Muons, short or long, won’t go wrong

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I don't want to look like him by the time we understand the origin of neutrino mass!

Neutrinos are massive – so what?

Neutrinos in the Standard Model (SM) are strictly massless, therefore the discovery of neutrino oscillation, which implies non-zero neutrino masses requires the addition of new degrees of freedom.

The discovery of a light sterile neutrino could well be the most significant piece of BSM physics in the last 30 years.

We always knew they are . . .

The SM is an effective field theory, *i.e.* at some high scale Λ new degrees of freedom will appear

$$\mathcal{L}_{SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \ldots$$

The first operators sensitive to new physics have dimension 5. It turns out there is only one dimension 5 operator

$$\mathcal{L}_5 = \frac{1}{\Lambda}(LH)(LH) \to \frac{1}{\Lambda}(L\langle H\rangle)(L\langle H\rangle) = m_\nu \nu\nu$$

Thus studying neutrino masses is, in principle, the most sensitive probe for new physics at high scales

Weinberg

Effective theories

The problem in effective theories is, that there are *a priori* unknown pre-factors for each operator

$$\mathcal{L}_{SM} + \frac{\#}{\Lambda}\mathcal{L}_5 + \frac{\#}{\Lambda^2}\mathcal{L}_6 + \ldots$$

Typically, one has $\# = \mathcal{O}(1)$, but there may be reasons for this being wrong

- lepton number may be conserved $\rightarrow$ no Majorana mass term
- lepton number may be approximately conserved $\rightarrow$ small pre-factor for $\mathcal{L}_5$

Therefore, we do not know the scale of new physics responsible for neutrino masses.

Flavor models

Simplest un-model – anarchy Murayama, Naba, DeGouvea

$$dU = ds_{12}^2\, dc_{13}^4\, ds_{23}^2\, d\delta_{CP}\, d\chi_1\, d\chi_2$$

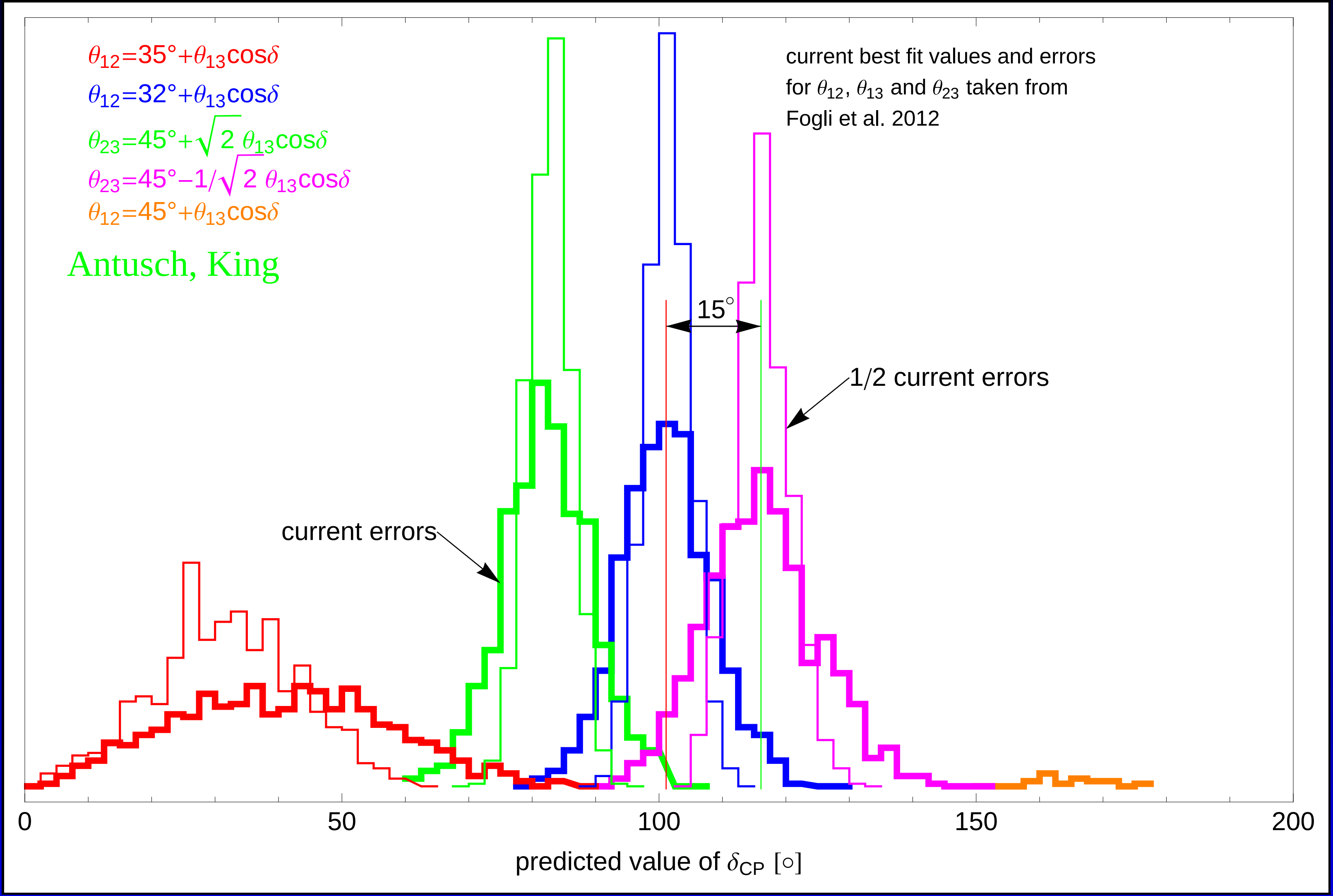
predicts flat distribution in δ_{CP}

Simplest model – Tri-bimaximal mixing Harrison, Perkins, Scott

$$\begin{pmatrix} \sqrt{\frac{1}{3}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{6}} & -\frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

to still fit data, obviously corrections are needed – predictivity?

