Physics performance of a Low Energy Low-Luminosity Neutrino Factory

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Based on the collaboration
Christensen, Coloma, Huber, 1301.7727 [hep-ph]

NuFact2013
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The golden channel

The best chance to measure CPV is through:

$$P_{e\mu}^{\pm}(\theta_{13},\delta) = X_{\pm}\sin^2 2\theta_{13}$$
$$+ Y_{\pm}\cos\theta_{13}\sin 2\theta_{13}\cos\left(\pm\delta - \frac{\Delta m_{31}^2 L}{4E}\right)$$
$$+ Z$$

Cervera et al., hep-ph/0002108

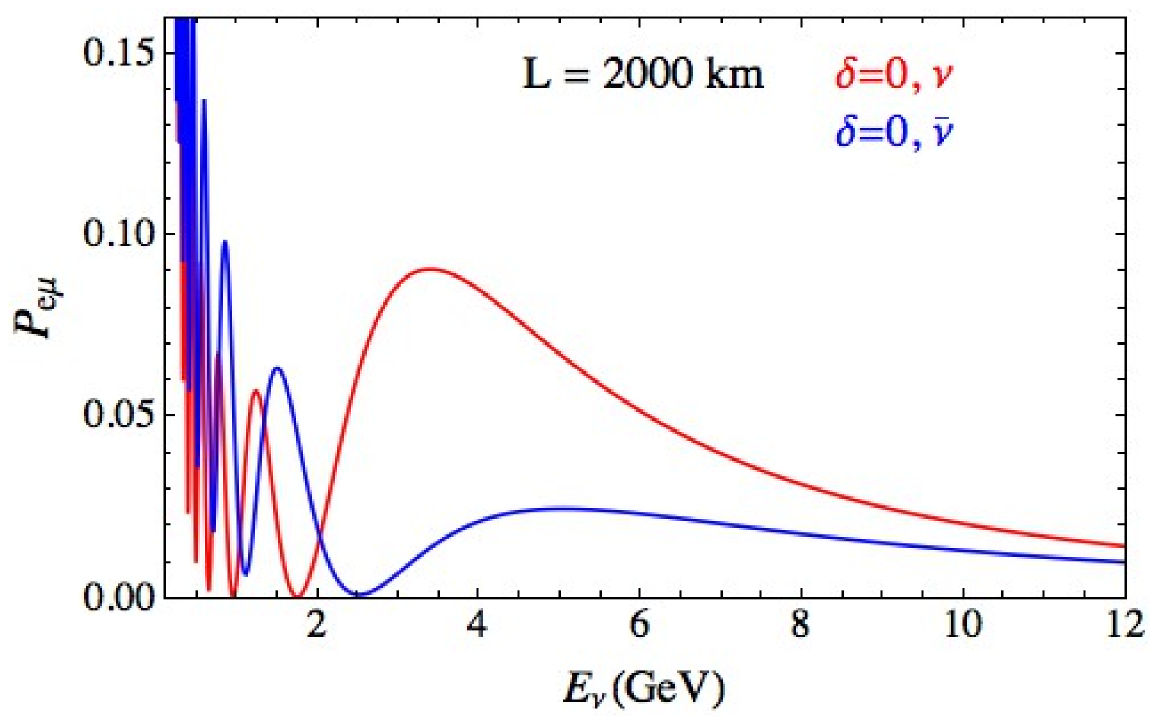
In vacuum: $\begin{cases} X_{vac} \propto \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right) \\ Y_{vac} \propto \sin\left(\frac{\Delta m_{31}^2 L}{4E}\right)\sin\left(\frac{\Delta m_{21}^2 L}{4E}\right) \end{cases}$

The golden channel

The best chance to measure CPV is through:

$$P^{\pm}_{e\mu}(\theta_{13},\delta) = X_{\pm}\sin^2 2\theta_{13} + Y_{\pm}\cos\theta_{13}\sin 2\theta_{13}\cos\left(\pm\delta - \frac{\Delta m^2_{31}L}{4E}\right) + Z$$

In matter:



The platinum channel

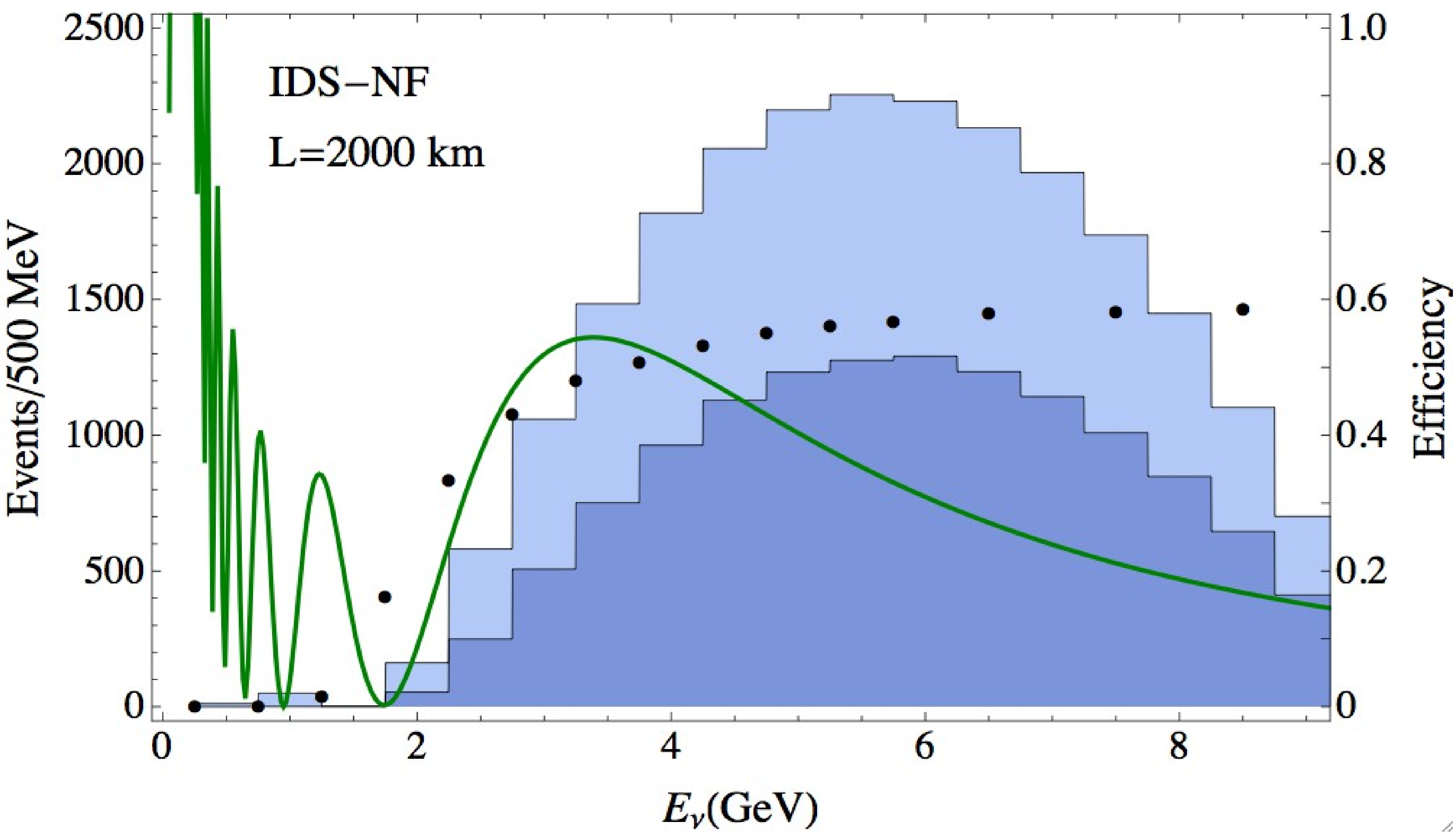
$$P_{e\mu}^{\pm}(\theta_{13},\delta) = X_{\pm}\sin^2 2\theta_{13} + Y_{\pm}\cos\theta_{13}\sin 2\theta_{13}\cos\left(\pm\delta - \frac{\Delta m^2_{31}L}{4E}\right) + Z$$

$$P_{\mu e}{}^{\pm}(\theta_{13},\delta) = X_{\pm}\sin^2 2\theta_{13} + Y_{\pm}\cos\theta_{13}\sin 2\theta_{13}\cos\left(\mp\delta - \frac{\Delta m^2_{31}L}{4E}\right) + Z$$

