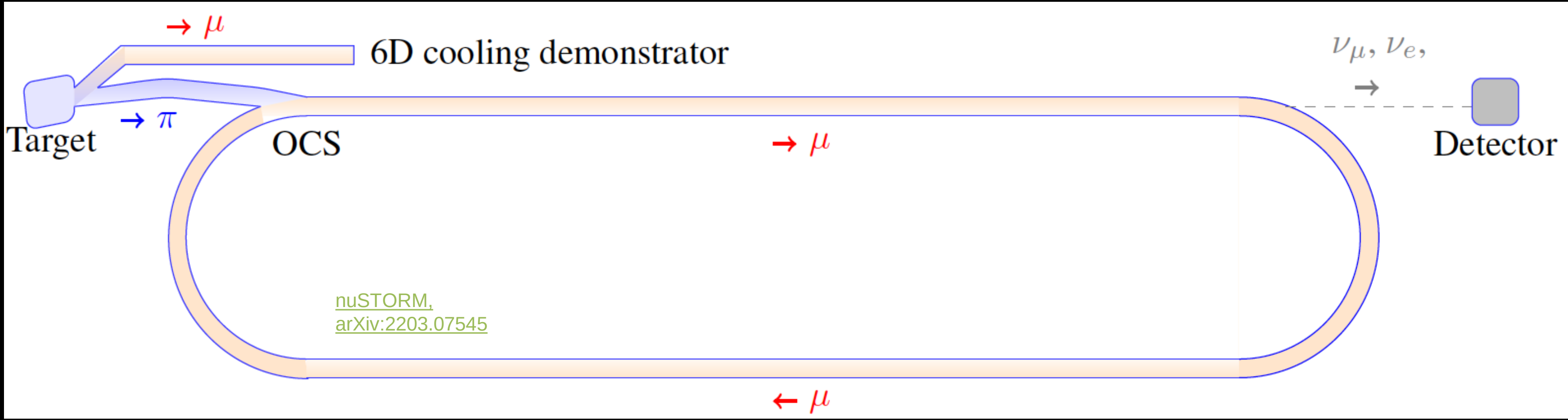
Synergies with nuSTORM

K. Long, 13 October, 2022

Neutrinos from stored muons

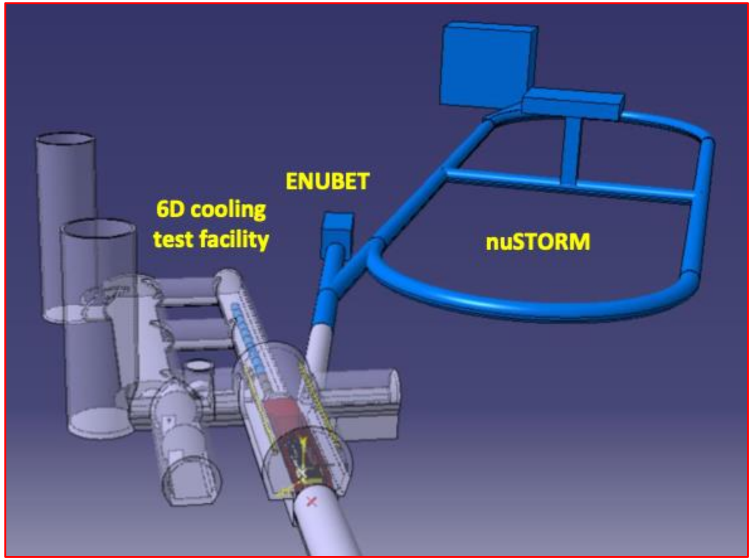


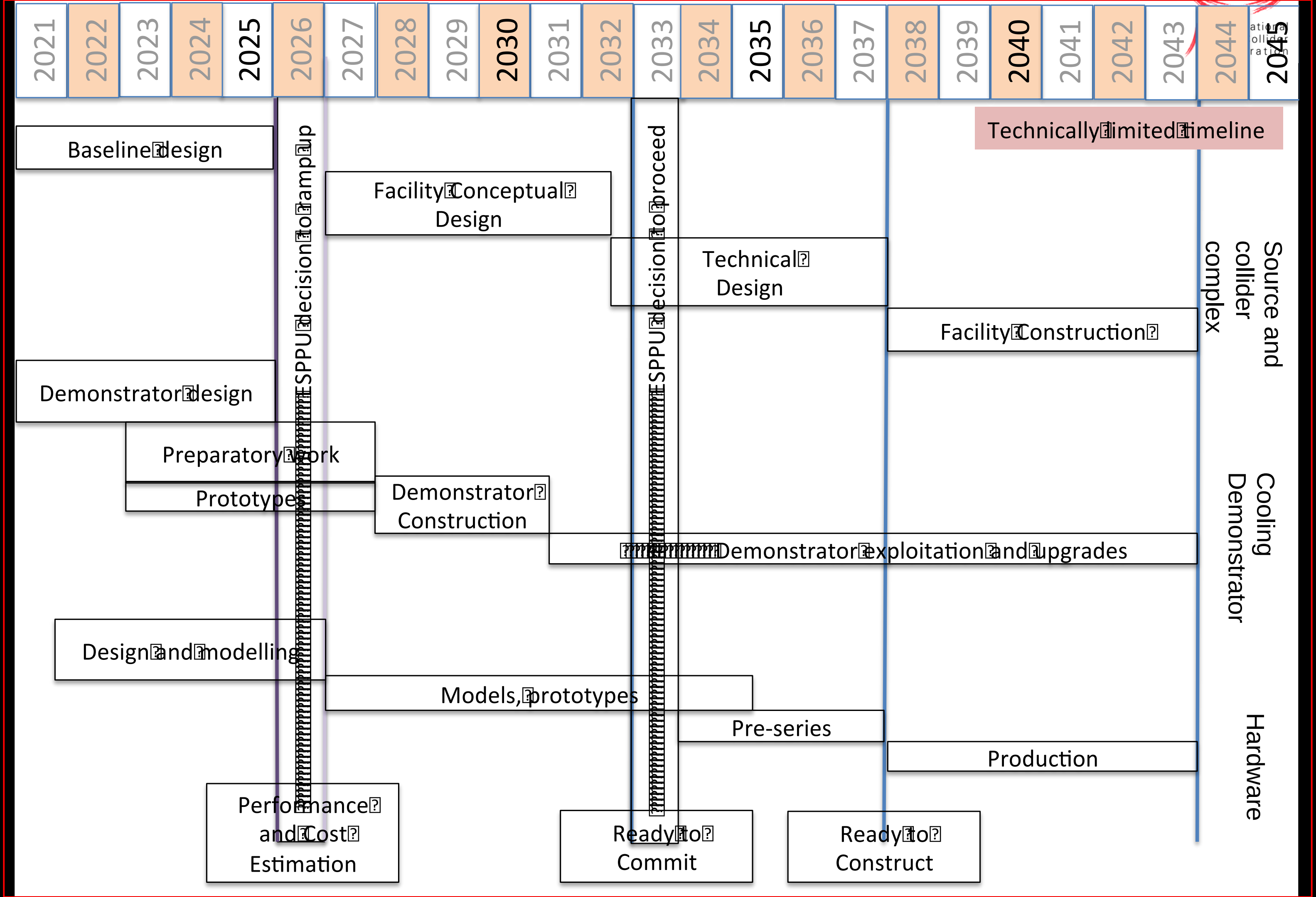
- **Scientific objectives:**
  1. **%-level ($\nu_e N$) cross sections**
     - **Double differential**
  2. **Search for physics "BSM"**
     - **Beyond Fermilab SBN**

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

ENUBET and nuSTORM

- **Scientific programme**
  - Precise, systematic, ν_e, cross section
  - Exquisite sensitivity to BSM
- **Capability**
  - Uniquely high quality neutrino beam
  - Path to new horizon at energy frontier
- **Opportunity**
  - ESPP:
    - Neutrino cross sections and muon collider
- **Partnership:**
  - ENUBET, nuSTORM; PBC & iMC

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Technically limited timeline
Baseline design
ESPPU decision to ramp up
Facility Conceptual Design
ESPPU decision to proceed
Technical Design
Facility Construction
Source and collider complex
Demonstrator design
Preparatory work
Prototypes
Demonstrator Construction
Demonstrator exploitation and upgrades
Cooling Demonstrator
Design and modelling
Models, prototypes
Pre-series
Production
Hardware
