Systematics Uncertainties at NOvA

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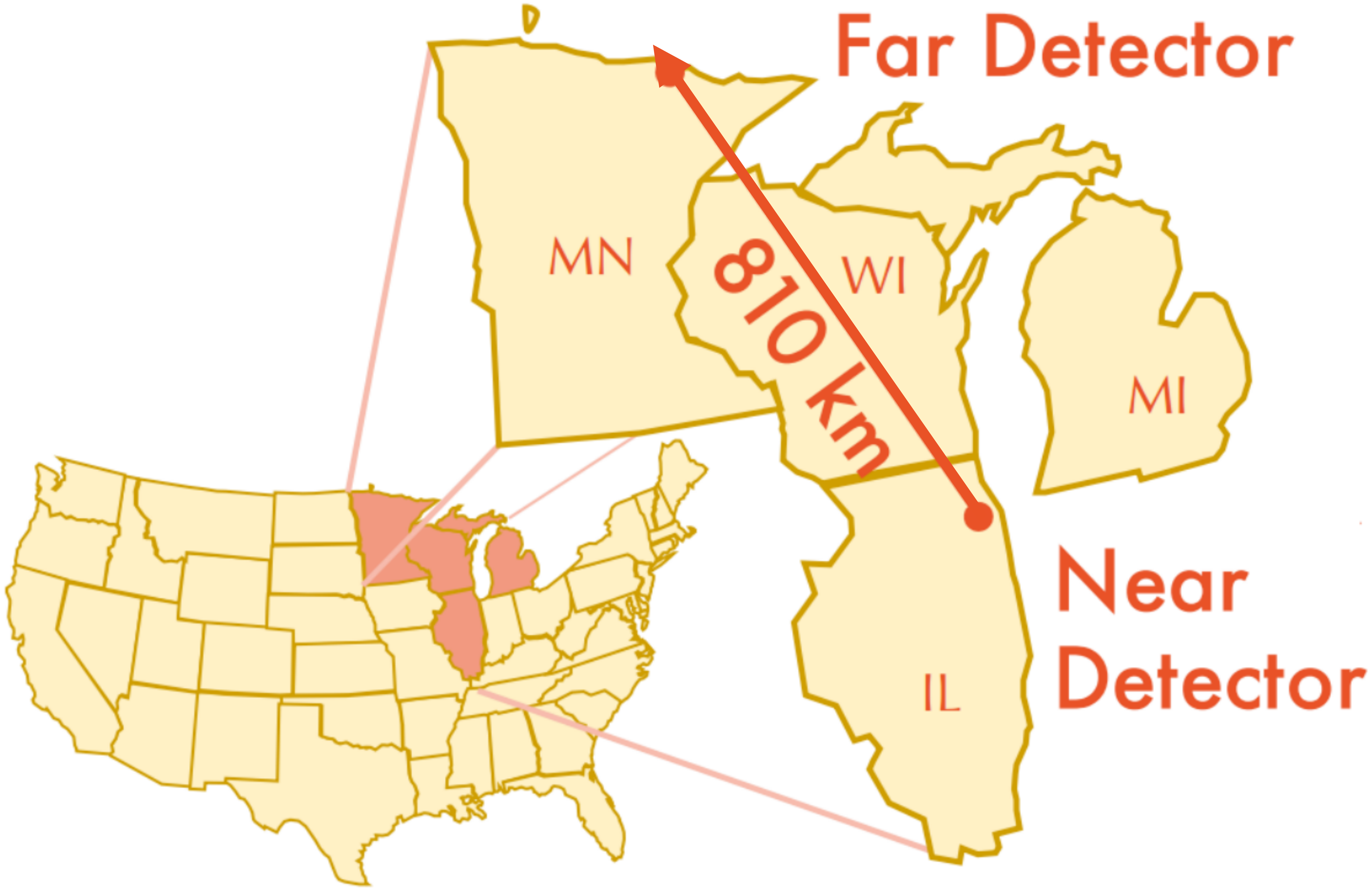
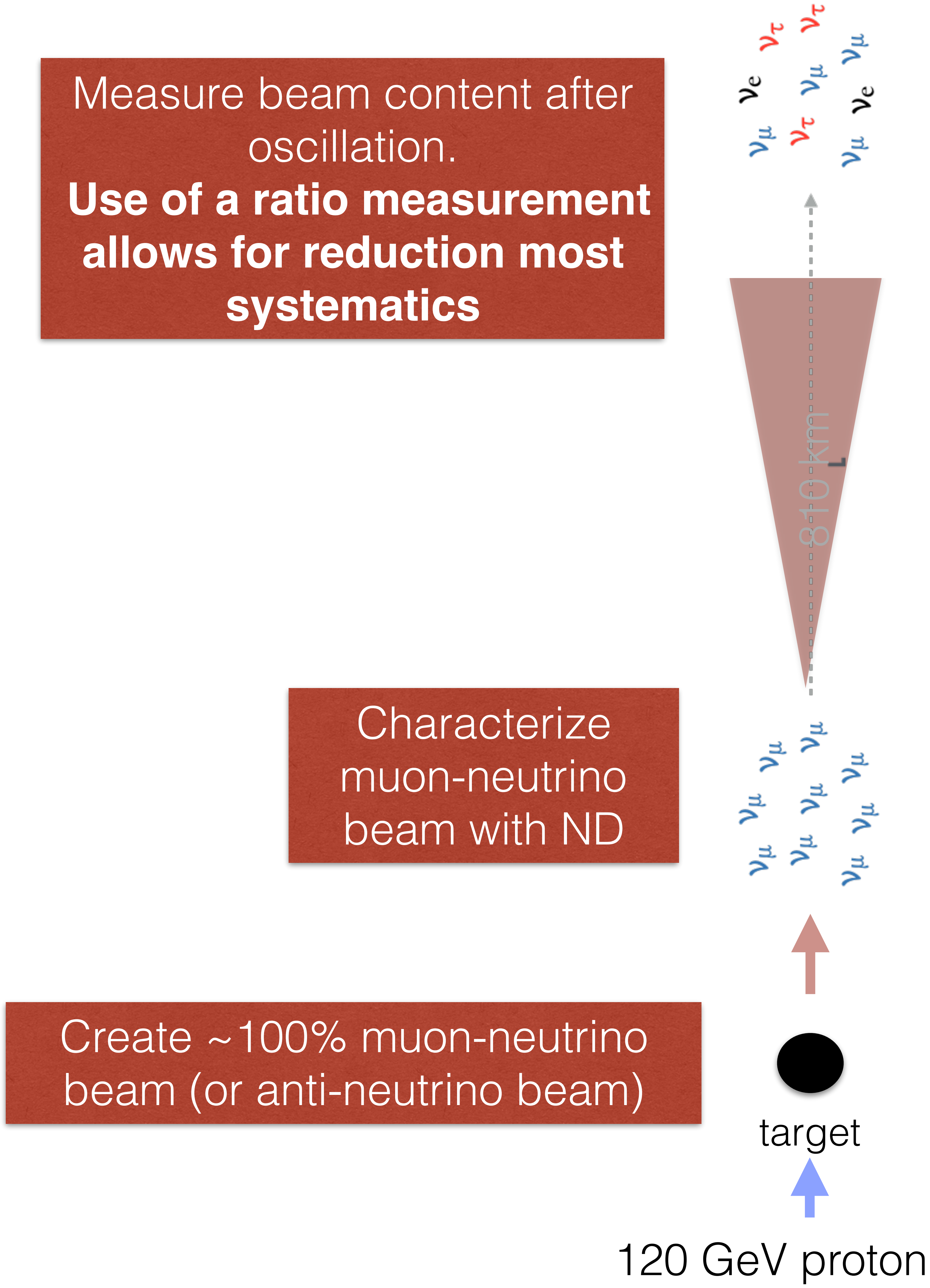
NOvA: Off-axis long-baseline neutrino oscillation experiment

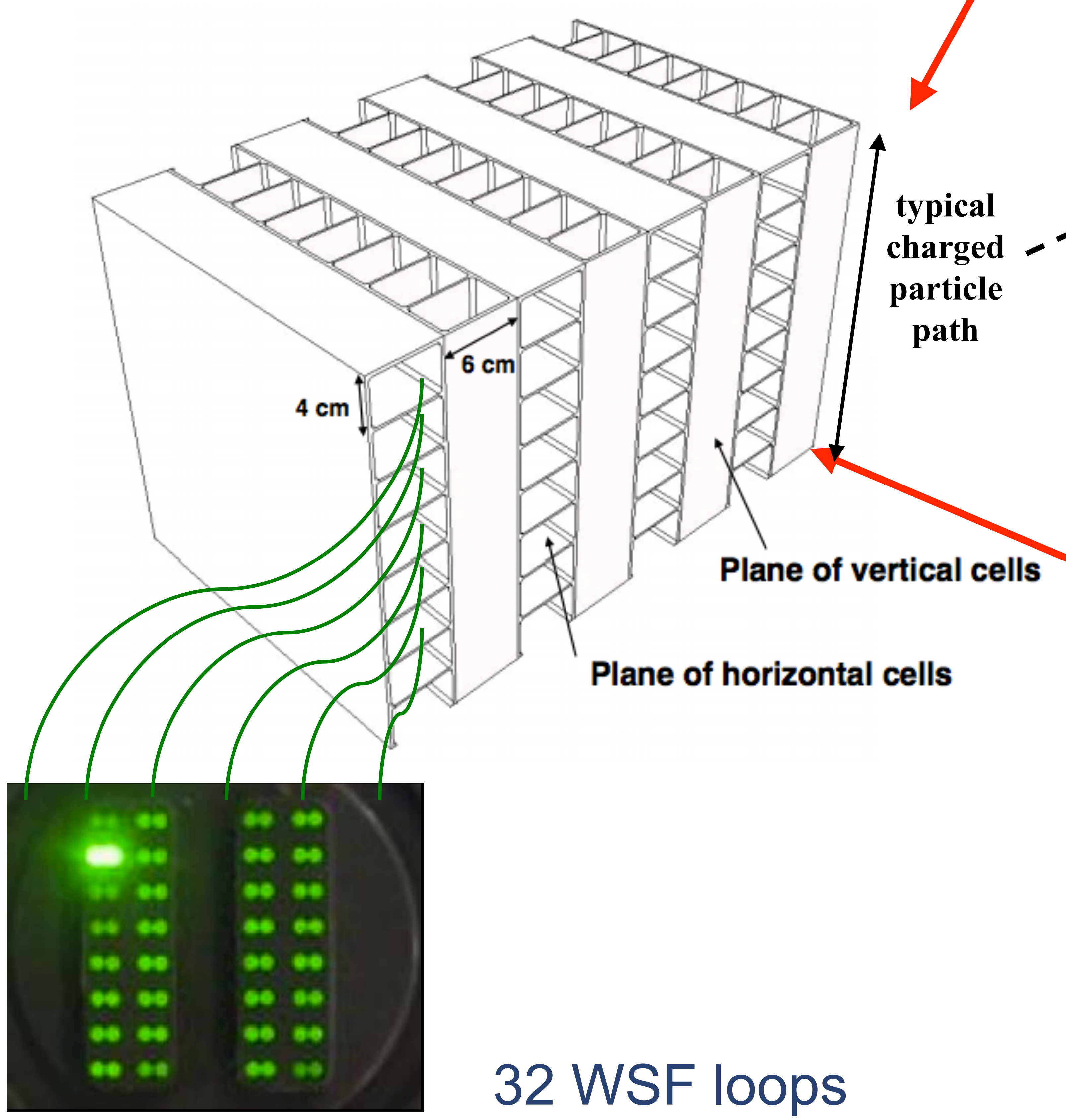




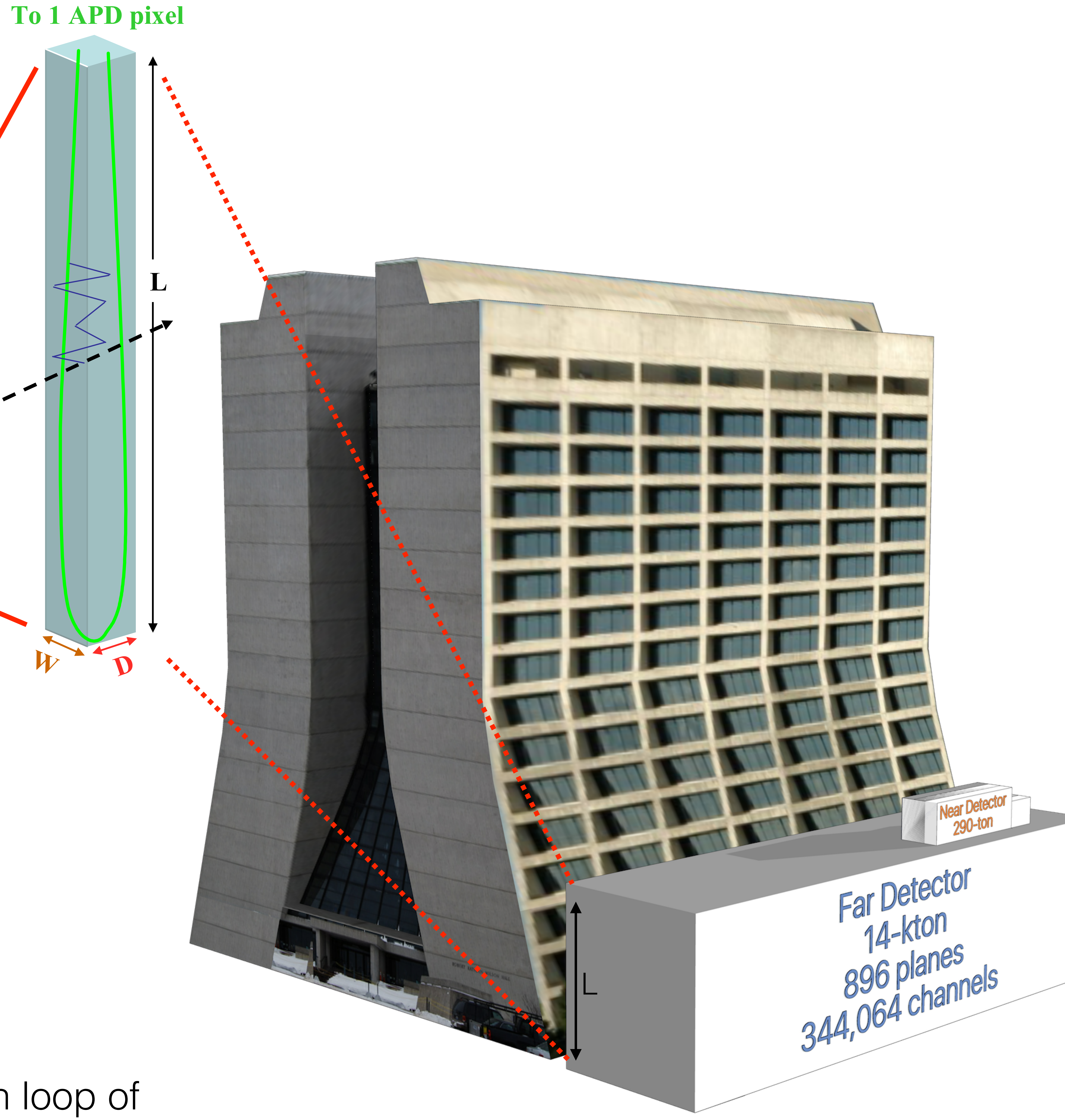
- Oscillation analysis consists of four samples
  - ν_e appearance ($\nu_\mu \longrightarrow \nu_e$)
  - ν_μ surval ($\nu_\mu \longrightarrow \nu_\mu$)
  - and the anti-neutrino versions of the same

NOvA Detectors: two basically identical liquid scintillator 65% active tracking calorimeters

32 pixel APD

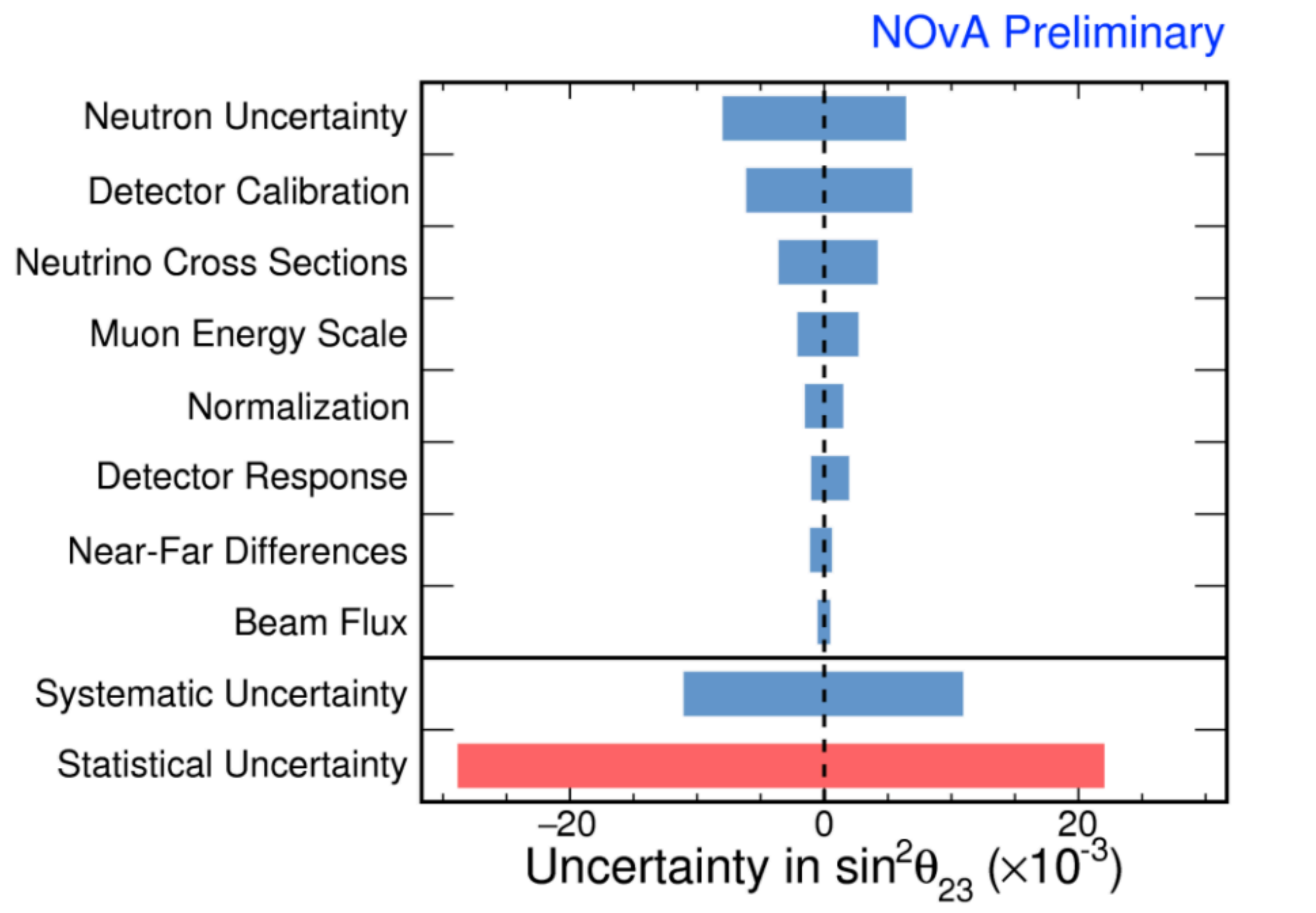


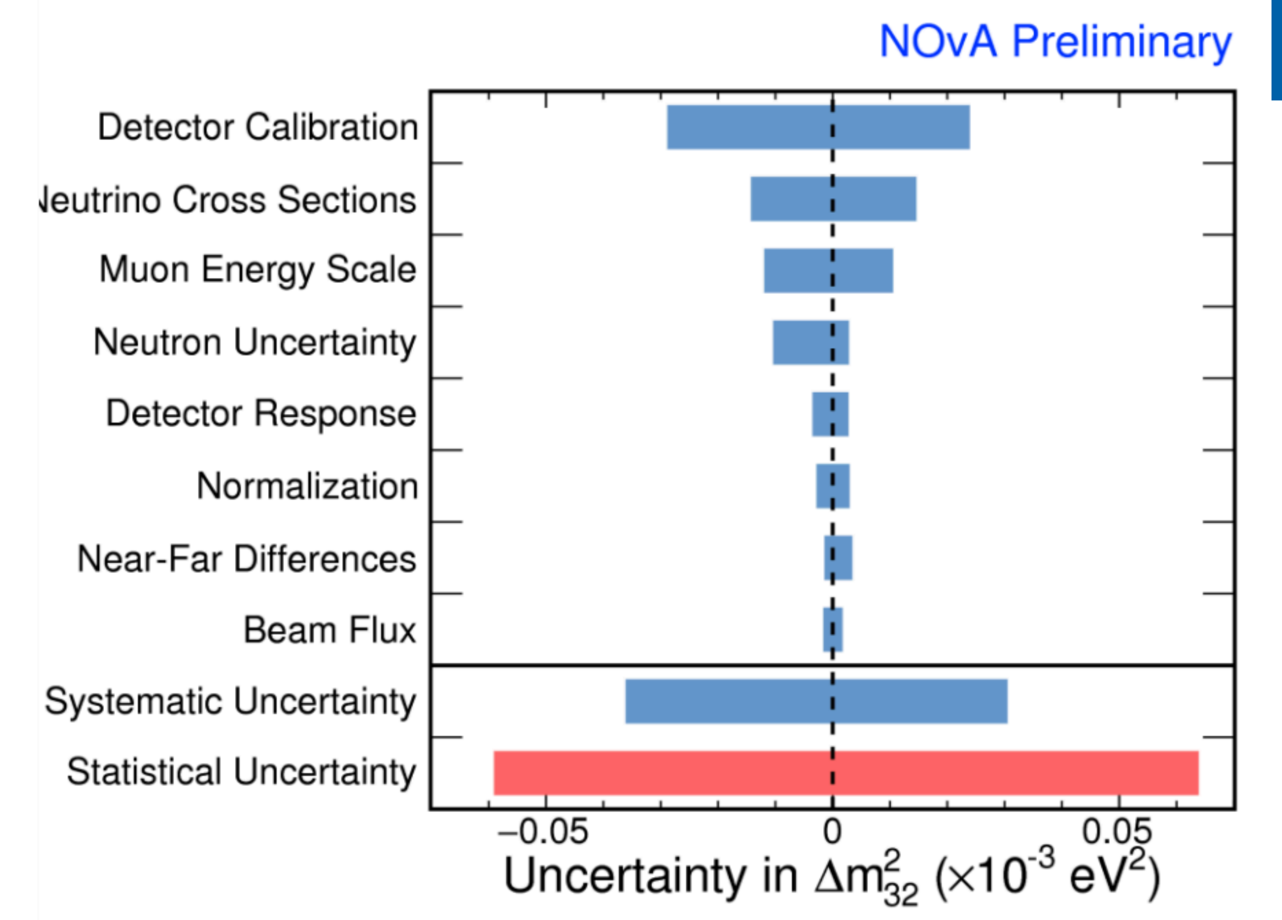
32 WSF loops



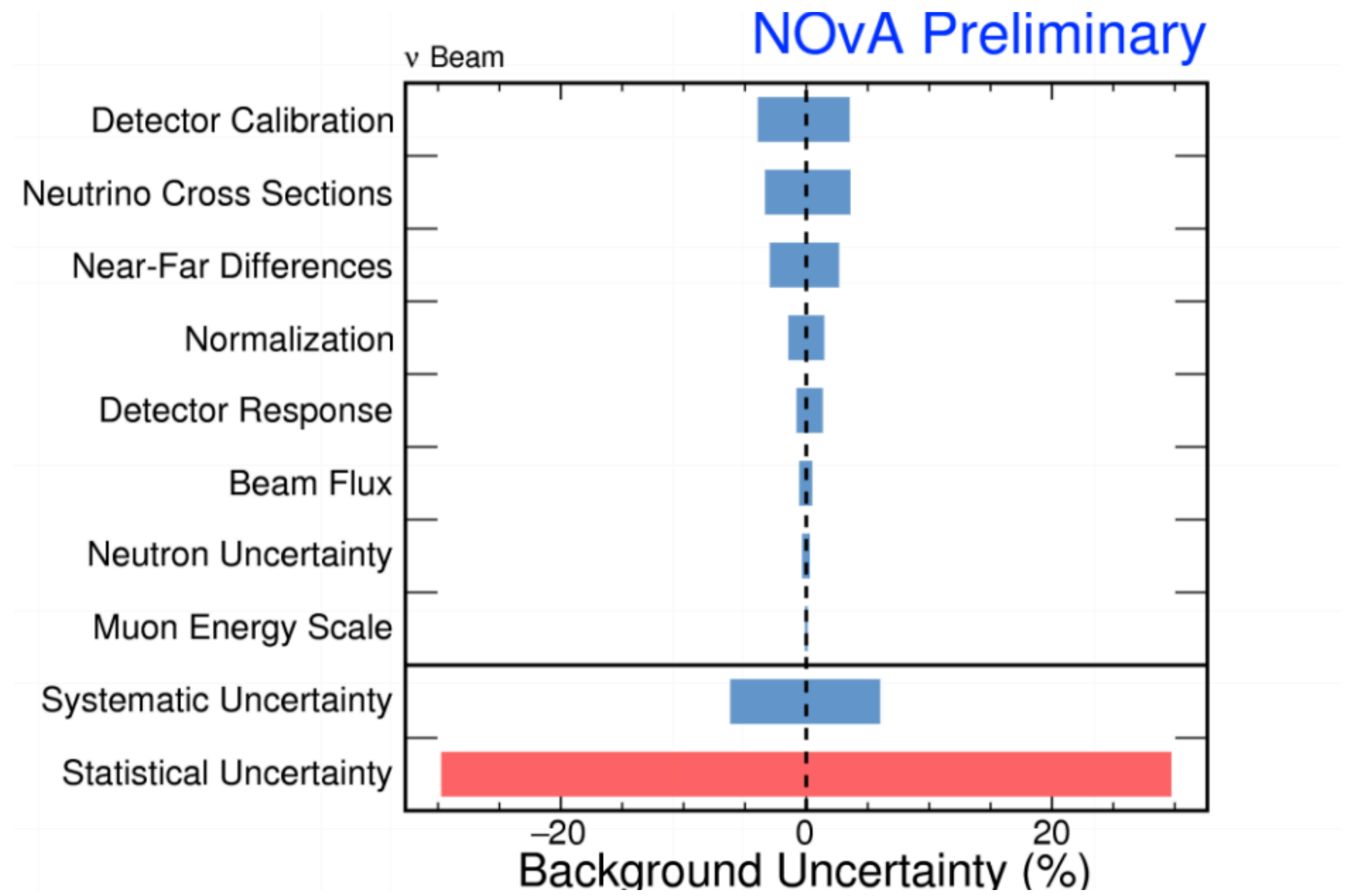
15 m PVC cell, filled with liquid scintillator with 5% pseudocumene, with loop of wavelength shifting fiber read out in groups of 32 by a 32 pixel Avalanche Photodiode

