LBN* AND INO: PHYSICS ASPECTS

Raj Gandhi

Harish Chandra Research Institute
and
Fermi National Accelerator Laboratory

Introduction…..

Post P5 report, many changes and churning in pre-P5 LBNE, mainly as a consequence of full internationalization effort.

Details in M Diwan, this conf

An important consequence of this has been the re-opening of many issues previously considered as settled, e.g baseline, beam design , physics priorities etc.

Quoting from recently concluded IIEB meeting decision,

> **"Two Flagship measurements...CP and Mass Hierarchy (in that order 5 sigma for both) but also a broad program of supporting important science e.g. mixing from atmospheric neutrinos, proton decay, SN neutrinos, cross sections.... "**

This has led to a re-opening of the questions (among others) : Is 1300 km the best baseline for the physics of CP and hierarchy determination? Is something closer to 2500 km better? How good a near detector does one need to achieve the necessary precision to reach these goals?

I will try to report on on-going physics discussions and calculations on the above questions…

CP Violation and a long baseline: some general features.....

The determination of CP violation depends on the appearance probability , and certain important and nice conclusions follow from an examination of the basic expression :

Marciano hep-ph 0108181 , Marciano and Parsa, hep-ph 0610258

$O(\alpha^2)$

$$P(\nu_\mu \to \nu_e) = PI(\nu_\mu \to \nu_e) + PII(\nu_\mu \to \nu_e) + PIII(\nu_\mu \to \nu_e) + \text{matter} + \text{smaller terms}$$

not necessarily small, depending on L

"atmospheric" term, large

$$P_I(\nu_\mu \to \nu_e) = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{31}L}{4E_\nu}\right)$$

"interference" term, CP dependent

$$\begin{aligned} P_{II}(\nu_\mu \to \nu_e) &= \frac{1}{2}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}\cos\theta_{13} \\ &\sin\left(\frac{\Delta m^2_{21}L}{2E_\nu}\right) \times \left[\sin\delta\sin^2\left(\frac{\Delta m^2_{31}L}{4E_\nu}\right)\right. \\ &\left. + \cos\delta\sin\left(\frac{\Delta m^2_{31}L}{4E_\nu}\right)\cos\left(\frac{\Delta m^2_{31}L}{4E_\nu}\right)\right] \end{aligned}$$

$$P_{III}(\nu_\mu \to \nu_e) = \sin^2 2\theta_{12}\cos^2\theta_{13}\cos^2\theta_{23}\sin^2\left(\frac{\Delta m^2_{21}L}{4E_\nu}\right)$$

"solar" term, small

CP Violation and a long baseline: some general features.....

This allows us to write the CP asymmetry, defined as

$$A_{CP} \equiv \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)}$$

in the form,

$$A_{CP} \simeq \frac{\cos\theta_{23}\sin 2\theta_{12}\sin\delta}{\sin\theta_{23}\sin\theta_{13}}\left(\frac{\Delta m^2_{21} L}{4E_\nu}\right)$$

$$+\text{matter effects}$$

Can define a (statistical) FOM,

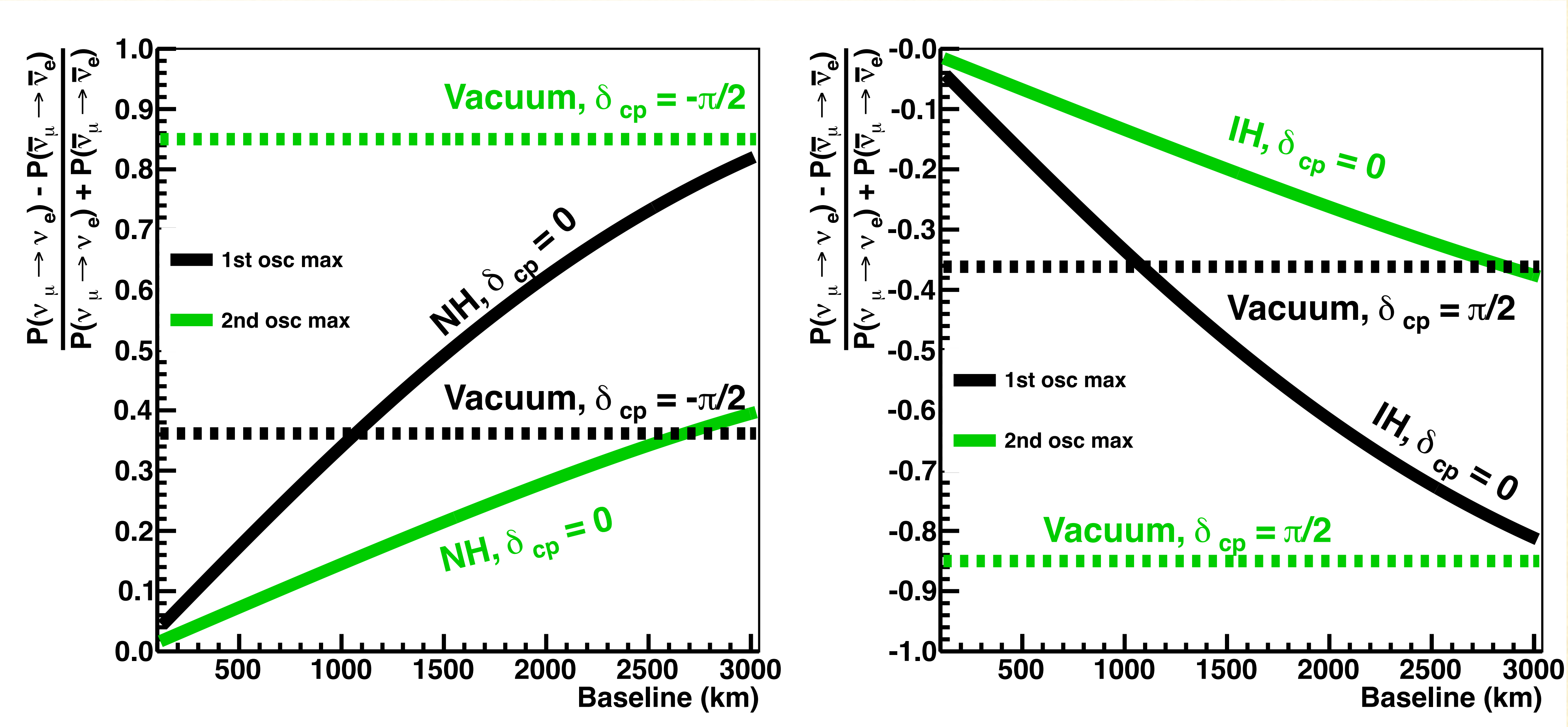
$$\left(\frac{\delta A_{CP}}{A_{CP}}\right)^{-2} = \frac{A^2_{CP} N}{1 - A^2_{CP}}$$

Note the conclusions which follow:

To a reasonable approximation, the "goodness" of the CP measurement is independent of L and sinΘ_13

CP Violation and a long baseline: some general features.....

Look at first two oscillation maxima



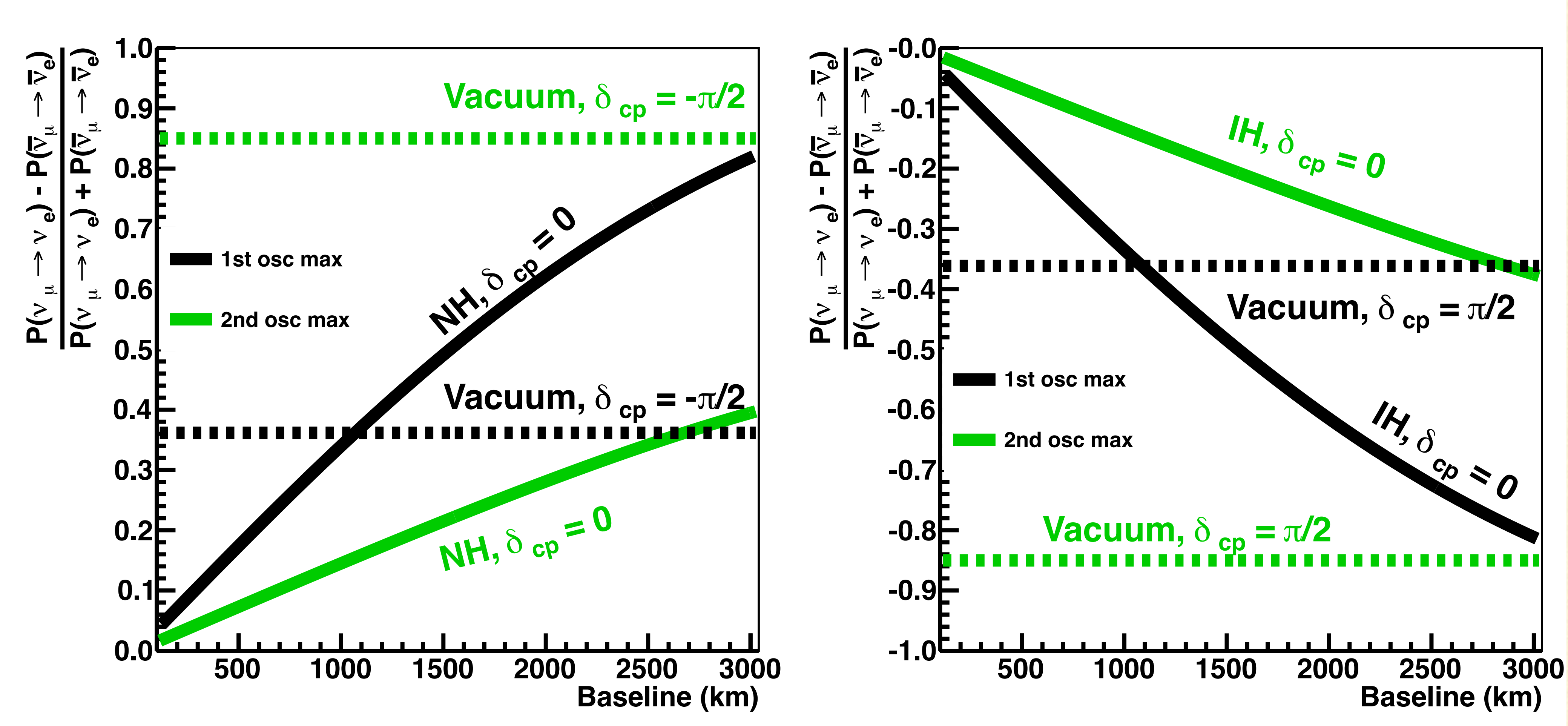
LBNE Physics WG, M Bass et al 1311.0212

Once L / E is fixed to maxima, CP asymmetry due to to δ_{cp} alone is constant with baseline, while that due to matter grows with the baseline.

Thus, hierarchy determination will be benefited by a longer baseline, because the intrinsic difference between neutrinos and anti-neutrinos increases, provided appearance event rate is constant.

CP Violation and a long baseline: some general features.....

Look at first two oscillation maxima



LBNE Physics WG, M Bass et al 1311.0212

At first oscillation max , intrinsic CP asymmetry larger than matter asymmetry for baselines less than 1000 km.
At second oscillation max, intrinsic CP asymmetry larger than matter asymmetry for all baselines. Thus second oscillation max offers good CP sensitivity for both hierarchies. However, rates at second max are typically 10% of those at the first max.

The "constant" event rate..........

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

$$\begin{aligned} \Phi^{\nu_\mu}(E_\nu, L) &\approx \frac{C}{L^2}, \quad C = \text{number of } \nu_\mu/\text{m}^2/\text{GeV}/(\text{MW-yr}) \text{ at 1 km} \\ P^{\nu_\mu \to \nu_e}(E_\nu, L) &\approx \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2(1.27\Delta m^2_{31} L/E_\nu) \\ \sigma^{\nu_e}(E_\nu) &= 0.67 \times 10^{-42} (\text{m}^2/\text{GeV}/N) \times E_\nu, \quad E_\nu > 0.5 \text{ GeV} \\ N_{\rm target} &= 6.022 \times 10^{32} N/\text{kt} \end{aligned}$$

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

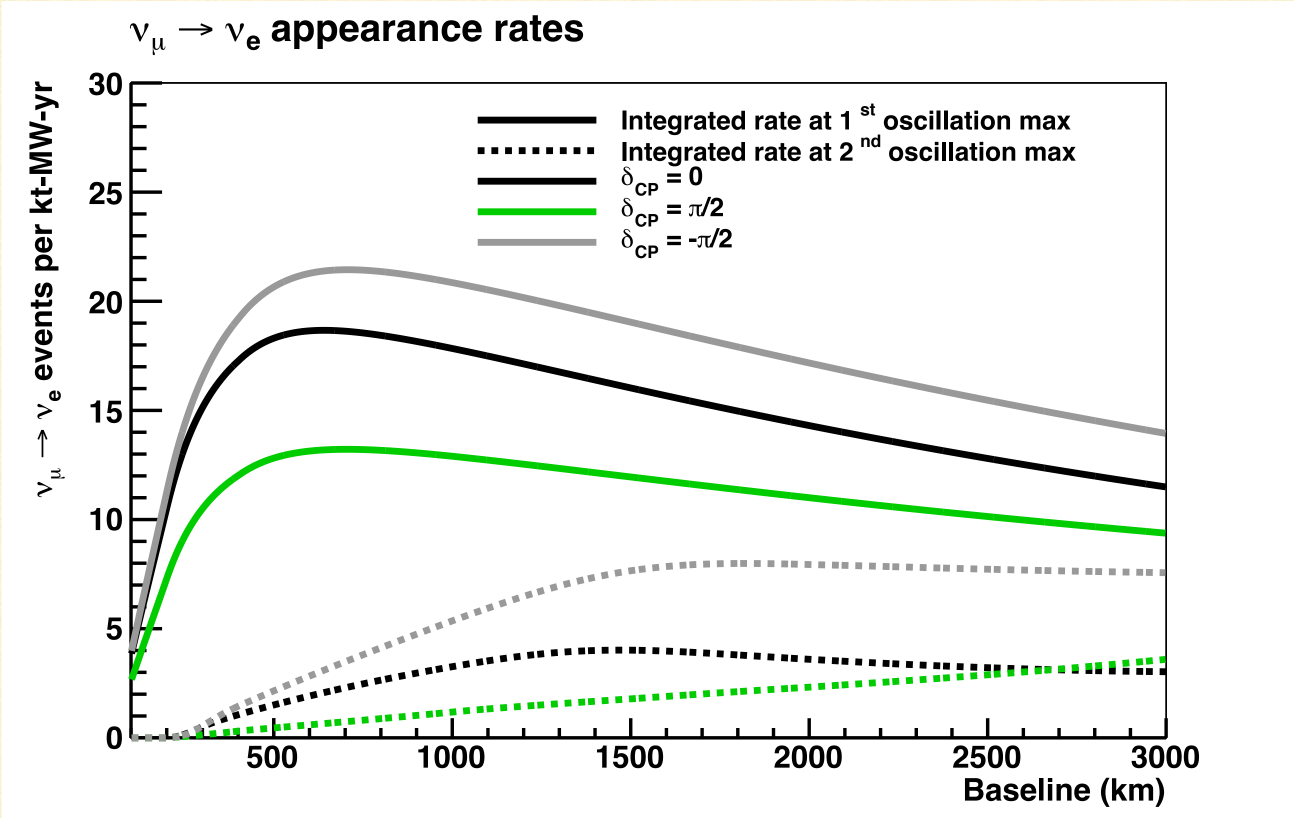
$$x \equiv L/E_\nu, \; a \equiv 1.27\Delta m^2_{31}.$$

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

Event rate roughly indépendant of L ....

