Overview of Neutrino Physics and Motivation:

Stephen Parke
Fermilab

- Nu Standard Model
- Beyond Nu SM
- Summary & Conclusions

Unanswered Questions !

- Nature of the Nu: Majorana v Dirac (2 v 4 components)
- CPV in the neutrino sector (determining Dirac phase) credibility of Leptogenesis!
- Ordering of mass eigenstates (atmospheric or [31] mass hierarchy)
- Octant of theta_23 (|U_mu3|^2 < or > |U_tau3|^2)
- Majorana phases
- Absolute Neutrino Mass; m_lite

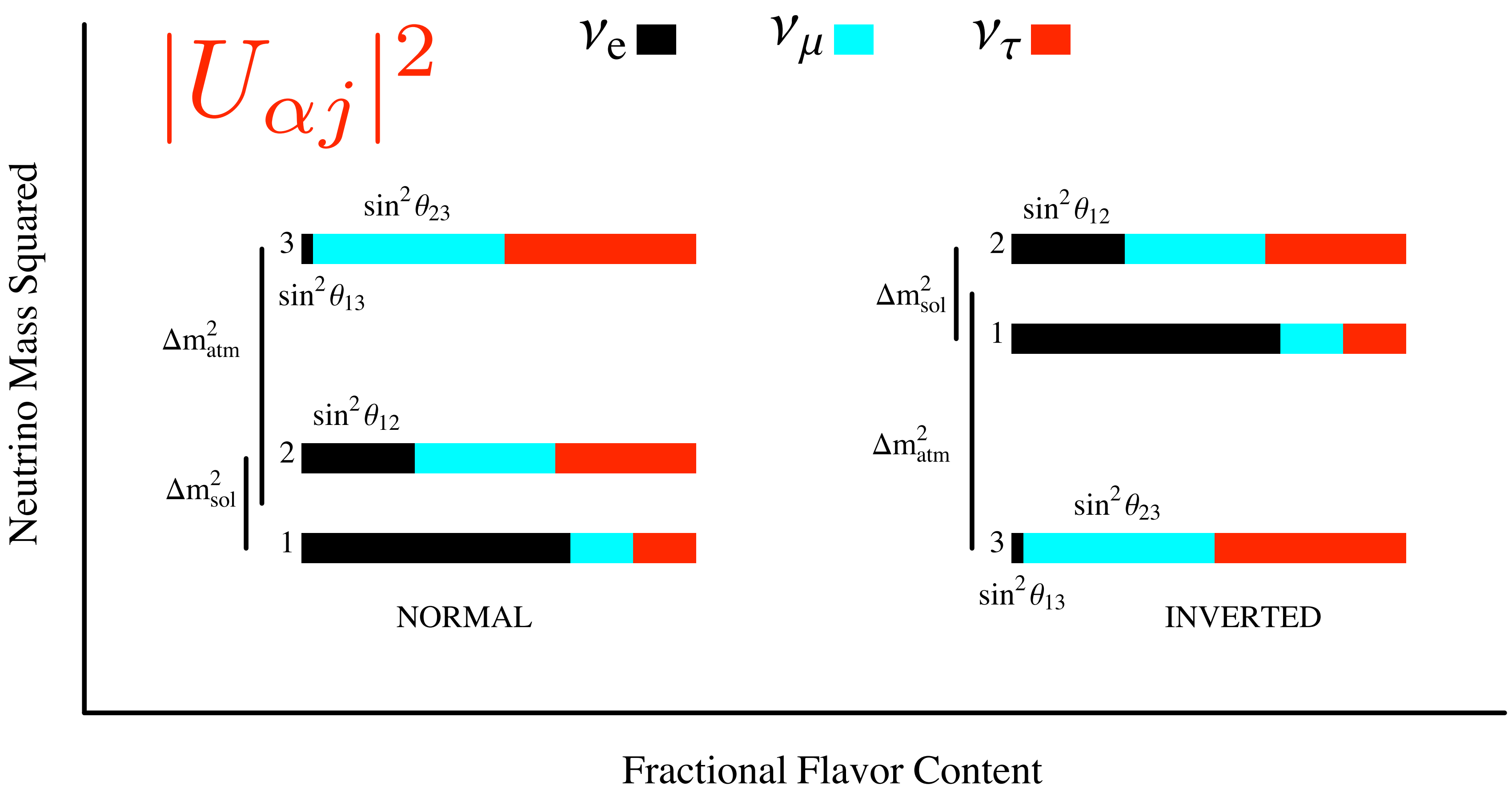
- What is the mass of Sterile neutrinos? light? superheavy?
- What is the size of the Non-Standard Interactions?
- Where are the true Surprises?

Nu Standard Model:

Label the Neutrino mass eigenstates such that:

ν_e component of ν_1 > ν_e component of ν_2 > ν_e component of ν_3

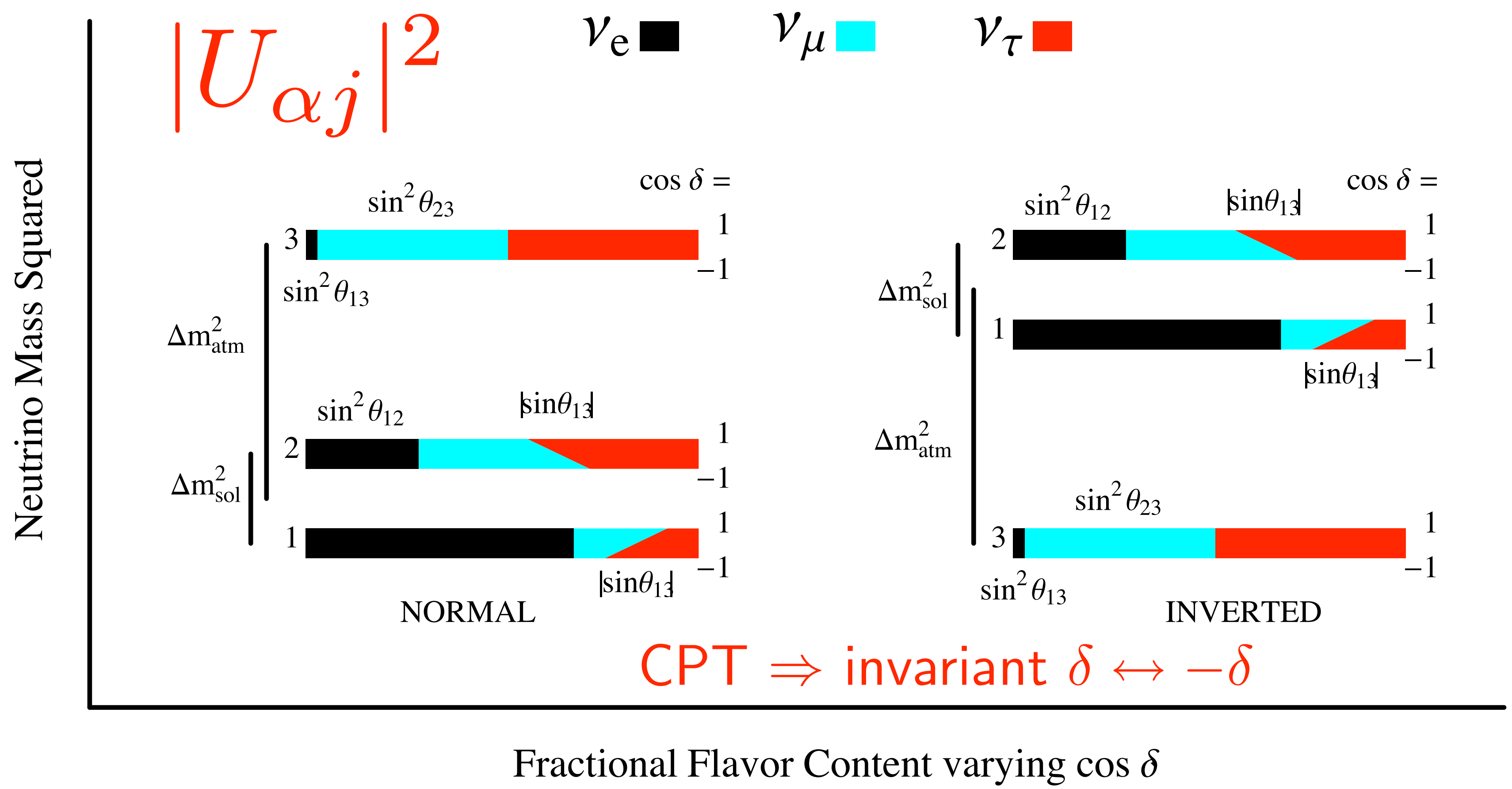
i.e. $|U_{e1}|^2 > |U_{e2}|^2 > |U_{e3}|^2$



SNO determined the solar mass hierarchy (1 <-> 2) !!!

$$\sin^2\theta_{13} \equiv |U_{e3}|^2, \quad \sin^2\theta_{12} \equiv \frac{|U_{e2}|^2}{(1-|U_{e3}|^2)}, \quad \sin^2\theta_{23} \equiv \frac{|U_{\mu 3}|^2}{(1-|U_{e3}|^2)}$$

Nu Standard Model:



$$\delta m^2_{sol} = +7.6 \times 10^{-5}\ eV^2 \qquad \sin^2\theta_{12} \sim \frac{1}{3}$$

$$|\delta m^2_{atm}| = 2.4 \times 10^{-3}\ eV^2 \qquad \sin^2\theta_{23} \sim \frac{1}{2}$$

$$|\delta m^2_{sol}|/|\delta m^2_{atm}| \approx 0.03 \qquad \sin^2\theta_{13} \sim 0.02$$

$$\sqrt{\delta m^2_{atm}} = 0.05\ eV < \sum m_{\nu_i} < 0.5\ eV = 10^{-6} * m_e \qquad 0 \leq \delta < 2\pi$$

Masses & Mixings:

$$\sin^2\theta_{13} \quad \approx \quad 0.02 \pm 0.01$$

$$|\sin^2\theta_{12} - \frac{1}{3}| \qquad < 0.04$$

$$|\sin^2\theta_{23} - \frac{1}{2}| \qquad < 0.12$$

Close to Tri-Bi-Maximal: Accident or Symmetry ?

Are the deviations from TBM or BM or ... related?

Masses & Mixings (conti.)

- BM, TBM, GR might only apply to neutrino mixing and $U_{PMNS} = U_e U_\nu^\dagger$ implies $\theta_{13} \approx \frac{\theta_{12}^e}{\sqrt{2}}$
- **Solar Sum Rules** — Sum Rule: King ('05); Masina ('05); Antusch, King ('05)

  Charged Lepton Corrections: King ('02), Frampton, Petcov, Rodejohann ('04), Altarelli, Feruglio, Masina ('04), Antusch, King ('04), Ferrandis, Pakvasa ('04), Feruglio ('05), Datta, Everett, Ramond ('05), Mohapatra, Rodejohann ('05) Antusch, Maurer ('11) Mazocca, Petcov, Romanino, Spinrath ('11)
- Bimaximal $\theta_{12} = 45^o + \theta_{13} \cos\delta \rightarrow \delta \approx \pi$
- Tri-bimaximal $\theta_{12} = 35^o + \theta_{13} \cos\delta \rightarrow \delta \approx \pm\frac{\pi}{2}$
- Golden ratio $\theta_{12} = 32^o + \theta_{13} \cos\delta$

Experiment $\theta_{12} = 34^o \pm 1^o$ $\qquad$ $\theta_{13} = 9^o \pm 1^o$

Masses & Mixings (conti.)

- Quark-Lepton Complementarity $\theta_{12} + \theta_C = 45^o$
- Solar sum rules
  - Bimaximal $\theta_{12} = 45^o + \theta_{13} \cos\delta$
  - Tri-bimaximal $\theta_{12} = 35^o + \theta_{13} \cos\delta$
  - Golden Ratio $\theta_{12} = 32^o + \theta_{13} \cos\delta$

Plus HO corrections...

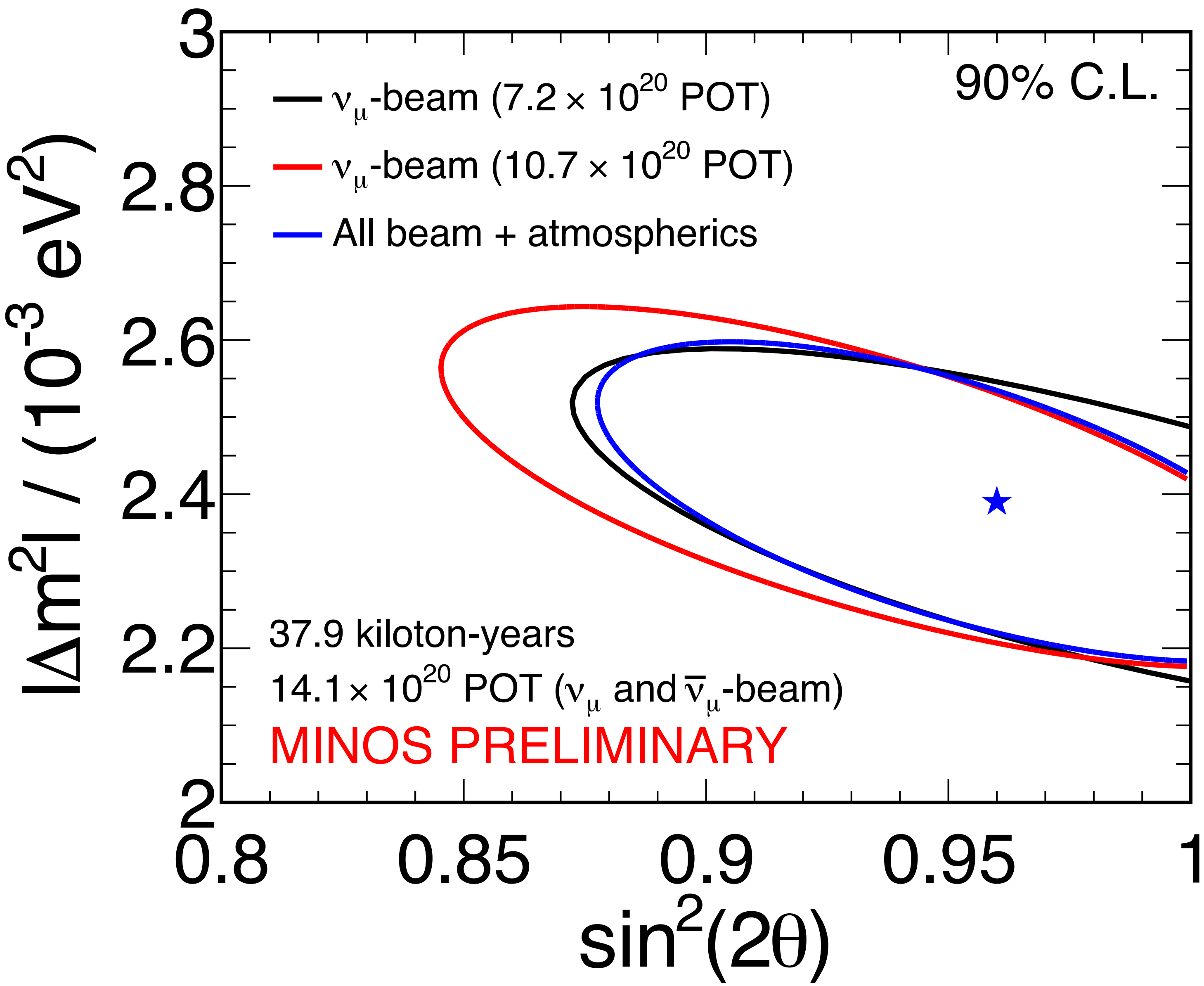
- Atm. sum rules
  - Tri-bimaximal-Cabibbo $\theta_{12} = 35^o \quad \theta_{23} = 45^o$, $\theta_{13} = \theta_C/\sqrt{2} = 9.2^o$
  - Trimaximal1 $\theta_{23} = 45^o + \sqrt{2}\theta_{13} \cos\delta$
  - Trimaximal2 $\theta_{23} = 45^o - \frac{\theta_{13}}{\sqrt{2}} \cos\delta$

Plus Charged Lepton Corrections...

Now that θ_{13} is measured these predict $\cos\delta$

Non-Maximal Theta_23

Contours



23 MINOS @ Neutrino 2012 by Ryan Nichol

Adding in the extra data and the atmospherics

New MINOS neutrino oscillation parameters

$$\Delta m^2 = 2.39^{+0.09}_{-0.10} \times 10^{-3} eV^2$$

$$\sin^2(2\theta) = 0.96^{+0.04}_{-0.04}$$

$$\sin^2(2\theta) > 0.90 \text{ at } 90\% \text{ C.L.}$$

New

4*0.4*0.6=0.96

Sausages!

