# On-axis and off-axis neutrinos in the DUNE near detector

Jarrett Fein, Minerba Betancourt

Michigan State University, Fermilab

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On-axis and Off-axis Neutrino Detection

- ND-LAr detects different kinematics depending on its position relative to the beam axis, we are interested in the affects this has on different interaction channels

- We study interactions from both neutrino and antineutrino beam modes and for both electron and muon neutrinos

- We explore neutrino energy, muon p_z, and $cos(\theta)$ for the different off-axis locations and neutrino beams

- POT: 10^{19}

- All events examined at truth level from GENIE simulation
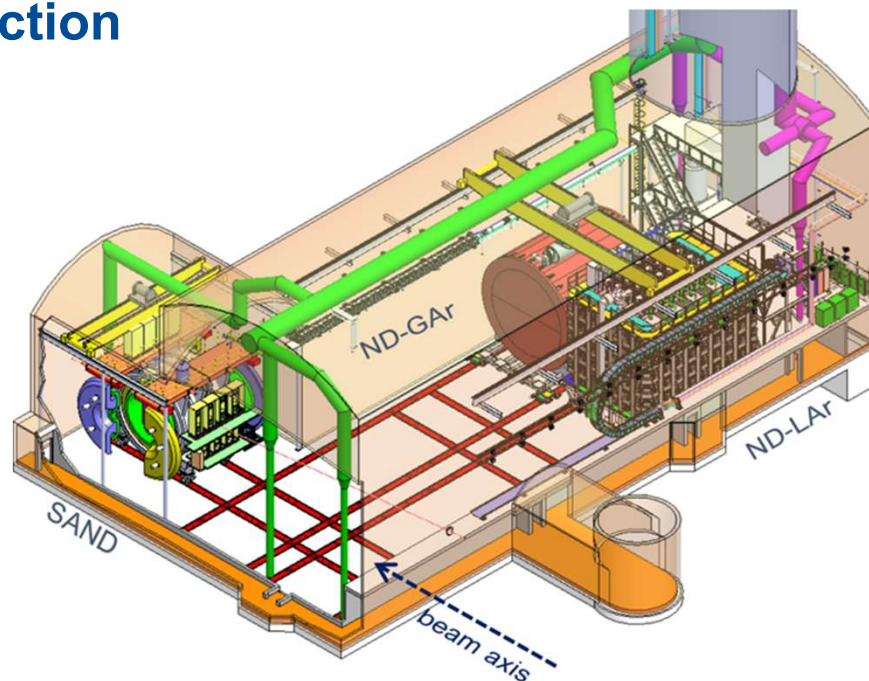
- Events obtained from: /pnfs/dune/persistent/physicsgroups/dunelbl/abooth/PRISM/Production/Simulation/ND_CAFMaker/v7/CAF

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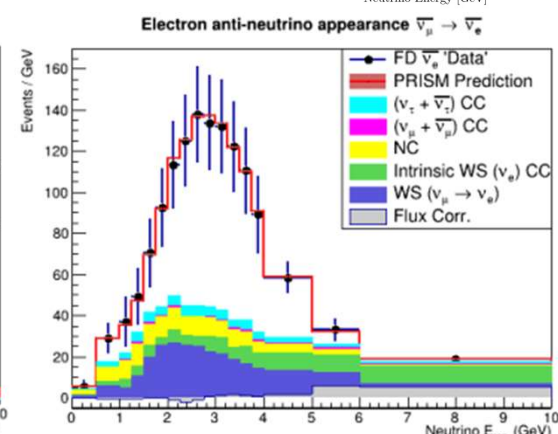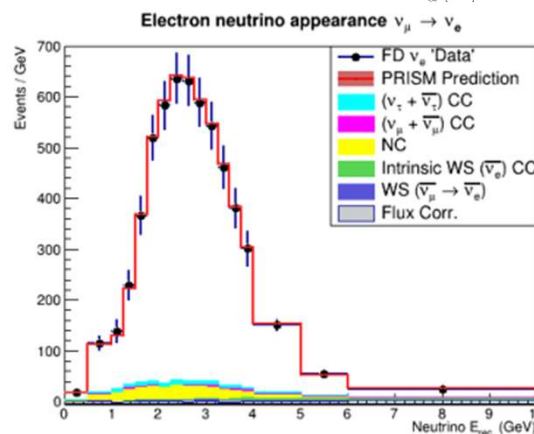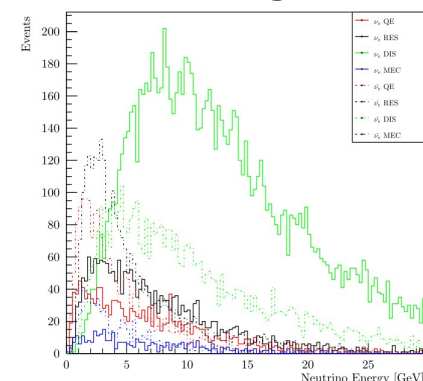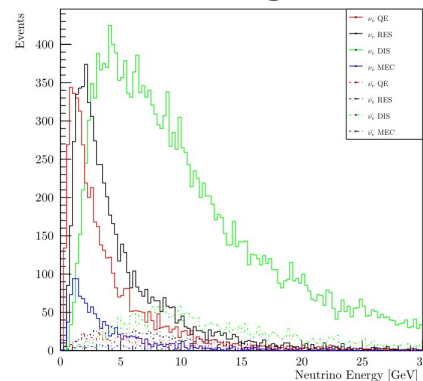# Comparing Spectra in Near and Far Detectors – Electron Neutrinos

- The energy distribution of electron neutrinos greatly differs between the near and far detectors

- Near detector data can be used to constrain different channels

Near Detector

Far Detector

FHC

RHC

Caracas, I. DUNE-PRISM: An innovative technique for neutrino oscillation analysis.

