Systematics for Oscillation Analyses at T2K

Asher Kaboth
for the T2K Collaboration

NuFact 2013, 20 August 2013

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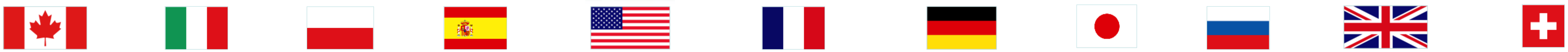
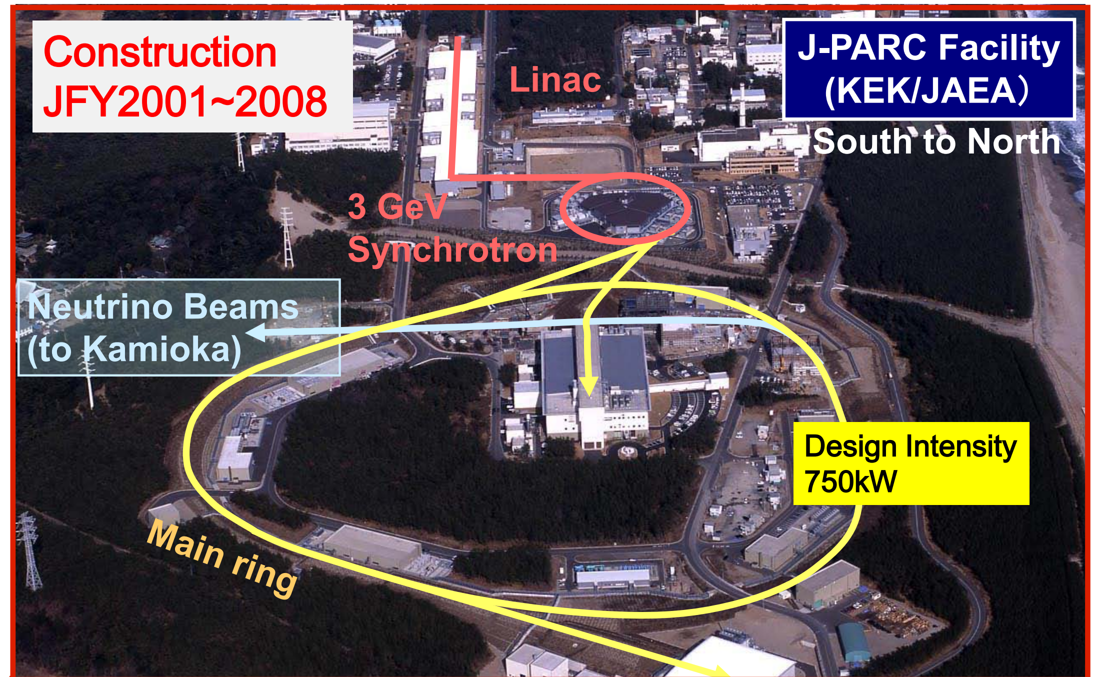
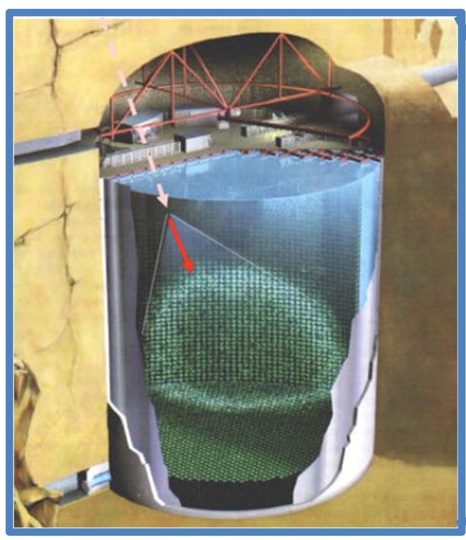
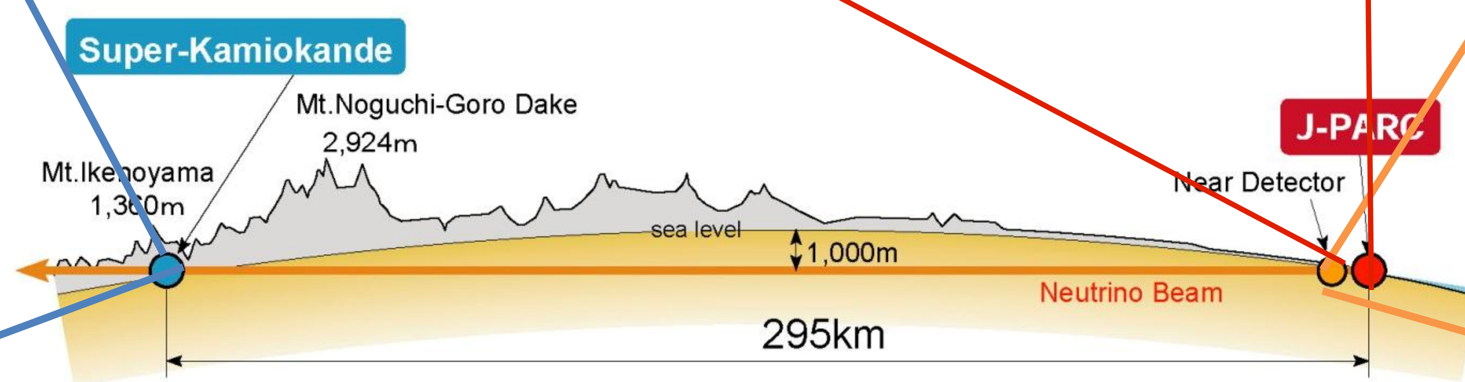
T2K

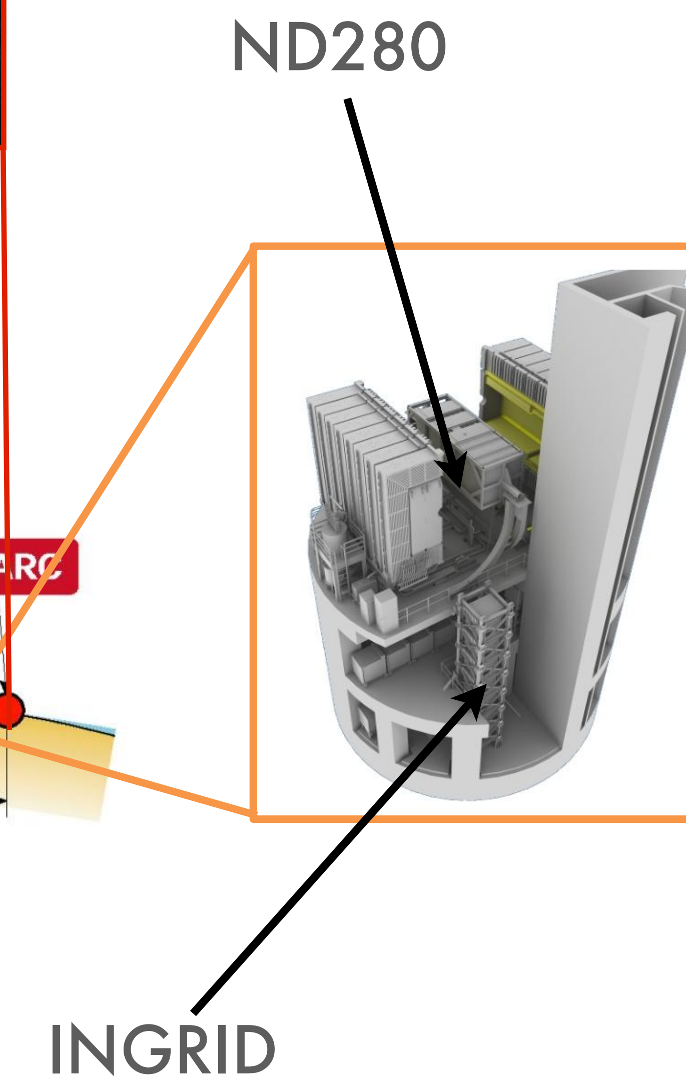


11 countries
59 institutions
~500 people









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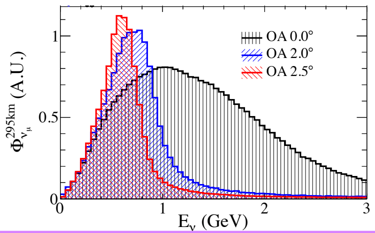
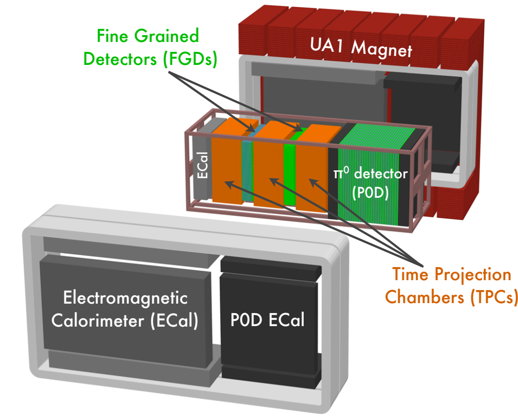


NA61/SHINE Data → Flux Model

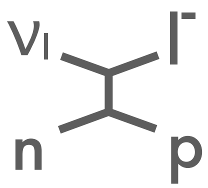
INGRID/Beam Monitor Data → Flux Model

ND280 Detector Model

ND280 Data



External Cross Section Data → Cross Section Model

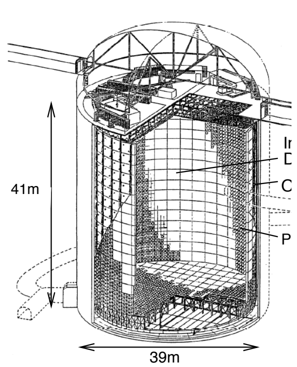


Flux Model, ND280 Detector Model, ND280 Data, Cross Section Model → ND280 Fit

Use data to drive constraints as much as possible

ND280 Fit → ND280 Covariance Matrix

SK Detector Model



SK Data

ND280 Covariance Matrix, SK Detector Model, Cross Section Model, SK Data → Oscillation Fit

Oscillation Fit → Oscillation Parameters

See M. Friend's talk

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Oscillation Analysis Systematic Uncertainties

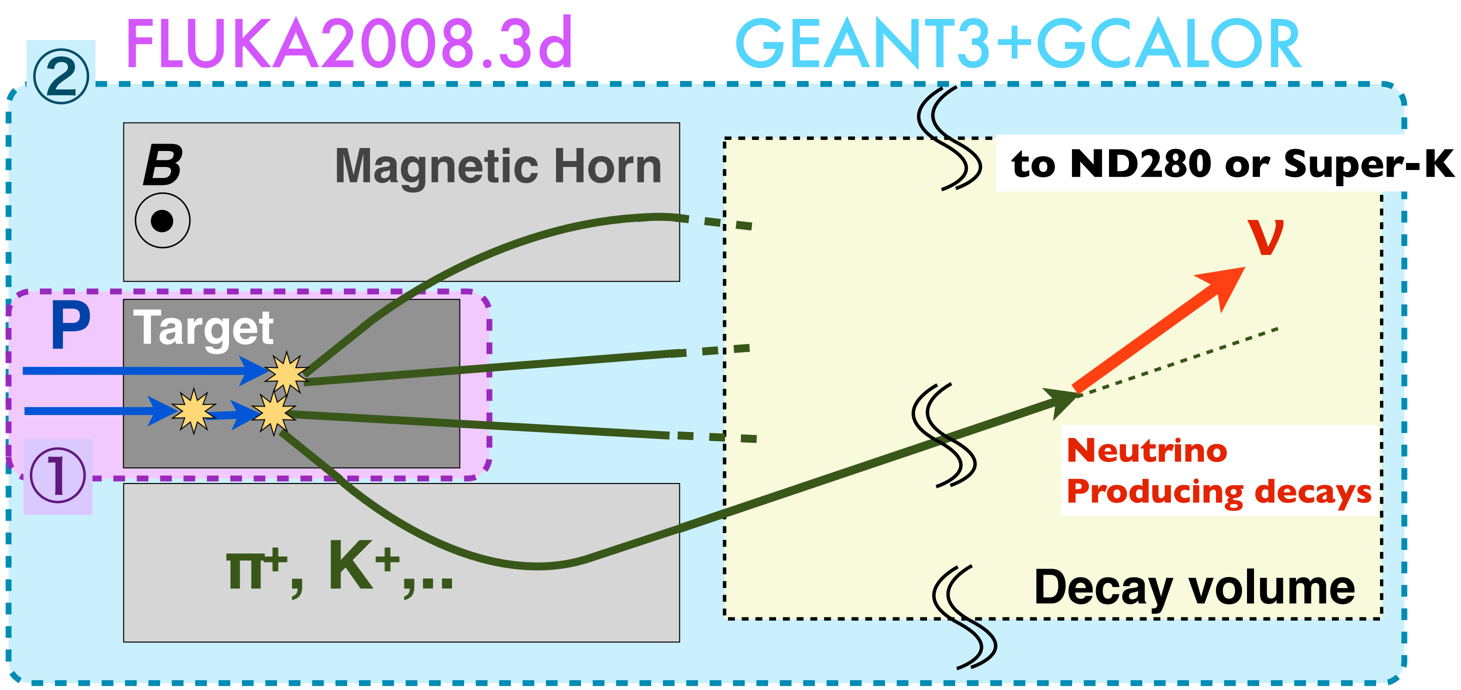
Error source	$\sin^2 2\theta_{13} = 0.1$ w/o ND280 fit	$\sin^2 2\theta_{13} = 0.1$ w/ ND280 fit
Beam only	11.6	7.5
M_A^{QE}	21.5	3.2
M_A^{RES}	3.3	0.9
CCQE norm. ($E_\nu < 1.5$ GeV)	9.3	6.3
CC1π norm. ($E_\nu < 2.5$ GeV)	4.2	2.0
NC1π^0 norm.	0.6	0.4
CC other shape	0.1	0.1
Spectral Function	6.0	6.0
p_F	0.1	0.1
CC coh. norm.	0.3	0.2
NC coh. norm.	0.3	0.2
NC other norm.	0.5	0.5
$\sigma_{\nu_e}/\sigma_{\nu_\mu}$	2.9	2.9
W shape	0.2	0.2
pion-less Δ decay	3.7	3.5
SK detector eff.	2.4	2.4
FSI	2.3	2.3
PN	0.8	0.8
SK momentum scale	0.6	0.6
Total	28.1	8.8

