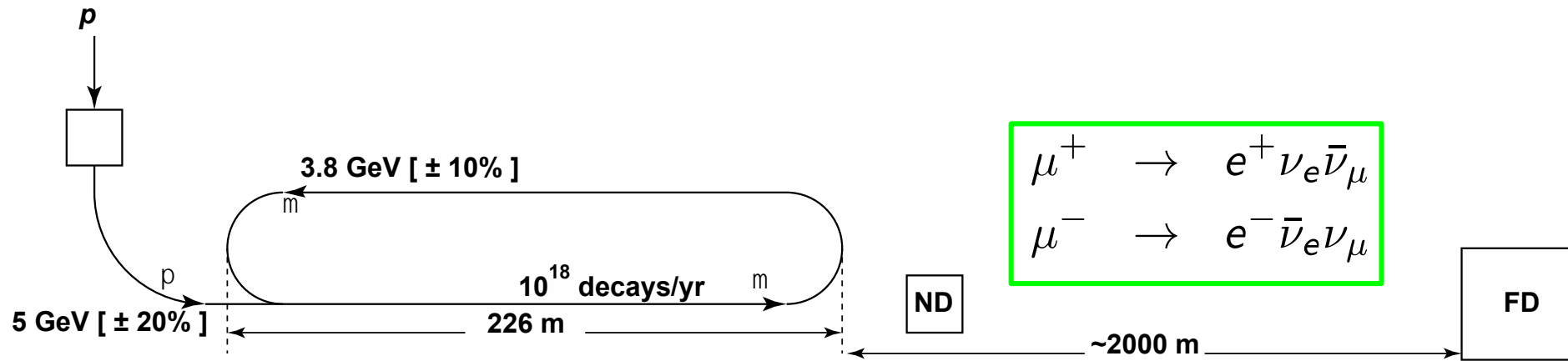


nuSTORM

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

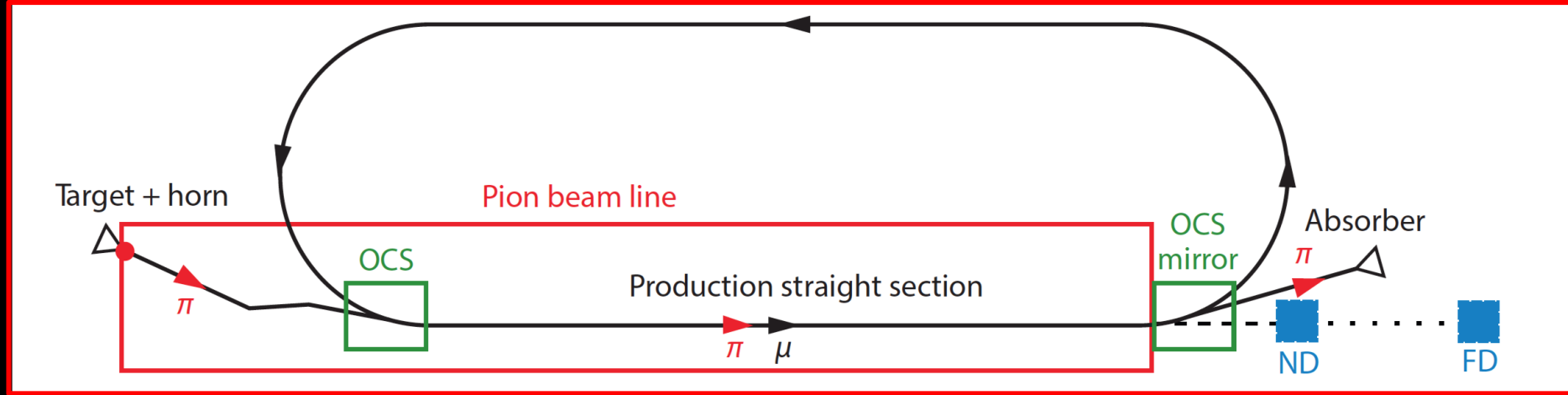
• Precise neutrino flux:

- Normalisation: $< 1\%$
- Energy (and flavour) precise

• $\pi \rightarrow \mu$ injection pass:

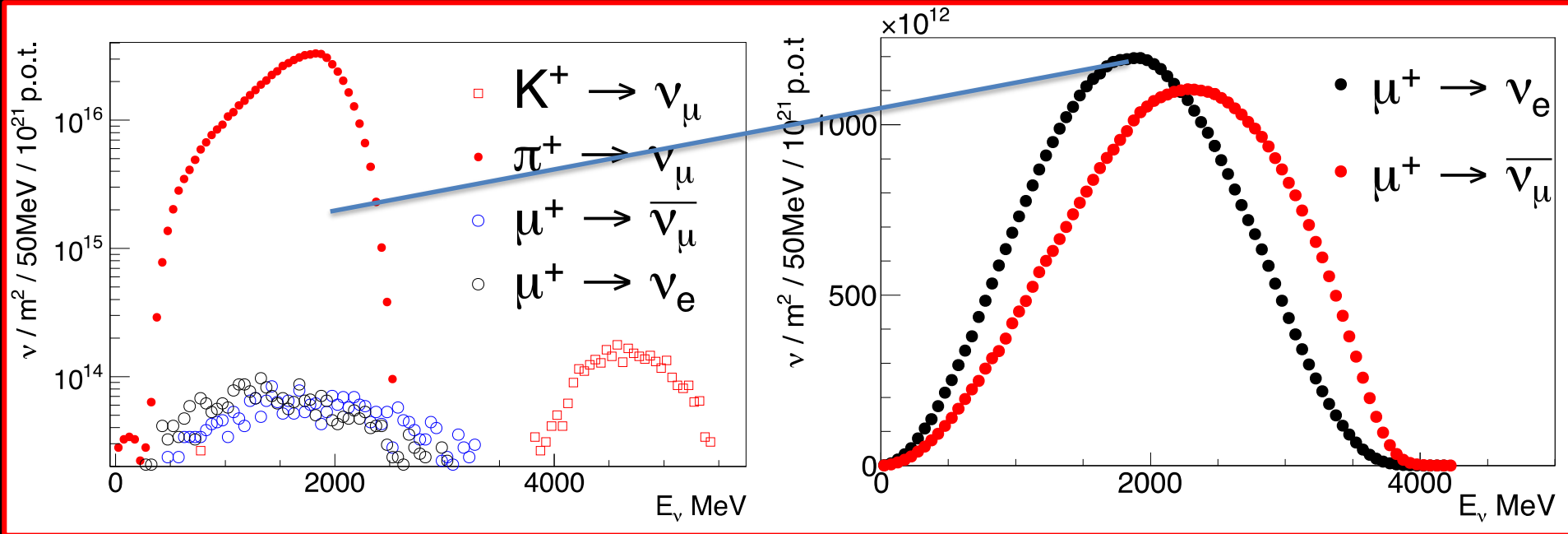
- “Flash” of muon neutrinos

nuSTORM overview



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

Neutrino flux



- ν_μ flash:

- Pion: $6.3 \times 10^{16} \text{ m}^{-2}$ at 50m
- Kaon: $3.8 \times 10^{14} \text{ m}^{-2}$ 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?

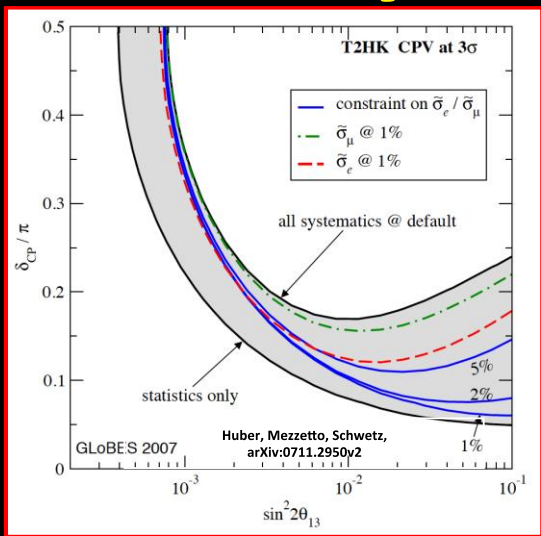
**To understand the nucleus, nucleon and
contribute to nuclear physics**

... but also ...

