Imperial College London

Science & Technology Facilities Council

νSTORM

… neutrino factory and muon collider

K. Long, 21 March, 2019

Authors and acknowledgements …

Input to the European Particle Physics Strategy Update 2018-2020

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

nuSTORM at CERN: Executive Summary

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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.

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Addendum to the Executive Summary of nuSTORM at CERN

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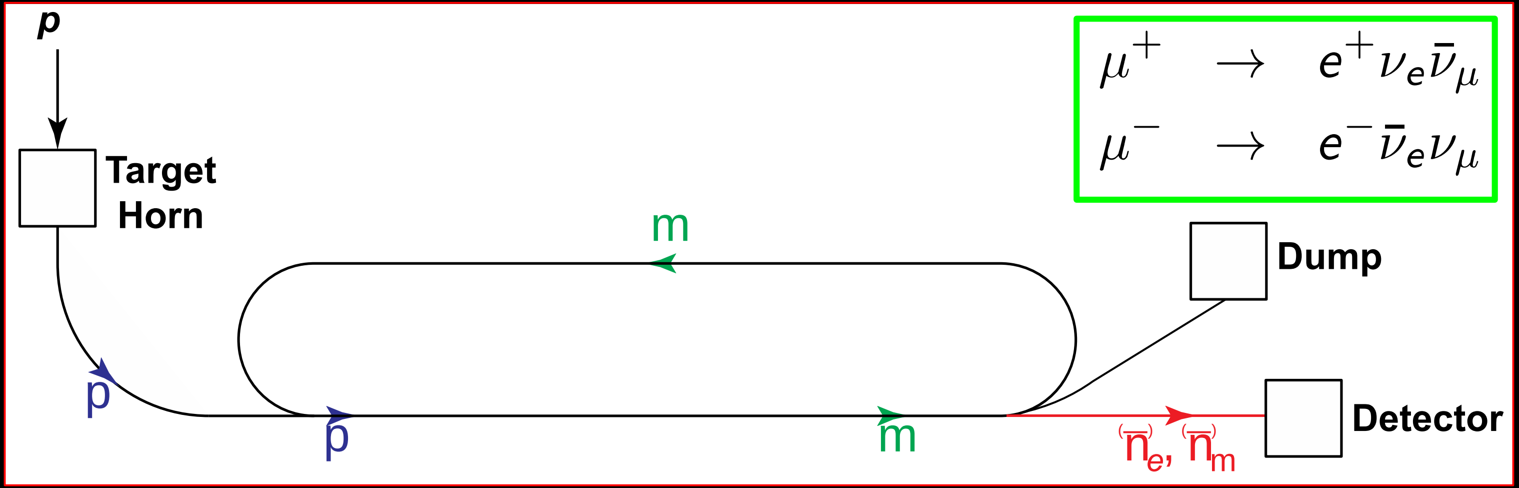
Neutrinos from stored muons



$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$
$$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$$

- **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

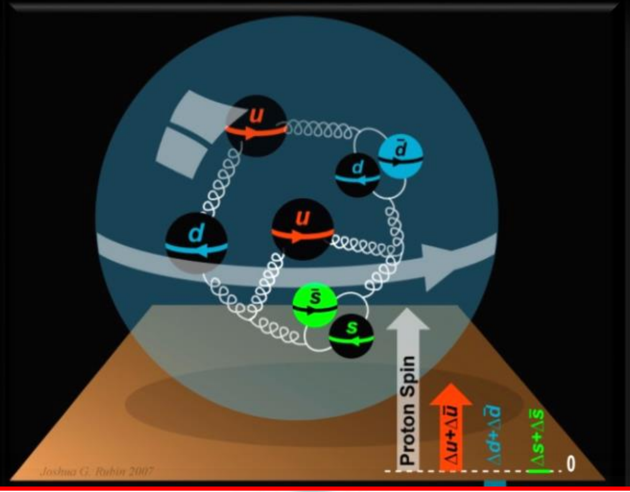
To understand the nucleon and the nucleus

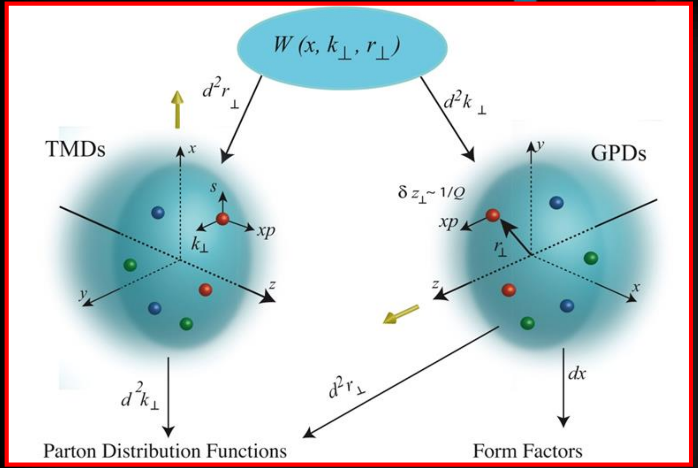
- Neutrino unique probe: weak and chiral:
  - Sensitive to flavour/isospin and 100% polarised

- How could neutrino scattering help?
  - Development of understanding of nucleus/nucleon (e.g.):
    - Multi-nucleon correlations
    - Precise determination of:
      - Model parameters or, better,
      - Theoretical (ab initio) description

- Precise νN scattering measurements to:
  - Constrain models of nucleus/nucleon:
    - Exploiting isospin dependence, chirality, …