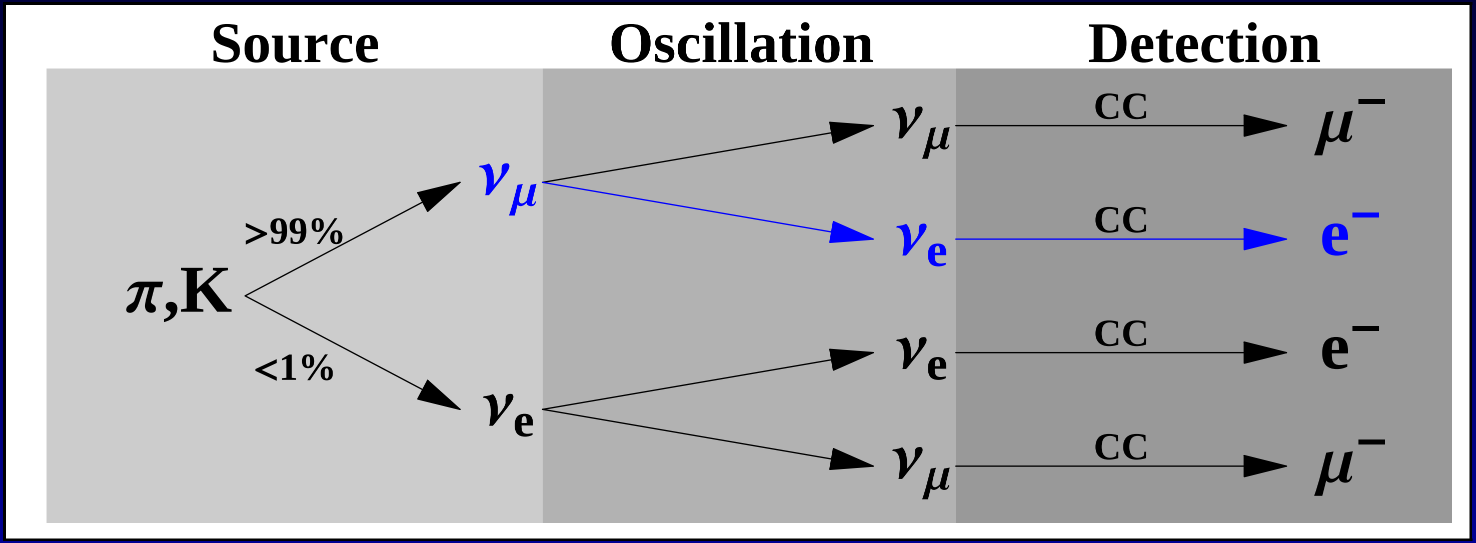
Sum rules



$3\,\sigma$ resolution of 15° distance requires 5° error. NB – smaller error on θ_{12} requires dedicated experiment like Daya Bay II

