Imperial College London

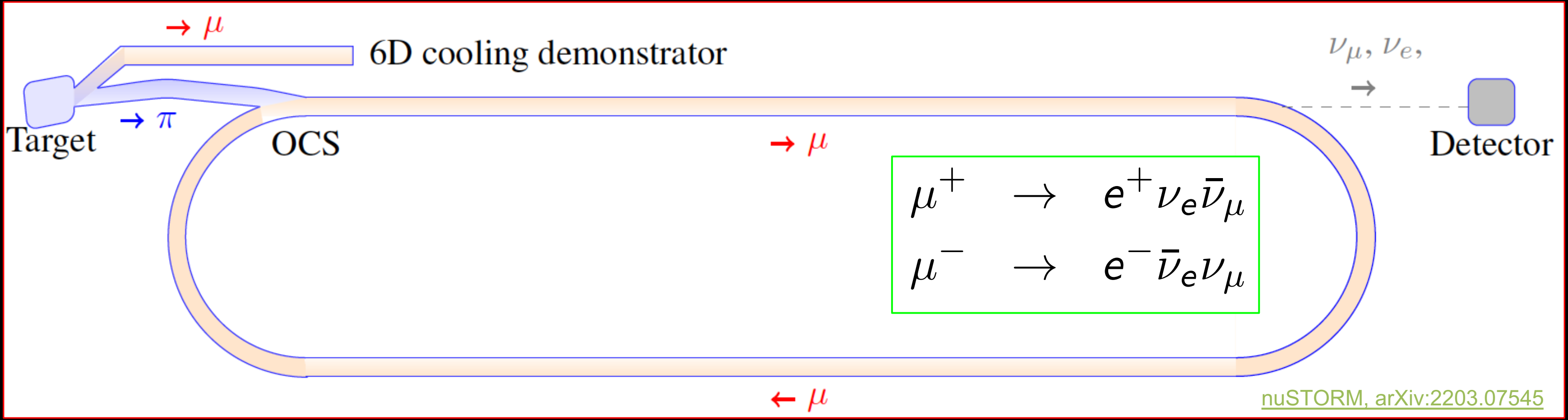
Science & Technology Facilities Council

nuSTORM

Unique facility for neutrino physics and muon-collider test bed

K. Long, 23 August, 2023 *… on behalf of the nuSTORM colaboration*

Neutrinos from stored muons



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

nuSTORM, arXiv:2203.07545

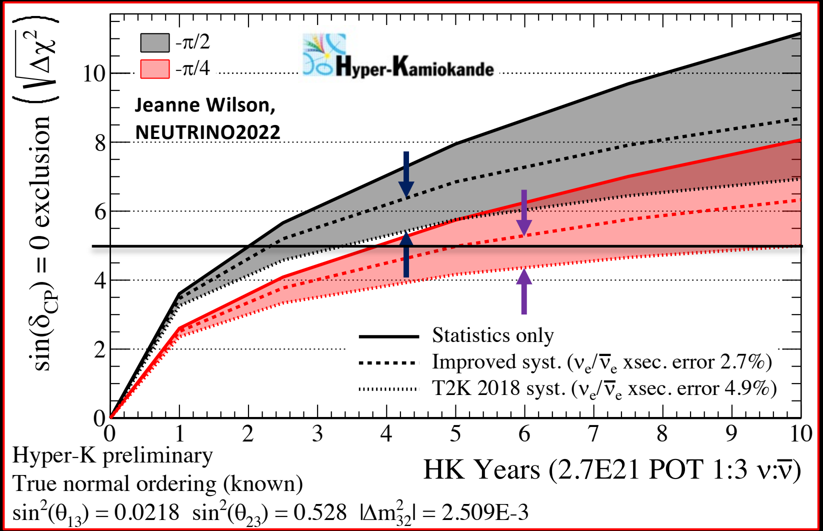
- **Scientific objectives:**
  1. **%-level ($\overset{(-)}{\nu}_e N$) cross sections**
     - **Multi differential / E_ν scan**
  2. **BSM searches**
     - **E.g. steriles beyond FNAL SBN**
  3. **Muon collider demonstrator**

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

- **$\pi \dashrightarrow \mu$ 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

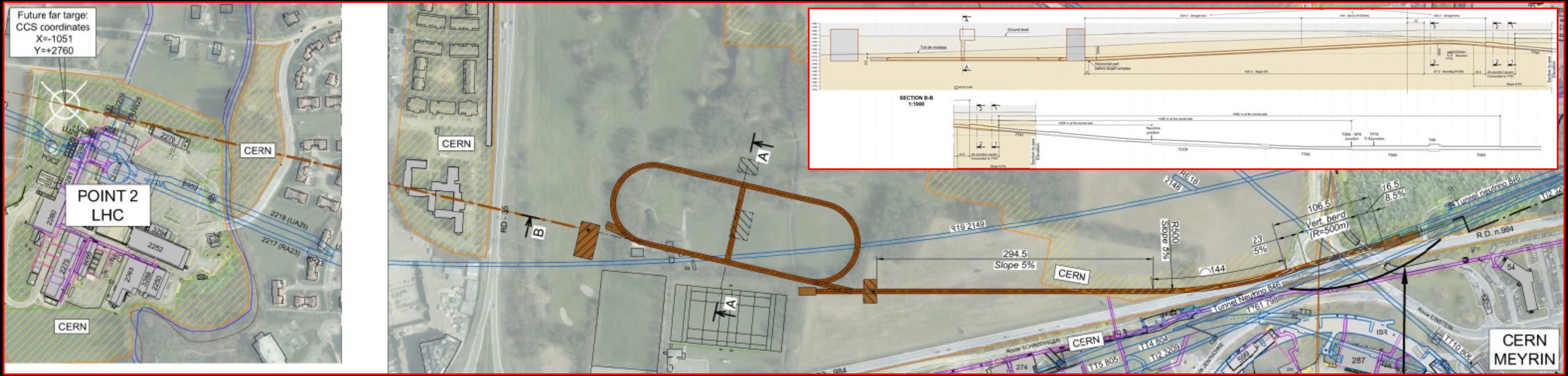


$$E_\nu^{\text{tree-level}} = \frac{\overbrace{m_\ell^2}^{\textit{Lepton mass correction}} + \overbrace{Q^2}^{\textit{Hadronic/nuclear response}}}{\underbrace{2\left(E_\ell - p_\ell \cos\theta_\ell\right)}_{\textit{Lepton observables}}}$$

❖ QED radiative corrections and lepton mass “nudge” Q^2, shifting internal $(q_0, \vec{q}_3)$ phase space

Overview

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



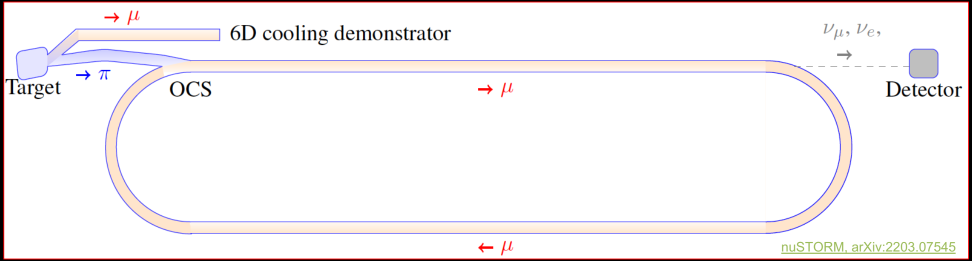
- Extraction from SPS through existing tunnel
- Siting of storage ring:
  - Allows measurements to be made on or off axis
  - Preserves sterile-neutrino search option

