nuSTORM

K. Long, 4 April, 2017

Acknowledgements

- **nuSTORM collaboration and FNAL study of nuSTORM (A.Bross et al) and especially**

First discussion of nuSTORM in the context of the Physics Beyond Colliders workshop

Thursday 16 Feb 2017, 13:00 → 16:00 Europe/London

Seminar Room 109 (Sir Alexander Fleming Building, Imperial College London)

Kenneth Richard Long (Imperial College (GB))

https://indico.cern.ch/event/606246/

Description The physics potential of nuSTORM was presented in the September 2016 "Physics Beyond Colliders" (PBC) workshop kick-off meeting. A work-package has been created in the PBC workshop to consider the feasibility of implementing nuSTORM in the North Area at CERN and to evaluate its performance.

The meeting will review briefly the neutrino physics of nuSTORM and the work that has been done to date on its design. Time has been set aside in the agenda of the meeting for the discussion of the studies to be pursued in the context of the PBC workshop.

Please make your way to the Exhibition Road entrance of Imperial College London. The Sir Alexander Fleming (SAF) building is located on the road that leads from entrance to the College on the left-hand side. It is a large, modern glass structure. Please see the map of the College below.

To reach Seminar Room 109, enter the SAF building and go up the short flight of stairs directly opposite the entrance. Walk to the end of the mezzanine. Seminar Room 109 is located on the right hand side towards the end of the passage.

The times in the agenda below are local times; i.e. all times are in GMT.

Phone conference details for remote participants are listed in the second attachment below.

Map-of-South-Kensin... Phone-details.pdf

- Executive summary of:
  - Physics case and motivation
  - FNAL-based design:
    - Extraction, beam onto target
    - Pion capture and transport
    - Stochastic injection
    - Storage ring (two options) and extraction
    - Beamline instrumentation
    - Civil and implementation considerations

13:00 → 13:10 **Welcome and introduction**
Speaker: Kenneth Richard Long (Imperial College (GB))
01-2017-02-16-Lon... 01-2017-02-16-Lon...

13:10 → 13:30 **Motivation for neutrino cross-section measurements at nuSTORM**
Speaker: Patrick Huber (Virginia Tech)
02-nuSTORM-01Hu...

13:30 → 13:50 **The challenges in neutrino-nucleus scattering physics to be addressed by nuSTORM**
Speaker: Jorge G. Morfin (Fermilab)
Morfin-Challenges...

13:50 → 14:10 **nuSTORM and the Physics Beyond Colliders workshop**
Speaker: Mike Lamont (CERN)
PBC-nuSTORM-Feb... PBC-nuSTORM-Feb...

14:10 → 14:30 **nuSTORM at FNAL - performance of target, horn, injection and FODO ring**
Speaker: Dr. Ao Liu (Fermilab)
nuSTORM_first_Ao...

14:30 → 14:50 **nuSTORM at FNAL: consideration of implementation**
Speaker: Alan Bross (Fermilab)
06-nuSTORM.pdf 06-nuSTORM.pptx

14:50 → 15:10 **nuSTORM: design of an FFAG-based storage ring**
Speaker: Jaroslaw Pasternak (Imperial College, London)
FFAG_nustorm_JP...

15:10 → 15:30 **nuSTORM: performance of an FFAG focussing ring**
Speaker: Sam Tygier
sam_slides.pdf

15:30 → 15:50 **Discussion with a view to agreeing the next steps**

15:50 → 16:00 **Conclusions and next meeting**
Speaker: Kenneth Richard Long (Imperial College (GB))
09-2017-02-16-Lon... 09-2017-02-16-Lon...

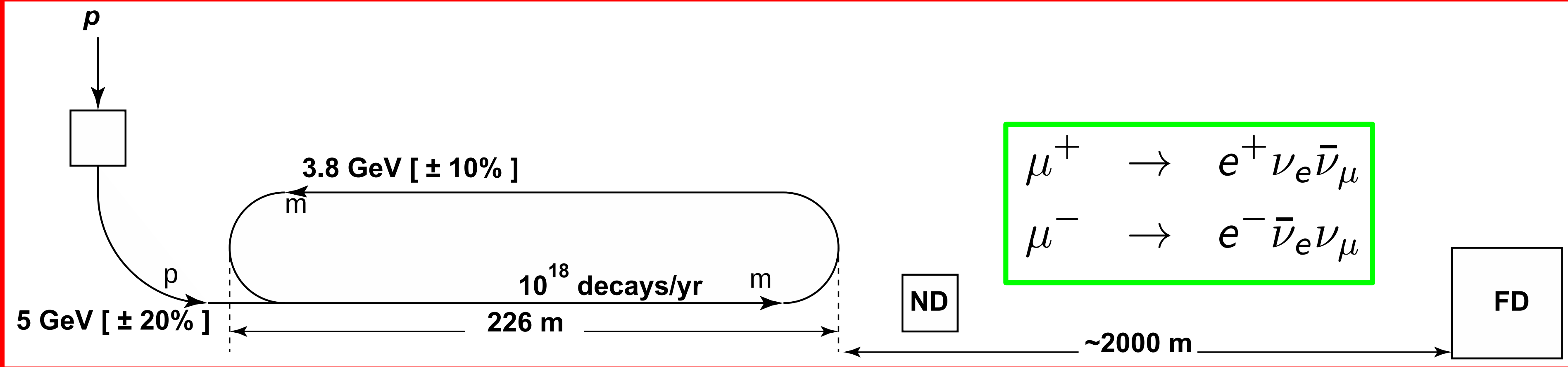
Plan

- What is nuSTORM?
- Why study neutrino interactions?
- The benefit of nuSTORM
- nuSTORM & the CERN Physics Beyond Colliders study
- Conclusions

nuSTORM

WHAT IS nuSTORM?

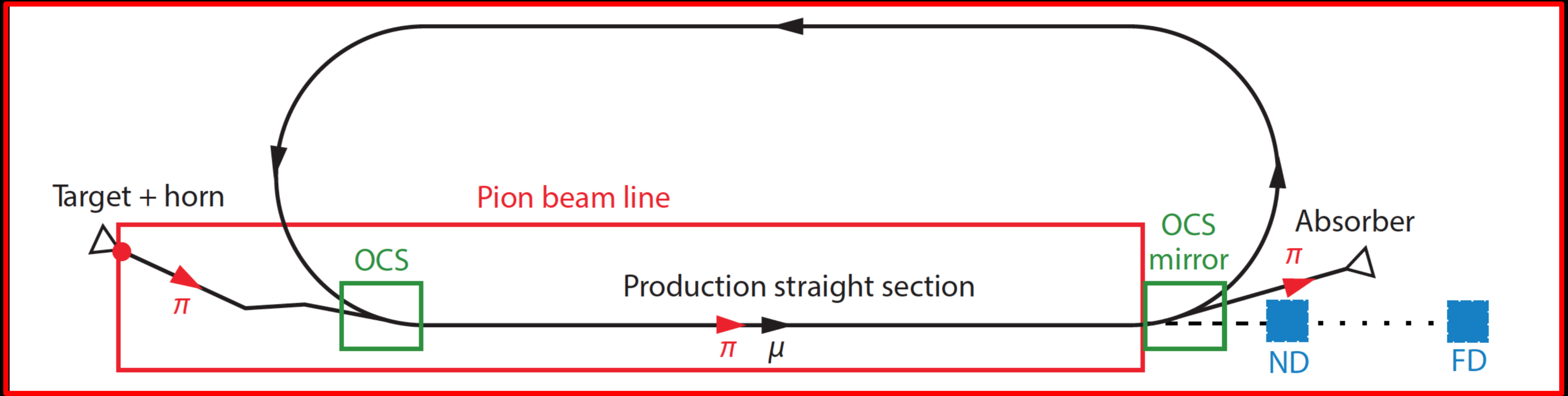
Neutrinos from stored muons



- **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 → ↗ injection pass:
  - "Flash" of muon neutrinos

