Muon Collider and nuSTORM

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On behalf of the nuSTORM Collaboration
PPAP community meeting
Manchester, 22 Sept. 2022

Latest mission statement

- PPAP IF Preliminary Activity Submission Wave 3 (Sept, 2022)
  - Neutrinos from Stored Muons, nuSTORM, will serve a first-rank neutrino-physics programme, provide the ideal muon-collider test bed, and prove novel particle-accelerator techniques.
  - The principal objectives of the 3-year Preliminary Activity (PA) are:
    - The completion of the detailed conceptual design for nuSTORM located at CERN, including the design of the detector suite that maximises its physics potential; and
    - The detailed conceptual design of the 6D cooling experiment.

  The designs will be presented in definitive Conceptual Design Reports (CDRs). The CDRs will be submitted to the next update of the European Strategy for Particle Physics (ESPP) to make the case for nuSTORM and the 6D-ionization-cooling demonstrator to enter the pre-construction phase.

Recent Community Feedback

- 2020 update to the European Strategy for Particle Physics (ESPP)
  - highlighted the consideration of a European infrastructure for precision measurements of neutrino scattering cross sections and muon beam R&D as a High Priority Initiative.
- Accelerator R&D Roadmap prepared by the European Laboratory Directors Group
  - highlighted the need to complete the design of 6D muon-cooling demonstrator before the next ESPP update and noted synergy with nuSTORM
- PPAP 2021 roadmap
  - "The UK should maintain its recognized expertise in Muon Collider studies concentrating on medium-term projects focused on feasibility demonstration exploring synergies with neutrino physics such as nuSTORM"
  - "To extract the most physics out of the long-baseline neutrino experiments the UK should build on its existing expertise to pursue a complementary programme of precision measurements of neutrino interaction cross-sections and neutrino fluxes."
- nuSTORM and the international Muon Collider (IMC) are now being reviewed in the US Snowmass2021 summer study.
  - expected to conclude that development of the IMC is important for the US particle physics programme and to recommend principal risk mitigation R&D be carried out by 2035.
- The IMC programme has successfully attracted European Horizon Europe funding (muCol project, 2022-INFRA-DEV-01-01), scoring 14.5/15.
- September 2022: Invited for PPAP Preliminary Activity Submission, not endorsed by STFC.

CERN
Horn and bubble chamber
First neutrino beam

BNL
first neutrino “beam”

CERN
Horn #2 & Gargamelle

IHEP
SKAT, JINR

CERN
Gargamelle, Aachen/Padova, CDHS, CHARM, BEBC, CCFR, NOMAD, CHORUS

BNL/FNAL
CITF, HPWF, 7’ BC, 15’ BC, E605, E613, E734, E776, NuTEV

FNAL
MINOS, MINOS+, NOvA

CERN
OPERA, ICARUS

KEK/J-PARC
K2K, T2K

Global neutrino progamme
Hyper-K
LBNF/DUNE
CERN Neutrino Platform

1950 1960 1970 1980 1990 2000 2010 2020 2030

ν_μ discovery

ν_e/ν_μ universality

Neutral Current discovery

Development of E/w SM, QPM, QCD

Development of Standard Neutrino Model

Discovery of CP-invariance violation?

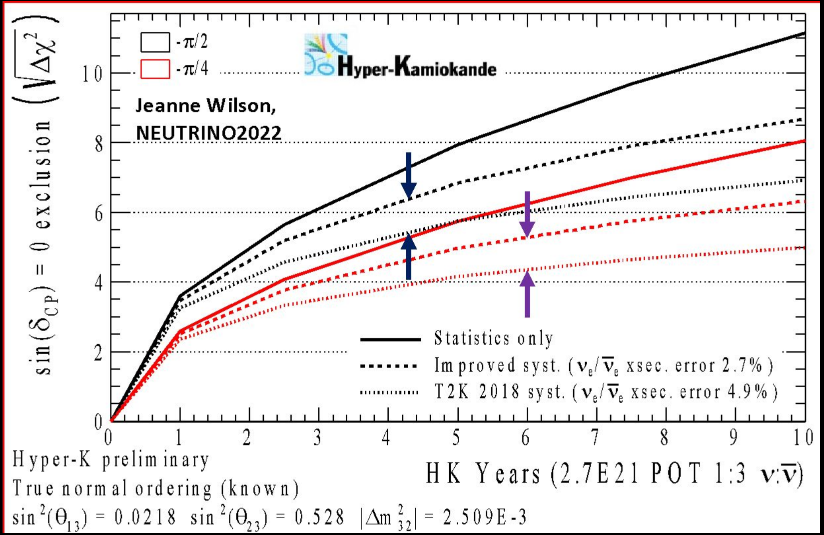
Simon van der Meer
CERN, 1961

Innovation in detectors to provide:
- — High-precision
  - — Large data sets
  - — Control of systematics