Performance and Cost Estimation
Ready to Commit
Ready to Construct

EP-NU Group Meeting

https://indico.cern.ch/event/1201923/

Thursday 22 Sept 2022, 11:30 → 13:00 Europe/Zurich

304/1-001 (CERN)

Description Special Session on NuStorm with invited guest speakers

Videoconference EP-NU Group Meeting — Please log in

11:30 → 11:40	**News and updates**	
11:40 → 11:50	**Introduction to Nustorm**	Speaker: Kenneth Richard Long (Imperial College (GB)); 2022-09-22-nuSTO... ; 2022-09-22-nuSTO...
11:50 → 12:00	**nuSTORM physics opportunities**	Speaker: Luis Alvarez Ruso; LAR_nuSTORMv1.pdf
12:00 → 12:10	**Experiments and detectors for nuSTORM**	Speakers: Xianguo Lu, Dr Xianguo Lu (University of Oxford); 20220922_CERN_N... ; 20220922_CERN_N...
12:10 → 12:20	**Overview of accelerator design**	Speakers: Jaroslaw Pasternak (European Organization for Nuclear Research (CERN)), Jaroslaw Pasternak (Imperial College, Lon; nuSTORM_Accelera...
12:20 → 12:30	**Simulation tools and fluxes**	Speaker: Paul Kyberd (Brunel University (GB)); nuSIMReport20220... ; nuSIMReport20220...
12:30 → 12:40	**nuSTORM and muon collidser demonstrator synergies**	Speaker: Chris Rogers (Imperial College); 2022-09-20_demon...
12:40 → 13:00	**AOB**	

