A Road to the NOvA Experiment: Status and Prospectus

NOW 2010

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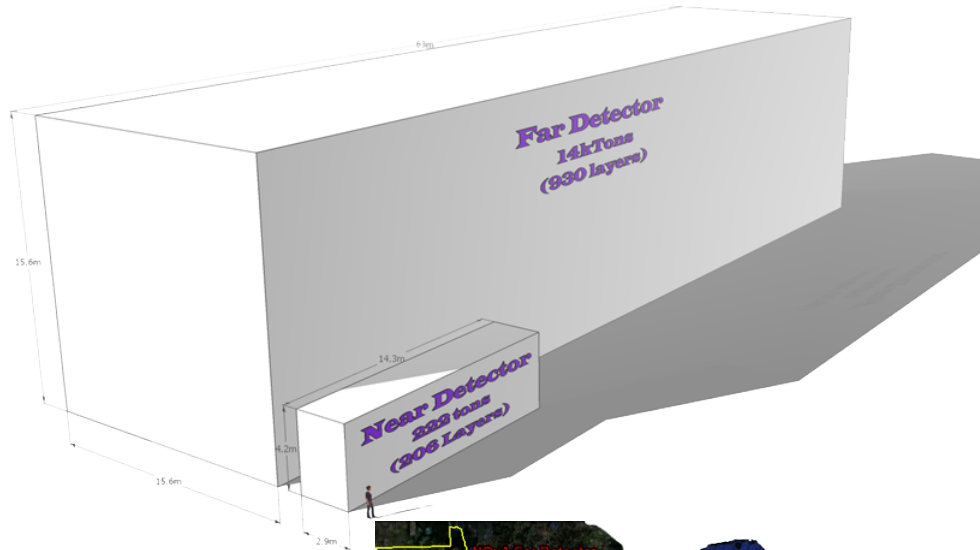
for the NOvA Collaboration

NOvA Overview

- *NOvA* is a second generation accelerator based neutrino oscillation experiment, optimized for detection of the oscillations:

$$\nu_\mu \rightarrow \nu_e \quad \text{and} \quad \bar{\nu}_\mu \rightarrow \bar{\nu}_e$$

- *NOvA* is:
  - A 14-15 kton, “totally active”, far site detector
  - A 222 ton near detector, utilizing an identical detector technology and geometry
  - An upgrade of the FNAL NuMI beam intensity from 320 kW to 700 kW
- Both detectors use a highly segmented “totally active” liquid scintillator calorimeter design (70% active volume)
- The detectors are both 14mrad off the primary beam axis to achieve narrow ν energy spectrum, peaked at 2GeV.
- The far detect is located on a 810km baseline between Chicago and Northern Minnesota at the first oscillation maximum



Baseline: Fermilab to Ashriver, MN
Dist: 810km
Angle: 14mrad from primary beam axis

Sept 2010

PROJECT STATUS

NOvA (1 year ago)

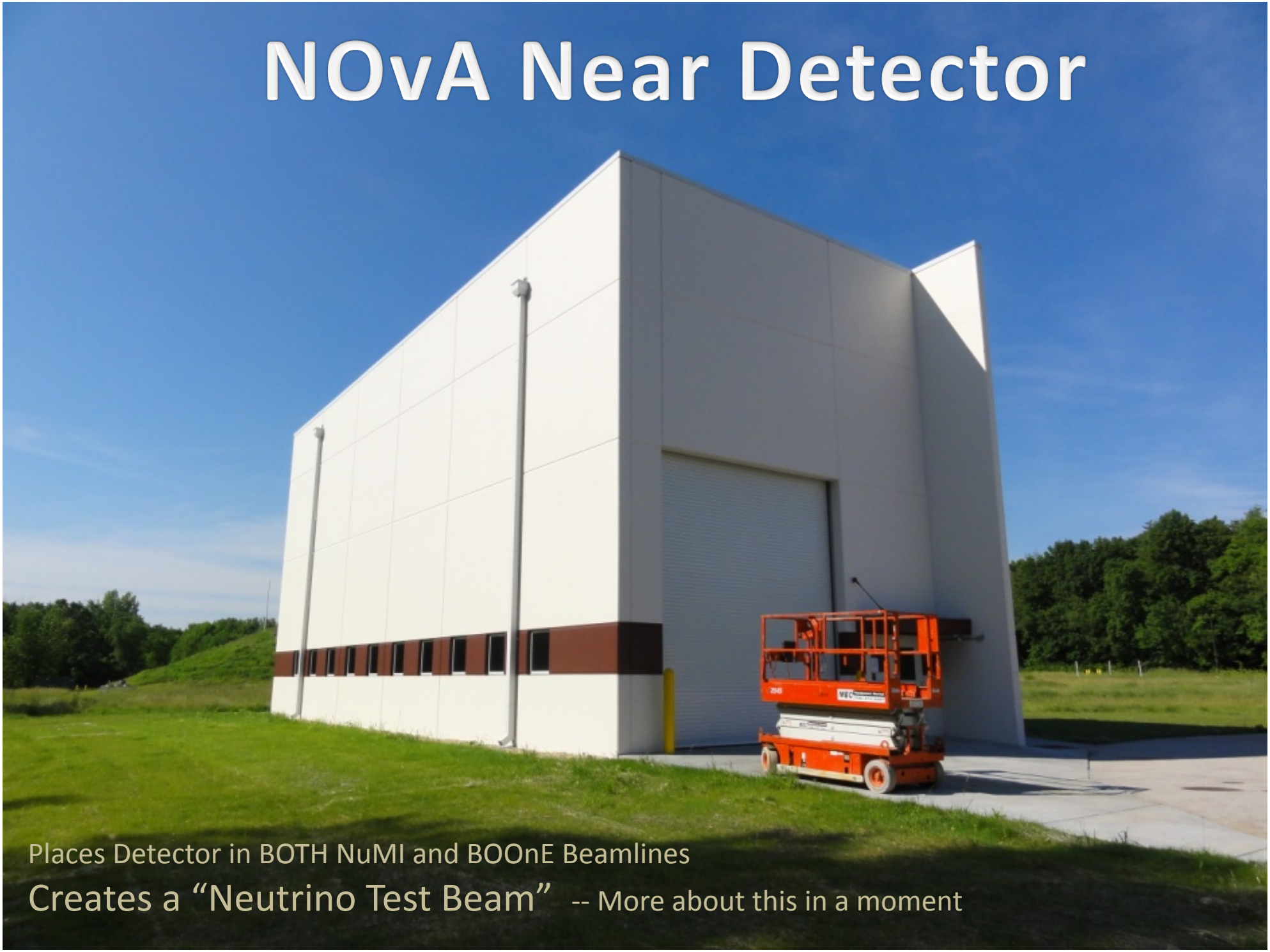
NOvA Today

- ✓ >100 kTons of rock removed
- ✓ 50 kTons used to build access road
- ✓ Remaining rock used for shielding around building

NOvA Today

- ✓ Concrete being poured at a rate of 1000yards/weeks
- ✓ Occupancy may start as early as December 2010

