FERMILAB-SLIDES-24-0316-STUDENT

Simulated Neutrino Interactions in DUNE PRISM ND-LAr – Predicted Kinematics and Event Generator Dependence in Quasi-Elastic Events

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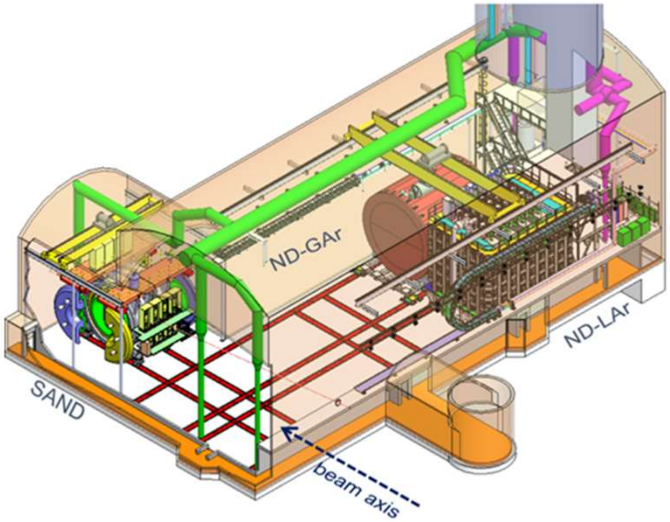
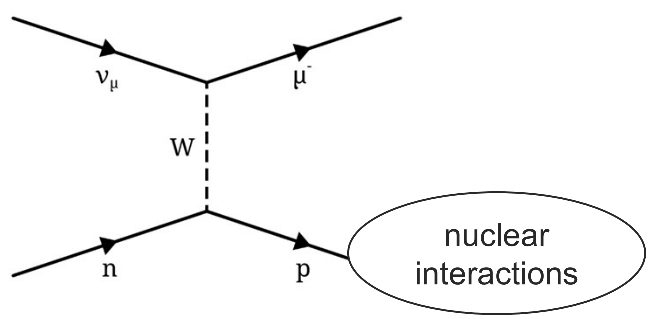
Overview…

- **Neutrino interactions in ND-LAr as a whole**
  - We will compare spectra between horn configurations, interaction channels, and axis positions
    - Movable transverse to beam to detect off-axis events which have varying spectra (PRISM concept – better characterize beam for FD)
    - Looking at simulated data from GENIE event generator (truth level) corresponding to roughly 4 days of real data (POT=10^19)
- **Main study focused on QE exclusive events (self-generated)**
  - Experimentally measurable observables of interest
  - Compare results between event generators and models (Achilles and GENIE)





On-Axis ND vs FD ν_μ Spectra

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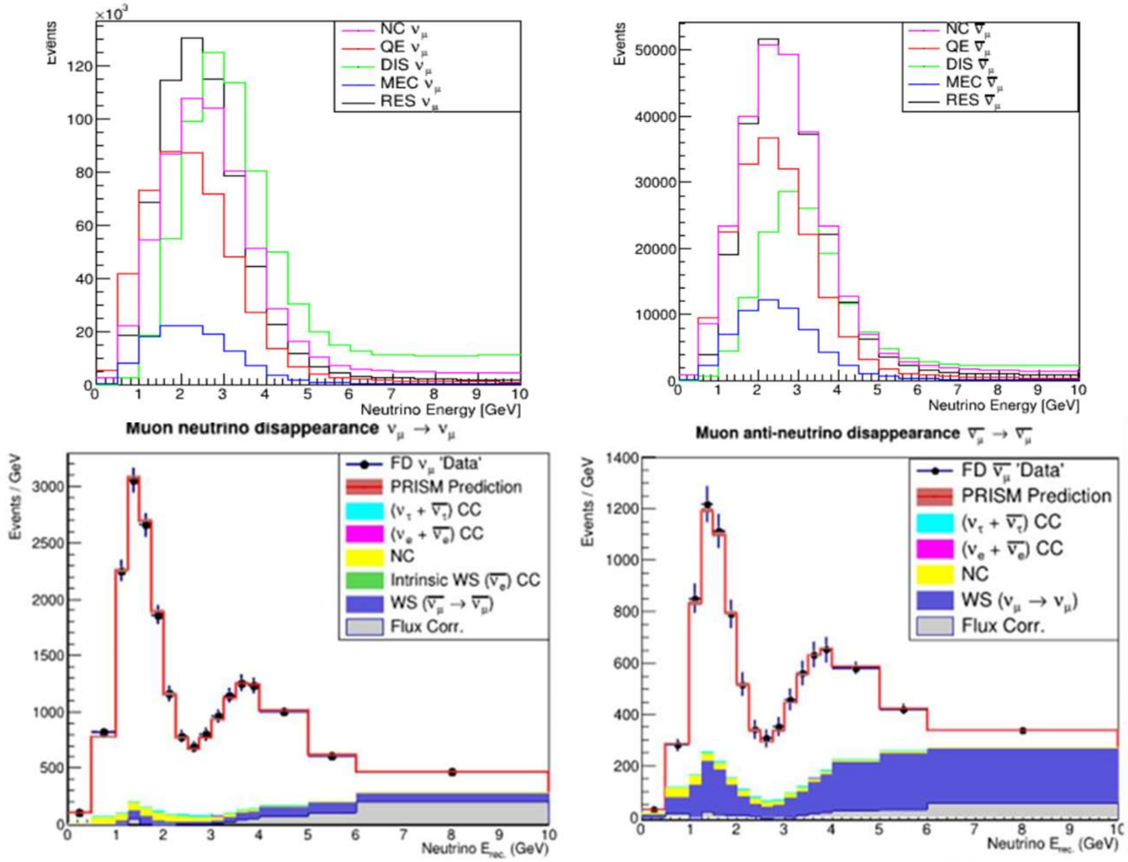
- ν_μ and $\bar{\nu}_\mu$ spectra similar between each other in ND and FD
- RES and DIS leading in FHC and RES and NC leading in RHC
- Many NC events in ND to help constrain NC FD events
- Oscillation prominent between 2-3 GeV

FHC

RHC

Near Detector

Far Detector



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

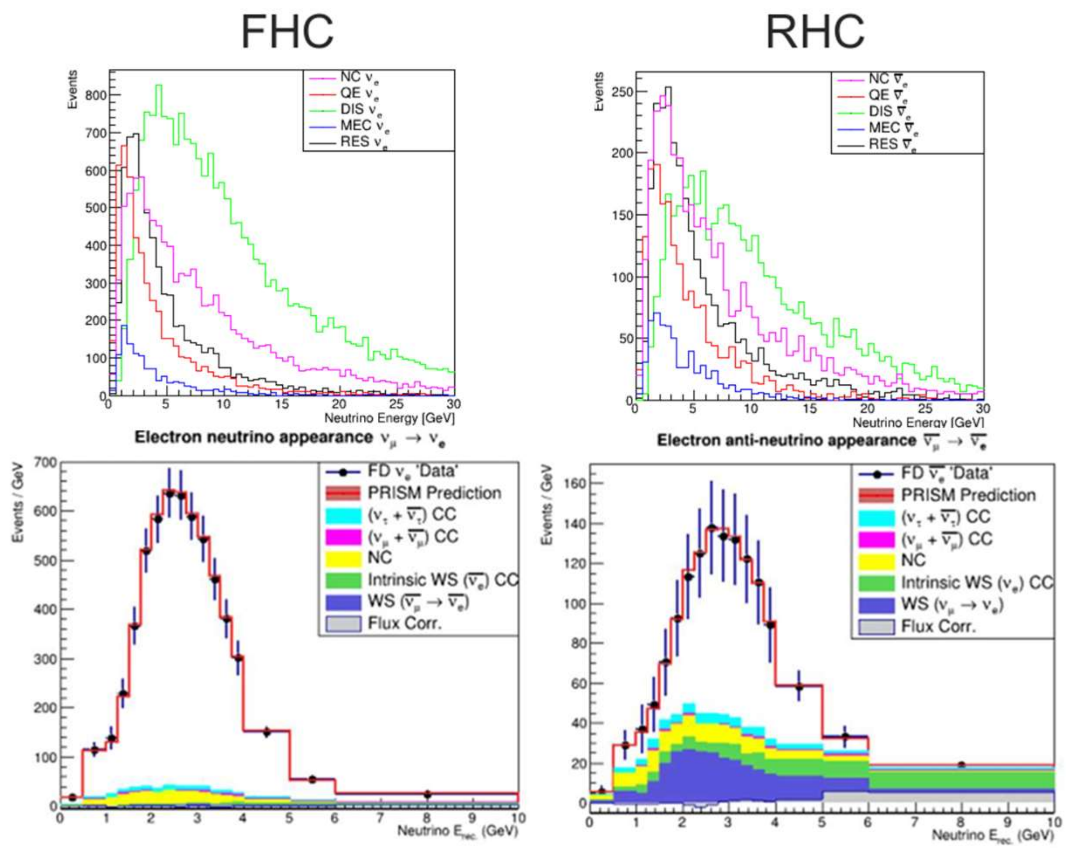
On-Axis ND vs FD ν_e Spectra

/pnfs/dune/persistent/physicsgroups/dunelbl/ abooth/PRISM/Production/Simulation/ ND_CAFMaker/v7/CAF

- ND and FD spectra differ dramatically (specifically DIS)
- ND spectra differences useful for eliminating non-oscillated background ν_e
- Again, NC contributes to ND and FD spectra

