Imperial College London

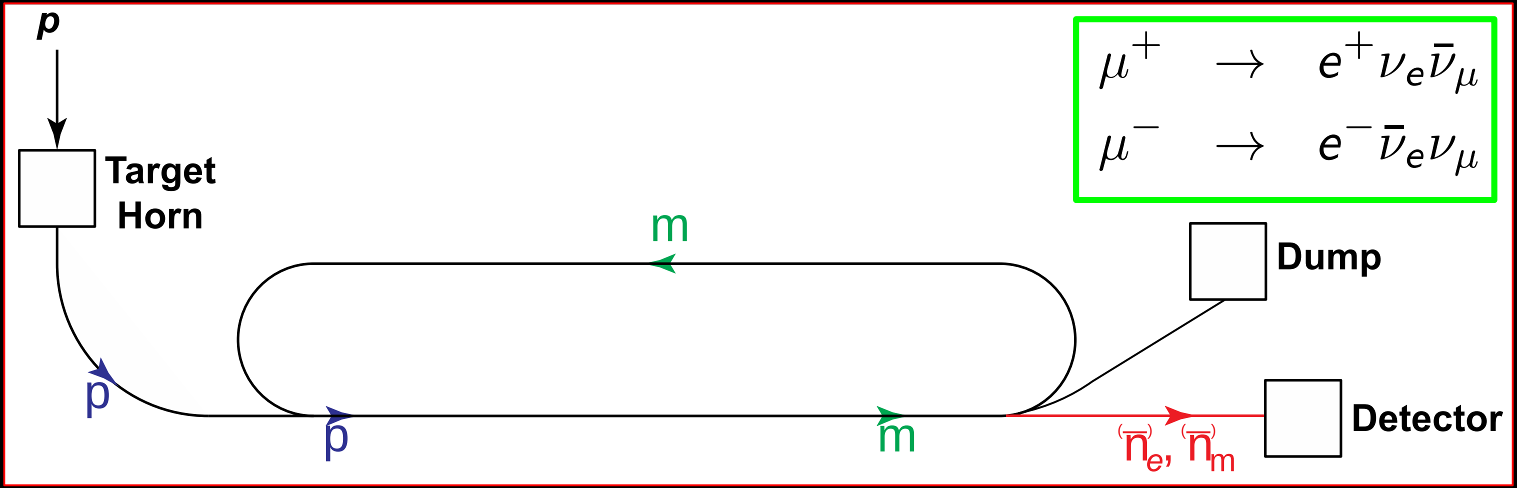
Science & Technology Facilities Council

νSTORM

unique facility for neutrino physics and muon-collider test bed

K. Long, 29 July, 2020

Neutrinos from stored muons



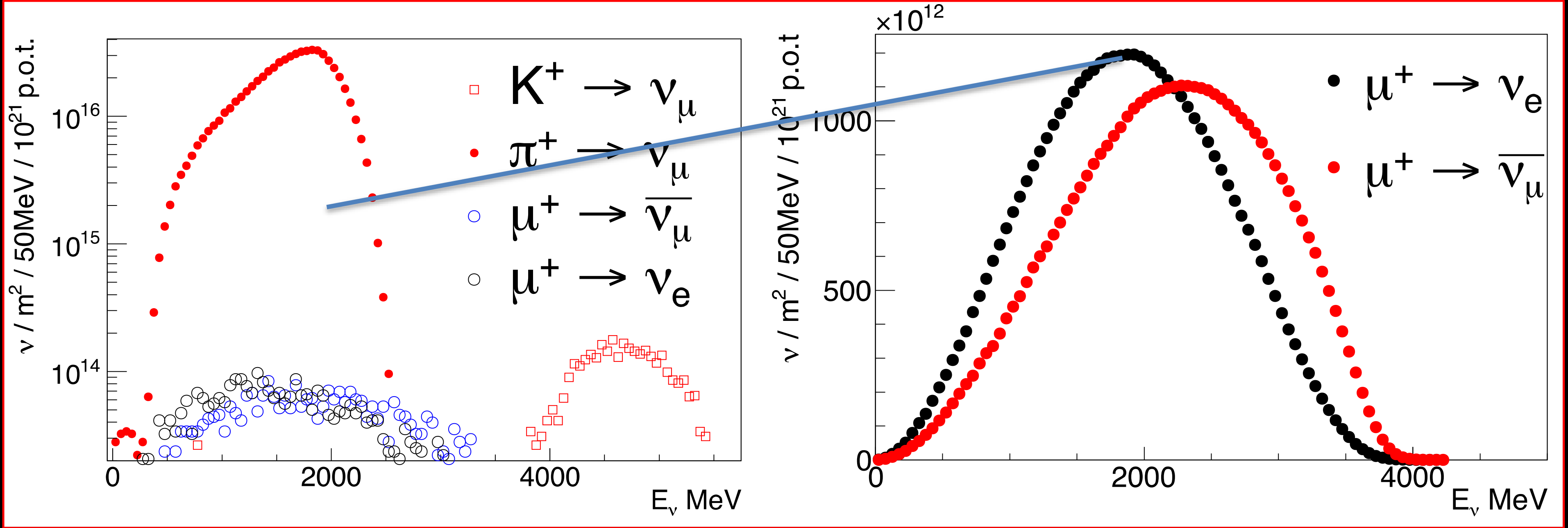
- **Scientific objectives:**
  1. %-level ($\nu_e N$) cross sections
     - Double differential
  2. Sterile neutrino search
     - Beyond Fermilab SBN