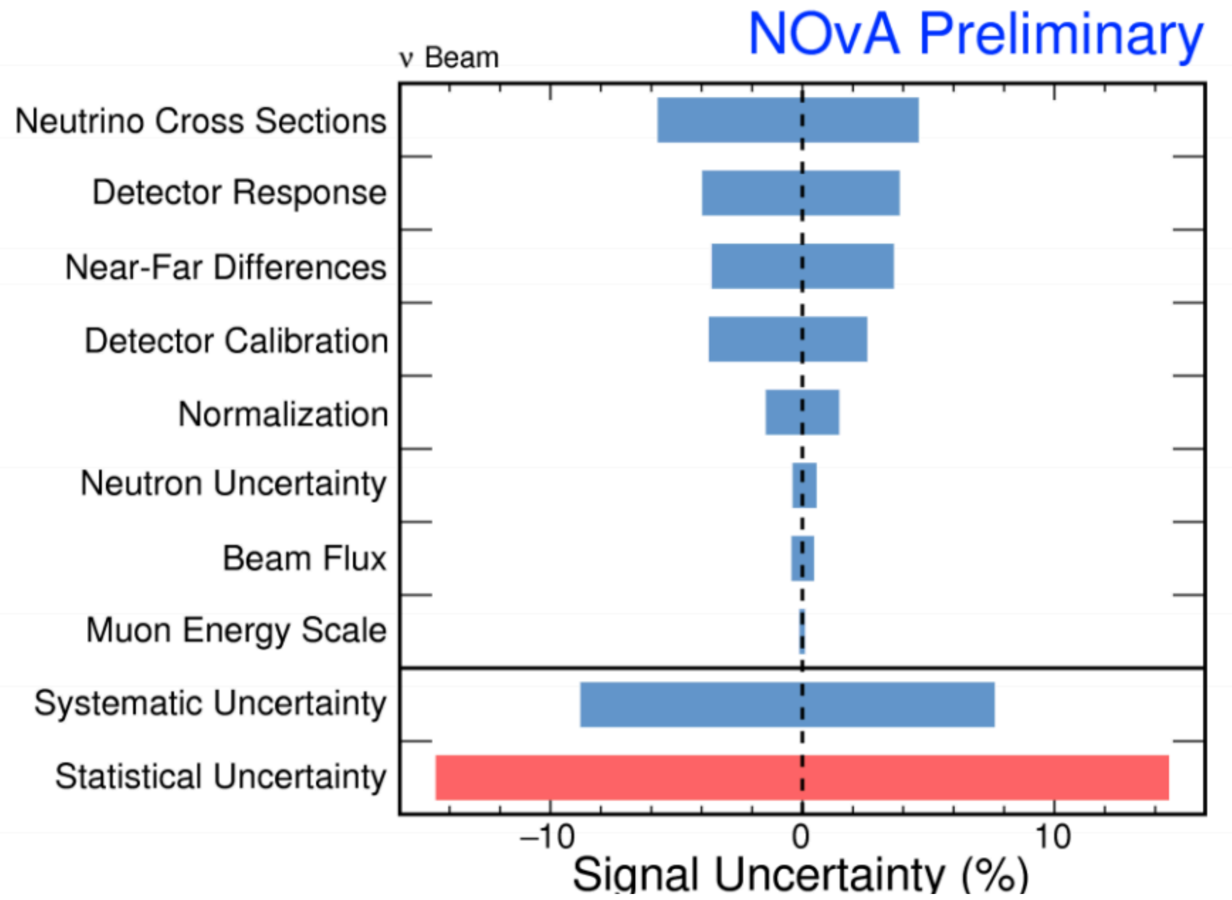
Muon Neutrino and Antineutrino



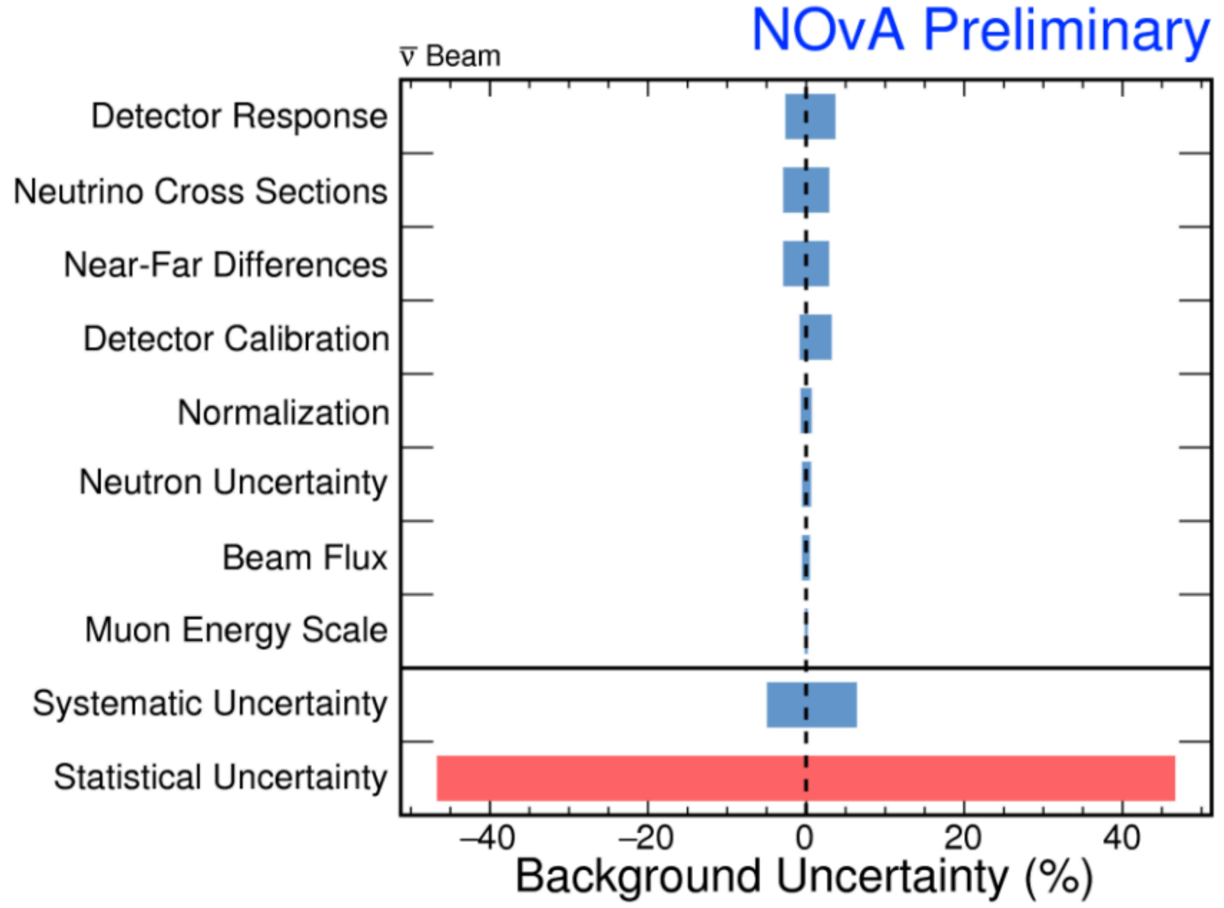


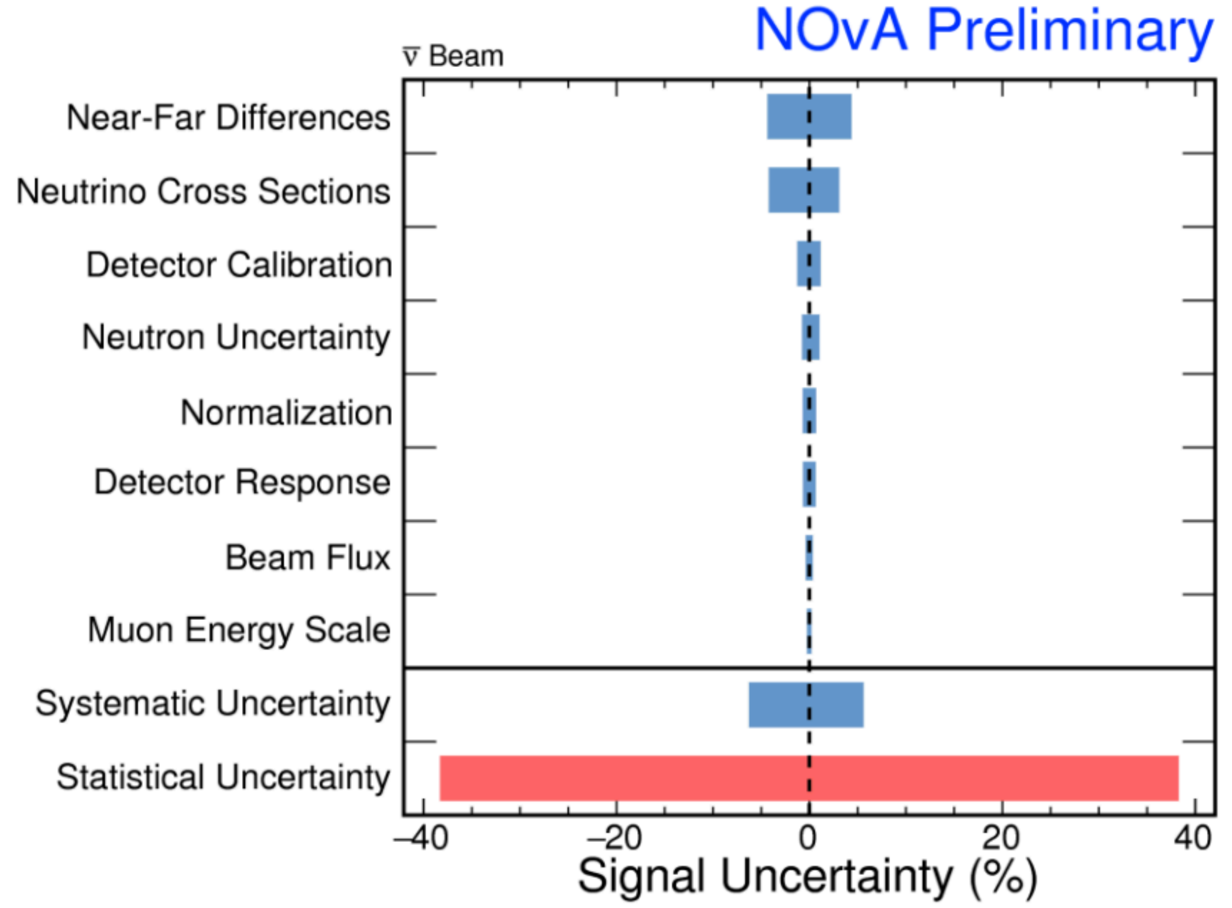
Electron Neutrino





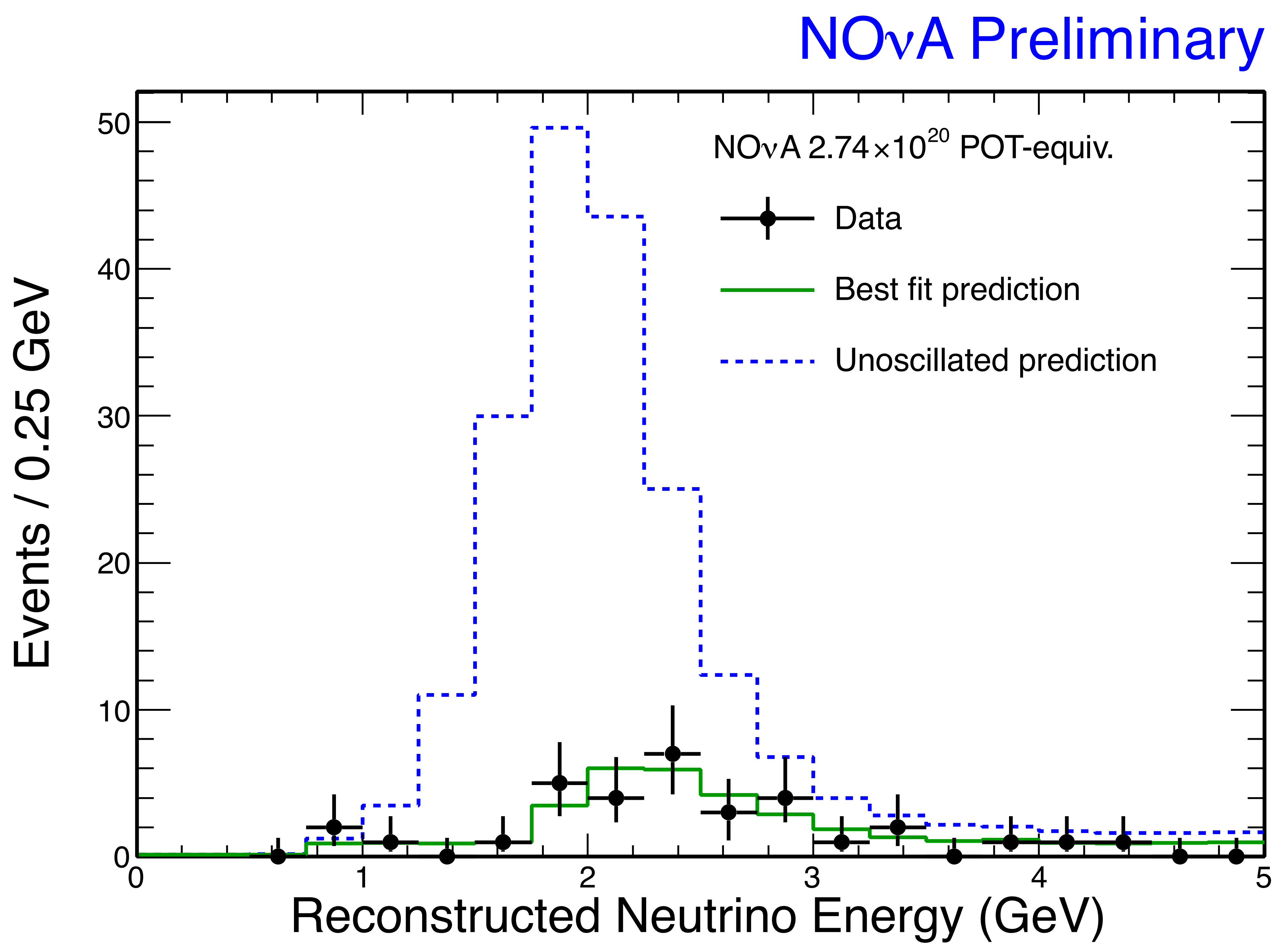
Electron Antineutrino



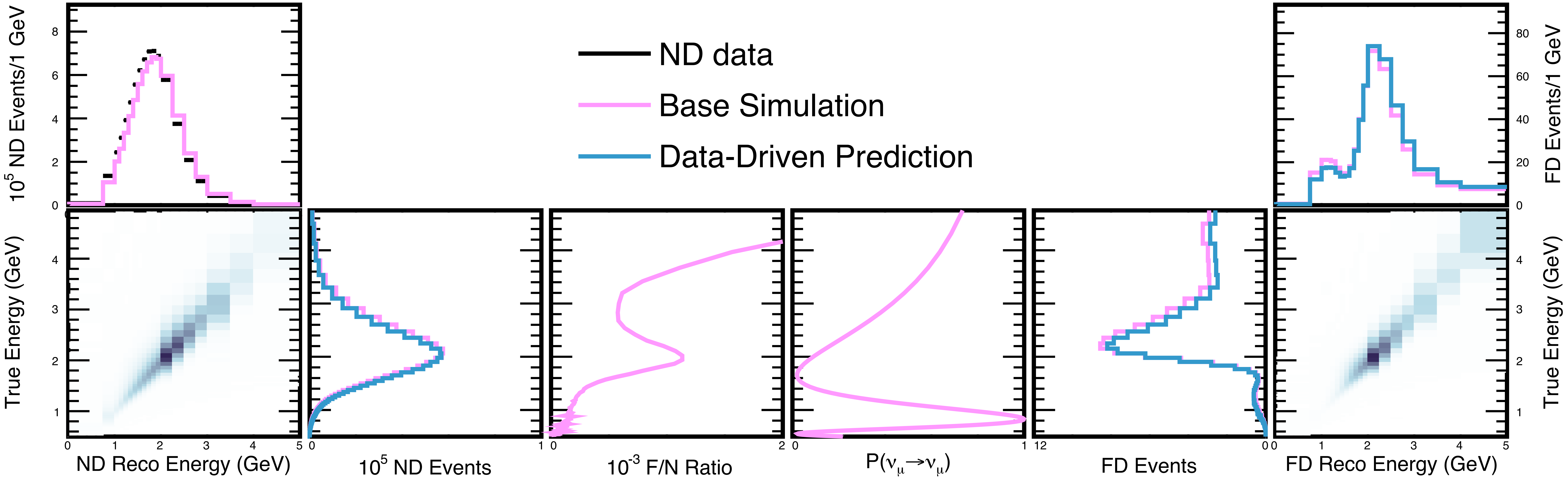


NOvA's oscillation analysis method

- To extract oscillation parameters we calculate likelihood ratio between observed FD data best fit and our data-driven 'extrapolated' prediction under different oscillation predictions
- NOvA's two detector analyses rely heavily on systematic cancellation between the two detectors
- Extrapolation/decomposition not done including systematics, instead the full analysis chain is repeated for each systematically shifted universe
- Produce 'extrapolated' uncertainty, the residual which survives the extrapolation, which are included as pull terms



Lets step through how NOvA uses two detectors to reduce systematics

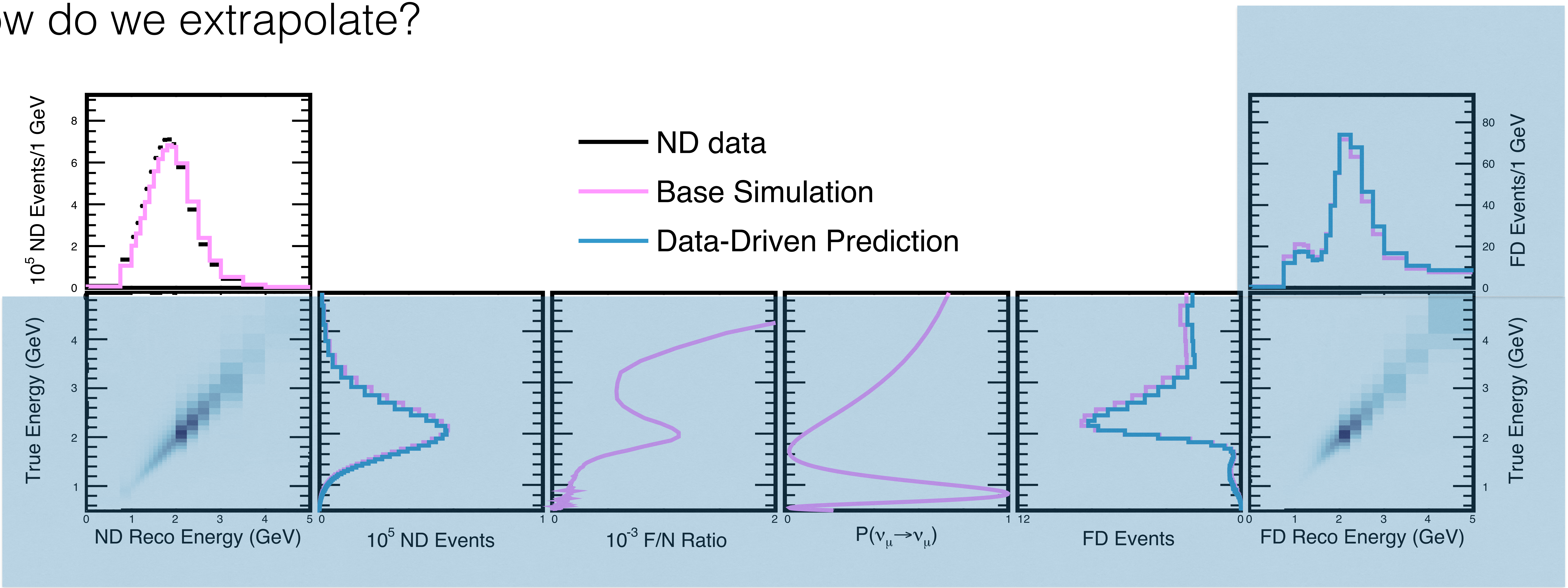


Bin-by-bin direct extrapolation using Far/Near ratio method

Example shown is ν_μ events

This is a cartoon

How do we extrapolate?



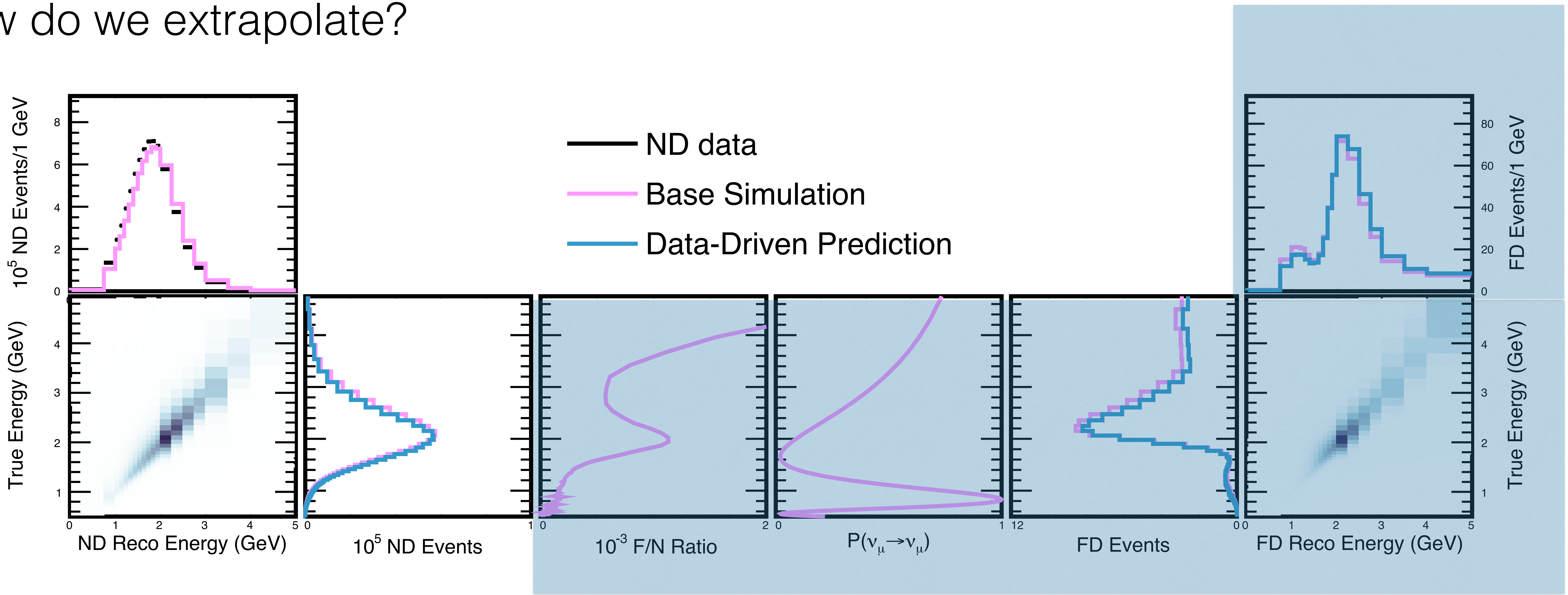
ND **data** broken down into components ($\nu_e/\nu_\mu/\nu_t$ CC or NC) either by data driven methods or just proportionally based on simulation

This ‘decomposition’ is needed so we can apply correct oscillation probability

Example shown is ν_μ events

This is a cartoon

How do we extrapolate?

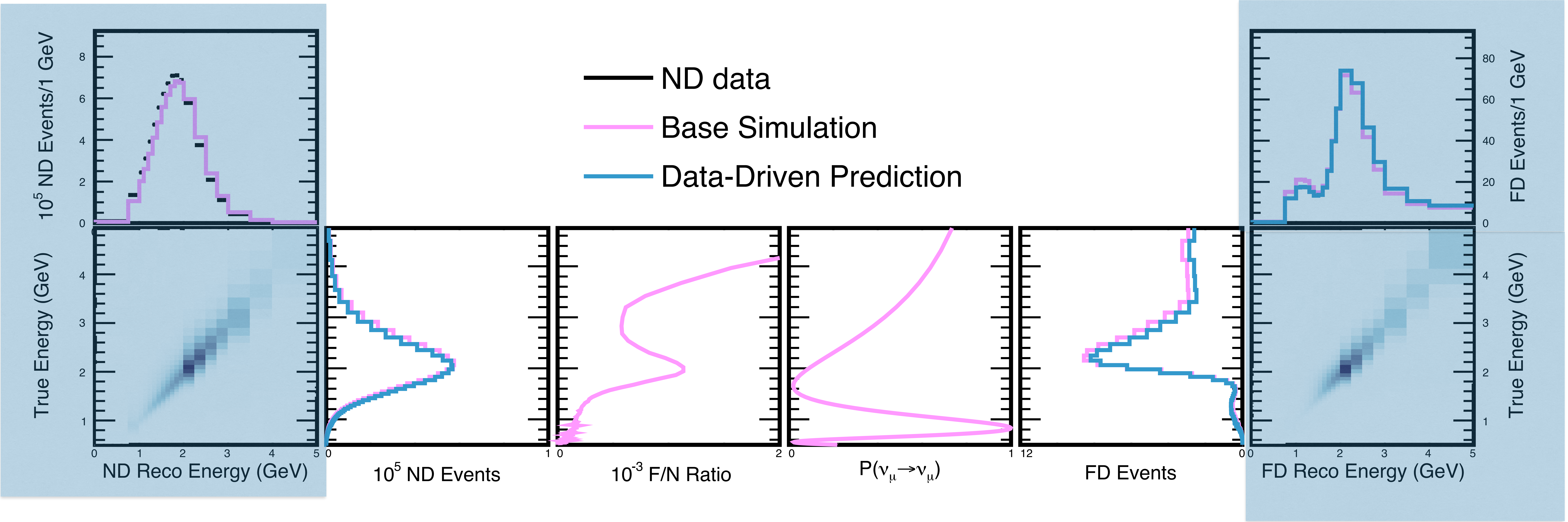


Reconstructed neutrino energy in **data** migrated to true neutrino energy based on **MC simulation**

Example shown is ν_μ events

This is a cartoon

How do we extrapolate?

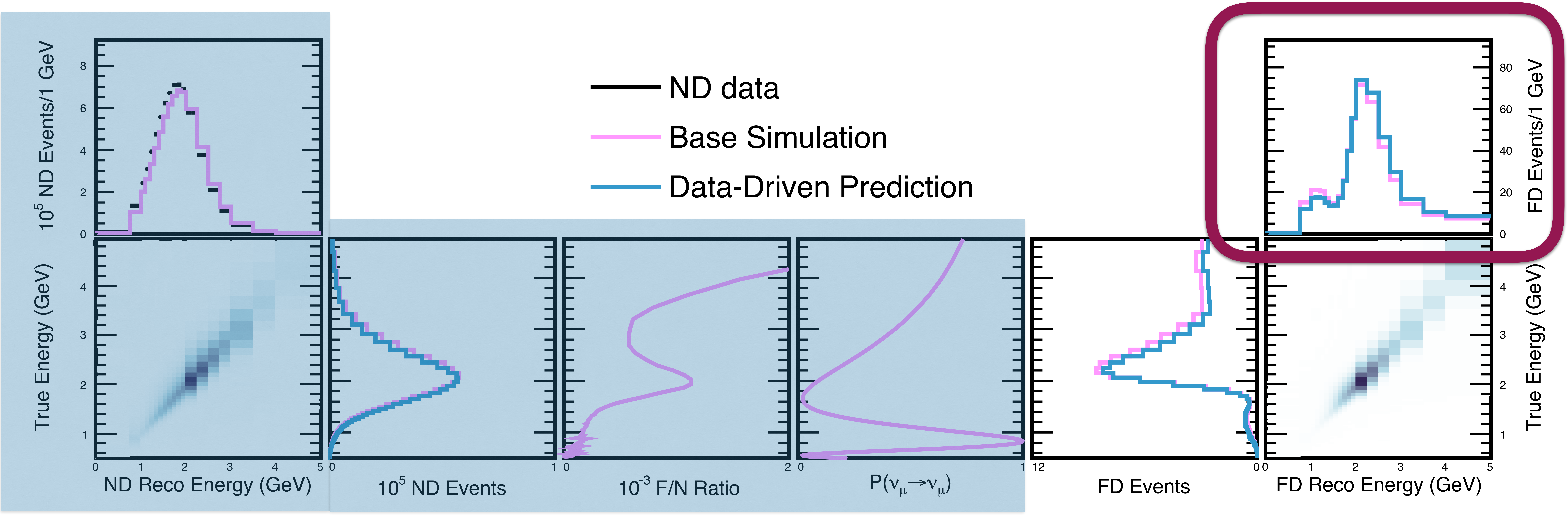


Apply Far/Near ratio from **MC** to the ND **data** component, correcting for flux, efficiency and acceptance effects, to **produce data-driven FD prediction.** Apply oscillation probabilities to data-driven FD prediction

Example shown is ν_μ events

This is a cartoon

How do we extrapolate?



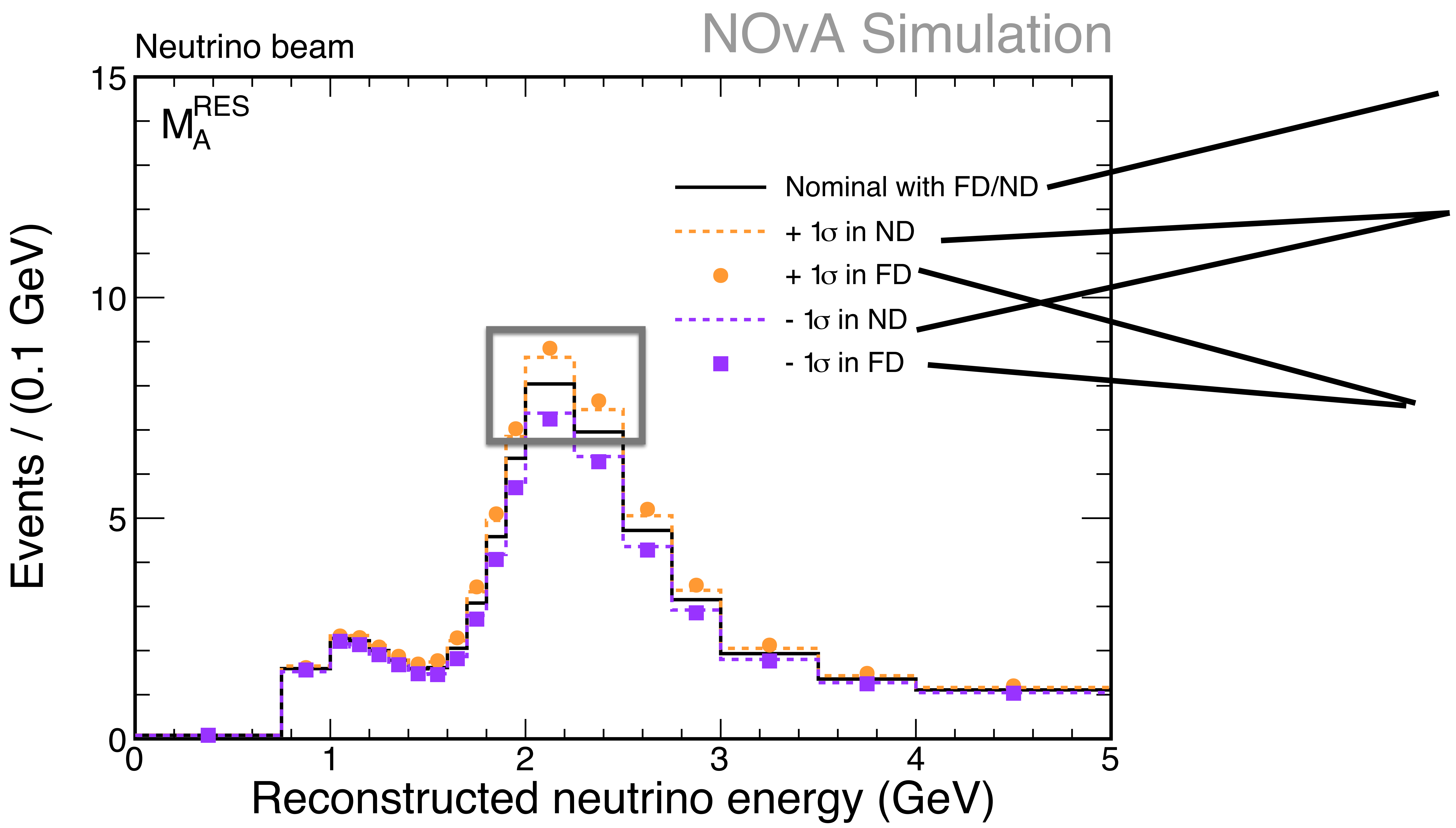
Translate **data-driven FD prediction** back to reconstructed energy using FD component migration matrix

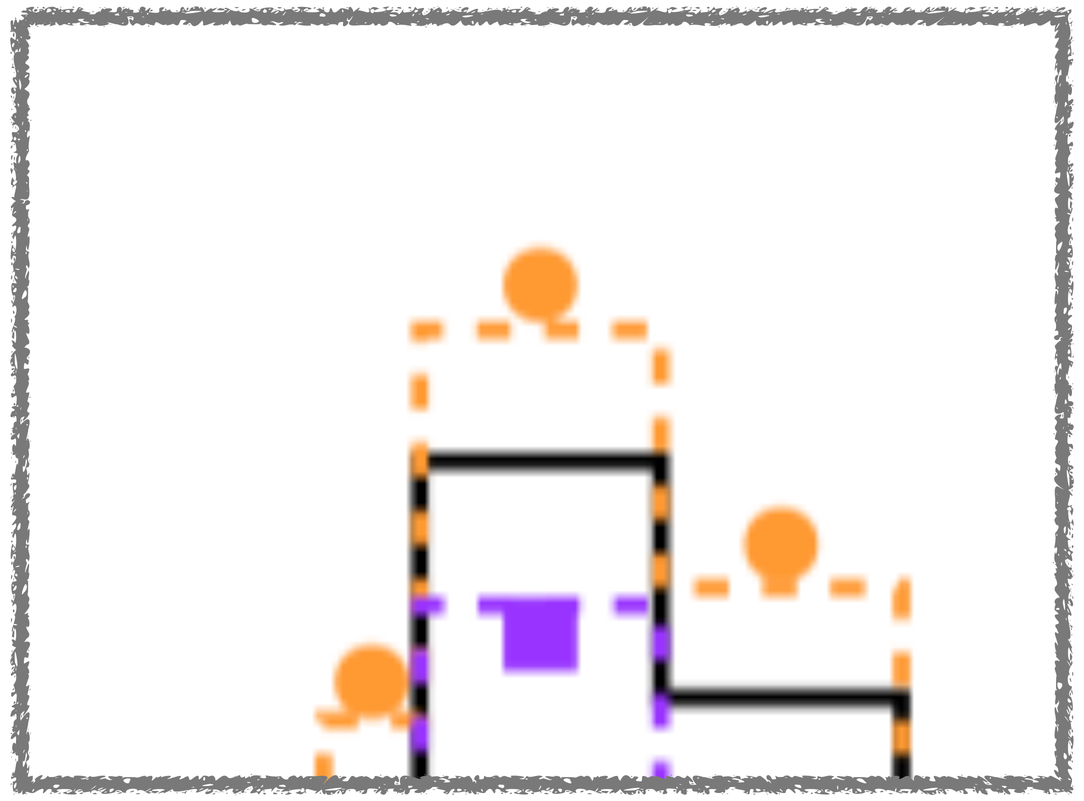
This **method** translates data-mc differences observed in the ND to the FD

