DUNE-PRISM

Experimentally Constraining E_{true} ➜ E_{rec}

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LBNC Meeting
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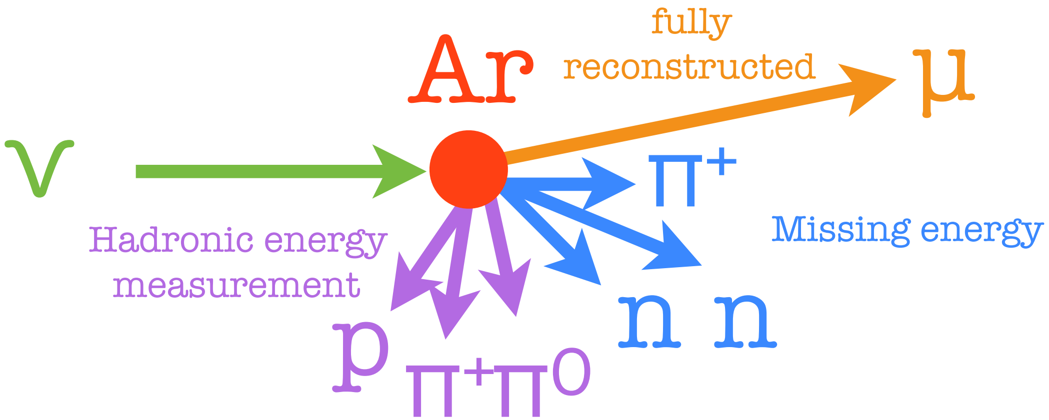
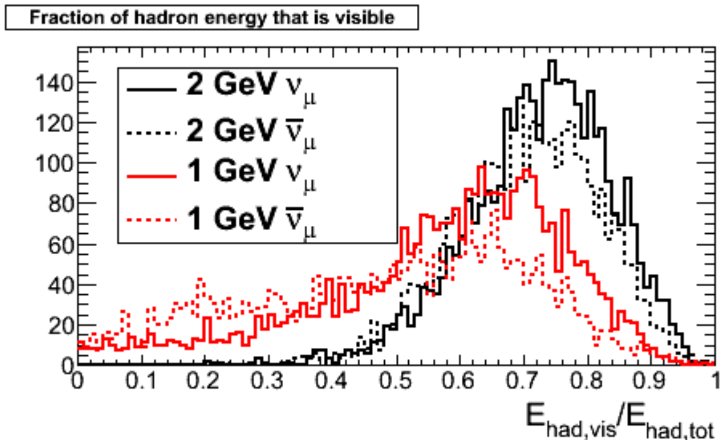
The E_ν Measurement Problem



- Typically, E_ν is “measured” via the observed final state
  - However, the final state is subject to **missing energy** (e.g. neutrons) & **nuclear physics** (e.g. MEC, FSI, off-shell effects, …)
  - This causes smearing of E_{rec} relative to E_{true} (typically feed-down)
- E_{rec} ➜ E_{true} translation depends on **poorly understood neutrino interaction models**
  - 1p1h, 2p2h, npnh, RPA, pion production, FSI, multi-pi transition, DIS, etc.
- Within DUNE, the near detector (ND) will be used to experimentally constrain E_{rec} ➜ E_{true} using off-axis measurements

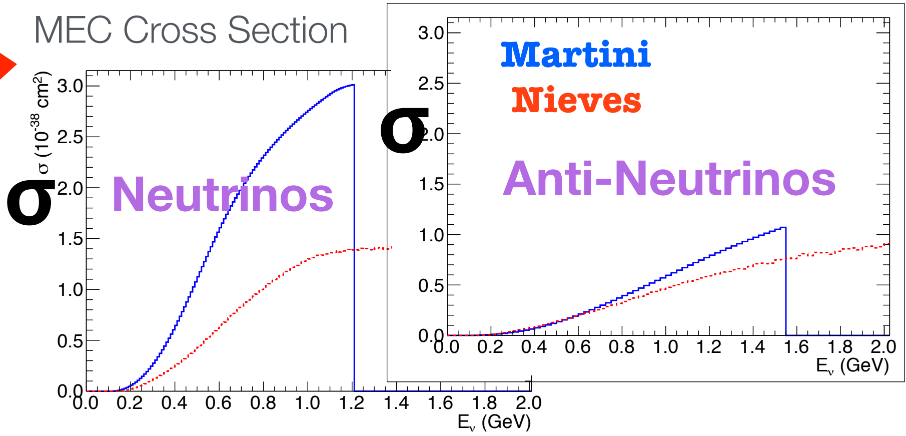
http://public.lanl.gov/friedland/LBNEApril2014/LBNEApril2014talks/McGrew_LANL_Apr2014.pdf



GEANT4 Simulation of a large LAr volume

(True deposited hadronic energy)/
(True initial hadronic energy)

