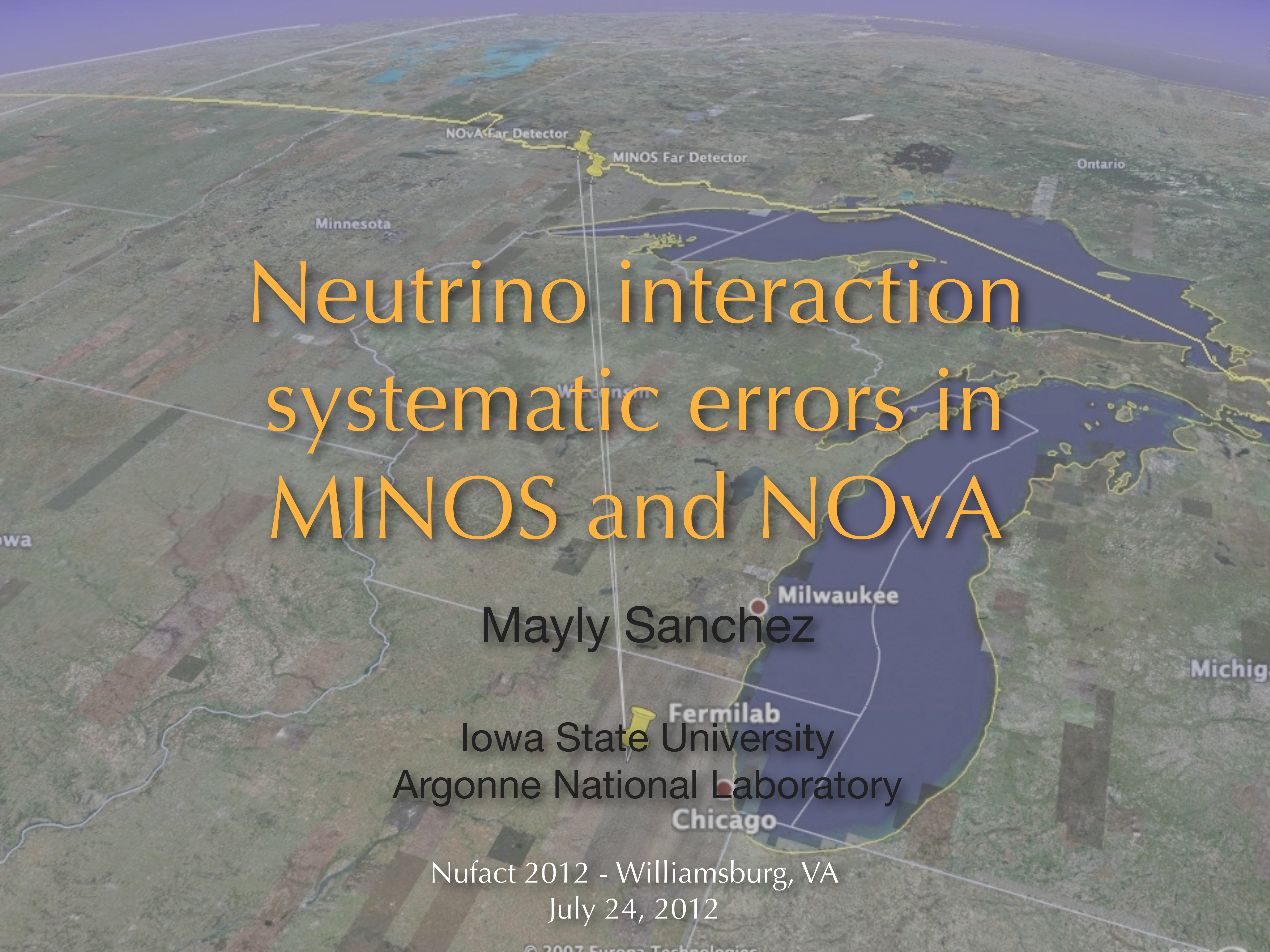


Neutrino interaction systematic errors in MINOS and NOvA

Mayly Sanchez

Iowa State University
Argonne National Laboratory

Nufact 2012 - Williamsburg, VA
July 24, 2012

MINOS and NOvA in a nutshell

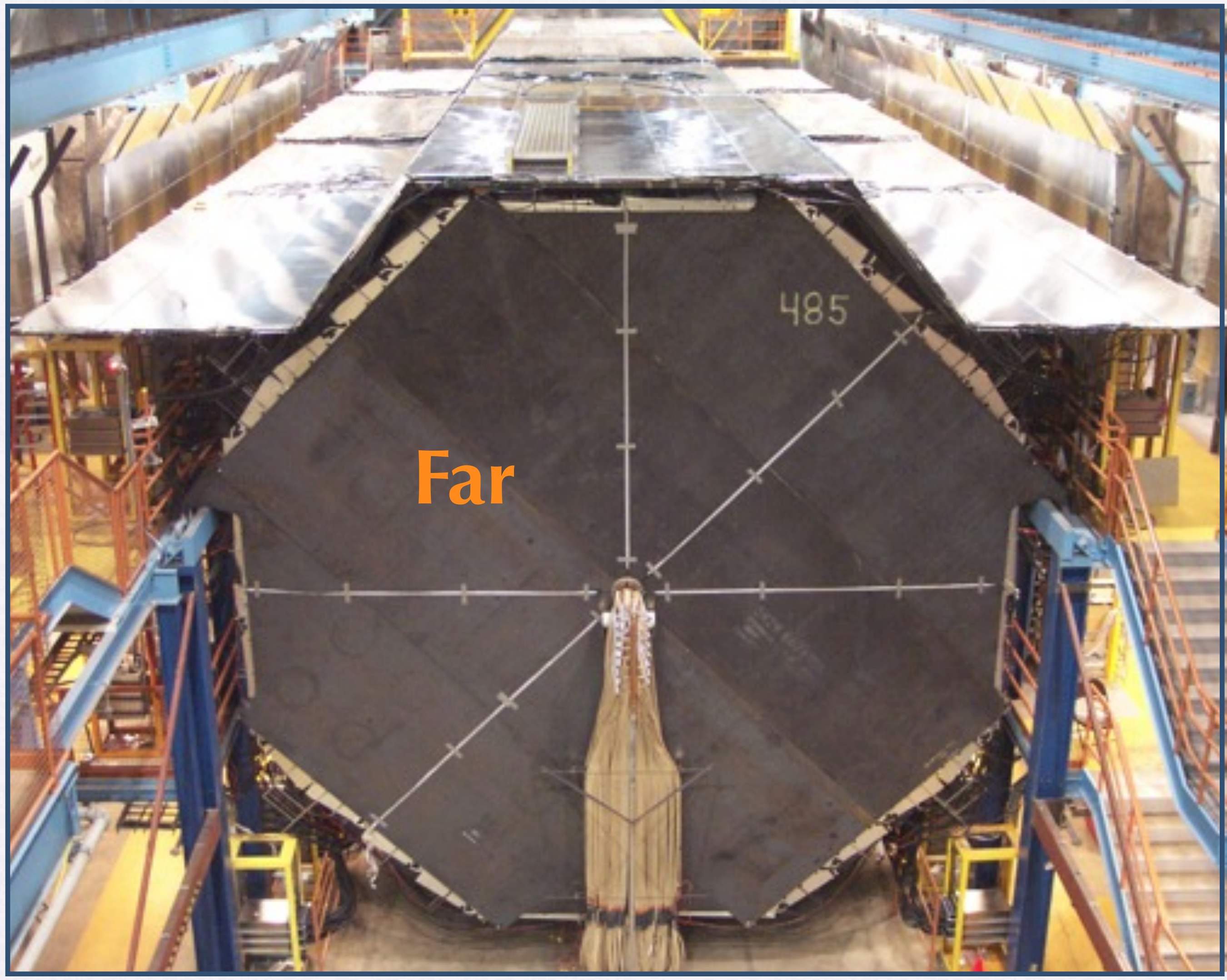
- Produce a high intensity beam of muon neutrinos at Fermilab.
- Measure background at the Near Detector and use it to predict the Far Detector spectrum.
  - Many uncertainties are expected to cancel.
  - Similar detectors ensure that **neutrino interaction related uncertainties** largely cancel.
- If neutrinos oscillate we will observe a distortion in the data at the Far Detector at either site.

1st/2nd generation
← long baseline →

See more general MINOS and NOvA talks on Friday

The MINOS detectors

- Functionally identical: **Near and Far detectors**
- Octogonal steel planes (2.54cm thick ~1.44X_0)
- Alternating with planes of scintillator strips (4.12cm wide, Moliere rad ~3.7cm).
  - **Near (ND)**: ~ 1kton, 282 steel squashed octagons. Partially instrumented.
  - **Far (FD)**: 5.4 kton, 486 (8m/octagon) fully instrumented planes.



Neutrino event topologies in MINOS

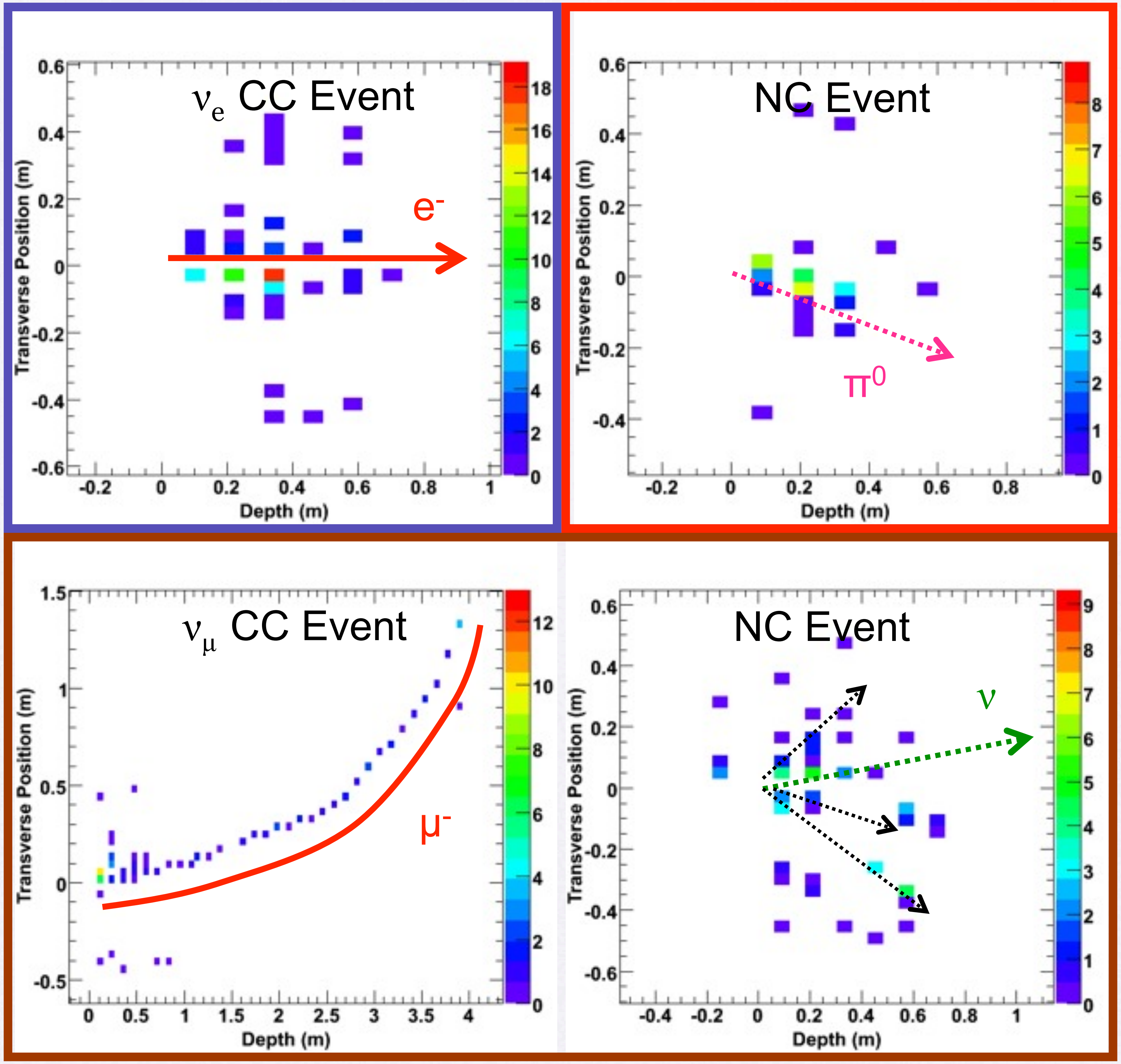
To select ν_e CC we focus on finding compact showers.

