Future Facilities in Europe
Challenges and Opportunities

Elena Wildner, CERN

The EUROnu Project 2008-2012

- FP7 Design Study of

Next generation neutrino oscillation facilities in Europe

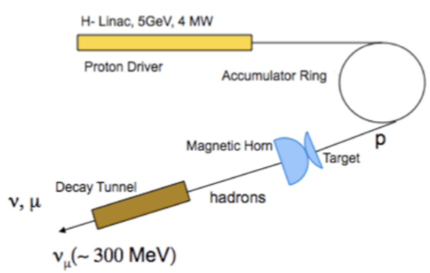
"Precision facilities"…

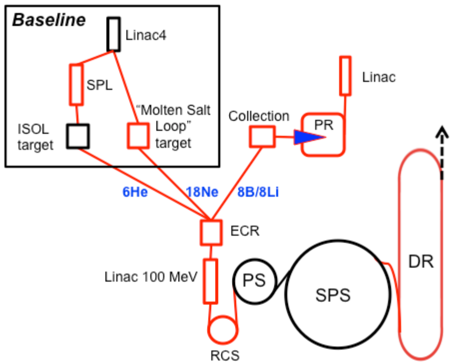
- CERN to Frejus Superbeam (SB)
- Neutrino Factory (NF), in collaboration with IDS-NF
- Beta Beams (BB)
- Performance of baseline detector / near detector
- Physics reach

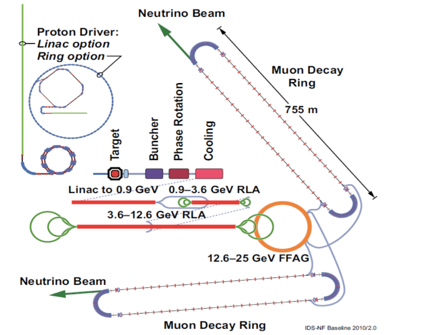
EUROnu outcome

Design
Cost
Safety
Risk
Time scale

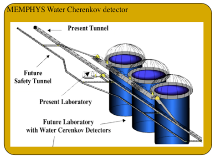
Facility







Detectors



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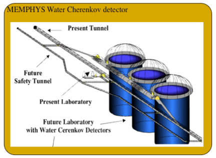
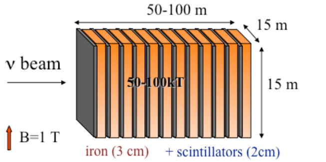
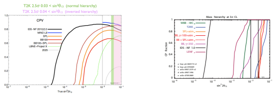
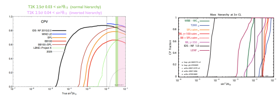
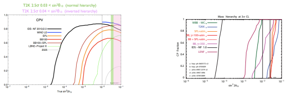




Physics







Comparison: performance – cost – safety – risk

Input to the definition of a Road Map for neutrino physics in Europe 31/7
(together with other neutrino facilities studies)
Report to CERN Council via Stragey Group and ECFA

Partners

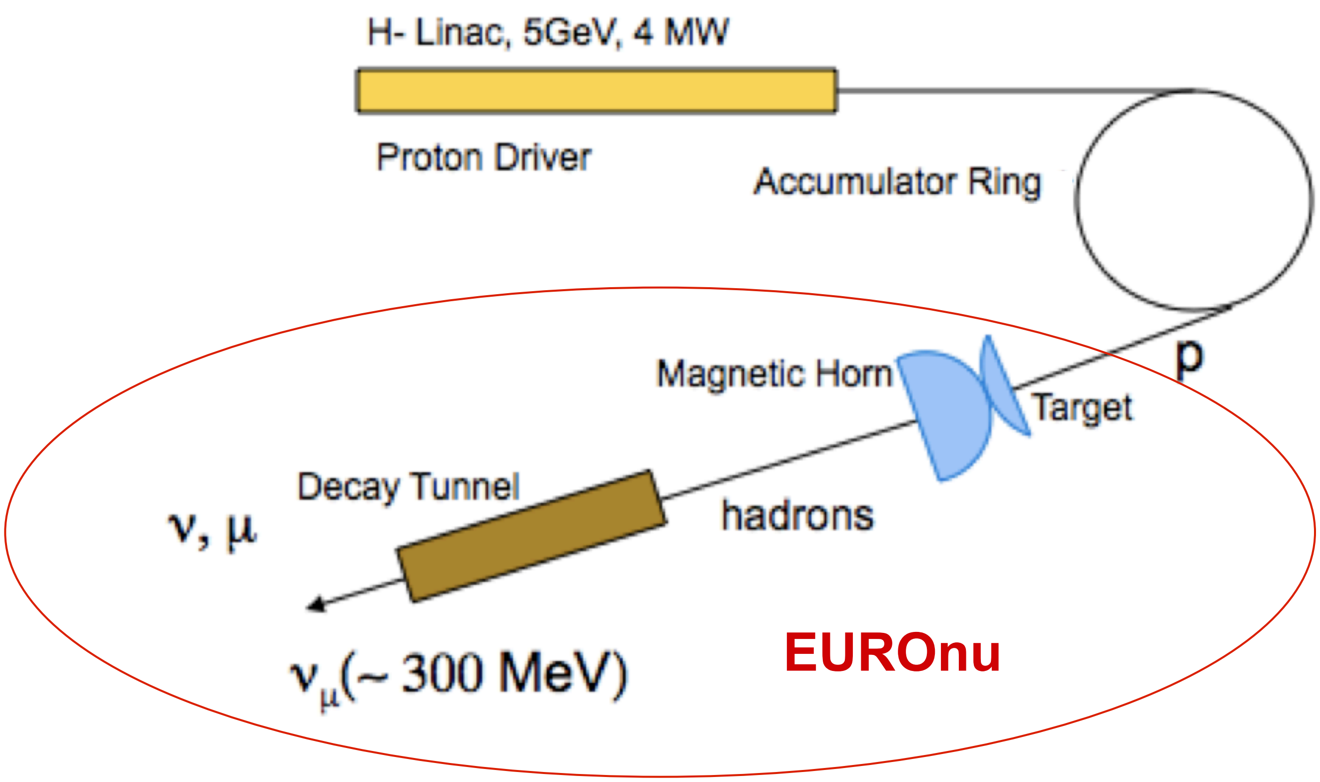
Country	Partner
Belgium	Louvain
Bulgaria	Sofia
France	CEA
	CNRS (4)
Germany	MPG (3)
Italy	INFN (3)
Poland	Cracow
Spain	CSIC (2)
Switzerland	CERN
UK	Durham
	Glasgow
	Imperial
	Oxford
	STFC
	Warwick

Country	Associate
Canada	TRIUMF
France	GANIL
Germany	Aachen
India	INO
Israel	Weizmann
Portugal	Lisbon
Russia	IAP, Novgorad
	JINR, Dubna
Switzerland	Geneva
UK	Brunel
USA	Argonne
	Brookhaven
	FNAL
	Virginia Tech
	Muon Collaboration

EUROnu physics

- Precision measurements of neutrino oscillation parameters
  - θ_{13} , δ_{cp}, mass hierarchy
  - However θ_{13} was measured (> 5σ)
    - Recent: updates of facilities not yet final
- Document for European strategy being prepared
    - Has to be there for the 31st of July 2012

The Superbeam



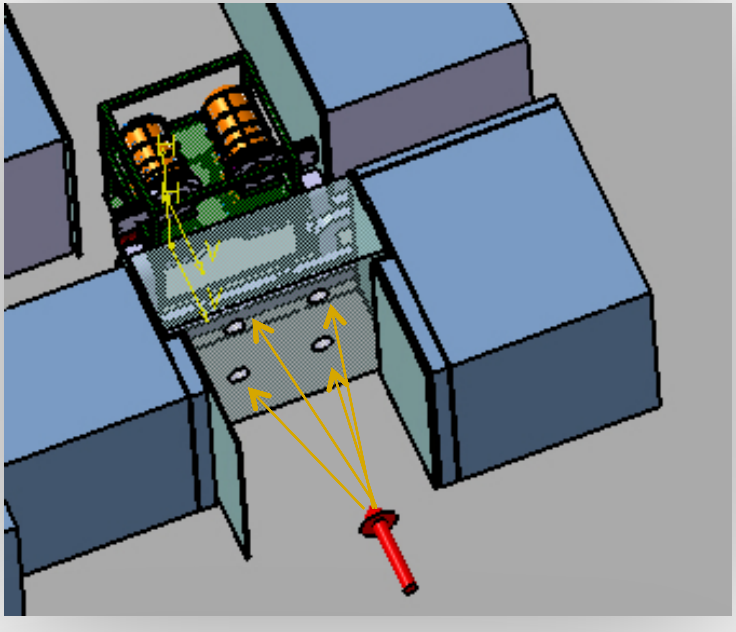
Parameter	Value
Beam Power	4 MW
Beam energy	4.5 GeV
Target length	78 cm
Target radius	1.2 cm
Decay tunnel radius	2m
Decay tunnel length	25m

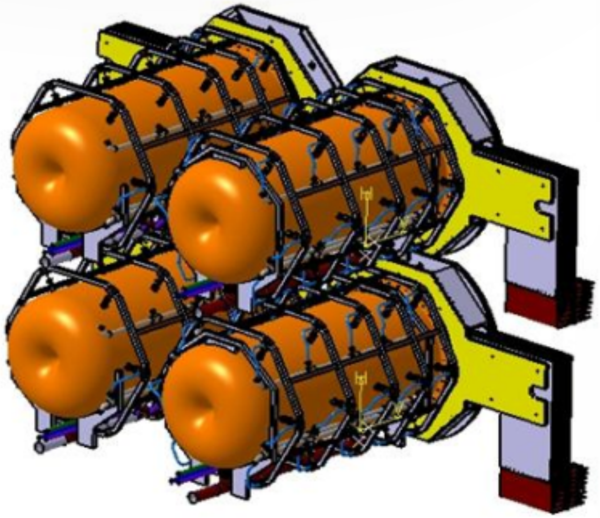
Detector in the Fréjus tunnel

Superbeam favored by T2K hints

4MW accommodation

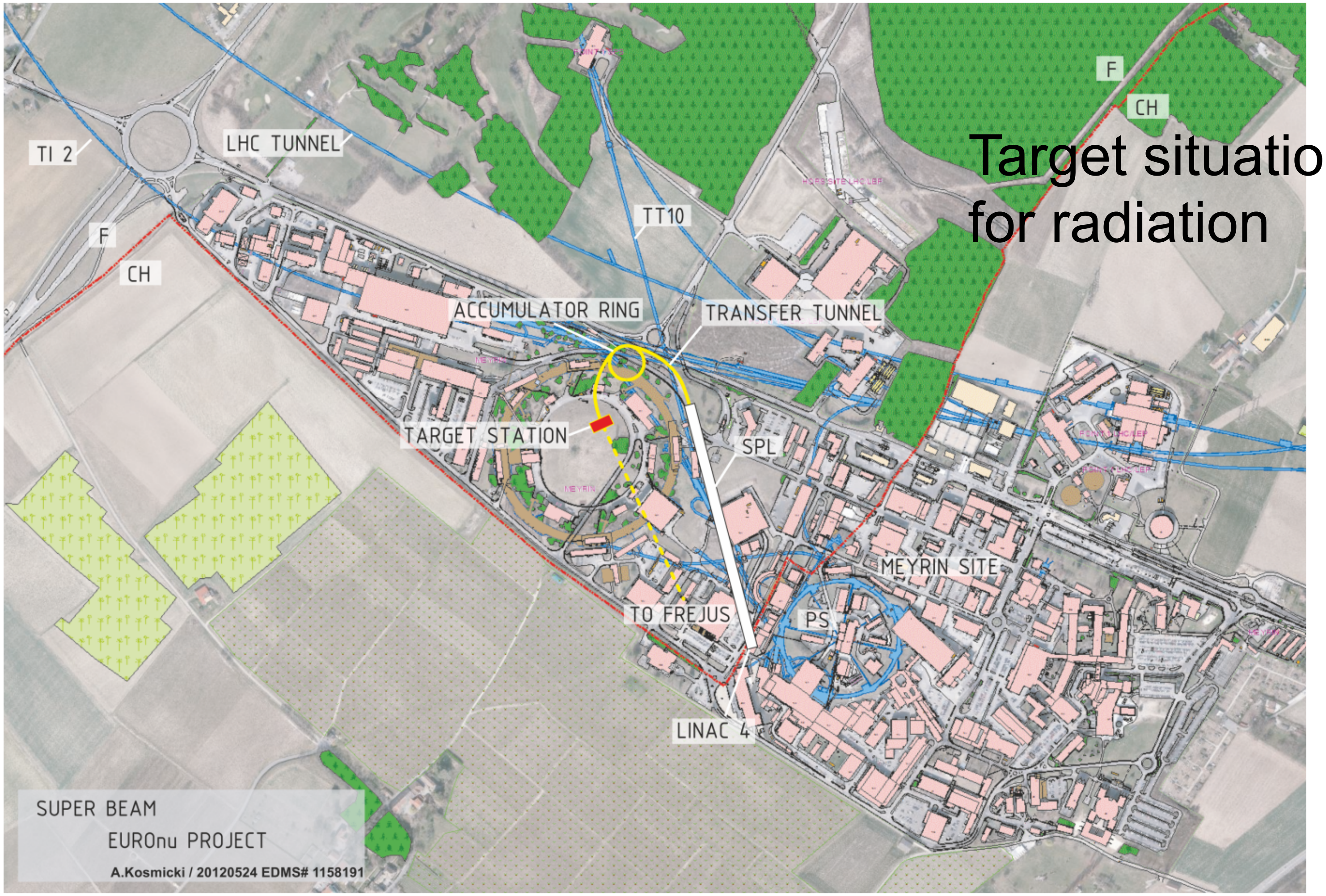
- E_b = 4.5 GeV
- Beam Power = 4MW -> 4x1-1.3MW
- Repetition Rate = 50Hz -> 12.5Hz
- Protons per pulse = 1.1 x 10^{14}
- Beam pulse length = 0.6ms





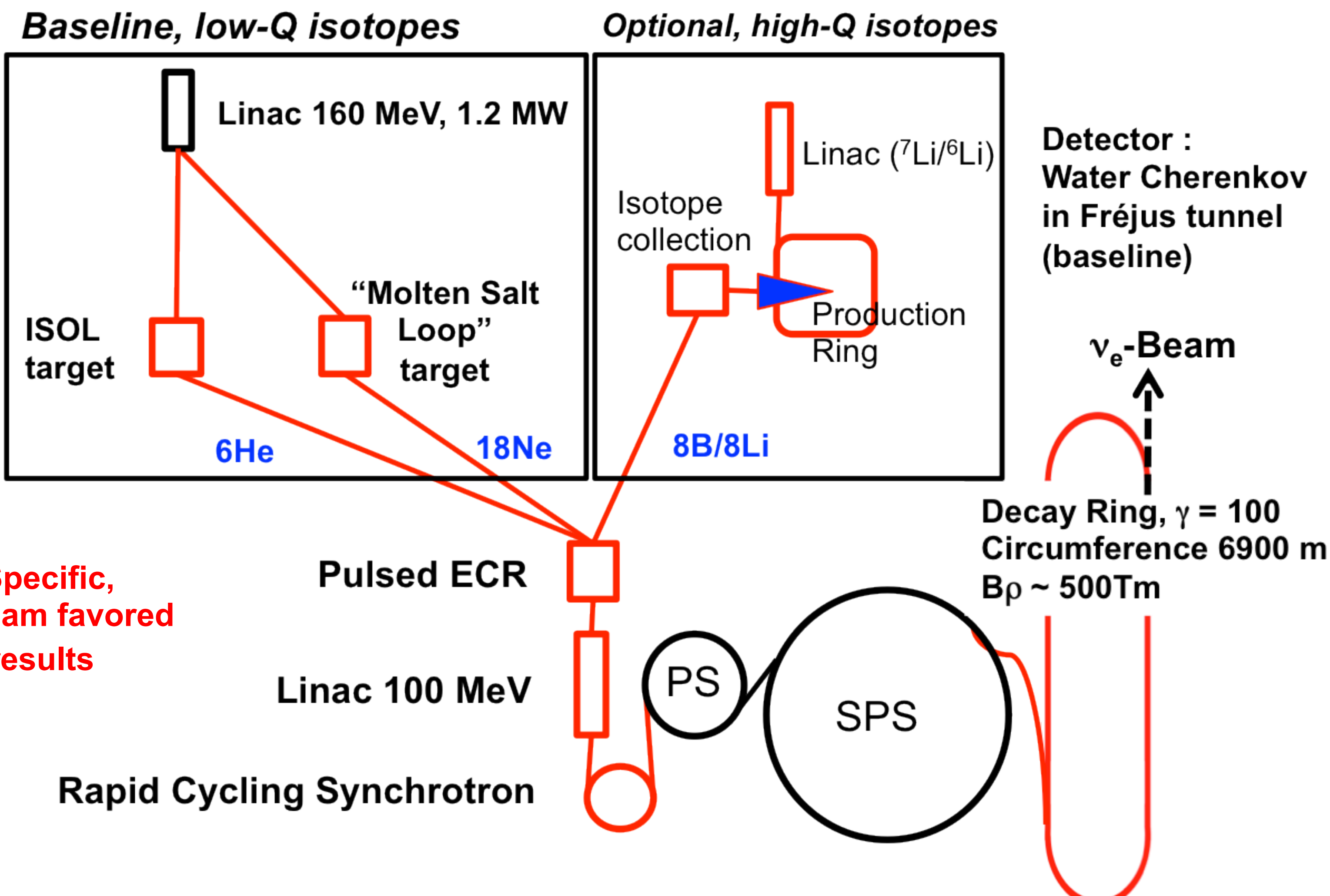
- 4-horn/target system in order to accommodate the 4MW
- power @ 1-1.3MW, repetition rate @ 12.5Hz for each target

EUROnu Super Beam



Target situation checked for radiation

The CERN Beta Beam



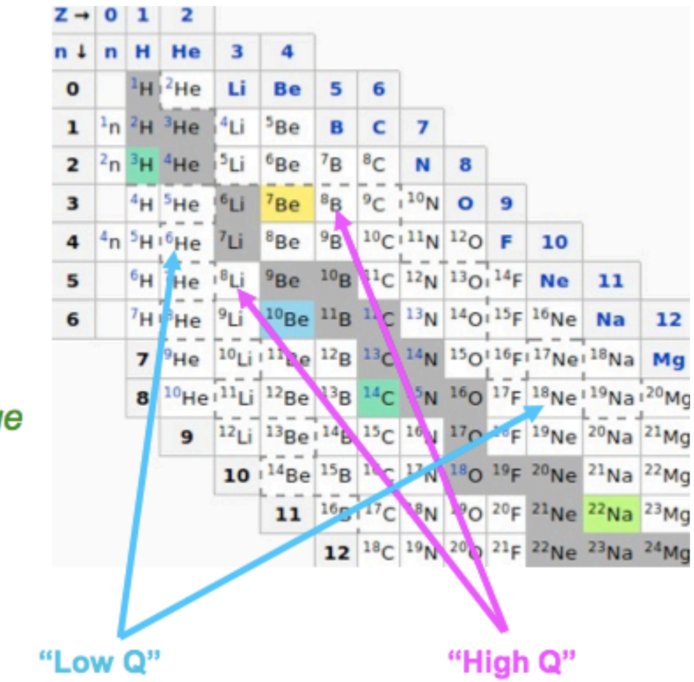
CERN Specific, Beta Beam favored by θ_{13} results

Decay Ring: $B\rho \sim 500$ Tm, $B = \sim 7$ T, $C = \sim 6900$ m, $L_{ss} = \sim 2500$ m, $\gamma = 100$, all ions

Choice of beta (+ and -) active isotopes

Considerations

- **Pair of β⁺ and β⁻ active ions**
  for ν and anti-ν …
- **Production rates**
  isol method or production ring
- **Life time**
  optimized for baseline ~1s
- **Reactivity**
  noble gases are good
- **Low Z preferred**
  minimize accelerated mass per charge
  reduce space charge problems
- **Q value**
  defines ν-energy & baseline



Isotope	^{18}Ne	^{6}He		^{8}B	^{8}Li
A/Z	1.8	3		1.6	2.7
Emitter	β⁺ (ν)	β⁻ (anti-ν)		β⁺ (ν)	β⁻ (anti-ν)
$\tau_{1/2}$ [s]	1.67	0.81		0.77	0.83
Q [MeV]	3.3	3.5		13.9	13.0

"Q value" is the kinetic energy release of a particle at rest

E.g. for the neutron decay

$$Q = m_n - m_p - m_{\bar{\nu}} - m_e$$

Production of Beta Beam isotopes

Aim ^{6}He and ^{18}Ne: 2 10^{13}/s **Targets below MWatt is a considerable advantage!**

Isotope	^{6}He	^{18}Ne	^{8}Li	^{8}B
Prod.	ISOL(n)	ISOL	P-Ring	P-Ring
Beam	SPL(p)	Linac4(p)	d	^{3}He
I [mA]	0.07	6	0.160	0.160
E [MeV]	2000	160	25	25
P [kW]	140	960	4	4
Target	W/BeO	^{23}Na, ^{19}F	^{7}Li	^{6}Li
r [10^{13}/s]	5	0.9	0.1	0.08