From ND280 (Beam only through NC1π^0 norm.) — Correlated

SK only (CC other shape onward) — Uncorrelated

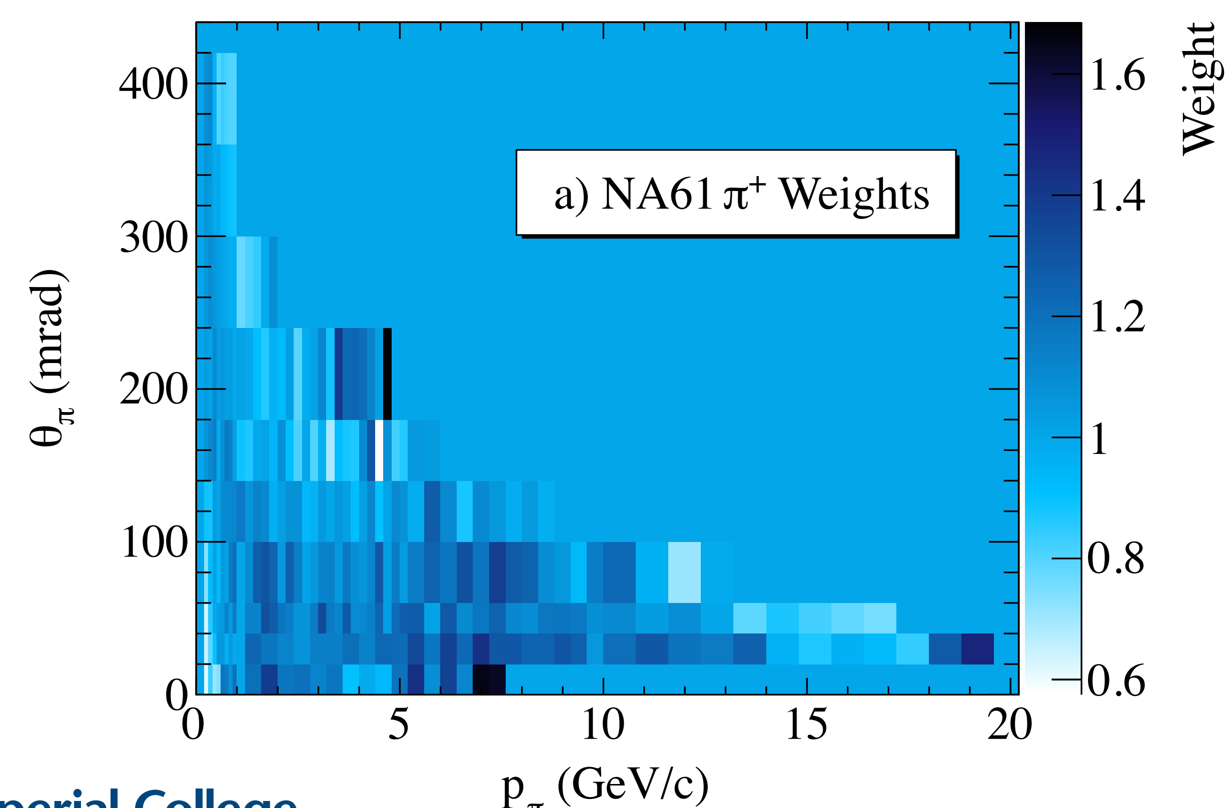
units: percentage error on N_{SK}

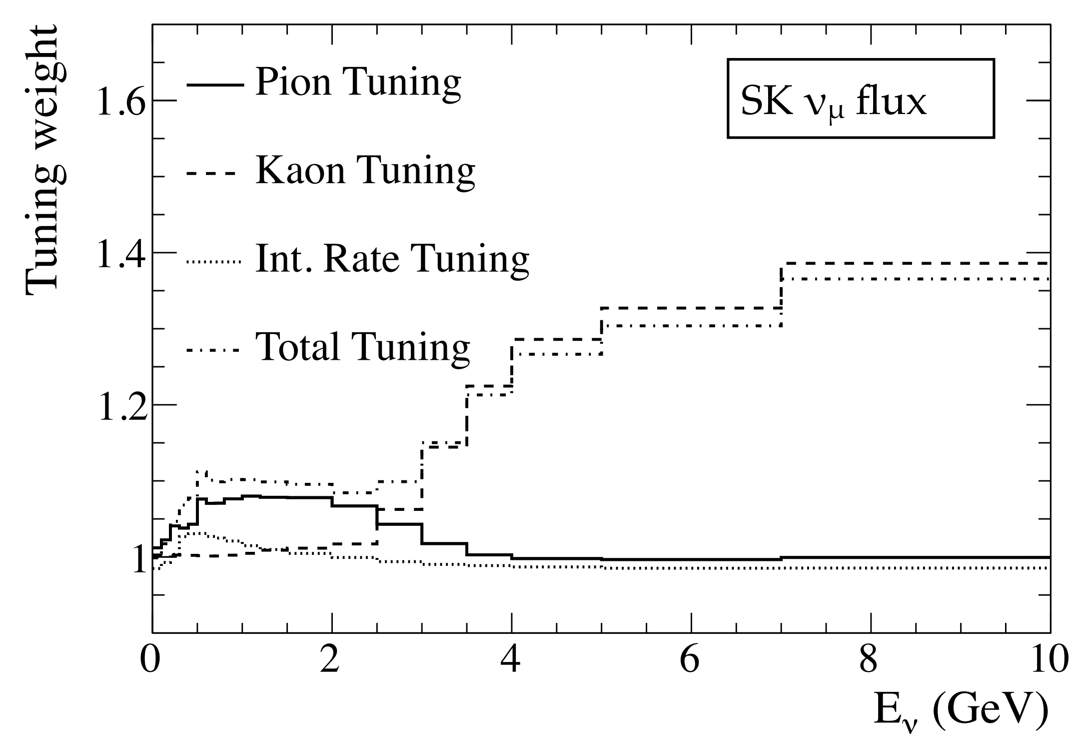
Flux Simulation



Use NA61/SHINE data for π, K production to tune simulation

Phys.Rev.C 84, 034604 (2011)
Phys.Rev.C 85, 035210 (2012)

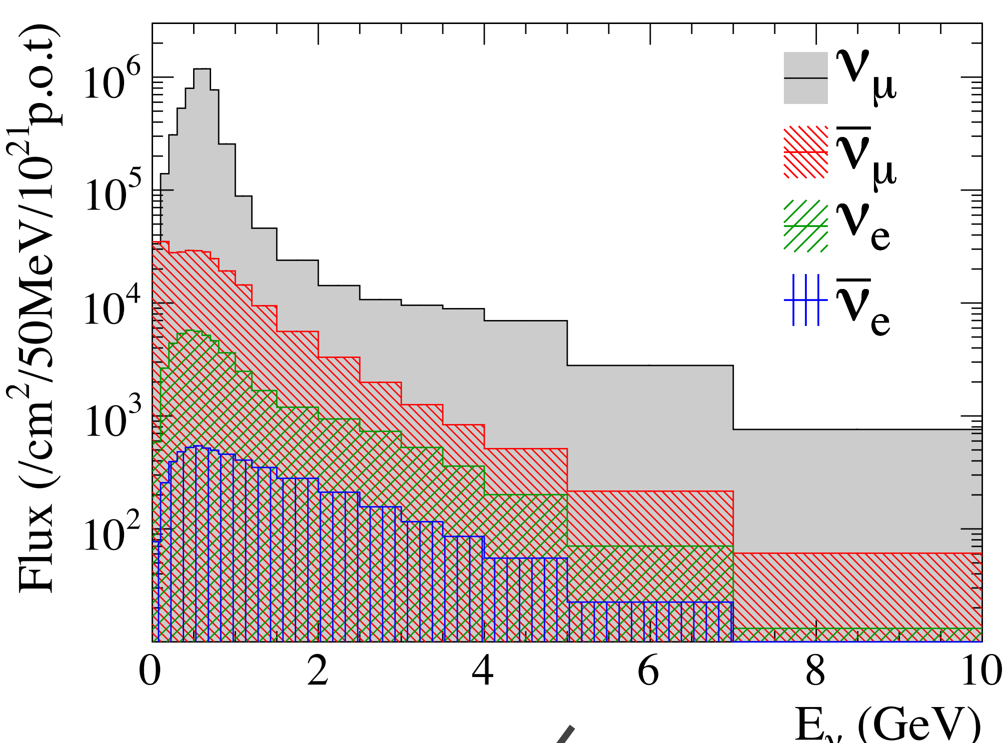




Flux

Category	$\sin^2 2\theta_{13}$=0.0	$\sin^2 2\theta_{13}$=0.1
$\nu_\mu \rightarrow \nu_e$ signal	0.4	17.36
ν_e background	3.26	3.02
ν_μ background	1.05	1.05
$\overline{\nu}_\mu$ background	0.06	0.06
$\overline{\nu}_e$ background	0.16	0.15
Total	4.93	21.64

Far detector flux



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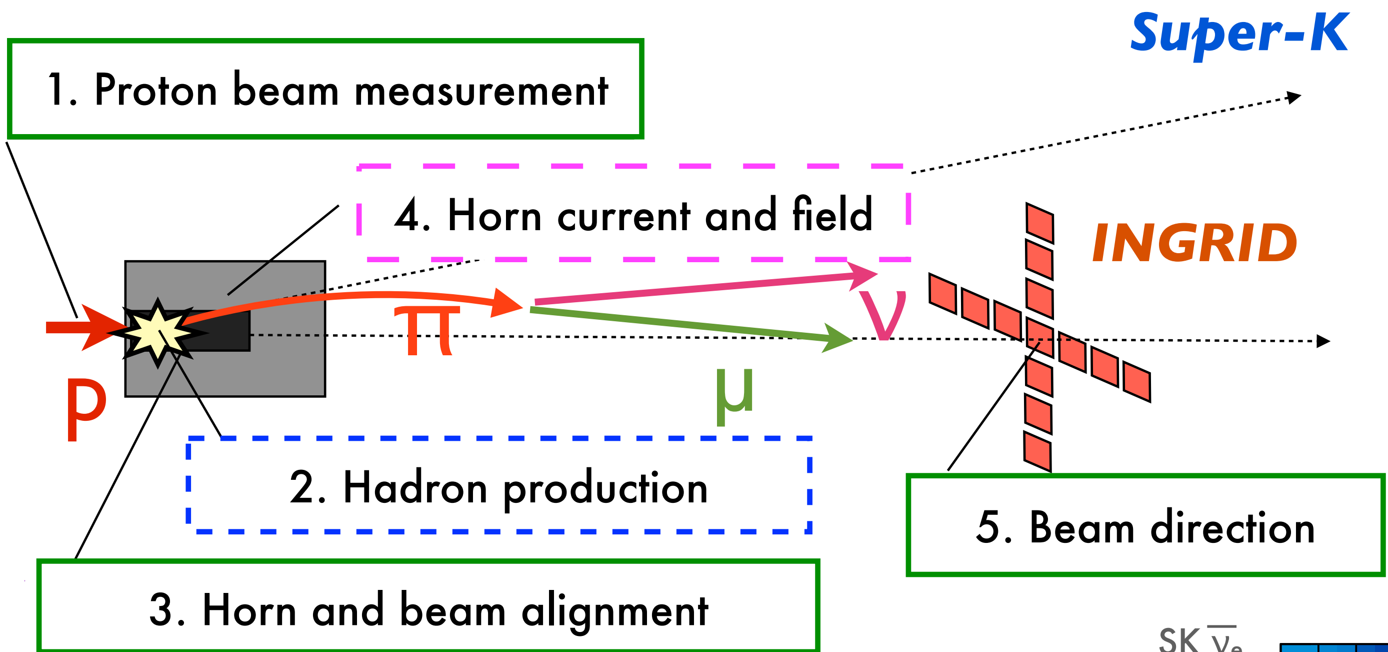
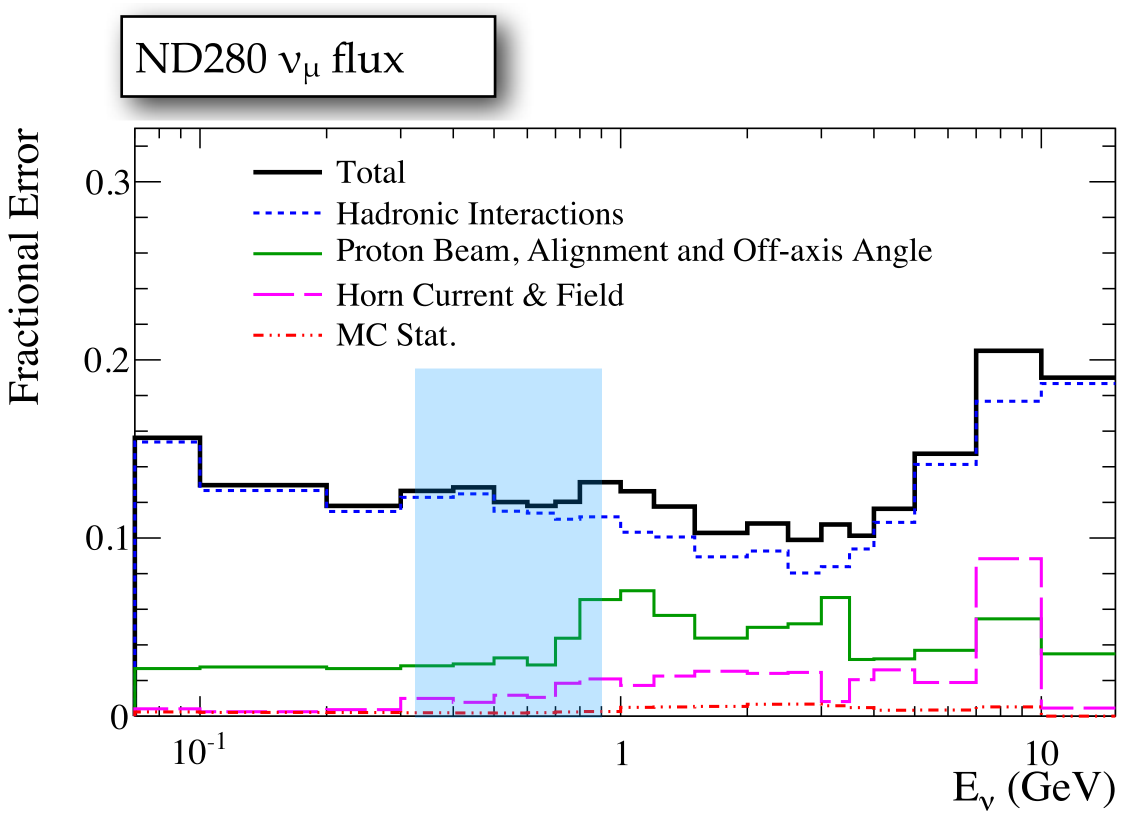
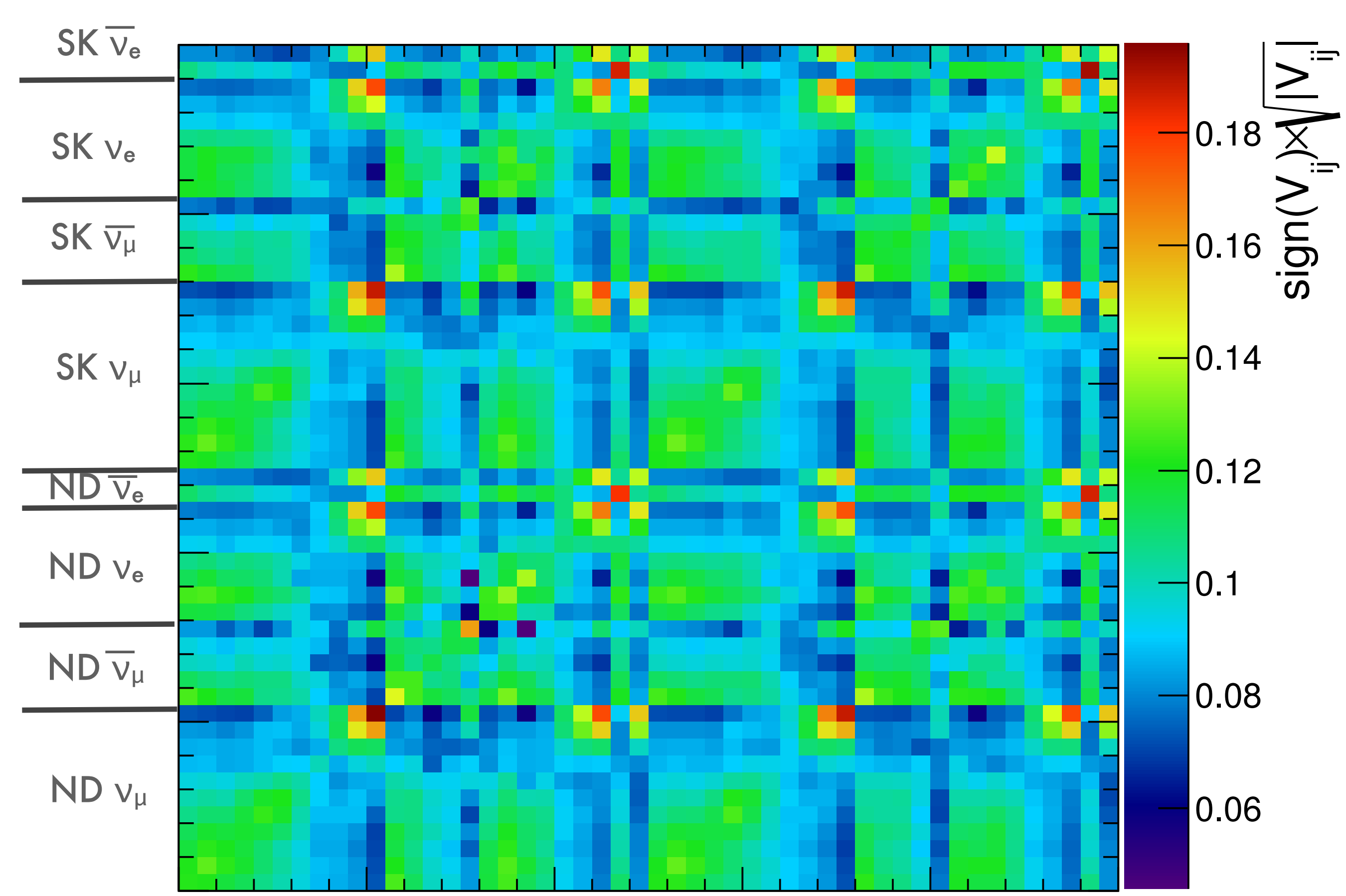
Flux Systematic



