νSTORM

Neutrinos from stored muons: the nuSTORM facility

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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

Contents:

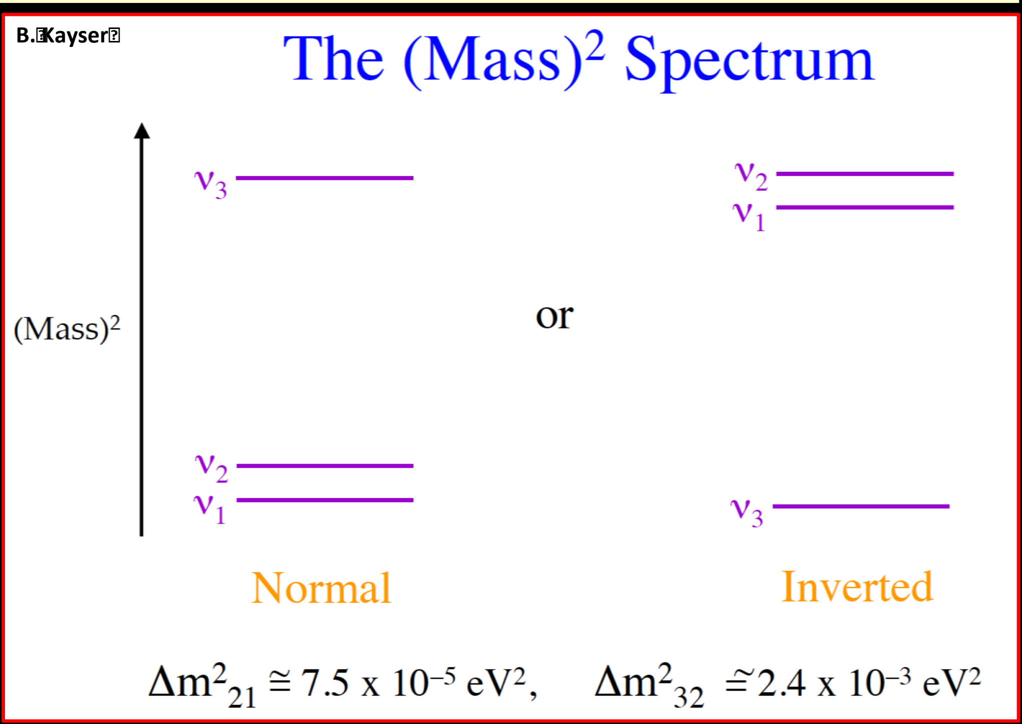
- Introduction
- nuSTORM motivation:
  - Long-baseline neutrino oscillations
  - Sterile neutrino search
- nuSTORM:
  - Concept, detector and performance
- Facility
- Conclusion

Introduction

Standard Neutrino Model:

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

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



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

A window on the unknown:

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

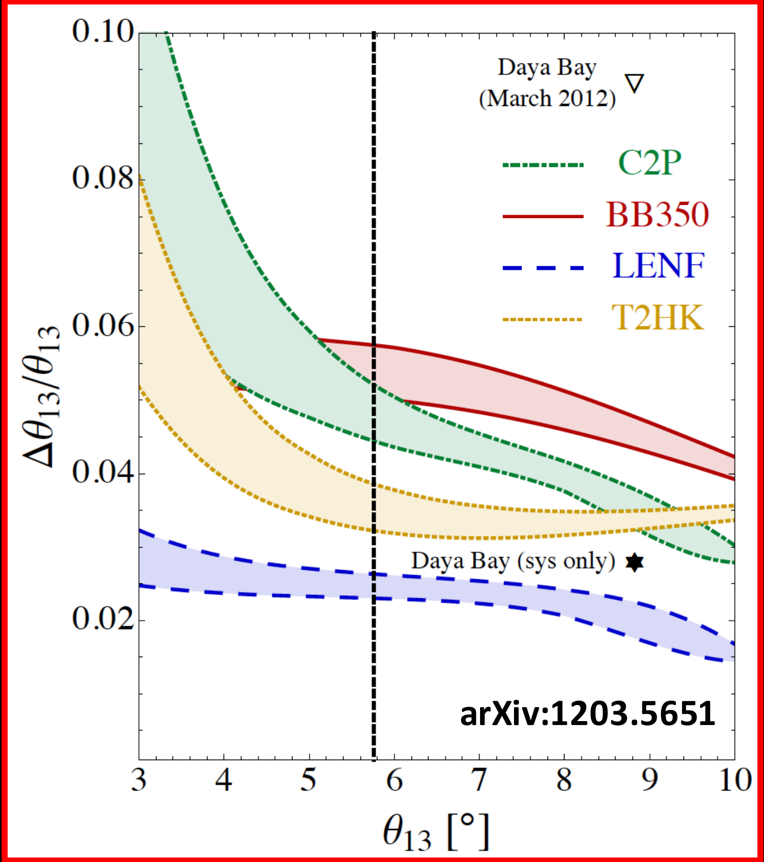
Option thumbnails:

- 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

The SνM measurement programme:

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

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



Neutrinos from stored muons:
the nuSTORM facility

nuSTORM Motivation:

LBL programme

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:*

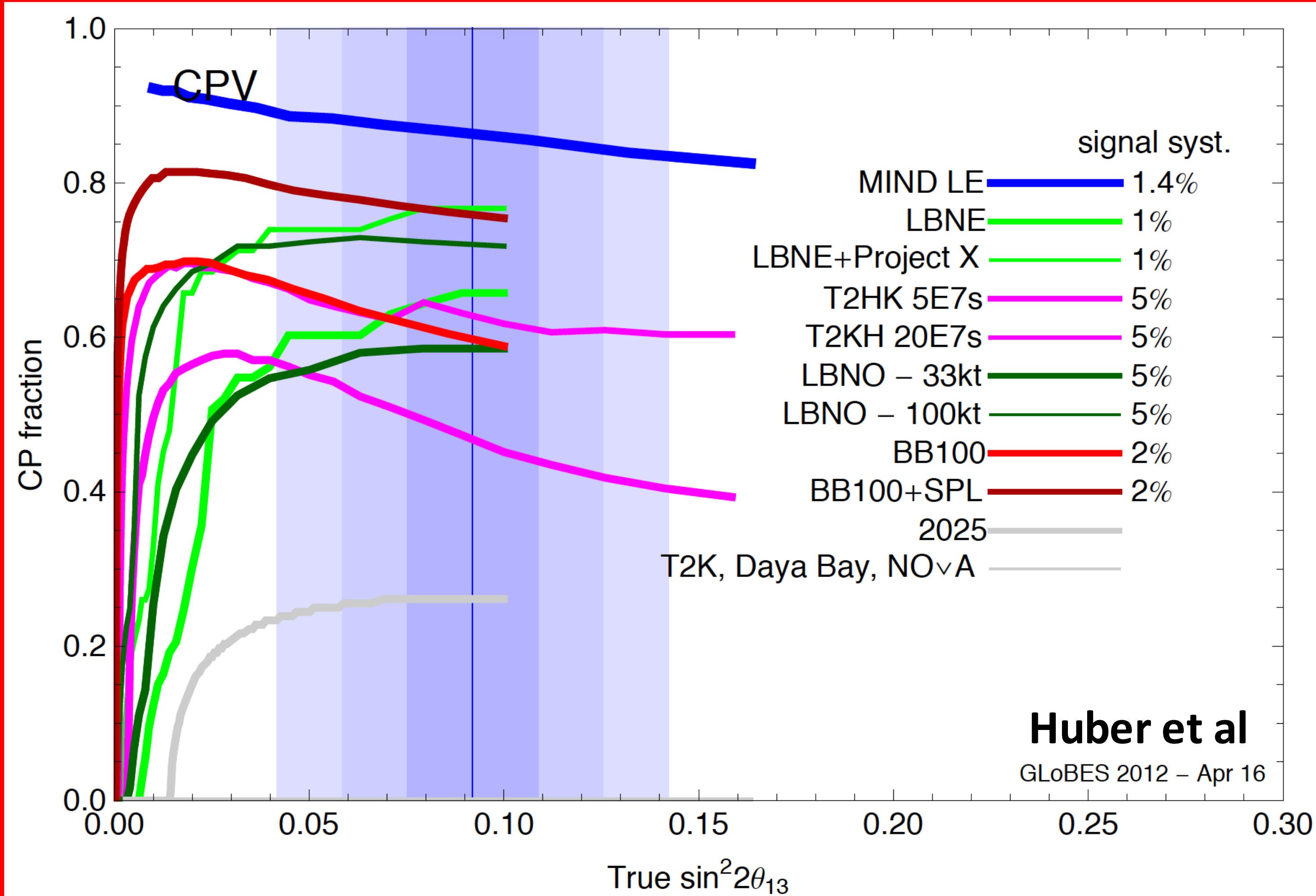
$$\frac{P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)}{P(\nu_\alpha \to \nu_\beta) + P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)} \propto \frac{1}{\sin 2\theta_{13}}$$

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

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

Discovery reach:

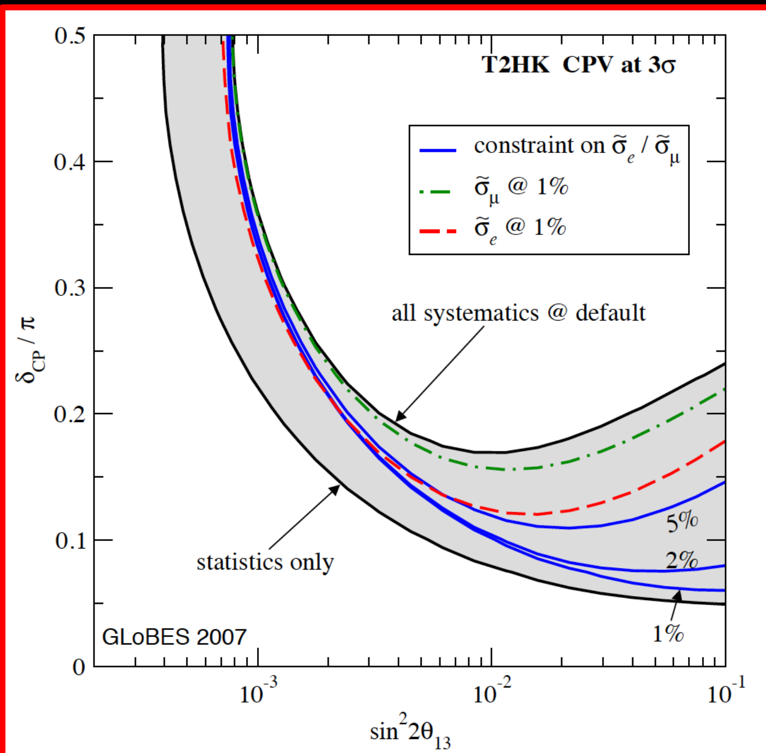
- **Discovery reach at 3σ:**
  - **Neutrino Factory: 85—90%**
  - **Beta beam and SPL: 70—80%**
  - **Super beam: 60—75%**