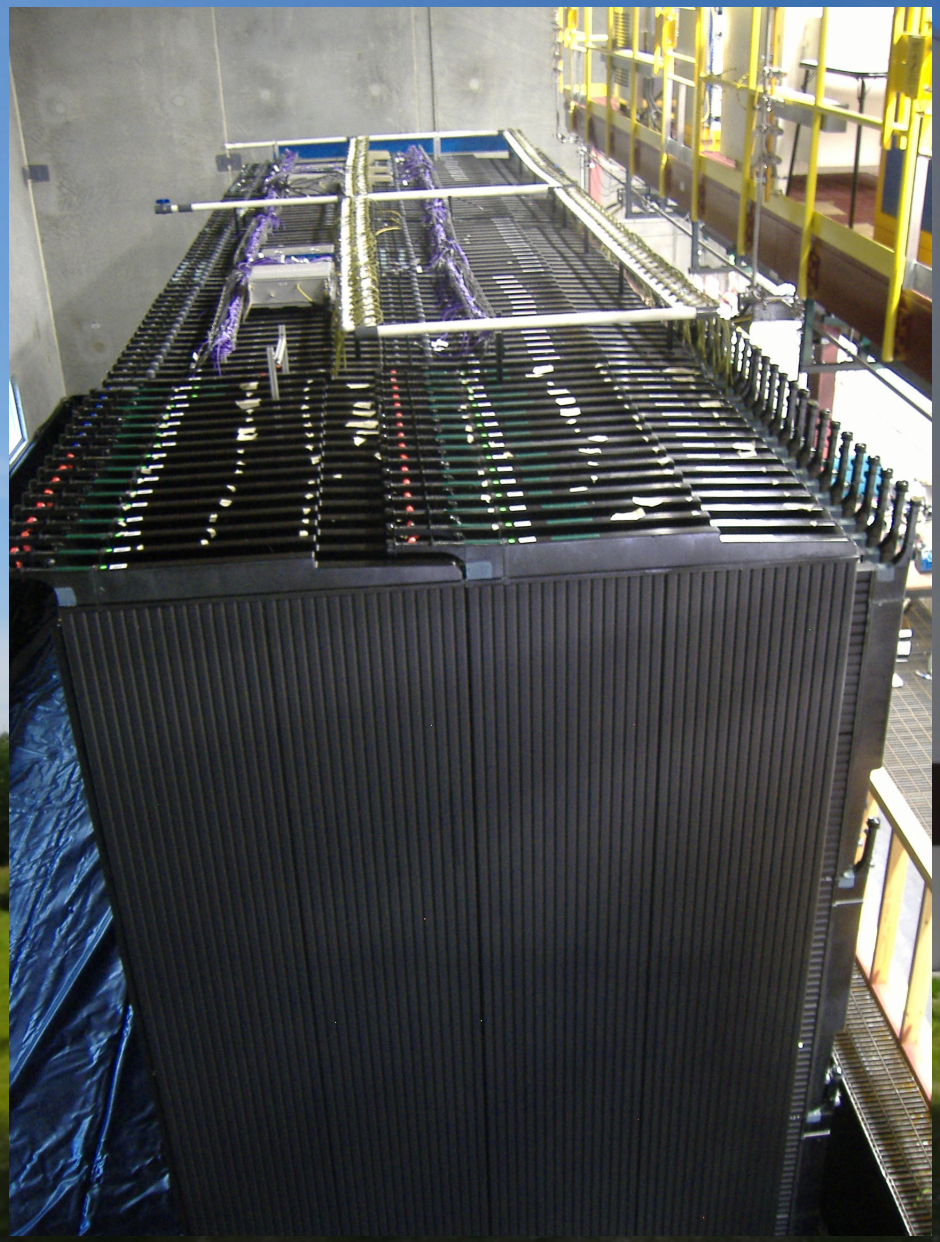
NOvA Near Detector



Places Detector in BOTH NuMI and BOOnE Beamlines

Creates a “Neutrino Test Beam” -- More about this in a moment

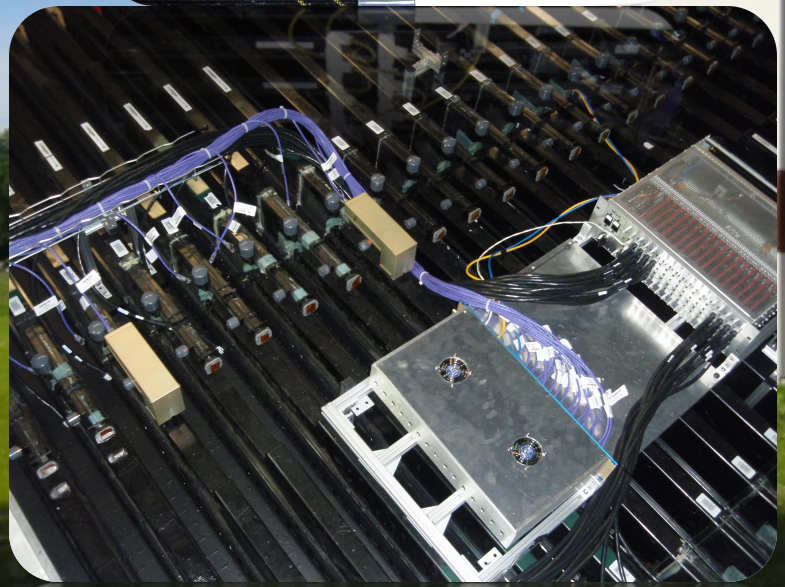
NOvA Near Detector



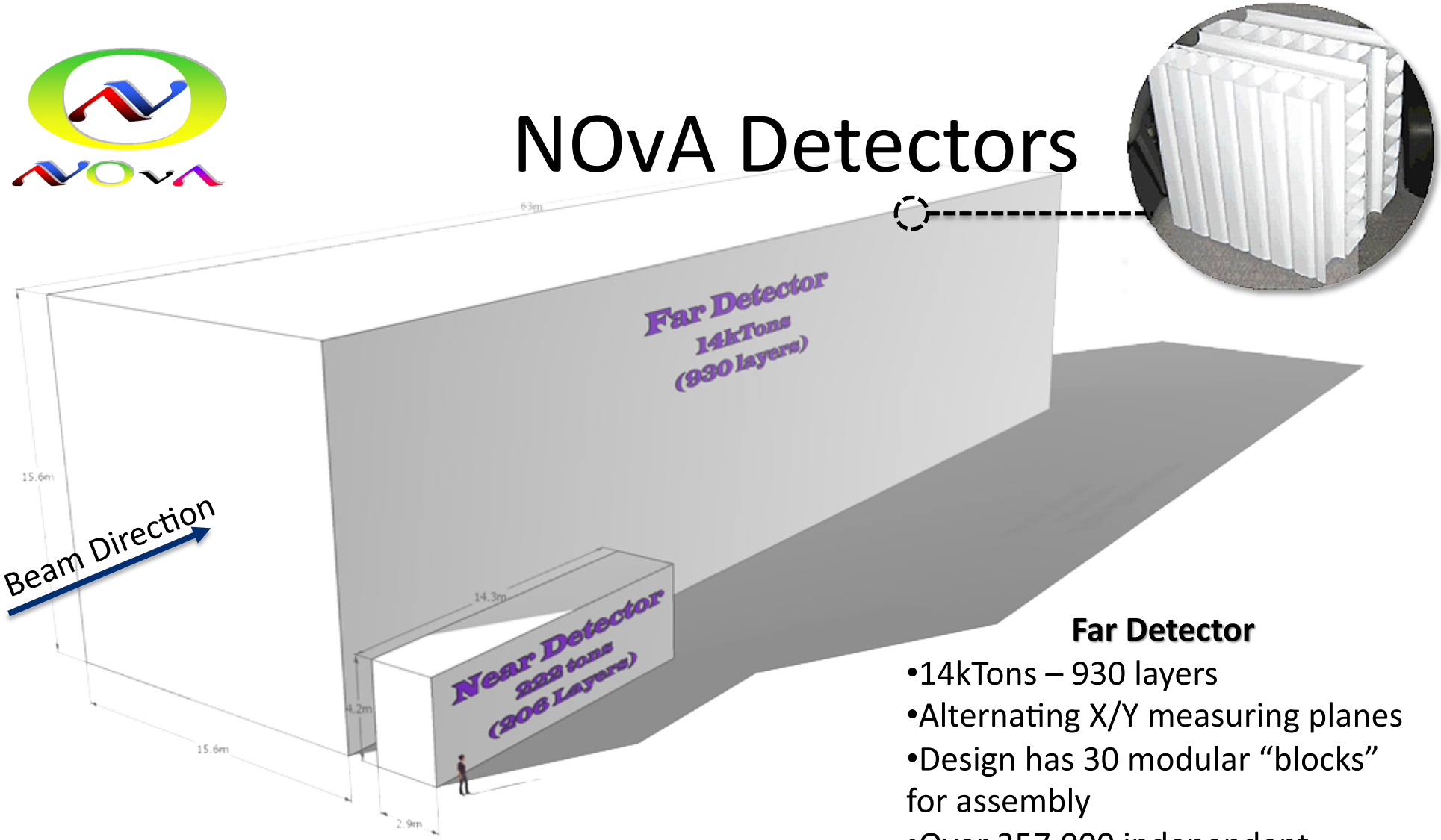
Near Detector installation is almost complete.

- 5 of 6 detector blocks are in place
- Muon catcher in construction
- Detector outfitting/commissioning has started

NOvA Near Detector



NOvA Detectors



Near Detector

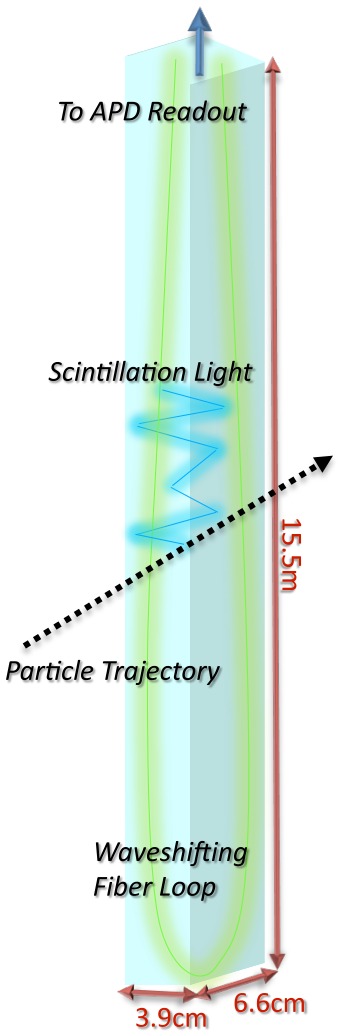
- 222 Tons – 206 layers
- 2 modules wide, six blocks deep
- Includes muon catcher for ranging out μ's
- Located 14mrad off axis in NuMI, next to MINOS cavern

Far Detector

- 14kTons – 930 layers
- Alternating X/Y measuring planes
- Design has 30 modular "blocks" for assembly
- Over 357,000 independent measurement cells
- > 70% of total mass is active
- Located 14mrad off axis
- 810km baselines

Detector Cell

Single Cell



There are 357,120 cells in NOνA

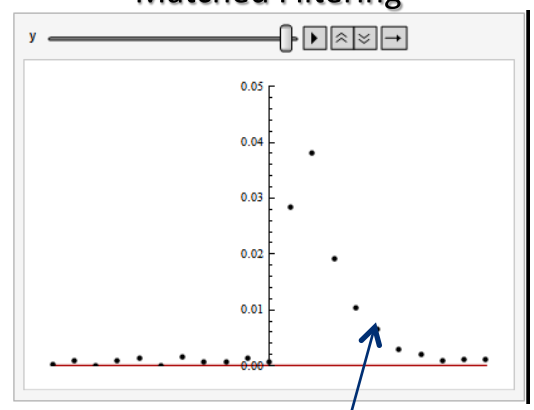
NOvA Detection Cell

- The base detector unit 3.9x6.6cm cell 15.7m long, filled with a mineral oil based liquid scintillator.
- Passage of MIPP through the cell (longitudinal to beam) results in dE/dx ≈12.9 MeV across the cell.
  - Roughly 10% of energy loss is in the PVC wall
  - Yields 10-12MeV of deposition in the scint.
- The measured light output is 30-38 p.e. from the far end of the cell into the APD readout
- Light yield gives a minimum Sig/Noise 10:1 (far end)

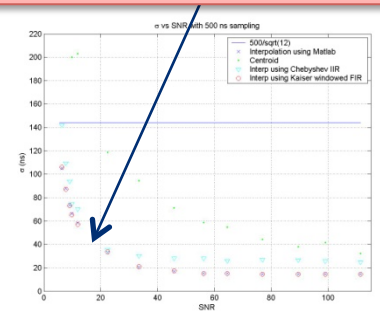
Zero Suppression

- Expected noise (electronic) 300e ≅ 3 p.e.
- Continuously digitizes w/ 500ns sampling
- Zero suppress (0.5-0.66) MIPP (15-20pe) depending on final light yields
- Results in a single cell, lower energy detection threshold of 6-8 MeV (far end)