End-to-end simulation for (re)optimisation

P. Kyberd et al

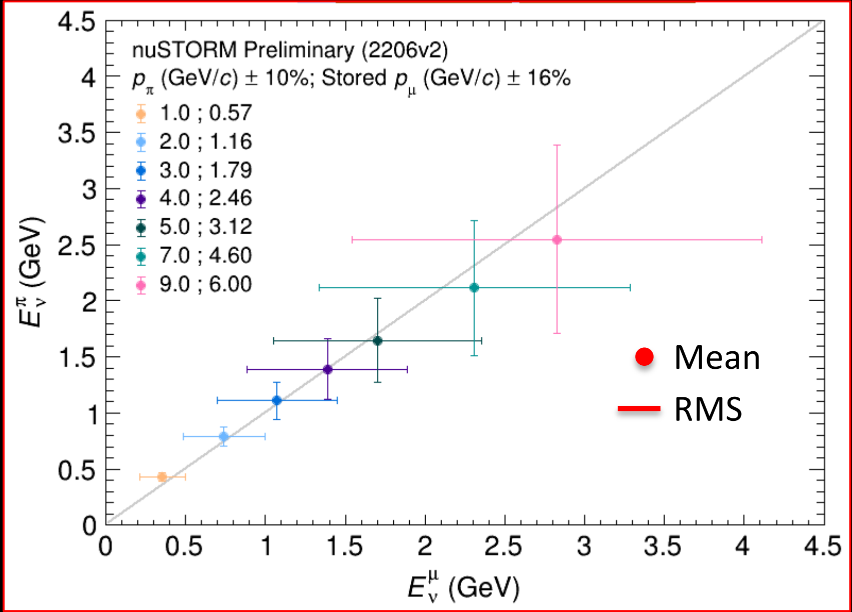
- "nuSIM" under development to:
  - Simulate facility "from target to detector":
    - Pragmatic approach:
      - Fast simulation, parametric approach
      - Tracking using G4 based code; "BDSIM"

T. Alves, M. Pfaff



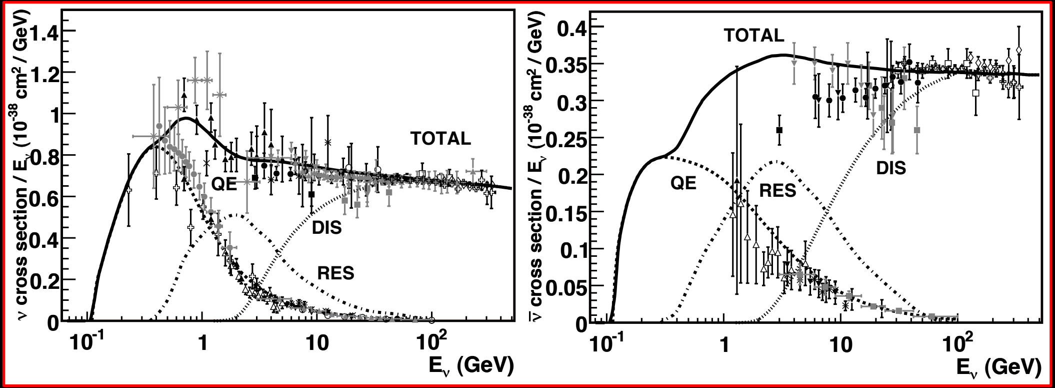
nuSTORM, arXiv:2203.07545

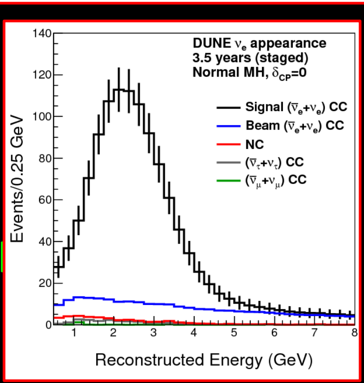
- Neutrino energy scan:
  - "Pion flash" in first pass
  - Subsequently neutrinos from muon decay
    - Spectrum determined by accelerator tune

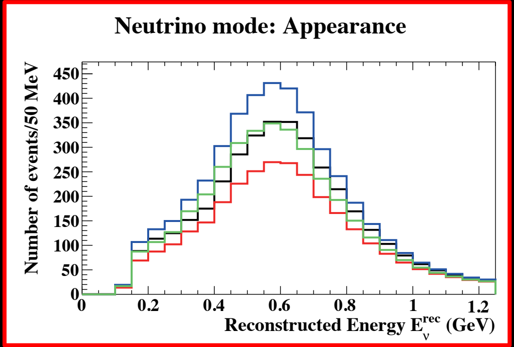


nuSTORM specification: energy range

- Guidance from:
  - Models:
    - Region of overlap 0.5—8 GeV
  - DUNE/Hyper-K far detector spectra:
    - 0.3—6 GeV







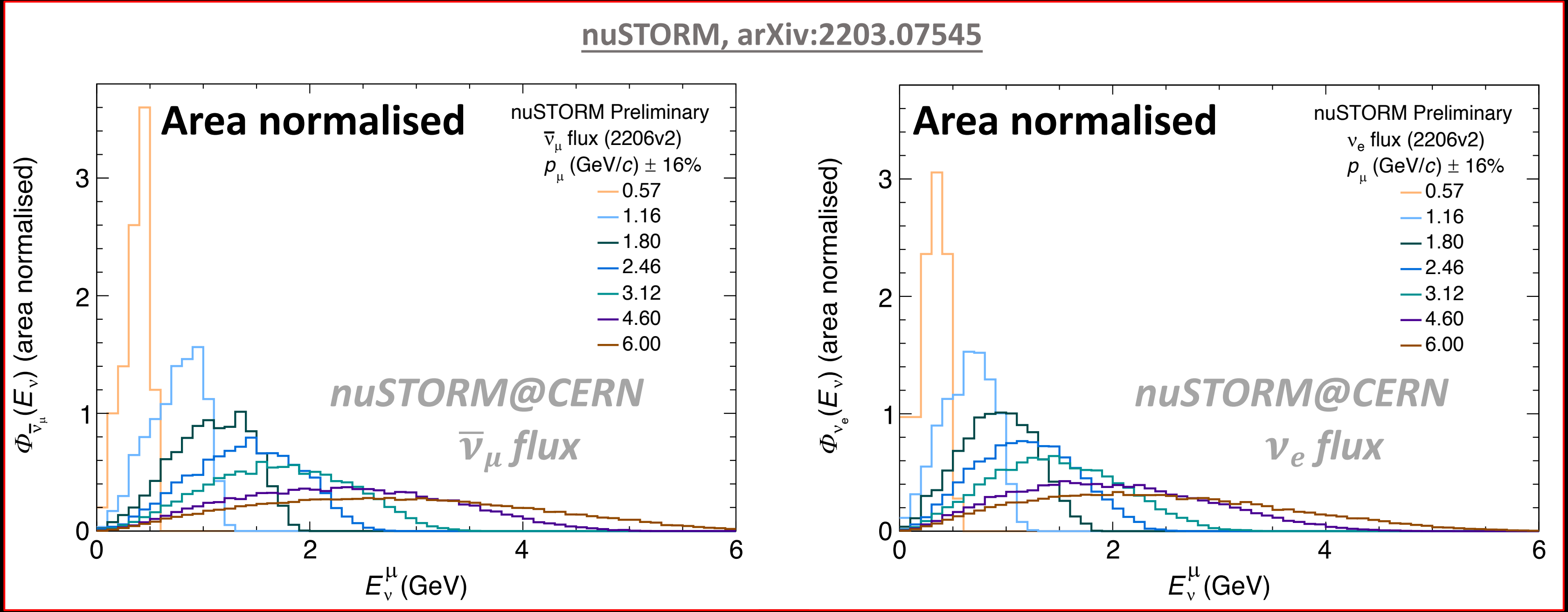
- Cross sections depend on:
  - *Q^2* and *W*:
    - Assume (or specify) a detector capable of measuring exclusive final states
    - → $E_\mu < 6$ GeV
- So, stored muon energy range:

$$\boxed{1 \leq E_\mu \leq 6 \text{ GeV}}$$

T. Alves, M. Pfaff

nuSTORM@CERN: flux estimation

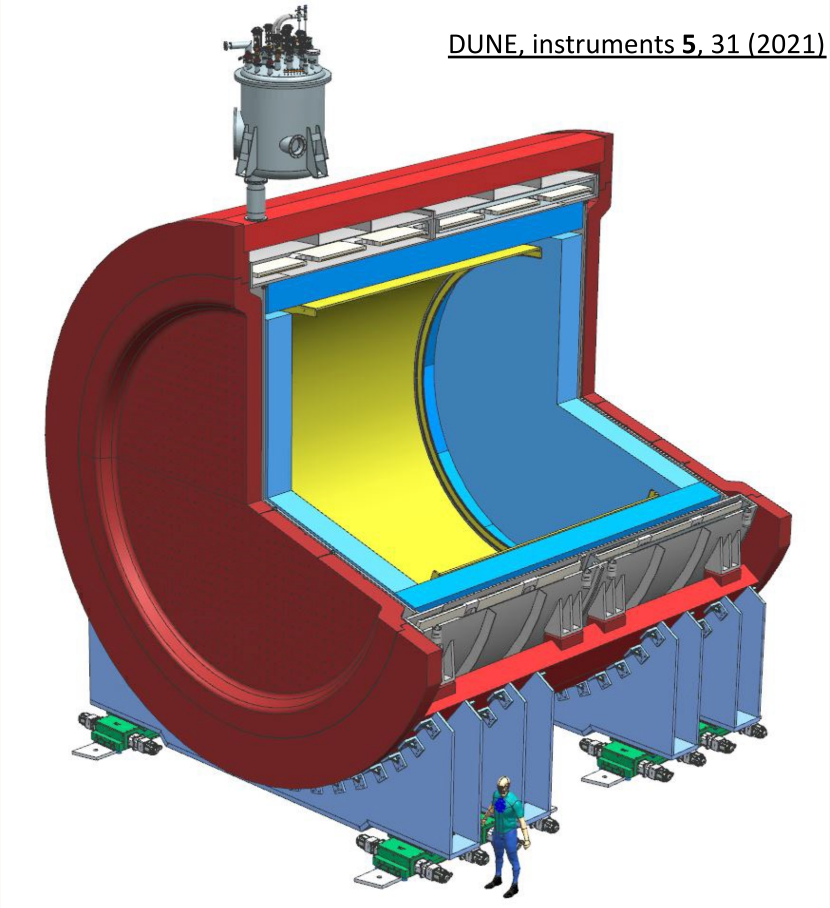
nuSTORM, arXiv:2203.07545



- 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

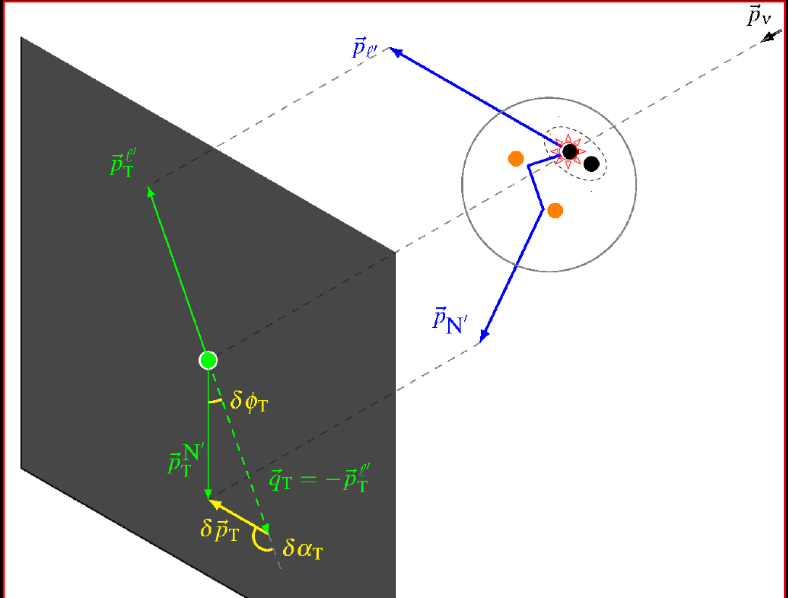
- nuSIM ready to allow performance evaluation:
  - Require “highly capable” detector:
    - Scattered lepton
    - Inclusive and exclusive final states
- Initial study use DUNE ND-GAr:
  - TPC reference design
    - 10-bar argon-based gas TPC
    - Large gas volume
    - Surrounded by calorimeter
  -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



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

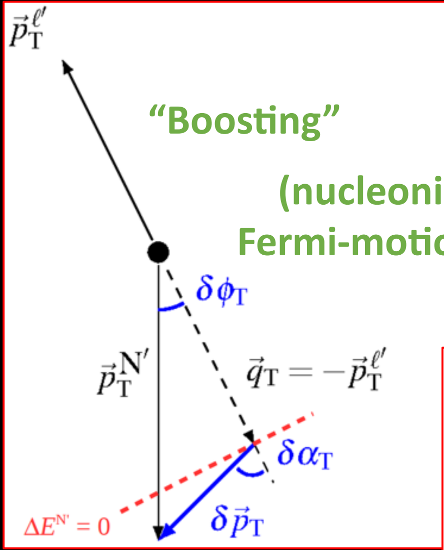
nuSTORM@CERN: E_ν-scan measurements

X. Lu



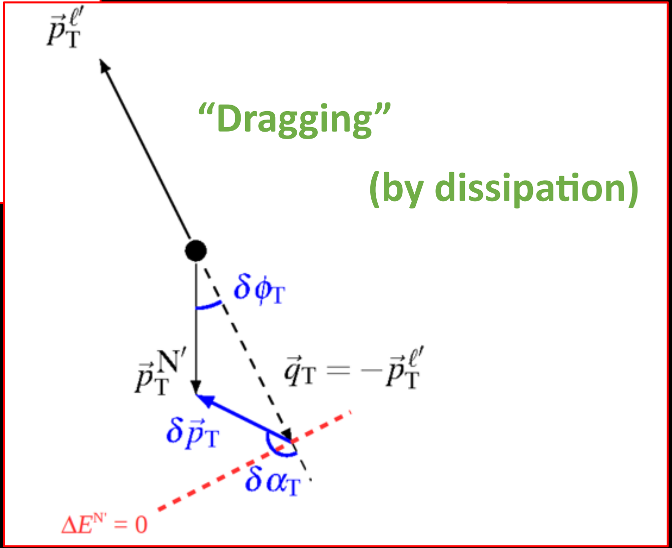
Transverse boosting angle

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



"Boosting"