- Benefit of nuSTORM:
  - Precise flux and energy distribution

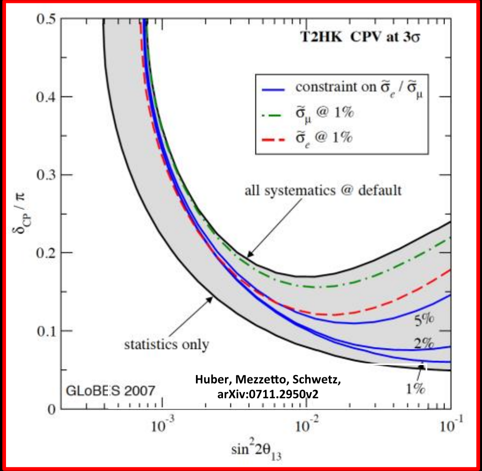


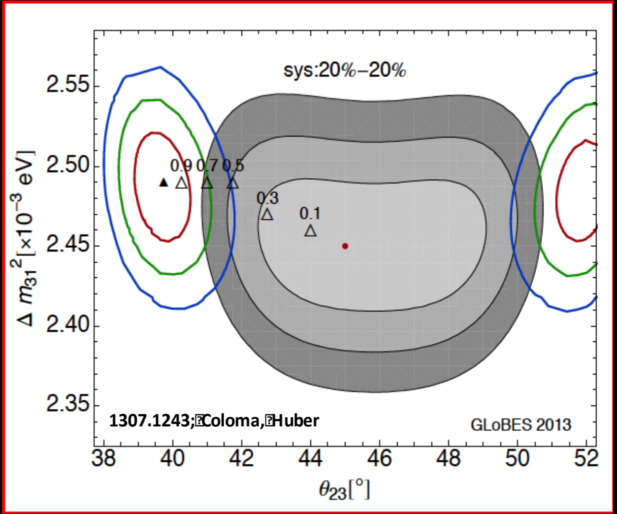


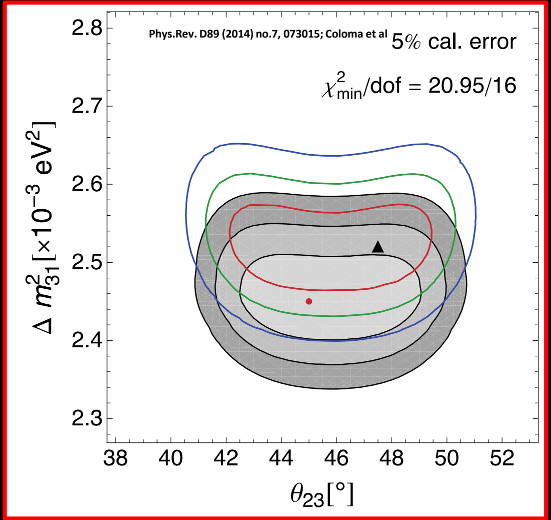
Search for CPiV in lbl oscillations

- Seek to measure asymmetry:
  - $P(\nu_\mu \blacktriangleright \nu_e) - P(\bar{\nu}_\mu \blacktriangleright \bar{\nu}_e)$
- 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
- Lack of knowledge of cross-sections leads to:
  - Systematic uncertainties; and
  - Biases; pernicious if ν and $\bar{\nu}$ differ

Systematic uncertainty and/or bias

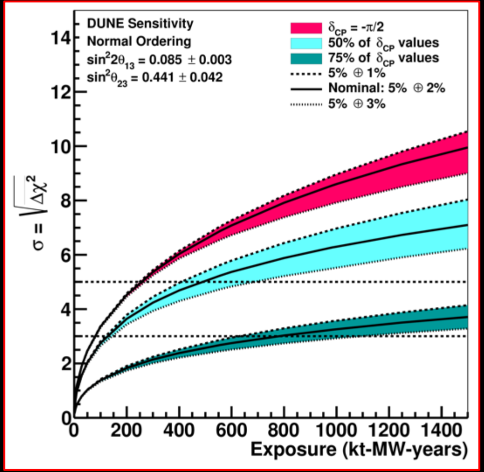






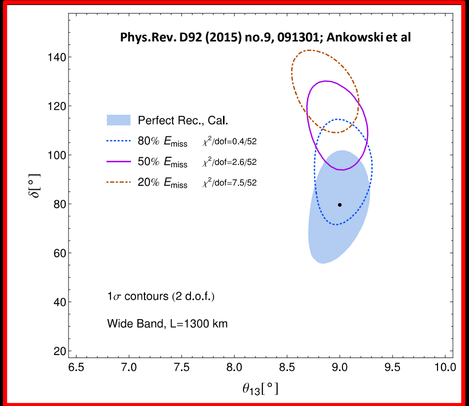
Event mis-classification

Energy scale mis-calibration



Uncertainty
(cross section
and ratio)

Missing energy (neutrons)



nuSTORM for *νN* scattering @ CERN — parameters

- **New specification!**
  - **Design update:**
    - **$1 < E_\mu < 6$ GeV**
  - **Challenge for accelerator design!**
  - **Benefit:**
    - **Calibration via energy spectrum**
    - **Statistical ‘mono-energetic beam’**

- **SPS requirements table**

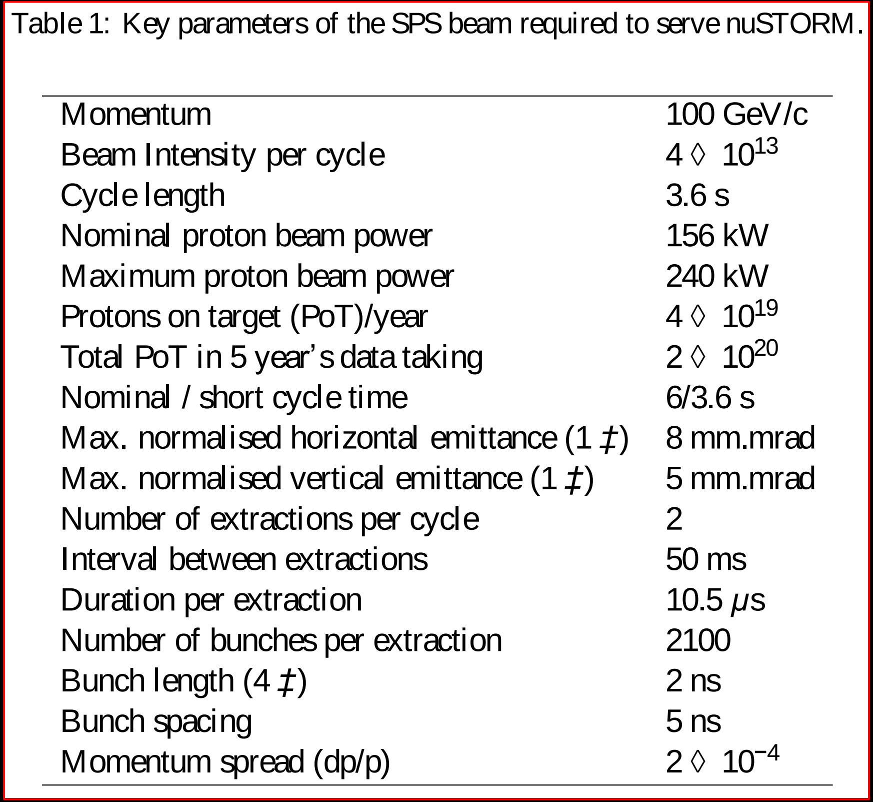
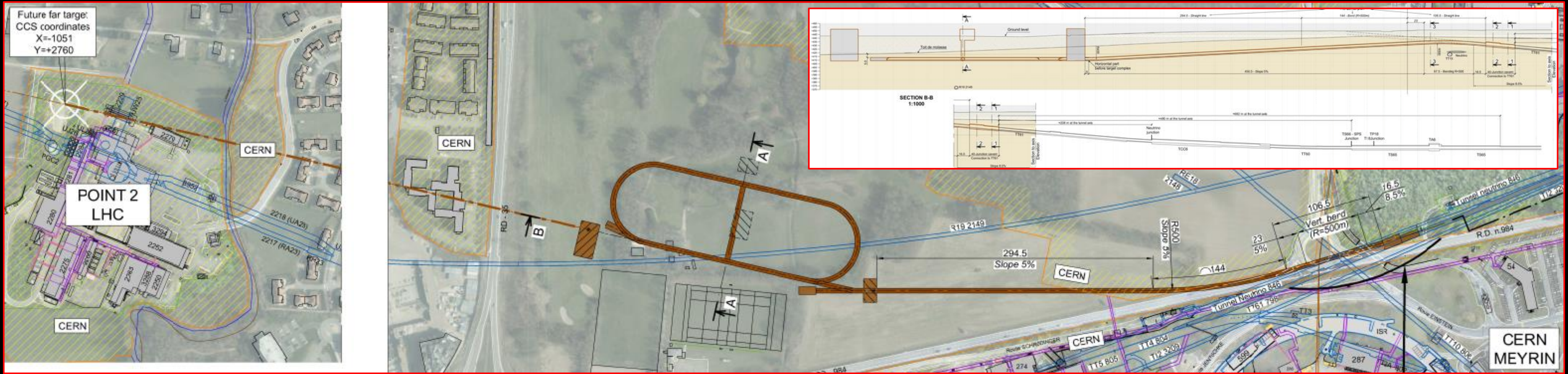


Table 1: Key parameters of the SPS beam required to serve nuSTORM.

