the covariance matrix, but not details of exactly where components come from (additive or multiplicative)

MB CC1π^0 by interaction type 1



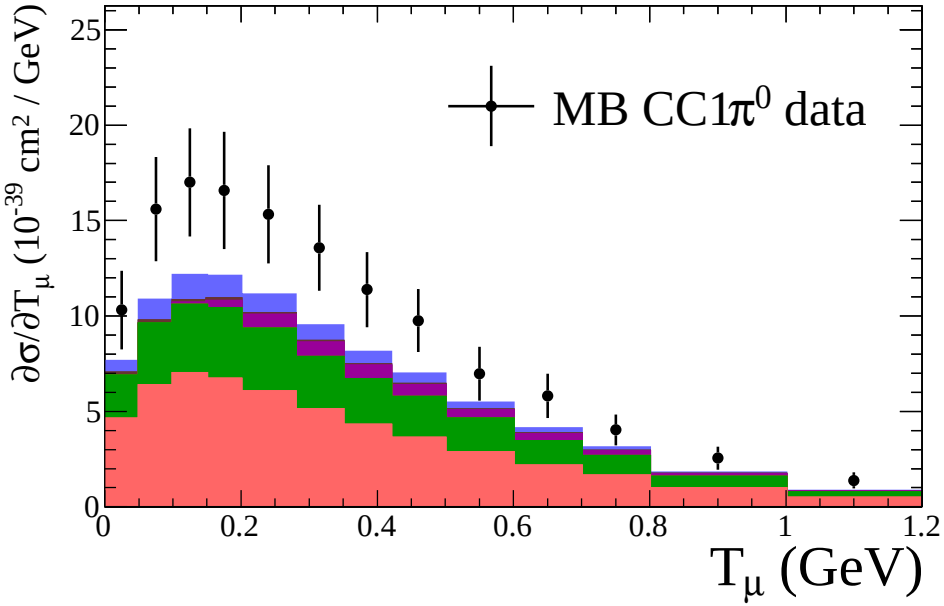


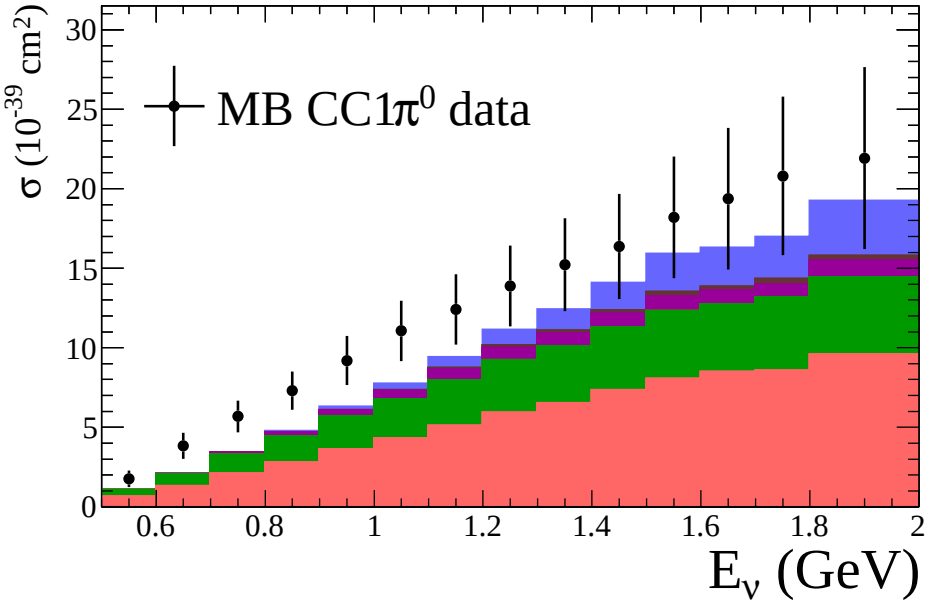


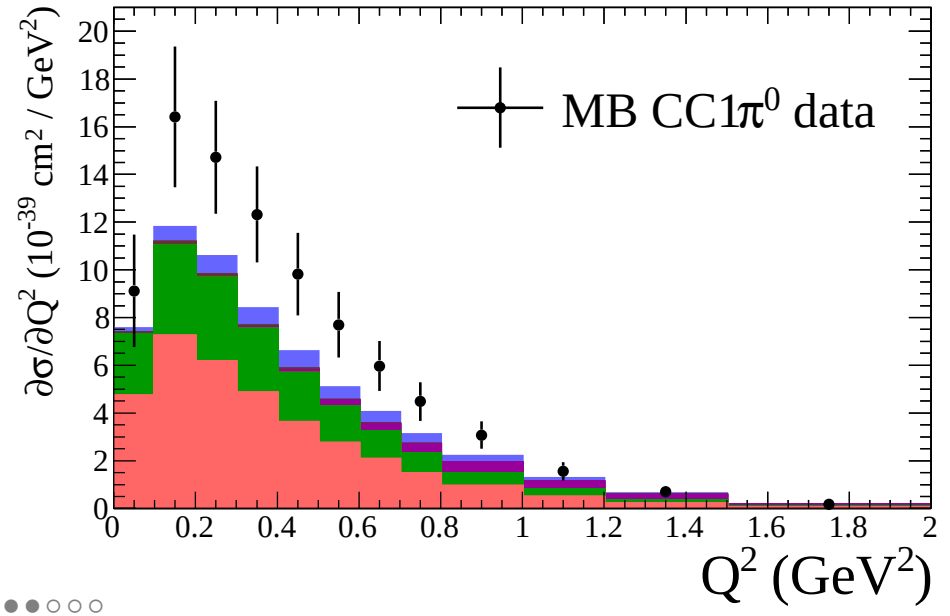
NEUT interaction

- Resonant π^0
- Resonant π^+
- Coherent