Near Detector

Far Detector



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

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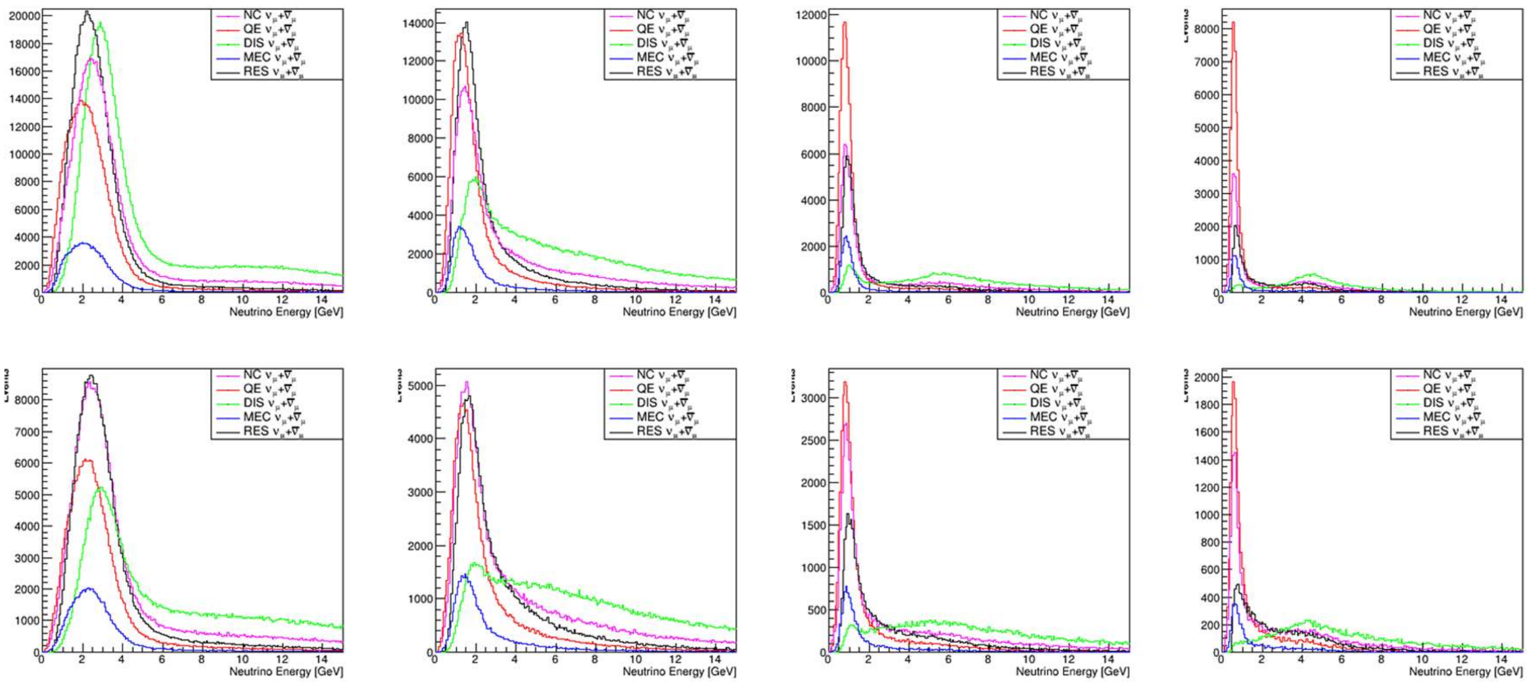
$\nu_\mu + \bar{\nu}_\mu$ Spectra as a Function of PRISM ND-LAr Positions

$0m$ | $8m$ | $16m$ | $20m$

FHC

RHC



- Peaks narrow and shift as position increases (ignoring DIS tail)
- QE dominates low energy region as position increases
- NC more dominate in RHC for all positions

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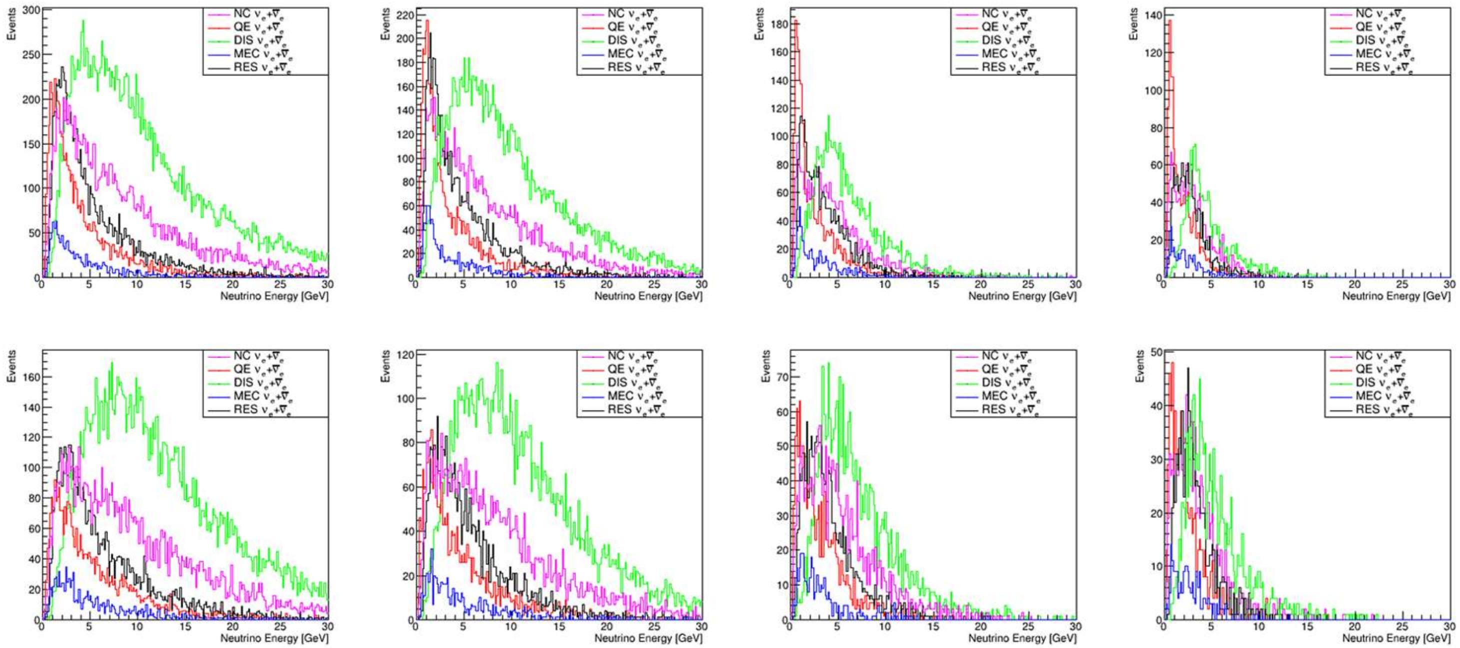
abooth/PRISM/Production/Simulation/ ND_CAFMaker/v7/CAF

$\nu_e + \bar{\nu}_e$ Spectra as a Function of PRISM ND-LAr Positions

$0m$ | $8m$ | $16m$ | $20m$

FHC

RHC



- Again, peaks narrow and shift as position increases
- DIS dominates total events – less so as position increases
- Again, QE dominates low energy region as position increases

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abooth/PRISM/Production/Simulation/ ND_CAFMaker/v7/CAF

Going More In-depth with QE Events…

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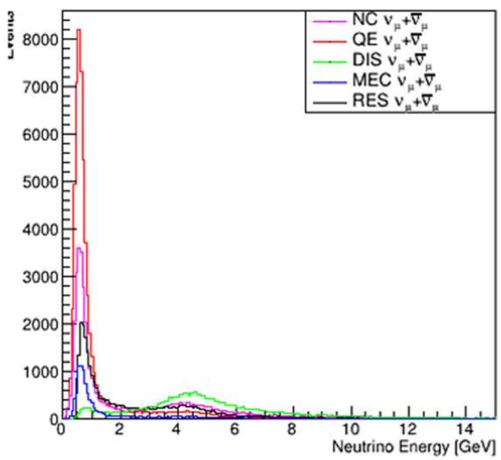
abooth/PRISM/Production/Simulation/ ND_CAFMaker/v7/CAF

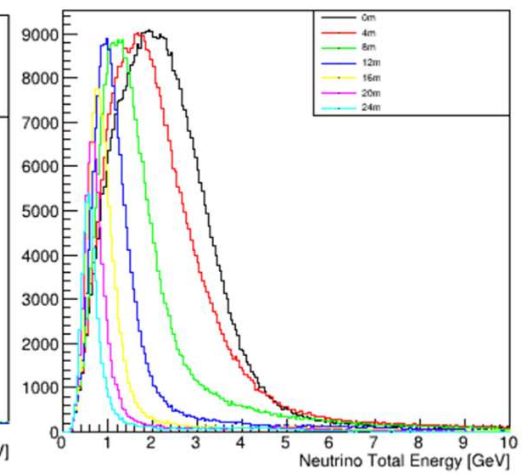
- QE provides the most statistics for off-axis events which are interesting for FD constraints

- What we will look at:
    - Electron to muon neutrino ratios
    - Strong similarities between DUNE off-axis and MicroBooNE neutrino spectra
    - Muon and proton kinematics compared between Achilles and GENIE models

