Hitting from the Baseline: Long-baseline Neutrino Studies

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OCTOBER 17, 2014

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Outline

- Neutrino oscillations
- Beam simulations and experimental assumptions
- Analysis: mass hierarchy, CP violation, octant
- Further study
- Conclusion

Neutrino Mixing

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

3x3 mixing: three mixing angles and one phase that affect neutrino oscillations

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

$\sin^2\theta_{23} = 0.514^{+0.055}_{-0.056}$

T2K (PRL 112, 181801 2014)

$\delta = ?$

$\sin^2 2\theta_{13} = 0.084\ \pm 0.005$

Daya Bay (Neutrino 2014)

$\tan^2\theta_{12} = \ 0.443^{+0.030}_{-0.025}$

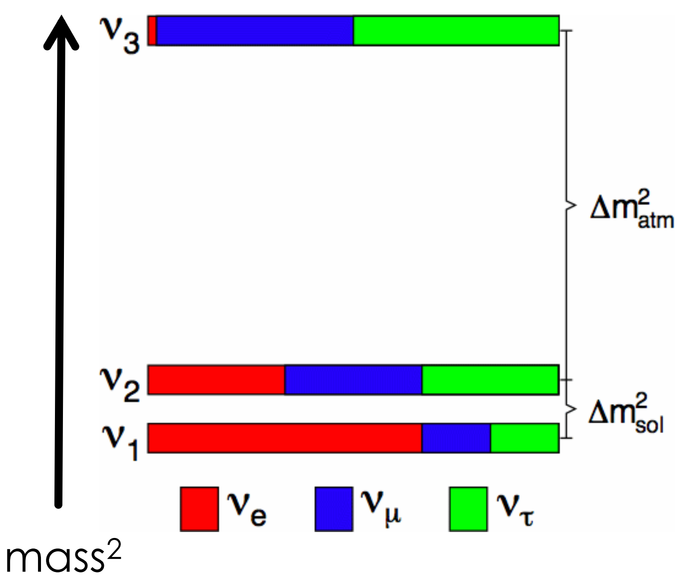
Solar + KamLAND (PRC 88, 025501 2013)

Neutrino Oscillations

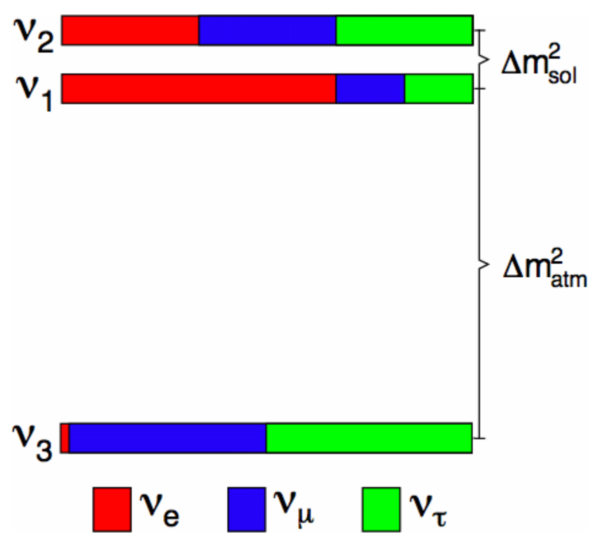
Probability of flavor change (2-flavor approximation):

$$P(\nu_\alpha \longrightarrow \nu_\beta) = \sin^2 2\theta \ \sin^2(1.27\,\Delta m^2 L/E)$$

L **= baseline,** ***E*** **= neutrino energy,** $\Delta m^2_{ij} = m^2_i - m^2_j$



Normal Hierarchy



Inverted Hierarchy

Color represents $|U_{\alpha j}|^2$

$|\Delta m^2_{atm}| = 2.37^{+0.11}_{-0.07} \times 10^{-3}\text{eV}^2$

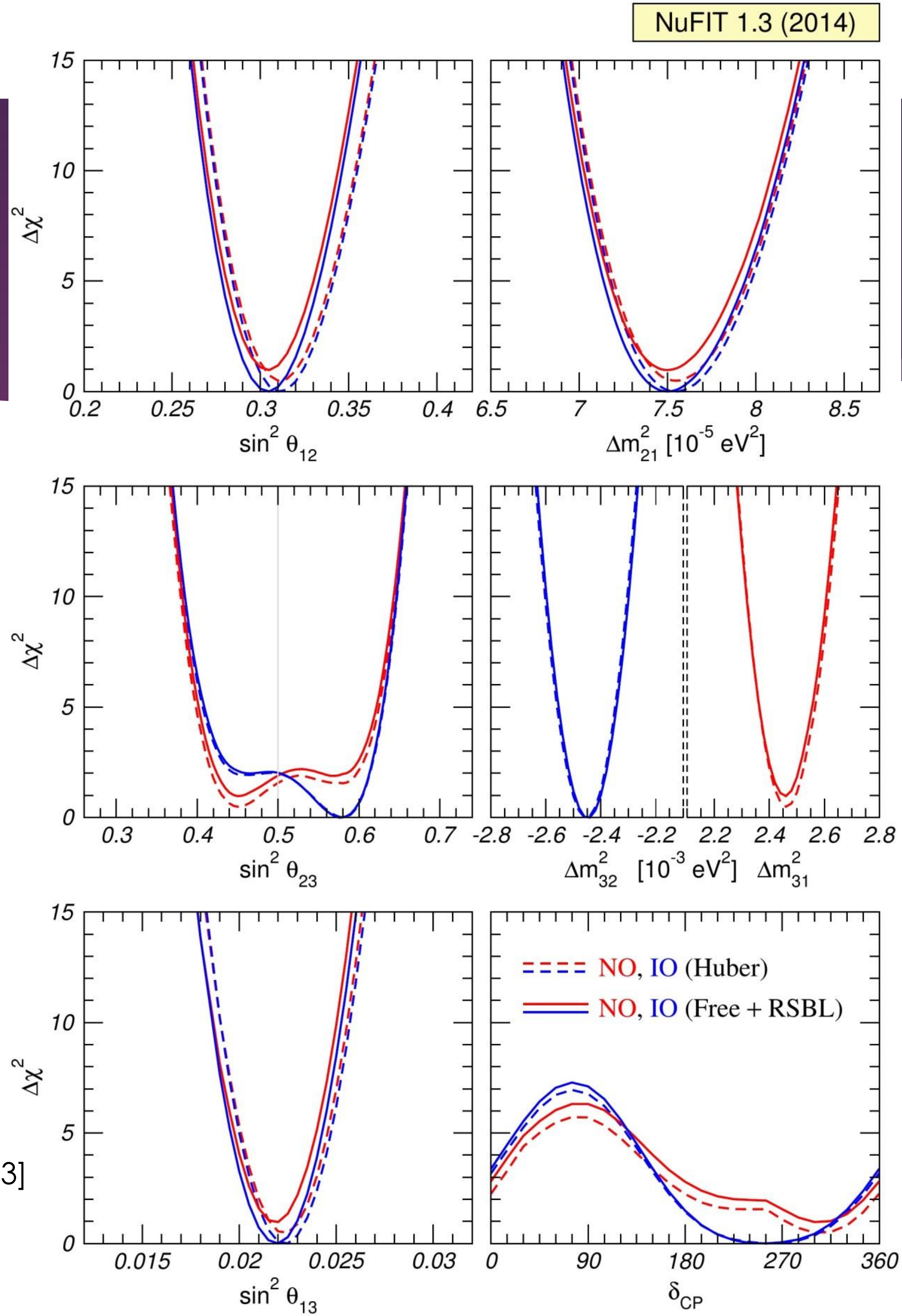
MINOS/MINOS+
Neutrino 2014
(Similar: Daya Bay, T2K)

$\Delta m^2_{sol} = 7.46^{+0.20}_{-0.19} \times 10^{-5}\text{eV}^2$

Solar + KamLAND
PRC 88, 025501 2013

Recent Global Fit

After Neutrino2014:
http://www.nu-fit.org/?q=node/75



JHEP 12 (2012) 123 [arXiv:1209.3023]

Best fit δ $= 251°^{+67°}_{-59°}$

Nothing excluded at 3σ

Open Questions

- What is the neutrino mass ordering (sign of Δm^2_{31})?
- Is CP violated in neutrinos oscillations ($\delta \neq 0$ and $\delta \neq \pi$)?
- Is ν_3 mostly ν_μ or ν_τ (the octant of θ_{23}: $\theta_{23} < \pi/4$ or $> \pi/4$)?

All of these questions can be addressed in a long-baseline neutrino experiment with a muon neutrino beam.

What is the optimal L/E (ratio of baseline to neutrino energy) to observe these effects?

Muon Neutrino to Electron Neutrino Oscillations

Oscillations in vacuum:

M. Freund, PRD 64, 053003 (2001), arXiv:hep-ex/0103300[hep-ph]

(θ_{13} term)

$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2(\Delta)$$

(CP-violating term)

$$+\alpha\,\underline{\sin\delta_{CP}}\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}\sin^3(\Delta)$$

$$+\alpha\cos\delta_{CP}\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}\cos(\Delta)\sin^2(\Delta)$$

$$+\alpha^2\cos^2\theta_{23}\sin^2 2\theta_{12}\sin^2(\Delta)$$

(solar term)

$$\alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \qquad \Delta = \frac{\Delta m^2_{31} L}{4E}$$

For antineutrinos, δ → -δ

Muon Neutrino to Electron Neutrino Oscillations

Oscillations in matter with constant density:

M. Freund, PRD 64, 053003 (2001), arXiv:hep-ex/0103300[hep-ph]

$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23}\frac{\sin^2 2\theta_{13}}{(\hat{A}-1)^2}\sin^2((\hat{A}-1)\Delta)$$
$$+\alpha\frac{\sin\delta_{CP}\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}}{\hat{A}(1-\hat{A})}\sin(\Delta)\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)$$
$$+\alpha\frac{\cos\delta_{CP}\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}}{\hat{A}(1-\hat{A})}\cos(\Delta)\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)$$
$$+\alpha^2\frac{\cos^2\theta_{23}\sin^2 2\theta_{12}}{\hat{A}^2}\sin^2(\hat{A}\Delta)$$

For antineutrinos, V → -V and δ → -δ

$$\alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \qquad \Delta = \frac{\Delta m^2_{31}L}{4E} \qquad A = \frac{2VE}{\Delta m^2_{31}}$$

V = matter potential ~ matter density

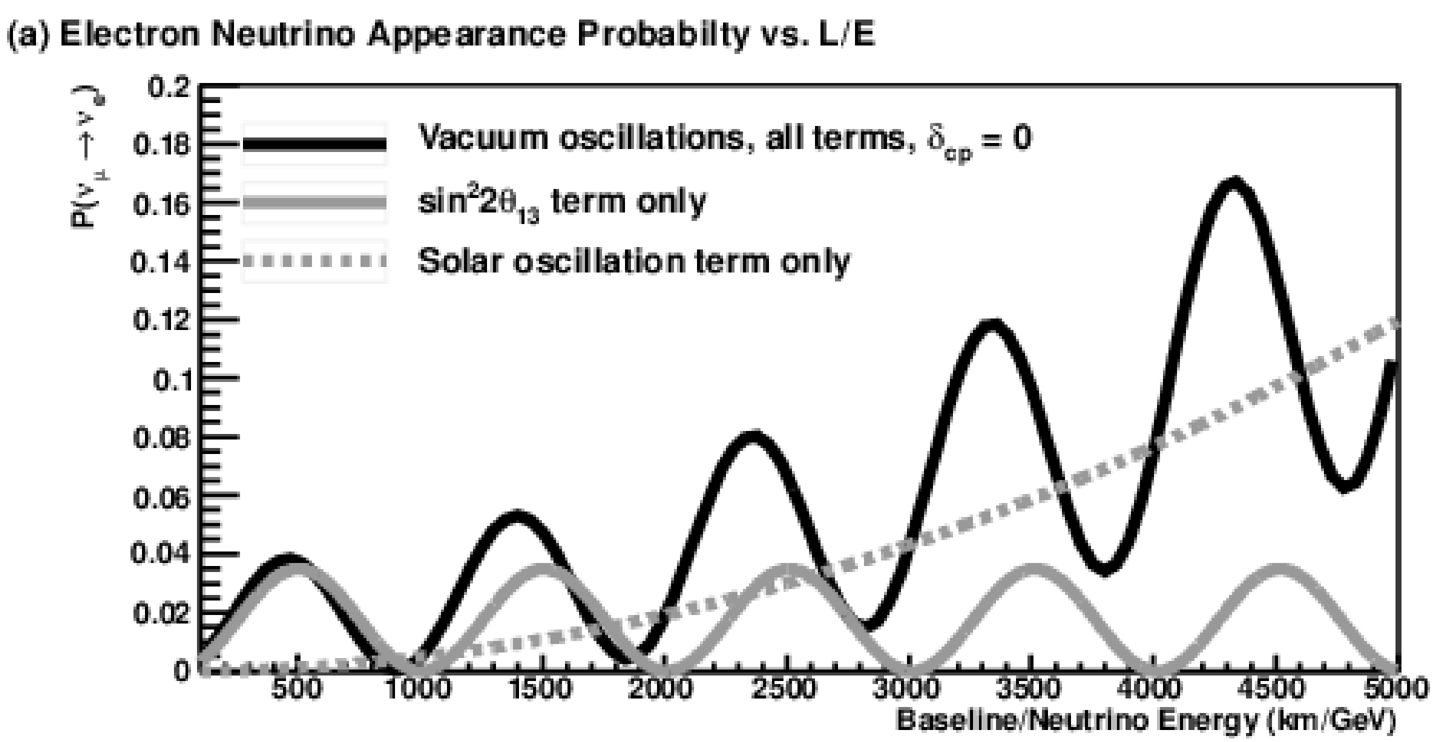
Muon Neutrino to Electron Neutrino Oscillations

The maximum oscillation probabilities (in vacuum) occur at values

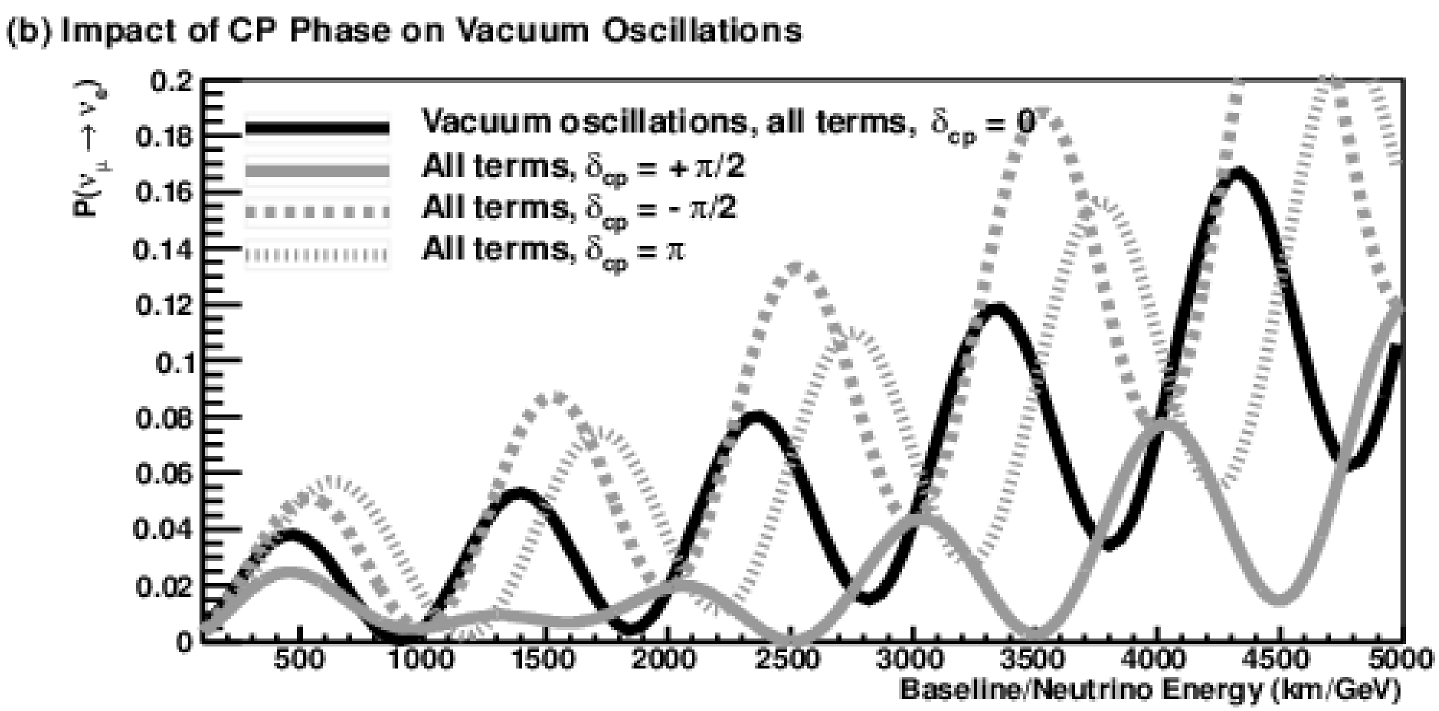
$$\frac{L}{E_n}\left(\frac{\mathrm{km}}{\mathrm{GeV}}\right) \approx (2n-1)\left(\frac{\pi}{2}\right)\frac{1}{1.267 \times \Delta m_{32}^2(\mathrm{eV}^2)}$$

- The energy of the beam must scale with the baseline to observe oscillations
- At longer baselines (and thus higher energies), it is possible to observe multiple oscillation maxima in the spectra if the neutrino flux covers a wide enough range of energy
- At short baselines, n>1 maxima are typically too low in energy to be observable (with high-energy accelerator beams)

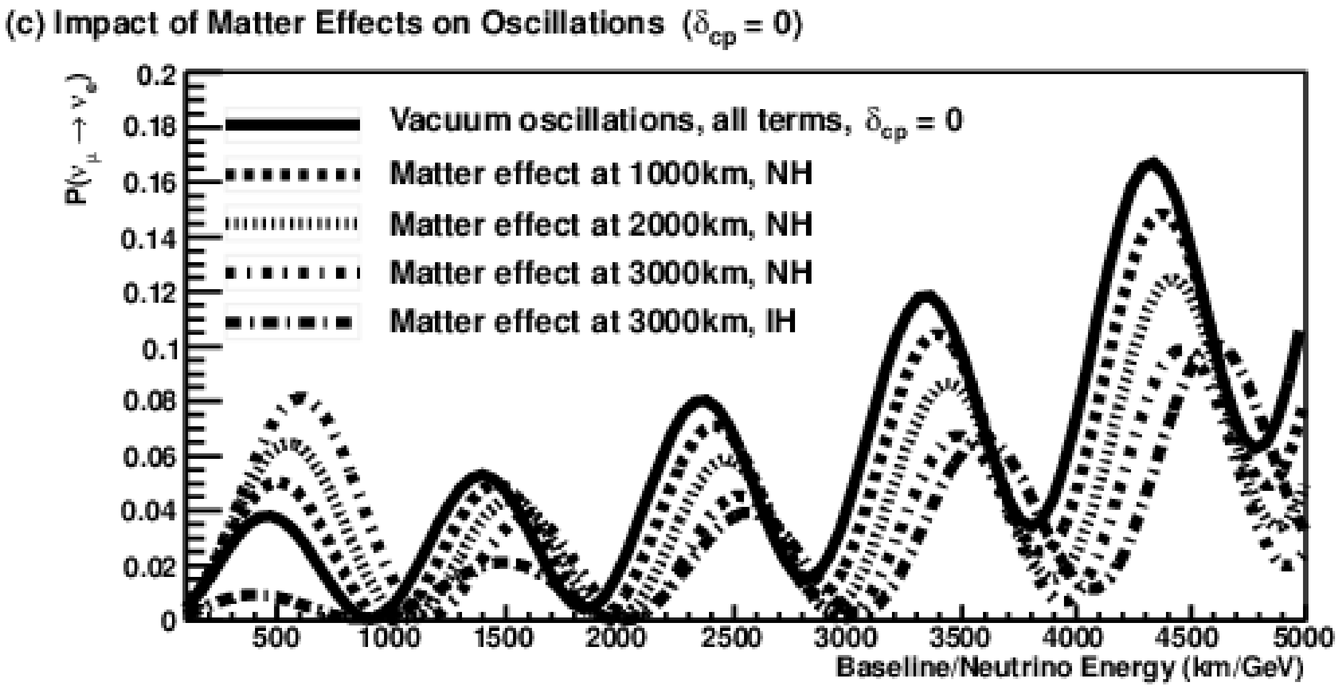
Muon Neutrino to Electron Neutrino Oscillations