Momentum	100 GeV/c
Beam Intensity per cycle	4 ◊ 10^{13}
Cycle length	3.6 s
Nominal proton beam power	156 kW
Maximum proton beam power	240 kW
Protons on target (PoT)/year	4 ◊ 10^{19}
Total PoT in 5 year’s data taking	2 ◊ 10^{20}
Nominal / short cycle time	6/3.6 s
Max. normalised horizontal emittance (1 ǂ)	8 mm.mrad
Max. normalised vertical emittance (1 ǂ)	5 mm.mrad
Number of extractions per cycle	2
Interval between extractions	50 ms
Duration per extraction	10.5 μs
Number of bunches per extraction	2100
Bunch length (4 ǂ)	2 ns
Bunch spacing	5 ns
Momentum spread (dp/p)	2 ◊ 10^{-4}

Overview

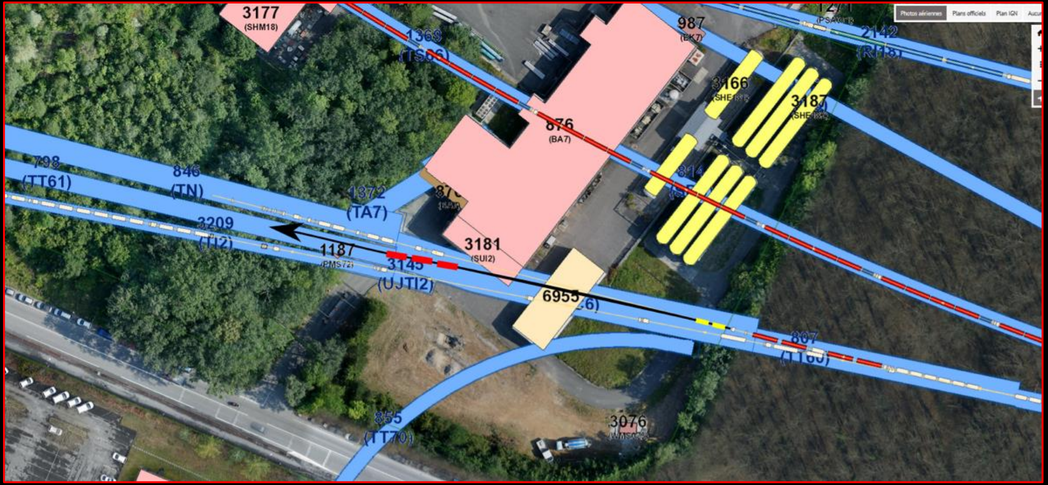


- **Extraction from SPS through existing tunnel**
- **Siting of storage ring:**
  - **Allows measurements to be made ‘on or off axis’**
  - **Preserves sterile-neutrino search option**

Extraction and *p*-beam transport to target

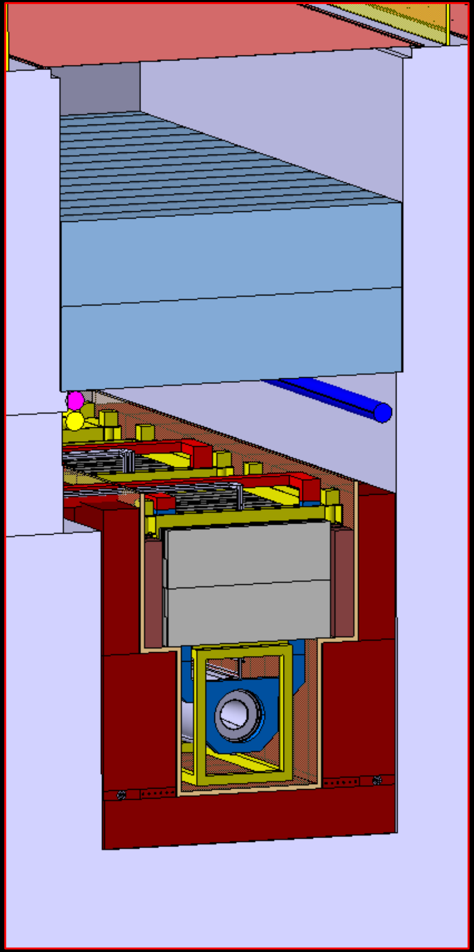
- **Fast extraction at 100 GeV:**
  - CNGS-like scheme adopted;
    - Apertures defined by horizontal and vertical septa reasonable
    - Pulse structure (2 x 10.5 ms pulses) requires kicker upgrade

- **Beam transport to target:**
  - Extraction into TT60:
    - Branch from HiRadMat beam line at 230 m (TT61)
  - Require to match elevation and slope
  - New tunnel at junction cavern after 290 m
  - 585 m transport to target



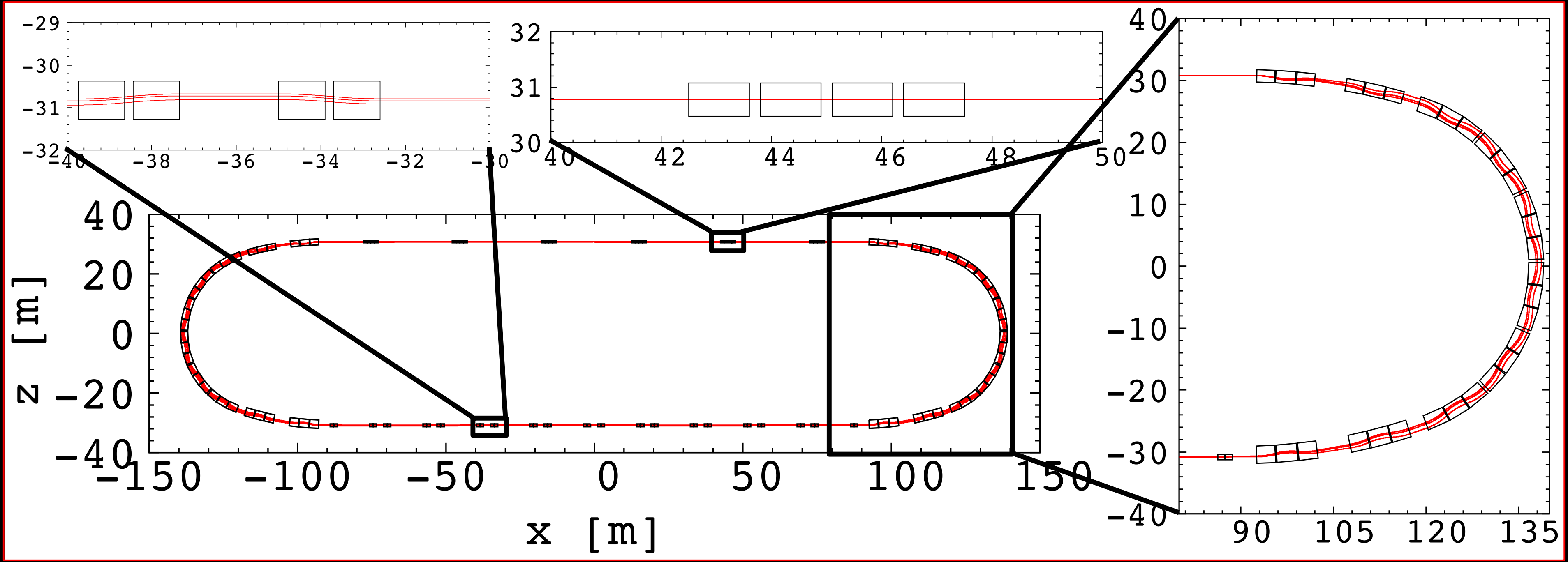
Target and capture

- **FNAL scheme adopted:**
  - Low-Z target in magnetic horn
  - Pair of quadrupoles collect particles horn focused
  - Target and initial focusing contained in inert helium atmosphere
- **Graphite target, based on CNGS experience:**
  - Radiation-cooled graphite target embedded in water-cooled vessel
- **Containment and transport of pion beam with a 10% momentum spread:**
  - Base on scheme used successfully for AD in PS complex
- **Target complex design:**
  - Exploit extensive work done for CENF