Example shown is ν_μ events

This is a cartoon

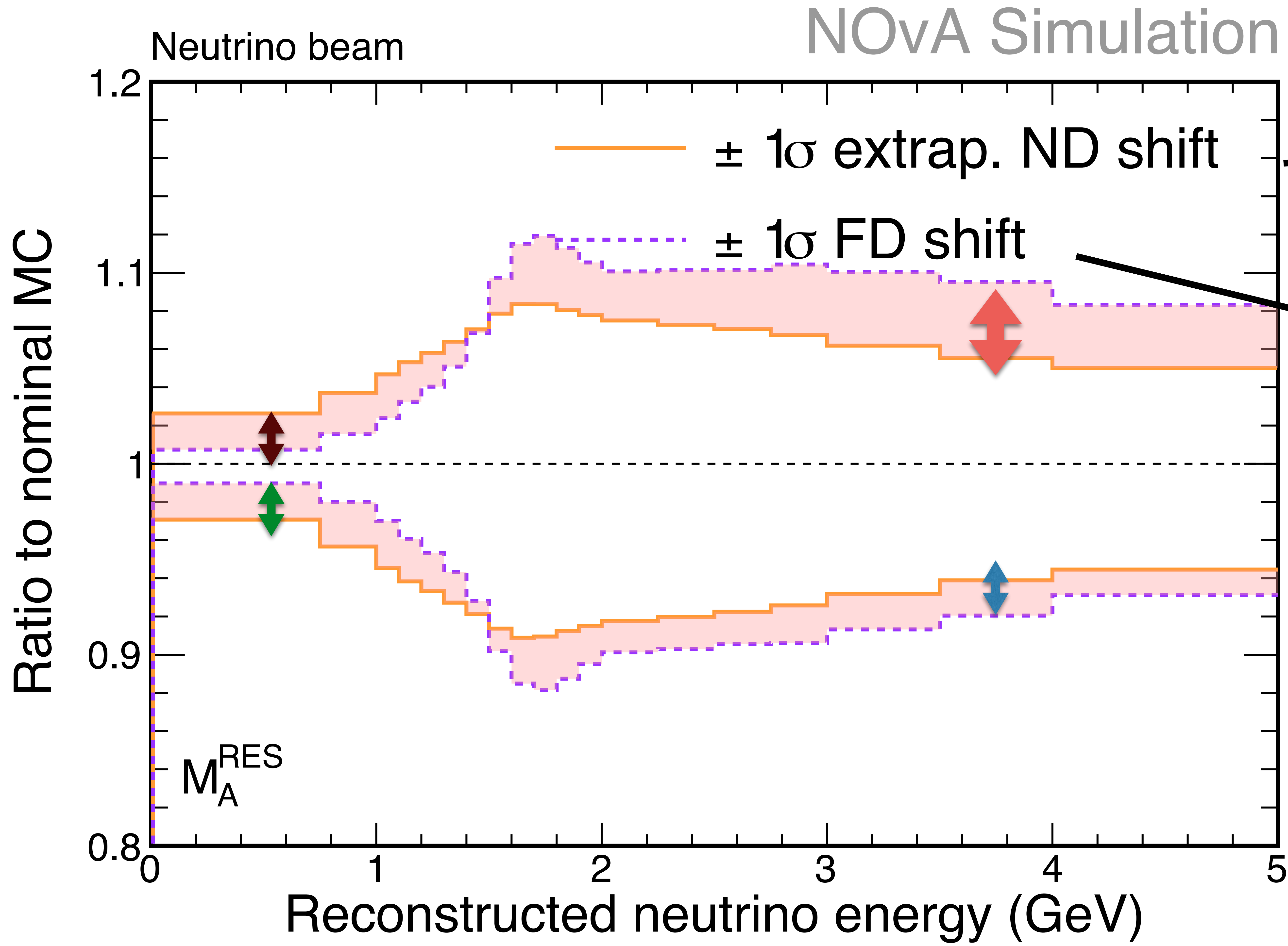
A worked example — inserting a fake discrepancy





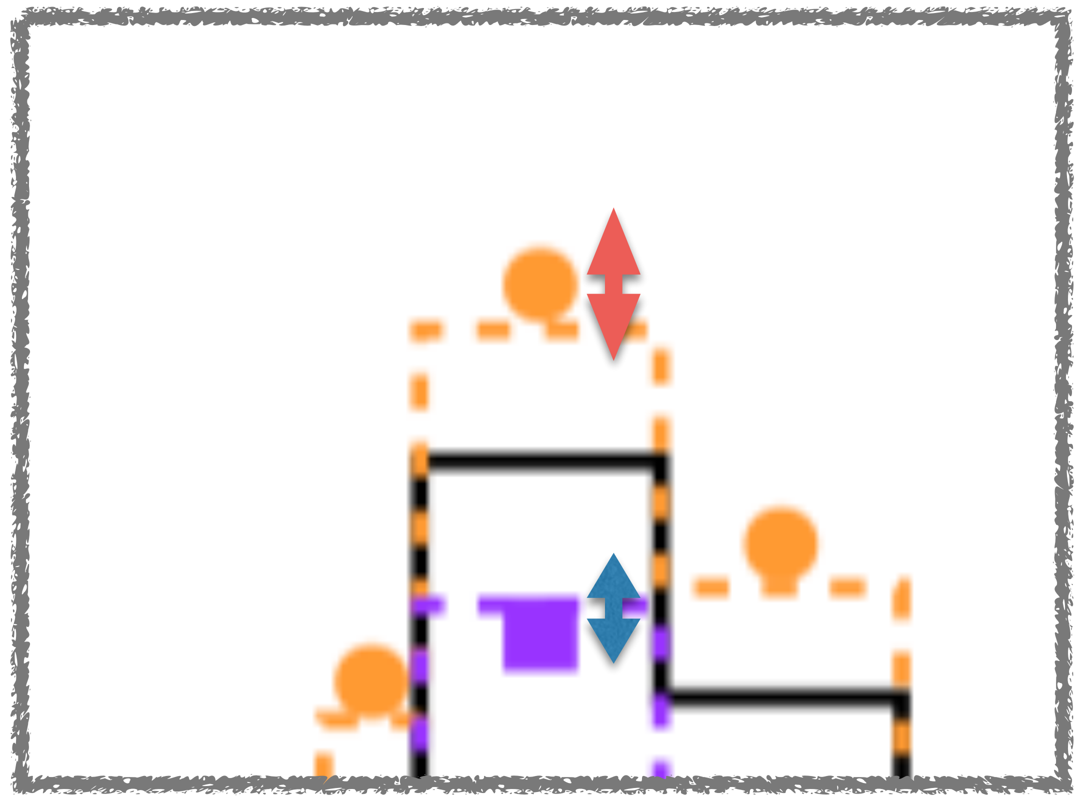
For perfect extrapolation dots and dashed lines should match perfectly
What you care about is how much this extrapolation does not correct for the effect.

A worked example — inserting a fake discrepancy



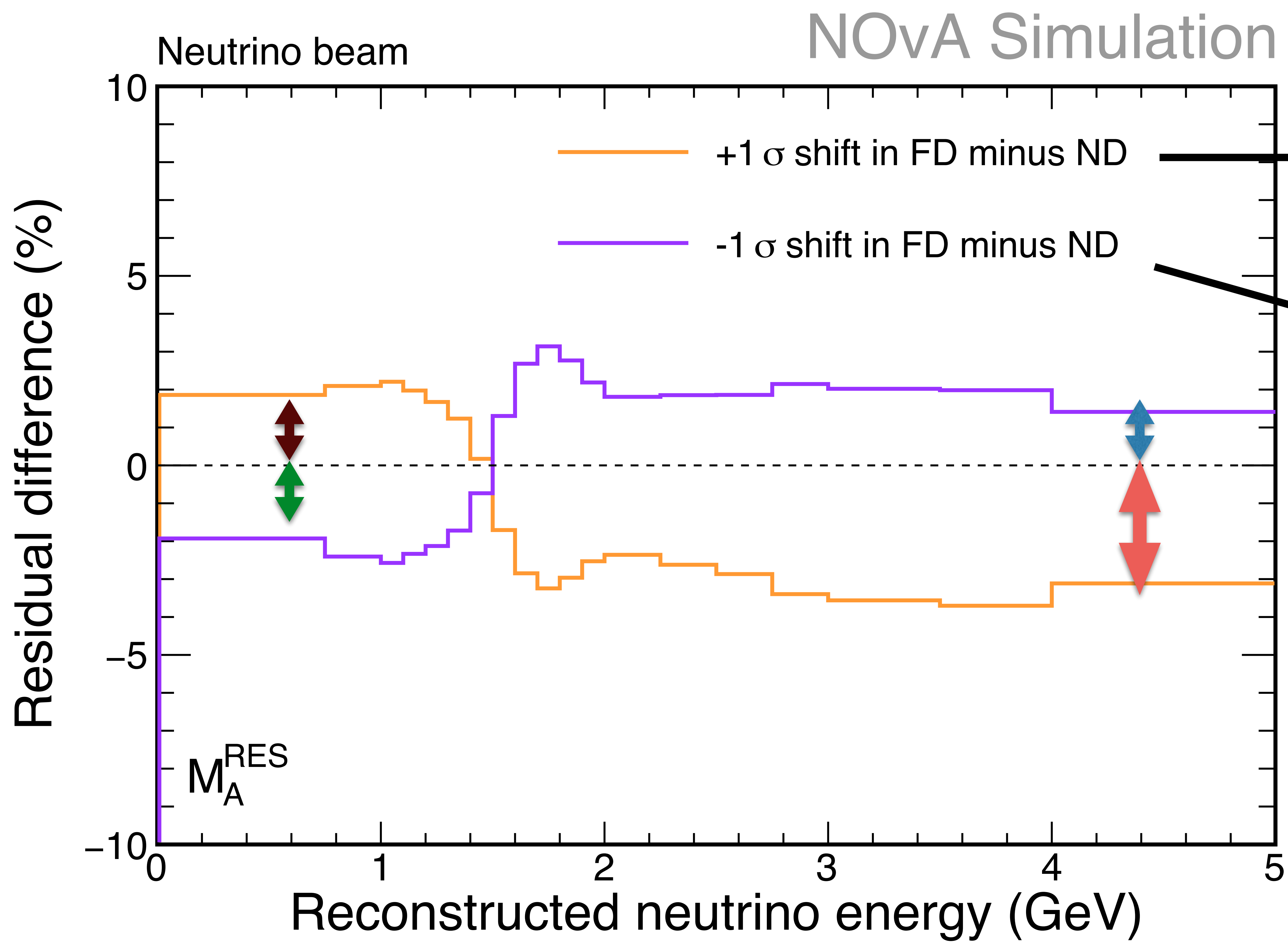
discrepancy inserted into ND and used to predict FD

discrepancy inserted into FD base MC



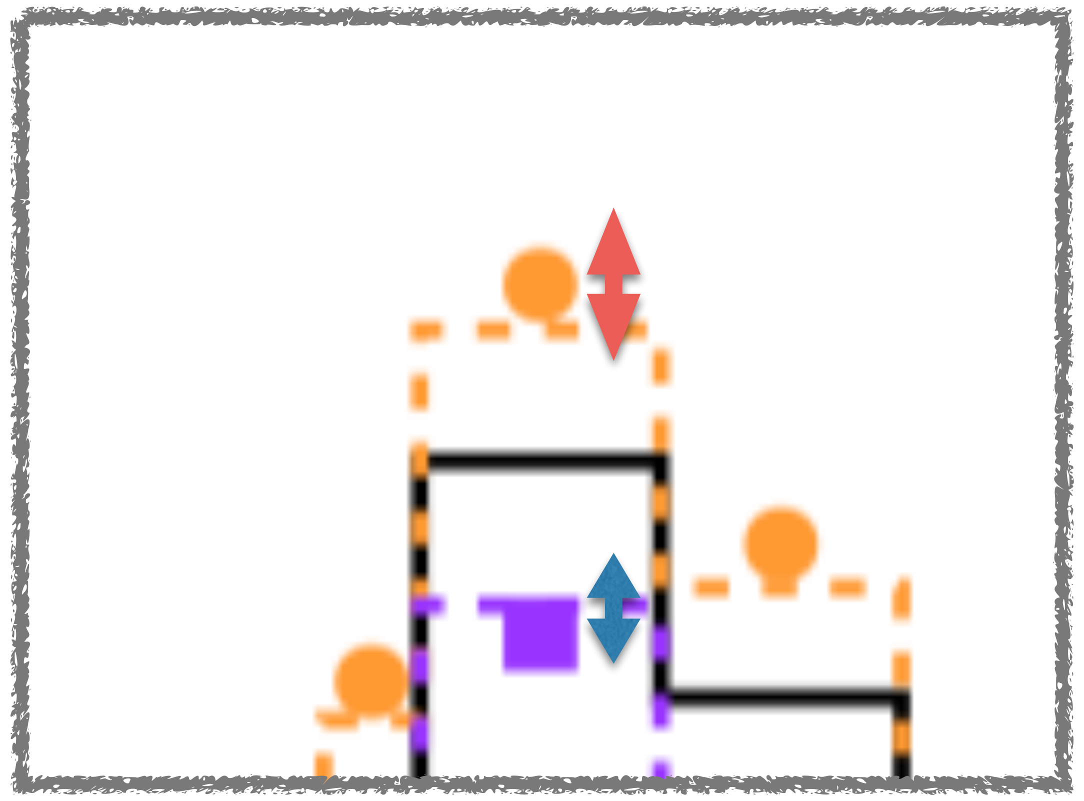
- Any data-mc discrepancy correlated between the two detectors will be reduced to this residual difference,
- This residual is what our ‘extrapolated’ systematics are designed to cover

A worked example — inserting a fake discrepancy



discrepancy inserted in to ND and used to predict FD

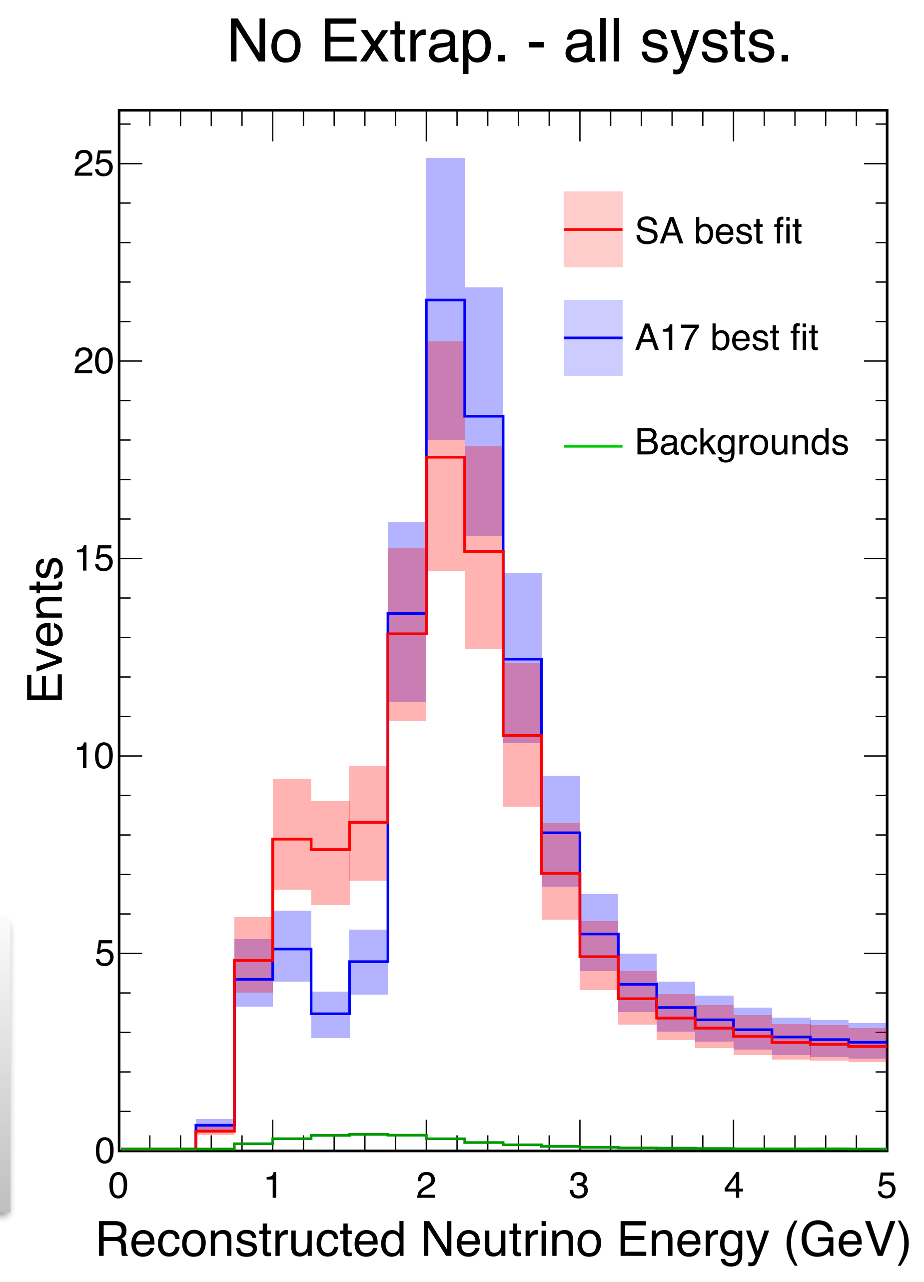
discrepancy inserted into FD base MC



- Any data-mc discrepancy correlated between the two detectors will be reduced to this residual difference,
- This residual is what our 'extrapolated' systematics are designed to cover

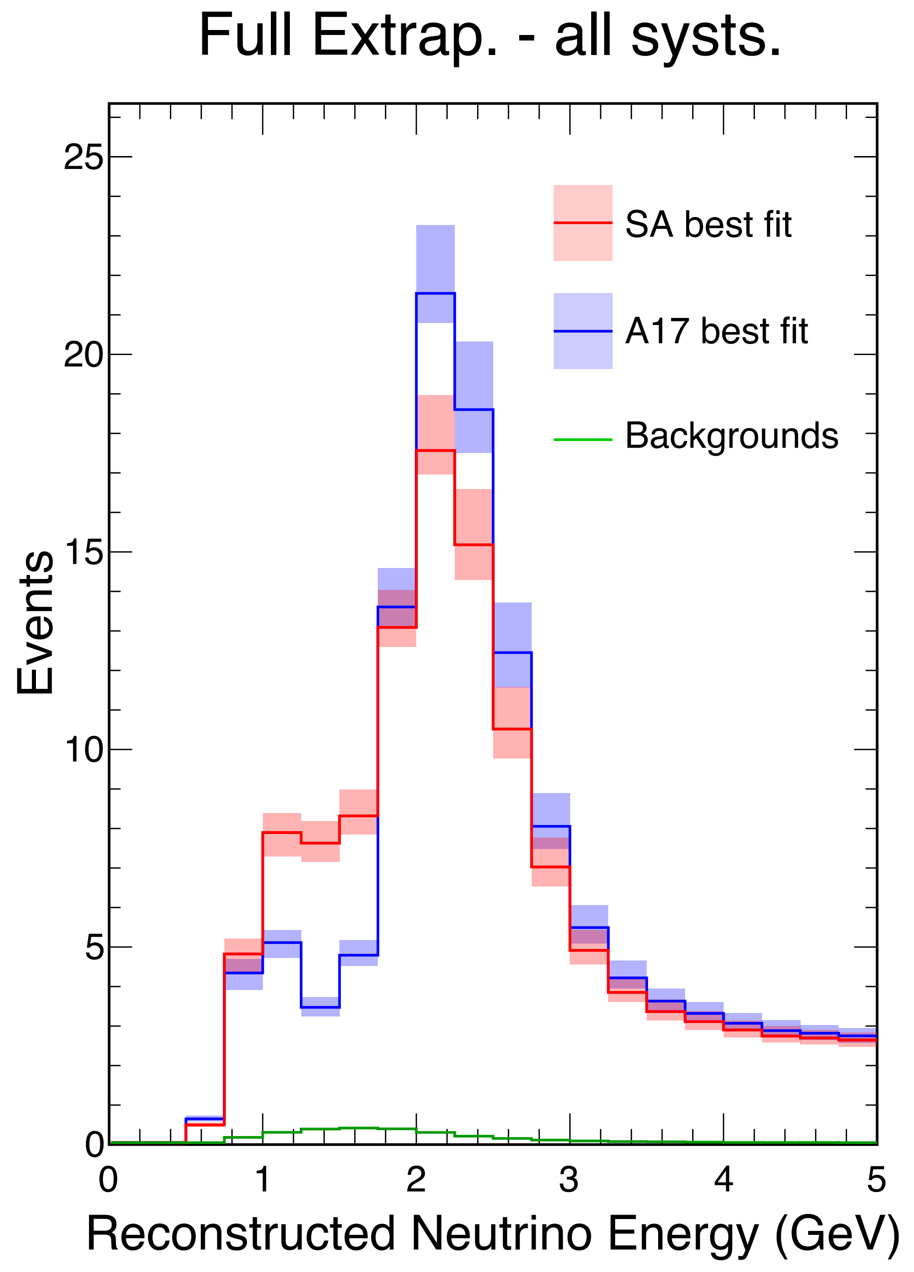
But what about systematics?

- All systematics are assessed by propagating these samples through the entire framework
    - Same systematic samples and techniques used for oscillation and cross section measurements
    - Multi-universe technique: ensemble of alternative predictions done by weights (flux and GENIE).
    - Sample of Shifted MC: generated shifting a response by 1σ and 2σ
- Detector-to-to detector corrections are explicitly included in the extrapolation procedure, as are correlations between oscillated components.
    - Correlations are included in joint fits — treated either fully correlated or uncorrelated
    - No correlation between different systematics included - i.e all GENIE knobs treated independent



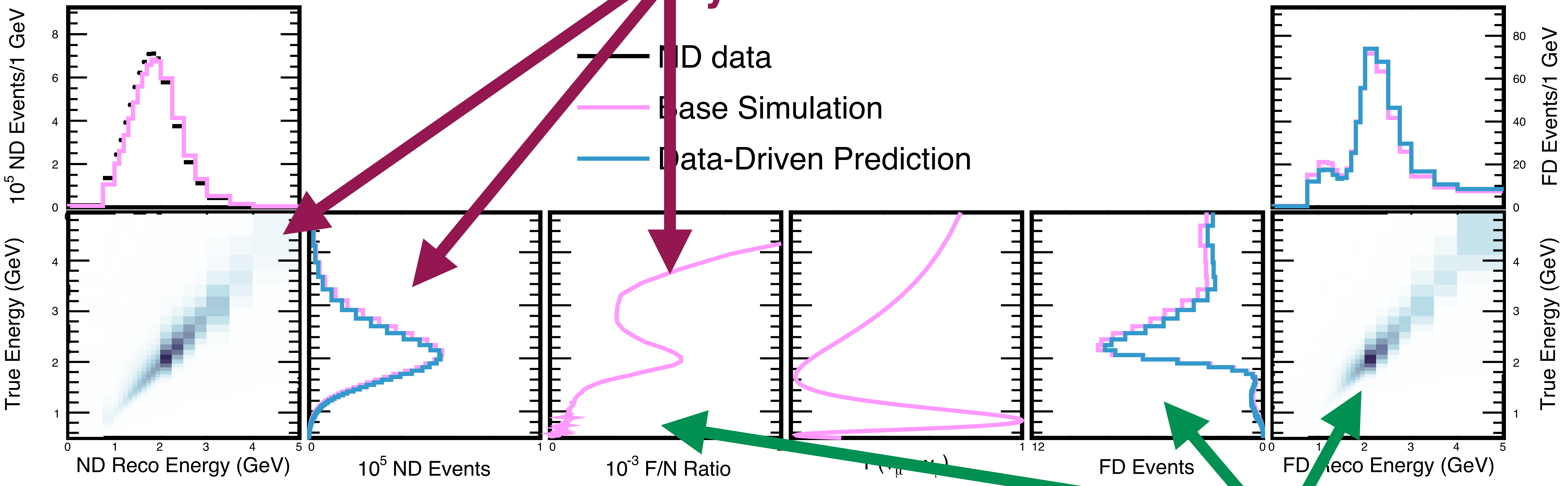
Far Detector MC and systematic bands

Far Detector extrapolated prediction and extrapolated systematic bands



Correlated, shift Near **and** Far detector - Absolute Uncertainties
Uncorrelated, shift either Near **or** Far Detector - Relative Uncertainties

Replace ND MC with systematic shifted version

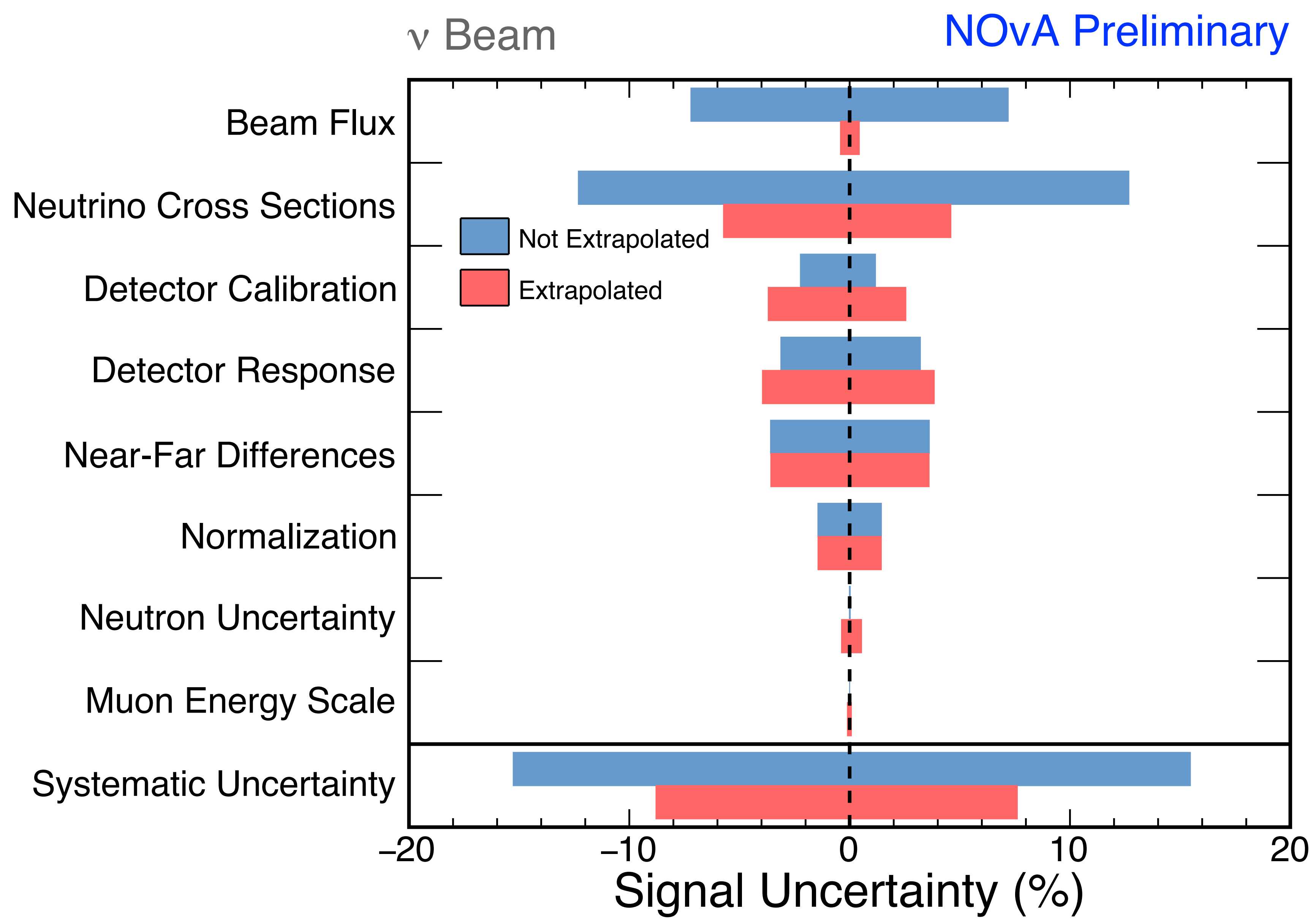


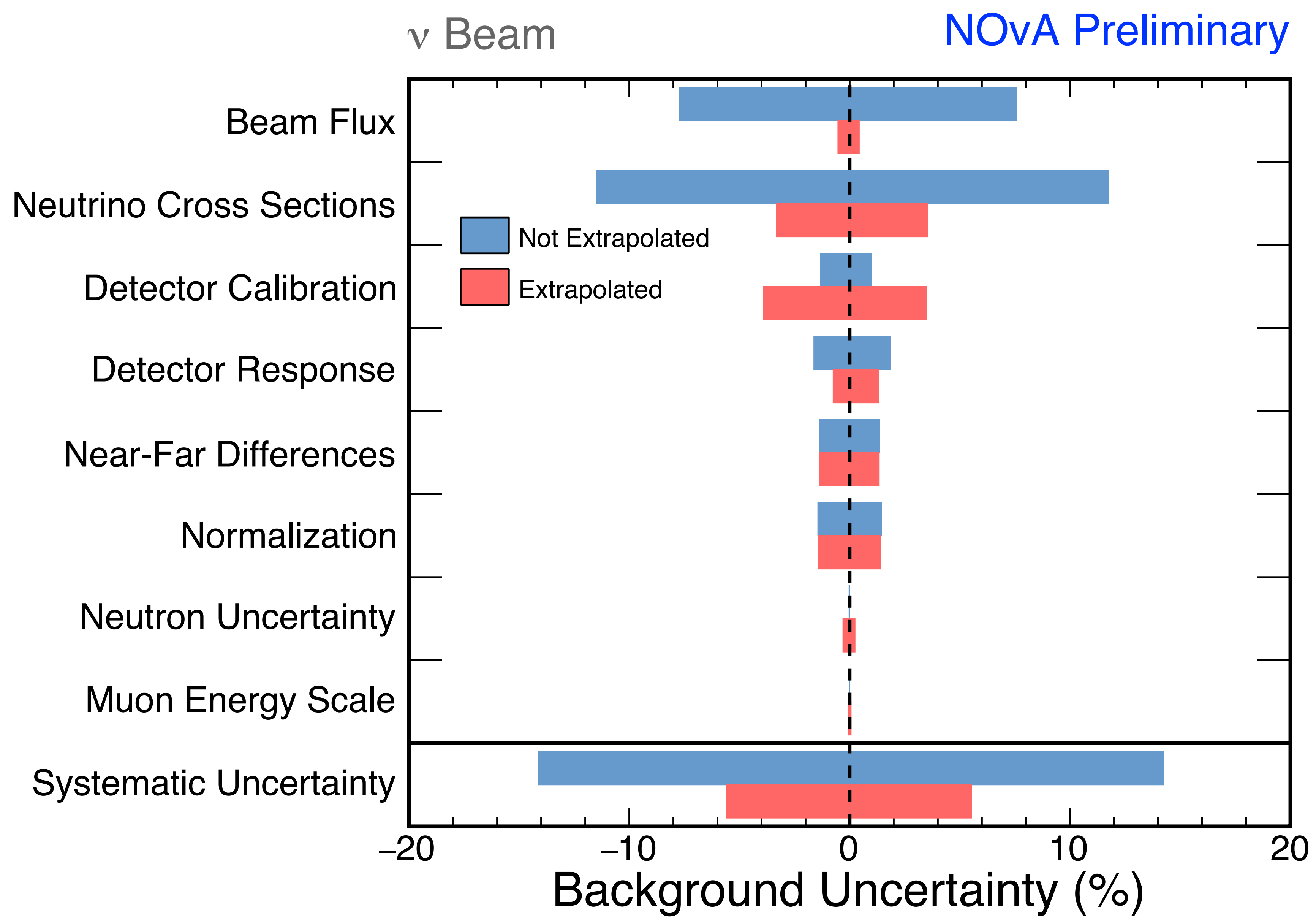
Systematic uncertainty defined as non-cancelling difference in systematically-shifted prediction and Asimov prediction

Replace FD Base Simulation with systematic shifted version

Example of extrapolated systematics:

Electron neutrino Appearance analysis

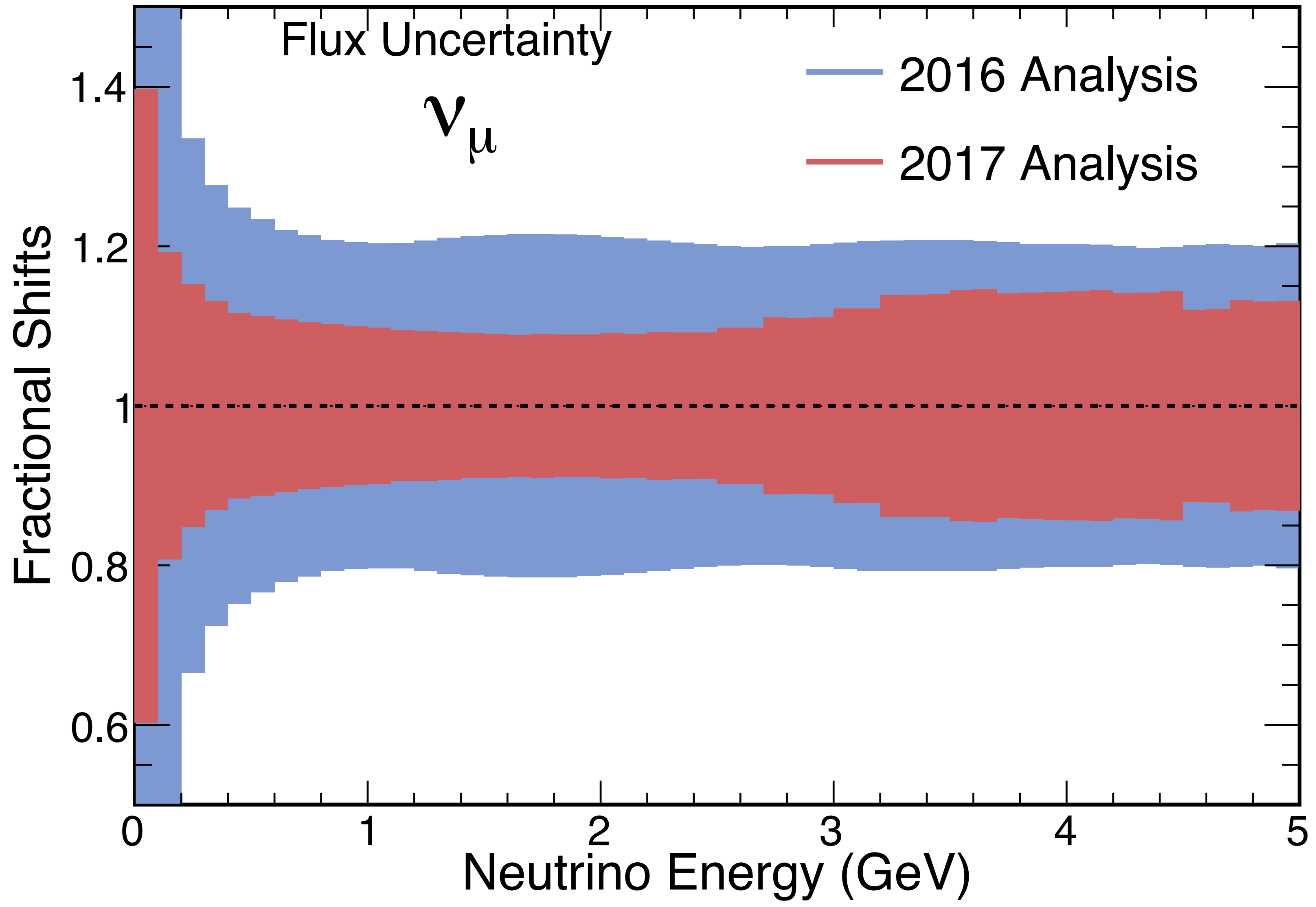


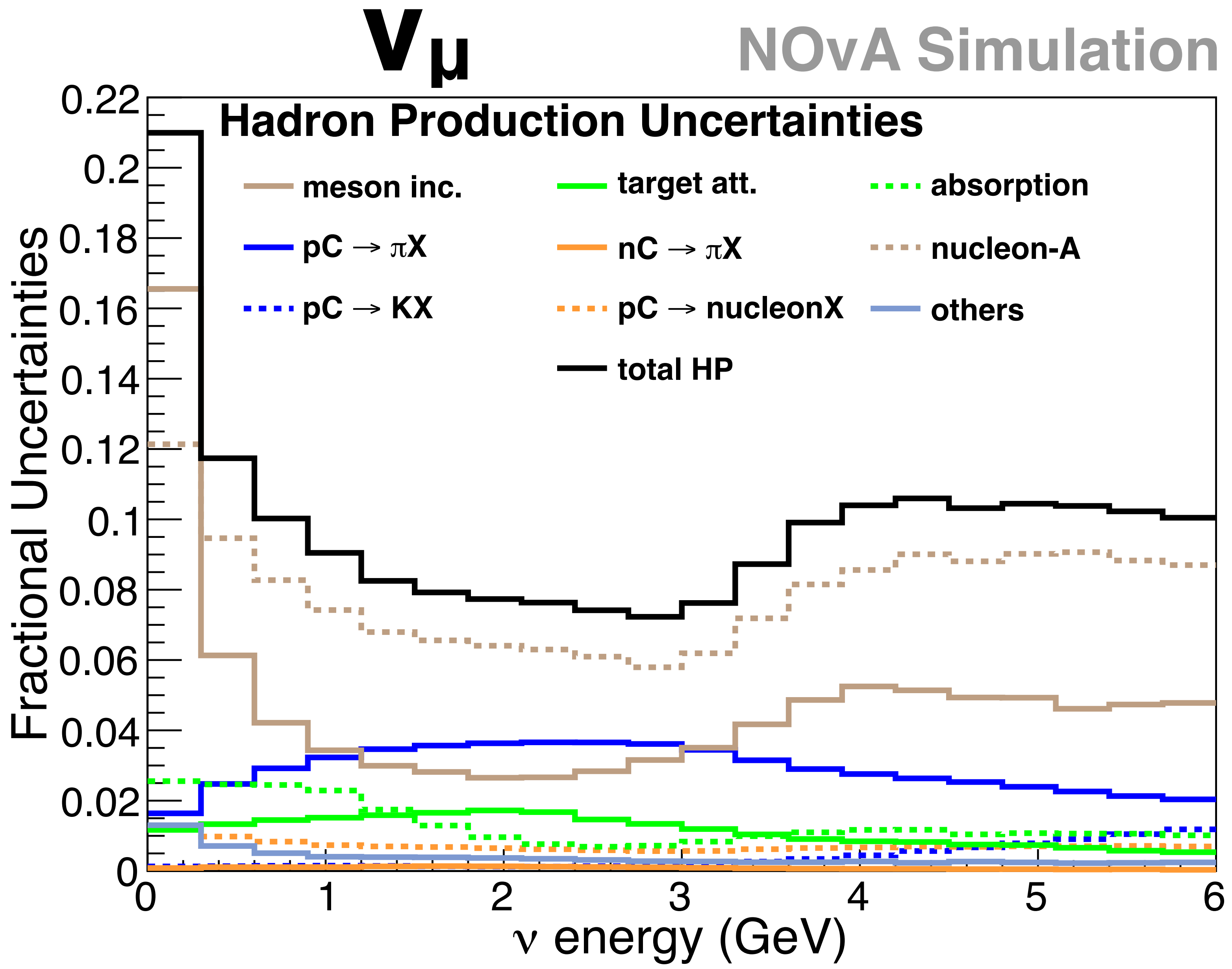


Beam

- We use G4NuMI for the beam simulation, with PPFX (Package to Predict the FluX) correction to central value
- Flux uncertainty in the peak comes from
  - Hadron production: 8% and Focusing: 4%
  - This uncertainty is mainly normalization and almost flat in 1-3 GeV, highly correlated between detectors
- Hadron transport uncertainties are also included
  - NuMI target and horn positions, horn current and magnetic field uncertainties, and beam spot size and position
- Multi-universe approach: Covariance matrix of 2000 universes in F/N space, including PPFX and hadron transport
- Use 'Principal Component Analysis' method to pull main shape and normalization features out of matrix, which we can use as pull terms in the fit. Use 5 PCs in fit.

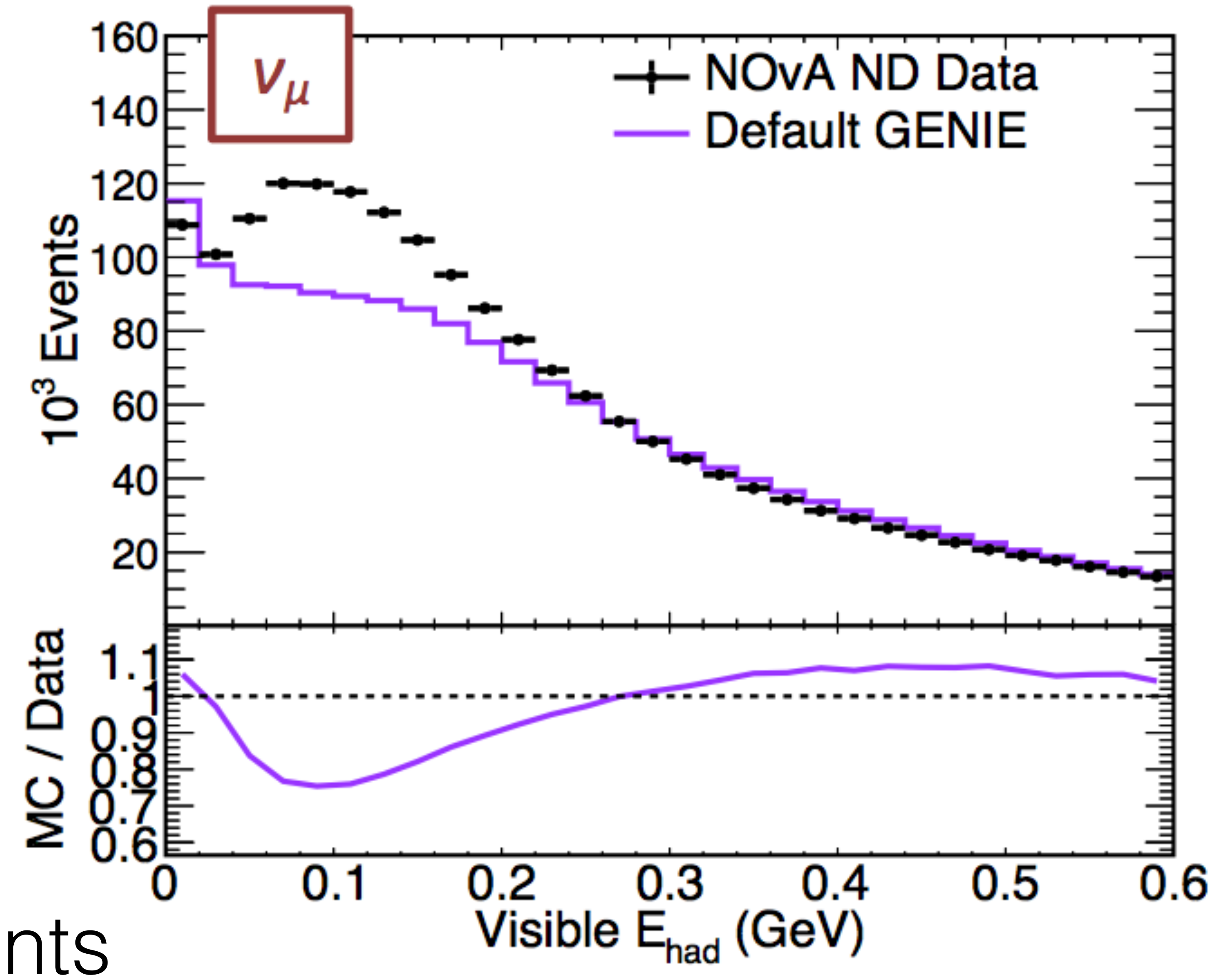
PPFX *(Phys. Rev. D 94, 092005 2016).*





Cross section systematics

- **GENIE** (2.12.2) for the neutrino interactions and **GEANT4** (4.10.1) for propagating the particles.
- **Default is not seen to well reproduce our data**
- Produce a NOvA specific tune based on theoretical input and our observed data-mc discrepancy
- Systematic uncertainties
  - GENIE reweighted based uncertainties
    - Using all non-degenerate knobs ~50, but no alternative models run
    - No correlations assumed, all knobs treated uncorrelated
  - Uncertainties driven by NOvA's tune and data-mc differences
    - MEC, RPA, enlarged GENIE DIS
  - 2% uncertainty on the ν_e/ν_μ cross section ratio to account for radiative corrections
  - 2% uncertainty anti-correlated between ν_e and ν_e to allow for second class currents
    -



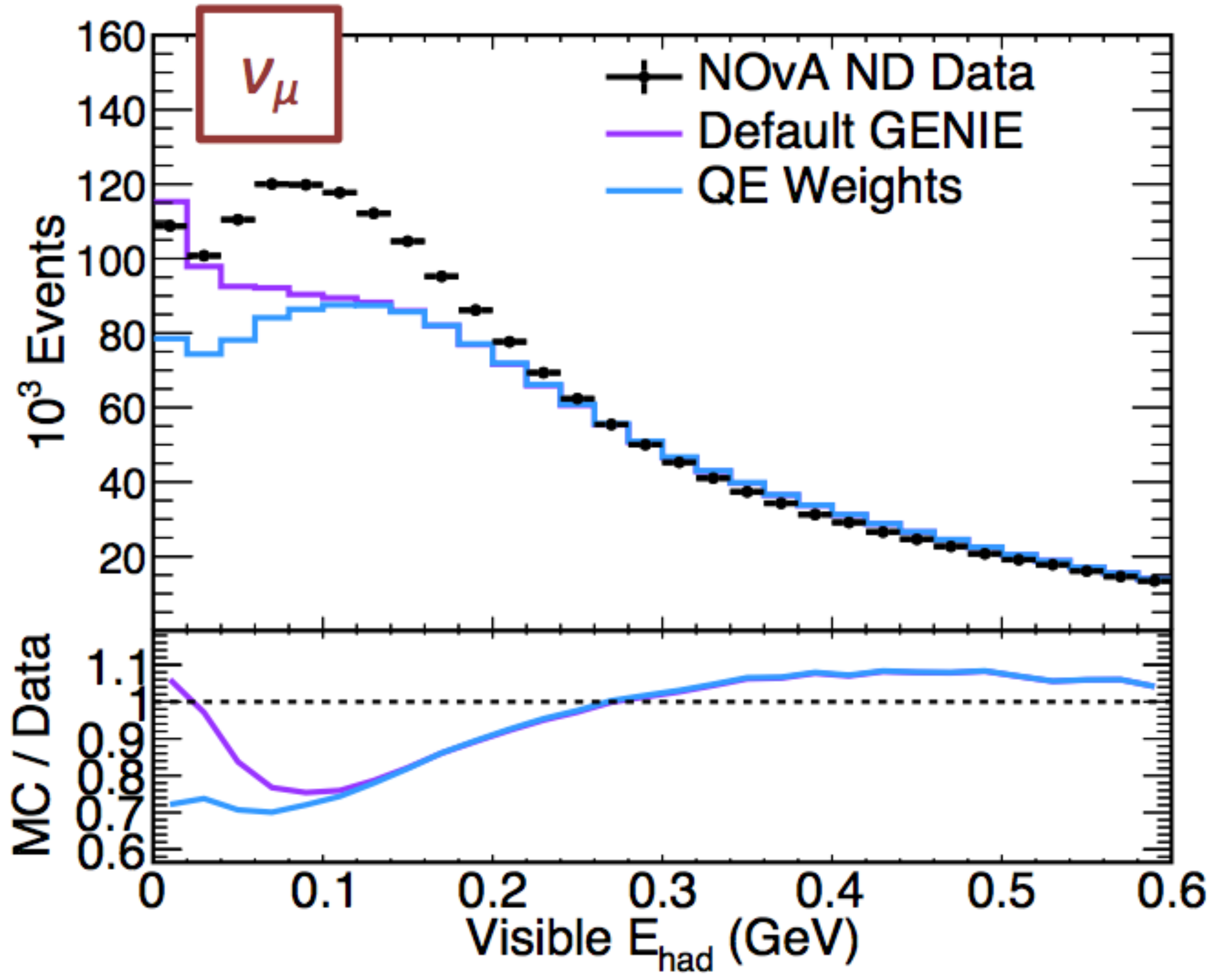
- Largest systematics (after extrapolation) included as individual pulls in fit
- Small systematics included via multi-universe approach. Covariance matrix (in F/N) and then collapsed down into 'principle components', dominant eigenvalues to be used as pulls in the fit

Cross section: Central Value tune and Uncertainties

QE weighs

- Apply nuclear screening through RPA
  - Using calculations from the Valencia group for CCQE with associated uncertainties

- Reduce the MA in the Llewellyn-Smith quasi-elastic cross section by ±5%. Dipole axial form factor set to M_a^{QE} = 1.04 ± 0.05 GeV (GENIE default: 0.99 GeV)
  - Based on error-weighted mean we calculated from bubble chamber data [collected in PRD 93, 113015].
  - Investigating z-expansion

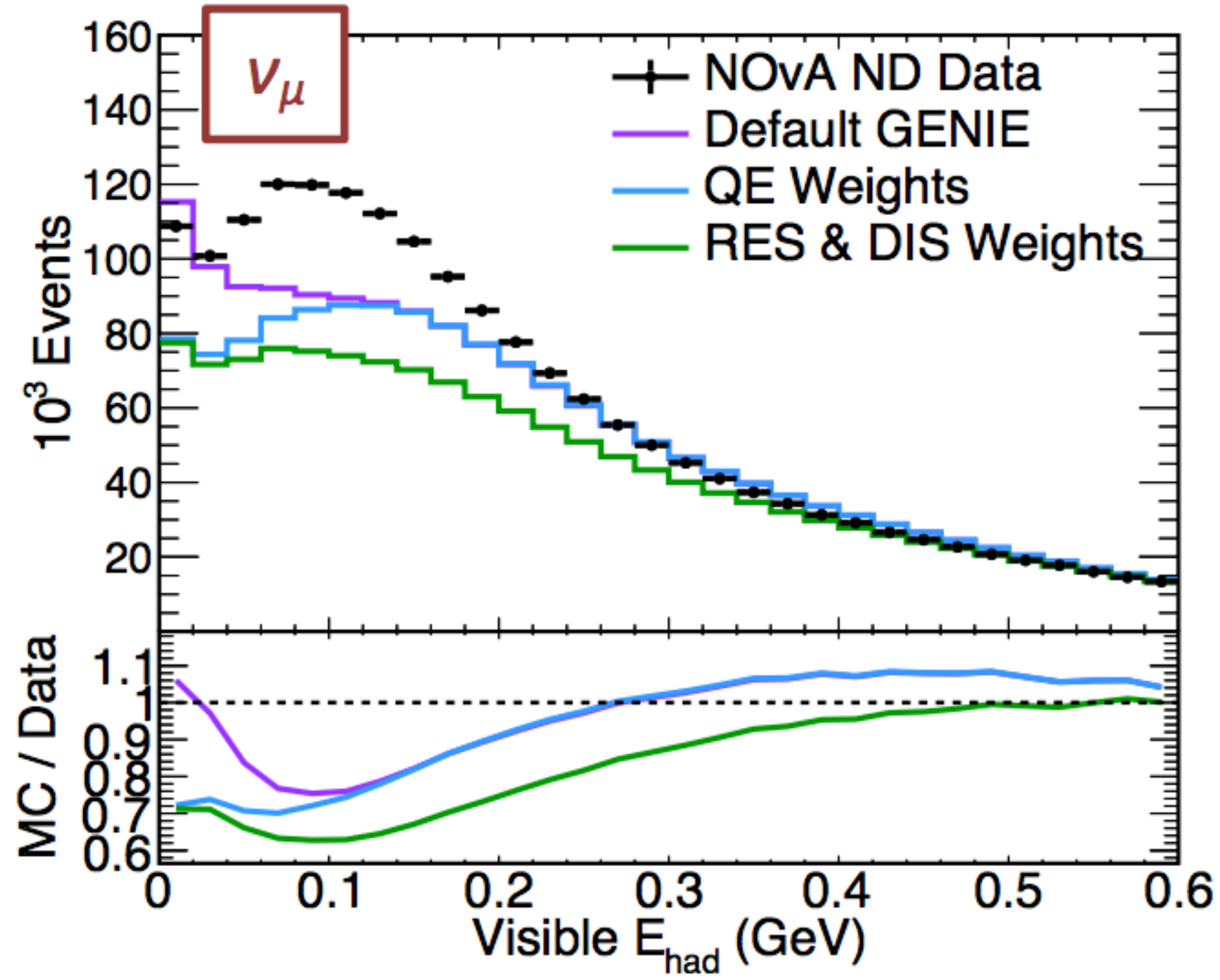


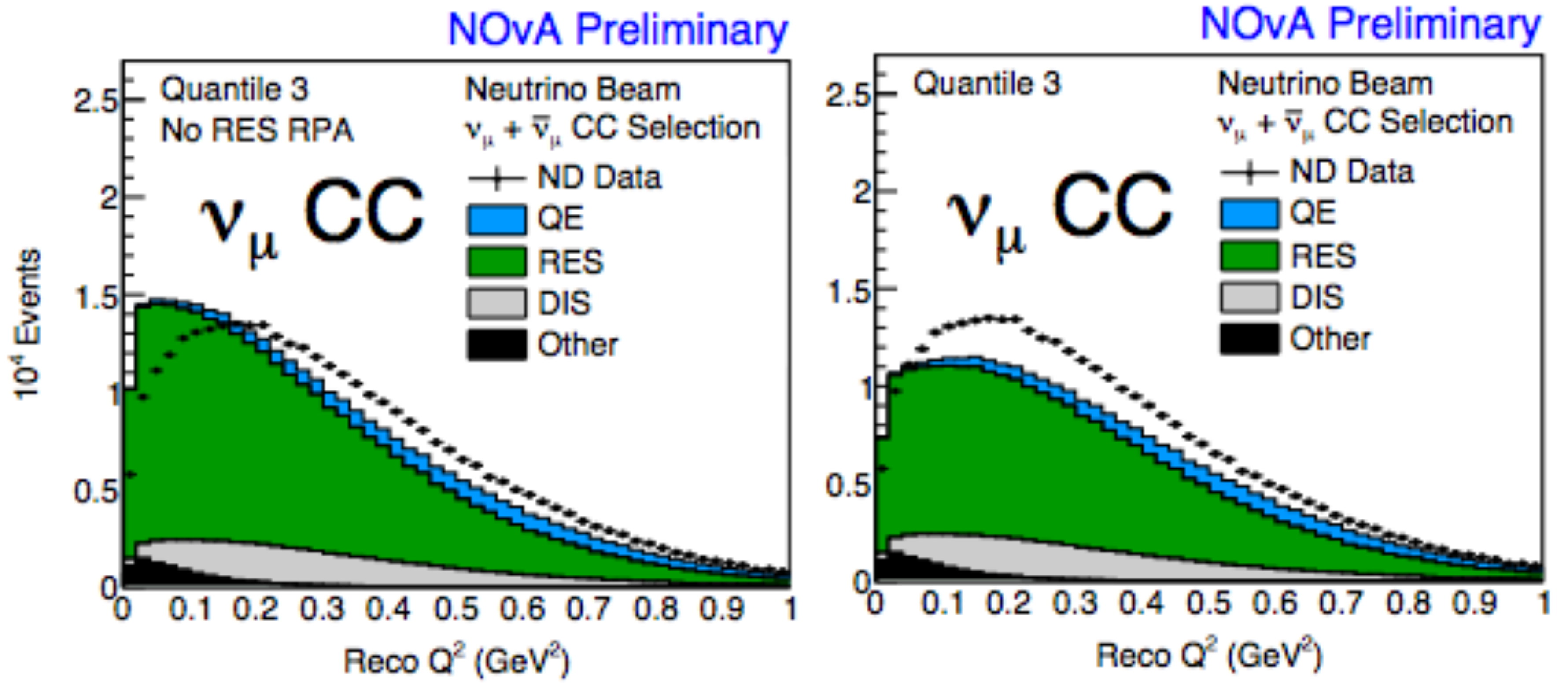
"Model uncertainties for Valencia RPA effect for MINERvA", Richard Gran, FERMILAB-FN-1030-ND, arXiv:1705.02932

Cross section: Central Value tune and Uncertainties

RES and GENIE DIS weights

- Include RPA effect for resonant events, motivated by external and NOvA data.
  - Use Q^2 parameterization of the Valencia CCQE RPA effect, taking the uncertainty as the whole size of the effect.
- Reduce GENIE non-resonant single pion production with W < 1.7 GeV by 57% (only for neutrinos),
  - Based on the reanalyzed ANL & BNL bubble chamber data,[Eur.Phys.J. C76, 474]
- 10% increase in non-resonant inelastic scattering (GENIE DIS), above transition region of W > 1.7 GeV, and increase uncertainty of 50% (10%) for DIS events 3+pi events with W < 3 GeV (W > 3 GeV)
  - Based on discrepancies observed by NOvA



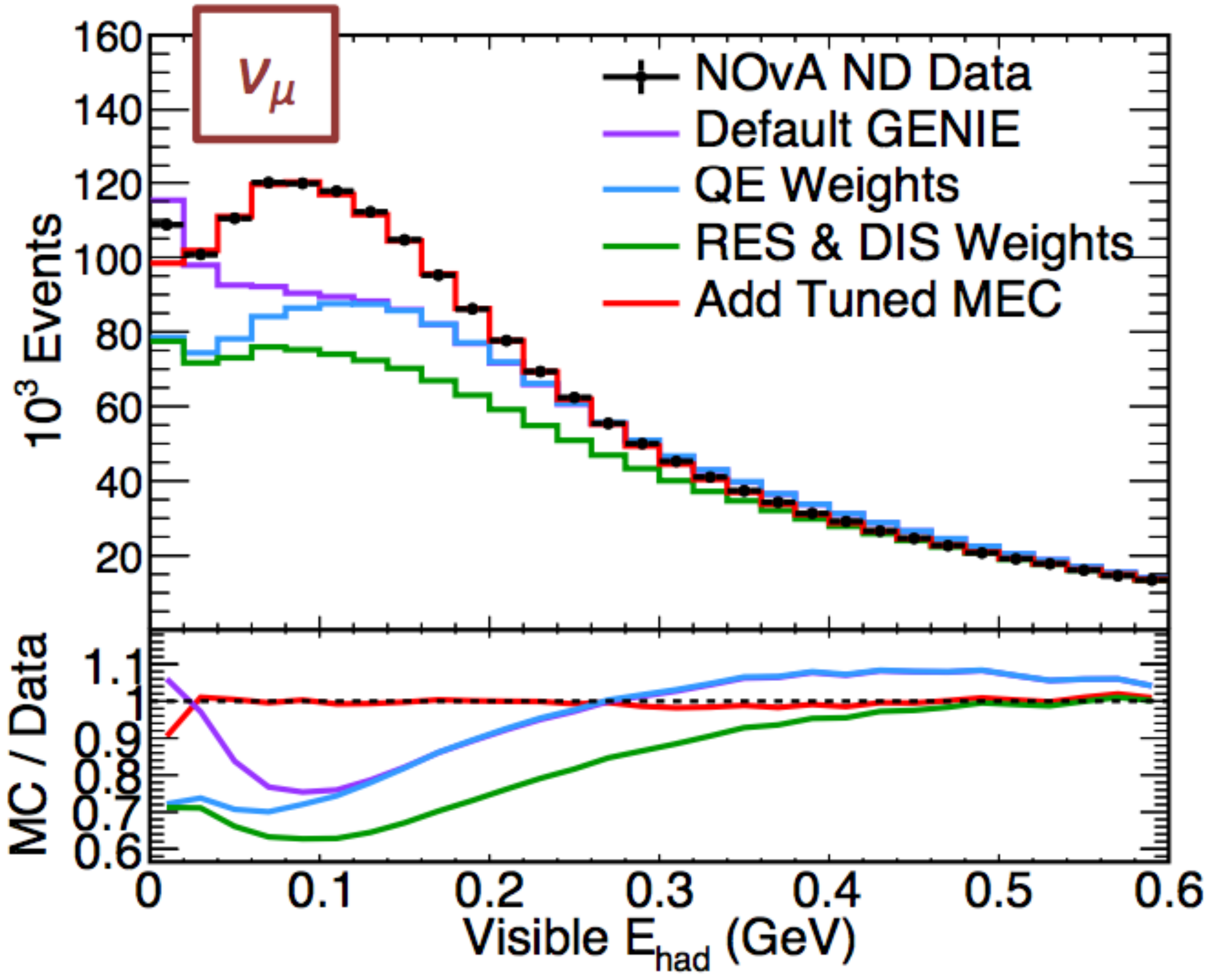


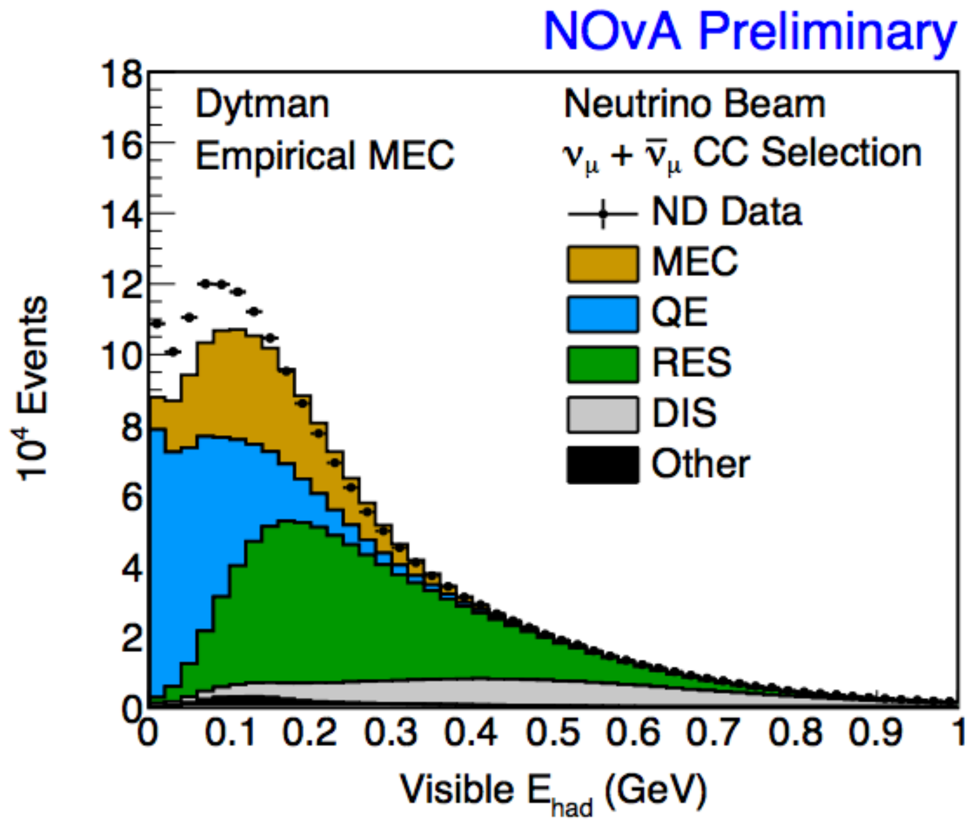
Applying $f(Q^2)$ Valencia CCQE RPA effect to RES

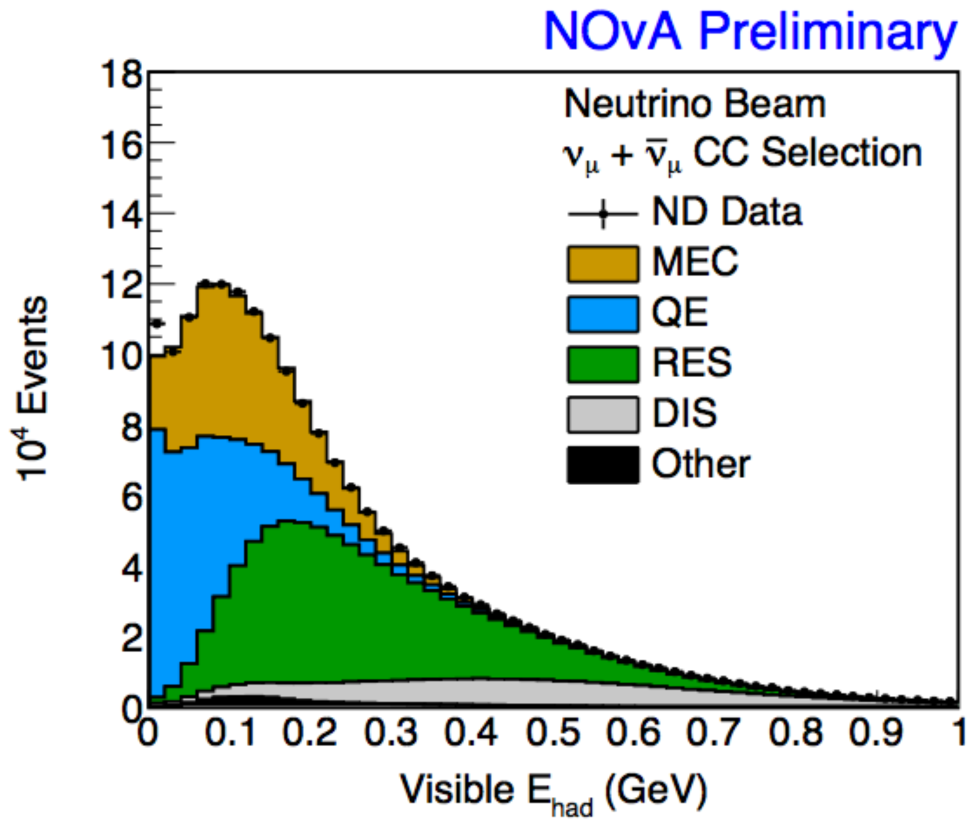
Cross section: Central Value tune and Uncertainties

