Optimization of Neutrino Factory for large θ_{13}

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2011-2012: Important Breakthroughs in 1-3 mixing

- ☐ *T2K (Neutrino 2012):* $\sin^2 2\theta_{13} = 0.036 – 0.21$ *@ 90% C.L.*

Talk by T. Nakaya at Neutrino 2012 [T2K collaboration]

- ☐ *MINOS (Neutrino 2012):* $\sin^2 2\theta_{13} \neq 0$ *@ 96% C.L.*

Talk by Ryan Nichol at Neutrino 2012 [MINOS collaboration]

- ☐ *Double Chooz (Neutrino 2012):* $\sin^2 2\theta_{13} = 0.109 \pm 0.030 \pm 0.025$ *@ 68% C.L.*

Talk by Masaki Ishitsuka at Neutrino 2012 [Double Chooz collaboration]

$$\sin^2 2\theta_{13} \neq 0 \ @ \ 3.1\sigma$$

- ☐ *Daya Bay (March 2012):* $\sin^2 2\theta_{13} = 0.092 \pm 0.016 \pm 0.005$ *@ 68% C.L.*

Daya Bay collaboration, arXiv:1203.1669 [hep-ex]

$$\sin^2 2\theta_{13} \neq 0 \ @ \ 5.2\sigma$$

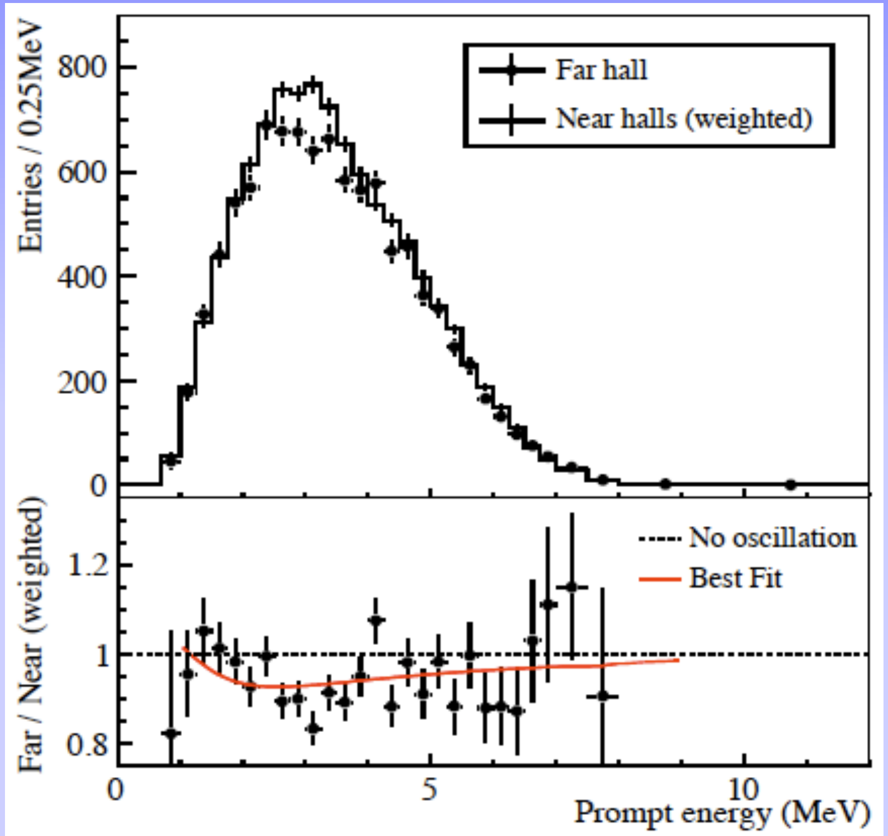
- ☐ *RENO (April 2012):* $\sin^2 2\theta_{13} = 0.113 \pm 0.013 \pm 0.019$ *@ 68% C.L.*

RENO collaboration, arXiv:1204.0626v2 [hep-ex]

$$\sin^2 2\theta_{13} \neq 0 \ @ \ 4.9\sigma$$

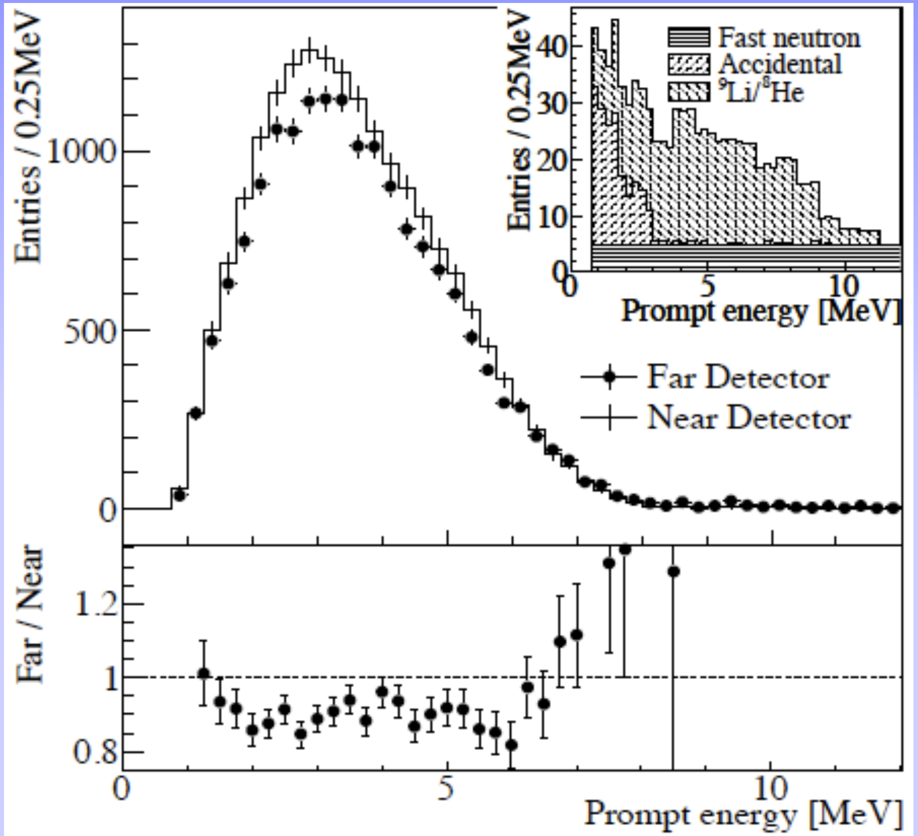
The θ_{13} Revolution

Daya Bay (5.2σ)



$$\sin^2 2\theta_{13} = 0.092 \pm 0.016 \pm 0.005$$

RENO (4.9σ)

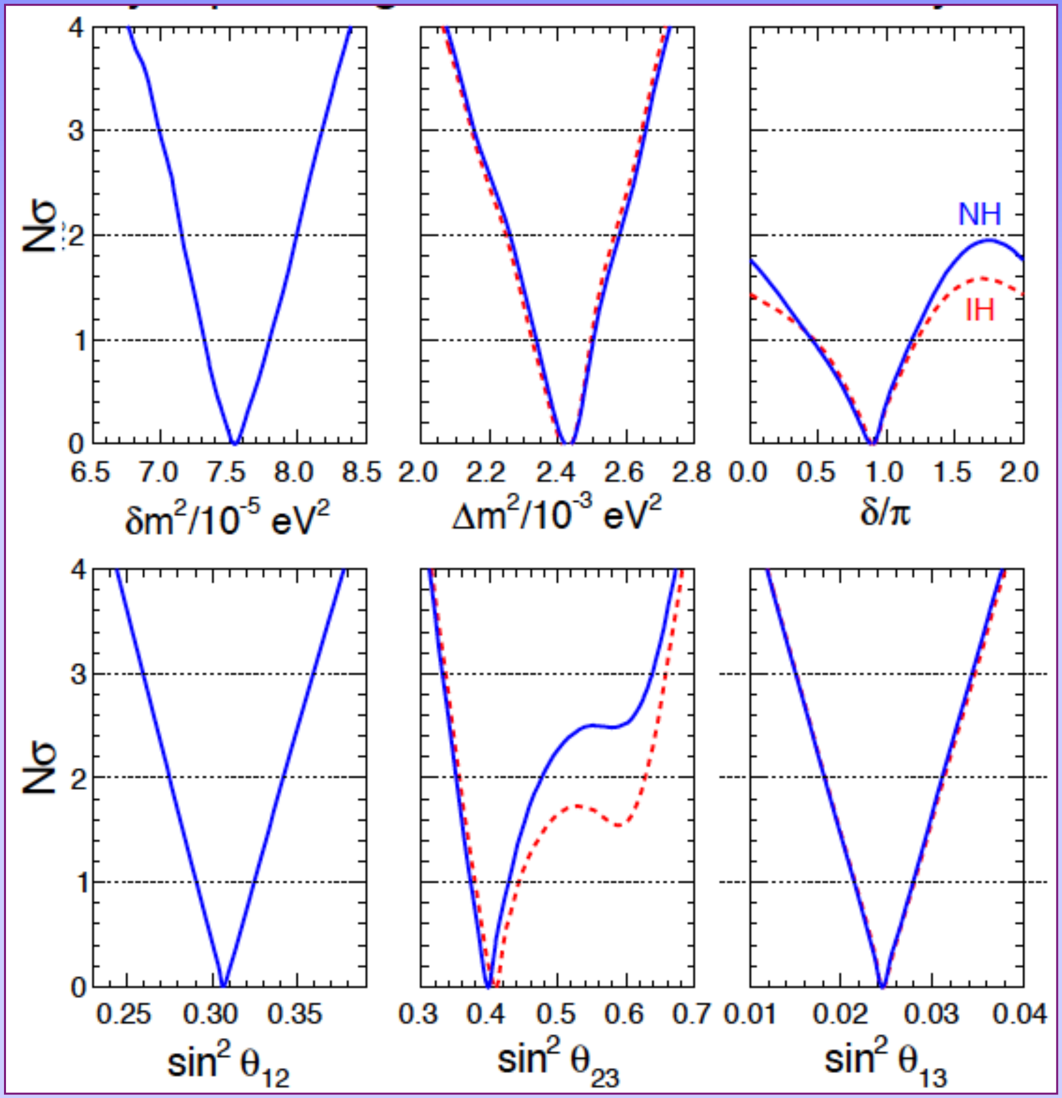


$$\sin^2 2\theta_{13} = 0.113 \pm 0.013 \pm 0.019$$

Big News: We have discovered the 1-3 mixing angle!

By the end of 2012, this will be the most precisely known mixing angle in the PMNS matrix!

Global Analysis of World Neutrino Data



G.L. Fogli etal., arXiv: 1205.5254v2
See also, the talk by M. Tortola (in this meeting)

Pre Neutrino 2012 data!