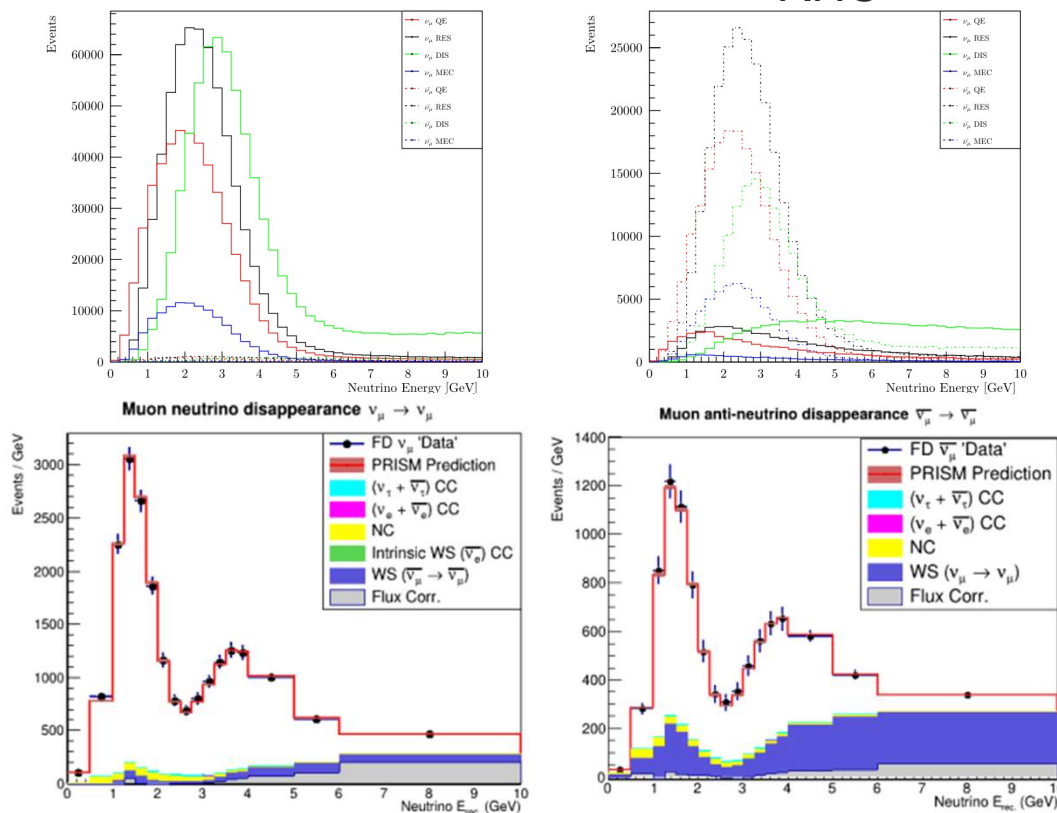# Comparing Spectra in Near and Far Detectors – Muon Neutrinos

- Muon neutrino energy distributions are more similar between near and far detectors than electron neutrinos, but some amount of oscillation can still be seen
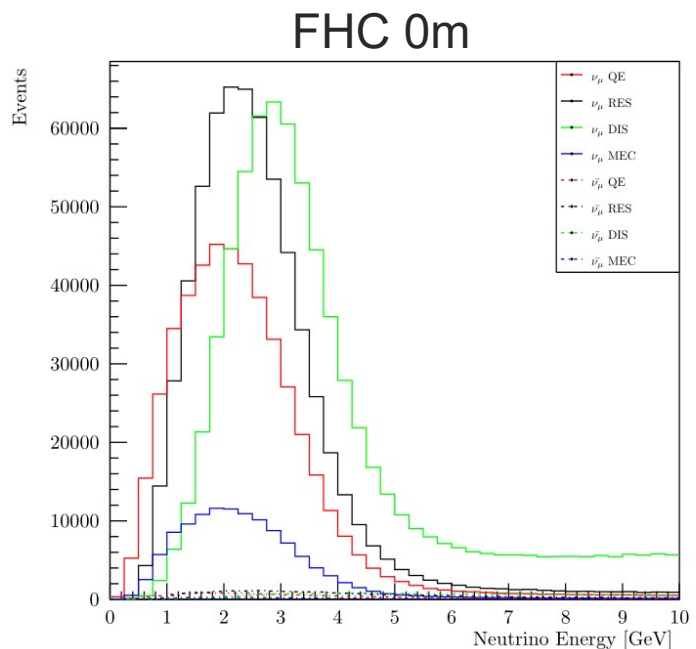
Near Detector

Far Detector

FHC

RHC

Caracas, I. DUNE-PRISM: An innovative technique for neutrino oscillation analysis.

FHC vs RHC Muon Neutrino Energy – 0m

FHC 0m

RHC 0m

- DIS is most prominent in FHC
- RES is most prominent in RHC

0m FHC	QE	RES	DIS	MEC	COH	Sum
$\nu_\mu + \bar{\nu}_\mu$	494500	655594	722291	124947	11576	2008908
$\nu_e + \bar{\nu}_e$	5094	6573	12522	1281	210	25680
Sum	499594	662167	734813	126228	11786	2034588
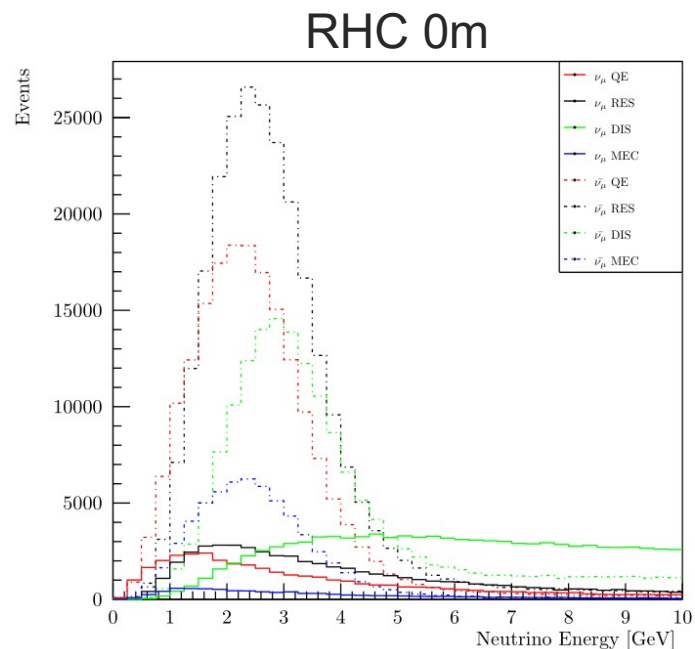
0m RHC	QE	RES	DIS	MEC	COH	Sum
$\nu_\mu + \bar{\nu}_\mu$	222747	303875	258150	70278	10492	865542
$\nu_e + \bar{\nu}_e$	2772	3918	6888	854	136	14568
Sum	225519	307793	265038	71132	10628	880110

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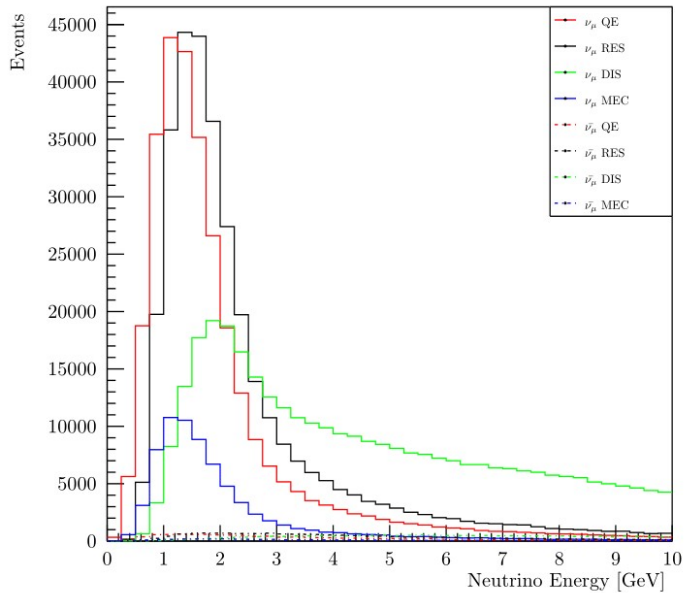
FHC vs RHC Muon Neutrino Energy – 8m

FHC 8m

8m FHC	QE	RES	DIS	MEC	COH	Sum
$\nu_\mu + \bar{\nu}_\mu$	307013	342093	338668	75102	5770	1068646
$\nu_e + \bar{\nu}_e$	3745	4704	8055	998	136	17638
Sum	310758	346797	346723	76100	5906	1086284

RHC 8m

8m RHC	QE	RES	DIS	MEC	COH	Sum
$\nu_\mu + \bar{\nu}_\mu$	126113	149671	139785	37846	5304	458719
$\nu_e + \bar{\nu}_e$	2113	2864	4925	589	98	10589
Sum	128226	152535	144710	38435	5402	469308

- DIS is still dominant at high energy in FHC, QE similarly prominent as RES
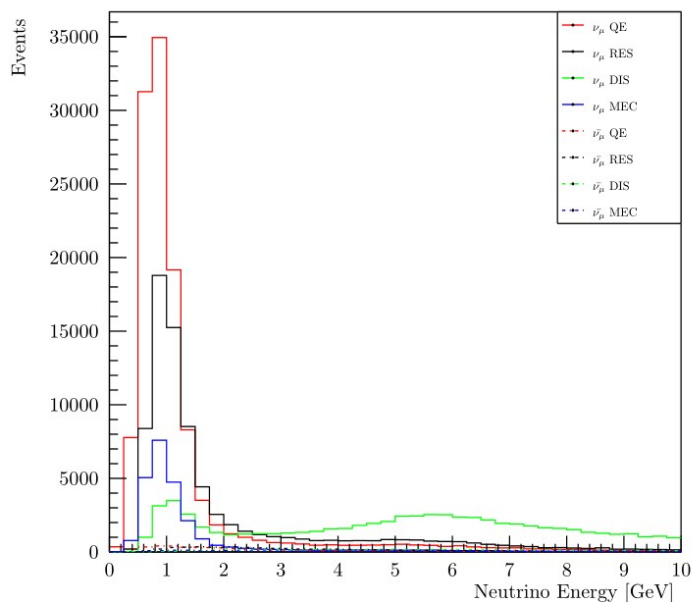
- QE becomes more in RHC, though RES continues to dominate

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FHC vs RHC Muon Neutrino Energy – 16m

FHC 16m

16m FHC	QE	RES	DIS	MEC	COH	Sum
$\nu_\mu + \bar{\nu}_\mu$	124307	84159	71351	26334	1440	307591
$\nu_e + \bar{\nu}_e$	2326	2546	3599	590	77	9138
Sum	126633	86705	74950	26924	1517	316729

RHC 16m

16m RHC	QE	RES	DIS	MEC	COH	Sum
$\nu_\mu + \bar{\nu}_\mu$	44689	36717	35908	11119	1278	129711
$\nu_e + \bar{\nu}_e$	1282	1617	2394	345	59	5697
Sum	45971	38334	38302	11464	1337	135408

- QE becomes the dominant channel, particularly at low energy, for both FHC and RHC
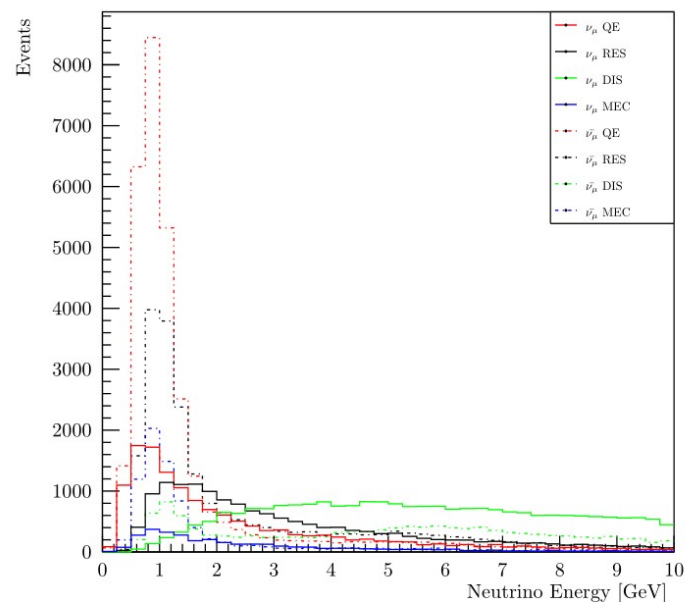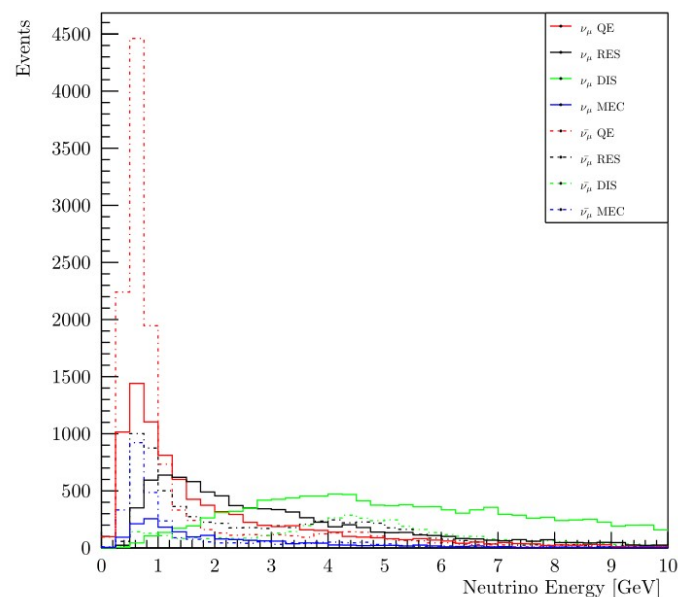
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FHC vs RHC Muon Neutrino Energy – 24m
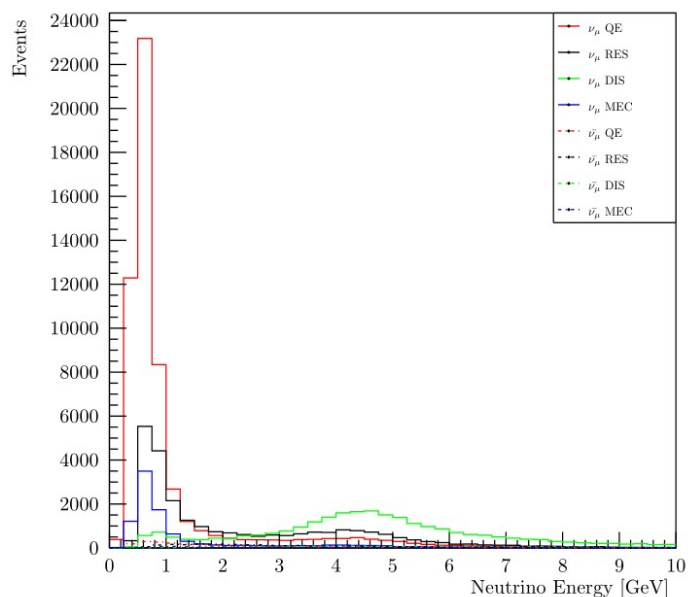
FHC 24m

- QE increases its dominance over the other channels in both FHC and RHC

RHC 24m

24m FHC	QE	RES	DIS	MEC	COH	Sum
$\nu_\mu + \bar{\nu}_\mu$	58198	28629	28071	10139	562	125599
$\nu_e + \bar{\nu}_e$	1380	1331	1504	309	28	4552
Sum	59578	29960	29575	10448	590	130151

24m RHC	QE	RES	DIS	MEC	COH	Sum
$\nu_\mu + \bar{\nu}_\mu$	20960	14860	15873	4754	518	56965
$\nu_e + \bar{\nu}_e$	764	889	1125	220	34	3032
Sum	21724	15749	16998	4974	552	59997

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Muon Neutrino Energy – 0m, 8m, 16m, 24m

8/8/2024   Jarrett Fein

FHC vs RHC Electron Neutrino Energy – 0m

FHC 0m

Legend
ν_e QE
ν_e RES
ν_e DIS
ν_e MEC
$\bar{\nu}_e$ QE
$\bar{\nu}_e$ RES
$\bar{\nu}_e$ DIS
$\bar{\nu}_e$ MEC

0m FHC	QE	RES	DIS	MEC	COH	Sum
$\nu_\mu + \bar{\nu}_\mu$	494500	655594	722291	124947	11576	2008908
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RHC 0m

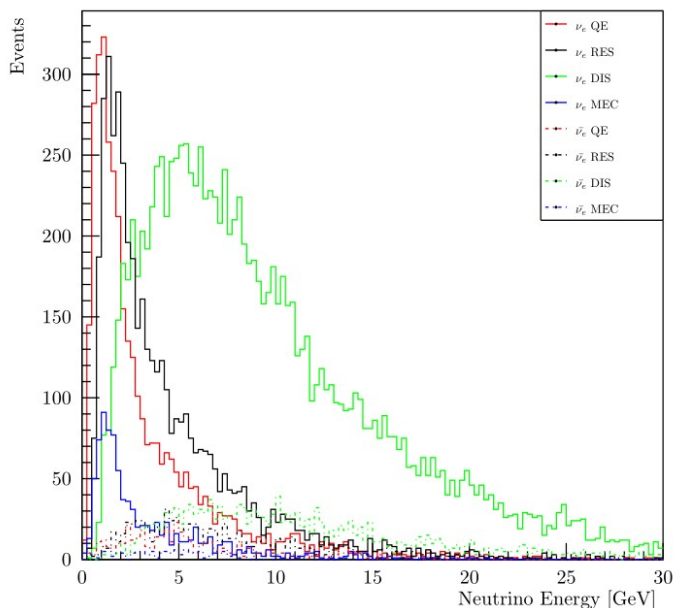| 0m RHC	QE	RES	DIS	MEC	COH	Sum
$\nu_\mu + \bar{\nu}_\mu$	222747	303875	258150	70278	10492	865542
$\nu_e + \bar{\nu}_e$	2772	3918	6888	854	136	14568
Sum	225519	307793	265038	71132	10628	880110

- DIS is dominant in FHC
- DIS is dominant in RHC, notably ν_e is more prominent than $\overline{\nu_e}$
- DIS is substantially more prominent at high energies than any other channel
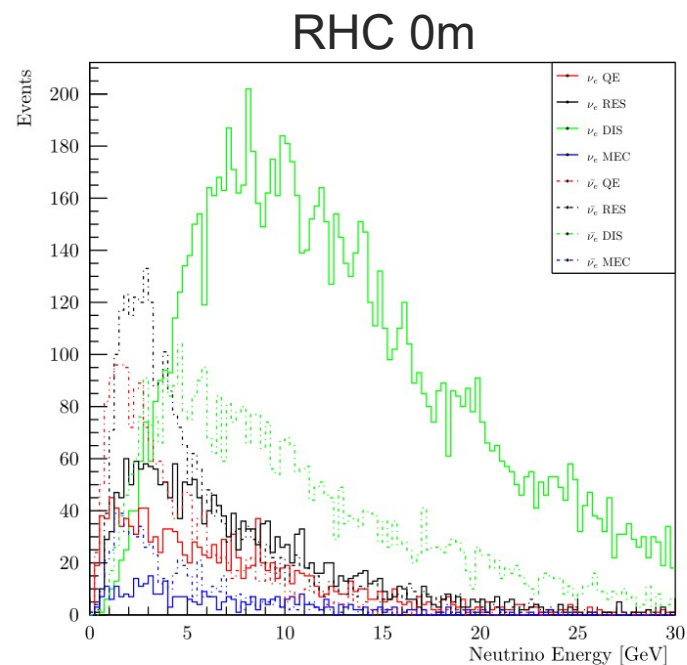
🔷 **Fermilab**

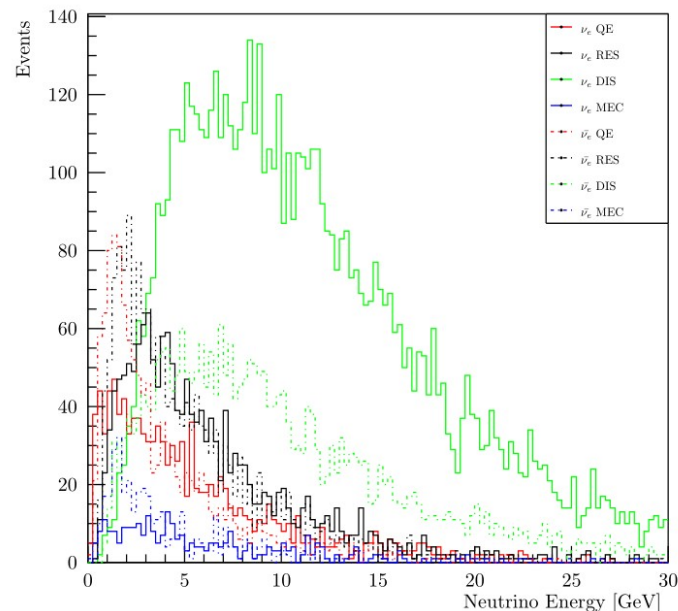# FHC vs RHC Electron Neutrino Energy – 8m

FHC 8m

- DIS remains dominant in FHC and RHC at high energies, RES dominates at low energies
- ν_e remains more prominent than $\overline{\nu_e}$ in RHC

RHC 8m

8m FHC	QE	RES	DIS	MEC	COH	Sum
$\nu_\mu + \bar{\nu}_\mu$	307013	342093	338668	75102	5770	1068646
$\nu_e + \bar{\nu}_e$	3745	4704	8055	998	136	17638
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FHC vs RHC Electron Neutrino Energy – 16m

FHC 16m

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RHC 16m

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Sum	45971	38334	38302	11464	1337	135408

- DIS remains dominant as before in both FHC and RHC, but QE and RES gain prevalence at low energies
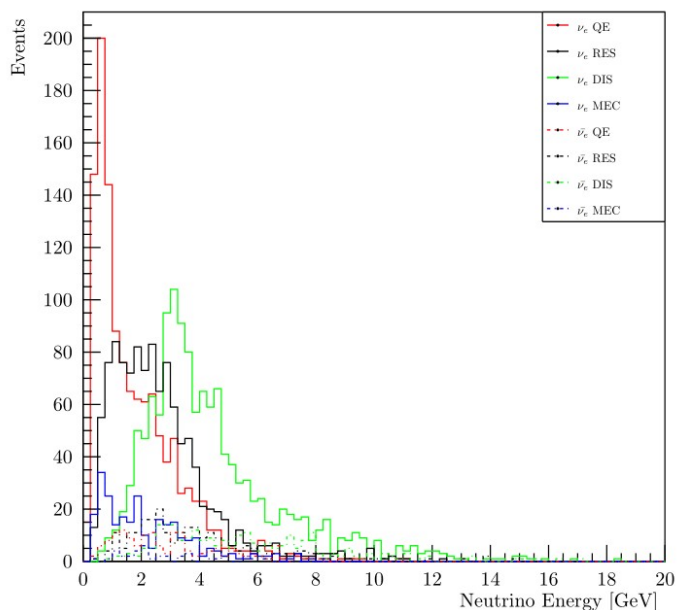- The tail occupied by high energy DIS events is less populated
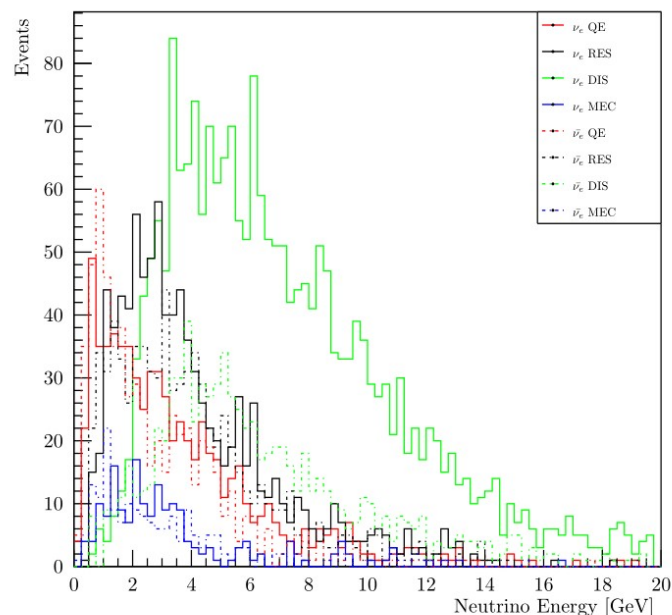
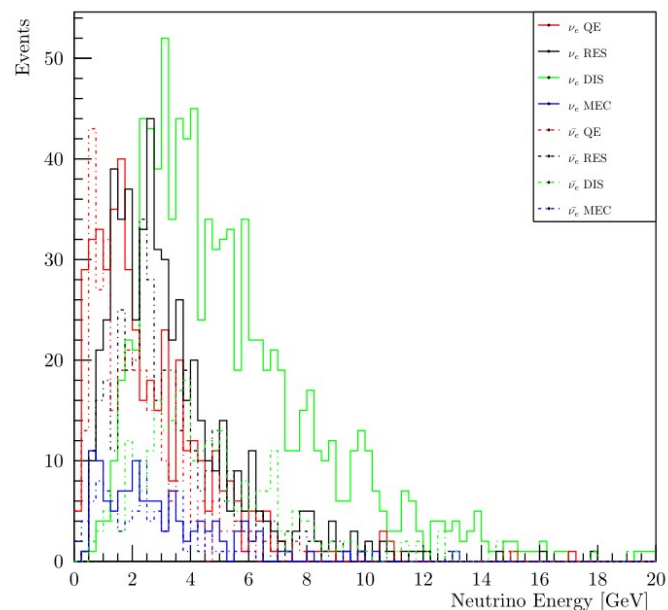**🔷 Fermilab**

FHC vs RHC Electron Neutrino Energy – 24m

FHC 24m

- QE and RES are dominant at low energies, while DIS is dominant at higher energies

- The high energy DIS tail continues to shrink

RHC 24m

24m FHC	QE	RES	DIS	MEC	COH	Sum
$\nu_\mu + \bar{\nu}_\mu$	58198	28629	28071	10139	562	125599
$\nu_e + \bar{\nu}_e$	1380	1331	1504	309	28	4552
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Electron Neutrino Energy – 0m, 8m, 16m, 24m

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Electron Neutrino to Muon Neutrino Ratio

