NuFact 2011

Optimized Neutrino Factory for small and large θ_{13}

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Oscillation parameters

Parameter	Best fit$\pm 1\sigma$	3σ range
Δm^2_{21} $[10^{-5}\ eV^2]$	$\mathbf{7.59^{+0.20}_{-0.18}}$	**7.09 - 8.19**
$\|\Delta m^2_{31}\|$ $[10^{-3}\ eV^2]$	**2.45±0.09**	**2.18 - 2.73**
$\sin^2\theta_{12}$	$\mathbf{0.312^{+0.017}_{-0.015}}$	**0.27 - 0.36**
$\sin^2\theta_{23}$	**0.51±0.06**	**0.39 - 0.64**
$\sin^2\theta_{13}$	$\mathbf{0.010^{+0.009}_{-0.006}}$	$\leq$ **0.035**

T. Schwetz, M.A. Tortola, J.W.F. Valle, arXiv:1103.0734v2

Best-fit for normal ordering with new reactor fluxes

Including latest solar (SK II+III), atmospheric (SK I+II+III), KamLAND & MINOS (before June, 2011) data. New reactor fluxes & SBL data

New T2K and MINOS results

- In June, 2011, new exciting results announced by the T2K and MINOS long-baseline experiments
- T2K experiment observed 6 electron-like events with an estimated background of 1.5 events in the Super-K

  K. Abe *et al.*, [T2K Collaboration], arXiv:1106.2822

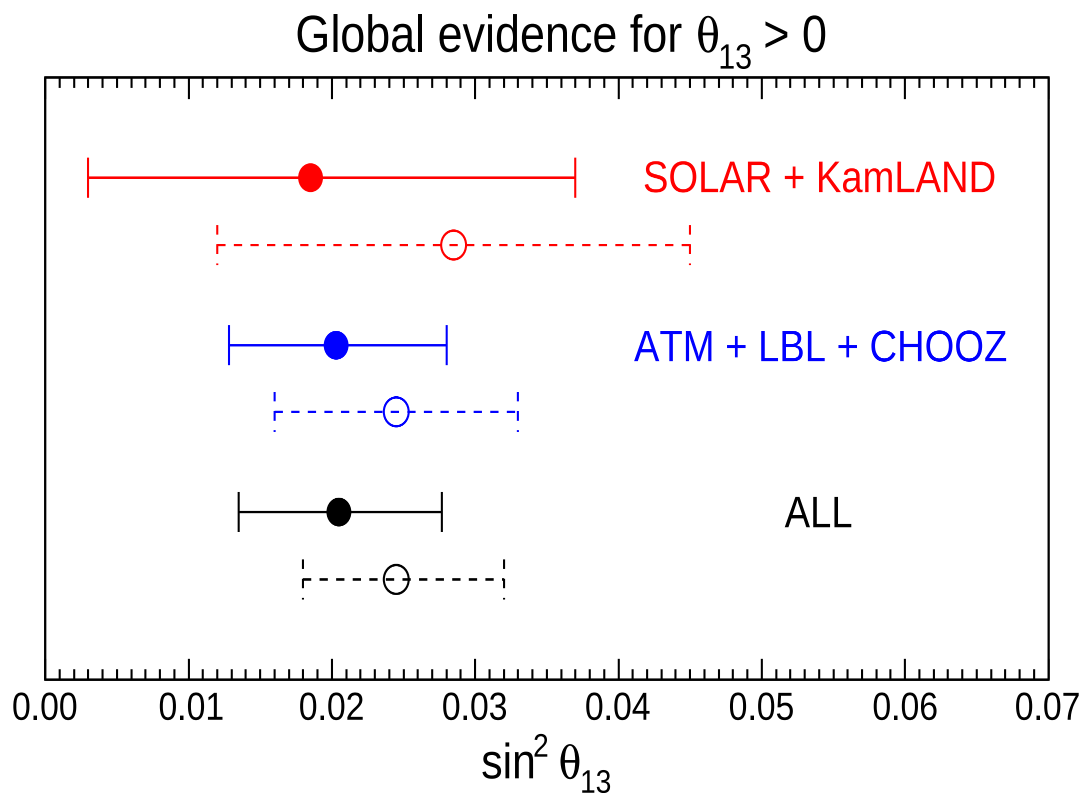
- It indicates towards θ_{13} driven $\nu_\mu \to \nu_e$ appearance signal, rejecting $\theta_{13} = 0$ at the level of $2.5\,\sigma$
- The MINOS experiment has observed 62 electron-like events with an estimated background of 49 events

  P. Adamson *et al.*, [MINOS Collaboration], arXiv:1108.0015

- This favors a non-zero θ_{13} at $1.5\,\sigma$ confidence level
- Recent global fit suggests $> 3\,\sigma$ evidence for non-zero θ_{13}

  G.L. Fogli *et al.*, , arXiv:1106.6028

Global Picture of θ_{13}



G.L. Fogli *et al.*, , arXiv:1106.6028

$$\sin^2 2\theta_{13} = \begin{cases} 0.082 \pm 0.028\,, & \text{old reactor fluxes} \\ 0.098 \pm 0.028\,, & \text{new reactor fluxes} \end{cases} \quad (1\sigma)$$

Big Issues in Neutrino Mixing

- 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 – $\Delta m^2_{31} < 0$

- The value of θ_{13}

There is evidence of $\theta_{13} > 0$ from global data
What is the exact value of θ_{13}?
What is the precision in the measurement of θ_{13}?

- CP violation in neutral lepton sector

Do neutrinos exhibit CP violation? Is $\delta_{CP} \neq 0$?
Any value of δ_{CP} between 0 to 2π is possible

Upcoming experiments

Upcoming superbeam and reactor experiments

Setup	t_ν [yr]	$t_{\bar\nu}$ [yr]	P_{Th} or P_{Target}	L [km]	Detector tech	m_{Det}
Double Chooz	-	3	8.6 GW	1.05	Liquid scint	8.3 t
Daya Bay	-	3	17.4 GW	1.7	Liquid scint	80 t
RENO	-	3	16.4 GW	1.4	Liquid scint	15.4 t
T2K	5	-	0.75 MW	295	Water Cerenkov	22.5 kt
NOνA	3	3	0.7 MW	810	TASD	15 kt

Standard set-ups at their nominal luminosities

P. Huber *et al.*, JHEP 11 044 (2009)

Can play a crucial role in planning a possible next generation of LBL neutrino experiments to address CPV and MH

Ultimate Message

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

- Size of $\theta_{13} \Rightarrow$ if $\sin^2 2\theta_{13} > 0.01$
- Mass ordering $\Rightarrow$ if $\sin^2 2\theta_{13} > 0.04$ for at most 30% of all CP phases
- CP violation in leptons $\Rightarrow$ if $\sin^2 2\theta_{13} > 0.02$ for at most 20% of all CP phases

Even for the largest currently allowed θ_{13} more than 70% of parameter space are not accessible