	Best-fit	**1σ range**
$\sin^2\theta_{13}$ =	**0.0245 (NH)**	**0.0214 - 0.0279**
$\sin^2\theta_{13}$ =	**0.0246 (IH)**	**0.0215 – 0.0280**

G.L. Fogli etal., arXiv: 1205.5254v2

$\sin^2\theta_{13}$ =	**0.026 (NH)**	**0.022 - 0.029**
$\sin^2\theta_{13}$ =	**0.027 (IH)**	**0.023 – 0.030**

D.V. Forero etal., arXiv: 1205.4018v2

Relative Precision ~ 13%

$\sin^2 2\theta_{13} \neq 0$ @ 8σ

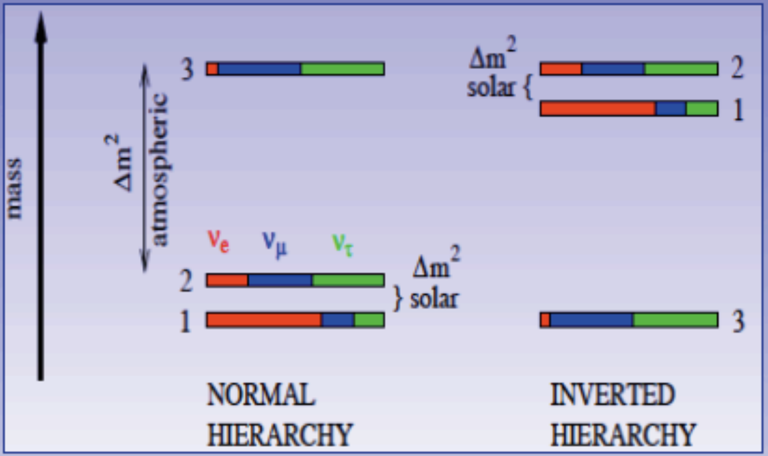
Big Issues in Neutrino Oscillation

- The sign of Δm^2_{31} $(m^2_3 - m^2_1)$ is not known

It can be normal – $\Delta m^2_{31} > 0$

or

inverted hierarchical – $\Delta m^2_{31} < 0$



- Like in the quark sector, mixing can cause CP violation in leptonic sector

$P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) \neq 0$ (where $\alpha \neq \beta$)

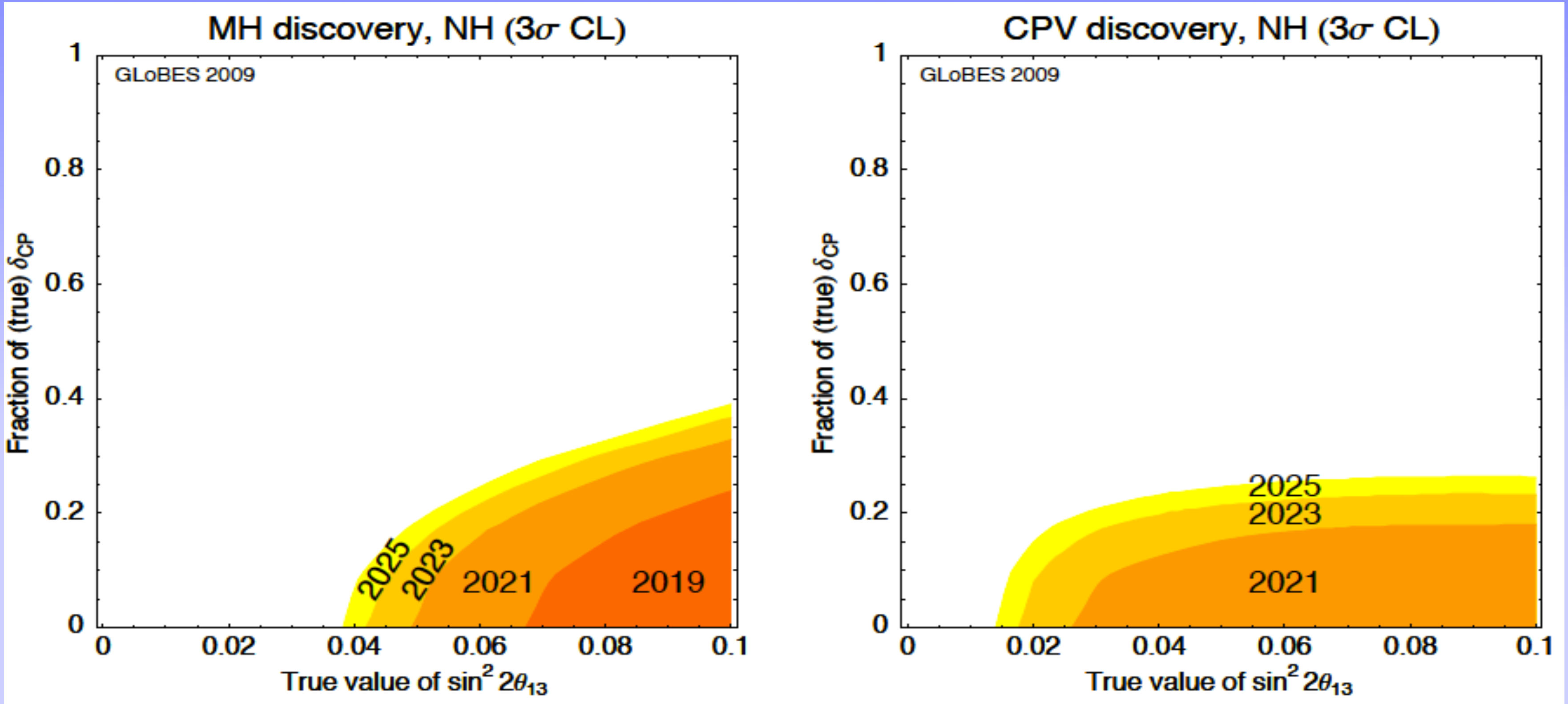
CP-odd asymmetries : ➔ $\boxed{\Delta P_{ab} \equiv P(\nu_a \to \nu_b; t) - P(\bar{\nu}_a \to \bar{\nu}_b; t)}$

$$\Delta P_{e\mu} = \Delta P_{\mu\tau} = \Delta P_{\tau e} = 4 s_{12}\, c_{12}\, s_{13}\, c^2_{13}\, s_{23}\, c_{23}\, \sin\delta \\ \times \left[\sin\left(\frac{\Delta m^2_{21}}{2E}t\right) + \sin\left(\frac{\Delta m^2_{32}}{2E}t\right) + \sin\left(\frac{\Delta m^2_{13}}{2E}t\right)\right]$$

➢ δ is unknown, asymmetry vanishes if δ is 0° or 180° and maximum for 90° or 270°

➢ Need at least 3 generations to observe leptonic CP-violation, suppressed by θ_{13}

MH & CPV discovery without new experiments



P. Huber etal., JHEP 11 044 (2009)

Expectation in 2025 without new facilities at 3σ C.L.

Combined results expected from: T2K + NOνA + Double Chooz + Daya Bay + RENO
(Including Project X and T2K operating at 1.66 MW)

More than 70% of parameter space are not accessible. New experiments needed

Neutrino Factory: Ultimate Facility

Powerful tool for CP violation discovery for large θ_{13}

Excellent sensitivity to neutrino mass hierarchy for 100% values of δ_{CP}

Marvelous sensitivity to θ_{23}, can resolve the issue of θ_{23} octant

Better than all other proposed facilities

Best bet to look for NSI, Non-Unitarity

An incremental approach can also be adopted
VLENF → LENF → HENF (if needed !)

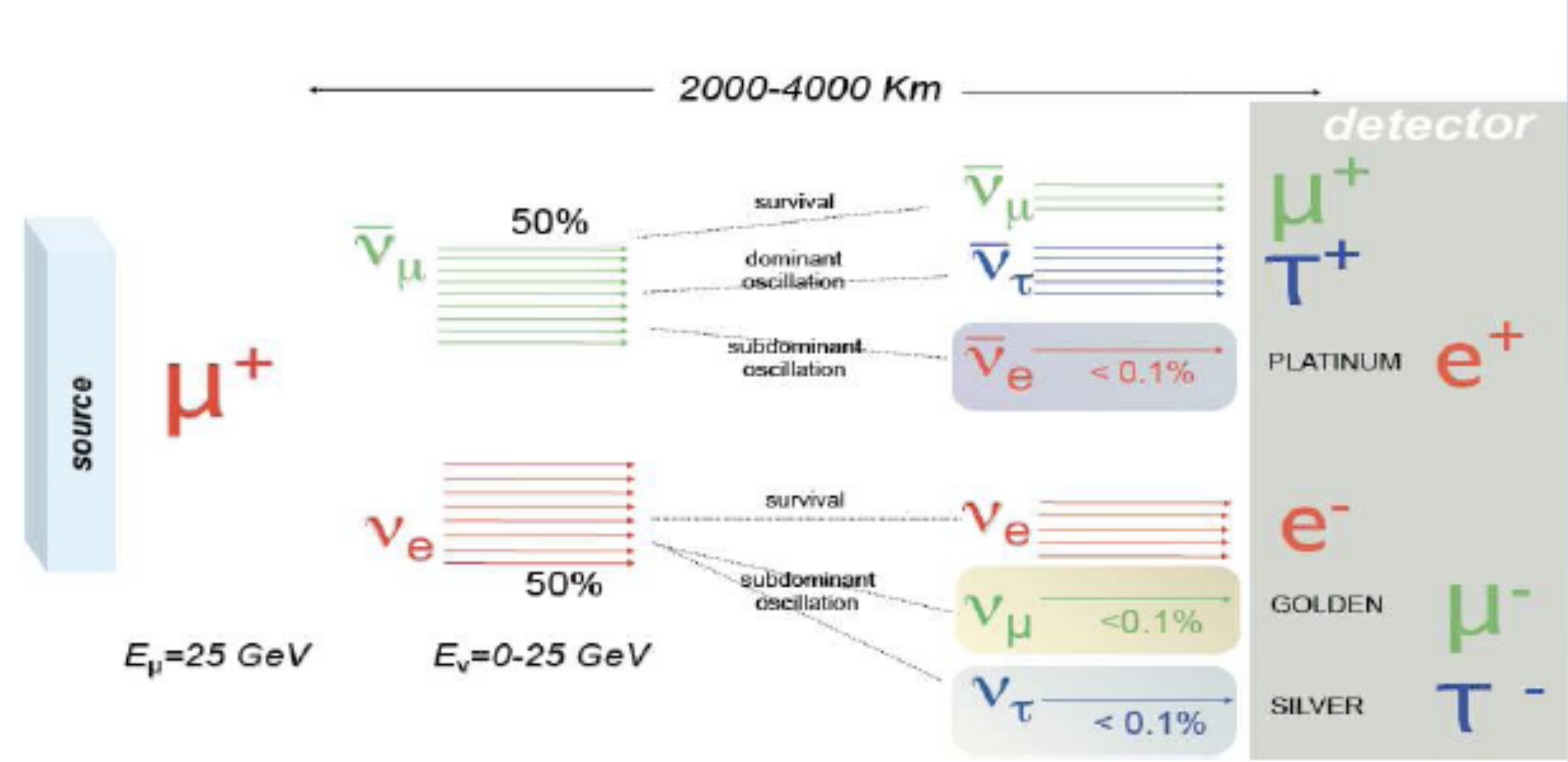
A good candidate for short baseline searches and cross-section measurement

It may be the first step towards the high energy frontier in form of a muon collider

IDS-NF 1.0

- Two magnetized iron calorimeters (fiducial mass 50 kt) at $L = 4000$ km and $L = 7500$ km
- Two racetrack-shaped storage rings pointing towards these detectors
- 2.5×10^{20} useful muon decays per polarity, decay straight, and year, *i.e.*, 10^{21} useful muon decay per year
- Total run time of 10 years, *i.e.*, 10^{22} useful muon decay in total
- The parent muon energy is assumed to be $E_\mu = 25\,\text{GeV}$

Signal



A. Cervera, WIN 2011

Requires a detector which can distinguish μ^- from μ^+

MIND can do that with a magnetic field of around 1 T

Oscillation Channels & Backgrounds

- ν_μ appearance: $\nu_e \rightarrow \nu_\mu$ for μ^+ stored
- $\bar{\nu}_\mu$ appearance: $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$ for μ^- stored
- ν_μ disappearance: $\nu_\mu \rightarrow \nu_\mu$ for μ^- stored
- $\bar{\nu}_\mu$ disappearance: $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ for μ^+ stored
- Include backgrounds from ⇒

