K. Long, 23 November 2012

Imperial College London

Neutrino experiments:

… input to discussion

Apologies:

- With 35 submissions on neutrinos to the ESPG it is difficult to cover all issues in a short talk. I've tried to "hit the highlights" and apologise for the inevitable omissions!

… and acknowledgements:

- Many thanks to all those who knowingly or unknowingly provided information or material:
  - And in particular the International Design Study for the Neutrino Factory (the IDS-NF), EUROnu, Laguna-LBNO, NESSiE and nuSTORM collaborations

Contents:

- Neutrinos; beyond the Standard Model
- Mass scale, Dirac or Majorana
- The Standard Neutrino Model
- Sterile neutrinos
- Elements of a strategy, introduction to discussion

Neutrino experiments:

Neutrinos;
physics beyond the Standard Model

Standard Model:

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix} \quad \begin{pmatrix} e^+ \\ \bar{\nu}_e \end{pmatrix}$$

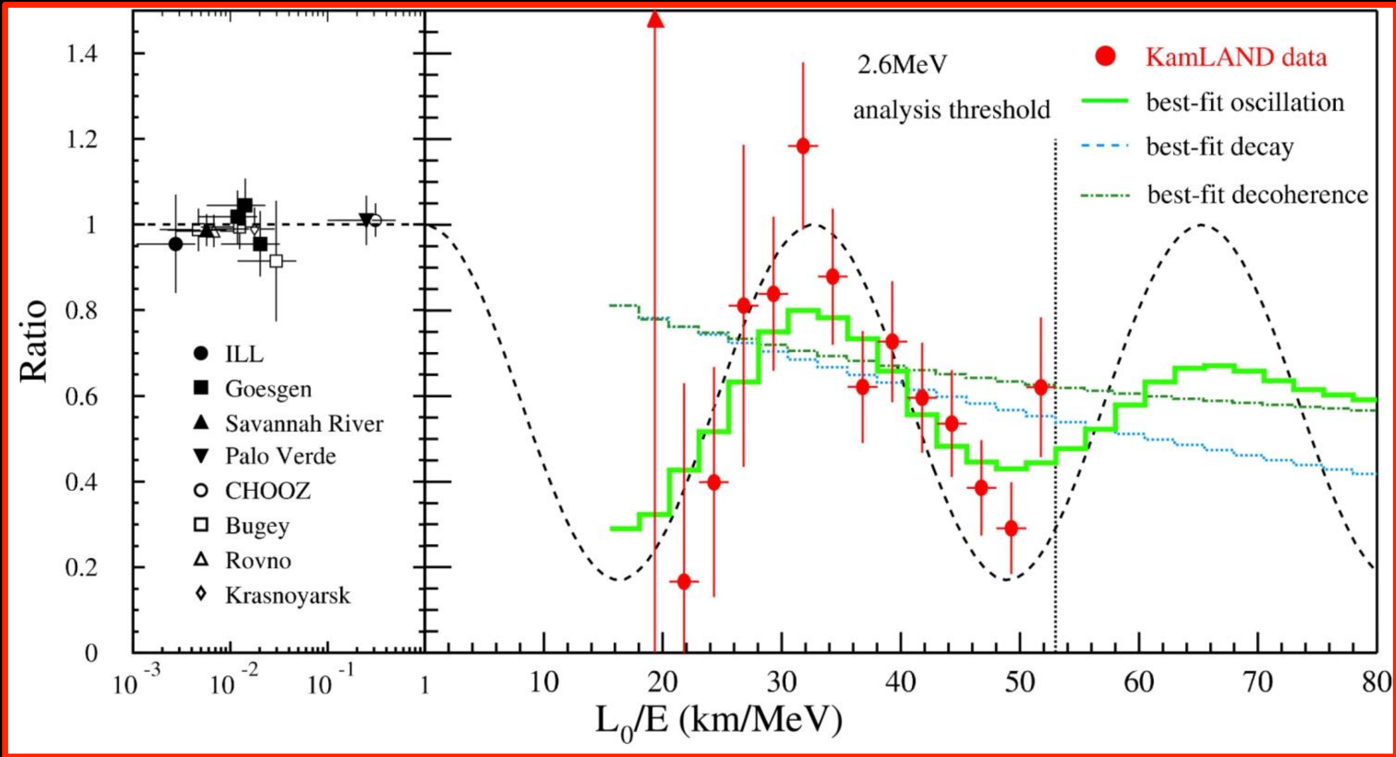
$$\begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix} \quad \begin{pmatrix} \mu^+ \\ \bar{\nu}_\mu \end{pmatrix}$$

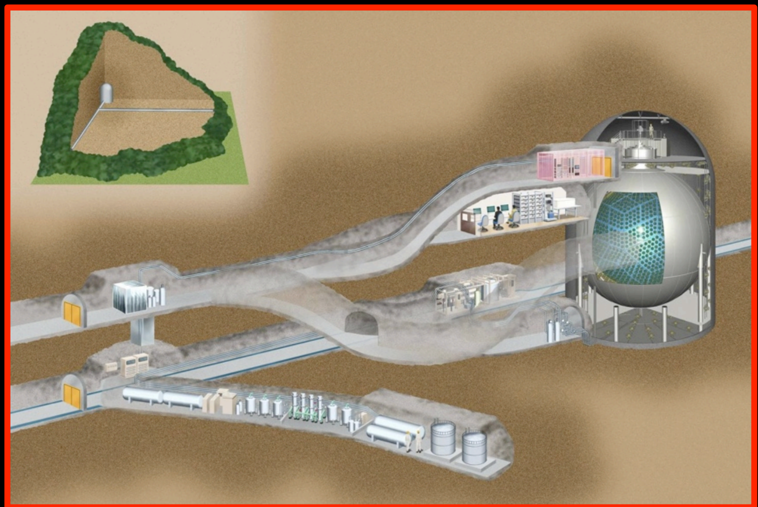
$$\begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix} \quad \begin{pmatrix} \tau^+ \\ \bar{\nu}_\tau \end{pmatrix}$$

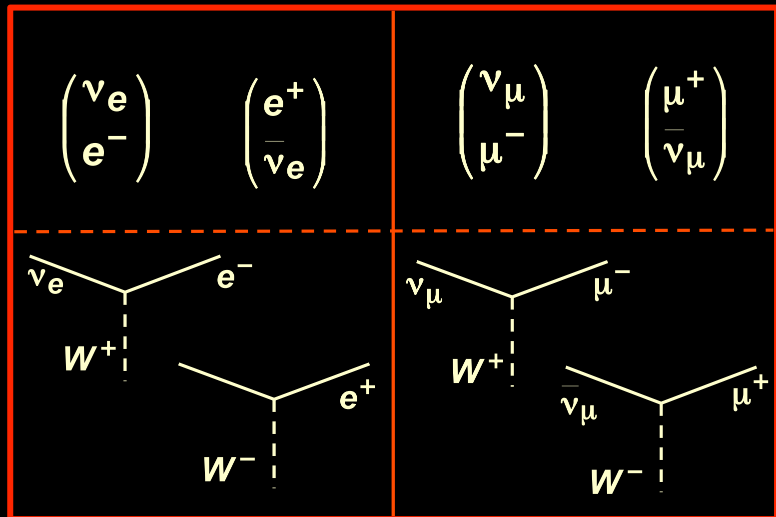
The Standard Model neutrino was:

- *Massless*
- Chargeless
- Helicity eigenstate

Neutrino oscillations: an example:



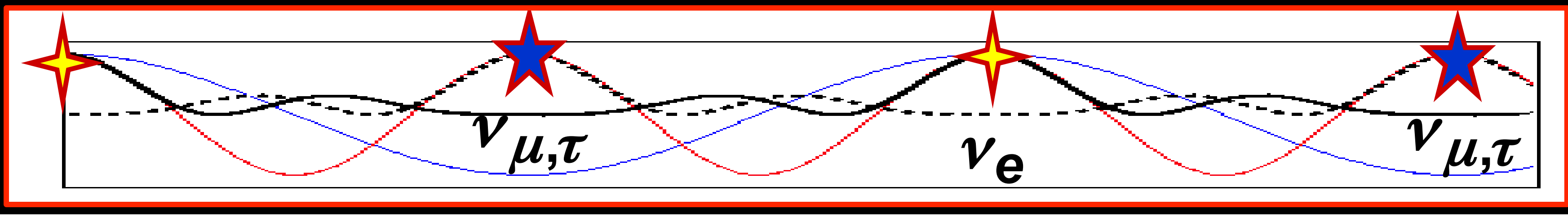




Physics beyond the Standard Model:

- Massive neutrino *NOT* helicity eigenstate, and …
  - since neutrino has no conserved quantum numbers
    - (except, perhaps, a global lepton number)

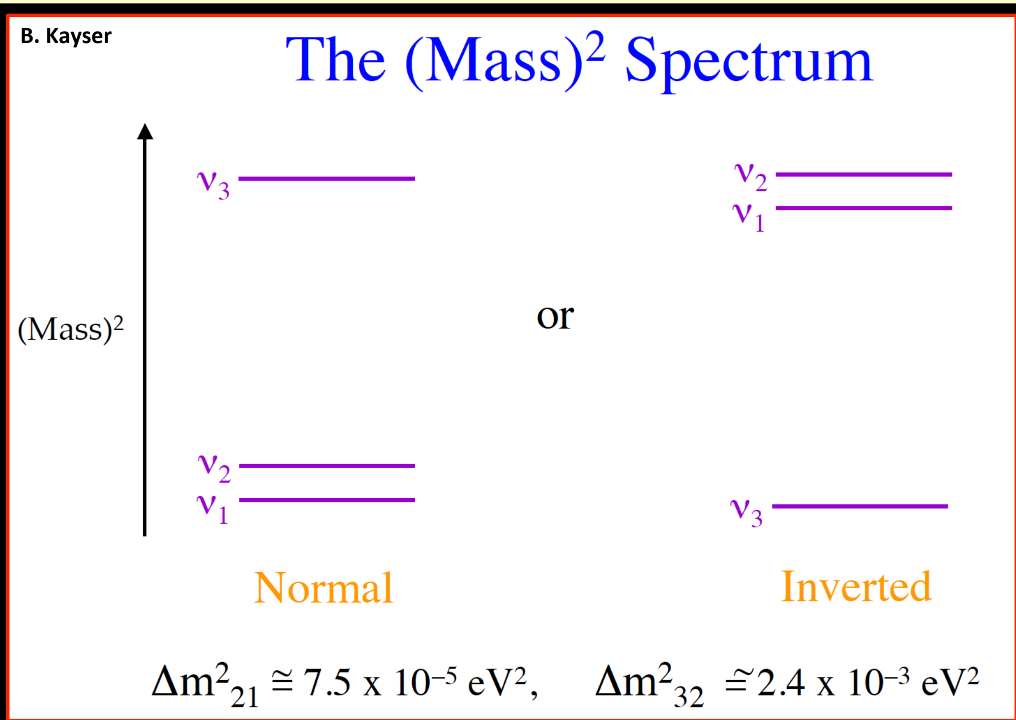
  quantum mechanics implies neutrinos will mix
- Neutrino oscillations imply BSM physics:
  - Either:
    - Conserved lepton number distinguishes neutrino from antineutrino; or
    - Neutrino is its own antiparticle; a new state of matter, a Majorana fermion
- Mixing among three neutrino flavours admits possibility of CP-invariance violation



Standard Neutrino Model:

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{-i\delta} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

$$\times\begin{bmatrix}e^{i\alpha_1/2} & 0 & 0\\ 0 & e^{i\alpha_2/2} & 0\\ 0 & 0 & 1\end{bmatrix}$$



- Three mass states linked to three flavour states via *unitary* mixing matrix;
- Additional, *sterile*, states conceivable:
  - Would imply:
    - 3-neutrino mixing matrix not unitary

A window on the unknown:

- Neutrino masses are tiny compared to those of the other fermions:
  - Hint that neutrino masses do not arise from the same mechanism?
  - Related to physics at very high mass scales as in “see-saw models”?
- If Standard Model Lagrangian is treated as an effective theory:
  - Dimensional analysis [Weinberg] indicates that:
    - Majorana mass term for neutrinos is first term beyond the Standard Model Lagrangian
- Fundamental questions:
  - What is the nature of the neutrino, Majorana or Dirac?
  - What is the absolute neutrino-mass scale?
  - Is CP-invariance violated in neutrino oscillations?
  - Is the neutrino-mass spectrum normal or inverted?
  - Is the neutrino-mixing matrix unitary?
  - Are there sterile neutrinos?
  - Is there a connection between quark and lepton flavour?