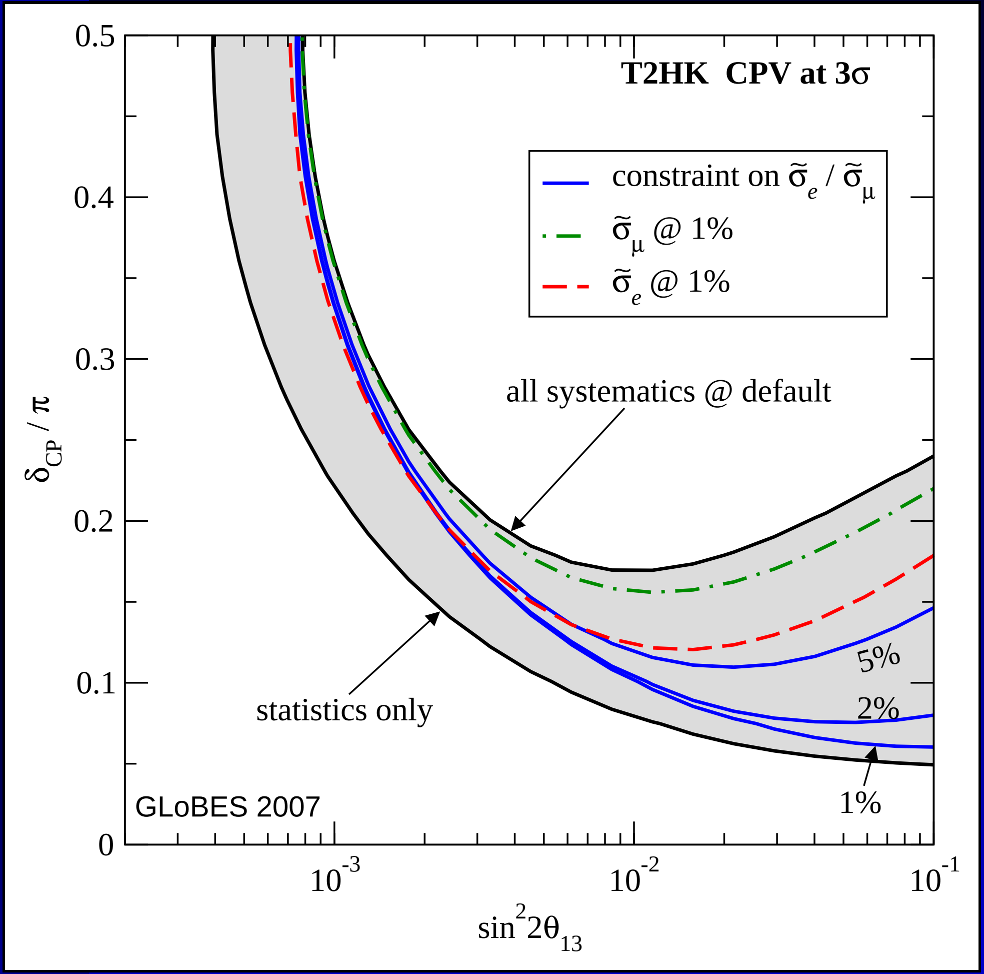
Traditional beam

Neutrino beam from π-decay



- primary ν_μ flux constrained to 5-15%
- ν_e component known to about 20%
- anti-neutrino beam systematically different – large wrong sign contamination
- ν_e difficult to distinguish from NC events

Limitations

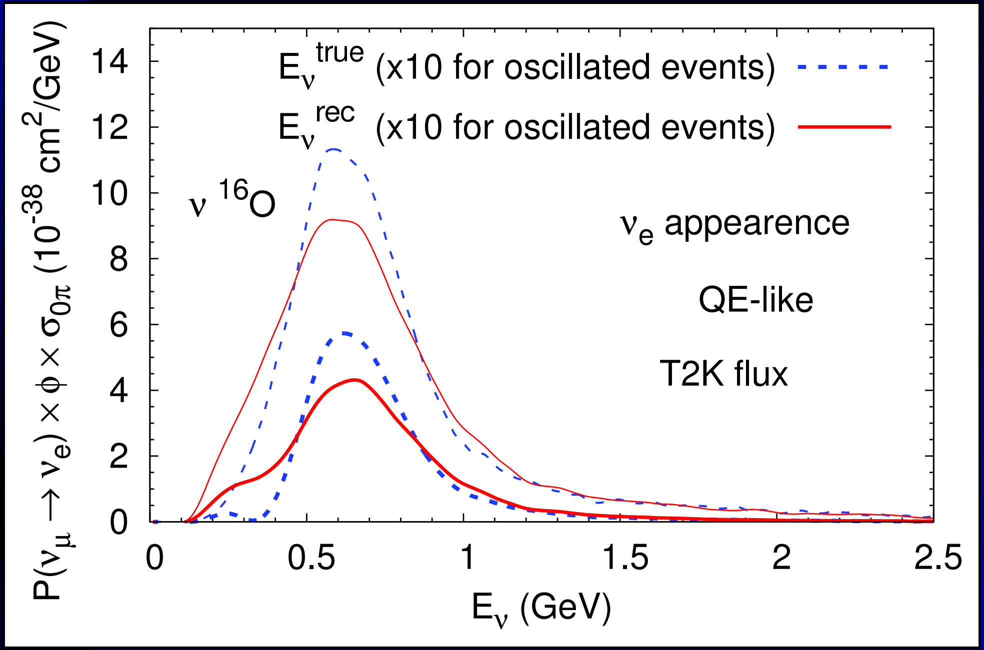


PH, M. Mezzetto, T. Schwetz
arXiv:0711.2950

Appearance experiments using a (nearly) flavor pure beam can not rely on a near detector to predict the signal at the far site!

For short-baseline experiments, we are looking for a 0.3% $\bar{\nu}_e$-appearance on top of a 1% beam background!

More limitations



Lalakulich, Mosel, arXiv:1208.3678.

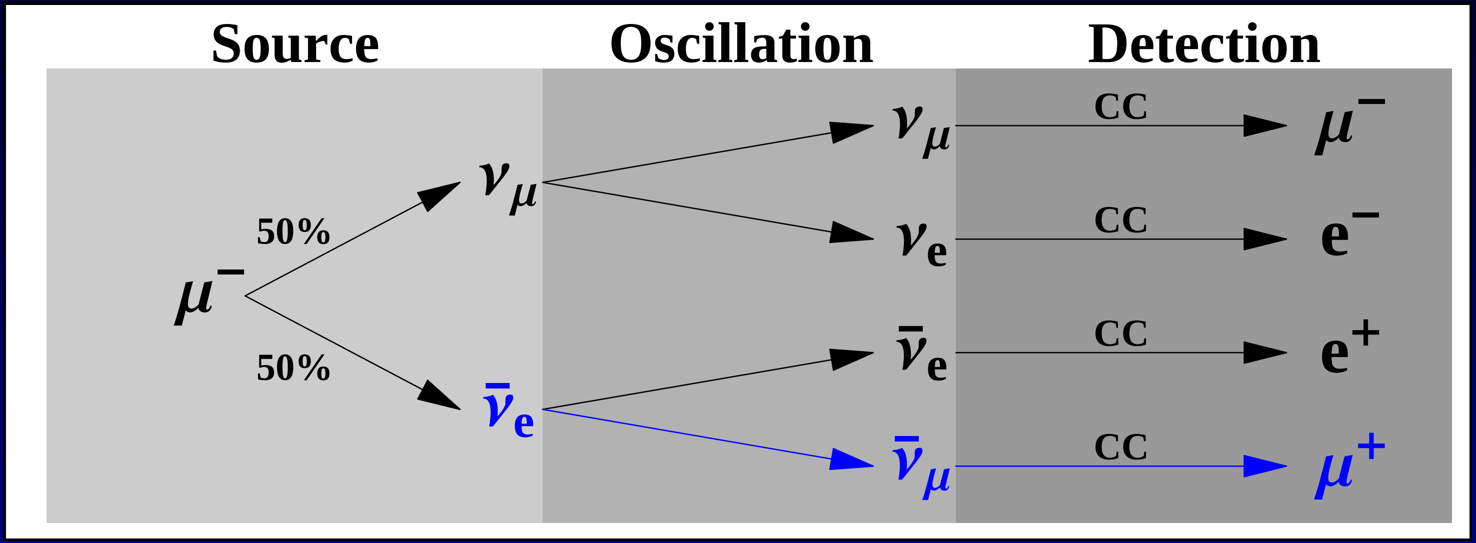
Nuclear effects change the relation between true neutrino energy and lepton energy