  1. charge mis-identification
  2. (electron) flavor mis-identification
  3. neutral current

- We use the GLoBES software for the simulation

P. Huber etal, hep-ph/0407333 and hep-ph/0701187

Golden Channel ($P_{e\mu}$) & Eight-fold Degeneracy

The appearance probability $(\nu_e \rightarrow \nu_\mu)$ in matter, upto second order in the small parameters $\alpha \equiv \Delta m^2_{21}/\Delta m^2_{31}$ and $\sin 2\theta_{13}$,

$$\begin{aligned}
P_{e\mu} \;\simeq\;& \sin^2 2\theta_{13}\,\sin^2\theta_{23}\,\frac{\sin^2[(1-\hat{A})\Delta]}{(1-\hat{A})^2} \quad\Rightarrow\ \theta_{13}\ \text{Driven}\\
&+\ \alpha\,\sin 2\theta_{13}\,\xi\,\sin\delta_{CP}\,\sin(\Delta)\,\frac{\sin(\hat{A}\Delta)}{\hat{A}}\,\frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})} \quad\Rightarrow\ \text{CP odd}\\
&+\ \alpha\,\sin 2\theta_{13}\,\xi\,\cos\delta_{CP}\,\cos(\Delta)\,\frac{\sin(\hat{A}\Delta)}{\hat{A}}\,\frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})} \quad\Rightarrow\ \text{CP even}\\
&+\ \alpha^2\,\cos^2\theta_{23}\,\sin^2 2\theta_{12}\,\frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2}; \quad\Rightarrow\ \text{Solar Term}
\end{aligned}$$

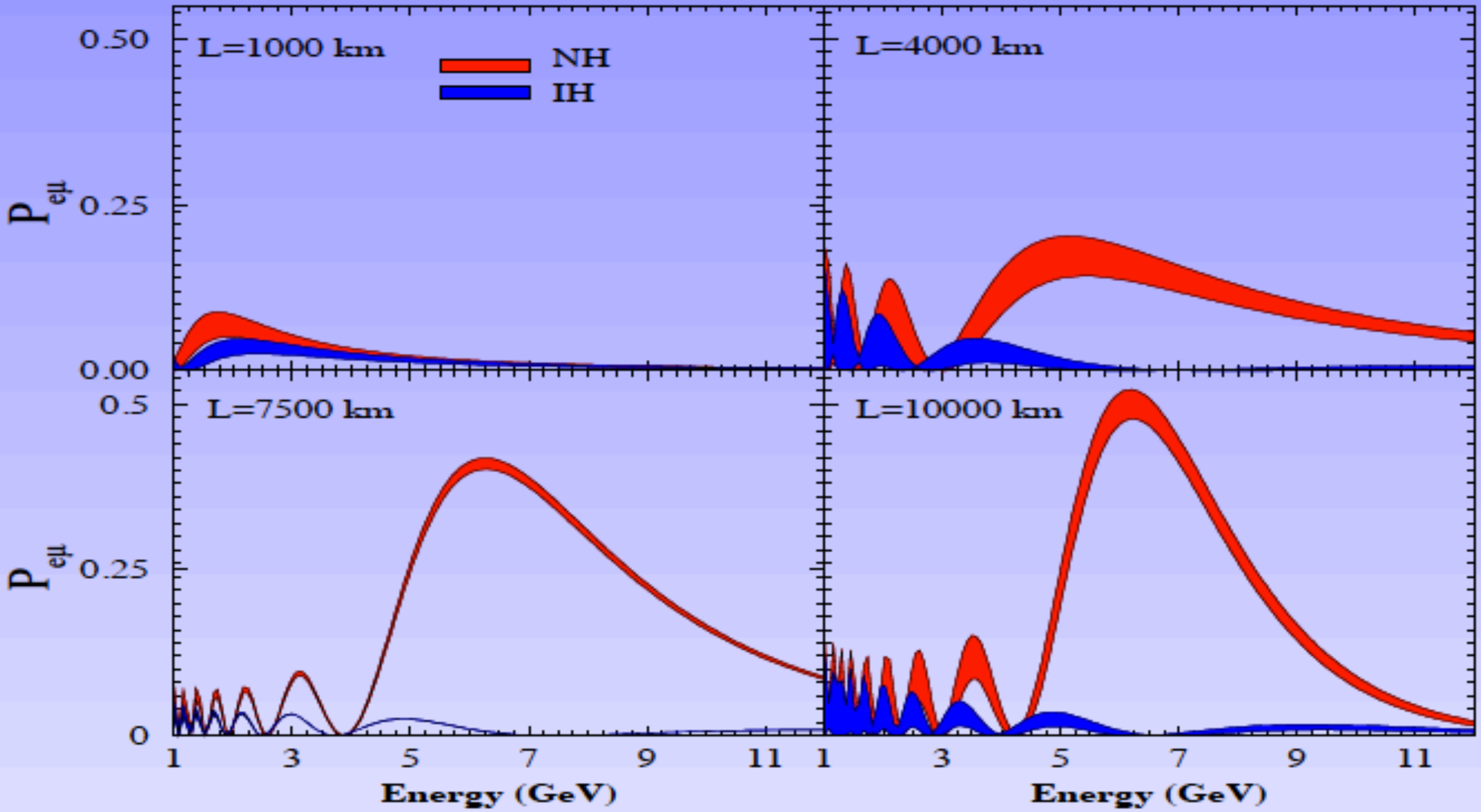
where $\Delta \equiv \Delta m^2_{31} L/(4E)$, $\xi \equiv \cos\theta_{13}\,\sin 2\theta_{21}\,\sin 2\theta_{23}$,
and $\hat{A} \equiv \pm(2\sqrt{2}G_F n_e E)/\Delta m^2_{31}$

- $(\theta_{13},\ \delta_{CP})$ **intrinsic degeneracy**
- $(sgn(\Delta m^2_{31}),\ \delta_{CP})$ **degeneracy**
- $(\theta_{23},\ \pi/2-\theta_{23})$ **degeneracy**

Severely deteriorates the sensitivity

How can we get rid of these degeneracies?

Transition Probability ($P_{e\mu}$)

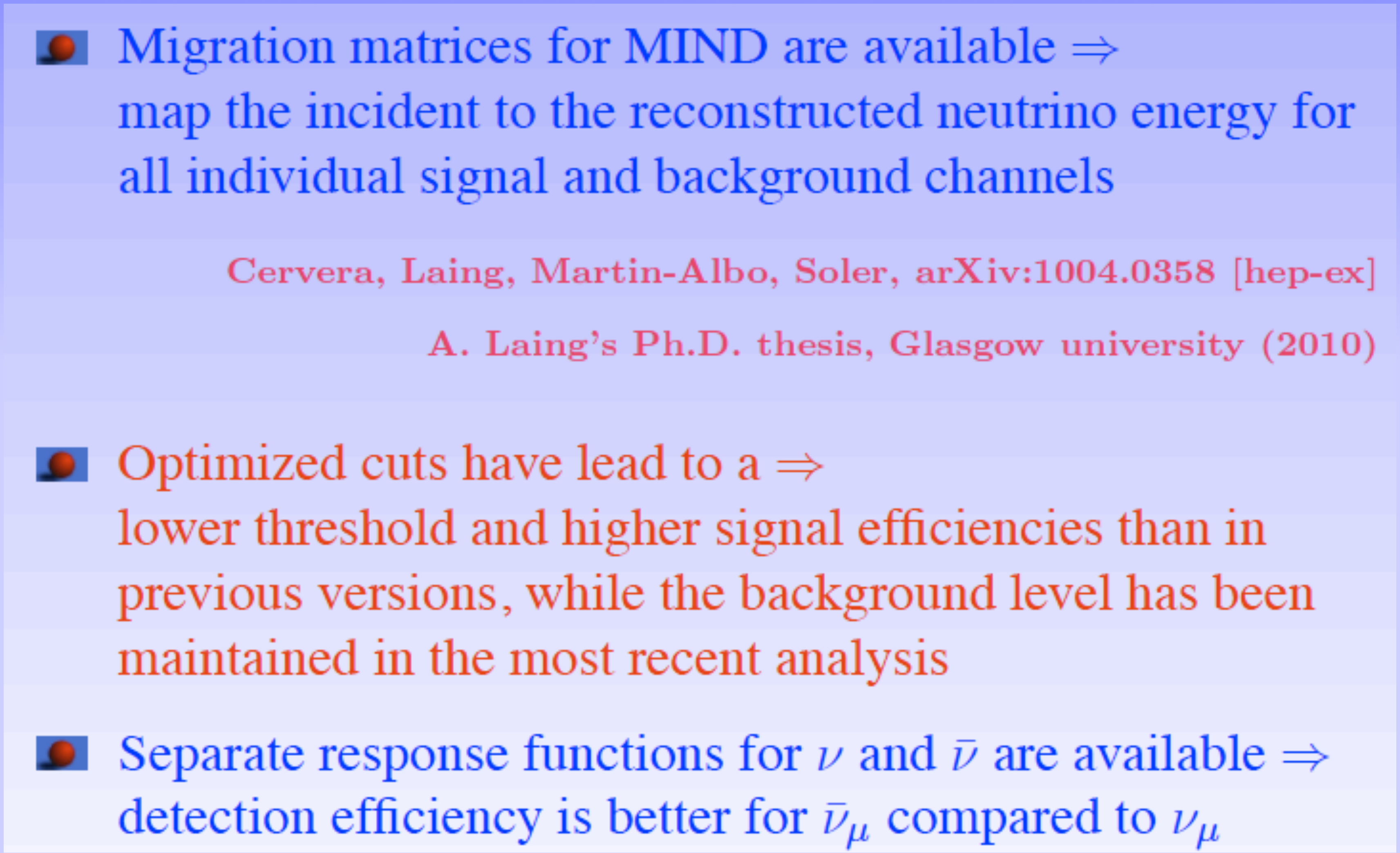


Agarwalla, Choubey, Raychaudhuri, hep-ph/0610333

Normal .vs. Inverted hierarchy

$\sin^2 2\theta_{13} = 0.1$

MIND Simulations



- Migration matrices for MIND are available ⇒ map the incident to the reconstructed neutrino energy for all individual signal and background channels

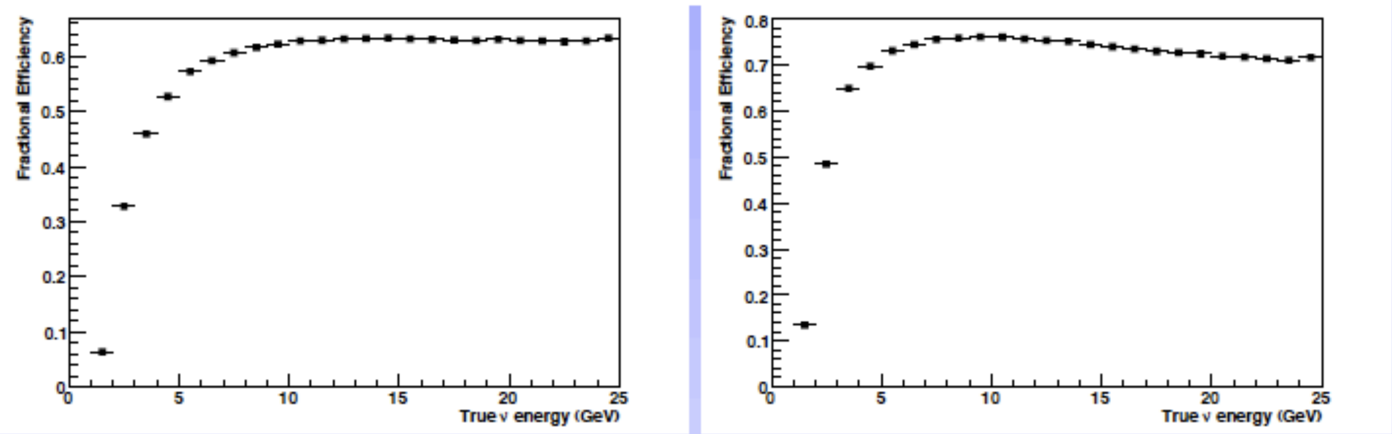
Cervera, Laing, Martin-Albo, Soler, arXiv:1004.0358 [hep-ex]