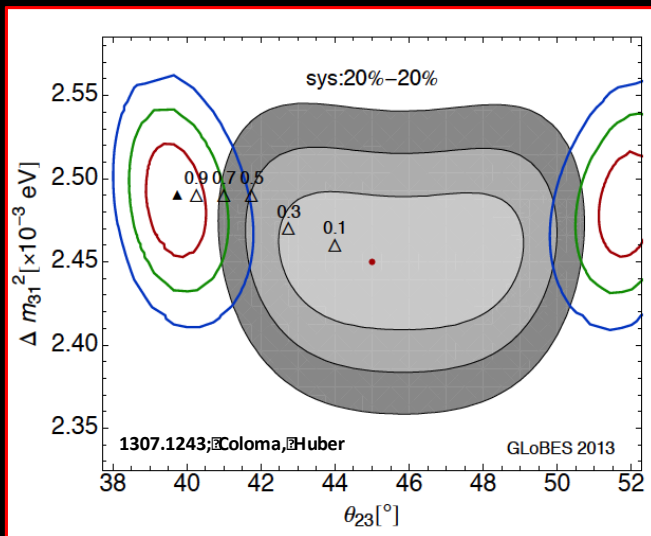
Search for CPiV in $l\bar{l}$ oscillations

- 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

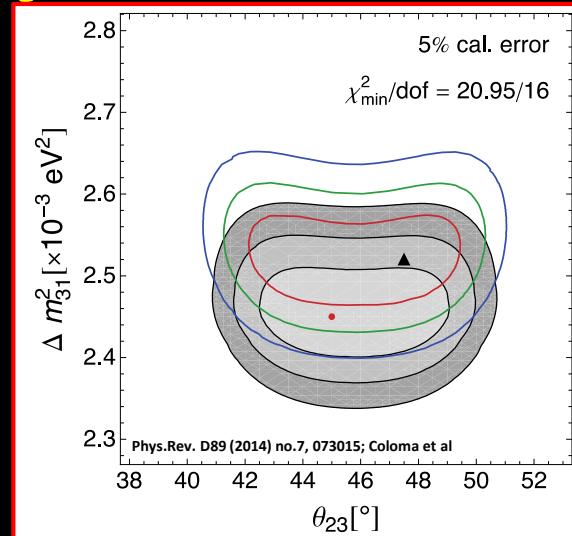


**Uncertainty
(cross section
and ratio)**

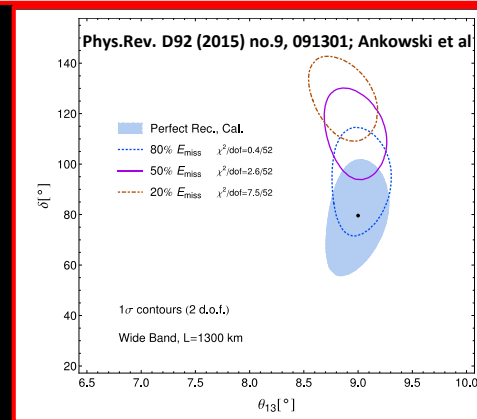


Event mis-classification

Energy scale mis-calibration



Missing energy (neutrons)