Inferring the CP phase from QE spectrum seems quite difficult – no quantitative analysis with respect to oscillation physics, yet.

Not obvious that near detectors alone can solve this problem.

NB – in $\bar{\nu}$ events the outgoing neutron is invisible

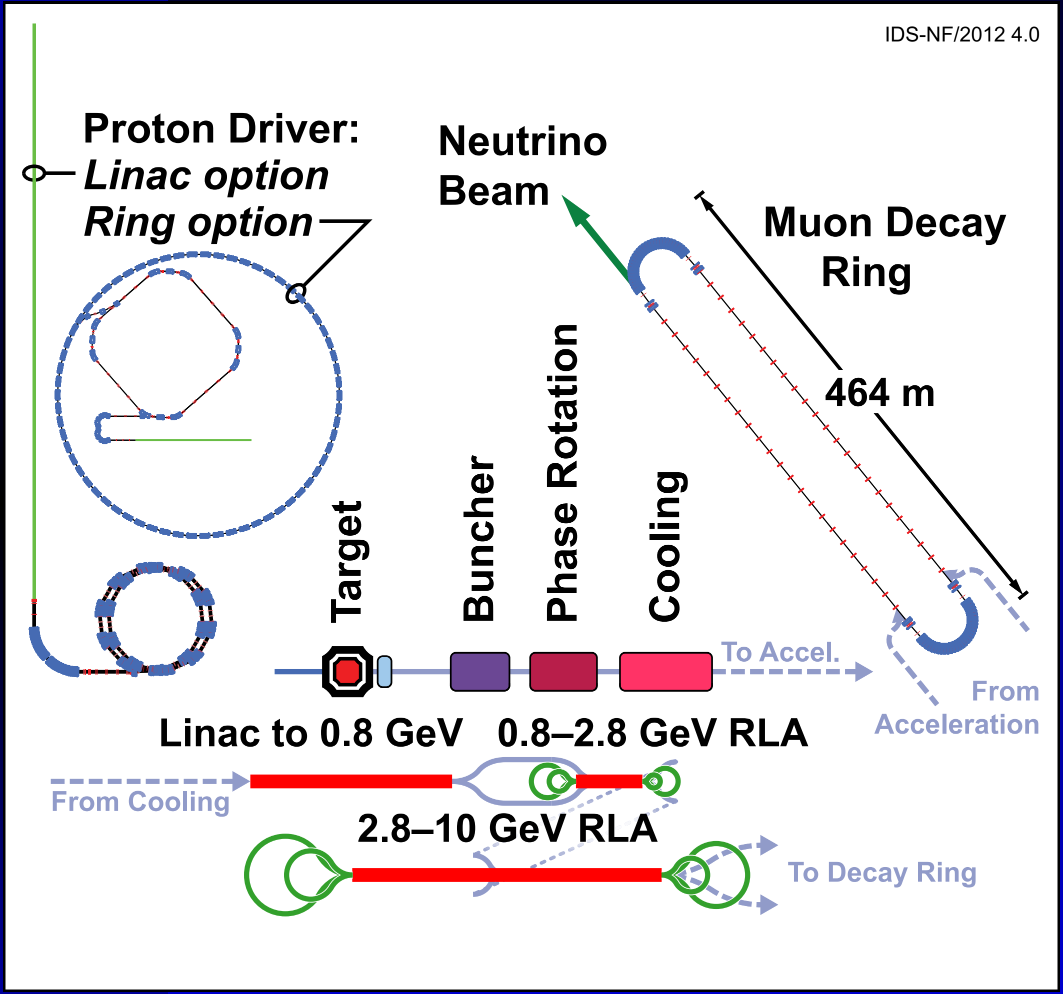
Stored muon beam



This requires a detector which can distinguish μ^+ from μ^- $\Rightarrow$ magnetic field of around 1T

- beam known to %-level or better
- muon detection very clean
- multitude of channels available