Innovation in accelerators to go beyond

$\nu_e/\bar{\nu}_e$ interactions for oscillations

- δ_{CP} requires ν_e and ν_e appearance
  - Suppress ν_e and ν_e background in beams
- Need $\nu_e/\bar{\nu}_e$ interaction data
- At 1st order precision:
  - ν_μ–A + lepton universality constrains ν_e–A
- δ_{CP} requires requires 2nd order precision!
  - Large data sets & better-understood fluxes
- High-specification detector:
  - Measure lepton & hadronic final state



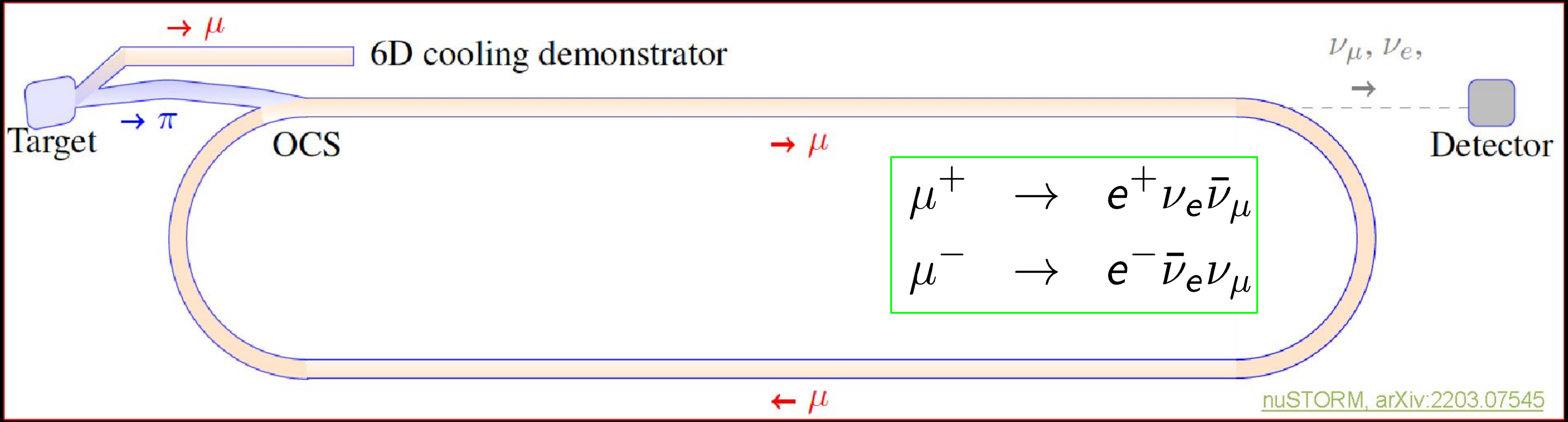
Lepton mass correction *Hadronic/nuclear response*

$$E_\nu^{\text{tree-level}} = \frac{m_\ell^2 + Q^2}{2\,(E_\ell - p_\ell \cos\theta_\ell)}$$

Lepton observables

- QED radiative corrections and lepton mass “nudge” �, shifting internal (�, �) phase space