A. Laing's Ph.D. thesis, Glasgow university (2010)

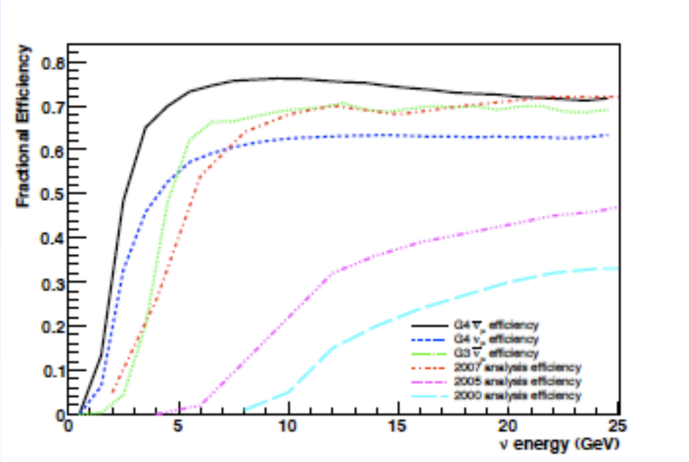
- Optimized cuts have lead to a ⇒ lower threshold and higher signal efficiencies than in previous versions, while the background level has been maintained in the most recent analysis
- Separate response functions for ν and $\bar{\nu}$ are available ⇒ detection efficiency is better for $\bar{\nu}_\mu$ compared to ν_μ

For latest simulation results on MIND: attend the talks in WP5 (tomorrow)!

Improved Signal Efficiencies



Left : μ^- appearance & Right : μ^+ appearance



QES & RES events added, threshold ∼ 2 GeV, plateau ∼ 5 GeV

!Very crucial!

What is the threshold?

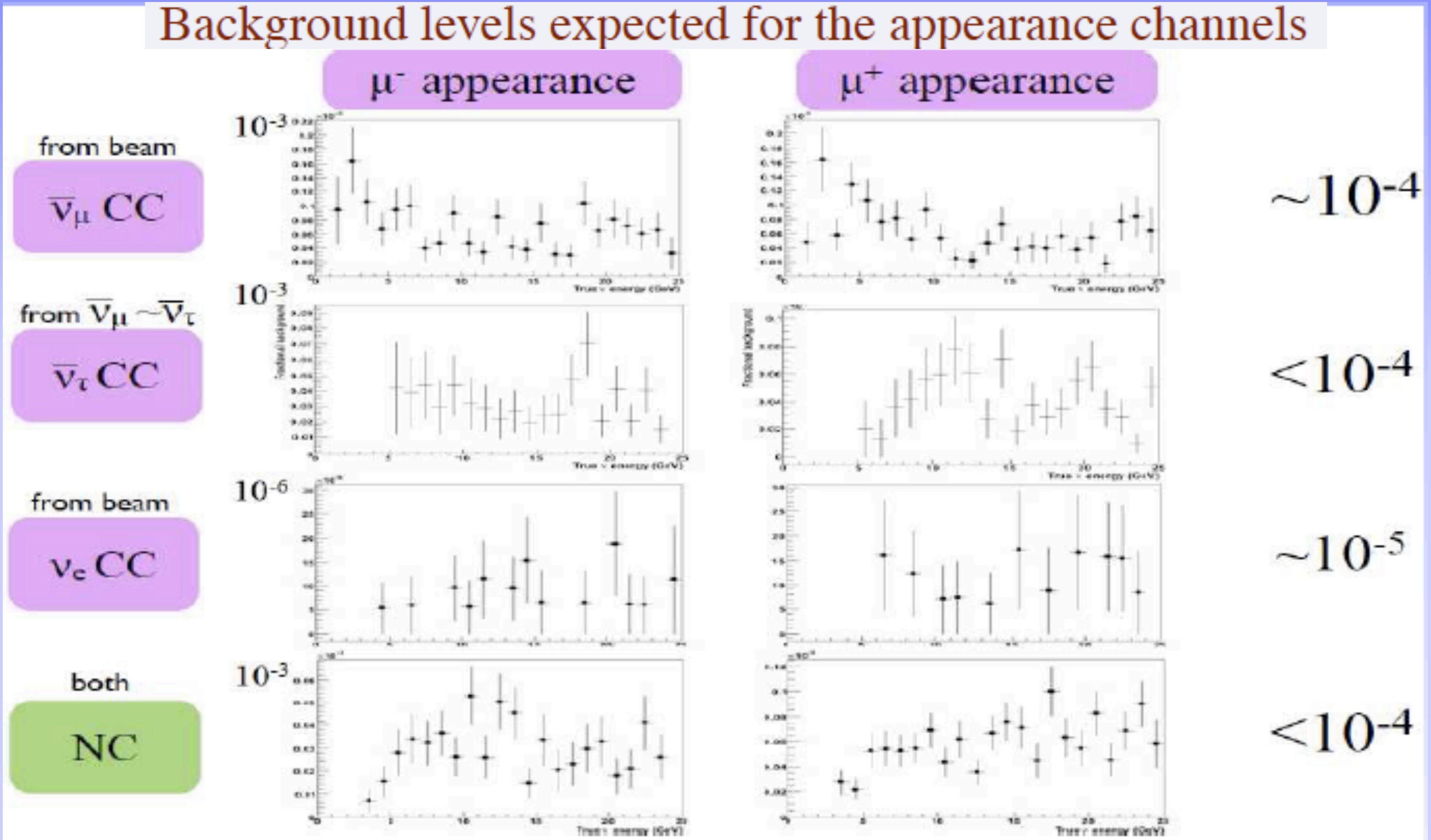
Where the plateau is?

What is the level of charge Id?

A realistic magnetic field might have serious impact!

For E_μ= 10 GeV, the average neutrino energy is around 6.5 GeV
How safe is to fully rely around plateau?

Fractional Backgrounds



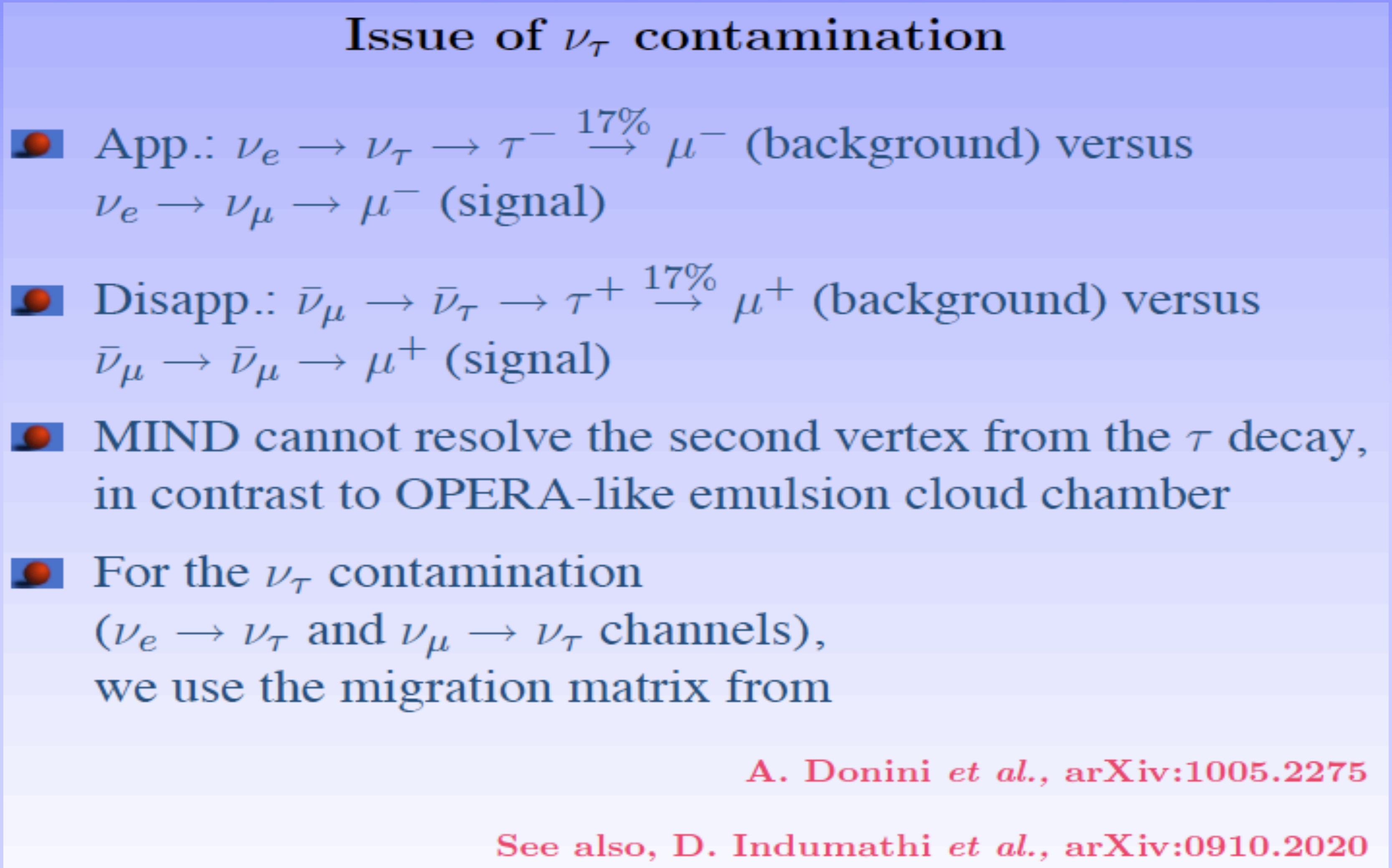
Background levels expected for the appearance channels

	μ^- appearance	μ^+ appearance	
from beam $\bar{\nu}_\mu$ CC	10^{-3}		$\sim 10^{-4}$
from $\bar{\nu}_\mu \to \bar{\nu}_\tau$ $\bar{\nu}_\tau$ CC	10^{-3}		$< 10^{-4}$
from beam ν_e CC	10^{-6}		$\sim 10^{-5}$
both NC	10^{-3}		$< 10^{-4}$

A. Cervera, WIN 2011

For large θ_{13}, event rates are higher, can we relax the cuts to allow more backgrounds which can also increase the efficiency?