- Quasielastic
- Multi-π
- Other

MB CC1π^0 by interaction type 2



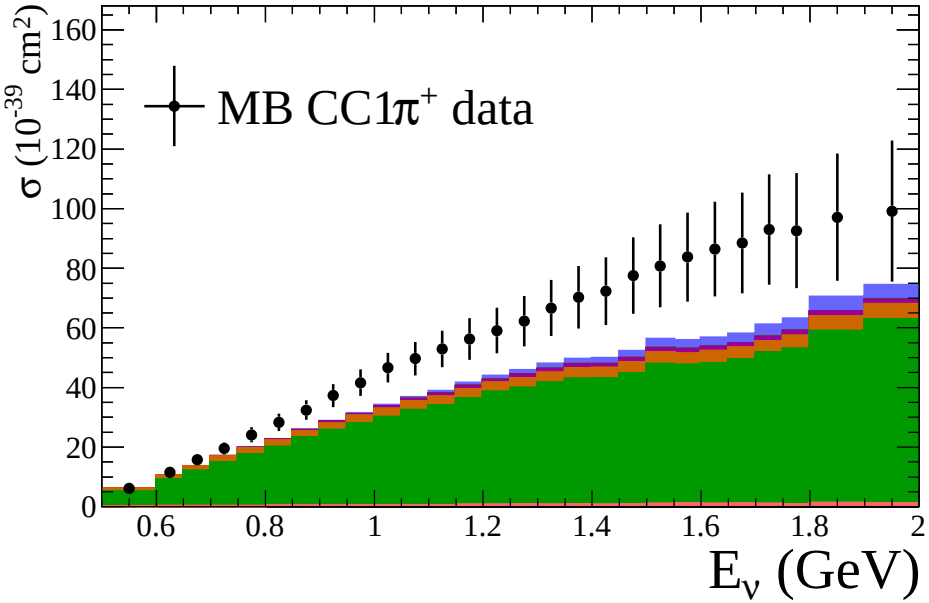


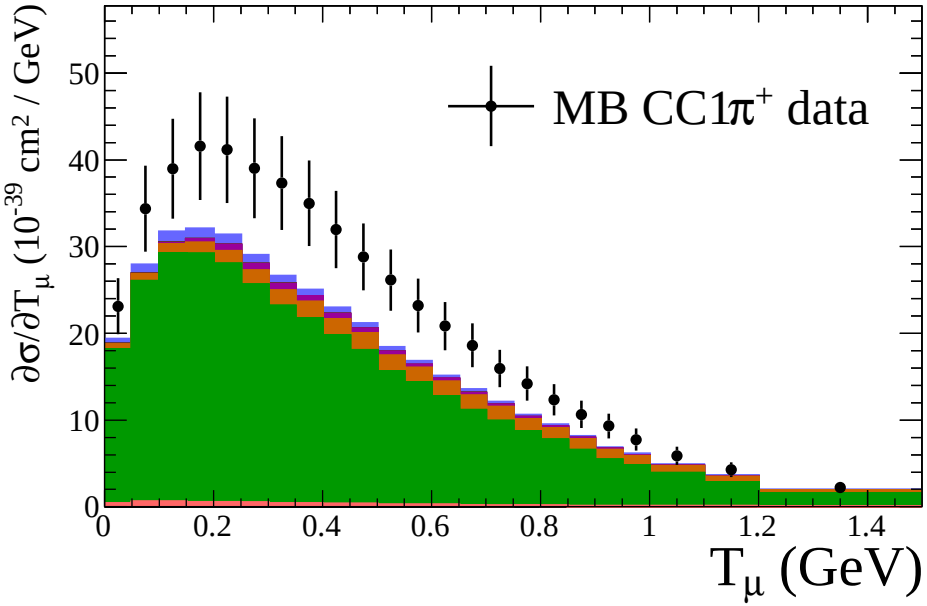


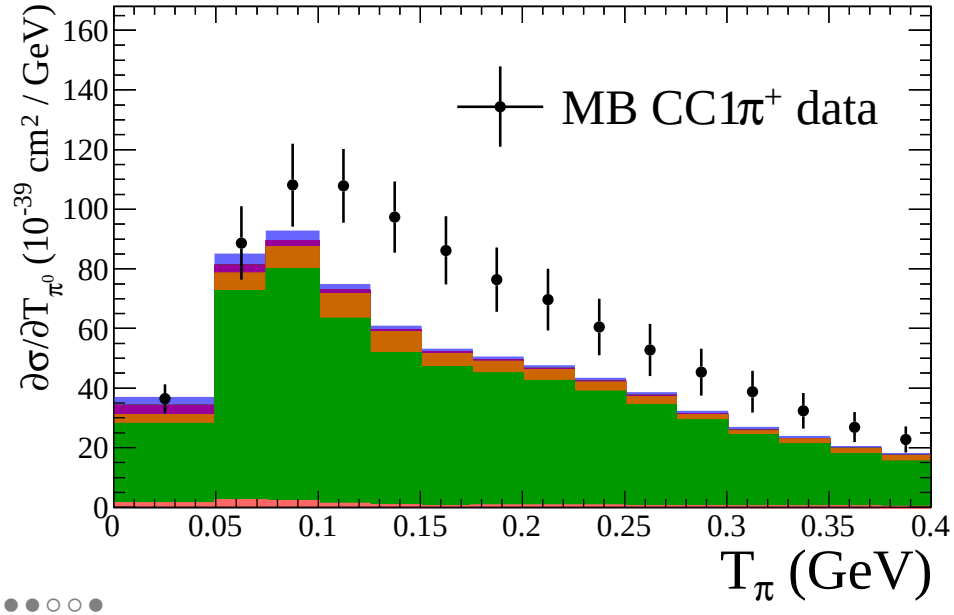
NEUT interaction

- Resonant π^0
- Resonant π^+
- Coherent
- Quasielastic
- Multi-π
- Other

MB CC1π^+ by interaction type