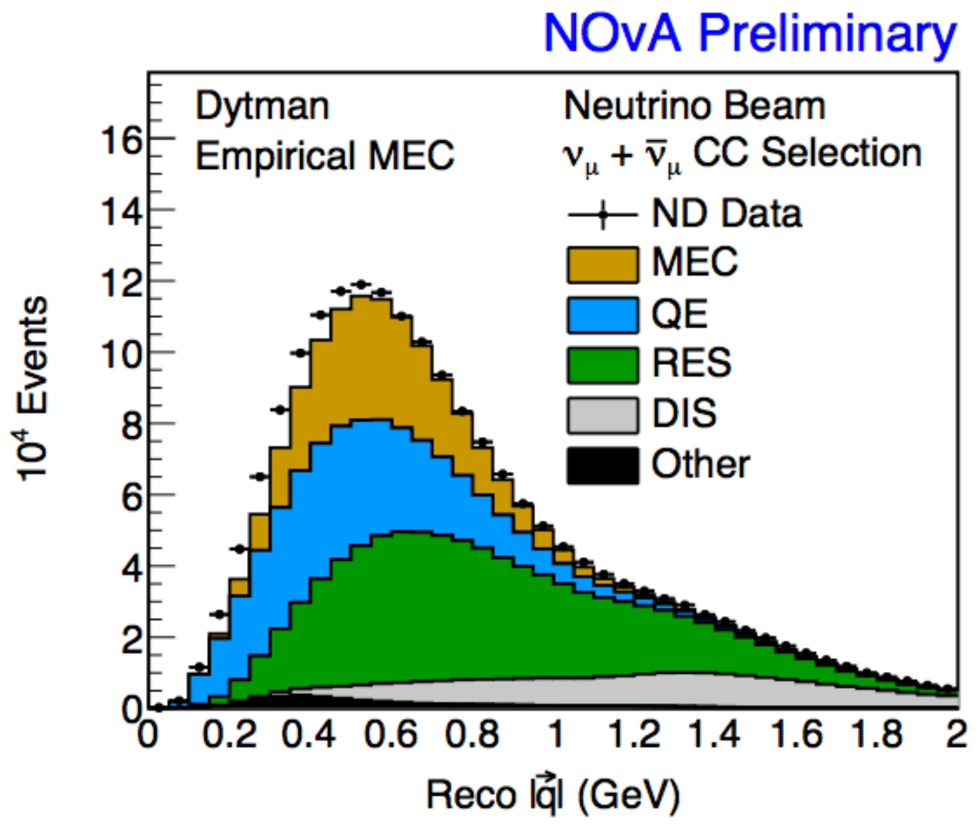
Tuned MEC

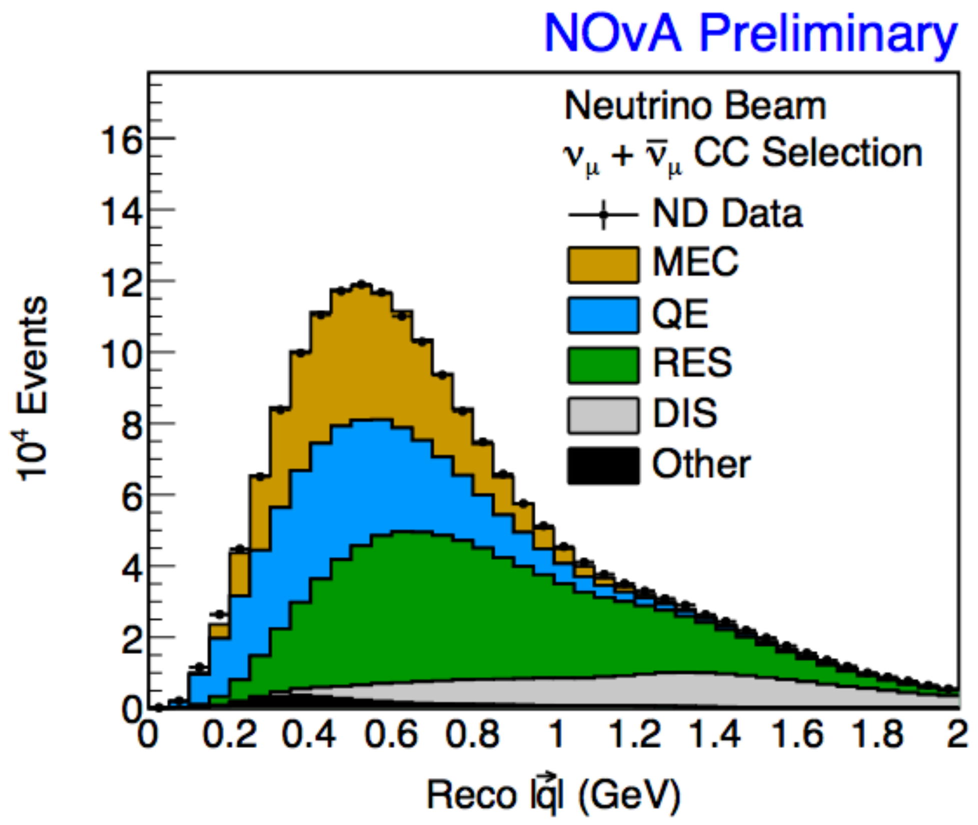
- Finally add in 2p2h 'Multi-nucleon knockout'.
- Use GENIEs "Empirical MEC" tuned in (q_0, |q|) to match our data.

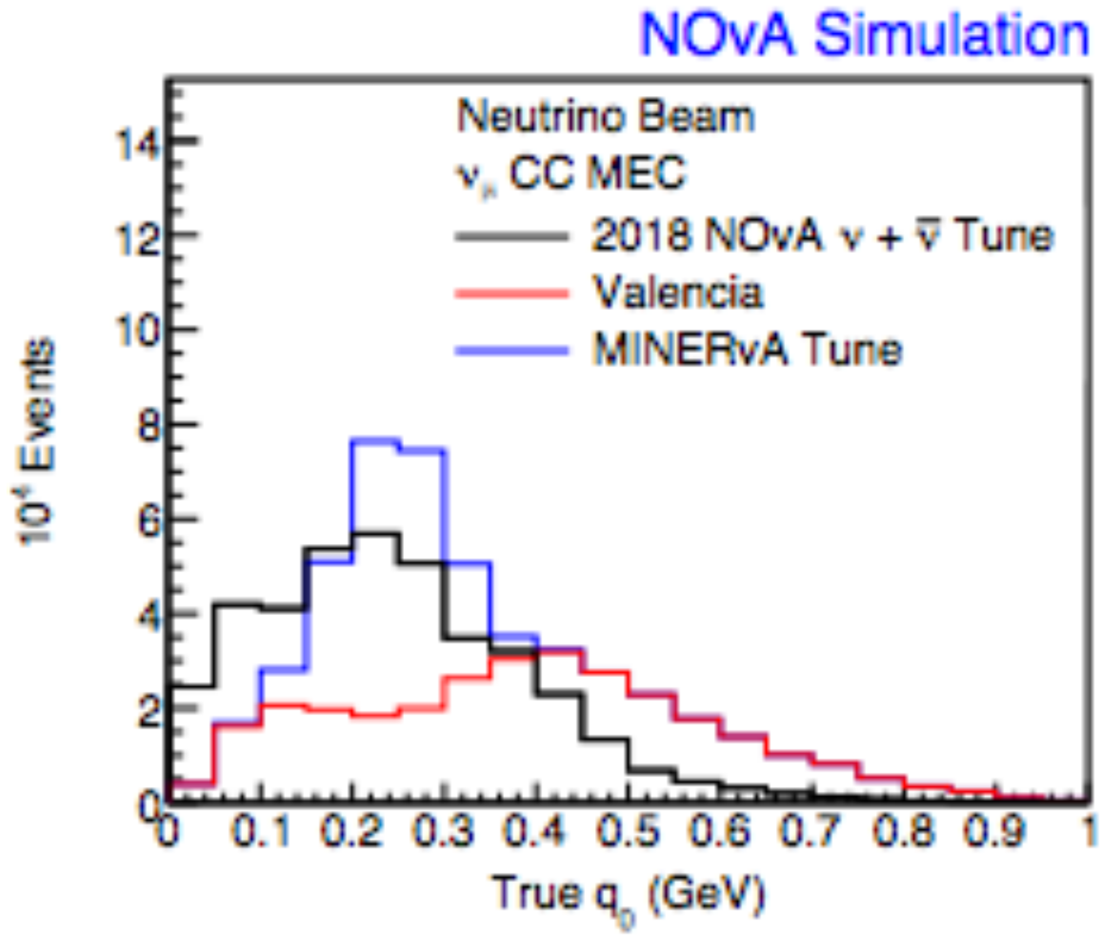


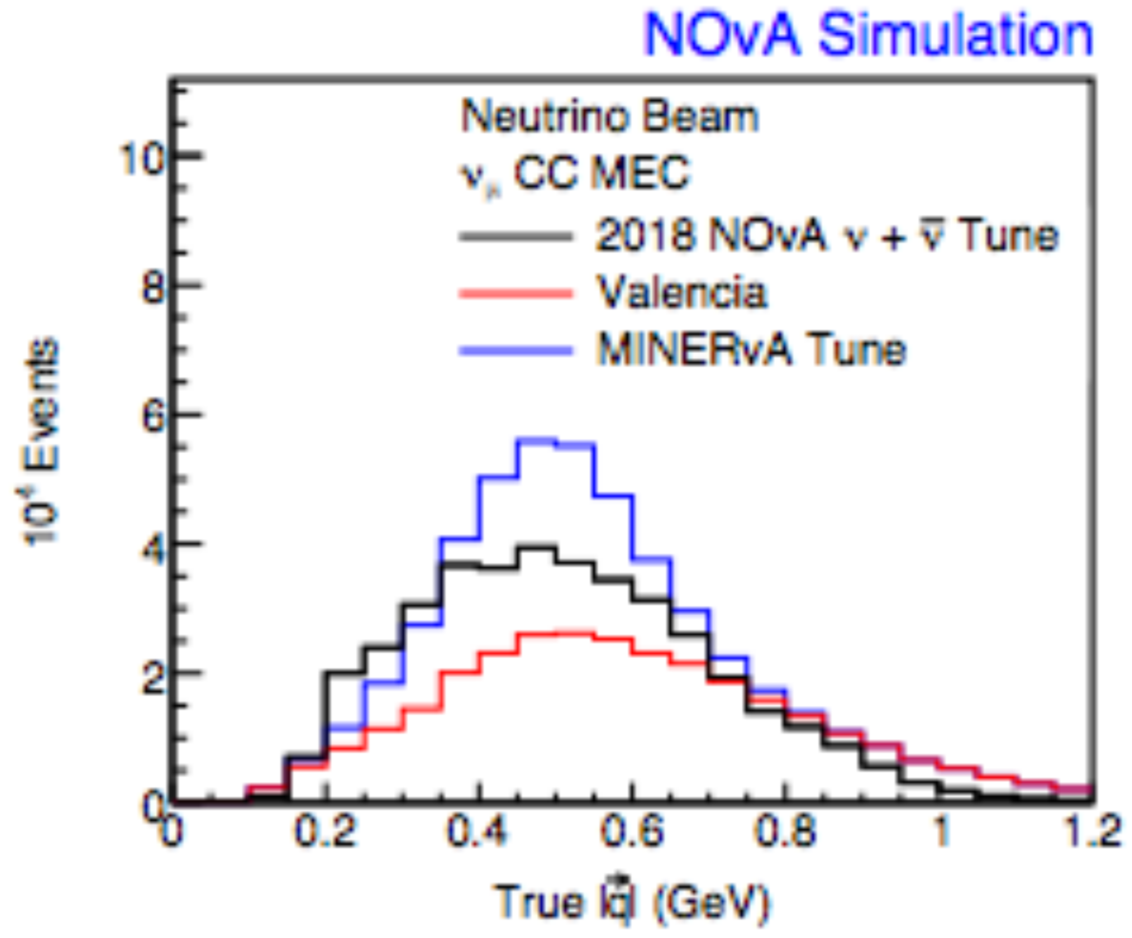




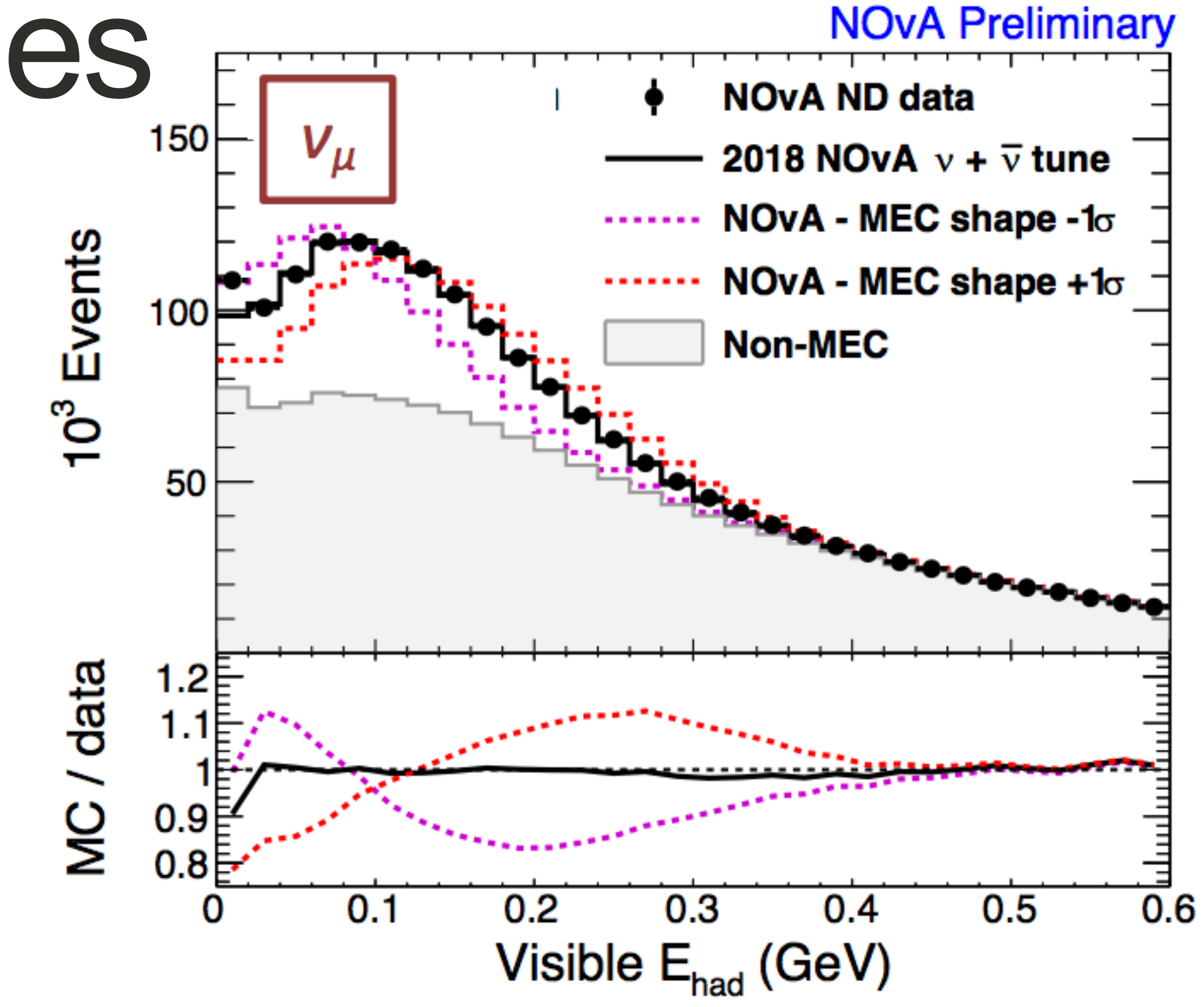






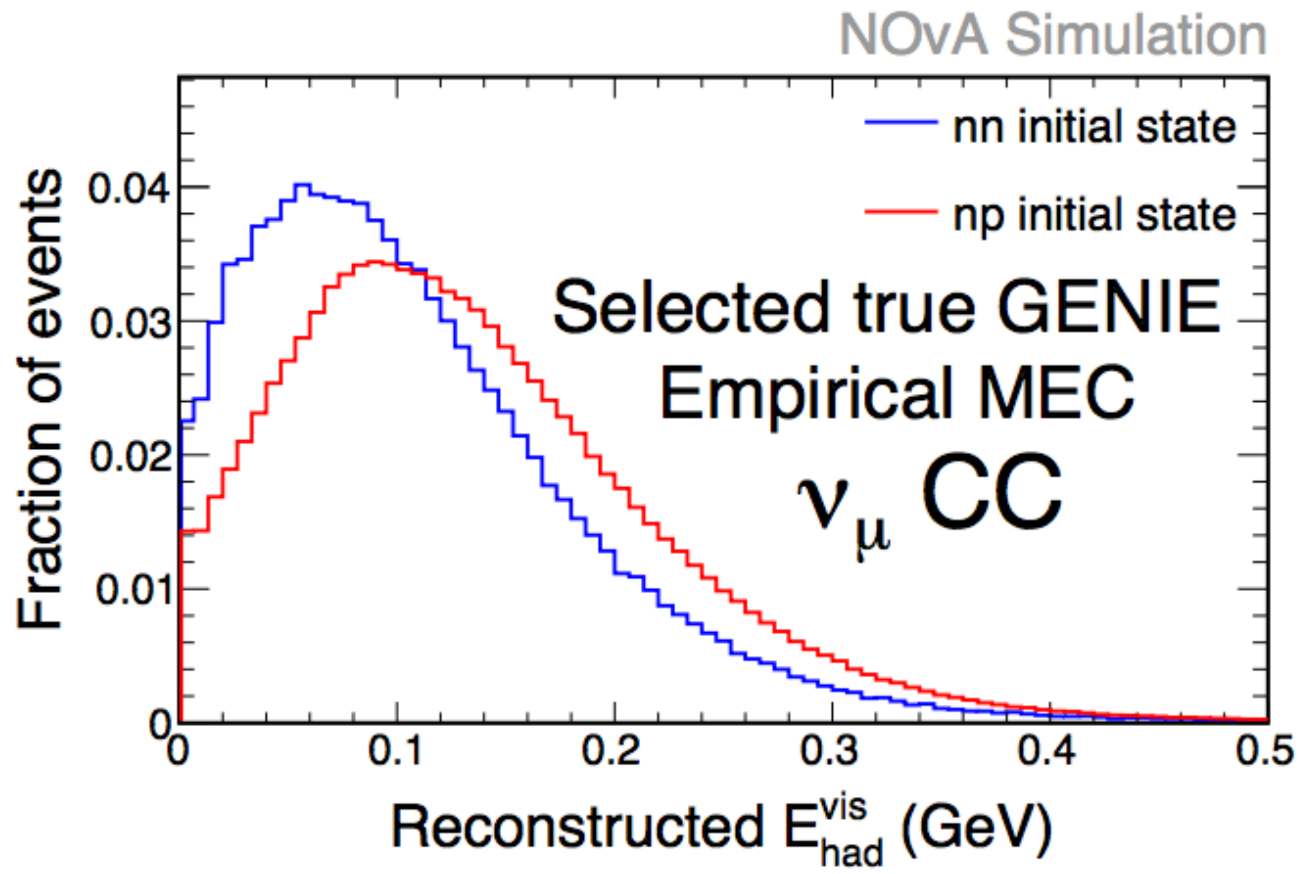


Cross section: Central Value tune and Uncertainties



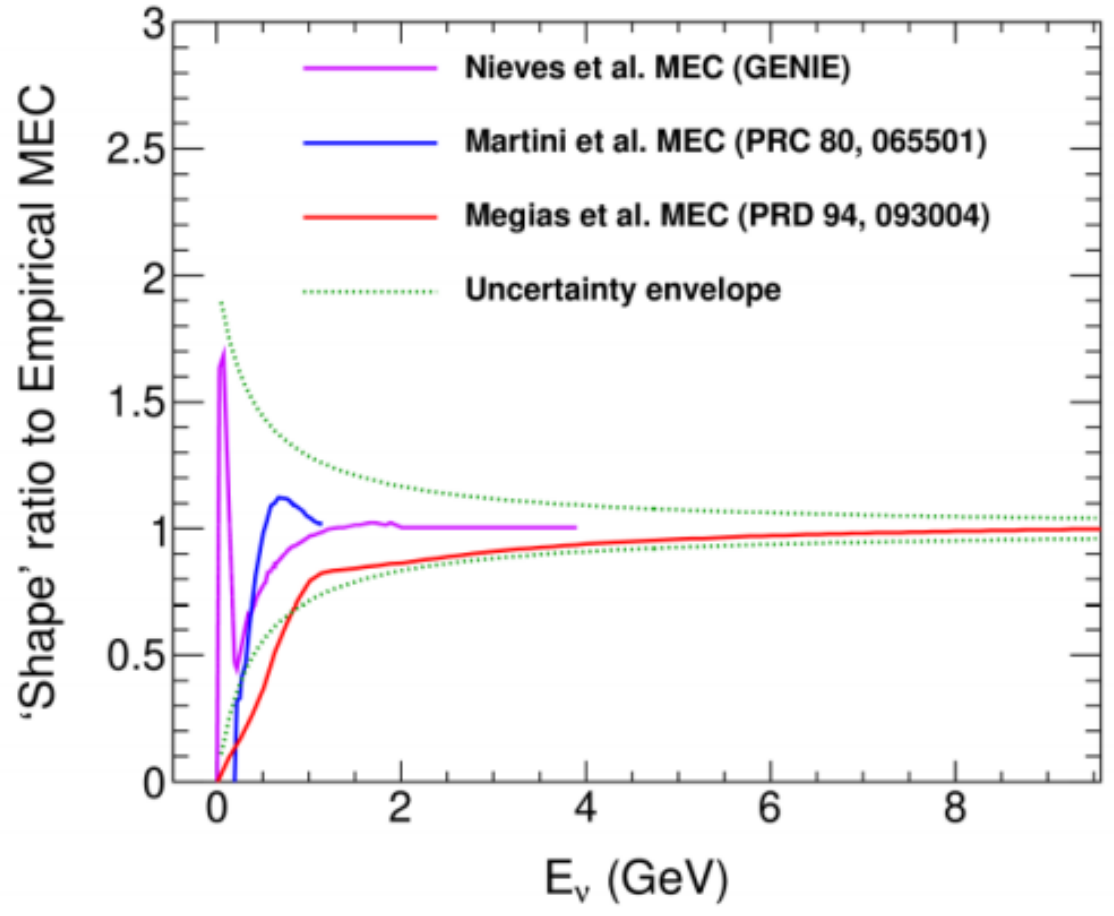
Tuned MEC Uncertainties

- **MEC shape**:
  Retune in (q_0, |q|) with correlated systematic shifts both enhancing and suppressing the QE and RES regions,
  - Treated as uncorrelated between neutrinos and antineutrinos



- **Initial State np Fraction**:
  Uncertainties on np-nn initial state composition from model comparisons (or np-pp for anti-neutrons) For 1σ NOvA chooses: $0.7 \leq \frac{np}{np+nn} \leq 0.9$

- **Neutrino energy dependence**:
  designed to bracket theoretical models

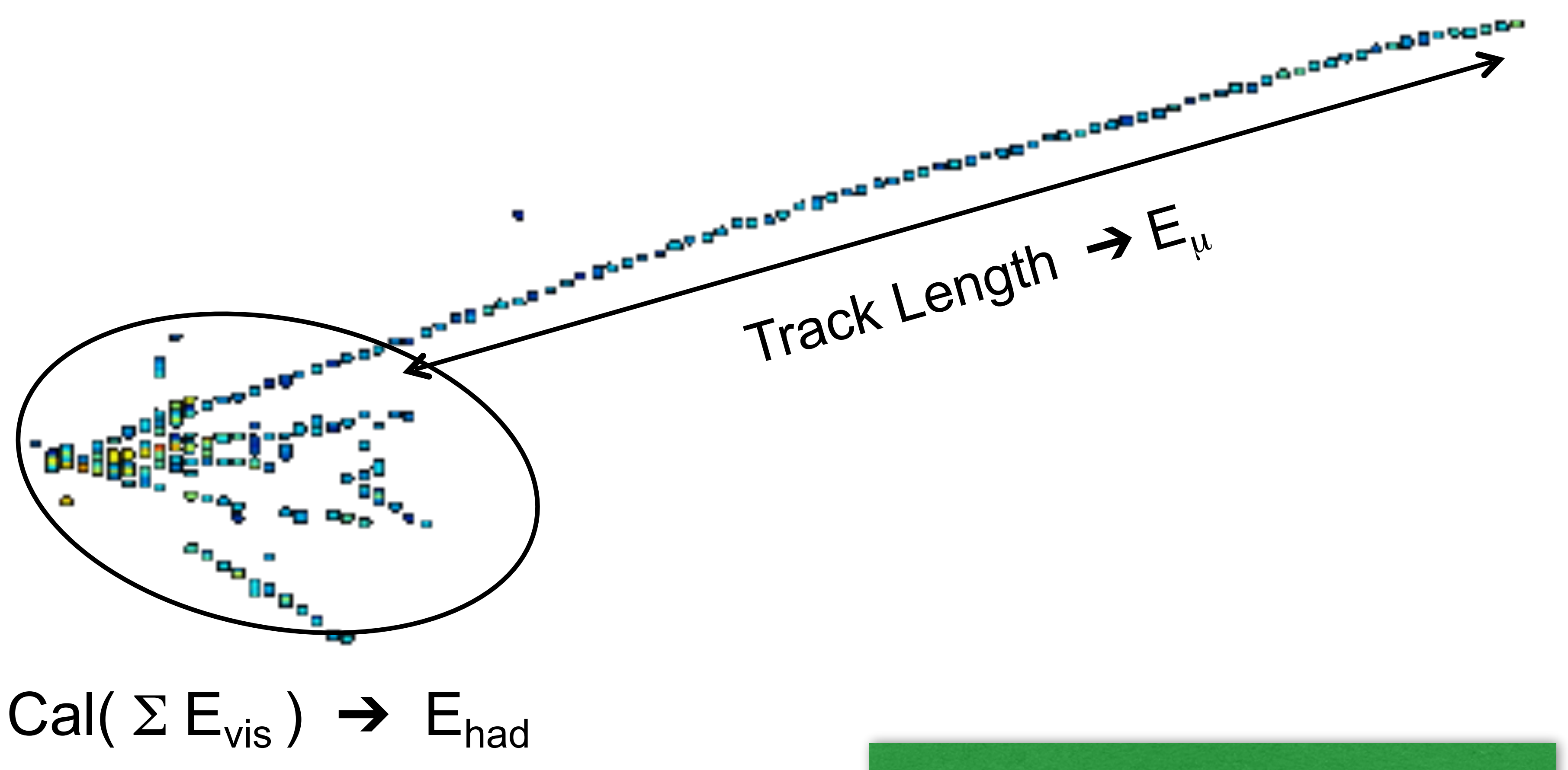


Detector Calibration

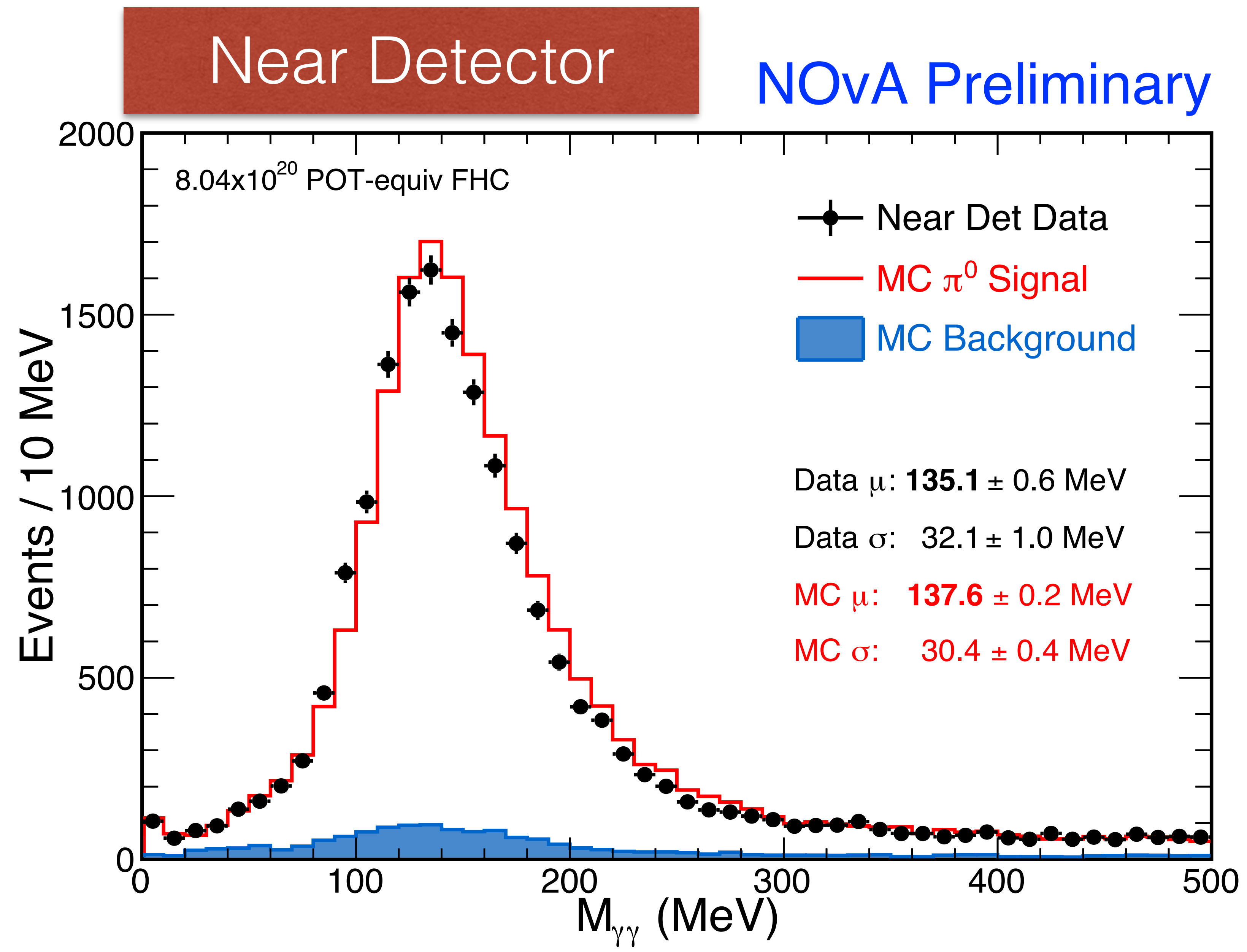
Energy scale: Stopping muons provide standard candle for setting absolute energy scale

- Uncertainty estimated from maximum difference between the multiple probes, Michele e- spectrum, π^0 mass, dE/dx of μ, p.
  - Most discrepant is the dE/dx of proton. **This discrepancy is interpreted as a 5% absolute calibration uncertainty.**
- Produce samples with energy shifted 5% lower and 5% higher. Applied as both correlated and uncorrelated between detectors