Matched Filtering

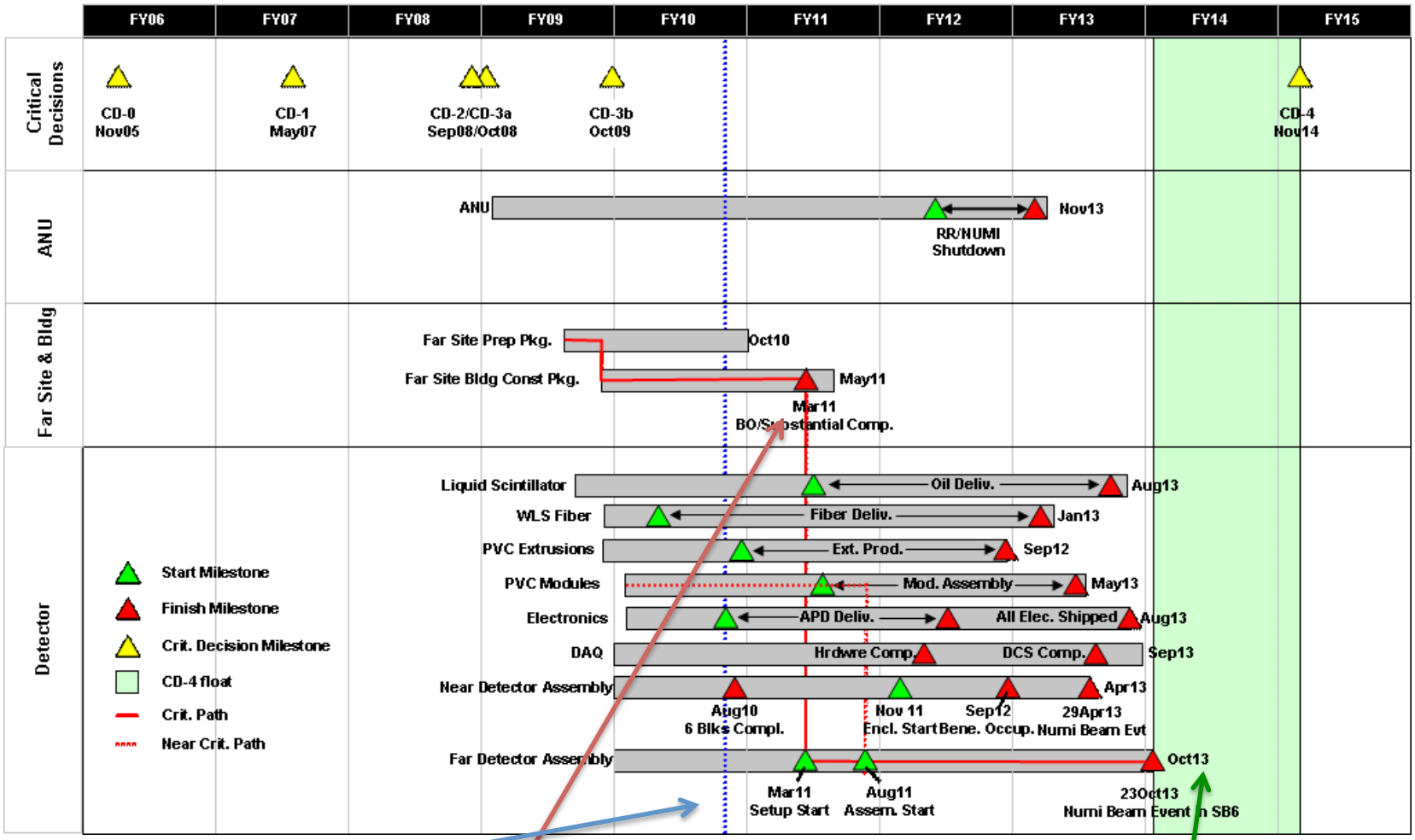


Raw data is matched to ideal response function in the FPGA, to extract pulse height and timing edge.
Timing resolution is a function of Sig/Noise (10:1 min) giving a timing resolution of < 30ns



NOvA Schedule & Milestones

- NOvA is fully on schedule
  - Sept. 2010:
    Near Detector completes construction and instrumentation
  - Oct. 2010:
    Near detector starts operation in "surface configuration"
  - Dec. 2010:
    Far site building occupancy for installation of detector construction infrastructure
  - July 2011:
    Start Far Detector Construction
    - *Goal is to have 1-2kT operational prior to 2012 accelerator shutdown*
    - At end of accelerator shutdown NOvA has >10kT detector active and 700kW beam ready for commissioning
- Due to Recovery Act funding, NOvA is on an entirely "technically driven" schedule
  - As a result we are looking to significantly advance the schedule relative to the original (funding limited) baseline



Blue Line is NOW

Critical Path is still the Far Detector building with full beneficial occupancy granted March 2011.
Trying to advance this to Dec 2011

274 Days of "float" for our last milestone "Observe NuMI beam events in last detector block"

Sensitivities and Opportunities

NOVA PHYSICS

Neutrino Mixing

- We know from the Z width that there are three active (weak coupling) neutrino species
- We have observed oscillations between these which implies a mixing through the near degenerate mass eigenstates
- In analogy to CKM mixing we setup a mixing structure

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \qquad \begin{pmatrix} u \\ c \\ t \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$U_{PMNS} \sim \begin{pmatrix} 0.8 & 0.5 & \text{small} \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \qquad \boldsymbol{V_{CKM}} \simeq \begin{pmatrix} 0.97 & 0.22 & 0.0036 \\ 0.22 & 0.97 & 0.041 \\ 0.0087 & 0.04 & 0.99 \end{pmatrix}$$

Very different structure

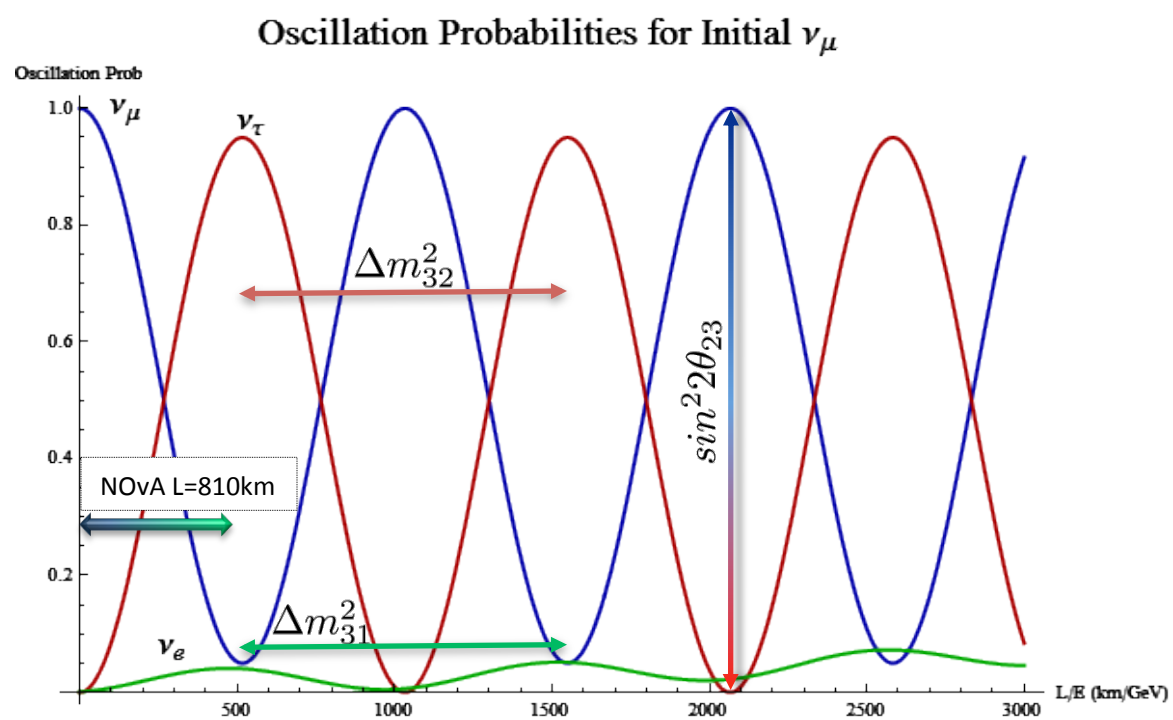
Near Unity

Neutrino Mixing

- Re-parameterize as a rotation in 3 angles and a phase

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- If we examine the oscillation probabilities it becomes clear how to read off PMNS parameters.



Neutrino Mixing

The NOvA Core measurements

- Re-parameterize as a rotation in 3 angles and a phase

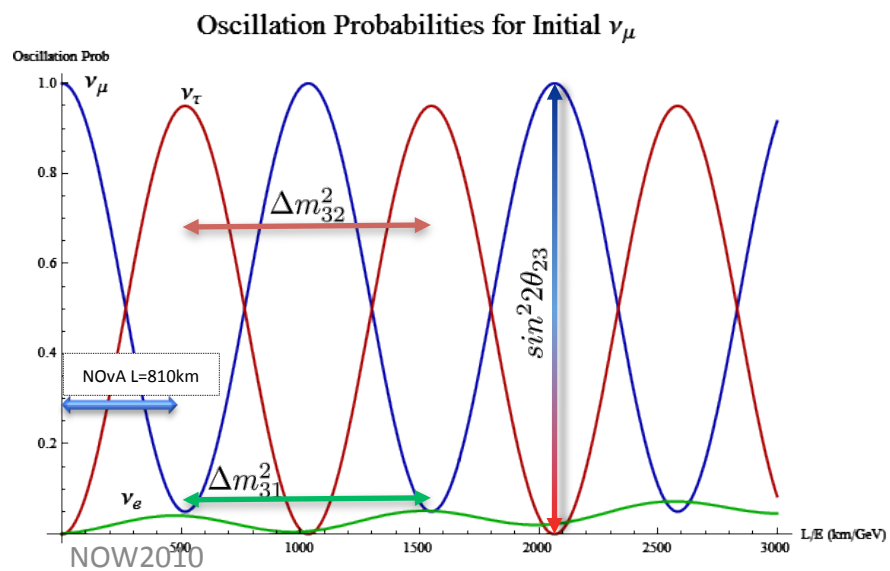
$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric/Accelerator ν_μ disappearance

Accelerator $\nu_\mu \rightarrow \nu_e$ appearance
Reactor $\bar{\nu}_e$ disappearance

Solar ν_e and $\bar{\nu}_e$ disappearance

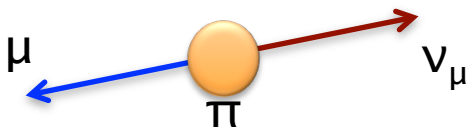
- If we examine the oscillation probabilities it becomes clear how to read off PMNS parameters.
- This leads to the classification of the mixing angles in terms of the characteristic L/E scale that is needed to view the oscillation



