ND in LBL sensitivity: past, present, future

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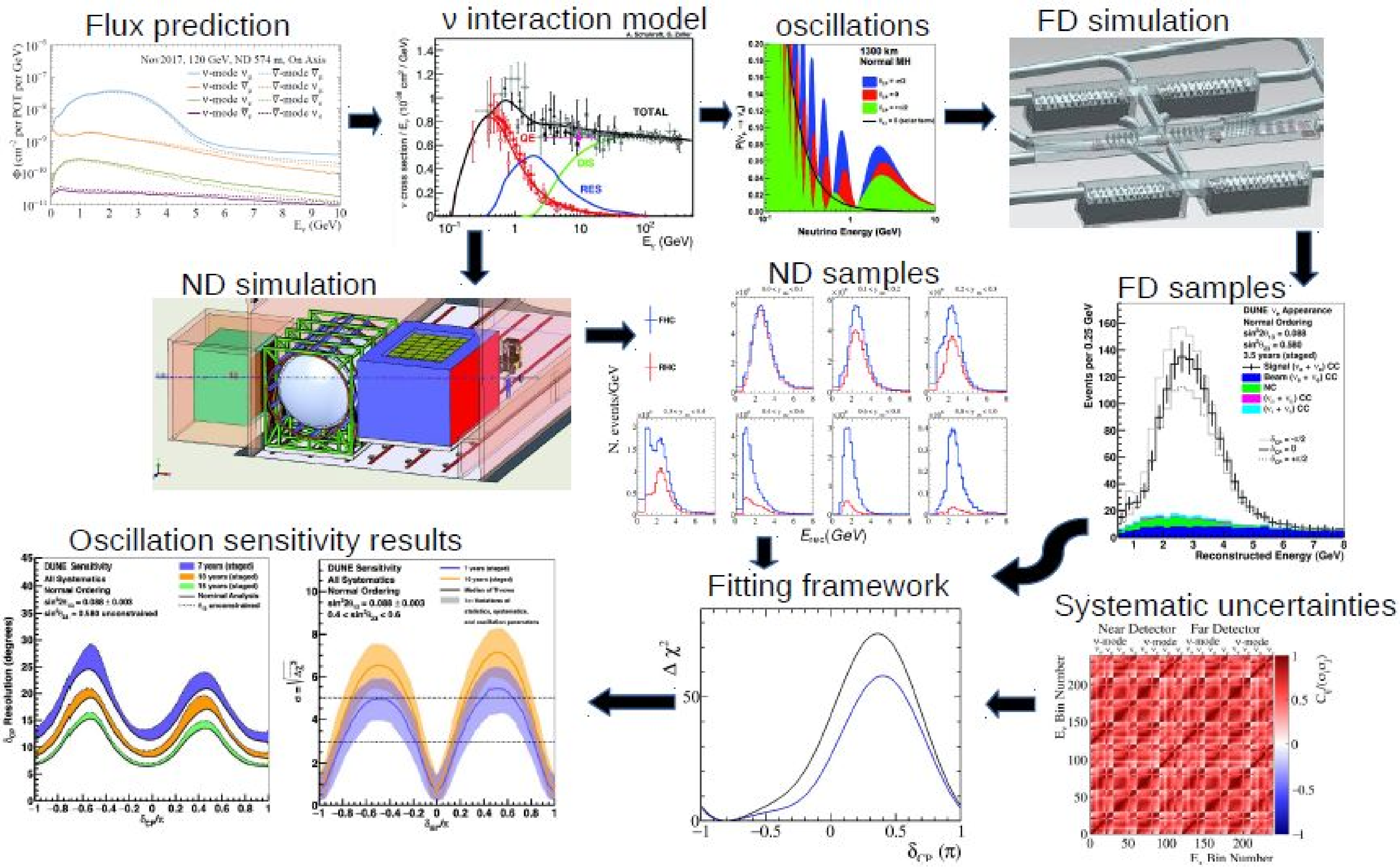
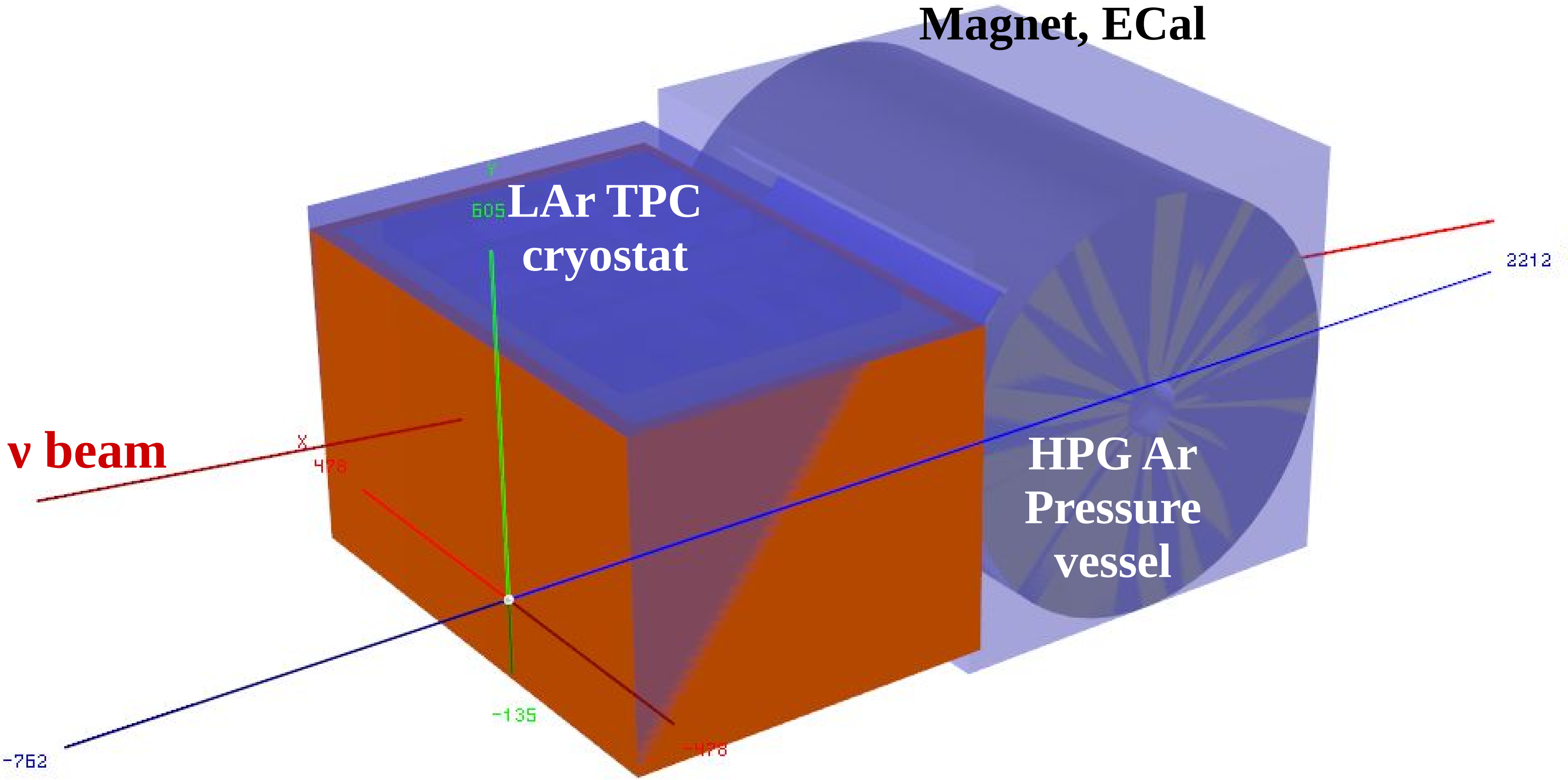
DESY ND workshop
21 October, 2019