Muon Neutrino to Electron Neutrino Oscillations



Muon Neutrino to Electron Neutrino Oscillations



Neutrino-Antineutrino Asymmetry

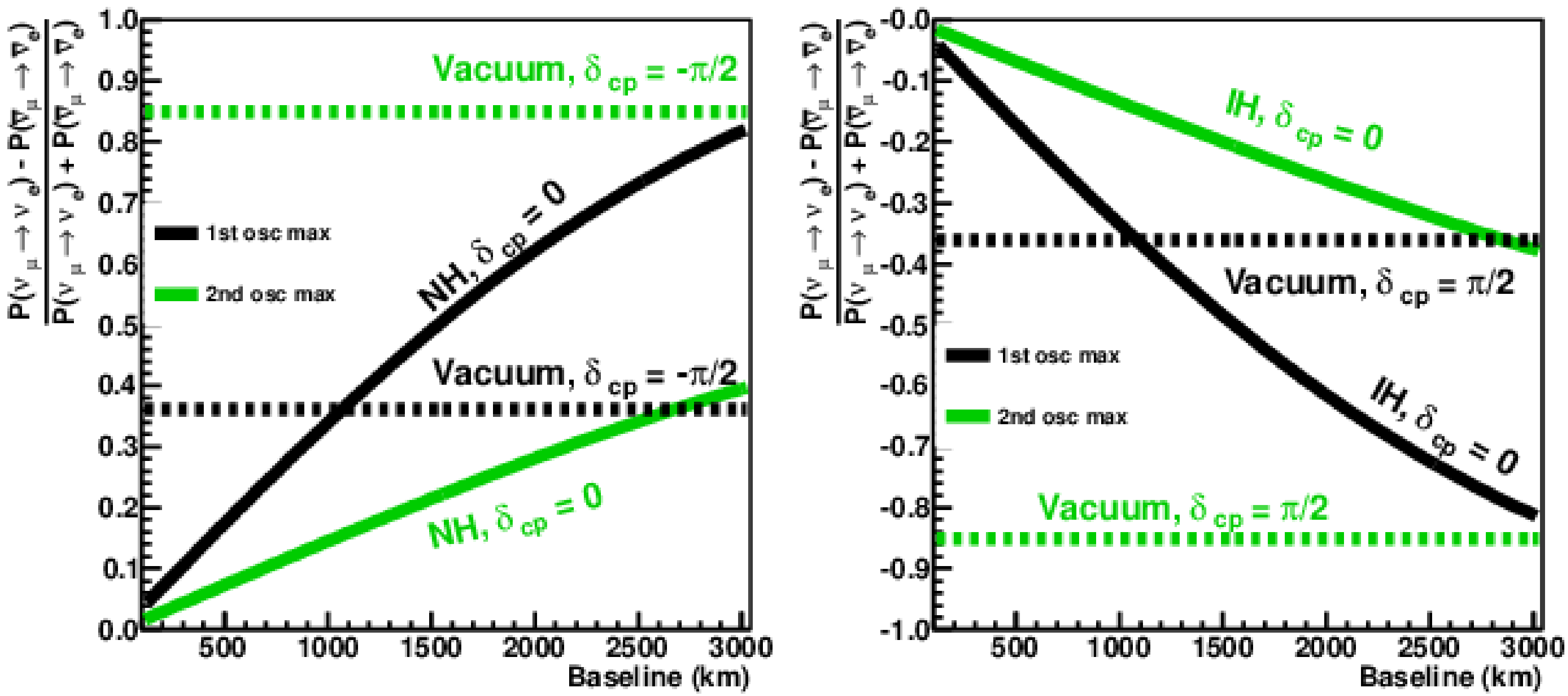
$$\mathcal{A}_{cp}(E_\nu) = \left[\frac{\mathrm{P}(\nu_\mu \to \nu_e) - \mathrm{P}(\bar{\nu}_\mu \to \bar{\nu}_e)}{\mathrm{P}(\nu_\mu \to \nu_e) + \mathrm{P}(\bar{\nu}_\mu \to \bar{\nu}_e)}\right]$$

$$\mathcal{A}_{cp}(E_\nu) \approx \frac{\cos\theta_{23}\sin 2\theta_{12}\sin\delta}{\sin\theta_{23}\sin\theta_{13}}\left(\frac{\Delta m^2_{21} L}{4E_\nu}\right) + \text{ matter effects.}$$

W. Marciano and Z. Parsa, Nucl. Phys. Proc. Suppl. 221, 166 (2011), arXiv:hep-ph/0610258[hep-ph].

- For $\delta = 0$ or π, the transition probability for oscillations in vacuum is the same for neutrinos and antineutrinos.
- In matter, the matter effect creates a difference between the neutrino and antineutrino probabilities, even for $\delta = 0$ or π
- In matter with $\delta \neq 0$ and $\delta \neq \pi$ there is an asymmetry due to both CP violation and the matter effect

Neutrino-Antineutrino Asymmetry

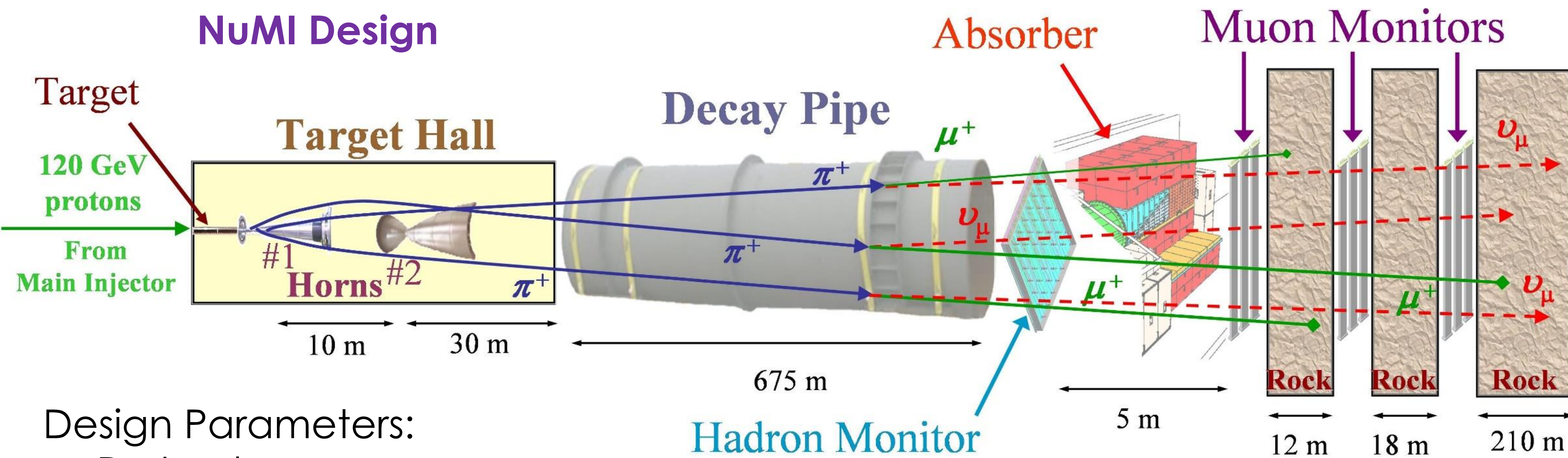


Neutrino-Antineutrino Asymmetry

- Matter asymmetry grows as function of baseline
- Asymmetry due to δ is constant as a function of baseline at both the 1st and 2nd max
- At the 2nd max, the CP asymmetry dominates the matter asymmetry at all baselines
- Expect the 2nd max to be important to observe CP violation

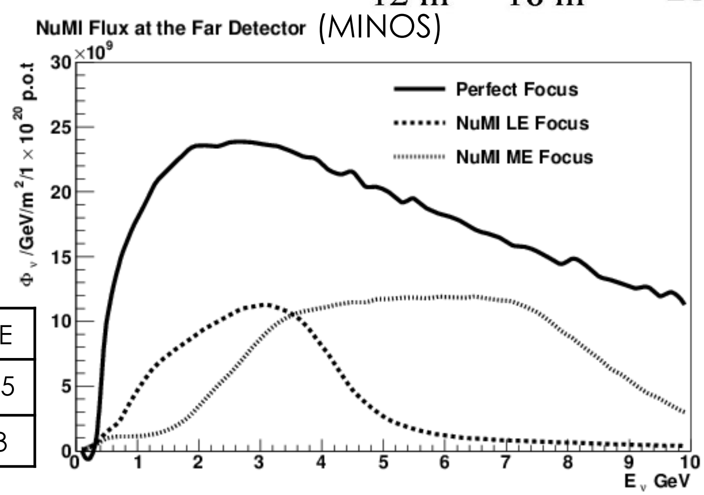
Horn-focused neutrino beams

NuMI Design



Design Parameters:

- Proton beam energy
- Target type/size
- Target-horn 1, Horn 1-Horn 2 distance
- Horn current
- Decay pipe width/length
- Off-axis angle



	LE	ME
Target-horn1 (cm)	45	135
Horn1-Horn2 (m)	10	23

L. Whitehead, University of Houston

Expected Event Rate

$$N_{\nu_e}^{\text{appear}}(L) = N_{\text{target}} \int \Phi^{\nu_\mu}(E_\nu, L) \times P^{\nu_\mu \to \nu_e}(E_\nu, L) \times \sigma^{\nu_e}(E_\nu) dE_\nu$$

$$\Phi^{\nu_\mu}(E_\nu, L) \approx \frac{C}{L^2}, \quad C = \text{number of } \nu_\mu/\text{m}^2/\text{GeV}/(\text{MW-yr}) \text{ at 1 km}$$

$$P^{\nu_\mu \to \nu_e}(E_\nu, L) \approx \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2(1.27\Delta m_{31}^2 L/E_\nu)$$

$$\sigma^{\nu_e}(E_\nu) = 0.67 \times 10^{-42}(\text{m}^2/\text{GeV}/N) \times E_\nu, \quad E_\nu > 0.5 \text{ GeV}$$

$$N_{\text{target}} = 6.022 \times 10^{32} N/\text{kt}$$

Expected Event Rate

Assuming a constant flux (determined by the simulated peak flux of a perfectly-focused beam produced by the Fermilab proton complex):

$$N_{\nu_e}^{\text{appear}}(L) \approx (1.8 \times 10^6 \text{events}/(\text{kt-MW-yr}))(\text{km}/\text{GeV})^2 \times \int_{x_0}^{x_1} \frac{\sin^2(ax)}{x^3} dx,$$

$$x \equiv L/E_\nu, \;\; a \equiv 1.27\Delta m_{31}^2$$

Integrating over the first two oscillation maxima:

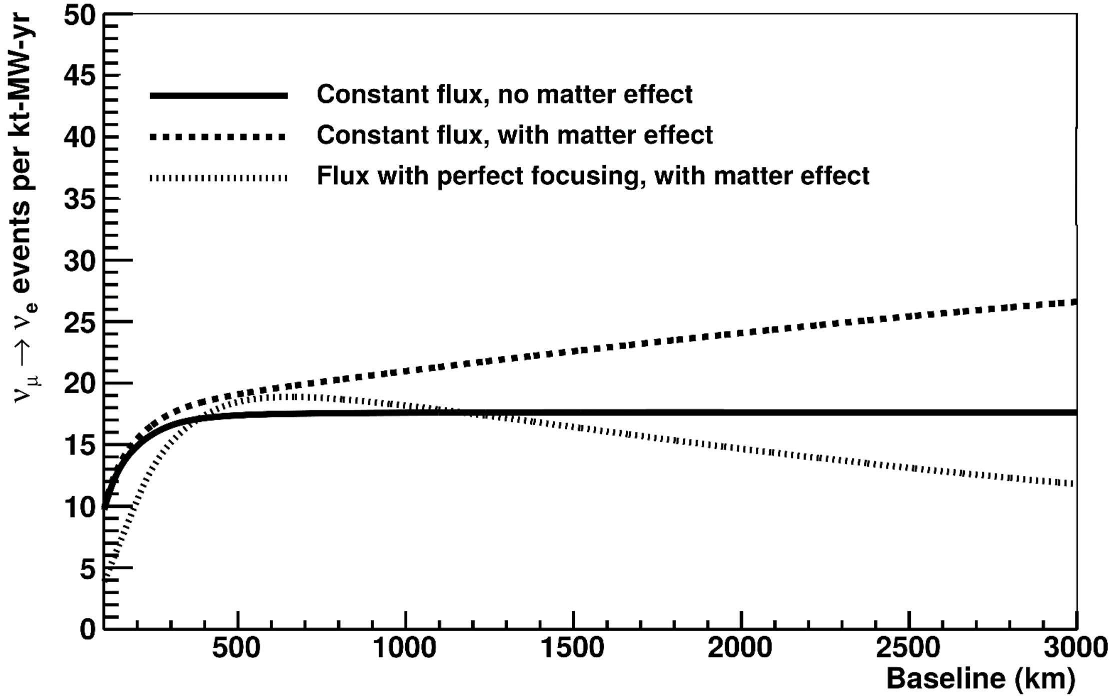
$$N_{\nu_e}^{\text{appear}}(L) \sim \mathcal{O}(20) \;\; \text{events}/(\text{kt-MW-yr})$$

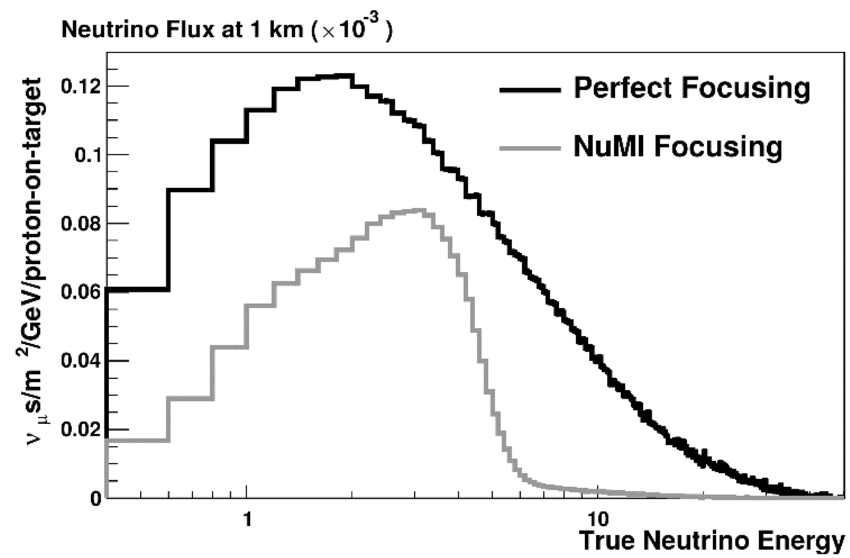
Independent of baseline!

$C = 1.2 \times 10^{17} \nu_\mu$/m^2/GeV/(MW-yr)

$\theta_{23} = 0.670, \theta_{13} = 0.156, \Delta m_{31}^2 = 0.00247$ eV^2

Expected Event Rate

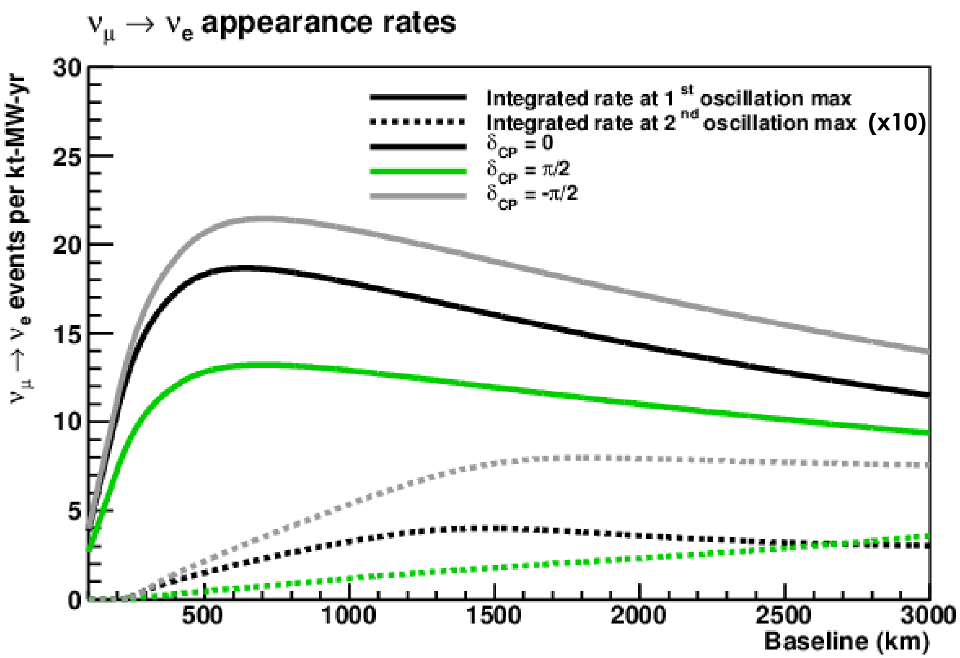


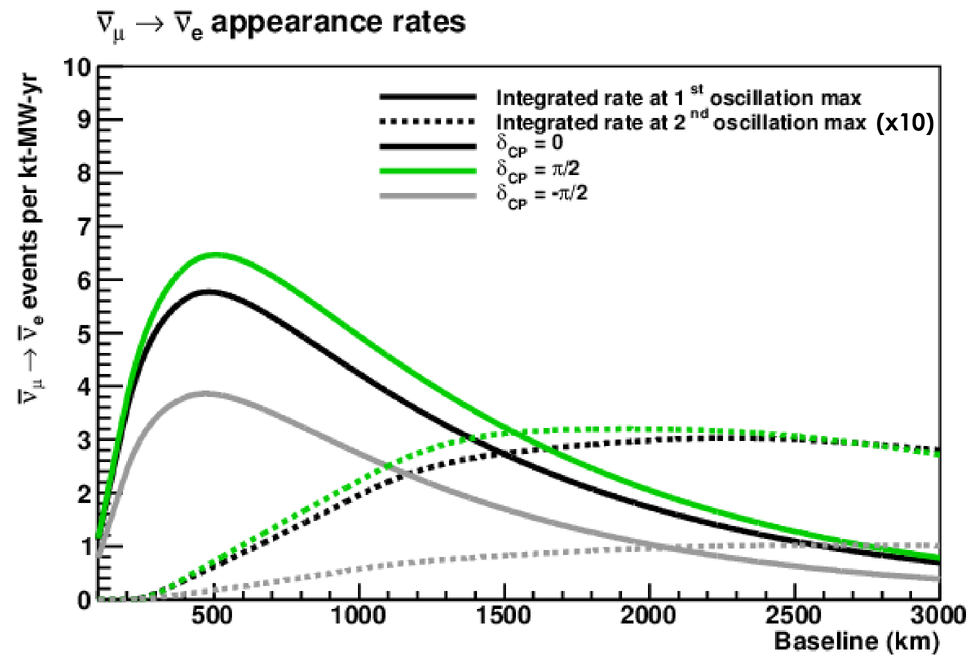


- Using full probability and cross-section
- Integrated rate over 1st and 2nd maximum

Decay pipe: 380 m length, 4 m diameter

Expected Event Rate – 1st vs 2nd Maximum





Expected Dependence of Sensitivity on Baseline

- Sensitivity to mass hierarchy should increase as a function of baseline, because the matter asymmetry grows as a function of baseline and the rates are roughly constant.
- The CP sensitivity will mostly depend on the 1st max because that's where the statistics are. Therefore the sensitivity should be roughly constant for baselines >1000 km.
- There is an ambiguity between matter asymmetry and CP asymmetry. At short baselines the 2nd max is too low in energy to be observable, and therefore the ambiguity can't be resolved - this will degrade the CP sensitivity. At longer baselines, observing the 2nd max breaks this degeneracy.

