Long-Baseline Neutrino-Nucleus Interaction Systematics

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Measuring ν Oscillations

$$N_{pred}(E_\nu^{reco}) = \Phi(E_\nu^{true}) \boxed{\sigma(E_\nu^{true})} \boxed{P(\alpha \rightarrow \beta, E_\nu^{true})} \epsilon(E_\nu^{true}) S(E_\nu^{true}, E_\nu^{reco})$$

$N_{pred}(E_\nu^{reco})$ = Expected number of events

$\Phi(E_\nu^{true})$ = Neutrino flux

$\sigma(E_\nu^{true})$ = Interaction cross sections

$P(\alpha \rightarrow \beta, E_\nu^{true})$ = Oscillation probability

$\epsilon(E_\nu^{true})$ = Selection efficiency

$S(E_\nu^{true}, E_\nu^{reco})$ = Smearing matrix

How can uncertainties on cross sections mimic the effects of oscillation parameters on analysis spectra?

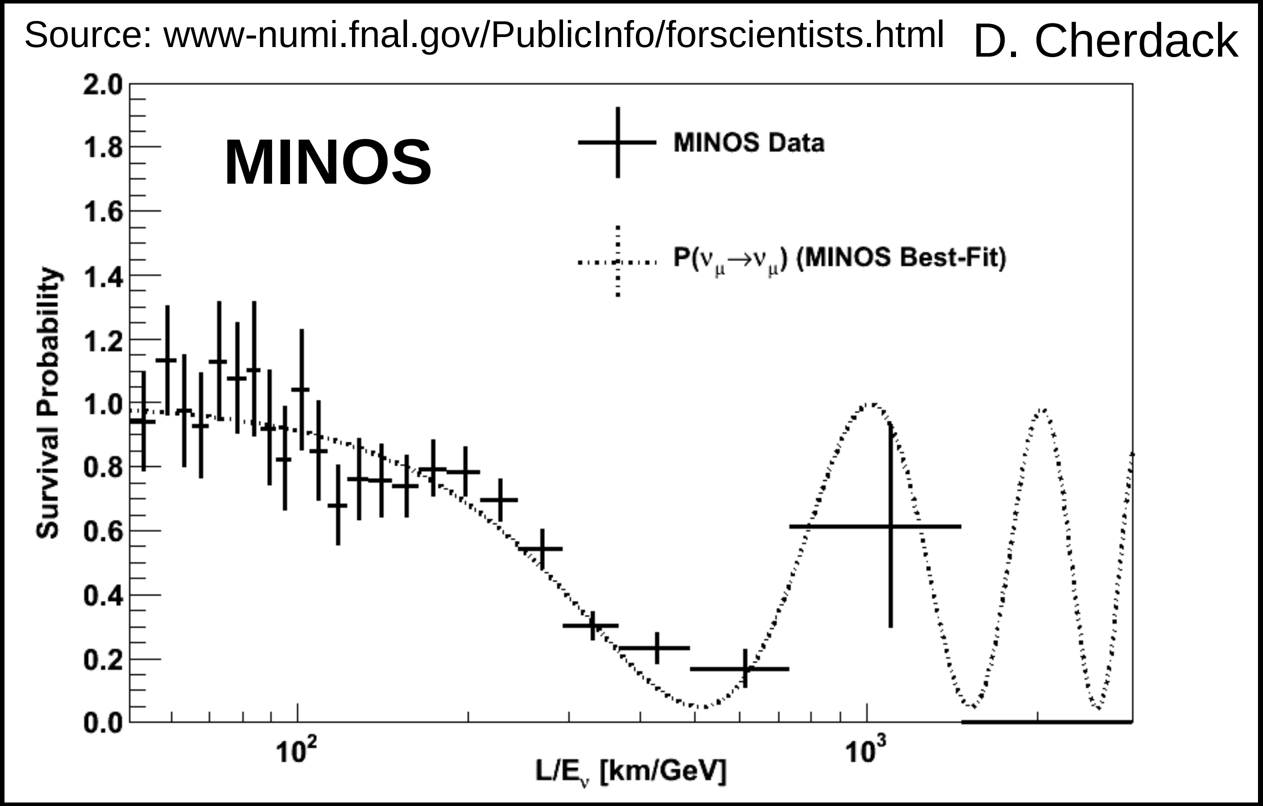
Review of Experiments Discussed

Experiment	Baseline [km]	Peak Energy [GeV]	Flux Width	Identical ND	FD Target	Primarily Sensitive to (so far)
MINOS	735	3	Broad Band	yes	Iron	$\mathbf{\Delta m^2_{32}}$ θ_{23}
T2K	295	0.6	Narrow Band	no	Water	$\boldsymbol{\theta_{13}}$ θ_{23}, Δm^2_{32}
NOvA	810	2	Narrow Band	yes	CH	$\boldsymbol{\theta_{23}}$ θ_{13}, Δm^2_{32}/MH
DUNE	1300	2.5	Broad Band	?	Argon	Budget Cuts

Statistical Limitations of Data Samples

- Review current and possible future long-baseline ν oscillation data as a function of L/E_ν
- “Where we are now” versus “where we hope to get”
- Compare oscillation probability variations with statistical uncertainties
- Sets the scale for experimental sensitivities and systematic uncertainty targets
- Note the difference between best-fit oscillation probabilities (true E_ν) and data (reco. E_ν)

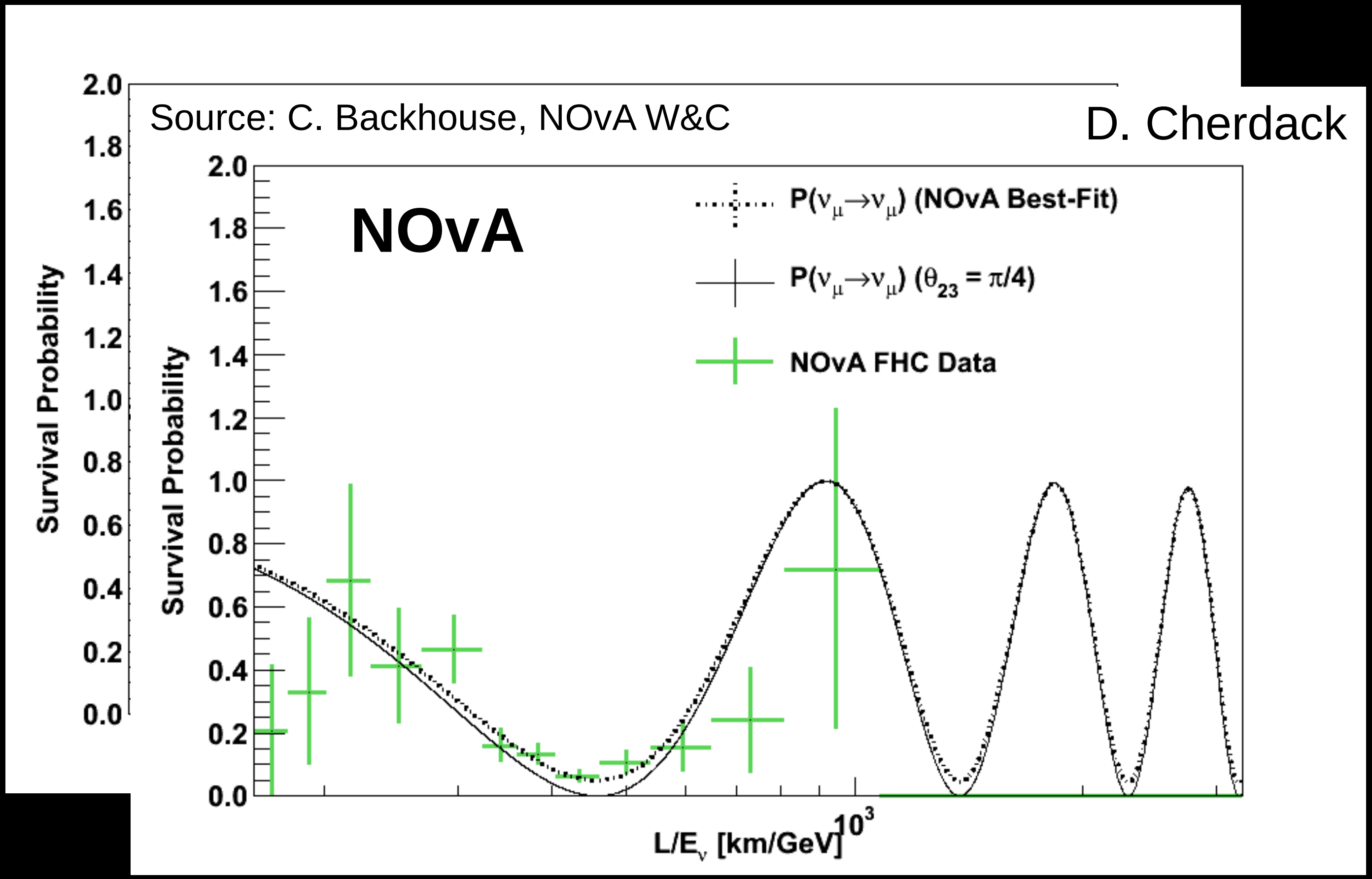
ν_μ Disappearance in L/E_ν



- Plot of MINOS ν_μ data as a function of L/E_ν
- Good stats along falling edge constrain Δm^2_{32}
- Low statistics near oscillation minimum limit θ_{23} resolution
- All errors stat only

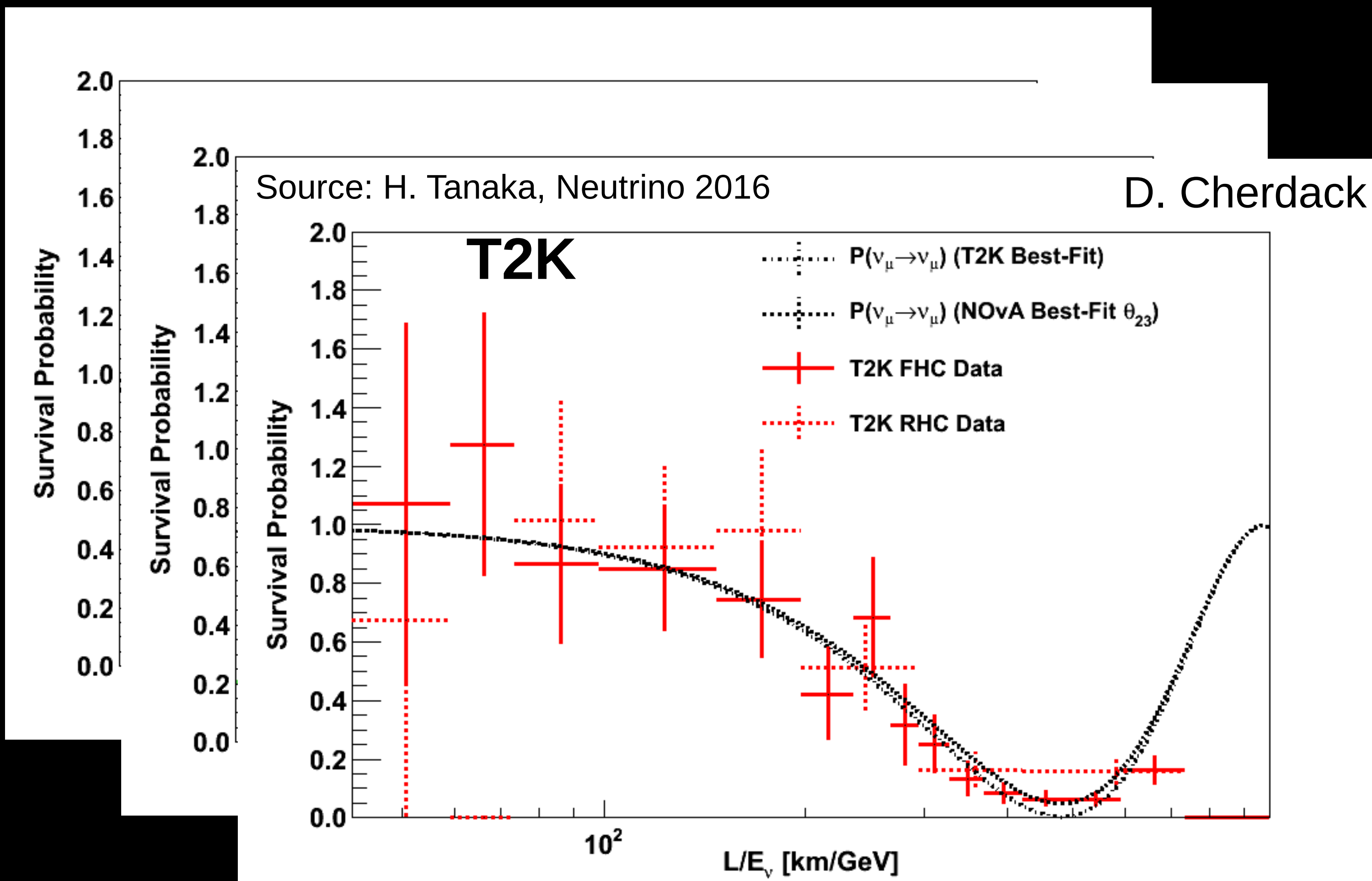
- How does this compare with NOvA, T2K, and prospects for DUNE?