- **Precise neutrino flux:**
  – Normalisation: < 1%
  – Energy (and flavour) precise

- **π ®μ injection pass:**
  – "Flash" of muon neutrinos

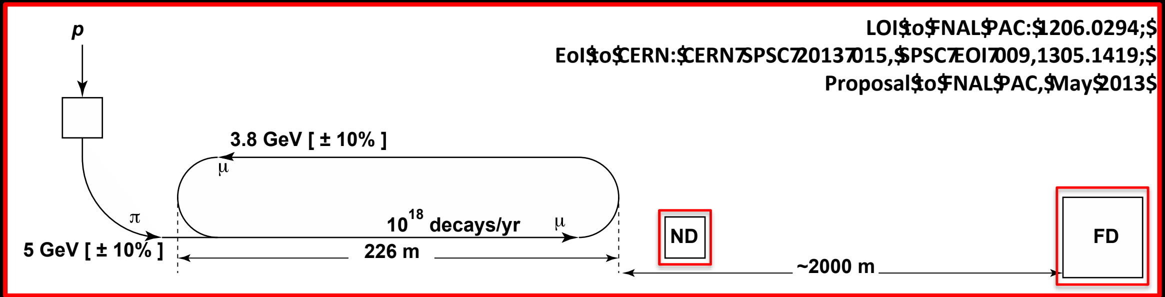
10.1146/annurev-nucl-102014-021930

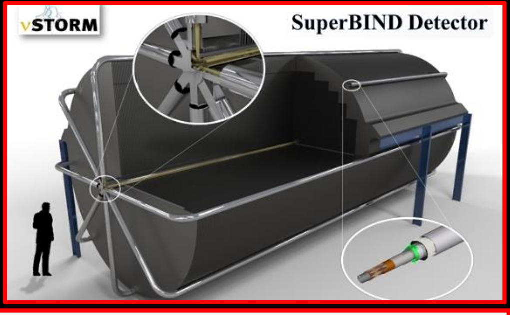
Neutrino flux

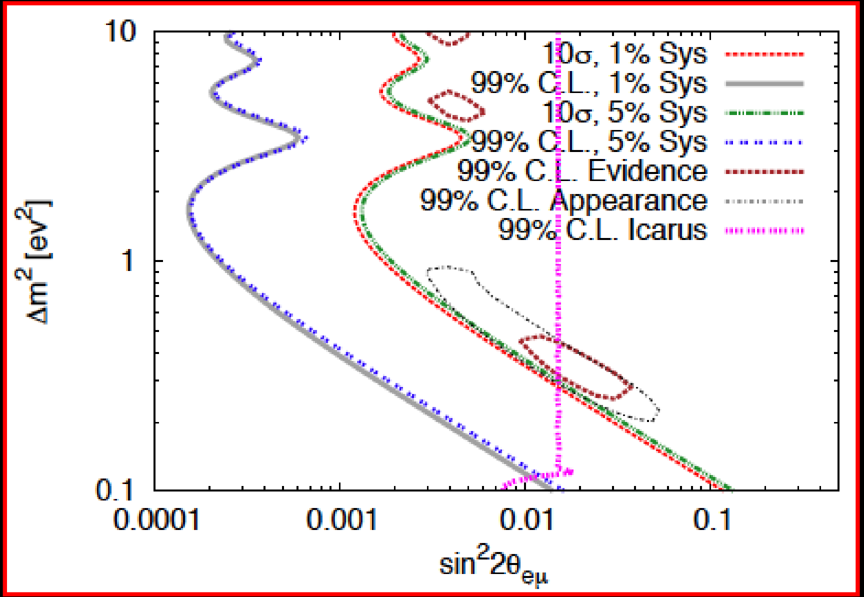


