Imperial College London

Science & Technology Facilities Council

nuSTORM and the Muon Collider

K. Long, 22 June, 2023

CERN
Horn and bubble chamber
First neutrino beam

IHEP
SKAT, JINR

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

FNAL
MINOS, MINOS+, NOvA

CERN
OPERA, ICARUS

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

BNL
first neutrino "beam"

CERN
Horn #2 & Gargamelle

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

KEK/J-PARC
K2K, T2K

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

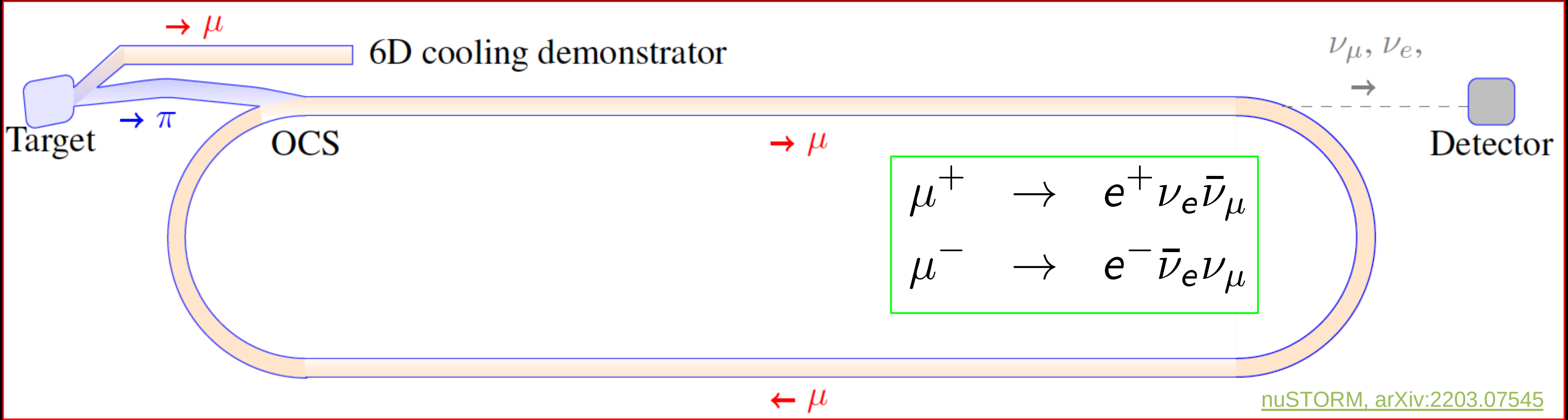
Discovery of CP-invariance violation?

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

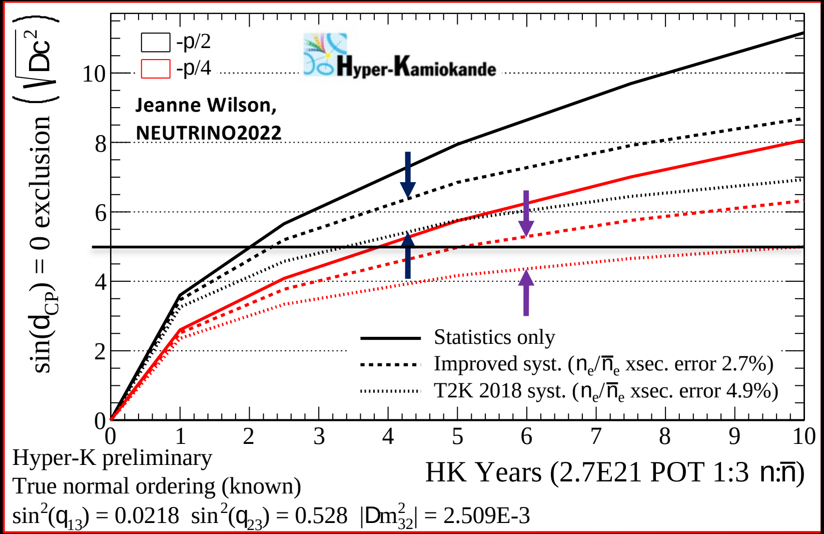


- **Scientific objectives:**
  1. %-level ($\overset{(-)}{\nu}_e N$) cross sections
     - Multi differential / E_ν scan
  2. BSM searches
     - E.g. steriles beyond FNAL SBN
  3. Muon collider demonstrator

- **Precise neutrino flux:**
  - Normalisation: < 1%
  - Energy (and flavour) precise
- **π ®μ 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 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, → 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

Final

Neutrinos from Stored Muons (nuSTORM)

Submitted to the Snowmass 2021 DPF Community Planning Exercise

arXiv:2203.07545

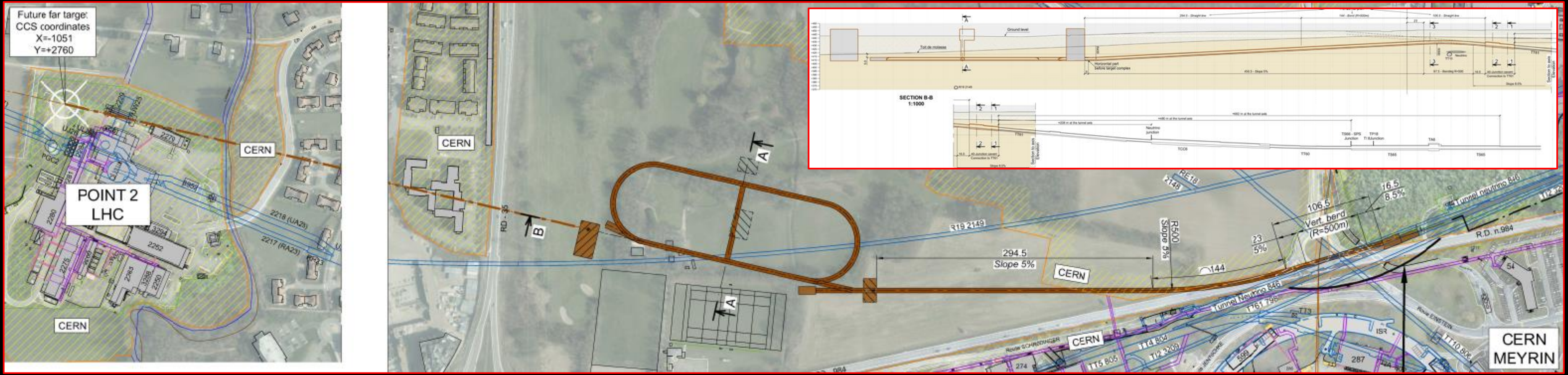
ESPPU 202x

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

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

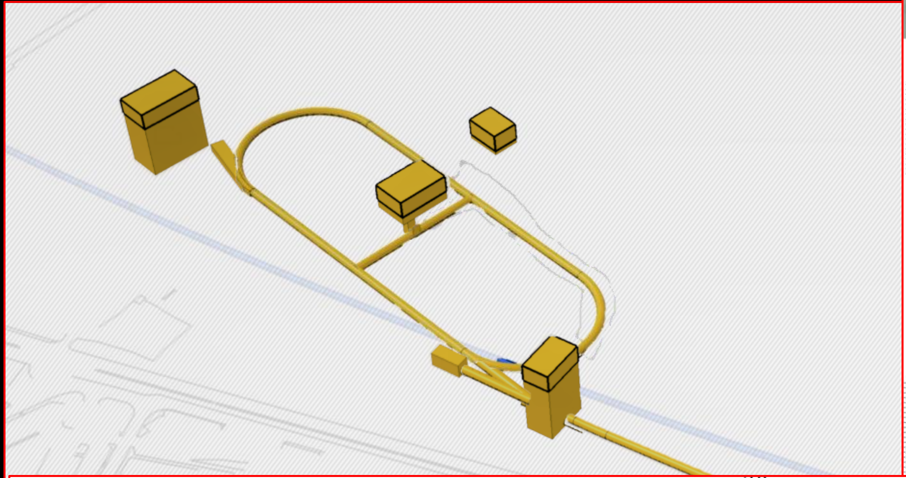
Table 1: Key parameters of the SPS beam required to serve nuSTORM.

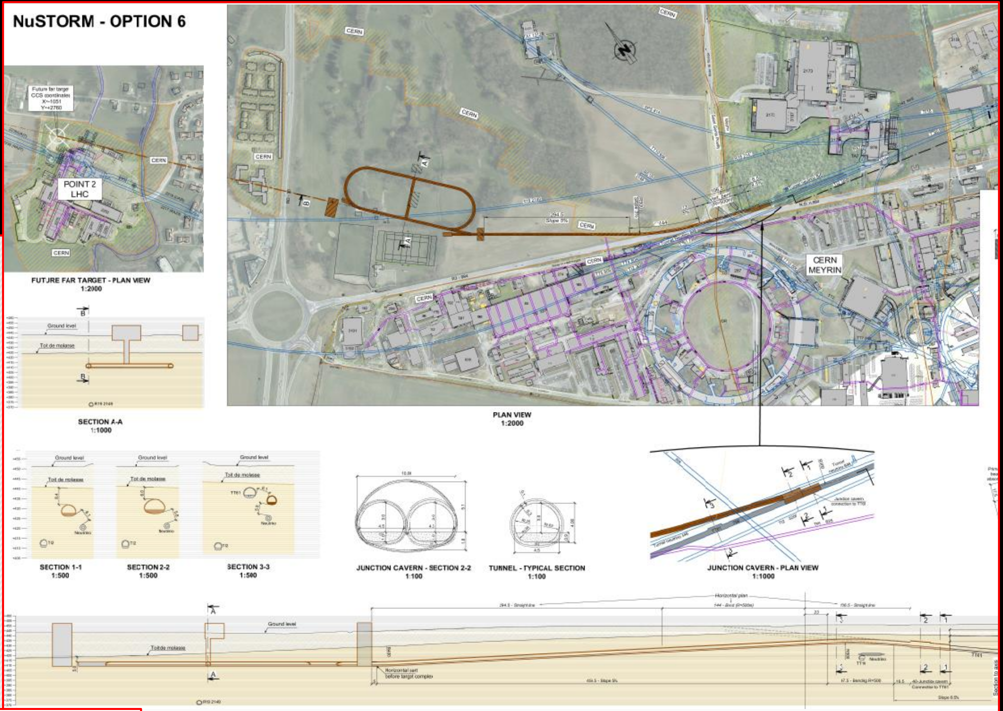
Momentum	100 GeV/c
Beam Intensity per cycle	4 ◊ 10^{13}
Cycle length	3.6 s
Nominal proton beam power	156 kW
Maximum proton beam power	240 kW
Protons on target (PoT)/year	4 ◊ 10^{19}
Total PoT in 5 year's data taking	2 ◊ 10^{20}
Nominal / short cycle time	6/3.6 s
Max. normalised horizontal emittance (1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

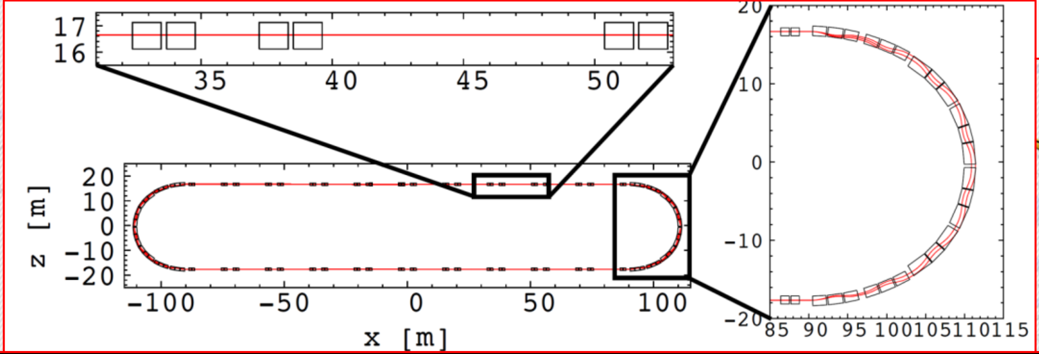
Accelerator

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





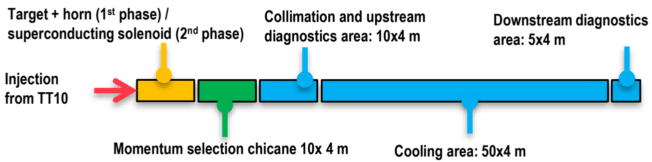
Jonathan Gall



Ximines et al

Conceptual layout

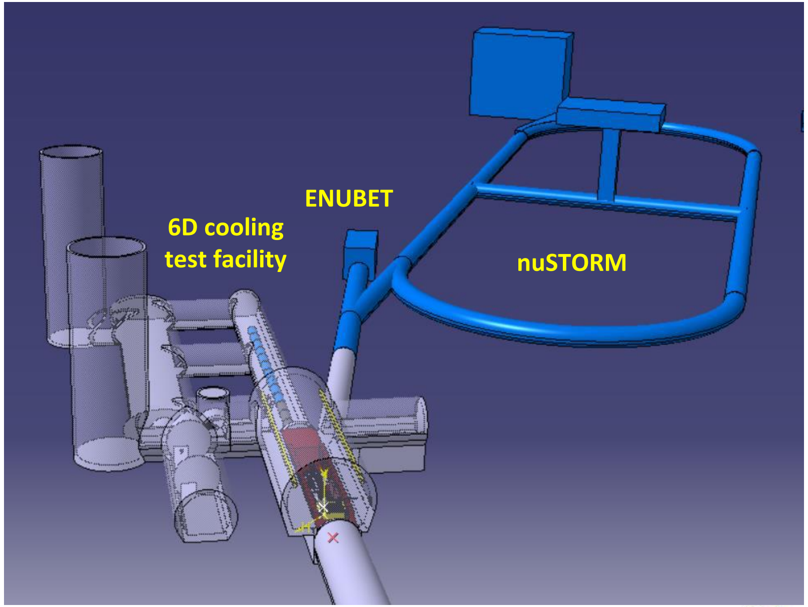
Under discussion!



MUC Demonstrator

- 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?

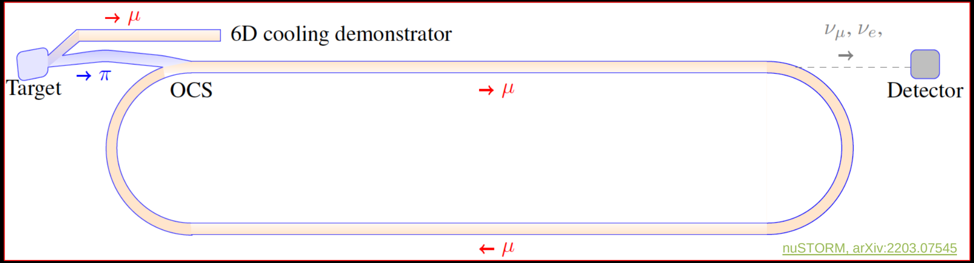
Under study



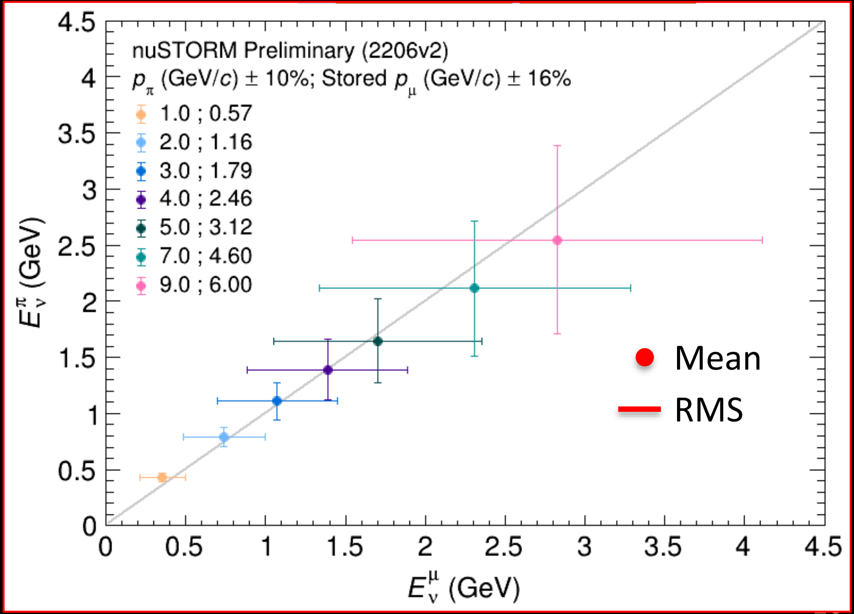
End-to-end simulation for (re)optimisation

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"

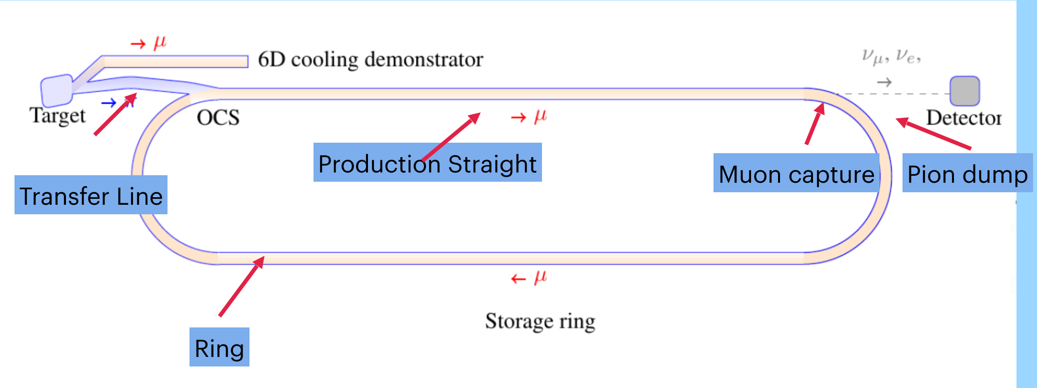


T. Alves, M. Pfaff



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

nuSTORM simulation



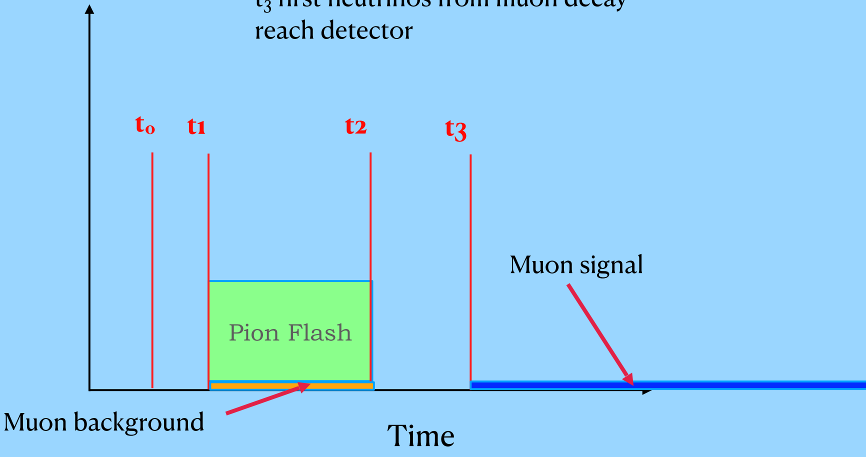
Only particles which decay in the production straight give a significant signal in the detector.

t_0, first pions leave the target.

t_1 first neutrinos from pion decay reach detector

t_2 last neutrinos from pion decay reach detector

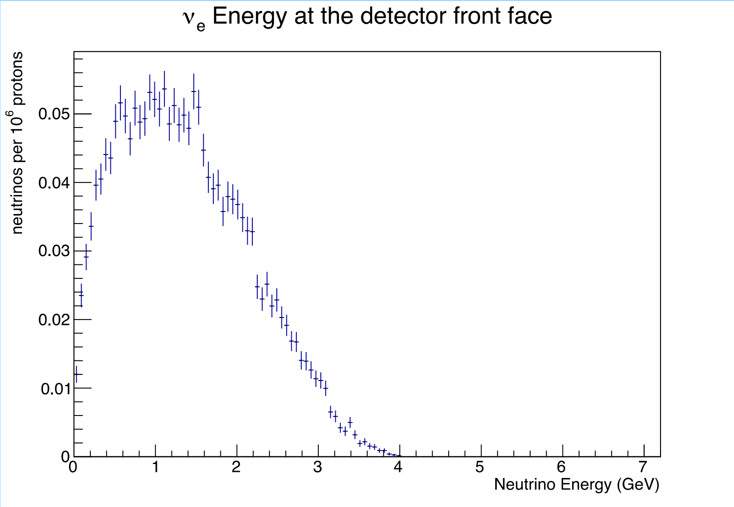
t_3 first neutrinos from muon decay reach detector

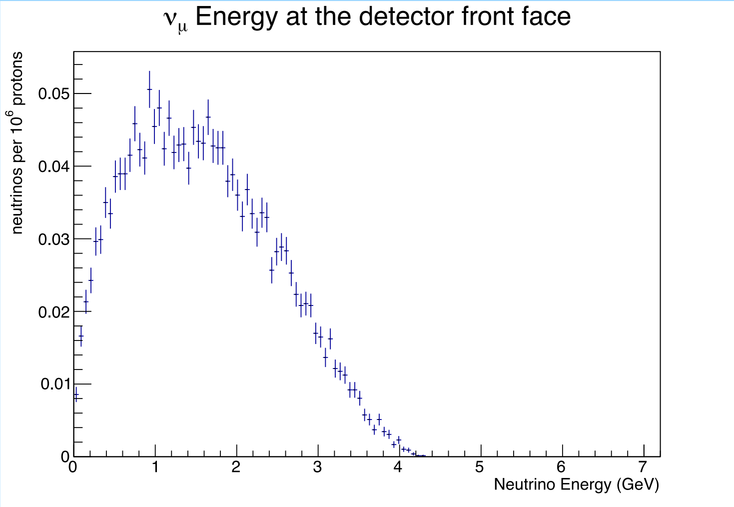


- Pion Flash … υ_μ produced by the pions in the production straight
- Muon background … υ_μ and υ_e produced by muons which decay before they are captured. Background to flash signal
- Muon Signal … υ_μ and υ_e produced by muons captured in the ring.

nuSIM Results

Finally a plot of the neutrino energy spectrum for those neutrinos which pass through the detector is stored in a separate file.

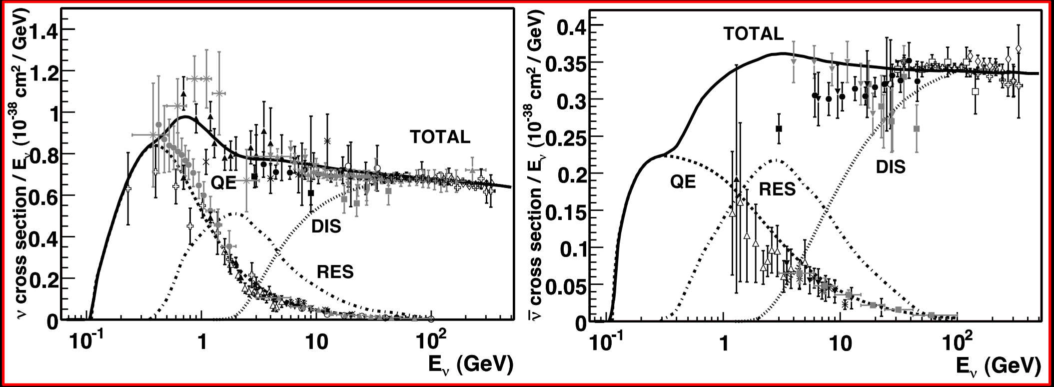


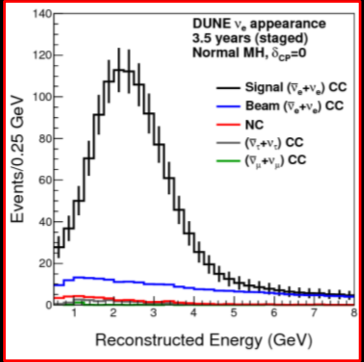


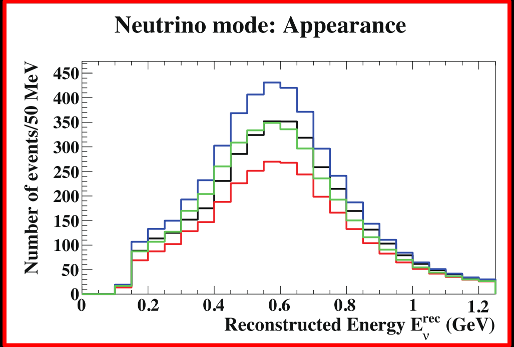
Normalised to protons on target.
Errors are statistical from the simulation.
Working to produce higher statistics runs

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
      - Reconstructing Q^2 and W
    - → $E_\mu < 6$ GeV
- So, stored muon tunable in energy range:



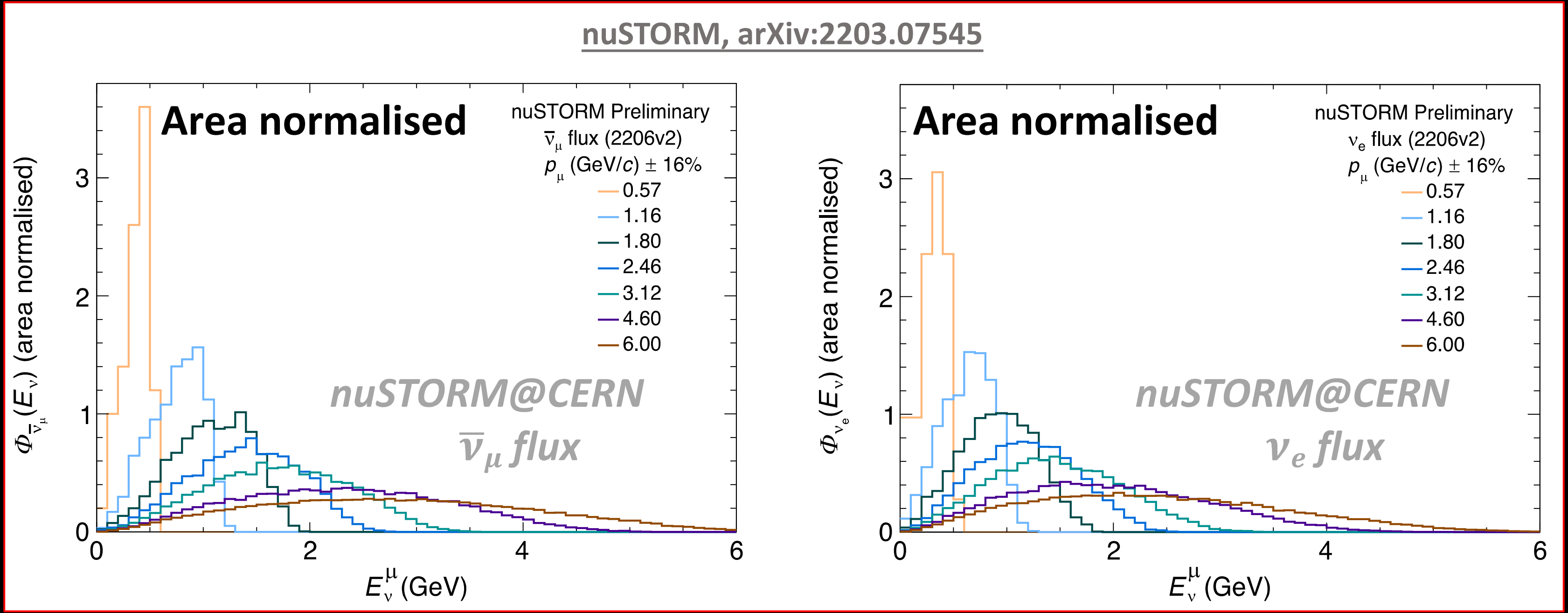




$$1 \leq E_\mu \leq 6 \text{ GeV}$$

T. Alves, M. Pfaff

nuSTORM@CERN: flux estimation

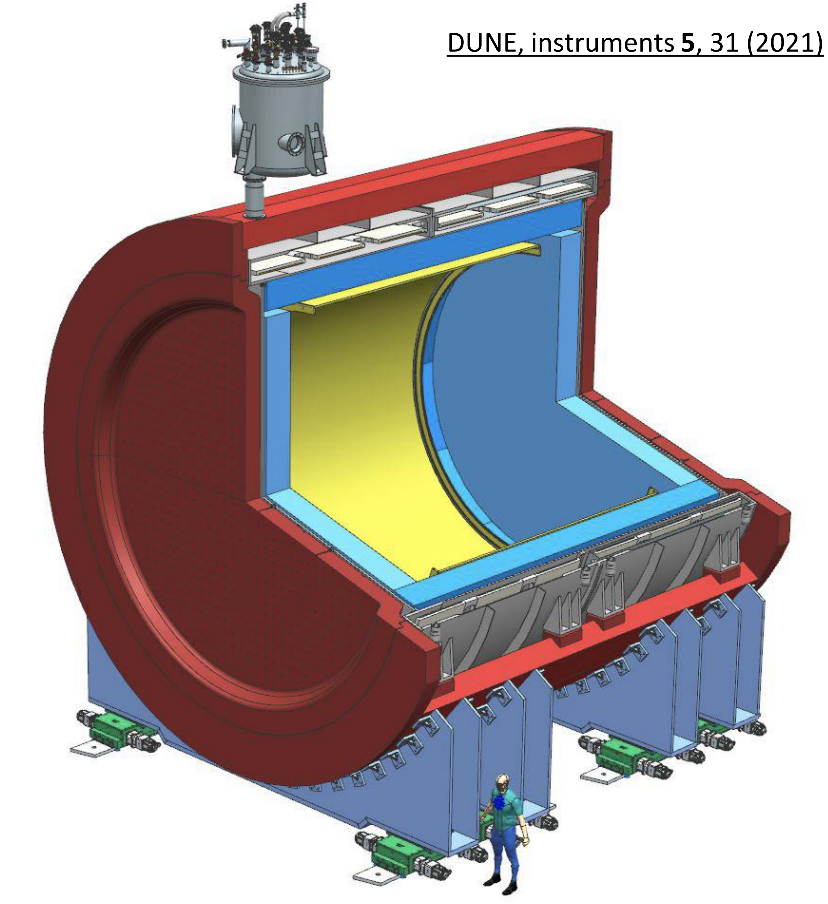


- **Oscillation-relevant energy regime**
  - Hyper-K: 0.6 GeV
  - DUNE.   : 2.4 GeV
- **Set by stored-muon momentum**

- **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

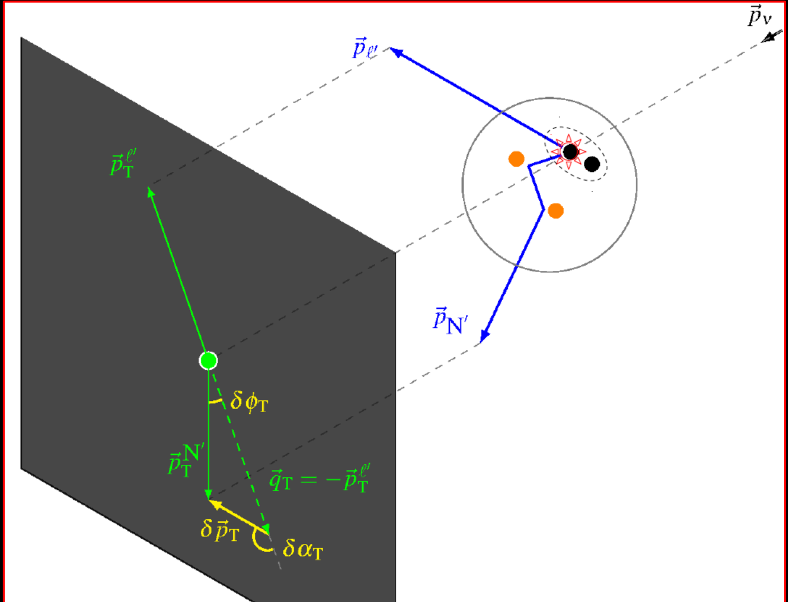
- nuSIM ready to allow performance evaluation:
  - Require “highly capable” detector:
    - Scattered lepton
    - Inclusive and exclusive final states
- Initial study use DUNE ND-GAr:
  - TPC reference design
    - 10-bar argon-based gas TPC
    - Large gas volume
    - Surrounded by calorimeter
  -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



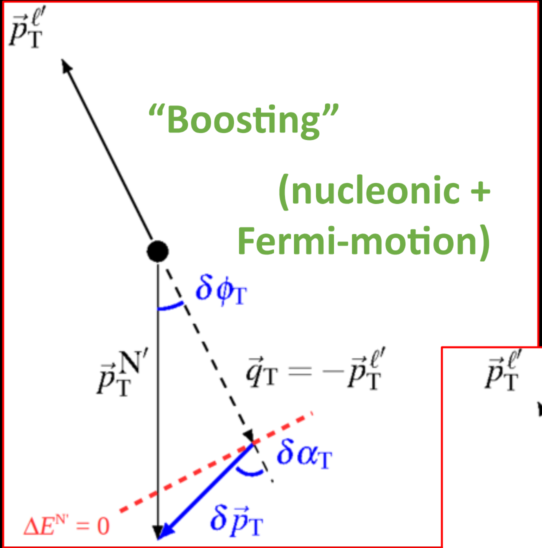
DUNE, instruments **5**, 31 (2021)

nuSTORM@CERN: E_ν-scan measurements

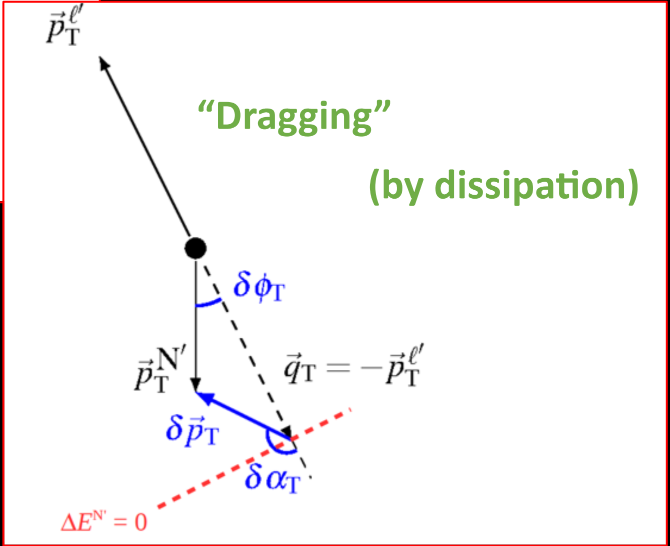
X. Lu



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



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

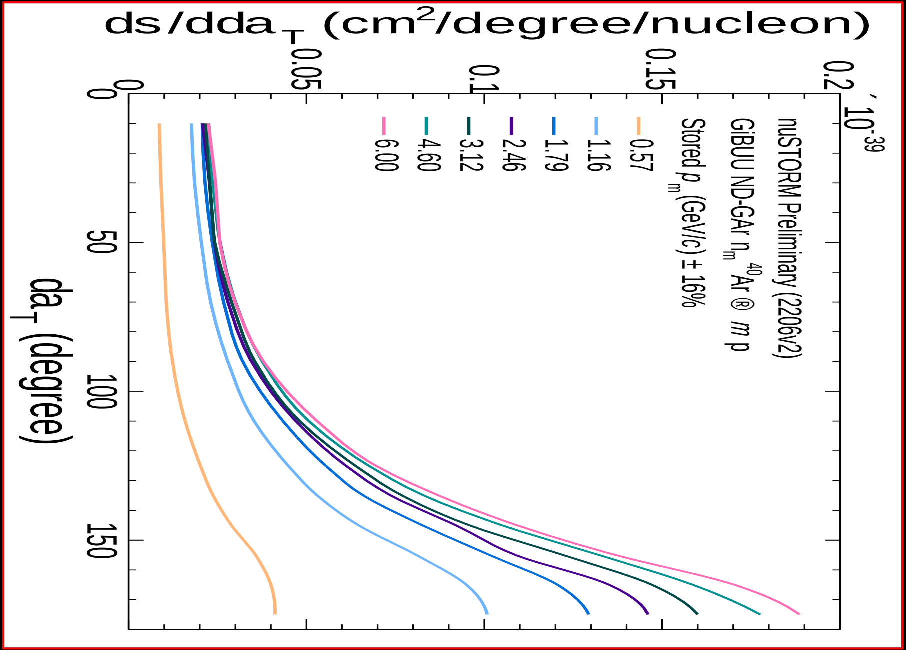


- Low $\delta\alpha_T$: impact of nuclear effects low:
  - "Nuclear model calibration"
- High $\delta\alpha_T$: energy-dependent nuclear effects:
  - Constrain nuclear models of, e.g. 2p2h, pion absorption, …

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

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

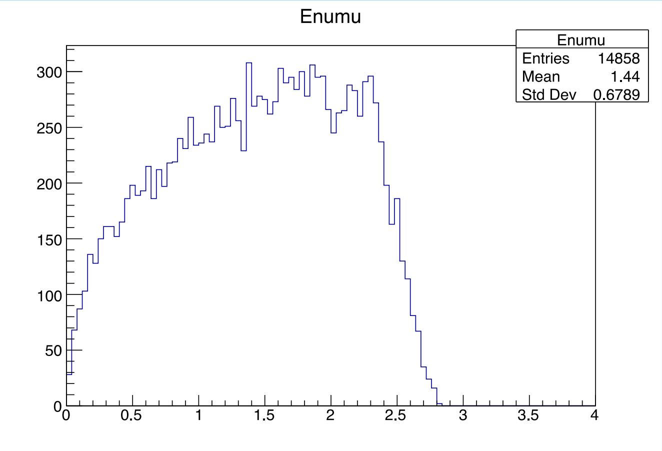
Recordings: part 1 MhE^W=!6, part 2 S33$$fP5 (auto-delete in 15 days, i.e. on ~ 21 April)

Studies with the nuSIM simulations

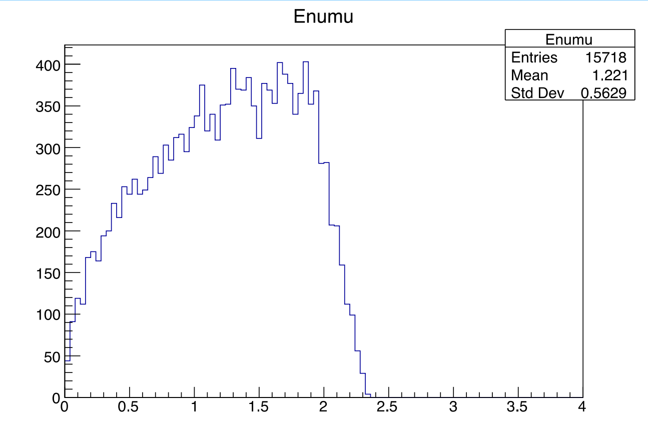
Is the PRISM technique (DUNE) applicable to nuSTORM.?

In particular can we create a synthetic beam with a narrower effective energy range.

The DUNE-PRISM Near Detector. Cai et. al. *"Specifically, the relationship between the energy of the decay parent particle and the final state neutrino energy changes as a function of observation angle away from the parent boost direction; this can be seen in Figure 1a. The NOvA and T2K long-baseline oscillation experiments already use this feature—often called 'the off axis effect'—to achieve a more narrowly peaked neutrino energy spectrum than can be achieved by a purely on-axis experiment."*



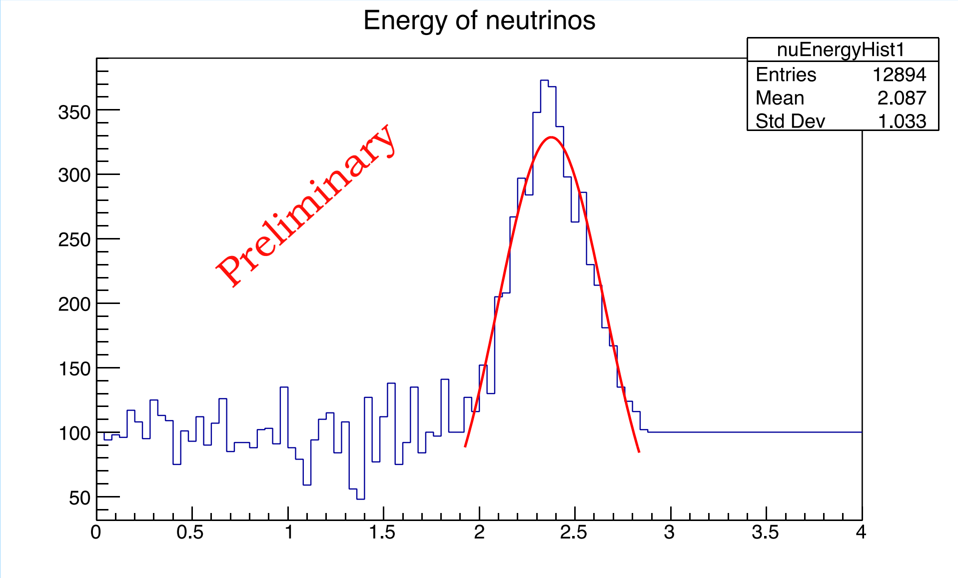
6 GeV pions



5 GeV pions

Pion Flash Spectra

Synthetic Beam



Pion flash neutrinos - bin by bin subtraction with the 5 GeV spectra normalised by the ratio of the number of entries - and by the ratio of the spectrum end points. Offset of 100 so negative values visible

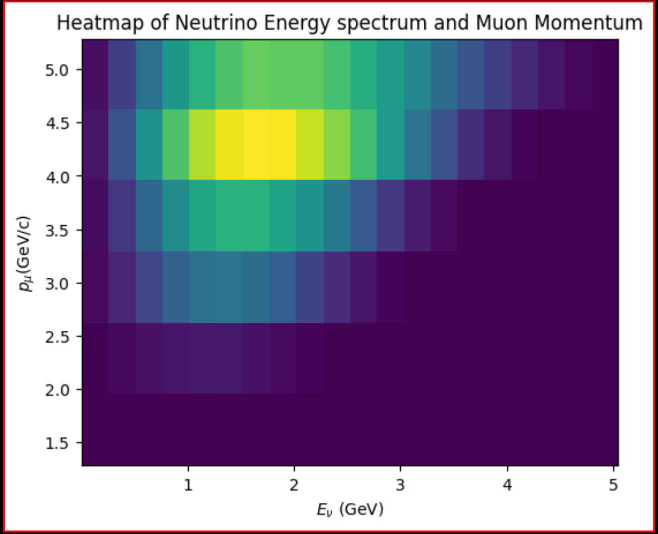
A Gaussian fit to estimate the peak and width
2.38 +/- 0.28

