May 26 – 30, 2025, Venezia, Istituto Veneto di Lettere, Scienze ed Arti -Palazzo Franchetti

NuSTORM perspectives

Stefania Ricciardi, STFC RAL

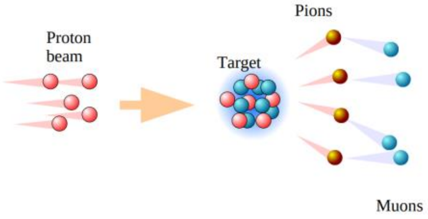
on behalf of the nuSTORM Collaboration

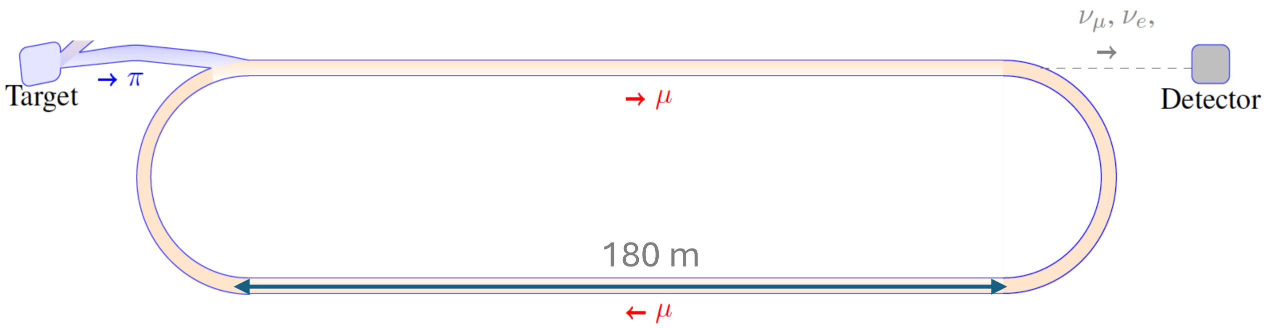
Science and Technology Facilities Council

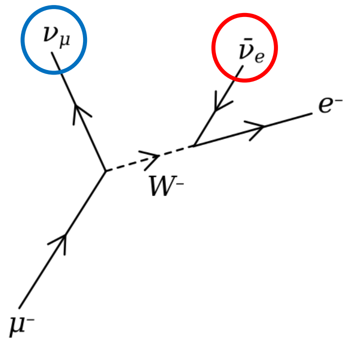
νSTORM

International MUON Collider Collaboration

Muons 4 future... neutrino beams!



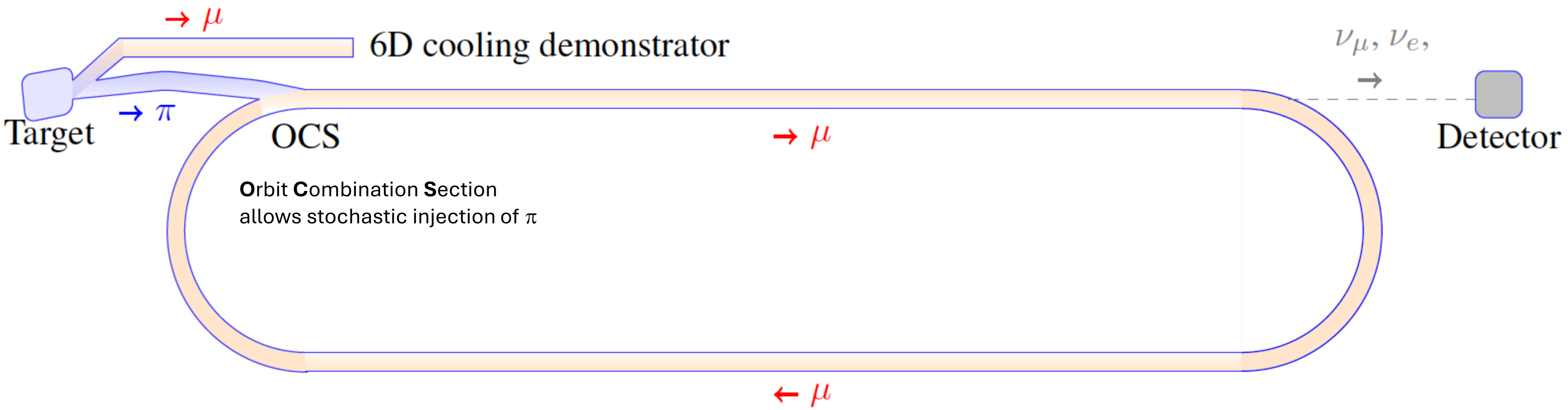




- Well-controlled neutrino beams, via circulation and decay of muons in a storage ring
- Compact storage ring for muon energies in the GeV range
  - Energy range relevant for oscillations at long-baseline experiments
- Simple muon production method
  - Can exploit existing proton beam facilities at laboratories like FNAL and CERN

Innovative concept! First ν beam facility based on a stored muon beam

NuSTORM concept – Main advantages

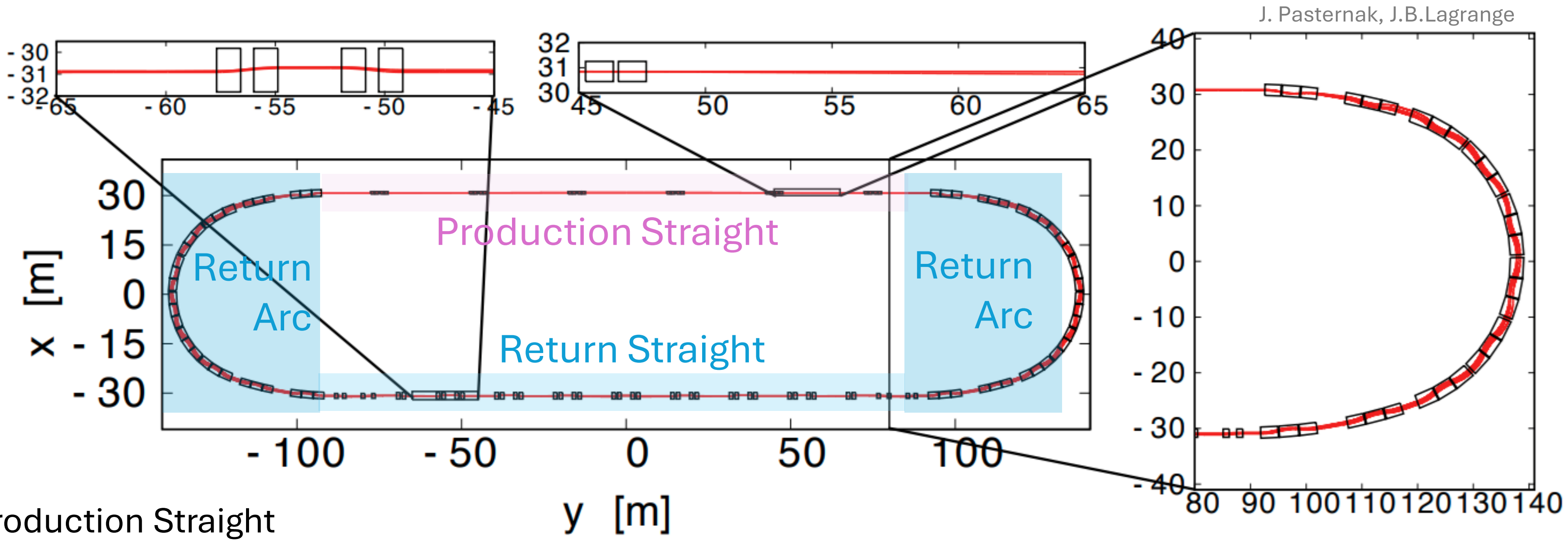


- **Unique beam composition: 50% ν_e, 50% anti-ν_μ**
- **Precise flux, no hadronic uncertainties!**
- **Energy of the stored beam tunable, allows neutrino energy scan**
- **Synergies with muon collider:**
  - Production target and pion handling possibly shared with muon cooling demonstrator
    - O(GeV) pions used for neutrino source
    - O(200 MeV) pions used for demonstrator

Scientific objectives

- %-level (ν_eA) cross sections
- BSM searches, e.g. sterile neutrinos
- Muon collider testbed