(nucleonic + Fermi-motion)



"Dragging"

(by dissipation)

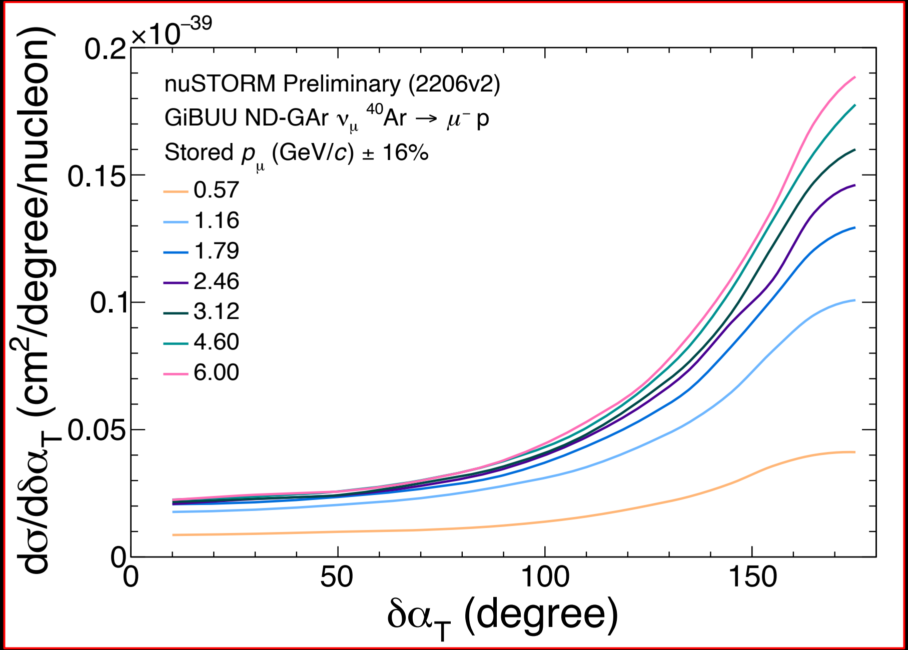
Quasi-elastic cross section function of $\delta\alpha_{\mathrm{T}}$

- Low $\delta\alpha_{\mathrm{T}}$: impact of nuclear effects low:
  - "Nuclear model calibration"
- High $\delta\alpha_{\mathrm{T}}$: 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 $\delta\alpha_T$

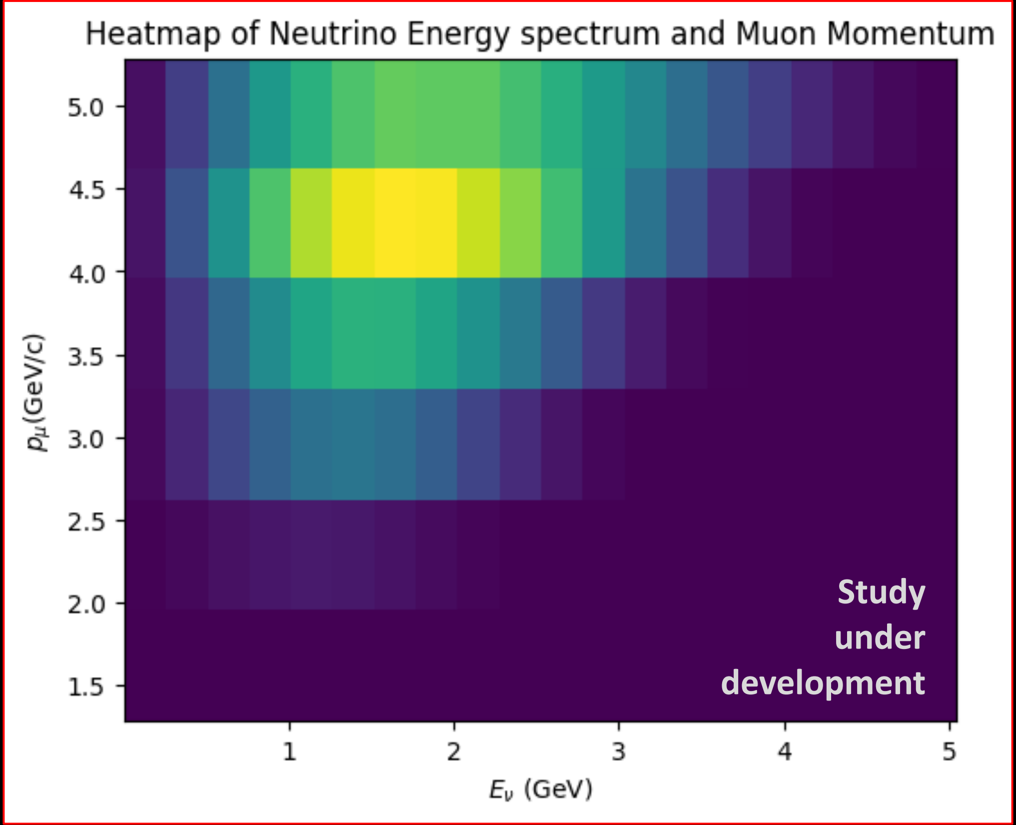


- Cross-section estimation using (preliminary) nuSTORM flux
- Energy evolution “tunable” to optimise sensitivity of measurement
- Start of study of energy dependence of various exclusive measurements:
  - To provide precise constraints on nuclear effects and their evolution