Baseline neutrino factory



10 GeV muon energy

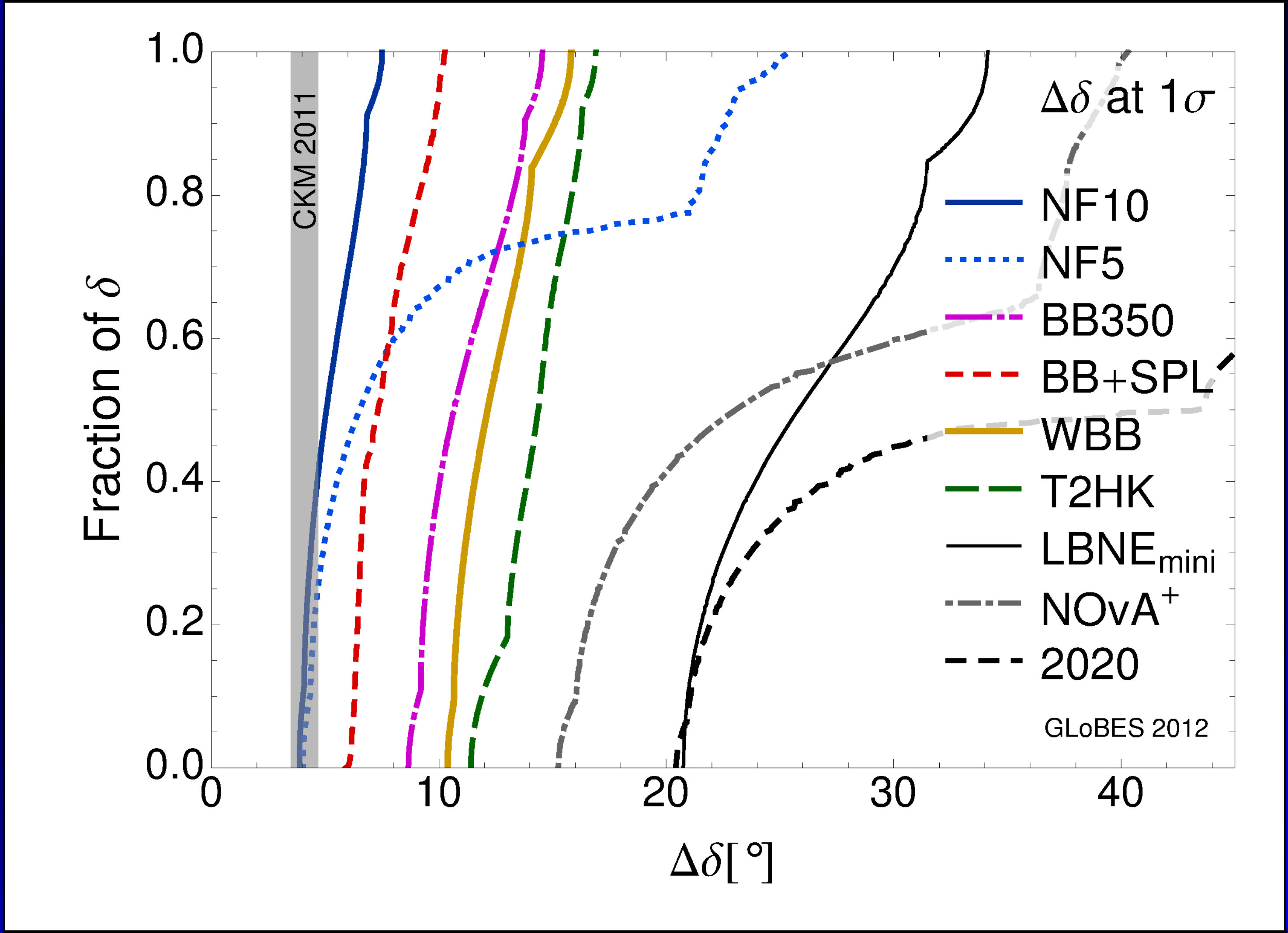
1E21 useful muon decays per straight and polarity, in 1E7 s

2 000 km baseline

100 kt magnetized iron detector (MIND)

Based on a 4 MW proton driver, which is going to become available as part of Project X phase IV, *i.e.* in the 2030s

Performance



2020 – T2K, NOνA and Daya Bay nominal runs

LBNE – 1300 km, 34 kt
0.7 MW, 2×10^8 s

WBB – 2300 km, 100 kt
0.8 MW, 1×10^8 s

T2HK – 295 km, 560 kt
0.7 MW, 1.2×10^8 s

all masses are fiducial

LBNO EOI submitted to CERN – 20 kt LAr + MIND, similar beam power to above, but Finish government will not support Pyhäsalmi lab