EP-NU Group Meeting CERN

νSTORM physics opportunities

Luis Alvarez Ruso

IFIC — CSIC — Universitat de València

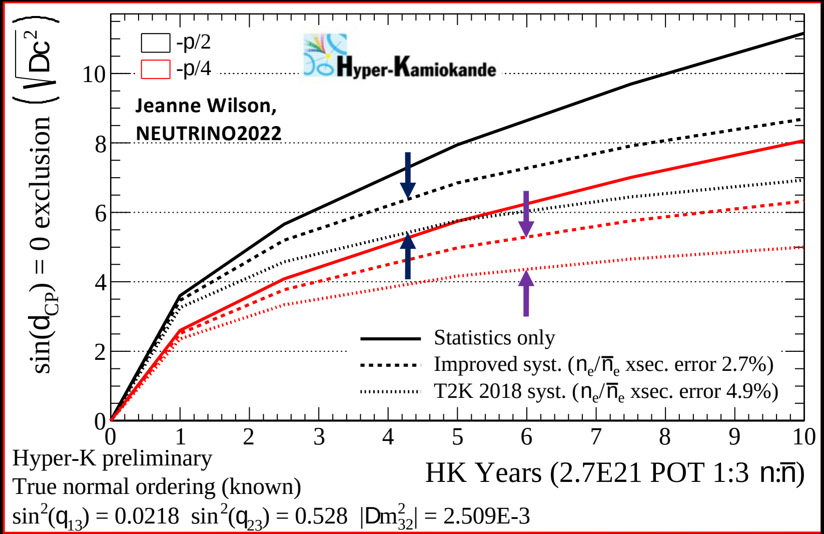
Outlook

- Our present understanding of (few-GeV) neutrino interactions with matter would be **greatly improved** by new precise measurements with well-understood ν**STORM** flux at **advanced detectors.**
- The future neutrino oscillation program can **greatly benefit**.
- Progress in **hadron** and **nuclear physics**.
- Potential to **discover/constrain non-standard interactions** and **exotic processes.**
- Sensitive searches for **short-baseline flavor transitions**: potential to **discover sterile neutrinos** or **exclude (10 σ)** the presently allowed parameter space.

Key: discussion of impact of cross section measurement and BSM processes

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

- δ_{CP} requires ν_e and $\bar{\nu}_e$ 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*

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

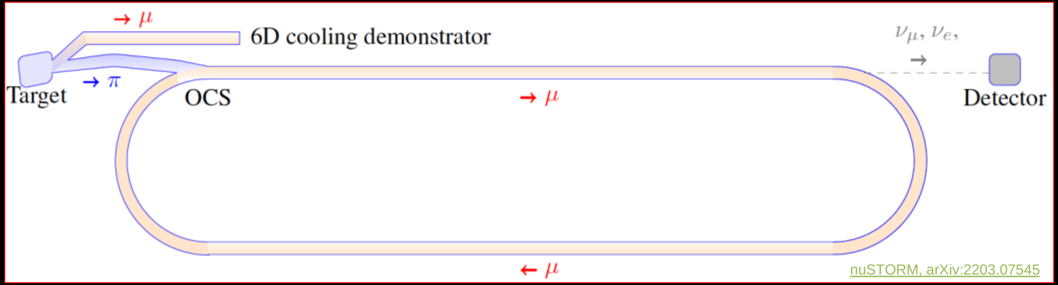
Lepton observables

- ❖ QED radiative corrections and lepton mass “nudge” ^{2}, shifting internal ($_0$, $\vec{}_3$) phase space

End-to-end simulation for (re)optimisation

P. Kyberd et al

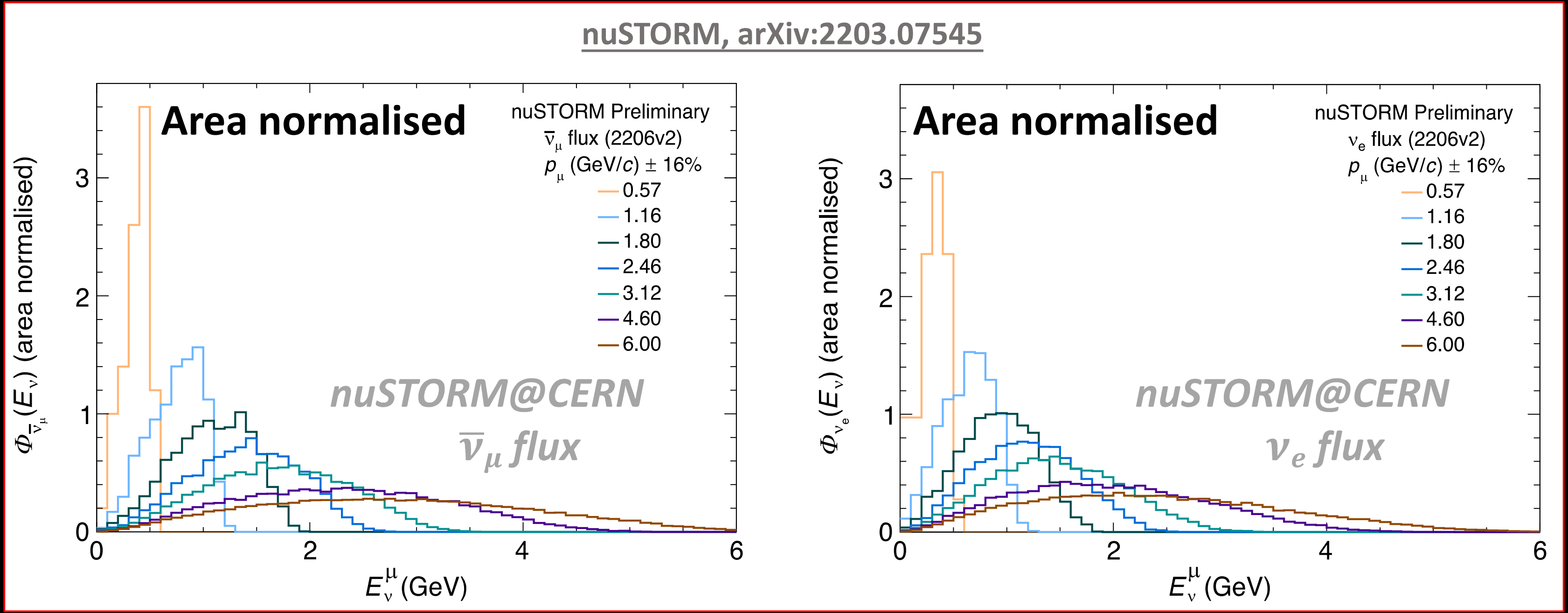
- "nuSIM" under development to:
  - Simulate facility "from target to detector":
    - Pragmatic approach:
      - Fast simulation, parametric approach
      - Full tracking using G4 based code; "BDSIM"



