Neutrinos from stored muon beams:

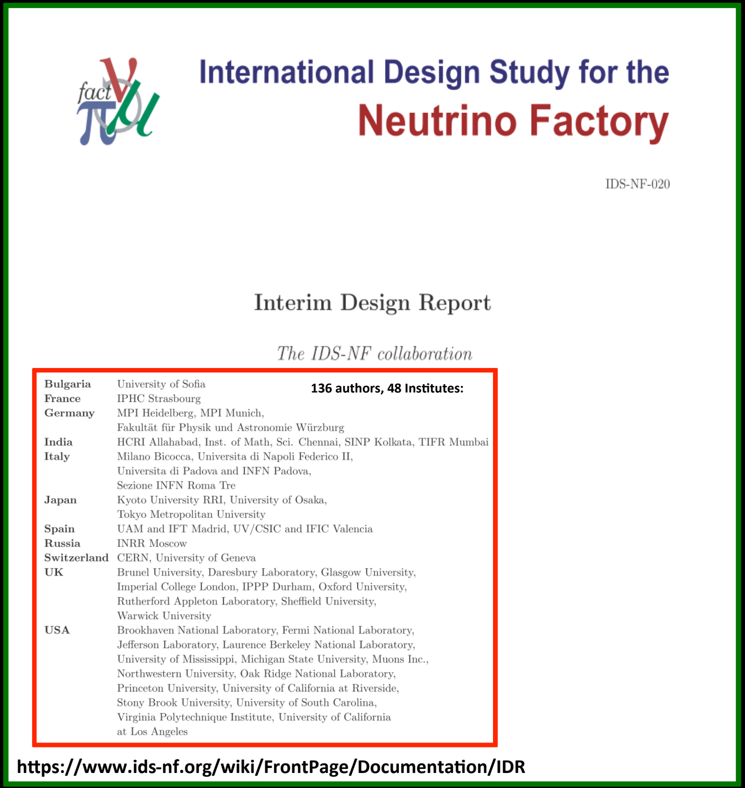
… an incremental approach to the Neutrino Factory

Imperial College London

K. Long,
24 May 2013

Acknowledgements:

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



International Design Study for the
Neutrino Factory

IDS-NF-020

Interim Design Report

The IDS-NF collaboration

136 authors, 48 Institutes:

Bulgaria	University of Sofia
France	IPHC Strasbourg
Germany	MPI Heidelberg, MPI Munich, Fakultät für Physik und Astronomie Würzburg
India	HCRI Allahabad, Inst. of Math, Sci. Chennai, SINP Kolkata, TIFR Mumbai
Italy	Milano Bicocca, Universita di Napoli Federico II, Universita di Padova and INFN Padova, Sezione INFN Roma Tre
Japan	Kyoto University RRI, University of Osaka, Tokyo Metropolitan University
Spain	UAM and IFT Madrid, UV/CSIC and IFIC Valencia
Russia	INRR Moscow
Switzerland	CERN, University of Geneva
UK	Brunel University, Daresbury Laboratory, Glasgow University, Imperial College London, IPPP Durham, Oxford University, Rutherford Appleton Laboratory, Sheffield University, Warwick University
USA	Brookhaven National Laboratory, Fermi National Laboratory, Jefferson Laboratory, Laurence Berkeley National Laboratory, University of Mississippi, Michigan State University, Muons Inc., Northwestern University, Oak Ridge National Laboratory, Princeton University, University of California at Riverside, Stony Brook University, University of South Carolina, Virginia Polytechnique Institute, University of California at Los Angeles

https://www.ids-nf.org/wiki/FrontPage/Documentation/IDR

Contents:

- Neutrinos; beyond the Standard Model
- The Standard Neutrino Model
- R&D and control of systematics
- Sterile neutrinos
- nuSTORM
- Elements of the future programme
- Conclusions

Neutrinos from stored muon beams:

Neutrinos;
physics beyond the Standard Model

Standard Model:

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

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

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

The Standard Model neutrino was:

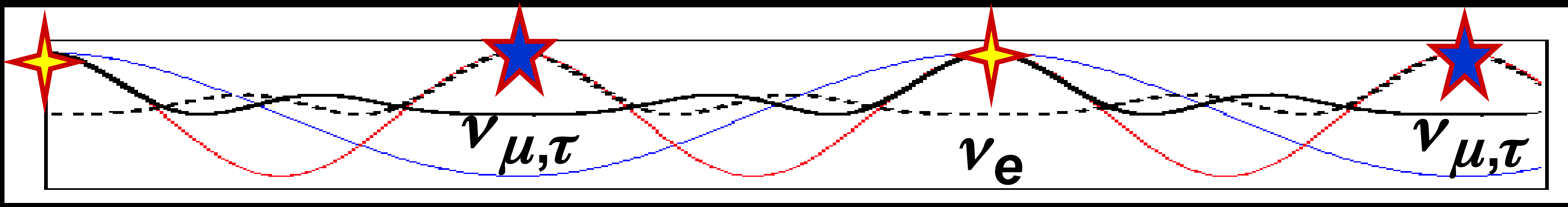
- *Massless*
- Chargeless
- Helicity eigenstate

Extend SM to include neutrino mass:

- 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

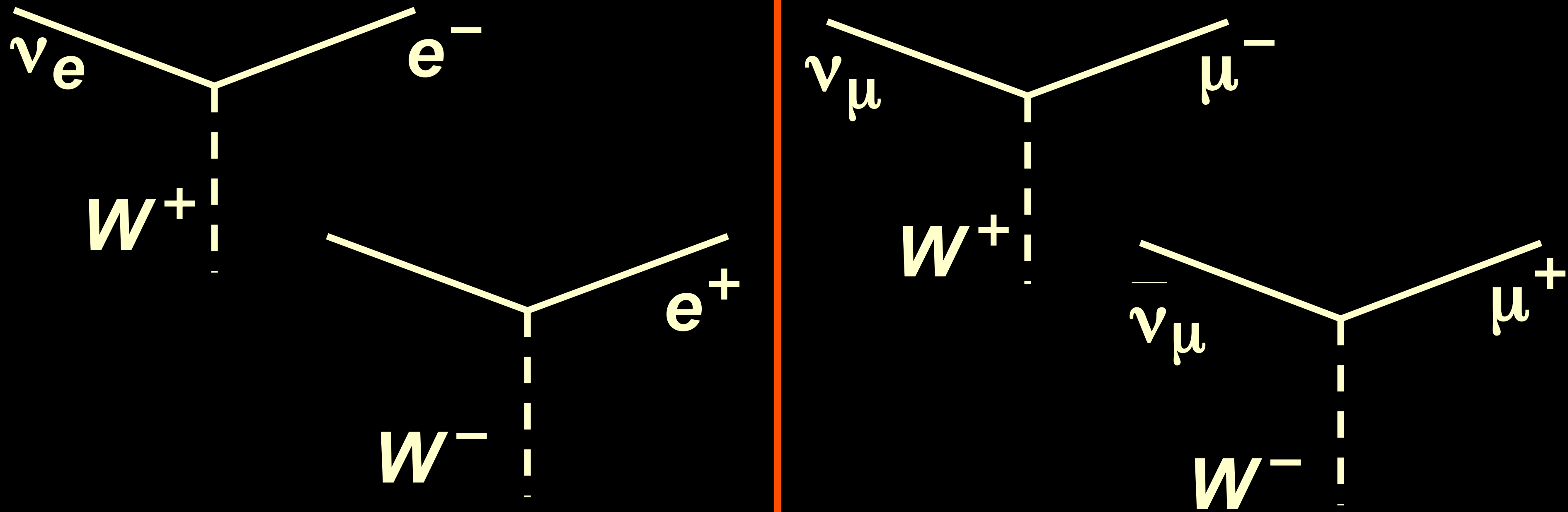
ν_e created



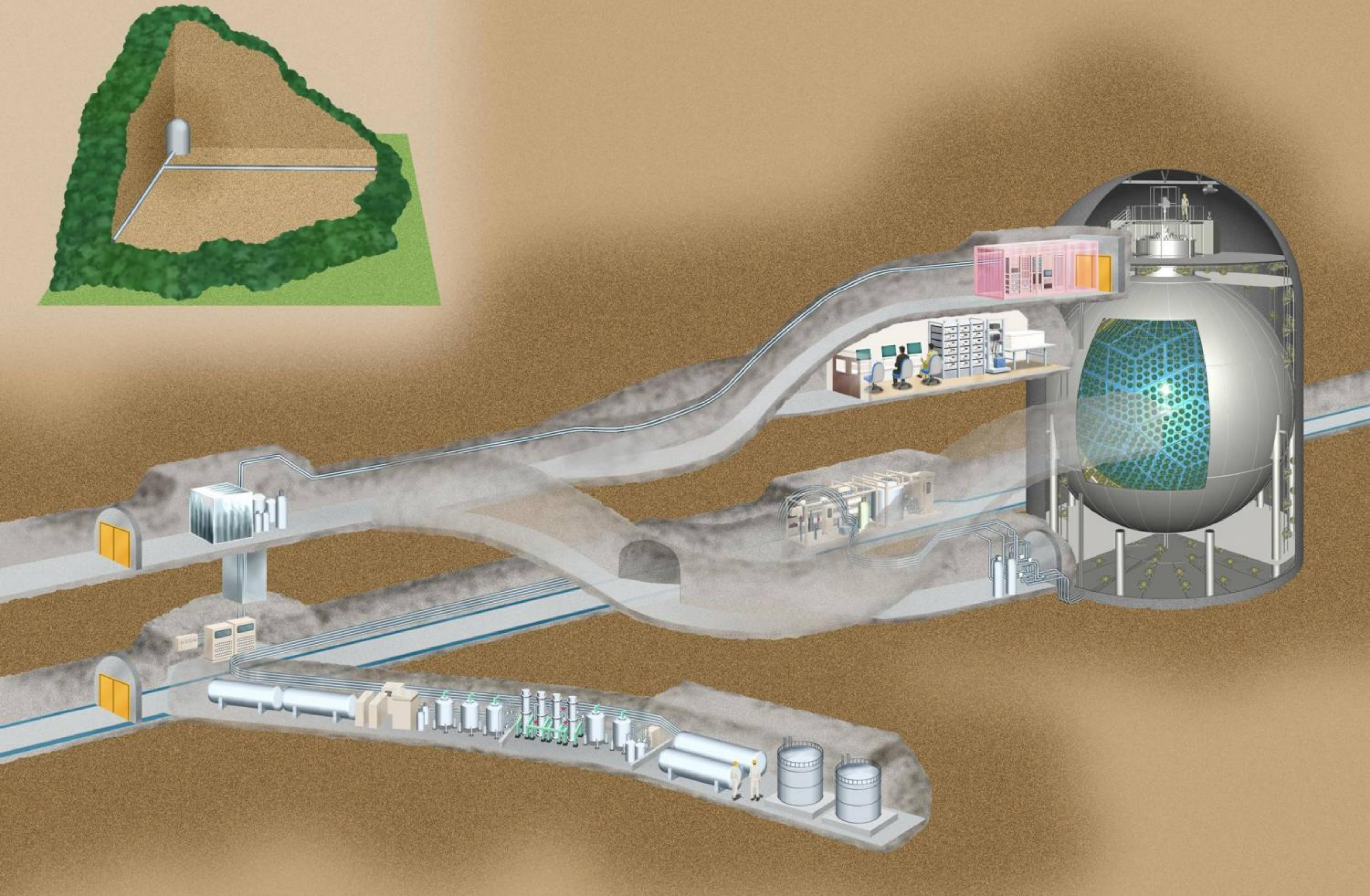
Space or time

Schrödinger's neutrino:

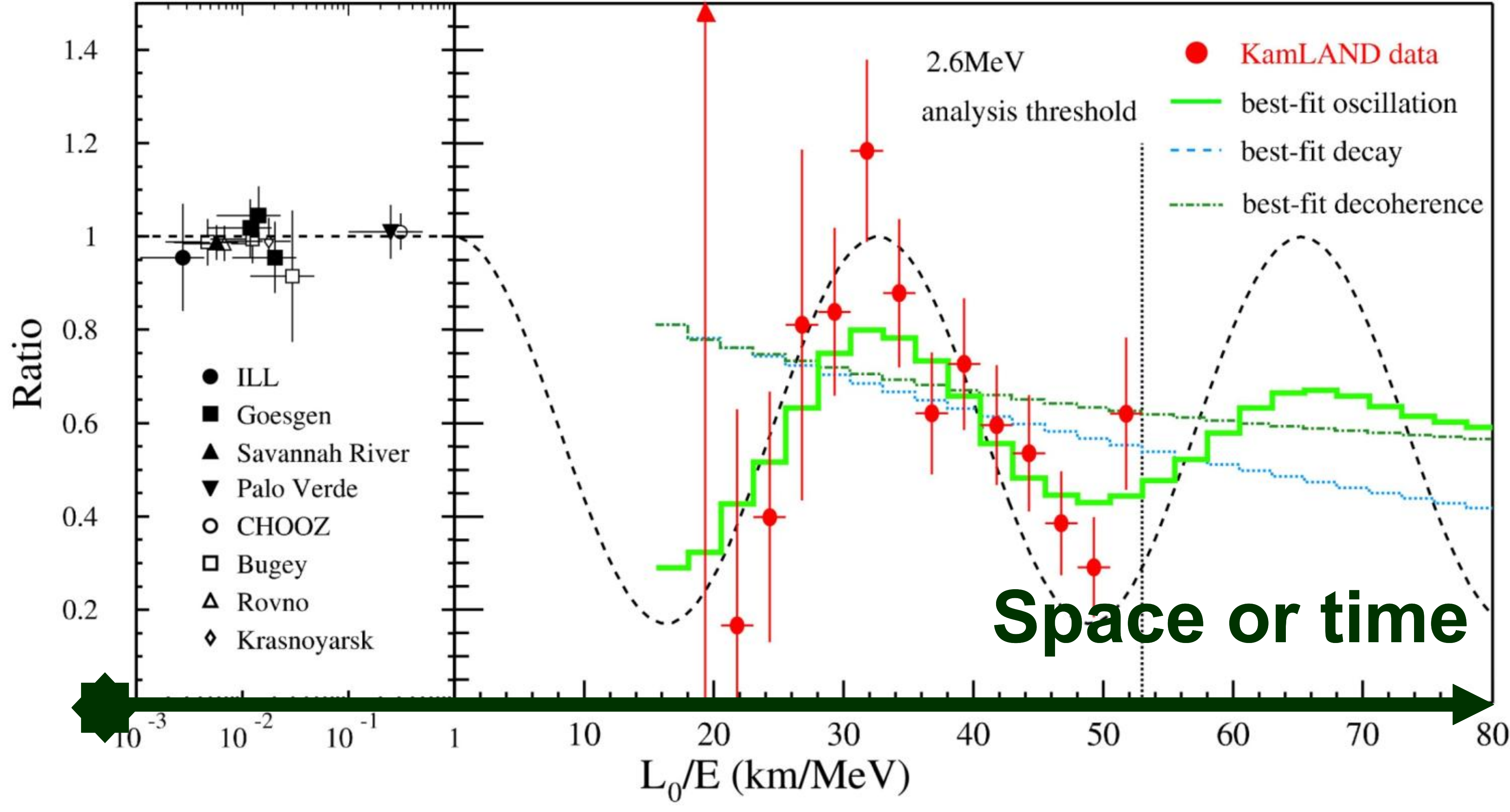
$$\begin{pmatrix}\nu_e \\ e^-\end{pmatrix} \quad \begin{pmatrix}e^+ \\ \bar{\nu}_e\end{pmatrix} \qquad \begin{pmatrix}\nu_\mu \\ \mu^-\end{pmatrix} \quad \begin{pmatrix}\mu^+ \\ \bar{\nu}_\mu\end{pmatrix}$$



Reactor neutrinos: Kamland:



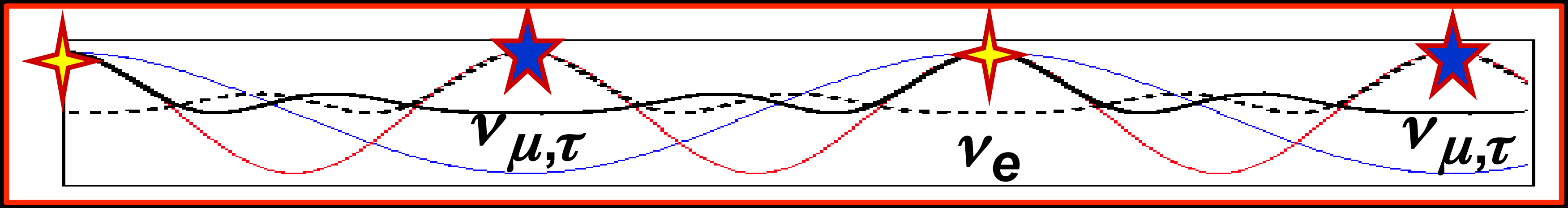
Oscillating electron (anti-)neutrinos



Space or time

Physics beyond the Standard Model:

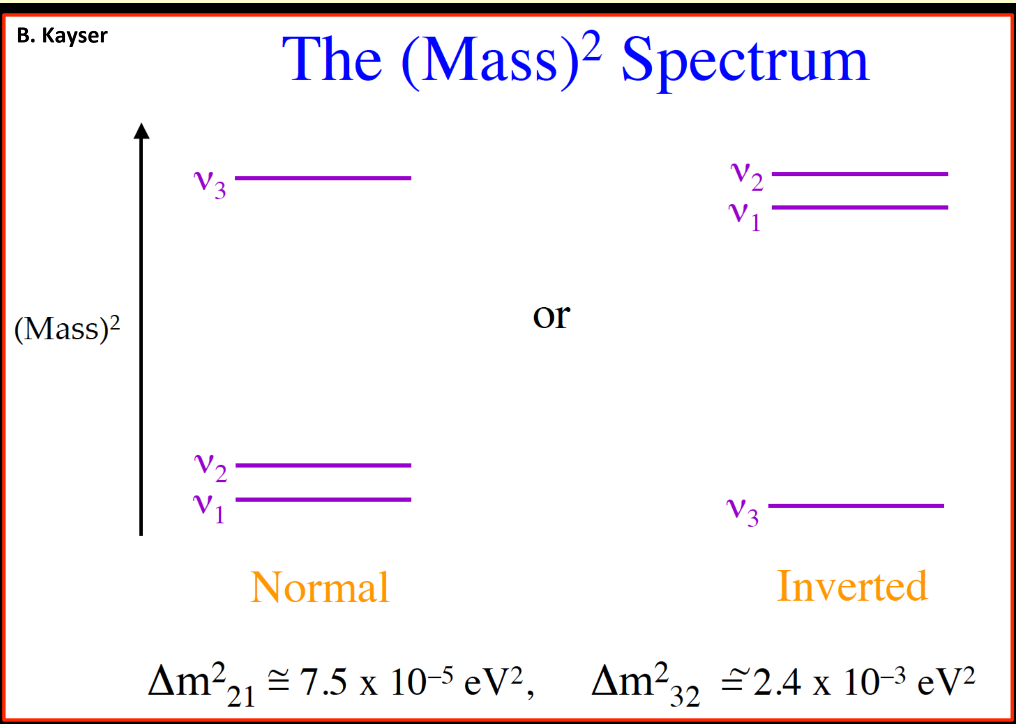
- Neutrino oscillations imply BSM physics:
  - Either:
    - Conserved lepton number distinguishes neutrino from antineutrino; or
    - Neutrino is its own antiparticle; a new state of matter, a Majorana fermion
- Mixing among three neutrino flavours admits possibility of CP-invariance violation



Standard Neutrino Model:

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

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



$\Delta m^2_{21} \cong 7.5 \times 10^{-5}\ \text{eV}^2$, $\Delta m^2_{32} \cong 2.4 \times 10^{-3}\ \text{eV}^2$

- 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

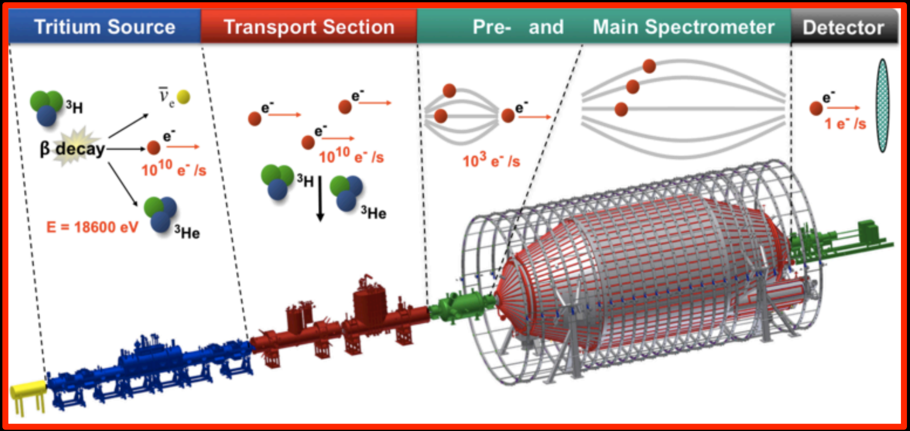
- Fundamental questions:
  - What is the nature of the neutrino, Majorana or Dirac?
  - What is the absolute neutrino-mass scale?
  - Is CP-invariance violated in neutrino oscillations?
  - Is the neutrino-mass spectrum normal or inverted?
  - Is the neutrino-mixing matrix unitary?
  - Are there sterile neutrinos?
  - Is there a connection between quark and lepton flavour?