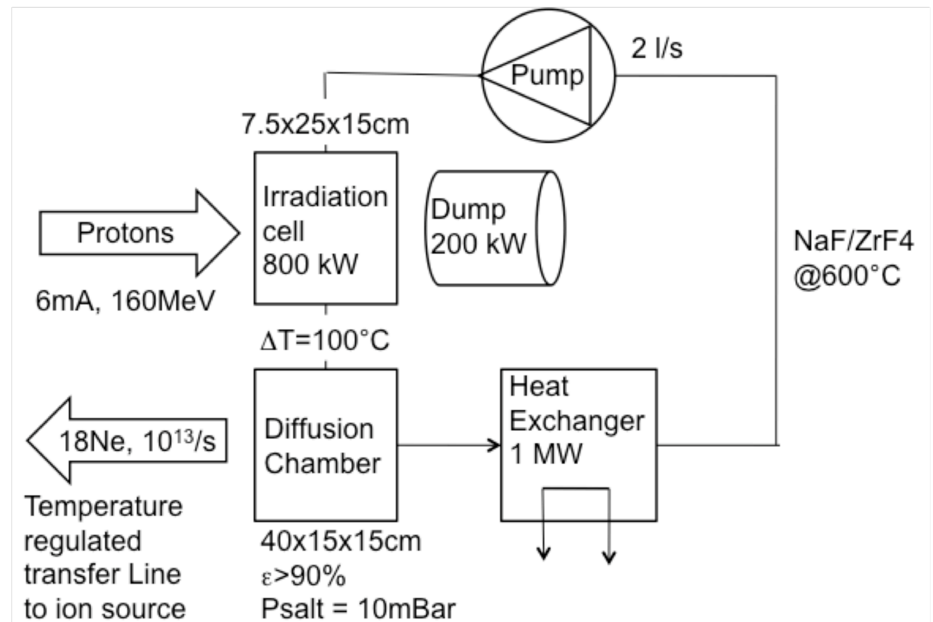
^{6}He production exp. T. Stora, CERN-2010-003, pp. 110-117

^{18}Ne Experiments for Beta Beams

- Molten salt loop experiment to produce 18Ne
  - experiments at CERN & LPSC (Grenoble)
  - Very positive results from mid June 2012

NaF salt loop → 2 reactions

$$^{19}F(p,2n)^{18}Ne$$
$$+$$
$$^{23}Na(p,X)^{18}Ne$$

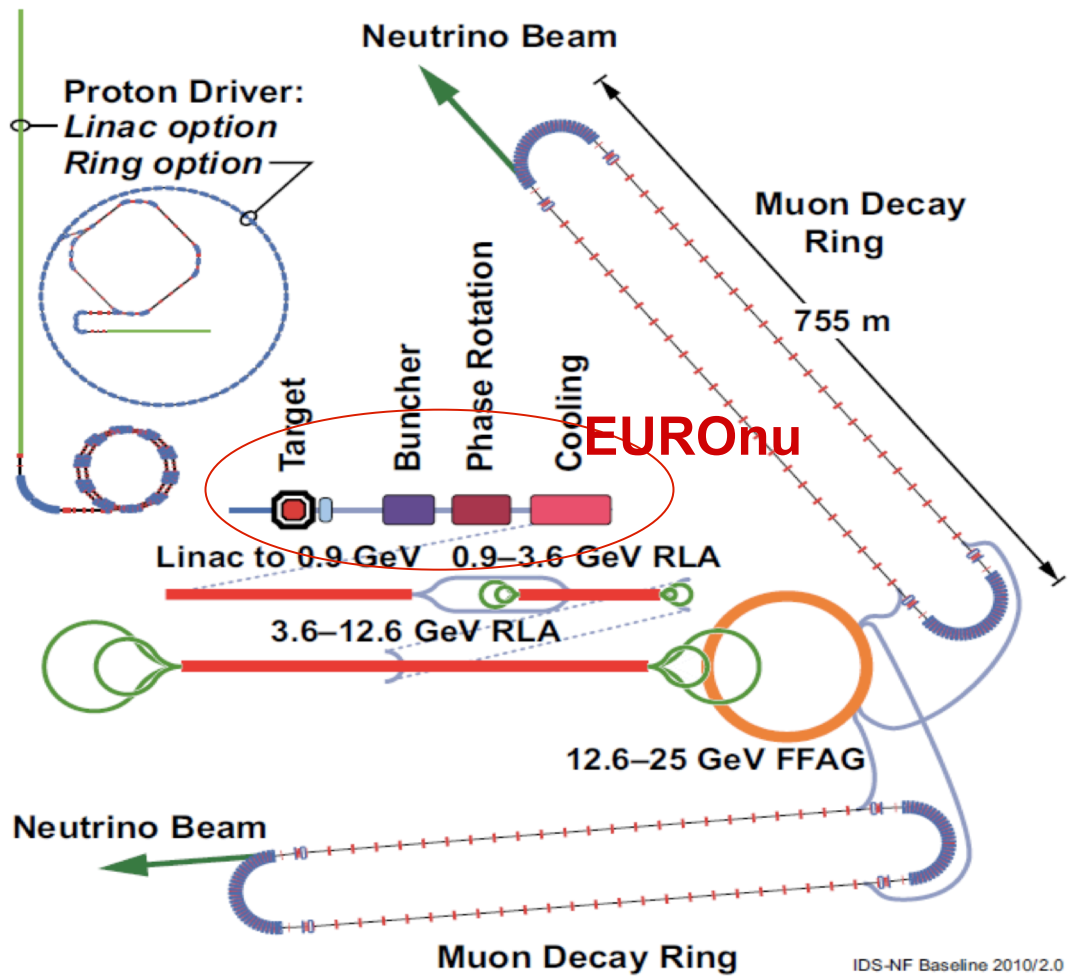


^{18}Ne production rate estimated to 1×10^{13} ions/s (dc) for 960 kW on target.

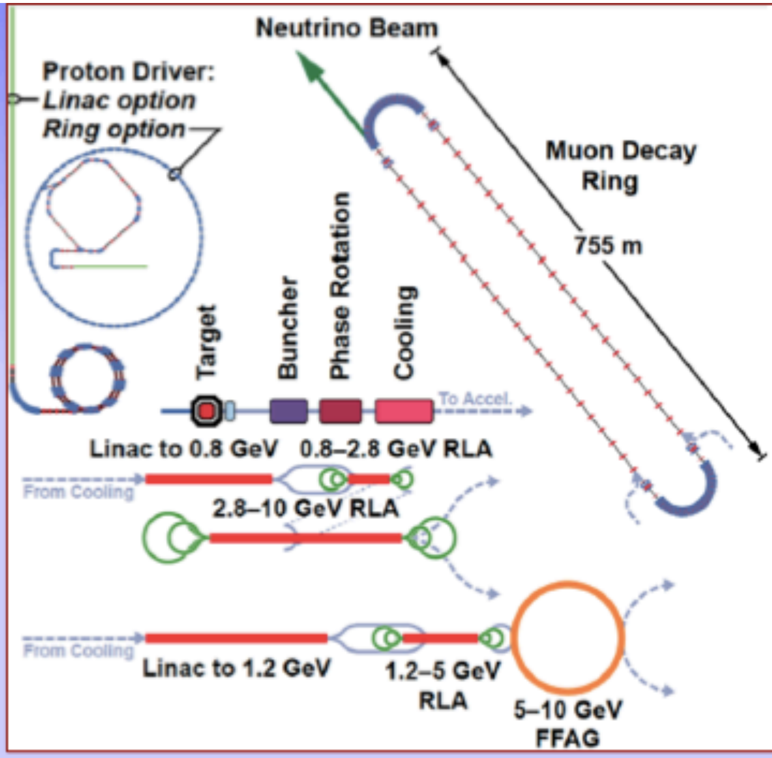
Beta Beam

Decay Ring
Point 2
ALICE
Site Prevessin
SPS
Point 1
ATLAS
TI8
CNGS
Beta Beams / Full Project
EUROnu project

The Neutrino Factory…



The Neutrino Factory, NOW



- **Proton Driver**

HARP: primary beam on production target

- **Target, Capture and Decay**

MERIT: first create π and later decay into μ

- **Bunching and Phase Rotation**

Reduce the spread in energy (ΔE) of bunch

- **Cooling**

MICE: Reduce the transverse emittance

- **Acceleration**

EMMA: go from 130 MeV to 10 GeV with RLAs or FFAGs

- **Decay Ring**

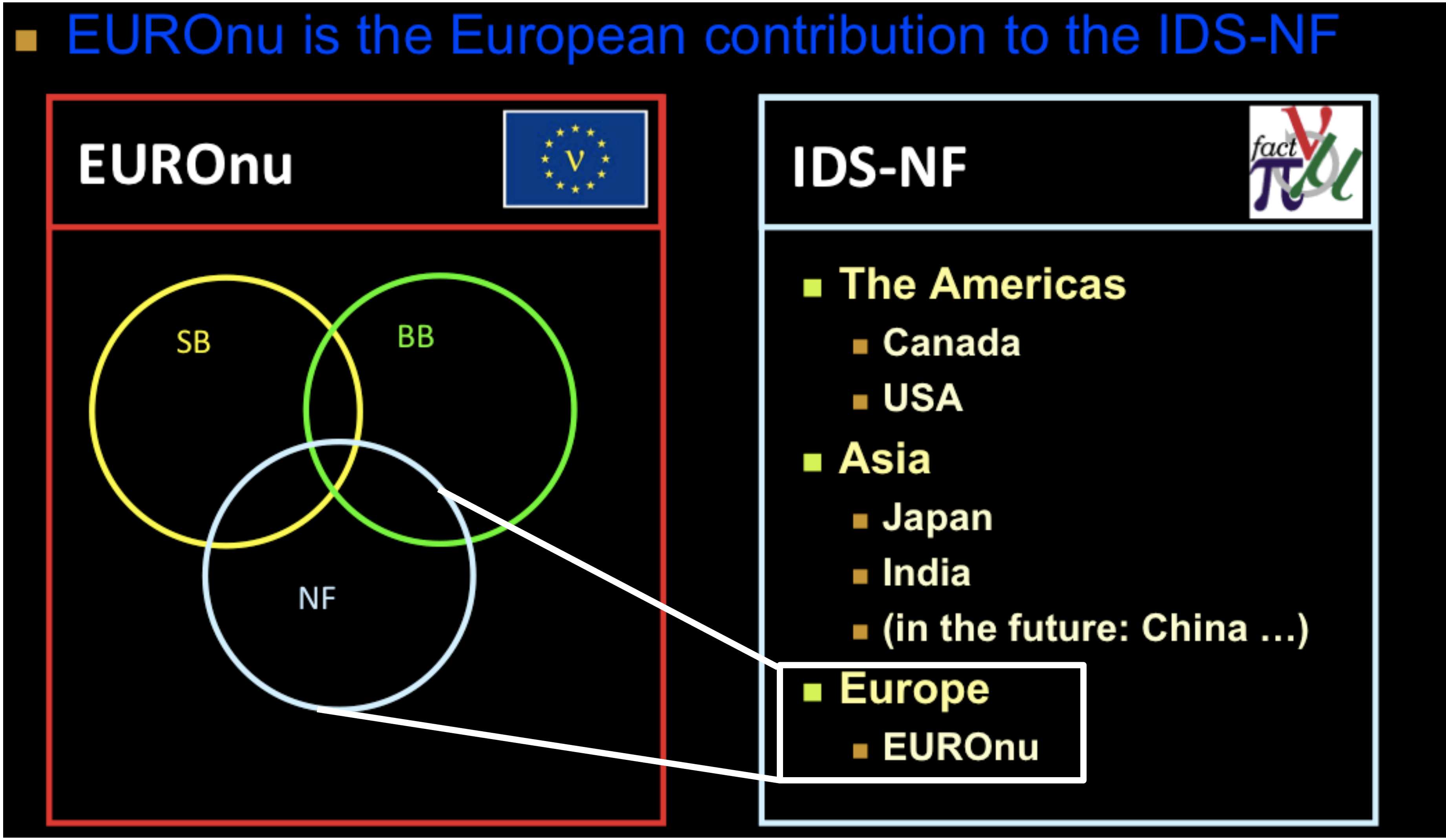
Store for roughly 1000 turns; long straight sections

One 2000 km baseline, 100 kt MIND, 10 GeV muons, 10^{21} useful decays/year

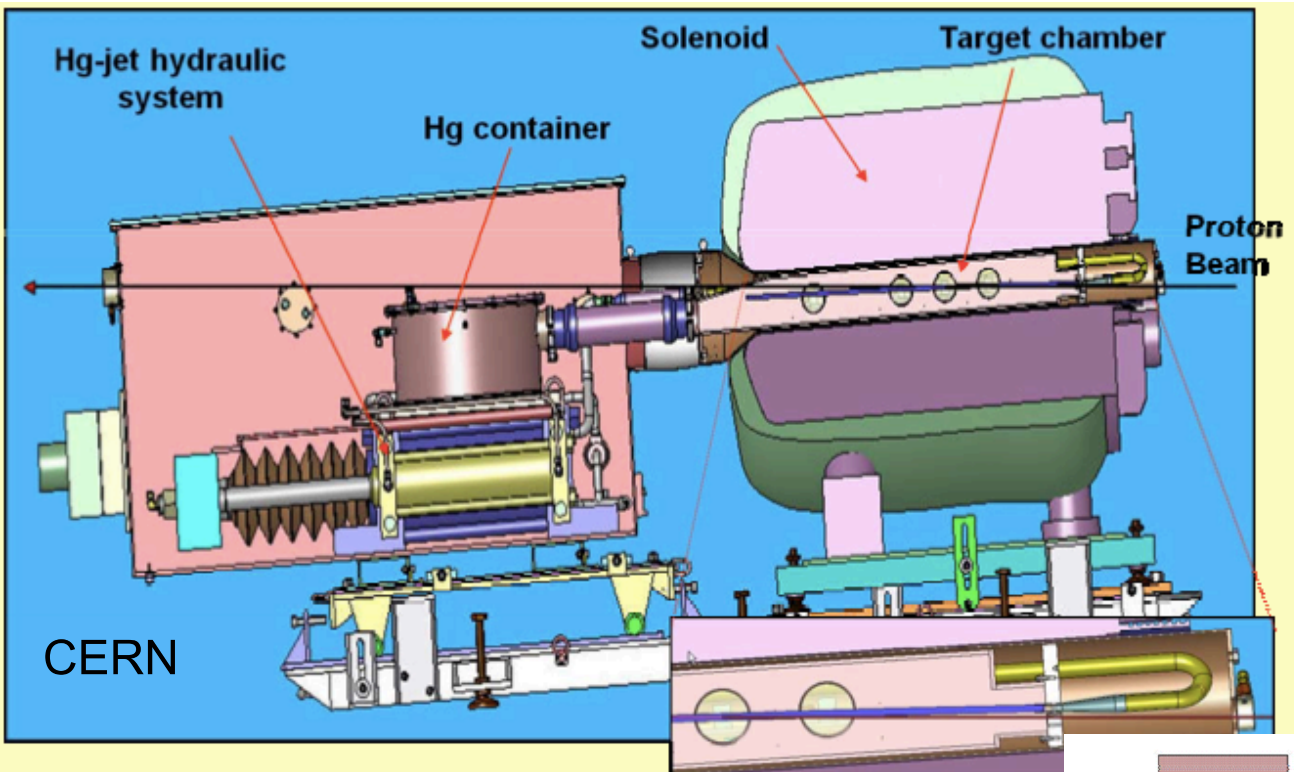
A Staged Approach is conceivable with outstanding physics cases at each stage!

S. K. Agarwalla, 4th EUROnu Annual Meeting, APC, Paris, 13th June, 2012 21/28

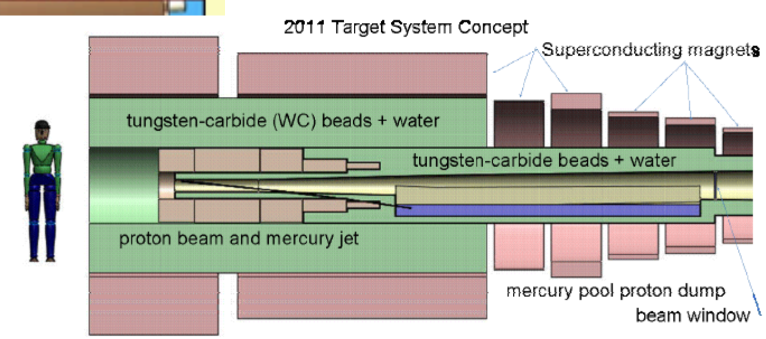
EUROnu and IDS-NF



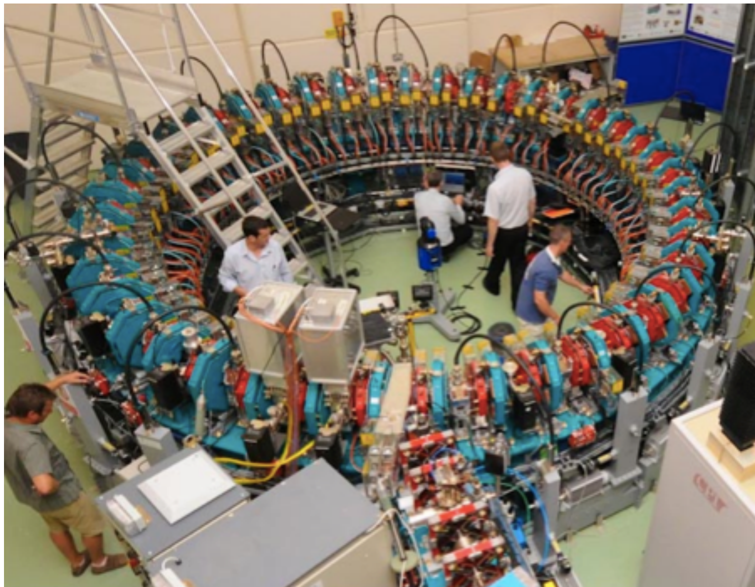
MERIT: Hg targets



- Free mercury jet target
- Intercepting a 4-MW proton beam
- Surrounding solenoid of 15 T

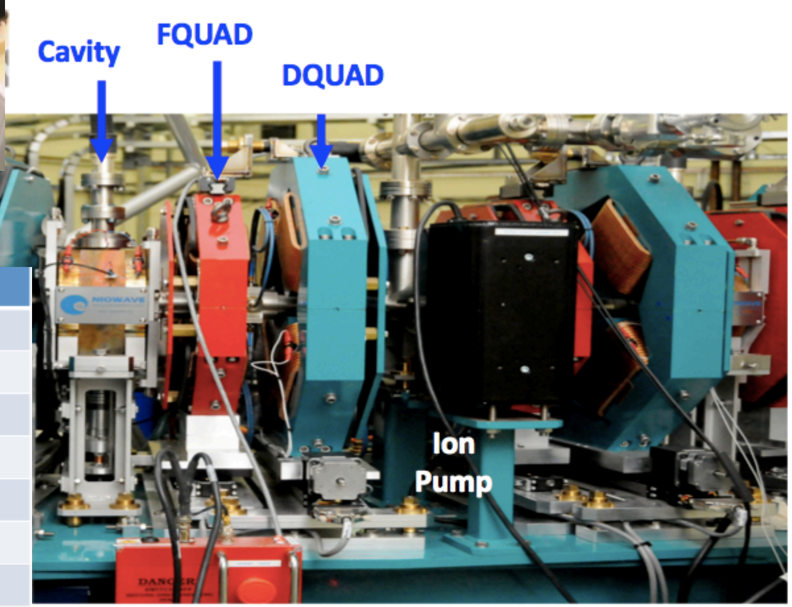


EMMA: Linear nonscaling FFAG



Science & Technology Facilities Council

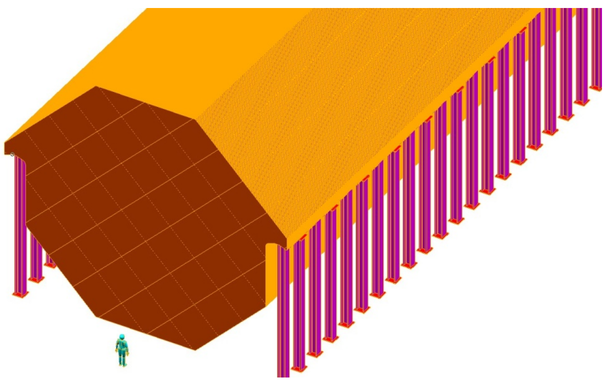
- EMMA electron model of muon accelerator
- Commissioning without surprises
- Proof of principle!