Storage ring

- New design for decay ring:
  - Central momentum between 1 GeV/c and 6 GeV/c;
  - Momentum acceptance of up to ±16%



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
    - Require magnet development to allow production at a reasonable cost
  - **Detailed evaluation of:**
    - Proton-beam extraction, target and target complex
    - Civil engineering studies and radiological implications

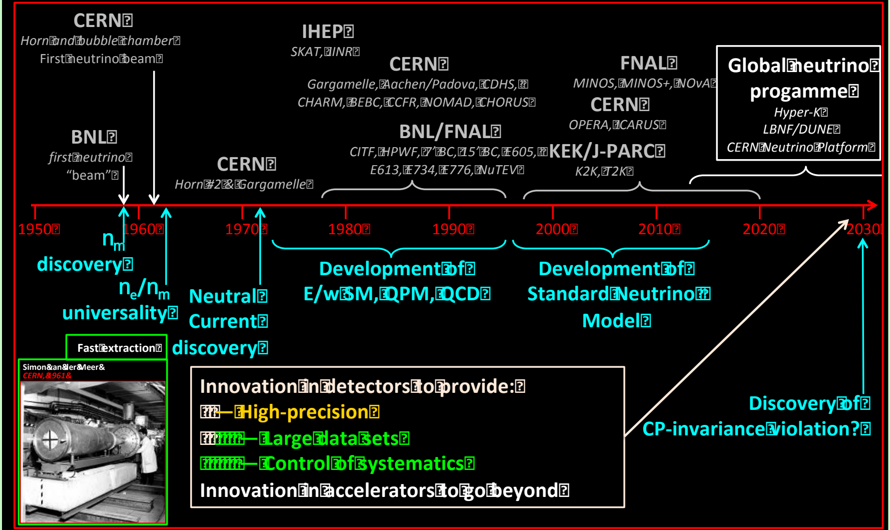
Unique advantages of muon accelerators

l^+l^- at very high energy

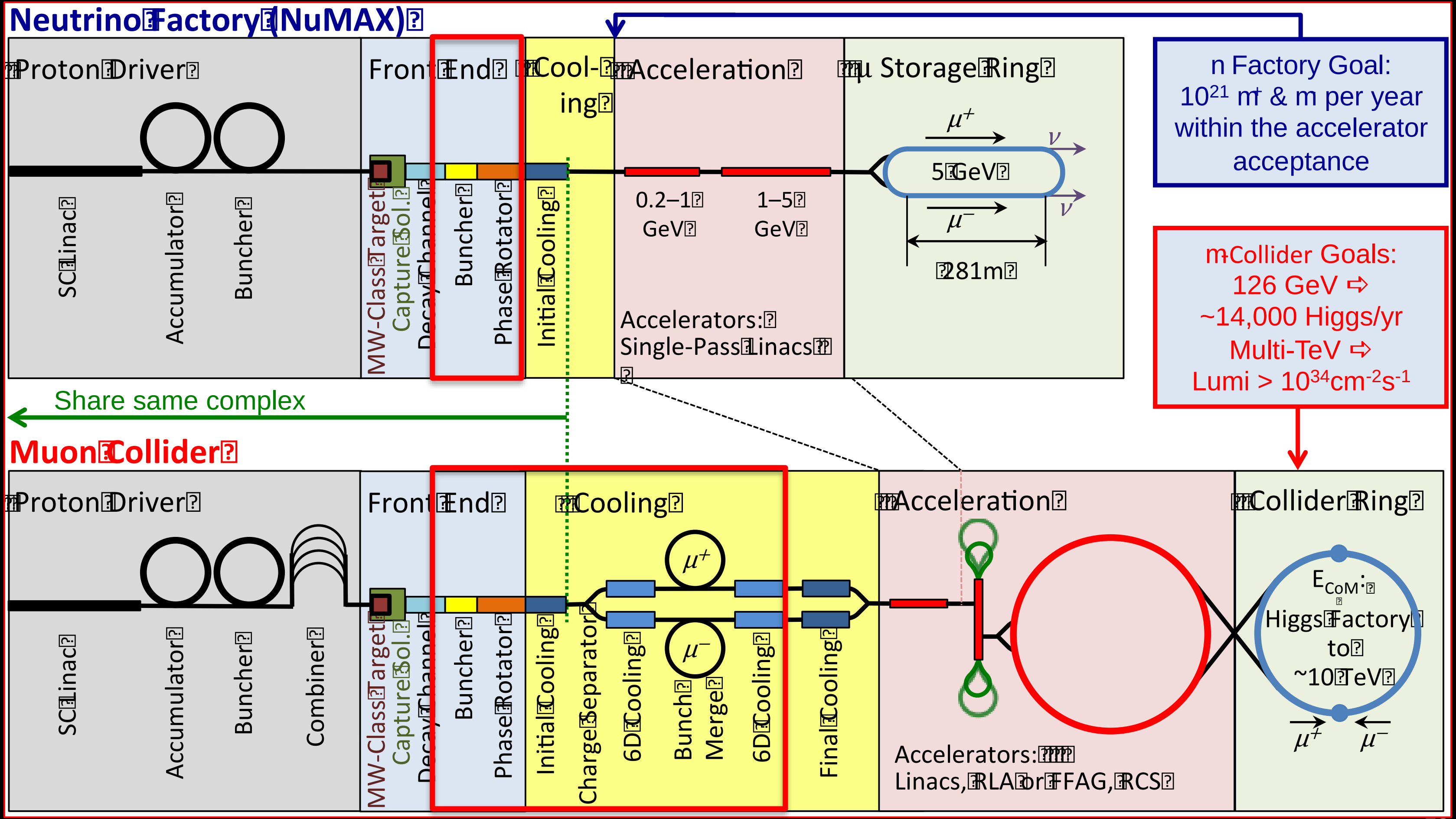
- No brem-/beam-strahlung
  - Rate ∝ m^{-4} [5 × 10^{-10} cf e]
- Efficient acceleration
  - Favourable rigidity
- Enhanced Higgs coupling
  - Production rate ∝ m^2 [5 × 10^4 cf e^+e^-]

