# SUMMARY OF THE ANALYSIS AND SYSTEMATICS SESSION

D. Harris, M. Hartz, K. Terao, R. Wendell

NNN 2018, Vancouver, Nov. 3

# WHY A SYSTEMATIC UNCERTAINTIES AND ANALYSIS SESSION?

- Current and next generation neutrino and nucleon decay experiments present challenges for analysis of data
- Increased statistics are moving experiments into systematics dominated regimes
  - Need systematic error reduction
- New detection technologies can increase the information in events
  - Can we take full advantage of information for event reconstruction and event classification in an unbiased manner?

# AGENDA

## Thursday:

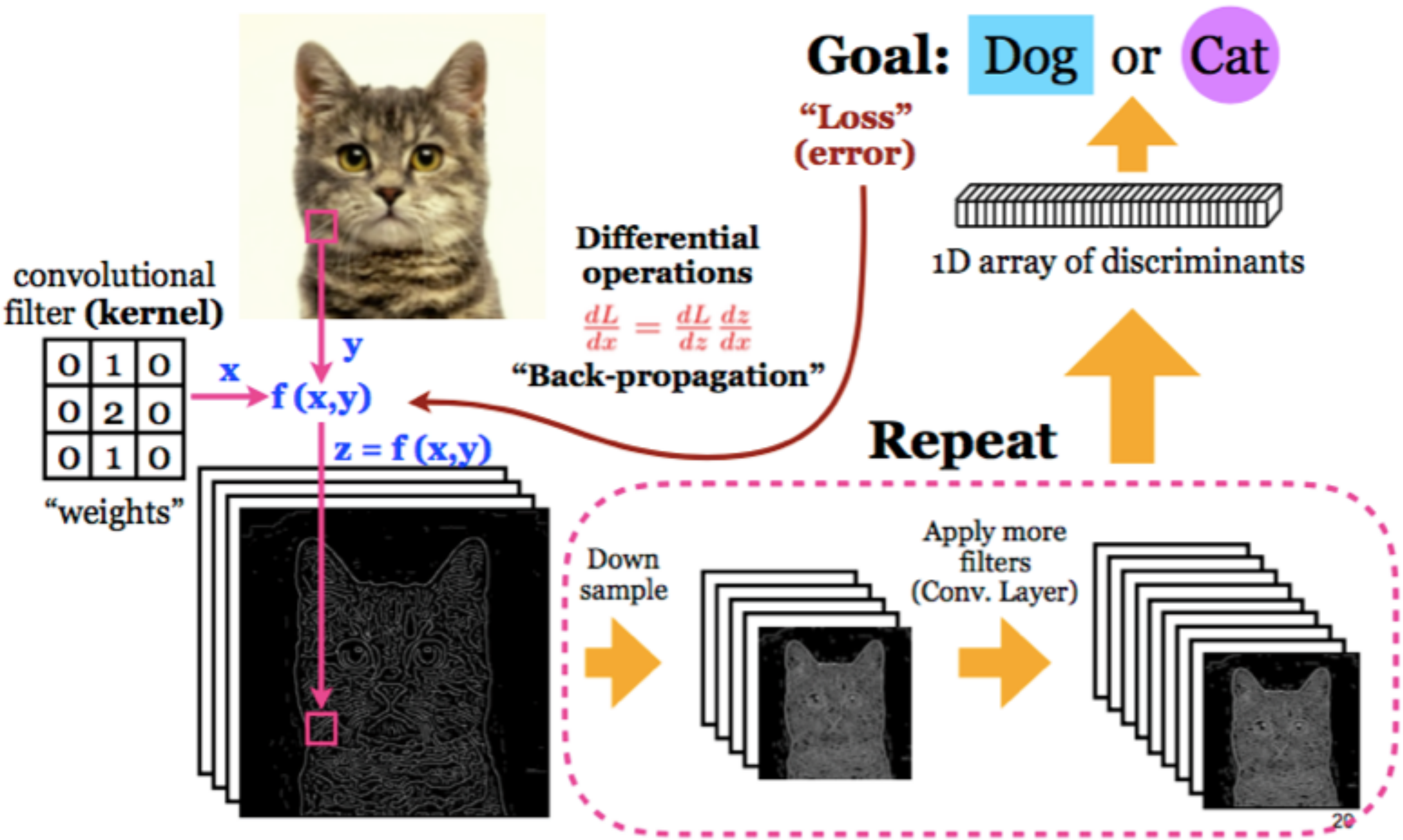
| | | |
|---|---|---|
| 14:00 | Deep Learning Techniques Overview | KAZUHIRO, Terao |
| 14:30 | Machine Learning Techniques on NOvA | GROH, Micah |
| 14:50 | Machine Learning at MINERvA | GHOSH, Anushree |
| 15:10 | Machine Learning in MicroBooNE | WONGJIRAD, Taritree |
| 15:30 | Coffee Break | |
| 15:55 | Systematics, calibration and analysis techniques in JUNO | TANG, Jian |
| 16:20 | Systematic errors in Borexino Solar and Geoneutrino Analyses | LUDHOVA, Livia Ludhova |
| 16:45 | Systematic Uncertainties for Atmospheric Neutrino Measurements | YAÑEZ, Juan Pablo |
| 17:10 | Test Beam Experiments for the Future Generation of LBL Experiments | BORDONI, Stefania |

## Friday:

| | | |
|---|---|---|
| 14:00 | Neutrino Interaction Uncertainties in Long Baseline Oscillation Experiments | MARSHALL, Chris |
| 14:30 | DUNE Analysis Methods and Systematic Uncertainties | BACKHOUSE, Christopher |
| 14:55 | Systematics in Hyper-Kamiokande experiment | YOSHIDA, Tomoyo |
| 15:20 | Analysis and Systematic Uncertainty Experience from MicroBooNE | PORZIO, Salvatore Davide |
| 15:45 | Coffee Break | |
| 16:10 | Uncertainties from Neutrino Interactions at T2K | MCFARLAND, Kevin |
| 16:35 | Details of Systematic Uncertainties at NOvA | SUTER, Louise |
| 17:00 | Interaction Modeling Uncertainties at MINERvA | MCFARLAND, Kevin |

# DEEP NEURAL NETWORKS (K. TERAO)

- How to identify a cat with a convolutional neural net (CNN)

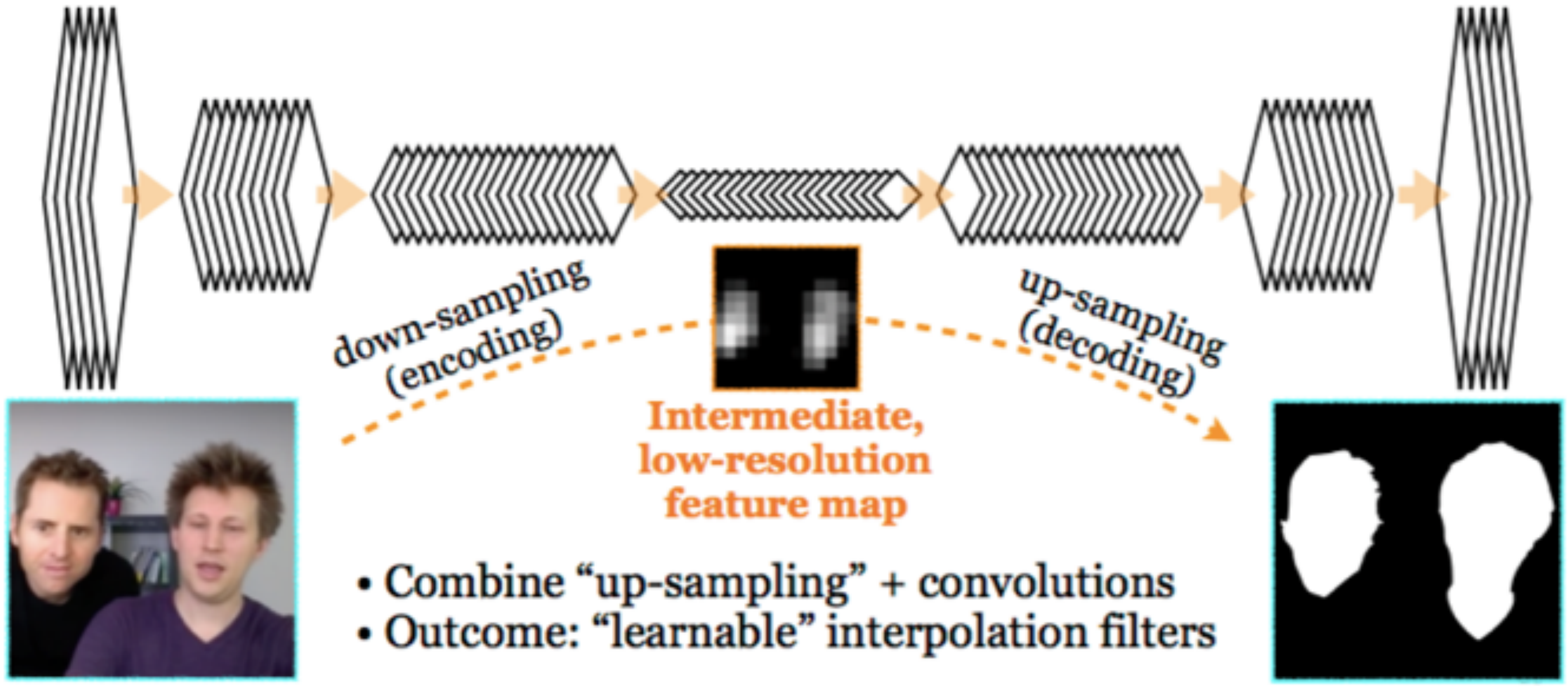



- Down-sampling and filtering of images to make 1-D array of discriminants that can be input to a deep neural net

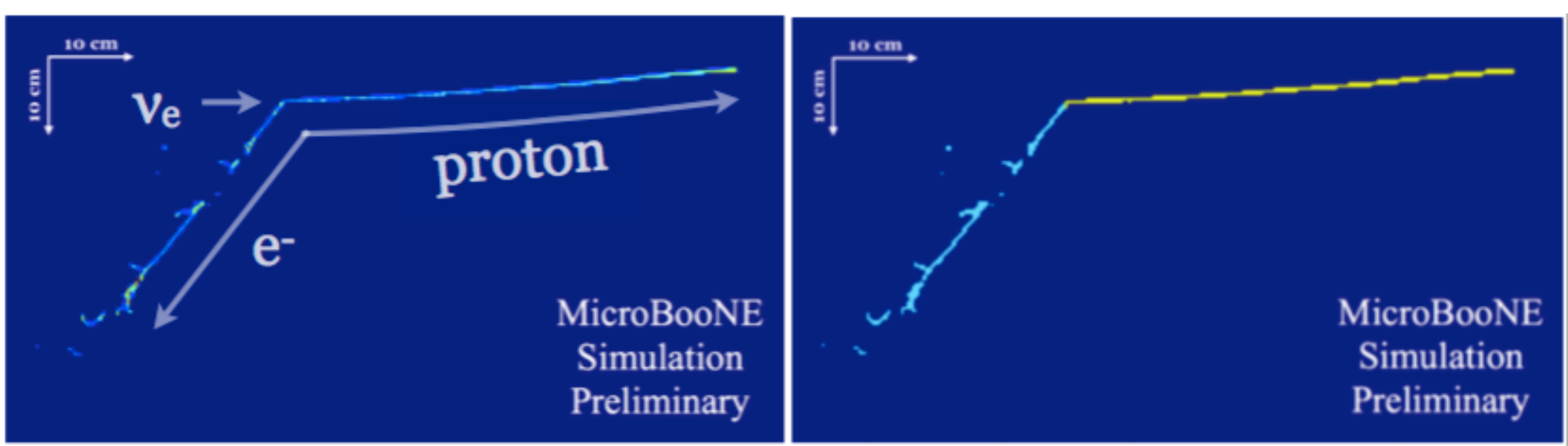
- Images can be views of events from detectors

# UP-SAMPLING (K. TERAO)

- Up-sampling of the feature map to classify pixels in the image



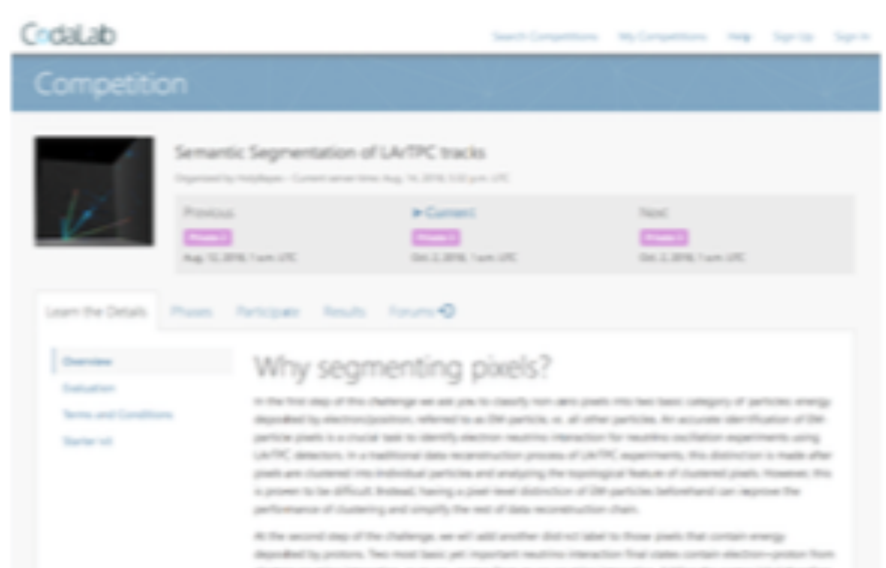

- Apply to neutrino events to cluster charge and classify as particle types



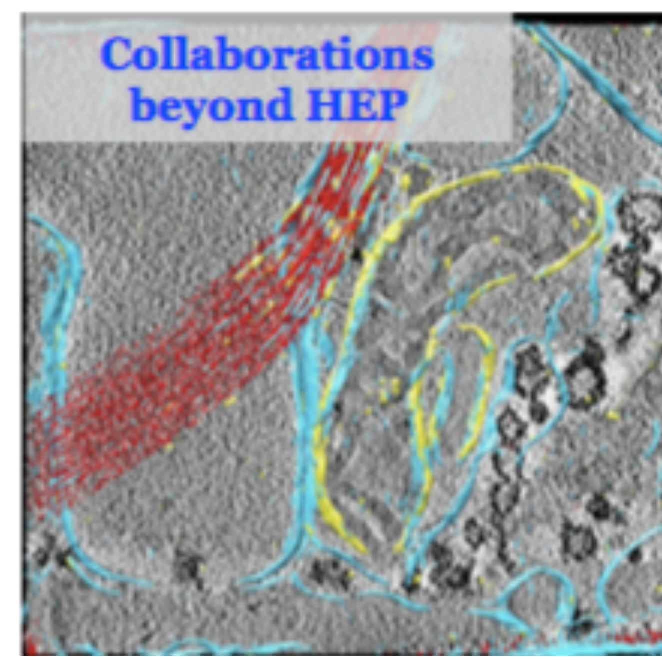
# BUILDING A COMMUNITY


## DeepLearnPhysics (deeplearnphysics.org)

- Collaboration for ML technique R&D
  - ~70 members including HEP exp/theory, nuclear physics, BES (LCLS, SSRL), Cryo-EM, accelerator, AI/CS community
- Open source software/tools, containers, open data
  - our framework to collaborate & share reproducible results
- Community building
  - Workshops (done at many universities/national labs)
  - Sharing opportunities (talks, jobs/fundings, etc.)

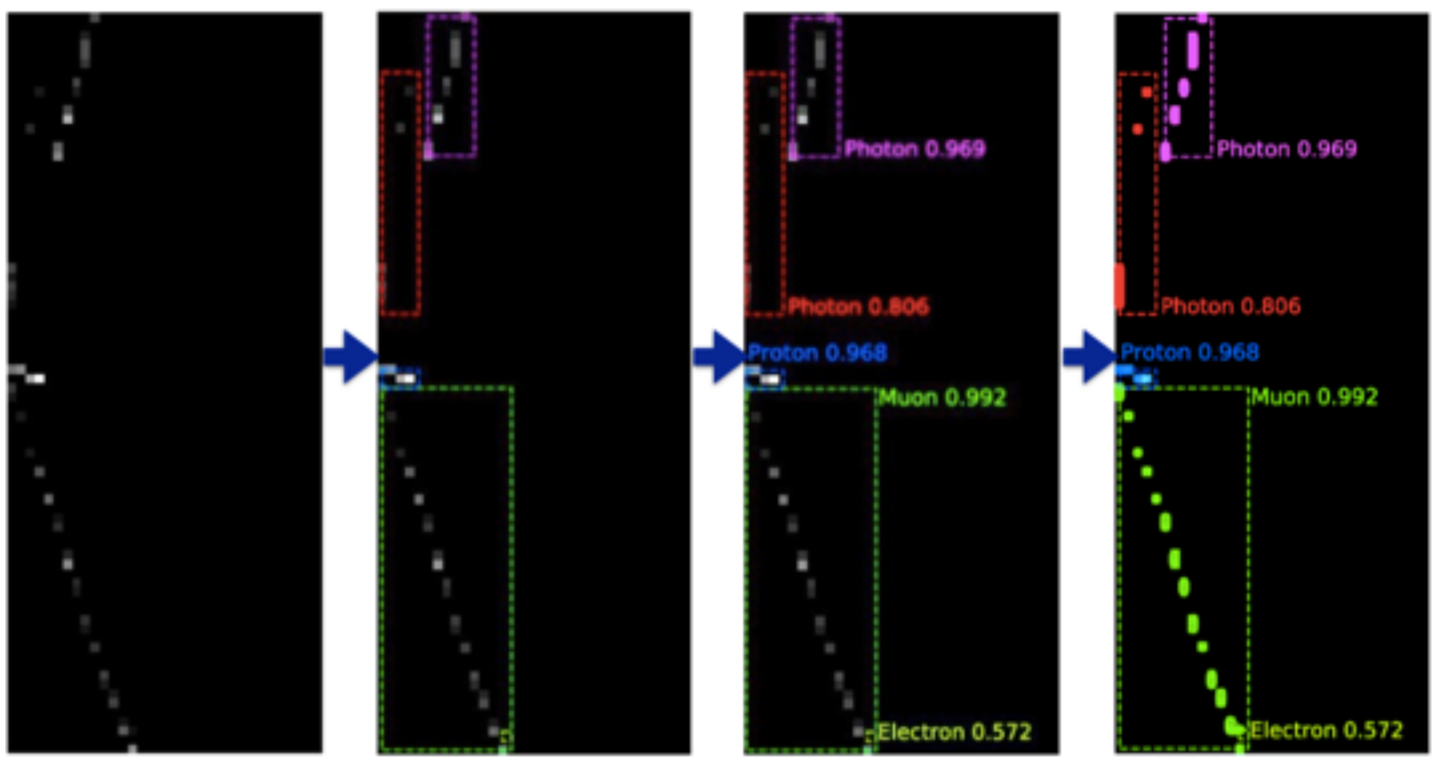

Public challenge (collab. w/ LHC)



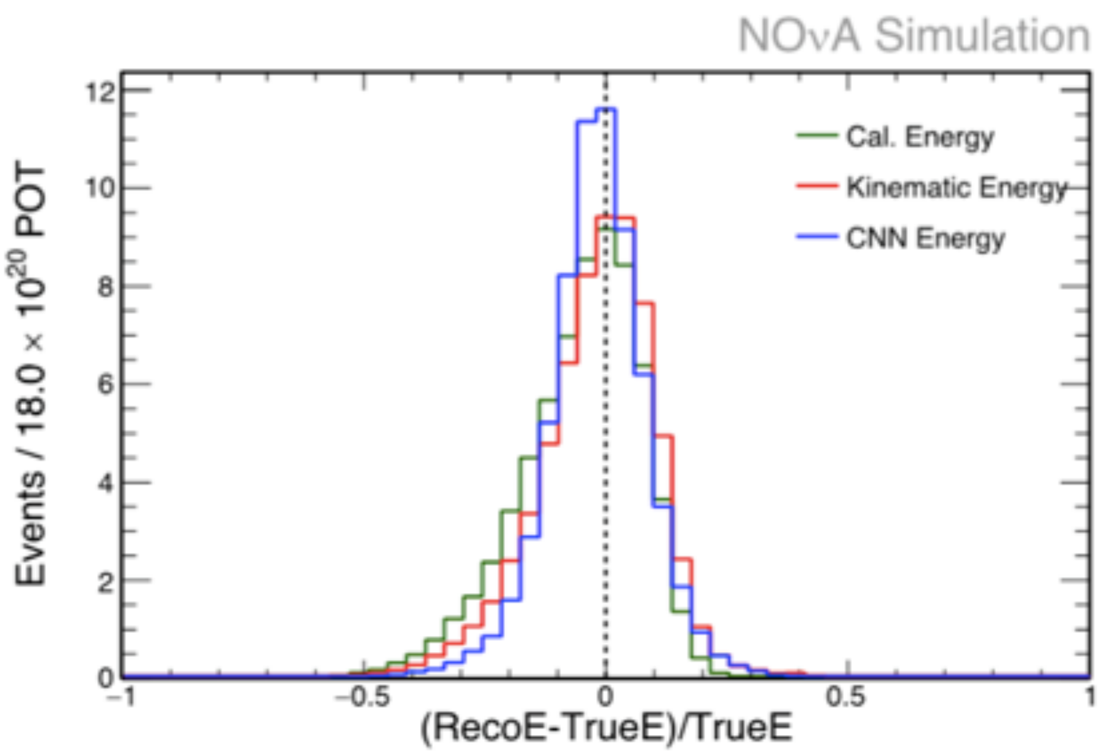
# DEEP LEARNING AT NOVA (M. GROH)

- NOvA applies CNN that improved their yield by 30%
- Use two views of event for classification
- New applications of deep learning include:

**Cluster and classify objects simultaneously**

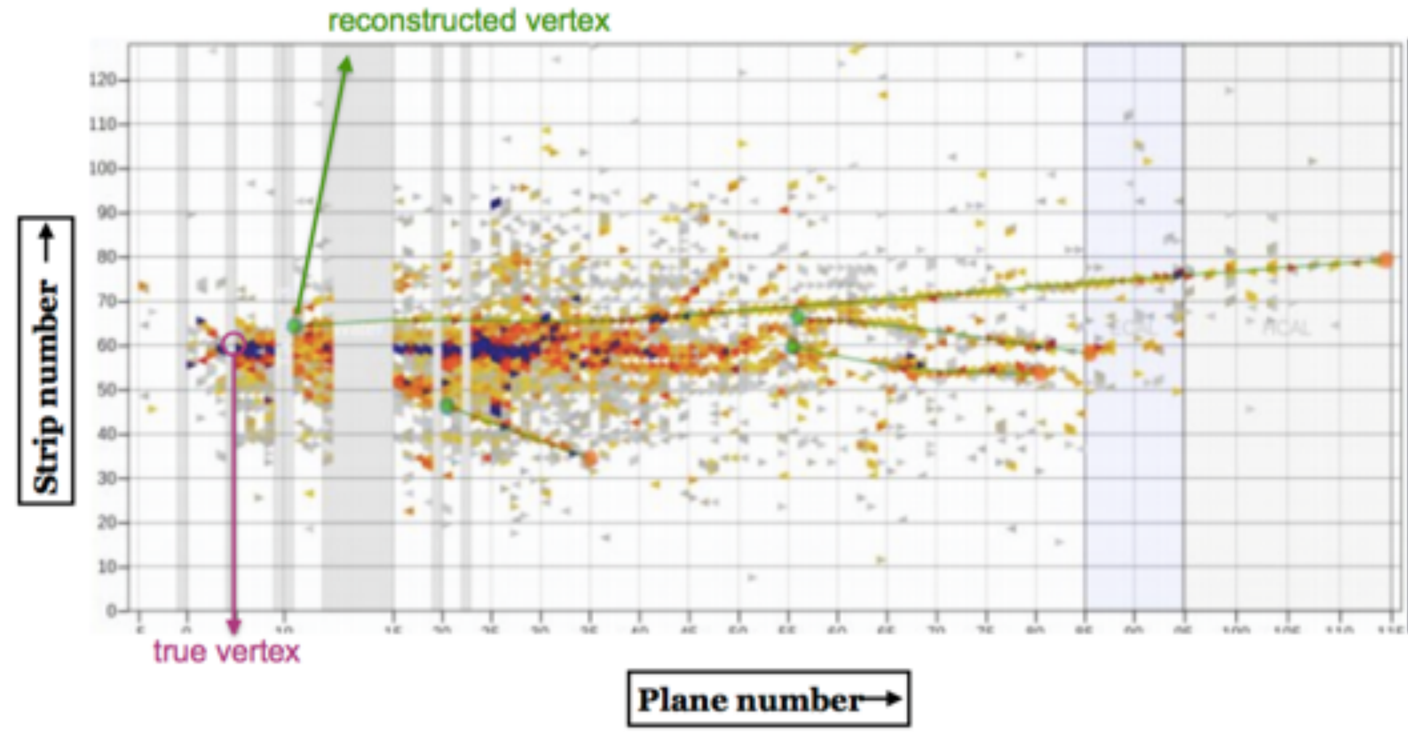


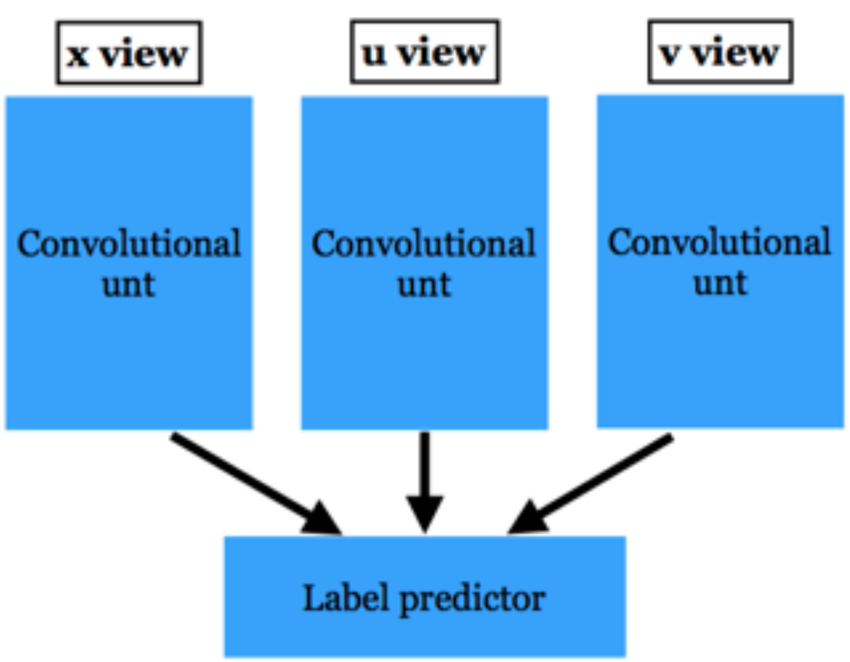

**Use linear output of NN as energy estimator**

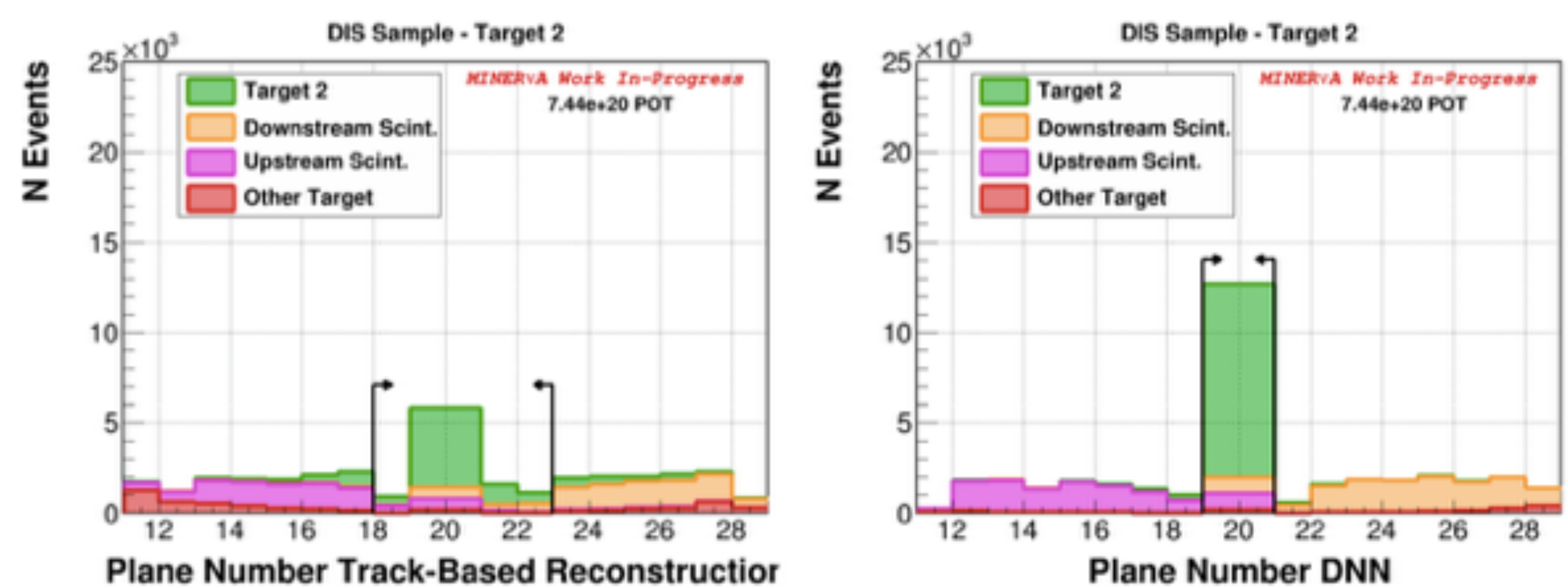


# DEEP LEARNING AT MINERVA (A. GHOSH)

- Using a CNN to find vertices for events
    - Three towers for each view
- Factor of 2-3 improvement in the purity compared to track-based reconstruction

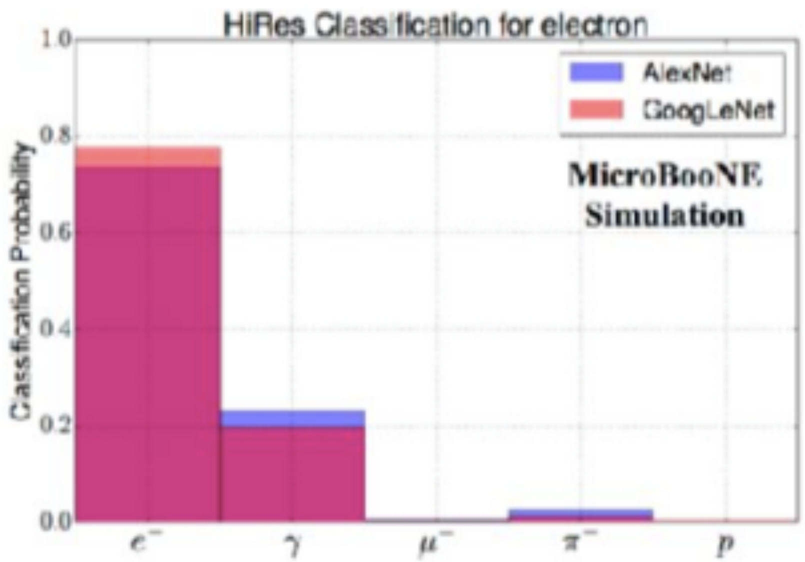


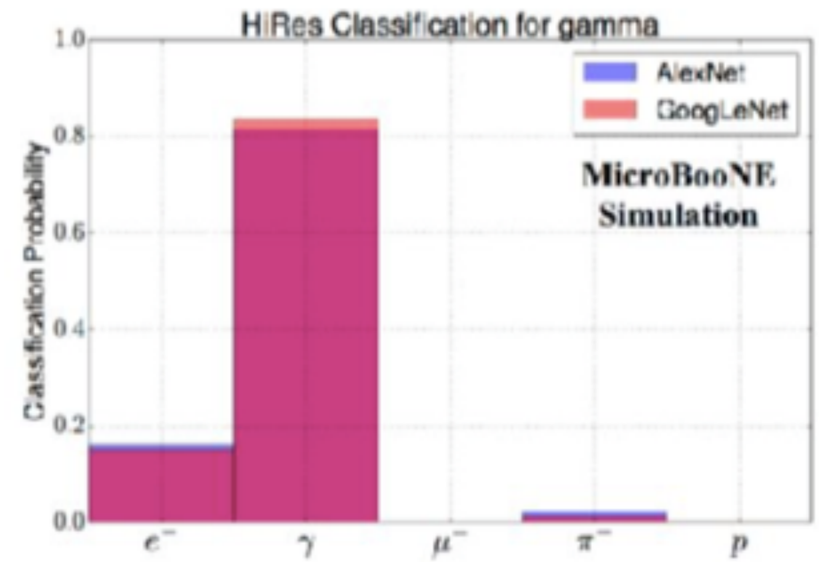



# MACHINE LEARNING AT MICROBOONE (T. WONGJIRAD)

- Initial work with single particle classifier




**$e^-$ classification performance**




**$\gamma$ classification performance**

- CNNs applied in low energy nue analysis for track/shower pixel labeling and particle ID

| Sample | ICPF mean | ICPF 90% | Shower | Track |
|---|---|---|---|---|
| Test | 1.9 | 4.6 | 4.1 | 2.6 |
| $\nu_e$ | 6.0 | 13.8 | 7.6 | 13.8 |
| $\nu_\mu$ | 3.9 | 4.5 | 14.2 | 4.3 |
| 1e1p | 2.2 | 5.7 | 2.8 | 4.0 |
| $1\mu$1p-LE | 2.3 | 2.2 | 6.2 | 2.4 |
| 1e1p-LE | 3.9 | 11.5 | 3.8 | 8.0 |

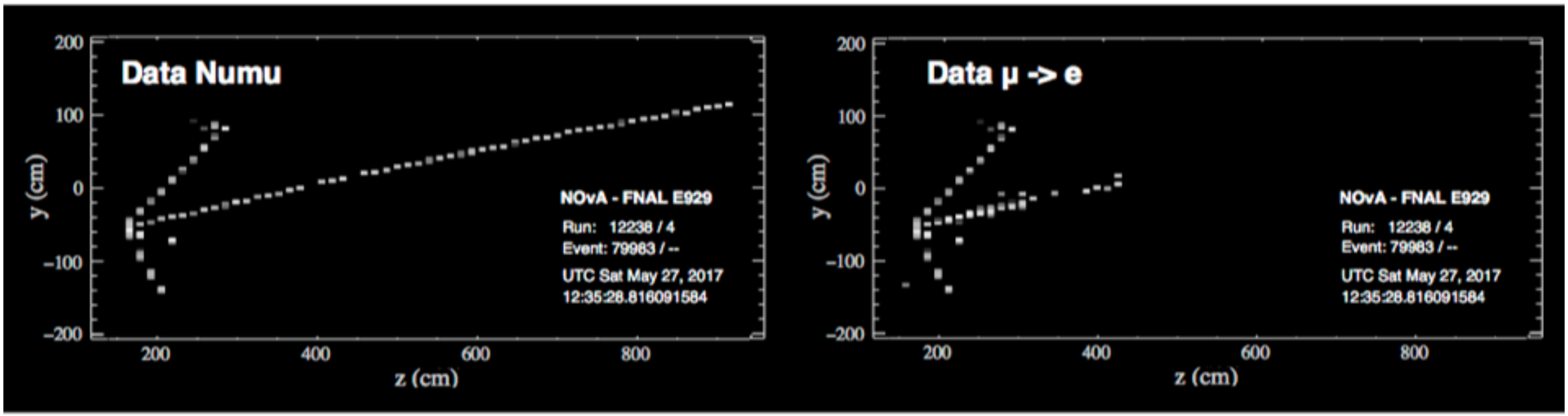
MicroBooNE: arxiv:1808.07629

- Incorrect pixel fraction is at the few percent level

# HOW TO AVOID BIAS WHEN USING CNNS?

- All experiments ask the question: "How to avoid training on features of MC that aren't in the data?"

NOvA removes muon from data and adds simulated electron



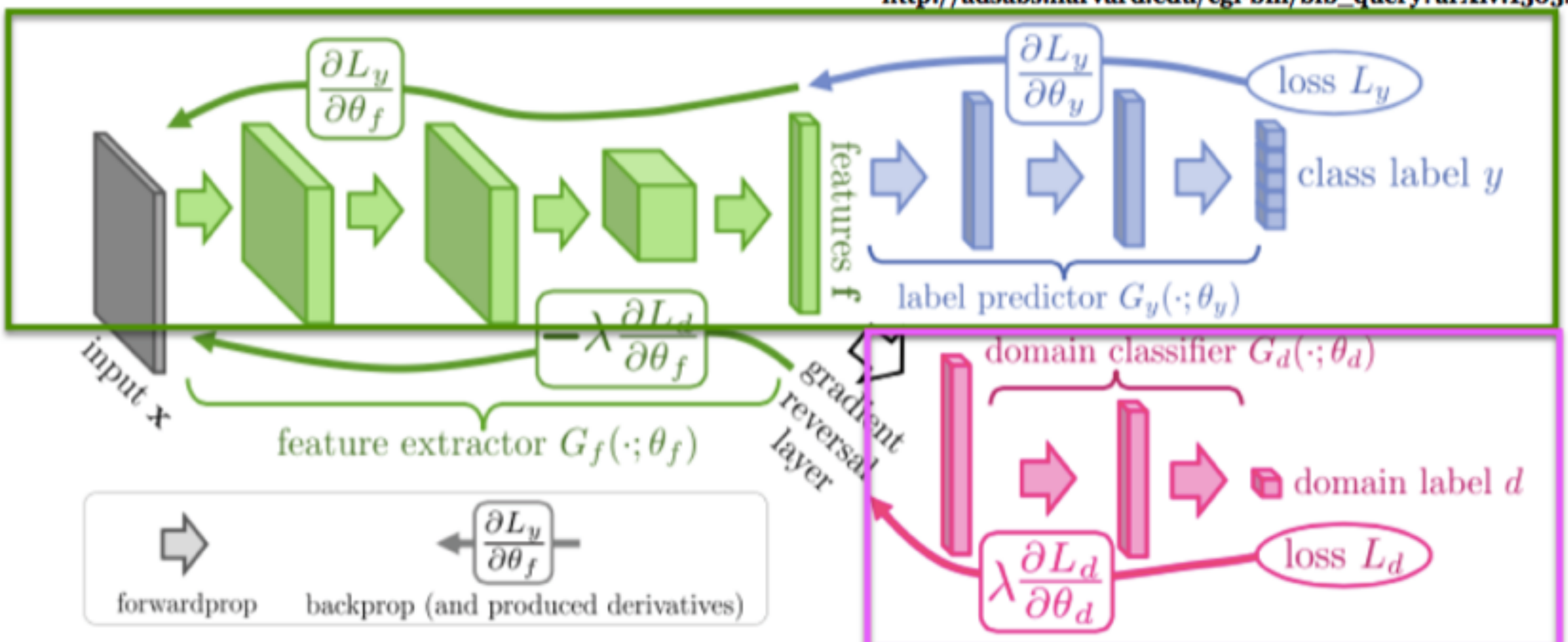

See consistent efficiency in data and MC

| | Pre Selection | Full Selection | Efficiency |
|---|---|---|---|
| Data Events | 486083 | 316009 | 0.6501 |
| MC Events | 511287 | 341119 | 0.6672 |

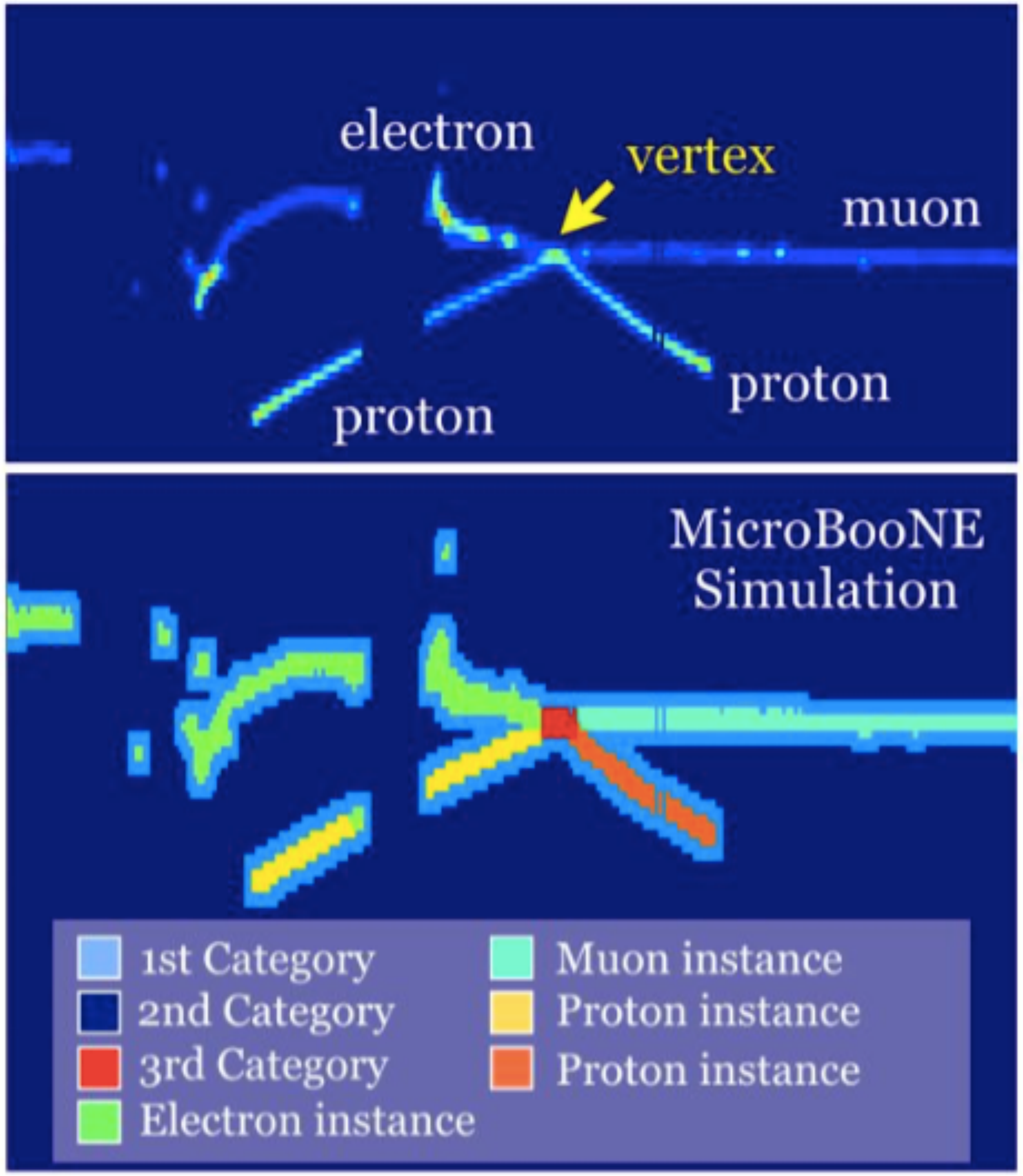
# DOMAIN ADVERSARIAL NEUTRAL NETWORK

- Being applied by MINERvA to avoid selection on features that are in MC (training sample), but not data
- Label classifier: does the classification you are interested in
- Domain classifier: train to be indiscriminate between domains (data and training sample)

http://adsabs.harvard.edu/cgi-bin/bib_query?arXiv:1505.07818



# TRAINING WITH UNBIASED KINEMATICS




- MicroBooNE trains “particle-bomb” MC generated with
  - Uniform distribution of number of particles
  - Uniform distribution of momenta
  - Isotropic direction of particles
- Can’t train on kinematics and correlations from neutrino interaction model

