Experiment Optimization

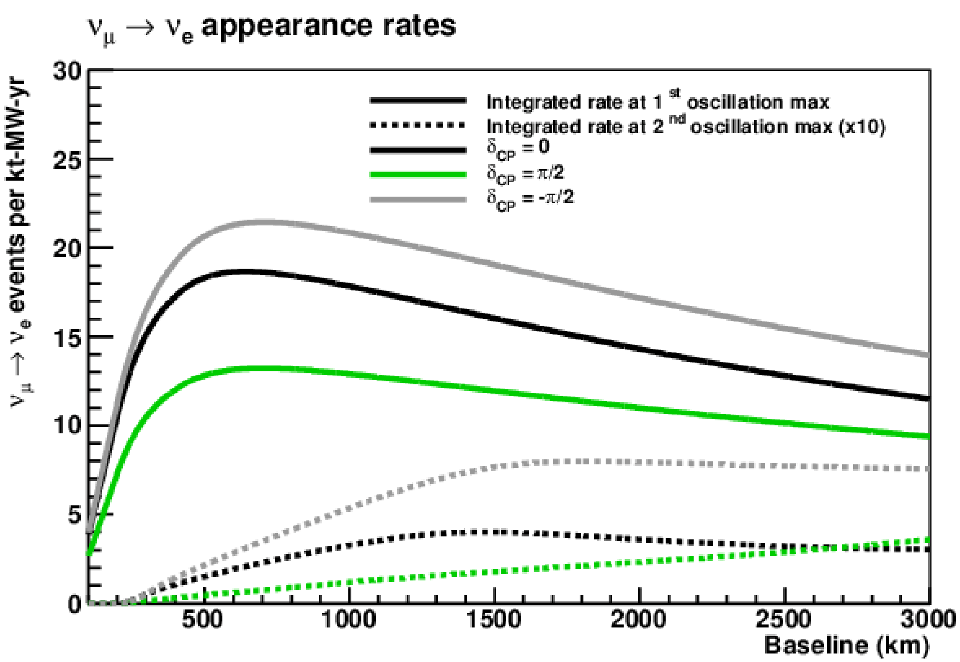
Lisa Whitehead, University of Houston
Mary Bishai, BNL

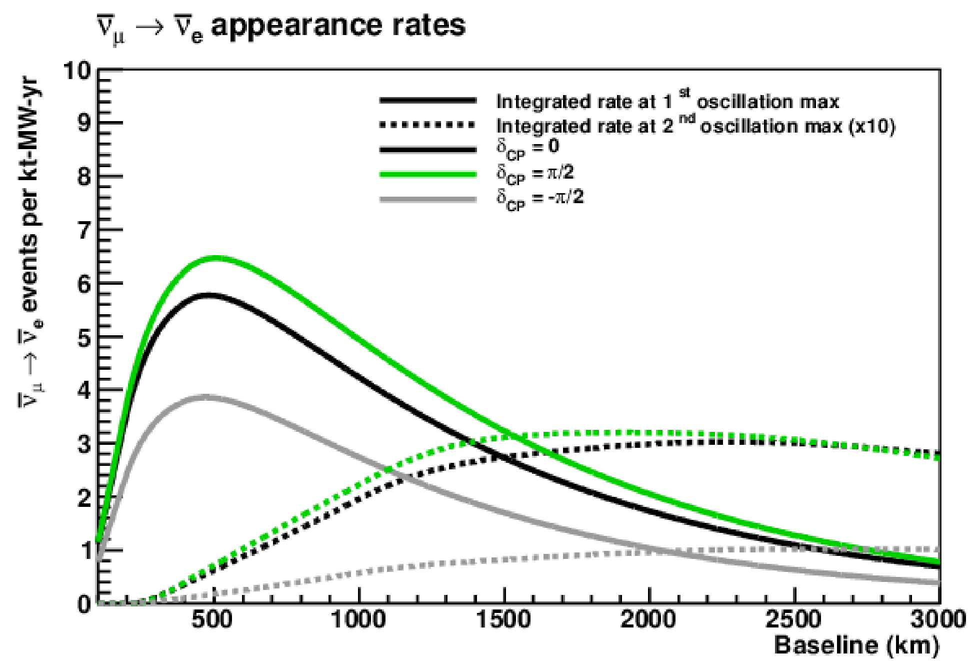
January 22, 2015

Outline

- Brief summary of some experimental design studies carried out by the LBNE long-baseline working group (M. Bass, M. Bishai, D. Cherdack, L. Fields, X. Qian, L. Whitehead, E. Worcester)
- Baseline, 1st vs 2nd oscillation max, proton beam energy, neutrino/antineutrino running
- See LBNE DocDB-9976 for a more complete summary
- A paper describing the baseline study has been submitted to PRD. See arXiv:1311.0212.

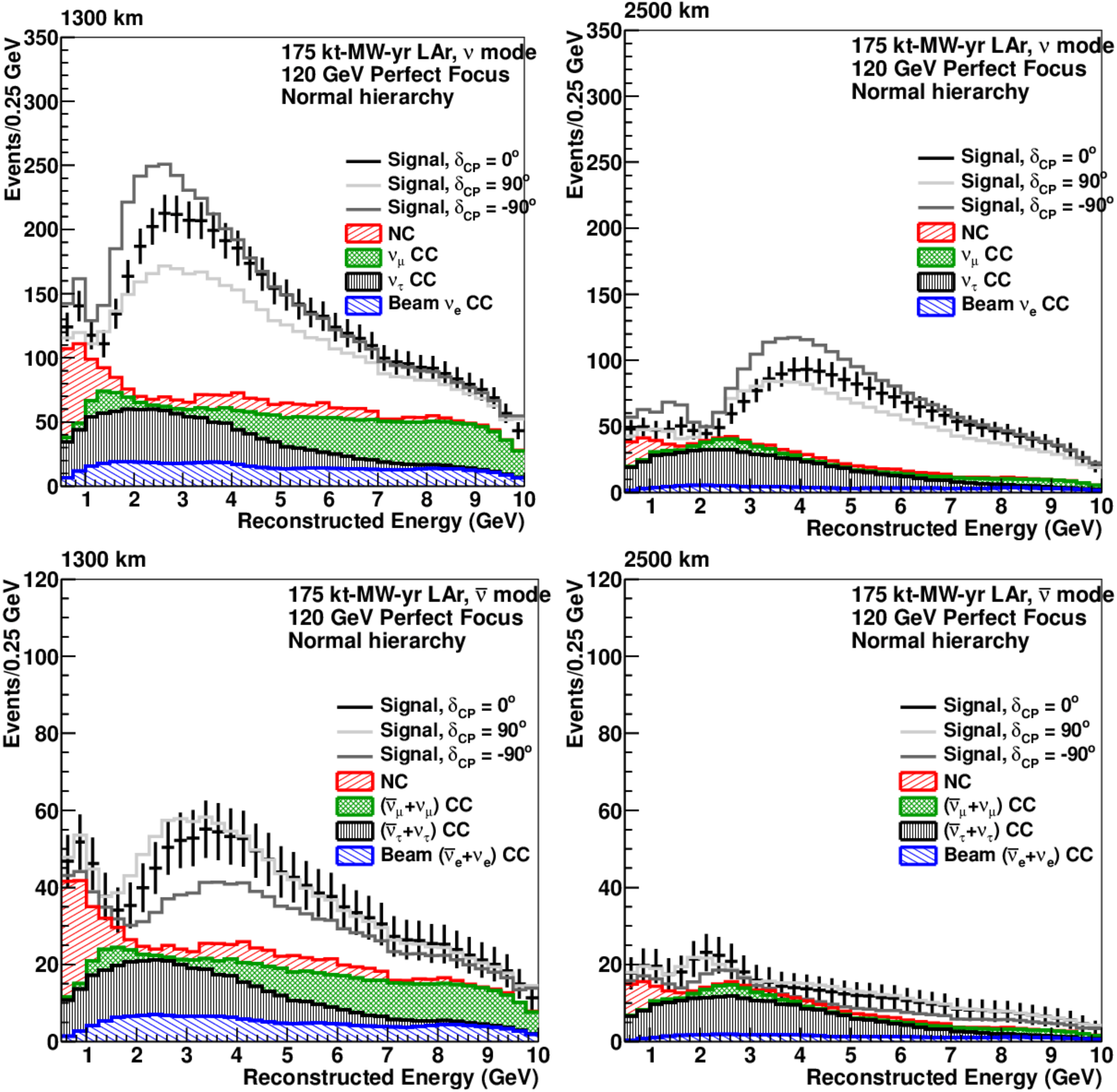
Expected Event Rate vs Baseline
1^{st} vs 2^{nd} Maximum