ν_τ contamination



Issue of ν_τ contamination

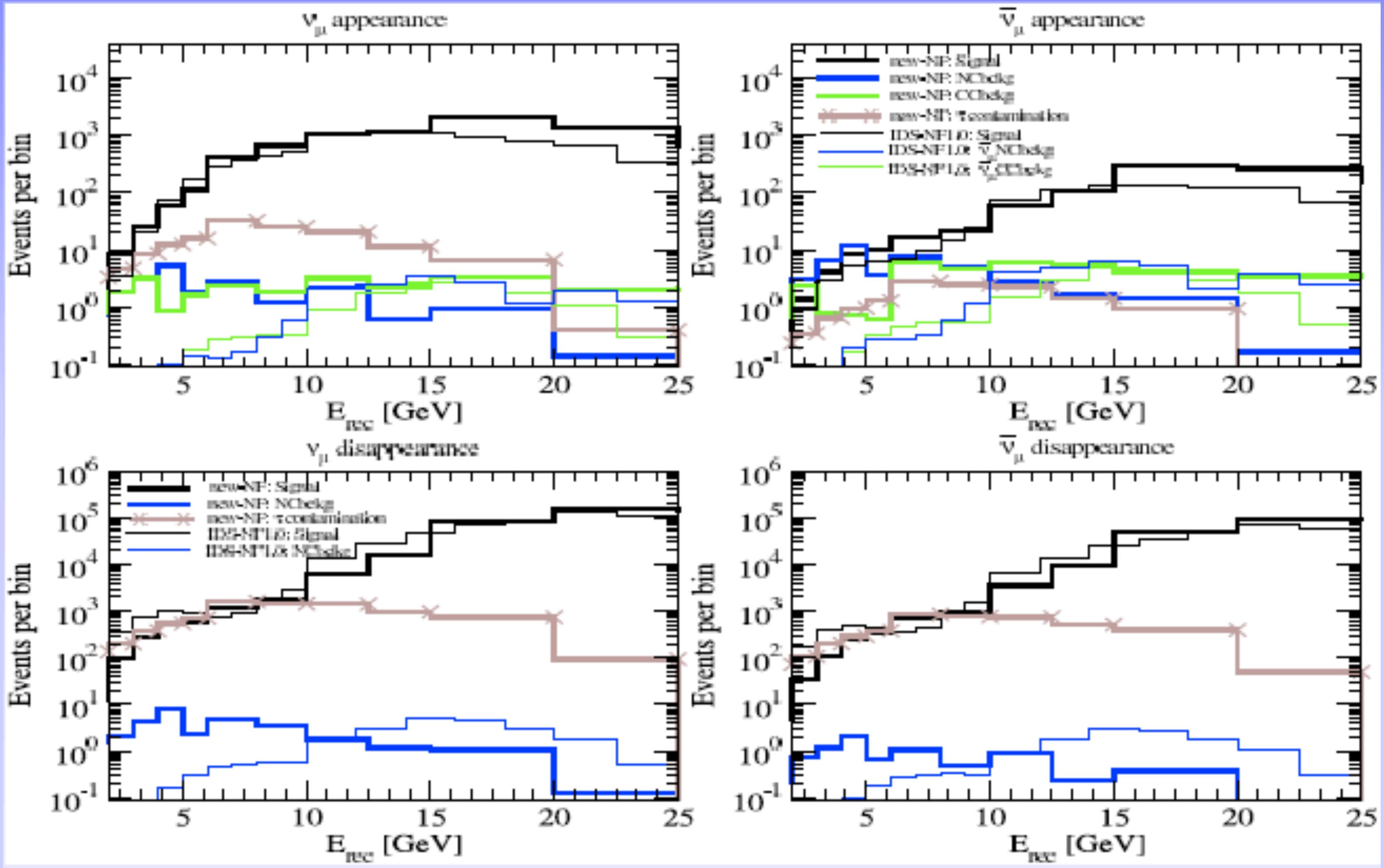
- App.: $\nu_e \longrightarrow \nu_\tau \longrightarrow \tau^- \xrightarrow{17\%} \mu^-$ (background) versus $\nu_e \longrightarrow \nu_\mu \longrightarrow \mu^-$ (signal)
- Disapp.: $\bar{\nu}_\mu \longrightarrow \bar{\nu}_\tau \longrightarrow \tau^+ \xrightarrow{17\%} \mu^+$ (background) versus $\bar{\nu}_\mu \longrightarrow \bar{\nu}_\mu \longrightarrow \mu^+$ (signal)
- MIND cannot resolve the second vertex from the τ decay, in contrast to OPERA-like emulsion cloud chamber
- For the ν_τ contamination ($\nu_e \longrightarrow \nu_\tau$ and $\nu_\mu \longrightarrow \nu_\tau$ channels), we use the migration matrix from

A. Donini *et al.*, arXiv:1005.2275

See also, D. Indumathi *et al.*, arXiv:0910.2020

Recent study with improved MIND suggests, this issue is not going to affect the CP violation and mass hierarchy discovery! may affect the θ_{23} precision!

Event Rate Comparison

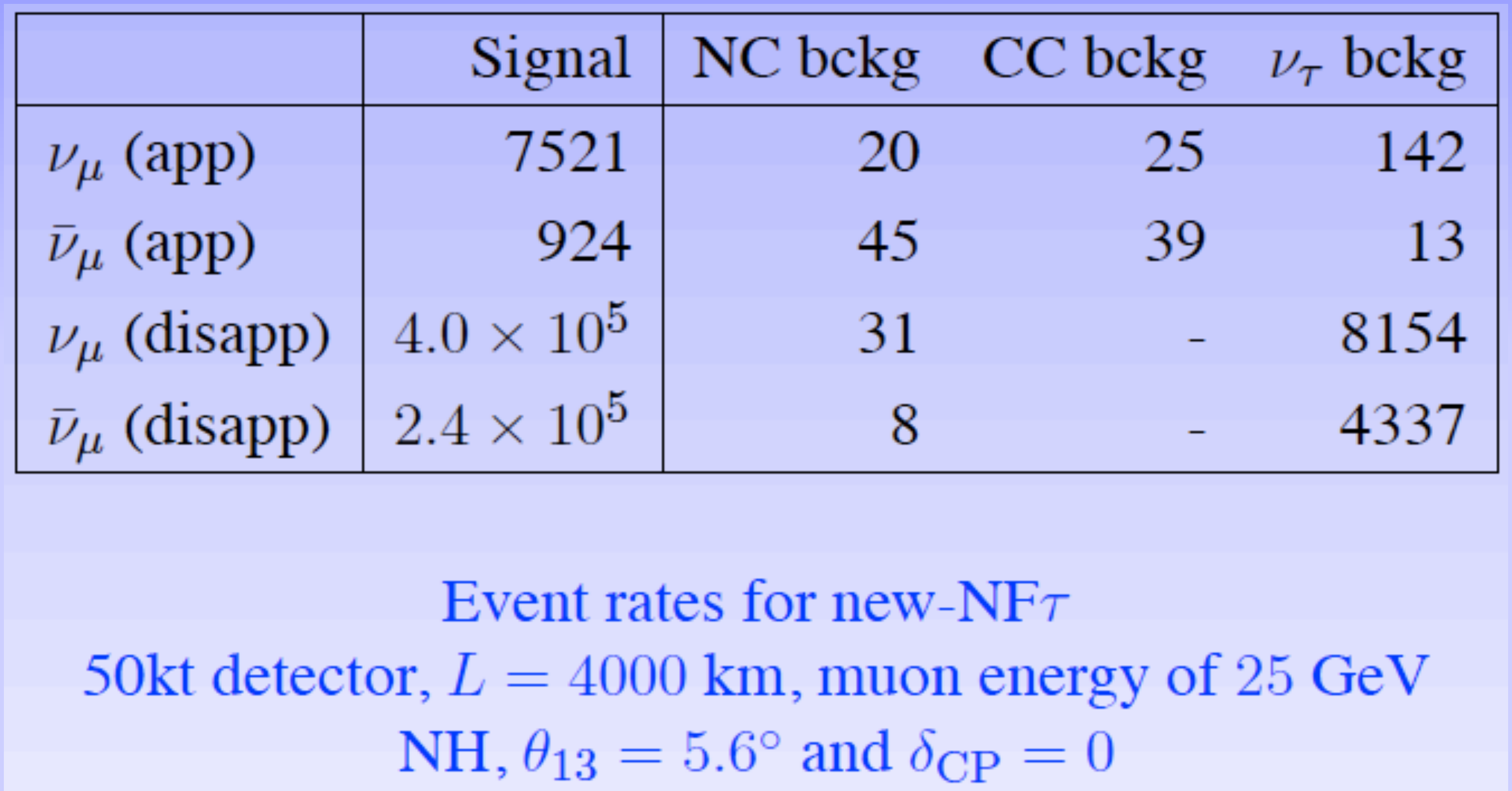


Agarwalla, Huber, Tang, Winter, JHEP 01 120 (2011)

Thin curves : IDS-NF 1.0 and thick curves : new-NF including backgrounds from ν_τ

Muon energy = 25 GeV, detector mass = 50kt, $L = 4000$ km, $\theta_{13} = 5.6^\circ$ & $\delta_{CP} = 0$

Event Rates



	Signal	NC bckg	CC bckg	ν_τ bckg
ν_μ (app)	7521	20	25	142
$\bar{\nu}_\mu$ (app)	924	45	39	13
ν_μ (disapp)	4.0×10^5	31	-	8154
$\bar{\nu}_\mu$ (disapp)	2.4×10^5	8	-	4337

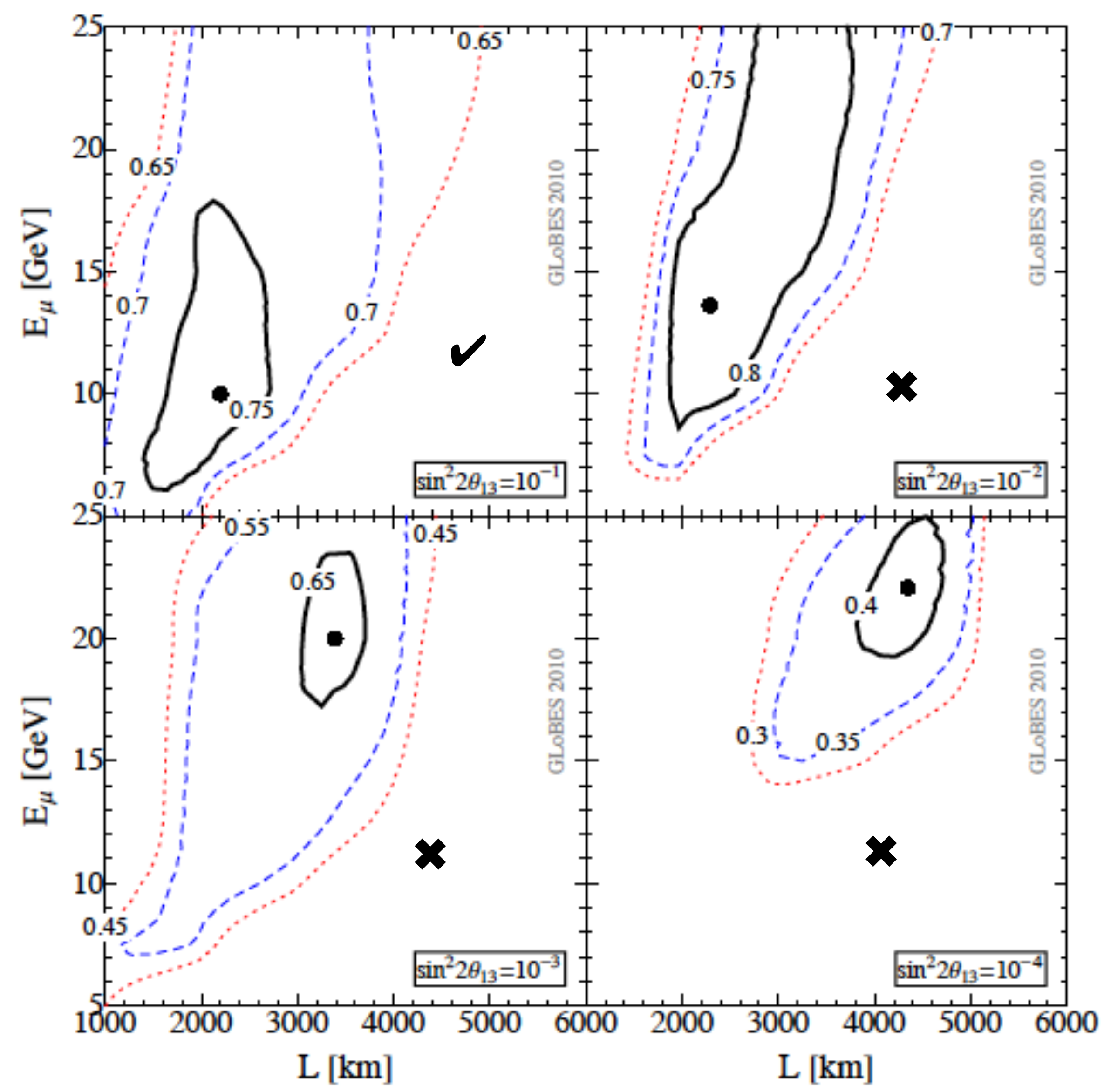
Event rates for new-NFτ

50kt detector, $L = 4000$ km, muon energy of 25 GeV

NH, $\theta_{13} = 5.6°$ and $\delta_{\mathrm{CP}} = 0$

Agarwalla, Huber, Tang, Winter, JHEP 01 120 (2011)