# SYSTEMATIC UNCERTAINTIES

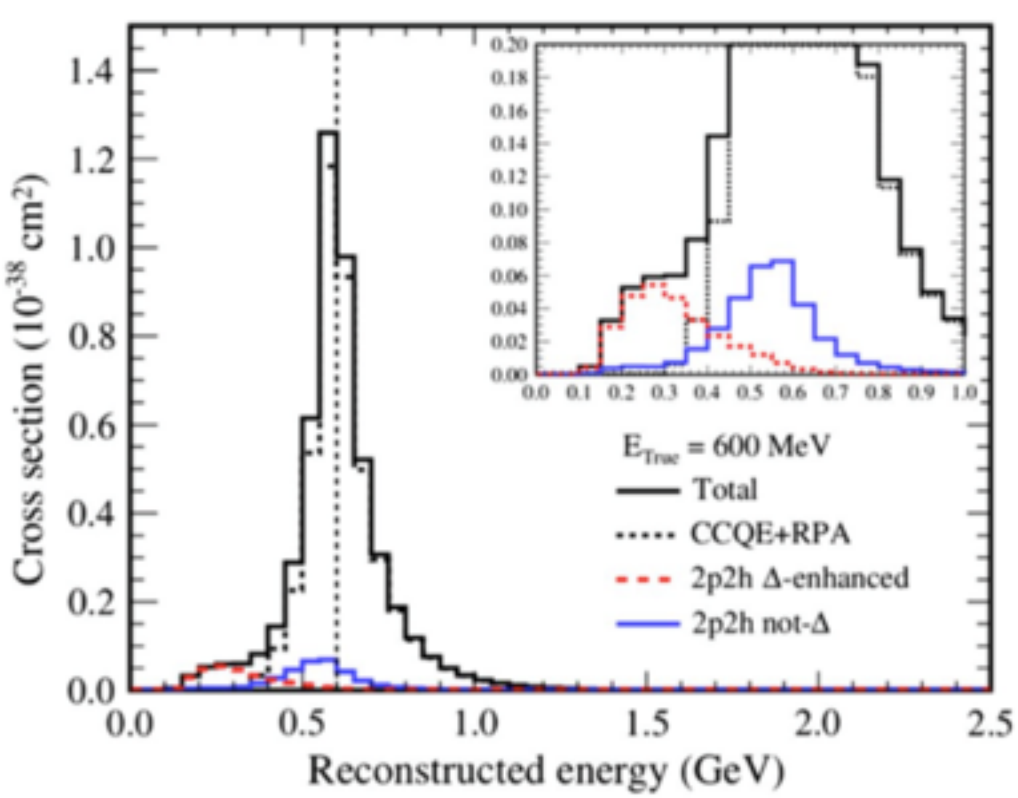
# NEUTRINO INTERACTION UNCERTAINTIES (C. MARSHALL)

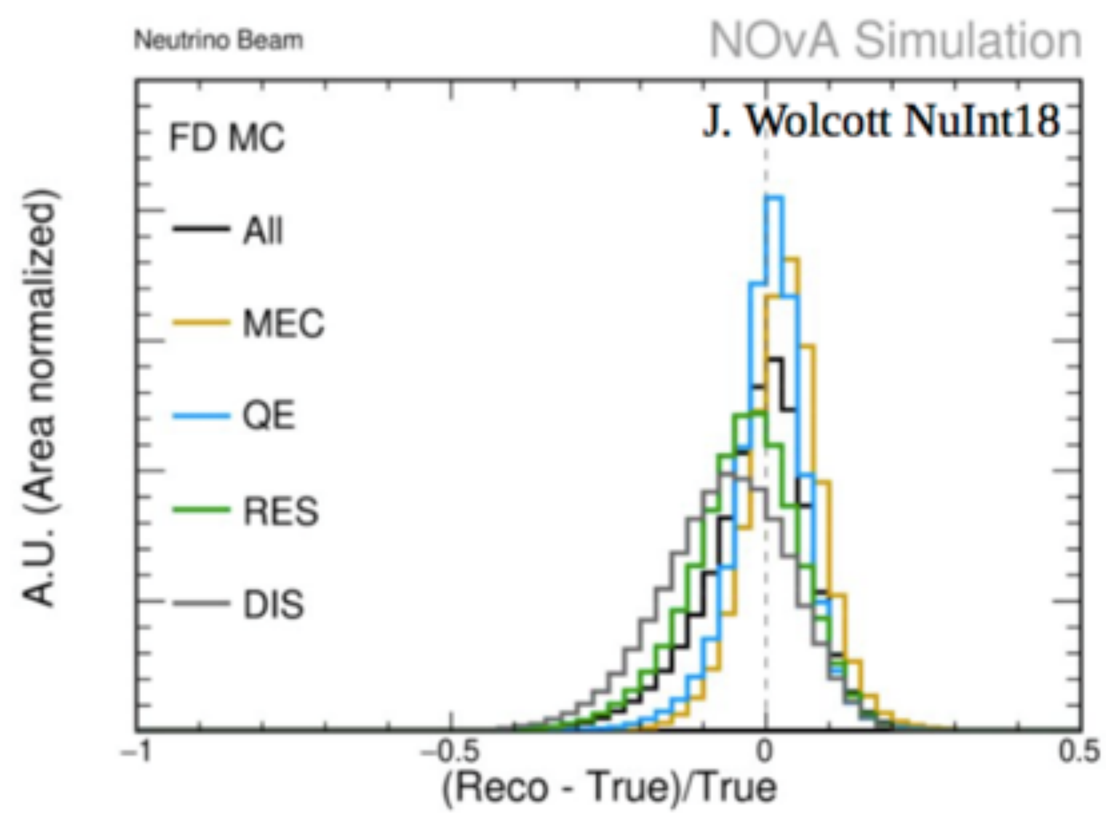
- Review of where systematic errors enter when extrapolating from near detectors

$$N_{\nu_e}^{far}(E_{reco}) = \int \Phi_{\nu_e}(E_\nu, L) \times \sigma_{\nu_e}(E_\nu) \times \epsilon^{far}(E_\nu) \times \mathbf{D}_{\nu_e}^{far}(E_\nu \to E_{reco}) dE_\nu$$

$$N_{\nu_\mu}^{near}(E_{reco}) = \int \Phi_{\nu_\mu}(E_\nu, 0) \times \sigma_{\nu_\mu}(E_\nu) \times \epsilon^{near}(E_\nu) \times \mathbf{D}_{\nu_\mu}^{near}(E_\nu \to E_{reco}) dE_\nu$$

- Systematic uncertainties on energy reconstruction are important
  - Non-quasielastic contributions for kinematic reconstruction
  - Dependence on final state for calorimetric reconstruction

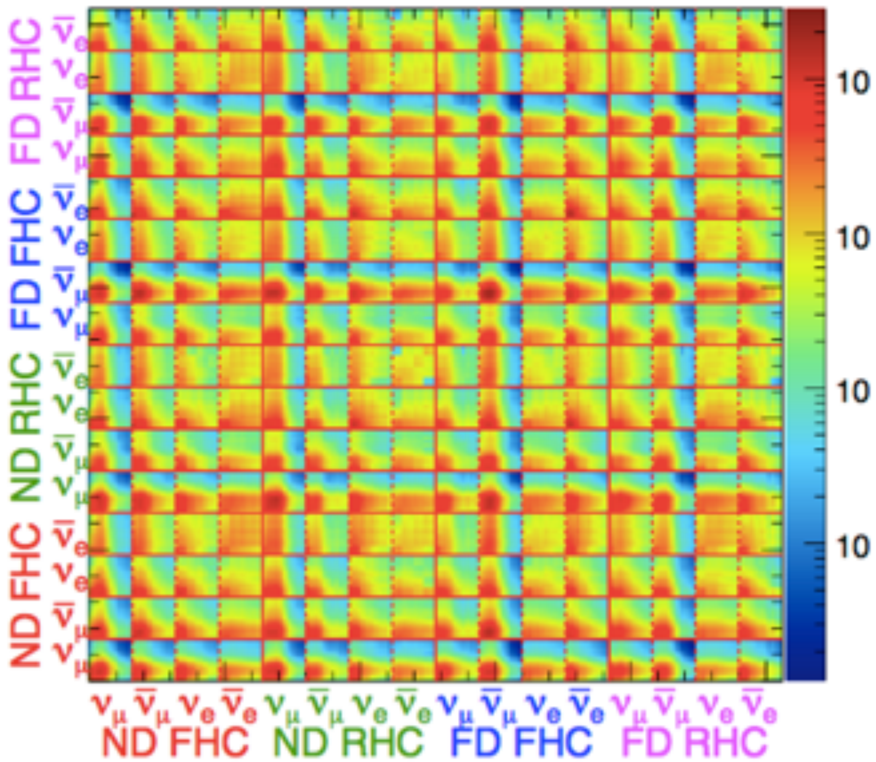


# DUNE SYSTEMATICS (C. BACKHOUSE)

- DUNE is developing a comprehensive systematic error model

## Flux Error Matrix




## Cross Section Systematics

**GENIE dials** (v2.12.10c)
- Default priors where they don't double count
- Plus. . .

**QE-like**
- *Z*-expansion axial FF
- MINERvA's 2p2h enhancement (low recoil data)[1]
- 2p2h energy dependence – MINERvA/DUNE energies not equal

**Low-W**
- Swap MK model for Rein-Sehgal – interference of RES+non-RES
- Empirical fit to low $Q^2$ suppression for RES needed by NuMI expts

**High-W**
- Uncorrelated normalization uncertainties for non-resonant pion production for 1,2,3+ pions, up to $W$=5 GeV

**FSI-like**
- Inflation of smearing of $E_{avail}$ reflecting C→Ar

**Other**
- Potential $\nu_e/\bar{\nu}_e$ xsec differences
- $\nu_\mu/\nu_e$ differences from lepton mass differences[2]

- Combination of smaller effects can be treated with PCA
- Ideally also swap in entirely different models

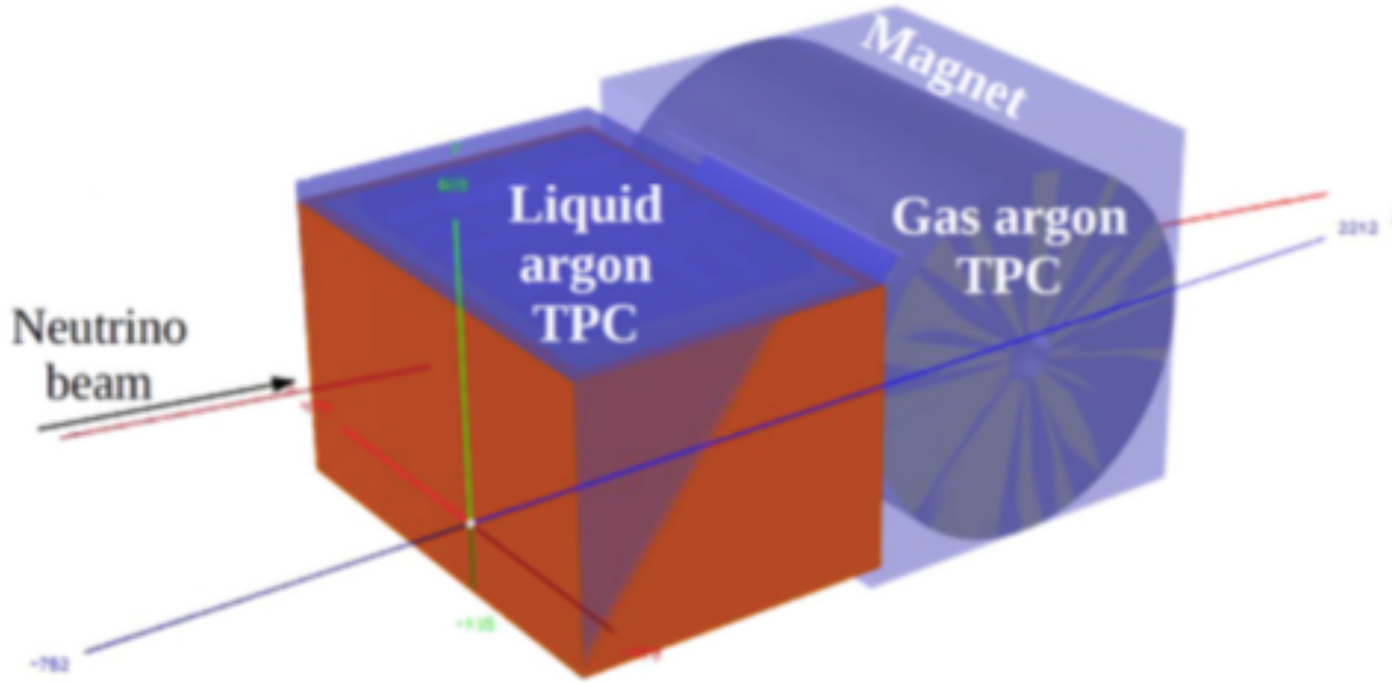
## Detector Model

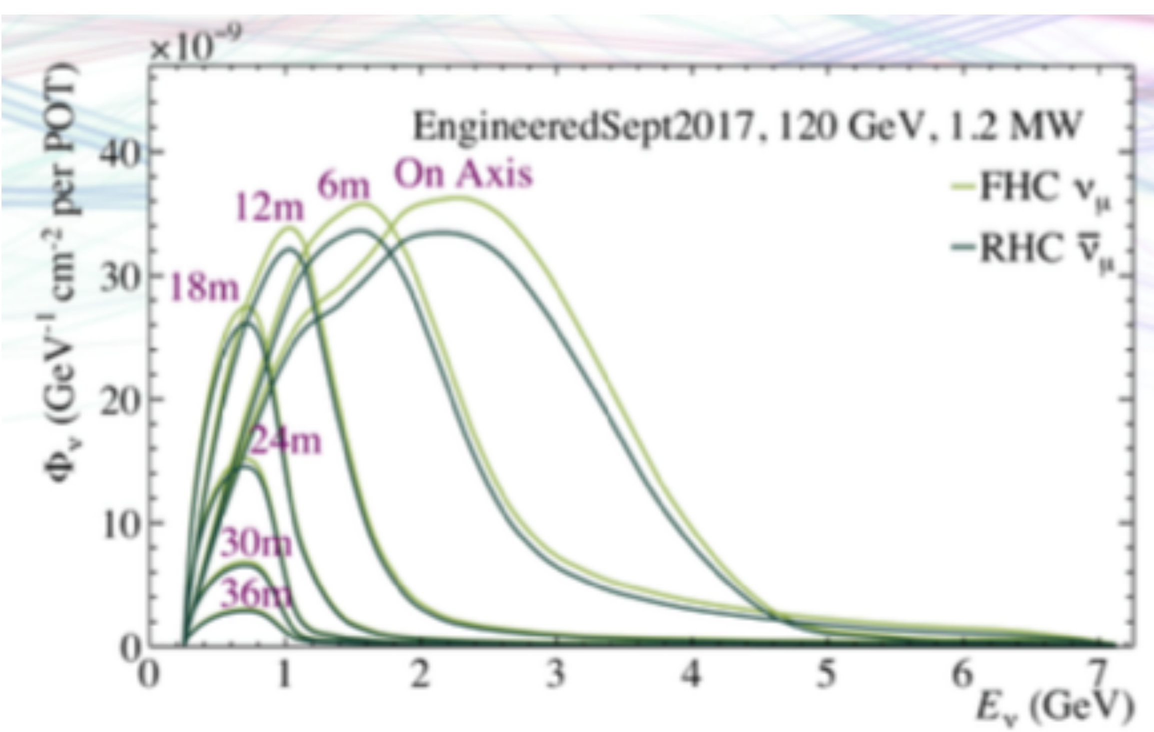
**Actively pursuing**
- *E*-field distortions
- Alignment

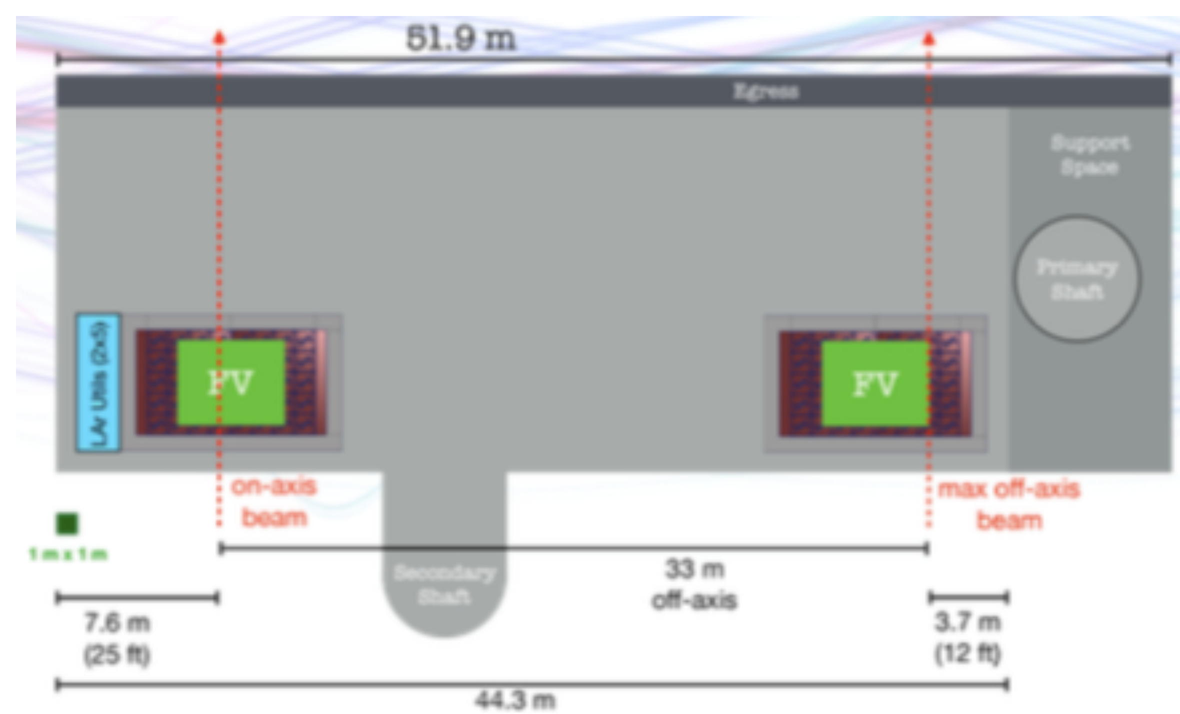
**Others**
- Calibrations – absolute scale, channel-to-channel variations
- Dead channels
- Neutron-Ar cross-section
- . . .

# DUNE SYSTEMATIC ERROR MITIGATION

- Near detector suite with option to vary off-axis angle
- Liquid argon TPC and gas argon TPC in magnetic field




*Possible layout*

# HYPER-K SYSTEMATICS (T. YOSHIDA)

- Hyper-K has T2K systematic error estimates as a starting point

| | | Flux & ND-constrained cross section | ND-independent cross section | Far detector | Hadronic re-interaction | Total |
|---|---|---|---|---|---|---|
| ν-mode | Appearance | 3.2% | 7.8% | 2.9% | 3.0% | 8.8% |
| | Disappearance | 3.3% | 2.4% | 2.4% | 2.2% | 5.1% |
| $\bar{\nu}$-mode | Appearance | 2.9% | 4.8% | 3.8% | 2.3% | 7.1% |
| | Disappearance | 2.7% | 1.7% | 2.0% | 2.0% | 4.3% |

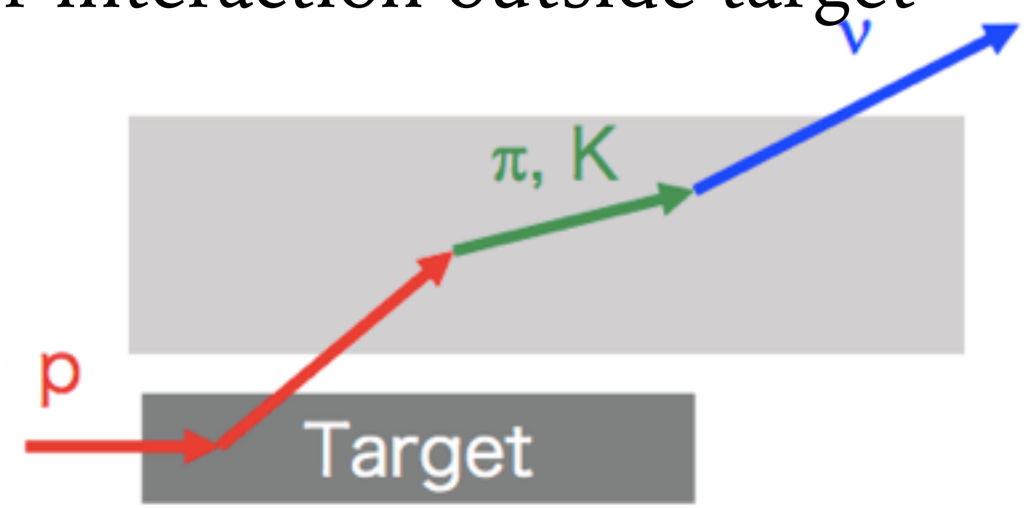
- Goal is to reduce total systematic error to ~3% or better

Systematics errors **assumed** in Design Report

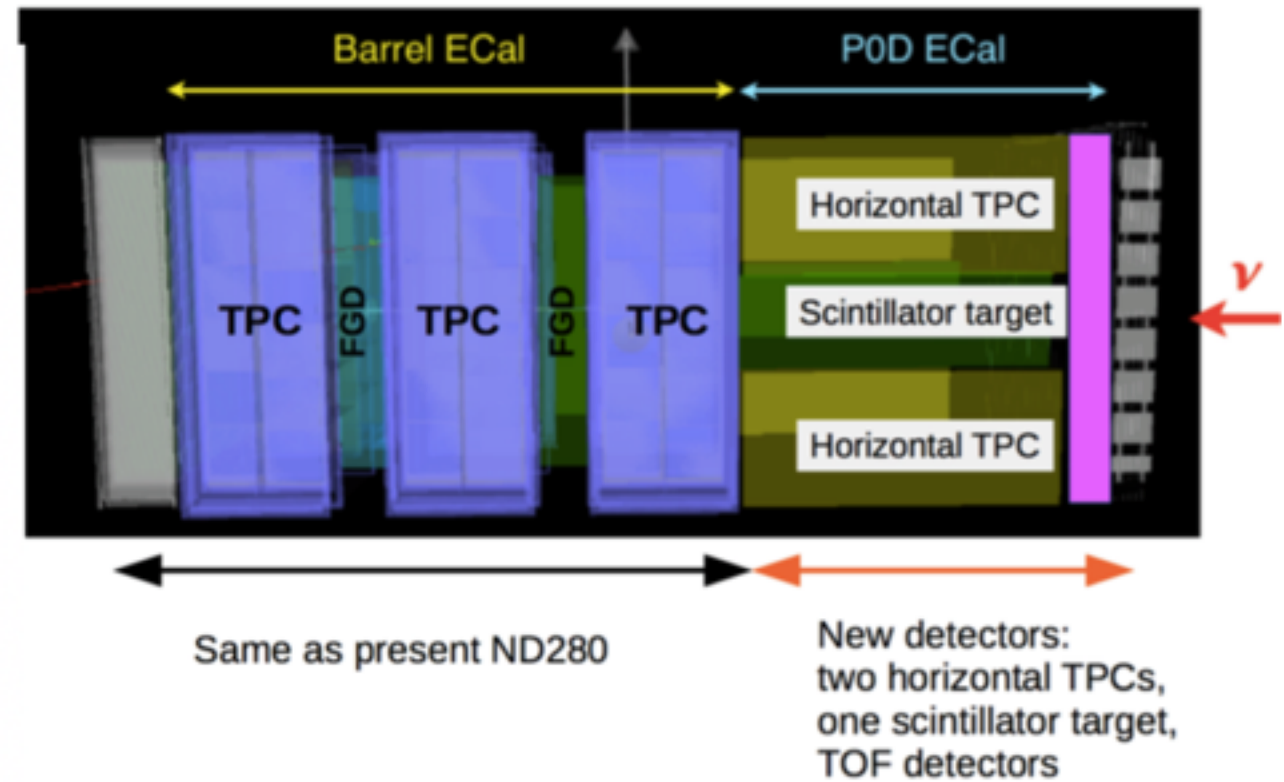
| | | Flux & ND-constrained cross section | ND-independent cross section | Far detector | Total |
|---|---|---|---|---|---|
| $\nu$ mode | Appearance | 3.0% | 0.5% | 0.7% | 3.2% |
| | Disappearance | 3.3% | 0.9% | 1.0% | 3.6% |
| $\bar{\nu}$ mode | Appearance | 3.2% | 1.5% | 1.5% | 3.9% |
| | Disappearance | 3.3% | 0.9% | 1.1% | 3.6% |

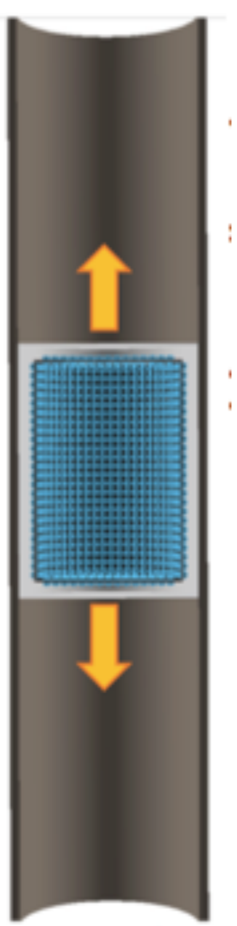
# SYSTEMATIC ERROR MITIGATION IN HYPER-K

New hadron production measurements for interaction outside target




Upgrades to ND280 detector. Additional upgrades after T2K may be necessary.