Just text

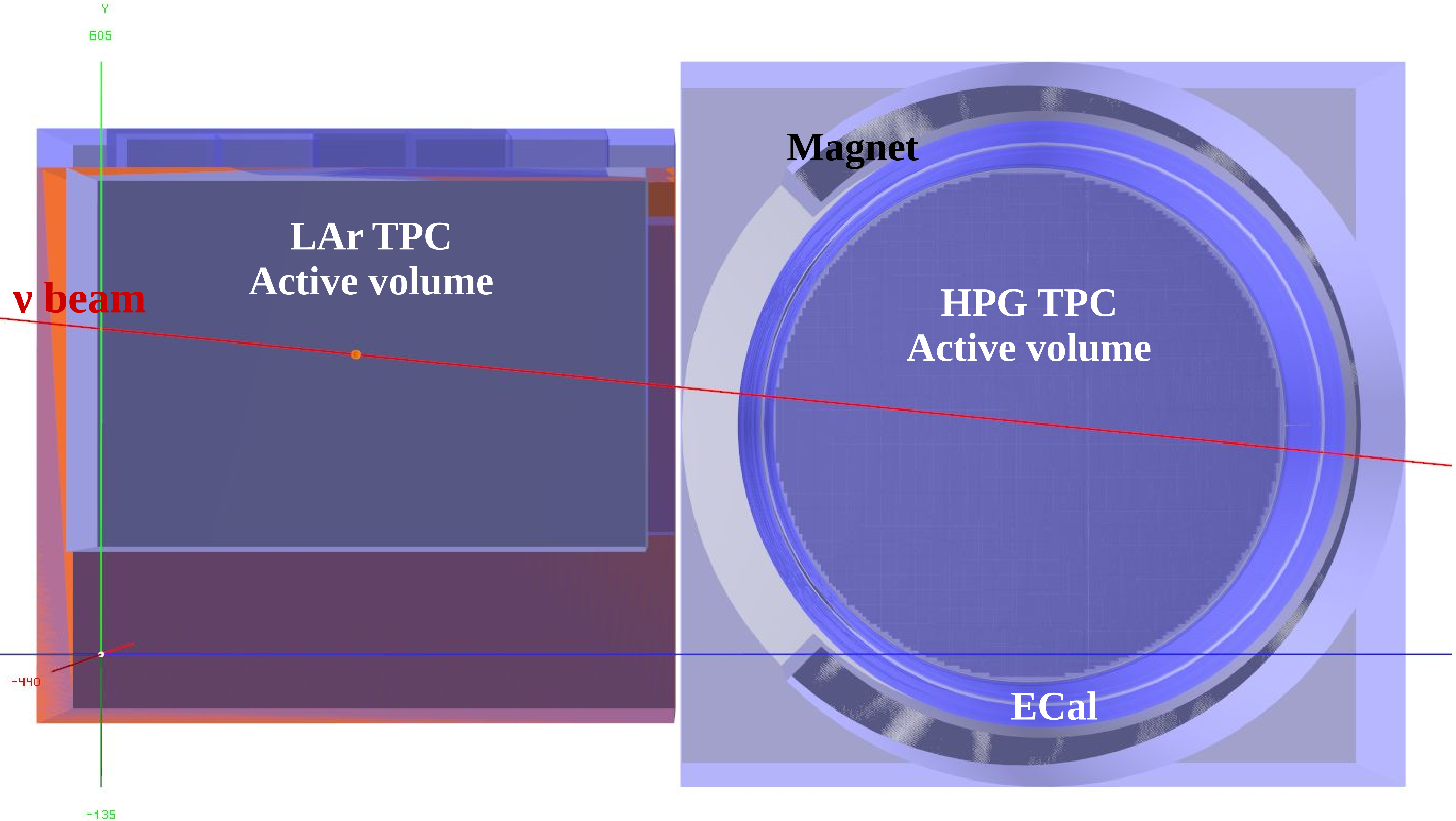
TDR analysis flow chart



ND geometry: 7x3x5m active LAr + gas TPC in solenoid magnet



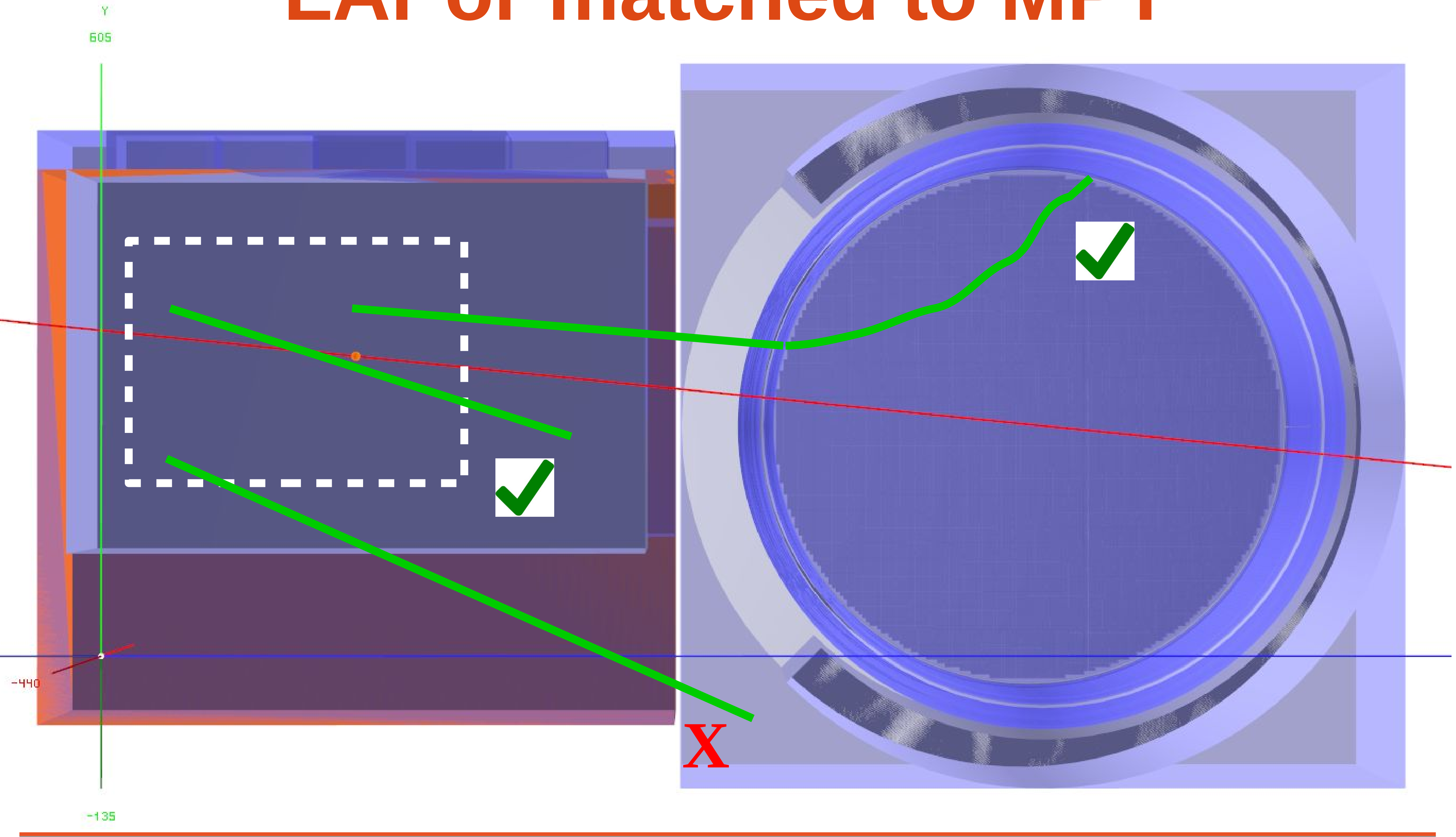
Side view, with neutrino beam



Near detector strategy

- Generate events with GENIE, with same reweighting framework used in FD
- Propagate final-state particles through detector geometry with Geant4
- Pseudo-reconstruction based in Geant4 energy deposits
- Form ν_μ CC samples to use in analysis

Muon acceptance: contained in LAr or matched to MPT



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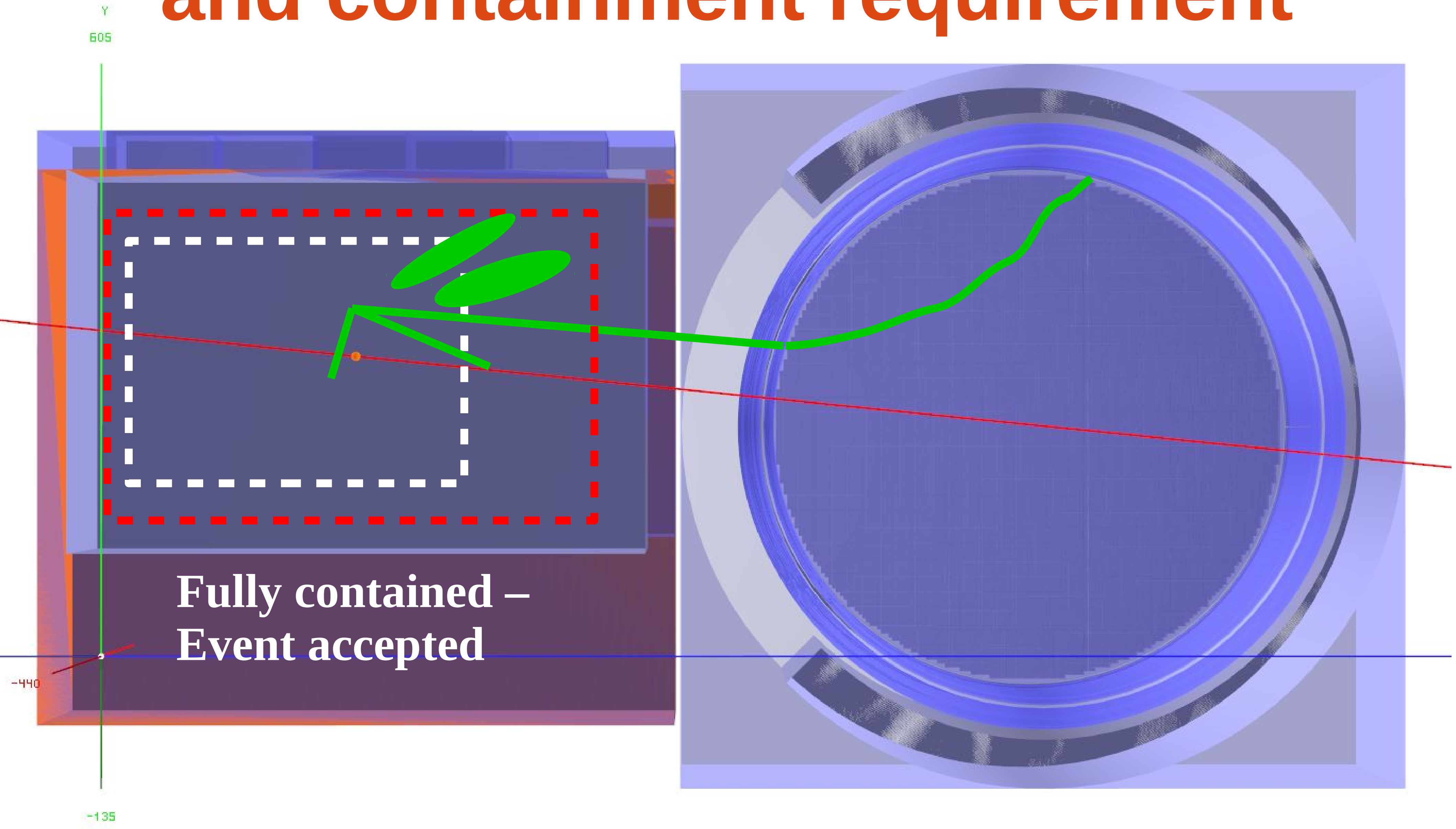
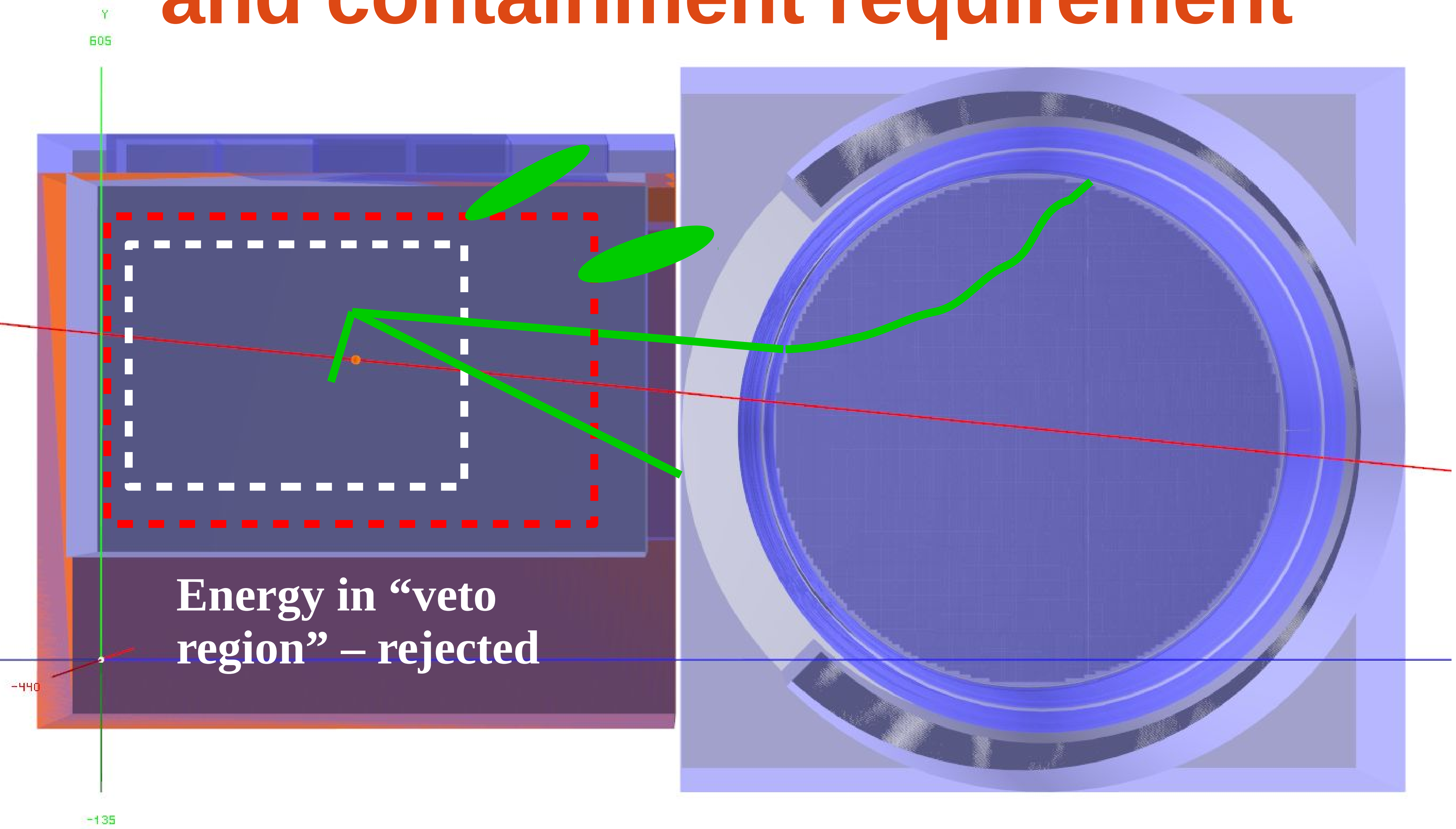
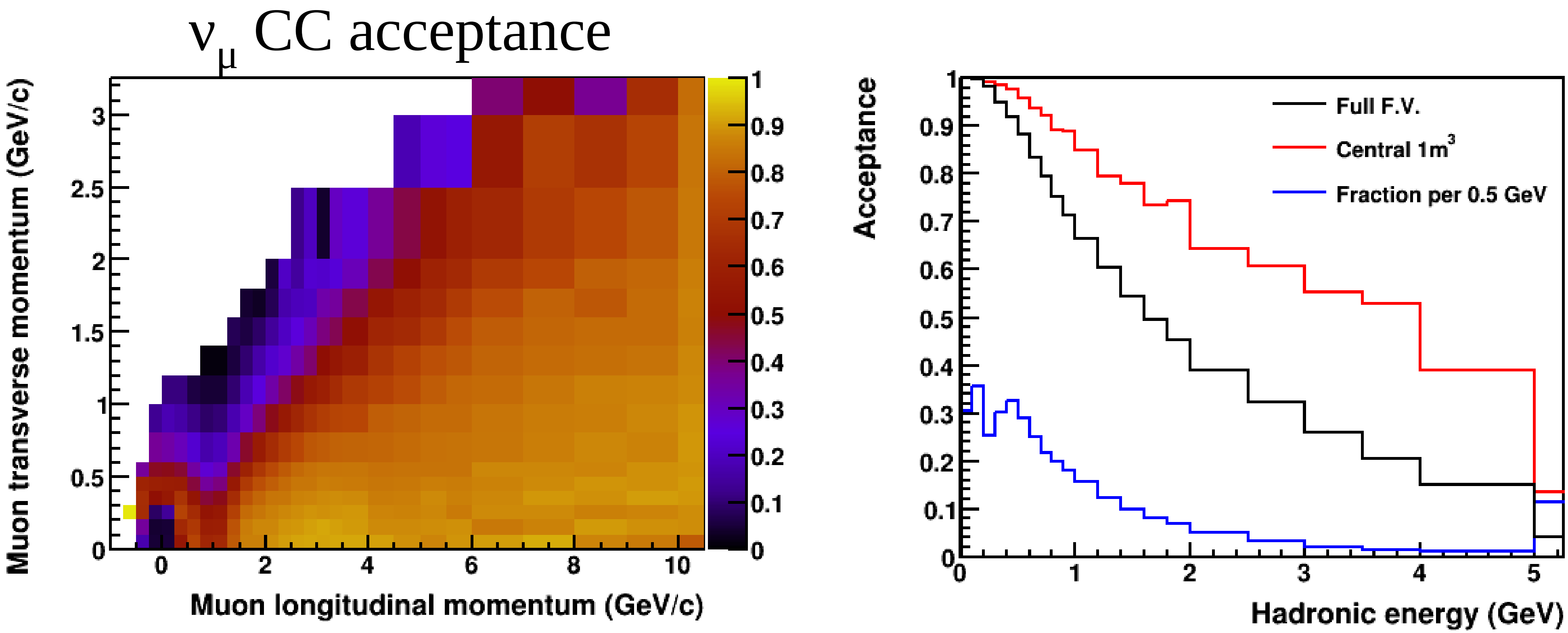
Hadronic energy reconstruction and containment requirement