24m FHC $\boldsymbol{\nu_\mu} + \bar{\nu}_{\boldsymbol{\mu}}$
all channels



FHC QE $\boldsymbol{\nu_\mu} + \bar{\nu}_{\boldsymbol{\mu}}$
different positions

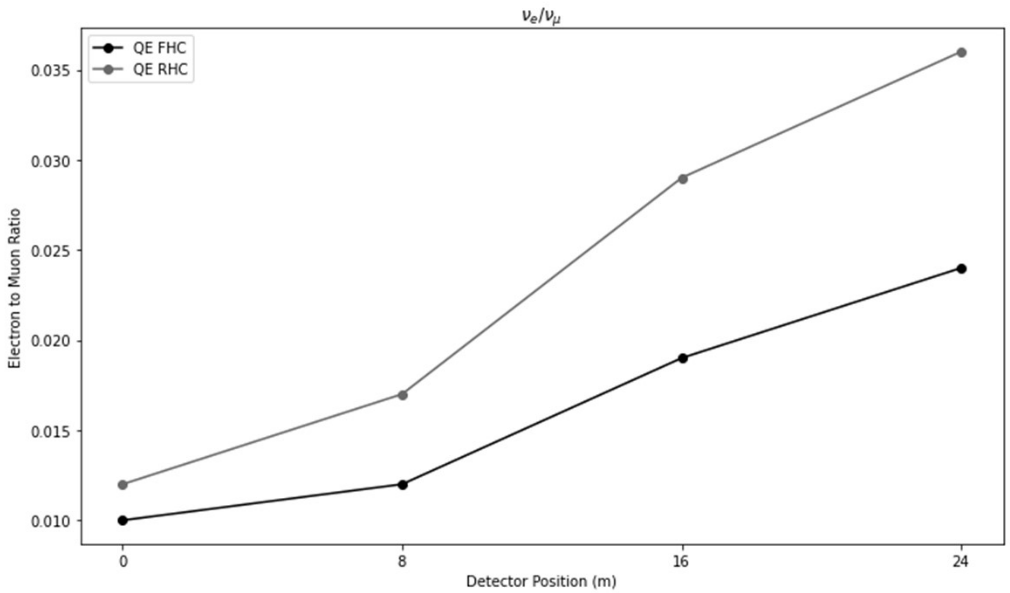


24m FHC	QE	RES	DIS	MEC	COH	NC	Sum
$\nu_\mu + \bar{\nu}_\mu$	58198	28629	28071	10139	562	41781	167380
$\nu_e + \bar{\nu}_e$	1380	1331	1504	309	28	1552	6104
$\frac{\nu_e+\bar{\nu}_e}{\nu_\mu+\bar{\nu}_\mu}$	0.024	0.046	0.053	0.030	0.050	0.037	0.036
Sum	59578	29960	29575	10448	590	43333	173484

$\nu_e + \bar{\nu}_e / \nu_\mu + \bar{\nu}_\mu$ vs PRISM ND-LAr Position (QE Events)

/pnfs/dune/persistent/physicsgroups/dunelbl/

abooth/PRISM/Production/Simulation/ ND_CAFMaker/v7/CAF



QE FHC	0m	8m	16m	24m
$\nu_\mu + \bar{\nu}_\mu$	494500	307013	124307	58198
$\nu_e + \bar{\nu}_e$	5094	3745	2326	1380
$\frac{\nu_e+\bar{\nu}_e}{\nu_\mu+\bar{\nu}_\mu}$	0.010	0.012	0.019	0.024

QE RHC	0m	8m	16m	24m
$\nu_\mu + \bar{\nu}_\mu$	222747	126113	44689	20960
$\nu_e + \bar{\nu}_e$	2772	2113	1282	764
$\frac{\nu_e+\bar{\nu}_e}{\nu_\mu+\bar{\nu}_\mu}$	0.012	0.017	0.029	0.036

- Ratio increases monotonically with off-axis position for both FHC and RHC
  - Due to off-axis kaons in neutrino beam production which favor ν_e decays

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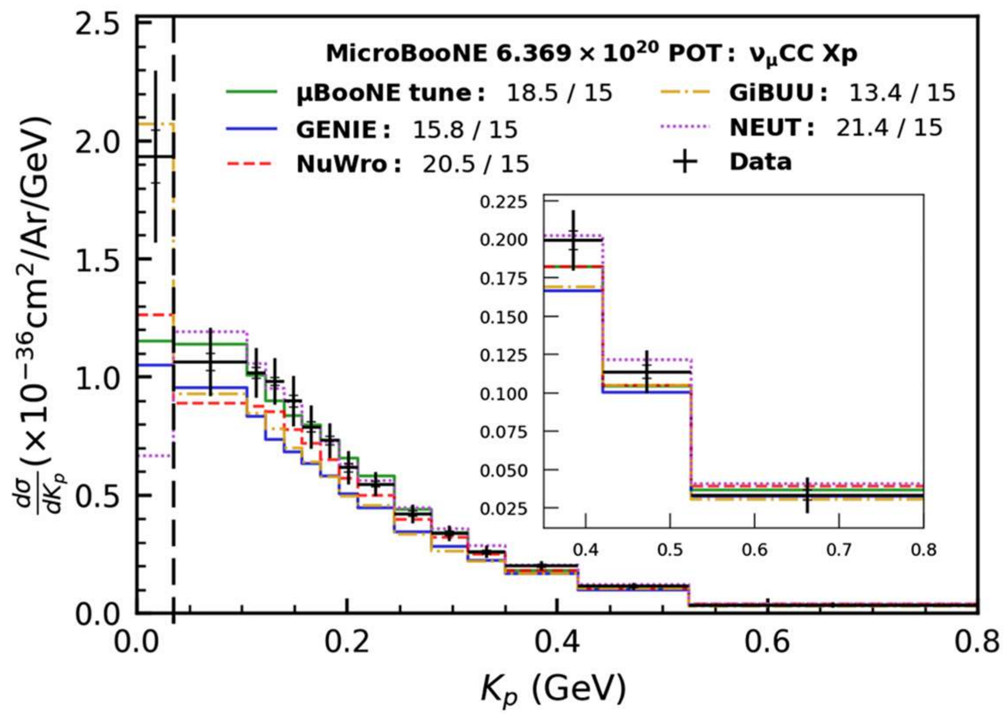
QE Kinematics Between Achilles and GENIE

- Past results have shown models disagree at low proton energies
- We did a similar study with Achilles and GENIE with QE events only
- Generated events information:
  - 100,000 **muon neutrino exclusive** events analyzed at truth level for both Achilles and GENIE
  - n=1, n=2, n>2 **proton exclusive** cases
  - 0.3 GeV momentum cut on protons dependence (current LAr measurement threshold)
  - FSI dependence



journals.aps.org/prl/pdf/10.1103/PhysRevLett.133.041801
(MicroBooNE Collaboration)

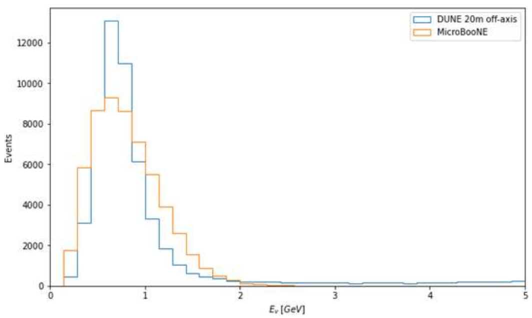
Event Generators/Model Information

Generator	QE Model	Nuclear Model	Form Factors
Achilles	Spectral function approach	LocalFGM	Vector: Kelly Axial: z-expansion https://arxiv.org/abs/0708.1946
GENIE (AR23_20i)	Nieves, RPA	LocalFGM	Vector: BBBA parameterization Axial: z-expansion [0708.1946] Vector and Axial Nucleon Form Factors:A Duality Constrained Parameterization

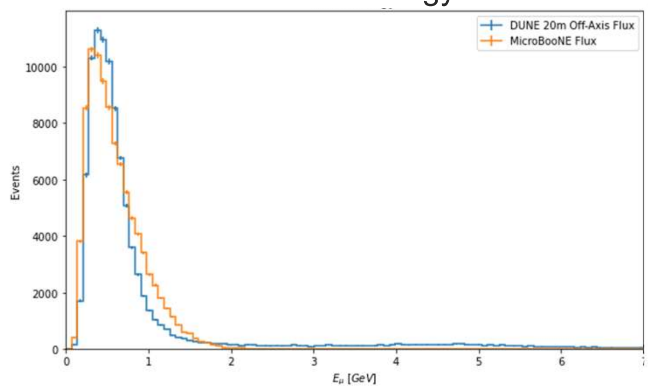
FSI Model	Pauli-Blocking	Cascade
Achilles	Yes	Yes (INLC like)
hA2018	No https://arxiv.org/pdf/2103.07535	No (uses fits from data) https://arxiv.org/pdf/2103.07535
hN2018	No https://arxiv.org/pdf/2103.07535	Yes https://arxiv.org/pdf/2103.07535

Comparing DUNE 20m Off-Axis with MicroBooNE (Achilles)