Off-axis spanning intermediate water Cherenkov detector

Energy reconstruction constraint like Dune-PRISM

Electron neutrino cross section and background measurements

# MICROBOONE ANALYSIS EXPERIENCE (S. D. PORZIO)

- Detailed description of electron and light propagation modeling, calibration and systematic errors

$$\frac{dE}{dX} \times \frac{1}{W} \times R \times L \times D \times C = \frac{dQ}{dX}$$

**Current implementation:**
Using alternative model externally constrained with other argon detectors measurements

**Future implementation:**
Internal constraints from ongoing MicroBooNE calibration measurements

**Current implementation:**
Infinite lifetime for default
"Extreme case" simulation (10 ms) for uncertainty

**Future implementation:**
- Ongoing MicroBooNE calibration measurements to disentangle it from other effects.

**Current implementation: 1σ**
- External constraints on argon for L
- T less studied in literature, using external measurements and theoretical extrapolation to MicroBooNE field strength

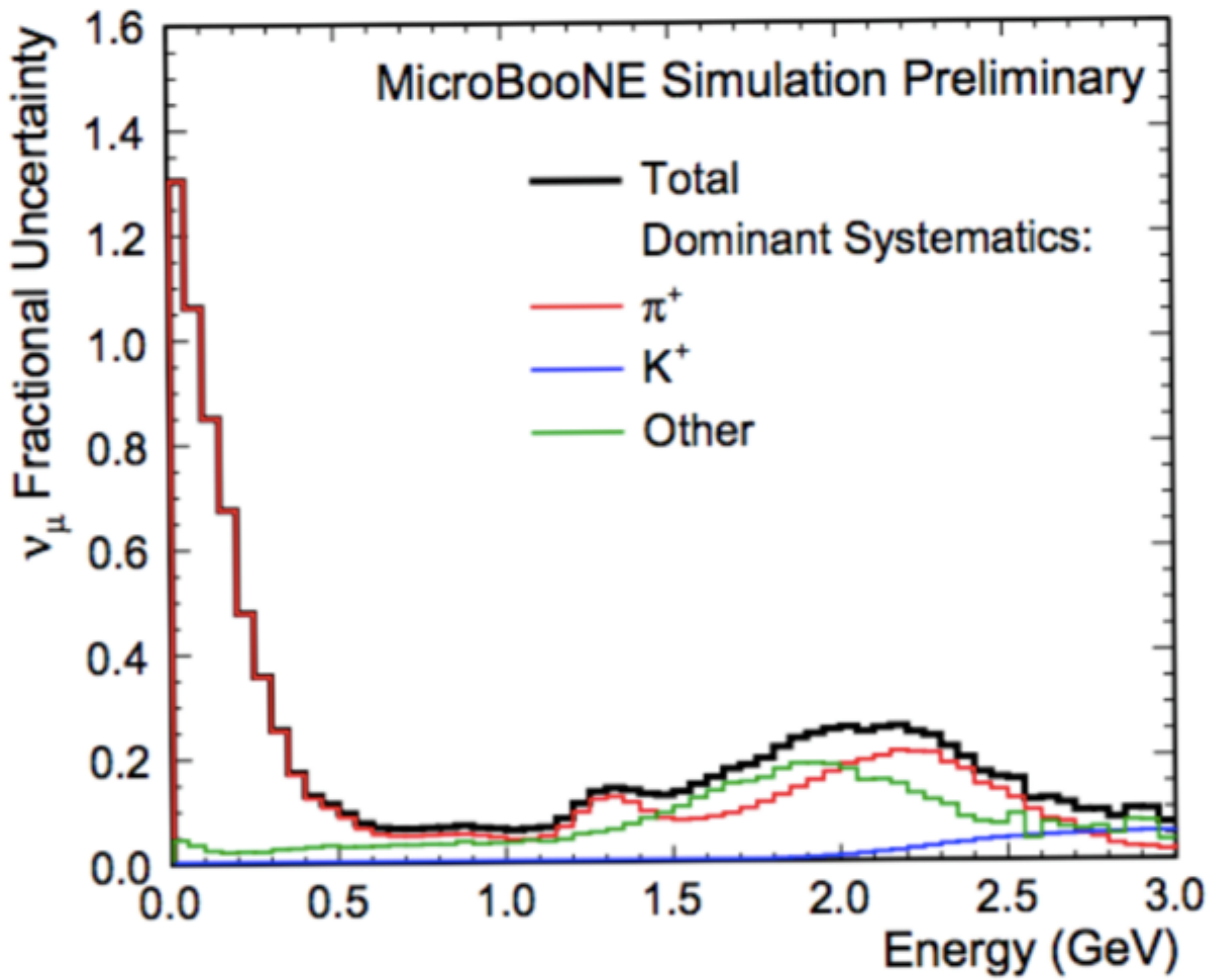
**Possible future implementation:**
- Internal constraints from ongoing MicroBooNE calibration measurements
- $^{39}Ar$ to disentangle L/T components

…

Systematic errors on detector response are still dominant, but many approaches to reduce systematic error are being pursued

| | $\nu_\mu$ CC incl. | $\nu_\mu$ CC $\pi^0$ |
|---|---|---|
| Total systematic uncertainty | 25% | 31% |
| Detector response uncertainty | 19% | 21% |
| Dynamic induced charge uncertainty | 15% | ≈15% |

# MICROBOONE FLUX UNCERTAINTY?



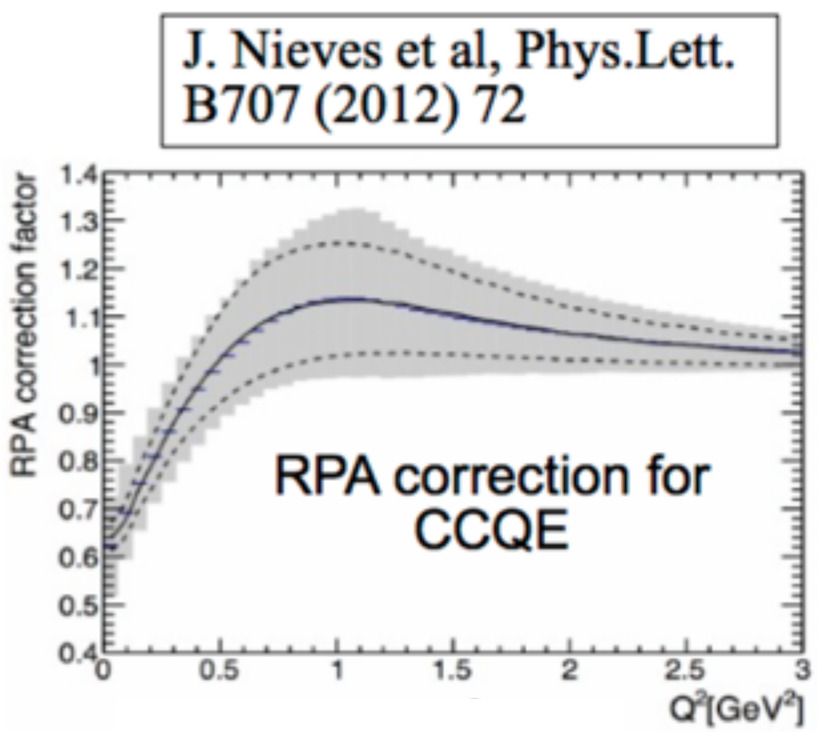

Large uncertainty on the low energy flux prediction

Are new hadron production measurements needed?

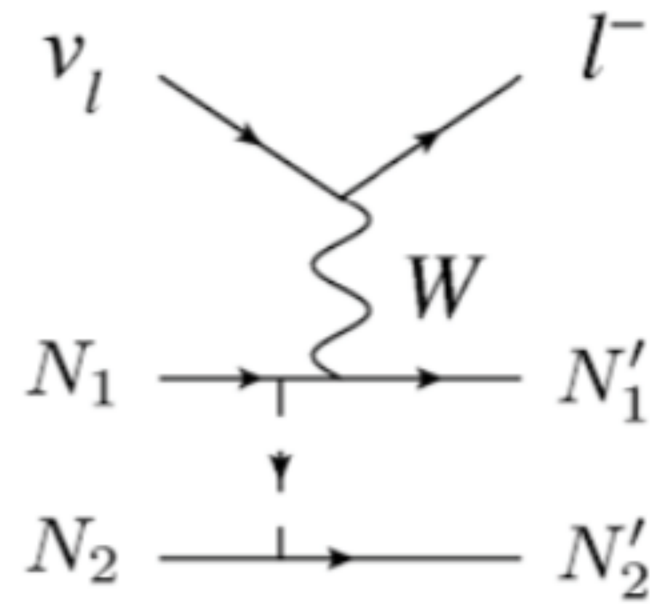
# NEUTRINO INTERACTION UNCERTAINTIES AT T2K (K. MCFARLAND)

- Comprehensive description of T2K's neutrino interaction model

Uncertainties in the quasielastic-like channels:




Uncertainty on low $Q^2$ suppression from long-range correlations

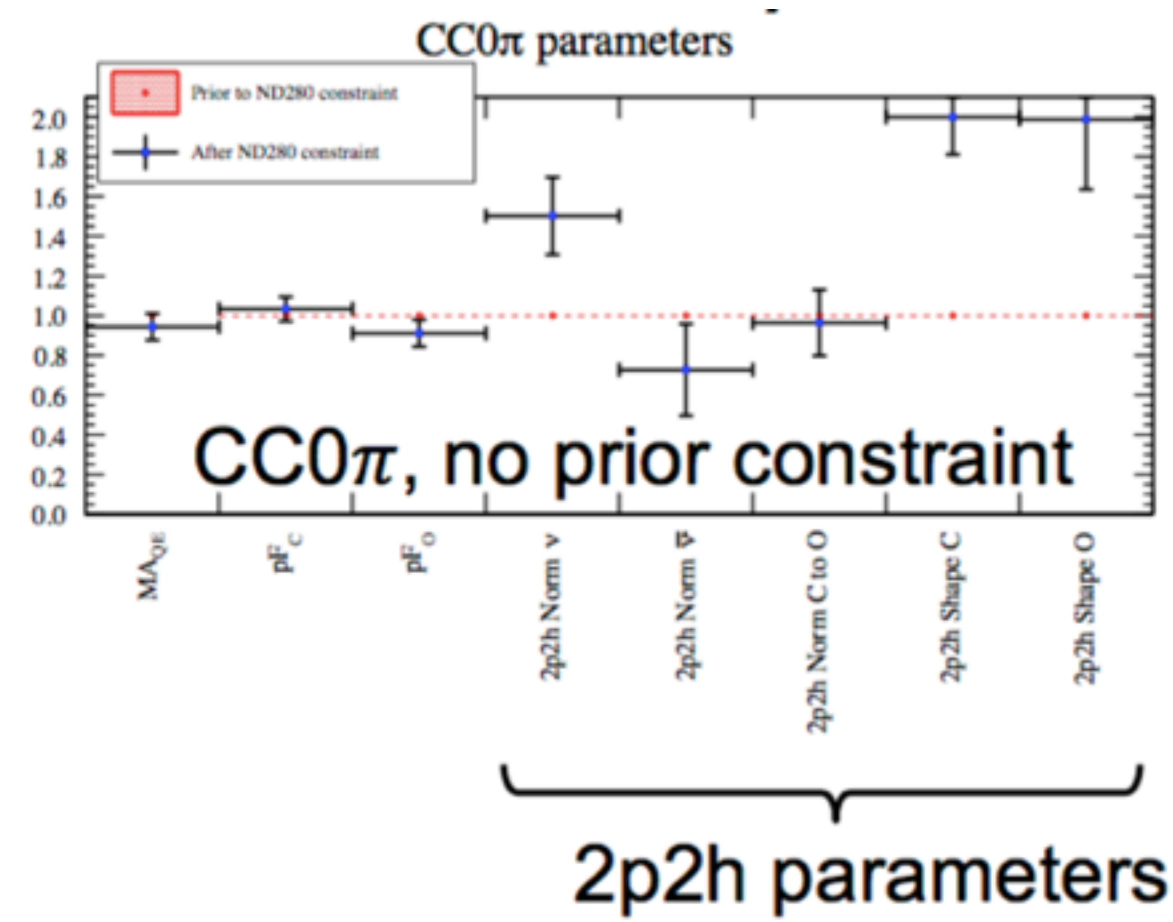



Implementation of Nieves et. al. 2p-2h

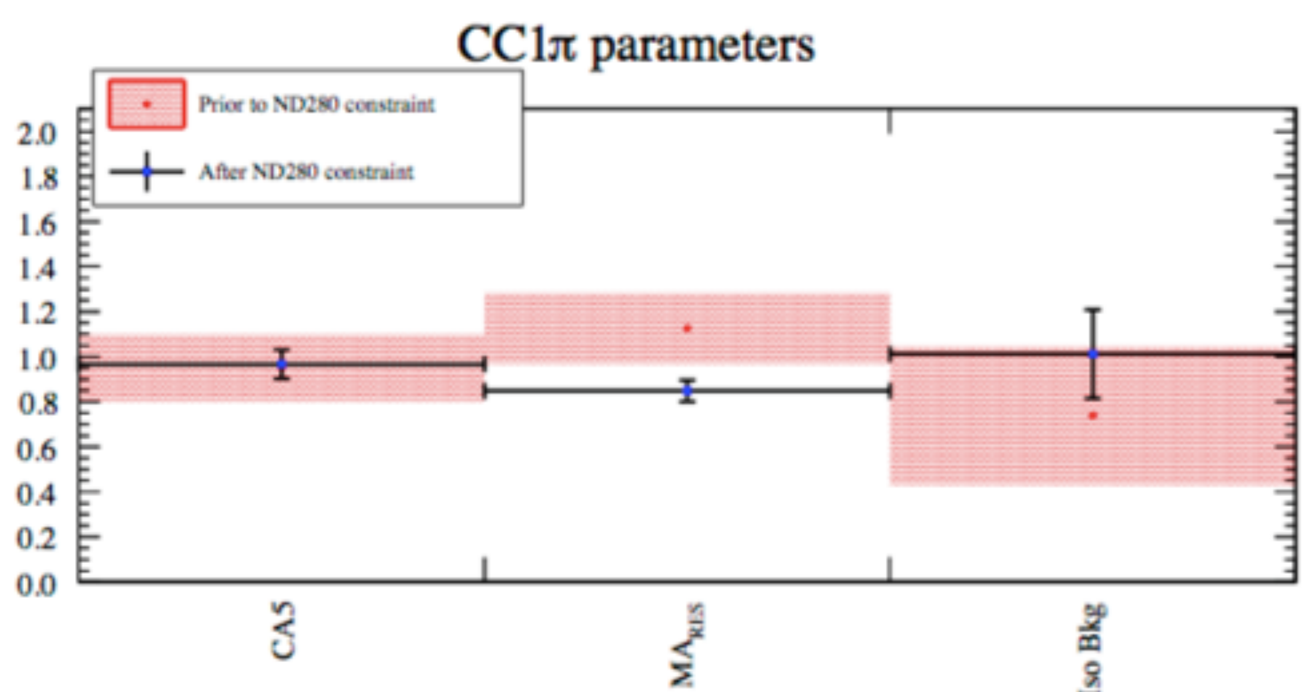
Allow total cross section to vary

Allow relative fraction of Δ-like and non-Δ-like to vary

# CONSTRAINTS BY T2K NEAR DETECTOR



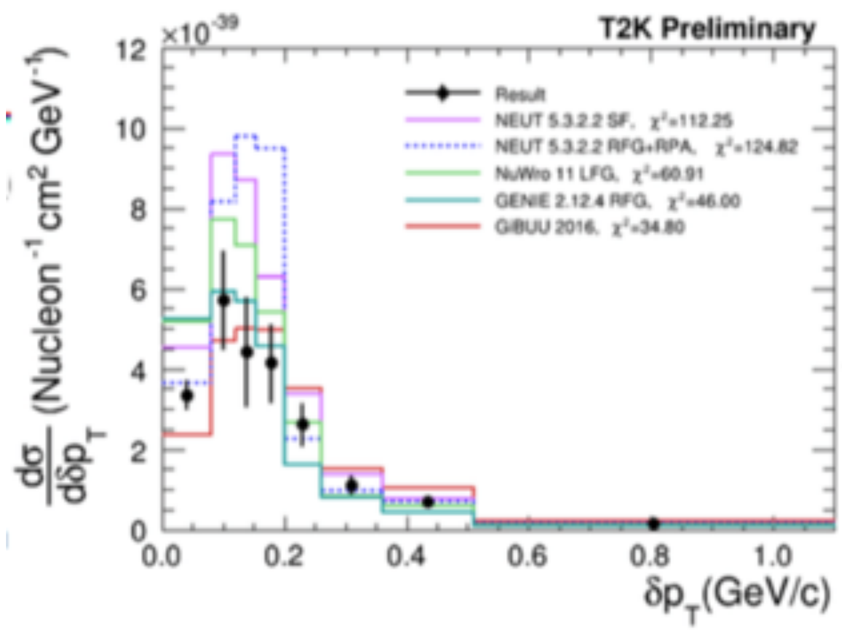

- 2p-2h for neutrinos is enhanced
- Δ-like contribution to 2p-2h is maximized

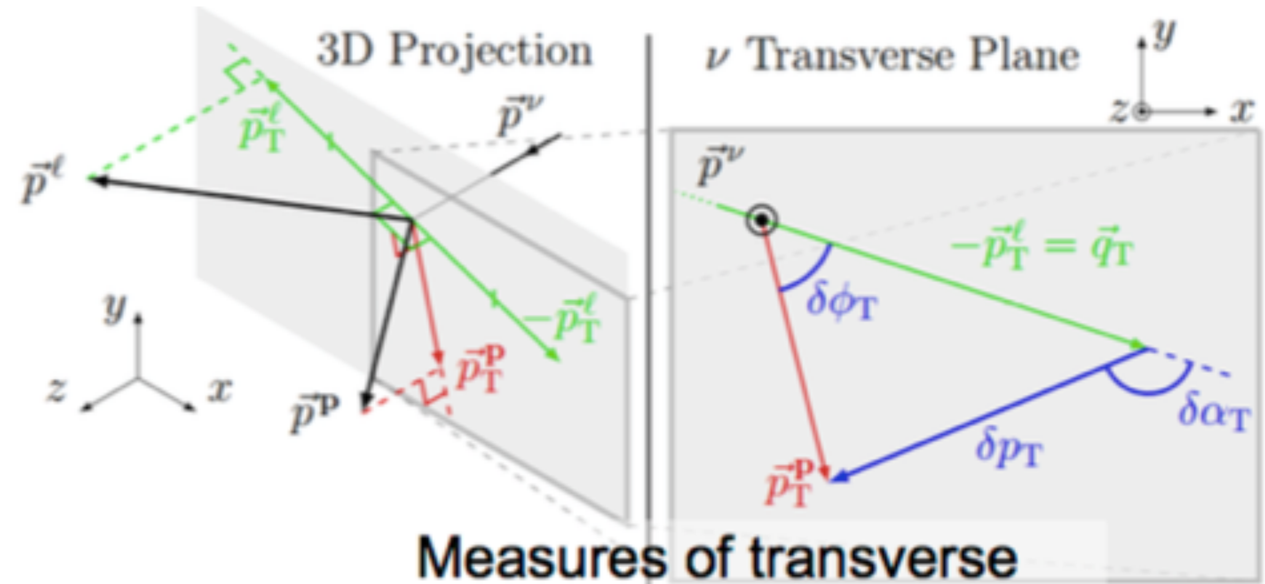



- Significant pull on axial mass for pion production mode
- Pointing to not-modeled nuclear effects that effect?