- 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

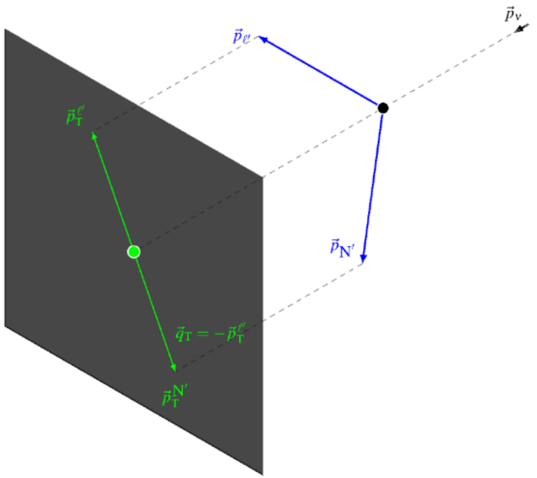


- **Oscillation-relevant energy regime**
  - **Hyper-K: 0.6 GeV**
  - **DUNE.   : 2.4 GeV**
- **Set by stored-muon momentum**
- **Accelerator "tune" gives fine control**
  - **E.g. optimise flux shape (or spread) by adjusting the ring acceptance**

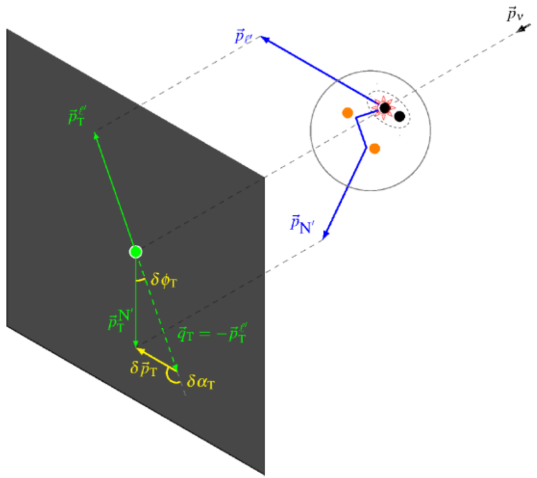
- **Unique opportunity:**
  - **E_ν-scan measurements**
  - **Monoenergetic flux (ν_e!!) emulated by flux combination**
    - **Like PRISM, but with more degree of freedom in component shaping**

nuSTORM@CERN: first analysis concept

Transverse Kinematic Imbalance (TKI)



Stationary free nucleon target



Nuclear target ($A > 1$)

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

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

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

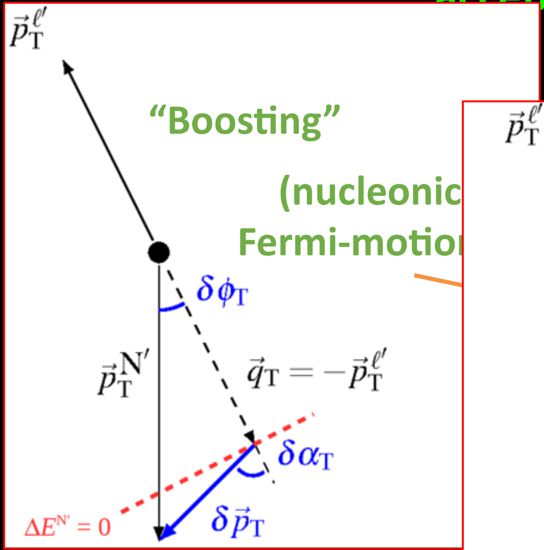
Community efforts:

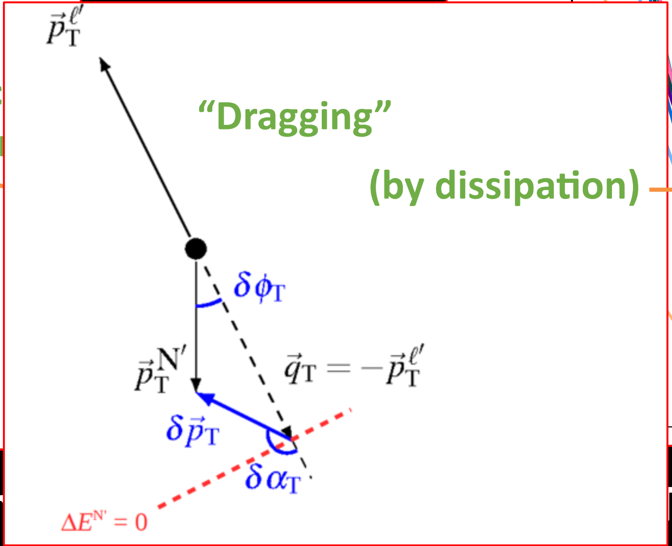
T2K, MINERvA, MicroBooNE, SBND, …

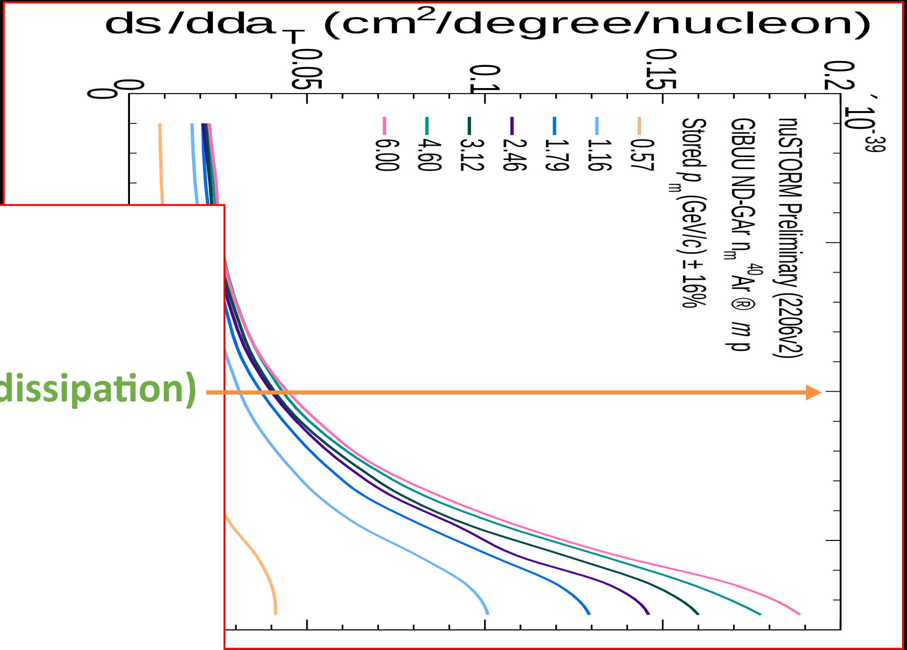
nuSTORM@CERN: E_ν-scan measurements

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

Imperial College London

ISIS

Overview of nuSTORM accelerator design

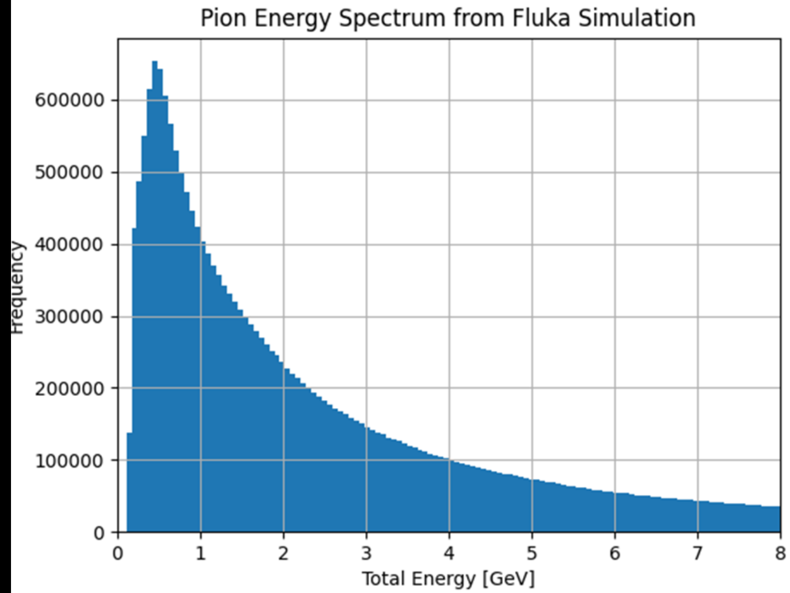
J. Pasternak,
on behalf of nuSTORM study team