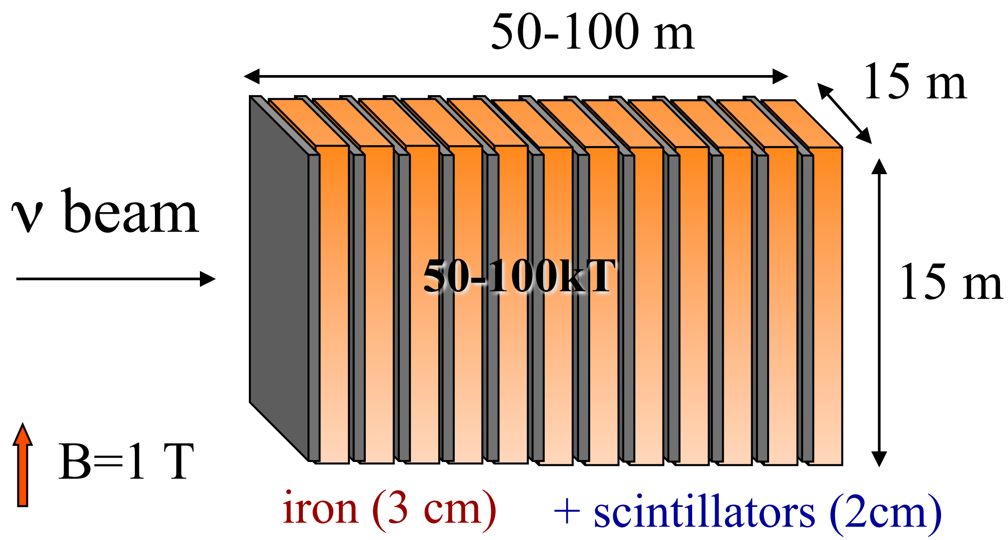


	Muon FFAG	EMMA	Ratio
Momentum	12.6 – 25 GeV/c	10 – 20 MeV/c	1 : 0.001
rf voltage	1214 MV	2.28 MV	1 : 0.002
Number of cell	64	42	1 : 0.66
Circumference	667 m	16.6 m	1 : 0.025
QD/QF length	2.251/1.087 m	0.0777/0.0588 m	1 : 0.035/0.054
Straight section	5 m	0.2 m	1 : 0.04
Aperture	~ 300 mm	~ 30 mm	1 : 0.1

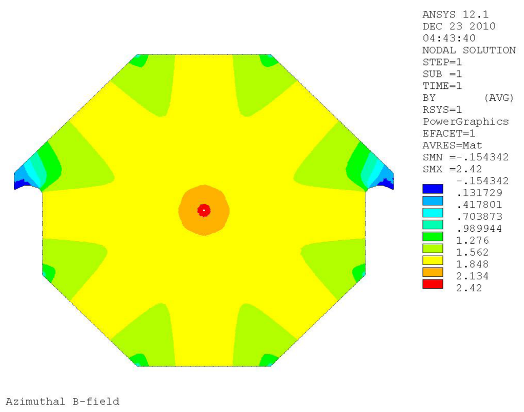
Neutrino Factory

Detectors: MIND for NF, 25 GeV



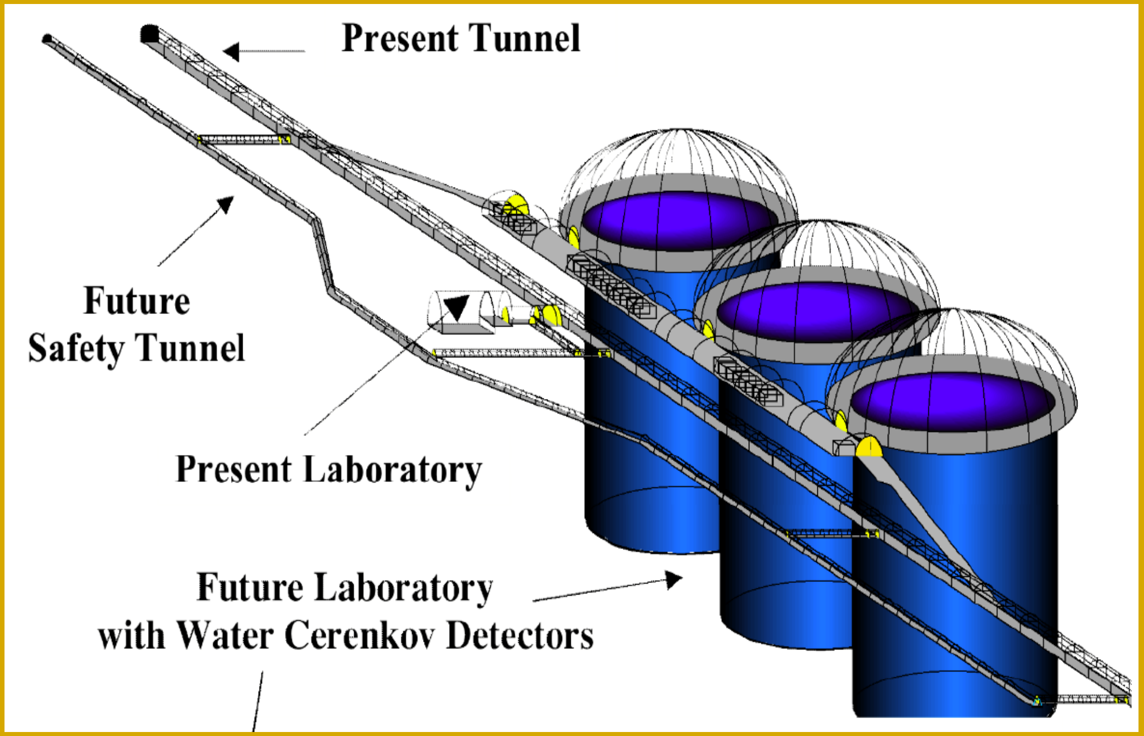


- Far detector: 100 kton at 2000-4000 km
- Magic detector: 50 kton at 7500 km
- Appearance of “wrong-sign” muons
- Segmentation: 3 cm Fe + 2 cm scintillator
- 1 T magnetic field



The MEMPHYS Detector

MEMPHYS Water Cherenkov detector



1 shaft = 215 kt

Water target

Possible location: extension of Fréjus laboratory

Ongoing R&D for single photo detection

Synergy with HK (Japan) and UNO (USA)

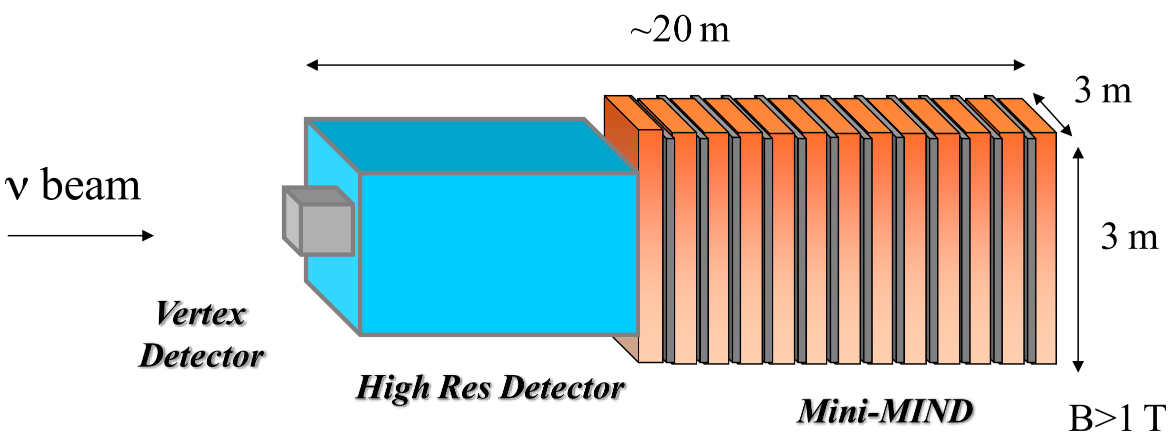
Near Detectors

Control of the systematics for the long baseline neutrino oscillation

* Characterize neutrino beam

in addition to moun/ion beam instrumentation

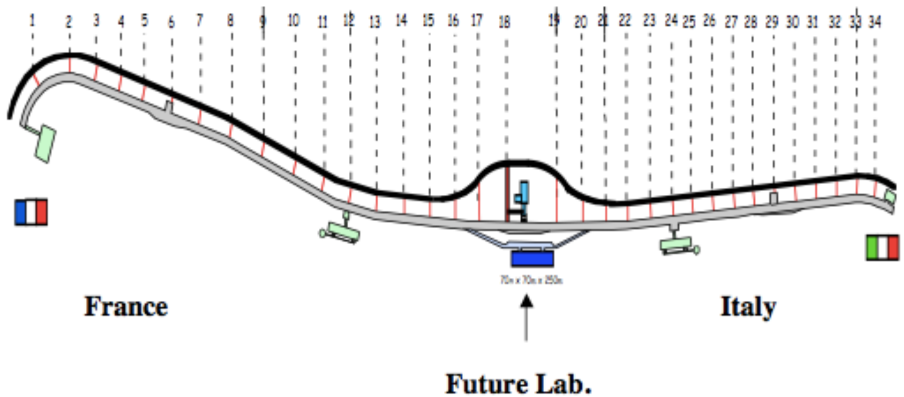
* Cross section measurements



Studied Options in LAGUNA

Fréjus

130 km



2300 km

Pyhäsalmi

2500-4000 m.w.e

Synergies essential: Detectors/Beams

The outcome of the detector study may be decisive for the future of the neutrino-facilities due to cost of the detector and the cavern.

European sites: LAGUNA-LBNO

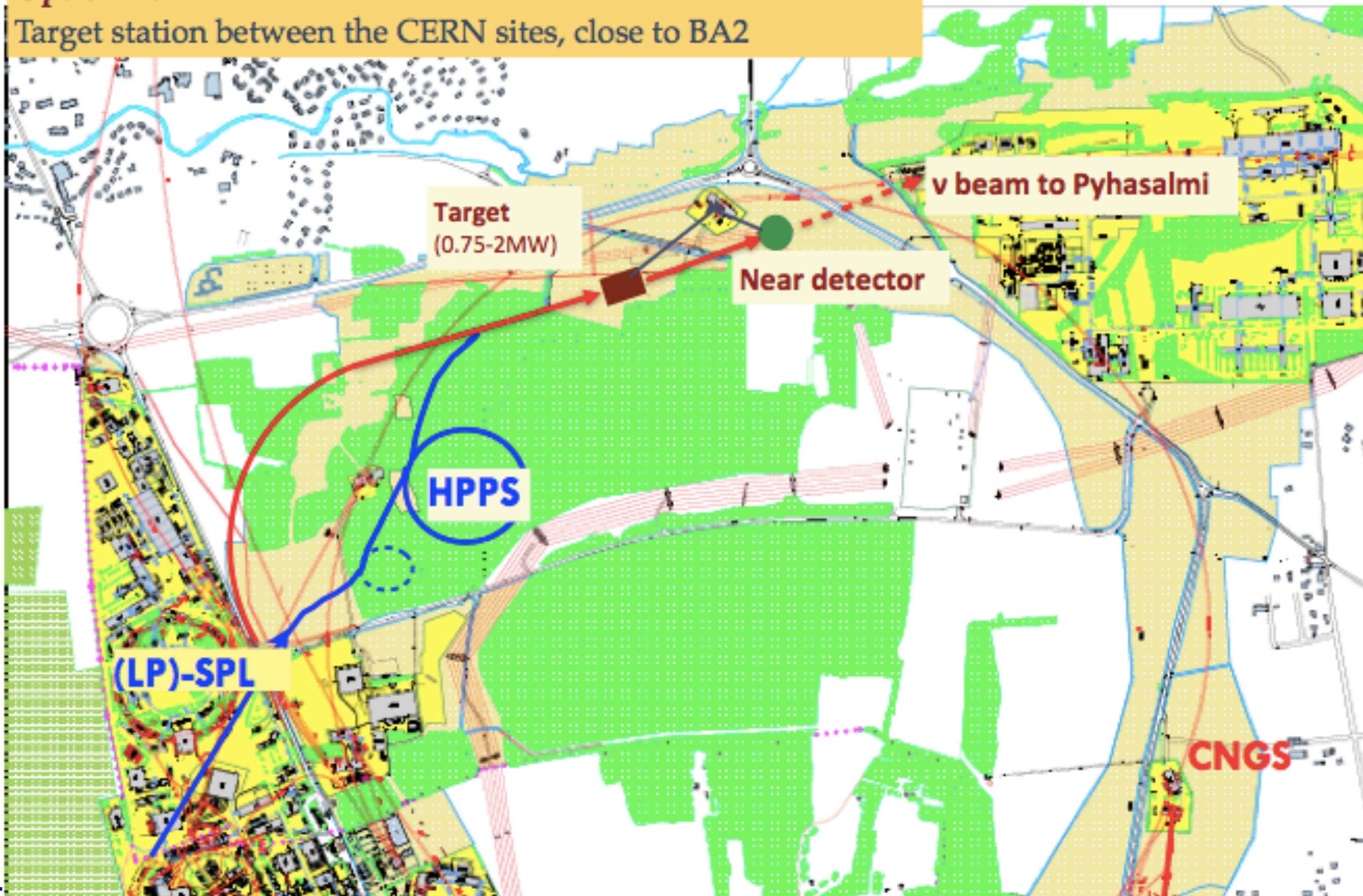
arXiv:1003.1921 [hep-ph]

Three far sites considered in details

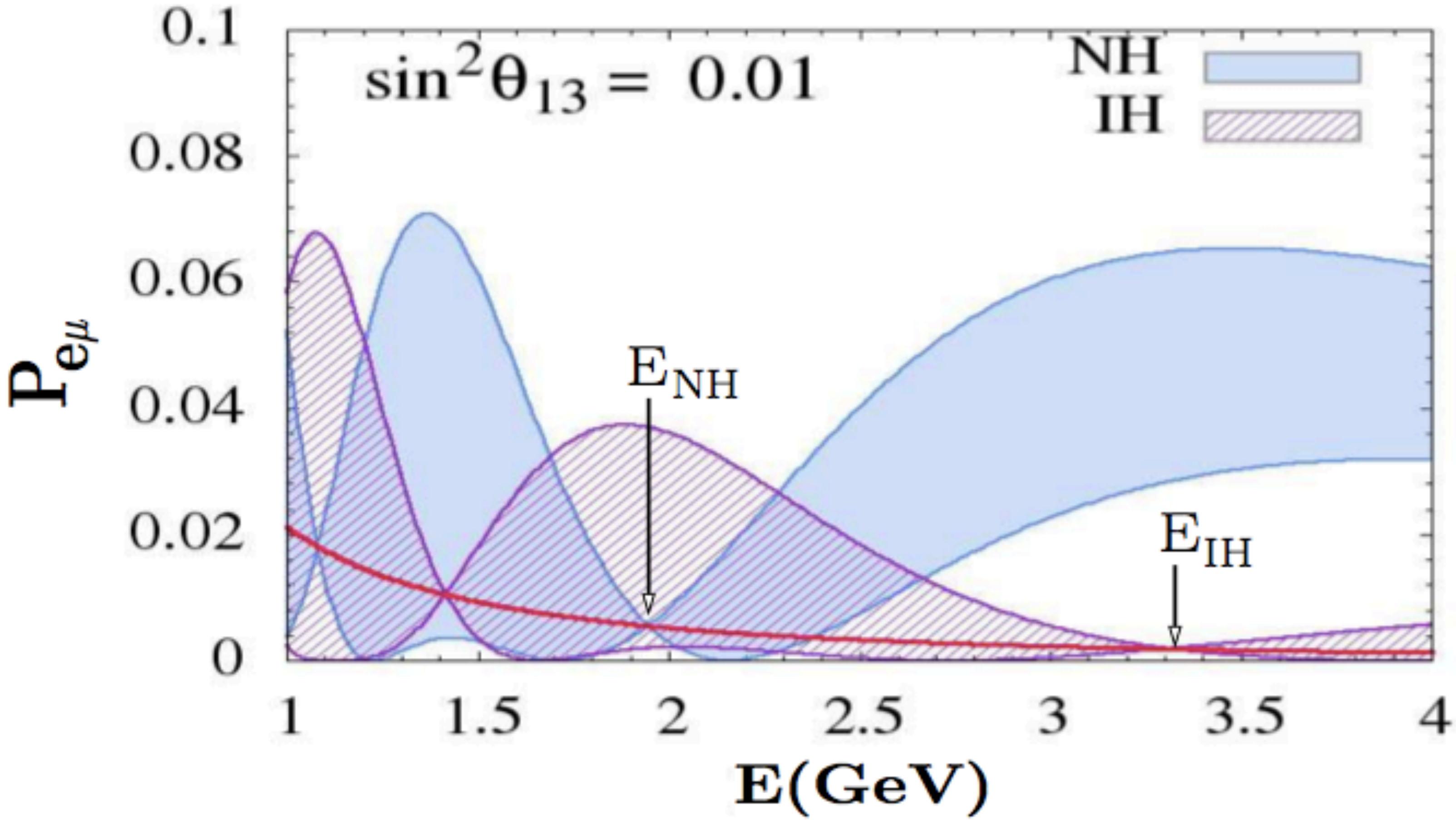
- Large Water Cerenkov Detector. CERN-Fréjus is a short baseline. It offers good synergy for enhanced physics reach with β-beam at γ=100
- Liquid Argon TPC & magnetized iron + Liquid Scintillator detectors CERN-Pyhäsalmi is the longest baseline. It offers good synergy for enhanced physics reach with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

C2P

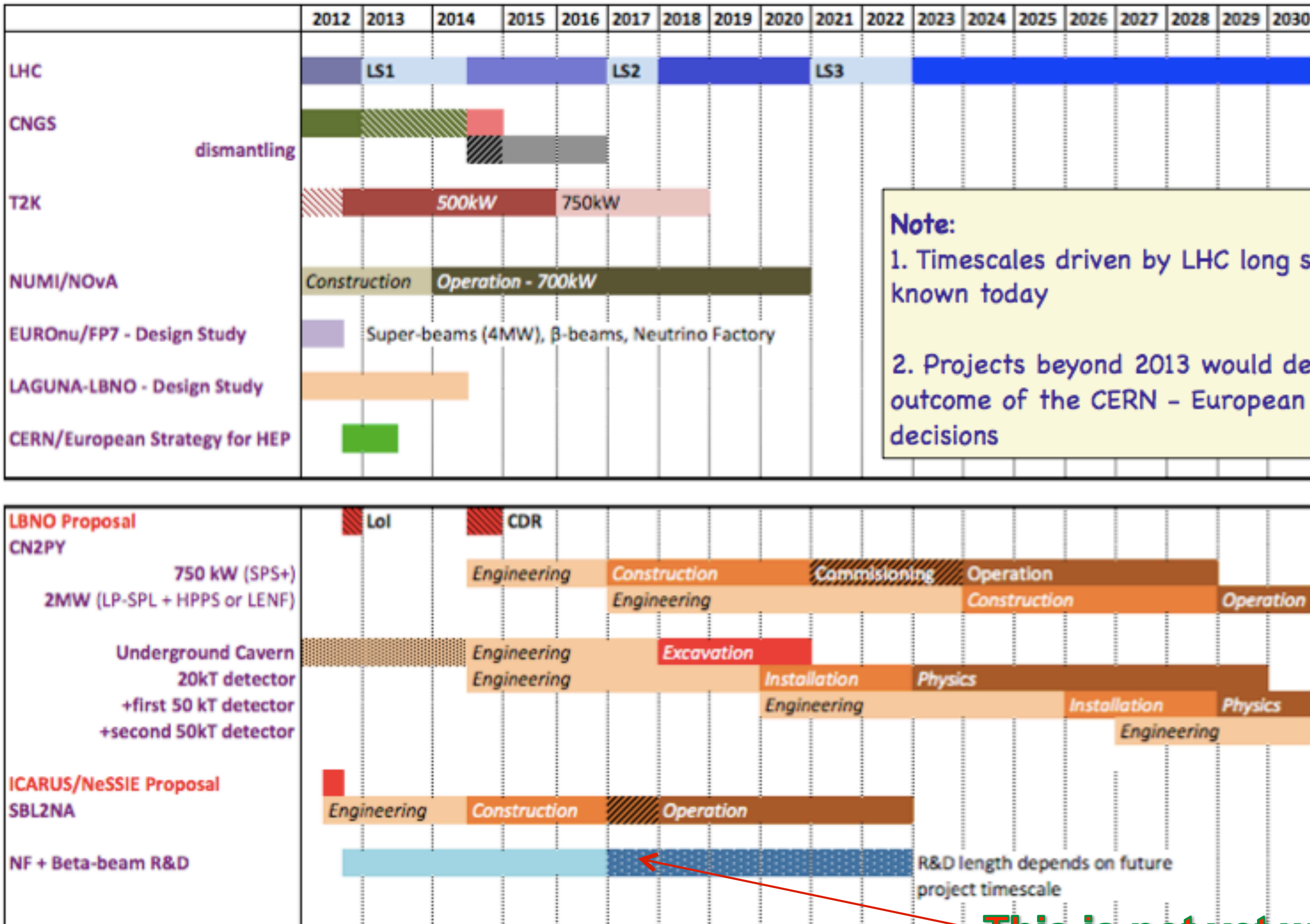
Option A:
Target station between the CERN sites, close to BA2



C2P: Bi Magic Baseline



Future Neutrino Beams – possible timeline



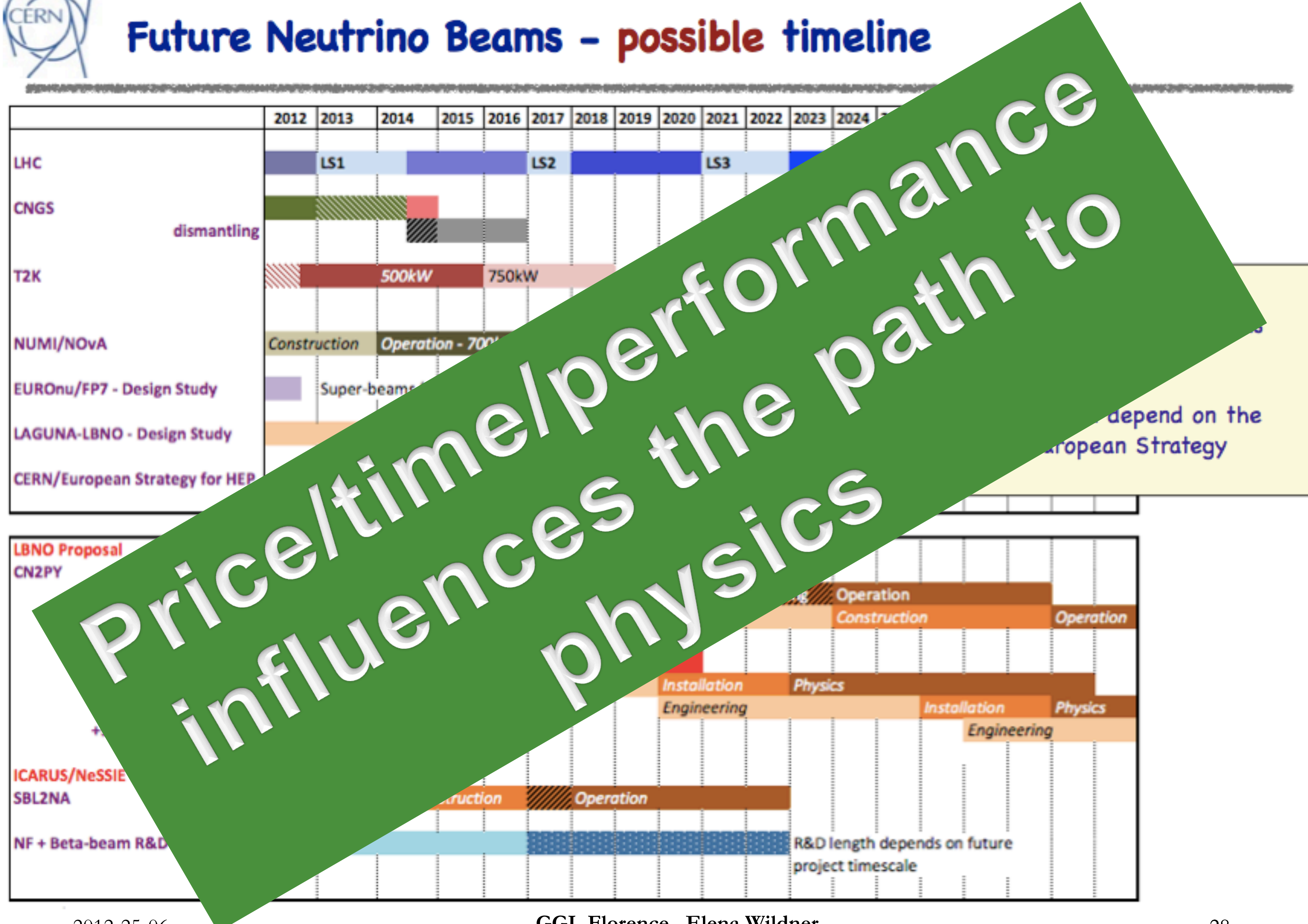
Note:

1. Timescales driven by LHC long shutdowns as known today

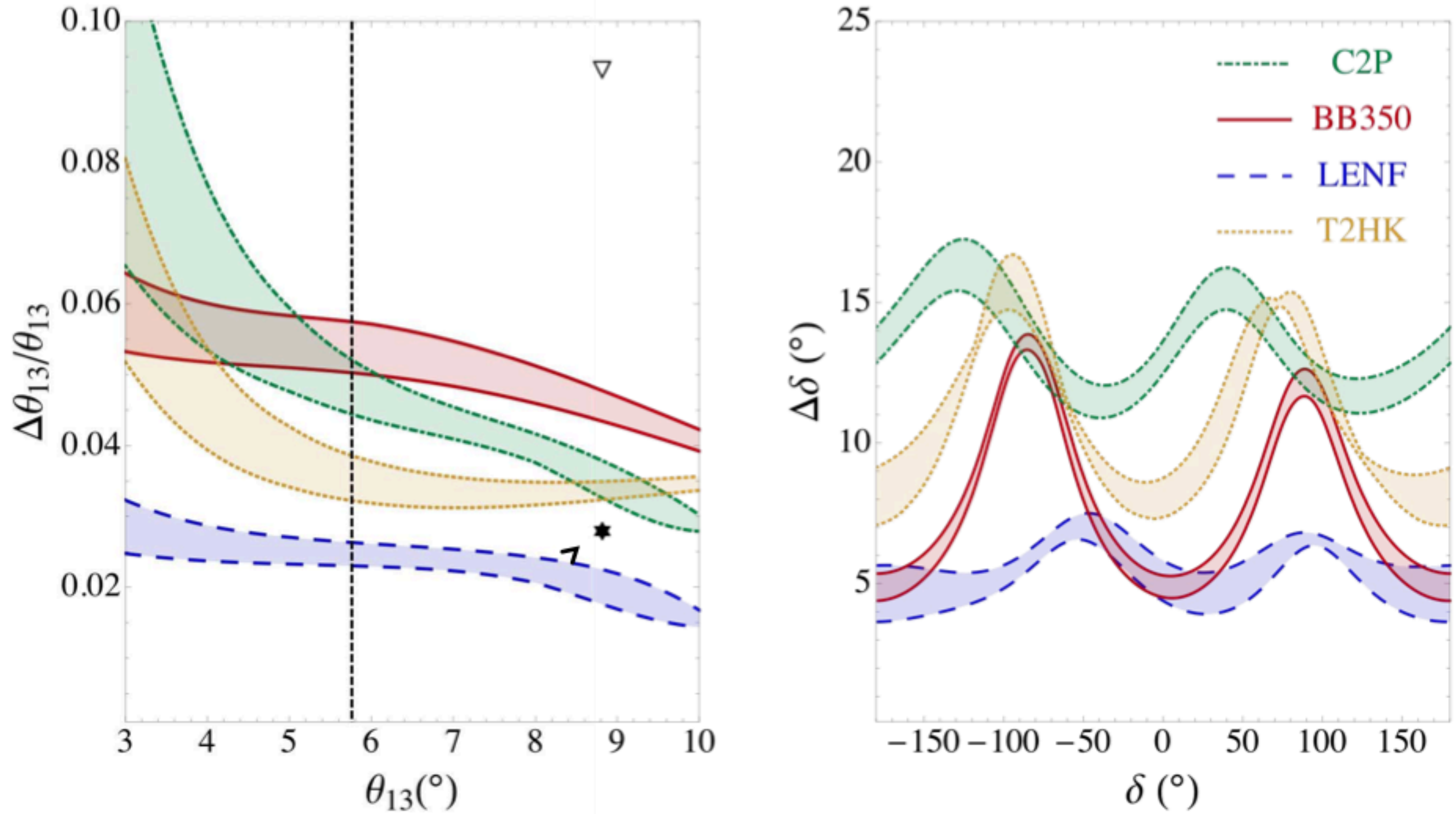
2. Projects beyond 2013 would depend on the outcome of the CERN – European Strategy decisions

This is not yet worked on

Future Neutrino Beams – possible timeline



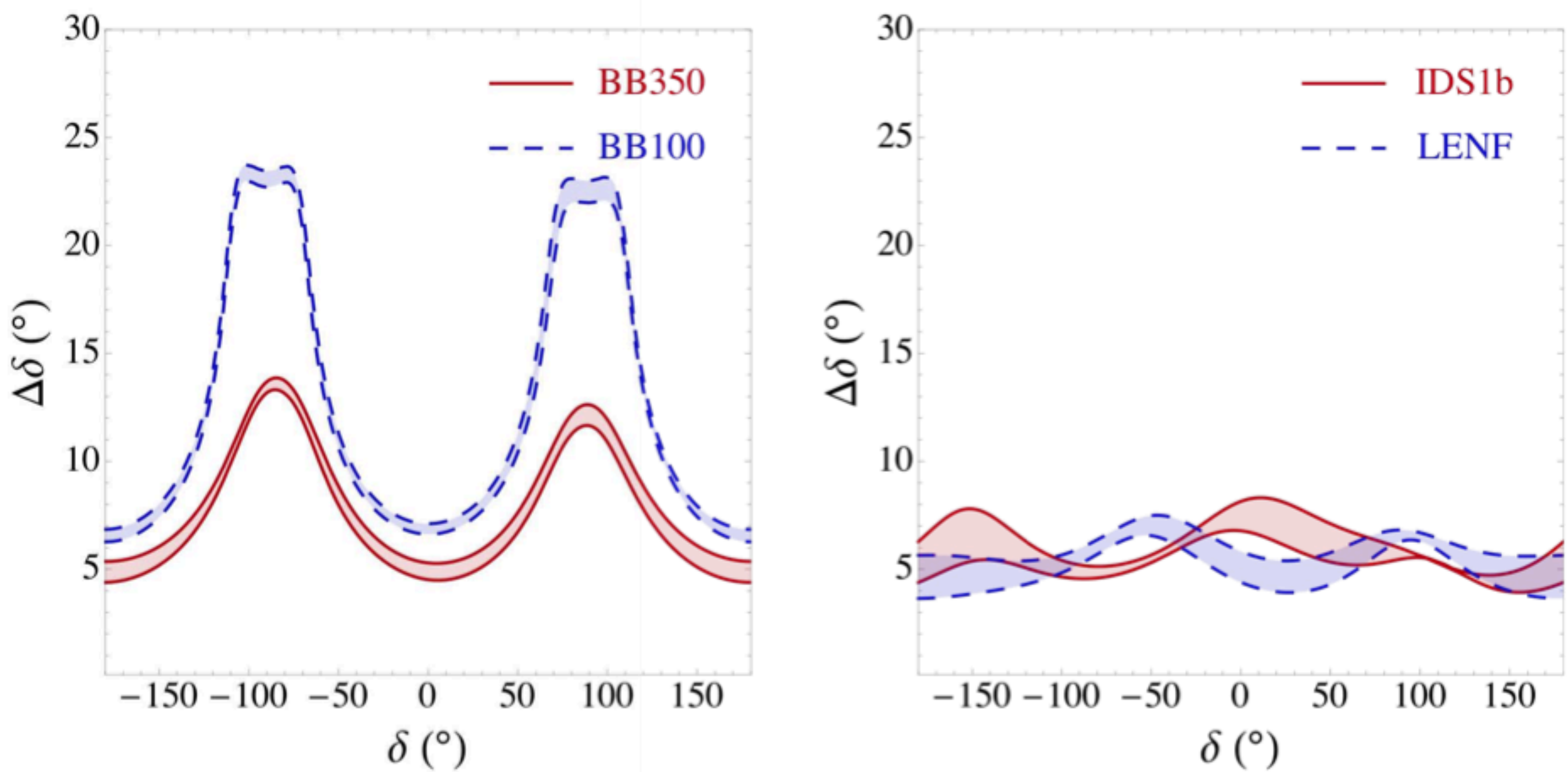
Large θ_{13}: from discovery reach to precision



Daya Bay limit !

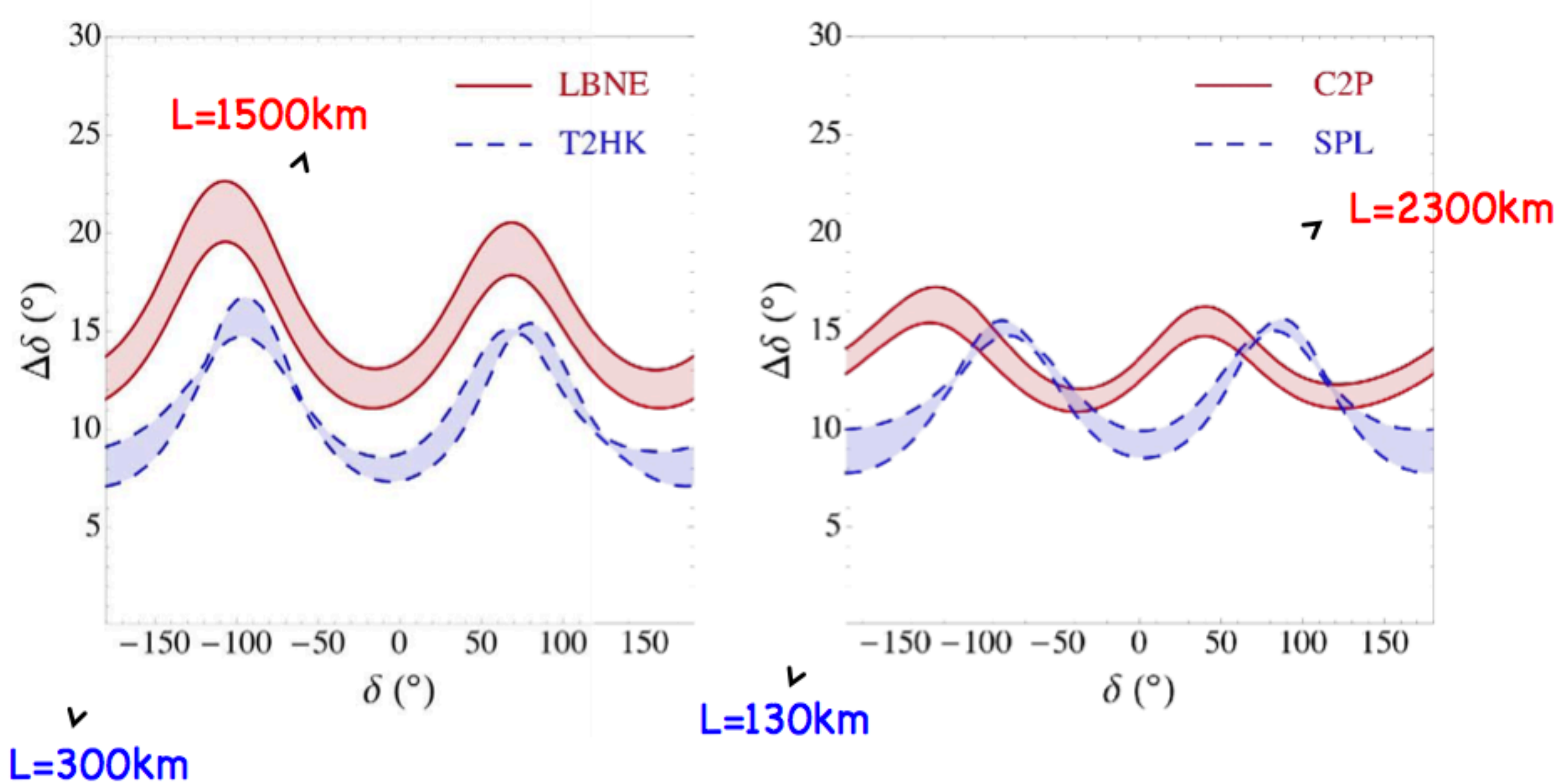
Coloma, Donini, Fernandez-Martinez,PH arXiv:1203.5651

Nufact: 25 GeV (IDS1b), 10 GeV (LENF)



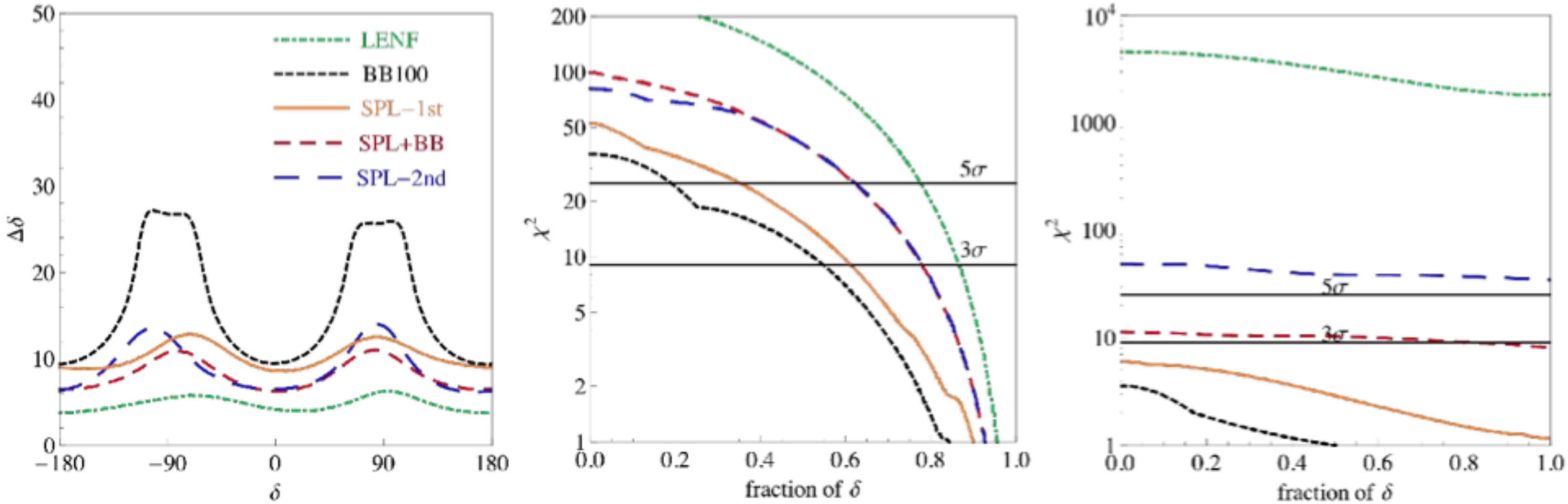
BB: not so good in precision ...
(not enough spectral info, statistics)

Superbeams here and there (really super)



Shorter baselines outperform longer ones for precision (obviously not matter) but SPL baseline maybe not fully optimal…

EURONU contenders



Courtesy of E. Fernandez-Martinez

Official systematic errors: signal 1% (Nufact), 5% (rest)
background 10% all

Physicswise: 1) Nufact absolute winner 2) SPL very good for CP (better at ~700km 3) BB-100 precision limited 4) SB+BB synergetic

Challenges

- Statistics !!!
  - big detectors & powerful, well understood beams
- Systematics !!!
  - vacuum (true) CP asymmetry < 0.3
- Resources !!!
  - 1 to 5 Billion units
- Patience & Good Health !!!
  - more than 10 years before results on MH and CPV

Opportunities

- Mass Hierarchy (other exp.)
- Precision measurement of Theta_23, including quadrant (other exp.)
- CPV
- If detector underground (not NuFactory)
  - proton decay, atmos. nu's and supernova nu's

LBL Challenges and Opportunities !

Organization:

- Physics and Opportunities in Japan & USA
  - Stephen Parke, Fermilab
- Future Facilities in Europe
  - Elena Wildner, CERN
- Questions and Discussion
  - All of you

20 mins each !

Part I:

- Light Speed Summary of Long Baseline Physics
- Japanese opportunities: brief
- USA opportunities: LBNE reconfiguration

$$\nu_\mu \longrightarrow \nu_e$$

CP

$$\nu_\mu \to \nu_e \quad \Longleftrightarrow \quad \bar{\nu}_\mu \to \bar{\nu}_e$$

T $\Updownarrow$ CPT across diagonals $\Updownarrow$ T

$$\nu_e \to \nu_\mu \quad \Longleftrightarrow \quad \bar{\nu}_e \to \bar{\nu}_\mu$$

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:

$$\nu_\mu \longrightarrow \nu_e$$

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

$\updownarrow$

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

Vacuum LBL:

$$\nu_\mu \longrightarrow \nu_e$$

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

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

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

only CPV

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

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

$\nu_\mu \rightarrow \nu_e$

In Matter:

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

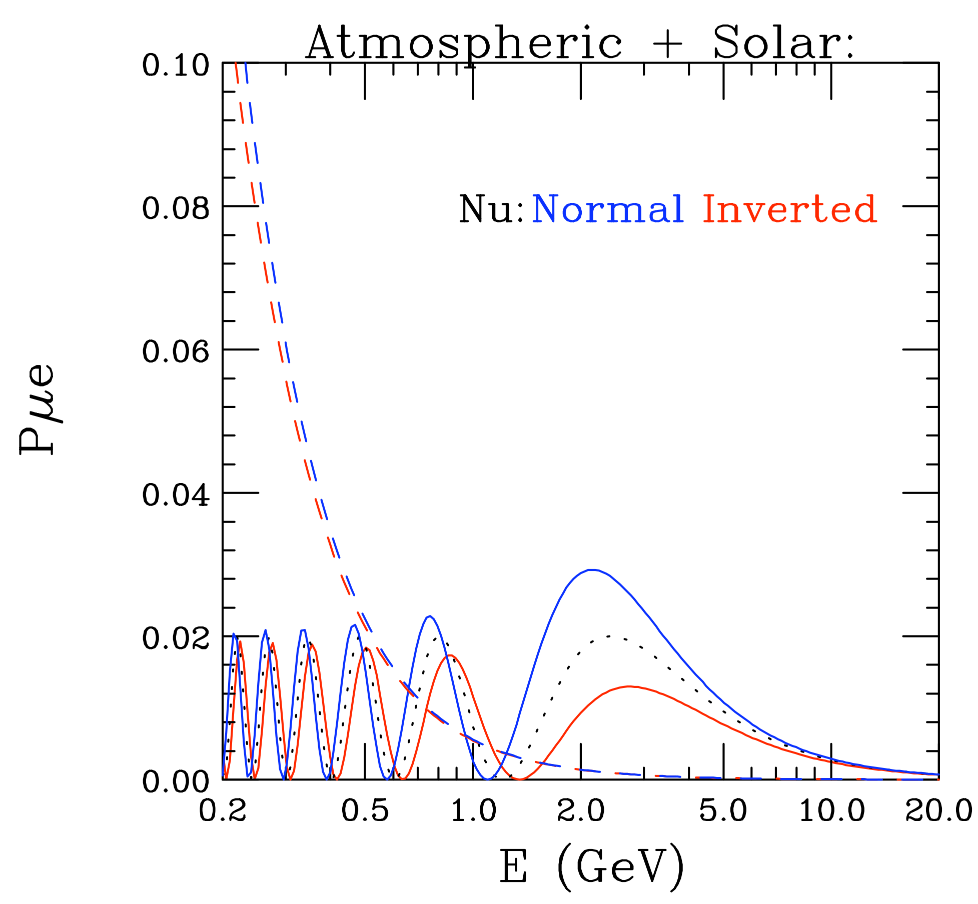
where $\sqrt{P_{atm}} = \sin\theta_{23} \sin 2\theta_{13} \frac{\sin(\Delta_{31} \mp aL)}{(\Delta_{31} \mp aL)} \Delta_{31}$

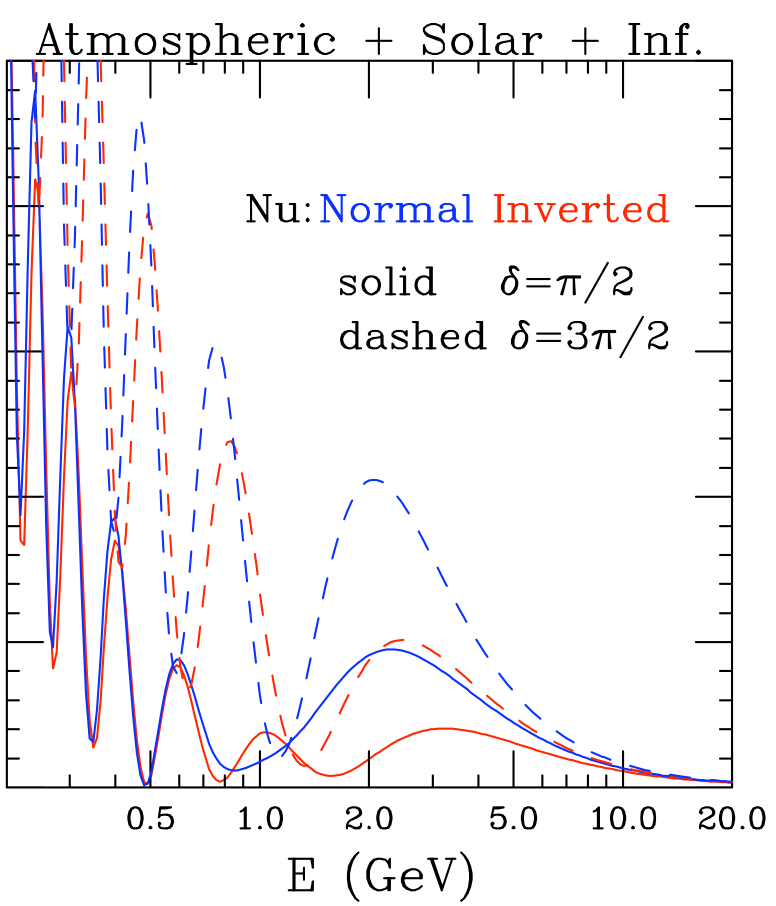
and $\sqrt{P_{sol}} = \cos\theta_{23} \sin 2\theta_{12} \frac{\sin(aL)}{(aL)} \Delta_{21}$