P. Coloma, PH, J. Kopp and W. Winter, arXiv:1209.5973.

An entry level neutrino factory

5 GeV muon energy

Running time increase to 2E7 s – luminosity × 2

A 700 kW proton driver, maybe 60 GeV (MI) – luminosity × 0.1-0.2

No muon cooling – luminosity × 0.5

⇒ 1E20 useful muon decays per straight and polarity,

based on existing proton beams and technology

1 300 km baseline

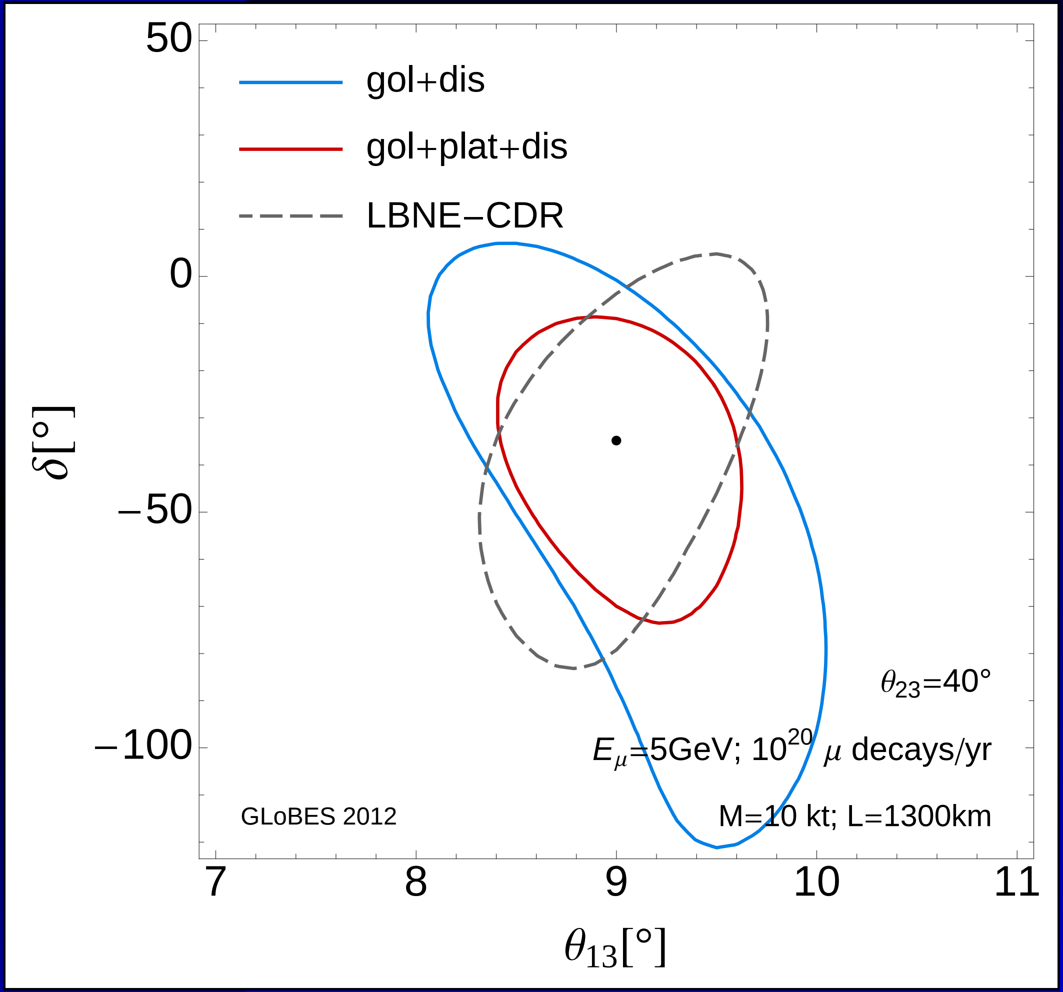
10 kt magnetized liquid argon detector

⇒ reuse as much as possible from LBNE phase I

The following is based on

E. Christensen, P. Coloma, PH, arXiv:1301.7727

The platinum channel



The $\nu_\mu \rightarrow \nu_e$ channel is the CPT conjugate of the $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$ channel

As a result matter effects effectively cancel

This has been know for quite a while, but the effect is only relevant for large θ_{13}

NB: LBNE-mini corresponds to the LBNE CDR (CD1)

Detector assumptions

TASD – based on simulation Fernandez-Martinez, *et al.*, arXiv:0911.3776.

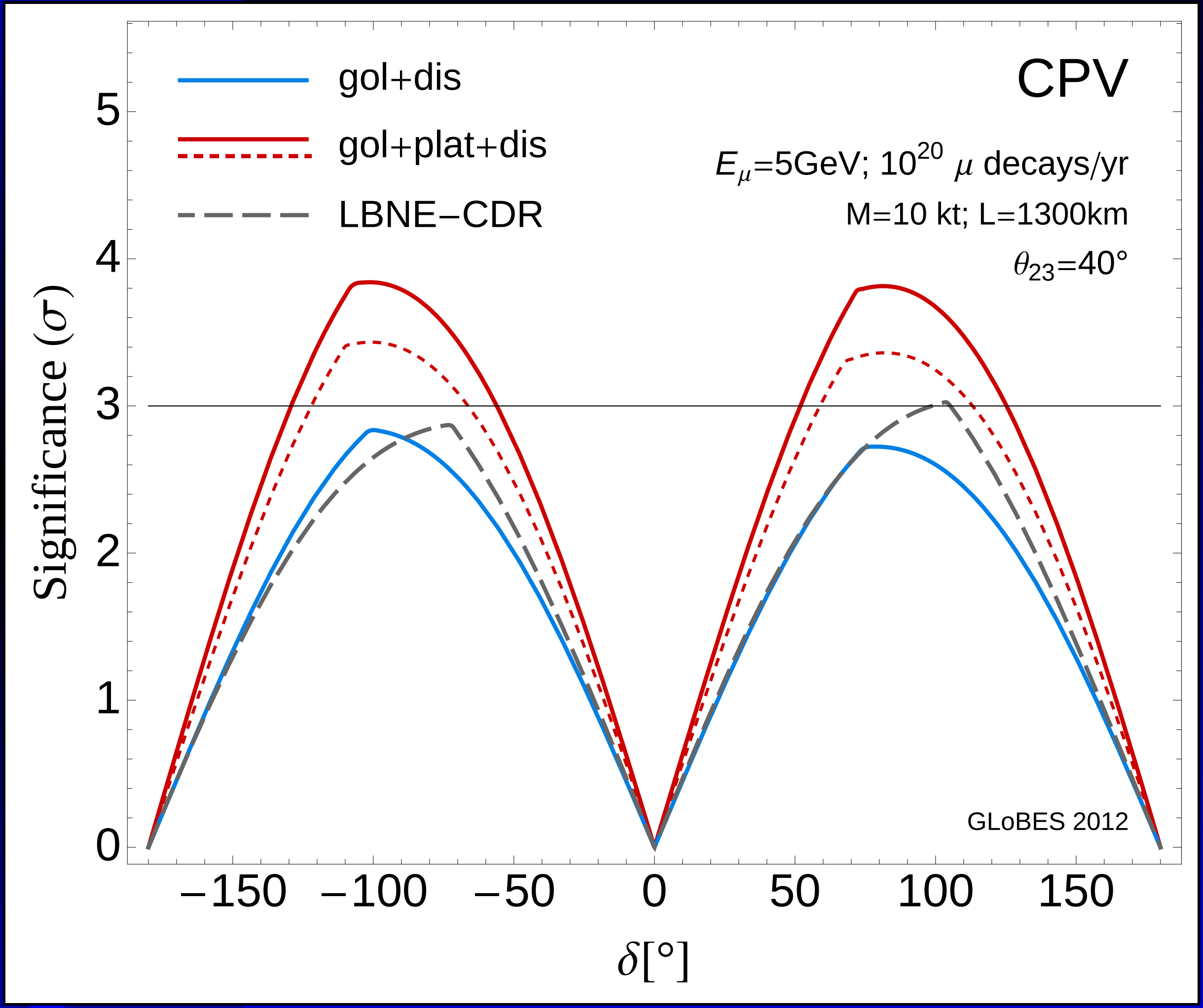
Channel	Effs.	τ Rej.	NC/CID/FID Rej.	$\Delta E/E$
ν_μ app.	73%-94%	0%	99.9%	$0.2/\sqrt{E}$
ν_e app.	37%-47%	0%	99%	$0.15/\sqrt{E}$
ν_μ dis.	73%-94%	0%	99.9%	$0.2/\sqrt{E}$