ν_μ Disappearance in L/E_ν



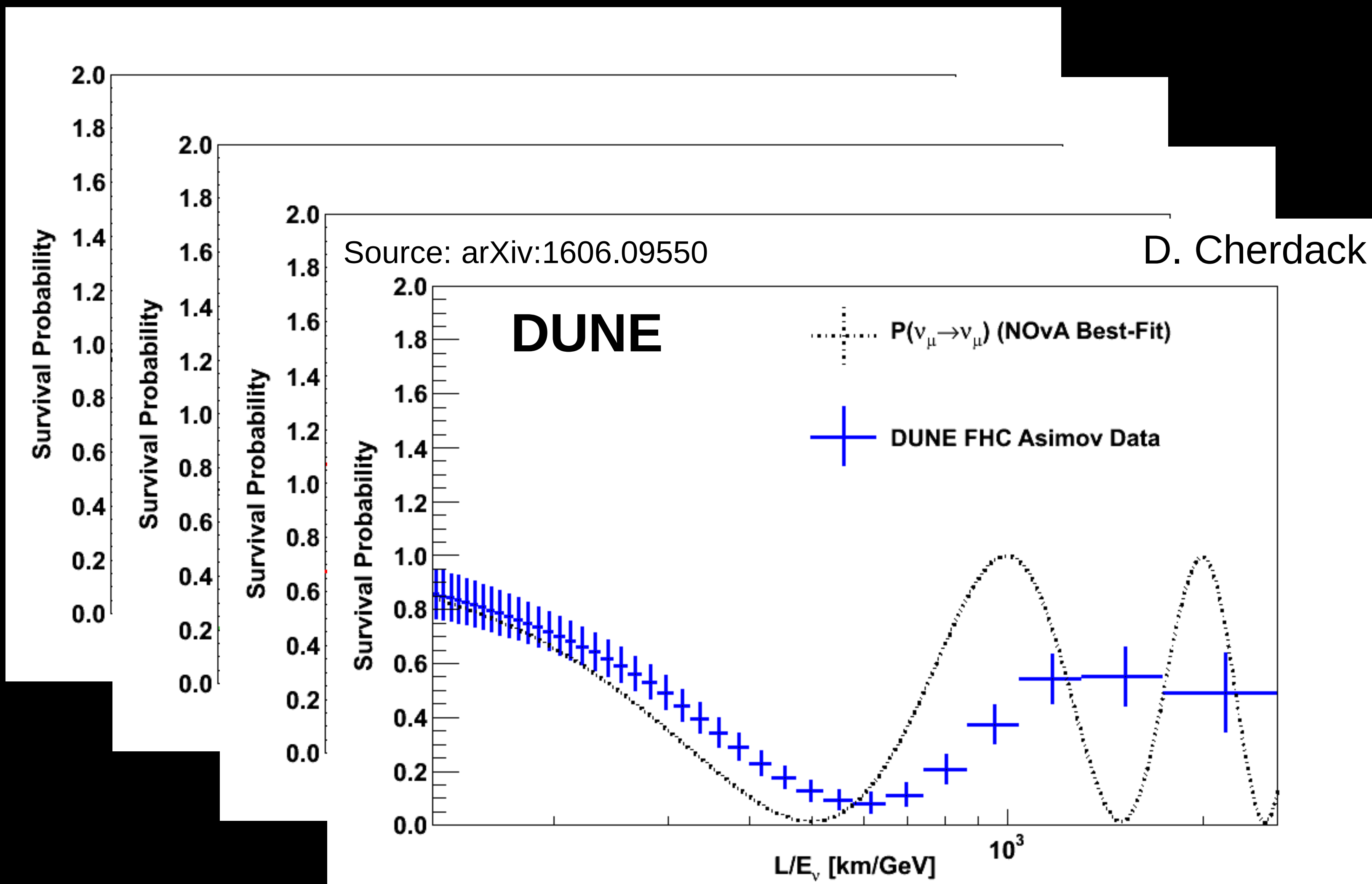
- NOvA has excellent statistics at the oscillation minimum and can exclude maximal mixing at ~2.5σ

ν_μ Disappearance in L/E_ν



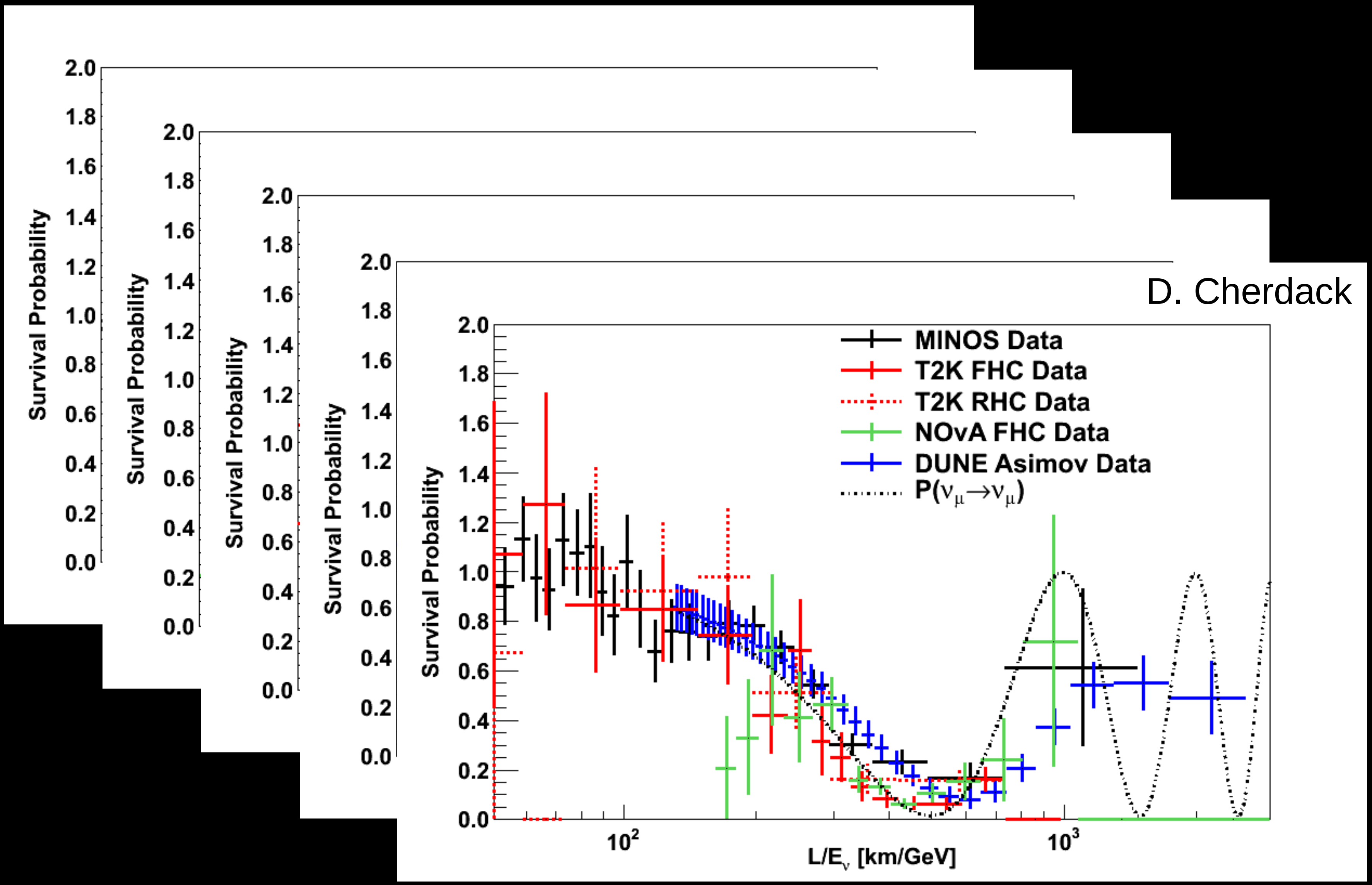
- T2K also has excellent statistics at the oscillation minimum (and $\bar{\nu}_\mu$ data too), and is still consistent with maximal mixing