# CROSS SECTION MEASUREMENTS AT T2K

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



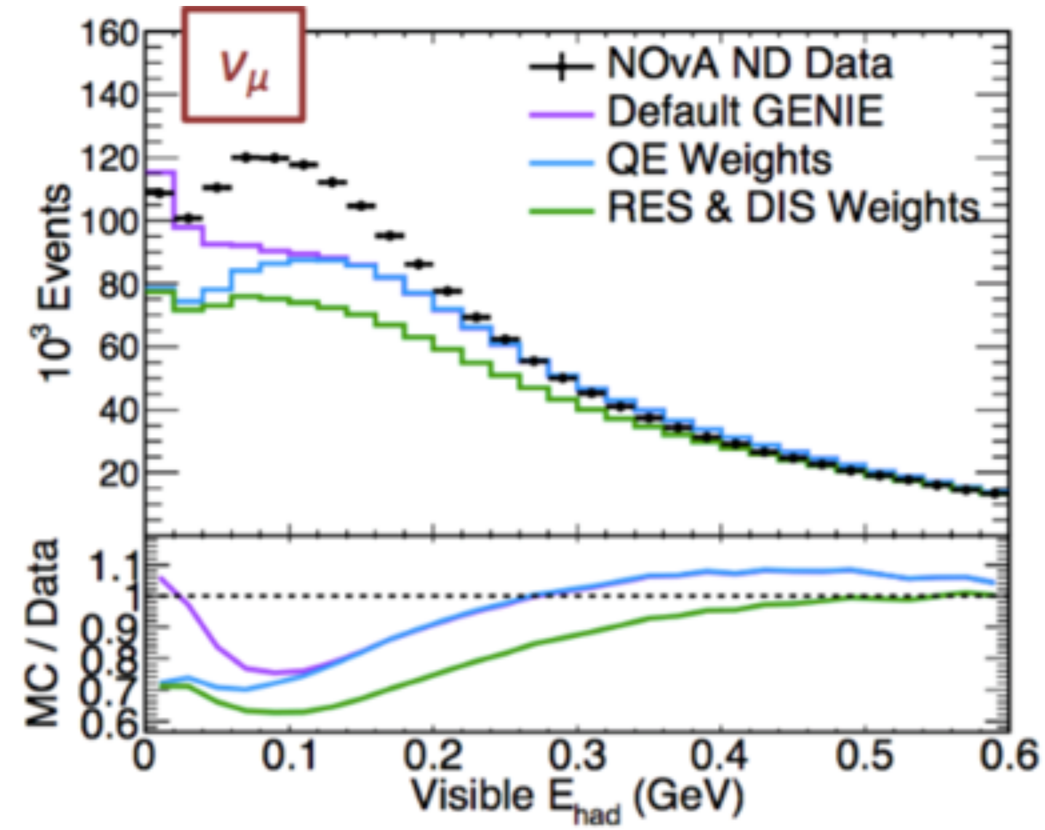




Measures of transverse kinematic balance

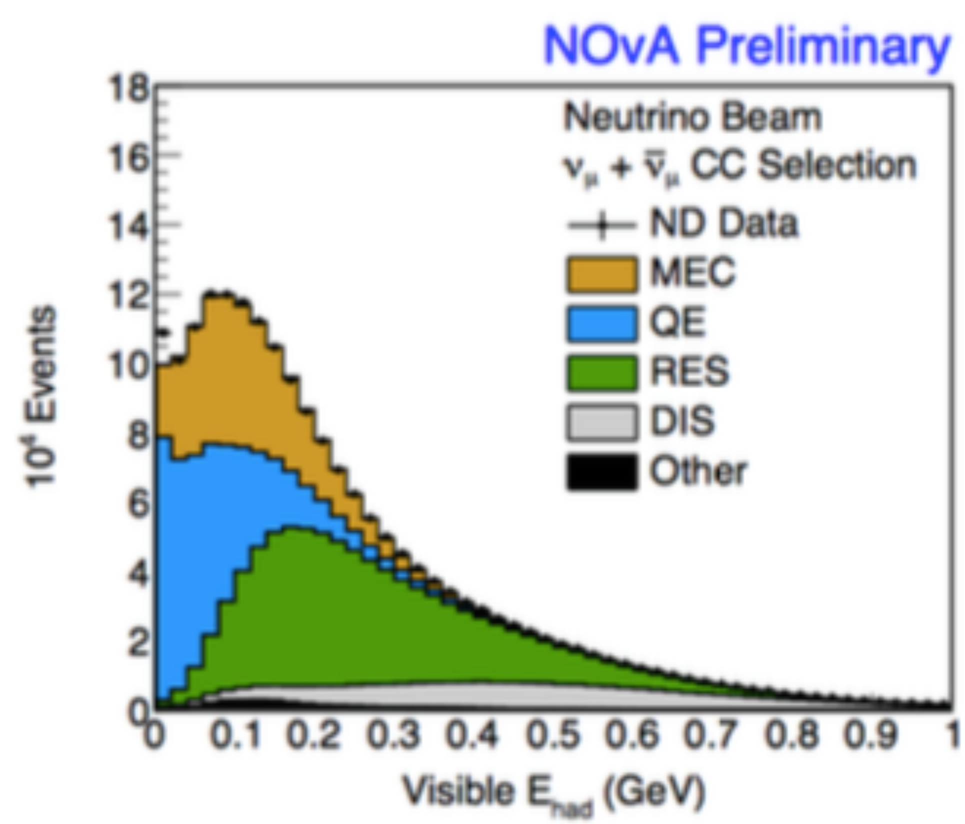
- Reconstruct muon and proton candidates to construct variables in the transverse plane
- Have shown capability to discriminate between models
- Improvement with more stats.  Can ND280 upgrade improve with lower thresholds and improved resolution?

# SYSTEMATICS UNCERTAINTIES AT NOVA (L. SUTER)

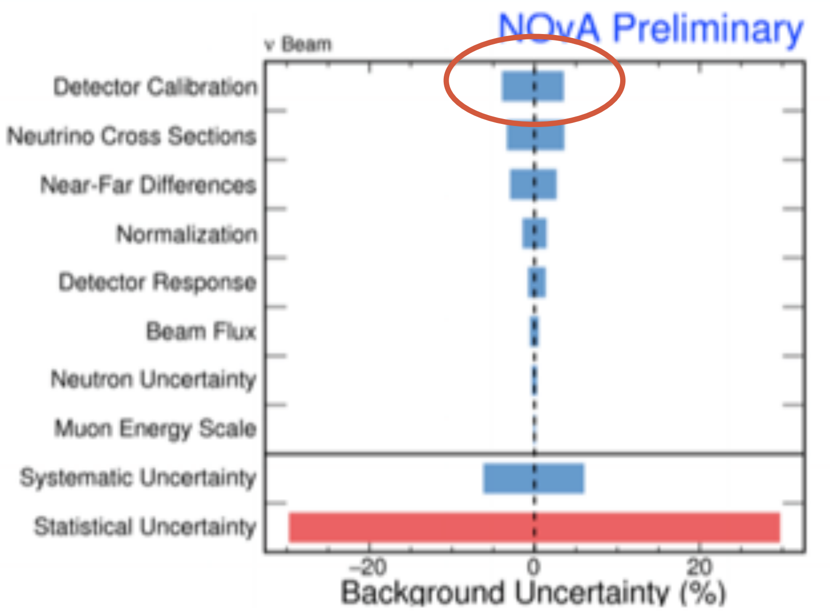
- Apply RPA with uncertainties
- Vary axial mass by ±5%
- Include RPA-like effect for resonant events
- Tuning of non-resonant single pion and DIS processes with associated uncertainties
- After Genie tuning, still discrepancy in hadronic energy distribution



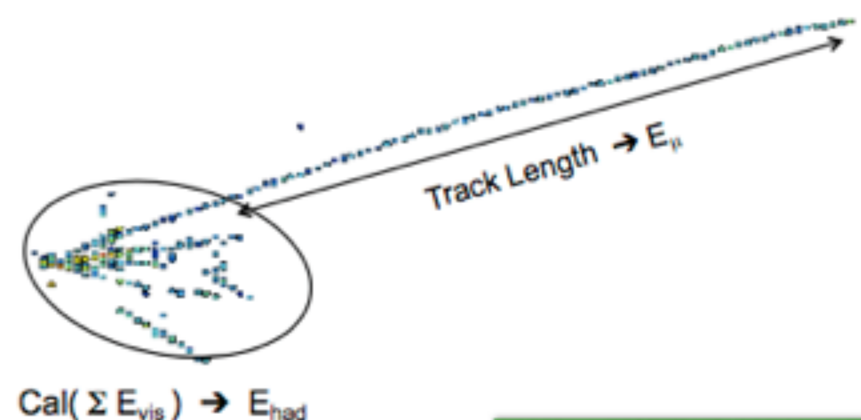

- Empirical MEC (2p-2h) model is added to achieve agreement with data
- Systematic error shifts enhancement between QE and resonant region
- Vary the fraction of np and nn(pp) pairs in initial state



# NOVA DETECTOR CALIBRATION



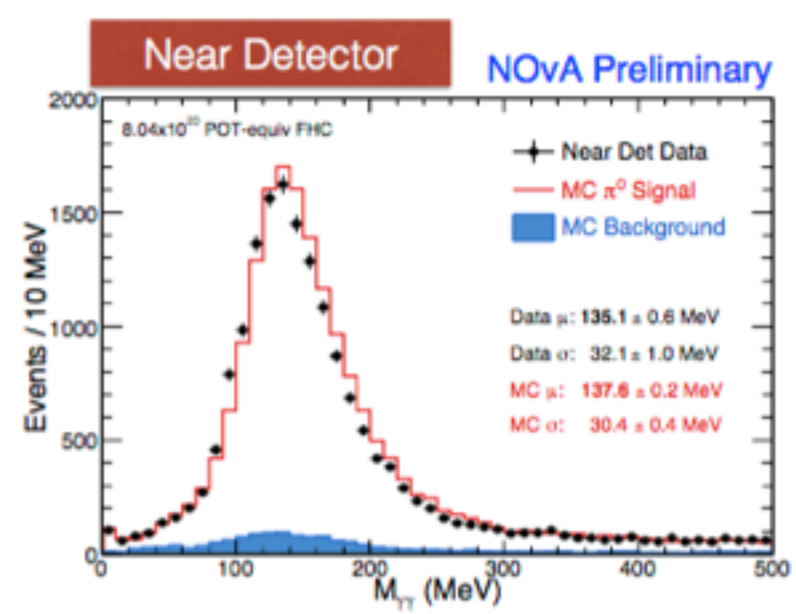

Detector Calibration is also a dominant source of systematic error




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

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

- Uncertainty estimated from maximum difference between the multiple probes, Michele e- spectrum, $\pi^0$ 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

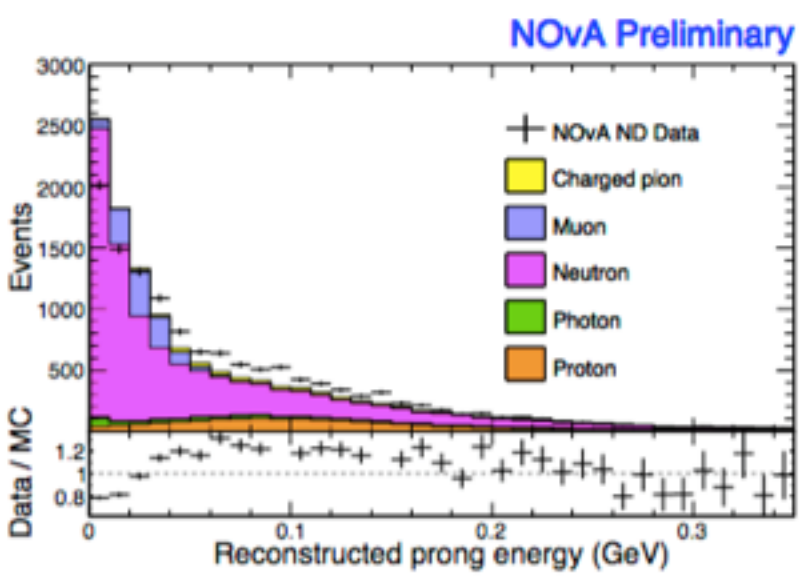


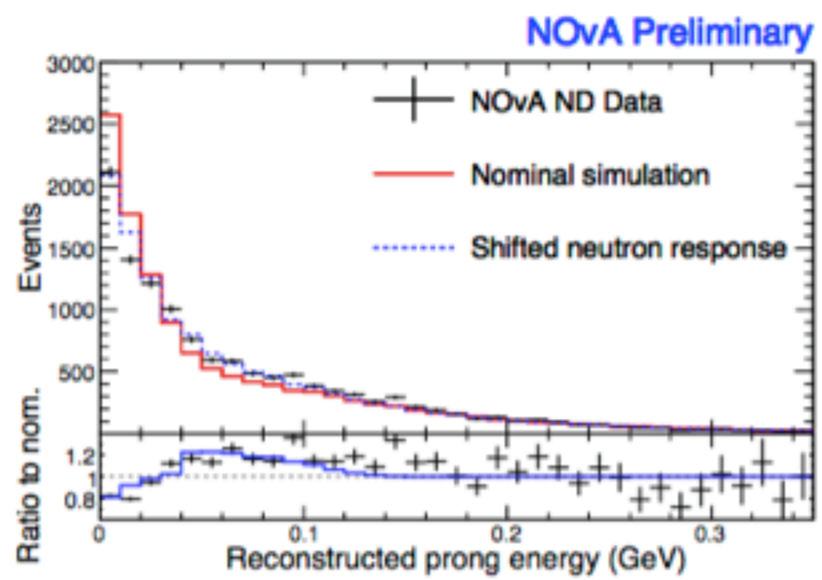

**Attenuation:** Using through going muons (cosmic or ν induced). Include WSF attenuation uncertainty to cover to differences seen in data and MC attention fits

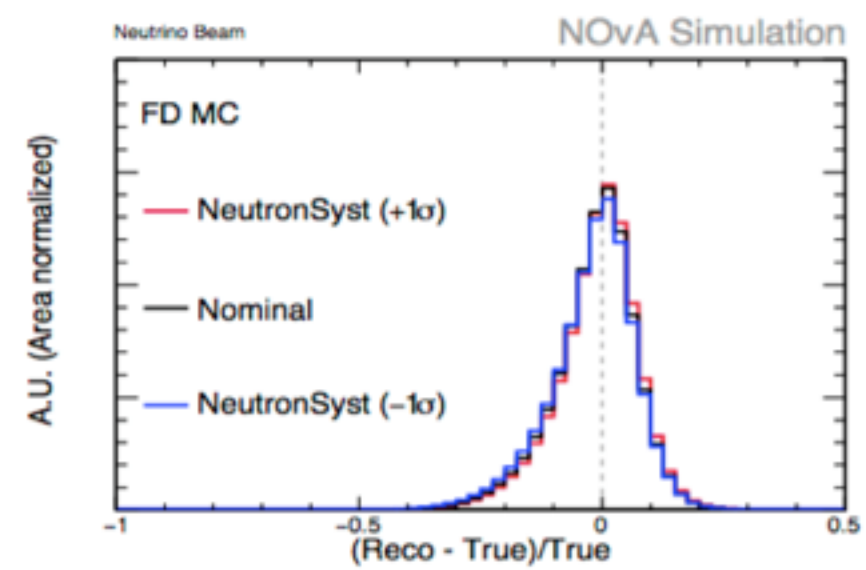
# NEUTRON UNCERTAINTY AT NOVA

NOvA observes discrepancy in neutron energy distribution

Scale low energy neutrons to cover the discrepancy



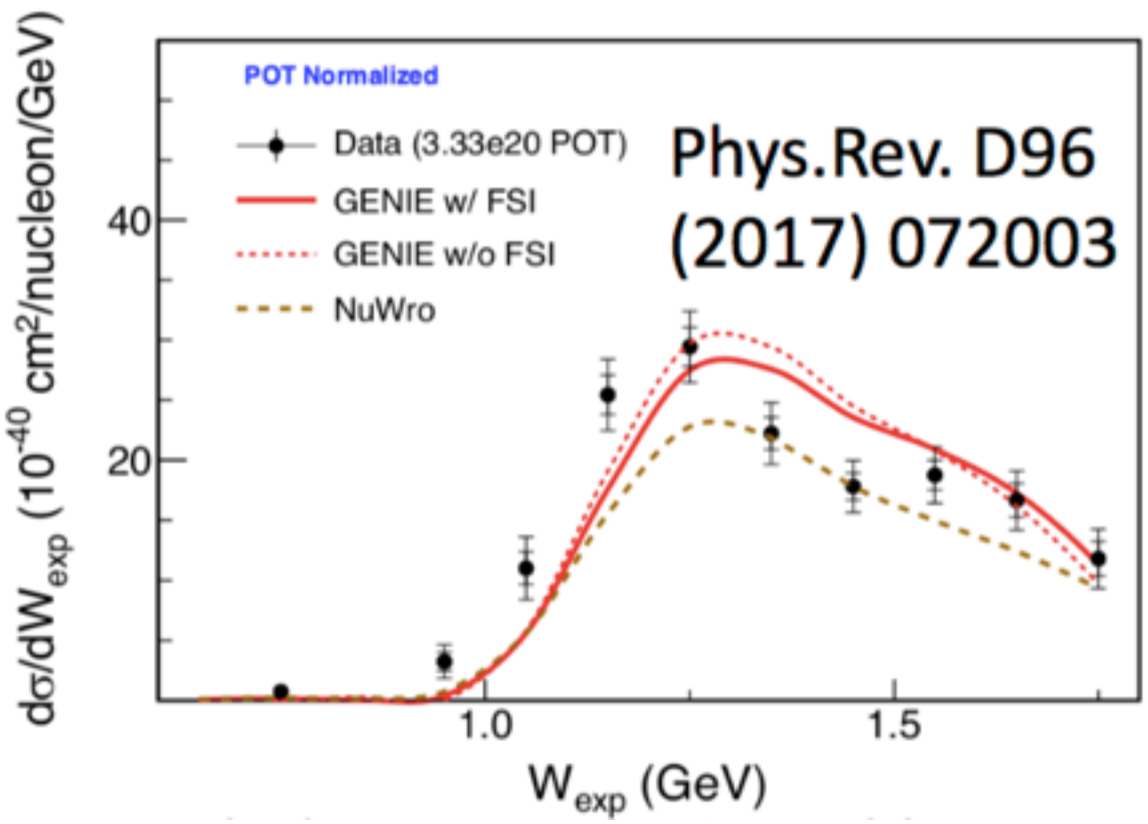



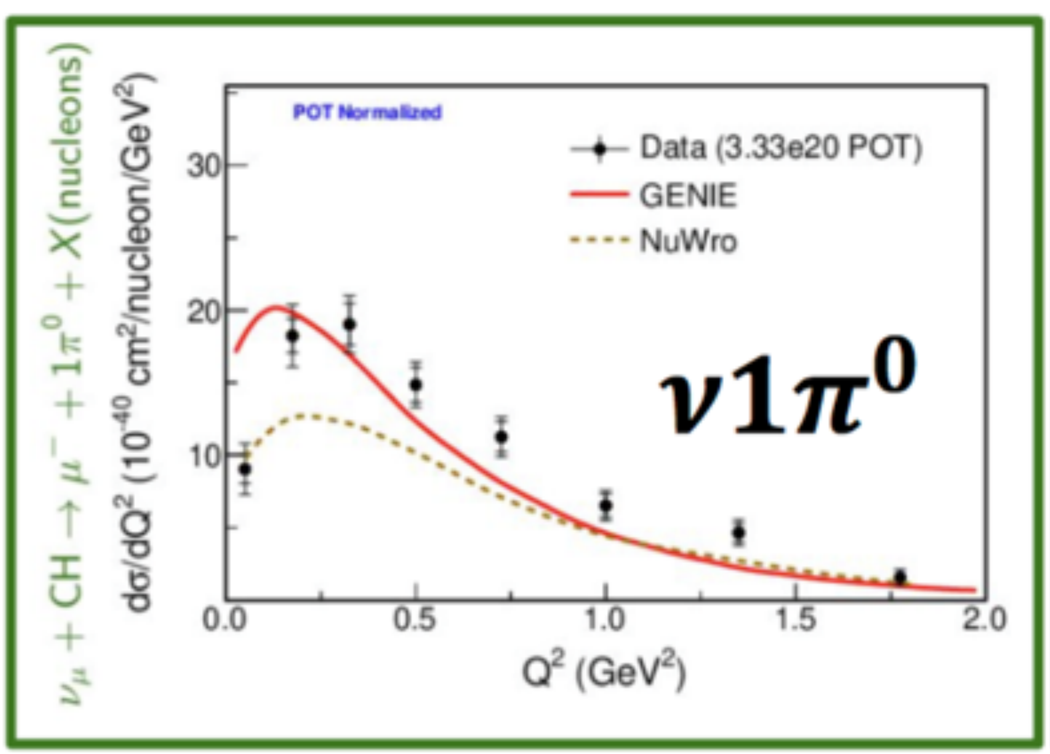

Many questions about this neutron energy distribution

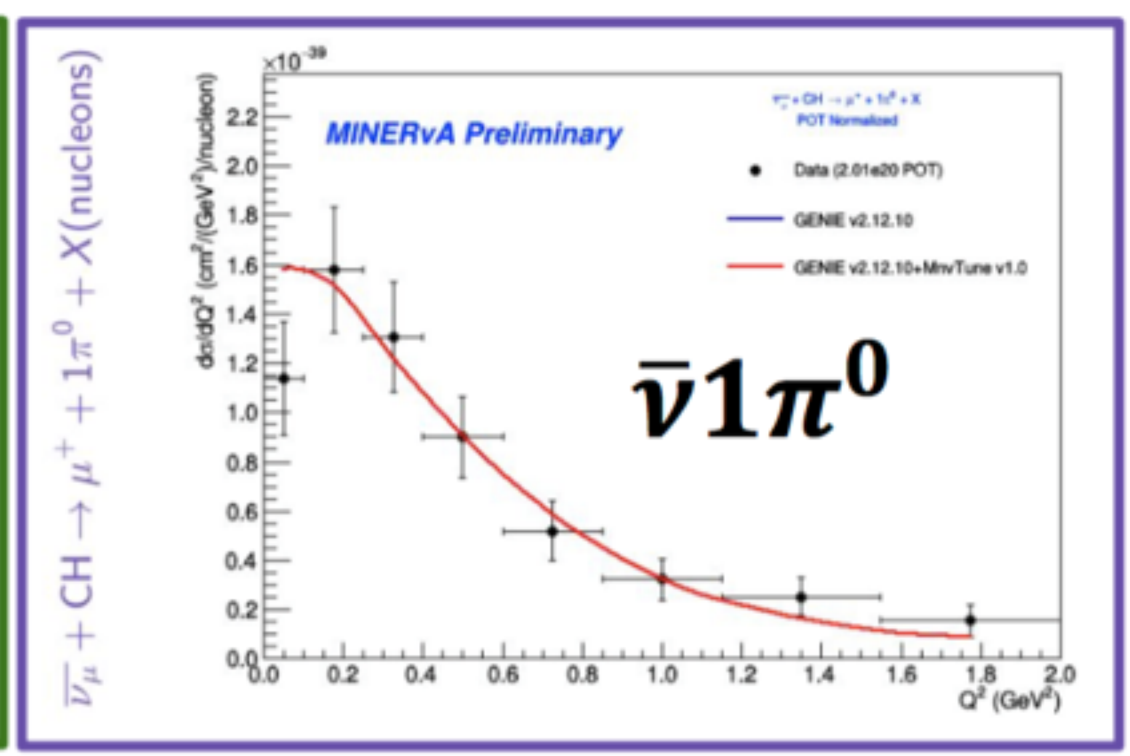
Community is interested in neutron reconstruction