22/09/2022, CERN, Geneva

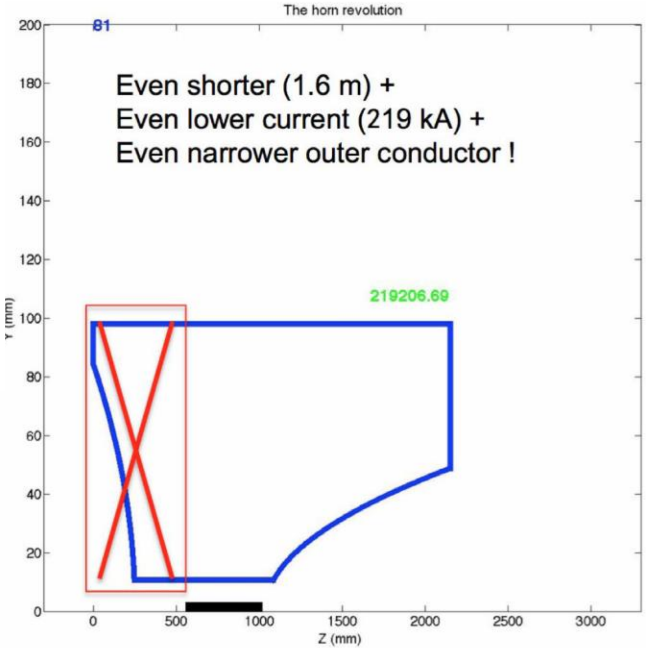
Imperial College London

Science & Technology Facilities Council ISIS

Target and horn simulations



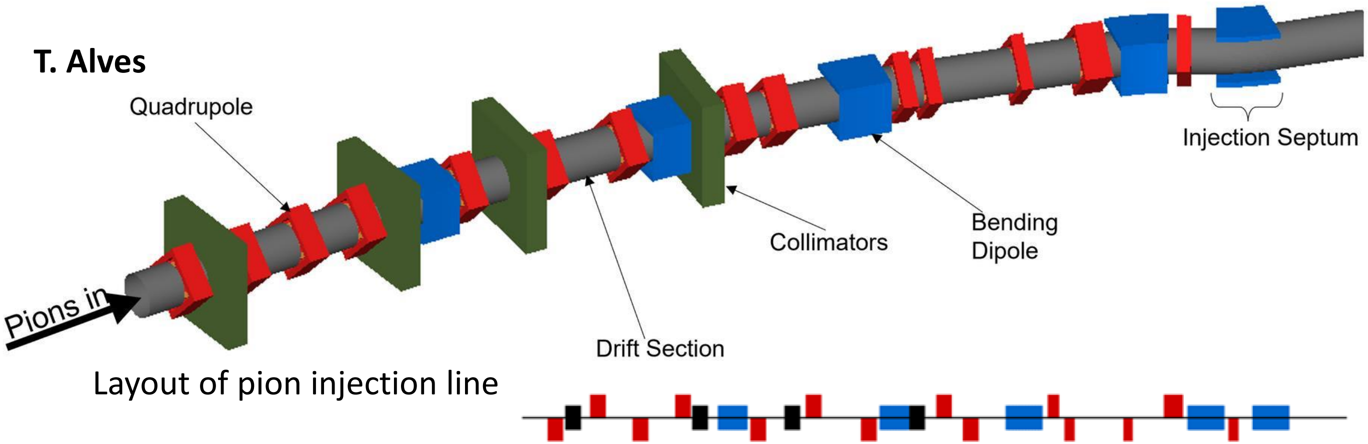
Horn geometry (Tupri005, IPAC'14)



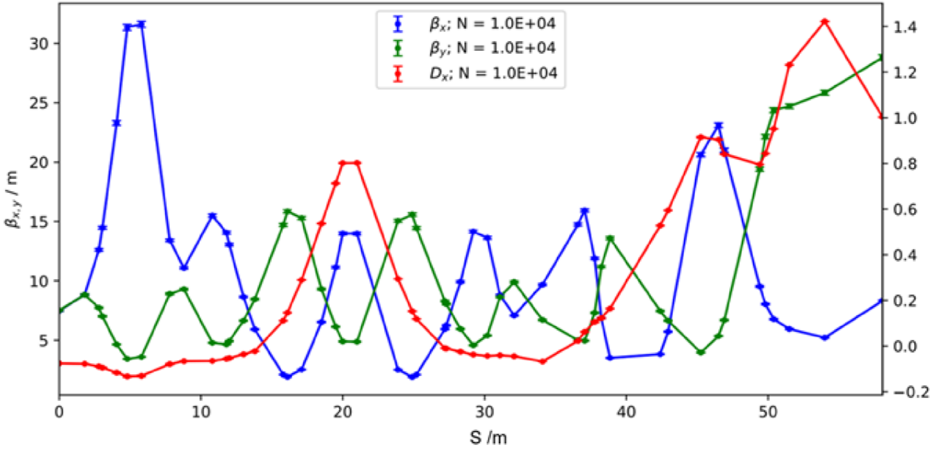
- Target simulated in FLUKA (J. Back)
- Parameters of the target adopted from the FNAL study
    - Inconel target, 46cm in length
- Horn geometry and current adopted from the FNAL study (A. Liu)

Pion beam line simulation in BDSIM

T. Alves



Layout of pion injection line



Betatron functions and dispersion for pion beam from the horn until the injection point in the nuSTORM ring calculated by tracking in BDSIM

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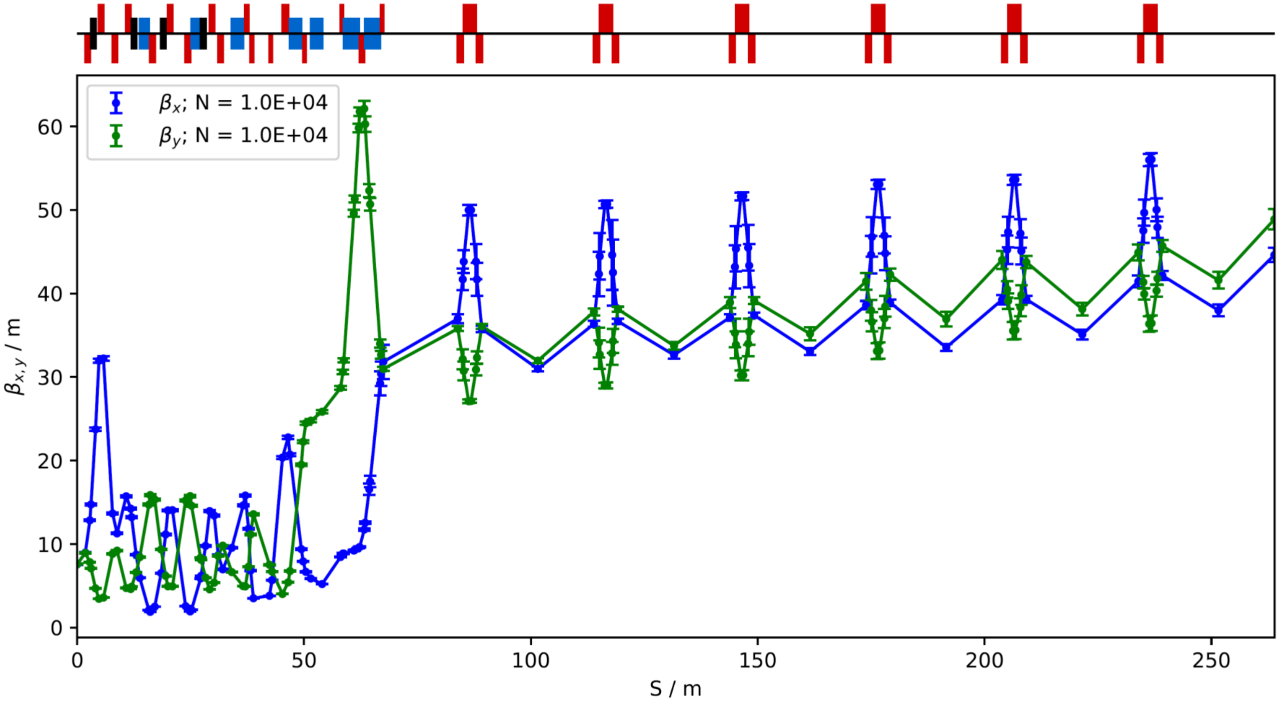
BDSIM study extended till the end of the production straight



Betatron functions of pions from the horn until the end of the production straight in the nuSTORM ring calculated by tracking in BDSIM

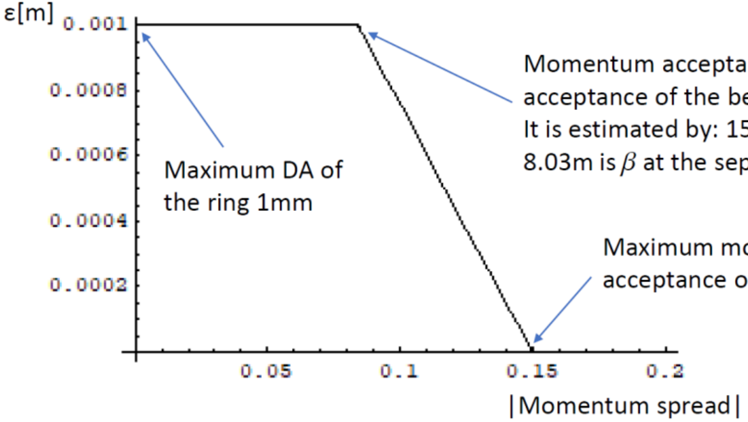
Acceptance cut at the end of the quad straight

- $\frac{x^2}{\beta_x^q} + \beta_x^q (\frac{p_x}{p_z})^2 \leq \varepsilon(|\frac{\Delta p}{p_0}|)$

$\frac{\Delta p}{p_0} = \frac{p - p_0}{p_0}$

p_0=3.8 GeV/c (muon central momentum for 5 GeV/c pions injection)

β_x^q=19.98m (periodic beta of the quad straight)



Maximum DA of the ring 1mm

Momentum acceptance at which septum starts to limit the acceptance of the beam in the ring ~8.41%.
It is estimated by: 15%-Sqrt[0.001*8.03]/1.36,
8.03m is β at the septum, 1.36m is D at the septum

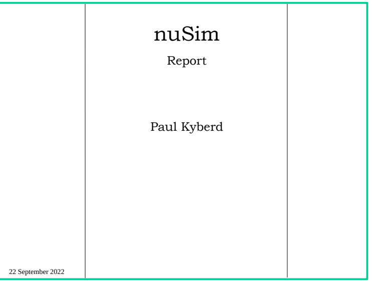
Maximum momentum acceptance of the ring 15% (16% used in the calculations)

PS/SPS feeding comparison

T. Alves

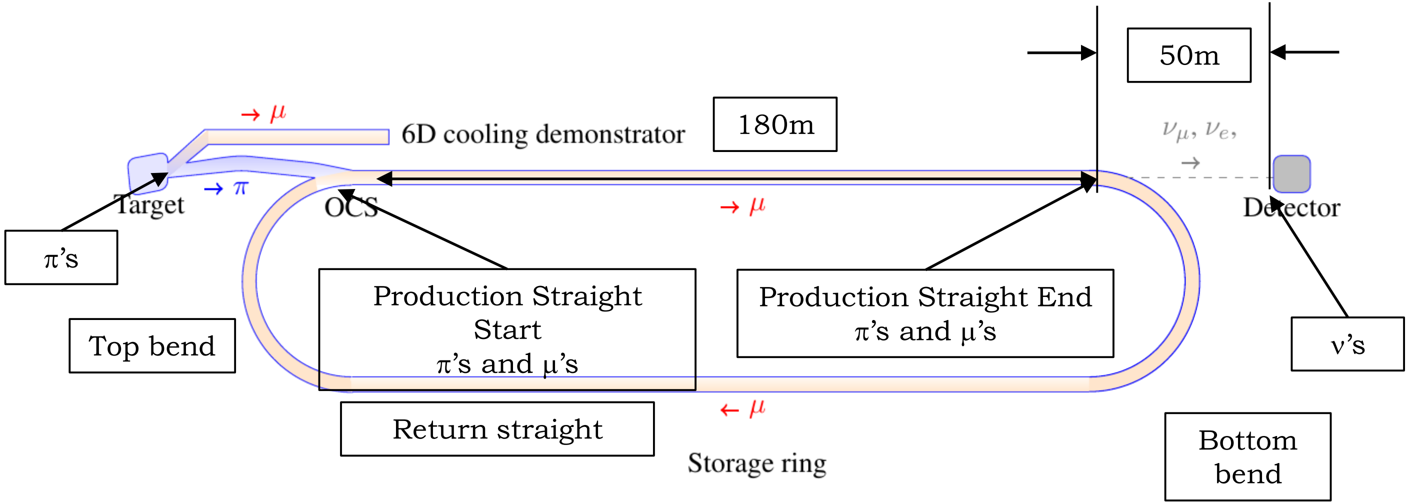
Proton Energy on target	π^+ Central Momentum	μ^+ Central Momentum	Starting π^+	Undecayed π^+ at end of decay straight	Total μ^+ produced	Accepted μ^+
$100GeV$	$5GeV/c$	$3.8GeV/c$	$986,303$	$221,718$	$192,932$	$19,074$
$100GeV$	$7.2GeV/c$	$5.42GeV/c$	$834,311$	$255,522$	$156,019$	$24,694$
$100GeV$	$2.64GeV/c$	$2.0064GeV/c$	$746,499$	$65,540$	$90,593$	$2,187$
$26GeV$	$5GeV/c$	$3.8GeV/c$	$230,775$	$53,484$	$47,438$	$4,650$