ν_μ Disappearance in L/E_ν

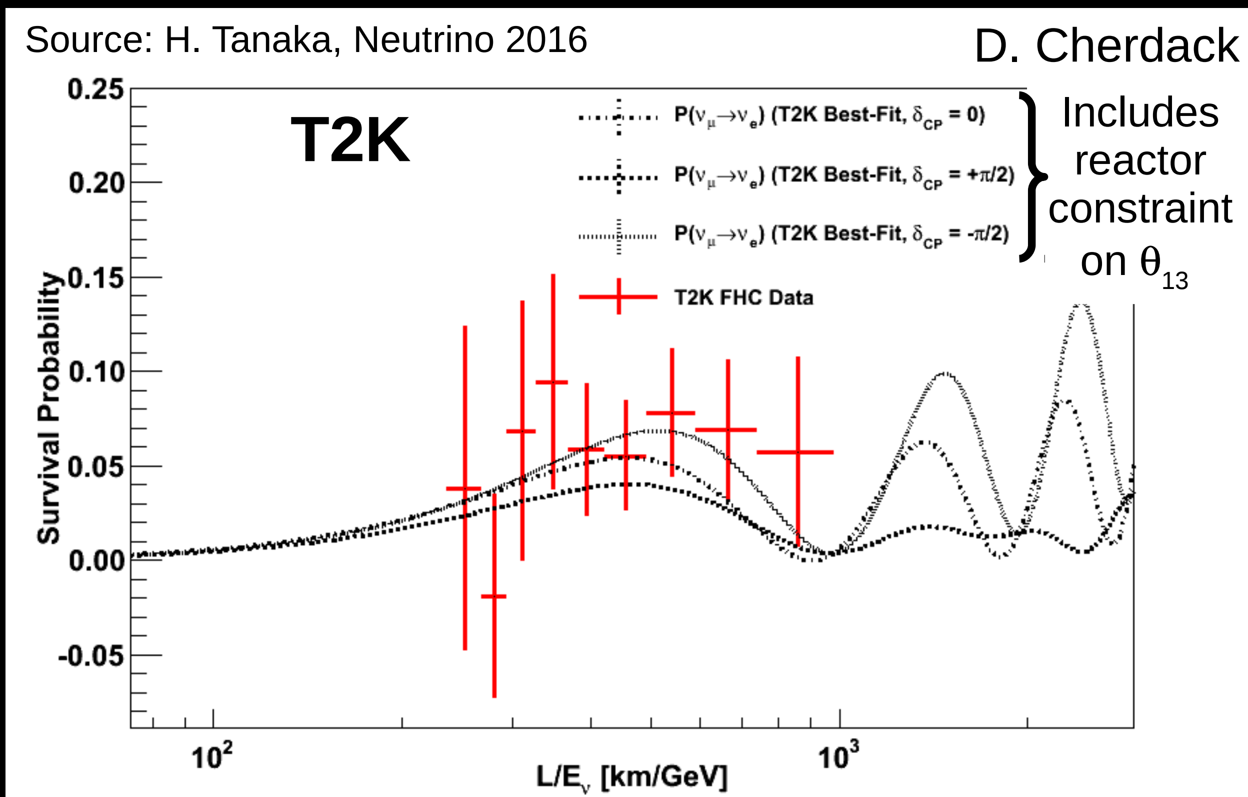


- DUNE will have good statistics over a broad range of L/E

ν_μ Disappearance in L/E$_\nu$



ν_e Appearance in L/E_ν

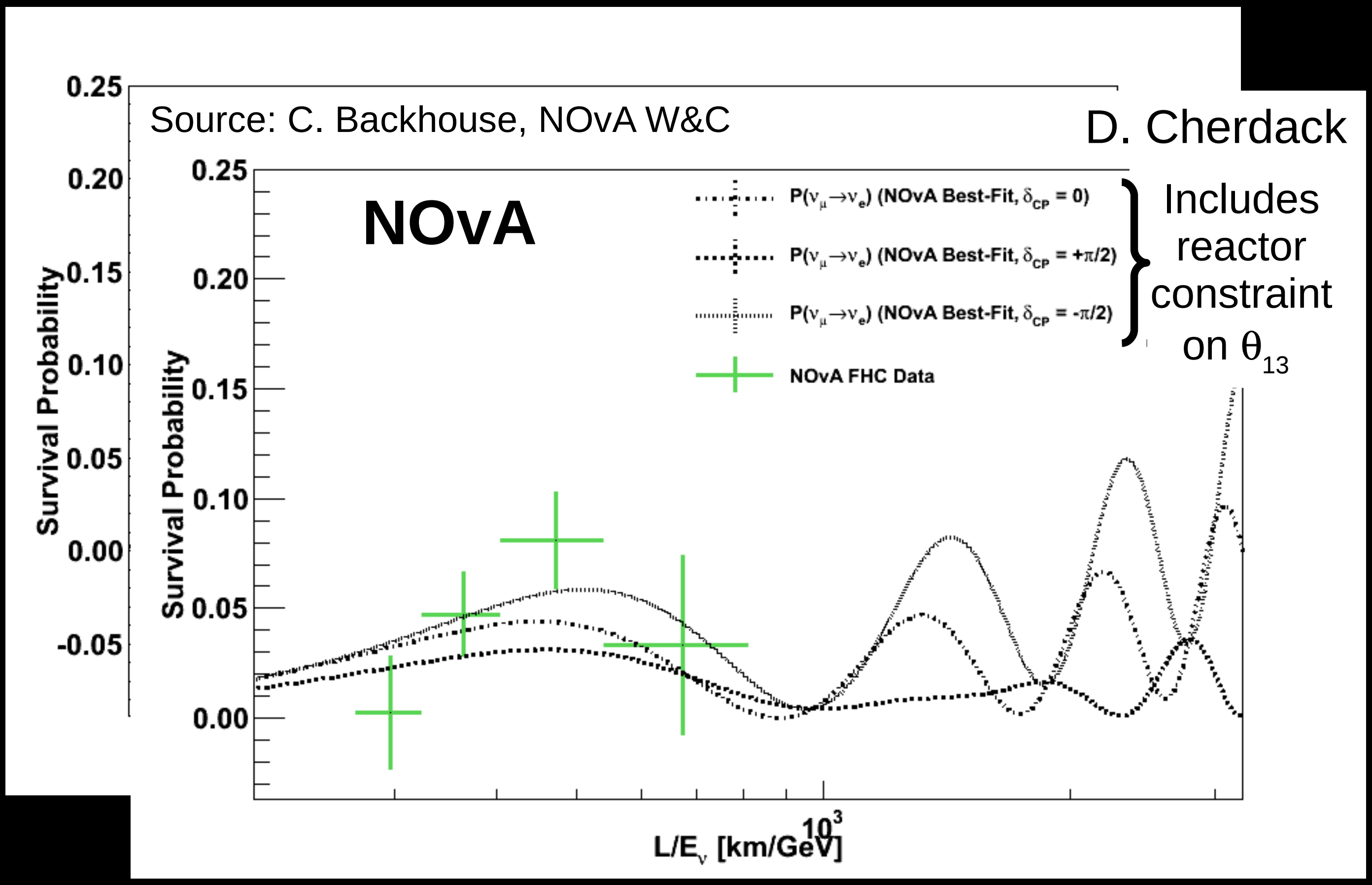


- Plot of T2K ν_e data as a function of L/E_ν
- Discovery of long-baseline ν_e appearance
- First $\bar{\nu}_e$ events (not shown)
- Clearly pulls toward

  $\delta_{CP} = -\pi/2$, with reactor constraint
- Data prefer $\delta_{CP} = -\pi/2$, but statistical uncertainties cover wide range of allowed δ_{CP}

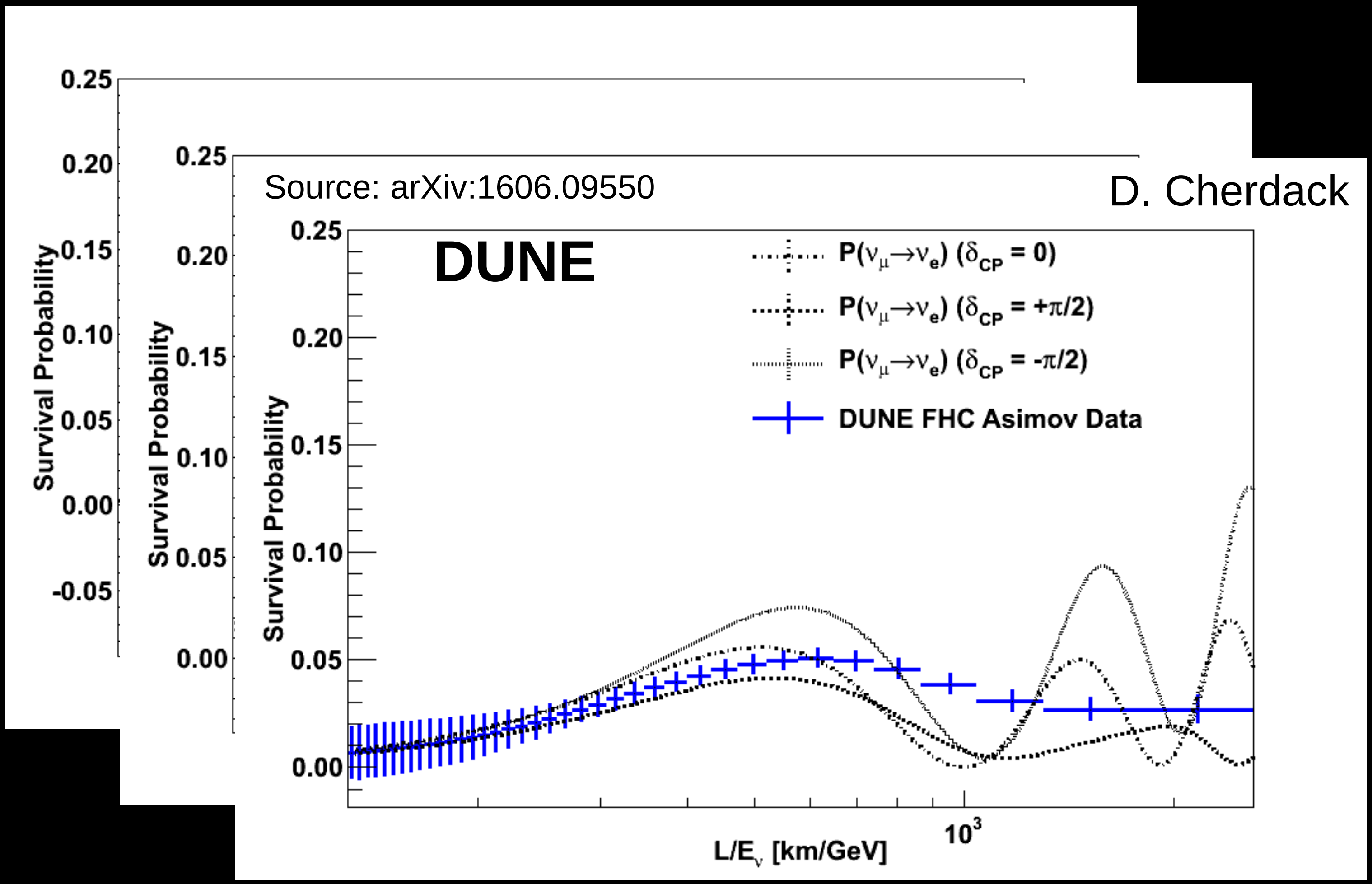
- How does this compare with NOvA, and prospects for DUNE?

ν_e Appearance in L/E_ν



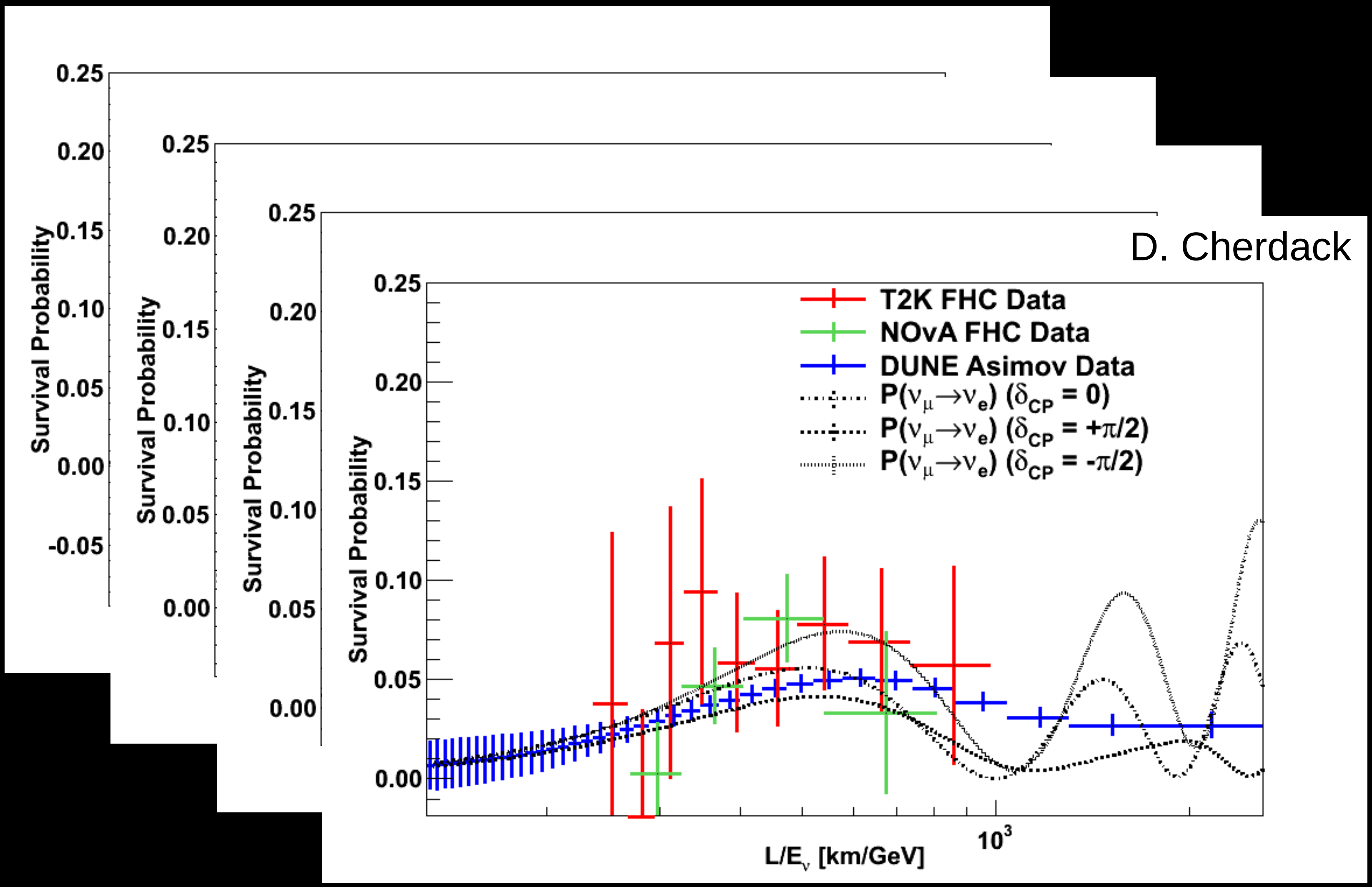
- NOvA is quickly compiling statistics, and also favors δ_{CP} = -π/2, but is still very statistically limited

ν_e Appearance in L/E_ν

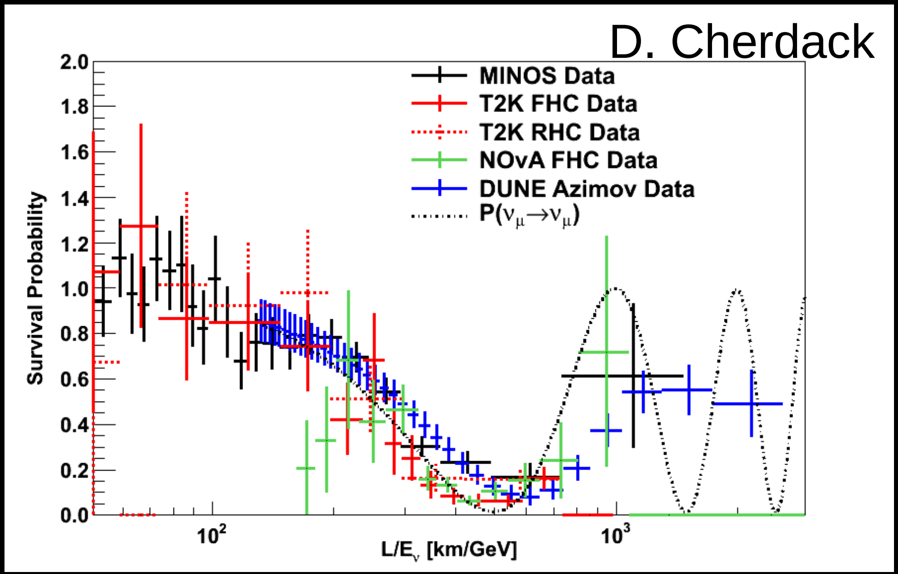


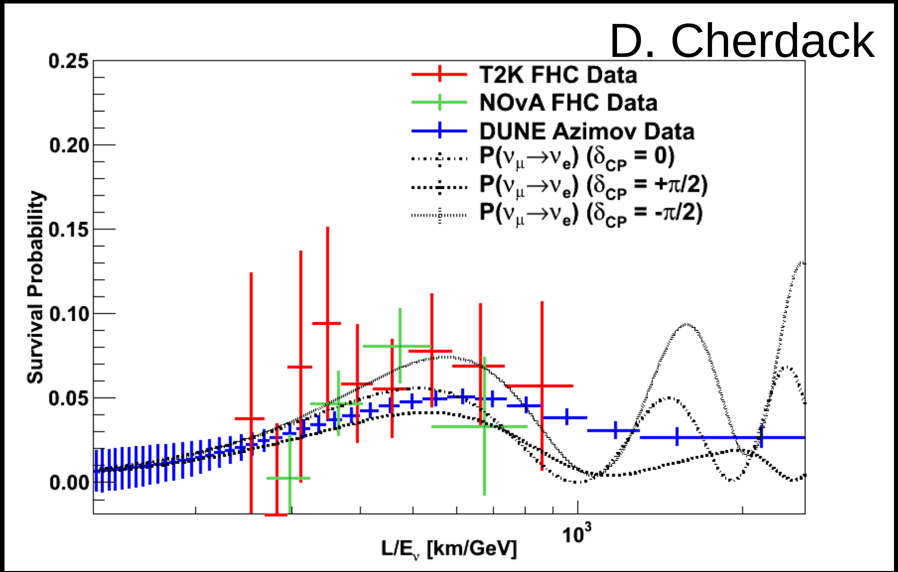
- DUNE will cover a wide range in L/E, and will have the statistical power to discern the value of δ_{CP}

