DUNE-PRISM Status

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DUNE ND Workshop
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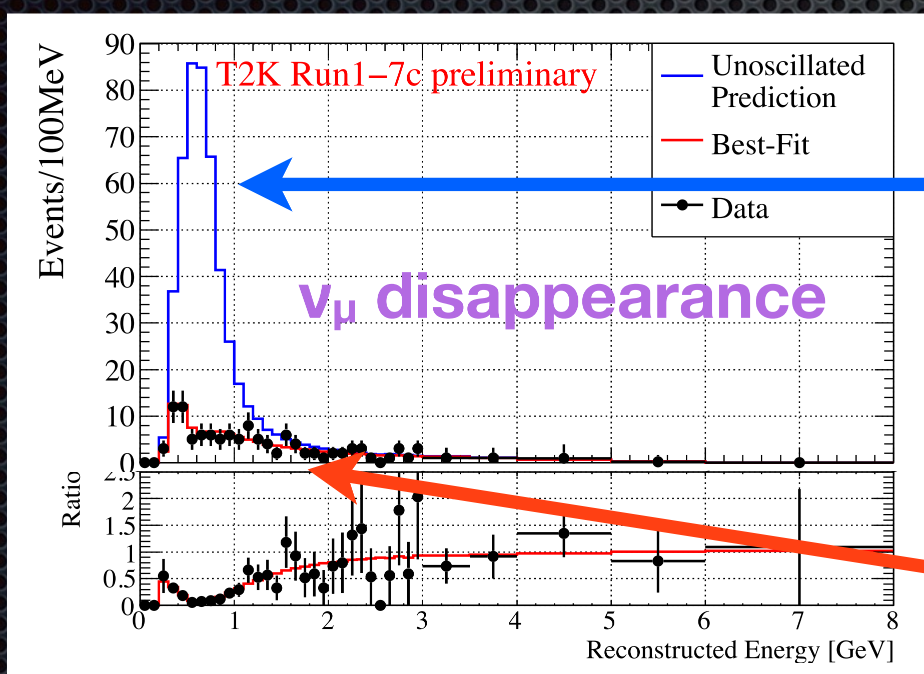
Measuring Neutrino Oscillations

In a near/far experiment, σ uncertainties will cancel?

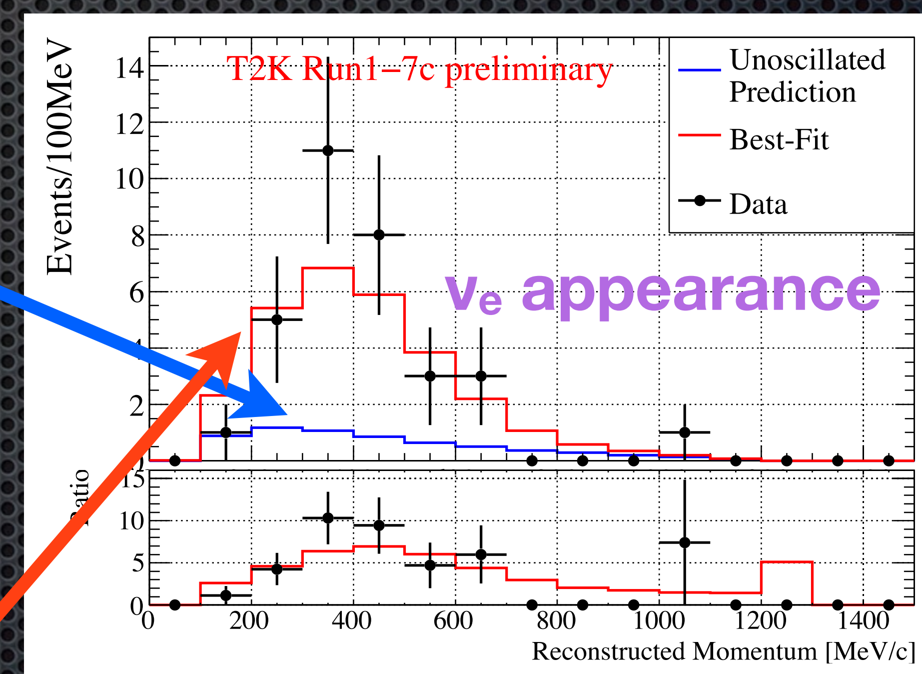
$$ND(\nu_\mu) = \boxed{\Phi(E_\nu) \times \sigma(E_\nu, A)} \times \epsilon_{ND} \times M_{E_{true}}^{E_{rec}}$$
$$FD(\nu_\mu) = \boxed{\Phi(E_\nu) \times \sigma(E_\nu, A)} \times \epsilon_{FD} \times P_{osc} \times M_{E_{true}}^{E_{rec}}$$

Cancelations of uncertainties in both flux and cross sections are spoiled by energy migrations