Neutrinos from stored muon beams:

Mass scale, Dirac or Majorana

Neutrino mass-scale:

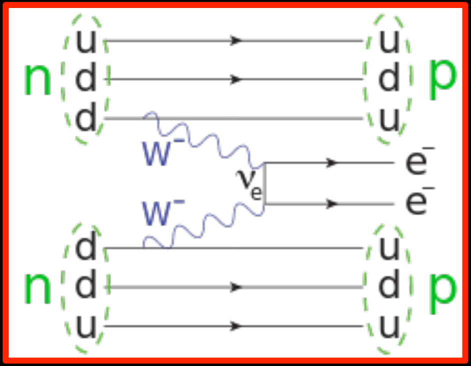
- Determination of neutrino mass:
  - Electron spectrum in nuclear beta decay
  - If observed, through neutrino-less double beta decay (0νββ)

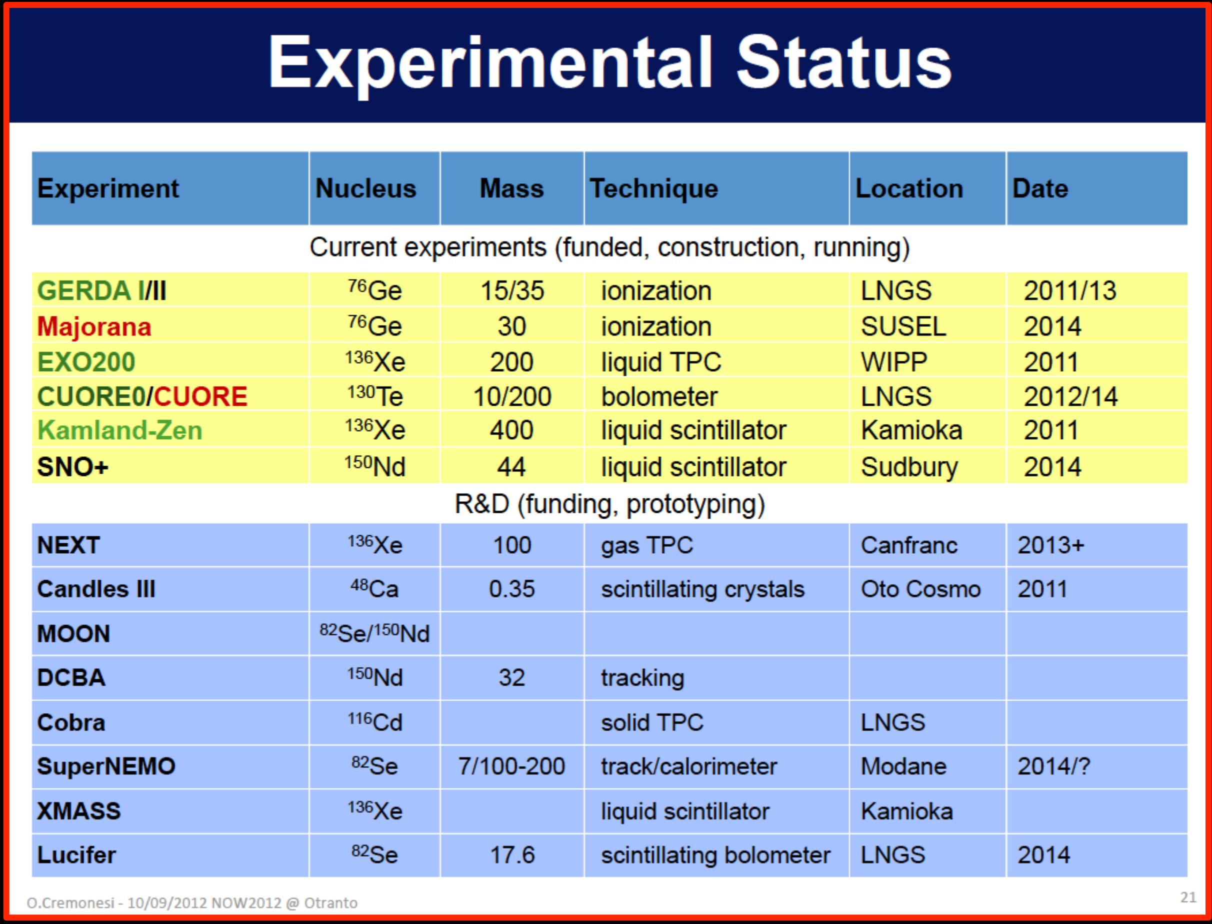


  - Cosmological observables, e.g.:
    - Large-scale structure;
    - Cosmic microwave background temperature fluctuations

- 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

O.Cremonesi - 10/09/2012 NOW2012 @ Otranto

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

Neutrinos from stored muon beams:

Standard Neutrino Model

Daya Bay and RENO:

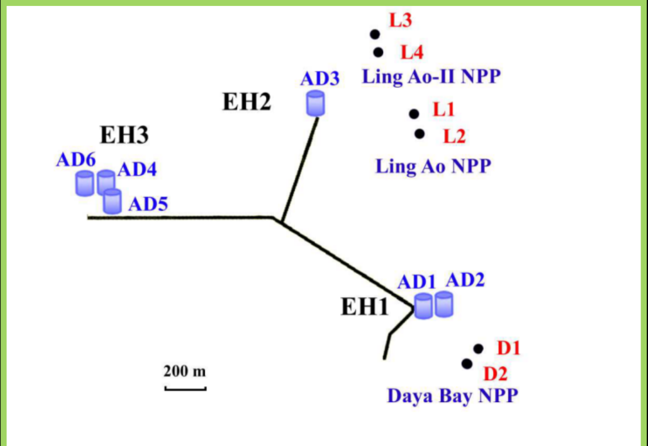
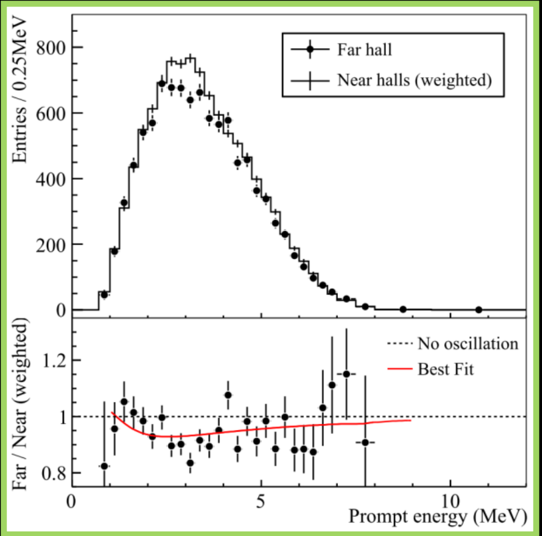
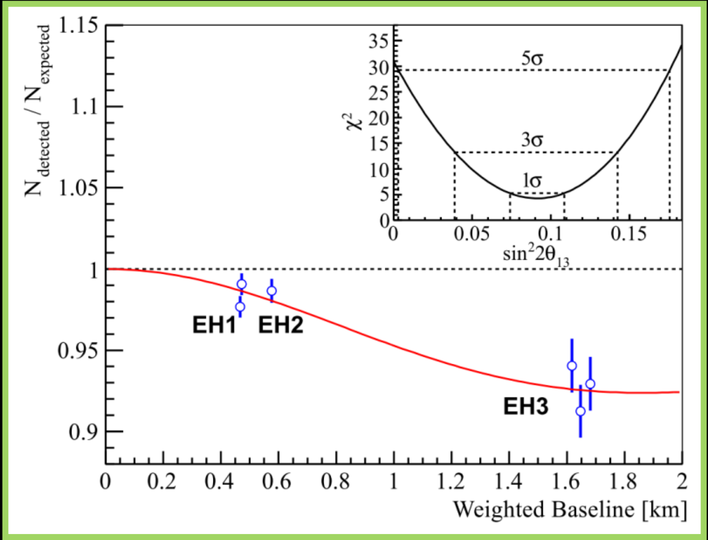
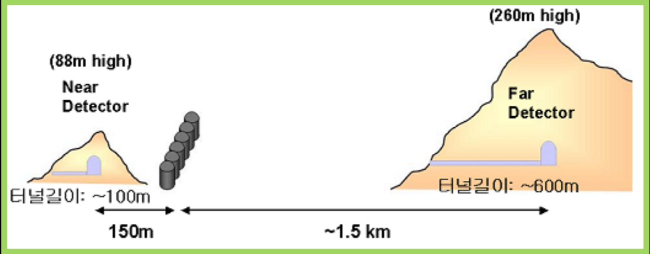
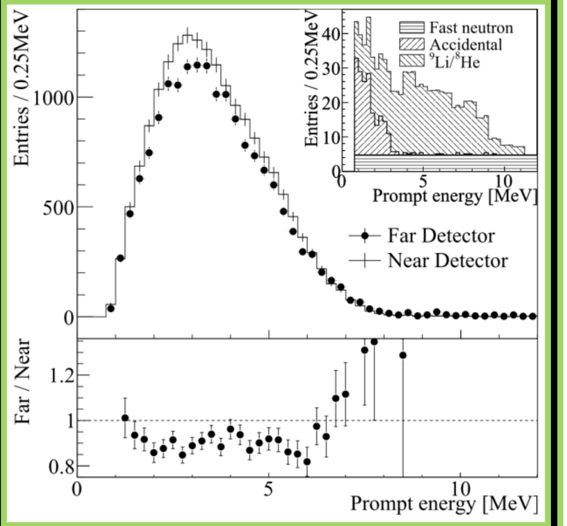


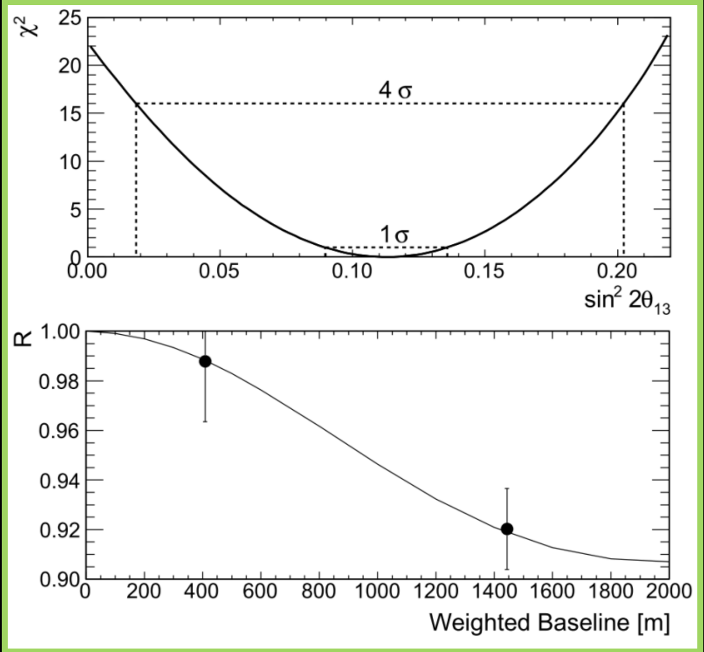
FIG. 1. Layout of the Daya Bay experiment. The dots represent reactors, labeled as D1, D2, L1, L2, L3 and L4. Six ADs, AD1–AD6, are installed in three EHs.











	$\sin^2 2\theta_{13}$		
	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*

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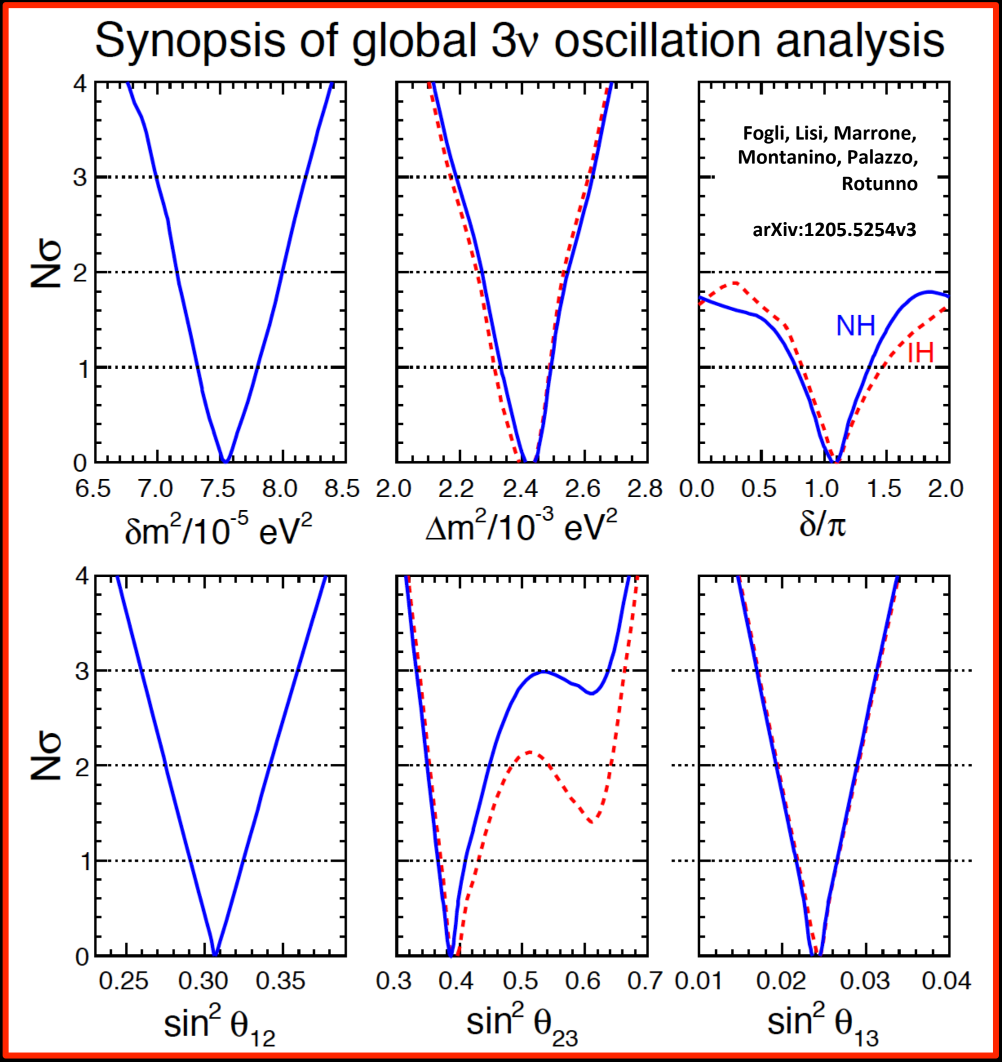
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\begin{pmatrix}1&0&0\\0&c_{23}&s_{23}\\0&-s_{23}&c_{23}\end{pmatrix}\begin{pmatrix}c_{13}&0&s_{13}e^{i\delta}\\0&1&0\\-s_{13}e^{-i\delta}&0&c_{13}\end{pmatrix}\begin{pmatrix}c_{12}&s_{12}&0\\-s_{12}&c_{12}&0\\0&0&1\end{pmatrix}\begin{pmatrix}\nu_1\\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



Fogli, Lisi, Marrone, Montanino, Palazzo, Rotunno

arXiv:1205.5254v3

- **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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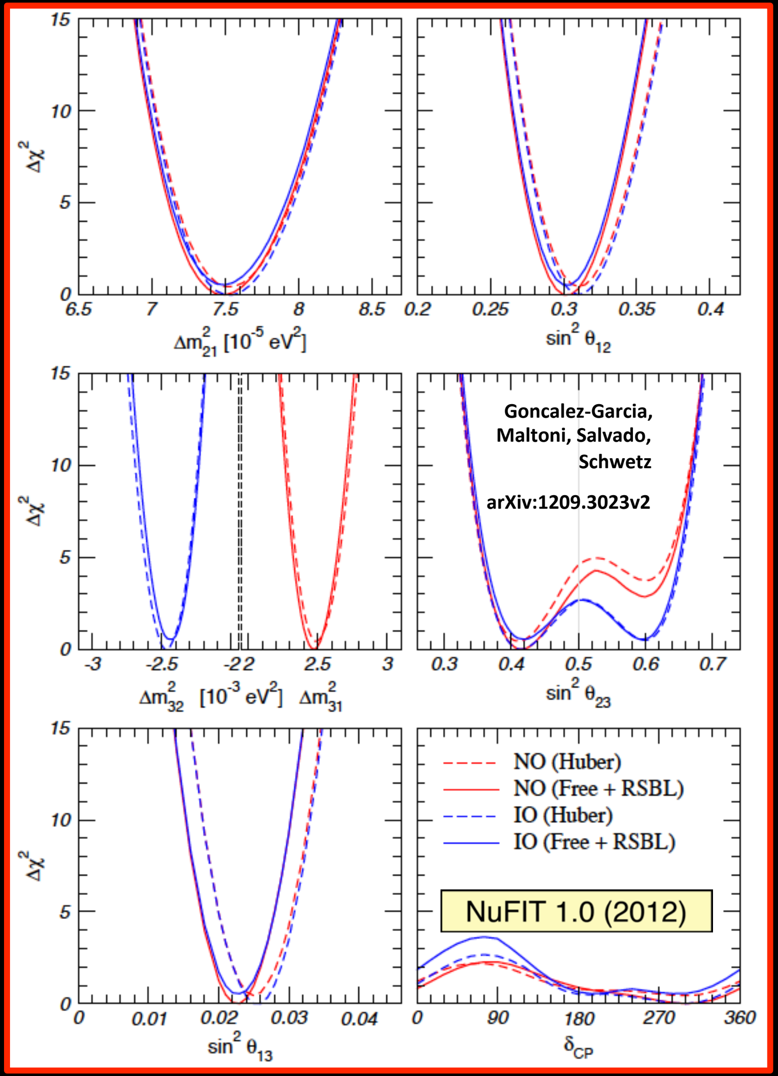
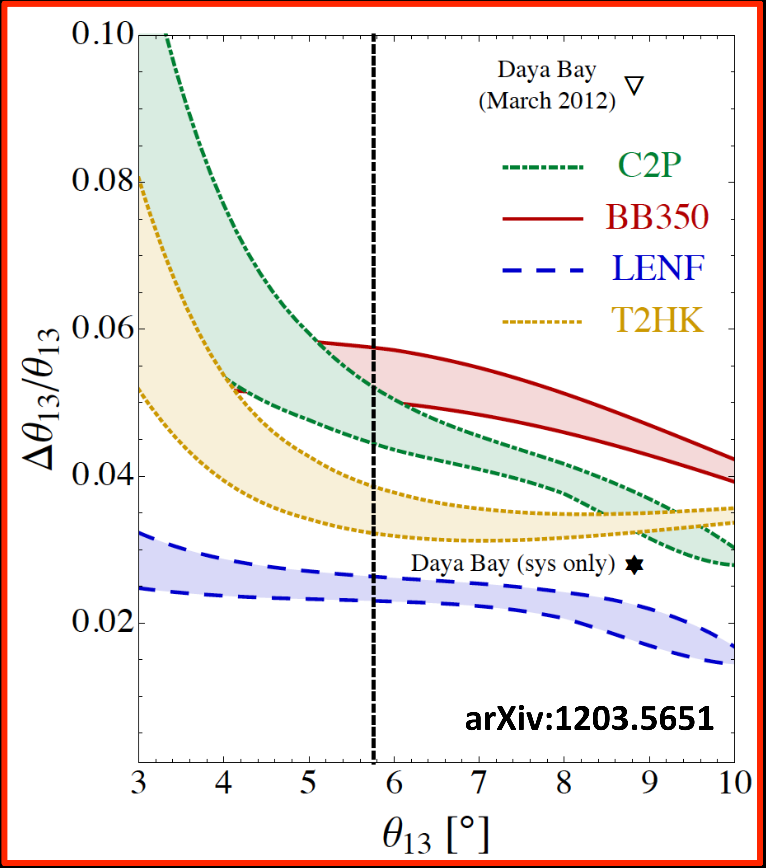


Goncalez-Garcia, Maltoni, Salvado, Schwetz

arXiv:1209.3023v2

- **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:



arXiv:1203.5651

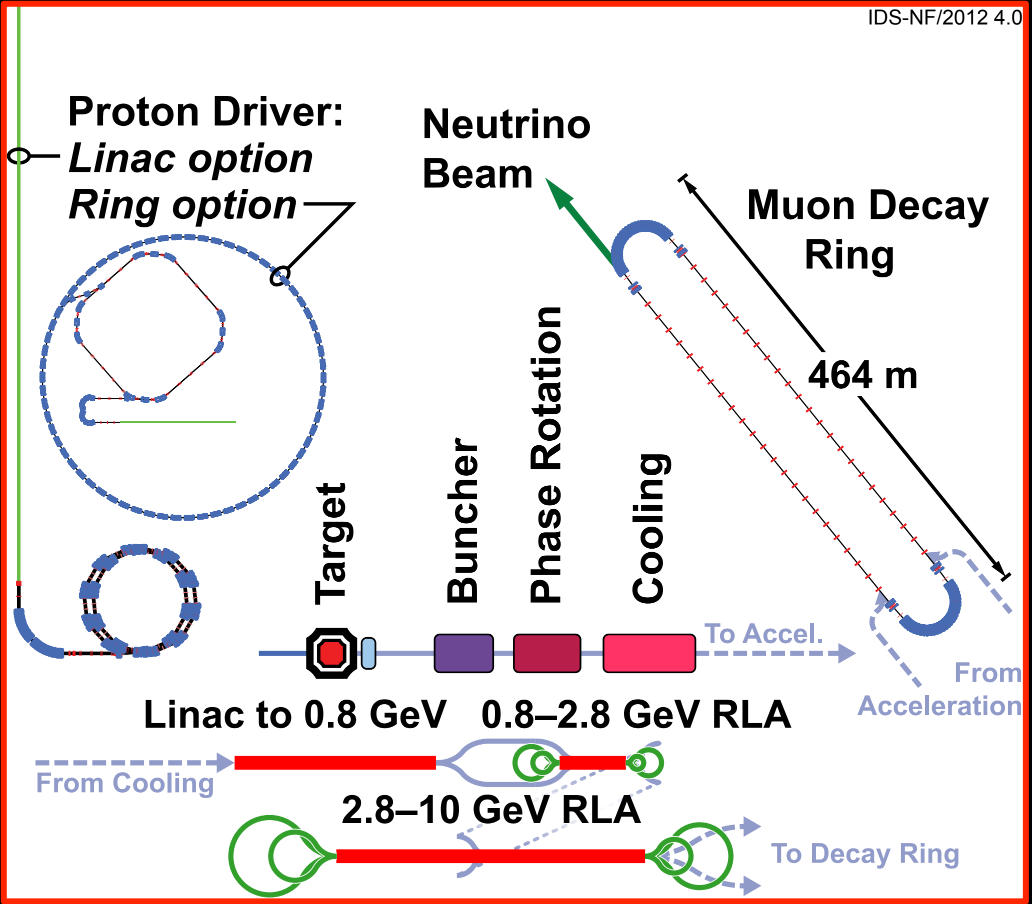
- Looking beyond MINOS, T2K, NOνA, DChooz, Daya Bay, Reno, …
  - θ_{13} will be very well known
- Therefore future programme must:
  - Complete the "Standard Neutrino Model" (SνM):
    - Determine the mass hierarchy
    - Search for (and discover?) leptonic CP-invariance violation
  - Establish the SνM 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_μ> ~ 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_μ> ~ 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_μ> ~ 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

Neutrino Factory:

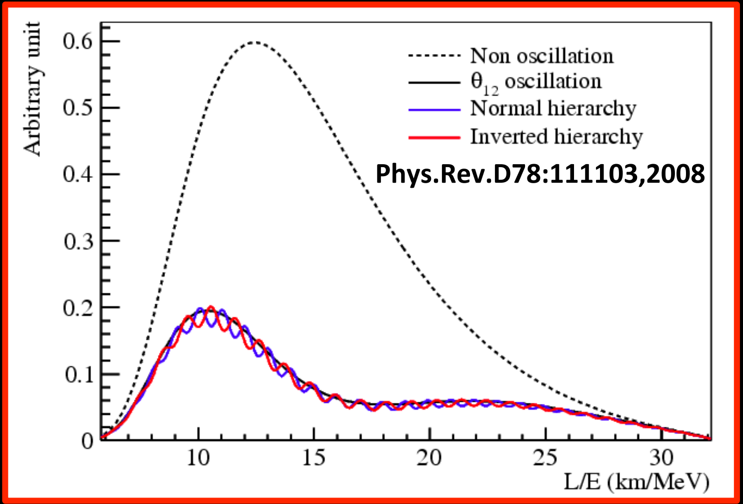
- Optimise discovery potential for CP and MH:
  - Requirements:
    - Large ν_e ($\bar{\nu}_e$) flux
      - Detailed study of sub-leading effects



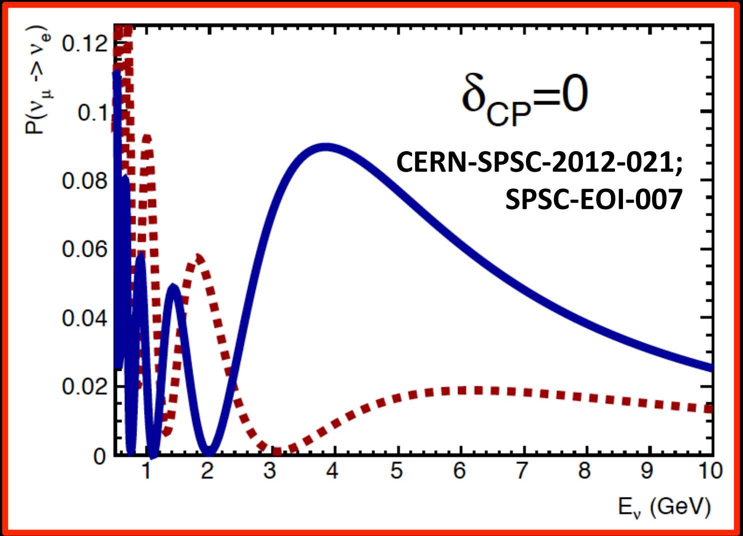
- Unique:
  - (Large) high-energy ν_e ($\bar{\nu}_e$) flux
    - Optimise event rate at fixed *L/E*
    - Optimise MH sensitivity
    - Optimise CP sensitivity