Consider 5 sources of systematic uncertainty

Generate covariance matrix for near-far effects

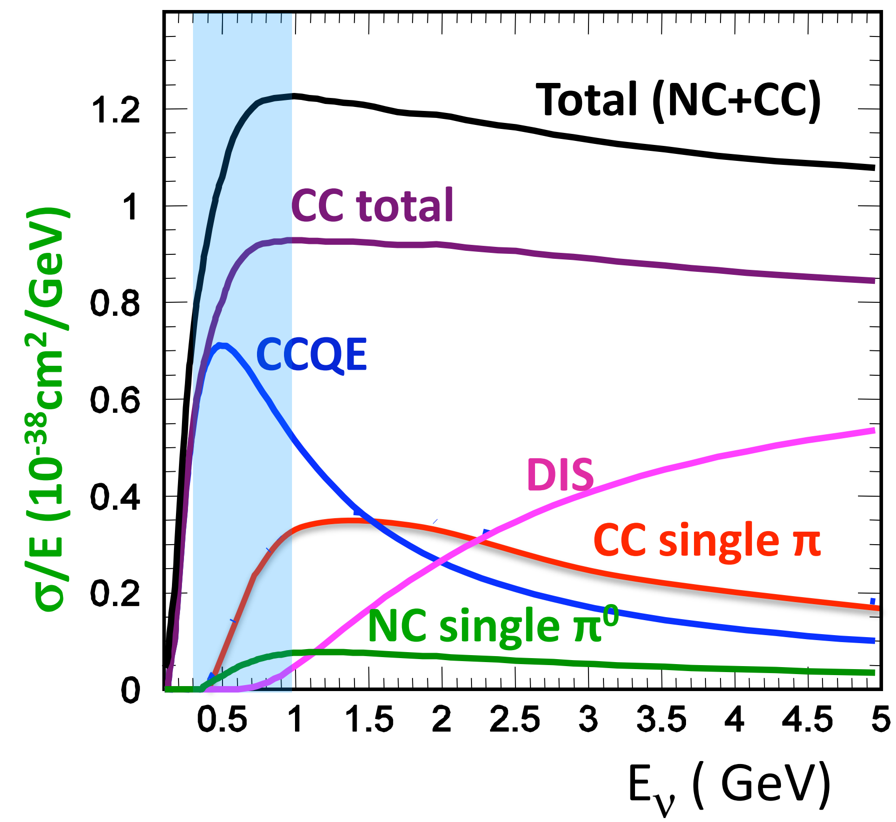




Cross Section Model

(NEUT/GENIE)

- Charged Current Quasi-Elastic (CCQE)
  - Llewellyn-Smith base model
  - Smith-Moniz fermi gas model for nucleus
- Single Pion Production (CC/NC1π) with Rein-Seghal resonance model
- Deep Inelastic Scattering (DIS) and Charged Current multi-π
  - GRV98 PDF
  - Bodek-Yang correction
- Final State Interactions (FSI)
  - Cascade model—track secondary particles until they exit the nucleus
  - Separate models used for low (<500 MeV) and high momentum



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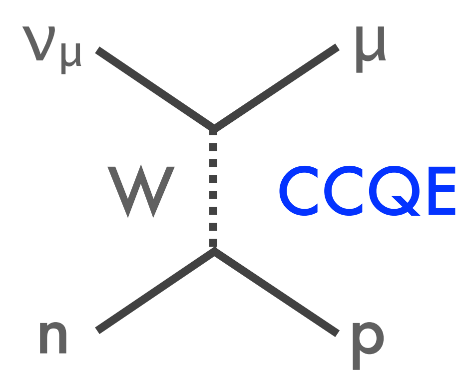

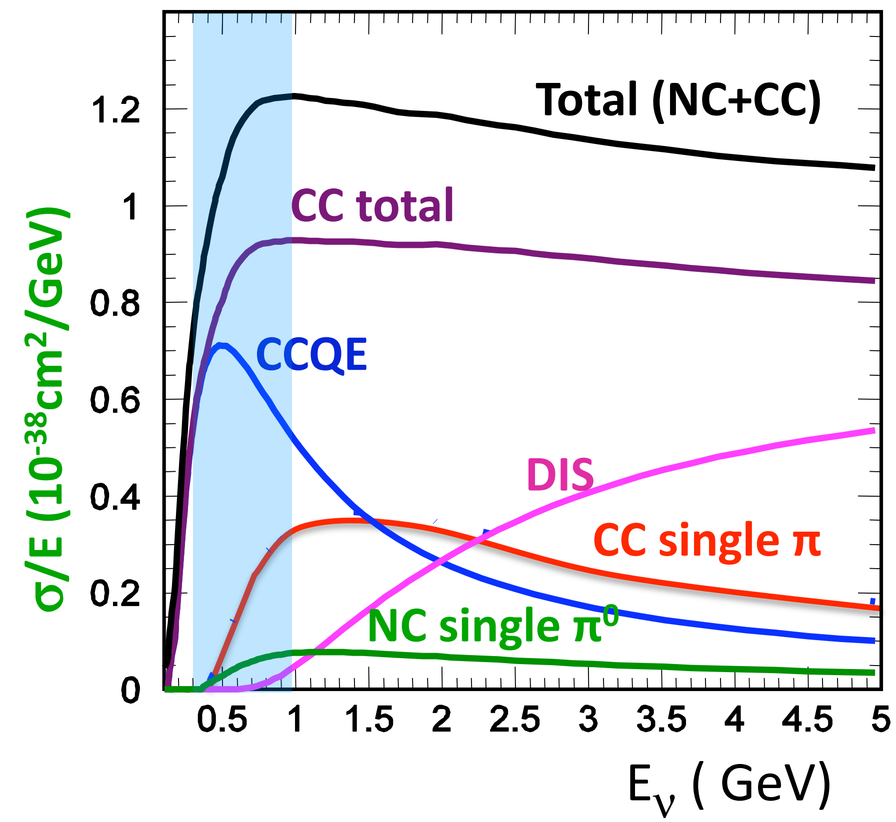

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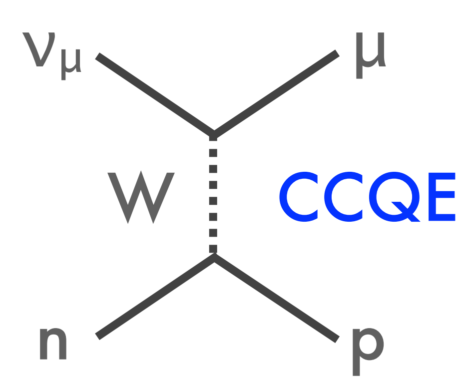