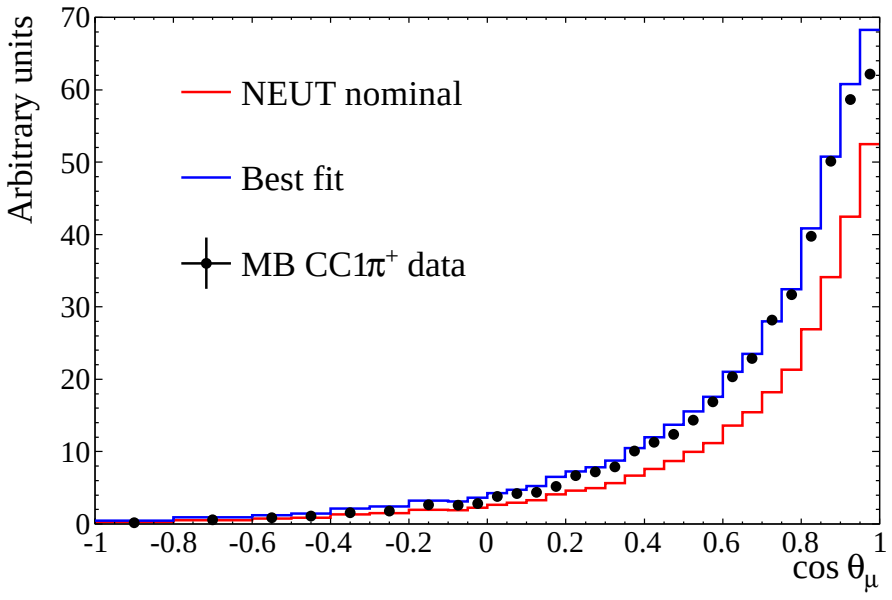


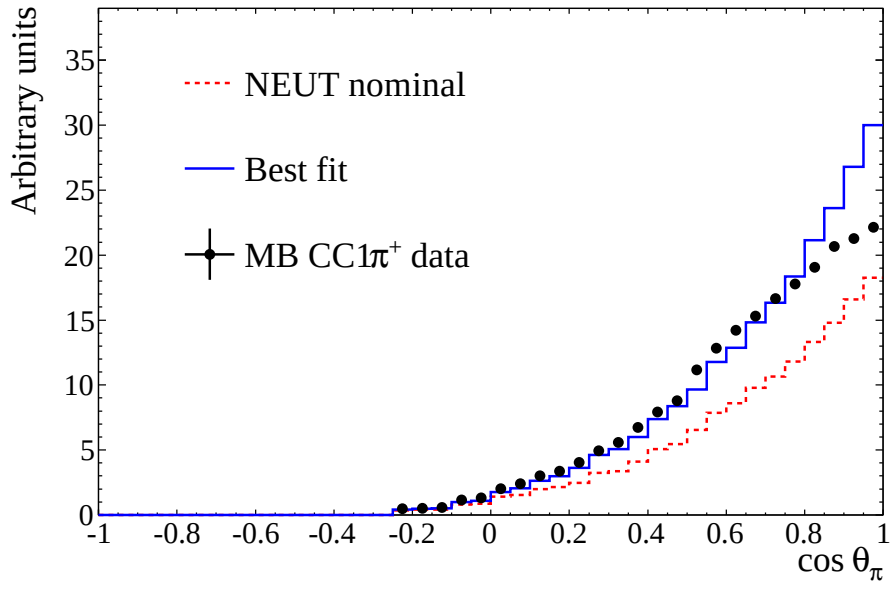


NEUT interaction

- Resonant π^0
- Resonant π^+
- Coherent
- Quasielastic
- Multi-π
- Other

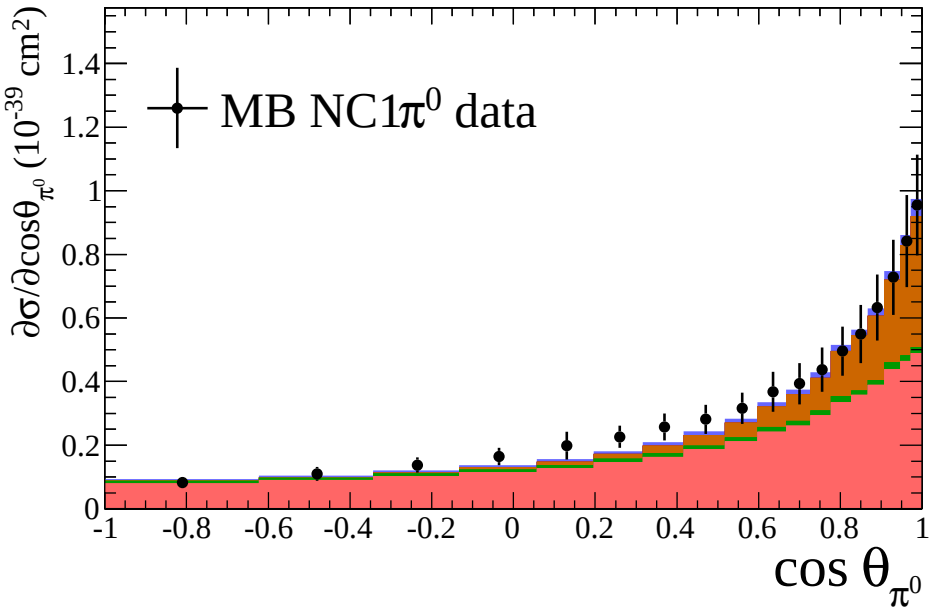
MB CC1π^+ angular distributions

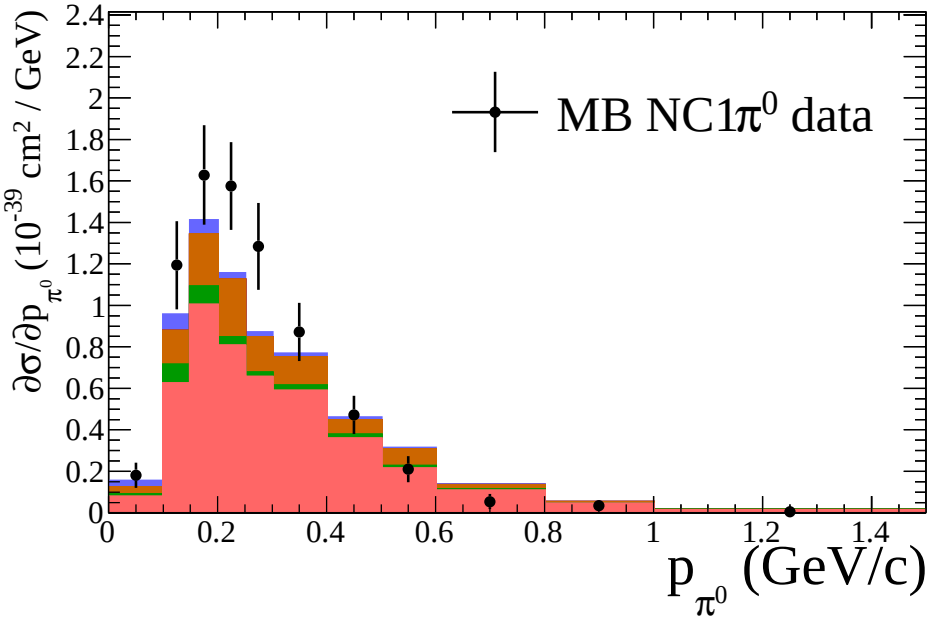




