Neutrino Interaction Uncertainties at T2K

T2K jargon for "Neutrino Interactions Working Group", prounced "noog"

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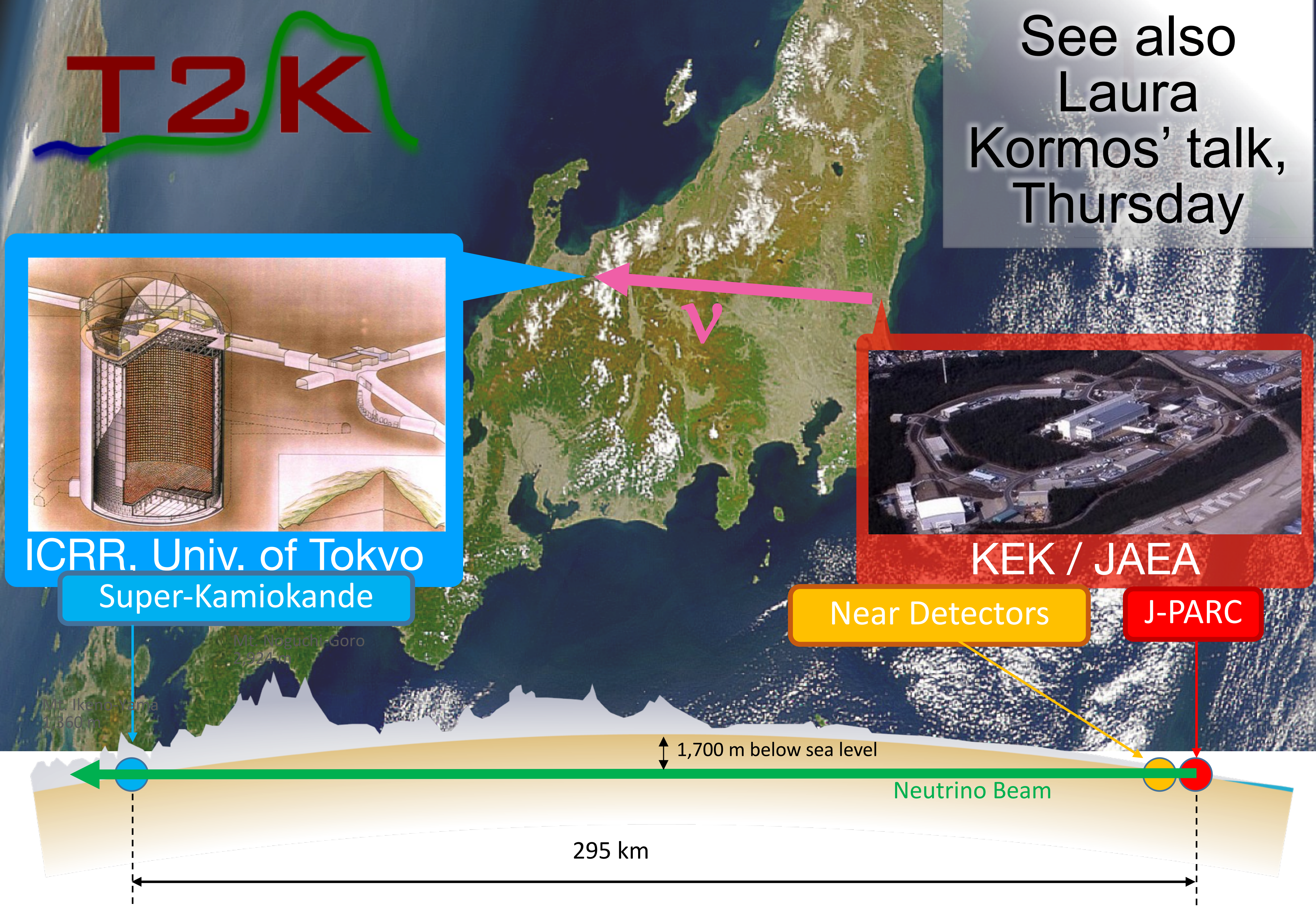
representing the T2K collaboration