Neutrino beams

- ν_e, ν_μ
- Precisely known energy spectrum



Neutrino factory and muon collider

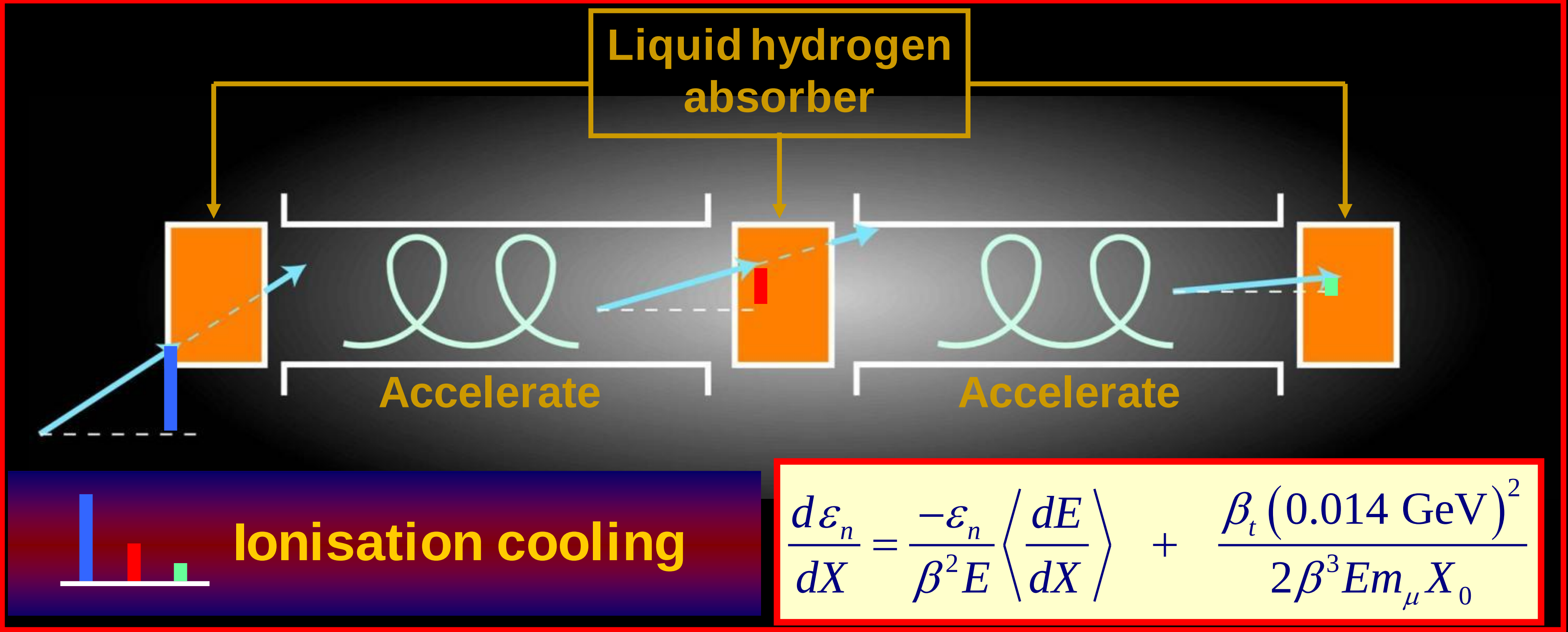


n Factory Goal:
10^{21} m+ & m per year
within the accelerator
acceptance

m Collider Goals:
126 GeV ⇨
~14,000 Higgs/yr
Multi-TeV ⇨
Lumi > 10^{34}cm^{-2}s^{-1}

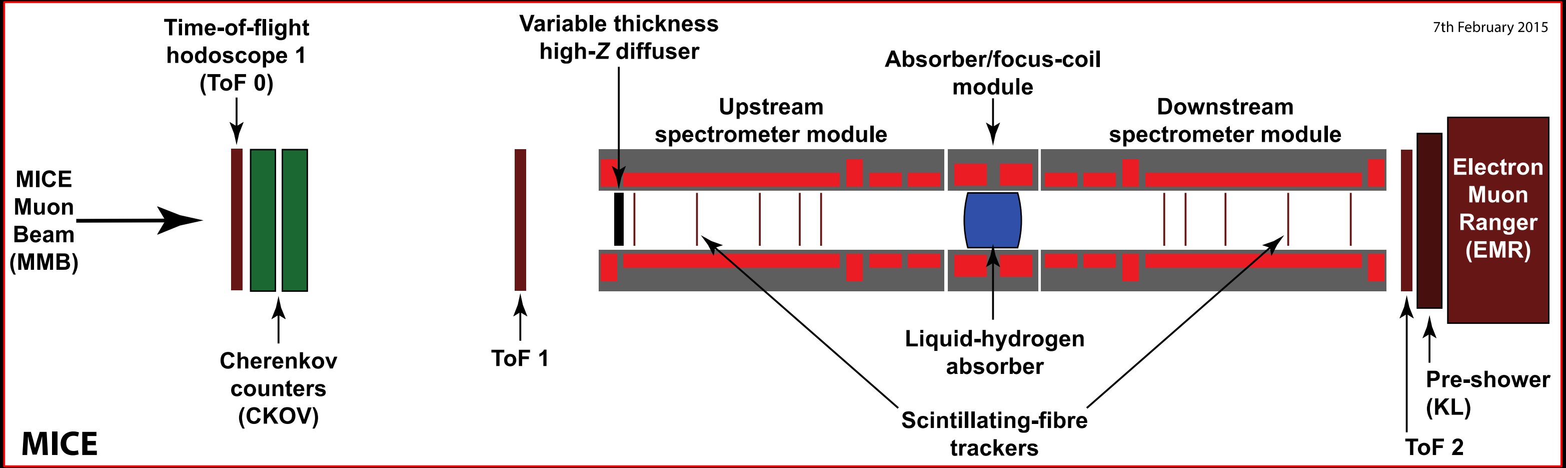
Note: LEMMA:
cold muons at 22 MeV
from e^+e^- annihilation

The principle of ionization cooling



$$\frac{d\varepsilon_n}{dX} = \frac{-\varepsilon_n}{\beta^2 E}\left\langle \frac{dE}{dX} \right\rangle + \frac{\beta_t \left(0.014\ \mathrm{GeV}\right)^2}{2\beta^3 E m_\mu X_0}$$

The experiment



Time-of-flight hodoscope 1 (ToF 0)

Variable thickness high-*Z* diffuser

7th February 2015

Absorber/focus-coil module

Upstream spectrometer module

Downstream spectrometer module

MICE Muon Beam (MMB)

Electron Muon Ranger (EMR)

Cherenkov counters (CKOV)

ToF 1

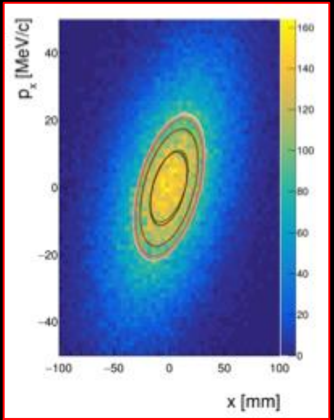
Liquid-hydrogen absorber

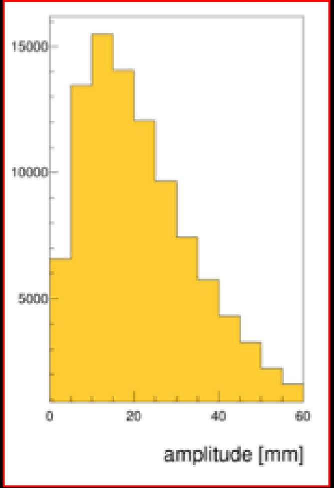
Pre-shower (KL)