Hadronic energy reconstruction and containment requirement

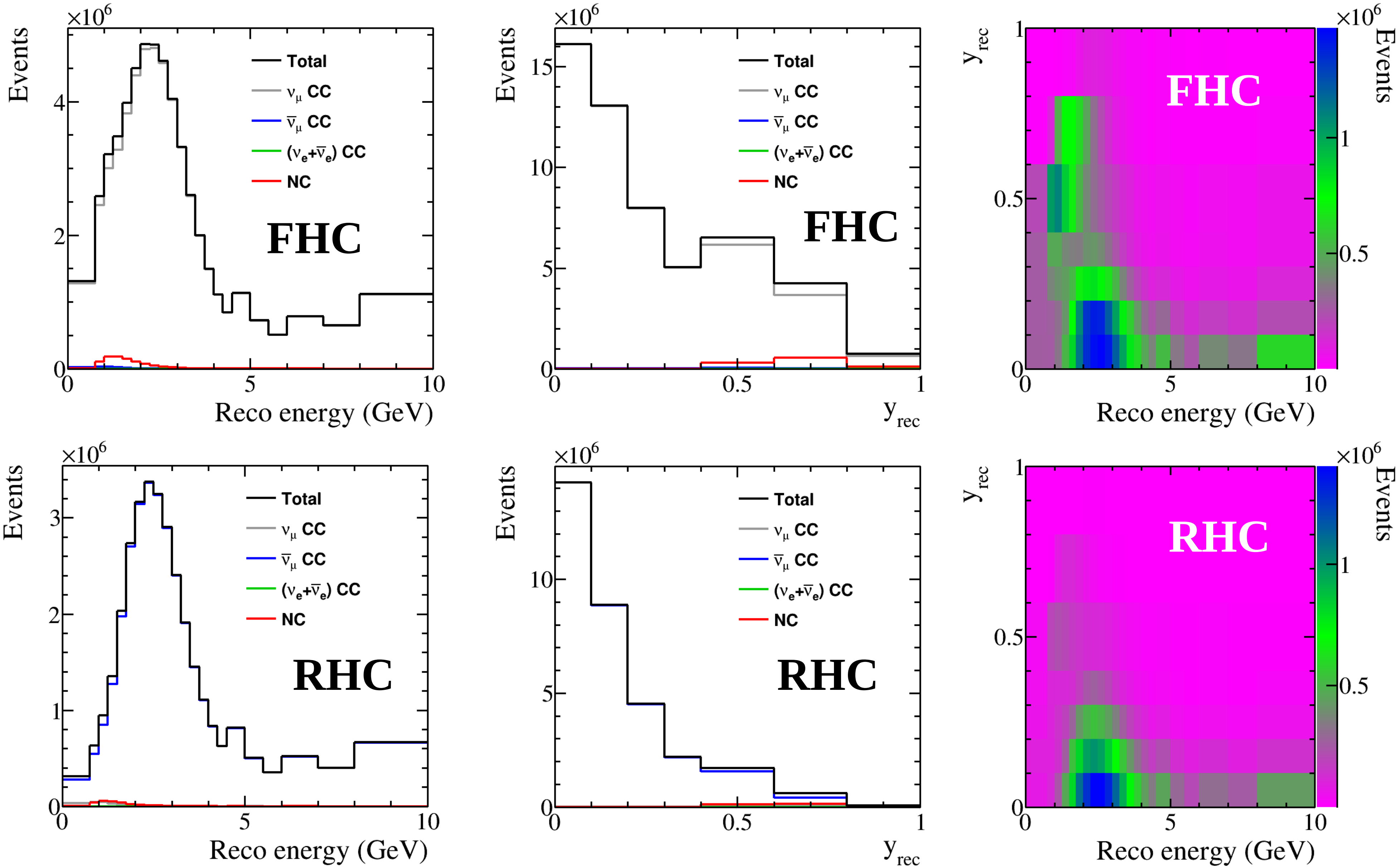


LAr ND event acceptance



- Left: CC acceptance vs. muon kinematics
- Right: Acceptance vs. hadronic energy – events with exiting hadrons are rejected, hence the lower efficiency at very high energy

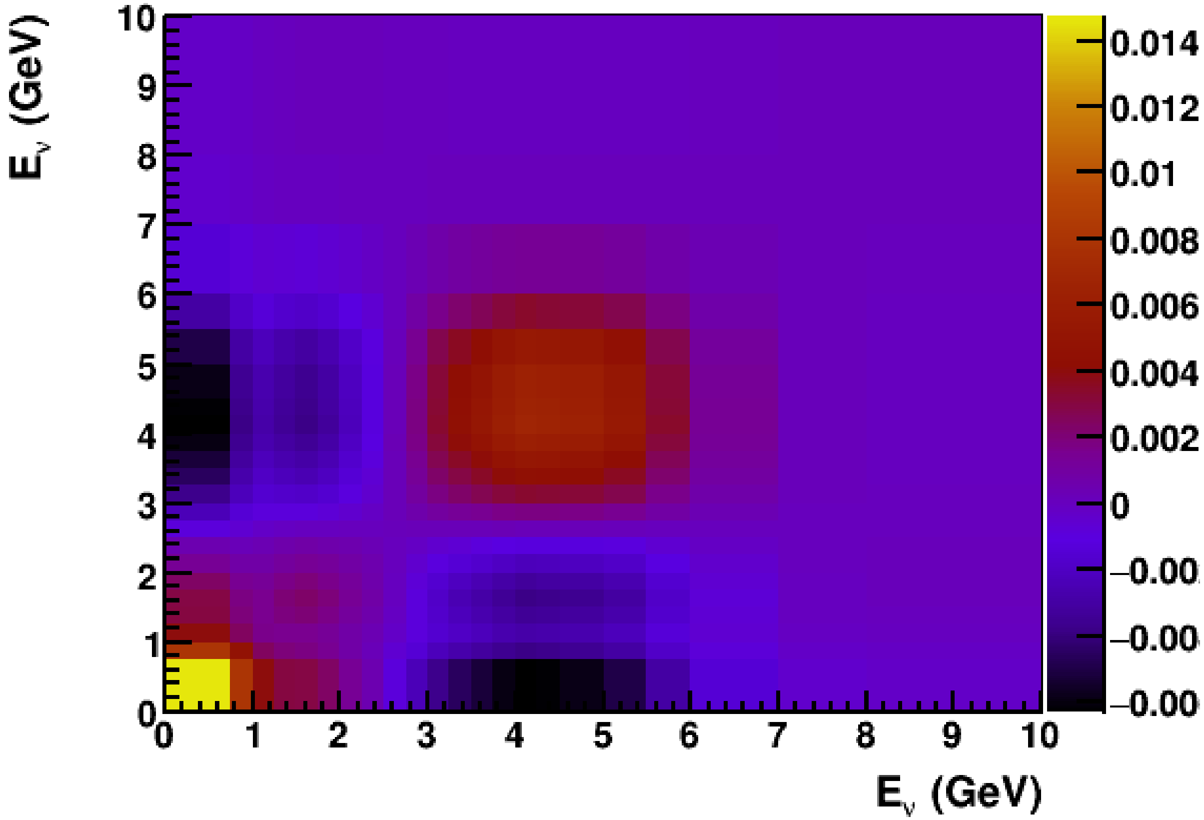
Selected ND analysis samples



Systematic uncertainties

- Uncertainty on CC event acceptance
- Energy scale uncertainties for each particle species:
  - Muons 2% in LAr, 1% in ND gas TPC
  - Charged hadrons (p, $\pi^{\pm}$) 5%
  - Electromagnetic showers (e, π^{0}) 5%
  - Visible energy from neutrons 20%
- Additional energy scale parameters that have dependence on energy
- Uncertainty on energy resolution, uncorrelated between different particle species

ND uncertainty implementation in covariance matrix



- Construct a covariance matrix in (E_ν, y) from the ND uncertainties with many universes approach
- Equivalent to including nuisance parameters in fit, but prevents these parameters from being further constrained by the ND data

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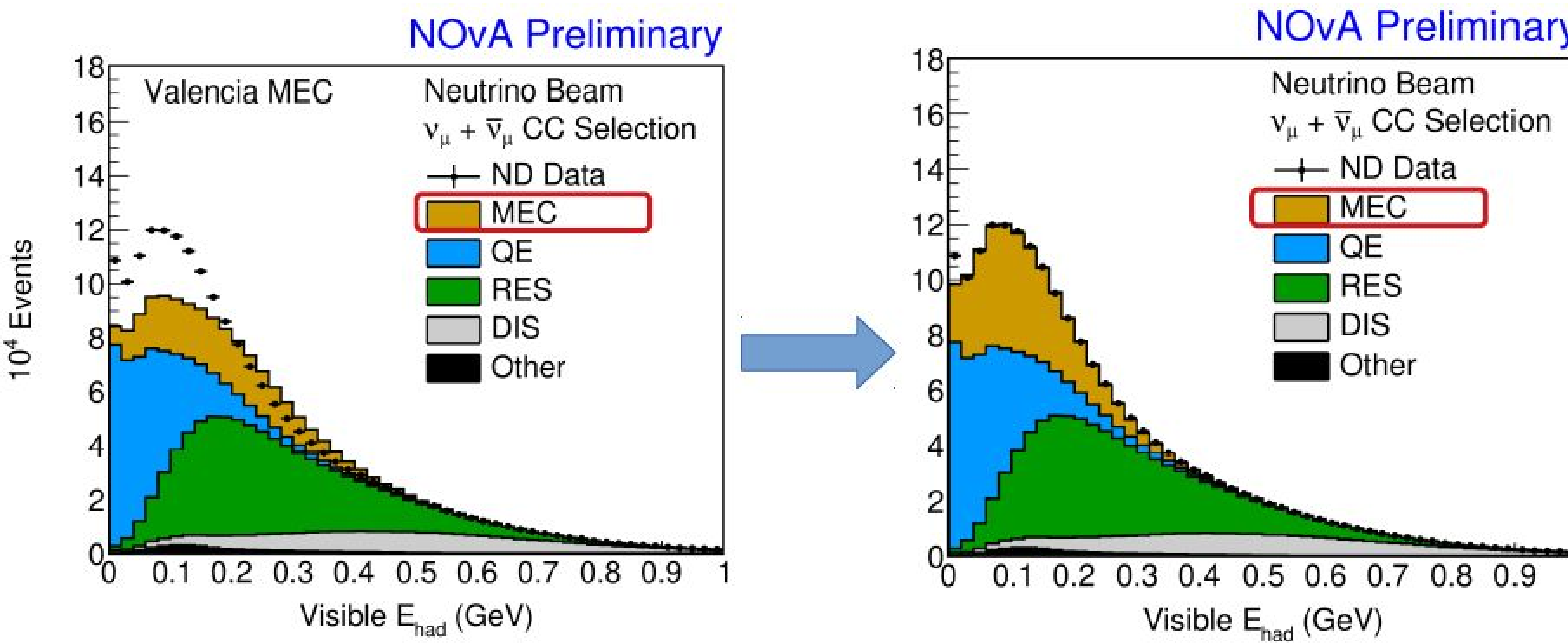
Drawbacks

- Uses a single ND sample – not practical to directly implement dozens of possible selected samples in LAr, GAr, 3DST
- With covariance matrix you lose access to parameter constraints – difficult to show how the ND is constraining uncertainties
- Implicitly assumes that interaction and detector models are correct and describe the data, up to the included uncertainties – not the experience of every experiment ever
- Uncertainties only impact FD when there is degeneracy – i.e. two parameters that have the same effect on the ND – which never happens when you include enough bins with no statistical uncertainty

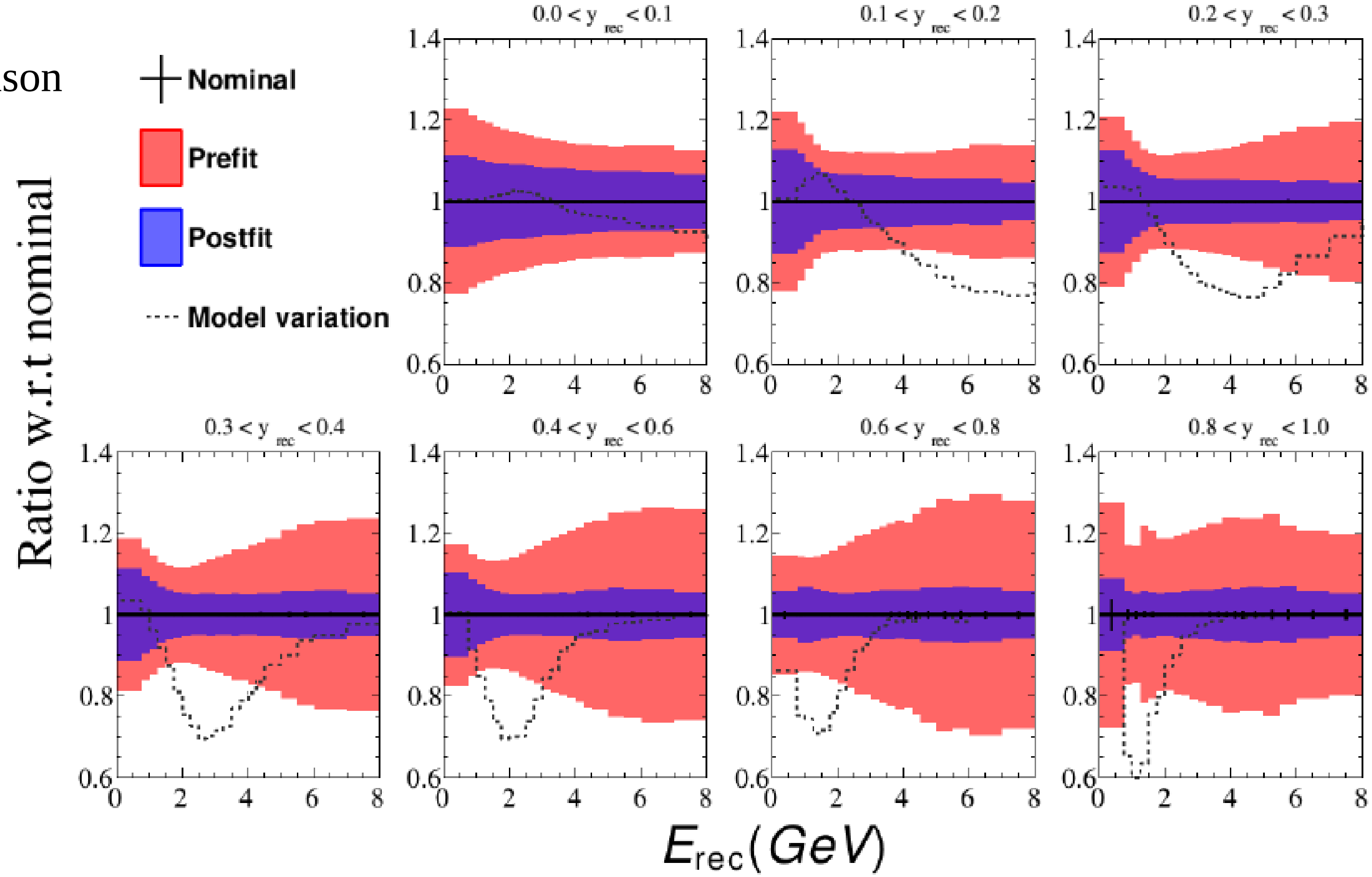
How it works in experiments



- ND data will **not** be described by our model
- We will modify our model to describe the ND data in many different projections, and add systematic uncertainties for the many different ways this can be done

Example: MK single pion

C. Wilkinson



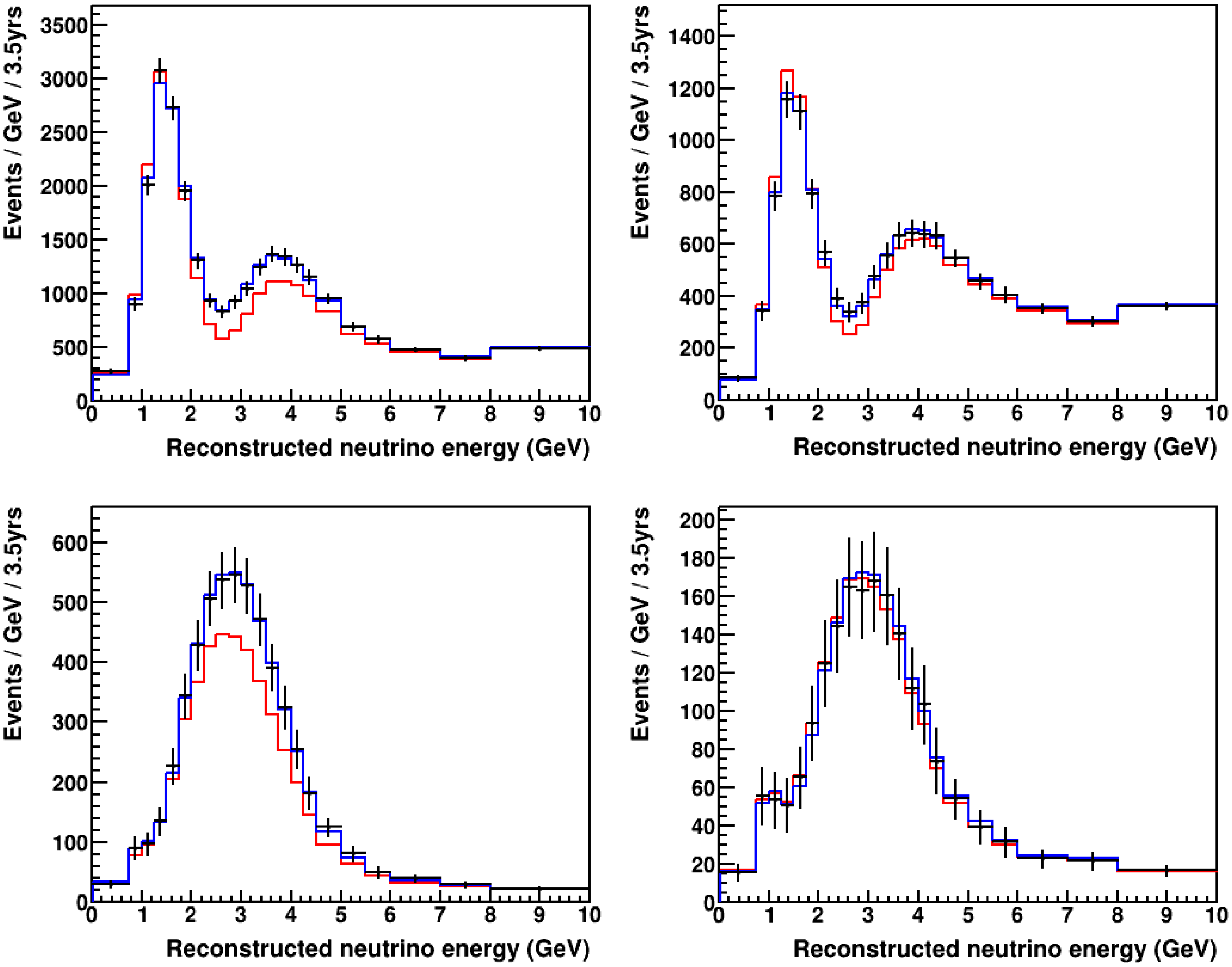
- Easy to see why this on/off dial (MK SPP reweight) is simply resolved by the ND... it simply knows whether it's on or off.

Bias studies with mock data

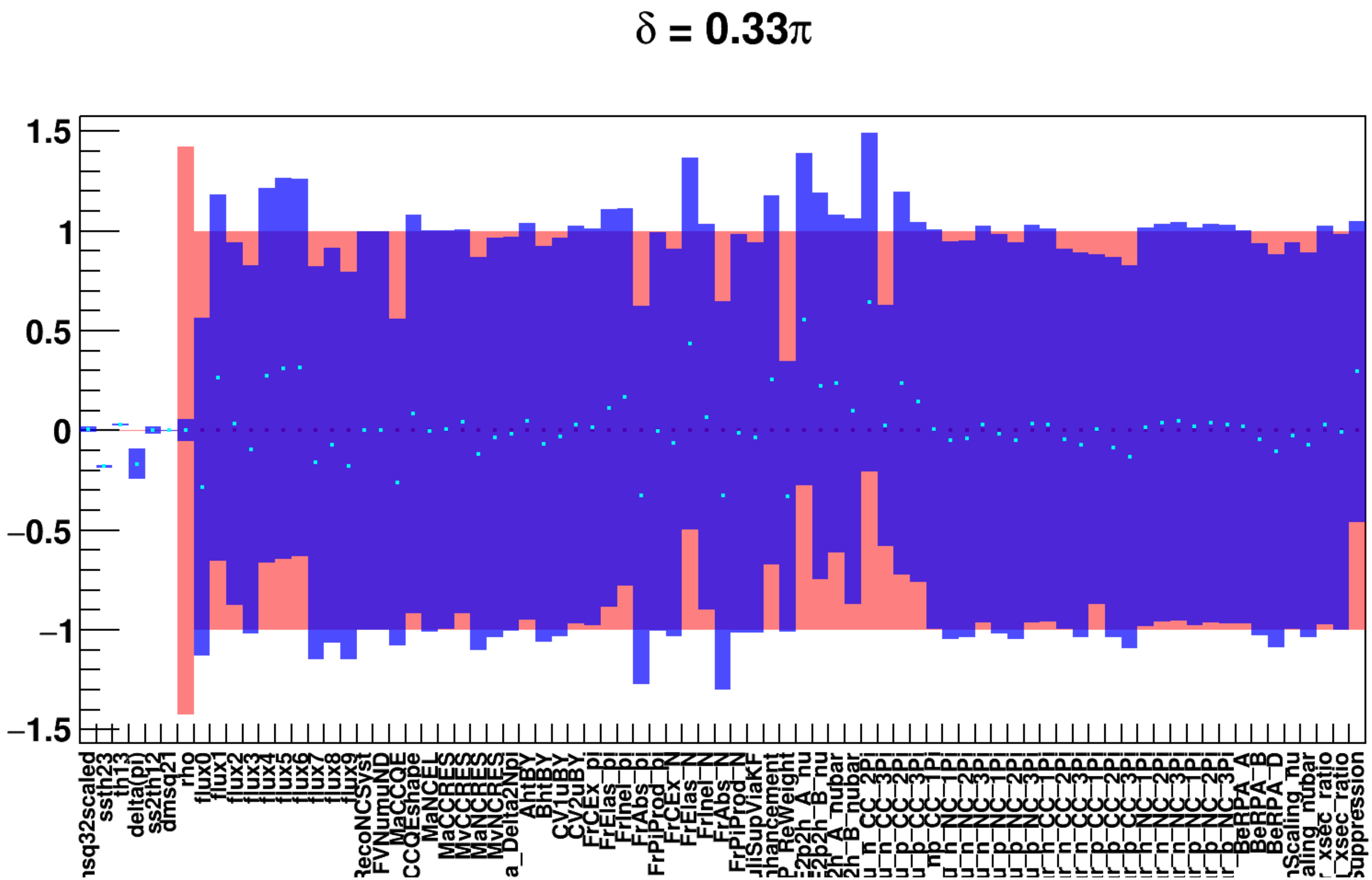
- Consider alternative MC "mock data" samples, and evaluate potential bias on analysis
  - "NuWro mock data", where a BDT is trained to generate event weights to make GENIE reproduce NuWro prediction in 18 kinematic quantities
  - "Missing proton energy", where 20% of proton energy is removed (i.e. converted to unobserved neutrons), and cross sections are adjusted so that on-axis hadronic energy spectrum is unchanged

FD-only fits

- FD-only we get very good fit, with $\chi^2 \sim 10$
- No evidence of any problems with model



FD-only nuisance parameter post-fits are < 0.5σ of pre-fit values



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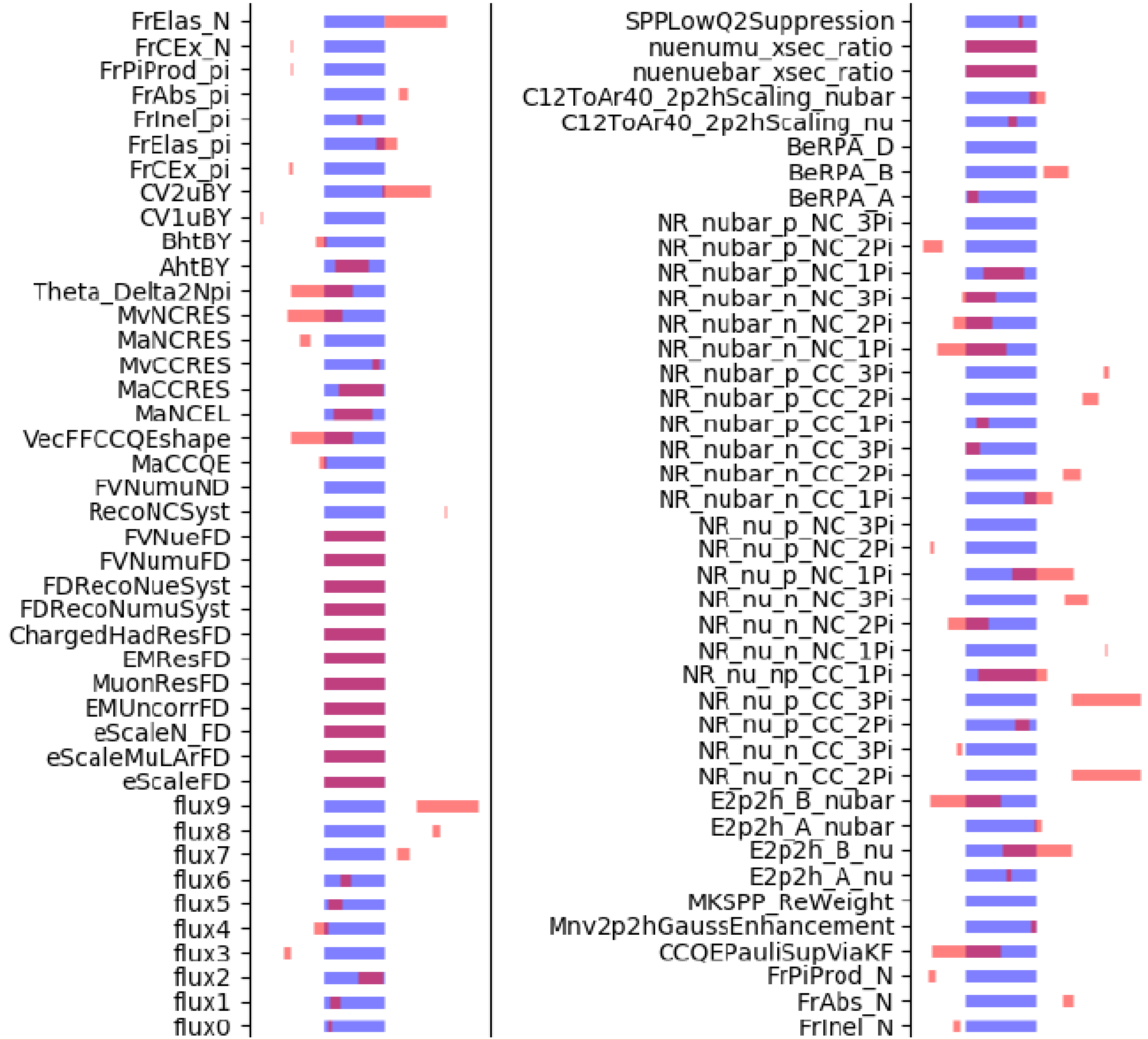
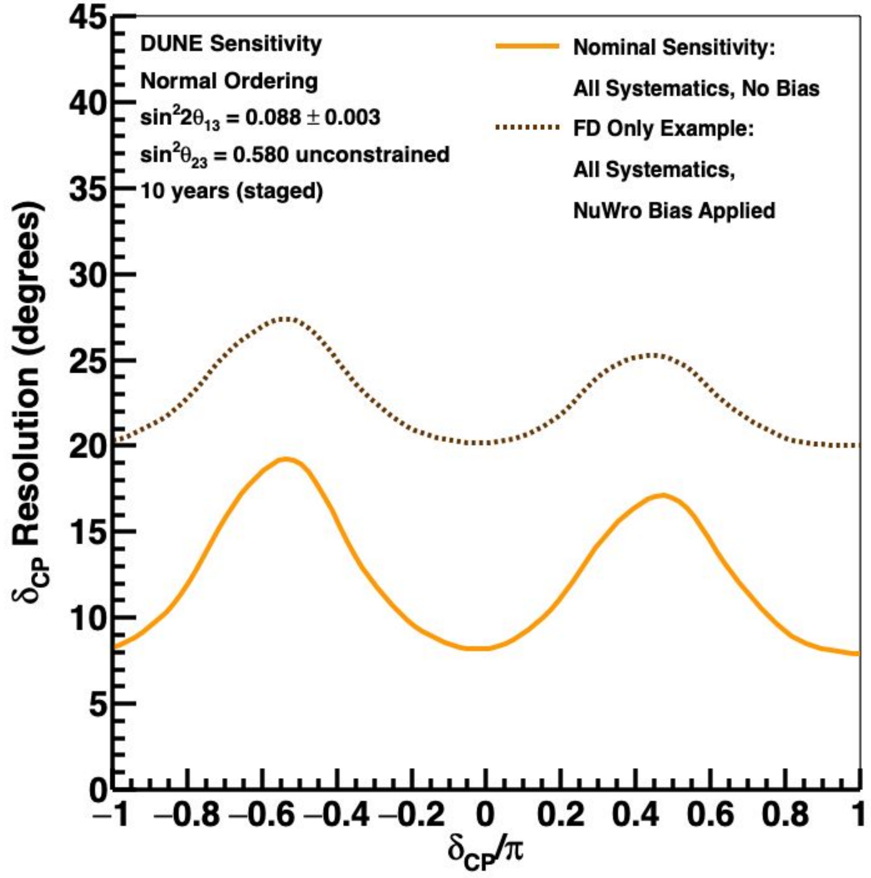
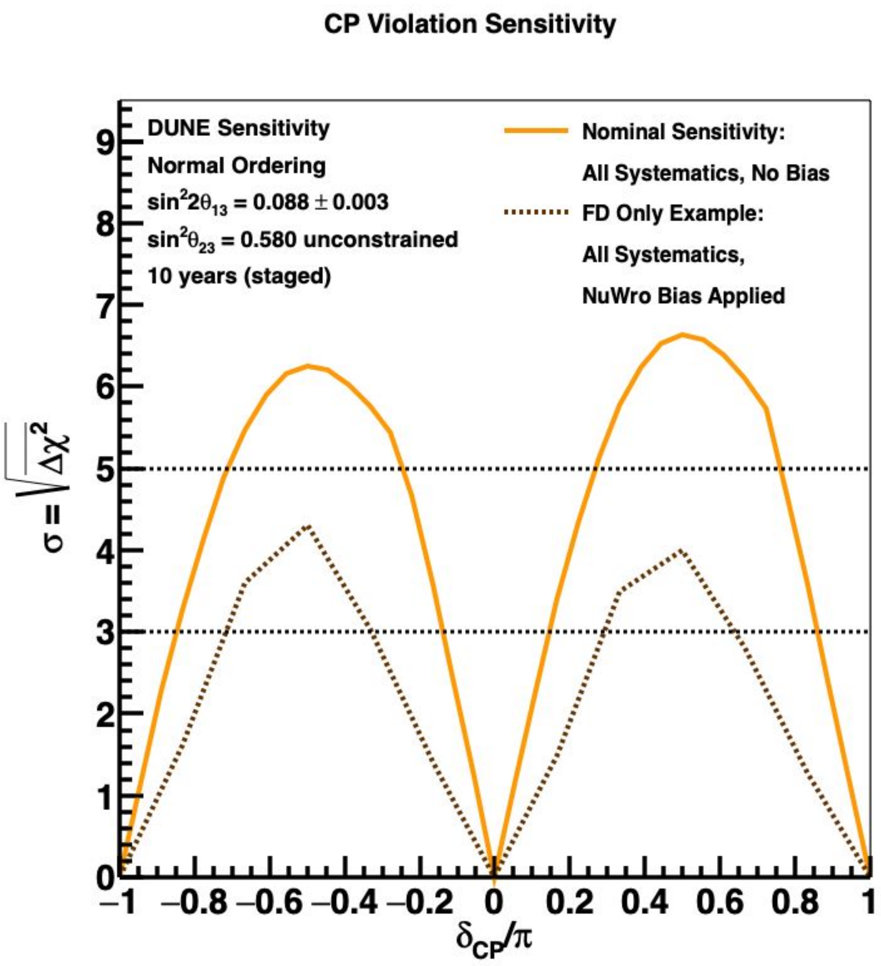
ND+FD fit $\chi^2 = 10879.2$

- Post-fit parameter uncertainties are shown as red bands
- Parameters get pulled way outside their pre-fit ranges, with tiny constraints
- Fit to ND data is terrible – we would definitely know there is a problem, although we do not yet show how we would fix it

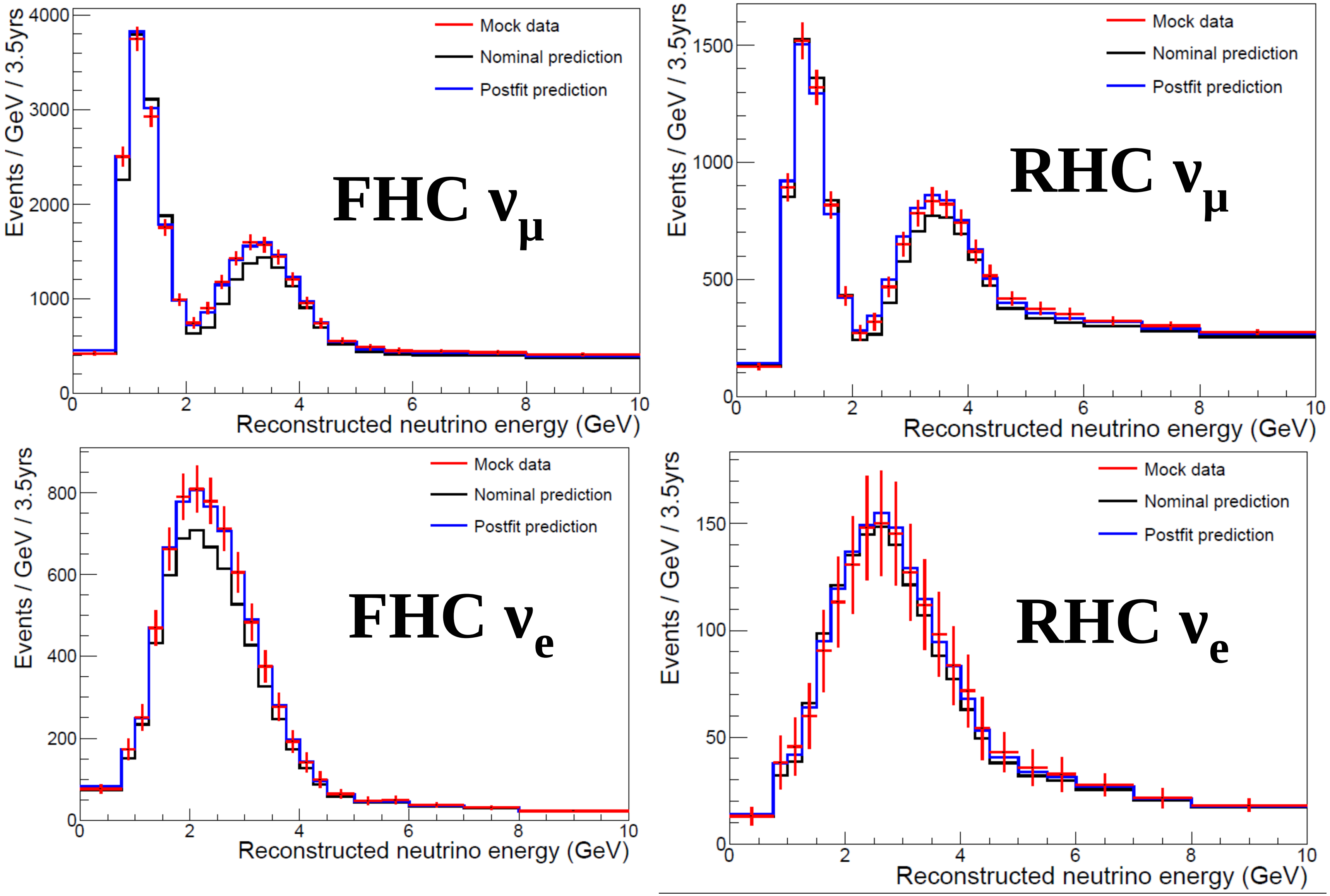


Sensitivities with bias applied



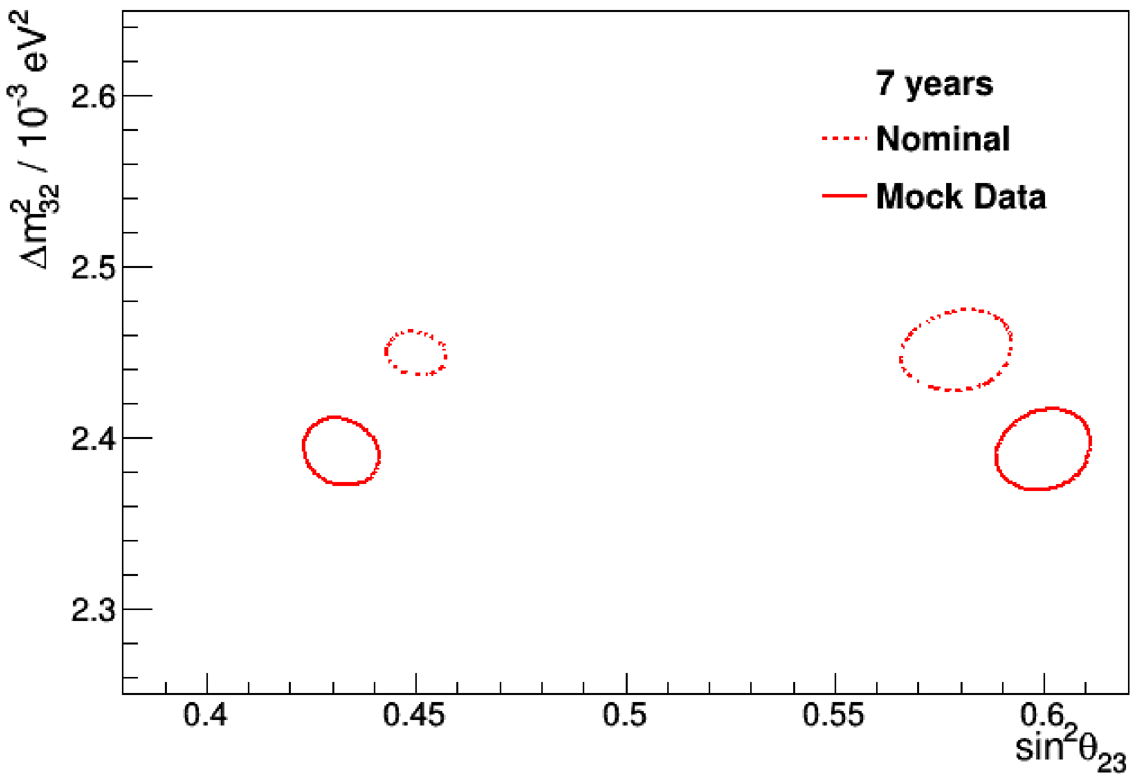


Missing proton mock data



Missing proton bias

- Best-fit gives significant bias to Δm^2 and θ_{23}, several sigma outside uncertainties



- Additional uncertainty would be required to cover the bias
- Effect is easily detected with off-axis ND data

How this could work for other ND studies

- What follows is a step-by-step for creating mock data studies to demonstrate how ND constrains specific uncertainties

Step 1: build the mock data

- Consider as an example for HPgTPC
- Example: Weight up CC3π, and weight down CC2π, such that the total rate stays constant as a function of Ehad
- CC2π and CC3π have different Eν → Erec maps, so this will modify the reconstructed energy at the far detector
- LAr ND might struggle to isolate these samples, but HPgTPC can do it cleanly

Step 2: Fit FD-only

- Create a “knob” in the CAF for this shift
- Fill the weights
- Add the knob in CAFAna and turn it on
- Run a FD-only fit
- Run LAr ND+FD fit
- LBL experts can help with these steps

Step 3: Reconstruct events

- Reconstruct the HPgTPC events
  - Could use pseudo-reconstruction & CAF maker developed by Tanaz, Justo, CM
  - Could use garsoft + CAF maker
- Produce CAF files for the HPgTPC, including the reweight knob from before

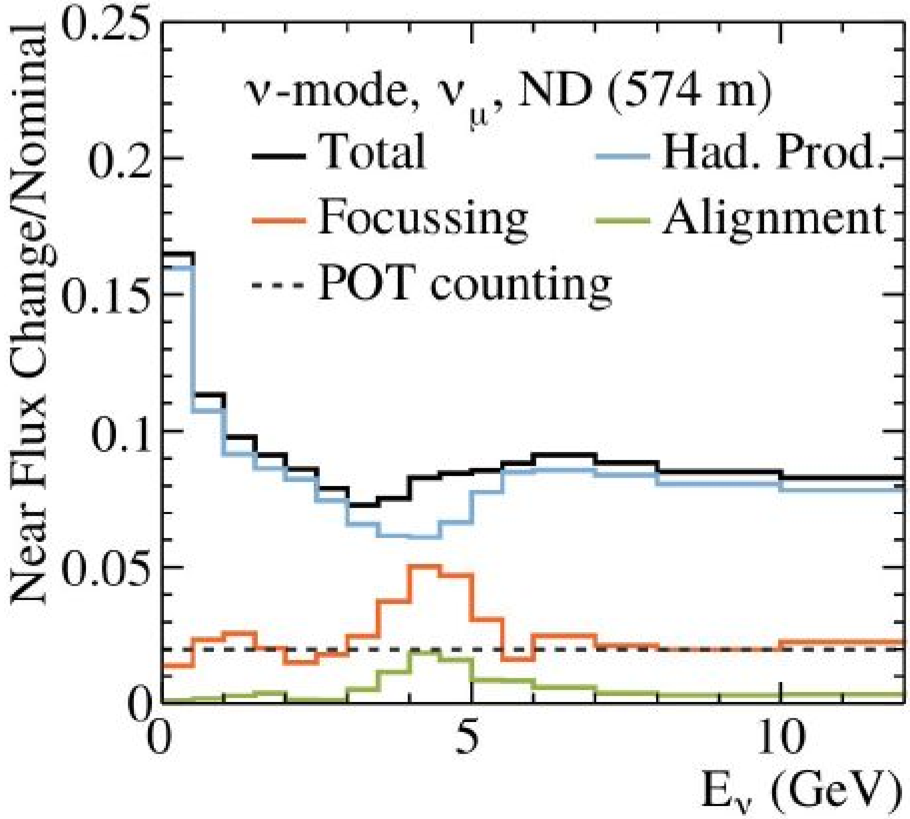
Step 4: Make HPgTPC distributions

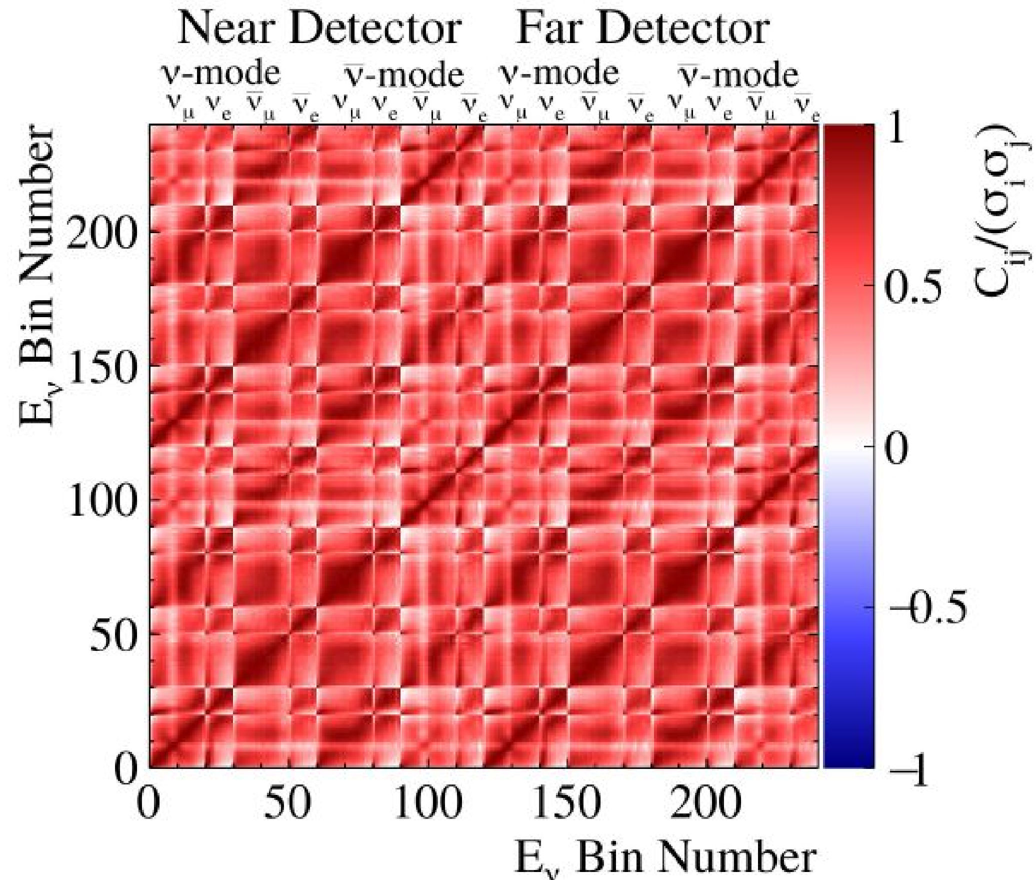
- HPgTPC can resolve CC2π and CC3π separately
  - Low pion thresholds
  - Excellent π/p PID up to ~1 GeV/c
- Maybe flux-integrated leading and sub-leading pion energy distributions for the two samples
- Show that you can tell that the relative normalizations of the two samples is off