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



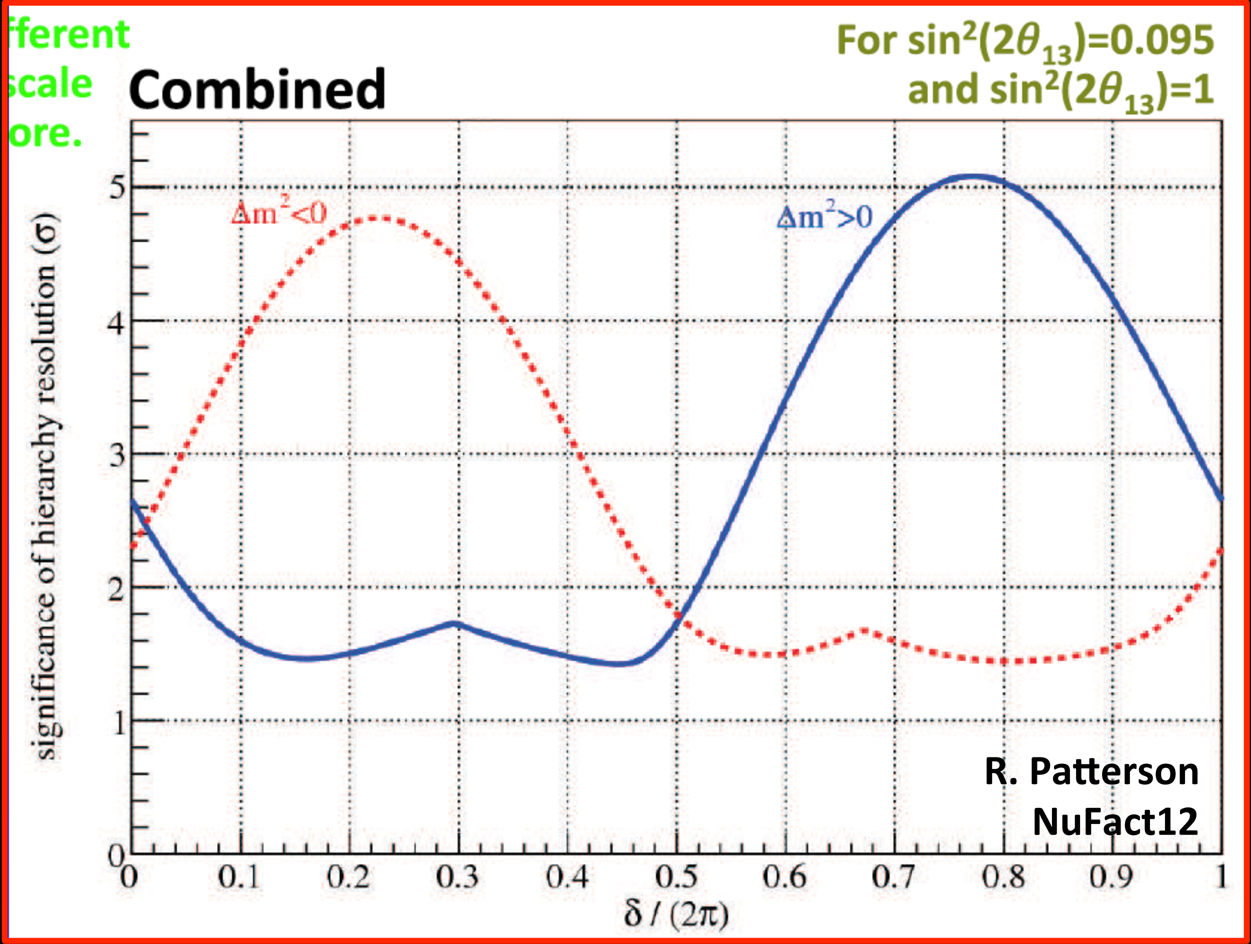
Phys.Rev.D78:111103,2008



CERN-SPSC-2012-021; SPSC-EOI-007

Mass hierarchy:

- Charged current $\nu_e e$ interactions in earth yields:
  - $P(\nu_\alpha \rightarrow \nu_\beta) \neq P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta)$
- Potential of present/planned experiments

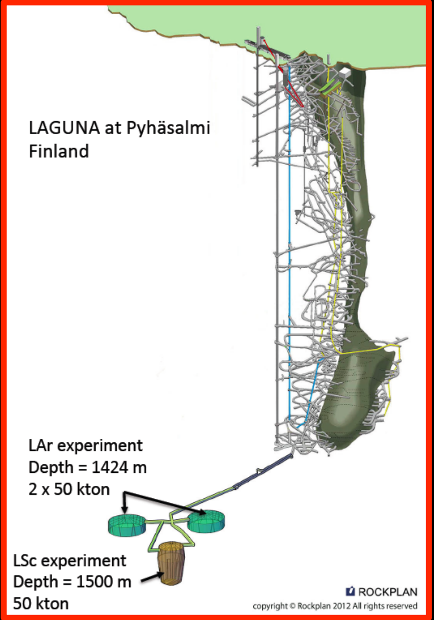


R. Patterson
NuFact12

Projection with T2K, NOvA and final Daya Bay

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



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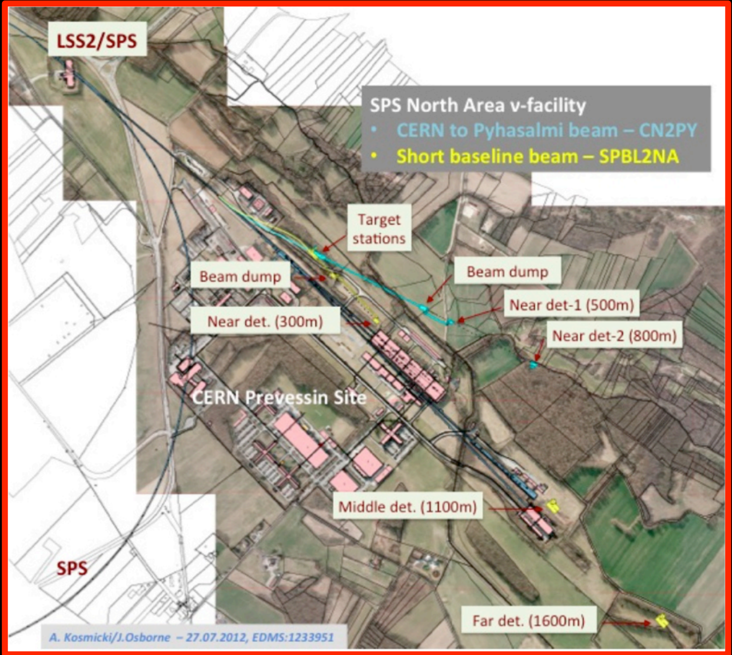
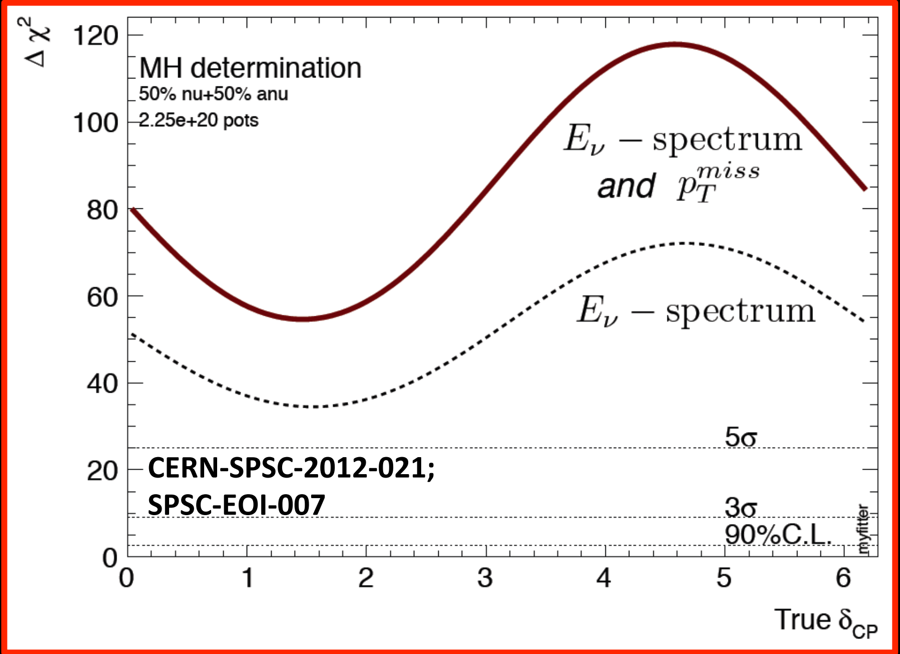
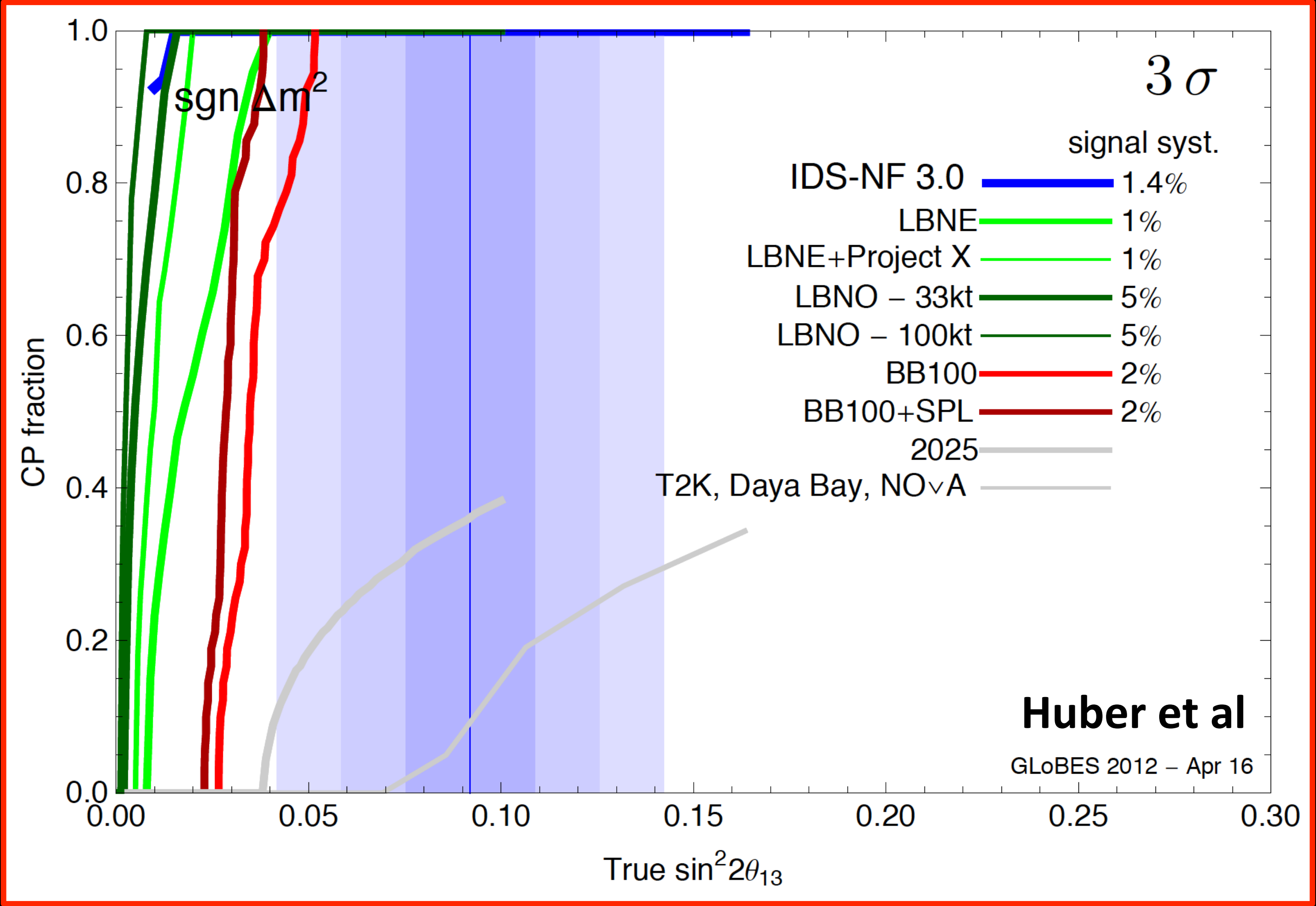


A. Kosmicki/J.Osborne – 27.07.2012, EDMS:1233951



CERN-SPSC-2012-021;
SPSC-EOI-007

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 of 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:
  - $P(\nu_\alpha \rightarrow \nu_\beta) \neq P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta)$

  by measuring the *asymmetry:*

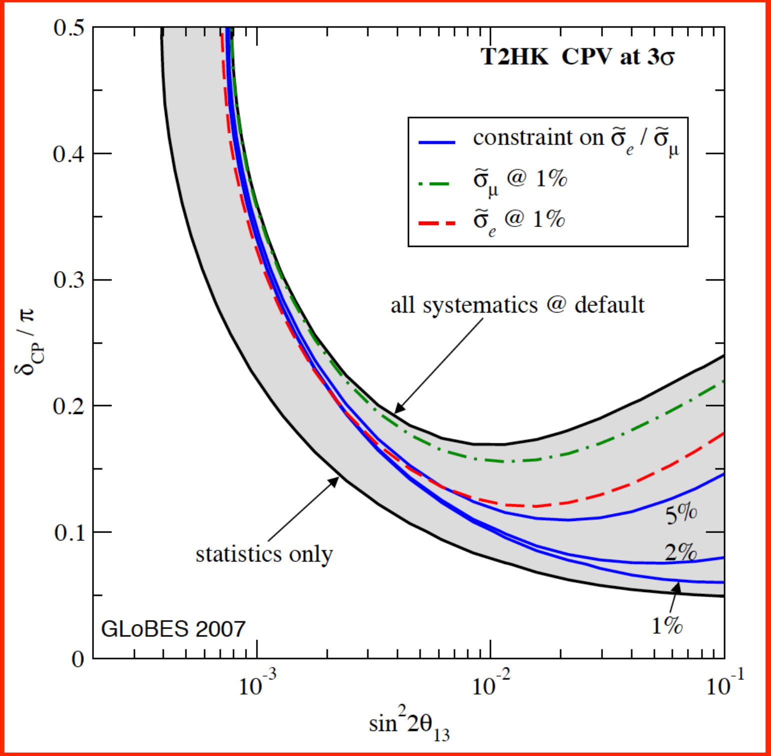
$$\boxed{\frac{P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)}{P(\nu_\alpha \to \nu_\beta) + P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)} \propto \frac{1}{\sin 2\theta_{13}}}$$

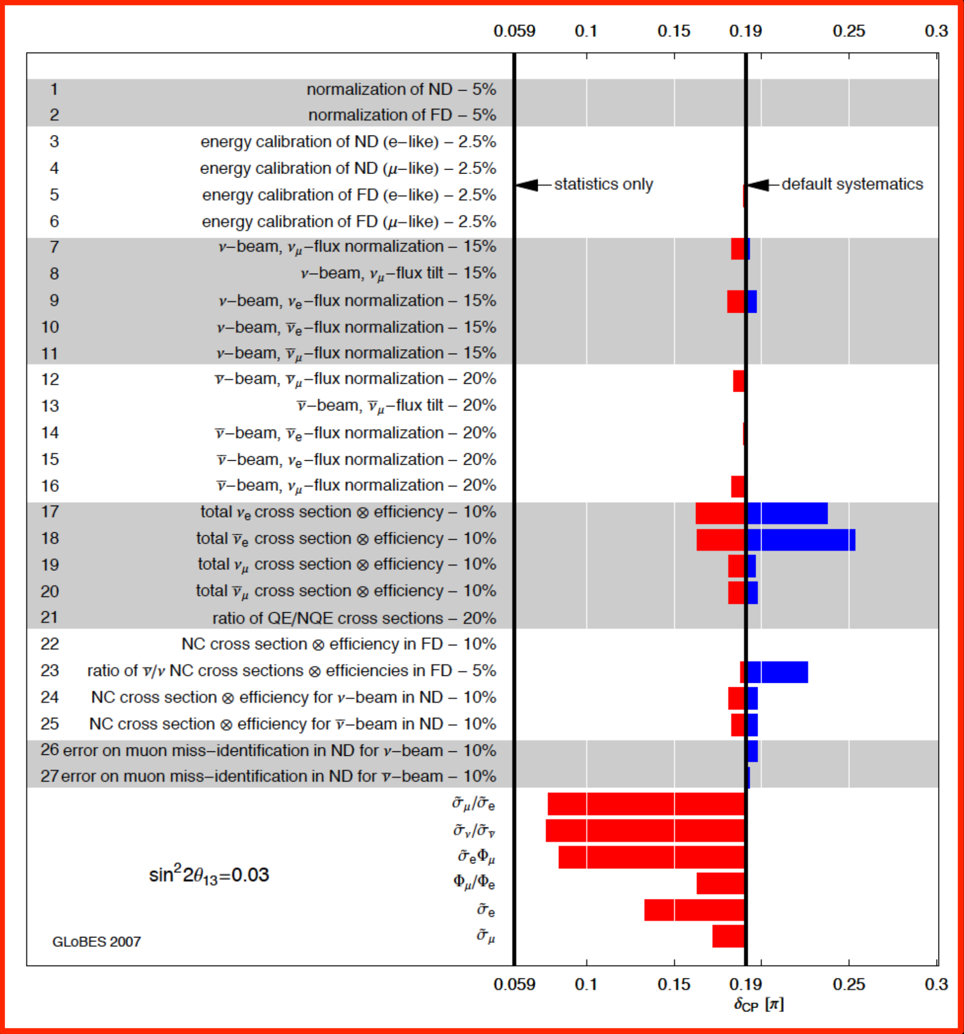
- Large θ_{13} makes discovery conceivable, *but*:
  - Places premium on the control of systematic uncertainties

Systematic uncertainties:

— critical at large θ_{13}

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



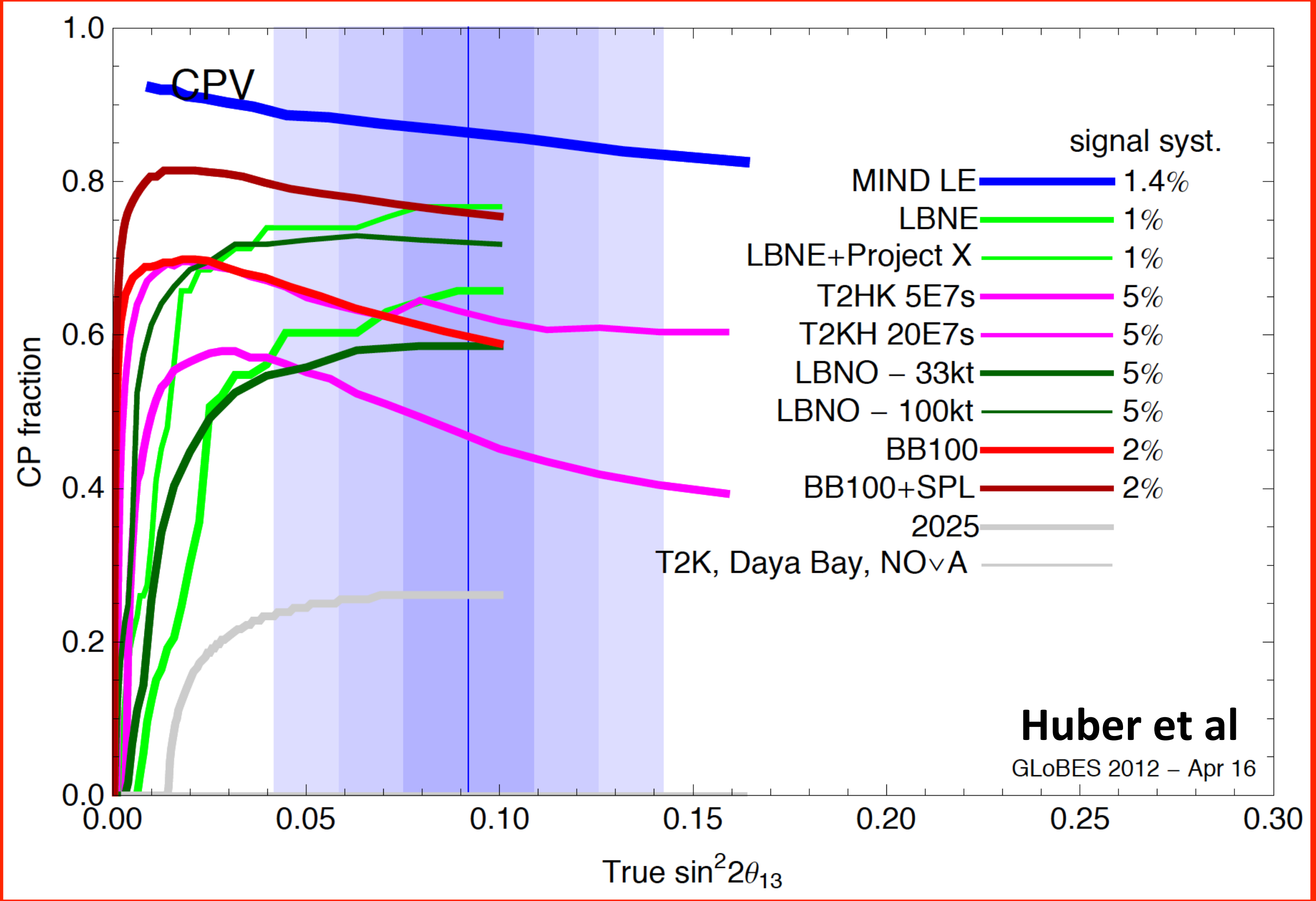


Huber, Mezzetto, Schwetz,
arXiv:0711.2950v2

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

Discovery reach:

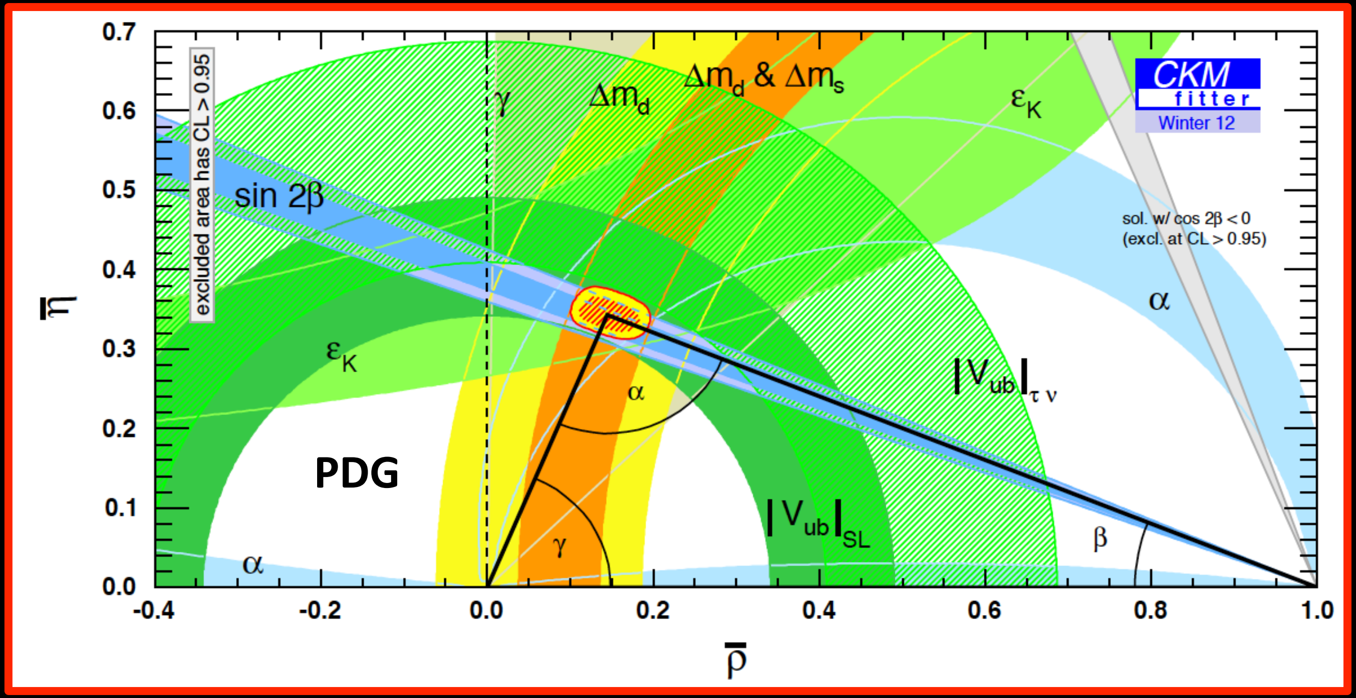
- Discovery reach at 3σ:
  - Neutrino Factory: 85—90%
  - Beta beam and SPL: 70—80%
  - Super beam: 60—75%