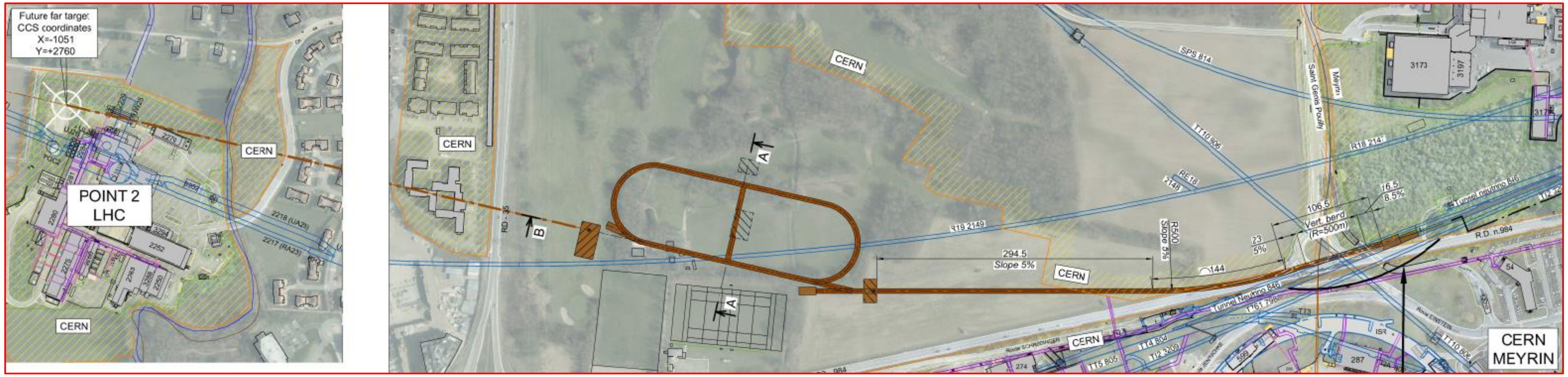
nuSTORM: a step towards the Muon Collider



- Production Straight
  - FODO lattice, to minimise dispersion
- Arcs and Return Straight
  - Fixed Field Alternating gradient (FFA) lattice, to improve acceptance of muons

R&D platform for technologies important for the realisation of a Muon Collider (MC)

- Complete implementation for large acceptance storage-ring (inc. injection and extraction sections); develop and test FFA magnet technology
- Ideal testbed for developing and validate beam-monitoring instrumentation for MC



Feasibility of nuSTORM at CERN

CERN-PBC-REPORT-2019-003

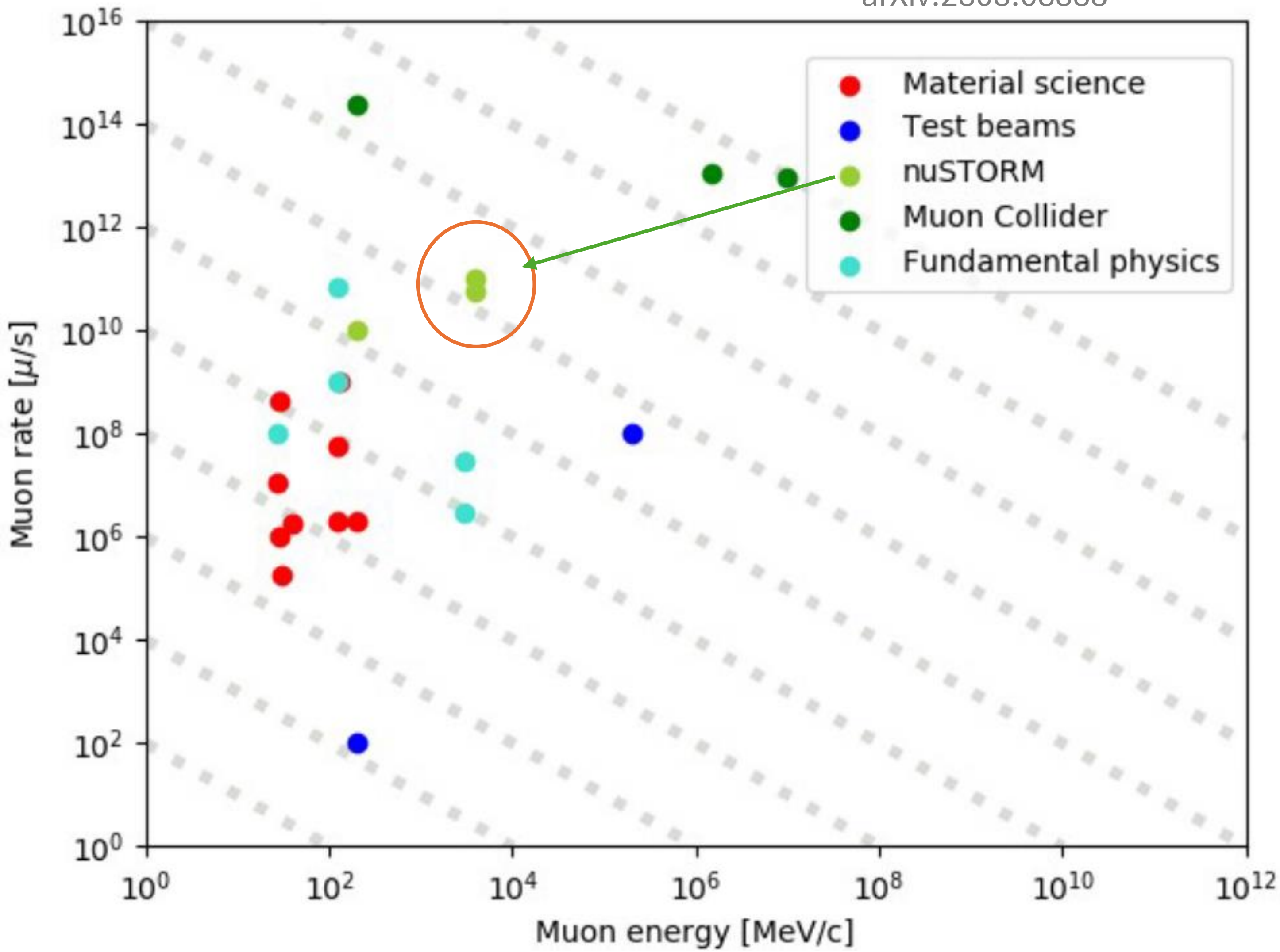
- **Extraction from SPS through existing tunnel**
- **Far detector location (2 km) available**
  - preserve highly sensitive oscillation searches in the region of LSND/MiniBoone anomalies (via $\nu_e \rightarrow \nu_\mu$)

Key beam parameters foreseen for nuSTORM (based on the analysis of CENF.

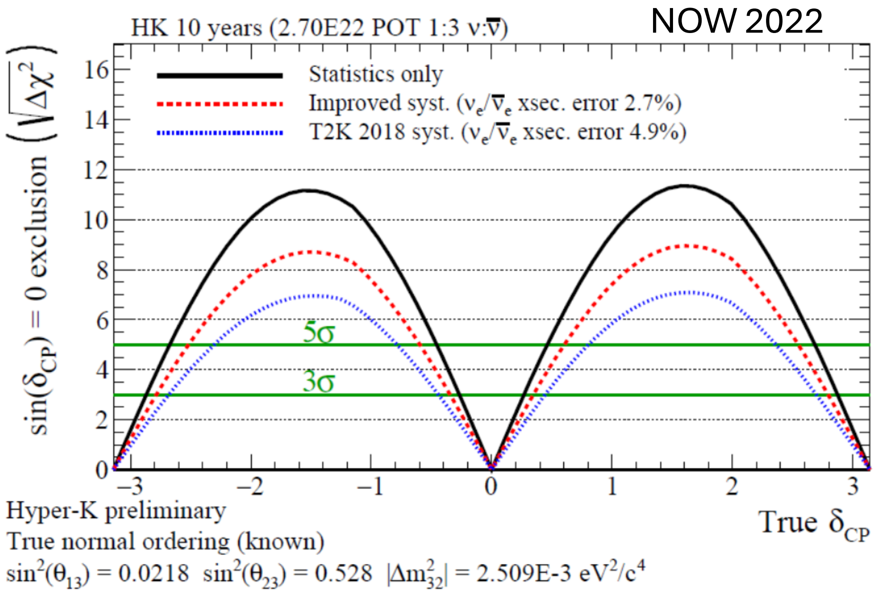
Momentum	100 GeV/c
Beam Intensity per cycle	4×10^{13}
Cycle length	3.6 s
Nominal proton beam power	156 kW
Maximum proton beam power	240 kW
Protons on target (PoT)/year	4×10^{19}
Total PoT in 5 year's data taking	2×10^{20}
Nominal / Maximum repetition rate	6/3.6 s
Max. normalized horizontal emittance (eh at 1 σ s)	8 mm.mrad
Max. normalized vertical emittance (ev at 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 (4s)	2 ns
Bunch spacing	5 ns
Momentum spread (dp/p at 1s)	2×10^{-4}

