Imperial College London

Science & Technology Facilities Council

νSTORM

… neutrino factory and muon collider

Lepton interactions w\ nucleus and nuclei

Marciana Marina, Isola d'Elba, Italy

K. Long, 2 July 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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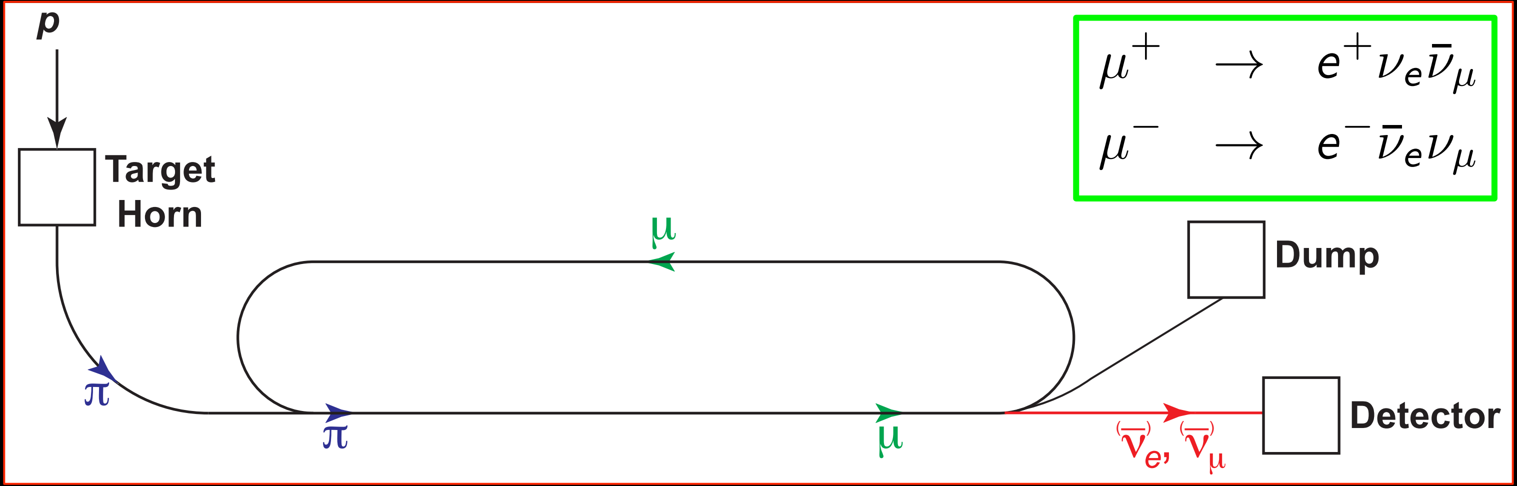
Neutrinos from stored muons

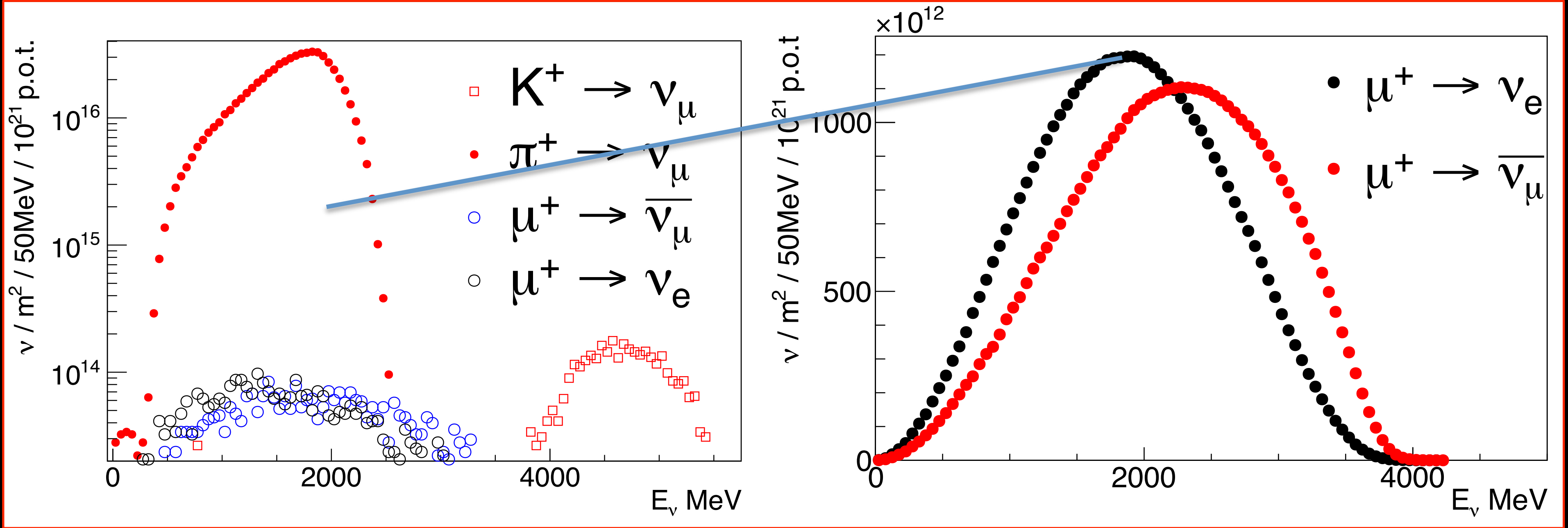


- **Scientific objectives:**
  1. %-level $(\nu_e N)$cross sections
     - Double differential
  2. Sterile neutrino search
     - Beyond Fermilab SBN

- Precise neutrino flux:
  - Normalisation: < 1%
  - Energy (and flavour) precise
- π ⇢ μ injection pass:
  - "Flash" of muon neutrinos