Neutrinos from stored muons



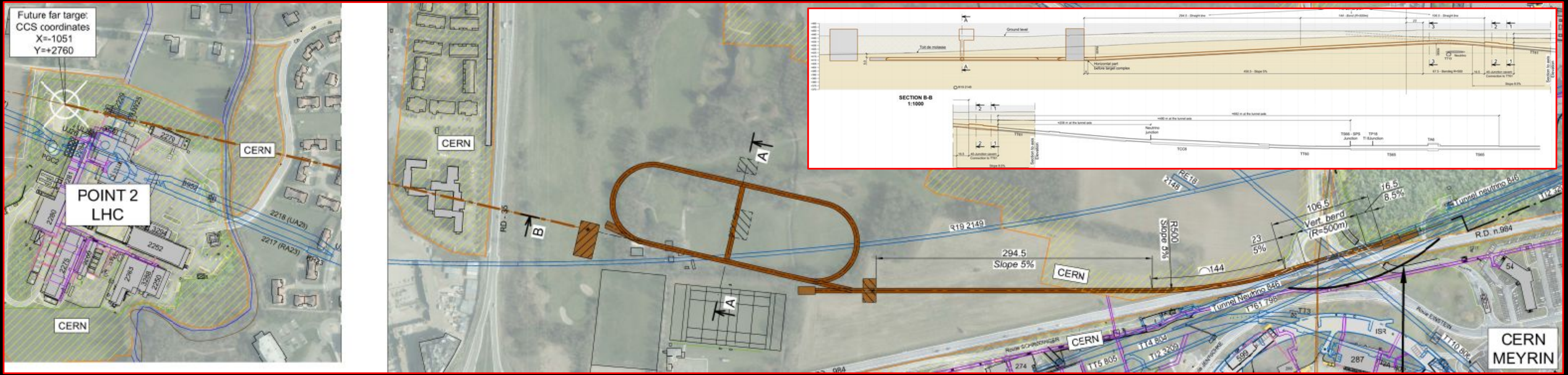
- **Scientific objectives:**
  1. %-level ($\overset{(-)}{\nu}_e N$) cross sections
     - Multi differential / E_ν scan
  2. BSM searches
     - E.g. steriles beyond FNAL SBN
  3. Muon collider demonstrator

- **Precise neutrino flux:**
  - Normalisation: < 1%
  - Energy (and flavour) precise

- **$\pi \rightarrow \mu$ injection pass:**
  - "Flash" of muon neutrinos

Overview

CERN-PBC-REPORT-2019-003
DOI:10.17181/CERN.FQTB.O8QN

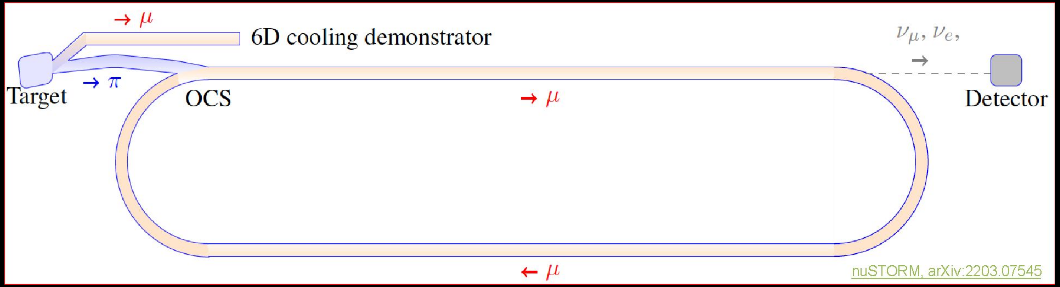


- **Extraction from SPS through existing tunnel**
- **Siting of storage ring:**
  - **Allows measurements to be made 'on or off axis'**
  - **Preserves sterile-neutrino search option**