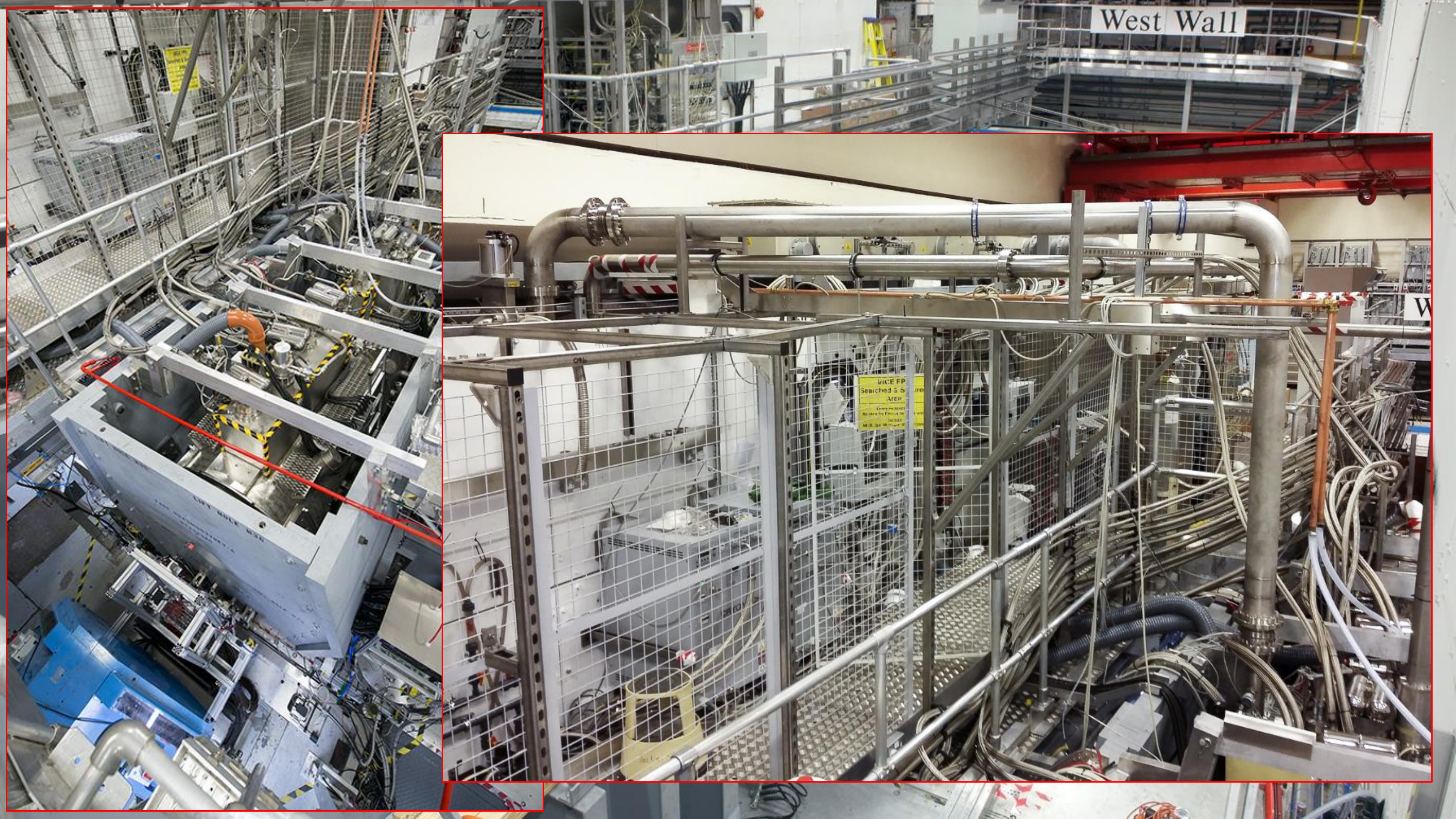
Scintillating-fibre trackers

ToF 2

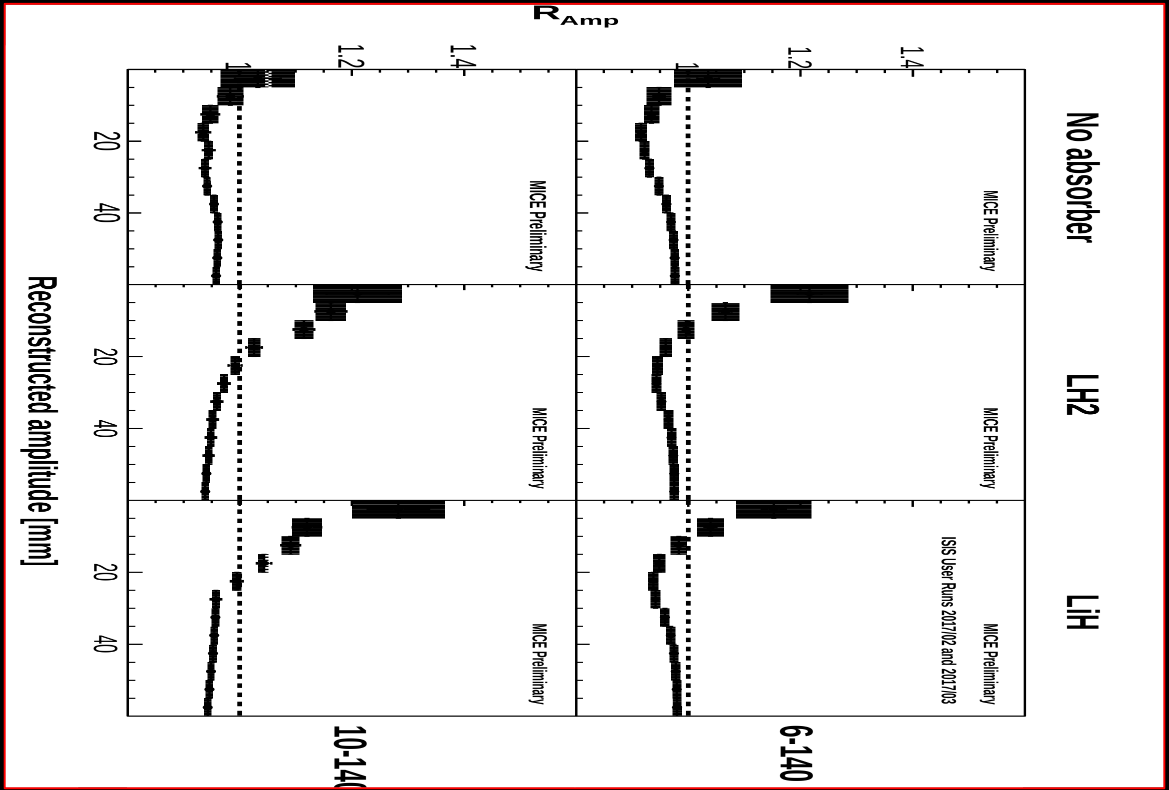
MICE






West Wall
MICE FP
Searched & Secured
Area

Core-density change across absorber



R_{amp} = ratio of cumulative density downstream to upstream

Core-density:

- *Increases* with LiH and LH2 absorbers
- *Consistent with 'no change'* for no absorber

Ionization-cooling signal

In conclusion

- **nuSTORM unique facility:**
  - **%-level *electron* and muon neutrino cross-sections**
  - **Exquisitely sensitive sterile neutrino searches**
- **Feasibility of executing nuSTORM at CERN:**
  - **Established through Physics Beyond Colliders study**

- **nuSTORM: a step towards the muon collider:**
  - **News: ionization cooling demonstrated by MICE collaboration**
    - **Required in *p*-driven neutrino factory and muon collider**
  - **nuSTORM:**
    - **Proof-of-principle and test bed for stored muons for particle physics**

Storage ring

- **New design for decay ring:**
  - Central momentum between 1 GeV/c and 6 GeV/c;
  - Momentum acceptance of up to ±16%

- **Hybrid FODO/FFA concept developed:**
  - Maintain large momentum and transverse dynamic acceptance simultaneously
  - FODO optics used in the production straight
  - Zero-chromaticity FFA cells used in arcs and return straight

- **Hybrid ring properties:**
  - Zero dispersion in the quadrupole injection/production straight; and
  - Zero chromaticity in the arcs and return straight
    - Limits overall chromaticity of ring.