Huber et al

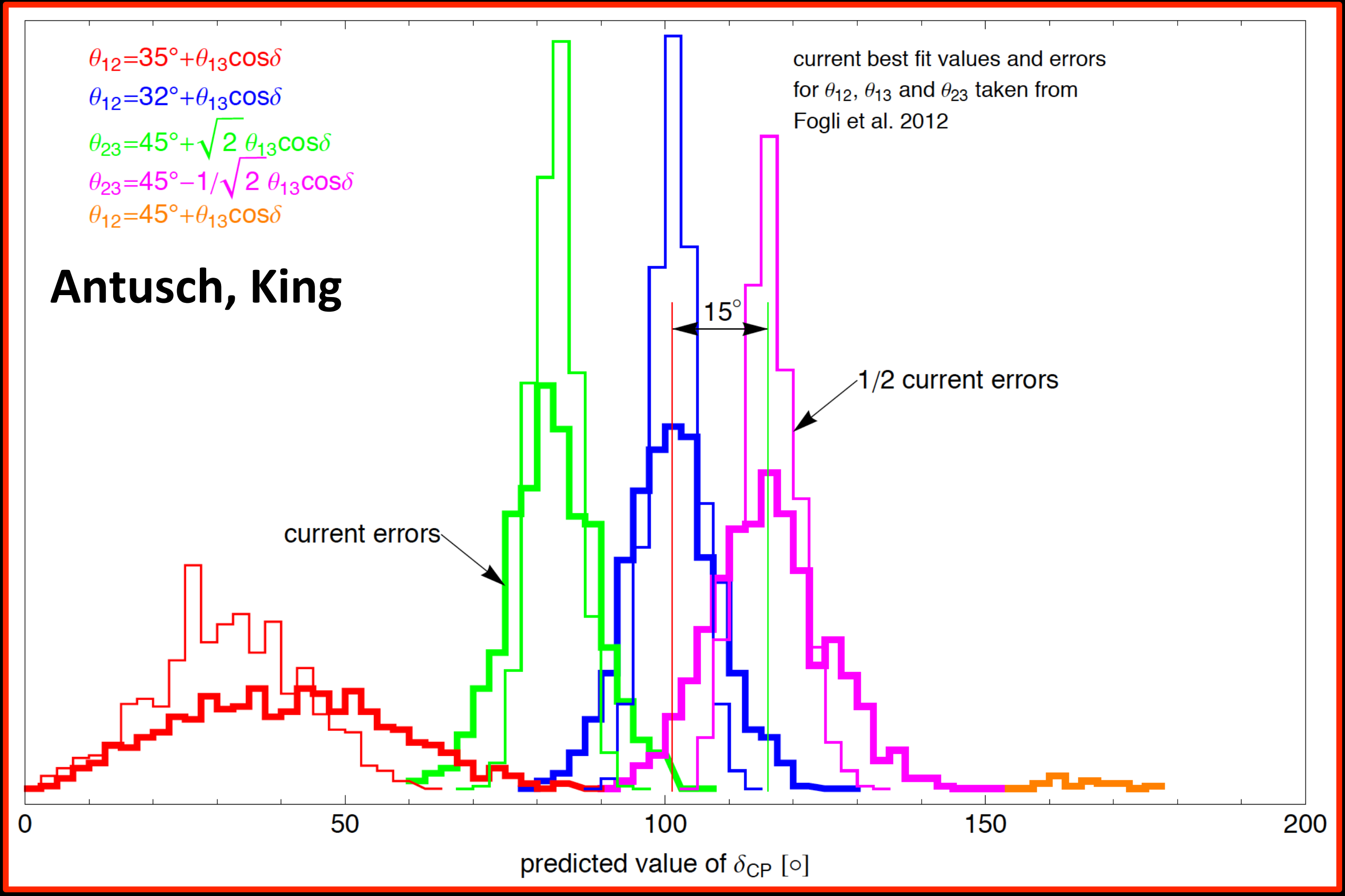
The case for precision:

- 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:

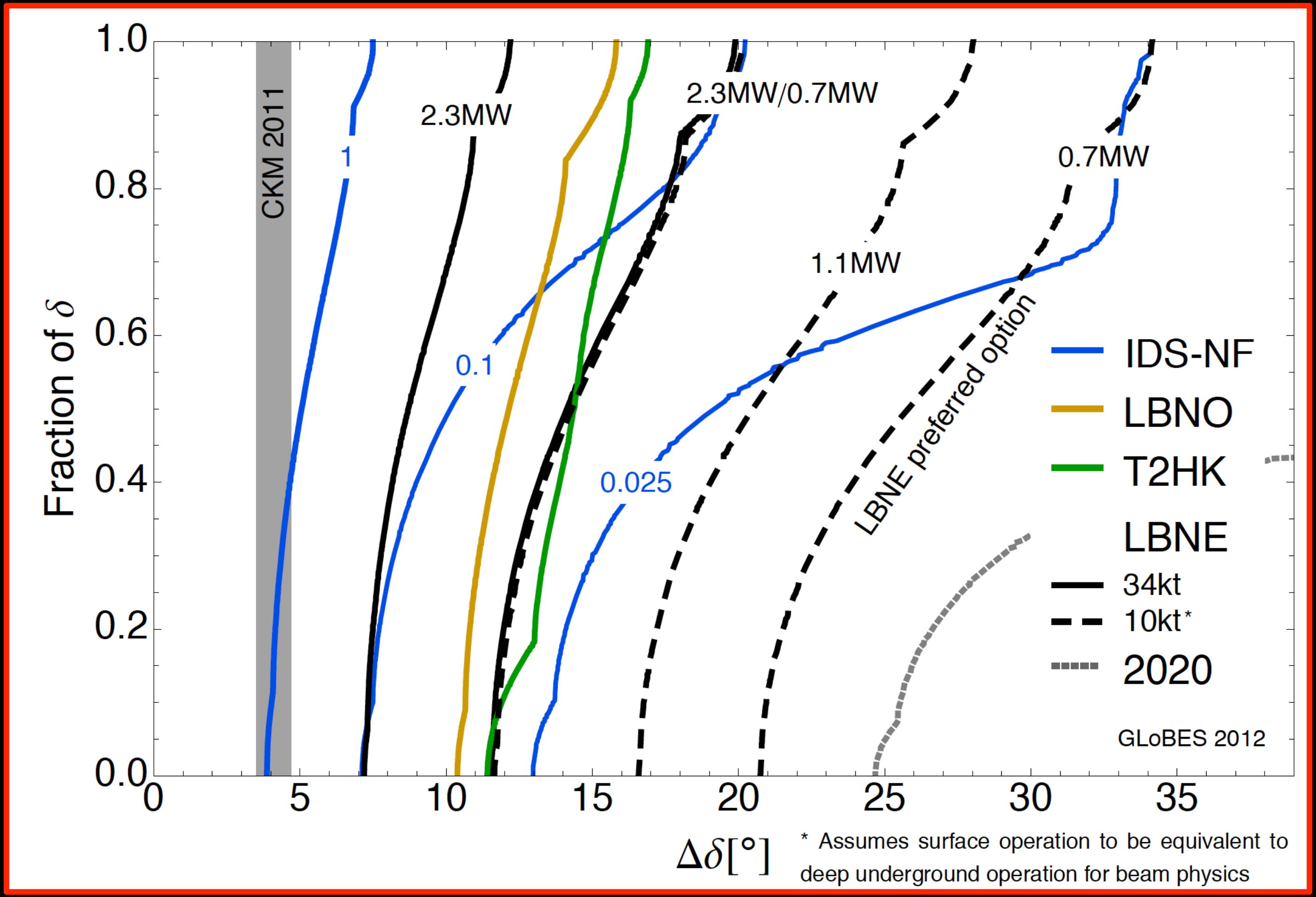
- Some guidance from theory:
  - Models that relate quarks and leptons lead to sum rules



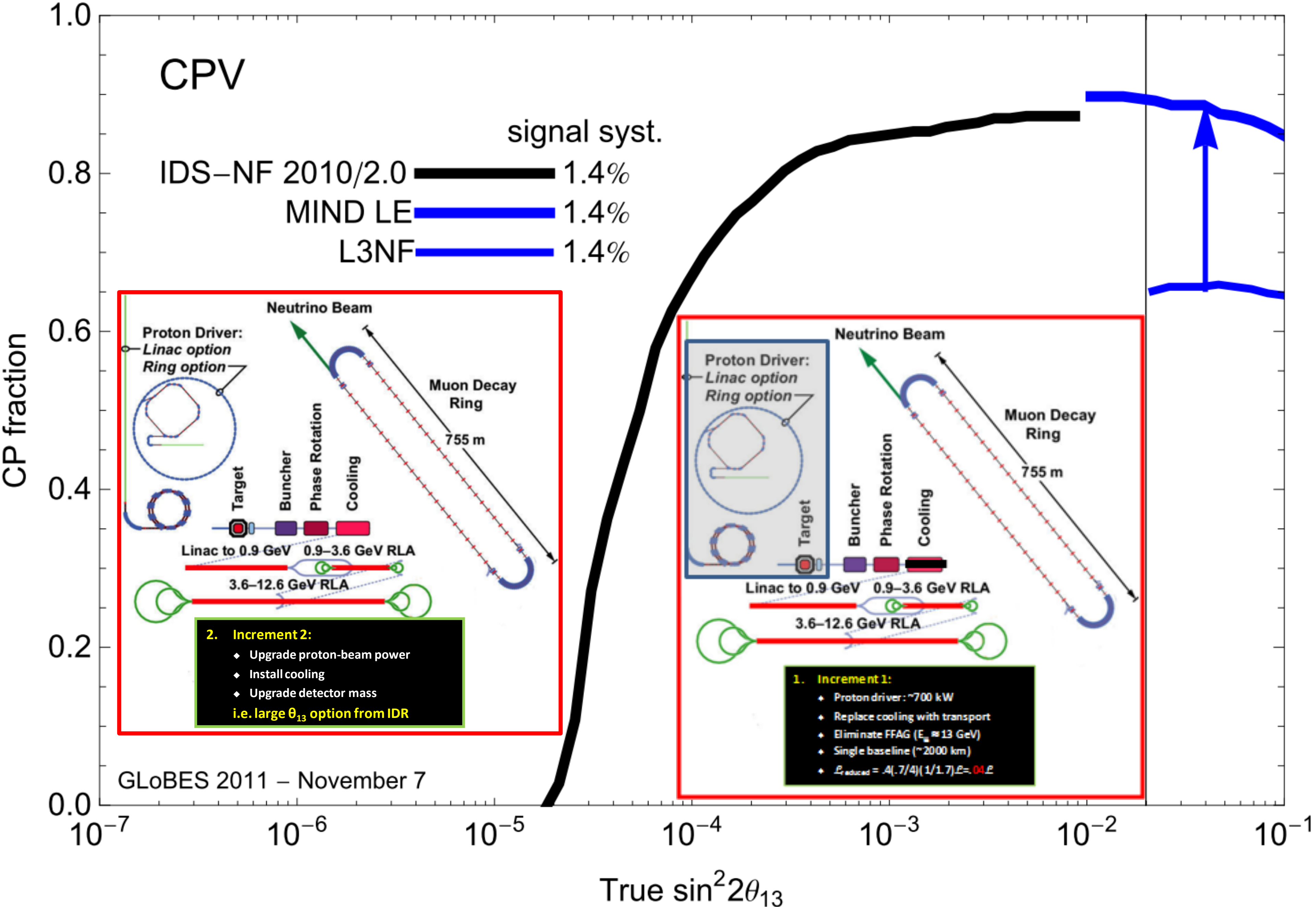
Antusch, King

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**



2. **Increment 2:**
   - Upgrade proton-beam power
   - Install cooling
   - Upgrade detector mass

   i.e. large θ_{13} option from IDR

1. **Increment 1:**
   - Proton driver: ~700 kW
   - Replace cooling with transport
   - Eliminate FFAG ($E_\mu \approx 13$ GeV)
   - Single baseline (~2000 km)
   - $\mathcal{L}_{reduced} = .4(.7/4)(1/1.7)\mathcal{L} = .04\mathcal{L}$

Neutrinos from stored muon beams:

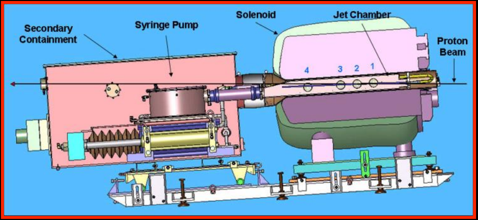
R&D and control of systematics

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

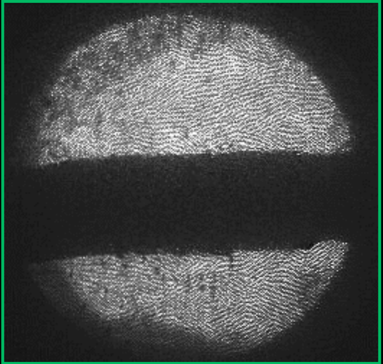
- Proton driver:
  - Development of high-power, pulsed proton source underway at proton labs
- Pion-production target:
  - MERIT experiment at CERN proved principle of mercury jet target
- Muon front end:
  - MuCool programme at FNAL:
    - Study of effect of magnetic field on high-gradient, warm, copper 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

Baseline target: proof of principle: MERIT:

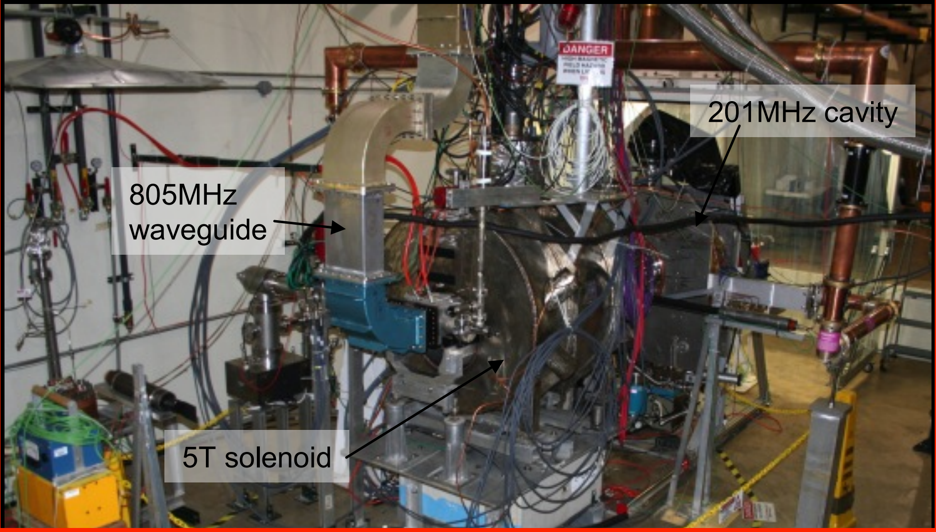


- ‘Disruption length’: 28 cm
- ‘Refill’ time: 14 ms
  - Corresponds to 70 Hz
- Hence:
  - Demonstrated operation at:
    - 60 kJ × 70 Hz = 8 MW

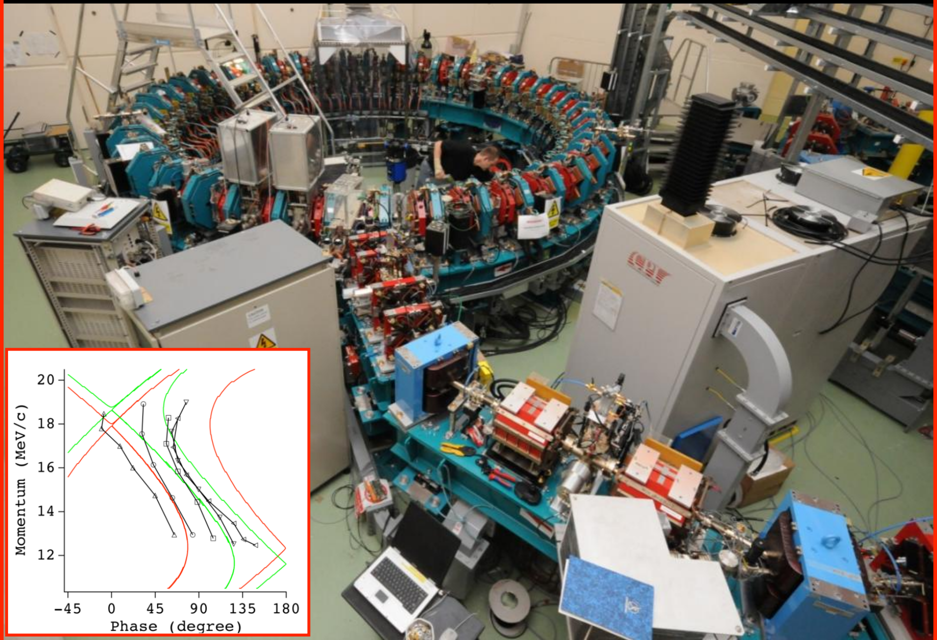
- 20 m/s liquid Hg jet in 15 T B field
- Exposed to CERN PS proton beam:
  - Beam pulse energy = 115 kJ
  - Reached 30 tera protons at 24 GeV



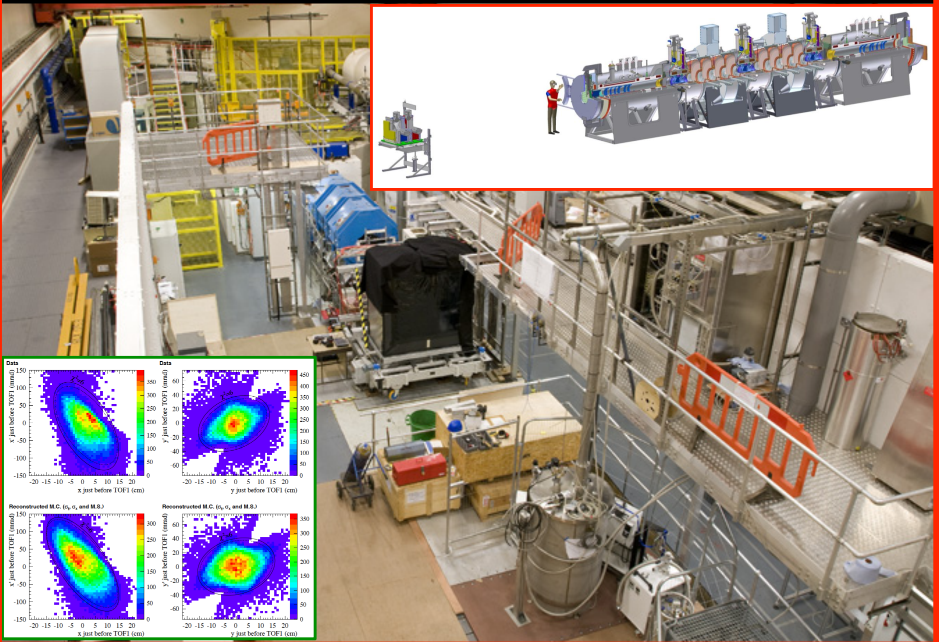
MuCool: cavities in magnetic field



Electron Model of Muon Acceleration (EMMA)



International Muon Ionization Cooling Experiment

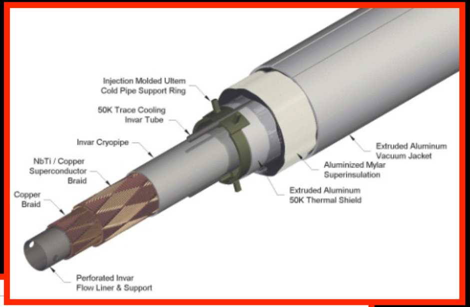


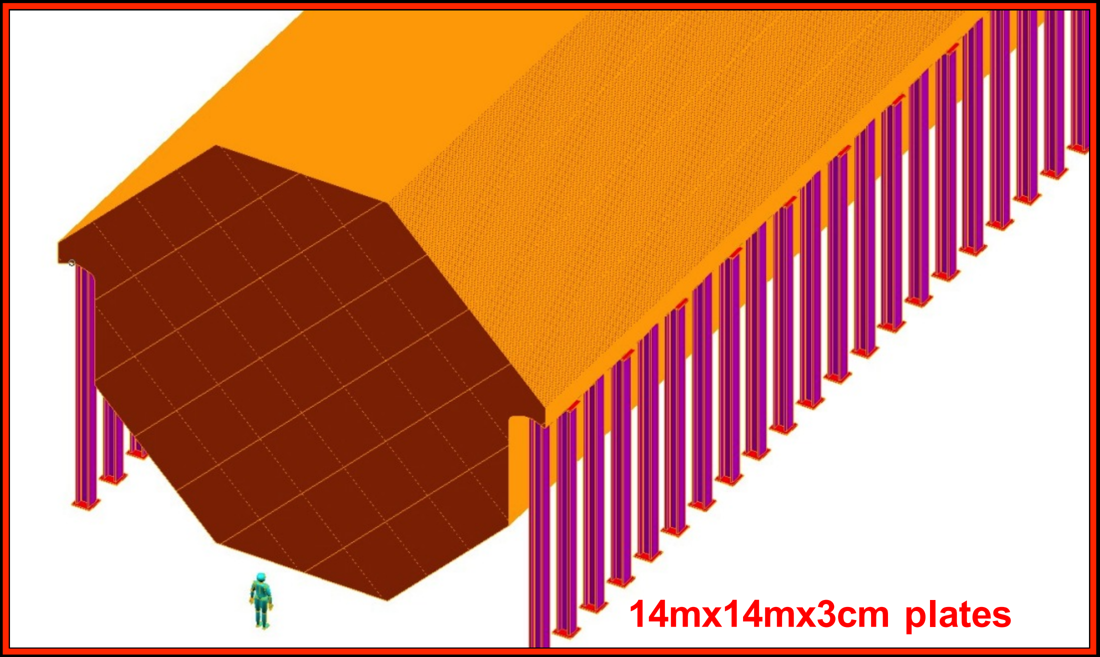
Detector challenges:

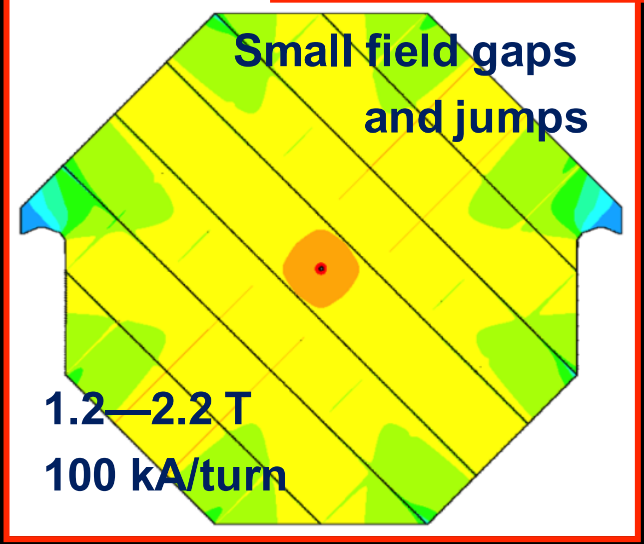
- Measurement of oscillations:
  - Requirements:
    - Large mass;
    - High granularity/resolution;
    - Magnetisation;
  - Options:
    - LAr:
      - Scaling to large mass needs to be demonstrated;
    - Totally active scintillator:
      - "Cost per channel" needs to be reduced;
    - Magnetisation:
      - 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

Magnetized Iron Neutrino Detector (MIND):

- IDS-NF baseline:
  - Intermediate baseline detector:
    - 100 kton at 1500—2500 km
  - Appearance of “wrong-sign” muons
  - Toroidal magnetic field > 1 T
    - Excited with “superconducting transmission line”
  - Segmentation: 3 cm Fe + 2 cm scintillator
  - 50-100 m long
  - Octagonal shape
  - Welded double-sheet
    - Width 2m; 3mm slots between plates