Global Fits:

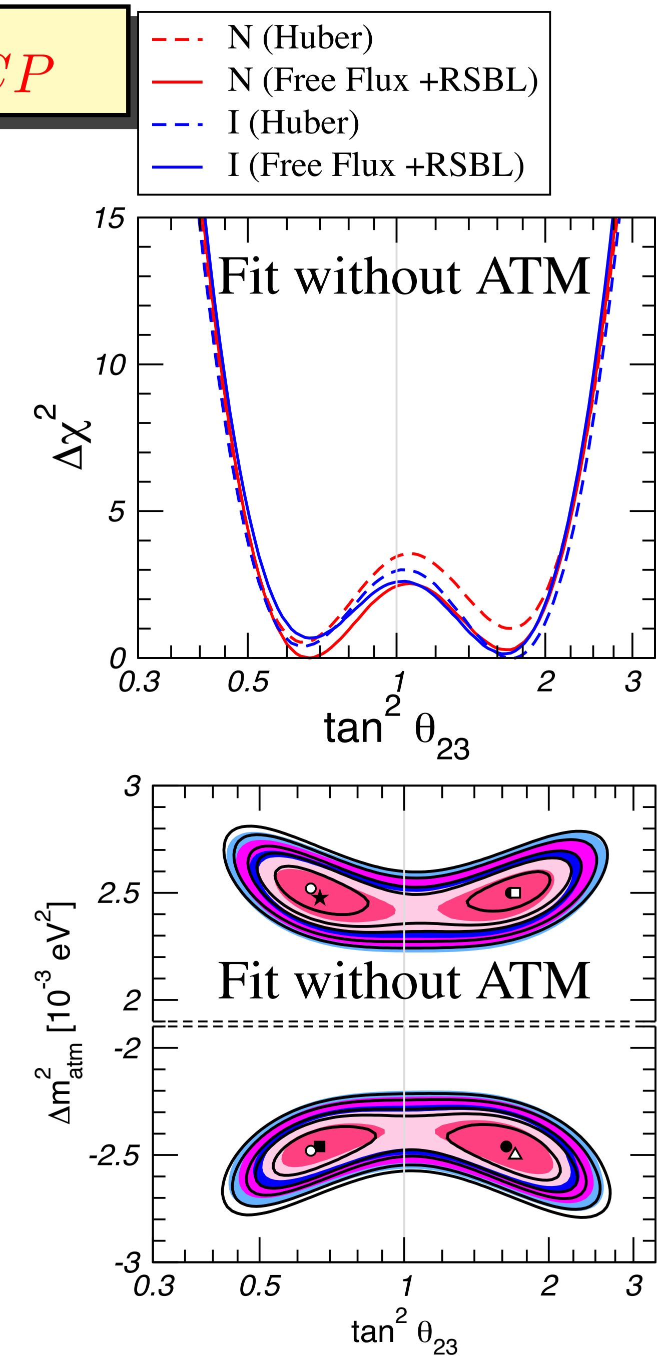
Global Fits 2012

parameter	best fit $\pm 1\sigma$ (Forero, Tortola, Valle, Vanegas '12)	best fit $\pm 1\sigma$ (Fogli, Lisi, Marrone, Montanino, Palazzo, Rotunno '12)
$\Delta m^2_{21}\ [10^{-5}\mathrm{eV}^2]$	7.62 ± 0.19	$7.54^{+0.26}_{-0.22}$
$\Delta m^2_{31}\ [10^{-3}\mathrm{eV}^2]$	$2.53^{+0.08}_{-0.10}$ $-(2.40^{+0.10}_{-0.07})$	$2.43^{+0.07}_{-0.09}$ $-(2.42^{+0.07}_{-0.10})$
$\sin^2\theta_{12}$	$0.320^{+0.015}_{-0.017}$	$0.307^{+0.018}_{-0.016}$
$\sin^2\theta_{23}$	$0.49^{+0.08}_{-0.05}$ $0.53^{+0.05}_{-0.07}$	$0.398^{+0.030}_{-0.026}$ $0.408^{+0.035}_{-0.030}$
$\sin^2\theta_{13}$	$0.026^{+0.003}_{-0.004}$ $0.027^{+0.003}_{-0.004}$	$0.0245^{+0.0034}_{-0.0031}$ $0.0246^{+0.0034}_{-0.0031}$
δ	$(0.83^{+0.54}_{-0.64})\,\pi$ 0.07π [a]	$(0.89^{+0.29}_{-0.44})\pi$ $(0.90^{+0.32}_{-0.43})\pi$

θ_{23}, Mass Ordering, δ_{CP}

- θ_{23} determination in global analysis:
  - Maximal $\theta_{23} = 45$ Disfavoured at 1.6–$2\ \sigma$ level

    Now mostly driven by MINOS ν_μ DIS

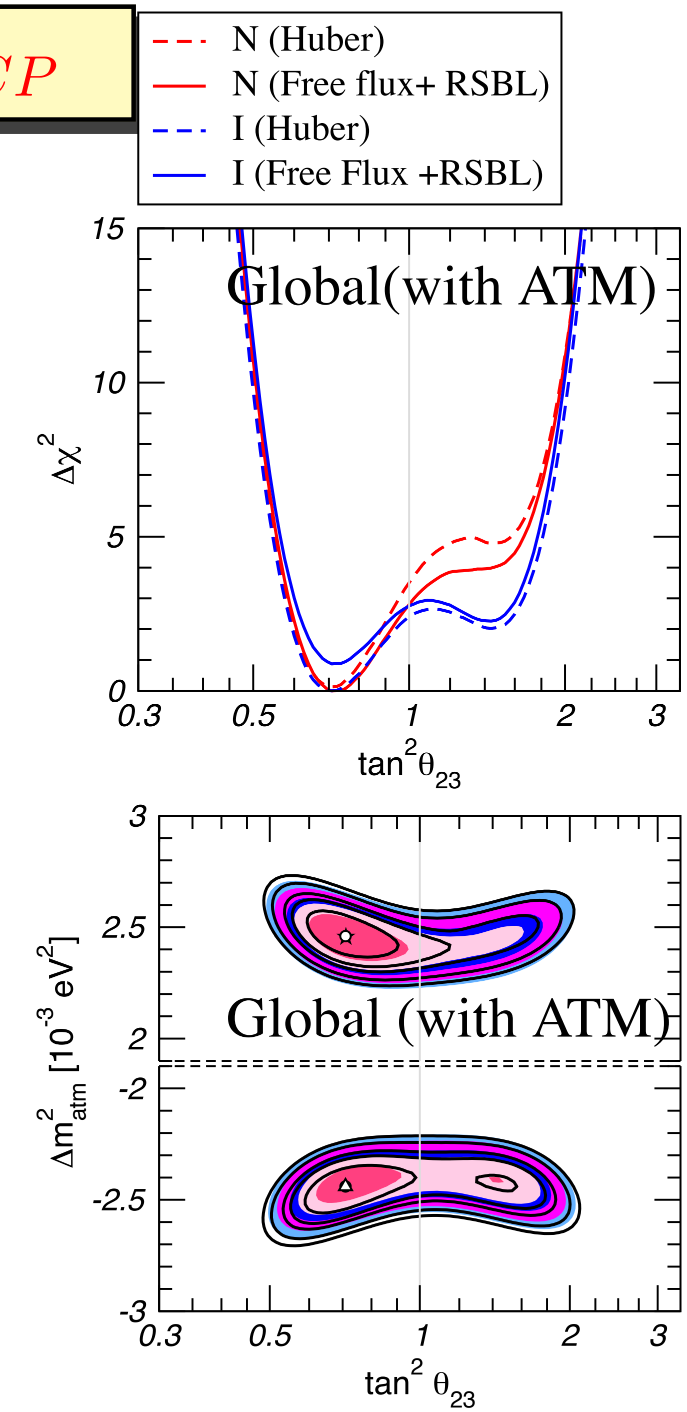


Neutrinos: Theory

Concha Gonzalez-Garcia

θ_{23}, Mass Ordering, δ_{CP}

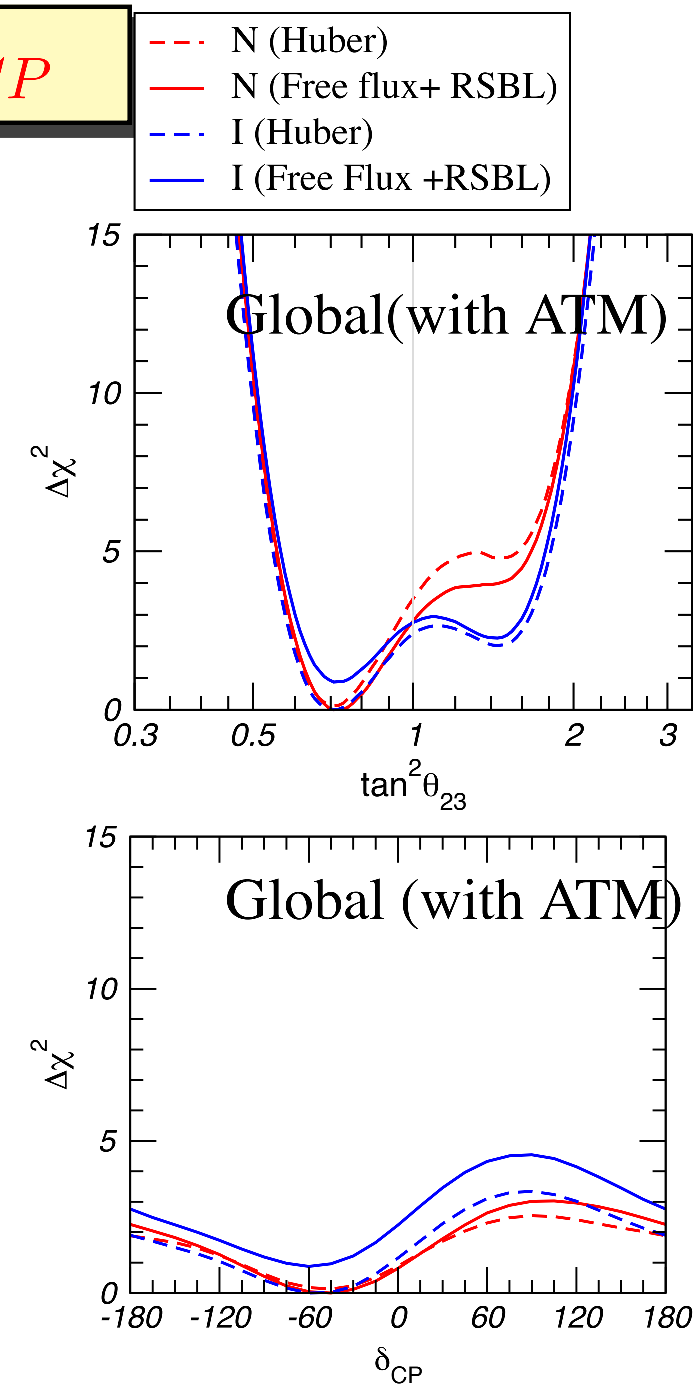
- θ_{23} determination in global analysis:
  - Maximal $\theta_{23} = 45$ Disfavoured at 1.6–$2\ \sigma$ level
    Now mostly driven by MINOS ν_μ DIS
  - First octant $\theta_{23} < 45$ Favoured at 1.6–$2\ \sigma$ level
    Driven by SK I–III ATM Sub-GeV ν_e excess
    It seems to be reduced in SK-IV analysis



Neutrinos: Theory   Concha Gonzalez-Garcia

θ_{23}, Mass Ordering, δ_{CP}

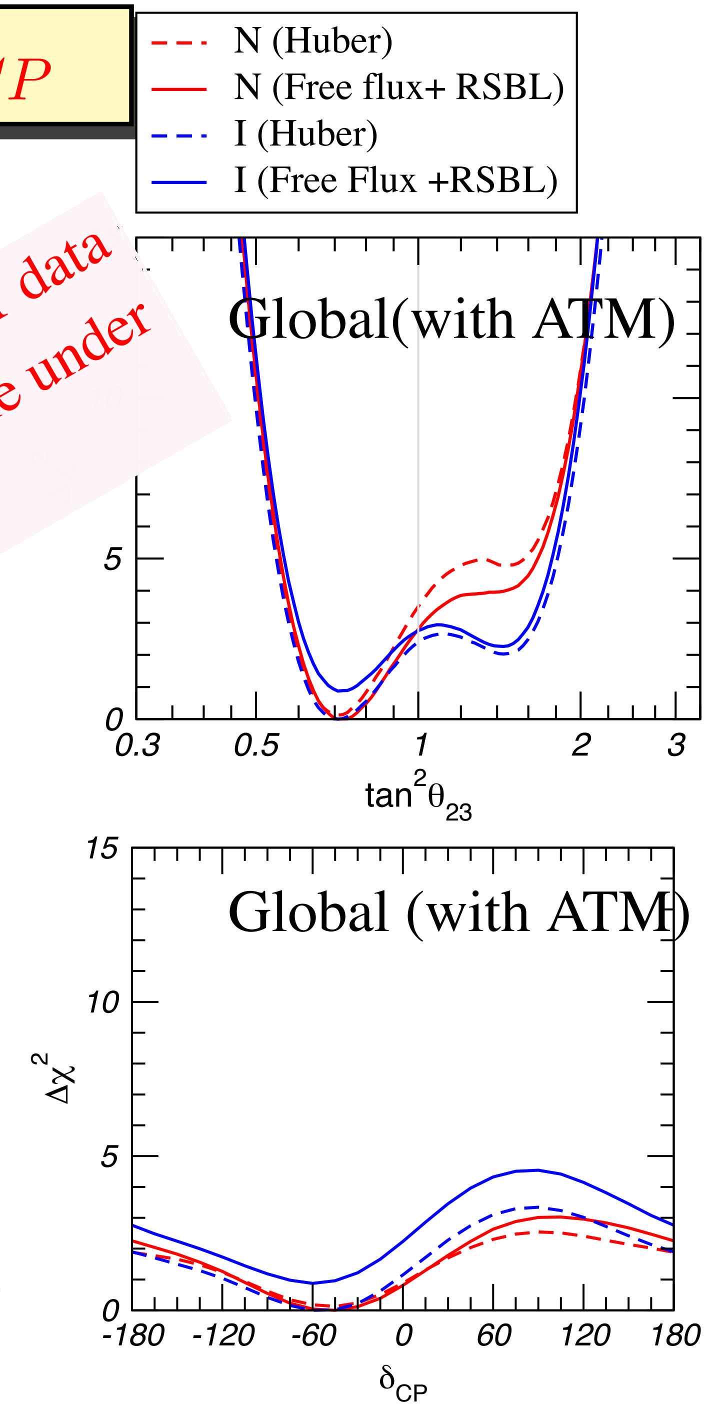
- θ_{23} determination in global analysis:
  - Maximal $\theta_{23} = 45$ Disfavoured at 1.6–$2\ \sigma$ level
    Now mostly driven by MINOS ν_μ DIS
  - First octant $\theta_{23} < 45$ Favoured at 1.6–$2\ \sigma$ level
    Driven by SK I–III ATM Sub-GeV ν_e excess
    It seems to be reduced in SK-IV analysis
- sign($\Delta m^2_{\rm atm}$) determination in global analysis:
  - No significant difference Normal versus Inverted
    Driven by SK ATM
- δ_{CP} determination in global analysis:
  - Signal at most at $1.7\ \sigma$ level
    Driven mostly by SK ATM (slight LBL ν_e app)



Neutrinos: Theory

Concha Gonzalez-Garcia

θ_{23}, Mass Ordering, δ_{CP}



- θ_{23} determination in global analysis:
  - Maximal $\theta_{23} = 45$ Disfavoured at 1.6–$2\ \sigma$ level
    Now mostly driven by MINOS ν_μ DIS
  - First octant $\theta_{23} < 45$ Favoured at 1 ...
    Driven by SK I–III ATM Sub-...
    It seems to be reduced i...
- sign($\Delta m^2_{\rm atm}$) det... ...alysis:
  - No signif... ...al versus Inverted
    Dri...
- ...ation in global analysis:
  - ...nificant at most at $1.7\ \sigma$ level
    Driven mostly by SK ATM (and slight LBL ν_e app)

Warning: Statistical Significance of these small effects in ATM data depends on details of ATM data analysis which can only be done under simplifications outside SK

Neutrinos: Theory | Concha Gonzalez-Garcia

3-flavor effects in atmospheric neutrinos

Peres, Smirnov, 99;
Gonzalez-Garcia, Maltoni, Smirnov, 04

???? pushes you into first quadrant

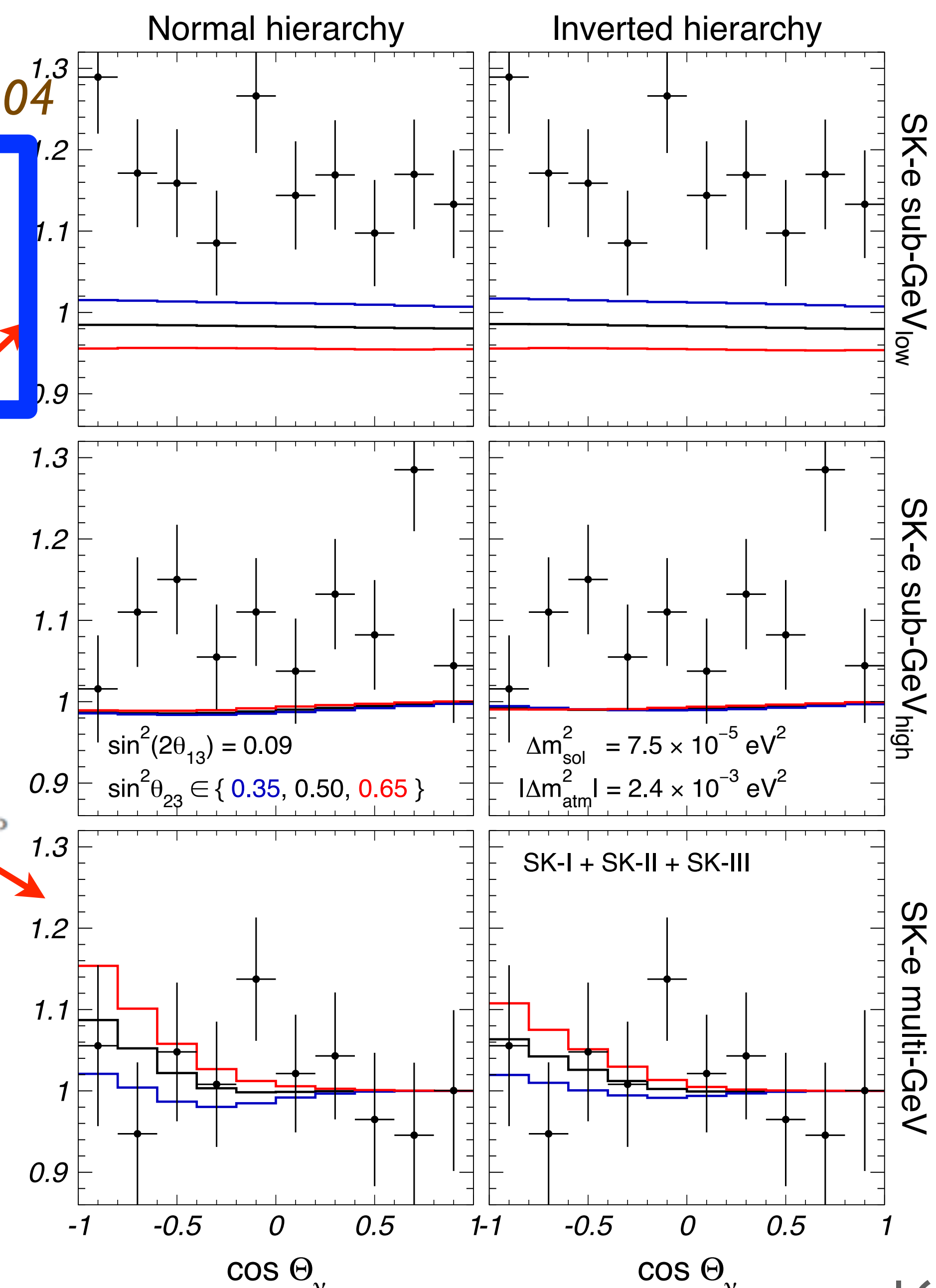
excess in electron-like events:

$$\frac{N_e}{N_e^0} - 1 \simeq (r\, s_{23}^2 - 1)\, P_{2\nu}(\Delta m_{31}^2, \theta_{13}) \qquad \theta_{13}\text{-effects}$$

$$+ \ (r\, c_{23}^2 - 1)\, P_{2\nu}(\Delta m_{21}^2, \theta_{12}) \qquad \Delta m_{21}^2\text{-effects}$$

$$- \ 2 s_{13} s_{23} c_{23}\, r\, \mathrm{Re}(A_{ee}^* A_{\mu e}) \qquad \text{interference: } \delta_{CP}$$

$$r = r(E_\nu) \equiv \frac{F_\mu^0(E_\nu)}{F_e^0(E_\nu)} \qquad r \approx 2 \ \text{(sub-GeV)} \qquad r \approx 2.6 - 4.5 \ \text{(multi-GeV)}$$