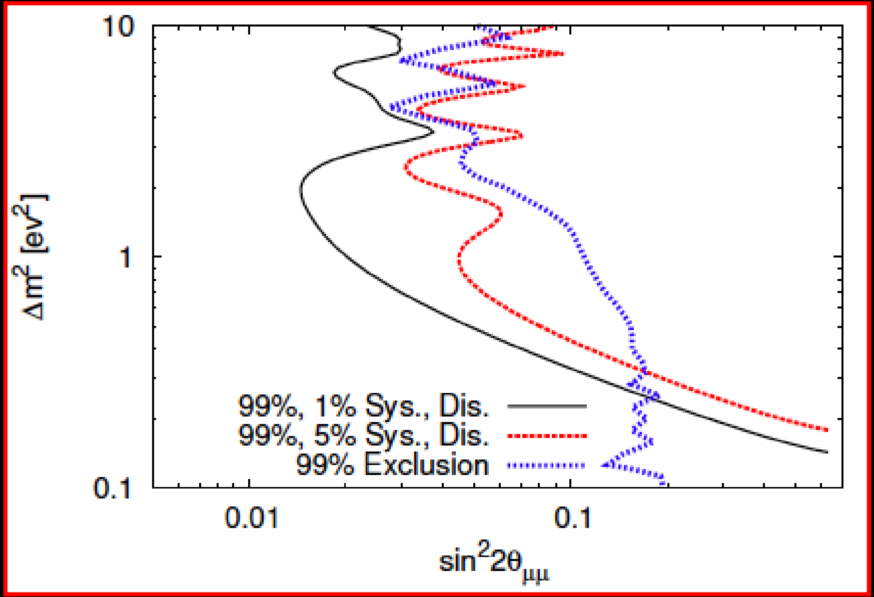
- ν_μ flash:
  - Pion: 6.3×10^{16} m^{-2} at 50m
  - Kaon: 3.8×10^{14} m^{-2} at 50m
    - Well separated from pion neutrinos
- ν_e and ν_μ from muon decay:
  - ~10 times as many ν_e as, e.g. J-PARC beam
  - Flavour composition, energy spectrum
    - Use for energy calibration