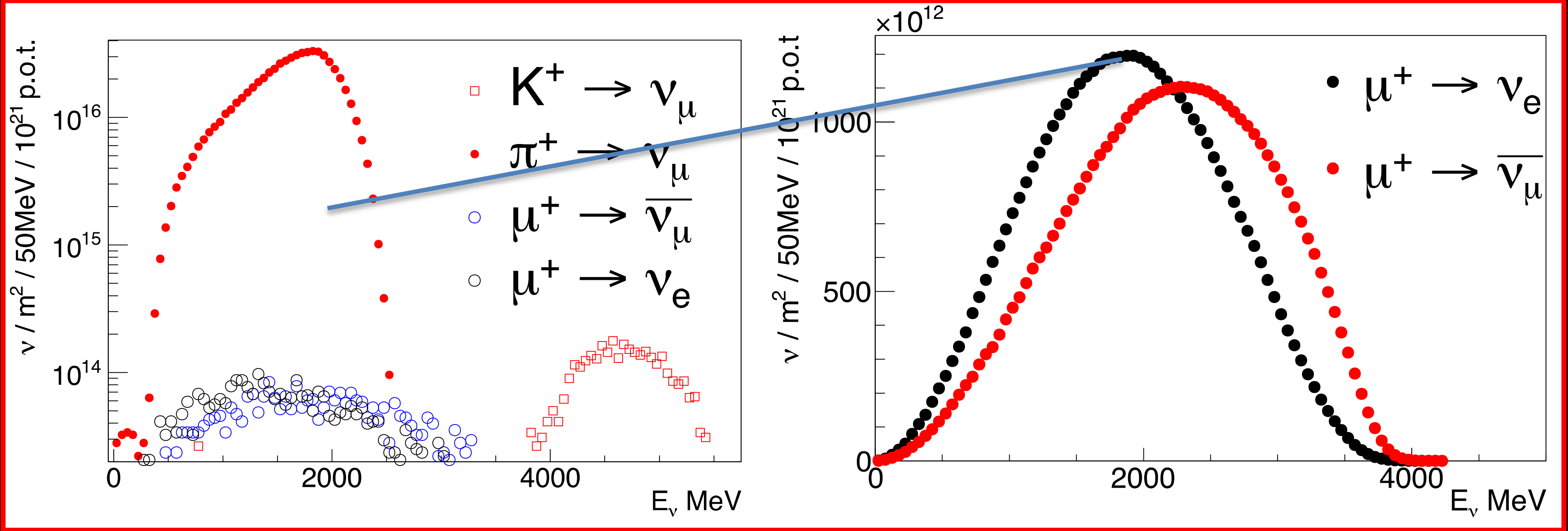
nuSTORM oveview



- Fast extraction at >~ 100 GeV
- Conventional pion production and capture (horn)
  - Quadrupole pion-transport channel to decay ring

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

10.1146/annurev-nucl-102014-021930

Event rates

Per 10^{21} POT illuminating 100 Tonne LAr detector at 50m

μ^+ Channel	N_{evts}	μ^- Channel	N_{evts}
$\bar{\nu}_\mu$ NC	1,174,710	$\bar{\nu}_e$ NC	1,002,240
ν_e NC	1,817,810	ν_μ NC	2,074,930
$\bar{\nu}_\mu$ CC	3,030,510	$\bar{\nu}_e$ CC	2,519,840
ν_e CC	5,188,050	$\bar{\nu}_\mu$ CC	6,060,580
π^+ Channel	N_{evts}	π^- Channel	N_{evts}
ν_μ NC	14,384,192	$\bar{\nu}_\mu$ NC	6,986,343
ν_μ CC	41,053,300	$\bar{\nu}_\mu$ CC	19,939,704

- 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

nuSTORM

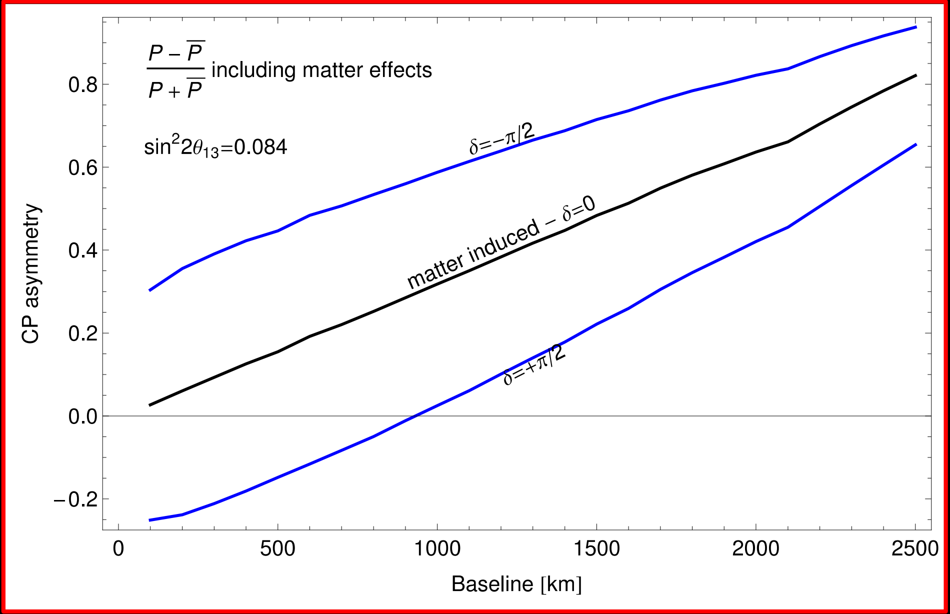
WHY STUDY NEUTRINO INTERACTIONS?

To understand the nucleus, nucleon and contribute to nuclear physics

… but also …

Search for CPiV in lbl oscillations

- Seek to measure asymmetry:
  - $P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)$
    - For DUNE/Hyper-K, true CP asymmetry < 25%
      - Matter effect contributes to observed asymmetry
      - Over much of parameter space, true CP asymmetry small (~5%)

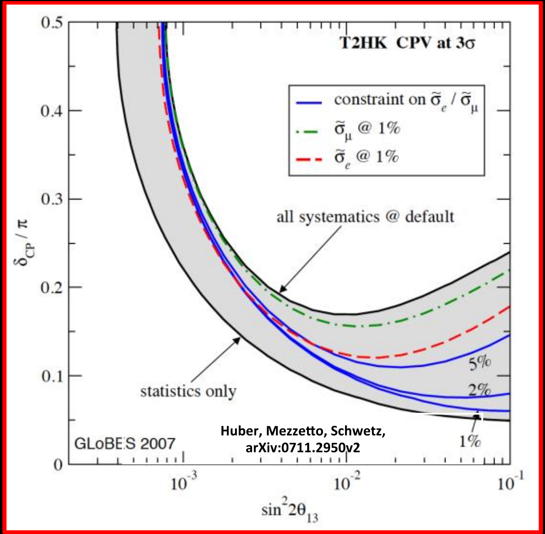


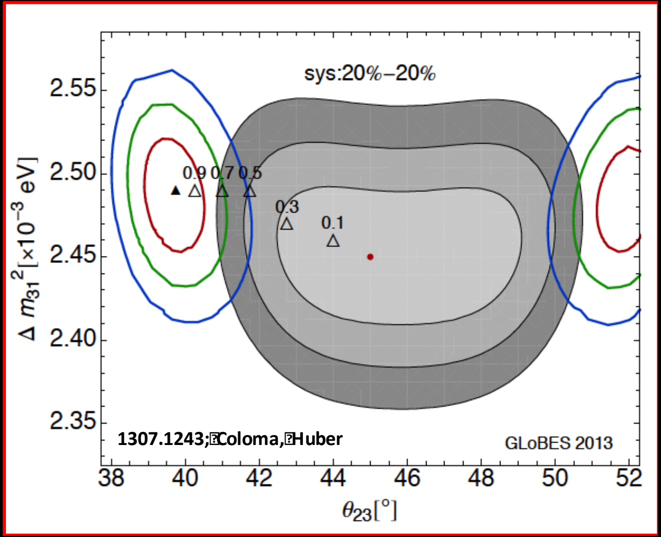
- → "few %-level" measurement of oscillation probabilities