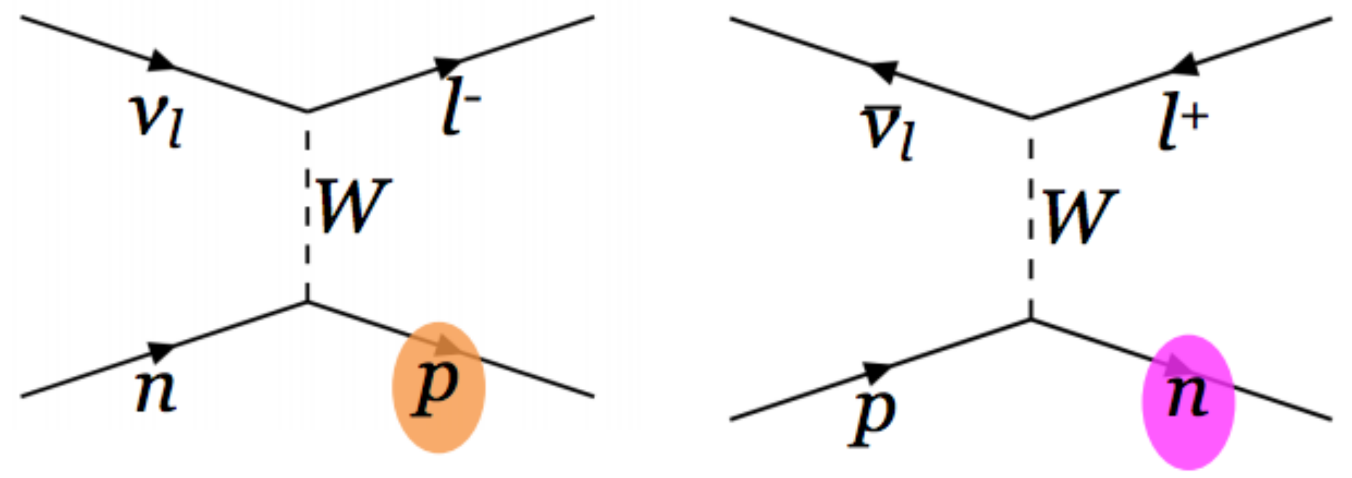
Attenuation: Using through going muons (cosmic or ν induced). Include WSF attenuation uncertainty to cover to differences seen in data and MC attention fits



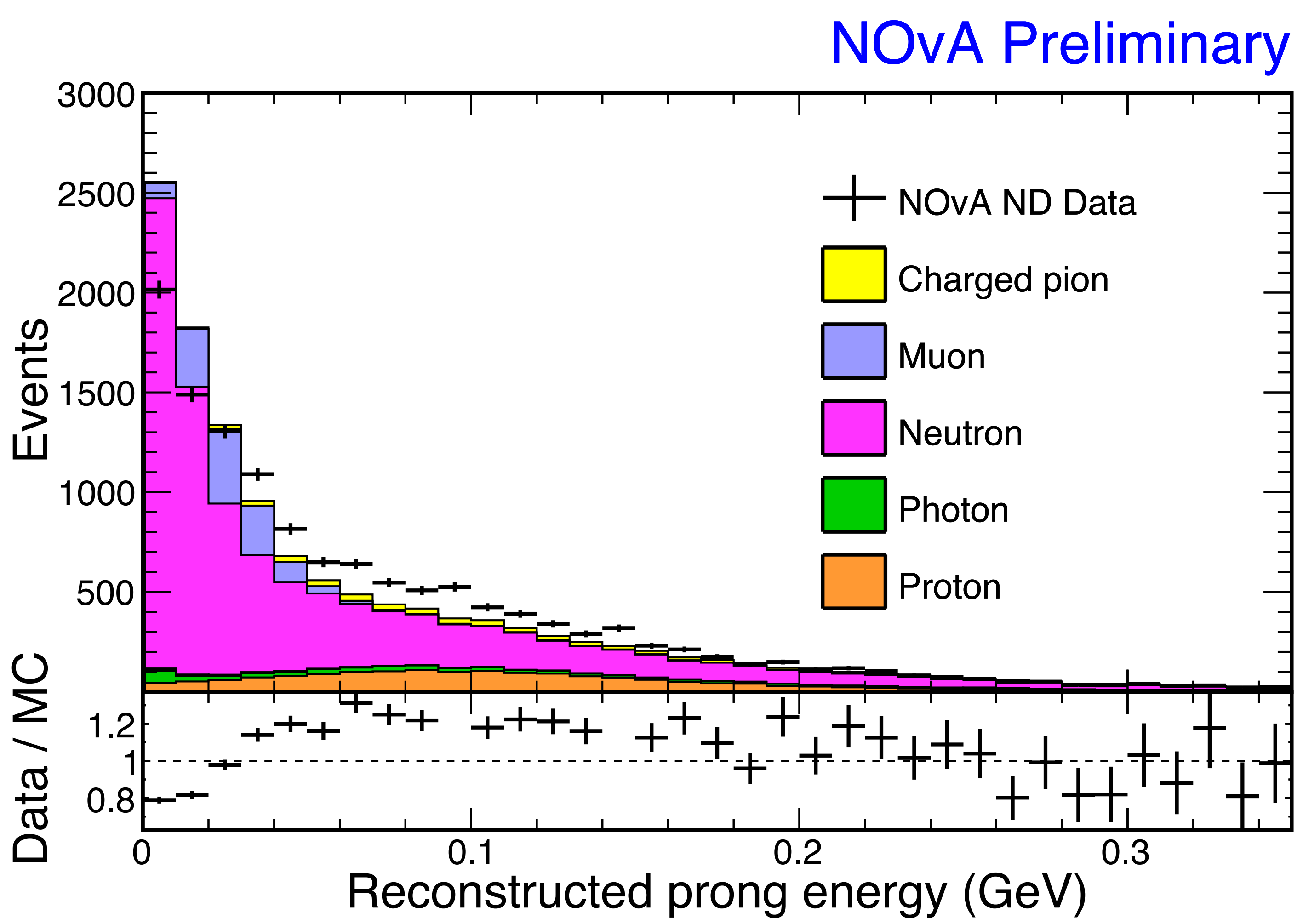
$$E_\nu = E_\mu + E_{had}$$

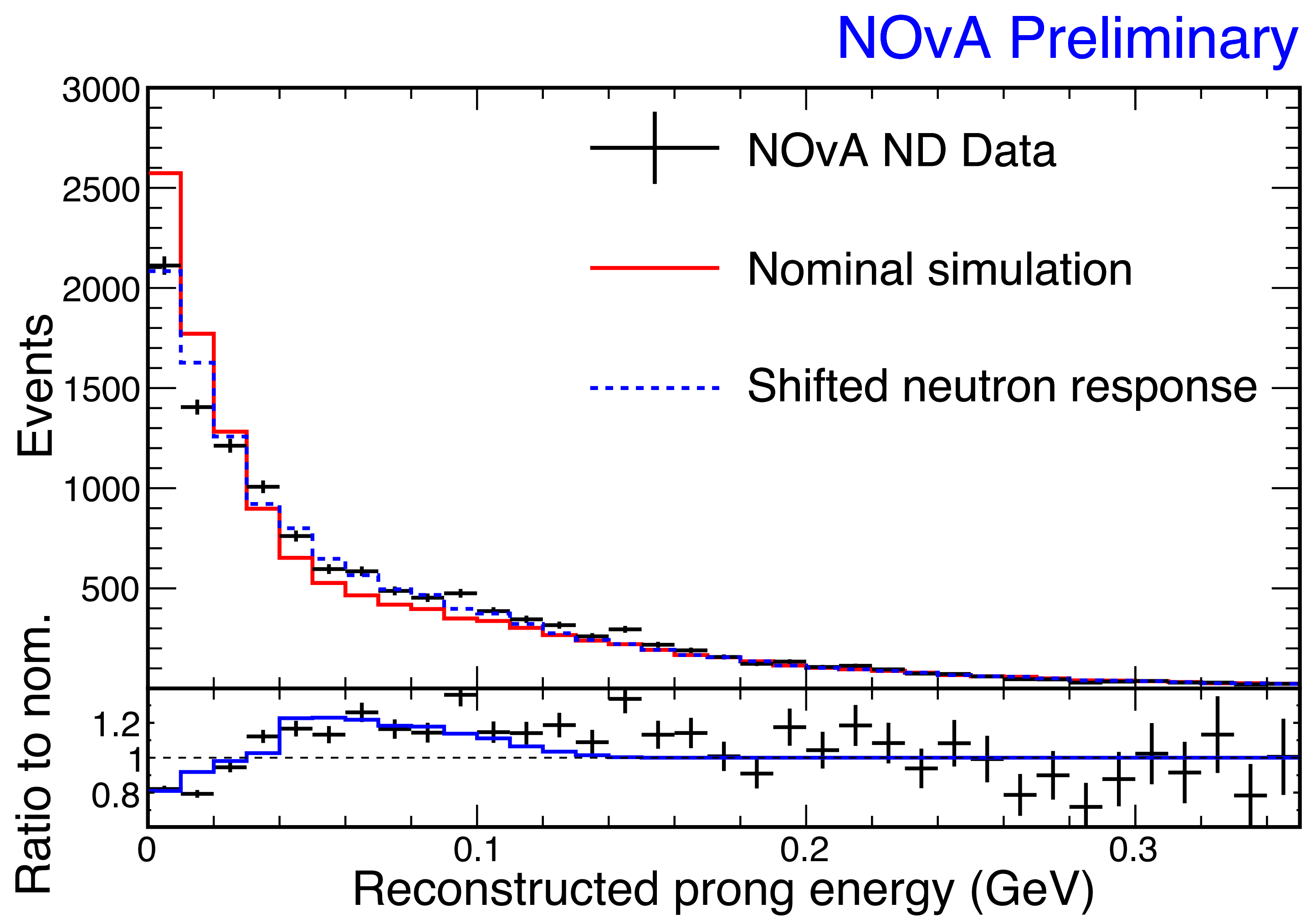


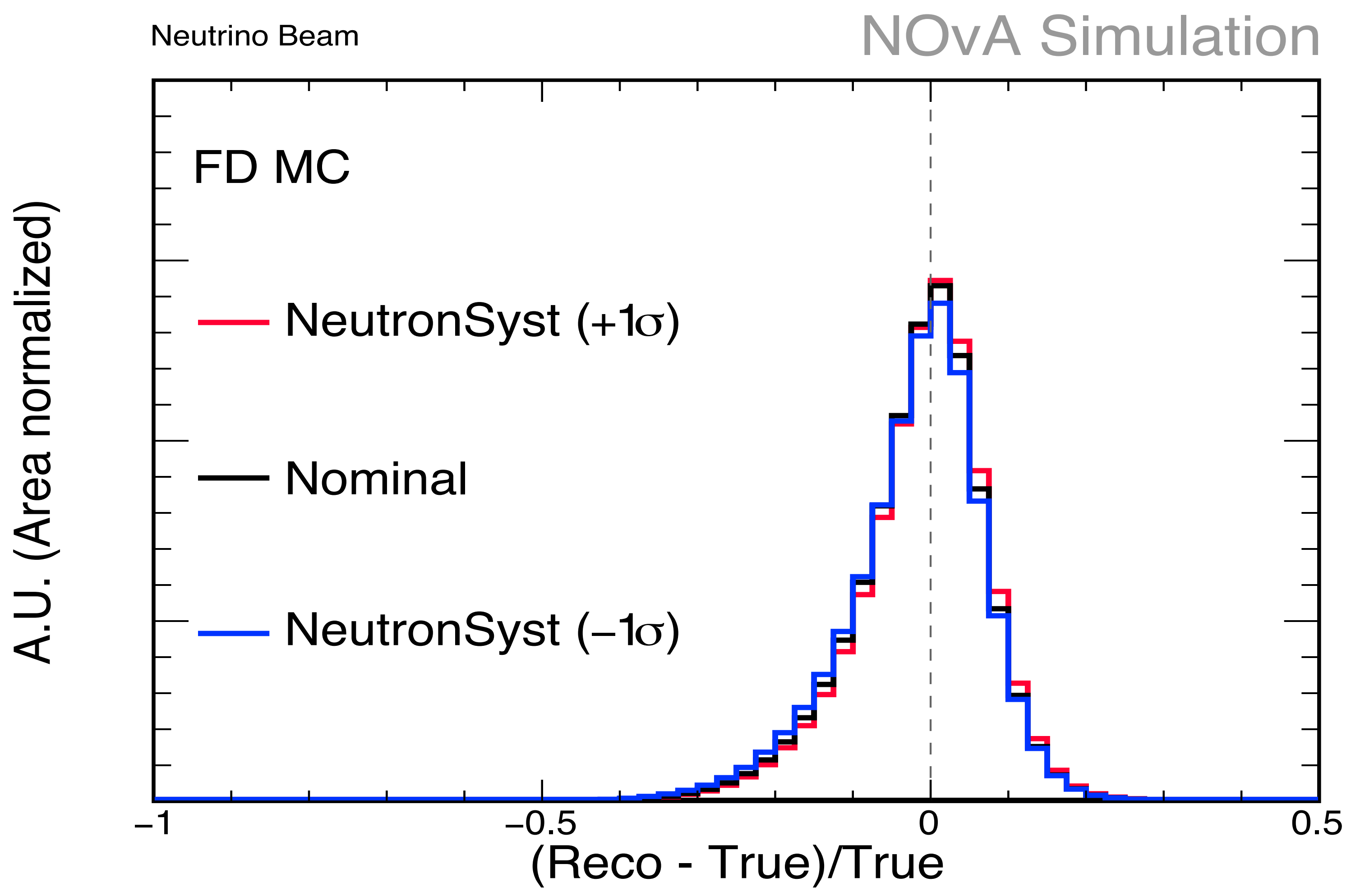
Neutron systematic uncertainty



- Data motivated systematic based on poor modeling seen
- Scales deposited energy of low energy neutrons to cover observed the low-energy discrepancy.
- Small effect, shifts the mean ν_μ energy by 1% (0.5%) in the antineutrino (neutrino) beam with negligible impact was seen on selection efficiencies





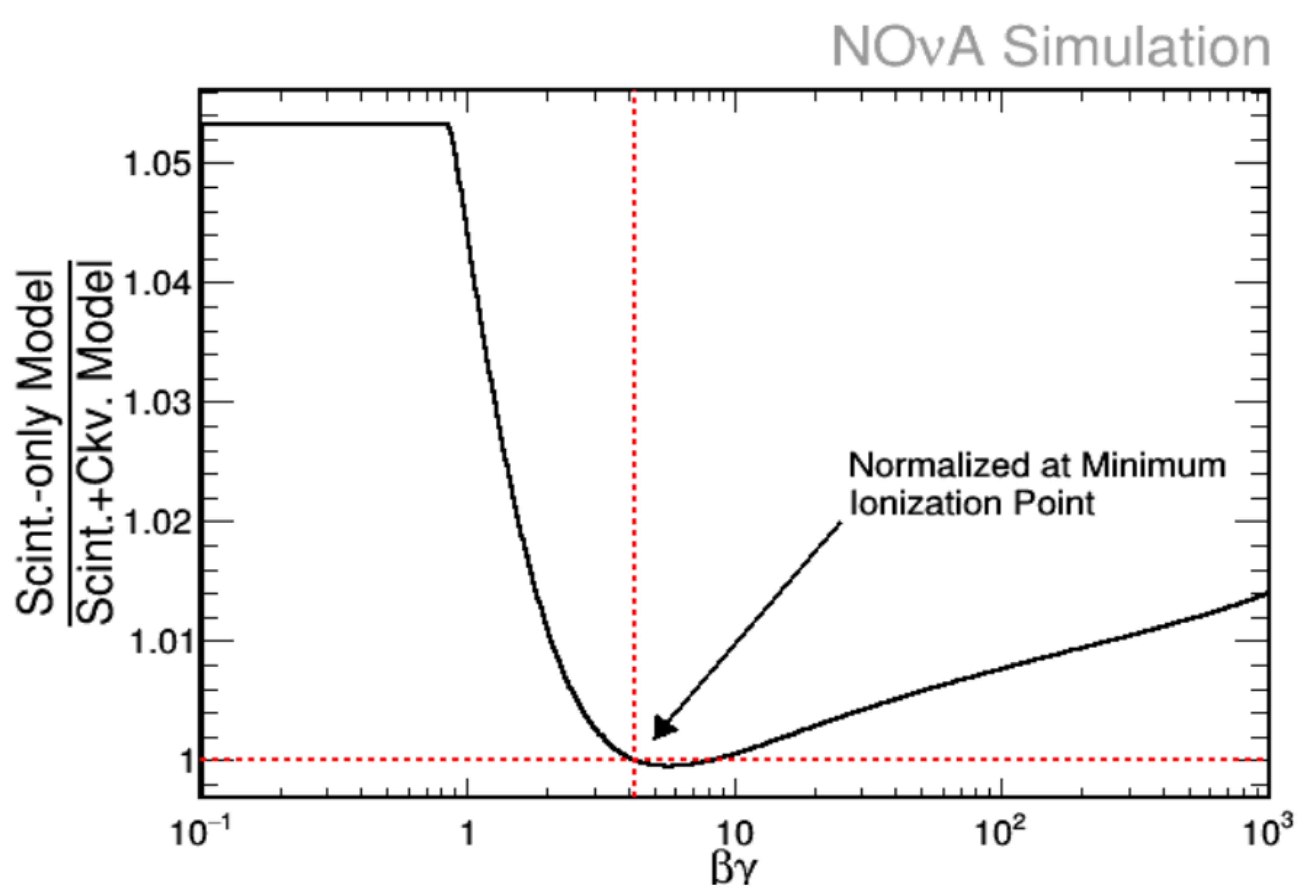


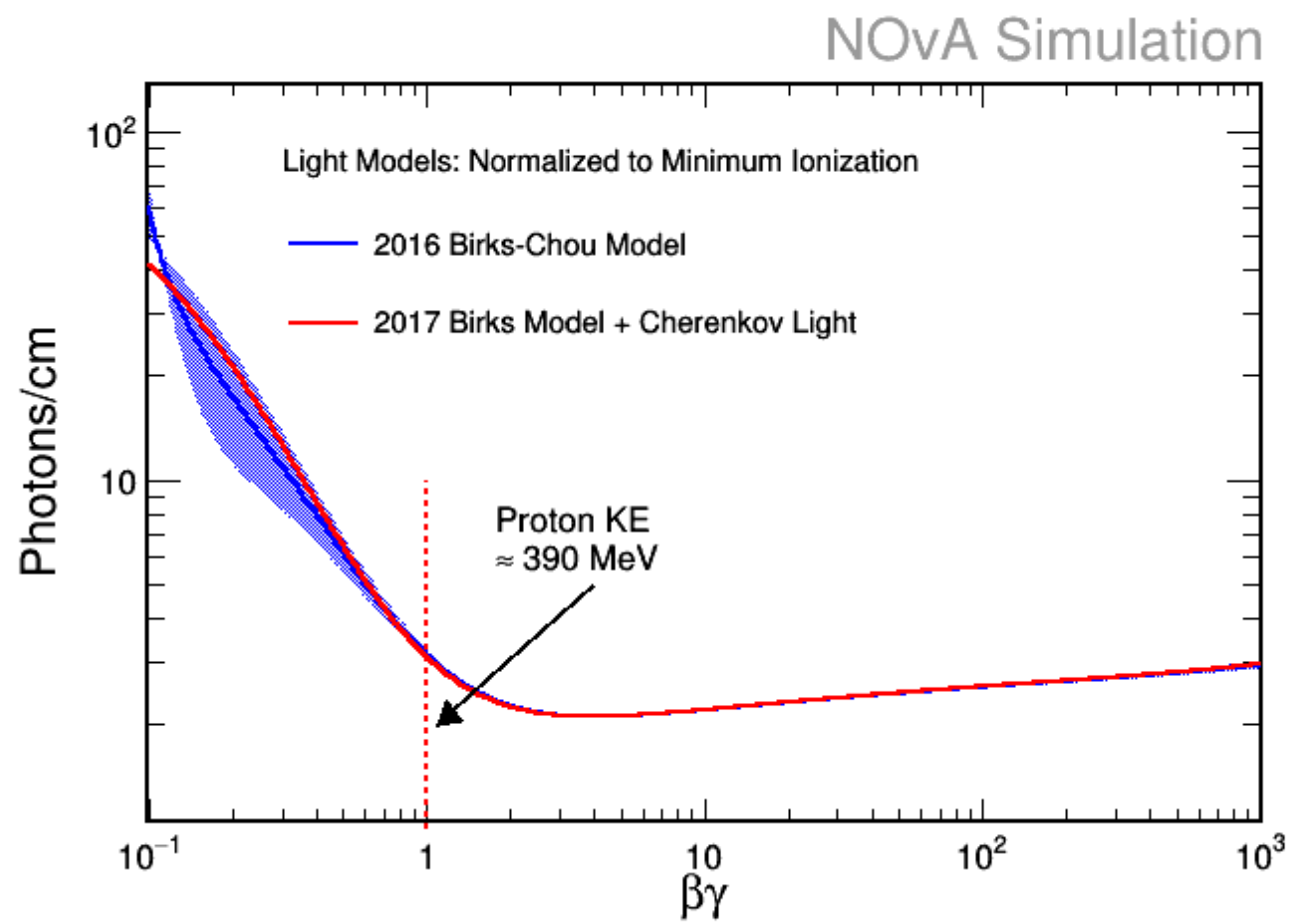
Detector Calibration: Test beam

- Six-month test beam run scheduled starting Jan. 2019, currently under construction and commissioning at Fermilab Test Beam Facility.
- Beams of tagged electrons, muons, pions, and protons in the momentum range of 0.3 to 2 GeV
- Precisely measure the detector's muon energy scale, electromagnetic and hadronic response, and event topologies of known energies

Detector Response

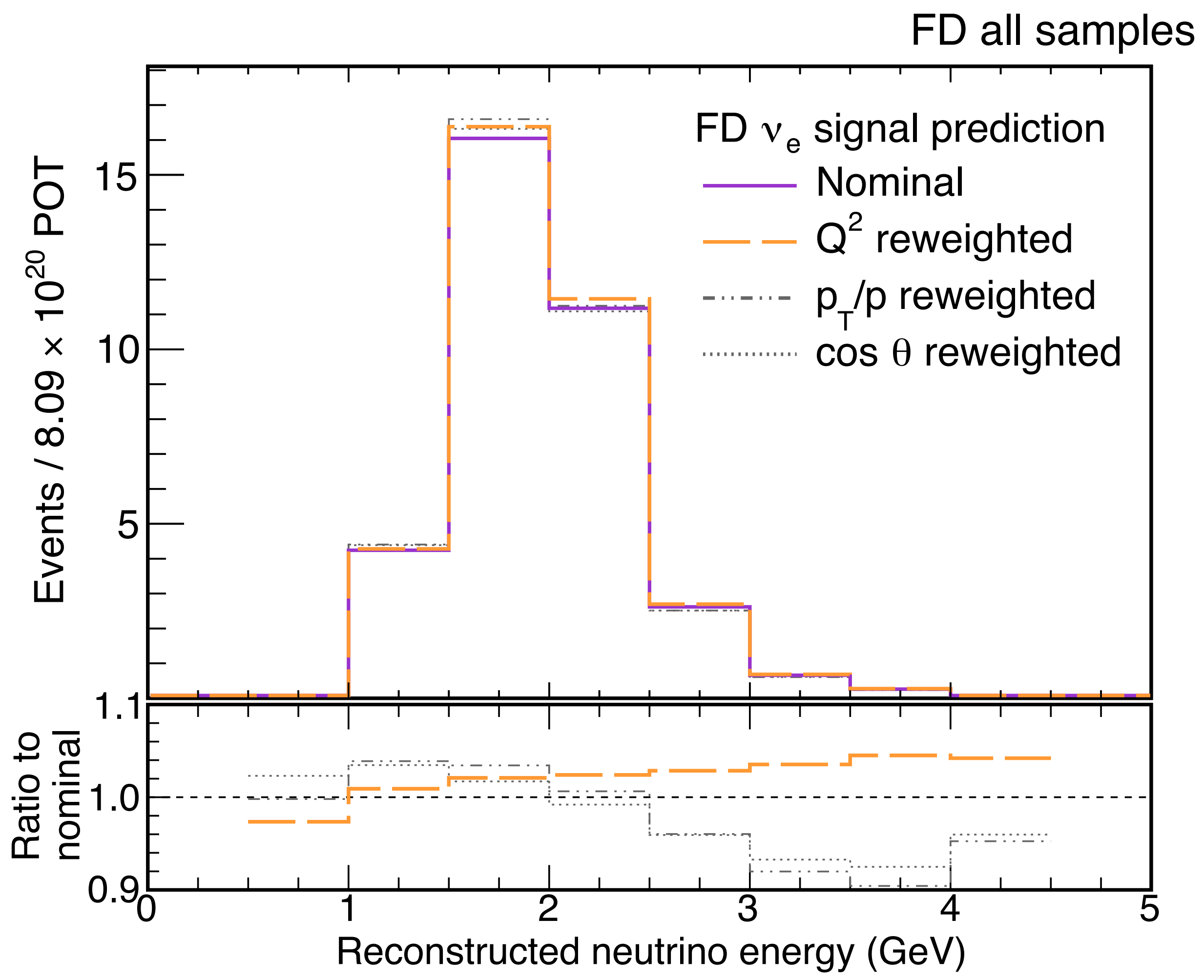
- Before 2017 was one of our largest uncertainties, reduced by an order of magnitude in latest analysis.
- Energy response is calibrated by stopping cosmic muons at their minimum ionization point
- Resulting hadronic data/MC disagreement used to be minimized by tuning scintillator quenching, requiring significant systematic uncertainties
- Absorbed and re-emitted Cherenkov light is a small but important for hadronic activity, biases the calibration of slow particles by ~ 5%.
- Produce two alternative MC samples with light level shifts
  - Shift proton response in Cherenkov model down by ~3% (based on dE/dx data-mc different observed)
  - Alter the light level by ±10% with a compensating change made to the absolute calibration constants, to model light levels and threshold uncertainties

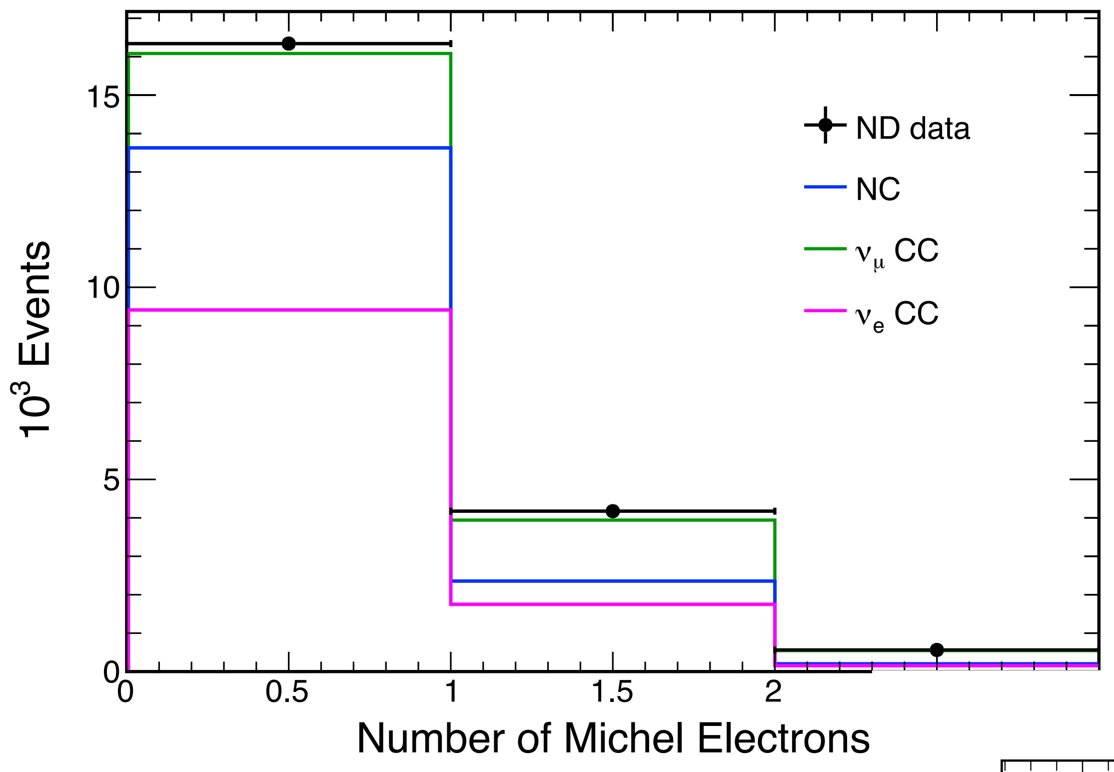




Near to Far differences

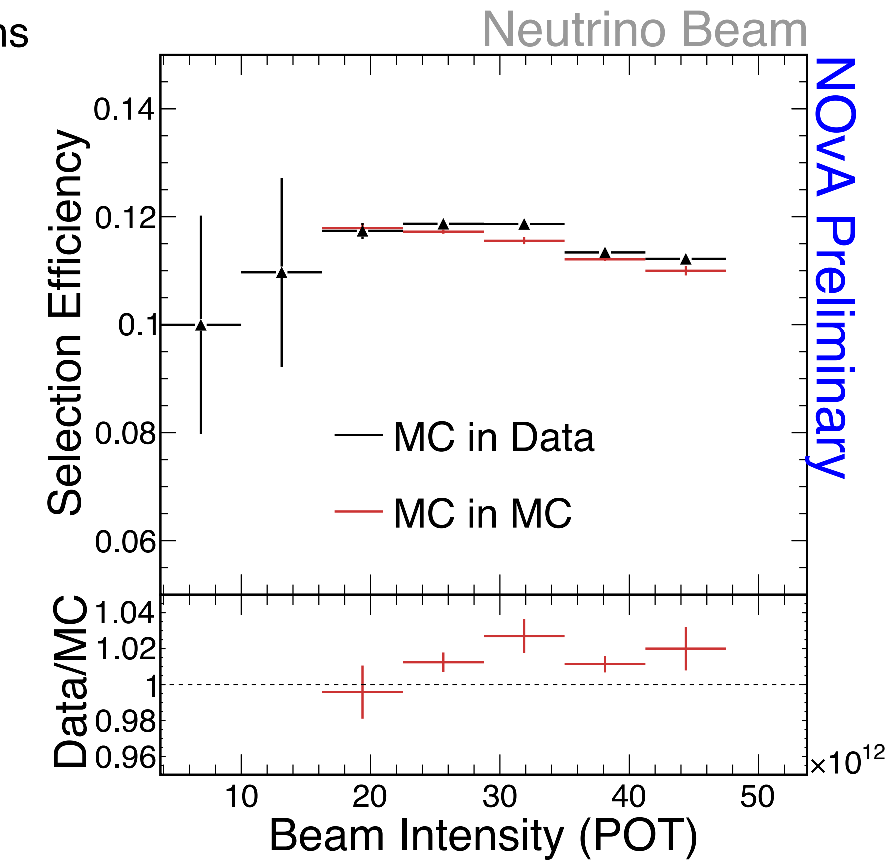
- **Acceptance systematic:** Cover limitation of the extrapolation technique to account for differences from near to far kinematics. Reweight Q, P_T/p and angle w.r.t the beam to match between detectors, observed difference at the far detector taken as a systematic
- **Michel electron tagging efficiency:** Michel electrons are used as in data-driven background constraint in the Near Detector. Michel tagging efficiency varied by ±5%





Normalization

- Includes **Uncorrelated Mass and POT uncertainty** (both 0.5%) and **Near detector reconstruction efficiency.** Inject MC signal into both data and MC, study pile up studies, efficiency effects due detector external event modeling and detector noise modeling



Muon Energy Scale

- Uncertainties from simulation and detectors' mass and composition are applied to the measured track length before conversion to total muon energy

Conclusions

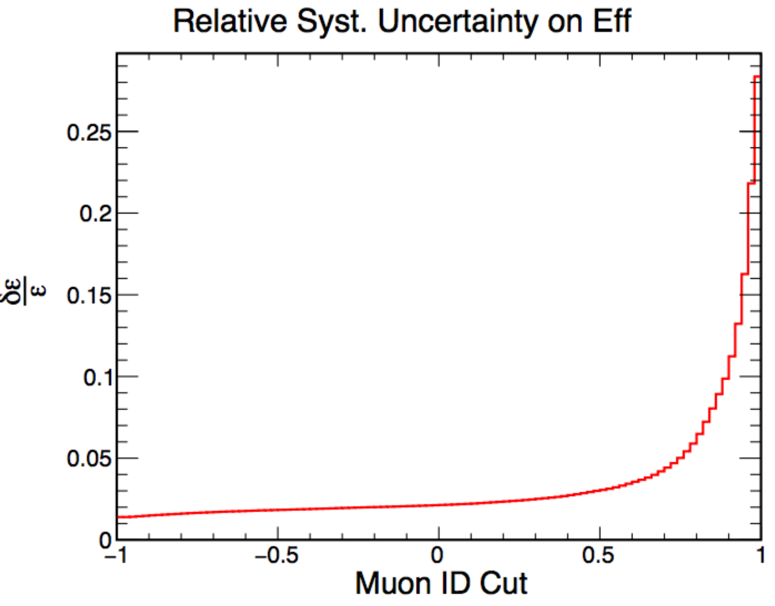
- NOvAs analyses oscillation analysis are still statically limited but approaching systematically limited
- NOvA has its first cross section results out and you can expect to see many more to come
- As we moved forward systematics will be increasing important
- Calibration, detector response, neutron and cross section systematics dominate
- NOvA has a test beam program planned to address some of these issues
- NOvA will continue to explore various options (data constraints, new models, alternate generators) to improve its interaction model

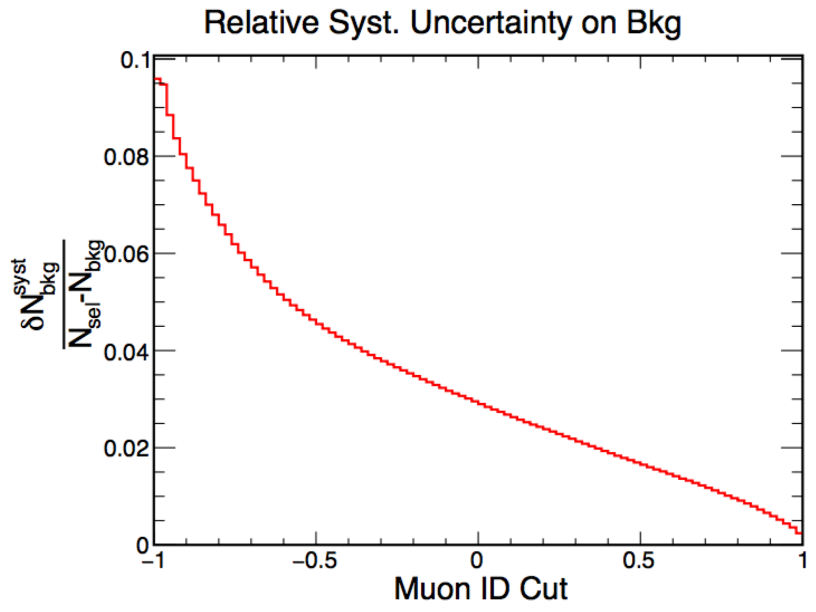
back up

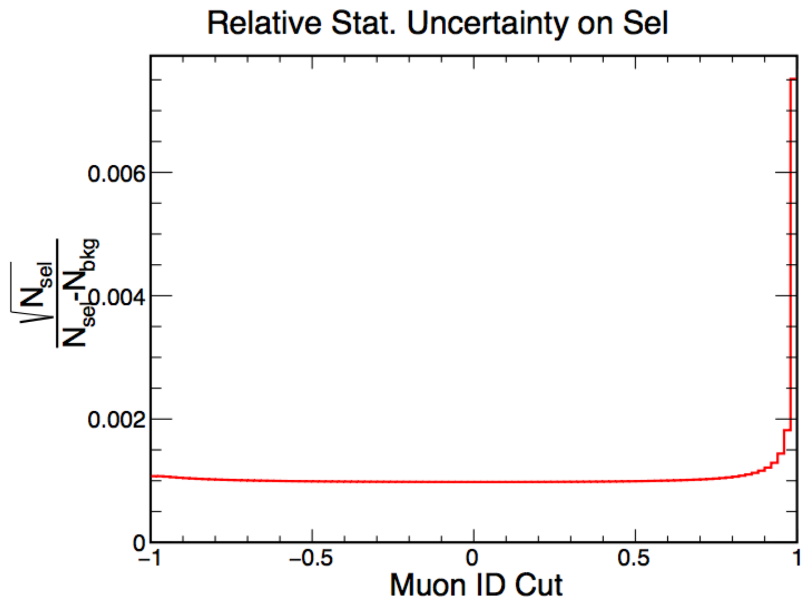
What about cross sections?