Optimization with one baseline



50 kt MIND

Agarwalla, Huber, Tang, Winter, JHEP 01 120 (2011)

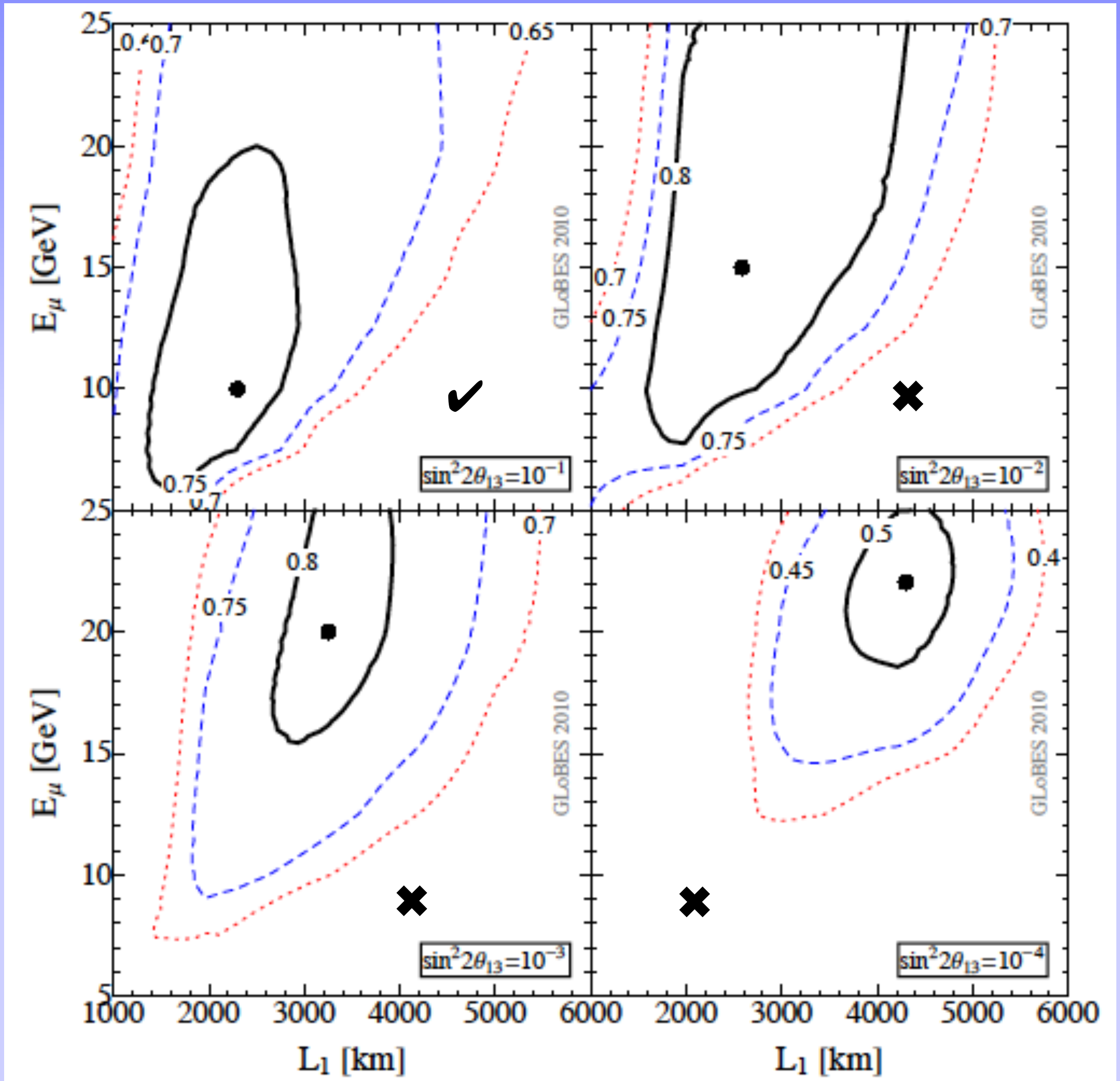
For large 1-3 mixing!
Best CPV discovery at:

E_μ = 10 GeV
L = 2000 km

CP fraction reach is 0.77

New Baseline design!

Optimization: Do we need the 2nd Baseline (7500 km)?



Agarwalla, Huber, Tang, Winter, JHEP 01 120 (2011)

Two 50 kt MIND detectors:
One at L_1 & other at 7500 km

For large 1-3 mixing!

2nd Baseline (magic) is not needed!

Optimum choice still holds!

E_μ = 10 GeV, L = 2000 km

CP fraction reach is 0.77

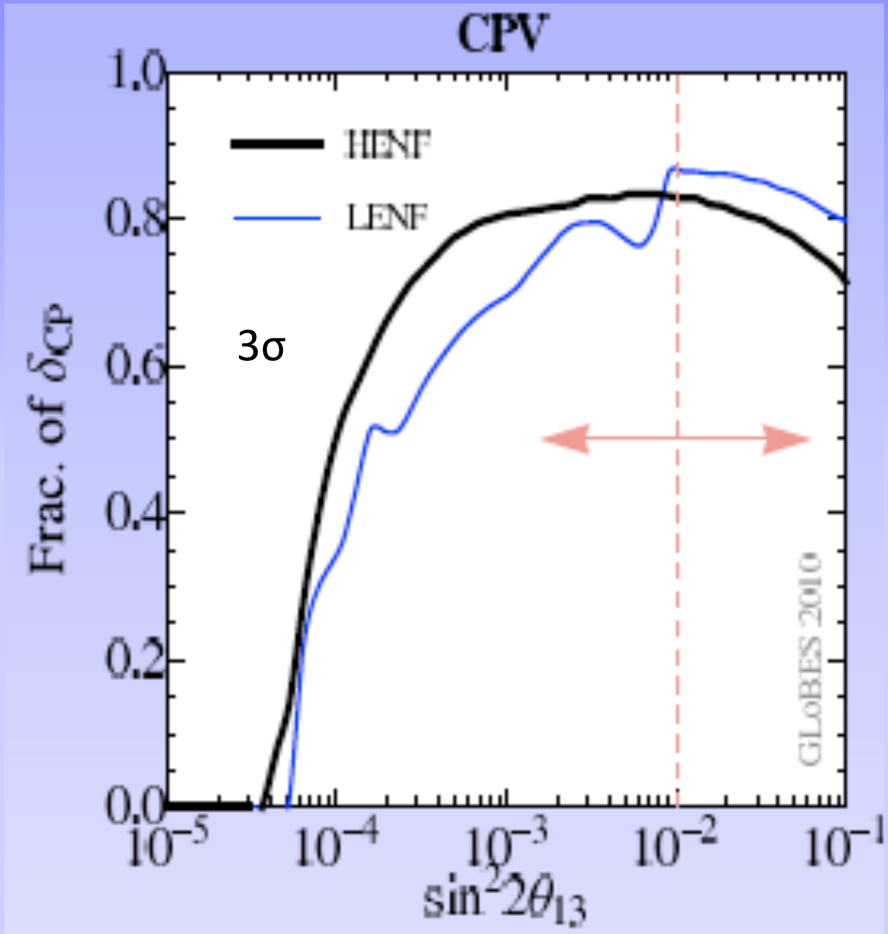
New Baseline design!

Only one storage ring!

Can we store all the muons in one storage ring?

Place (50+50) = 100 kt detector at one baseline

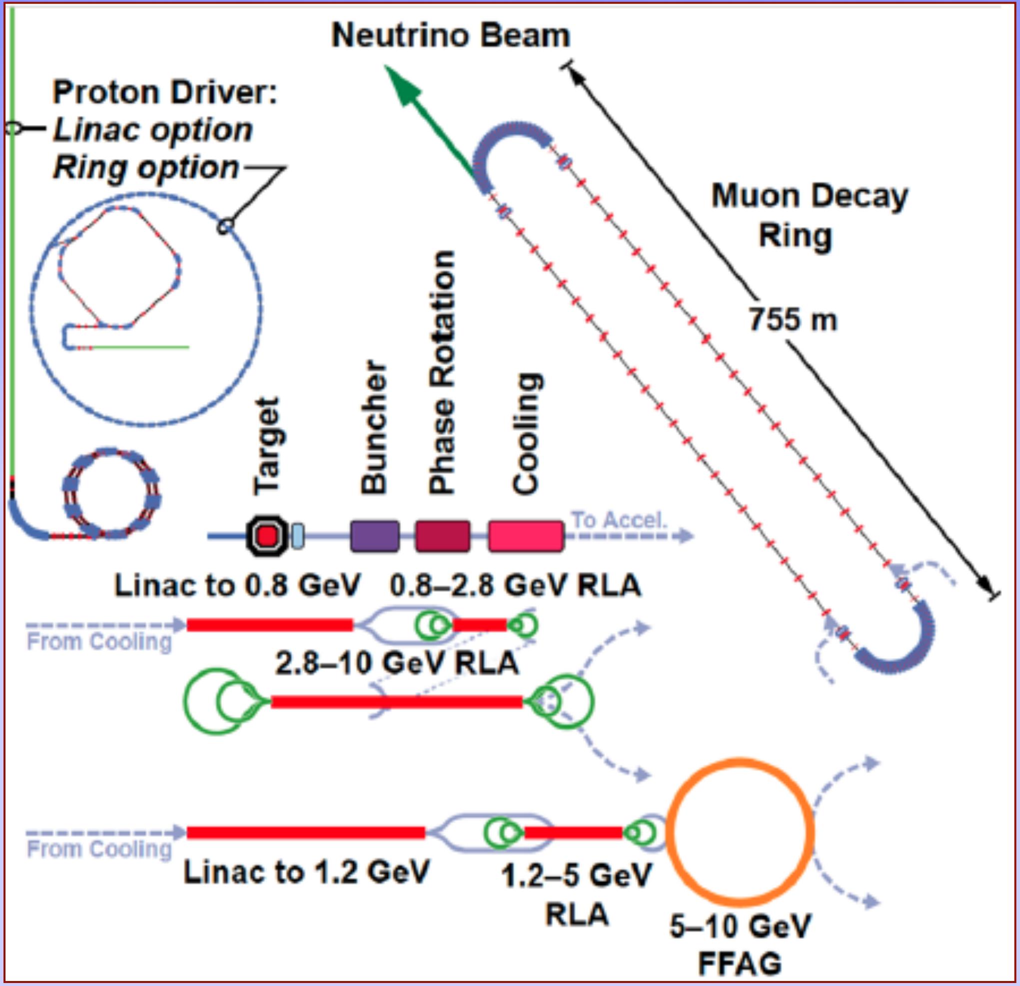
LENF .vs. HENF with MIND



Agarwalla, Huber, Tang, Winter, JHEP 01 120 (2011)

LENF: Single baseline at 2000 km, 10 GeV muons, all the muons at this baseline
HENF: Two baseline (4000km and 7500 km) with 25 GeV muons

IDS-NF updated baseline design



- ✧ **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

An Incremental Approach!