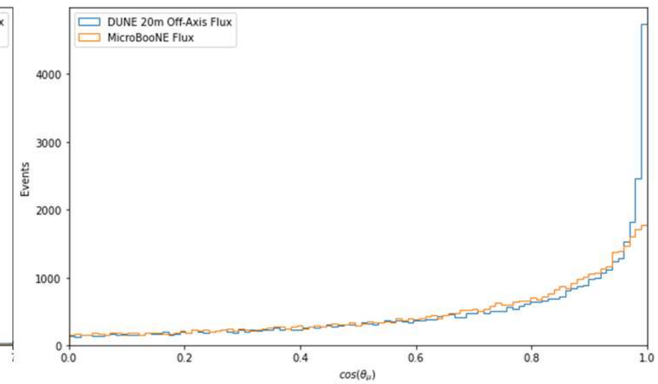
Neutrino Flux



Muon Energy

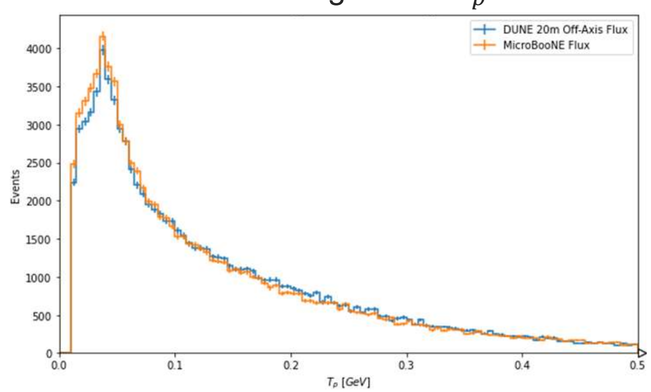


Muon Scattering Angle

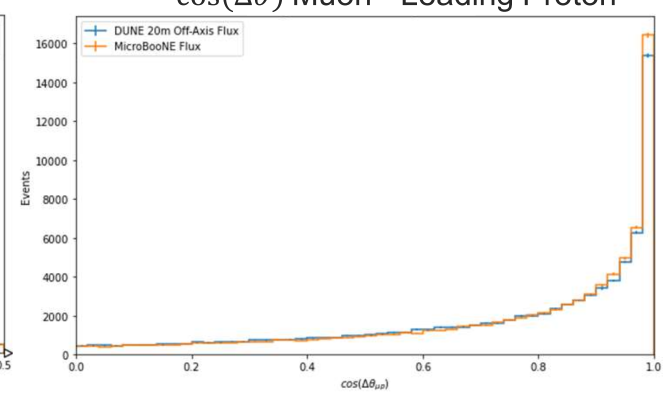


- Similarities show MicroBooNE and SBN measurements are applicable to DUNE
- MicroBooNE flux produces less on axis muons

Leading Proton T_p

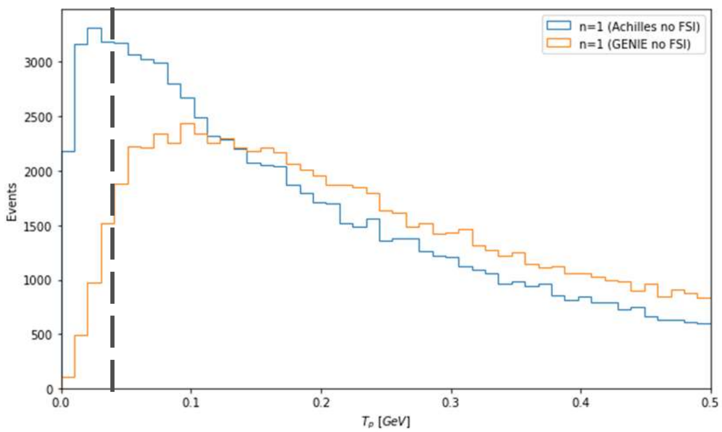


$\cos(\Delta\theta)$ Muon - Leading Proton



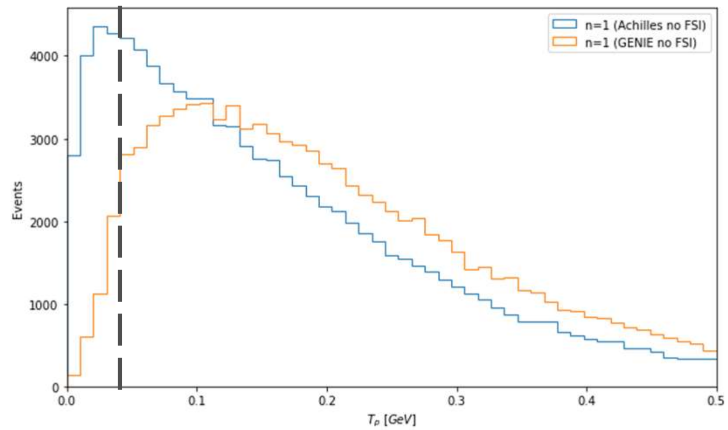
Comparing Achilles and GENIE: Single Proton T_p without FSI

On-Axis Single Proton T_p



Event Type	$n_p = 1$
Achilles	86293
GENIE	95823

20m Off-Axis Single Proton T_p



Event Type	$n_p = 1$
Achilles	82007
GENIE	94414

- Differences at low energies
- Adding cut shows proton momentum differences between models – Achilles has more low momentum protons that get cut

- With 0.3 GeV Cut
  - With 0.3 GeV Cut

Adding in FSI: Event Numbers for Proton Cases (100,000 Events)

- **Without 0.3 GeV Cut on protons**

On-Axis – more spread and higher energy neutrinos

Event Type	$n_p = 1$	$n_p = 2$	$n_p > 2$	Total
Achilles	45791	9003	1781	56575
hA	46001	4147	1075	51223
hN	46555	6989	2336	55880

20m Off-Axis – lower and more monoenergetic energies

Event Type	$n_p = 1$	$n_p = 2$	$n_p > 2$	Total
Achilles	46174	9104	1599	56877
hA	47130	4318	1113	52561
hN	47788	7610	2686	58084

- Similar $n_p = 1$ events across models and axis positions
- Achilles leads in $n_p = 2$ followed by hN
- hN leads in $n_p > 2$ followed by Achilles

- **With 0.3 GeV Cut on protons**

On-Axis:

Event Type	$n_p = 1$	$n_p = 2$	$n_p > 2$	Total
Achilles	41015	5910	623	47548
hA	46342	2380	460	49182
hN	48393	4364	407	53164

20m Off-Axis:

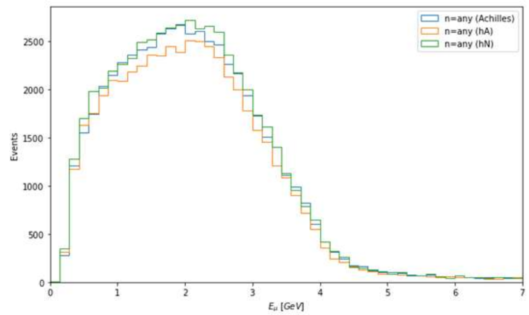
Event Type	$n_p = 1$	$n_p = 2$	$n_p > 2$	Total
Achilles	40198	4704	417	45319
hA	47344	2180	338	49862
hN	50219	4137	333	54689

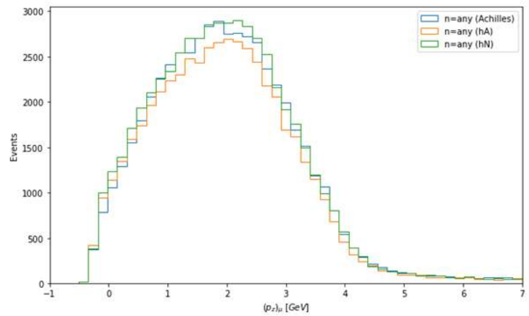
- Achilles loses events from all categories: energy spread between leading and subleading protons
- hA and hN gain n=1 events: more energy in leading proton – subleading protons get filtered out turning events into n=1 events

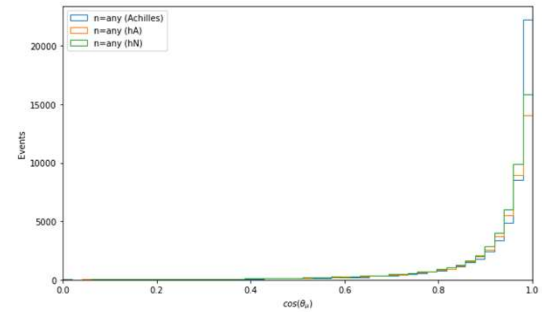
Muon Kinematics with FSI On: On-Axis and 20m Off-Axis

Muon Energy | Muon z-Momentum | Muon Scattering Angle

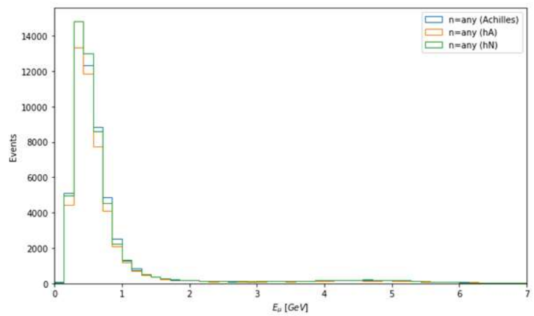
On-Axis

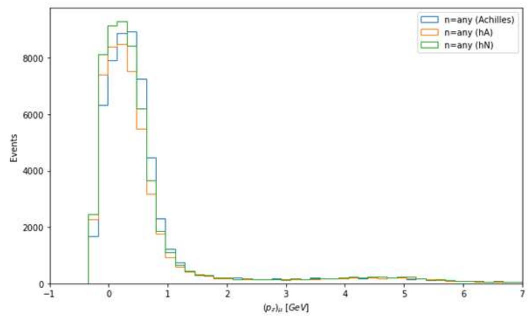


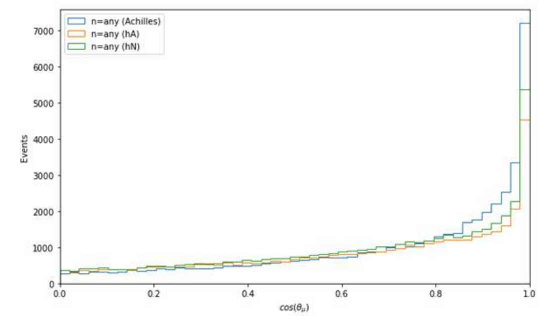




20m Off-Axis







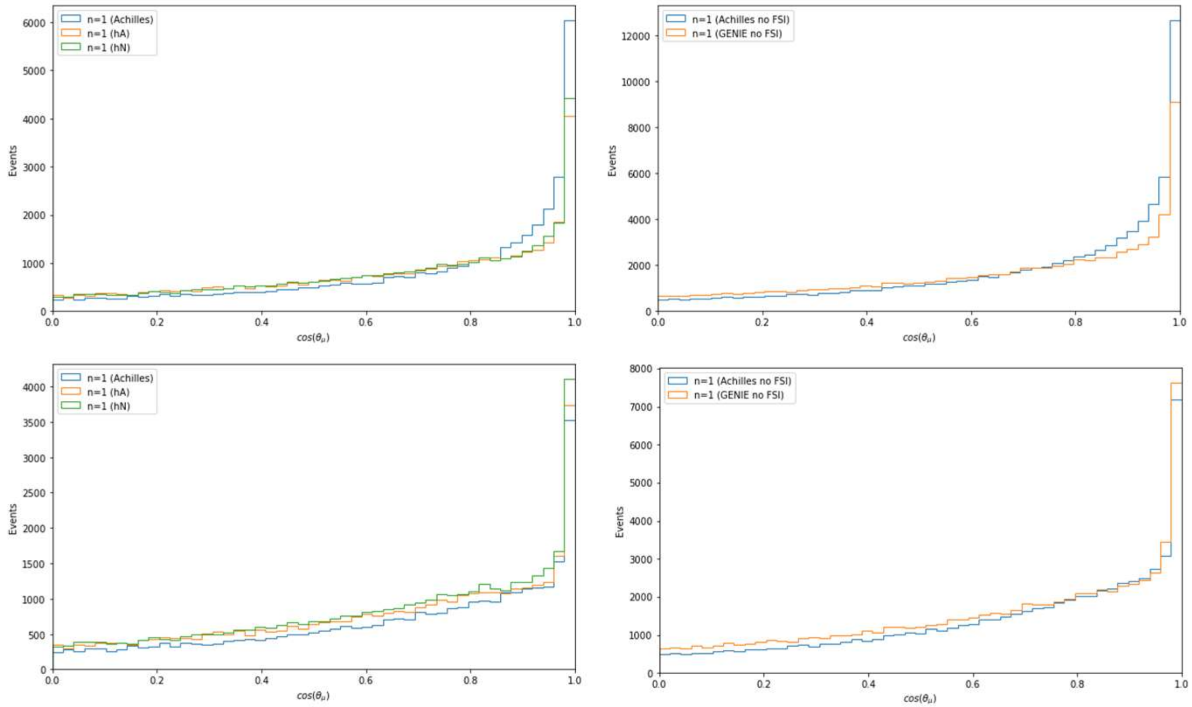
- Strong similarities across kinematics and axis-positions
- Achilles has more events with smaller scattering angle muons (more differences in 20m)

20m Muon Scattering Angle: Single Proton Events

FSI | No FSI

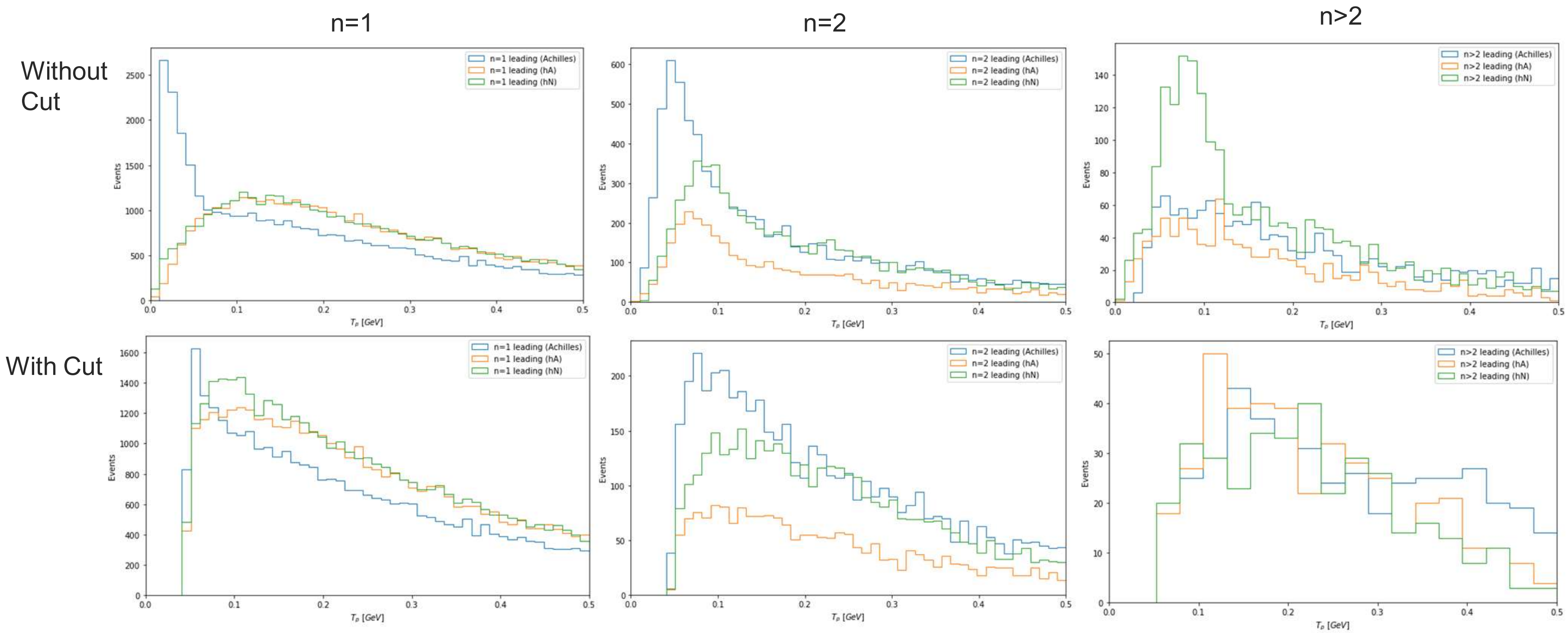
Without Cut

With Cut



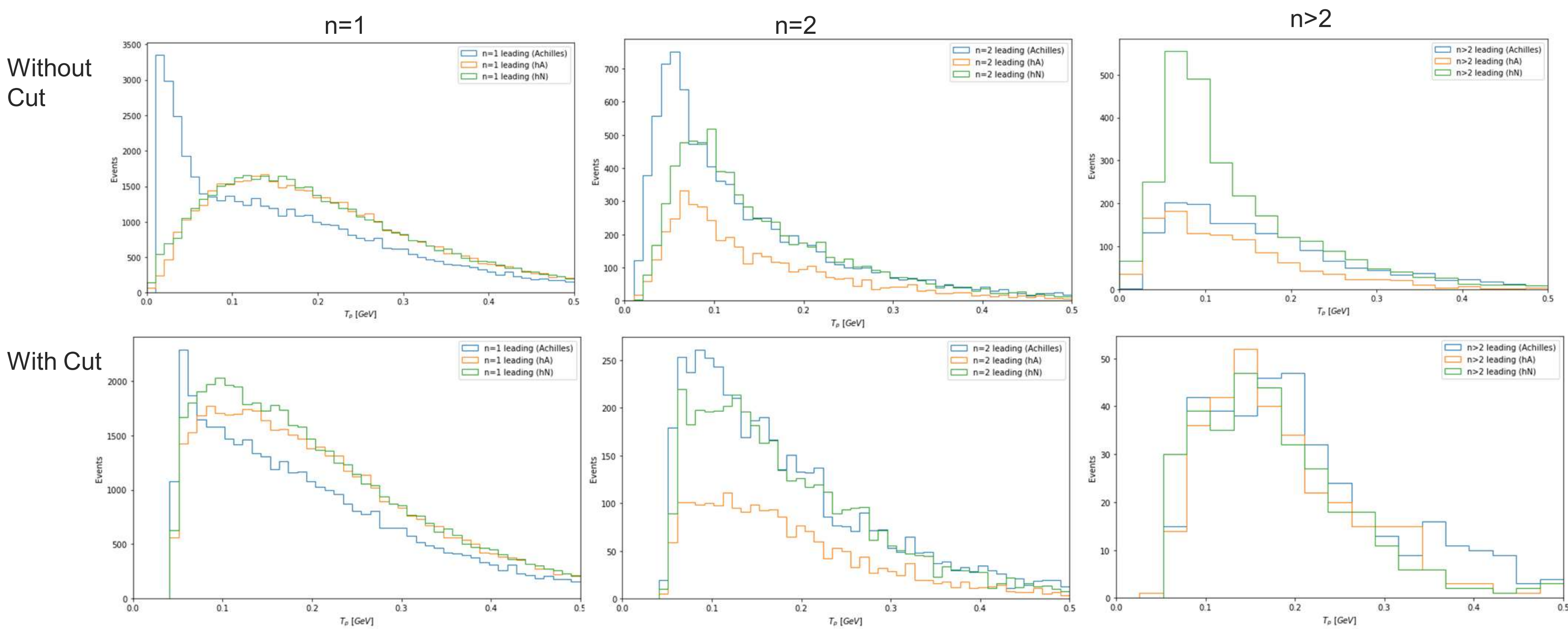
- Achilles difference in muon scattering angle is independent of FSI model
- Adding momentum cut helps – Achille’s additional low momentum protons causing muons to have small scattering angles

On-Axis Leading T_p: $n = 1,\ n = 2,\ n > 2$ Proton Cases with FSI



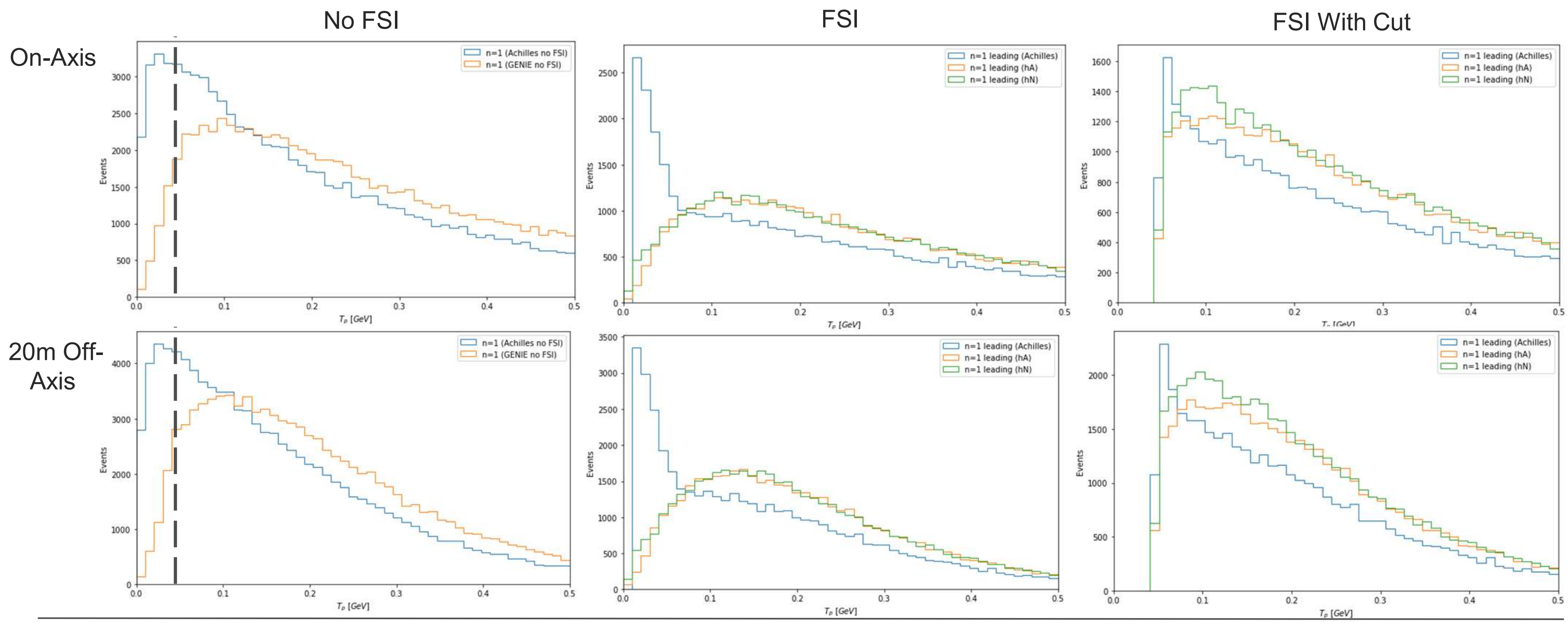
- Achilles peaks at lower energies for n=1: cut removes these extra low energy events
- Distribution shapes somewhat converge as proton number increases
- Without cut n>2 hN has low energy peak – hN's extra n>2 events are all low energy (cut removes this feature)

20m Leading T_p: $n = 1,\ n = 2,\ n > 2$ Proton Cases: Cut off/on



- Very similar model relations compared to the On-Axis case
- Axis position doesn't have much effect on proton energies or model relations

T_p with/without FSI: n=1 Proton Case: On-Axis/20m Off-Axis



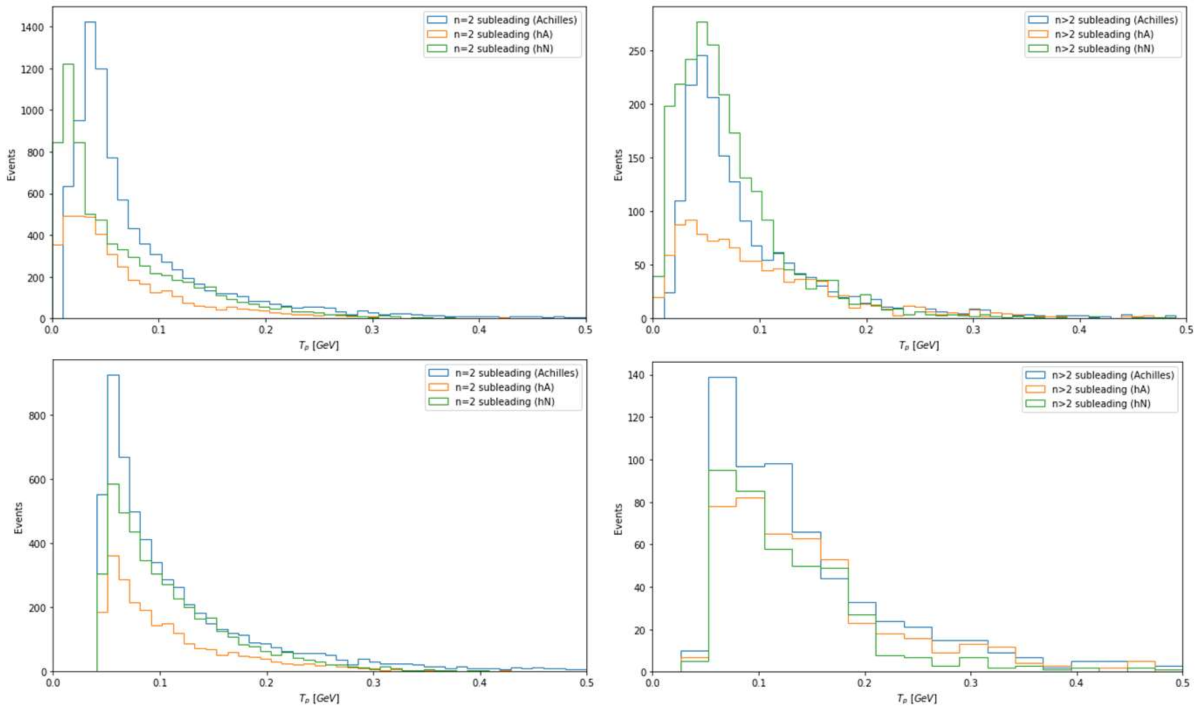
- As we have already seen – differences without FSI: Achilles QE model favors lower energy protons
- Adding FSI creates more differences – momentum cut helps dramatically but still some differences

On-Axis Subleading T_p: $n = 2,\ n > 2$ Proton Cases

n=2 n>2

Without Cut

With Cut



- Slightly different peaks between Achilles and hN for n=2 without cut – become more similar for n>2
- Adding cut makes distribution shapes very similar besides relative event numbers
- hA differences due to having way less multi-proton events

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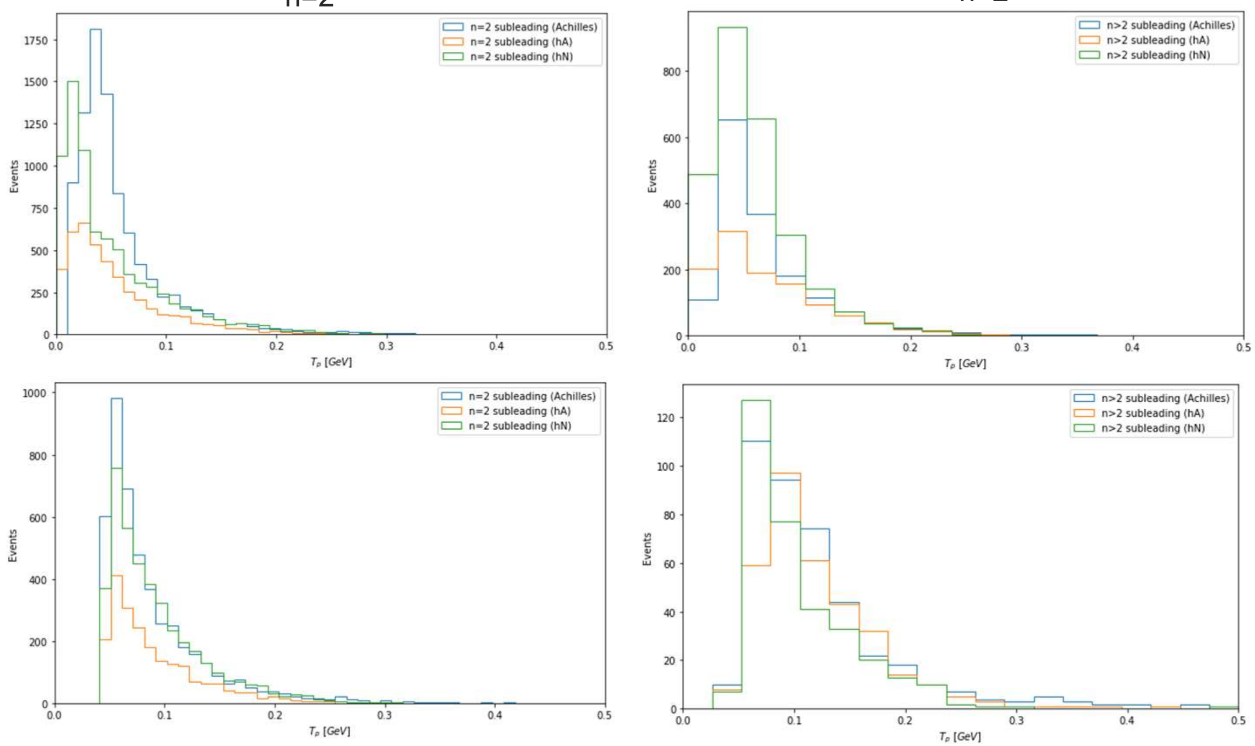
20m Subleading T_p: $n = 2,\ n > 2$ Proton Cases

n=2 n>2

Without Cut

With Cut



- Comparable to On-Axis distributions – subleading energies have very little dependence on axis position

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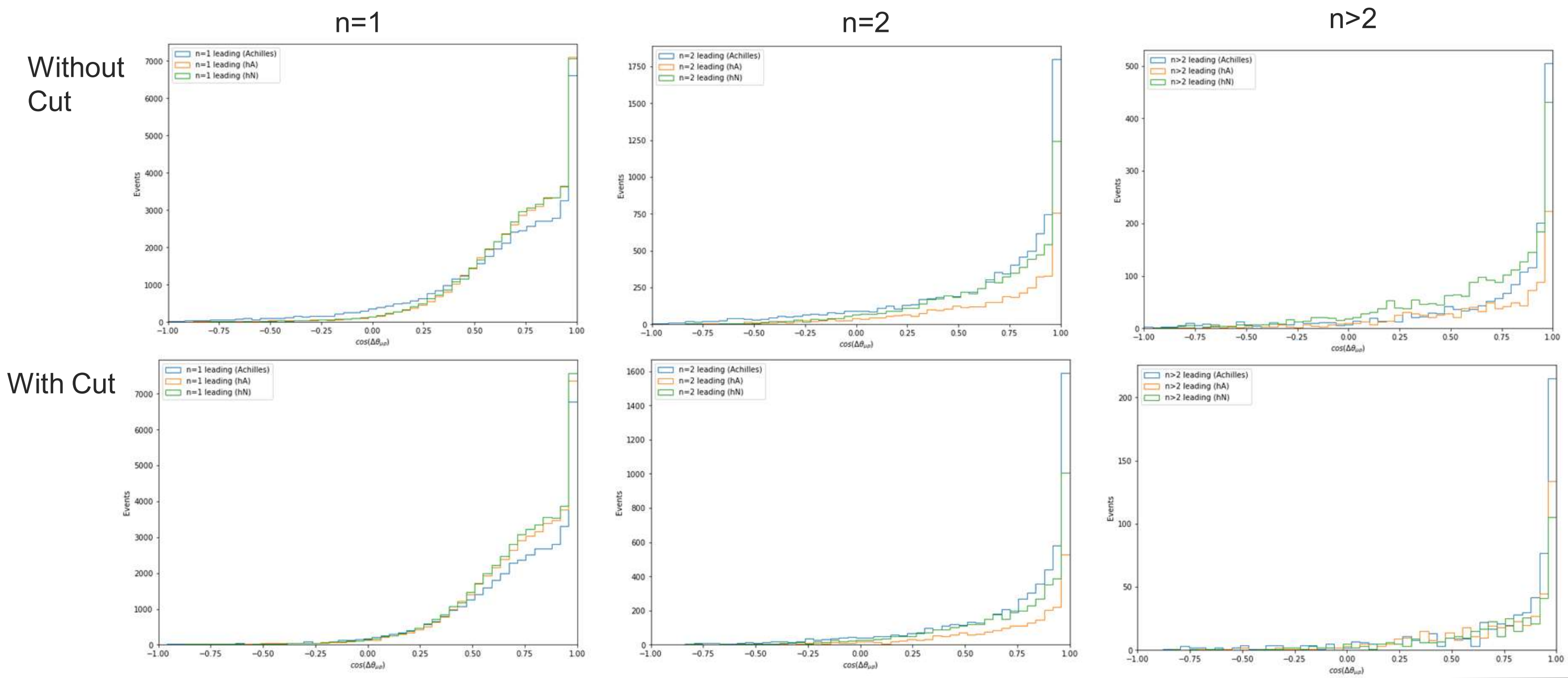
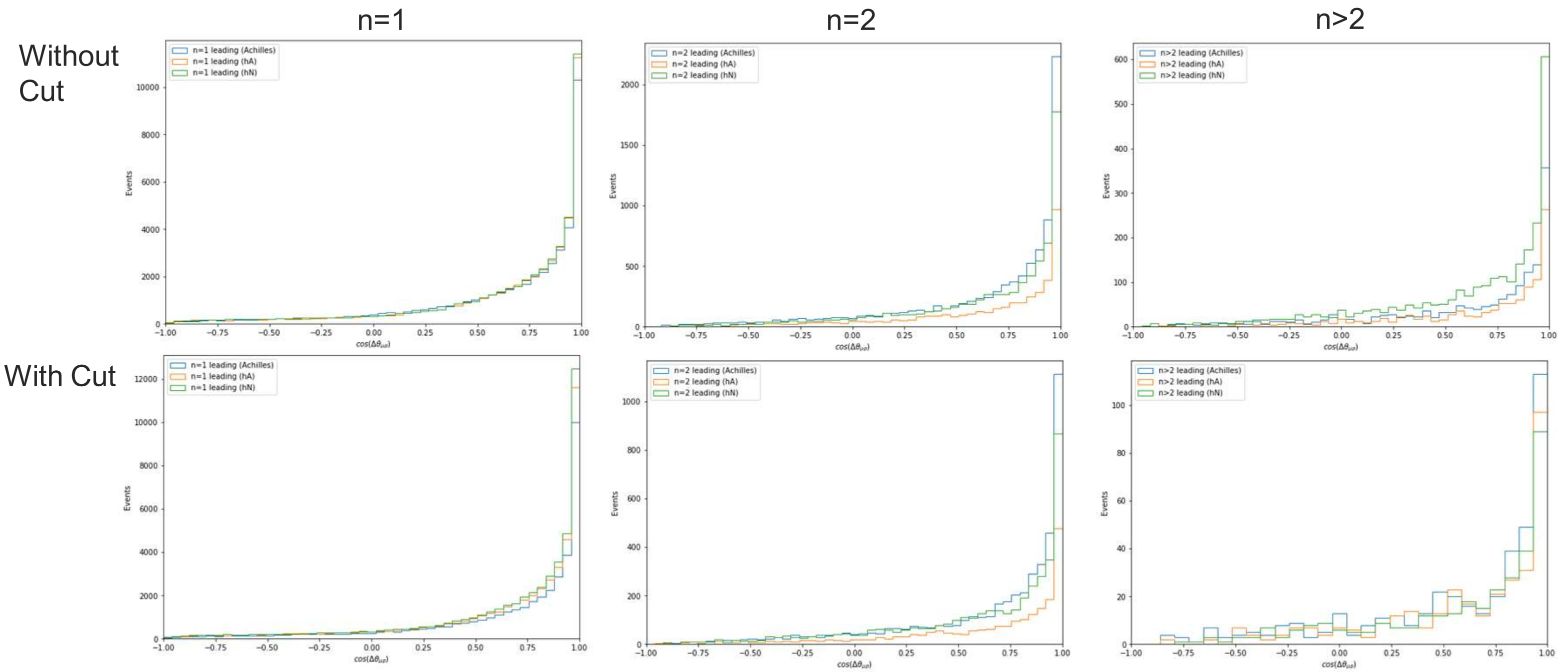
On-Axis Angle Between Muon and Leading Proton ($\cos(\Delta\theta)$)



- All models predict distinct n=1 distribution shape (quick increase of events towards $45°$)
- Achilles has slightly less events with small $\Delta\theta$ and slightly more events for large $\Delta\theta$ for single proton events
- Cut removes Achilles high $\Delta\theta$ events – but results are mostly cut independent
- Differences in multi-proton events appears to be due purely to event numbers (hA has less multi-proton events)

20m Off-Axis Angle Between Muon and Leading Proton (cos($\Delta\theta$))



- n=1 differences vanish compared to on-axis – more monoenergetic
- Again, differences between multi-particle events appear to be due to event number differences

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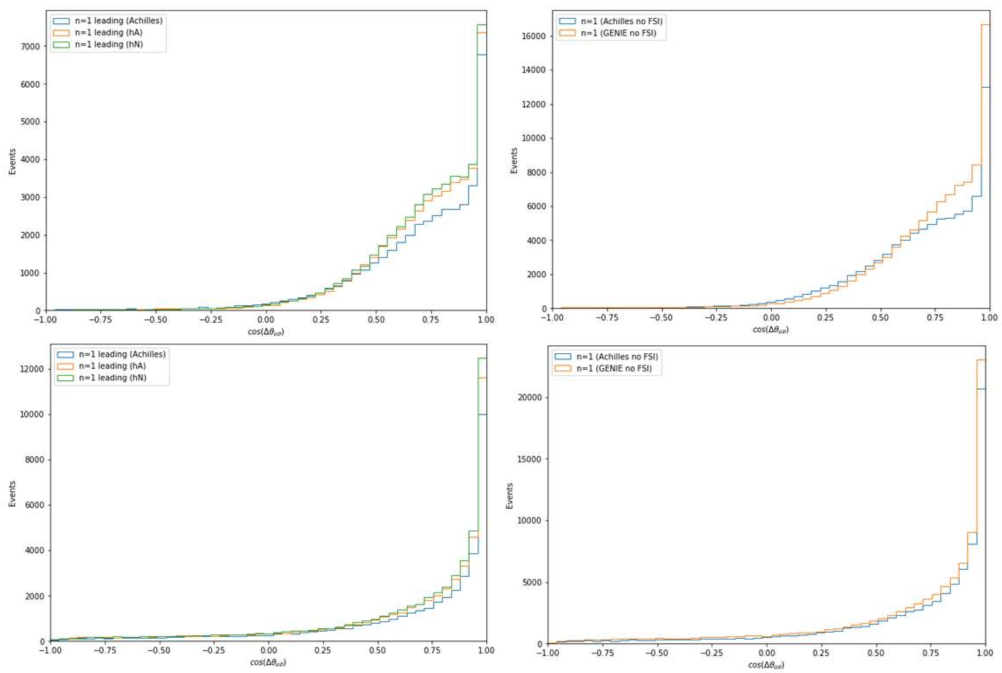
Proton-Muon cos($\Delta\theta$) : On-Axis/20m Off-Axis: FSI on/off

FSI on

FSI Off

On-Axis

20m off-Axis



- On-Axis differences due to QE model of form factors differences

Summary and Conclusions of Study

- **Neutrino interactions in DUNE ND-LAr in general…**
  - Spectra and channel contribution depend significantly on detector position and beam mode
    - RES,DIS, and NC are the largest contribution for on-axis events and QE dominate off-axis events
- **QE results…**
  - Electron to muon neutrino ratios increase as a function of position
  - Achilles and GENIE models predict similarities and differences in kinematics
    - Differences in event numbers for proton cases
    - Similar muon kinematics (slight difference in 20m scattering angle)
    - Significant differences in proton kinematics (differences still present when FSI turned off)
- **Results motivate future studies…**
  - Compare with more FSI models (INCL++)
  - Study how models differ for different interaction channels (RES pions events) and different final state cases
  - Pin down main sources of event numbers and kinematics differences between models (starting with QE models)

Affiliations

Event Statistics – All Channels and Positions

0m FHC	QE	RES	DIS	MEC	COH	NC	Sum
$\nu_\mu + \bar{\nu}_\mu$	494500	655594	722291	124947	11576	635632	2644540
$\nu_e + \bar{\nu}_e$	5094	6573	12522	1281	210	8301	33981
$\frac{\nu_e+\bar{\nu}_e}{\nu_\mu+\bar{\nu}_\mu}$	0.010	0.010	0.017	0.010	0.018	0.013	0.013
Sum	499594	662167	734813	126228	11786	643933	2678521

8m FHC	QE	RES	DIS	MEC	COH	NC	Sum
$\nu_\mu + \bar{\nu}_\mu$	307013	342093	338668	75102	5770	338636	1407282
$\nu_e + \bar{\nu}_e$	3745	4704	8055	998	136	5732	23370
$\frac{\nu_e+\bar{\nu}_e}{\nu_\mu+\bar{\nu}_\mu}$	0.012	0.014	0.024	0.013	0.024	0.017	0.017
Sum	310758	346797	346723	76100	5906	344368	1430662

16m FHC	QE	RES	DIS	MEC	COH	NC	Sum
$\nu_\mu + \bar{\nu}_\mu$	124307	84159	71351	26334	1440	98404	405995
$\nu_e + \bar{\nu}_e$	2326	2546	3599	590	77	2889	12027
$\frac{\nu_e+\bar{\nu}_e}{\nu_\mu+\bar{\nu}_\mu}$	0.019	0.014	0.024	0.013	0.023	0.029	0.017
Sum	126633	86705	74950	26924	1517	101293	418022

24m FHC	QE	RES	DIS	MEC	COH	NC	Sum
$\nu_\mu + \bar{\nu}_\mu$	58198	28629	28071	10139	562	41781	167380
$\nu_e + \bar{\nu}_e$	1380	1331	1504	309	28	1552	6104
$\frac{\nu_e+\bar{\nu}_e}{\nu_\mu+\bar{\nu}_\mu}$	0.024	0.046	0.053	0.030	0.050	0.037	0.036
Sum	59578	29960	29575	10448	590	43333	173484

0m RHC	QE	RES	DIS	MEC	COH	NC	Sum
$\nu_\mu + \bar{\nu}_\mu$	222747	303875	258150	70278	10492	335411	1200953
$\nu_e + \bar{\nu}_e$	2772	3918	6888	854	136	5089	19657
$\frac{\nu_e+\bar{\nu}_e}{\nu_\mu+\bar{\nu}_\mu}$	0.012	0.013	0.027	0.012	0.013	0.015	0.016
Sum	225519	307793	265038	71132	10628	340500	1220610

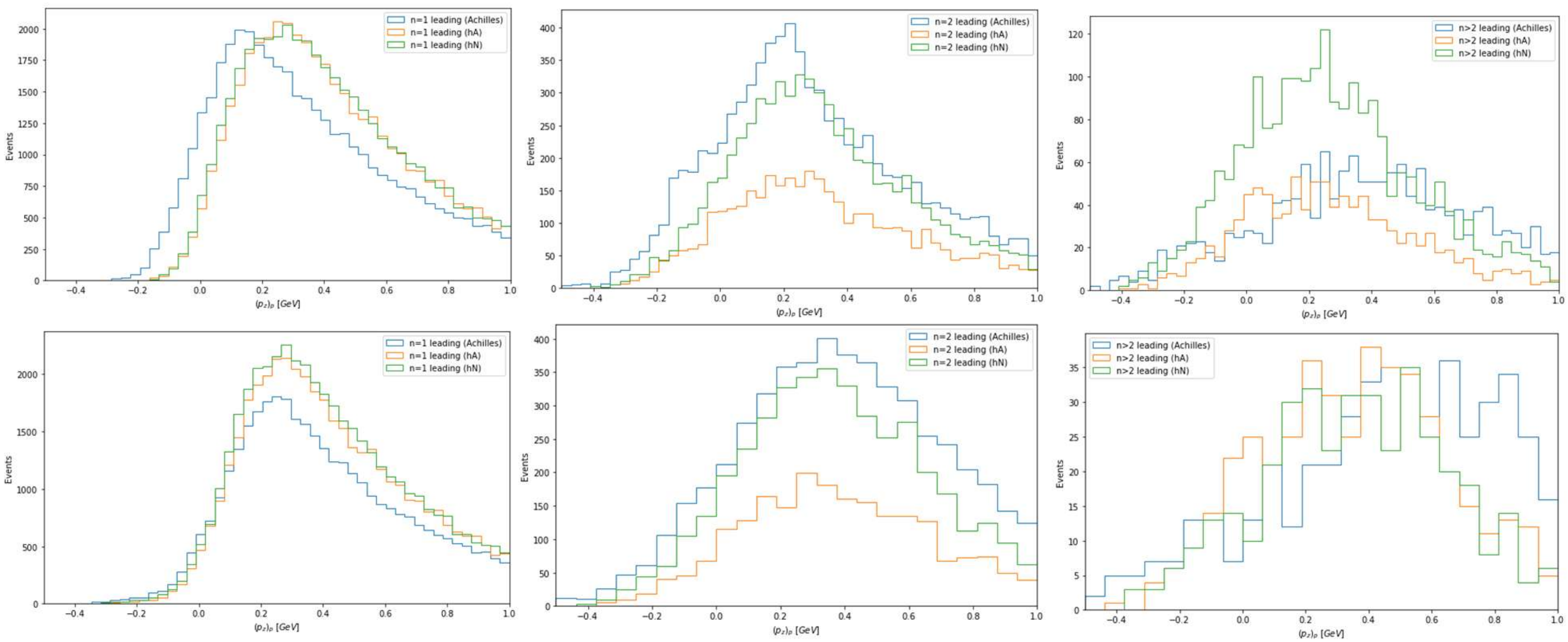
8m RHC	QE	RES	DIS	MEC	COH	NC	Sum
$\nu_\mu + \bar{\nu}_\mu$	126113	149671	139785	37846	5304	178054	636773
$\nu_e + \bar{\nu}_e$	2113	2864	4925	589	98	3664	14253
$\frac{\nu_e+\bar{\nu}_e}{\nu_\mu+\bar{\nu}_\mu}$	0.017	0.019	0.035	0.016	0.018	0.021	0.022
Sum	128226	152535	144710	38435	5402	181718	651026

16m RHC	QE	RES	DIS	MEC	COH	NC	Sum
$\nu_\mu + \bar{\nu}_\mu$	44689	36717	35908	11119	1278	51358	181069
$\nu_e + \bar{\nu}_e$	1282	1617	2394	345	59	1983	7683
$\frac{\nu_e+\bar{\nu}_e}{\nu_\mu+\bar{\nu}_\mu}$	0.029	0.044	0.067	0.031	0.046	0.039	0.042
Sum	45971	38334	38302	11464	1337	53341	188749

24m RHC	QE	RES	DIS	MEC	COH	NC	Sum
$\nu_\mu + \bar{\nu}_\mu$	20960	14860	15873	4754	518	22744	79709
$\nu_e + \bar{\nu}_e$	764	889	1125	220	34	1050	4082
$\frac{\nu_e+\bar{\nu}_e}{\nu_\mu+\bar{\nu}_\mu}$	0.036	0.060	0.071	0.046	0.066	0.046	0.051
Sum	21724	15749	16998	4974	552	23794	83791

/pnfs/dune/persistent/physicsgroups/dunelbl/ abooth/PRISM/Production/Simulation/ ND_CAFMaker/v7/CAF

On-Axis Leading p_z: $n = 1,\ n = 2,\ n > 2$ Proton Cases: Cut off/on

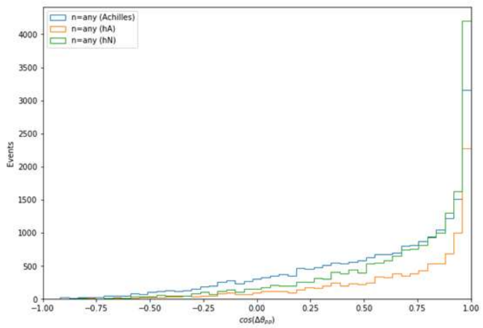


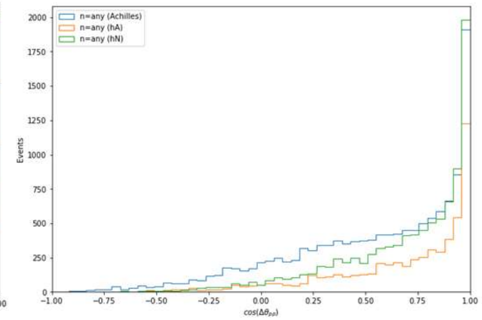
Leading – Subleading Proton cos($\Delta\theta$) – Events with $n \geq 2$ Protons

Without Cut

With Cut

On-Axis





20m off-Axis