T. Schwetz

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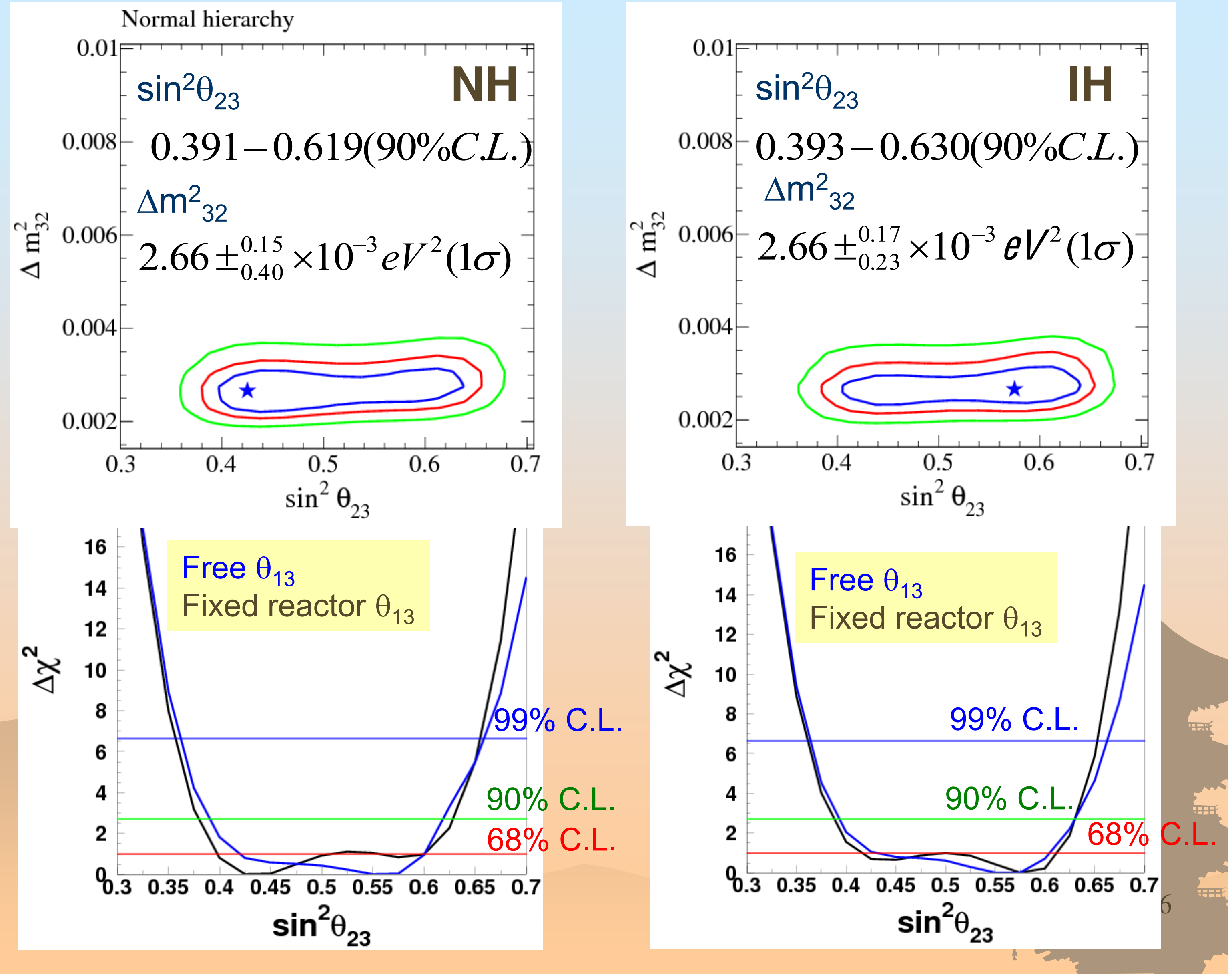
SuperK Fit: (Itow 2012)

Δm^2 and $\sin^2\theta_{23}$ with reactor constraint



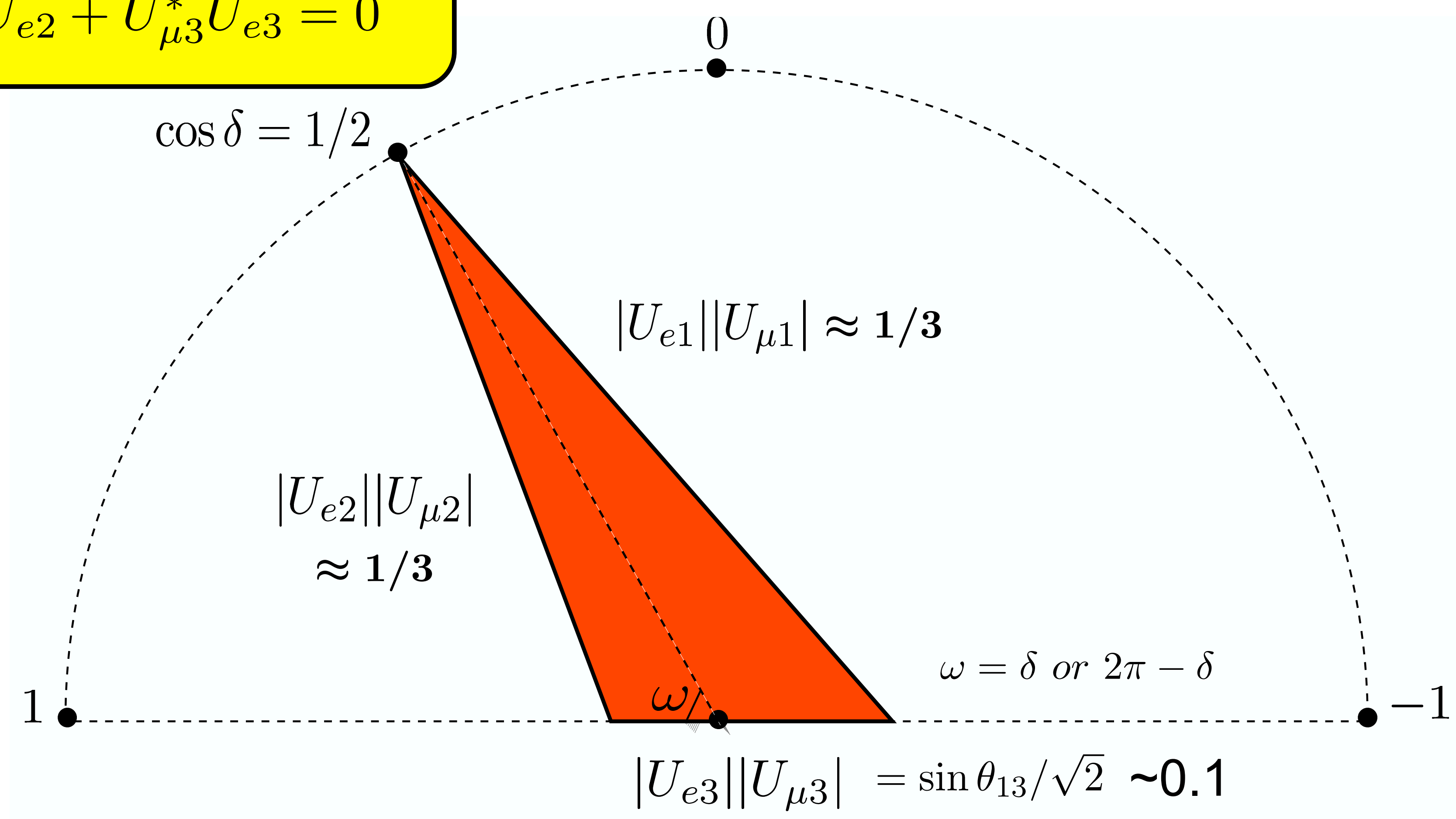
- Surprising large θ_{13} has opened the door to the next stage of atmospheric neutrino study.
  - Next goal ; mass hierarchy, the octant of θ_{23} and CP δ…

My Mother's Advice:

Before you eat a sausage, know what's inside !

Unitarity Triangle:

$$U^*_{\mu 1}U_{e1} + U^*_{\mu 2}U_{e2} + U^*_{\mu 3}U_{e3} = 0$$



$$|J| = 2 \times Area$$

$$J = s_{12}c_{12}s_{23}c_{23}s_{13}c^2_{13}\sin\delta$$

		CP		
	$\nu_\mu \longrightarrow \nu_e$	$\Longleftrightarrow$	$\bar{\nu}_\mu \longrightarrow \bar{\nu}_e$	
T	$\Updownarrow$	CPT across diagonals	$\Updownarrow$	T
	$\nu_e \longrightarrow \nu_\mu$	$\Longleftrightarrow$	$\bar{\nu}_e \longrightarrow \bar{\nu}_\mu$	
		CP		

- First Row: Superbeams where ν_e contamination ~1 %
- Second Row: ν-Factory or β-Beams, no beam contamination

However

for ν-Factory: Distinguish μ^+ from μ^- at 10^{-4}

for β-Beam: Distinguish μ from e in Water Cerenkov or LAr

Vacuum LBL:

$$\nu_\mu \rightarrow \nu_e$$

$$P_{\mu\to e} \approx |\ \sqrt{P_{atm}}\, e^{-i(\Delta_{32}\pm\delta)} + \sqrt{P_{sol}}\ |^2$$

CP violation !!!

$$\Delta_{ij} = \delta m^2_{ij} L/4E$$

where $\sqrt{P_{atm}} = \sin\theta_{23}\sin 2\theta_{13}\ \sin\Delta_{31}$

and $\sqrt{P_{sol}} = \cos\theta_{23}\sin 2\theta_{12}\ \sin\Delta_{21}$

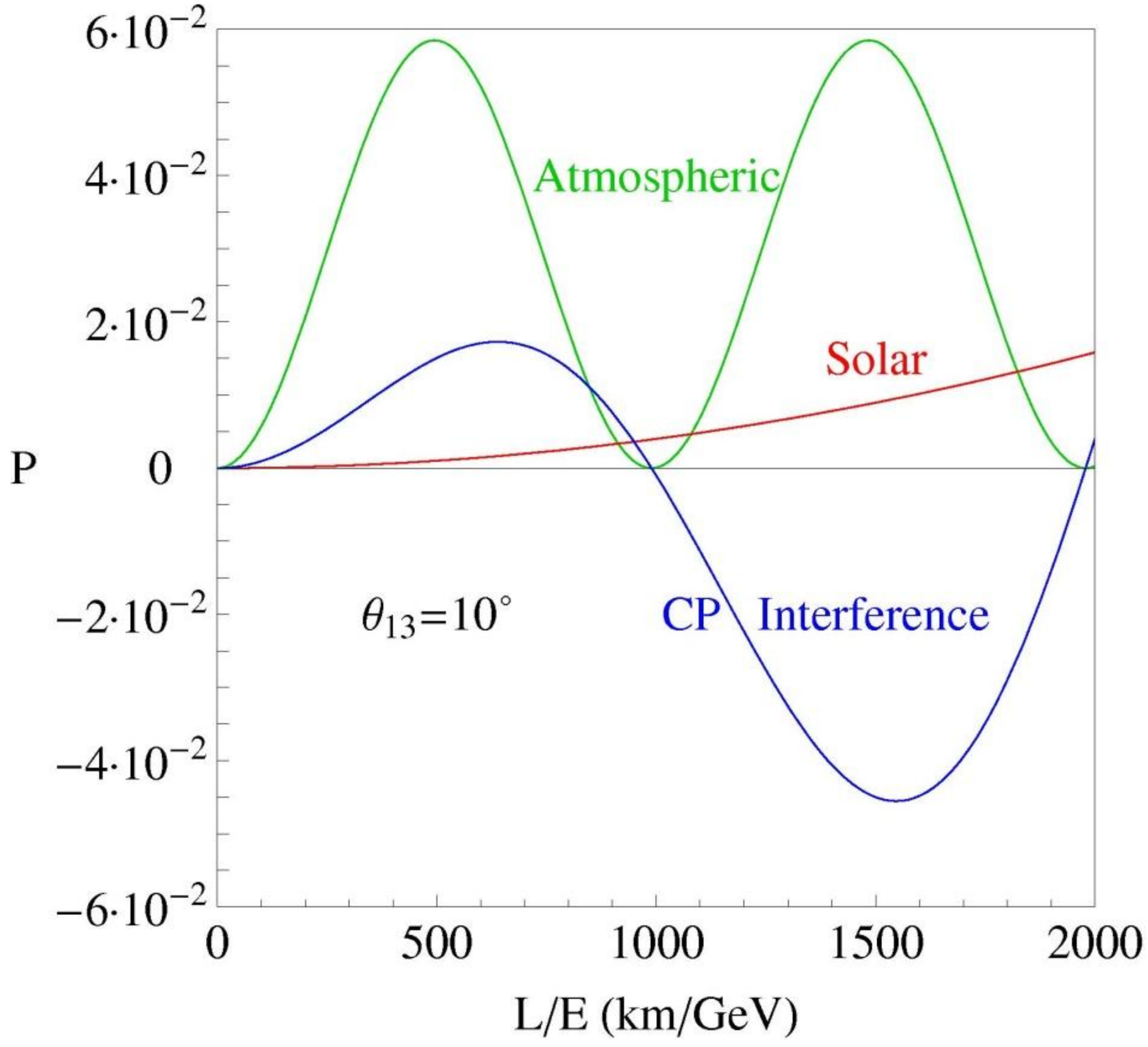
$$P_{\mu\to e} \approx P_{atm} + 2\sqrt{P_{atm}P_{sol}}\cos(\Delta_{32}\pm\delta) + P_{sol}$$

only CPV

$$\cos(\Delta_{32}\pm\delta) = \cos\Delta_{32}\cos\delta \mp \sin\Delta_{32}\sin\delta$$

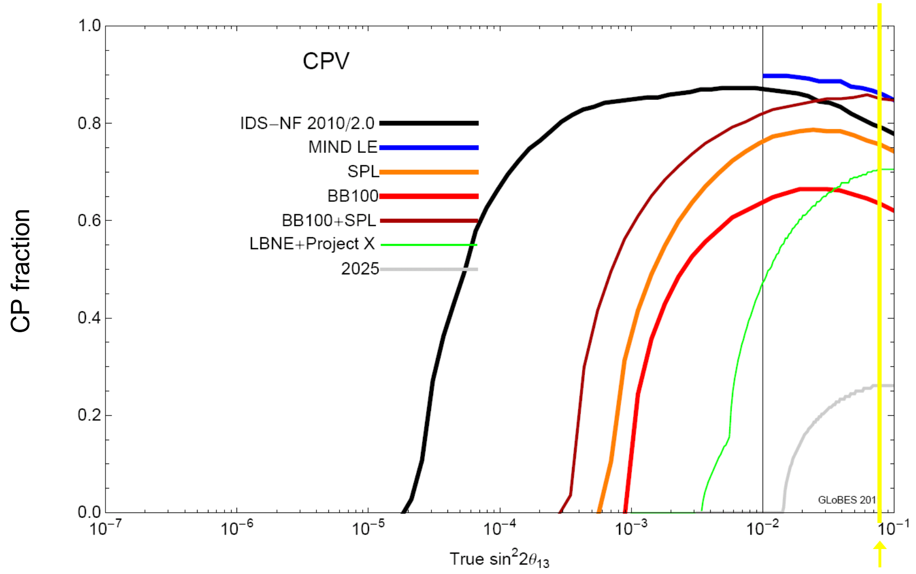
$$\Delta P_{cp} = 2\sin\delta\sin 2\theta_{13}\ \sin 2\theta_{23}\sin 2\theta_{12}\cos\theta_{13}\ \sin\Delta_{21}\sin\Delta_{31}\sin\Delta_{32}$$