MC events

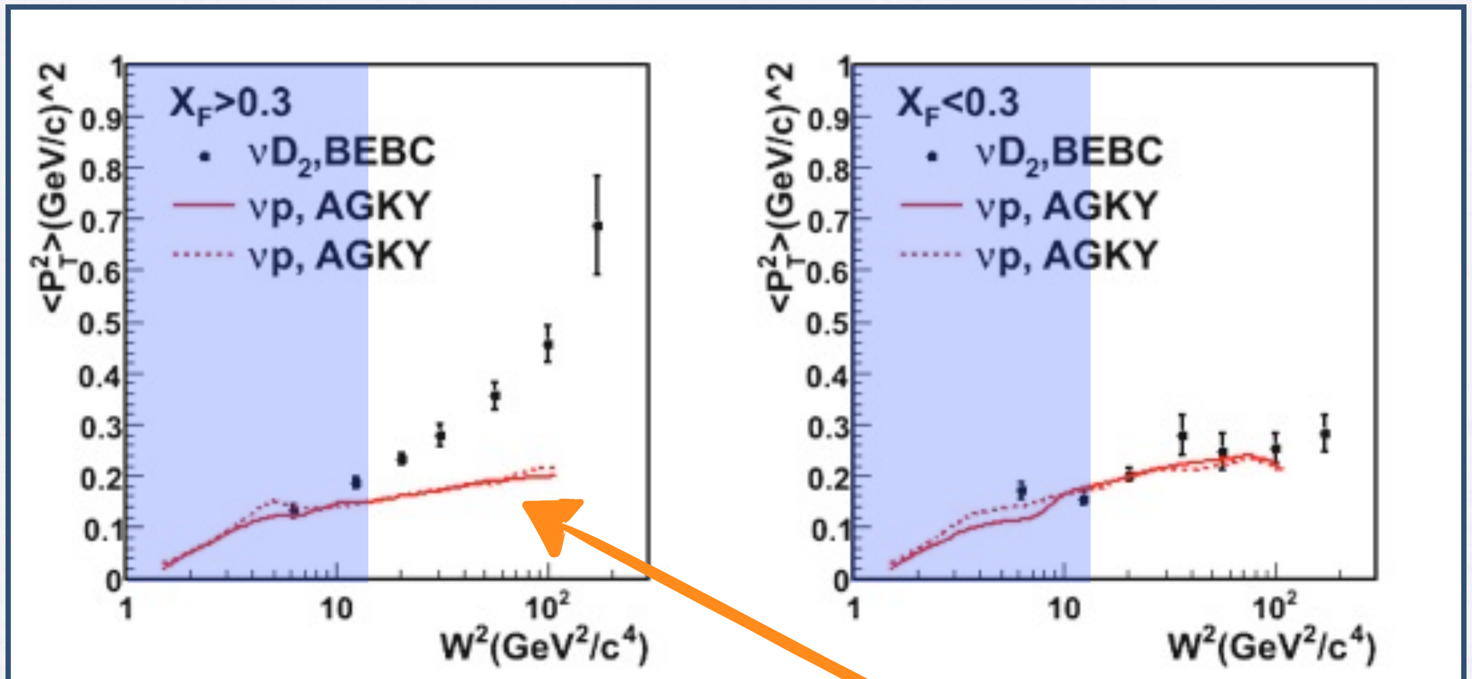
Signal

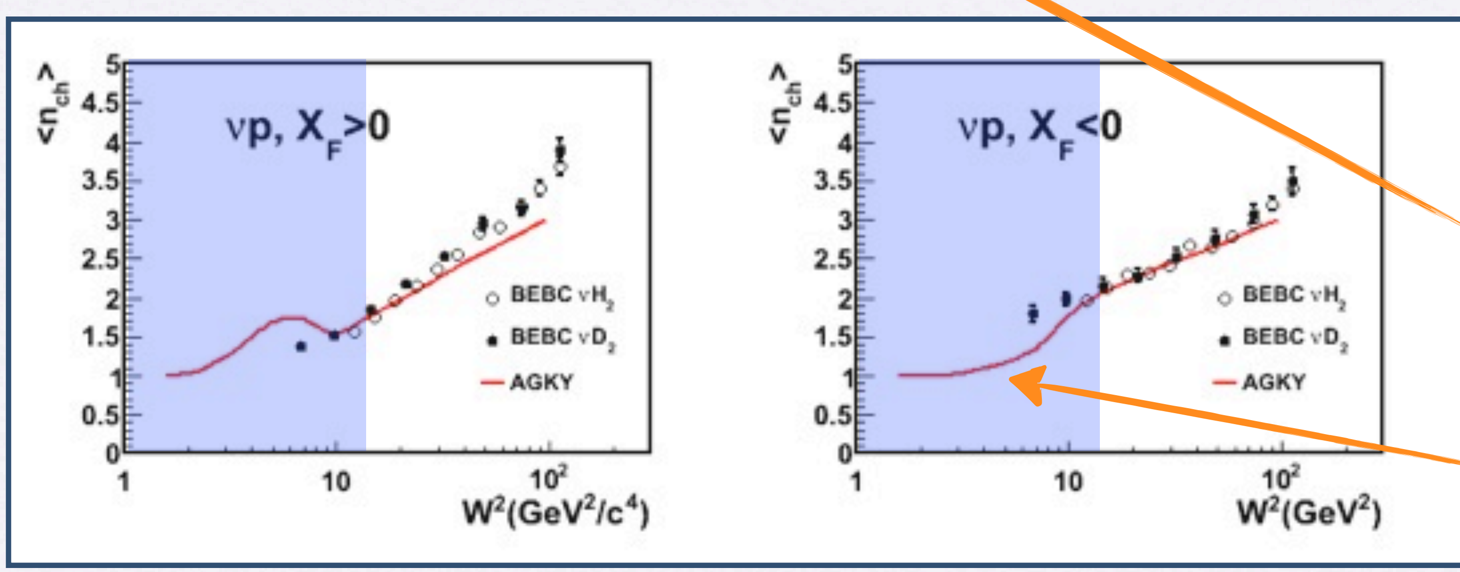
"Irreducible" Background

Reducible Background



MINOS Monte Carlo





Region of interest: 1 - 15 GeV^2 in W^2

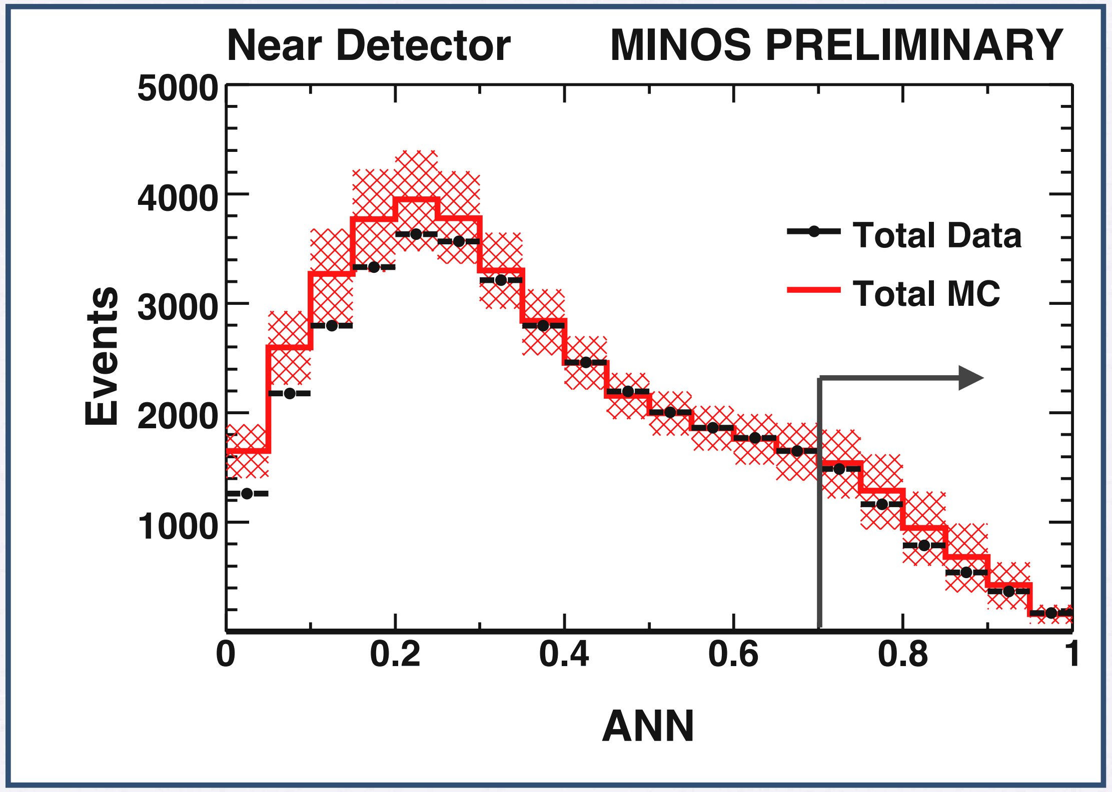
- MC tuned to external bubble chamber data for hadronization models.
- Tuning focused in the following quantities:
  - Charged/neutral pion multiplicity and dispersion.
  - Forward/backward fragments.
  - Fragmentation functions.
  - Transverse momentum.
- Transverse momentum still too low in forward hemisphere.
- Model at lower W^2 is an extrapolation.

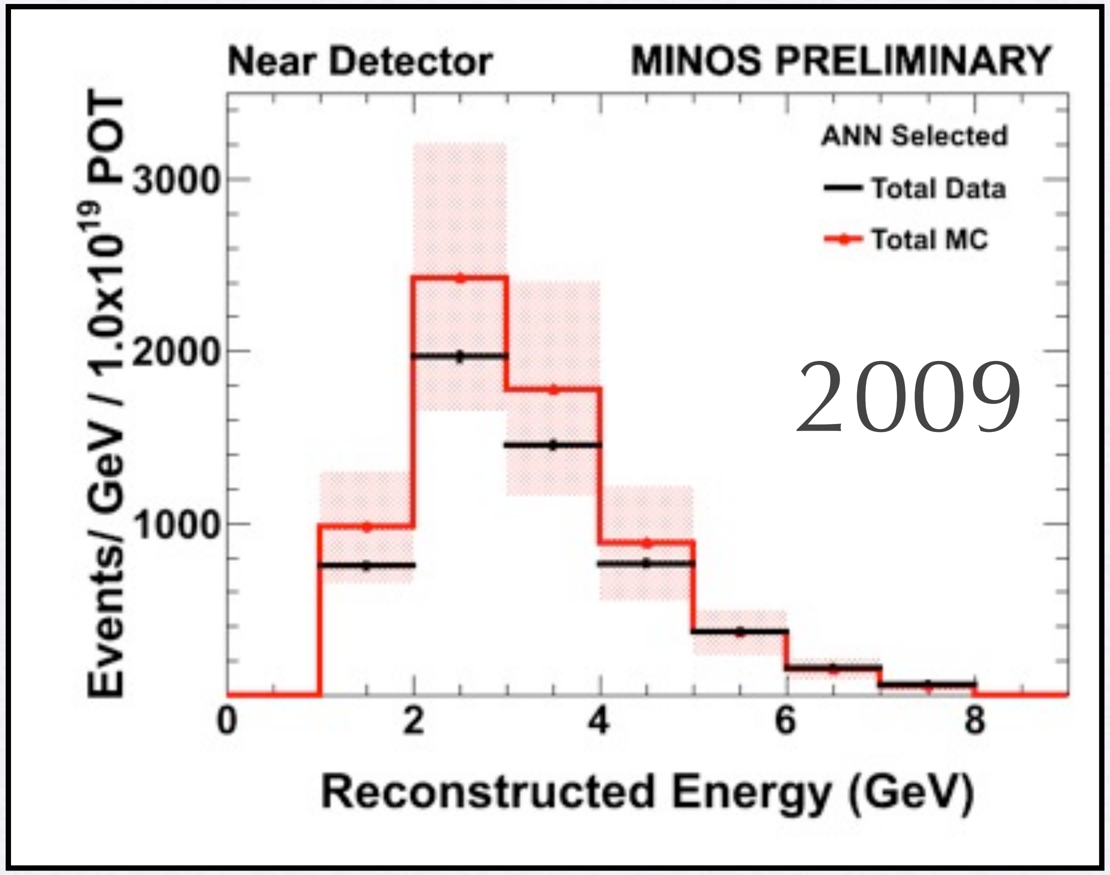
T. Yang et al., Eur. Phys. Jour. C 63:1-10 (2009)

Neutrino data taken with the Near Detector was used to correct the Far Detector expectation.

MINOS electron neutrino selection

- Initially the ND predicted backgrounds were 20% higher than observed in data.
  - Hadronization and final state interactions uncertainties give rise to large uncertainties in ND prediction.
  - External data is sparse in our region of interest.
  - Strong background suppression, since we select tails of BG distributions.
- Improvements to nuclear rescattering model in MC reduced data/MC discrepancies in current analyses.





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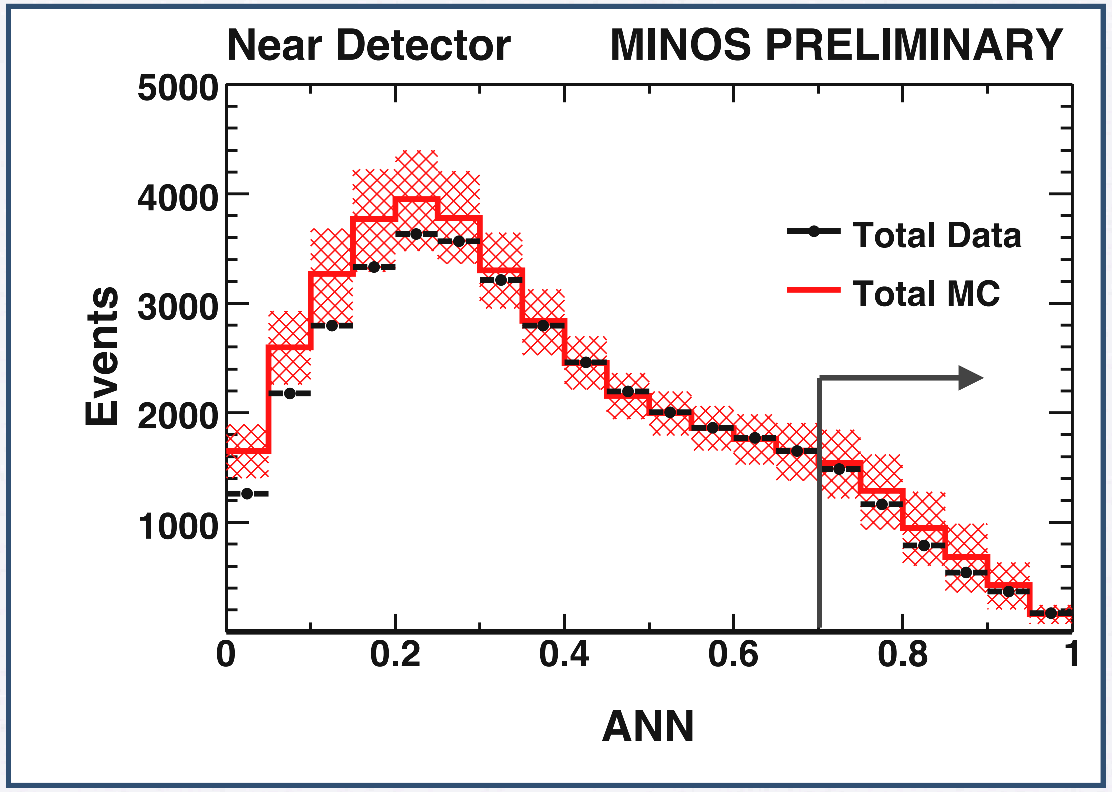
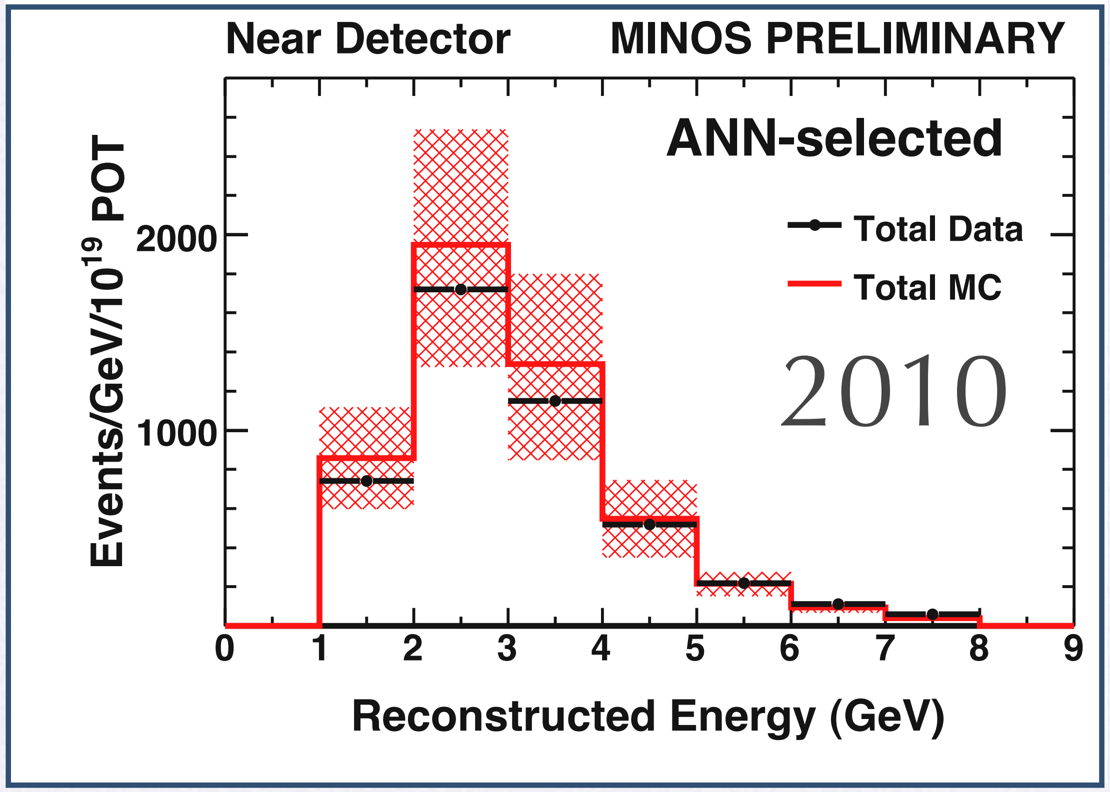




Predicting the FD background

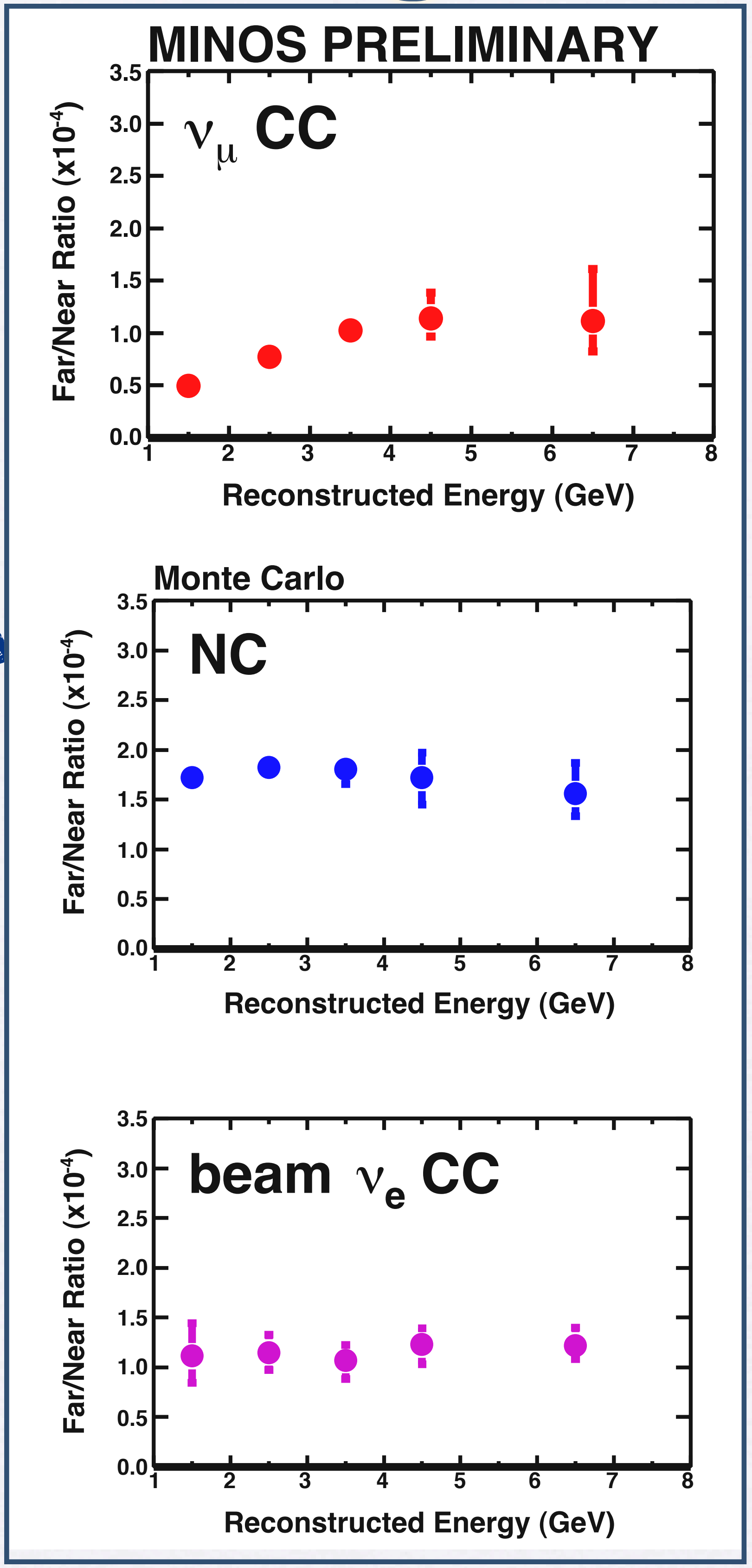
- The Near Detector ν_e selected **NC** and **ν_μ CC** background components are corrected by the Far/Near MC ratio.

