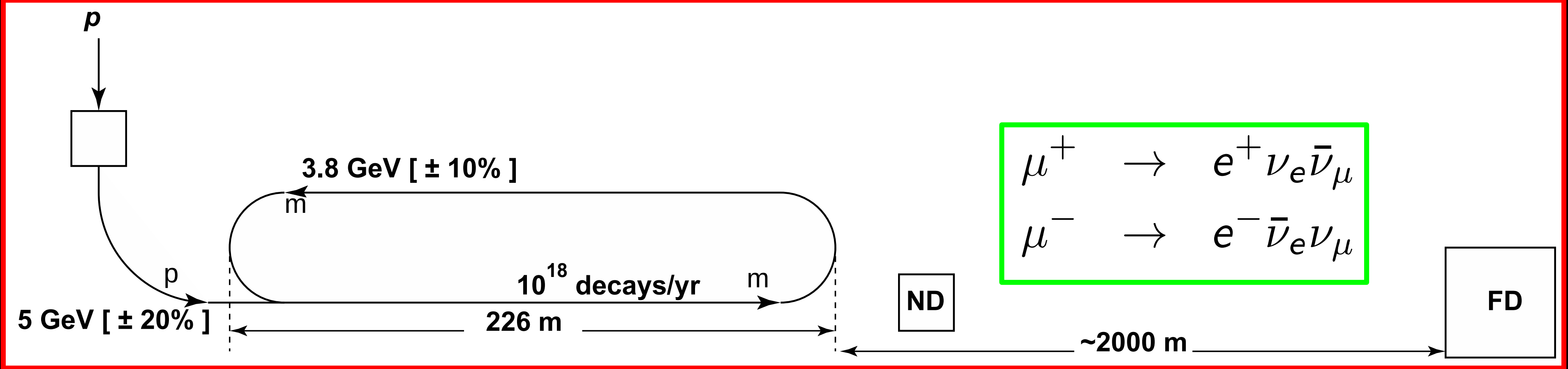
nuSTORM

K. Long, 26 October, 2017

nuSTORM

WHAT IS nuSTORM?