FHC ν_e/ν_μ

RHC ν_e/ν_μ

All Channels ν_e/ν_μ
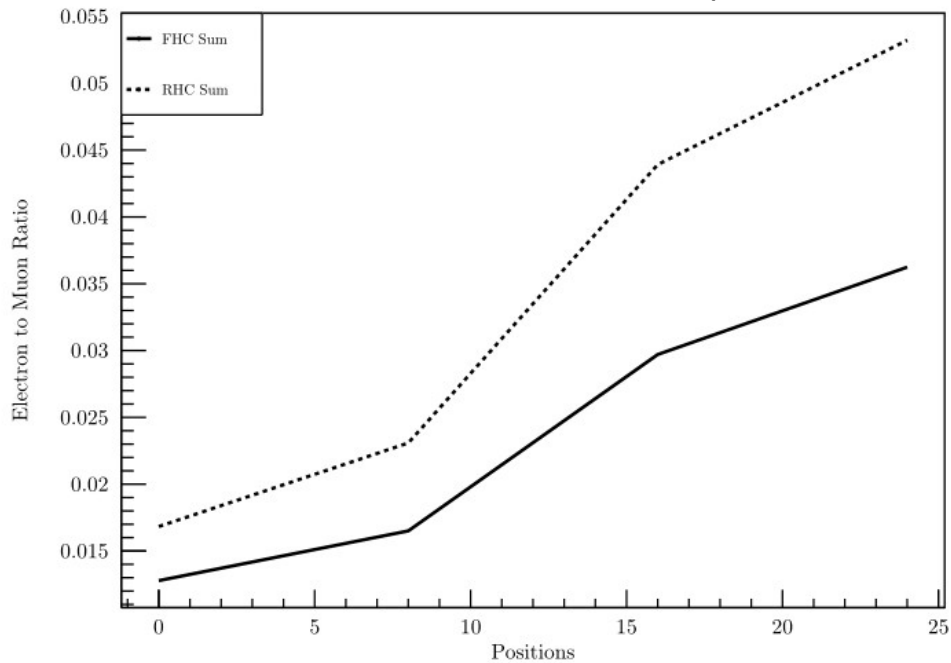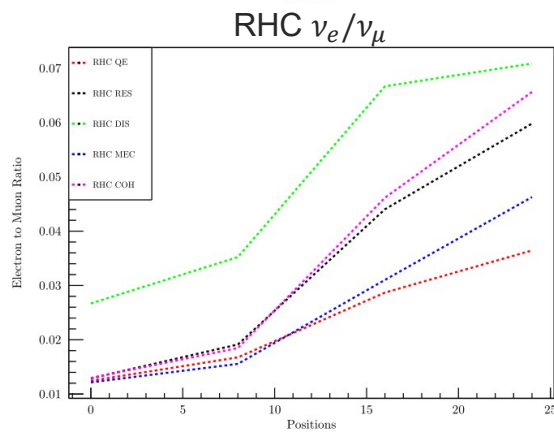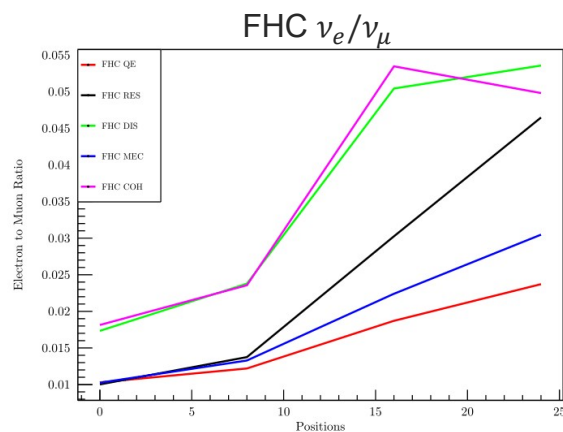
- The ratio ν_e/ν_μ varies by interaction channel, but it increases for all channels as a function of detector position

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Muon p_z - 0m, 8m, 16m, 24m
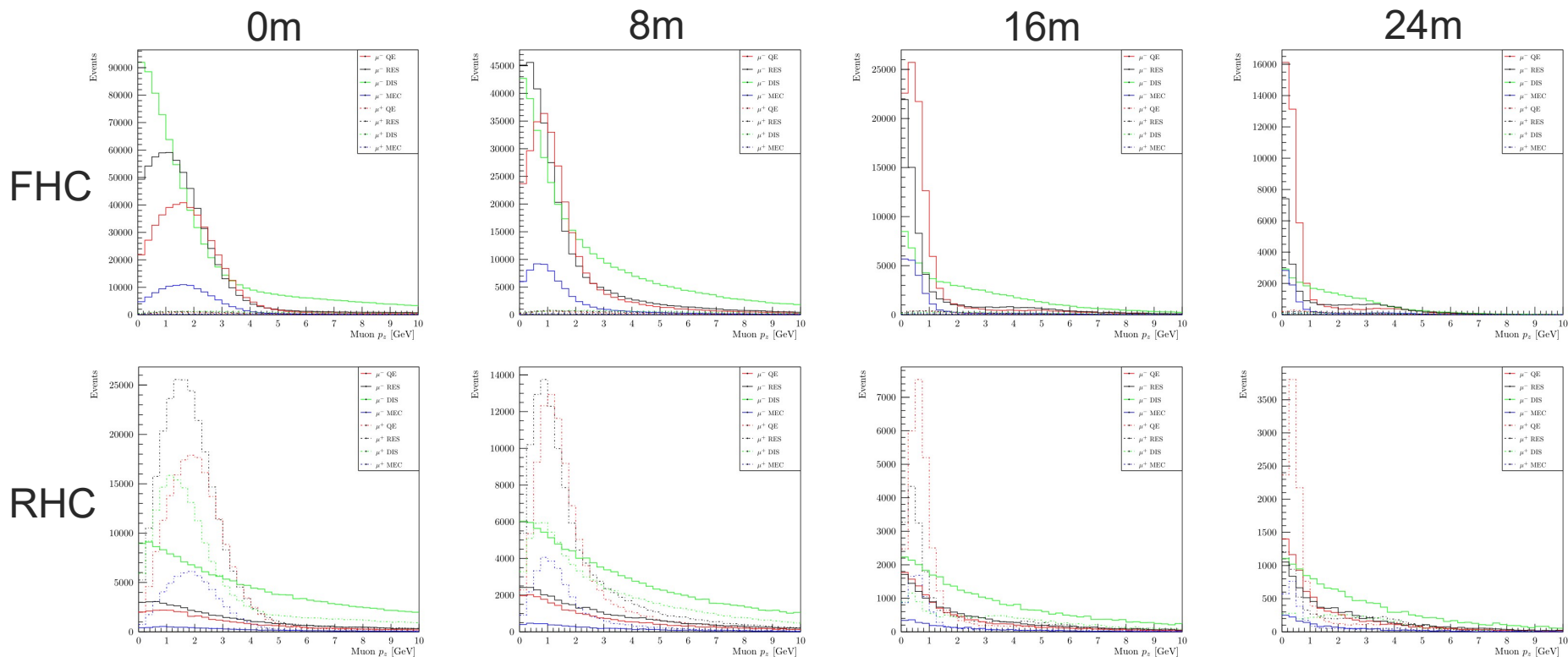
- DIS is dominant on-axis and QE is dominant off-axis, on-axis events span a wider band of momenta

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Interaction $\cos(\theta)$ - 0m, 8m, 16m, 24m
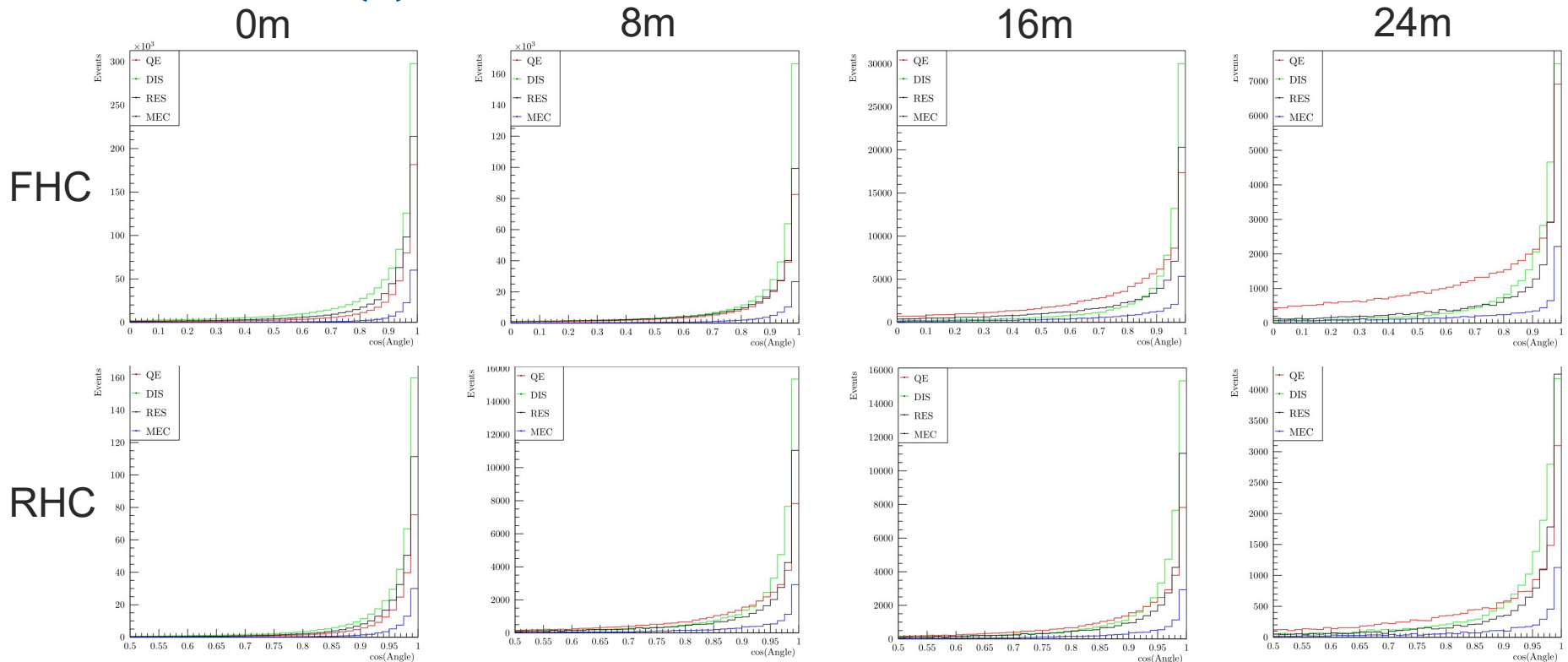
- Average interaction angle increases as off-axis position increases, DIS gives way to QE as most dominant as position increases

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Summary

- As off-axis position increases:

  - The dominant channel shifts from DIS to QE

  - Neutrino energy and muon p_z distributions sharpen

  - $\cos(\theta)$ distribution widens

- Muon neutrinos interact with much lower energy than electron neutrinos

- Electron neutrinos are more strongly dominated by DIS than muon neutrinos

- A greater portion of detected interactions come from electron neutrinos at further off-axis positions, but the statistics on such measurements are much lower

- Off-axis cross-section measurements will help to constrain QE and MEC

- On-axis cross-section measurements are more useful for constraining DIS and RES

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Statistics for all Channels, Modes, and Positions

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Affiliations