Ultimate Machine

Neutrino Factory → Ultimate facility

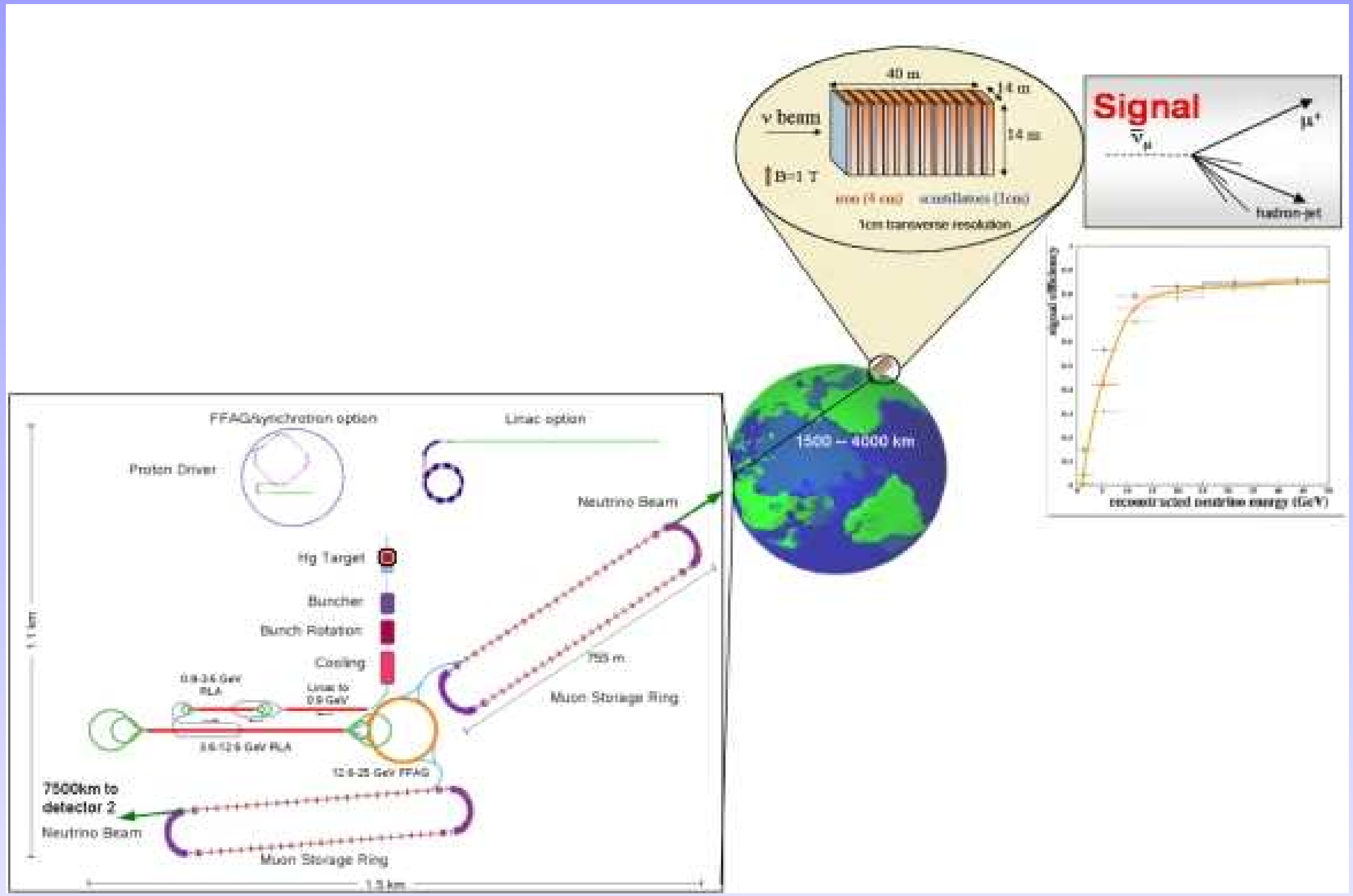
Powerful tool for CP violation discovery for small & large θ_{13}

Excellent sensitivity to $Sgn(\Delta m^2_{31})$ for 100% values of δ_{CP}

Neutrino Factory may be the first step towards

the high energy frontier in form of a muon collider

Baseline setup



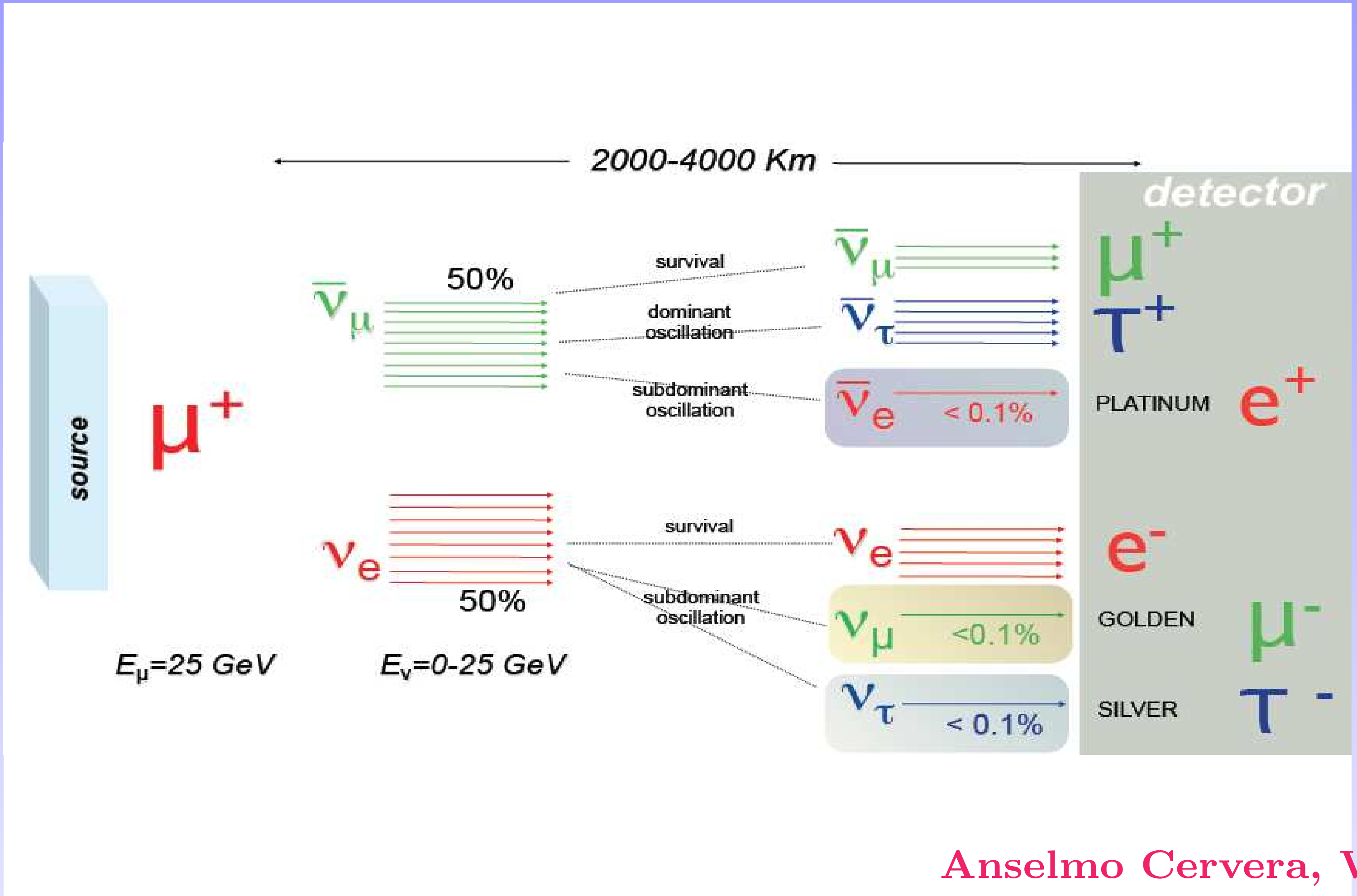
International Design Study for the Neutrino Factory