End-to-end simulation for (re)optimisation

P. Kyberd et al

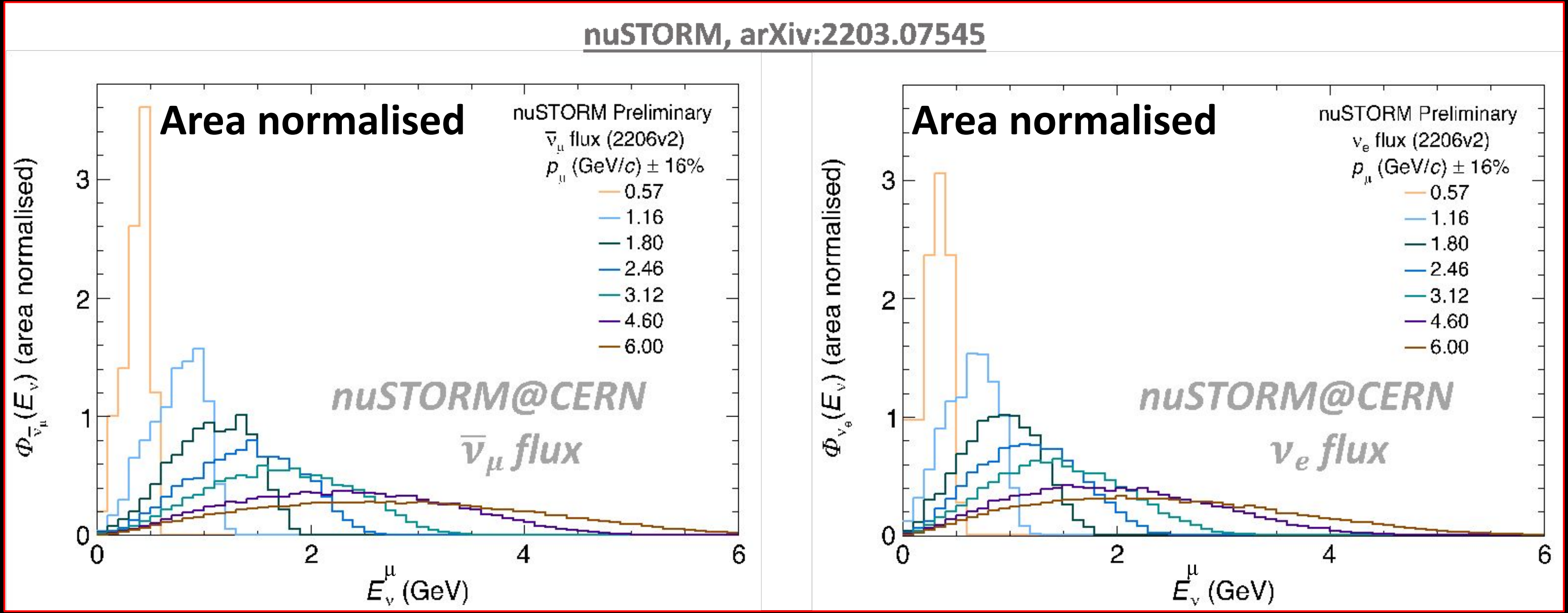
- “nuSIM” under development to:
  - Simulate facility “from target to detector”:
    - Pragmatic approach:
      - Fast simulation, parametric approach
      - Full tracking using G4 based code; “BDSIM”



- Neutrino energy scan:
  - “Pion flash” in first pass
  - Subsequently neutrinos from muon decay
    - Spectrum determined by accelerator tune
    - Normalization uncertainty < 1%