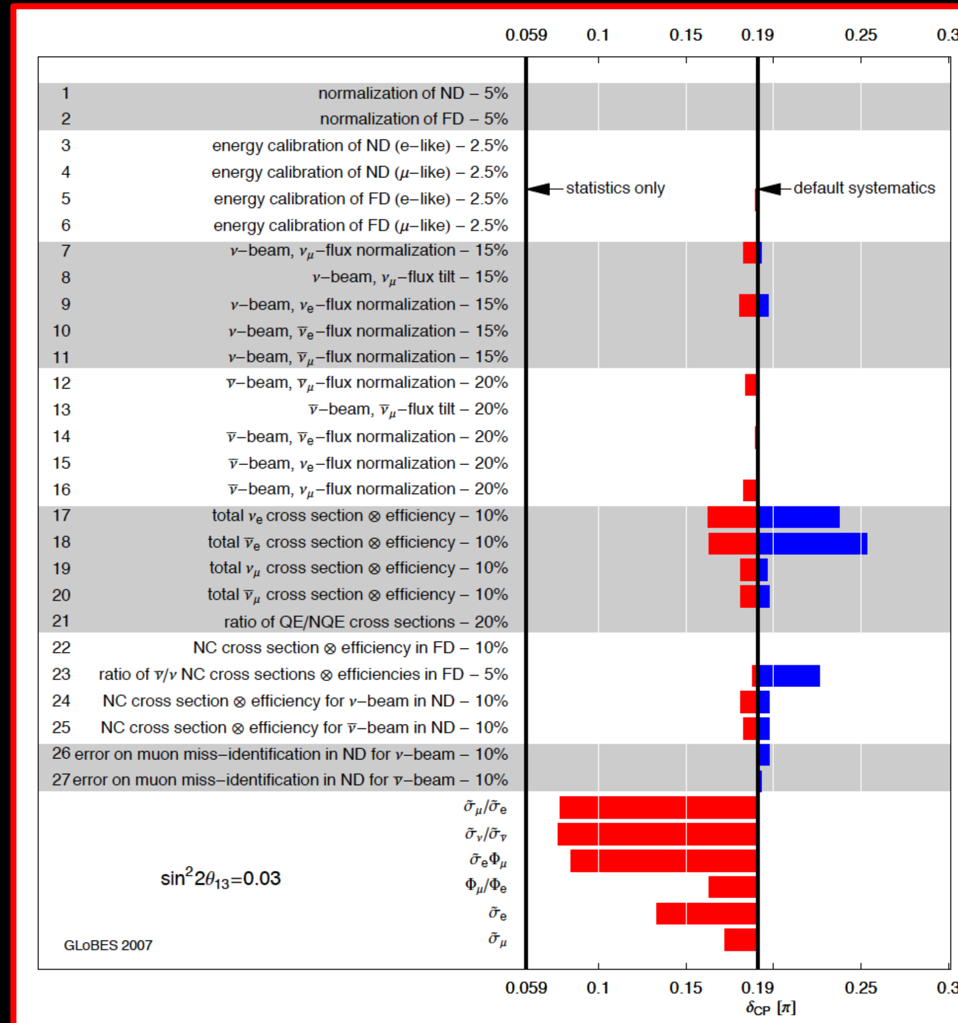


Systematic uncertainties:

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

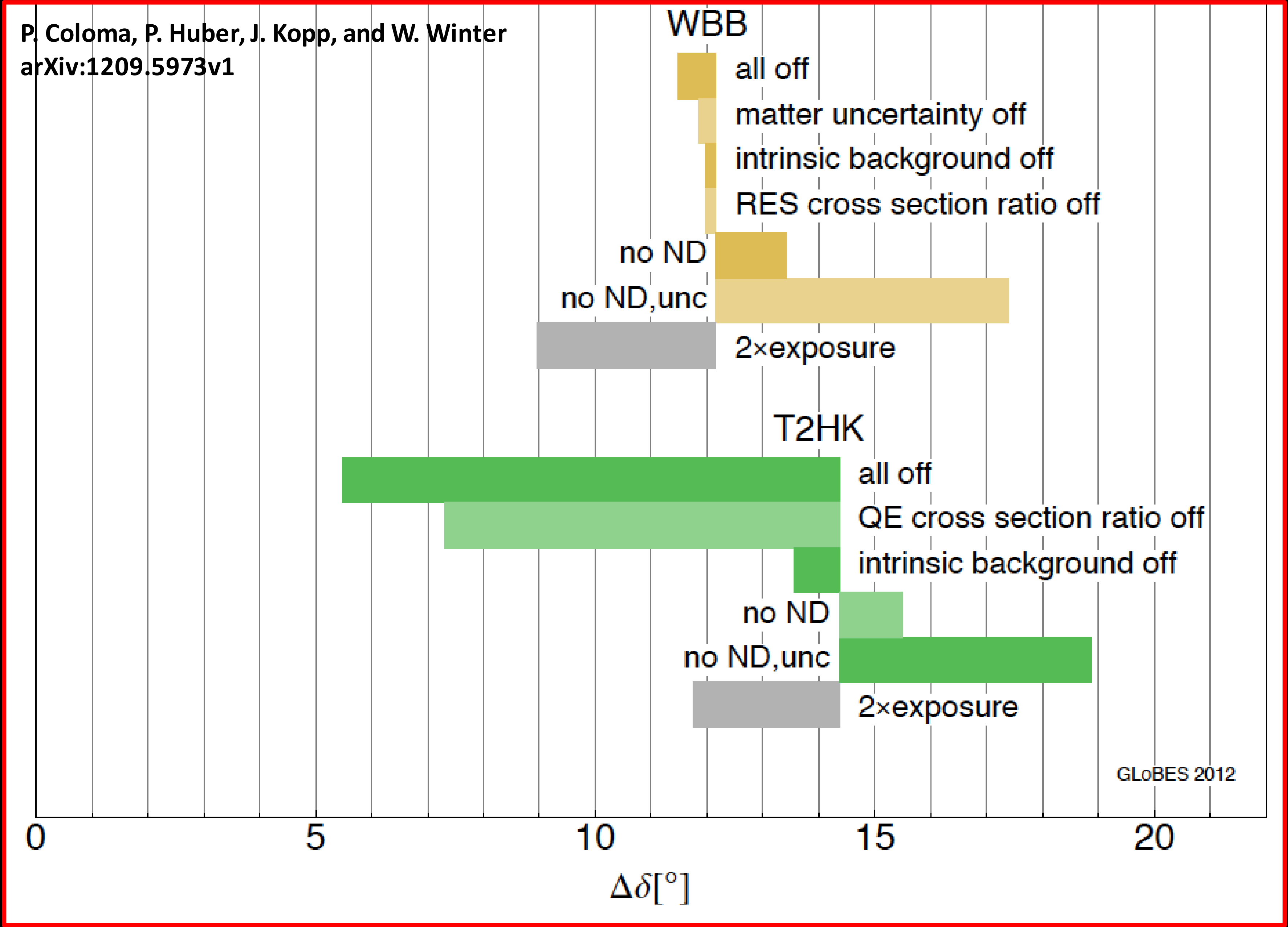
— critical at large θ_{13}





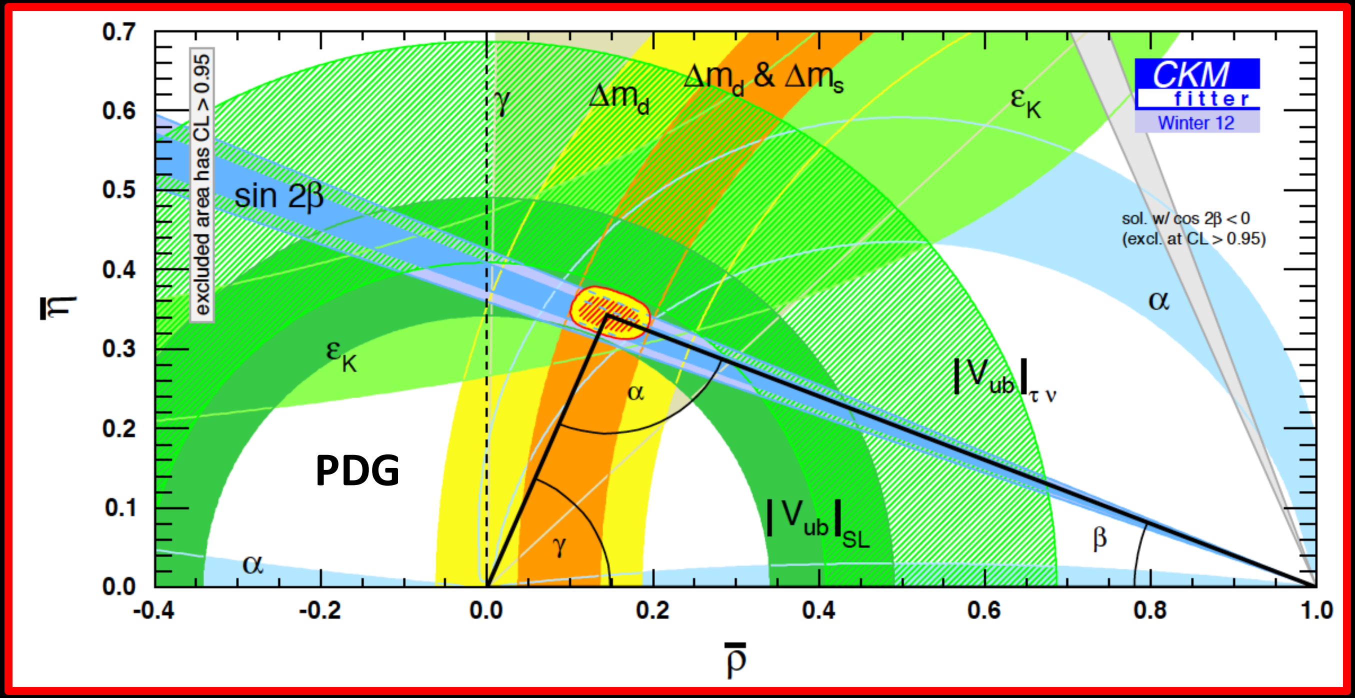
Huber, Mezzetto, Schwetz, arXiv:0711.2950v2