IDS-NF gives a 1st version baseline setup of HENF

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 $E_\mu = 25\,\mathrm{GeV}$

Signal



Anselmo Cervera, WIN'11

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

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

Osc. channels & Backgrounds

- ν_μ appearance: $\nu_e \to \nu_\mu$ for μ^+ stored
- $\bar{\nu}_\mu$ appearance: $\bar{\nu}_e \to \bar{\nu}_\mu$ for μ^- stored
- ν_μ disappearance: $\nu_\mu \to \nu_\mu$ for μ^- stored
- $\bar{\nu}_\mu$ disappearance: $\bar{\nu}_\mu \to \bar{\nu}_\mu$ for μ^+ stored
- Include backgrounds from $\Rightarrow$
    1. charge mis-identification
    2. (electron) flavor mis-identification
    3. neutral current
- We use the GLoBES software for the simulation

P. Huber *et al.*, hep-ph/0407333 and hep-ph/0701187

Golden Channel ($P_{e\mu}$)

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

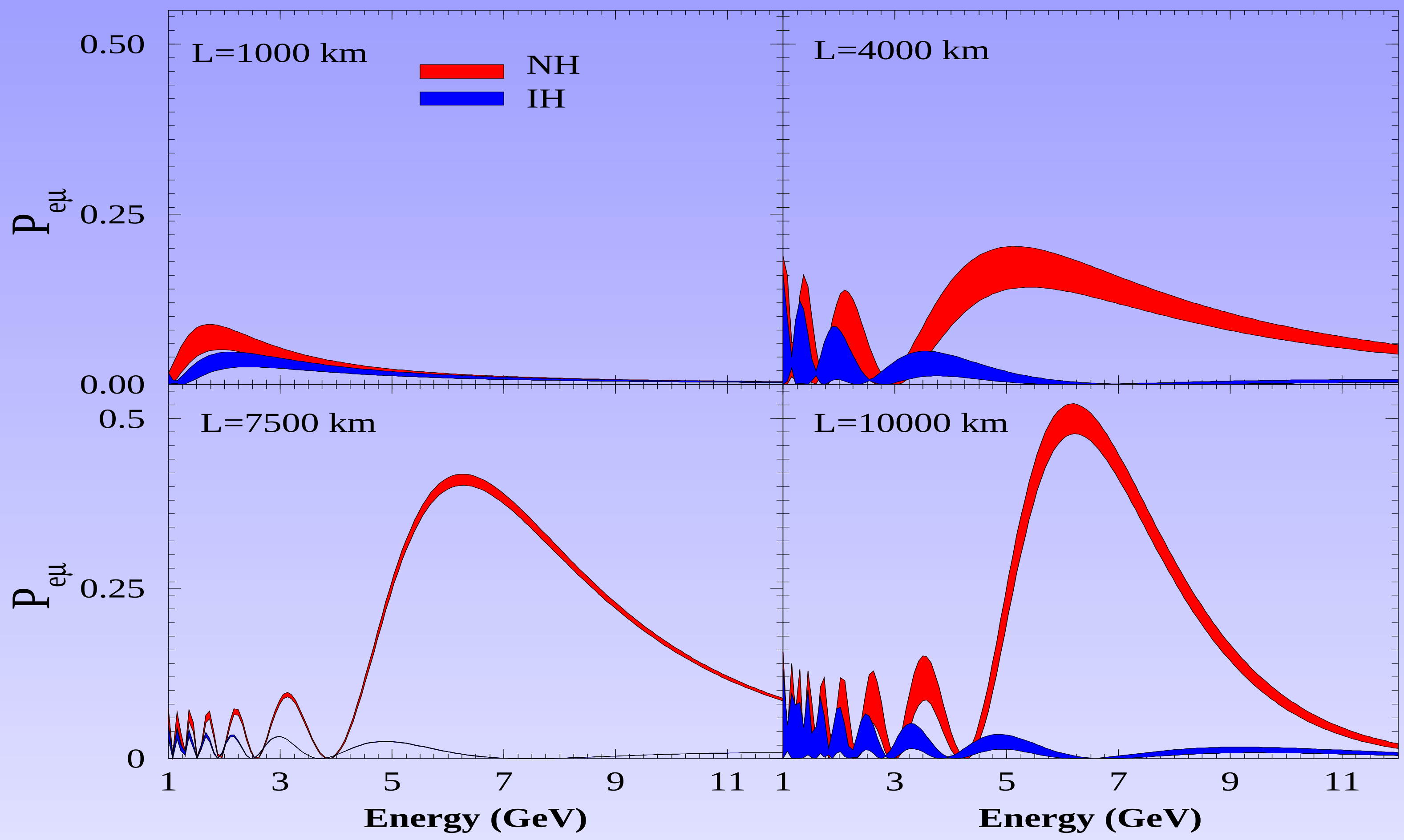
$$\begin{aligned}
P_{e\mu} \simeq & \quad \sin^2 2\theta_{13} \, \sin^2\theta_{23} \frac{\sin^2[(1-\hat{A})\Delta]}{(1-\hat{A})^2} \\
& + \alpha \, \sin 2\theta_{13} \, \xi \, \sin\delta_{CP} \sin(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})} \\
& + \alpha \,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