# TUNING INTERACTIONS AT MINERVA (K. MCFARLAND)



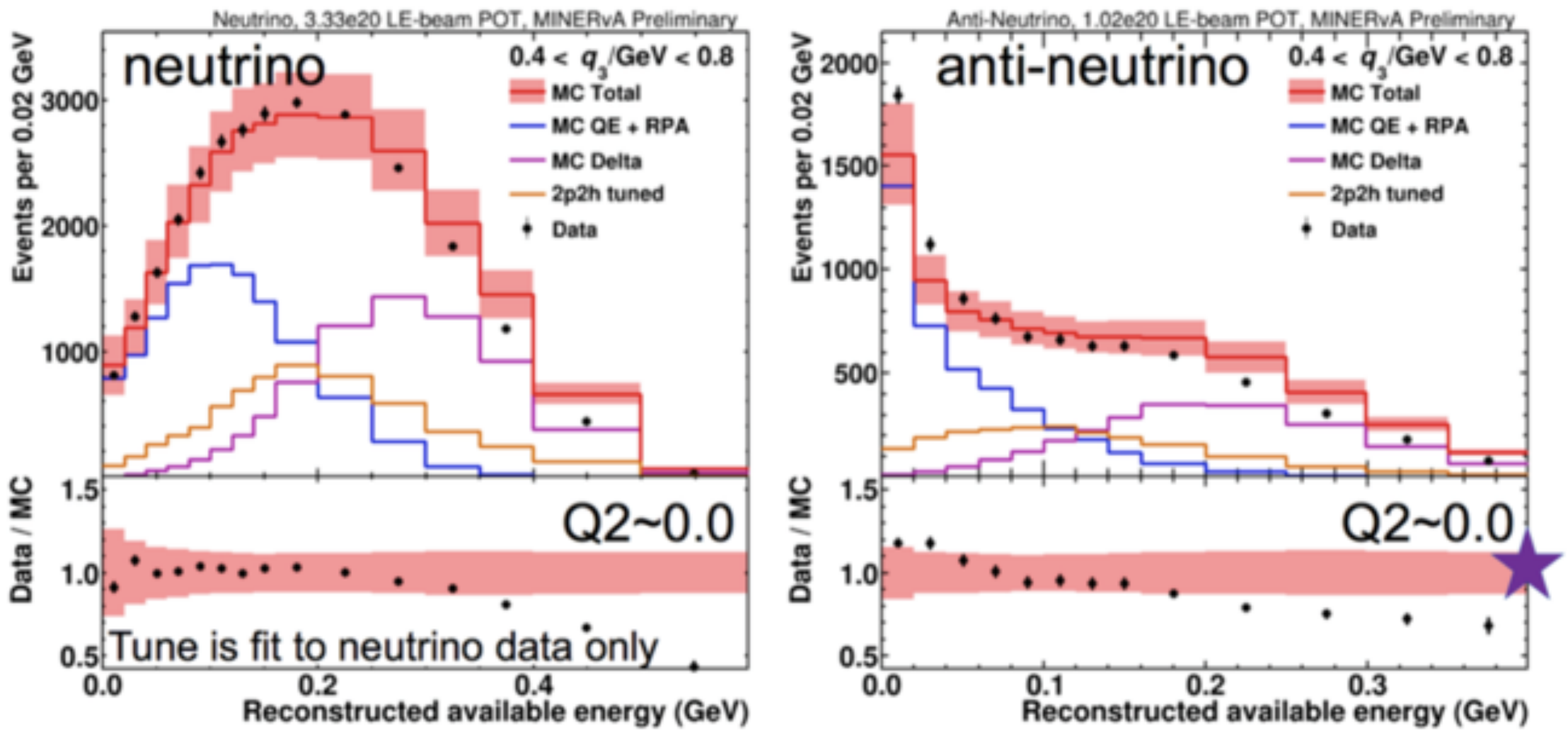

- W shift in single pion production
  - Fixed by correct treatment of interference terms or in-medium effects?
- Low $Q^2$ suppression appears in single pion (neutral) channels
  - Not-modeled nuclear effects?



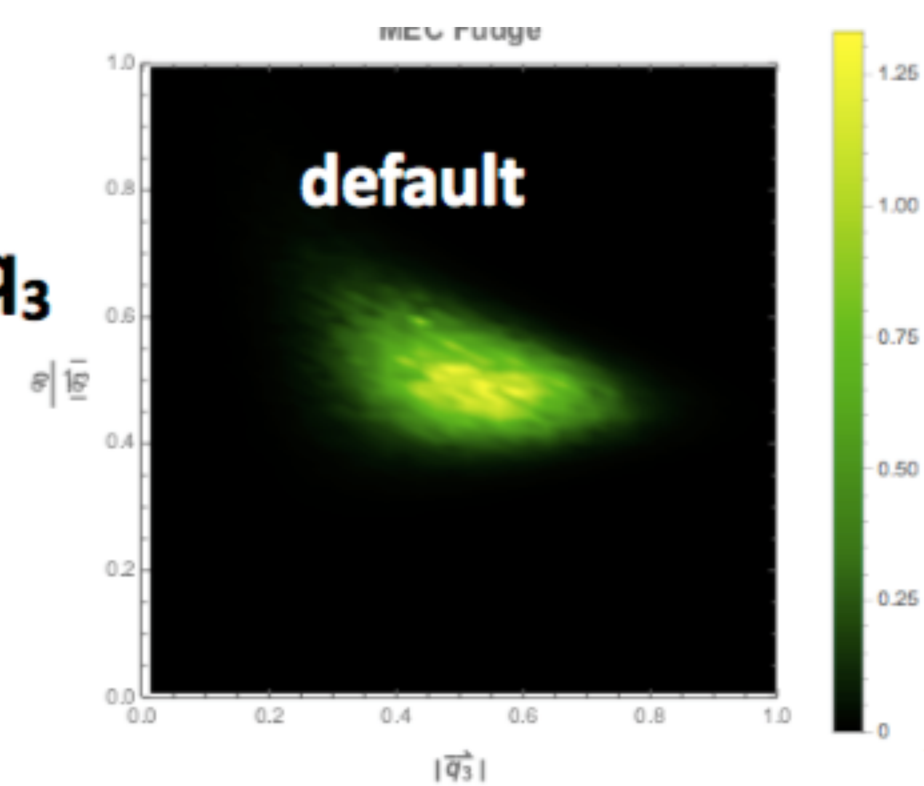

$$Q^2 = 2E_\nu\left(E_\mu - p_\mu \cos\theta_{\mu\nu}\right) - m_\mu^2 \quad (\mathrm{GeV^2/c^2})$$

# 2P-2H (?) ENHANCEMENT IN MINERVA DATA




- MINERvA observes excess where 2p-2h events typically reside in energy transfer
  - Larger than model of Nieves et. al.
- Empirical model can explain antineutrino data at MINERvA

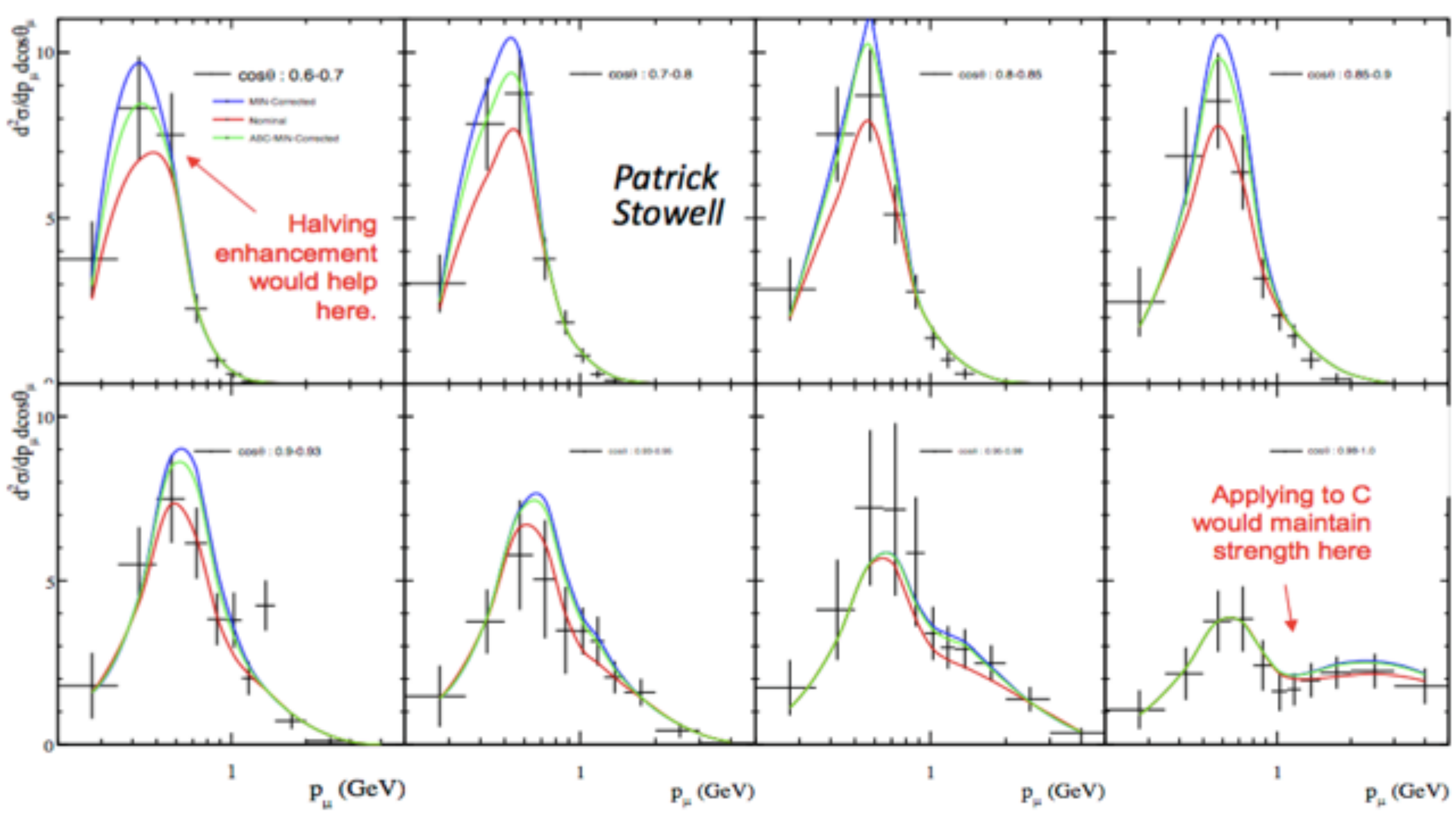
$q_0/q_3$



# COMPATIBLE WITH T2K AND NOVA

- Recall that T2K and NOvA both require enhancements of the 2p-2h to describe their near detector data
- Study applying MINERvA empirical model to T2K data (only constant energy term of cross section)

## Apply to T2K C term for CC0$\pi$

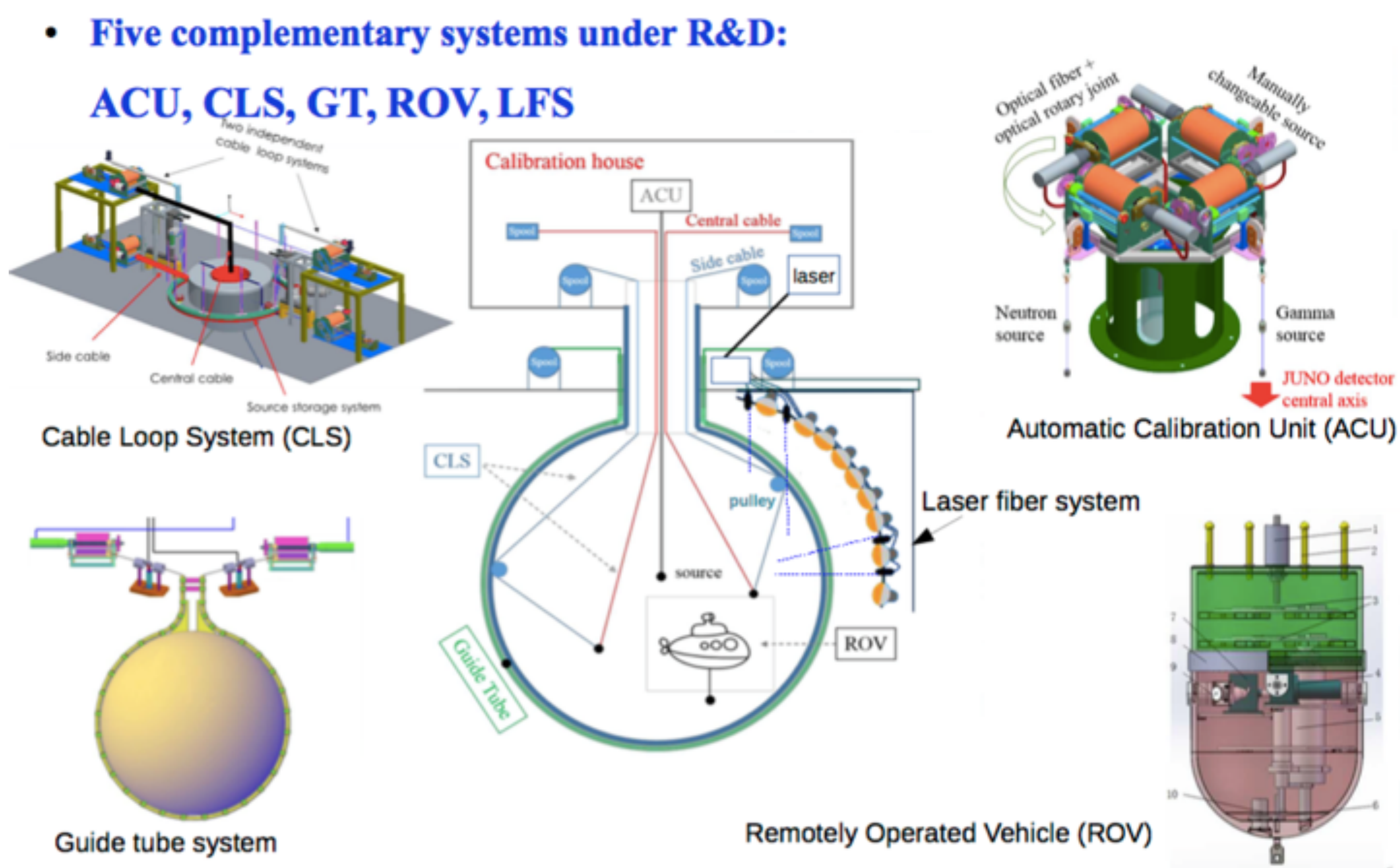



MINERvA tune, compared to data from Phys. Rev. D93, 112012 (2016)

Works well in some bins, no so well in others

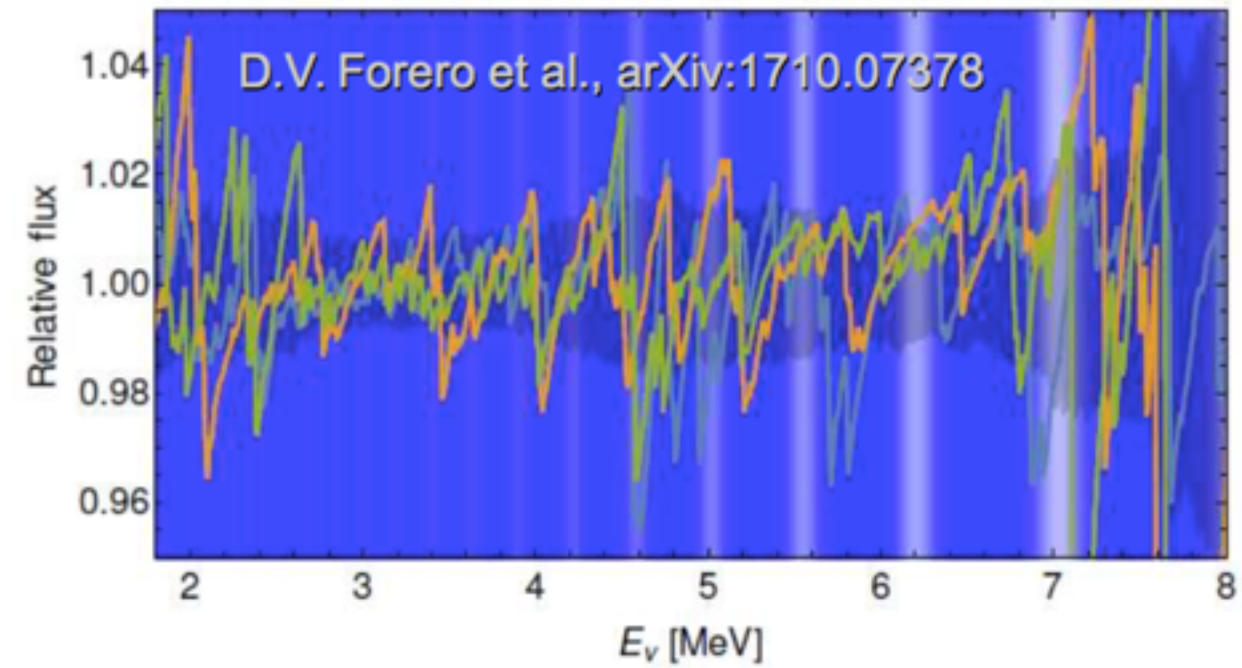
# SYSTEMATIC UNCERTAINTIES IN JUNO (J. TANG)

- Energy scale calibration at <1% is needed
- Daya Bay has achieved 0.5% through meticulous calibration
- R&D on multiple approaches to move deploy calibration sources in the detector volume
- Work to understand gamma and electron energy responses



# REACTOR NEUTRINO SPECTRUM

- ➤ The reactor flux can have structure
- ➤ If not measured and modeled, can effect mass hierarchy measurement




Relative difference of 3 synthetic spectra to spectrum predicted from ILL data (Huber+Mueller model)

Near detector to measure the flux:

- JUNO – Taishan Antineutrino Observatory (JUNO-TAO) acts as a near detector.
- Started R&D

- 2.9 ton Gd-LS in spherical vessel

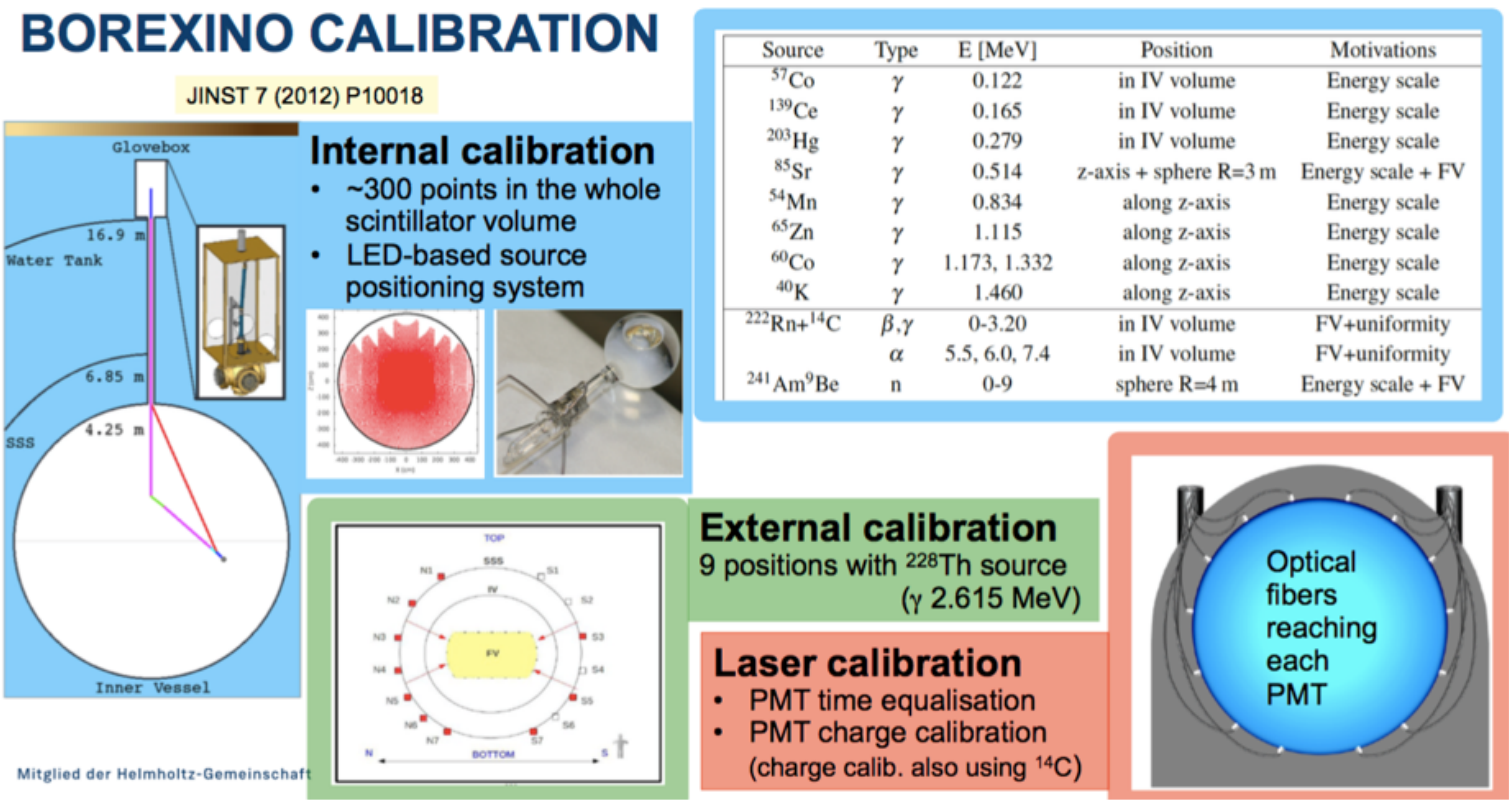
- Outer buffer oil in stainless steel vessel