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

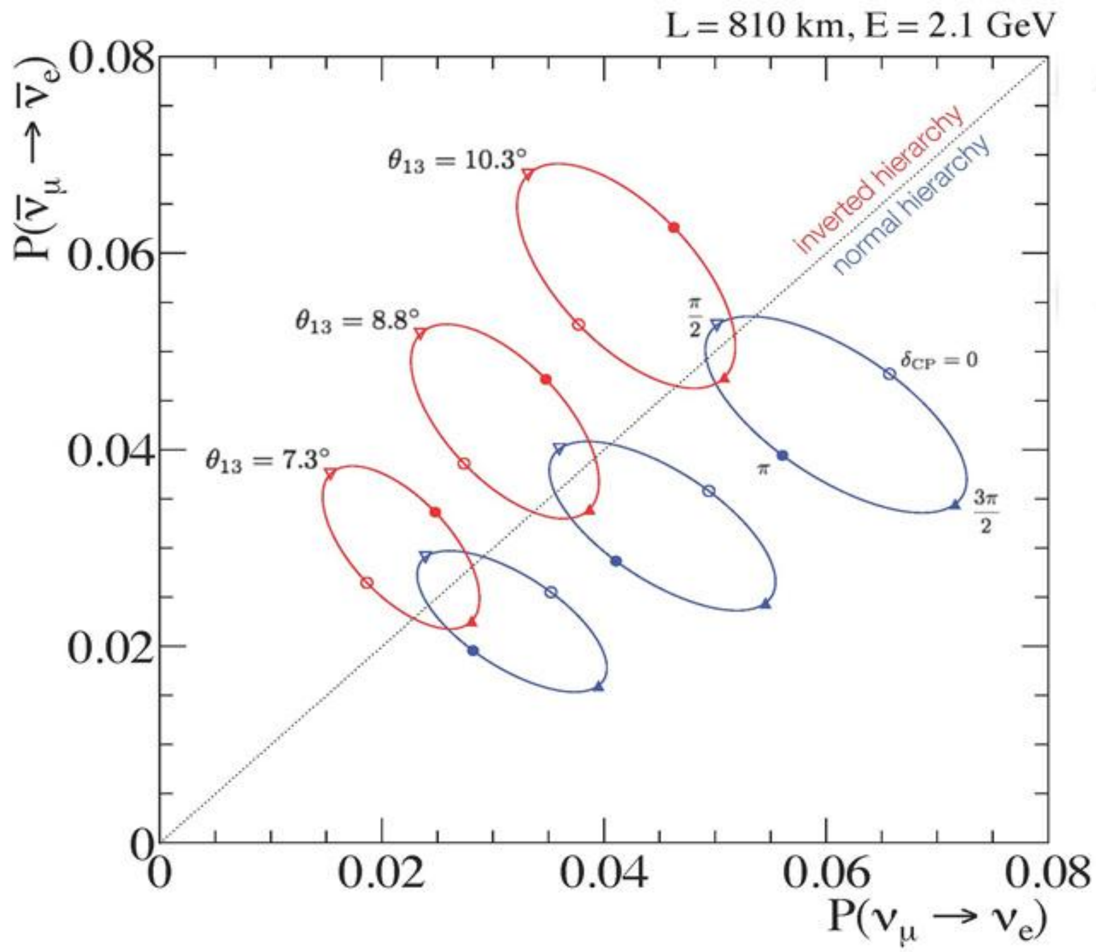
$$a = G_F N_e/\sqrt{2} = (4000\ km)^{-1},$$

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



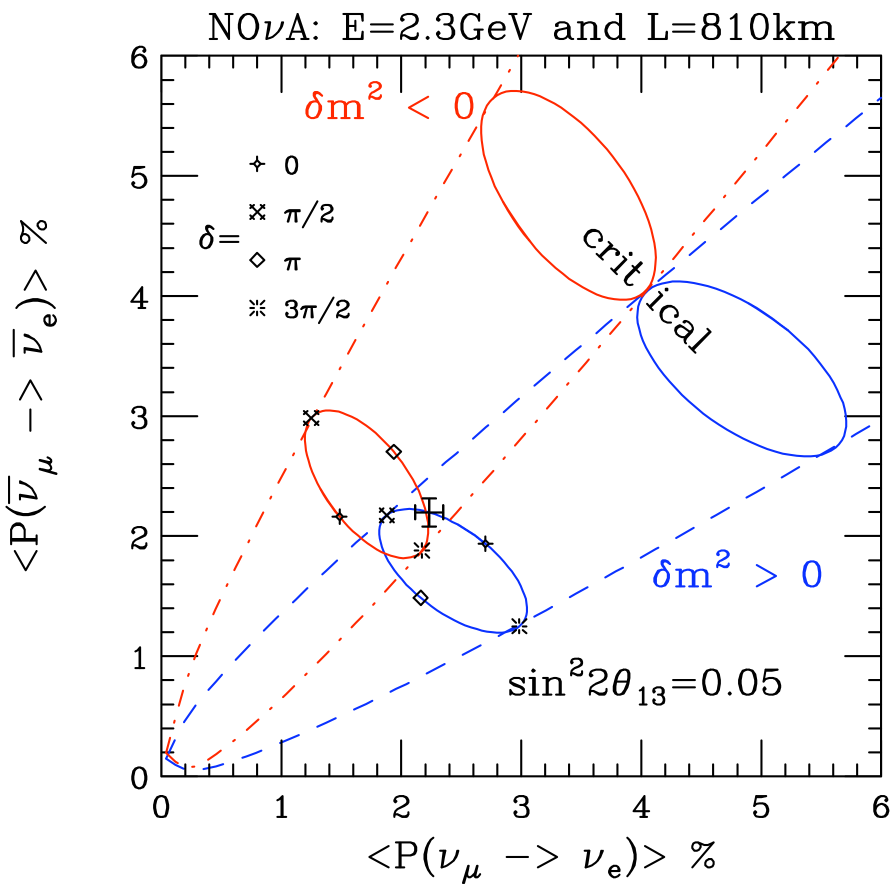


Bi-Probability Figures:



Neutrino oscillations in NOVA

For every baseline there is a critical value of θ_{13}: θ_{crit}



at Vac. Osc. Max $(\Delta_{31} = \frac{\pi}{2})$

$$\theta^{vom}_{crit} = \frac{\pi^2}{8}\,\frac{\sin 2\theta_{12}}{\tan\theta_{23}}\left(\frac{\delta m^2_{21}}{\delta m^2_{31}}\right)/(aL)$$

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

$$\theta_{crit}(\Delta_{31}) = \left[\frac{4\Delta^2_{31}/\pi^2}{1-\Delta_{31}\cot\Delta_{31}}\right]\theta^{vom}_{crit}$$

when $\Delta \equiv \frac{\delta m^2_{31} L}{4E} = \pi/2$ then $[\cdots] = 1$

for smaller Δ's $[\cdots] > 1$ and slowly varying

for larger Δ's $[\cdots] < 1$ and changing rapidily

for NOνA $\sin^2 2\theta_{crit} = 0.14$

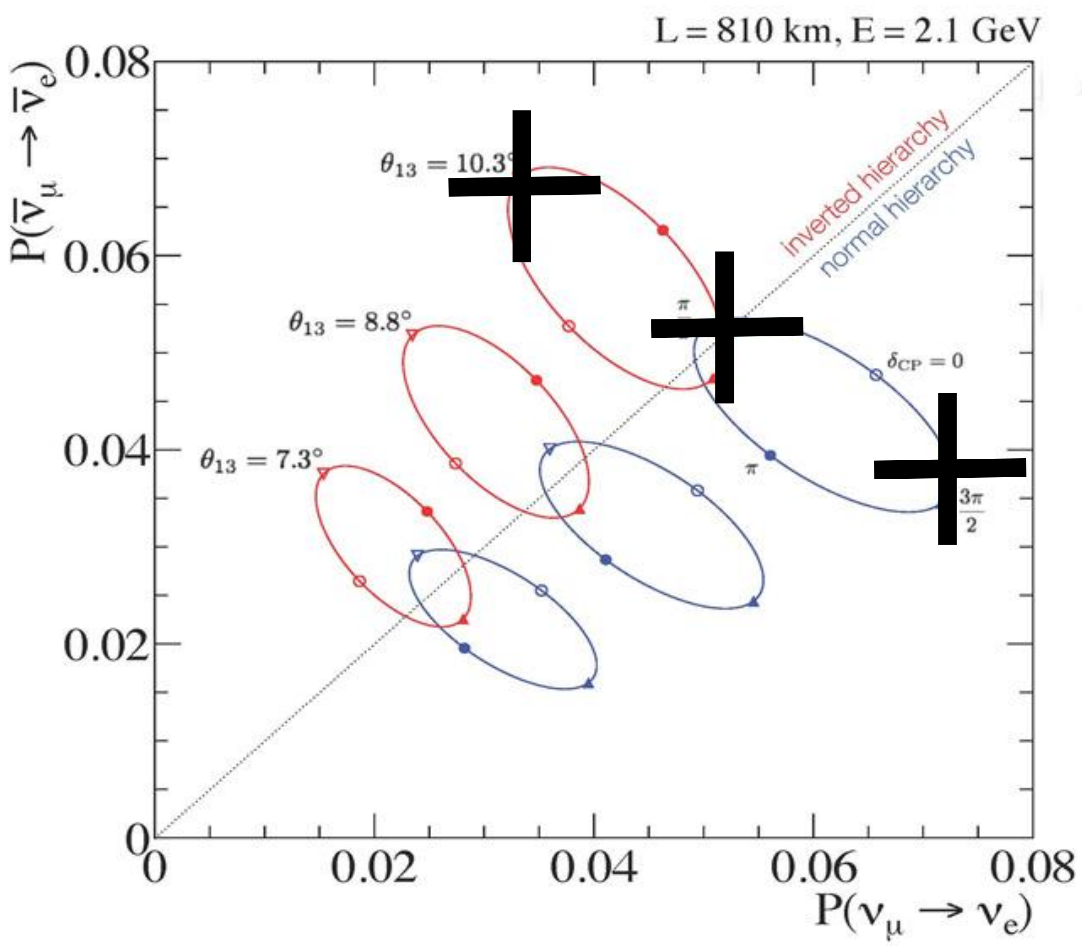
for LBNE $\sin^2 2\theta_{crit} = 0.05$

in the overlap region of the hierarchies:

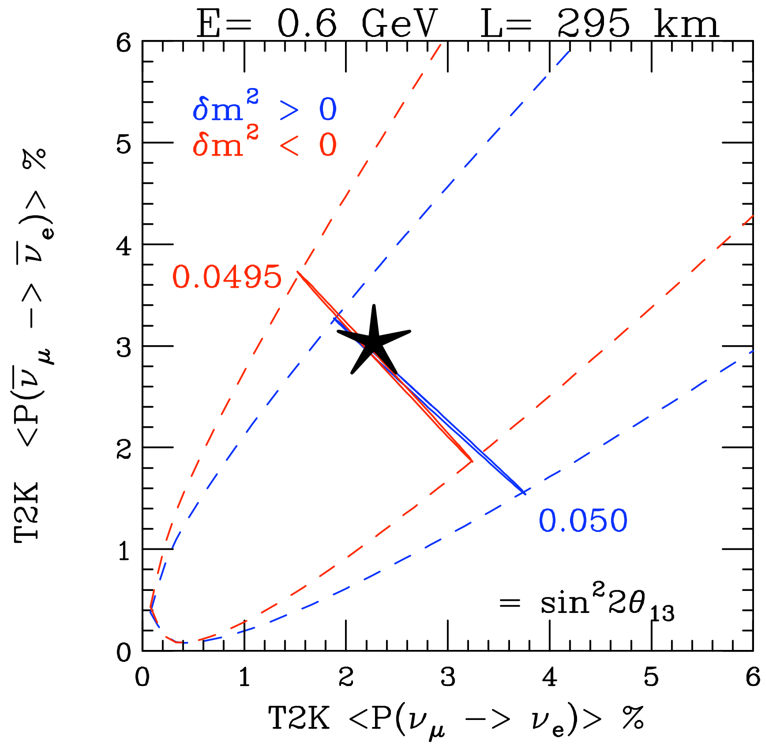
$$\langle\sin\delta\rangle_{NH} - \langle\sin\delta\rangle_{IH} = 2\ \theta/\theta_{crit} = \begin{cases} 1.7 & NO\nu A \\ 0.55 & T2K \\ 0.3 & C2F \end{cases}$$

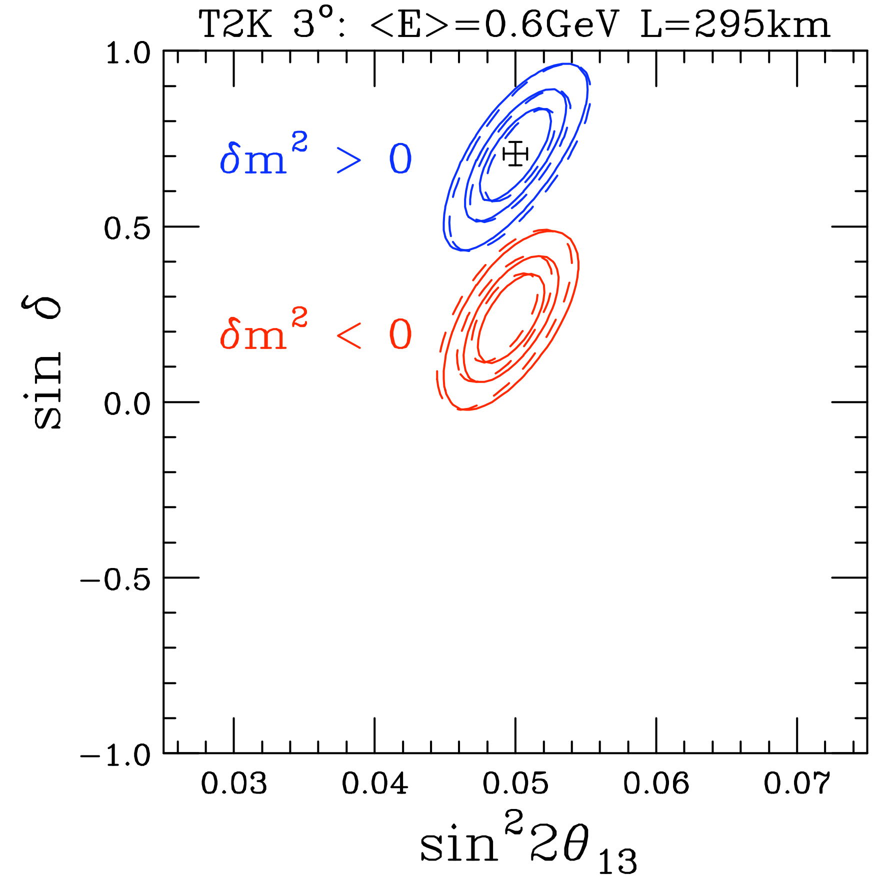
O. Mena et al hep-ph/0408070

With Uncertainties:



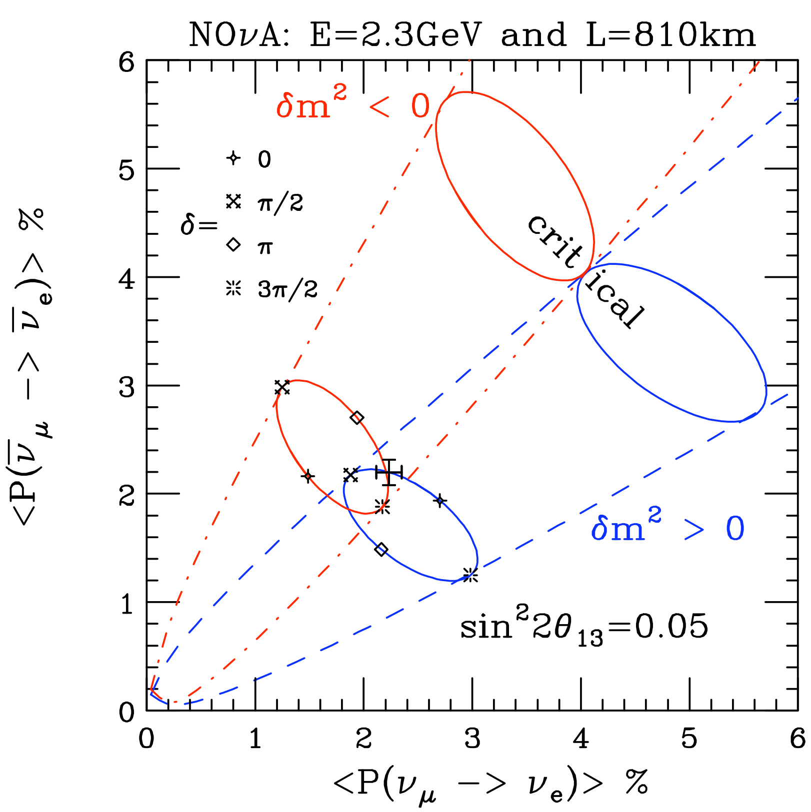
Neutrino oscillations in NOVA

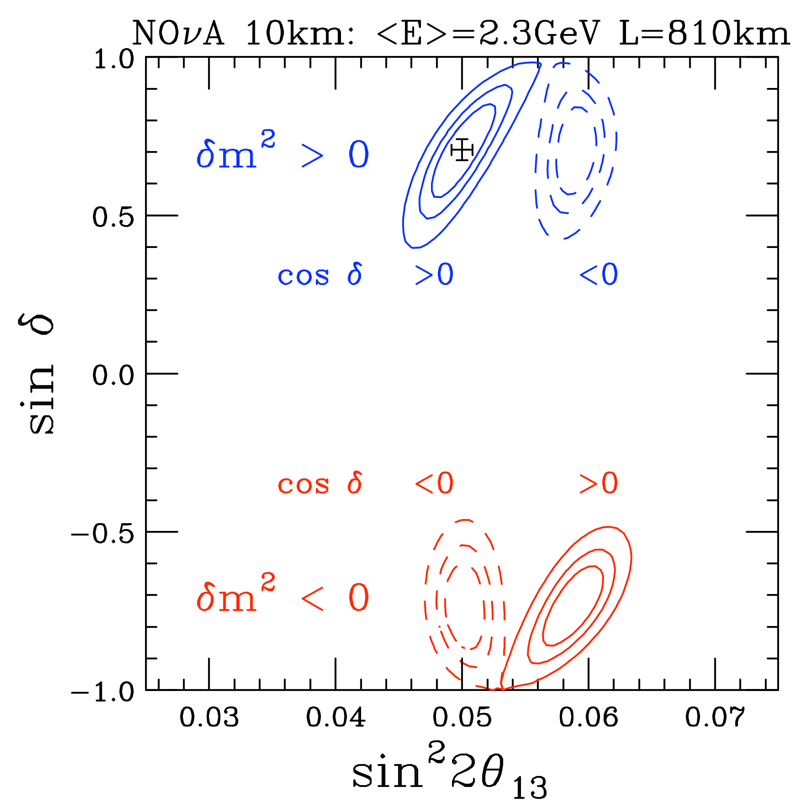




$$\langle \sin\delta \rangle_+ \quad - \quad \langle \sin\delta \rangle_-$$

$$\approx \quad 0.47\sqrt{\frac{\sin^2 2\theta_{13}}{0.05}}$$





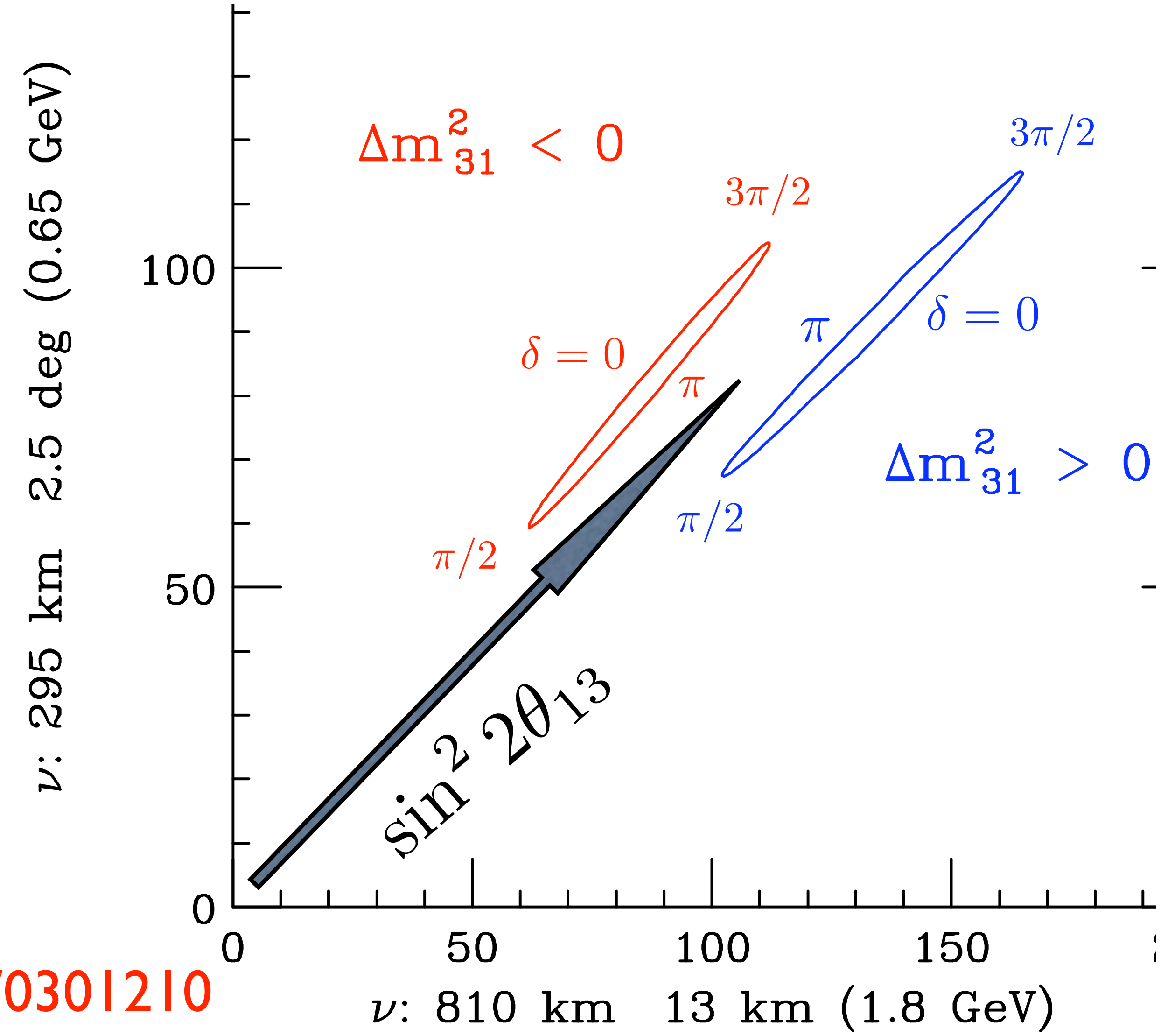
$$\langle \sin\delta \rangle_+ \quad - \quad \langle \sin\delta \rangle_-$$

$$\approx \quad 1.4\sqrt{\frac{\sin^2 2\theta_{13}}{0.05}}$$

Neutrino v Neutrino

Two Expts. Different L's

Same E/L !