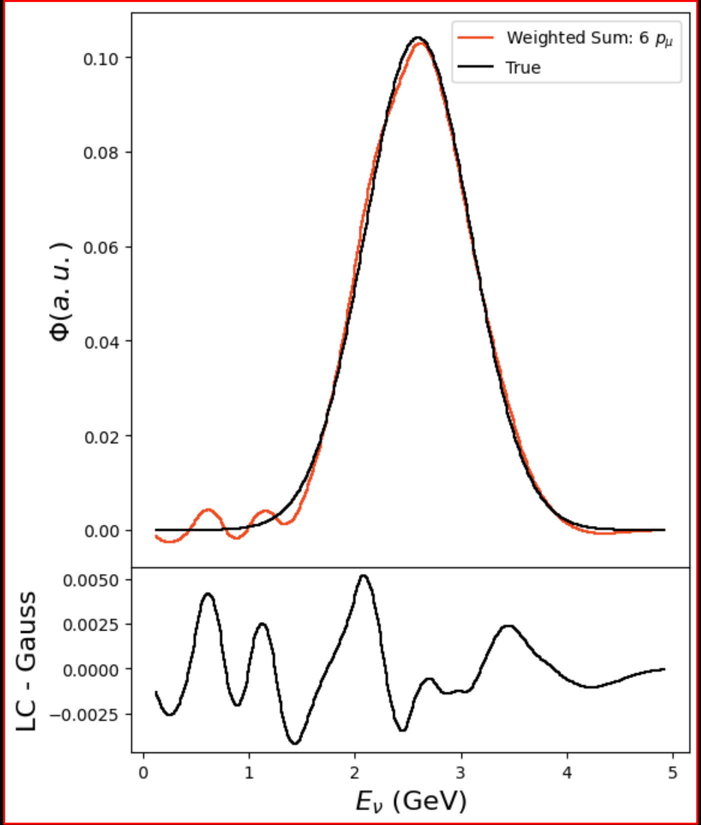
R. Kamath

Synthetic neutrino beam

By combining fluxes from 6 stored-muon beam energies



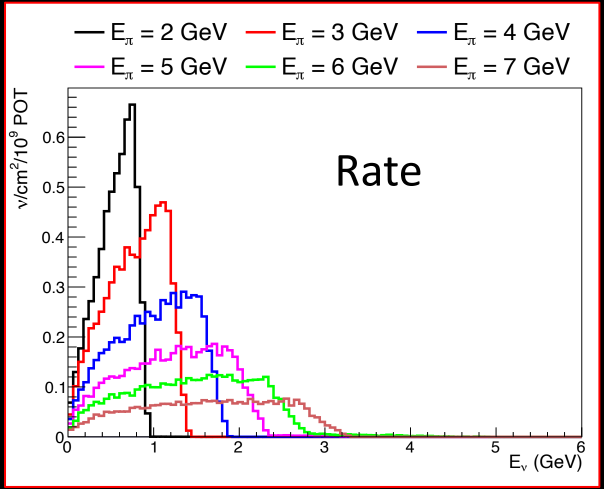
Study under development

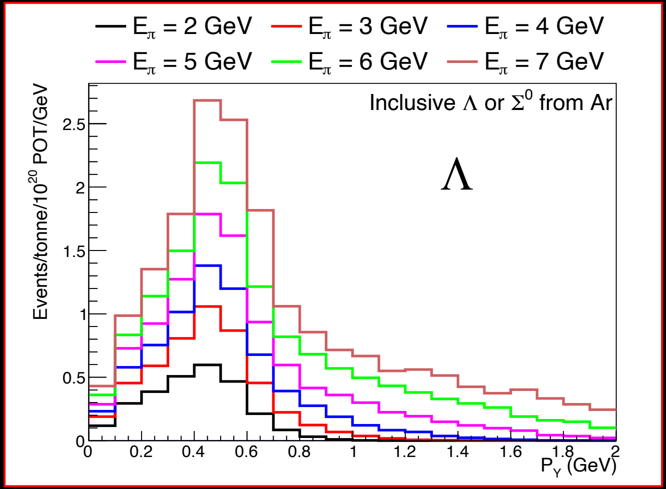


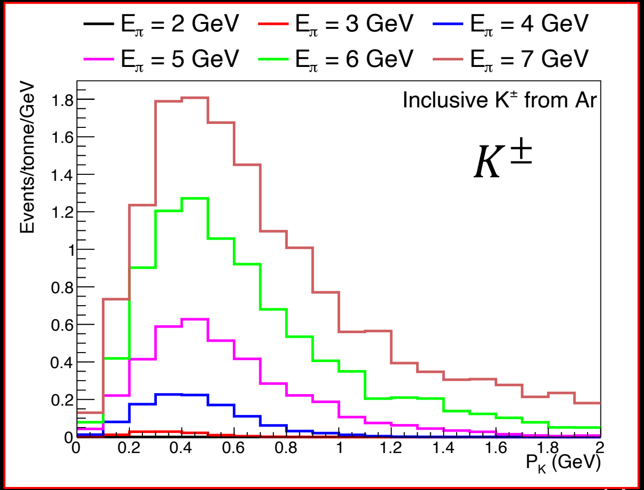
C. Thorpe

Case study: strangeness production

- Improve nuclear, final-state interaction models:
  - Presently, data is “sparse”
- Use nuSTORM flux to look at event rates:
  - NuWro used to simulate scattering
  - Assume energy threshold of 0.3 GeV, typical of LAr





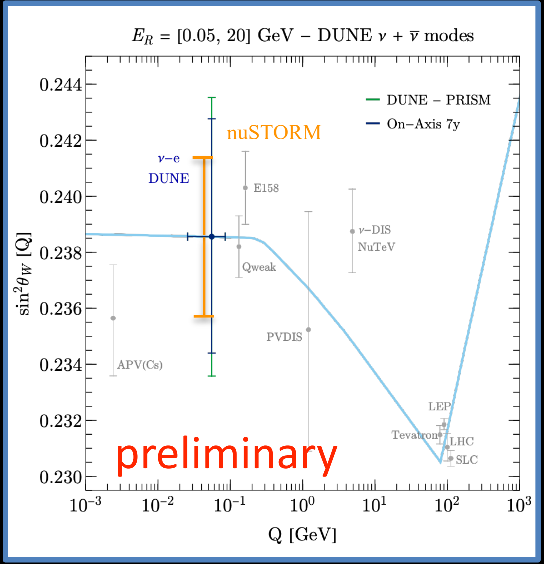


Y.F. Perez-Gonzalez

SM opportunities

- **Improving Standard Model Measurements**
  - **weak mixing angle measurement at low Q-value**
  - **SM Trident**

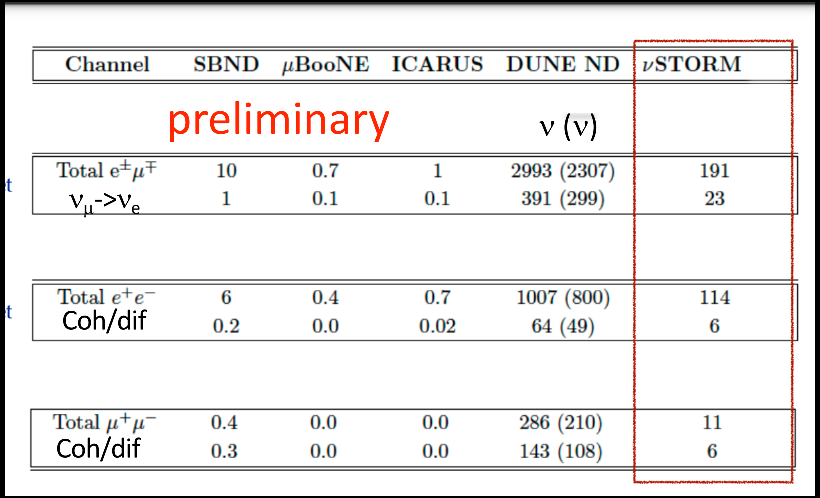
[PRL125, 051803](#)



