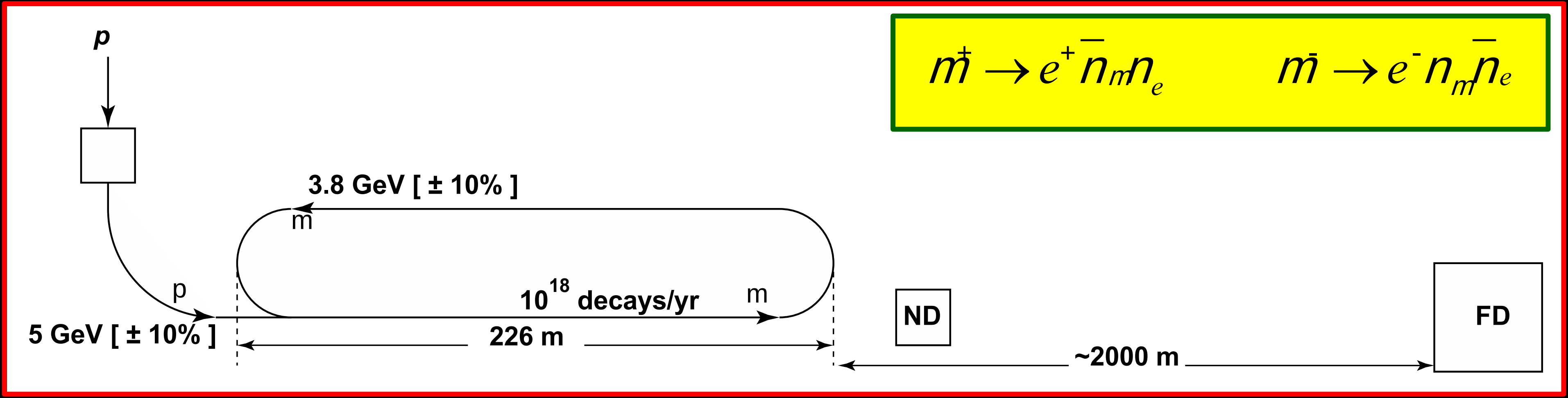
K. Long
on behalf of nuSTORM
25 June, 2013
Imperial College
London

Expression of interest for a facility for Neutrinos from Stored Muons (nuSTORM)

nuSTORM concept:



$$\mu^+ \to e^+ \bar{\nu}_\mu \nu_e \qquad \mu^- \to e^- \nu_\mu \bar{\nu}_e$$

- Neutrinos from the decay of stored muon beams:
  - Precisely known flavour composition;
  - Precisely known energy distribution

Contents:

- The case for nuSTORM
- The nuSTORM facility
- Expression of Interest
- Conclusions

The case for nuSTORM

The case for nuSTORM:

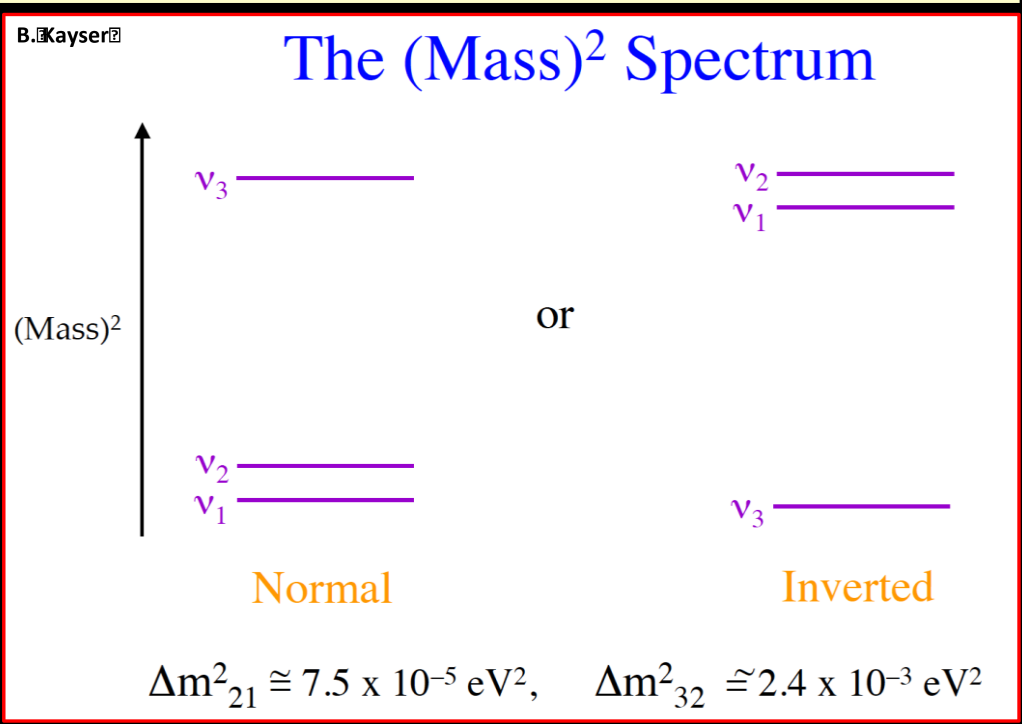
- **The nuSTORM facility will:**
  - **Serve the future long- and short-baseline neutrino-oscillation programmes by providing definitive measurements of $\nu_e N$ and $\nu_\mu N$ scattering cross sections with percent-level precision;**
  - **Allow searches for sterile neutrinos of exquisite sensitivity to be carried out; and**
  - **Constitute the essential first step in the incremental development of muon accelerators as a powerful new technique for particle physics.**

$\nu_e N$ and $\nu_\mu N$ scattering:

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**

The SνM measurement programme:

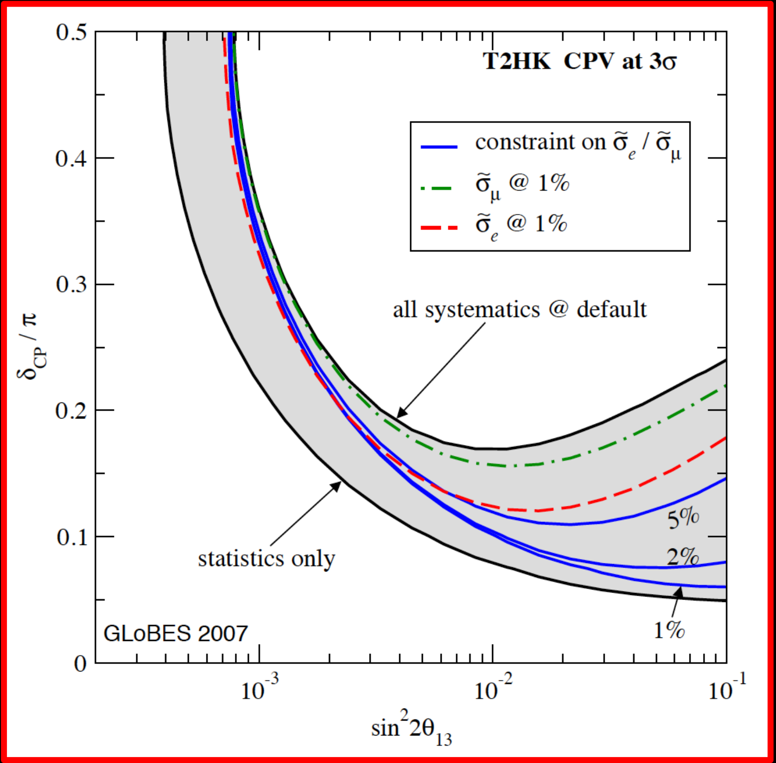
- Complete the “Standard Neutrino Model” (SνM):
  - Determine the mass hierarchy
  - Search for (and discover?) leptonic CP-invariance violation
- Establish the SνM as the correct description of nature:
  - Determine precisely the degree to which θ_{23} differs from $\pi/4$
  - Determine θ_{13} precisely
  - 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, …

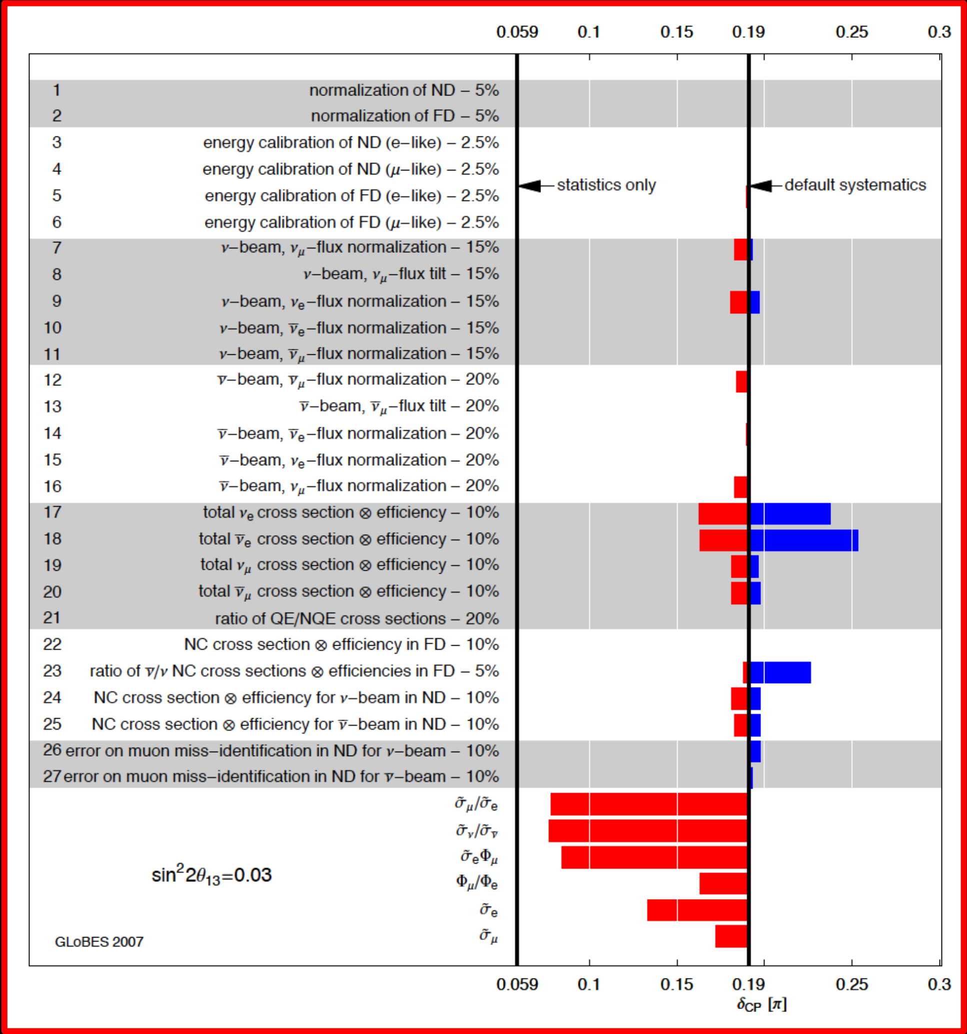
- Programme requirements:
  - Measure ν_e appearance in ν_μ beam
    - Exception: the Neutrino Factory
  - Control of systematic uncertainties

Systematic uncertainties:

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

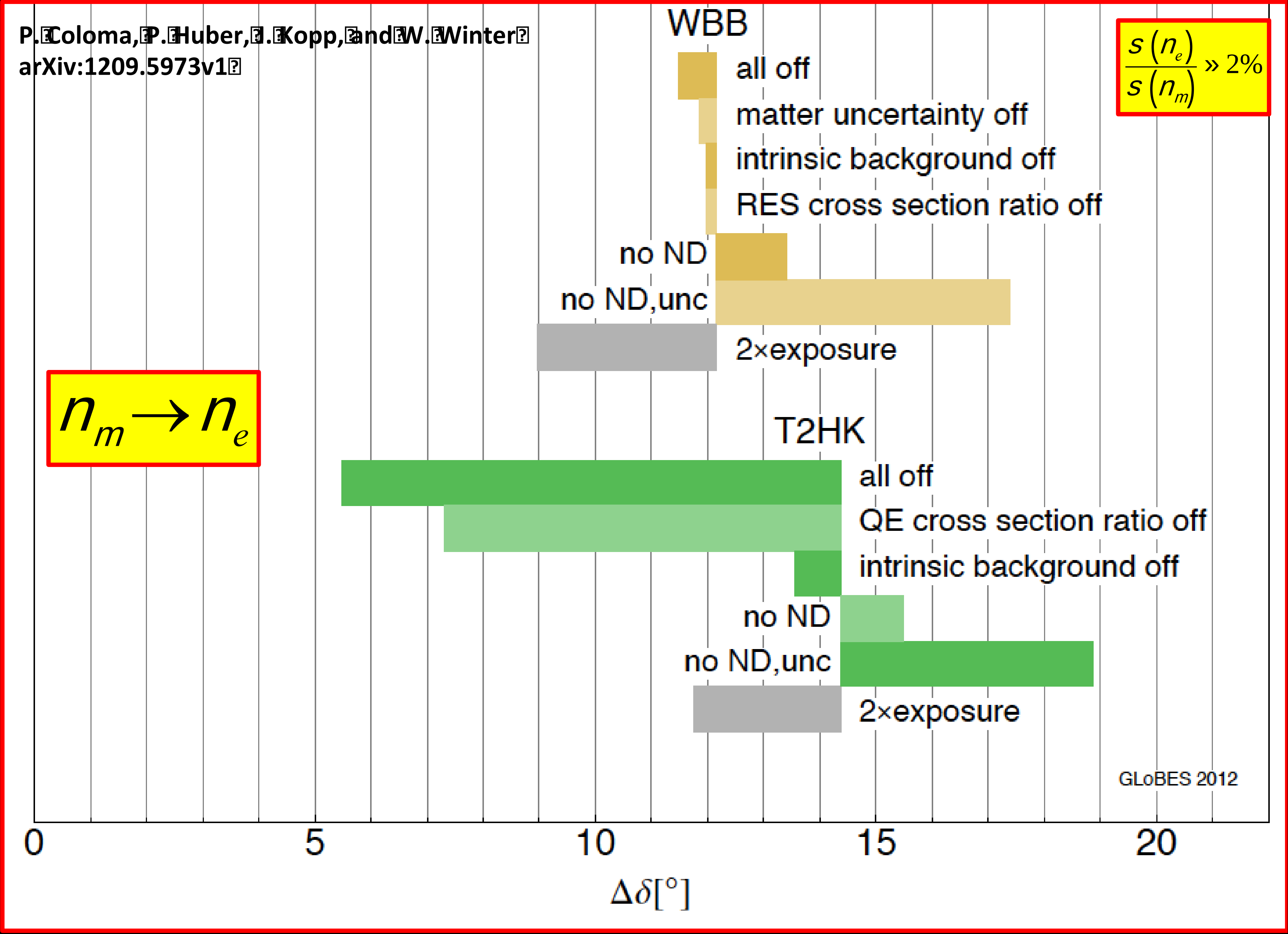
— critical at large θ_{13}





Huber, Mezzetto, Schwetz,
arXiv:0711.2950v2

Effect of systematic uncertainties:

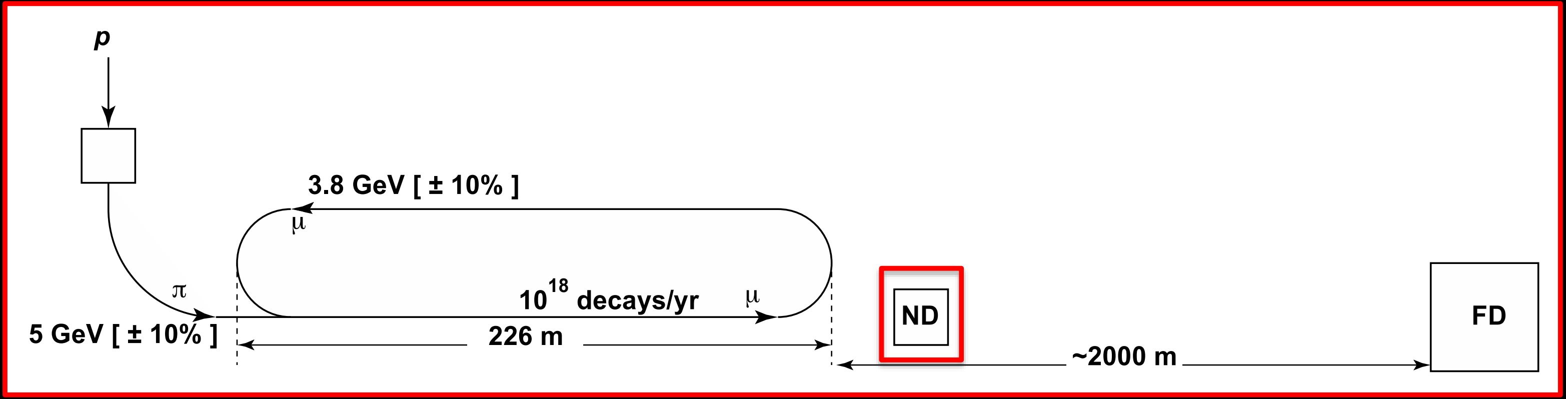


P. Coloma, P. Huber, J. Kopp, and W. Winter
arXiv:1209.5973v1

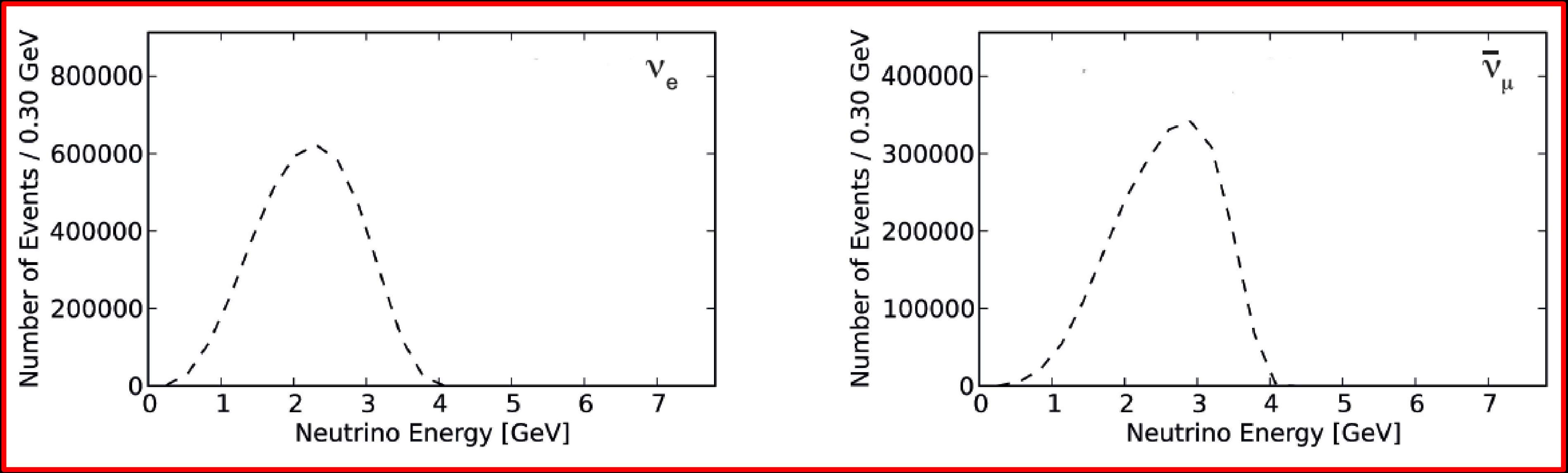
$$\frac{\sigma(\nu_e)}{\sigma(\nu_\mu)} \approx 2\%$$

$$\nu_\mu \to \nu_e$$

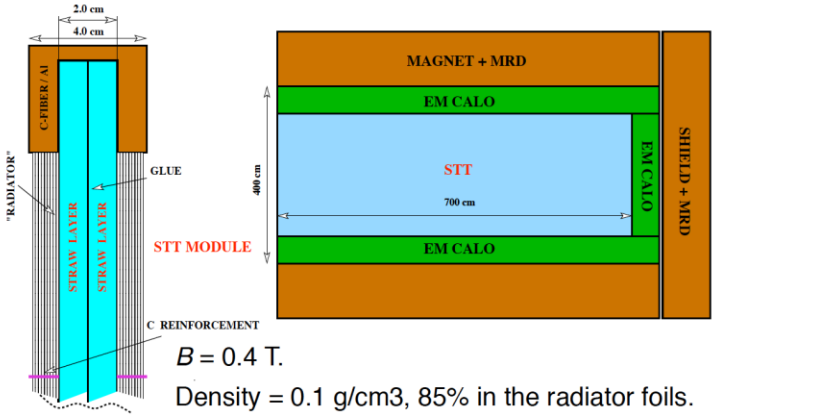
nuSTORM and cross section study:



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



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.

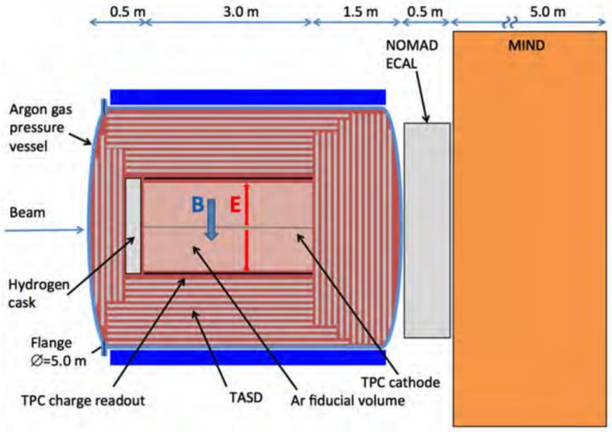
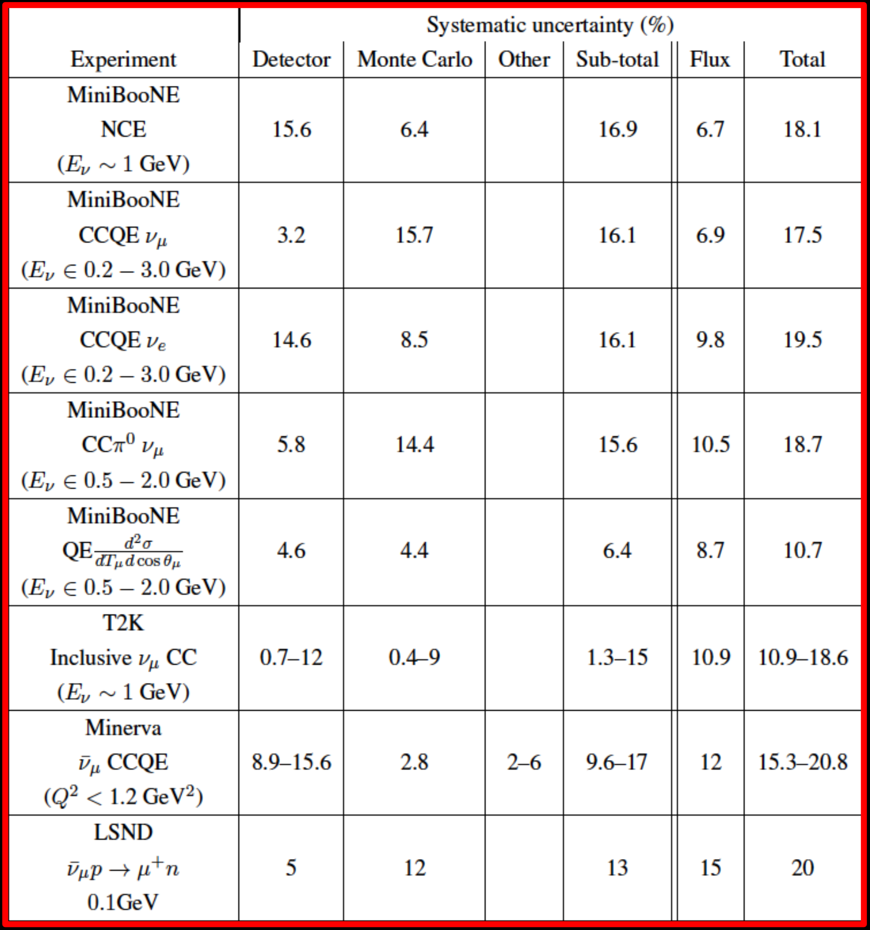


Figure 12: Schematic of the pressurized argon gas-based TPC detector. Both the TPC and scintillator calorimeter layers surrounding it are enclosed in a pressure vessel. A 0.5 T magnetic field is applied to the pressure vessel volume. Downstream of the TPC are also an electromagnetic calorimeter (ECAL) 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 could 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 …

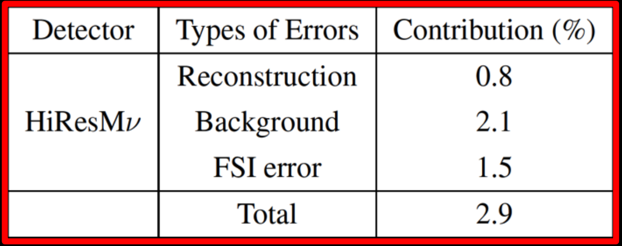
Cross section measurement performance:

- Existing experiments:
  - Sets the goal



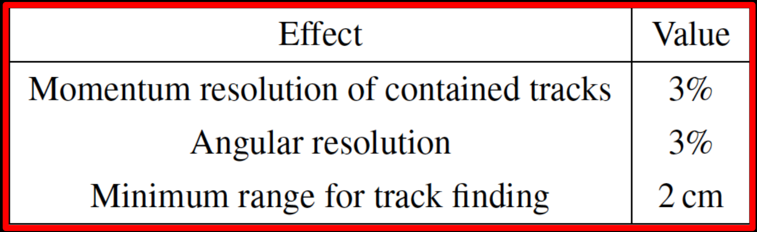
Experiment	Systematic uncertainty (%)					
	Detector	Monte Carlo	Other	Sub-total	Flux	Total
MiniBooNE NCE ($E_\nu \sim 1$ GeV)	15.6	6.4		16.9	6.7	18.1
MiniBooNE CCQE ν_μ ($E_\nu \in 0.2 - 3.0$ GeV)	3.2	15.7		16.1	6.9	17.5
MiniBooNE CCQE ν_e ($E_\nu \in 0.2 - 3.0$ GeV)	14.6	8.5		16.1	9.8	19.5
MiniBooNE 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 $\bar{\nu}_\mu p \to \mu^+ n$ 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:

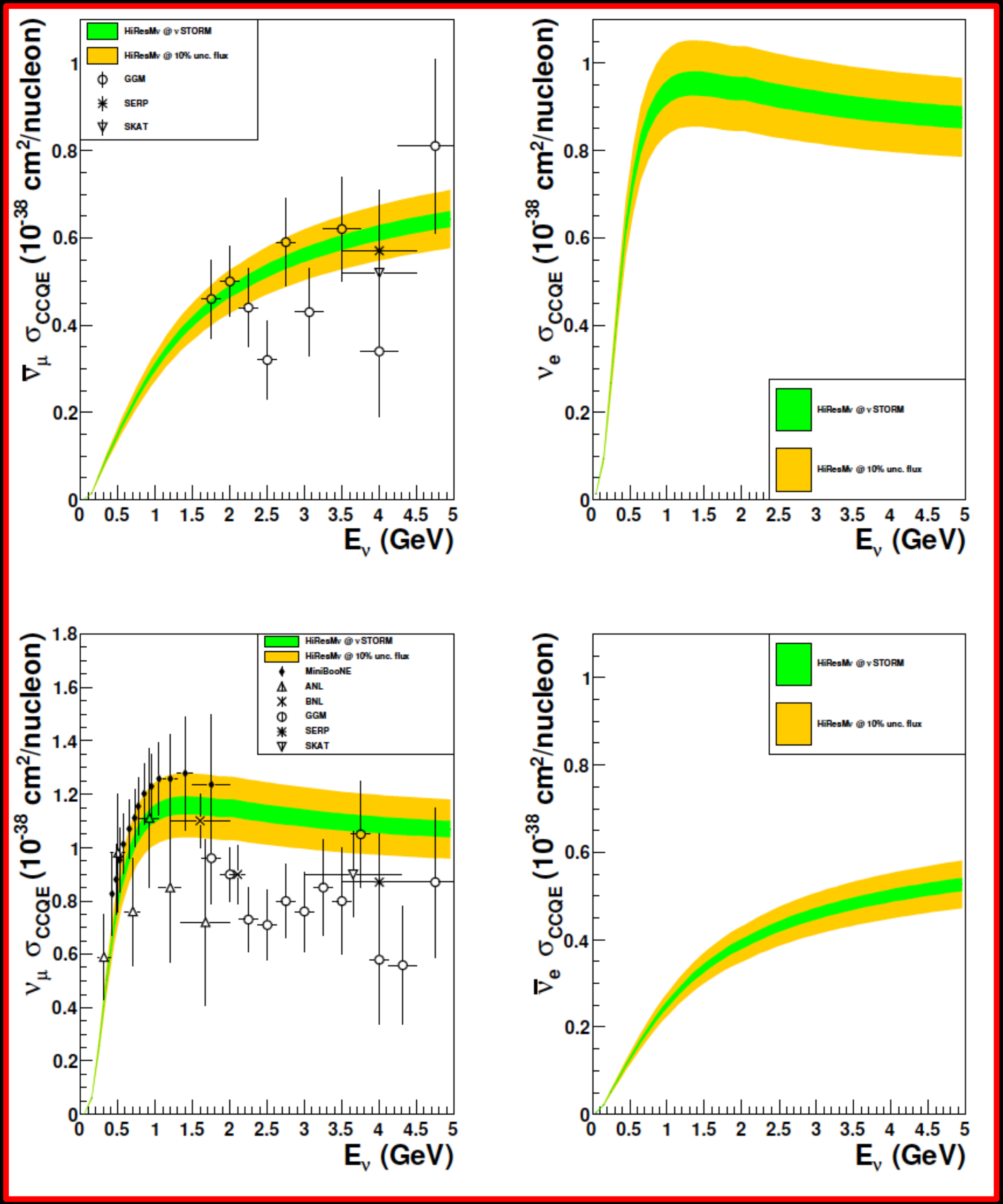


Effect	Value
Momentum resolution of contained tracks	3%
Angular resolution	3%
Minimum range for track finding	2 cm

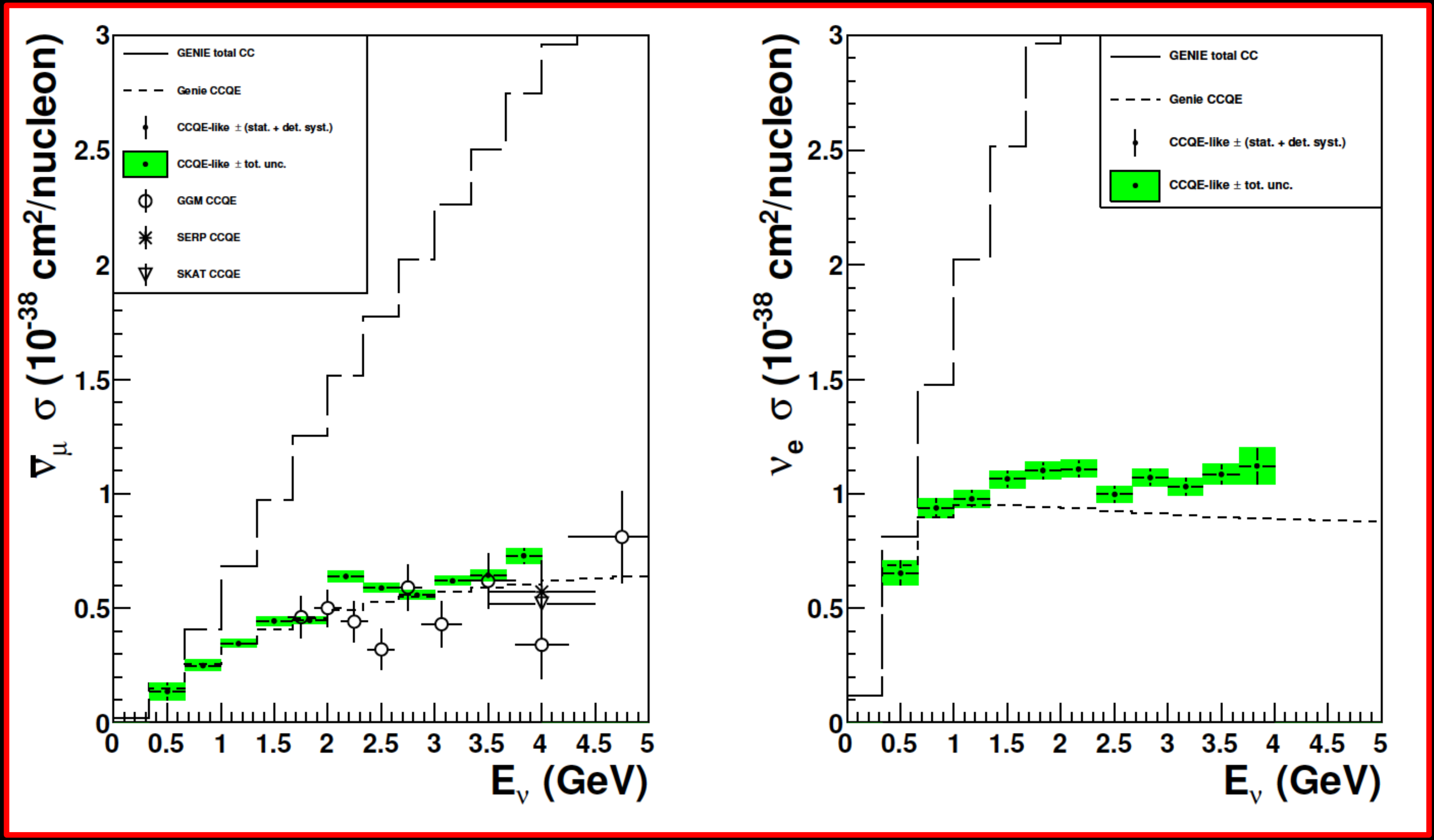
- Flux uncertainty varied:
  - 1% nuSTORM specification
  - 10% typical of conventional beams for comparison