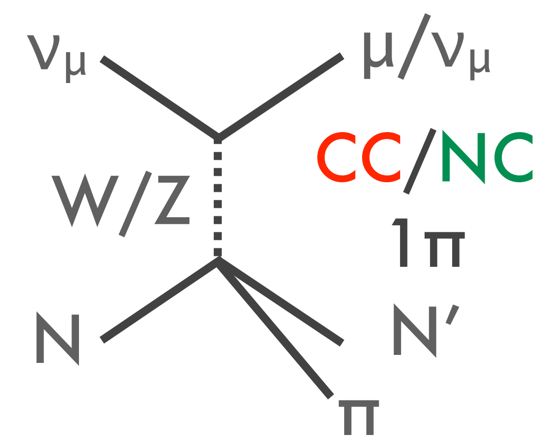

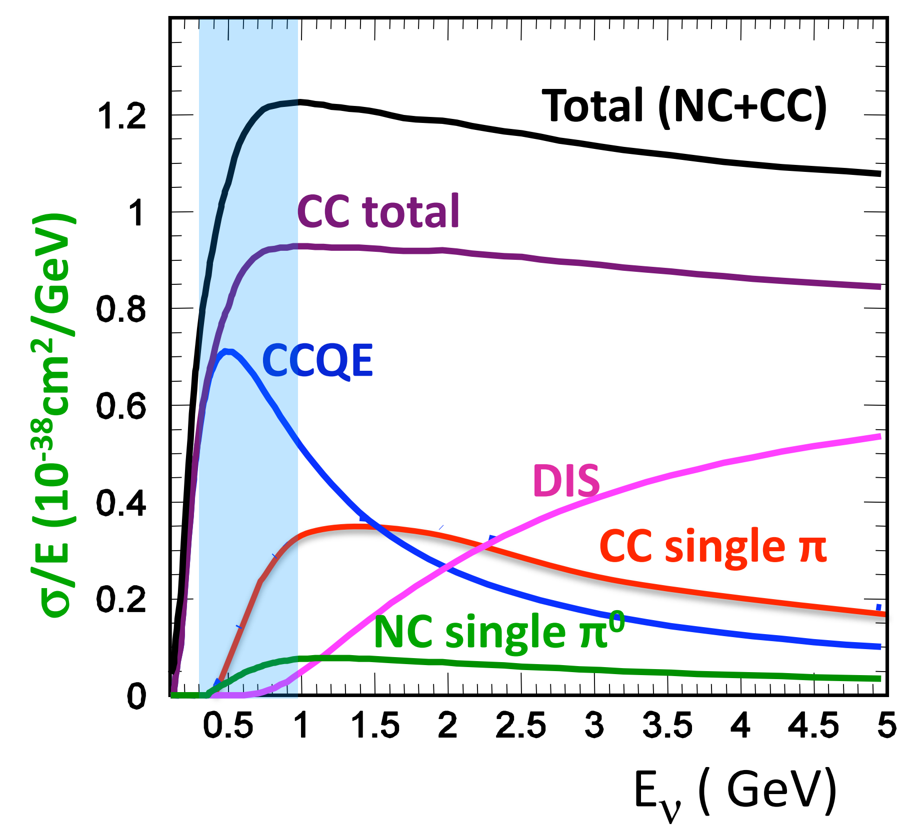

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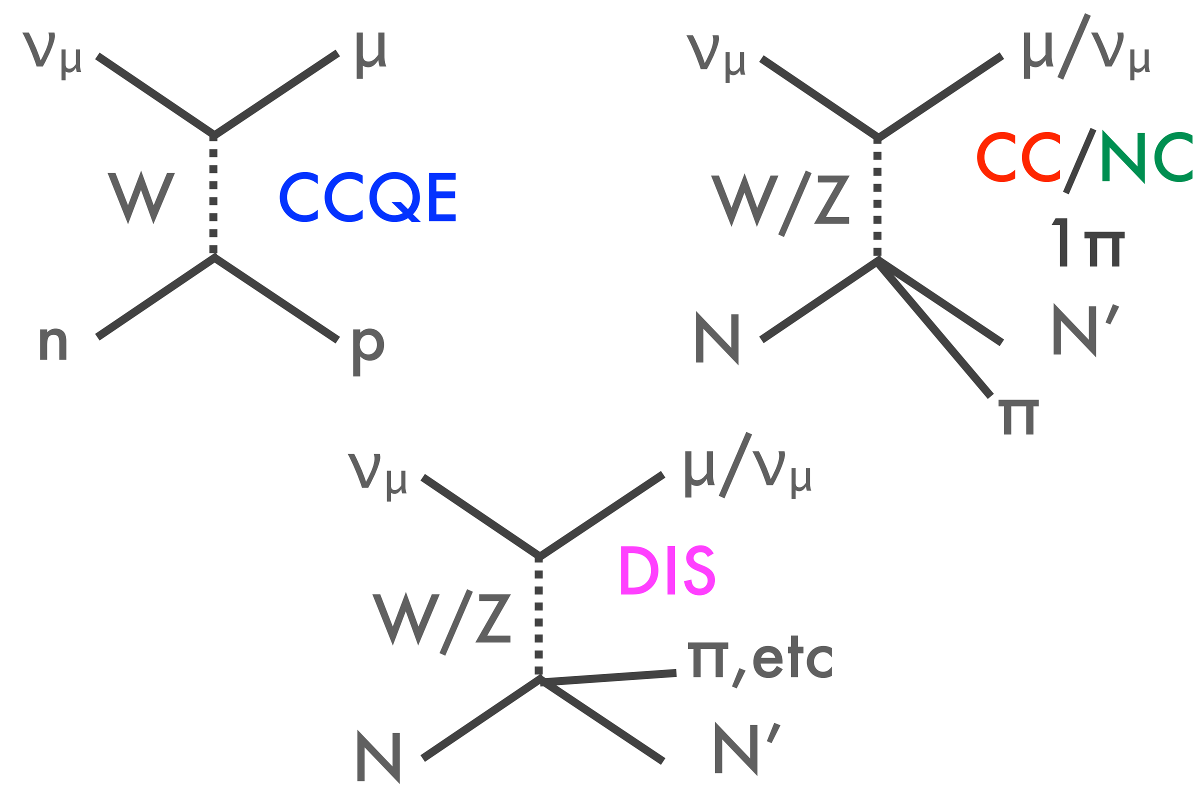
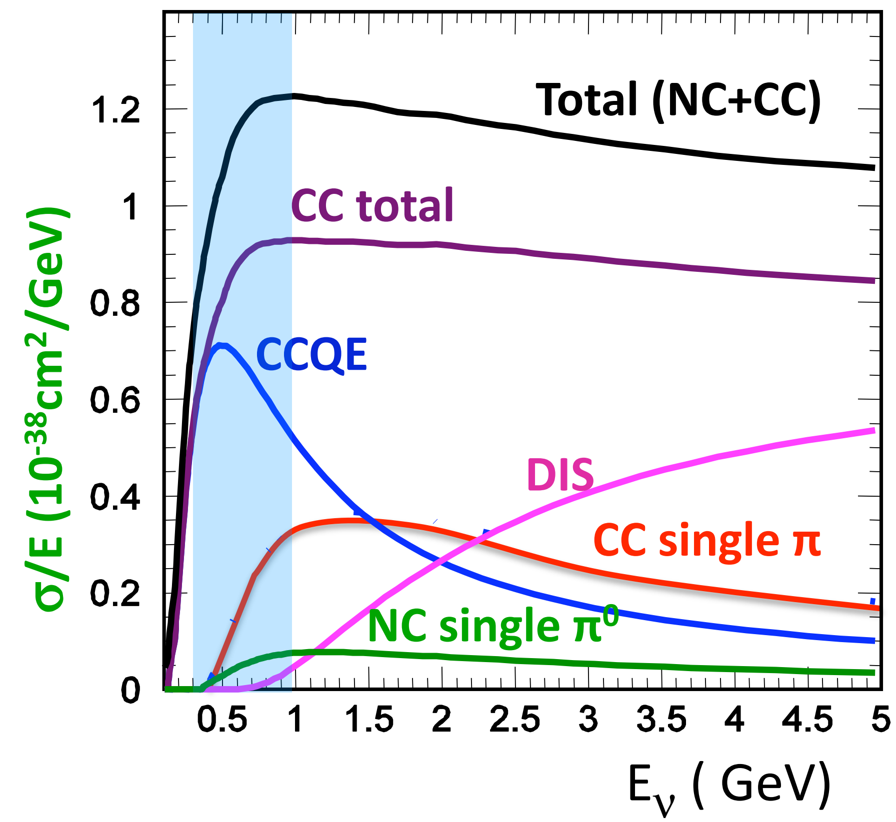
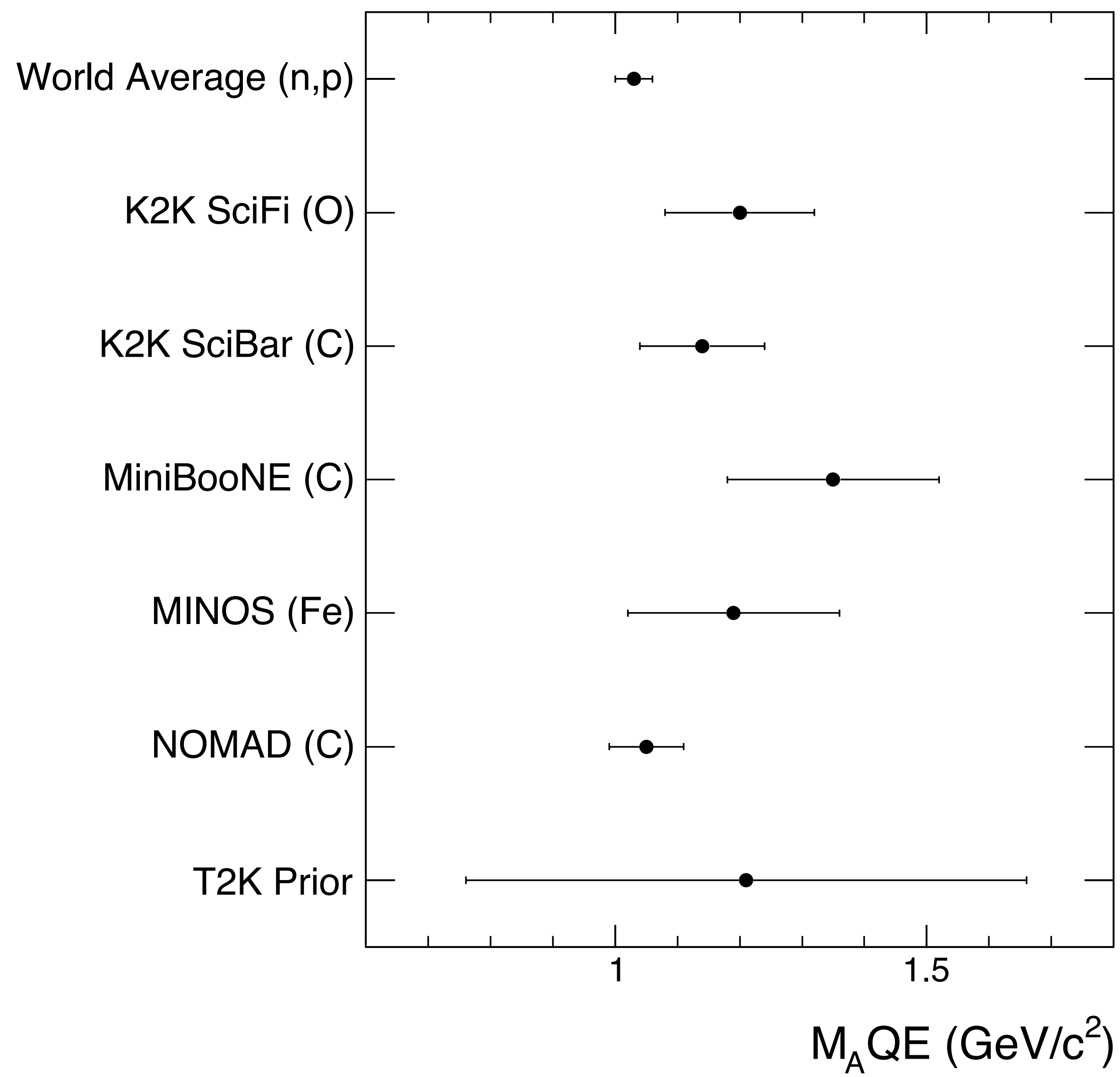




Cross Section Systematic Parameters

Parameter	Type	Interaction Type
$M_A QE$	axial mass	CCQE
$M_A RES$	axial mass	1π
CCQE (3)	normalization	CCQE
CC1π (2)	normalization	CC1π
$NC\pi^0$	normalization	NC1π
p_f	fermi momentum	CCQE/RFG
E_b	binding energy	CCQE/RFG
spectral function	model comparison	CCQE/SF



Also allow normalizations in three energy bins to allow for systematic error on shape variations

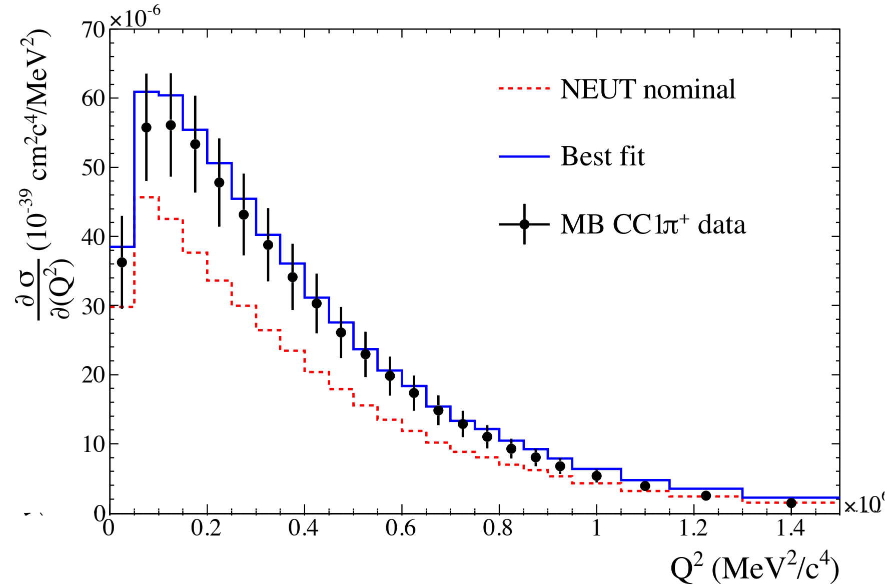
Cross Section Systematic Parameters

Parameter	Type	Interaction Type
M_AQE	axial mass	CCQE
M_ARES	axial mass	1π
CCQE (3)	normalization	CCQE
CC1π (2)	normalization	CC1π
NCπ^0	normalization	NC1π
p_f	fermi momentum	CCQE/RFG
E_b	binding energy	CCQE/RFG
spectral function	model comparison	CCQE/SF

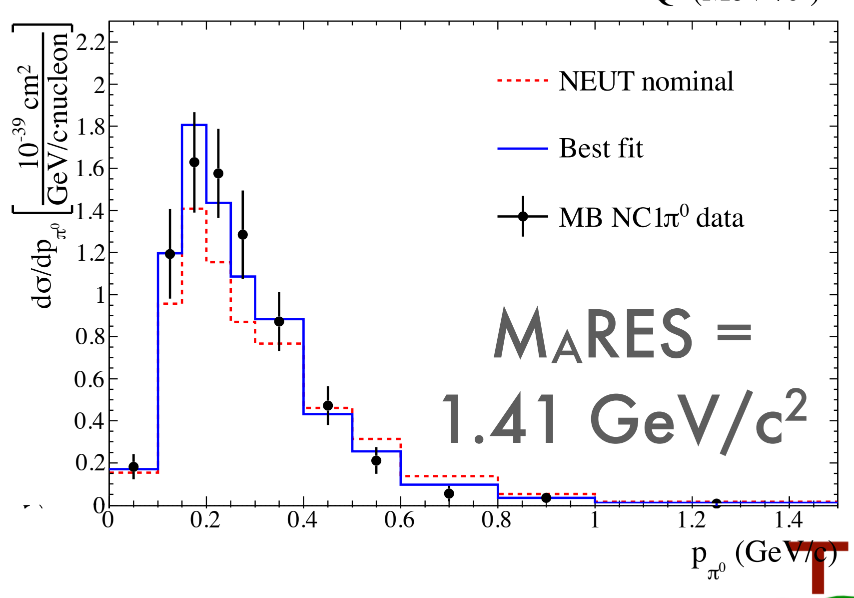
Use MiniBooNE 1π data (CC and NC) and fit to NEUT predictions to generate input value