Magnetized LAr

Channel	Effs.	τ Rej.	NC/CID/FID Rej.	ΔE
ν_μ app.	80%	0%	99.9%	$0.2/\sqrt{E}$
ν_e app.	80%	0%	99.9%	$0.15/\sqrt{E}$
ν_μ dis.	80%	0%	99.9%	$0.2/\sqrt{E}$

ν_τ backgrounds included.

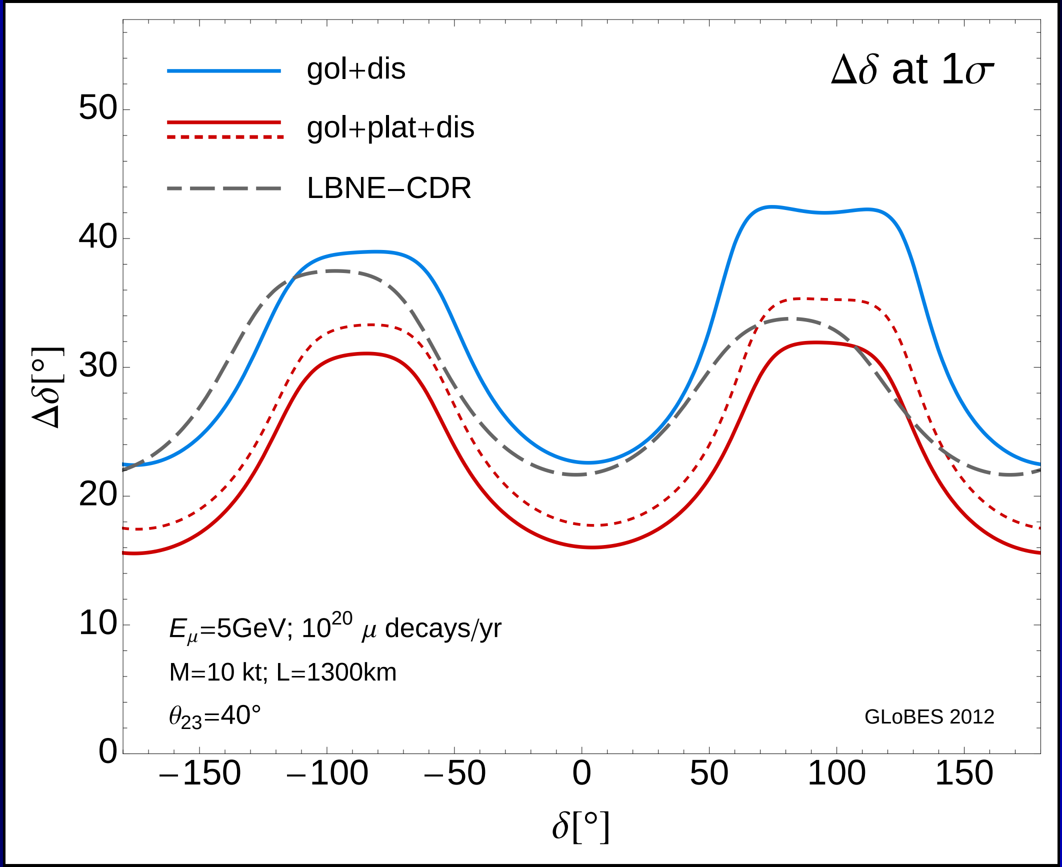
CP violation



Significant advantage for CP violation

Starting point for a staged scenario towards a full neutrino factory

CP precision



Solid line – magnetized LAr
Dashed line – magnetized TASD

The obtainable precision is nearly everywhere better than LBNE’s by about 9 degrees (1/3)