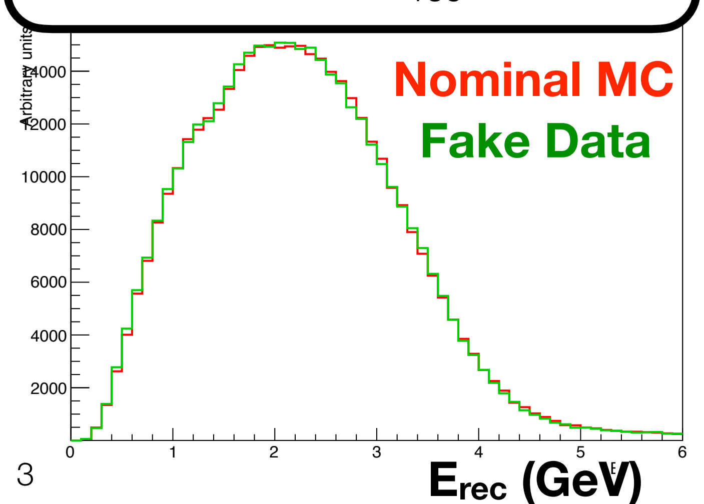
MEC Cross Section



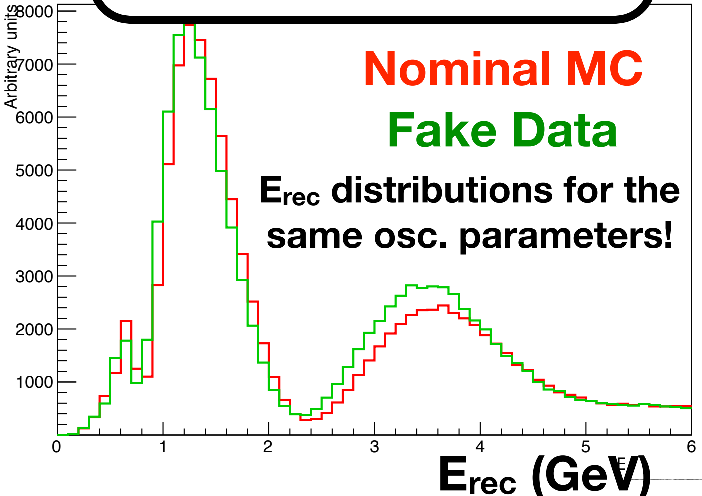
Mismodeling E_{true} ➜ E_{rec} Can Produce Biases

- In every long-baseline ν experiment:
  1. Event rate distributions are measured in the near detector
  2. The ν flux and ν cross section modeling are tuned to make the ND MC match ND data distributions
- **The problem**: there are many degenerate cross section model adjustments that can make (on-axis) ND MC match ND data (even if the flux prediction is perfect)
  - The wrong model can have a substantial impact at the far detector, even if it provides agreement in ~all on-axis near detector observables
  - i.e. **DUNE may report incorrect oscillation parameters without any evidence of a problem** if we use only on-axis ND measurements

Near Detector E_{rec} On-Axis

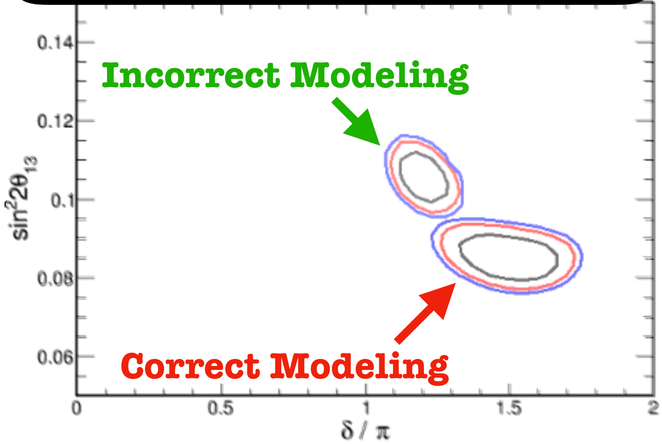


Far Detector E_{rec}



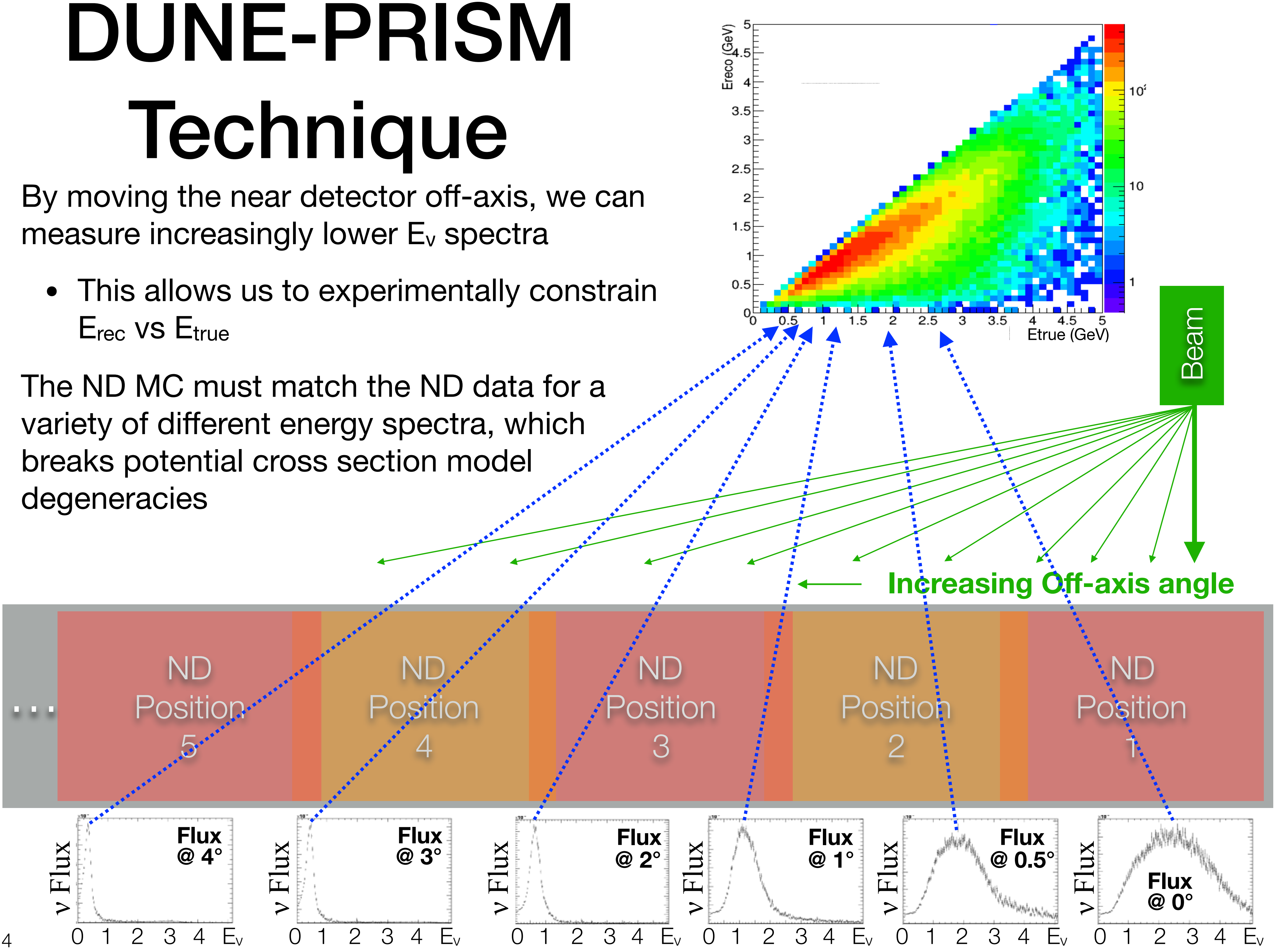
E_{rec} distributions for the same osc. parameters!