2 November 2018
NNN 2018, Vancouver

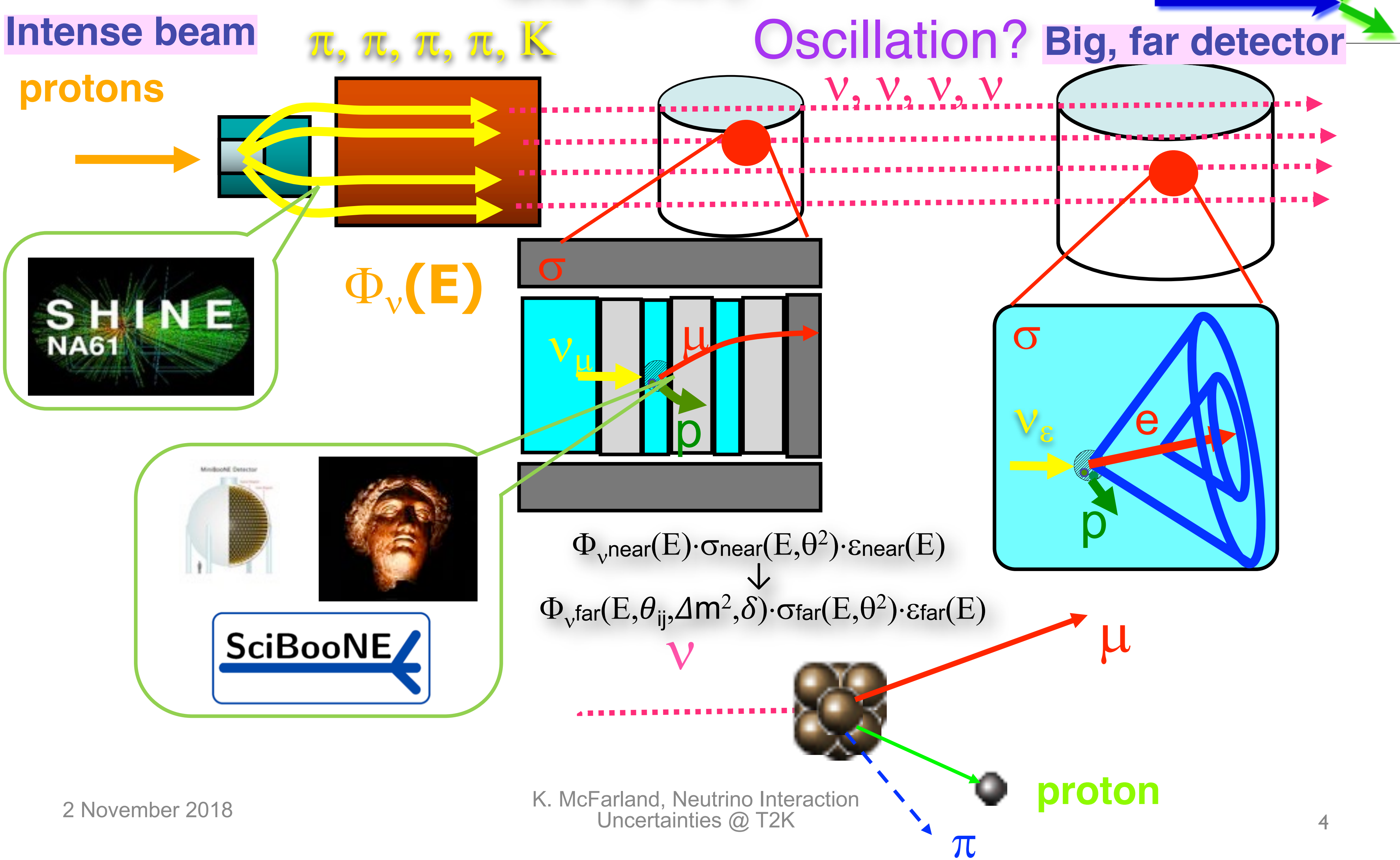
Outline

I. T2K's oscillation analysis
II. Neutrino Interaction Model
III. Key Uncertainties and Strategies for reducing them

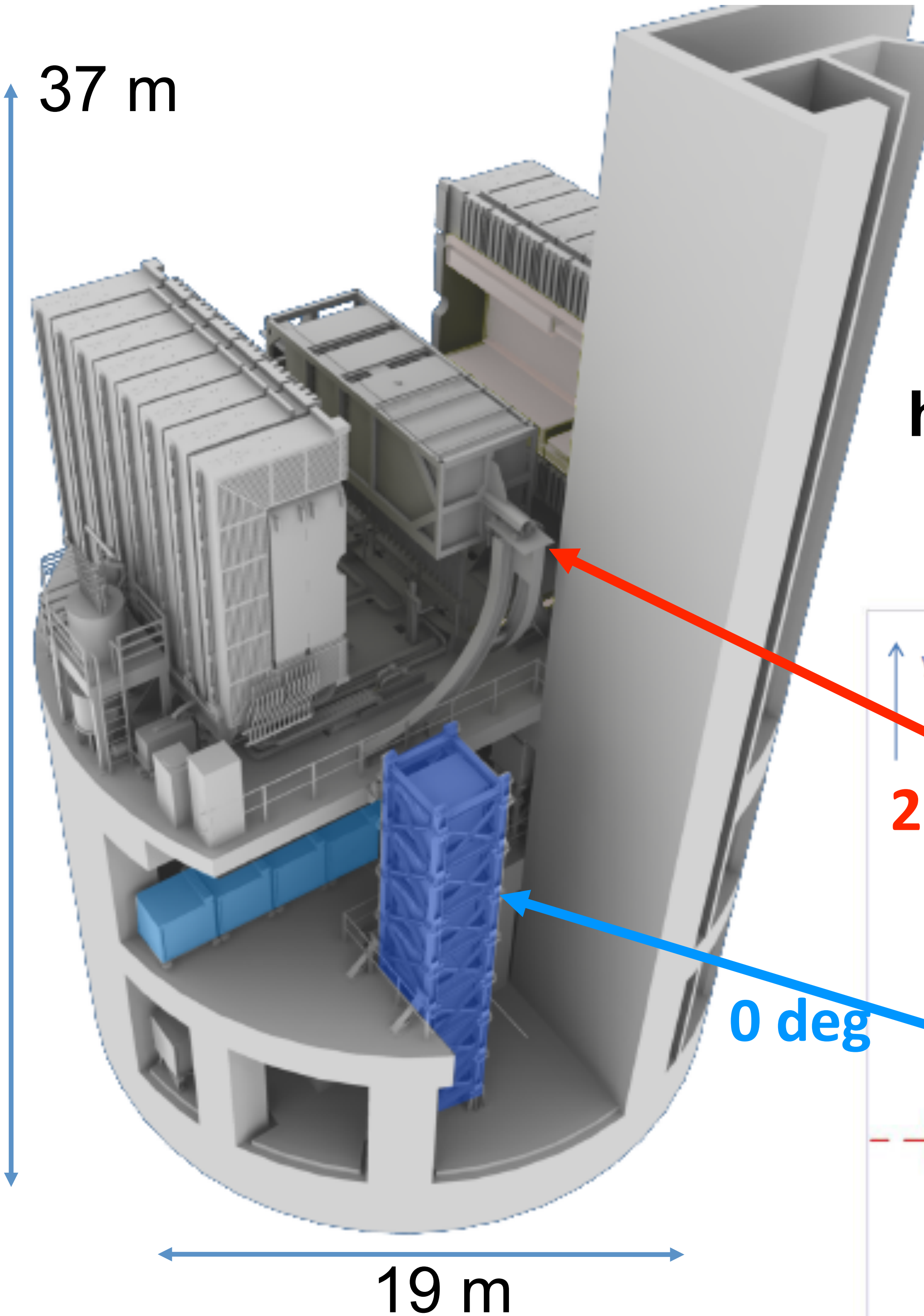

T2K
See also Laura Kormos' talk, Thursday
ν
ICRR, Univ. of Tokyo
Super-Kamiokande
KEK / JAEA
Near Detectors
J-PARC
1,700 m below sea level
Neutrino Beam
295 km

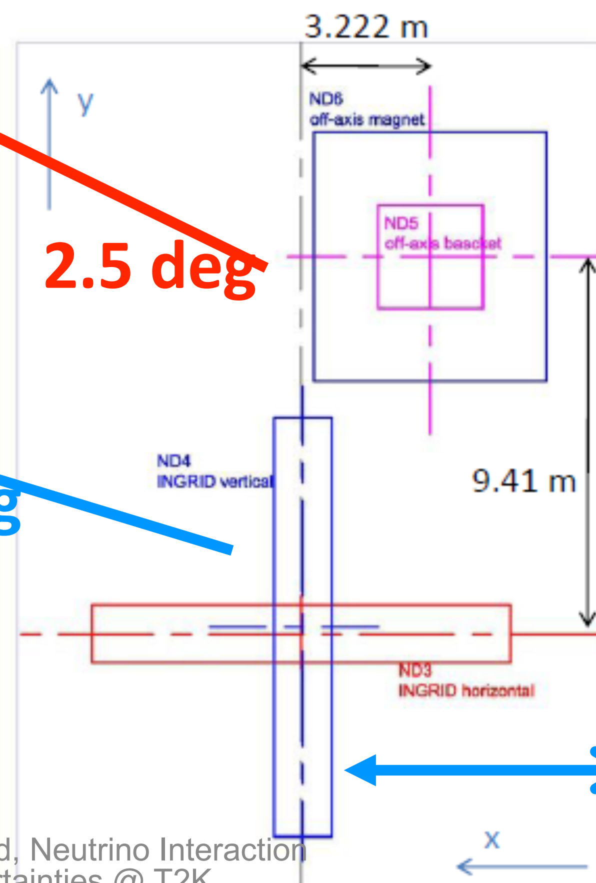
T2K experimental strategy

Search for CPV by comparing $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$.



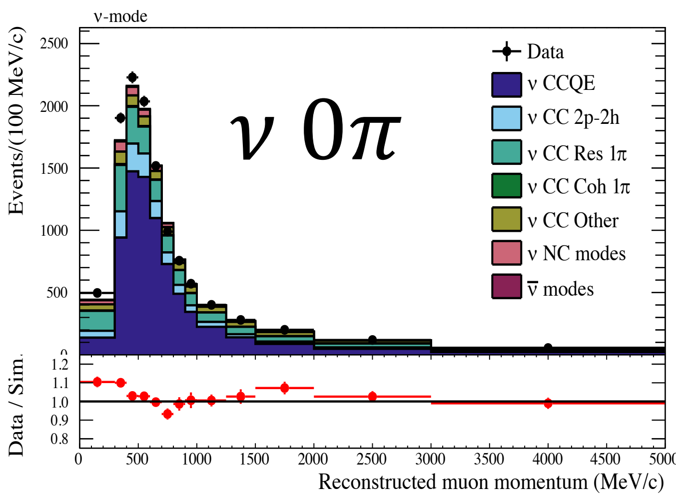
T2K Near Detector pit houses both off-axis (ND280) and on-axis (INGRID) detectors

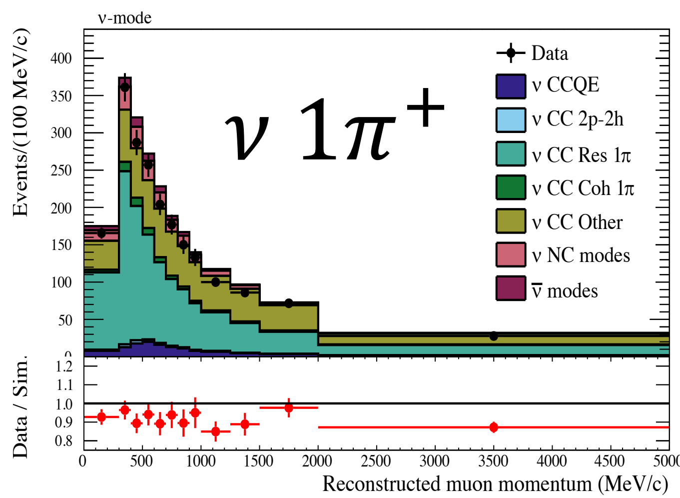


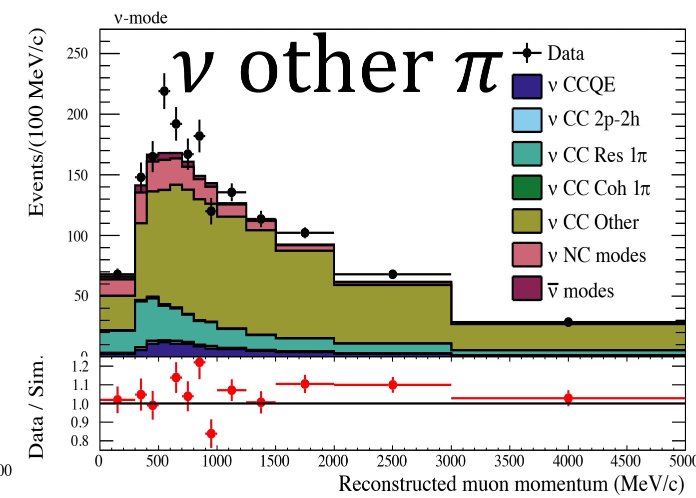


Samples: Near and Far

- Off-axis near detector samples divided by visible pion content, beam focusing

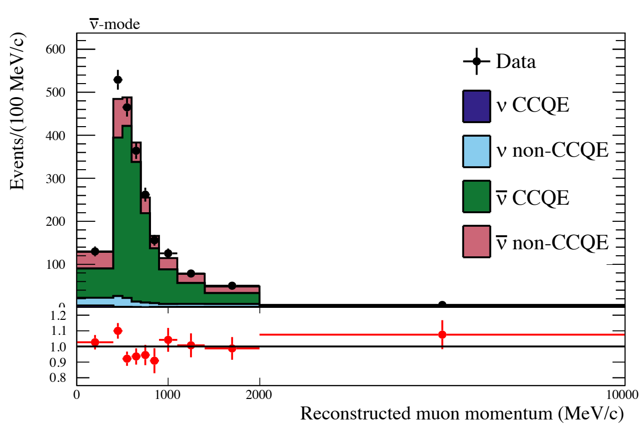






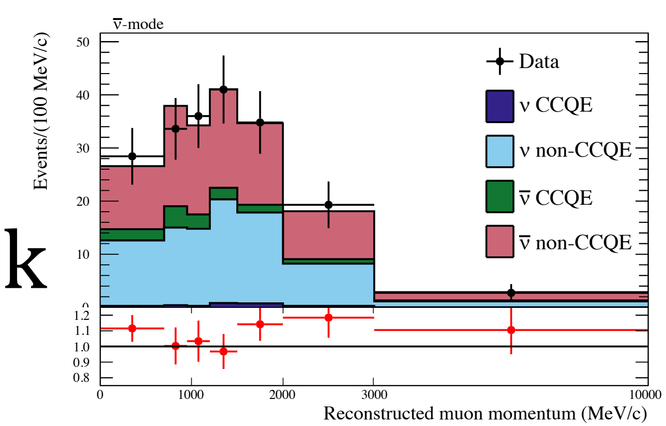
Reconstructed muon momentum (and angle)

for both CH target and CH+H_2O targets, separately.