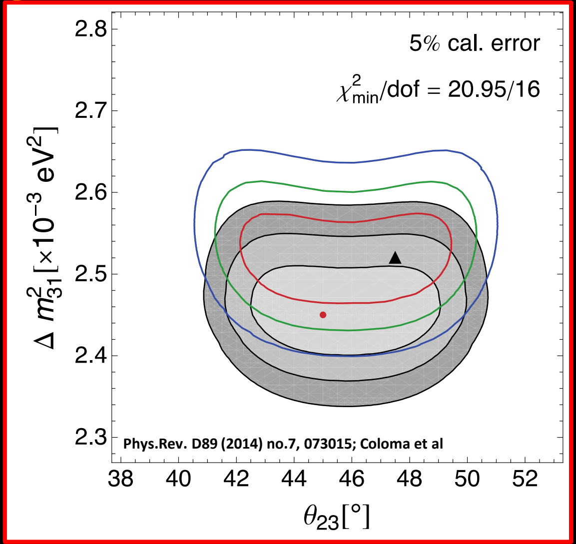
Search for CPiV in lbl oscillations

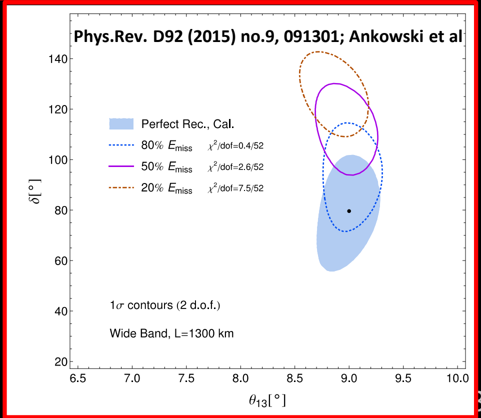
- Seek to measure asymmetry:
  - $P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)$
- Event rates, convolution of:
  - Flux, cross sections, detector mass, efficiency, *E*-scale
    - Measurements at %-level required
  - Theoretical description:
    - Initial state momentum, nuclear excitations, final-state effects

Systematic uncertainty and/or bias









Uncertainty
(cross section and ratio)

Event mis-classification

Energy scale mis-calibration

Missing energy (neutrons)

Search for CPiV in lbl oscillations

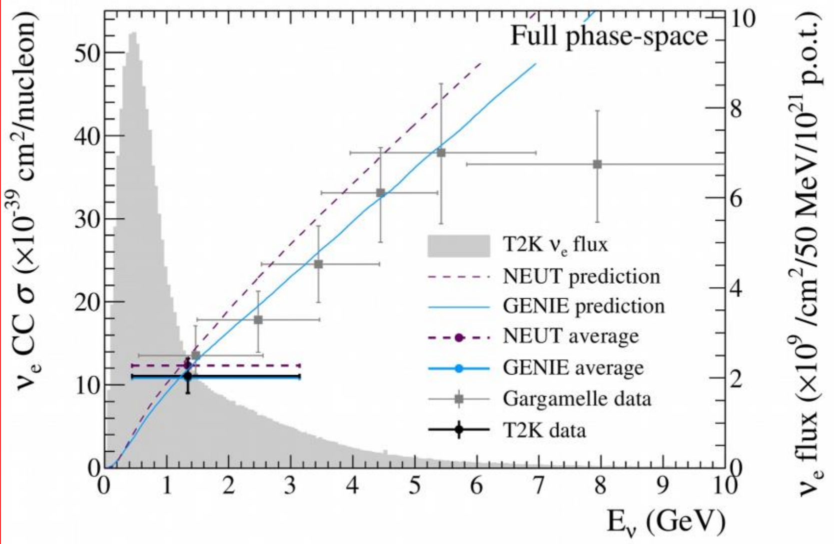
- Seek to measure asymmetry:
  - $P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)$
- Event rates convolution of:
  - Flux, cross sections, detector mass, efficiency, *E*-scale
    - Measurements at %-level required
- Lack of knowledge of cross-sections leads to:
  - Systematic uncertainties; and
  - Biases; pernicious if ν and $\bar{\nu}$ differ

nuSTORM

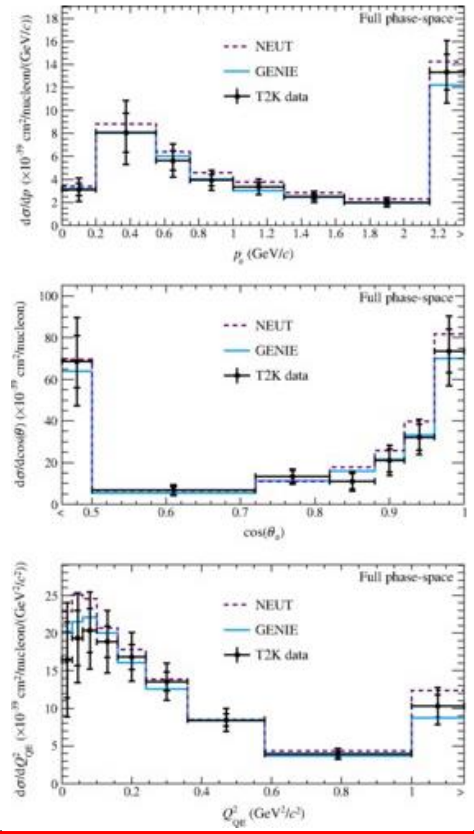
THE BENEFIT OF nuSTORM

$\nu_e N$ cross section measurements

Gargamelle: 244 events at ~90% purity
T2K: 315 events at ~65% purity



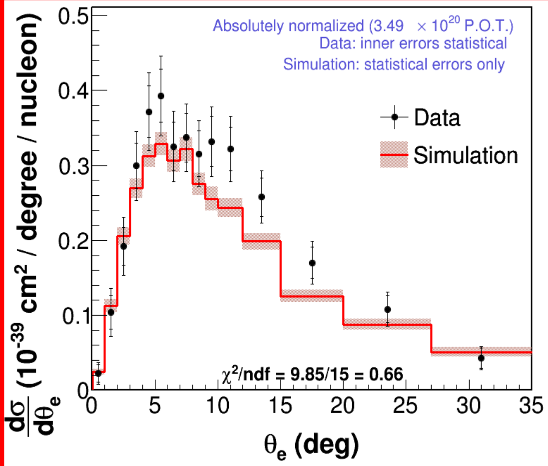
$\sigma_e(E_\nu)$:
Gargamelle (1978) on CF_3Br;
T2K (2014) on CH
Nucl. Phys. B133, 2015
Phys. Rev. Lett. 113, 241803

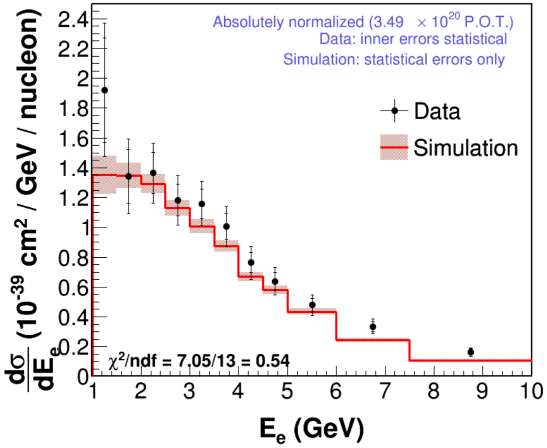


$d\sigma_e/dE_e$, $d\sigma_e/d\theta_e$, $d\sigma_e/dQ^2$:
T2K (2014) on CH
Phys. Rev. Lett. 113, 241803

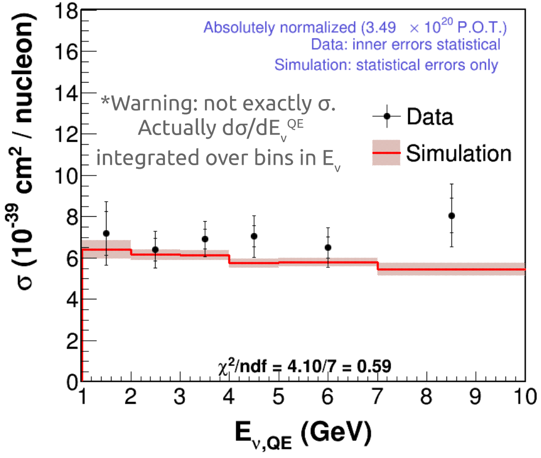
Morfin

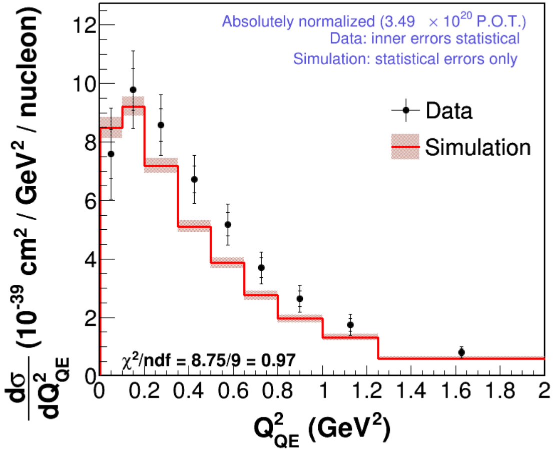
$\nu_e N$ cross section measurements



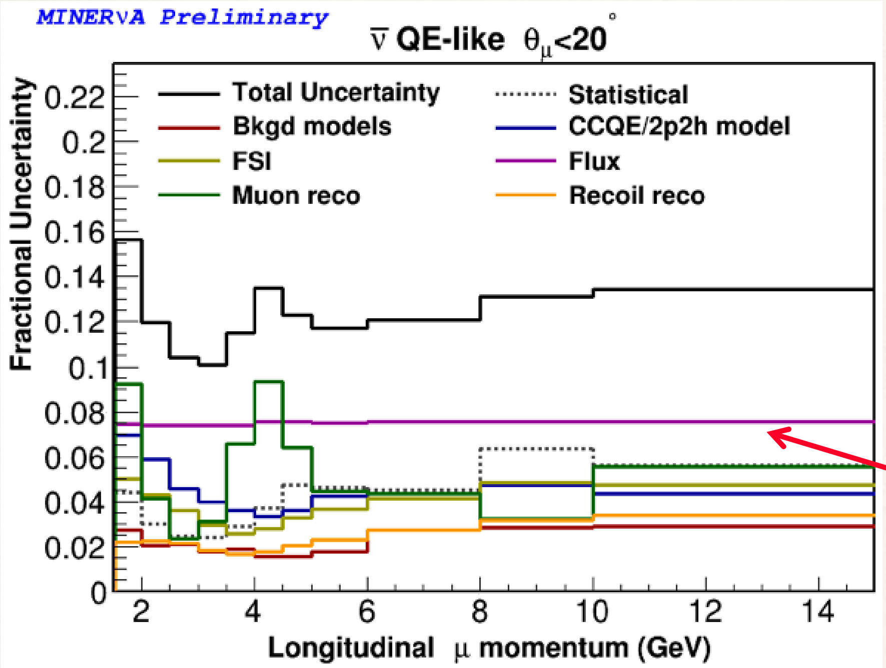


The result and the prediction from GENIE 2.6.2 are statistically consistent.





Systematic uncertainties



Uncertainties projected onto **longitudinal muon momentum**

- - - Statistical uncertainty

Background models

- **resonant** interactions affect background subtraction

CCQE / 2p2h model

- dominated by uncertainty in **correlation effect strength**

Final-state interactions

- **pion absorption** dominates

Flux

- beam focusing
- tertiary hadron production
- reweight to other experiments

Muon reconstruction

- **muon energy scale** dominates
- tracking efficiency
- muon angle and vertex position

Recoil reconstruction

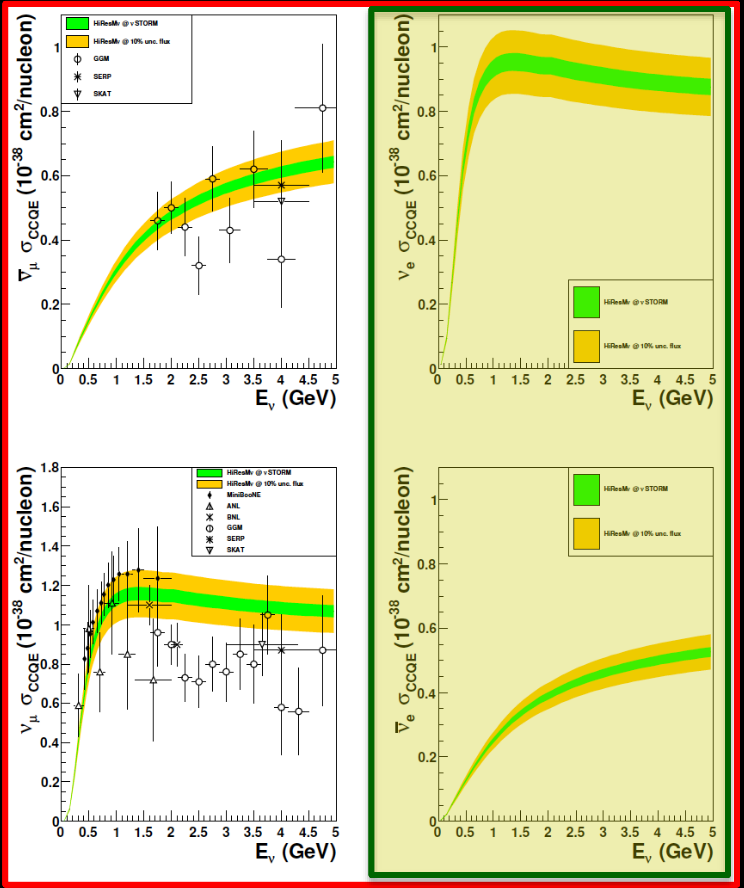
- detector response to different particles - **neutron** dominates

Cheryl Patrick, Northwestern University 42

CCQE measurement at nuSTORM

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

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

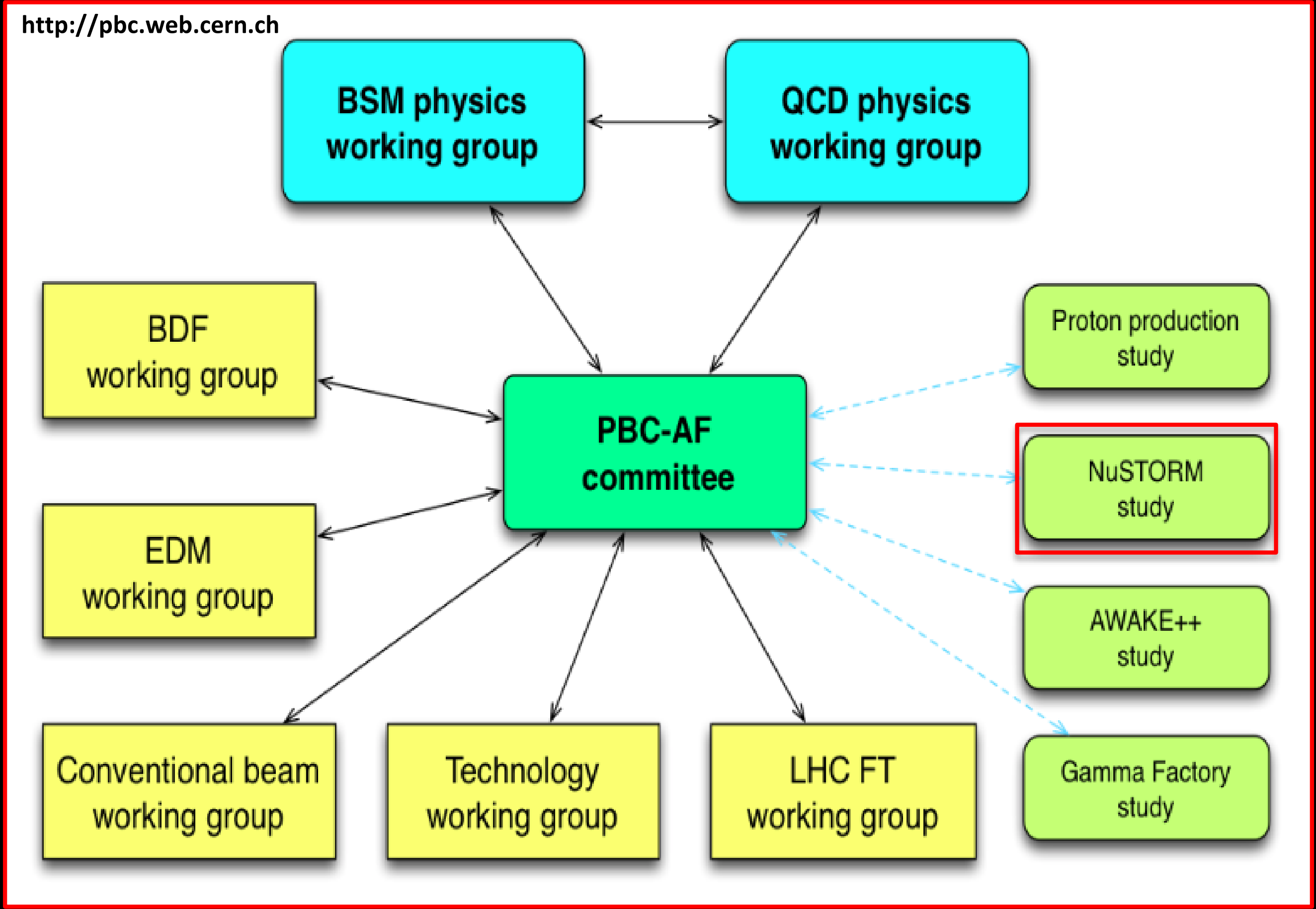


Individual ν_e measurements from T2K and MINERvA [10.1103/PhysRevLett.113.241803, 10.1103/PhysRevLett.116.081802]

10.1103/PhysRevD.89.071301; arXiv:1305.1419

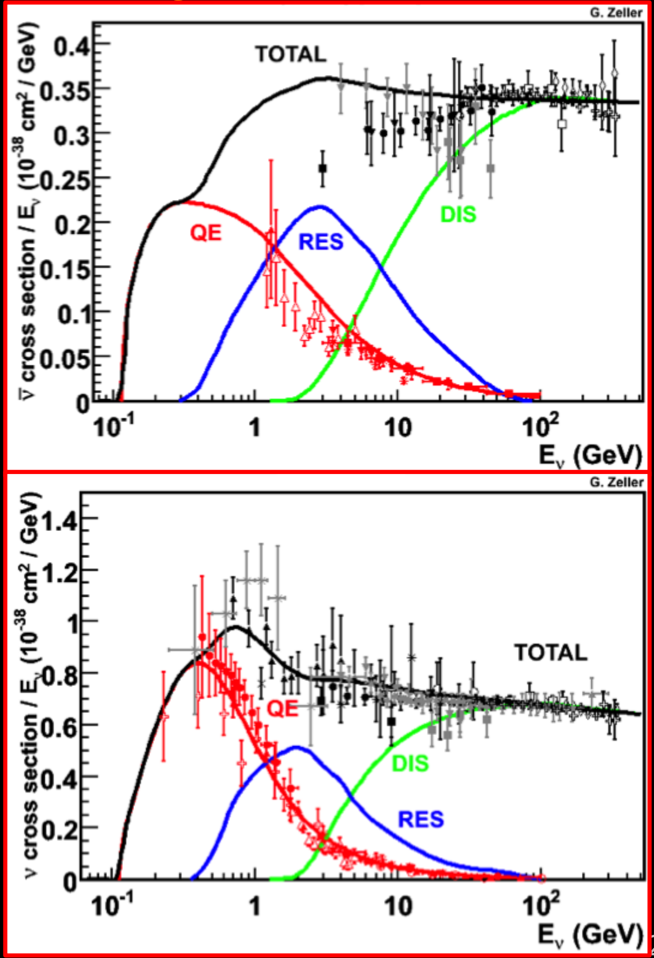
nuSTORM
& THE CERN PHYSICS BEYOND COLLIDERS STUDY GROUP

Physics Beyond Colliders study group



Towards a specification

- Considerations:
  - Energy range:
    - Long- and short-baseline neutrino
    - Nuclear and particle physics
  - Acceptance:
    - Rate
    - Neutrino-energy calibration
  - Experiment:
    - Migration/feed-down



IPPP/NuSTEC topical meeting on neutrino-nucleus scattering

http://conference.ippp.dur.ac.uk/event/583/

18-20 April 2017
Europe/London timezone

IPPP Durham

Search

- Overview
- Timetable
- Contribution List
- Accommodation
- Travel Information

Support

l.a.wilkinson@durham...

Neutrino-nucleus scattering is a critical input to present and future neutrino experiments. Uncertainties related to νA cross sections make a substantial contribution to the systematic-error budgets of, for example, T2K and NOνA, while hadronisation uncertainties need to be addressed in sterile-neutrino-search experiments such as MicroBooNE.

The future sensitivity of DUNE and Hyper-K will be no less sensitive to our understanding of νA scattering. The statistical weight of the data sets collected by each of these experiments will be such that uncertainties on the cross-section themselves and the uncertainty on the ν_e A to ν_μ A cross-section ratio must be reduced to the percent level. Such precise knowledge is required not only to manage the overall systematic uncertainty but also to avoid biases in the oscillation parameters extracted from the data. Evidence for CP-invariance violation (CPiV) will be sought by measuring the rate of ν_e appearance in a ν_μ beam. Therefore, a lack of understanding of ν_e A scattering will be a pernicious source of bias or uncertainty in the interpretation of any evidence for CPiV.

The measurement, theoretical understanding and phenomenological description of νA scattering are each challenging. To understand νA scattering in sufficient detail for the future neutrino-physics programme to reach its full potential will require the effective collaboration of experimenters, theorists and phenomenologists. Indeed, in the energy range of interest, the combined expertise of nuclear and particle theorists and phenomenologists will be required. Such a collaboration is also likely to generate new insights into long-range QCD and nuclear phenomena.

The goals of the workshop will be to:

- Take stock of the current status of , νA scattering data, the nuclear and particle theory through which it is understood and the phenomenological description of the cross sections and hadronic final states;
- Discuss the programme of measurement, theory and phenomenology required to develop an understanding commensurate with the future neutrino-physics programme; and to
- Evaluate the path towards "global fits" that can be used to make reliable predictions of neutrino-nucleus scattering.

The workshop will be organised jointly by the IPPP and NuSTEC and will include discussion, and appropriate development, of the NuSTEC white paper on neutrino scattering. The desired output of the workshop is a short document in which the status of the field is briefly reviewed and the way forward — experimental, theoretical and phenomenological — is outlined.

Will provide i/p to:

- **Nuclear physics case**
- **Energy**

Elements of study

- Physics case:
  - Neutrino-scattering for:
    - Oscillation
    - Nuclear
- Accelerator:
  - Full simulation that demonstrates <~1% flux precision
  - Energy range (i.e. sweep down from max)
- Implementation:
  - Feasibility at CERN (see next slide)
- Detector:
  - Others are "on this", so:
    - Adopt performance of typical, or assumed, detector

Implementation @ CERN Exploratory study

- A credible proposal for siting at CERN, including:
  - SPS requirements
  - Fast extraction, beam-line
  - Target and target complex
  - Horn
  - Siting
  - Civil engineering
  - Radio-protection implications

nuSTORM

Conclusions

Conclusions

- Muon accelerators have the potential to:
  - Revolutionise neutrino physics
  - Provide multi-TeV lepton-anti-lepton collisions

- nuSTORM can deliver:
  - n*N* scattering measurements with precision required to:
    - Serve the long- and short-baseline neutrino programmes
    - Provide a valuable probe for nuclear physics

- CERN PBC study: opportunity to define innovative programme:
    - nuSTORM:
      - Delivers critical measurement: ν_e/ν_μ *N* scattering;
      - Has discovery potential: sterile neutrinos;
      - Potential for 6D ionization-cooling programme to follow MICE

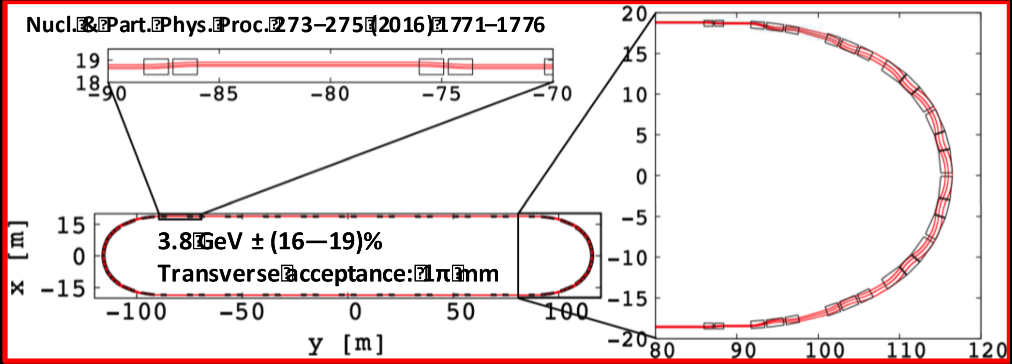
Project overview

BACKUP

Decay ring options

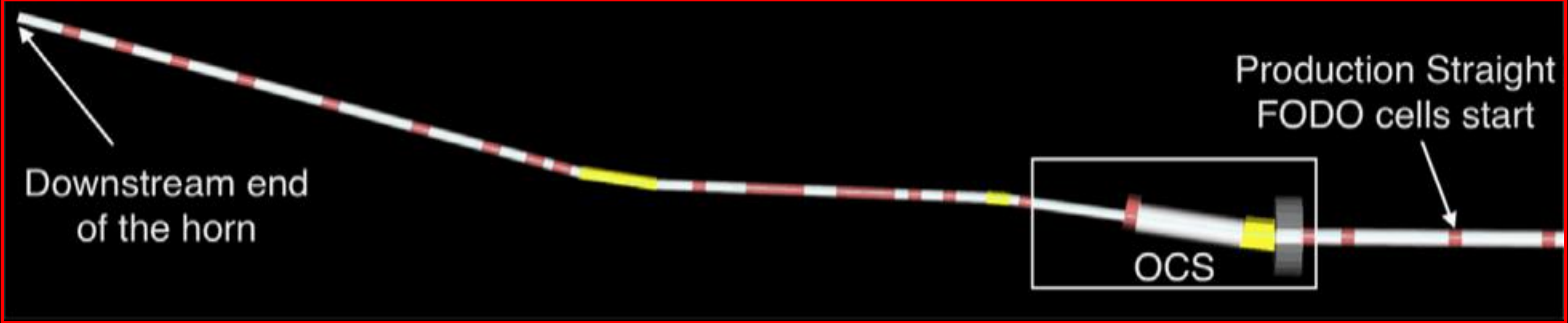
- Quad-focusing FODO ring
  - Low-beta optics in production straight
  - Chicane to minimise “off-momentum” muon decays

- Alternative:
  - Fixed-field alternating gradiant (FFAG) ring

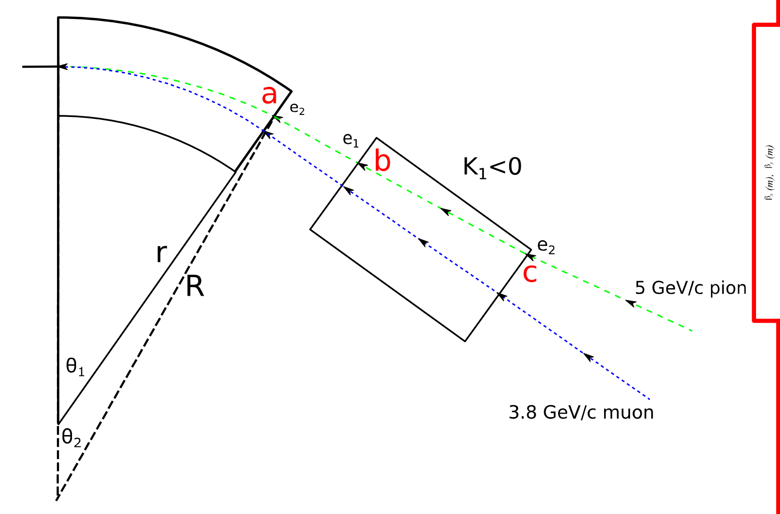


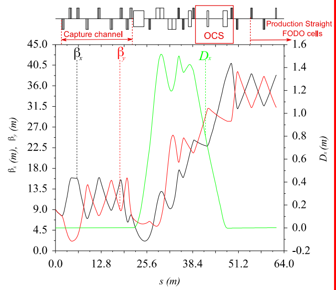
NIM A801 (2015) 44–50

Orbit combination section



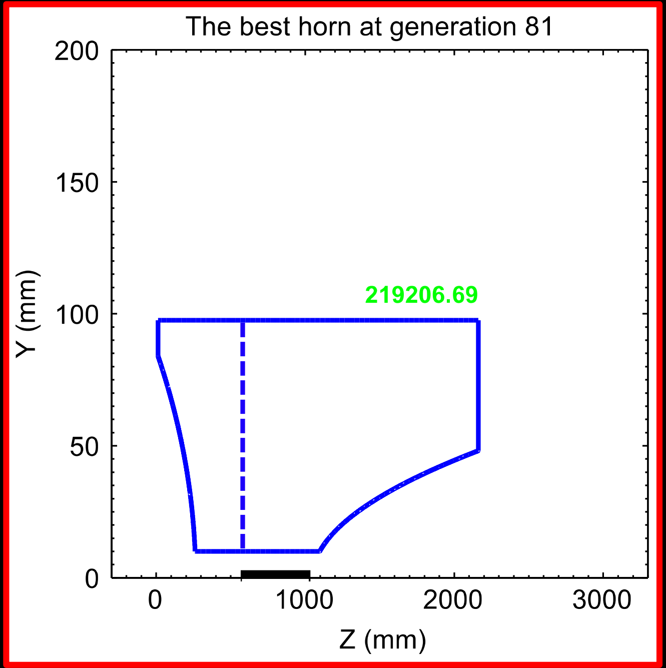
- $E_{pi} > E_{mu}$
  - "Stochastic injection":
    - Pion decay places muons in orbit

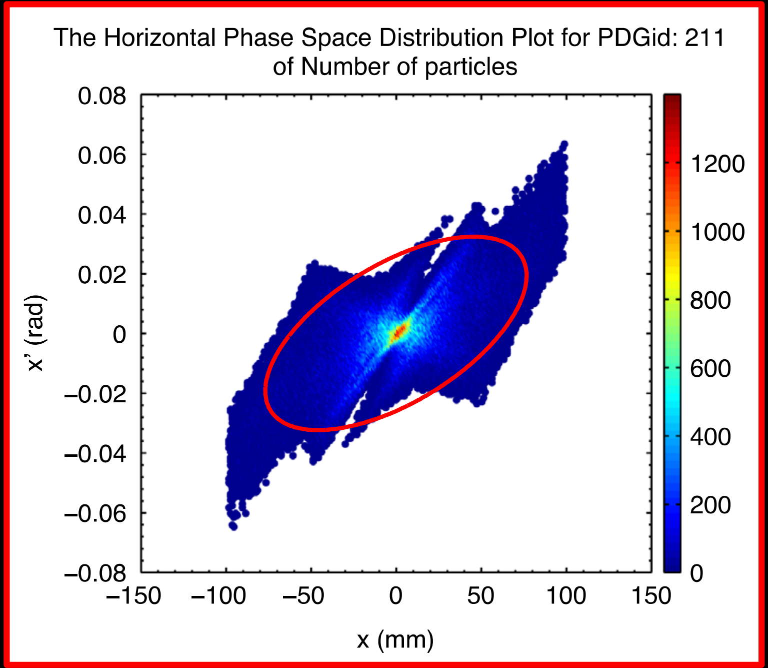




NIM A794 (2015) 200–205

Target and capture





- Horn optimised for pion capture in magnetic channel
  - Example:
    - Phase space obtained in optimisation of horn using inconel target

Documentation

Neutrinos from STORed Muons

Proposal to the Fermilab PAC

P. Kyberd and D.R. Smith

Brunel University, West London, Uxbridge, Middlesex UB8 3PH, UK

H.A. Tanaka

Department of Physics and Astronomy,

Hennings Building, The University of British Columbia,

6224 Agricultural Road, Vancouver, B.C., V6T 1Z1, Canada

L. Coney and G. Hanson

University of California, Riverside

S. Pascoli

Institute for Particle Physics Phenomenology, Durham University

D. Adey, S.J. Brice, A.D. Bross[a], H. Cease, M. Geelhoed,

T. Kobilarcik, A. Liu[b], N. Mokhov, J. Morfin, D. Neuffer,

S. Parke, M. Popovic, P. Rubinov, T. Sen, and S. Striganov

Fermi National Accelerator Laboratory,

Box 500, Batavia, IL 60510-5011, USA

E. Wildner

CERN,CH-1211, Geneva 23, Switzerland

R. Asfandiyarov, A. Blondel, A. Bravar, F. Cadoux, F. Dufour, A. Haesler, Y. Karadzh

A. Korzenev, C. Martin, E. Noah, M. Ravonel, M. Rayner, and E. Scantamburlo

University de Geneve, 24, Quai Ernest-Ansermet, 1211 Geneva 4, Suisse

[a] Corresponding author: bross@fnal.gov

[b] Also at Indiana University Bloomington, 107 S Indiana Ave, Bloomington, IN 47405, USA

May 2013

FESS/Engineering Project No. 6-13-1

nuSTORM Conventional Facilities

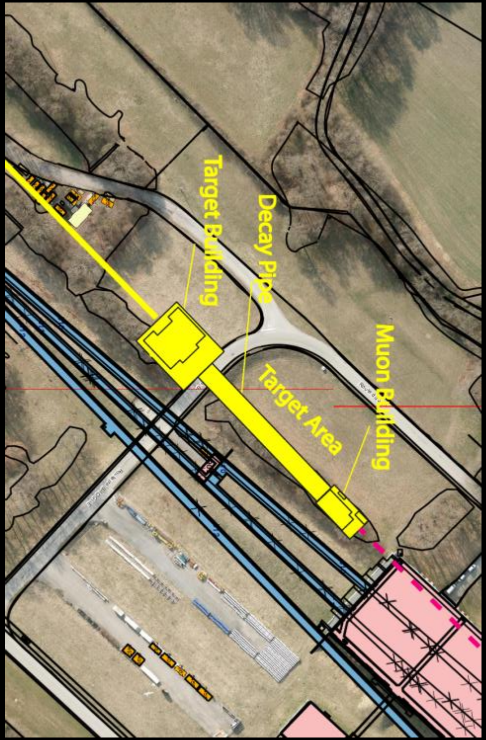
PDR

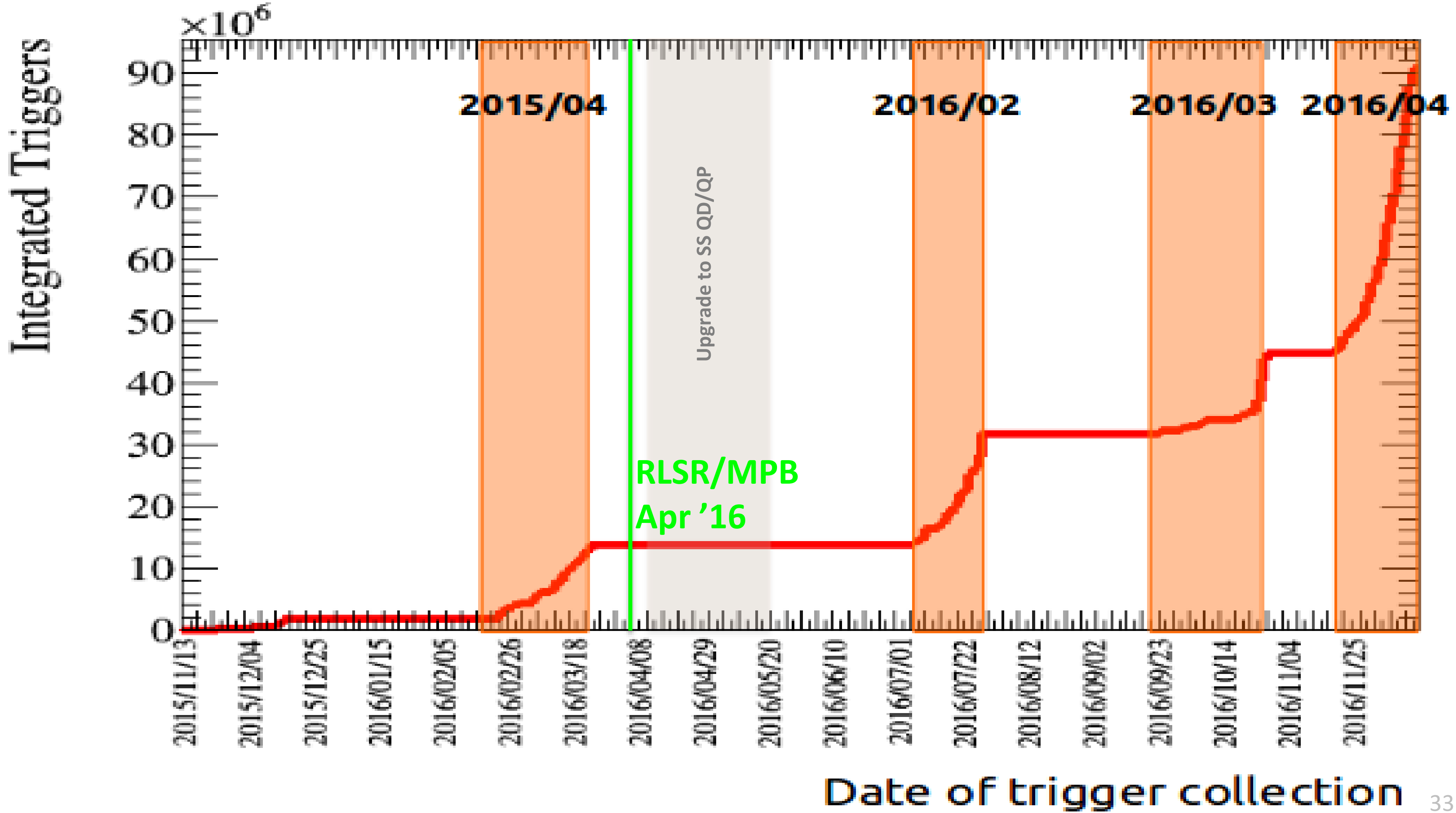
Project Definition Report for the conventional facilities to house the nuSTORM Facilities.