Search for CPiV in $\text{l}\nu\text{l}$ oscillations

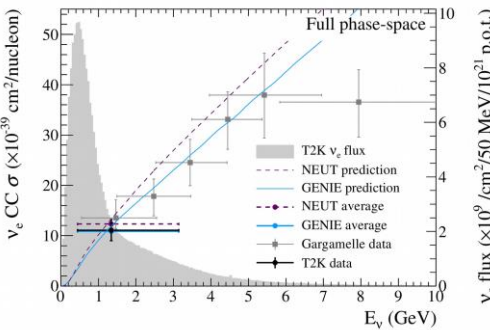
- Seek to measure asymmetry:
 - $P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$
- Event rates convolution of:
 - Flux, cross sections, detector mass, efficiency, E -scale
 - Measurements at %-level required
- Lack of knowledge of cross-sections leads to:
 - Systematic uncertainties;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

nuSTORM

THE BENEFIT OF nuSTORM

$\nu_e N$ cross section measurements

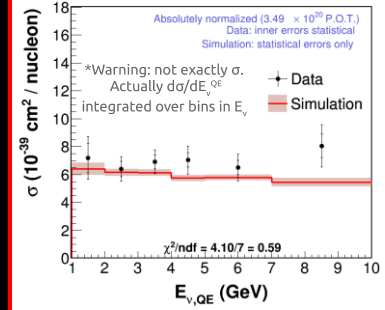
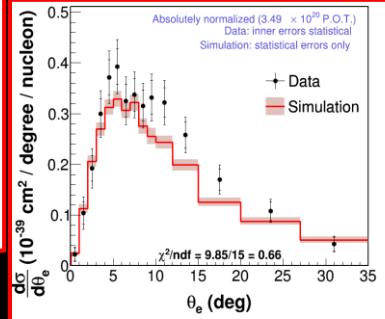
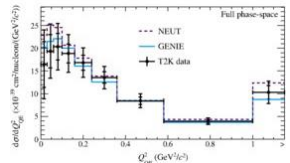
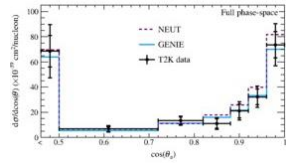
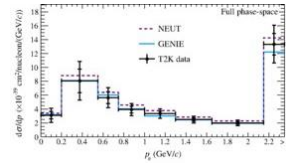
Gargamelle: 244 events at ~90% purity
T2K: 315 events at ~65% purity



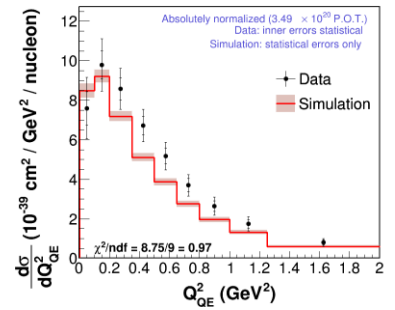
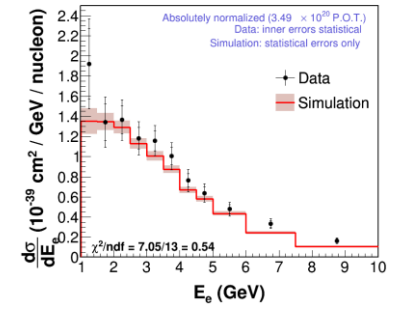
ν_e flux ($\times 10^9$ /cm²/50 MeV/10²¹ p.o.t.)

$\sigma_e(E_\nu)$:
 Gargamelle (1978) on CF₃Br;
 T2K (2014) on CH
 Nucl. Phys. B133, 2015
 Phys. Rev. Lett. 113, 241803