- **Magnets:**
  - Superconducting combined-function magnets (B up to 2.6 T) in arcs
  - Warm combined-function magnets used in return straight
  - Large-aperture warm quadrupoles used in production straight
  - Mean betatron functions in production and return straights large:
    - Minimise betatron oscillations to minimise spread of the neutrino beam

Civil engineering

- Major CE elements:
  - 40m long junction cavern
  - 545m long extraction tunnel
  - Target complex
  - 625m circumference decay ring
  - Near detector facility
  - Support buildings and infrastructure
  - Option: far detector on CERN land
- Ground well understood
  - Tunnelling within molasse
  - ~35m vertical clearance to LHC
- CE works believed to be ‘relatively straight forward’

Radiation protection

- ~200 kW proton beam required:
  - Radiation protection places strong constraints on facility design
  - Use radiological/environmental assessments carried out for CENF
- Preliminary evaluation:
  - General feasibility of project established in terms of:
    - Exposure of persons
    - Environmental impact
  - Detailed studies according to the ALARA principle required later
- Initial conclusion:
  - *“At the present state of technological development, engineering solutions by which the radiological impact can be minimised are available.”*

Timeline

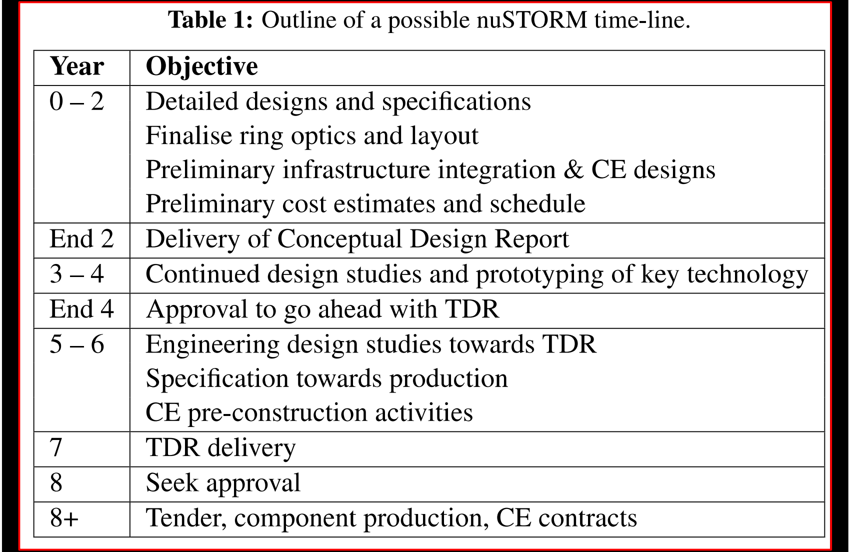


Table 1: Outline of a possible nuSTORM time-line.

Year	Objective
0 – 2	Detailed designs and specifications Finalise ring optics and layout Preliminary infrastructure integration & CE designs Preliminary cost estimates and schedule
End 2	Delivery of Conceptual Design Report
3 – 4	Continued design studies and prototyping of key technology
End 4	Approval to go ahead with TDR
5 – 6	Engineering design studies towards TDR Specification towards production CE pre-construction activities
7	TDR delivery
8	Seek approval
8+	Tender, component production, CE contracts

- Implicit:
  - Excellent detector required to exploit exquisite beam
  - So, require parallel development of detector concept

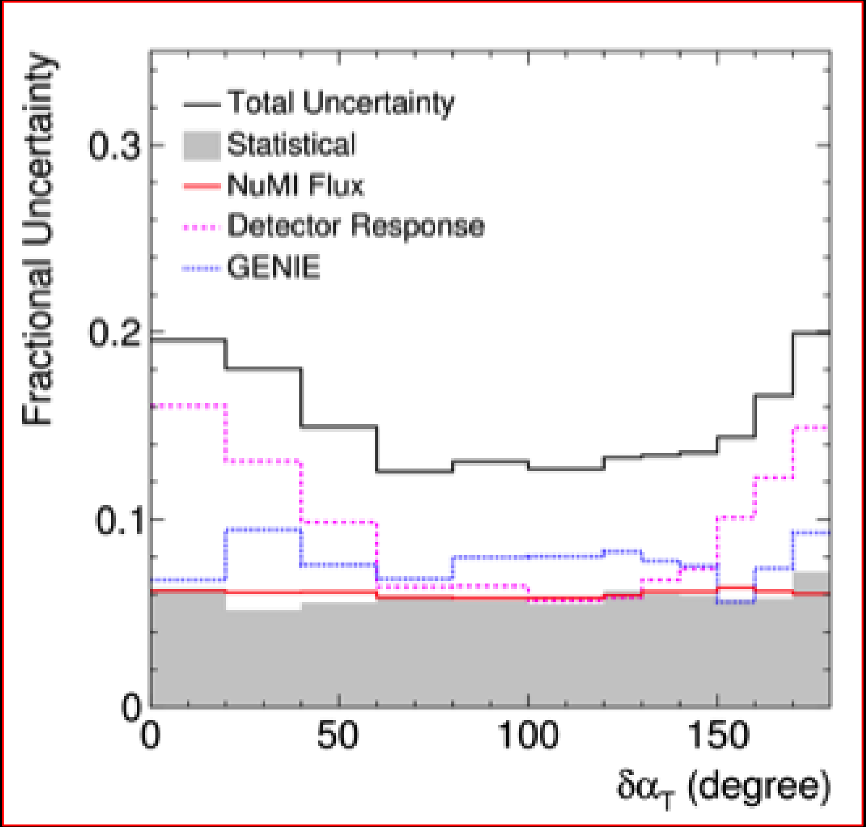
Cost

- ‘First cut’ cost estimate:
  - Based on well-developed FNAL proposal
  - Primary beam line and CE work packages:
    - Itemised evaluation based on best practice CERN experience
  - CENF used as basis for target, target hall, proton absorber and near detector hall estimate
  - Muon decay ring estimate scaled from FNAL study

- Overall material cost estimate (not including far detector): ~150 – 200 MCHF
  - Civil engineering (48 MCHF) and primary beam line (21 MCHF) included