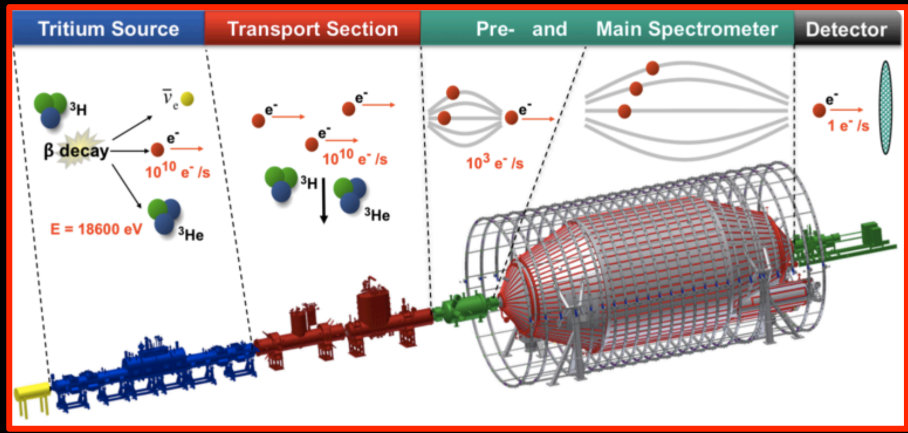
- **The study of the neutrino is the study of physics beyond the Standard Model and gives information complementary to the energy-frontier programme**
  - **This fundamental programme, to which Europe can make uniquely-important contributions, should be a priority in the European Strategy for Particle Physics**

Neutrino experiments:

Mass scale, Dirac or Majorana

Neutrino mass-scale:

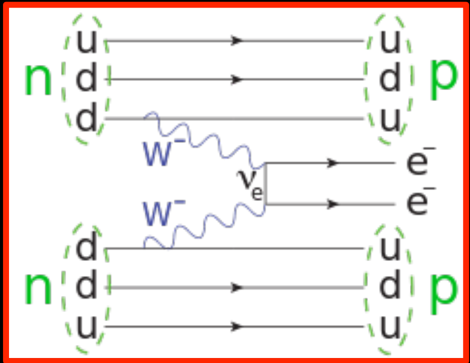
- Determination of neutrino mass:
  - Electron spectrum in nuclear beta decay
  - If observed, through neutrino-less double beta decay (0νββ)



  - Cosmological observables, e.g.:
    - Large-scale structure;
    - Cosmic microwave background temperature fluctuations

- Important measurements!
  - Clear programme with experiments of a scale that can be taken forward by appropriate laboratories

Dirac or Majorana:



Experimental Status

Experiment	Nucleus	Mass	Technique	Location	Date
Current experiments (funded, construction, running)					
GERDA I/II	^{76}Ge	15/35	ionization	LNGS	2011/13
Majorana	^{76}Ge	30	ionization	SUSEL	2014
EXO200	^{136}Xe	200	liquid TPC	WIPP	2011
CUORE0/CUORE	^{130}Te	10/200	bolometer	LNGS	2012/14
Kamland-Zen	^{136}Xe	400	liquid scintillator	Kamioka	2011
SNO+	^{150}Nd	44	liquid scintillator	Sudbury	2014
R&D (funding, prototyping)					
NEXT	^{136}Xe	100	gas TPC	Canfranc	2013+
Candles III	^{48}Ca	0.35	scintillating crystals	Oto Cosmo	2011
MOON	^{82}Se/^{150}Nd				
DCBA	^{150}Nd	32	tracking		
Cobra	^{116}Cd		solid TPC	LNGS	
SuperNEMO	^{82}Se	7/100-200	track/calorimeter	Modane	2014/?
XMASS	^{136}Xe		liquid scintillator	Kamioka	
Lucifer	^{82}Se	17.6	scintillating bolometer	LNGS	2014

- Discovery of 0νββ would be revolutionary:
  - New state of matter
- Importance justifies the variety of approaches:
  - Clear programme developed in collaboration with deep underground laboratories

- The search for 0νββ is of fundamental importance and the determination of the neutrino mass-scale is critical to the development of a full understanding of the neutrino:
  - Europe has an established position of leadership in these areas. The completion of the Katrin programme and the strategic development of low-background, deep-underground facilities should be a priority

Neutrino experiments:

Standard Neutrino Model

Daya Bay and RENO:

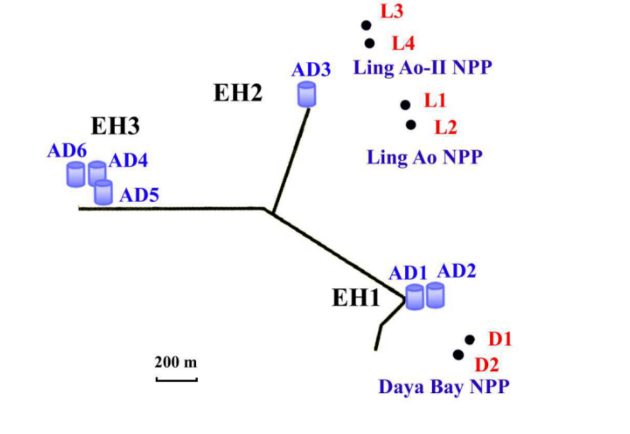
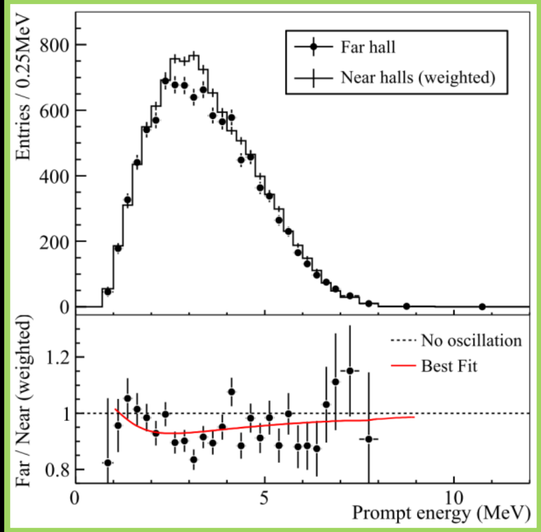
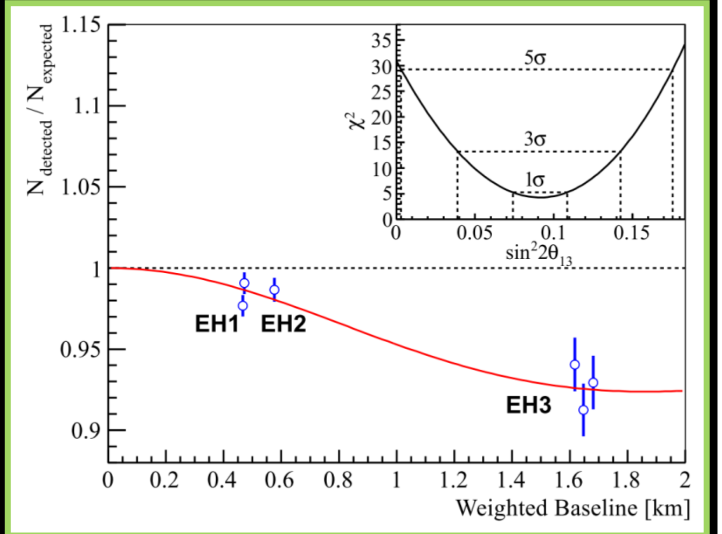
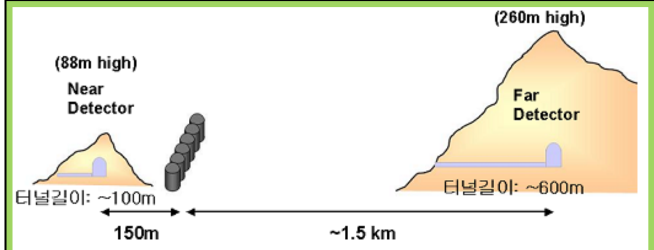
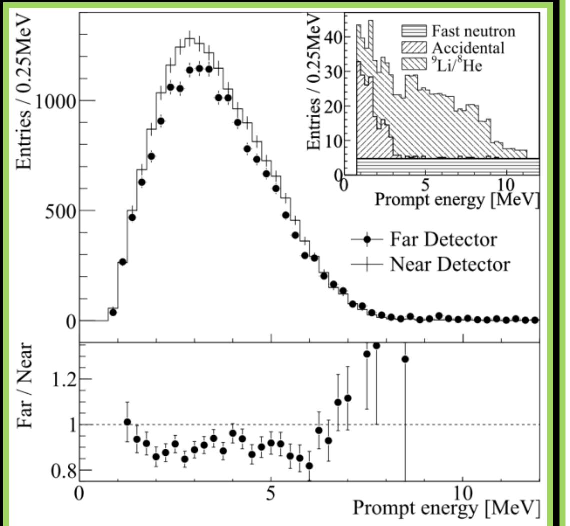


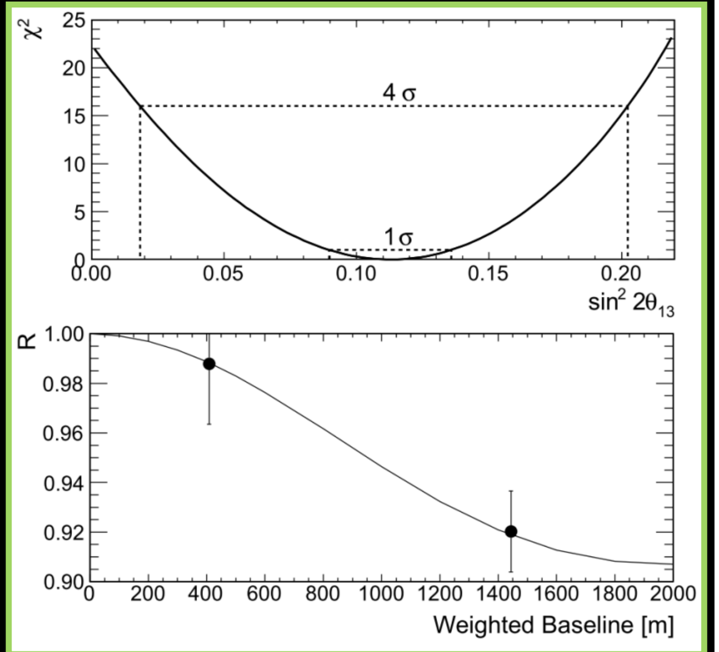
FIG. 1. Layout of the Daya Bay experiment. The dots represent reactors, labeled as D1, D2, L1, L2, L3 and L4. Six ADs, AD1–AD6, are installed in three EHs.