T. Alves, M. Pfaff

nuSTORM@CERN: flux estimation

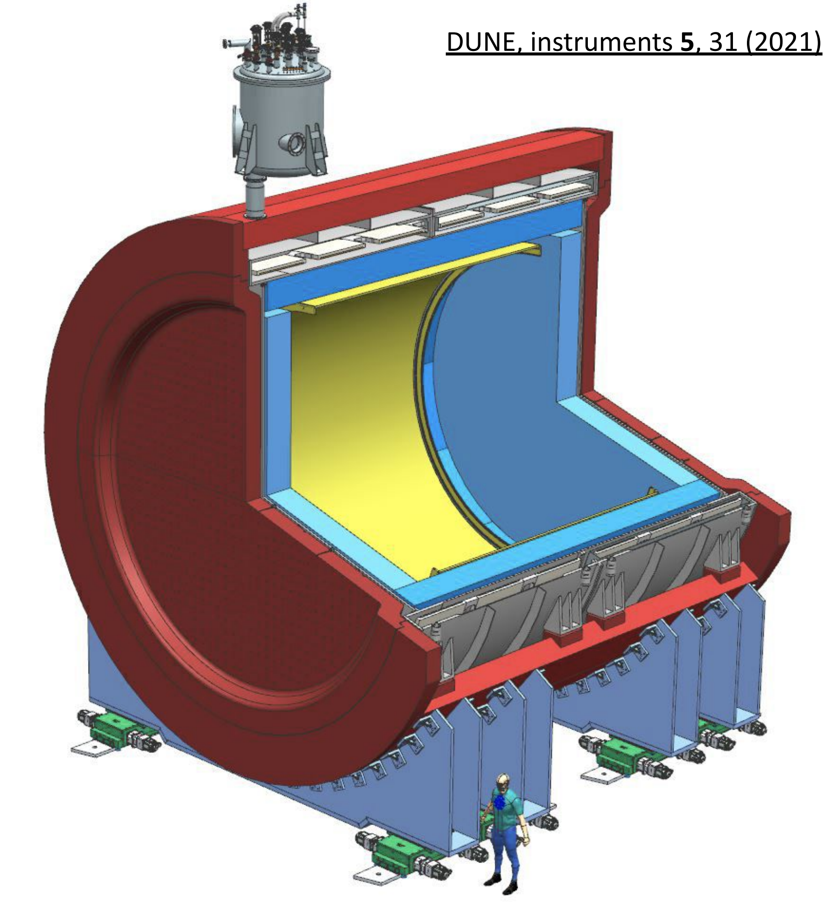


- **Oscillation-relevant energy regime**
  - **Hyper-K: 0.6 GeV**
  - **DUNE.   : 2.4 GeV**
- **Set by stored-muon momentum**
- **Accelerator "tune" gives fine control**
  - **E.g. optimise flux shape (or spread) by adjusting the ring acceptance**

- **Unique opportunity:**
  - **E_ν-scan measurements**
  - **Monoenergetic flux (ν_e!!) emulated by flux combination**
    - **Like PRISM, but with more degree of freedom in component shaping**

nuSTORM@CERN: working towards a detector concept

- **nuSIM ready to allow performance evaluation:**
  - **Require "highly capable" detector:**
    - **Scattered lepton**
    - **Inclusive and exclusive final states**
- **Initial study use DUNE ND-GAr:**
  - **TPC reference design**
    - **10-bar argon-based gas TPC**
    - **Large gas volume**
    - **Surrounded by calorimeter**
  - **4π acceptance, very low threshold**
  - **B-field provides sign selection**
  - **e/μ id; final state reconstruction**

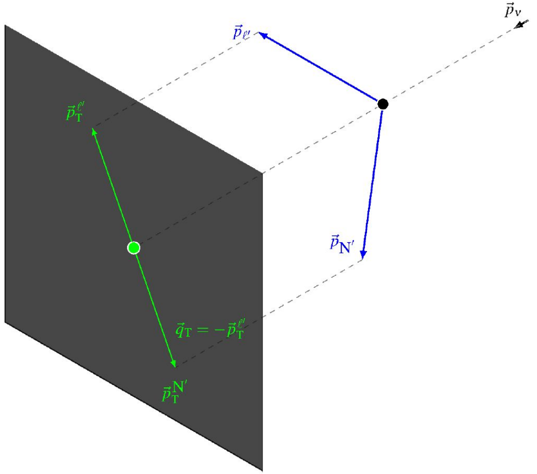


DUNE, instruments **5**, 31 (2021)

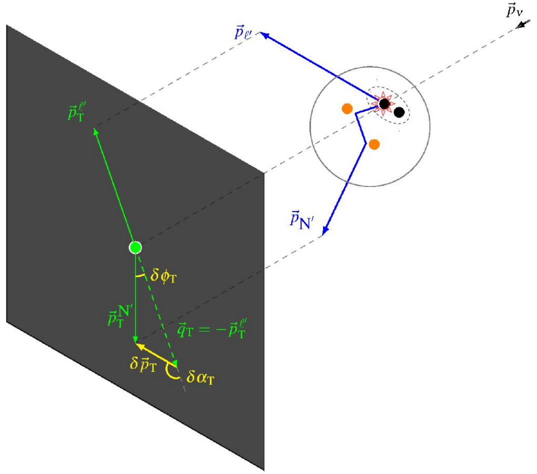
nuSTORM@CERN: first analysis concept

Our collider neighbors have been using something similar since a long time ago

Transverse Kinematic Imbalance (TKI)



Stationary free nucleon target



Nuclear target ($A > 1$)

- ❑ Fermi motion
- ❑ Removal energy
- ❑ FSI
- ❑ 2p2h

Missing energy

From Wikipedia, the free encyclopedia

[...] neutrinos.[1] In general, missing energy is used to infer the presence of non-detectable particles and is expected to be a signature of many theories of physics beyond the Standard Model.[2][3][4]

[...] hadron colliders.[5] The initial momentum of the colliding partons along the beam axis is not known —