Minakata et al hep-ph/0301210

Ellipses flatten as the (E/L)'s become equal.

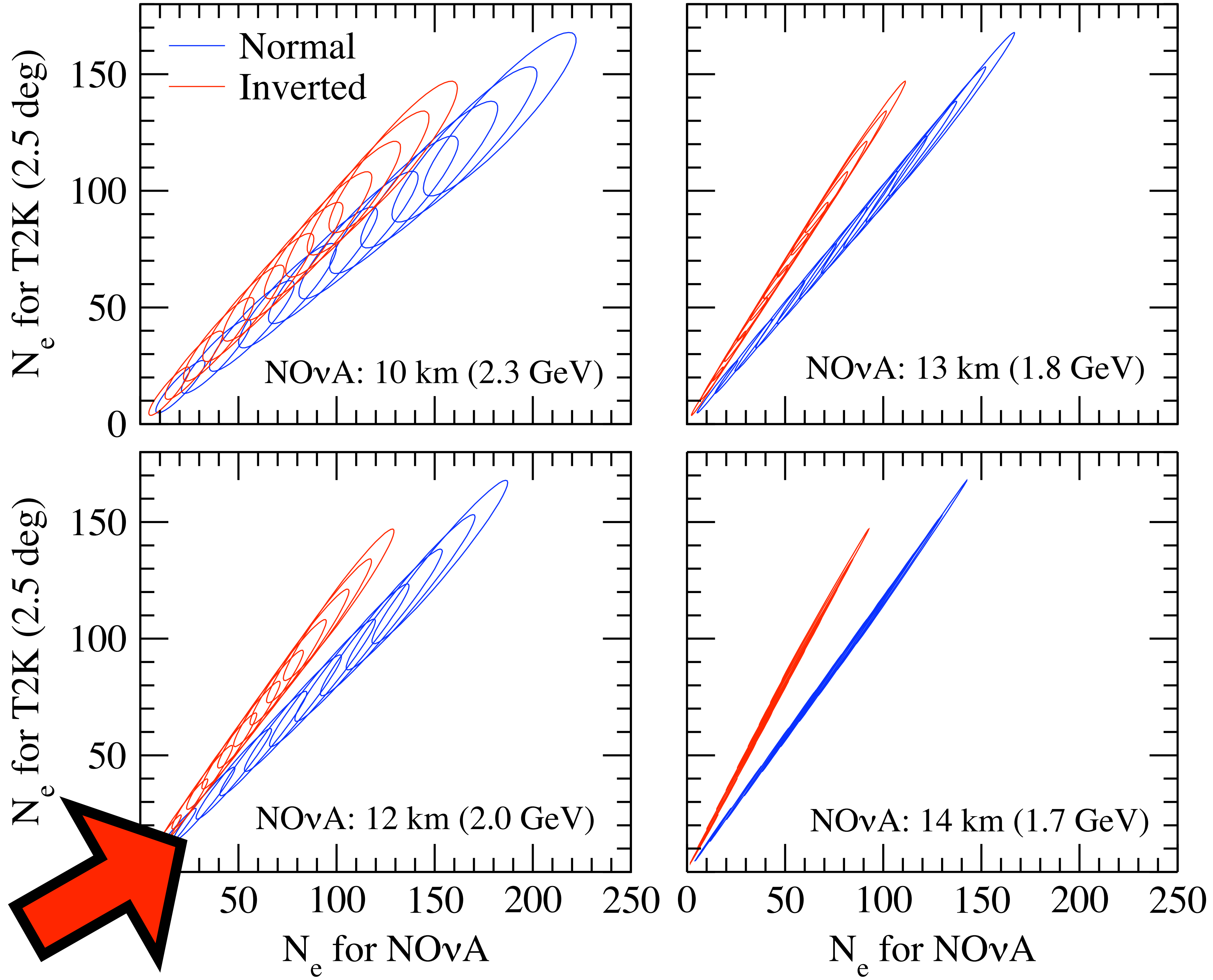
Horiz. separation caused by matter effect for NOvA,
The smaller Vert. separation by matter effect for T2K.

It is IMPORTANT that the matter effects are significantly different for the two experiments.

T2K + NOνA, Neutrino Only, $\sin^2 2\theta_{13}$=0.01,0.02,..,0.1

T2K: 0.75 MW, 5 yrs, 22.5 kton, Normalized to Mine's # (=87 % of QECC)

NOνA: 6.5e20 POT/yr, 5 yrs, 30 kton, 24%



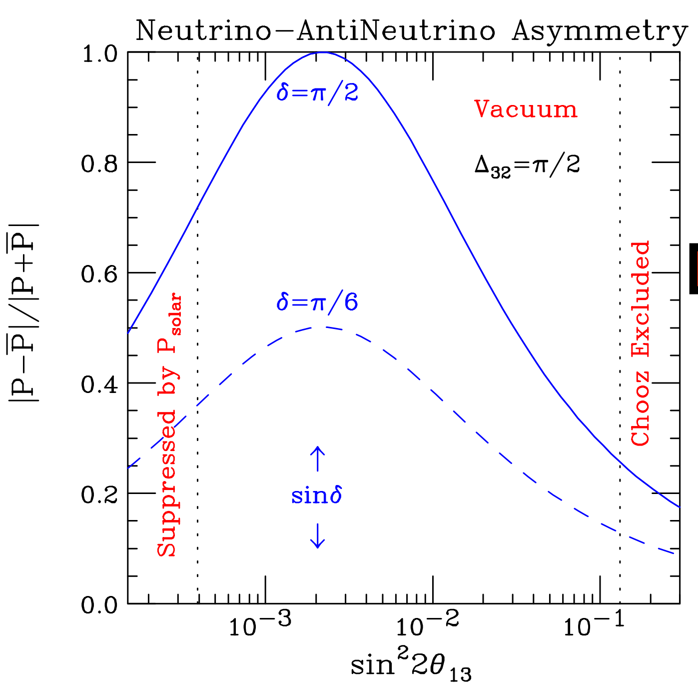
Mena, Nunokawa and SP hep-ph/0609011

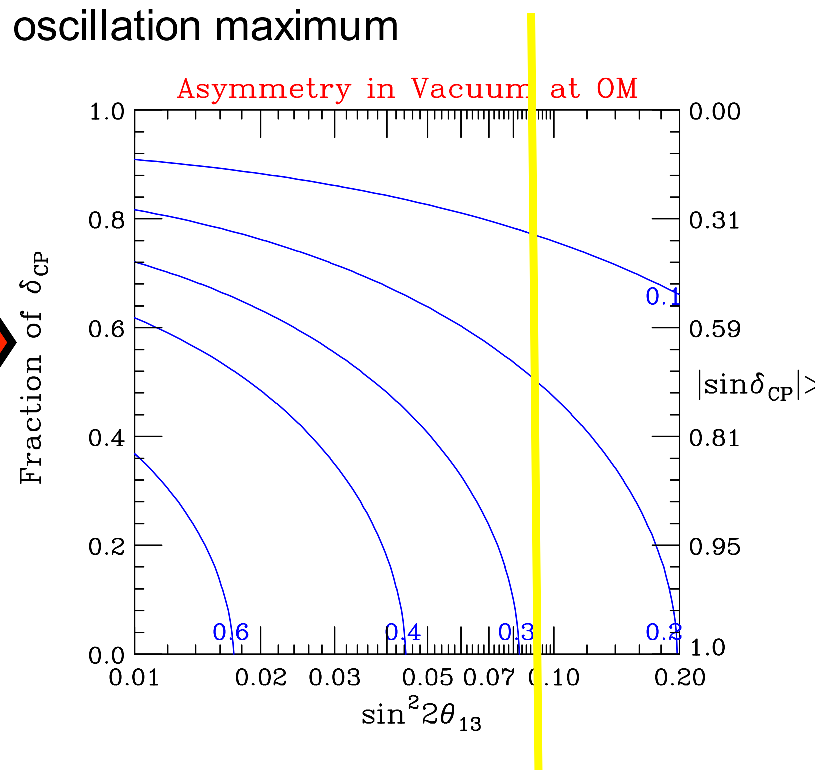
Asymmetry:

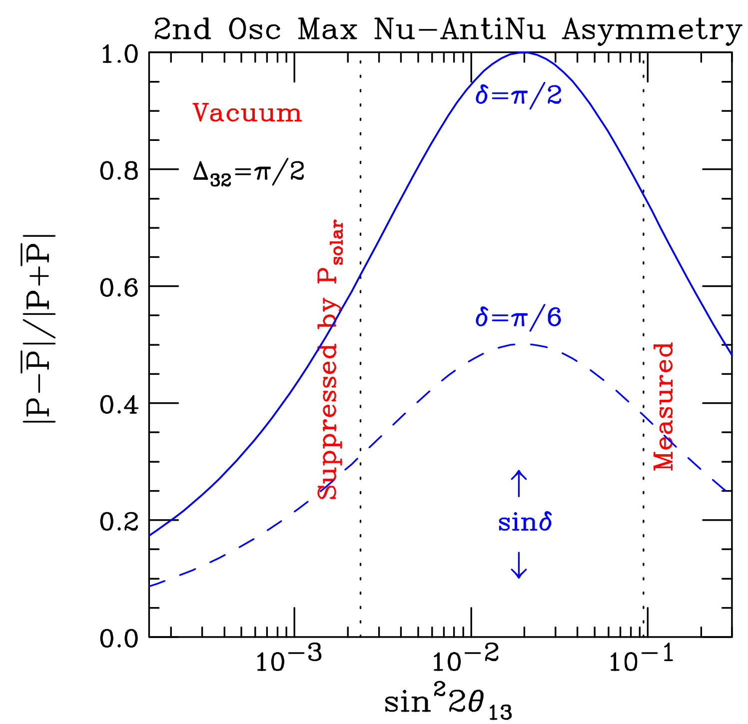
$$A_{vac} \approx \frac{1}{11} \frac{\sin 2\theta_{13} \sin\delta}{(\sin^2 2\theta_{13} + 0.002)} \approx 0.3 \sin\delta$$

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

Vacuum, at 1st oscillation maximum







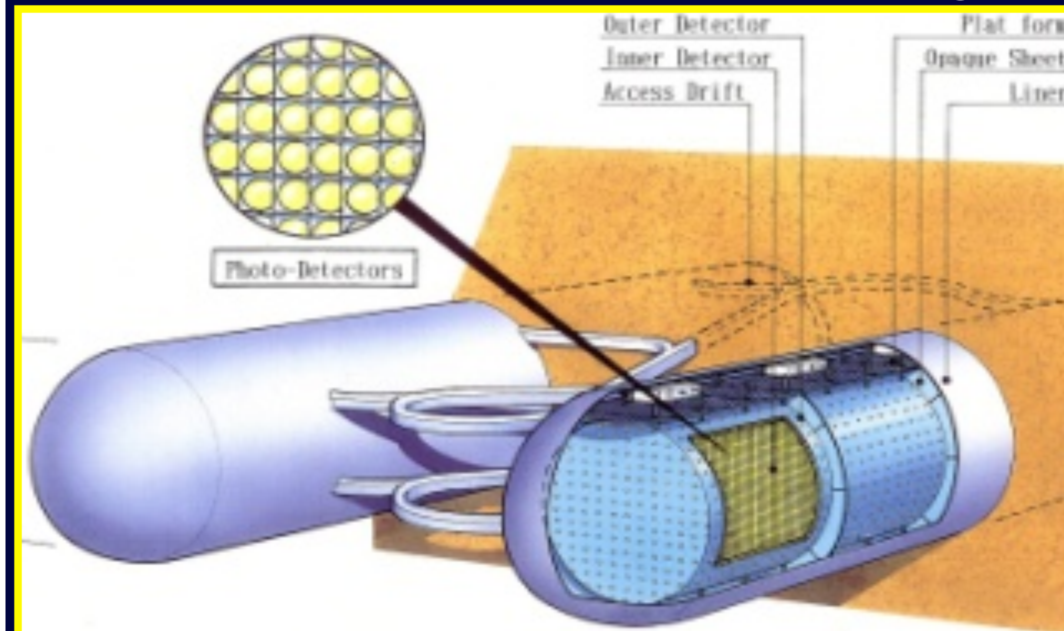
Energy 1/3,
flux and cross section reduced.

Japanese options:

Future LBL plans using J-PARC

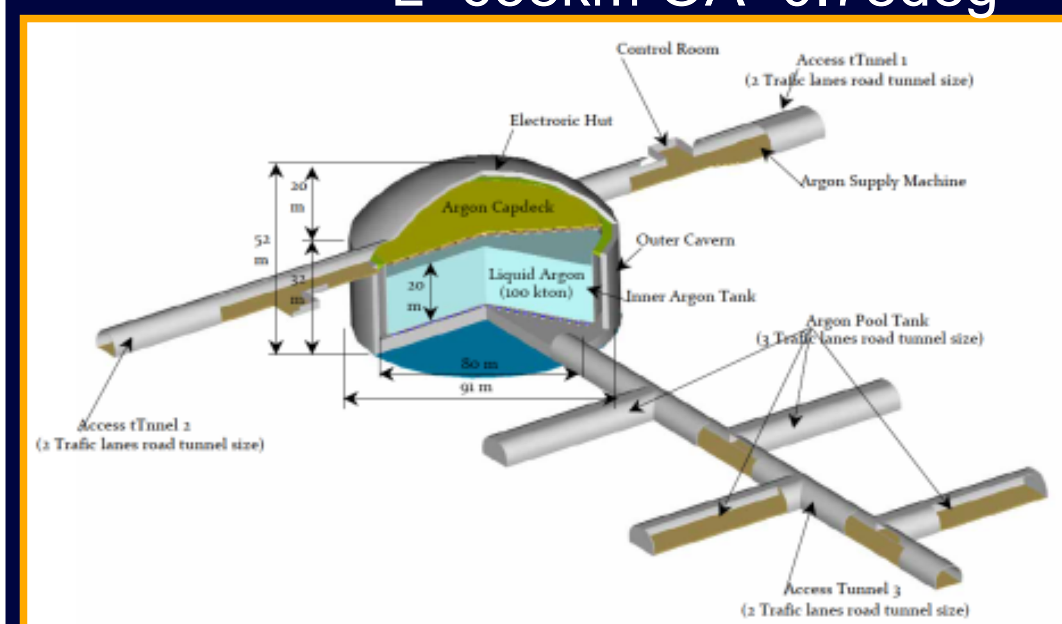
Current: T2K
J-PARC ~0.75MW
+ 50kt WC @ 295km 2.5°

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

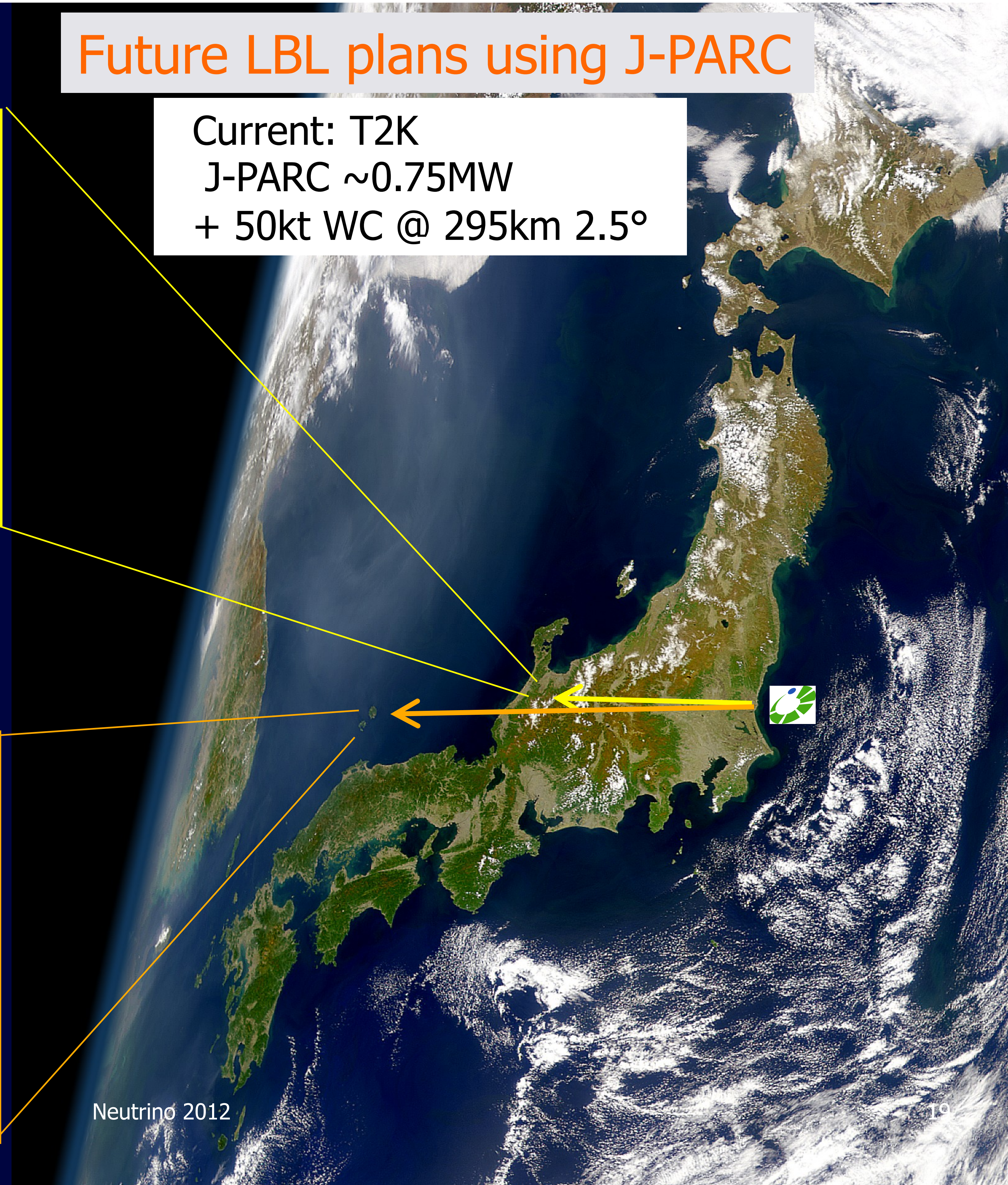
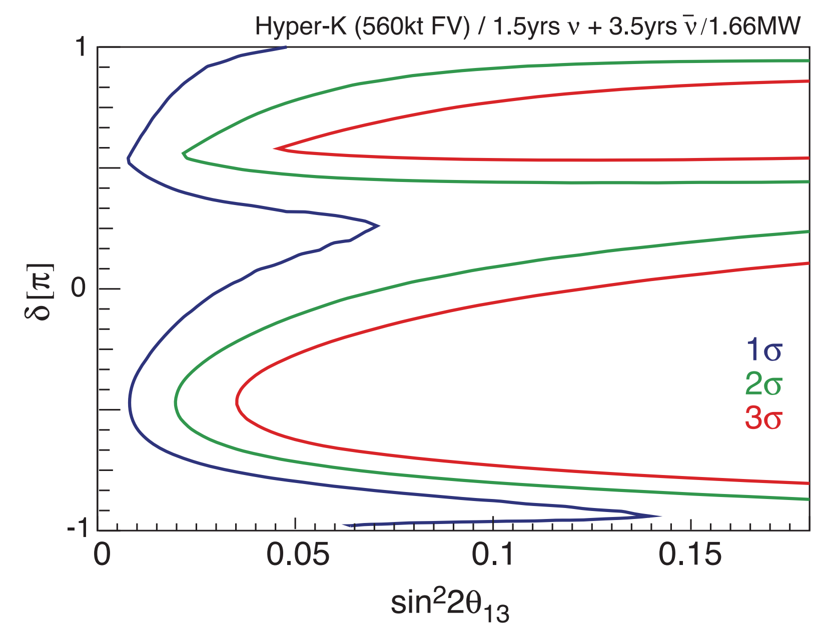


TABLE I. Detector parameters of the baseline design.