Types of neutrino beams

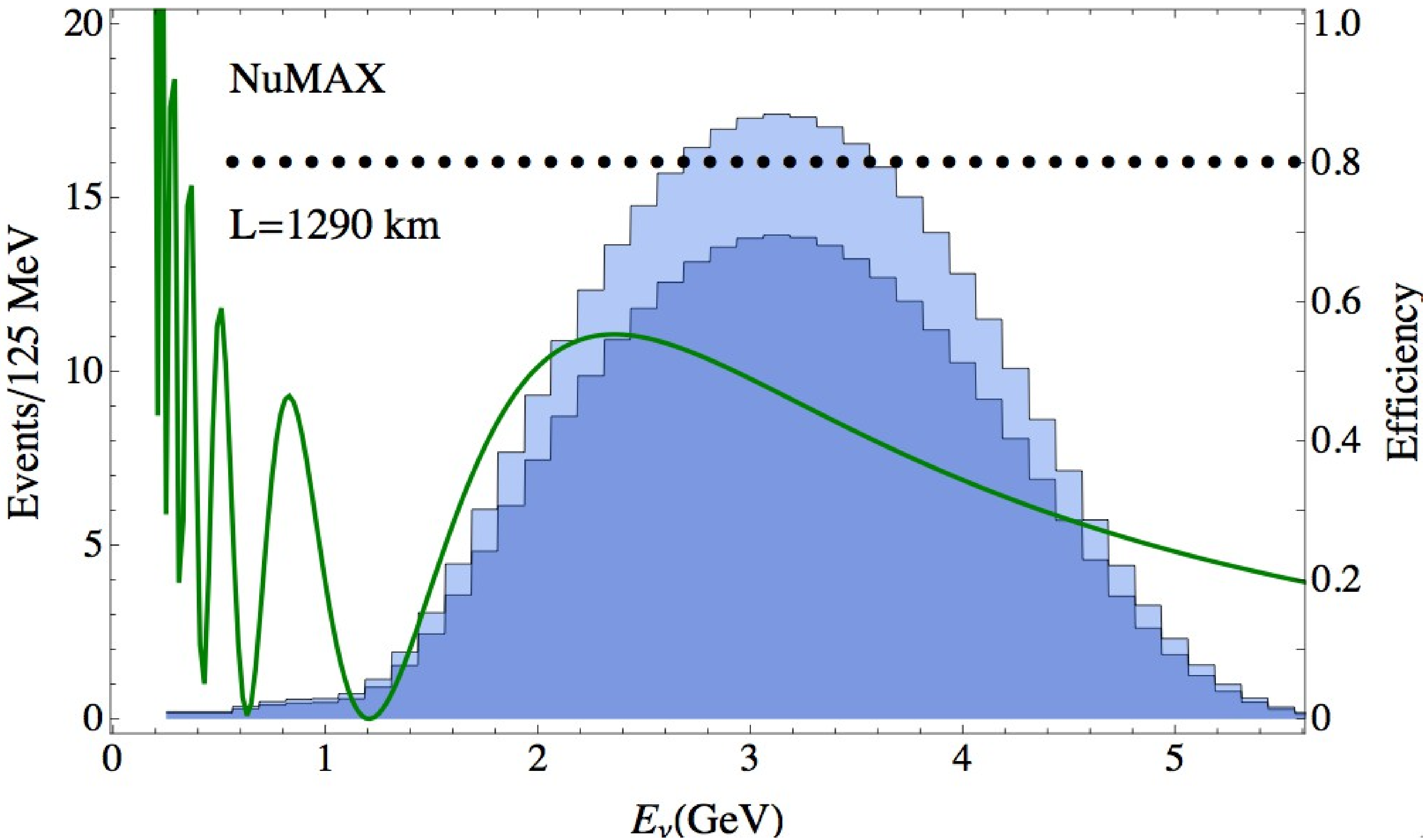
- Muon-based neutrino beams $\boxed{\mu^+ \to e^+ \nu_e \bar{\nu}_\mu}$
  - Low uncertainties, no intrinsic bg, flavor rich
  - Magnetization is in principle required
- Pion-based neutrino beams $\boxed{\pi^+ \to \mu^+ \nu_\mu}$
  - Intrinsic bg, large flux and cross section uncertainties
  - Technology already well-known
  - No magnetization required

The IDS-NF



IDS−NF
L=2000 km
Events/500 MeV
Efficiency
E_ν(GeV)
0
500
1000
1500
2000
2500
0
0.2
0.4
0.6
0.8
1.0
0
2
4
6
8

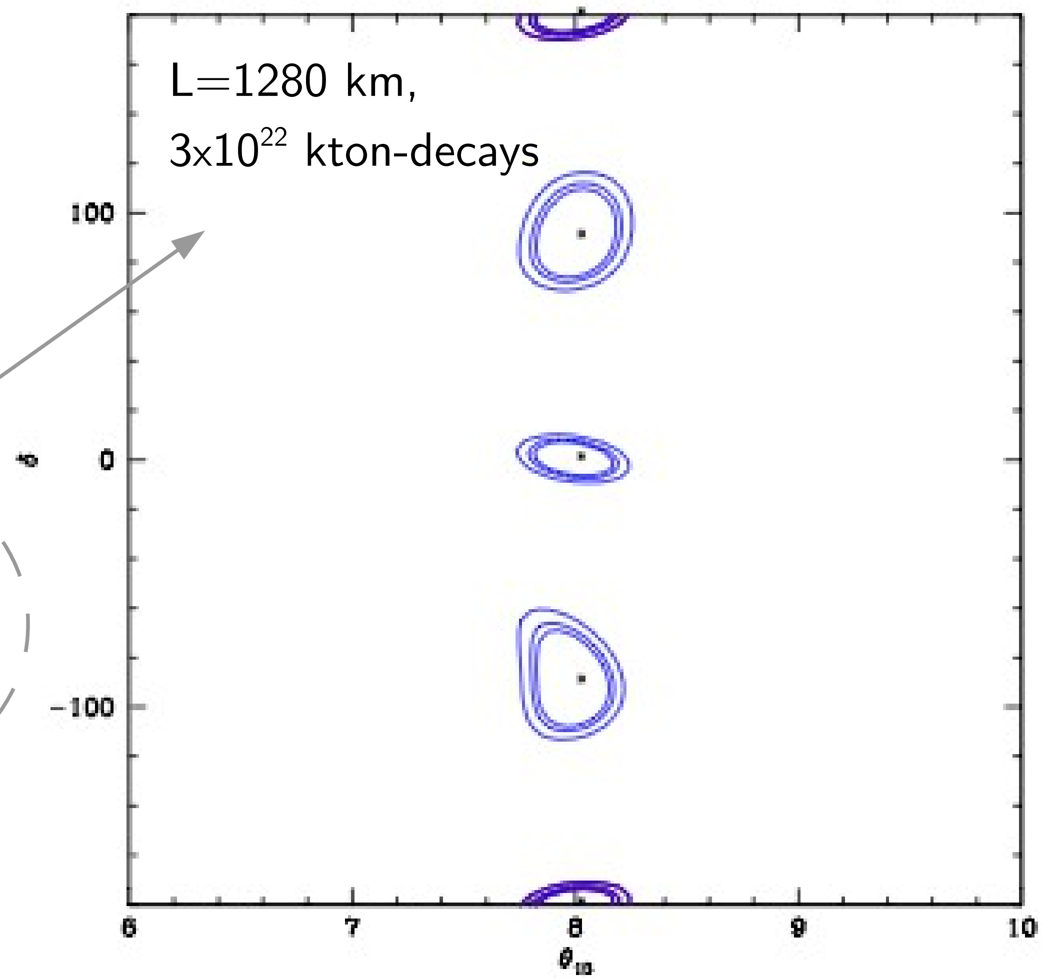
The Low Energy concept



The Low Energy Neutrino Factory

The golden channel at a low energy (4.12 GeV) neutrino factory is well-known to give an excellent performance in the large θ_{13} scenario