Baseline Optimization Study

- Generated optimized neutrino fluxes at nine baselines from 300 km to 3000 km
- Assume a liquid argon TPC exposed to a muon neutrino beam generated from the Fermilab proton complex
- Used GLoBES to study CP sensitivity and d resolution, mass hierarchy sensitivity, and octant sensitivity as a function of baseline
- The study is described in **arXiv:1311:0212**. Submitted to PRD.

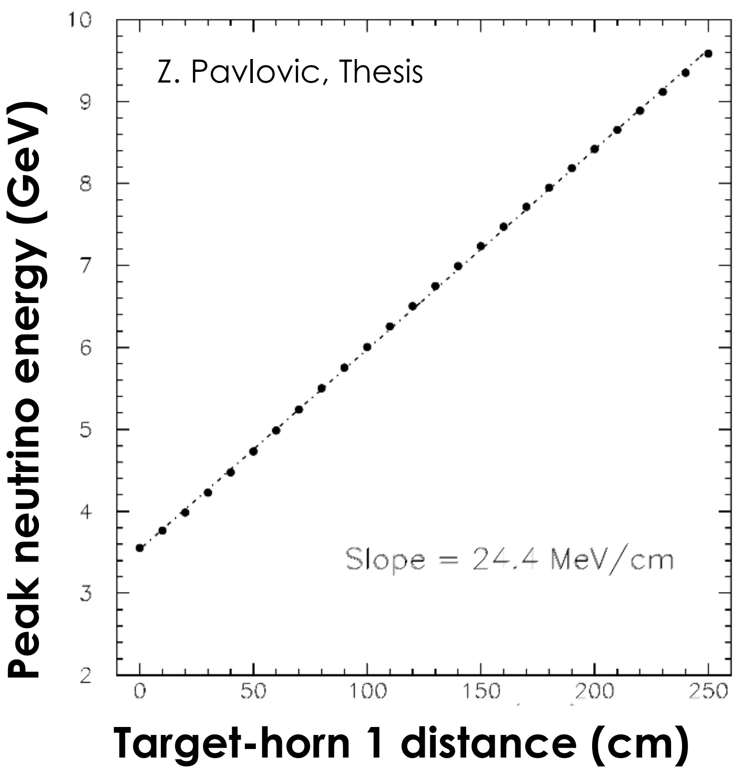
Beam simulation for each baseline

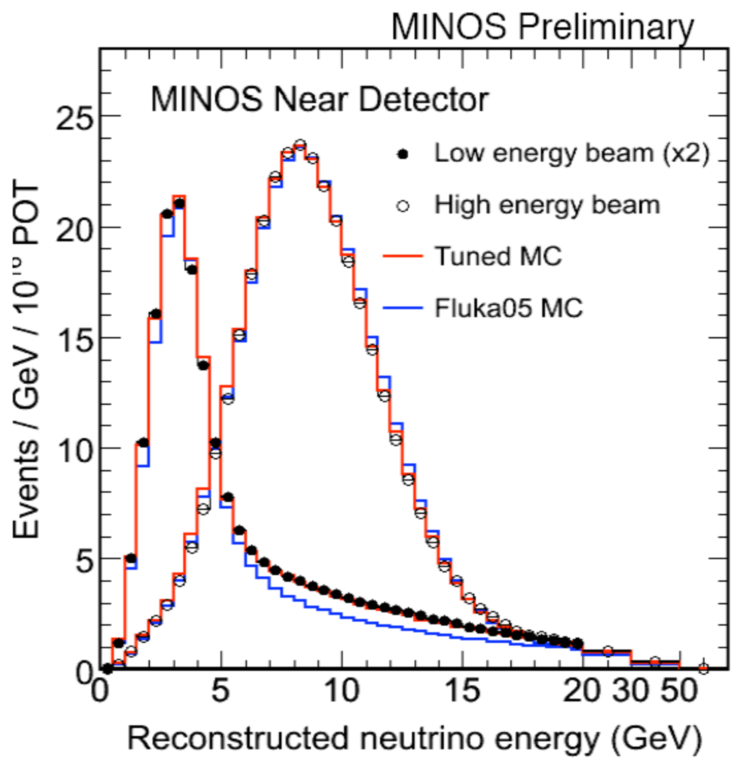
- The flux for each baseline was optimized to get a fair comparison of sensitivity
- Beamline parameters were chosen so that the neutrino flux covers the entire region of the first oscillation maximum and as much of the second as possible
- For different configurations that cover the oscillation energy region appropriately, the configuration was chosen based on CP sensitivity
- Off-axis beams are used for baselines < 1000 km
- Made realistic assumptions for a conventional neutrino beam from Fermilab

Beam simulation for each baseline – common parameters

- 1.2-MW 120-GeV primary proton beam (1x10^{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
- Other parameters (decay pipe length, off-axis angle, target-horn1 distance) were tuned for each baseline

Beam Simulation Parameters





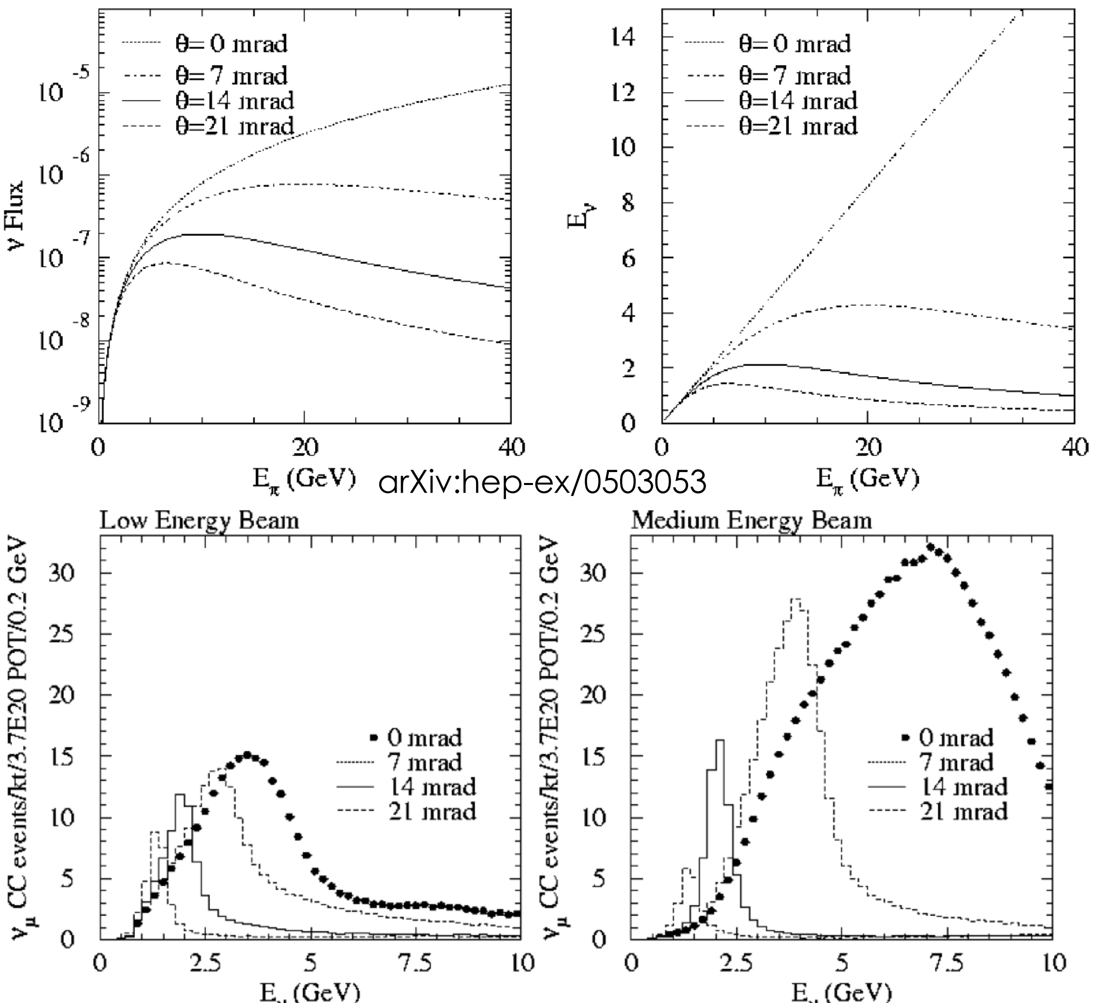
Both plots for NuMI-MINOS

Horn separation = 10 m

The blue line represents the beam simulation we used in our study.

Target-Horn 1 Distance

Beam Simulation Parameters



arXiv:hep-ex/0503053

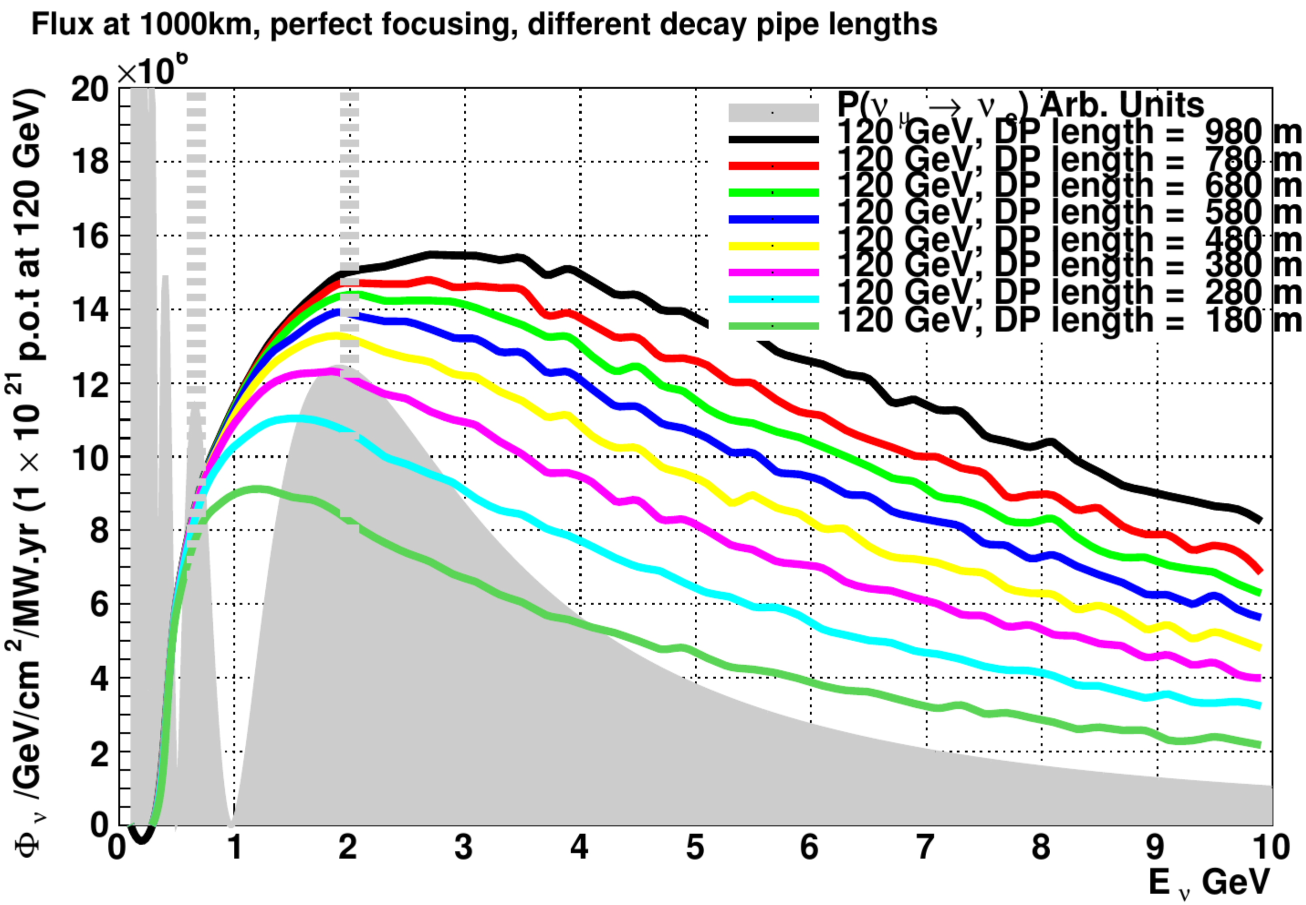
Off-Axis Angle

NuMI beam, for the NoVA proposal.

7 mrad = 0.4°

Beam Simulation Parameters

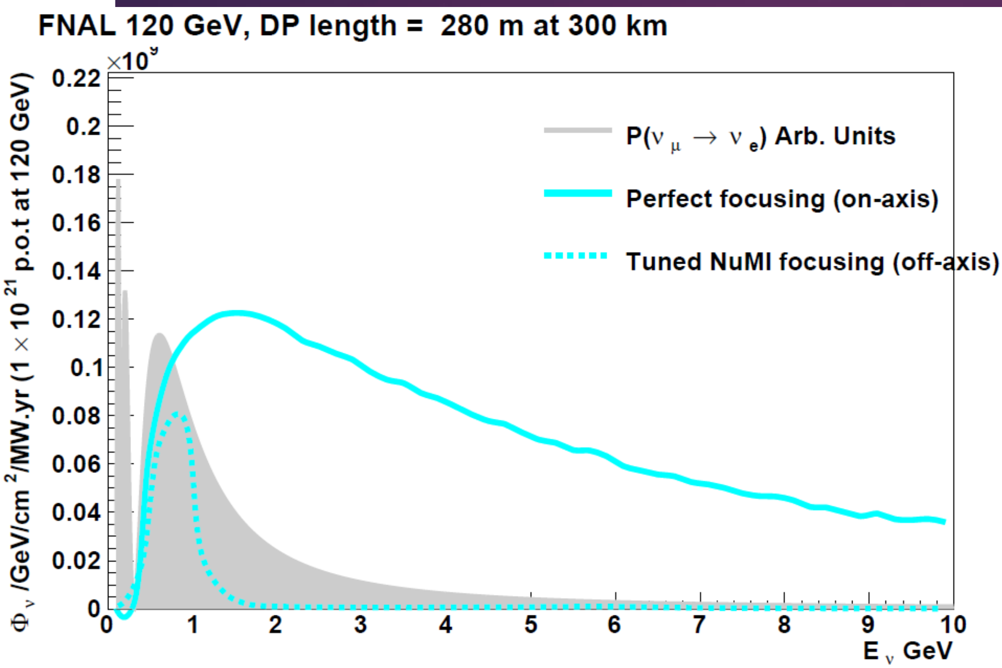
Decay Pipe Length

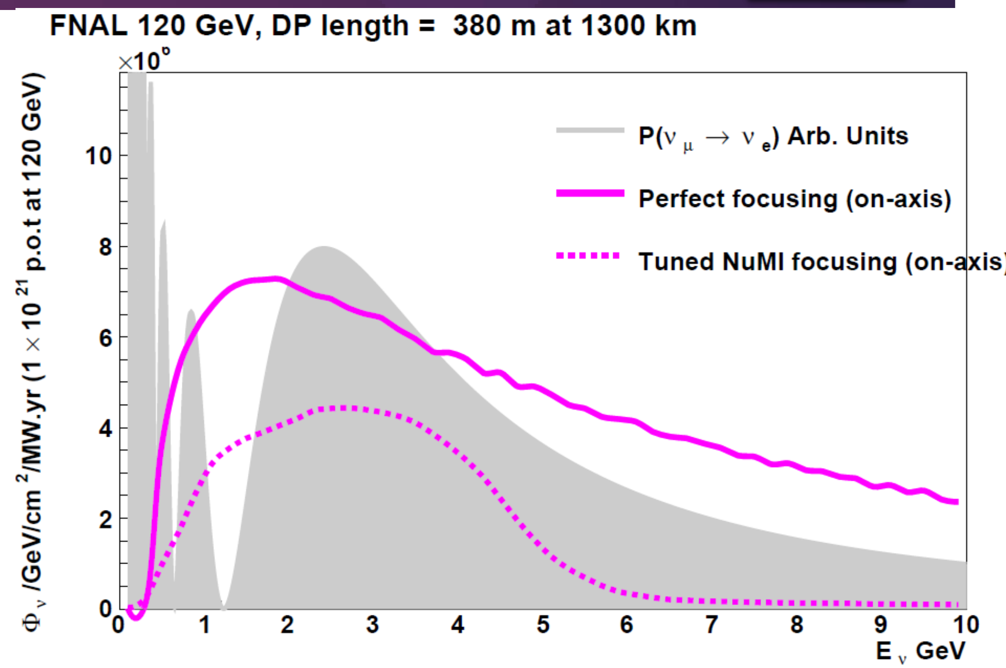


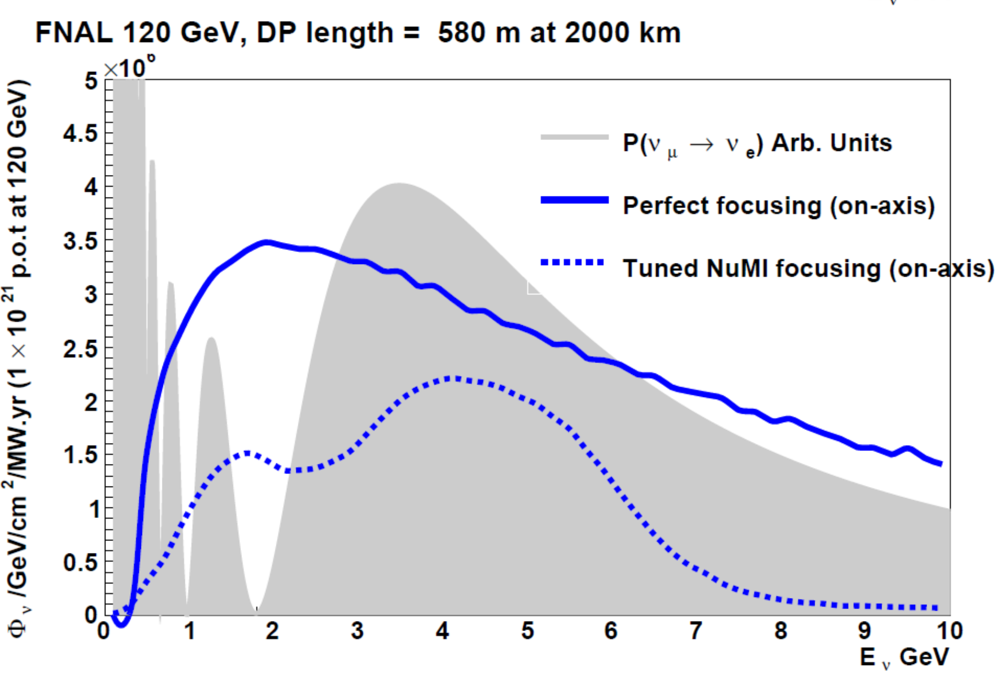
Beam simulation for each baseline – tuned parameters