Large Theta_13



from EFM

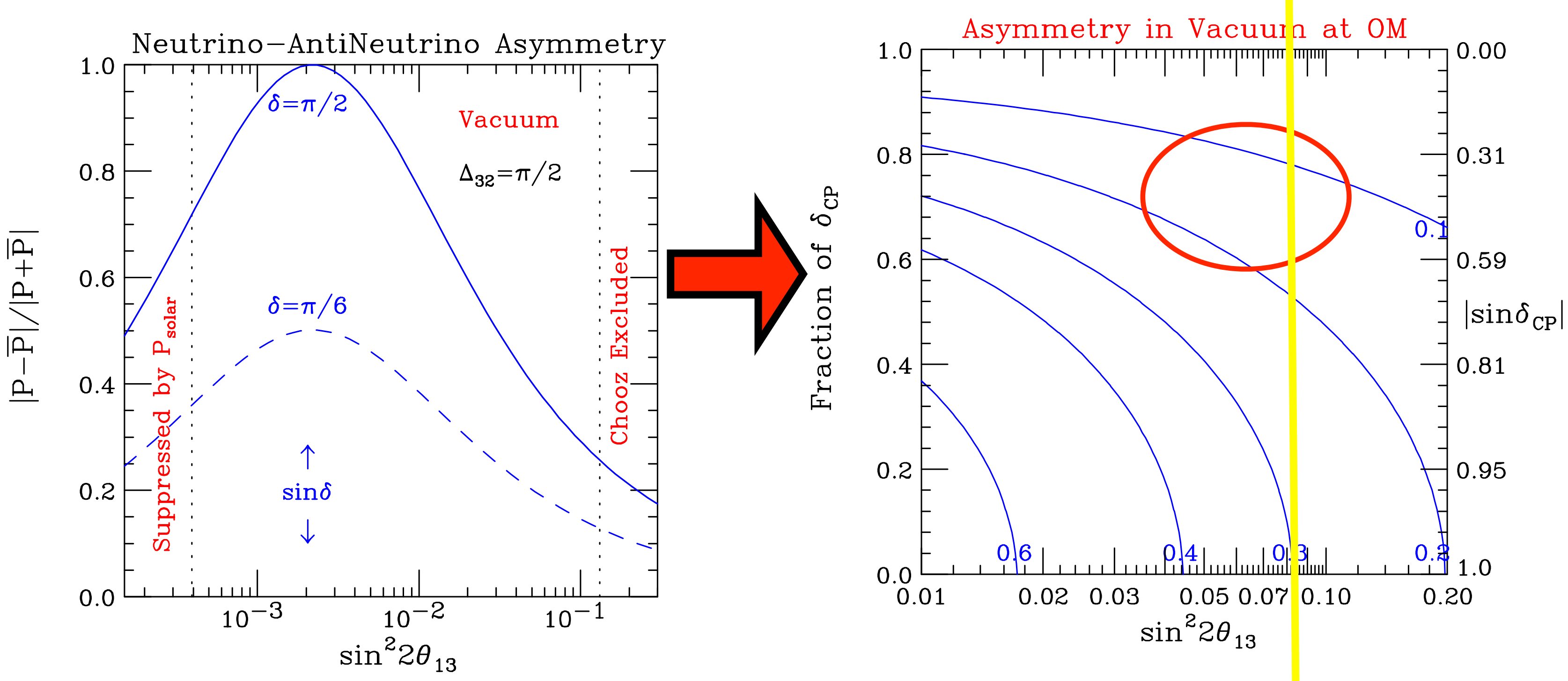
Asymmetry:



$$A_{vac} \approx \frac{1}{11} \frac{\sin 2\theta_{13} \sin \delta}{(\sin^2 2\theta_{13} + 0.002)}$$

$$[\ A_{vac} \equiv \frac{P - \bar{P}}{P + \bar{P}} = \frac{P_\delta - P_0}{P_0} \quad \text{at } \Delta_{31} = \frac{\pi}{2} \text{ (VOM) }]$$

Vacuum, at 1st oscillation maximum



$\nu_\mu \to \nu_e$

In Matter:

$$P_{\mu\to e} \approx |\sqrt{P_{atm}}e^{-i(\Delta_{32}\pm\delta)} + \sqrt{P_{sol}}|^2$$

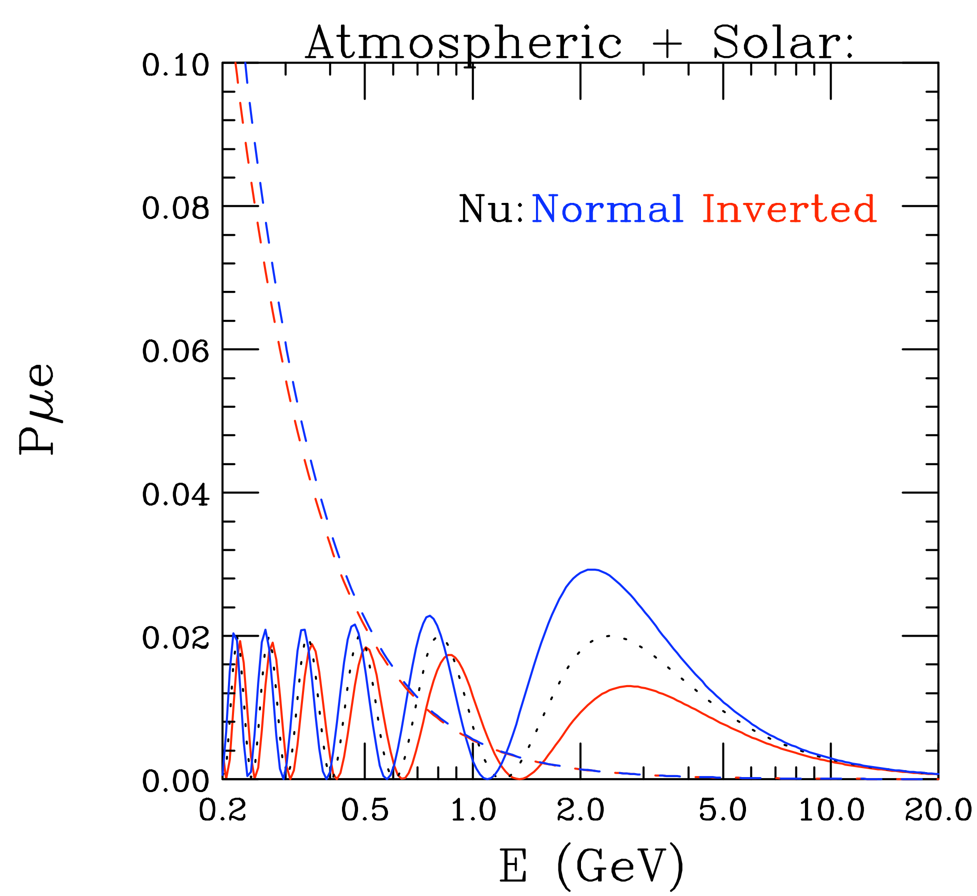
where $\sqrt{P_{atm}} = \sin\theta_{23}\sin 2\theta_{13}\frac{\sin(\Delta_{31}\mp aL)}{(\Delta_{31}\mp aL)}\Delta_{31}$

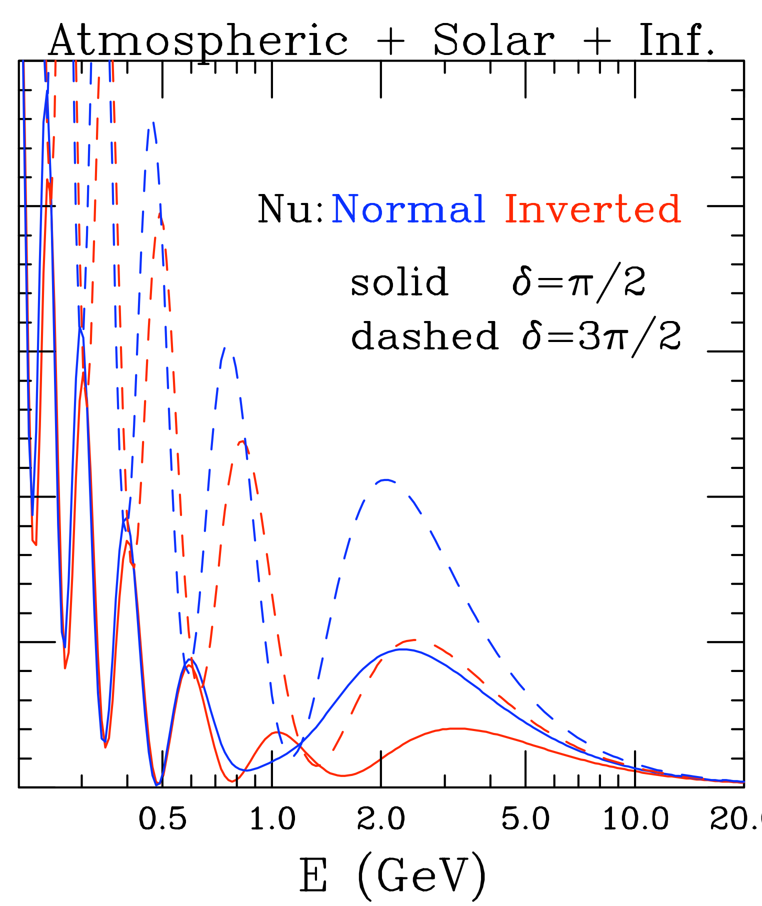
and $\sqrt{P_{sol}} = \cos\theta_{23}\sin 2\theta_{12}\frac{\sin(aL)}{(aL)}\Delta_{21}$

For $L = 1200\ km$
and $\sin^2 2\theta_{13} = 0.04$

$$a = G_F N_e/\sqrt{2} = (4000\ km)^{-1},$$

Anti-Nu: Normal Inverted
dashes $\delta = \pi/2$
solid $\delta = 3\pi/2$

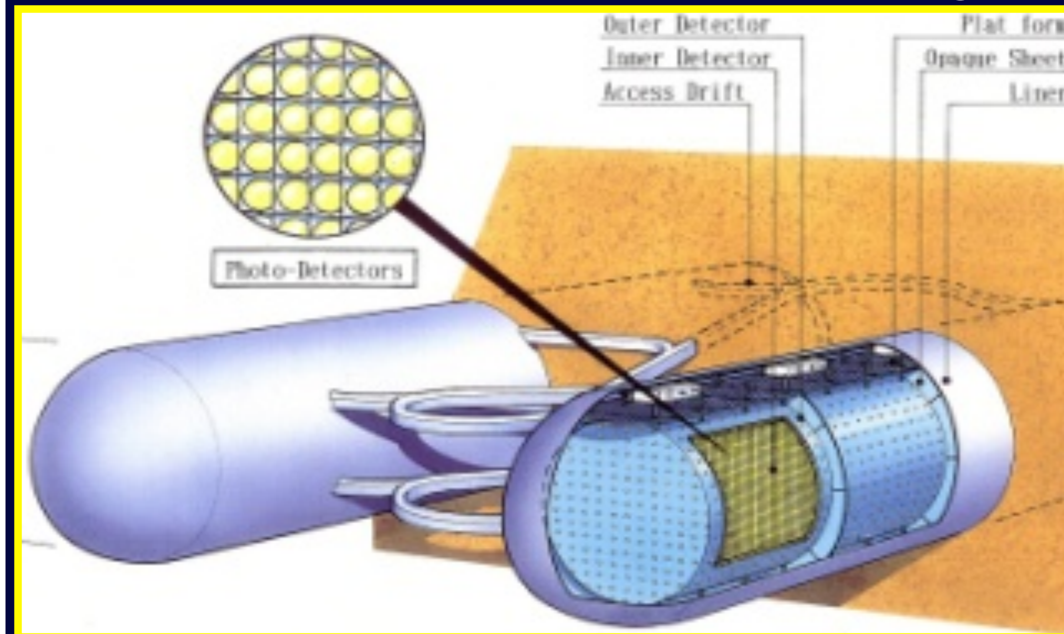




Future LBL plans using J-PARC

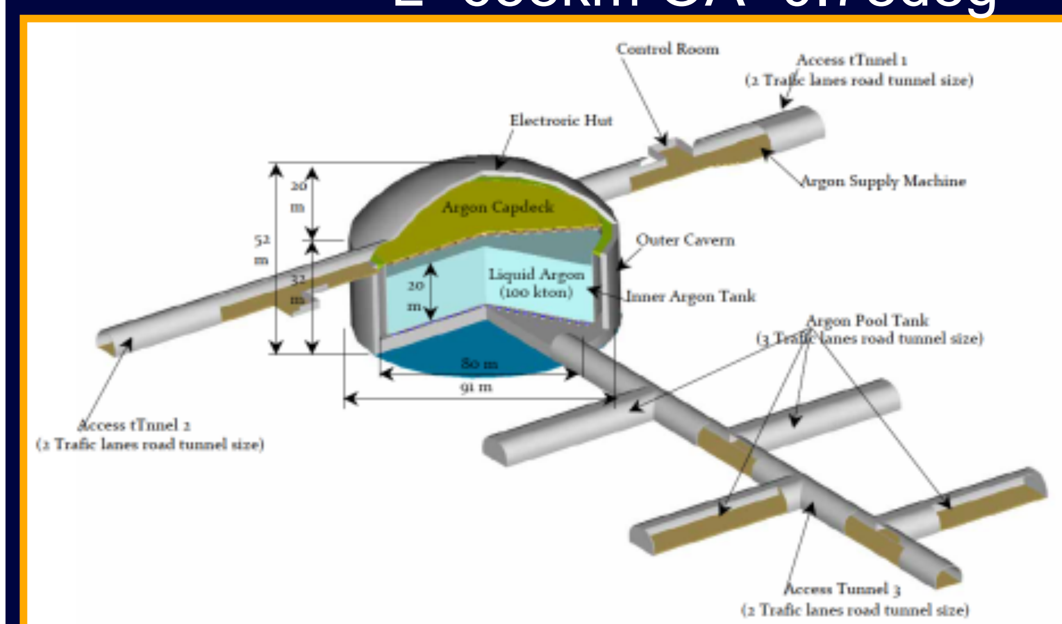
Current: T2K
J-PARC ~0.75MW
+ 50kt WC @ 295km 2.5°

J-PARC+HK @ Kamioka
L=295km OA=2.5deg



LoI: The Hyper-Kamiokande Experiment
arXiv:1109.3262v1

J-PARC+LAr @ Okinoshima
L=658km OA=0.78deg



J-PARC P32 (LAr TPC R&D), arXiv:0804.2111

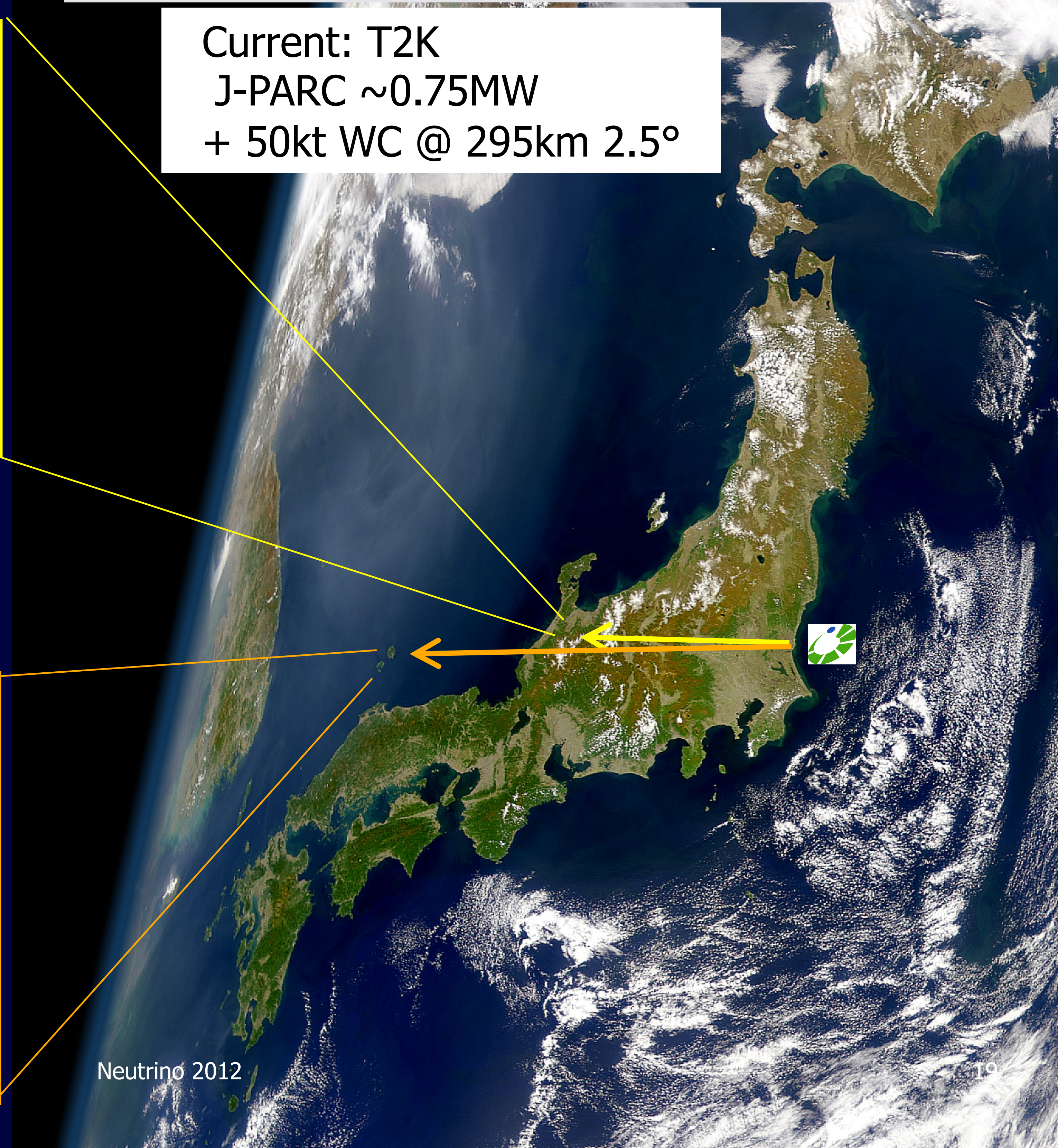
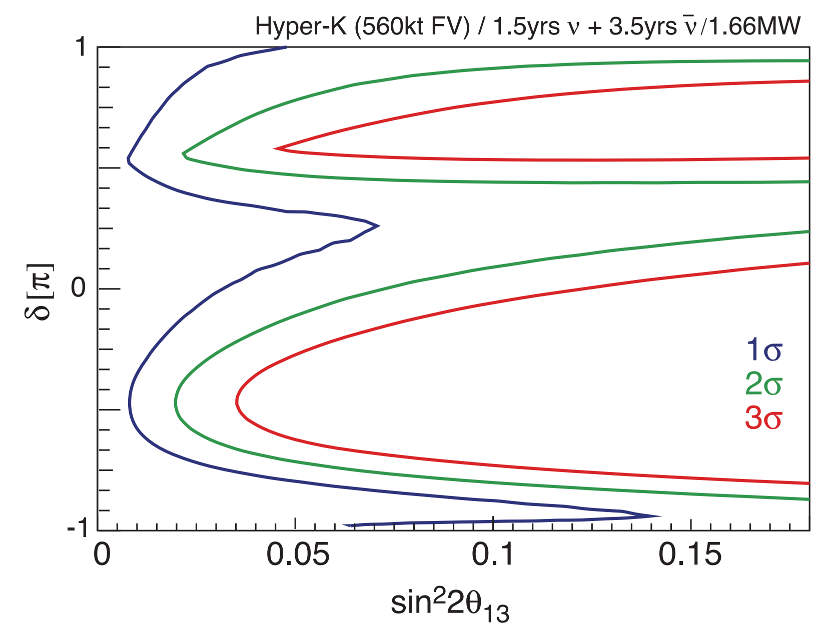


TABLE I. Detector parameters of the baseline design.