DUNE Oscillation Contours



DUNE-PRISM Technique

- By moving the near detector off-axis, we can measure increasingly lower E_ν spectra
  - This allows us to experimentally constrain E_{rec} vs E_{true}
- The ND MC must match the ND data for a variety of different energy spectra, which breaks potential cross section model degeneracies



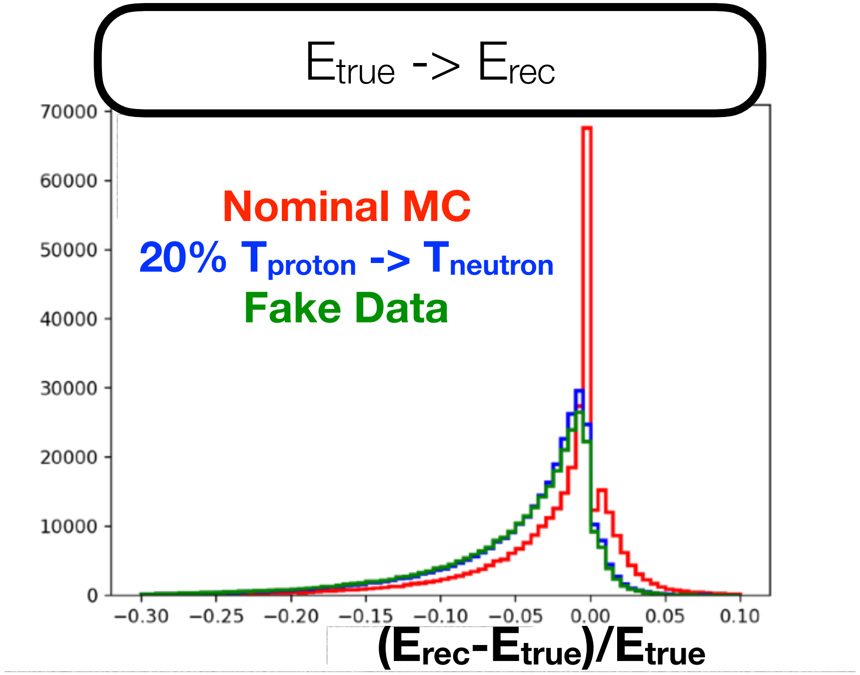
Using DUNE-PRISM Information

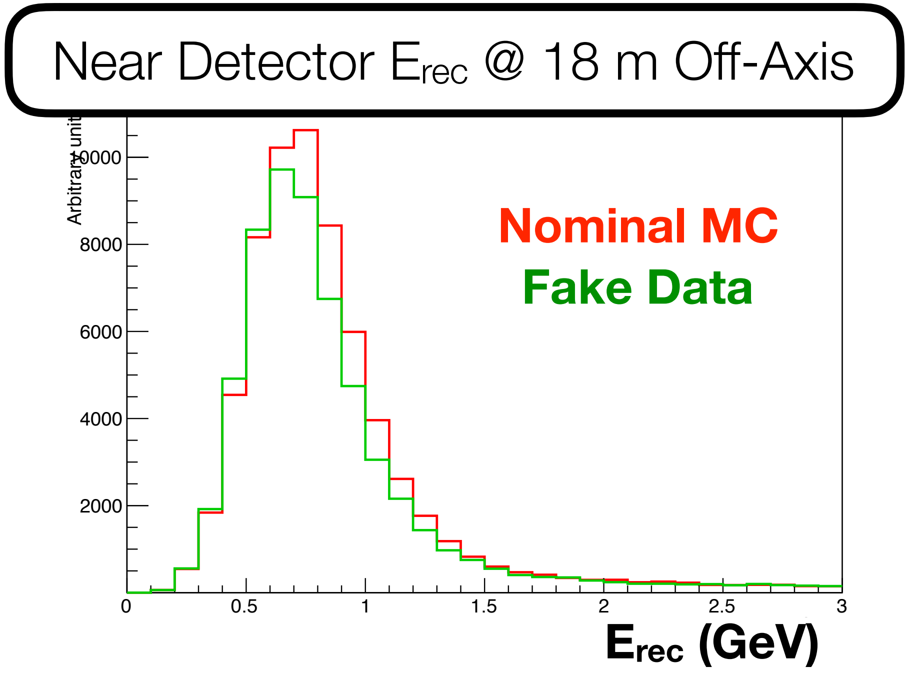
- Near detector measurements with a continuously varying energy spectra can be used to constrain cross section modeling and E_{true} ➜ E_{rec} mapping in two distinct ways:

1. Off-axis measurements will likely identify incorrect cross section models that nonetheless produce data/MC agreement on-axis (due to degenerate model effects)
    - This information will allow for iterative model improvements with theorists and model builders
2. Measurements of the continuously varying E_ν peak position in each off-axis slice can be combined to produce a data-driven far detector prediction that naturally incorporates unknown cross section effects
    - (more on this in 2 slides)

Identifying Poor Cross Section Modeling

- The previously shown fake data were produced by:
    - Transferring 20% of proton kinetic, T_p, energy to (unseen) neutrons
    - Adjusting other parts of the cross section model ($d\sigma/dT_p$, pion production, angular distributions, etc.) to achieve nearly perfect agreement in ~all ND observables
        - In every LBL experiment, cross section models are adjusted to make ND data match ND MC
        - Wrong choices for how to “fix” the ND data/MC agreement can result in an incorrect E_{true} -> E_{rec} relationship (and, hence, the wrong answer for δ_{CP})
- By making off-axis measurements, cross section modeling problems can be clearly identified

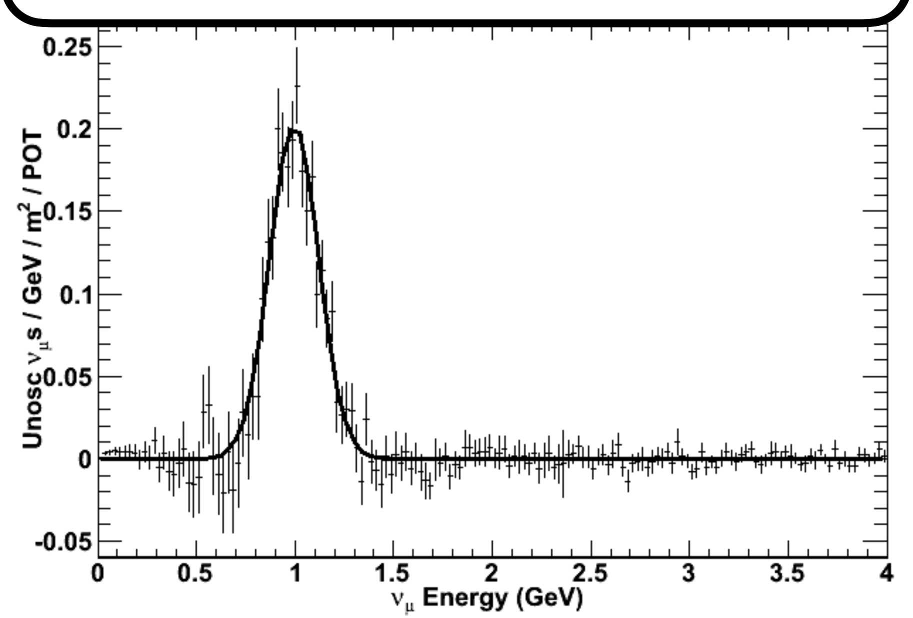

E_{true} -> E_{rec}


Near Detector E_{rec} @ 18 m Off-Axis

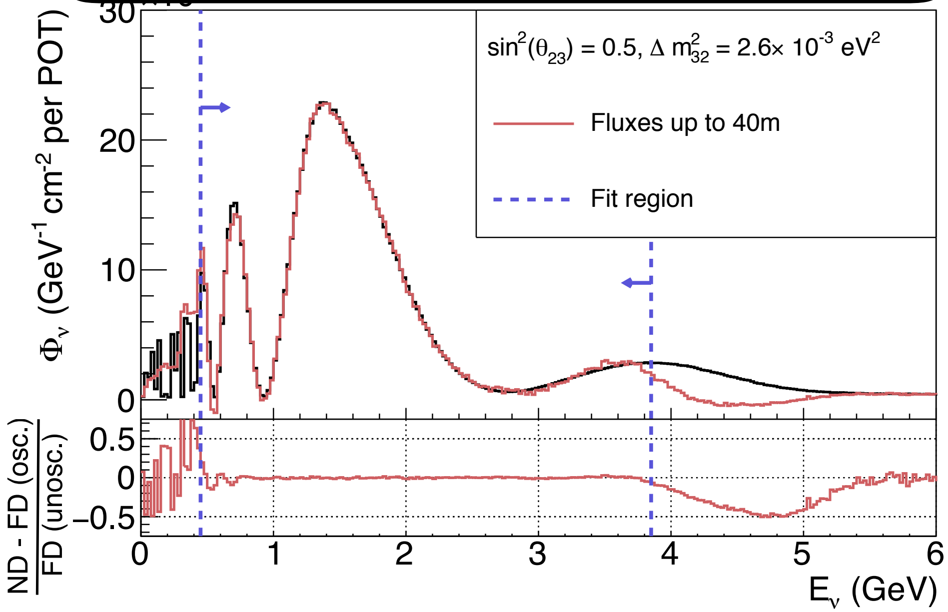
Creating New E_ν Spectra

- By taking linear combinations of measurements at different off-axis positions, we can determine observable distributions for a wide variety of energy spectra

Pseudo-Monoenergetic Beams



Oscillated Fluxes at the ND!