Add ad hoc parameters to improve the fit, but break internal theoretical purity

CCπ$^+$



NCπ^0



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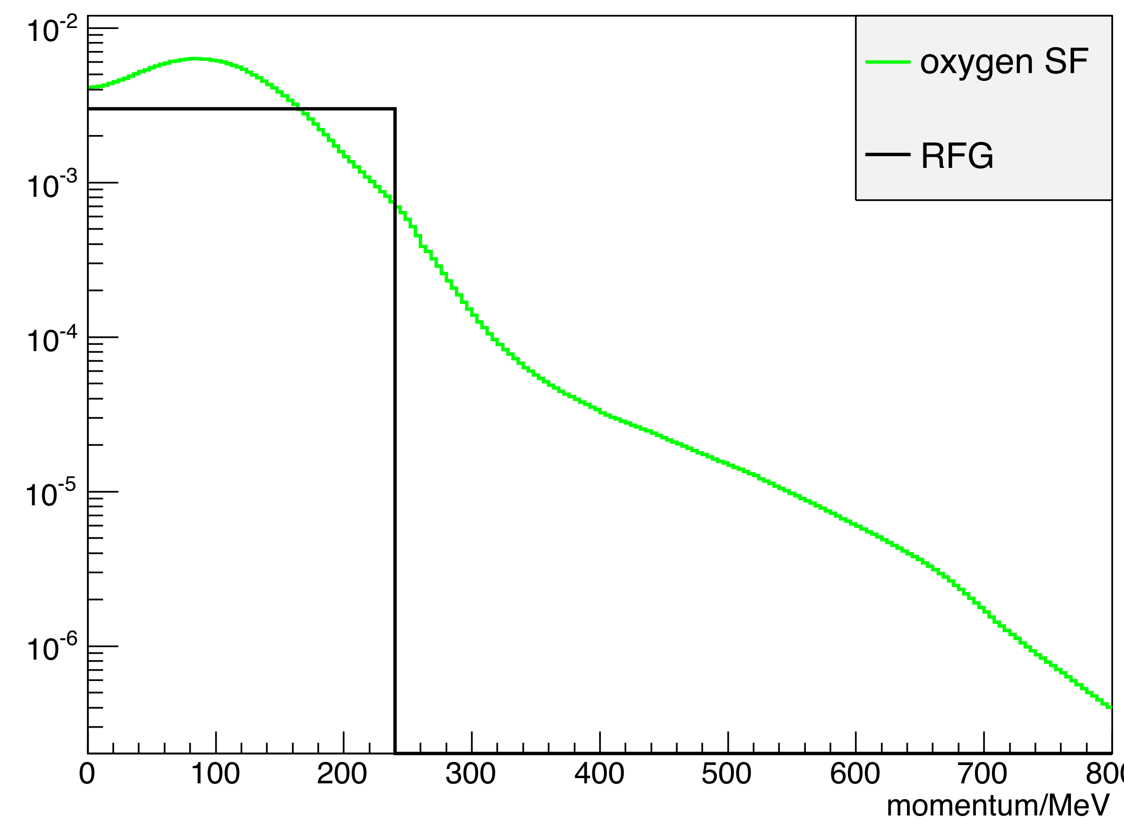
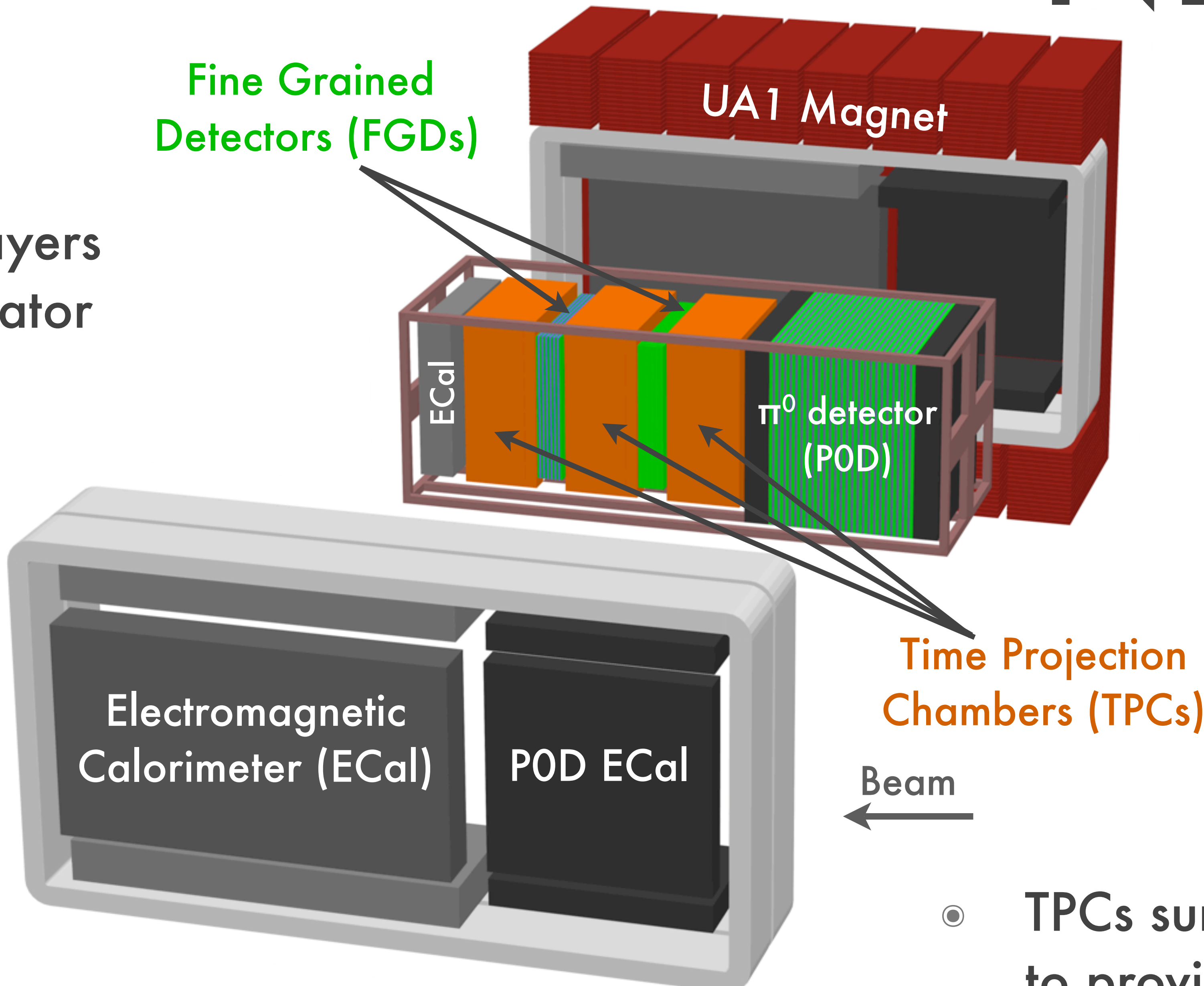
spectral function	model comparison	CCQE/SF



ND280

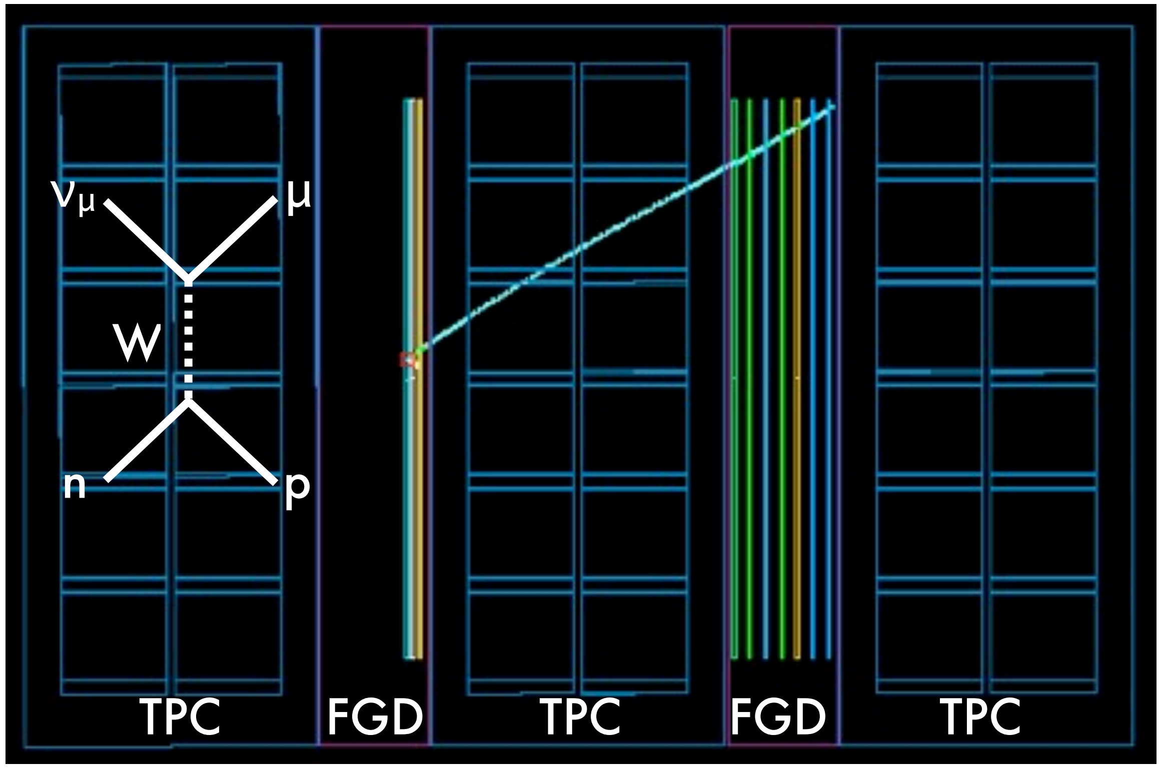
- FGDs are primary targets for interactions on carbon
- Composed of layers of plastic scintillator read out with MPPCs



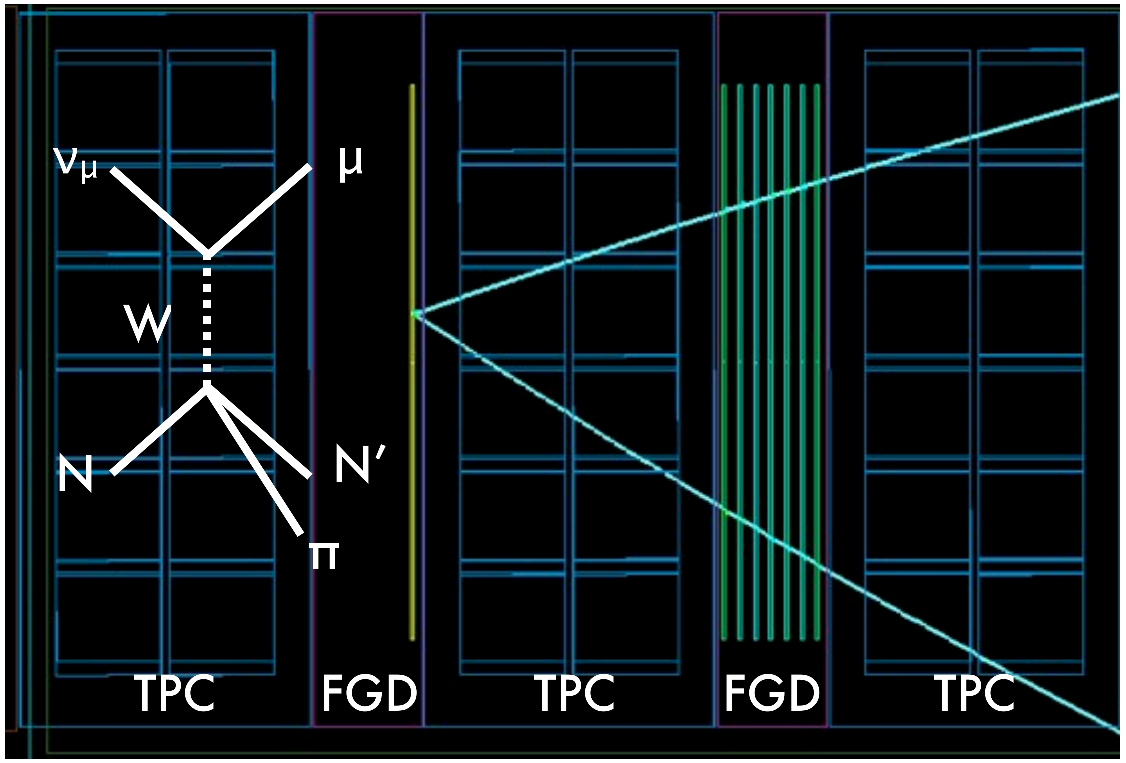
- UA1 magnet provides 0.2T field for momentum field determination
- Particle identification through dE/dx in TPCs, FGDs

- TPCs surround FGDs to provide precise determination of track properties
- Ar (95%), CF_4 (3%), iC_4H_{10} (2%)