- Using full probability and cross-section
- Integrated rate over 1^{st} or 2^{nd} maximum
- No detector effects
- Perfect focusing, 120 GeV

LBNE DocDB-7607
arXiv:1311.0212



Neutrino Mode Appearance Spectra (NH)

Perfect Focus 120 GeV (w/ detector effects)

Antineutrino Mode Appearance Spectra (NH)

LBNE DocDB-9792, 9794

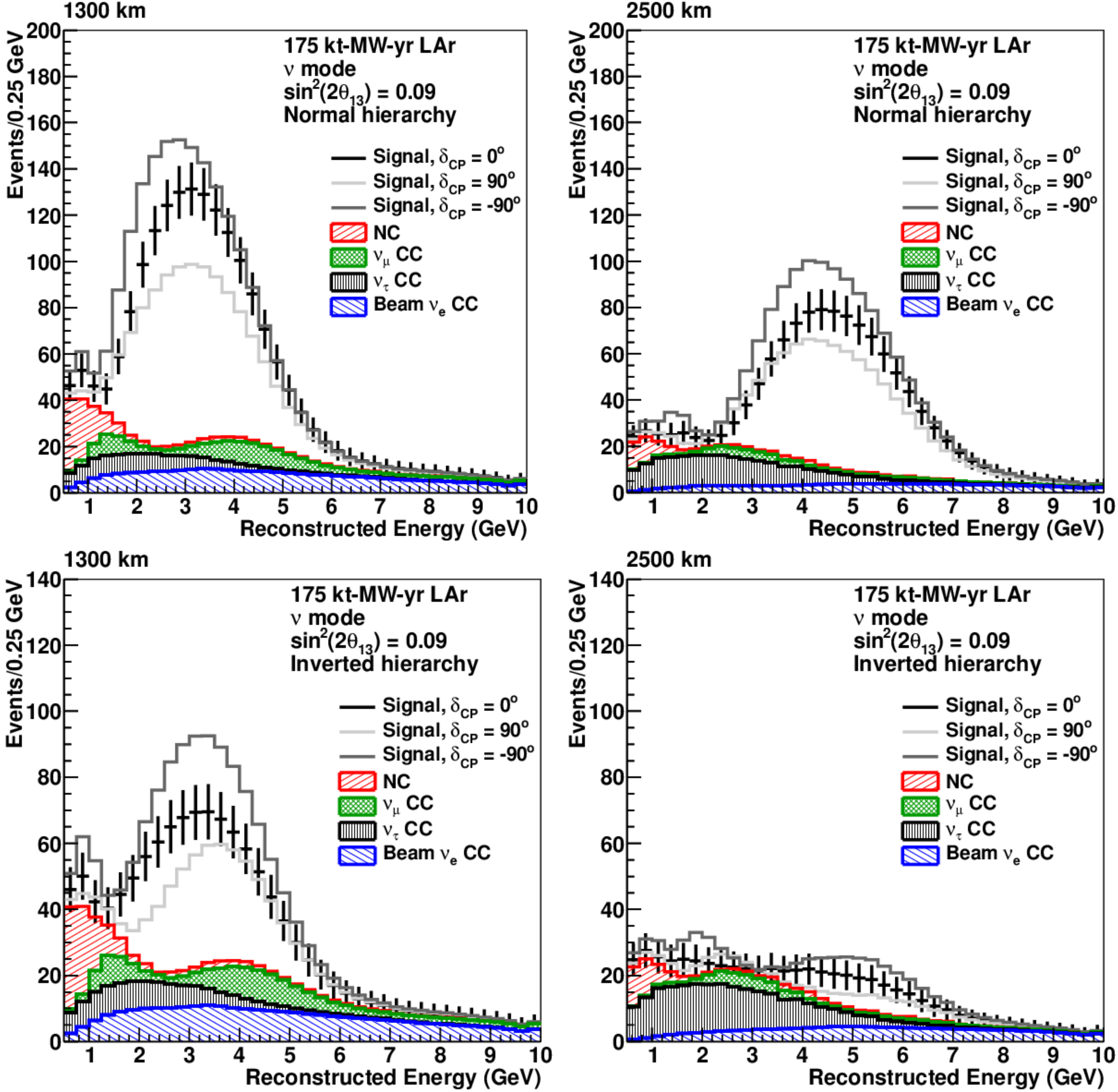
Beam simulation for each baseline

- The flux for each baseline was optimized to get a fair comparison of sensitivity
- Made realistic assumptions for a conventional neutrino beam from Fermilab
- Decay pipe length, off-axis angle, and target-horn1 distance were tuned for each baseline
  - Beamline parameters were chosen so that the neutrino flux covers the entire region of the first oscillation maximum and as much of the second as possible
  - For different configurations that cover the oscillation energy region appropriately, the configuration was chosen based on CP sensitivity
- Common parameters
  - 1.2-MW 120-GeV primary proton beam (1×10^{21} protons-on-target per year)
  - Graphite target with 1.2 cm in diameter and length equivalent to two interaction lengths
  - NuMI focusing horn design with 250 kA current
  - Horn 1 – Horn 2 separation distance of 6 m
  - Decay pipe diameter of 4 m, evacuated

Beam simulation for each baseline: tuned parameters

Baseline (km)	Decay Pipe Length (m) (4 m diameter)	Target-Horn 1 Distance (cm)	Off-axis Angle
300	280	30	2.0°
500	280	30	1.5°
750	280	30	1.0°
1000	280	0	0°
1300	380	30	0°
1700	480	30	0°
2000	580	70	0°
2500	680	70	0°
3000	780	100	0°

