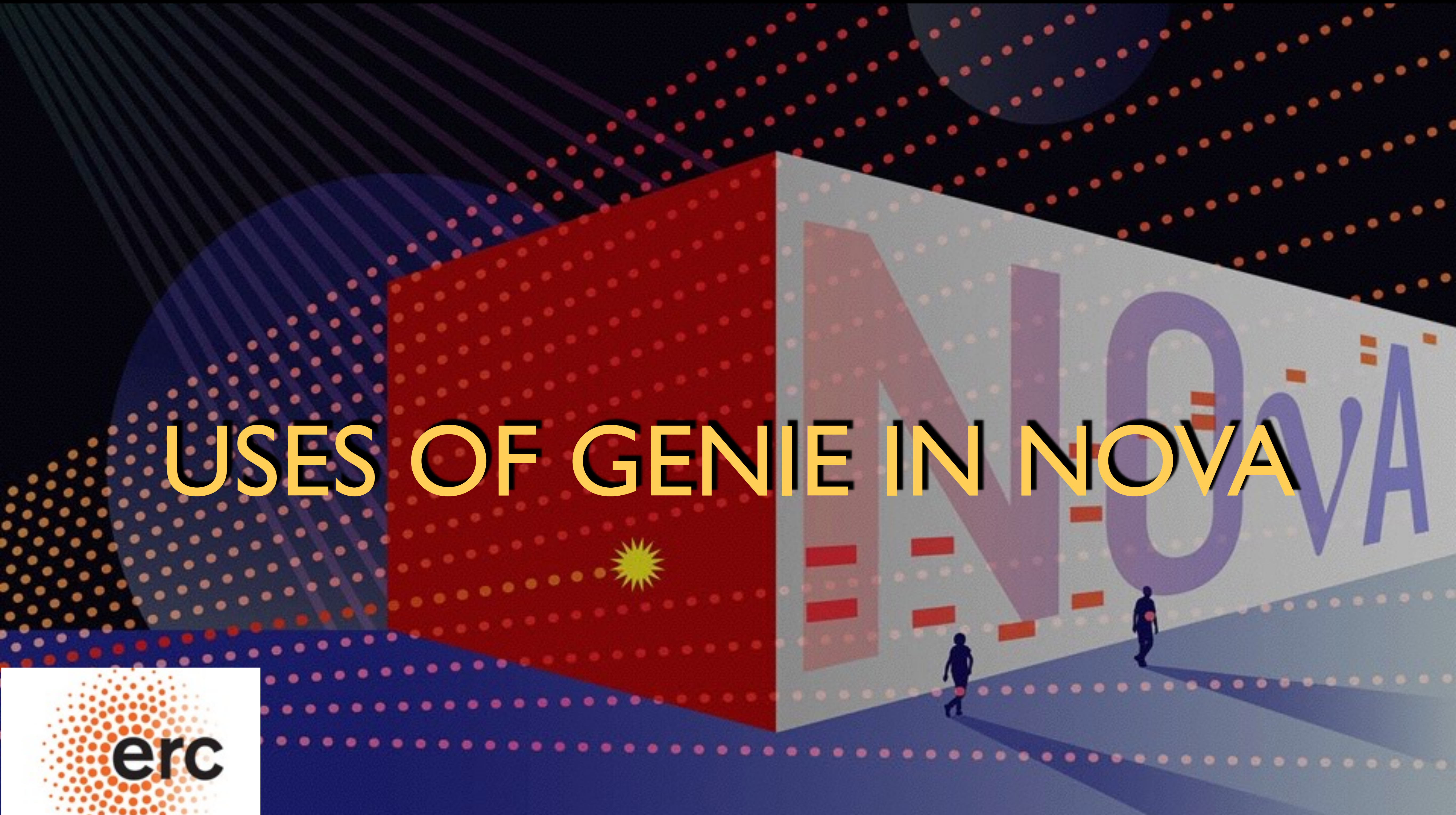
USES OF GENIE IN NOVA



Bruno Zamorano

NuTune (Liverpool) - 11th July 2016

European Research Council
Established by the European Commission
University of Sussex

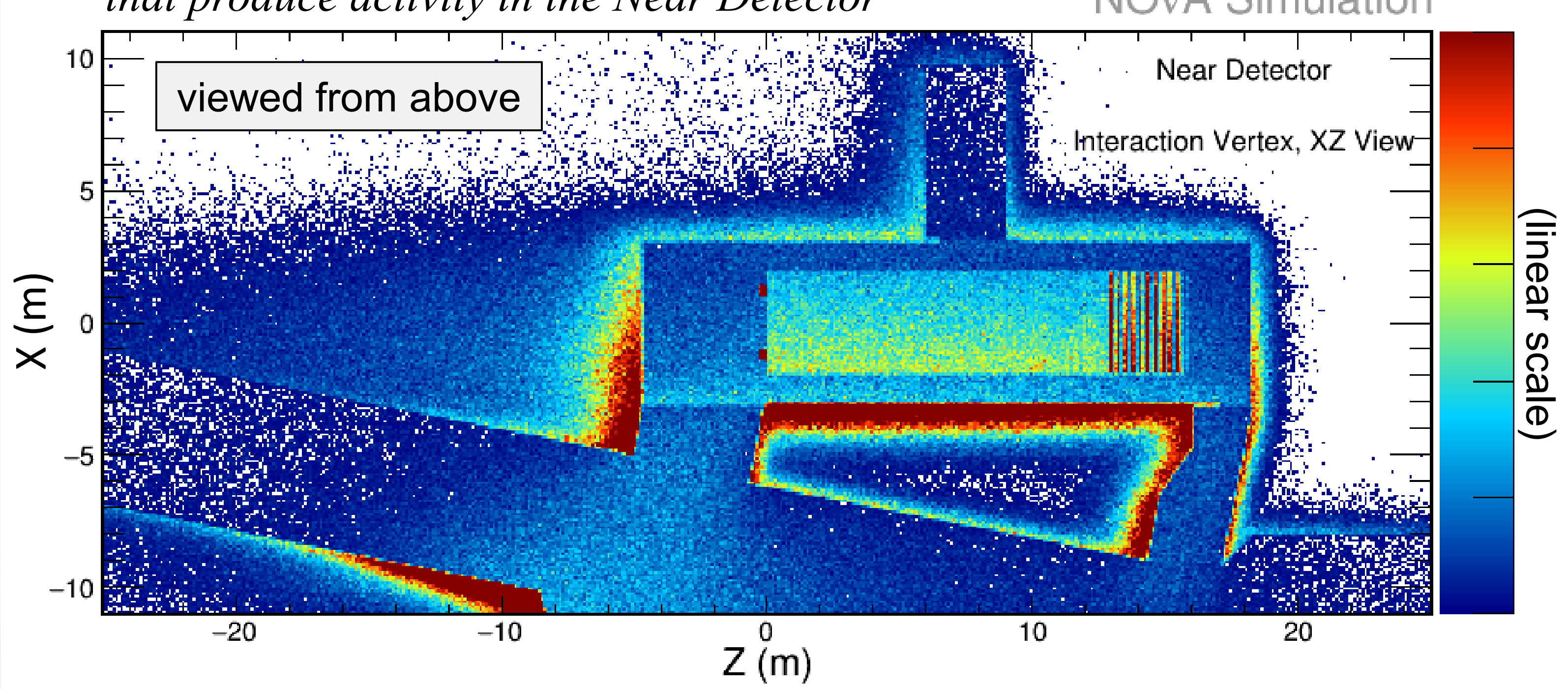
NOvA

Simulation in NOvA

Highly detailed end to end simulation chain

- Beam hadron production, propagation, neutrino flux: **FLUKA/FLUGG**
- Cosmic ray flux: **CRY** (CORSIKA soon)
- Neutrino interactions and FSI modelling: **GENIE**
- Detector simulation: **GEANT4**
- Readout electronics and DAQ: **custom simulation routines**

Simulation: Locations of neutrino interactions that produce activity in the Near Detector



Importance to the analyses

Neutrino cross sections and final state interactions

- Modelling the signal and background components in both detectors and measuring efficiencies and purities
- Estimating the final state hadronic energy scale based on the kinematic distributions of the final state particles
- Accounting for uncertainties in the knowledge of the underlying Physics

NuMI Off-Axis ν_e Appearance

• Flagship analysis of NOvA is electron-neutrino appearance

ν_e appearance:

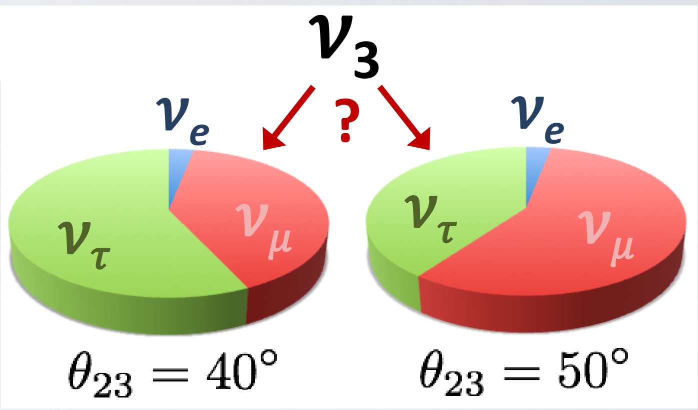
$$P(\nu_\mu \to \nu_e) \simeq \sin^2(\theta_{23}) \sin^2(2\theta_{13}) (\Delta m^2_{32} L/4E) + \ldots$$

Daya Bay reactor experiment:

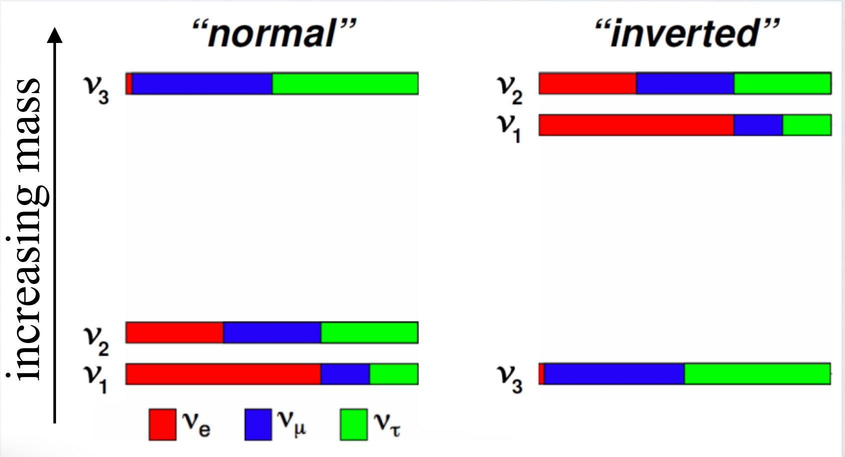
$$\sin^2(2\theta_{13}) = 0.0841 \pm 0.0033$$

CP-violation? and matter effect modifications

θ_{23} octant



Mass hierarchy



Access to CP violation and mass-hierarchy in second order terms of the appearance probability

Benefits from precise knowledge of $\sin^2\theta_{23}$ and Δm^2_{32} (disappearance analysis)

SUMMARY

The NOvA experiment

Muon neutrino disappearance

Electron neutrino appearance

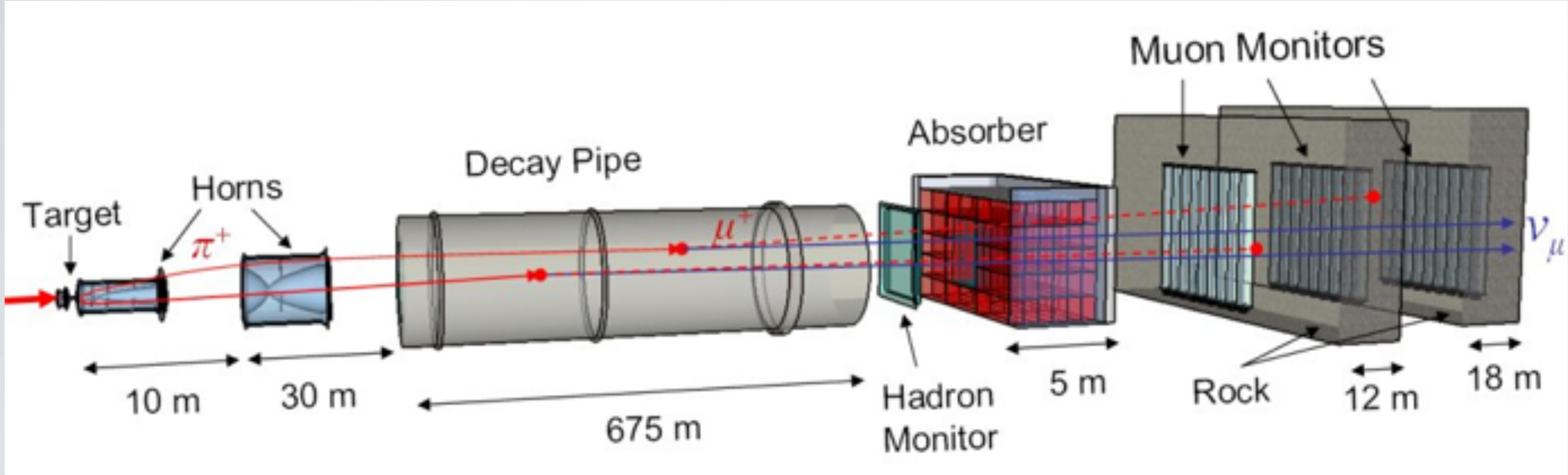
Future challenges

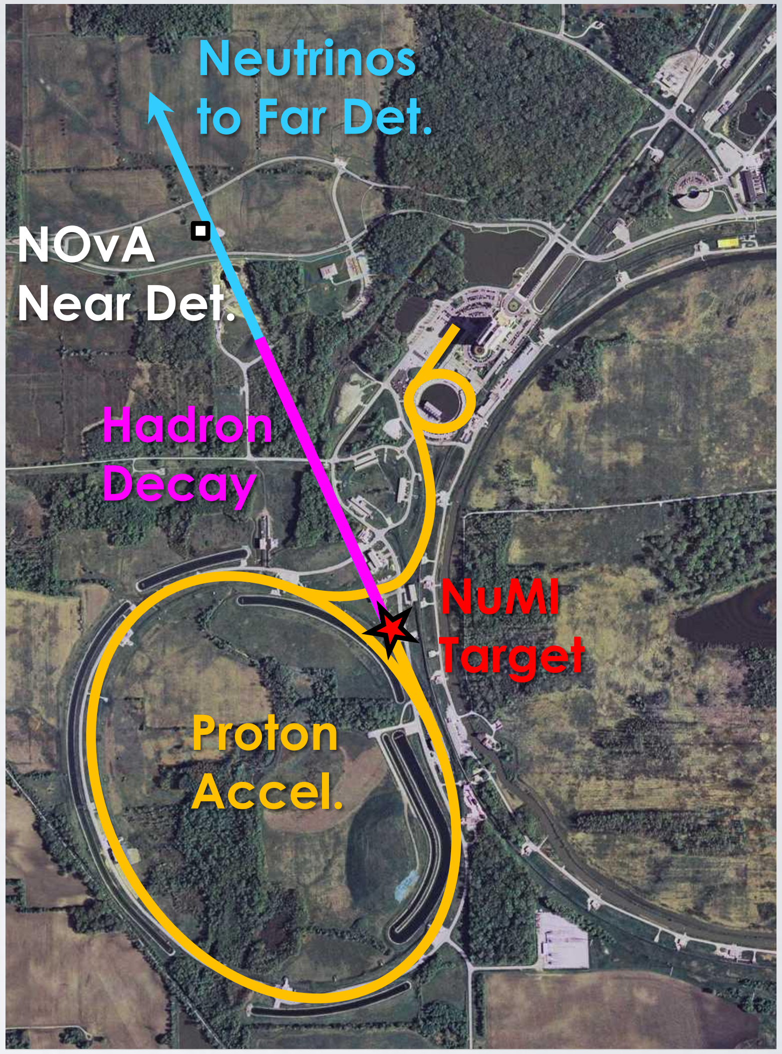
About 230 collaborators from 7 countries (list growing…)

2 UK institutions: Sussex (8 people, since 2012) and UCL (6 people, joined 2015)

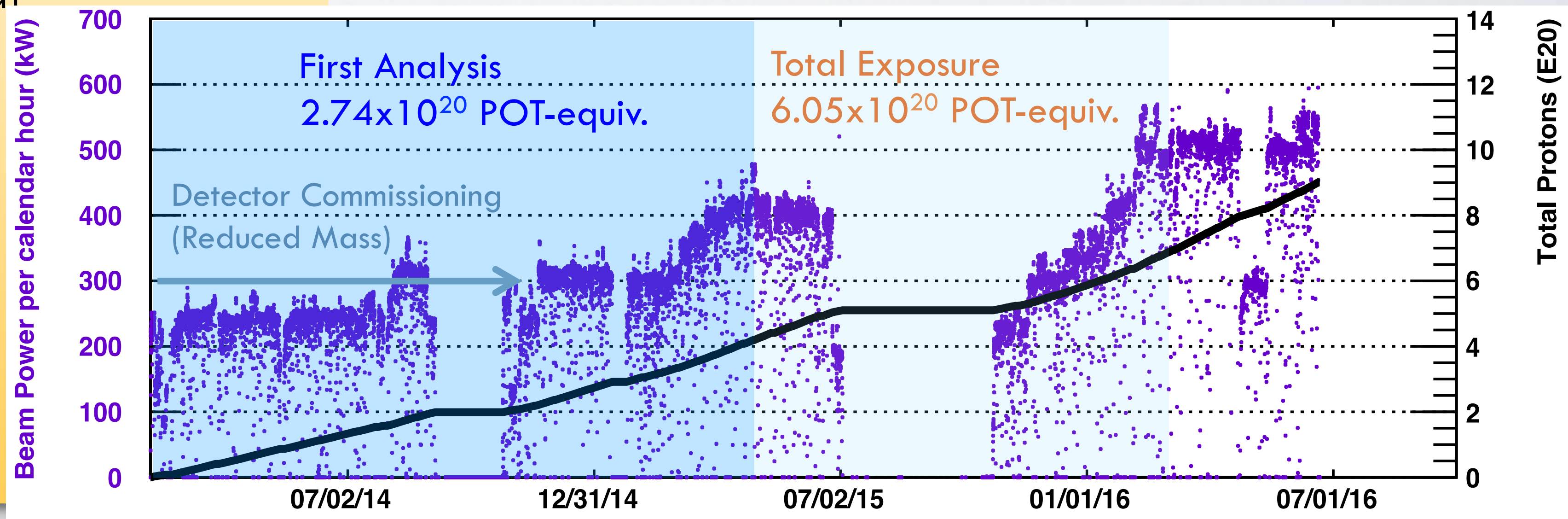
New collaborators and institutions welcome!