Systematic uncertainties:



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

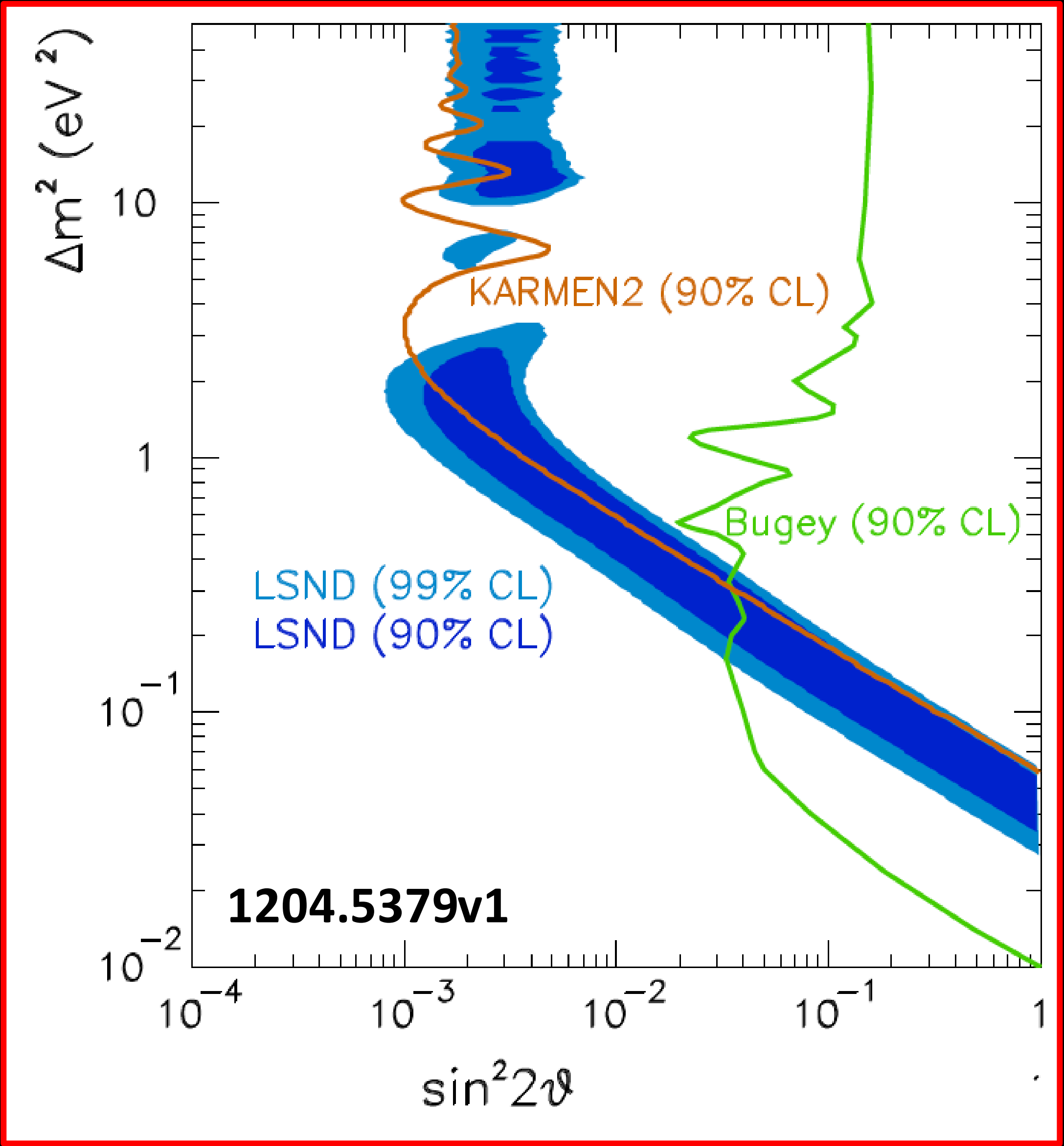


Neutrinos from stored muons:
the nuSTORM facility

nuSTORM motivation:

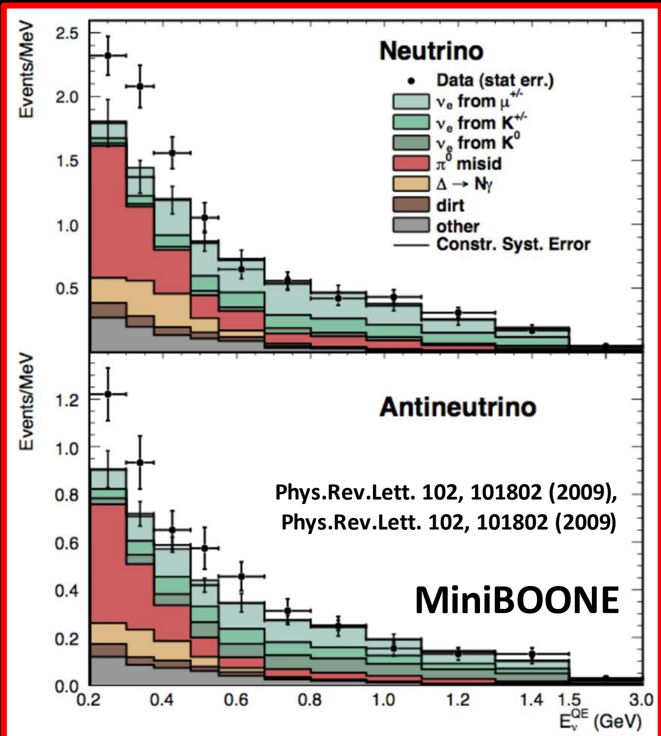
Sterile neutrino search

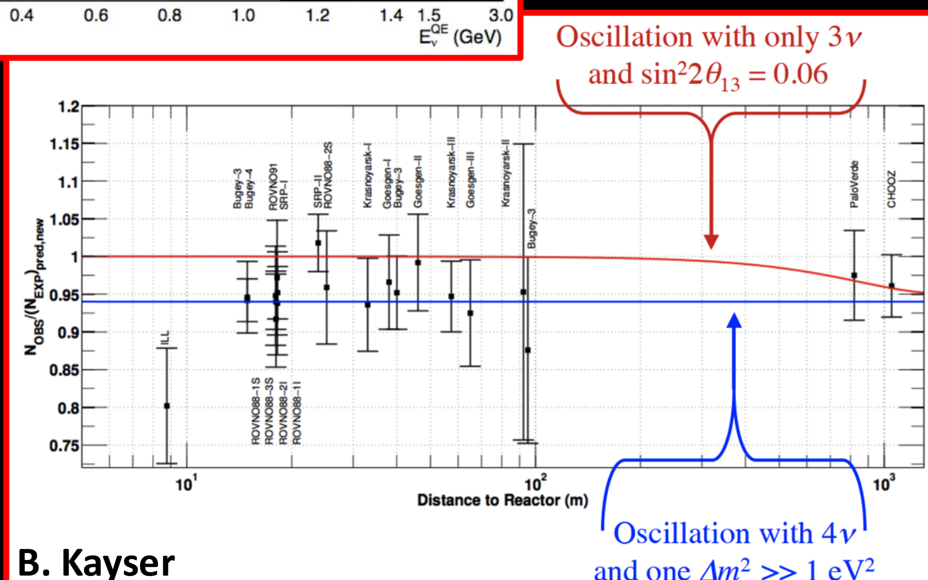
LSND:



- 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:





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

What we need to measure:

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

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

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

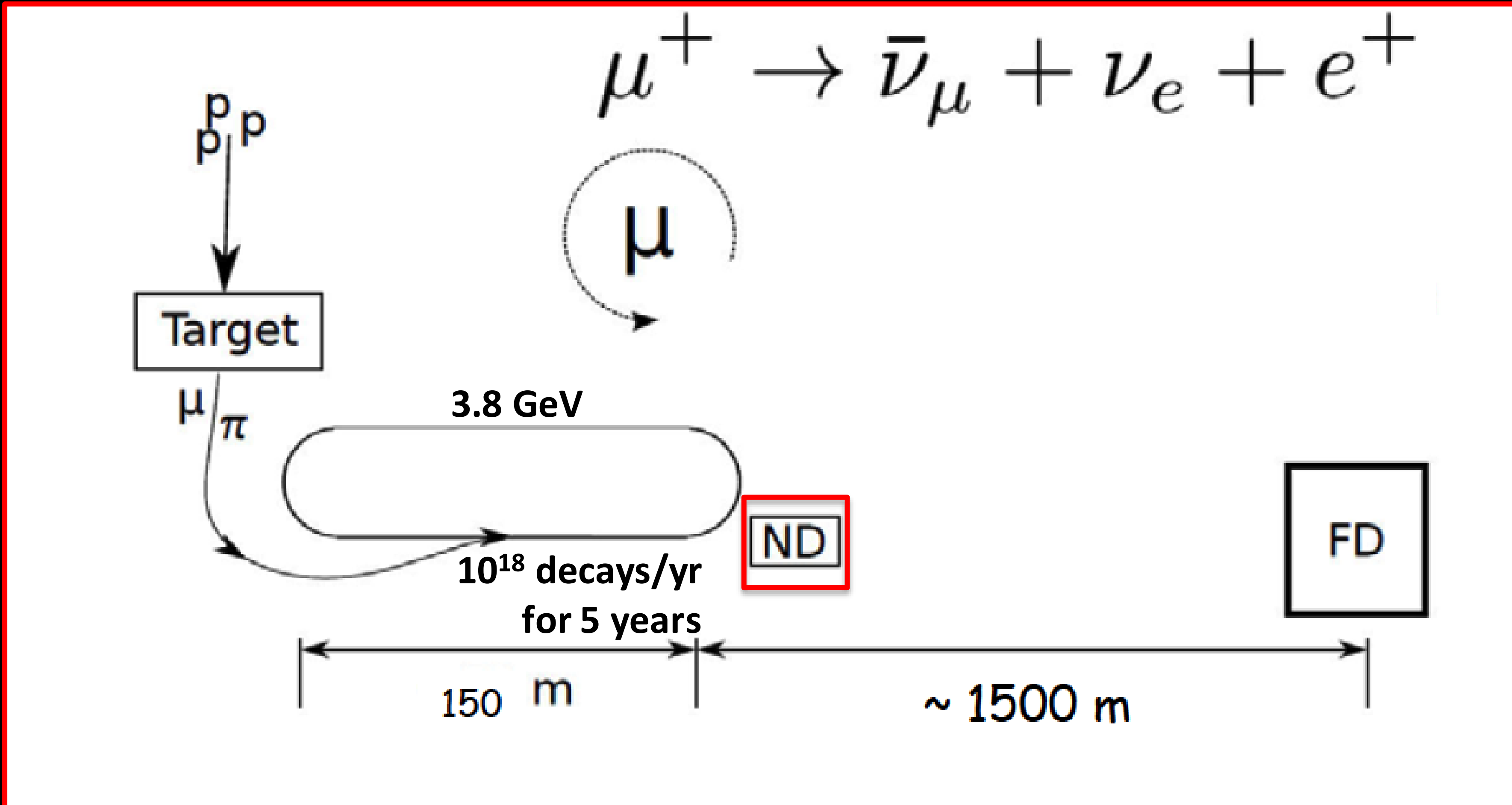
Present programme and future options:

- 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

Neutrinos from stored muons:
the nuSTORM facility

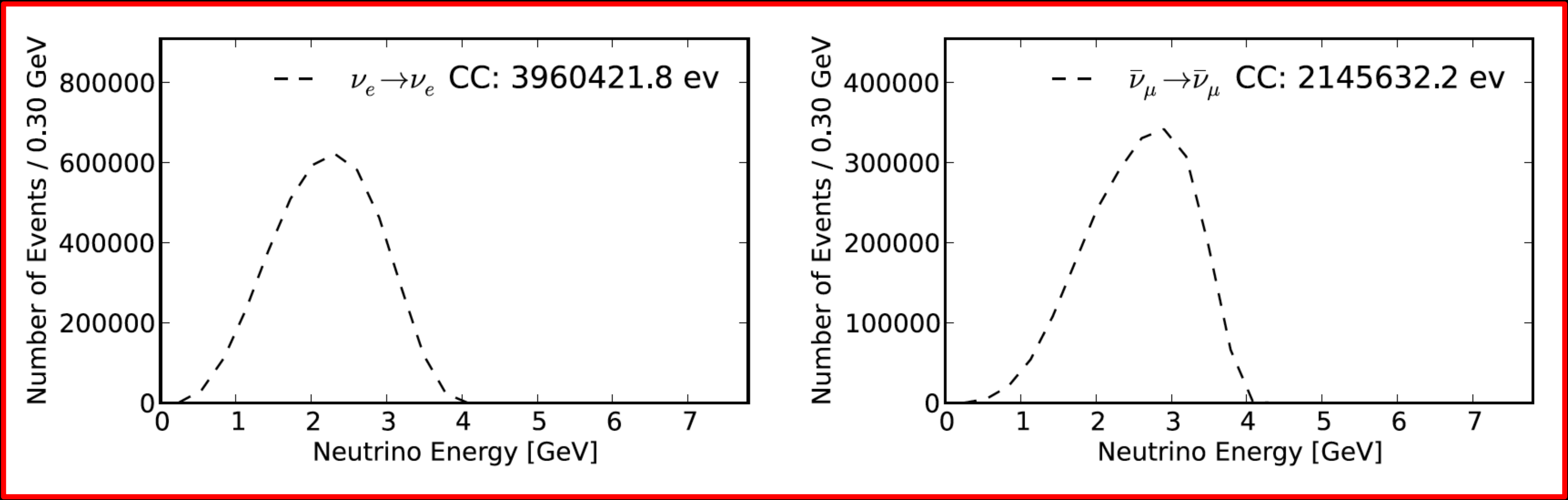
nuSTORM:
Concept, detectors and performance

Neutrino-nucleus scattering:



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:

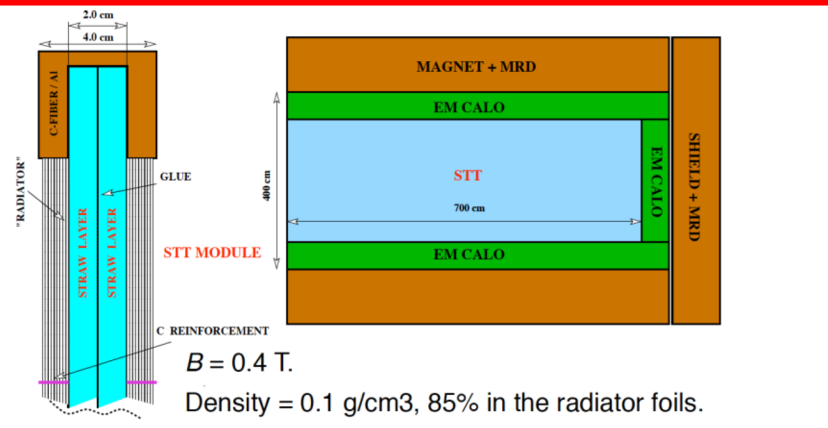


Figure 11: Schematic of the HIRESMNU concept showing the straw tube tracker (STT), the electromagnetic calorimeter (ECAL) and the magnet with the muon range detector (MRD). The STT is based upon ATLAS [174–176] and COMPASS [177, 178] trackers. Also shown is one module of the proposed straw tube tracker (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.

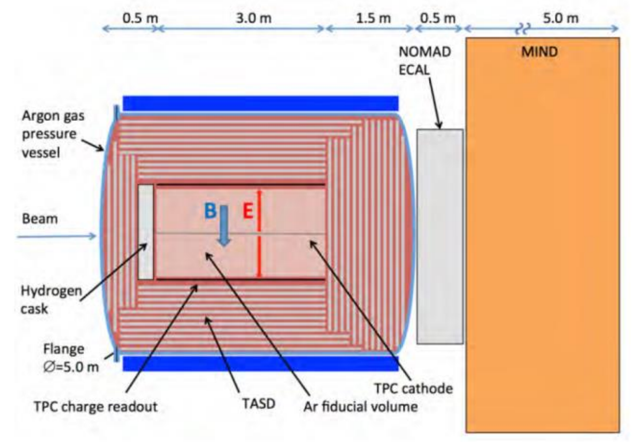


Figure 12: Schematic of the pressurized argon gas-based TPC detector. Both the TPC and scintillator calorimeter layers surrounding it are enclosed in a pressure vessel. A 0.5 T magnetic field is applied to the pressure vessel volume. Downstream of the TPC are also an electromagnetic calorimeter (ECAL)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

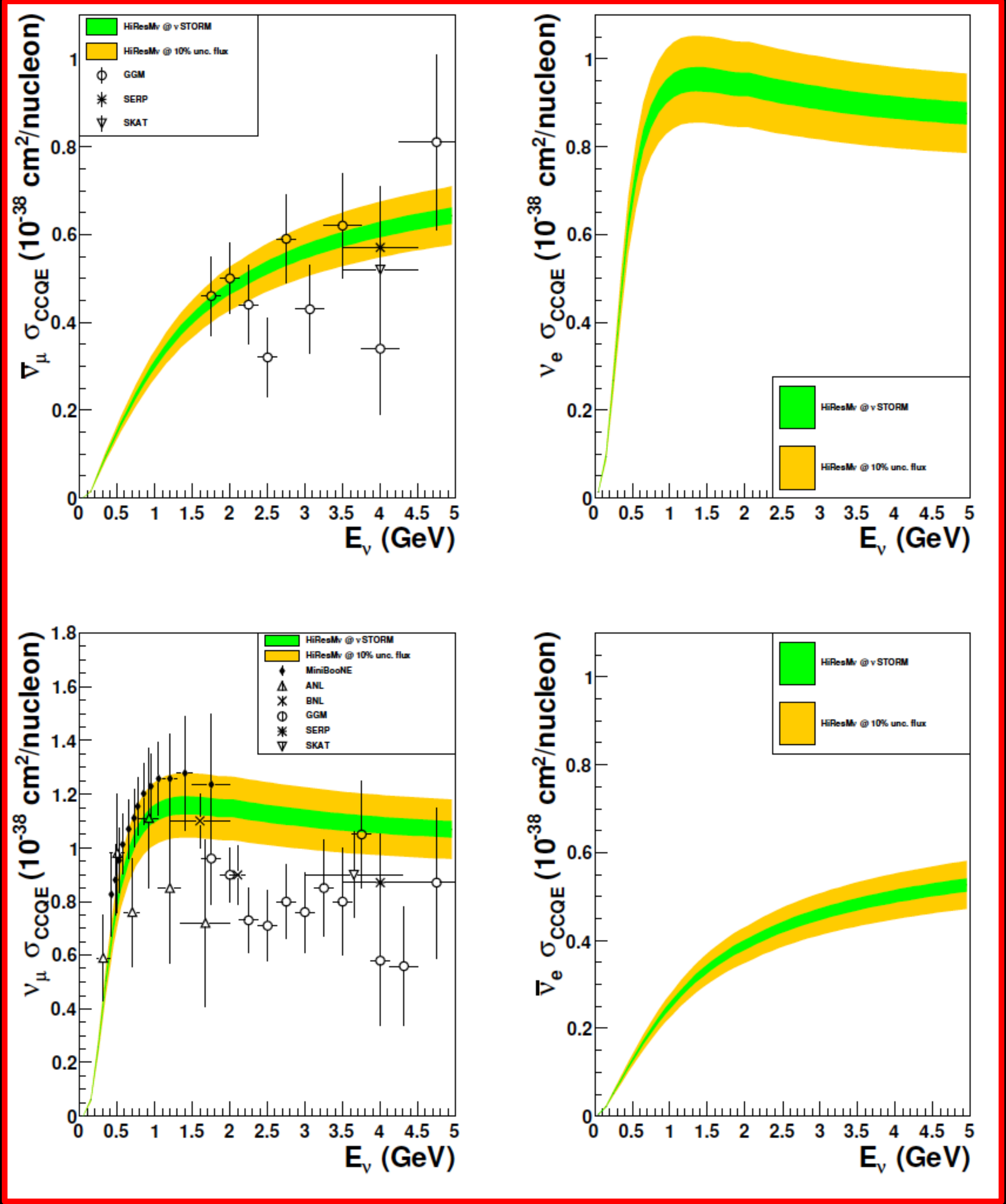
- **Assumed performance of generic detector for evaluation of precision of cross section measurement:**