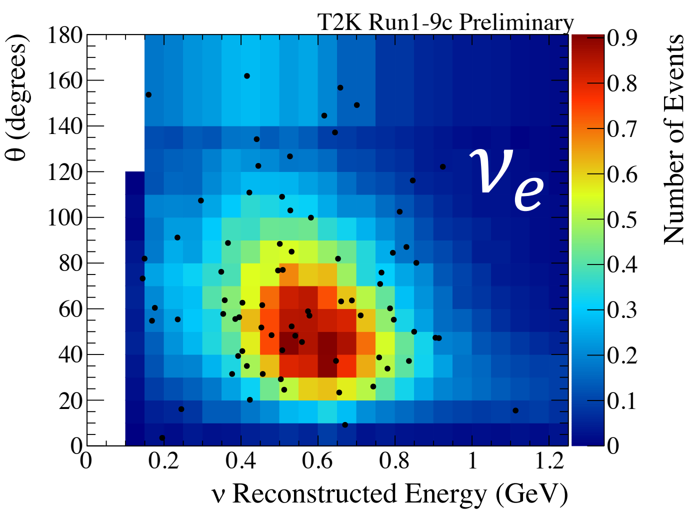
$\bar{\nu}$ 1 track

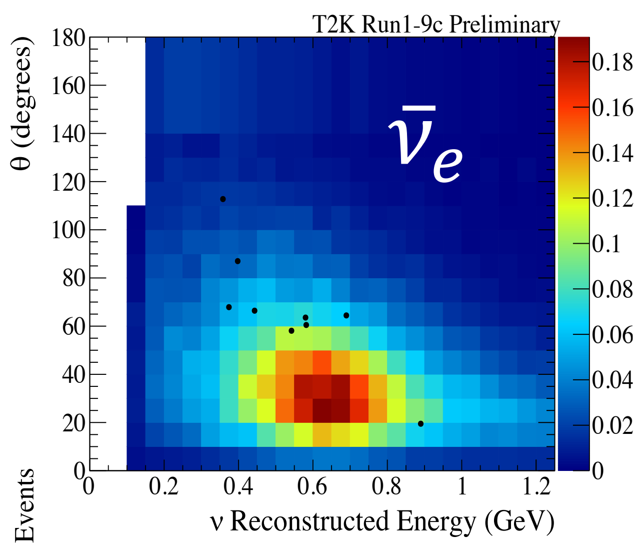
$\bar{\nu}$ >1 track

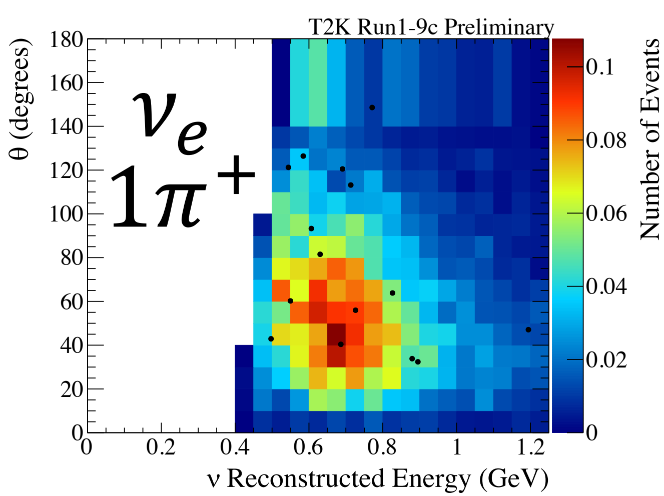


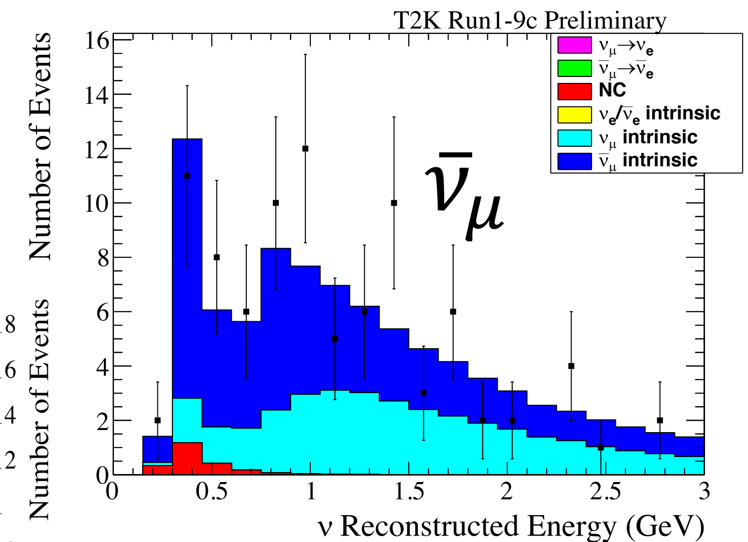
Samples: Near and Far

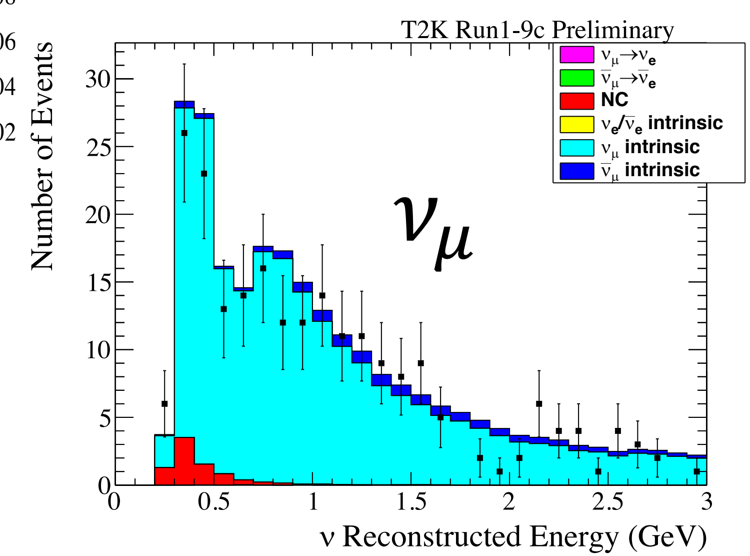
- Select events with no pions (& $\nu_e 1\pi^+$ sample).
- E_ν from lepton: $$E_\nu^{QE} = \frac{m_p^2 - m'^2_n - m_\mu^2 + 2m'_n E_\mu}{2(m'_n - E_\mu + p_\mu \cos\theta_\mu)}$$







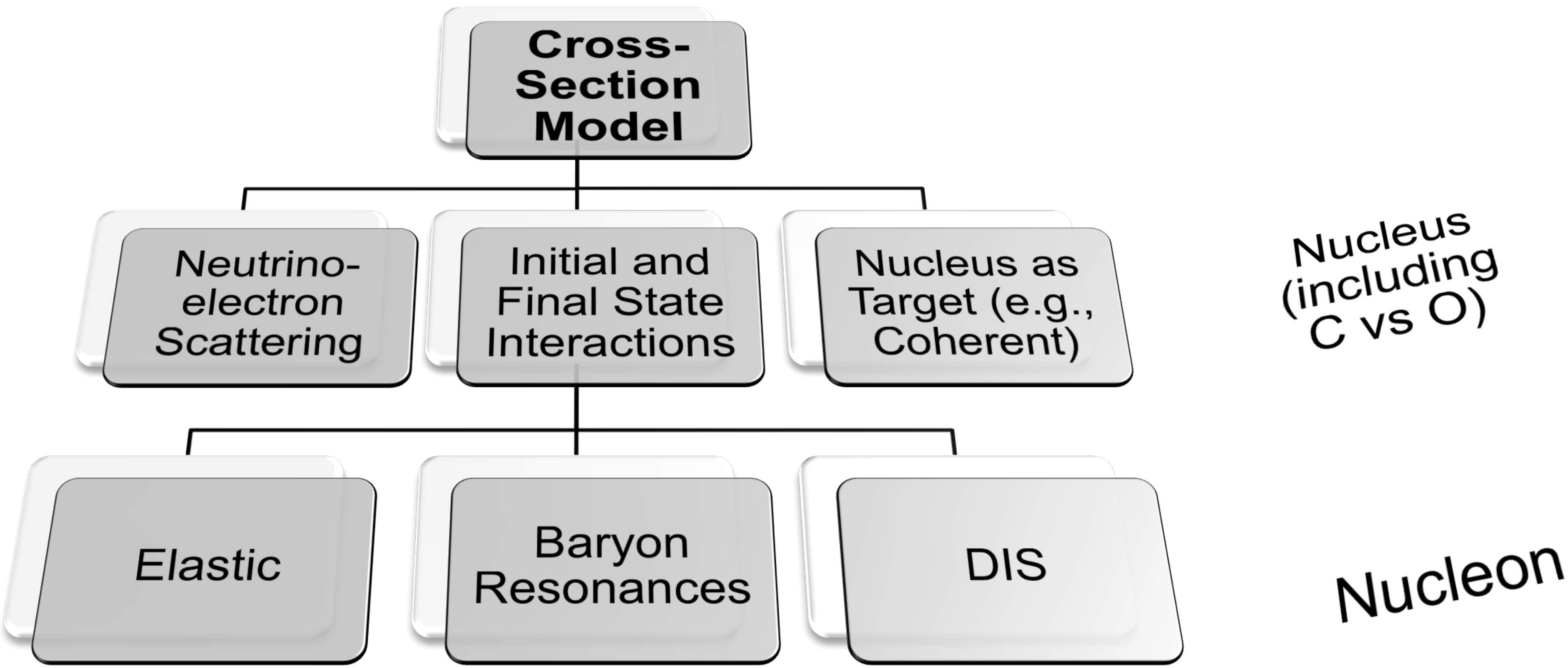




INTERACTION MODEL

- Ingredients
- Important uncertainties

Architecture of Model



Processes on Nucleons

- Llewlleyn-Smith CC elastic
  - BBBA07 vector form factors

A. Bodek et al, Eur.Phys.J. C53 (2008) 349

  - Axial Form factor from νD_2, π electroproduction: dipole → z-expansion (correct high Q^2 uncertainty)

A. Mayer et al, Phys.Rev. D93 (2016) 113015

  - Photon emission in CC radiative corrections
- Low W "resonant" single pion production
  - Rein-Sehgal w/ many unknown axial couplings and form factors, lumped into a dipole axial form factor, C_A^5, m_A^{RES}
  - Non interference *ad hoc* non-resonant "background" model also tuned to νD_2 data (after ANL/BNL "fix")

C. Wilkinson et al, Phys. Rev. D90, 112017 (2014). P. Rodrigues et al, Eur. Phys. J. C 76, 474 (2016)

  - Alternate model with resonant-background interference.

M. Kabirnezhad, Phys.Rev. D97 (2018), 013002

  - NC1γ from Alvarez-Ruso, scaled to Wang et al study, 100% uncertainty

E. Wang et al, Phys. Rev., D92, 053005 (2015)

Processes on Nucleons (cont'd)

- DIS and multi-pion production
  - Above W of 2 GeV, free-nucleon PDFs in LO model. Bodek-Yang extension to low Q^2 form factor.
  - Fragmentation from PYTHIA but W<2 GeV multipion fragmentation handled separately and tuned on hydrogen data (custom tune)

A. Bodek and U. Yang, Nucl. Phys. Proc. Suppl. 139 (2005) 113, also arXiv:1011.6592

C. Bronner and M. Hartz, JPS Conf.Proc. 12 (2016) 010041

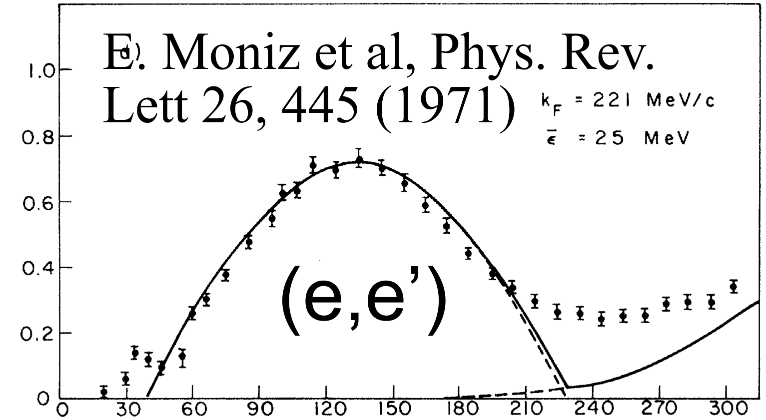
- Additional poorly constrained flavor uncertainties
  - Nuclear induced second class current effective form factors?
    - At T2K E_ν, ~2% difference in ν_e,ν_μ CC elastic cross sections possible
  - At all energies, electroweak vertex correction differences for ν_e and ν_μ thought to be "small" (KNL theorem), but there is no calculation
    - T2K puts in an additional 2% systematic
  - Lumped together as ν_e/ν_μ, $\bar{\nu}_e/\bar{\nu}_\mu$ uncertainties

M. Day and K. S. McFarland. Phys. Rev. D 86, 053003 (2012)

Nuclear Initial State (IS) Model

- Use a Fermi Gas model with binding (E_B) and Fermi momentum (k_F) parameters
  - e^- corrected to neutrino data
  - C/O differences included
- Concerns and shortcomings
  - FG association of kinetic energy to momentum known to poorly describe low momentum transfer
  - Not all parts of model use same IS
  - Concerns about consistency of (e,e') and (e,e'p), kinematic approximations led to large uncertainties. Recently resolved in Bodek study.

E. Moniz et al, Phys. Rev. Lett 26, 445 (1971)



A. Bodek, arXiv:1801.07975.

- Alternate IS models studied as systematic variations.
  - Local Fermi Gas (Nieves), Spectral function (Benhar)

J. Nieves et al, Phys.Lett. B707 (2012) 72

O. Benhar et al, Phys. Rev. Lett. 105 (2010) 132301

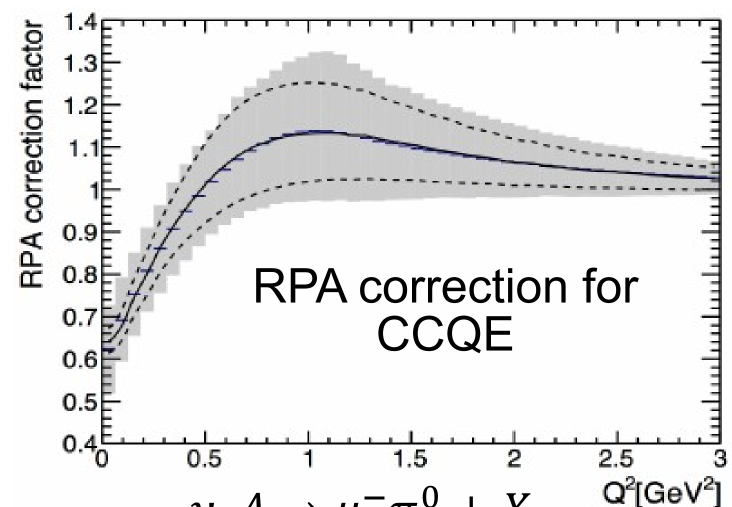
Nuclear Screening (RPA)

- Long-range nucleon-nucleon correlations screen low momentum transfer reactions
  - Random Phase Approximation or “RPA”
- Use calculation of Nieves et al
  - MINERvA, MiniBooNE data support it
- Evaluated theoretical uncertainties
  - “Effective RPA” model, constrained by these uncertainties: “BeRPA”

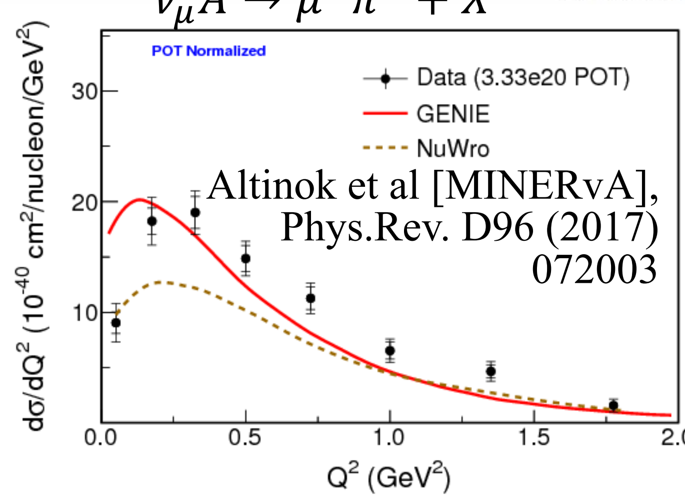
R. Gran, arXiv:1705.02932

- “RPA” only sensible for low momentum transfer processes, but data shows need for low Q^2 suppression in pion production. *Not incorporated.*

J. Nieves et al, Phys.Lett. B707 (2012) 72

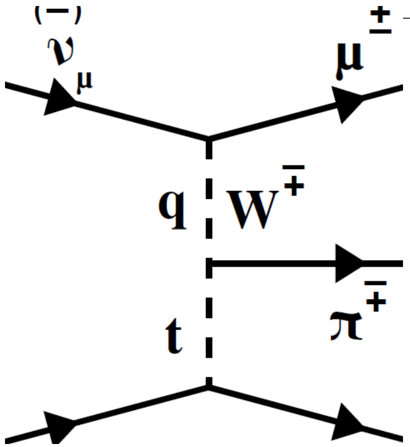


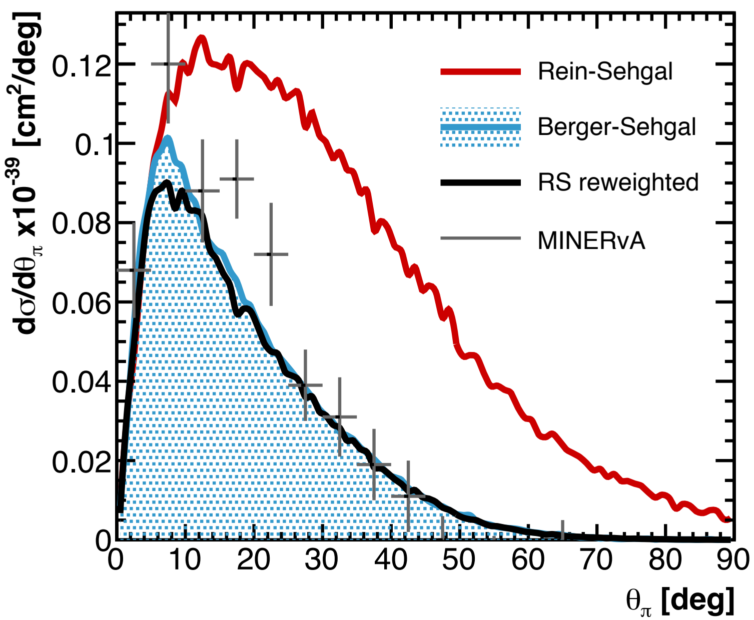
$\nu_\mu A \rightarrow \mu^- \pi^0 + X$



Coherent/Diffractive Pion Production

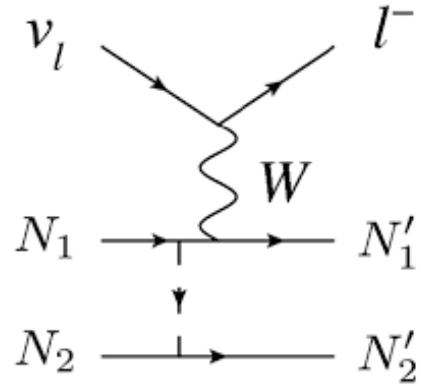
- Previous NEUT implementation of Rein-Sehgal had original πC elastic scattering cross-section
  - GENIE default has improved one based on new data
- Recently implemented Berger-Sehgal because of its good agreement with modern (MINERvA) data





2p2h processes

- Initial hints from MiniBooNE, T2K, and MINERvA in lepton kinematics that this effect exists.



- Now, we have strong evidence from MINERvA, NOvA, which can be interpreted as a measurement of the process.
- We use an *ab initio* calculation from Nieves et al, the same one that is in GENIE. But…
  - It is not complete.
  - Different (also incomplete) calculations get very different strengths and q_0 vs q_3 distributions
  - Differences are a significant systematic effect for T2K.

J. Nieves et al., Phys. Rev. C83:045501, 2011.

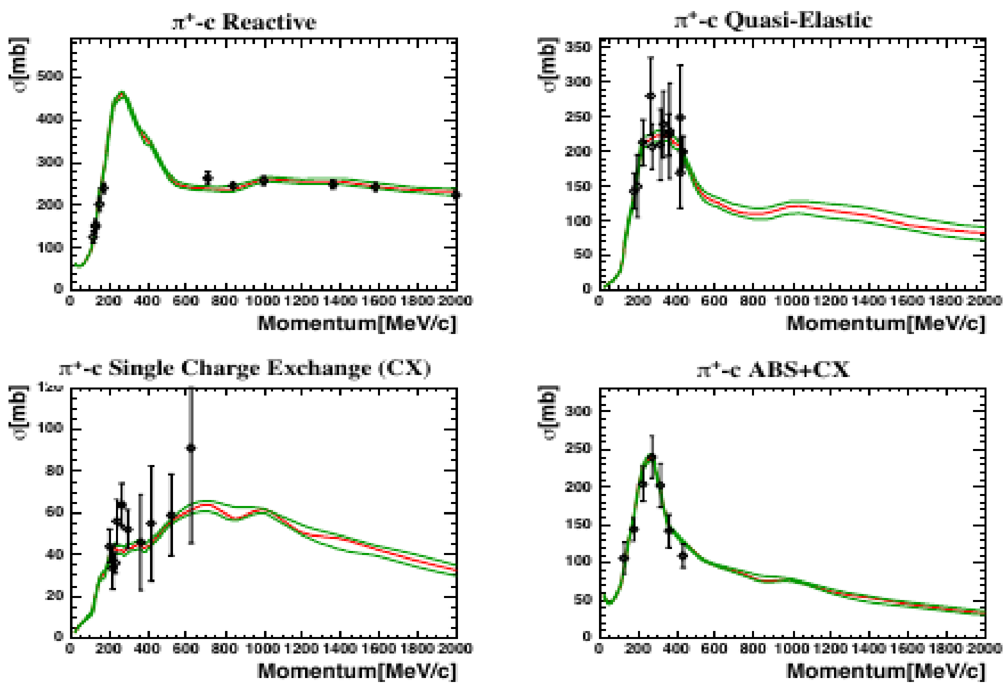
M. Martini et al., Phys. Rev., C80:065501, 2009.

2p2h processes (cont'd)

- What uncertainties are we using?
  - Strength of 2p2h is allowed to float within large uncertainties
  - Strength in delta vs non-delta processes will be allowed to vary radically, to ensure we cover the effect in reconstructed neutrino energy (new addition to our model)
  - C/O differences constrained (conservatively) by measurements of SRC in electron scattering
- Working out best practices for modeling and constraining uncertainties from MINERvA, NOvA, T2K "low recoil" style data could benefit from collaboration.
- Also, we don't have 2p2h processes for single pion production in our model (no calculation), but they should certainly be there, with similar effects.

Final State Interactions

- NEUT has its own cascade model
  - Tuned to pion and nucleon scattering on nuclei
  - Data is fairly precise
- Current approach is to use conservative uncertainties. Future oscillation analyses will use a recent T2K reanalysis (pub. in prep.).



Best fit
±1 sigma
error band

	X^2_{min}/N_{DOF}
C	1.95
O	3.54
Pb	2.69
Light nuclei	2.70
Heavy nuclei	2.09
All	2.74

Final State Interactions (cont'd)

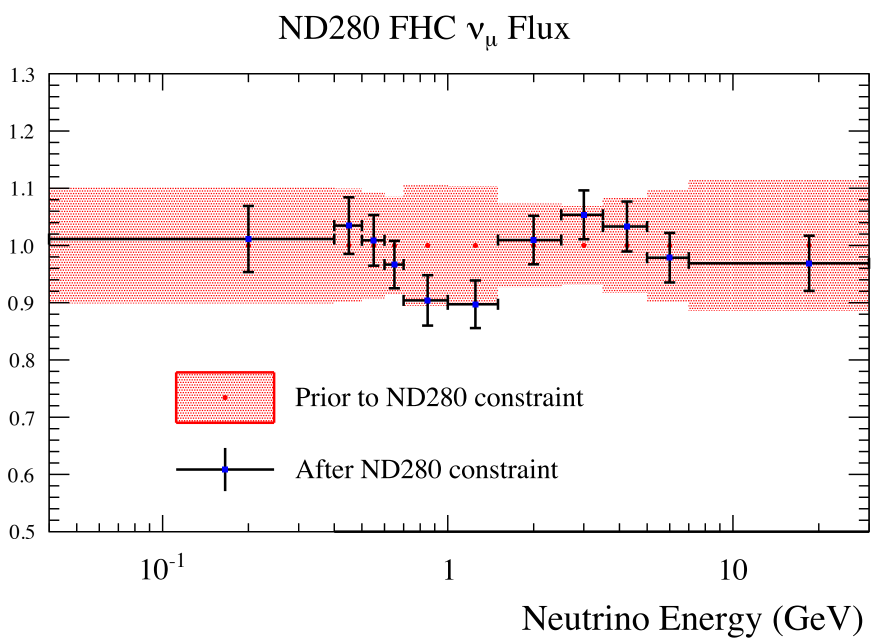
- Current development
  - Use data driven uncertainties, including C/O
  - Incorporate uncertainties on cascade model itself by comparison with transport models (e.g., GiBUU)
- Also working to unify the treatment of FSI uncertainties and secondary interactions (SI) in the detector
  - Both can be done with the same cascade model
- A joint cascade model is another possible area where one could imagine collaboration

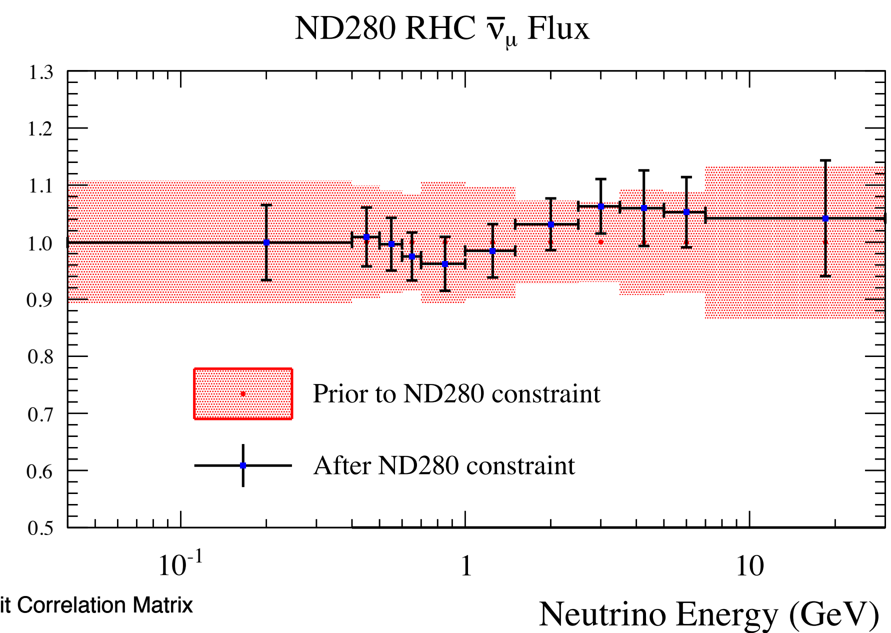
CONSTRAINTS

- Near Detector Oscillation Fits
- Near Detector Interaction Measurements

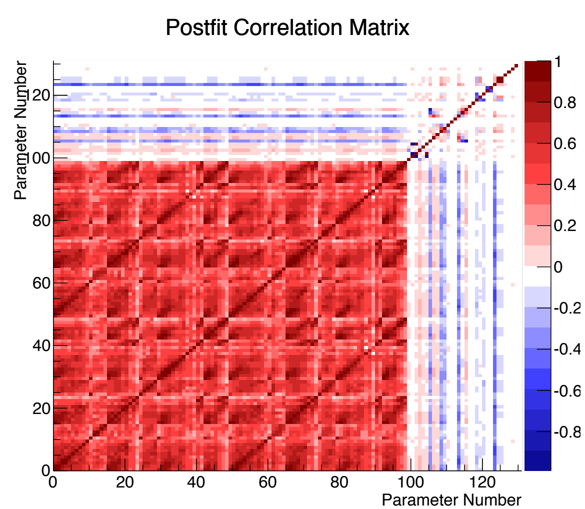
Near Detector Constraint

- Near detector samples simultaneously constrain flux and interaction uncertainties.





Flux is pulled modestly by ND280 data

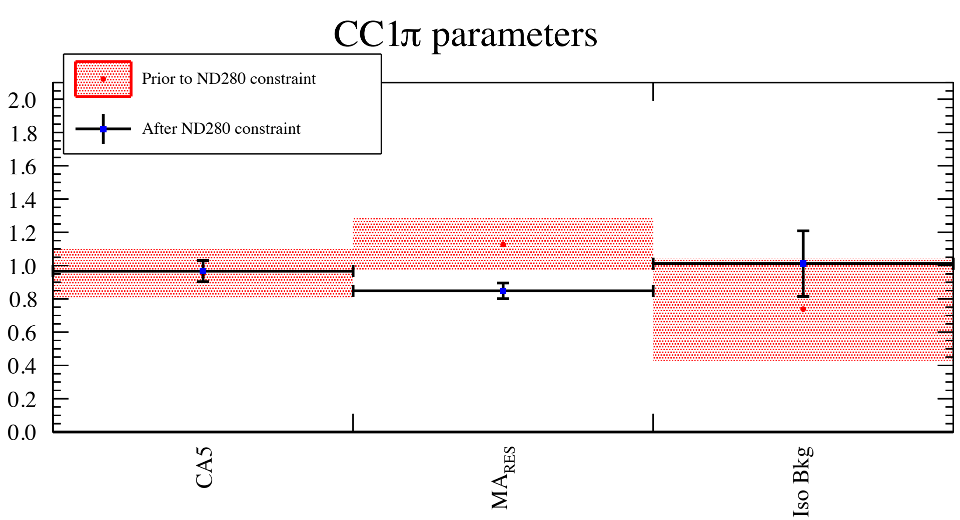


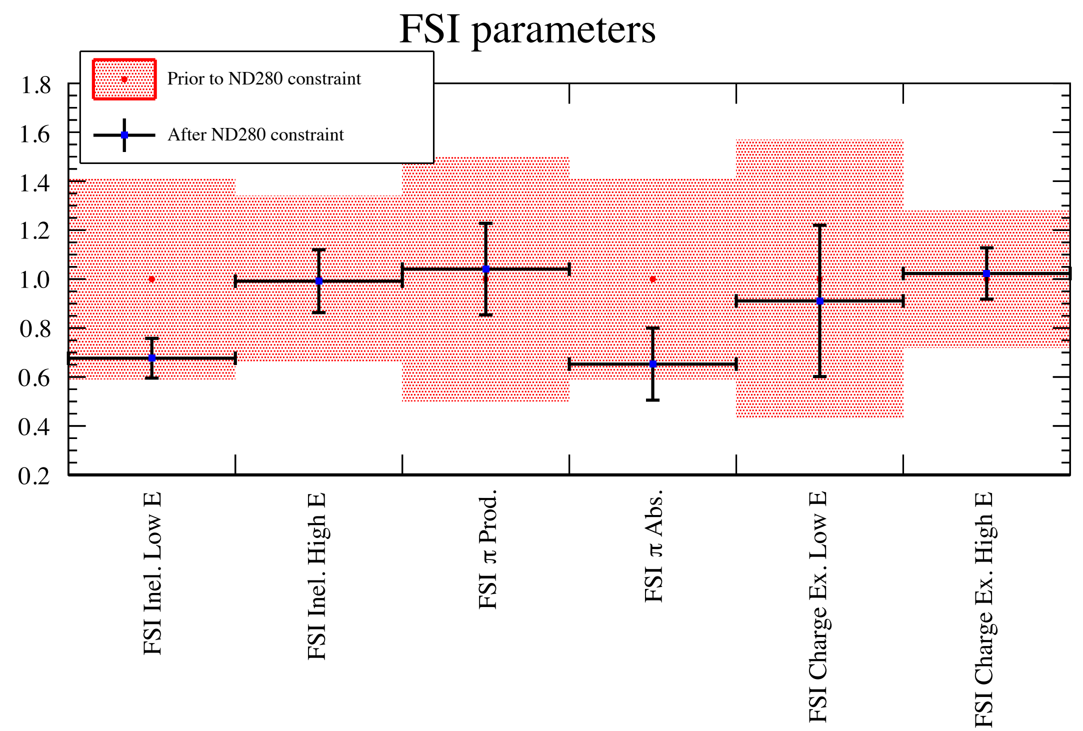
Pull is anti-correlated with increases in cross section.

Near Detector Constraint

- Some cross-section uncertainties better constrained by near detector than others.

Pion and FSI parameters effectively constrained by separation of pion multiplicity at ND280





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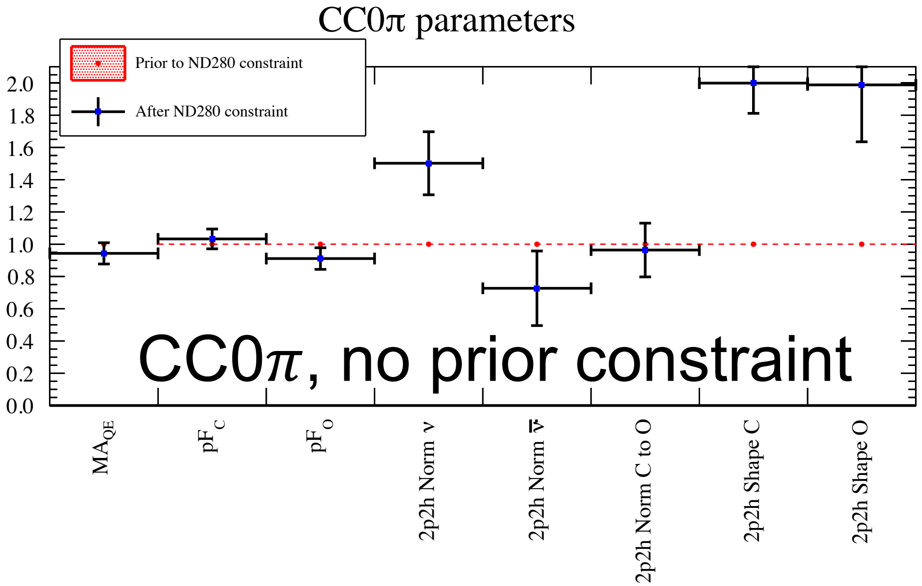
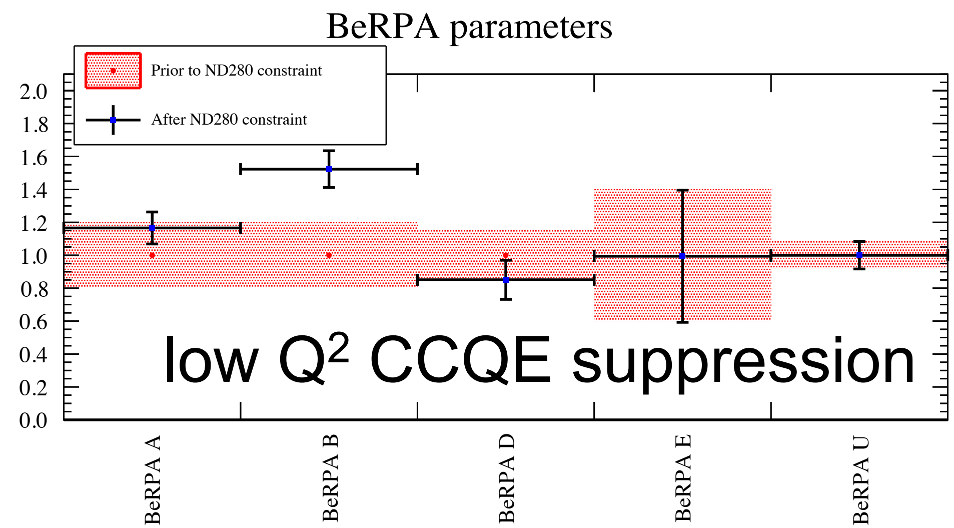
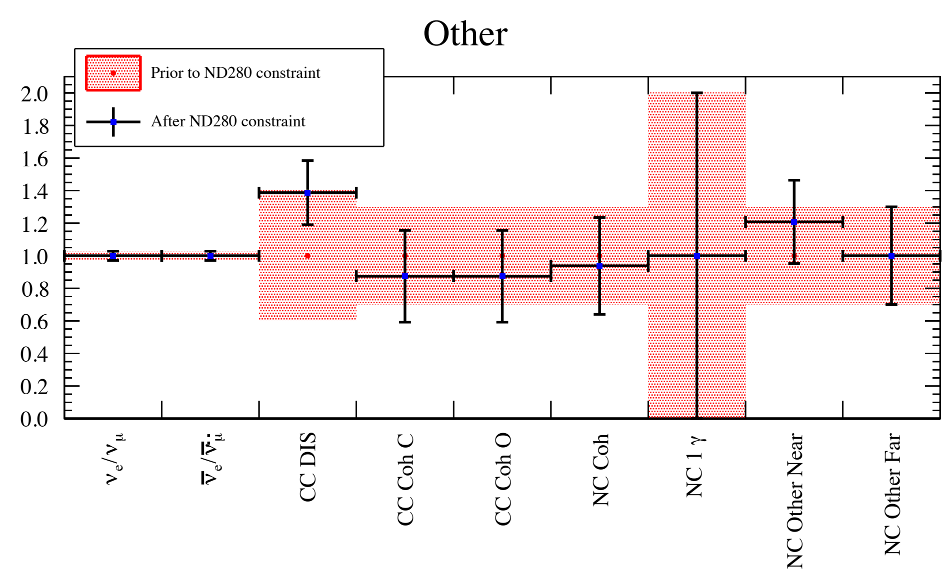


2p2h parameters





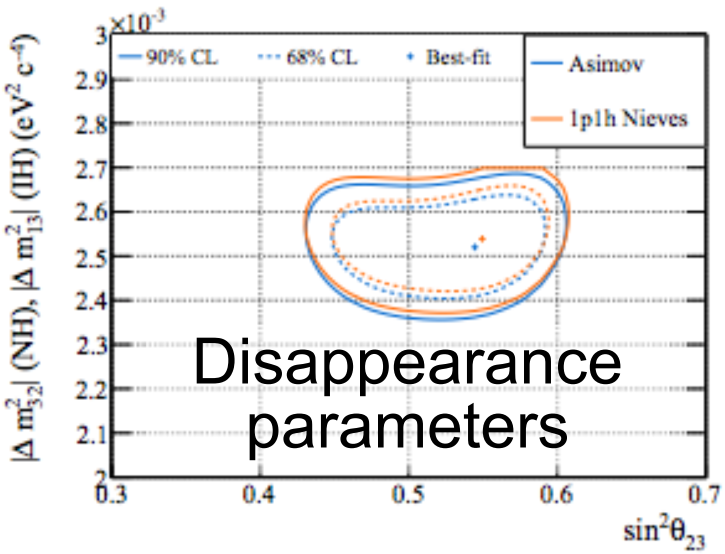
Counting Experiment Systematics with Constraint

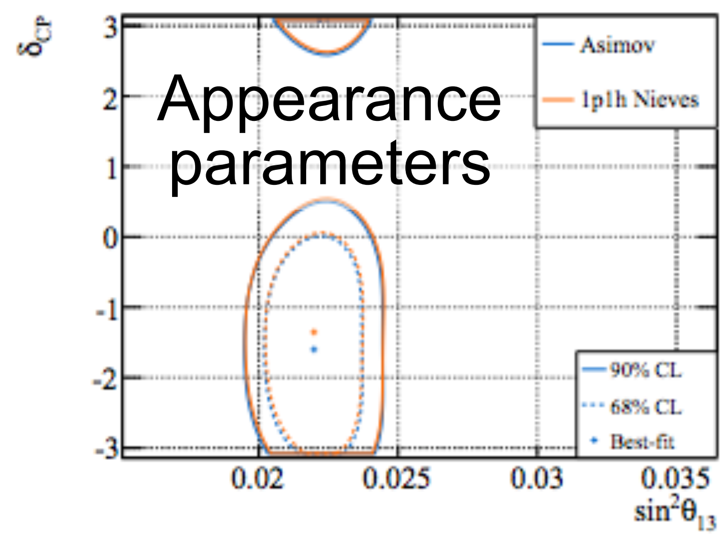
	1-Ring μ		1-Ring e			
Error source	FHC	RHC	FHC	RHC	FHC 1 d.e.	FHC/RHC
SK Detector	2.40	2.01	2.83	3.79	13.16	1.47
SK FSI+SI+PN	2.20	1.98	3.02	2.31	11.44	1.58
Flux + Xsec constrained	2.88	2.68	3.02	2.86	3.82	2.31
E_b	2.43	1.73	7.26	3.66	3.01	3.74
$\sigma(\nu_e)/\sigma(\bar{\nu}_e)$	0.00	0.00	2.63	1.46	2.62	3.03
NC1γ	0.00	0.00	1.07	2.58	0.33	1.49
NC Other	0.25	0.25	0.14	0.33	0.99	0.18
Osc	0.03	0.03	3.86	3.60	3.77	0.79
All Systematics	4.91	4.28	8.81	7.03	18.32	5.87
All with osc	4.91	4.28	9.60	7.87	18.65	5.93

Fractional uncertainties (%)

Alternate Models

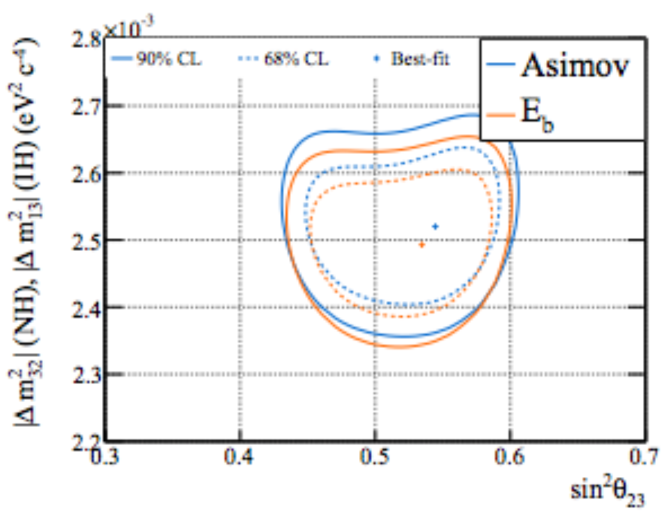
- Studies of alternate models difficult in reweighting framework. "Simulated data" study to measure effects.

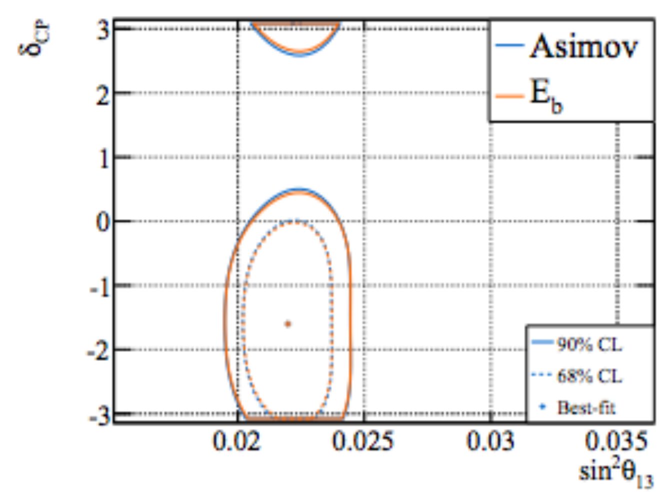




Alternate IS model (local Fermi gas, Nieves et al.)

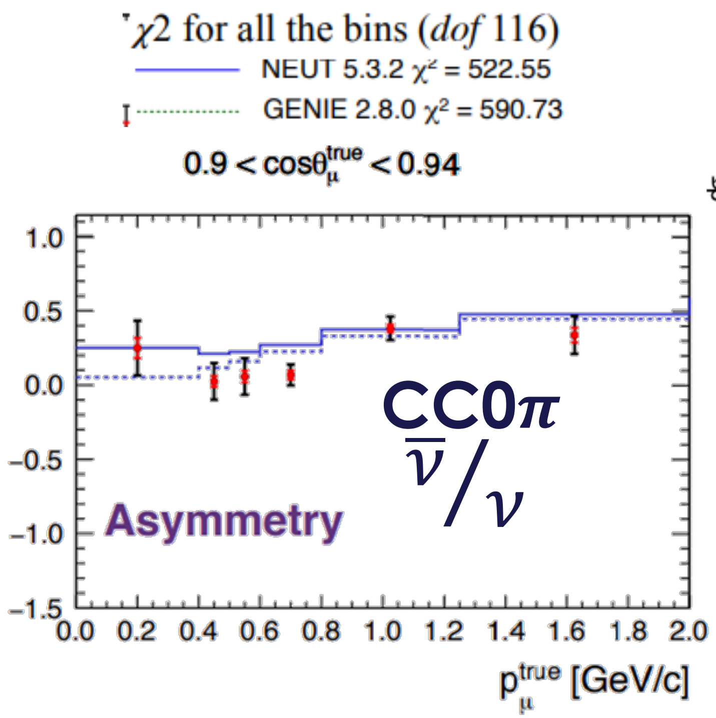
E_b from 25&27 MeV to 43&45 MeV

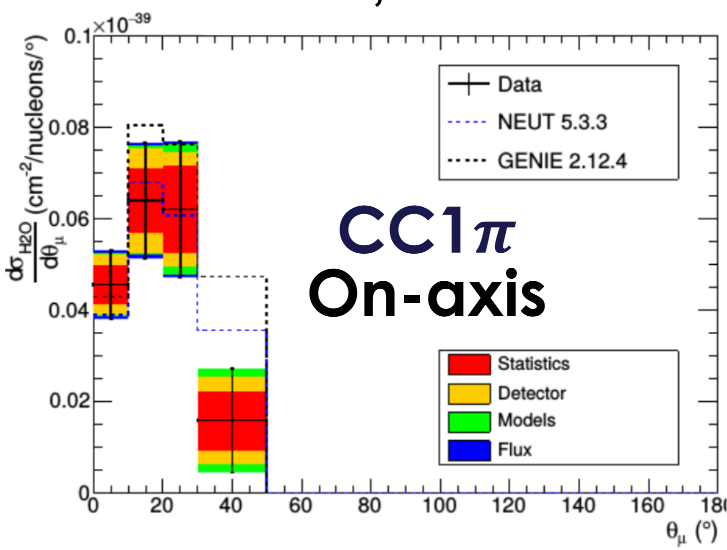




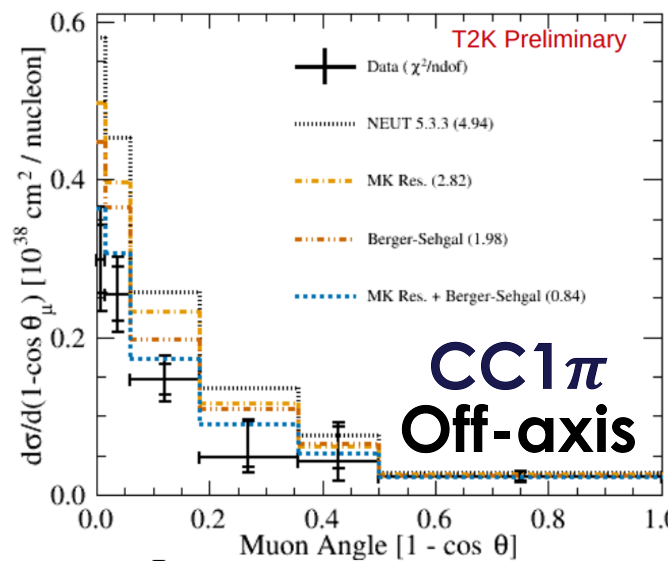
T2K Measurements: Lepton kinematics for 0, 1π States

- Typically more pure, exclusive selections than near detector constraint samples.
  - Use to inform model choices, but don't measure parameters.



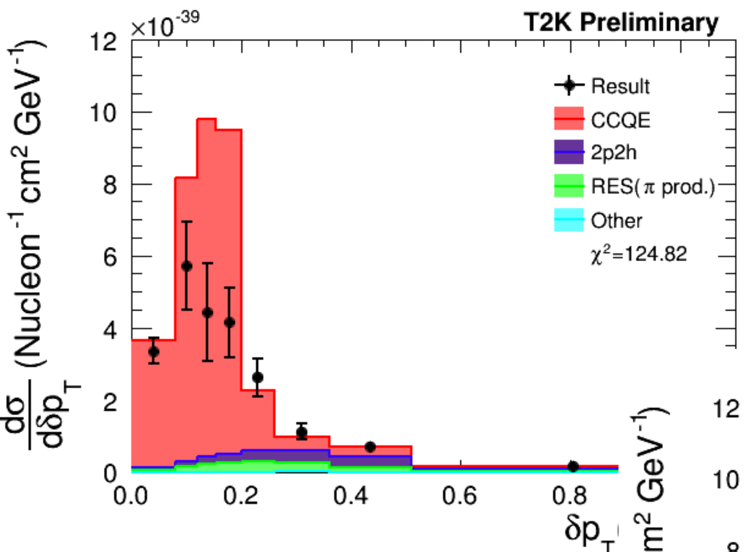


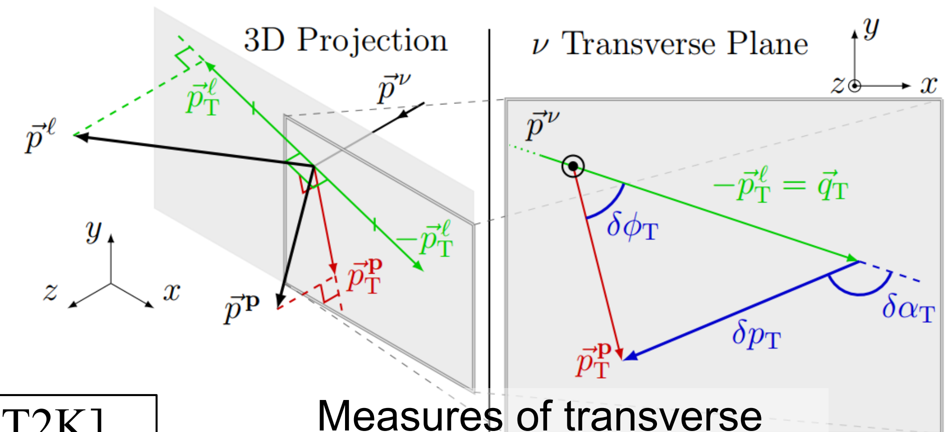
Recent T2K measurements from NuINT 2018



T2K Measurements: Lepton-Hadron Correlations

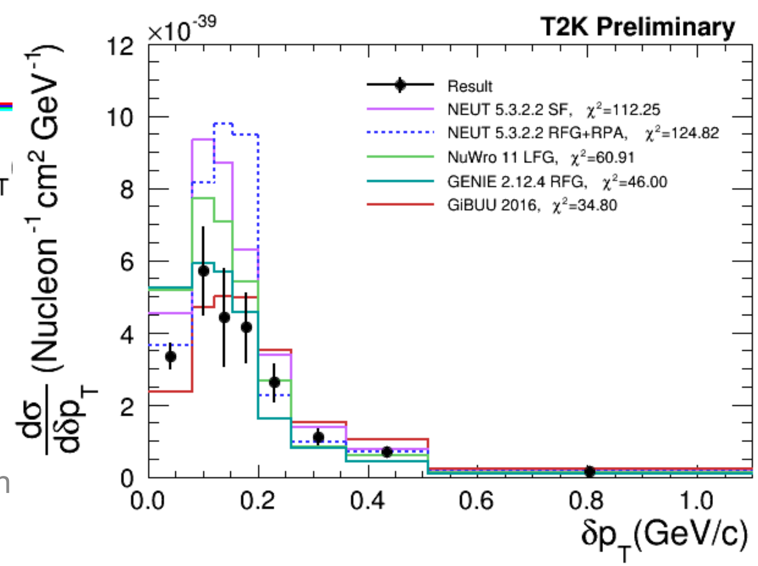
- Correlations do not enter in near detector fit.
- Correlations can measure nuclear model features.

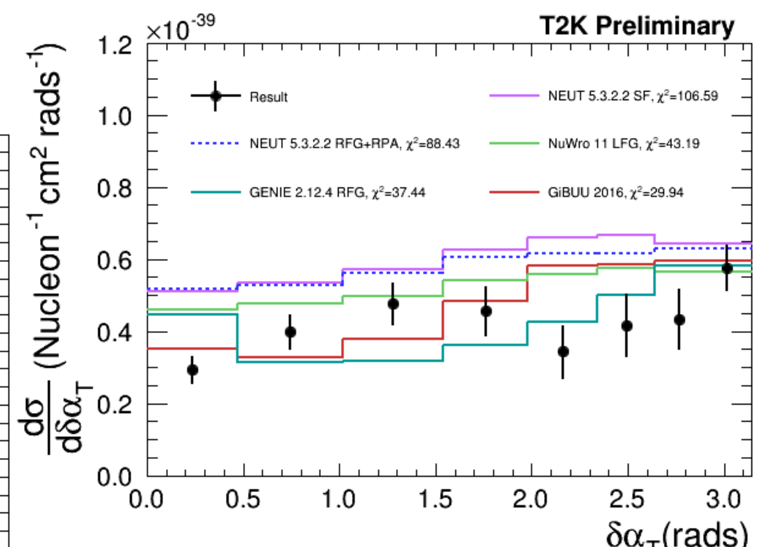




Measures of transverse kinematic balance

K. Abe et al [T2K] Phys.Rev. D98 (2018) 032003



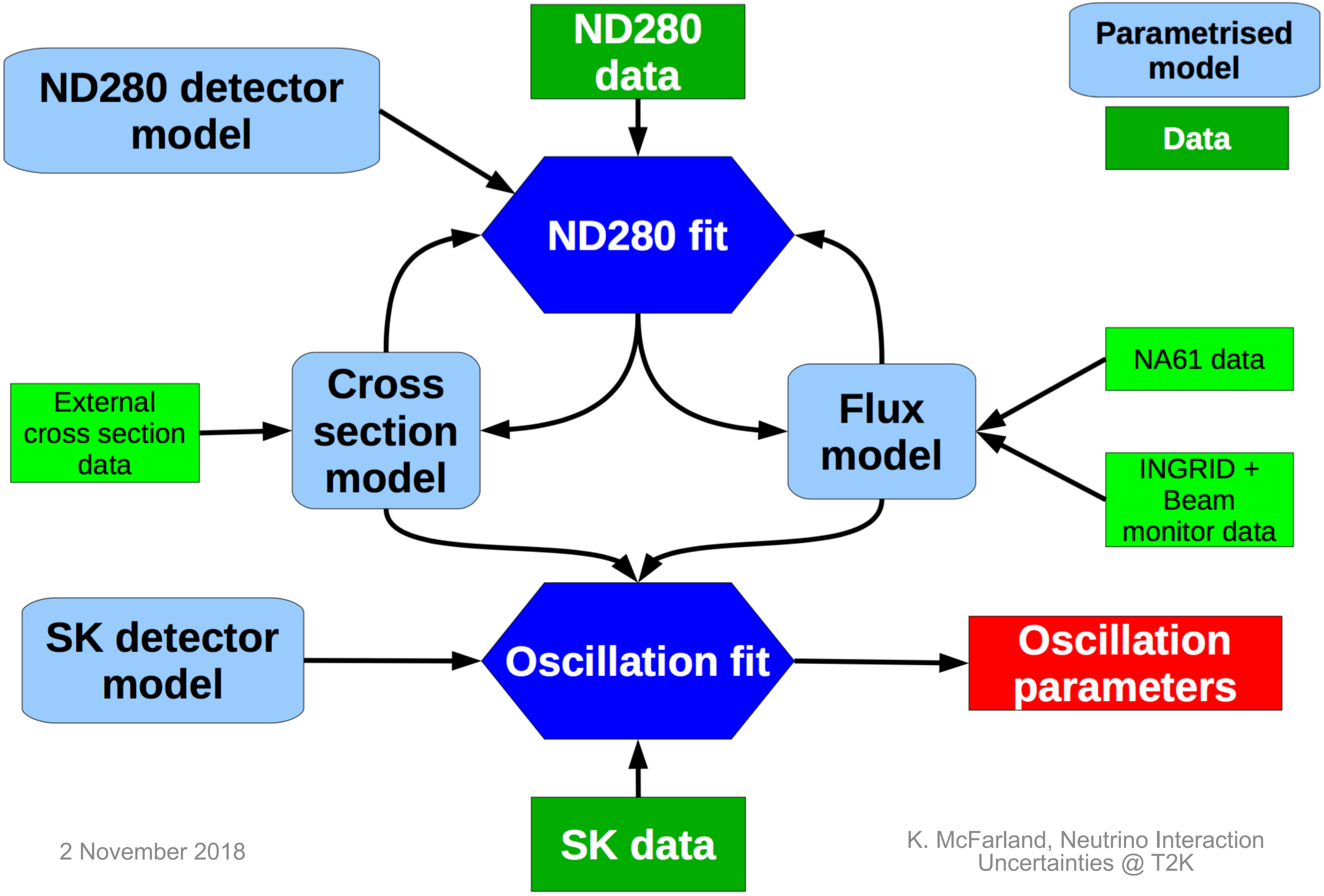


CONCLUSIONS

Conclusions

- T2K interaction model has evolved significantly throughout the lifetime of the experiment
  - Nuclear initial state, 2p2h, are usually biggest concerns. Significant freedom in assumptions.
  - Nucleon level inelastic models and flavor dependent effects also noticeable contributors.
- Working to reduce uncertainties through measurements with near detector, analyzing other data, improving models.

Schematic of Osc. Analysis



Graphic by Mark Scott