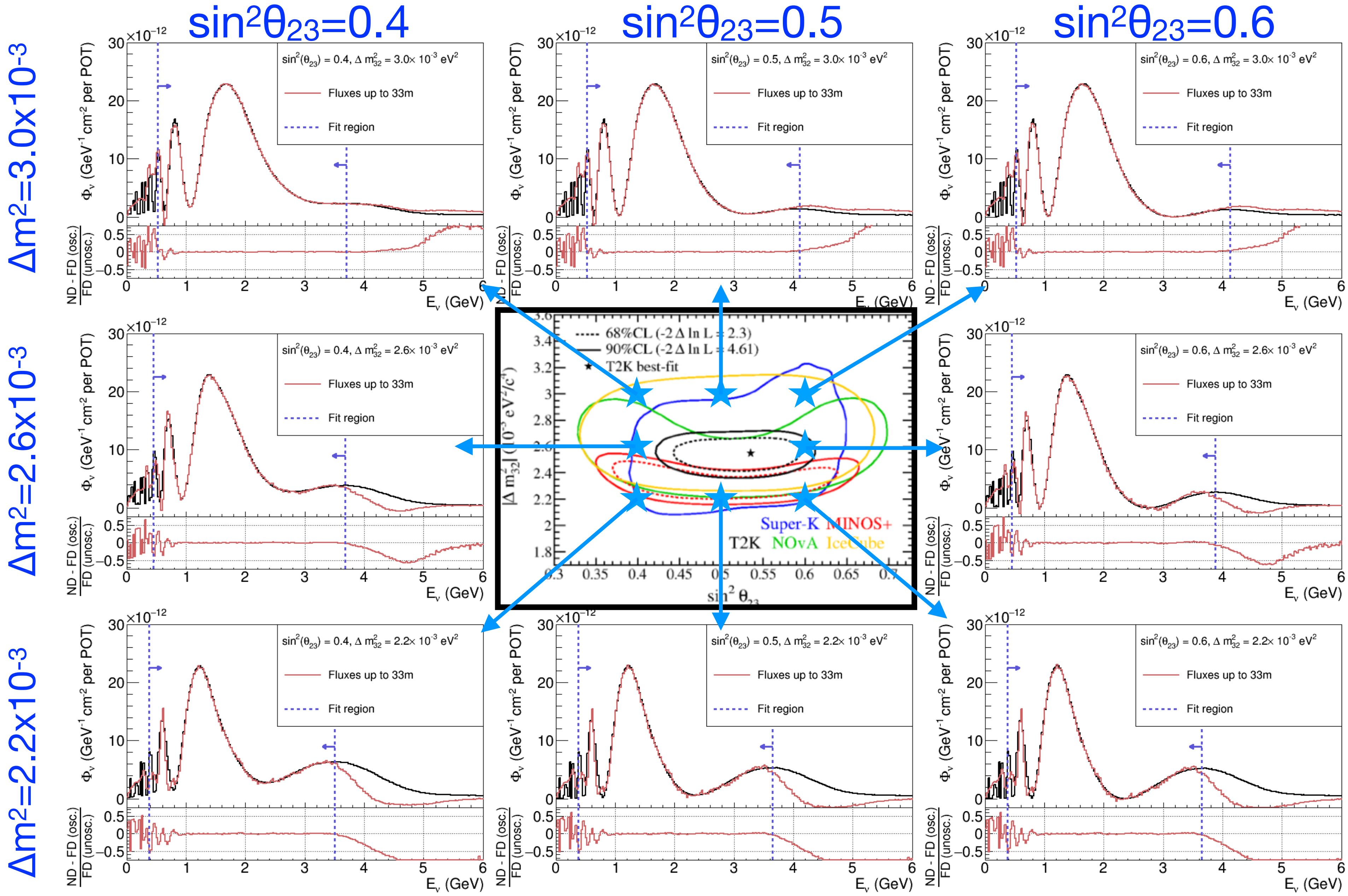


- Gaussian fluxes allow us to directly measure E_{rec} for a given E_{true}

- Oscillated fluxes allow us to directly measure oscillated far detector observables at the near detector

Oscillated Flux Fits

- DUNE-PRISM can match the far detector oscillated spectra for all currently allowed values of oscillation parameters



DUNE-PRISM Next Steps

- Detailed studies of off-axis information have been ongoing for that past 1+ years (e.g. fake data studies), but activity is increasing due to the DUNE Technical Design Report timescales

- Several topics are under active investigation:
    - Precise treatment of correlated flux uncertainties across all off-axis and E_ν bins
    - Minimizing the differential model dependence in the ND efficiency correction across off-axis angle
    - Detailed study of energy resolution differences between the ND and FD
    - Implementation of a data-driven far detector prediction in CAFAna for a complete end-to-end DUNE-PRISM analysis