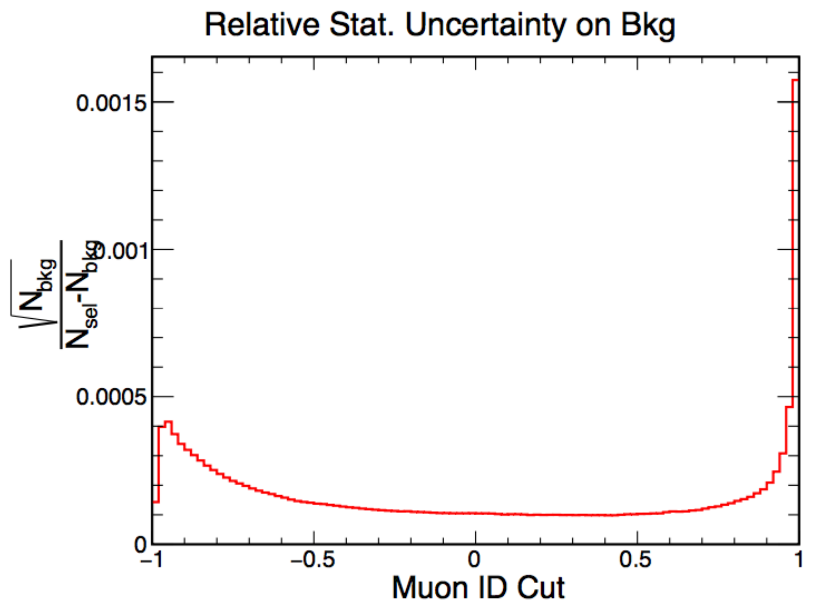
- Systematic shifts either produced in the same way using the same samples and techniques
  - Multi-universe technique or sample of shifted MC
- No detector-to-detector correlation but work to minimize systematic by other means.
- Optimization of selection criteria are based on a new FOM that reduces the uncertainty on the measured total cross section.

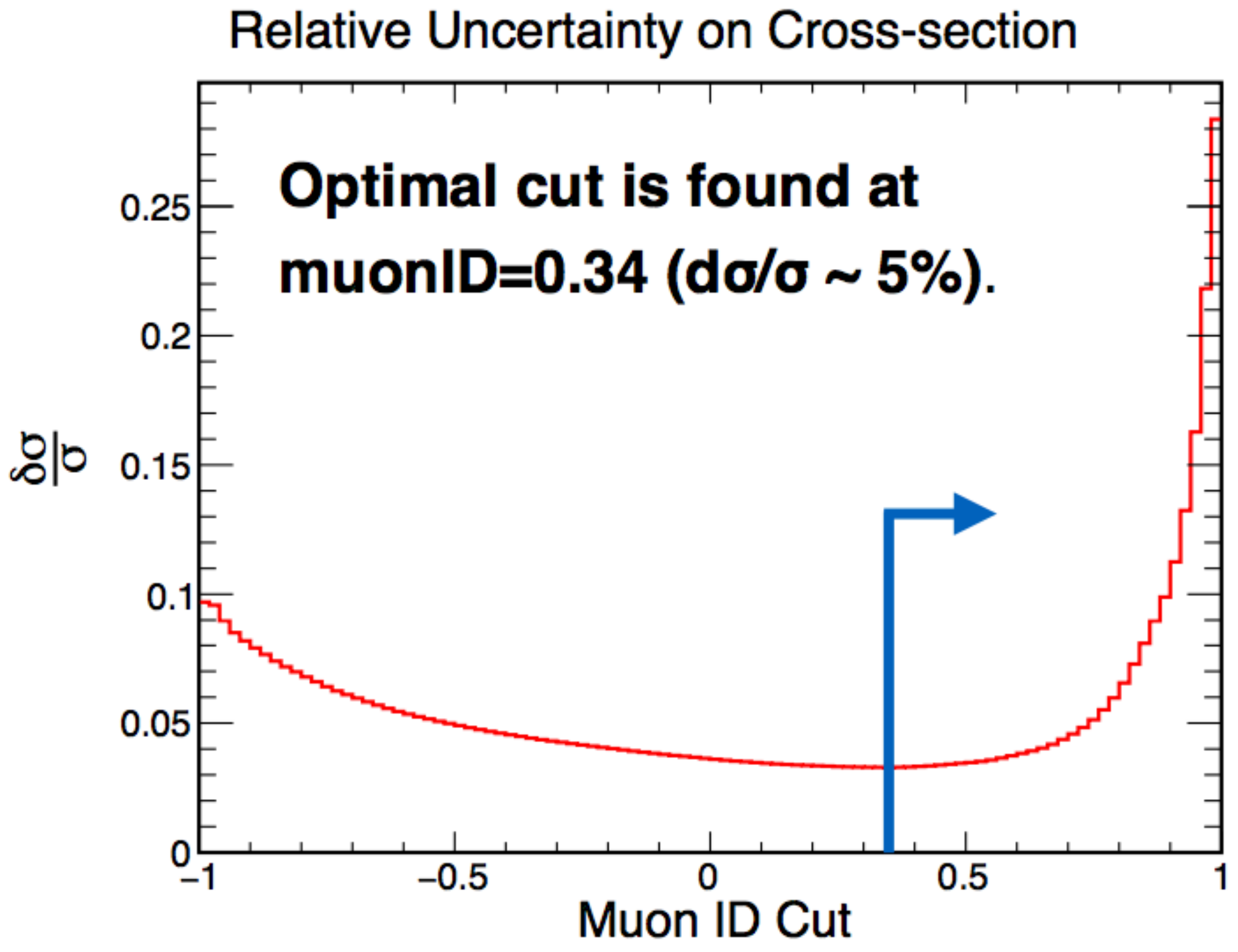
$$\frac{\delta\sigma}{\sigma} = \sqrt{\frac{(\delta N_{\rm sel}^{\rm stat})^2 + (\delta N_{\rm bkg}^{\rm stat})^2 + (\delta N_{\rm bkg}^{\rm syst})^2}{(N_{\rm sel} - N_{\rm bkg})^2} + \left(\frac{\delta\epsilon}{\epsilon}\right)^2}$$







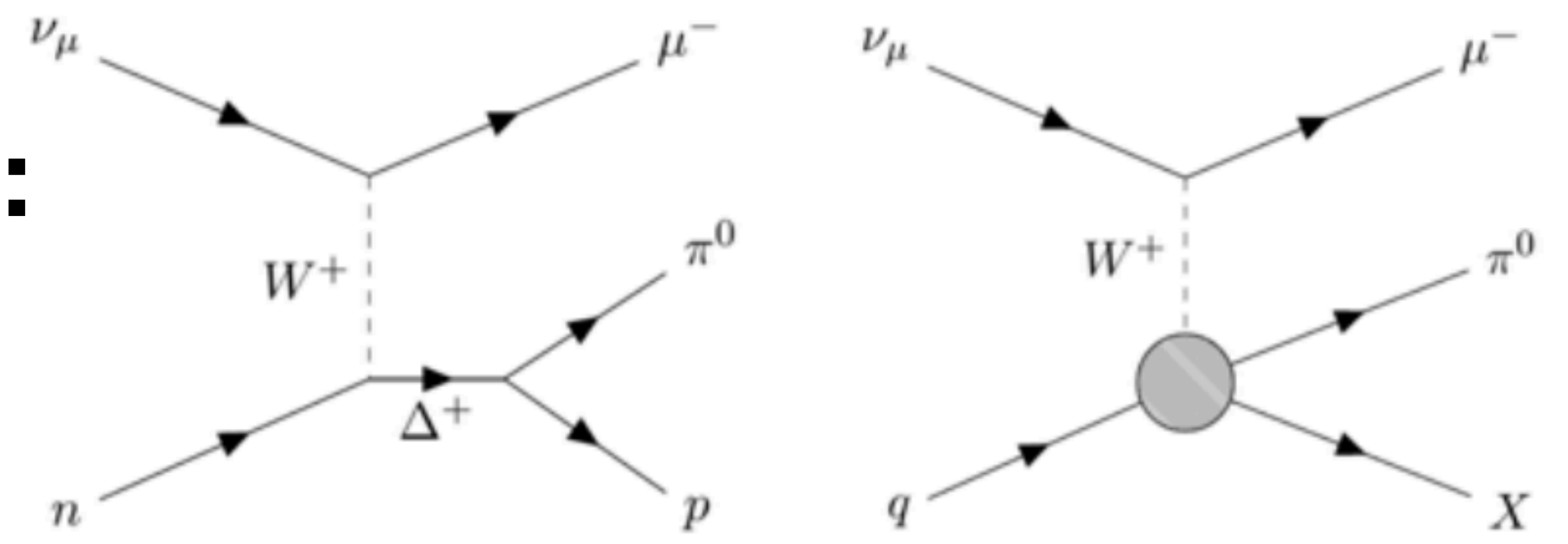


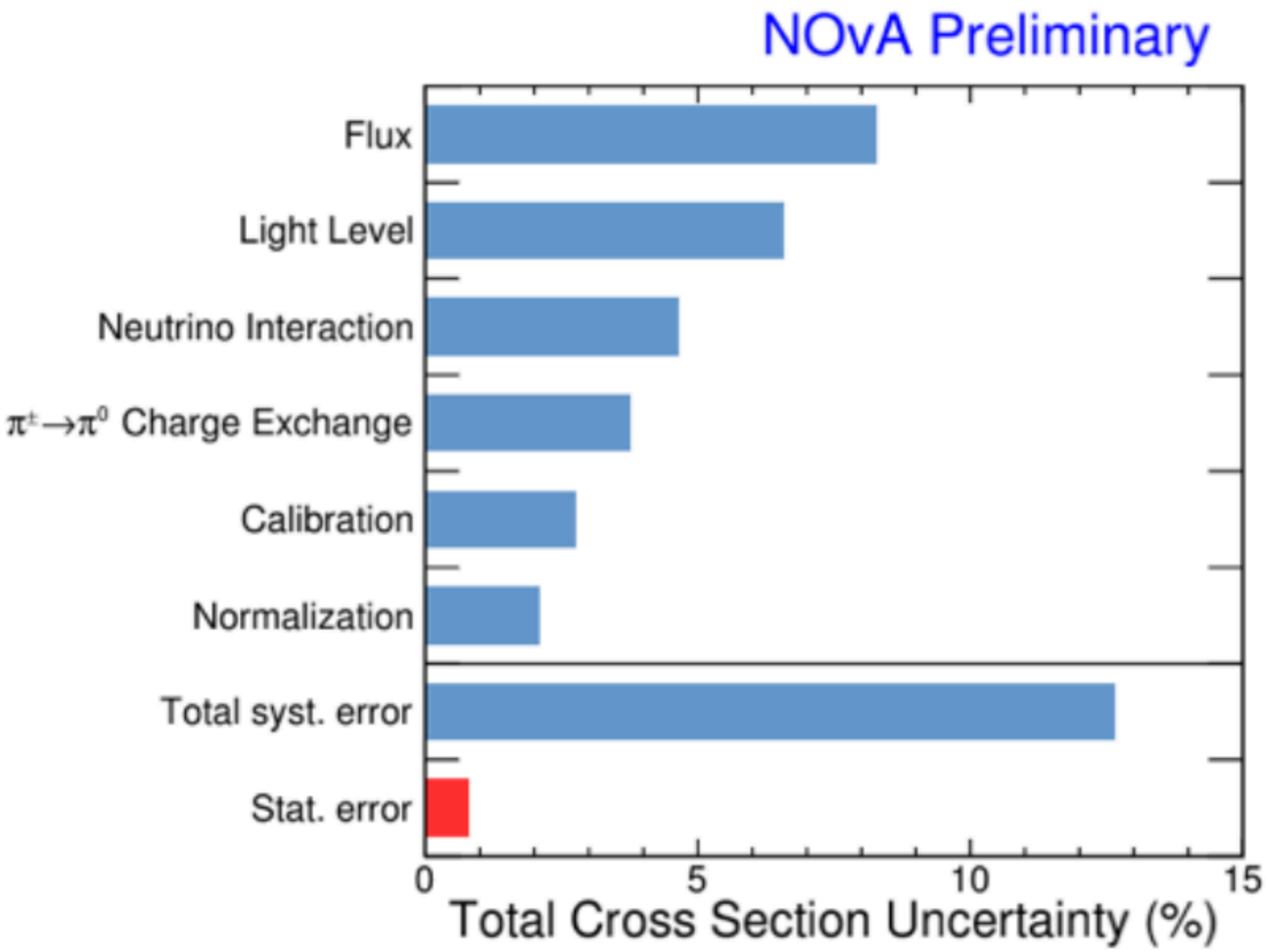


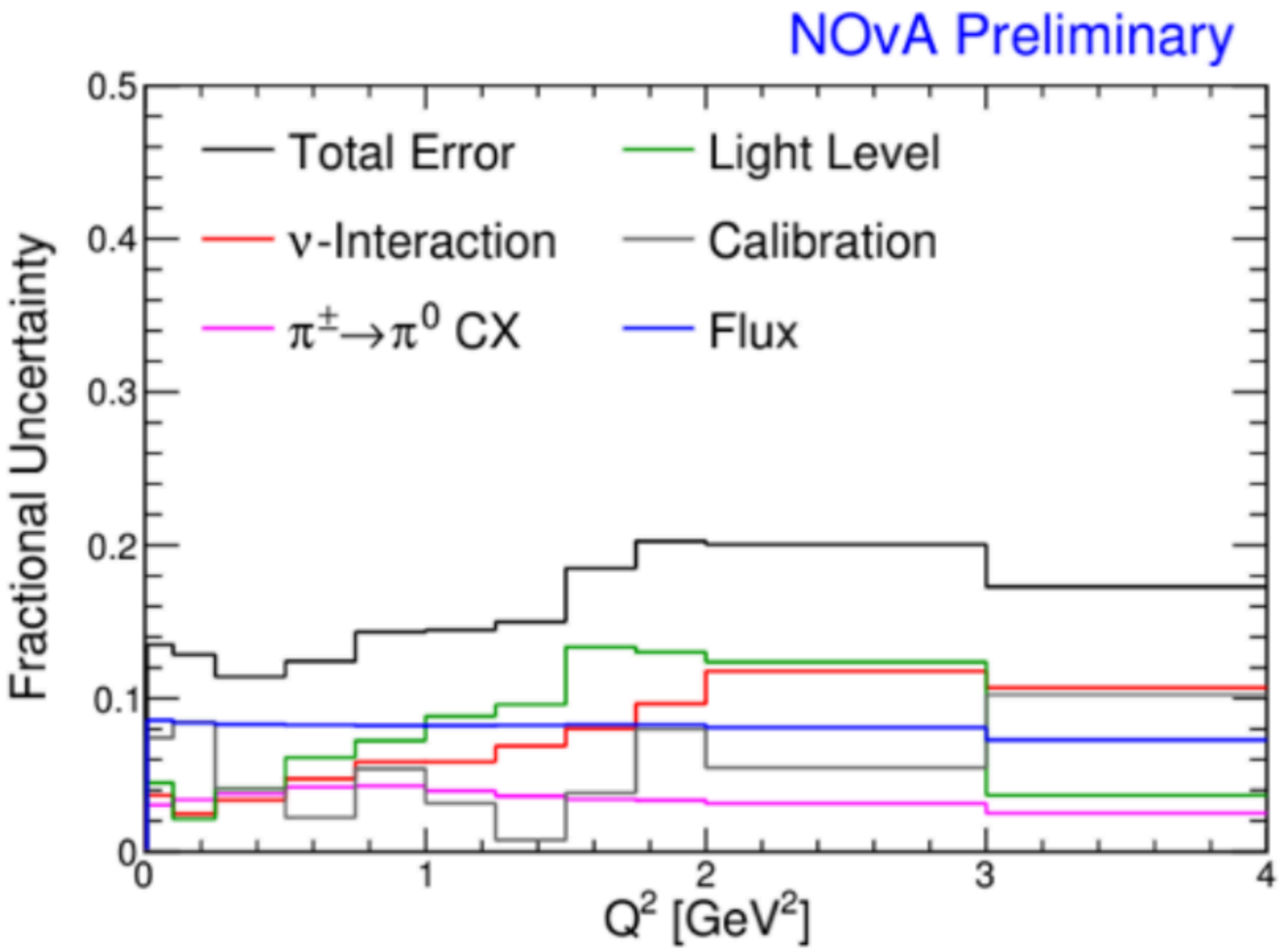
exception is NC Coherent π0, using earlier MC release and consequently earlier associated uncertainties

Example of cross section systematic uncertainties:

ν_μ + A -> μ^- + π^0 + X



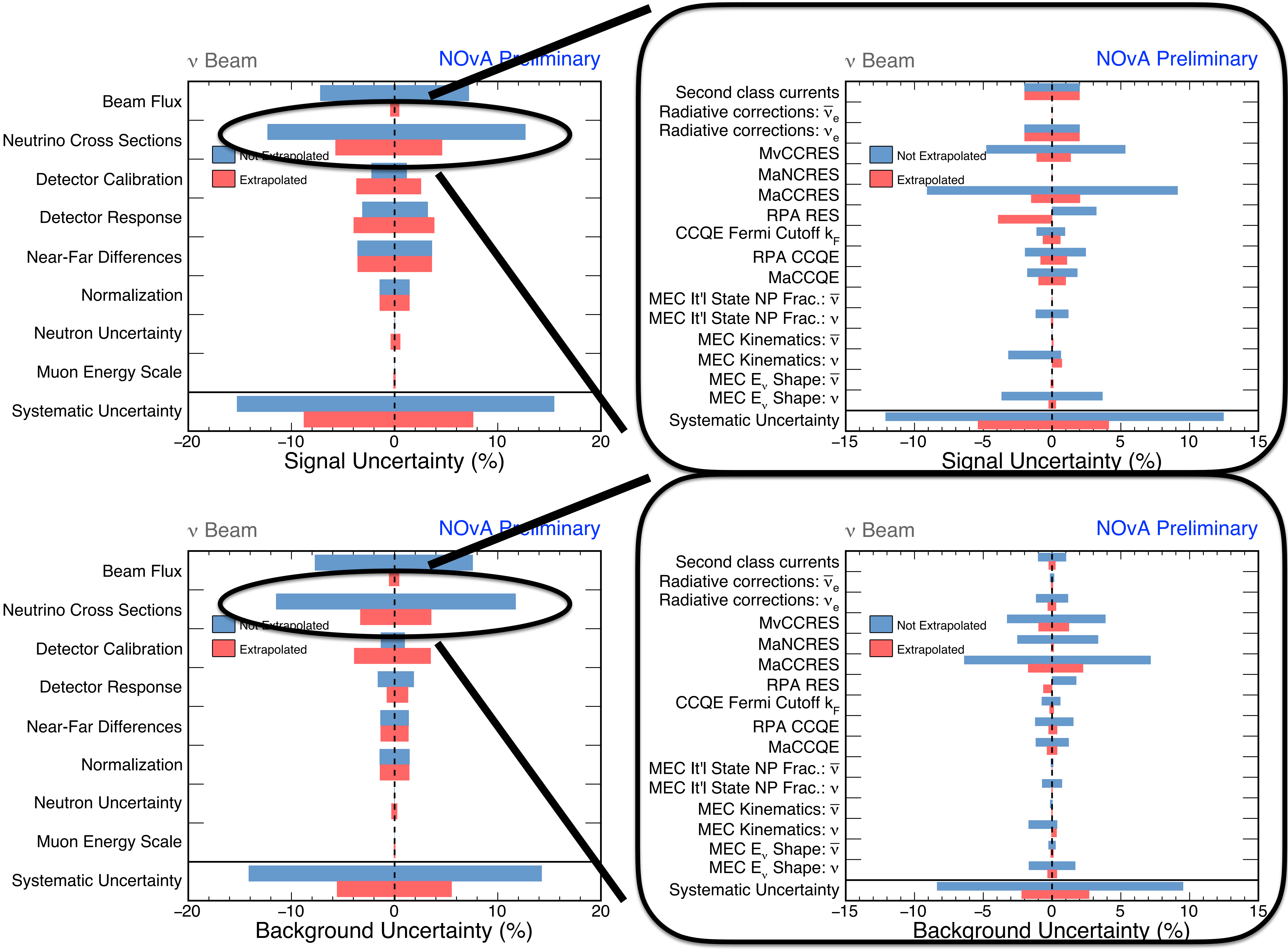


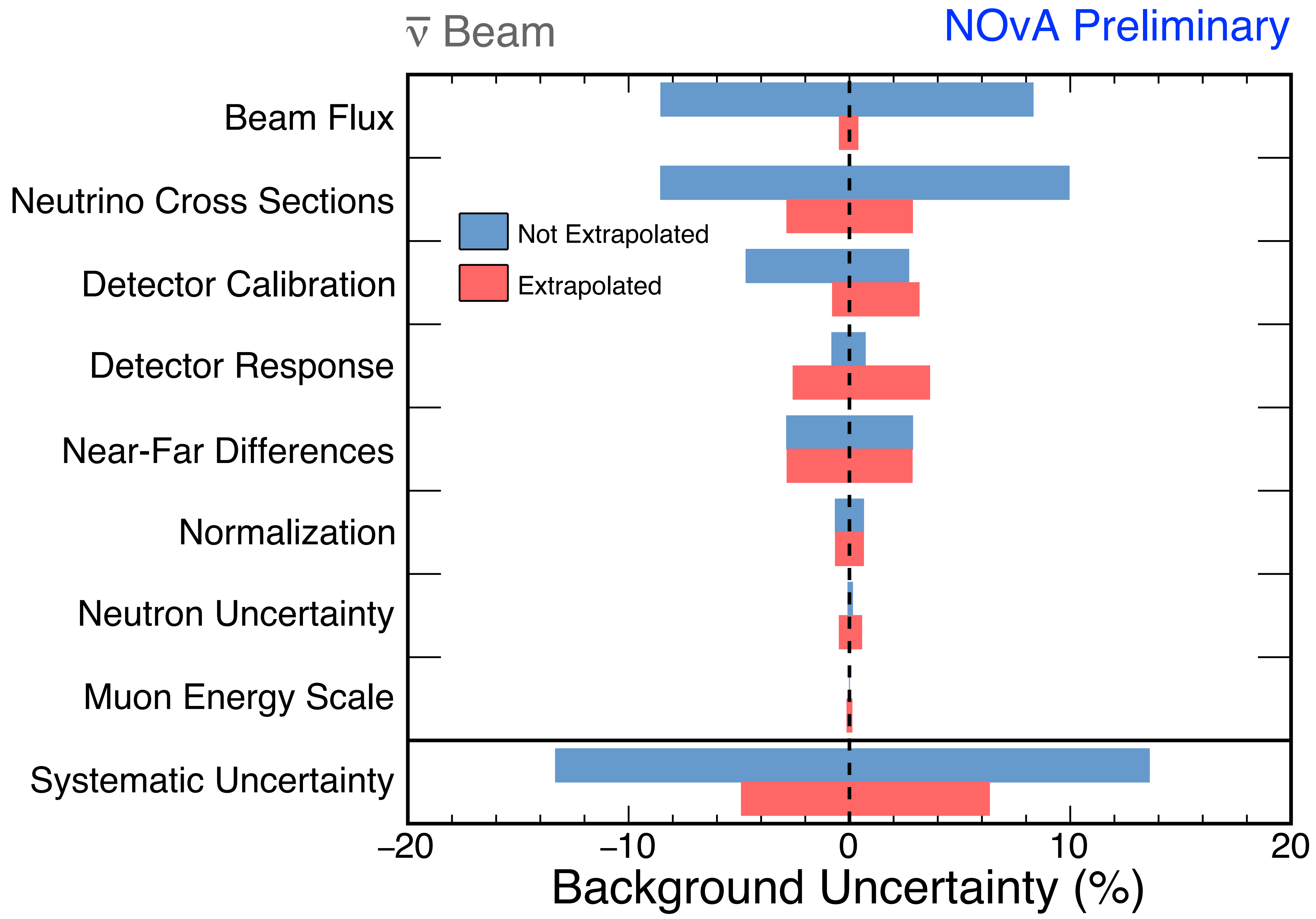


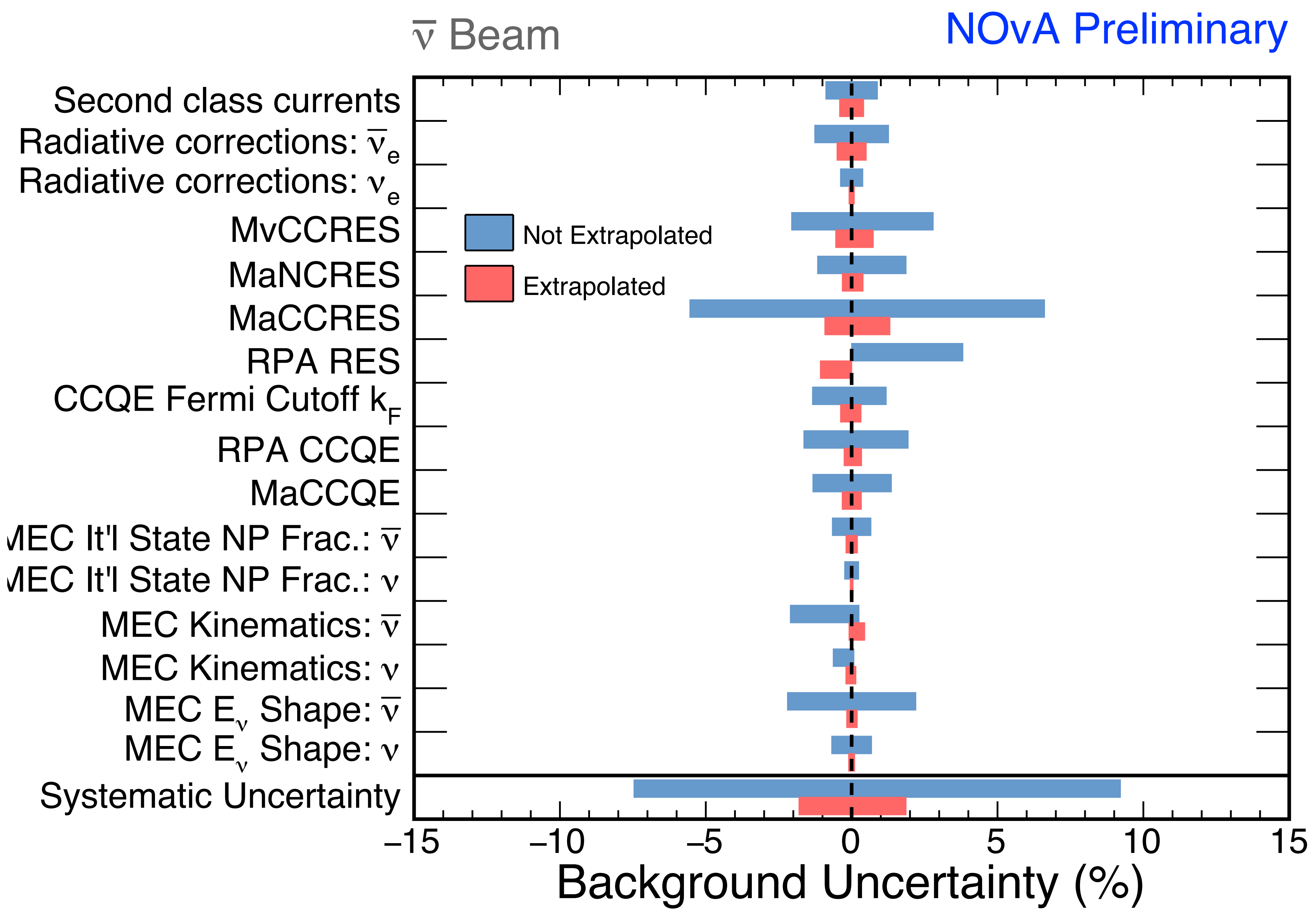
Systematic on $\pi^{+/-}$ -> π^0 Charge Exchange unique to this analysis - 4% effect