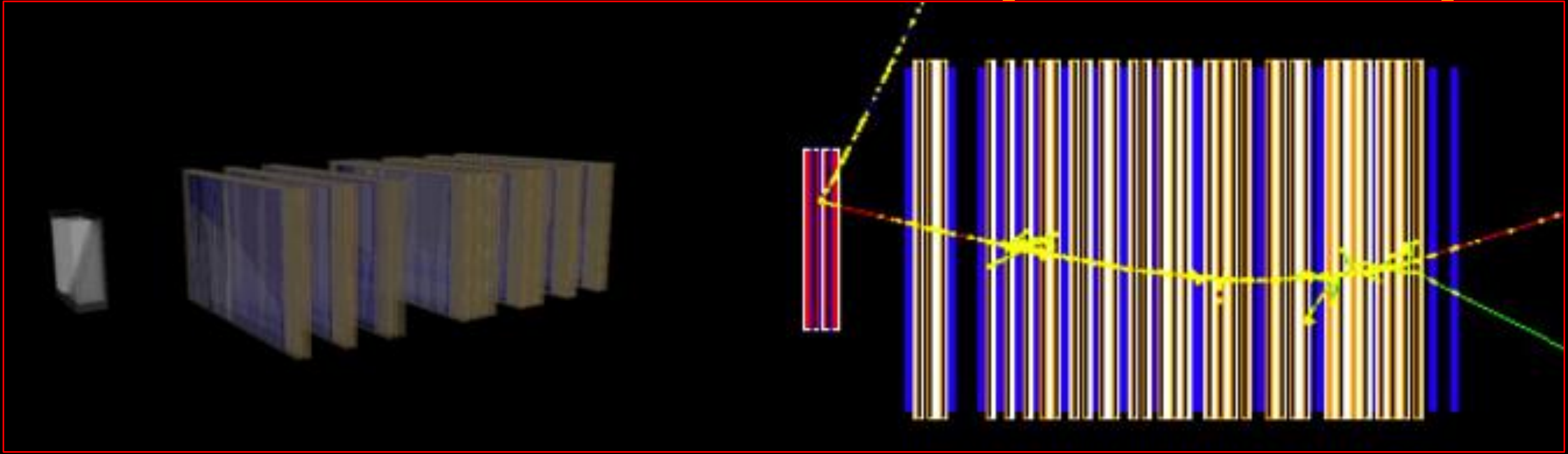
Systematic uncertainties

- **MINERvA example:**
  - Flux, detector and 'theory' contributions comparable
  - In some regions detector uncertainties dominate
- **So, to exploit nuSTORM require excellent detector**



Hallsjo, thesis

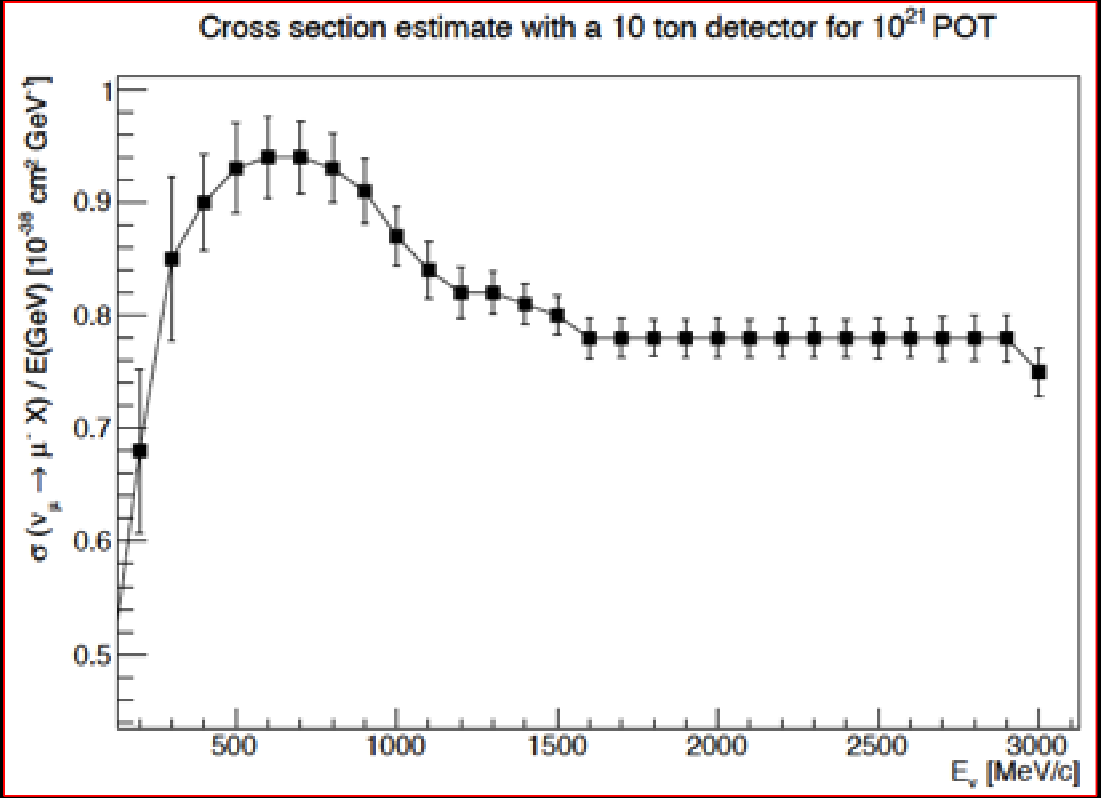
Preliminary CCQE analysis



- **TASD followed by BabyMIND**
- **Simulation with nuSTORM spectrum:**
  - **GENIE for event generation; and**
  - **GEANT4 for detector simultion**

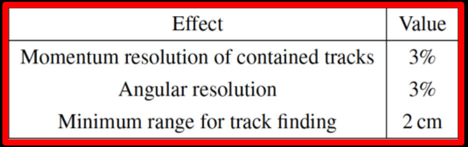
Hallsjo, thesis

CCQE performance



- CCQE cross section unfolded; 10 ton, 10^{21} POT

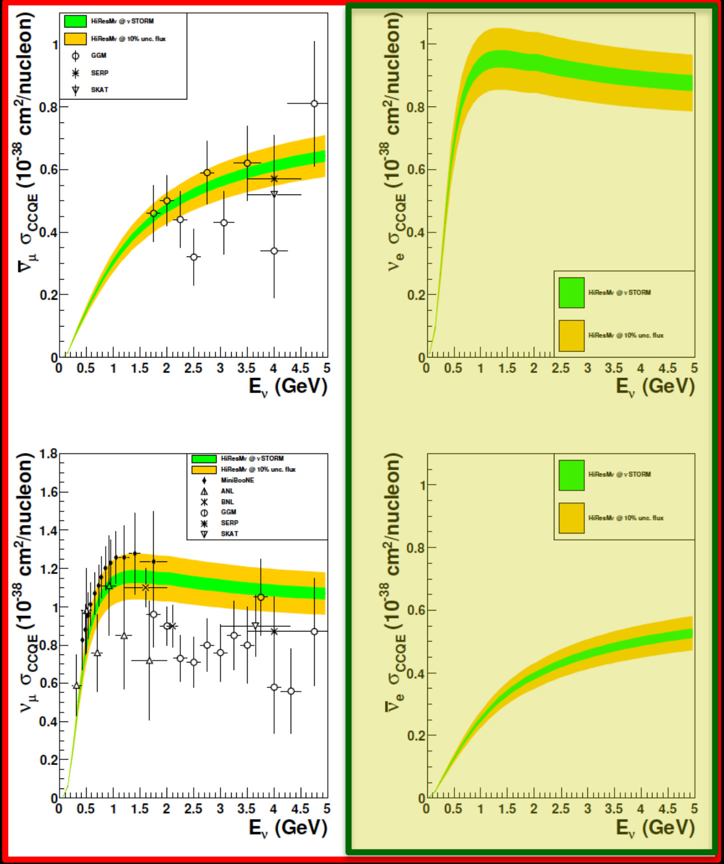
CCQE measurement at nuSTORM



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

1% & 10% flux uncertainty

10.1103/PhysRevD.89.071301; arXiv:1305.1419



- CCQE at nuSTORM:
  - Six-fold improvement in systematic uncertainty compared with (present) “state of the art”
  - Electron-neutrino cross section measurement unique
- Require to demonstrate:
  - ~<1% precision on flux

Cf/synergy with EnuBET

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