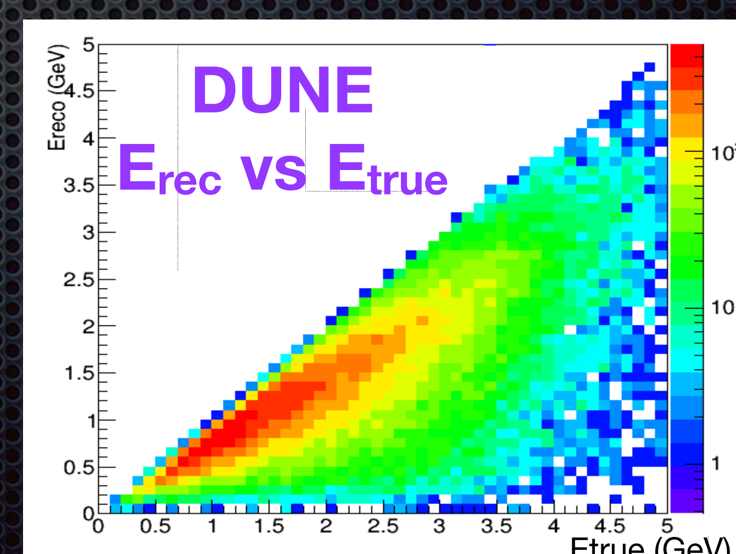


Near Detector Measures:
- ν_μ energy spectrum
- Small ν_e component

Far Detector Measures:
- Osc. ν_μ energy spectrum
- Large ν_e appearance signal

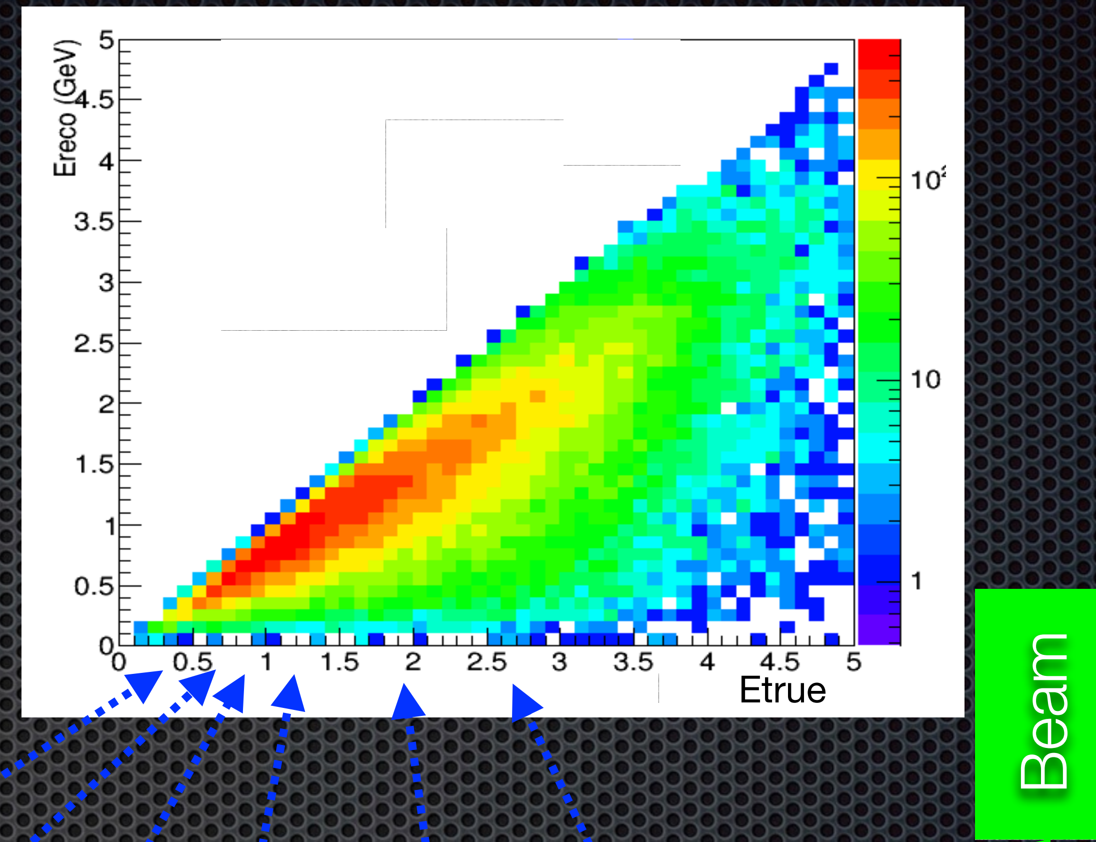


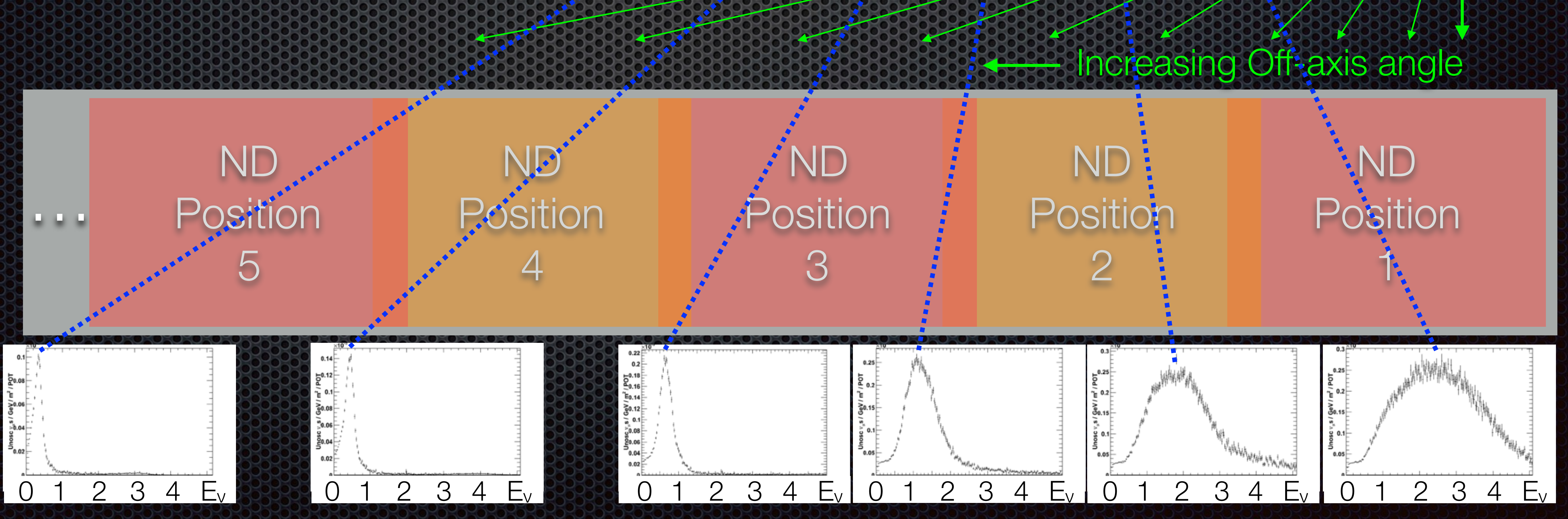
- E_{true} ➔ E_{rec} migration matrix will have significant off-axis components
  - Several important cross section uncertainties will not cancel



Off-Axis Detectors

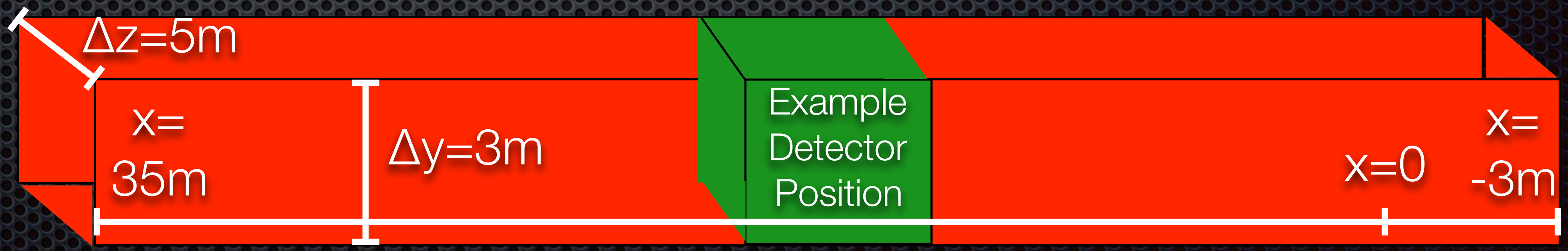
- By moving the detector off-axis, we can measure different E_ν spectra
- The provides a new degree of freedom over which we can constrain E_{rec} vs E_{true}
- There are various ways to combine such information to constrain the effects of cross section uncertainties on DUNE oscillation parameters
- One example: Produce "oscillated" Ev spectra in the near detector (Luke's talk)





DUNE-PRISM MC Sample

- We have a full simulation chain to produce events in a LAr detector at any off-axis position (more detail last at the last collaboration meeting)
  - Events are produced in a block of LAr that is 38 m wide (in the off-axis direction) x 3 m tall x 5 m deep (in the beam direction)
    - A 4 x 3 x 5 m^3 detector can then be placed at any arbitrary off-axis position
  - Note that a 3m wide FV (4m wide detector) requires ~11 positions to cover the full off-axis range (feasible statistics, even with 50% running on-axis; a reminder of event rates is given in later slides)