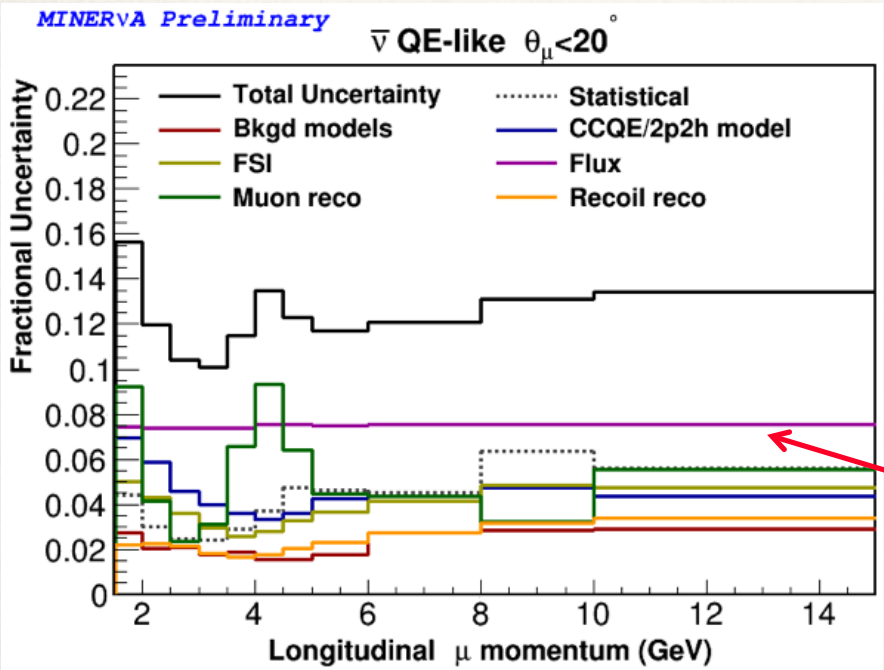
$d\sigma_e/dE_\theta_e, d\sigma_e/d\theta_e,$
 $d\sigma_e/dQ^2$:
 T2K (2014) on CH
 Phys. Rev. Lett. 113, 241803



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



Systematic uncertainties

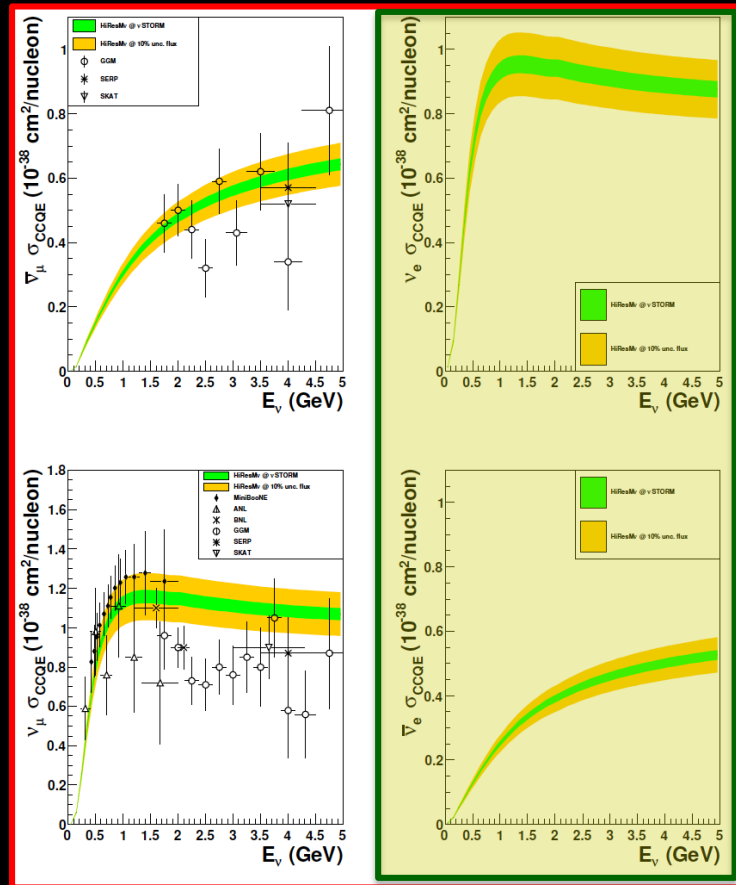


Uncertainties projected onto longitudinal muon momentum

- - - 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** dominates₄₂

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:
 - $\sim <1\%$ precision on flux