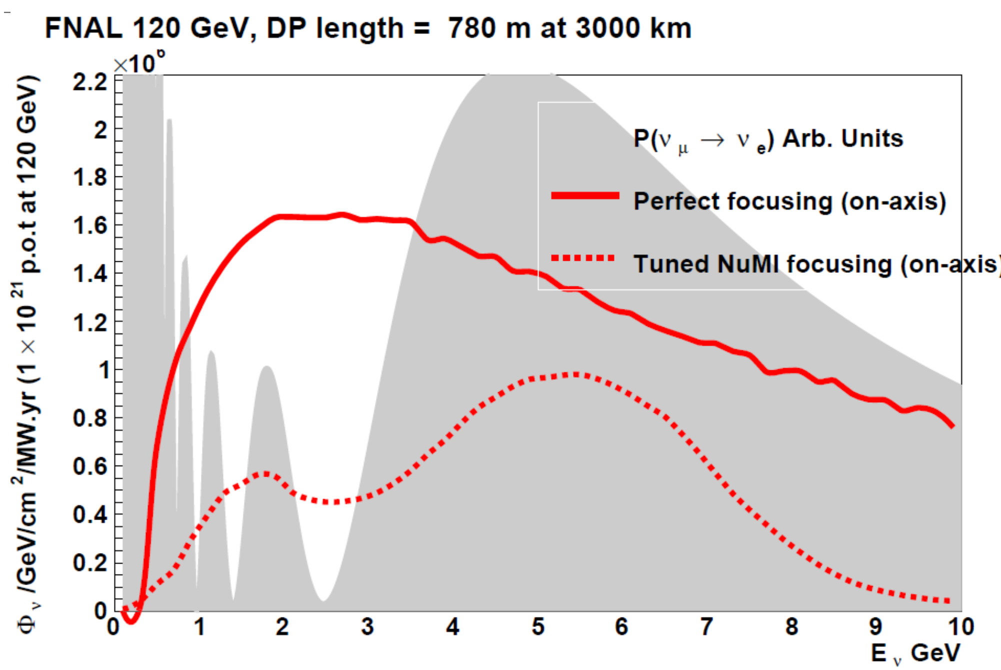
Baseline (km)	Decay Pipe Length (m) (4 m diameter)	Target-Horn 1 Distance (cm)	Off-axis Angle
300	280	30	2.0°
500	280	30	1.5°
750	280	30	1.0°
1000	280	0	0°
1300	380	30	0°
1700	480	30	0°
2000	580	70	0°
2500	680	70	0°
3000	780	100	0°

Comparison to Perfect Focusing

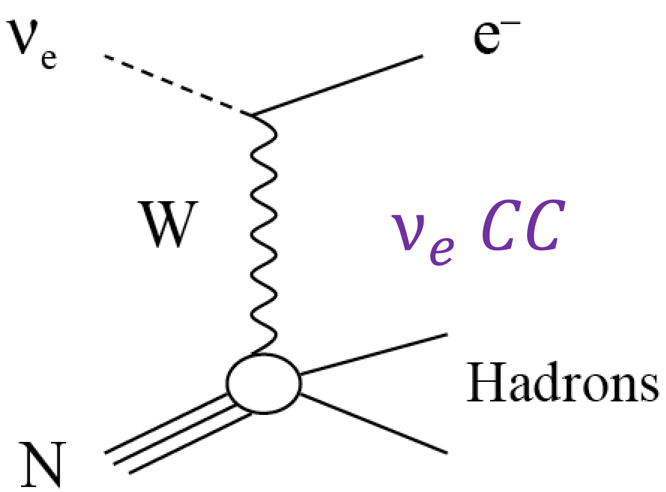


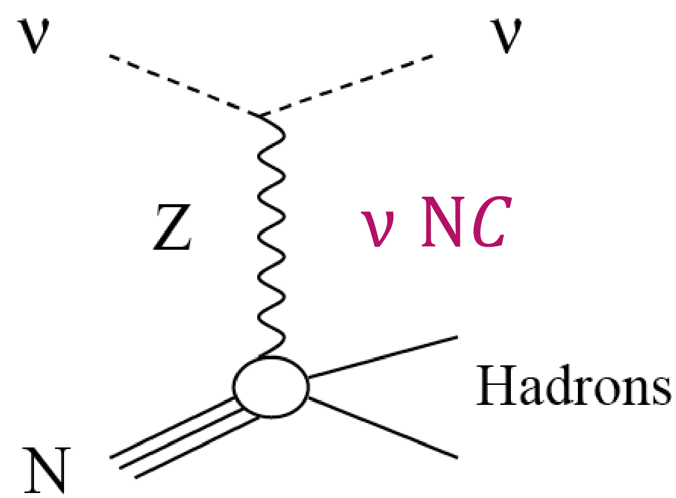


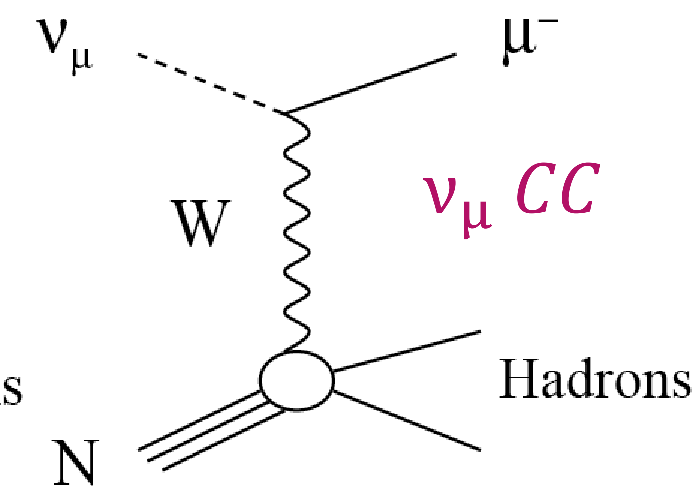




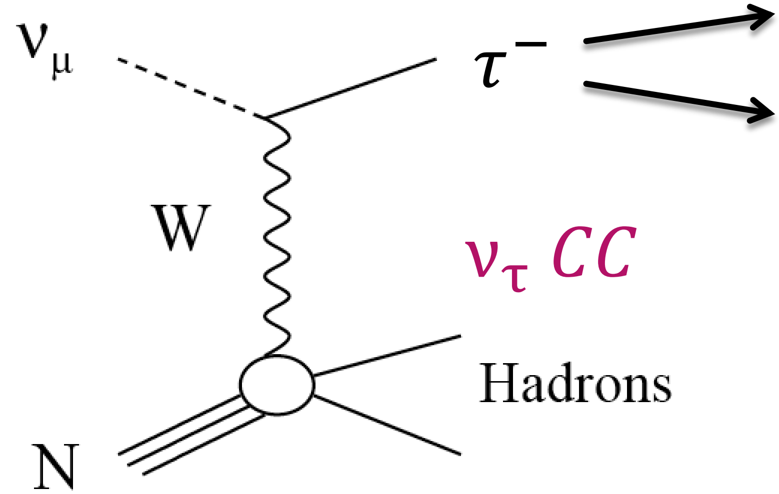
Signal and Background







- **Signal**
- **Irreducible beam background**



Leptonic (35%)

Hadronic (65%)

Backgrounds

Background from ν_τ CC

- ν_τ CC interactions in which the tau decays to an electron will create a background to ν_e CC appearance
- The tau production threshold is 3.5 GeV, so this background is negligible at short baselines, but is important for longer baselines due to the higher neutrino beam energy
- Our calculation of the ν_τ CC background includes any ν_τ CC interaction that passes the ν_e CC selection cuts
- This is an overestimate! Additional cuts can be made to reduce the background without significant loss of signal (for example, a cut based on transverse momentum imbalance)
- We calculate sensitivities both with and without the ν_τ CC background, so that we don't bias the results against the longer baselines due to a background that will likely be removed.

GLoBES

- GLoBES is a software package designed for the simulation of long-baseline neutrino oscillation experiments
- Given flux, cross-section, and detector parameters (resolution, efficiencies), GLoBES can be used to calculate rates and $\Delta\chi^2$ values
- Minimizes over all the oscillation parameters within given uncertainties. Correlations and degeneracies in the oscillation parameter space are fully incorporated.

$$\chi^2(\mathbf{n}^{true}, \mathbf{n}^{test}, f) = 2 \sum_{i}^{N_{reco}} \left(n_i^{true} ln \frac{n_i^{true}}{n_i^{test}(f)} + n_i^{test}(f) - n_i^{true}\right) + f^2$$

n = event rate in bins of reco energy
f = nuisance parameter to be profiled (oscillation parameters for example)

GLoBES:
P. Huber, M. Lindner, and W. Winter, Comput.Phys.Commun. 167, 195 (2005), arXiv:hep-ph/0407333 [hep-ph].
P. Huber, J. Kopp, M. Lindner, M. Rolinec, and W. Winter, Comput.Phys.Commun. 177,432 (2007), arXiv:hep-ph/0701187 [hep-ph].

Experimental Assumptions (GLoBES inputs)

- Nominal exposure of 175 kt-MW-yr (~150 kt-yr at 1.2 MW); 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

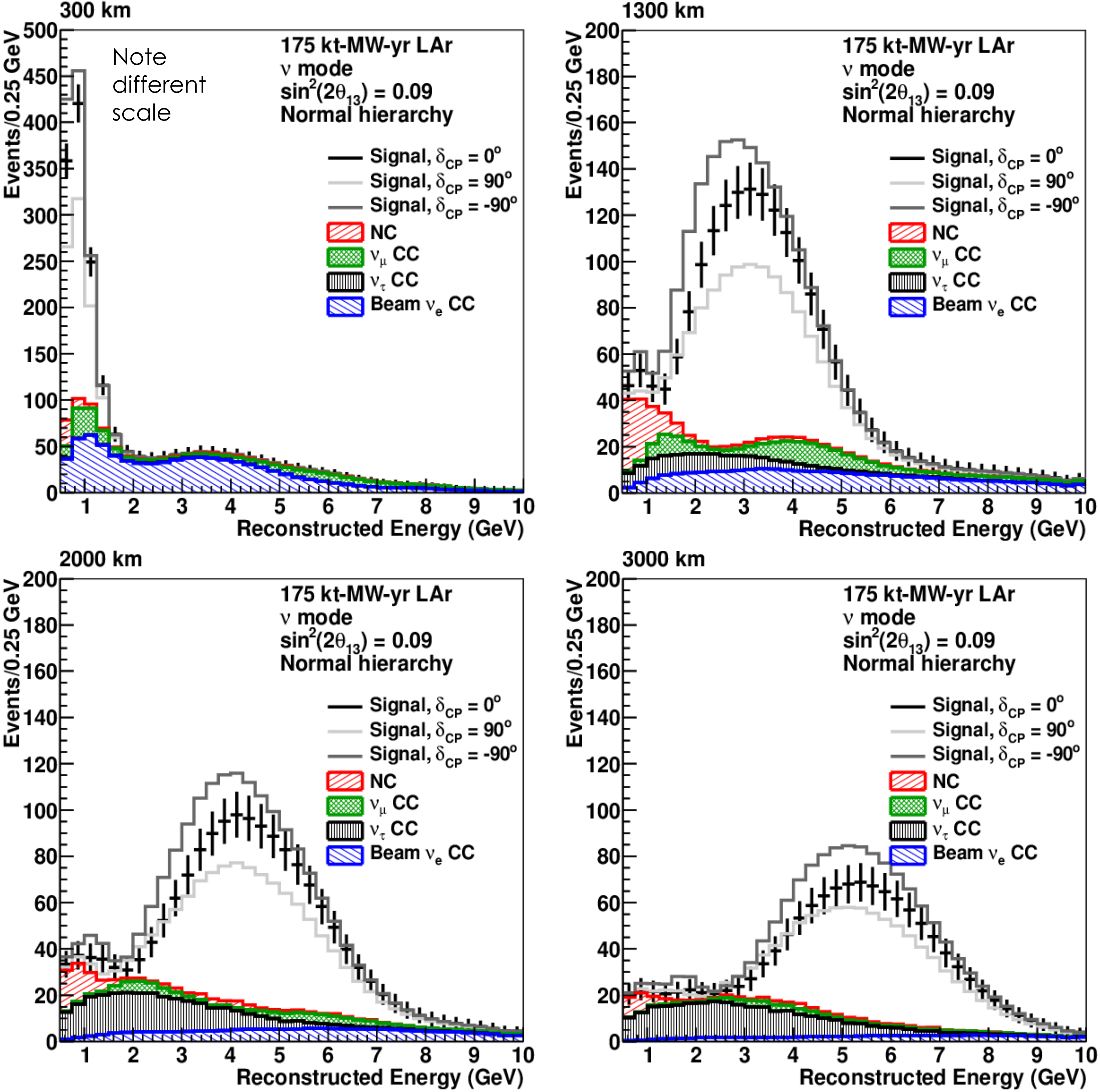
Fast MC and chosen performance parameters documented in the LBNE Science Document, arXiv:1307.7335

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.

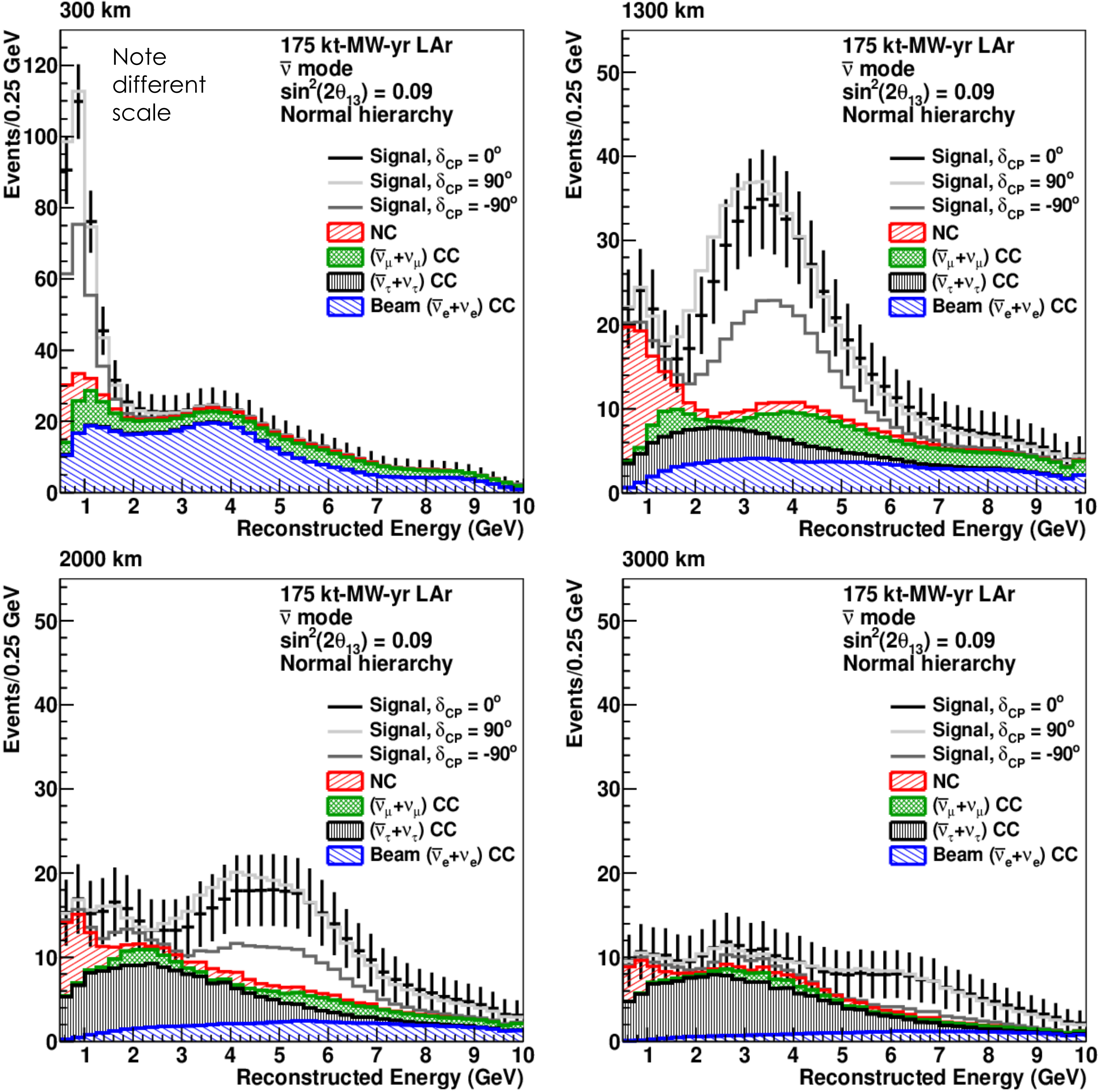
Using GENIE cross-sections

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

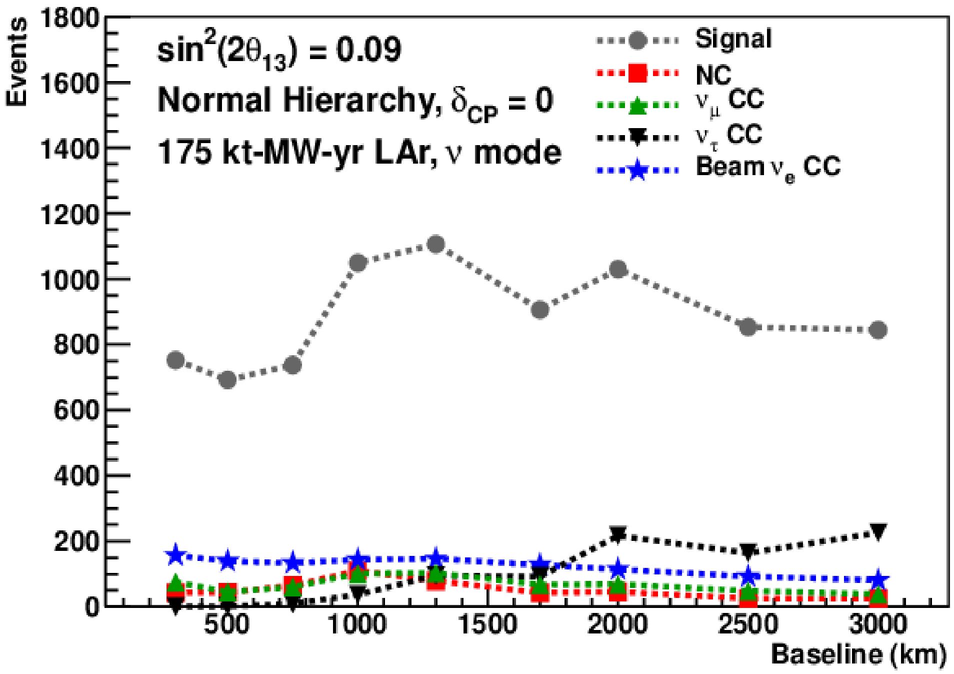
Neutrino Mode Appearance Spectra (Normal Hierarchy)

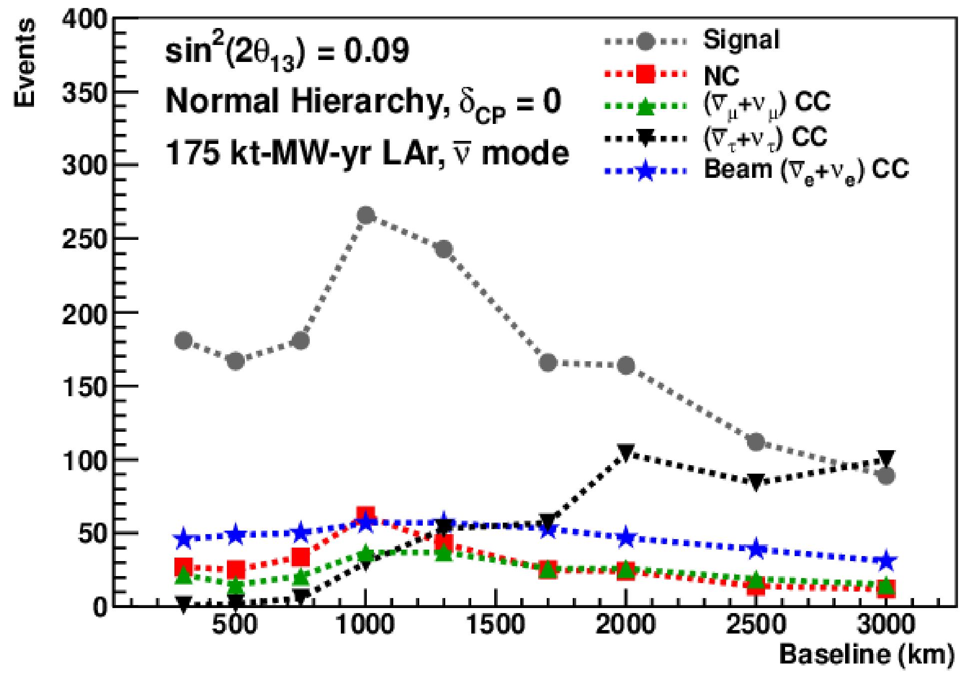


Antineutrino Mode Appearance Spectra (Normal Hierarchy)