Sterile neutrino search @ FNAL









Adey et al., PRD 89 (2014) 071301

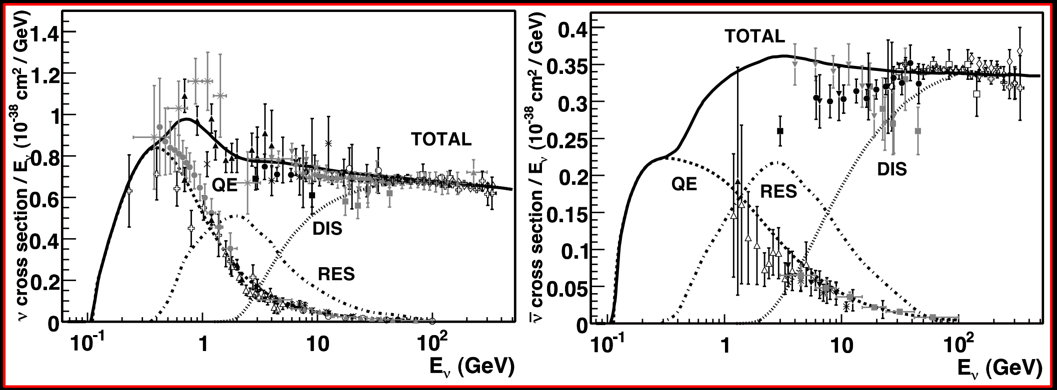
Search for CPiV in lbl oscillations

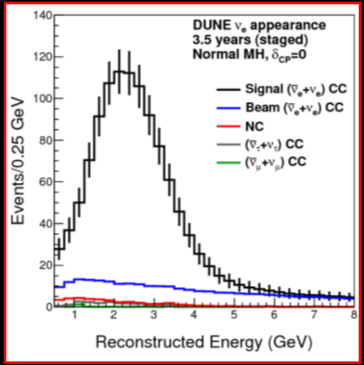
In search for CPiV in lbl experiments …

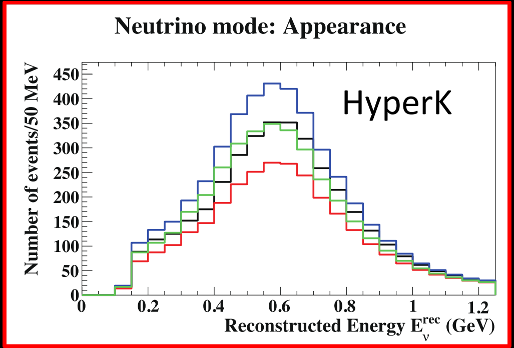
- **Lack of knowledge of cross-sections leads to:**
  - **Systematic uncertainties; and**
  - **Biases; pernicious if ν and $\bar{\nu}$ differ**

Specification: energy range

- Guidance from:
  - Models:
    - Region of overlap 0.5—8 GeV
  - DUNE/Hyper-K far detector spectra:
    - 0.3—6 GeV



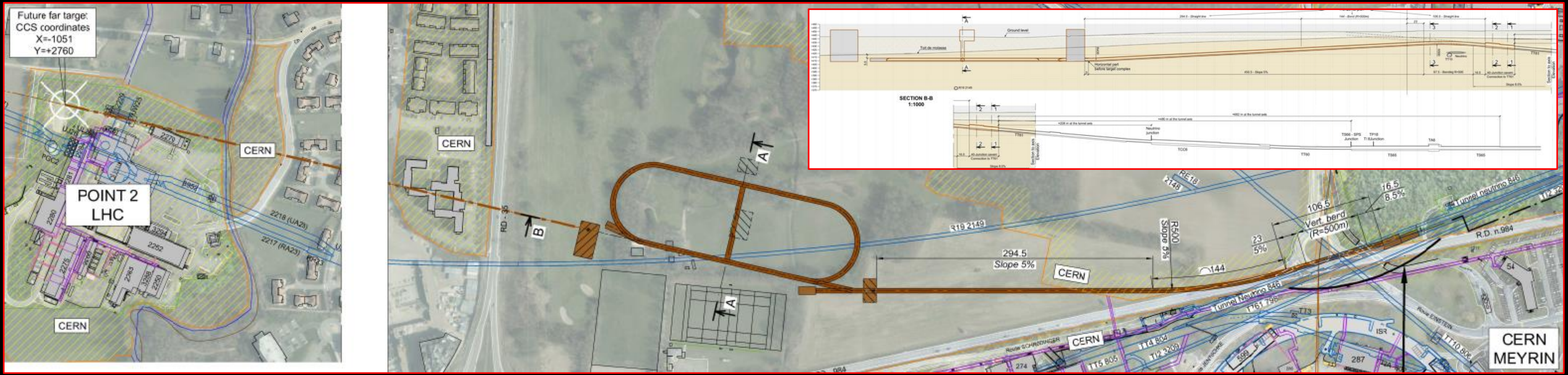




- Cross sections depend on:
  - Q^2 and W:
    - Assume (or specify) a detector capable of:
      - Measuring exclusive final states
      - Reconstructing Q^2 and W
    - → E_μ < 6 GeV
- So, stored muon energy range:

$1 < E_\mu < 6$ GeV

Overview



- Extraction from SPS through existing tunnel
- Siting of storage ring:
  - Allows measurements to be made 'on or off axis'
  - Preserves sterile-neutrino search option