The Event rate..........(more realistic calculation)

LBNE Physics WG, M Bass et al 1311.0212



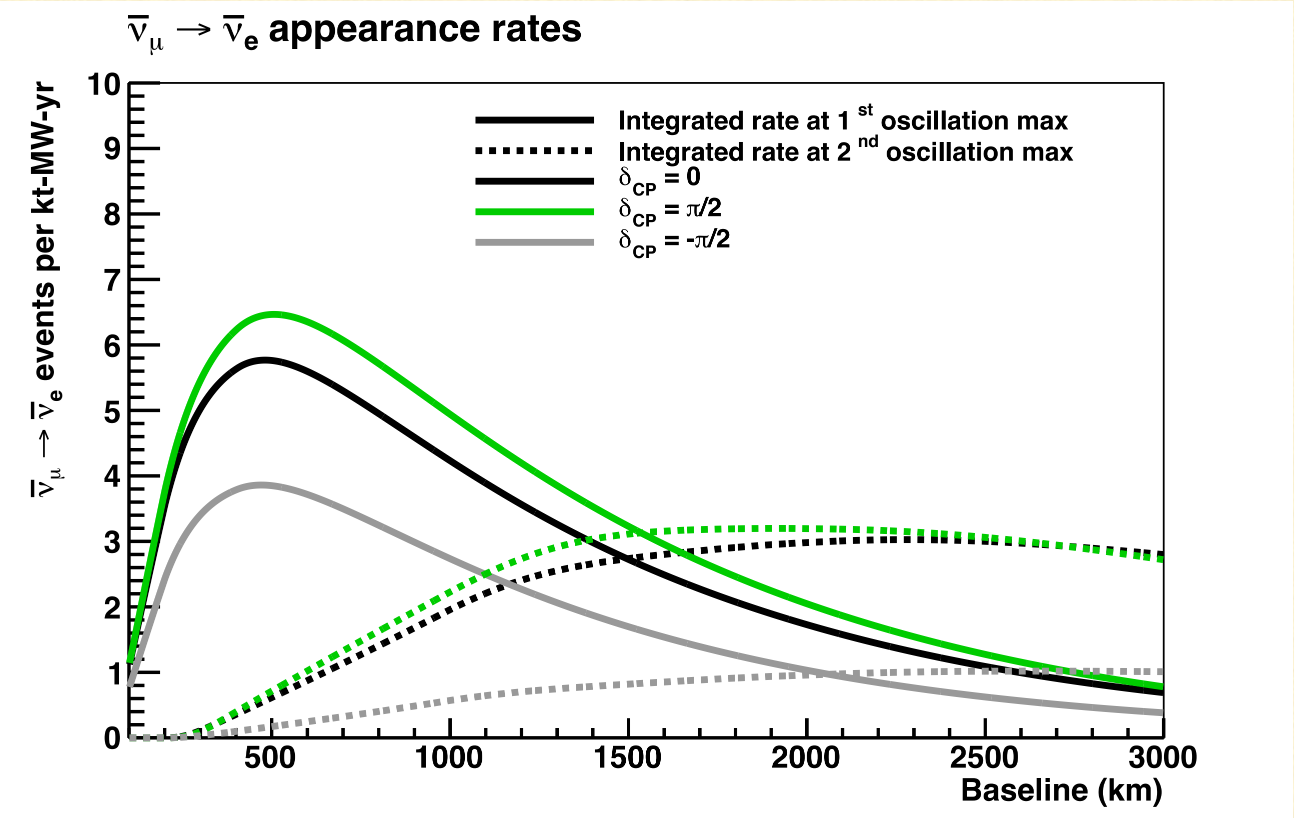


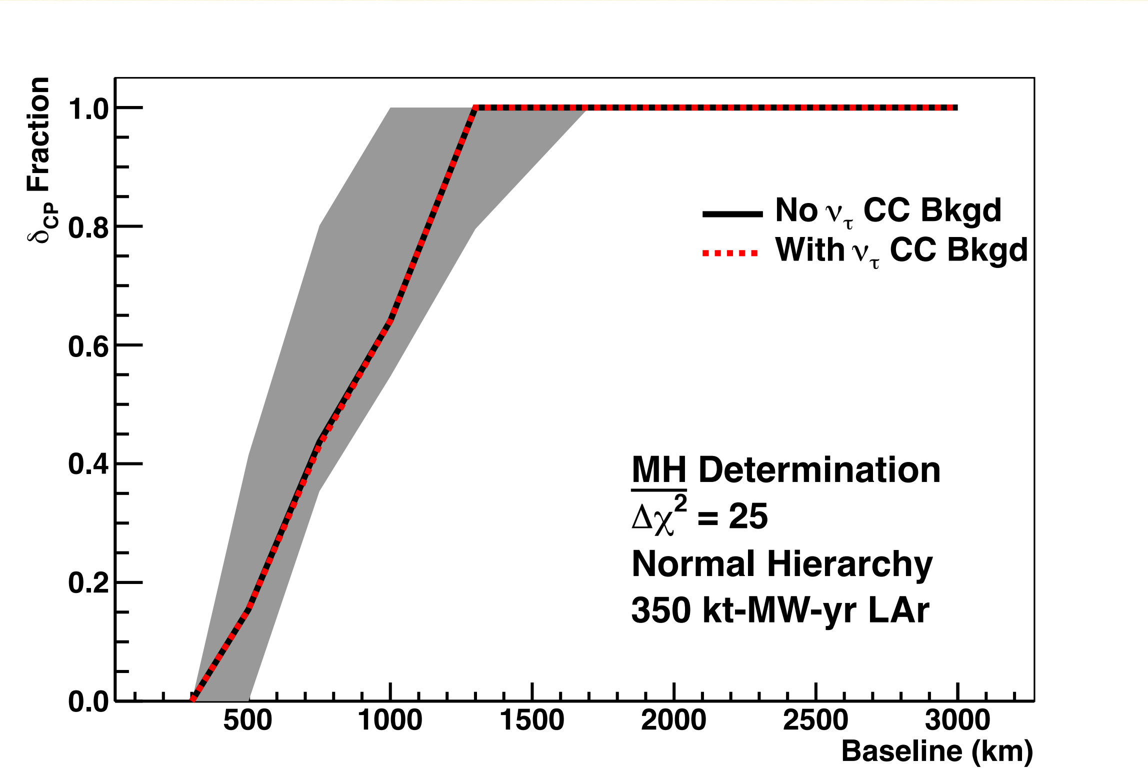
FIG. 5. Estimated ν_e (left) and $\bar{\nu}_e$ (right) appearance rates (with no detector effects) integrated over an energy region around the first oscillation maximum (solid line) or the second oscillation maximum (dashed line) assuming the flux obtained from a perfect-focusing system with a 120 GeV primary beam and a fixed decay pipe length of 380 m. The curves are shown for different values of δ_{CP}. Matter effects are included assuming normal hierarchy.

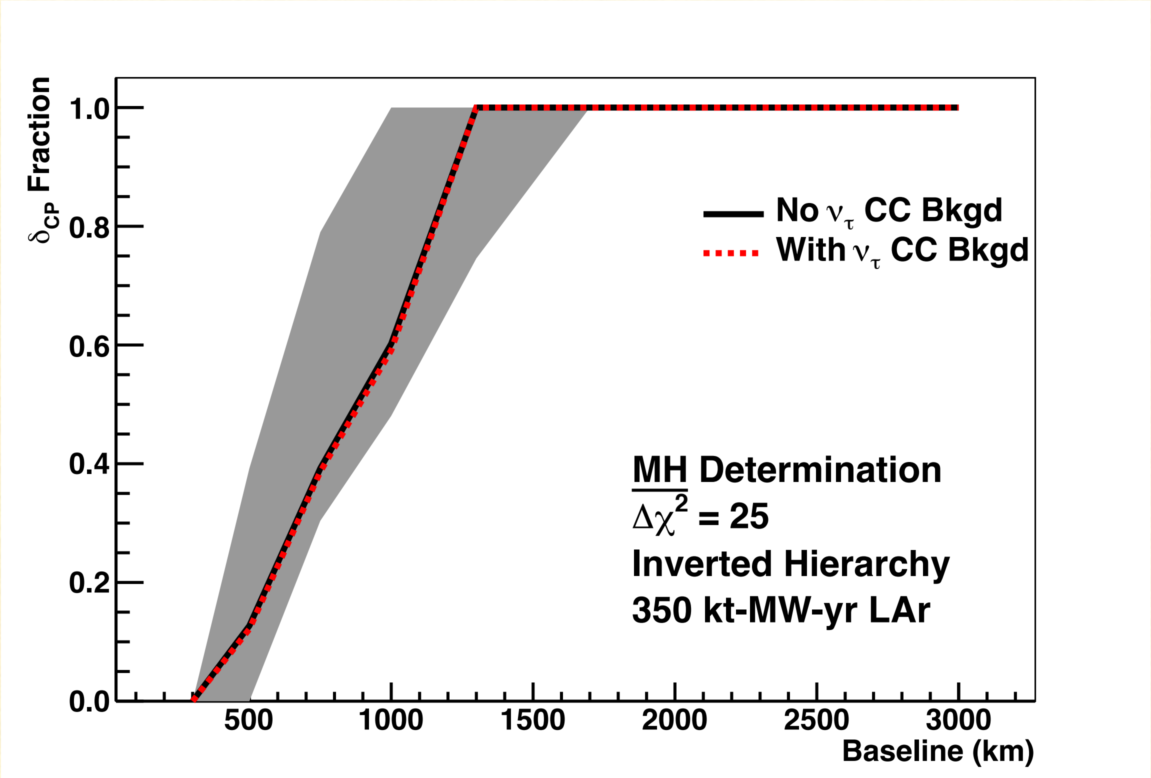
First oscillation max rates fall gradually for neutrinos with L after ~1000 km

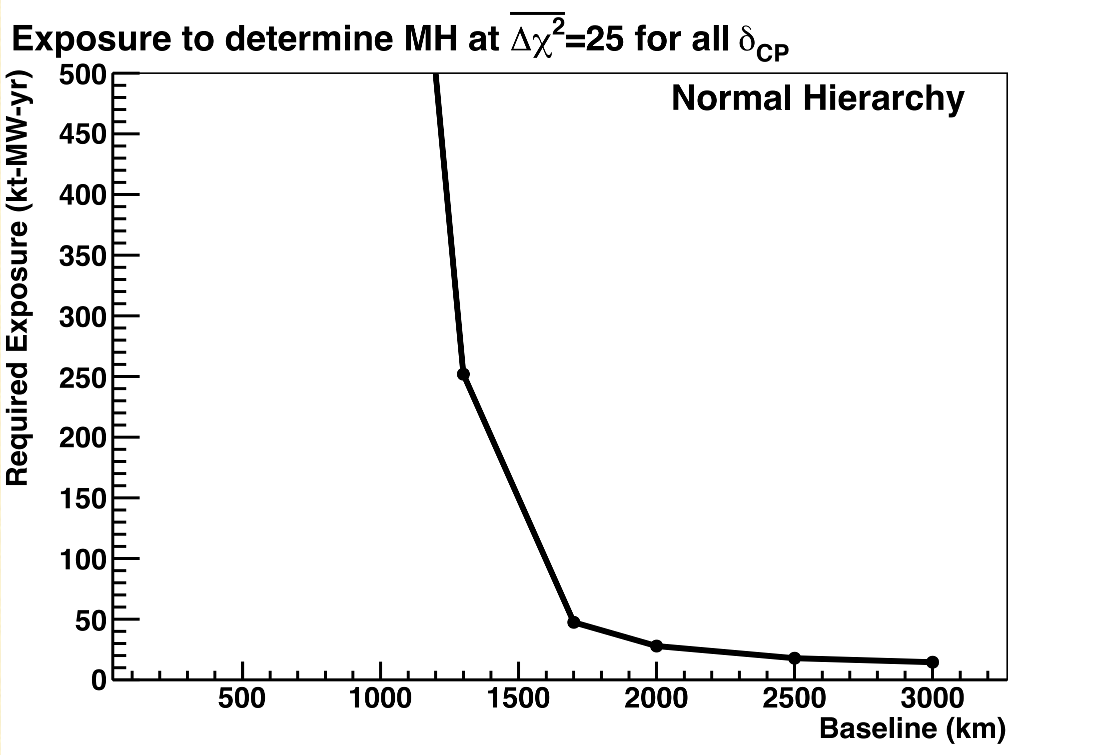
Second oscillation max rates ramp up and then stay constant for neutrinos with L after ~1500 km

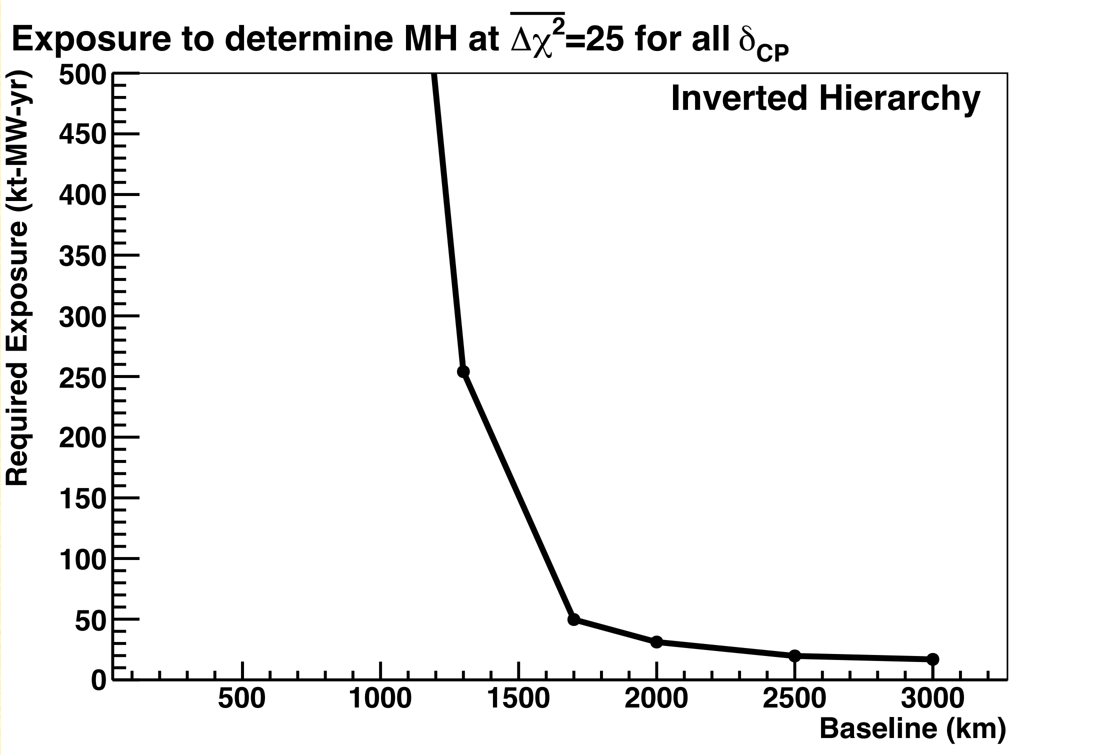
Second max important since it helps break degeneracy between matter Cp and intrinsic CP

Mass Hierarchy Sensitivity & Baseline ....