preliminary

Trident

$$\nu_\alpha + \text{Hadron} \to \nu_\alpha + \ell^+ + \ell^- + \text{Hadron}$$



Channel	SBND	μBooNE	ICARUS	DUNE ND	νSTORM
	preliminary			ν (ν)	
Total $e^\pm\mu^\mp$	10	0.7	1	2993 (2307)	191
ν_μ->ν_e	1	0.1	0.1	391 (299)	23
Total e^+e^-	6	0.4	0.7	1007 (800)	114
Coh/dif	0.2	0.0	0.02	64 (49)	6
Total $\mu^+\mu^-$	0.4	0.0	0.0	286 (210)	11
Coh/dif	0.3	0.0	0.0	143 (108)	6

nuSTORM POT = 14×10^{21}, 100t FID mass LArTPC

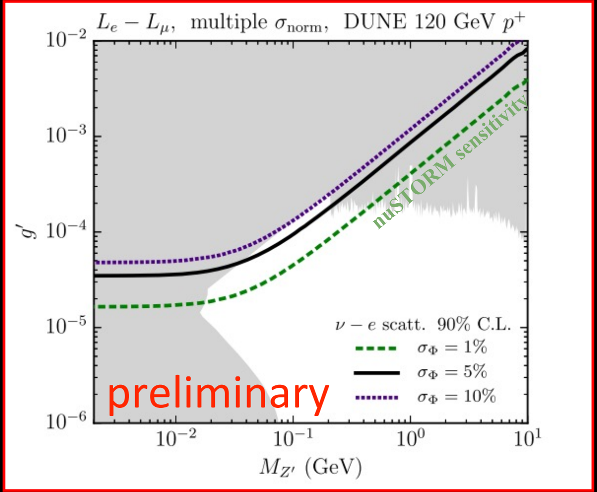
ProtoDUNE ~700t (FID) LArTPC

Y.F. Perez-Gonzalez
J. Turner

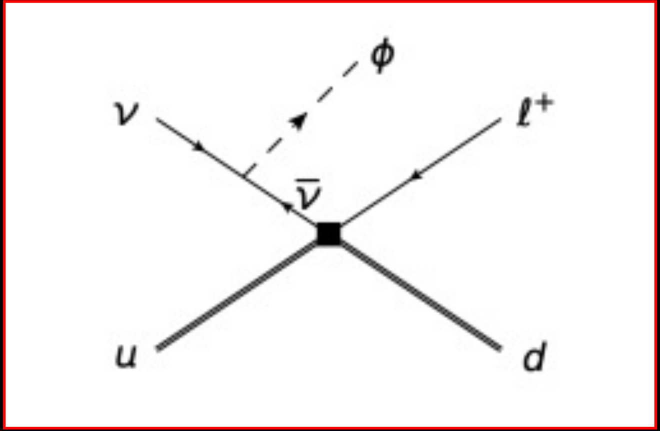
BSM opportunities ("beyond steriles")

- **nuSTORM sensitivity to new physics**
  - **- New Physics (Z') can appear in trident**
  - **- ν self interactions can be constrained (increase in expected $\overline{\nu}$)**
  - **- Searches for Large Extra dimensions (oscillations occur)**
  - **- Light Dark Matter Constraints from DM produced from $\pi^{\pm}$ decays**

BSM Trident [PRD.100.055012](PRD.100.055012)



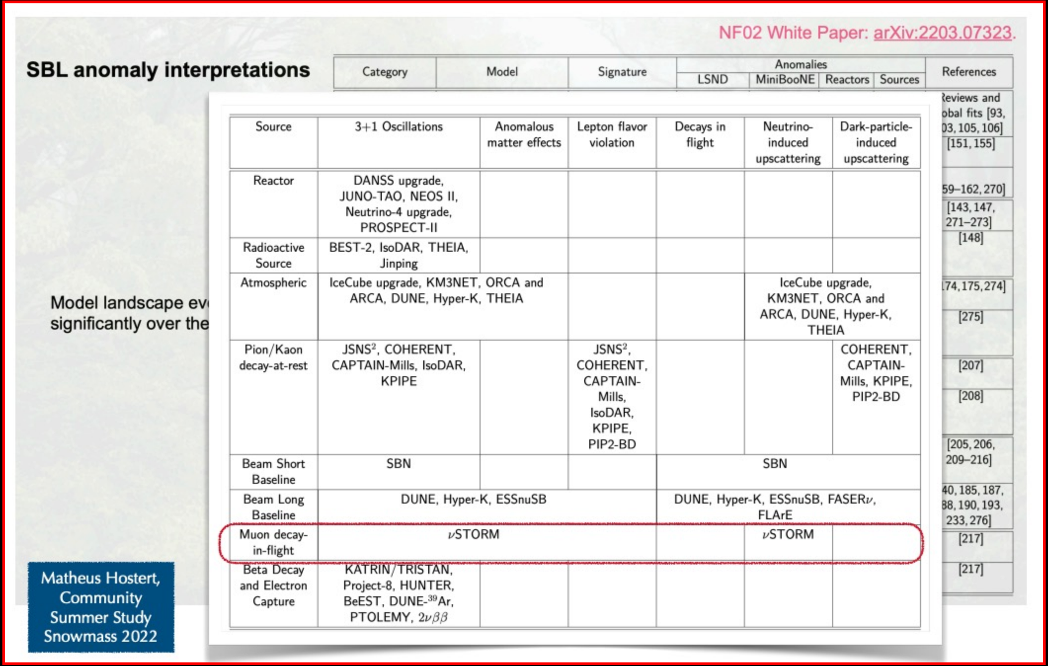
ν self interactions



Y.F. Perez-Gonzalez
J. Turner

BSM opportunities (“beyond steriles”)

- **nuSTORM can help resolve SBL anomalies**
- **Large Flux, low BGs, low systematics make nuSTORM the best place to constrain new physics**



NF02 White Paper: arXiv:2203.07323.