Backups

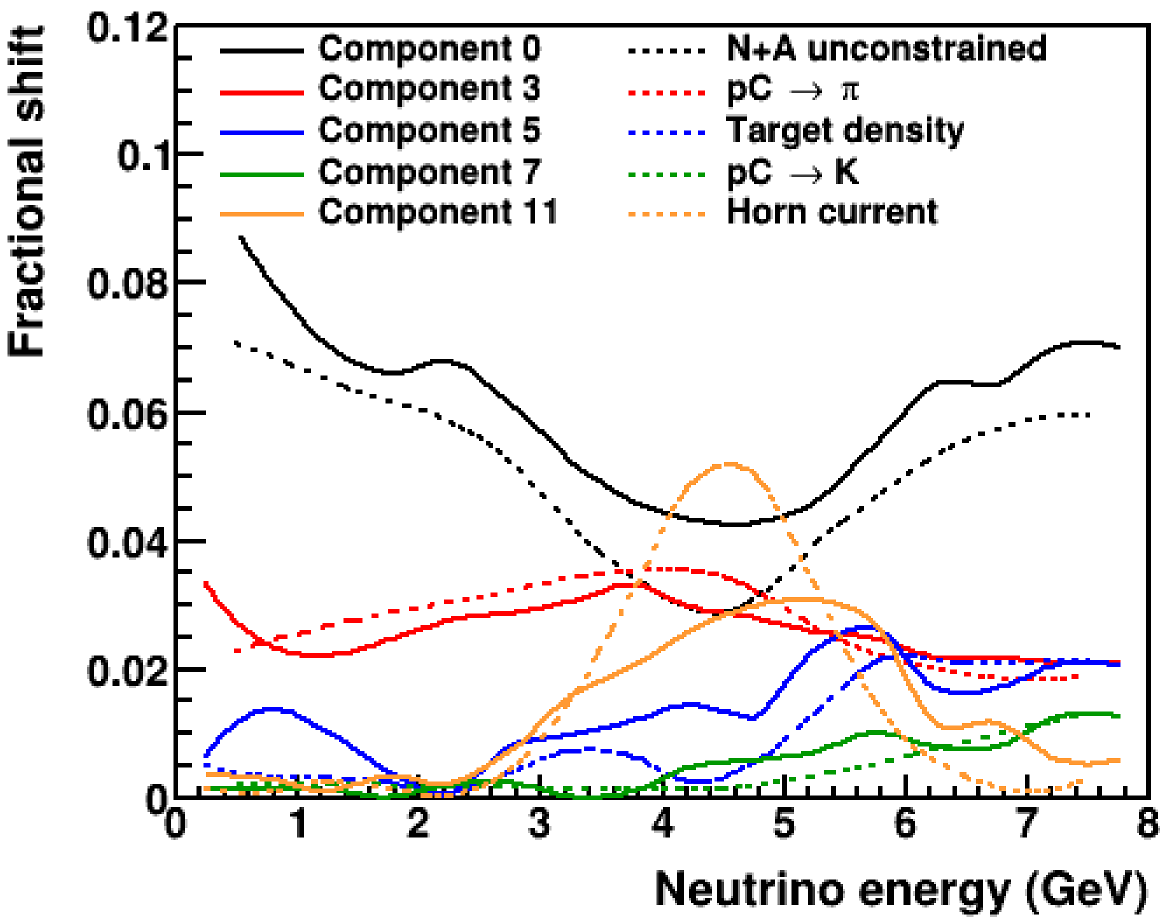
Flux uncertainties

- Flux uncertainties due to hadron production, beam focusing, and alignment are evaluated, including strong correlations between bins, beam modes, neutrino flavors





Principal component analysis is used to improve performance



- The largest HP & focusing uncertainties show up as principal components of the full covariance matrix
- Validates that our mathematical trick to diagonalize the uncertainty captures the same physics as varying individual parameters

Cross section uncertainties

MaCCQE
VecFFCCQEshape
CCQEPauliSupViaKF
MaNCEL
MaCCRES
MvCCRES
MaNCRES
MvNCRES
Theta_Delta2Npi
AhtBY
BhtBY
CV1uBY
CV2uBY
FrCEx_pi
FrElas_pi
FrInel_pi
FrAbs_pi
FrPiProd_pi
FrCEx_N
FrElas_N
FrInel_N
FrAbs_N
FrPiProd_N

Mnv2p2hGaussEnhancement
MKSPP_ReWeight
E2p2h_A_nu
E2p2h_B_nu
E2p2h_A_nubar
E2p2h_B_nubar
BeRPA_A
BeRPA_B
BeRPA_D
C12ToAr40_2p2hScaling_nu
C12ToAr40_2p2hScaling_nubar
nuenuebar_xsec_ratio
nuenumu_xsec_ratio
SPPLowQ2Suppression

NR_nu_n_CC_2Pi
NR_nu_n_CC_3Pi
NR_nu_p_CC_2Pi
NR_nu_p_CC_3Pi
NR_nu_np_CC_1Pi
NR_nu_n_NC_1Pi
NR_nu_n_NC_2Pi
NR_nu_n_NC_3Pi
NR_nu_p_NC_1Pi
NR_nu_p_NC_2Pi
NR_nu_p_NC_3Pi
NR_nubar_n_CC_1Pi
NR_nubar_n_CC_2Pi
NR_nubar_n_CC_3Pi
NR_nubar_p_CC_1Pi
NR_nubar_p_CC_2Pi
NR_nubar_p_CC_3Pi
NR_nubar_n_NC_1Pi
NR_nubar_n_NC_2Pi
NR_nubar_n_NC_3Pi
NR_nubar_p_NC_1Pi
NR_nubar_p_NC_2Pi
NR_nubar_p_NC_3Pi

GENIE ReWeight

MaCCQE
VecFFCCQEshape
CCQEPauliSupViaKF
MaNCEL
MaCCRES
MvCCRES
MaNCRES
MvNCRES
Theta_Delta2Npi
AhtBY
BhtBY
CV1uBY
CV2uBY
FrCEx_pi
FrElas_pi
FrInel_pi
FrAbs_pi
FrPiProd_pi
FrCEx_N
FrElas_N
FrInel_N
FrAbs_N
FrPiProd_N

GENIE reweight parameters affecting
CC quasi-elastic
CC resonance production
CC deep inelastic scattering
Final-state interactions
Neutral currents

DUNEint not covered in GENIE

Additional parameters:

CC QE

CC Resonance

2p2h

Scaling C → Ar

ν_e/ν_μ or $\nu_e/\bar{\nu}_e$

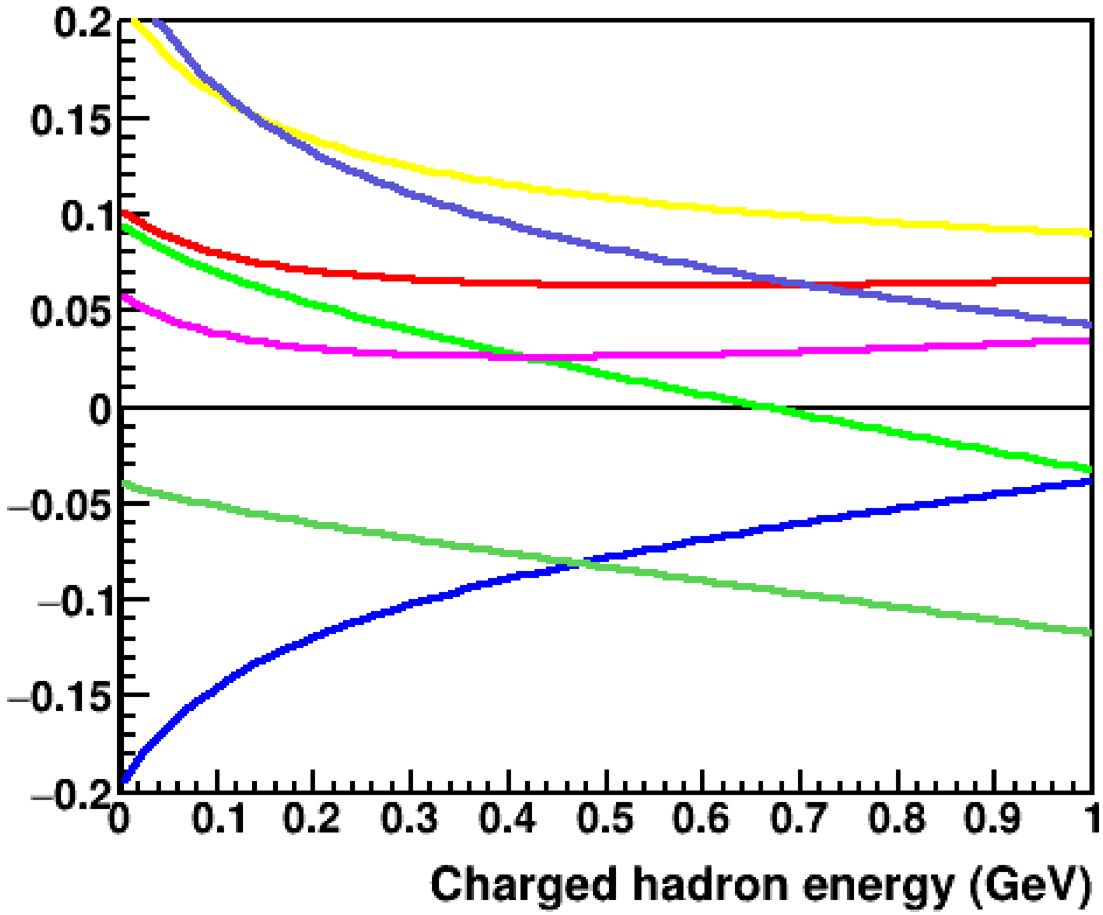
Mnv2p2hGaussEnhancement
MKSPP_ReWeight
E2p2h_A_nu
E2p2h_B_nu
E2p2h_A_nubar
E2p2h_B_nubar
BeRPA_A
BeRPA_B
BeRPA_D
C12ToAr40_2p2hScaling_nu
C12ToAr40_2p2hScaling_nubar
nuenuebar_xsec_ratio
nuenumu_xsec_ratio
SPPLowQ2Suppression