$3\text{x}10^{20}$ useful decays per year; 5 years; 20 kton TASD detector



A higher luminosity option ($1\text{x}10^{23}$ kton-decays) was also considered

Geer, Mena, Pascoli, hep-ph/0701258

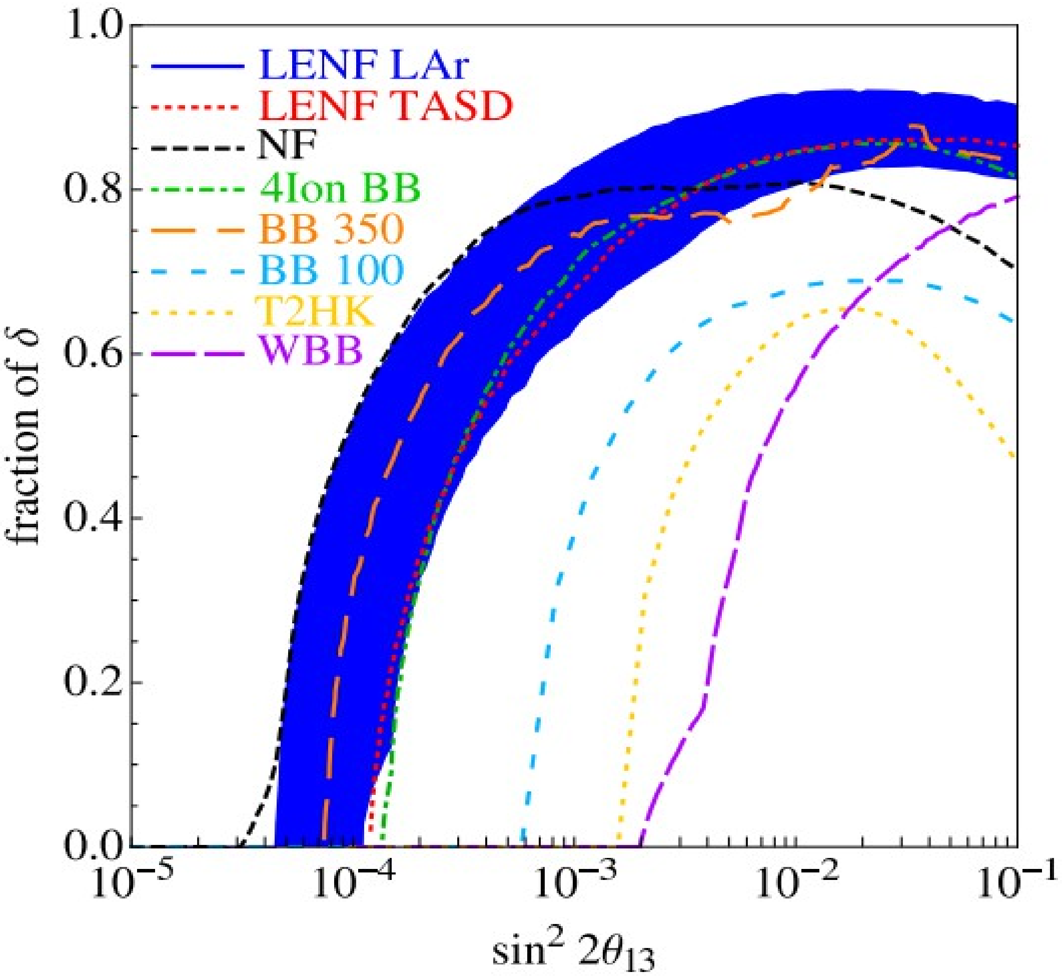
Bross, Ellis, Geer, Mena, Pascoli, 0709.3889 [hep-ph]

The Low Energy Neutrino Factory

The addition of the platinum channel was studied in 0911.3776 [hep-ph], assuming $5{\times}10^{20}$ or $1.4{\times}10^{21}$ useful decays per year, and 10 years

20 kton TASD detector, and 100 kton LAr detector were considered

Platinum channel effect was found to be negligible (for small θ_{13})



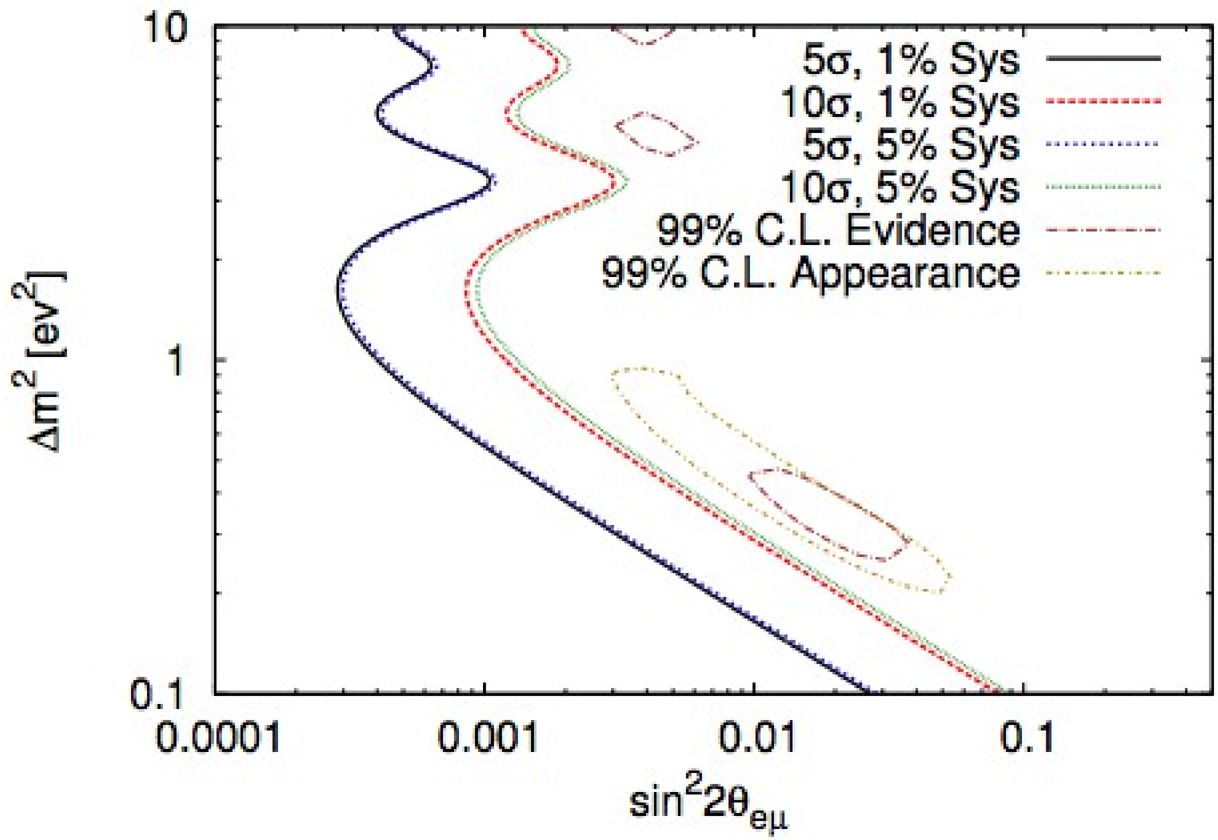
Fernandez-Martinez, Li, Pascoli, Mena, 0911.3776 [hep-ph]

NuSTORM

NuSTORM considers low energy muons (3.8 GeV)

Three main purposes:

- cross section measurements in the low energy regime
- sterile neutrino searches
- muon acceleration R&D



NuSTORM EoI, 1305.1419 [hep-ph]
NuSTORM coll., 1206.0294 [hep-ex]
Tunnell, 1205.6338 [hep-ph]

NuMAX

Neutrinos from Muon Accelerators at project X

NuMAX

- 1 MW, 3 GeV protons from PX-II
- No muon cooling
- Acceleration to 5 GeV
- 1.6×10^{20} useful muon decays per year

For details, see 1308.0494 [hep-ph]