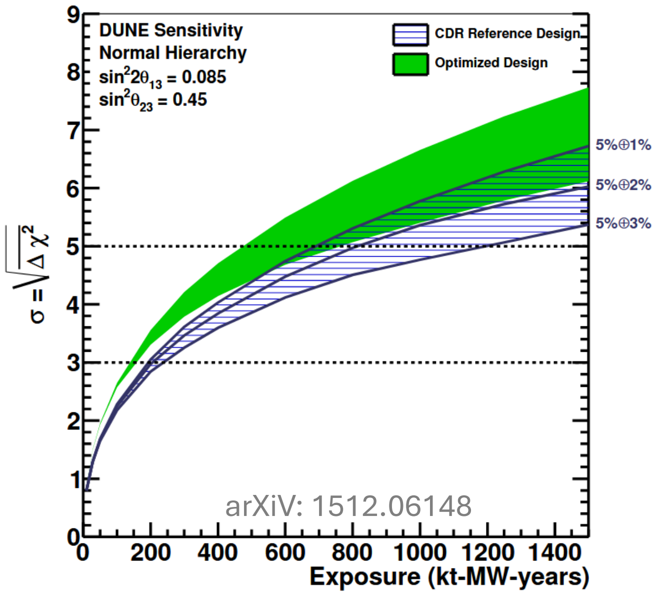
Highest stored-muon beam power

arXiv:2303.08533



Call for precise cross-section measurements



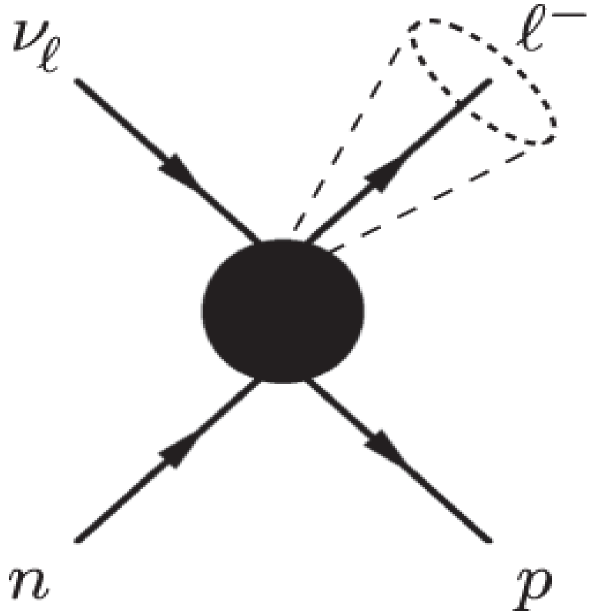


- LBL (Dune/HyperK) CP-violation search through ν_e (and $\bar{\nu}_e$) appearance in beam of mainly ν_μ (and $\bar{\nu}_\mu$)
- ν_e ($\bar{\nu}_e$) cross sections uncertainties: major δ_{CP} systematics

ESPPU 2020 - *To extract the most physics from DUNE and Hyper-Kamiokande, a complementary programme of experimentation to determine neutrino cross-sections and fluxes is required [..]The possible implementation and impact of a facility to measure neutrino cross-sections at the percent level should continue to be studied.*

ν_eA cross-sections measurements hurdles

Flavour-dependent corrections



Tomalak *et al.*, Nature Commun. 13, 5286 (2022)

ν_eA from ν_μA + lepton universality:
constraints not sufficient!

Phase-space, radiative corrections, nuclear effects
alter ν_e /ν_μ cross section ratio

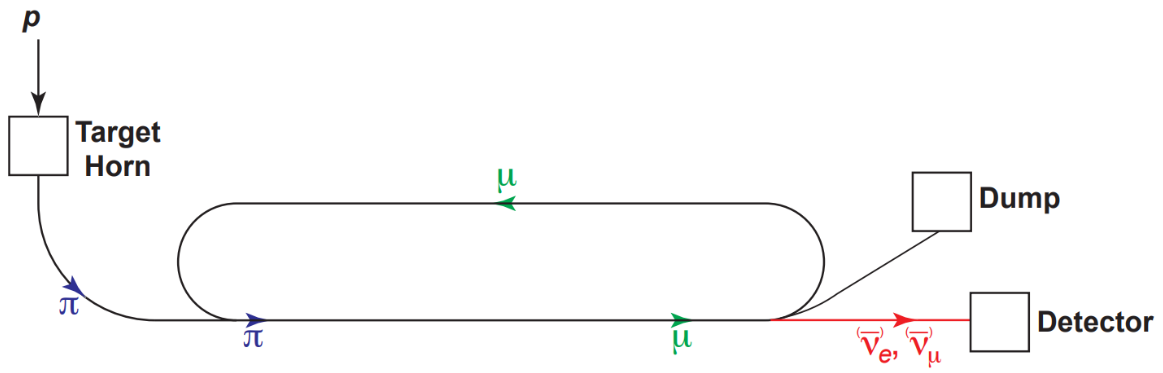
Effects in the low-energy region (0.2-5) GeV very hard to model and not negligible compared to expected statistical uncertainties for Hyper-K and DUNE
[e.g., S. Dolan, arXiv:2301.09555 and references therein]

Conventional neutrino beams:

- Low intrinsic ν_e and anti-ν_e flux (both at same time!)
- High flux uncertainties (hadron production uncertainties in proton interactions)
- Intrinsic ν_e flux spectrum does not match spectrum from ν_μ oscillation in far detectors

Not ideal for ν_eA cross-section measurements!

Precise cross-sections require precise ν fluxes



- In the detector for π^+ injection
  - *initial* $\boldsymbol{\nu_\mu}$ flux from $\pi^+ \to \mu^+ \nu_\mu$ ["pion flash"]
  - *then* $\boldsymbol{\nu_e + \bar{\nu}_\mu}$ flux from $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$

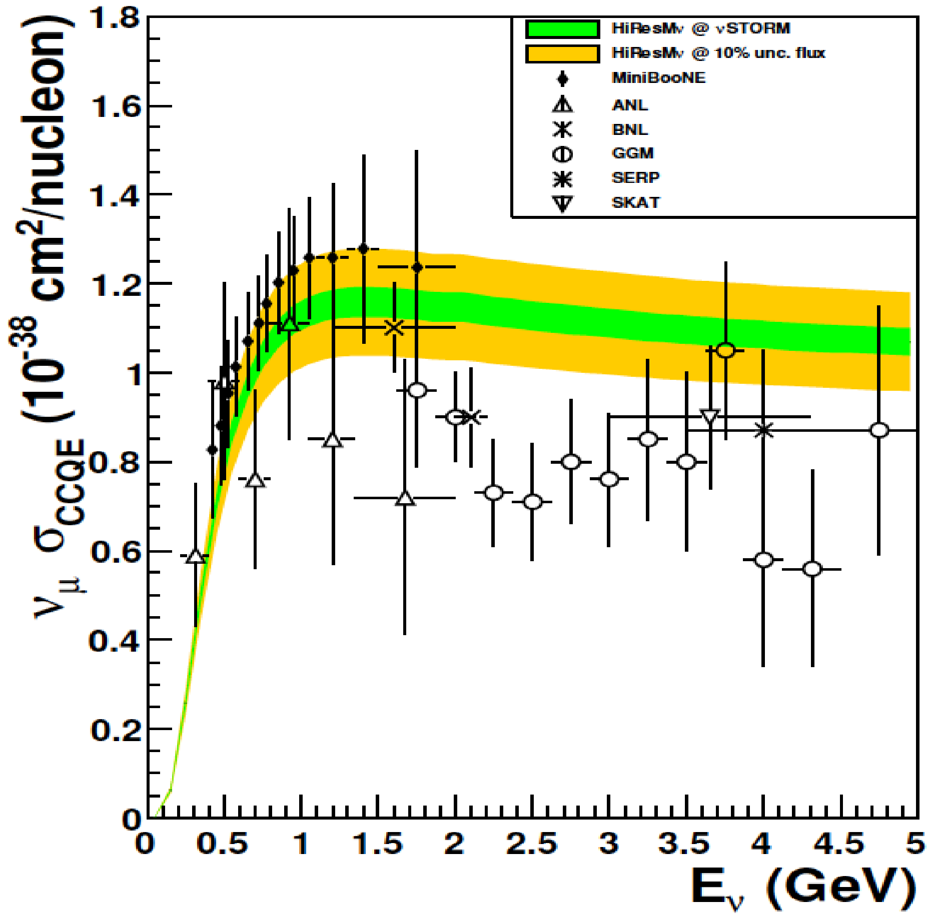
% level precision achievable on both electron and muon neutrino and antineutrino cross-sections