CCQE cross section measurement:

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



CCQE cross section measurement:

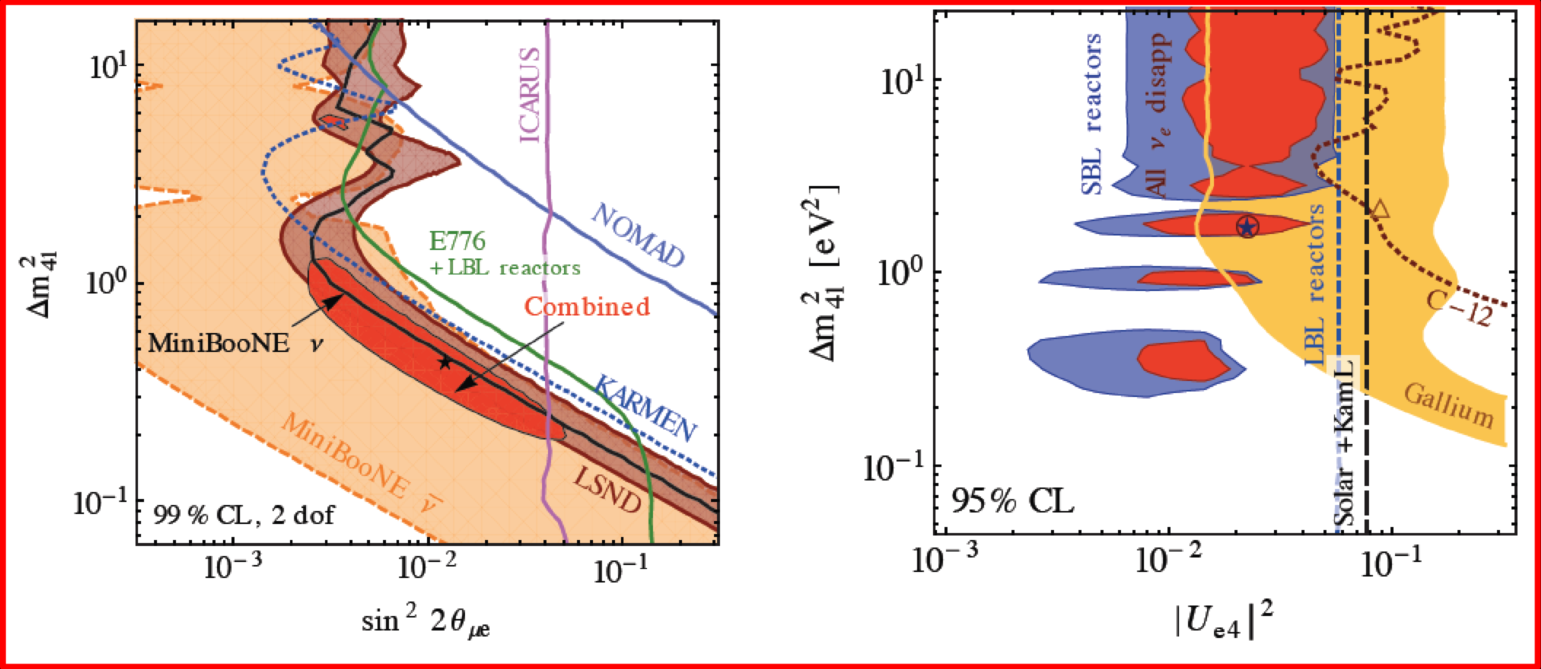


- Simulation of "generic detector":
  - Muon-neutrino CCQE cross section measurement substantially improves "state of the art"
  - Electron-neutrino CCQE measurement *unique*
  - Evaluation of other channels has begun

Sterile neutrino searches:

Global constraints [1]:

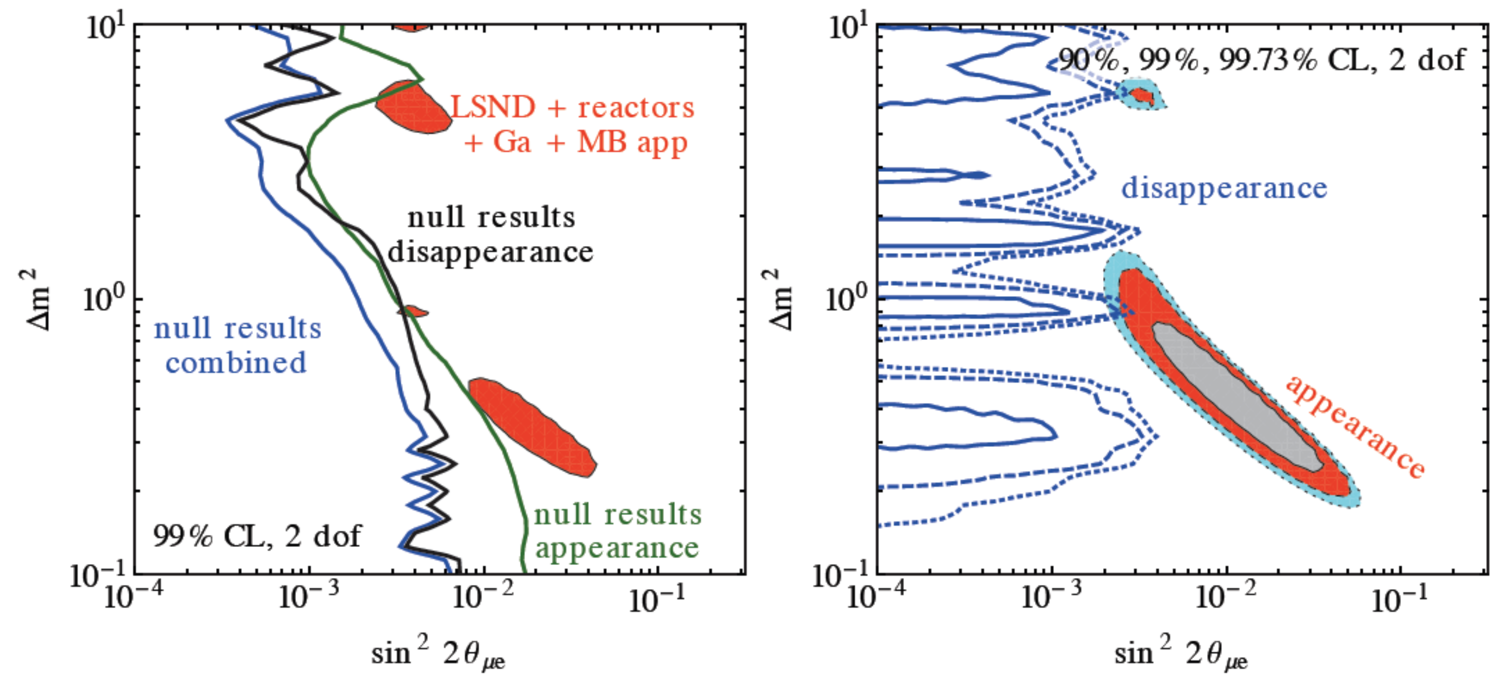
Sterile neutrino data		
	Appearance	**Disappearance**
Null hypothesis: SvM **Inconsistent**	LSND, MiniBOONE	Reactor flux, Gallium sources
Consistent	KARMEN, NOMAD, E776, ICARUS	Atmospheric, Solar, MiniBOONE, SciBOONE, MINOS, Reactor, CDHS, KARMEN, LSND, ^{12}C



- **Appearance and disappearance data sets self-consistent**

Global constraints [2]:

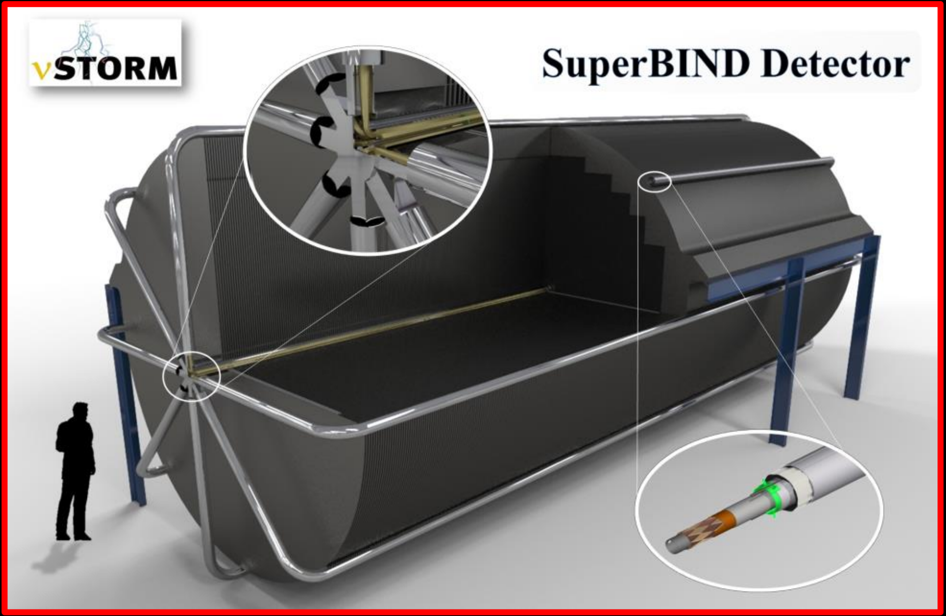
Sterile neutrino data		
	Appearance	**Disappearance**
Null hypothesis: SvM		
Inconsistent	LSND, MiniBOONE	Reactor flux, Gallium sources
Consistent	KARMEN, NOMAD,E776, ICARUS	Atmospheric,Solar, MiniBOONE, SciBOONE, MINOS, Reactor, CDHS, KARMEN, LSND, ^{12}C

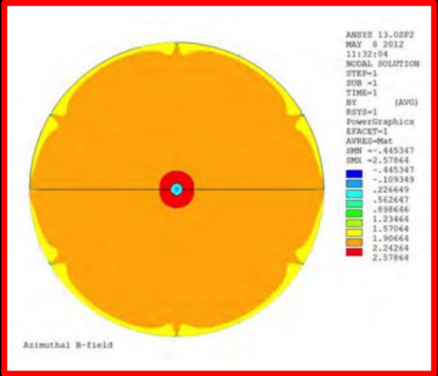


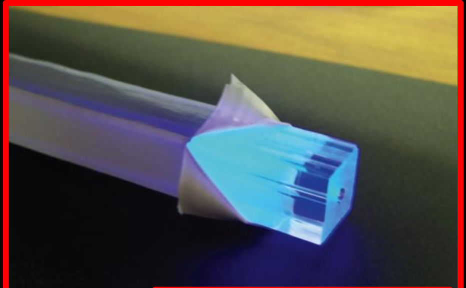
- Appearance and disappearance data sets self-consistent
- Tension between parameter regions in measurements consistent with the null hypothesis and those which are inconsistent with it
- ν_e appearance data in tension with exclusion limits from disappearance searches

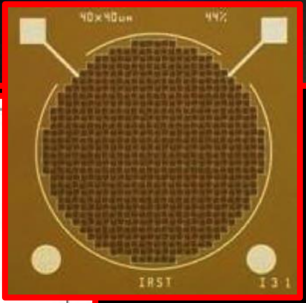
SuperBIND, baseline sterile detector:

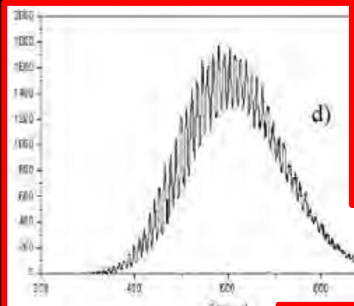
- Magnetised iron calorimeter:
  - MINOS-like, optimised for nuSTORM beam

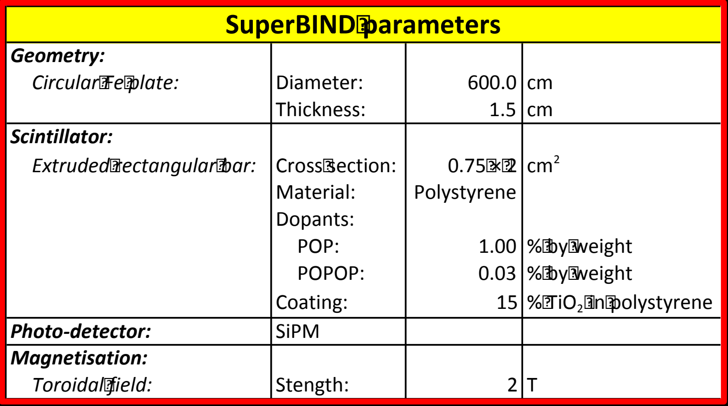




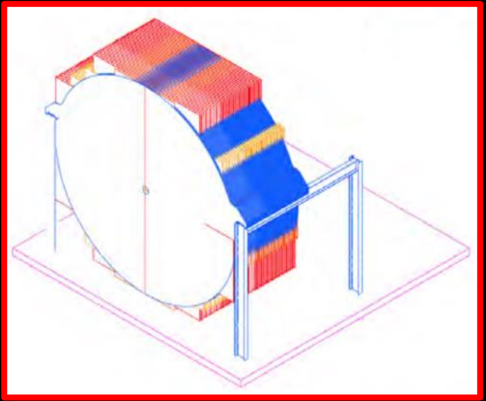








SuperBIND parameters			
Geometry:			
Circular Fe plate:	Diameter: Thickness:	600.0 1.5	cm cm
Scintillator:			
Extruded rectangular bar:	Cross section: Material: Dopants: POP: POPOP: Coating:	0.75 x 2 Polystyrene 1.00 0.03 15	cm^2 % by weight % by weight % TiO_2 in polystyrene
Photo-detector:	SiPM		
Magnetisation: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



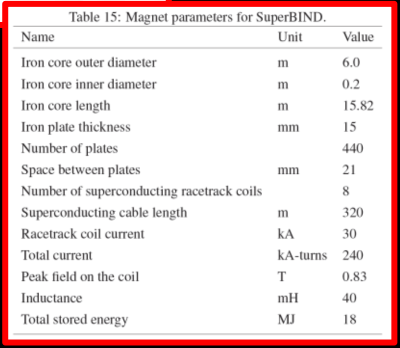
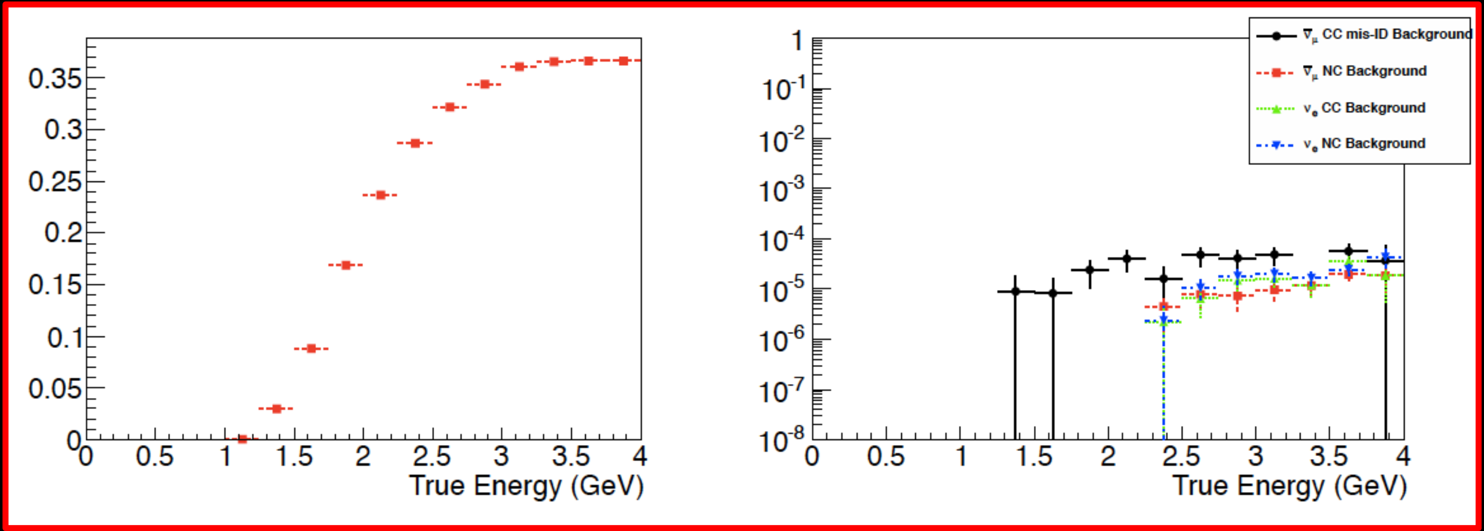


Table 15: Magnet parameters for SuperBIND.