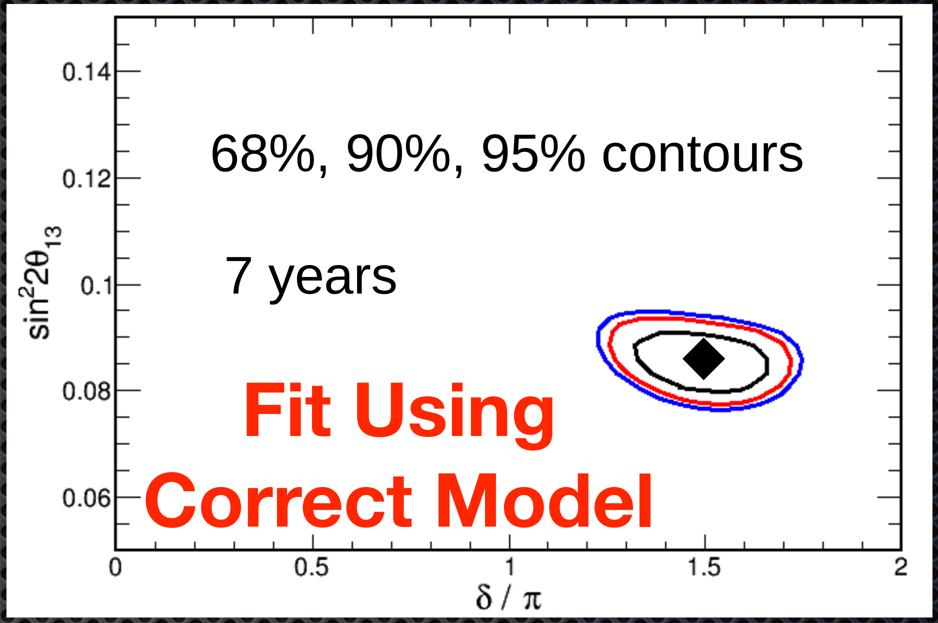
Reminder: DUNE-PRISM Physics Goals

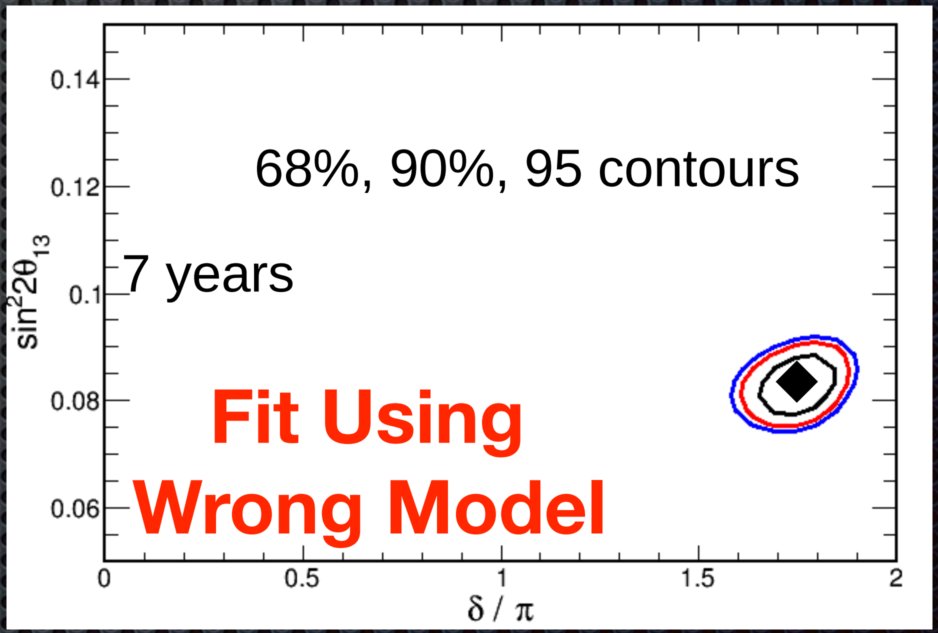
- A moving near detector can **reduce** the risk of **biases** in measured **oscillation parameters** due to incorrect neutrino interaction modeling:

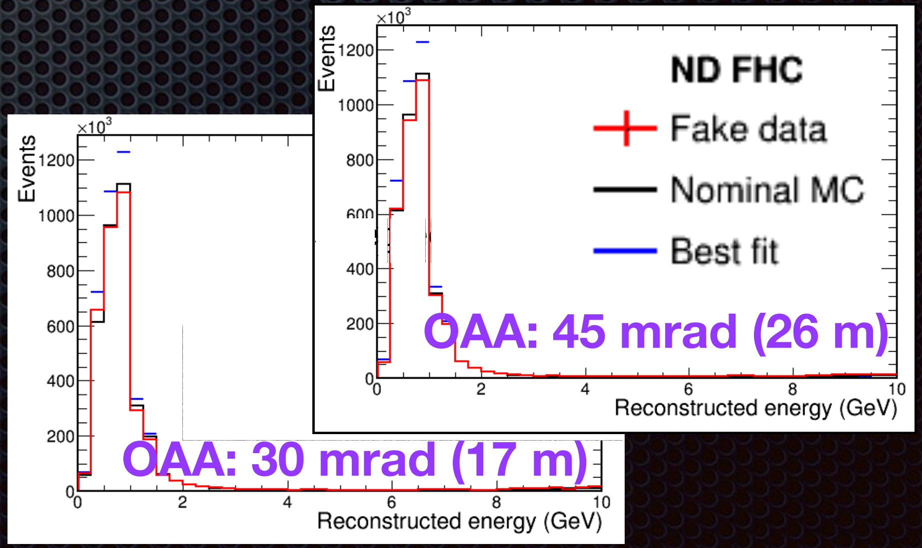
  1. Show that DUNE-PRISM can **identify** modeling problems that cannot be seen by a traditional near detector
     - This may be possible with just a few off-axis locations
     - Updated fake data studies that demonstrate oscillation parameter biases that cannot be easily detected with only an on-axis detector will be shown at this meeting
  2. Show that DUNE-PRISM can **correct/overcome** modeling problems that would exist in a traditional near detector
     - This will likely require a comprehensive set of off-axis angle measurements
     - Progress toward a full analysis will be shown at this workshop

Previous Fake Data Studies

- The goal of a fake data study is to explore potential problems for DUNE due to cross section mis-modeling
  - "Fake data" is MC in which the cross section model has been modified in a way that the model used in the fit does not know about
- Previous fake data studies:
  - 20% of pion KE (or proton KE) transferred to neutrons
  - Using ND task force MC (i.e. no realistic event selection)
  - Guang ran a full near+far oscillation fit in E_{rec} using only an on-axis near detector, which produced biases in oscillation parameters (CAFAna)
    - Off-axis positions clearly showed a problem in the cross section model not seen on axis
  - However, the near+far oscillation fit had to move the flux parameters by a large amount, which would have been identifiable in other distributions