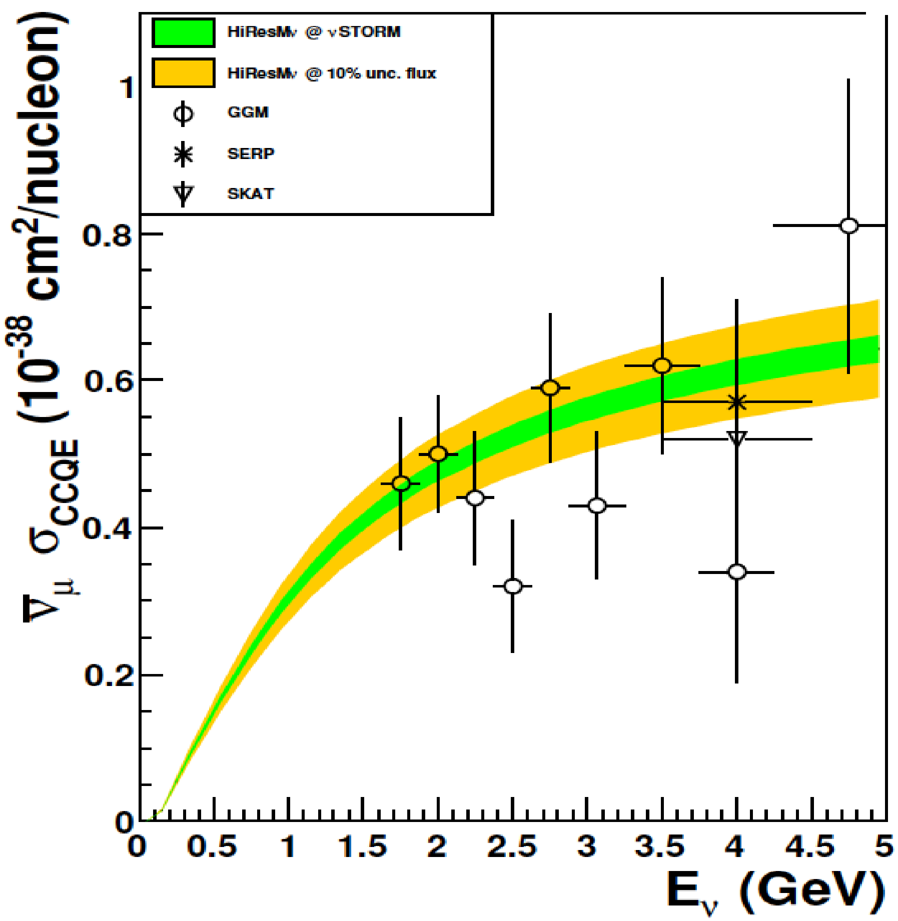
- **Well-understood fluxes, essentially no background**
  - Exact composition from muon decay kinematics
  - Energy spectrum from accelerator tune
  - Intensity %-level from ring instrumentation
- **High fluxes for both neutrino flavours**
- **Only one type of neutrino and anti-neutrino at one time (after injection)**
  - identity by lepton ID and/or charge in CC interactions

- **Beam spectrum tunable**
  - stored μ momentum can be varied between 1 and 6 GeV/*c*, acceptance ±16%
  - Precise control over the neutrino beam energy, to match oscillation regime

ν_μ and $\bar{\nu}_\mu$ QE cross Sections

arXiv:1308.6822

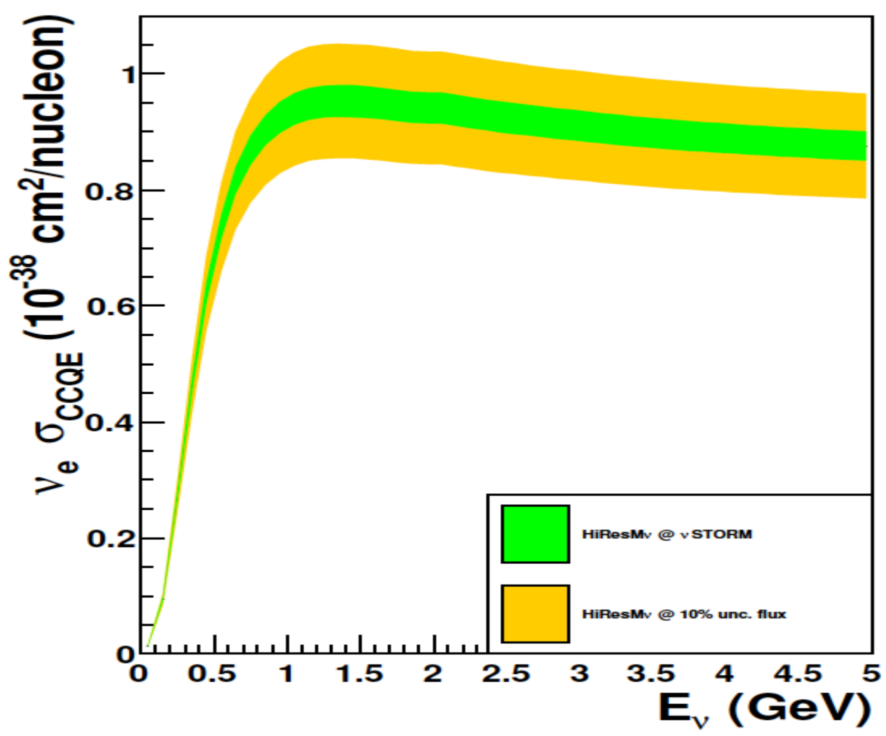


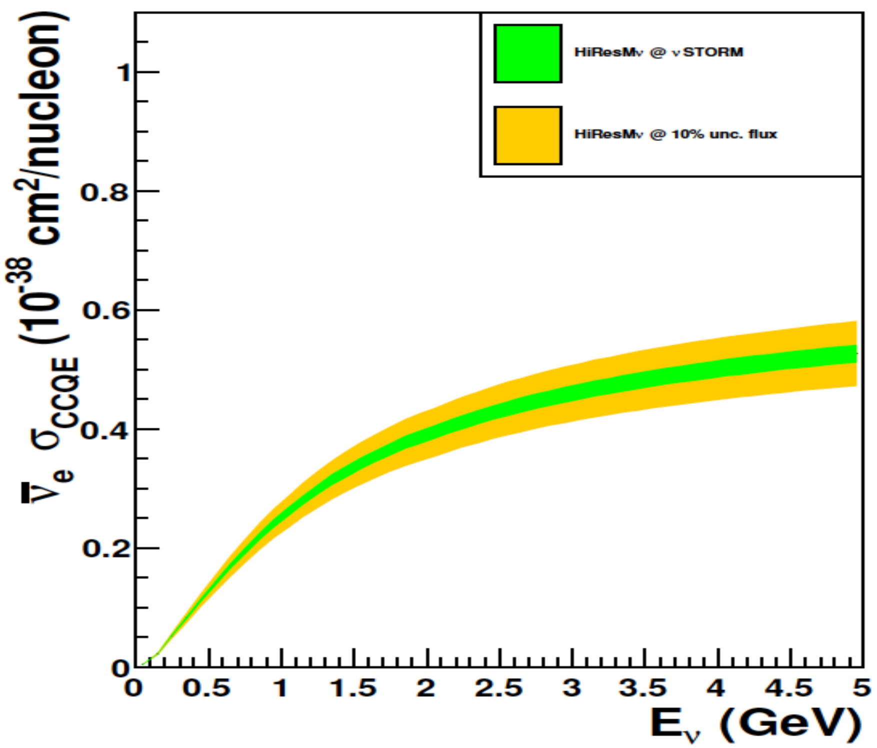


- O(10)-ton fiducial mass detector, 50 m from end of Production Straight, 10^{21} POT
- 1% (green) and 10% (yellow) flux uncertainty + detector systematics

ν_e and $\bar{\nu}_e$ QE cross Sections

arXiv:1308.6822





- O(10)-ton fiducial mass detector, 50 m from end of Production Straight, 10^{21} POT
- 1% (green) and 10% (yellow) flux uncertainty + detector systematics
- **Very sparse existing data (mainly from MINERvA and T2K)**

Detector considerations

Concepts developed for near detectors of long-baseline neutrino oscillation experiments are suitable options for nuSTORM detector

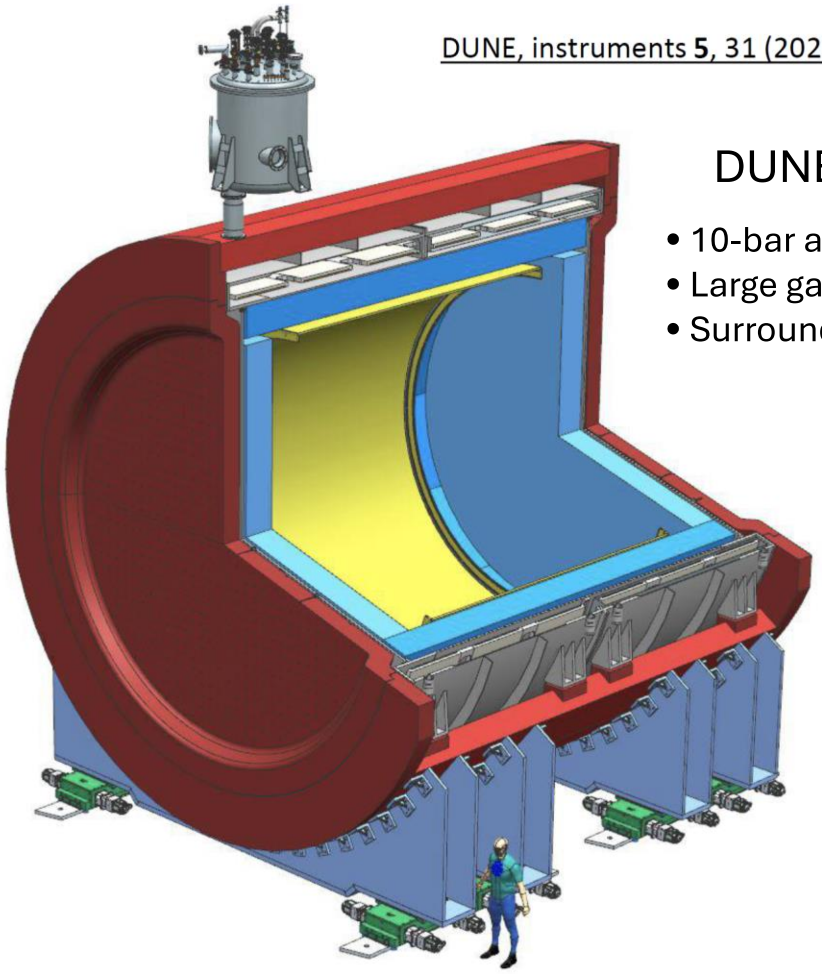
Ex. DUNE ND-GAr

High-specifications:

- 4π acceptance, very low threshold
- e/μ id;
- B-field for sign selection
- exclusive final state reconstruction

Preliminary studies show that superior performance allows to achieve desired precision despite relatively low mass (1t)

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



DUNE ND-GAr

- 10-bar argon-based gas TPC
- Large gas volume
- Surrounded by calorimeter

nuSTORM recent progress

ESPPU 2026 *– nuSTORM submission*
arXiv: 2505.06137

Optimisation of accelerator facility

- Horn geometry and target design simulation [FLUKA] aimed at improving the production and capture yield of low-energy pions ($p_\pi \leq 2$ GeV/c)
- Full simulation of transfer line, injection and production straight via Beam Delivery Software Simulation [BDSim] GEANT4 based

Potential of producing synthetic quasi-monoenergetic neutrino flux

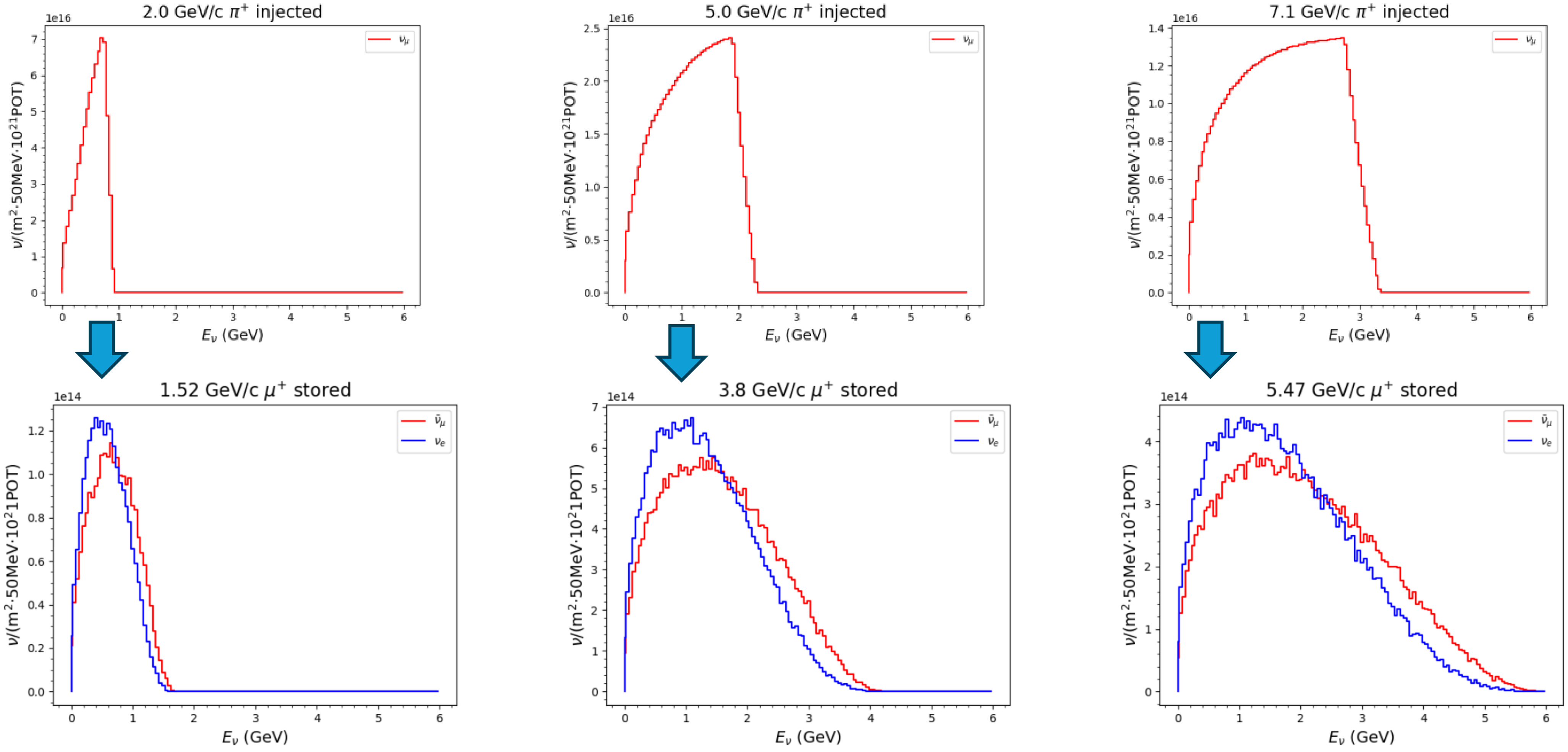
New phenomenological studies to extend physics programme

- Transverse Kinematic Imbalance (TKI) technique to study nuclear effects in νA interactions
- Neutrino Tridents production
- Oscillation disappearance searches
- Large Extra Dimensions
- Lepton Flavour Violation

Neutrino fluxes at nuSTORM

NEW

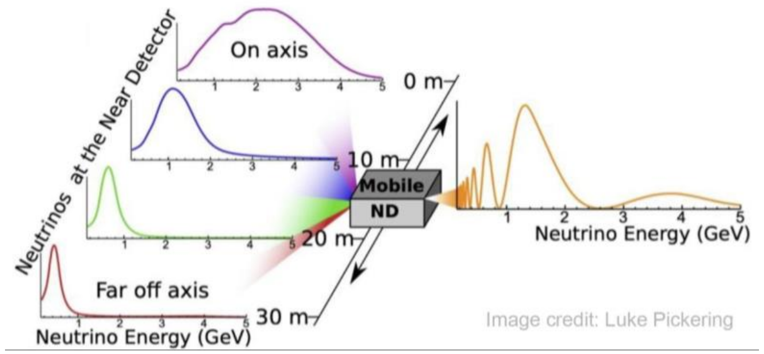
P. Jury
R. Kamath
P.Kyberd



State-of-the art flux with 5x5m detector at 50m from end of production straight

NEW

Synthetic flux at nuSTORM



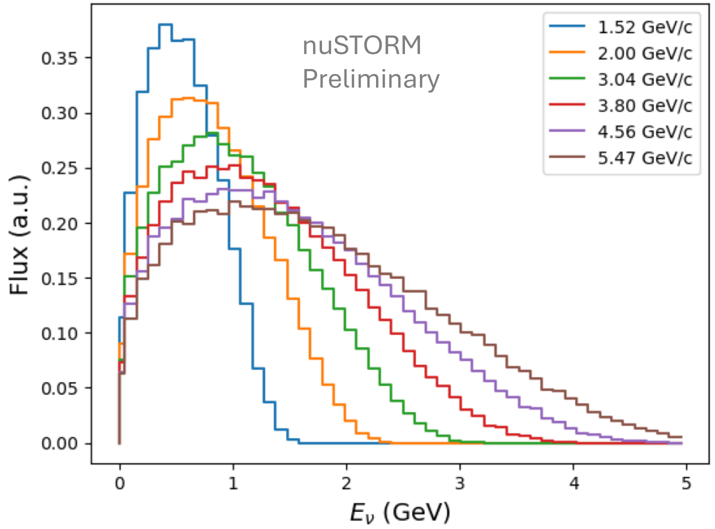
PRISM concept: combine multiple samples to synthetize in software a flux with spectrum equivalent to the desired one
Hyper-K or DUNE: **different near detector locations off-axis**

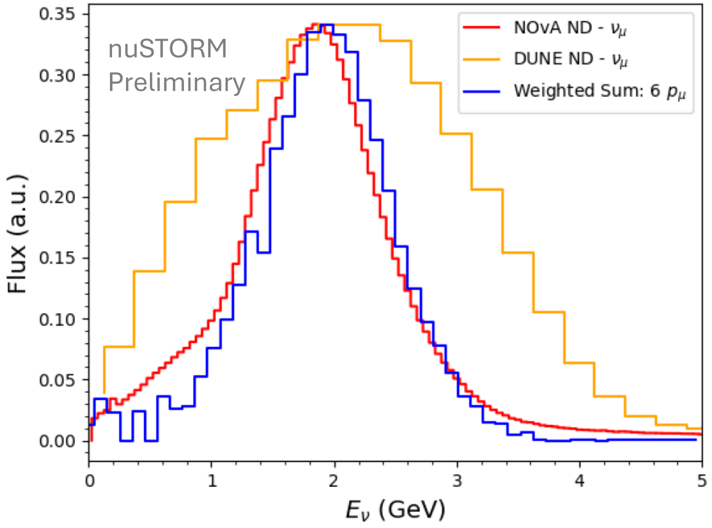
nuSTORM synthetic flux:
sample fluxes from muon beams of different momentum
detector fixed on-axis

nuSTORM synthetic beam:
significantly **narrower** and
more **Gaussian**

Unlike DUNE and Hyper-K,
nuSTORM can also produce **synthetic ν_e** beams by combining different ν_e spectra

R. Kamath

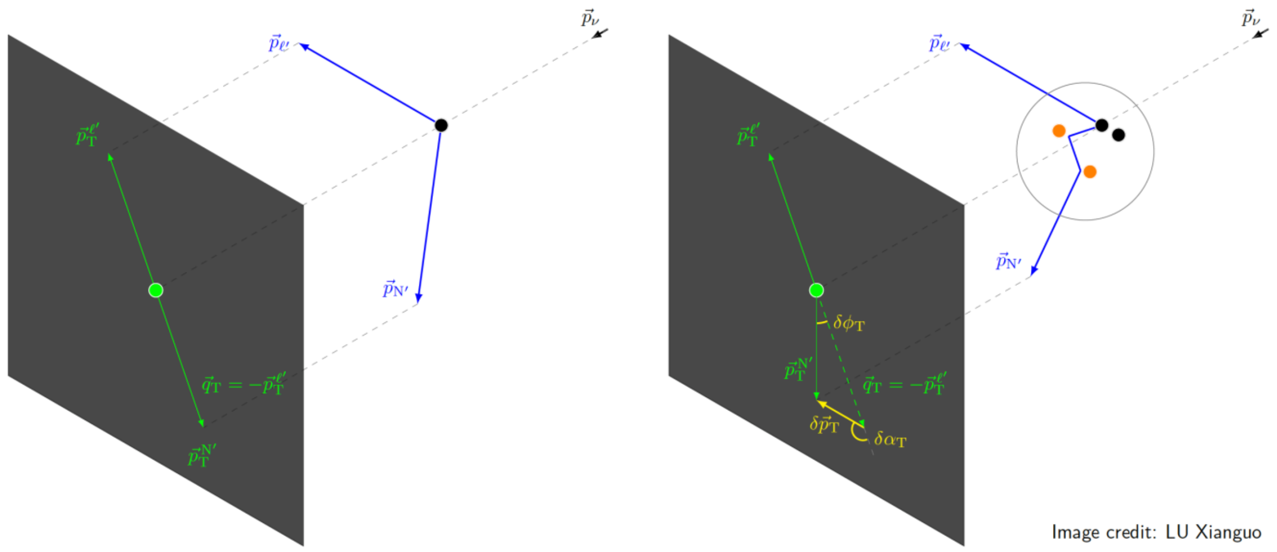


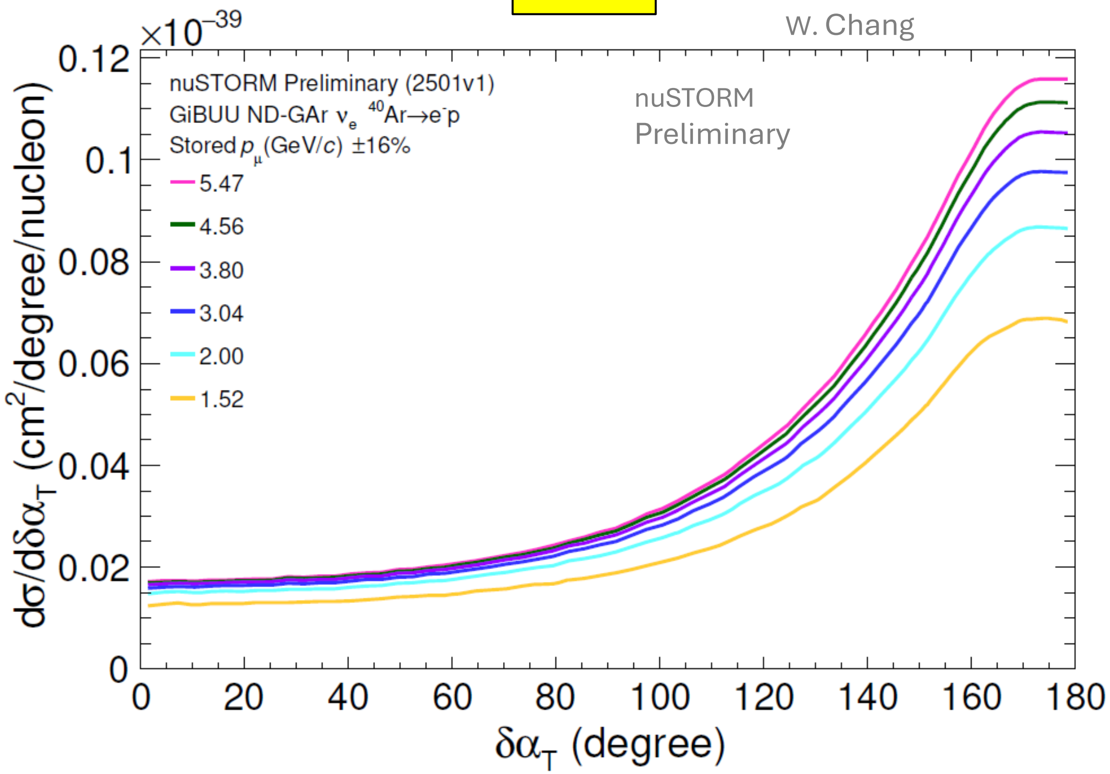


Nuclear dynamics and TKI

NEW

W. Chang





Energy scan to extract dynamical evolution of nuclear effects

Transverse Kinematic Imbalance (TKI)