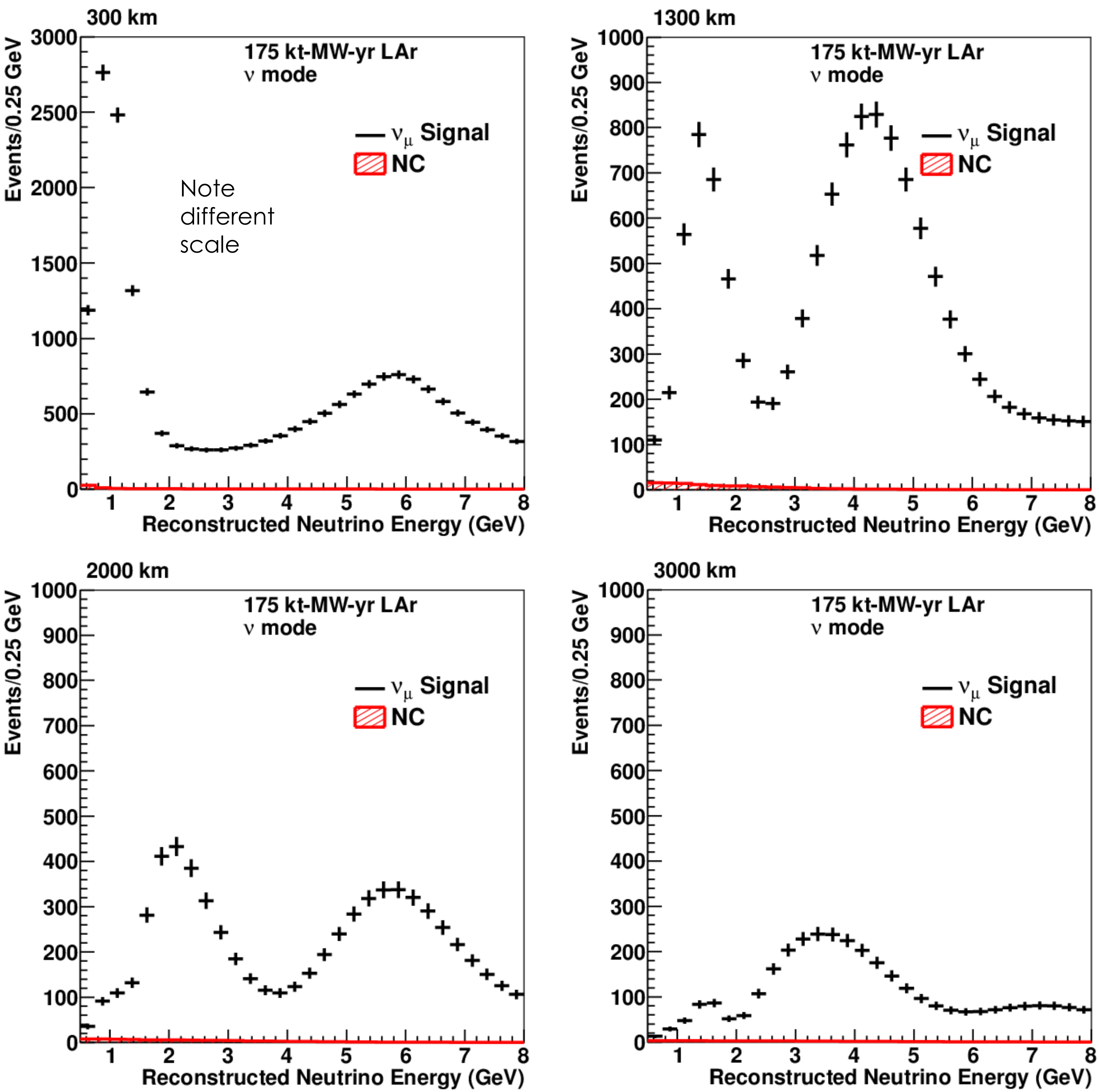


Integrated rate in oscillation energy range



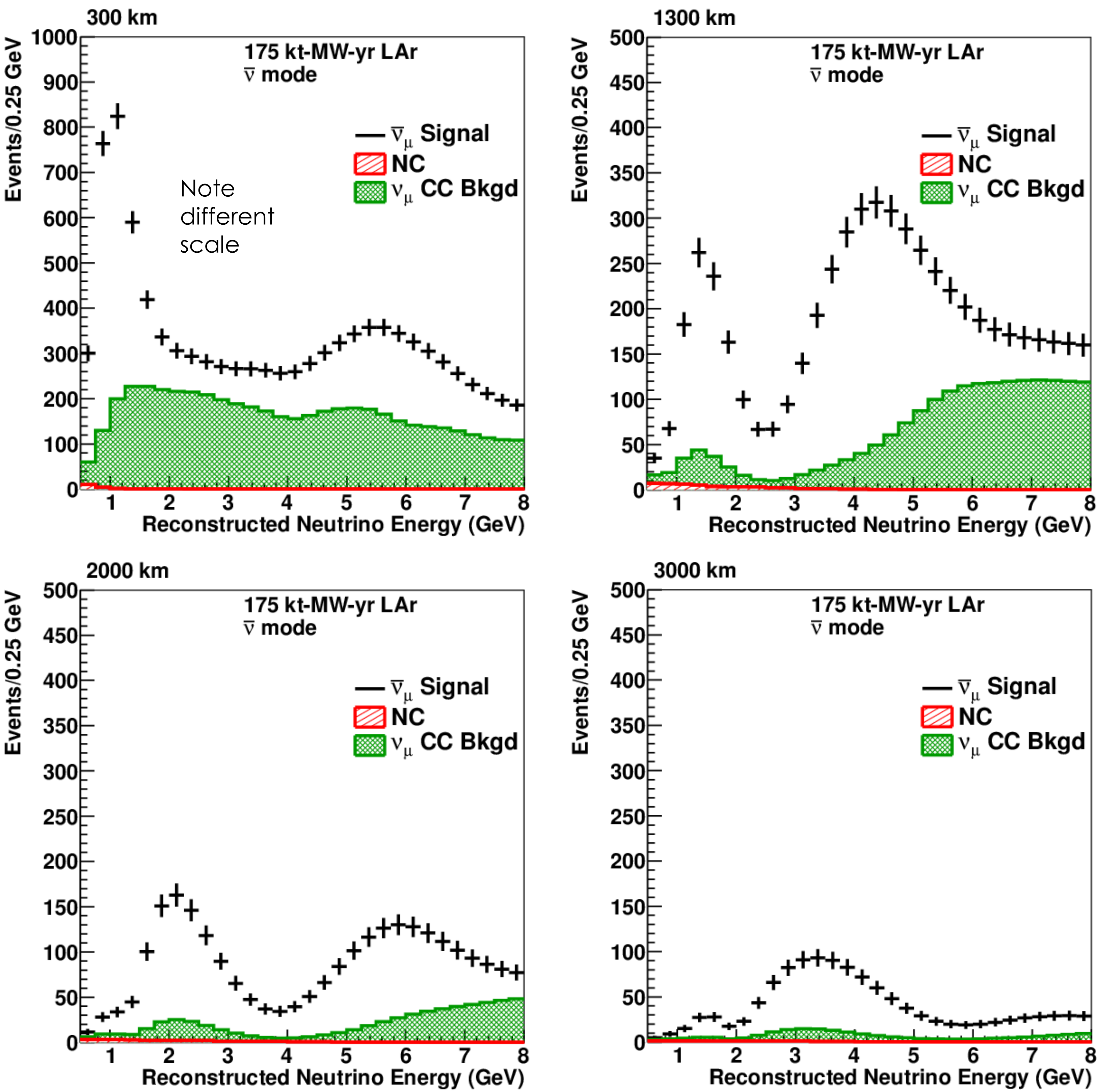


- Roughly constant vs baseline for neutrinos and antineutrinos decrease, as expected from naïve calculation
- ν_τ's increase due to increasing beam energy with baseline
- Other backgrounds roughly constant



Neutrino Mode Disappearance Spectra

Antineutrino Mode Disappearance Spectra

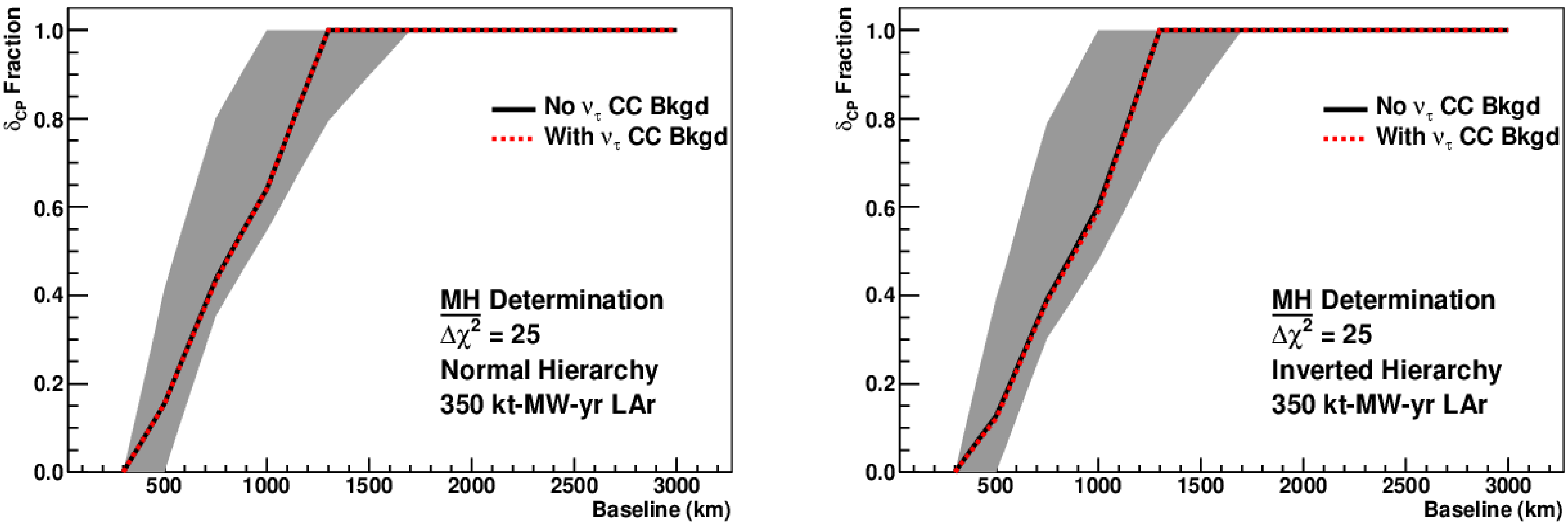


Analysis

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

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

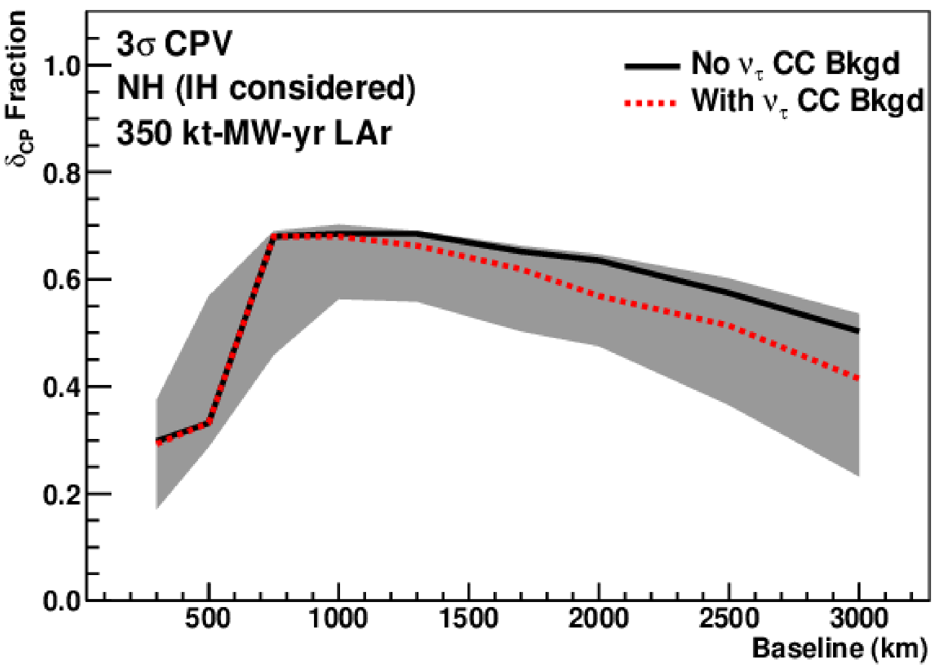
Mass Hierarchy Sensitivity

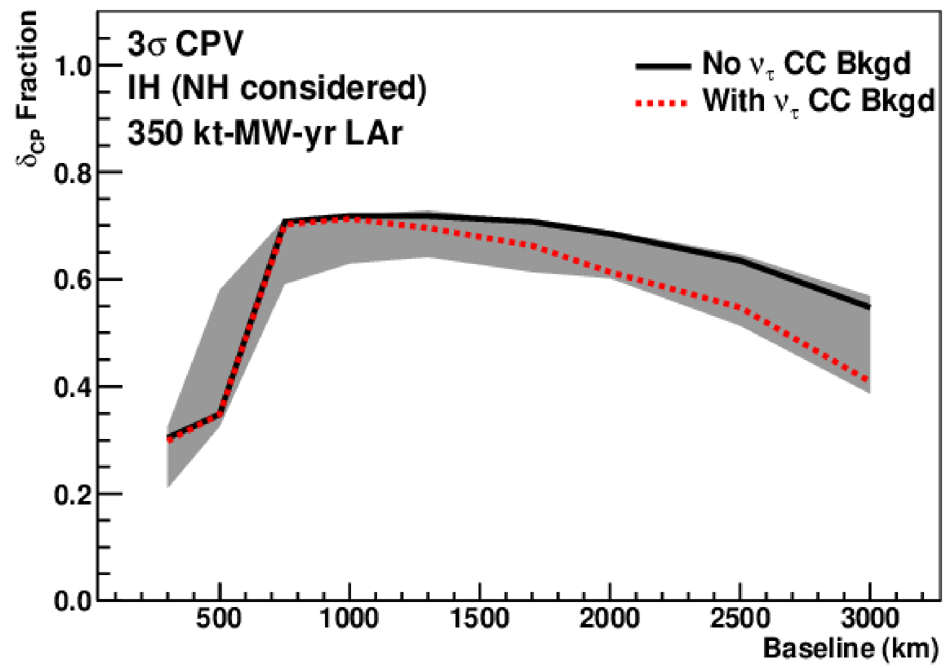


Gray band represents possible variation due to oscillation parameter uncertainty, dominated by the uncertainty in θ_{23}, and considers both octant solutions.

$\overline{\Delta\chi^2}$=25 corresponds to a 99.38% probability of rejecting the incorrect mass hierarchy. X. Qian et al, PRD 86, 113001 (2012), arXiv:1210.3651 [hep-ph].

CP Violation Sensitivity

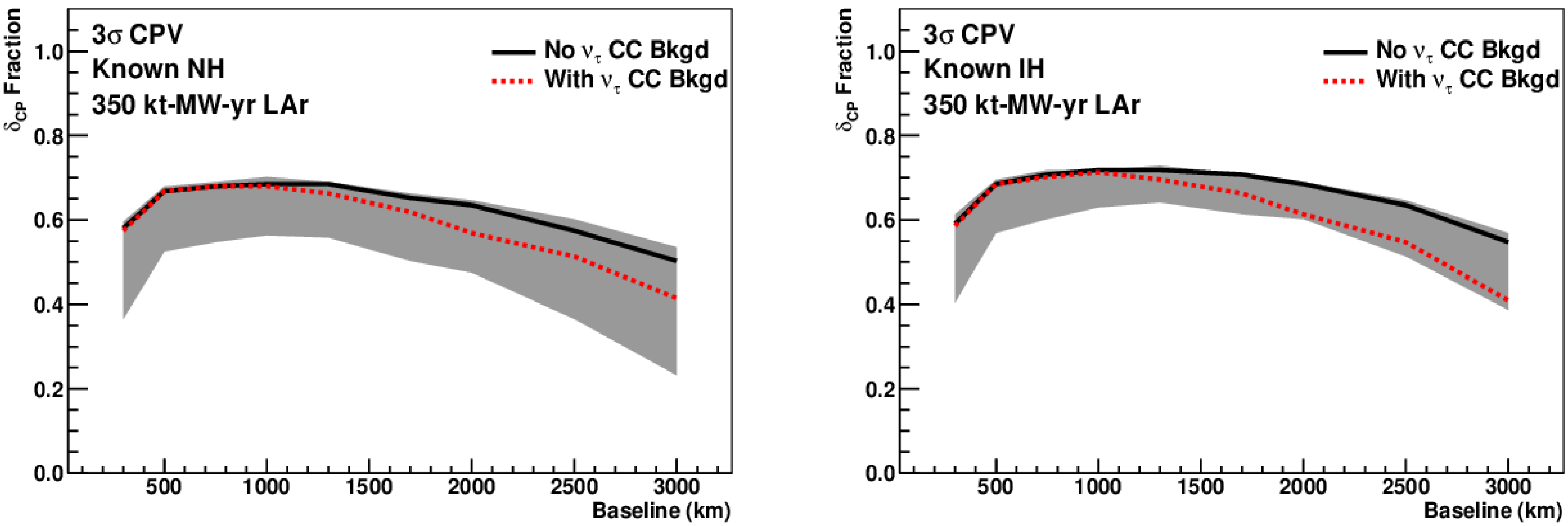




Gray band represents possible variation due to oscillation parameter uncertainty, dominated by the uncertainty in θ_{23}, and considers both octant solutions.

Considering both NH and IH in minimization.

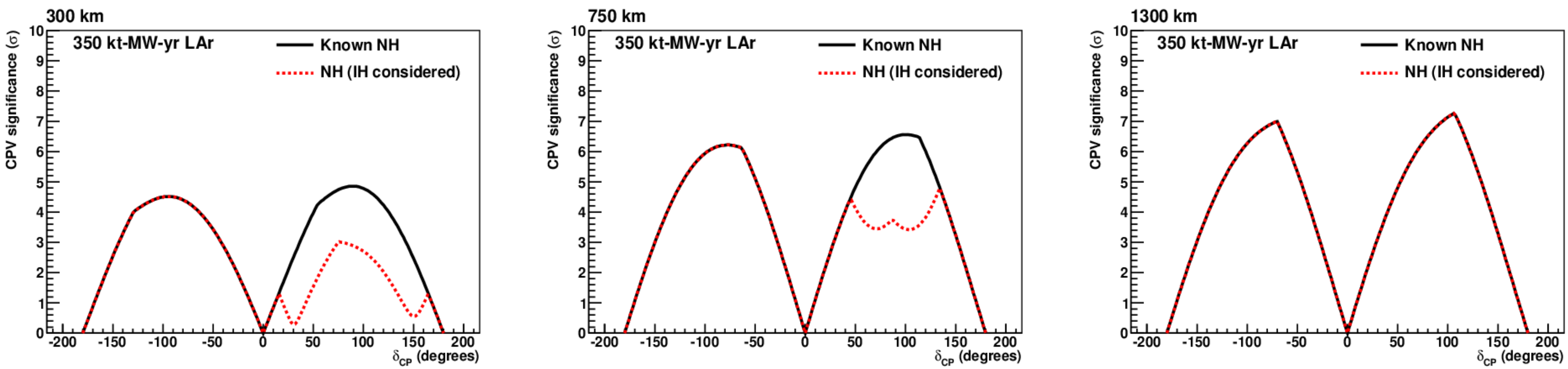
CP Violation Sensitivity – Known Mass Hierarchy



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

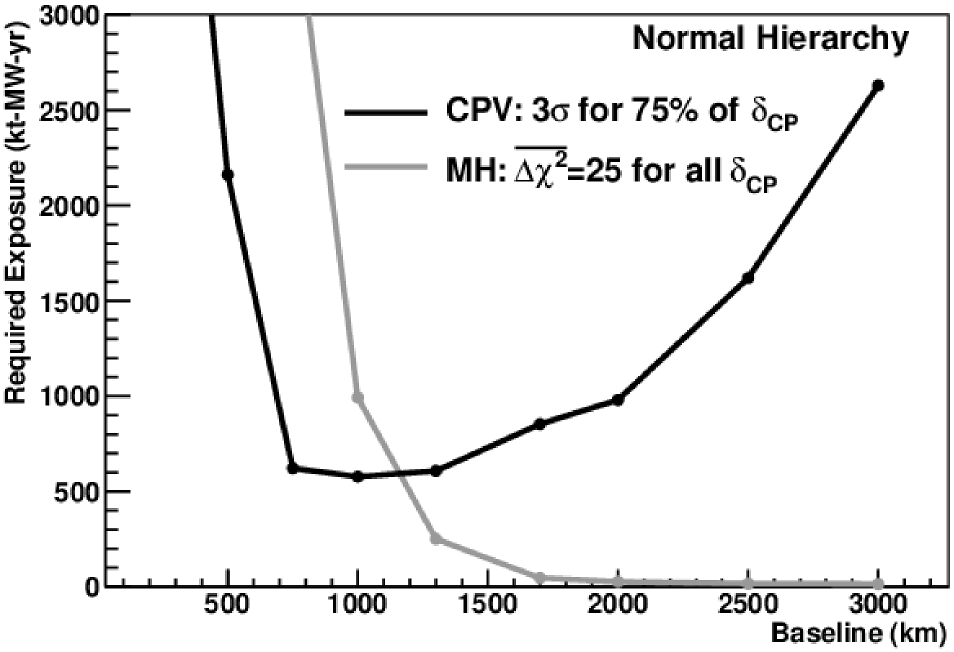
Considering only the true hierarchy in the minimization.