CCQE measurement at nuSTORM

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

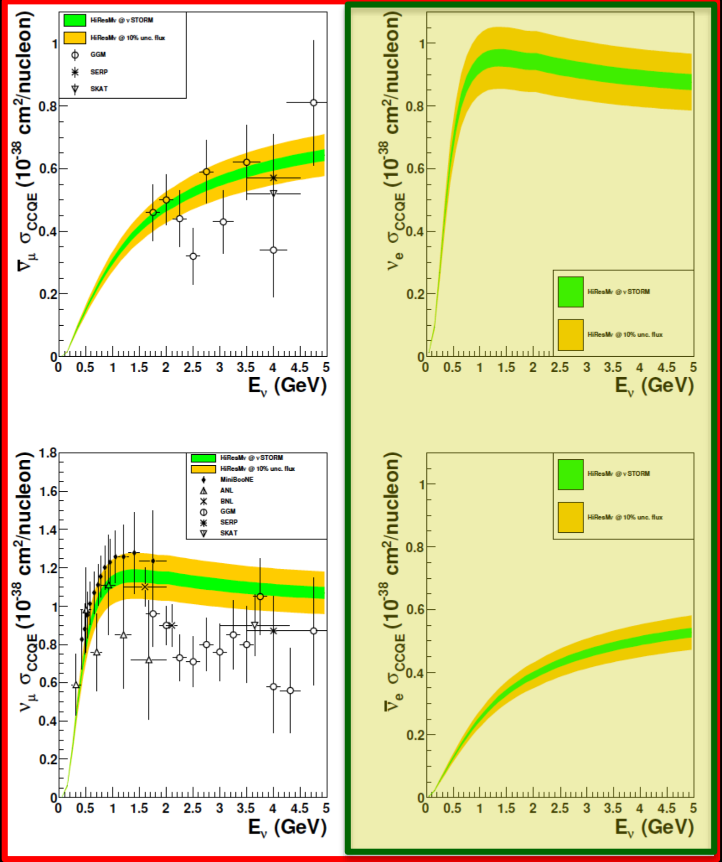
1% & 10% flux uncertainty

- **CCQE at nuSTORM:**
  - Six-fold improvement in beam systematic uncertainty compared with (present) "state of the art"
  - Electron-neutrino cross section measurement unique(ish)

- **Require to demonstrate:**
  - ~<1% precision on flux

Cf/synergy with EnuBET

10.1103/PhysRevD.89.071301; arXiv:1305.1419



Individual ν_e measurements from T2K and MINERvA [10.1103/PhysRevLett.113.241803, 10.1103/PhysRevLett.116.081802]

nuSTORM feasibility

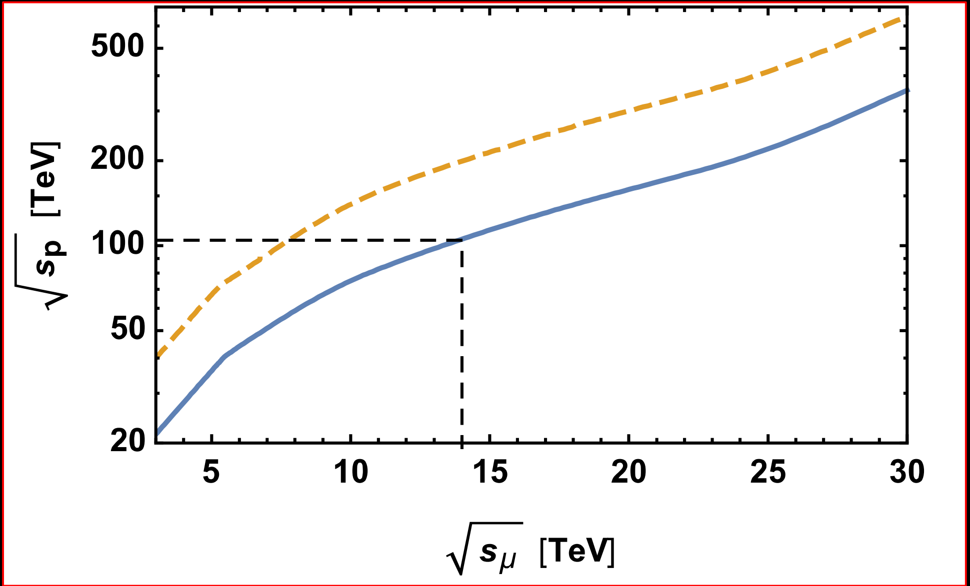
- Goal of PBC nuSTORM study:
  - *"A credible proposal for siting at CERN …"*

  achieved.

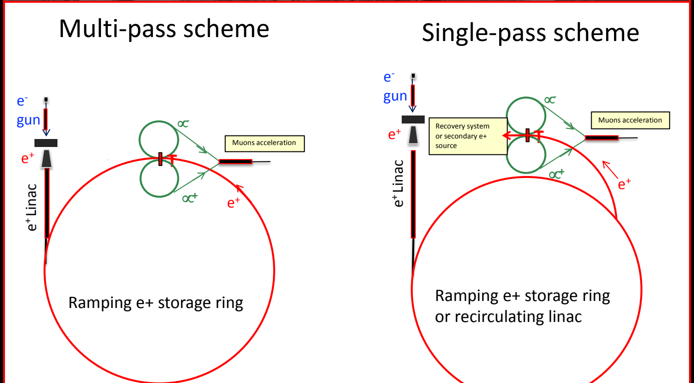
" … the SPS can provide the beam and offers a credible fast extraction location allowing the beam to be directed towards a green field site at a suitable distance from existing infrastructure. Initial civil engineering sketches have established a potential footprint and the geology is amenable to an installation at an appropriate depth."