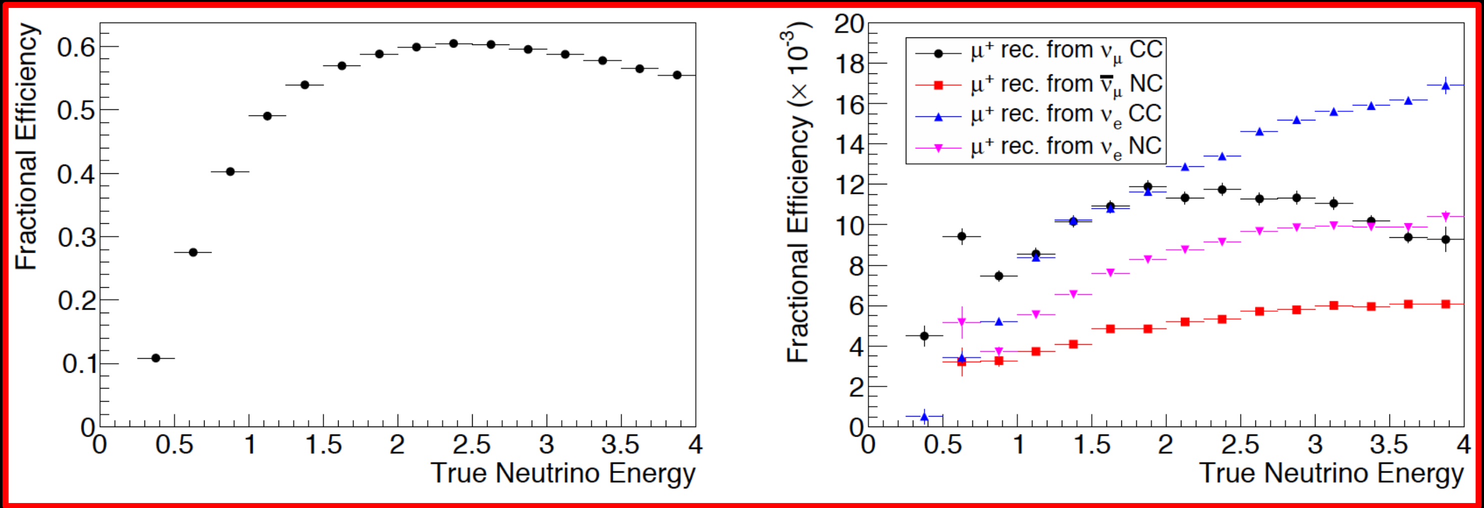
Name	Unit	Value
Iron core outer diameter	m	6.0
Iron core inner diameter	m	0.2
Iron core length	m	15.82
Iron plate thickness	mm	15
Number of plates		440
Space between plates	mm	21
Number of superconducting racetrack coils		8
Superconducting cable length	m	320
Racetrack coil current	kA	30
Total current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

SuperBIND: performance:

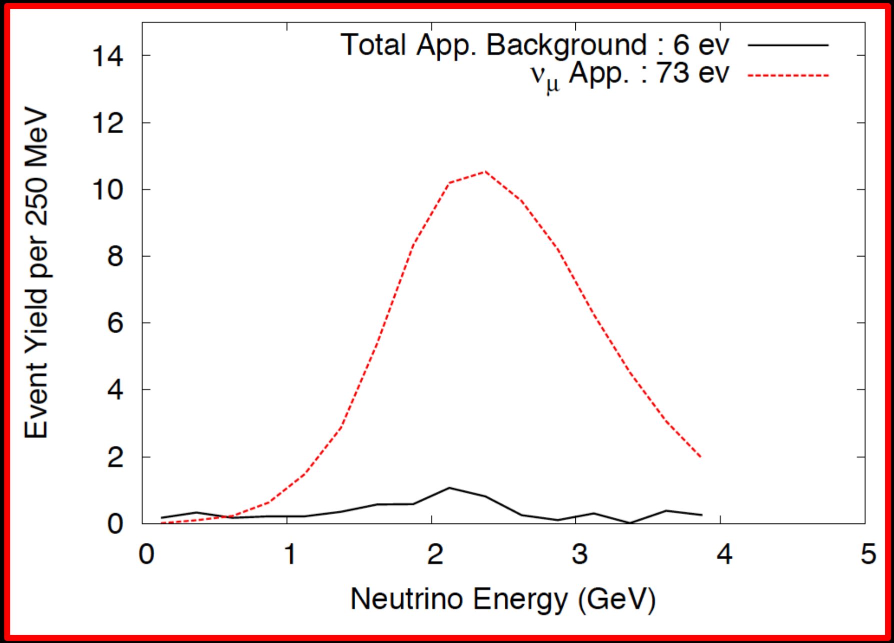
- Multi-variate, appearance analysis:

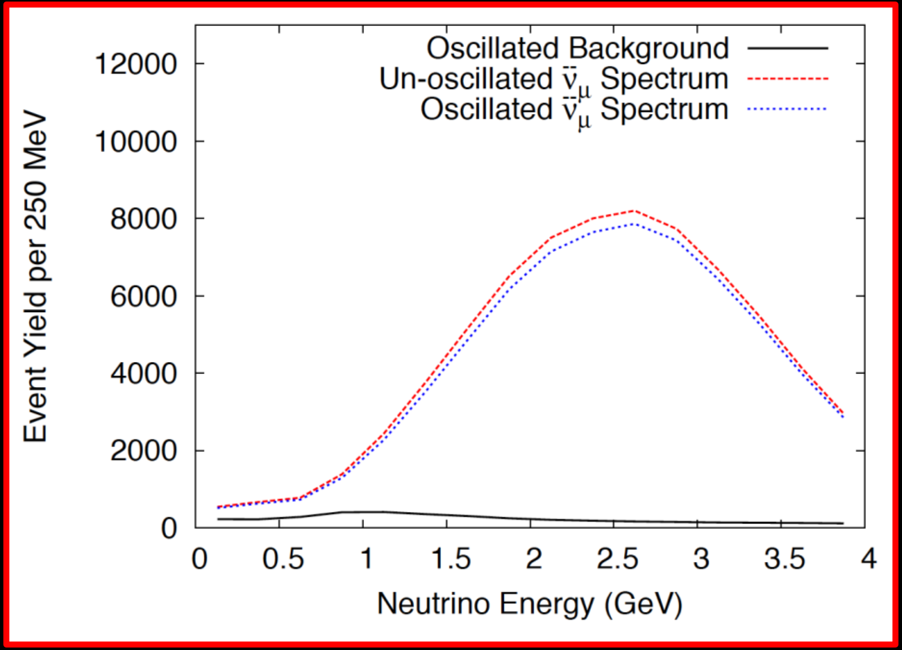


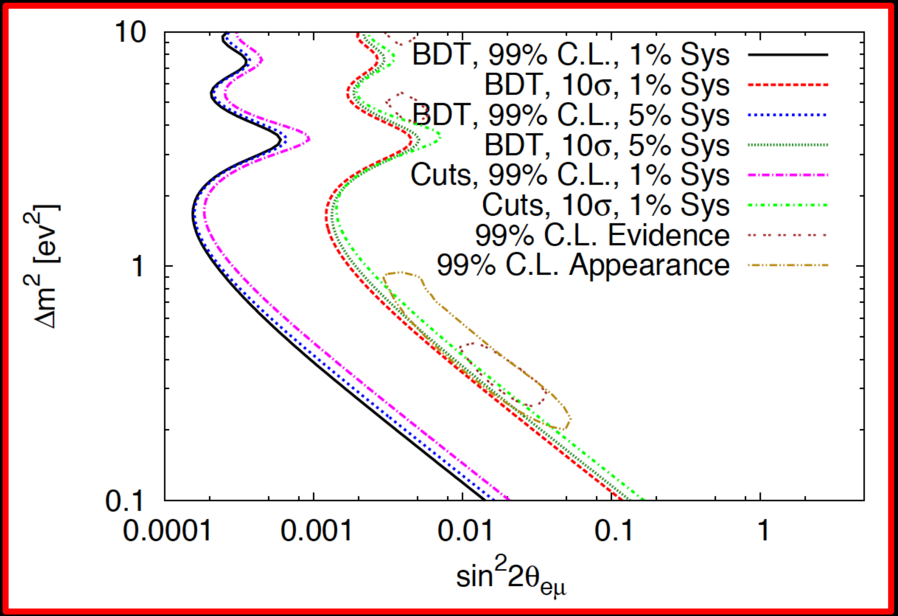
- Multi-variate, disappearance analysis:

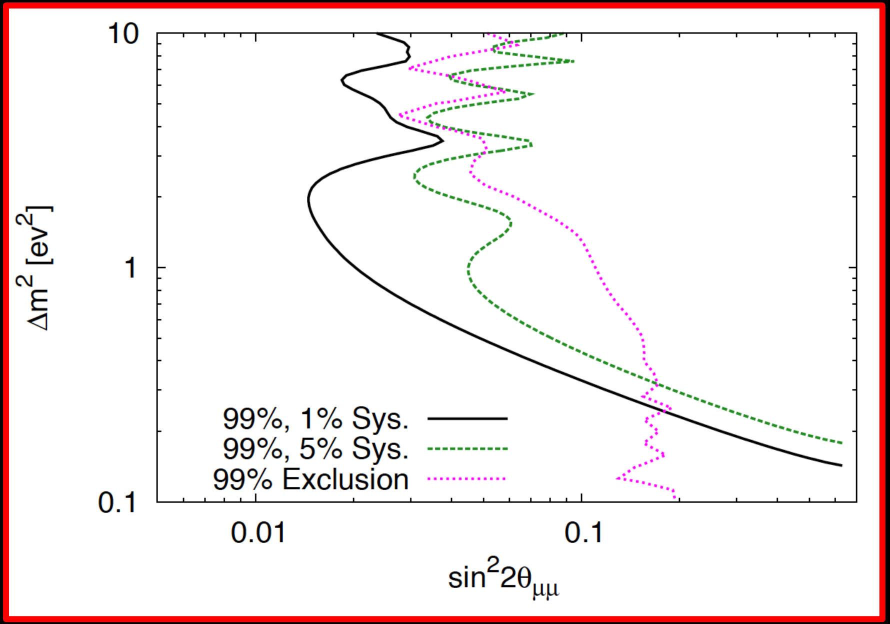


Sterile-neutrino search sensitivity:





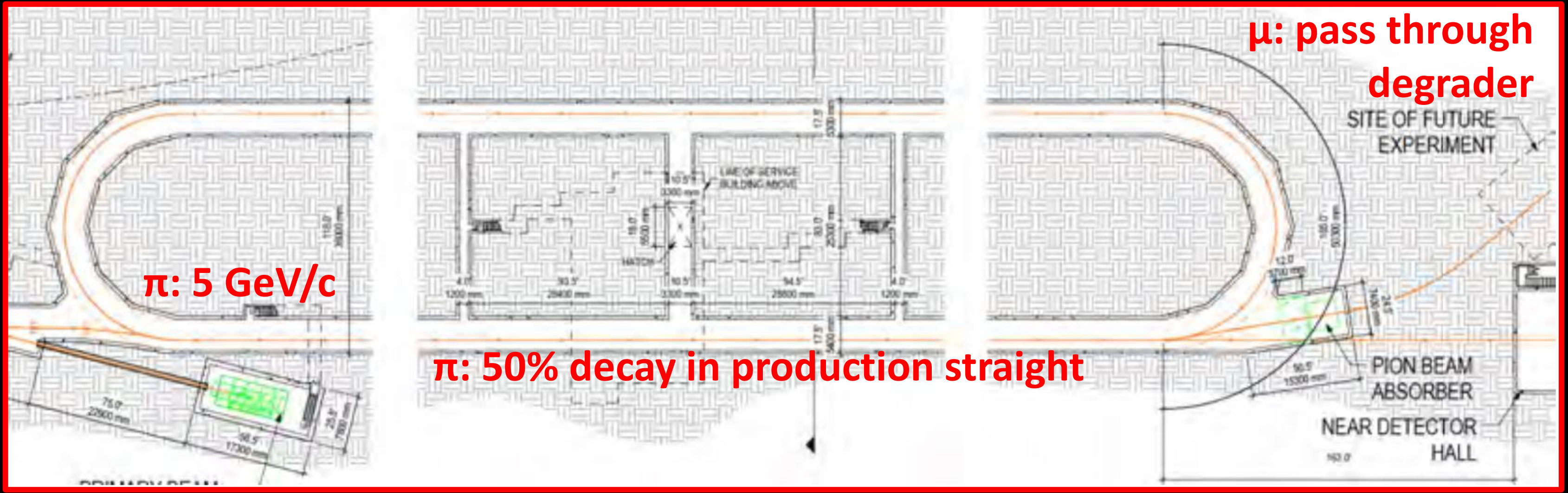




R&D for muon accelerators

6D ionization cooling experiment:

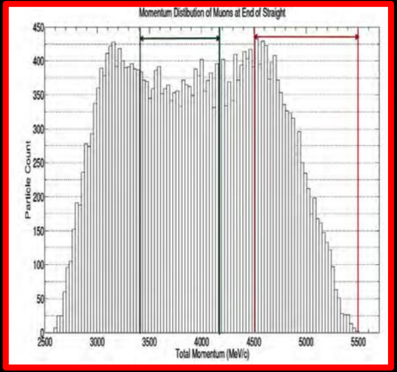
- Reduction of 6D phase space of muon beam essential for future Muon Collider
  - MICE will provide proof of the ionization-cooling principle in 4D using a single-particle technique
- nuSTORM will provide the pulsed, high-flux muon beam required for the development of ionization cooling