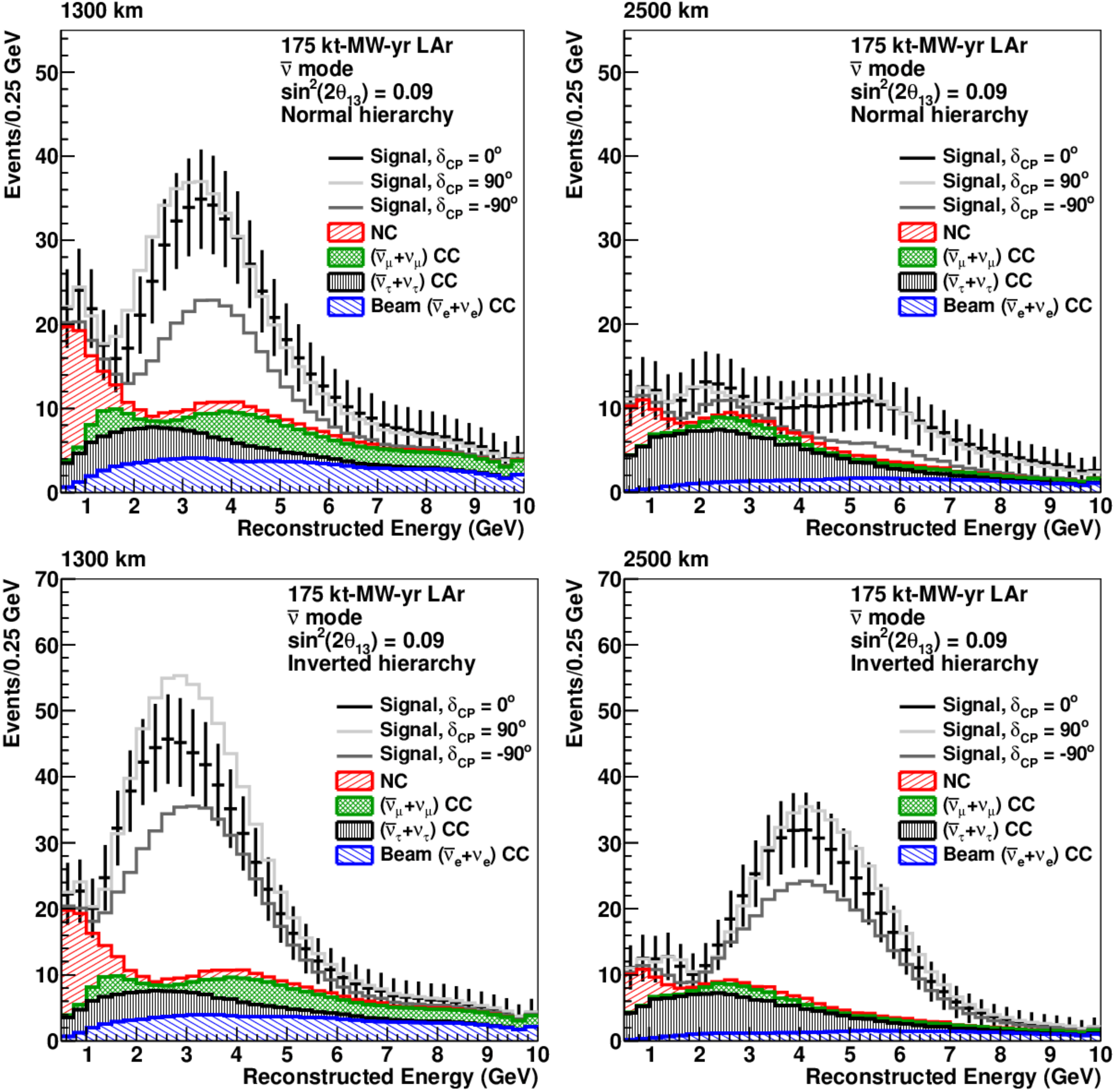
Decay pipe length was changed in 100m increments to match the decay length of a pion whose energy corresponds to the neutrino energy of the 1st oscillation max at each baseline



LBNE DocDB-7607
arXiv:1311.0212

Neutrino Mode Appearance Spectra

NH (top)
IH (bottom)



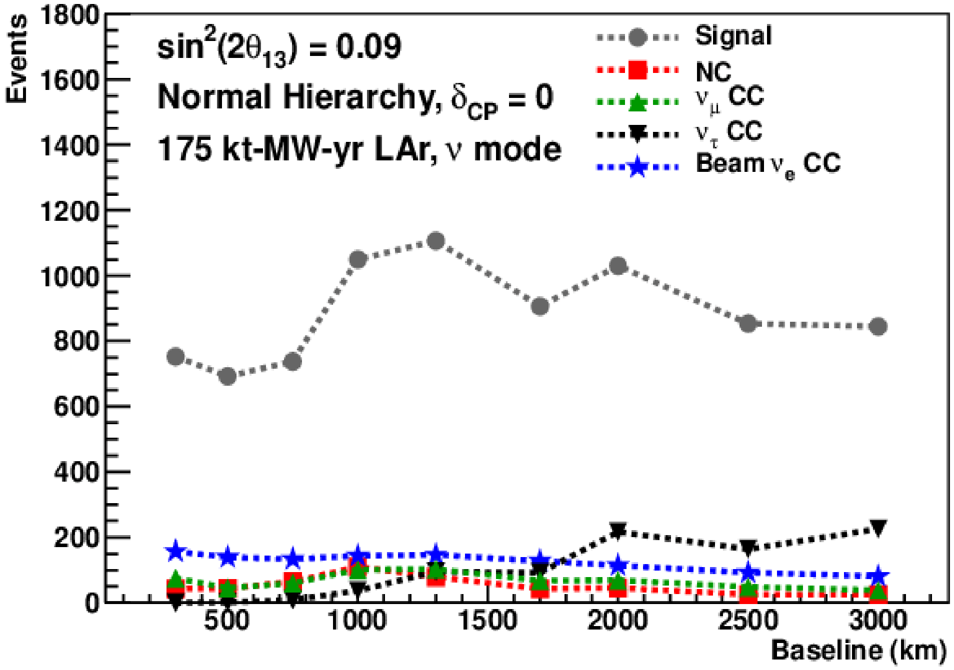
LBNE DocDB-7607
arXiv:1311.0212

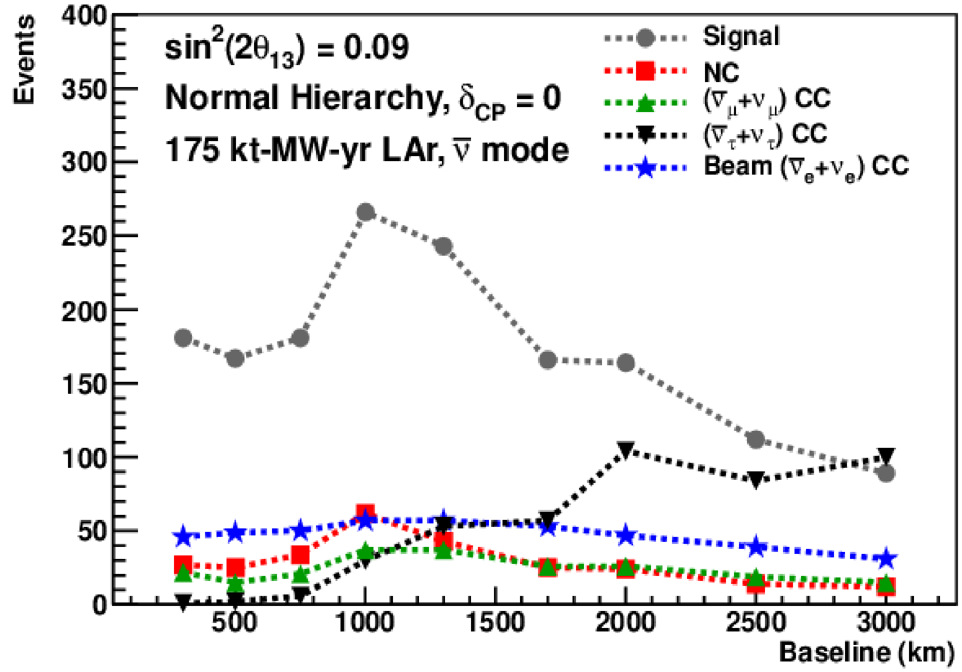
Antineutrino Mode Appearance Spectra

NH (top)
IH (bottom)