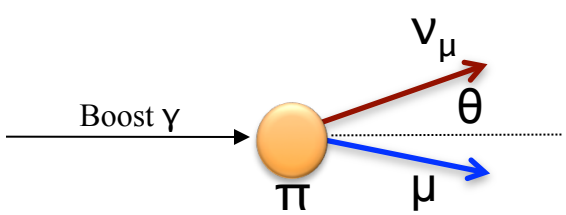
The Off-Axis Beam

The Off-Axis Effect

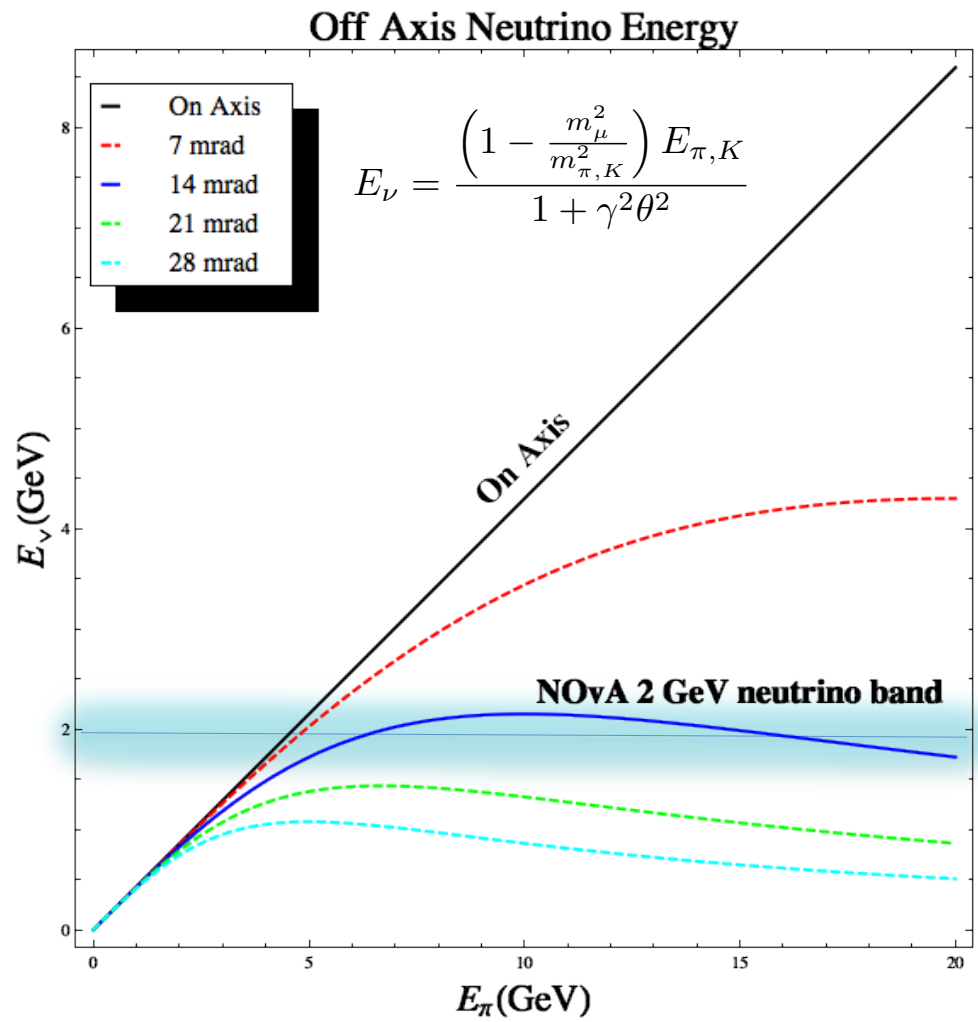
In the pion rest frame the kinematics are all completely determined for the decay



But when we boost into the lab frame the neutrino's energy depends on the angle relative to the boost direction.



This ends up projecting the neutrino energy spectrum down to be almost flat.



Off Axis Far Detector Neutrino Spectrum

- Moving off-axis, the flux is reduced as:

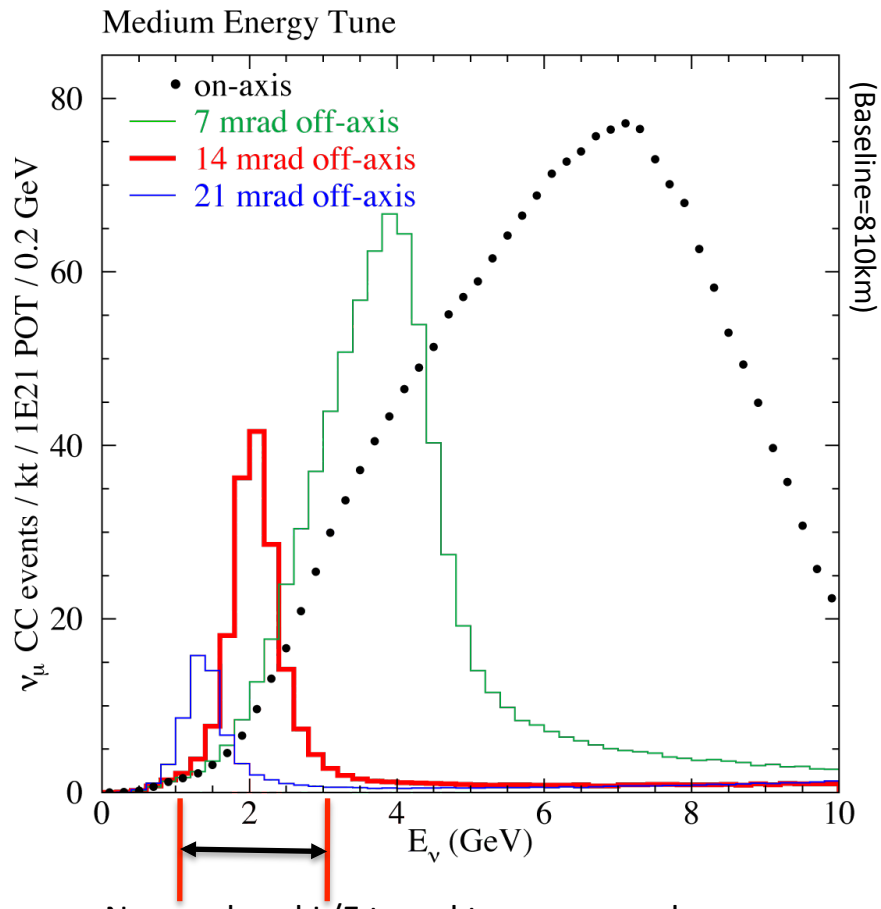
$$F = \left(\frac{2\gamma}{1+\gamma\theta^2}\right)^2 \frac{A}{4\pi z^2}$$

- But the resulting neutrino energy spectrum flattens out (tightens) as:

$$E_\nu = \frac{\left(1 - \frac{m_\mu^2}{m_{\pi,K}^2}\right) E_{\pi,K}}{1+\gamma^2\theta^2}$$

- For NOvA, moving 14 mrad off axis yields a narrows band beam
  - peaked at 2GeV
  - with E_ν width ≈20%
- The detector technology, geometry and baseline are then tuned to give:
  - L/E for 1st Oscillation Maximum
  - Energy resolution for ν_μ CC events ≈4%
  - High efficiency EM shower reconstruction in sub 2GeV region

Far Detector Flux × σ_ν



Narrow band L/E tuned to correspond to the first 1 Oscillation Maximum

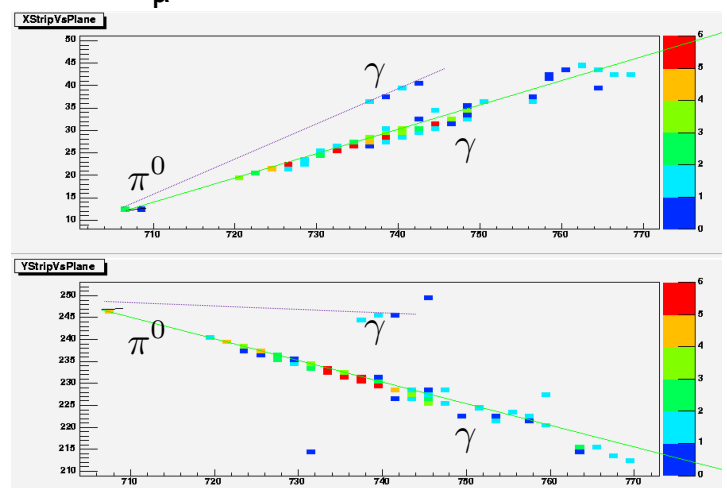
The Advantage of Going Off-Axis

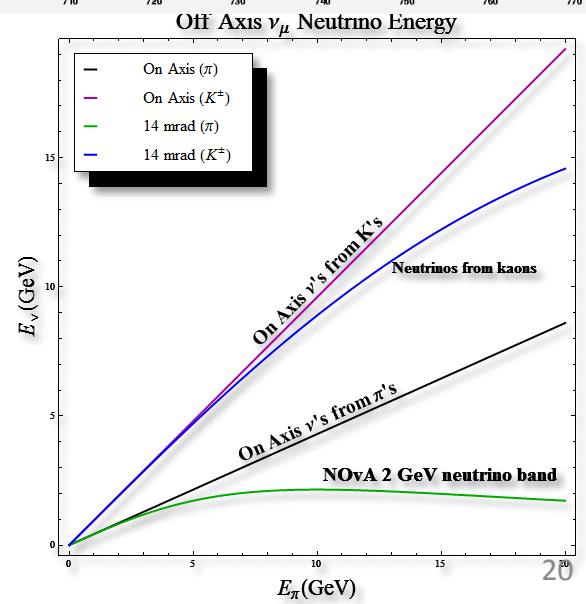
- To Make the ν_e appearance measurement you need to suppress backgrounds
  - Main background for the ν_e CC event topology is a ν_μ NC event with a π^0 that is not fully reconstructed
  - Off-axis projection (narrow energy band) suppresses the high energy NC tail
  - Other backgrounds are the intrinsic ν_e component of the beam (e.g. $K^\pm \to \pi^0 e^\pm \nu_e$) which are small (but so is θ_{13}) which get projected off the energy band.
- To improve the θ_{23} disappearance measurement:
  - Significantly reduces the backgrounds from kaons ($K^\pm \to \mu^\pm \nu_\mu$) by shifting the neutrino energy to a different band