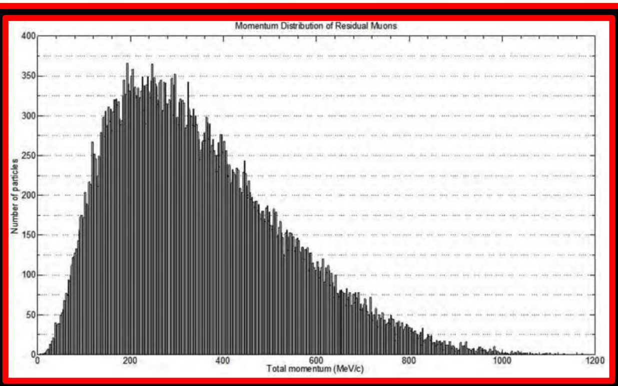


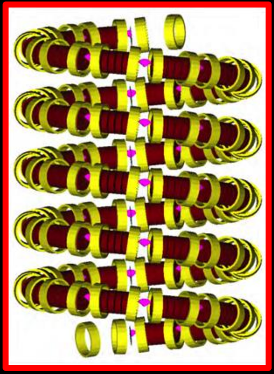
µ: pass through degrader

π: 5 GeV/c

π: 50% decay in production straight

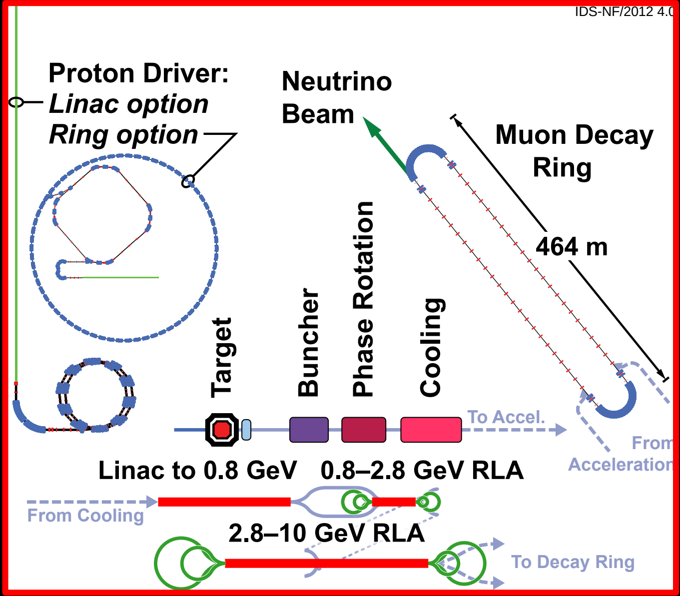


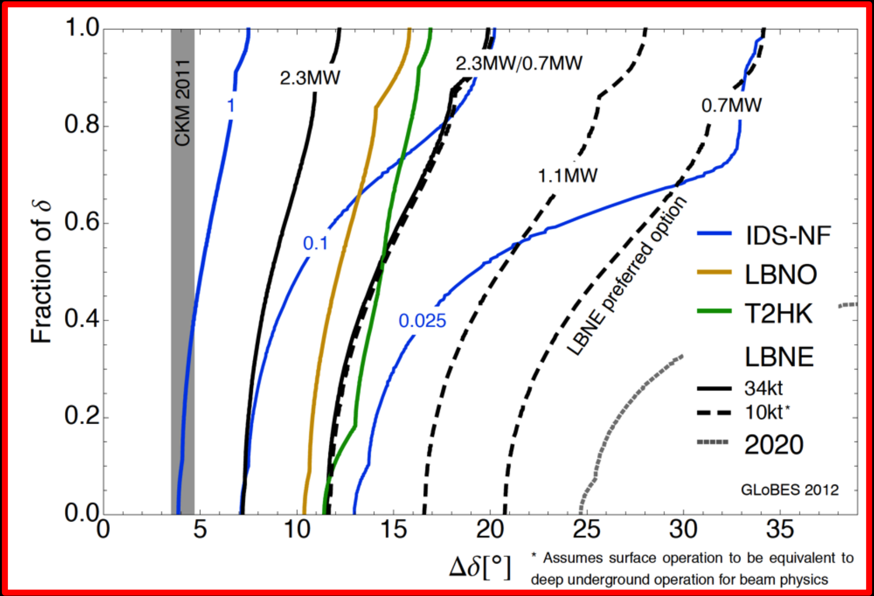




nuSTORM and muon accelerators for PP:

- Muon accelerators have the potential to:
  - Make definitive measurements of neutrino oscillations at the Neutrino Factory;
  - Provide multi-TeV lepton-antilepton collisions at the Muon Collider
- Incremental development of the Neutrino Factory programme offers exquisite sensitivity and precision:





* Assumes surface operation to be equivalent to deep underground operation for beam physics

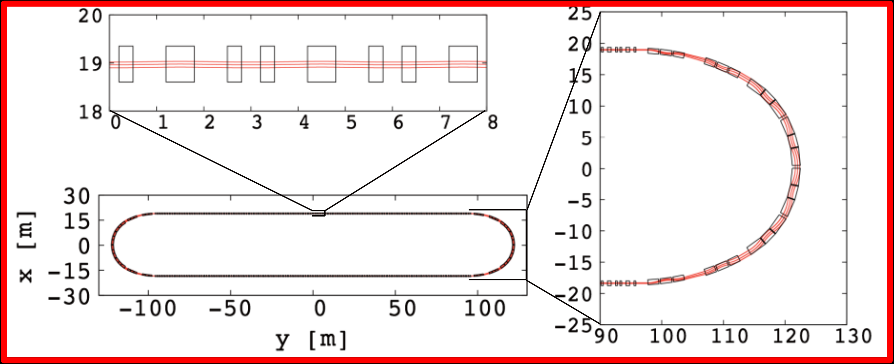
- nuSTORM is the essential first step in the incremental progamme:
  - Can be implemented “today” using known technologies
    - For the accelerator and the detectors
  - Capable of delivering a first-rate neutrino-physics programme *and* the R&D required to prepare the subsequent step

The nuSTORM facility

π injection and decay ring:

- Beam Combination Section (BCS) designed to deliver π-beam at start of straight
- Large aperture quad-focusing ring adopted as baseline
  - FFAG ring may be an attractive option

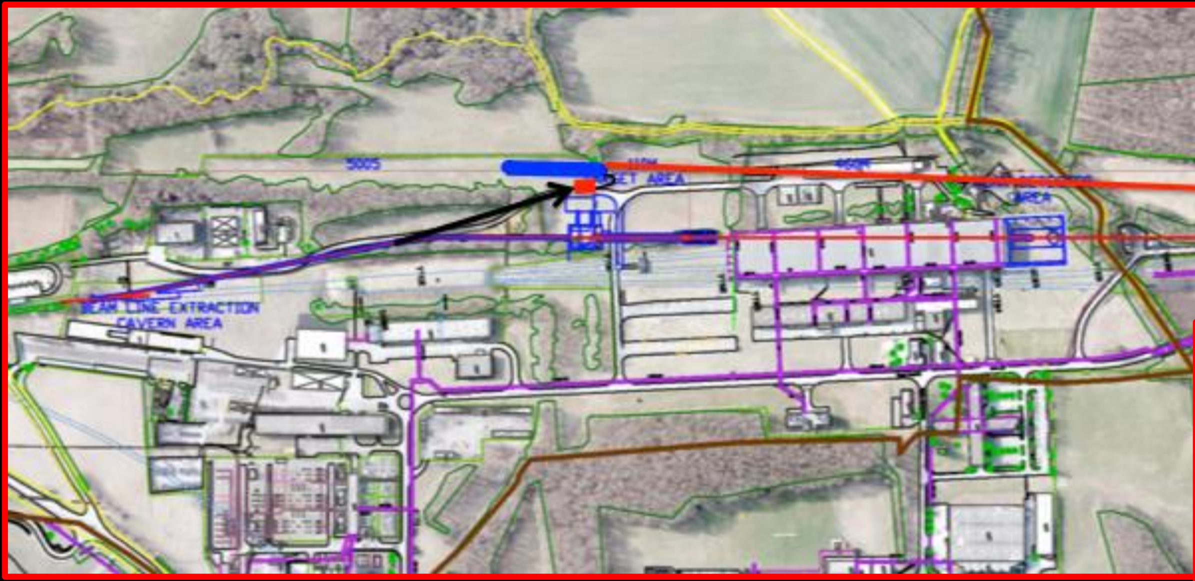
Parameter	FODO	FFAG with normal conducting arcs	FFAG with SC arcs
L_{Straight} (m)	185	240	192
Circumference [m]	480	706	527
Dynamical acceptance A_{dyn}	0.6	0.95	0.95
Momentum acceptance	±10%	±16%	±16%
μ/POT within momentum acceptance	0.094	0.171	0.171
Fraction of μ decaying in the straight (F_S)	0.52	0.57	0.54
Ratio of L_{Straight} to the ring Circ. (R)	0.39	0.34	0.36
Relative factor ($A_{\text{dyn}} \times$ μ/POT $\times F_S \times$ R)	0.011	0.031	0.033

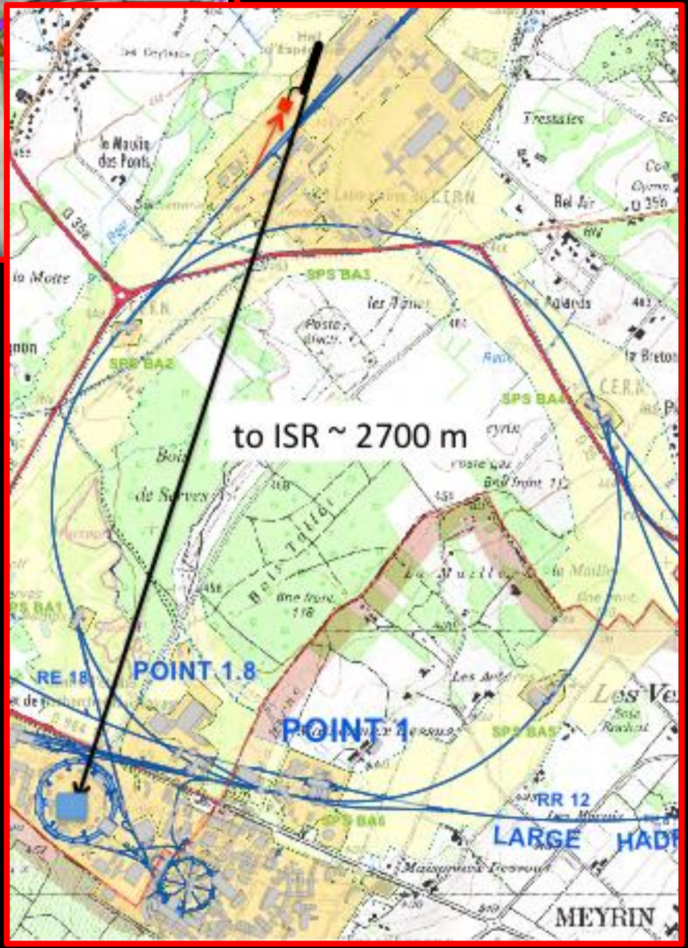


Implementation, at FNAL:

- 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:



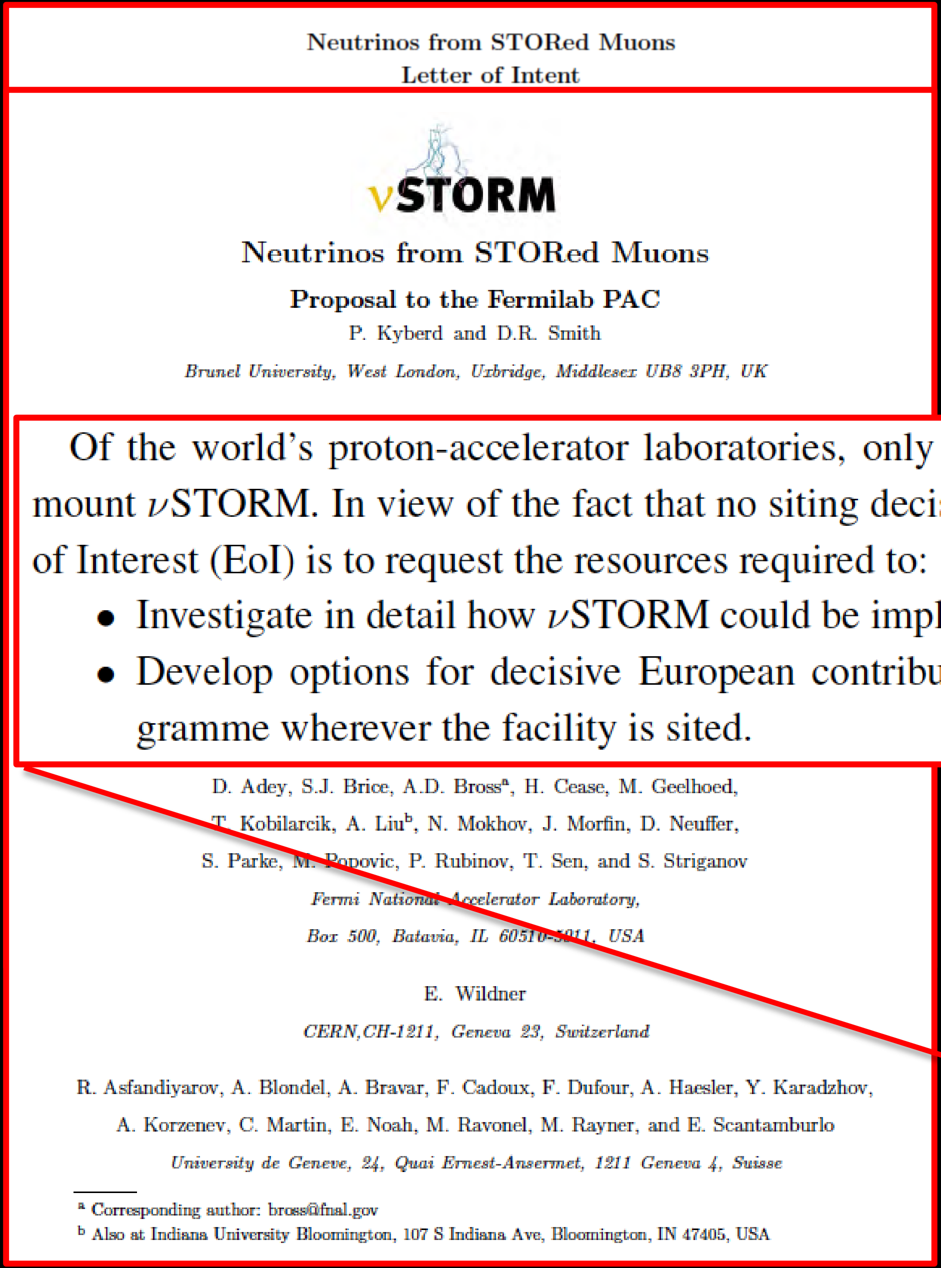

to ISR ~ 2700 m

- **Principal issue:**
  - SPS spill is 10 μs:
    - Implies bend for proton or pion beam
      - Or development of fast extraction
- **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 (possibly an advantage too)

EoI for nuSTORM

Expression of Interest

Twin-track approach:



Neutrinos from STORed Muons
Letter of Intent

νSTORM

Neutrinos from STORed Muons

Proposal to the Fermilab PAC

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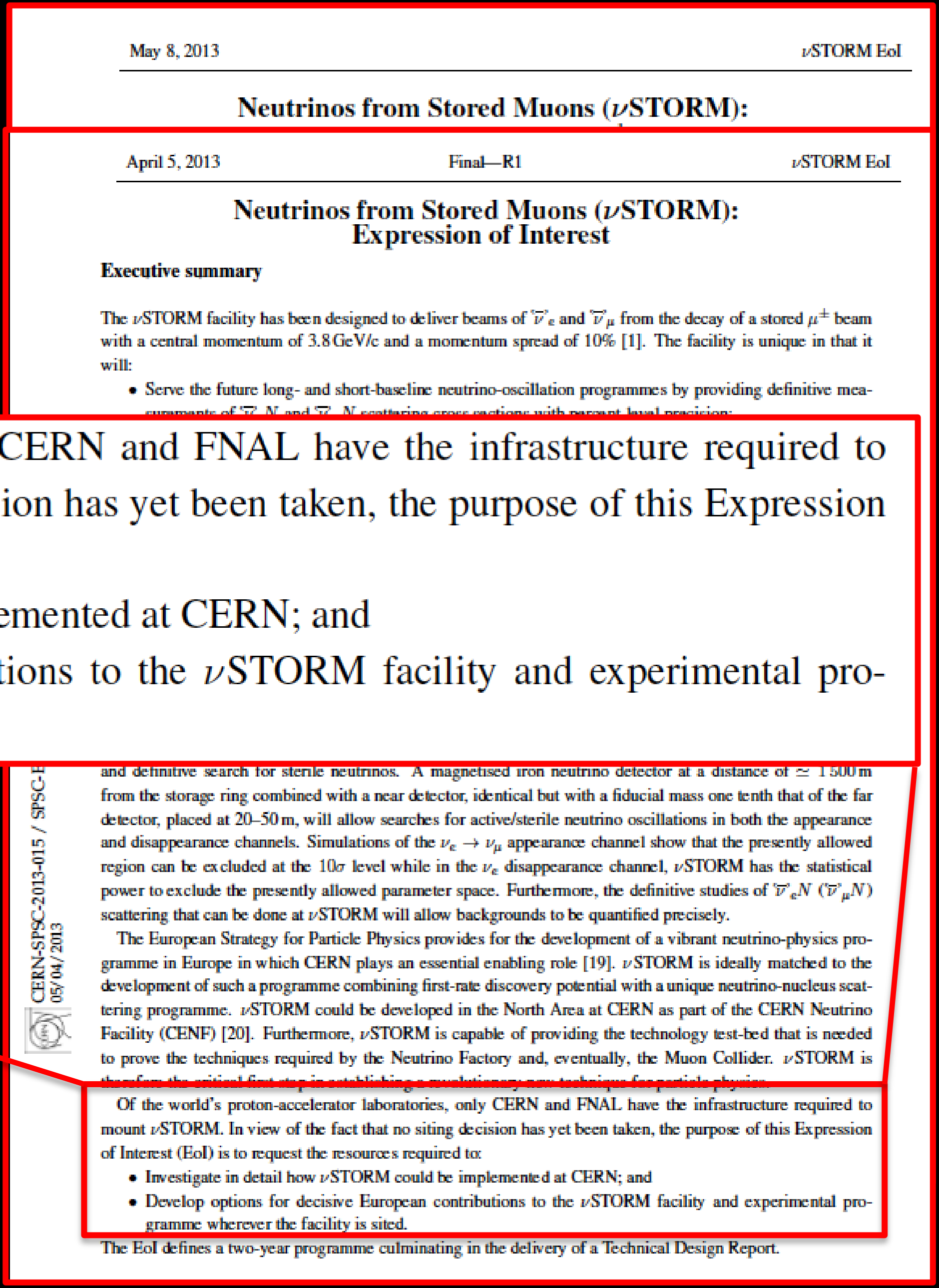
Of the world's proton-accelerator laboratories, only CERN and FNAL have the infrastructure required to mount νSTORM. In view of the fact that no siting decision has yet been taken, the purpose of this Expression of Interest (EoI) is to request the resources required to:

- 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.



Neutrinos from Stored Muons (νSTORM):

Neutrinos from Stored Muons (νSTORM): Expression of Interest

Executive summary

The νSTORM facility has been designed to deliver beams of $\overset{(-)}{\nu}_e$ and $\overset{(-)}{\nu}_\mu$ 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 measurements of $\overset{(-)}{\nu}_e N$ and $\overset{(-)}{\nu}_\mu N$ scattering cross sections with percent-level precision;

and definitive search for sterile neutrinos. A magnetised iron neutrino detector at a distance of $\simeq$ 1 500 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 $\nu_e \to \nu_\mu$ 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 $\overset{(-)}{\nu}_e N$ ($\overset{(-)}{\nu}_\mu N$) scattering that can be done at νSTORM will allow backgrounds to be quantified precisely.

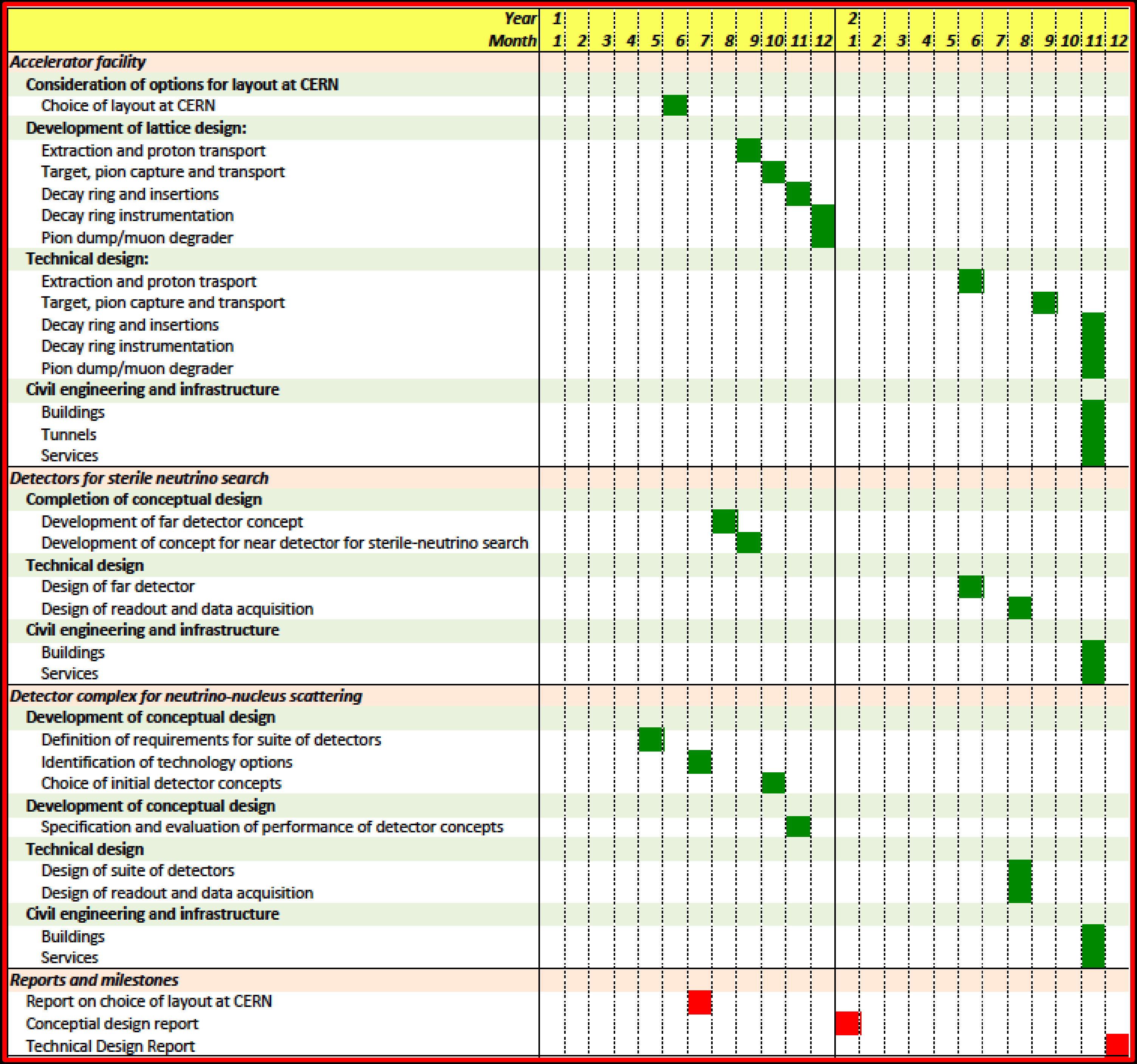
The European Strategy for Particle Physics provides for the development of a vibrant neutrino-physics programme in Europe in which CERN plays an essential enabling role [19]. νSTORM is ideally matched to the development of such a programme combining first-rate discovery potential with a unique neutrino-nucleus 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.

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



Year	1												2											
Month	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12
Accelerator facility																								
Consideration of options for layout at CERN																								
Choice of layout at CERN						🟩																		
Development of lattice design:																								
Extraction and proton transport									🟩															
Target, pion capture and transport										🟩														
Decay ring and insertions											🟩													
Decay ring instrumentation												🟩												
Pion dump/muon degrader												🟩												
Technical design:																								
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Decay ring instrumentation																							🟩	
Pion dump/muon degrader																							🟩	
Civil engineering and infrastructure																								
Buildings																							🟩	
Tunnels																							🟩	
Services																							🟩	
Detectors for sterile neutrino search																								
Completion of conceptual design																								
Development of far detector concept								🟩																
Development of concept for near detector for sterile-neutrino search									🟩															
Technical design																								
Design of far detector																		🟩						
Design of readout and data acquisition																				🟩				
Civil engineering and infrastructure																								
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Detector complex for neutrino-nucleus scattering																								
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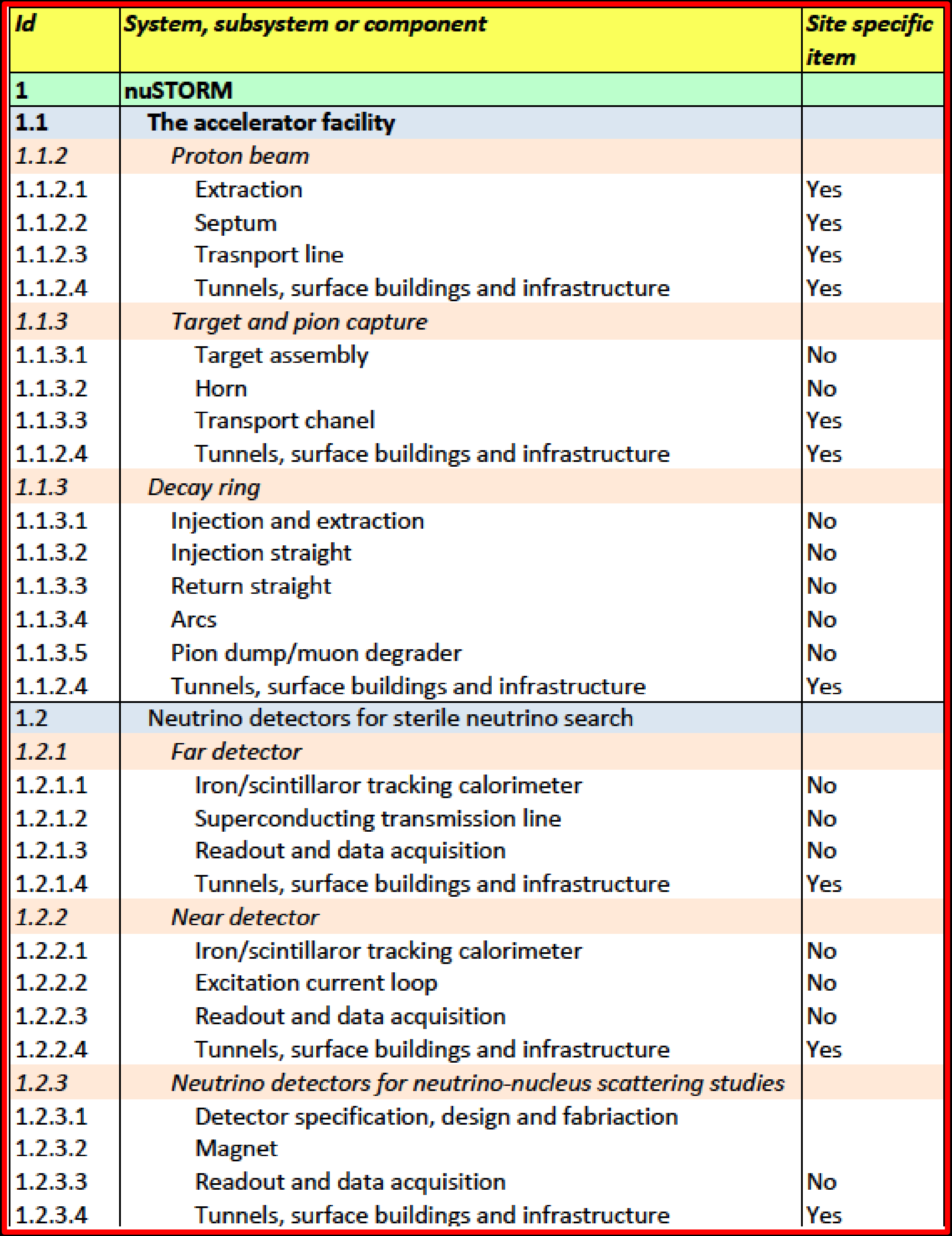
Definition of requirements for suite of detectors					🟩																			
Identification of technology options							🟩																	
Choice of initial detector concepts										🟩														
Development of conceptual design																								
Specification and evaluation of performance of detector concepts											🟩													
Technical design																								
Design of suite of detectors																				🟩				
Design of readout and data acquisition																				🟩				
Civil engineering and infrastructure																								
Buildings																							🟩	
Services																							🟩	
Reports and milestones																								
Report on choice of layout at CERN							🟥																	
Conceptial design report													🟥											
Technical Design Report																								🟥



Id	***System, subsystem or component***	***Site specific item***
1	**nuSTORM**	
1.1	**The accelerator facility**	
1.1.2	*Proton beam*	
1.1.2.1	Extraction	Yes
1.1.2.2	Septum	Yes
1.1.2.3	Trasnport line	Yes
1.1.2.4	Tunnels, surface buildings and infrastructure	Yes
1.1.3	*Target and pion capture*	
1.1.3.1	Target assembly	No
1.1.3.2	Horn	No
1.1.3.3	Transport chanel	Yes
1.1.2.4	Tunnels, surface buildings and infrastructure	Yes
1.1.3	*Decay ring*	
1.1.3.1	Injection and extraction	No
1.1.3.2	Injection straight	No
1.1.3.3	Return straight	No
1.1.3.4	Arcs	No
1.1.3.5	Pion dump/muon degrader	No
1.1.2.4	Tunnels, surface buildings and infrastructure	Yes
1.2	Neutrino detectors for sterile neutrino search	
1.2.1	*Far detector*	
1.2.1.1	Iron/scintillaror tracking calorimeter	No
1.2.1.2	Superconducting transmission line	No
1.2.1.3	Readout and data acquisition	No
1.2.1.4	Tunnels, surface buildings and infrastructure	Yes
1.2.2	*Near detector*	
1.2.2.1	Iron/scintillaror tracking calorimeter	No
1.2.2.2	Excitation current loop	No
1.2.2.3	Readout and data acquisition	No
1.2.2.4	Tunnels, surface buildings and infrastructure	Yes
1.2.3	*Neutrino detectors for neutrino-nucleus scattering studies*	
1.2.3.1	Detector specification, design and fabriaction	
1.2.3.2	Magnet	
1.2.3.3	Readout and data acquisition	No
1.2.3.4	Tunnels, surface buildings and infrastructure	Yes

Request:

- Seek to establish 2-year programme to deliver a Technical Design Report

- Programme encompasses contributions to:
  - Proton beam: SPS extraction, beam lines up to target
  - Pion-production target
  - Pion transport
  - Engineering study of pion-capture magnets
  - Contributions to the design of the muon storage ring
  - Contributions to design of storage ring diagnostics
  - Evaluation of a possible muon cooling experiment
  - Contributions to the design of the neutrino-scattering programme

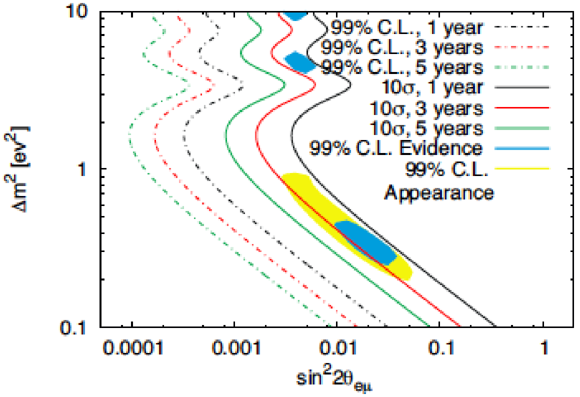
- SPSC endorsement critical for:
  - The development of the European nuSTORM collaboration
  - Securing the resources at CERN and across the European collaboration to deliver the TDR

Conclusions

nuSTORM Expression of Interest
response to questions from reviewers

Physics

1. **The sensitivity of nuSTORM to sterile neutrino search is given for 5 years, Could you provide it for 1 and 3 years runs as well, for both appearance and disappearance channels?**
   Contours showing both the 10σ exclusion limit and the 99% confidence-level limit obtained from exposures of 1, 3 and 5 years are presented in figure 1. The limits were calculated for the set-up described in the Expression of Interest (EoI), i.e. a neutrino flux corresponding to 3.6×10^{17} useful muon decays per year illuminating a 1.6 kTonne SuperBIND at a distance of 2 km from the nuSTORM decay ring. A systematic uncertainty of 1% has been assumed. For the appearance search, the statistical uncertainty is greater than the systematic uncertainty for exposures of less than 5 years. The region of the $\Delta m_{14} - \theta_{e\mu}$ parameter space allowed at the 99% confidence level by a fit to the data inconsistent with the three-neutrino-mixing paradigm [1] is also shown in figure 1 together with the region allowed by combining the results of the LSND and MiniBOONE $\bar{\nu}_e$-appearance data [1]. With an exposure of 1 year, the presently allowed regions lie comfortably within the 99% confidence-level contour. An exposure of a little over 3 years is required for the 10σ exclusion limit to cover the presently allowed regions.
   A muon-neutrino disappearance analysis has been performed [2] since the EoI was completed. The 99% confidence-level exclusion limits for exposures of 1, 3, and 5 years are shown in figure 2. An exposure of 1 year is sufficient to extend significantly the region of parameter space excluded by existing data. An electron-neutrino disappearance experiment is particularly challenging with SuperBIND and, while a feasibility study is in progress, exclusion limits are not yet available.
2. **Since both neutrino flux and spectra are expected to be known precisely thanks to the nuSTORM concept, what would be the sensitivity of the experiment for sterile neutrino search without using a near detector?**
   The storage-ring instrumentation has been specified such that the beam momentum distribution will be precisely known and the neutrino flux will be determined with a precision of 1%. The precise knowledge of the muon-beam properties, combined with the detailed understanding of the kinematics of muon decay, is sufficient for the sterile-neutrino search in the "golden" appearance channel, $\nu_e \rightarrow \nu_\mu$, to deliver the quoted sensitivities [2–4]. The near detector would allow the neutrino-nucleus scattering cross sections to be measured precisely in SuperBIND. In the absence of the near detector, existing measurements of the neutrino-scattering cross sections would have to be used. The systematic uncertainties (5% in the signal and 50% in the background) assumed in the analysis presented in the EoI are sufficient to deliver the quoted performance. As the appearance analysis is limited by the size of the data sample ("statistics limited") a near detector is important but not essential.
   The near detector is essential for the $\bar{\nu}_\mu$ disappearance measurement. A near-far comparison is under development but has not yet been used to derive limits. In the absence of a near-far analysis, use of the systematic uncertainties quoted above (5% in the signal and 50% in the background) yields a sensitivity contour that does not improve upon the limits obtained in fits to existing data. See also the comments made in answer to question 4.