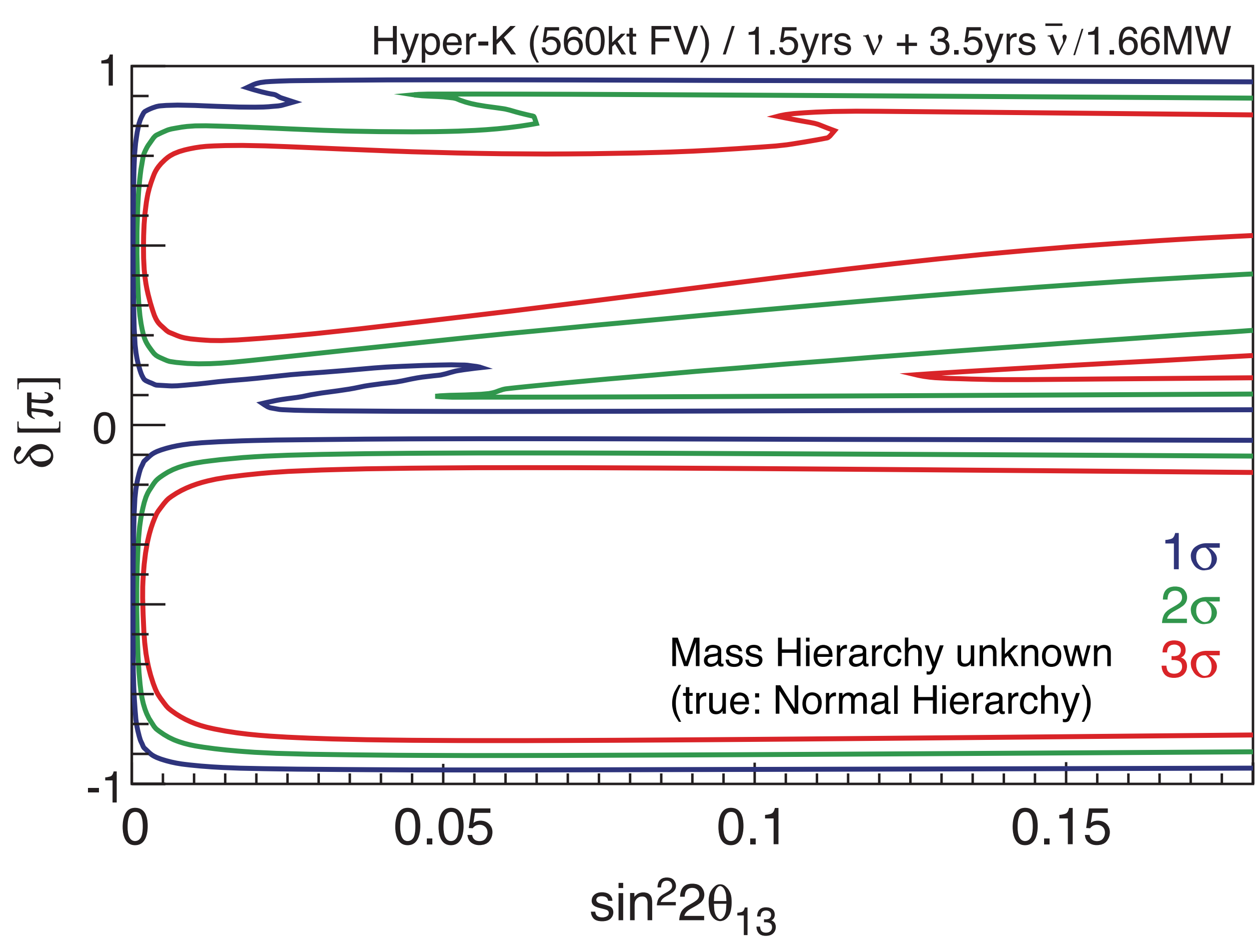
Detector type		Ring-imaging water Cherenkov detector
Candidate site	Address	Tochibora mine
		Kamioka town, Gifu, JAPAN
	Lat.	36°21′08.928″N
	Long.	137°18′49.688″E
	Alt.	508 m
	Overburden	648 m rock (1,750 m water equivalent)
	Cosmic Ray Muon flux	$1.0 \sim 2.3 \times 10^{-6}$ $\text{sec}^{-1}\text{cm}^{-2}$
	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:



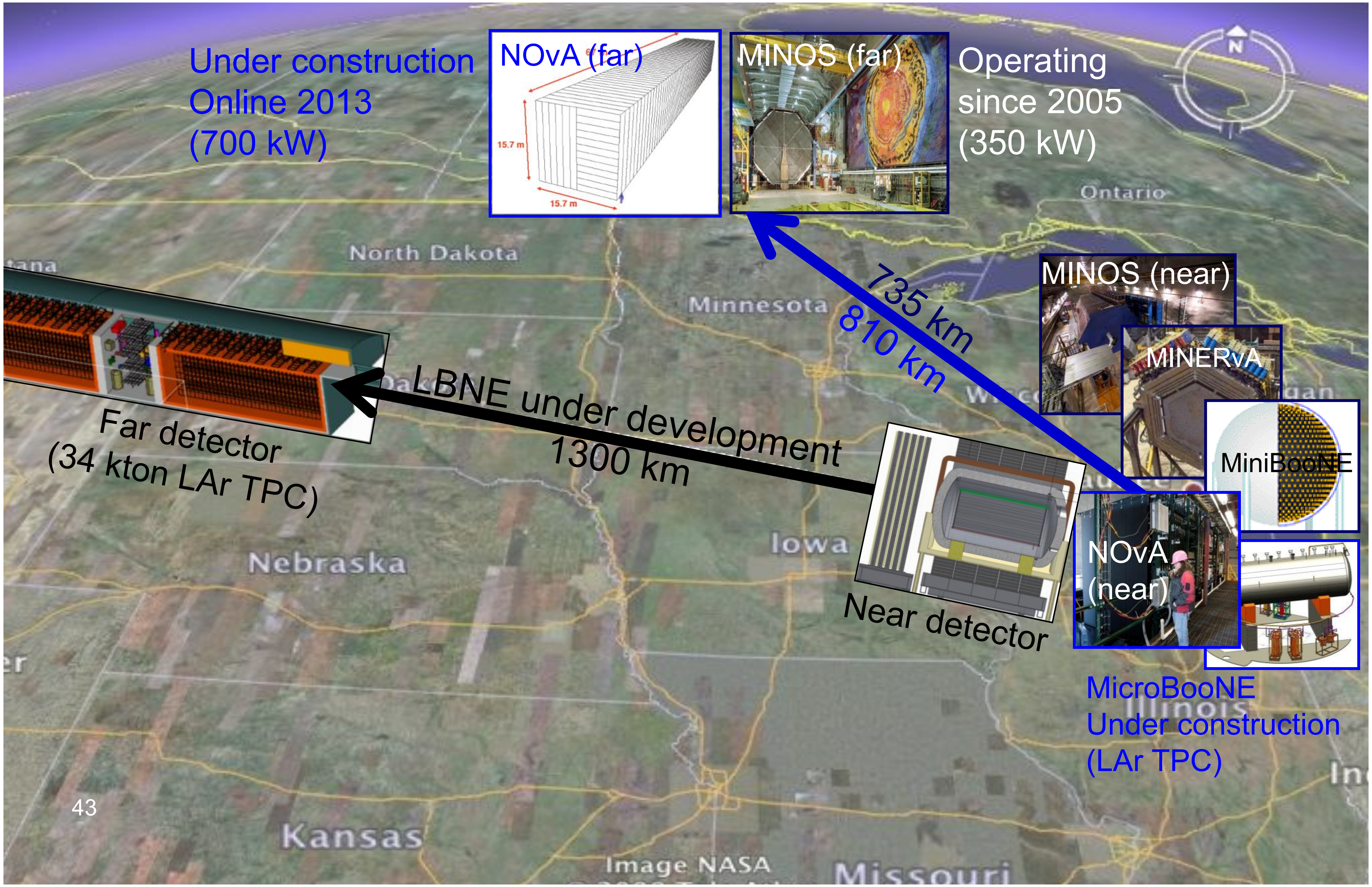
For $\sin^2 2\theta_{13} = 0.1$, the mass hierarchy can be determined with more than 3σ significance for 46% of the δ parameter space.

CPV:



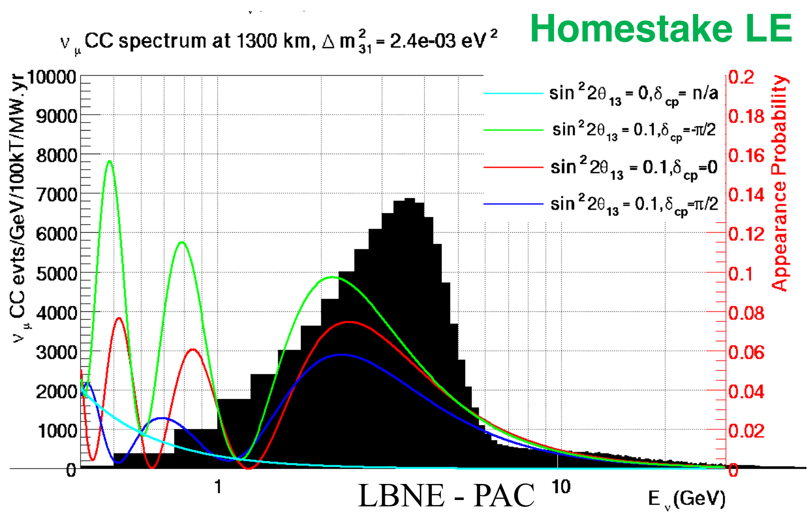
USA options:

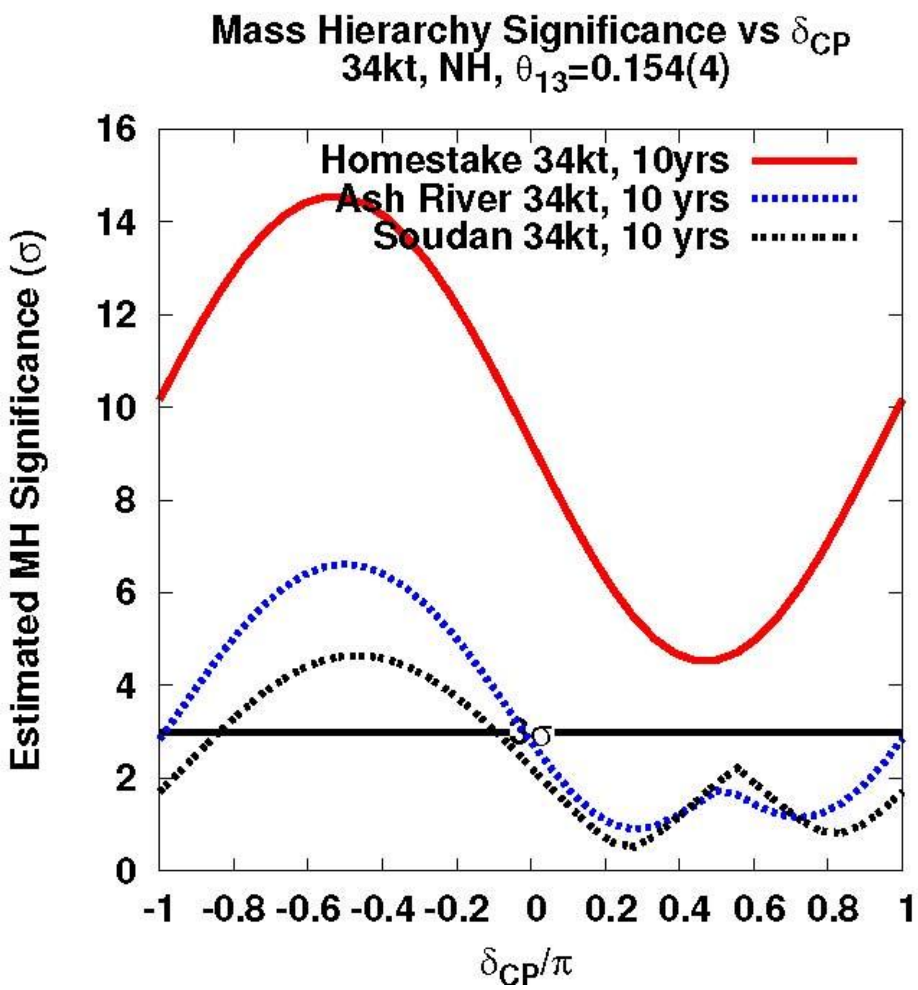
LBNE

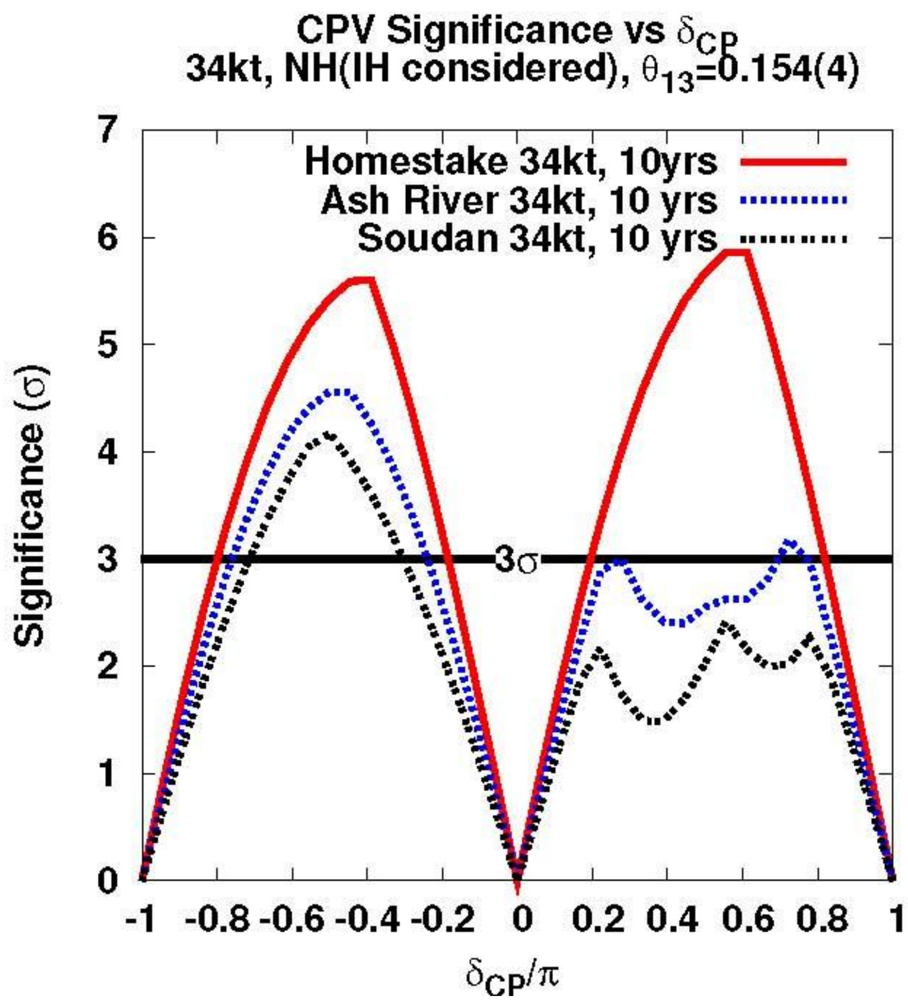

Under construction
Online 2013
(700 kW)
NOvA (far)
15.7 m
15.7 m
MINOS (far)
Operating
since 2005
(350 kW)
Ontario
North Dakota
Minnesota
735 km
810 km
MINOS (near)
MINERvA
MiniBooNE
LBNE under development
1300 km
Far detector
(34 kton LAr TPC)
Near detector
Iowa
Nebraska
NOvA
(near)
MicroBooNE
Under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