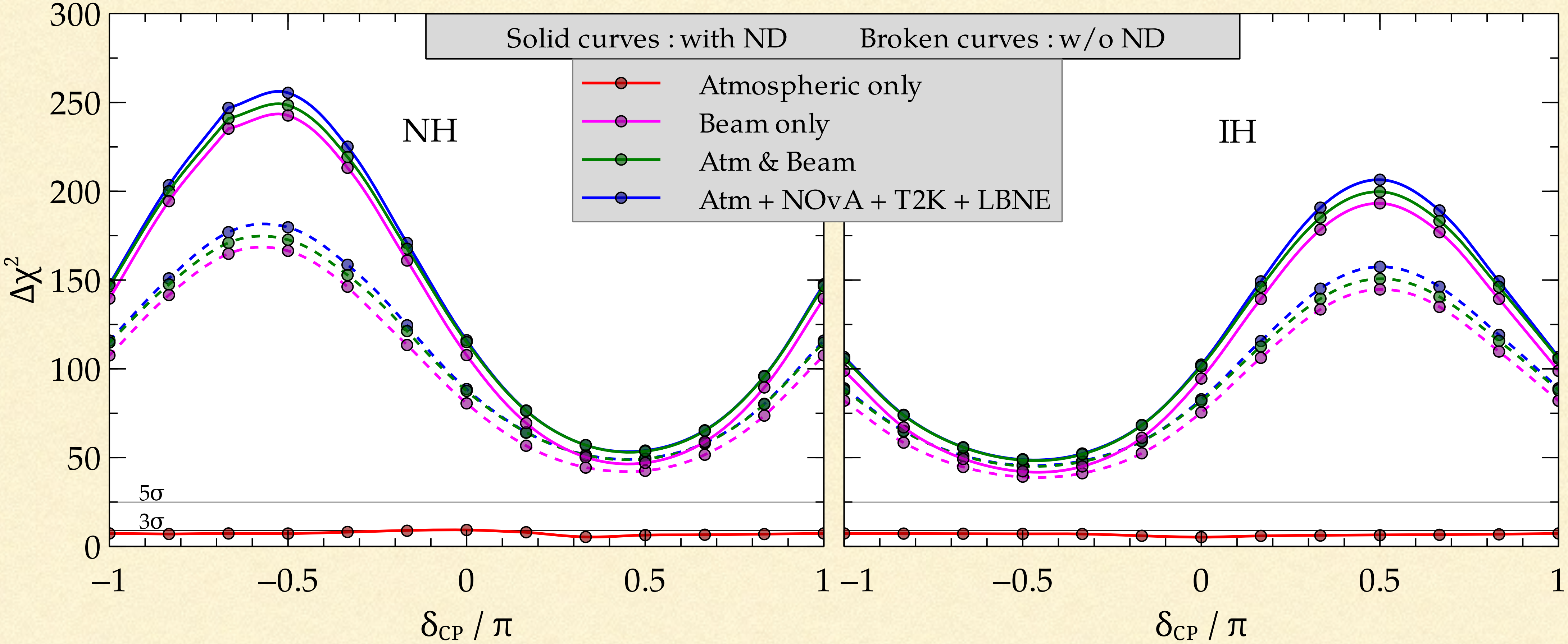








Mass Hierarchy Sensitivity at 1300 km ....



Barger et al, et al 1405.1054

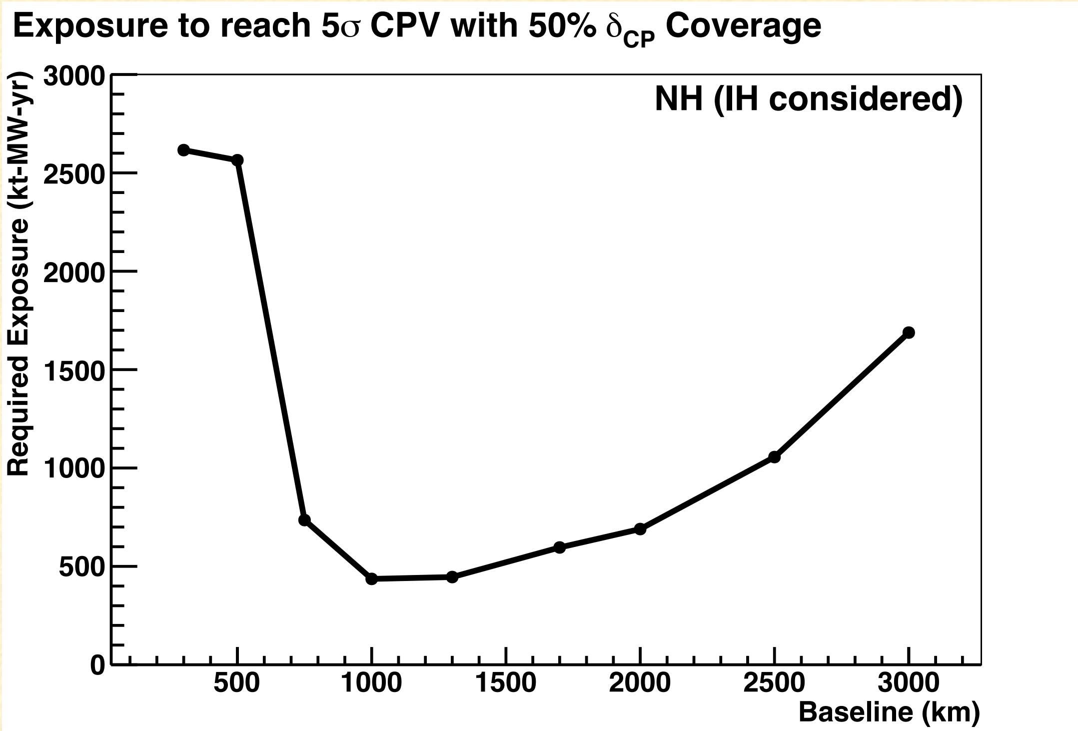
Addition of atmospheric data has no significant effect on sensitivity

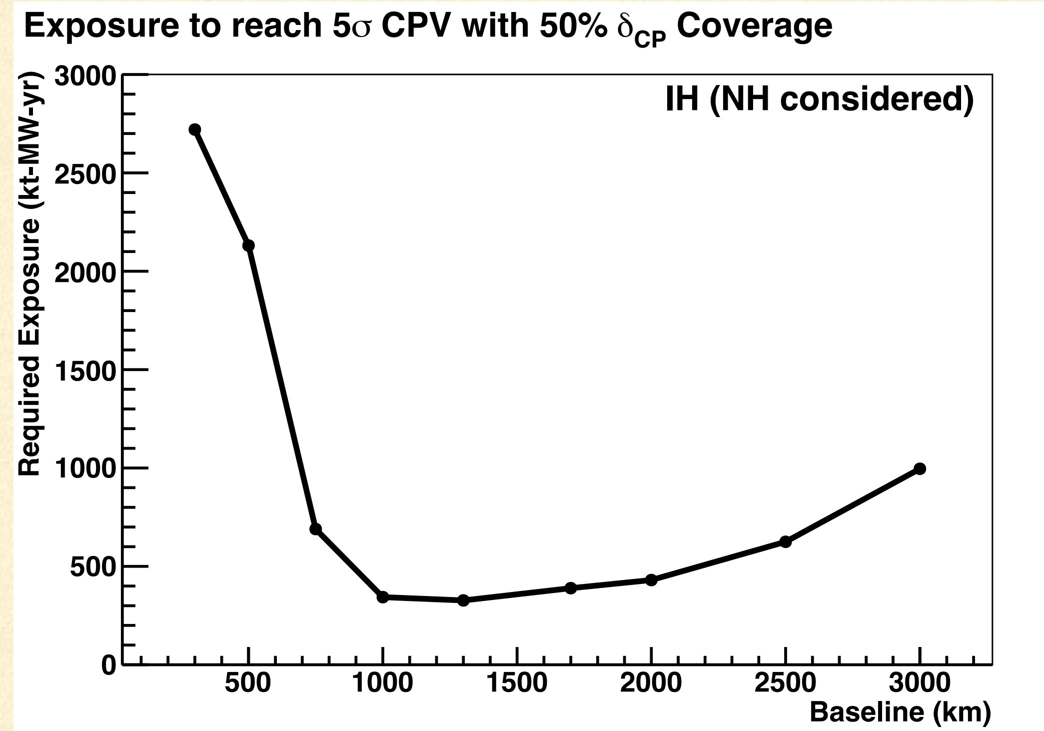
Precision ND plays a very significant role in enhancing sensitivity in favorable region of CP space.

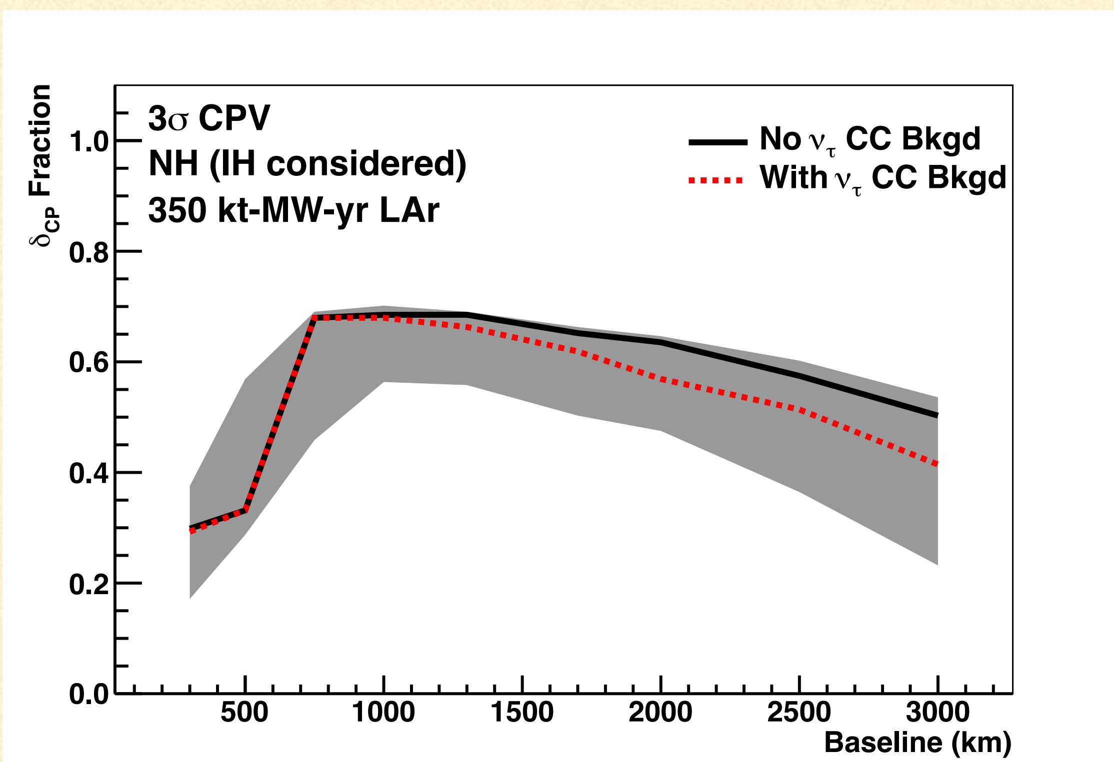
Addition of T2K + NoVa data has very small effect on sensitivity

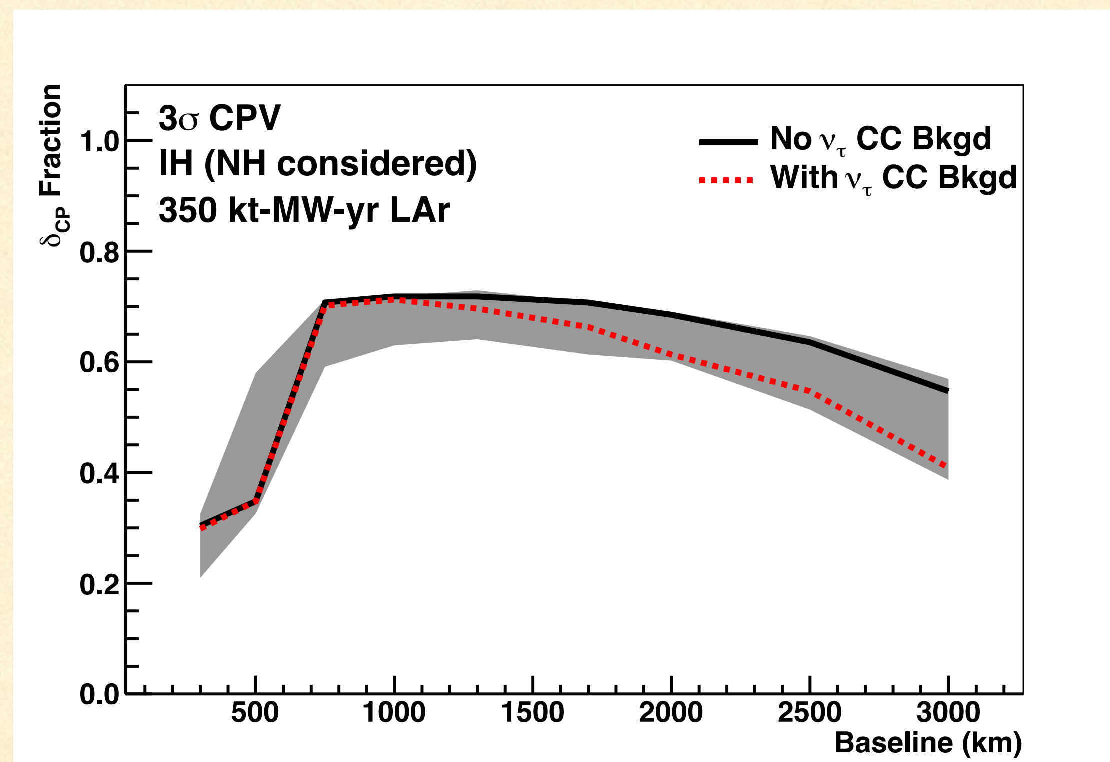
Nothing helps much in unfavorable CP region.