- Challenges:
  - Muon decay ring:
    - FFA concept though feasible requires magnet development
  - Detailed evaluation of:
    - Proton-beam extraction, target and target complex

Muon collider: benefit and options



- **Benefit:**
  - **Fundamental fermion:**
    - **Cf *pp* beam energy available in collision**
- **Options:**
  - **Proton driven (MAP); positron driven (LEMMA)**
- **Personal conviction:**
  - **Programme requires demonstrators of increasing complexity**



Nucl.Instrum.Meth. A807 (2016)

nuSTORM as muon-collider test bed

R&D that could be supported by nuSTORM facility:

- Target and capture
- Large-aperture ring
  - Demonstrator for, e.g.:
    - LEMMA accumulator ring, muon acceleration ring, …
- 6D cooling experiment to follow MICE
- Storage-ring instrumentation:
  - Luminosity, polarization, energy spectrum, …

European Strategy for PP update

Innovative accelerator technology underpins the physics reach of high-energy and high-intensity colliders… The technologies under consideration include high-field magnets, high-temperature superconductors, plasma wakefield acceleration and other high-gradient accelerating structures, bright muon beams, energy recovery linacs. The European particle physics community must intensify accelerator R&D and sustain it with adequate resources. …

High-priority future initiatives

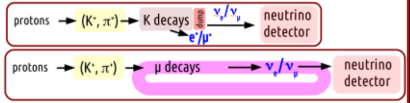
European Strategy for Particle Physics update

To extract the most physics from DUNE and Hyper-Kamiokande, a complementary programme of experimentation to determine neutrino cross-sections and fluxes is required. Several experiments aimed at determining neutrino fluxes exist worldwide. The possible implementation and impact of a facility to measure neutrino cross-sections at the percent level should continue to be studied.

Other essential scientific activities for particle physics

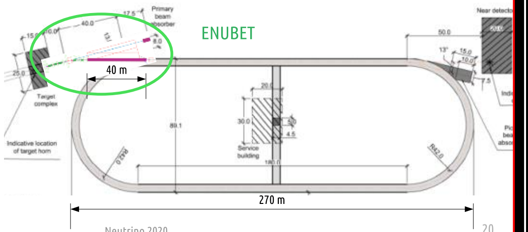
Andrea Longhin, Neutrino 2020

nuSTORM & ENUBET



	Decay region	Hadron dump	Proton extraction	Target, sec. transfer line, p-dump	Neutrino detector
ENUBET	~40 m. Instrumented.	Yes. Dumps muons in addition preventing a (small) ν_e pollution to K_{e3} - ν_e	Slow, 400 GeV (flexible)	Yes, similar	~100 m (some flexibility)
nuSTORM	Replaced by straight section of the ring (180 m).	No. Muons are kept: the most interesting flux parents.	Fast, 100 GeV	Yes, similar	> 300 m from target (ring straight section)

- Different concepts, budget, geometry.
- Main synergy: target facility, 1st stage of meson focusing, proton dump.



A. Longhin   Neutrino 2020   20

Opportunity …

Exploit synergies:

Articulate the need

Common requirement:

Advanced neutrino detector

Conclusions

- **nuSTORM will be a unique facility:**
  - **%-level *electron* and muon neutrino cross-sections**
  - **Exquisitely sensitive sterile neutrino searches**
  - **Serve 6D cooling experiment & muon accelerator test bed**

- **Feasibility of executing nuSTORM at CERN:**
  - **Established through Physics Beyond Colliders study**

- **nuSTORM: a step towards the muon collider:**
  - **Proof-of-principle and test bed for stored muons for particle physics**
  - **Ionization cooling:**
    - **Experimental demonstration of 6D ionization colling**
      - **Required in *p*-driven neutrino factory and muon collider**

nuSTORM:
authors and acknowledgements …

Potted history:

*nuSTORM*_v1: David Neuffer (1980) [non-interacting ν (Maurons) search]
nuSTORM_v2: At Fermilab (RIP 2013)
nuSTORM_v3: At CERN

Input to the European Particle Physics Strategy Update 2018-2020

Americas:	29
Asia:	7
Europe:	81
Total:	***117***

nuSTORM at CERN: Executive Summary

Contact*: *K. Long*
Imperial College London, Exhibition Road, London, SWZ 2AZ, UK; and
STFC, Rutherford Appleton Laboratory, Harwell Campus, Didcot, OX11 0QX, UK