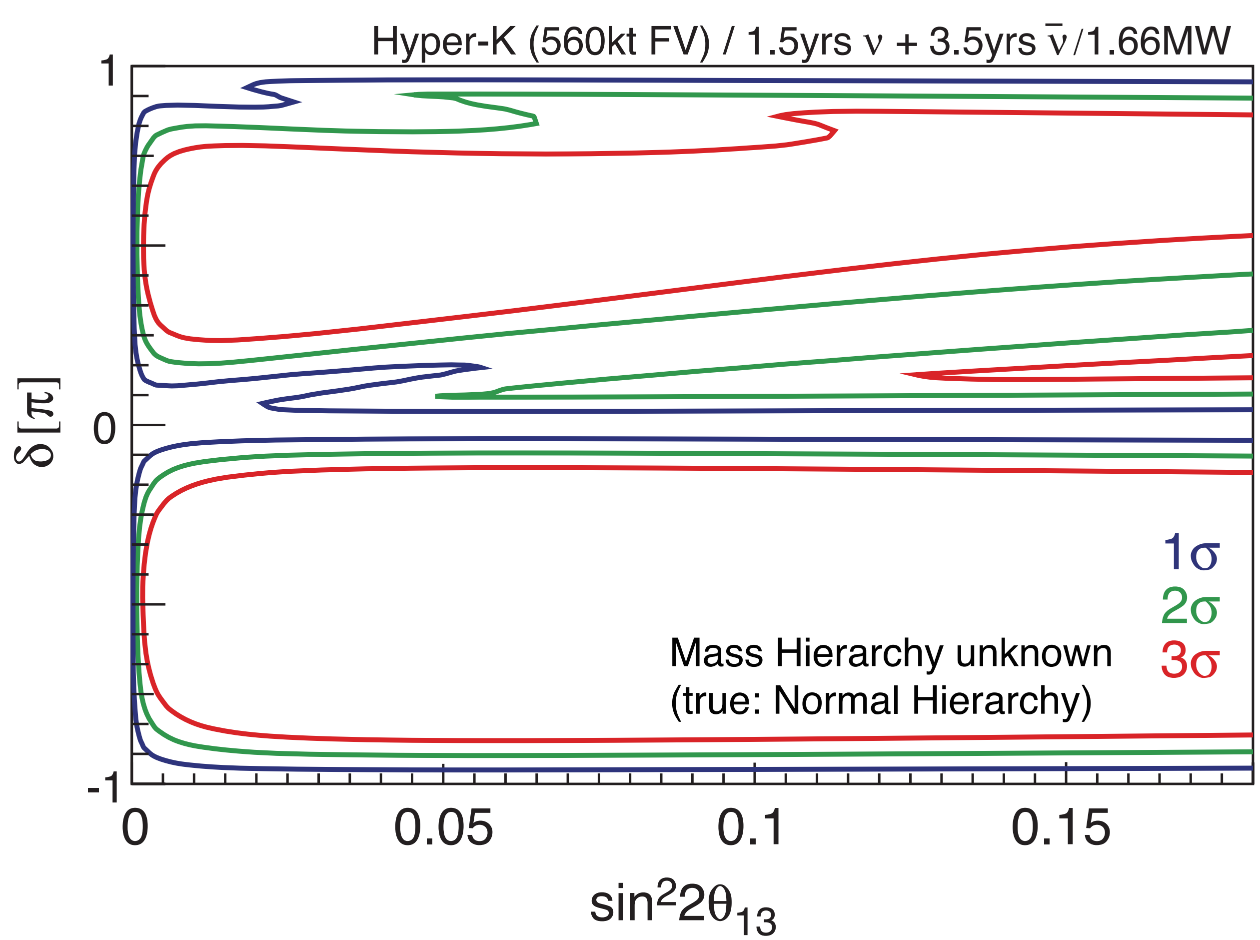
Detector type		Ring-imaging water Cherenkov detector
Candidate site	Address	Tochibora mine
		Kamioka town, Gifu, JAPAN
	Lat.	36°21′08.928″N
	Long.	137°18′49.688″E
	Alt.	508 m
	Overburden	648 m rock (1,750 m water equivalent)
	Cosmic Ray Muon flux	$1.0 \sim 2.3 \times 10^{-6}$ $\mathrm{sec}^{-1}\mathrm{cm}^{-2}$
	Off-axis angle for the J-PARC ν	2.5° (same as Super-Kamiokande)
	Distance from the J-PARC	295 km (same as Super-Kamiokande)
Detector geometry	Total Volume	0.99 Megaton
	Inner Volume (Fiducial Volume)	0.74 (0.56) Megaton
	Outer Volume	0.2 Megaton
Photo-multiplier Tubes	Inner detector	99,000 20-inch ϕ PMTs
		20% photo-coverage
	Outer detector	25,000 8-inch ϕ PMTs
Water quality	light attenuation length	> 100 m @ 400 nm
	Rn concentration	< 1 mBq/m^3

Mass Hierarchy:

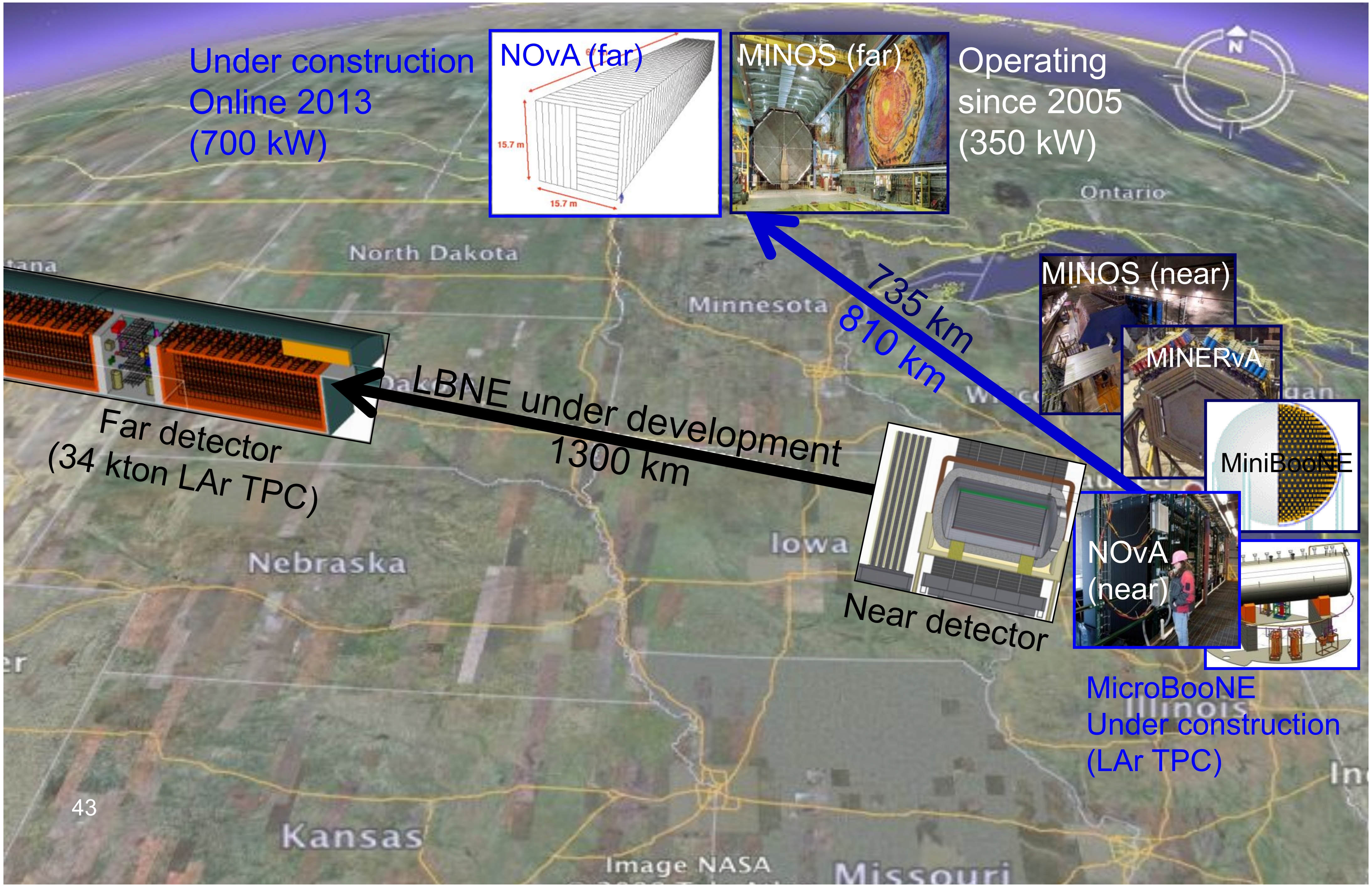


For $\sin^2 2\theta_{13} = 0.1$, the mass hierarchy can be determined with more than 3σ significance for 46% of the δ parameter space.

CPV:



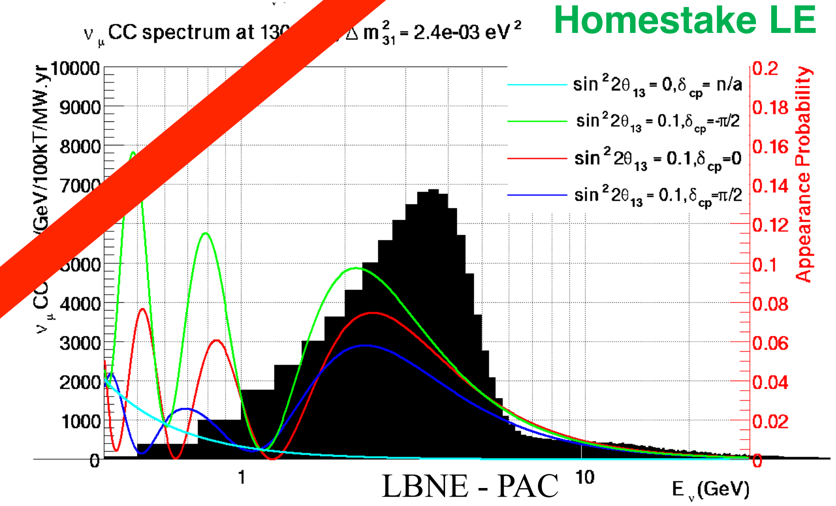
LBNE

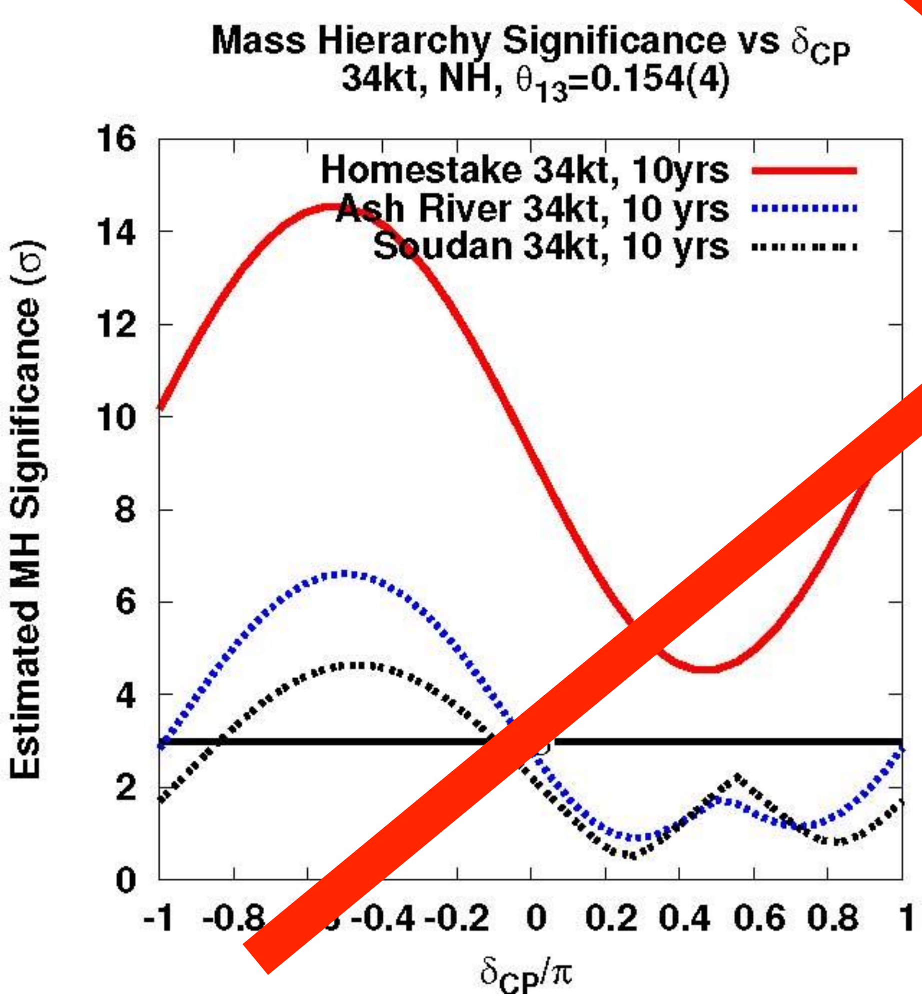

Under construction
Online 2013
(700 kW)
NOvA (far)
15.7 m
15.7 m
MINOS (far)
Operating
since 2005
(350 kW)
Ontario
North Dakota
Minnesota
735 km
810 km
MINOS (near)
MINERvA
MiniBooNE
LBNE under development
1300 km
Far detector
(34 kton LAr TPC)
Near detector
Iowa
Nebraska
NOvA
(near)
MicroBooNE
Under construction
(LAr TPC)
Kansas
Image NASA
Missouri

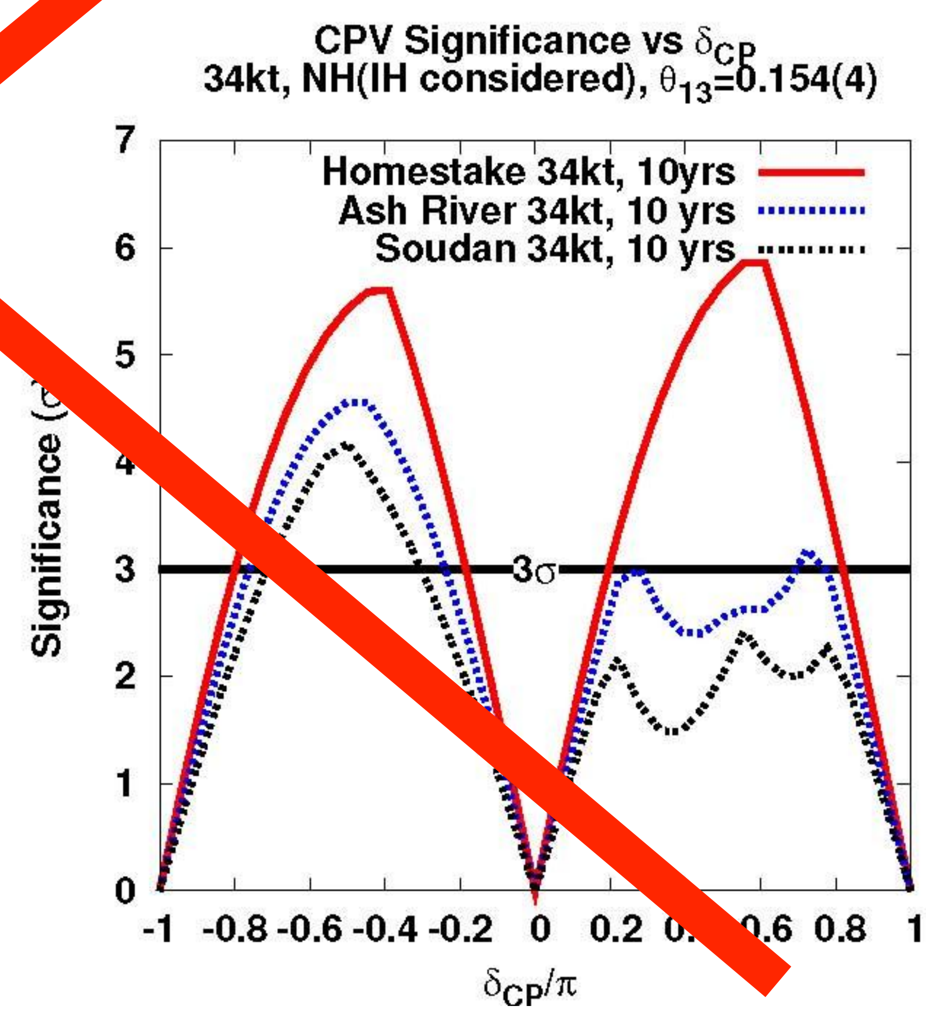
LBNE original

https://indico.fnal.gov/conferenceDisplay.py?confId=5622

- LBNE:
  - Beamline @ Fermilab: 1-5 GeV, 700 kW ---> 2.1 MW
  - Baseline: 1300 km on-axis, Fermilab to Homestake
  - Detector: 34 ktons LAr @ 4300 mwe in Homestake