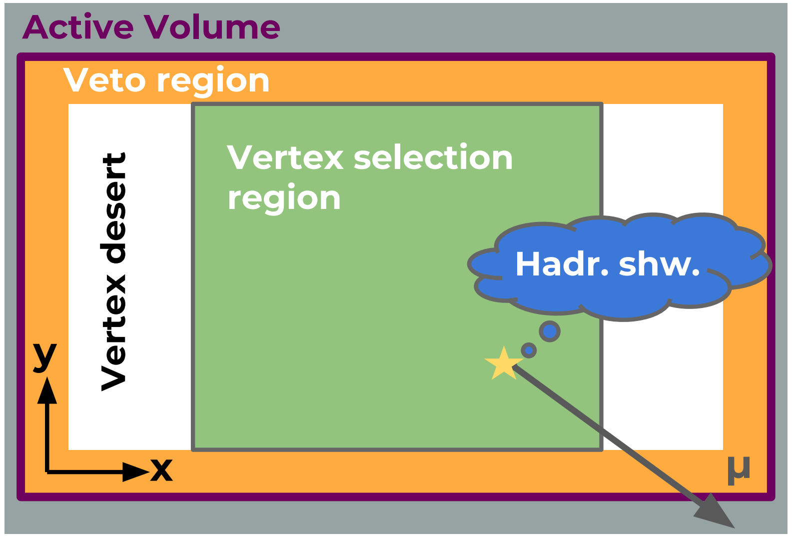
TDR Plans

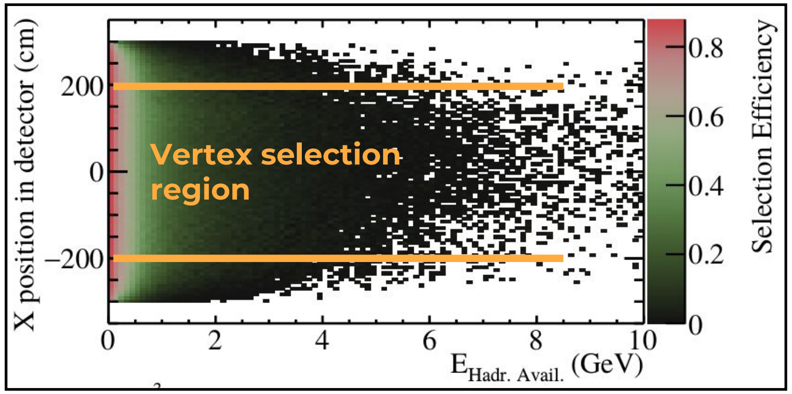
- Baseline plan
  - Fake data samples, such as the sample shown in this talk, can be used to set uncertainties on oscillation measurements
    - It can then be demonstrated that DUNE-PRISM disallows such variations and improves oscillation parameter sensitivities
  - Basic demonstration of DUNE-PRISM technique, including far detector E_{rec} predictions that are free from cross section modeling bias
- Stretch goals
  - Fitting on- & off-axis samples together in a “standard” near/far fit framework
  - Oscillation parameter sensitivities using far detector predictions produced by near detector linear combinations

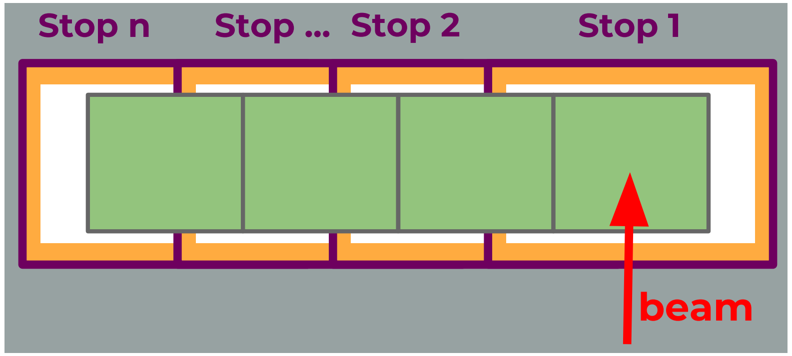
Supplement

Off-Axis Efficiency

- ND event selection requires minimal hadronic energy in the outer 50 cm of the active LAr
    - Ensures containment of non-neutron hadronic energy
- Events near the veto region often leak hadronic energy into the veto region
    - This produces a model-dependent efficiency drop
- To minimize model-dependent efficiency differences between off-axis slices, the fiducial volume is separated from the veto region by 1.5 m
- With the currently assumed 7-m-wide LAr detector, 8 off-axis positions are required for continuous coverage up to 32 m off-axis