Abstract

The Neutrinos from Stored Muons, nuSTORM, facility has been designed to deliver a definitive neutrino-nucleus scattering programme using beams of $\overset{(-)}{\nu}_e$ and $\overset{(-)}{\nu}_\mu$ from the decay of muons confined within a storage ring. The facility is unique, it will be capable of storing $\mu^\pm$ beams with a central momentum of between 1 GeV/c and 6 GeV/c and a momentum spread of 16%. This specification will allow neutrino-scattering measurements to be made over the kinematic range of interest to the DUNE and Hyper-K collaborations. At nuSTORM, the flavour composition of the beam and the neutrino-energy spectrum are both precisely known. The storage-ring instrumentation will allow the neutrino flux to be determined to a precision of 1% or better. By exploiting sophisticated neutrino-detector techniques such as those being developed for the near detectors of DUNE and Hyper-K, the nuSTORM facility will:

- Serve the future long- and short-baseline neutrino-oscillation programmes by providing definitive measurements of $\overset{(-)}{\nu}_e A$ and $\overset{(-)}{\nu}_\mu A$ scattering cross-sections with percent-level precision;
- Provide a probe that is 100% polarised and sensitive to isospin to allow incisive studies of nuclear dynamics and collective effects in nuclei;
- Deliver the capability to extend the search for light sterile neutrinos beyond the sensitivities that will be provided by the FNAL Short Baseline Neutrino (SBN) programme; and
- Create an essential test facility for the development of muon accelerators to serve as the basis of a multi-TeV lepton-antilepton collider.

To maximise its impact, nuSTORM should be implemented such that data-taking begins by $\approx 2027/28$ when the DUNE and Hyper-K collaborations will each be accumulating data sets capable of determining oscillation probabilities with percent-level precision.

With its existing proton-beam infrastructure, CERN is uniquely well-placed to implement nuSTORM. The feasibility of implementing nuSTORM at CERN has been studied by a CERN Physics Beyond Colliders study group. The muon storage ring has been optimised for the neutrino-scattering programme to store muon beams with momenta in the range 1 GeV to 6 GeV. The implementation of nuSTORM exploits the existing fast-extraction from the SPS that delivers beam to the LHC and to HiRadMat. A summary of the proposed implementation of nuSTORM at CERN is presented below. An indicative cost estimate and a preliminary discussion of a possible time-line for the implementation of nuSTORM are presented the addendum.

*Author list presented in the addendum.

J.T. Sobczyk
Institute of Theoretical Physics, University of Wroclaw, pl. M. Borna 9,50-204, Wroclaw, Poland

K.T. McDonald
Princeton University, Princeton, NJ, 0

G. Hanson
Department of Physics and Astronomy

D. Orestano, L. Tortora
INFN Sezione di Roma Tre and Dipar

R.E. Edgecock, J.B. Lagrange, W. Mu
STFC Rutherford Appleton Laborator

J.A. Hernando Morata
Universidade de Santiago de Compos ago de Compostela, Spain

C. Booth
University of Sheffield, Dept. of Physi

S.R. Mishra
Department of Physics and Astronomy

S. Bhadra
Department of Physics and Astronom Canada

L. Alvarez Ruso, A. Cervera, A. Do M. Sorel, P. Stamoulis
Instituto de Fisica Corpuscular (IFIC) terna, Apartado 22085, 46071 Valenc

M. Chung
UNIST, Ulsan, Korea

M. Hartz†
TRIUMF, 4004 Wesbrook Mall, Vanco
† *Also at Department of Physics, Universi*

M. Palmer
Brookhaven National Laboratory, P.O

P. Huber, C. Mariani, J.M. Link, V. Pa
Virginia Polytechnic Inst. and State U

J.J. Back, G. Barker, S.B. Boyd, P. Fra
Department of Physics, University of

N. McCauley, C. Touramanis
Department of Physics, Oliver Lodge La

J. Lopez Pavon†
Departamento de Física Teórica and Ins Madrid, Cantoblanco, 28049 Madrid, Sp
† *Theoretical Physics Department, CERN, 12*