Integrated rate in oscillation energy range

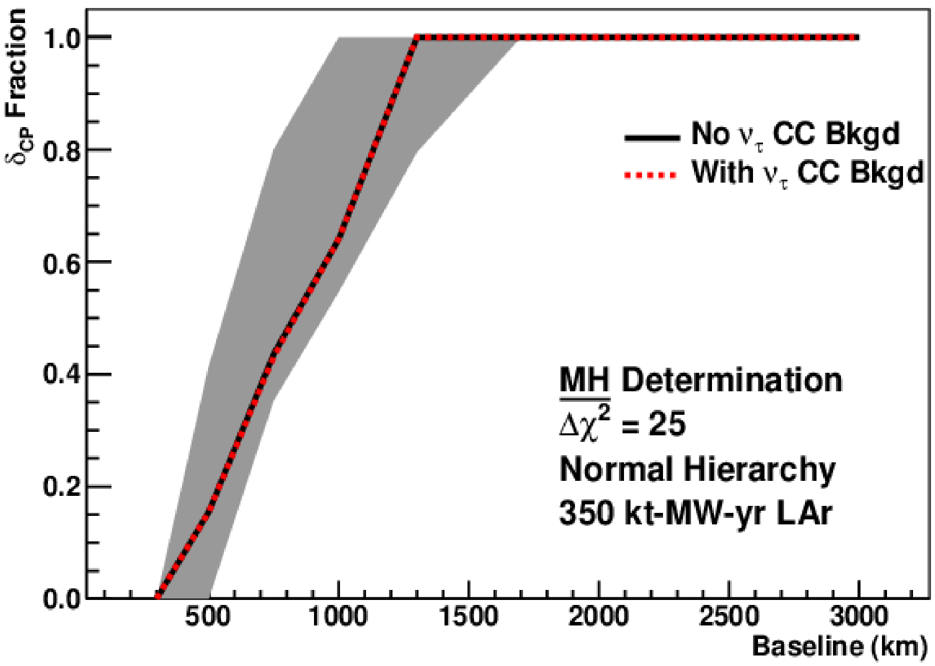
LBNE DocDB-7607
arXiv:1311.0212

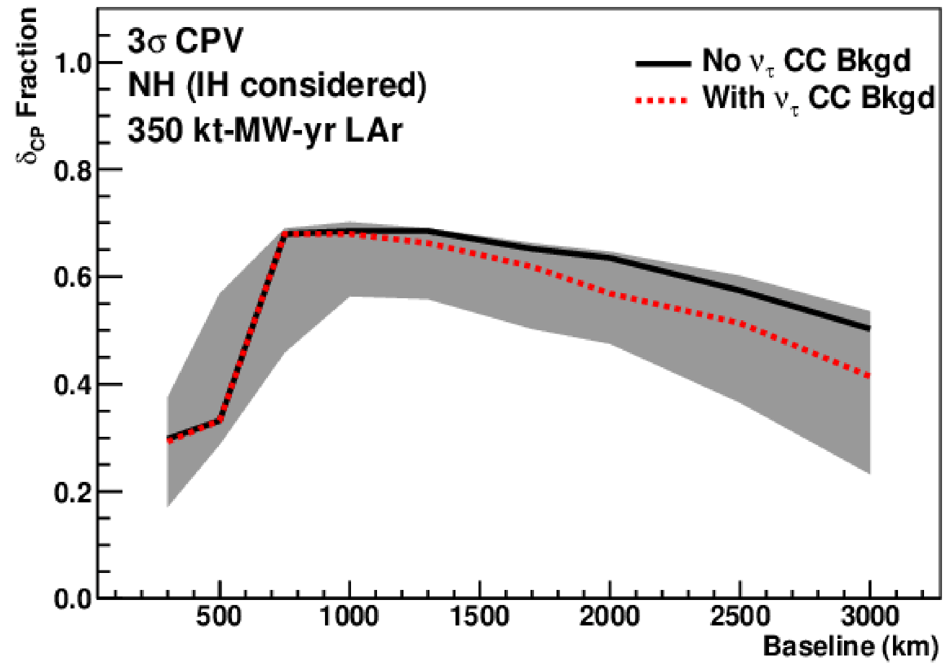


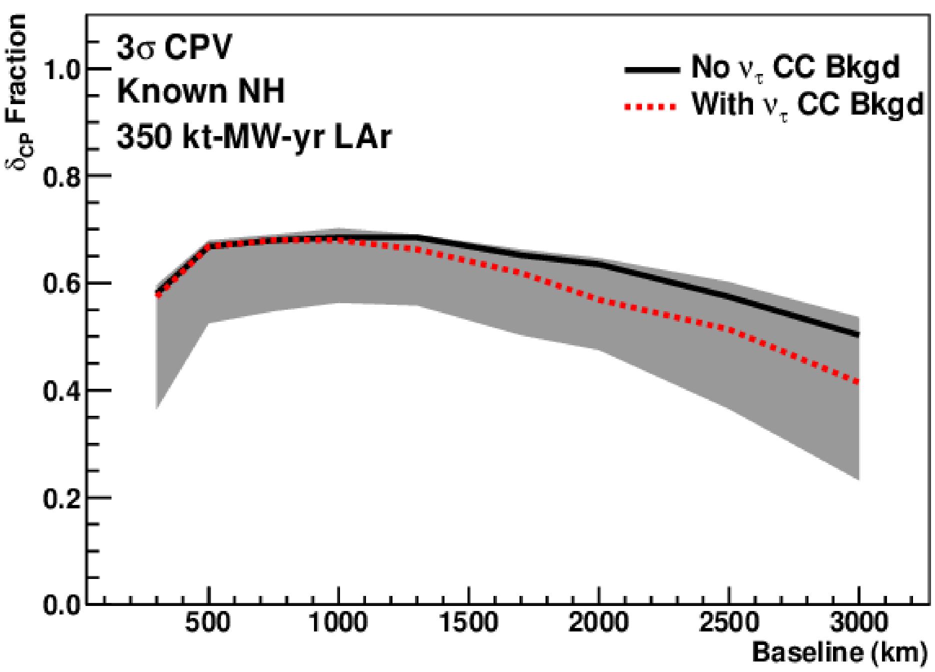


- Using beam simulation and including detector effects
- Roughly constant vs baseline for neutrinos and antineutrinos decrease, as expected from naïve calculation
- ν_τ's increase due to increasing beam energy with baseline
- Other backgrounds roughly constant

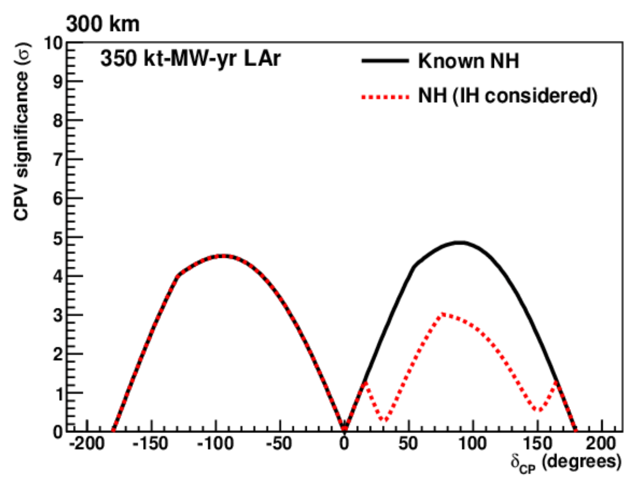
Sensitivity vs Baseline (NH)