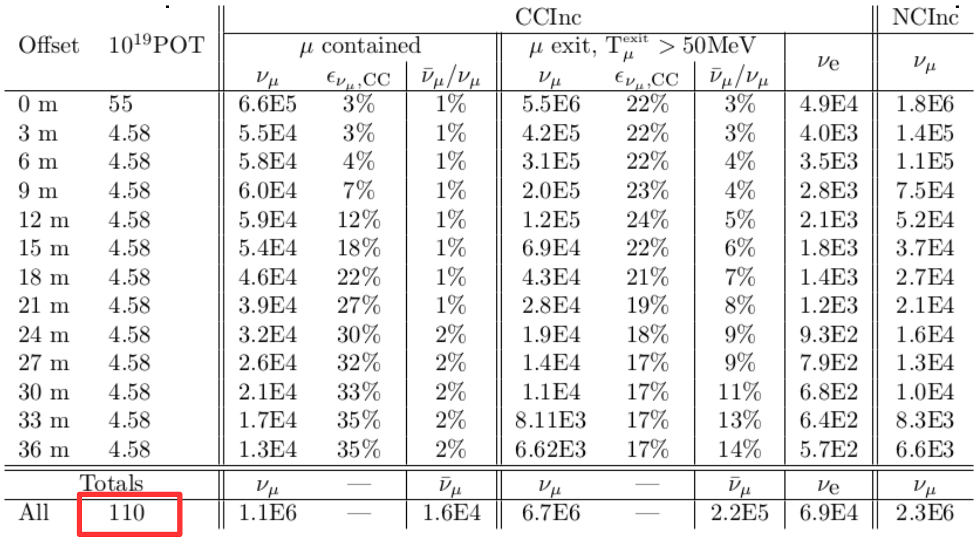




Off-Axis Event Rates

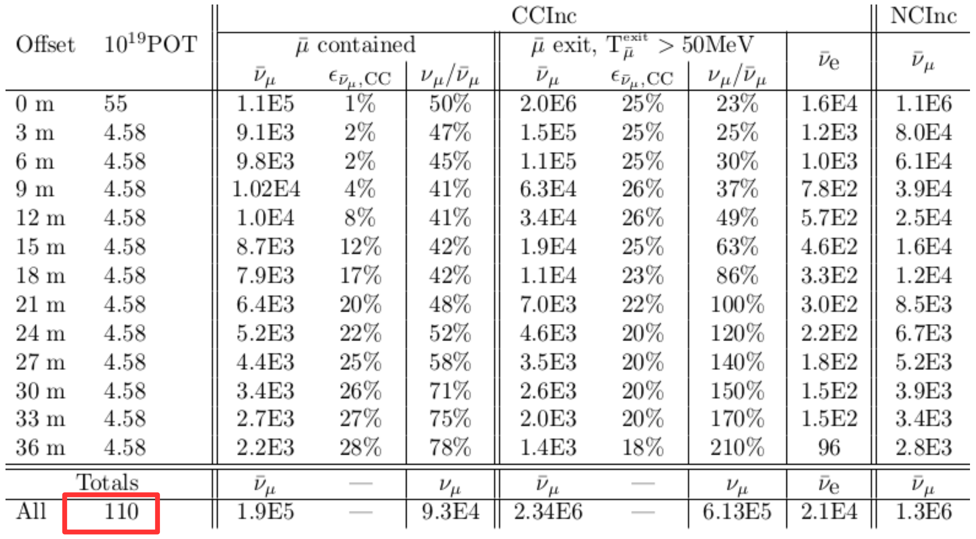
- The DUNE-PRISM run plan has not yet been optimized, but current working assumption is 50% on-axis, 50% off-axis running
    - Still allows for low statistics on-axis measurements, such as ν-e scattering
- Even with a few percent of the total run time, several thousand events are expected at each off-axis position

FHC (1 year of running)



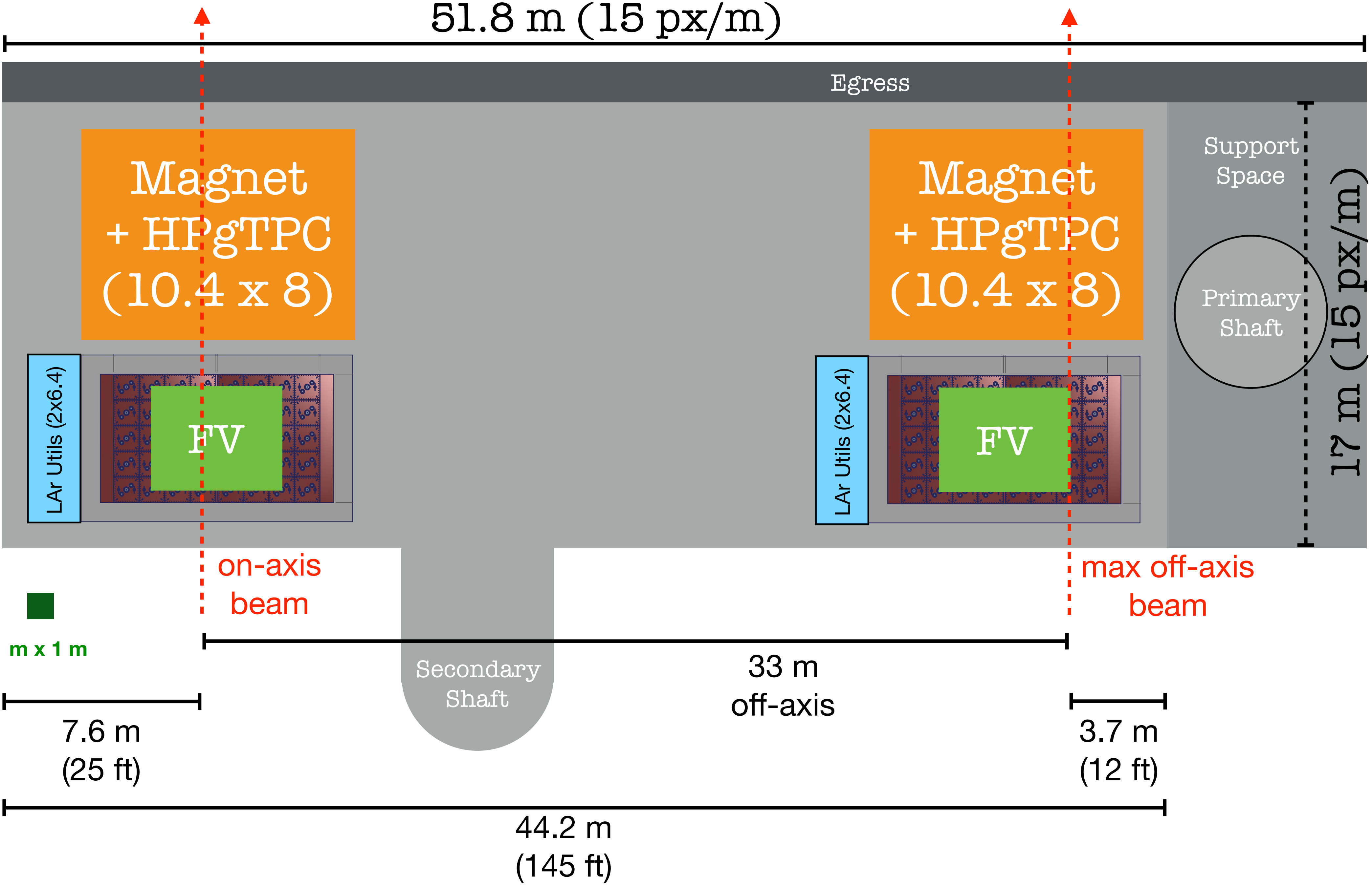
Offset	10^{19}POT	CCInc							NCInc
		μ contained			μ exit, $T_\mu^{exit} > 50$MeV			ν_e	ν_μ
		ν_μ	$\epsilon_{\nu_\mu,CC}$	$\bar{\nu}_\mu/\nu_\mu$	ν_μ	$\epsilon_{\nu_\mu,CC}$	$\bar{\nu}_\mu/\nu_\mu$		
0 m	55	6.6E5	3%	1%	5.5E6	22%	3%	4.9E4	1.8E6
3 m	4.58	5.5E4	3%	1%	4.2E5	22%	3%	4.0E3	1.4E5
6 m	4.58	5.8E4	4%	1%	3.1E5	22%	4%	3.5E3	1.1E5
9 m	4.58	6.0E4	7%	1%	2.0E5	23%	4%	2.8E3	7.5E4
12 m	4.58	5.9E4	12%	1%	1.2E5	24%	5%	2.1E3	5.2E4
15 m	4.58	5.4E4	18%	1%	6.9E4	22%	6%	1.8E3	3.7E4
18 m	4.58	4.6E4	22%	1%	4.3E4	21%	7%	1.4E3	2.7E4
21 m	4.58	3.9E4	27%	1%	2.8E4	19%	8%	1.2E3	2.1E4
24 m	4.58	3.2E4	30%	2%	1.9E4	18%	9%	9.3E2	1.6E4
27 m	4.58	2.6E4	32%	2%	1.4E4	17%	9%	7.9E2	1.3E4
30 m	4.58	2.1E4	33%	2%	1.1E4	17%	11%	6.8E2	1.0E4
33 m	4.58	1.7E4	35%	2%	8.11E3	17%	13%	6.4E2	8.3E3
36 m	4.58	1.3E4	35%	2%	6.62E3	17%	14%	5.7E2	6.6E3
	Totals	ν_μ	—	$\bar{\nu}_\mu$	ν_μ	—	$\bar{\nu}_\mu$	ν_e	ν_μ
All	110	1.1E6	—	1.6E4	6.7E6	—	2.2E5	6.9E4	2.3E6