- Simulation performed using FLUKA and BDSIM assuming 10^7 POT
- Horn current scaled with momentum
- PS would give 4.14 times less accepted muons for the same POT
    - Initial finding based of 5 GeV/c muon beam storage efficiency suggests that equivalent to SPS scheme PS-based target station would require ~165 kW
        - Looks difficult, but the final word is for the PS experts.
- Low pion momentum setting (2.64 GeV/c) requires further investigation due to high losses in the pion beam line (work in progress)
- Results will be used for the neutrino flux normalisation



nuSIM Planes

Plane contains particle position, momentum, particle type …



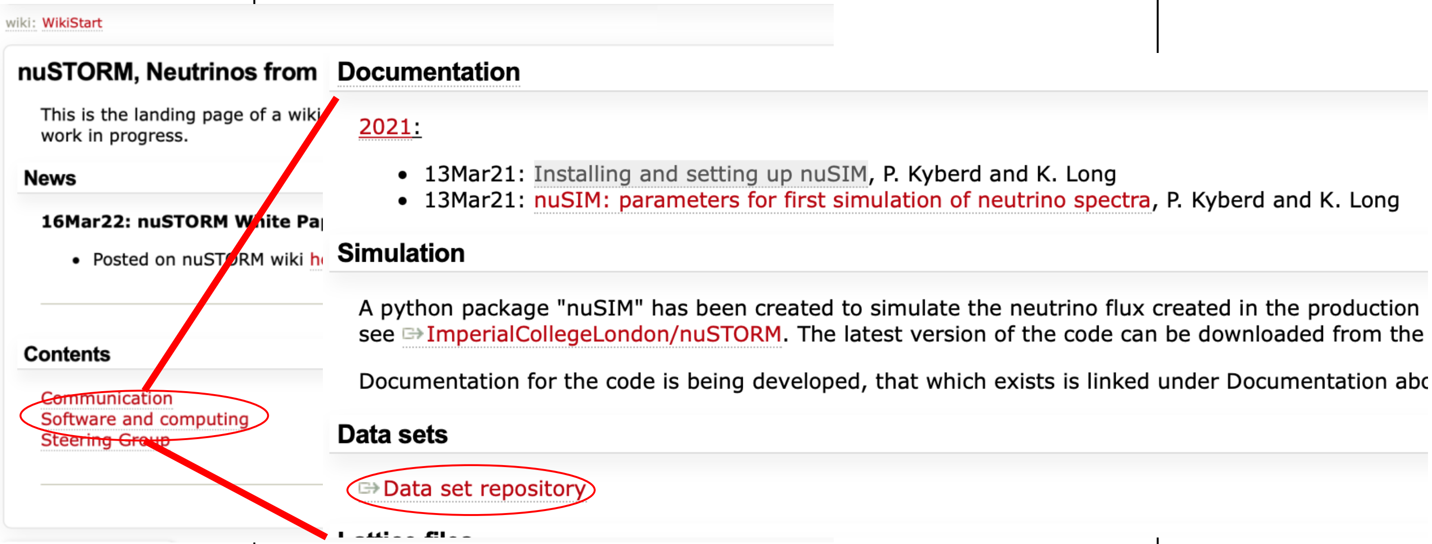
π's decay "plane"

μ's decay "plane"

π's and μ's treated in the same way as the planes with individual values of s – the path length from the pion production

Current status and results (iii)

Data available via the website nustorm.org



- Some simple energy distributions as a root histogram
- Also will post the full information for the neutrinos which cross the detector front face and supply a python and C++ example for reading such files … all available on the website

Conclusions

- nuSTORM physics case continues to be developed:
  - New: simulation now allows physics studies to be made
    - Paul Kyberd and his team offer to create new data sets on request
  - Now beginning: to work to understand detector requirements

- Progress in simulation:
  - Parallel approach to end-to-end simulation
    - Modularised, incremental improvement with best estimate of flux always available
  - nuSIM, provides flux that gives good representation of pion flash and neutrinos from stored muons
    - Normalisation (nu/POT) for all stored-muon energies, needs review of horn
  - BDSIM being used to make develop detailed accelerator design
    - Detailed transfer line studies; working towards complete description of ring

- nuSTORM: a necessary step on the way:
  - Science in the medium term
  - Production test bed for many of the techniques required to produce and handle high flux stored muon beam