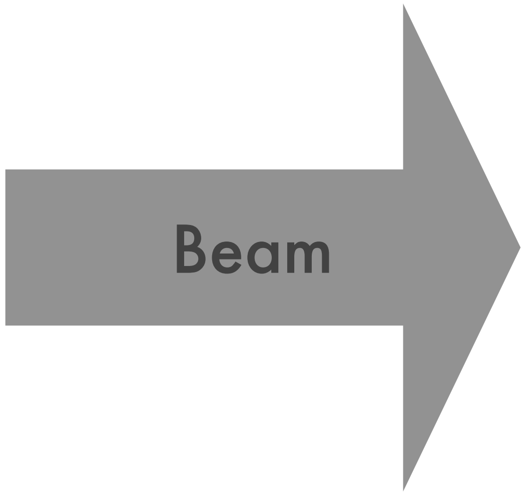
CC0π

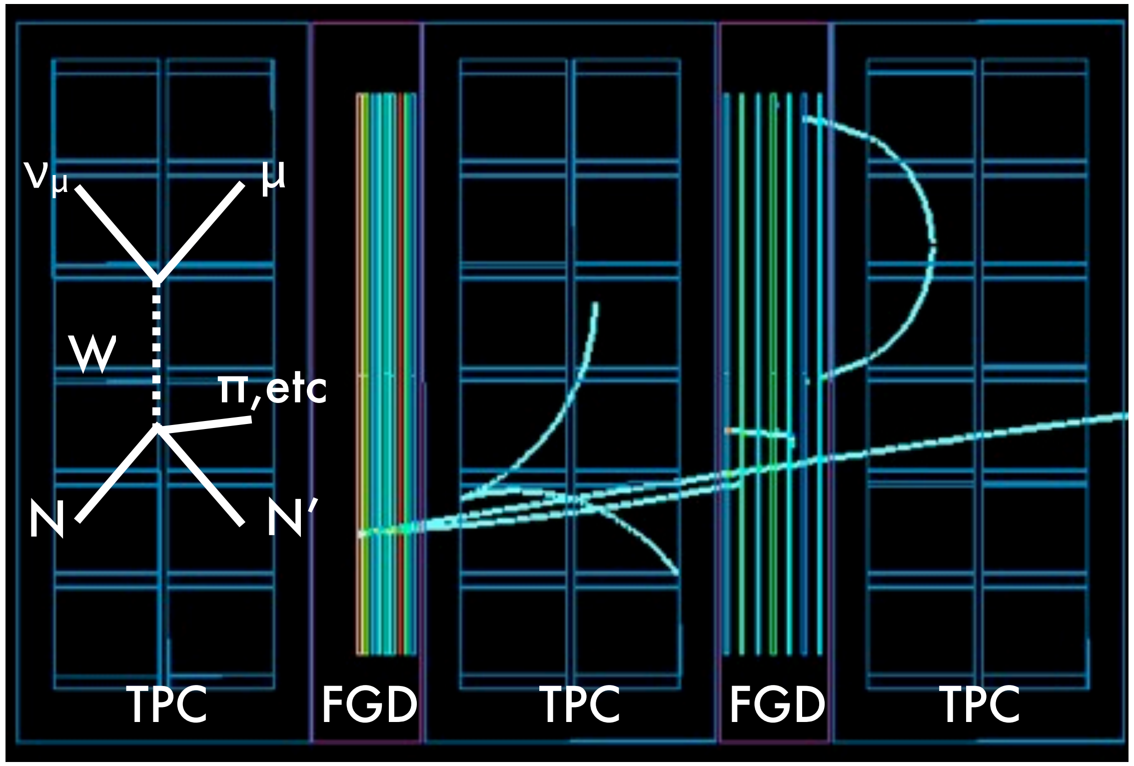


CC1π$^+$



CC other

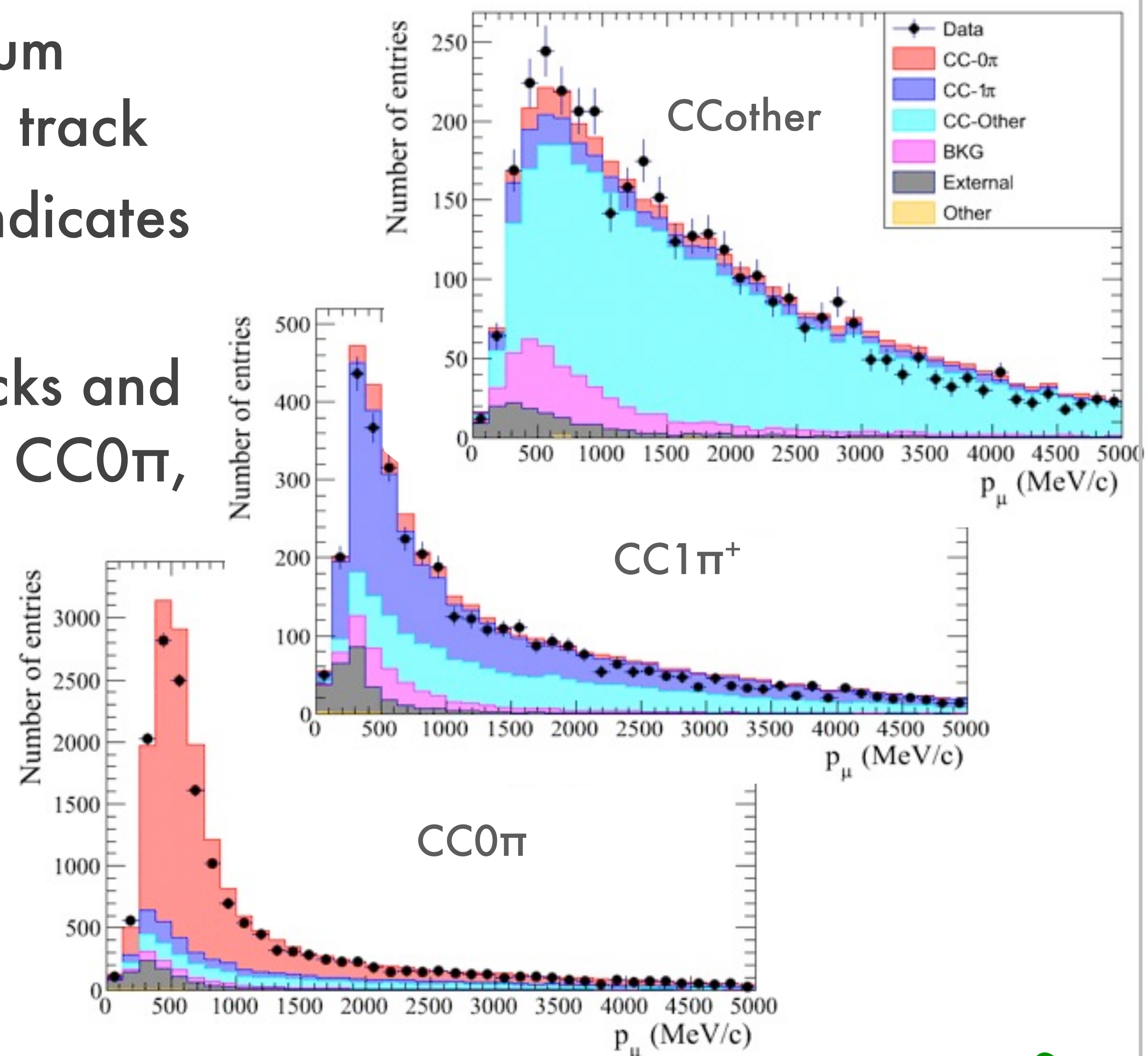




Near Detector Event Selection

- Select highest momentum negative, good quality track
- Check if the TPC PID indicates a muon
- Look at secondary tracks and identify three samples: $CC0\pi$, $CC1\pi^+$, and CC other

Sample	Purity
$CC0\pi$	72.6%
$CC1\pi^+$	49.4%
CC other	73.8%



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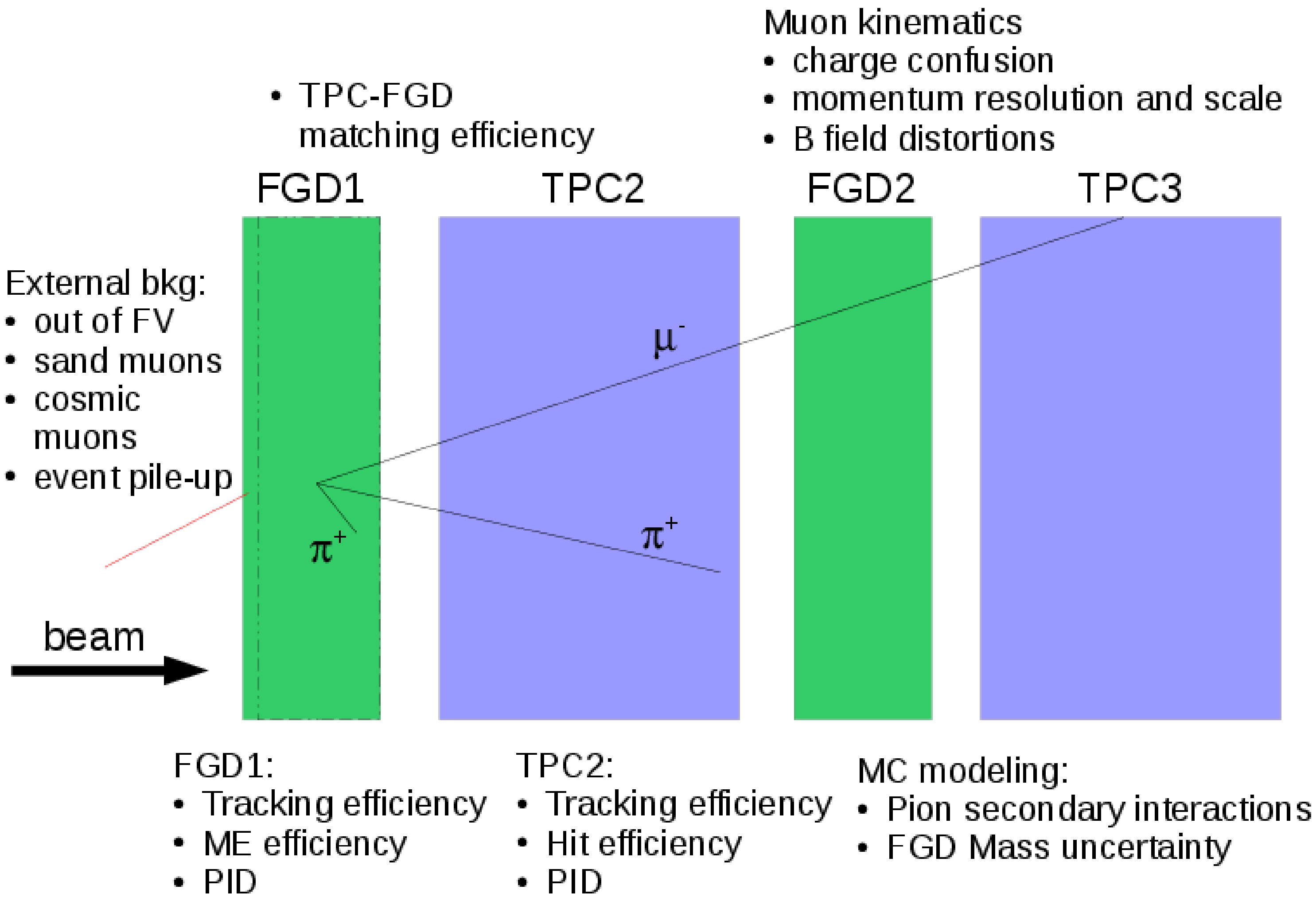
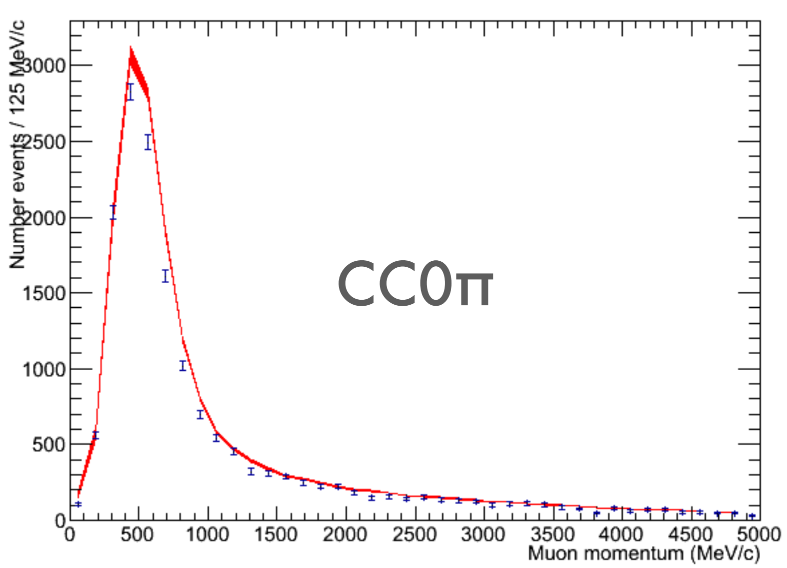
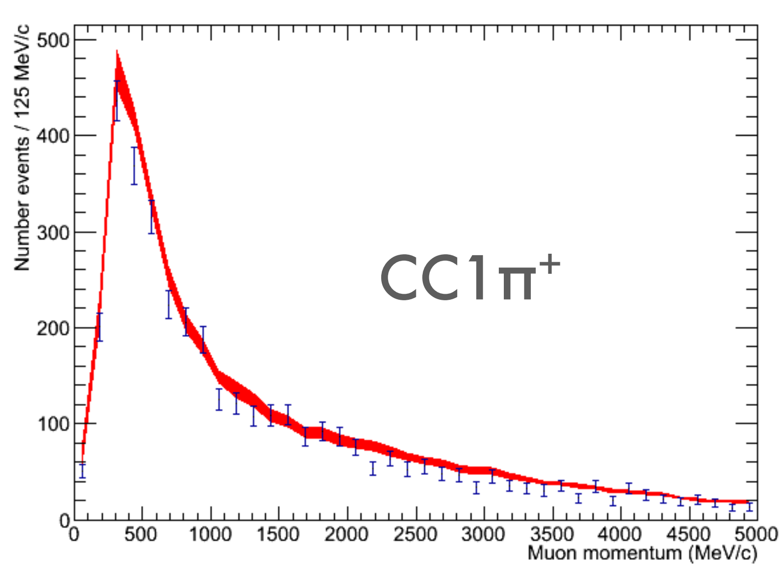
Detector Systematics

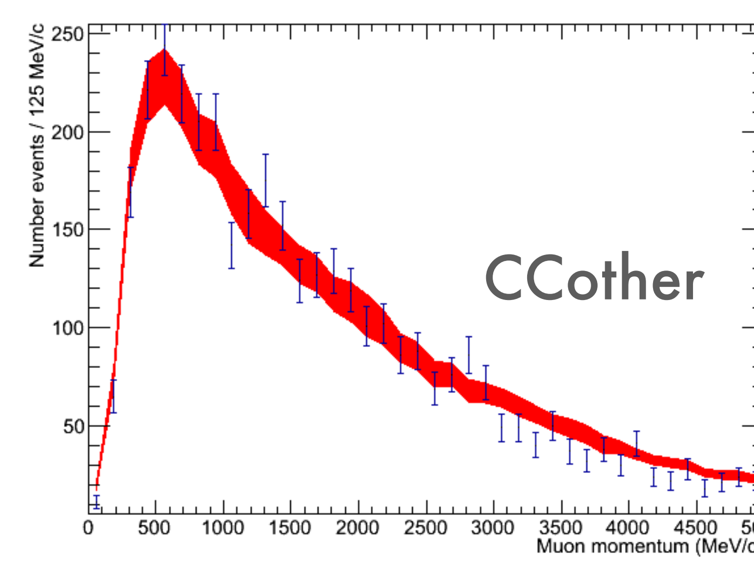


As far as possible, use data to constrain systematics; e.g. use cosmic samples to evaluate interdetector matching

Dominant systematics are pion secondary interactions and out of fiducial volume events







Putting It All Together

$$-\ln(P) = \sum_{i}^{ND280bins} N_i^p(\vec{b},\vec{x},\vec{f},\vec{d}) - N_i^d + N_i^d ln[N_i^d/N_i^p(\vec{b},\vec{x},\vec{f},\vec{d})]$$

$$+\frac{1}{2}\sum_{i}^{E_\nu bins}\sum_{j}^{E_\nu bins} \Delta b_i (V_b^{-1})_{i,j} \Delta b_j$$

$$+\frac{1}{2}\sum_{i}^{xsecpars}\sum_{j}^{xsecpars} \Delta x_i (V_x^{-1})_{i,j} \Delta x_j$$

$$+\frac{1}{2}\sum_{i}^{fsipars}\sum_{j}^{fsipars} \Delta f_i (V_f^{-1})_{i,j} \Delta f_j$$

$$+\frac{1}{2}\sum_{i}^{nd280det}\sum_{j}^{nd280det} \Delta d_i (V_d^{-1})_{i,j} \Delta d_j$$