R. Appleby, S. Tygier
The University of Manchester, 7.09, Sch Institute, Daresbury Laboratory, WA4 4A

H.A. Tanaka
SLAC National Accelerator Laboratory,

M. Bonesini
Sezione INFN Milano Bicocca, Dipartim

A. de Gouvêa
Northwestern University, Dept. of Phy 60208-3112 USA

Y. Kuno, A. Sato
Osaka University, Graduate School, Sch 0043, Japan

S.K. Agarwalla
Institute of Physics, Sachivalaya Marg, S

W. Winter
Deutsches Elektronen-Synchrotron, Notk

K. Mahn
High Energy Physics, Biomedical-Physic Rd, East Lansing, MI 48824, USA

D. Wark, A. Weber†
Particle Physics Department, The Denys
† *Also at STFC, Rutherford Appleton Labora*

L.Cremaldi, D. Summers
University of Mississippi, Oxford, MS, U

L. Stanco
INFN, Sezione di Padova, 35131 Padova

S.J. Brice, A.D. Bross, S. Feher, N. Mokhov, S. Striganov
Fermilab, P.O. Box 500, Batavia, IL 60510-50

C.C. Ahdida, W. Bartmann, J. Bauche, M. Ca ont, A. de Roeck, F.M. Velotti
CERN,CH-1211, Geneva 23, Switzerland
† *Also at PRISMA Cluster of Excellence, Johanne*

A. Blondel, E.N. Messomo, F. Sanchez Nieto
University de Geneve, 24, Quai Ernest-Anser

J.J. Gomez-Cadenas
Donostia International Physics Center (DIPC bastián, Gipuzkoa, Spain

U. Mosel
Justus Liebig Universität,m, Ludwigstraße 23

R. Bayes, S.-P. Hallsjö, F.J.P. Soler
School of Physics and Astronomy, Kelvin Buil UK

H.M. O'Keeffe, L. Kormos, J. Nowak, P. Rat
Physics Department, Lancaster University, L

D. Colling, P. Dornan, P. Dunne, P.M. Jonsso macher, J. Pasternak, M. Scott, J.K. Sedgbeer
Physics Department, Blackett Laboratory, I 2AZ, UK
† *Also at STFC, Rutherford Appleton Laboratory,*

F. di Lodovico
Queen Mary University of London, Mile End

R. Nichol
Department of Physics and Astronomy, Unive UK

S.A. Bogacz
Thomas Jefferson National Accelerator Facili

Y. Mori
Kyoto University, Research Reactor Institute, 0494 Japan

Addendum to the Executive Summary of nuSTORM at CERN

Editors of the ESPPU Executive Summary:

C.C. Ahdida [1], R. Appleby[2], W. Bartmann[1], J. Bauche[1], M. Calviani[1], J. Gall[1], S. Gilardoni[1], B. Goddard[1], C. Hessler[1], P. Huber[3], I. Efthymiopoulos[1], J.B. Lagrange[4], M. Lamont[1], K. Long[5,4], J.A. Osborne[1], J. Pasternak[5,4], F.J.P. Soler[6], S. Tygier[1], and F.M. Velotti[1]

[1] *CERN, Esplanade des Particules 1, 1217 Meyrin, Switzerland*
[2] *School of Physics & Astronomy, University of Manchester, Oxford Road, Manchester, M13 9PL, UK*
[3] *Virginia Polytechnic Institute and State University, 925 Prices Fork Road, Blacksburg, VA 24061, USA*
[4] *STFC, Rutherford Appleton Laboratory, Harwell Campus, Didcot, OX11 0QX*
[5] *Imperial College London, Exhibition Road, London, SWZ 2AZ, UK*
[6] *School of Physics and Astronomy, University of Glasgow, Glasgow, G12 8QQ, UK*

1 Full author list

The full author list is presented to indicate the community that is interested in the implementation and exploitation of nuSTORM.

S. Goswami
Physical Research Laboratory, Ahmedabad 380009, India

F. Filthaut†
Nikhef, Amsterdam, The Netherlands
† *Also at Radboud University, Nijmegen, The Netherlands*

J. Tang
Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China

P. Kyberd, D.R. Smith
College of Engineering, Design and Physical Sciences, Brunel University London, Uxbridge, Middlesex, UB8 3PH, UK

M.A. Uchida
Cavendish Laboratory (HEP), JJ Thomson Avenue, Cambridge, CB3 0HE, UK

D.M. Kaplan, P. Snopok
Illinois Institute of Technology, Chicago, IL, USA

M. Hostert, S. Pascoli
Institute for Particle Physics Phenomenology, Department of Physics, University of Durham, Science Laboratories, South Rd, Durham, DH1 3LE, UK