NuMI beam

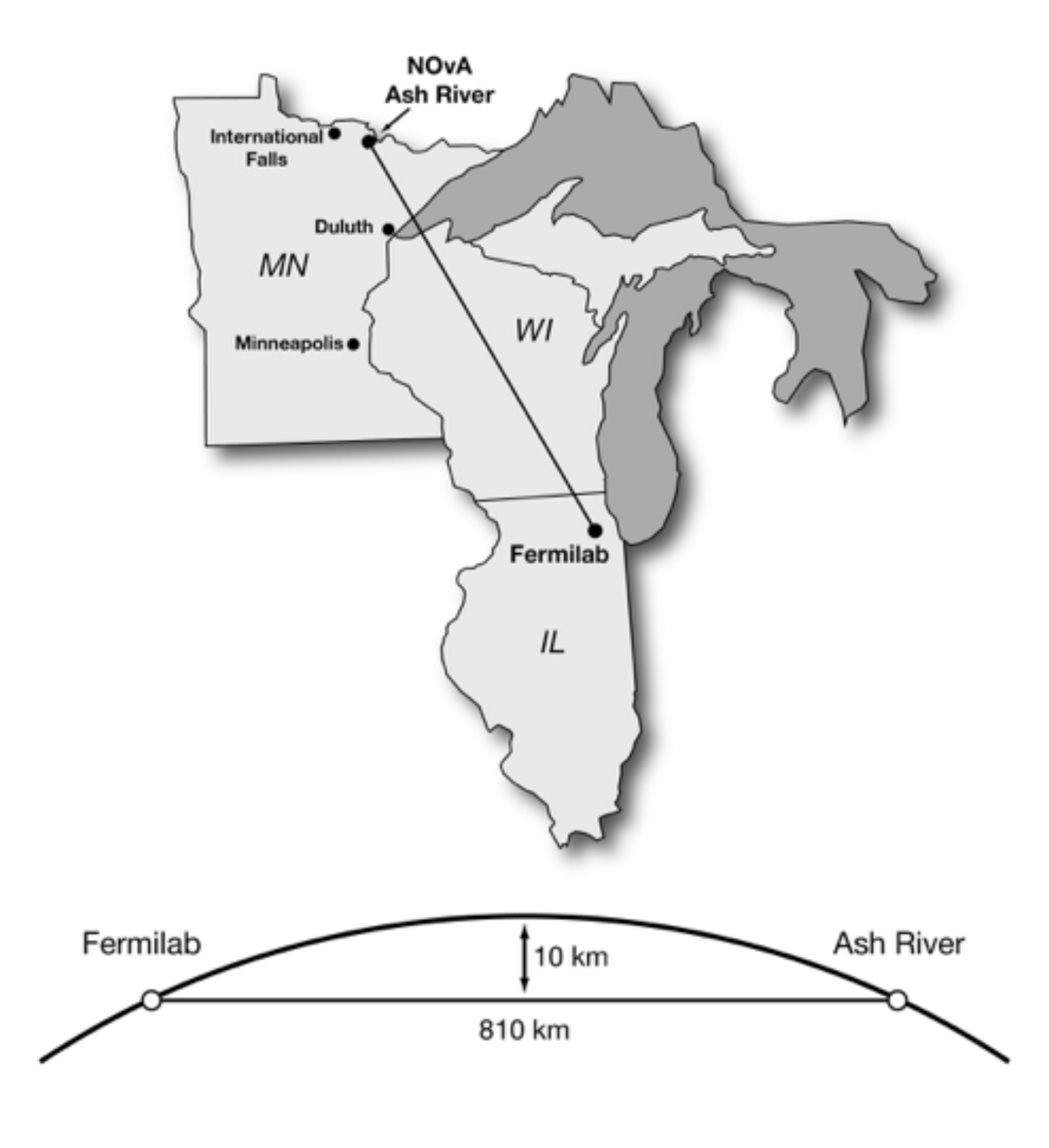




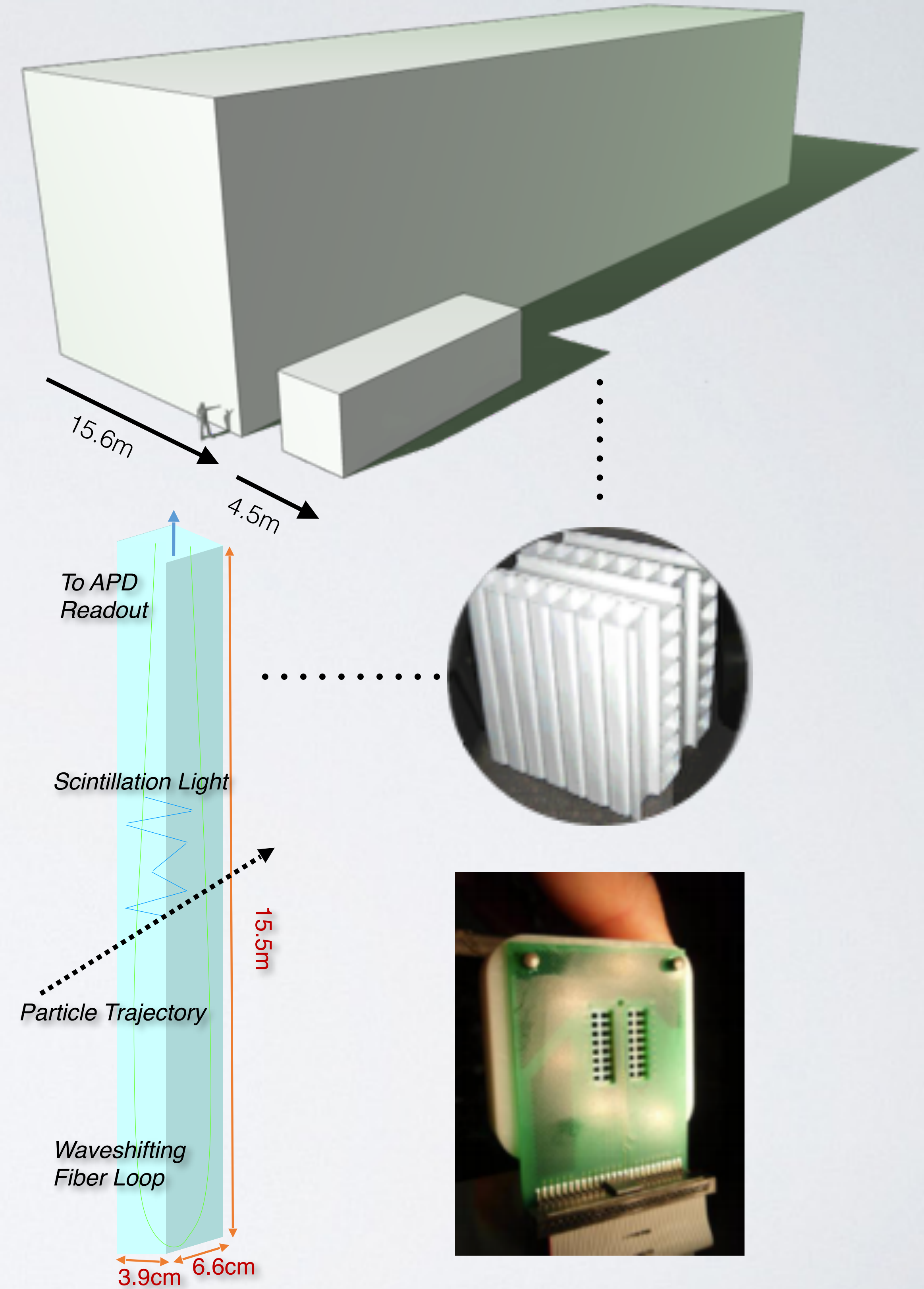
- Capable of running at 700 kW
- Reliably running at ~560 kW
- World record 700 kW for 1 hour
- Full power after 2016 shutdown
- 6.05 x 10^{20} POT 14 kTon-equiv
- Currently taking small RHC data



- NuMI Off-Axis ν_e Appearance
- Two totally active scintillator detectors:
  - Far Detector: 14 kT, on surface
  - Near Detector: 300 T, 105 m underground
- 14 mrad off-axis narrowly peaked muon neutrino flux at 2 GeV, L/E ~ 405 km/GeV
- ν_μ disappearance channel: θ_{23}, Δm^2_{32}
- ν_e appearance channel: mass hierarchy, δ_{CP}, θ_{13}, θ_{23} and octant degeneracy

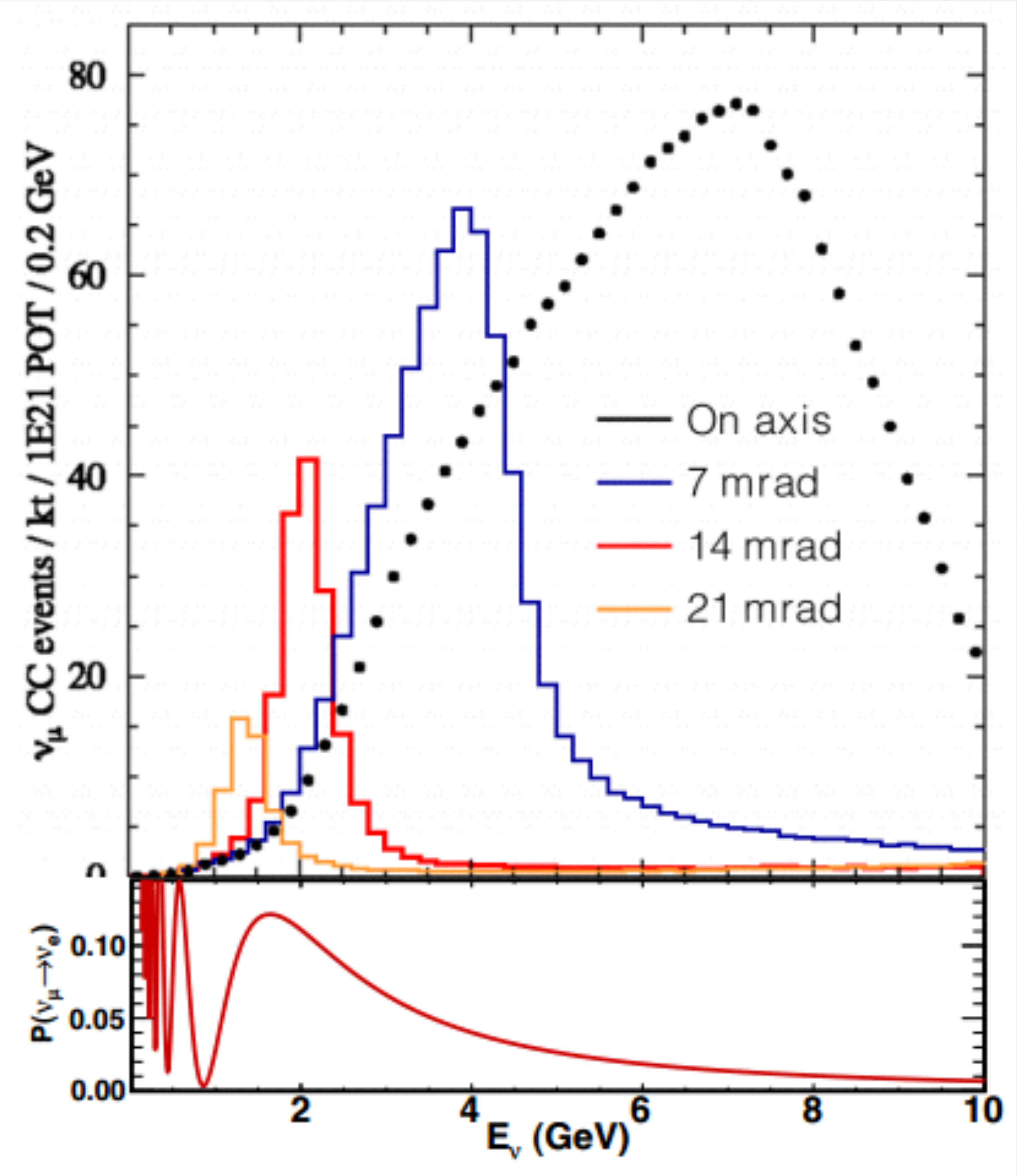


- NuMI Off-Axis ν_e Appearance
- Two highly active scintillator detectors:
  - Far Detector: 14 kT, on surface
  - Near Detector: 300 T, 105 m underground
- 14 mrad off-axis narrowly peaked muon neutrino flux at 2 GeV, L/E ~ 405 km/GeV
- ν_μ disappearance channel: θ_{23}, Δm^2_{32}
- ν_e appearance channel: mass hierarchy, δ_{CP}, θ_{13}, θ_{23} and octant degeneracy



The NOvA experiment

- NuMI Off-Axis ν_e Appearance
- Two highly active scintillator detectors:
  - Far Detector: 14 kT, on surface
  - Near Detector: 300 T, 105 m underground
- 14 mrad off-axis narrowly peaked muon neutrino flux at 2 GeV, L/E ~ 405 km/GeV
- ν_μ disappearance channel: θ_{23}, Δm^2_{32}
- ν_e appearance channel: mass hierarchy, δ_{CP}, θ_{13}, θ_{23} and octant degeneracy



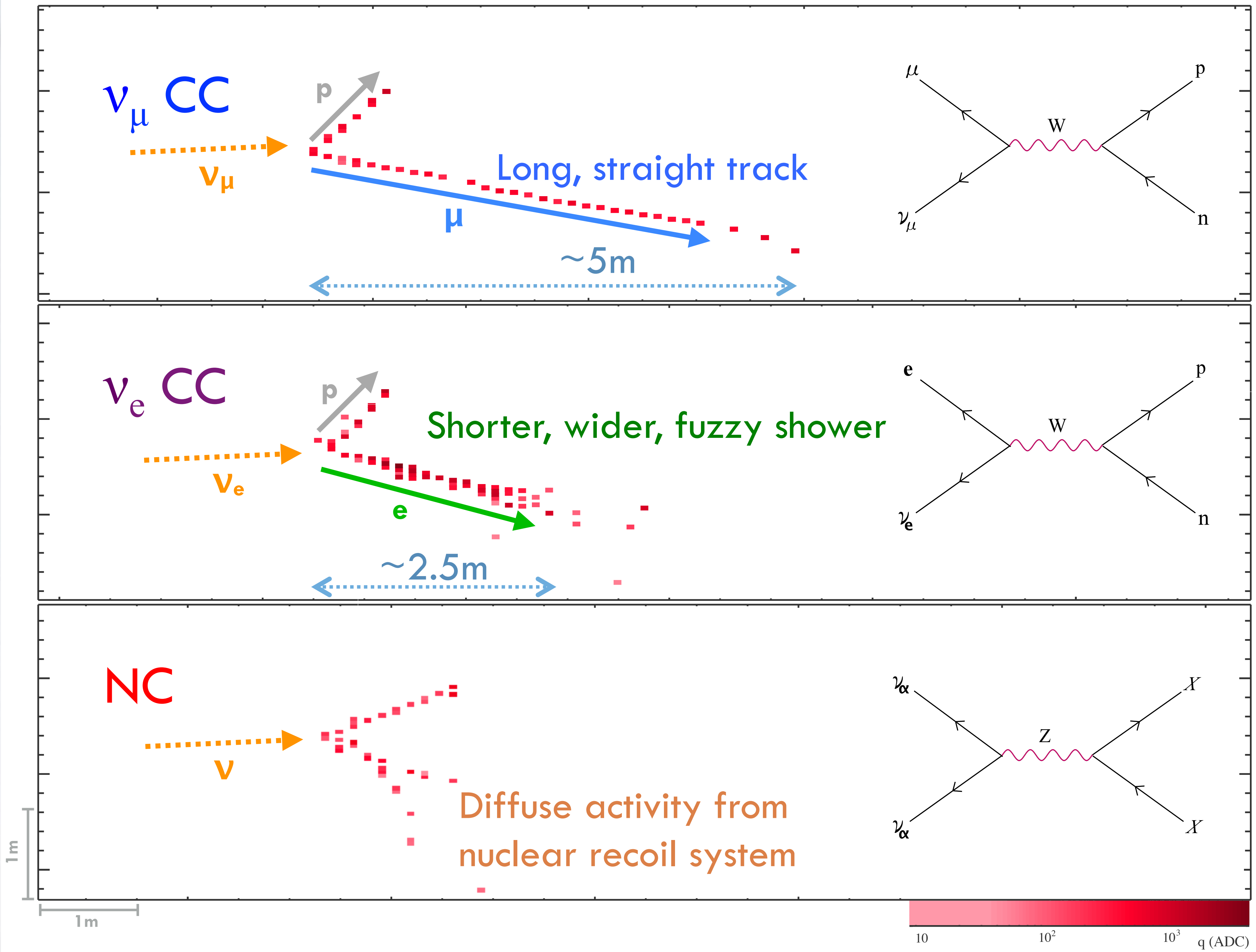
Also: neutrino cross sections at the ND, sterile neutrinos, supernovae…

How to enhance the appearance measurement?

Maximise signal	Reduce background	Detailed reconstruction
• Large and massive detector: 14 kT FD • Limited passive material (highly active)	• Off-axis: smaller NC and ν_μ background • low Z: identify gaps and distinguish electrons from photons	• High granularity: 6.6 x 3.9 cm cells • Efficient signal collection: APDs

These features enable NOvA to precisely measure kinematic and calorimetric quantities on an event-by-event basis

- Superb granularity for a detector this scale
- Outstanding event identification capability



1 radiation length = 38 cm

(6 cell depths, 10 cell widths)

Disappearance analysis in a nutshell…

arXiv 1601.05037

Identify contained ν_μ CC events in both detectors

- Containment
- PID
- NC rejection
- Cosmic rejection

Measure both energy spectra

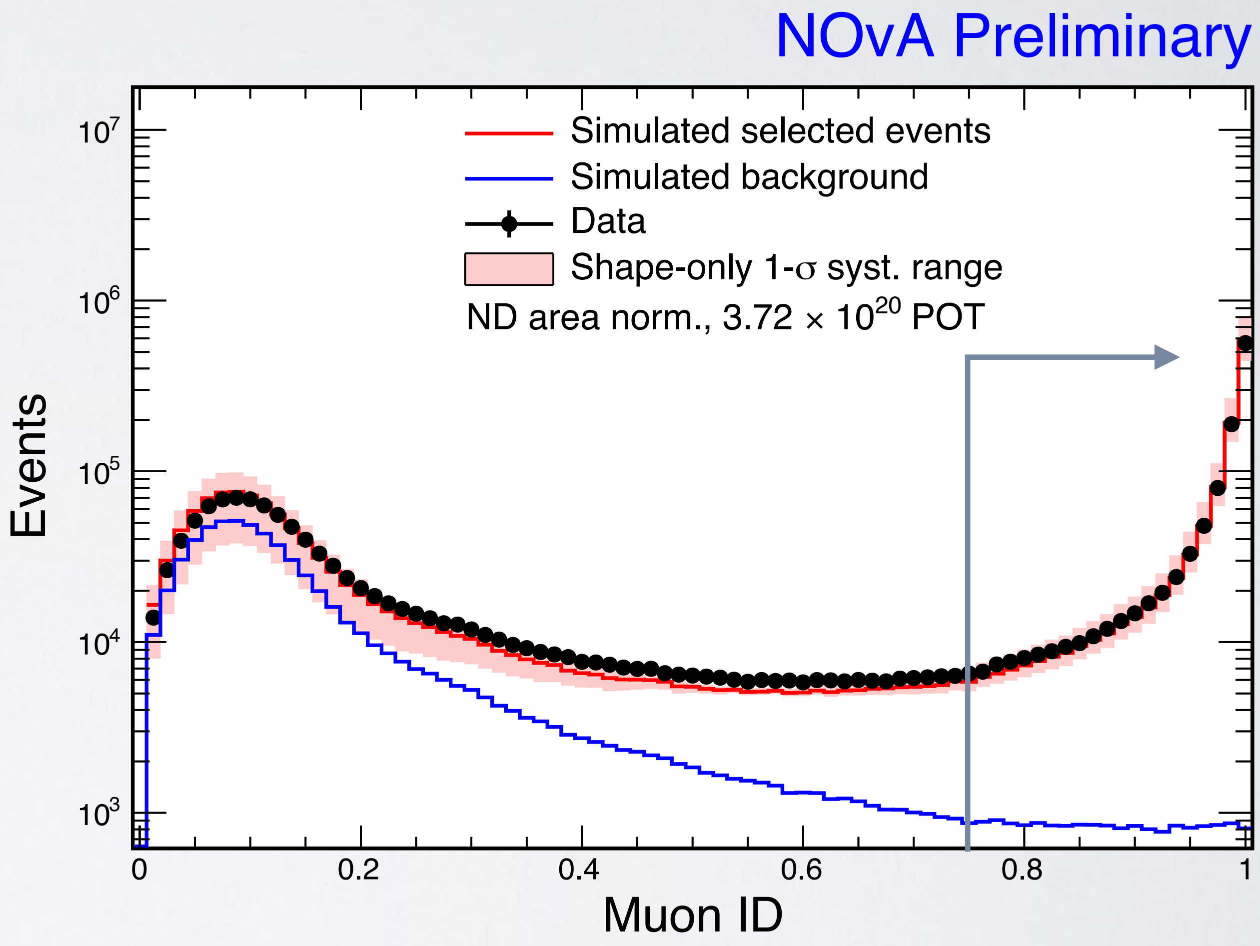
- Calibration
- Energy scale
- Hadronic energy

Infer on the oscillation mechanism from differences between near and far energy spectra

- Extrapolation
- Far / near ratio
- Best fit
- Contours
- Systematics

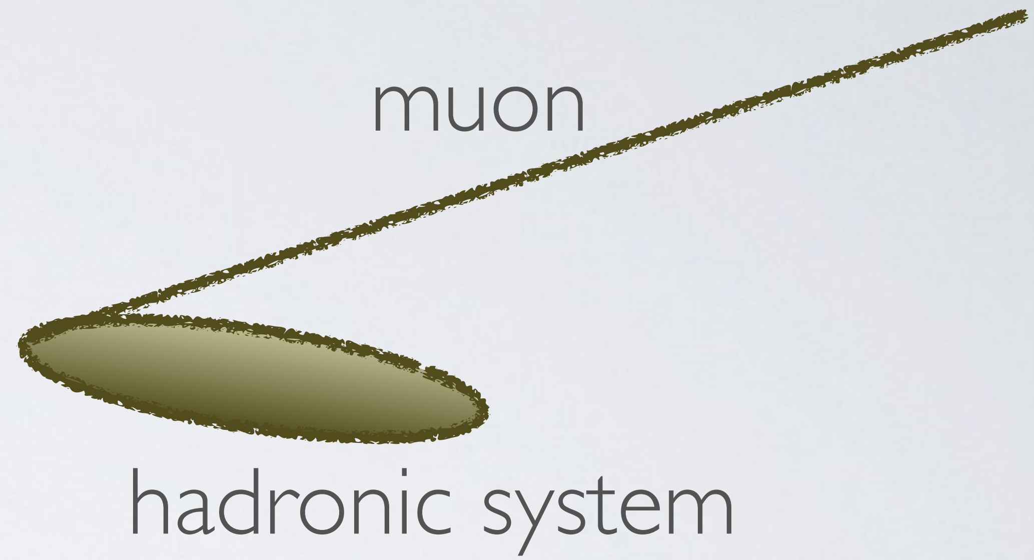
Signal selection: ν_μ CC

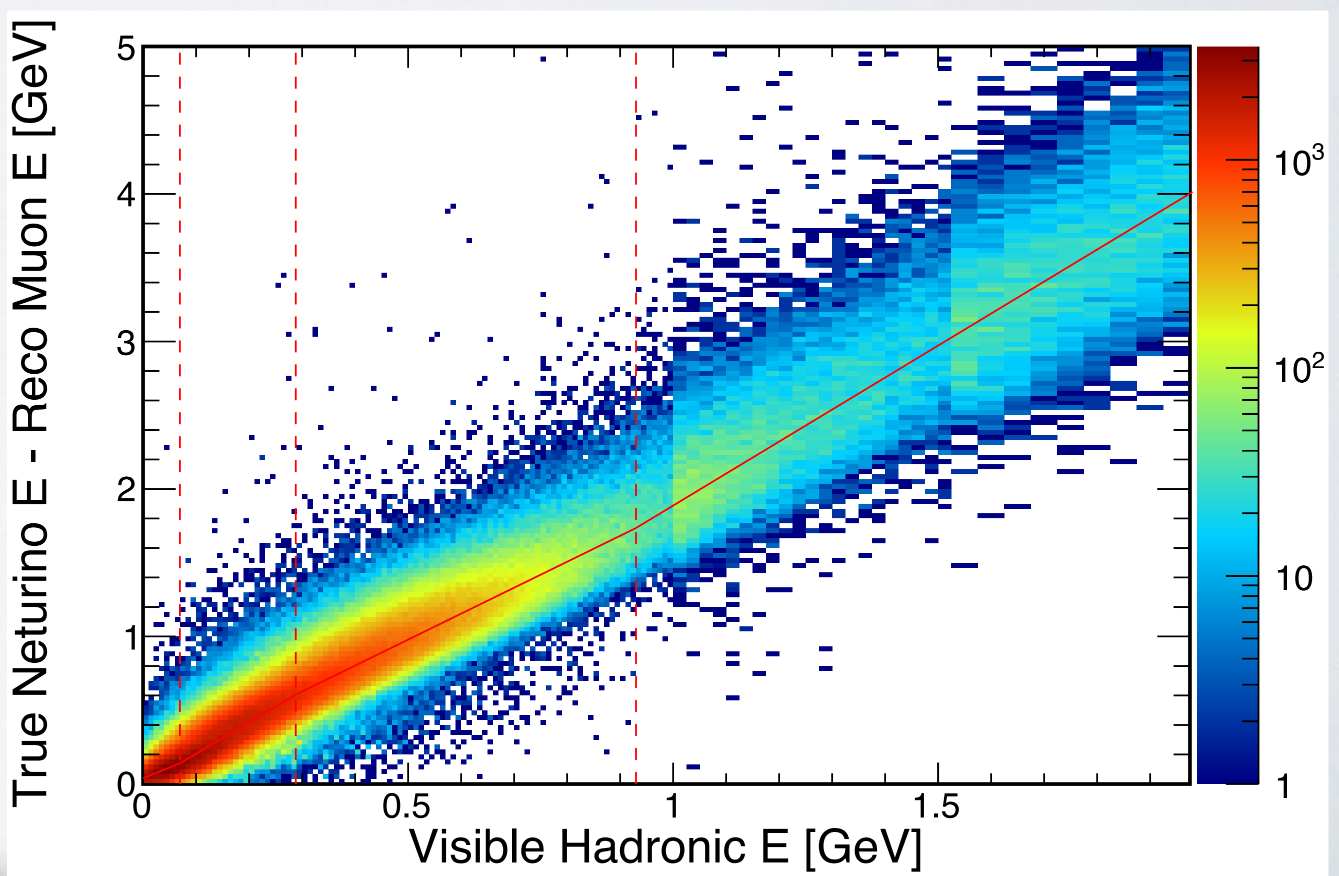
- First: basic containment cuts: require a buffer of no activity around the event
- Muon ID: 4-variable k-nearest neighbours algorithm to identify muons
  - Track length
  - dE/dx along track
  - Scattering along track
  - Track-only plane fraction
- Keep events with muon-ID > 0.75



Energy estimation

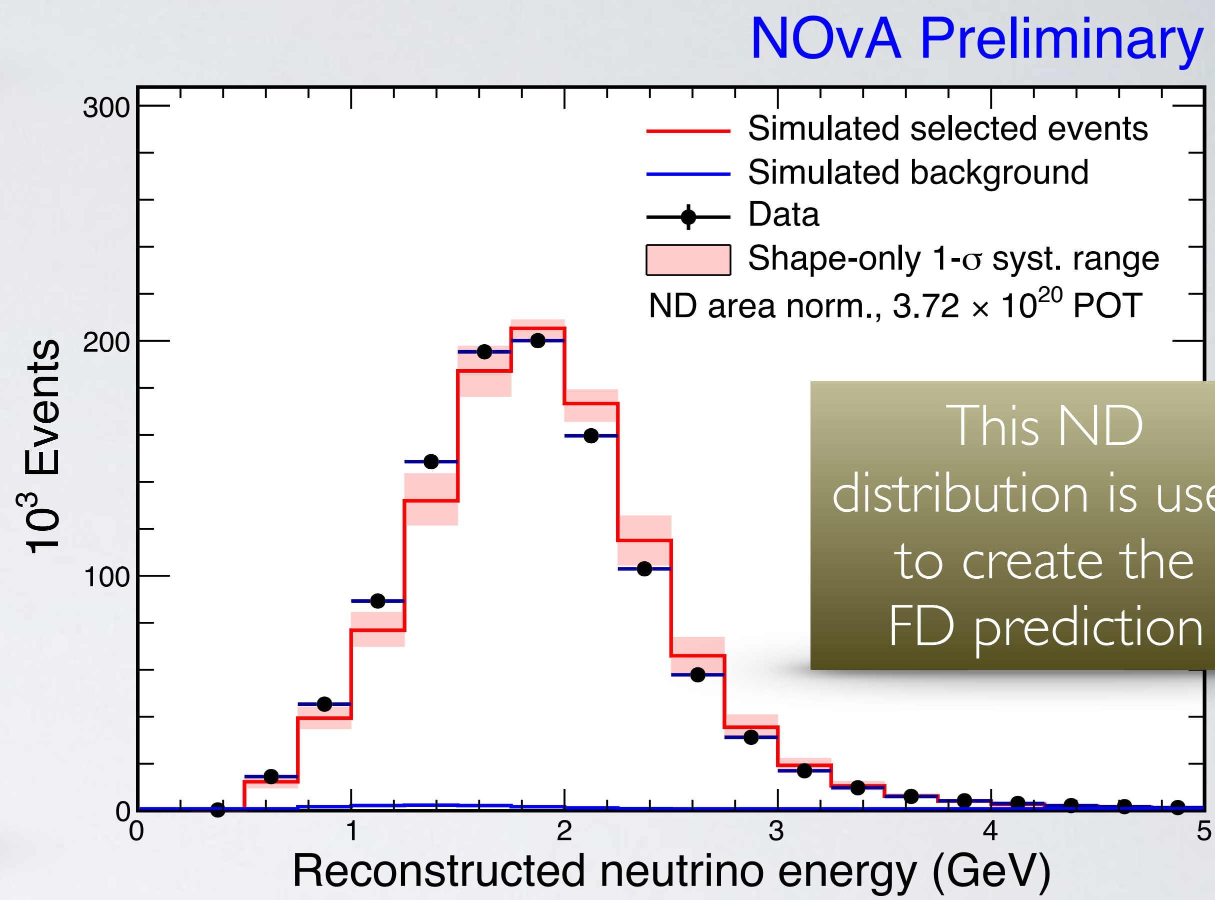
- Muon track: **length ⇒ E_μ** (Res: ~4%)
- Highly active detector: calorimetric measurement of E_{had}
- Hadronic system:
  Σ Total visible E ⇒ E_{had} (Res: ~20%)
- Reconstructed neutrino energy is the sum of them: **$E_\nu = E_\mu + E_{had}$**
- Neutrino energy resolution: 7% (~150 MeV in the neutrino beam peak, ~250 MeV in the tail)
- Narrow energy and identical detectors reduces impact of cross sections & FSI



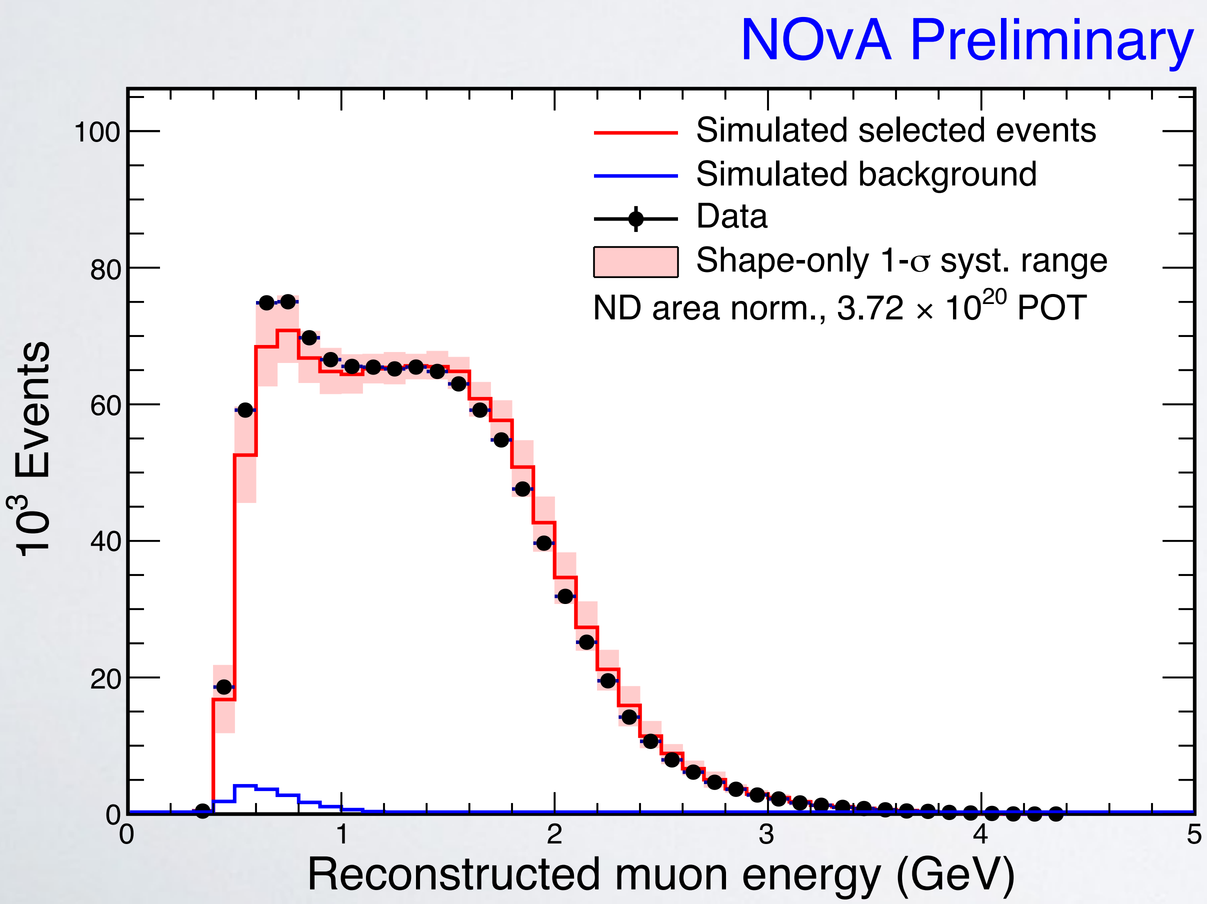


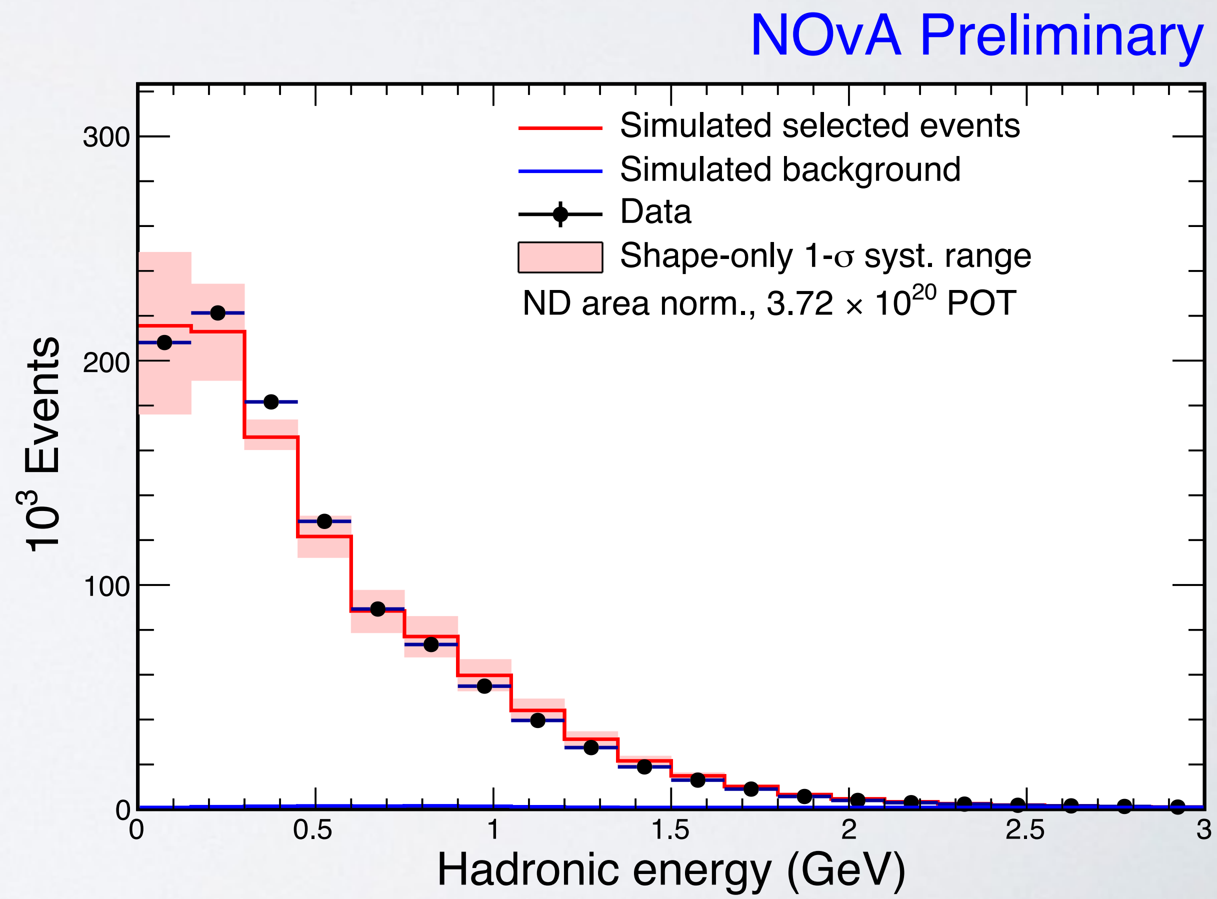
ND distributions

- Addition of 2p2h (MEC) events substantially improves data/MC hadronic energy agreement (see Jeremy's talk on Tuesday)



This ND distribution is used to create the FD prediction



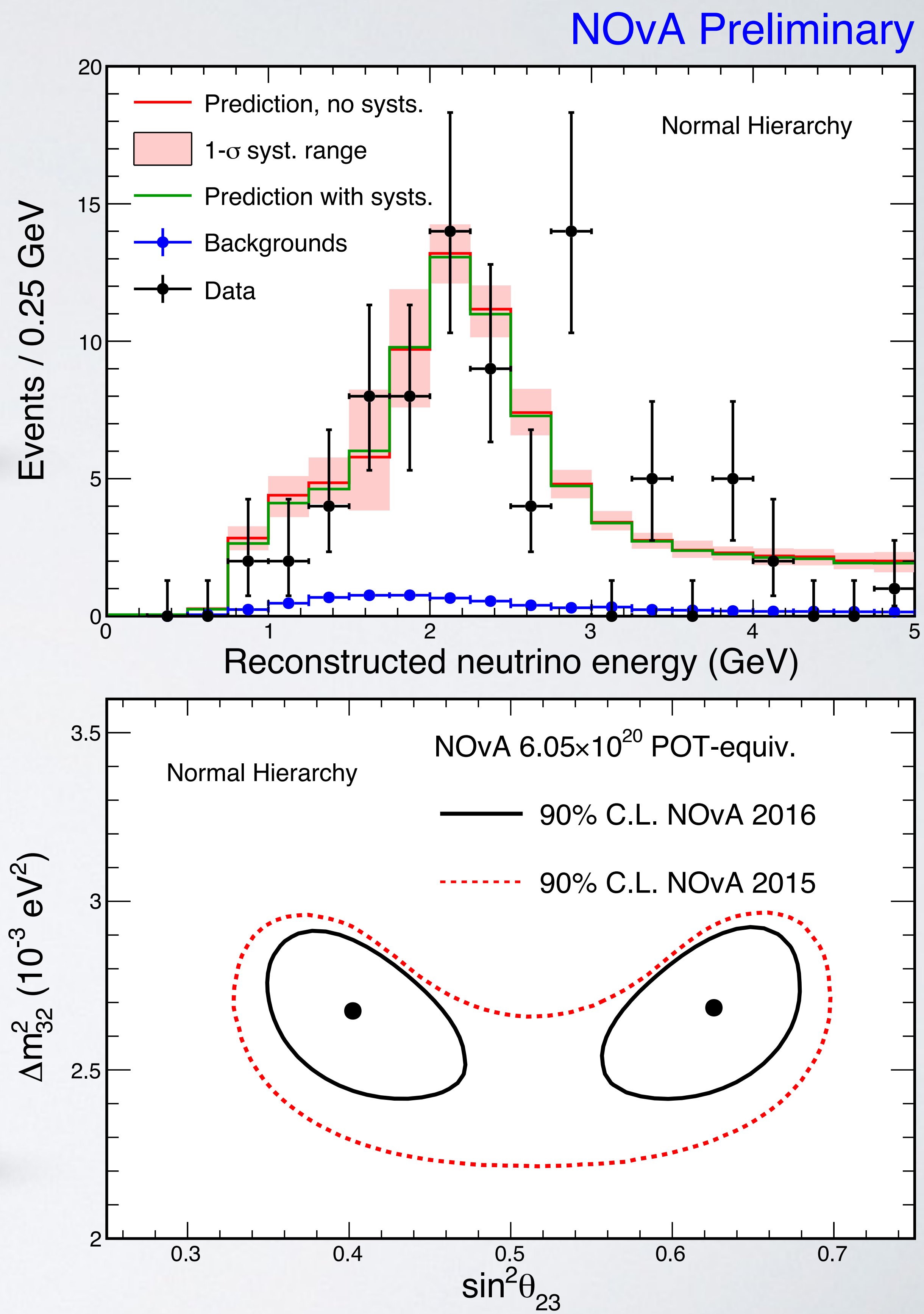


- 78 events in the FD for 473 w/o osc.
- 82 (3.7 beam bkg, 2.9 cosmic) at best fit
- X^2/NDF = 41.6/17 driven by tail
- Systematics included in the fit have negligible pull terms (< 0.5)

$|\Delta m^2_{32}| = 2.67 \pm 0.12 \times 10^{-3}\ eV^2$

$\sin^2\theta_{23} = 0.40\ (0.63) \pm 0.03$

Maximal mixing disfavoured at 2.5σ



Appearance analysis in a nutshell…

arXiv 1601.05022

Identify contained ν_e CC events in both detectors

- Containment
- PID
- NC rejection
- Cosmic rejection

Use ND candidates to predict beam backgrounds in the FD

- Extrapolation
- Far / near ratio
- Systematics

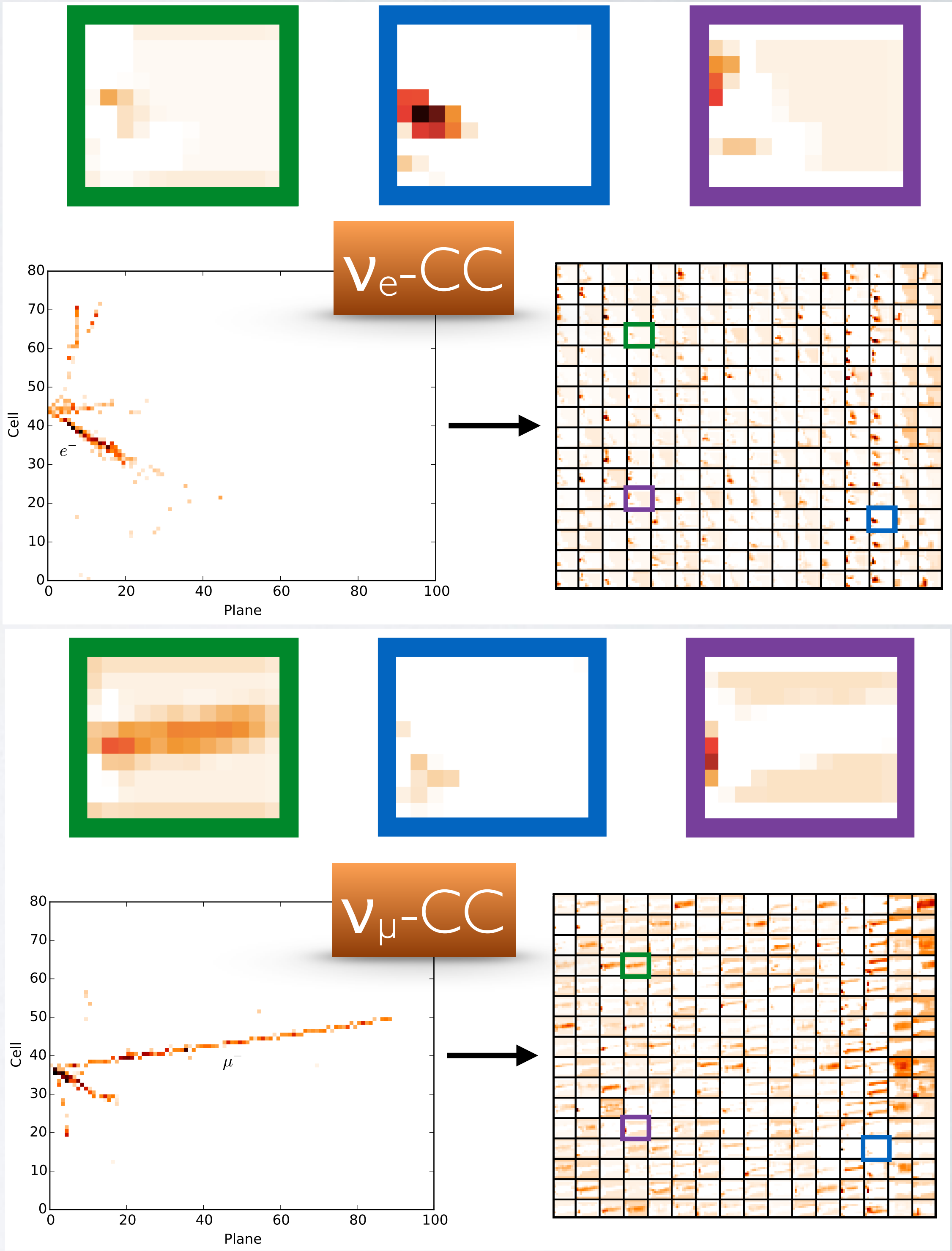
Interpret any FD excess over predicted backgrounds as ν_e appearance

- Exclusions
- Significance

Event selection

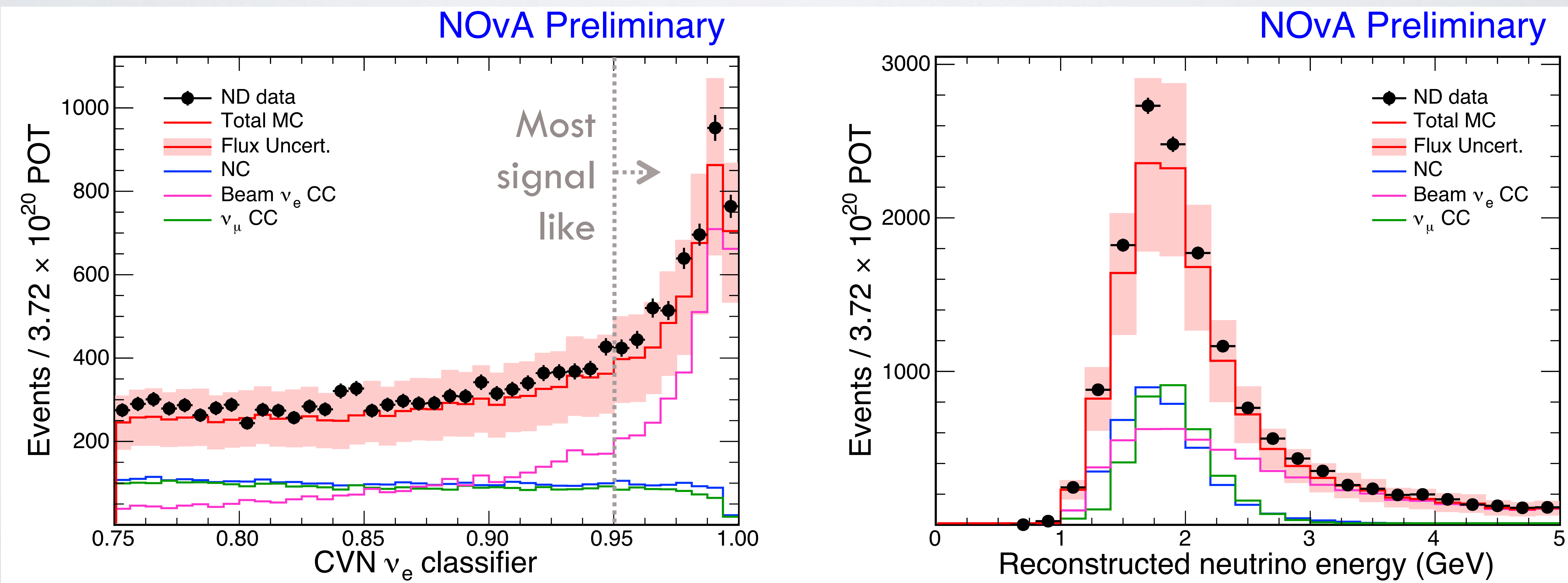
arXiv 1604.01444

- Event selection based on ideas from computer vision and deep learning
- Calibrated hit maps are inputs to Convolutional Visual Network (CVN)
- Series of image processing transformations applied to extract abstract features
- Extracted features used as inputs to a conventional neural network to classify the event
- **Improvement in sensitivity from CVN equivalent to 30% more exposure**

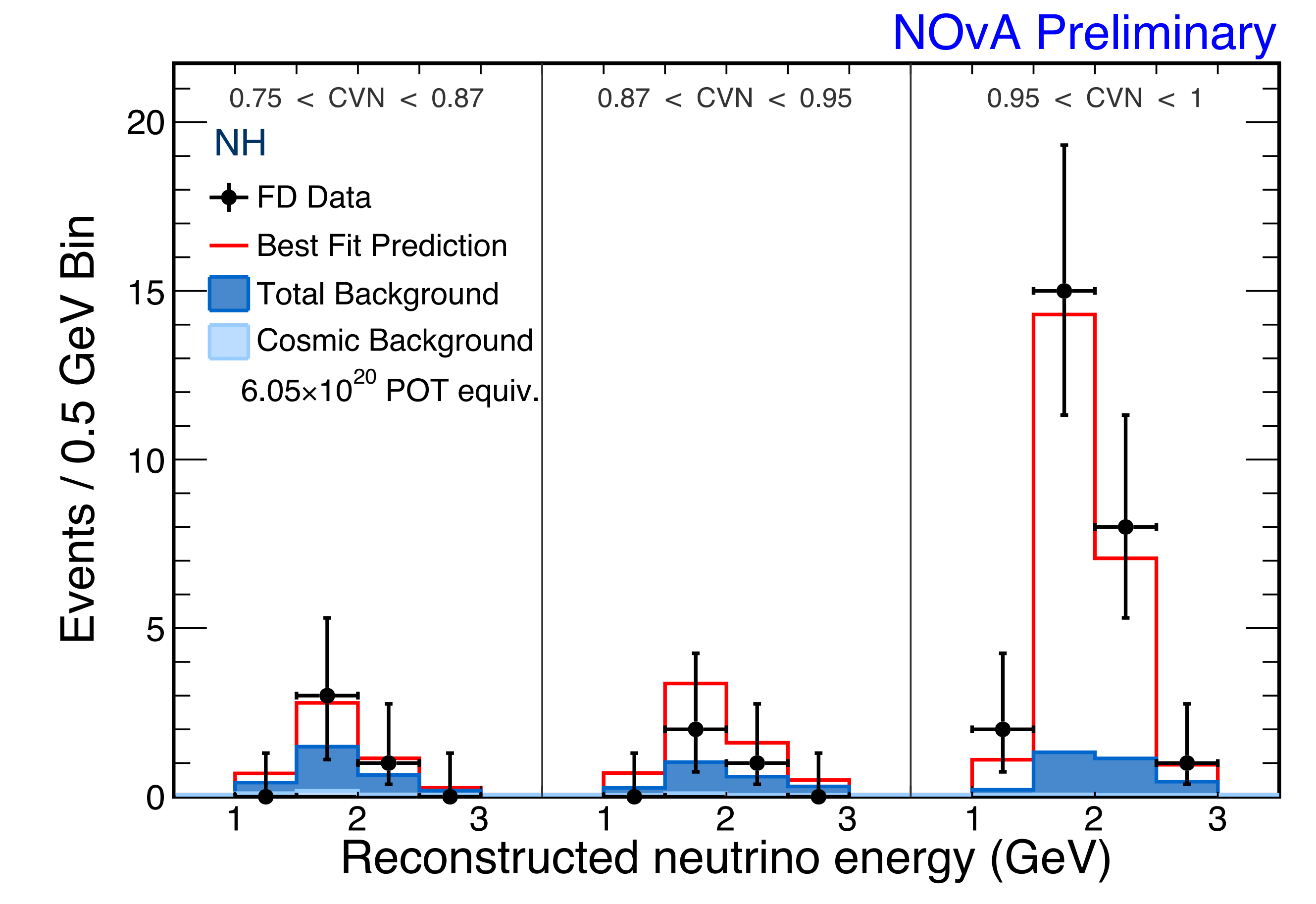


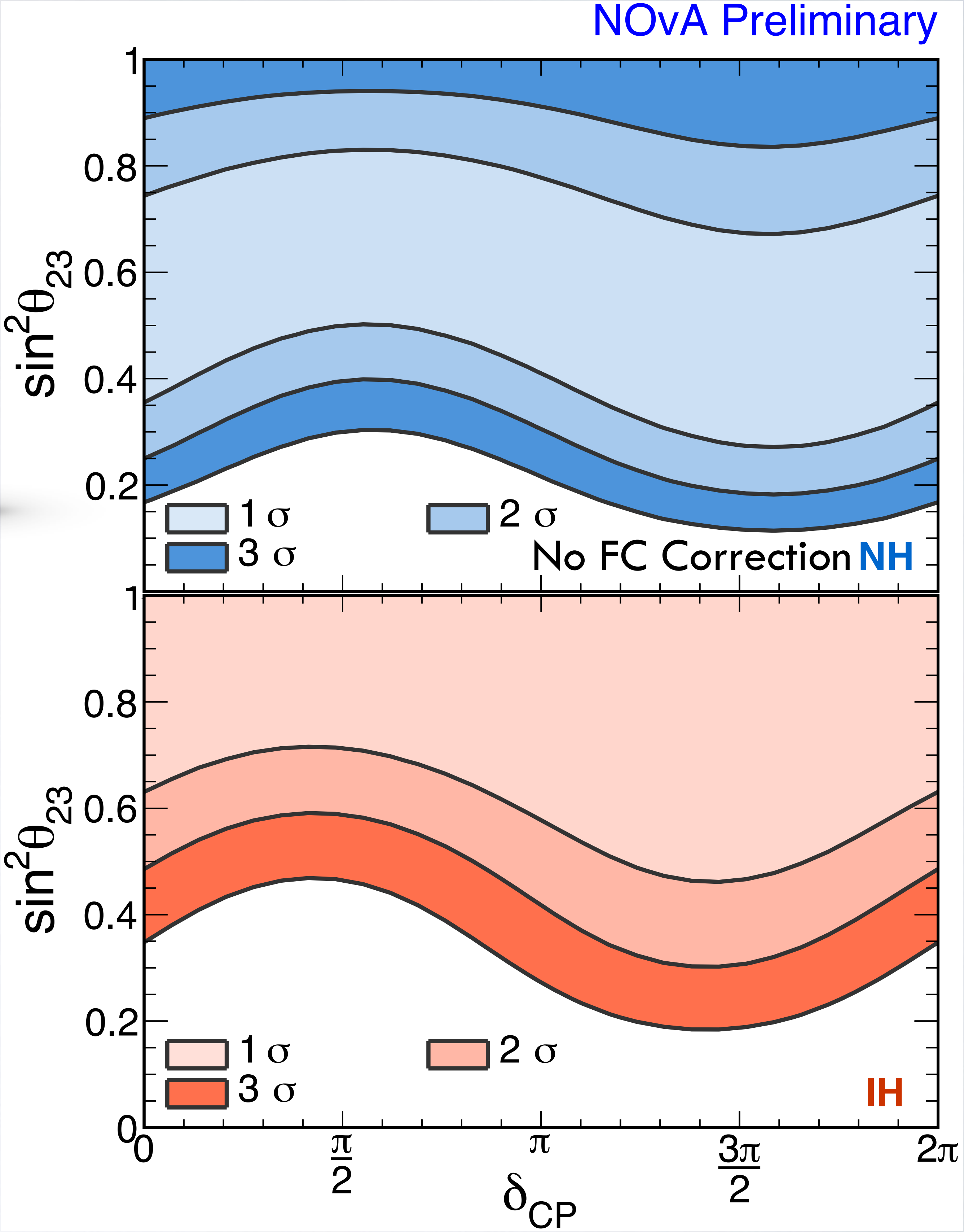
Electron neutrino appearance

- Selection optimised for parameter measurement (increased signal efficiency by including lower purity bins)
- Constrained beam backgrounds with dedicated decompositions: beam ν_e from ν_μCC and these from the distribution of Michel electrons

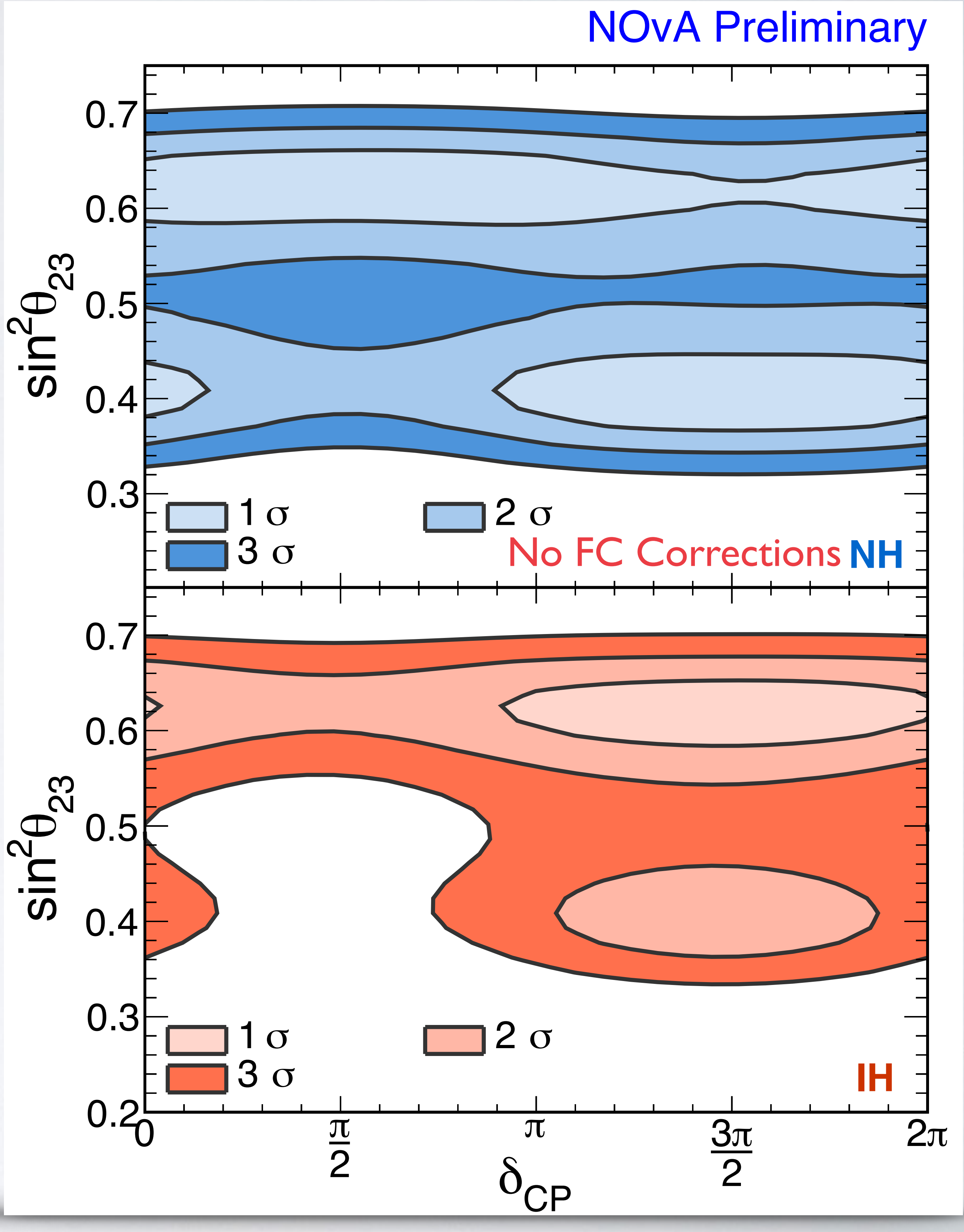


- 33 events in the FD
- 8.2 (3.7 NC, 3.1 beam ν_e) background
- ± 5% uncertainty (signal), ±10% bkg
- > 8σ ν_e appearance



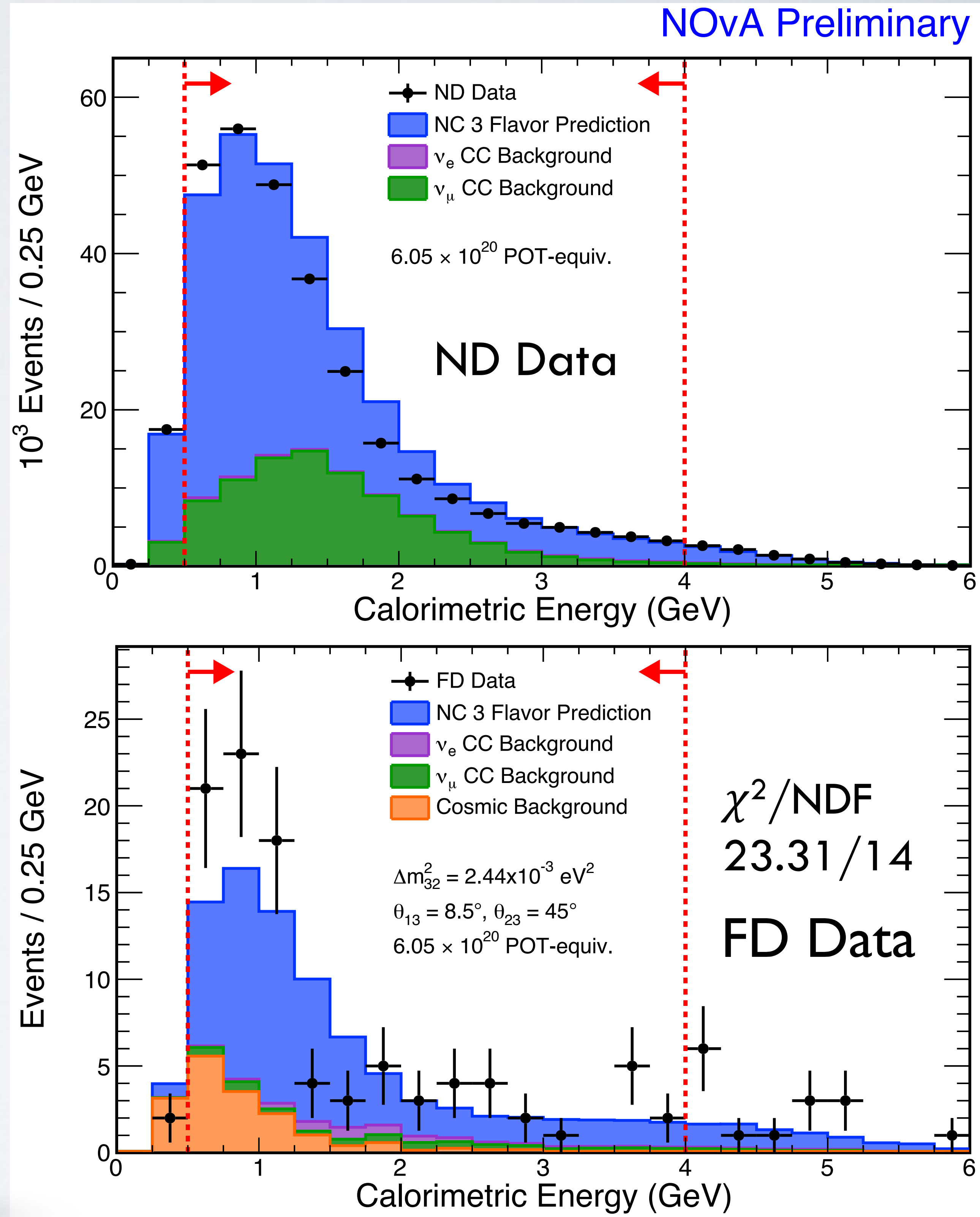


- Include disappearance constraints
- Not a joint analysis yet! Systematics and rest of the oscillation parameters not correlated
- Best fit to NH, δ_{CP} = 1.49π and $\sin^2(\theta_{23})$ = 0.40
- But best fit IH-NH has ΔX^2 = 0.47
- Both octants and hierarchies allowed at 1σ
- 3σ exclusion of IH, lower octant around δ_{CP} = π/2
- Antineutrino data planned for Spring 2017 will help resolve degeneracies



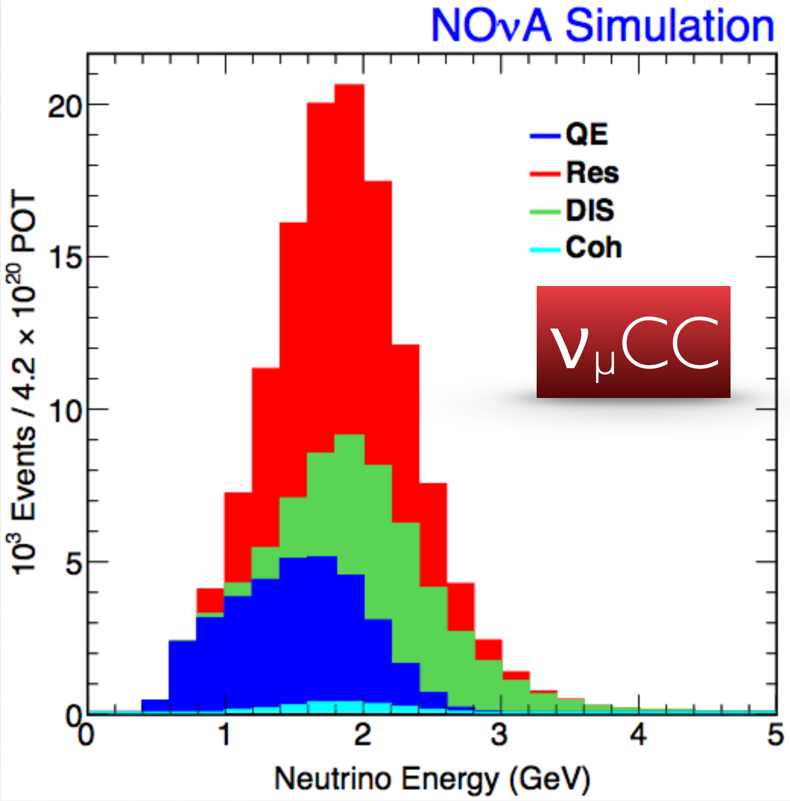
NC disappearance

- Data shifted to lower energy wrt MC
  - No MEC model for NC events
  - Large uncertainties on NC cross section
- 95 events observed for 83.7 ± 8.3 expected
- No evidence of oscillations involving sterile neutrinos
- Excellent NC efficiency and purity show promising future sensitivities



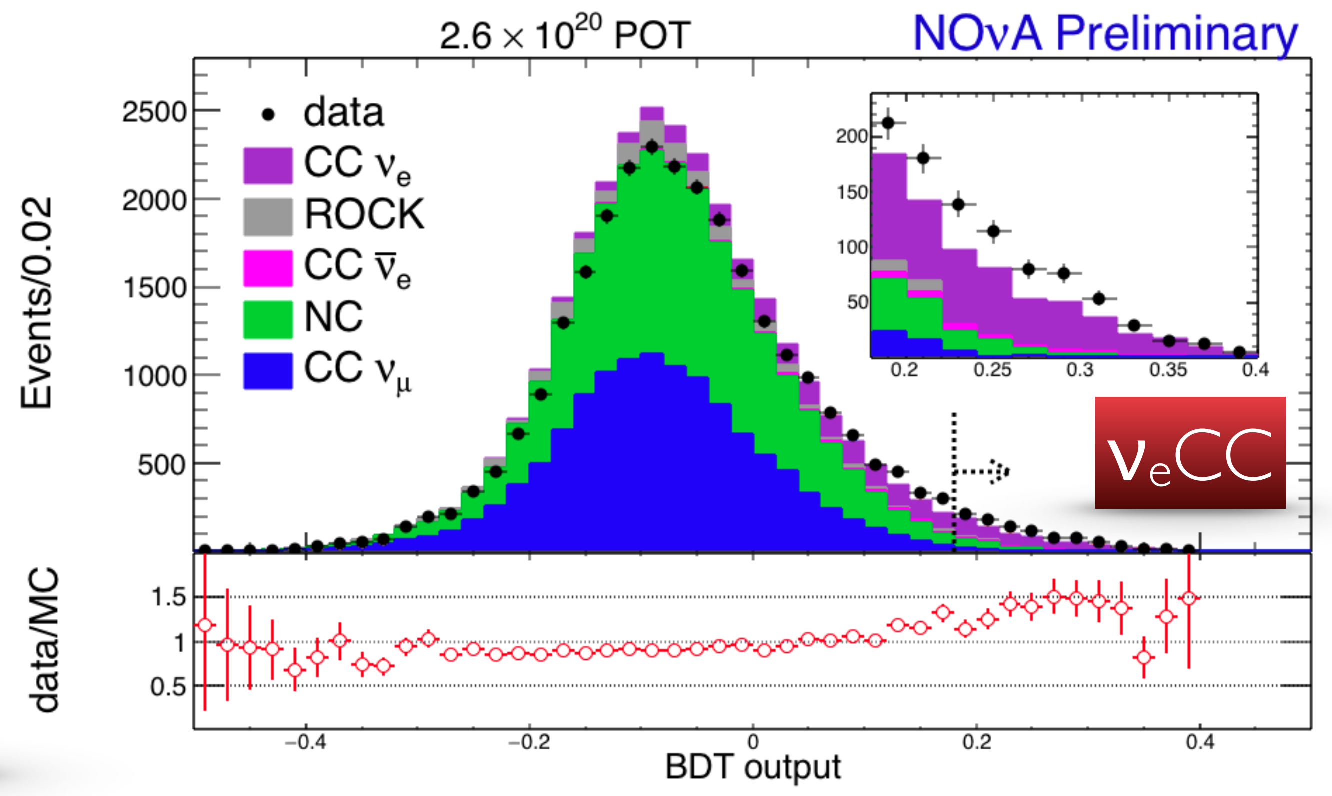
ND measurements

- Uniquely sensitive to QE, RES and DIS (almost equally across the three)
- Absolute cross section or yield measurements will be limited to ~10% due to flux uncertainties
- Ability to measure a huge number of FSI channels



- ν_μCC inclusive and channels (0-π, 2p2h, Coh, π^0, …)
- ν_eCC inclusive and channels (0-π, π^0, …)
- NC inclusive and channels (π^0, 2p2h, …)
- ν_μ on ν_e scattering (flux constraint)

And all of the above with antineutrinos



Cross section and FSI systematics in NOvA

- A whole new simulation is performed by varying each of these "knobs" in GENIE
- We played with all and found the ones that mattered for the oscillation analyses
- Question to you: Are these the right ones? Should we update? Please be in touch

- Adjust CC QE normalisation by +20% / -15% maintaining shape
- Adjust MA in Llewellyn-Smith cross section by ±10%, affecting shape only
- Adjust MA in Rein-Sehgal Coherent model by ±40%
- Adjust axial mass parameter in Rein-Sehgal resonance cross section model by ±20%
- Adjust vector mass parameter in Rein-Sehgal resonance cross section by ±10%
- Adjust Pauli blocking momentum cutofff by ±30%
- Adjust rate of pion production in CC and NC for non-resonant inelastic events by ±50% (4 knobs affecting single and double pion production, turned together)
- MEC model normalisation uncertainty of ±50%

- NOvA is in its precision era, especially in terms of ND data. We will soon need better models (statistical uncertainties rapidly becoming small)
- The current strategy to account for cross-section and FSI systematics is very computing-exhaustive. We would appreciate any input regarding this
- Ongoing analyses in the ND: ν_μCC inclusive, ν_μ on ν_e scattering, ν_τ/ν_e short-baseline appearance…
- MEC tuning works well for CC, but we don't have any model for NC
- Are there any measurements coming from us that could help you?

Please do contact Jeremy Wolcott and/or myself for any of these

Conclusions

- Indubitable observation of neutrino disappearance (78 obs, 473 exp.)
- Best fit is non-maximal. Maximal mixing disfavoured at 2.5σ
- Electron neutrino appearance observed with over 8σ
- Small preference for normal hierarchy. Region in inverted hierarchy, lower octant and around $\delta_{CP} = \pi/2$ excluded at 3σ
- Neutral current event rate shows no evidence of sterile neutrinos
- Many exciting cross-section analyses coming soon
- Looking forward to more neutrinos and antineutrinos!

THANK YOU!

www-nova.fnal.gov