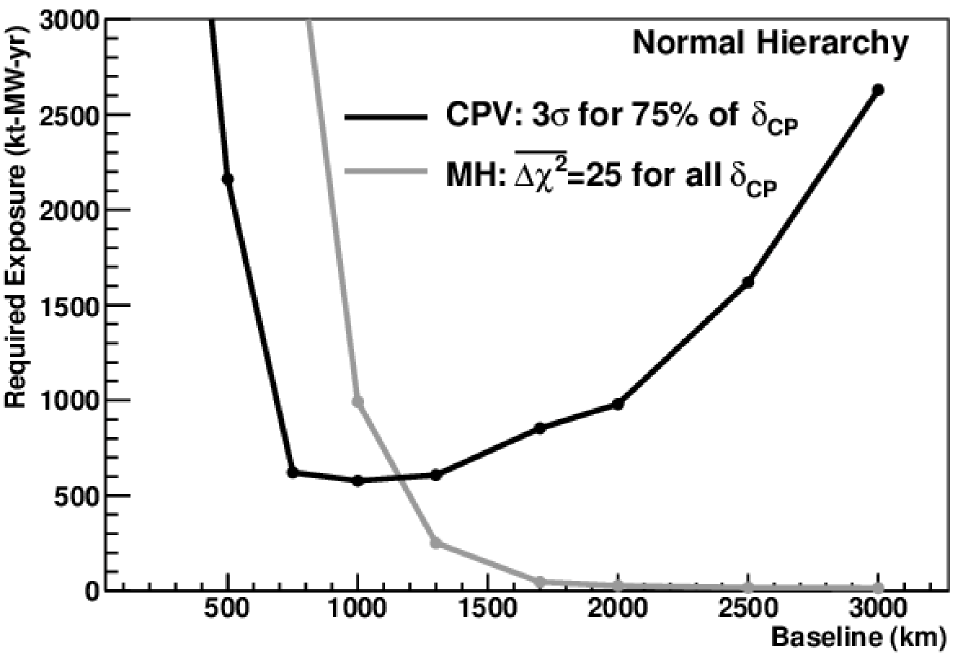


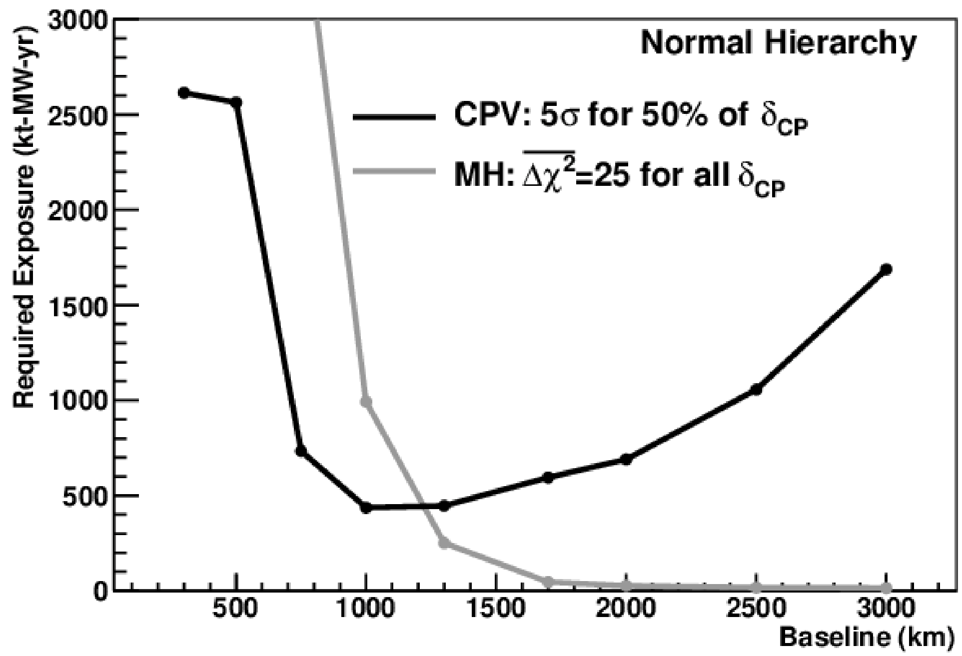
Gray band represents possible variation due to oscillation parameter uncertainty, dominated by the uncertainty in θ_{23}, and considers both octant solutions.



See reference docs for corresponding IH plots.

Sensitivity vs Exposure (NH)



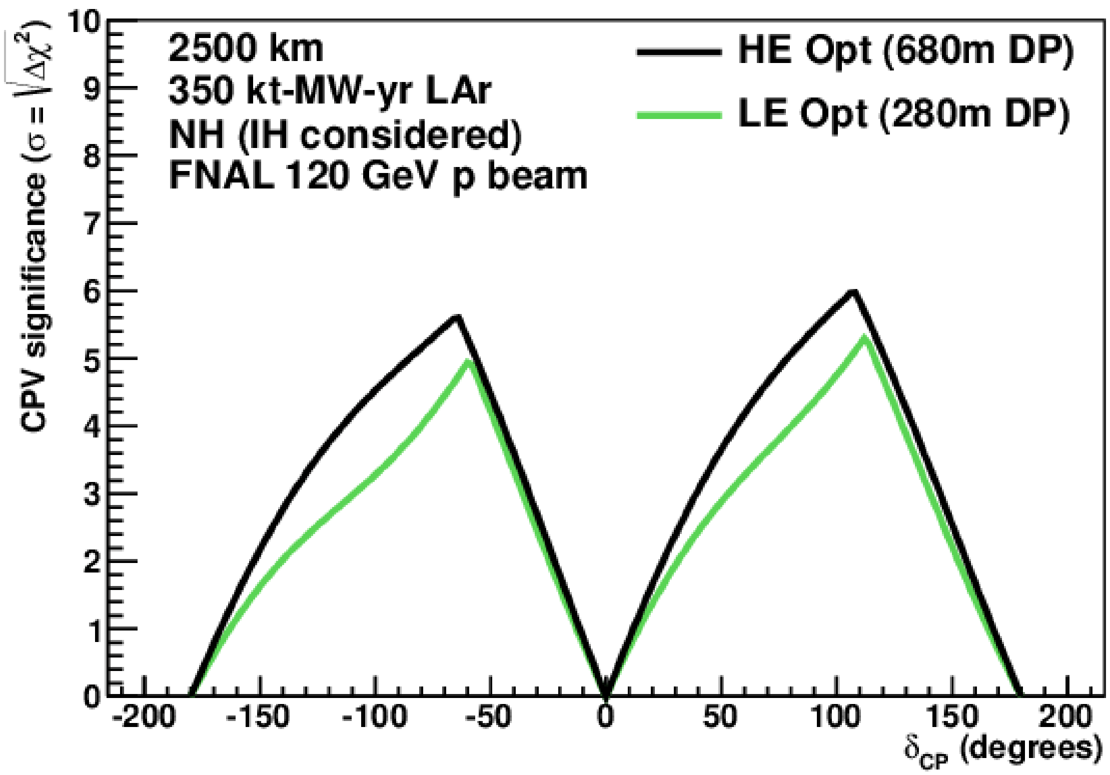


See reference docs for corresponding IH plots.

LBNE DocDB-9594

Optimize for 2nd max at 120 GeV?

LBNE DocDB-9537



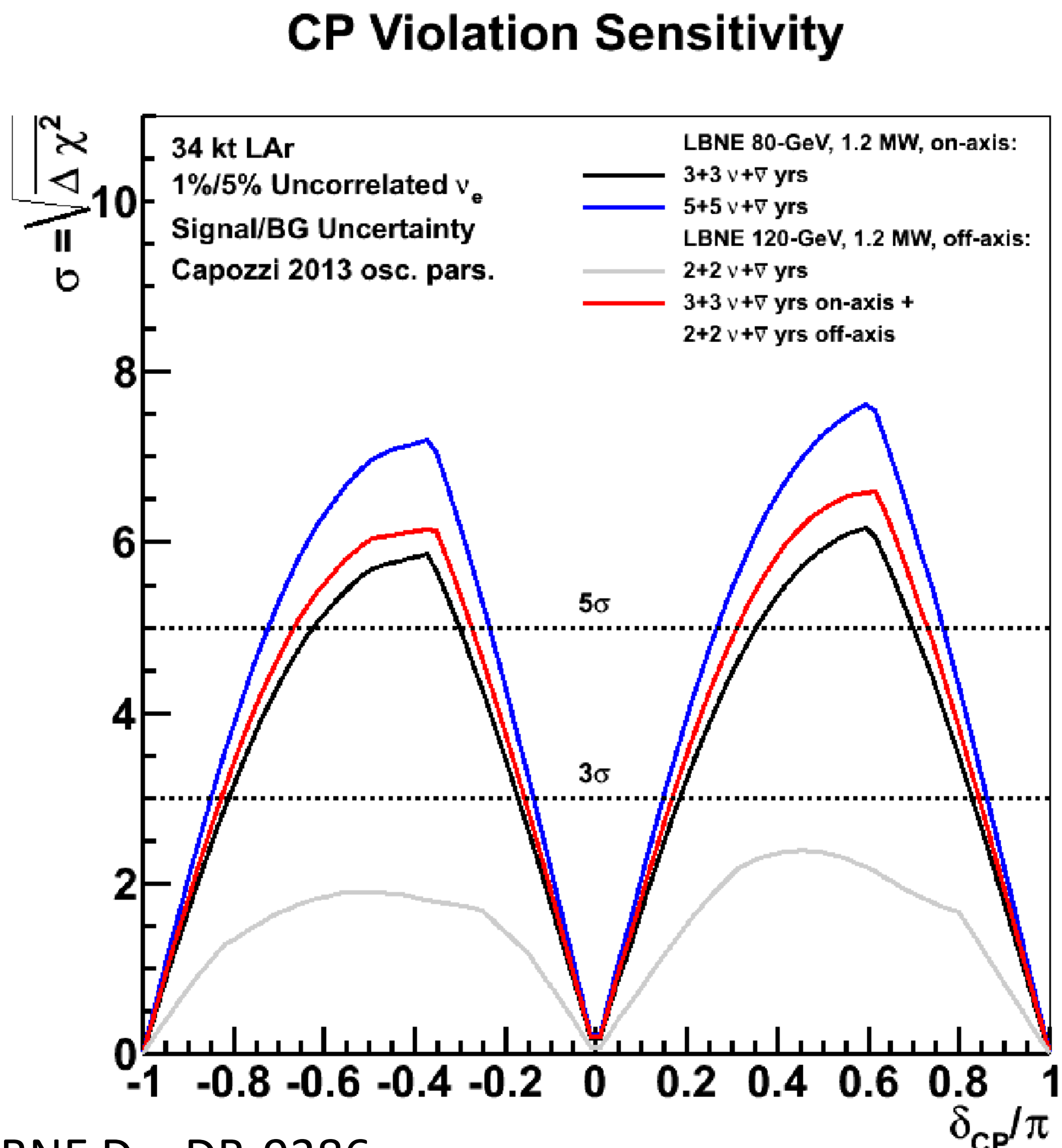
HE Opt (680m DP)
57% coverage at 3σ
19% coverage at 5σ