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

Cervera *et al.*, hep-ph/0002108

Freund, Huber, Lindner, hep-ph/0105071

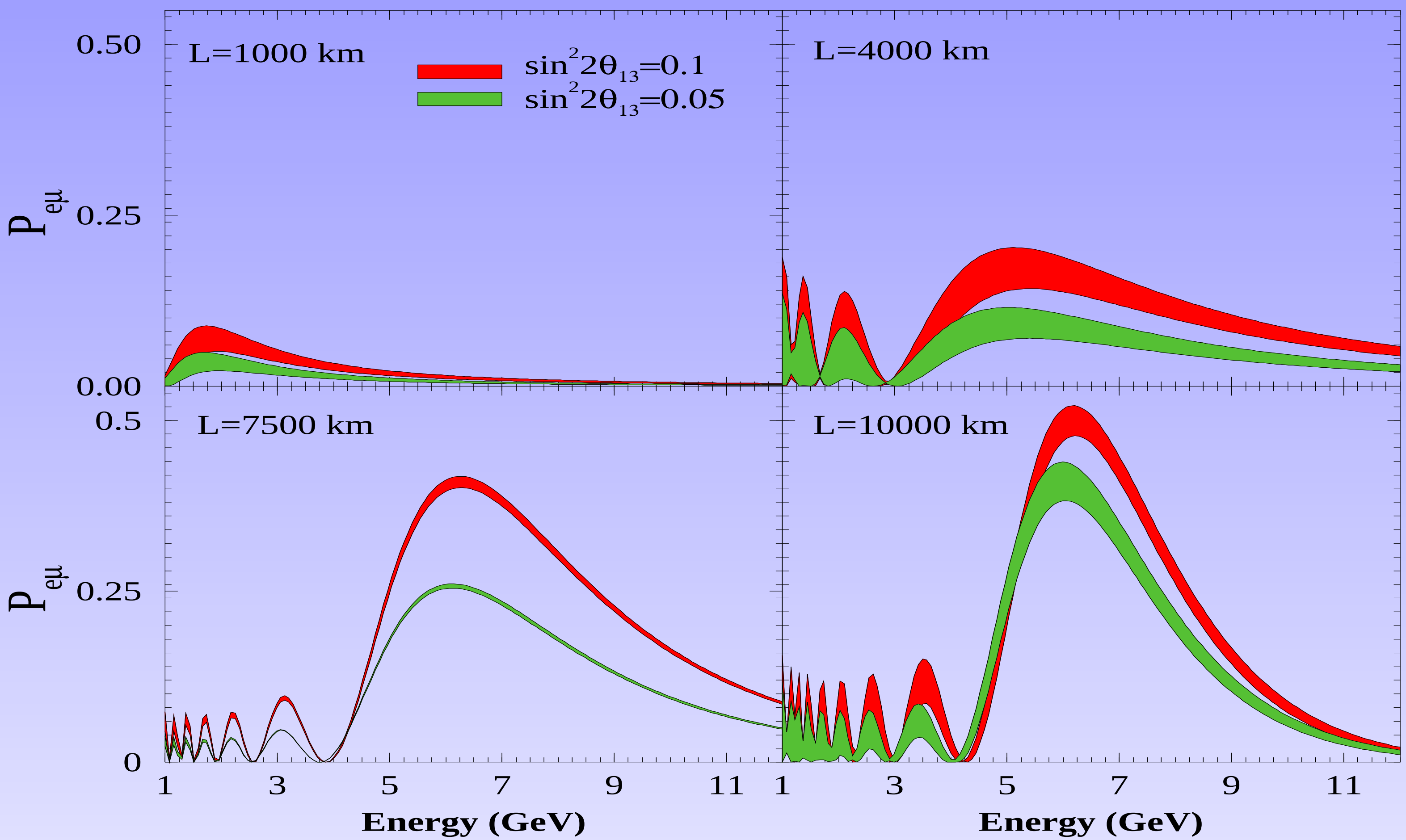
Transition Probability $P_{e\mu}$



Agarwalla, Choubey, Raychaudhuri, hep-ph/0610333

Normal .vs. Inverted hierarchy $\sin^2 2\theta_{13} = 0.1$

Transition Probability $P_{e\mu}$



Agarwalla, Choubey, Raychaudhuri, hep-ph/0610333

Two different values of $\sin^2 2\theta_{13}$ **Normal hierarchy**

Eight-fold Degeneracy

- $(\theta_{13},\ \delta_{CP})$ **intrinsic degeneracy**

  Burguet-Castell, Gavela, Gomez-Cadenas, Hernandez, Mena, hep-ph/0103258

- $(sgn(\Delta m^2_{31}),\ \delta_{CP})$ **degeneracy**

  Minakata, Nunokawa, hep-ph/0108085

- $(\theta_{23}, \pi/2 - \theta_{23})$ **degeneracy**

  Fogli, Lisi, hep-ph/9604415

Severely deteriorates the sensitivity

Recent MIND Simulations

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

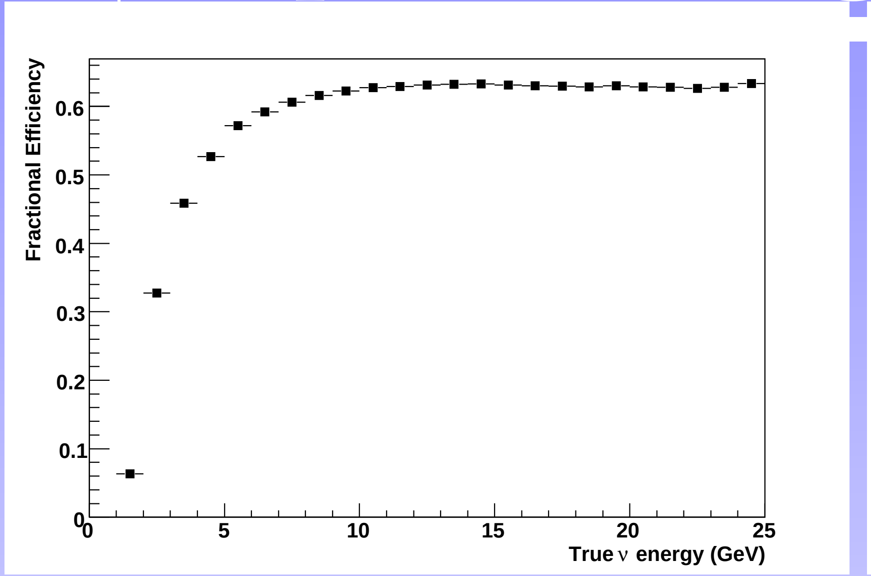
  Cervera, Laing, Martin-Albo, Soler, arXiv:1004.0358 [hep-ex]

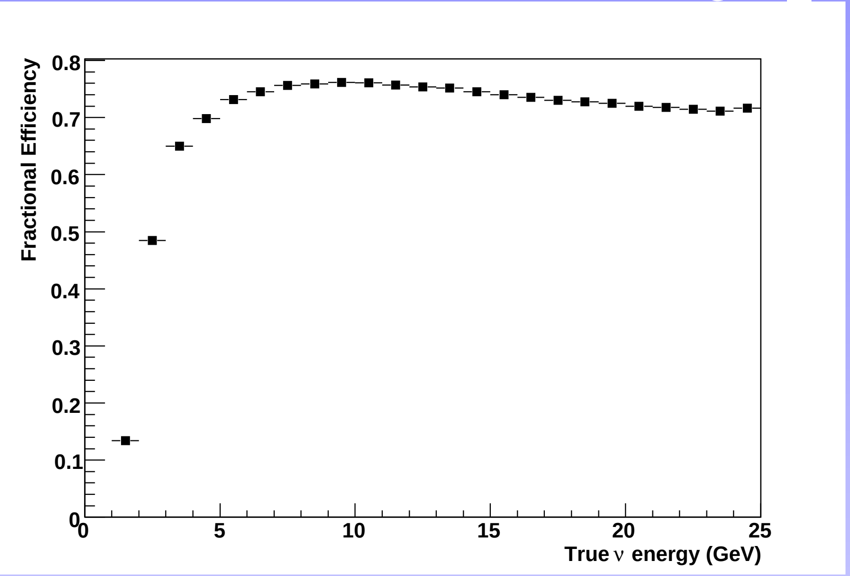
  A. Laing's Ph.D. thesis, Glasgow university (2010)

- 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

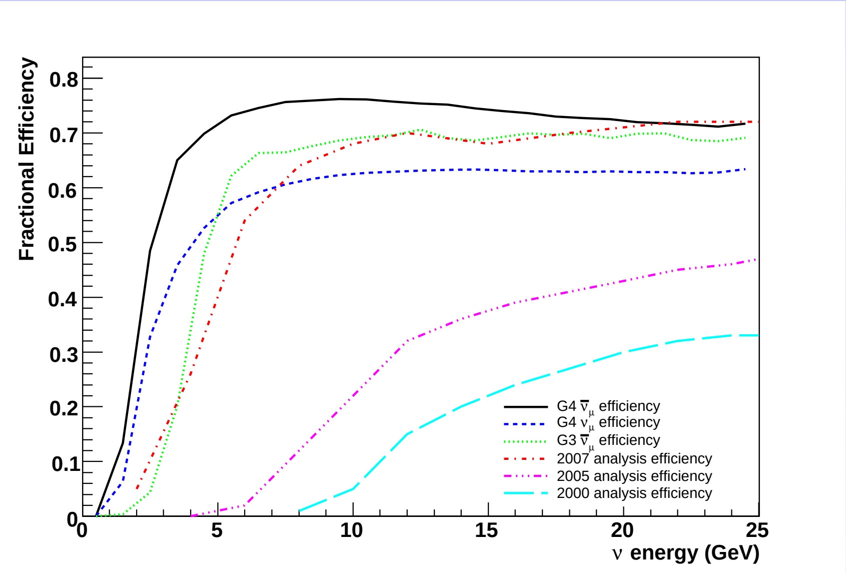
- Separate response functions for ν and $\bar{\nu}$ are available ⇒
  detection efficiency is better for $\bar{\nu}_\mu$ compared to ν_μ