$$FD_i^{predicted} = \frac{FD_i^{MC}}{ND_i^{MC}} ND_i^{Data}$$

~10^{-4} expected from geometry and fiducial volume ratio alone

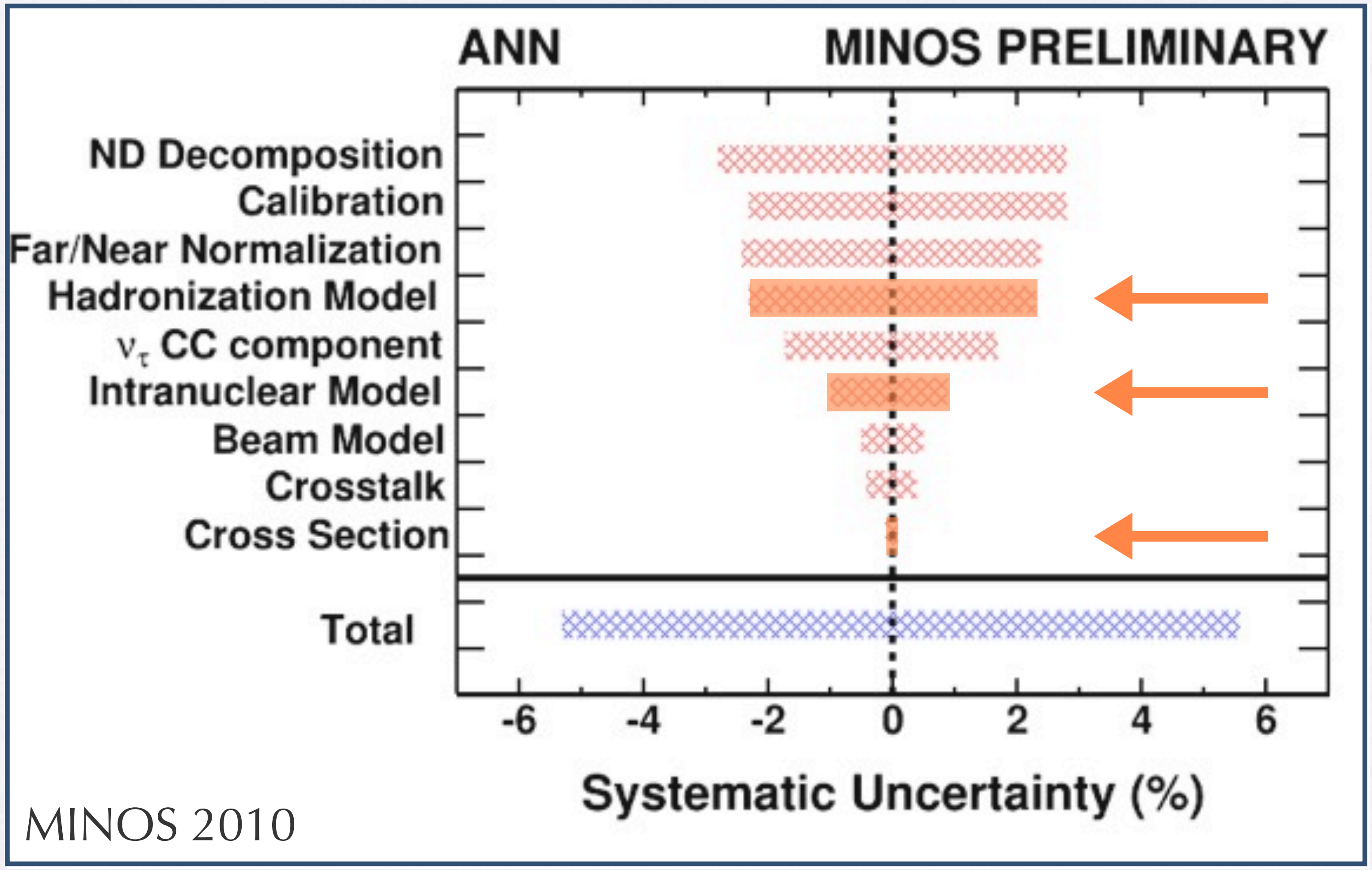
  - Far/Near ratio accounts for geometry, fiducial volume ratio, intensity, detector differences and oscillations.
  - Data-driven background decomposition techniques allow us to treat each component separately.

- The **signal ν_e** and the **ν_τ CC** from ν_μ oscillations are corrected using the extrapolation of the ν_μ CC spectrum.



MINOS systematic errors

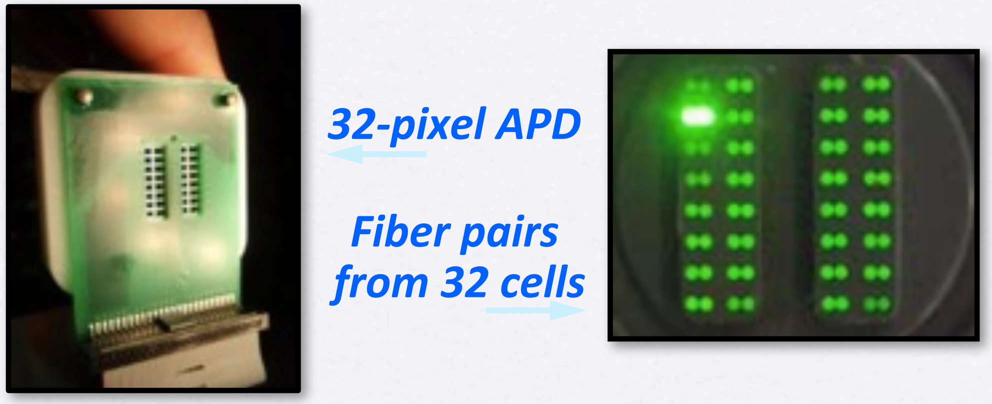
- To study the systematic errors, we generate special MC with the modified parameter in ND and FD. Using this modified MC for extrapolation and calculate the difference with the standard results.

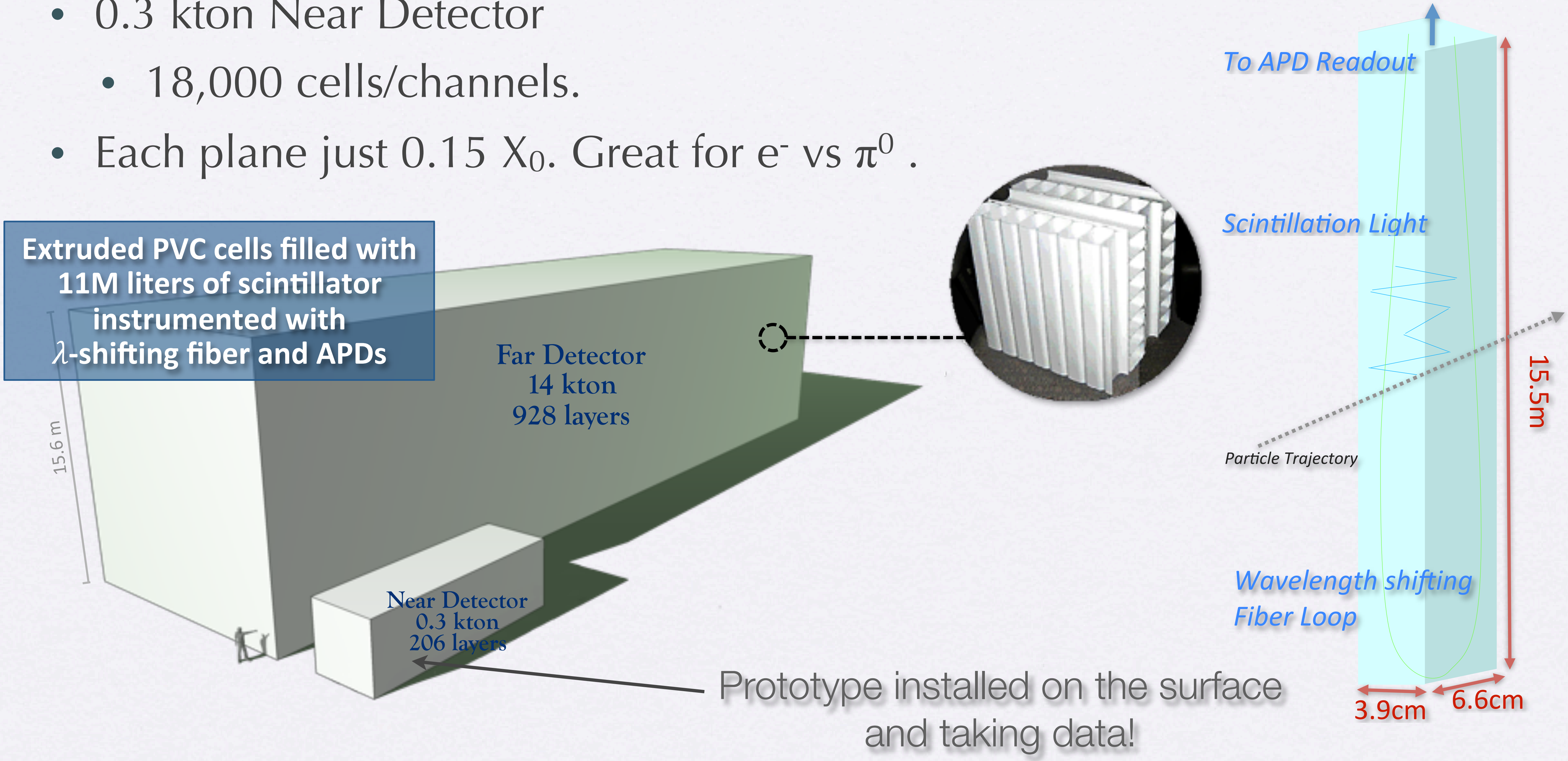


- For the main background components the hadronization model systematic is corrected to about 4%, while intranuclear and cross sections are down to 1% or less.
- More recent analyses have these below 2.5%.

The NOvA detectors

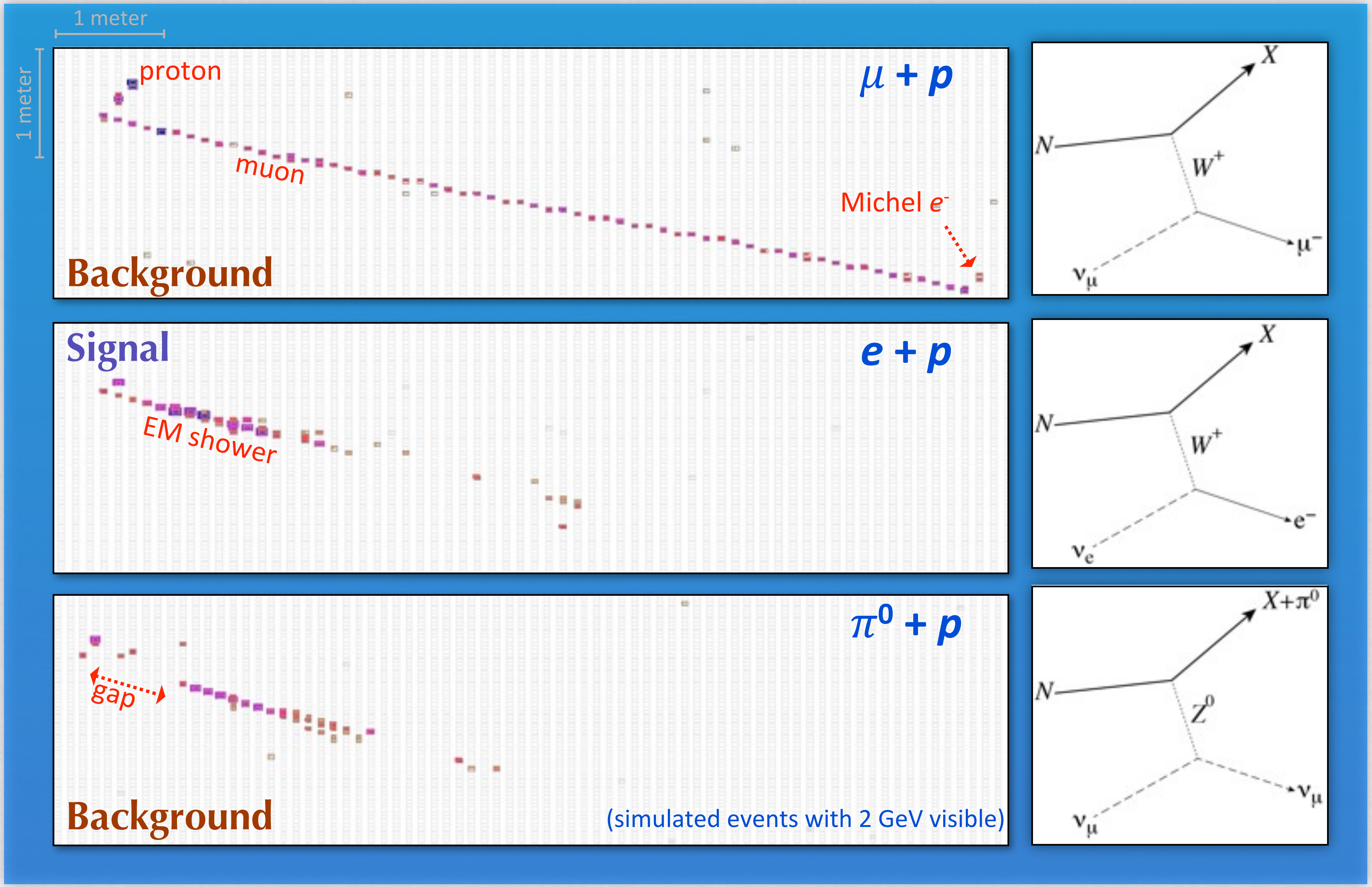
- 14 kton Far Detector (~3x MINOS).
  - >70% active detector.
  - 360,000 detector cells read by APDs.
- 0.3 kton Near Detector
  - 18,000 cells/channels.
- Each plane just 0.15 X_0. Great for e^- vs π^0 .





Neutrino event topologies in NOvA

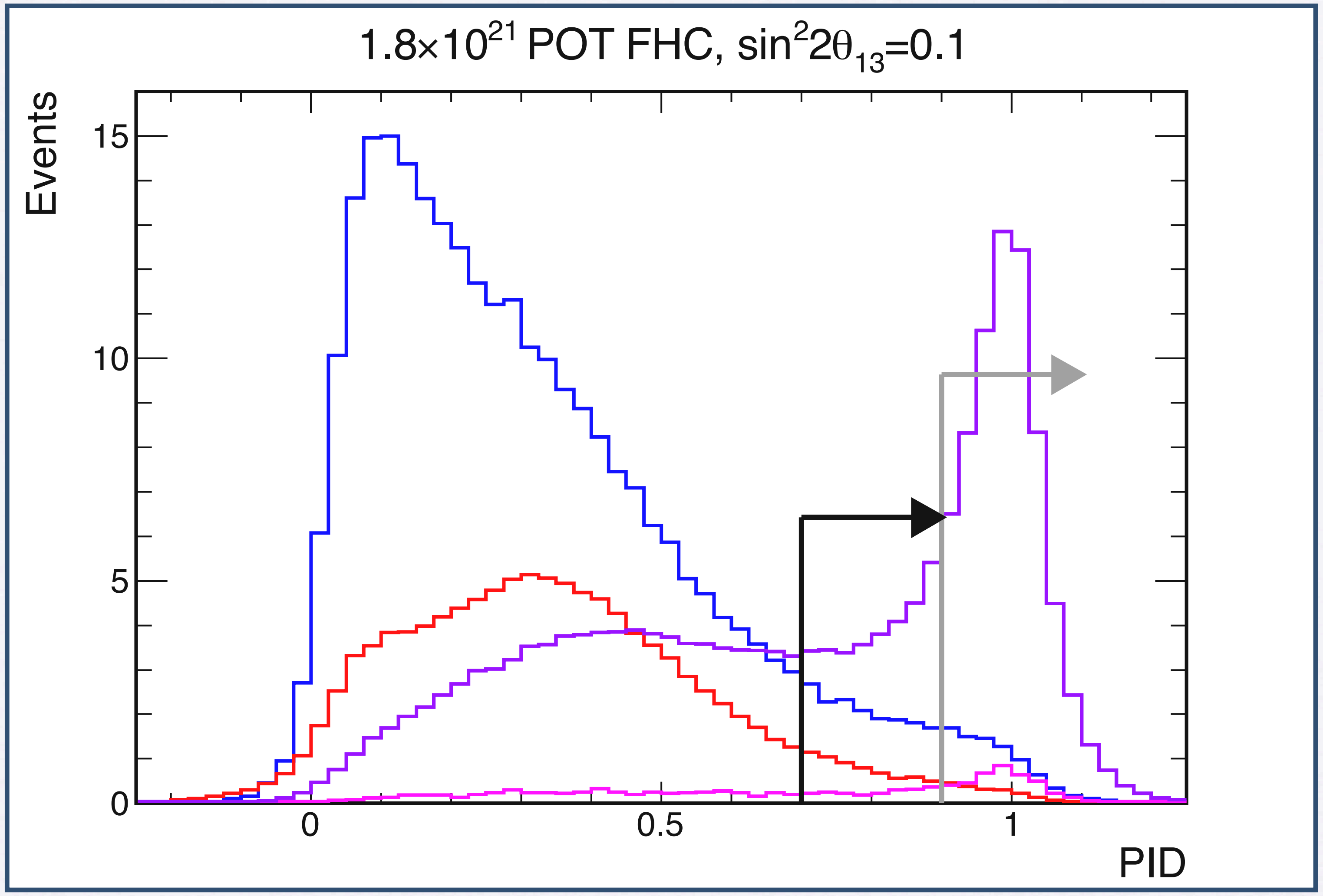
Monte Carlo events.



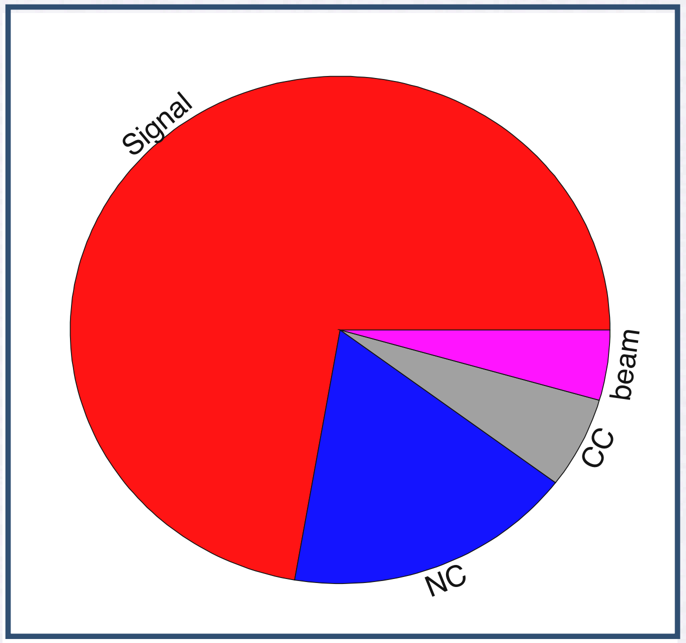
NOvA uses GENIE for neutrino interactions, same tuning as MINOS.

NOvA electron neutrino selection

- **Several electron neutrino identification techniques are being developed.**
    - Performance already comparable to the NOvA TDR.
    - PID re-optimized for large θ_{13}.
- Method used for this study is based on library matching algorithm (a la MINOS).
    - Current implementation is promising and has room for improvement.
- An alternate method based on transverse/longitudinal likelihoods of the shower energy profile will be shown in the poster session.