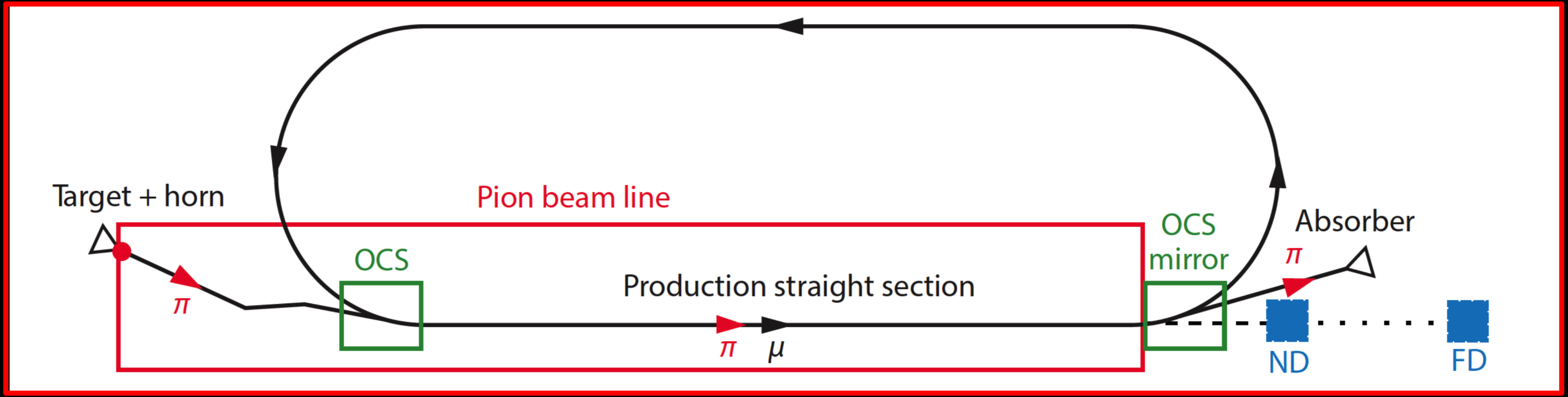
Neutrinos from stored muons



- 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

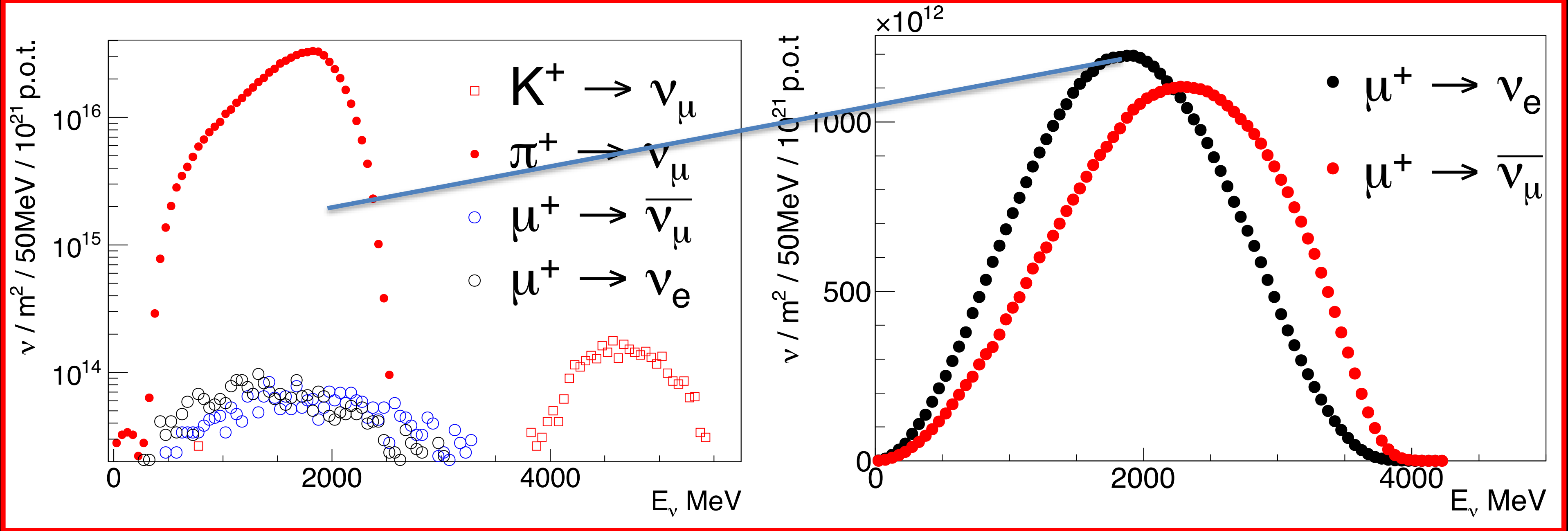
nuSTORM oveview



- **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

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WHY STUDY NEUTRINO INTERACTIONS?

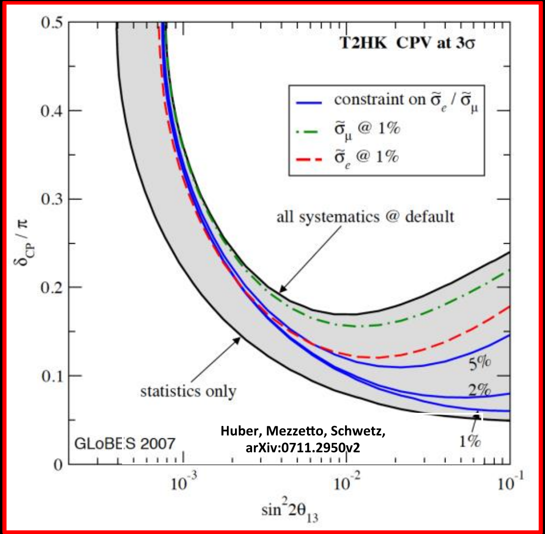
To understand the nucleus, nucleon and contribute to nuclear physics

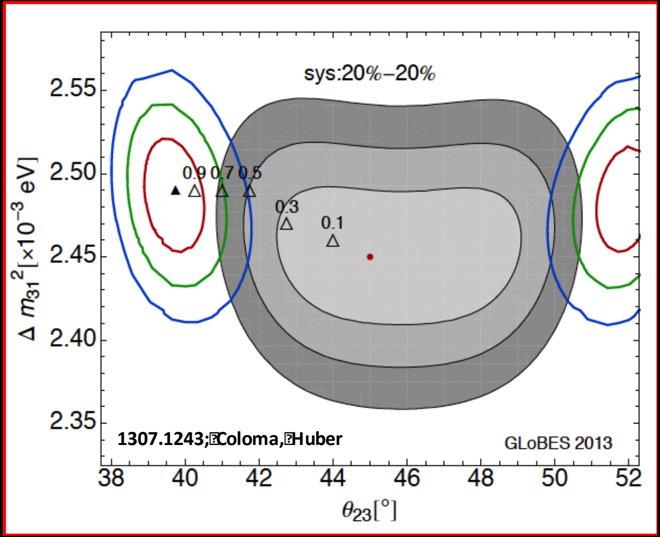
… but also …

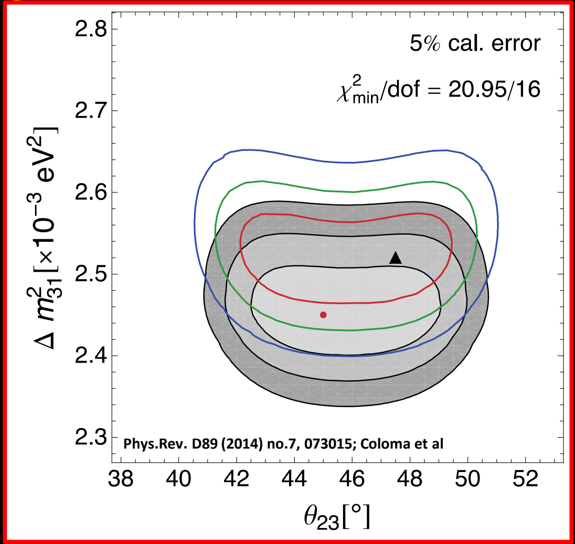
Search for CPiV in lbl oscillations

- Seek to measure asymmetry:
  - $P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$
- 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





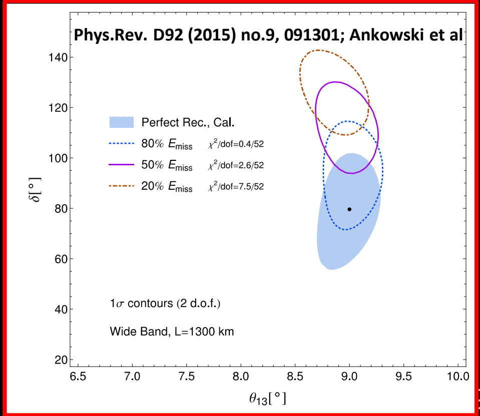


Uncertainty
(cross section and ratio)

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

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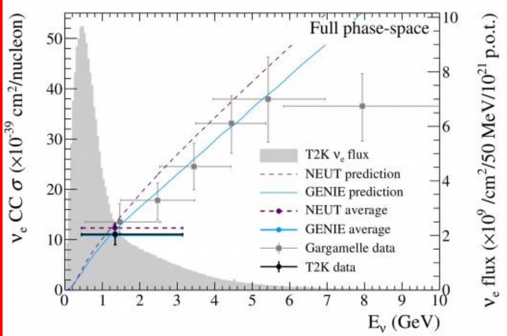
THE BENEFIT OF nuSTORM

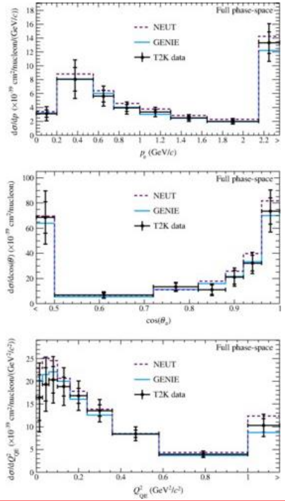
Morfin

$\nu_e N$ cross section measurements

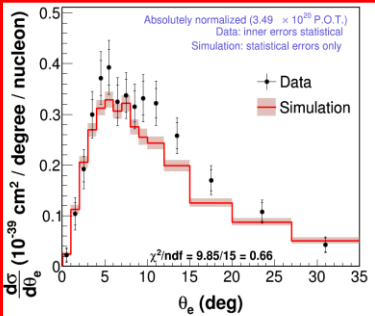
Gargamelle: 244 events at ~90% purity
T2K: 315 events at ~65% purity

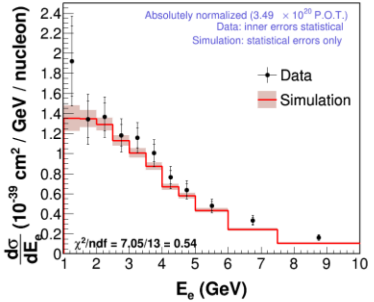


$\sigma_e(E_\nu)$:
Gargamelle (1978) on CF_3Br;
T2K (2014) on CH
Nucl. Phys. B133, 2015
Phys. Rev. Lett. 113, 241803

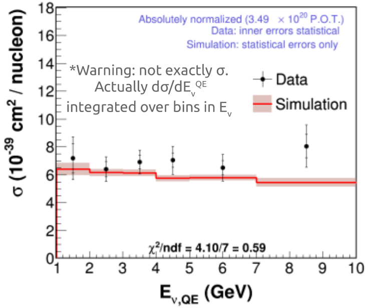


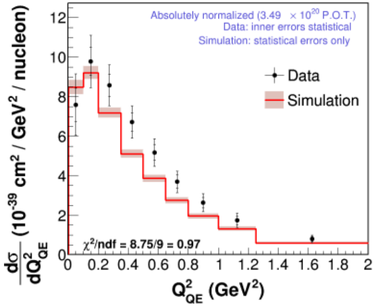
$d\sigma_e/dE_e$, $d\sigma_e/d\theta_e$, $d\sigma_e/dQ^2$:
T2K (2014) on CH
Phys. Rev. Lett. 113, 241803



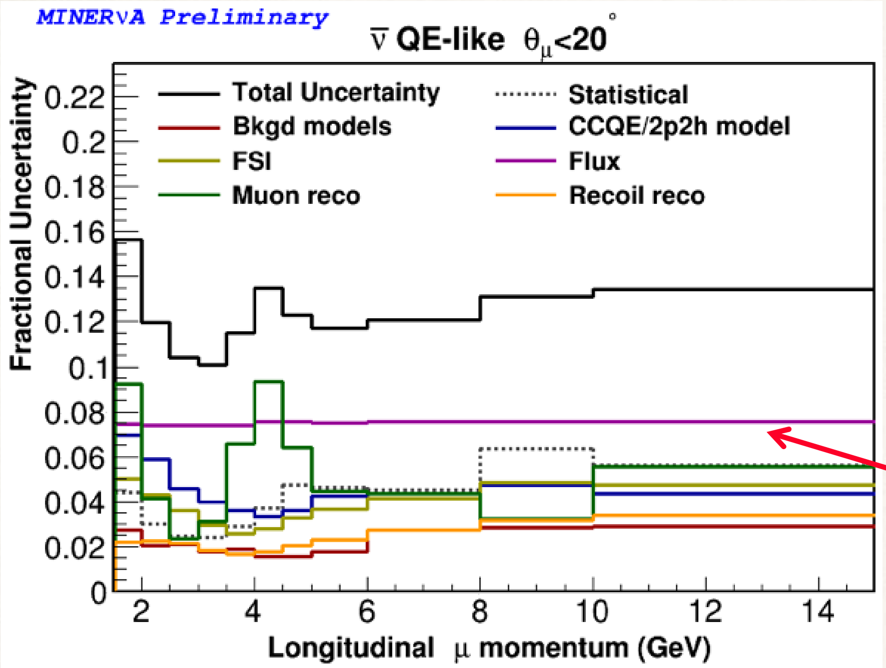


The result and the prediction from GENIE 2.6.2 are statistically consistent.





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

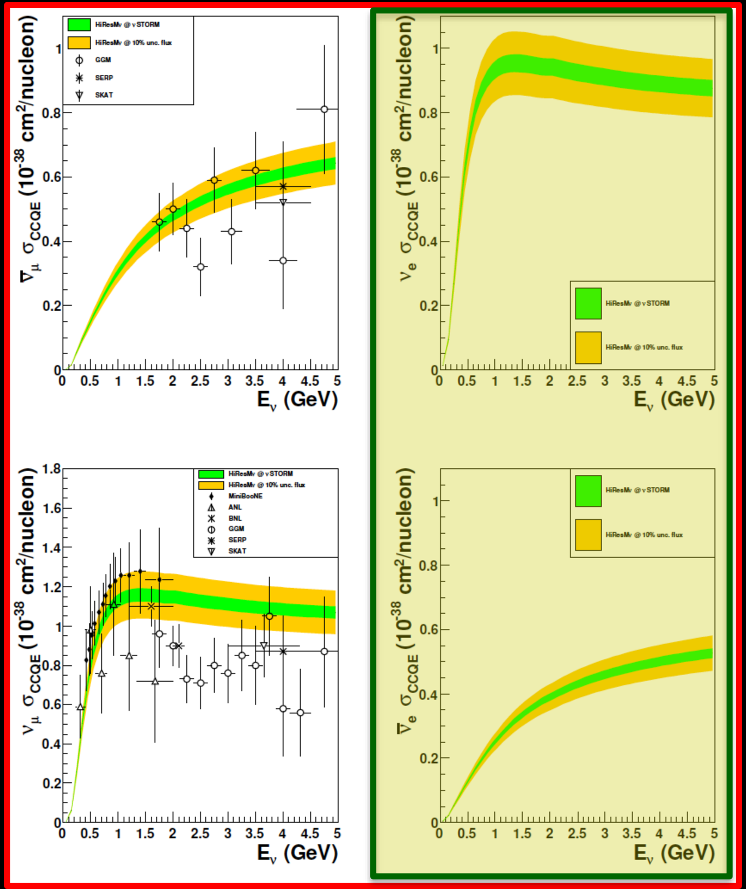
Recoil reconstruction

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

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

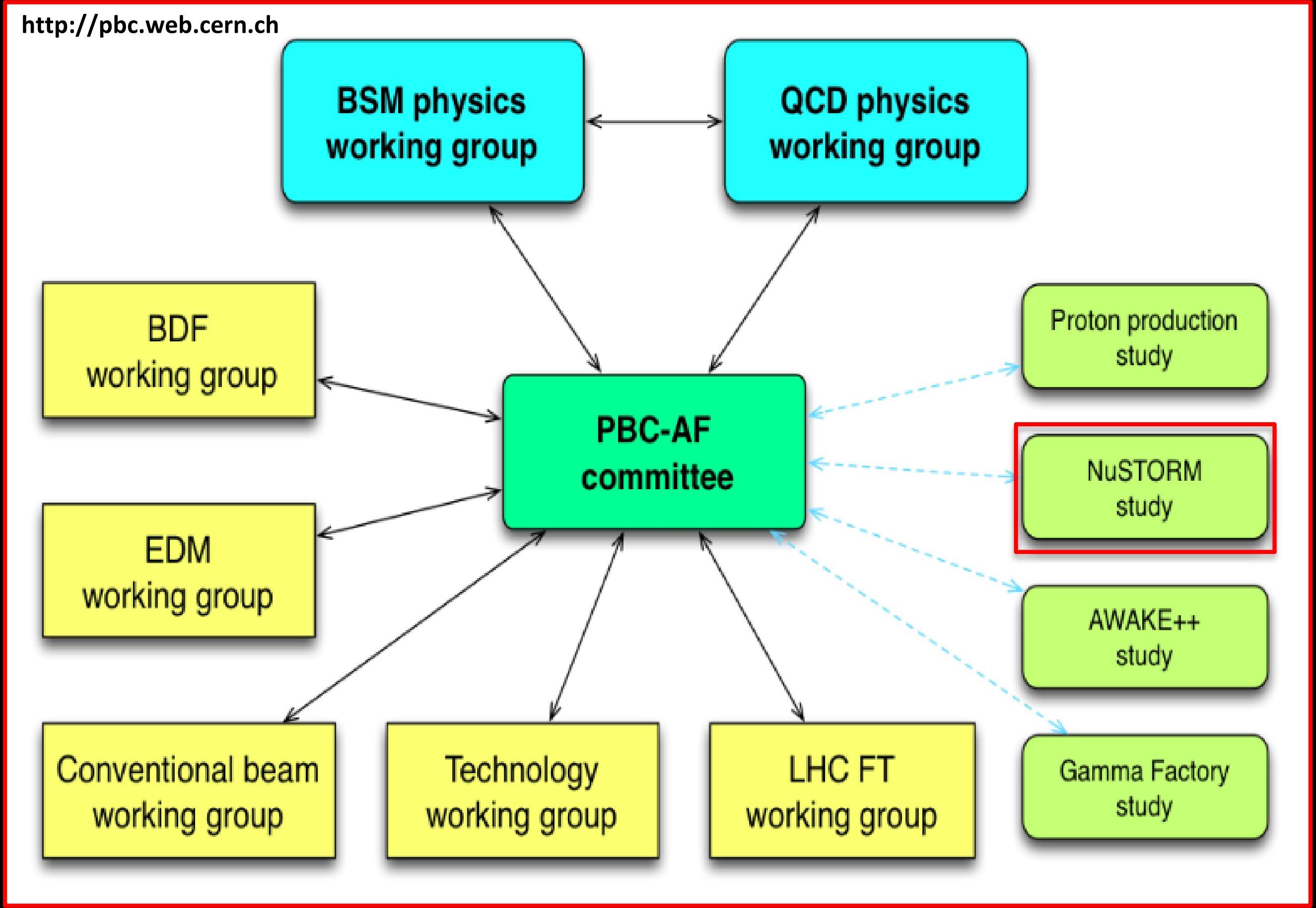


Individual ν_e measurements from T2K and MINERvA [10.1103/PhysRevLett.113.241803, 10.1103/PhysRevLett.116.081802]

10.1103/PhysRevD.89.071301; arXiv:1305.1419

nuSTORM
& THE CERN PHYSICS BEYOND COLLIDERS STUDY GROUP

Physics Beyond Colliders study group



Elements of study

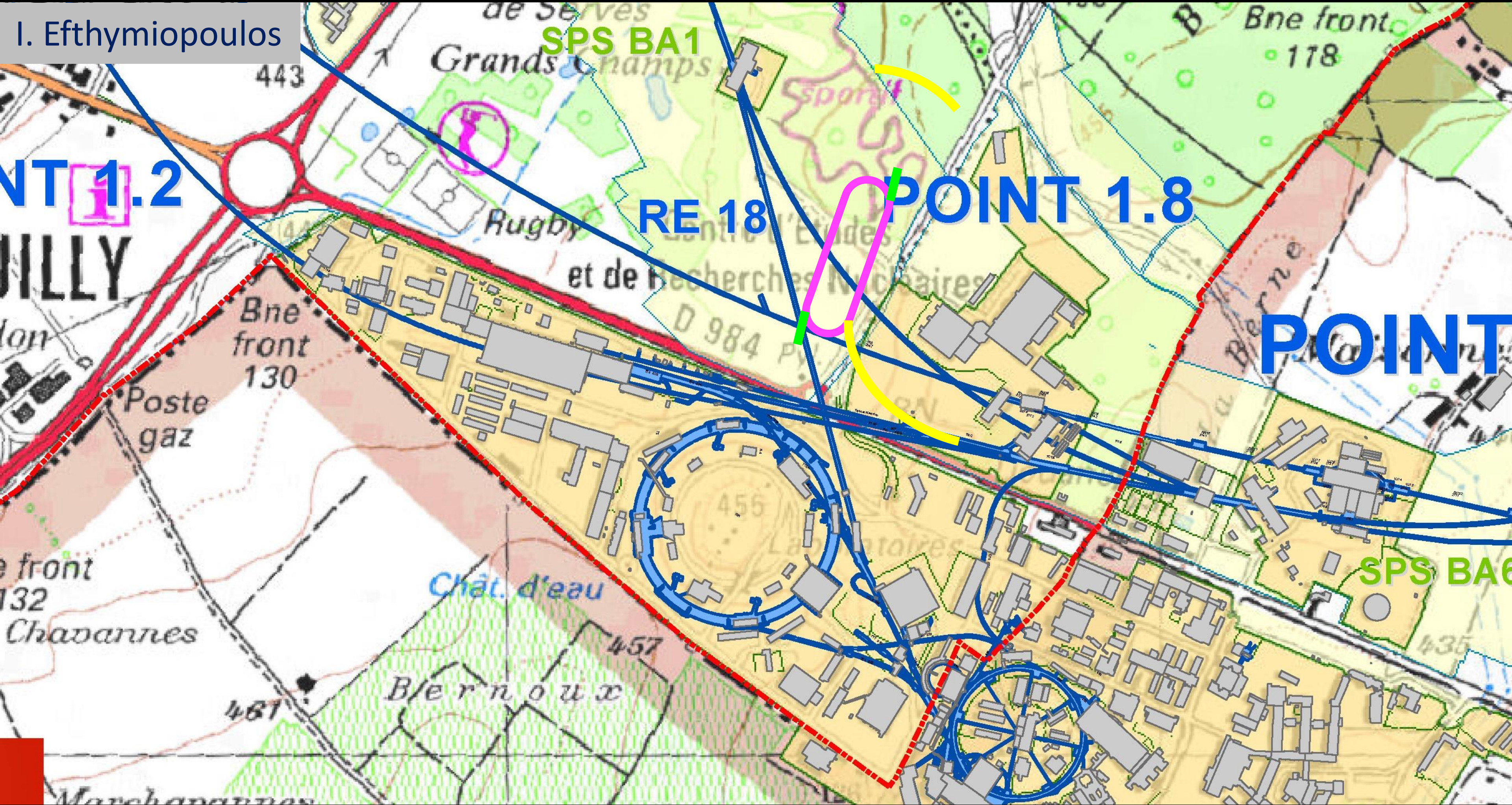
- Physics case:
  - Neutrino-scattering for:
    - Oscillation
    - Nuclear
- Specification:
  - Energy range:
    - Long- and short-baseline neutrino
    - Nuclear and particle physics
  - Acceptance:
    - Rate
    - Neutrino-energy calibration

- 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

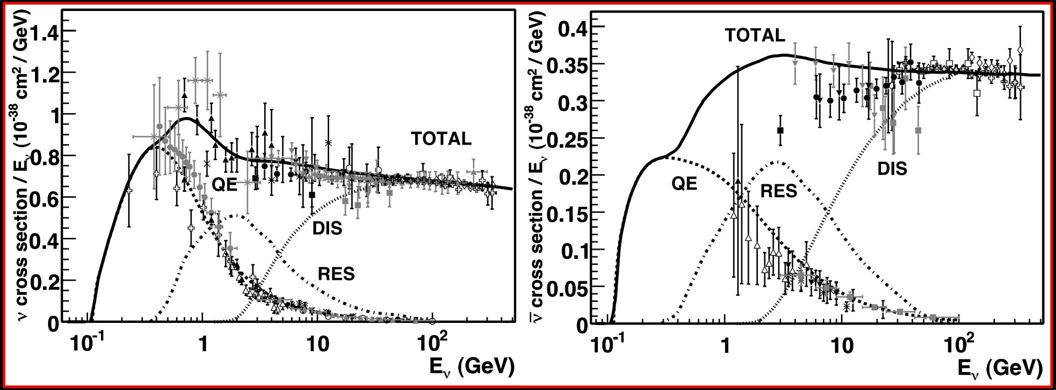
Implementation @ CERN Exploratory study

- 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

I. Efthymiopoulos



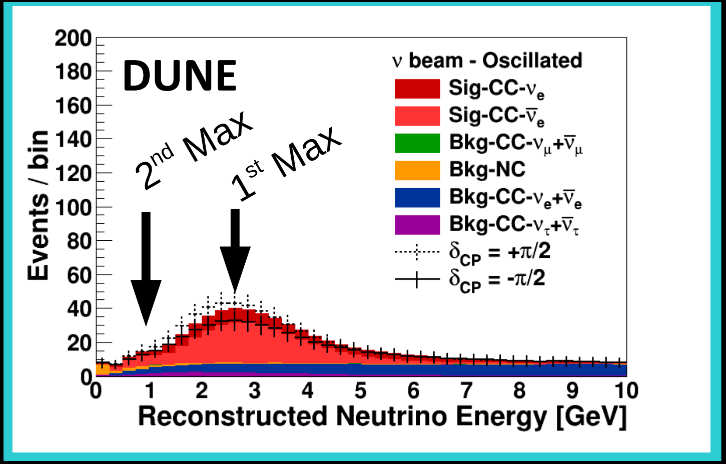
Initial specifications



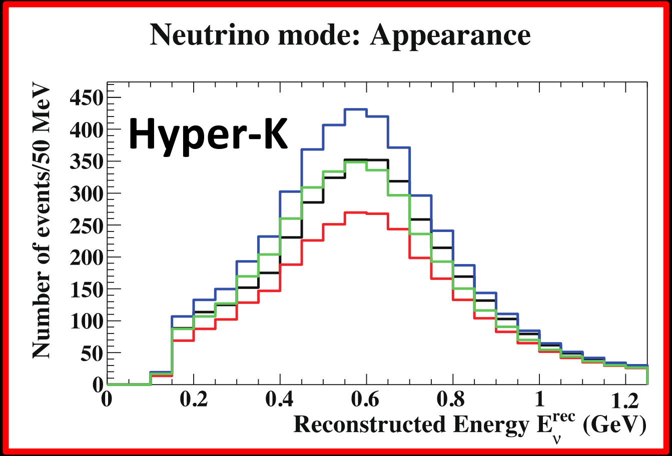
The sensitivity of all oscillation experiments depends on the precision of models of the structure of the nucleus and the details of simulations of neutrino scattering. nuSTORM will provide a beam of precisely known flavour for which the flux will be known to 1% or better. Instrumented with a detector capable of making measurements of exclusive final states and of reconstructing Q^2 and W, nuSTORM can deliver the data required for precise models of the nucleus and of neutrino-nucleus scattering to be developed if the neutrino-beam energy spans the range $1 \lesssim E_\nu \lesssim 6$ GeV. These considerations lead to the following specification for the energy of the circulating muon beam:

- Maximum stored muon energy, $E_\mu = 6$ GeV; and
- It must be possible to vary the muon-beam energy in the range $1 \lesssim E_\mu \lesssim 6$ GeV.

Since the neutrino-energy spectrum is precisely known once the muon-beam energy is specified, the falling edge of the neutrino-energy spectrum can be used to calibrate the energy response of the neutrino detectors. Further, by combining data taken with different stored-muon energies, as described for NuPRISM in [59], cross sections may be determined in narrow neutrino-energy bands.



Normal Hierarchy



nuSTORM

Conclusions

Conclusions

- **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**

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...

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