Improved Signal Efficiency



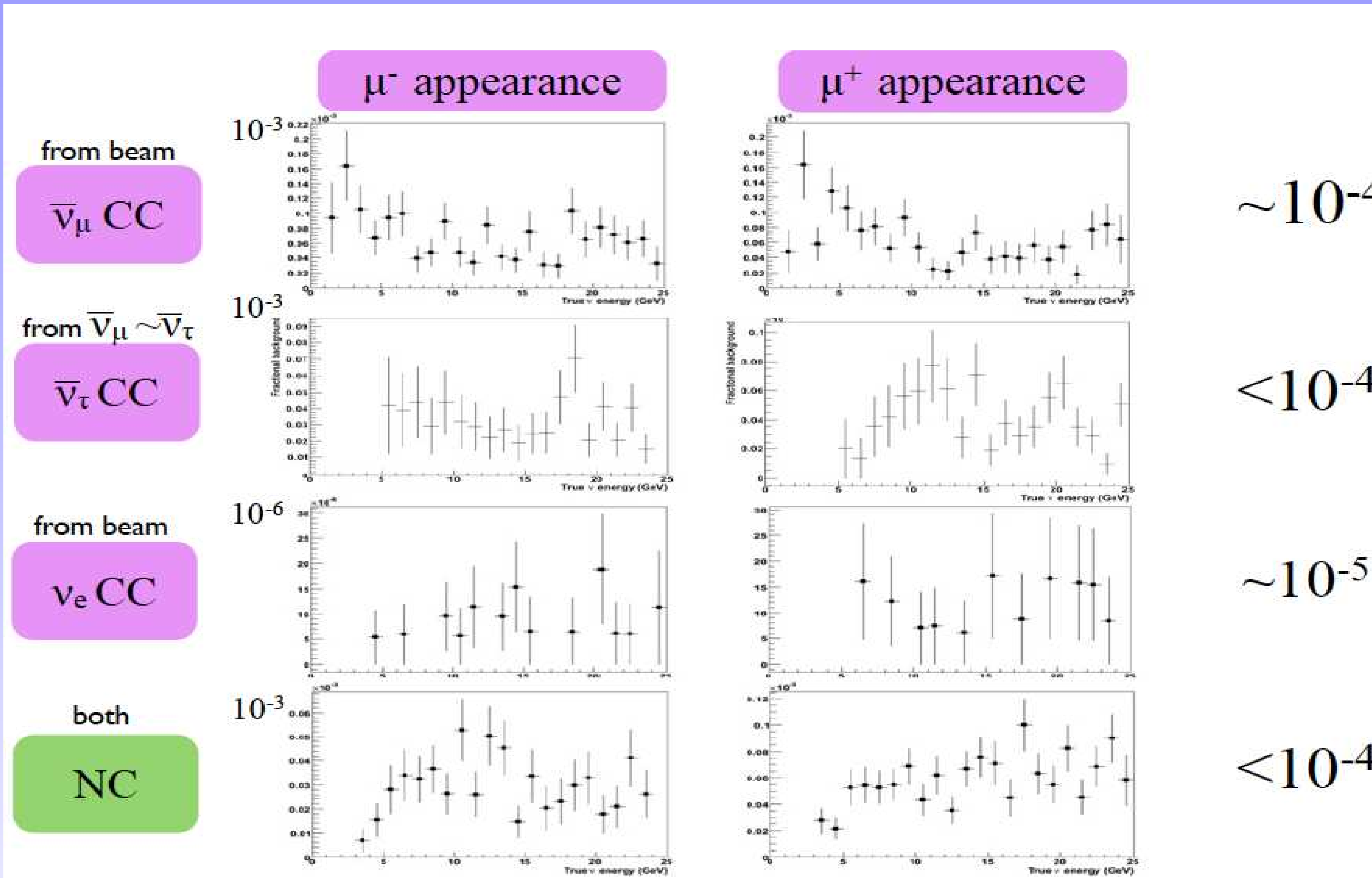


Left : μ^- appearance & Right : μ^+ appearance



QES & RES events added, threshold $\sim$ 2 GeV, plateau $\sim$ 5 GeV

Fractional Backgrounds



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Background levels expected for the appearance channels

ν_τ contamination

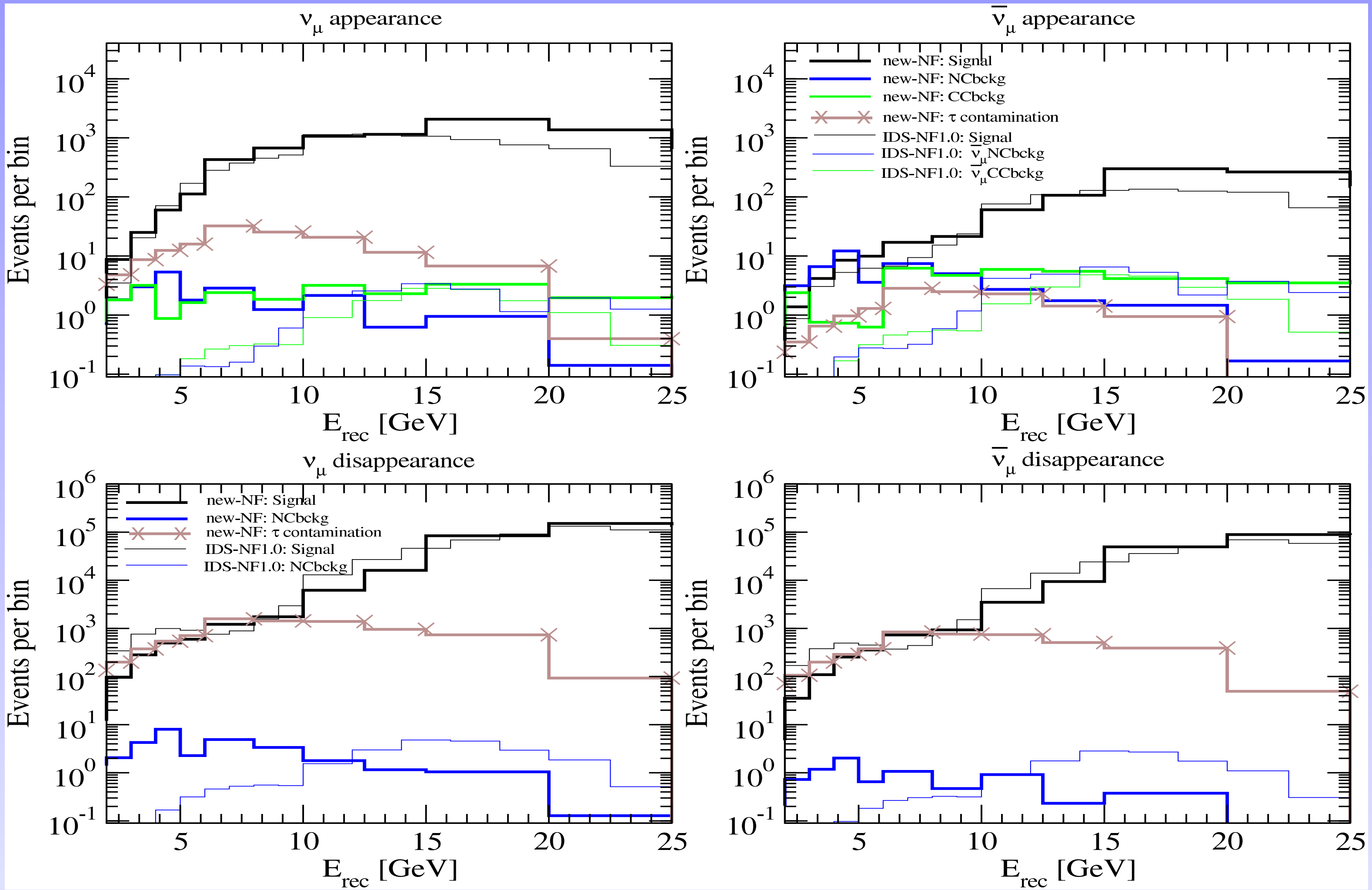
Issue of ν_τ contamination

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

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

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

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

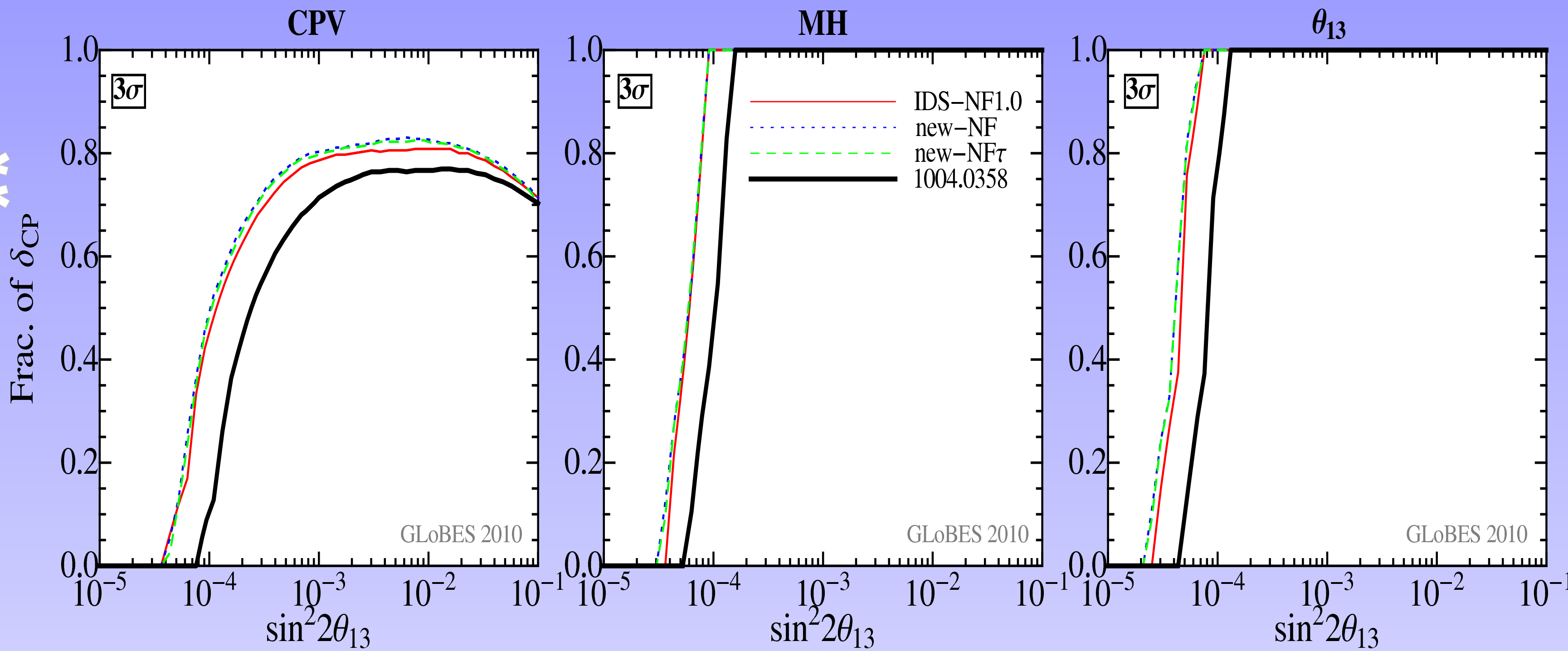
Event rates for new-NFτ

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

NH, $\theta_{13} = 5.6^\circ$ and $\delta_{\rm CP} = 0$

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

Comparison of discovery reach



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

"IDS-NF" refers to the detector in the IDS-NF baseline setup 1.0

Results with the migration matrices from arXiv:1004.0358 is indicated by the label "1004.0358"

The label "new-NF" refers to most up-to-date detector simulation in A. Laing's thesis

ν_τ contaminations in the app. and disapp. channels are, in addition, included in "new-NFτ" following arXiv:1005.2275

Two baselines 4 000 km and 7 500 km with two 50 kt MIND detectors and $E_\mu = 25$ GeV

More Results

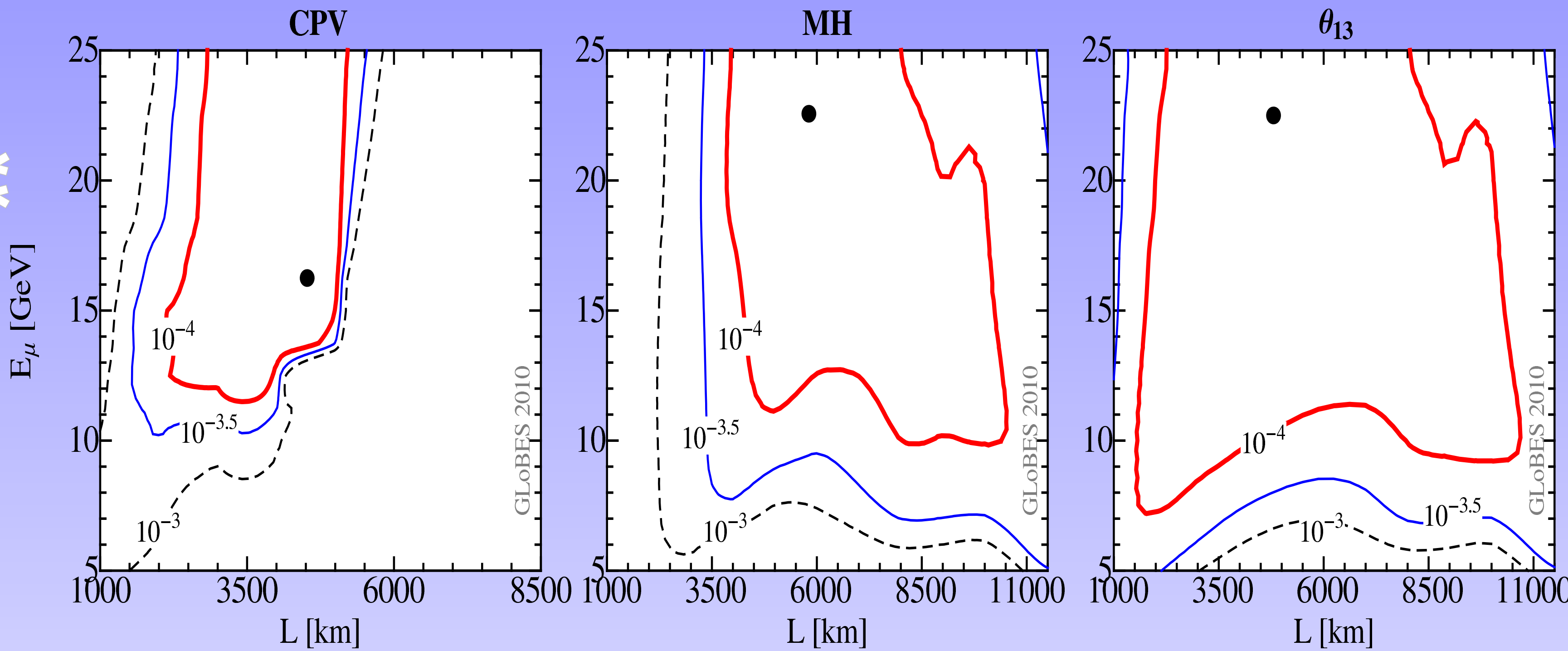
Optimization of a green-field setup

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

LENF .vs. HENF

- no particular accelerator and detector sites
- no constraints on the baselines and muon energy
- optimization is performed using the migration matrices from A. Laing's Ph.D. thesis
- Since the detection threshold has improved, can MIND detector interpolate between LENF and HENF?

Assume $\sin^2 2\theta_{13}$ is not known



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

Discovery reach in $\sin^2 2\theta_{13}$ for maximal CPV, MH, and θ_{13} as a function of L and E_μ

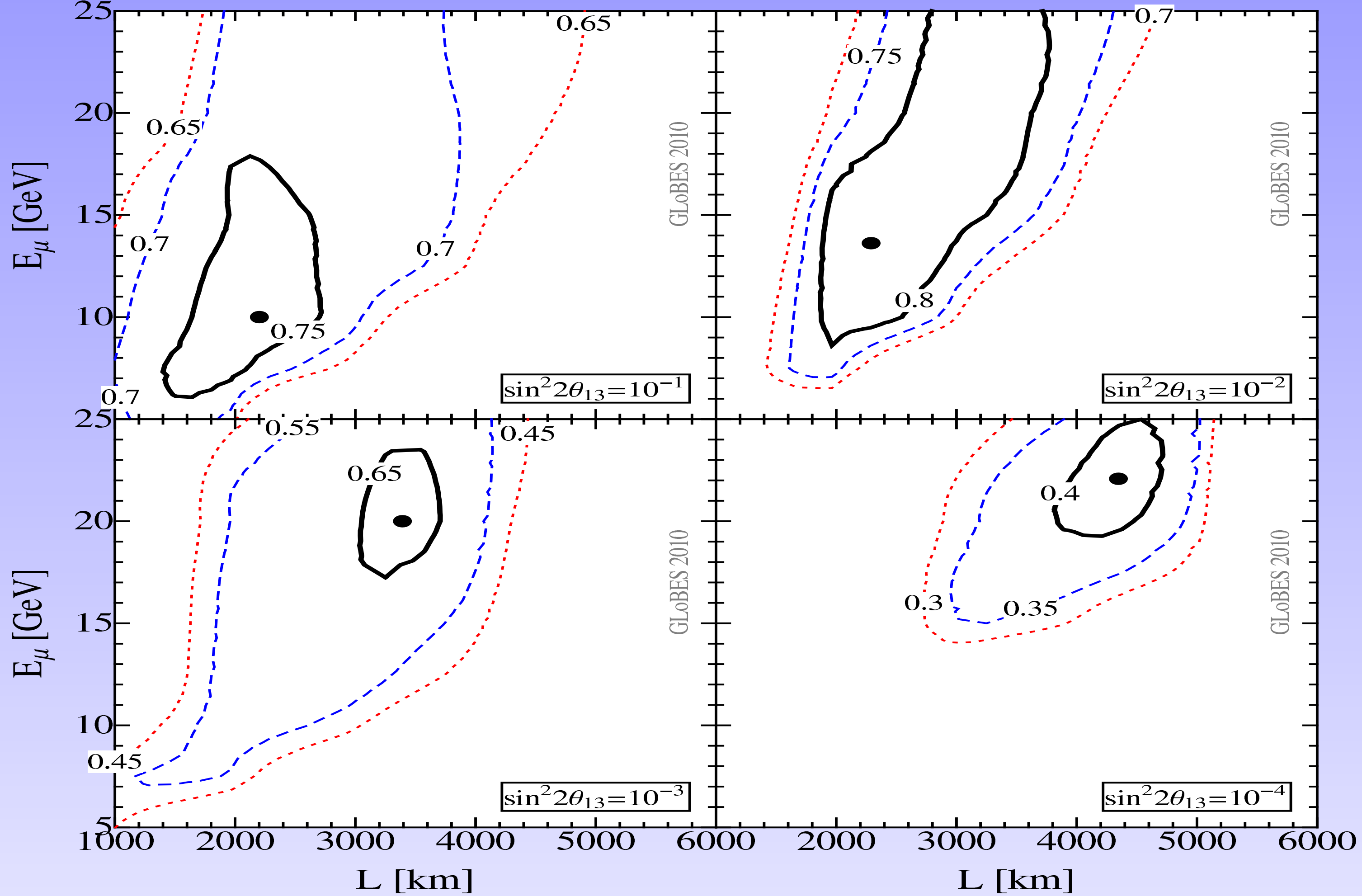
The contours show for how small (true) $\sin^2 2\theta_{13}$ the different quantities will be discovered at the 3σ CL, where $\delta_{\rm CP} = \pi/2$ is chosen as a true value in all cases

Optimal performance: (4519,16.25), (5805,22.57) and (4800,22.50). Here SF=1 is used with one 50 kt detector

What do we learn?

- CPV : 2500-5000 km baseline and E_μ above 12 GeV
- For $\delta_{\rm CP} = 3\pi/2$, a second baseline may be required
- Relatively low E_μ are allowed because of the low detection threshold
- MH : Baselines longer than 4000 km and E_μ larger than about 10-12 GeV are needed to cover the MSW resonance energy of about 8 GeV. Magic baseline (7500 km) is very useful for degeneracy resolution
- θ_{13} : Extremely wide baseline and energy range, posing the least constraints
- Note : All these results depend on the choice of $\delta_{\rm CP}$

Assume $\sin^2 2\theta_{13}$ is known



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

Frac. of δ_{CP} for which CPV will be discovered (3σ CL) as a function of L and E_μ for the single baseline NF. Here SF=1 is used with a 50 kt detector. Optimal performance: (2200,10.00), (2288,13.62), (3390,20.00) & (4345,22.08)

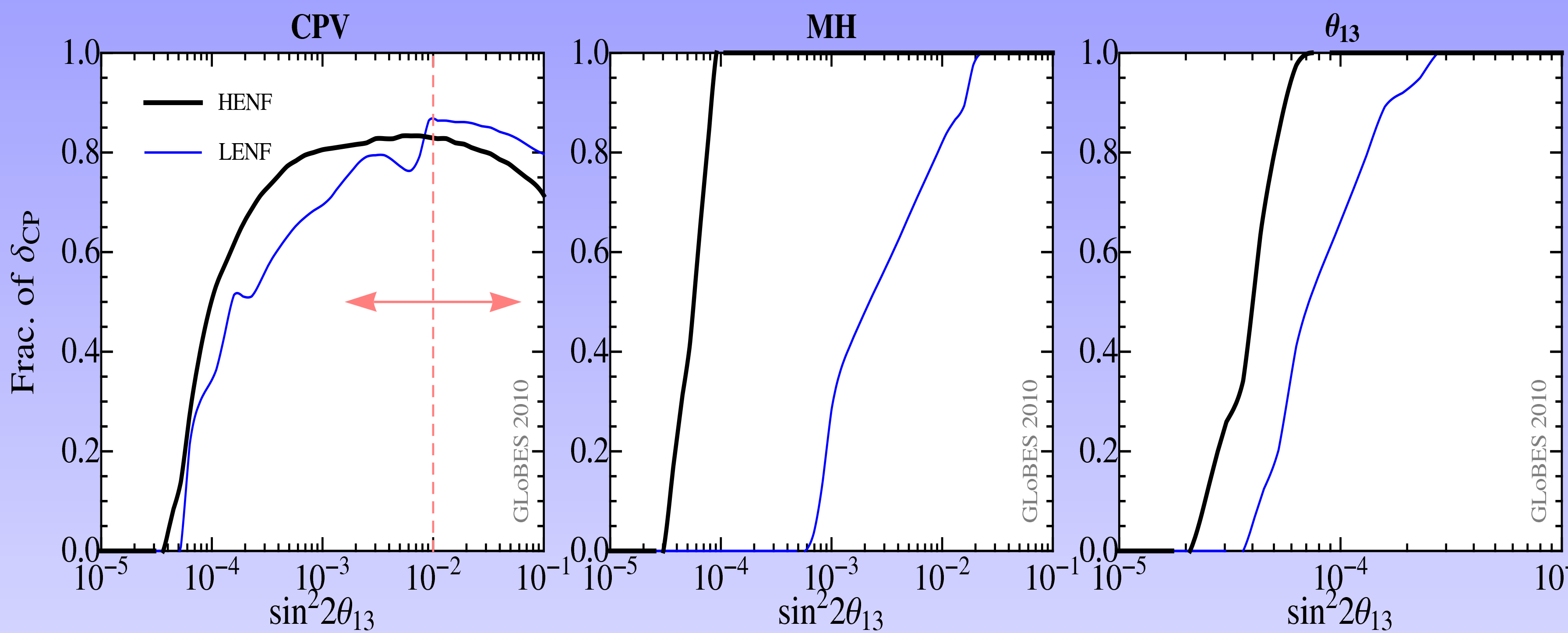
What is the message?

- Most interesting : optimization of the fraction of $\delta_{\rm CP}$ for which CPV can be discovered
- This strongly depends on the value of $\sin^2 2\theta_{13}$ chosen
- Large $\sin^2 2\theta_{13} \simeq 10^{-1}$: shorter baselines and lower energies are preferred. Even E_μ as low as 5 GeV at the FNAL-Homestake baseline of about 1300 km is not far from optimal
- MIND approaches the TASD performance of the LENF. Compared to earlier analyses without background migration, too high E_μ are in fact disfavored in the large $\sin^2 2\theta_{13}$ case

LENF .vs. HENF

LENF and HENF are just two versions of the same experiment in different optimization regions

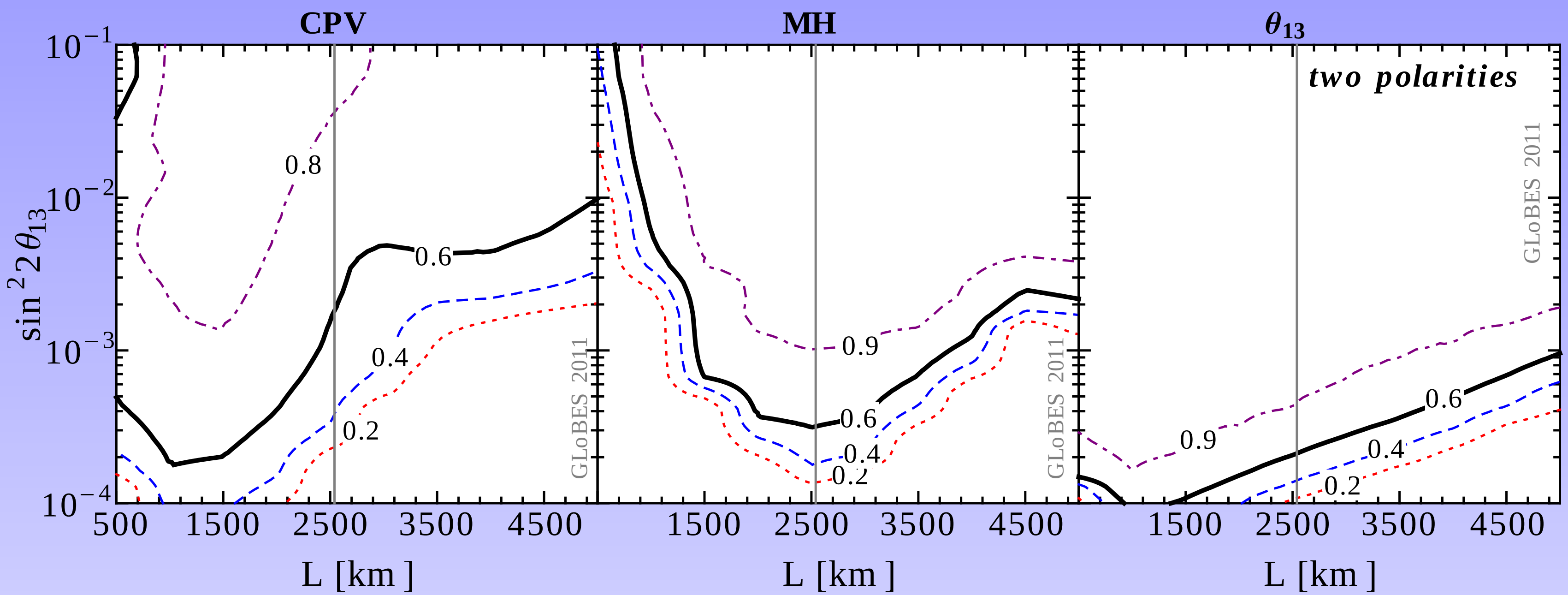
LENF .vs. HENF with MIND



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

Comparison of the discovery reaches of CPV, MH, and θ_{13} at the 3σ CL between a single baseline LENF with $E_\mu = 10$ GeV and $L = 2000$ km, and a two baseline HENF with $E_\mu = 25$ GeV, $L_1 = 4000$ km, and $L_2 = 7500$ km

LENF with Magnetized TASD



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

Total 1.25×10^{22} muons per polarity & E_μ = 5 GeV

25 kt magnetized TASD with 94% efficiency above 1 GeV, 10% energy resolution and 10^{-3} background level

Talk by Peter Ballett

Concluding remarks

- **Lower threshold and higher efficiencies compared to earlier simulations imply that the MIND detector characteristics are getting more similar to the characteristics of the detectors proposed for the LENF (magnetized TASD)**

- **We recover the L-E_μ-optimization of the LENF for large $\sin^2 2\theta_{13}$ with MIND : a single baseline NF with E_μ as low as 5 GeV and a baseline as short as FNAL-Homestake (about 1300 km) might be sufficient**

Thank You