- Integrated from "incomplete" 2D $(T, \cos\theta)$ distributions

MB NC1π^0 by interaction type

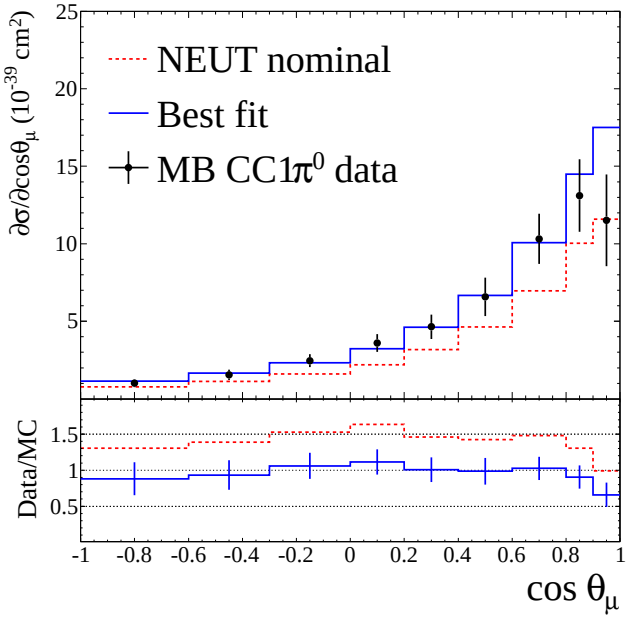


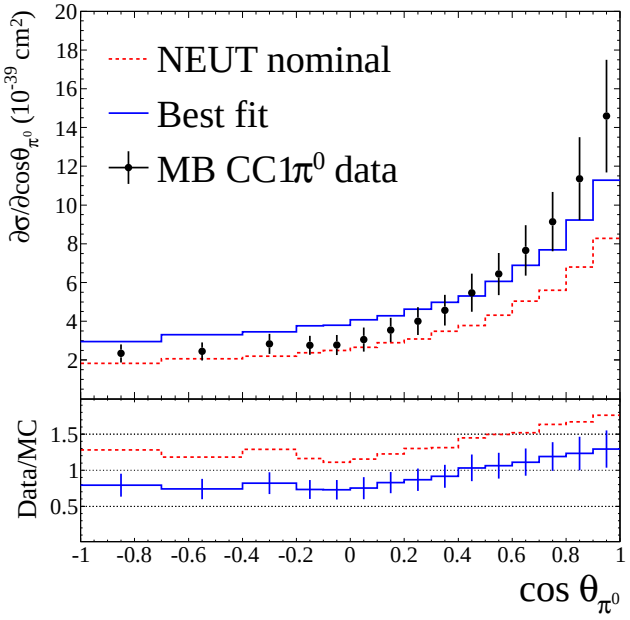


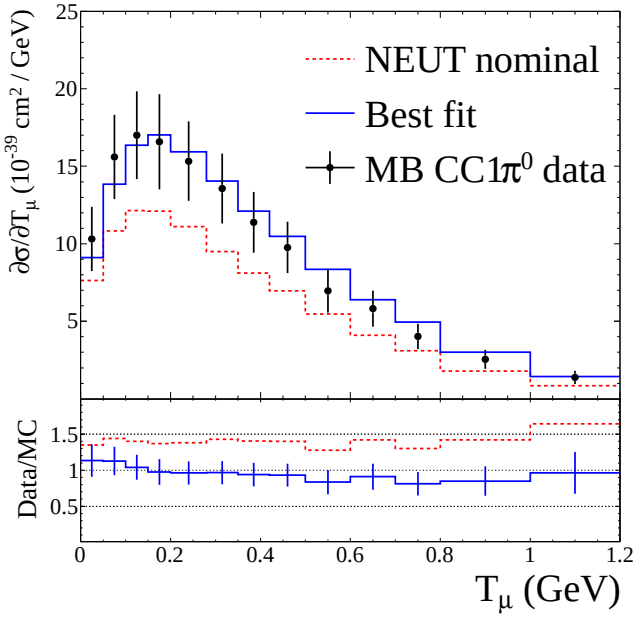
NEUT interaction

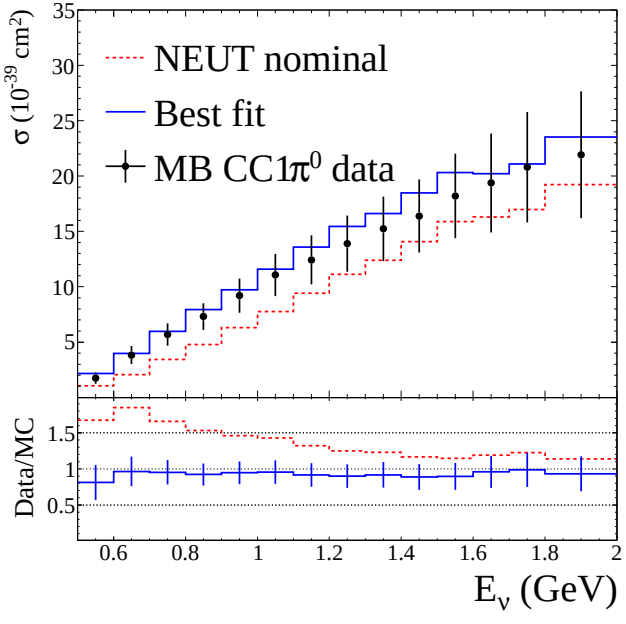
- Resonant π^0
- Resonant π^+
- Coherent
- Quasielastic
- Multi-π
- Other

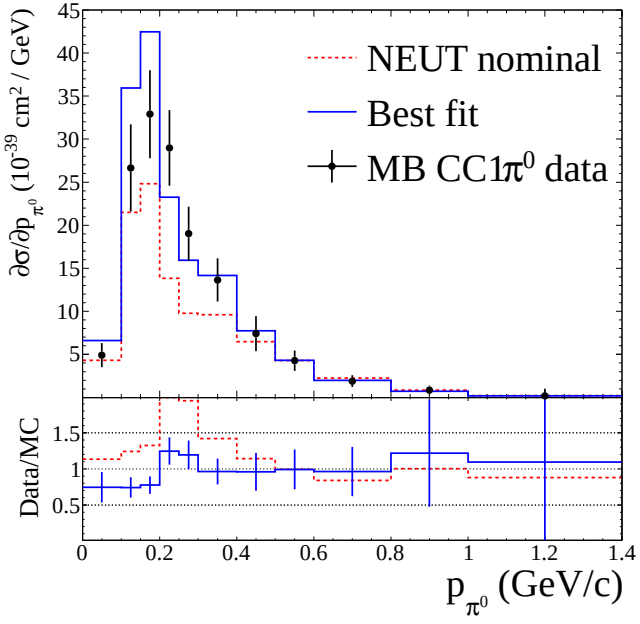
MB CC1π^0 best fit

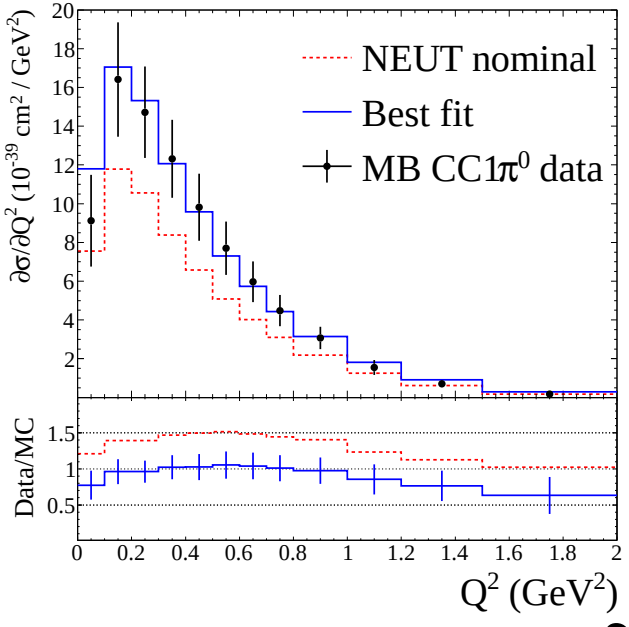




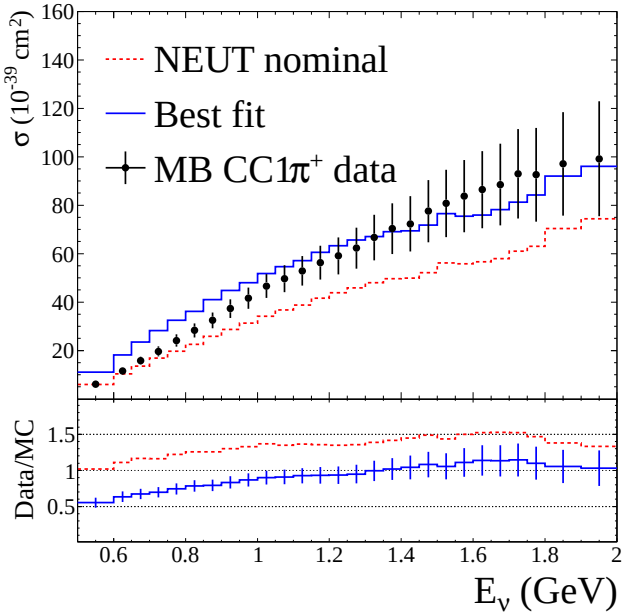


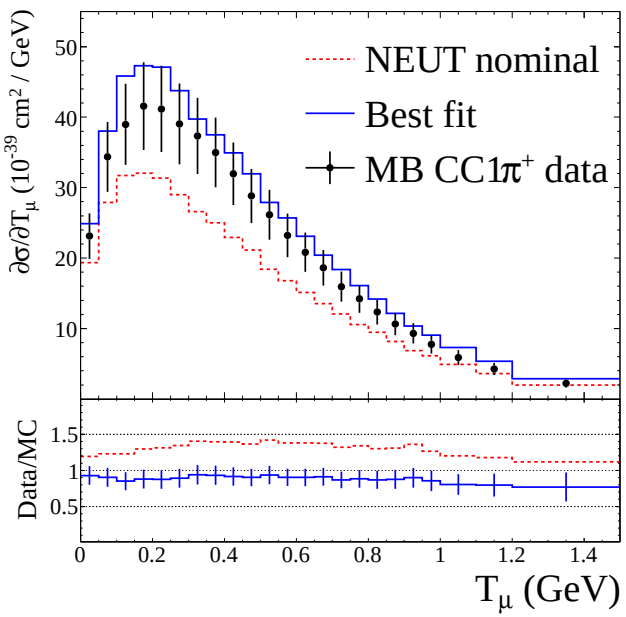


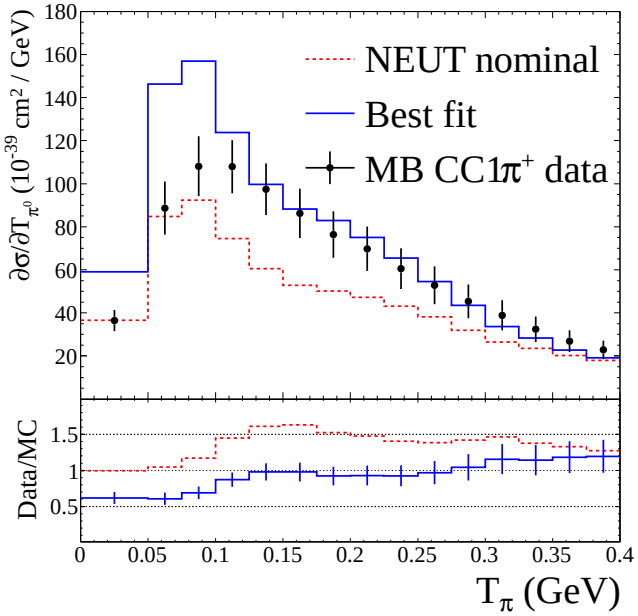




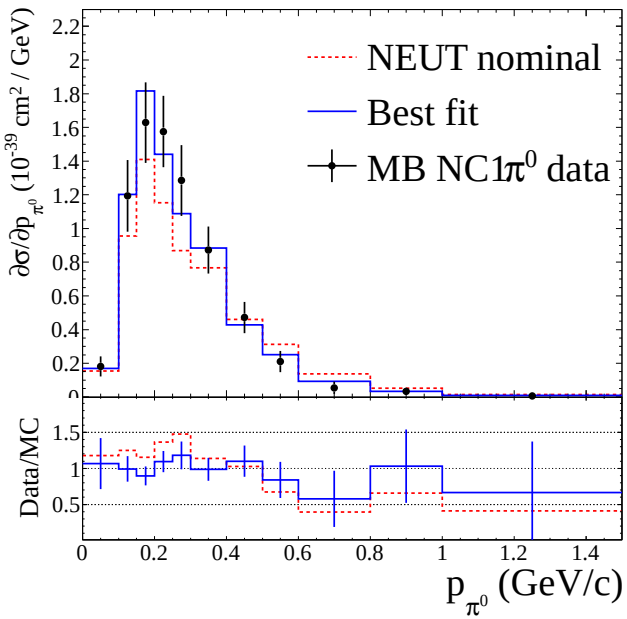
MB CC1π^+ best fit

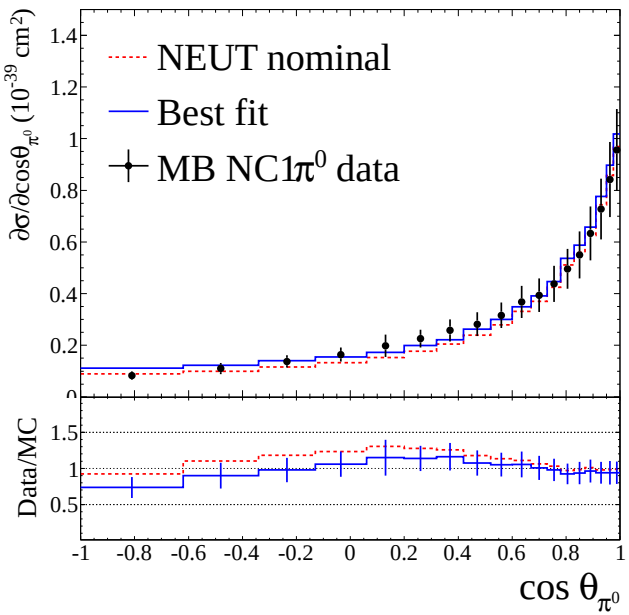




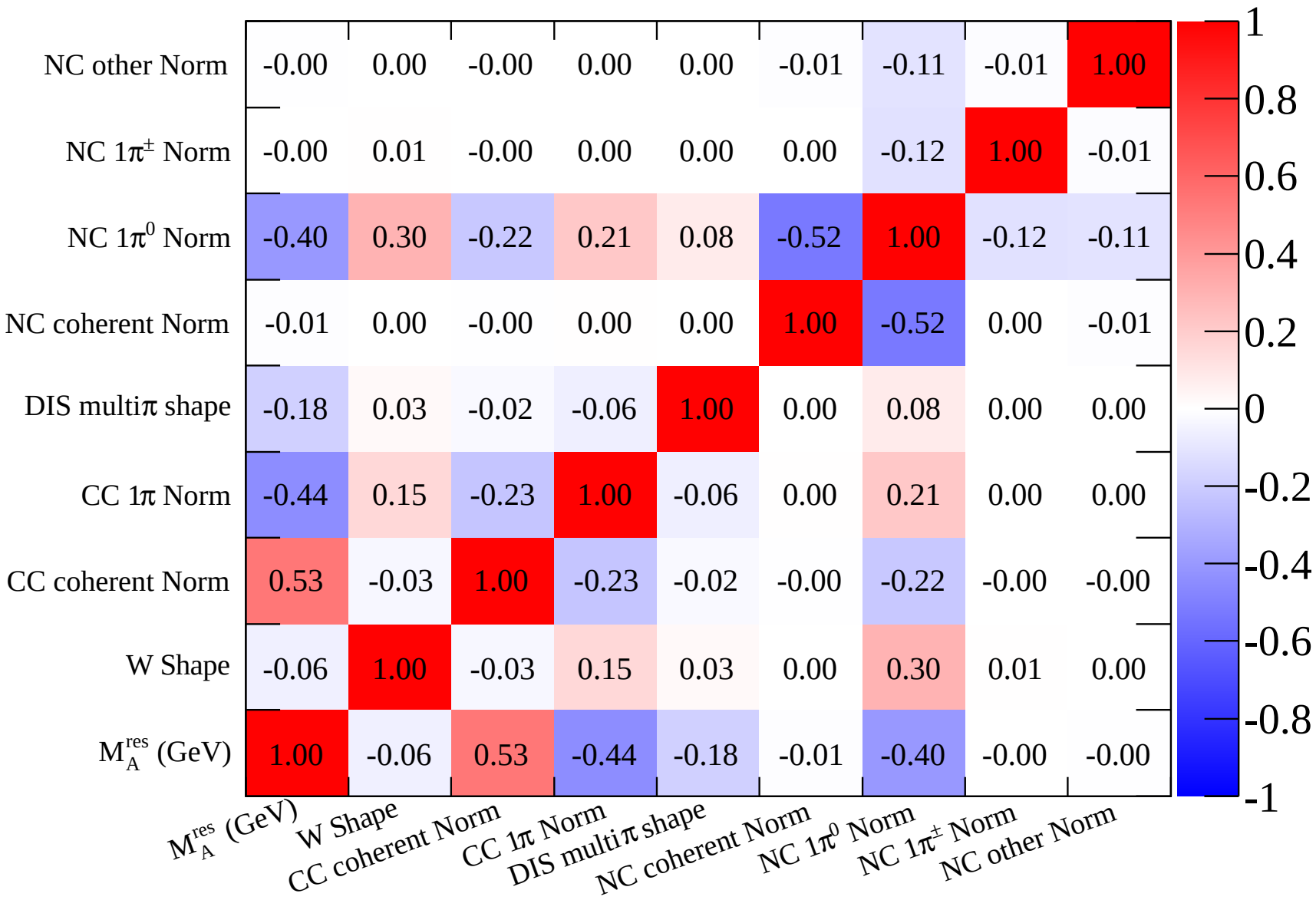


MB NC1π^0 best fit

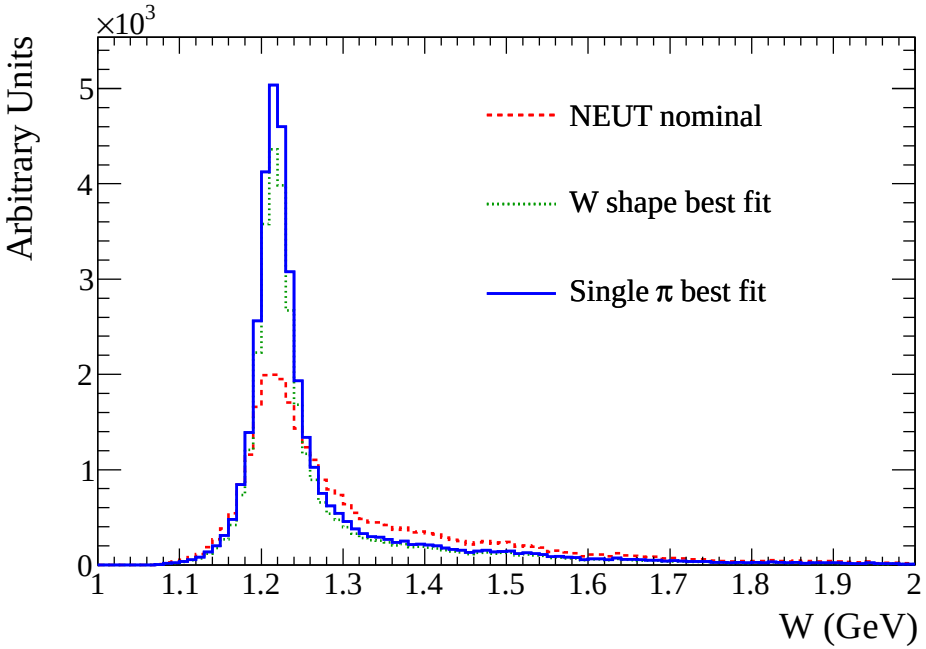


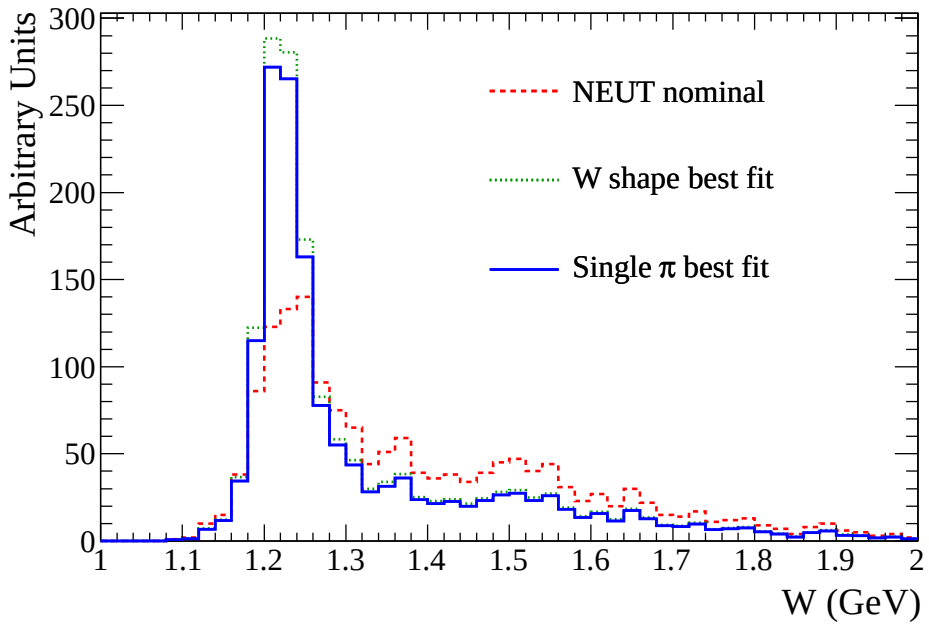


Single-π correlation matrix



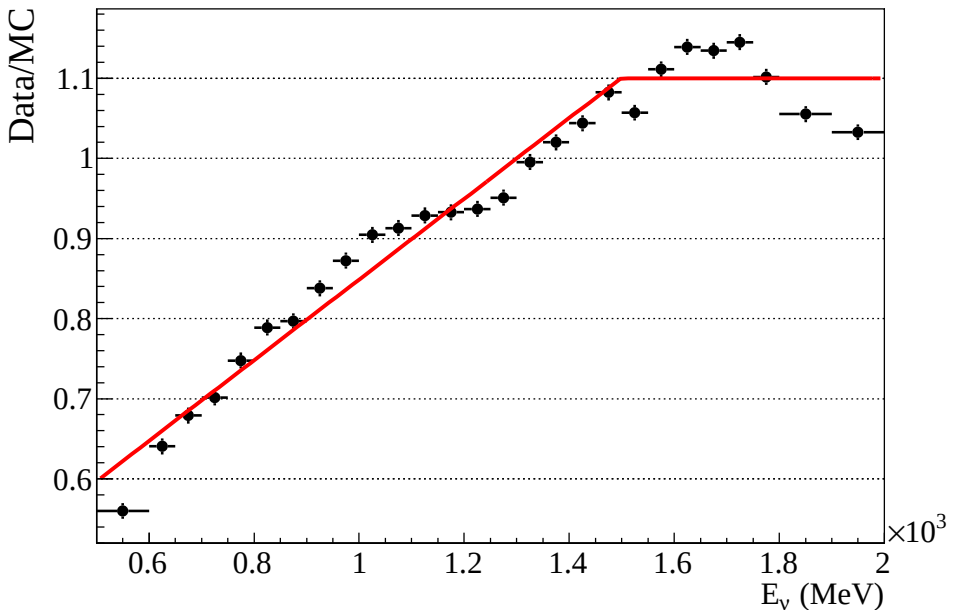
Effect of W shape on W distribution





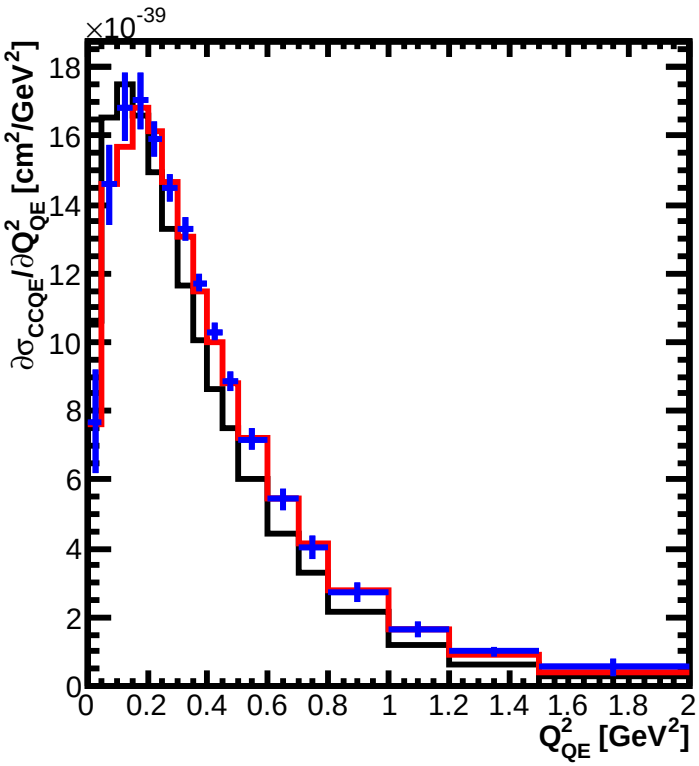
- Green is W shape parameter set to best fit value, others nominal
- Blue is all parameters at best fit

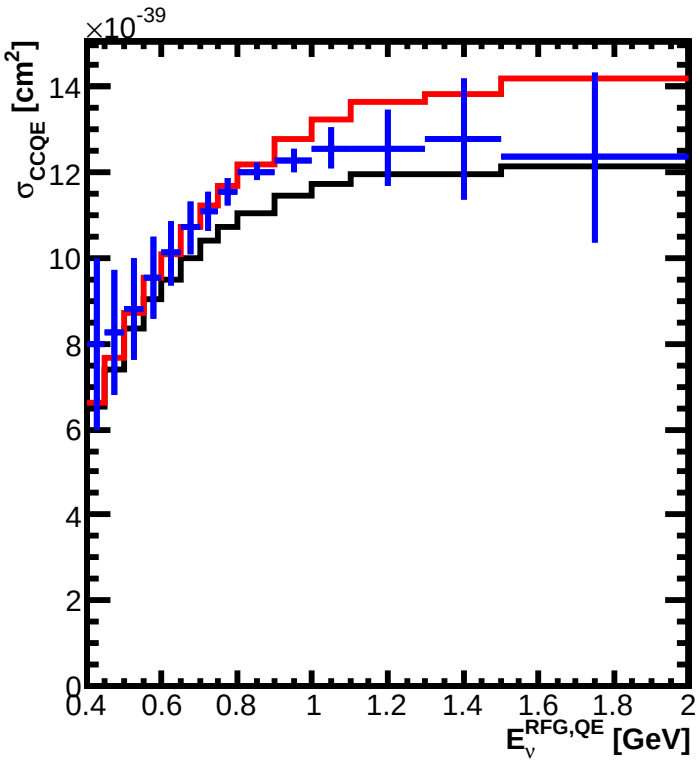
CC1π^+ E_ν shape correction



- Add difference between nominal and reweighted to ND covariance matrix

CCQE fit with FG params





NEUT nominal NEUT best fit MB CCQE data

$$M_A^{QE} = 1.45 \pm 0.05 \text{ GeV}$$

$$\text{CCQE Normalization} = 0.94 \pm 0.03$$

$$p_F = 261 \pm 13 \text{ MeV}$$

$$E_b = 24 \pm 4 \text{ MeV}$$

$$\chi^2_{\text{min}}/\text{dof} = 19.7/135$$

Parameter categories

1. Correlated between ND280 and SK; constrained by ND280 data and propagated to SK
2. Uncorrelated between ND280 and SK, therefore unconstrained by ND280 data and marginalized in the BANFF fit (not propagated to SK)
3. Correlated between ND280 and SK, but with a weak constraint by ND280 data and thus to be marginalized in the BANFF fit (not propagated to SK)

Parameters in osc ana: ND

Parameter	E_ν Range	Nominal	Error	CCQE	CCnQE	Total	Cat.
M_A^{QE}	all	1.21 GeV/c^2	0.45	15.5%	5.2%	10.5%	1
CCQE E1	$0 < E_\nu < 1.5$	1.0	0.11	6.7%	1.5%	4.2%	1
CCQE E2	$1.5 < E_\nu < 3.5$	1.0	0.30	6.7%	1.5%	4.2%	3
CCQE E3	$E_\nu > 3.5$	1.0	0.30	6.7%	1.5%	4.2%	3
p_F ^{12}C	all	217 MeV/c	30	1.6%	0.2%	0.8%	2
SF ^{12}C	all	0 (off)	1 (on)	0.9%	0.8%	0.6%	B/2
M_A^{RES}	all	1.16 GeV/c^2	0.11	3.7%	6.0%	4.8%	1
CC1π E1	$0 < E_\nu < 2.5$	1.63	0.43	3.7%	6.0%	4.8%	1
NC1π^0	all	1.19	0.43	3.7%	6.0%	4.8%	1
CC1π E2	$E_\nu > 2.5$	1.0	0.40	1.9%	4.8%	3.2%	3
CC Coherent	all	1.0	1.0	1.7%	3.9%	2.7%	3
CC Oth shp	all	0.0	0.40	0.7%	3.5%	2.0%	3
NC Other	all	1.0	0.30	0.5%	1.6%	1.0%	3
W Shape	all	87.7 MeV/c^2	45.3	0.6%	2.2%	0.9%	3
FSI	all	Section **??**		0.5%	0.7%	0.2%	3
Total				17.0%	10.1%	12.8%	

Parameters in osc ana: SK

Parameter	E_ν Range	Nominal	Error	ν_μ	ν_e Sig+Bkg	ν_e Bkg	Cat.
M_A^{QE}	all	1.21 GeV/c^2	0.45		18.7%	10.6%	1
CCQE E1	$0 < E_\nu < 1.5$	1.0	0.11		7.8%	4.6%	1
CCQE E2	$1.5 < E_\nu < 3.5$	1.0	0.30		Negligible		3
CCQE E3	$E_\nu > 3.5$	1.0	0.30		Negligible		3
p_F ^{16}O	all	225 MeV/c	30		0.1%	0.3%	2
SF ^{16}O	all	0 (off)	1 (on)		5.4%	3.1%	2
M_A^{RES}	all	1.16 GeV/c^2	0.11		2.3%	4.7%	1
CC1π E1	$0 < E_\nu < 2.5$	1.63	0.43		5.5%	5.3%	1
NC1π^0	all	1.19	0.43		2.4%	8.1%	1
CC1π E2	$E_\nu > 2.5$	1.0	0.40		Negligible		3
CC Coherent	all	1.0	1.0		0.2%	0.2%	3
CC Oth shp	all	0.0	0.40		0.1%	0.2%	3
NC Coherent	all	1.0	0.30		0.6%	2.1%	3
NC Other	all	1.0	0.30		0.8%	2.6%	3
W Shape	all	87.7 MeV/c^2	45.3		0.9%	2.0%	3
CC ν_e	all	1.0	0.03		2.6%	1.8%	3
PDD	all	0.2	0.2		3.5%	0.5%	3
1π E_ν shp	all	0 (off)	0.5		2.2%	2.5%	3
FSI (SK)	all	Section **??**			2.4%	3.1%	3
Total							