CP Sensitivity & Baseline ....



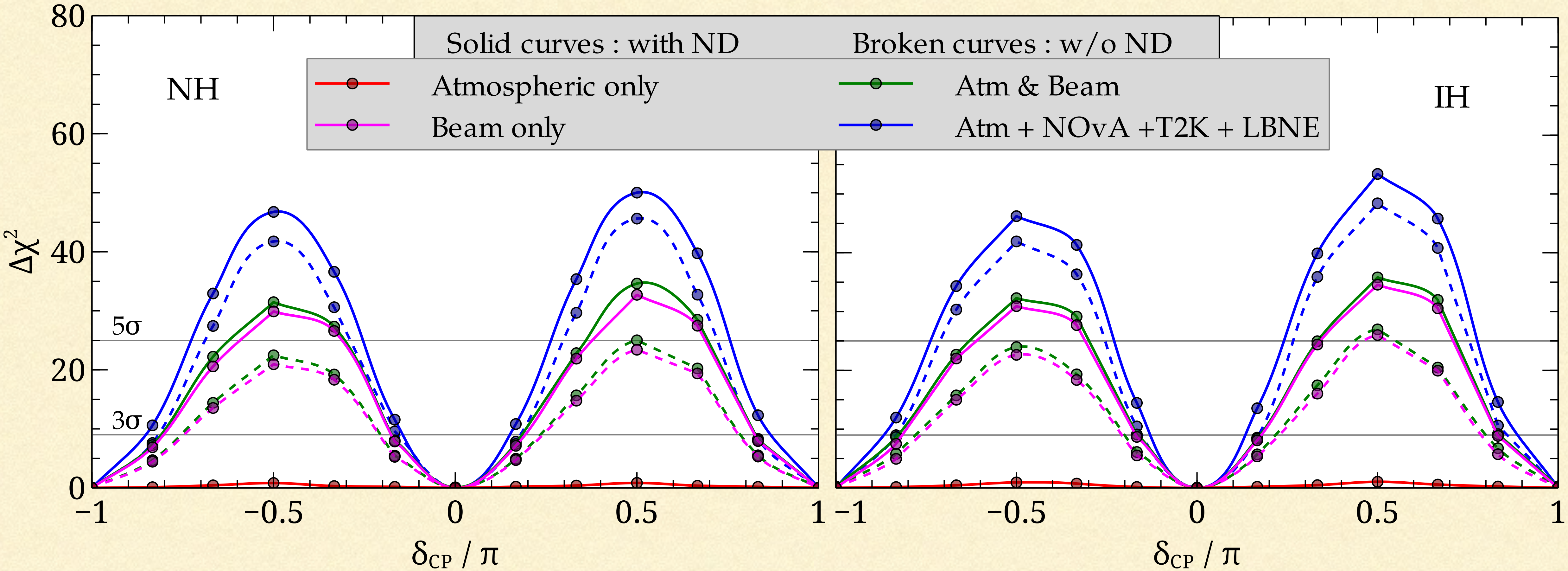






Assumes hierarchy is unknown.No significant change in shape/magnitude if hierarchy known if baseline is above 1300 km. At shorter baselines, this does hold because access to second max is difficult since it is too low in energy

CP Sensitivity with ND and combined data ……….



Barger et al, et al 1405.1054

Addition of atmospheric data has no significant effect on sensitivity

Precision ND plays a significant role in enhancing sensitivity

Combining data from NoVa and T2K has a large effect on sensitivity

LBNE ND Physics ....

MASSIVE CALORIMETER vs PRECISE TRACKER .... Schematic

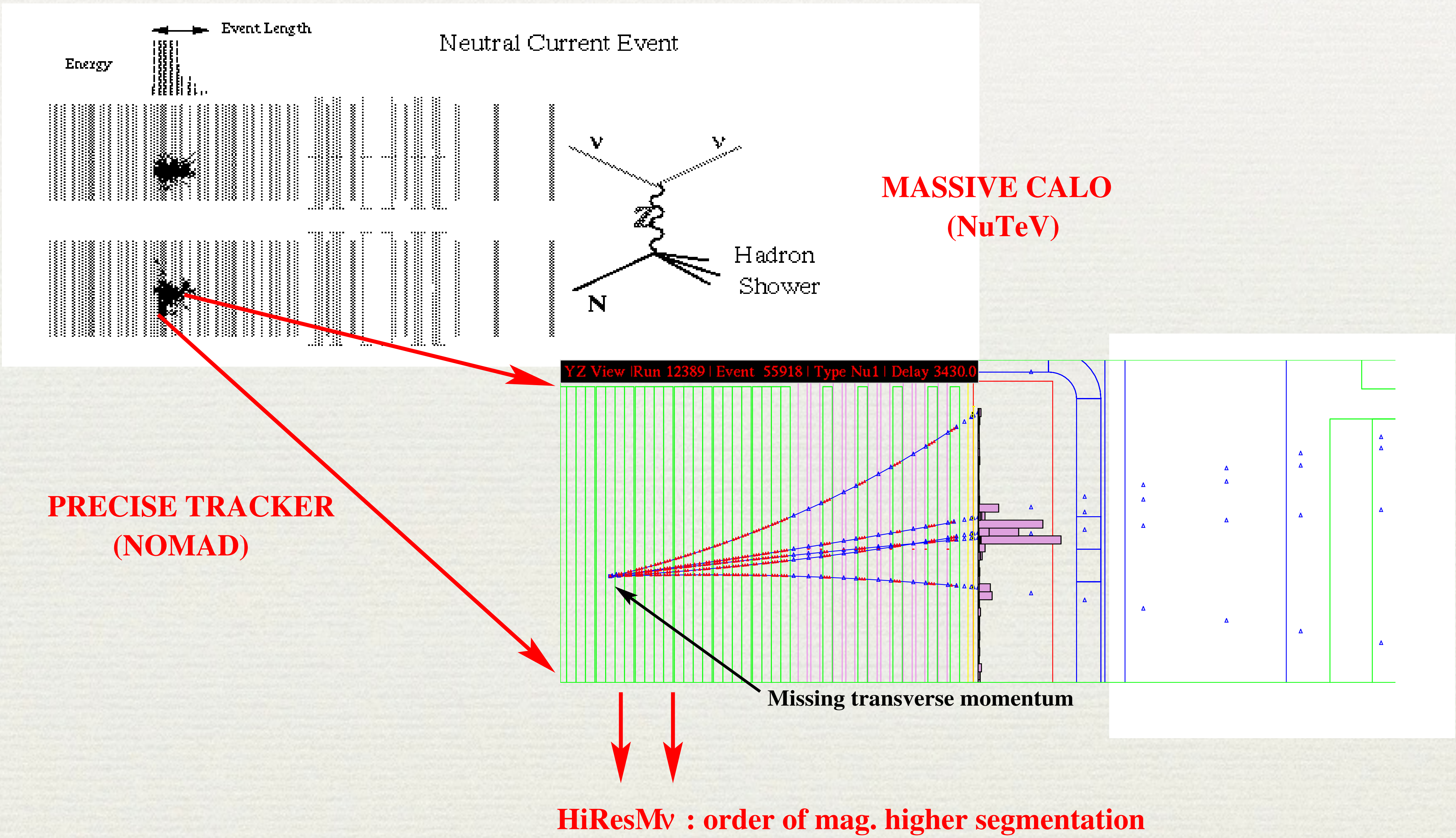
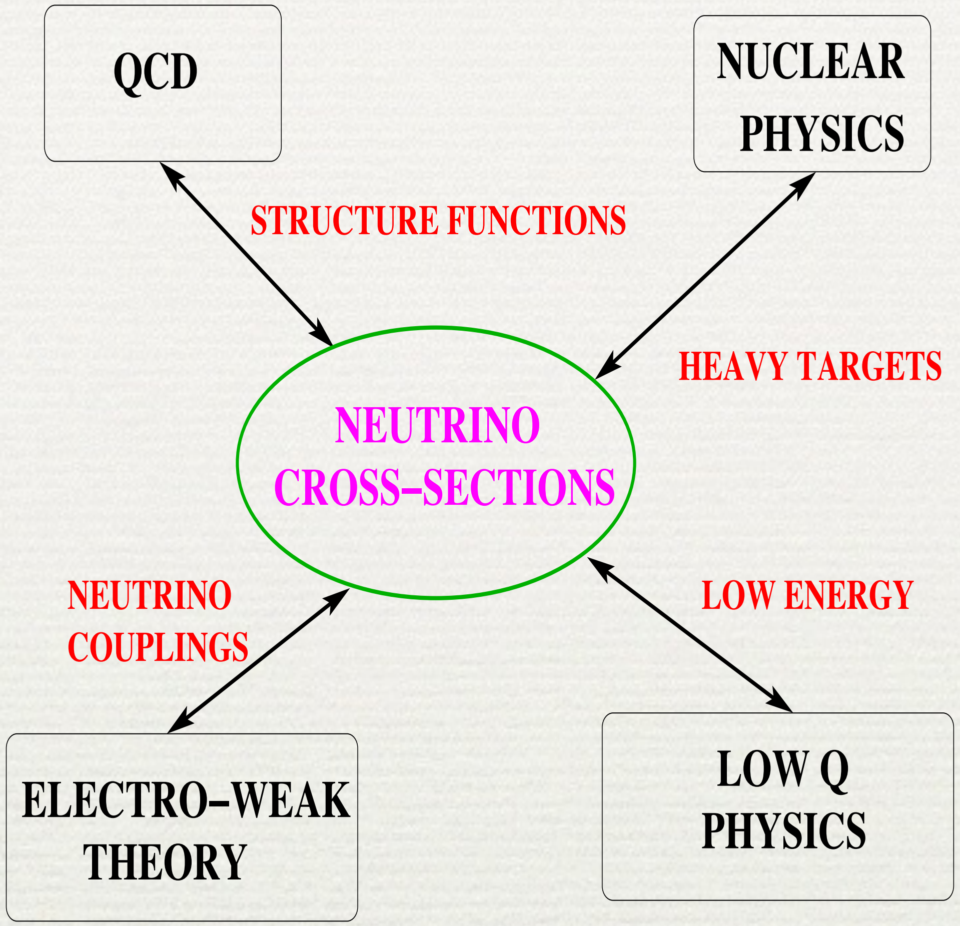


Figure 3–3: Candidate NC Event in NuTeV and NOMAD. In tracking charged particles HIRESMNU will provide a factor of two higher segmentation along z-axis and a factor of six higher segmentation in the transverse-plane compared to NOMAD.

Table 3–2: Expected Events in a 5-Year ν-Run: Events in the fiducial volume for various interactions are shown.

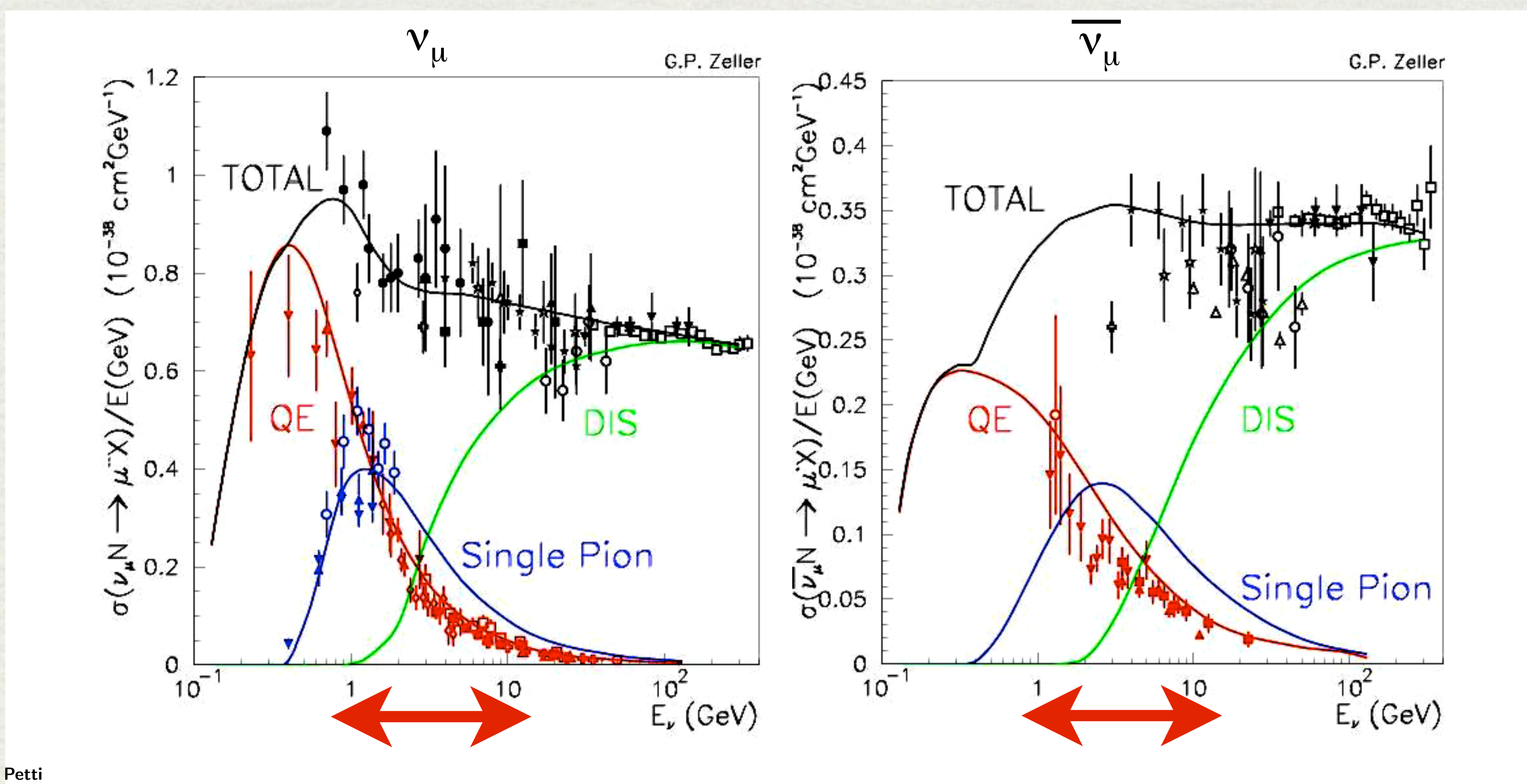
Interaction	Events	Cuts
Inclusive ν_μ-CC	38.2×10^6	FV
ν_μ-QE	8.1×10^6	FV
ν_μ-Res	11.0×10^6	FV
ν_μ Coherent-π^+	0.63×10^6	FV
Inclusive ν_μ-NC	4.1×10^6	FV & $E_{Had} \geq 3$ GeV
Coherent-π^0	0.32×10^6	FV
IMD	1944	FV ($E_\nu \geq 11$ GeV)
ν_μ-e NC	4700	FV
Contaminant CC's		
ν_e-CC	4.2×10^5	FV
$\bar{\nu}_e$-CC	4.2×10^4	FV
$\bar{\nu}_\mu$-CC	2.5×10^6	FV

Neutrino-nucleon Cross-section measurements in the ND



(Figure: R. Petti)

A physics- rich interplay of several fields



(Figure: G. Zeller)

LBNE range

Neutrino-nucleon Cross-section measurements in the ND

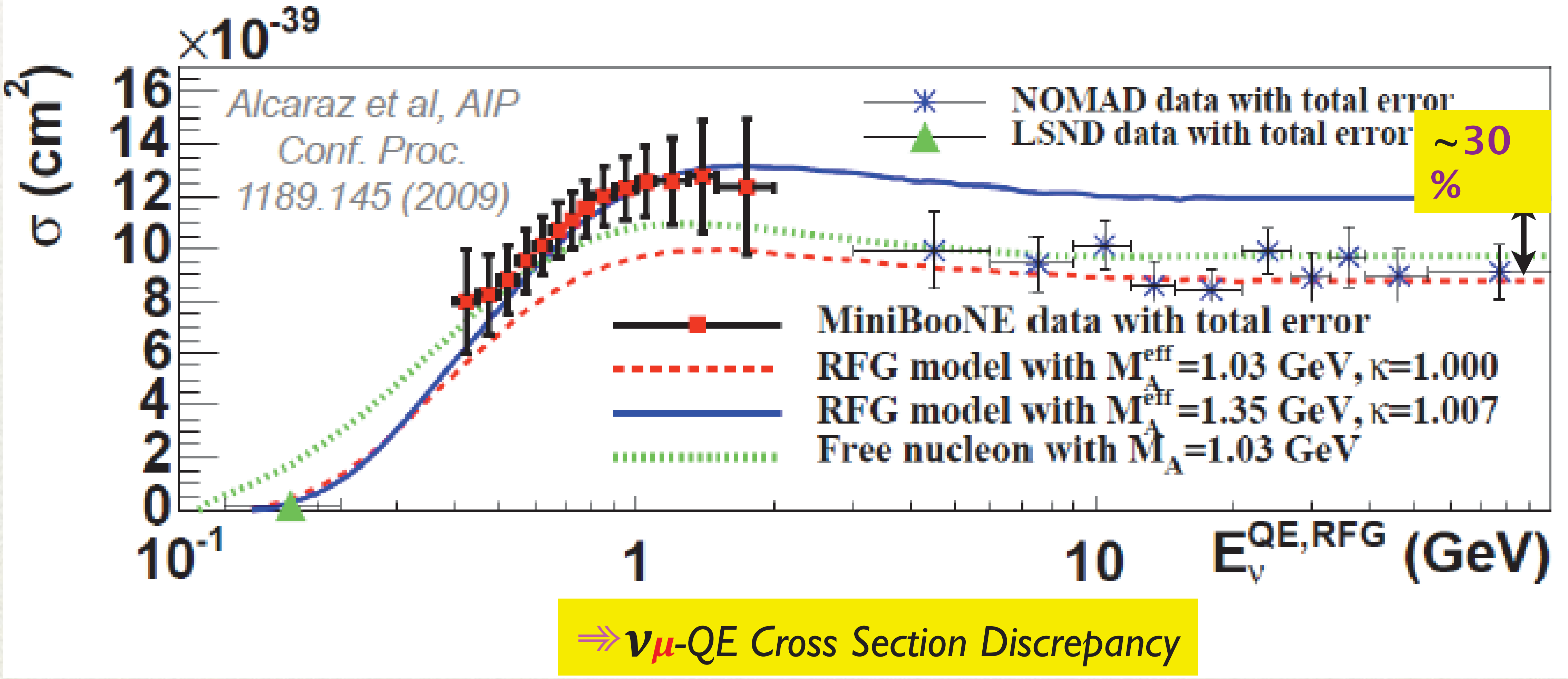


Figure 3–13: Neutrino quasi-elastic cross section by NOMAD and MiniBOONE experiments

ND will attempt to resolve the large exisiting discrepancy between NOMAD and MiniBoone

Precision Neutrino Interaction measurements......... The Weak Mixing Angle

The weak mixing angle can be extracted by the ND using 3 NC processes

1. Deep Inelastic Scattering off quarks inside nucleons: $\nu N \to \nu X$;
2. Elastic Scattering off electrons: $\nu e^- \to \nu e^-$;
3. Elastic Scattering off protons: $\nu p \to \nu p$.

Needs low density magnetized tracker for accurate reconstruction of event kinematics

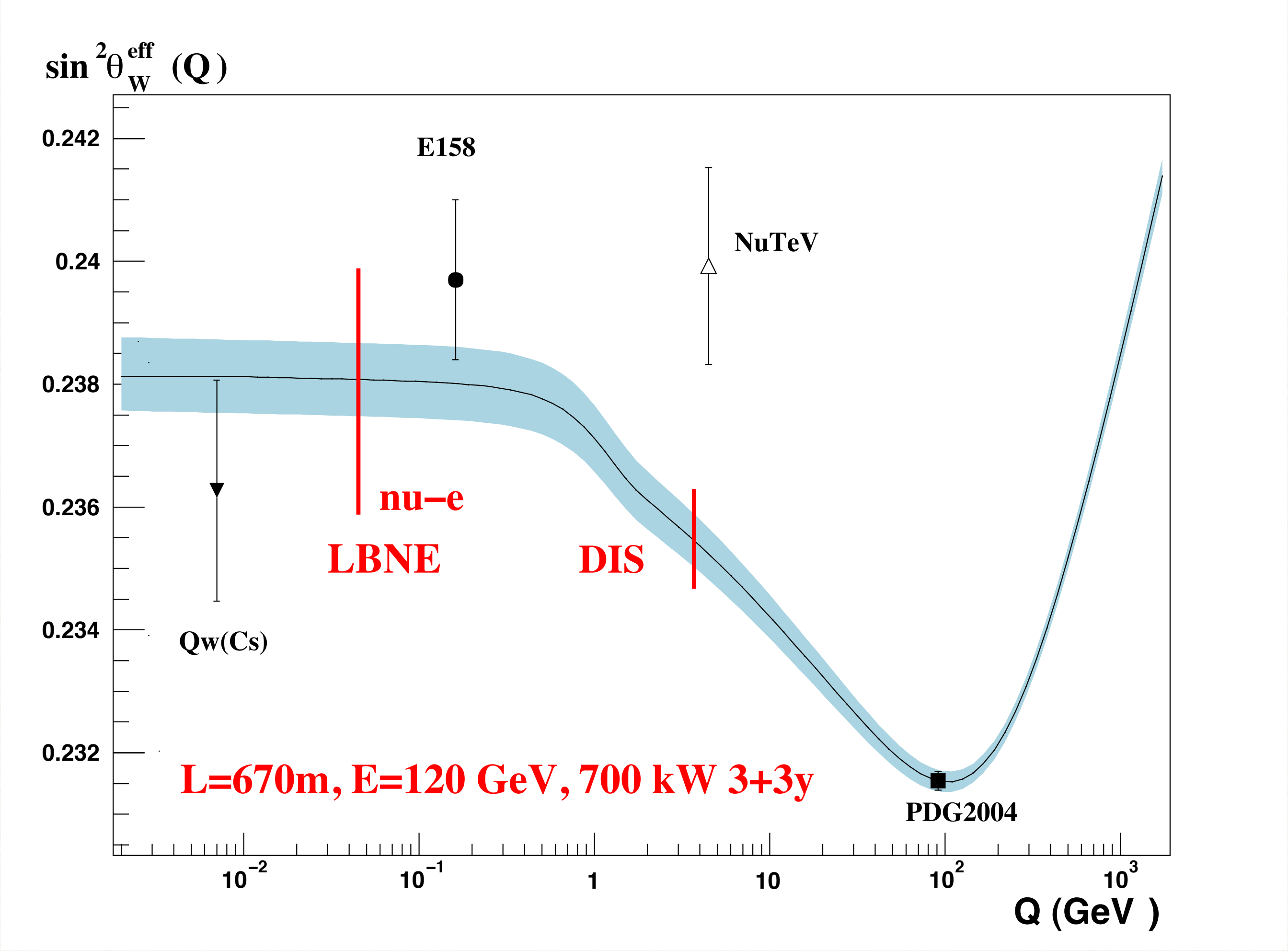
Low systematics, since no nucleus involved, but also low statistics, since xsec is low

DIS

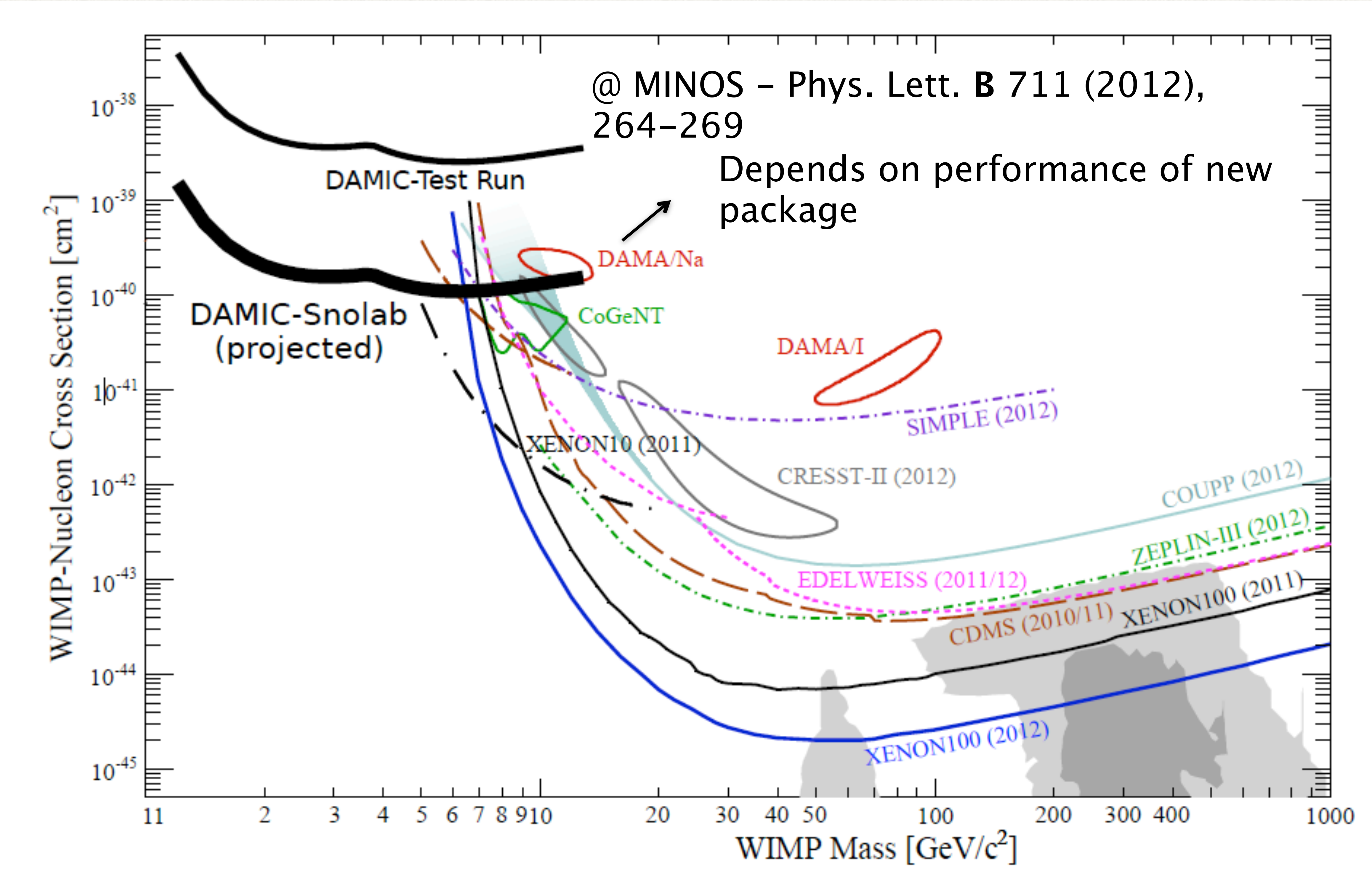
$$\mathcal{R}^\nu \equiv \frac{\sigma^\nu_{\rm NC}}{\sigma^\nu_{\rm CC}} \simeq \rho^2 \left(\frac{1}{2} - \sin^2\theta_W + \frac{5}{9}(1+r)\sin^4\theta_W \right)$$

Neutrino-electron NC

$$\mathcal{R}_{\nu e}(Q^2) \equiv \frac{\sigma(\bar\nu_\mu e \to \bar\nu_\mu e)}{\sigma(\nu_\mu e \to \nu_\mu e)}(Q^2) \simeq \frac{1 - 4\sin^2\theta_W + 16\sin^4\theta_W}{3 - 12\sin^2\theta_W + 16\sin^4\theta_W}$$

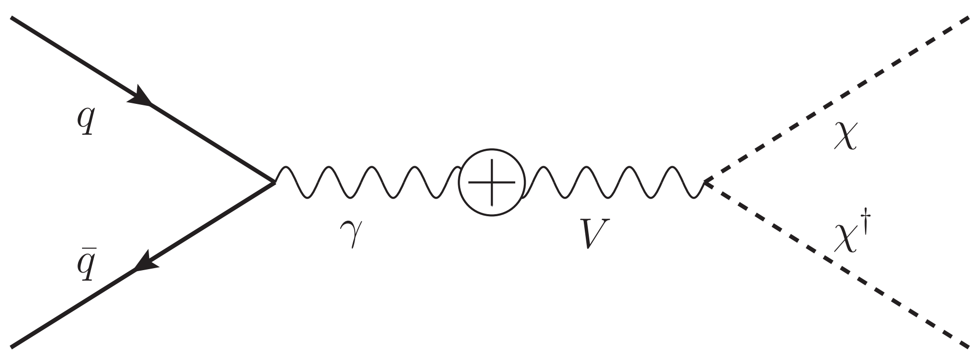


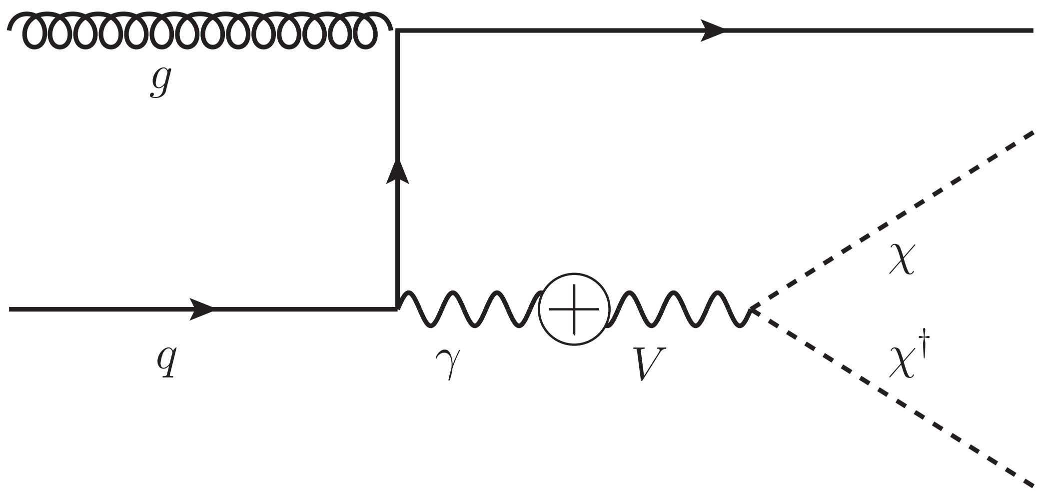
The Search for New Physics....... Light Dark Matter

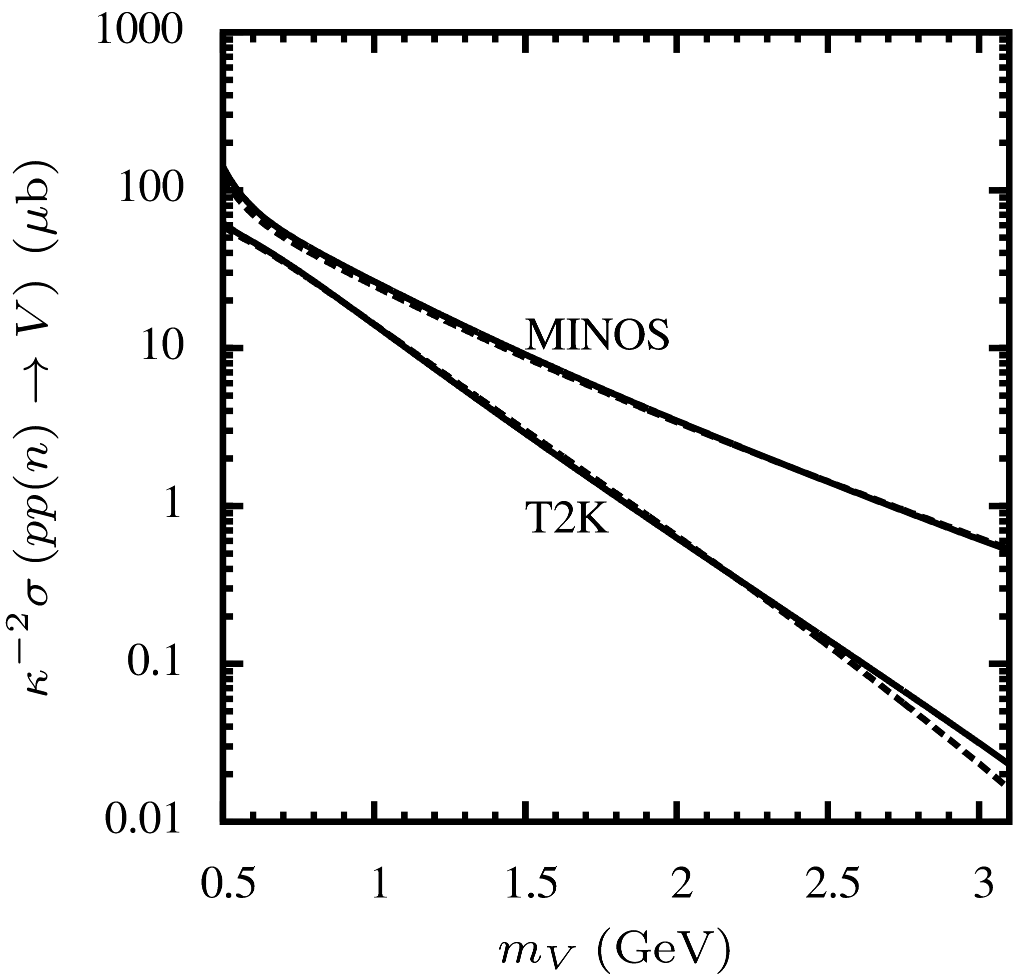


Production

Mediator can be a vector or a scalar, leading to:

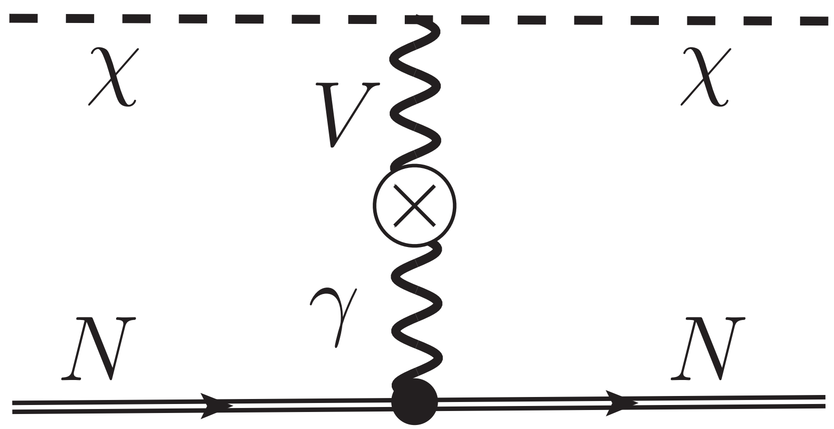






arXiv: 1205.3499

Detection



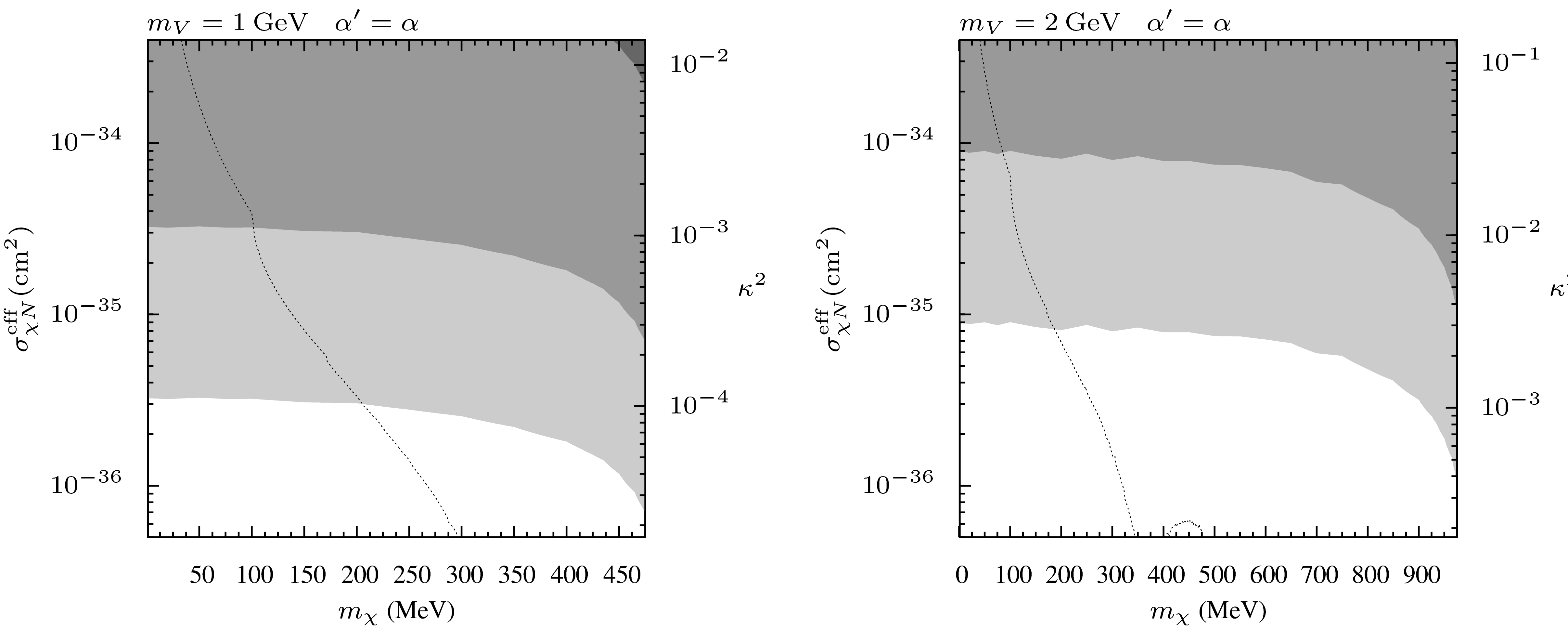


FIG. 12. Expected number of neutral current-like dark matter nucleon scattering events through direct V production for the MINOS near detector with two different vector mediator masses ($m_V = 1$ GeV on the left and $m_V = 2$ GeV on the right). The contours are described in Fig. 8.

Conclusions ....

Sensitivity to CP is approximately the same for baselines between 1000-2000 km

The ν_e appearance rate falls gradually with baseline as a result of increased hadro-production in the target and decay kinematics.

The second maxima, while typically yielding a event rate which is only about 10% of that from the first maximum, is important because it helps break the degeneracy between the matter and intrinsic CP asymmetries.

The appearance rate at the second maxima is roughly constant beyond 1500 km

Sensitivity to CP is best between 750 km-1300 km. It drops gradually beyond this.

Exposure needed to reach a specific sensitivity to CP is lowest between 1000 km - 13

Precision ND plays a significant role in enhancing sensitivity

Combining data from NoVa and T2K has a large effect on sensitivity

Conclusions ....

5σ determination of the hierarchy should be possible with a baseline ≧ 1300 km,
although exposure necessary is significantly larger than that at ≧ 2000 km (factor of about 4)

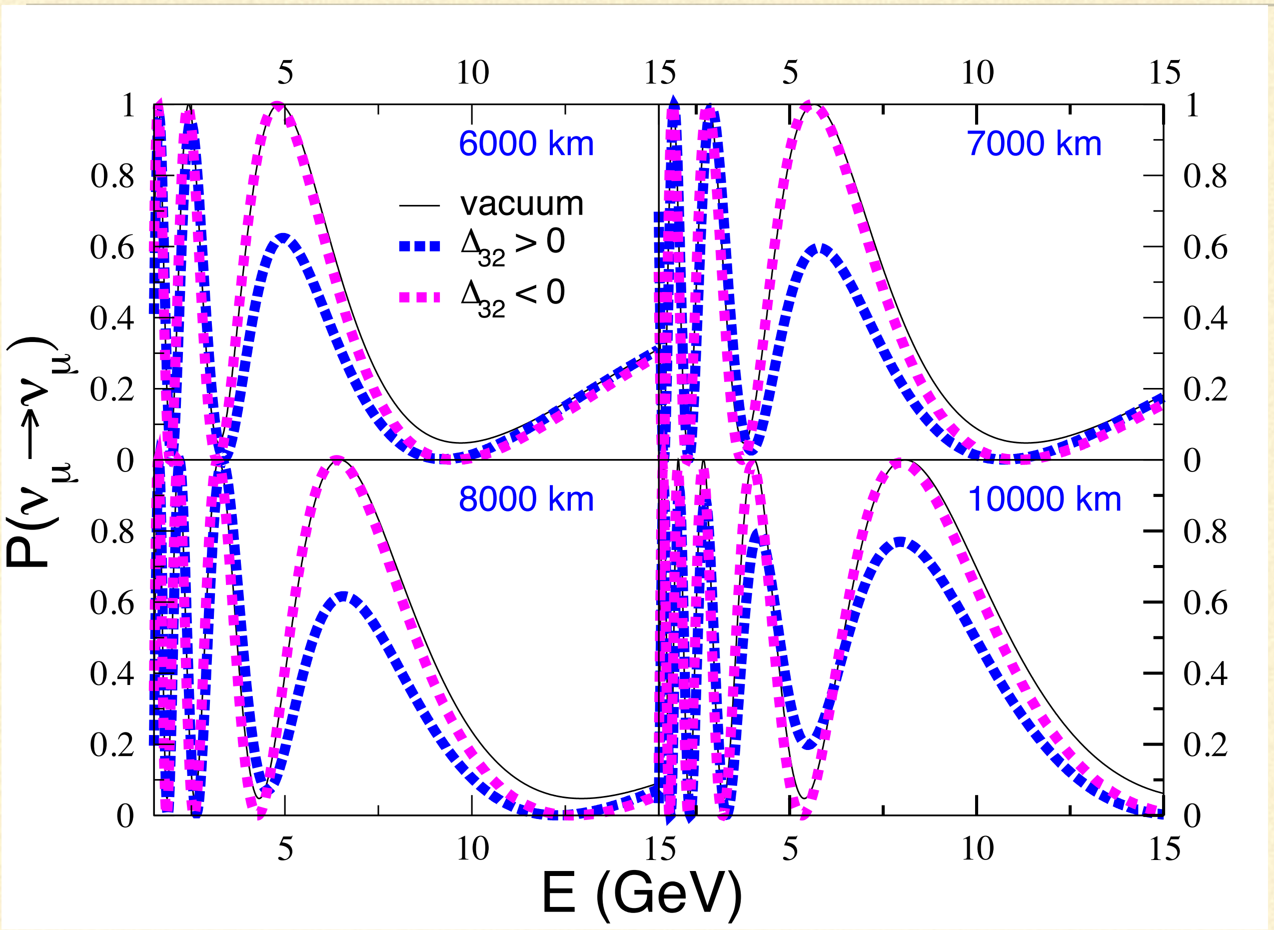
Precision ND has significant effect in enhancing hierarchy sensitivity in favorable region of CP space.

Addition of atmospheric, NoVa and T2K data has negligible effect on hierarchy sensitivity of LBN*

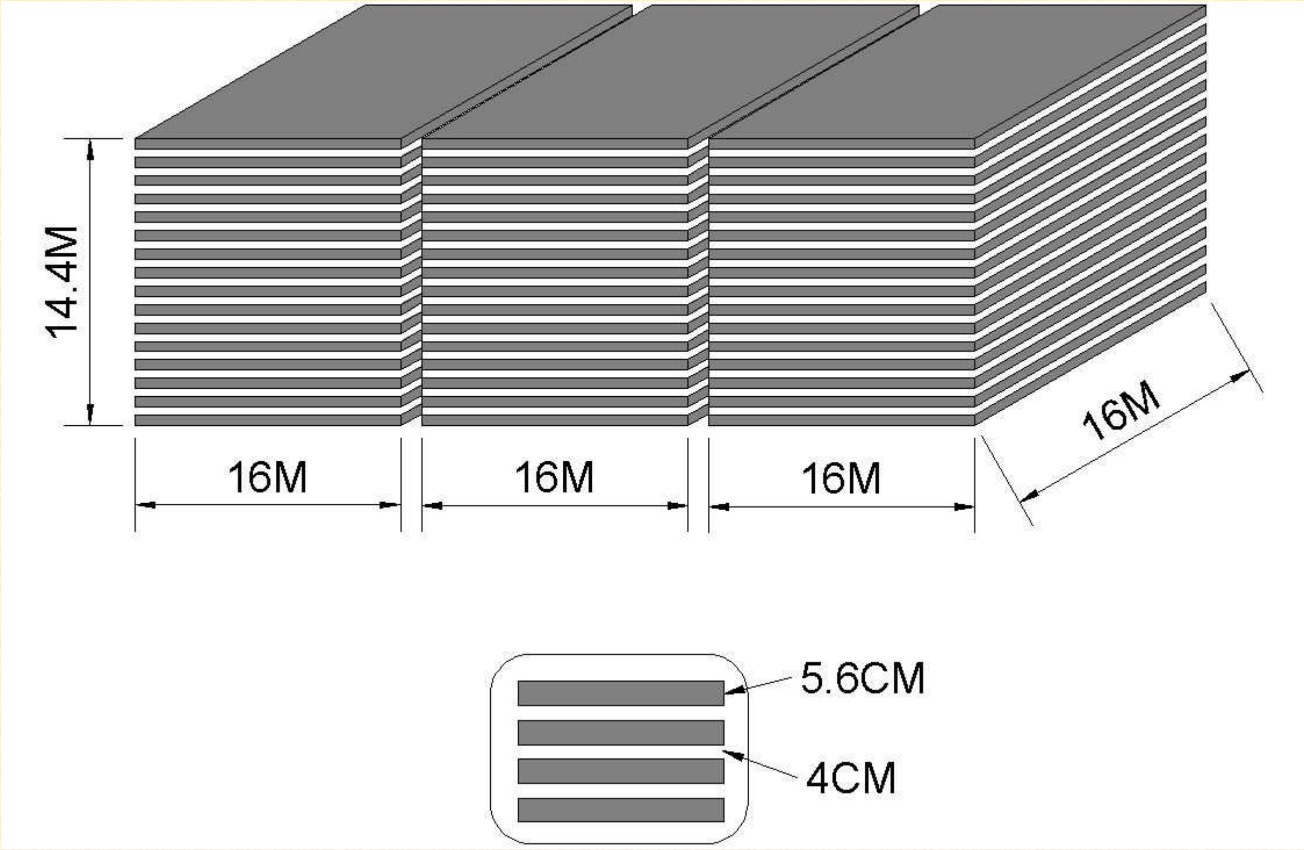
On its own, LBNE-ND would provide both excellent systematics reduction for the FD oscillation measurements, as well as a host of precision measurements to test electroweak and hadronic physics.

Switch gears……. Brief update on status of INO

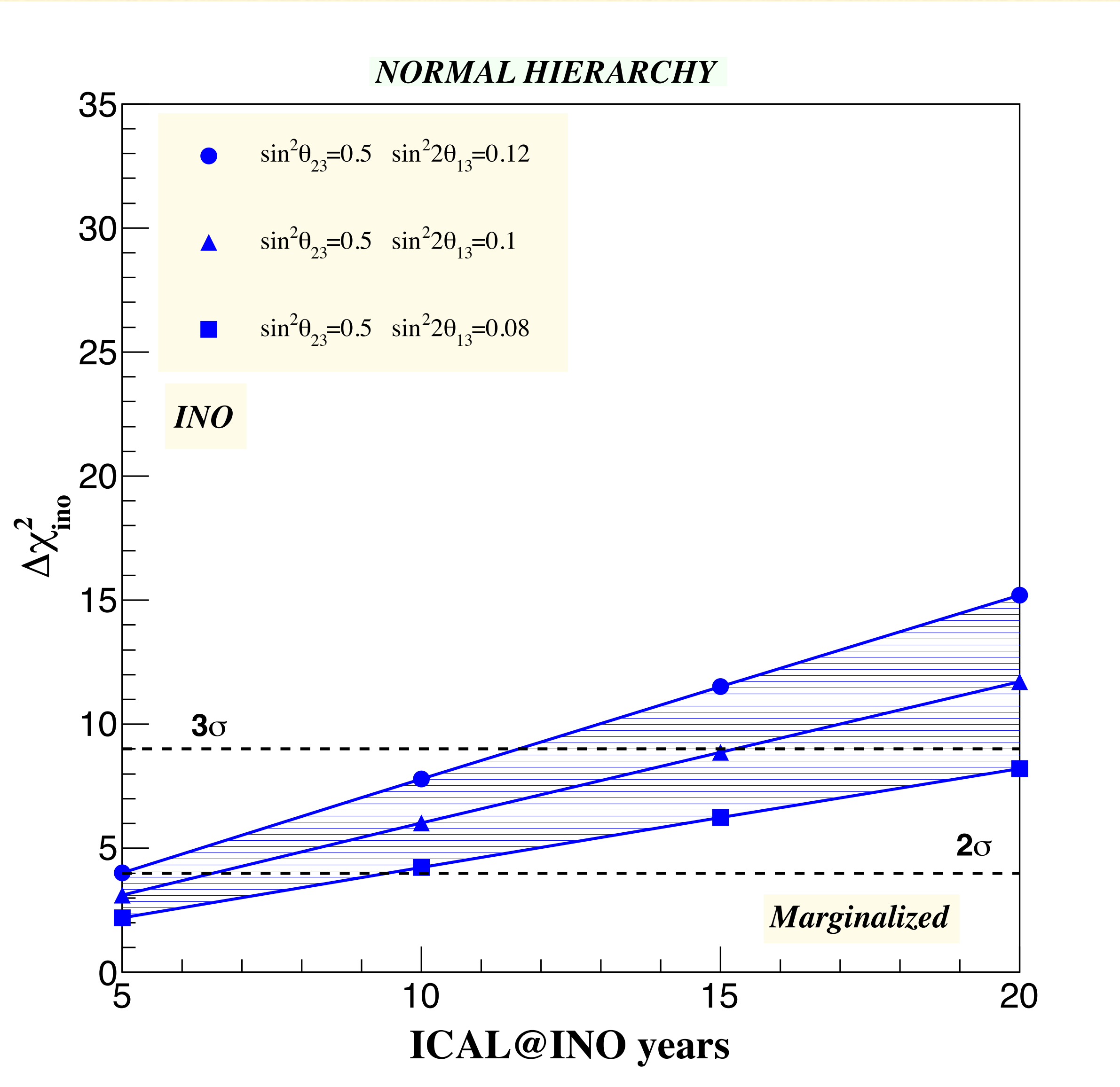

India-based Neutrino
Observatory

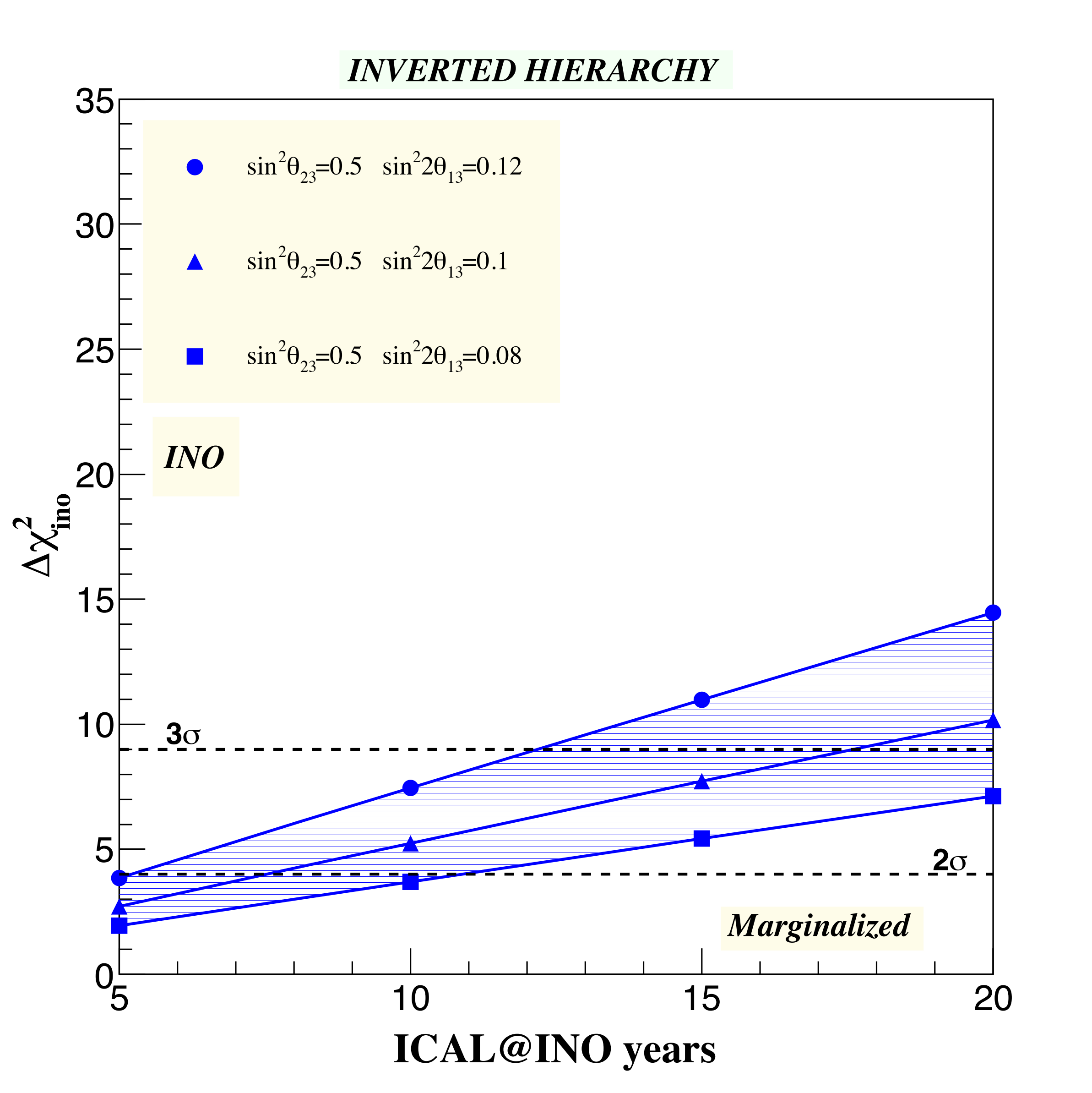


Hierarchy measurement based on matter effects in the survival probability



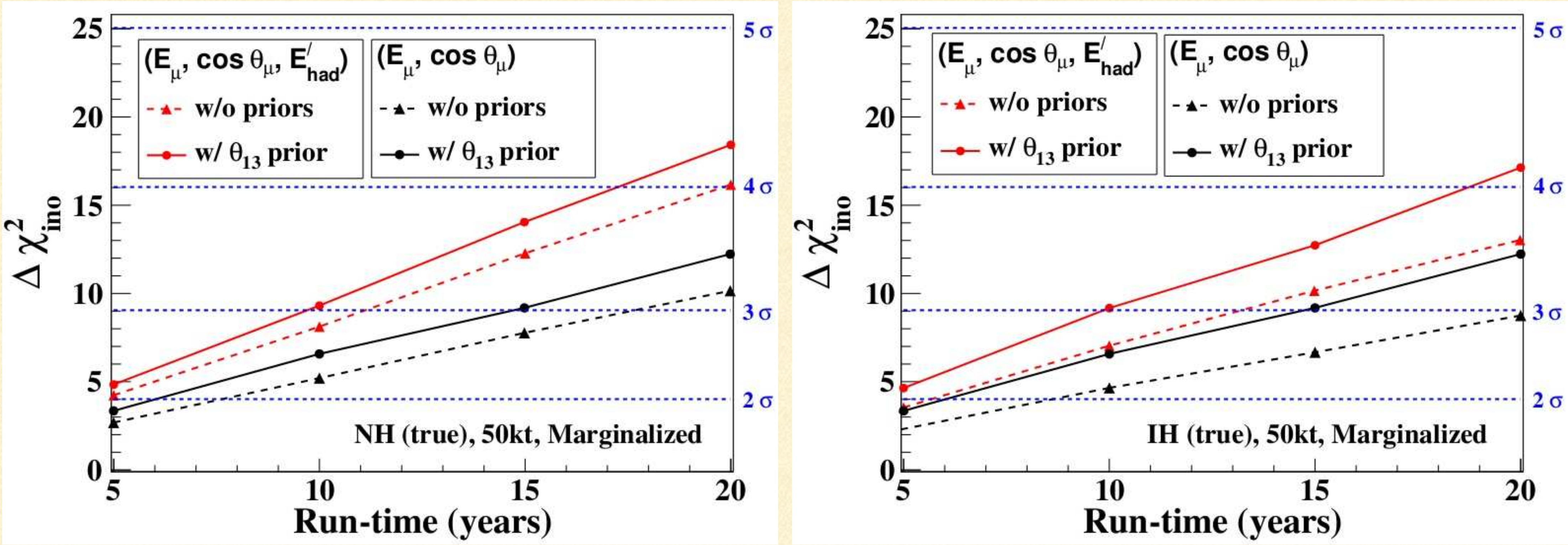
ICAL	
No. of modules	3
Module dimension	16 m × 16 m × 14.4 m
Detector dimension	48 m × 16 m × 14.4 m
No. of layers	150
Iron plate thickness	5.6 cm
Gap for RPC trays	4.0 cm
Magnetic field	1.5 Tesla





Muon only analysis. 15 year run for 3σ sensitivity in favorable region

θ_{23} in second octant helps significantly



New analysis with hadrons included improves sensitivity to hierarchy. 3**σ** in about 12 years running.

Additional physics possible….

Complementary support to contemporaneous accelerator based neutrino experiments for atmospheric parameters

Bounds on CPT

Measurements of VHE muons

Status………

Road, fencing, power and water-supply work started at site. Civil consultants for tunnel/cavern short-listed.

Work on 1/8 scale prototype initiated.

Land procured and initial planning for Inter-Institutional Centre for High Energy Physics (IICHEP) at Madurai started . This will be the R&D, training, and project monitoring center for the experiment.

0

4 year time estimate for tunnel and cavern completion. 1 module per year estimate for assembly.

Full funding approval expected very soon. (t_0 ~ months)

First neutrinos in 5-6 years after t_0…………………………………………

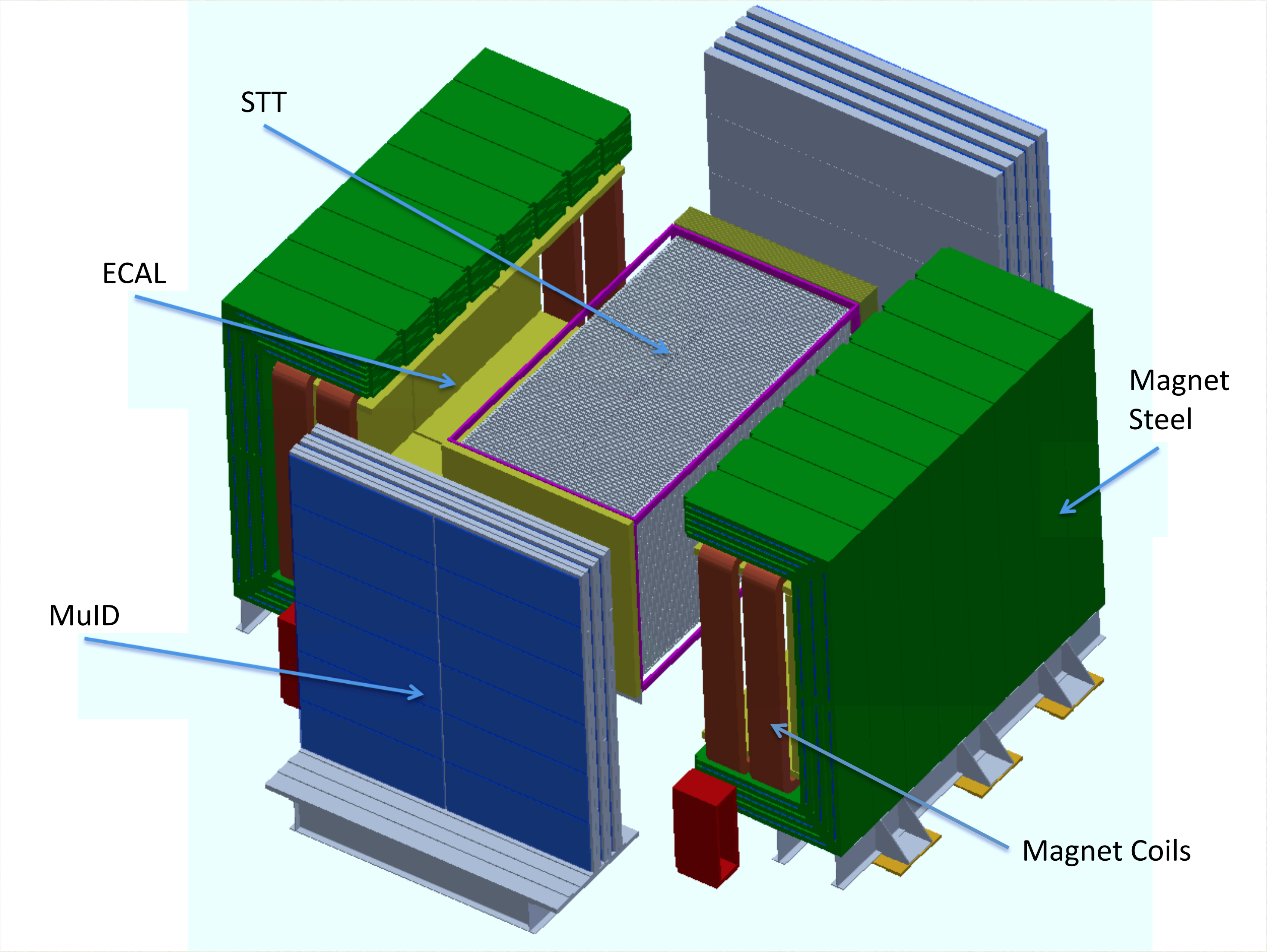
Back-up slides

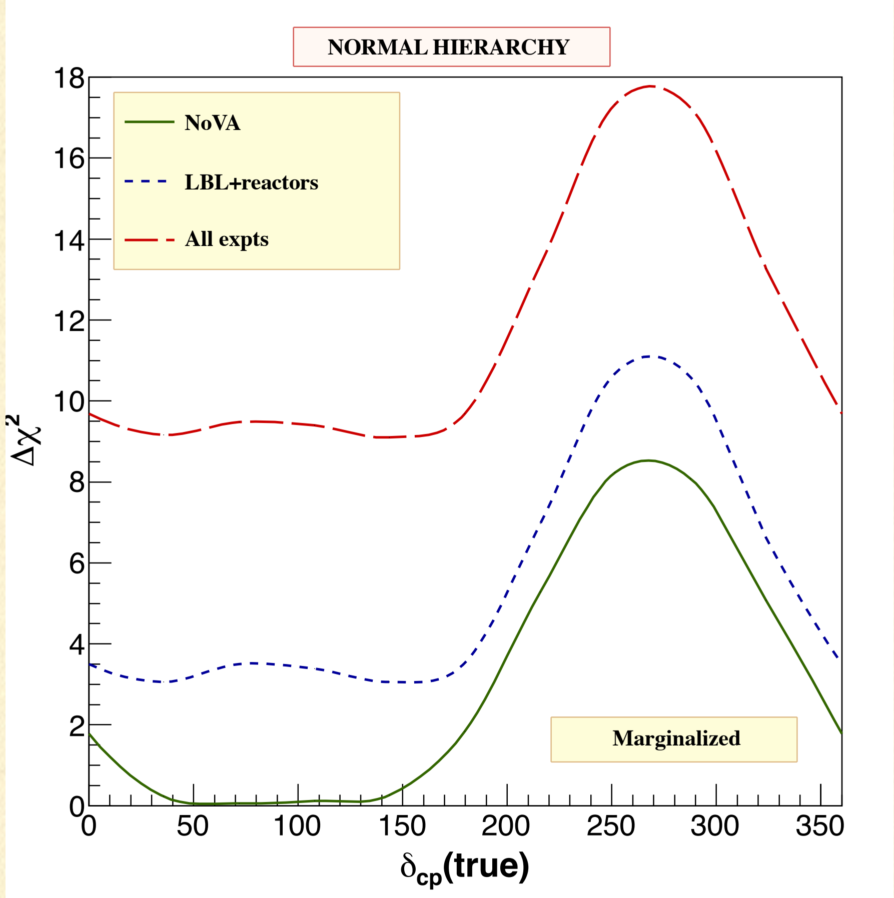
LBNE-ND........The highest precision neutrino detector

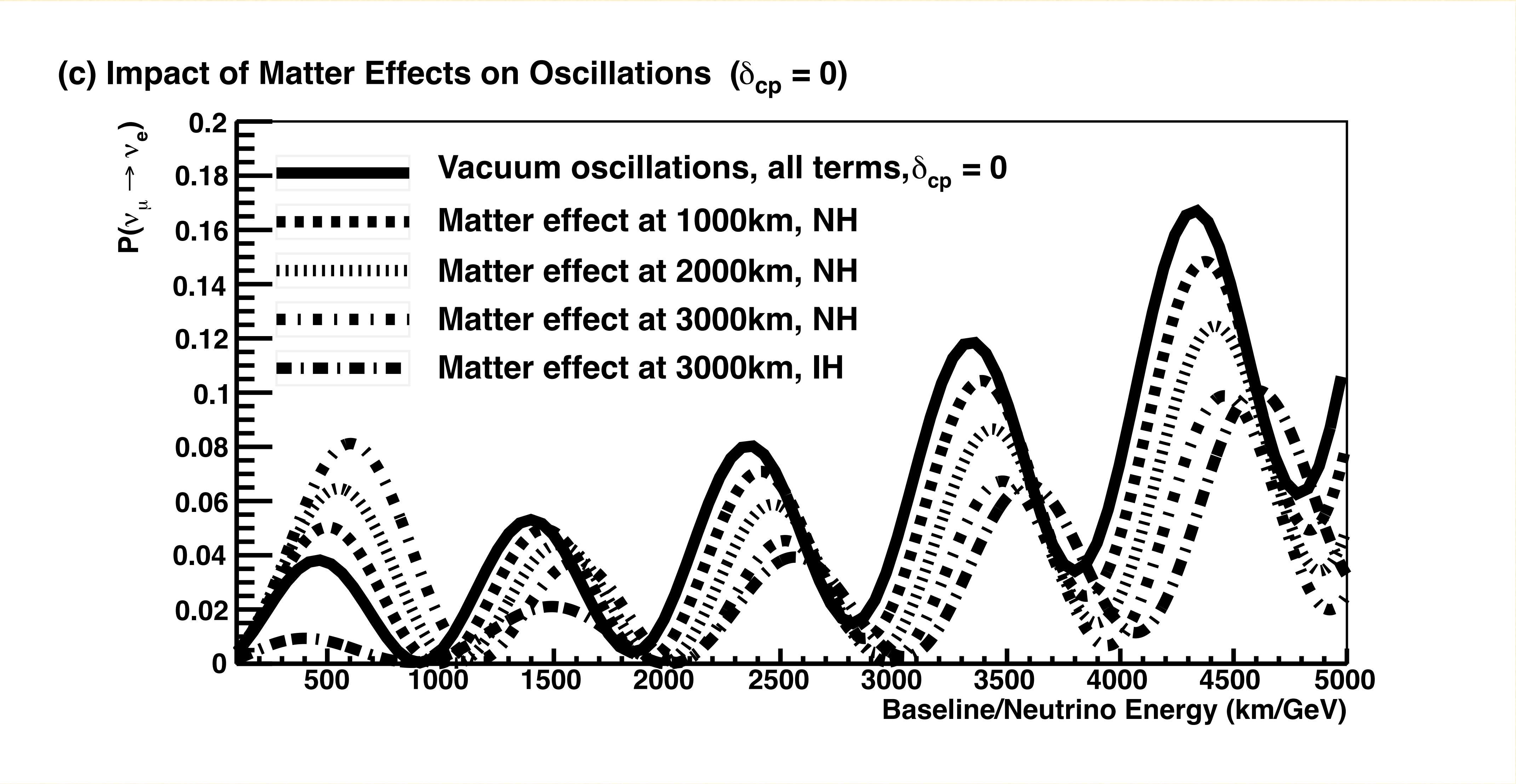
(More in tomorrow's talks)

Currently, the highest precision neutrino detector is NOMAD.

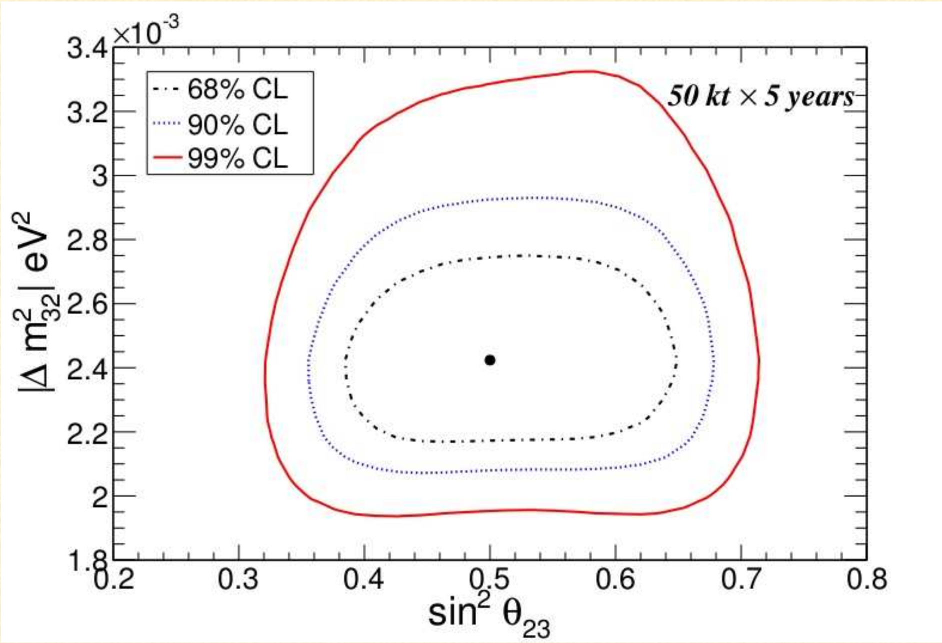
When built, HIRESMNU will be a generational advance over NOMAD in particle identification capability and precision vector momentum measurement.

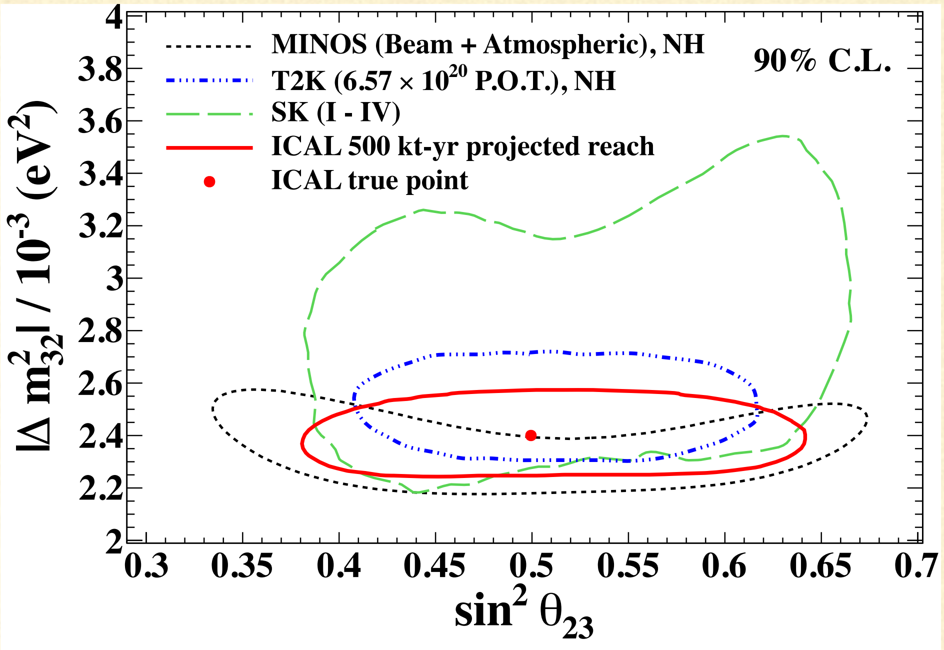



NORMAL HIERARCHY
NoVA
LBL+reactors
All expts
Marginalized
$\Delta\chi^2$
δ_{cp}(true)
0
2
4
6
8
10
12
14
16
18
0
50
100
150
200
250
300
350



(c) Impact of Matter Effects on Oscillations (δ_{cp} = 0)
$P(\nu_\mu \rightarrow \nu_e)$
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
Baseline/Neutrino Energy (km/GeV)
Vacuum oscillations, all terms, δ_{cp} = 0
Matter effect at 1000km, NH
Matter effect at 2000km, NH
Matter effect at 3000km, NH
Matter effect at 3000km, IH





Complementary measurements of atmospheric oscillation parameters