LE Opt (280m DP)
44% coverage at 3σ
3% coverage at 5σ

See LBNE DocDB-9976 for corresponding MH plots.

- What if we make a beam that is optimized for lower energy to further exploit the 2nd max? Can we enhance the CP sensitivity at baselines >2000 km?
- LE optimized (focus on 2nd max): 280 m DP, target-horn 1 distance = 0 cm
- HE optimized (focus on 1st max): 680 m DP, target-horn 1 distance = 70 cm (the 2500 km baseline study flux)
- HE optimization has better sensitivity for CP and MH (not shown). **At 120 GeV, optimal strategy is focusing on 1st max.**

Accessing the 2nd oscillation maximum with an off-axis beam



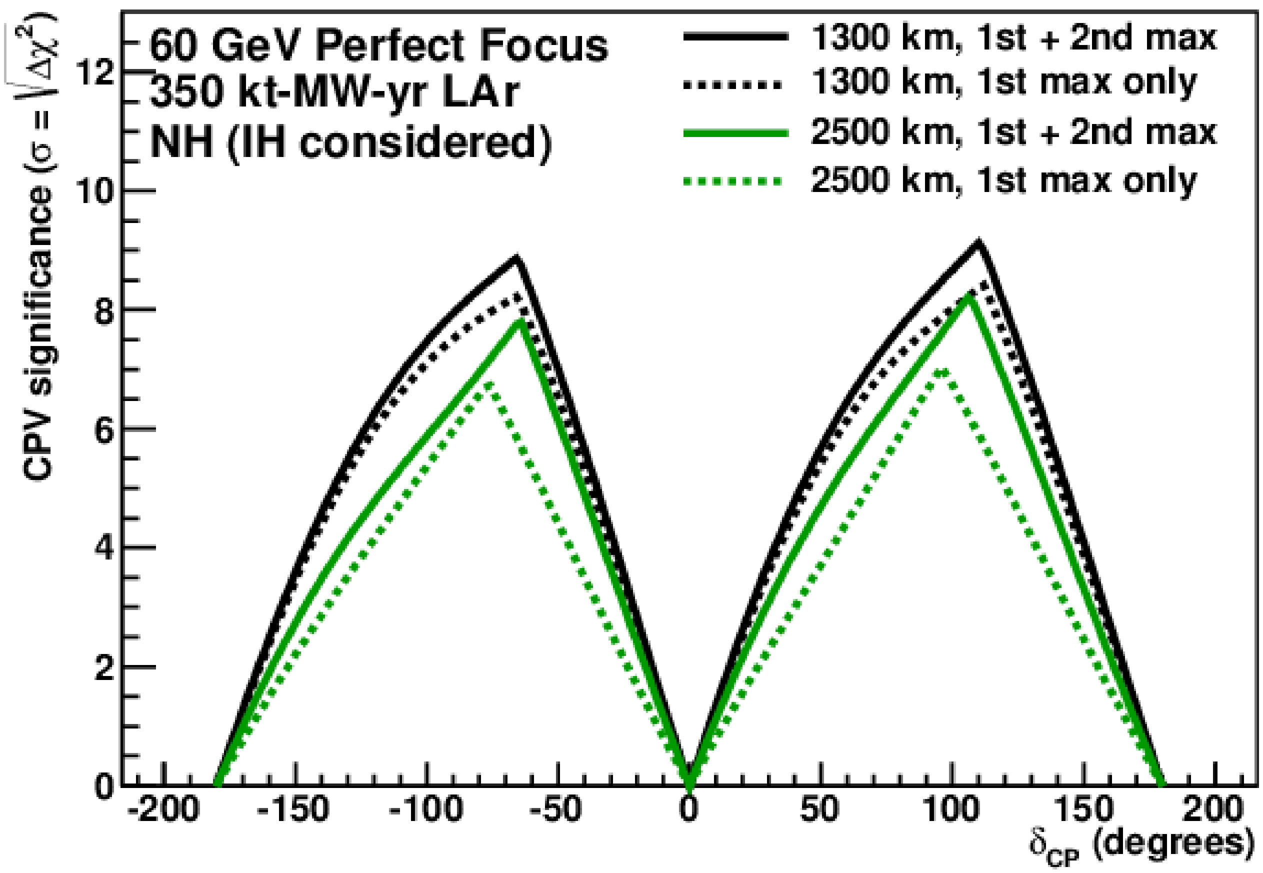
LBNE DocDB-9386

Looked at combining an on-axis 80-GeV beam to cover the 1st max with a 30 mrad off-axis 120-GeV beam to cover the 2nd max.

Using an off-axis beam to access the 2nd max is generally not more effective than collecting additional statistics with an on-axis beam.

(Came to similar conclusions by artificially enhancing the event rate in the 2nd maximum.)

1^{st} vs 2^{nd} max contribution at different baselines



1^{st} max only vs 1^{st}+2^{nd} combined:

2^{nd} max contributes more to the sensitivity at the longer baseline.

1300 km 1^{st}+2^{nd}	1300 km 1^{st} only	2500 km 1^{st} + 2^{nd}	2500 km 1^{st} only
74% coverage at 3σ	73% coverage at 3σ	68% coverage at 3σ	57% coverage at 3σ
55% coverage at 5σ	53% coverage at 5σ	43% coverage at 5σ	29% coverage at 5σ

See LBNE DocDB-9976 for corresponding MH plots.

Proton beam energy

120 GeV Perfect
73% coverage at 3σ
53% coverage at 5σ

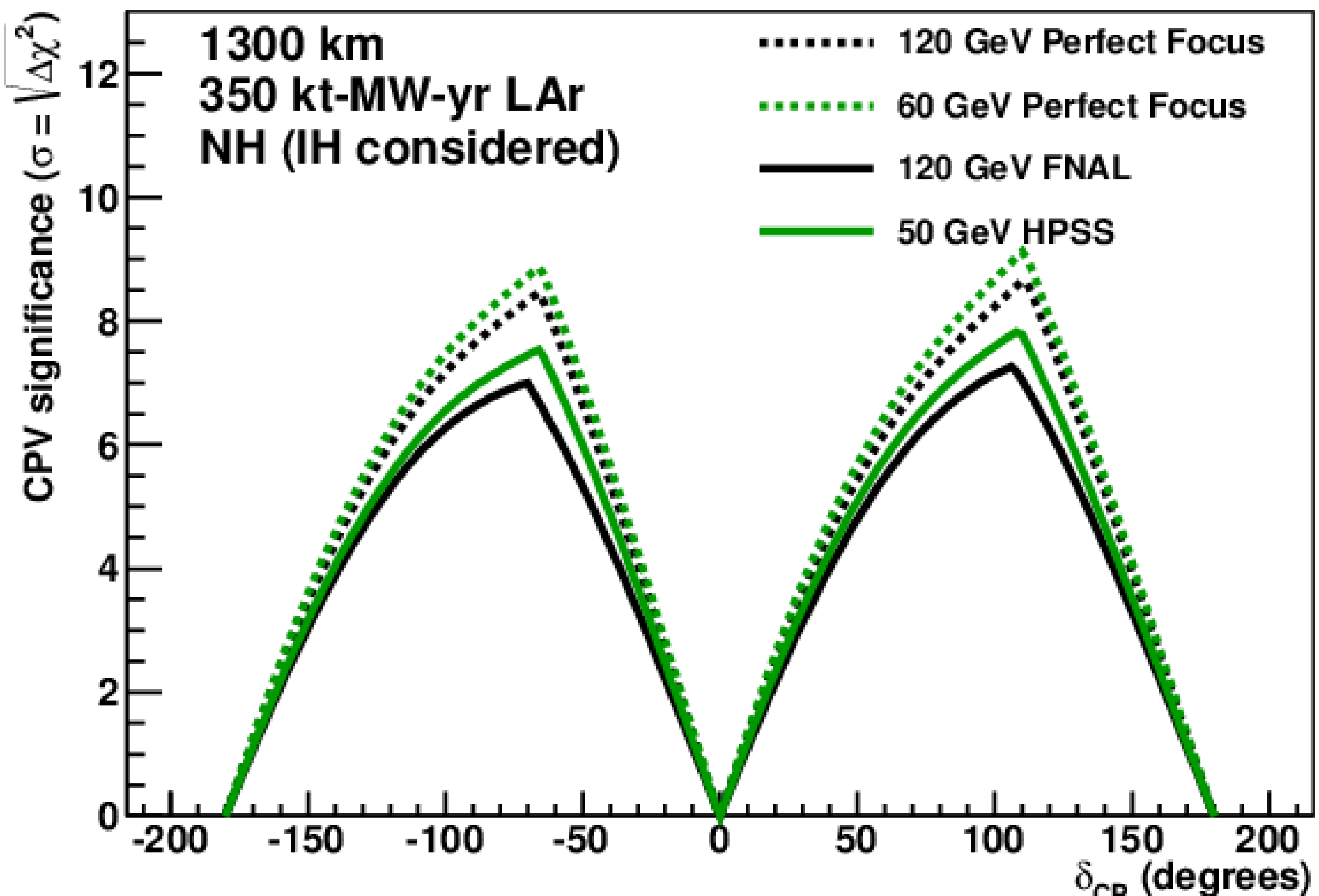
60 GeV Perfect
74% coverage at 3σ
55% coverage at 5σ

120 GeV FNAL
69% coverage at 3σ
44% coverage at 5σ

50 GeV HPSS
70% coverage at 3σ
48% coverage at 5σ

Lower beam energy gives slightly better sensitivity for CP and MH (not shown)

See LBNE DocDB-9976 for corresponding MH plots.



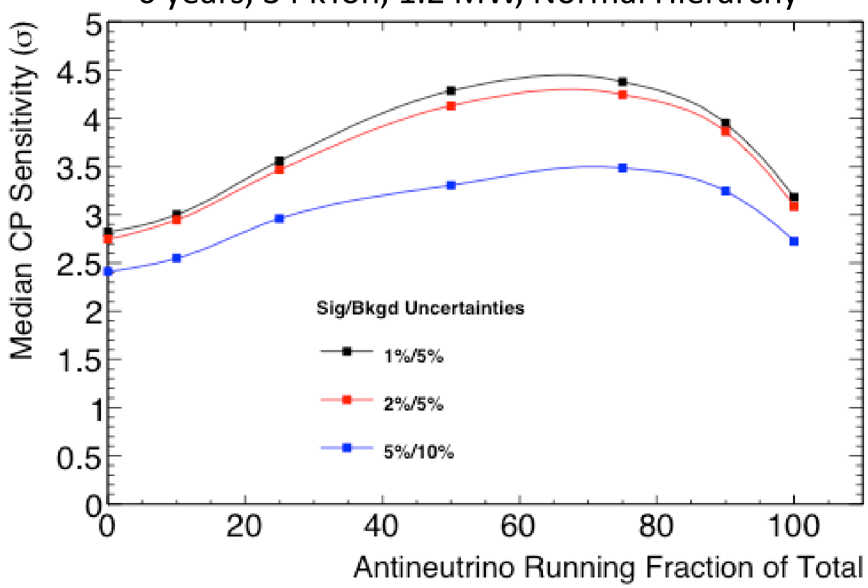
LBNE DocDB-9794,9537

Assumes equal power

Neutrino Mode / Antineutrino Mode Optimization

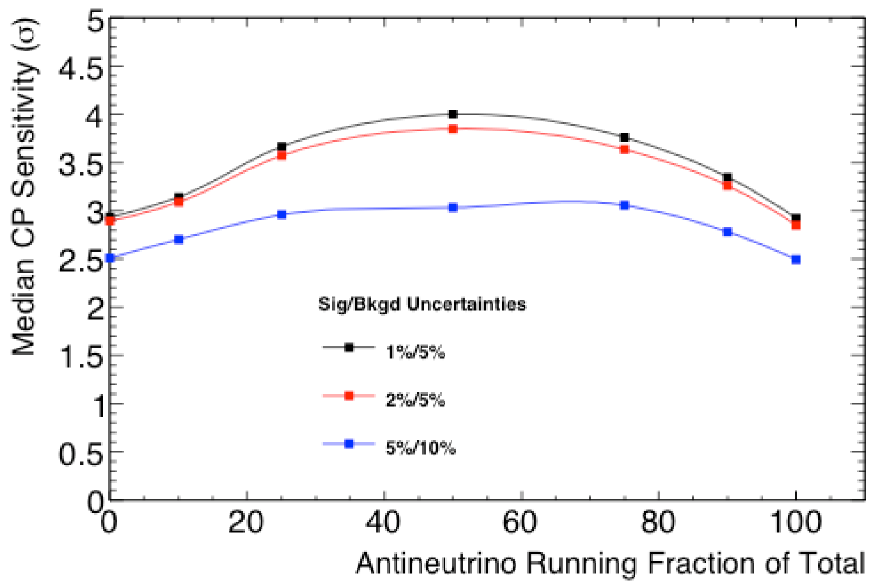
A more modern Fast MC study of best neutrino/antineutrino fraction (see LBNE DocDB 10084)

6 years, 34 kTon, 1.2 MW, Normal Hierarchy



This is for 1300 km. At longer baselines, more neutrino running (75/25) is slightly more optimal.

6 years, 34 kTon, 1.2 MW, Inverted Hierarchy



Something close to 50/50 neutrino/antineutrino running appears optimal for CP sensitivity; Slightly more antineutrino running is better if hierarchy is normal

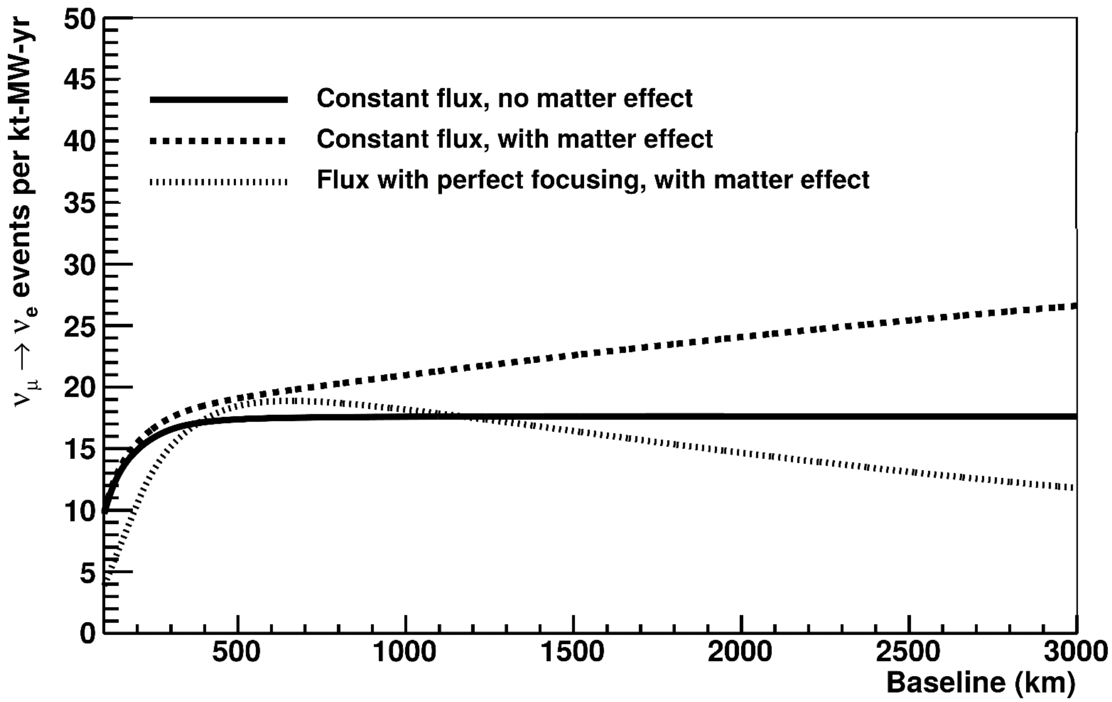
Conclusions

- Baselines of at least 1000 km are optimal for determining the mass hierarchy and observing CP violation in a wide-band muon neutrino beam from Fermilab.
  - We can resolve the mass hierarchy at $\overline{\Delta\chi^2}$=25 for baselines 1300 km and greater. Mass hierarchy determination can be made more quickly at long baselines.
  - The CP sensitivity is best around 750-1500 km, even without knowing the mass hierarchy. The sensitivity isn't much worse beyond 1500 km, especially if the ν_τ CC background can be efficiently removed. The exposure required to observe CP violation is at a minimum for baselines between 1000-1500 km.
  - The δ resolution is best for baselines 1000 km and greater, regardless of the value of δ.
- At 1300 km, much of the sensitivity comes from rate at the 1st oscillation max. The 2nd max is useful for breaking degeneracies.
- At longer baselines (especially with a lower energy proton beam designed to focus on the 2nd max), shape is a bigger factor in the sensitivity, and thus the 2nd max becomes more important in the CP measurement
- 50/50 neutrino/antineutrino data (our usual assumption for sensitivity calculations) is close to optimal at 1300 km

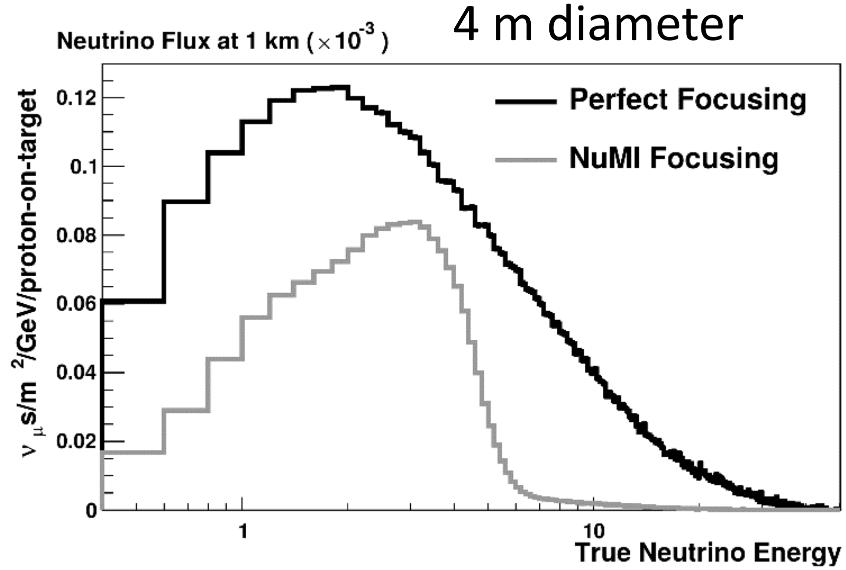
BACKUP

Expected Event Rate vs Baseline

Doc-7607
arXiv:1311.0212



Decay pipe:
380 m length
4 m diameter



- Using full probability and cross-section
- Integrated rate over 1st and 2nd maximum

Experimental Assumptions (GLoBES inputs)

- Nominal exposure of 175 kt-MW-yr (~150 kt-yr at 1.2 MW) for baseline study; varied in study
- Oscillation parameter values and uncertainties from Fogli 2012 global fit*
- Matter effects incorporated in GLoBES assuming constant matter density
- Liquid argon TPC performance parameters:

Parameter	Value
ν_e CC efficiency	80%
NC mis-ID rate	1%
ν_μ CC mis-ID rate	1%
ν_τ CC mis-ID rate	~20% (E-dependent)
Other background	0%
ν_e CC energy resolution	15%/√E
ν_μ CC energy resolution	20%/√E

From the LBNE fast MC:

- NC and ν_τ CC true-to-visible energy conversion
- Energy-dependent mis-ID rate for ν_τ's

Fast MC and chosen performance parameters documented in the LBNE Science Document, arXiv:1307.7335

ν_τ CC background includes all ν_τ CC interactions that pass the ν_e CC selection cuts. The ~20% mis-ID is due to the branching ratio for $\tau \rightarrow e$ branching ratio.

Using GENIE cross-sections

*G. Fogli, E. Lisi, A. Marrone, D. Montanino, A. Palazzo, et al., Phys.Rev. D86, 013012 (2012), arXiv:1205.5254[hep-ph].

Oscillation parameters and uncertainties from global fit

$$\theta_{12} = 0.587 \ \pm 3\%$$
$$\theta_{13} = 0.156 \ \pm 3\%$$
$$\theta_{23} = 0.670 \ \pm 8\%$$
$$\Delta m^2_{21} = 7.54 \times 10^{-5} \mathrm{eV}^2 \pm 3\%$$
NH: $\Delta m^2_{31} = 2.47 \times 10^{-3} \ \mathrm{eV}^2 \pm 3\%$

IH: $\Delta m^2_{31} = -2.39 \times 10^{-5} \ \mathrm{eV}^2 \pm 3\%$

θ_{13} uncertainty is taken to be Daya Bay's systematic uncertainty (as the statistical uncertainty is expected to be negligible in a few years)

*G. Fogli, E. Lisi, A. Marrone, D. Montanino, A. Palazzo, et al., Phys.Rev. D86, 013012 (2012), arXiv:1205.5254[hep-ph].

All of the plots in this document assume these parameters unless otherwise noted.

Constant Matter Density

Baseline (km)	Density (g/cm^3)
300	2.8
500	2.8
750	2.8
1000	2.87104
1300	2.95674
1700	3.1153
2000	3.18318
2500	3.24316
3000	3.28642

Constant density assumed for each baseline from GLoBES.

Matter effects are incorporated in GLoBES, assuming a constant matter density equal to the average matter density from the PREM onion shell model of the earth.

A. M. Dziewonski and D. L. Anderson, Phys. Earth Planet. Interiors 25, 297 (1981).
F. D. Stacey, Physics of the earth, 2nd ed. (Wiley, 1977).

Sensitivity Analysis

- Assume equal exposure in neutrino and antineutrino mode
- Combined fit of four samples: $\nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu$
- 1% (5%) signal and 5% (10%) background uncorrelated normalization uncertainty for appearance (disappearance) samples
- $\Delta\chi^2$ defined differently for CP and mass hierarchy sensitivity:

$$
\begin{aligned}
\Delta\chi^2_{MH} &= \left|\chi^2_{MH^{test}=IH} - \chi^2_{MH^{test}=NH}\right|, \\
\Delta\chi^2_{CPV} &= \min\left(\Delta\chi^2_{CP}(\delta^{test}_{\mathrm{CP}} = 0), \Delta\chi^2_{CP}(\delta^{test}_{\mathrm{CP}} = \pi)\right), \text{ where} \\
\Delta\chi^2_{CP} &= \chi^2_{\delta^{test}_{\mathrm{CP}}} - \chi^2_{\delta^{true}_{\mathrm{CP}}}.
\end{aligned}
$$