NuMAX

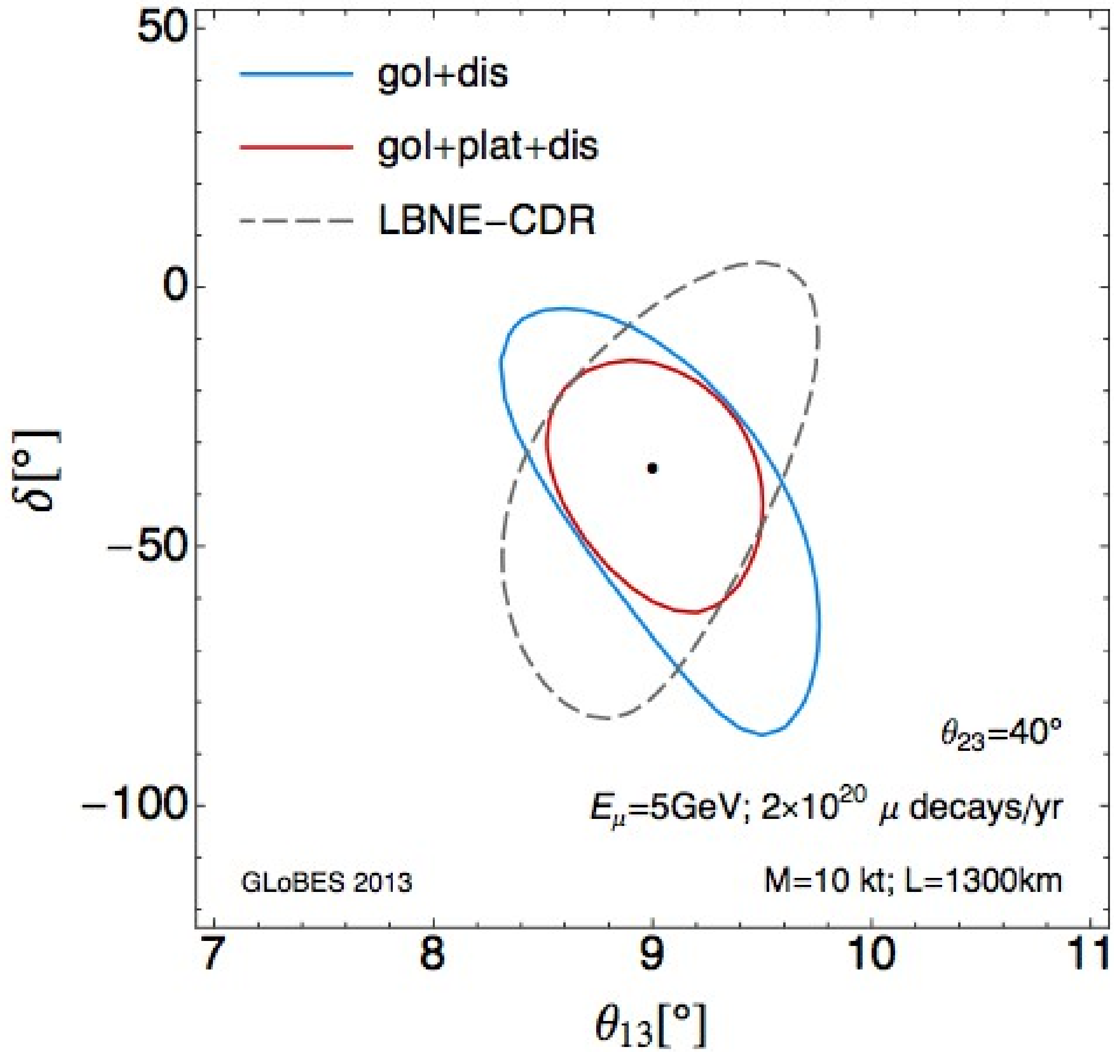
A magnetized 10 kton LAr detector is considered:

- Efficient at low energies
- High energy resolution
- Synergy with LBNE-phase I
- Other applications: atmospherics, supernova, proton decay

	Channel	Effs.	Bg. Rej.	$\sigma(E_\nu)$	E_ν (GeV)
LAr	ν_μ	80%	99.9%	$0.2\sqrt{E}$	$[0.5, 5]$
	ν_e	80%	99%	$0.15\sqrt{E}$	$[0.5, 5]$
TASD	ν_μ	73%-94%	99.9%	$0.2\sqrt{E}$	$[0.5, 5]$
	ν_e	37%-47%	99%	$0.15\sqrt{E}$	$[0.5, 5]$

LBNE coll., 1110.6249 [hep-ex]
Bross et al., 0709.3889 [hep-ph]
Fernandez-Martinez et al., 0911.3776 [hep-ph]

Results



Christensen, Coloma, Huber, 1301.7727 [hep-ph]

Non-magnetized LAr?

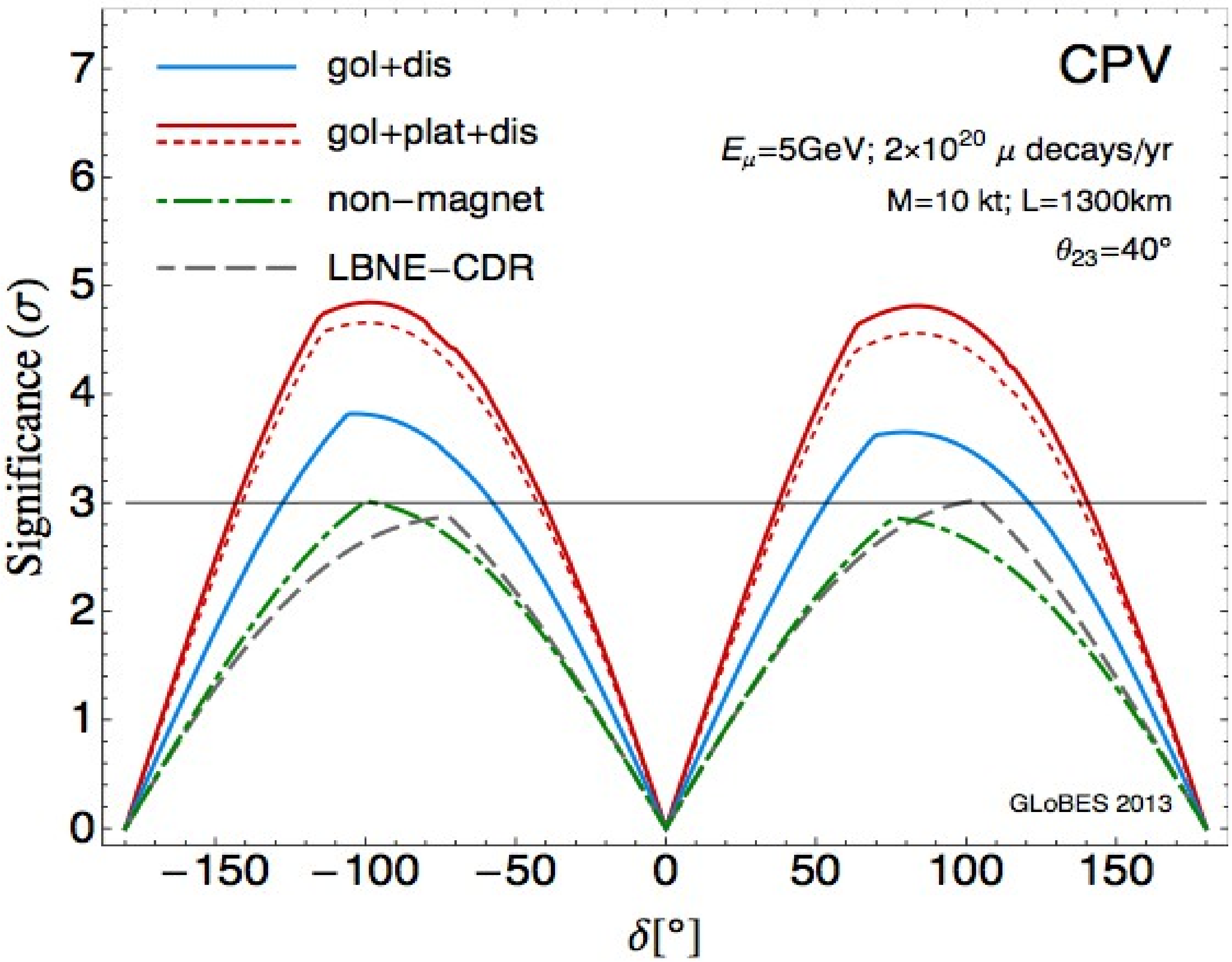
Charge separation can in principle be done statistically:

- Protons can in principle be tagged in ν interactions
- Different absorption rates for μ^+ and μ^-. (Michel electron is not observed for μ^-)
- Different momentum distribution for the charged lepton

We consider also a non-magnetized detector, with charge separation between 70% and 90%

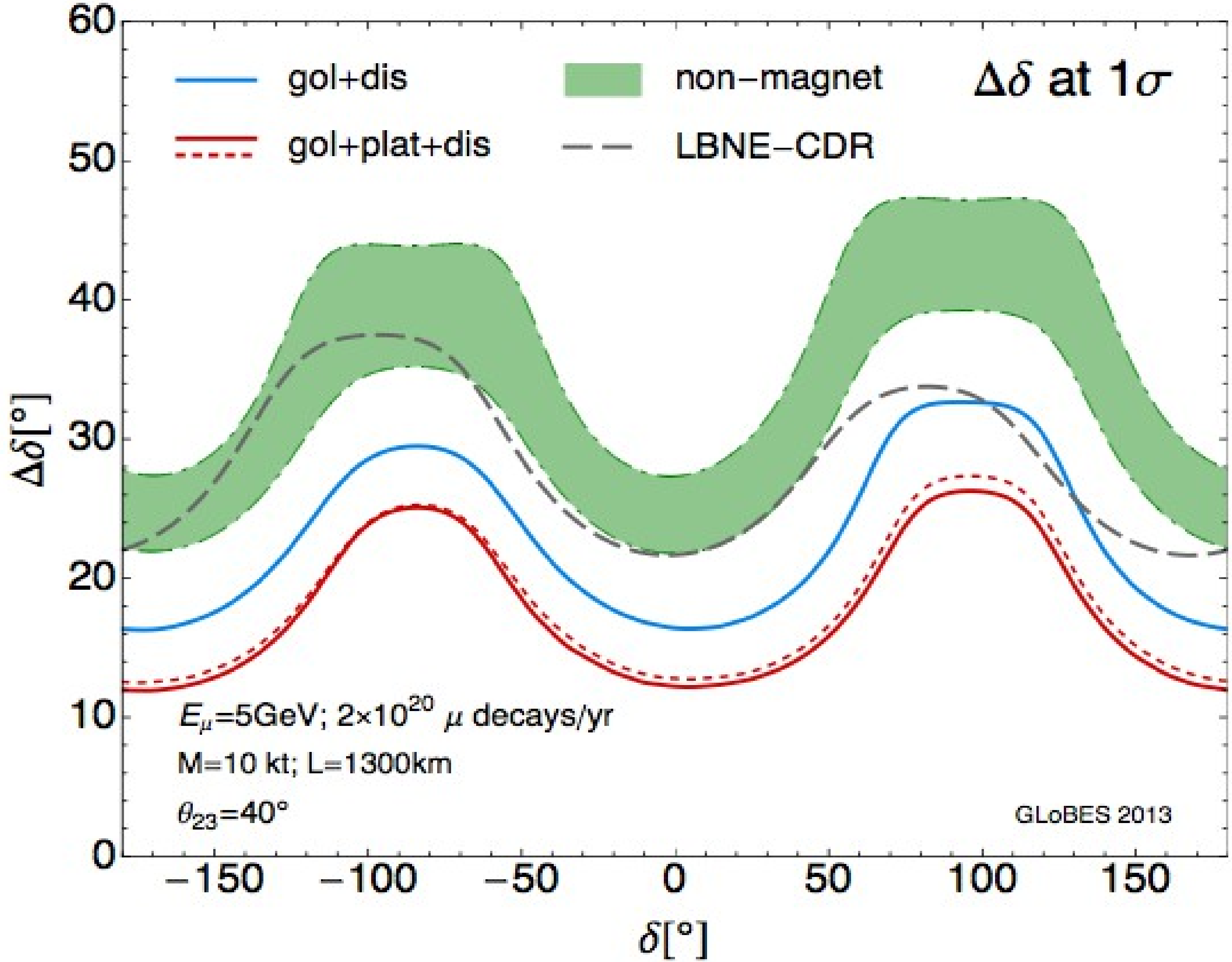
(see, for instance, 0805.2019 [hep-ph] or 1102.1964 [hep-ex])

Results



Christensen, Coloma, Huber, 1301.7727 [hep-ph]

Results



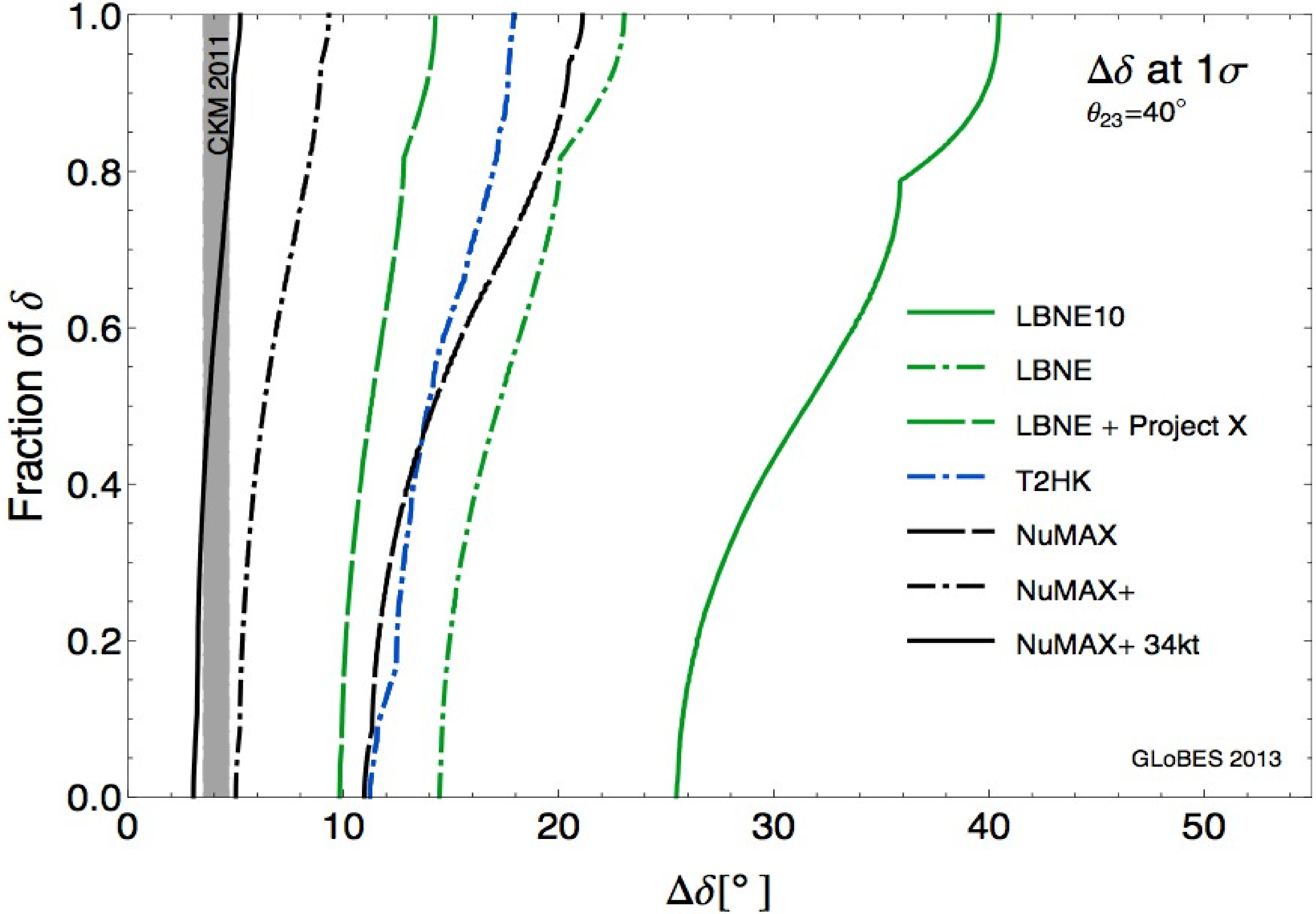
Christensen, Coloma, Huber, 1301.7727 [hep-ph]