Individual ν_e measurements from T2K and MINERvA

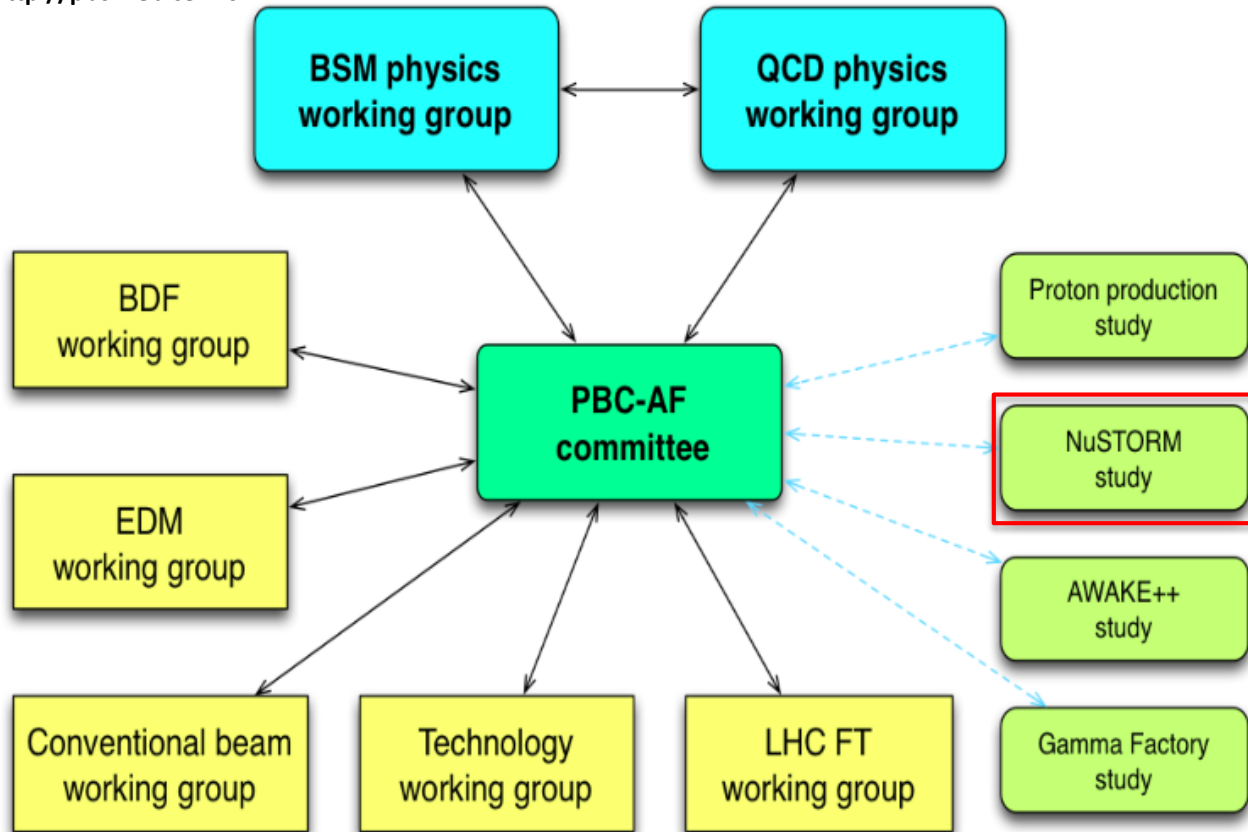
nuSTORM

nuSTORM

**& THE CERN PHYSICS BEYOND COLLIDERS
STUDY GROUP**

Physics Beyond Colliders study group

<http://pbc.web.cern.ch>



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 $< \sim 1\%$ 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