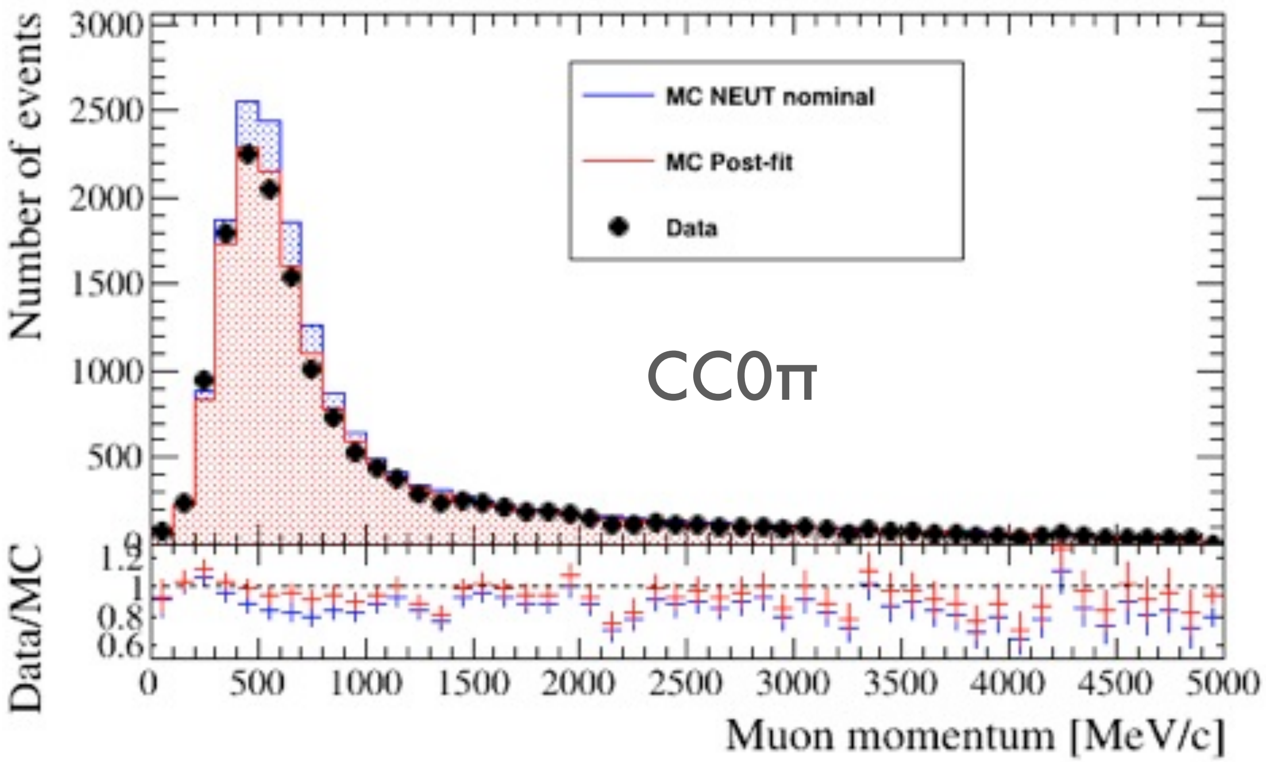
ND280 Data

Flux Model

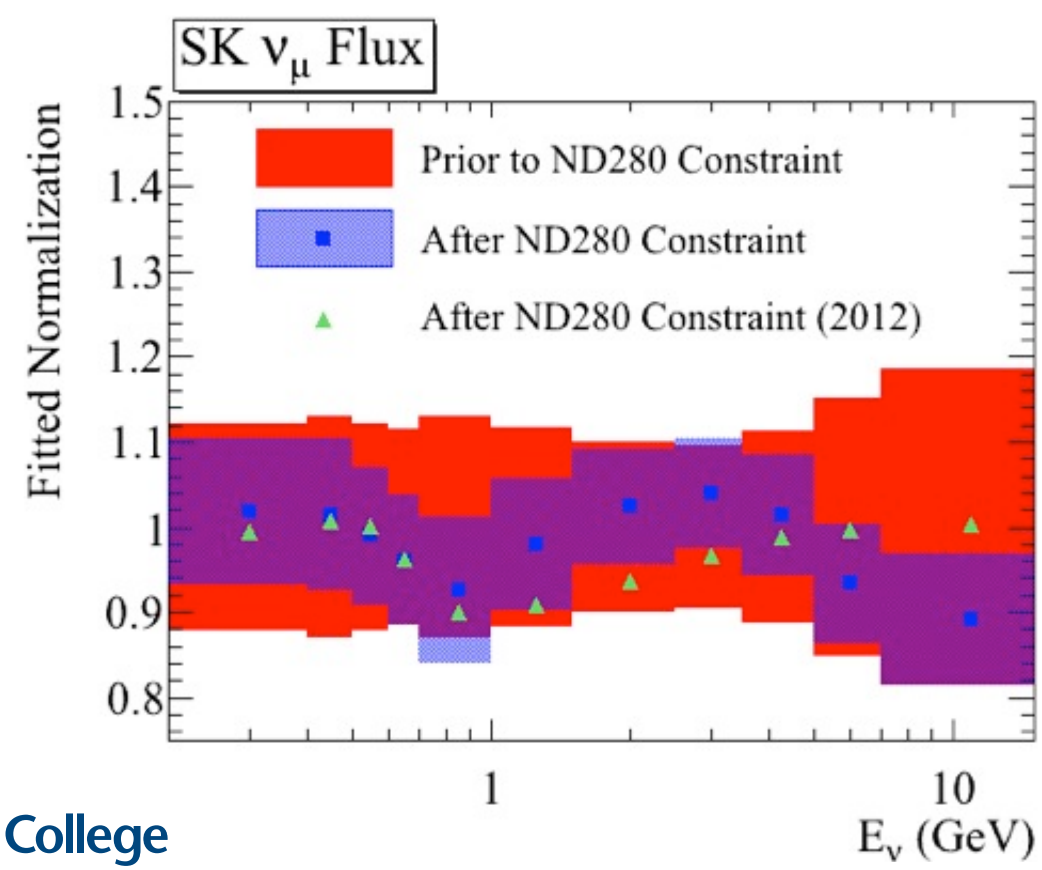
Cross Section Model

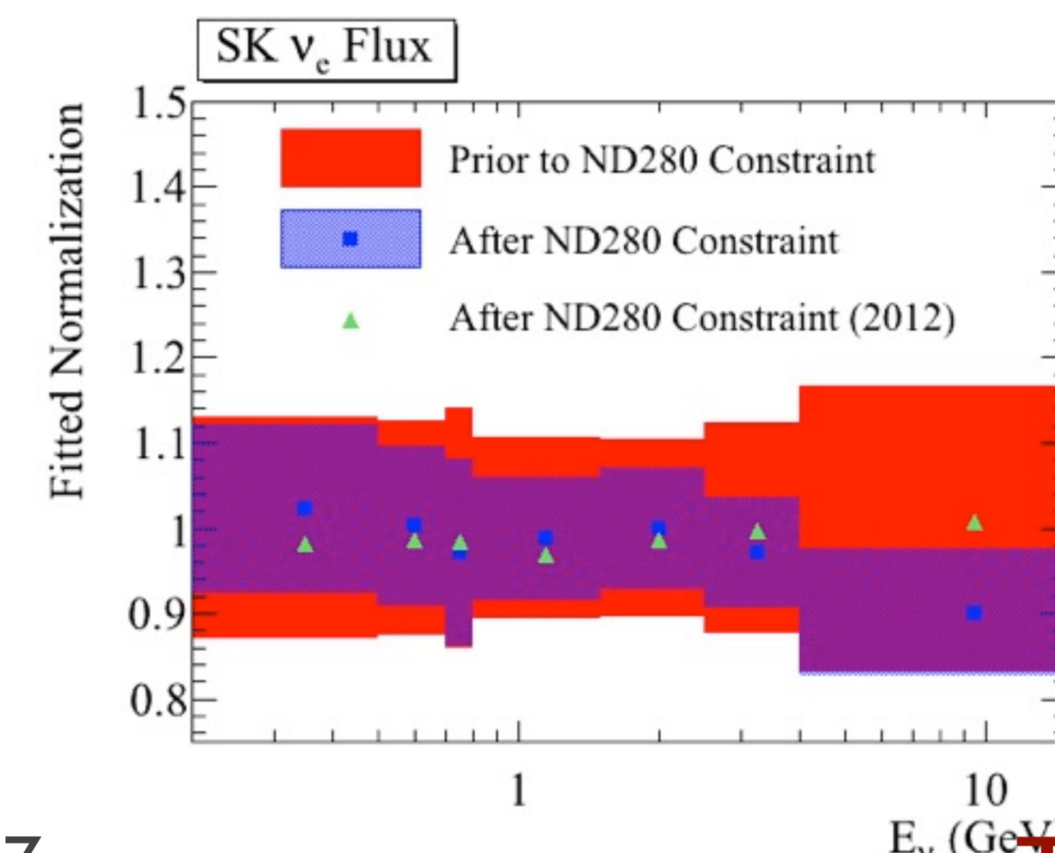
ND280 Detector Model

ND280 Constraints



Parameter	Prior	Constraint (2013)
M_AQE (GeV)	1.21±0.45	1.223±0.072
M_ARES (GeV)	1.41±0.22	0.963± 0.063





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Comparison to 2012 Results

- The 2012 ND analysis comprised only two samples: CCQE and CCnonQE.
- The three-sample analysis done for 2013 improves the constraints due to:
  - The increased purity of the samples
  - Finer binning of the data to increase the power of the shape information

Change in M_A parameters

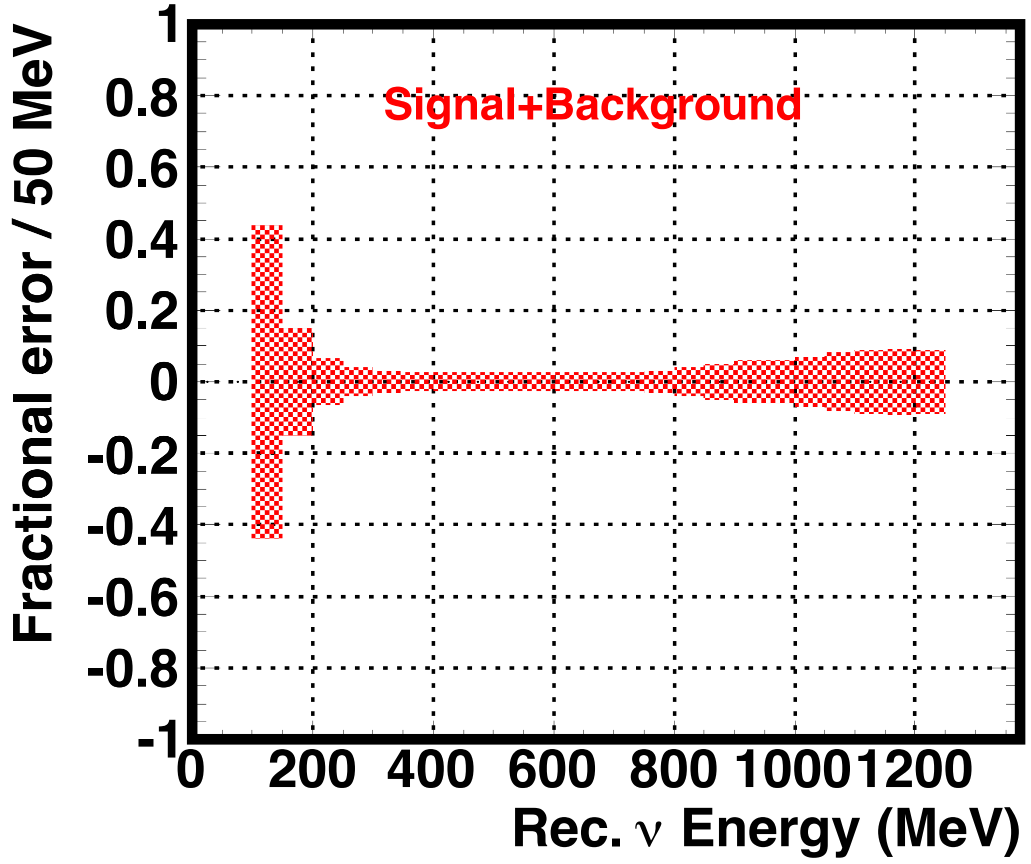
Parameter	Prior	Constraint (2012)	Constraint (2013)
M_AQE (GeV)	1.21±0.45	1.27±0.19	1.223± 0.072
M_ARES (GeV)	1.41±0.22	1.22±0.13	0.963± 0.063

Appearance analysis predictions

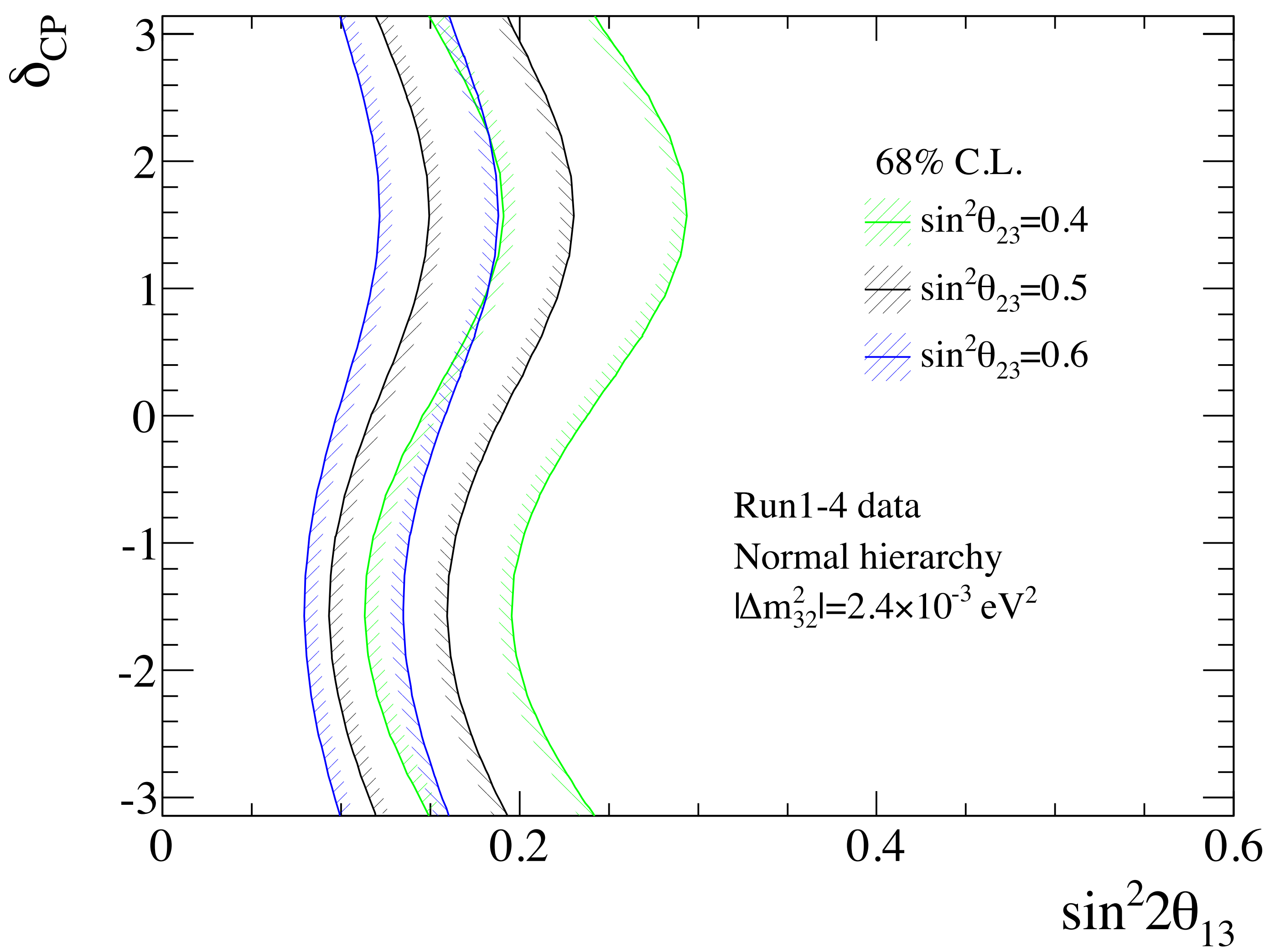
	Predicted N_{SK}	Percent Error
No ND280 constraint	22.6	26.5%
ND280 constraint 2012	21.6	4.7%
ND280 constraint 2013	20.4	3.0%

SK Detector Parameters

- Evaluated using SK atmospheric samples
- Use the tails of the distributions and the data/MC comparison to evaluate the systematic
- Additionally use new π^0-like samples to evaluate NC systematics for appearance