NuMAX

Neutrinos from Muon Accelerators at project X

NuMAX		NuMAX+
• 1 MW, 3 GeV protons from PX-II	→	• 3 MW, 3 GeV protons from PX-II
• No muon cooling	→	• Muon cooling
• Acceleration to 5 GeV		• Acceleration to 5 GeV
• $1.6\text{x}10^{20}$ useful muon decays per year	→	• $1\text{x}10^{21}$ useful muon decays per year

Future upgrades to a full NuFact



Conclusions

- A low energy low luminosity neutrino factory represents the logical intermediate step between:
  - A very low energy physics programme, which includes sterile neutrino searches as well as neutrino cross section measurements in the low energy regime
  - A discovery and precision physics programme: a full luminosity NF is giving the best chances to discover CP violation, plus is the only facility capable of reaching precision comparable to the quark sector
- Such facility can be built without muon cooling in its first stage

Conclusions

- We have restricted the baseline to match the Fermilab-Homestake distance (1300 km). We find that:
  - We find that, for a large value of θ_{13}, the combination of golden and platinum channels gives optimal performance for both CP violation and mass hierarchy discovery potentials
  - Further upgrades include: muon cooling, proton driver, and detector mass. After upgrading, performance is comparable to the IDS-NF
- We have also checked that the performance of NuMAX with a non-magnetized detector would still be comparable to that of LBNE-I

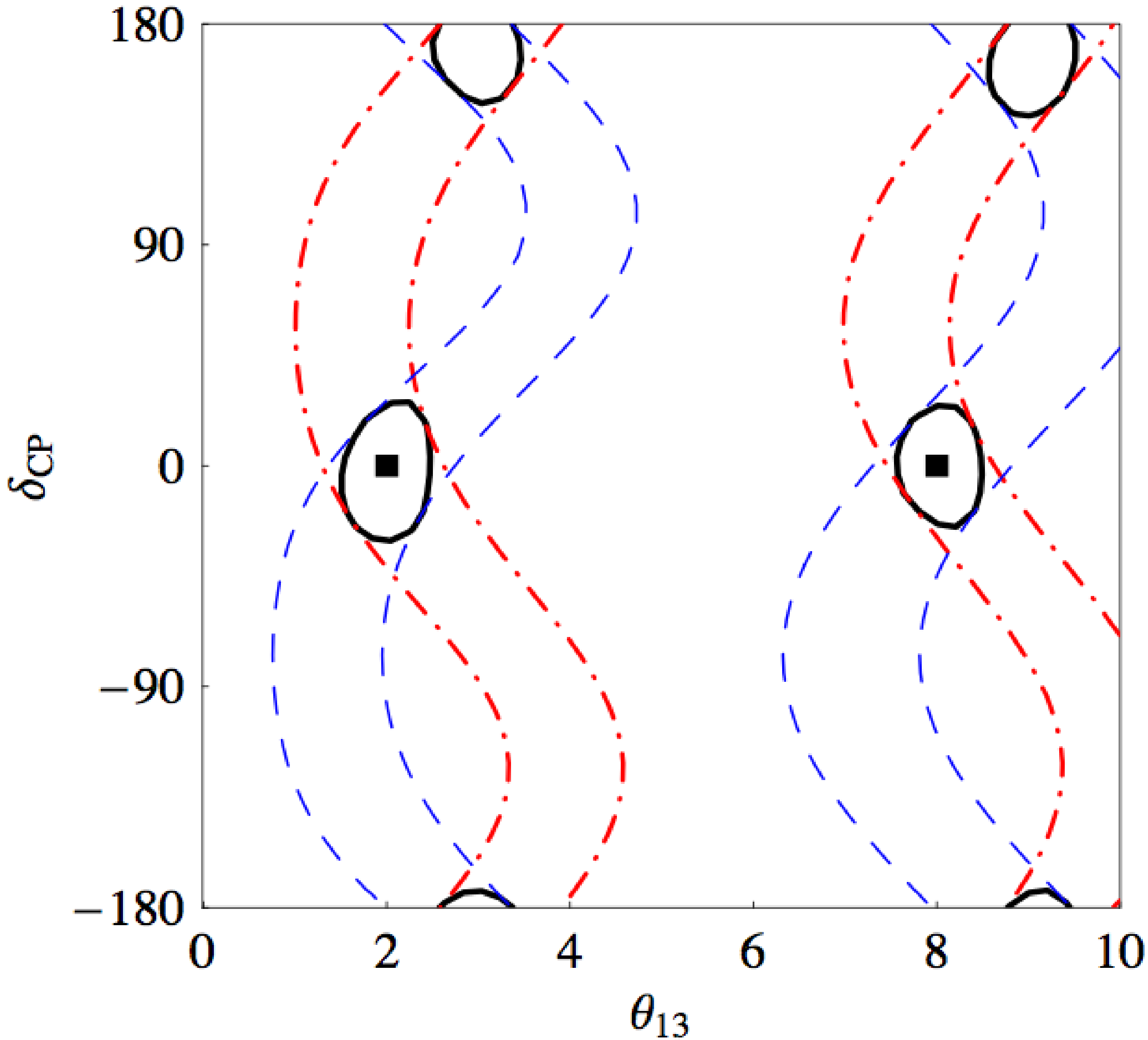
Thank you!