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

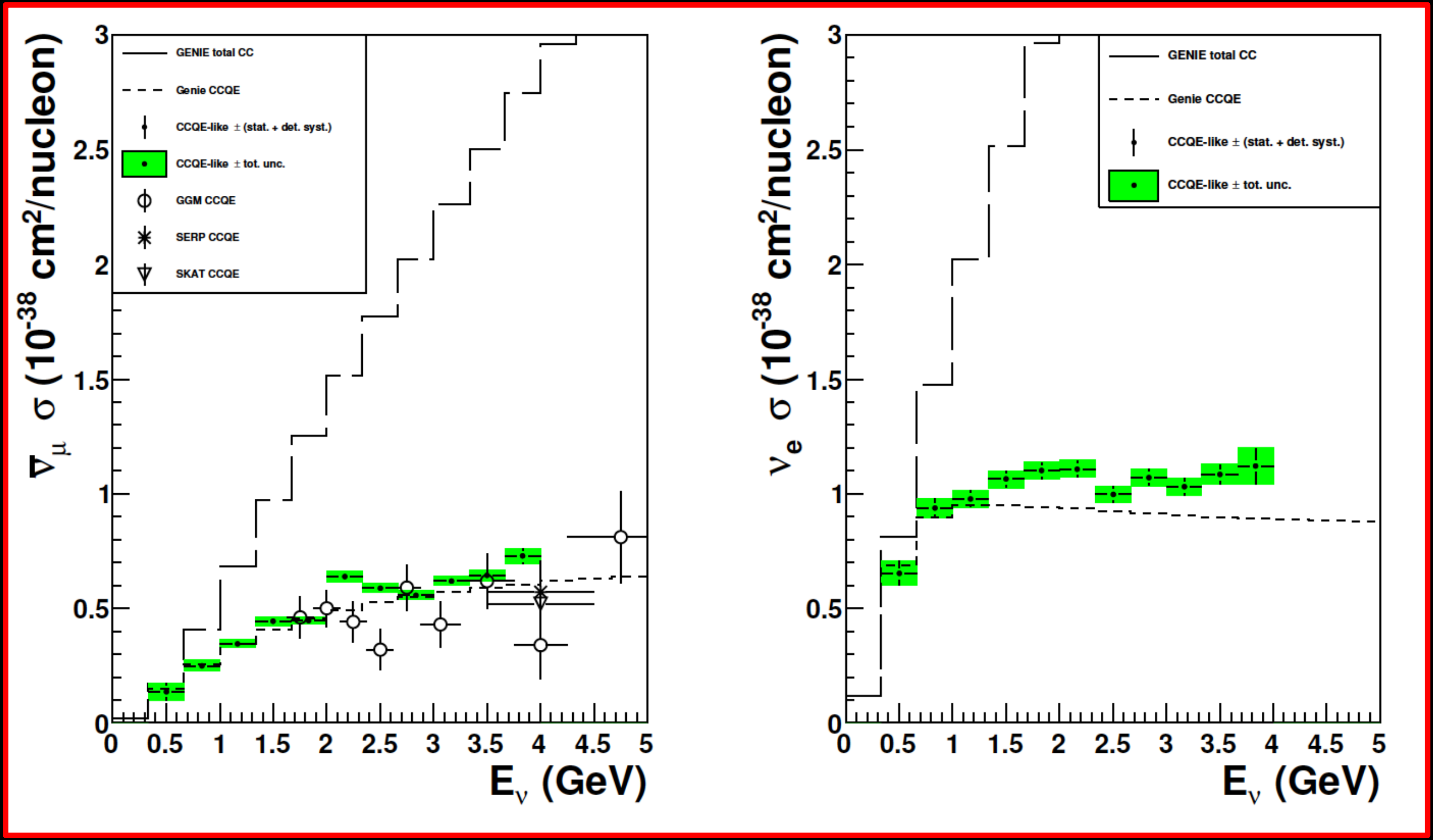
- **Flux uncertainty varied:**
  - **1% nuSTORM specification**
  - **10% typical of conventional beams for comparison**

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

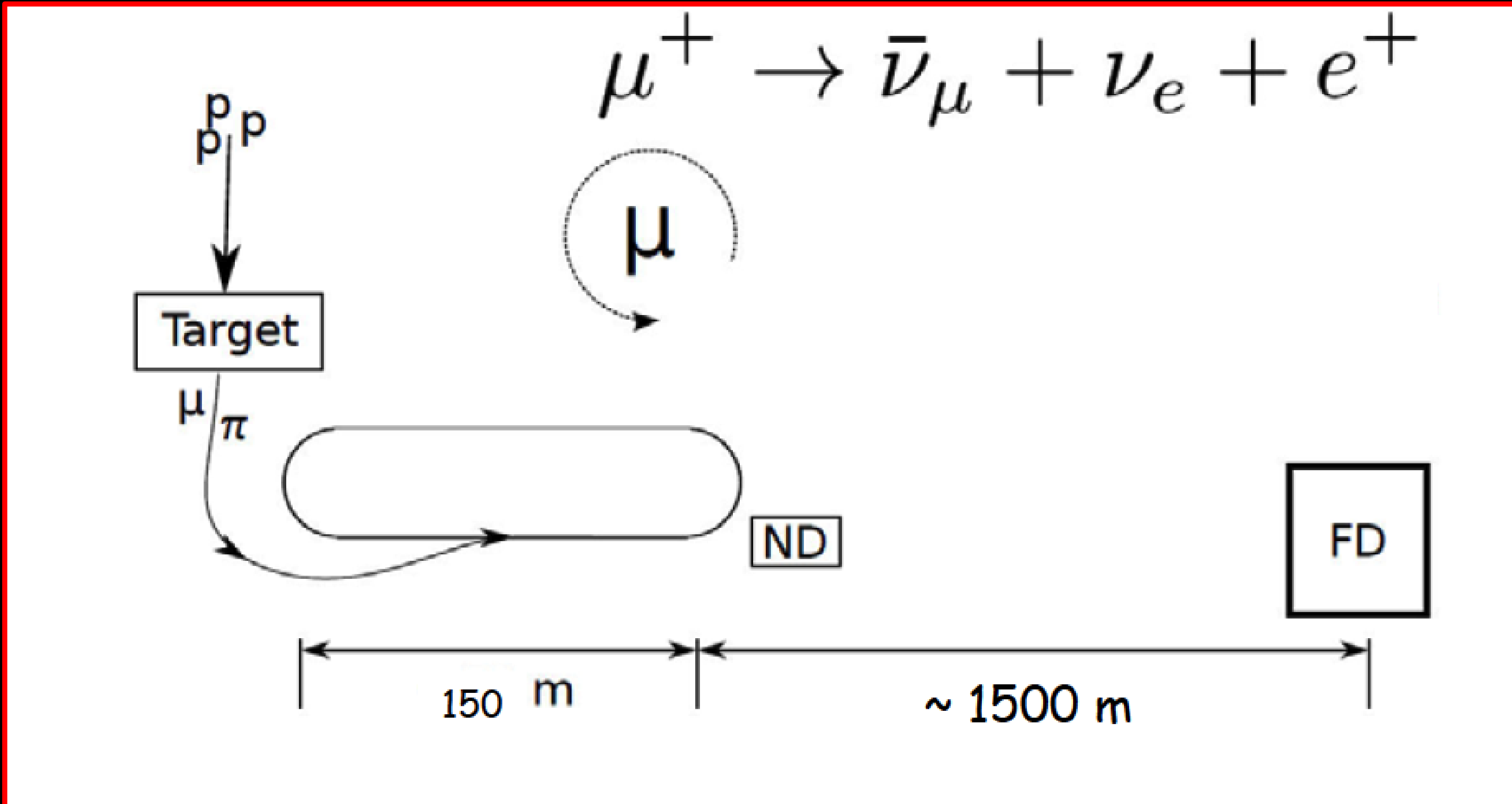


CCQE cross section measurement:



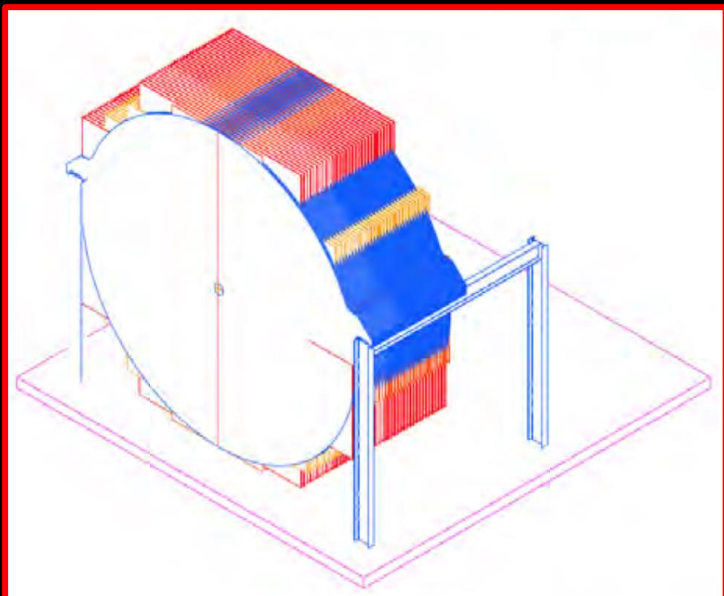
- Simulation of "generic detector":
  - Muon-neutrino CCQE cross section measurement substantially improves "state of the art"
  - Electron-neutrino CCQE measurement *unique*
  - Evaluation of other channels has begun