SBL anomaly interpretations

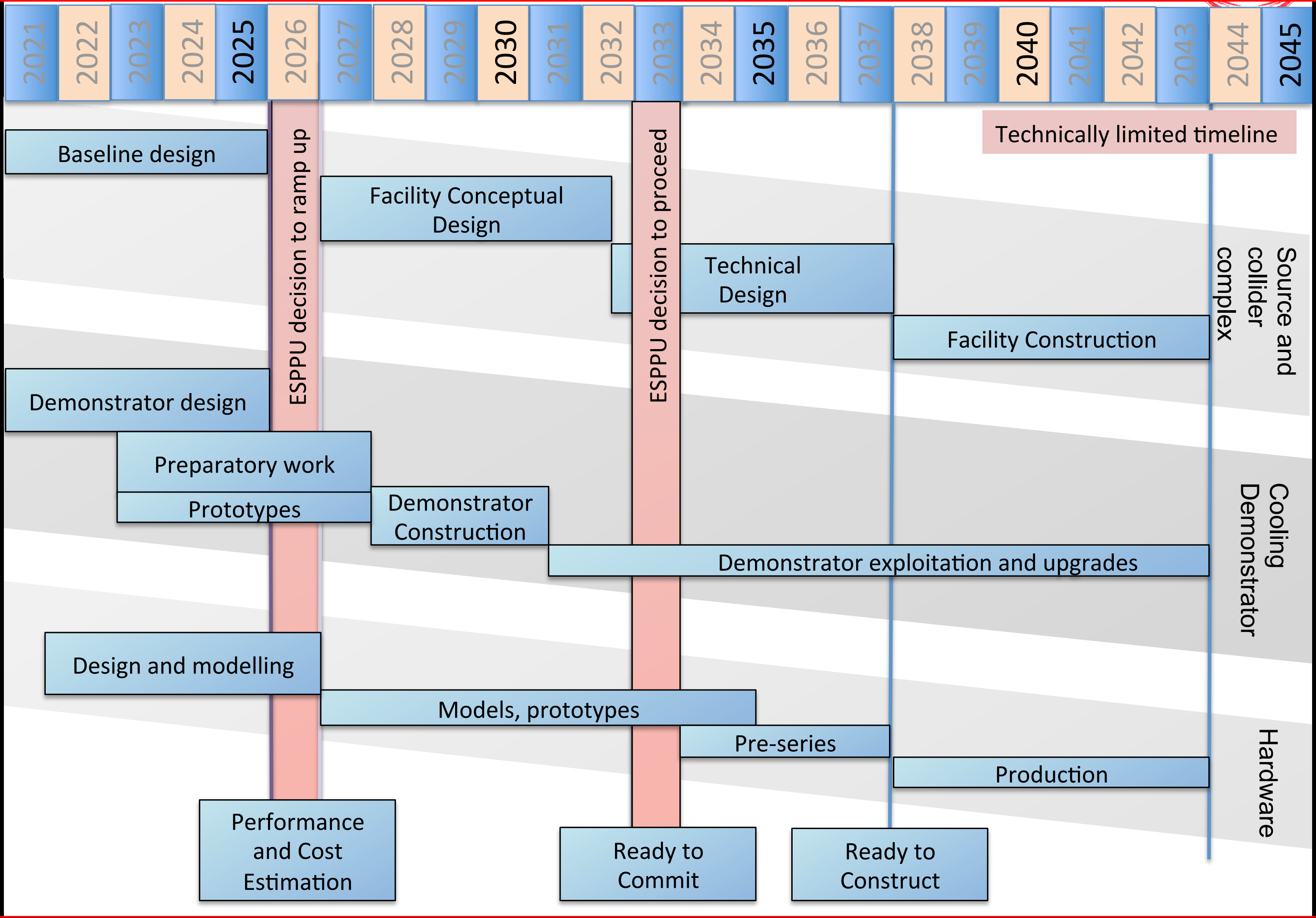
Category	Model	Signature	Anomalies				References
			LSND	MiniBooNE	Reactors	Sources	

eviews and
obal fits [93,
03, 105, 106]
[151, 155]
59–162, 270]
[143, 147,
271–273]
[148]
74, 175, 274]
[275]
[207]
[208]
[205, 206,
209–216]
40, 185, 187,
88, 190, 193,
233, 276]
[217]
[217]

Model landscape ev
significantly over the

Source	3+1 Oscillations	Anomalous matter effects	Lepton flavor violation	Decays in flight	Neutrino-induced upscattering	Dark-particle-induced upscattering
Reactor	DANSS upgrade, JUNO-TAO, NEOS II, Neutrino-4 upgrade, PROSPECT-II					
Radioactive Source	BEST-2, IsoDAR, THEIA, Jinping					
Atmospheric	IceCube upgrade, KM3NET, ORCA and ARCA, DUNE, Hyper-K, THEIA				IceCube upgrade, KM3NET, ORCA and ARCA, DUNE, Hyper-K, THEIA	
Pion/Kaon decay-at-rest	JSNS^2, COHERENT, CAPTAIN-Mills, IsoDAR, KPIPE		JSNS^2, COHERENT, CAPTAIN-Mills, IsoDAR, KPIPE, PIP2-BD			COHERENT, CAPTAIN-Mills, KPIPE, PIP2-BD
Beam Short Baseline	SBN			SBN		
Beam Long Baseline	DUNE, Hyper-K, ESSnuSB			DUNE, Hyper-K, ESSnuSB, FASERν, FLArE		
Muon decay-in-flight	νSTORM				νSTORM	
Beta Decay and Electron Capture	KATRIN/TRISTAN, Project-8, HUNTER, BeEST, DUNE-^{39}Ar, PTOLEMY, $2\nu\beta\beta$					

Matheus Hostert,
Community
Summer Study
Snowmass 2022



2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035 2036 2037 2038 2039 2040 2041 2042 2043 2044 2045

Technically limited timeline

ESPPU decision to ramp up

ESPPU decision to proceed

Source and collider complex
- Baseline design
- Facility Conceptual Design
- Technical Design
- Facility Construction

Cooling Demonstrator
- Demonstrator design
- Preparatory work
- Prototypes
- Demonstrator Construction
- Demonstrator exploitation and upgrades

Hardware
- Design and modelling
- Models, prototypes
- Pre-series
- Production

Performance and Cost Estimation

Ready to Commit

Ready to Construct

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


Final

Neutrinos from Stored Muons (nuSTORM)

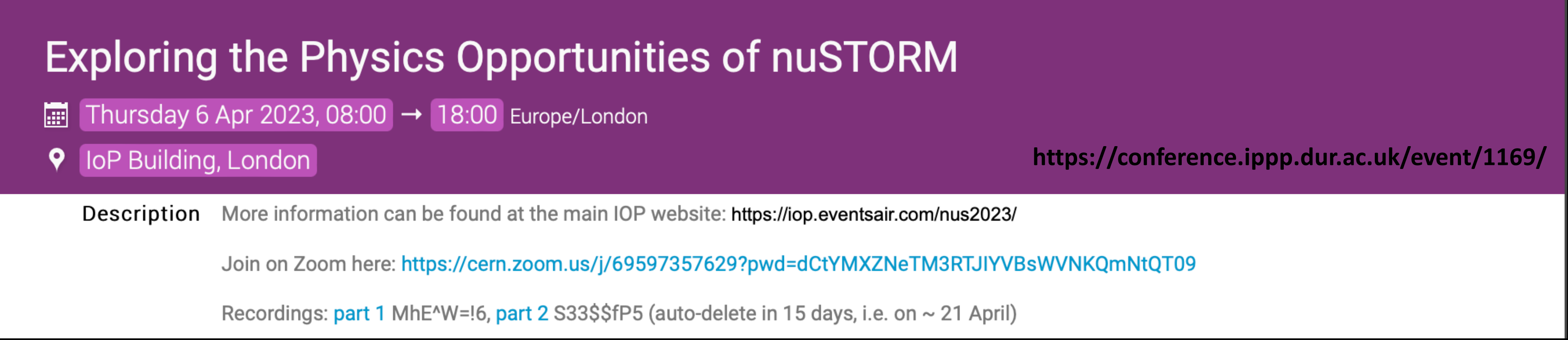
Submitted to the Snowmass 2021 DPF Community Planning Exercise

arXiv:2203.07545

ESPPU 202x

Goal:* *over next ~3 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**



Exploring the Physics Opportunities of nuSTORM

Thursday 6 Apr 2023, 08:00 → 18:00 Europe/London

IoP Building, London

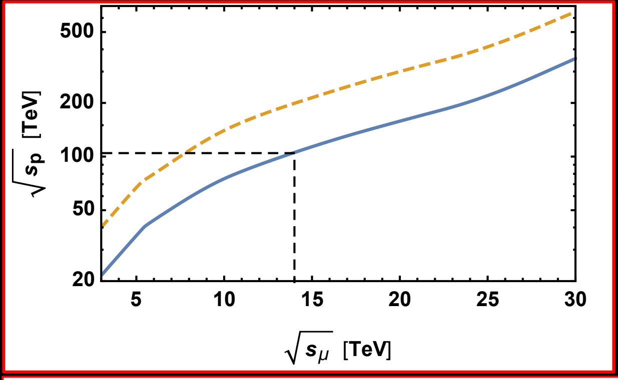
https://conference.ippp.dur.ac.uk/event/1169/