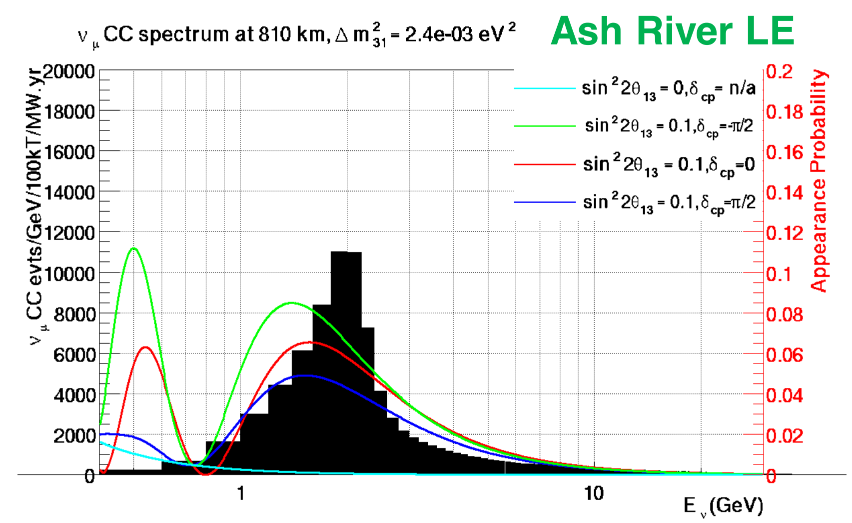




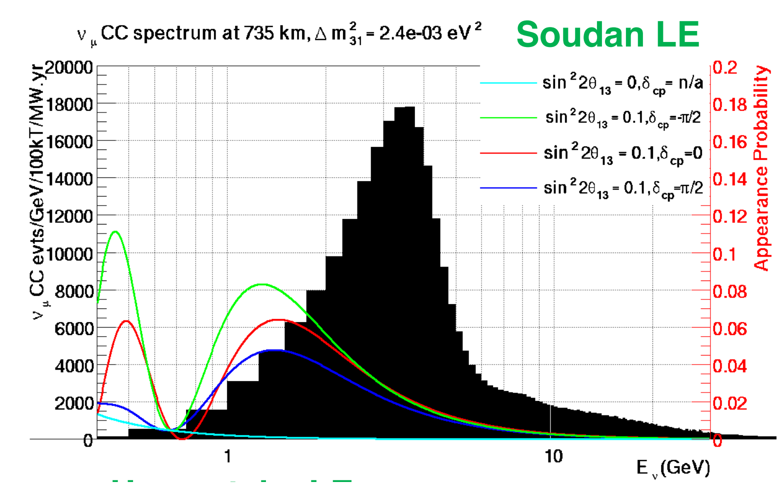


LBNE-lite: three options

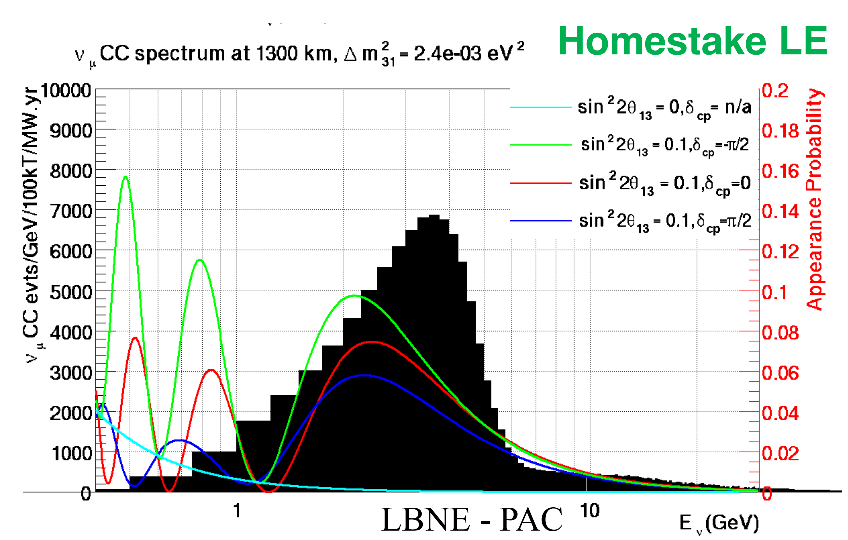
- 30 kton LAr @ Ash River next to NOvA on surface
  - off axis, narrow band beam, little spectral info.
  - surface detector (?): no proton decay or supernova nus or atmos nus



- 15 kton LAr @ Soudan next to MINOS at 2100 mwe
  - on axis, but spectrum is at higher energy than optimal
  - under ground detector, proton decay (K+nu), supernova nus and atmos nus. Broader program.



- 10 kton LAr @ Homestake on surface
  - NEW NEUTRINO BEAMLINE required, can be optimize
  - surface detector (?): no proton decay,supernova nus or atmos nus
  - upgrade potential



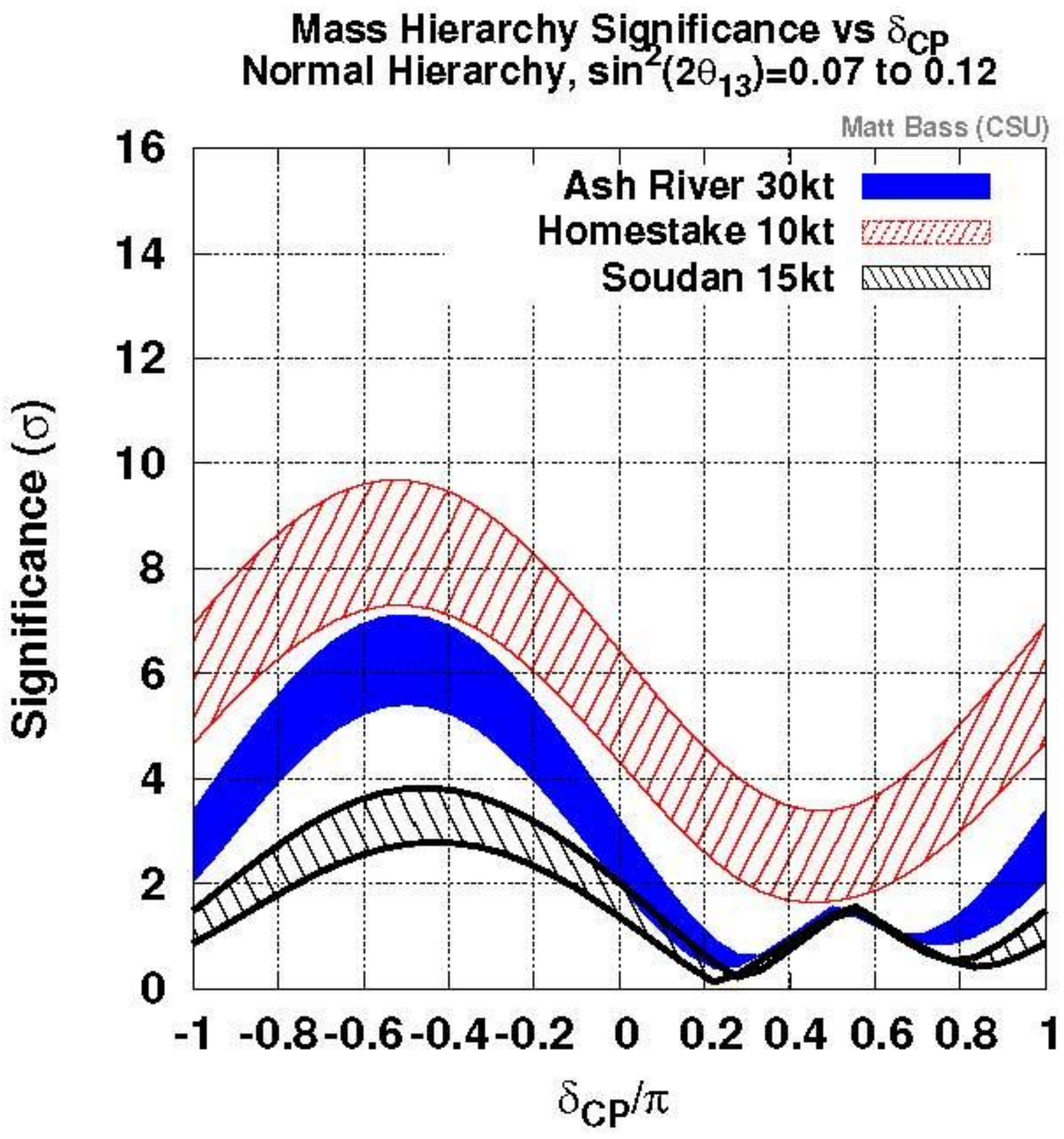
All fiducial masses

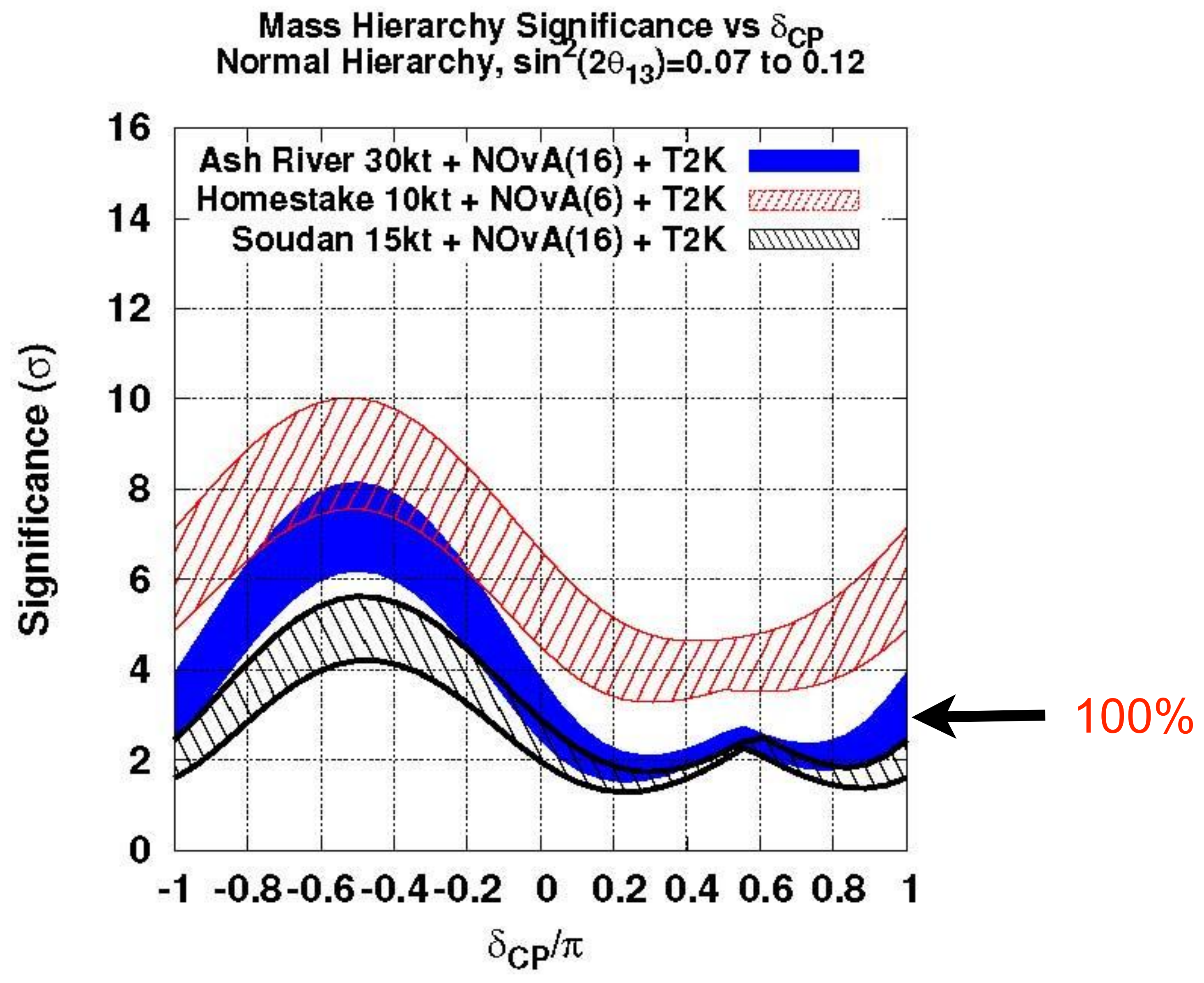
LBNE-lite Summary:

	Ash River	Soudan	Homestake
Baseline	810 km	735 km	1300 km
Detector Mass	30 kt	15 kt	10 kt
Detector position	Surface	Underground 2300 ft	Surface
Beamline	Existing NuMI	Existing NuMI	New

Preferred Option,
best upgrade potential,
most expensive

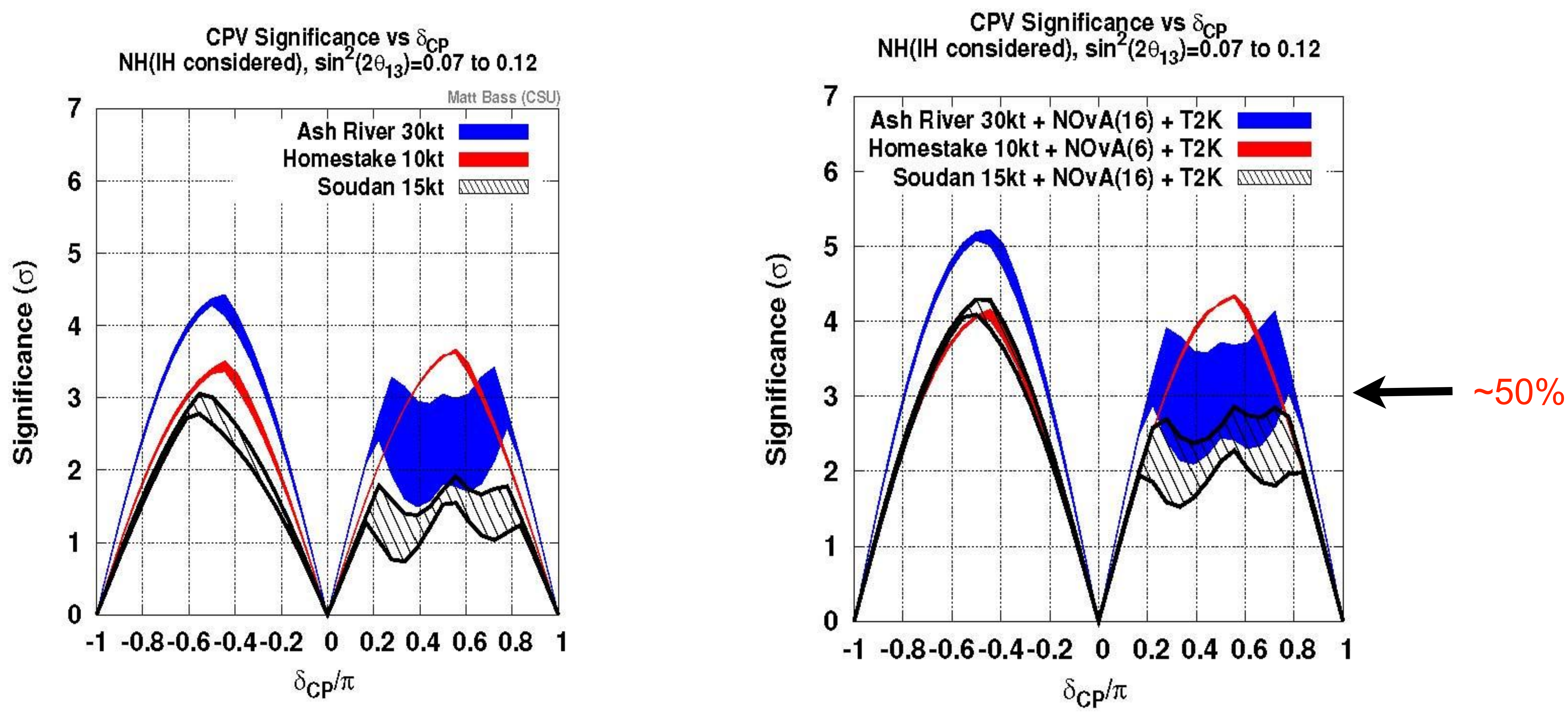
Atmospheric (31) Mass Hierarchy





Physics Reach (conti)

CPV

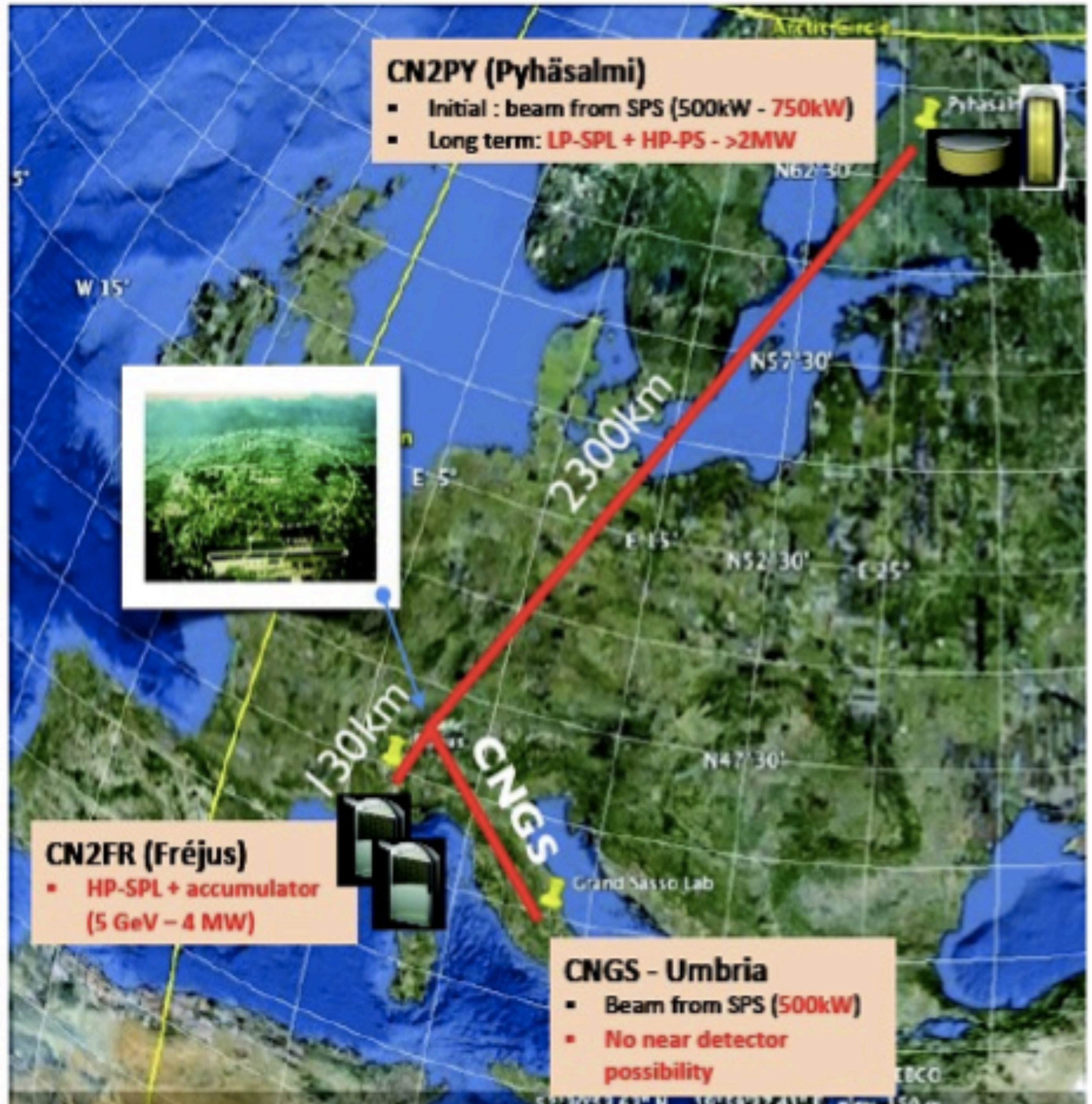


European sites: LAGUNA-LBNO

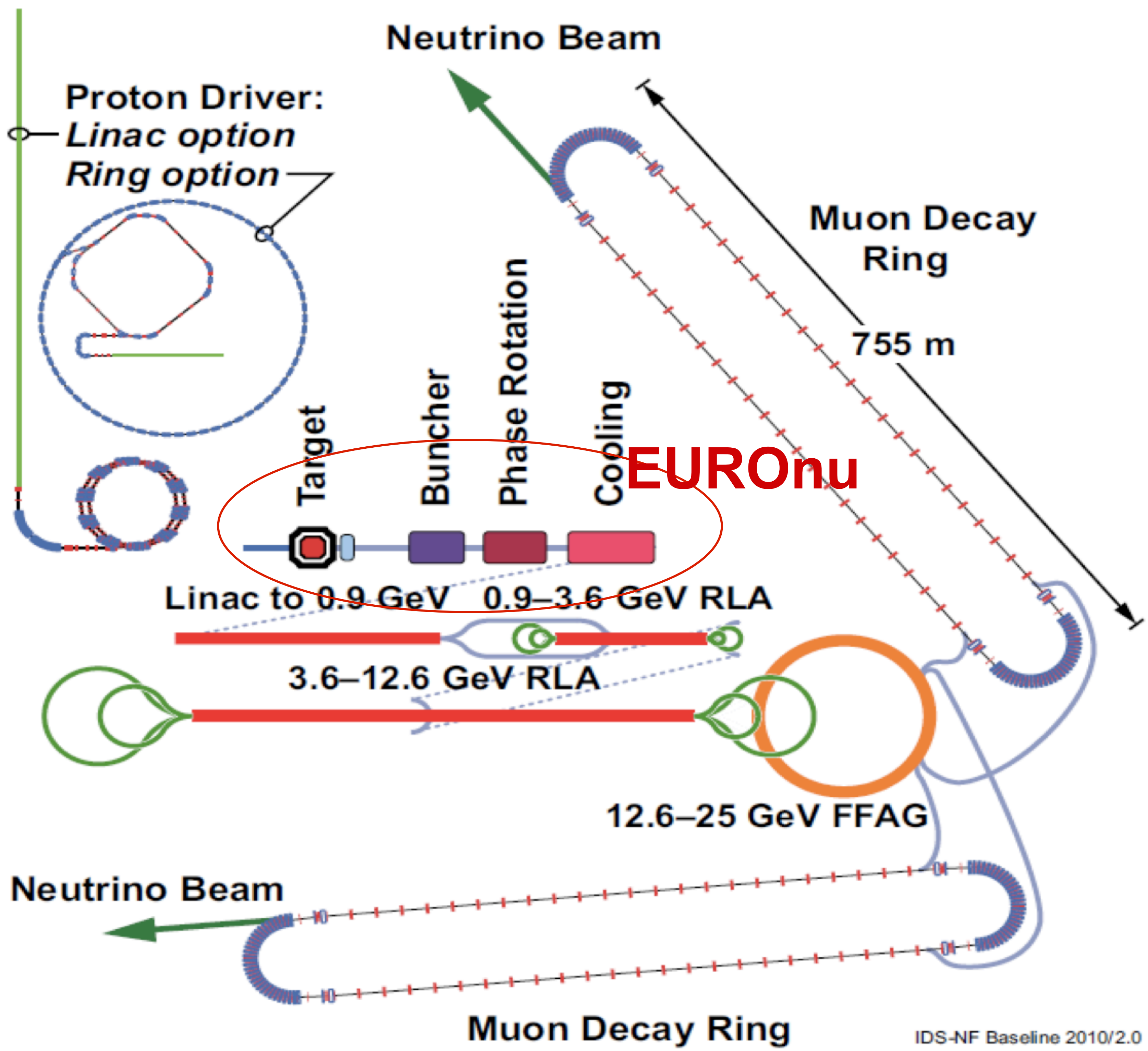
arXiv:1003.1921 [hep-ph]

Three far sites considered in details

- Large Water Cerenkov Detector. CERN-Fréjus is a short baseline. It offers good synergy for enhanced physics reach with β-beam at γ=100
- Liquid Argon TPC & magnetized iron + Liquid Scintillator detectors CERN-Pyhäsalmi is the longest baseline. It offers good synergy for enhanced physics reach with a NF
- [CNGS is an existing beam but is considered at lower priority (missing near detector, limited power upgrade scenarios)]



The Neutrino Factory…



Special Baselines:

$$P_{\mu\to e} \approx \left| \sqrt{P_{atm}}\, e^{-i(\Delta_{32}\pm\delta)} + \sqrt{P_{sol}} \right|^2$$

($\sqrt{P_{sol}}$ → 0)

"Magic" Baseline

$P_{sol} = 0$ when $aL = \pi, 2\pi, \ldots$

in earth this happens for L≈7500 km

then $P_{\mu e} \approx P_{atm} = \sin^2\theta_{23} \sin^2\theta_{13} \frac{\sin^2(\Delta_{31} \mp aL)}{(\Delta_{31} \mp aL)^2} \Delta_{31}^2$

No sensitivity to CPV (δ)

CERN to INO

JPARC to INO

Good for measuring $\sin^2\theta_{13}$ and Mass Hierarchy

In Matter:

Bi-Magic Baseline:

Max for one Hierarchy and 0 other

$$P_{\mu\to e} \approx | \sqrt{P_{atm}} e^{-i(\Delta_{32}\pm\delta)} + \sqrt{P_{sol}} |^2$$

where $\sqrt{P_{atm}} = \sin\theta_{23}\sin 2\theta_{13} \frac{\sin(\Delta_{31}\mp aL)}{(\Delta_{31}\mp aL)} \Delta_{31}$

and $\sqrt{P_{sol}} = \cos\theta_{23}\sin 2\theta_{12} \frac{\sin(aL)}{(aL)} \Delta_{21}$

$$a = G_F N_e/\sqrt{2} = (4000\ km)^{-1},$$

Sushant K. Raut, Ravi Shanker Singh, S.Uma Sankar **arXiv:0908.3741**

Amol Dighe, Srubabati Goswami, Shamayita Ray **arXiv:1009.1093**

"Bi-Magic" Baseline and Energy

Choose L such that

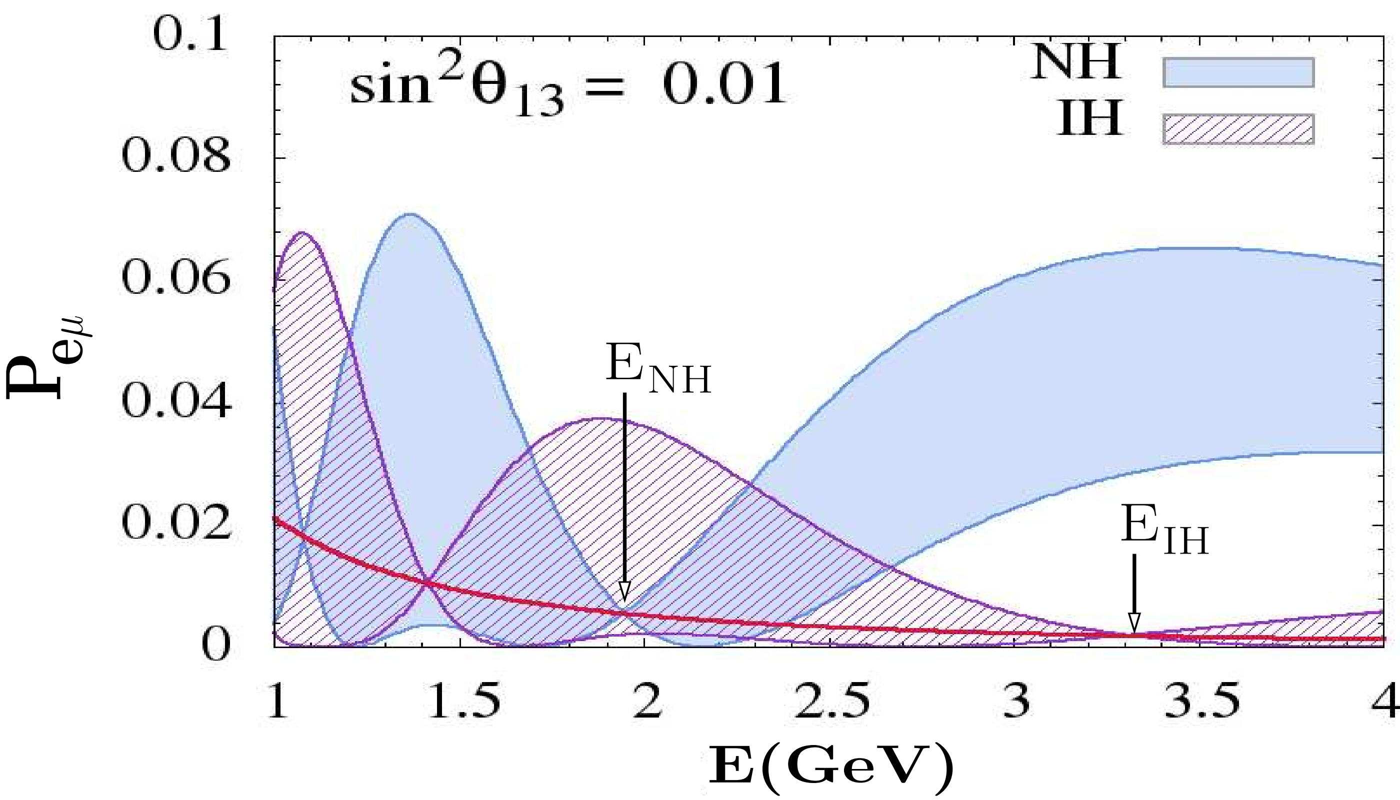
$P_{atm}|_{IH} = 0$ and $P_{atm}|_{NH}$ is max. at E_{IH}

and

$P_{atm}|_{NH} = 0$ and $P_{atm}|_{IH}$ is max. at E_{NH}

L=2540 km and E_{IH}=3.3 GeV and E_{NH}=1.9 GeV

flip when ν and $\bar{\nu}$ interchange



Approx. Fermilab to Yucca Mtn:

Another Special Baseline & Energy !

Can we chose a baseline and energy such that for neutrino we sit at the 1^{st} oscillation maximum (OM) and anti-neutrinos we sit at 2^{nd} OM (or vice versa, depending on hierarchy) ?

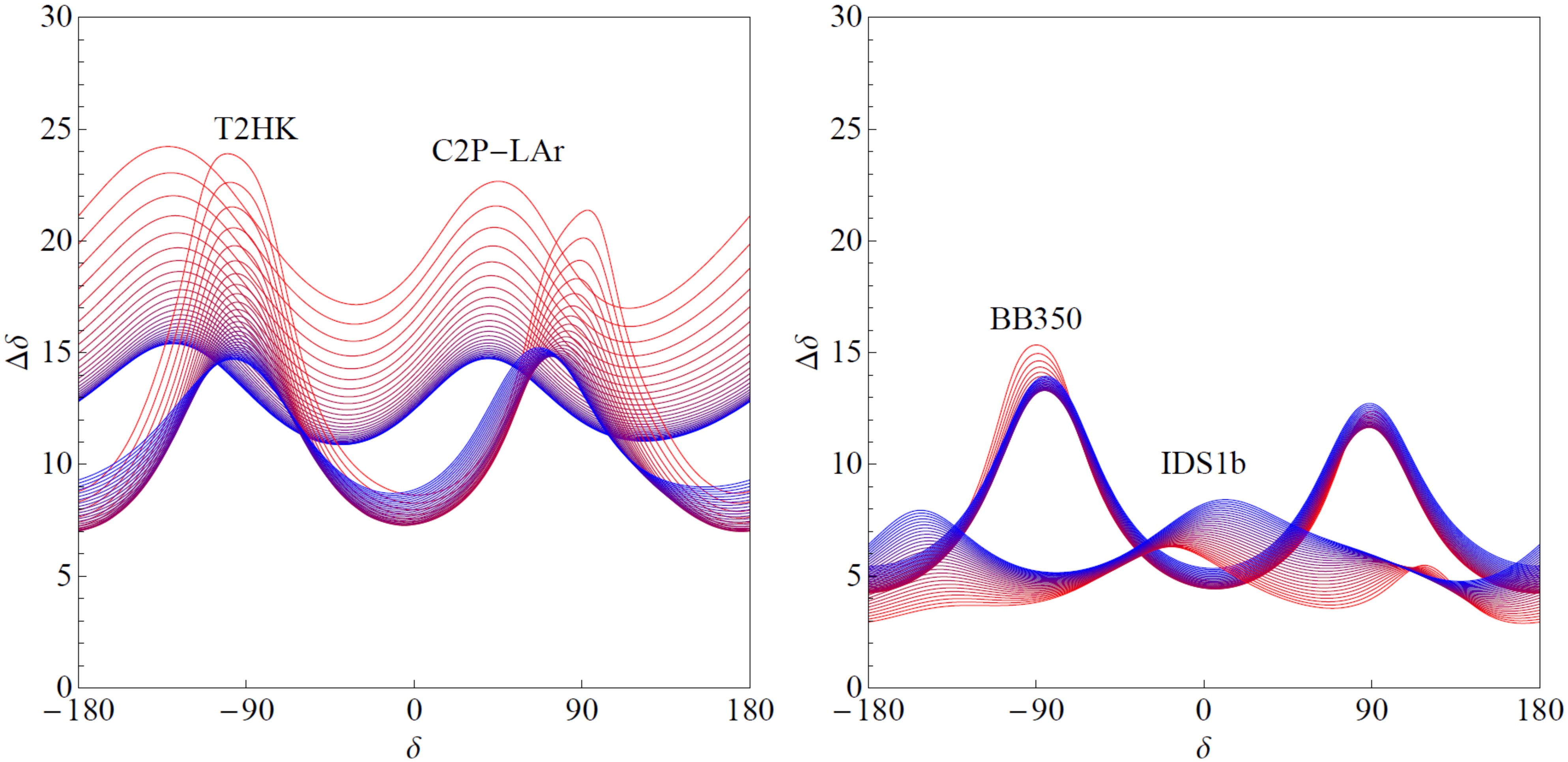
$$\Delta_{31} + (aL) = 3\pi/2 \text{ and } \Delta_{31} - (aL) = \pi/2$$

$$\Rightarrow \Delta_{31} = \pi \quad \text{and} \quad (aL) = \pi/2$$

Baseline is 4000-4500 km and neutrino energy 4.0-4.5 GeV
i.e stored muons of around 9 GeV or so !!!