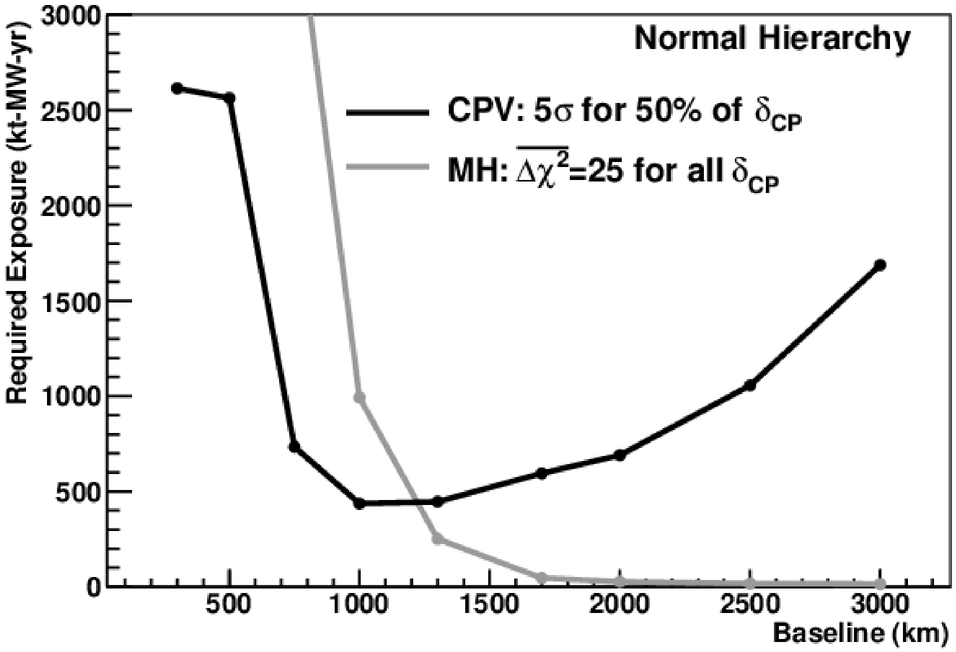
CP Violation Sensitivity – Known Mass Hierarchy



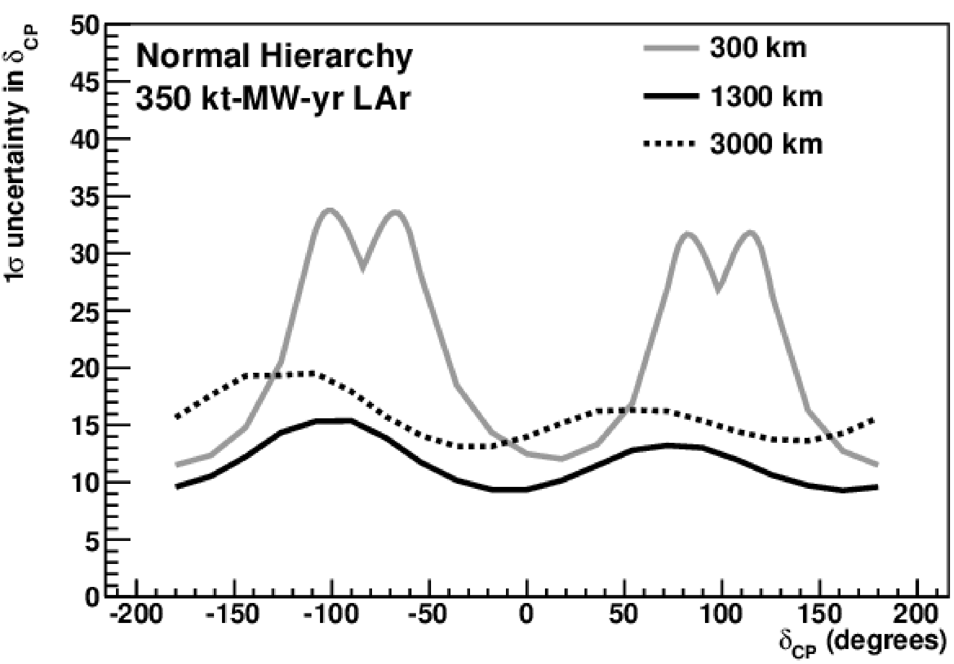
At shorter baselines, there is a difference in the sensitivity to CP violation depending on whether or not the mass hierarchy is known. This is due to the fact that there is no information from the 2nd max to unravel the combined effects of matter and CP asymmetry. At 1300 km and greater, there is no difference between knowing the hierarchy or not.

Sensitivity vs Exposure

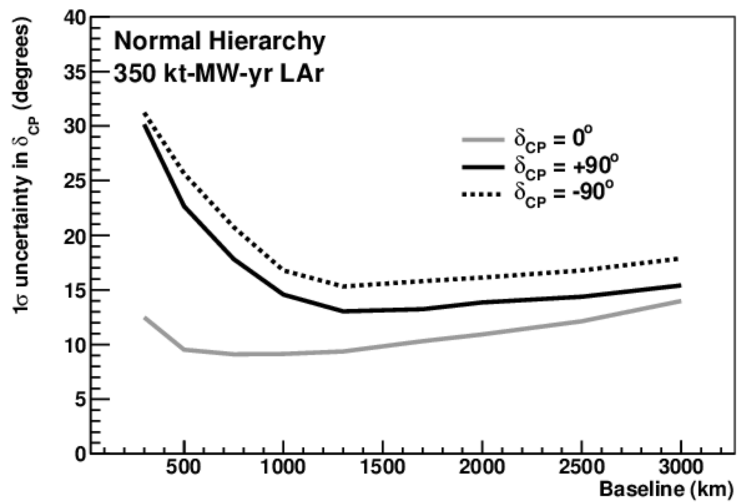


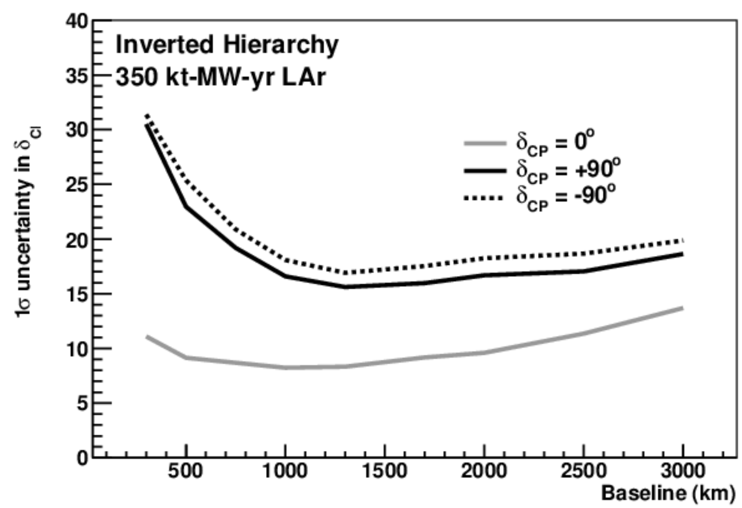


δ_{CP} Parameter Measurement

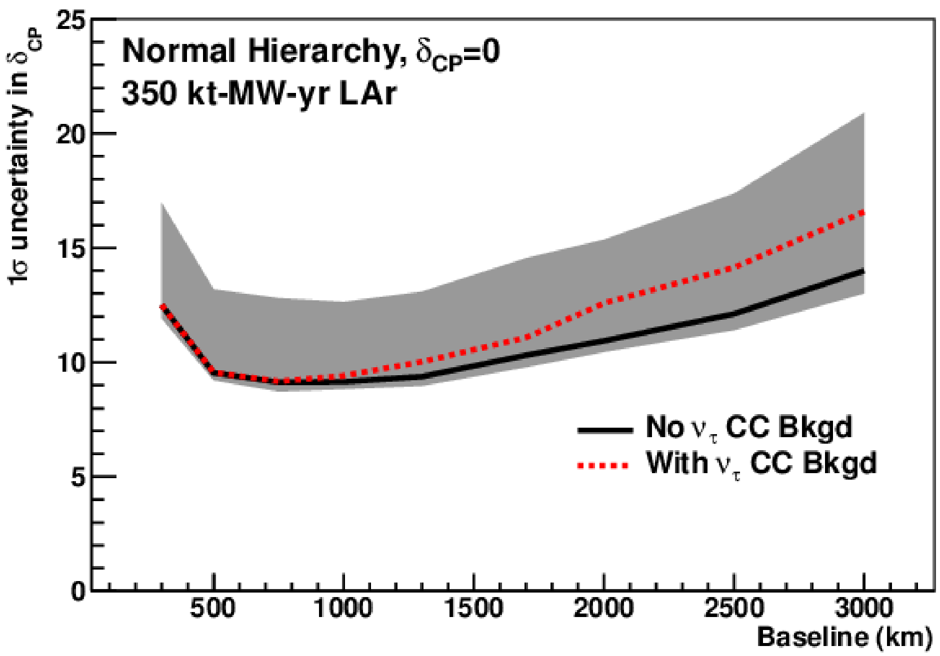


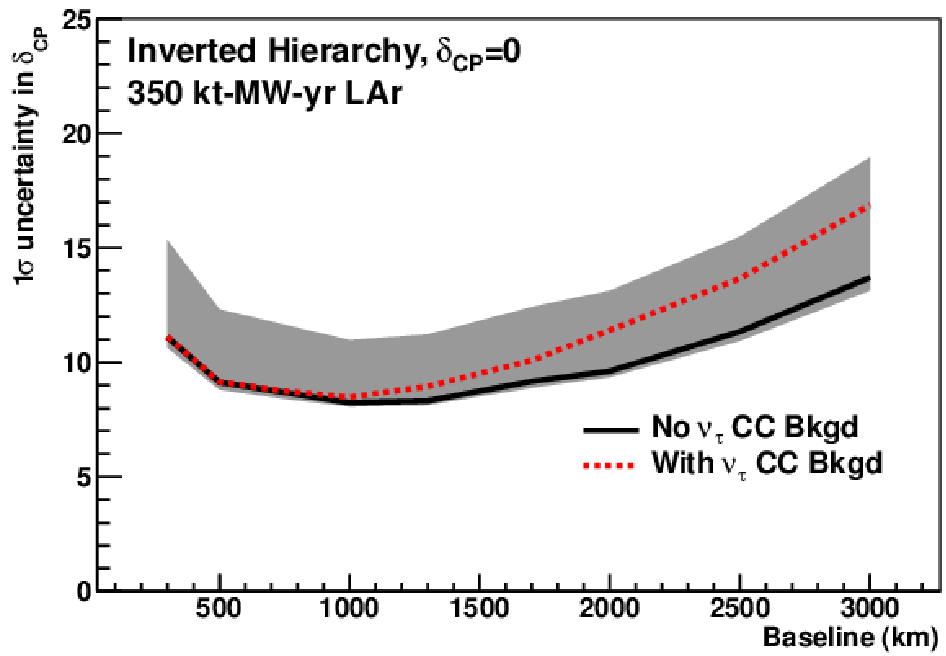
Resolution depends on the δ value – more so at short baselines than at the longer baselines.





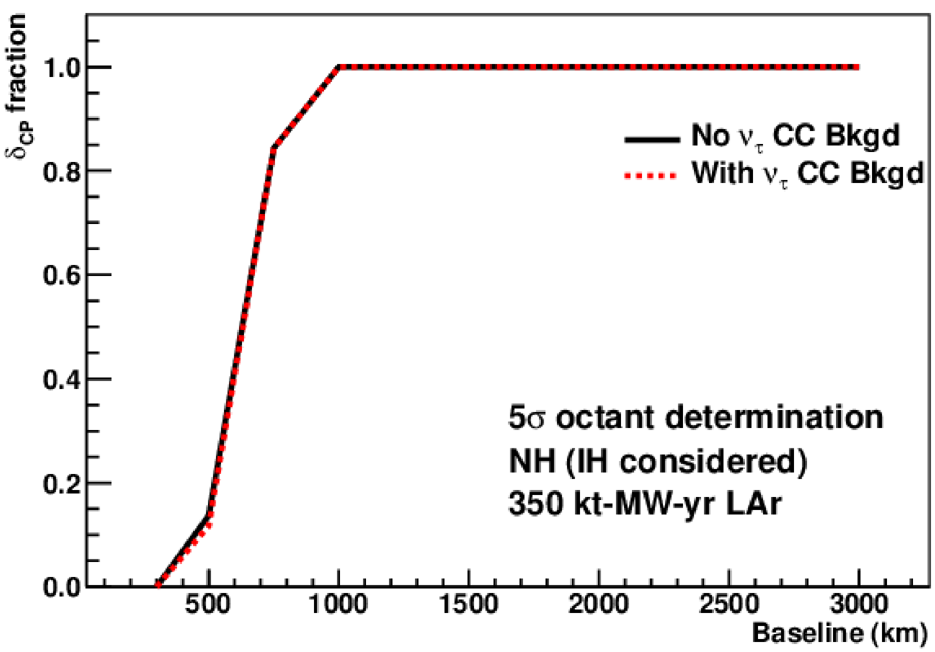
δ_{CP} Parameter Measurement

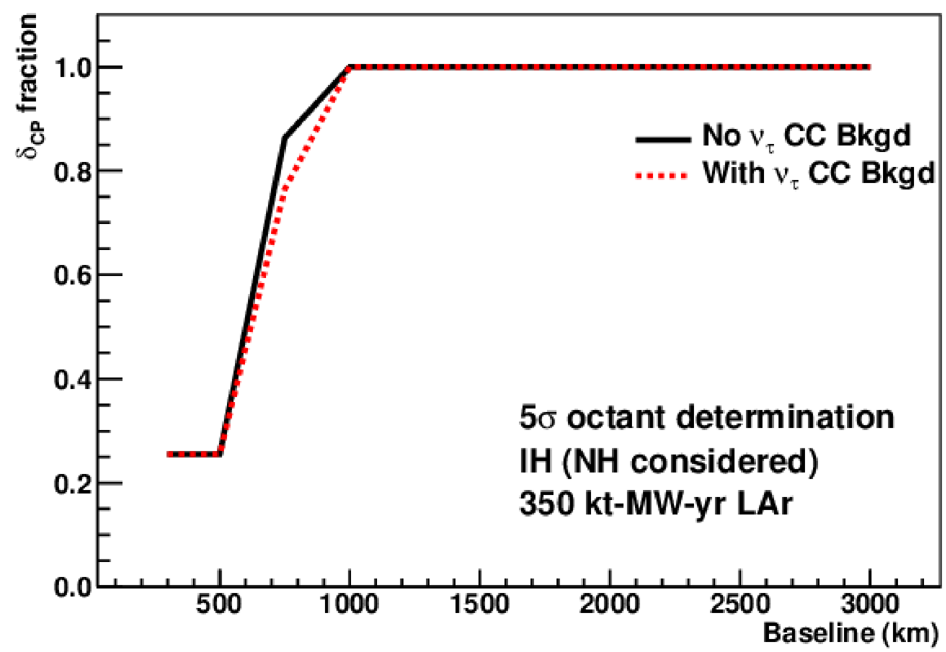


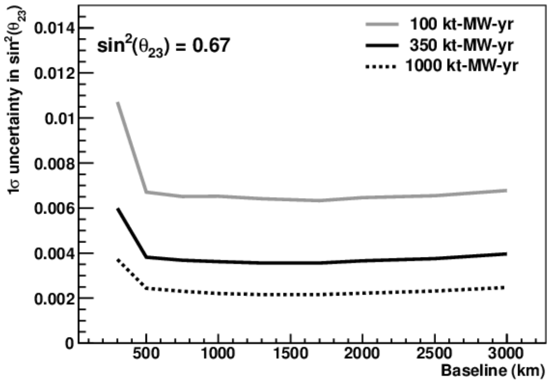


Gray band represents possible variation due to oscillation parameter uncertainty, dominated by the uncertainty in θ_{23}, and considers both octant solutions.