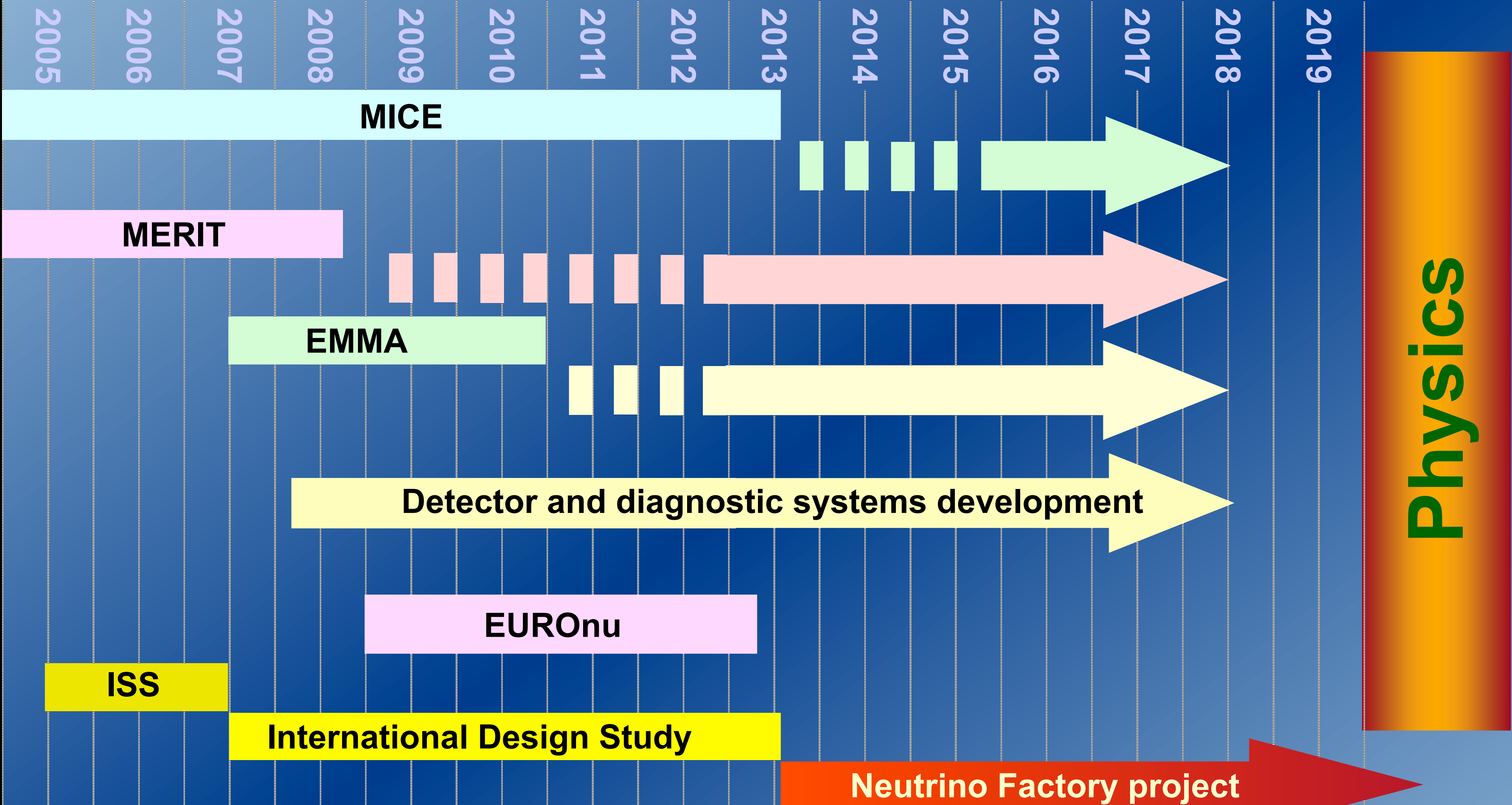




Bross, Soler, Bayes, Cervera

05May12

Neutrino Factory roadmap



MICE

MERIT

EMMA

Detector and diagnostic systems development

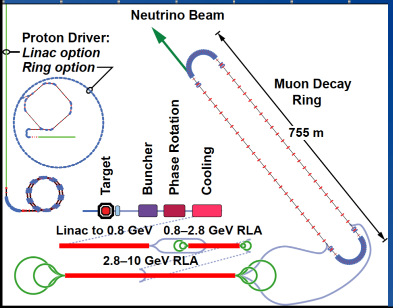
EURONu

ISS

International Design Study

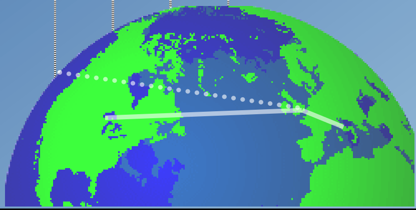
Neutrino Factory project

Physics



◇◆ Interim Design Report

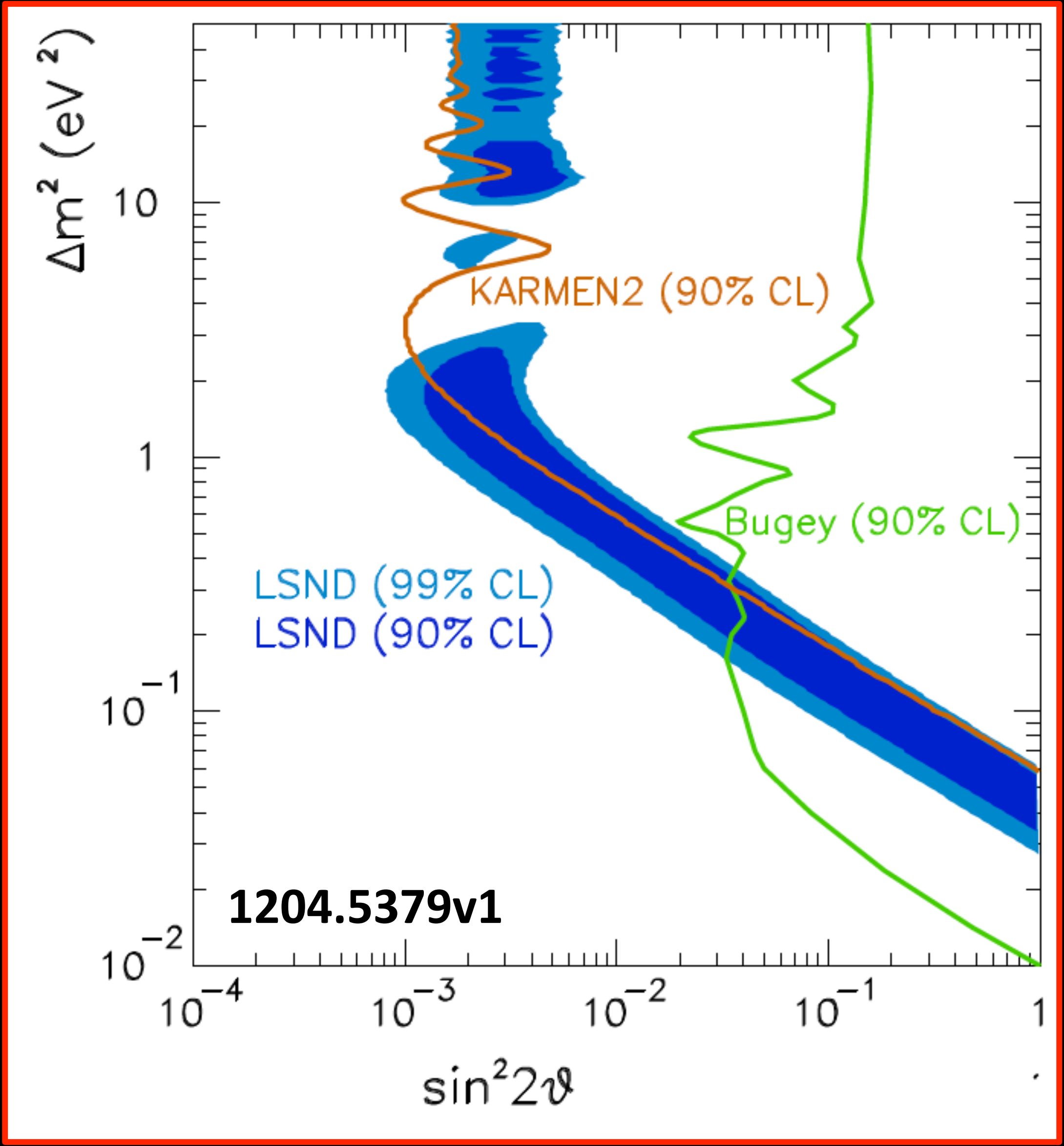
◇◆ Reference Design Report



Neutrinos from stored muon beams:

Sterile neutrinos

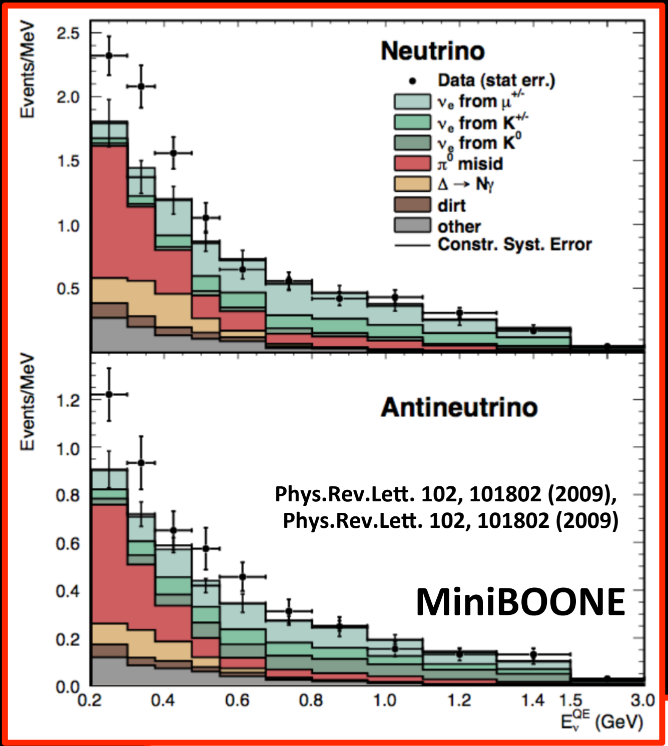
LSND:



1204.5379v1

- LSND reported evidence for an oscillation with $\Delta m^2 \sim 1\ \mathrm{eV}^2$:
  - 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:

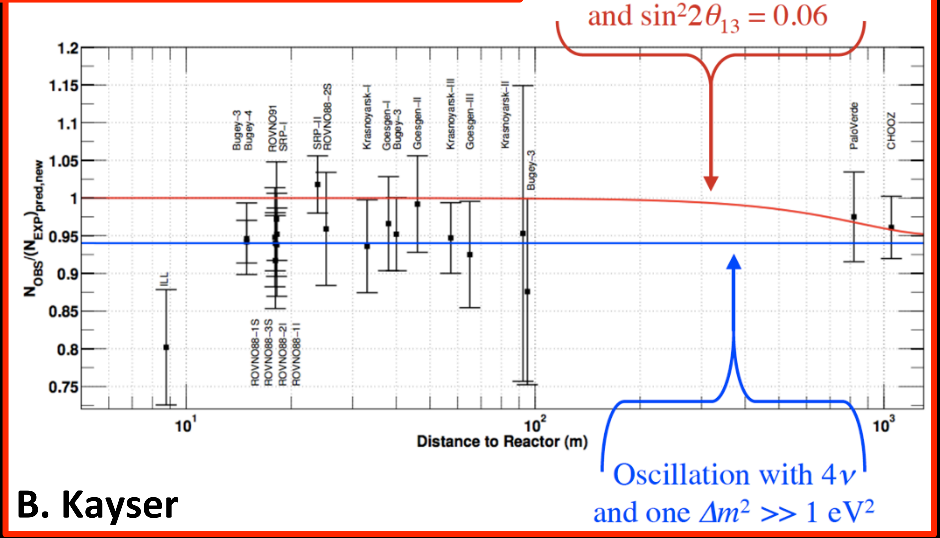


Phys.Rev.Lett. 102, 101802 (2009),
Phys.Rev.Lett. 102, 101802 (2009)

MiniBOONE

- 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

Oscillation with only 3ν
and $\sin^2 2\theta_{13} = 0.06$



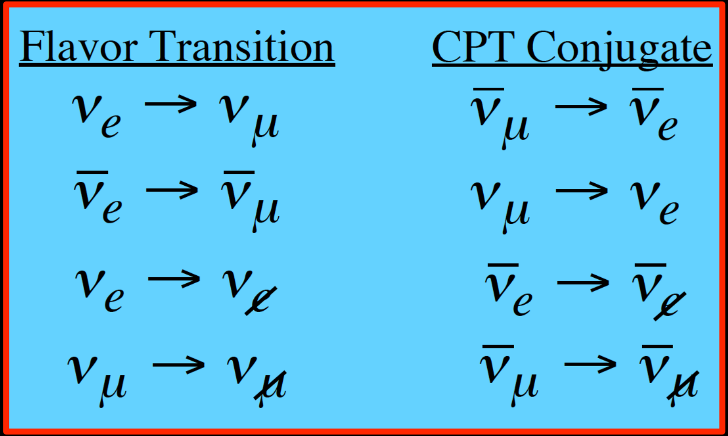
Oscillation with 4ν
and one $\Delta m^2 >> 1$ eV^2

B. Kayser

- 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:



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

and

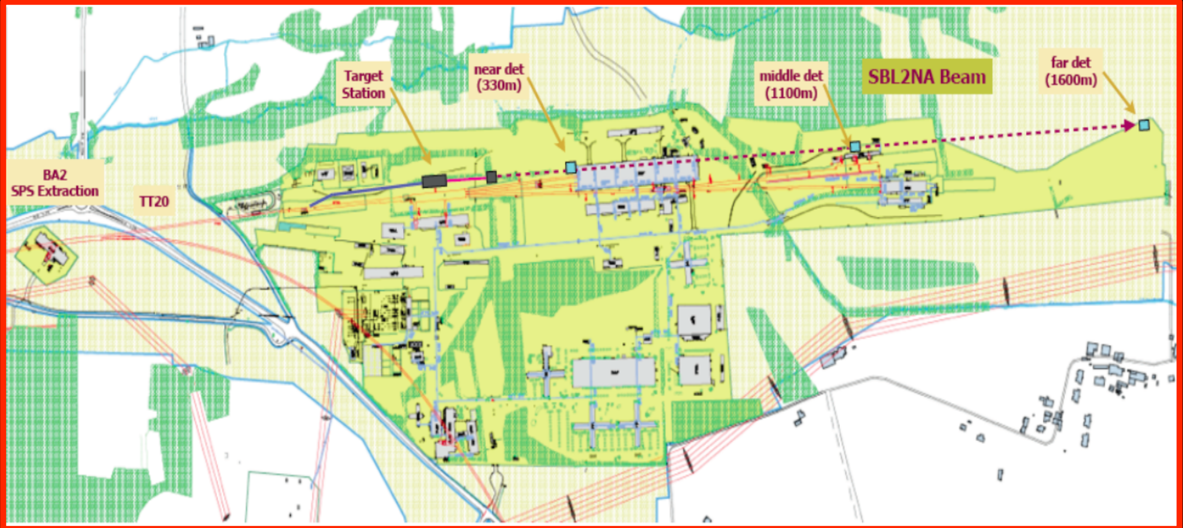
- Determine neutral current rate
  - oscillation to steriles will change neutral current rate
- Study $\nu_e N$ and $\nu_\mu N$ scattering
  - including hadronic final states to eliminate background uncertainties

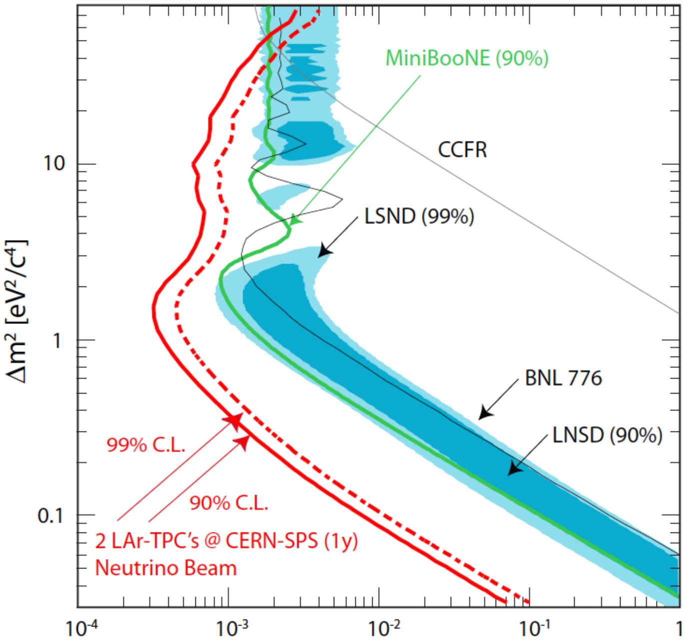
Present programme and future options:

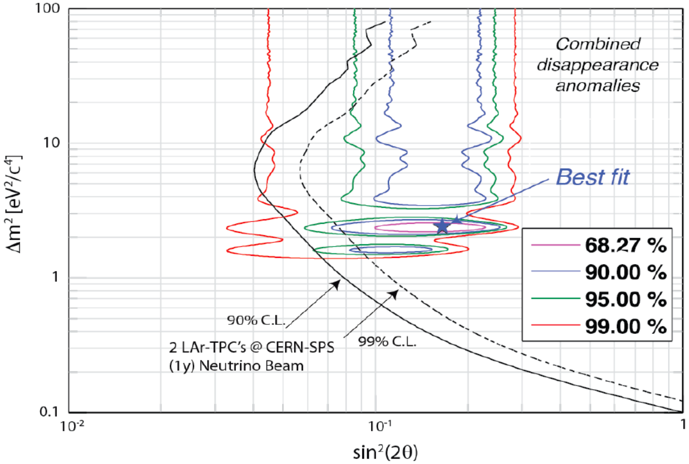
- Present programme:
  - Super-Kamiokande, MiniBooNE, SciBooNE, …
- Electron-(anti)neutrino sources:
  - Mono-energetic neutrinos from electron capture
  - IsoDAR: ^{8}Li produced in a cyclotron; observe $\bar{\nu}_e$
- Muon-(anti)neutrino sources:
  - LArl/NESSIE: near/far LAr detector combination at 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
    - Neutrinos from stored muon beams 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

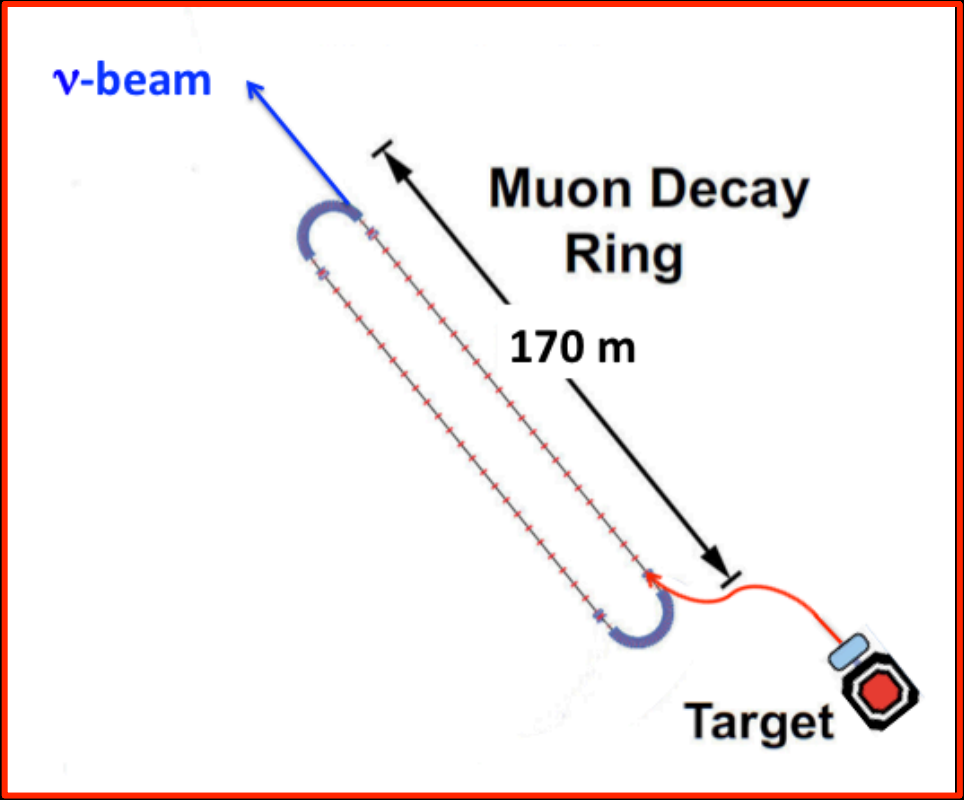
Neutrinos from stored muon beams:

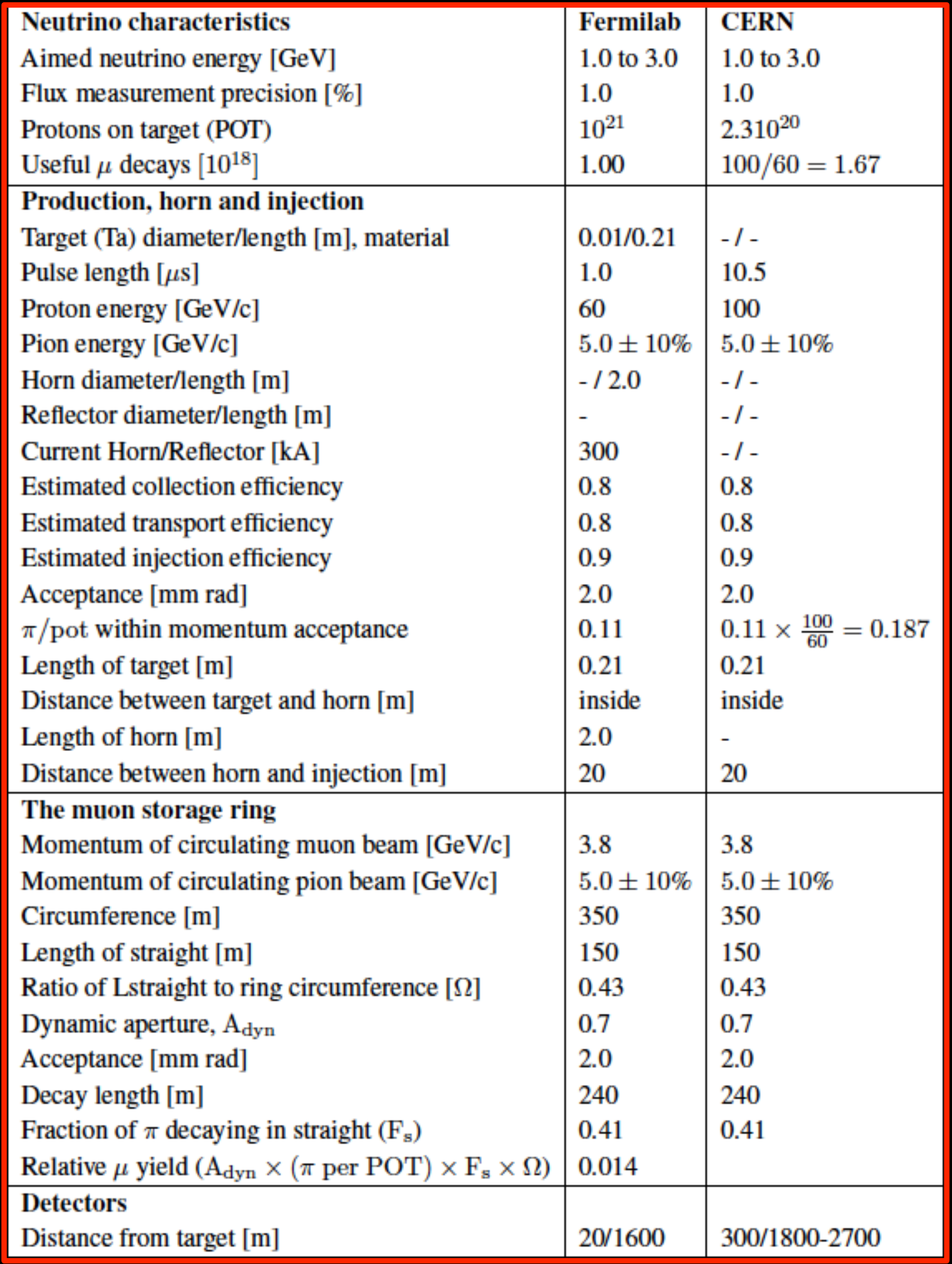
nuSTORM

- Entry-level Neutrino Factory:
  - Known technology

Concept:

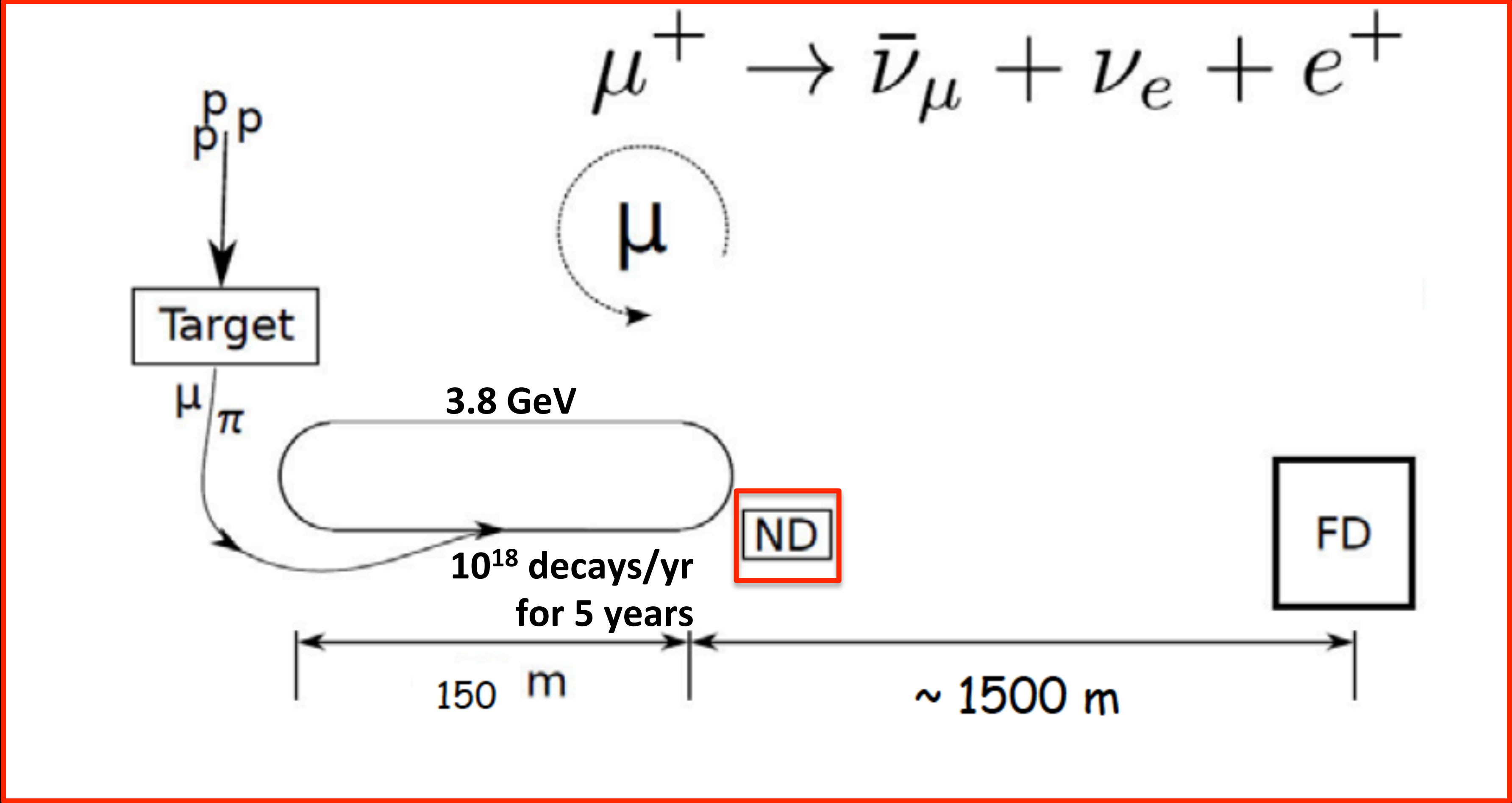
- 100 kW Target Station
  - FNAL:
    - 60 GeV protons from MI in PIP era
  - CERN:
    - 100 GeV protons from SPS post Linac4
- Target and collection:
  - "Heavy metal"
  - Optimization on-going
  - Horn collection baseline
    - Li lens has also been explored
- Collection/transport, two options:
  - Stochastic injection of π
  - Kicker with π → μ decay channel
- Decay ring
  - Large aperture FODO
  - Racetrack FFAG
- Instrumentation
  - BCTs, mag-Spec in arc, polarimeter





Neutrino characteristics	**Fermilab**	**CERN**
Aimed neutrino energy [GeV]	1.0 to 3.0	1.0 to 3.0
Flux measurement precision [%]	1.0	1.0
Protons on target (POT)	10^{21}	2.310^{20}
Useful μ decays $[10^{18}]$	1.00	$100/60 = 1.67$
Production, horn and injection		
Target (Ta) diameter/length [m], material	0.01/0.21	- / -
Pulse length [μs]	1.0	10.5
Proton energy [GeV/c]	60	100
Pion energy [GeV/c]	$5.0 \pm 10\%$	$5.0 \pm 10\%$
Horn diameter/length [m]	- / 2.0	- / -
Reflector diameter/length [m]	-	- / -
Current Horn/Reflector [kA]	300	- / -
Estimated collection efficiency	0.8	0.8
Estimated transport efficiency	0.8	0.8
Estimated injection efficiency	0.9	0.9
Acceptance [mm rad]	2.0	2.0
π/pot within momentum acceptance	0.11	$0.11 \times \frac{100}{60} = 0.187$
Length of target [m]	0.21	0.21
Distance between target and horn [m]	inside	inside
Length of horn [m]	2.0	-
Distance between horn and injection [m]	20	20
The muon storage ring		
Momentum of circulating muon beam [GeV/c]	3.8	3.8
Momentum of circulating pion beam [GeV/c]	$5.0 \pm 10\%$	$5.0 \pm 10\%$
Circumference [m]	350	350
Length of straight [m]	150	150
Ratio of Lstraight to ring circumference [Ω]	0.43	0.43
Dynamic aperture, $\mathrm{A_{dyn}}$	0.7	0.7
Acceptance [mm rad]	2.0	2.0
Decay length [m]	240	240
Fraction of π decaying in straight ($\mathrm{F_s}$)	0.41	0.41
Relative μ yield ($\mathrm{A_{dyn}} \times (\pi$ per POT$) \times \mathrm{F_s} \times \Omega$)	0.014	
Detectors		
Distance from target [m]	20/1600	300/1800-2700

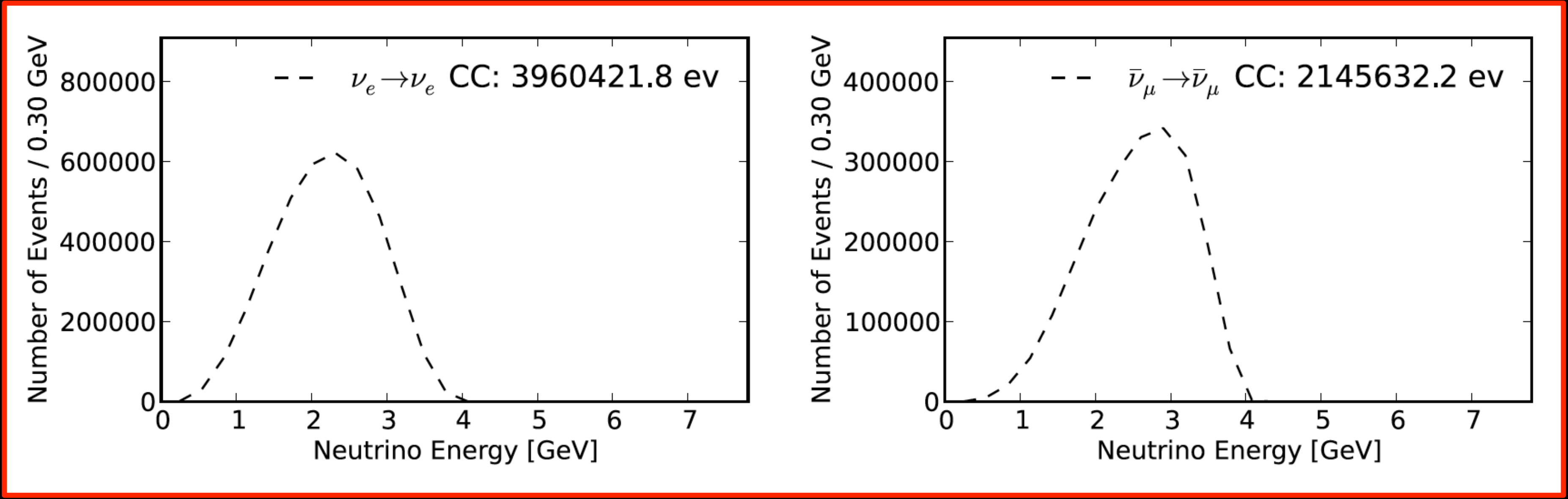
Neutrino-nucleus scattering:



$$\mu^+ \rightarrow \bar{\nu}_\mu + \nu_e + e^+$$

nuSTORM and cross section study:

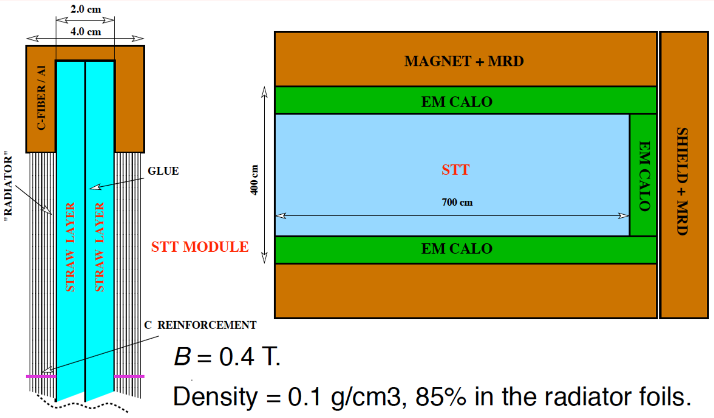
- nuSTORM event rate is large:
  - Statistical precision high:
    - Can measure double-differential cross sections



  - Event rates for 100 T fiducial mass

- Neutrino flavour-composition and flux very well known:
  - Storage ring instrumentation will yield flux uncertainty of 1%

Detector options:



$B = 0.4$ T.

Density = 0.1 g/cm3, 85% in the radiator foils.

Figure 11: Schematic of the HIRESMNU concept showing the straw tube tracker (STT), the electromagnetic calorimeter (ECAL) and the magnet with the muon range detector (MRD). The STT is based upon ATLAS [174–176] and COMPASS [177, 178] trackers. Also shown is one module of the proposed straw tube tracker (STT). Interleaved with the straw tube layers are plastic foil radiators, which provide 85% of the mass of the STT. At the upstream end of the STT are layers of nuclear-target for the measurement of cross sections and the π^0s on these materials.

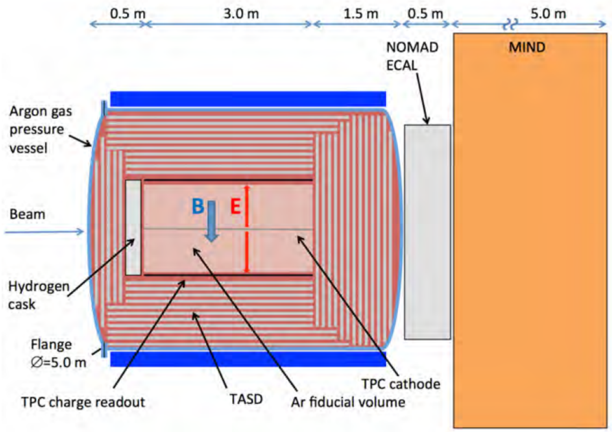
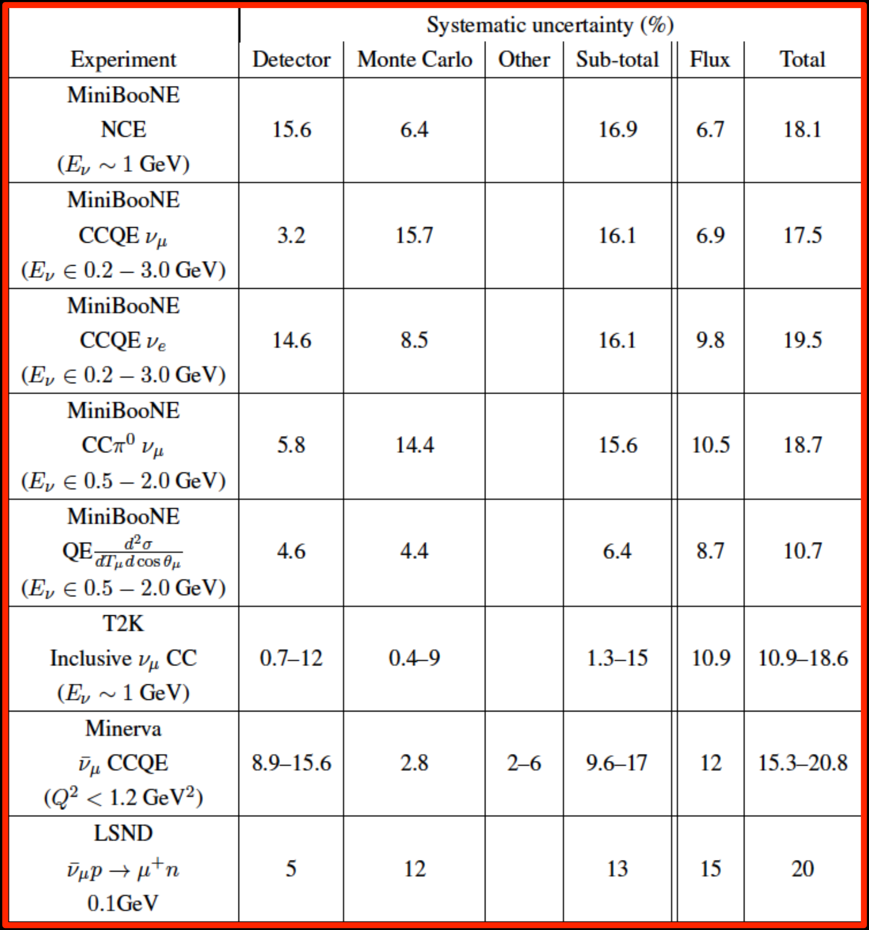


Figure 12: Schematic of the pressurized argon gas-based TPC detector. Both the TPC and scintillator calorimeter layers surrounding it are enclosed in a pressure vessel. A 0.5 T magnetic field is applied to the pressure vessel volume. Downstream of the TPC are also an electromagnetic calorimeter (ECAL) and a magnetized iron neutrino detector (MIND). The latter acts as a muon spectrometer for neutrino interactions occurring in the TPC and as an independent near detector for the sterile neutrino program.

- Staged approach possible:
  - Initial measurements exploit existing detector:
    - If at FNAL Minerva, Mini/MicroBOONE are candidates
  - Possible exploitation of LAr detector developed for LAGUNA or ICARUS/NESSiE etc.
  - Implementation of one or more dedicated detectors to make definitive measurements
- Generic study performed to evaluate performance …

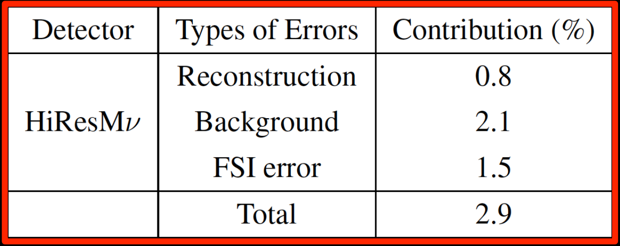
Cross section measurement performance:

- **Existing experiments:**
  - Sets the goal



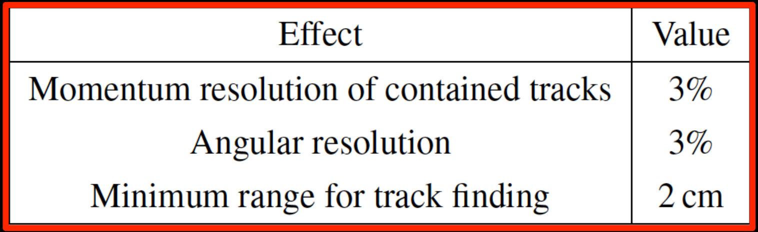
Experiment	Systematic uncertainty (%)					
	Detector	Monte Carlo	Other	Sub-total	Flux	Total
MiniBooNE NCE ($E_\nu \sim 1$ GeV)	15.6	6.4		16.9	6.7	18.1
MiniBooNE CCQE ν_μ ($E_\nu \in 0.2 - 3.0$ GeV)	3.2	15.7		16.1	6.9	17.5
MiniBooNE CCQE ν_e ($E_\nu \in 0.2 - 3.0$ GeV)	14.6	8.5		16.1	9.8	19.5
MiniBooNE CCπ^0 ν_μ ($E_\nu \in 0.5 - 2.0$ GeV)	5.8	14.4		15.6	10.5	18.7
MiniBooNE QE$\frac{d^2\sigma}{dT_\mu d\cos\theta_\mu}$ ($E_\nu \in 0.5 - 2.0$ GeV)	4.6	4.4		6.4	8.7	10.7
T2K Inclusive ν_μ CC ($E_\nu \sim 1$ GeV)	0.7–12	0.4–9		1.3–15	10.9	10.9–18.6
Minerva $\bar{\nu}_\mu$ CCQE ($Q^2 < 1.2$ GeV^2)	8.9–15.6	2.8	2–6	9.6–17	12	15.3–20.8
LSND $\bar{\nu}_\mu p \rightarrow \mu^+ n$ 0.1GeV	5	12		13	15	20

- **Performance of HiResMnu:**



Detector	Types of Errors	Contribution (%)
HiResMν	Reconstruction	0.8
	Background	2.1
	FSI error	1.5
	Total	2.9

- **Assumed performance of generic detector for evaluation of precision of cross section measurement:**

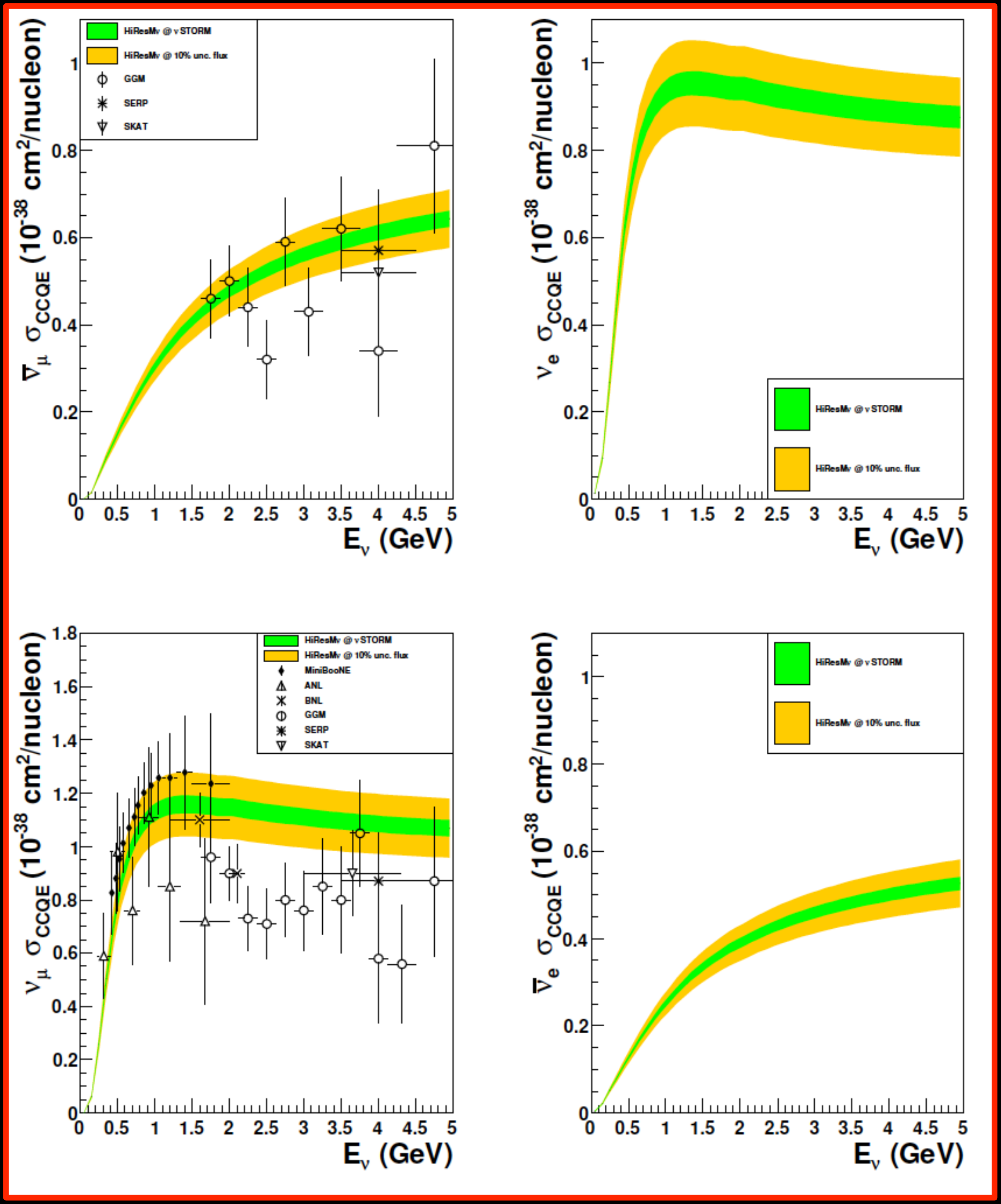


Effect	Value
Momentum resolution of contained tracks	3%
Angular resolution	3%
Minimum range for track finding	2 cm

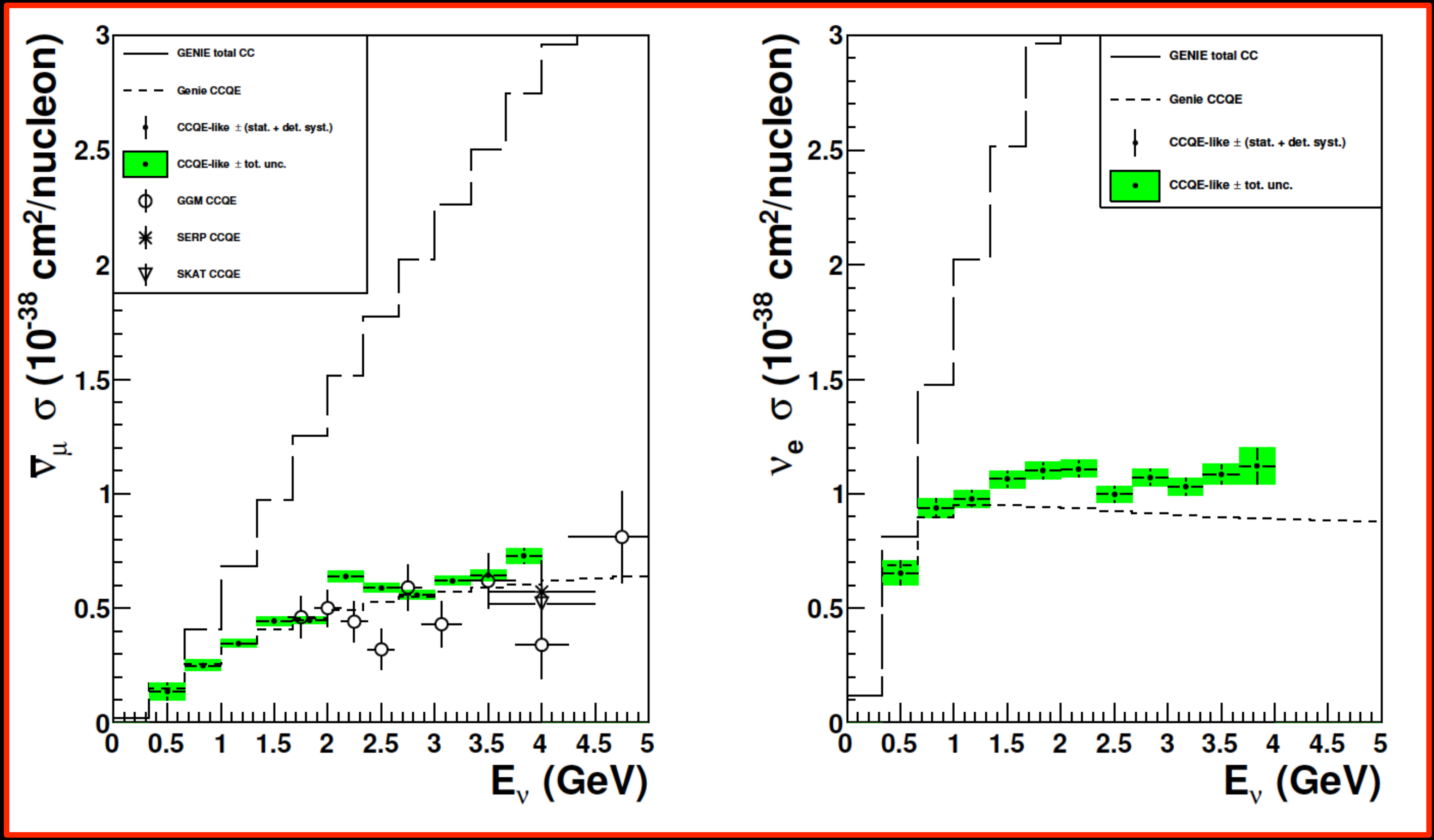
- **Flux uncertainty varied:**
  - 1% nuSTORM specification
  - 10% typical of conventional beams for comparison