DUNEint not covered in GENIE

Additional parameters affecting non-resonant pion production

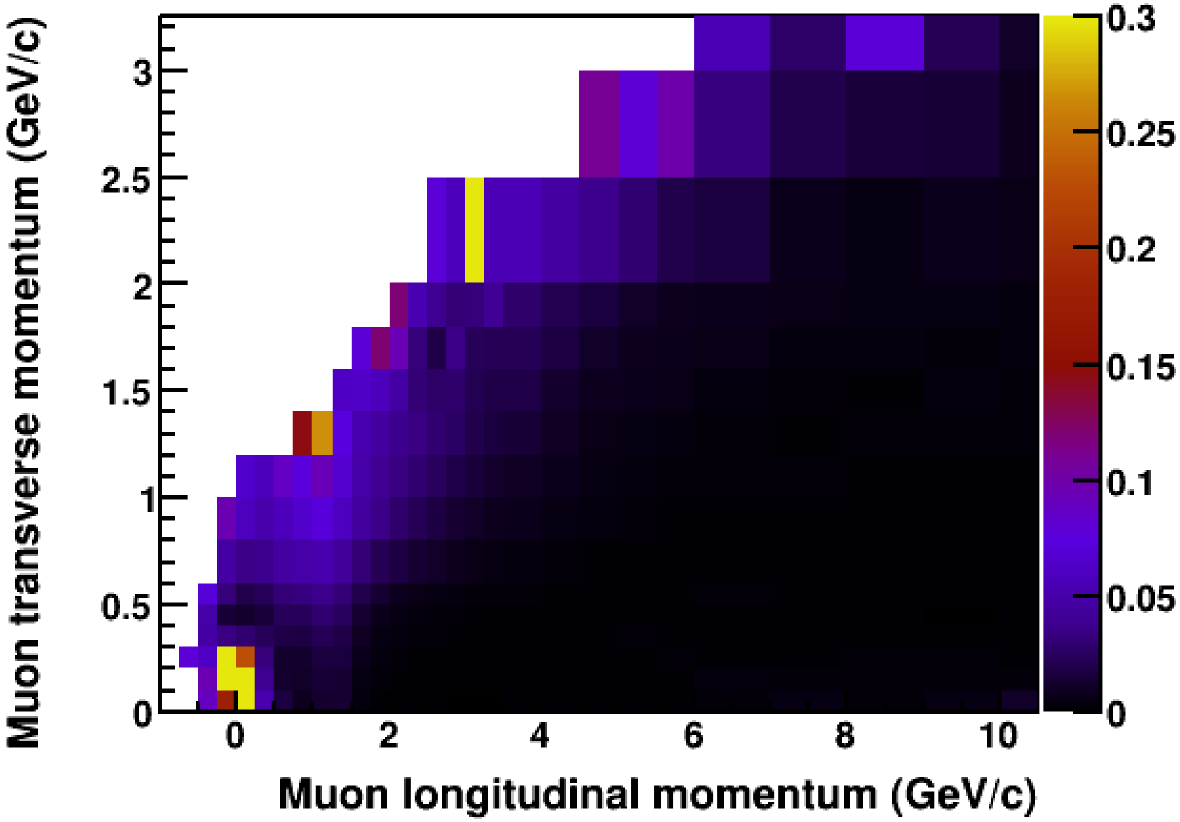
NR_nu_n_CC_2Pi
NR_nu_n_CC_3Pi
NR_nu_p_CC_2Pi
NR_nu_p_CC_3Pi
NR_nu_np_CC_1Pi
NR_nu_n_NC_1Pi
NR_nu_n_NC_2Pi
NR_nu_n_NC_3Pi
NR_nu_p_NC_1Pi
NR_nu_p_NC_2Pi
NR_nu_p_NC_3Pi
NR_nubar_n_CC_1Pi
NR_nubar_n_CC_2Pi
NR_nubar_n_CC_3Pi
NR_nubar_p_CC_1Pi
NR_nubar_p_CC_2Pi
NR_nubar_p_CC_3Pi
NR_nubar_n_NC_1Pi
NR_nubar_n_NC_2Pi
NR_nubar_n_NC_3Pi
NR_nubar_p_NC_1Pi
NR_nubar_p_NC_2Pi
NR_nubar_p_NC_3Pi

Example: charged hadron response



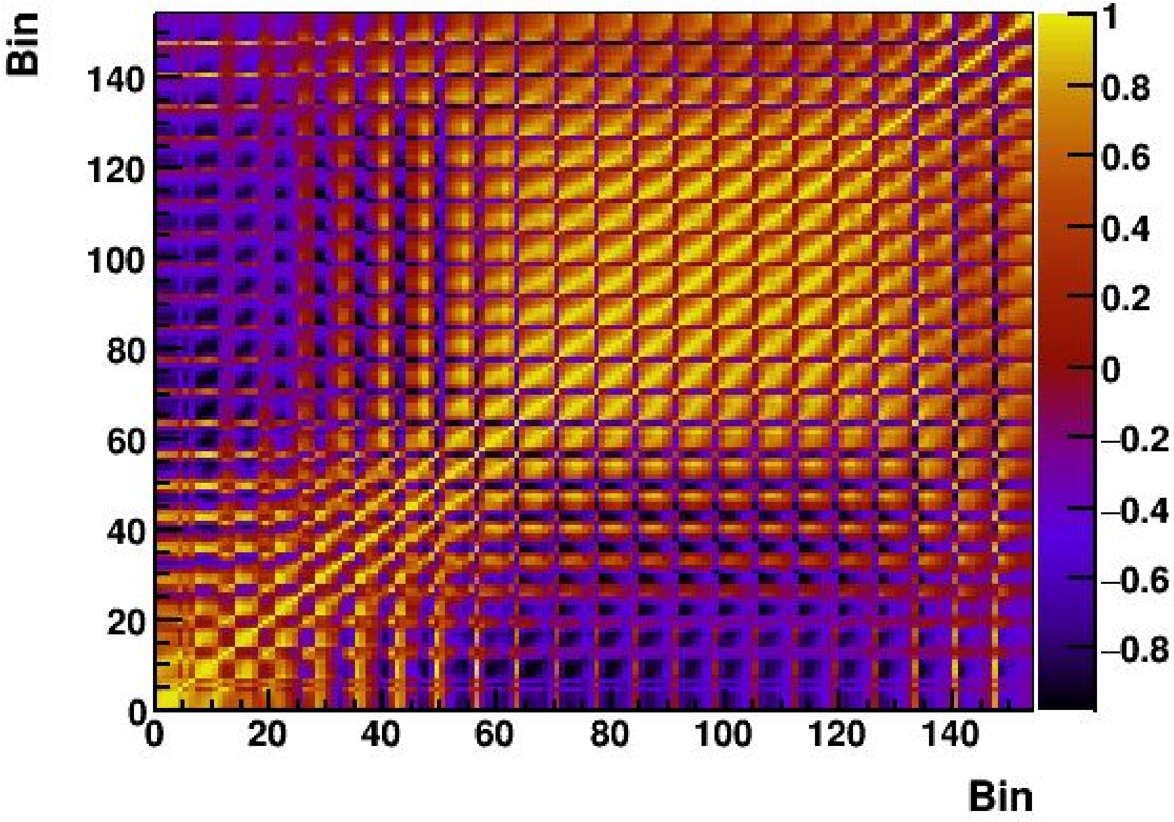
- Each curve represents the energy response bias in a particular universe, where the parameters have been chosen randomly consistent with the energy-dependent uncertainty

ND CC ν_μ acceptance fractional uncertainty



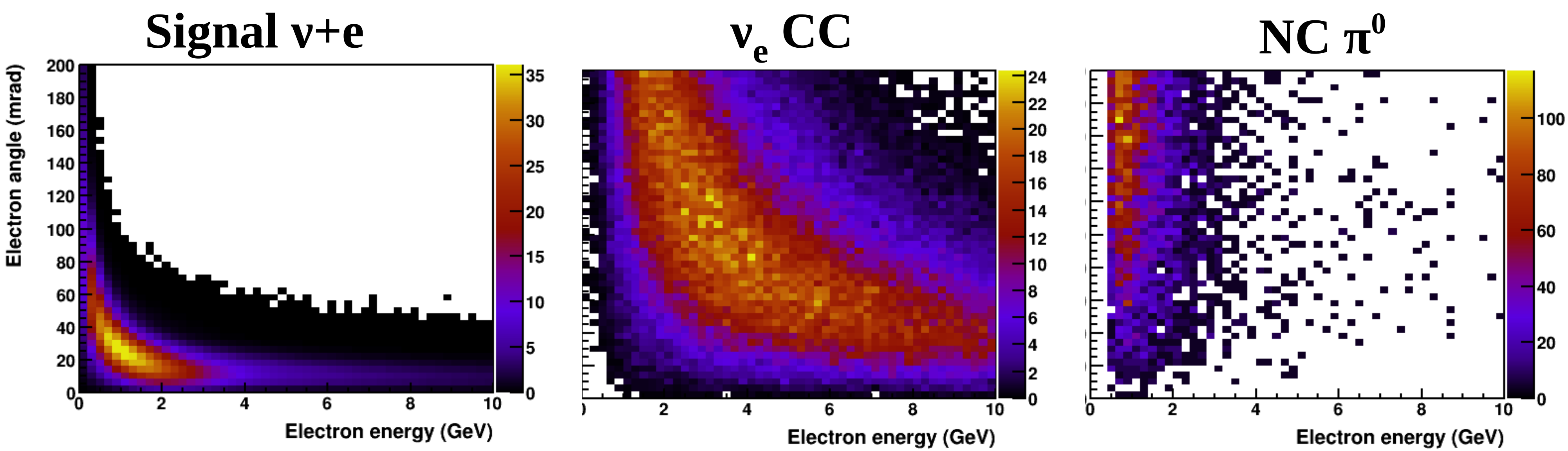
- CC events are rejected when
  - Muon is reconstructed as $\pi^\pm$ (low energy)
  - Muon exits sides
  - Muon exits downstream but does not enter gas TPC
- Acceptance is sensitive to detector modeling in phase space where muon acceptance is rapidly changing
- Uncertainty is evaluated as a function of muon momentum in transverse and neutrino direction (equivalently, energy and angle)

The actual matrix, in the analysis 2D binning



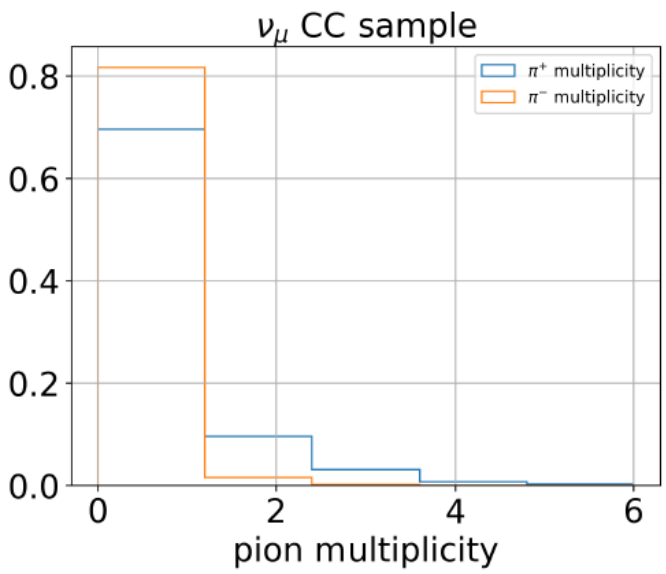
- The ND binning in the fit is two-dimensional in E_ν and y, so the full covariance matrix includes this full binning

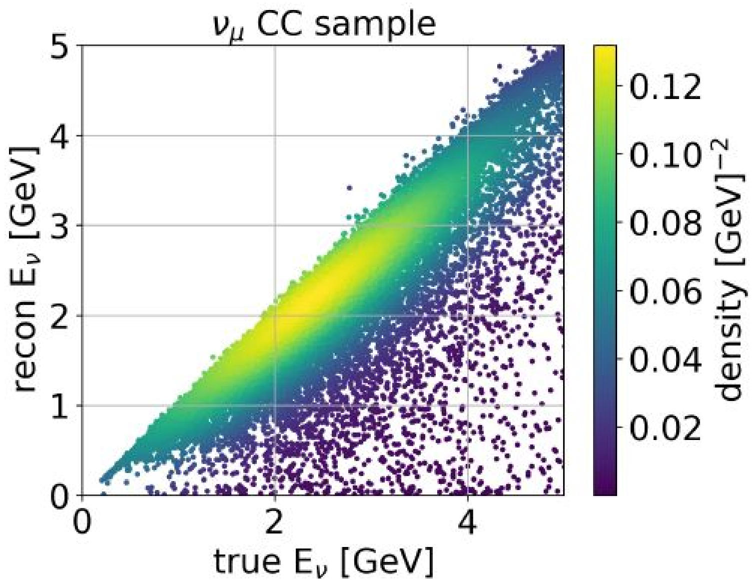
Additional LAr sample: ν+e scattering



- Pure EW process with known cross section → sensitive to flux only
- Signal is subject to kinematic constraint $E_e\theta_e^2 < 2m_e$
- Dominant background is ν_e CC at low Q^2
- Signal and background samples are ready, but have yet to be included in fit

Additional sample: Gas TPC





- Leverage low threshold, excellent PID of gas TPC, with very different detector systematics
- Binned in reconstructed E_ν separately for CC0π, 1π, >2π
- Complements LAr TPC by constraining some cross section parameters that are hard to access with dense LAr