$$(E_{\nu_\mu})_K = \frac{0.96 E_K}{1+\gamma^2\theta^2}$$

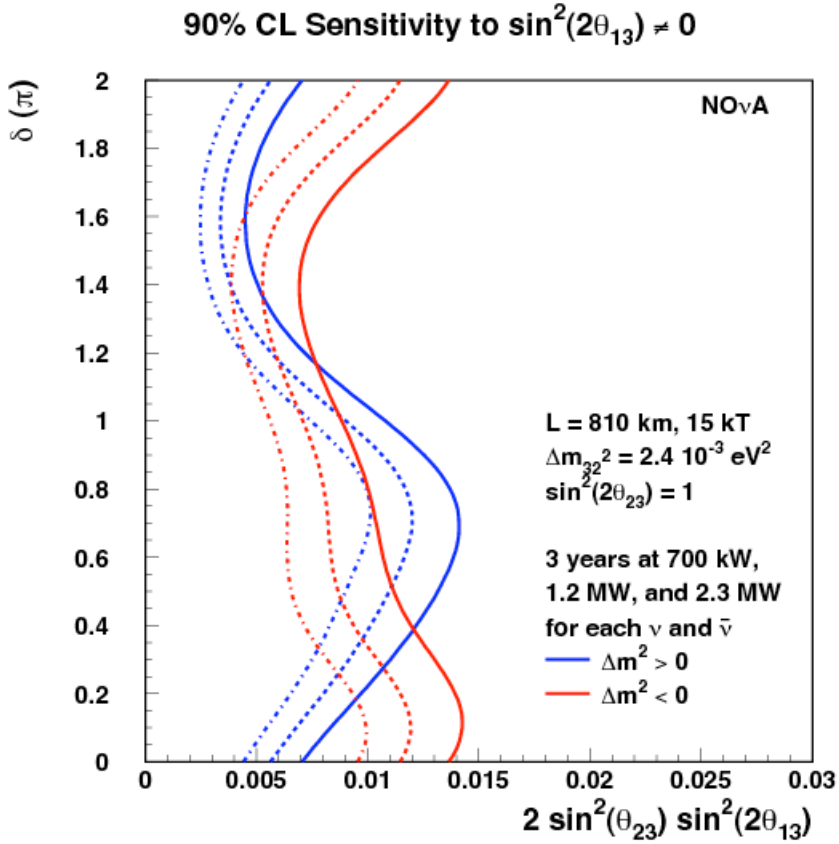
  - Resulting neutrino peak is primarily from π decays
  - Energy spectrum in the signal region becomes almost insensitive to the π/K ratio

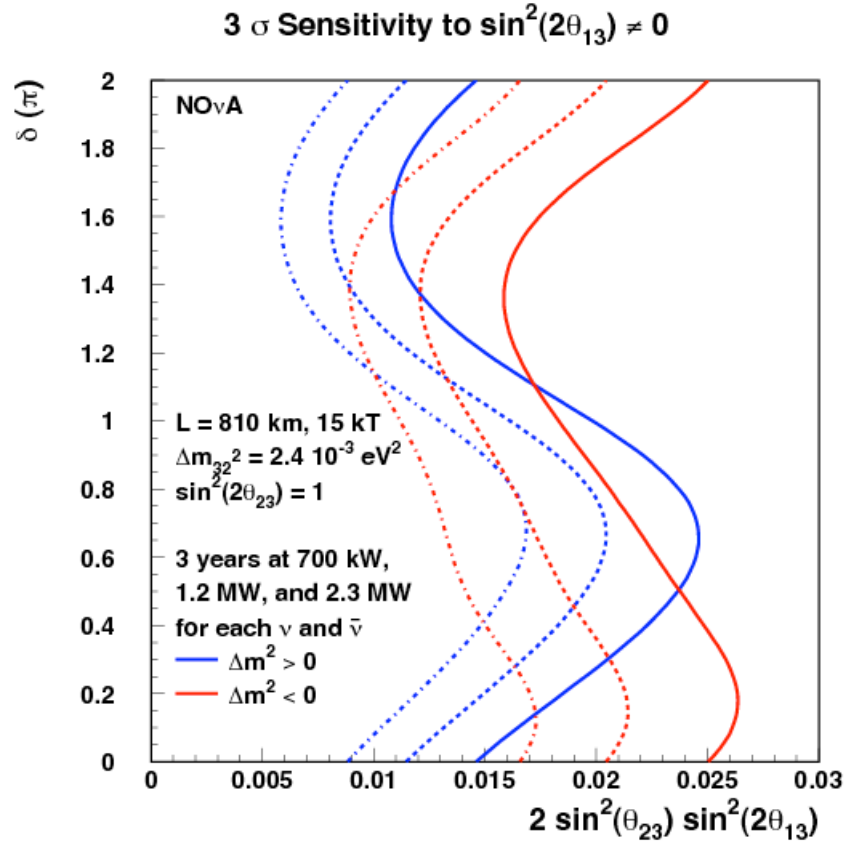
ν_μ NC + π^0 BKG Topology



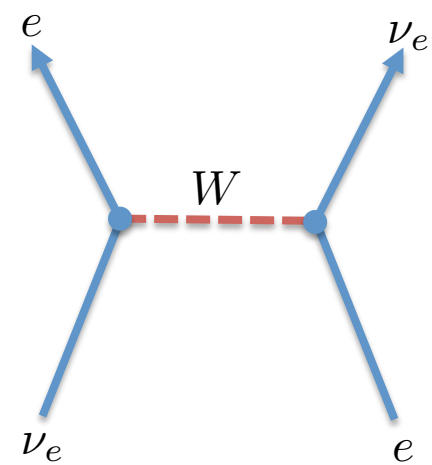


Sensitivity to θ_{13}





Matter Effect



- The forward scattering amplitudes for neutrinos and anti-neutrinos through normal matter differ due to the inclusion of the extra diagram for interactions off electrons
- This difference breaks the degeneracy in the neutrino mass spectrum and modify the oscillation probability

$$P_{mat}\left(\nu_\mu \to \nu_e\right) \neq P_{mat}\left(\bar{\nu}_\mu \to \bar{\nu}_e\right)$$

- If the experiment is performed at the first peak in the oscillation then the matter effects are primarily a function of the beam energy and approximated by:

$$P_{mat}\left(\nu_\mu \to \nu_e\right) \approx \left(1 + E/E_R\right) P_{vac}\left(\nu_\mu \to \nu_e\right)$$

$$E_R = \frac{\Delta m_{23}^2}{2\sqrt{2} G_F N_e} \approx 11 GeV$$

- In the normal hierarchy this matter effect enhances the transition probability for neutrinos and suppresses the probability for antineutrinos transitions
- With an inverted hierarchy the effect is reversed
- For the 2 GeV neutrino beam used for NOvA, the matter effect gives a 30% enhancement/suppression in the transition probability.

Matter Effect

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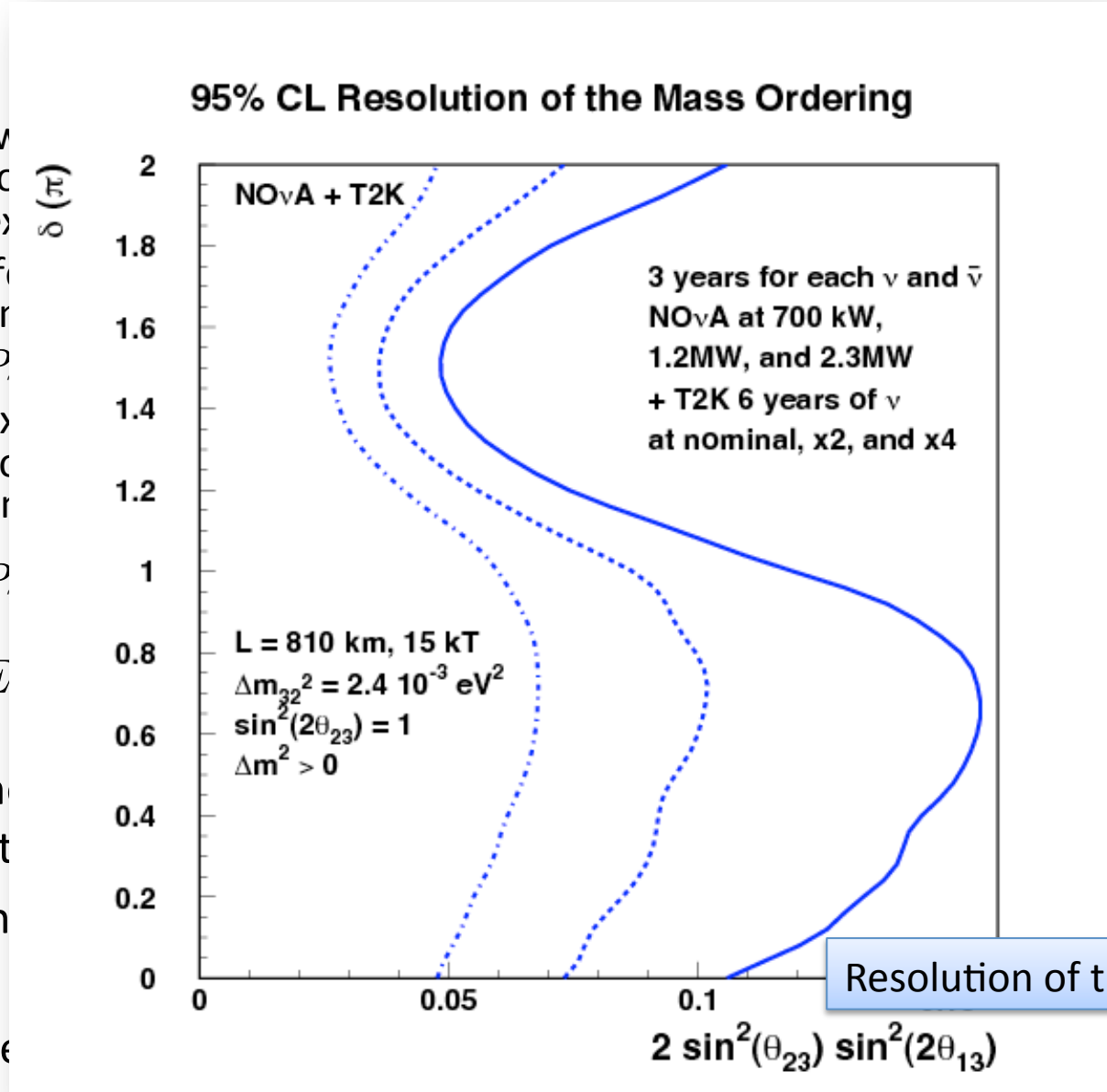
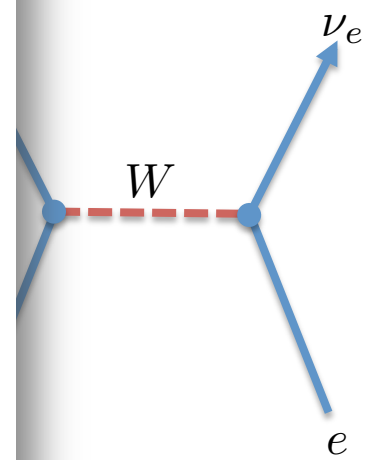