→ Central detector size ~ 2 m x 2 m x 2 m

→ @35 m to reactor (4.6GW): 10x JUNO statistics (6yr) after 1 year

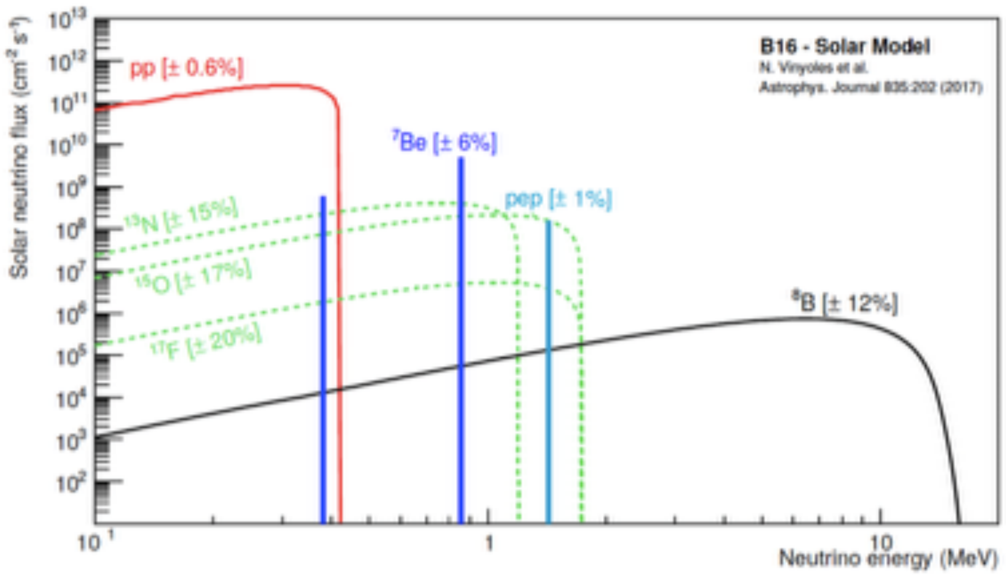
# BOREXINO SYSTEMATIC ERRORS & ANALYSIS (L. LUDHOVA)

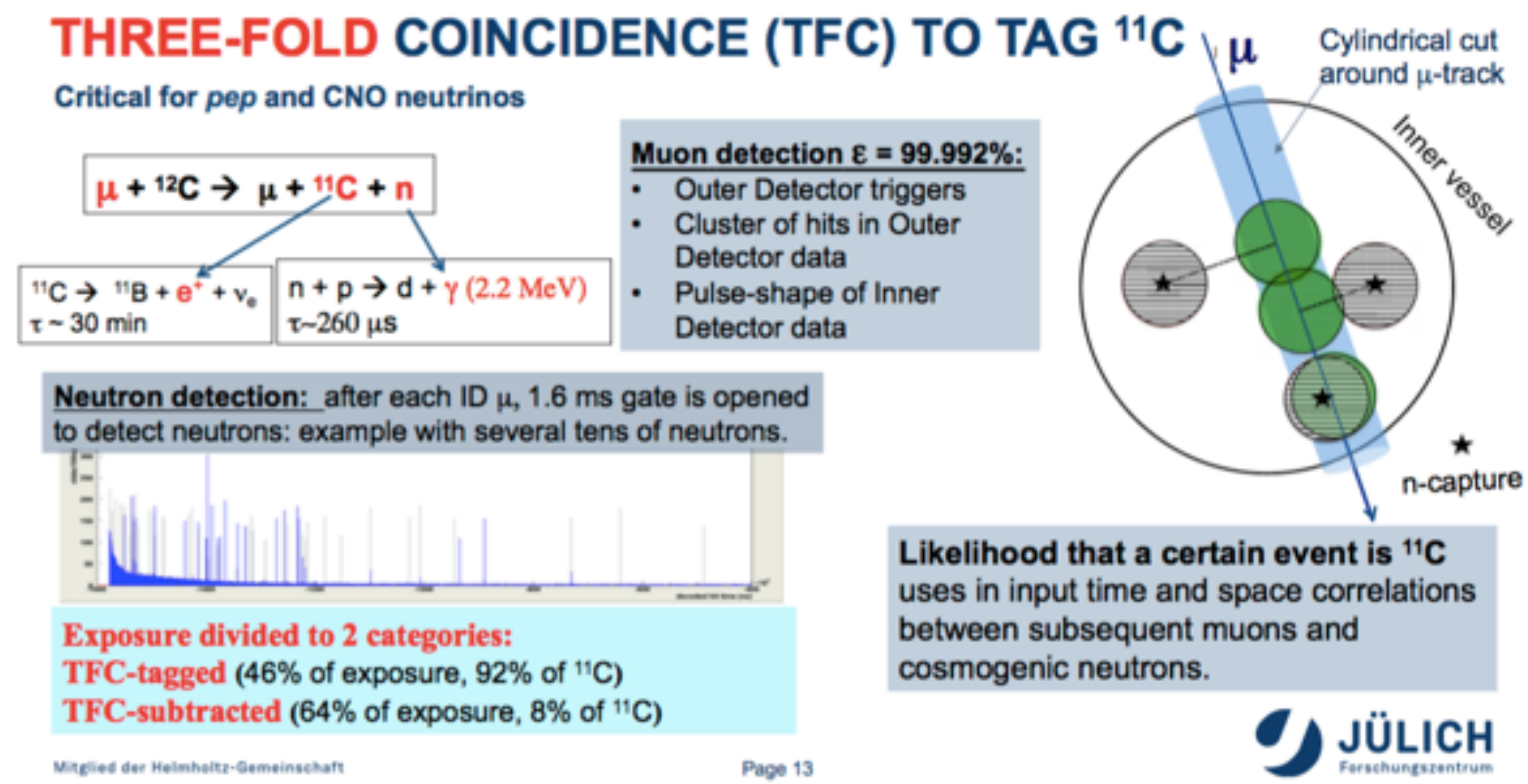
- Calibration includes radioactive sources (internal and external), laser calibration




| Source | Type | E [MeV] | Position | Motivations |
|---|---|---|---|---|
| $^{57}$Co | $\gamma$ | 0.122 | in IV volume | Energy scale |
| $^{139}$Ce | $\gamma$ | 0.165 | in IV volume | Energy scale |
| $^{203}$Hg | $\gamma$ | 0.279 | in IV volume | Energy scale |
| $^{85}$Sr | $\gamma$ | 0.514 | z-axis + sphere R=3 m | Energy scale + FV |
| $^{54}$Mn | $\gamma$ | 0.834 | along z-axis | Energy scale |
| $^{65}$Zn | $\gamma$ | 1.115 | along z-axis | Energy scale |
| $^{60}$Co | $\gamma$ | 1.173, 1.332 | along z-axis | Energy scale |
| $^{40}$K | $\gamma$ | 1.460 | along z-axis | Energy scale |
| $^{222}$Rn+$^{14}$C | $\beta,\gamma$ | 0-3.20 | in IV volume | FV+uniformity |
| | $\alpha$ | 5.5, 6.0, 7.4 | in IV volume | FV+uniformity |
| $^{241}$Am$^{9}$Be | n | 0-9 | sphere R=4 m | Energy scale + FV |

# DETECTING CNO?

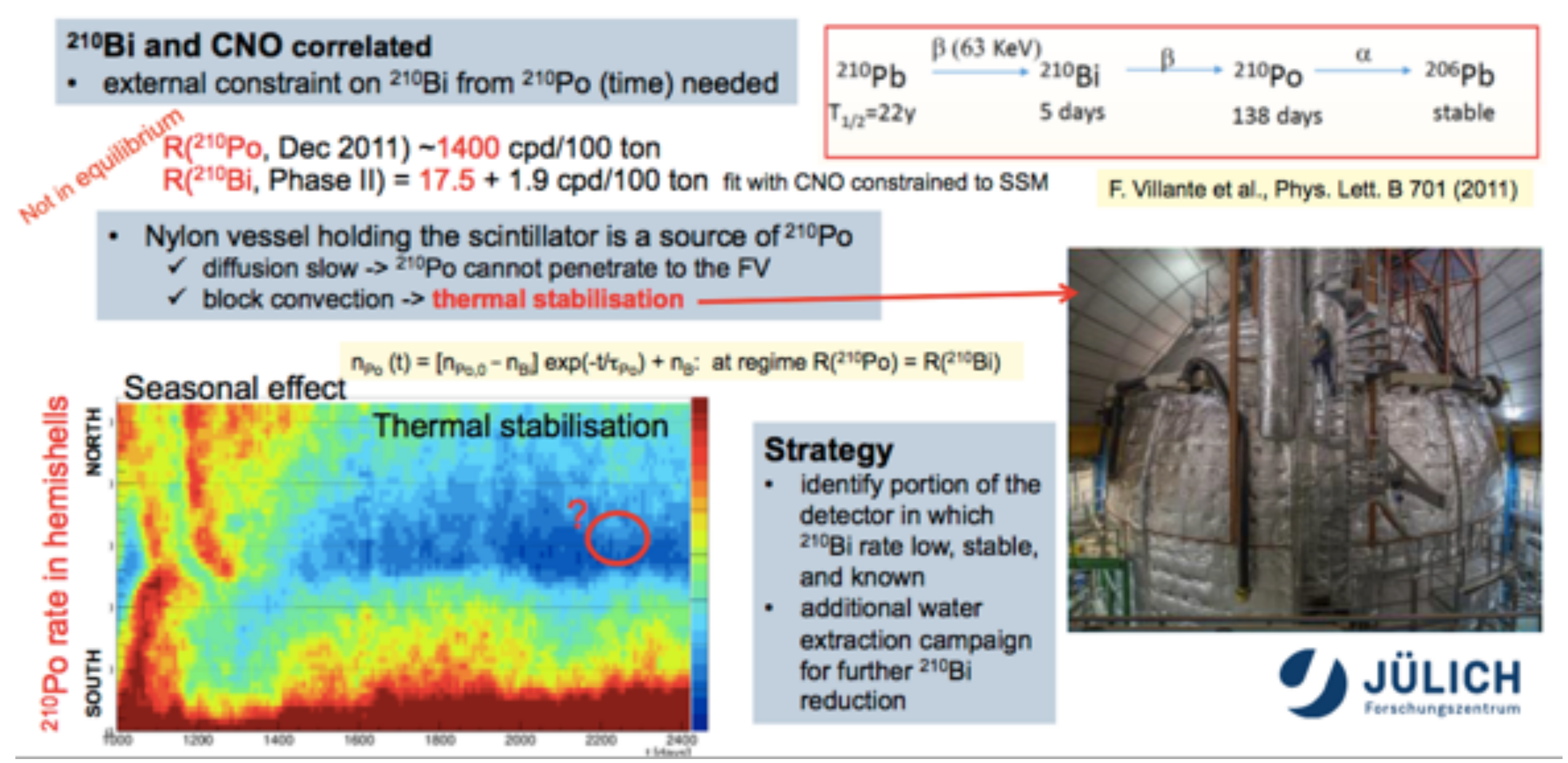



Borexino aims to detect CNO neutrinos

Tag cosmogenic $^{11}$C

Constrain $^{210}$Bi background



# UNCERTAINTIES IN ATMOSPHERIC NEUTRINOS (J. P. YANEZ)

- Review of systematic errors for atmospheric neutrino oscillation measurements
- Experiments generally don't give the relevance of systematic errors
- Sometimes give the pulls on systematic parameters from fits

IceCube DeepCore Oscillations

| Parameters | Priors | Best Fit NO | Best Fit IO |
|---|---|---|---|
| Flux and cross section parameters | | | |
| Neutrino event rate [% of nominal] | no prior | 85 | 85 |
| $\Delta\gamma$ (spectral index) | 0.00±0.10 | -0.02 | -0.02 |
| $M_A$ (resonance) [GeV] | 1.12±0.22 | 0.92 | 0.93 |
| $\nu_e + \bar{\nu}_e$ relative normalization [%] | 100±20 | 125 | 125 |
| NC relative normalization [%] | 100±20 | 106 | 106 |
| Hadronic flux, energy dependent [$\sigma$] | 0.00±1.00 | -0.56 | -0.59 |
| Hadronic flux, zenith dependent [$\sigma$] | 0.00±1.00 | -0.55 | -0.57 |
| Detector parameters | | | |
| overall optical eff. [%] | 100±10 | 102 | 102 |
| relative optical eff., lateral [$\sigma$] | 0.0±1.0 | 0.2 | 0.2 |
| relative optical eff., head-on [a.u.] | no prior | -0.72 | -0.66 |
| Background | | | |
| Atm. $\mu$ contamination [% of sample] | no prior | 5.5 | 5.6 |

Flux and cross section parameters pulled significantly in the fit, indicating these are dominant systematic effects

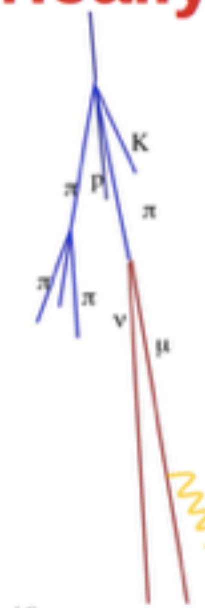
Better reporting of systematic errors in the future?

# IMPROVING FLUX CALCULATIONS

- MCEq numerical calculation tool
- New hadron production data
- Using fits measurements of primary fluxes

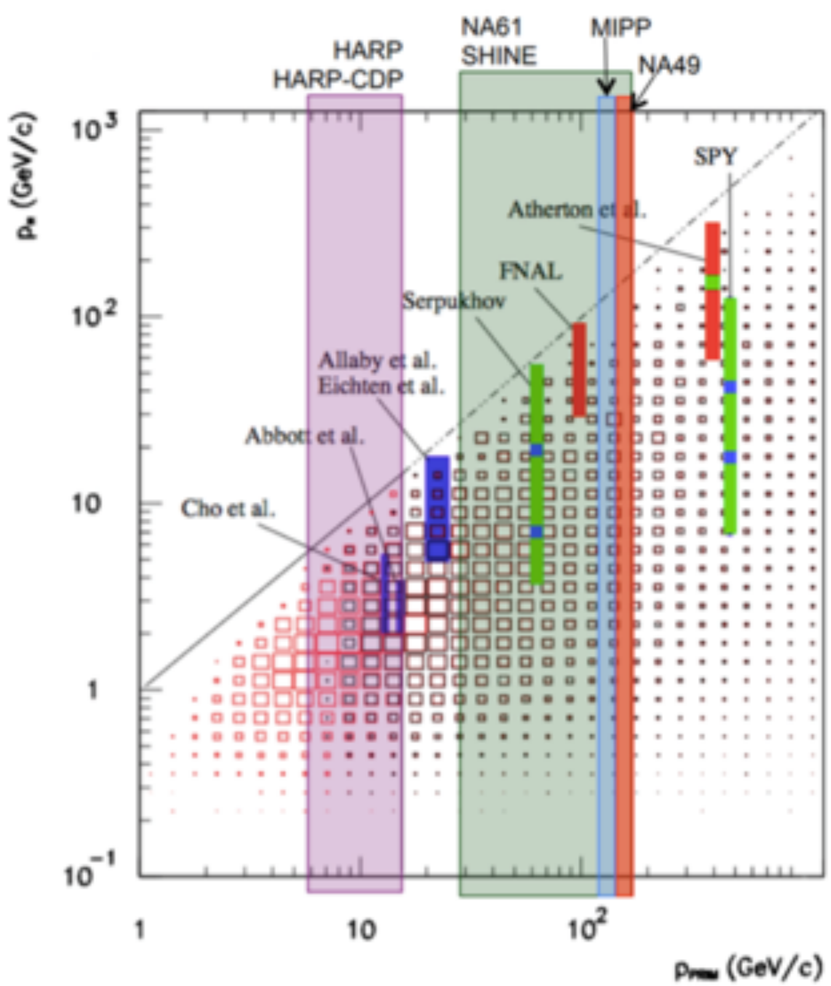
## -solving transport equations numerically

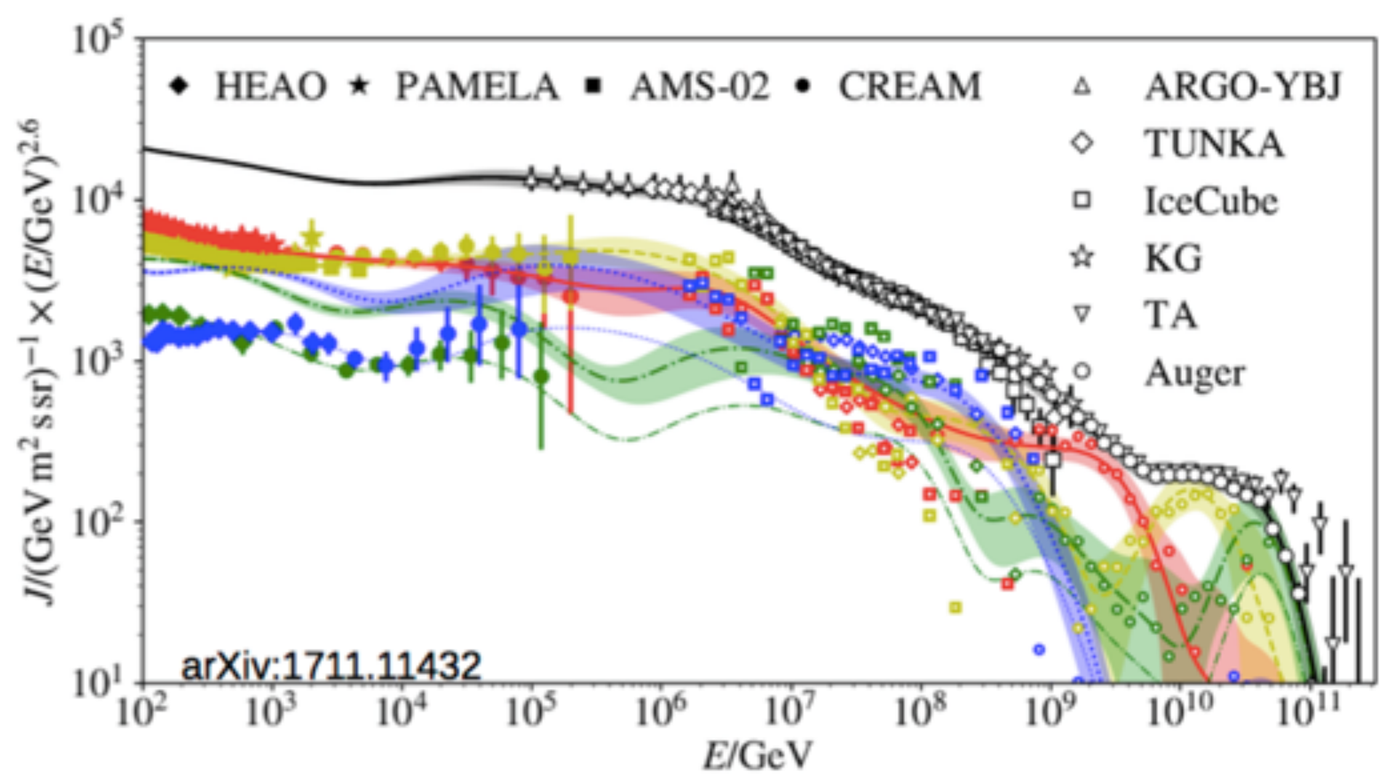
$$\frac{\mathrm{d}\Phi_h(E,X)}{\mathrm{d}X} = -\frac{\Phi_h(E,X)}{\lambda_{\mathrm{int},h}(E)} \quad \text{Interactions with air}$$
$$-\frac{\Phi_h(E,X)}{\lambda_{\mathrm{dec},h}(E,X)} \quad \text{Decays}$$
$$-\frac{\partial}{\partial E}(\mu(E)\Phi_h(E,X)) \quad \text{Continuous losses}$$
$$+\sum_k \int_E^\infty \mathrm{d}E_k \frac{\mathrm{d}N_{k(E_k)\to h(E)}}{\mathrm{d}E} \frac{\Phi_k(E_k,X)}{\lambda_{\mathrm{int},k}(E_k)} \quad \text{Re-injection from interactions}$$
$$+\sum_k \int_E^\infty \mathrm{d}E_k \frac{\mathrm{d}N^{\mathrm{dec}}_{k(E_k)\to h(E)}}{\mathrm{d}E} \frac{\Phi_k(E_k,X)}{\lambda_{\mathrm{dec},k}(E_k,X)} \quad \text{Re-injection from decays}$$