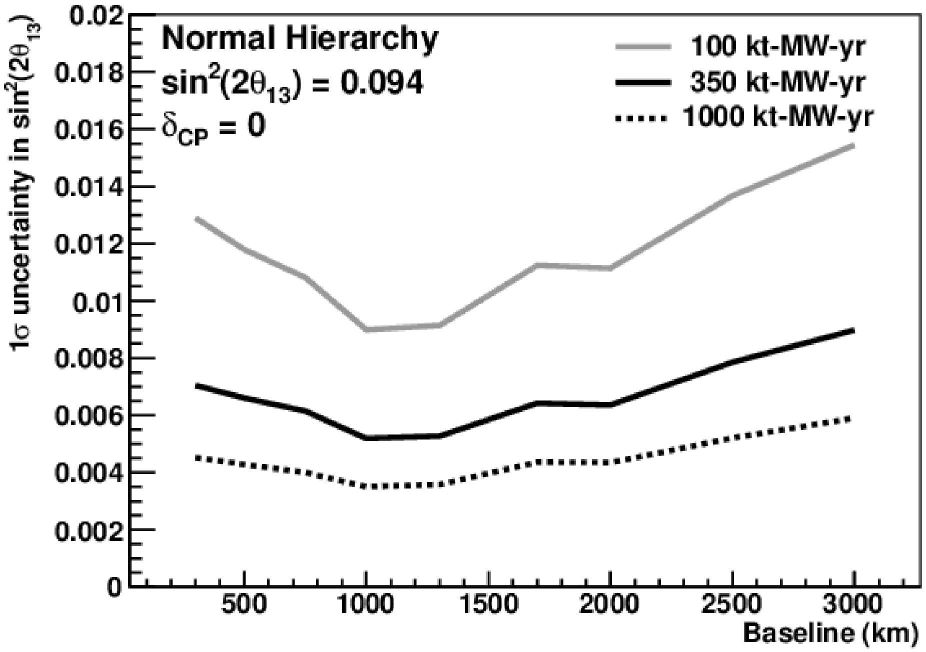
θ_{23} Octant Sensitivity

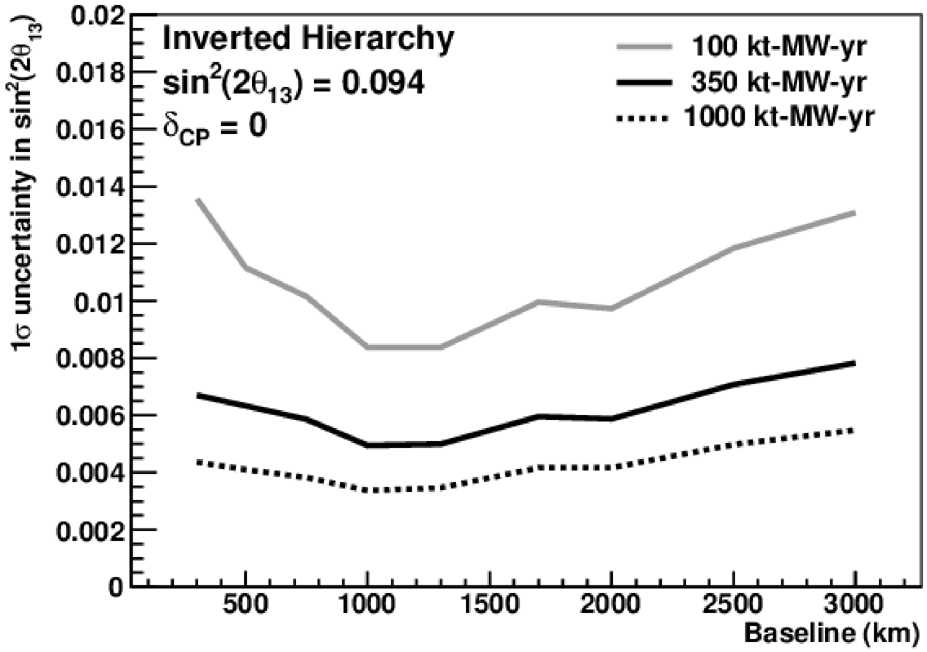






θ_{13} Resolution





Baseline Study Conclusions

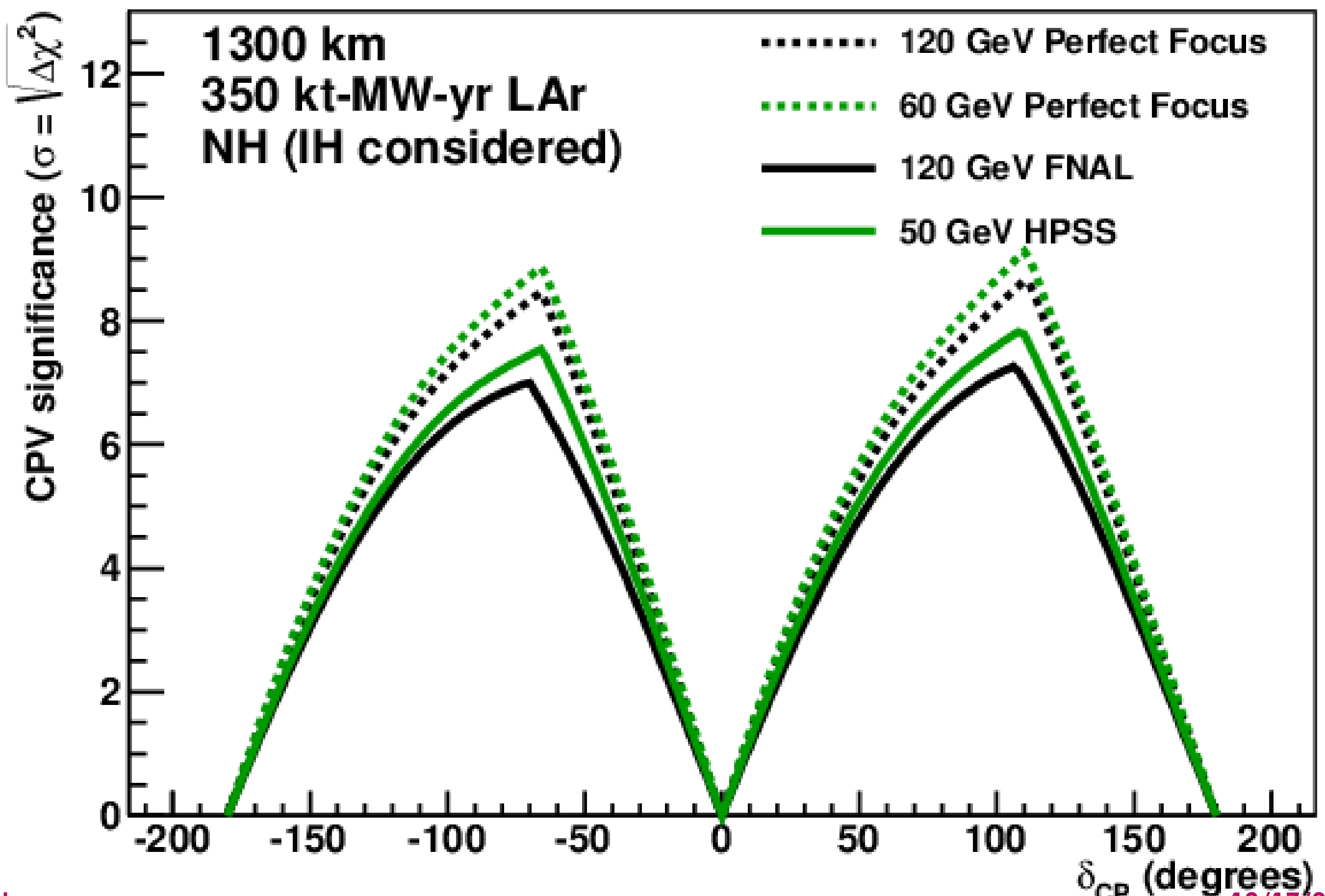
- We can resolve the mass hierarchy at $\overline{\Delta\chi^2}$=25 for baselines 1300 km and greater. Mass hierarchy determination can be made more quickly at long baselines.
- The CP sensitivity is best around 750-1500 km, even without knowing the mass hierarchy. The sensitivity isn't much worse beyond 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.
- **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.**

Proton beam energy

- The highest power from the Fermilab proton complex comes at 120 GeV, so our study used this assumption.
- Lowest energy without significant power loss is 60 GeV. (1.04 MW at 60 GeV vs. 1.2 MW at 120 GeV with PIP-II)
- What if we try to further exploit the information in the 2nd max by using a lower proton beam energy?
- Compare 120 GeV and 60 GeV perfect-focusing Fermilab beams (assuming equal power) to the realistic 120 GeV Fermilab beam from the baseline study and the 50 GeV HPSS beam designed for LBNO (European long-baseline proposal)

Proton beam energy

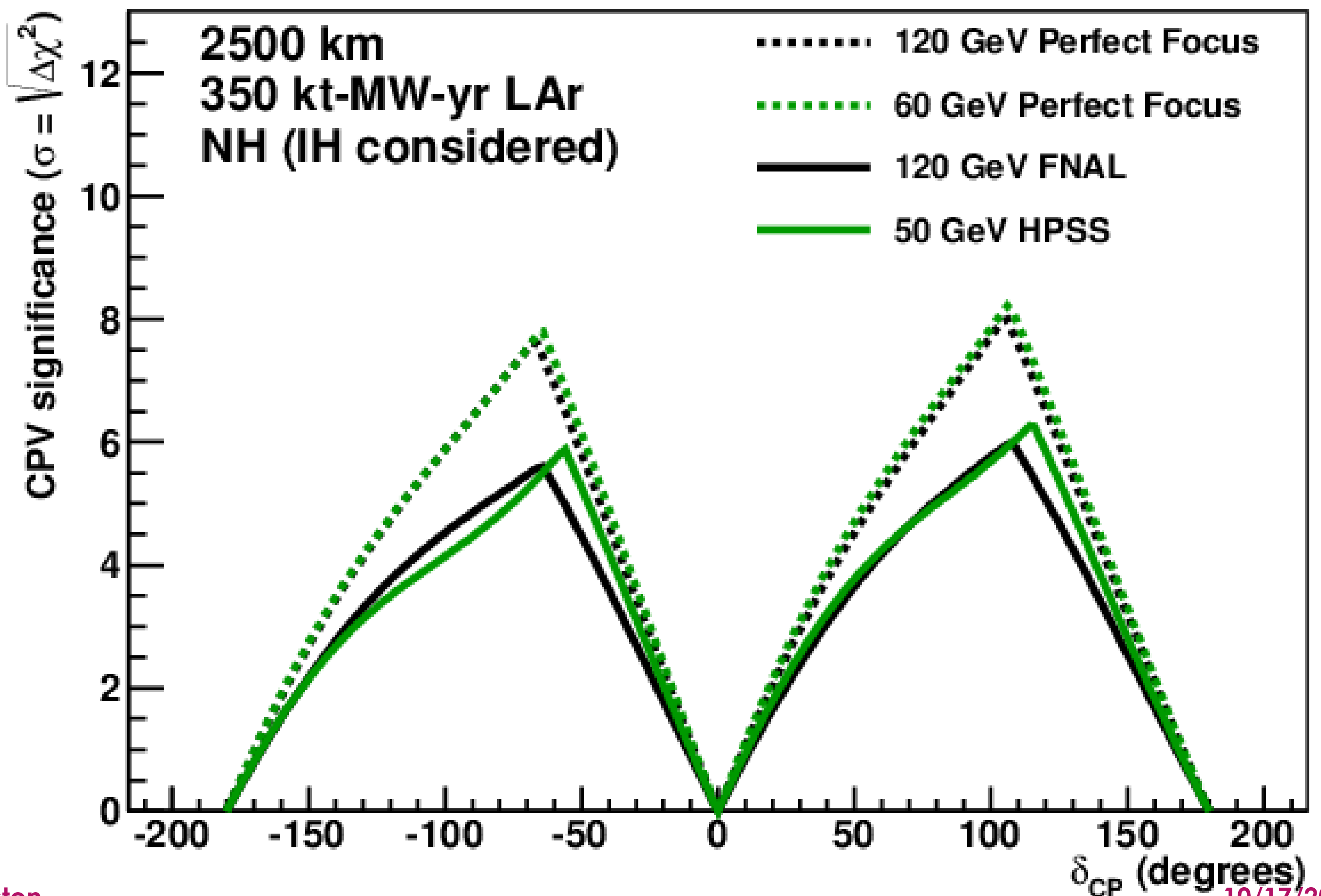
Lower beam energy gives slightly better sensitivity



Proton beam energy

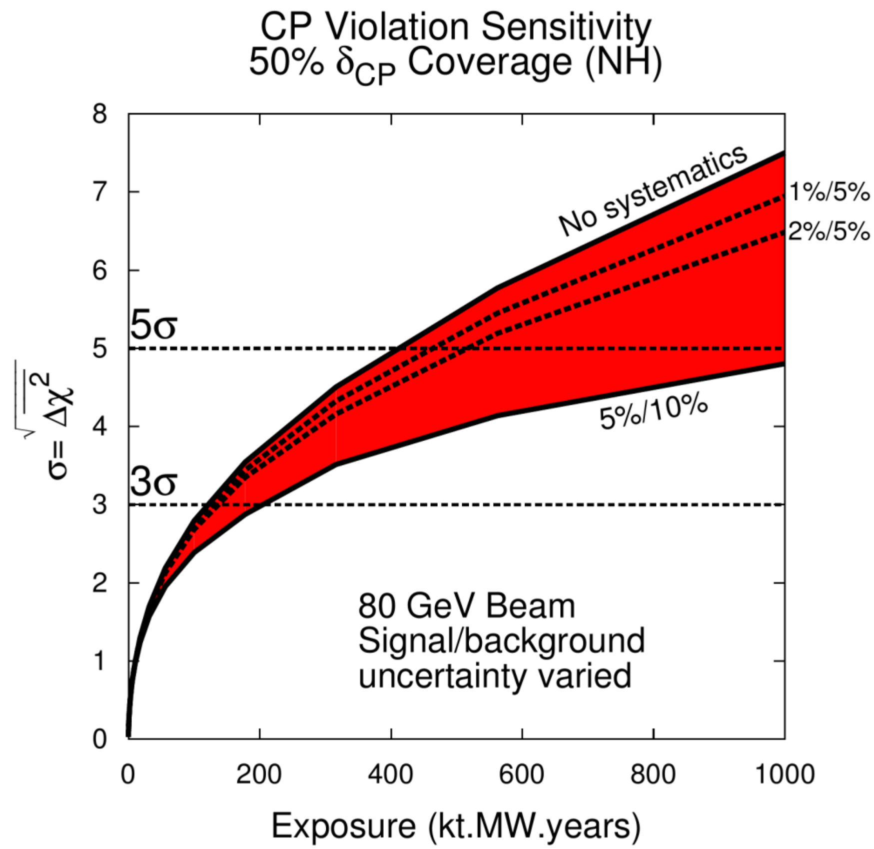
Lower beam energy gives slightly better sensitivity

1300 km has better sensitivity at either energy



Systematics

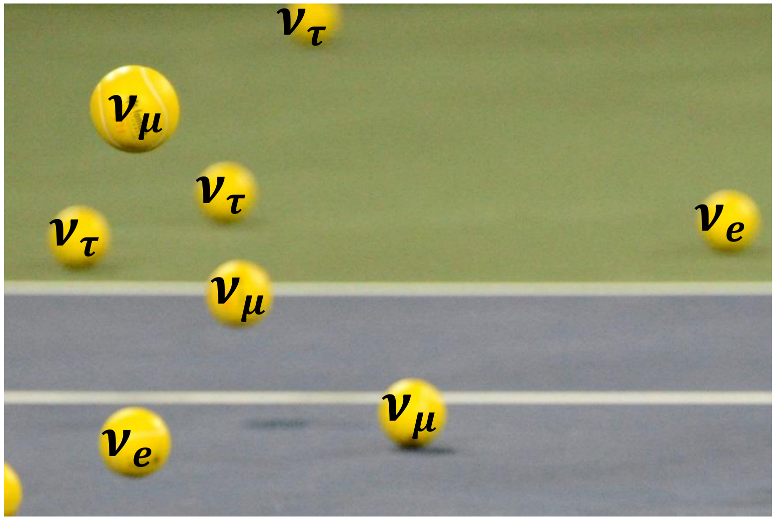
- GLoBES allows us to specify the uncorrelated signal and background normalization uncertainties. The values chosen are well-justified based on previous experiments
- Evaluation of the extent to which more detailed treatment of systematic uncertainties affect sensitivity and the extent to which these uncertainties can be constrained by event samples in the near and far detectors are currently underway (fast MC for example)
- Example: the four-sample fit significantly constrains cross-section uncertainties
- Detailed plan to evaluate sources of systematic uncertainty not currently considered by current tools has been developed.



LBNE Science Doc: arXiv:1307.7335

Summary

- We have conducted a detailed study to determine the optimal baseline for a long-baseline neutrino experiment using a neutrino beam from Fermilab.
- We find that a baseline of at least 1000 km is optimal
- Results are documented in **arXiv:1311.0212**
- Further studies on design optimization are ongoing, including beam parameters, systematics, and others



FERMILAB-PUB-14-379-PPD

Baseline optimization for the measurement of CP violation and mass hierarchy in a long-baseline neutrino oscillation experiment

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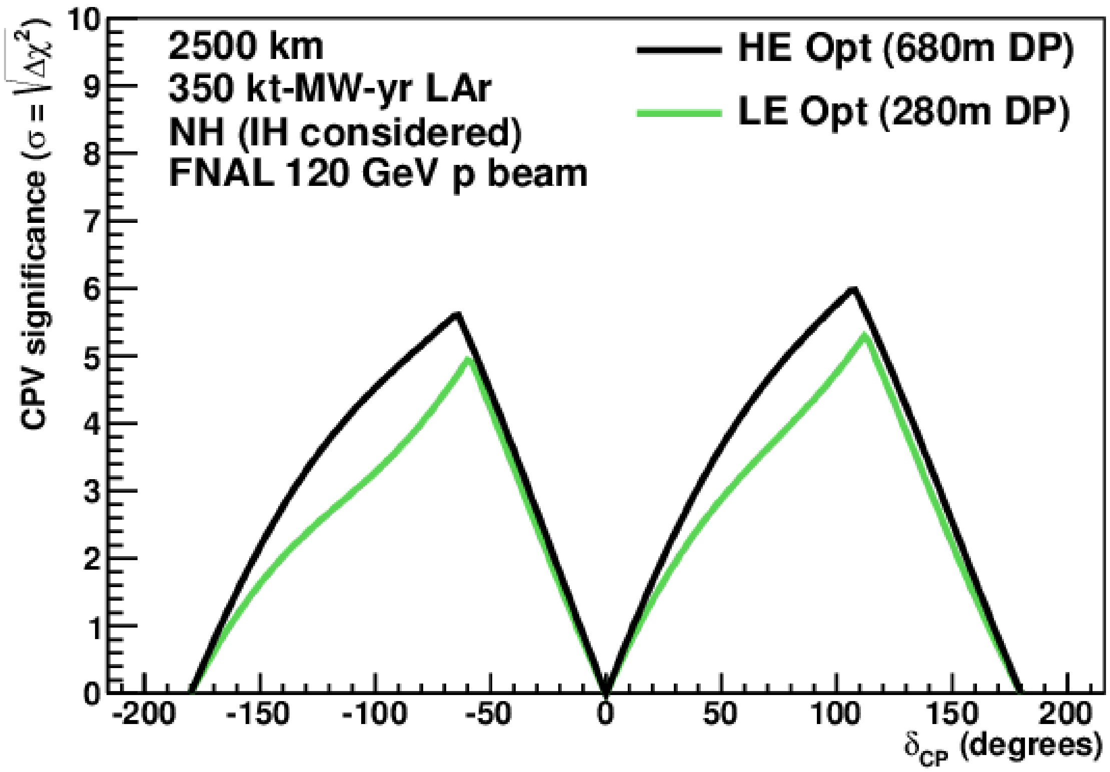
[6] *Univ. of Pittsburgh, Pittsburgh, PA 15260, USA*

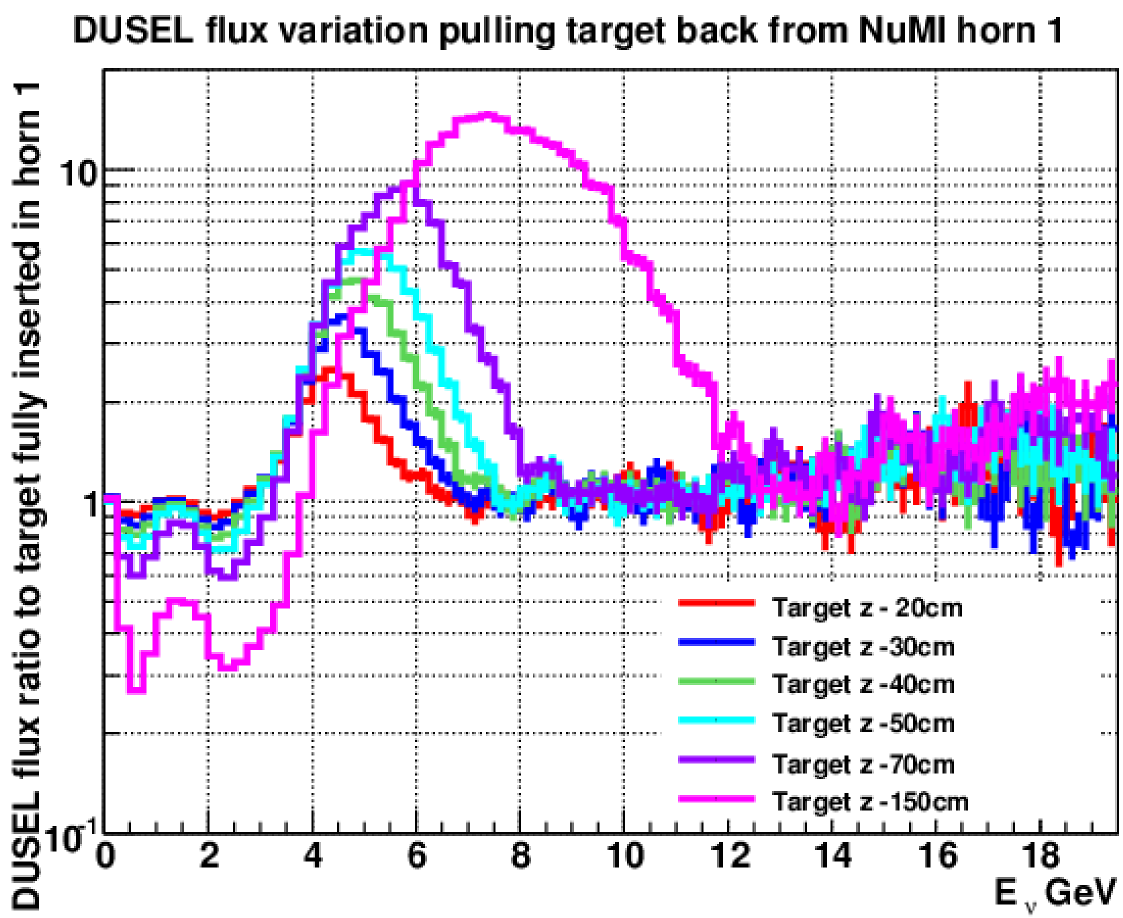
(Dated: October 7, 2014)

Optimize for 2nd max?