U.S. Department of Energy, Office of Science — Fermi Research Alliance LLC — Fermilab

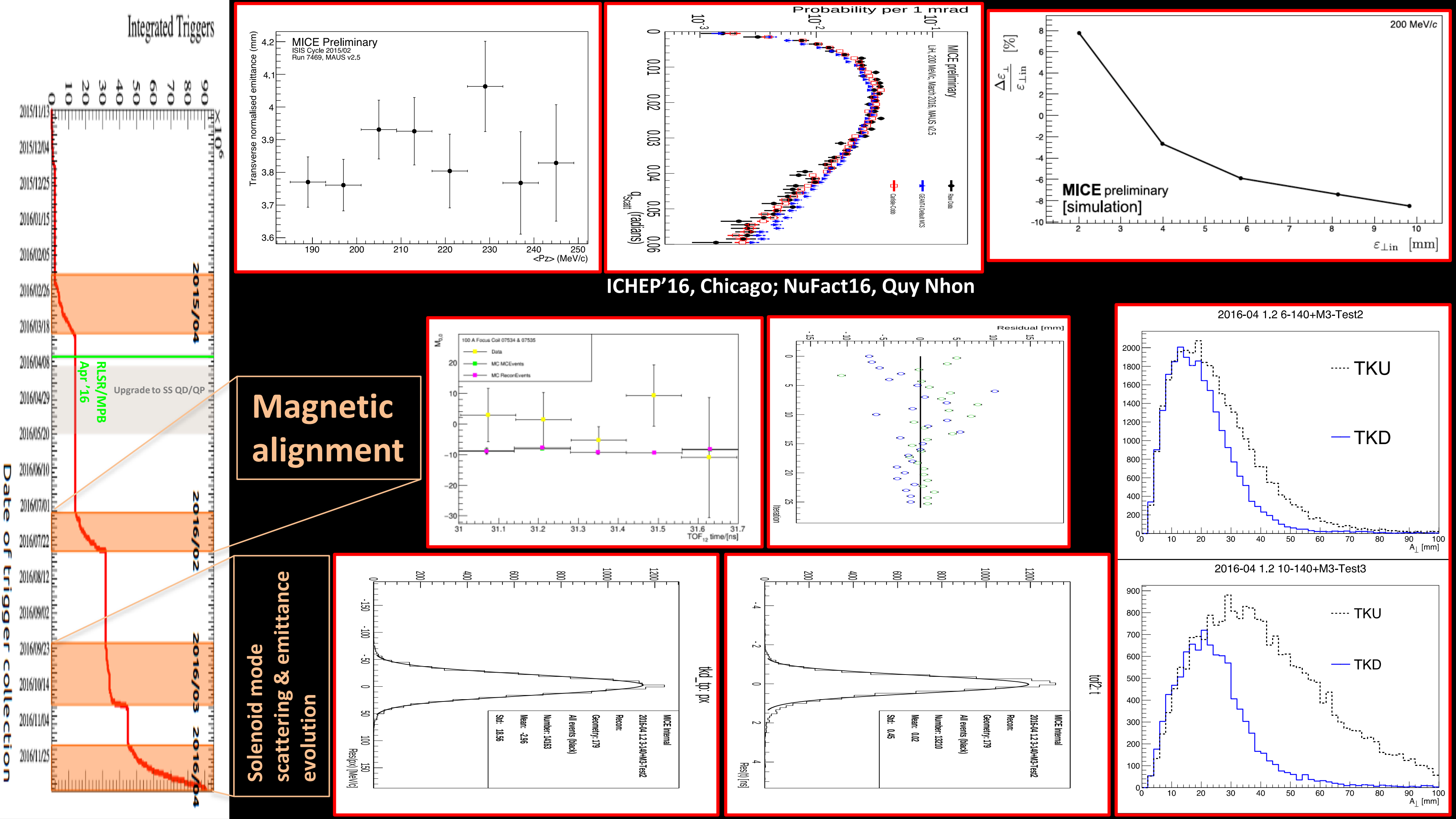
CERN studies:

- LBNO
- SBLNF





$\times 10^6$
Integrated Triggers
90
80
70
60
50
40
30
20
10
0
2015/04
2016/02
2016/03
2016/04
Upgrade to SS QD/QP
RLSR/MPB
Apr '16
2015/11/13
2015/12/04
2015/12/25
2016/01/15
2016/02/05
2016/02/26
2016/03/18
2016/04/08
2016/04/29
2016/05/20
2016/06/10
2016/07/01
2016/07/22
2016/08/12
2016/09/02
2016/09/23
2016/10/14
2016/11/04
2016/11/25
Date of trigger collection



Integrated Triggers
Date of trigger collection
2015/04
2016/02
2016/03
2016/04
RLSR/MPB Apr '16
Upgrade to SS QD/QP
MICE Preliminary
ISIS Cycle 2015/02
Run 7469, MAUS v2.5
Transverse normalised emittance (mm)
<Pz> (MeV/c)
Probability per 1 mrad
MICE preliminary
LiH, 200 MeV/c, March 2016, MAUS v2.5
Raw Data
GEANT4 Default MCS
Carlisle-Cobb
θScatt (radians)
200 MeV/c
MICE preliminary
[simulation]
ICHEP'16, Chicago; NuFact16, Quy Nhon
Magnetic alignment
100 A Focus Coil 07534 & 07535
Data
MC MCEvents
MC ReconEvents
TOF12 time/[ns]
Residual [mm]
Iteration
2016-04 1.2 6-140+M3-Test2
TKU
TKD
A⊥ [mm]
2016-04 1.2 10-140+M3-Test3
Solenoid mode scattering & emittance evolution
tkd_tp: px
MICE Internal
2016-04 1.2 3-140+M3-Test2
Recon:
Geometry: 179
All events (black)
Number: 14163
Mean: -2.56
Std: 18.56
Res(px) [MeV/c]
tof2: t
Number: 13210
Mean: 0.02
Std: 0.45
Res(t) [ns]

Scientific programme

Step IV:

Material properties of LH_2 and LiH that determine the ionization-cooling performance

Observation of $\epsilon_\perp^{n}$ reduction

MICE demonstration of ionization cooling:

Observation of $\epsilon_\perp$ reduction with re-acceleration

Observation of $\epsilon_\perp$ reduction and $\epsilon_{||}$ evolution

Observation of $\epsilon_\perp$ reduction and $\epsilon_{||}$ and angular momentum evolution†

† Requires systematic study of "flip" optics.

ISIS Cycle	From	To	MICE Step IV Programme	Absorber
2015/04	16-Feb-16	25-Mar-16	*Field-off scattering*	*Lithium-hydride*
2016/01	12-Apr-16	20-May-16	*QD/QP upgrade*	*Lithium-hydride*
2016/02	28-Jun-16	29-Jul-16	*Magnetic-channel commissioning*	*Lithium-hydride*
2016/03	13-Sep-16	28-Oct-16	*Field-on scattering*	*Lithium-hydride*
2016/04	15-Nov-16	16-Dec-16	*Solenoid-mode emittance evolution*	*Lithium-hydride*
2016/05	14-Feb-17	31-Mar-17	*Flip-mode emittance evollution*	*Lithium-hydride*
2017/01	02-May-17	02-Jun-17	*Emittance evolution/scattering*	*Liquid hydrogen*
2017/02	11-Jul-17	04-Aug-17	*Cancelled/postponed*	
	19-Sep-17	27-Oct-17	*Emittance evolution/scattering*	*Liquid hydrogen*
2017/03	14-Nov-17	20-Dec-17