on probability
ransitions

Resolution of the hierarchy

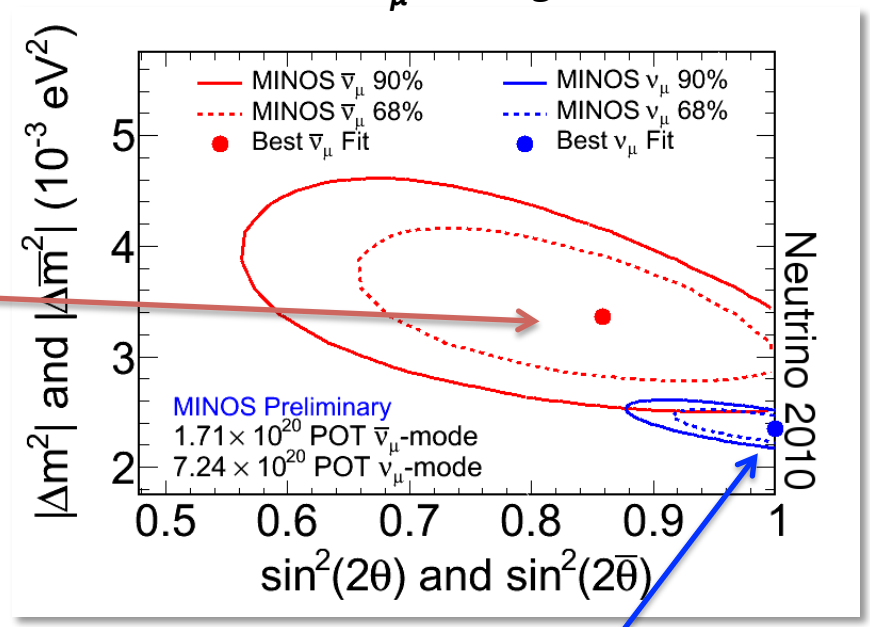
Anti-ν_μ Oscillation Parameters

- MINOS has reported new mixing values for anti-ν_μ which deviate from the ν_μ channel by ≈ 2σ

$$\sin^2(2\overline{\theta_{23}}) = 0.86$$
$$\Delta\overline{m^2_{23}} = 3.36 \times 10^{-3} eV^2$$

- If this discrepancy persists into the NOvA Era, can NOvA can address the effect?

MINOS ν_μ Mixing Results



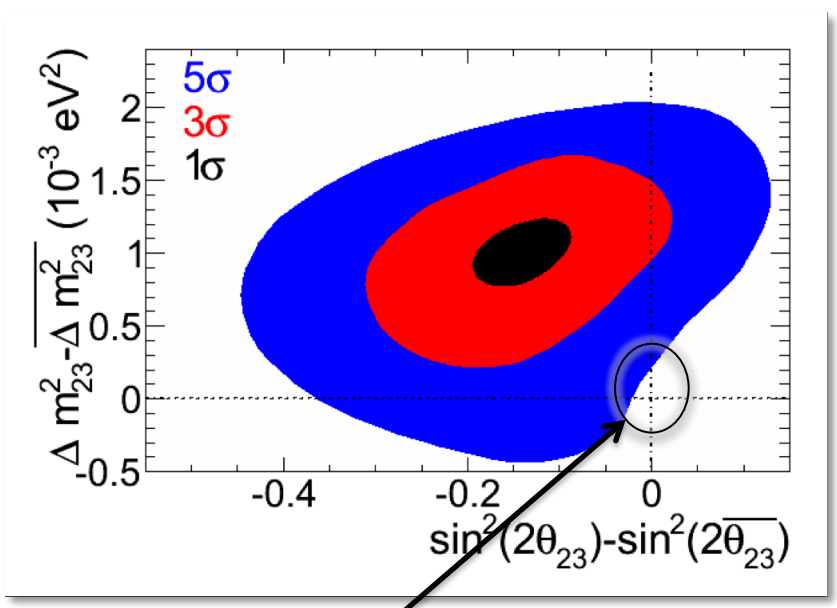
P.Valhe, Neutrino 2010

$$\sin^2(2\theta_{23}) = 1$$
$$\Delta m^2_{23} = 2.35 \times 10^{-3} eV^2$$

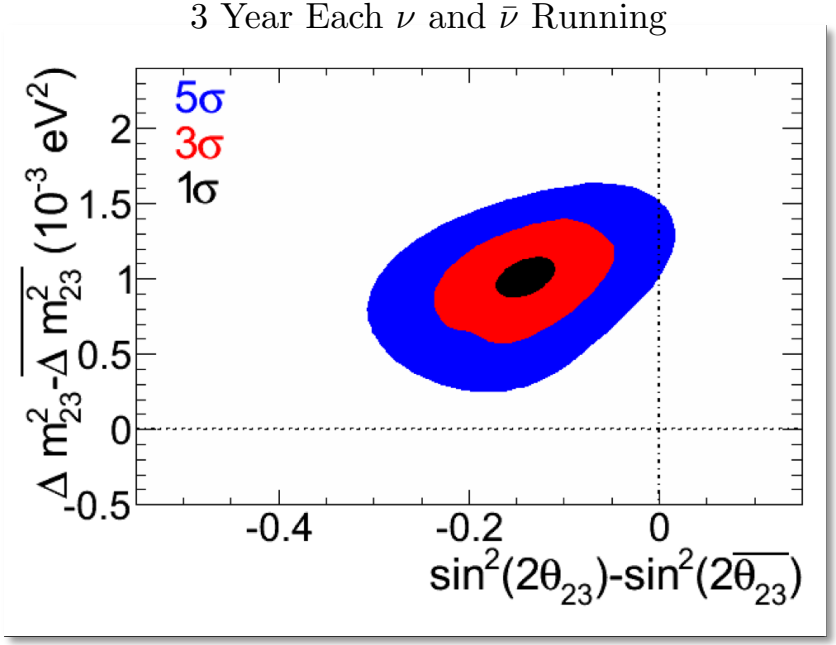
NOvA Sensitivity to CPT Violation

Projected NOvA Sensitivites
Assuming MINOS best fit values for $\bar{\nu}_\mu$ mixing

1 Year Each ν and $\bar{\nu}$ Running



3 Year Each ν and $\bar{\nu}$ Running



With current projected resolution and reconstructions, NOvA is sensitive at 5σ to a non-zero mixing asymmetry

The full NOvA run would easily be able to confirm or rebut this type of signature.

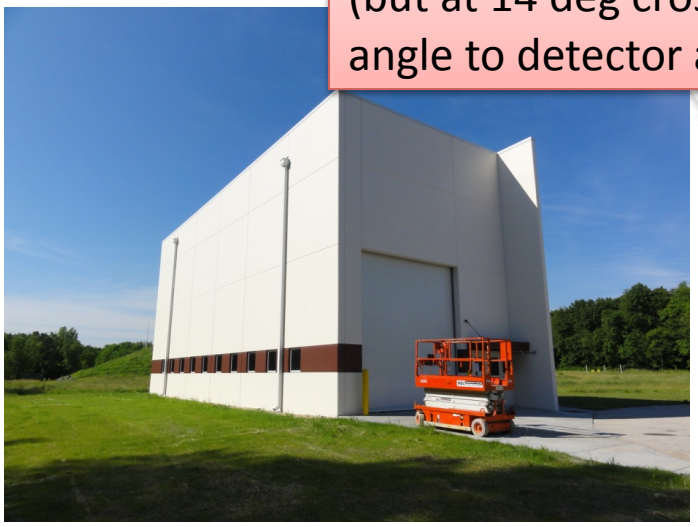
NOvA Near Detector Surface Site & Building

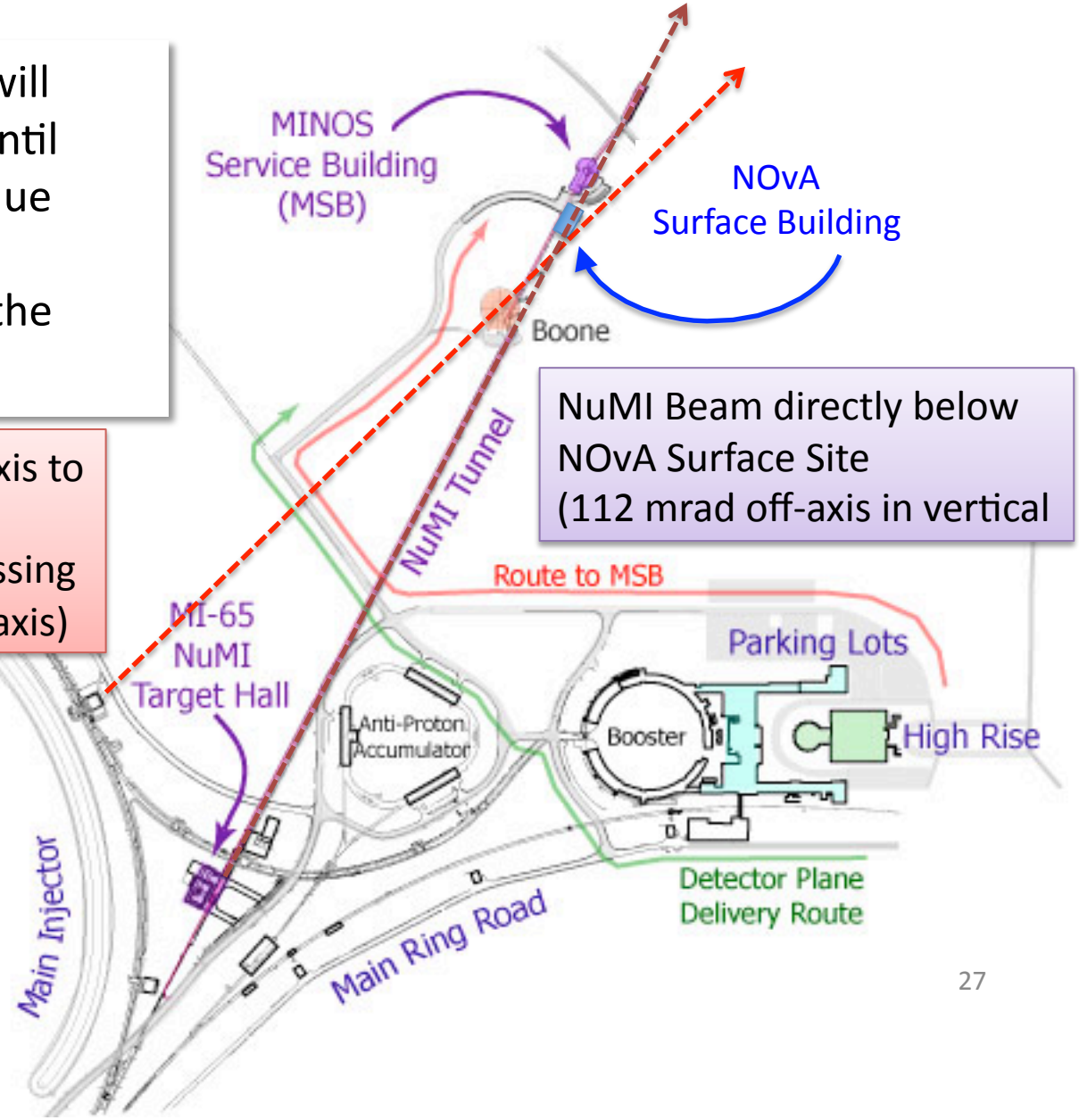
A NEUTRINO “TEST BEAM” AT FNAL

Surface Building Site

- The surface building that will house the near detector until 2012 was chosen at a unique location where it can see significant flux from both the NuMI and BOOnE beams

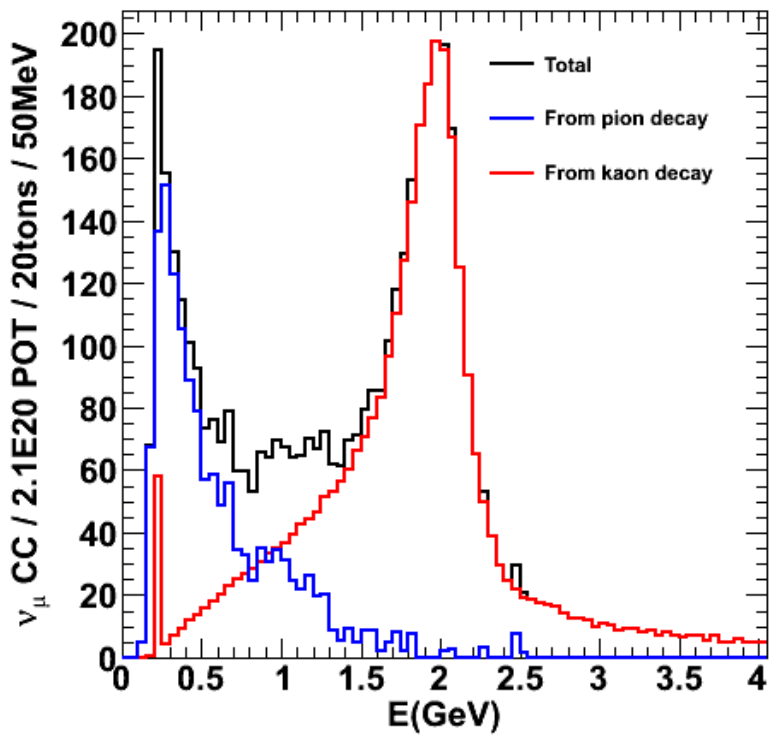
BooNE Beam on axis to NOvA Surface Site (but at 14 deg crossing angle to detector axis)





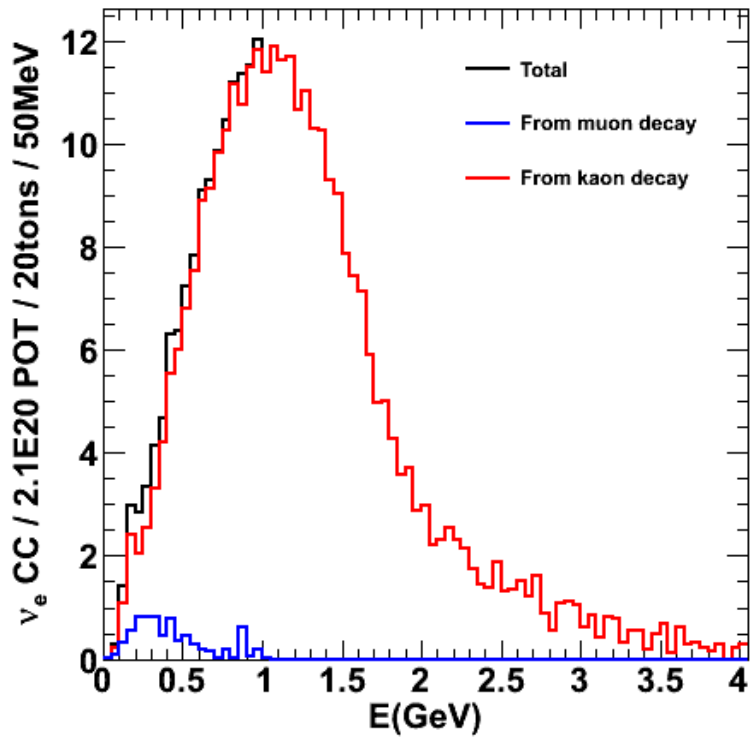
Surface Site ν_μ Flux × σ_ν

- At the surface site, the NuMI beam in neutrino mode, is projected in such a way that the principle flux comes from kaon decay ($K^+ \rightarrow \mu^+ \nu_\mu$) where the neutrino energy is projected down into a sharp peak at 2GeV
- A secondary flux from π decay is projected down into a peak < 300 MeV



Surface Site ν_e Flux × σ_ν

- At the same time there is a roughly 6% ν_e flux from kaon decay ($K^+ \rightarrow \pi^0 e^+ \nu_e$) that is projected into a broader distribution around 1GeV
- This ν_e flux will allow us to study the detector response in detail prior to operation of the far detector
- This intrinsic ν_e beam content mimics 5% appearance signal, similar to what a large θ_{13} would yield
  - "Dry run" for real analysis



Near Detector on the Surface (NDoS) Physics for 2010/2011

- Operations start Sept/Oct 2010, run till 2012 shutdown
  - Begin operations in Forward Horn Current (neutrino) mode, then switch to Reverse Horn Current (anti-neutrino), then switch back to Forward Horn Current
  - Expect 1.7E20 PoT in RHC, 2.1E20 PoT in FHC
- Operate as a Neutrino Testbeam
  - Measure detector response functions for ν_μ and ν_e CC interaction
  - Measure the Kaon content and ν_e contamination of the NuMI beam
- Physics Opportunities
  - Measure ν_μ Quasi-elastic σ
  - Measure ν CC/NC single π production σ

Improves MINOS/Minerva systematics

Projected Events Rates for Forward Horn Current Running (2.1E20 PoT)

Type	Total CC	CC-QE	CC-RES	CC-DIS	CC-COH	NC
ν_μ+ anti-ν_μ	5375	2511	1712	964	52	2264
1.6-2.4GeV	2063	609	897	535	20	841
ν_e+ anti-ν_e	377	185	131	55		144
1.6-2.4GeV	57	17	25	39		20

Further Down the Road

The past year has been exciting...

We have transformed a remote field in Minnesota the home of the next generation of neutrino detectors

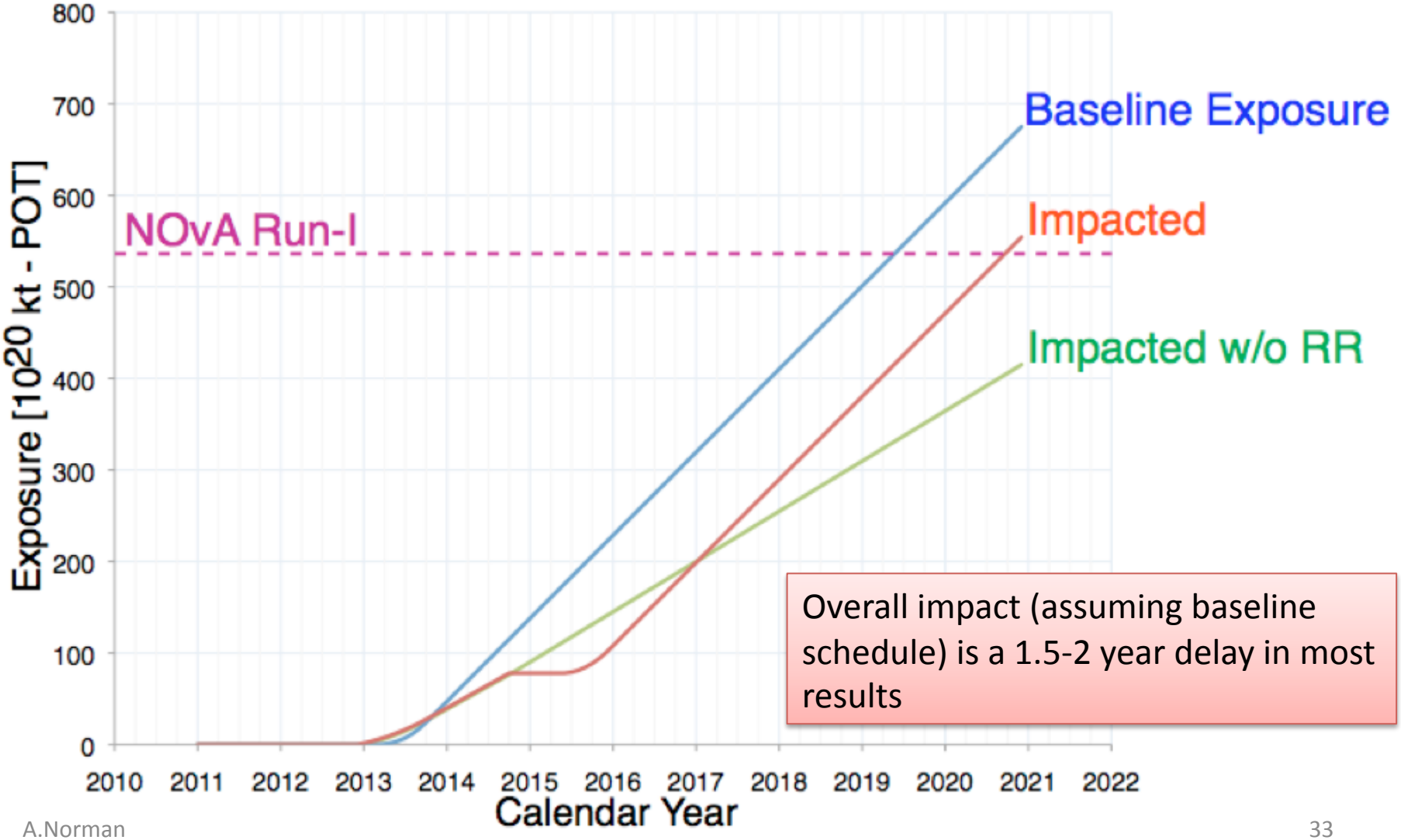
We have built our near detector, built a home for it, and placed it in a unique position that will allow us an early start a robust physics program