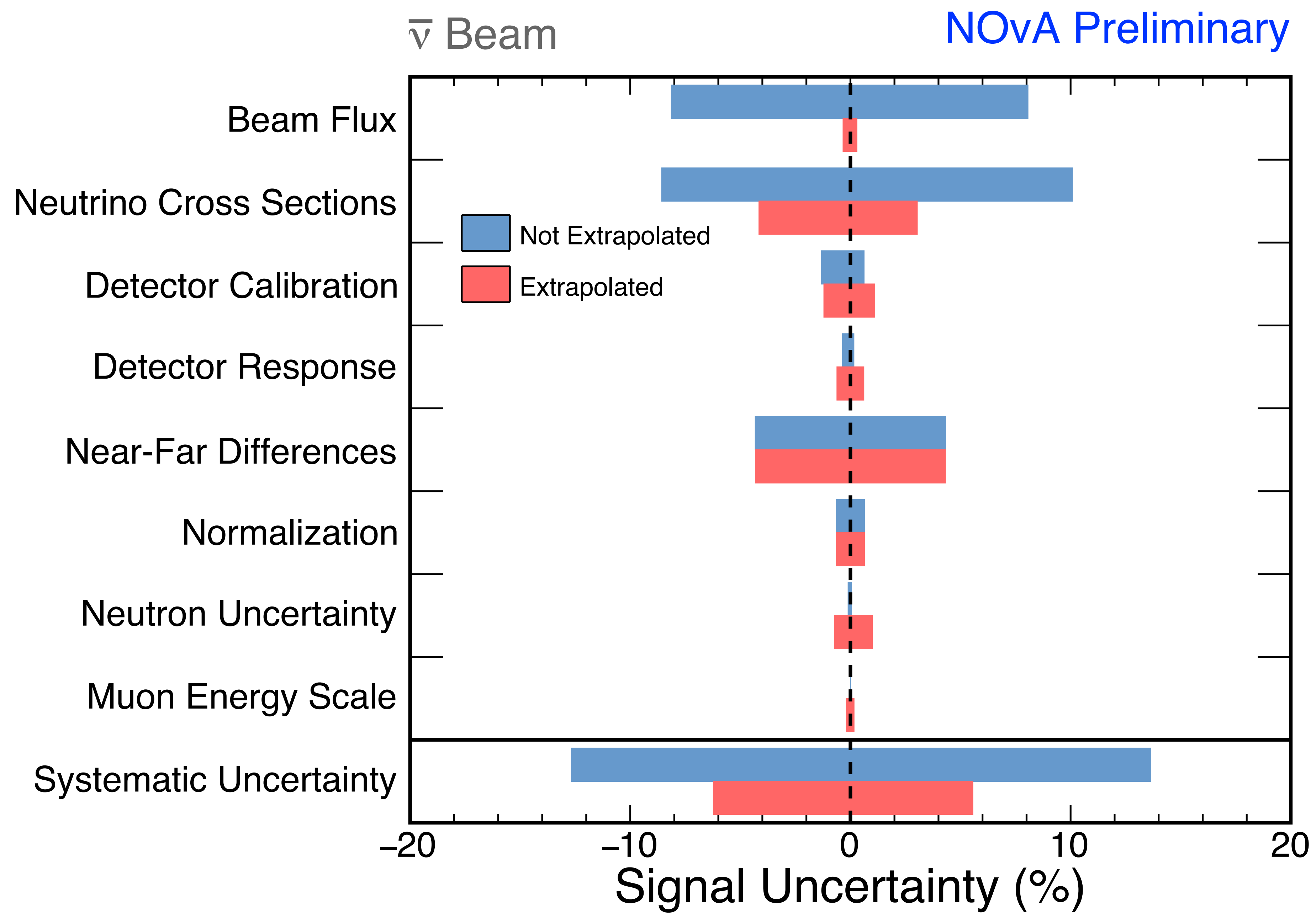
Example of extrapolated systematics:

Electron neutrino Appearance analysis




$\bar{\nu}$ Beam
NOvA Preliminary
Beam Flux
Neutrino Cross Sections
Detector Calibration
Detector Response
Near-Far Differences
Normalization
Neutron Uncertainty
Muon Energy Scale
Systematic Uncertainty
Not Extrapolated
Extrapolated
–20
–10
0
10
20
Background Uncertainty (%)


$\bar{\nu}$ Beam
NOvA Preliminary
Second class currents
Radiative corrections: $\bar{\nu}_e$
Radiative corrections: ν_e
MvCCRES
MaNCRES
MaCCRES
RPA RES
CCQE Fermi Cutoff k_F
RPA CCQE
MaCCQE
MEC It'l State NP Frac.: $\bar{\nu}$
MEC It'l State NP Frac.: ν
MEC Kinematics: $\bar{\nu}$
MEC Kinematics: ν
MEC E_ν Shape: $\bar{\nu}$
MEC E_ν Shape: ν
Systematic Uncertainty
Not Extrapolated
Extrapolated
–15
–10
–5
0
5
10
15
Background Uncertainty (%)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Not Extrapolated
Extrapolated
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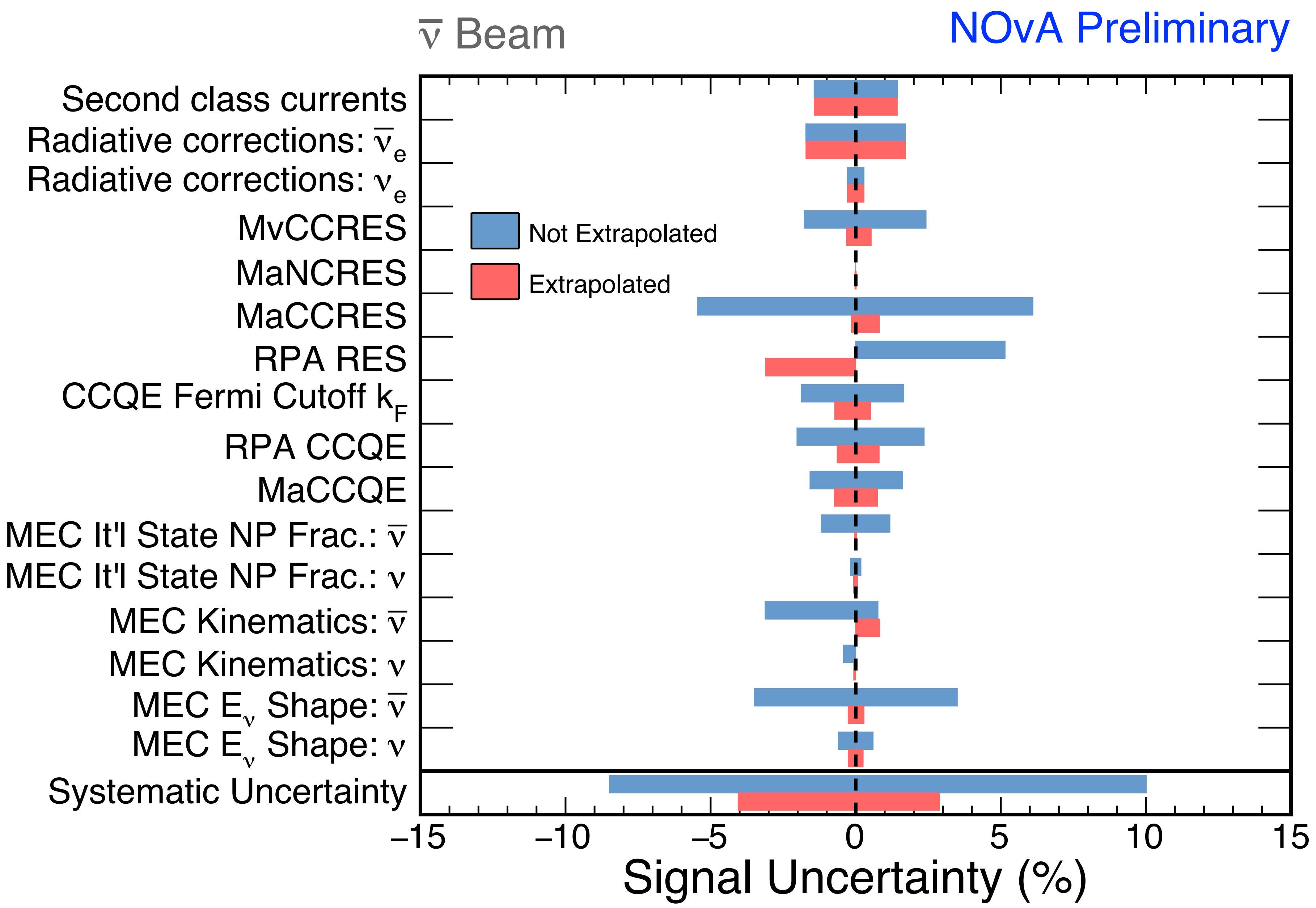
0
10
20
Signal Uncertainty (%)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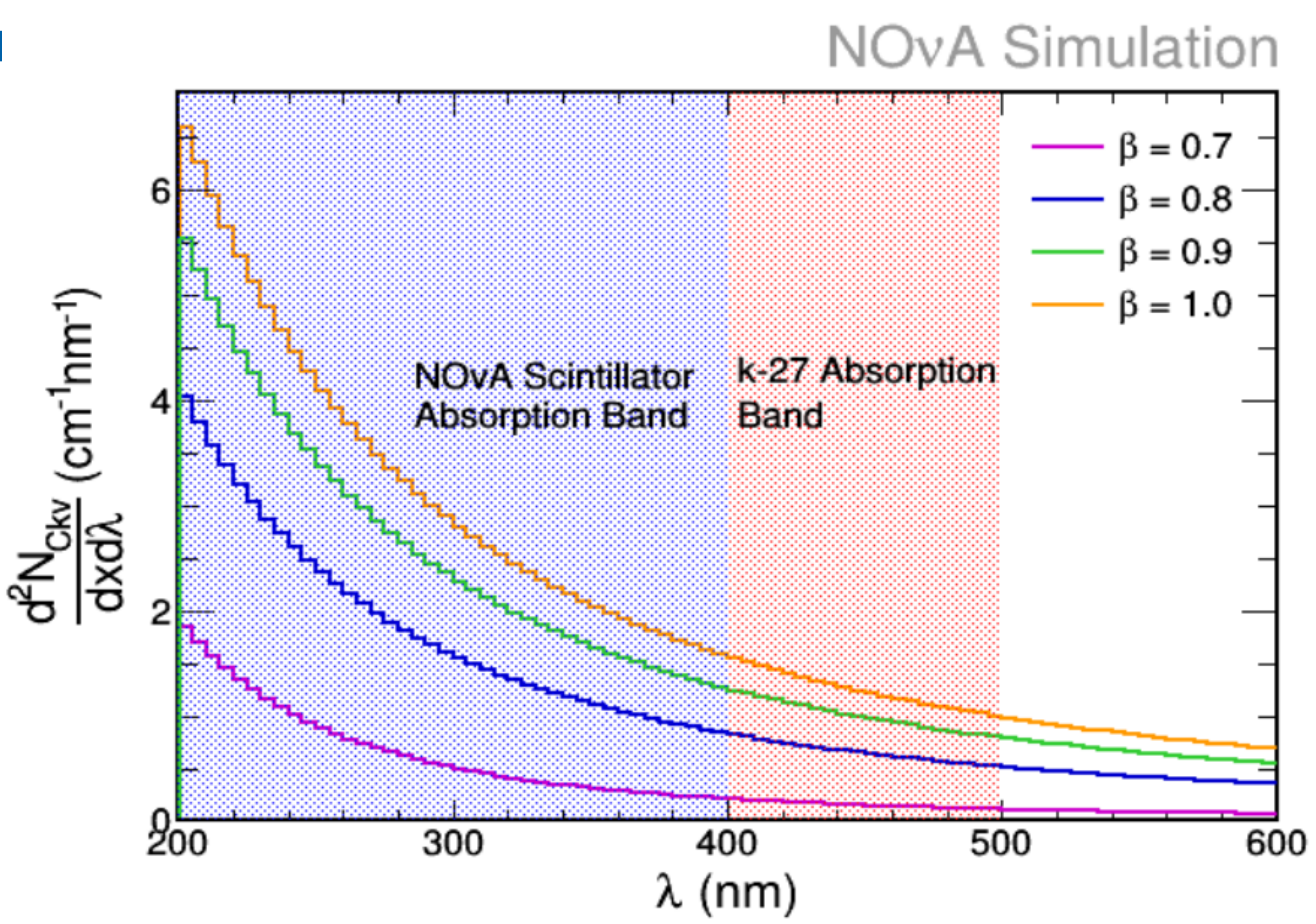
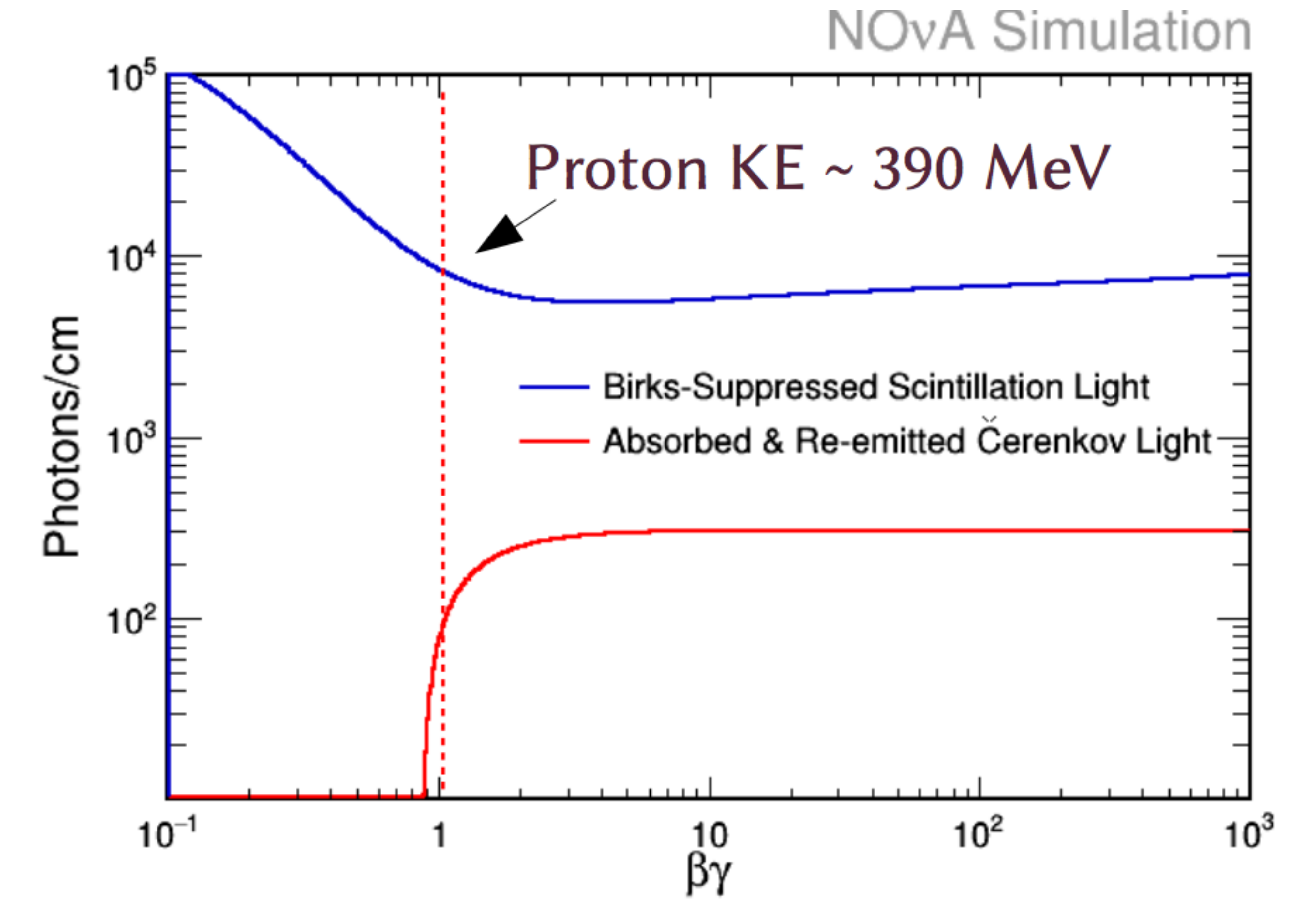
MEC It'l State NP Frac.: $\bar{\nu}$
MEC It'l State NP Frac.: ν
MEC Kinematics: $\bar{\nu}$
MEC Kinematics: ν
MEC E_ν Shape: $\bar{\nu}$
MEC E_ν Shape: ν
Systematic Uncertainty
Not Extrapolated
Extrapolated
–15
–10
–5
0
5
10
15
Signal Uncertainty (%)

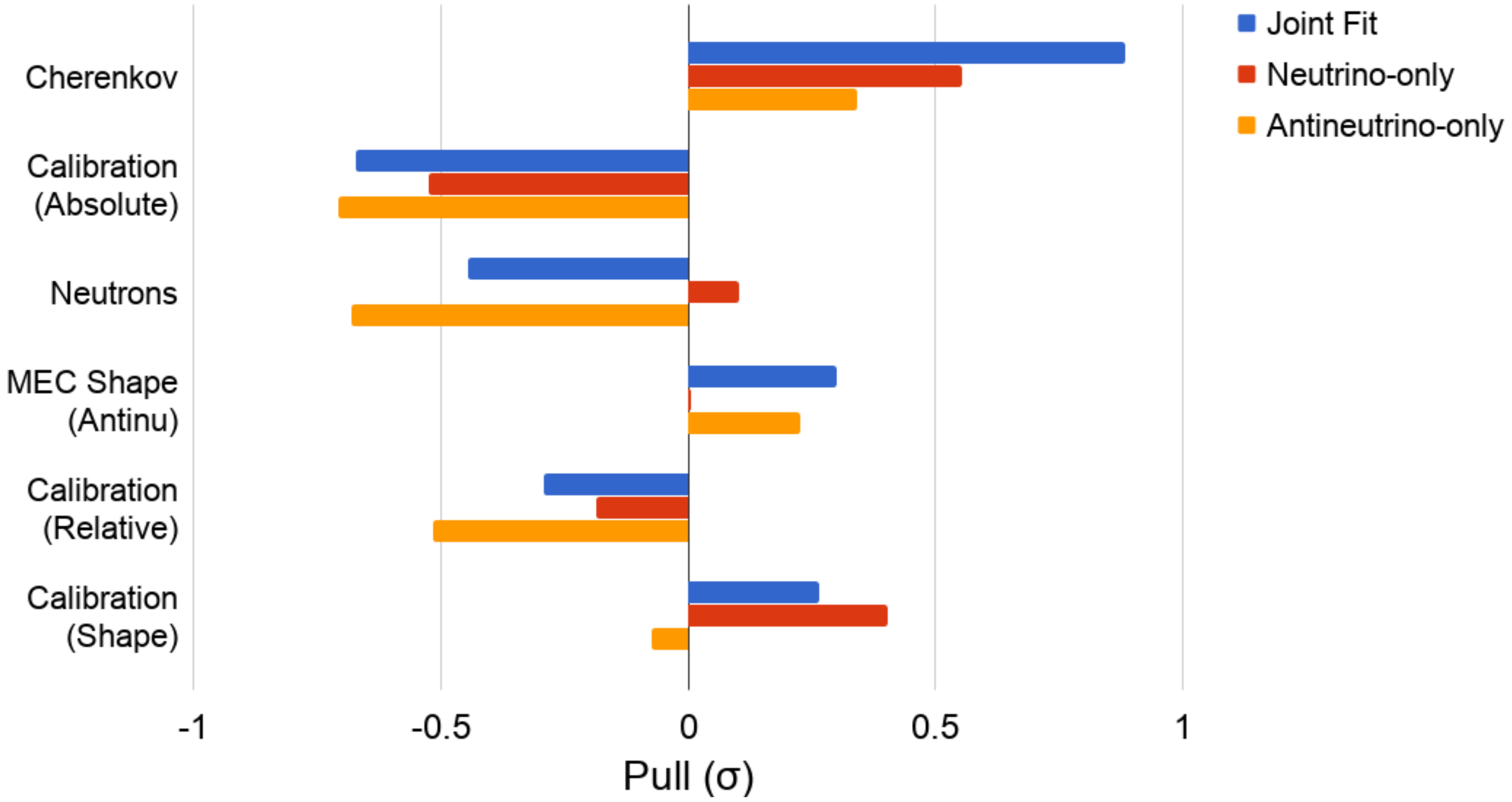
Detector Response

- In scintillation-based experiments, Cherenkov light is often neglected
- Scintillation yields are very large compared to Cherenkov light yields
- Most Cherenkov light is produced at short wavelengths that cannot be absorbed by NOvA
- However, short wavelength light can be absorbed by the pseudocumene, PPO, and bis-MSB in scintillator
- Absorbed and re-emitted Cherenkov light is a small but important signal that is particularly important for the modeling of the detector response to hadronic activity



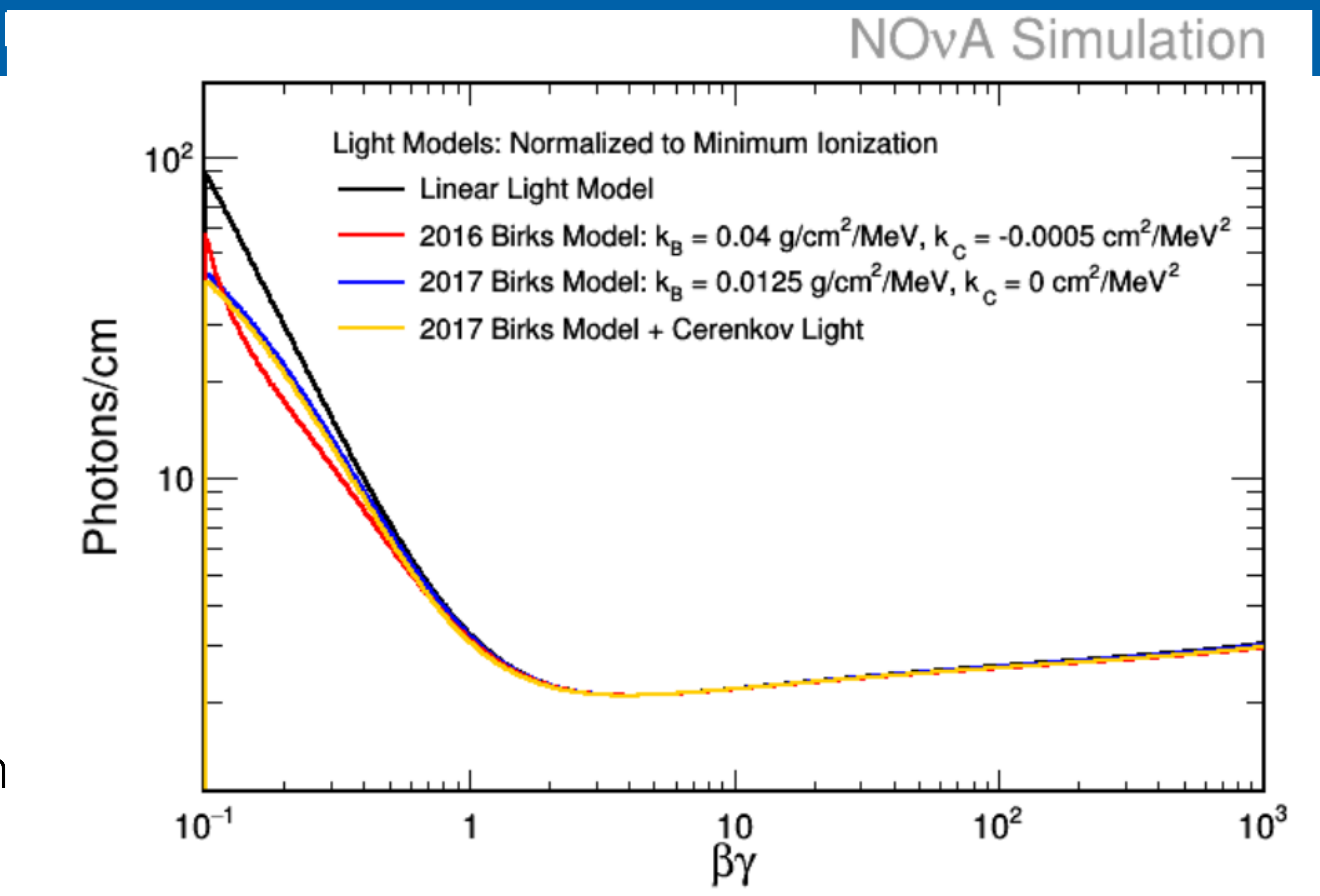


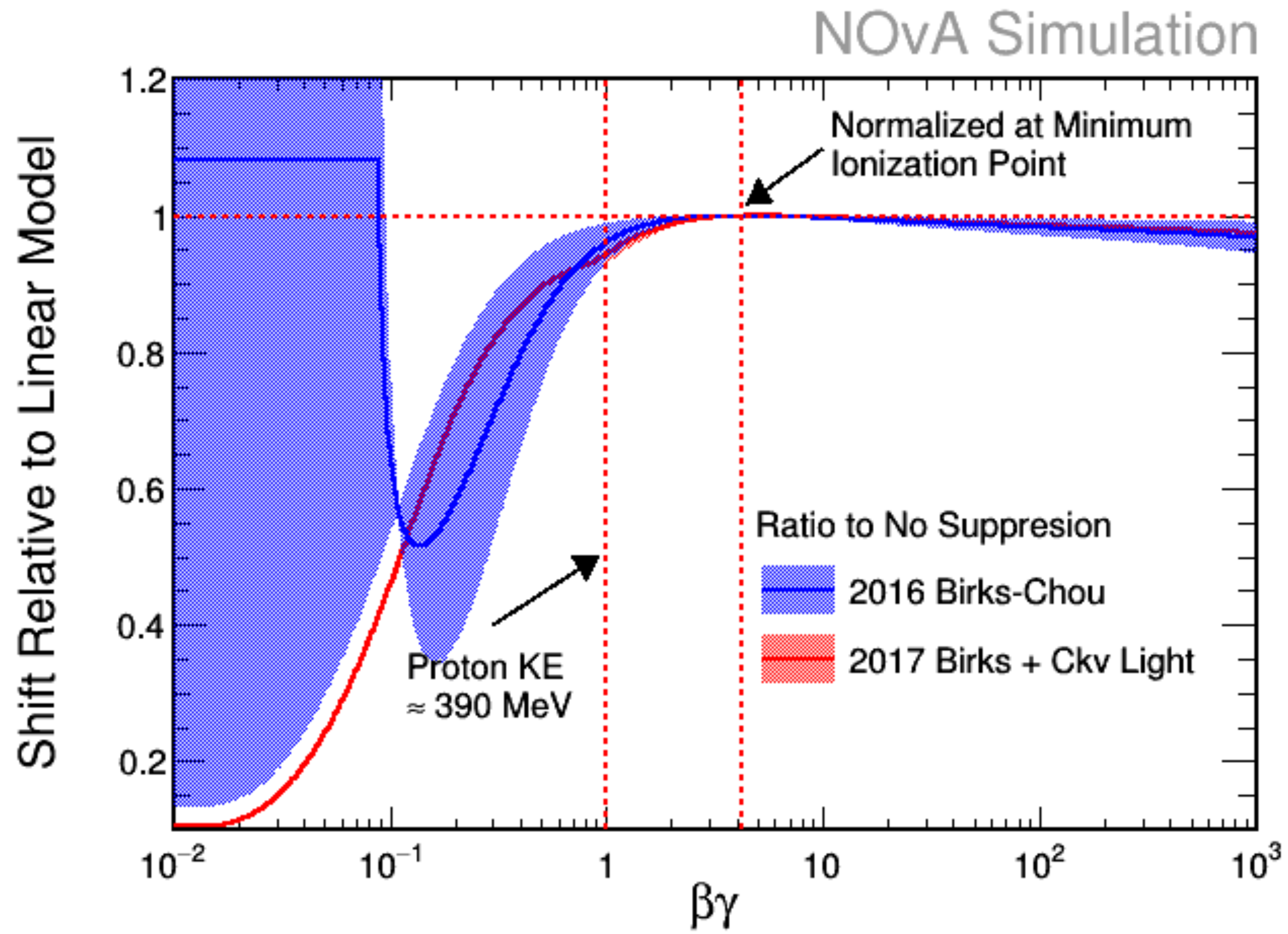
- Key systematic pulls in the joint-fit, for neutrino data only (red), antineutrino data only (yellow) and both neutrino and antineutrino data (blue).



Detector Response

- Previously was one of our largest, reduced by an order of magnitude in latest analysis.
- Energy response is calibrated by stopping cosmic muons at their minimum ionization point
- Resulting hadronic data/MC disagreement used to be minimized by tunin scintillator quenching, requiring significant systematic uncertainties
- Absorbed and re-emitted Cherenkov light is a small but important for hadronic activity, biases the calibration of slow particles by ~ 5%.
- Produce two alternative MC samples with light level shifts
    - Shift proton response in Cherenkov model down by ~3% (based on de/dx data-mc different observed)
    - Alter the light level by ±10% with a compensating change made to the absolute calibration constants, to model light levels and threshold uncertainties

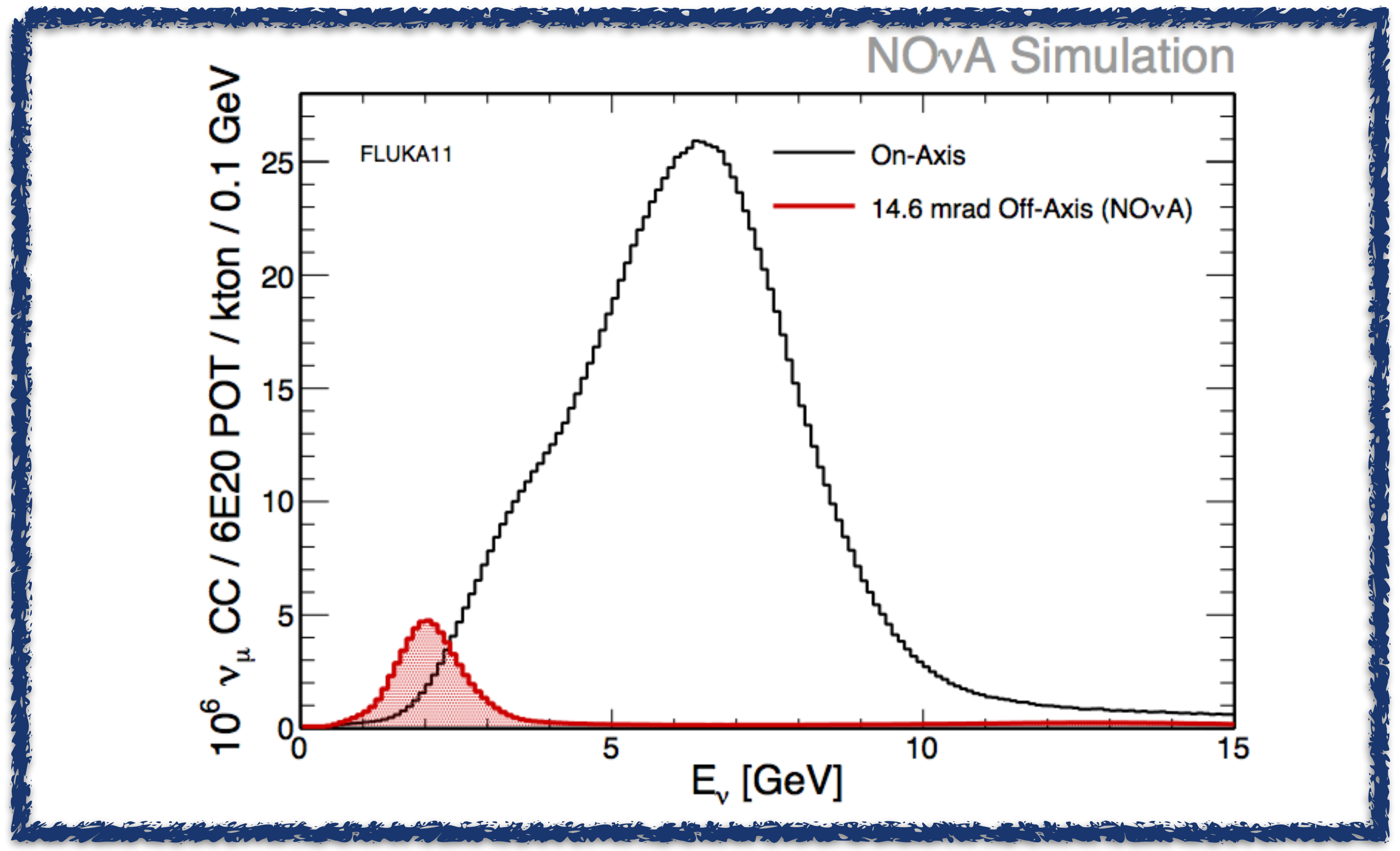




Beam

PPFX *(Phys. Rev. D 94, 092005 2016).*

Near Detector



Far Detector