CCQE cross section measurement:

- HiResMnu at nuSTORM:
  - Six-fold improvement in systematic uncertainty compared with “state of the art”
  - Electron-neutrino cross section measurement unique

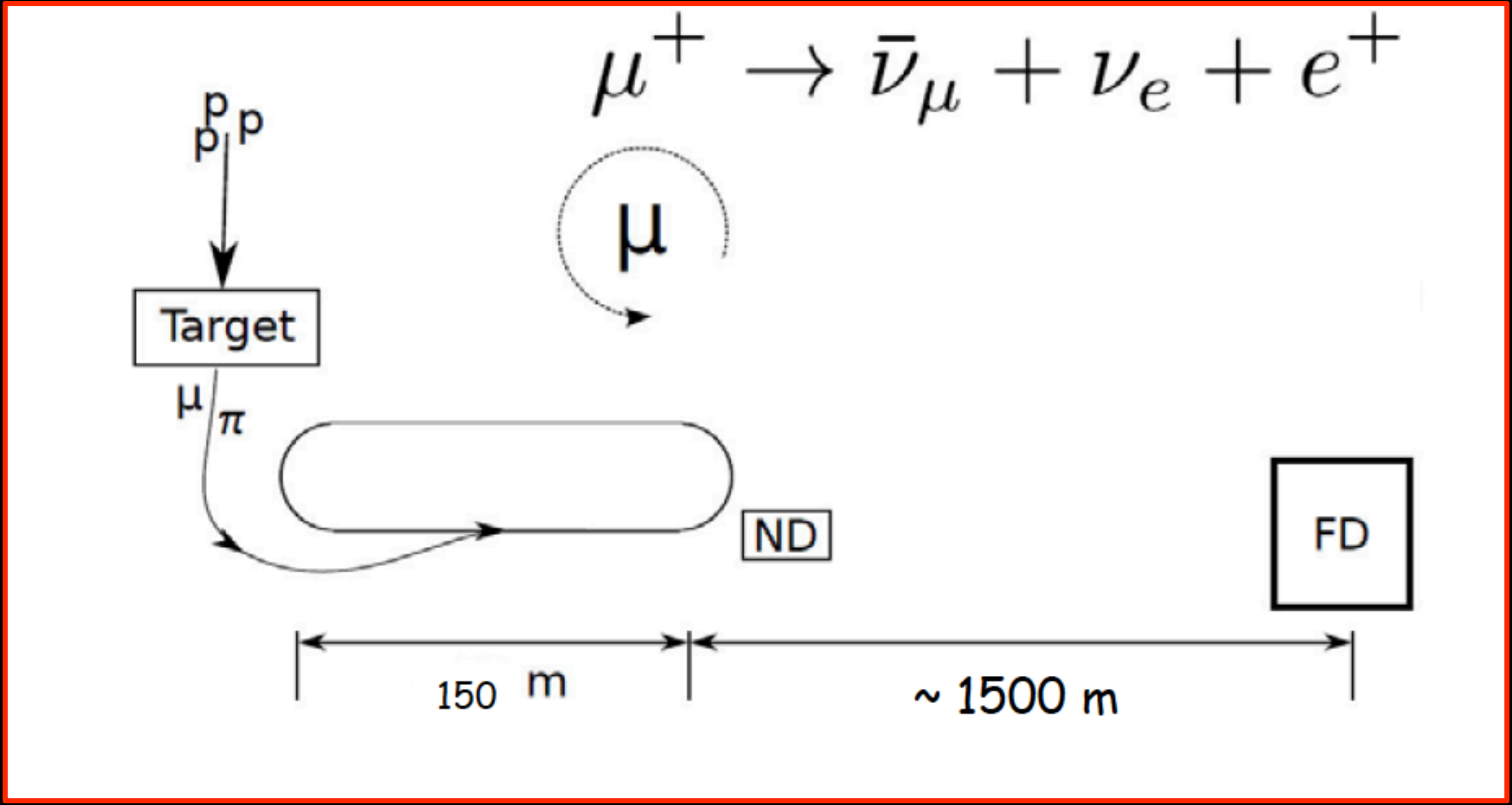


CCQE cross section measurement:



- **Simulation of "generic detector":**
  - Muon-neutrino CCQE cross section measurement substantially improves "state of the art"
  - Electron-neutrino CCQE measurement *unique*
  - Evaluation of other channels has begun

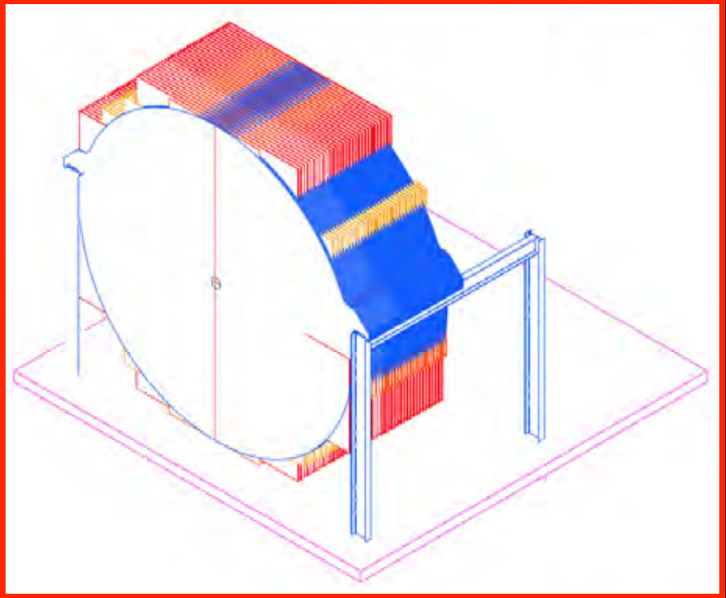
Sterile neutrino search concept:

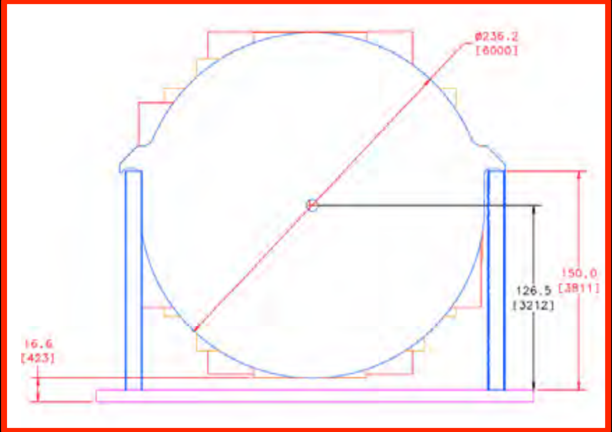


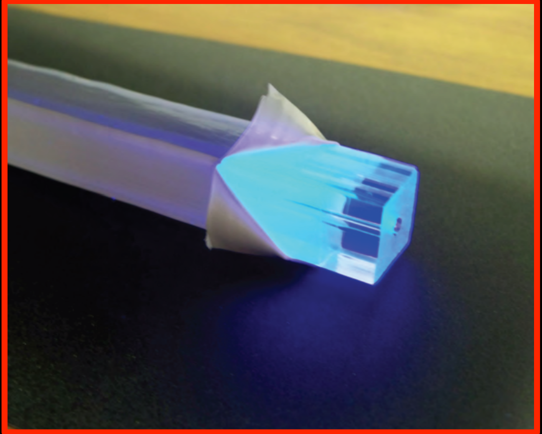
$$\mu^+ \rightarrow \bar{\nu}_\mu + \nu_e + e^+$$

SuperBIND, baseline sterile detector:

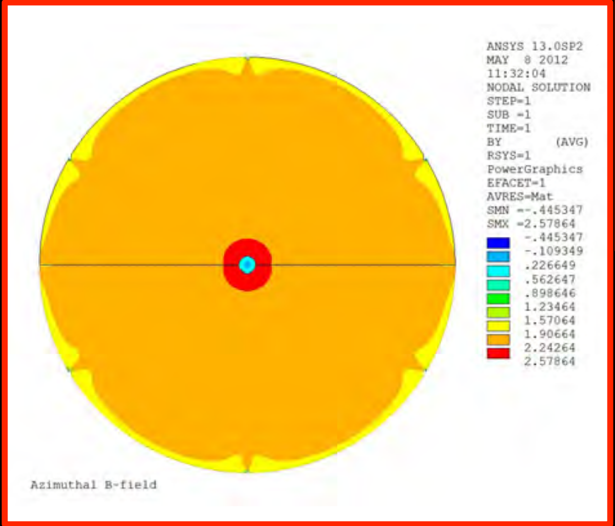
- Magnetised iron calorimeter:
  - MINOS-like, optimised for nuSTORM beam

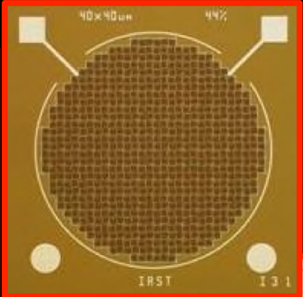


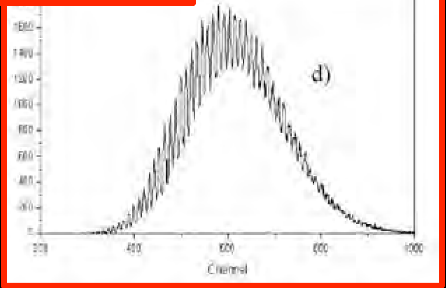




SuperBIND parameters			
Geometry:			
Circular Fe plate:	Diameter:	600.0	cm
	Thickness:	1.5	cm
Scintillator:			
Extruded rectangular bar:	Cross section:	0.75 × 2	cm^2
	Material:	Polystyrene	
	Dopants:		
	POP:	1.00	% by weight
	POPOP:	0.03	% by weight
	Coating:	15	% TiO_2 in polystyrene
Photo-detector:	SiPM		
Magnetisation:			
Toroidal field:	Stength:	2	T

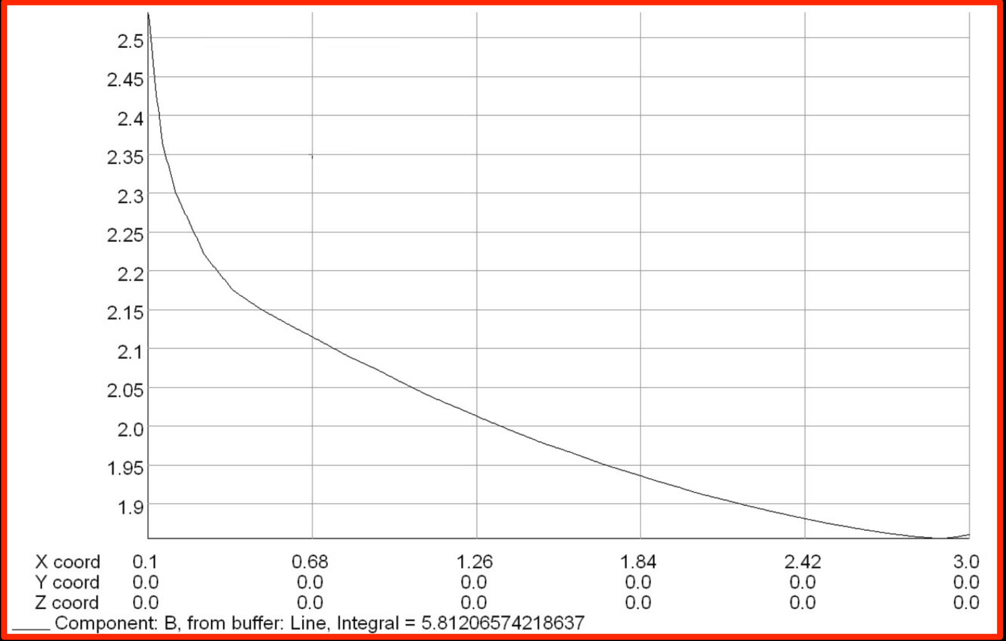






SuperBIND: magnetisation:

- **Superconducting transmission line:**
  - Developed for VLHC and prototyped at FNAL



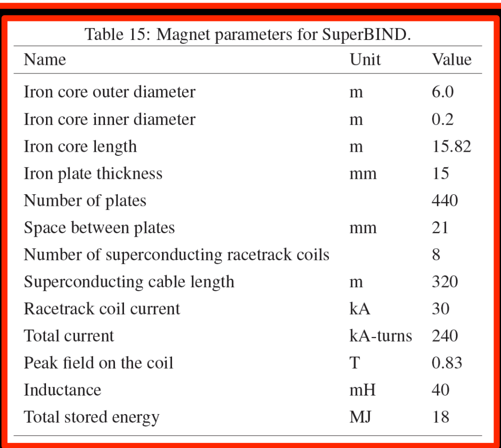
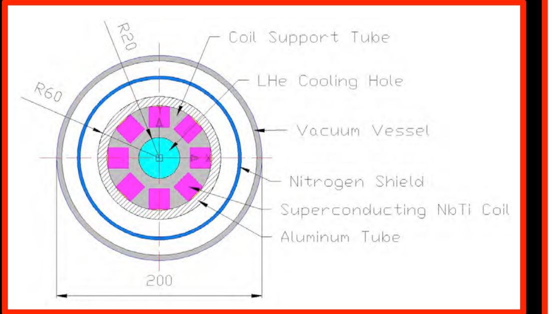
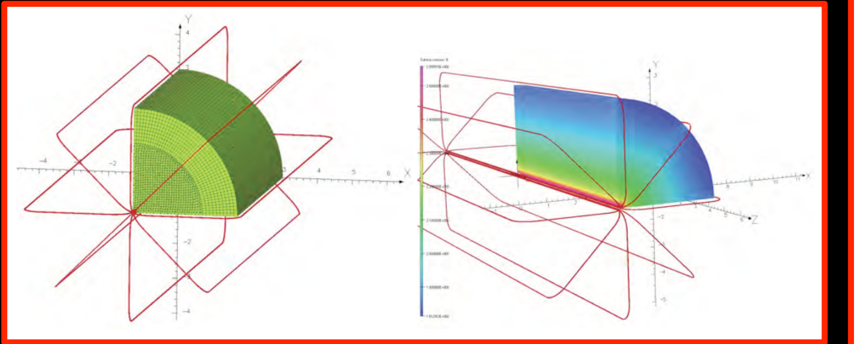


Table 15: Magnet parameters for SuperBIND.

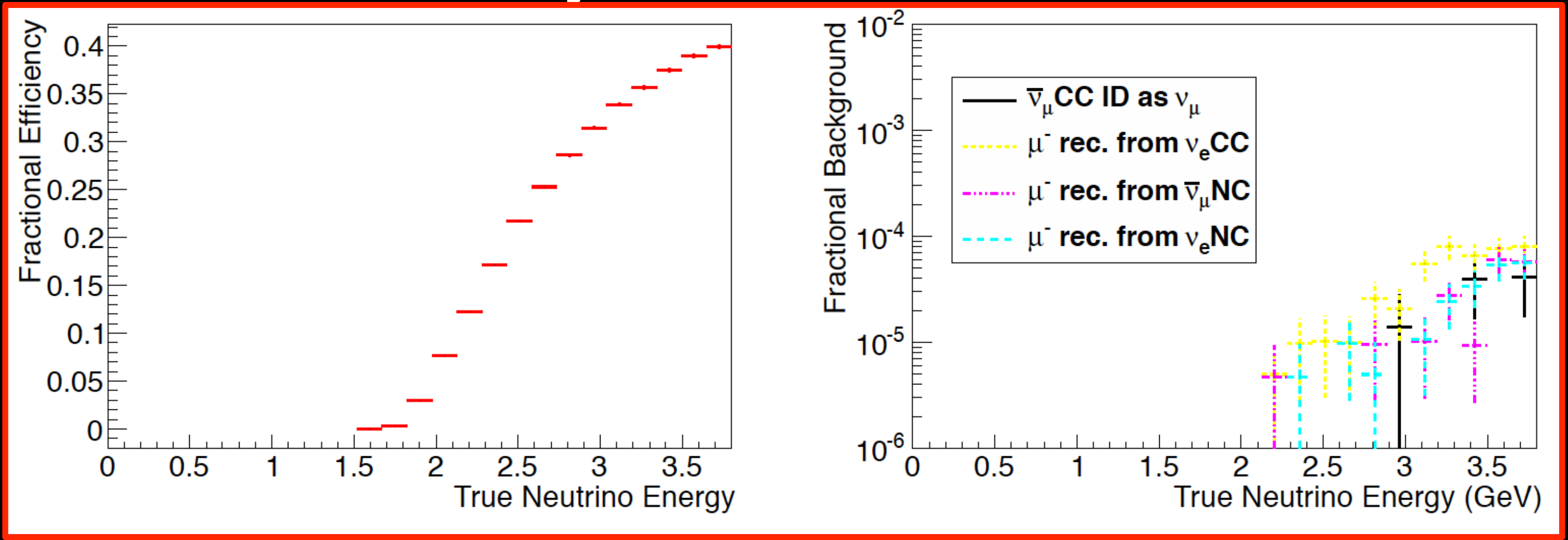
Name	Unit	Value
Iron core outer diameter	m	6.0
Iron core inner diameter	m	0.2
Iron core length	m	15.82
Iron plate thickness	mm	15
Number of plates		440
Space between plates	mm	21
Number of superconducting racetrack coils		8
Superconducting cable length	m	320
Racetrack coil current	kA	30
Total current	kA-turns	240
Peak field on the coil	T	0.83
Inductance	mH	40
Total stored energy	MJ	18



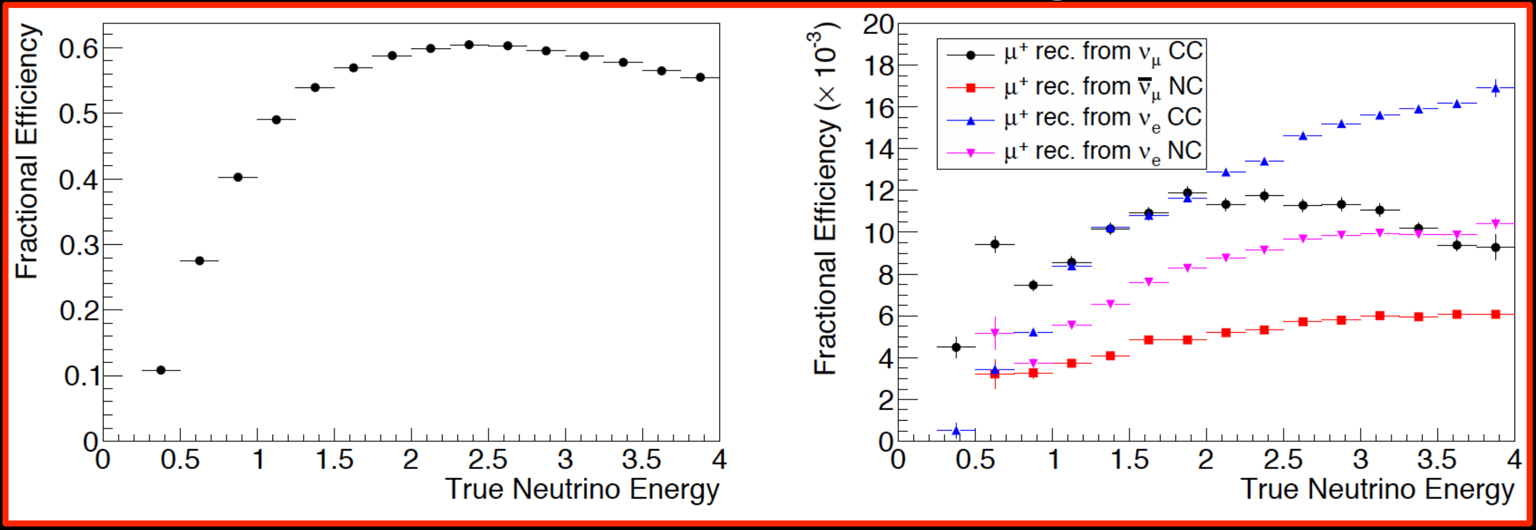


SuperBIND: performance:

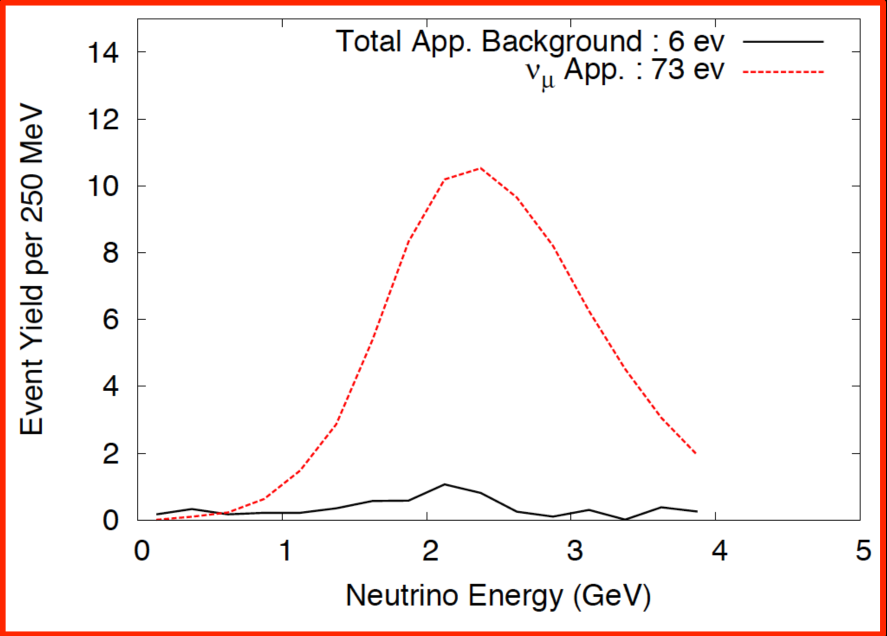
- Cuts-based analysis:

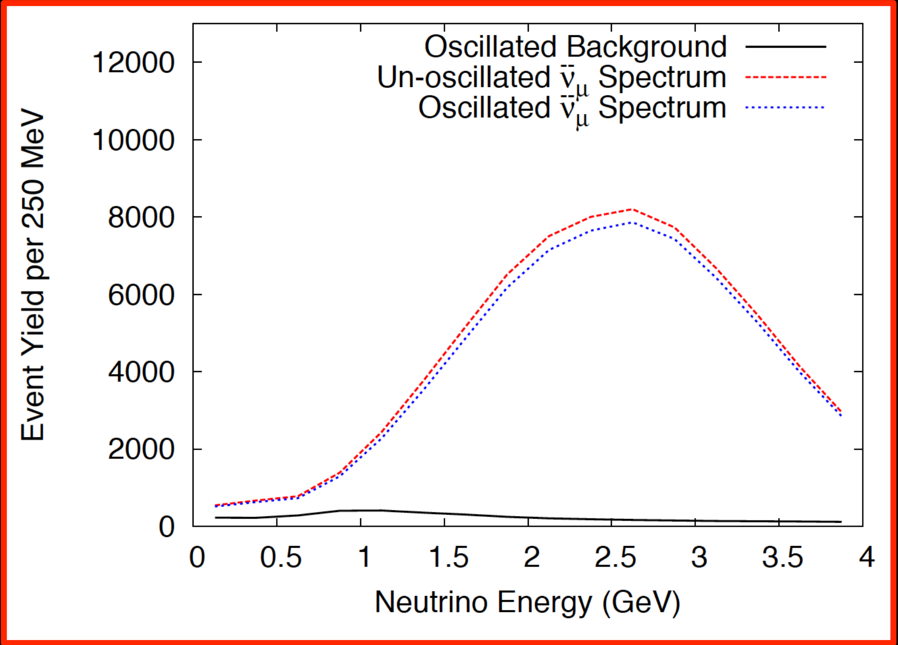


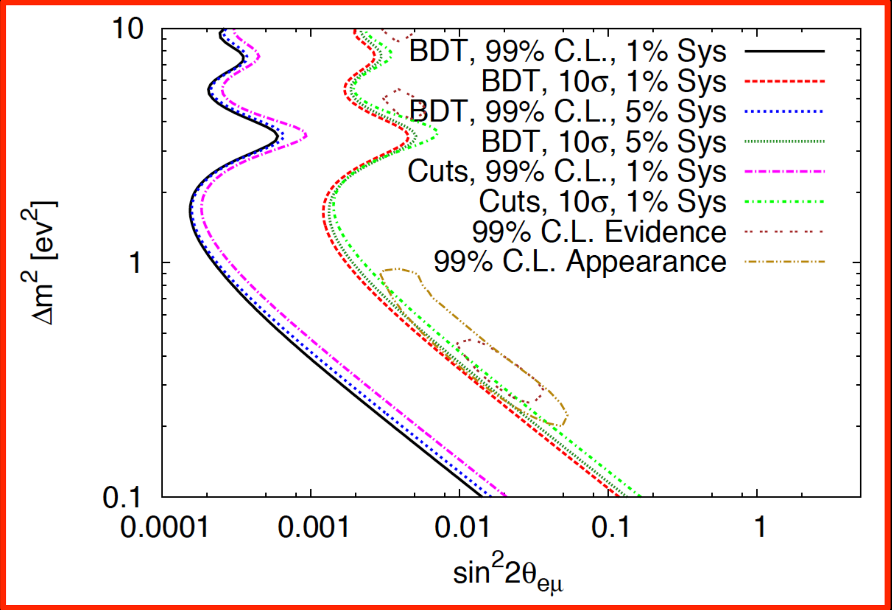
- Optimised multi-variate analysis:

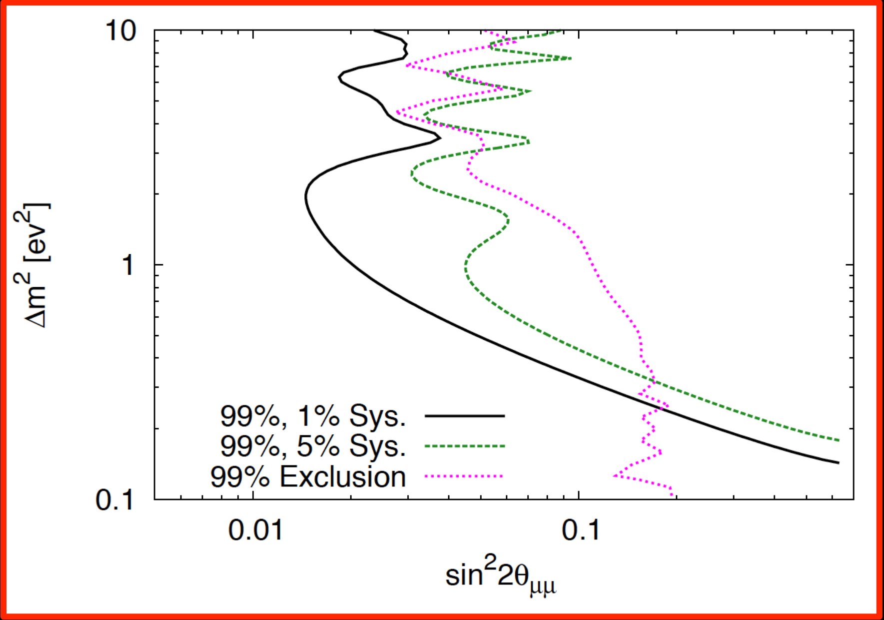


Sterile-neutrino search sensitivity:





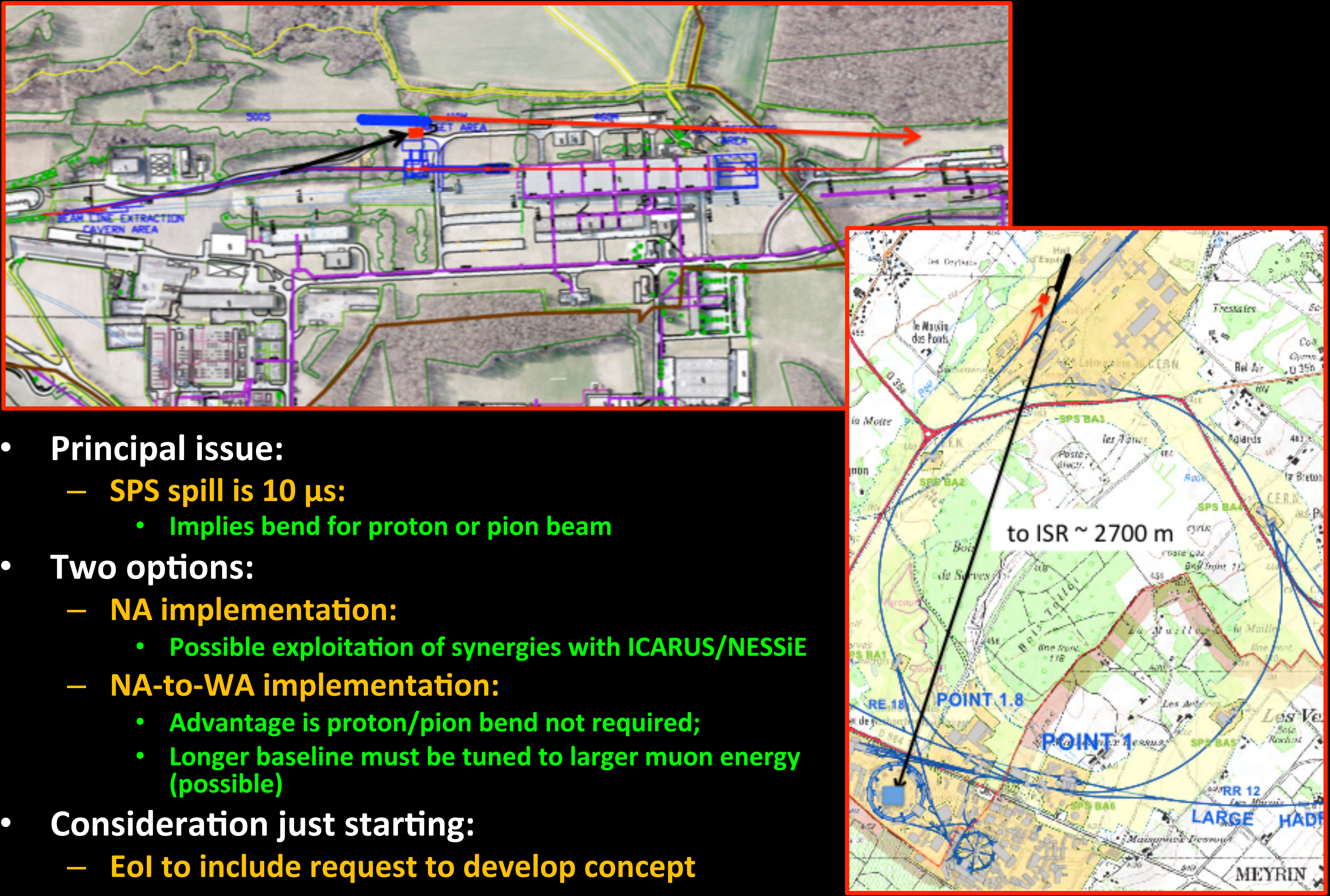




Implementation, at FNAL:

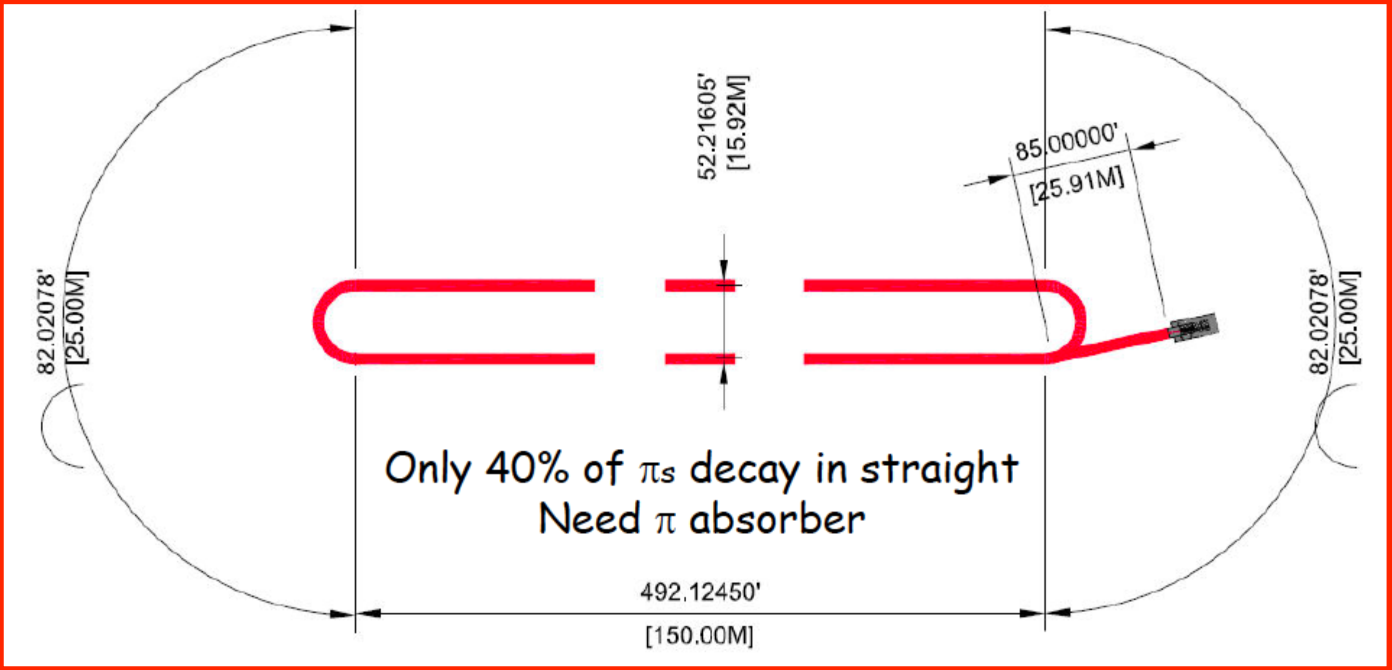
- Benefits from existing extraction tunnel;
- Ideal baseline from storage ring to D0 assembly building:
  - Space and infrastructure for SuperBIND and LAr detector;
- Space and access for near detector

Implementation, at CERN:

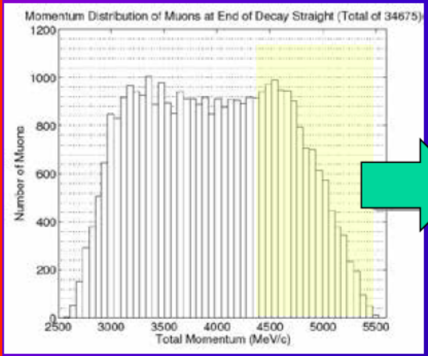


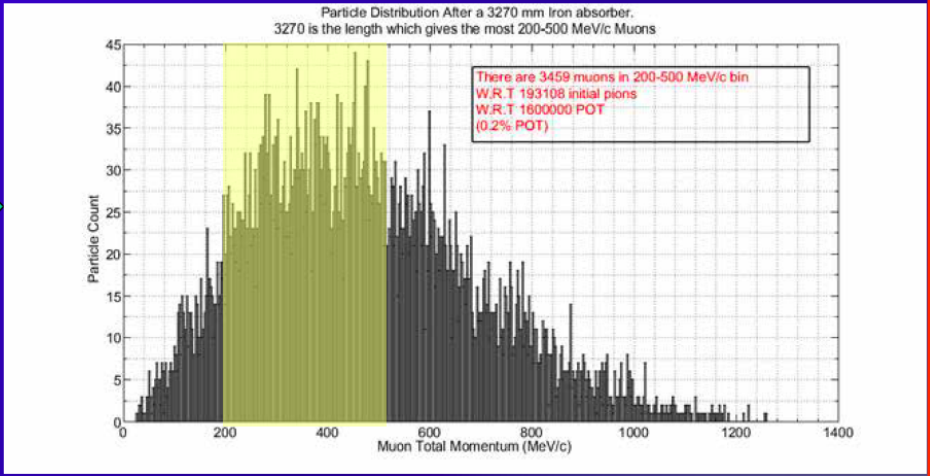
- Principal issue:
  - SPS spill is 10 μs:
    - Implies bend for proton or pion beam
- Two options:
  - NA implementation:
    - Possible exploitation of synergies with ICARUS/NESSiE
  - NA-to-WA implementation:
    - Advantage is proton/pion bend not required;
    - Longer baseline must be tuned to larger muon energy (possible)
- Consideration just starting:
  - EoI to include request to develop concept

Technology test-bed:



Only 40% of πs decay in straight
Need π absorber





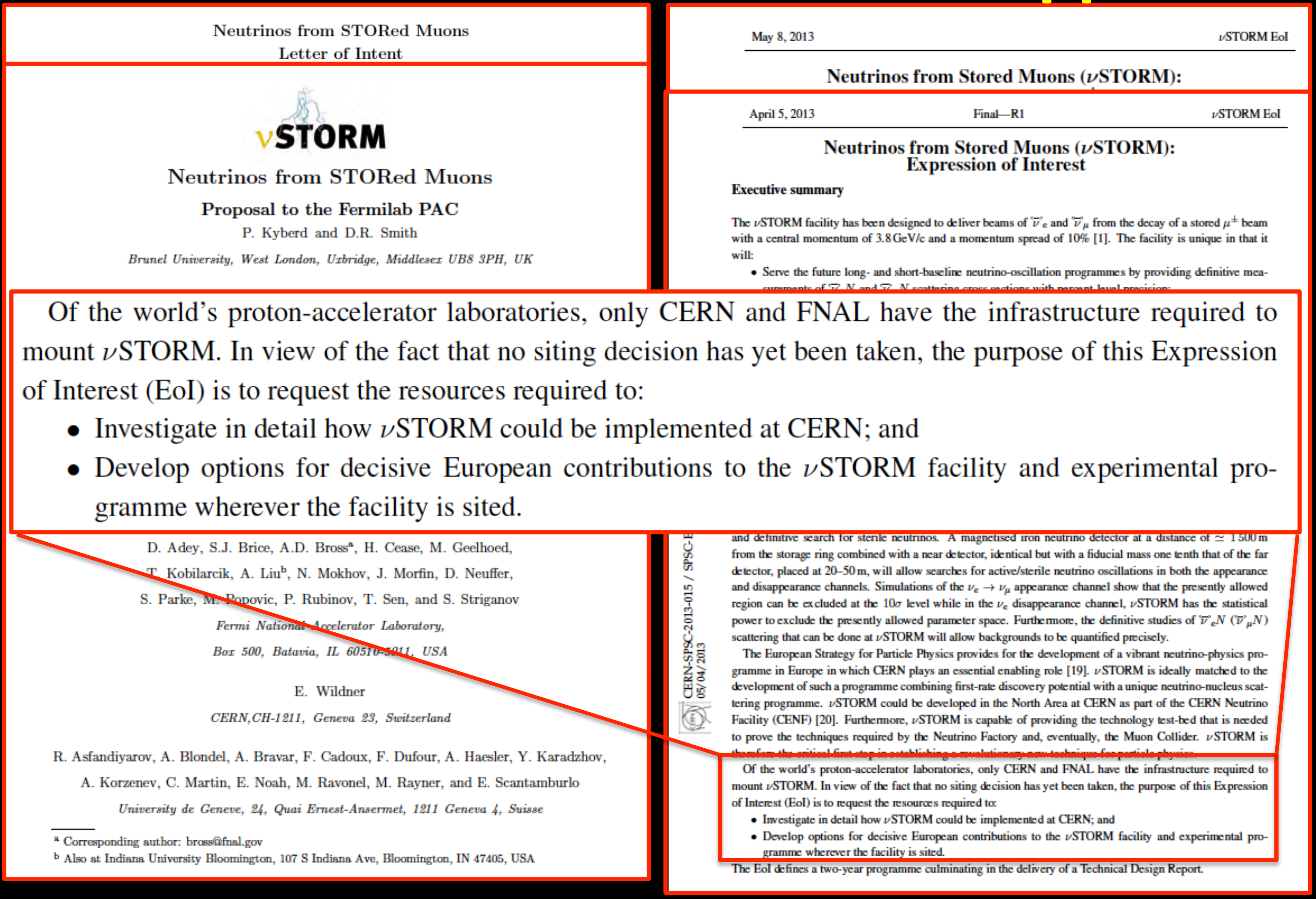
At end of straight we have a lot of πs, but also a lot of μs with $4.5 < P(\text{GeV}/c) < 5.5$

After 3.27m Fe, we have $\approx 10^{10}$ μ/pulse in $200 < P(\text{MeV}/c) < 500$

nuSTORM, the next steps:

- The nuSTORM has the potential to deliver:
  - Unique programme of ν_e and ν_μ cross-section measurements:
    - In kinematic region of interest to LBL experiments;
      - Critical contribution to search for CP violation and precise determination of neutrino-oscillation parameters
  - Exquisitely sensitive searches for sterile neutrinos:
    - Technique that is qualitatively different to, and quantitatively better than, LSND, MiniBOONE and other proposed experiments;
  - A programme of accelerator and detector R&D towards future LBL (SBL) neutrino facilities, the Neutrino Factory and the Muon Collider.
- nuSTORM collaboration enthusiastic and growing:
  - Has defined twin track approach:

Twin-track approach:



Neutrinos from STORed Muons
Letter of Intent

νSTORM

Neutrinos from STORed Muons

Proposal to the Fermilab PAC

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May 8, 2013 νSTORM EoI

Neutrinos from Stored Muons (νSTORM):

April 5, 2013 Final—R1 νSTORM EoI

Neutrinos from Stored Muons (νSTORM): Expression of Interest

CERN-SPSC-2013-015 / SPSC-I
05/04/2013

Executive summary

The νSTORM facility has been designed to deliver beams of $\overline{\nu}_e$ and $\overline{\nu}_\mu$ from the decay of a stored $\mu^\pm$ beam with a central momentum of 3.8 GeV/c and a momentum spread of 10% [1]. The facility is unique in that it will:

- Serve the future long- and short-baseline neutrino-oscillation programmes by providing definitive mea-

and definitive search for sterile neutrinos. A magnetised iron neutrino detector at a distance of $\simeq 1500$ m from the storage ring combined with a near detector, identical but with a fiducial mass one tenth that of the far detector, placed at 20–50 m, will allow searches for active/sterile neutrino oscillations in both the appearance and disappearance channels. Simulations of the $\nu_e \rightarrow \nu_\mu$ appearance channel show that the presently allowed region can be excluded at the 10σ level while in the ν_e disappearance channel, νSTORM has the statistical power to exclude the presently allowed parameter space. Furthermore, the definitive studies of $\overline{\nu}_e N$ ($\overline{\nu}_\mu N$) scattering that can be done at νSTORM will allow backgrounds to be quantified precisely.

The European Strategy for Particle Physics provides for the development of a vibrant neutrino-physics programme in Europe in which CERN plays an essential enabling role [19]. νSTORM is ideally matched to the development of such a programme combining first-rate discovery potential with a unique neutrino-nucleus scattering programme. νSTORM could be developed in the North Area at CERN as part of the CERN Neutrino Facility (CENF) [20]. Furthermore, νSTORM is capable of providing the technology test-bed that is needed to prove the techniques required by the Neutrino Factory and, eventually, the Muon Collider. νSTORM is therefore the critical first step in establishing a revolutionary new technique for particle physics.

Of the world's proton-accelerator laboratories, only CERN and FNAL have the infrastructure required to mount νSTORM. In view of the fact that no siting decision has yet been taken, the purpose of this Expression of Interest (EoI) is to request the resources required to:

- Investigate in detail how νSTORM could be implemented at CERN; and
- Develop options for decisive European contributions to the νSTORM facility and experimental programme wherever the facility is sited.

The EoI defines a two-year programme culminating in the delivery of a Technical Design Report.

Of the world's proton-accelerator laboratories, only CERN and FNAL have the infrastructure required to mount νSTORM. In view of the fact that no siting decision has yet been taken, the purpose of this Expression of Interest (EoI) is to request the resources required to:

- Investigate in detail how νSTORM could be implemented at CERN; and
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Elements of a programme

Elements of a staged programme: [1]

- Large value of θ_{13}, makes it likely that the next generation long-baseline experiments will determine the neutrino mass hierarchy;
  - However, sensitivity to CP violation will be limited;
- In the first instance, a combination of long-baseline (wide-band beam) experiments (e.g. LBNE/LBNO) and short baseline experiments (e.g. T2HK) may offer an attractive way forward:
  - In such an approach:
    - CP reach is limited by systematic effects;
    - Hints of CP violation would require follow up by the Neutrino Factory.
- Search for sterile neutrinos has the potential to revolutionize the field

Elements of a staged programme: [2]

- The Neutrino Factory *is* the facility of choice for detailed studies of neutrino oscillations;
  - Consensus:
    - Will be required to:,
      - Complete the Standard Neutrino Model and to test whether it is a good description of nature

- But, stored muon beams have not yet been shown to be capable of serving a world-class neutrino programme:
  - Require to push through R&D and complete IDS-NF, considering an incremental implementation in parallel; and
  - Establish a first, realistic, scientifically first-rate neutrino experiment based on a stored muon beam
    - nuSTORM has the potential to:
      - Serve the neutrino programme by making unique $\nu_e N$ and $\nu_\mu N$ cross section measurments; and
      - Provide potentially decisive information on the existence of sterile neutrinos

Neutrinos from stored muon beams:

Conclusions

Conclusions [1]:

- The study of the neutrino is the study of physics beyond the Standard Model:
  - Possibly a window on extremely large mass scale
- Exciting new data; exciting opportunities:
  - Measurement of θ_{13} emphasises:
    - Discovery sensitivity for:
      - CP-invariance violation;
      - Mass hierarchy;
    - Precision measurement of neutrino oscillations
  - Sterile neutrinos situation unclear:
    - Confirmation, or discovery of sterile state, would revolutionize our field

Conclusions [2]:

- New data, new Design Studies, new accelerator R&D allow definition of powerful incremental programme encompassing:
  - Conventional super-beam experiment(s):
    - Determination of mass hierarchy;
    - Initial scan of δ_{CP} space;
      - Critical contribution: ν_e cross section measurements from nuSTORM
  - Development of the Neutrino Factory:
    - Unique; meeting the sensitivity and precision goals;
    - Mature; key issues addressed, or being addressed;
    - Incremental approach to full Neutrino Factory conceivable;
    - nuSTORM achievable, early first step that is essential for the LBL programme to meet its precision and sensitivity goals
  - Programme of sterile neutrino searches:
    - Development of existing sterile-neutrino search programme;
    - nuSTORM offers a qualitatively new technique that can address each of the channels of interest

All together a wonderful programme!

Thank you