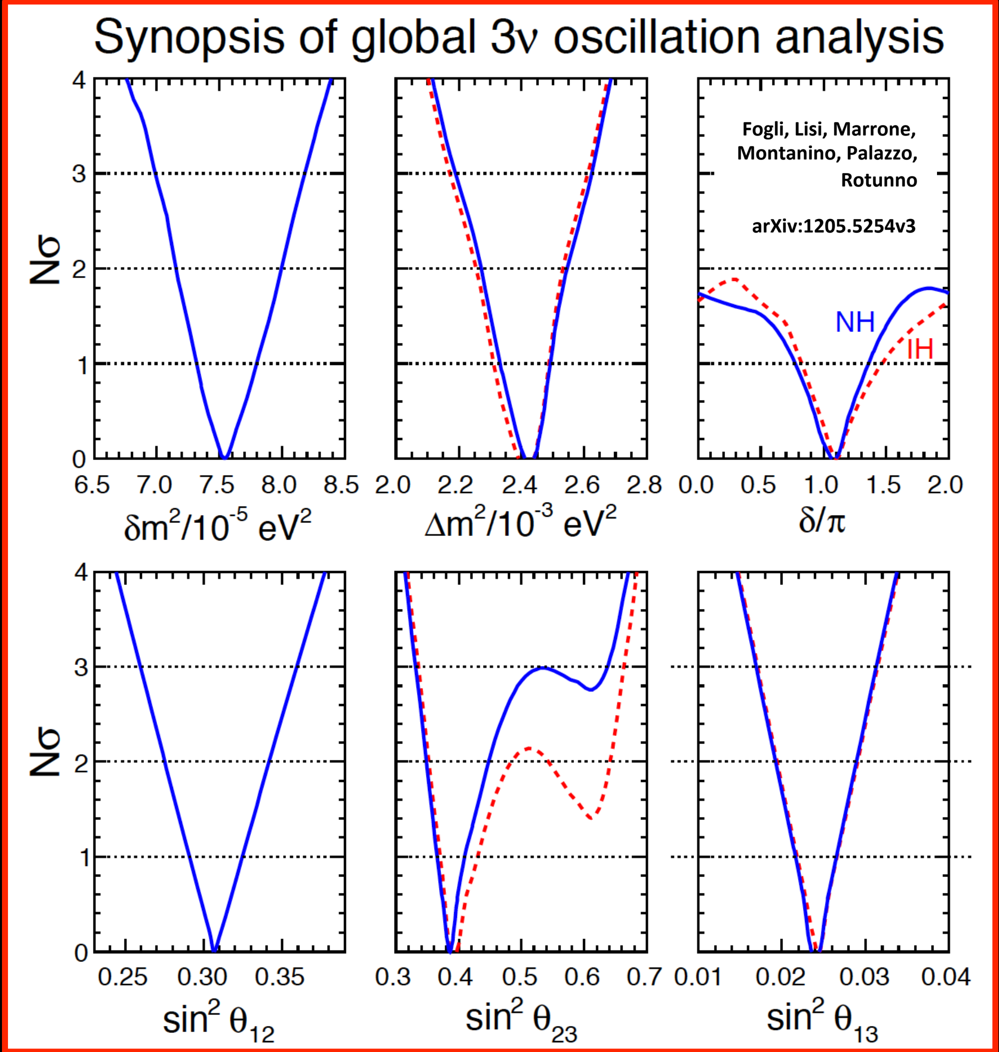


	$\sin^2 2\theta_{13}$		
	Value	Statistical	Systematic
D-Chooz	0.086	0.041	0.030
Daya Bay	0.092	0.016	0.005
RENO	0.113	0.013	0.019
Mean	***0.098***	***0.013***	

	$\sin^2 \theta_{13}$	
Mean	***0.025***	***0.003***

Standard Neutrino Model:

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\begin{pmatrix}1&0&0\\0&c_{23}&s_{23}\\0&-s_{23}&c_{23}\end{pmatrix}\begin{pmatrix}c_{13}&0&s_{13}e^{i\delta}\\0&1&0\\-s_{13}e^{-i\delta}&0&c_{13}\end{pmatrix}\begin{pmatrix}c_{12}&s_{12}&0\\-s_{12}&c_{12}&0\\0&0&1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$



- **Exciting new data!**
- **Discovery of leptonic CP-violation is possible**
- **Increases motivation for precision determination of the parameters and search for "non-standard effects"**

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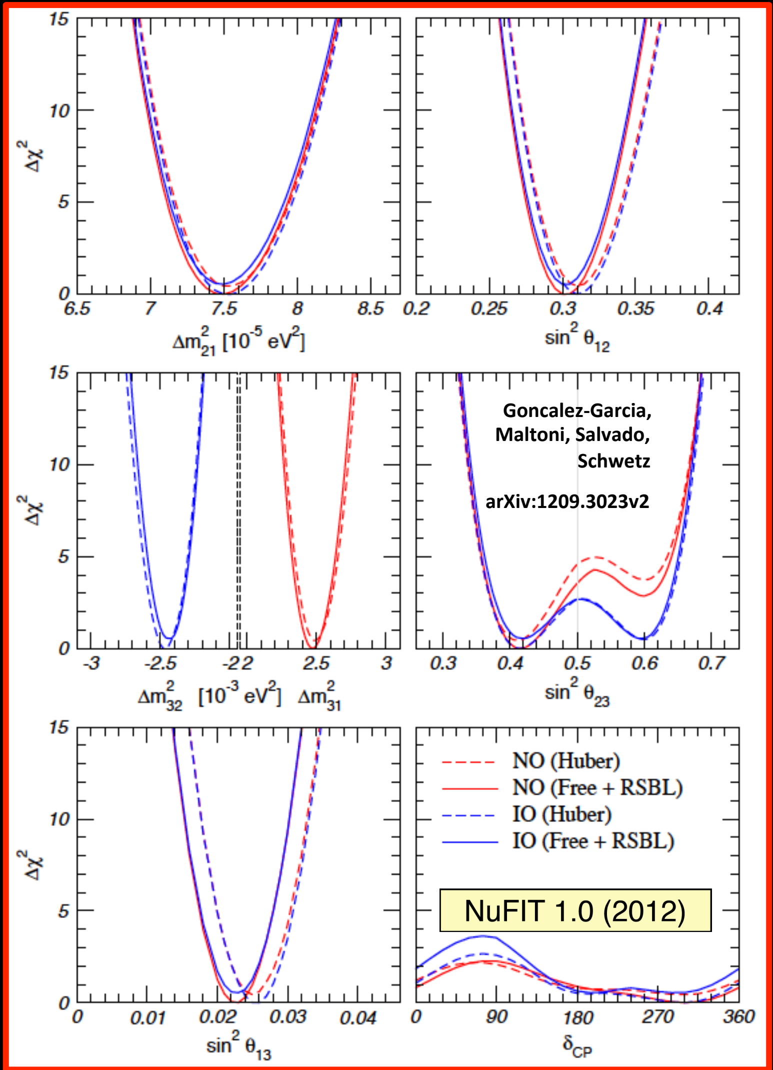
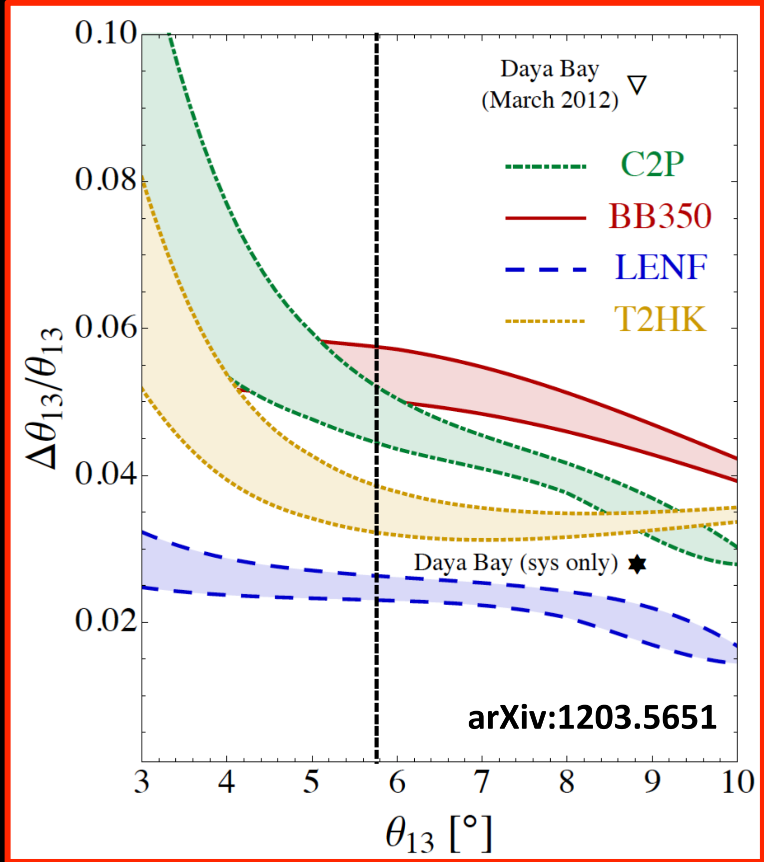


- **Exciting new data!**
- **Discovery of leptonic CP-violation is possible**
- **Increases motivation for precision determination of the parameters and search for "non-standard effects"**

The SνM measurement programme:

- Looking beyond MINOS, T2K, NOνA, DChooz, Daya Bay, Reno, …
  - θ_{13} will be very well known



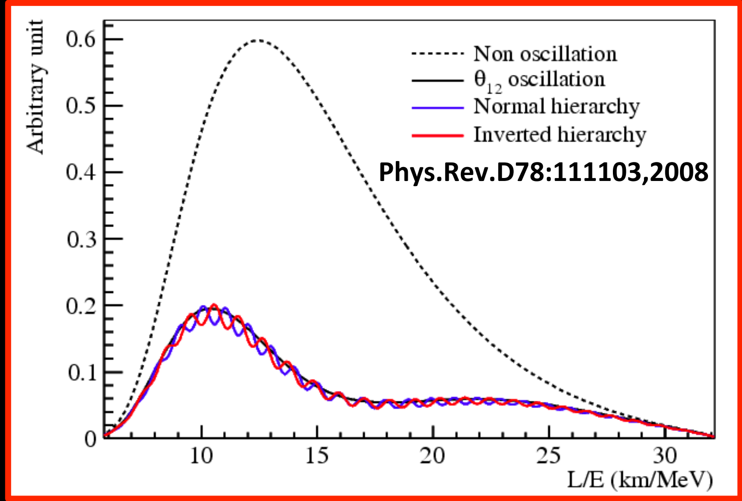
- Therefore future programme must:
  - Complete the "Standard Neutrino Model" (SνM):
    - Determine the mass hierarchy
    - Search for (and discover?) leptonic CP-invariance violation
  - Establish the SνM as the correct description of nature:
    - Determine precisely the degree to which θ_{23} differs from $\pi/4$
    - Determine θ_{13} precisely
    - Determine θ_{12} precisely
  - Search for deviations from the SνM:
    - Test the unitarity of the neutrino mixing matrix
    - Search for sterile neutrinos, non-standard interactions, …

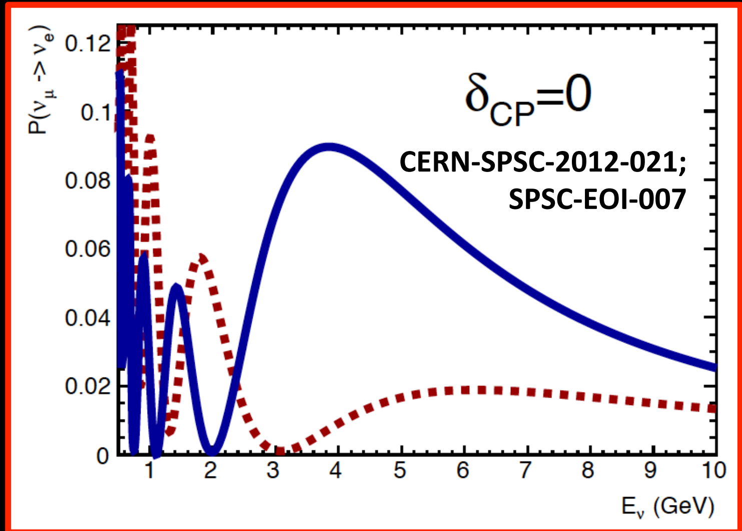
Option thumbnails:

- **Conventional super-beams:**
  - **Wide-band, long baseline: e.g. LBNE, LBNO**
    - **$<E_{\mu}>$ ~ 2—3 GeV; matched to LAr or Fe calorimeter;**
    - **Long-baseline allows observation of first and second maximum**
    - **Near detector exploited to reduce systematic errors**
  - **Narrow-band, short baseline: e.g. T2HK, SPL**
    - **$<E_{\mu}>$ ~ 0.5 GeV; matched to H_20 Cherenkov;**
    - **Short-baseline allows observation of first maximum**
    - **Near detector exploited to reduce systematic errors**
- **Beta-beam, short baseline: e.g. CERN γ=100;**
  - **$<E_{\mu}>$ ~ 0.5 GeV; matched to H_20 Cherenkov;**
  - **Short-baseline allows observation of first maximum**
  - **Requires short-baseline super-beam to deliver competitive performance**
- **Neutrino Factory: IDS-NF baseline E_{μ}=10 GeV;**
  - **Uniquely well known flux (flavour content and energy spectrum);**
  - **Baseline 1500—2500 km**
  - **Requires a magnetised detector**
  - **Identified by EUROnu as the facility for the high-precision programme**

Mass hierarchy:

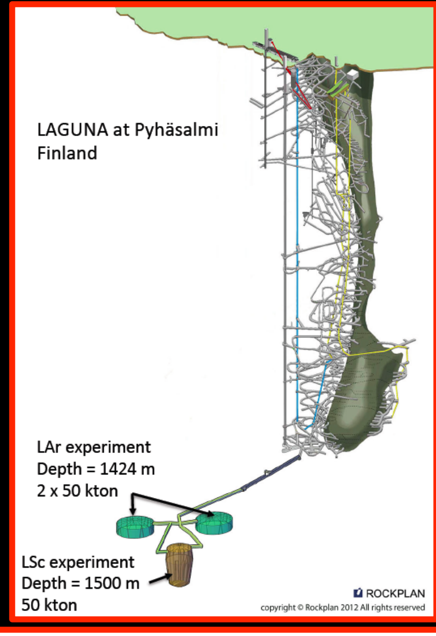
- Two options:
  - Exploit *L/E* spectrum:
    - E.g. Daya Bay II:
      - Liquid scintillator detector at 60 km
      - Requires exquisite energy resolution
  - Exploit matter effect:
    - Electron-neutrino charged current interactions in the earth receive additional "charge-exchange" contribution
    - Leads to a modification of the oscillation probability for long (~1000 km) baselines

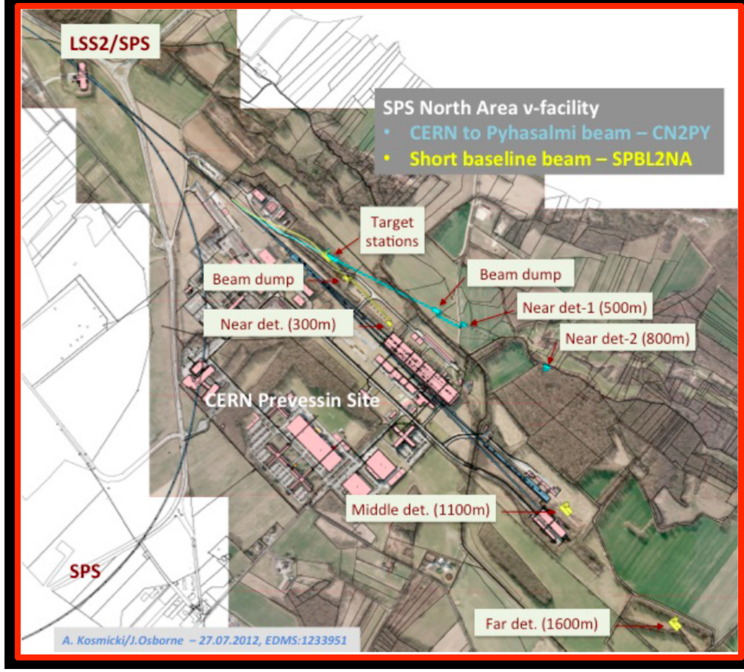


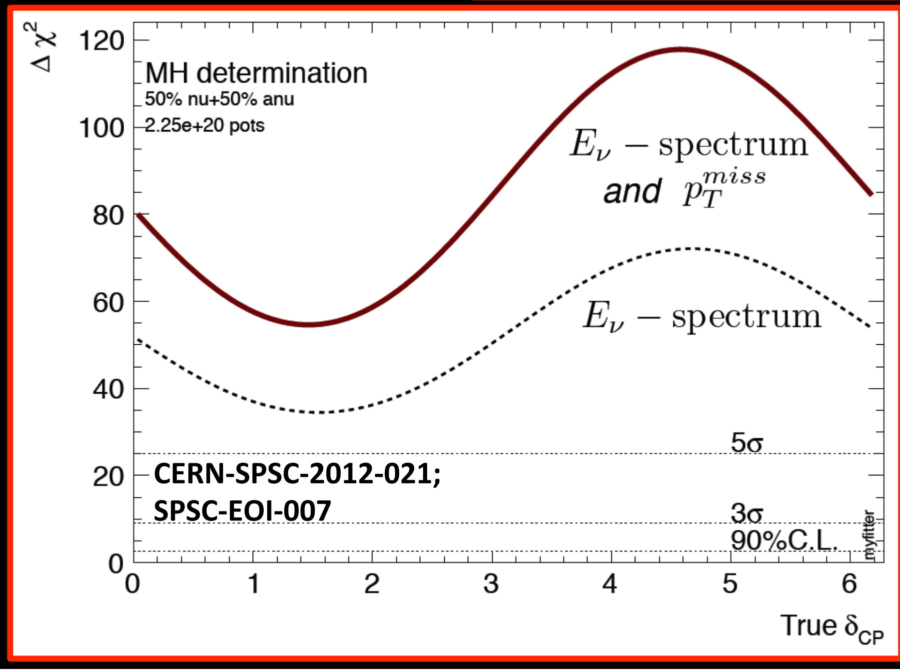


Exploiting the matter effect:

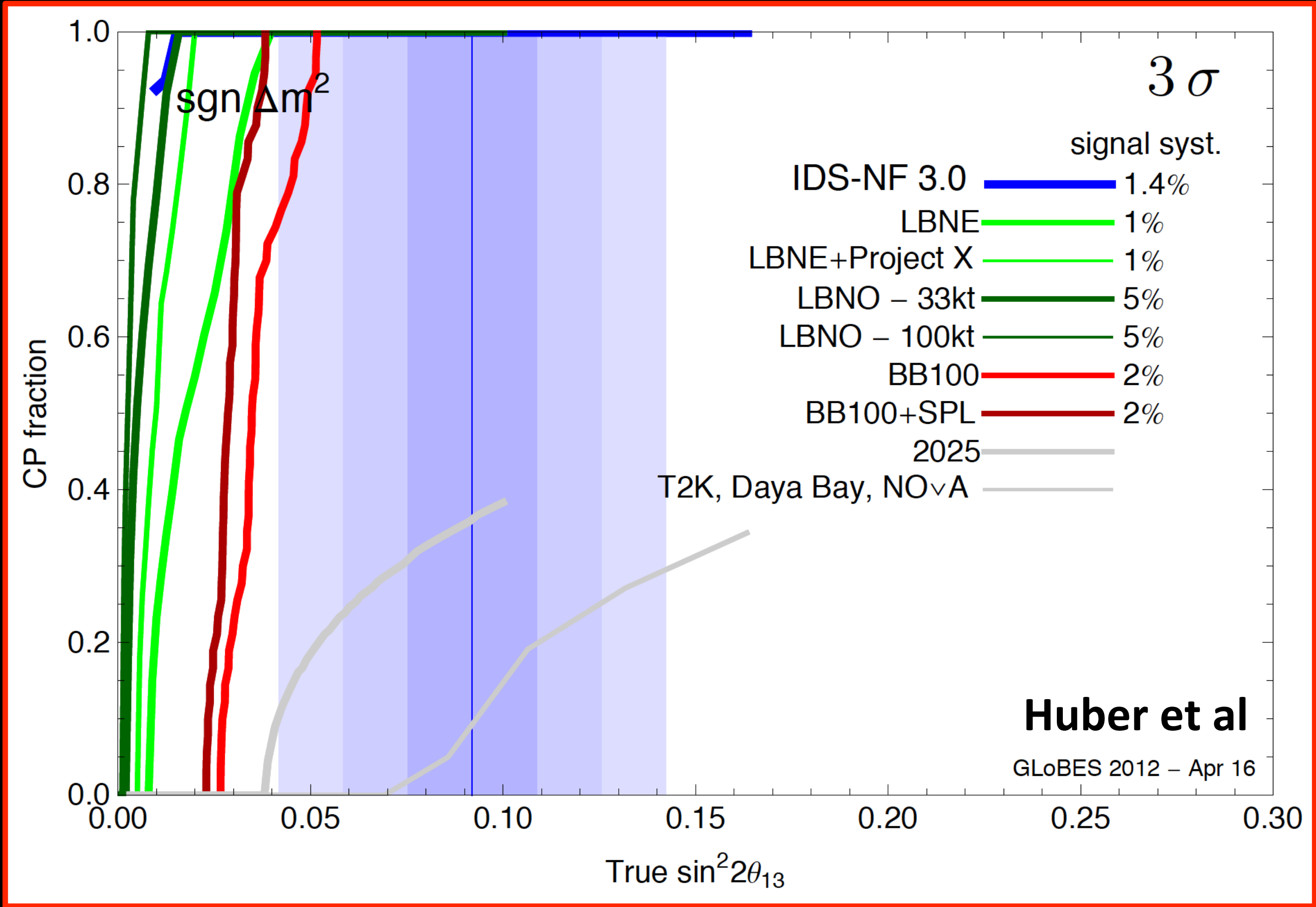
- The matter effect may be exploited to determine the mass hierarchy:
  - LBNO: > 5σ sensitivity for all δ
    - Source: North Area at CERN;
    - Detector at Phyasalmi, Finland
      - Suite of detectors:
        - » LAr + MIND
        - » L-scintillator
      - Strong astro-particle and nucleon-decay case too







Mass hierarchy potential:



- **All options proposed for next-generation long-baseline experiment can determine the hierarchy**
  - **Mass hierarchy determination may come with a hint of CP-invariance violation**

Mass hierarchy summary:

- In addition to reactor and LBL experiments:
  - Atmospheric neutrinos:
    - ORCA:
      - Augment KM3Net with closely packed strings:
    - PINGU:
      - Augment Ice Cube with closely packed strings:
    - Issues:
      - Requires extremely large data set;
      - Sufficient rejection of downward going muons; and
      - Sufficient energy resolution (3 GeV)
    - Iron calorimeter (ICAL) at the Indian Neutrino Observatory (INO):
      - Opportunity:
        - » Detector is magnetised, can distinguish muon-neutrino- from anti-muon-neutrino-induced interactions;
      - Issue:
        - » Detector resolution limits sensitivity to ~3σ
- It is possible that a global fit to the results present and near future experiments will allow mass hierarchy to be determined;
  - Assumes validity of the Standard (three) Neutrino Model

CP-invariance violation:

- **Seek to establish:**
  - $P(\nu_\alpha \rightarrow \nu_\beta) \neq P(\nu_\alpha \rightarrow \nu_\beta)$

  by measuring the *asymmetry:*

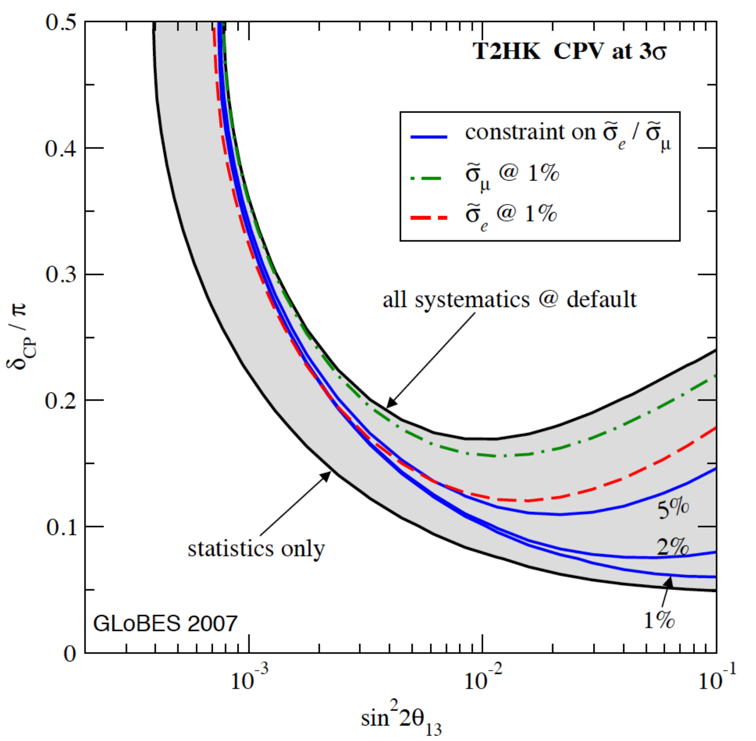
$$\frac{P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)}{P(\nu_\alpha \to \nu_\beta) + P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)} \propto \frac{1}{\sin 2\theta_{13}}$$