LBNE original

- 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



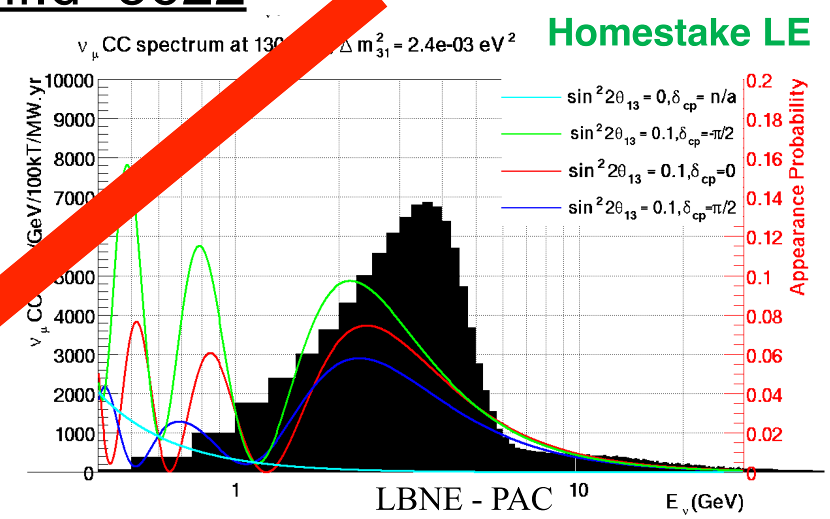


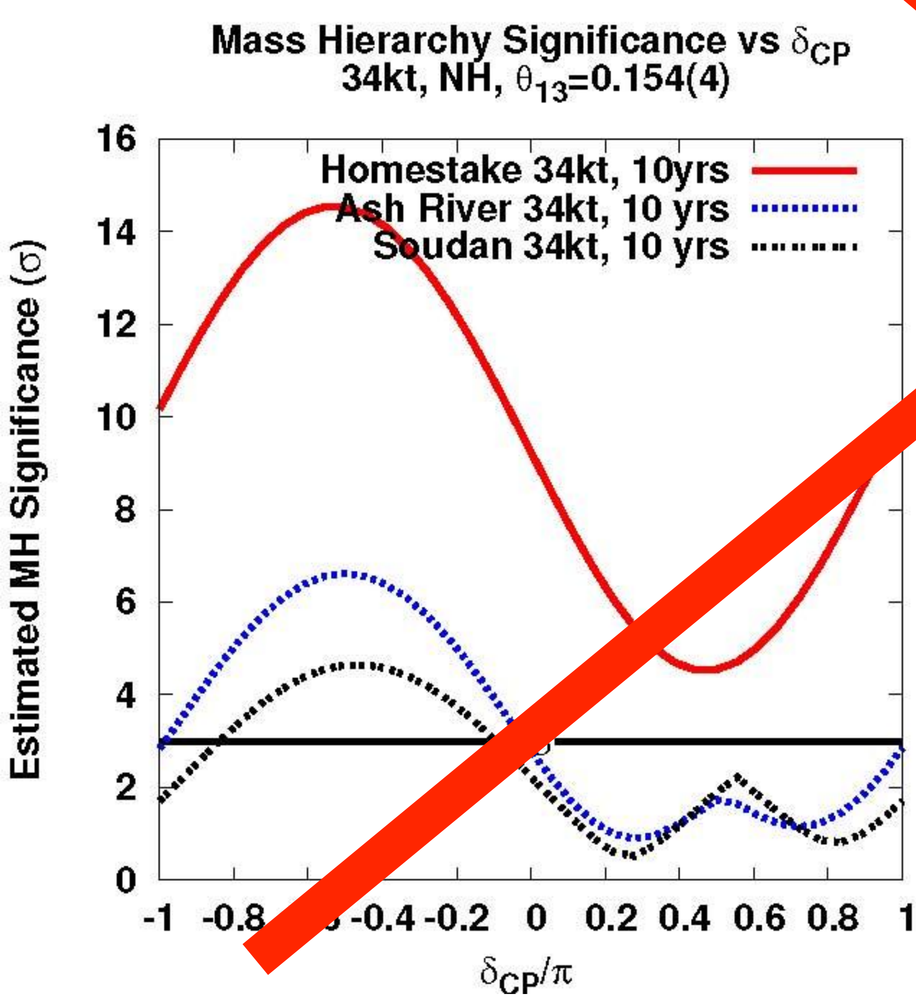


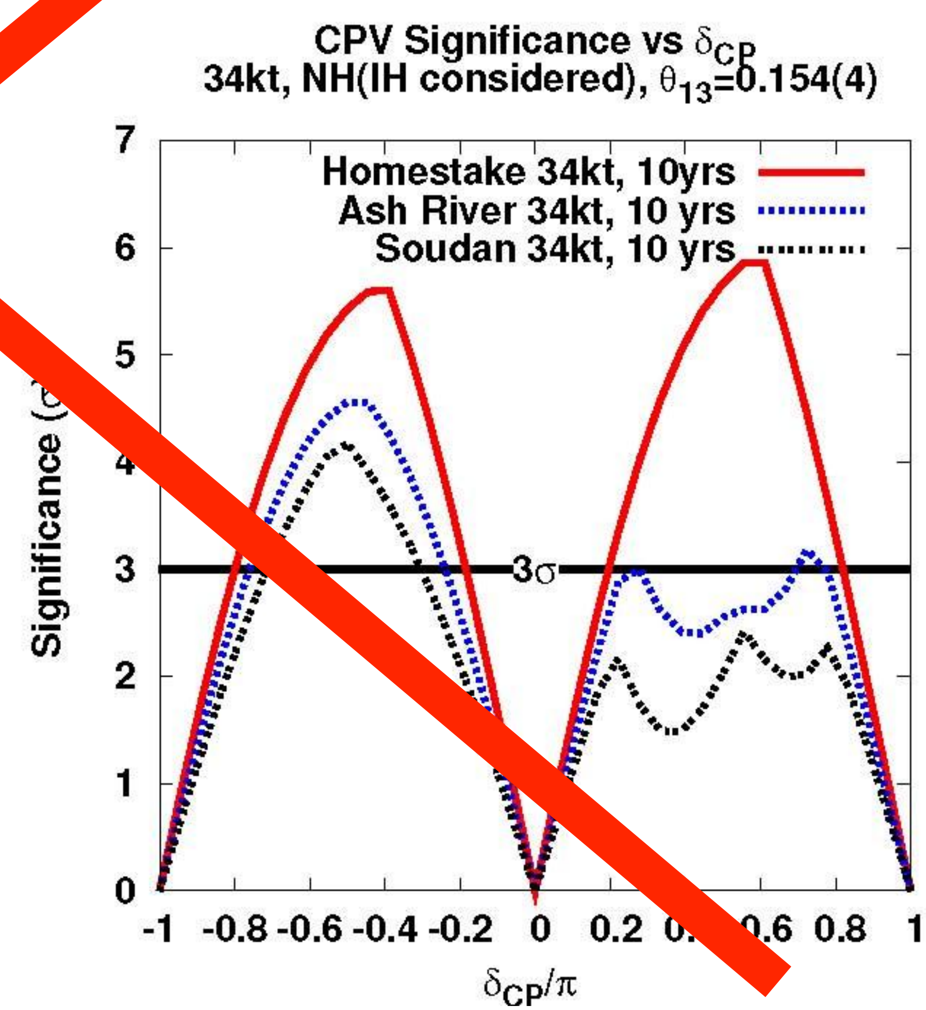
LBNE original

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

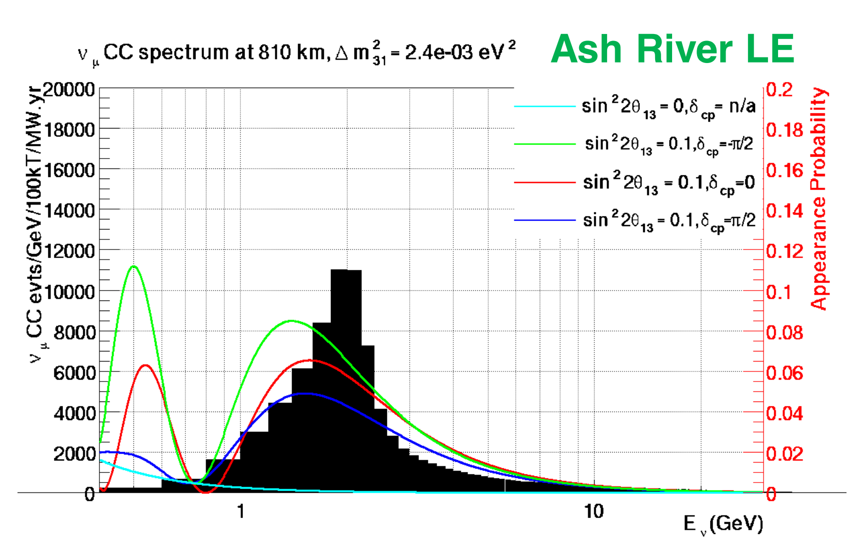




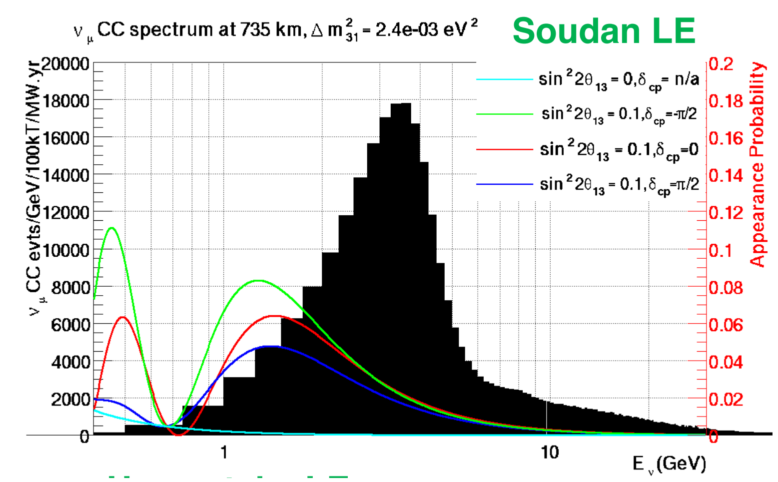


redo LBNE: three options

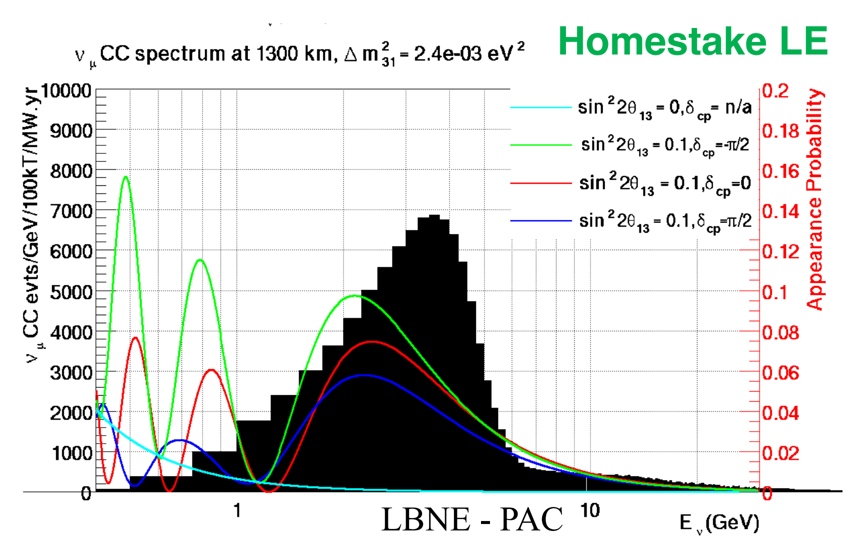
- 30 kton LAr @ Ash River next to NOvA on surface
  - off axis, narrow band beam, little spectral info.
  - surface detector (?): no proton decay or supernova nus or atmos nus



- 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

redo LBNE Summary:

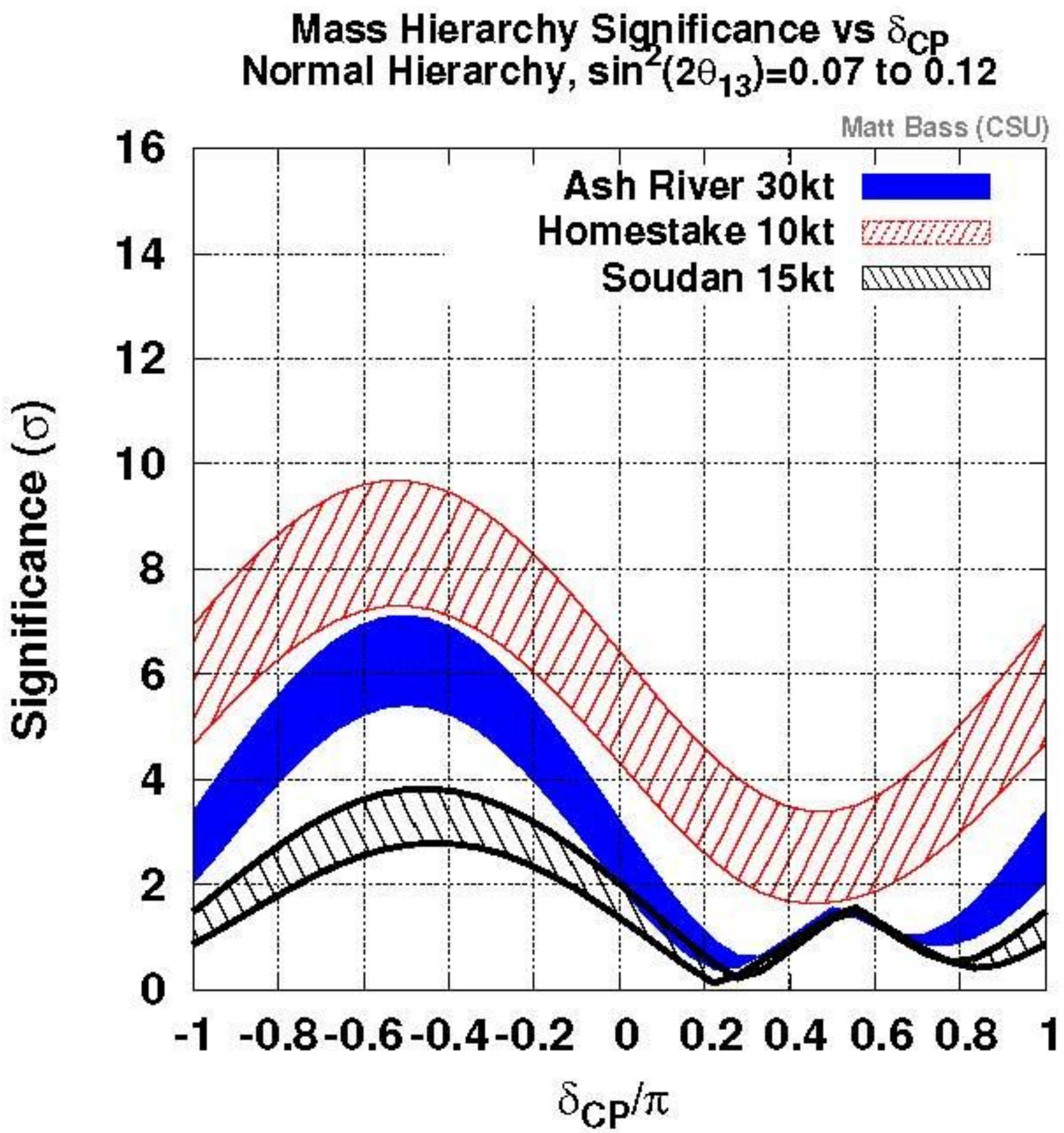
	Ash River	Soudan	Homestake
Baseline	810 km	735 km	1300 km
Detector Mass	30 kt	15 kt	10 kt
Detector position	Surface ?	Underground 2300 ft	Surface ?
Beamline	Existing NuMI	Existing NuMI	New

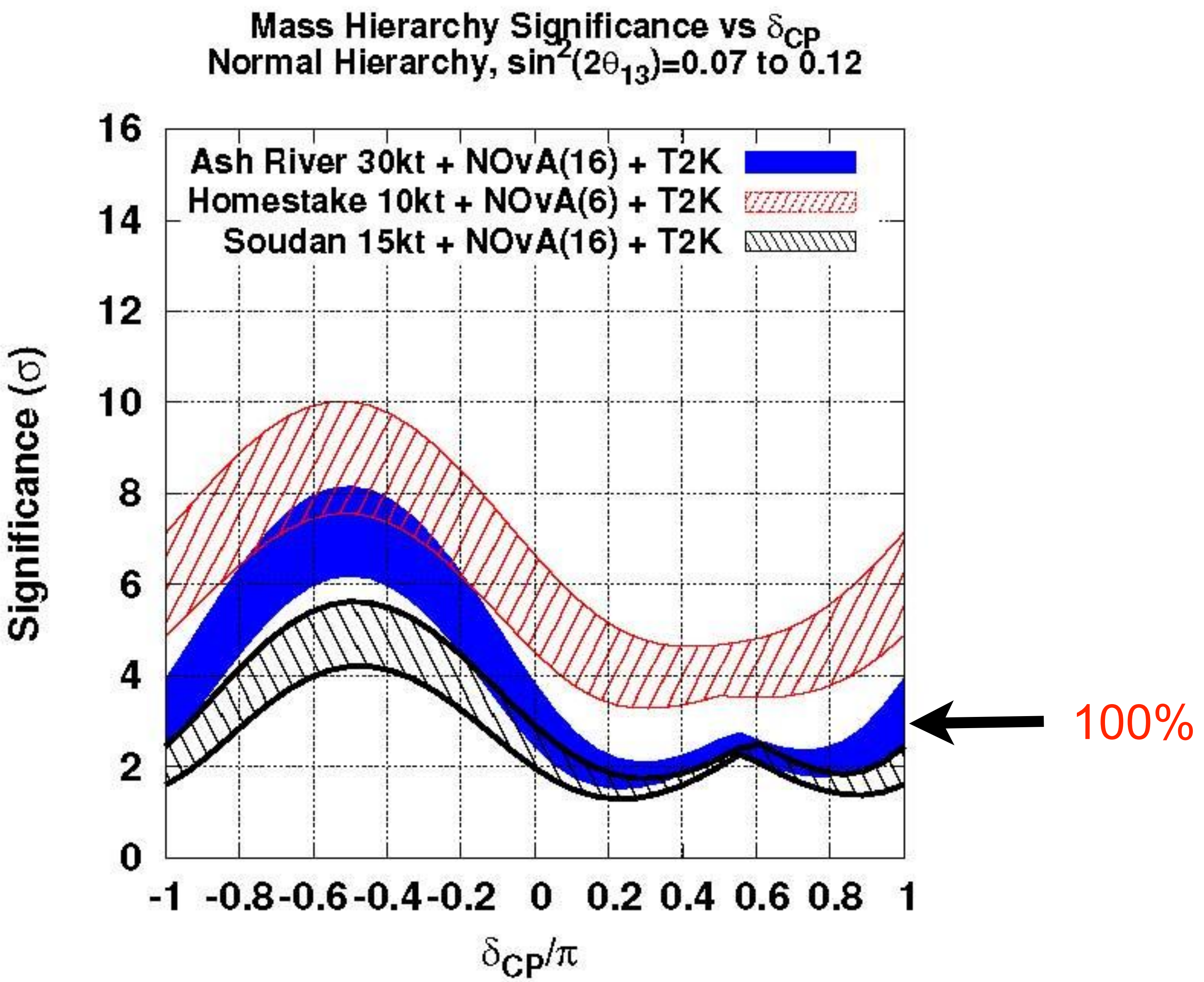
Preferred Option,
best upgrade potential,
most expensive

? = Can one operate a LAr detector on surface for LBL physics ?

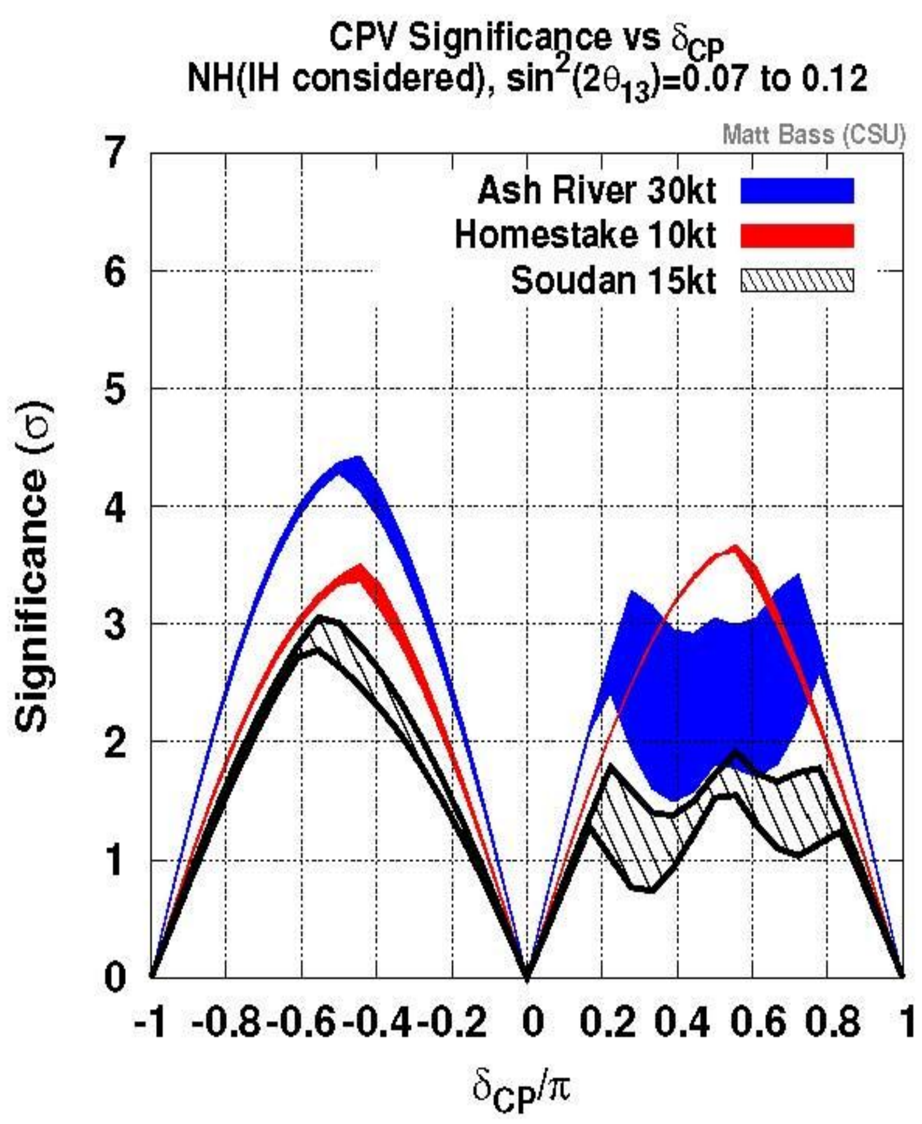
Physics Reach of these Options:

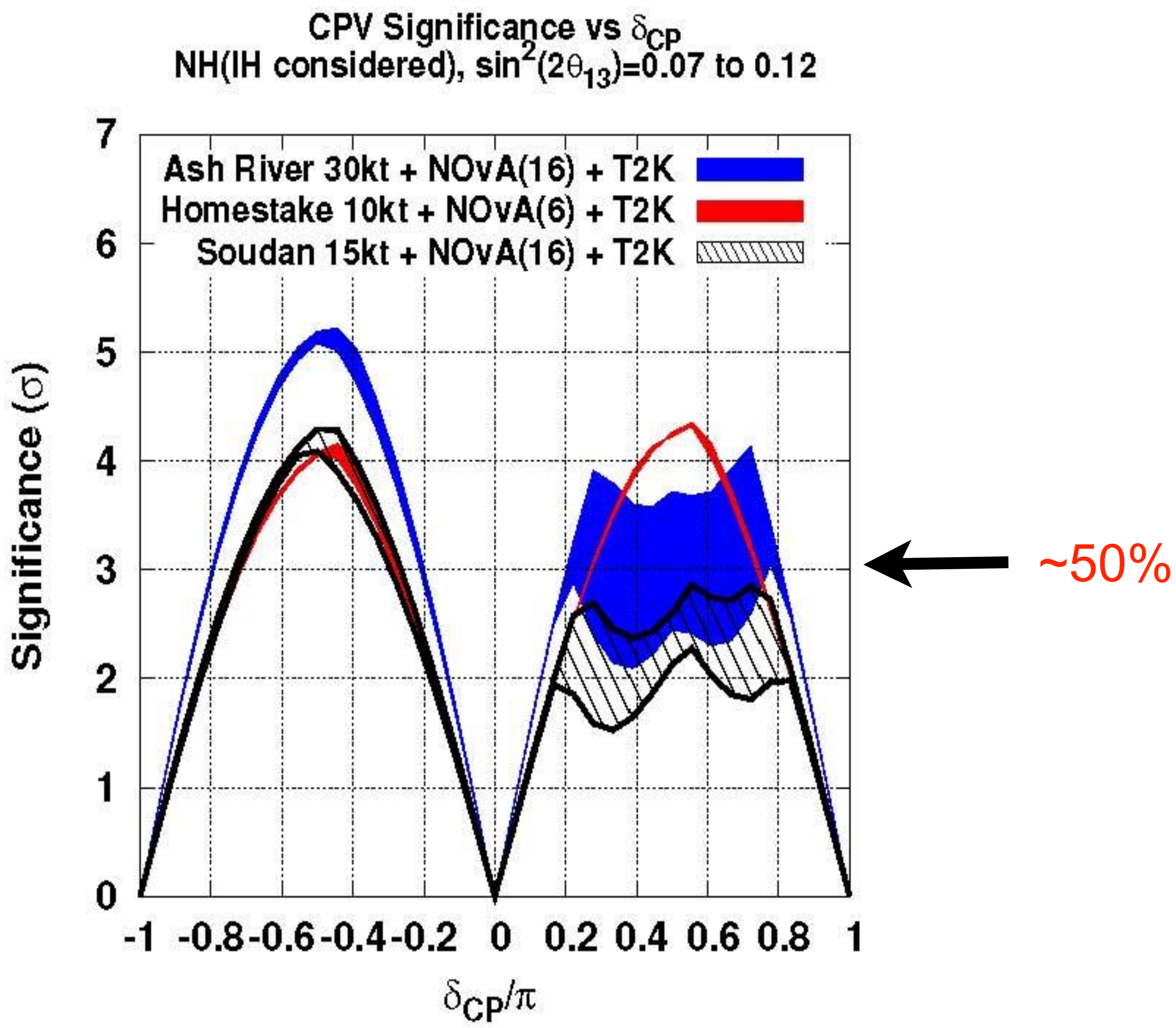
Atmospheric (31) Mass Hierarchy





CPV


CPV Significance vs δ_{CP}
NH(IH considered), $\sin^2(2\theta_{13})$=0.07 to 0.12
Matt Bass (CSU)
Ash River 30kt
Homestake 10kt
Soudan 15kt
Significance (σ)
δ_{CP}/π


CPV Significance vs δ_{CP}
NH(IH considered), $\sin^2(2\theta_{13})$=0.07 to 0.12
Ash River 30kt + NOvA(16) + T2K
Homestake 10kt + NOvA(6) + T2K
Soudan 15kt + NOvA(16) + T2K
Significance (σ)
δ_{CP}/π
~50%

Now for European Opportunities: