Imperial College London

M. Scott
on behalf of the nuSTORM collaboration
2 August, 2022

nuSTORM

neutrinos from stored muons

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

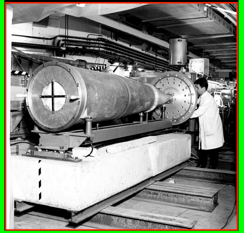
Neutral Current discovery

Development of E/w SM, QPM, QCD

Development of Standard Neutrino Model

Discovery of CP-invariance violation?

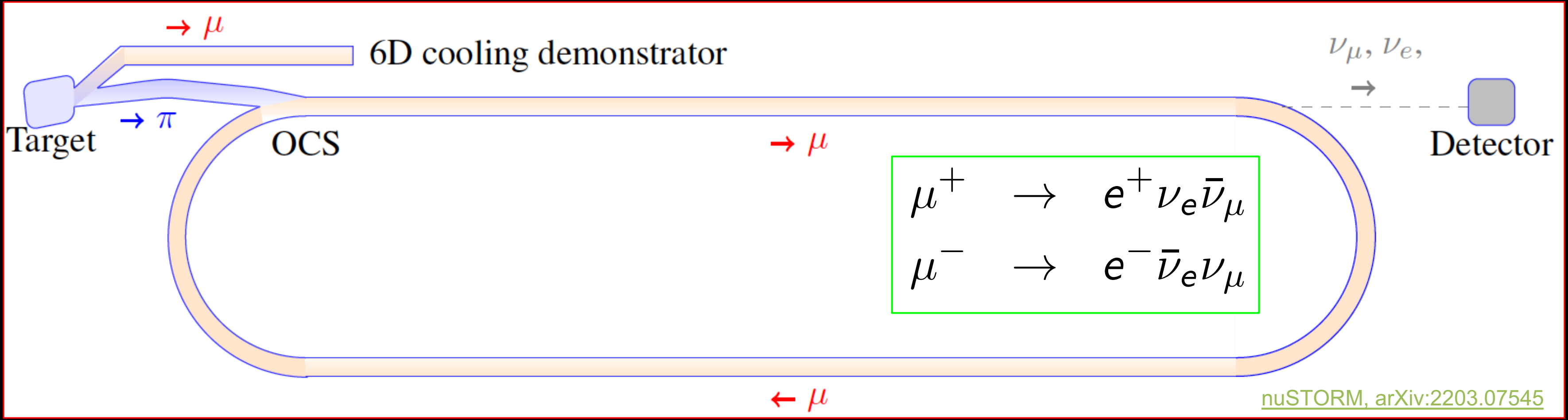
Simon van der Meer
CERN, 1961



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

Innovation in accelerators to go beyond

Neutrinos from stored muons



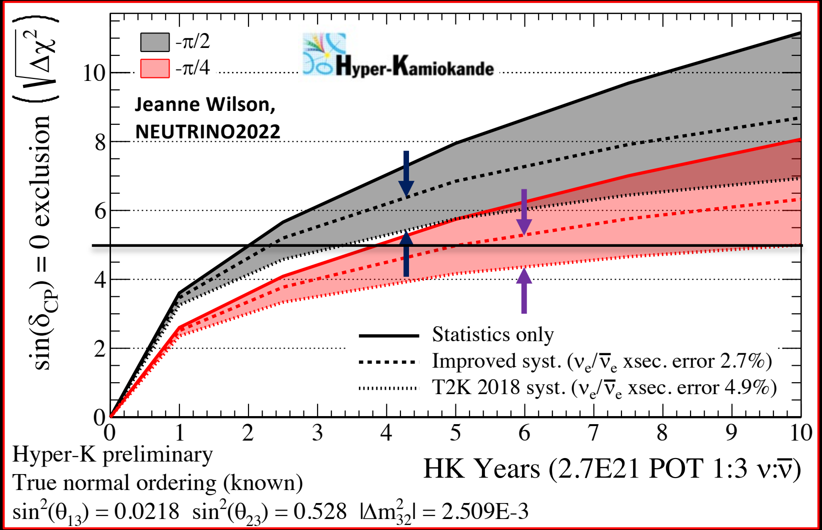
- **Scientific objectives:**
  1. %-level $(\overset{(-)}{\nu}_e N)$ cross sections
     - Multi differential / E_ν scan
  2. BSM searches
     - E.g. steriles beyond FNAL SBN
  3. Muon collider demonstrator

Focus of this talk

- **Precise neutrino flux:**
  - Normalisation: < 1%
  - Energy (and flavour) precise
- **$\pi \dashrightarrow \mu$ injection pass:**
  - "Flash" of muon neutrinos

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

- δ_{CP} requires ν_e and $\bar{\nu}_e$ appearance
  - Suppress ν_e and $\bar{\nu}_e$ 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" Q^2, shifting internal $(q_0, \vec{q}_3)$ phase space

Strategic mid-term goal

Innovative accelerator technology underpins the physics reach of high-energy and high-intensity colliders… The technologies under consideration include high-field magnets, high-temperature superconductors, plasma wakefield acceleration and other high-gradient accelerating structures, bright muon beams, energy recovery linacs. The European particle physics community must intensify accelerator R&D and sustain it with adequate resources. …

High-priority future initiatives

European Strategy for Particle Physics 2020 update

To extract the most physics from DUNE and Hyper-Kamiokande, a complementary programme of experimentation to determine neutrino cross-sections and fluxes is required. Several experiments aimed at determining neutrino fluxes exist worldwide. The possible implementation and impact of a facility to measure neutrino cross-sections at the percent level should continue to be studied.

Other essential scientific activities for particle physics

Opportunity …

Exploit synergies with ENUBET:
- **Articulate the need**

Common requirement:
- **Advanced neutrino detector**

See Antonio Branca's talk this morning
ENUBET: the first monitored neutrino beam

Final

Neutrinos from Stored Muons (nuSTORM)
Submitted to the Snowmass 2021 DPF Community Planning Exercise

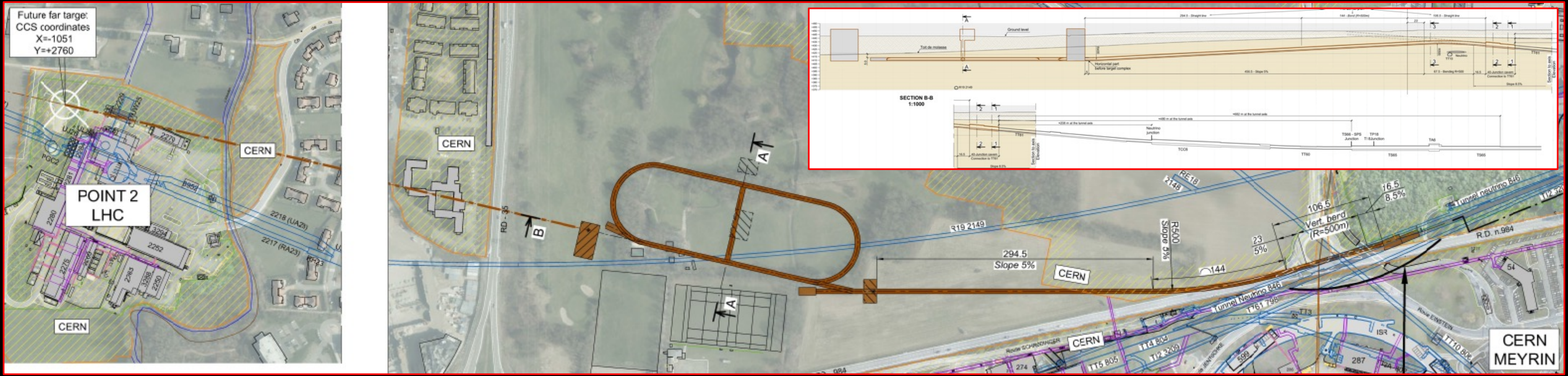
arXiv:2203.07545

ESPPU 202x

Goal:* *over next ~5 years, prepare for next ESPPU:
- **Study and document the science case:**
  - **Cross sections, BSM, and MC demonstrator**
- **Prepare "pre-CDR" as input to the Strategy Update**

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

nuSTORM for νN scattering @ CERN — parameters

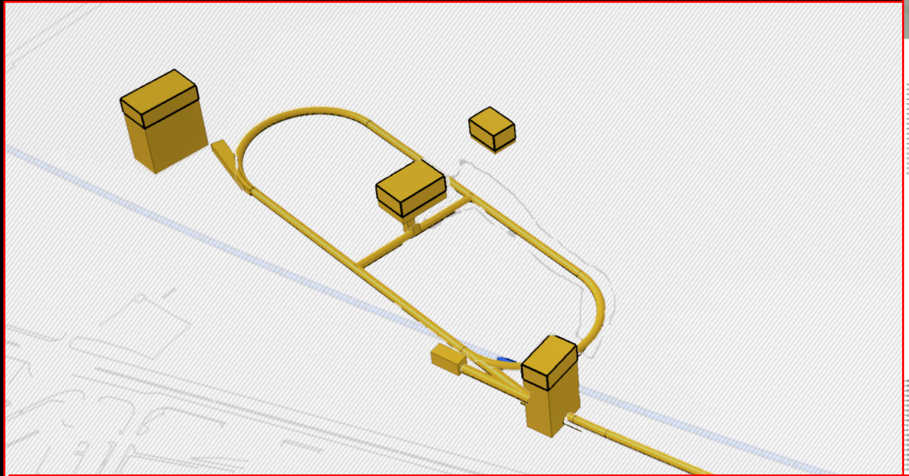
Table 1: Key parameters of the SPS beam required to serve nuSTORM.

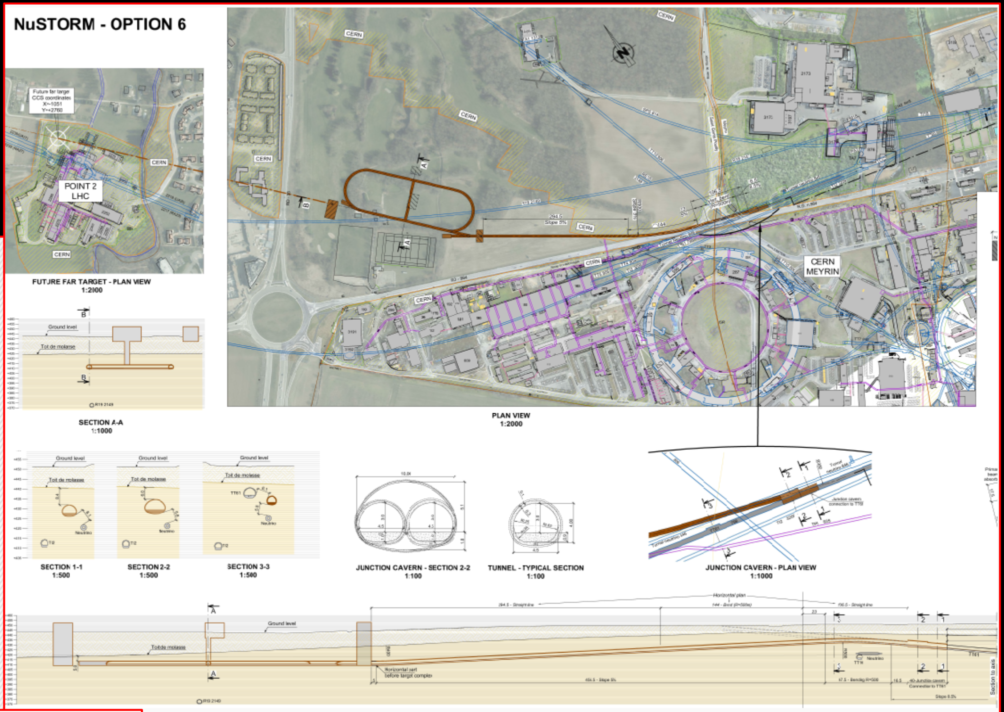
Momentum	100 GeV/c
Beam Intensity per cycle	4×10^{13}
Cycle length	3.6 s
Nominal proton beam power	156 kW
Maximum proton beam power	240 kW
Protons on target (PoT)/year	4×10^{19}
Total PoT in 5 year's data taking	2×10^{20}
Nominal / short cycle time	6/3.6 s
Max. normalised horizontal emittance (1 σ)	8 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}

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

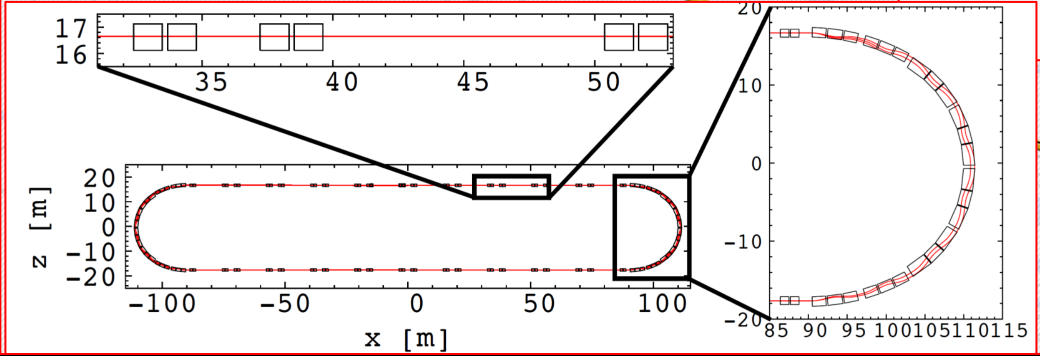
Accelerator

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



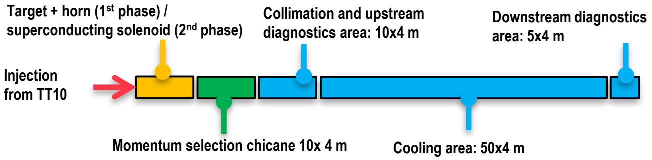


Jonathan Gall



Conceptual layout

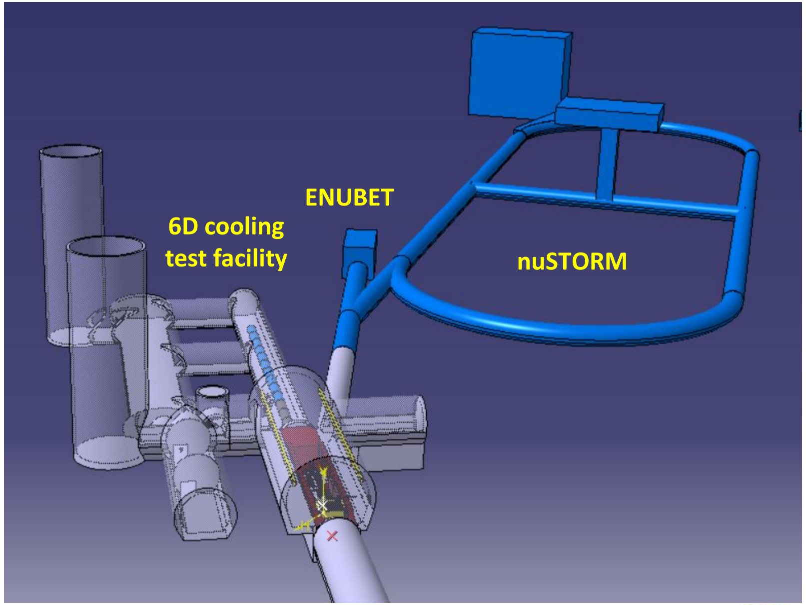
Under discussion!