We have built the road to the NOvA and the Intensity Frontier program at Fermilab

NOvA 2010

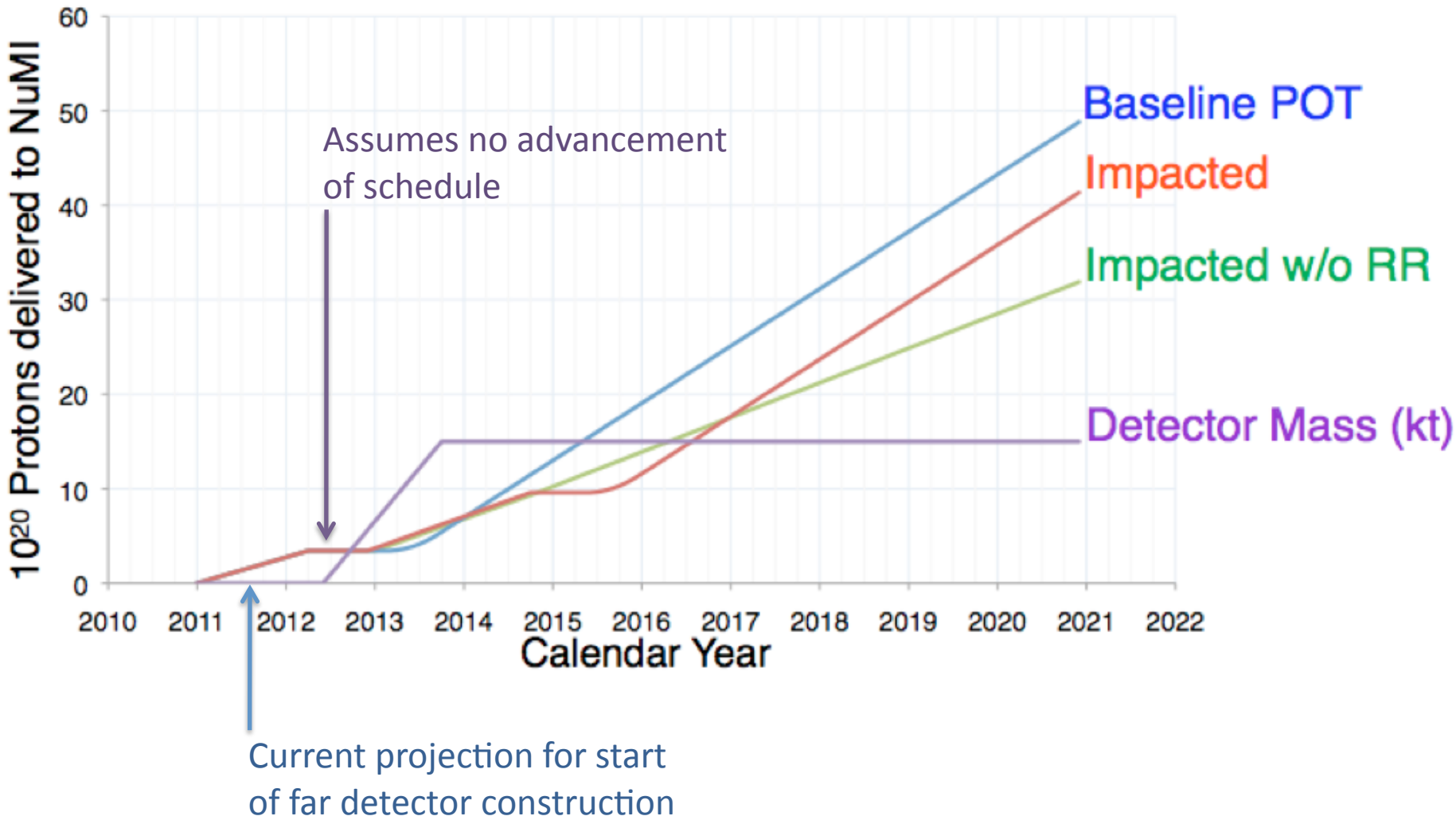
ADDITIONAL MATERIAL

Tevatron Run II Extension Impact on NOvA

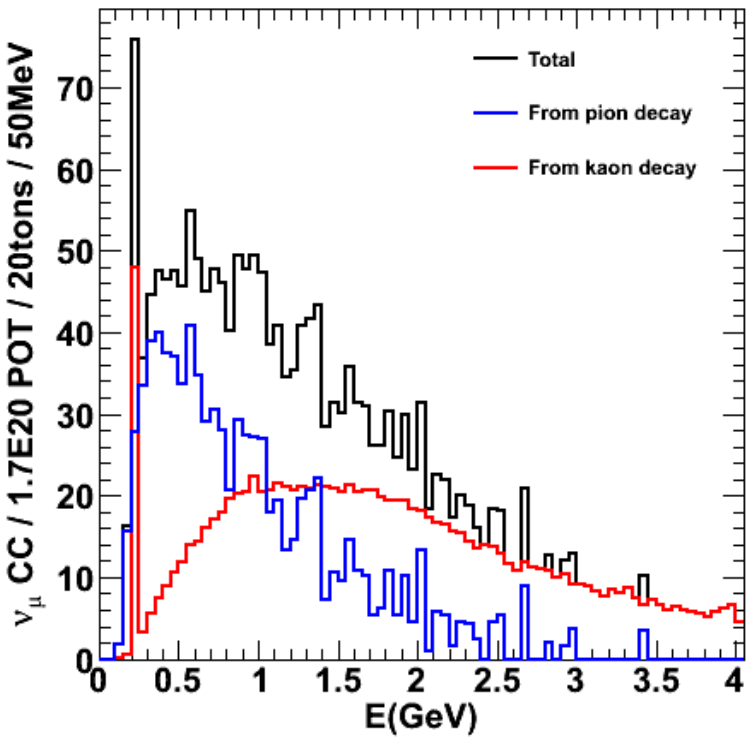


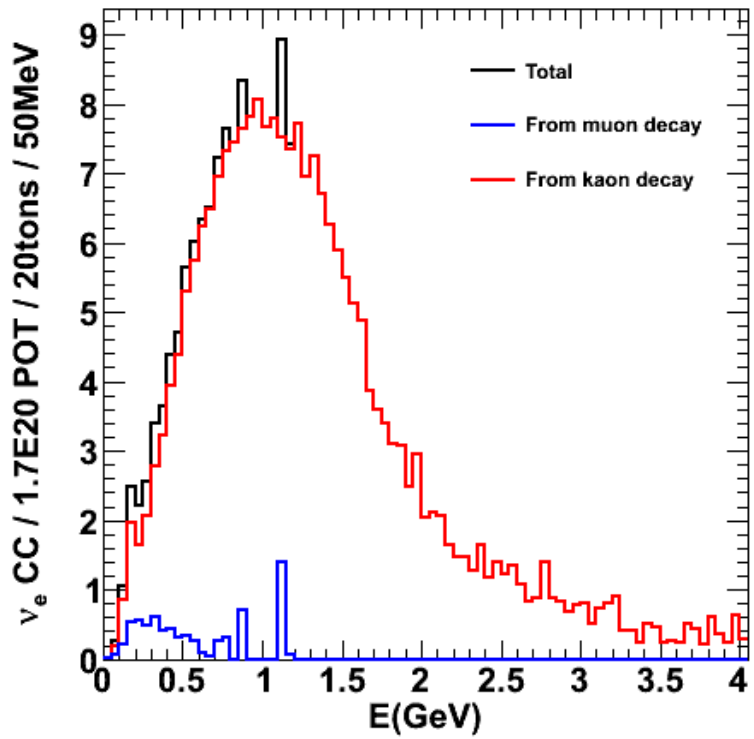
Overall impact (assuming baseline schedule) is a 1.5-2 year delay in most results

Tevatron Run II Extension Impact on NOvA



Reverse Horn Current Flux × σ





Projected Event Rates Reverse Horn Current (1.7E20 PoT)

Type	Total CC	CC-QE	CC-RES	CC-DIS	CC-COH	NC
ν_μ	2157	1019	638	409	17	855
1.6-2.4GeV	402	116	174	108		146
ν_e	248	120	86	39		92
1.6-2.4GeV	42	12	18	11		15
anti-ν_μ	873	471	262	119	19	507
1.6-2.4GeV	363	139	151	65		170
anti-ν_e	42	22	14	5		22

Projected Event Rates Forward Horn Current (2.1E20 PoT)

Type	Total CC	CC-QE	CC-RES	CC-DIS	CC-COH	NC
ν_μ	4751	2288	1533	861	38	1911
1.6-2.4GeV	1931	559	842	511	20	699
ν_e	340	166	119	50		125
1.6-2.4GeV	57	17	25	39		20
anti-ν_μ	624	323	179	103	14	353
1.6-2.4GeV	132	50	55	24		142
anti-ν_e	37	19	12	5		19