[Phys.Rev.C 94, 015503,2016]

Insights on nuclear effects with minimal dependence on neutrino energy

- Measured at T2K, MINERvA, MicroBooNE

- Low $\delta\alpha_T$: impact of nuclear effects low: "Nuclear model calibration"
- High $\delta\alpha_T$: energy-dependent nuclear effects: dissipative processes e.g. FSI

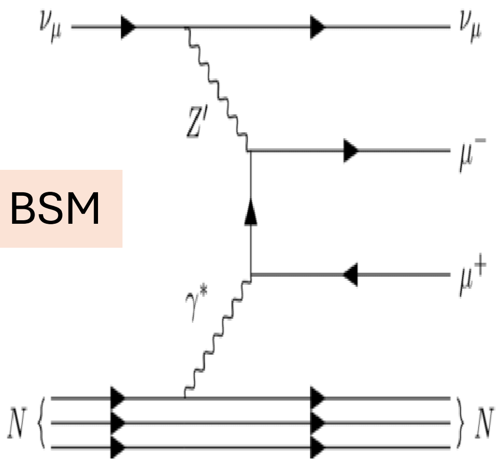
Rare SM processes: tridents

NEW

J,Turner et al.
arXiv: 2505.06137

$\nu_\alpha\ A \rightarrow \nu_\alpha + l^-\ l^+\ A$

BSM



Channel	SBND	μBooNe	ICARUS	DUNE	nuSTORM
$e^\pm\mu^\mp$	10	0.7	1	2993 (2307)	173
	2	0.1	0.2	692 (530)	29
e^+e^-	6	0.4	0.7	1007 (800)	107
	0.7	0	0.1	143 (111)	5
$\mu^+\mu^-$	0.4	0	0.0	286 (210)	14
	0.4	0	0.0	196 (147)	9

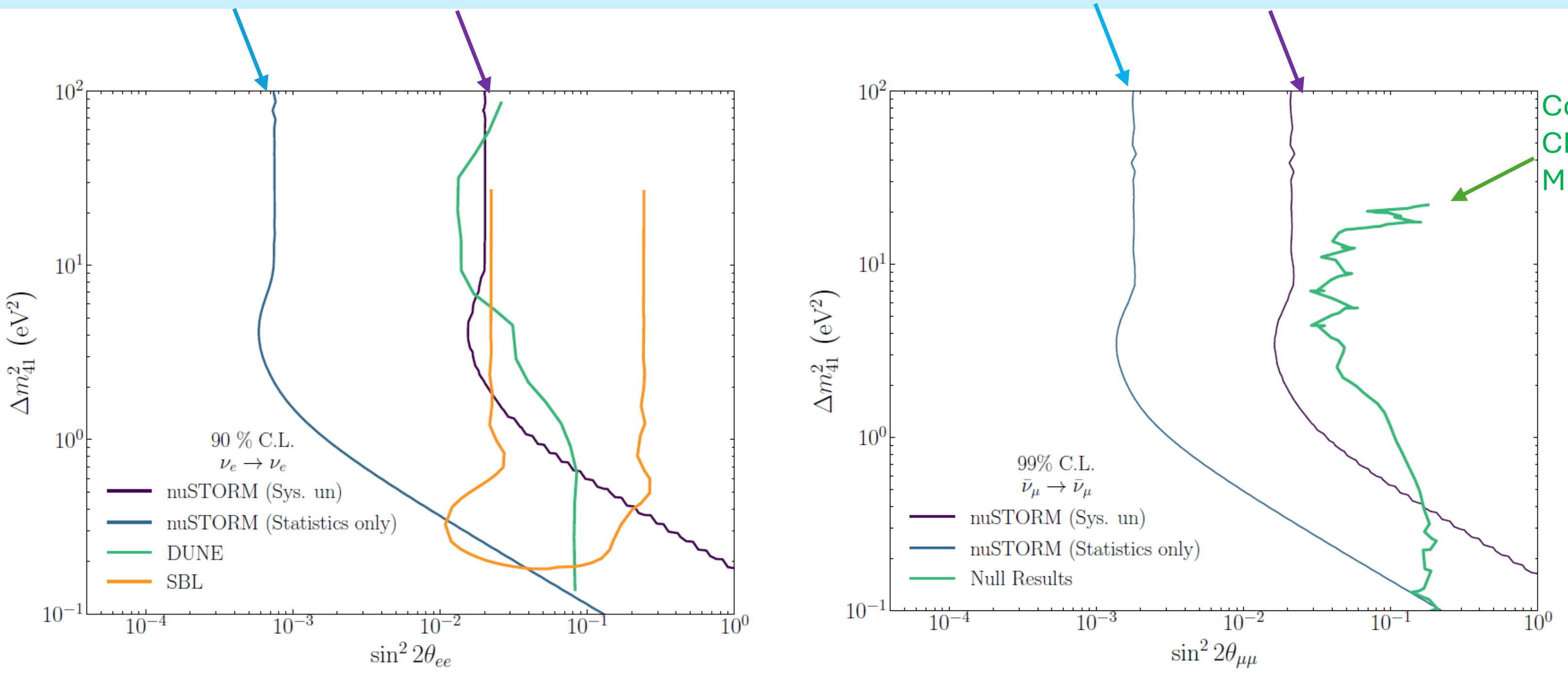
- The dominant source of ν_μ at nuSTORM is pion decay, flux approximately 100x that from muon decay
- At nuSTORM energies, dominated by coherent interactions mediated by W or Z
- Sensitive to physics BSM: e.g., Z'
- **nuSTORM projected trident SM yields could exceed those of all existing facilities [not competitive with DUNE]**

BSM: light sterile neutirnos

Survival probability in 3+1 sterile neutrino parameter space (short-baseline approximation):

$$P_{\alpha\alpha}^{\mathrm{SBL}} = 1 - \sin^2(2\theta_{\alpha\alpha})\,\sin^2\!\left(\frac{\Delta m_{41}^2 L}{4E}\right)$$

Sensitivity to disappearance with 100t detector at 50 m from end of production straight, 10^{21} POT