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



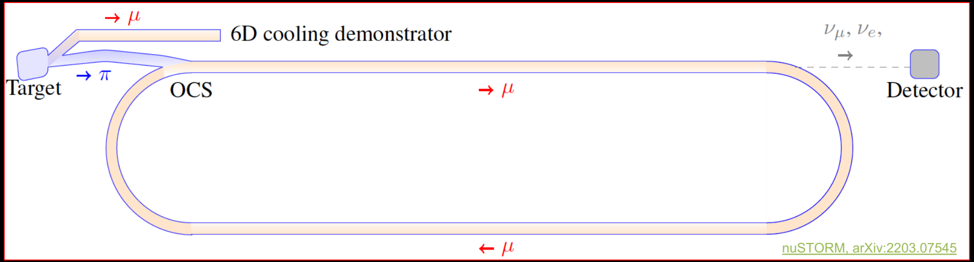
End-to-end simulation for (re)optimisation

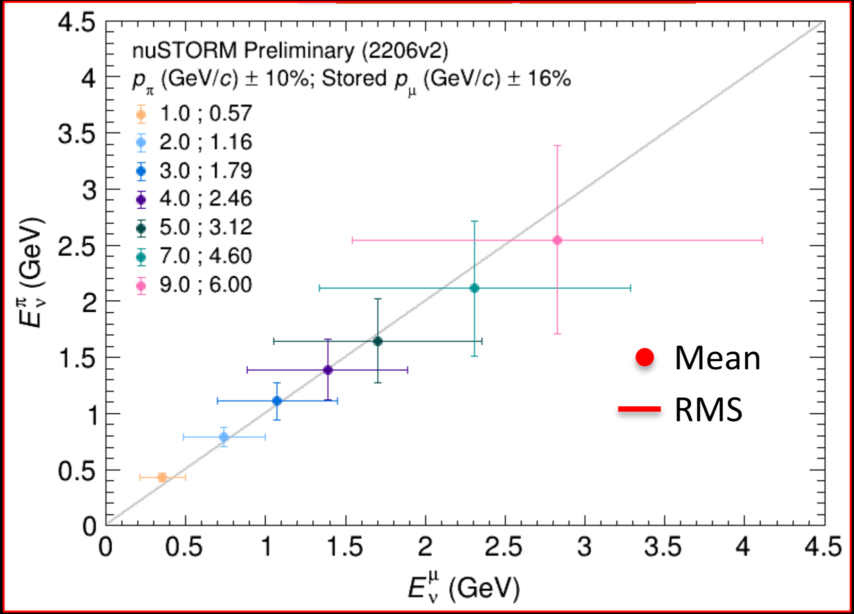
- "nuSIM" under development to:

P. Kyberd et al

  – Simulate facility "from target to detector":
    - Pragmatic approach:
      – Fast simulation, parametric approach
      – Full tracking using G4 based code; "BDSIM"