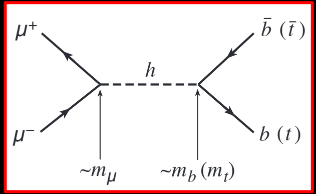
Description More information can be found at the main IOP website: https://iop.eventsair.com/nus2023/

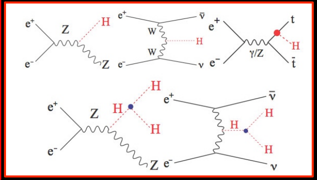
Join on Zoom here: https://cern.zoom.us/j/69597357629?pwd=dCtYMXZNeTM3RTJIYVBsWVNKQmNtQT09

Recordings: part 1 MhE^W=!6, part 2 S33$$fP5 (auto-delete in 15 days, i.e. on ~ 21 April)

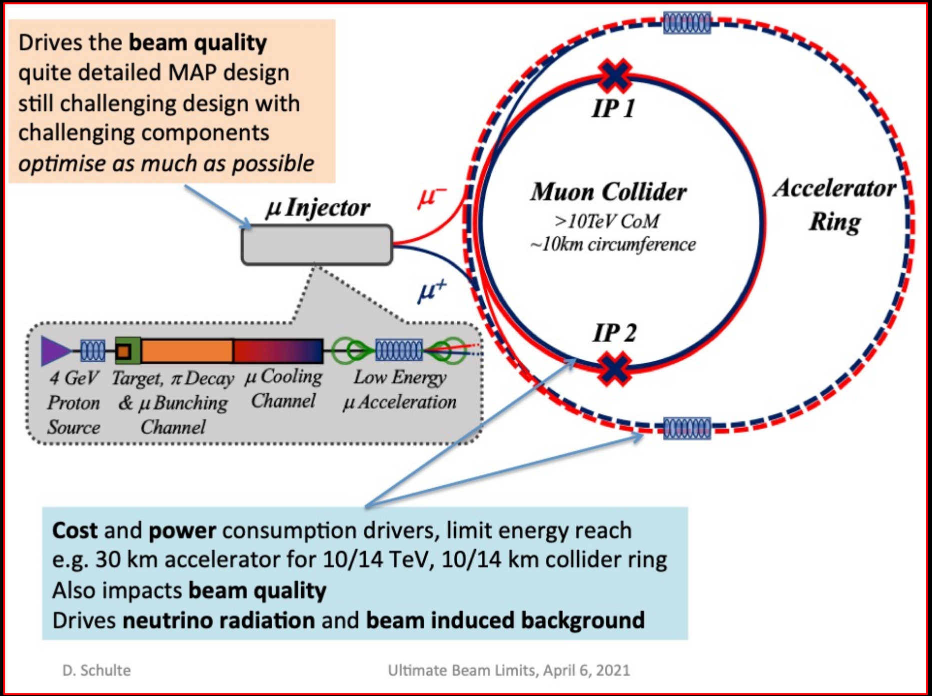
- ✓ Review landscape were nuSTORM will contribute
- ✓ Seek to identify key topics and directions
- ✓ Plot a course towards follow-up workshop:
  - In around 9 to 12 months
  - Which quantifies cross section, BSM, … opportunities
- Ideally:
  - “Proceedings” of follow-up workshop:
    - Document science case for nuSTORM in peer-reviewed publication
    - Provide evidence to support submission to ESPPU27





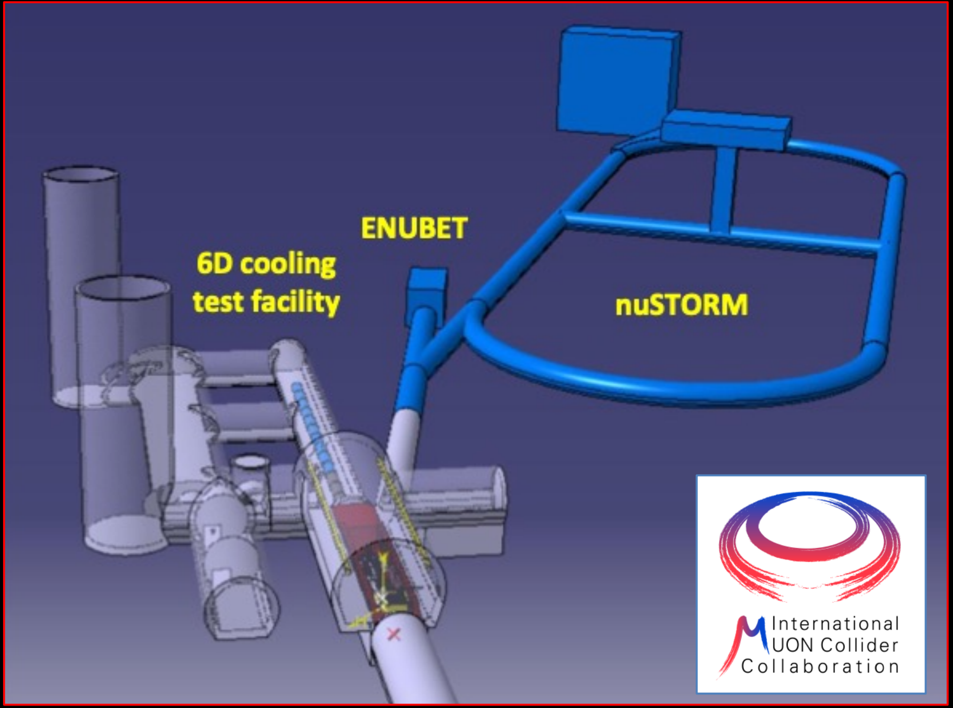


- Science case remains fantastic
- Technological R&D still ground-breaking
- ***Risks*** **to programme** ***remain too***
- **Demonstrator is critical to the programme:**
  - 6D cooling *and* world-leading particle physics


Drives the **beam quality**
quite detailed MAP design
still challenging design with
challenging components
optimise as much as possible

Cost and **power** consumption drivers, limit energy reach
e.g. 30 km accelerator for 10/14 TeV, 10/14 km collider ring
Also impacts **beam quality**
Drives **neutrino radiation** and **beam induced background**

D. Schulte Ultimate Beam Limits, April 6, 2021



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**

Thank you