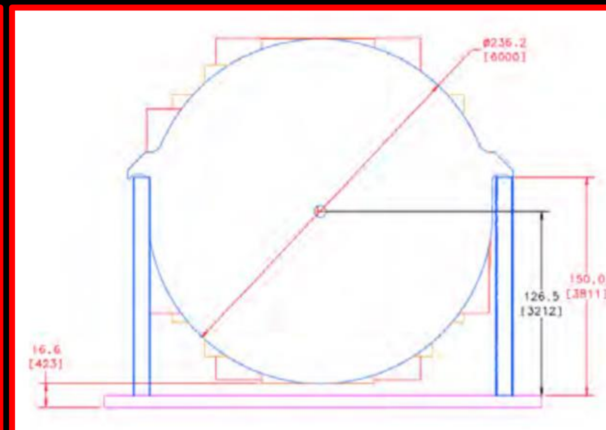
Sterile neutrino search concept:

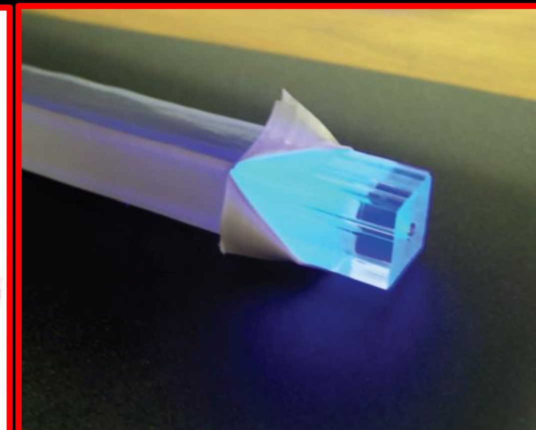


SuperBIND, baseline sterile detector:

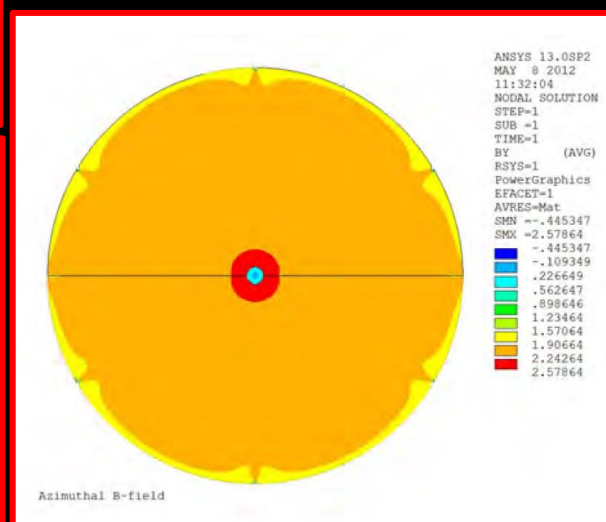
- **Magnetised iron calorimeter:**
  - MINOS-like, optimised for nuSTORM beam

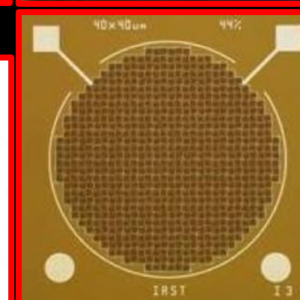


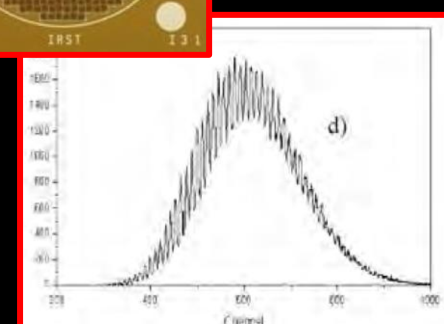




SuperBIND parameters			
Geometry:			
Circular Fe plate:	Diameter:	600.0	cm
	Thickness:	1.5	cm
Scintillator:			
Extruded rectangular bar:	Cross section:	0.75 x 2	cm^2
	Material:	Polystyrene	
	Dopants:		
	POP:	1.00	% by weight
	POPOP:	0.03	% by weight
	Coating:	15	% TiO_2 in polystyrene
Photo-detector: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







SuperBIND: magnetisation:

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

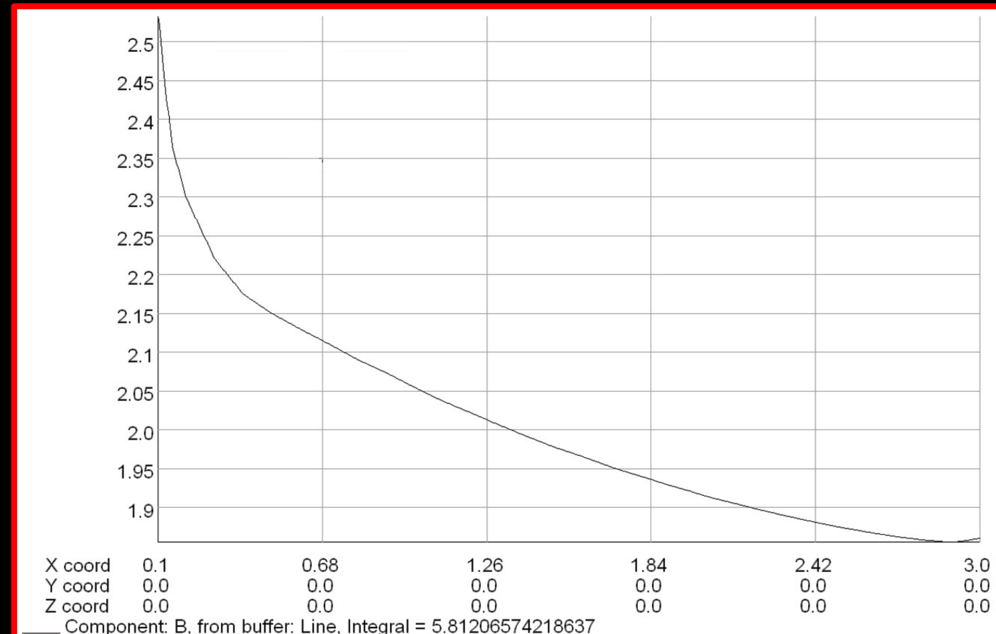
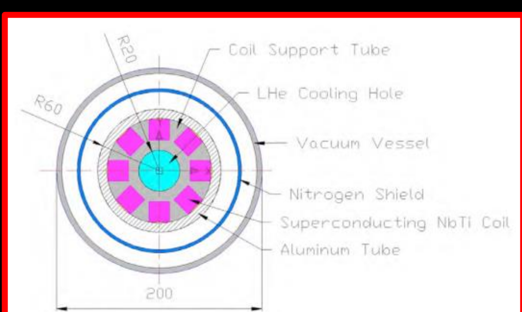
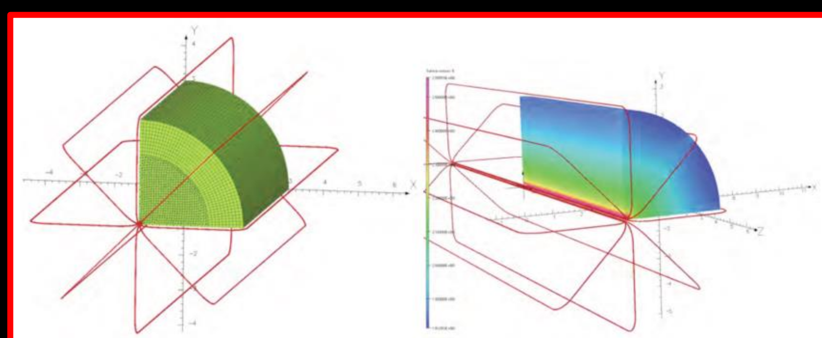


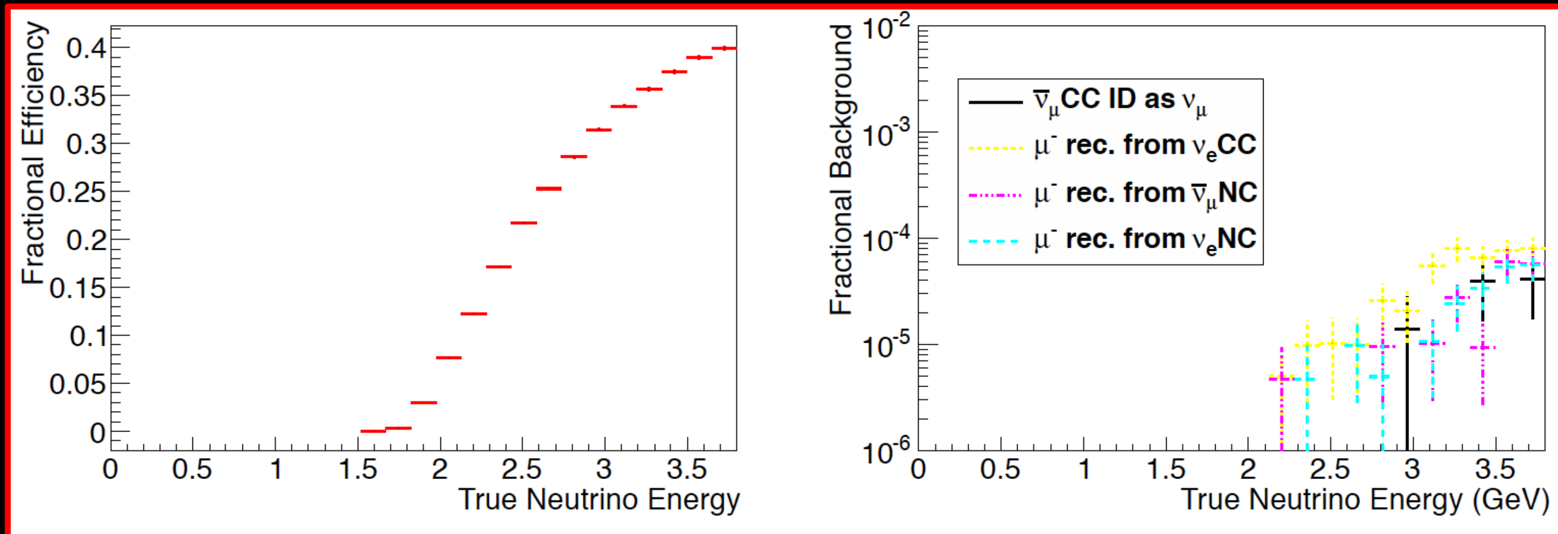
Table 15: Magnet parameters for SuperBIND.		
Name	Unit	Value
Iron core outer diameter	m	6.0
Iron core inner diameter	m	0.2
Iron core length	m	15.82
Iron plate thickness	mm	15
Number of plates		440
Space between plates	mm	21
Number of superconducting racetrack coils		8
Superconducting cable length	m	320
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



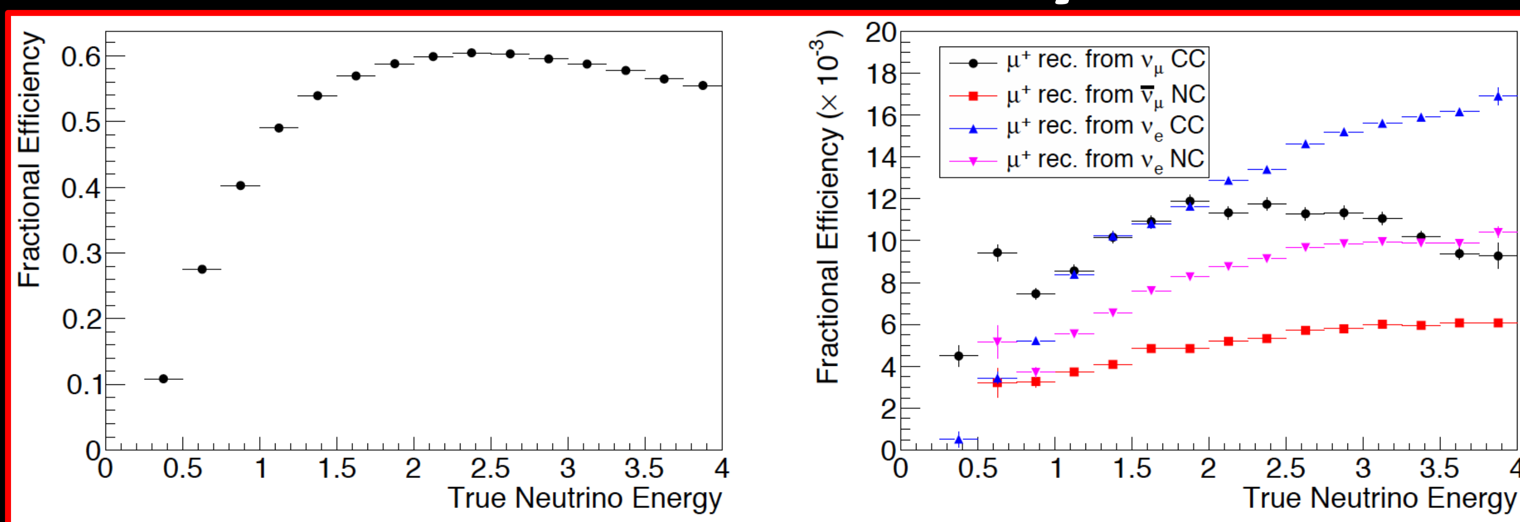


SuperBIND: performance:

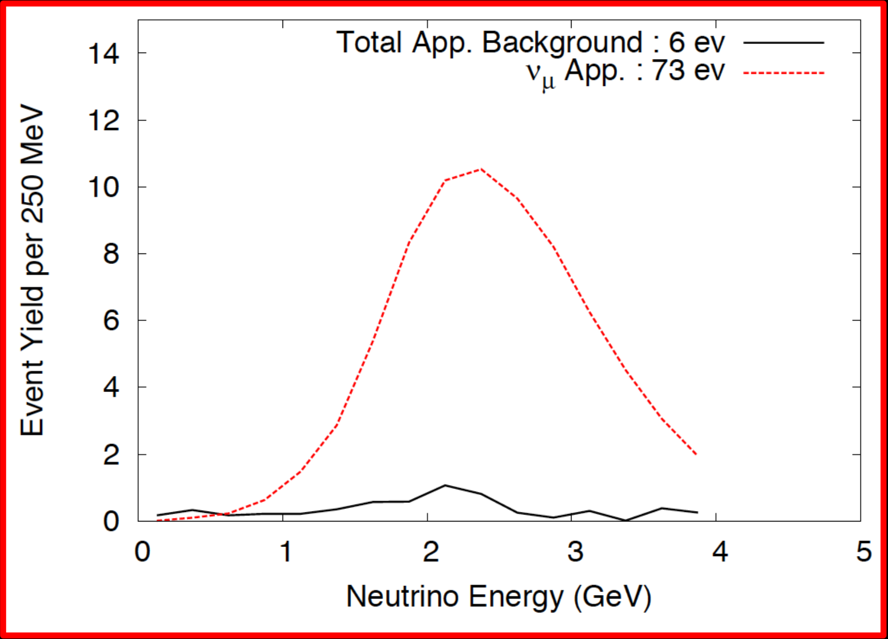
- **Cuts-based analysis:**

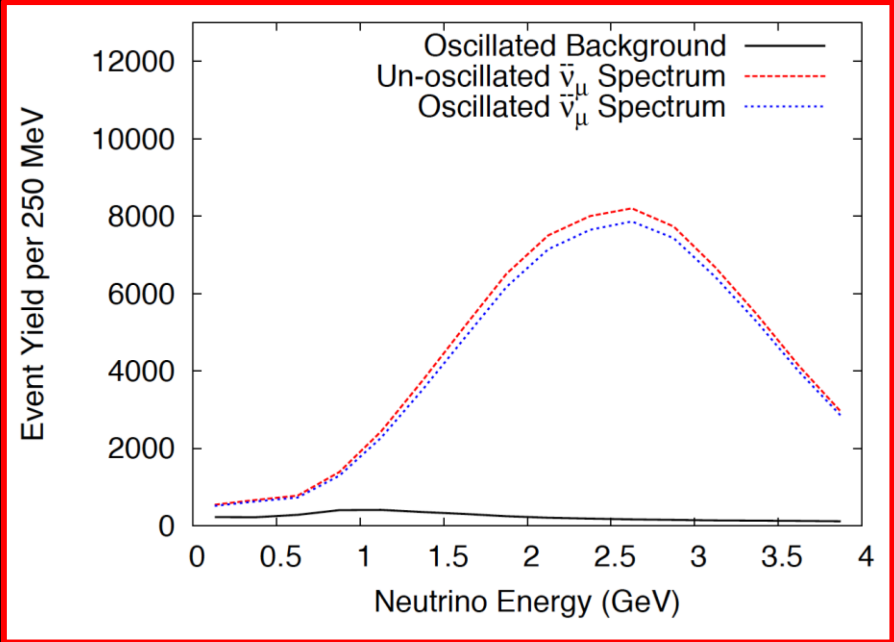


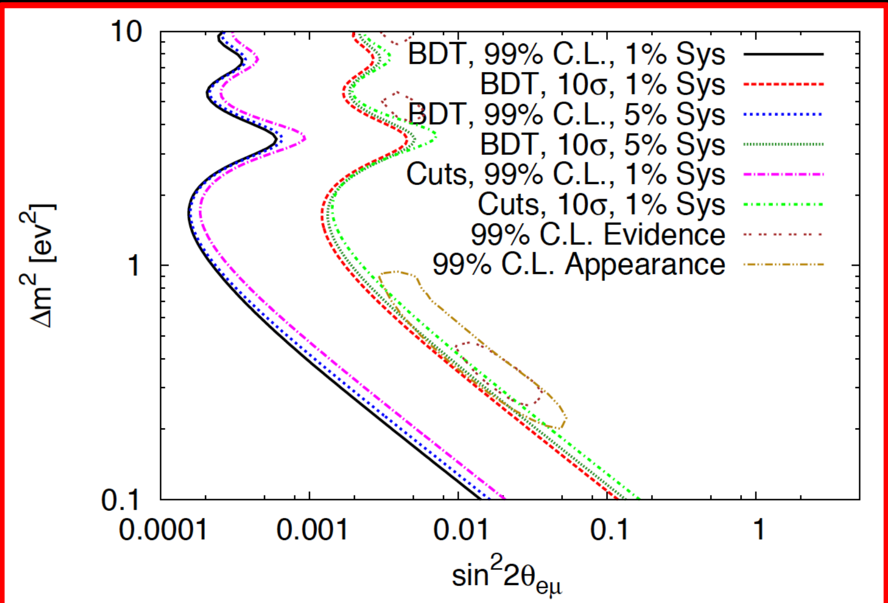
- **Optimised multi-variate analysis:**

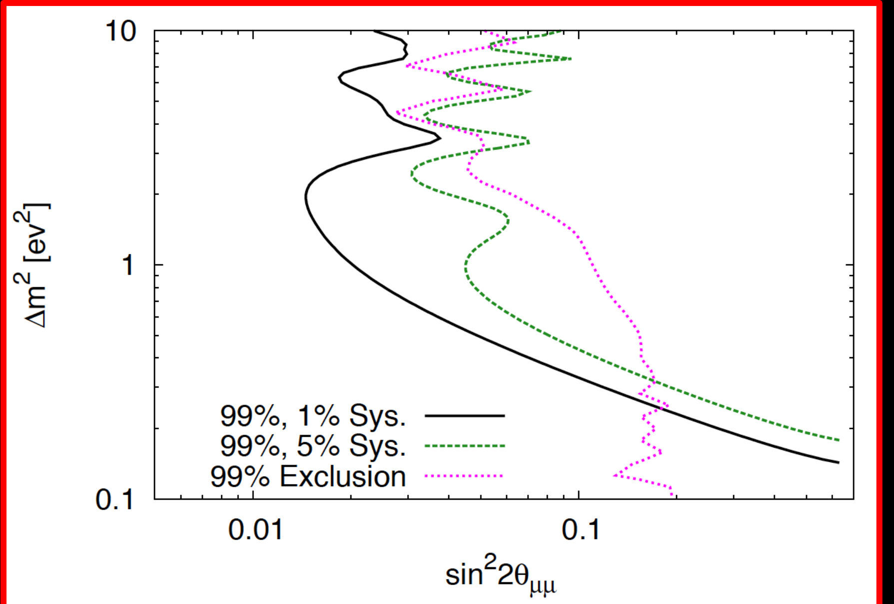


Sterile-neutrino search sensitivity:









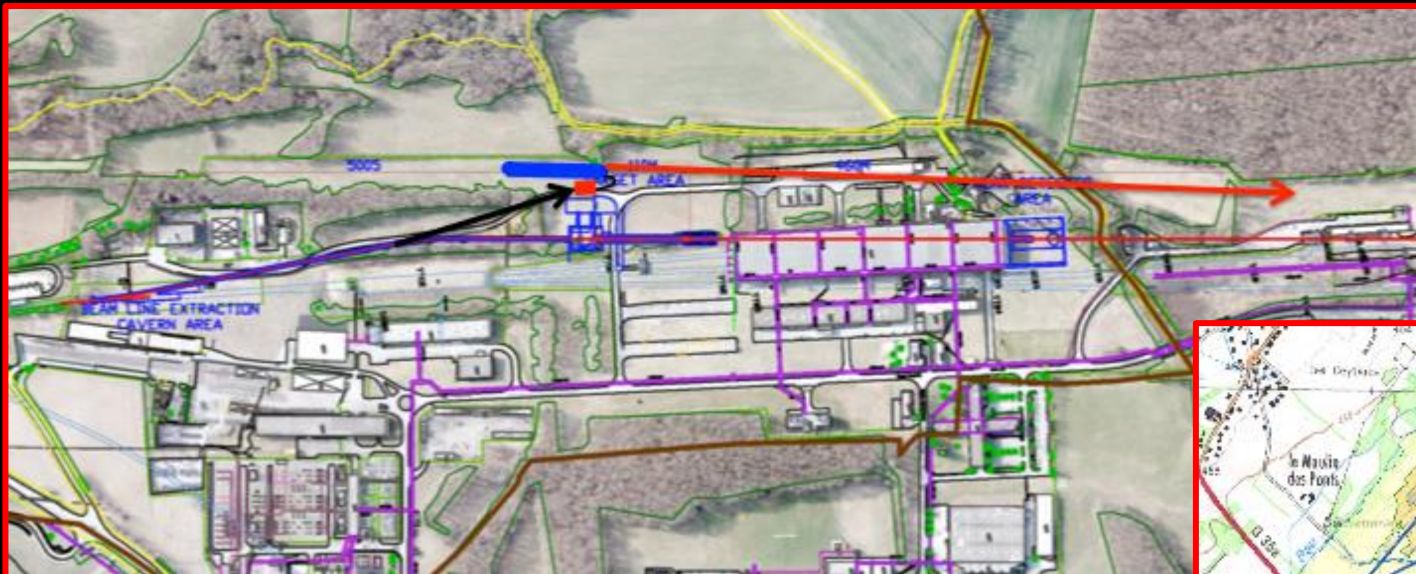
Neutrinos from stored muons:
the nuSTORM facility

Facility

Implementation, at FNAL:

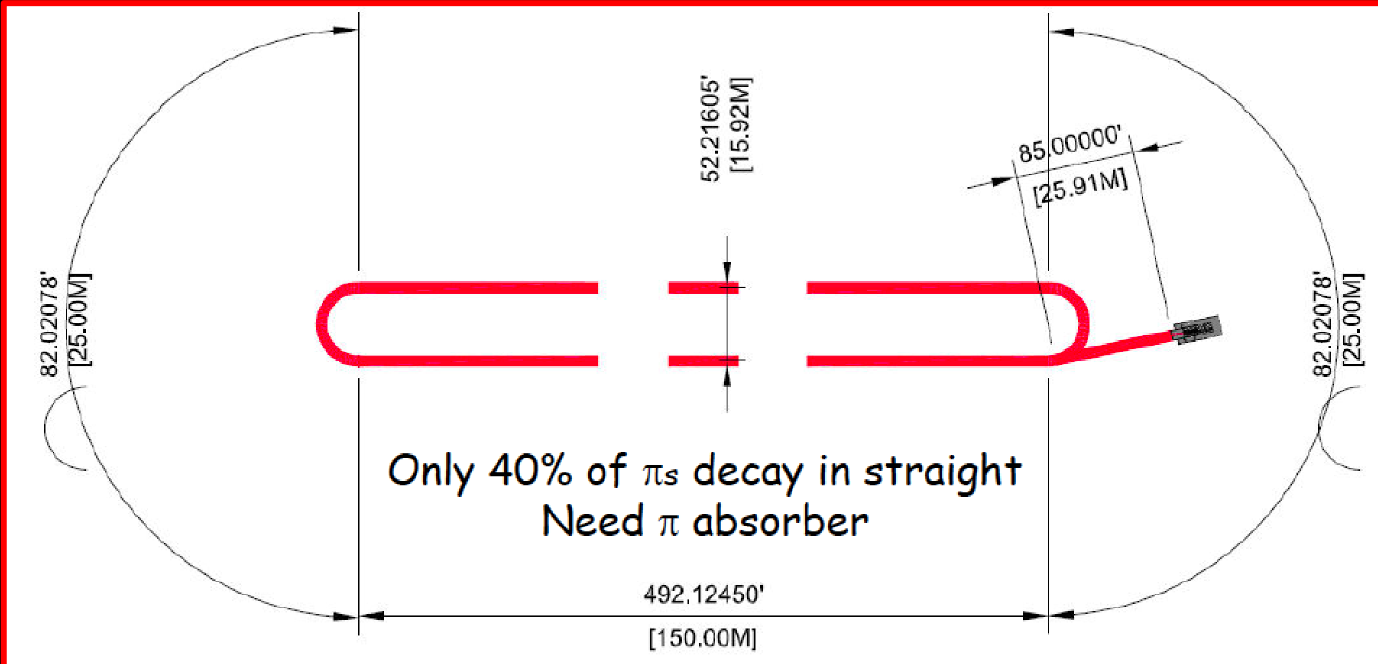
- Benefits from existing extraction tunnel;
- Ideal baseline from storage ring to D0 assembly building:
  - Space and infrastructure for SuperBIND and LAr detector;
- Space and access for near detector

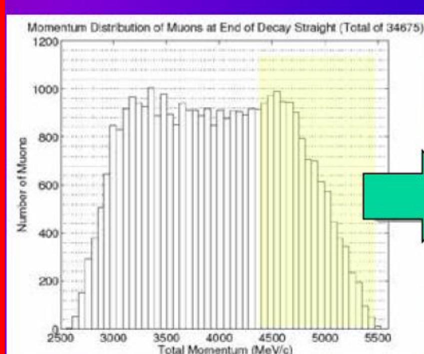
Implementation, at CERN:

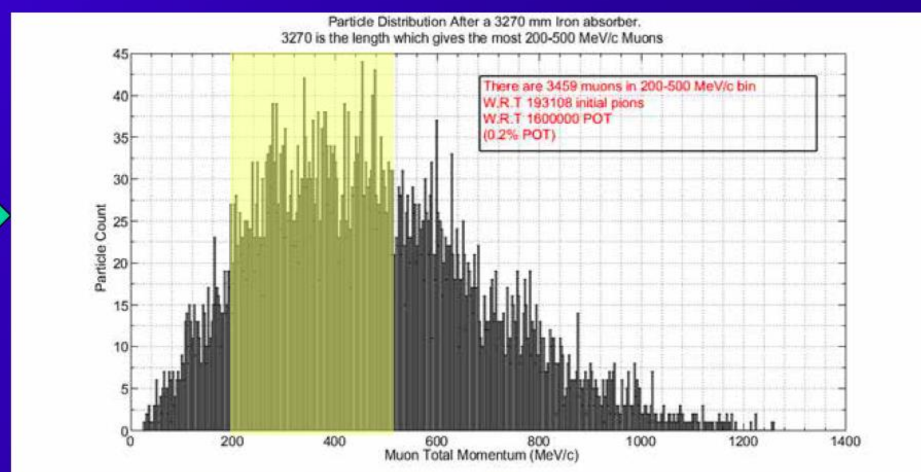


- **Principal issue:**
  - SPS spill is 10 μs:
    - Implies bend for proton or pion beam
- **Two options:**
  - NA implementation:
    - Possible exploitation of synergies with ICARUS/NESSiE
  - NA-to-WA implementation:
    - Advantage is proton/pion bend not required;
    - Longer baseline must be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

Technology test-bed:







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

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

Conclusion

Conclusion:

- The nuSTORM has the potential to deliver:
  - Unique programme of ν_e and ν_μ cross-section measurements:
    - In kinematic region of interest 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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Neutrinos from Stored Muons (νSTORM):

Neutrinos from Stored Muons (νSTORM): Expression of Interest

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

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 $\simeq 1500$ 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 $\overset{(-)}{\nu}_e N$ ($\overset{(-)}{\nu}_\mu N$) 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.

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Conclusion:

- The nuSTORM has the potential to deliver:
  - Unique programme of ν_e and ν_μ cross-section measurements:
    - In kinematic region of interest 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 Phase I approval submitted
    - CERN:
      - EOI submitted to SPSC:
        - » To be considered at the June SPSC meeting
- An exciting opportunity!