Combined null result from MINOS, CDHS Super-Kamiokande and MiniBooNE

NEW

J,Turner et al.
arXiv: 2505.06137

SBL is evidence from reactor anomaly

NEW

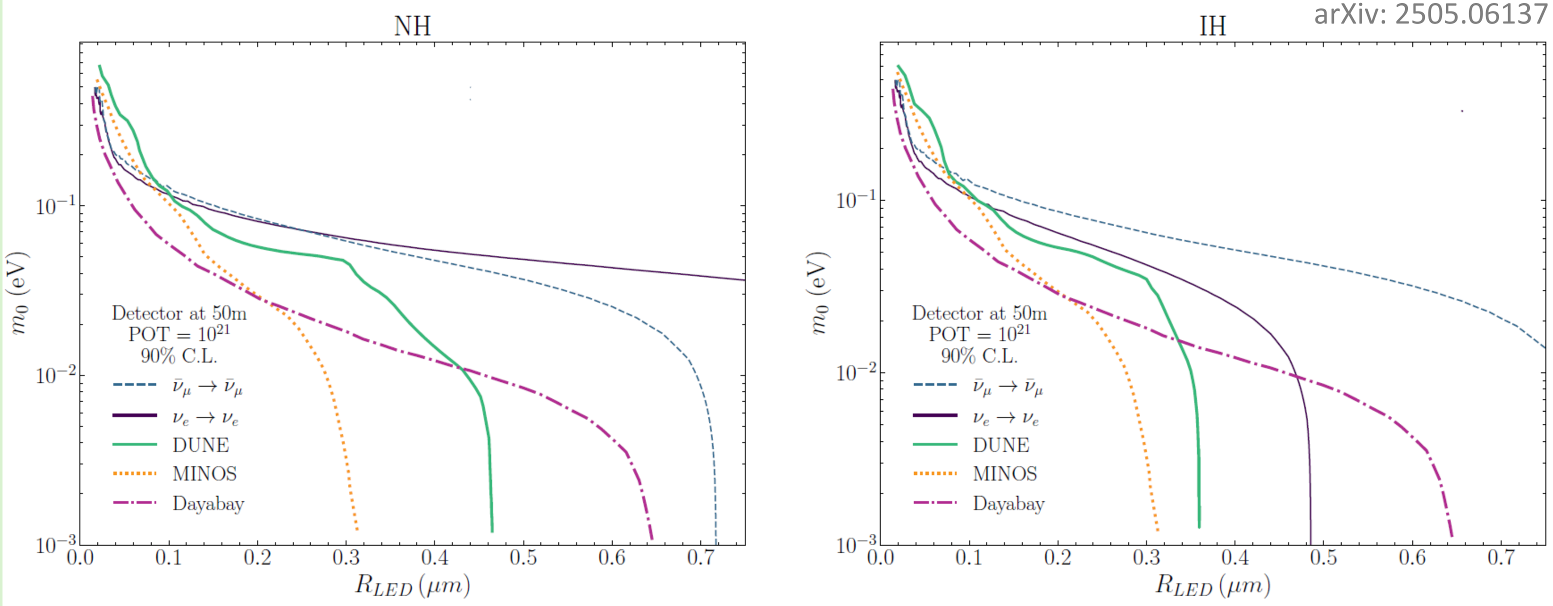
BSM: Large Extra-Dimensions

Large Extra Dimensions (LED) can explain the lightness of neutrino masses

- Dirac neutrinos are confined on a “brain” (our 3+1D Universe)
- Sterile neutrinos can propagate through higher-dimensional “bulk” and mix with active ones, which modifies oscillation probabilities
- nuSTORM has sensitivity to μm LED length scales
- nuSTORM can set competitive limits on LED length scale for lightest neutrino mass, m_0 >0.1 eV

J,Turner et al.

arXiv: 2505.06137



NEW

BSM: LFV and LNV in pion decays

Only loose bounds exist from BEBC

- $LFV: BR(\pi^+ \to \mu^+ \nu_e) <$ 8 x 10^{-3}
- $LNV: BR(\pi^+ \to \mu^+ \overline{\nu}_e) <$ 1.5 x 10^{-3}

At injection, 3 neutrino species

- **Pion decay [SM]** : $\pi^+ \to \mu^+ \nu_\mu$
- **Muon decay [SM]:** $\mu^+ \to e^+ \nu_e \overline{\nu}_\mu$

nuSTORM can look for:

- Excess of ν_e (signal for LFV pion decay)
- Excess of $\overline{\nu}_e$ (signal for LNV pion decay, background free)

- Exquisite precision and high brightness of pion flash, allows for statistical sensitivity <10^{-4} in both LFV and LNV [just using counting information]
- Including systematics, nuSTORM still improves on BEBC and on SBND-PRISM expectations

J,Turner et al.

arXiV:2405.00777

arXiv: 2505.06137

Experiment (Uncertainty)	BR $(\pi^+ \to \mu^+ \nu_e)$
BEBC	8×10^{-3}
SBND (10%)	1.5×10^{-3}
SBND-PRISM (10%, 5%)	1.2×10^{-3}
SBND-PRISM (10%, 2%)	8.9×10^{-4}
nuSTORM(1%)	7.1×10^{-4}
Statistics only	4.7×10^{-5}

LFV sensitivity at 90% CL

Conclusions

nuSTORM will be an innovative neutrino facility

- %-level electron neutrino cross-sections in the energy range of interest to CPV searches
- nuclear dynamics and collective effects in nuclei with 100% polarised probe sensitive to isospin
- sensitive searches of exotic processes
- preparation of phenomenological paper in progress

Recent developments:

optimisation of the beamline; simulation developments; synthetic beam

nuSTORM is a step towards muon collider

- serves as muon collider test-bed
- proof of principle of stored high-brightness muon beams

- Feasibility of executing nuSTORM at CERN established through Physics Beyond Collider
- Studies progressing in collaboration with International Muon Collider Collaboration

“There are concrete studies of how NuSTORM can be connected to a muon collider demonstrator. Similar opportunities – and more ambitious ones – should also be present at any muon collider facility in the future”

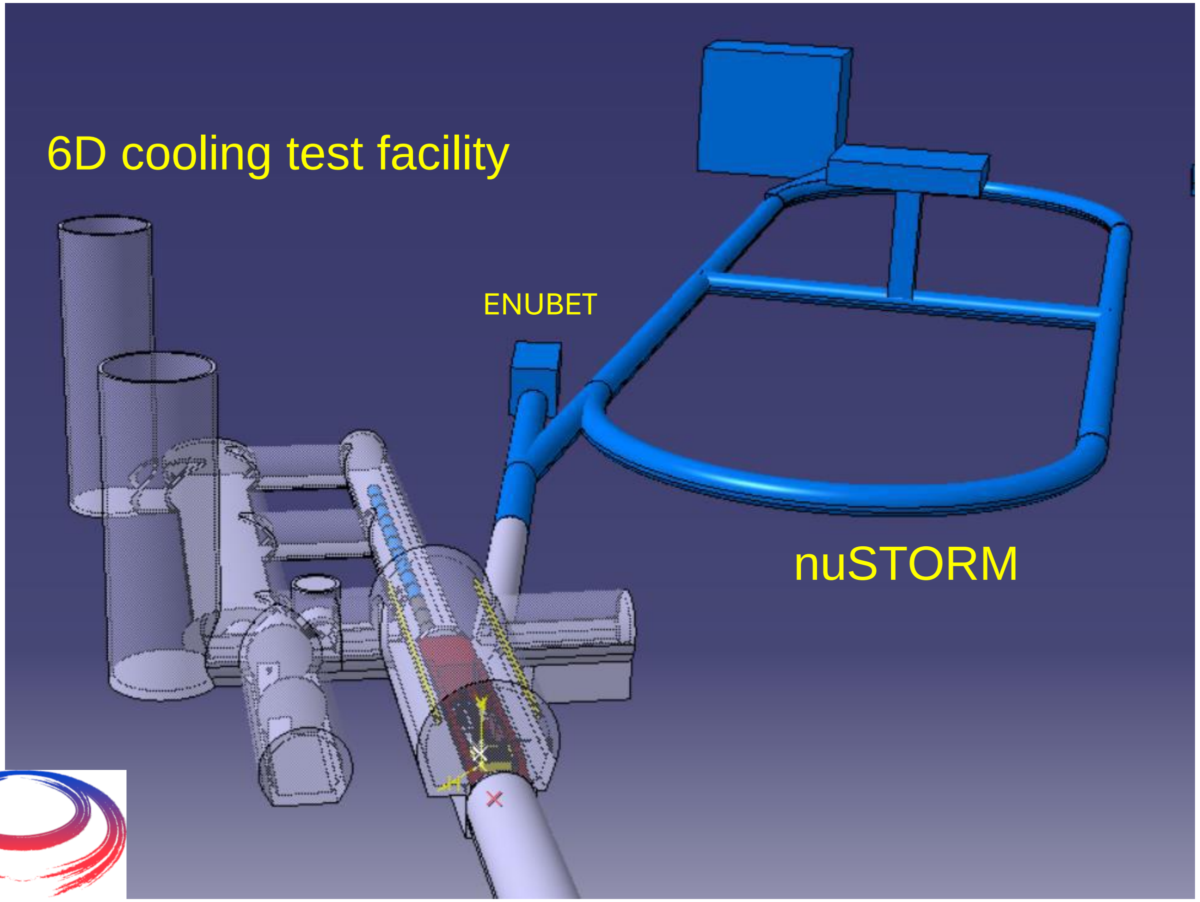
from IMCC ESPPU 2026 submission

nuSTORM will nurture a compelling **physics programme** alongside **technological R&D!**

Thank you

Integration with Muon Collider Demonstrator

doi:10.18429/JACoW-IPAC2022-THPOTK052



- Demonstrator facility flexible enough to accommodate other experiments
- nuSTORM, and potentially ENUBET, could be branched from the 6D cooling demonstrator
- Same target complex, shielding and general target infrastructure
- Deflection of beamline could reduce radiation streaming towards nuSTORM ring
- Synergies between experiments would reduce costs