POINT 1.2

CHAVANNES

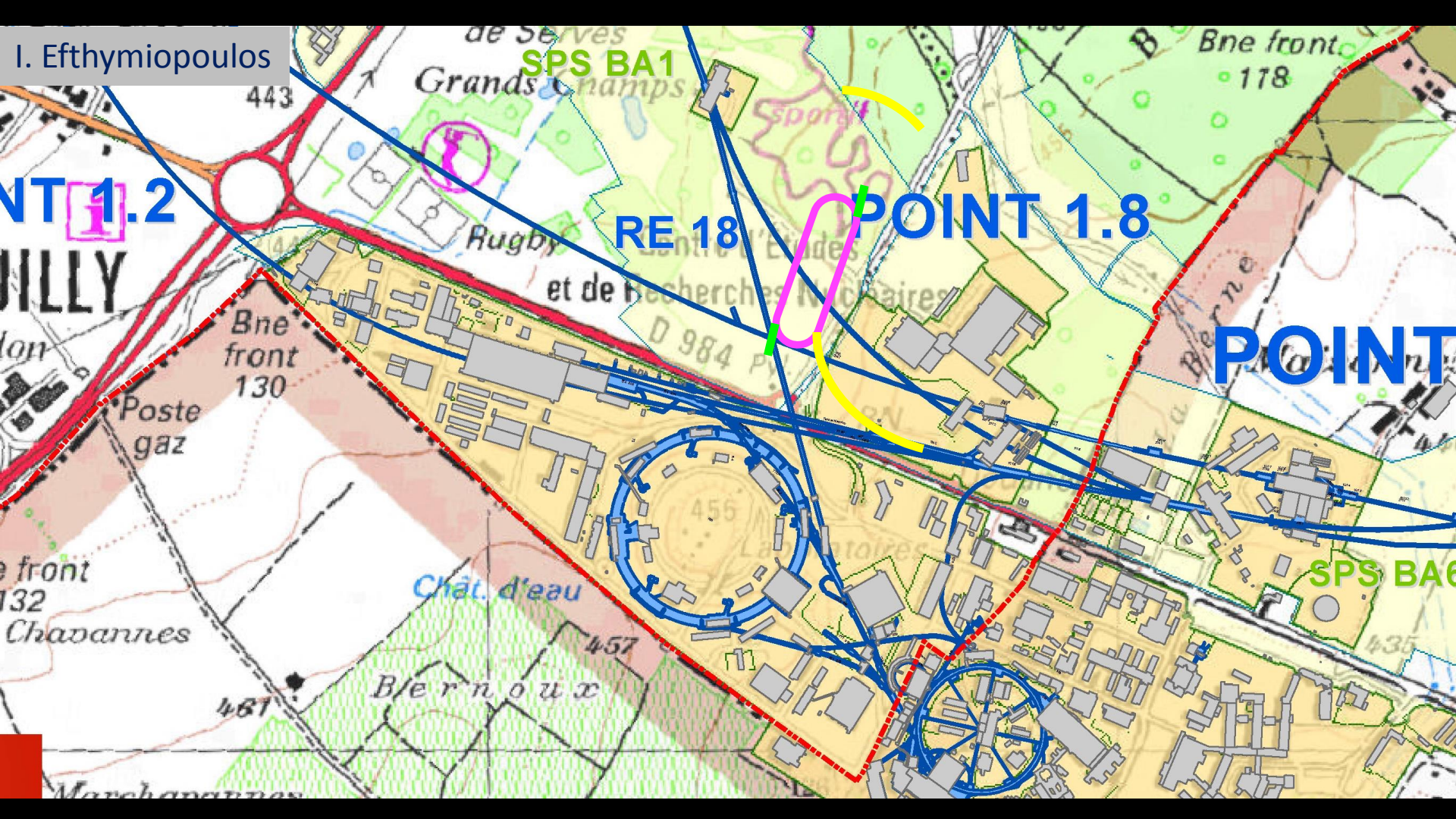
SPS BA1

RE 18

POINT 1.8

POINT

SPS BA6



nuSTORM

Conclusions

Conclusions

- **nuSTORM can deliver:**
 - **nN 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 workpackage 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: Jaroslav Pasternak (Imperial College, London)

📎 FFAG_nustorm_JP...

15:10 → 15:30 **nuSTORM: performance of an FFAG focussing ring**

Speaker: Sam Tygler

📎 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...](#)

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: $6.3 \times 10^{16} \text{ m}^{-2}$ at 50m
- Kaon: $3.8 \times 10^{14} \text{ m}^{-2}$ at 50m
- Well separated from pion neutrinos

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