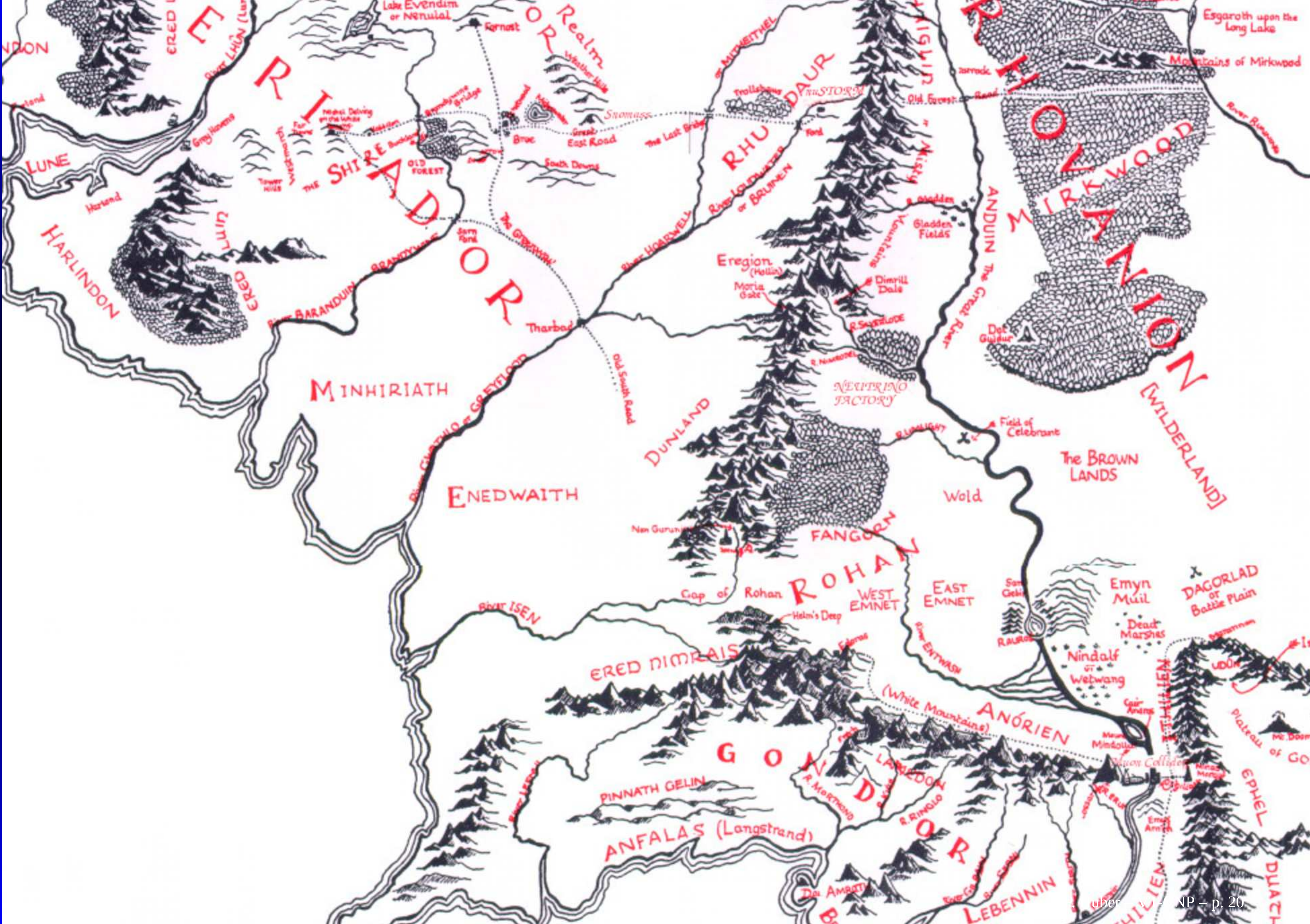
Summary

Observations

- Detectors probably have to be underground because of large duty factor
- 4 GeV muon energy probably works equally well
- The end goal in this case will be a 5 GeV machine. Potentially, with a larger LAr detector – performance en par with NF baseline

Open issues

- Can one magnetize a liquid argon detector?
- Performance of magnetized LAr?


ERIADOR
ERED LUIN
LINDON
LUNE
Grey Havens
Harlond
Forlond
HARLINDON
River Lhûn
Lake Evendim or Nenuial
Fornost
Realm
Weather Hills
THE SHIRE
OLD FOREST
Michel Delving
Tower Hills
Bree
Brandywine Bridge
Buckland
Sarn Ford
South Downs
Great East Road
Snomass
The Last Bridge
Trollshaws
RHUDAUR
nuSTORM
Ford
River Hoarwell
River Loudwater or Bruinen
River Baranduin
Tharbad
Old South Road
The Greenway
MINHIRIATH
River Gwathlo or Greyflood
ENEDWAITH
Eregion (Hollin)
Moria Gate
Dimrill Dale
Misty Mountains
Gladden Fields
NEUTRINO FACTORY
DUNLAND
Nan Curunír
FANGORN
Gap of Rohan
River Isen
Helm's Deep
ROHAN
WEST EMNET
EAST EMNET
Wold
Field of Celebrant
The BROWN LANDS
RHOVANION
MIRKWOOD
Old Forest Road
Esgaroth upon the Long Lake
Mountains of Mirkwood
Dol Guldur
ANDUIN The Great River
[WILDERLAND]
Emyn Muil
Dead Marshes
DAGORLAD or Battle Plain
Nindalf or Wetwang
Rauros
River Entwash
ERED NIMRAIS (White Mountains)
ANÓRIEN
Minas Tirith
Muon Collider
Minas Morgul
Cair Andros
EPHEL DÚATH
Plateau of Gorgoroth
Mt. Doom
ITHILIEN
GONDOR
LAMEDON
PINNATH GELIN
ANFALAS (Langstrand)
R. Morthond
R. Ringló
LEBENNIN
Dol Amroth