	Signal:Bkg
PID>0.7	**100:40**
PID>0.9	70:15



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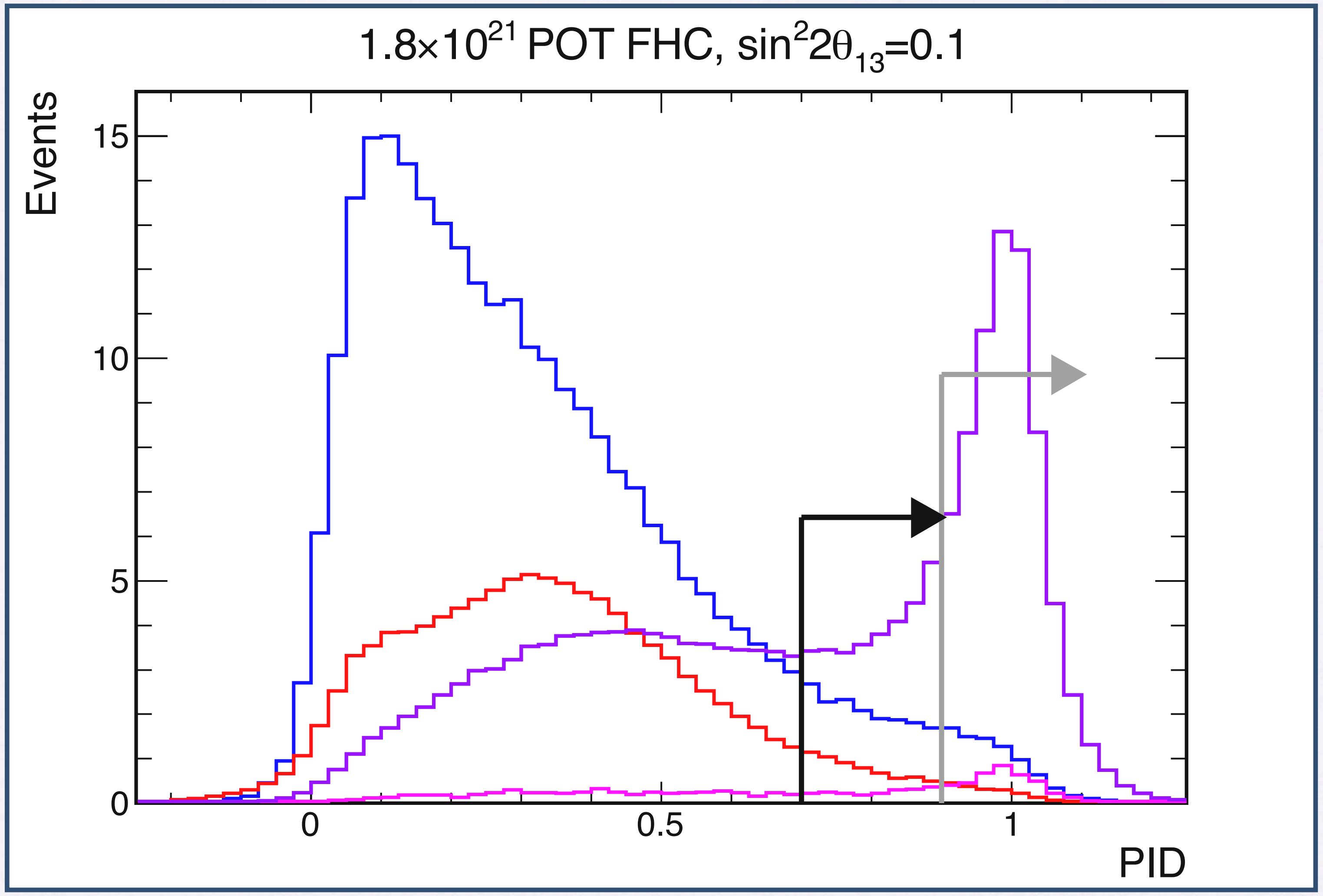

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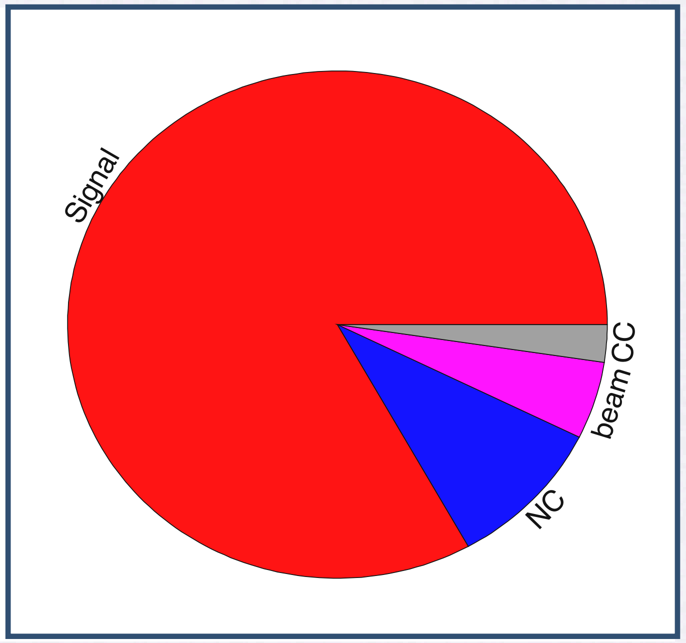

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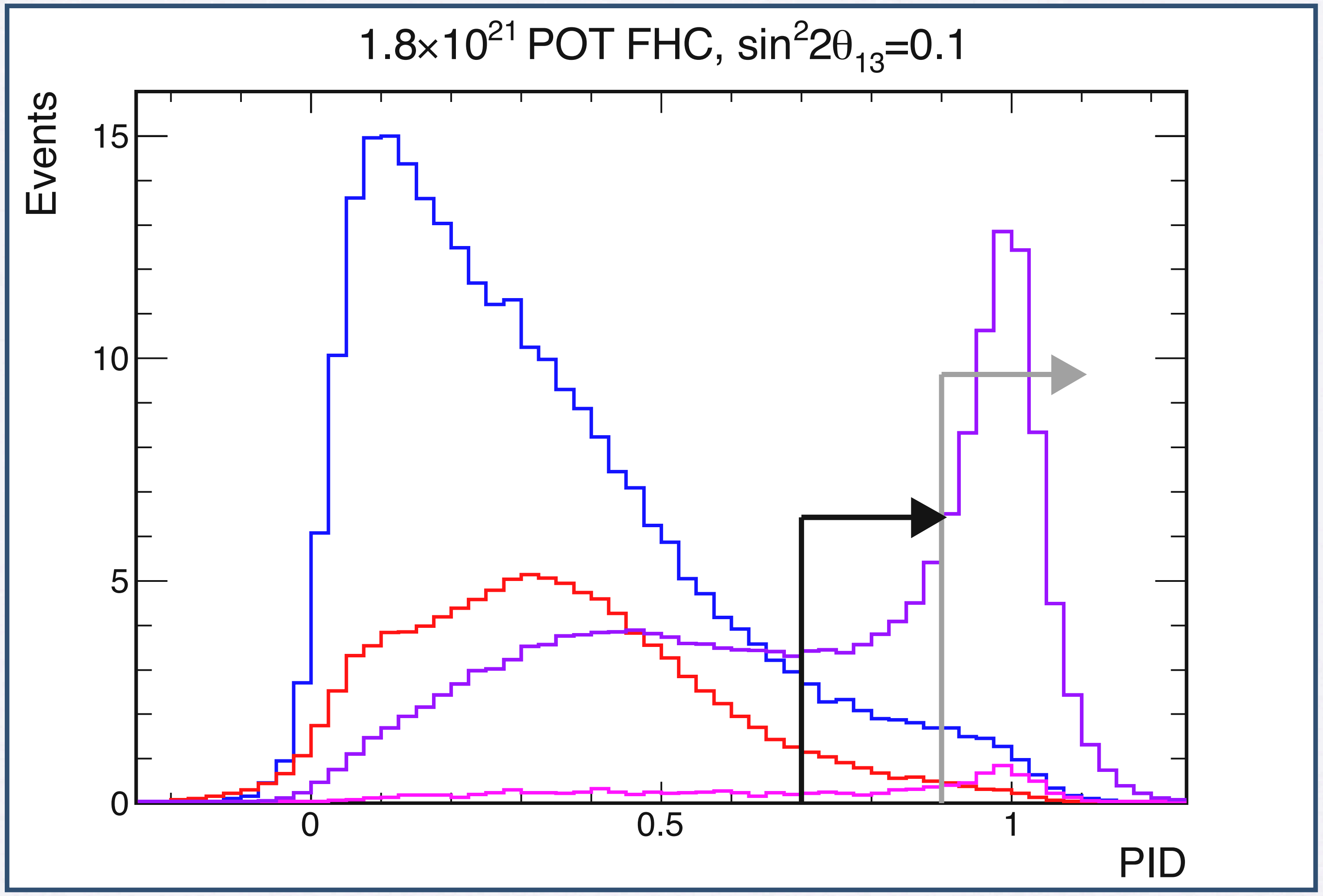

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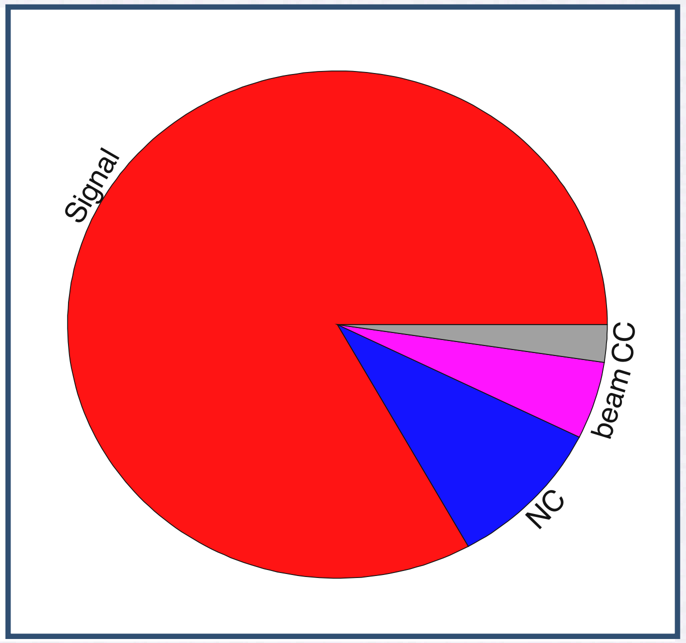
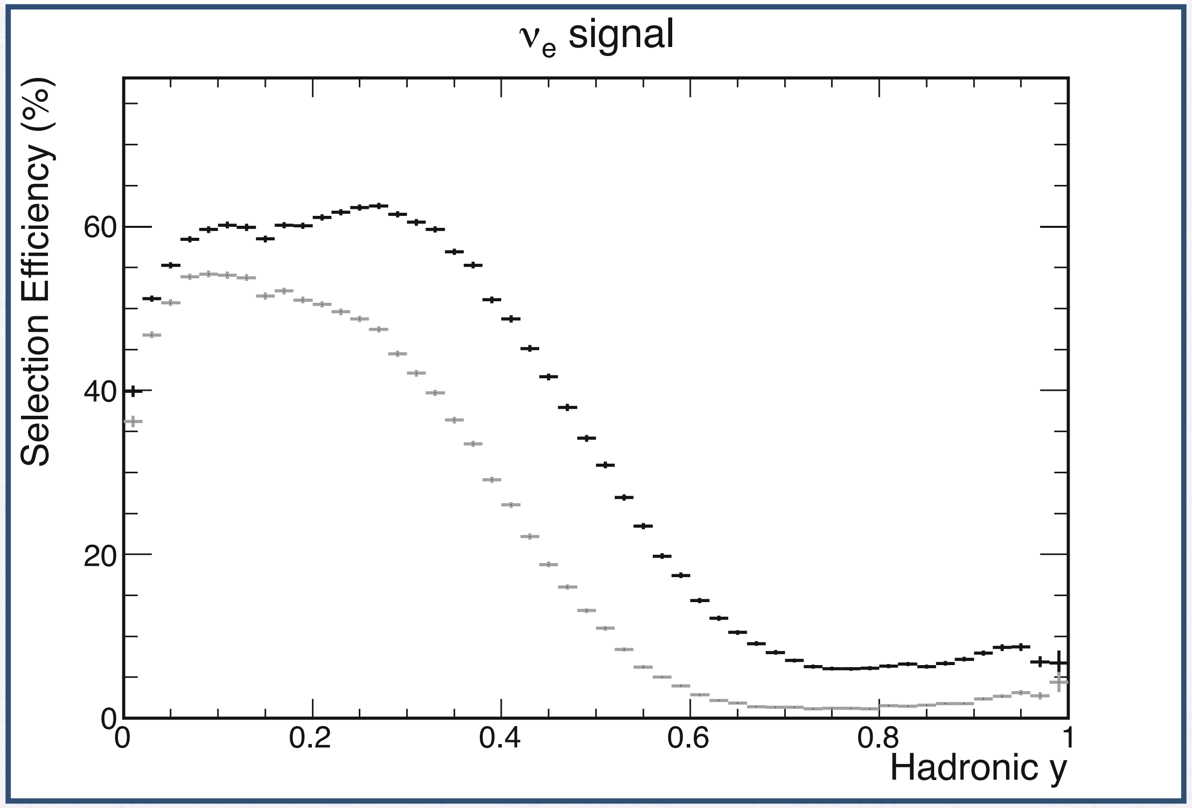
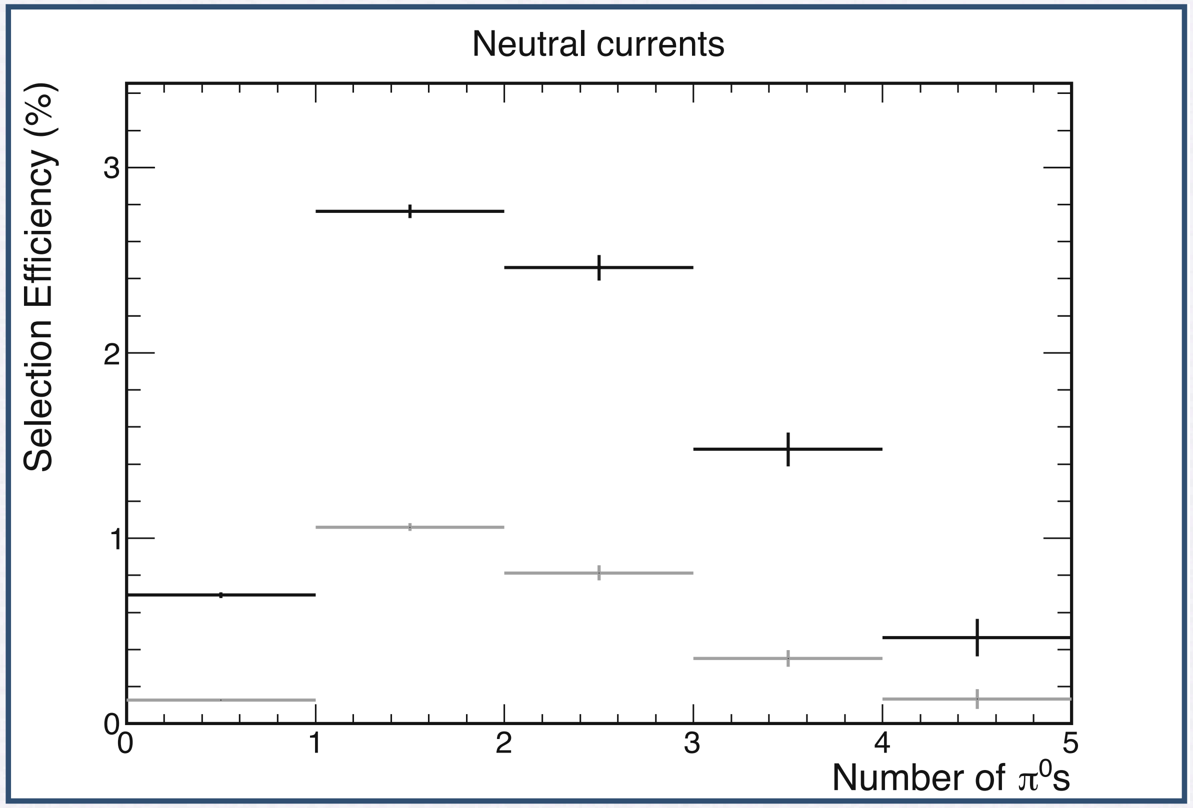
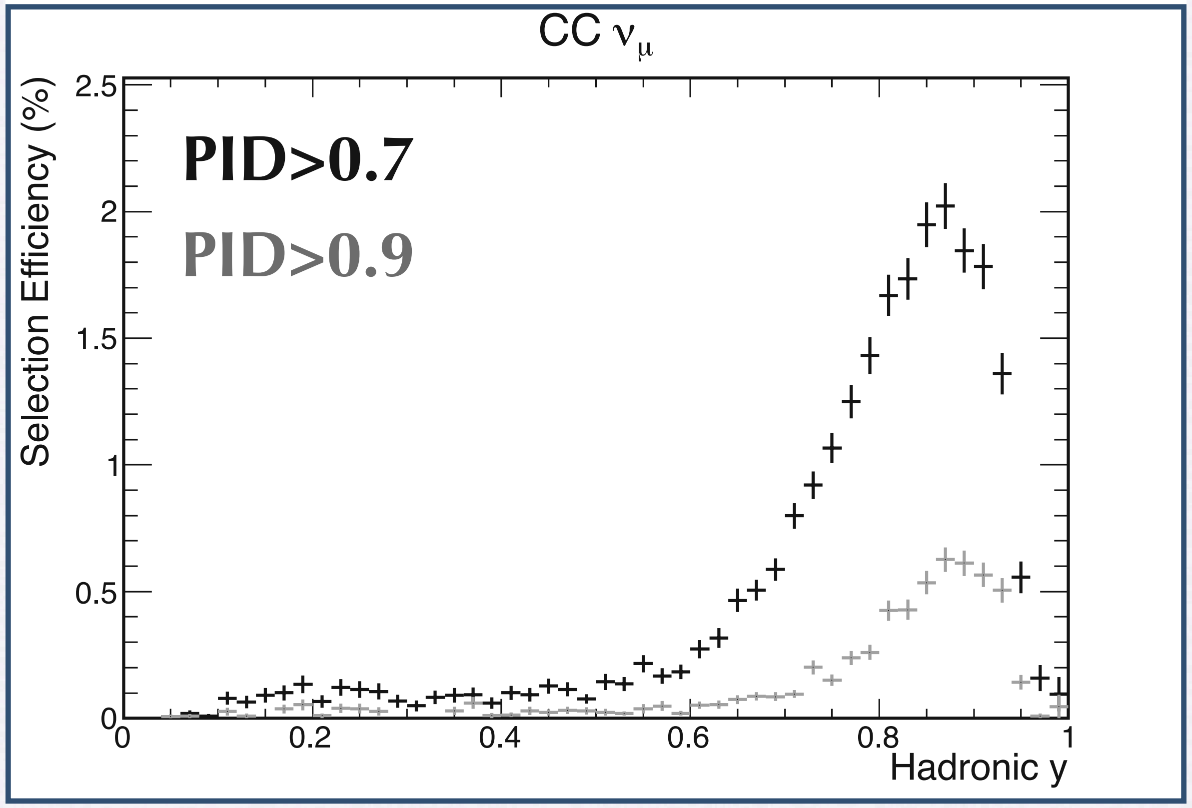


NOvA electron neutrino selection

- The electron neutrino selection prefers **low hadronic y ν_e signal events** and **high hadronic y ν_μ CC background** events.
- For **neutral current events** the main background arises from events with **one or more π^0**.