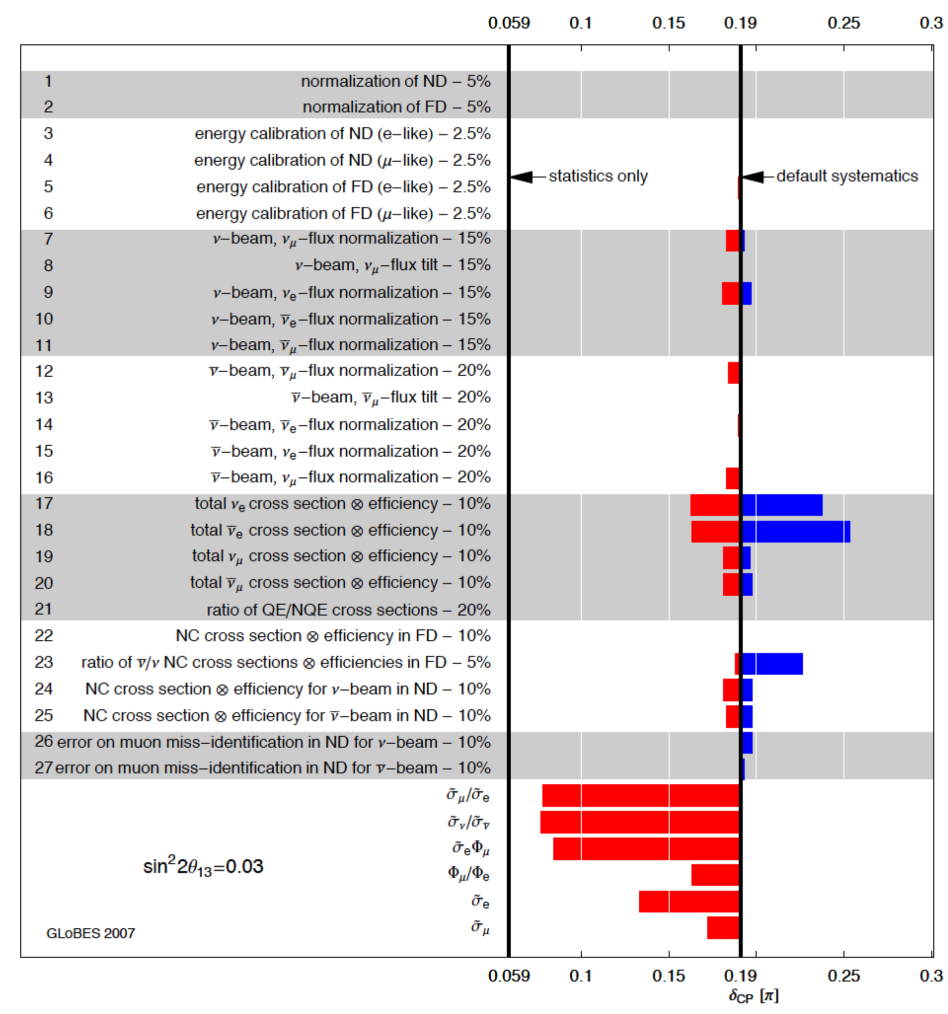
- **Large θ_{13} makes discovery conceivable, *but*:**
  - **Places premium on the control of systematic uncertainties**

Systematic uncertainties:

- T2HK, a case study:
  [applicable to, e.g. C2CF, …]
  – Narrow-band beam
  – Near and far detector

— critical at large θ_{13}



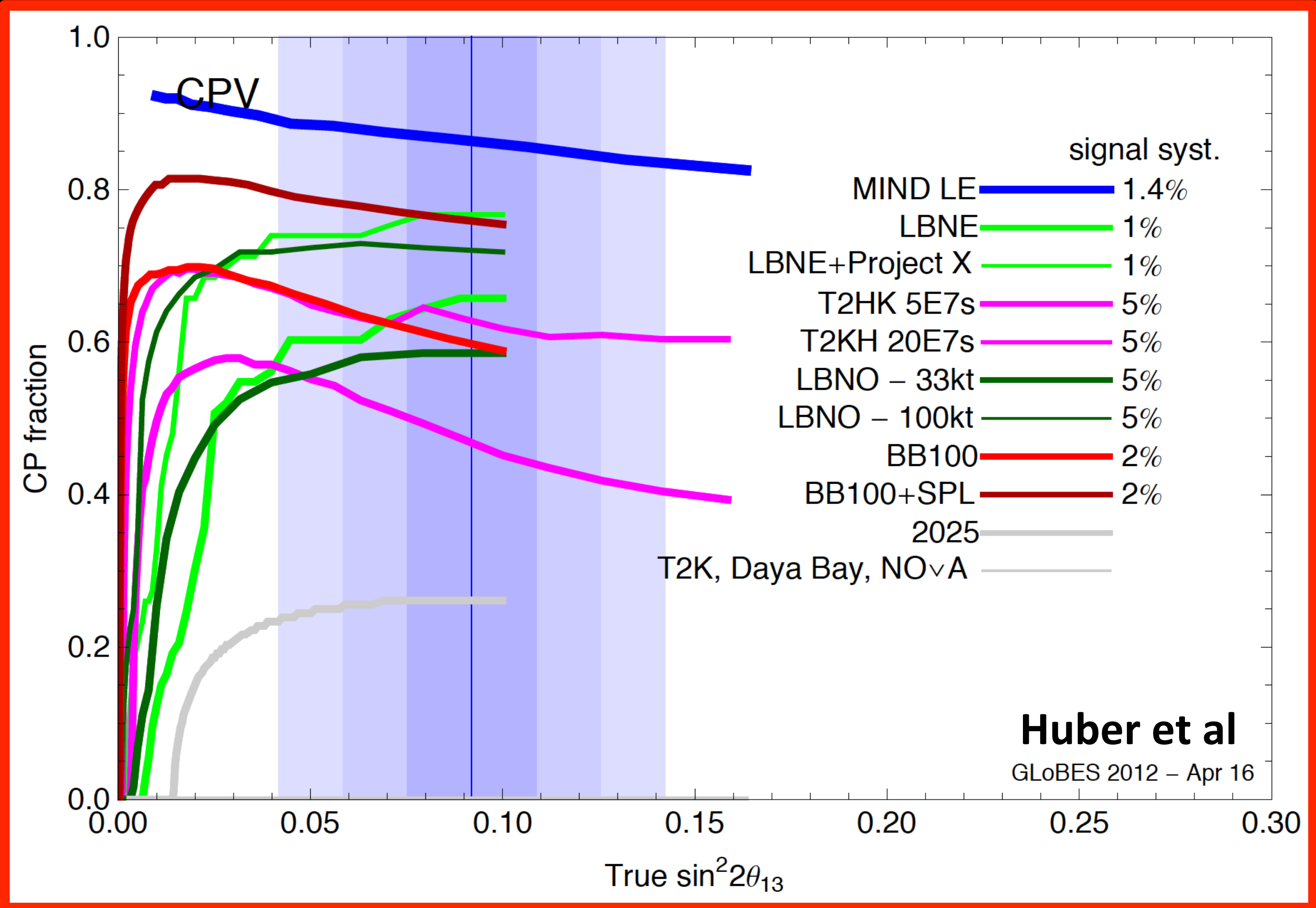


Huber, Mezzetto, Schwetz, arXiv:0711.2950v2

P. Coloma, P. Huber et al, IDS-NF#8:
https://www.ids-nf.org/wiki/GLA-2012-04-18/Agenda

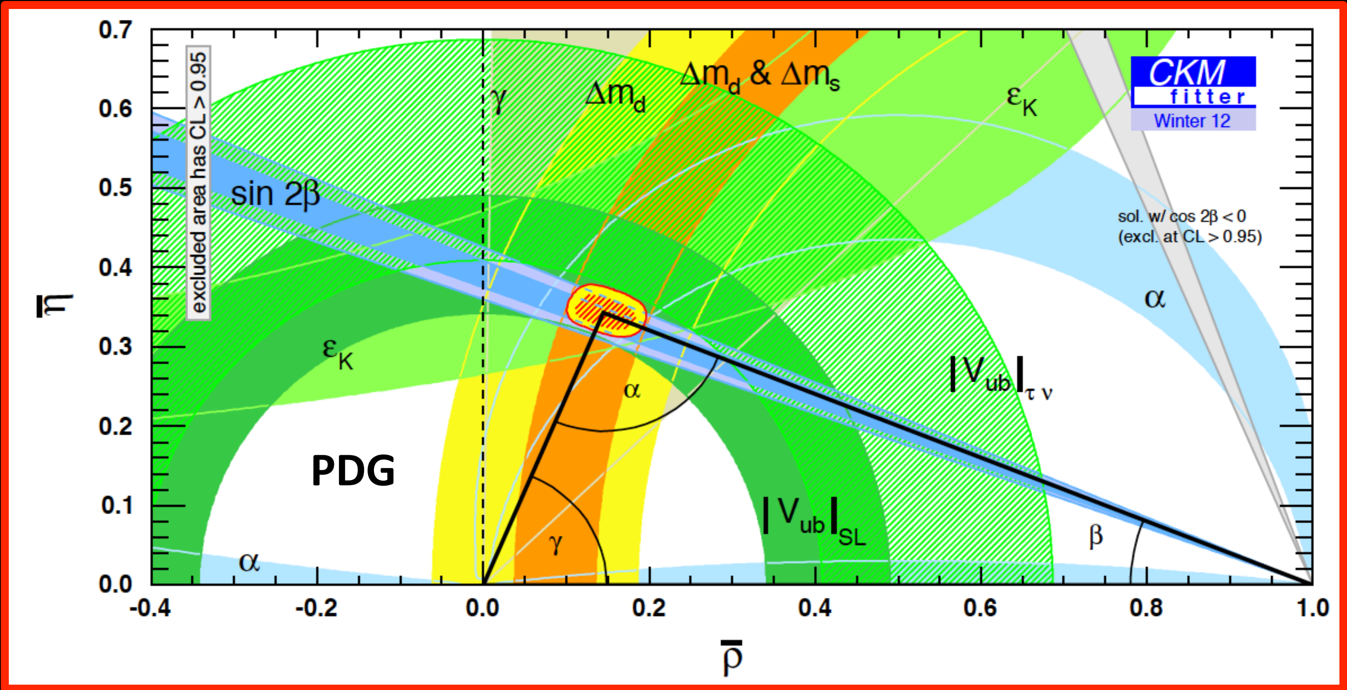
Discovery reach:

- Discovery reach at 3σ:
  - Neutrino Factory: 85—90%
  - Beta beam and SPL: 70—80%
  - Super beam: 60—75%