T. Alves, M. Pfaff

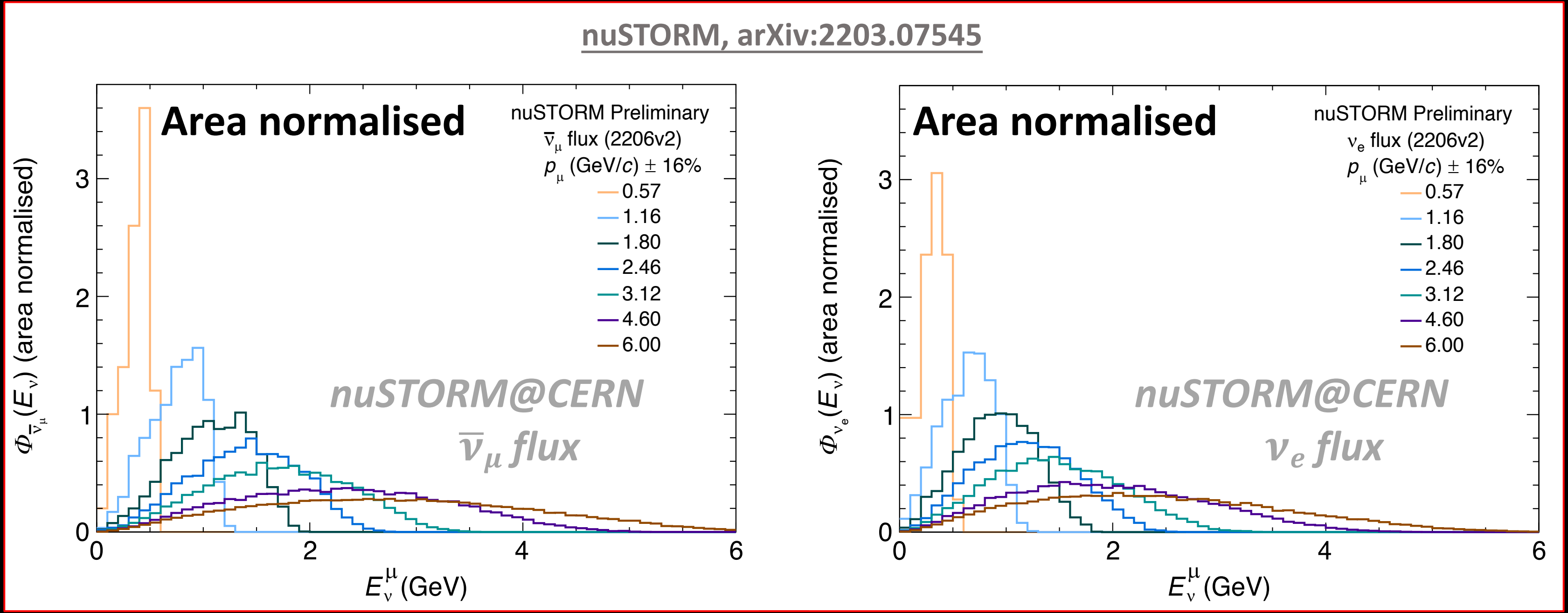




- Neutrino energy scan:
  – "Pion flash" in first pass
  – Subsequently neutrinos from muon decay
    - Spectrum determined by accelerator tune

T. Alves, M. Pfaff

nuSTORM@CERN: flux estimation

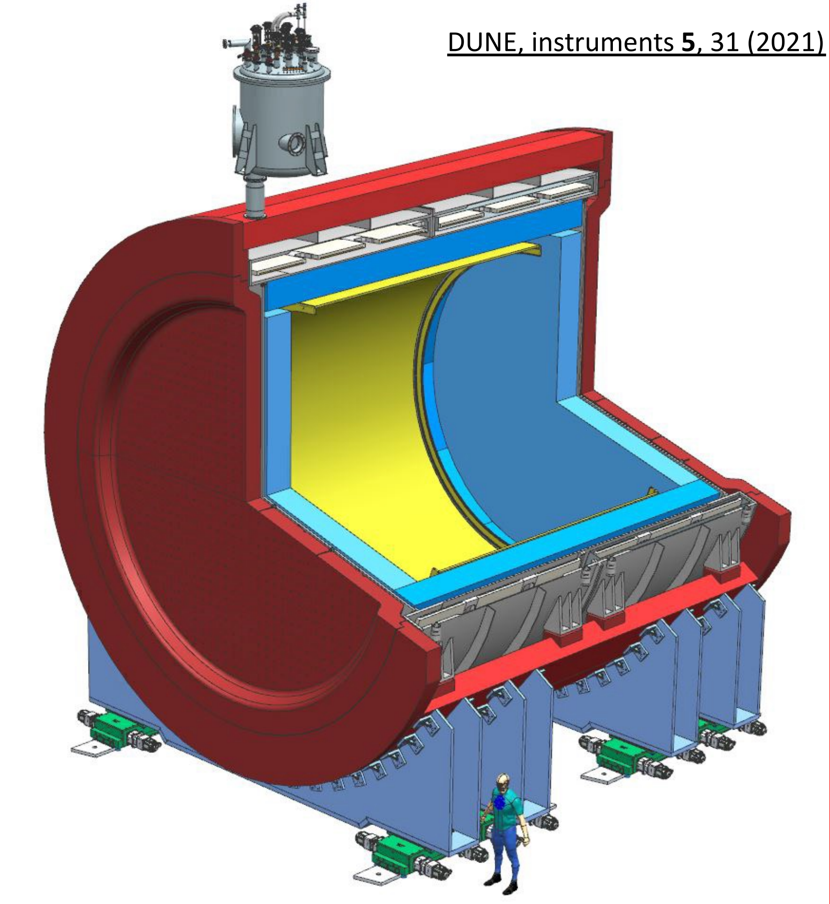


- Oscillation-relevant energy regime
  - Hyper-K: 0.6 GeV
  - DUNE.   : 2.4 GeV
- Set by stored-muon momentum