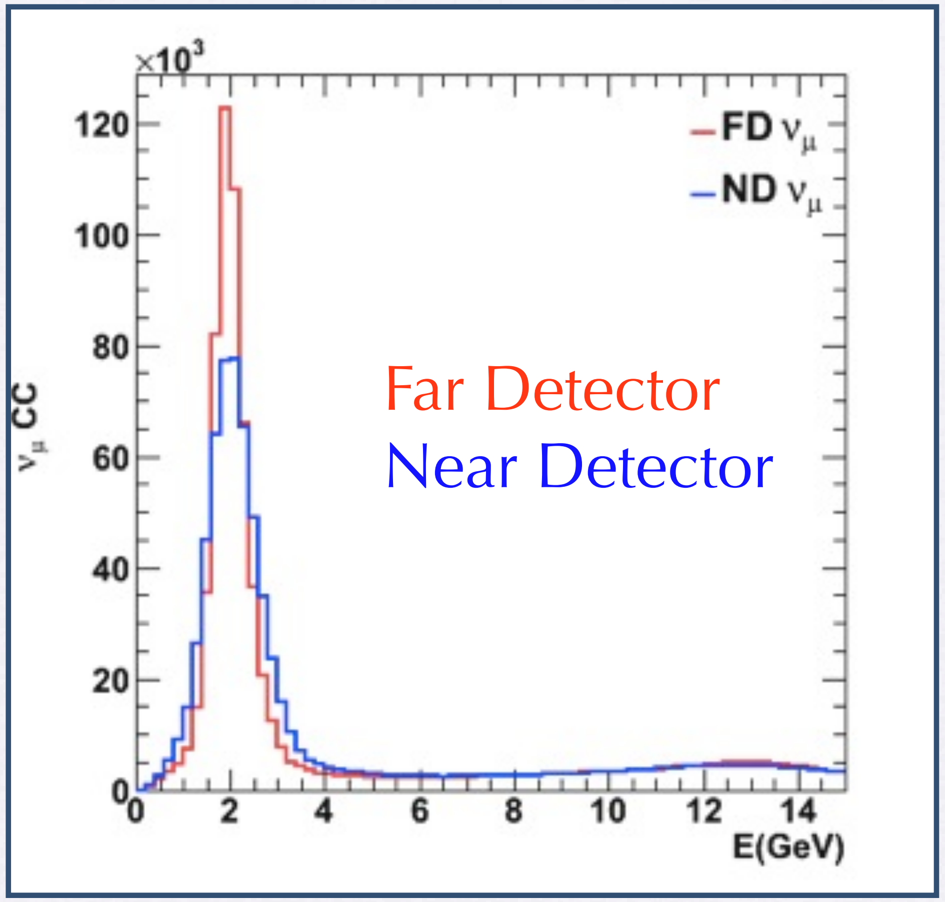


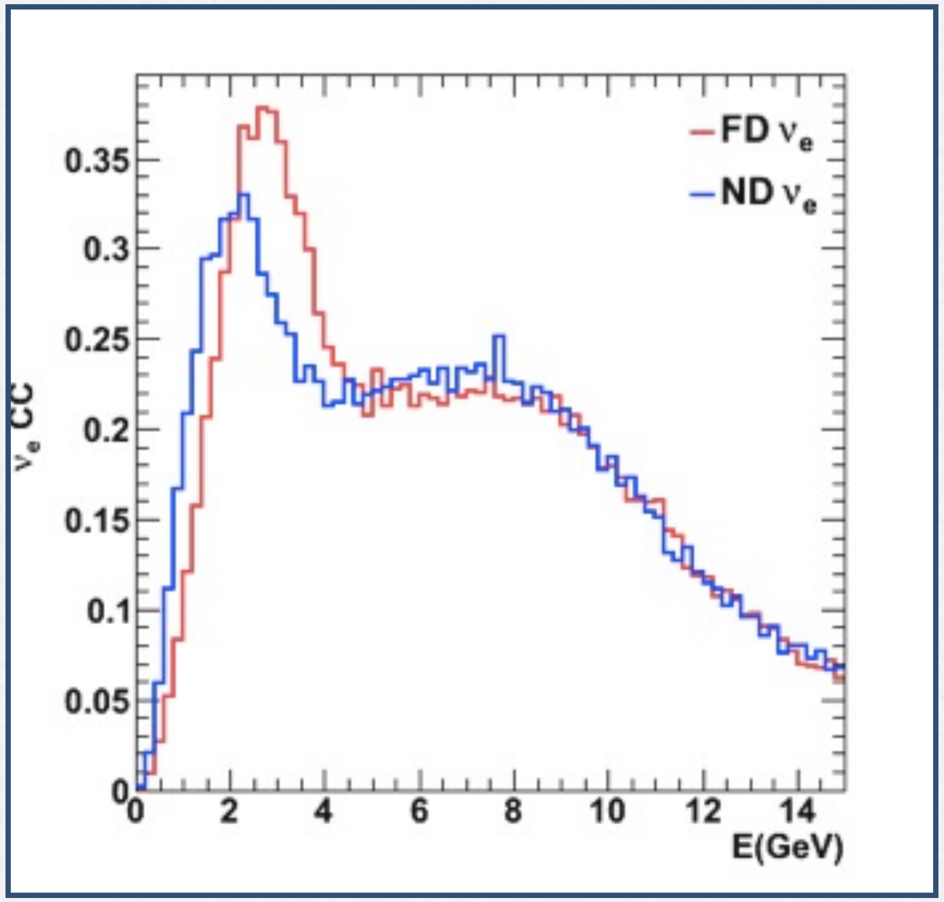
Studying systematic errors in NOvA

- The **neutrino interaction systematic errors** are modified in this study:
  - **Cross-section**: M_A(QE) and M_A(RES) varied by ± 20%.
  - **Hadronization model** changes:
    - The π^0 selection probability in the hadronization model changed by ± 33%.
    - Change in average P_t resulting in broader showers.
    - Re-weighting P_t and X_f distributions of hadron distribution.
  - **Intranuclear** formation zone changed by ± 50%.
- These **systematics should mostly cancel**, however they can be affected by **Far/Near detector differences**.
  - We expect the most significant of them to be:
    energy spectra, light levels and event energy containment.

Energy spectra differences

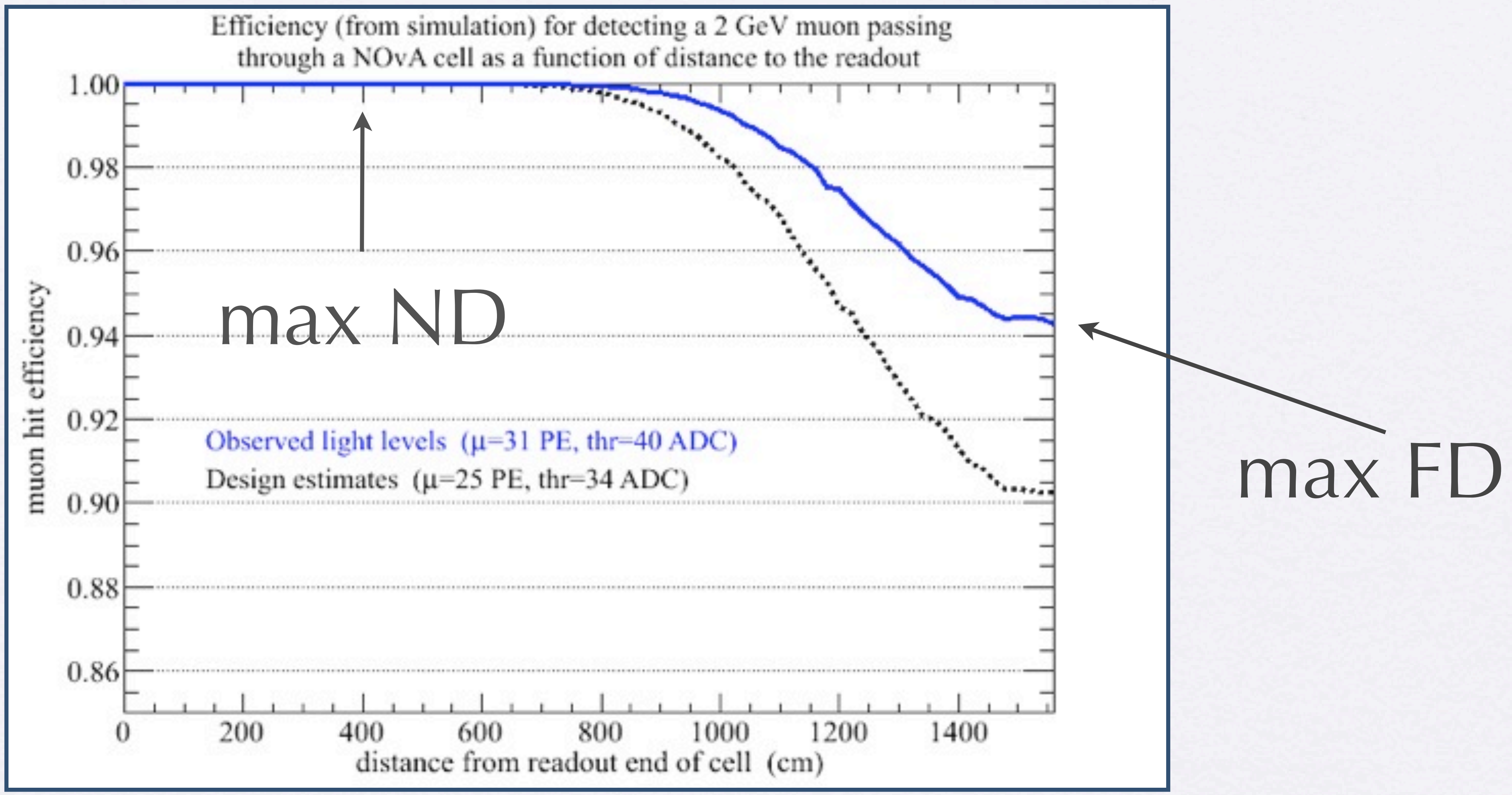
- Neutrino energy depends on angle with respect to original meson direction and energy.
- Angular distributions different between neutrinos seen at Near and Far detectors.





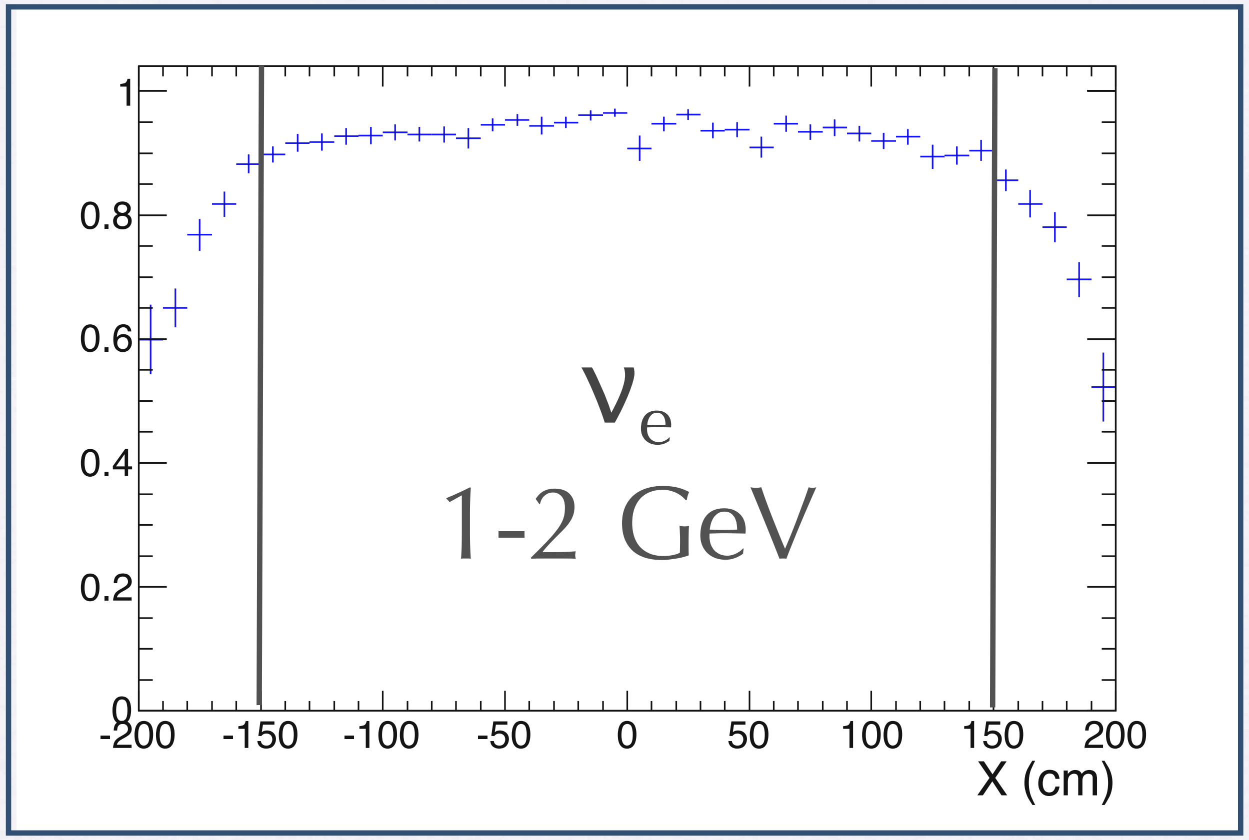
Light level differences

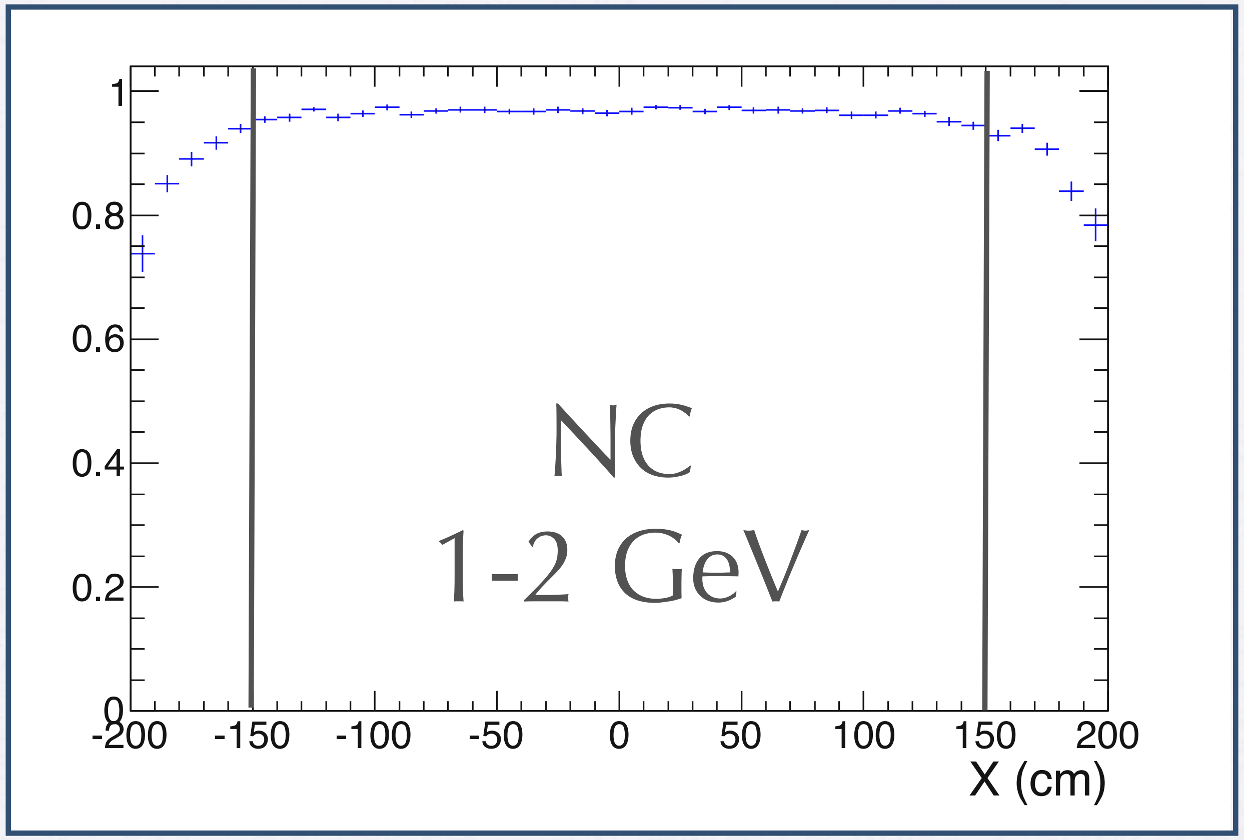
- The Far and Near Detectors are different sizes.
- Events in the Far Detector can have different detection efficiency depending on distance to readout.



Event containment differences

- In the NOvA Near Detector 82-87% of neutrino events are contained. Also Up to 10% of the NC lose a π^0.
- We do not expect these effects to be present in the Far Detector.

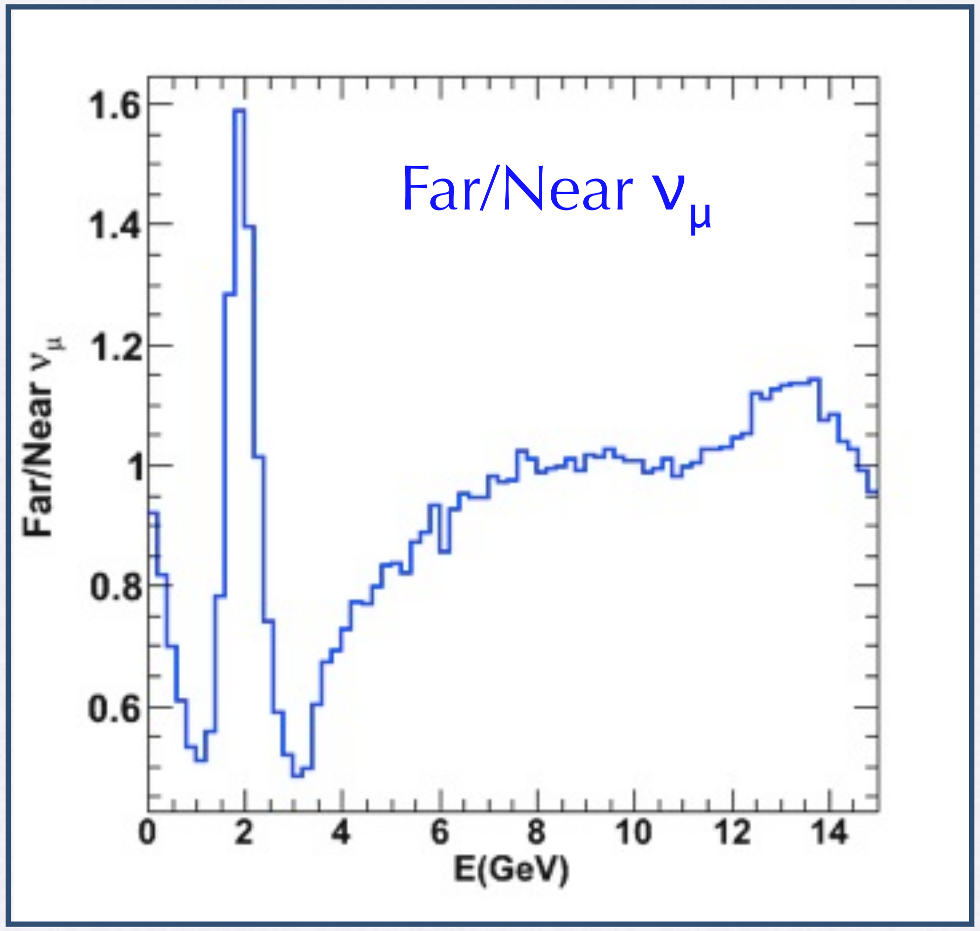


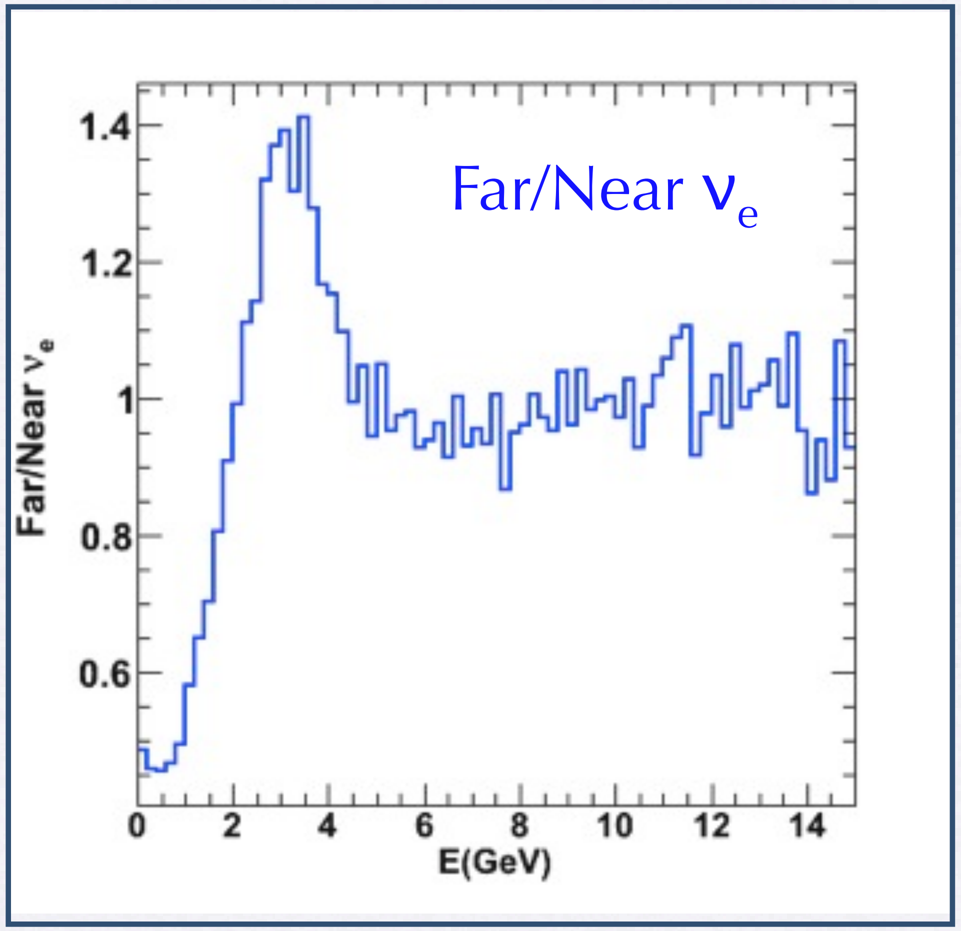


Energy	ν_e CC	ν_μ CC	NC	NC w/lost π^0
1-2 GeV	85 ± 1%	59 ± 1%	87 ± 2%	10 ± 2%
2-3 GeV	85 ± 1%	48 ± 1%	82 ± 3%	8 ± 2%

Predicting the FD background

- As in MINOS we plan to predict the event rate at each energy bin by correcting the expected Monte Carlo rate using the ratio of data to Monte Carlo in the Near Detector.
  - Far/Near ratio accounts for geometry, fiducial volume ratio, intensity, detector differences and oscillations.
  - The Far/Near ratios for muon and electron neutrinos in the beam before selection are shown below.





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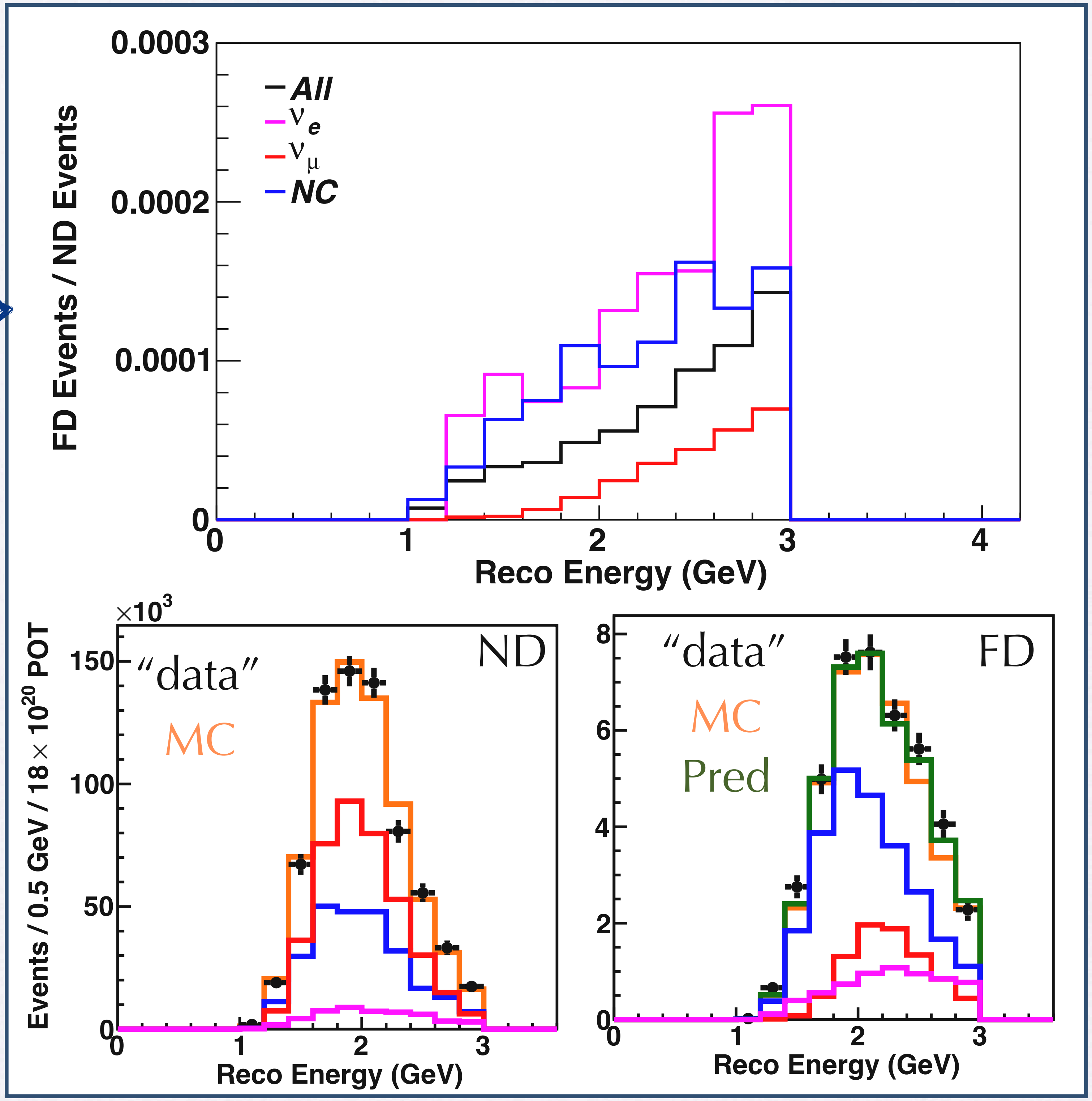
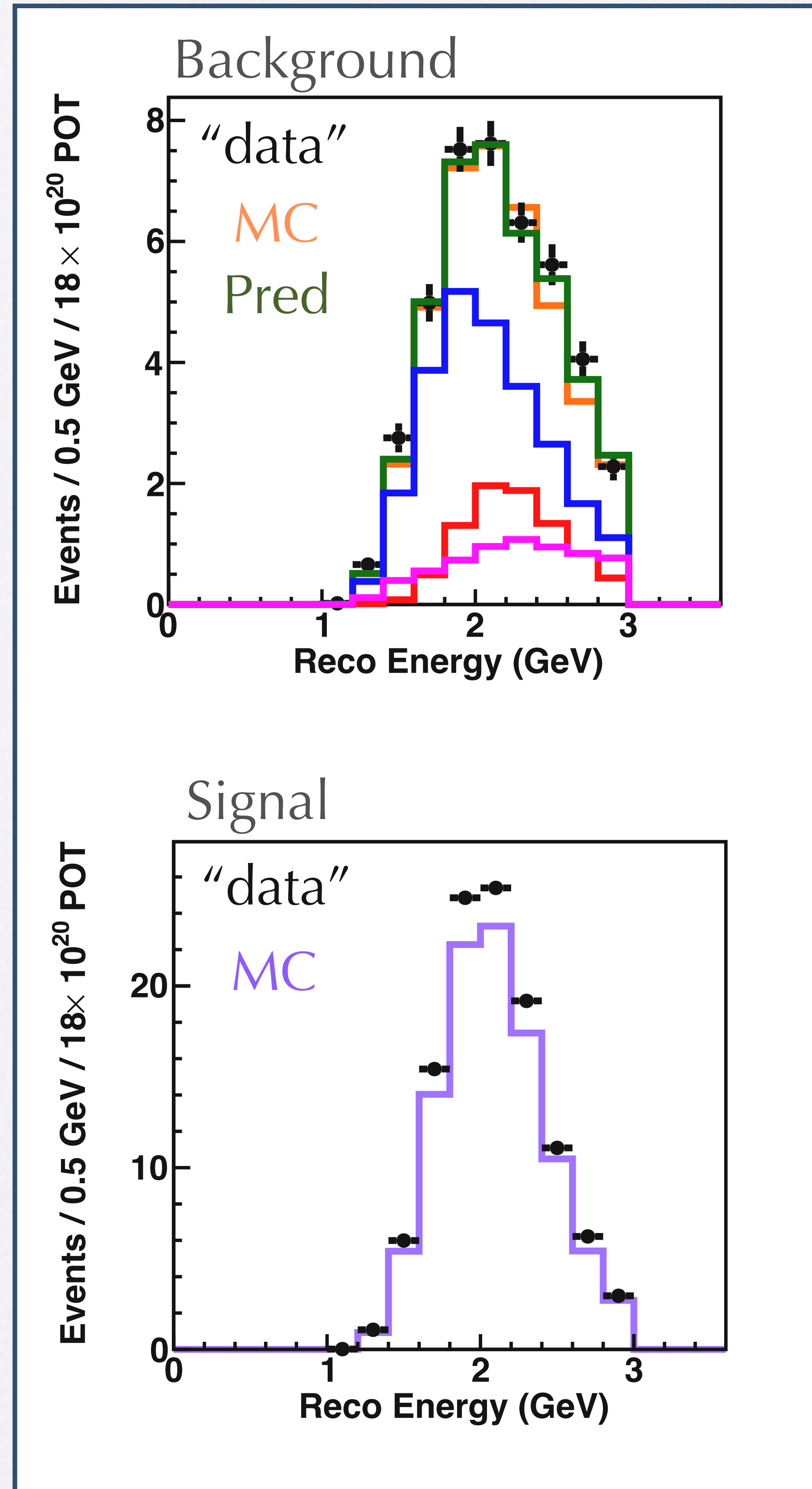


Ratios and energy distributions for M_A(QE) changed by +30%

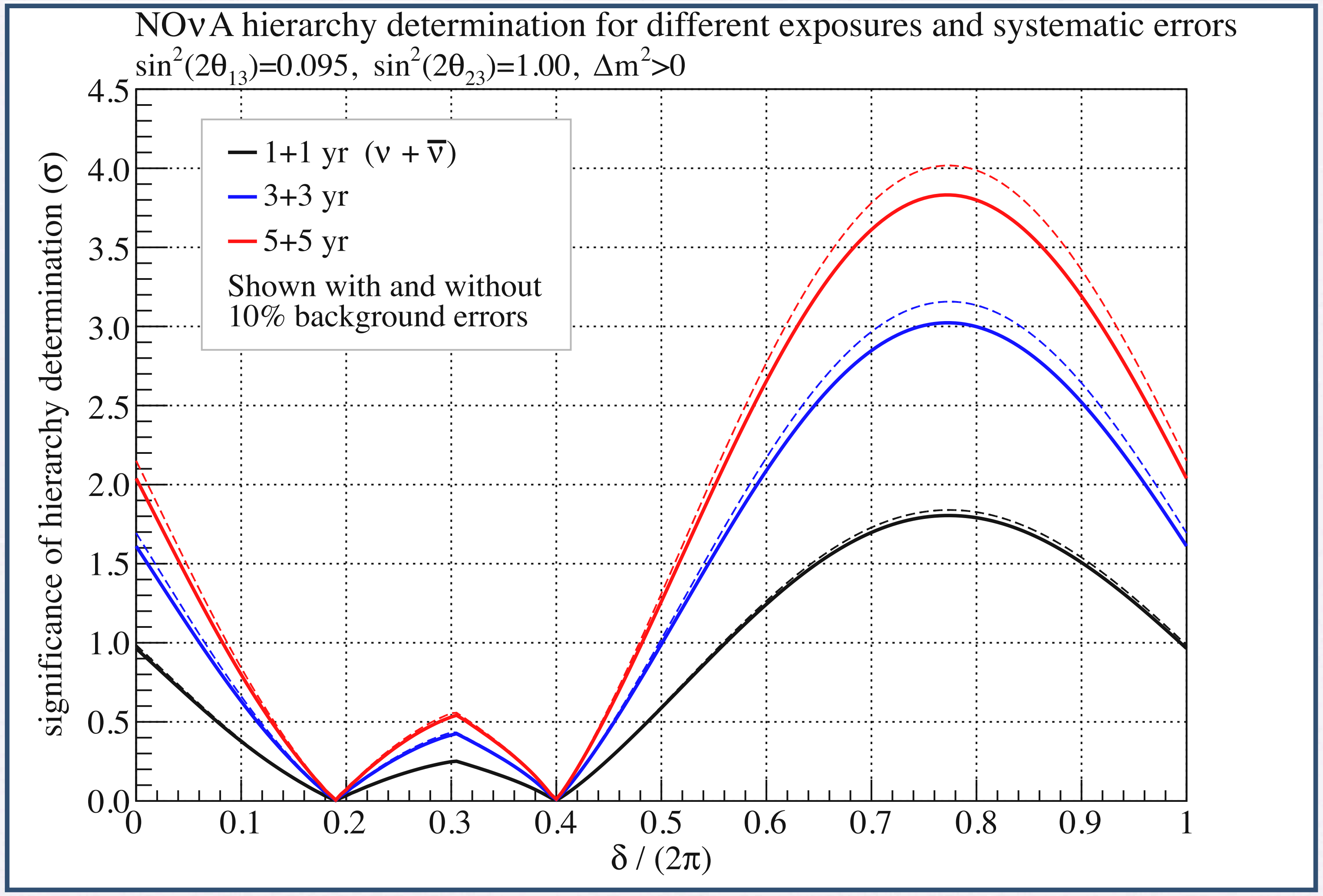
- Data (modified Monte Carlo in this case) and MC are compared in the ND. The ratio is used to modify the prediction int he FD.
- The prediction is expected to be a closer match to the Data in the FD having been corrected.

Expected NOvA systematic errors

- We evaluated a set of neutrino interaction systematic uncertainties on the background for electron neutrino appearance in NOvA.
  - The largest systematic error arises from the P_t and X_f changes at 5%.
  - All other errors are within 3% for background, currently limited by the statistics of the study.
- For the signal the largest uncertainties correspond to the cross section systematics.
  - These are expected to be corrected using the extrapolation of the ν_μ CC spectrum from the Near Detector to less than 1%.
- All others systematics on the signal are also within the statistics of the study.



Effects on NOvA sensitivities



- **Neutrino interaction systematics on background for NOvA are well within the required 10% overall systematics.**
  - In this study we estimated them to be within 3%, with the largest one possibly reaching 5%.

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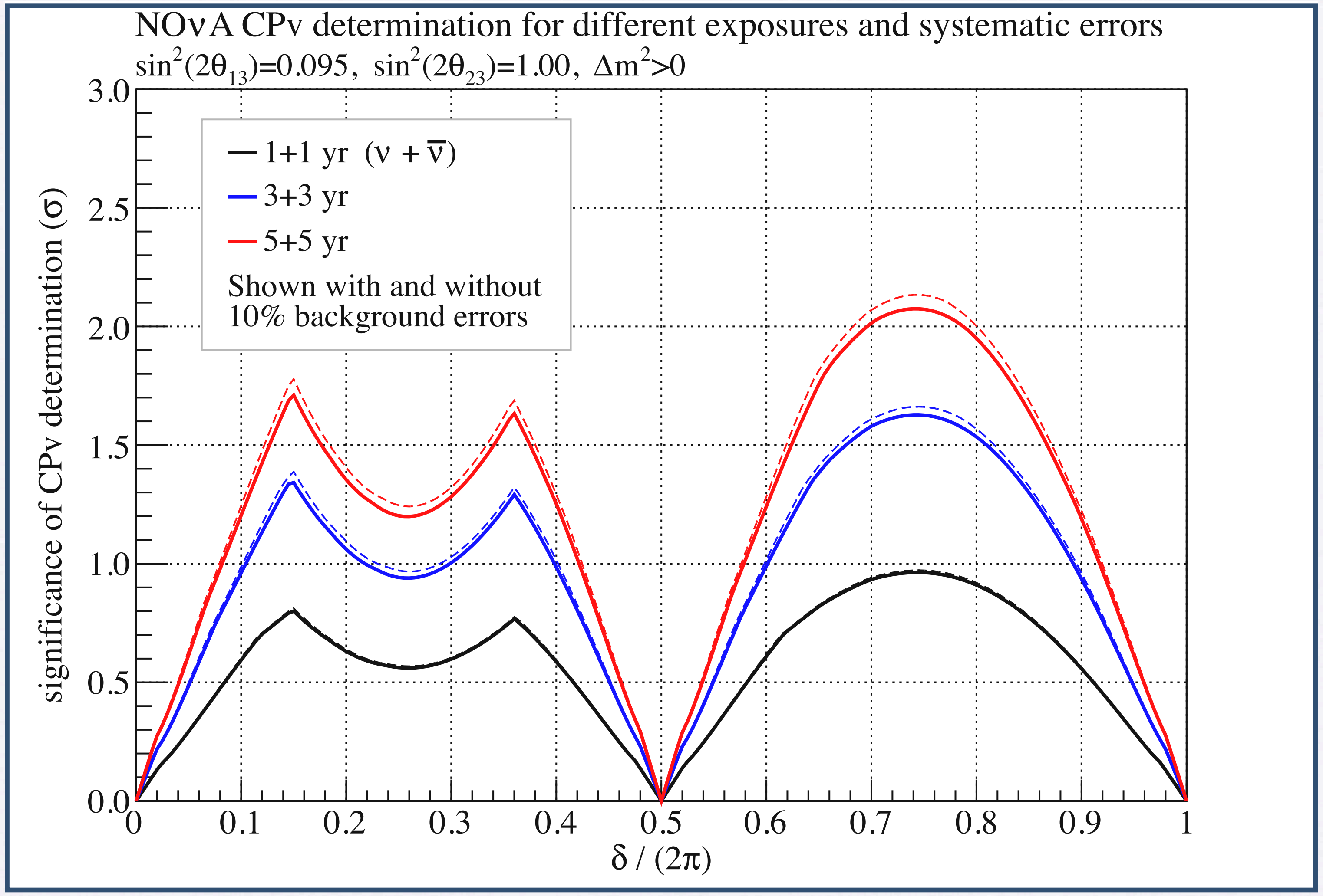

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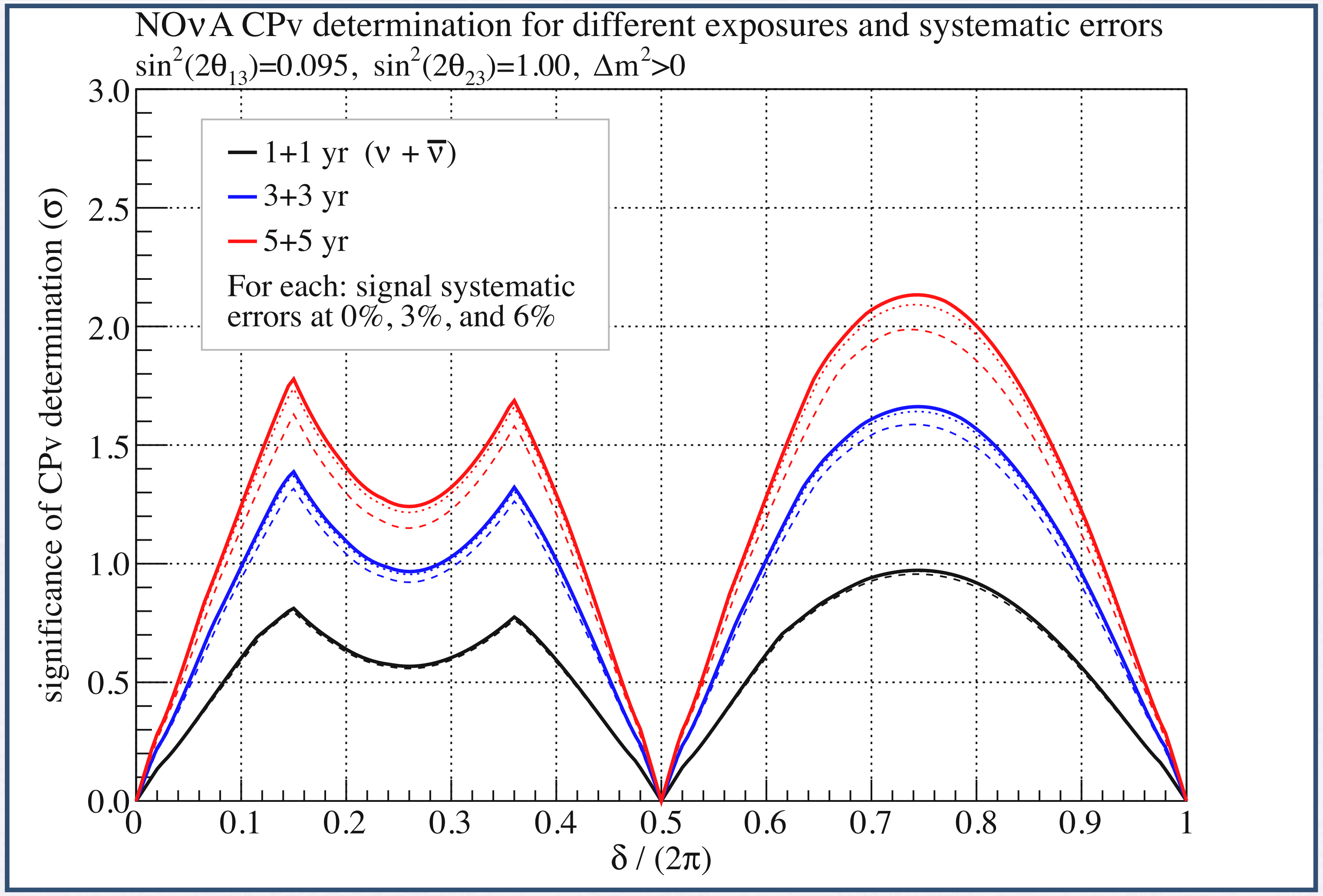


- **Neutrino interaction systematic uncertainties on the signal for NOvA are expected to be very small.**
- Other systematic effects unrelated to neutrino interactions are under consideration.
  - We do not expect these systematic errors to be an issue in our first analysis.

Conclusions

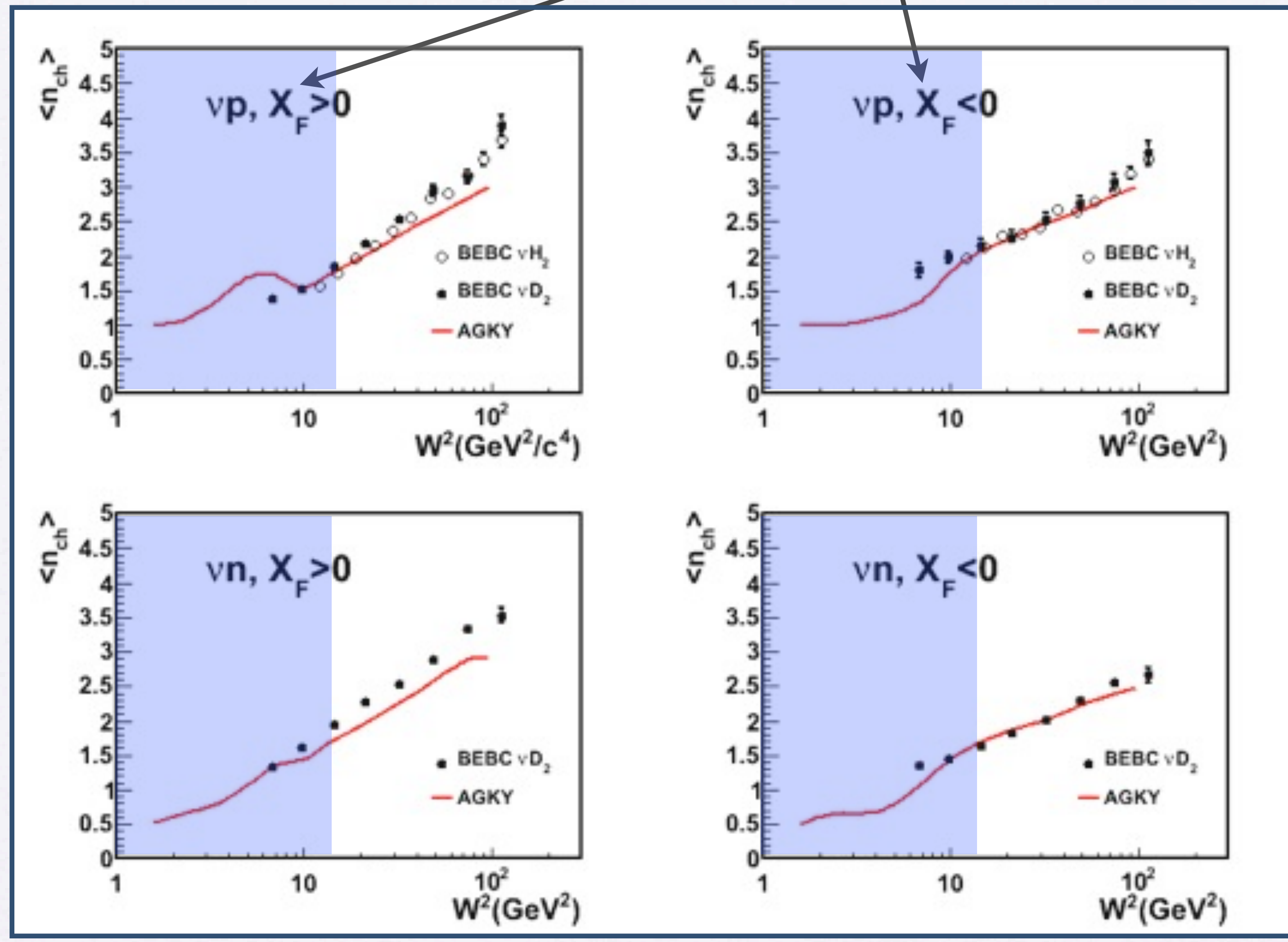
- **The two detector technique allows significant cancellation of neutrino interaction (cross-section, hadronization model and intranuclear rescattering) systematic errors.**
  - In MINOS first analyses, it resulted in a reduction of systematic errors from 20% to about 4% demonstrating the power of this technique.
  - In the most recent analyses these uncertainties are below 2.5%.
- **In a preliminary study for NOvA, we have determined these systematic uncertainties are small and cancel to less than 3% (limited by the statistics of the study).**
  - Current studies are based on models and studies done for MINOS, tuning and studies with other models within GENIE are expected as part of the NOvA program.
  - Hadronization and intranuclear model uncertainties such as those on the P_t and X_f hadron distributions are expected to be the larger systematic errors in this class.
  - Cross section systematic uncertainties on the electron neutrino signal can be corrected down to 1% using muon neutrino charge current interactions. Other systematic errors will dominate the signal.
- **This level of systematic errors are well within the tolerance of NOvA sensitivities to mass hierarchy, CP violation and the octant determination.**

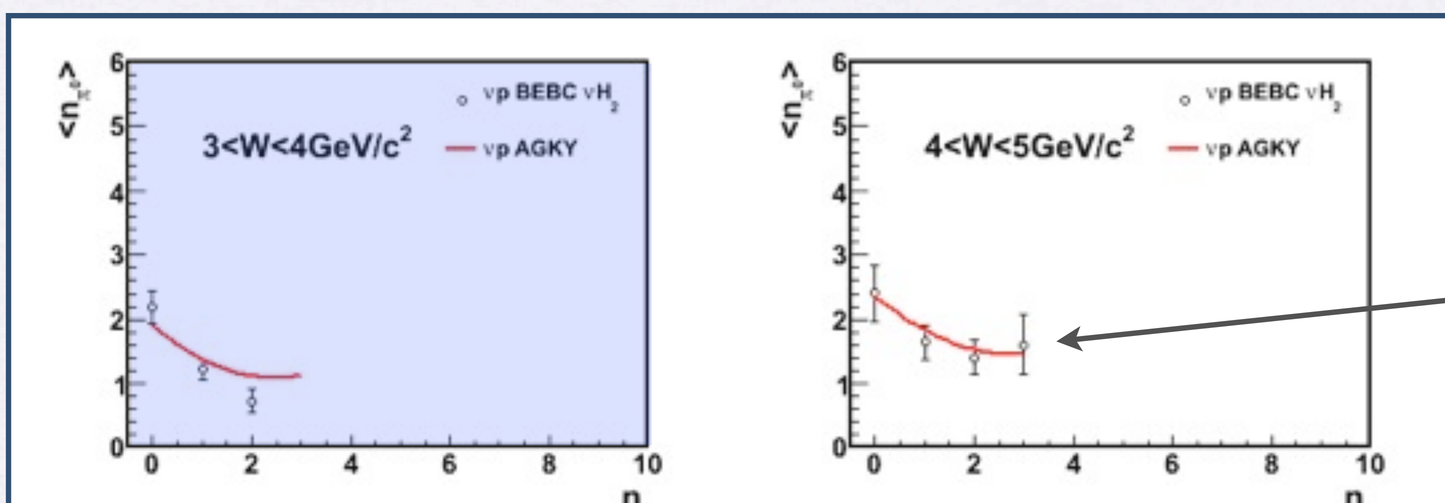
Backup

MINOS Monte Carlo

- MC tuned to external bubble chamber data for hadronization (or fragmentation) models.
- Region of interest in mass of hadronic system: 1 - 15 GeV^2 in W^2 or 1 - 4 GeV in W.
- However, data available is for relatively higher energy than the region of interest for this analysis.

Good agreement in W^2 for forward and backward hemispheres





Also agreement for π_0 vs charged hadron multiplicities for different W^2

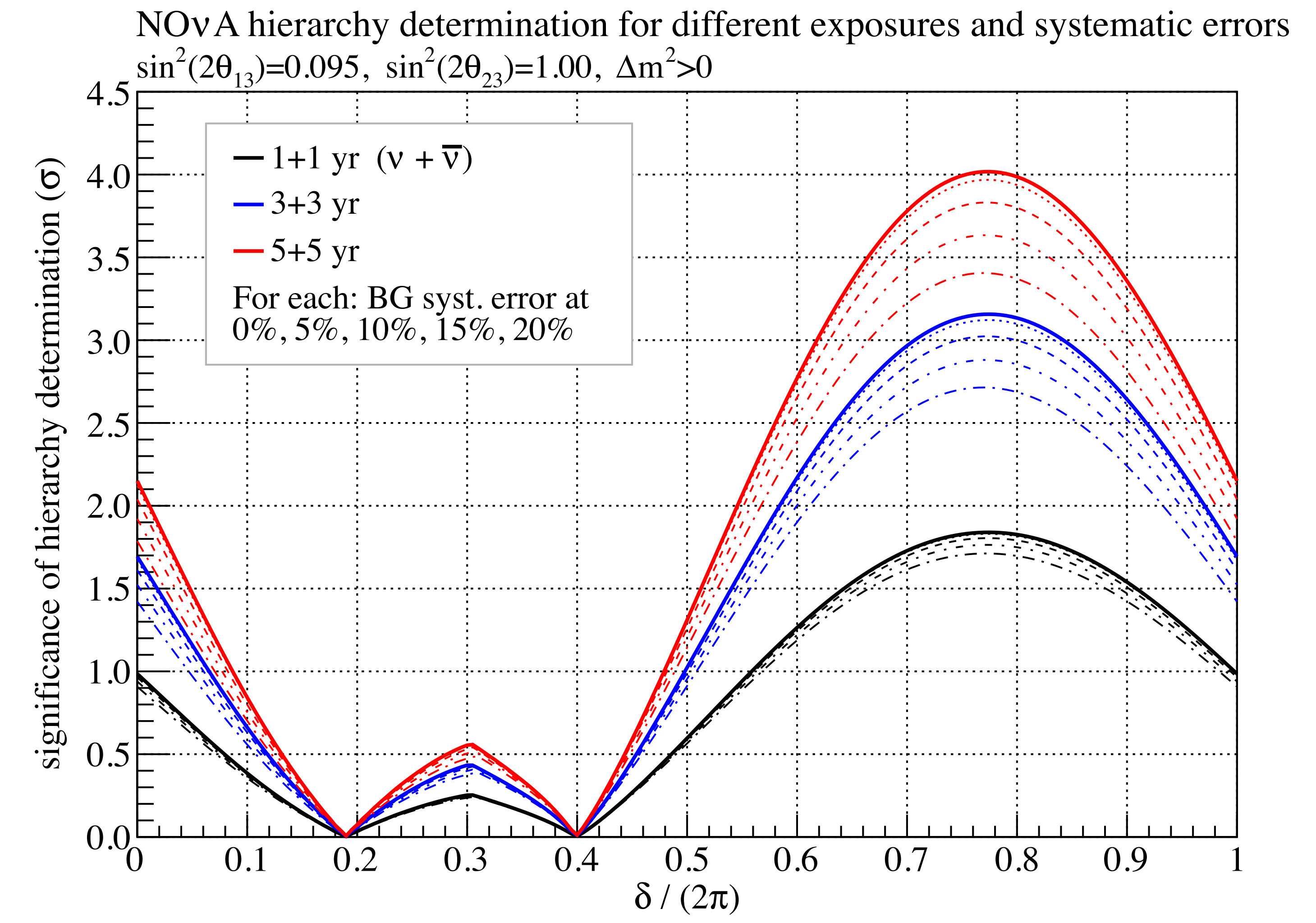
Other Far/Near differences

MINOS detectors are very similar, however there are small differences:

- Far/Near spectrum different due to **beamline geometry and oscillations** in the Far.
- **Readout patterns:**
  - Light level differences due to differences in fiber length.
  - Multiplexing in the Far (8 fibers per PMT pixel).
  - Partial (one-sided) readout in the Near.
- **Photomultipliers (M64 in Near Detector, M16 in Far):**
  - Different gains/front end electronics.
  - Different crosstalk patterns (also related to readout patterns).
- **Neutrino intensity:**
  - higher rates in the Near Detector thus faster readout.
- **Relative energy calibration.**

These considerations **affect the Far/Near ratio** and are considered in the extrapolation uncertainties

Effects on NOvA sensitivities



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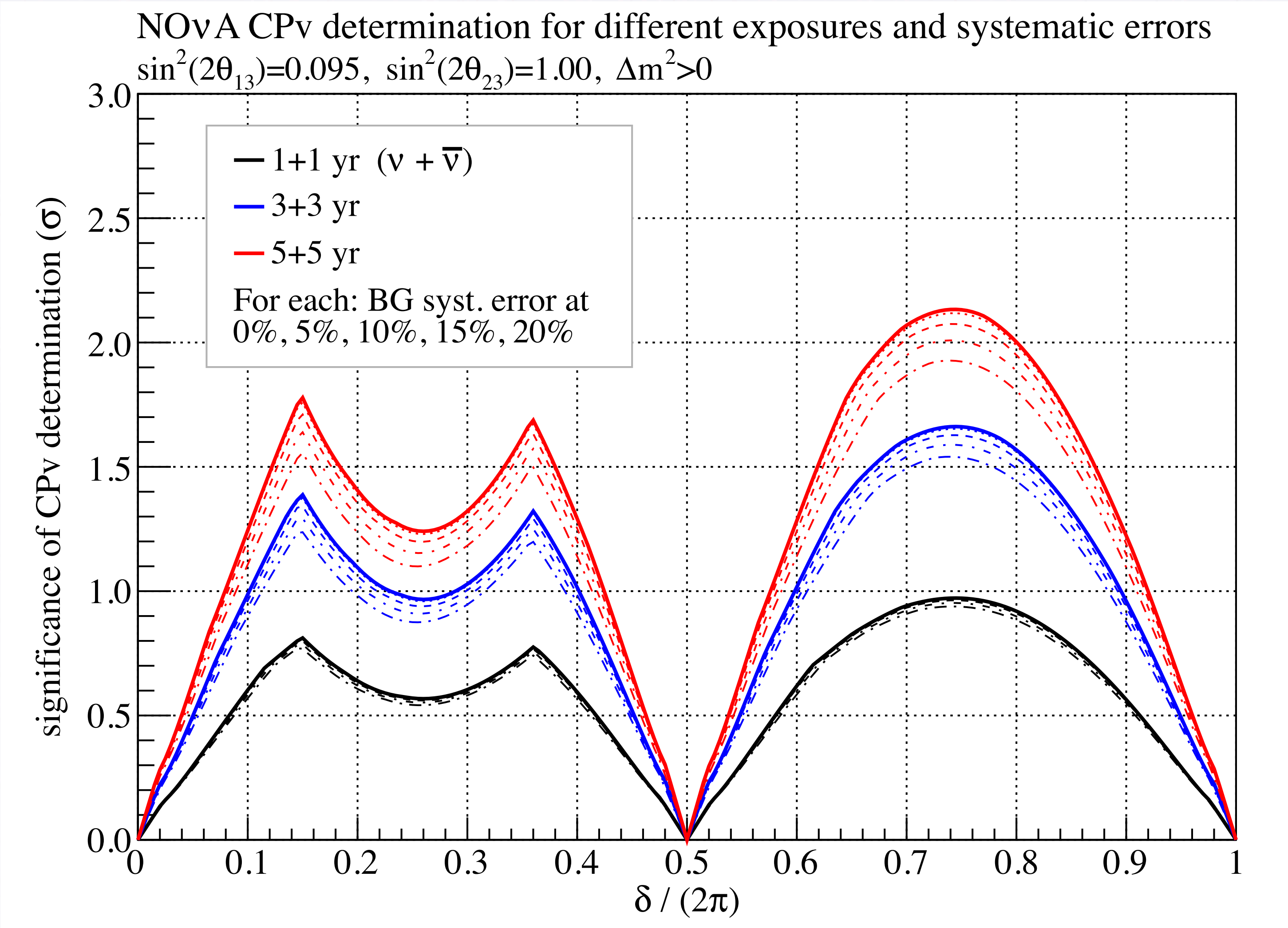

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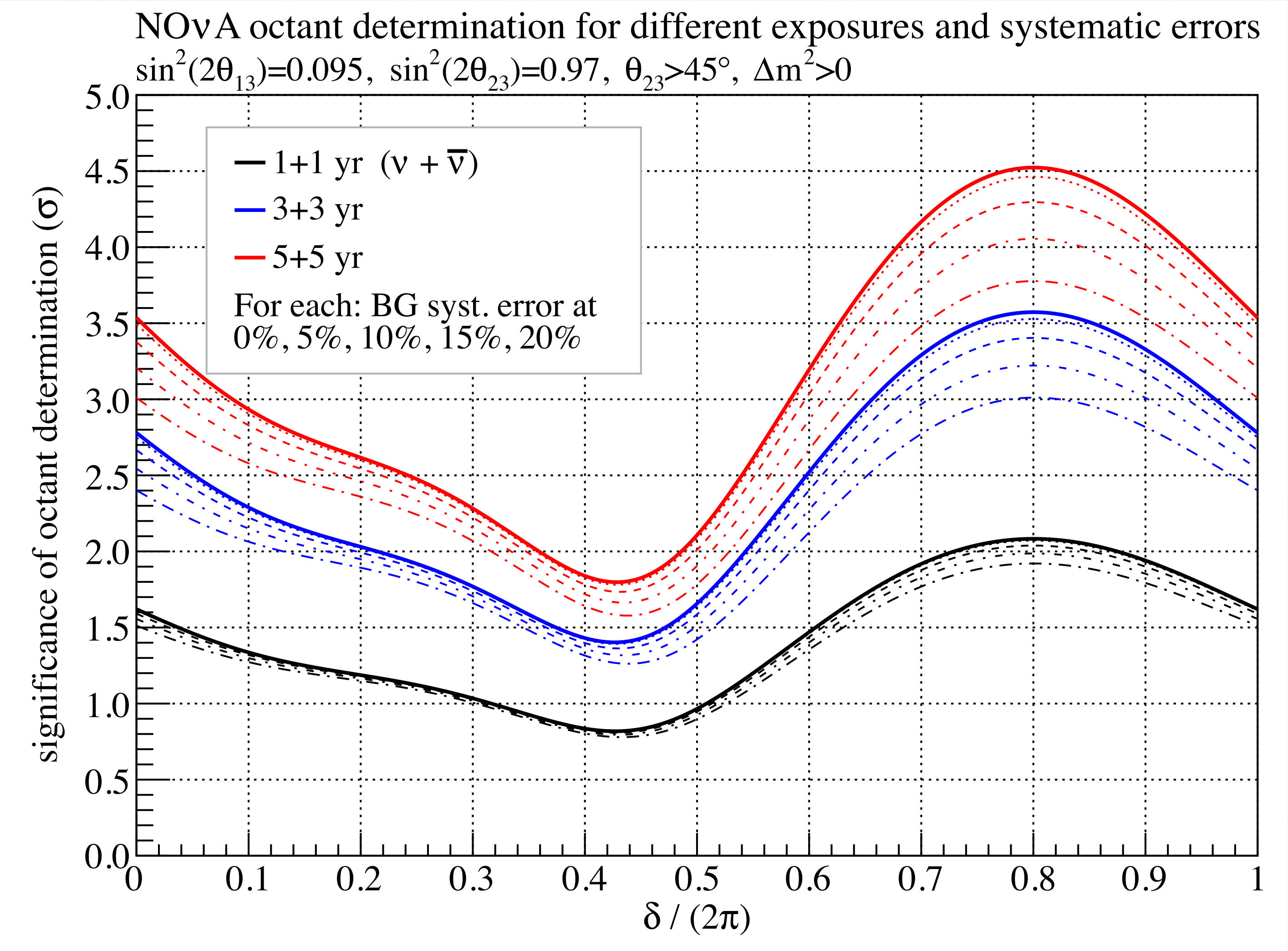

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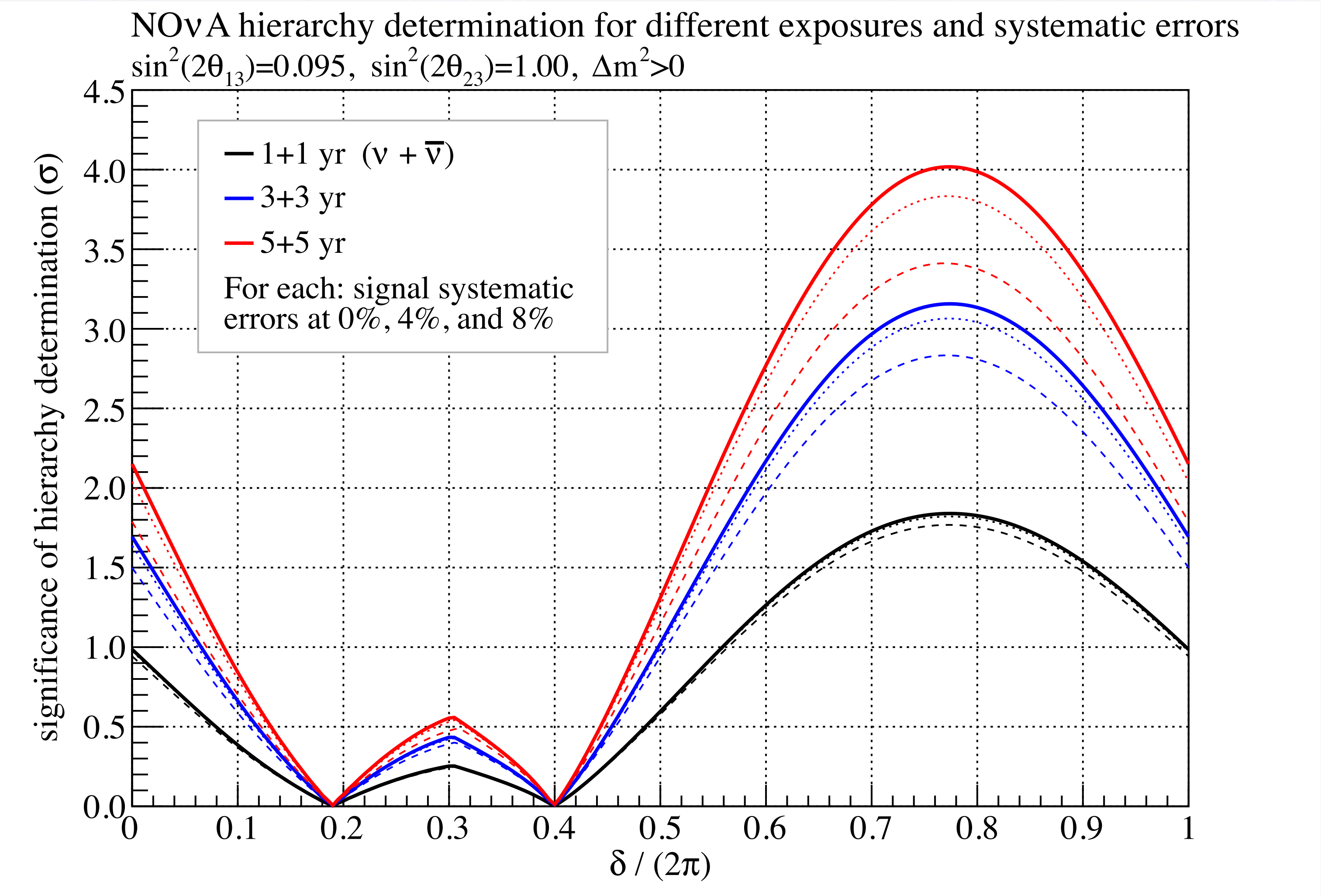

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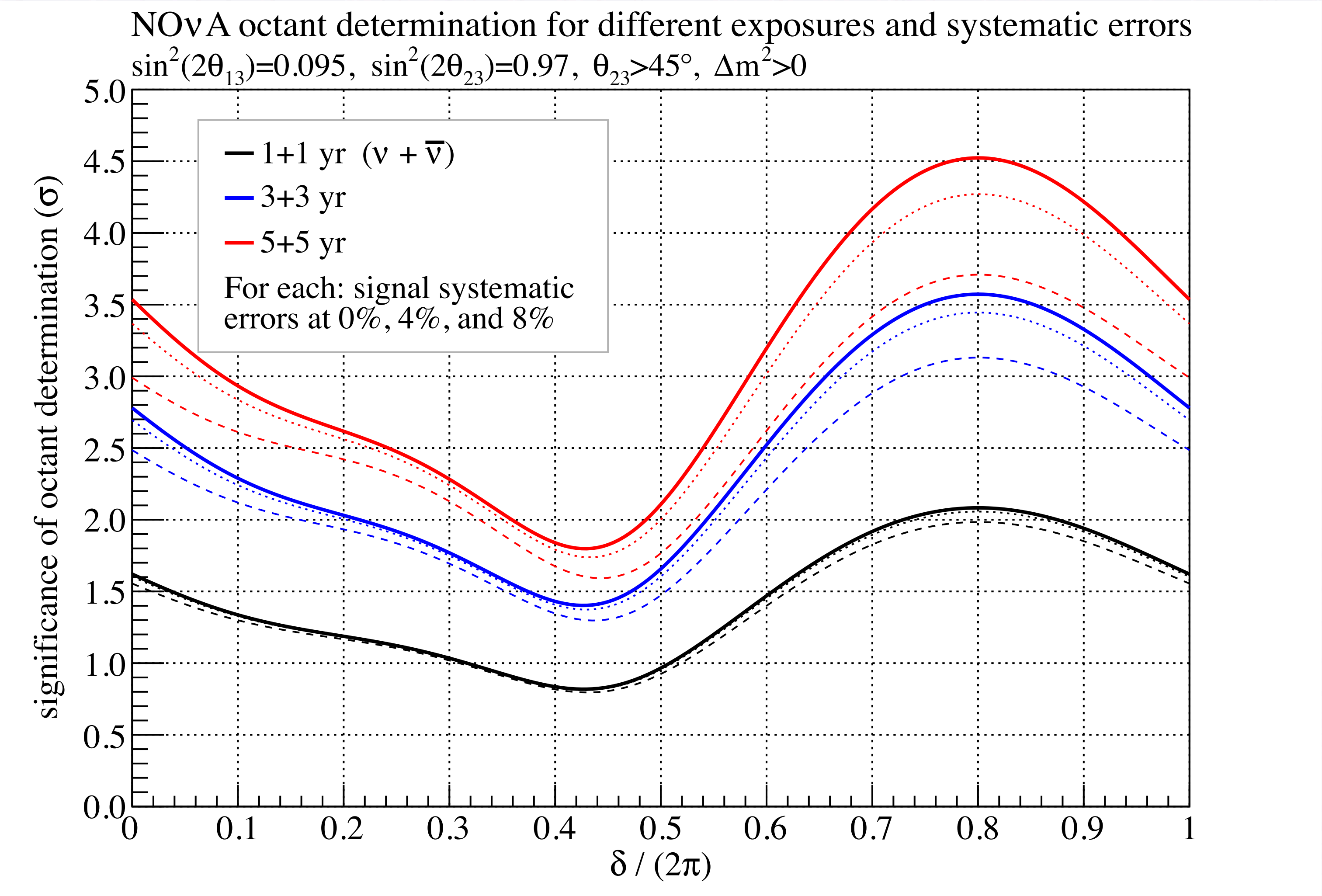

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