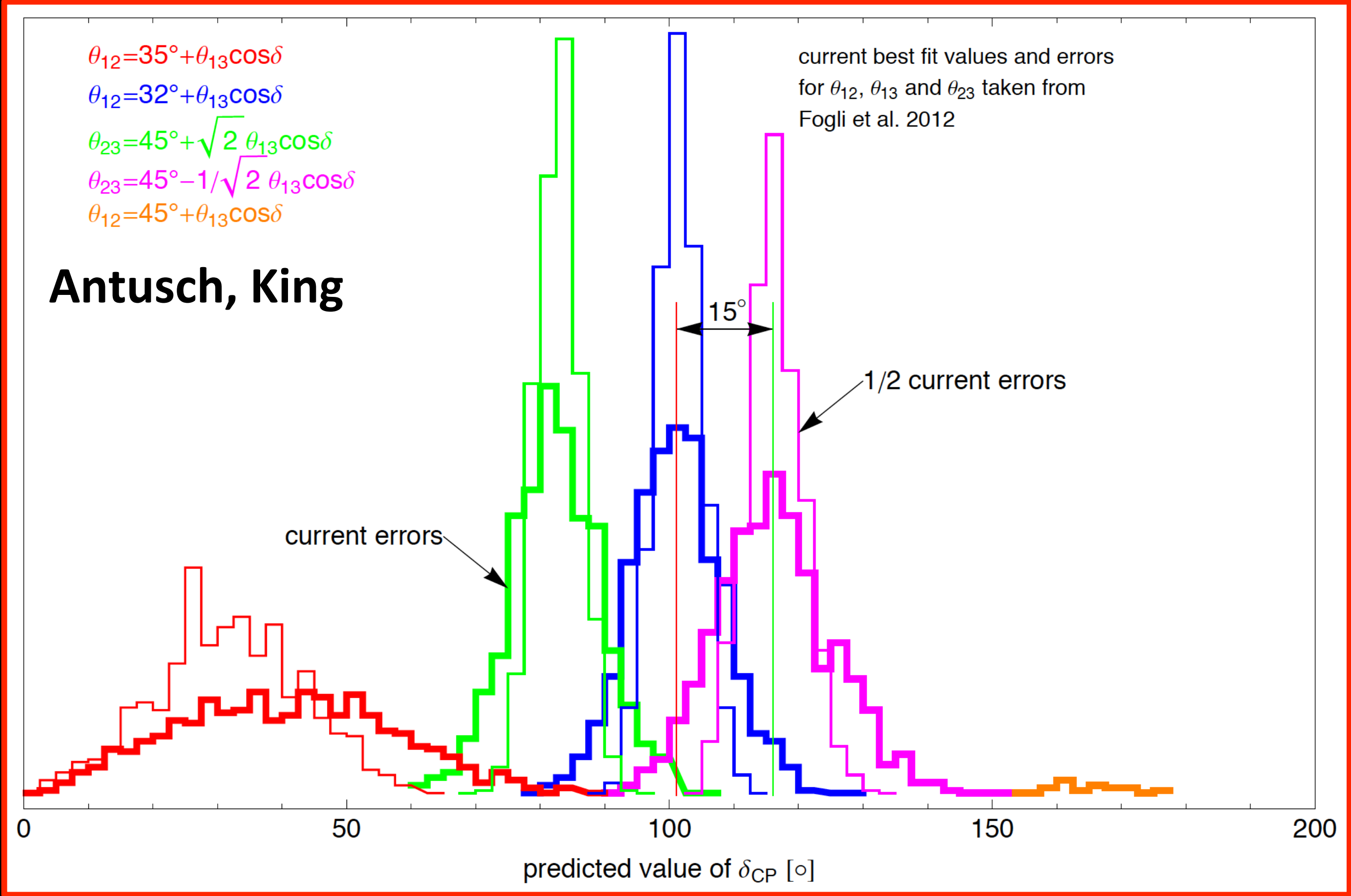
The case for precision:

- What determines the goal for sensitivity and precision?
  - Sensitivity:
    - Definitive discovery!
      - Must have sensitivity of "~5σ"
      - To resolve the LSND/miniBooNE "suite of anomalies" may set the bar higher!
  - Precision:
    - Field presently led by experiment;
      - Too many, or too few, theories;
    - Goal to determine parameters with a precision comparable to that with which the quark-mixing parameters are known



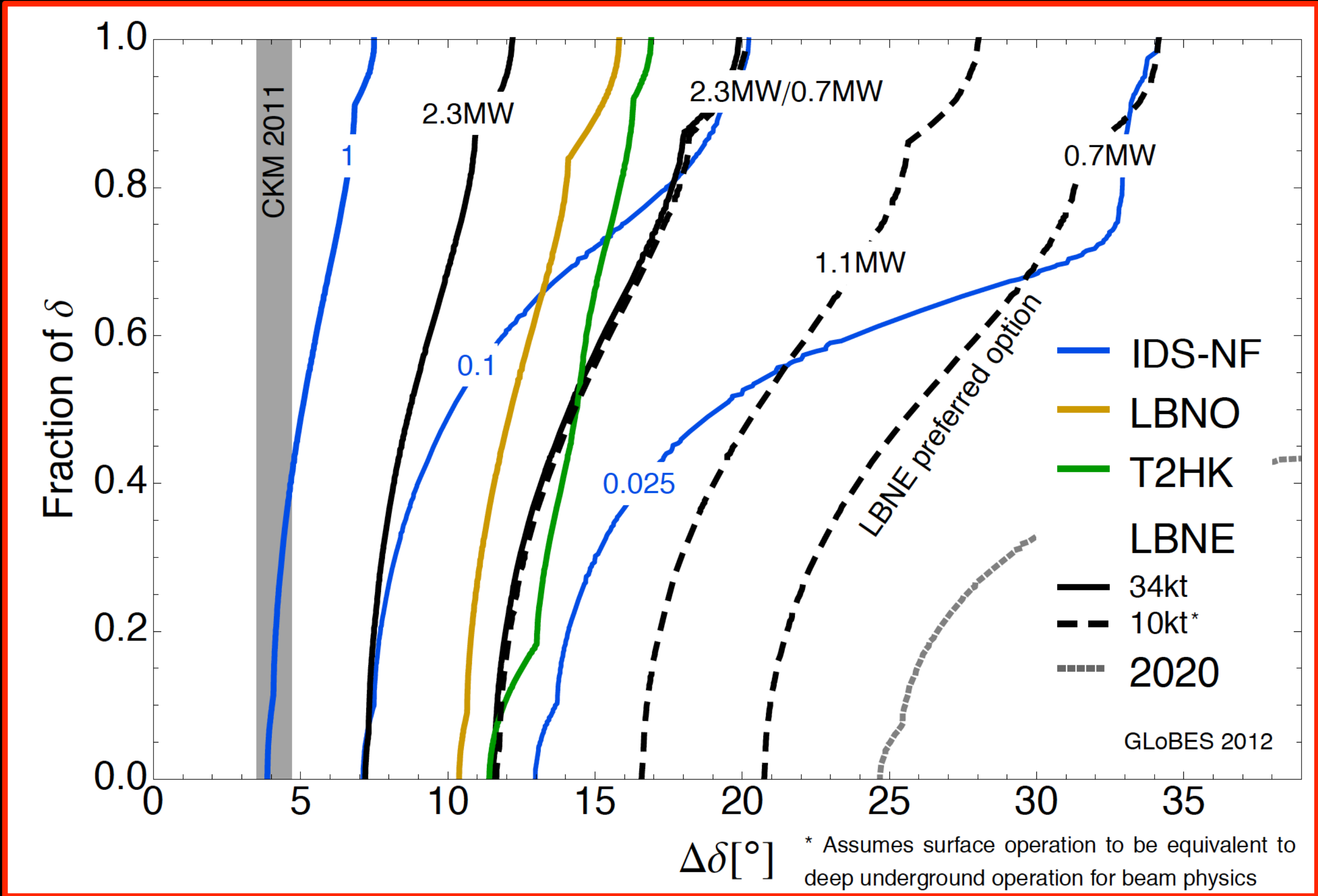
The case for precision:

- Some guidance from theory:
  - Models that relate quarks and leptons lead to sum rules



Coloma, Huber, Kopp, Winter
arXiv:1209.5973

Comparison:



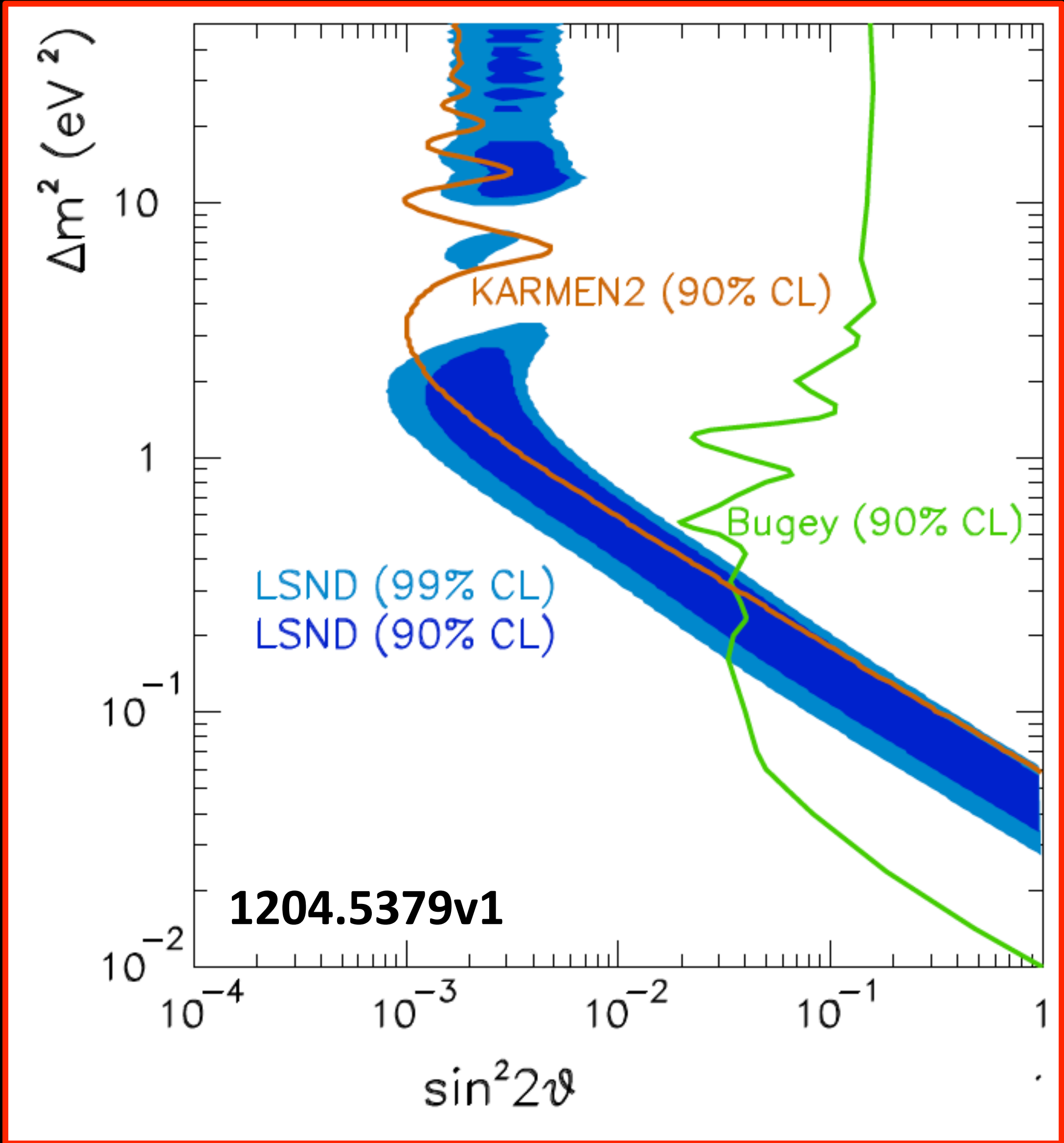
- **Benefit of luminosity:**
  - **Solid blue lines show effect on precision of scaling luminosity from baseline 10^{21} decays per year**
  - **Potential for definition of staged upgrade programme**

- In the first instance, a combination of long-baseline (wide-band beam) experiments (e.g. LBNE/LBNO) and short baseline experiments (e.g. T2HK) offers an attractive way forward
- However, in such an approach:
  - CP reach is limited by systematic effects;
  - Hints of CP violation would require follow up by the Neutrino Factory
- The Neutrino Factory will be required to make the detailed and precise measurements required to elucidate the physics of flavour. The European Strategy should therefore:
  - Recognise that the Neutrino Factory:
    - Meets the sensitivity and precision goals;
    - Is mature; key issues addressed, or being addressed;
  - Give priority to the incremental development of the facility

Neutrino experiments:

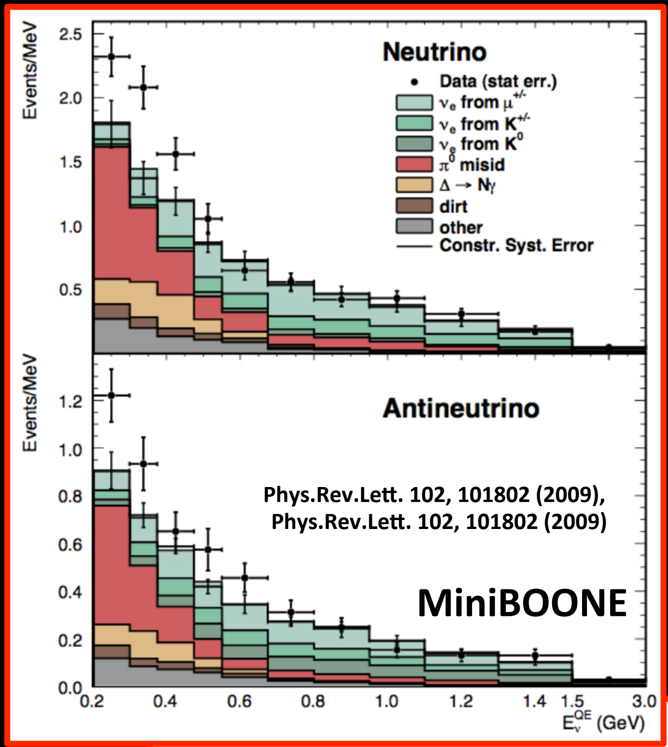
Sterile neutrinos

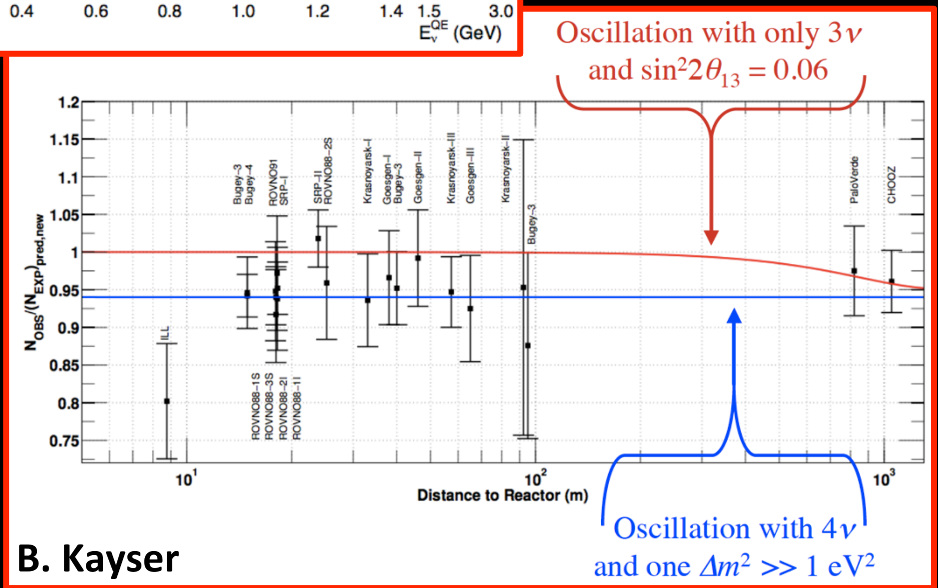
LSND:



- LSND reported evidence for an oscillation with Δm^2 ~ 1 eV^2:
  - If confirmed, implies at least one neutrino state that does not couple to Standard Model *W* or *Z*
    - I.e. one or more “sterile” neutrinos

Further information on sterile neutrinos:





- **Additional information:**
  - MiniBooNE low E_ν excess
  - Reactor neutrino flux
  - ^{51}Cr and ^{37}Ar ν_e rates
  - Cosmic microwave background
- **Individually, or taken together, the "hints" are not convincing**
- **However:**
  - Revolutionary if any one of the "hints" would be confirmed
  - Clear need to resolve the issue

What we need to measure:

- **Present, inconclusive, information from $\nu_e \rightarrow \nu_X$ and $\nu_\mu \rightarrow \nu_X$ transitions**
- **Ideally, study:**

<u>Flavor Transition</u>	<u>CPT Conjugate</u>
$\nu_e \rightarrow \nu_\mu$	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
$\bar{\nu}_e \rightarrow \bar{\nu}_\mu$	$\nu_\mu \rightarrow \nu_e$
$\nu_e \rightarrow \nu_{\not{e}}$	$\bar{\nu}_e \rightarrow \bar{\nu}_{\not{e}}$
$\nu_\mu \rightarrow \nu_{\not{\mu}}$	$\bar{\nu}_\mu \rightarrow \bar{\nu}_{\not{\mu}}$

and

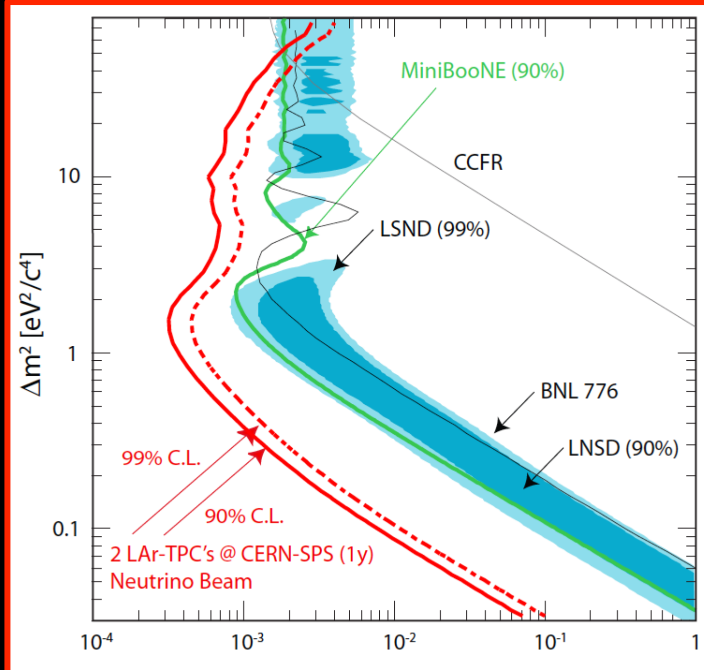
- **Determine neutral current rate**
  - **oscillation to steriles will change neutral current rate**
- **Study $\nu_e N$ and $\nu_\mu N$ scattering**
  - **including hadronic final states to eliminate background uncertainties**

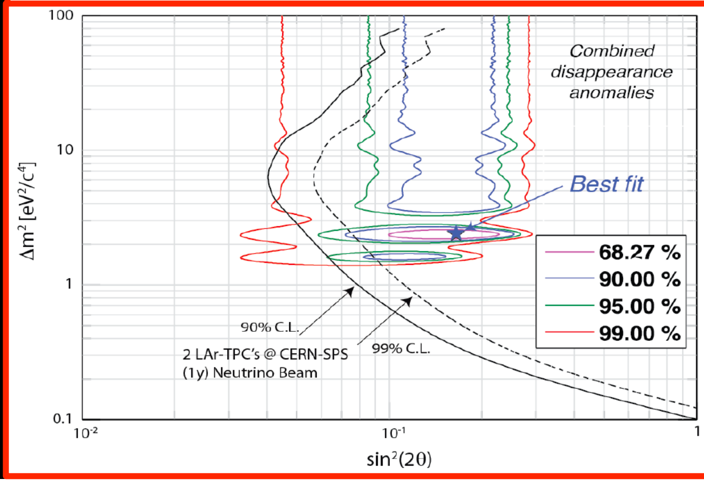
Present programme and future options:

- Present programme:
  - Super-Kamiokande, MiniBooNE, SciBooNE, …
- Electron-(anti)neutrino sources:
  - Mono-energetic neutrinos from electron capture
  - IsoDAR: ^{8}Li produced in a cyclotron; observe $\bar{\nu}_e$
- Muon-(anti)neutrino sources:
  - LArl/NESSIE: near/far LAr detector combination at FNAL/CERN
- Muon- and electron-(anti-)neutrino sources:
  - LENA + cyclotron to produce muons
    - Rate vs distance measurement from neutrinos produced in muon decay at rest
  - nuSTORM
    - Neutrino experiments illuminating near/far detector combination

NESSiE

Neutrino Experiment with SpectrometerS in Europe

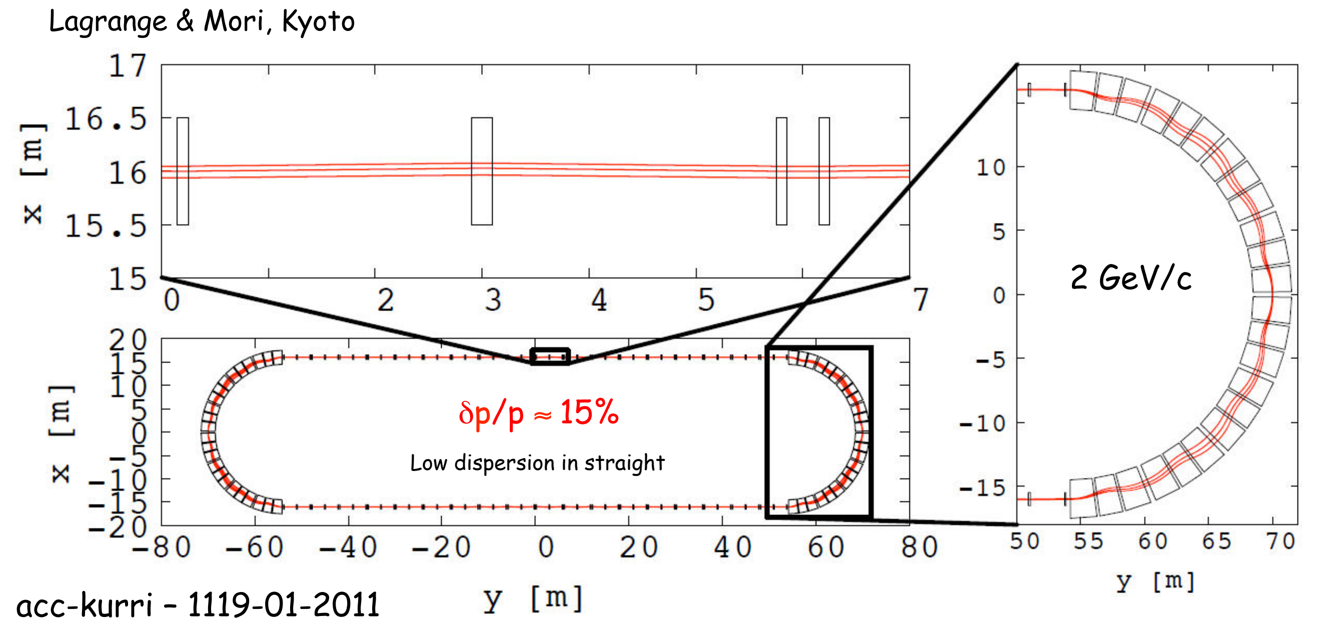


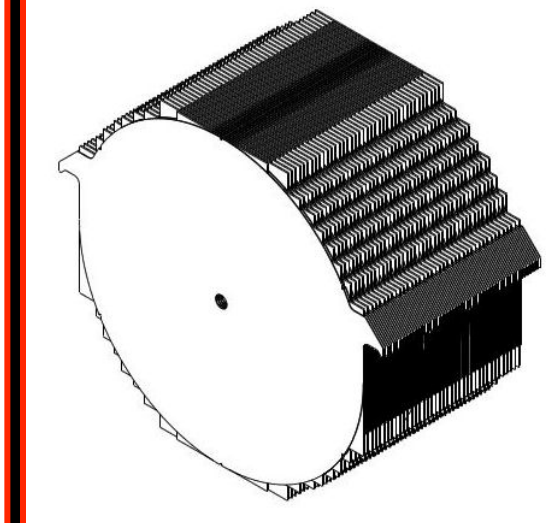


- **Two-baseline approach:**
  - **Two LAr TPCs with MIND**
- **Requires fast extraction at ~40 GeV from SPS to NA**
- **Ambition:**
  - **Implement for data taking start in 2016**

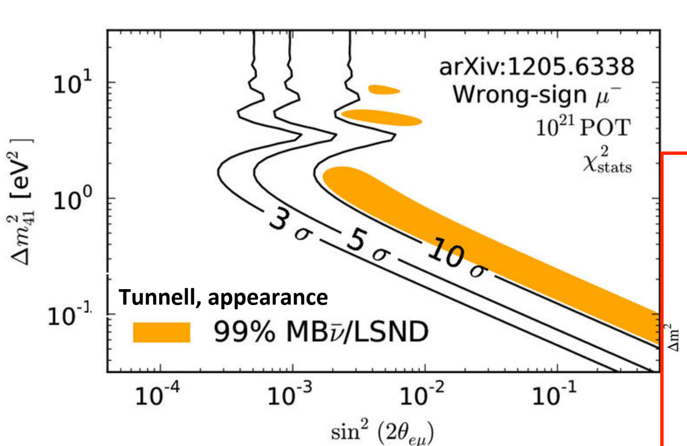
LOI [Bross et al];
Fermilab proposal P-1080 &
arXiv:1206.0294

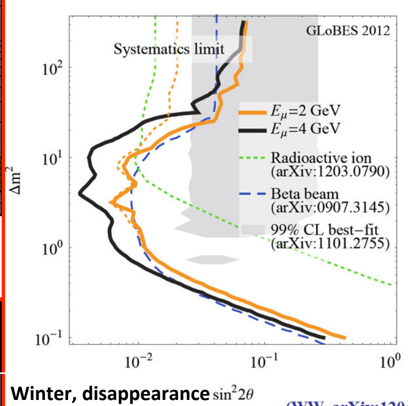
nuSTORM: conceptual design:





- Magnetized Iron
  - 1 kT fiducial volume
    - Following MINOS ND ME design
    - 1 cm Fe plate
    - 5 m diameter
  - Utilize superconducting transmission line for excitation
    - Developed 10 years ago for VLHC
  - Extruded scintillator +SiPM



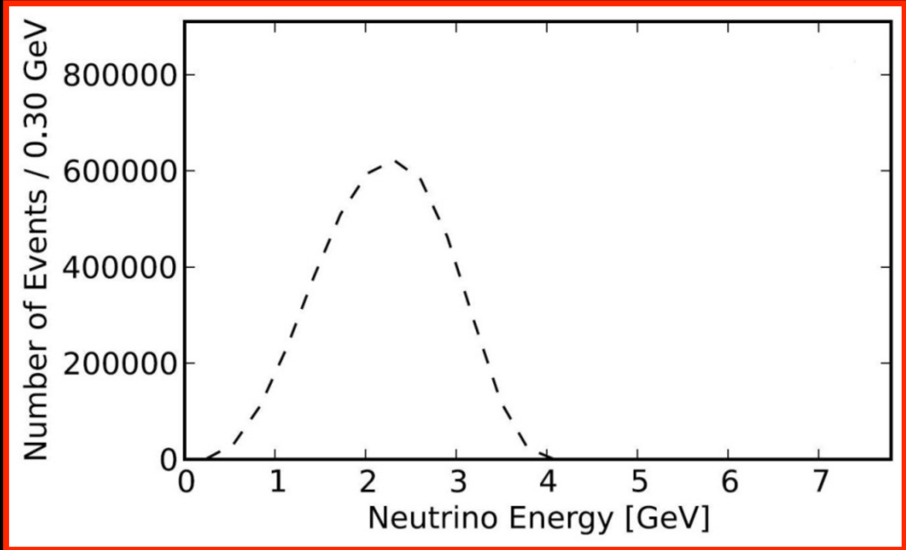


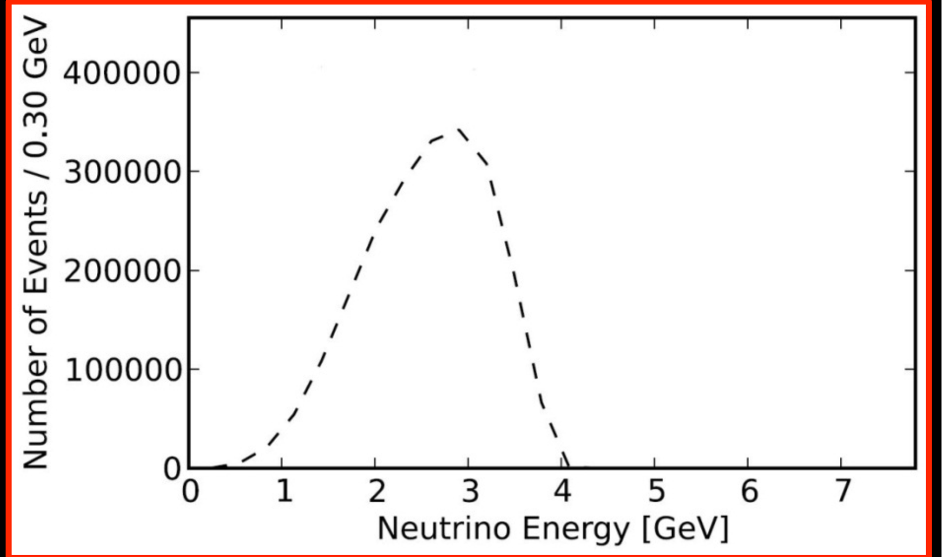
(WW, arXiv:1204.2671)

- Need either E_μ=4 GeV or 10^{19} useful muon decays/polarity to cover best-fit
- Highly competitive compared to alternatives (⇨Sterile neutrino white paper)
- Can one improve on "systematics limit"?

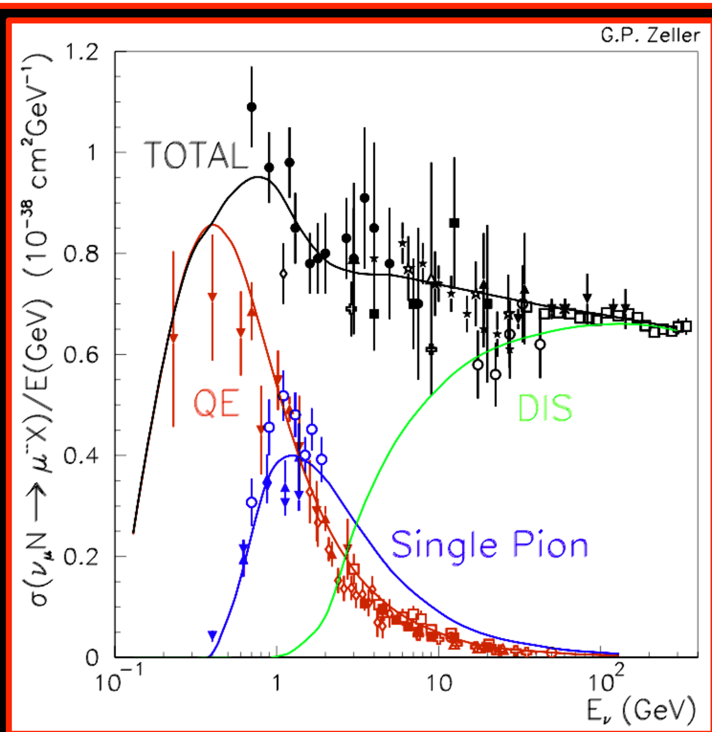
- Unique opportunity to measure electron-neutrino cross sections
- Also, measure muon-neutrino cross sections
- Full set of neutrino-scattering physics:
  - QCD
  - Structure functions & form factors
  - Electroweak
  - ...

nuSTORM x-section measurement potential:





- **Above:**
  - **nuSTORM event rates/100T at near detector 50 m from straight with μ^+ stored**
- **Right:**
  - **State of the art:**
    - **Almost no ν_e measurements**



- **Confirmation of one of the "hints", or discovery of a sterile-neutrino state would revolutionise the field:**
  - **Europe has the opportunity to contribute with techniques that are both quantitatively and *qualitatively* different. The strategic development of a definitive programme should be a priority;**

Neutrino experiments:

R&D and control of systematics

Accelerator challenges:

- Proton driver:
  - 4 MW; 5 < Ep < 15 GeV; bunch length 1—3 ns
  - Linac (CERN, FNAL) and ring (RAL, JPARC) options: Progress: costing based on SPL
- Pion-production target:
  - Baseline: liquid mercury jet
  - Options: powder jet or solid
  - Progress: particle shielding, magnetic lattice
- Muon front end:
  - Chicane (new) to remove secondary hadrons:
    - Bent solenoid transport & beryllium absorber
  - Buncher & rotator:
    - Progress: lattice revision in response to engineering study
  - Cooling:
    - Baseline: solenoid transport, LiH absorber
    - Options: bucked coils or high-pressure H2
    - Progress: lattice revision in response to engineering study
- Rapid acceleration:
  - Two options considered for acceleration to 10 GeV:
    - Linac, RLA I and RLA II;
    - Linac, RLA I and FFAG
  - Choice based on cost and performance estimates

- Proton driver:
  - Development of high-power, pulsed proton source underway at proton labs
- Pion-production target:
  - MERIT experiment at CERN proved principle of mercury jet target
- Muon front end:
  - MuCool programme at FNAL:
    - Study of effect of magnetic field on high-gradient, warm, copper cavities;
  - MICE experiment at RAL:
    - Proof of principle of ionization-cooling technique
- Rapid acceleration:
  - EMMA experiment at DL:
    - Proof of principal of non-scaling FFAG technique;
      - Novel technology allows circular acceleration without magnet ramp

Detector challenges:

- **Measurement of oscillations:**
  - Requirements:
    - Large mass;
    - High granularity/resolution;
    - Magnetisation;
  - Options:
    - LAr:
      - Scaling to large mass needs to be demonstrated;
    - Totally active scintillator:
      - "Cost per channel" needs to be reduced;
    - Magnetisation:
      - Need to develop (or prove) a technique by which a large volume empty of ferrous material can be magnetised
- **Control of systematics:**
  - Require to develop a high-resolution detector or detectors capable of determining the νN cross sections and studying the hadronic final states with appropriate precision;
  - Require to continue the programme of hadroproduction measurements required to improve the conventional flux models and simulation codes

- Given the likely scale of the integrated investment required to determine the properties of the neutrino and elucidate the physics of flavour an incremental approach must be adopted in which each increment:
  - Makes cutting-edge contributions to neutrino physics;
  - Delivers the measurements by which the systematic errors are reduced to a level appropriate to the increment; and
  - Delivers the R&D (and design work) required to implement the subsequent increment

Neutrino experiments:

Elements of a strategy; introduction to discussion

- **The study of the neutrino is the study of physics beyond the Standard Model and gives information complementary to the energy-frontier programme**
  - **This fundamental programme, to which Europe can make uniquely-important contributions, should be a priority in the European Strategy for Particle Physics**

- **The search for $0\nu\beta\beta$ is of fundamental importance and the determination of the neutrino mass-scale is critical to the development of a full understanding of the neutrino:**
  - **Europe has an established position of leadership in these areas. The completion of the Katrin programme and the strategic development of low-background, deep-underground facilities should be a priority**

- In the first instance, a combination of long-baseline (wide-band beam) experiments (e.g. LBNE/LBNO) and short baseline experiments (e.g. T2HK) offers an attractive way forward
- However, in such an approach:
  - CP reach is limited by systematic effects;
  - Hints of CP violation would require follow up by the Neutrino Factory
- The Neutrino Factory will be required to make the detailed and precise measurements required to elucidate the physics of flavour. The European Strategy should therefore:
  - Recognise that the Neutrino Factory:
    - Meets the sensitivity and precision goals;
    - Is mature; key issues addressed, or being addressed;
  - Give priority to the incremental development of the facility

- **Confirmation of one of the "hints", or discovery of a sterile-neutrino state would revolutionise the field:**
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- **Given the likely scale of the integrated investment required to determine the properties of the neutrino and elucidate the physics of flavour an incremental approach must be adopted in which each increment:**
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All together a wonderful programme!

Thank you