Backups

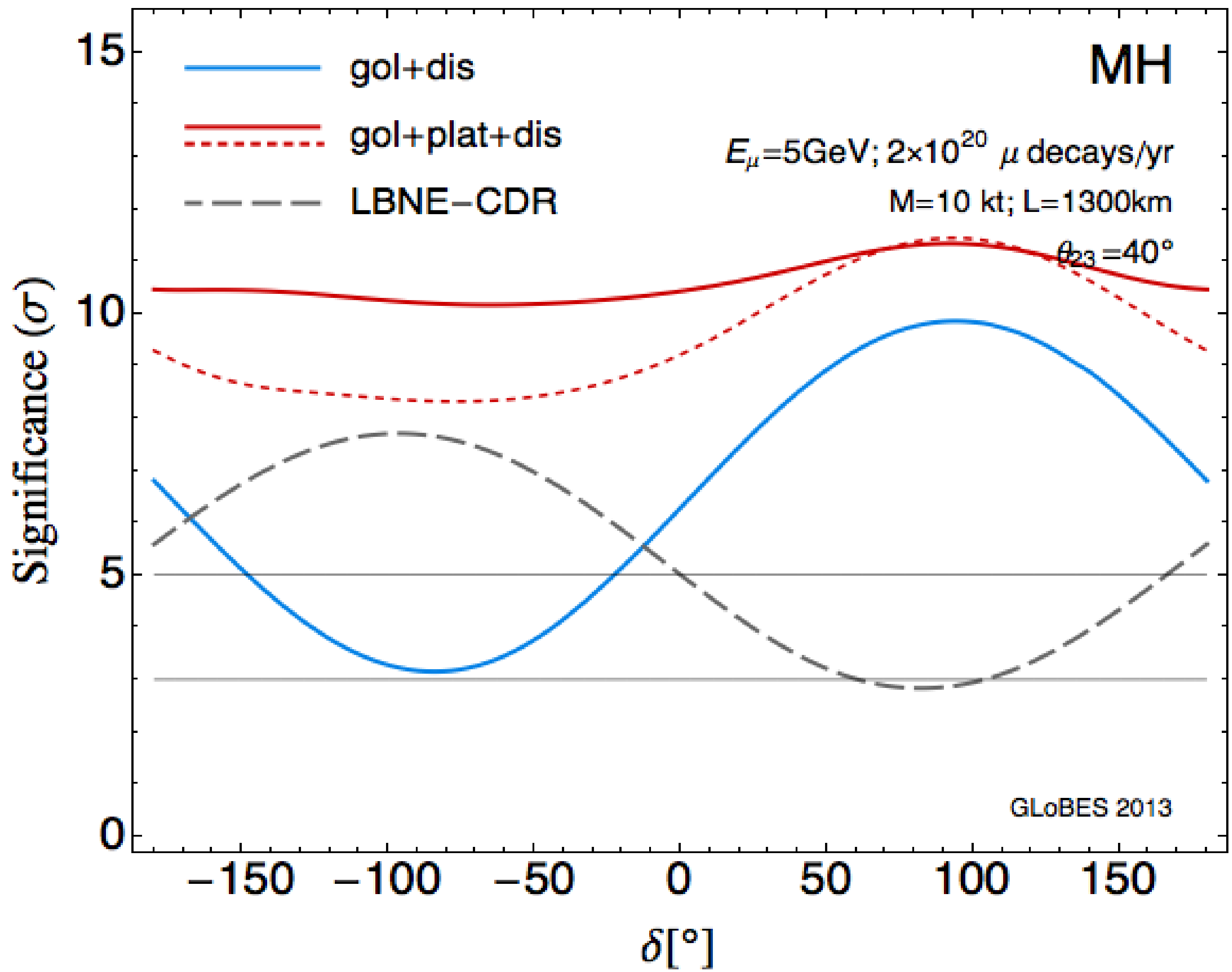
Number of events

Channel	$\nu_e \to \nu_\mu$	$\nu_\mu \to \nu_e$	$\nu_\mu \to \nu_\mu$
Signal	267	276	1485
Background	7	73	17
Channel	$\bar{\nu}_e \to \bar{\nu}_\mu$	$\bar{\nu}_\mu \to \bar{\nu}_e$	$\bar{\nu}_\mu \to \bar{\nu}_\mu$
Signal	52	59	562
Background	6	73	6

Combination of ν and $\bar{\nu}$ data



MH discovery potential

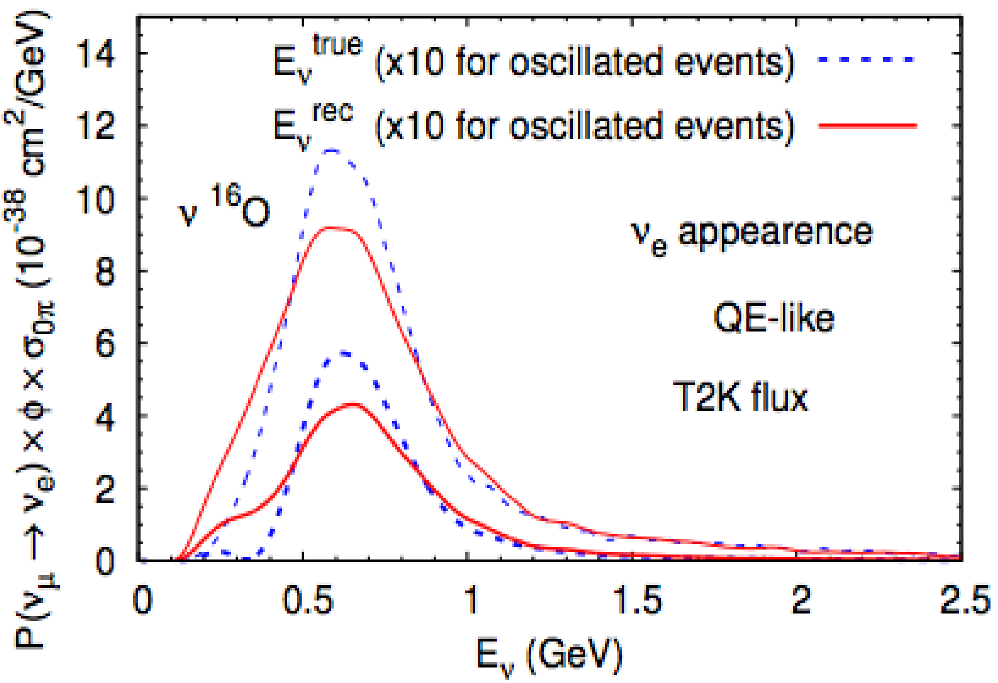


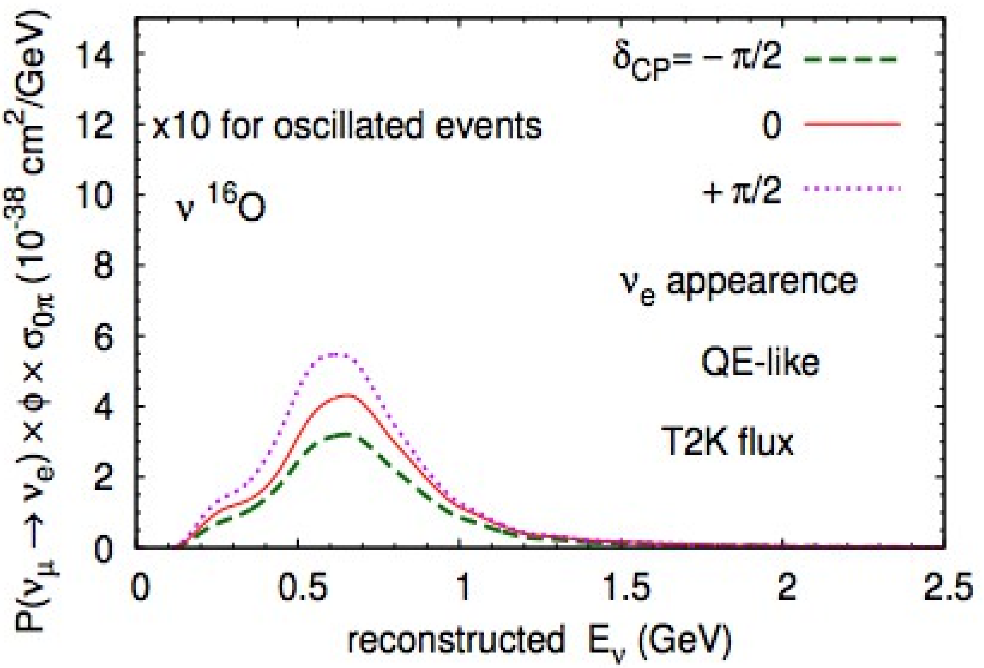
Low Luminosity scenarios

	Useful decays per year	Detector Mass	Number of years	Exposure (in kton-decays)
Geer et al., hep-ph/0701258	3×10^{20} 5×10^{20}	20 20	5 10	3×10^{22} 1×10^{23}
Bross et al., 0709.3889 [hep-ph]	5×10^{20} 1×10^{21}	20* 30*	10 10	1×10^{23} 3×10^{23}
Fernandez-Martinez et al., 0911.3776 [hep-ph]	5×10^{20} 1.4×10^{21}	20 100	10 10	1×10^{23} 1.4×10^{24}
This work	2×10^{20}	10	10	2×10^{22}