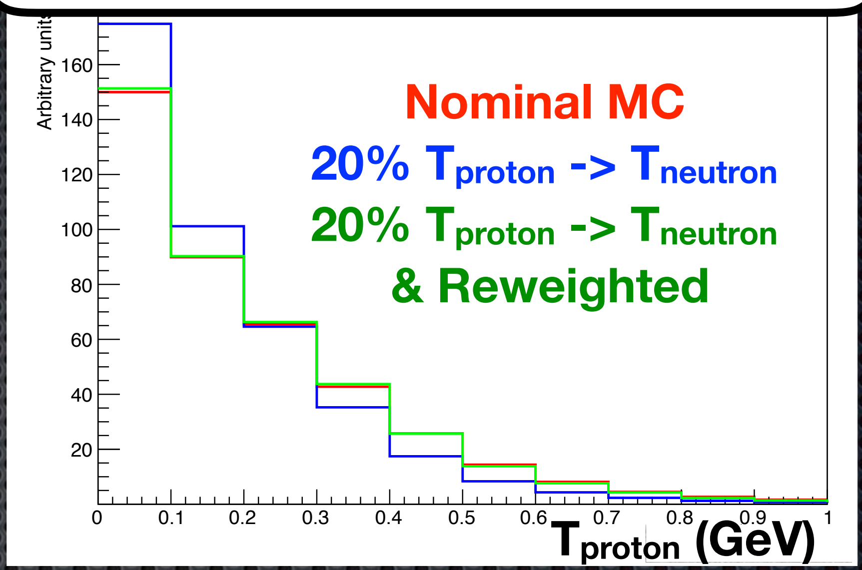




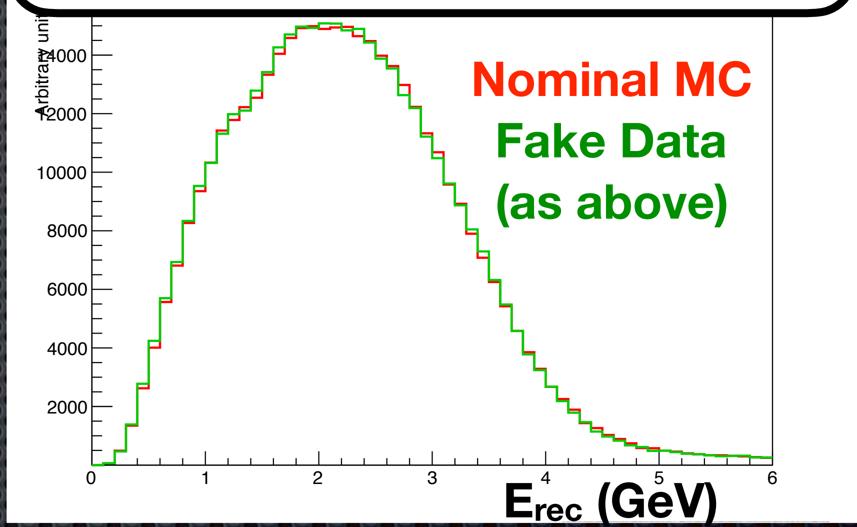
New Fake Data Studies

- In new fake data, still transfer 20% of proton energy to neutrons, but also modify $d\sigma/dT$ to make T_{proton} distribution agree with MC at the near detector (& E_{rec})
  - (Alternatively, suppose our near+far oscillation fit fixed up the T_{proton} distribution by modifying the cross section, NOT the relative energy in protons vs neutrons)
- In this fake data set, all the above mentioned observable distributions agree perfectly in the near detector
  - A near + far fit will not modify flux or cross section parameters
    - The ND constraint will fix them at their default values
- These new results use new DUNE-PRISM MC with realistic selection efficiencies

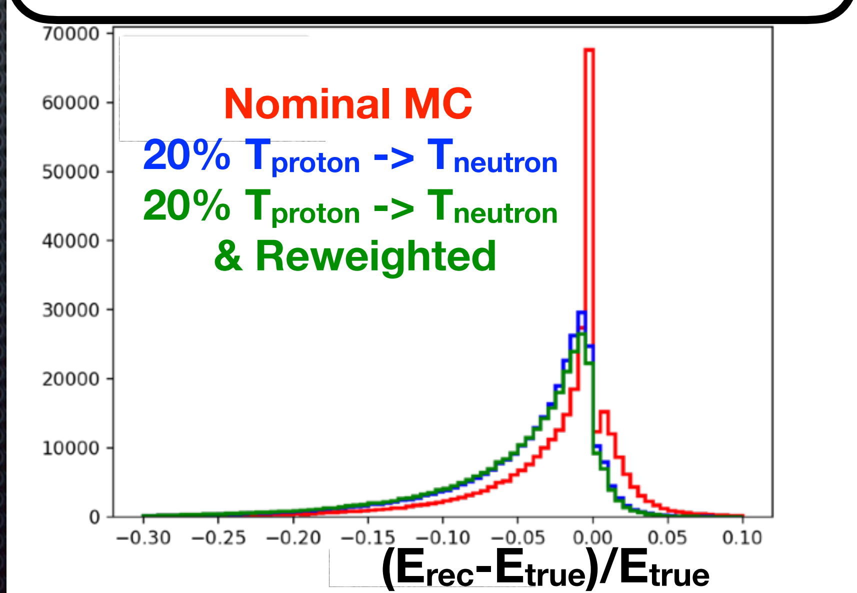
Near Detector T_{proton} On-Axis



Near Detector E_{rec} On-Axis



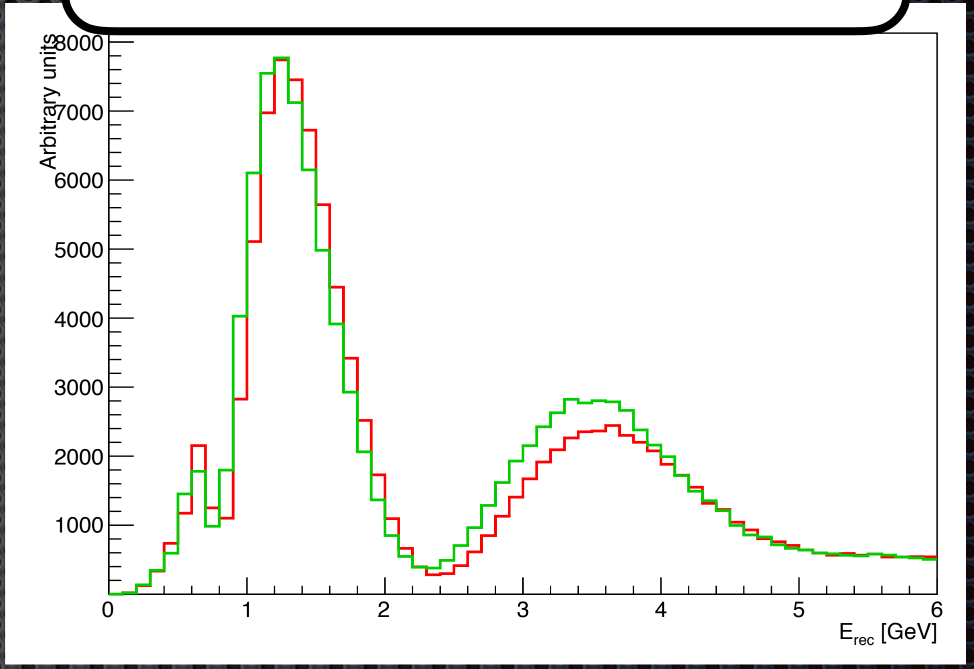
E_{true} -> E_{rec}



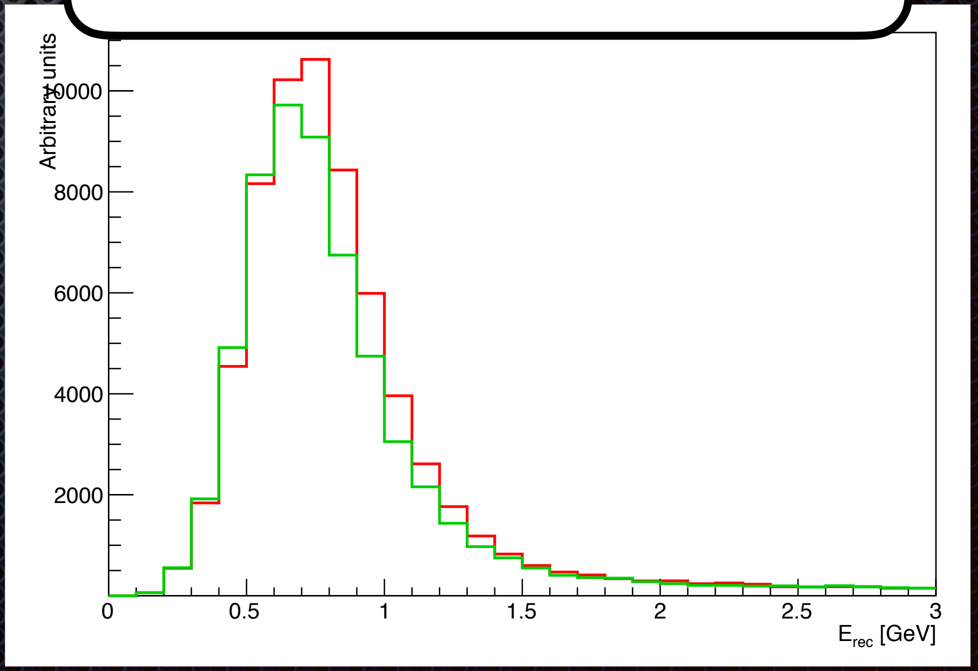
New Fake Data Studies II

- However, the far detector fake data can be significantly distorted relative to our default model, since the FD flux is very different from the ND flux (and the efficiencies are different)
    - i.e. we would measure the **wrong oscillation parameters**, and it would be **VERY** difficult to detect a problem with only an on-axis ND
      (even if the ND was very high precision)
    - Unfortunately, we could not get the exact value of the measured biases in time for this meeting due to incompatibilities between our new DUNE-PRISM MC files and CAFAna
        - (no talk by G. Yang today)
        - However, by looking at the FD distributions it seems clear that θ_{23}, Δm^2_{32}, and CP will all be biased (talk by C. Vilela)
- By looking off-axis, once again, the problem can be easily identified (all the details will be given in talk by C. Vilela)

Far Detector E_{rec}



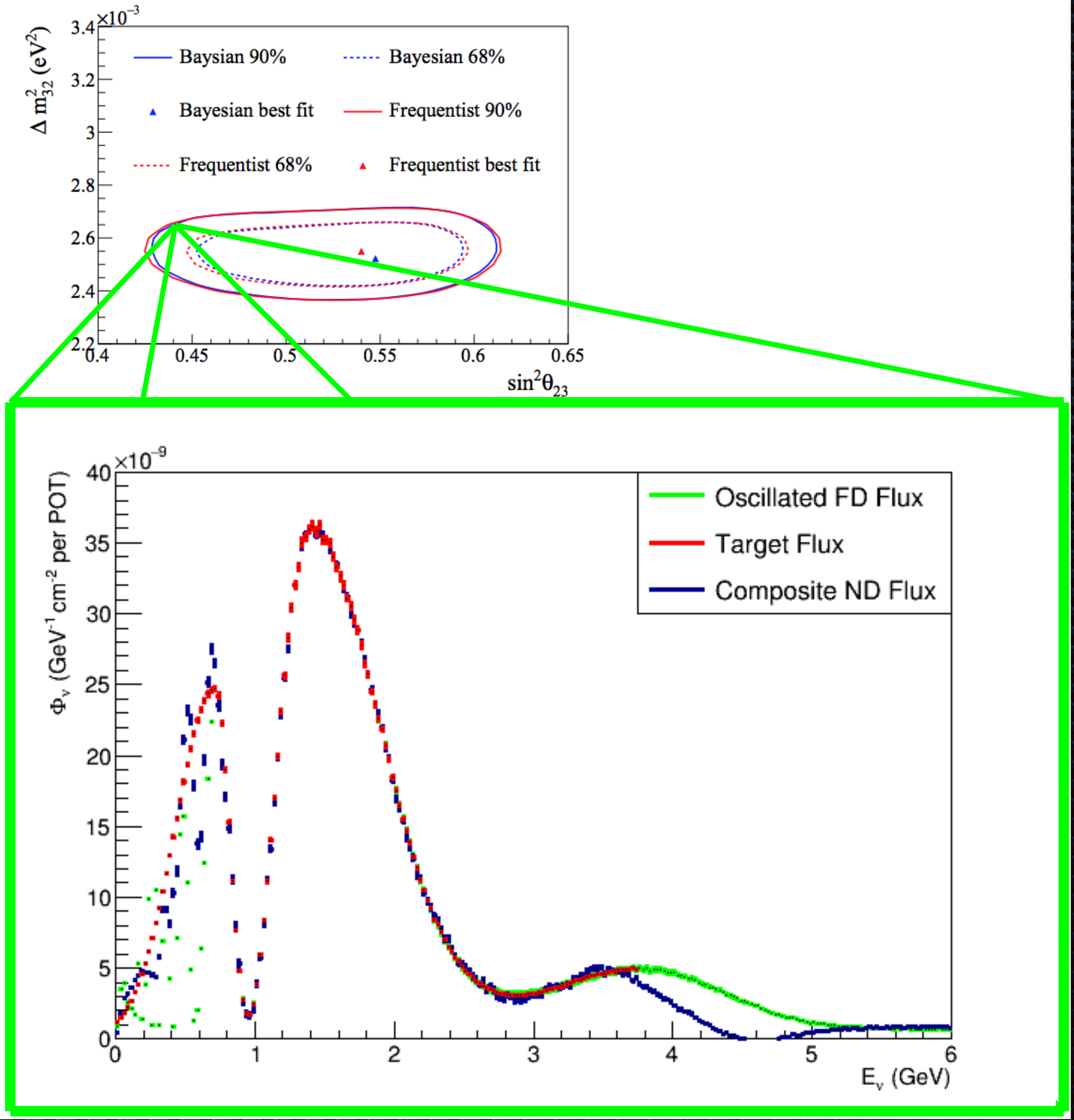
Near Detector E_{rec}
18 m Off-Axis



"Oscillated" Flux at the Near Detector

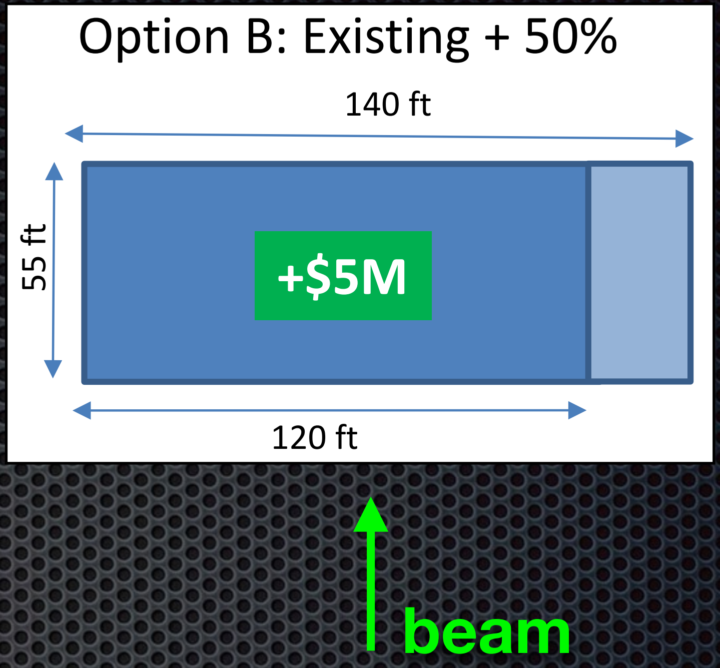
(i.e. data-driven far detector predictions in the oscillation analysis)

- By taking linear combinations of the flux at each off-axis position, it is possible to construct an "oscillated" flux at the near detector (for any choice of oscillation parameters)
- The same linear combination of any detector observable (e.g. Erec) gives the predicted FD distribution (for that choice of oscillation parameters)
  - Any un-modeled Etrue -> Erec effects are directly transferred from the ND measurements to the FD prediction
    - i.e. you do not have to go through the cross section model
  - Other indirect sources of model dependence (e.g. background treatment, detector efficiency)
- Progress shown at this meeting (L. Pickering), but still a work in progress

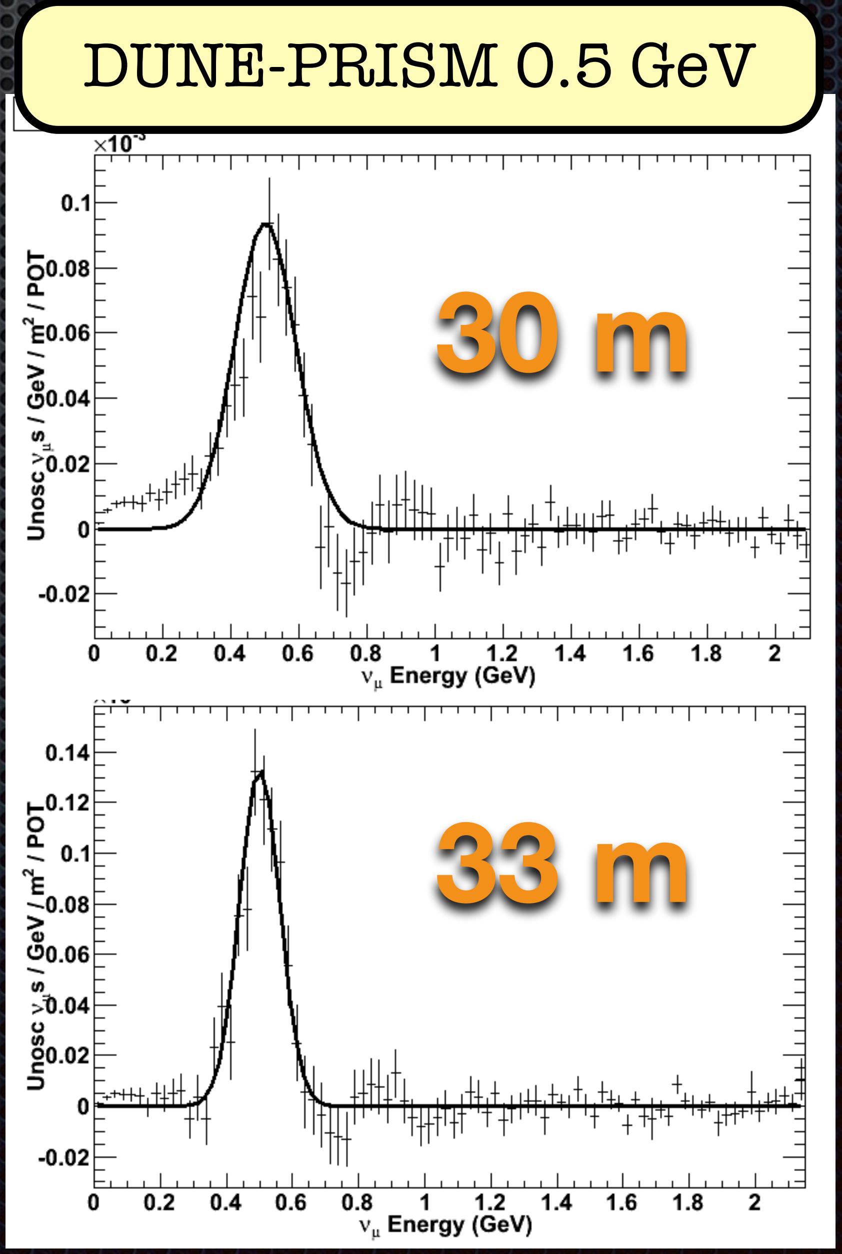


Flux fit improvements (D. Douglas)
Now well-behaved at low E_ν

ND Hall Requirements



- Making off-axis measurements requires a ND hall with its long-axis perpendicular to the beam direction
- "Default" ND hall size already provides sufficient off-axis angle to probe 2nd oscillation maximum: 140/120 ft (= 42.7/36.6 m)
- Hall "width" depends on the length of the detector in the beam direction
    - 5 ft of 55 ft is reserved for egress hallway, so max detector length is 15.2 m in the current footprint
    - LAr cryostat is ~7 m long (5 m of active LAr), and both magnet designs currently occupy 6 m in the beam direction (13 m total)



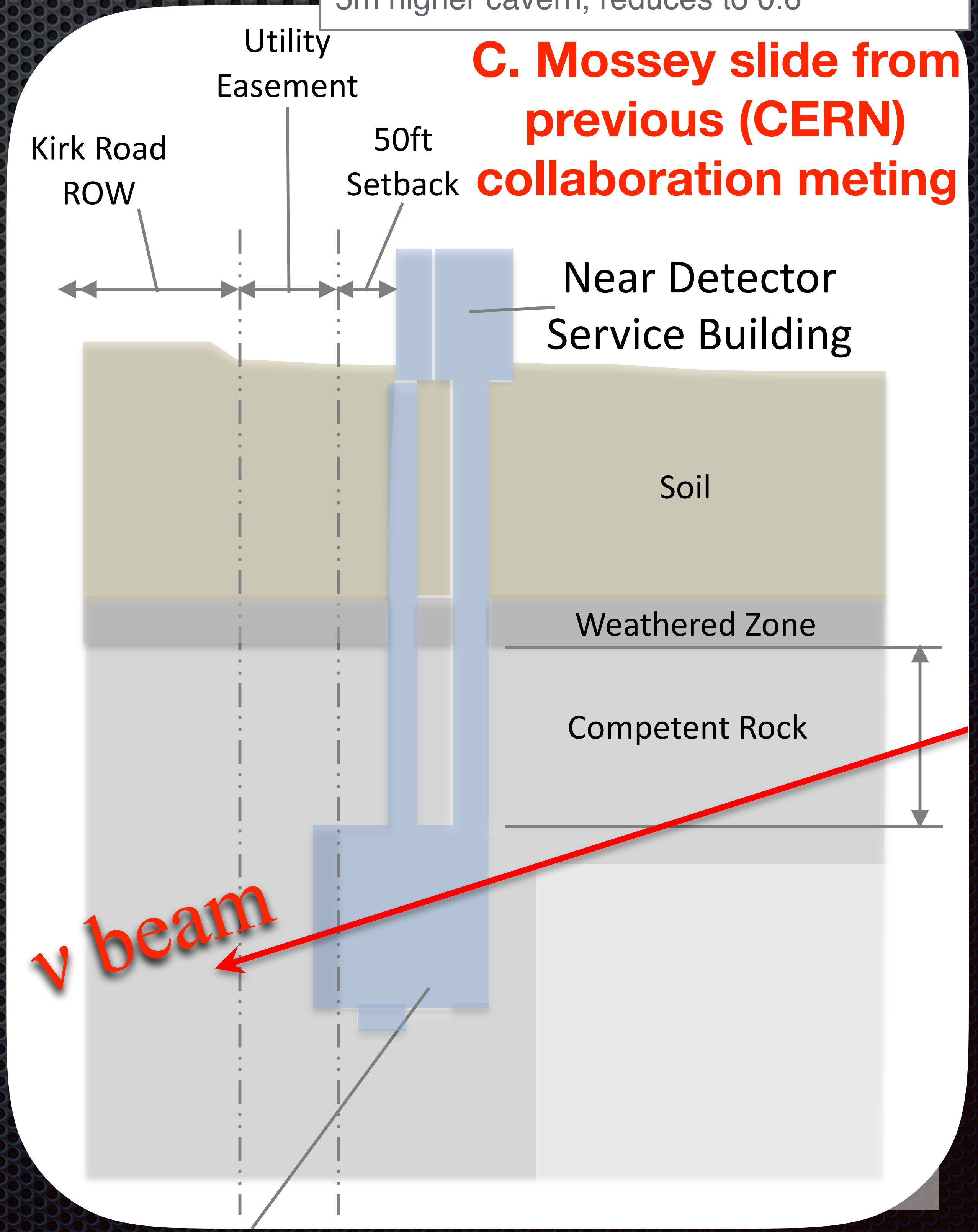
ND Hall Constraints

- We don't really know how wide the ND hall can be
- "Rule of thumb" given by LBNF engineers is ratio of competent rock above cavern to cavern width should be close to 1
  - Exact height of competent rock is not precisely known
  - Assumed location for ND hall may not be where we want it
  - Required ceiling height is not yet defined (see next slide)
- Planning is underway to work with LBNF to understand the cavern cost vs "rule of thumb" ratio

"Rule-of-Thumb"
Ideal ratio of thickness of competent rock to excavation span is 1.0 or greater

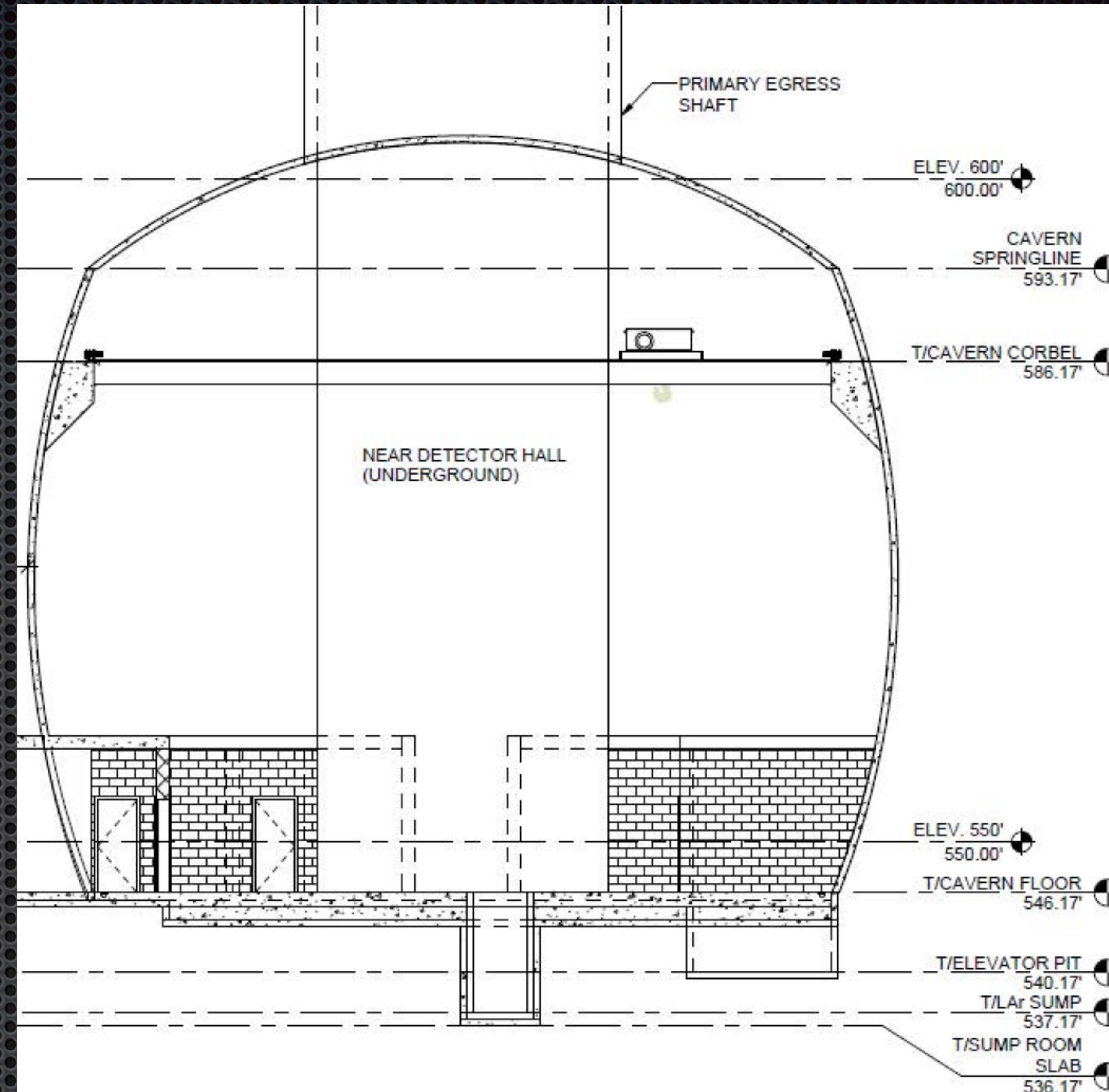
Current ratio = 1.1
Possible weathering impact, reduces to 0.9

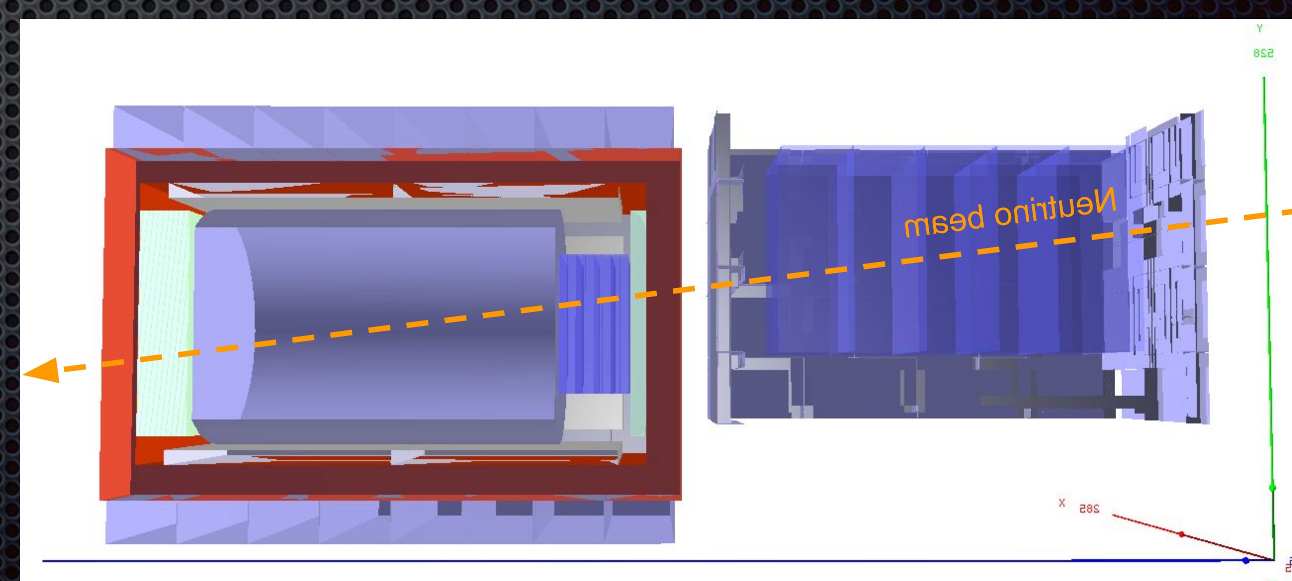
5m higher cavern, reduces to 0.6



Ceiling Height

- It is likely possible to increase the crane height without changing the hall cutout
- Decision on whether the ArgonCube modules should be “cold swappable” can also affect required ceiling height
- LAr detector is elevated with respect to tracker
  - An elevated platform is being explored, which may also lessen the ceiling height burden
- If ceiling height can be reduced (currently 40 ft / 12.2 m), the width of the hall can be increased without an increase in civil construction cost



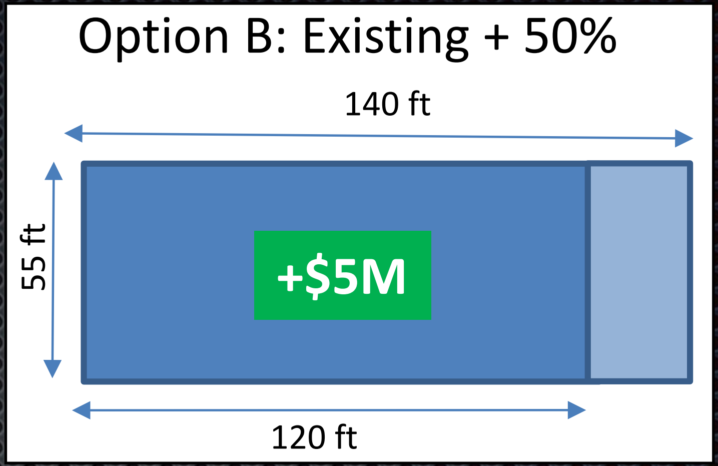


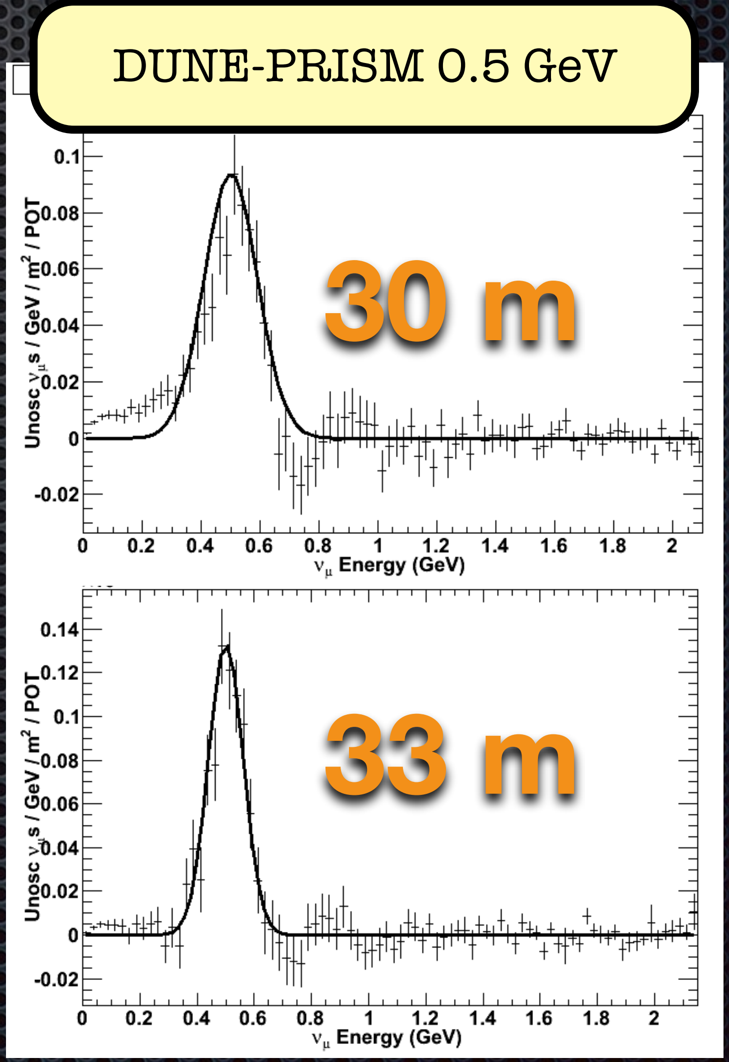
Decision Stages

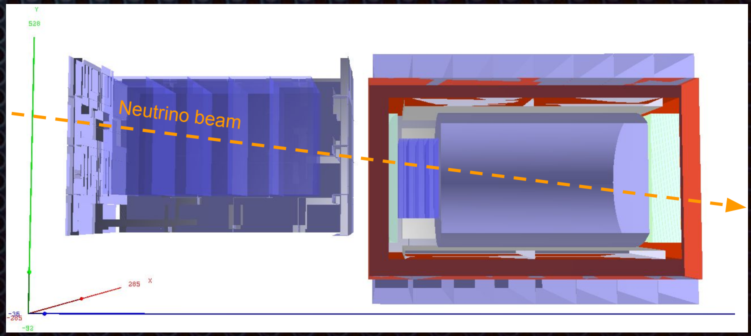
1. ND Cavern Orientation
    - Should the cavern be oriented along the beam, or transverse to the beam (i.e. along the off-axis direction), regardless of whether our primary detectors are movable?
2. Detector Mobility
    - Can (and should) the ND be moved to at least 1 off-axis position?
    - Should the entire detector move, or just the LAr detector (+ a separate muon spectrometer)?
3. Run Plan
    - What run plan is needed to carry out the full (or partial) DUNE-PRISM program?
    - Are such plans feasible given the expected beam power, near detector mass/acceptance, and other ND physics requirements?

ND Cavern Orientation

- Even if our primary near detector is not moved, where will the extra cavern space most benefit DUNE?
  - To better decouple flux and cross sections, there is a good chance we will want future detectors placed off-axis
  - To study the ~600 MeV 2nd oscillation maximum in detail, we need to reach ~35 m off-axis.
  - As the off-axis angle increases, the ν_e/ν_μ ratio increases, allowing for a more pure measurement of $\sigma(\nu_e)/\sigma(\nu_\mu)$ and $\sigma(\text{anti-}\nu_e)/\sigma(\text{anti-}\nu_\mu)$
- Ironically, extending the hall along the beam direction will necessarily result in (shallow) off-axis measurements due to the beam angle
  - Since the "extra space" in the default hall will be off-axis in any case, we should try to optimize this to maximize DUNE physics output







Detector Mobility

- How do we optimize the use of the cavern space to maximally constrain DUNE systematic uncertainties (e.g. due to neutrino interaction modeling)?
- The ideal case is to make off-axis measurements with the same detector (LAr + tracker) as used for on-axis measurements to reduce detector cross-calibration uncertainties at different positions
    - Also, the budget can not yet accommodate additional highly capable near detectors
- Since technical feasibility requires additional input from LBNF, then, at this stage, if the DUNE ND group decides that DUNE-PRISM is useful, we may have to make a statement such as the following:
    - "There are significant physics benefits to making ND measurements at positions off-axis to the beam. In the baseline plan, the near detector will be designed to be moved to one or more off-axis positions. The technical feasibility of this plan, including the additional engineering constraints this will impose, is under evaluation in conjunction with LBNF."
- Note: If it is decided that only the LAr detector can be moved, an additional muon spectrometer (e.g. a magnetized muon range detector) will be required that can be moved in conjunction with the LAr detector

Run Plan Questions

- Can sufficient statistics be collected at each off-axis position for the full DUNE-PRISM program?
  - At last collaboration meeting, Jake showed that at least a few thousand events can be collected for [both contained and exiting muon samples] and [FHC or RHC] with 1 year of running, and half the POT collected on-axis
  - From a physics perspective, this run plan looks feasible (more from L. Pickering this meeting)
  - Remaining issues are purely technical (how frequently, and to how many positions, can we move the detector)
- If the primary DUNE-PRISM program encounters technical limitations, it is possible to revert to just a few off-axis positions
  - e.g. one intermediate position to identify cross section modeling issues, and a position near 30 m to study the 2nd oscillation maximum

Event Rates (see J. Calcutt talk from CERN collaboration meeting)

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	$\boxed{110}$	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	$\boxed{110}$	1.9E5	—	9.3E4	2.34E6	—	6.13E5	2.1E4	1.3E6

Summary

- With only an on-axis near detector, it is possible to get the wrong oscillation parameters due to imperfect cross section modeling
  - New fake data studies show that such cross section models exist that would be very difficult to probe with only an on-axis near detector
  - These modeling difficulties can be detected via off-axis measurements
- Full data-driven DUNE-PRISM analysis is underway, but significant work remains, and this may not be ready for April/May
- DUNE-PRISM program (moving LAr + MPT) appears to fit in the existing ND hall footprint, but additional hall width would be welcome, and this is being pursed with LBNF
  - In the near term, hall orientation must be fixed
    - It is likely preferable to orient the hall off-axis, even one or more of the primary detectors do not move
- Sufficient event rates exist to take half POT on-axis, and half POT across 10+ off-axis positions — this depends on the ability to design a sufficiently agile detector

Supplement

DUNE-PRISM Questions

1. **Can DUNE-PRISM help constrain the focusing errors at the FD?**

    - Answer: not really, since beam errors are expected to be small, but unexpectedly large effects (e.g. 2-3 sigma) should be detectable

- **Related question: what is the impact of focusing errors (such as the NuMI ME focusing effect) on DUNE-PRISM linear combinations**

    - Answer: impact appears to be (very) small (see talk by L. Pickering)

2. **To what extent can DUNE-PRISM with realistic hall size deconvolute xsec and flux errors?**

    - Answer: currently planned hall size should be sufficient (although rotated), assuming the length of the detector is less than ~15-18m

        - Realistic run plan and event rates (with realistic efficiencies) give in J. Calcutt talk

3. **What is the FOM/study for this?**

    - Answer: Identification of cross section modeling with a few off-axis measurements has been demonstrated (G. Yang talk)

    - Answer 2: Full oscillation analysis using off-axis linear combinations is next step; the goal is to show insensitivity to cross section modeling issues via fake data studies