Conventional Staging: Low energy, 1 Baseline setups to high energy, 2 baseline setups

First discussed by Tang, Winter, PRD81, (2010) 033005

For large 1-3 mixing: we need only low energy and one baseline around 2000 km!

Stage 1: A very low energy neutrino factory (VLENF or νSTORM)

LOI: P. Kyberd etal., arXiv:1206.0294 [hep-ex]

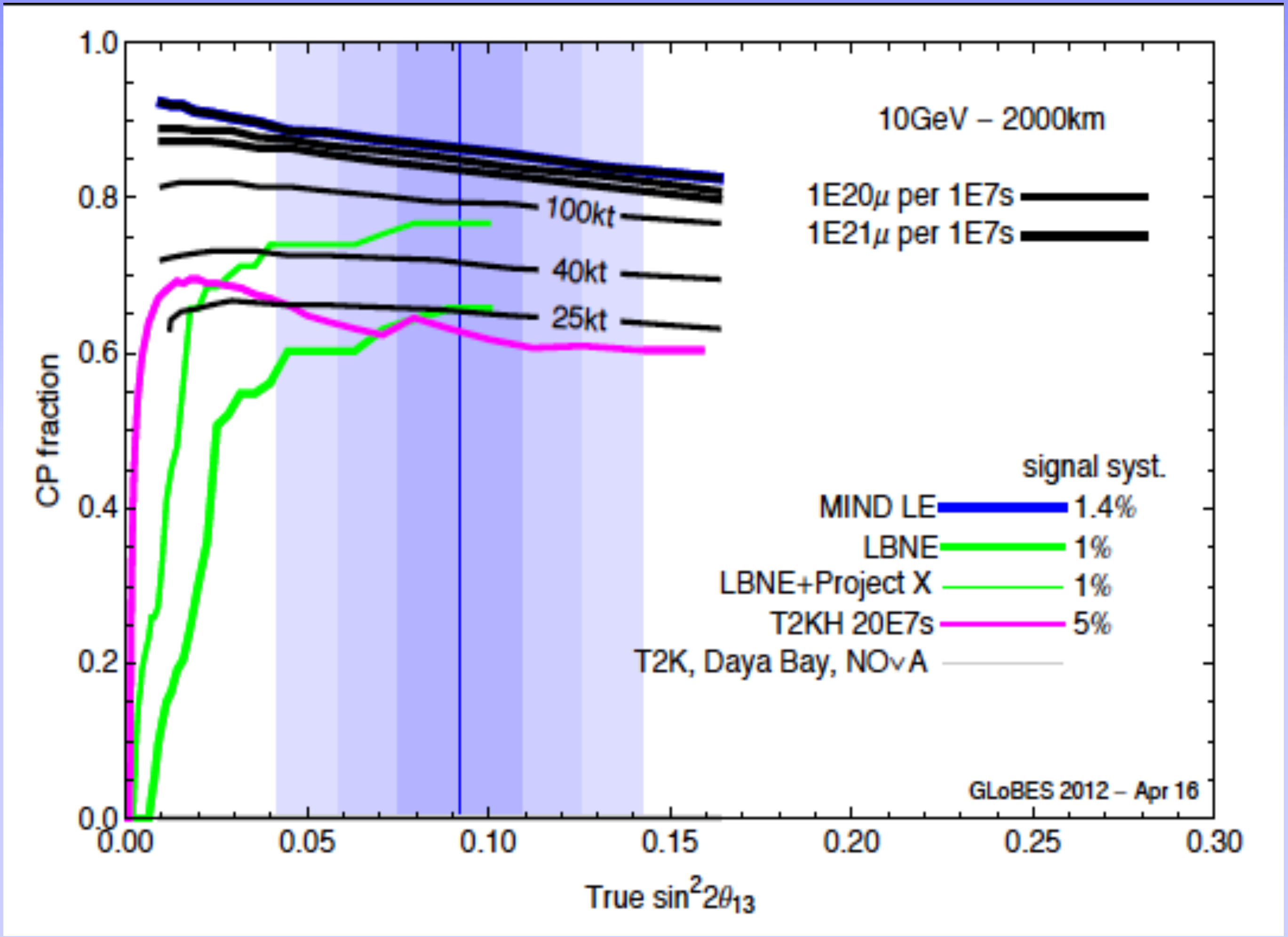
Precise cross-section and flux measurements, Sterile Neutrino searches!

Stage 2: Present IDS-NF baseline: 10 GeV neutrino factory with a baseline of 2000 km, 100 kt MIND detector + near detector

CPV and MH discovery, precise measurement of 2-3 mixing, New physics

Stage 3: Is it worthwhile to use 25 GeV muons?

Does staging work for us?



Talk by P. Huber at 8th IDS-NF Plenary meeting

Start with 25 times less luminosity as compared To default setup!

Reduce the beam power!
4 MW → 800 kW

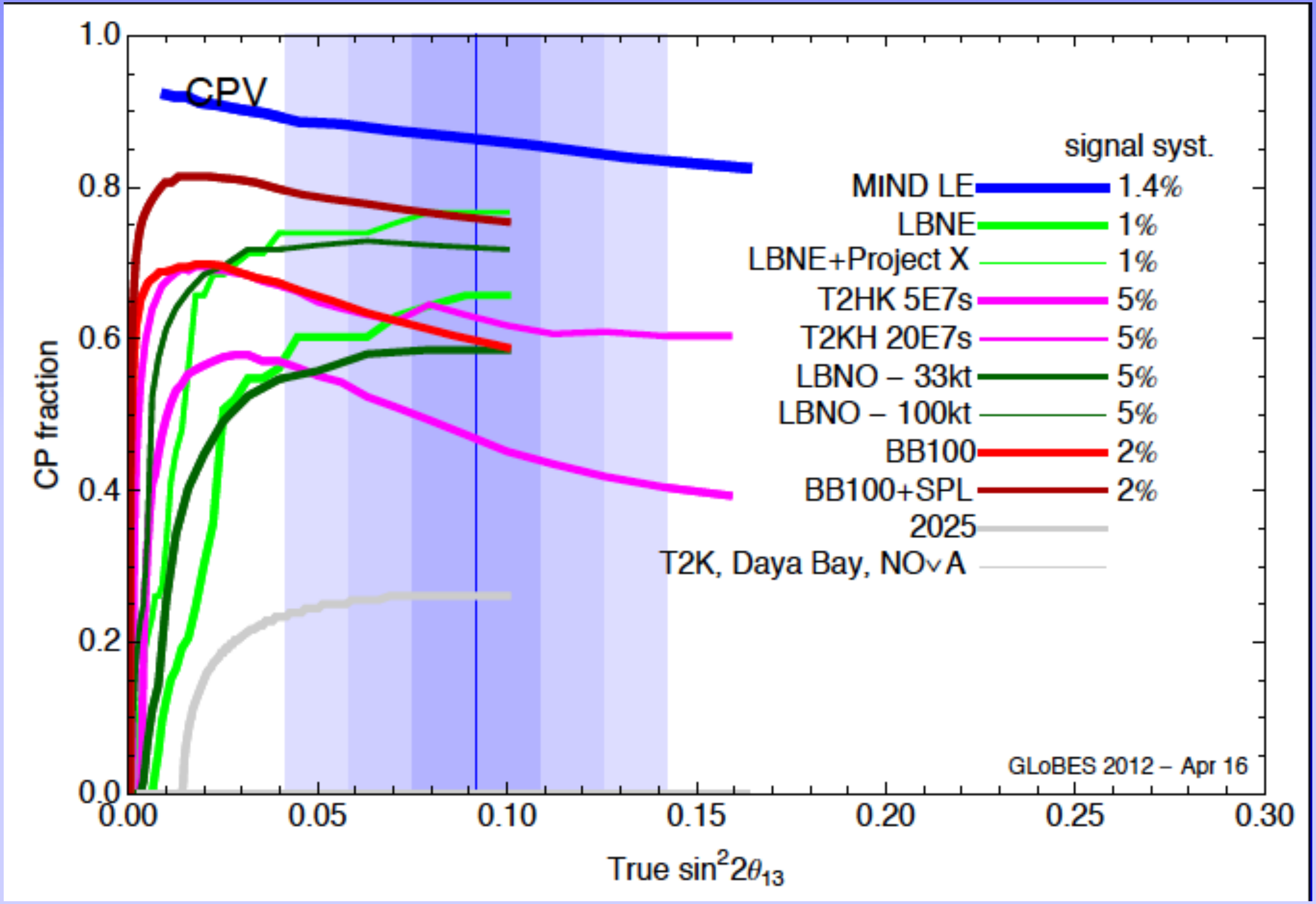
Reduce the MIND size!
100 kt → 20 kt

Still the NF performance is comparable with best Superbeam option

No Project X, no cooling!
Detailed R&D required!

Staging is possible for NF with excellent physics reach at each stage!