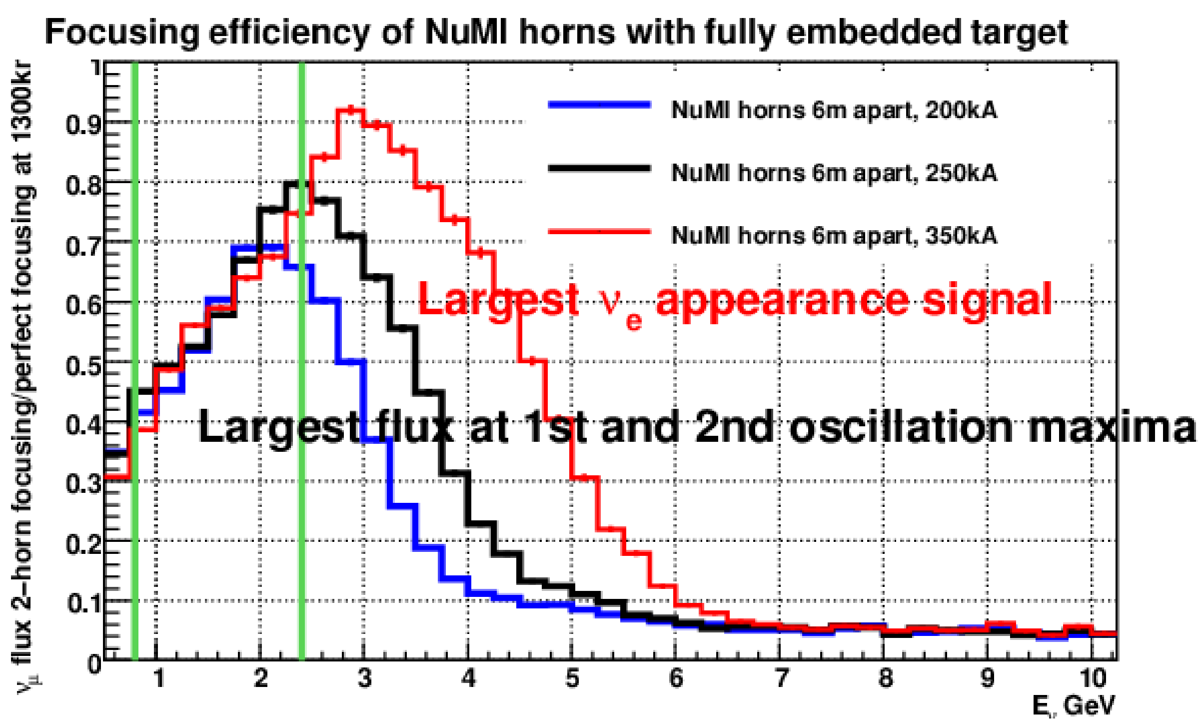


- What if we make a beam that is optimized for lower energy to further exploit the 2nd max? Can we enhance the CP sensitivity at baselines >2000 km?
- LE optimized (focus on 2nd max): 280 m DP, target-horn 1 distance = 0 cm
- HE optimized (focus on 1st max): 680 m DP, target-horn 1 distance = 70 cm (the 2500 km baseline study flux)
- HE optimization has better sensitivity. **At 120 GeV, optimal strategy is focusing on 1st max.**

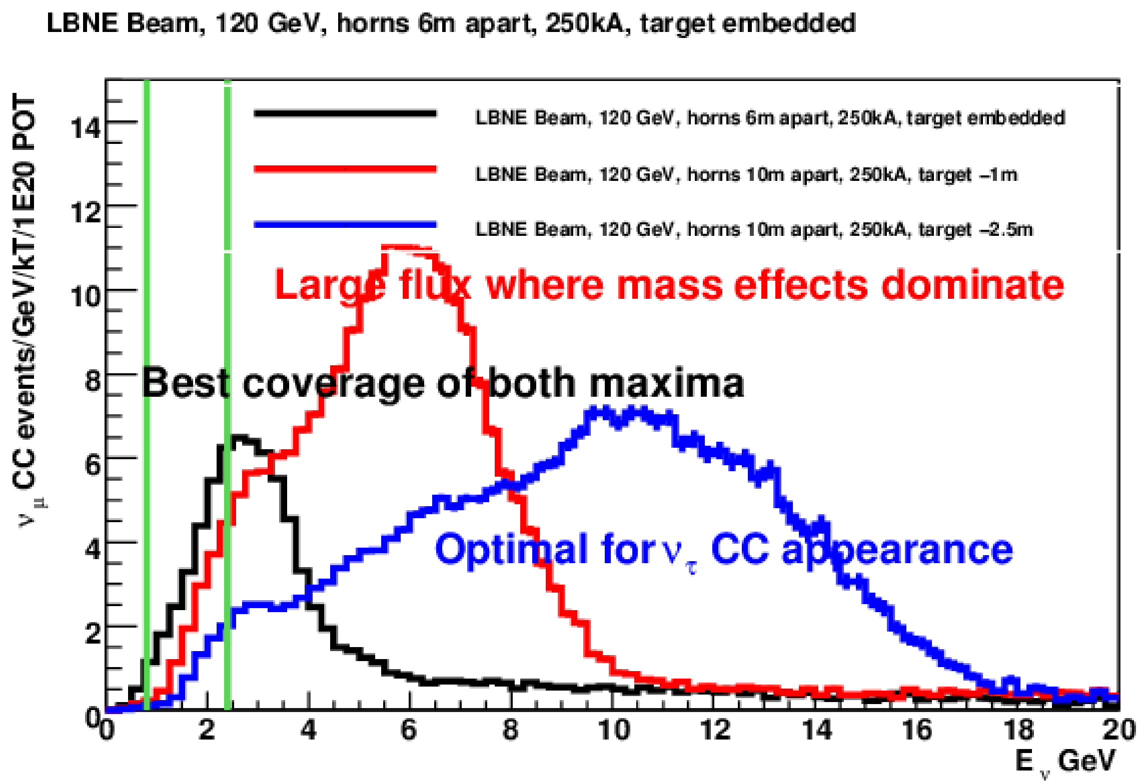
Beamline parameters – Target-horn 1 distance



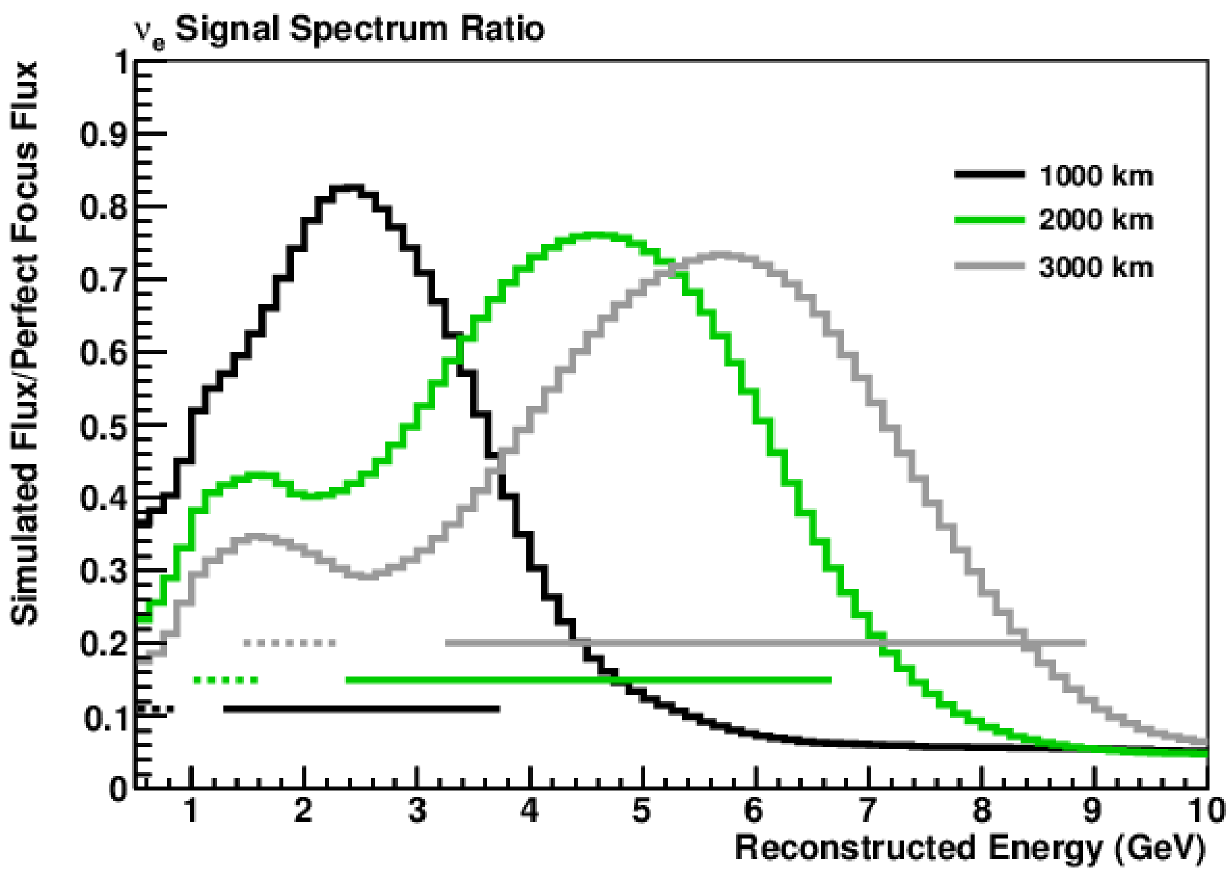
Beamline parameters – Horn current



Beamline parameters – Horn 1-Horn 2 distance and Target-Horn 1 distance

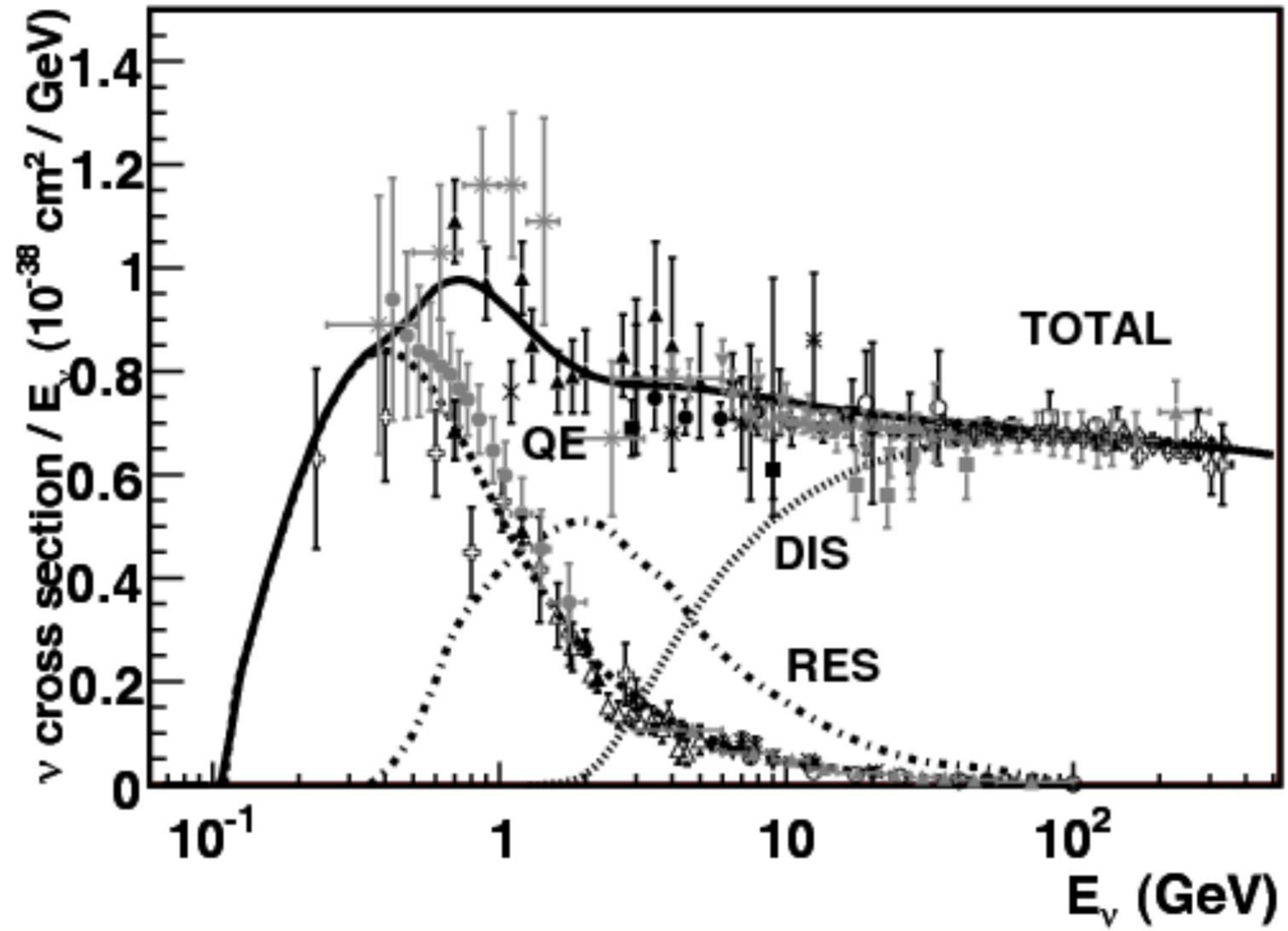


Comparison to Perfect Focusing

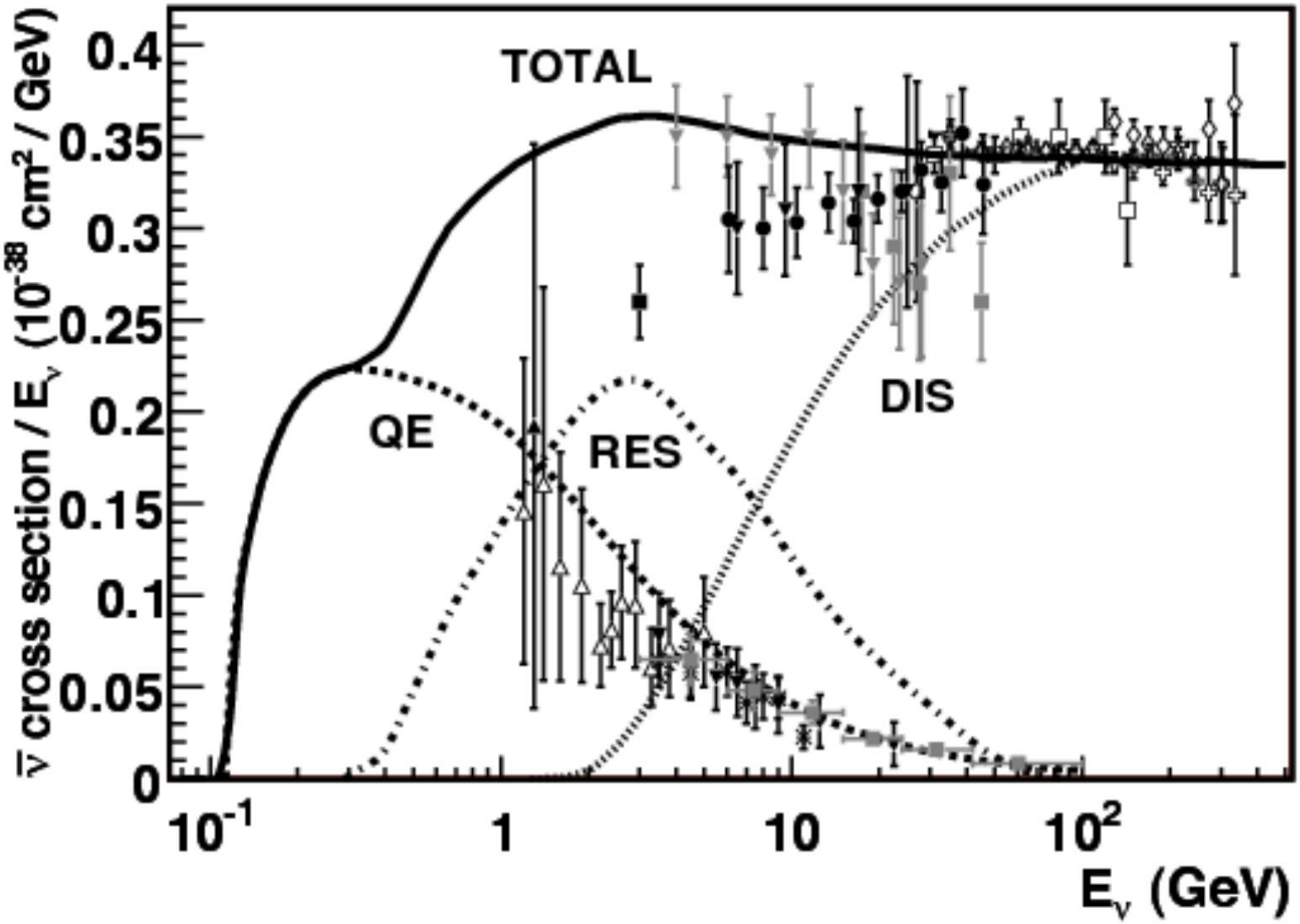


Source of Uncertainty	MINOS Absolute/ν_e	T2K ν_e	LBNE ν_e	Comments
Beam Flux after N/F extrapolation	3%/0.3%	2.9%	2%	MINOS is normalization only. LBNE normalization and shape highly correlated between ν_μ/ν_e.
		Detector effects		
Energy scale (ν_μ)	7%/3.5%	included above	(2%)	Included in LBNE ν_μ sample uncertainty only in three-flavor fit. MINOS dominated by hadronic scale.
Absolute energy scale (ν_e)	5.7%/2.7%	3.4% includes all FD effects	2%	Totally active LArTPC with calibration and test beam data lowers uncertainty.
Fiducial volume	2.4%/2.4%	1%	1%	Larger detectors = smaller uncertainty.
		Neutrino interaction modeling		
Simulation includes: hadronization cross sections nuclear models	2.7%/2.7%	7.5%	$\sim 2\%$	Hadronization models are better constrained in the LBNE LArTPC. N/F cancellation larger in MINOS/LBNE. X-section uncertainties larger at T2K energies. Spectral analysis in LBNE provides extra constraint.
Total	**5.7%**	**8.8%**	**3.6 %**	**Uncorrelated ν_e uncertainty in full LBNE three-flavor fit = 1-2%.**

Goals/ reasonable expectations based on previous experience



$$\sigma^{\nu}(E_\nu) \sim 0.75 \times 10^{-42}(\mathrm{m}^2/\mathrm{GeV}/N) \times E_\nu, \quad E_\nu > 1\ \mathrm{GeV}$$



$$\sigma^{\bar{\nu}}(E_\nu) \sim 0.34 \times 10^{-42}(\mathrm{m}^2/\mathrm{GeV}/N) \times E_\nu, \quad E_\nu > 1\ \mathrm{GeV}$$