$$X(h_0) = \int_0^{h_0} \mathrm{d}\ell\, \rho_{\mathrm{air}}(\ell)$$

A. Fedynitch, PANE2018
https://github.com/afedynitch/MCEq

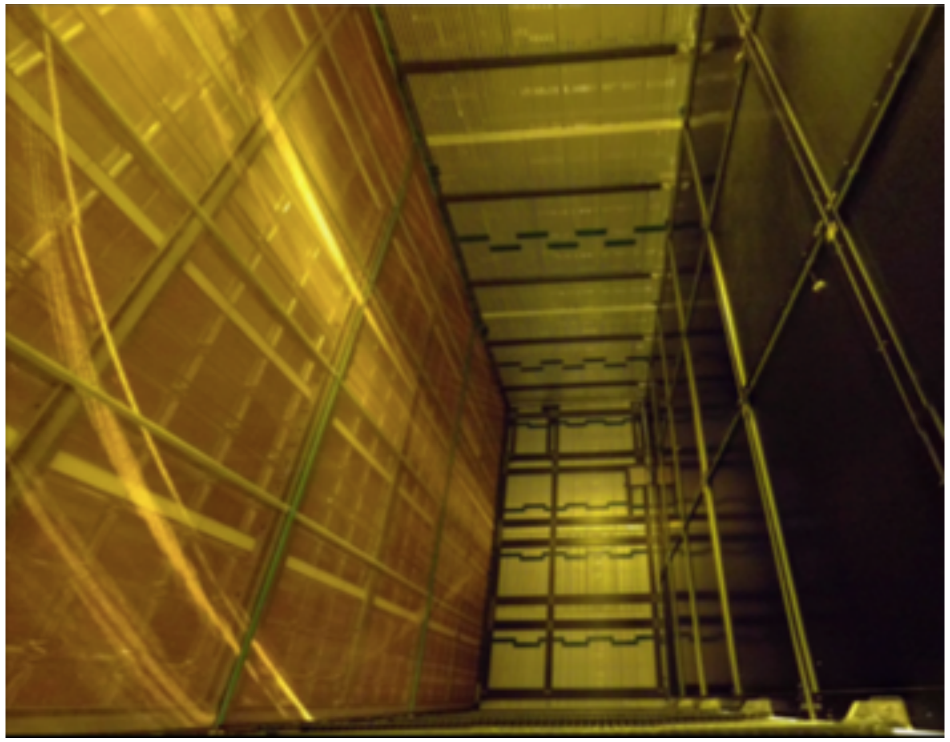


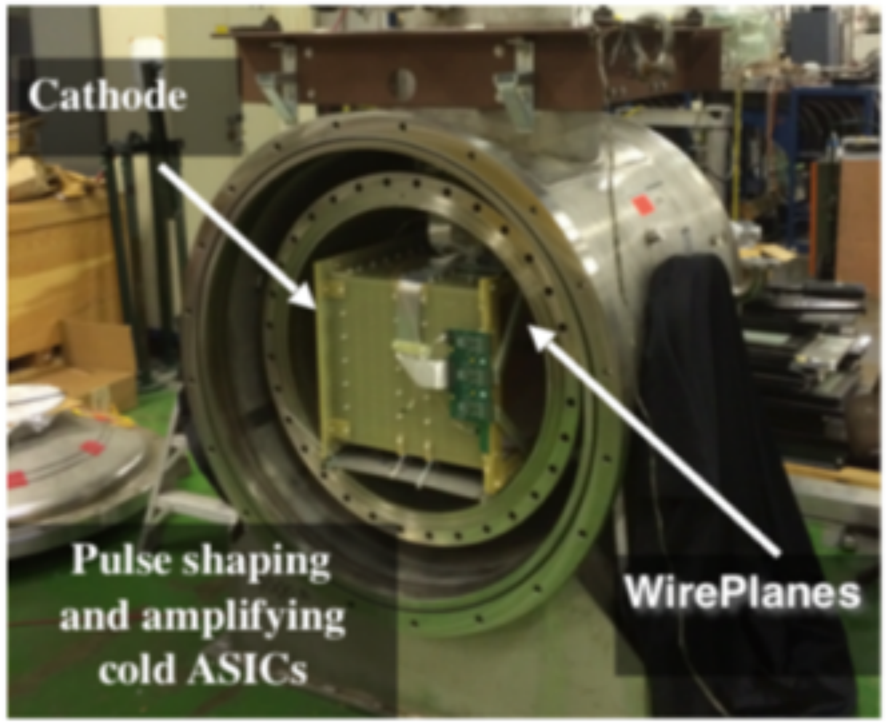
# TEST EXPERIMENTS (S. BORDONI)

- Test beam experiments will be necessary to understand detector responses and model them with 1% level accuracy

Proto-DUNE at CERN NP



LArIAT at Fermilab MCenter

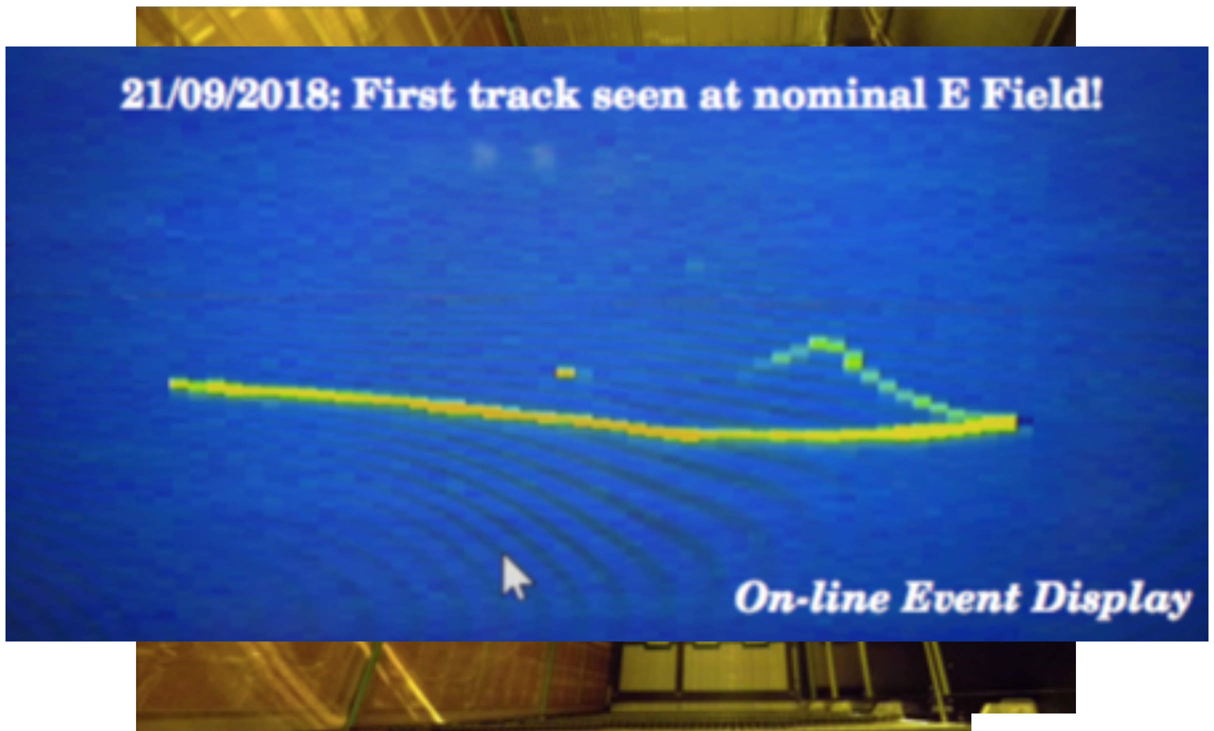



HPTC at CERN T10

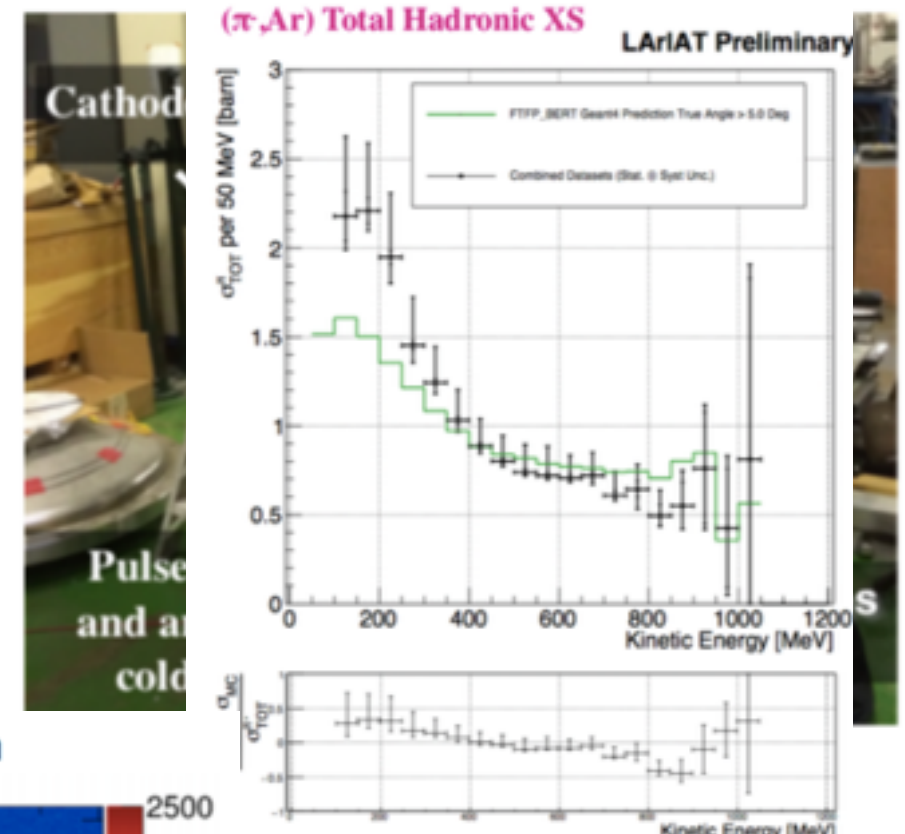
# TEST EXPERIMENTS (S. BORDONI)

- Test beam experiments will be necessary to understand detector responses and model them with 1% level accuracy

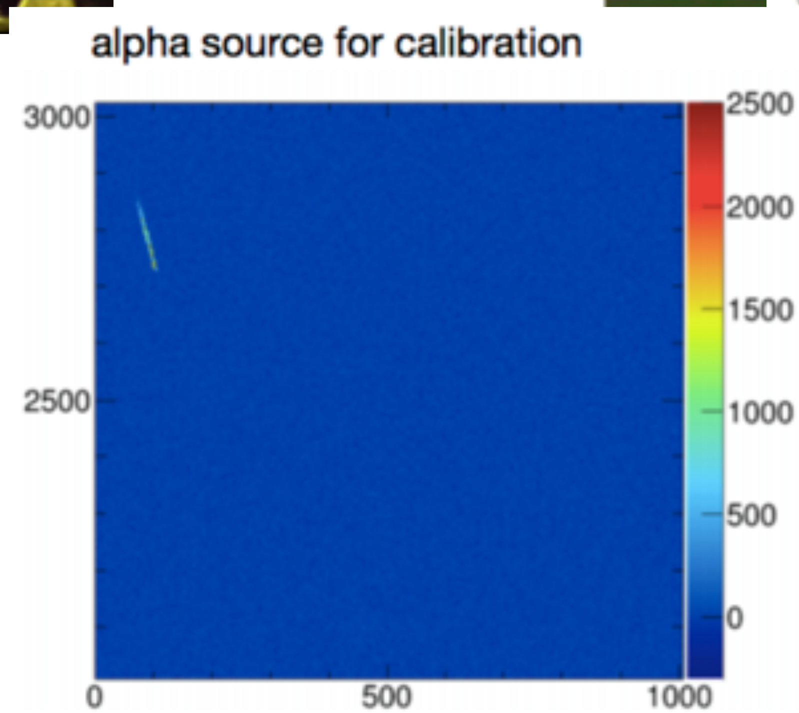
Proto-DUNE at CERN NP




LArIAT at Fermilab MCenter

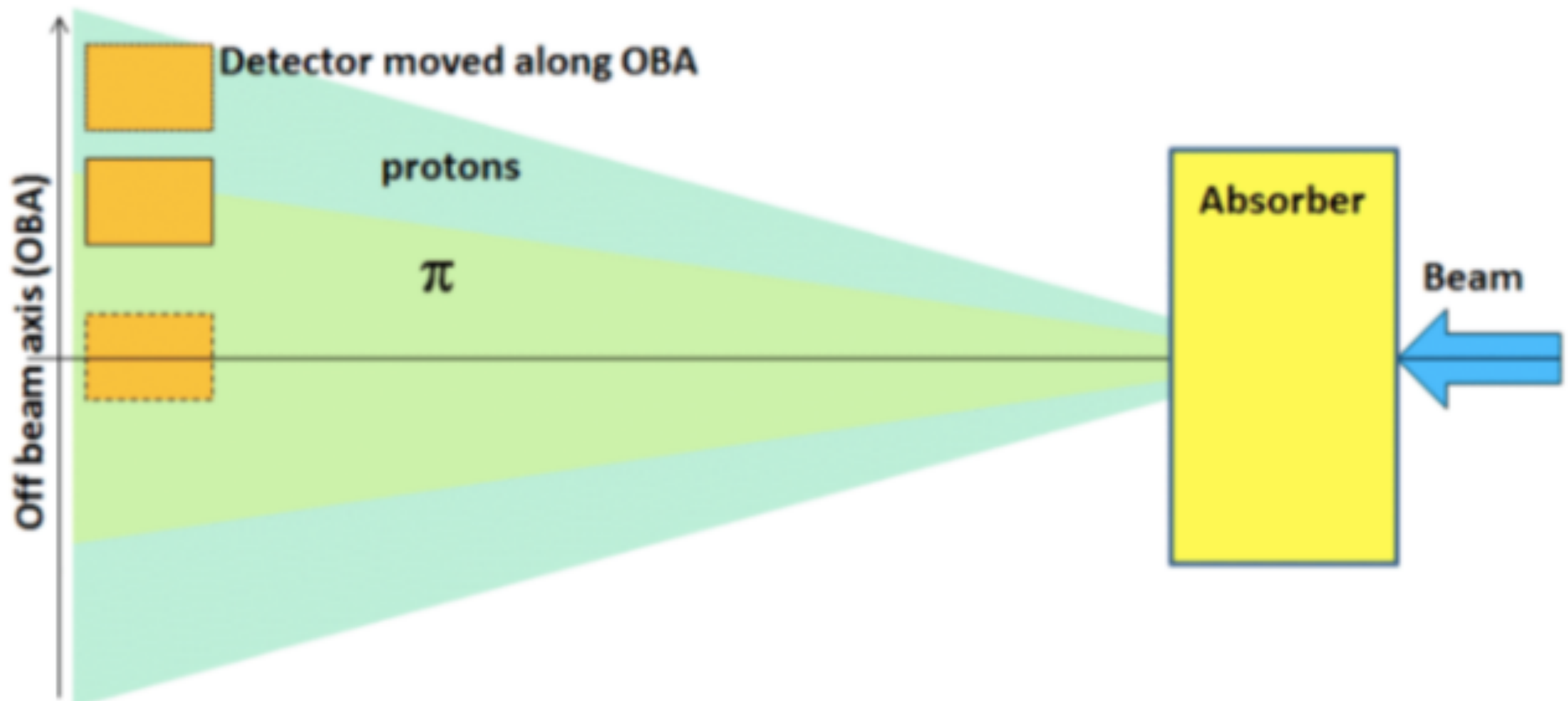



HPTC at CERN T10



# GETTING LOWER ENERGY BEAMS

- The HPTPC uses an off-axis beam to get lower energy particles



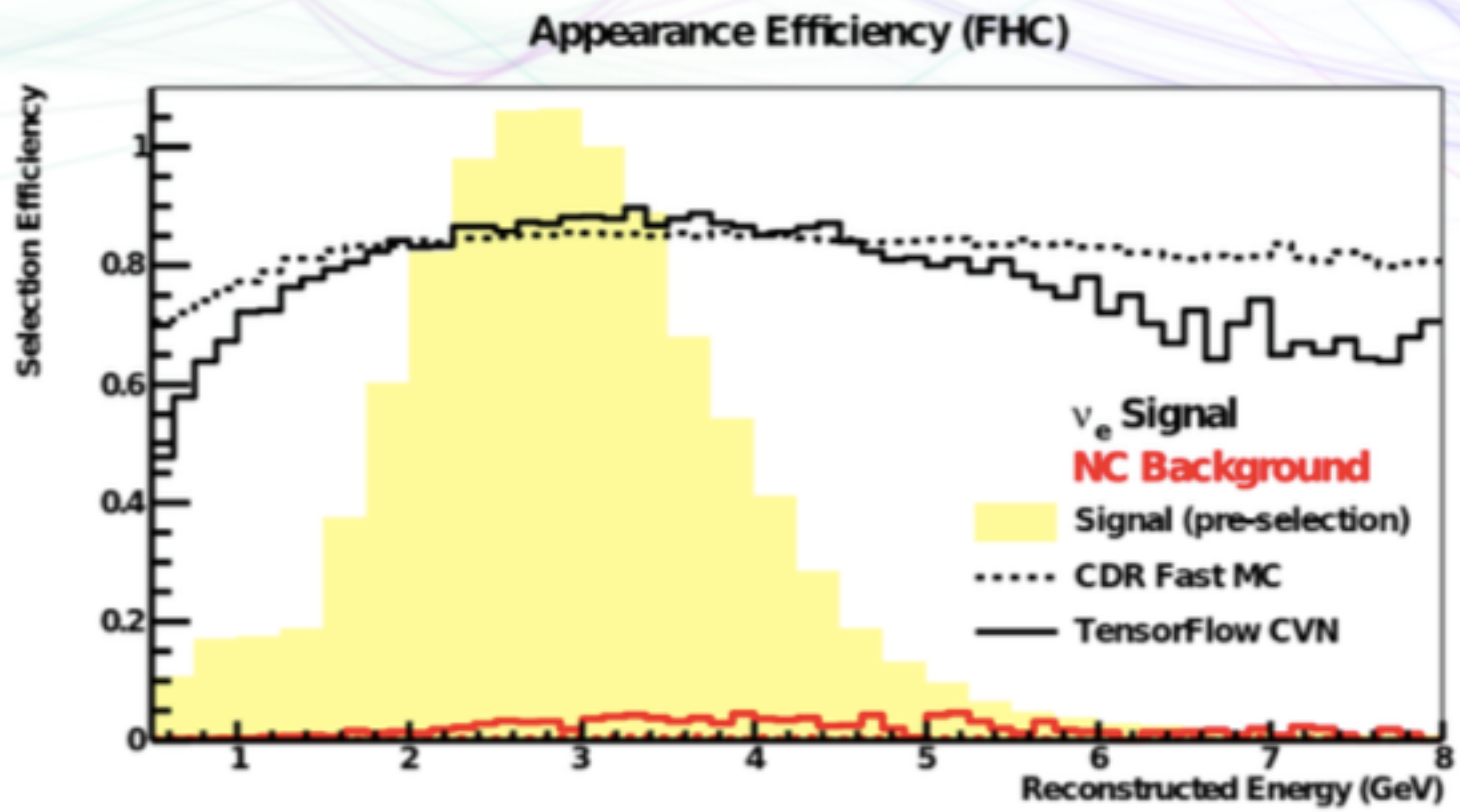

- Is there need for a low energy beam line at CERN after the shutdown

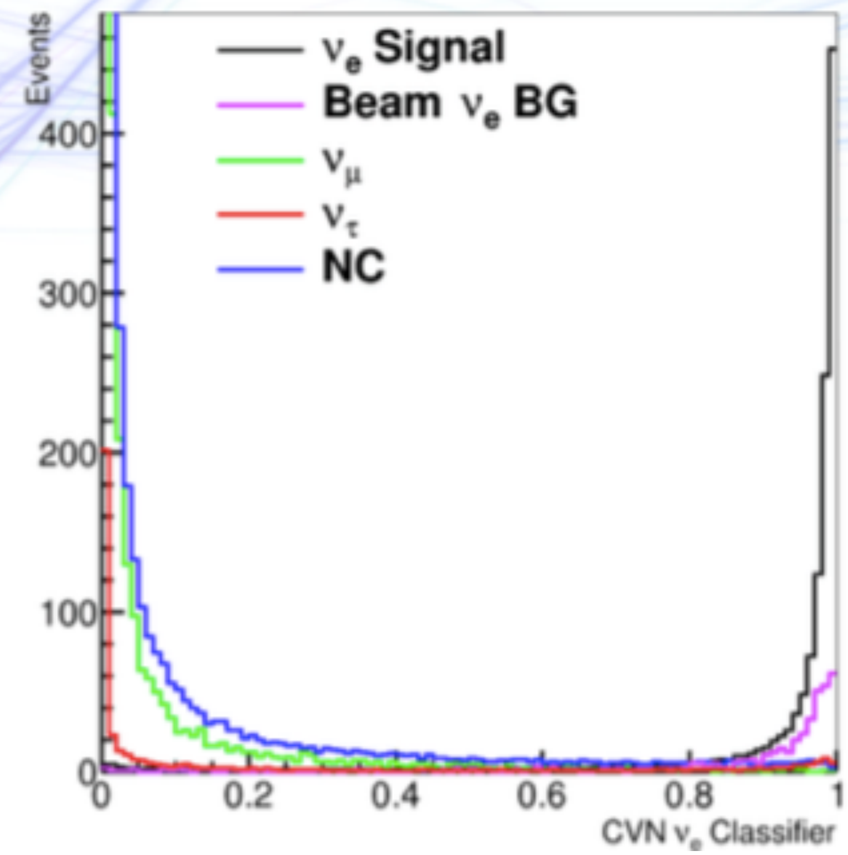
# SOME FINAL THOUGHTS

- Multiple experiments using machine learning techniques
  - Methods to avoid bias are being developed and applied
  - Are machine learning techniques applicable to WC and LS detectors?
- Control of systematic errors in neutrino interaction modeling critical for next generation oscillation experiments
  - We can't solely rely on models and trust that model development will be sufficient to control systematic errors
    - MINERvA, NOvA and T2K show enhancements of 2p-2h - no major model developments based on this data yet?
  - PRISM approaches adopted by Hyper-K and DUNE to over-constrain models
  - Interest in neutron detection - let's have more talks at next NNN
- Detector calibration is critical for all experiments
  - How are DUNE and Hyper-K planning to meeting their goals - more details at next NNN?

# THANK YOU

# MACHINE LEARNING AT DUNE (C. BACKHOUSE)




- CNN applied to event classification
- Can achieve signal efficiency similar to the fast MC from the CDR
- Also using CNN to classify and cluster hit-by-hit information - input to traditional reconstruction