*detector mass times efficiency

Nuclear effects and FSI



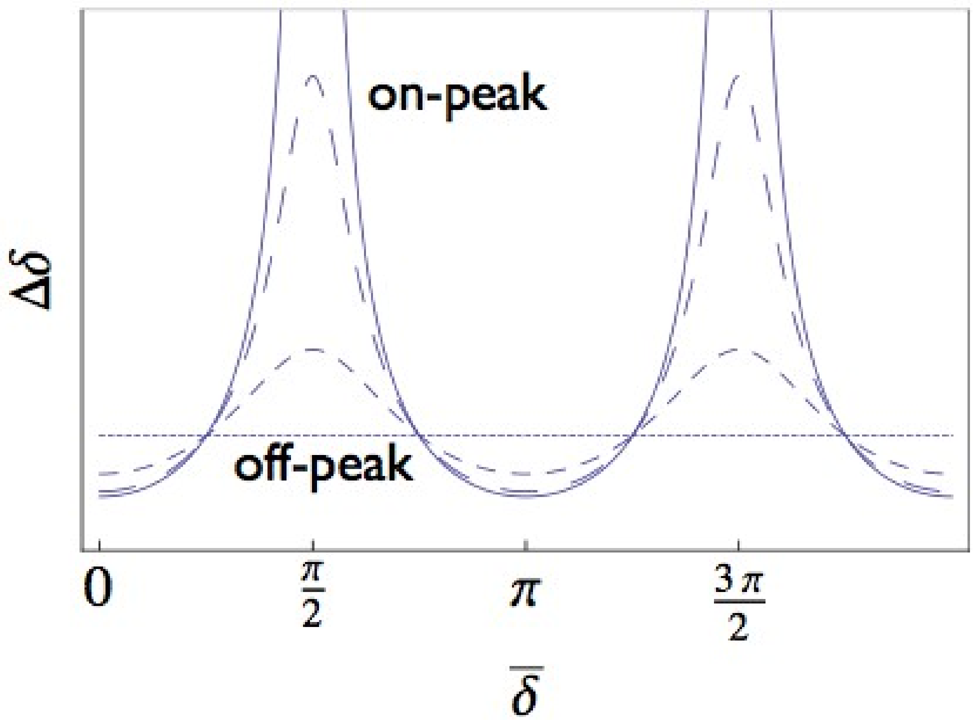


Lalakulich, Mosel and Gallmeister, 1208.3678 [nucl-th]

Precision

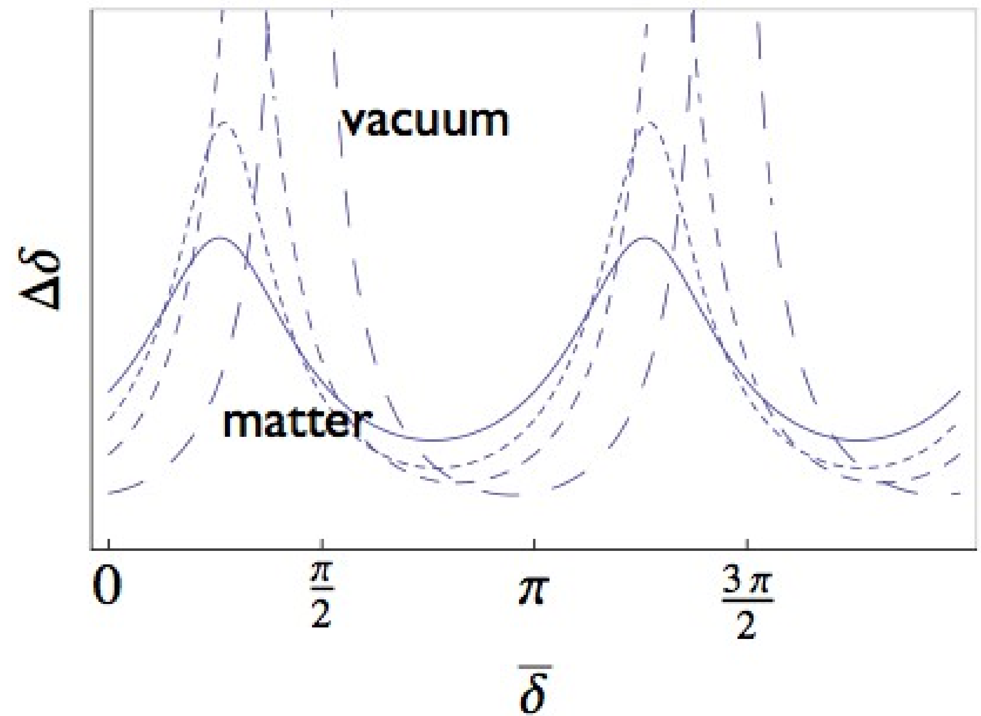
VACUUM

$$(\Delta\delta)_\pm \propto f[\Delta]\frac{1}{\sin\left(\frac{\pi}{2} \mp \delta\right)}$$



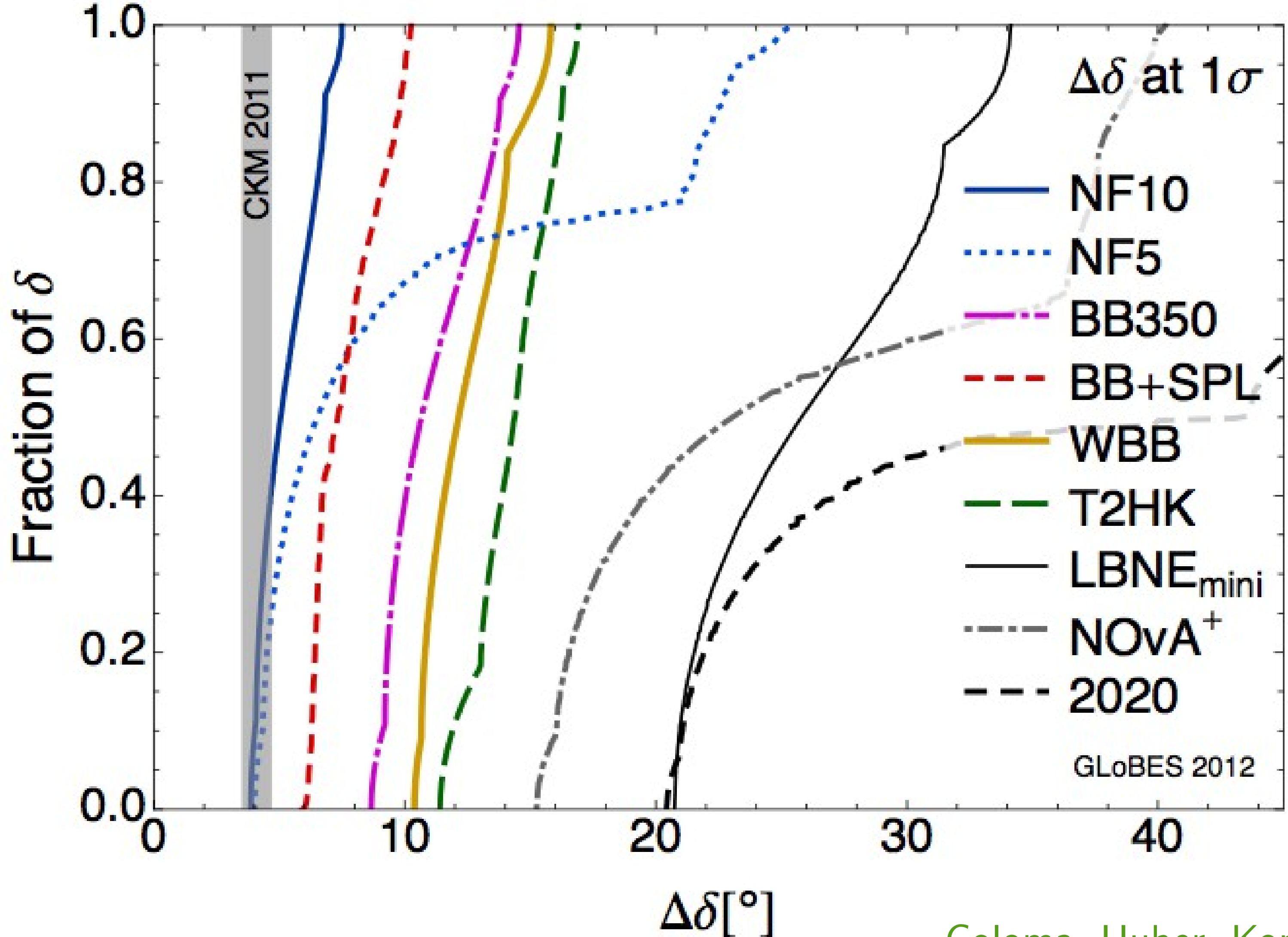
MATTER

$$(\Delta\delta)_\pm \propto \tilde{f}[\Delta,\hat{A}]\frac{1}{\sin\left(\frac{\pi}{2}\frac{\hat{A}}{(1\mp\hat{A})} \mp \delta\right)}$$



Coloma, Donini, Fernandez-Martinez and Hernandez, 1203.5651 [hep-ph]

Precision



Coloma, Huber, Kopp, Winter,
1209.5973 [hep-ph]