Compare Neutrino Factory with other facilities

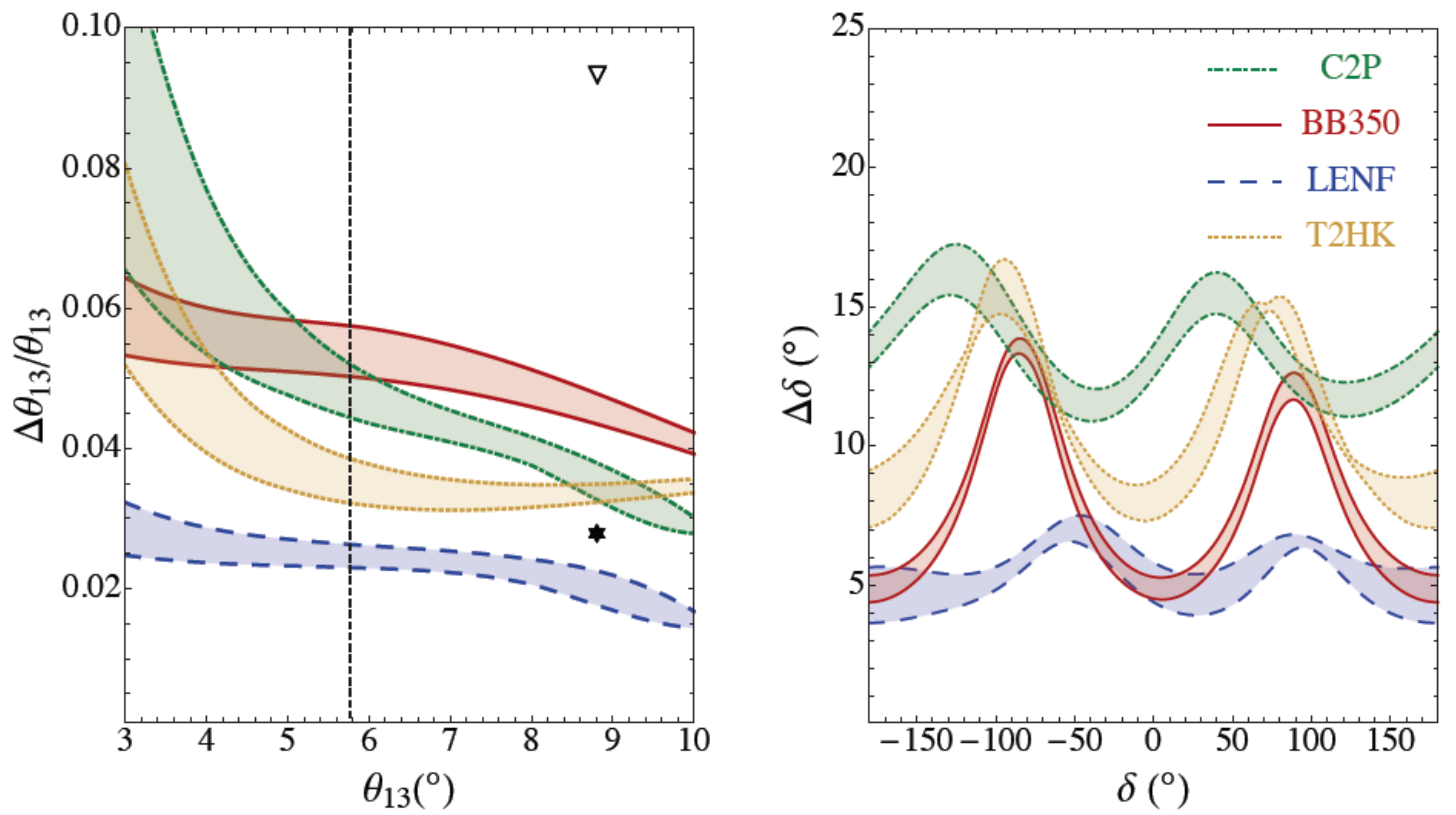


Talk by P. Huber at 8th IDS-NF Plenary meeting

MIND LE: 100 kt MIND at 2000 km with 10 GeV Muons

Superbeam can reach 0.7 to 0.75 CP fraction; NF can reach 0.85 to 0.9

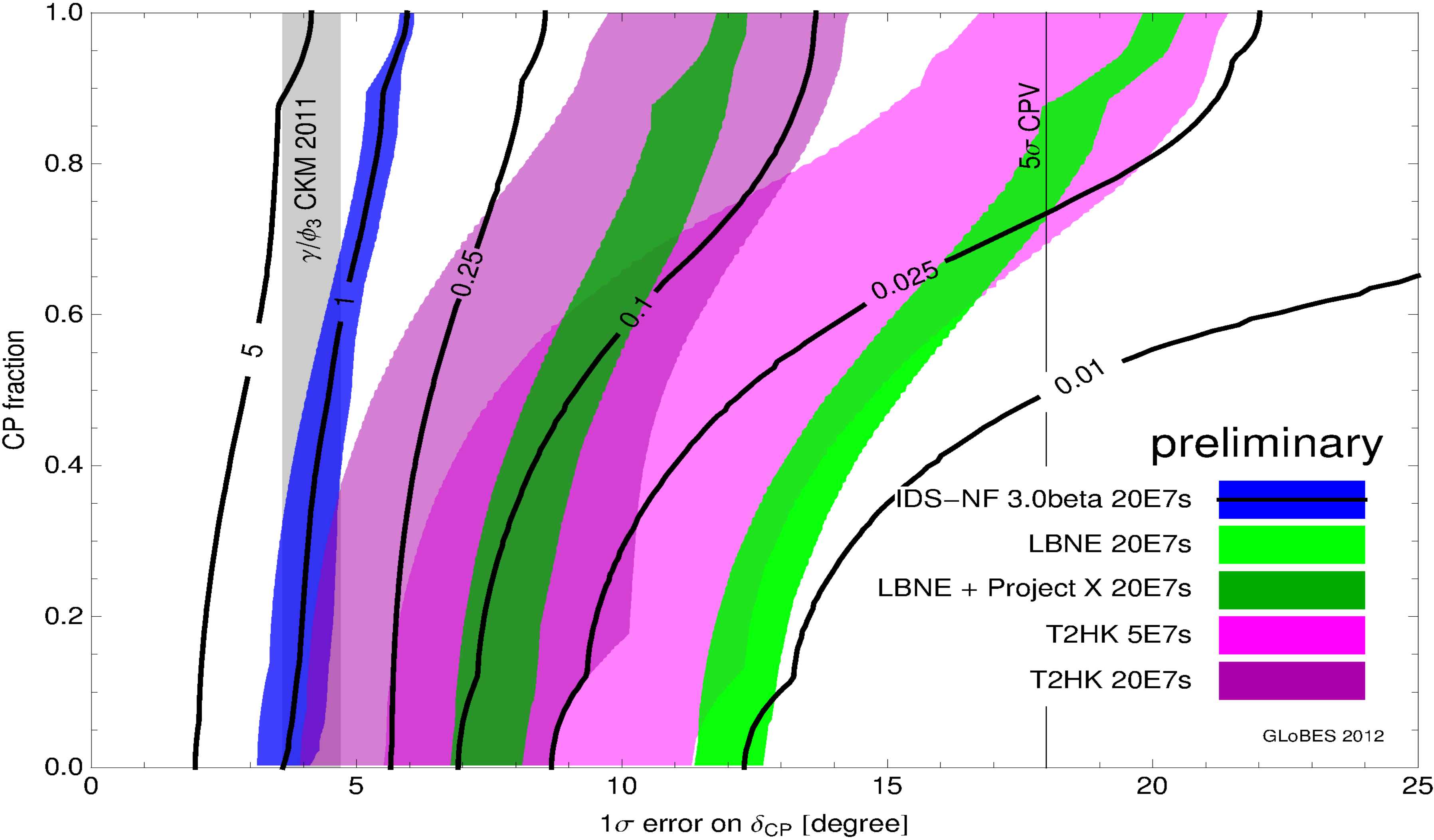
The Issue of Precision



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

NF is the best precision machine!

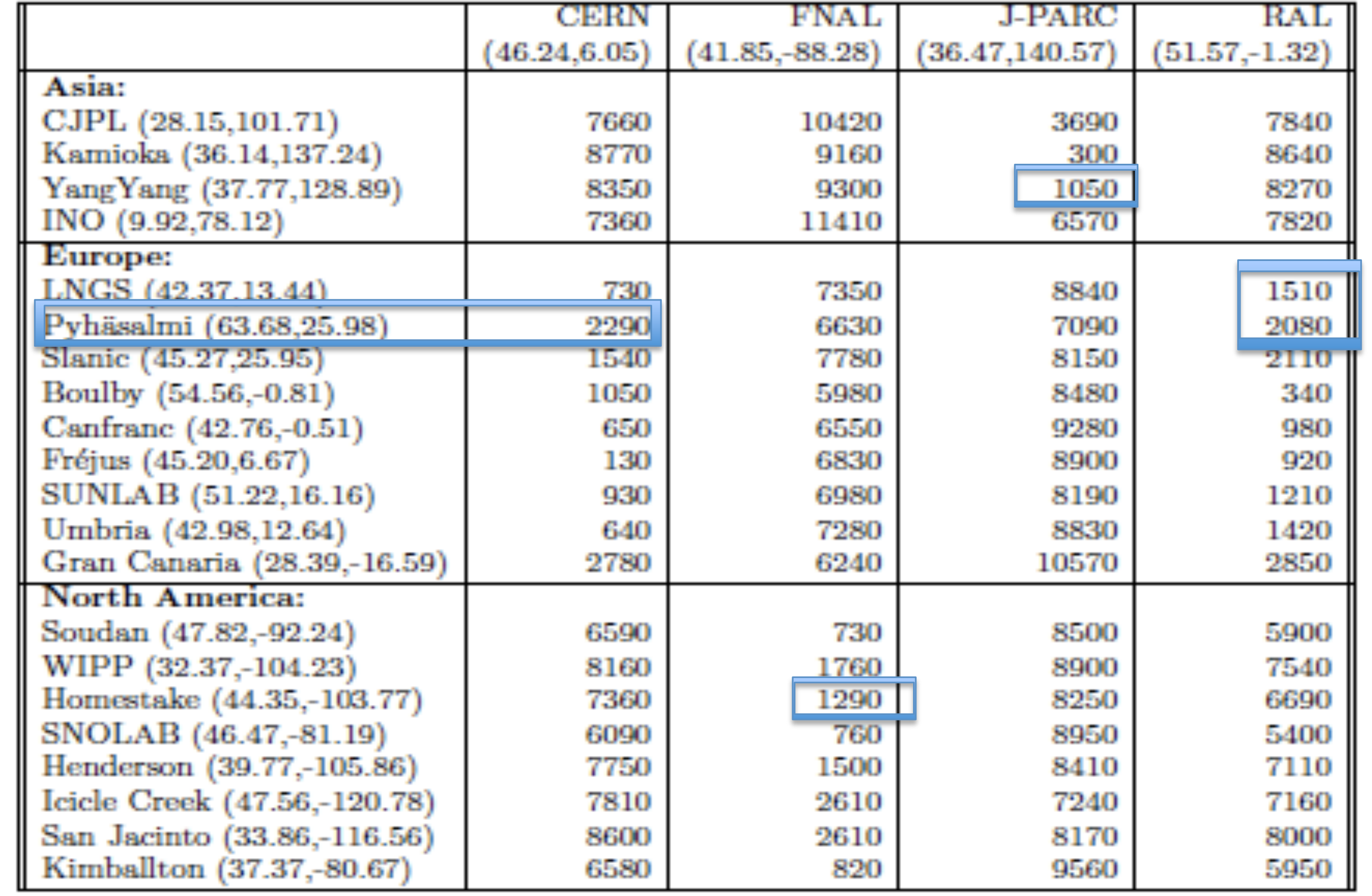
The Impact of Systematics for CP precision



Coloma, Huber, Kopp, Winter, in preparation

Bands represent variation of input systematics!

Possible Baseline options



	CERN (46.24,6.05)	FNAL (41.85,-88.28)	J-PARC (36.47,140.57)	RAL (51.57,-1.32)
Asia:				
CJPL (28.15,101.71)	7660	10420	3690	7840
Kamioka (36.14,137.24)	8770	9160	300	8640
YangYang (37.77,128.89)	8350	9300	1050	8270
INO (9.92,78.12)	7360	11410	6570	7820
Europe:				
LNGS (42.37,13.44)	730	7350	8840	1510
Pyhäsalmi (63.68,25.98)	2290	6630	7090	2080
Slanic (45.27,25.95)	1540	7780	8150	2110
Boulby (54.56,-0.81)	1050	5980	8480	340
Canfranc (42.76,-0.51)	650	6550	9280	980
Fréjus (45.20,6.67)	130	6830	8900	920
SUNLAB (51.22,16.16)	930	6980	8190	1210
Umbria (42.98,12.64)	640	7280	8830	1420
Gran Canaria (28.39,-16.59)	2780	6240	10570	2850
North America:				
Soudan (47.82,-92.24)	6590	730	8500	5900
WIPP (32.37,-104.23)	8160	1760	8900	7540
Homestake (44.35,-103.77)	7360	1290	8250	6690
SNOLAB (46.47,-81.19)	6090	760	8950	5400
Henderson (39.77,-105.86)	7750	1500	8410	7110
Icicle Creek (47.56,-120.78)	7810	2610	7240	7160
San Jacinto (33.86,-116.56)	8600	2610	8170	8000
Kimballton (37.37,-80.67)	6580	820	9560	5950

Agarwalla, Huber, Tang, Winter, JHEP 01 120 (2011)

Conclusions

- Improved simulations on MIND suggest that it can work well at low energy and small baseline scenario
- In the light of large θ_{13}, we need to optimize again the detector characteristics to get the best out of it
- Systematics affect the performance of Low energy neutrino factory setup
- A clear understanding of detector systematics is needed !