ν_e Appearance in L/E_ν



Statistical Limits vs. Systematics

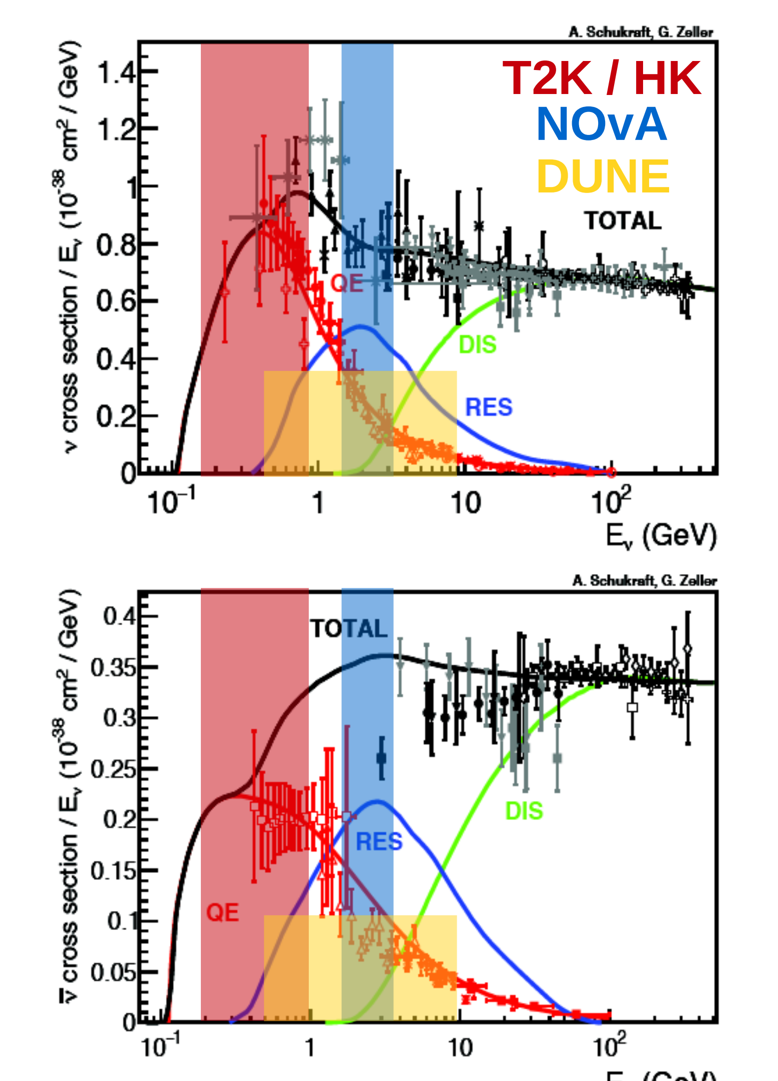




- Current measurements are statistically limited
- Requirements for systematic constraints set by statistical limits
- Continued running and next generation experiments will require increasingly strong systematic constraints
- Four sample fits provide some systematic cancellations
  - ν_μ dis + $\bar{\nu}_\mu$ dis + ν_e app+ $\bar{\nu}_e$ app
  - Systematics that mimic oscillation parameter changes still dangerous
- Energy scale systematics are crucial
- What do we already know and what can we learn from current experiments? …

Cross Sections of Interest

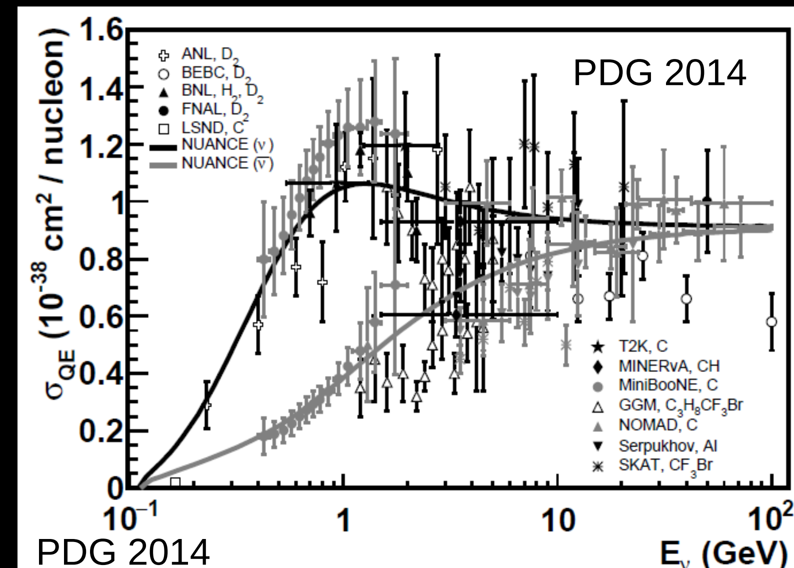
- The energy range of the flux determines the cross sections of interest
- T2K / HK
  - Mostly quasi-elastic
  - Some single pion production
  - Very few DIS
- NOvA
  - Mostly single pion production
  - Some quasi-elastic
  - Some DIS
- DUNE
  - Wide-band beam
  - All three contribute roughly equally

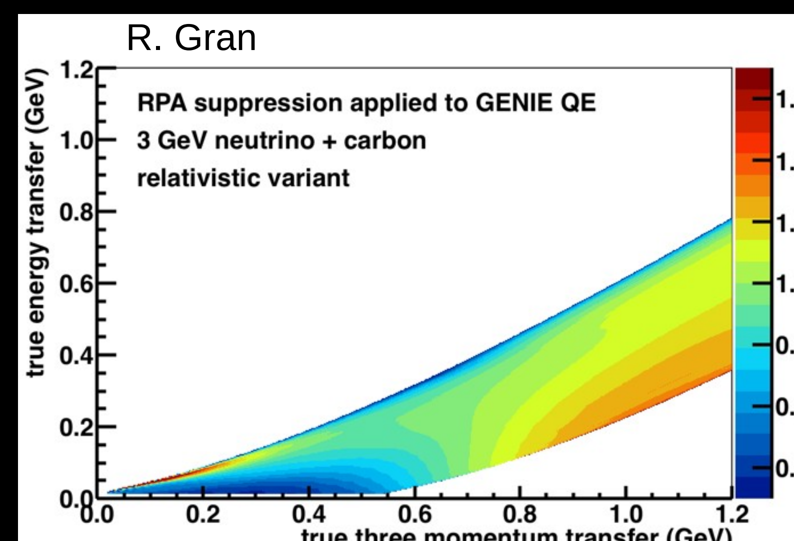


Adapted/updated from
J.A. Formaggio, G.P. Zeller, Rev. Mod. Phys. 84 (2012) 1307

Cross Section Models: Quasi-elastic (QE)

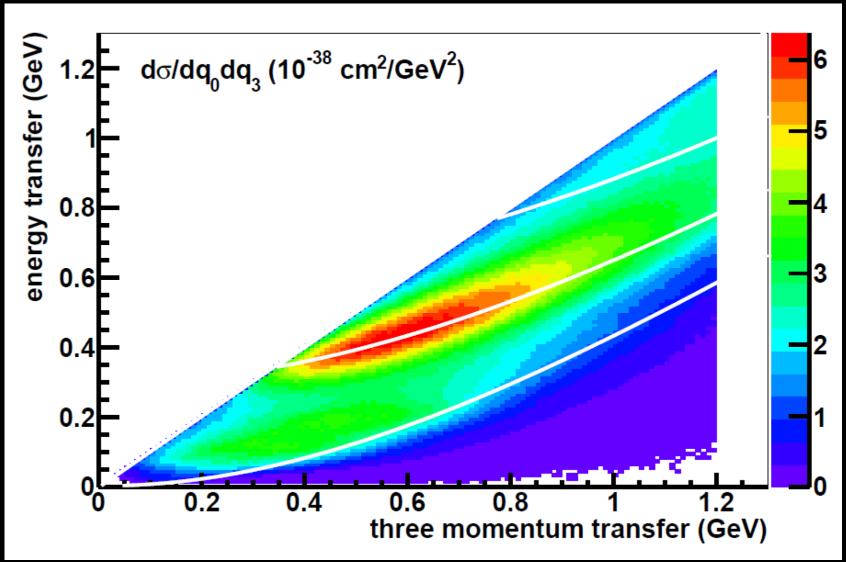
- Well understood ν-N interaction model
  - Single free parameter, M_A, of the axial form factor
  - All other free parameters measured in electron scattering
  - M_A measured to a few % in ^1H & ^2D bubble chamber data
- Measurements on nuclear matter have been less conclusive
  - Low Q^2 means nucleon momenta are important
  - Nuclear models are “too good to be true or too true to be good”
  - M_A has been used as an effective parameter to describe nuclear effects (poorly)
  - Ongoing work to implement and test new nuclear models (1p1h, SF, RPA corrections)



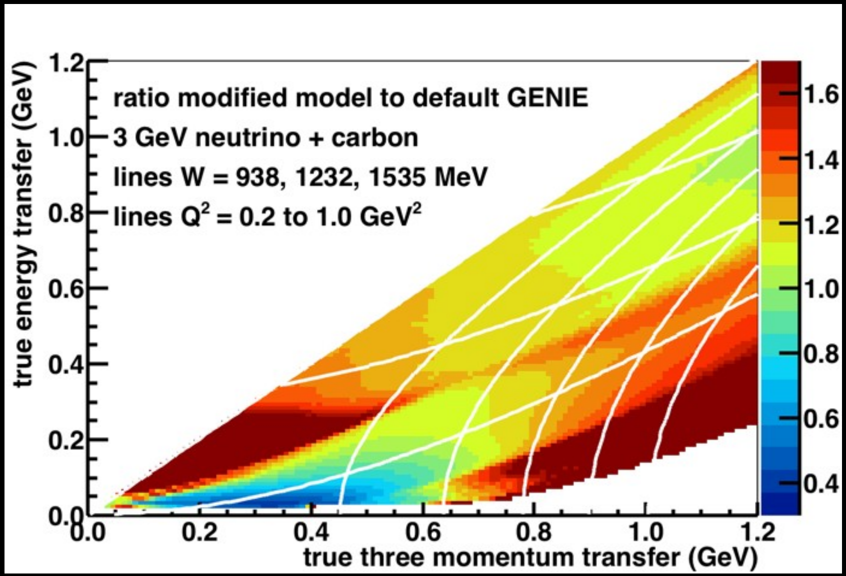


Cross Section Models: Quasi-elastic (QE)

- Other processes can look like QE (produce CC0π interactions)
  - Interactions on correlated nucleon pairs (2p2h)
  - Interactions on nuclear exchange particles (MEC)
  - Interactions involving virtual delta particles / excited nucleon states (PDD)
  - FSI induced CC0π (e.g. π abs)
- Need high-statistics, low nucleon detection threshold, data to untangle all contributions to CC0π interaction processes



R. Gran, arXiv:1601.02038



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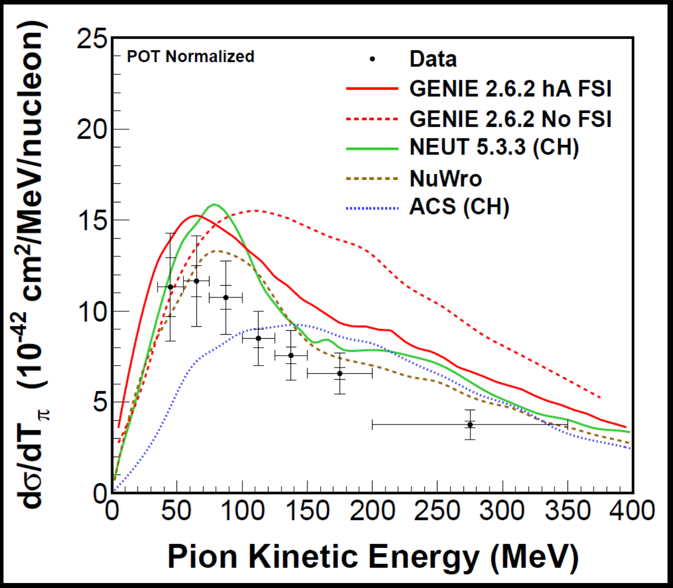
Cross Section Models: Single π Production

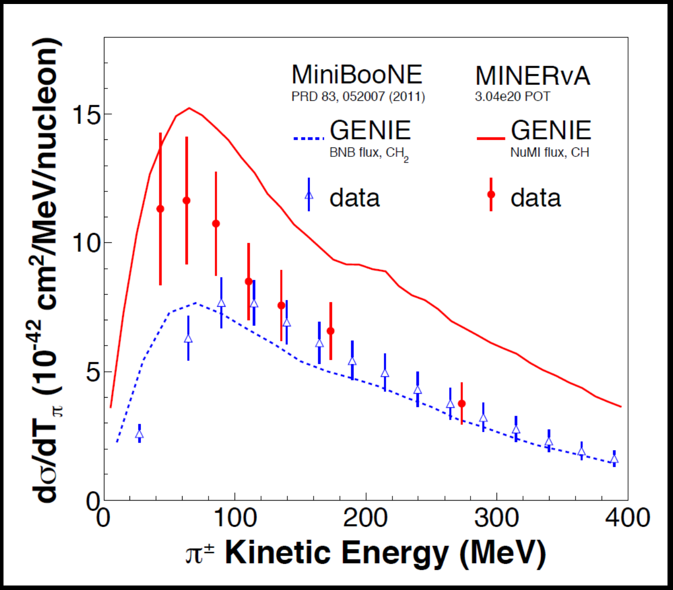
- Many contributing channels
  - Resonance production
  - DIS single pion production
  - Resonance-DIS interference
  - Pionless Δ decay
  - Coherent scattering
  - FSI-induced pion production

Negative Contributions?

- Misidentified pions are the largest source of oscillation analysis backgrounds
  - Predicting pion kinematics very important
  - Data disagree with models
  - Data disagree across experiments



arxiv: 1406.6415v3



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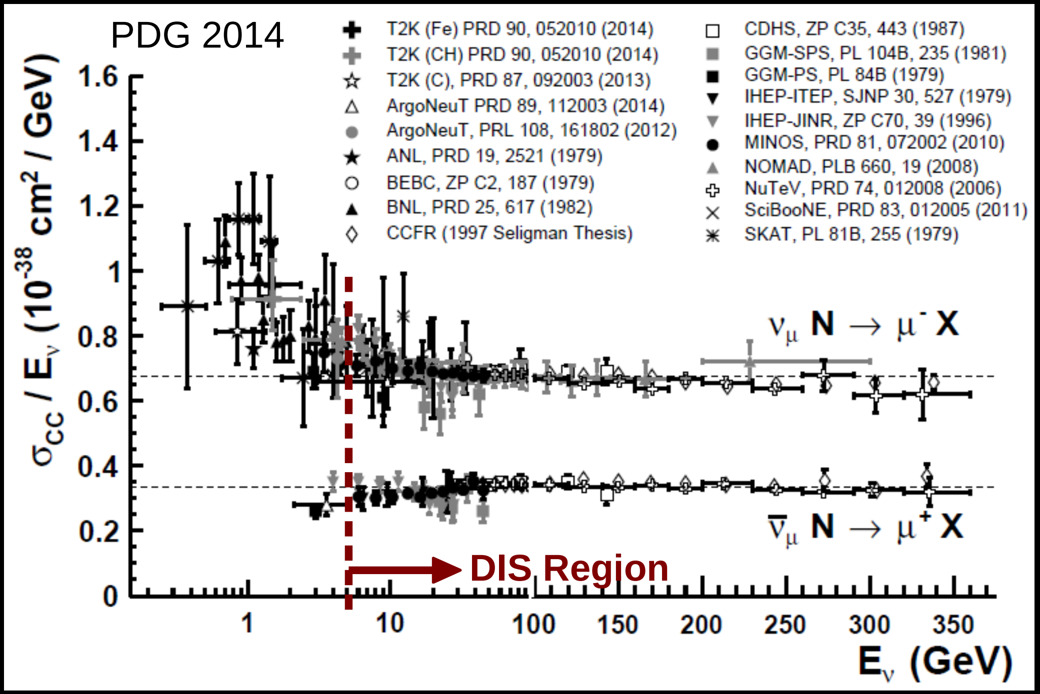
Cross Section Models: Deep Inelastic Scattering (DIS)

- Inclusive DIS is well modeled and constrained by ν-N interaction data
- Exclusive channel rates are much harder to predict and measure
  - Hadronization models have large uncertainties and are difficult to reweight
  - Hadronization models are especially tricky in the low W^2 region important for oscillation experiments
  - Formation zone uncertainties complicate estimates of FSI effects
  - High multiplicity events are difficult to reconstruct and thus exclusive channel selections are ineffective



- Exclusive channel measurements are important for estimating misidentified pion induced background rates

T2K Cross Section Model Parameterization

- The T2K beam is narrow band, peaking at 600 MeV
- Mostly QE events
  - Large impact from nuclear initial-state models
  - Multi-nucleon interactions contributions are important
  - A-scaling uncertainties
- Some single-π and a few DIS events
- Flux parameters are bin normalizations in true E_ν
- Detector response uncertainties
  - Ignoring here for brevity
  - Uncertainties are marginalized over in fit results

- CC0π events
  - QE axial mass (M_A^{QE})
  - Binding energy (Eb)
  - Fermi momentum (p_F)
  - Multi-nucleon (MEC)

  Separate Parameters For ^{12}C and ^{16}O

- Resonance Events
  - Res. axial mass (M_A^{RES})
  - C_5^A ($CA5^{RES}$)
  - I=½ backgrounds

  Separate ν and $\bar{\nu}$ Parameters

- Other interactions
  - CC other shape
  - CC coherent
  - NC coherent
  - NC other
- Final State interactions x6 (FSI)

T2K Cross Section Model Parameterization

Cross Section Parameter	Prefit
M_A^{QE} (GeV/c^2)	1.2 ± 0.069607
p_F ^{12}C (MeV/c)	217.0 ± 12.301
MEC ^{12}C	100.0 ± 29.053
E_B ^{12}C (MeV)	25.0 ± 9.0
p_F ^{16}O (MeV/c)	225.0 ± 12.301
MEC ^{16}O	100.0 ± 35.228
E_B ^{16}O (MeV)	27.0 ± 9.0
$CA5^{RES}$	1.01 ± 0.12
M_A^{RES} (GeV/c^2)	0.95 ± 0.15
Isospin=$\frac{1}{2}$ Background	1.3 ± 0.2
CC Other Shape	0.0 ± 0.4
CC Coh	1.0 ± 0.3
NC Coh	1.0 ± 0.3
NC Other	1.0 ± 0.3
MEC $\bar{\nu}$	1.0 ± 1.0

Nieves Model

Scaled RS→BS

- CC0π events
  - QE axial mass (M_A^{QE})
  - Binding energy (Eb)
  - Fermi momentum (p_F)
  - Multi-nucleon (MEC)

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Separate ν and $\bar{\nu}$ Parameters

- Other interactions
  - CC other shape
  - CC coherent
  - NC coherent
  - NC other
- Final State interactions x6 (FSI)

Unconstrained FD Parameters

NC Other (far)
NC 1γ
FSI (x6)
CC ν_e/ν_μ & $\bar{\nu}_e/\bar{\nu}_\mu$

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No Priors

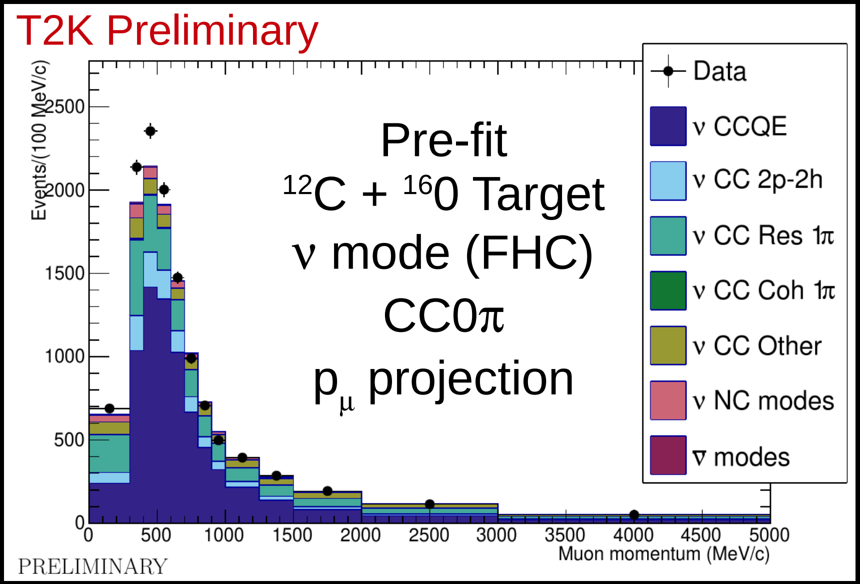
Scaled RS→BS

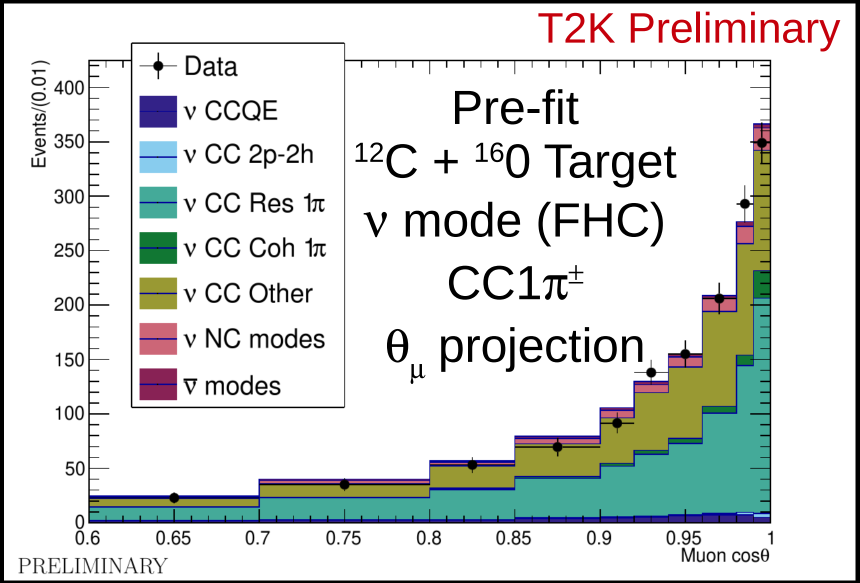
- Fits to external CC0π data disagree with ND280 data
  - MiniBooNE double-differential shape uncertainties not understood
  - MINERνA flux underestimated
  - Explicit or implicit removal of PDD events
- ND280 data now provides strong constraints
- Extracted priors in CC0π tension with ND280 data
- Decision: Use NEUT default values with no priors

ND280 Data-Fitting Procedure

- Inputs (examples on right):
  - Data and MC p_μ-θ_μ spectra by observable channel
    - 7 CC ν_μ samples each on ^{12}C & ^{12}C+^{16}O
    - Samples based in number of π tracks:

      0, 1, N π for ν in FHC (ν mode)
      0, N π for $\nu/\bar{\nu}$ in RHC ($\bar{\nu}$ mode)
  - Prior constraints on:
    - Flux
    - Cross sections (no CC QE)
    - Detector uncertainties
- Fit data to MC within constraints
- Outputs: covariance matrix of constraints on parameters
- Note: There is also a combined ND/FD fit analysis





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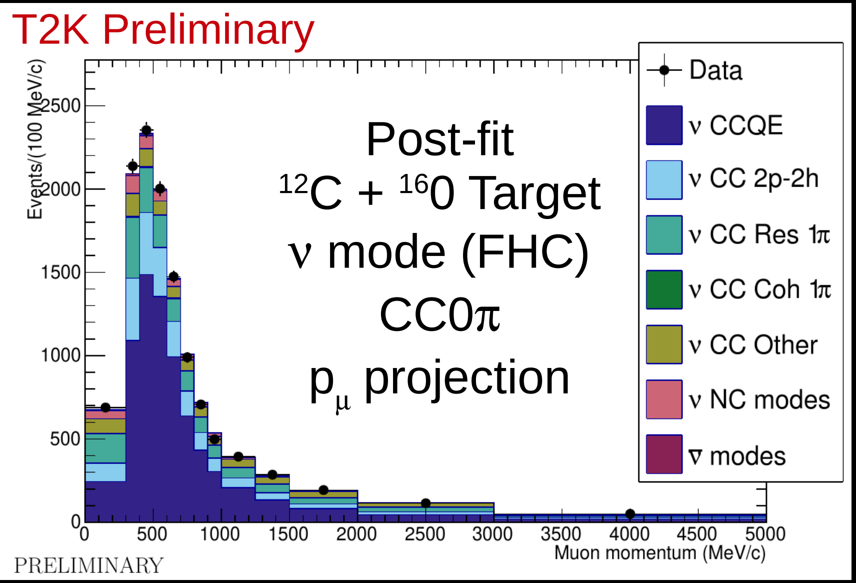
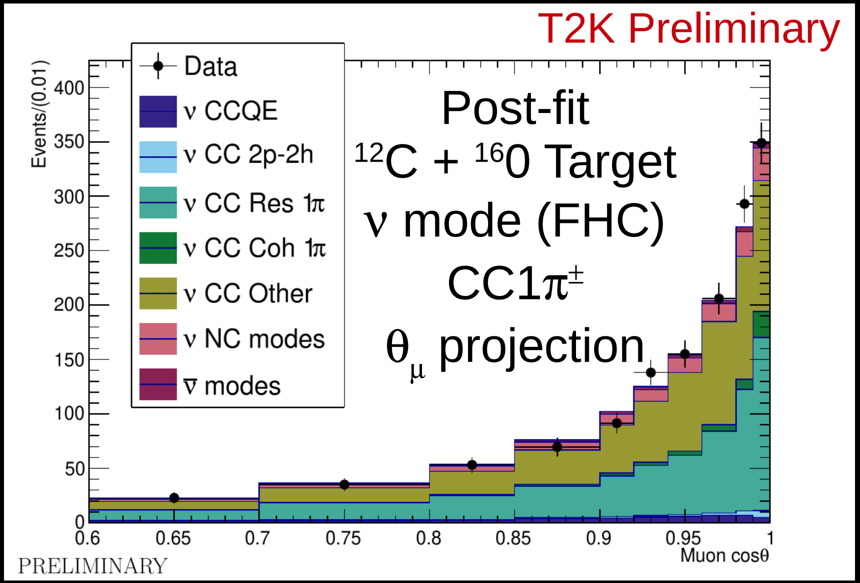


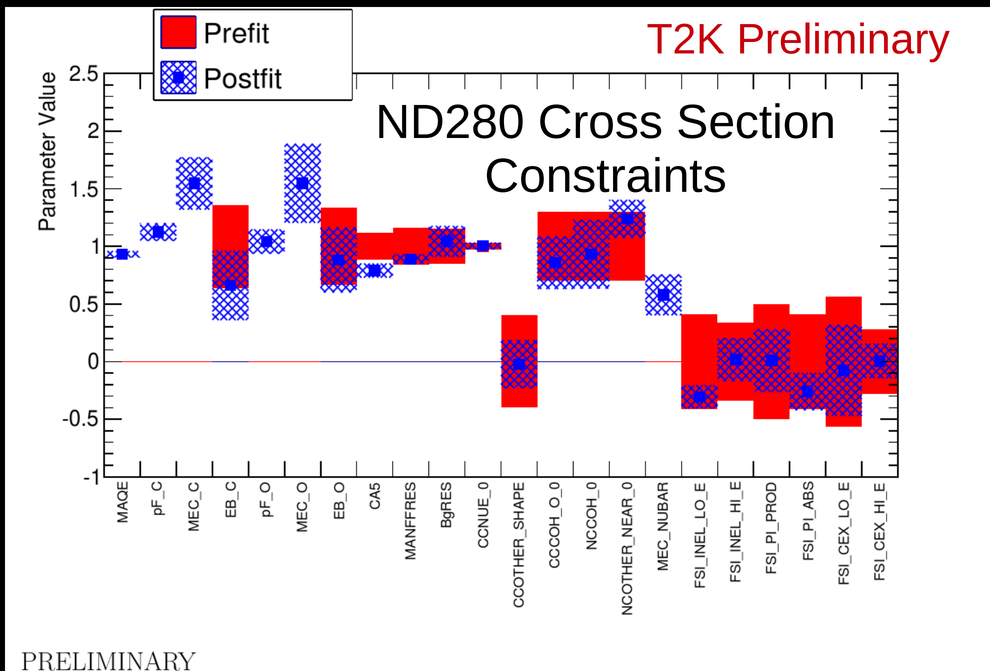


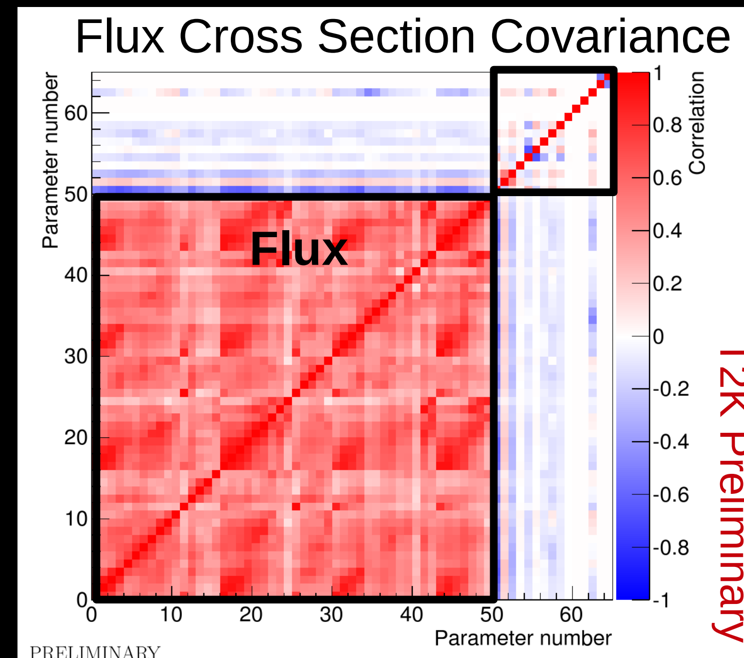
ND280 Cross Section Constraints

Cross Section Parameter	Prefit	ND280 postfit
M_A^{QE} (GeV/c^2)	1.2 ± 0.069607	1.1113 ± 0.033281
p_F ^{12}C (MeV/c)	217.0 ± 12.301	248.71 ± 16.048
MEC ^{12}C	100.0 ± 29.053	156.9 ± 22.635
E_B ^{12}C (MeV)	25.0 ± 9.0	16.846 ± 7.5097
p_F ^{16}O (MeV/c)	225.0 ± 12.301	239.22 ± 23.246
MEC ^{16}O	100.0 ± 35.228	155.89 ± 34.243
E_B ^{16}O (MeV)	27.0 ± 9.0	24.262 ± 7.5922
$CA5^{RES}$	1.01 ± 0.12	0.78601 ± 0.060705
M_A^{RES} (GeV/c^2)	0.95 ± 0.15	0.84904 ± 0.038442
Isospin=$\frac{1}{2}$ Background	1.3 ± 0.2	1.3633 ± 0.17371
CC Other Shape	0.0 ± 0.4	-0.024697 ± 0.17809
CC Coh	1.0 ± 0.3	0.85333 ± 0.22835
NC Coh	1.0 ± 0.3	0.9308 ± 0.29816
NC Other	1.0 ± 0.3	1.3066 ± 0.15511
MEC $\bar{\nu}$	1.0 ± 1.0	0.6109 ± 0.1672

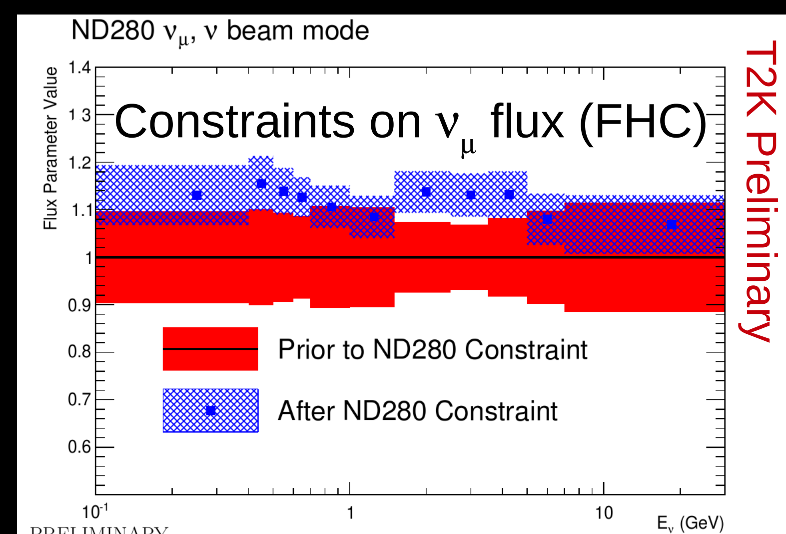
- Best-fit values and fit errors after fit to ND280 data
  - Decrease to QE MA
  - Increase ν MEC (^{12}C and ^{16}O) by 56%
  - Decrease $\bar{\nu}$ MEC by 39%
  - Resonant and coherent pion production reduced
  - Background pion production unchanged

Correlations With Flux Constraints

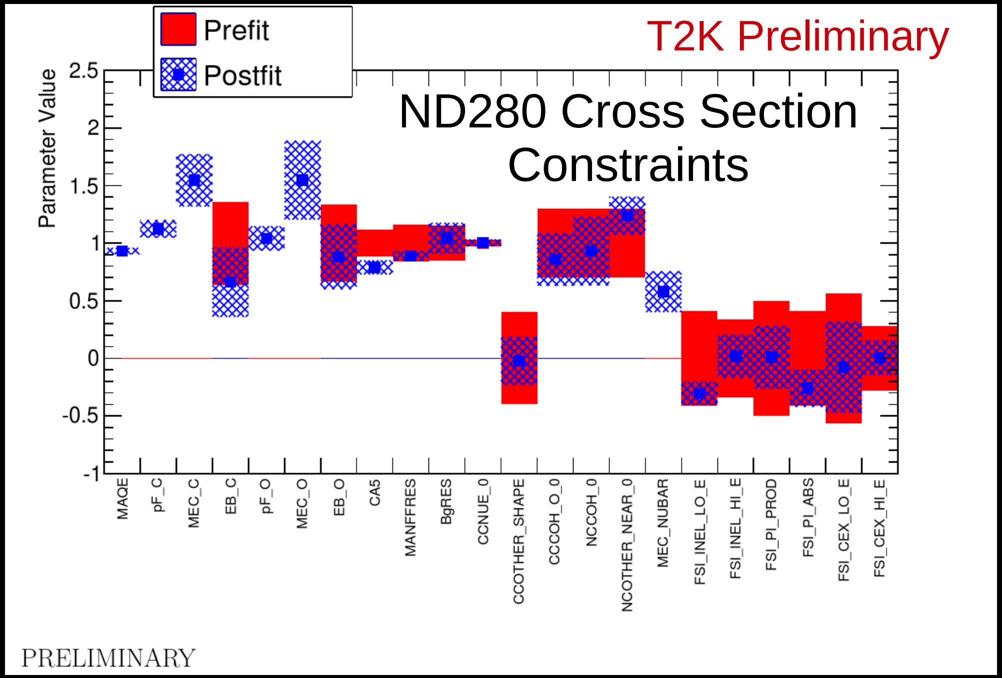


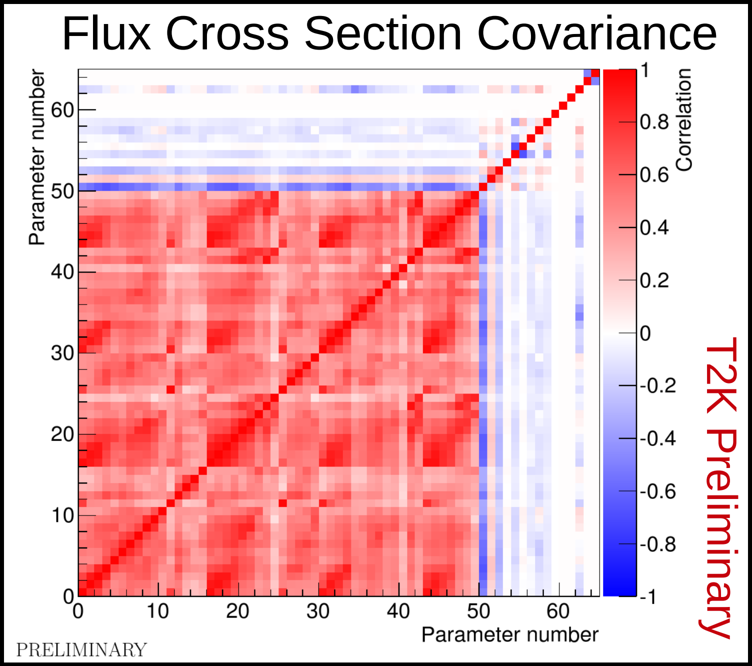


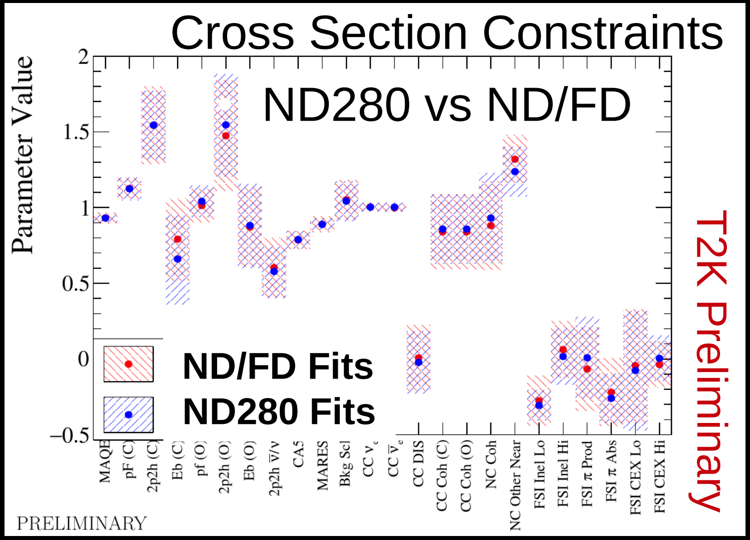
- Flux increased by 10% - 15% (~1.0 - 1.5 σ)
- Tighter post-fit constraints
- Plot: ν_μ FHC Indicative of all flux constraints
- Flux and cross section parameters anti-correlated
- Exception: pF(0_{16}), which decreases predicted rate with positive fluctuation