- Unique opportunity:
  - E_ν-scan measurements
- Accelerator "tune" gives fine control
  - E.g. optimise flux shape (or spread) by adjusting the ring acceptance

nuSTORM@CERN: working towards a detector concept

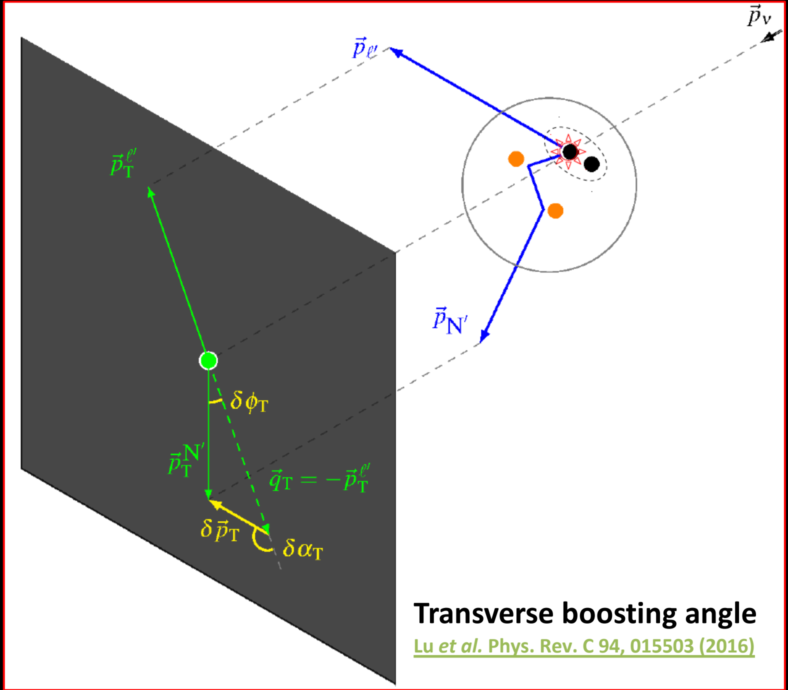
- nuSIM ready to allow performance evaluation:
  - Require "highly capable" detector:
    - Scattered lepton
    - Inclusive and exclusive final states
- Initial study use DUNE ND-GAr:
  - TPC reference design
    - 10-bar argon-based gas TPC
    - Large gas volume
    - Surrounded by calorimeter
  -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



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

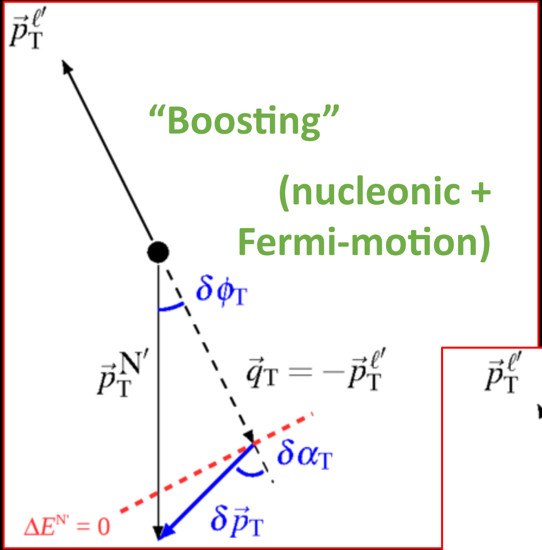
nuSTORM@CERN: E_ν-scan measurements

X. Lu

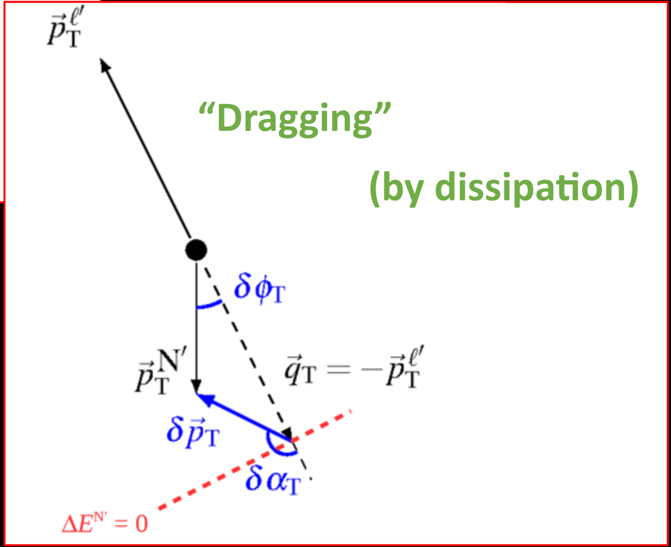


Transverse boosting angle

Lu *et al.* Phys. Rev. C 94, 015503 (2016)



Quasi-elastic cross section function of $\delta\alpha_T$

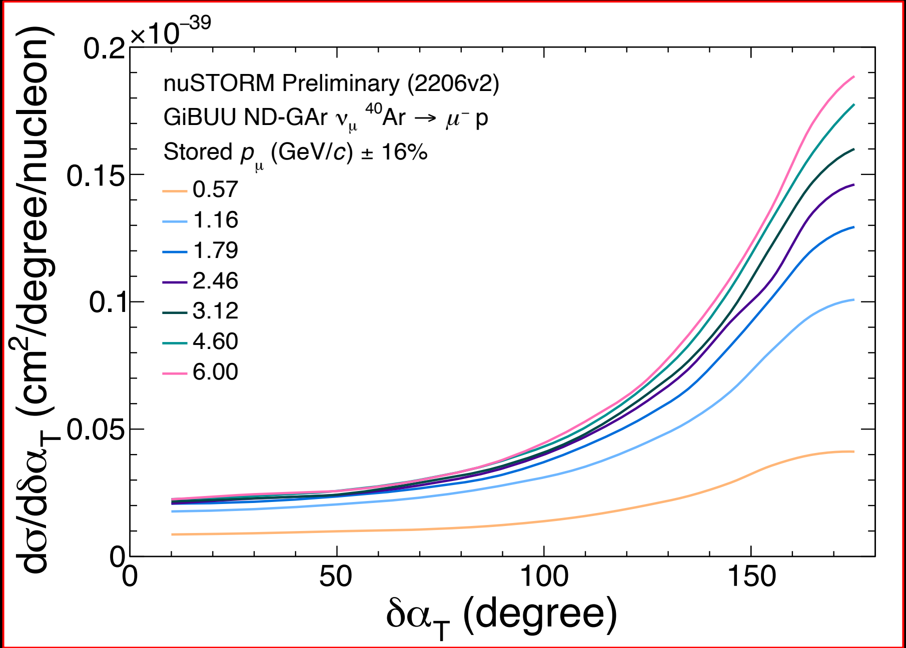


- Low $\delta\alpha_T$: impact of nuclear effects low:
  - "Nuclear model calibration"
- High $\delta\alpha_T$: energy-dependent nuclear effects:
  - Constrain nuclear models of, e.g. 2p2h, pion absorption, …

nuSTORM@CERN: E_ν-scan measurements

T. Alves
M. Pfaff
X. Lu

Quasi-elastic Differential cross section vs $\delta\alpha_T$



- Cross-section estimation using (preliminary) nuSTORM 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 evolution

Conclusions

- **nuSTORM will be a unique facility:**
  - **%-level *electron* and muon neutrino cross-sections**
    - **Neutrino energy scan; spectrum at each point precisely known**
  - **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: ← nuSTORM
    - Target, high-field solenoid capture
  - 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