Can probe 1^{st} and 2^{nd} Oscillation Maxima with same facilities!

Precision:



θ_{13}: 3º - 10º

P. Coloma, A. Donini, EFM and P. Hernandez 1203.5651

Are $\delta = 6^\circ \pm 2^\circ$ and $\delta = 84^\circ \pm 2^\circ$ equally good measurements?

We need more precision around 0, π, . . . !

Maybe uncertainty in $\sin\delta$ is a better measure !

Testing the Paradigm:

For small values of $\left(\frac{L}{E_\nu}\right) \ll 500\left(\frac{\mathrm{km}}{\mathrm{GeV}}\right)$, we can expand the appearance probability in powers of $\left(\frac{L}{E_\nu}\right)$ as follows: $(\sin(1) = 0.84)$

$$\begin{aligned} P_{\nu_e \to \nu_\mu} \sim \quad & \left(\frac{L}{E_\nu}\right)^2 + \left(\frac{L}{E_\nu}\right)^4 + \ldots & \quad \mathrm{CPC} \\ & + \left(\frac{L}{E_\nu}\right)^3 + \left(\frac{L}{E_\nu}\right)^5 + \ldots & \quad \mathrm{CPV} \end{aligned}$$

All parameters are determined by first few terms!!! To test the form Oscillation Probability we need $\left(\frac{L}{E_\nu}\right) \sim$ or even $> 500\left(\frac{\mathrm{km}}{\mathrm{GeV}}\right)$.

Are smaller values of E_ν worth probing,
even if it costs some precision ???

(matter effects complicate this discussion!)

Precision v Sensitivity to New Physics:

How much precision in δ would we sacrifice for additional sensitivity to New Physics ! ! !

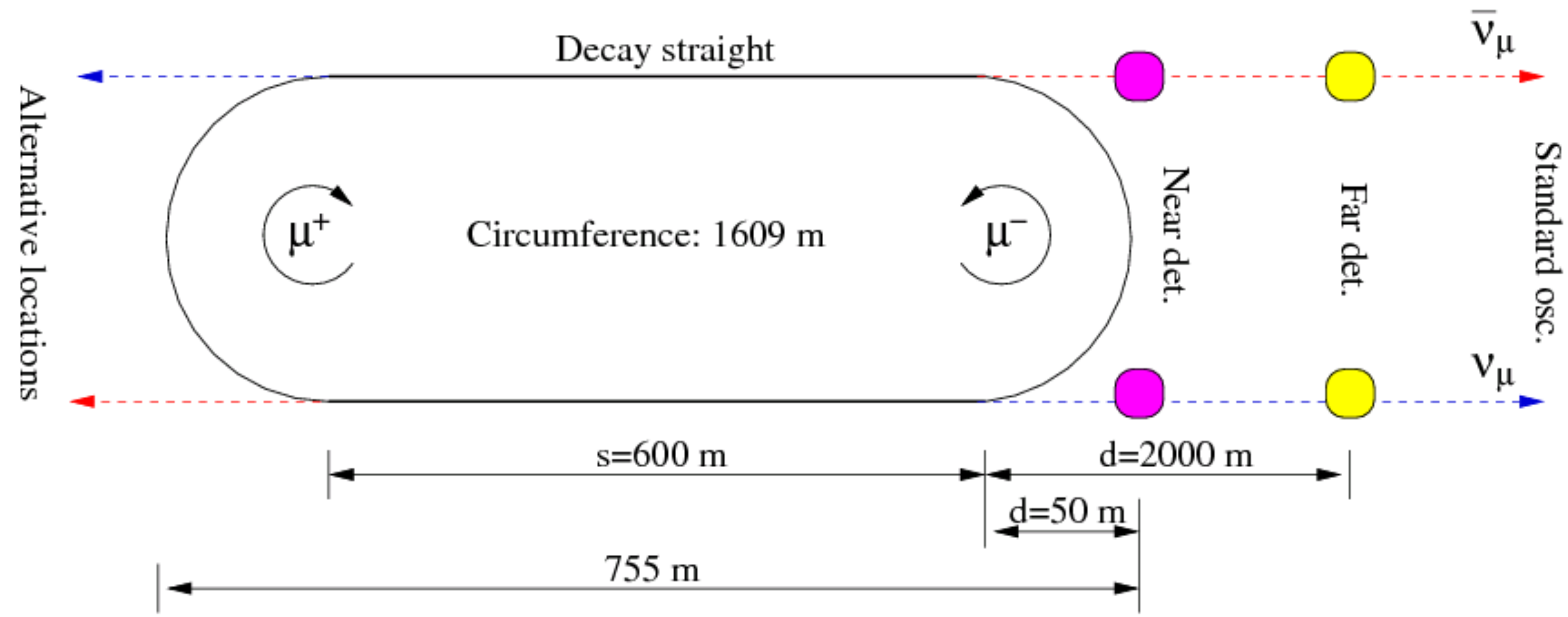
What about around $\delta = 0,\ \pi, \ldots$?

Beyond Nu SM

- Sterile
- Non-Standard Interactions (NSI)
- Premature Decoherence
- Neutrino Decay
- Effects of Extra Dimensions
- Surprises !

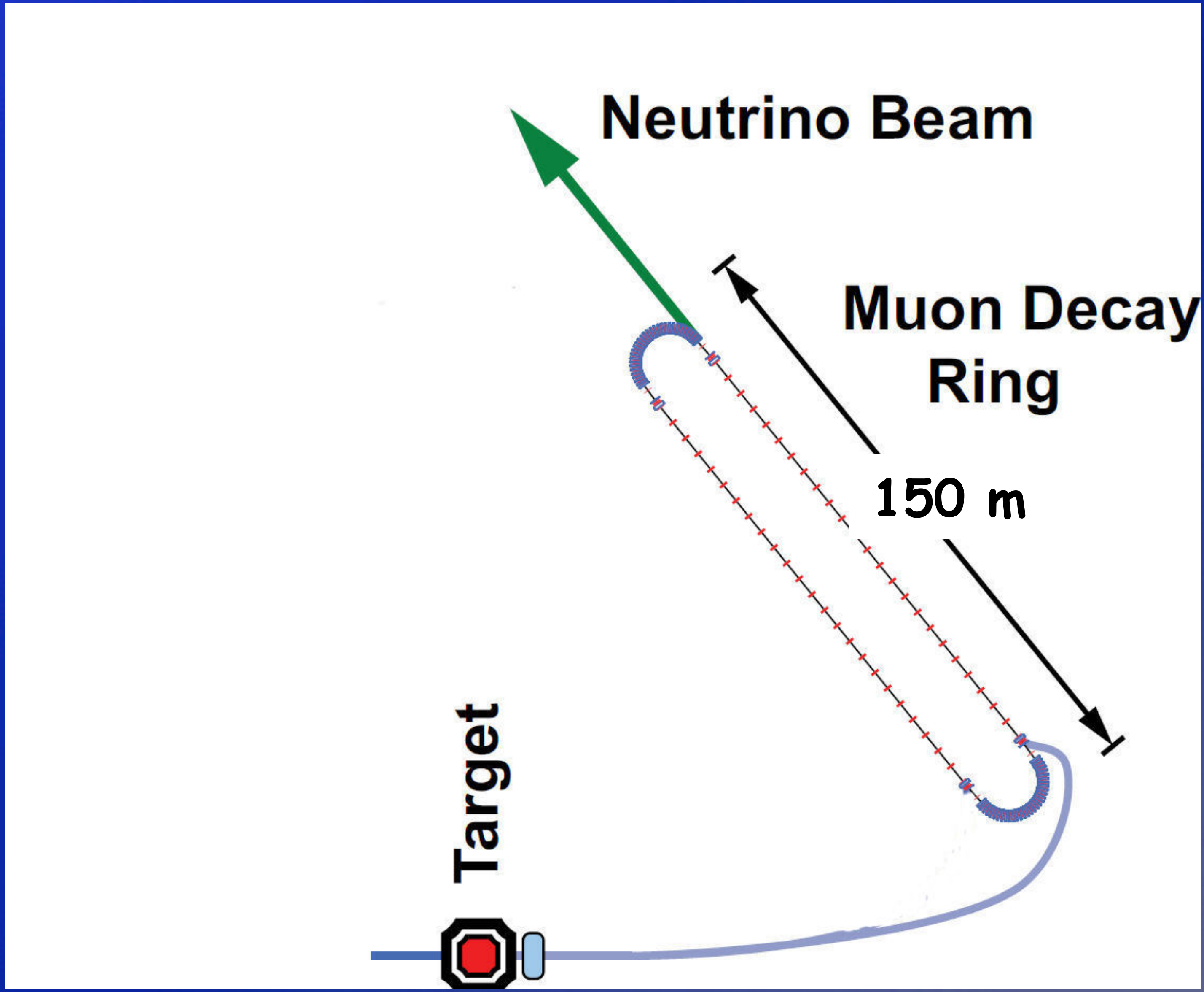
Sterile Neutrinos:

- hints of Sterile Neutrinos
  - LSND (3.8 sigma)
  - miniBooNE neutrinos & anti-neutrinos (?)
  - Reactor Anomaly
  - Gallium Anomaly



nuSTORM:

- 100 kW Target Station
  - Assume 60 GeV proton
    - Fermilab PIP era
  - Ta target
    - Optimization on-going
  - Horn collection after target
    - Li lens has also been explored
- Collection/transport channel
  - Two options
    - Stochastic injection of π
    - Kicker with $\pi \rightarrow \mu$ decay channel
    - At present NOT considering simultaneous collection of both signs
- Decay ring
  - Large aperture FODO
  - Racetrack FFAG
  - Instrumentation
    - BCTs, mag-Spec in arc, polarimeter

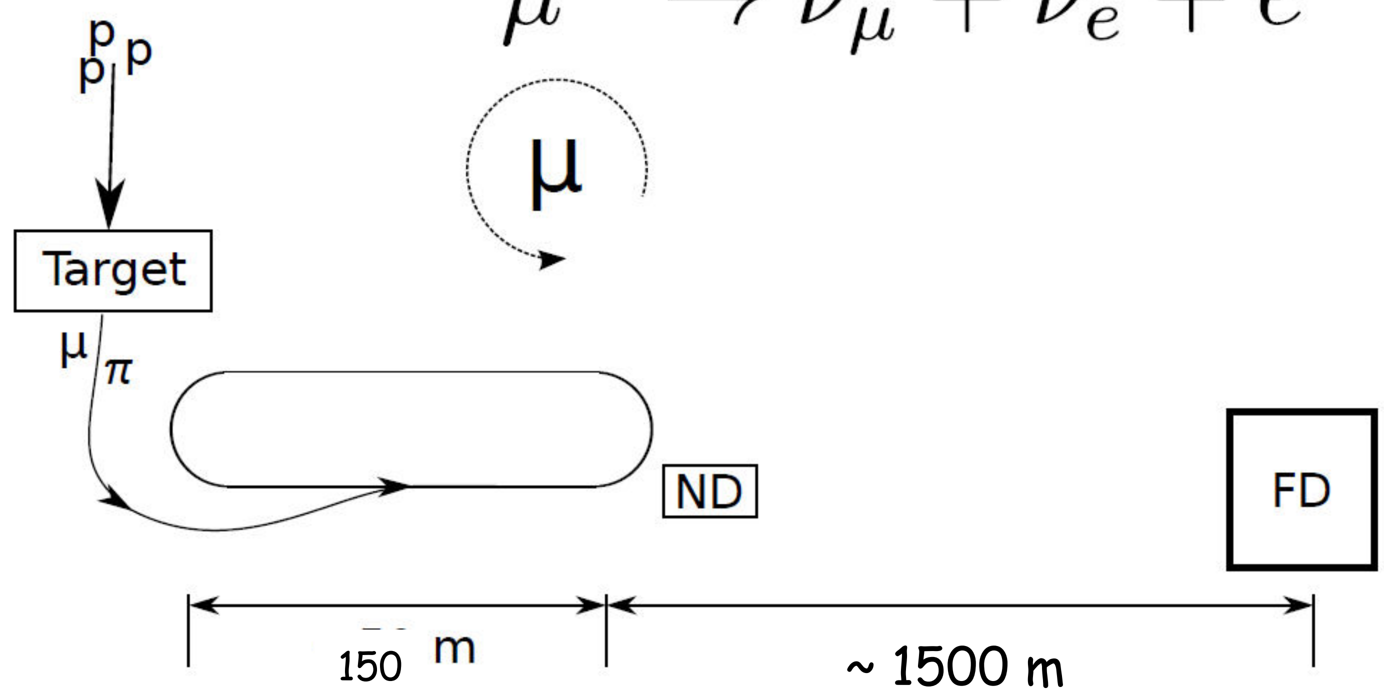


Alan Bross | Fermilab Physics Advisory Committee | June 21, 2012 | 9

Experimental Layout

νSTORM

$$\mu^+ \rightarrow \bar{\nu}_\mu + \nu_e + e^+$$



Appearance-only (though disappearance good too!)

$$Pr[e \rightarrow \mu] = 4|U_{e4}|^2|U_{\mu 4}|^2 \sin^2(\frac{\Delta m^2_{41} L}{4E})$$

Appearance Channel:

$\nu_e \rightarrow \nu_\mu$

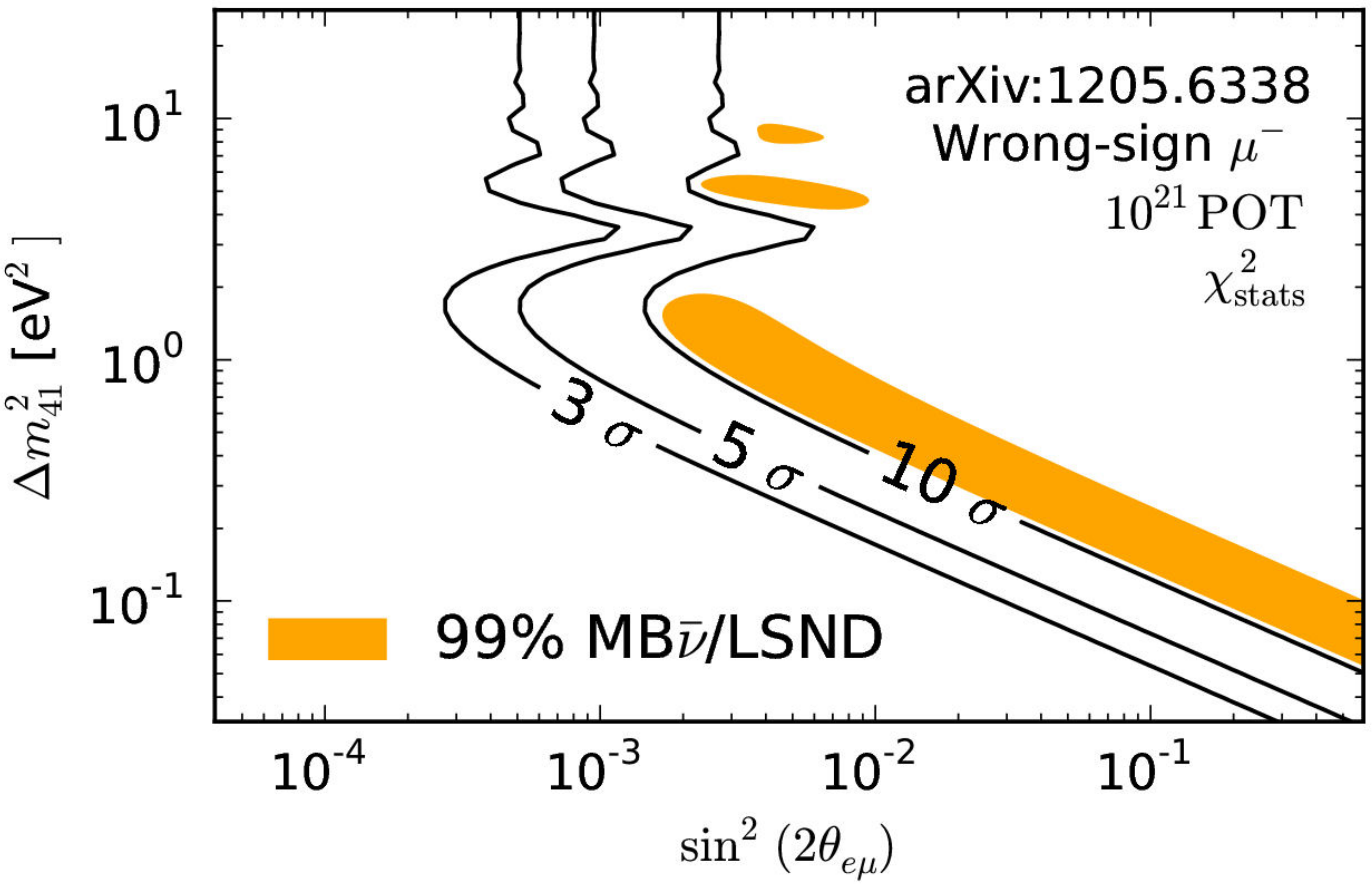
Golden Channel

Must reject the "wrong" sign μ with great efficiency

Why $\nu_\mu \rightarrow \nu_e$ Appearance Ch. not possible

$\nu_e \rightarrow \nu_\mu$ appearance

CPT invariant channel to MiniBooNE



3+1
Assumption

Summary & Conclusion:

- Large Theta_13
  - wonderful opportunity for all !!!
    - Double Chooz, Daya Bay and Reno
    - SuperK Atm, T2K, NOvA
    - LBNE, T2HK, etc
    - precision determination of Theta_13
    - exclude wrong Hierarchy at high CL
    - CPV, precision dominated by systematic effects!
    - New Physics less likely to be entangled with Theta_13 effects !

- Re-Optimization of NuFact is required !