Comparison to Combined ND/FD Fits

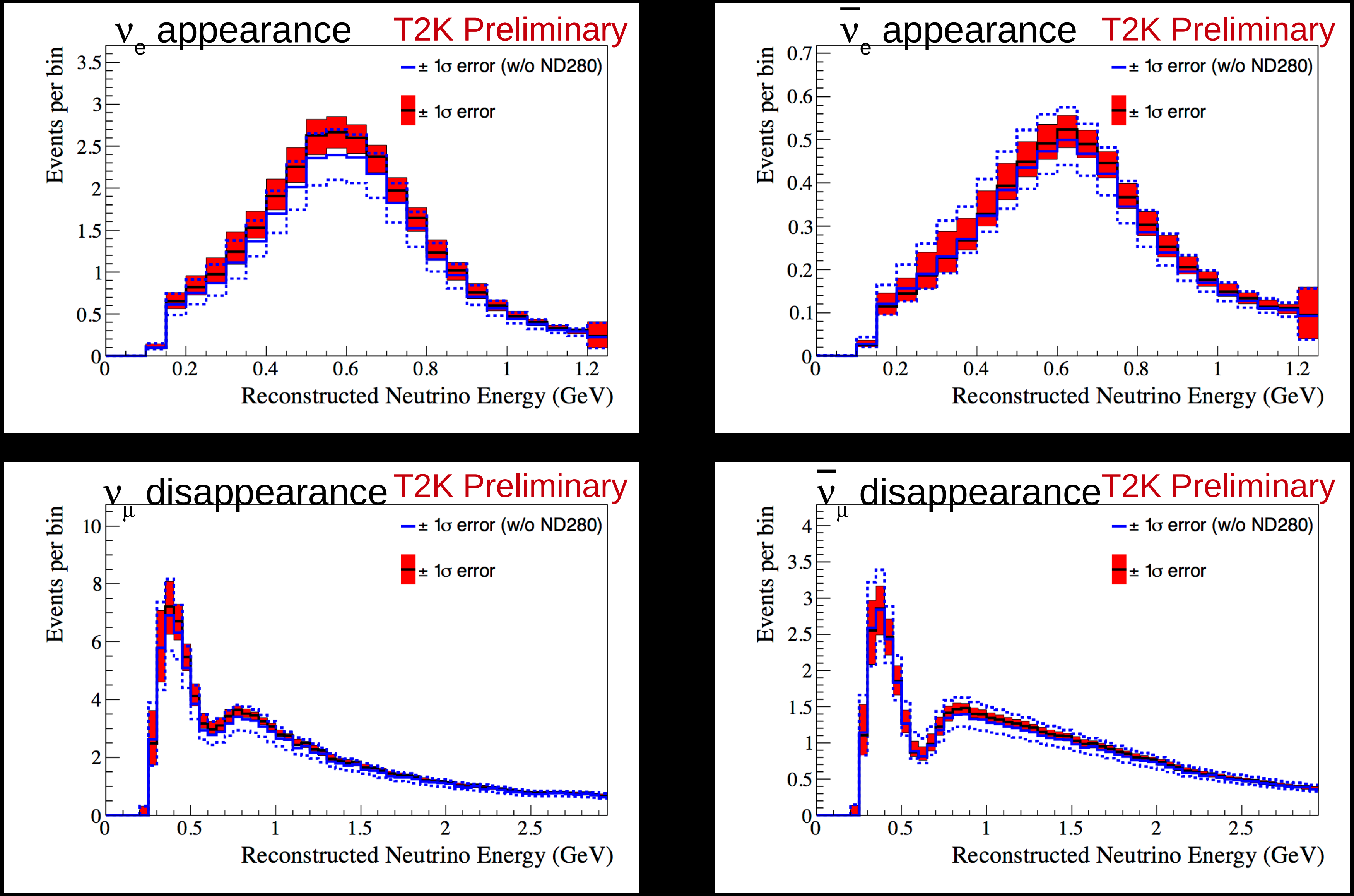






- Central values and constraints from combined ND/FD fits consistent with ND280 only fits
- Difference not observed to affect oscillation analysis results

Overall Effect Of ND280 Constraints on Predicted SK Spectra



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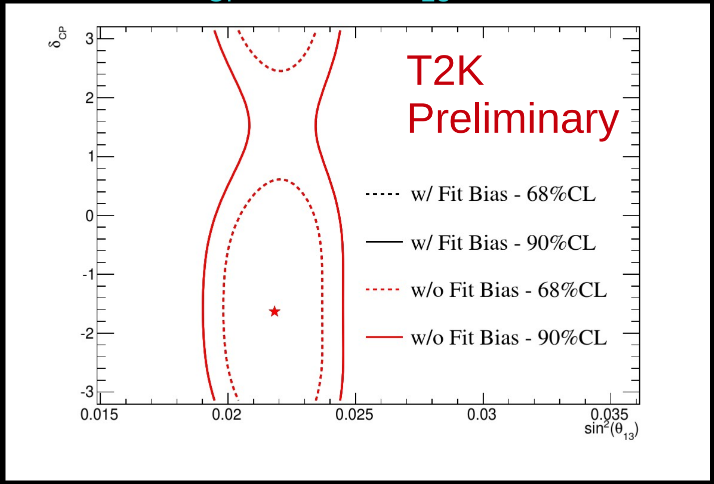
- Fit validated with 444 Mock Data experiments
- The best-fit $\Delta\chi^2$ > 91% of Mock Data Experiments $\Delta\chi^2$
  - Tension between MC and data
  - Large correlated flux pulls
- Observed bias on best-fit param. values w.r.t. true values
  - Average bias was used to correct best-fit values
  - All such corrections within 1σ of post-fit error
  - No changes in the oscillation parameters of C.I. curves were observed
  - Oscillation fits were performed with and without bias corrections

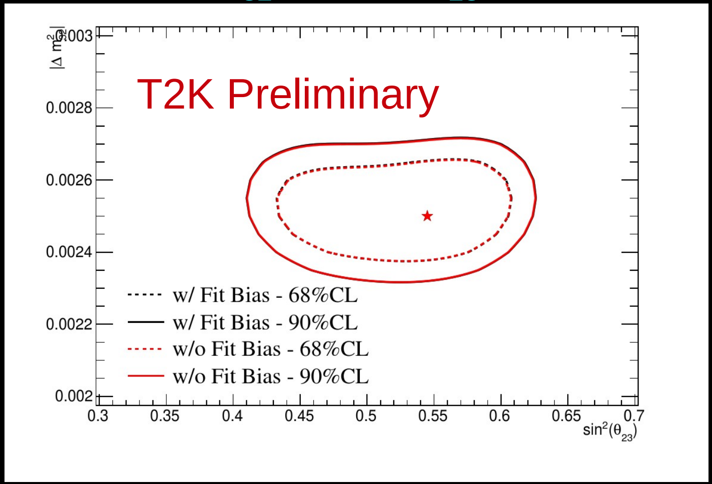
ND280 Cross Section Constraints

Cross Section Parameter	ND280 postfit	Corrected ND280 postfit
M_A^{QE} (GeV/c^2)	1.1113 ± 0.033281	1.1173 ± 0.033882
p_F ^{12}C (MeV/c)	248.71 ± 16.048	243.9 ± 16.608
MEC ^{12}C	156.9 ± 22.635	154.45 ± 22.691
E_B ^{12}C (MeV)	16.846 ± 7.5097	16.512 ± 7.5267
p_F ^{16}O (MeV/c)	239.22 ± 23.246	234.24 ± 23.732
MEC ^{16}O	155.89 ± 34.243	154.59 ± 34.254
E_B ^{16}O (MeV)	24.262 ± 7.5922	23.802 ± 7.6101
$CA5^{RES}$	0.78601 ± 0.060705	0.79724 ± 0.06235
M_A^{RES} (GeV/c^2)	0.84904 ± 0.038442	0.84426 ± 0.038816
Isospin=$\frac{1}{2}$ Background	1.3633 ± 0.17371	1.3551 ± 0.17389
CC Other Shape	-0.024697 ± 0.17809	-0.022288 ± 0.20831
CC Coh	0.85333 ± 0.22835	0.85798 ± 0.22842
NC Coh	0.9308 ± 0.29816	0.93101 ± 0.29816
NC Other	1.3066 ± 0.15511	1.2376 ± 0.16482
MEC $\bar{\nu}$	0.6109 ± 0.1672	0.57804 ± 0.17661

δ_{CP} vs $\sin^2\theta_{13}$ NH

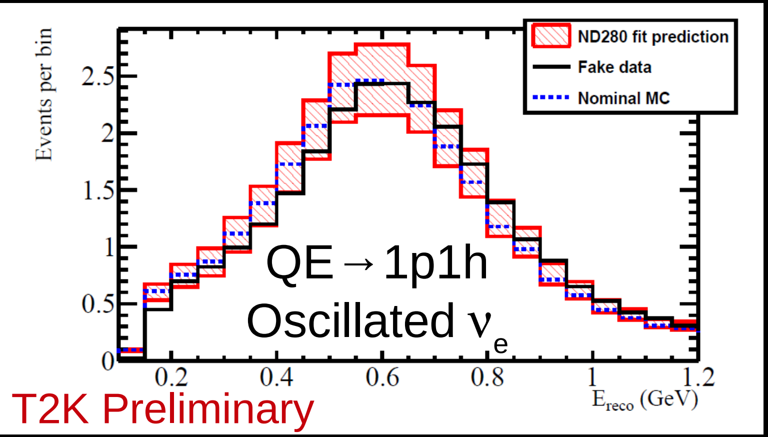


Δm^2_{32} vs $\sin^2\theta_{23}$ NH



Additional Uncertainties: Model Choices

- Use "Mock Data" studies to determine impact of model selection on oscillation parameter measurements
  - Create "Mock Data" using an alternate model
  - Fit using the nominal MC models
  - Take action if best-fit oscillation parameters change (bias)
    - Introduce addition freedom into fits
    - If not feasible, expand C.L. contours
- Explore effects for current exposure and for high-statistics samples



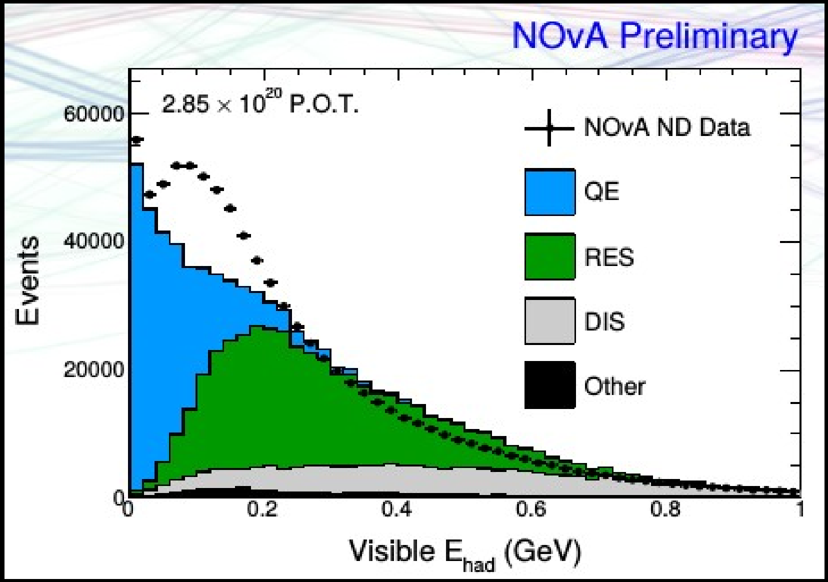
- Alternate models
  - RFG → SF
  - NEUT QE (RFG) → Nieves 1p1h (LFG)
  - Nieves 2p2h → Martini 2p2h
    - Δ-MEC
    - NN-correlations + NN/MEC interference
  - Nieves RPA → Effective RPA
  - DIS pion multiplicities
- Results
  - Effects generally small compared to current statistical uncertainties
  - Martini 2p2h changes ν more than $\bar{\nu}$; separate 2p2h for ν and $\bar{\nu}$
  - QE → 1p1h changes μ p-θ; Add systematic to cover changes
  - As SK statistics increase so will impact of model choices