TKI

Multi-dimensional observation

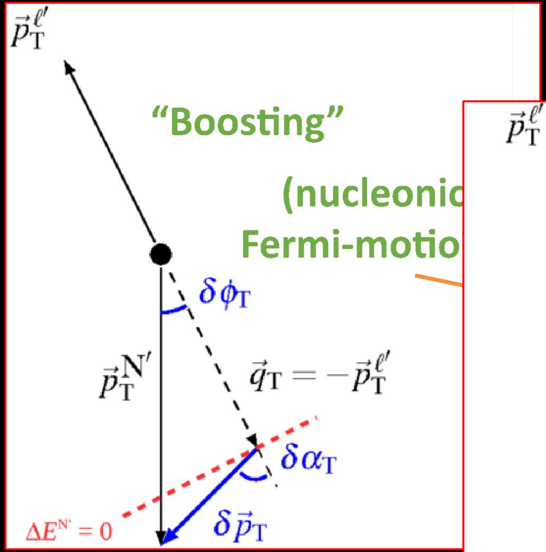
- ❑ Momentum (magnitude)
- ❑ Angle
- ❑ Asymmetry

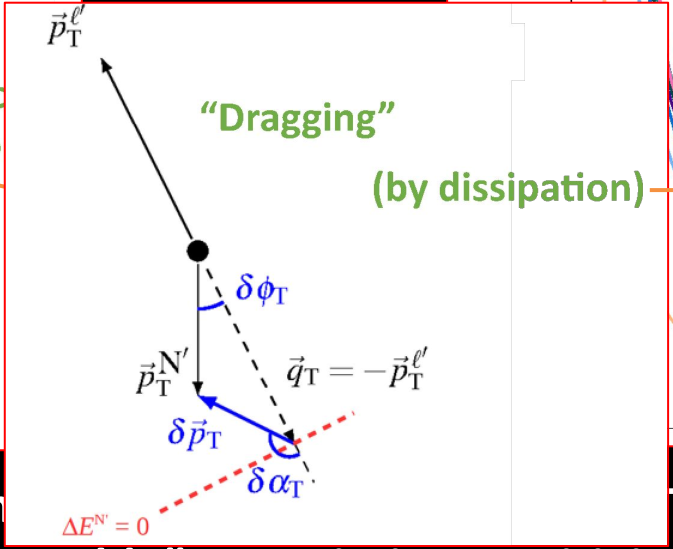
Community efforts:
T2K, MINERvA (analysis coordinator in the UK), MicroBooNE, SBND, …

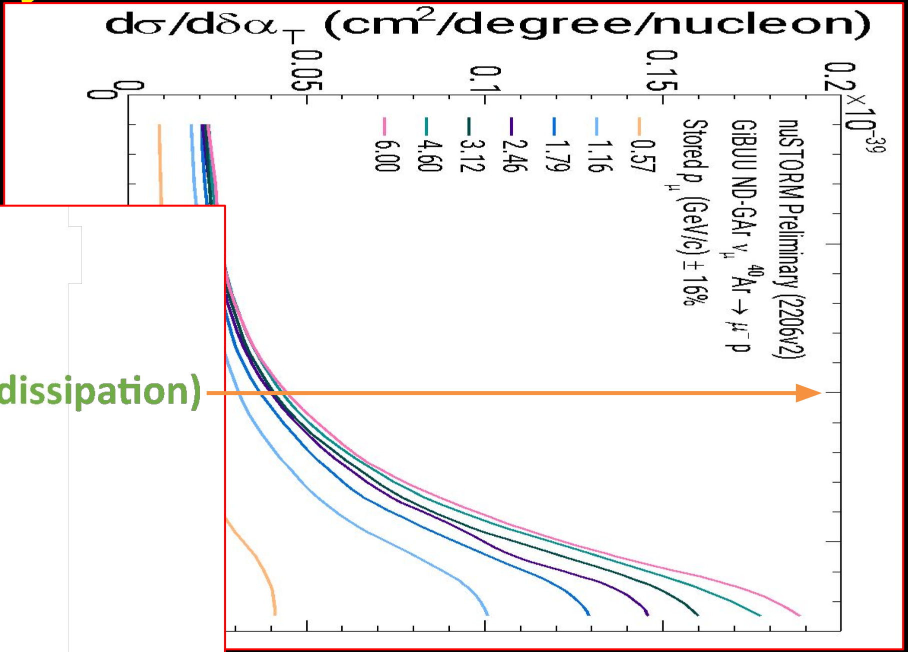
nuSTORM@CERN: E_ν-scan measurements

High-pressure gas TPC acceptance

T. Alves
M. Pfaff
X. Lu







- **Cross-section estim… …TORM flux**
- **Energy evolution "tunable" to optimise sensitivity of measurement**
- **Start of study of energy dependence of various exclusive measurements:**
  - **To provide precise constraints on nuclear effects and their *energy* evolution**

