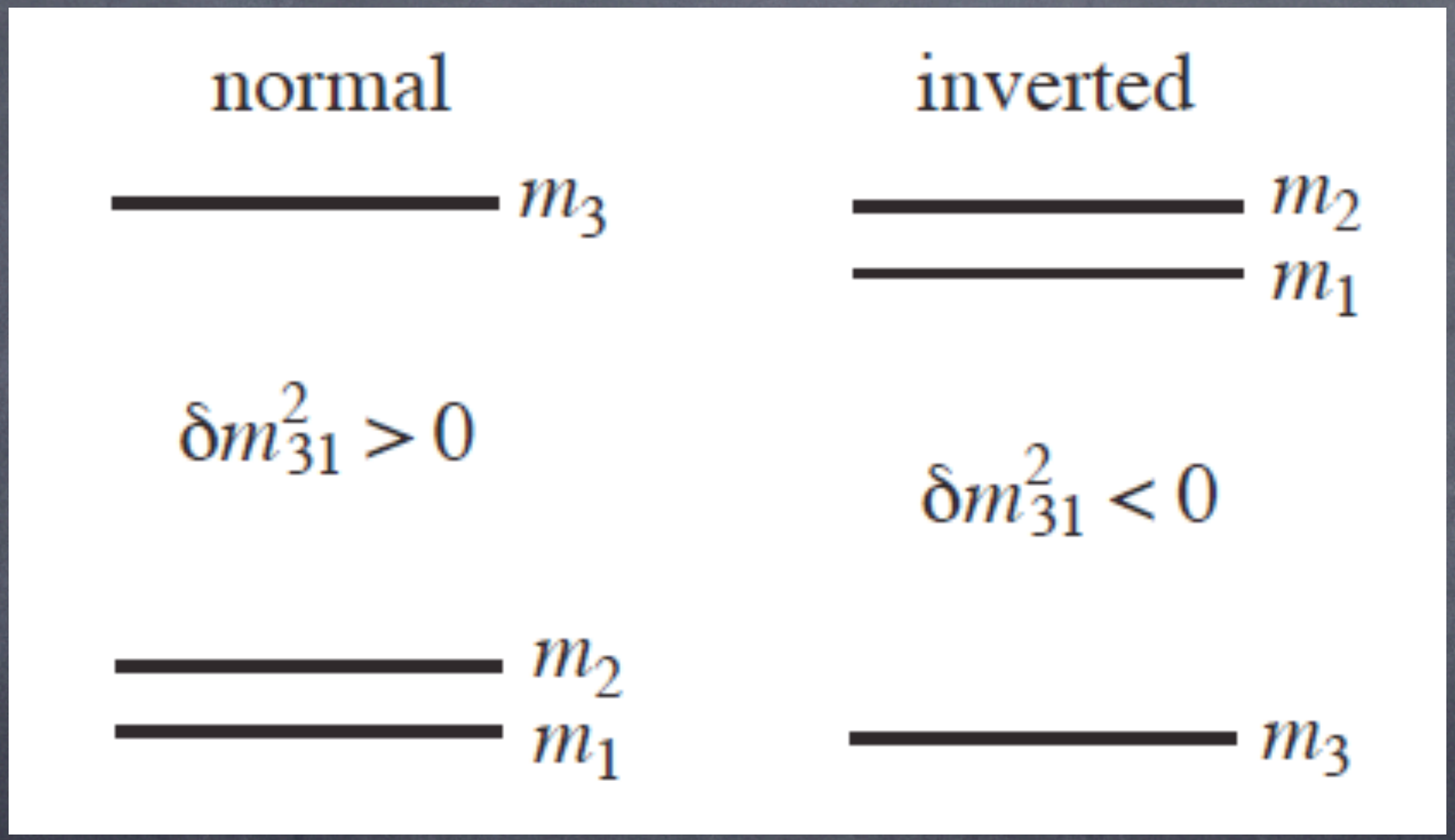
The Neutrino Mass Hierarchy

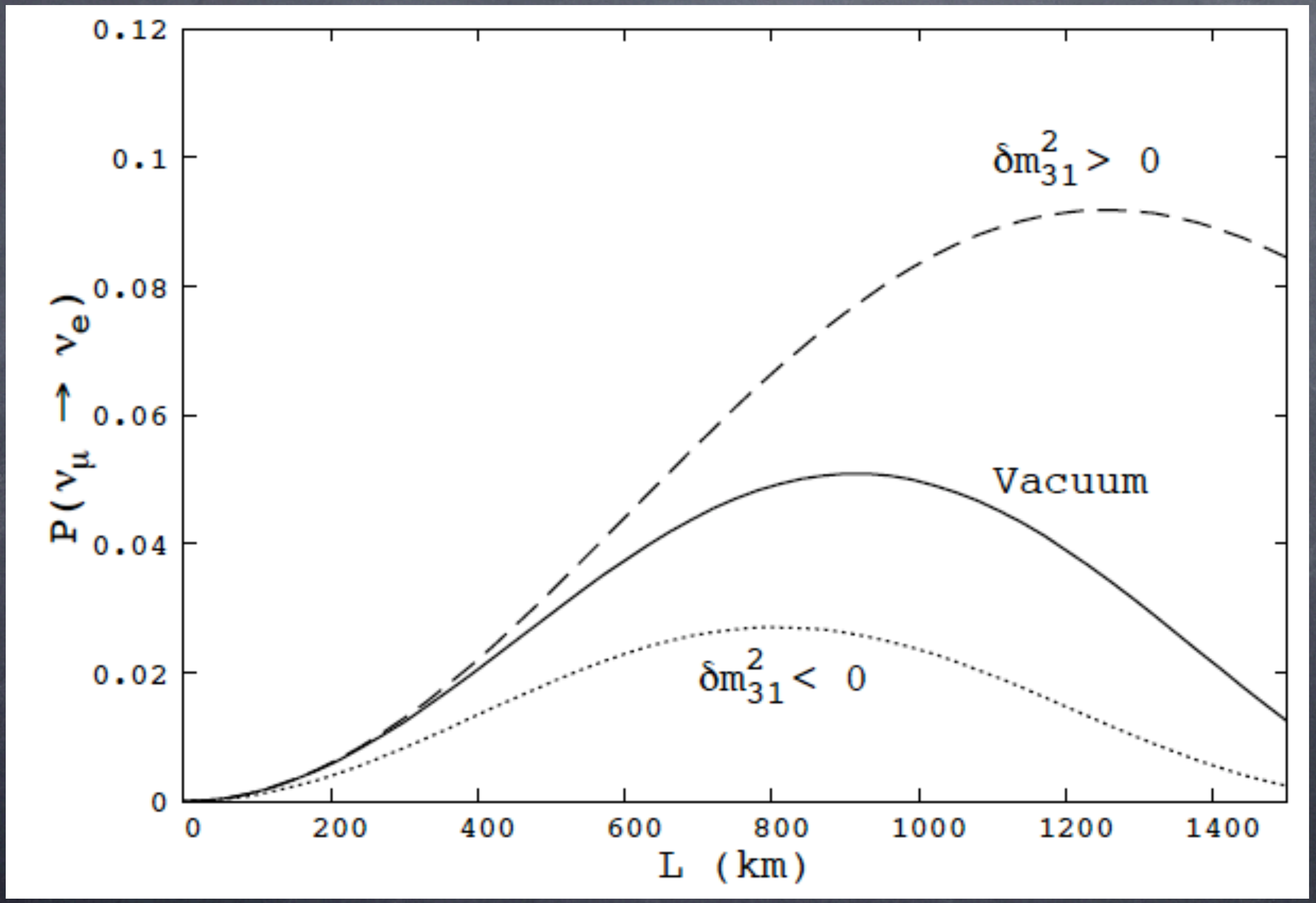
Danny Marfatia

Which spectrum?

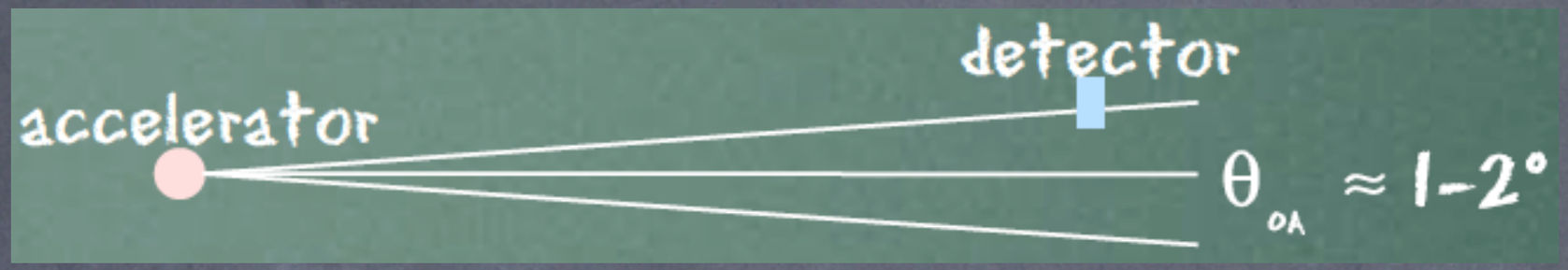


Goal: at least a 3σ (CP phase independent) determination

Long-baseline experiments rely on matter effects



Off-axis beams (T2K, NOvA, T2HK):

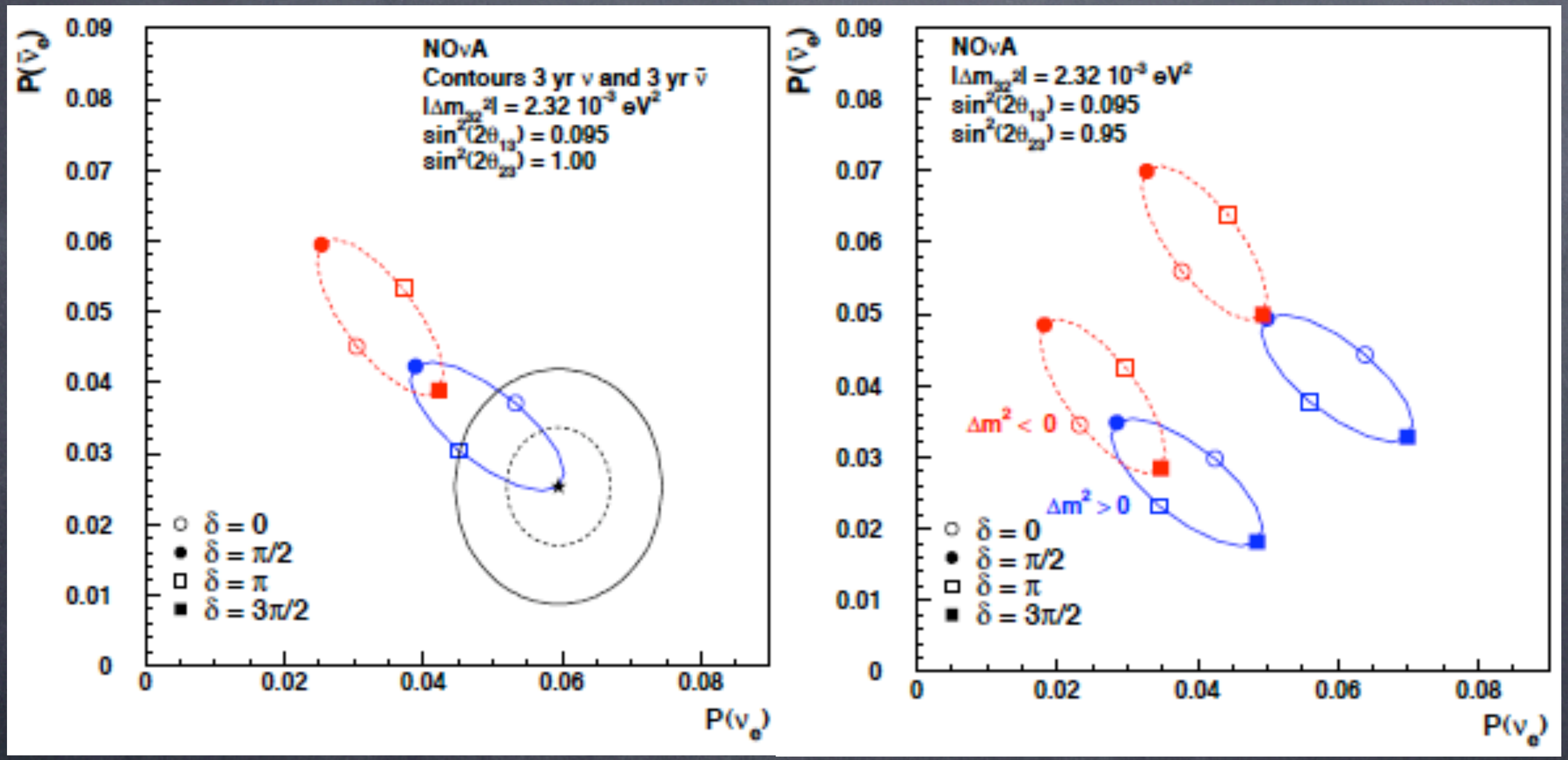


- narrow beam E can be tuned to oscillation max
- lower backgrounds from NC feed down
- can only do counting expt, so no spectral info
- multiple measurements at different off-axis angles/baselines needed to break degeneracies

Wide-band beams (LBNE?):

- higher on-axis flux and broad energy spectrum
- degeneracies can be resolved in a single expt
- need detectors with good energy resolution and NC rejection

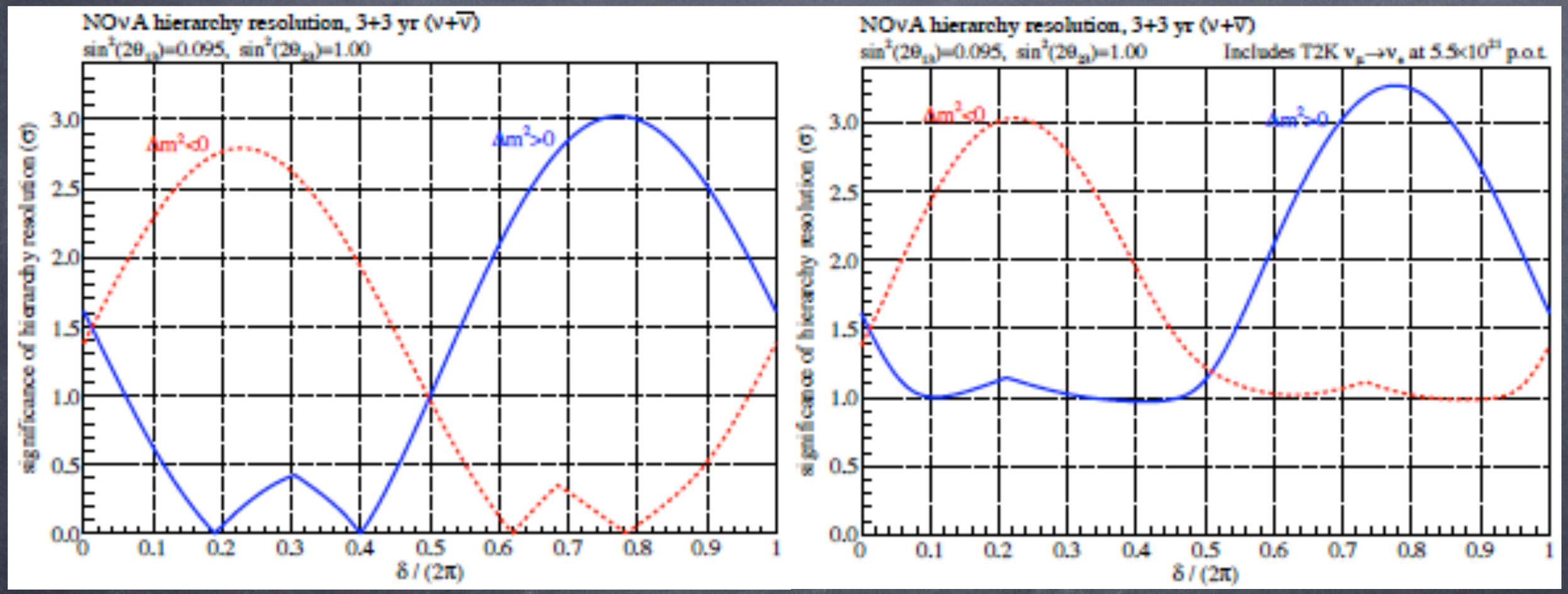
Can NOvA do it?



Patterson 1209.0716

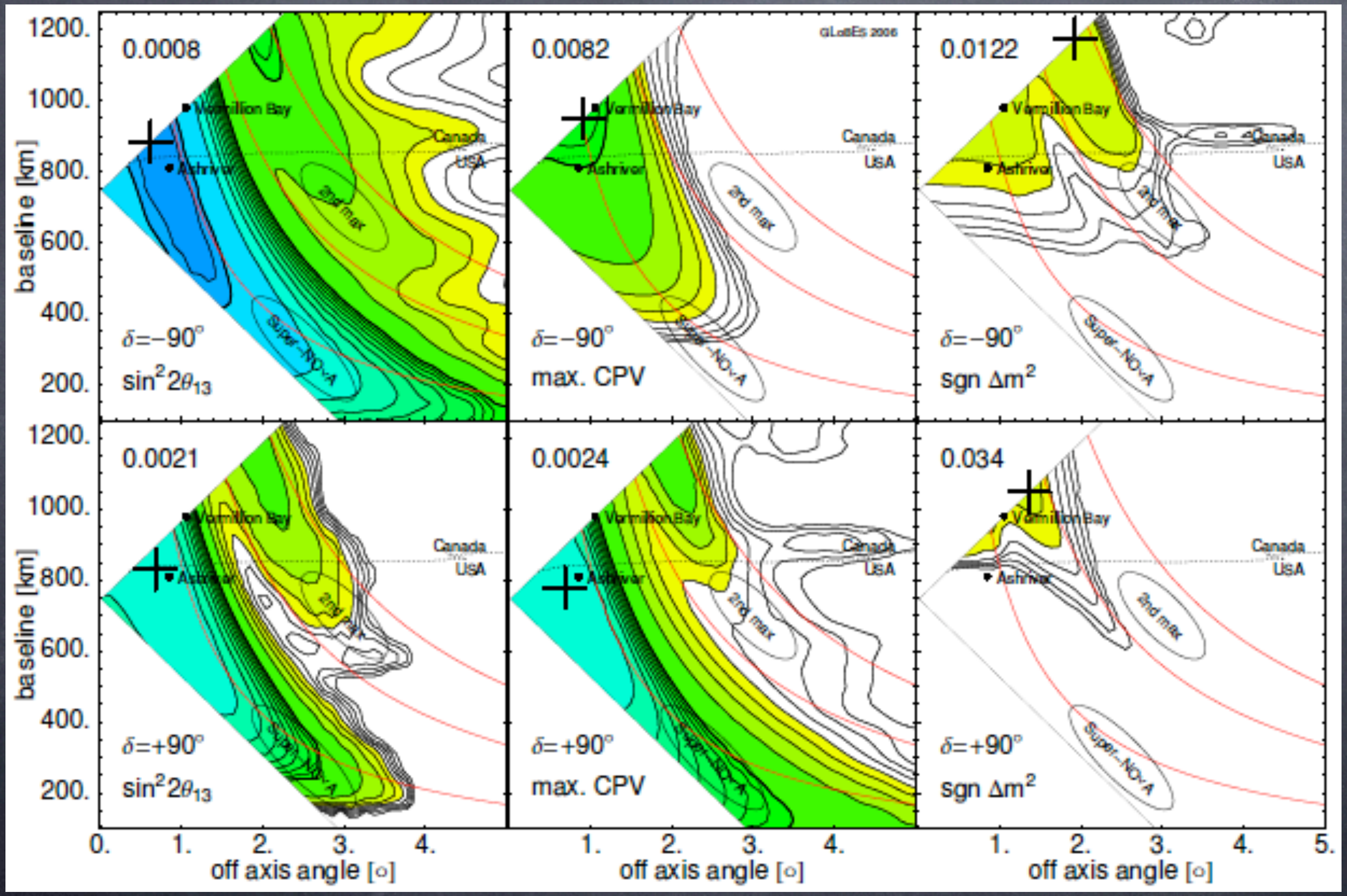
3.6x10^(21) p.o.t.

+T2K



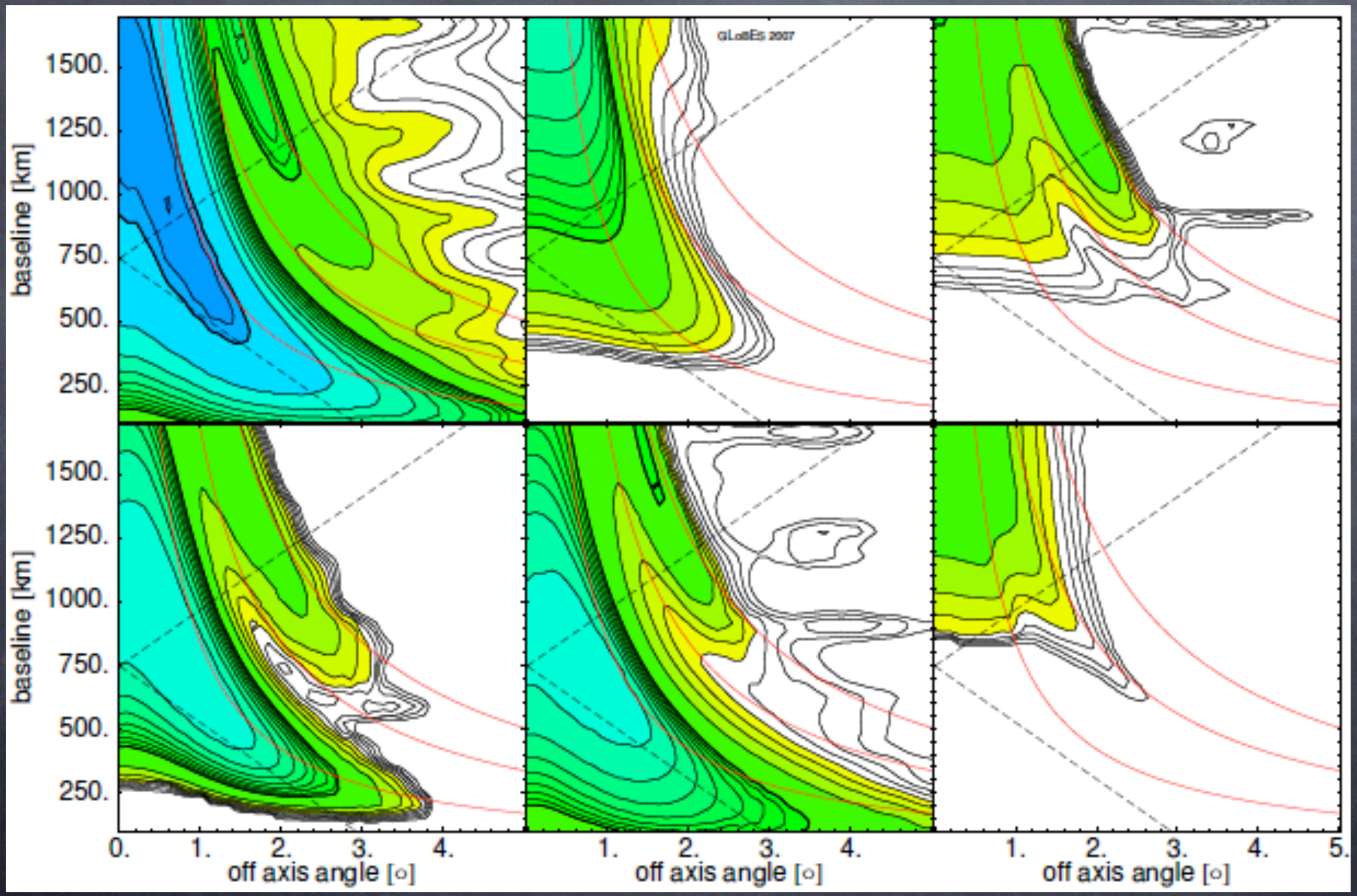
Patterson 1209.0716

Where to place a detector in the NuMI beamline?

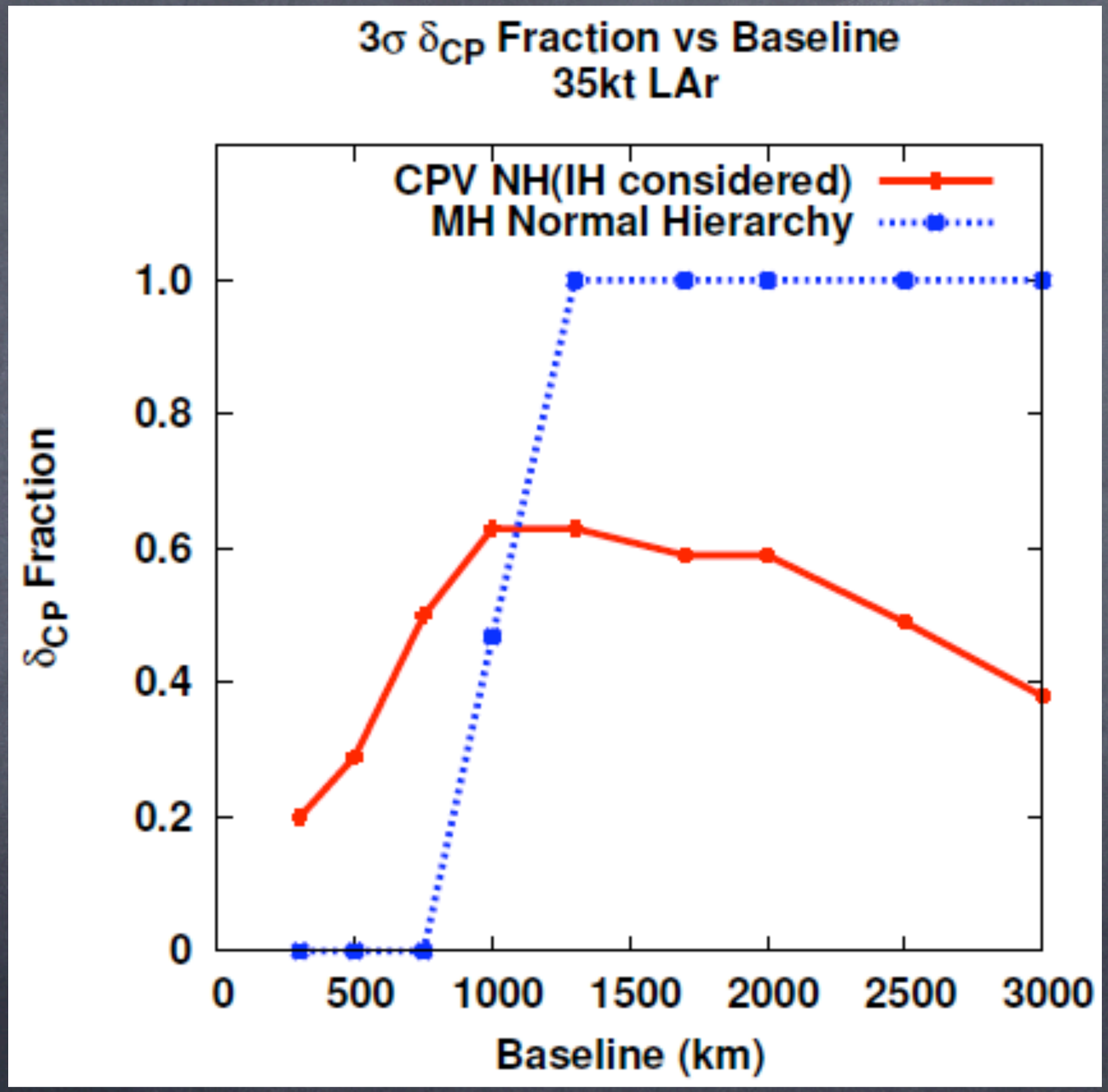


Barger, Huber, Marfatia, Winter hep-ph/0703029

On-axis or off-axis?

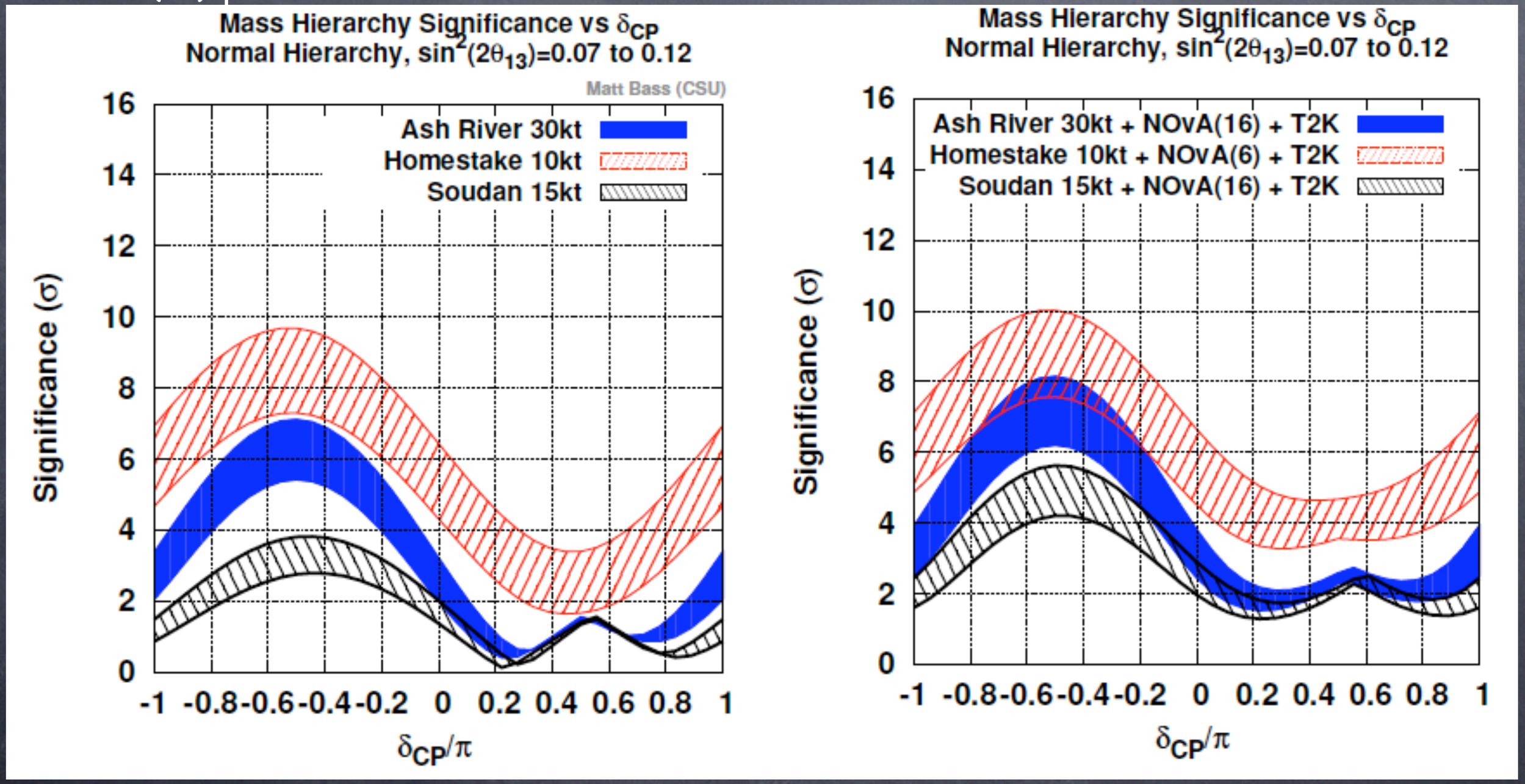


Barger, Huber, Marfatia, Winter hep-ph/0703029



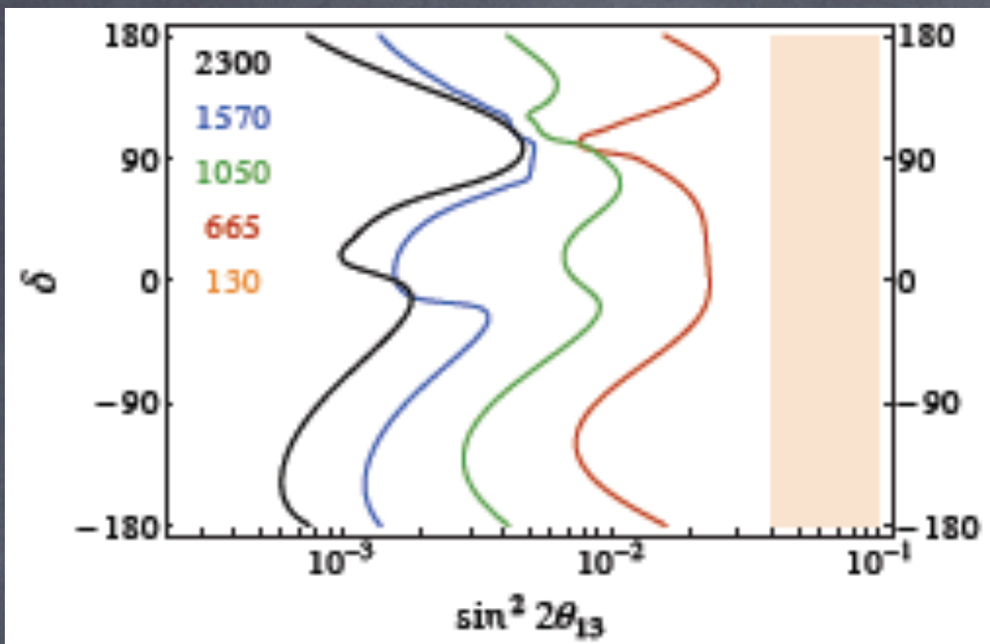
LBNE Reconfiguration Report

6x10^(21) p.o.t.

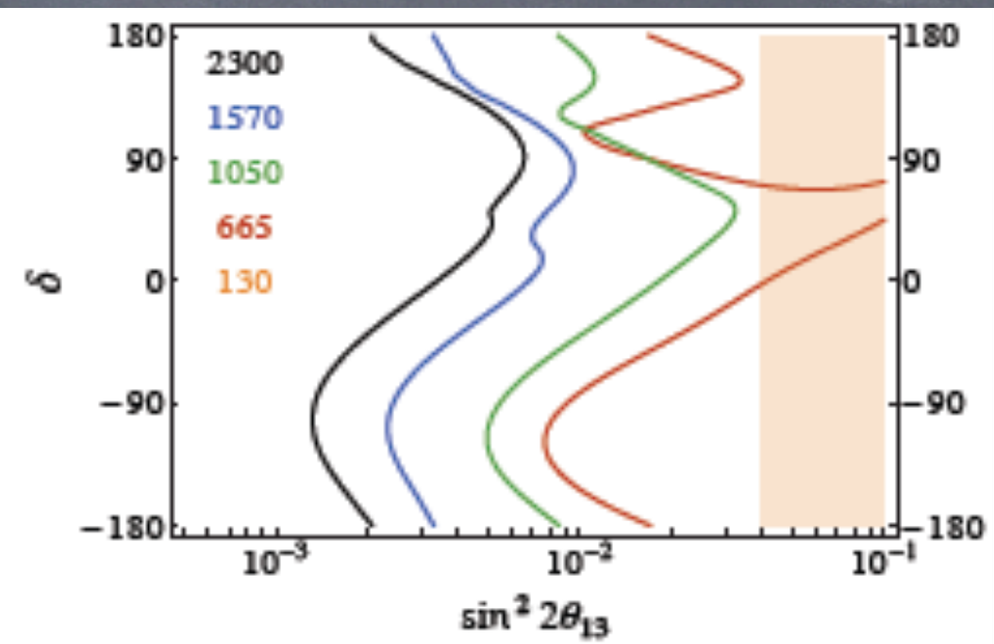


LBNE Reconfiguration Report

LAGUNA:

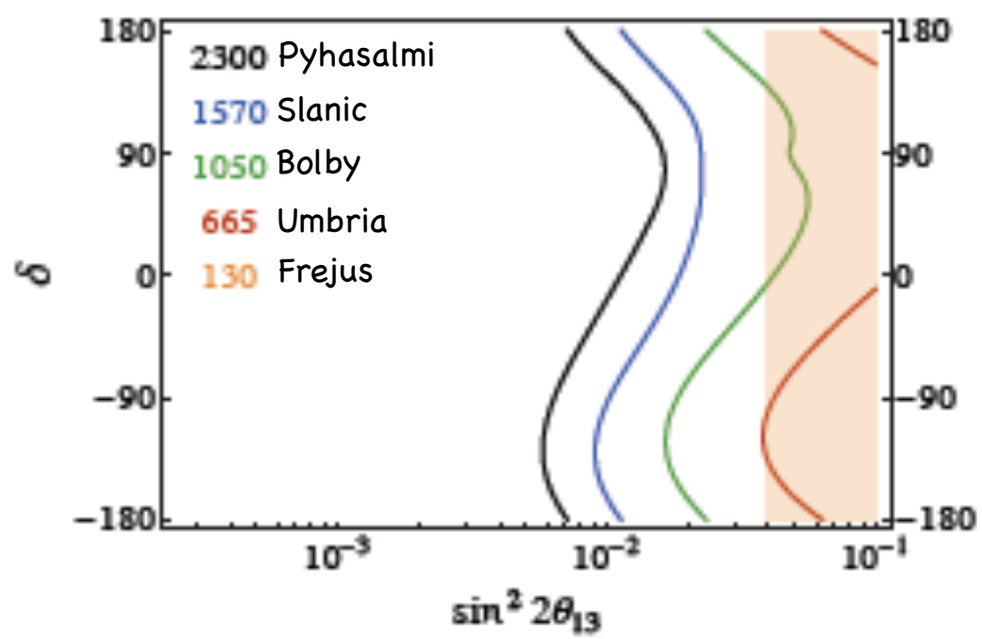


(a) LAr or GLACIER (100 kt)



(b) WC or MEMPHYS (440 kt)

3x10^(22) p.o.t



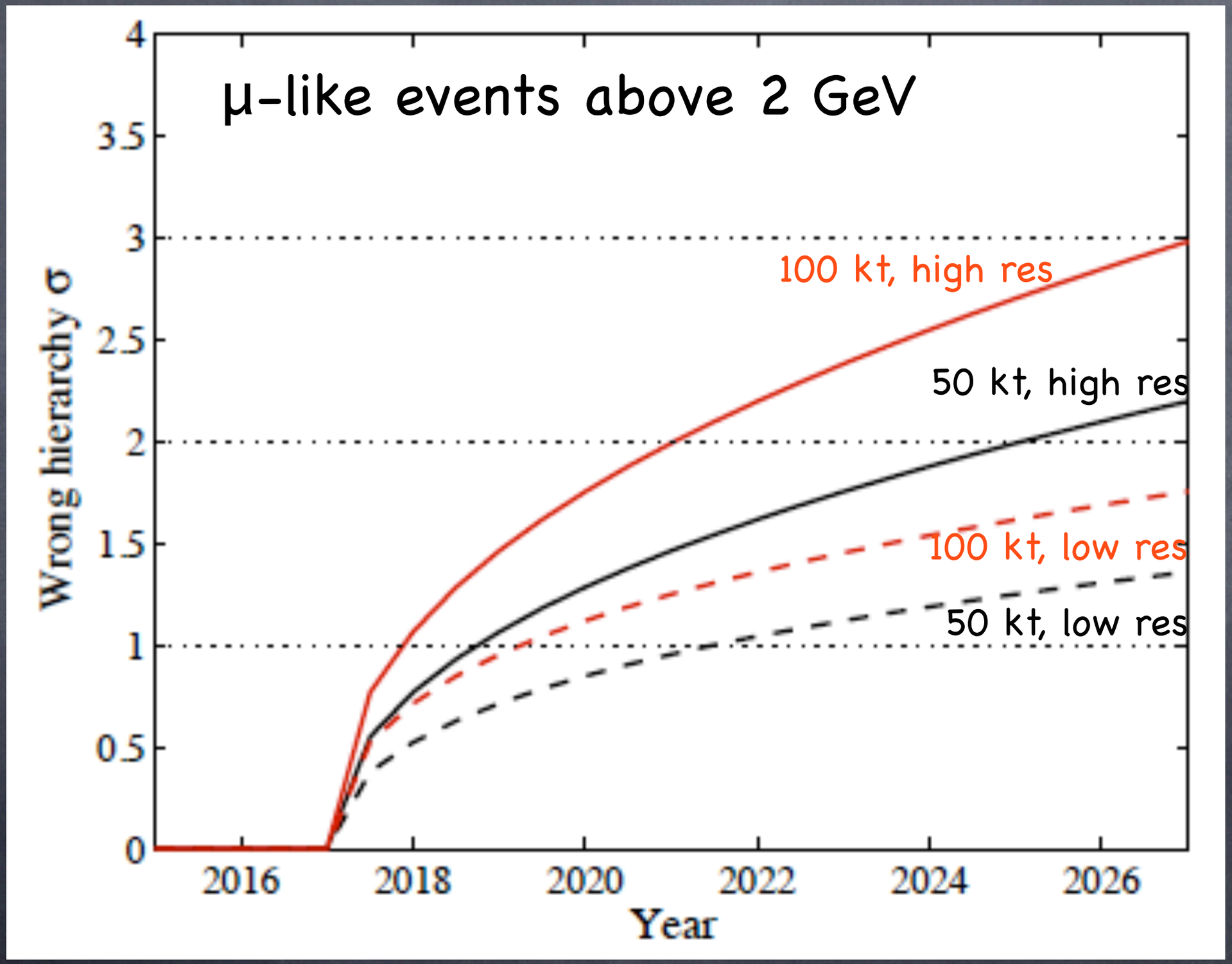
(c) LSc or LENA (50 kt)

Coloma, Li, Pascoli 1206.4038

Atmospheric neutrinos

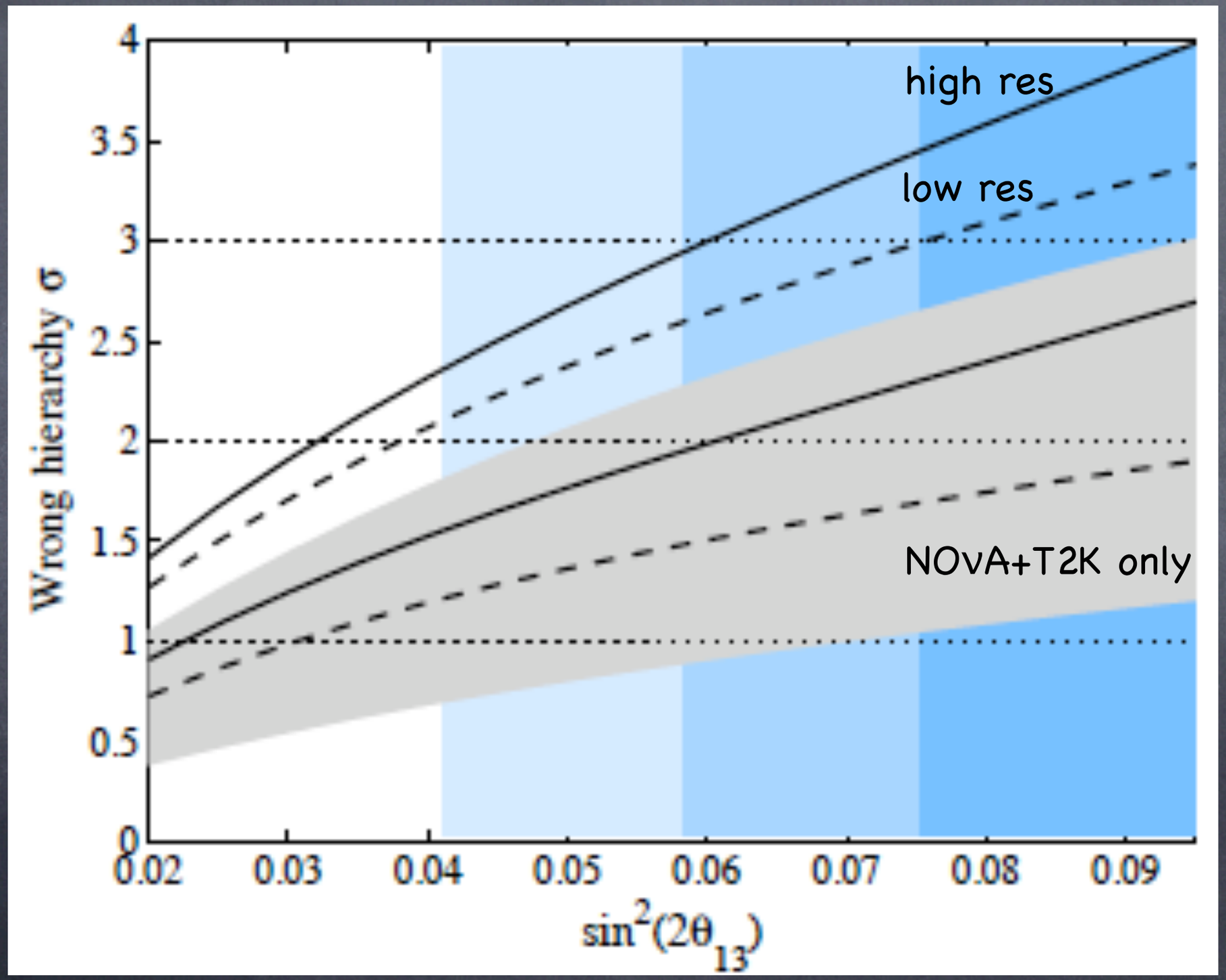
- broad range in baselines: 20 - 12500 km
- probes resonance between 4-8 GeV
- muon ν survival probability depends weakly on CP phase
- help resolve degeneracies when combined with LBL data
- need huge detectors for high statistics in few GeV range
- cannot measure L/E precisely
- separating ν and anti-ν events not always feasible

ICAL@INO (magnetized iron calorimeter)



Blennow, Schwetz 1203.3388

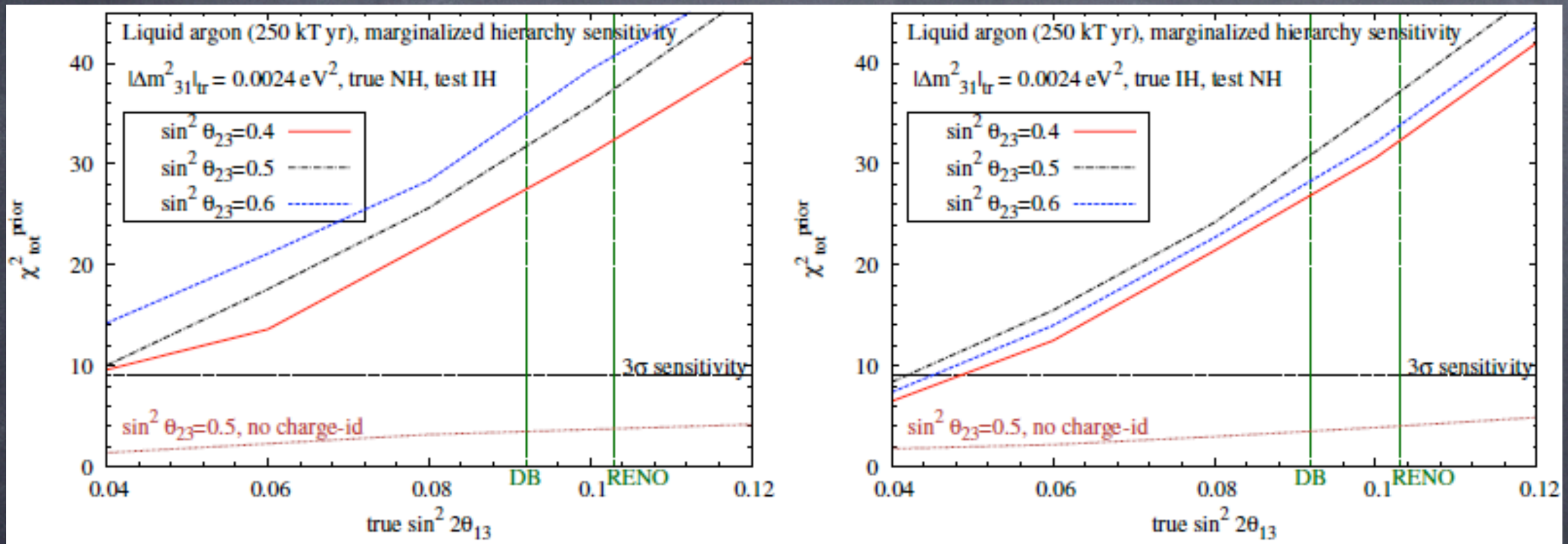
500 kt-yr ICAL@INO + NOνA + T2K



Blennow, Schwetz 1203.3388

Liquid Argon (magnetized)

Sensitivity driven by muon events

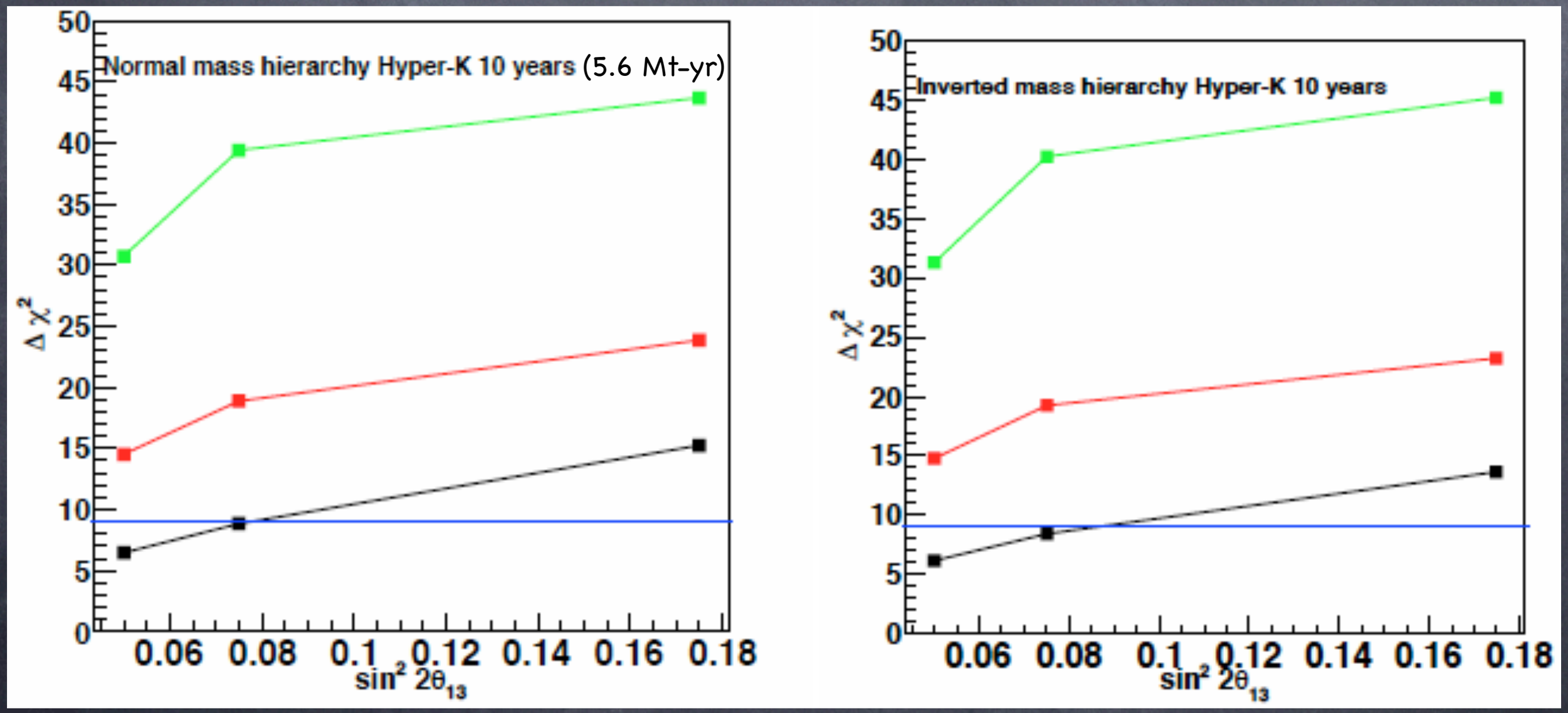


Barger et al. 1203.6012

100 kt-yr can give 4σ discrimination for NH or IH

Hyper-Kamiokande

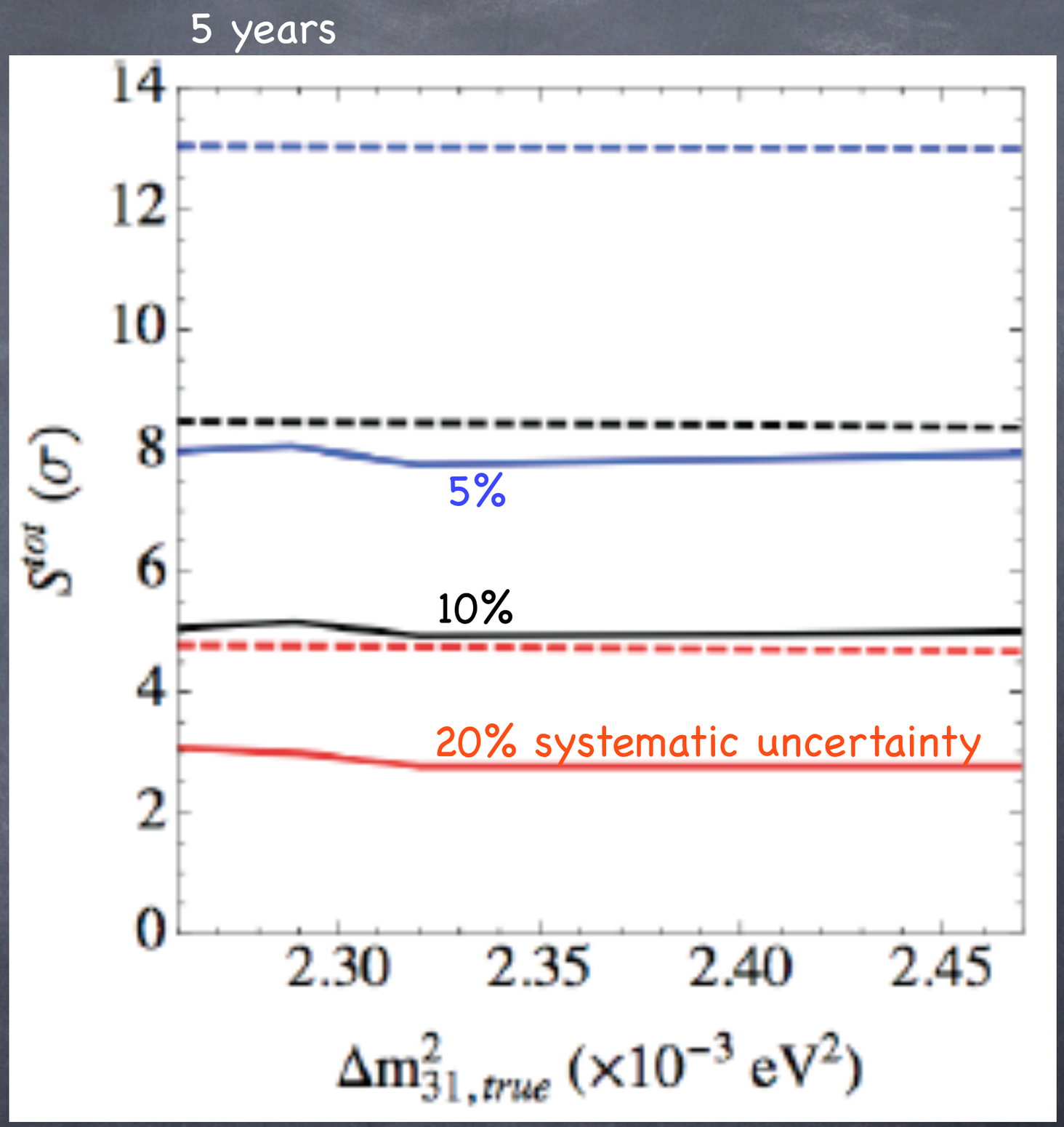
Using multi-GeV $\nu_e-\text{like and } \bar{\nu}_e-\text{like}$ events



Hyper-K LoI 1109.3262

PINGU

- 20 strings added to DeepCore
- GeV threshold
- multi-Mt volume



Akhmedov, Razzaque, Smirnov 1205.7071

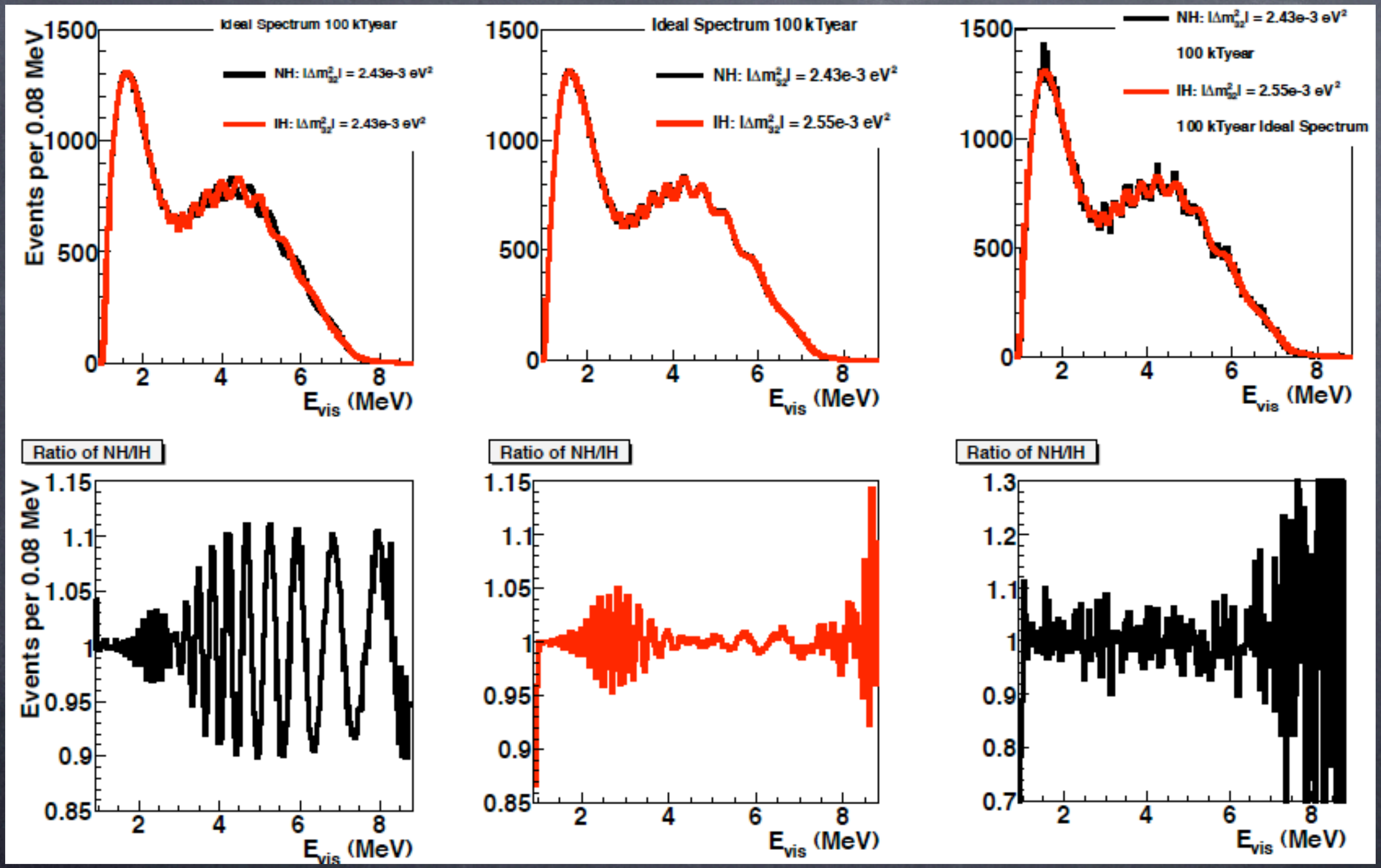
Reactor neutrinos

- Vacuum oscillations in disappearance channel
- For L about 60 km modulation due to solar parameters is broad...
- so that narrower modulation due to atmospheric oscillations is easier to identify
- Survival probability depends on δm^2_{31} and δm^2_{32}

$$\delta m^2_{31} = \delta m^2_{32} + \delta m^2_{21}$$

$$NH: \quad |\delta m^2_{31}| = |\delta m^2_{32}| + |\delta m^2_{21}|$$

$$IH: \quad |\delta m^2_{31}| = |\delta m^2_{32}| - |\delta m^2_{21}|$$



Qian et al. 1208.1551

Summary

Goal: at least a 3σ (CP phase independent) determination

- need the Homestake option for LBNE...
- preferably underground to use atmospheric neutrinos
- adding ICAL@INO to NOνA+T2K not enough
- magnetized LAr detector ideal for atm neutrinos
- 5.6 Mt-yr exposure at Hyper-K works
- PINGU could succeed with 5 years of data
- reactor expt promising, but need order of magnitude improvement in understanding of nonlinearity of detector energy scale compared to KamLAND

Project			Separation of IH and NH	Pre-requisite and date of achievement	Reference
DayaBay II	reactor 60km	20 kt LS	3 σ in 6 years	R&D on E-resolution 2020 ?	Karsten Heeger at Neutrino 2012
ICAL@INO	atmospherics	50 kt MID (RPCs)	2.7 σ in 10 years	2027	Sandhya Choubey at Neutrino 2012
HyperK	atmosherics	1 Mt Water Cerenkov	3 σ in 5 years 4 σ in 10 years	2027/28 2033/34	HyperK LOI Sandhya Choubey at Neutrino 2012
T2HK	LBL accel. 295 km	1 Mt Water Cerenkov	0..3 σ in 10 years	2028	Masashi Yokoyama at Neutrino 2012
PINGU	atmospheircs	Ice (South pole)	3...11 σ in 5 years	feasibility study ongoing, understanding of resolution and systematics on atmospherics Around 2020 if it works.	Uli Katz at neutrino Town meeting
MINOS+	LBL accel. 735 km	MID 5.4 kt	no claim on mass hierarchy	---	Jenny Thomas at neutrino Town meeting
GLADE	LBL accel. 810 km	LAr 5 kt	In combination with NOvA and T2K: ≤ 2 σ	Letter-of-Intent	
NOvA	LBL AshRiver 810 km	TASD 14 kt	0...3 σ in 6 years depending on δ	Full operation in 2014 2020	Ryan Patterson at Neutrino 2012
LBNE	LBL Homestake LBL Soudan LBL AshRiver	LAr 10 kt LAr 15 kt LAr 30 kt	1.5...7 σ in 10 y 0...3 σ in 10 y 0.5...5 σ in 10 y	2030	Bob Swoboda at Neutrino 2012
LBNO	LBL accel. 2300 km	LAr 20 kt	> 5σ in a few y.	2023 + If decision in 2015	André Rubbia at Neutrino 2012
LENA	LBL accel. 2300 km	Liq. Scint. 50 kt	5 σ in 10 years	2028 + number of years to the decision	Lothar Oberauer at Neutrino 2012
Neutrino Factory	LBL accel. 2000 km	MIND 100kton	>> 5 σ		Ken Long at Neutrino 2012

Bertolucci et al. 1208.0512