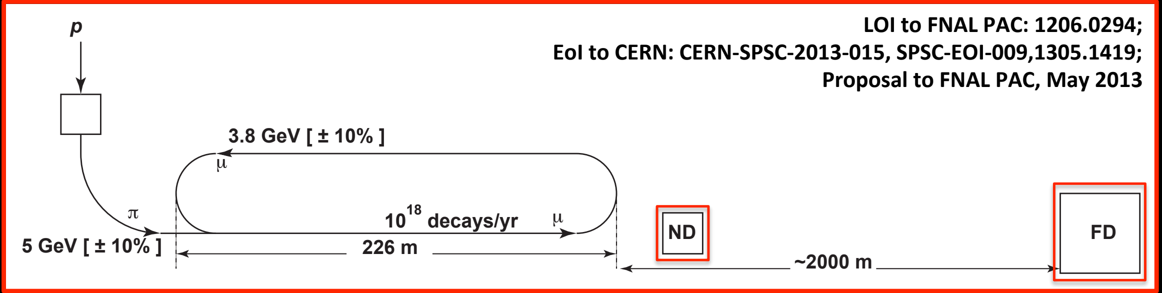
10.1146/annurev-nucl-102014-021930

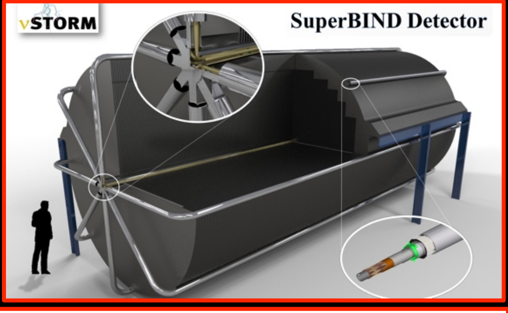
Neutrino flux

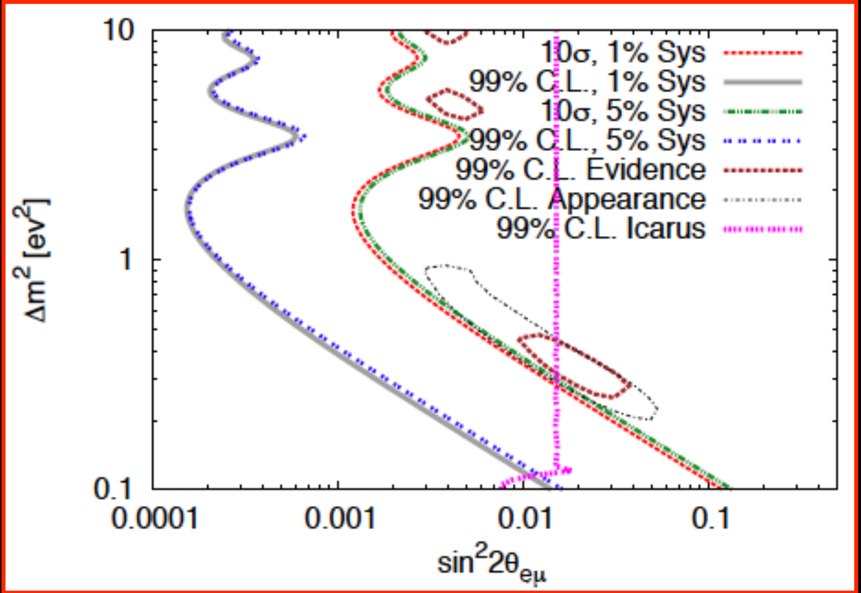


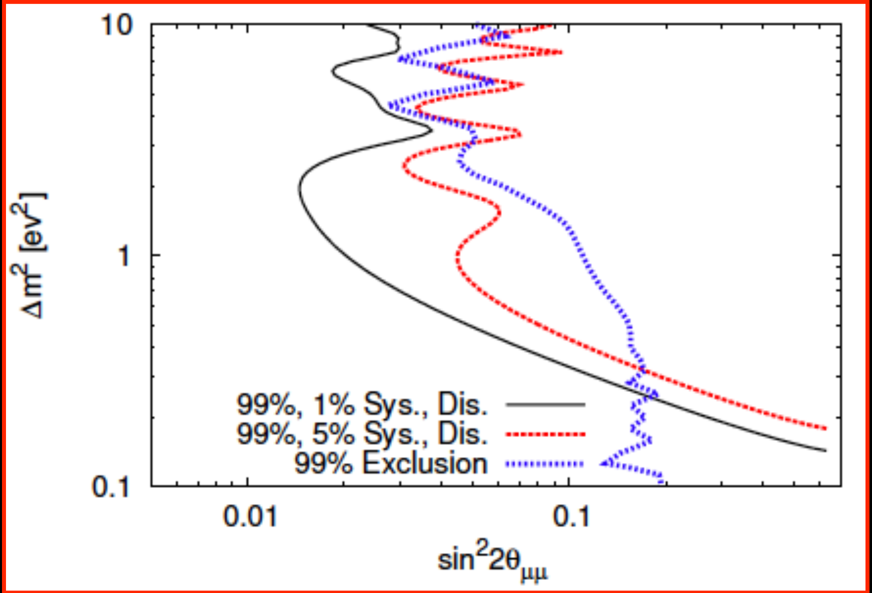
- **ν_μ flash:**
  - Pion: 6.3×10^{16} m^{-2} at 50m
  - Kaon: 3.8×10^{14} m^{-2} at 50m
    - Well separated from pion neutrinos
- **ν_e and ν_μ from muon decay:**
  - ~10 times as many ν_e as, e.g. J-PARC beam
  - Flavour composition, energy spectrum
    - Use for energy calibration

Sterile neutrino search @ FNAL





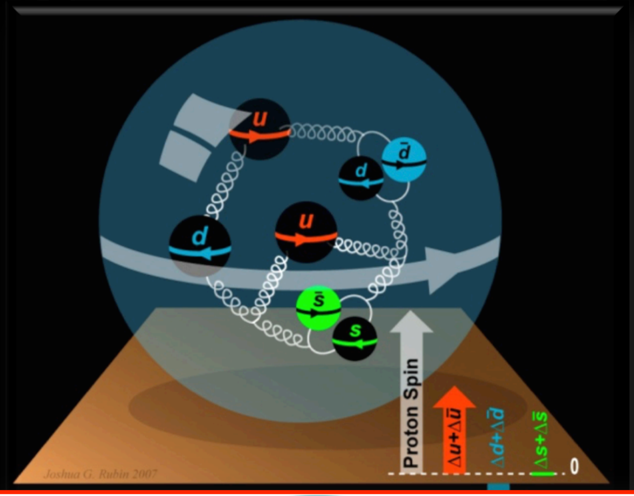


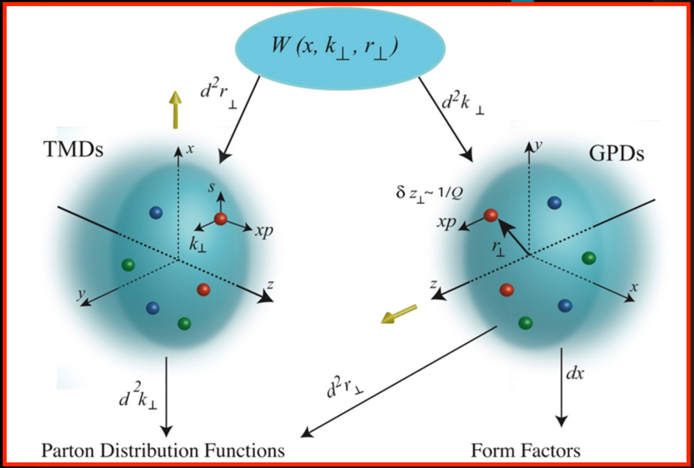


Adey et al., PRD 89 (2014) 071301

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

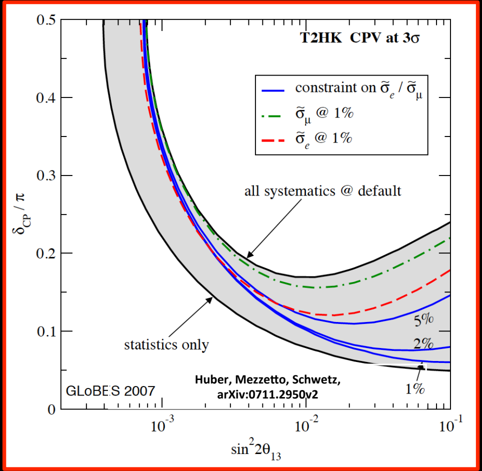


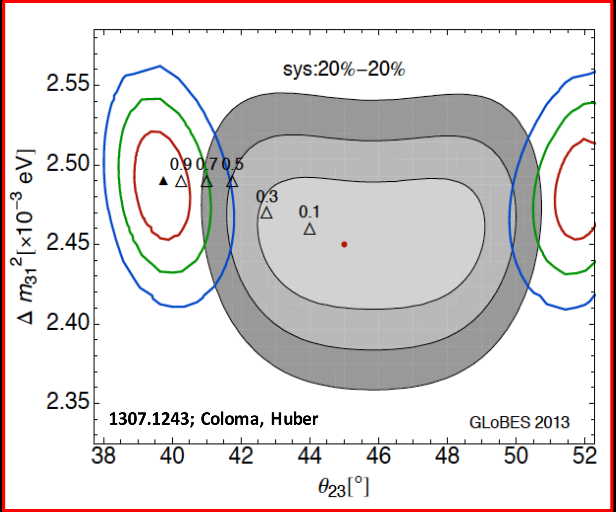


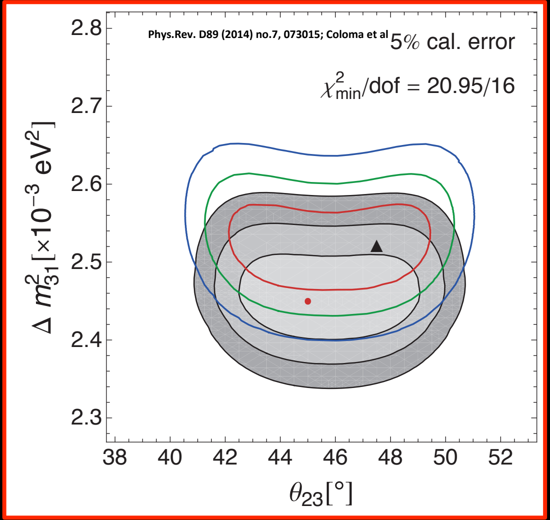
Search for CPiV in lbl oscillations

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

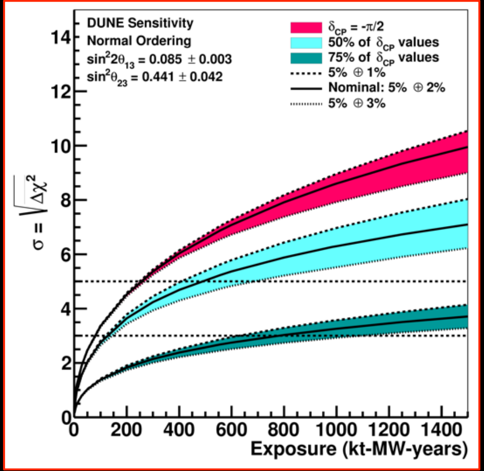






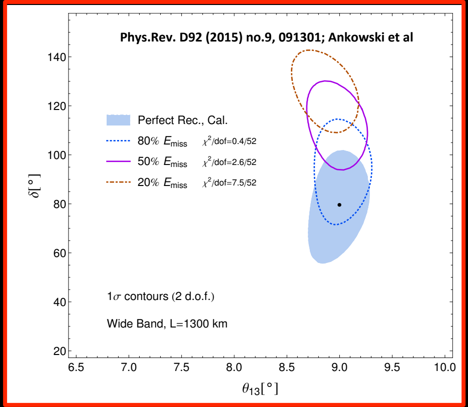
Event mis-classification

Energy scale mis-calibration



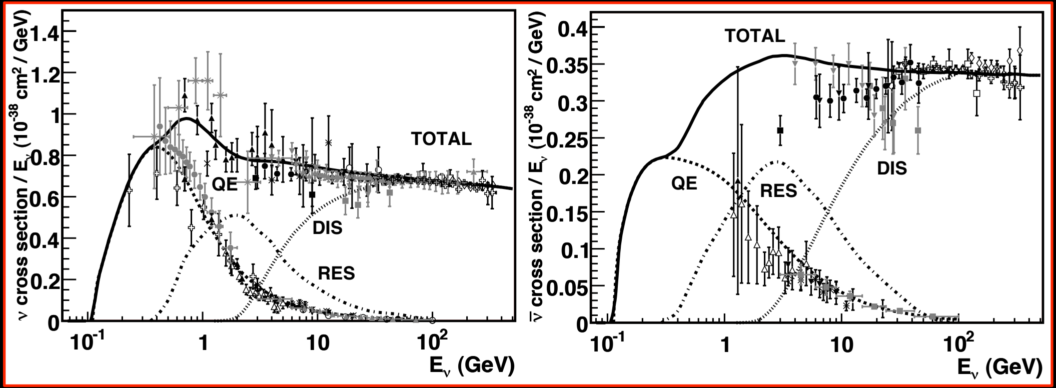
Uncertainty
(cross section and ratio)

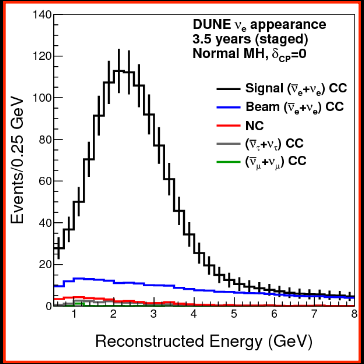
Missing energy (neutrons)

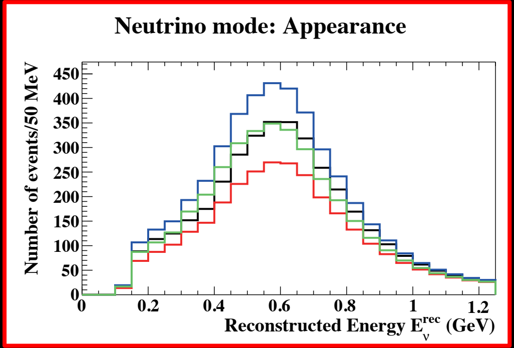


Specification: energy range

- 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
    - → $E_\mu < 6$ GeV
- So, stored muon energy range:







$$1 < E_\mu < 6 \text{ GeV}$$

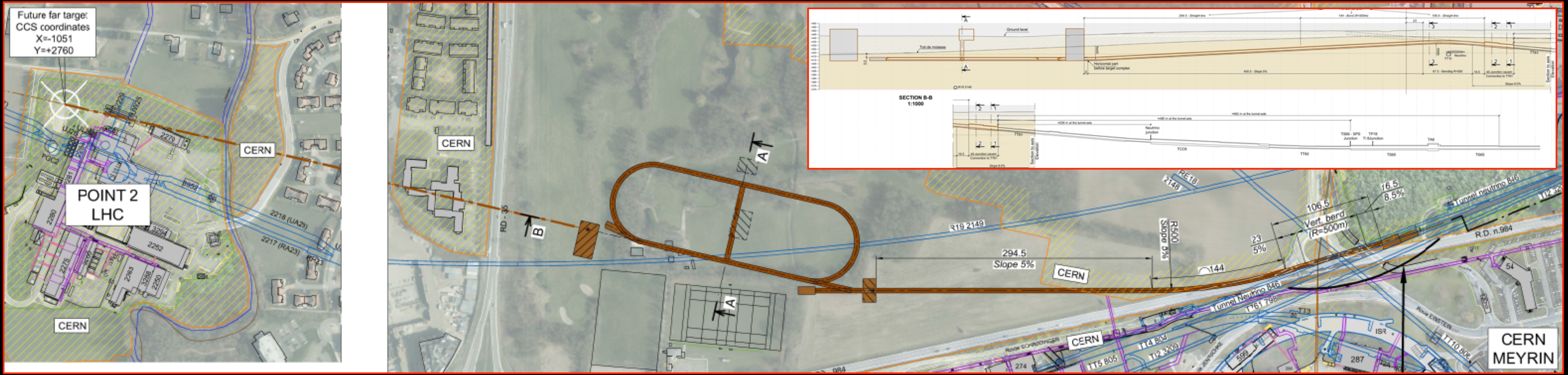
nuSTORM for νN scattering @ CERN — parameters

- **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 σ)	8 mm.mrad
Max. normalised vertical emittance (1 σ)	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 σ)	2 ns
Bunch spacing	5 ns
Momentum spread (dp/p)	2×10^{-4}

Overview

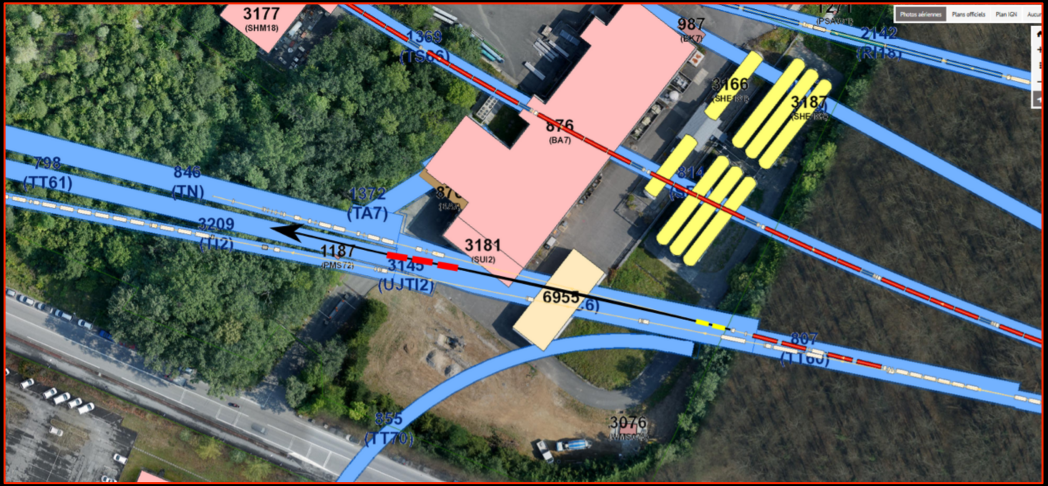


- **Extraction from SPS through existing tunnel**
- **Siting of storage ring:**
  - **Allows measurements to be made ‘on or off axis’**
  - **Preserves sterile-neutrino search option**

Extraction and *p*-beam transport to target

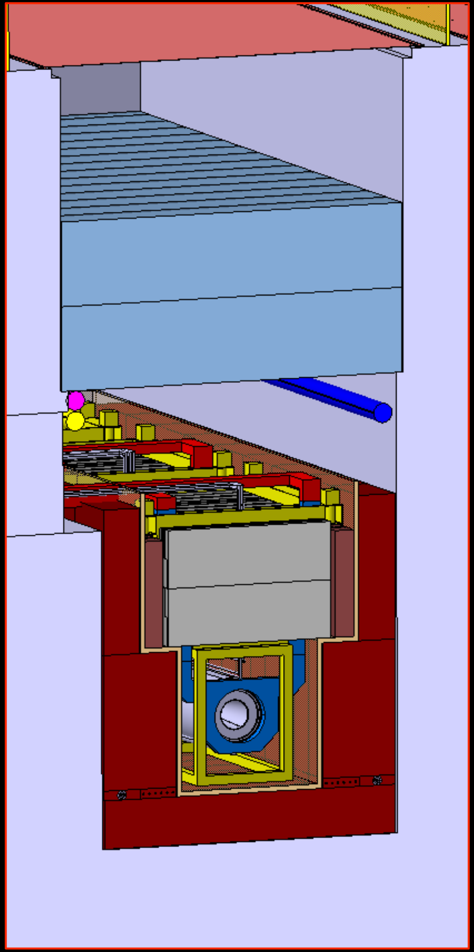
- **Fast extraction at 100 GeV:**
  - CNGS-like scheme adopted;
    - Apertures defined by horizontal and vertical septa reasonable
    - Pulse structure (2 x 10.5 ms pulses) requires kicker upgrade

- **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



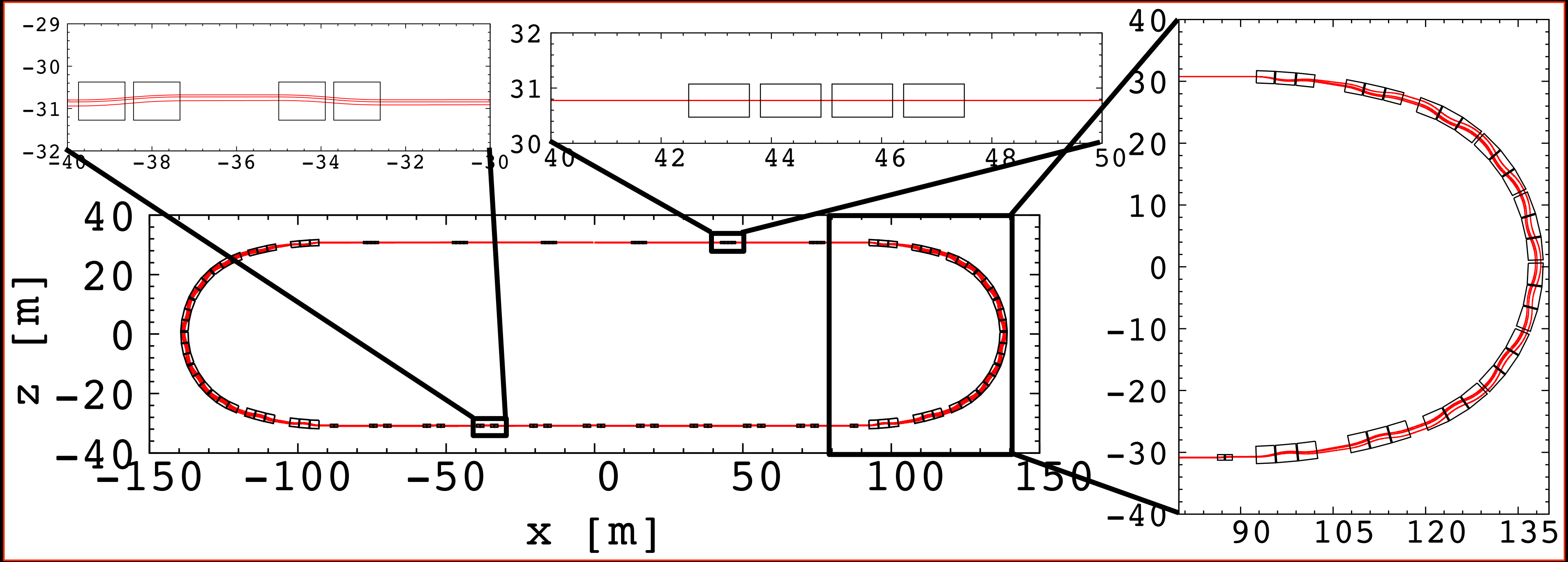
Target and capture

- **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



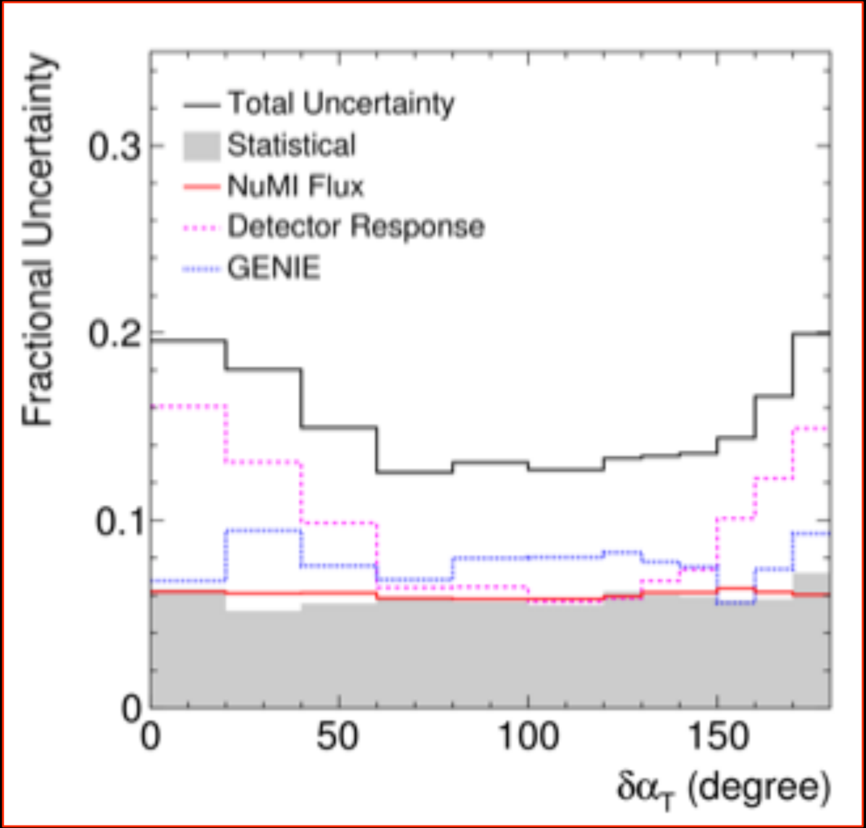
Storage ring

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



Systematic uncertainties

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

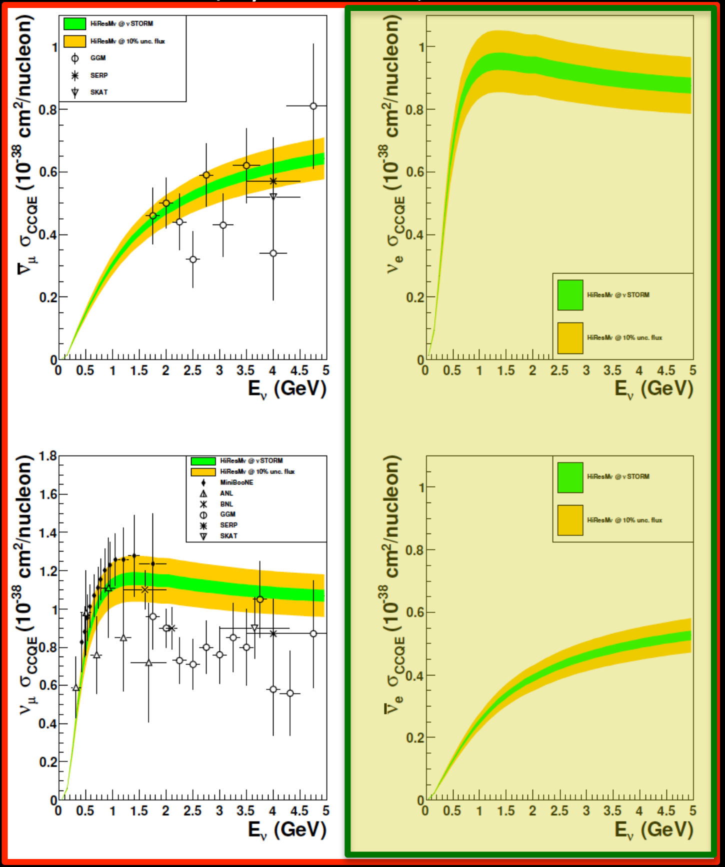


CCQE measurement at nuSTORM

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



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

- 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

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
- Conclusion:
  - *“At the present state of technological development, engineering solutions by which the radiological impact can be minimised are available.”*

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."*

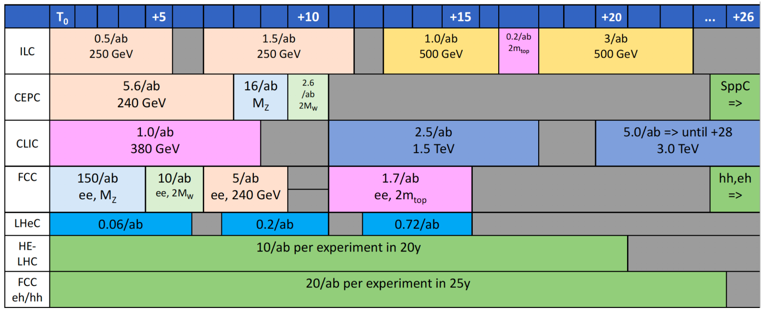
- **Challenges:**
  - **Muon decay ring:**
    - **FFA concept though feasible**
    - **Require magnet development to allow production at a reasonable cost**
  - **Detailed evaluation of:**
    - **Proton-beam extraction, target and target complex**
    - **Civil engineering studies and radiological implications**

Energy frontier, pptions

FCC hh ee he

Timescales are long

Proposed Schedules and Evolution



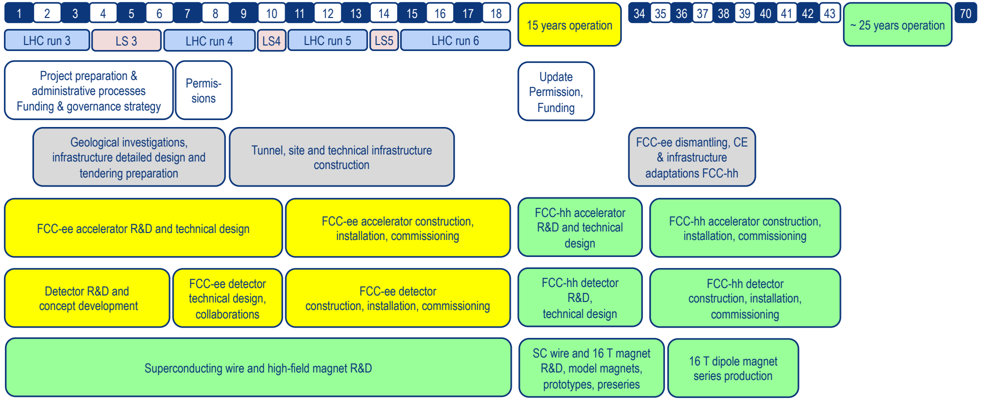
Project	Start construction	Start Physics (higgs)
CEPC	2022	2030
ILC	2024	2033
CLIC	2026	2035
FCC-ee	2029	2039 (2044)
LHeC	2023	2031

Proposed dates from projects

Would expect that technically required time to start construction is O(5-10 years) for prototyping etc.

D. Schulte 2019

FCC integrated project technical schedule



FCC integrated project is fully aligned with HL-LHC exploitation and provides for seamless continuation of HEP in Europe with highest performance EW factory followed by highest energy hadron collider.

M. Benedikt **Overview Future Circular Colliders**, EPPSU, Granada 13

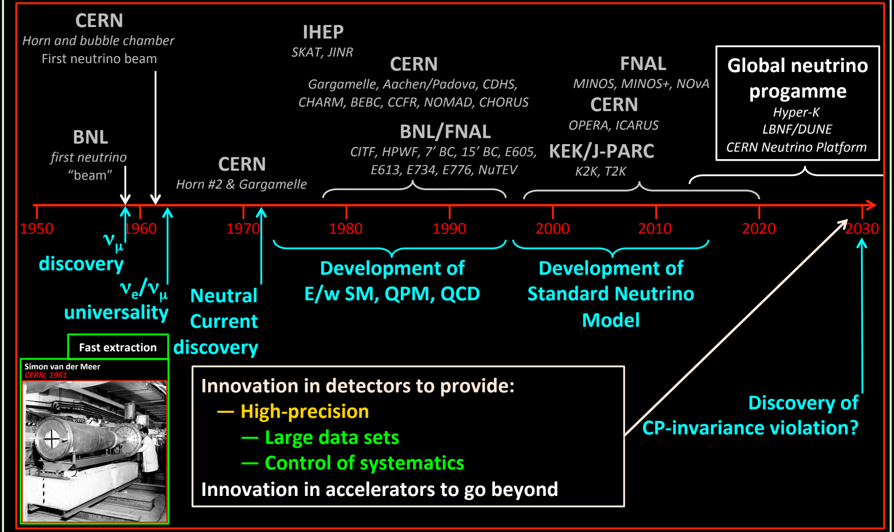
Unique advantages of muon accelerators

l^+l^- at very high energy

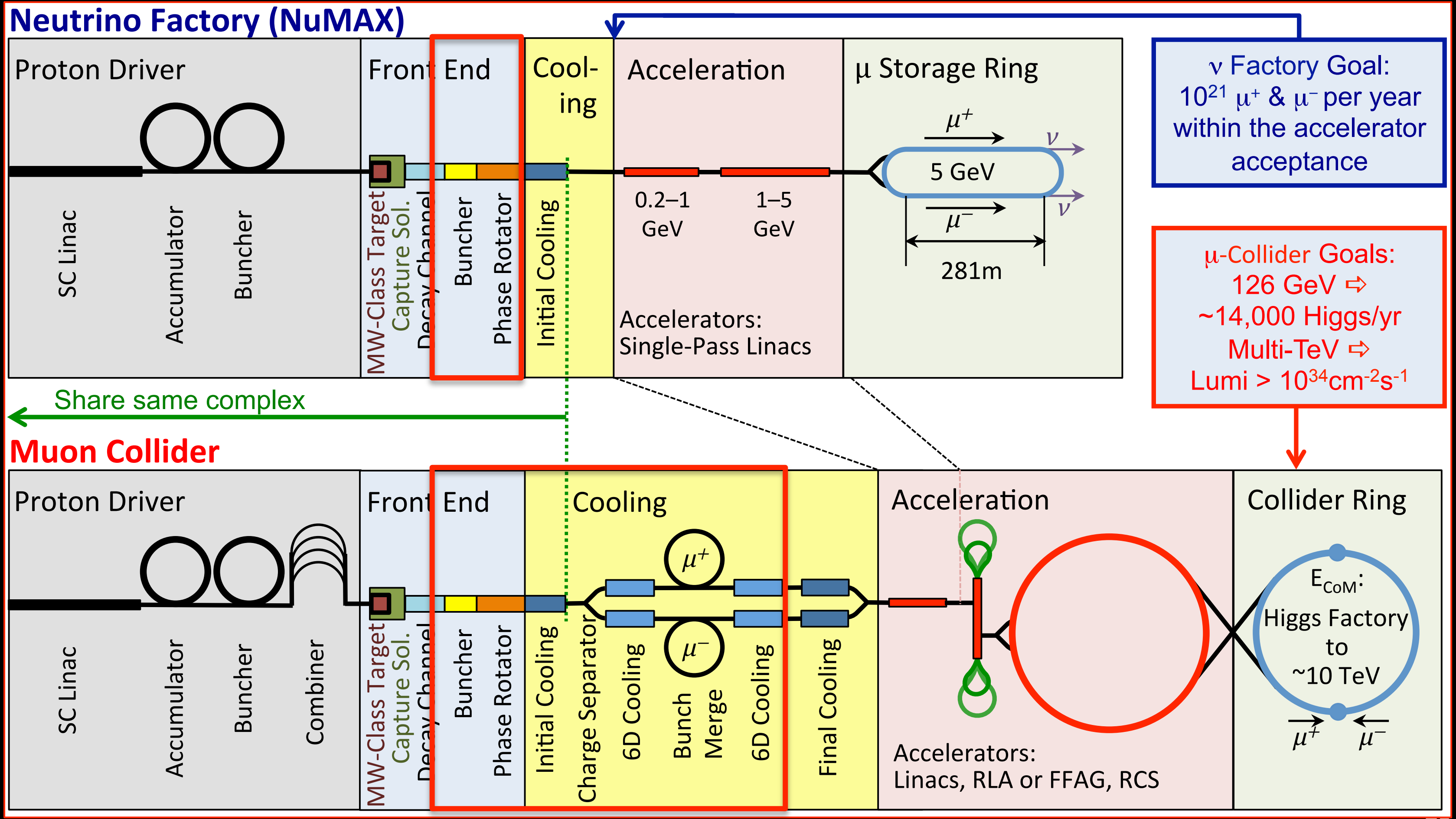
- No brem-/beam-strahlung
  - Rate $\propto m^{-4}$ [5×10^{-10} cf e]
- Efficient acceleration
  - Favourable rigidity
- Enhanced Higgs coupling
  - Production rate $\propto m^2$ [5×10^4 cf e^+e^-]

Neutrino beams

- ν_e, ν_μ
- Precisely known energy spectrum

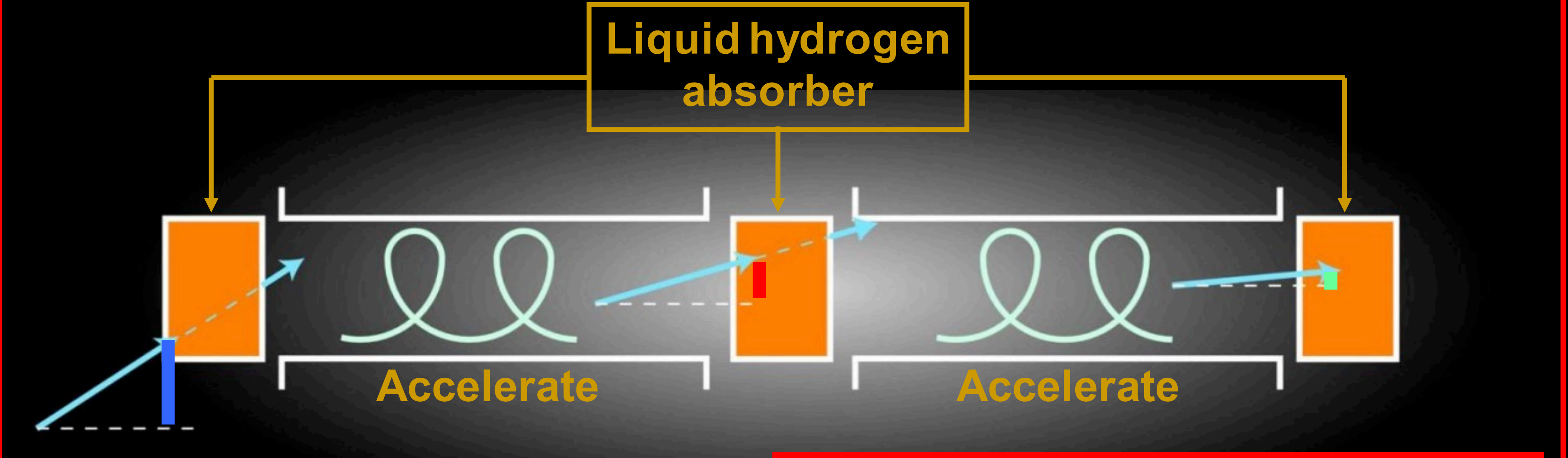


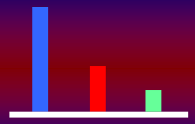
Neutrino factory and muon collider



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

The principle of ionization cooling

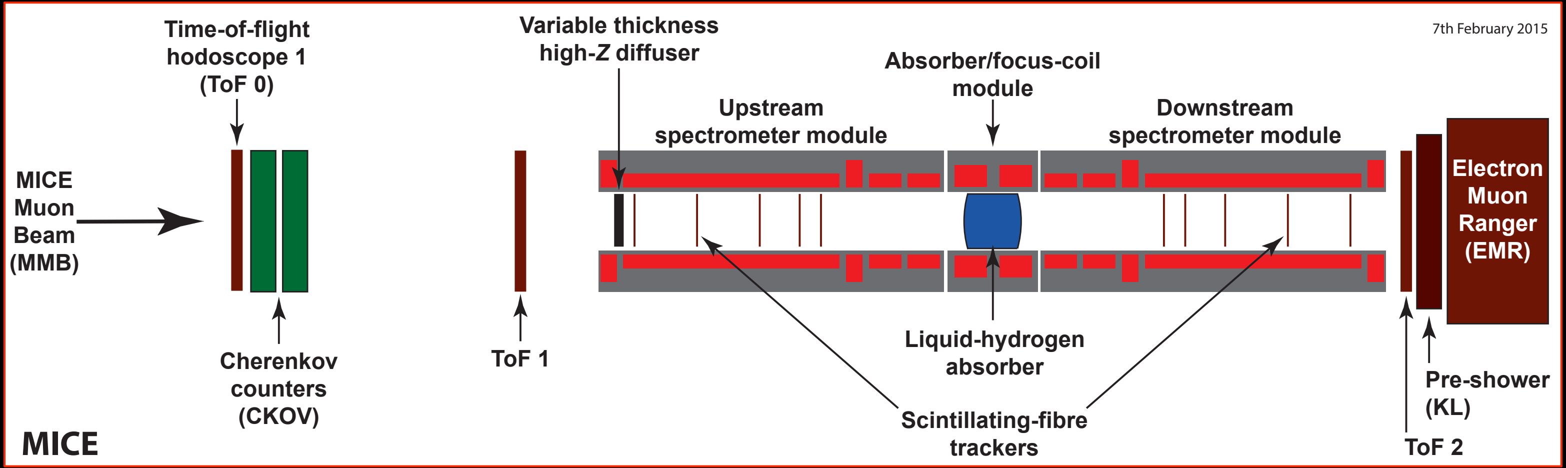


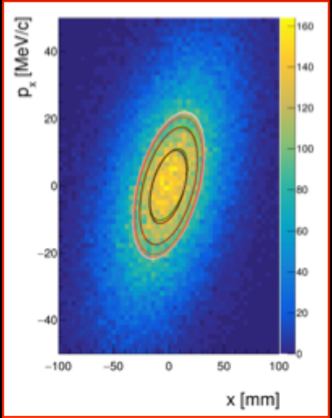


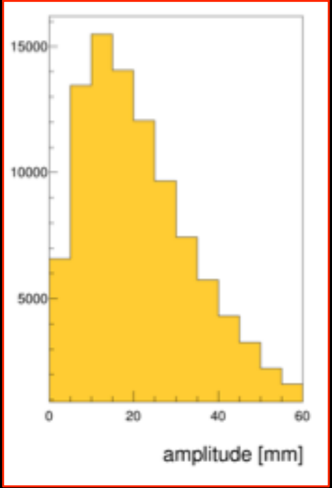
Ionisation cooling

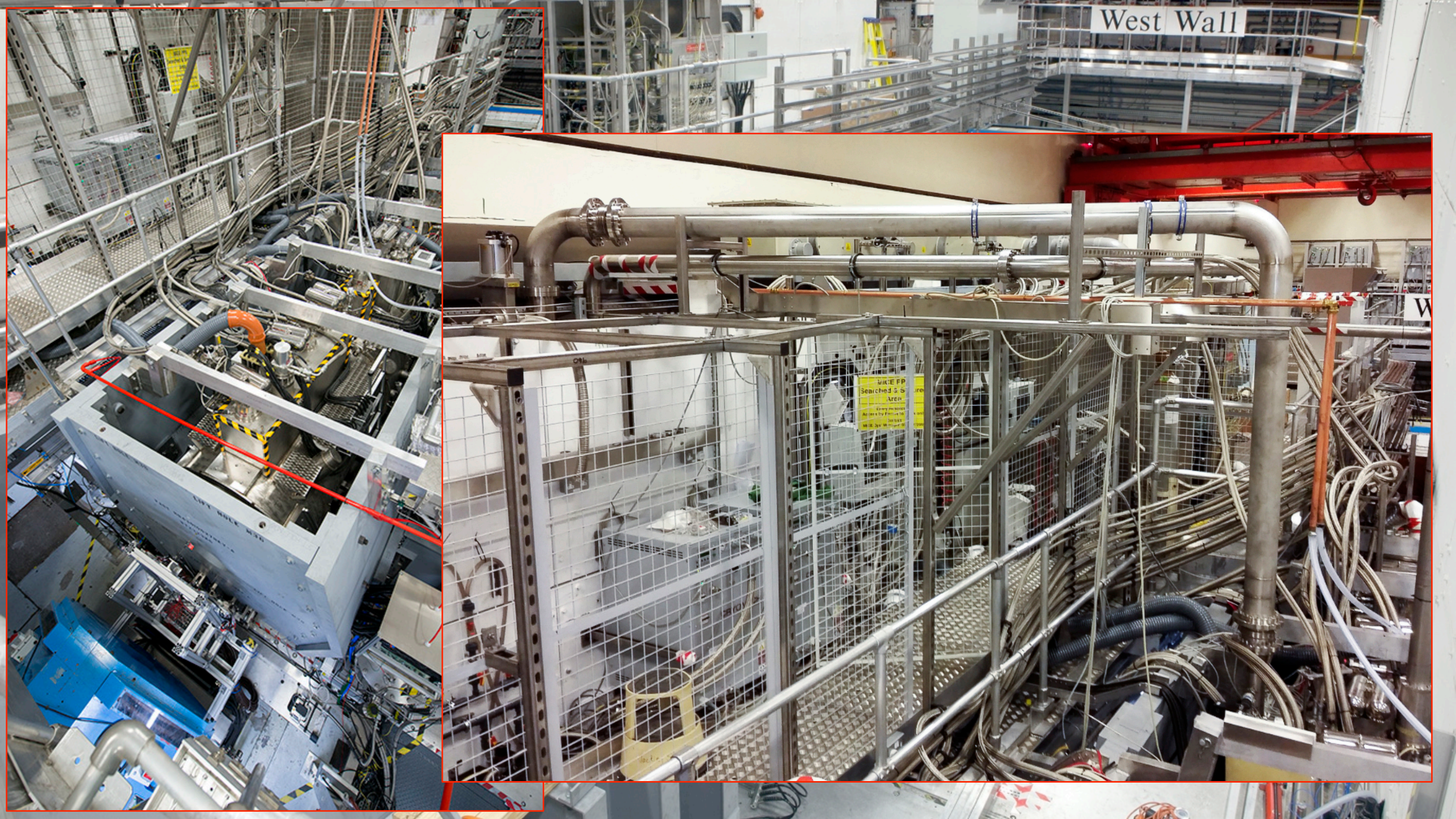
$$\frac{d\varepsilon_n}{dX} = \frac{-\varepsilon_n}{\beta^2 E}\left\langle \frac{dE}{dX} \right\rangle + \frac{\beta_t (0.014\ \mathrm{GeV})^2}{2\beta^3 E m_\mu X_0}$$

The experiment

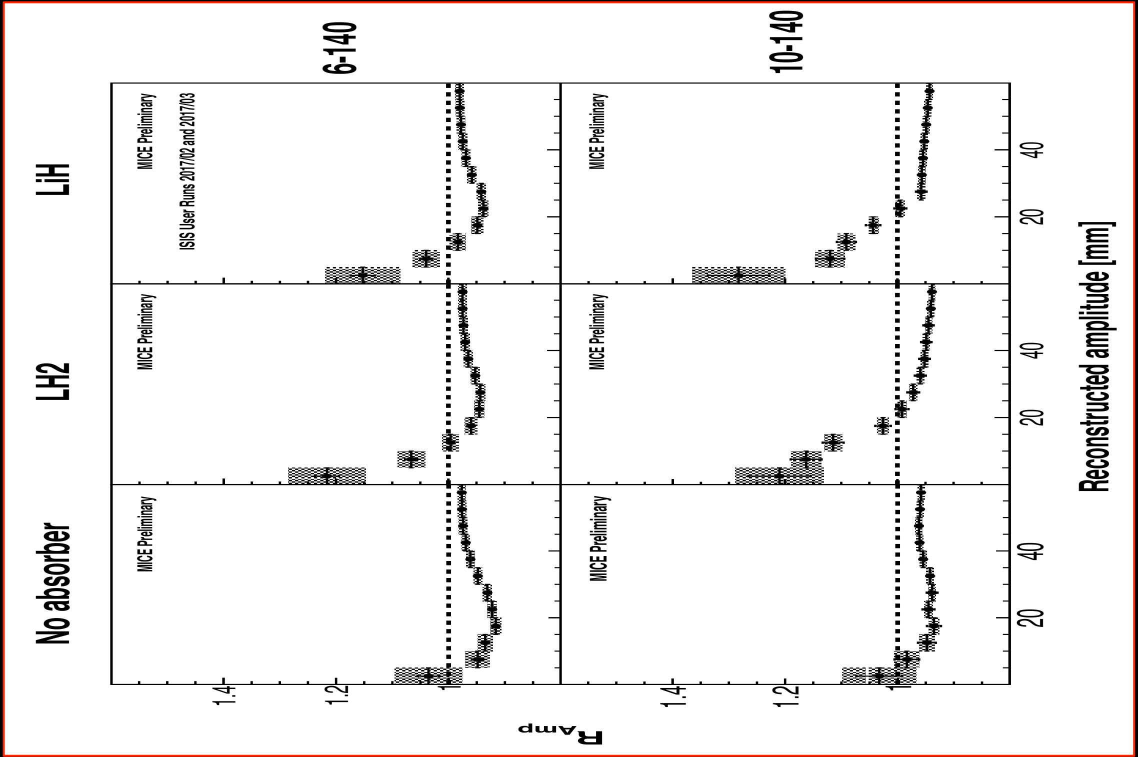







West Wall

Core-density change across absorber



Core-density:

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

Ionization-cooling signal

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

Muon collider

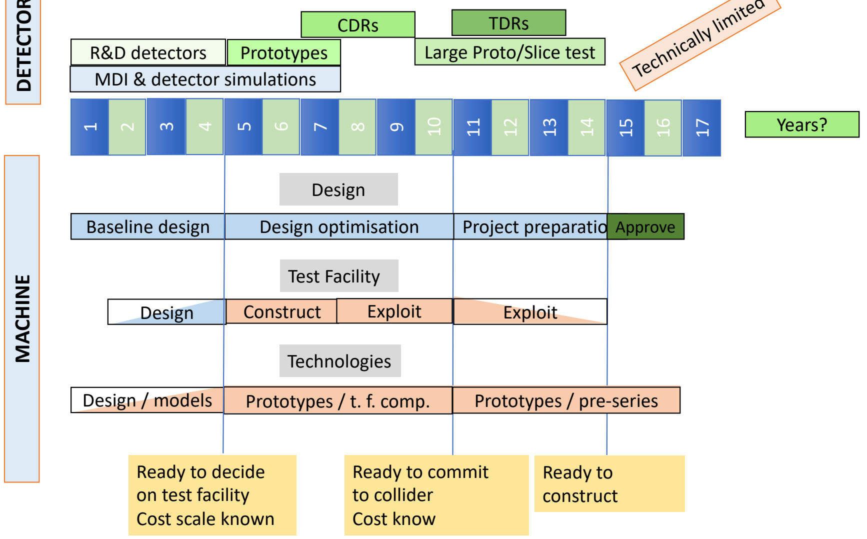
Answers to the Key Questions

- **Can muon colliders at this moment be considered for the next project?**
  - Enormous progress in the proton driven scheme and new ideas emerged on positron one
  - But at this moment not mature enough for a CDR, need a careful design study done with a coordinate international effort

- **Is it worthwhile to do muon collider R&D?**
  - Yes, it promises the potential to go to very high energy
  - It may be the best option for very high lepton collider energies, beyond 3 TeV
  - It has strong synergies with other projects, e.g. magnet and RF development
  - Has synergies with other physics experiments
  - **Should not miss this opportunity?**

- **What needs to be done?**
  - Muon production and cooling is key => A new test facility is required.
    - Seek/exploit synergy with physics exploitation of test facility (e.g. nuSTORM)
  - A conceptual design of the collider has to be made
  - Many components need R&D, e.g. fast ramping magnets, background in the detector
  - Site-dependent studies to understand if existing infrastructure can be used
    - limitations of existing tunnels, e.g. radiation issues
    - optimum use of existing accelerators, e.g. as proton source
  - **R&D in a strongly coordinated global effort**

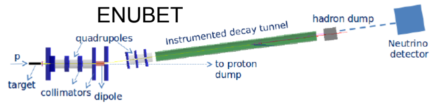
Proposed tentative timeline

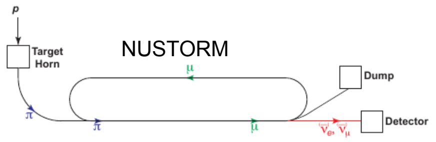


Neutrinos

Precision program in Europe

- Squeezing every bit of information out of the future experiments requires a complementary program (special rôle for Europe) to
  - Measure hadroproduction for the neutrino flux prediction (NA61)
  - Understand the neutrino-nucleus cross-section at the % level, both theoretically and with new facilities (Enubet, Nustorm)
  - Collaboration to be developed with nuclear physicists
- Next-to-next generation facilities (ESSnuSB, …) are also under study





Neutrino oscillations

- Vibrant program (DUNE, Hyper-Kamiokande, JUNO, ORCA) to fully measure the PMNS mixing matrix and especially the Mass Ordering and the CP violation phase delta, with strong European contribution. Perceived by the community as a priority.
- Neutrino experiments need cutting-edge detectors and % precision on the flux and cross-sections: leading rôle for Europe (NA61, Neutrino Platform). New facilities currently under study.
- Long term future for high precision LBL measurements with new techniques. Time to prepare for it !

Neutrino Physics
(accelerator and non-accelerator)
summary of the session

Conveners: Stan Bentvelsen, Marco Zito

ESPPU Open Symposium Granada
May 16, 2019

In the session we also covered astroparticle physics

In conclusion

- **nuSTORM 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:**
  - 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

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

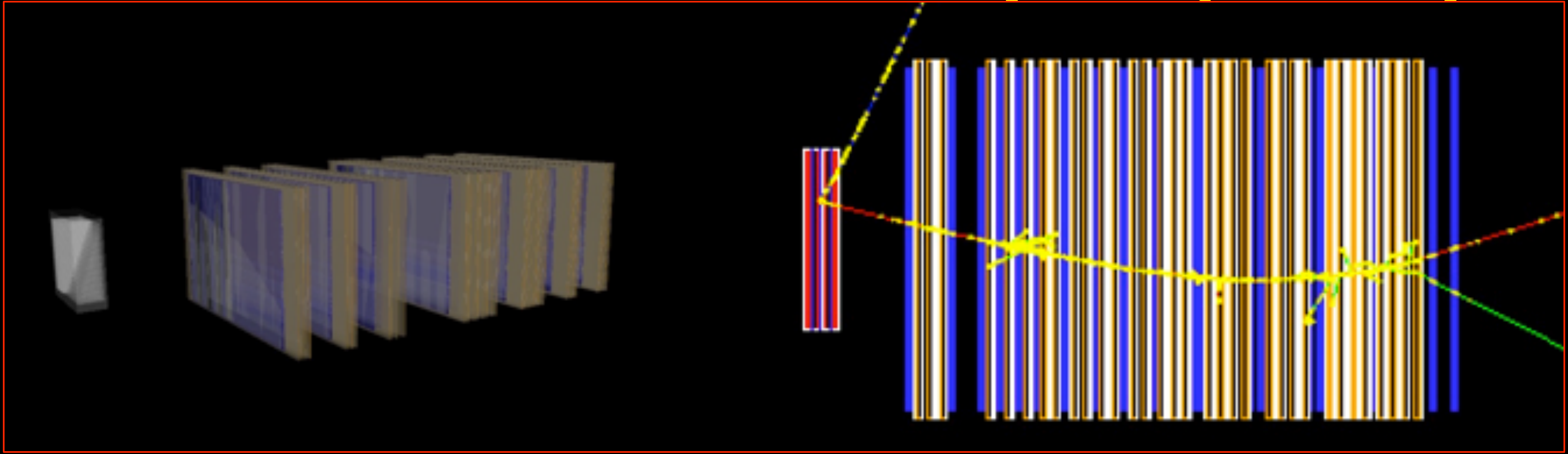
- Implicit:
  - Excellent detector required to exploit exquisite beam
  - So, require parallel development of detector concept

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

Hallsjo, thesis

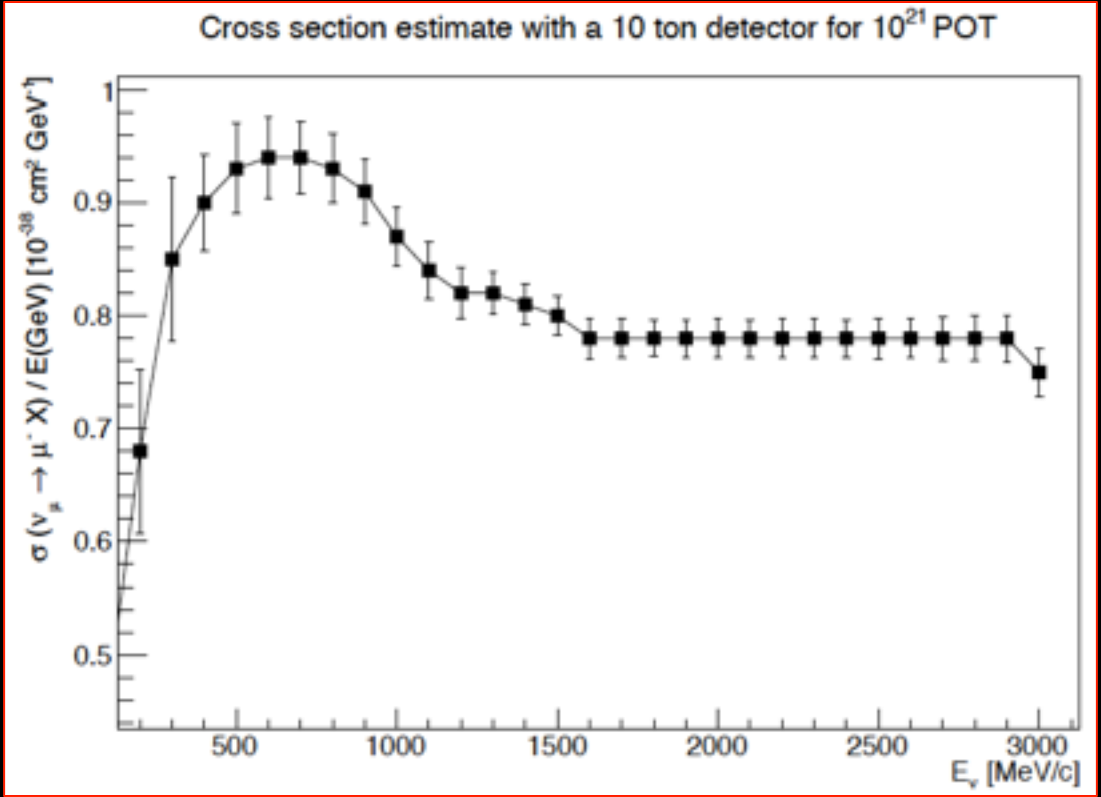
Preliminary CCQE analysis



- 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**