Conclusions

- nuSTORM will be a unique facility (perfect synergy with accelerator neutrino community):
  - %-level *electron* and muon neutrino cross-sections
    - Neutrino energy scan; spectrum at each point precisely known
    - Monoenergetic flux (ν_e!!) emulated by flux combinations with flexible component shaping
  - Exquisitely sensitive BSM & sterile neutrino searches
  - Serve as muon accelerator test bed

- Feasibility of executing nuSTORM at CERN:
  - Established through Physics Beyond Colliders study

- nuSTORM: a step towards the muon collider:
  - Proof-of-principle of high brightness stored muons beams

- 5-year goal: prepare robust case and "pre-CDR" for nuSTORM

nuSTORM on the route to the Muon Collider

- Accelerator key systems/technology issues:
  - High power, pulsed proton beam
  - Pion production target and capture:
    - Target, high-field solenoid capture ← nuSTORM
  - 6D ionization cooling to achieve luminosity goals: ← nuSTORM
    - High-field solenoids, compact lattice
    - High-gradient RF in magnetic field
  - Rapid acceleration:
    - RCS or FFA ← nuSTORM
  - Collider ring:
    - Combined function magnets ← nuSTORM
    - Beam protection ← nuSTORM
    - Strong focusing at IP and maintenance of short bunch length
- In a facility that delivers neutrino physics

nuSTORM for νN scattering @ CERN — parameters

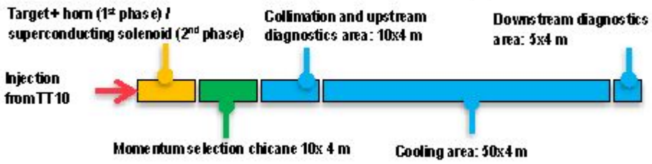
Table 1: Key parameters of the SPS beam required to serve nuSTORM.

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

CERN-PBC-REPORT-2019-003
DOI:10.17181/CERN.FQTB.O8QN

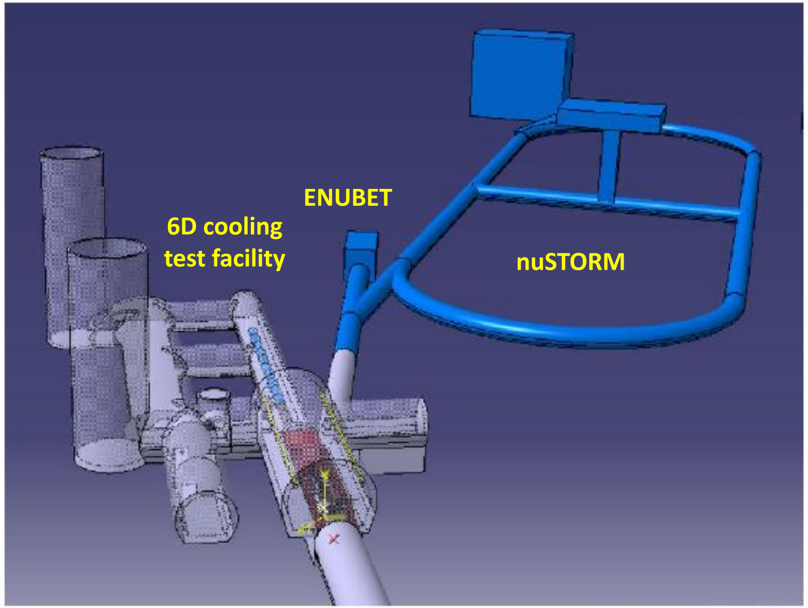
Conceptual layout

Under discussion!



MUC Demonstrator VERY Conceptual layout → To be taken with a "grain of salt"

- The Facility is flexible enough to accommodate other experiments.
- nuSTORM and potentially ENUBET could be branched from the MUC Demonstrator Facility.
- The same target complex would be used profiting from its shielding and general target systems infrastructure, utilities, and accesses.
- The double deflection of the beamline could reduce radiation streaming towards the nuSTORM ring.
- Synergies between experiments would reduce costs on both sides.
- Is the 26 GeV/c beam from the PS appropriate for these two experiments?



Under study