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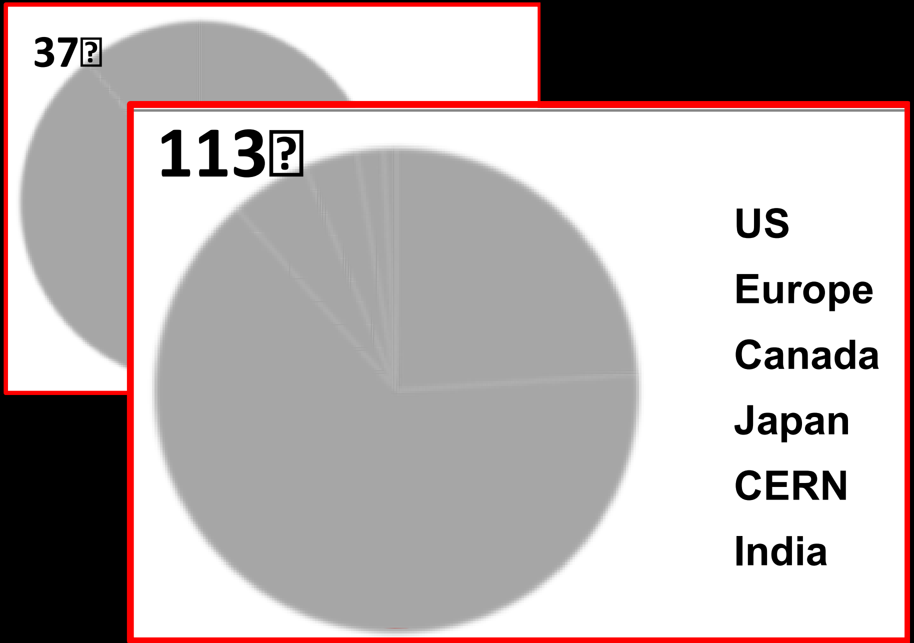
3. **What is limiting the sensitivity of nuSTORM to the ν_e and ν_μ disappearance oscillation channels?**
   The disappearance experiment is potentially more sensitive to the oscillation amplitudes than is the appearance analysis. However, the disappearance channel is more sensitive to the signal normalisation than the appearance experiment. The neutrino flux is extremely well understood for nuSTORM, but a further understanding of the measured spectrum that results from the convolution of efficiencies and cross sections is required.
   To control effects related to cross section and efficiency, a near detector identical in construction to the far detector is required. This is the motivation for the 200 Tonne version of SuperBIND at the near-detector site. A simulation of such a near detector is in progress, so only an approximate estimation of the anticipated systematic uncertainties has been made to date. The sensitivity of the experiment has been computed using GLoBES. Exclusion contours are plotted as a function of the effective mixing angle $\sin^2 2\theta_{\mu\mu} = 4U_{\mu4}^2(1 - U_{\mu4}^2)$ in figure 3.
   We believe that a percent-level systematic uncertainty (efficiency times cross section) is achievable in SuperBIND.
4. **One of the physics cases of nuSTORM is the sterile neutrino search. How the sensitivity of nuSTORM compare with the one claimed by the ICARUS-NESSiE project?**
   The sensitivity of the ICARUS/NESSiE experiment has been presented in the joint proposal [5] and in a recent study of ν_μ disappearance [6]. Exclusion limits are derived from electron-neutrino charged-current samples obtained in the ICARUS liquid-argon TPC and from muon-neutrino charged-current samples

Conclusion:

- 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:
    - FNAL:
      - LoI and (recently) proposal for Stage I approval submitted
    - CERN:
      - EOI to SPSC



- An exciting opportunity!

EoI for nuSTORM

Response to questions

June 24, 2013 Final–revision 1 νSTORM

nuSTORM Expression of Interest
response to questions from reviewers

Physics

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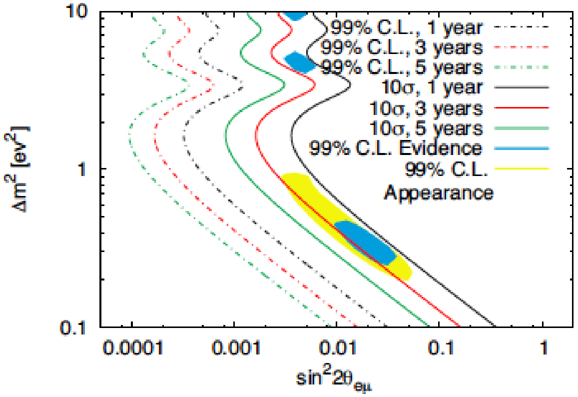

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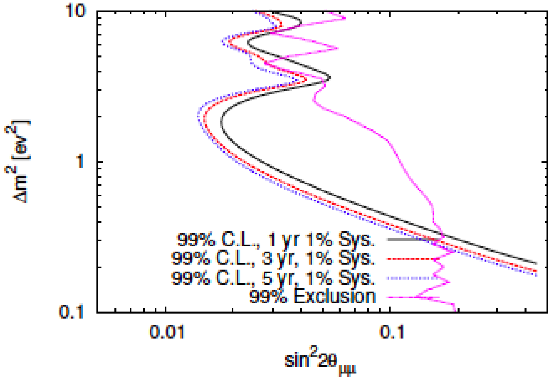


Figure 2: 99% exclusion limits derived from a search for $\bar{\nu}_\mu$ disappearance at nuSTORM assuming 3.6×10^{17} useful μ^+ decays per year collected over 1, 3, and 5 years (solid black, dashed red and dashed blue lines respectively). The 99% exclusion limit obtained from existing data is shown by the dotted red line in a fit assuming one sterile neutrino [1].

obtained using the NESSiE spectrometers. ICARUS/NESSiE is unable to exploit the nuSTORM golden channel $\nu_e \rightarrow \nu_\mu$. The golden channel is a unique opportunity for nuSTORM.

The nuSTORM sensitivity derived from the appearance channel (see figure 107 of the nuSTORM proposal to the FNAL PAC [2]) encompasses the region allowed by the combination of the appearance data from LSND and MiniBOONE, reactor experiments and the gallium experiments at a confidence level of 10σ. For comparison, the sensitivity presented by the ICARUS/NESSiE collaborations (see figure 6 of [5]) encompasses the same region at a confidence level of 95%. For the appearance channel, therefore, the performance of nuSTORM is superior to that of NESSiE.

The nuSTORM $\bar{\nu}_\mu$ disappearance sensitivity is competitive with the original result presented by NESSiE which was obtained with neutrino events interacting in the ICARUS liquid-argon TPC (see figure 7 in [5]). However, the nuSTORM disappearance sensitivity is not as good as the latest expectations from a NESSiE–like detector in which neutrino events arising in the NESSiE spectrometers are considered. This is shown in figure 4. Figure 4a shows figure 8 from [6]) while figure 4b shows the 95% confidence level contour from the nuSTORM disappearance experiment for comparison. Work will continue on understanding and mitigating the systematic uncertainties in order to exploit the statistical power of nuSTORM. Table 1 reproduces table 23 from [2] and shows that, if systematic uncertainties can be reduced to an appropriate level, the nuSTORM sensitivity to the disappearance signal can be substantially improved.

5. **For the CPV measurement the LBNO consortium plans to control the neutrino flux with a near detector. The systematic precision requirements for LBNO are below the 5% level and possibly at ±2% (LBNO EoI). For their sensitivity estimations the LBNO consortium assumes the following systematic uncertainties: 5% signal normalisation, 5% beam electron contamination normalisation, 20% tau normalisation. However in page 5 of the nuSTORM EOI it is mentioned that the**

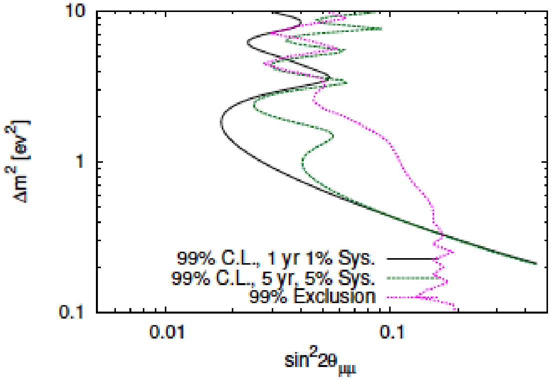
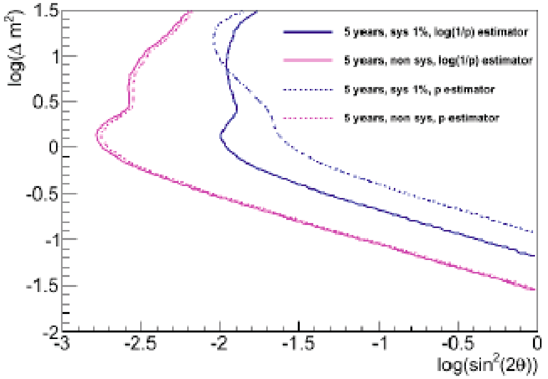


Figure 3: The sensitivity of a disappearance experiment at nuSTORM to the presence of a light sterile neutrino. The contour were generated using GLoBES, assuming a 1.6 kTonne far detector, sited 2 km from the muon storage ring, exposed to neutrinos resulting from an exposure of 3.6×10^{17} useful muon decays per year. The solid black contour shows the 99% confidence level exclusion limit obtained in an exposure of 1 year assuming a 1% signal and 10% background systematic uncertainty. The dashed green line shows the 99% exclusion contour for a five-year exposure and systematic uncertainties of 5% in the signal and a 50% in the background. The existing experimental bound at 99% confidence level is shown by the purple dotted contour. A recent, detailed analysis may be found in [1].

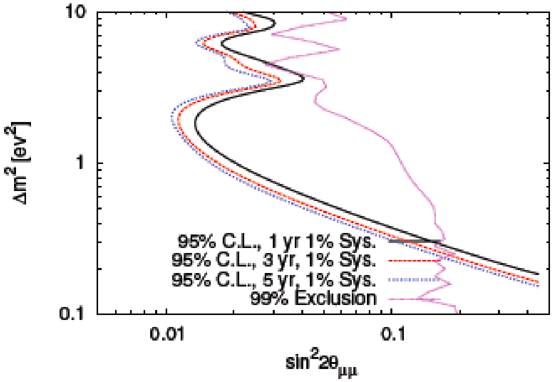
precision of the neutrino-nucleon cross-sections are not better than 20%-30%. Although LBNO is planning to use a near detector, are these two set of information consistent? Or do you consider that the LBNO assumptions are two optimistic as suggested in page 10 of the nuSTORM EOI. We would appreciate a quantitative answer.

The use of a near detector will certainly help to decrease the present uncertainties on neutrino interaction cross sections which are currently around 20%–30%. However, it is important to note that it is not just the error on the cross sections that must be considered. The neutrino energy spectra entering the near and far detectors are different due both to geometry and oscillations and therefore the convolution of flux times cross section times nuclear effects will be different in the near and far detectors. The challenge is to estimate how big the difference is and the uncertainty on this estimate.

MiniBooNE data for charged current (CC) quasi-elastic (QE) interactions suggest that spectral functions need to be implemented as a substitute for the Fermi gas model when calculating neutrino interactions with nuclei. Furthermore, two-particle interactions within the nucleus need to be implemented since these interactions give large corrections to the cross section. Finally, a wide variety of different models of final-state interactions are employed to generate the "observable" final-state particles. Currently no quantitative treatment of these effects is available across the full spectrum of channels open to a wide-band beam. However, the authors of reference [7] have provided first-estimates of these effects for the QE channel, as explained below. Considering the range of models that exist for each step of the interaction process, it may be possible to reduce the uncertainties to the 5% level but this has not been demonstrated;



(a) 95% confidence intervals for the observation of ν_μ and $\bar{\nu}_\mu$ disappearance in NESSiE.



(b) 95% confidence levels for the observation of $\bar{\nu}_\mu$ disappearance at nuSTORM.

Figure 4: Comparison of 95% confidence level contours from NESSIE and nuSTORM. (a) The NESSIE limits assume a two detector experiment with masses of 770 tons and 330 tons with a 90% inner fiducial with a total of 22.5×10^{19} p.o.t. The difference in the p and $(1/p)$ limits are the choice in the energy parameterisation used for the analysis. Figure taken from figure 8 of [6]. (b) The nuSTORM disappearance sensitivity plotted at 95% confidence level.

Table 1: Event rates in the nuSTORM far detector for the nominal exposure of 10^{21} protons on target. The column headed $N_{\text{osc.}}$ gives the number of events expected for the sample point in the LSND anomaly region defined in [2]. The column N_{null} gives the expected event rate of the null hypothesis (i.e. the standard three-neutrino-mixing model). The column headed "Diff" reports the value of $(N_{\text{osc.}} - N_{\text{null}})/N_{\text{null}}$, while the final column gives the statistical significance of the raw oscillation signal.

Neutrino mode with stored μ^+.

Channel	$N_{\text{osc.}}$	N_{null}	Diff.	$(N_{\text{osc.}} - N_{\text{null}})/\sqrt{N_{\text{null}}}$
$\nu_e \to \nu_\mu$ CC	332	0	∞	∞
$\bar{\nu}_\mu \to \bar{\nu}_\mu$ NC	47679	50073	-4.8%	-10.7
$\nu_e \to \nu_e$ NC	73941	78805	-6.2%	-17.3
$\bar{\nu}_\mu \to \bar{\nu}_\mu$ CC	122322	128433	-4.8%	-17.1
$\nu_e \to \nu_e$ CC	216657	230766	-6.1%	-29.4

Anti-neutrino mode with stored μ^-.