RHC (1 year of running)



Offset	10^{19}POT	CCInc							NCInc
		$\bar{\mu}$ contained			$\bar{\mu}$ exit, $T_{\bar{\mu}}^{exit} > 50$MeV			$\bar{\nu}_e$	$\bar{\nu}_\mu$
		$\bar{\nu}_\mu$	$\epsilon_{\bar{\nu}_\mu,CC}$	$\nu_\mu/\bar{\nu}_\mu$	$\bar{\nu}_\mu$	$\epsilon_{\bar{\nu}_\mu,CC}$	$\nu_\mu/\bar{\nu}_\mu$		
0 m	55	1.1E5	1%	50%	2.0E6	25%	23%	1.6E4	1.1E6
3 m	4.58	9.1E3	2%	47%	1.5E5	25%	25%	1.2E3	8.0E4
6 m	4.58	9.8E3	2%	45%	1.1E5	25%	30%	1.0E3	6.1E4
9 m	4.58	1.02E4	4%	41%	6.3E4	26%	37%	7.8E2	3.9E4
12 m	4.58	1.0E4	8%	41%	3.4E4	26%	49%	5.7E2	2.5E4
15 m	4.58	8.7E3	12%	42%	1.9E4	25%	63%	4.6E2	1.6E4
18 m	4.58	7.9E3	17%	42%	1.1E4	23%	86%	3.3E2	1.2E4
21 m	4.58	6.4E3	20%	48%	7.0E3	22%	100%	3.0E2	8.5E3
24 m	4.58	5.2E3	22%	52%	4.6E3	20%	120%	2.2E2	6.7E3
27 m	4.58	4.4E3	25%	58%	3.5E3	20%	140%	1.8E2	5.2E3
30 m	4.58	3.4E3	26%	71%	2.6E3	20%	150%	1.5E2	3.9E3
33 m	4.58	2.7E3	27%	75%	2.0E3	20%	170%	1.5E2	3.4E3
36 m	4.58	2.2E3	28%	78%	1.4E3	18%	210%	96	2.8E3
	Totals	$\bar{\nu}_\mu$	—	ν_μ	$\bar{\nu}_\mu$	—	ν_μ	$\bar{\nu}_e$	$\bar{\nu}_\mu$
All	110	1.9E5	—	9.3E4	2.34E6	—	6.13E5	2.1E4	1.3E6

ND Hall Layout



Flux Uncertainties

- Haven't we just replaced **unknown cross section errors** with **unknown flux errors**?
    - Yes! But only relative flux errors are important!
    - Significant cancelation between PRISM and far detector variations
- **Normalization uncertainties will cancel** in the PRISM analysis
    - Cancelations persist, even for the PRISM linear combination
- Variations that affect off-axis angle shape are most important
    - Horn current, beam direction, alignment, etc.
- First analyses indicate that flux variations do not significantly impact PRISM analyses