Other Neutrino Oscillation Parameters



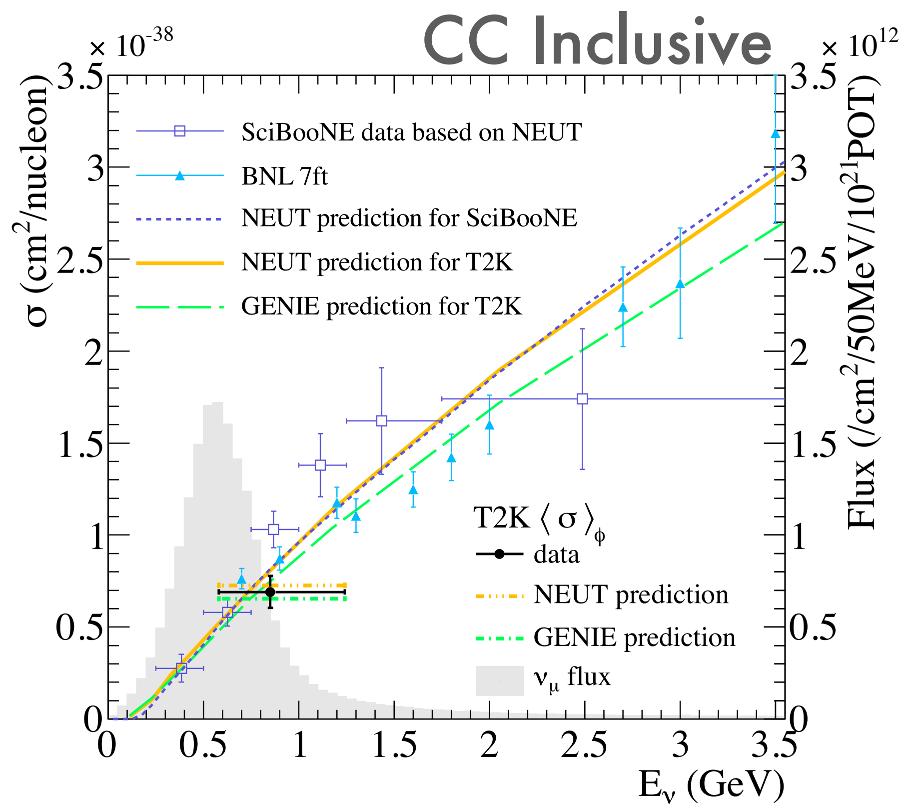
The value of θ_{23} has a significant impact on the measurement of θ_{13}

This effect is now similar in size to other systematic effects in the analysis

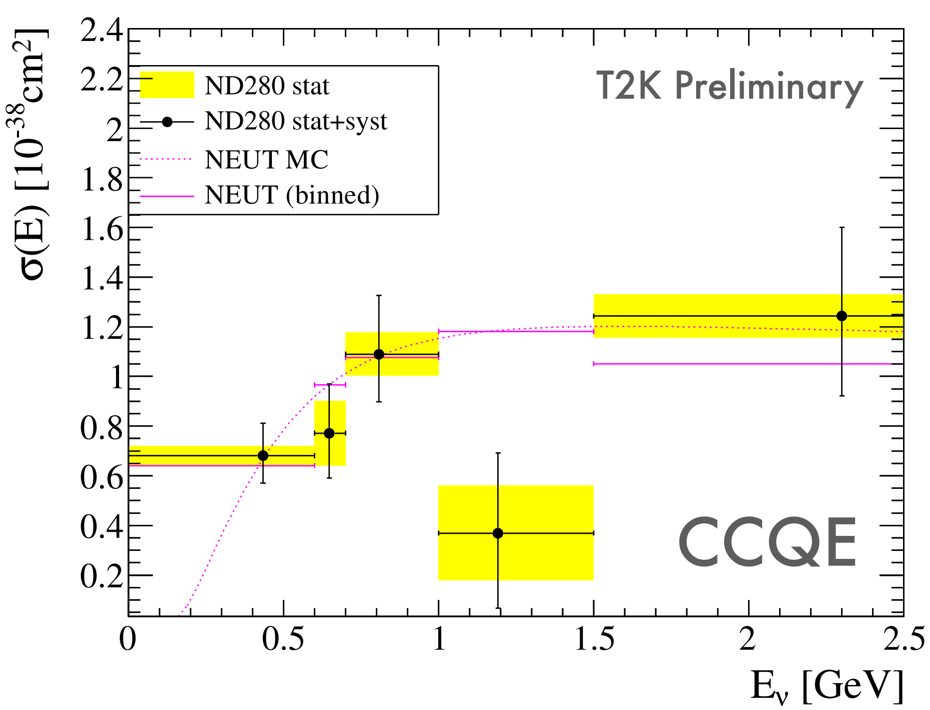
Where to from here?

- Refine cross section model
  - Implement alternative models (spectral function, MEC, etc.)
  - T2K cross section measurements
  - External cross section measurements (MINERνA, NOνA, etc)
- Extra samples
  - Near detector electron neutrino
  - Far detector π^0
- Joint appearance and disappearance analyses

Cross Section Measurements



Abe, K., et al. *PRD* 87.9 (2013): 092003.



- Use the T2K data more fully to constrain cross section model
- Sample specific measurements:
  - CCQE (see D. Hadley's talk)
  - CC1π
  - NCπ^0
  - ν_e
  - $\overline{\nu}_\mu$
  - NC elastic (see D. Ruterbories's talk)

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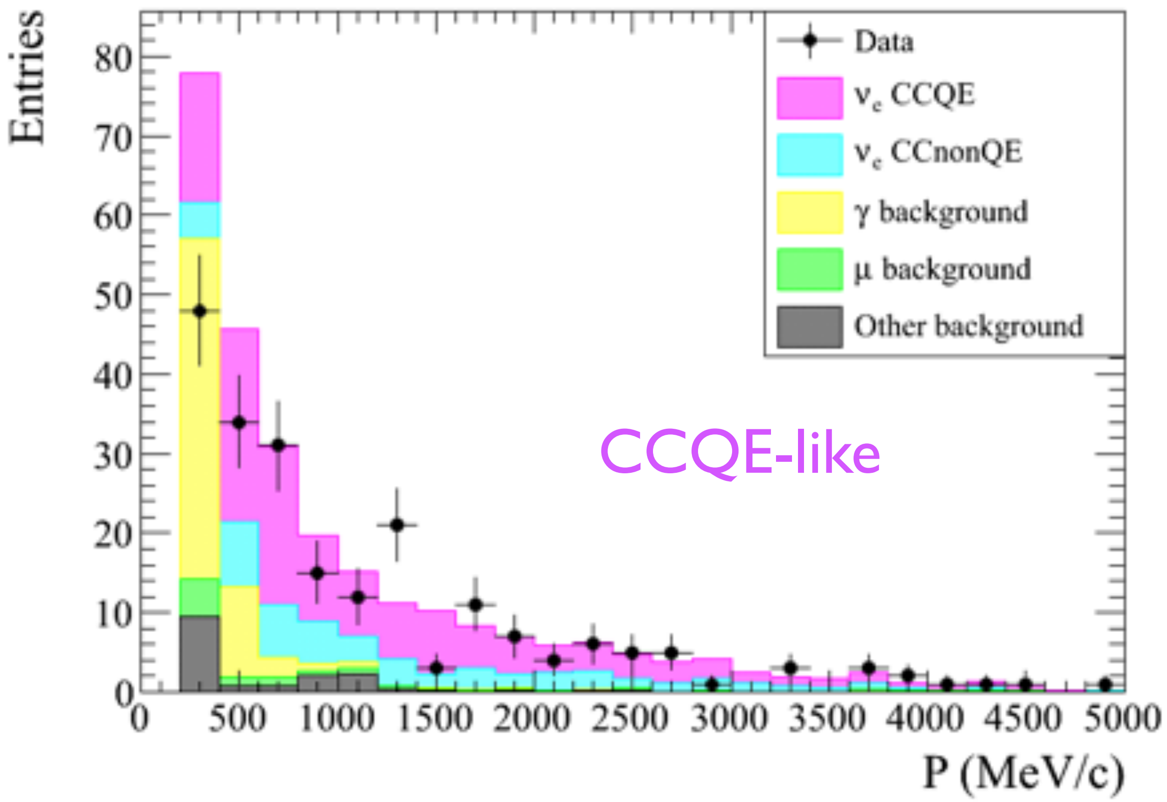
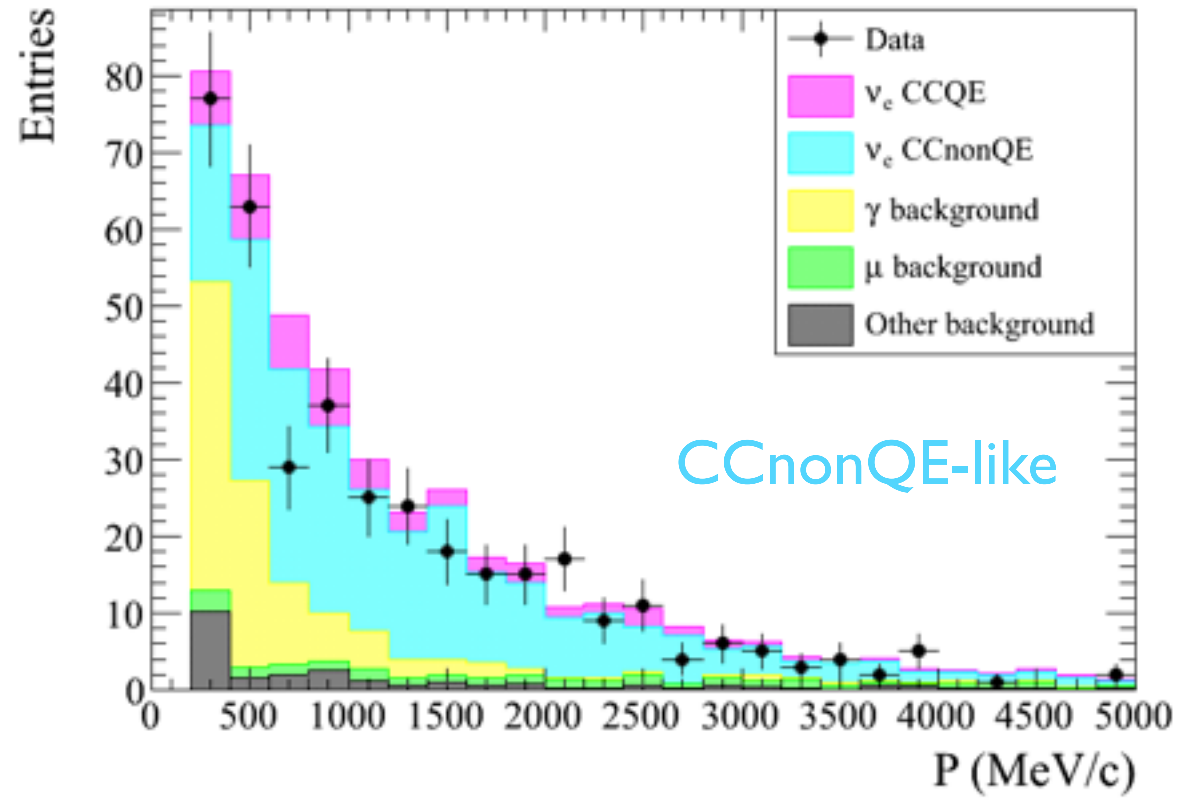
Intrinsic Beam ν_e





Use a selection of electron neutrino events and fit for the ratio of observed to expected ν_e events.

Find good agreement between this sample and the expectation from the ν_μ analysis

$$f(\nu_e) = 1.055 \pm 0.058(\text{stat.}) \pm 0.079(\text{syst.})$$

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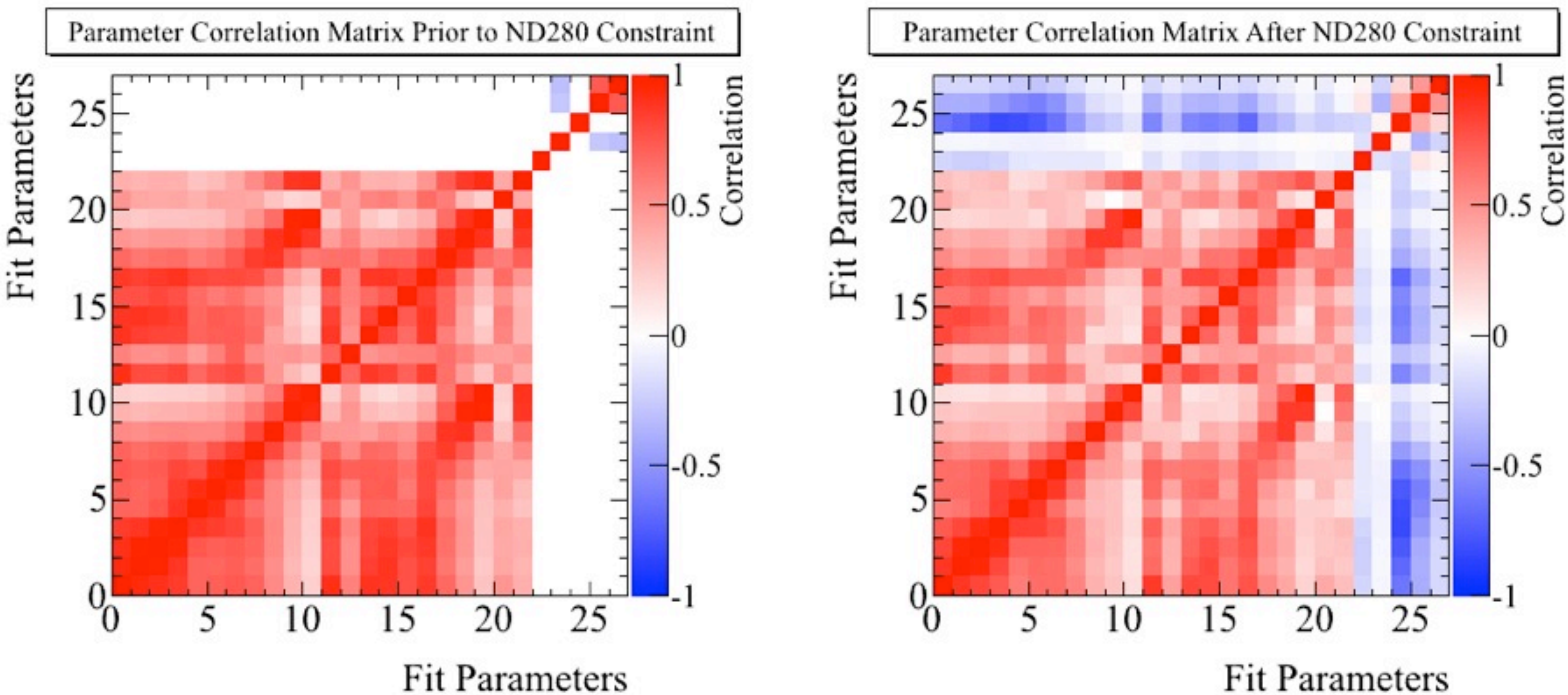
Summary

- T2K has implemented improvements to the near-far extrapolation and reduced systematic uncertainty for oscillation measurements
- There are still many additional improvements available to T2K, including improved cross section measurements and models and additional event samples

Correlations



Imperial College London

M_ARES

- Big shift from 2012!
  - New data?
  - New binning?
  - New samples?
- Test by using old binning/selection with new data
- Appears to be combination of all factors

Parameter	BANFF 2012	Old Bins, Select.	New Bins, Old Select.	Old Bins, New Select.	New Bins, Select.
M_A^{RES} (GeV)	1.223 ± 0.127	1.133 ± 0.105	1.064 ± 0.057	1.003 ± 0.119	0.963 ± 0.063
CC1π Norm E0	1.370 ± 0.204	1.405 ± 0.202	1.403 ± 0.164	1.331 ± 0.204	1.217 ± 0.161

Oscillation Results