Channel	$N_{\text{osc.}}$	N_{null}	Diff.	$(N_{\text{osc.}} - N_{\text{null}})/\sqrt{N_{\text{null}}}$
$\bar{\nu}_e \to \bar{\nu}_\mu$ CC	117	0	∞	∞
$\bar{\nu}_e \to \bar{\nu}_e$ NC	30511	32481	-6.1%	-10.9
$\nu_\mu \to \nu_\mu$ NC	66037	69420	-4.9%	-12.8
$\bar{\nu}_e \to \bar{\nu}_e$ CC	77600	82589	-6.0%	-17.4
$\nu_\mu \to \nu_\mu$ CC	197284	207274	-4.8%	-21.9

without a dedicated measurement programme it will be very hard to the 2% level. The difficulty of doing the analysis for a wide band beam is considerable, since many different reaction channels take place and, in addition, the details of the analysis depend on the particular type of detector used.

In the following, we give a quantitative example to illustrate what the impact of final state interactions may be on the extraction of oscillation parameters using QE events only. For a CC-QE event, the neutrino energy is usually reconstructed using the kinematic variables of the charged lepton. This method always gives a successful reconstruction for QE events up to experimental limitations. However, for non-QE events there is a certain probability that final-state particles are absorbed by the nucleus through the final-state interactions and are therefore not detected. If the only observable particle in the final state is the charged lepton, these events will unavoidably be added to the QE-like event sample. This will lead to a reconstructed energy smaller than the true energy of the incident neutrino. The number of non-QE events produced with no pions in the final state depends on the nuclear model of final state interactions assumed.

In order to evaluate to what degree these effects can be ignored in the nuclear model without affecting the results, we have done the following. The true distribution of events was computed including migration from non-QE events to the QE-like sample:

$$N_i^{QE-like} = \sum_j M_{ij}^{QE} N_j^{QE} + \sum_{non-QE} \sum_j M_{ij}^{non-QE} N_j^{non-QE} \, .$$

Here, M_{ij} are the migration matrices that account for the impact of final state interactions. M^{QE} will mostly be diagonal, while M^{non-QE} will generally be non-diagonal and will depend on the particular non-QE process. Migration matrices have been computed using GiBUU [8], following reference [9].

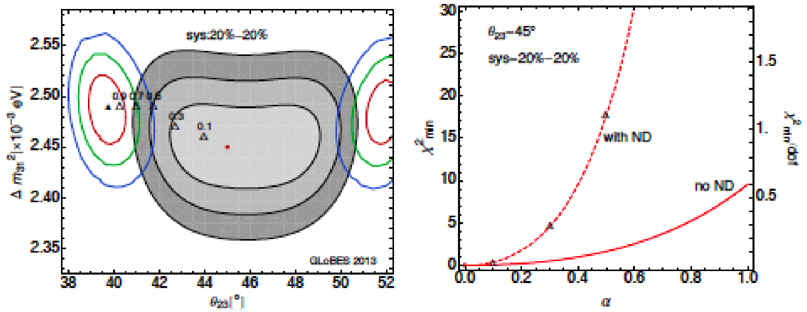


Figure 5: Left: Confidence region in the $\Delta m^2 - \theta$ plane for 2 d.o.f. for different scenarios, a near detector (ND) is assumed in each case. The grey shaded areas show the results assuming that the nuclear effects are perfectly understood. The coloured lines show the 1, 2 and 3σ regions for a fit taking $\alpha = 1$, see text for details on the definition of α. The empty triangles indicate the location of the best fit for different values of α between 0 (red dot, true input value) and 1 (filled black triangle). Right: Minimum χ^2 as a function of α. The solid lines show the results without a ND while the dashed lines show the results including a ND.

The distribution was then fitted using the following ansatz:

$$N_i^{\rm test}(\alpha) = \alpha \times N_i^{QE} + (1-\alpha) \times N_i^{QE-like}; \qquad (1)$$

where α parameterises, in a phenomenological way, the amount of migration that is neglected in the nuclear model: $\alpha = 0$ corresponds to a fit using the full QE-like sample, while $\alpha = 1$ corresponds to a fit using the true-QE events only.

A fit is performed for the atmospheric parameters, using a simulation of ν_μ disappearance for a low-energy neutrino-oscillation experiment that observes QE-like events, such as the T2K experiment [10]. We consider 5 years of data taking at nominal exposure, which yields a total number of ~ 850 truly-QE events and ~ 1300 QE-like events. The fit is performed using a modified version of GLoBES [11]. 20% shape and normalisation uncertainties are considered and an ideal near detector is included in the analysis. The left panel in figure 5 shows the impact that an underestimation of the migration due to nuclear effects would have on the fit. The location of the best fit is shown for different values of α (empty triangles). As can be seen from the figure, the deviation of the best fit from the true input value progressively increases with α. The impact of adding a near detector is shown in the right panel of figure 5, where the minimum value of the χ^2 is shown as a function of α. If only the far detector is used in the analysis, the χ^2 would remain low enough that the fit would, most likely, be accepted, even for $\alpha = 1$. Once a near detector is added, the minimum value of the χ^2 increases very rapidly with the amount of migration neglected in the fit and for large values of α the fit would, most likely, be rejected. From this plot it is evident that a near detector would certainly help, but it would not cure the problem. For relatively large values of $\alpha \sim 0.3 - 0.4$ the minimum value of χ^2 would still be low enough that the fit may be accepted even if a near detector is included in the fit, and a significant bias in the determination of the oscillation parameters would result. Therefore, we find that the only way to cure the problem completely is through the correct determination of the nuclear model lying behind the final state interactions.

We would like to stress out that the results are obtained for ν_μ disappearance under the assumption of an ideal near detector. The search for CP violation is a much more delicate topic and we expect it to be affected significantly by systematic uncertainties due to the large value of θ_{13}. Furthermore, if the spectra observed at the near and far detectors are different, we expect nuclear effects to be much more difficult to constrain. Therefore, a dedicated study, based on detailed measurements, is needed to determine the impact of these effects on a given experiment.

Setup

6. **The CERN fast extraction scheme has been tested at low intensity. What is the risk of extrapolating this test for the higher intensities required for nuSTORM?**
   The present estimate is based on operational experience in general, simulations and tests with beams having an emittance comparable to those of high intensity beams. The evaluation presented in the νSTORM EoI was based on the work done for the NESSiE proposal which assumed data taking before the injector upgrade. The estimate presented in the EoI should therefore be conservative compared to an estimate based on the extraction of a beam provided by the new Linac4 and the new booster injection scheme which will yield a smaller emittance. Tests show that steering beams at higher energy from the SPS into TT20 would be possible up to an energy of 440 GeV using non-local fast extraction, see [12].
   Studies are needed for the νSTORM beam (beam stability, machine protection and working points for high intensity).
7. **Some of the magnets needed for the decay ring have challenging specifications. Can the collaboration give more details about to which extent they are within current state-of-art and which kind of studies/R&D are being pursued by the collaboration to design and built them?**
   The specifications for each of the magnets in the baseline, quad-focusing decay ring are well within the current state-of-the-art. No fundamental R&D to develop, for example, new types of conductor, new fabrication techniques, etc. is required. A preliminary costing of the magnets (both conventional and superconducting) has been been done (see the costing document prepared for the FNAL PAC [13]).
   In the case of the alternative FFAG decay ring, the magnets in the production straight are normal conducting and a prototype magnet has been designed, constructed and successfully tested at KURRI [14]. Two lattices have been develop, the first can be implemented using normal-conducting magnets. The second delivers a more compact arc at the expense of requiring superconducting magnets in the arcs. Should the compact, FFAG ring be adopted, it would be necessary to build and test a prototype magnet since no superconducting, scaling FFAG magnets have yet been demonstrated.
8. **What is the length of the straight portion of the muon decay ring? On figure 4 it is quoted to be 150 meters, whereas it is mentioned to be 170 m on figure 9?**
   The length of the straight section is 184 m. The lattice, taking into account the magnet space envelopes etc. has evolved since the EoI was written. The dimension reported in figure 9 of the EoI includes the arcs. We consider that the decay ring developments made at FNAL can be re-used at CERN. The implementation of the nuSTORM ring at CERN has to be adapted to the final machine design; the footprint at CERN is one of the first tasks to be undertaken.
9. **In table 1 page 18 what are the uncertainties on the estimated collection efficiency, transport efficiency, and injection efficiency?**
   A complete G4Beamline [15] simulation of pion capture, transport, injection into the decay ring and propagation down the injection straight of the decay ring (first pass) has now been performed. A muon yield of 8×10^{-3} muons within the decay ring acceptance (3.8 GeV/c ± 10%) per 120 GeV proton on target (POT) was obtained. A study of proton-beam, target and magnet mis-alignment has not yet been

done. With typical magnet-alignment procedures, we estimate an overall uncertainty to the figure of merit of muons/POT of $\sim 5\%$.

While the necessary calculations have yet to be performed in detail, particle tracking calculations using FLUKA or MARS give a statistical contribution to the uncertainty that should be very small. FLUKA—especially for carbon targets—is bench-marked with NA61/SPY [16–22] data in the region of interest.

Experience suggests that the horn current will stable at the 1% level and should not contribute significant uncertainties in the yield. Taking the displacement accuracy of the CNGS secondary-beam elements (0.1 mm lateral and 0.1 mrad angular uncertainties) as a guide and taking into account that the transport solenoid will be placed close to (or next to) the horn, no significant change in the number of pions transported is to be expected. The injection will be designed to have very limited loss; this is the aim of the stochastic-injection scheme. To demonstrate this will require some experimentation.

10. **Concerning the detector to be used for sterile neutrino searches, what are the challenges operating an instrument at a very short baseline of approx. 50 meters?**

    The rates in the near detector for the oscillation searches (200 Tonne SuperBIND) are less than 1 event per spill and present no issues. Rates in a near detector designed for studies of neutrino-nucleus scattering should be even smaller. Backgrounds generated by particles produced in the pion absorber can be rejected using timing cuts.

11. **One of the main motivations of nuSTORM is to test/develop technology for the future muon colliders. Can you provide a list of the main technological challenges/risks anticipated and, if existing, the corresponding mitigation plans considered.**

    A muon collider requires a range of technologies that push the state of the art, including high-field magnet technology (solenoids for the cooling channel, muon acceleration systems and the storage ring) and development of RF cavities that can operate in strong magnetic fields. Active development and experimentation in these areas is underway, supported, in particular, by the Muon Accelerator Program (MAP) in the US as well as by groups with affiliated interests (for example, high-field solenoid technology is also desired for high-field user magnets). The highest priority technological challenges for a muon collider facility are:

    - The successful implementation of a multi-MW Proton Driver: development of this core capability is currently being pursued by multiple laboratories [23];
    - Development of a high power target station capable of handling $\geq$ 4 MW of proton-beam power along with a solenoid capture system capable of collecting both species of muon is a significant challenge:
        - The MERIT experiment [24] has demonstrated the feasibility of a liquid mercury-jet target to handle the necessary beam power, however, the engineering challenges of such a target station remain significant;
        - The capture solenoid design requires the development of a 15–20 T magnet surrounding the target module the design of which is compatible with the intense radiation environment in the region of the target;
        - To mitigation the risks in the developments required to meet these challenges, staging plans which focus on initial operation with a proton driver of lower power (1 MW class) and target station (consistent with a low luminosity Neutrino Factory entry point for a facility) and will draw on the broader community interest in higher power target stations (e.g. spallation sources) to achieve the ultimate multi-MW capability which is required. The significant overlap of the parameters of the capture solenoid with those of magnets currently under development for other projects significantly increases the likelihood that reliable engineering solutions can be devised.

    - Reduction of the phase-space volume occupied by the muon beam (cooling) is required in order to achieve the beam parameters for a high performance Neutrino Factory and for all Muon Collider designs under consideration. This requires development of:
        - Technology enabling RF cavities to work in magnetic fields;
        - High-field solenoid magnets (up to $\sim$ 30 T for the final stages of the cooling channel);
        - A clear understanding of the physics processes when muons interact with absorbers including collective effects that may impact high intensity muon beams with momenta on the order of 200 MeV/c;
        - The risk-mitigation strategy is being carried out as part of the MAP Feasibility Assessment. In particular, MAP-supported efforts presently hold the world record for the on-axis field in a high-temperature superconductor solenoid [25] and recent results in the operation of RF cavities in high magnetic fields show promise for moving forward [26, 27]. Experiments based at the nuSTORM facility would provide both a platform for beam tests of 6D-cooling-channel components and the possibility of studying intensity-dependent effects with beam intensities up to 10^{10} muons/pulse in a 100–300 MeV/c momentum slice. In the staging plan currently being considered by the Muon Accelerator Staging Study (MASS) of the US MAP, further tests at higher beam intensities would take place as part of a staged neutrino factory program.
    - Muon Collider detector backgrounds represent one of the most important issues for the experimental high energy physics community. Current studies indicate that the backgrounds from muon decays in the collider ring can successfully be mitigated by means of pixelated and time-resolved detector technologies [28, 29]. Once again, assessment of these issues are being included in the MAP Feasibility Assessment which will conclude near the end of this decade.

    While other R&D issues are also relevant, the above items represent the most prominent ones. nuSTORM has great potential to address a number of the technology challenges associated with the physics and technology relevant to the design of the 6D ionisation-cooling channel. It will also allow the validation of a number of other, less challenging, elements of the muon-collider program. These include the development of suitable ring diagnostics for storage rings with decaying beams, demonstration of the precision energy-calibration techniques proposed for a Higgs Factory and familiarity with the operation of a high intensity muon storage ring.

12. **Comment about synergies on the detector side, between nuSTORM and LBNO/LBNE.**

    To distinguish the "golden" appearance channel, $\nu_e \rightarrow \nu_\mu$, from charged-current interactions arising from the un-oscillated $\bar{\nu}_\mu$ in the beam, requires that the sterile-neutrino detector at nuSTORM be magnetised. The choice of SuperBIND has been made because a strong magnetic field may readily be excited in the iron. The technologies under consideration for the far detectors at LBNO and LBNE are liquid-argon and liquid scintillator. While these detector technologies offer the possibility of an improved energy threshold and improved energy resolution, it would be necessary to demonstrate the excitation of an appropriate magnetic field throughout the detector volume to make their use attractive at nuSTORM.

    In contrast, the synergy between the near detectors at nuSTORM and at LBNO or LBNE is large. In each case, neutrino beams with energies in the GeV range must be detected. Indeed, in preparing the case studies of the precision with which the neutrino-nucleus scattering cross sections can be measured at nuSTORM, the near detectors proposed for LBNO and LBNE were taken as reference designs [2].

13. **When estimating the available POT/year did you consider any beam sharing with other projects? Could you present the possible scenarios? What are the paths to gain a factor 2 in POT with respect to the current estimate?**

    In the document EDMS 1259817 v.2 [30] several scenarios for sharing beam between the LHC and the CERN Neutrino Facility (CENF) are presented. Consideration was given to electricity consumption and done. With typical magnet-alignment procedures, we estimate an overall uncertainty to the figure of merit of muons/POT of $\sim 5\%$.

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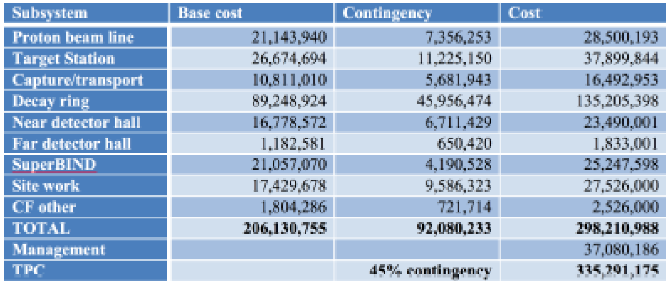
Table 2: Summary of the cost (in 2013 US Dollars) of implementing the nuSTORM facility at FNAL. The cost model is consistent with DOE guidelines and includes the cost of manpower and a contingency of 45%. Full details of the costing are presented in [13].



Subsystem	Base cost	Contingency	Cost
Proton beam line	21,143,940	7,356,253	28,500,193
Target Station	26,674,694	11,225,150	37,899,844
Capture/transport	10,811,010	5,681,943	16,492,953
Decay ring	89,248,924	45,956,474	135,205,398
Near detector hall	16,778,572	6,711,429	23,490,001
Far detector hall	1,182,581	650,420	1,833,001
SuperBIND	21,057,070	4,190,528	25,247,598
Site work	17,429,678	9,586,323	27,526,000
CF other	1,804,286	721,714	2,526,000
TOTAL	**206,130,755**	**92,080,233**	**298,210,988**
Management			37,080,186
TPC		**45% contingency**	**335,291,175**

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