T2K Summary

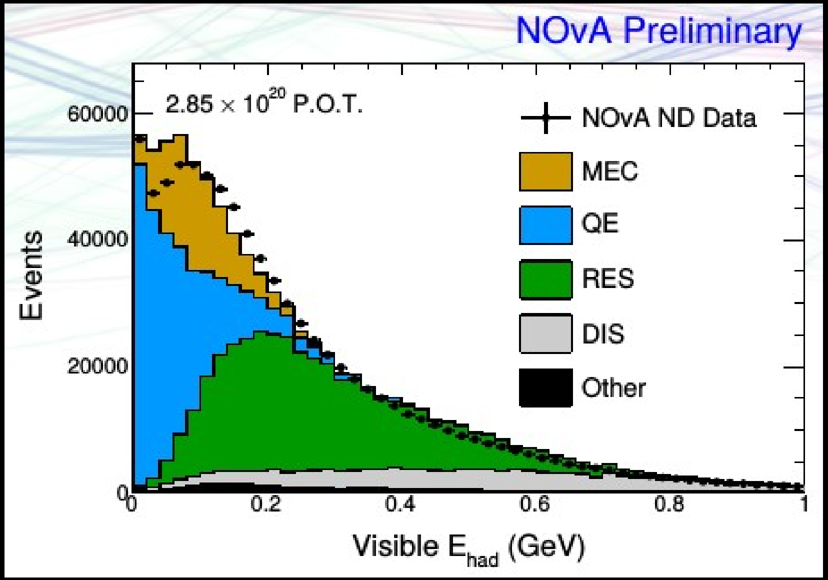
- CC0π events dominate the T2K data
- Fits to external data:
  - Used to set priors on cross section model parameters
  - Prefer to reduce NEUT default predictions
  - Details of how model dependencies were removed are crucial (e.g. PDD contributions in QE)
- Fits to T2K ND280 data
  - Increase rates compared to NEUT nominal predictions
  - Flux parameters increase by ~1σ across the board
  - Prefers CC QE M_A closer to unity than NEUT default
  - Prefers more (less) ν ($\bar{\nu}$) multi-nucleon interactions than predicted by the Nieves model
  - Reduce ν_e (ν_μ) (dis)appearance cross section uncertainties from 7.0% (7.5%) to 5.1% (3.9%)
  - Reduce the combined propagated flux and cross section uncertainties for parameters constrained by the fit from the ~10% level to ~3%
- Effects of model selection biases, and model parameterization biases are small compared to statistical uncertainties, but will need more attention as statistics increase

NOvA Cross Section Systematics

- NOvA uses GENIE (2.10.x) physics models and related uncertainties
- Fit CC QE M_A shape and normalization separately
- Add MEC to default models
  - 50% normalization uncertainty
  - Fit to NOvA data as a function of $|\bar{q}_3|$
- Additional RPA uncertainty considered
- Cross section + FSI uncertainties on oscillation measurements:
  - $\sin^2\theta_{23}$: 0.6% of 3.4% syst + 4.1% stat
  - Δm^2_{32}: 0.5% of 2.4% syst + 3.5% stat
  - ν_e app: ~2% of ~5% syst + 21% stat
- New GENIE tune should have impact on NOvA predictions and uncertainties



C. Backhouse, NOvA W&C



C. Backhouse, NOvA W&C

Upcoming GENIE Updates

- GENIE is continually adding models and validation data
- Workshops in London and Pittsburgh in the last few months
- GENIE is working towards a new “tune” that will fit self-consistent sets of models to available validation data
- This procedure will yield a new set of default models and uncertainties
- How will they tackle the challenges faced by the T2K external data fits?

- New GENIE models in the works:
  - Valencia MEC
  - Nieves 1p1h model
  - z-expansion of the QE axial form factor
  - Local Fermi Gas
  - QE Hyperon generation
  - K+ in FSI
  - Alvarez-Ruso Coherent Pion Model
  - Berger-Sehgal Coherent Pion Model
  - Re-vamp of the diffractive pion production model
  - Reweighting for the Dytman MEC model

DUNE ND Constraint strategy

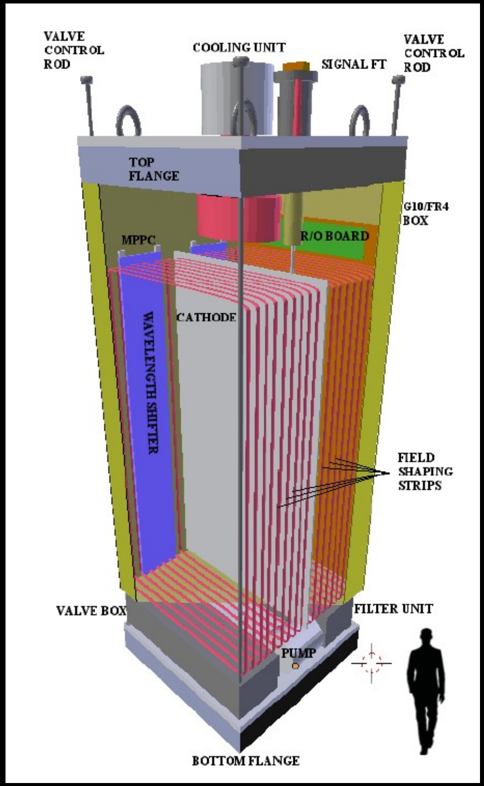
- Flux is usually largest cross section uncertainty
- So, first constrain flux
- Constrain flux with well known cross section processes
  - ν + e scattering (abs., E_ν < 10 GeV)
  - Inverse μ decay (abs., E_ν > 10 GeV)
  - Low-ν method (shape, QE events)
  - Coherent ($\nu/\bar{\nu}$ ratio)
- Cross section measurements require an argon target
- Flux can be studied with all nuclear target materials

- Based on T2K ND280 strategy
- Uses VALOR analysis framework
- Attempting a (relatively) model independent parameterization
  - QE and single pion production normalizations in bins of Q^2
  - DIS normalizations in bins of E_ν
  - Uncorrelated ν and $\bar{\nu}$ parameters
- Flux has 104 parameters in bins of E_ν
- Detector systematics still in planning stages

DUNE Near Detector Task Force

- Charge:
  - Develop full GEANT4 simulation of 3 technology options
    - Fine-Grained Tracker (FGT)
    - Modular Liquid Argon TPC (LAr TPC / ArgonCube)
    - High-Pressure Gaseous Argon TPC (HP GAr TPC)
  - Develop end-to-end simulation and analysis chain to evaluate the impact of each ND on CPV sensitivity
- Status:
  - Each step in the simulation and analysis chain, and interfaces between each step, have been developed
  - Full GEANT4 simulations have been completed
  - The VALOR framework is used for ND fits and a DUNE-specific oscillation analysis framework has been developed
  - Progress on event reconstruction is hard fought
  - Detector uncertainties represent the next (and last) big challenge

ArgonCube



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Important Topics Not Covered

- Cross section ratio (ν_e/ν_μ, ν_τ/ν_μ, $\bar{\nu}/\nu$) uncertainties

- Interplay between cross sections and nuclear models, and neutrino energy scale
- Final-state interactions (FSI)
- Ideas for disentangling low-Q^2 interactions from nuclear initial-state effects and FSI

- Challenges for global cross section fits
- Best practices for reporting cross section analysis results

Summary

- Statistical limits on current experiments reduce sensitivity to cross section systematics
- Continued running and next-generation experiments will require increasingly tighter constraints
- Near detector measurements are crucial and building capable NDs will determine ultimate sensitivities to oscillation physics
- Understanding the interplay between cross sections (especially nuclear model effects) and energy scale is crucial
- Deriving cross section constraints from external data is currently very difficult, and better cross collaboration communication is essential
- Continued generator development and validation against data is crucial to the future of long-baseline neutrino oscillation physics

Questions?

Special Thanks to:

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Kirsty Duffy,
Gabe Perdue,
& Chris Backhouse

For providing input and advice

Backup Slides

Plenary talk: “Long Baseline Neutrino Nucleus Interaction Systematics”

20+5 min

The presentation should review recent results on neutrino interaction systematics/issues in accelerator based long-baseline neutrino oscillation (LBL) experiments with emphasis on the impact of neutrino interaction uncertainties to the measurement of CP phases and mass hierarchy. Your thoughts on attempts and strategy in LBL experiments to minimize or eliminate the uncertainties would be appreciated.

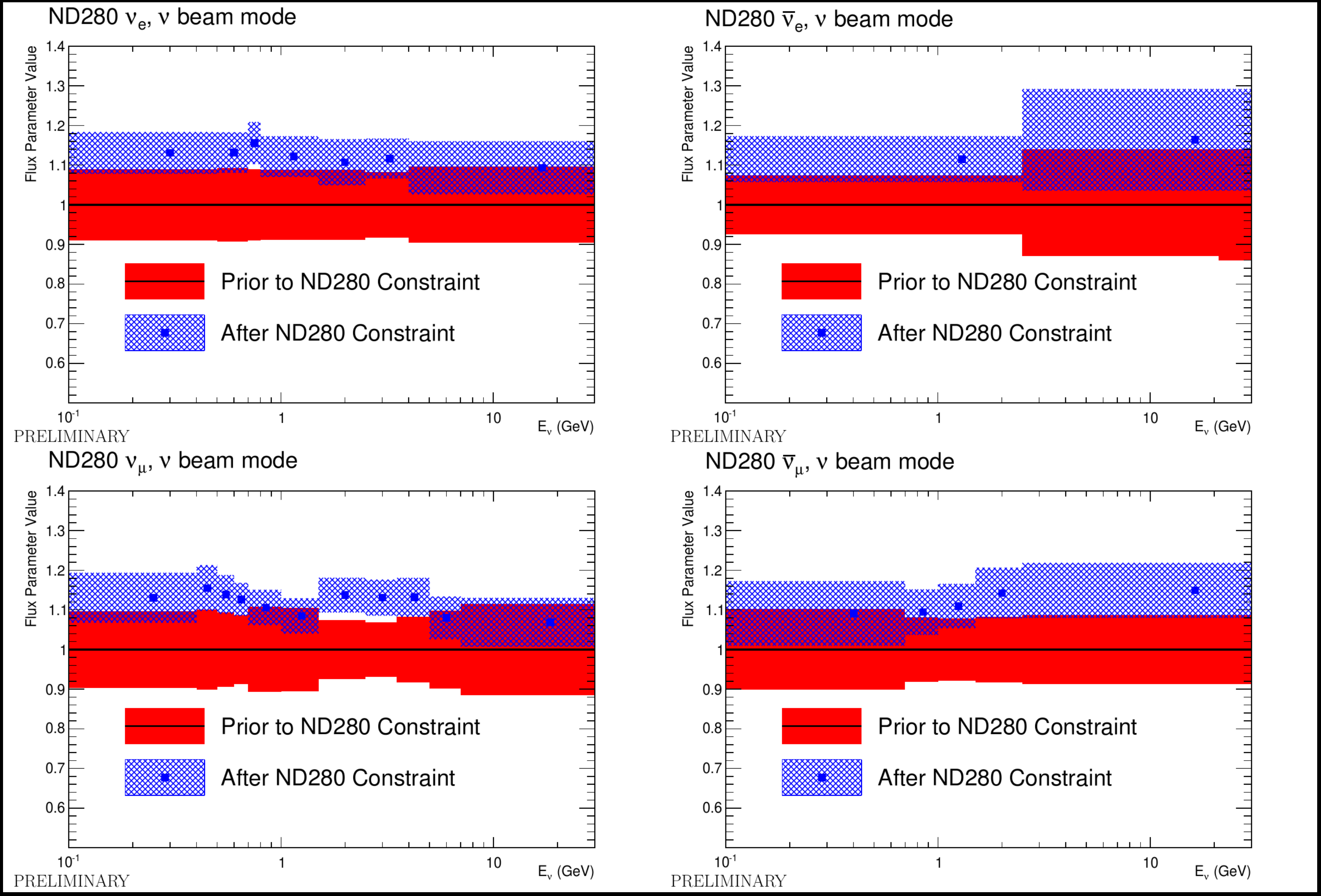
ND280 Fit Likelihood Function

$$\Delta\chi^2_{ND280} = 2\sum_{i}^{Nbins} N_i^p(\vec{b},\vec{x},\vec{d}) - N_i^d + N_i^d \ln[N_i^d/N_i^p(\vec{b},\vec{x},\vec{d})] +$$

$$\sum_{i}^{E_\nu\ bins}\sum_{j}^{E_\nu\ bins} \Delta b_i (V_b^{-1})_{i,j} \Delta b_j + \sum_{i}^{xsec\ pars}\sum_{j}^{xsec\ pars} \Delta x_i (V_x^{-1})_{i,j} \Delta x_j +$$

$$\sum_{i}^{N_{bins}}\sum_{j}^{N_{bins}} \Delta d_i (V^{-1})_d \Delta d_j$$

Flux Constraints, ν mode (FHC) Beam



Flux Constraints, $\bar{\nu}$ mode (RHC) Beam