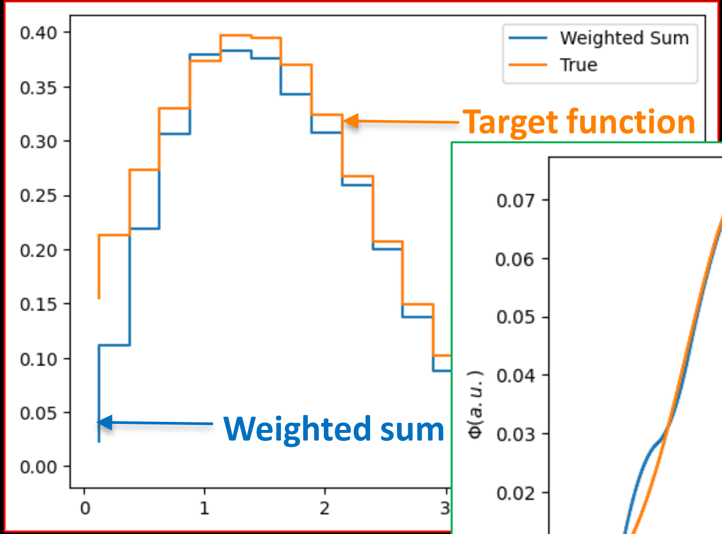
Only two datasets are required

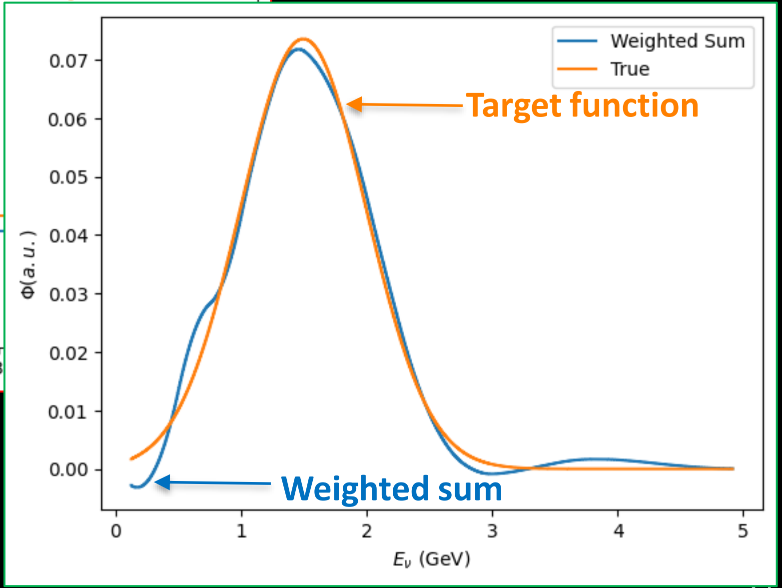
R. Kamath

nuSTORM-PRISM

- Just starting, so indicative study:
  - Take 6 data sets that are available





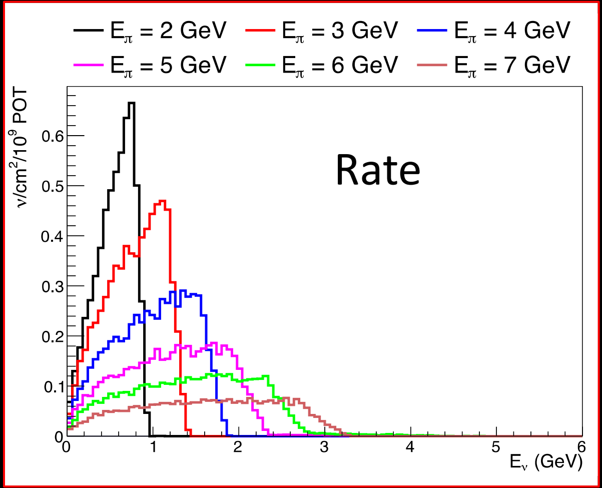


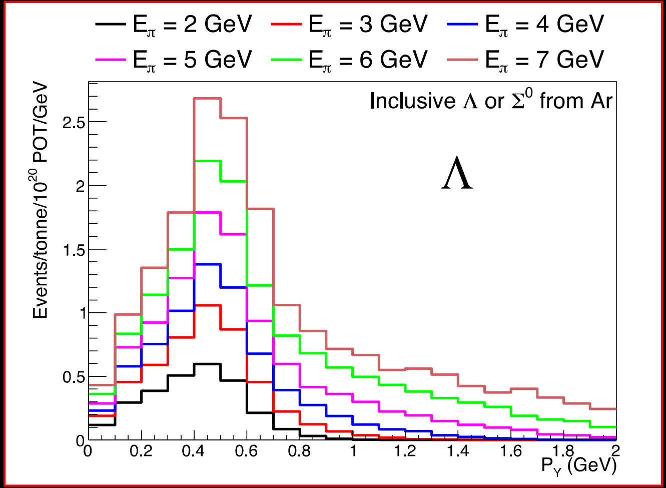
60 stored muon energies:
Created using (spline) interpolation for now

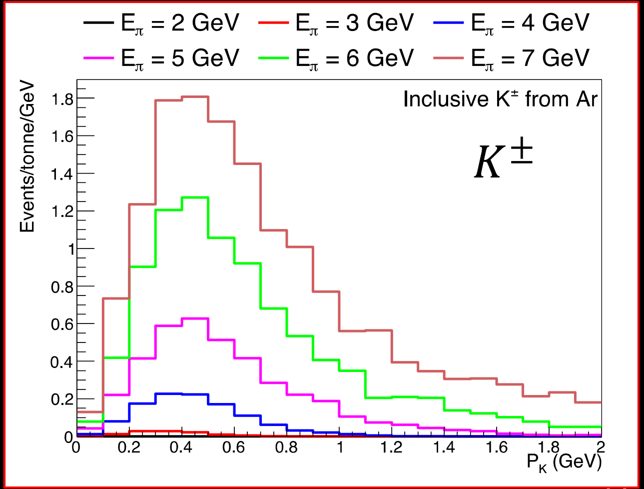
C. Thorpe

Case study: strangeness production

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

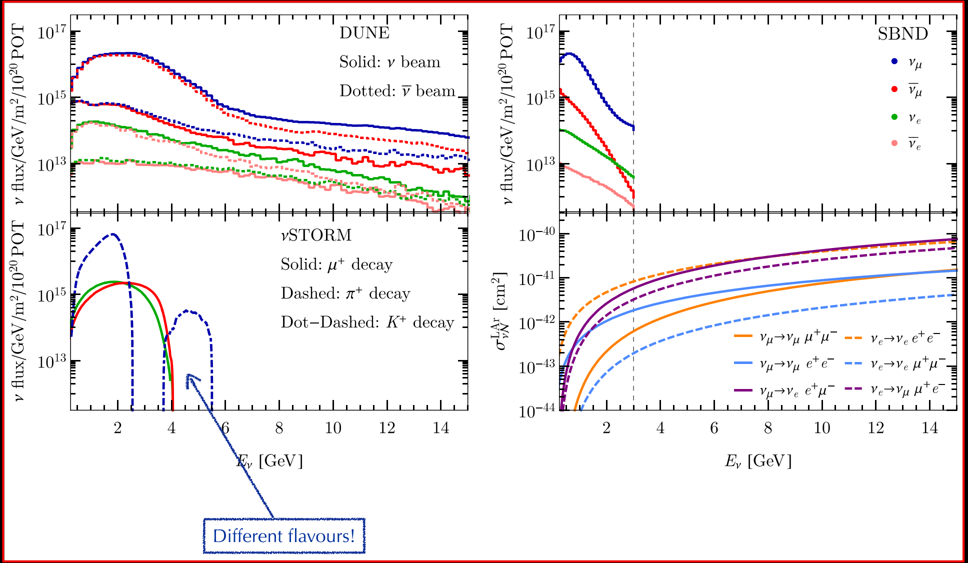


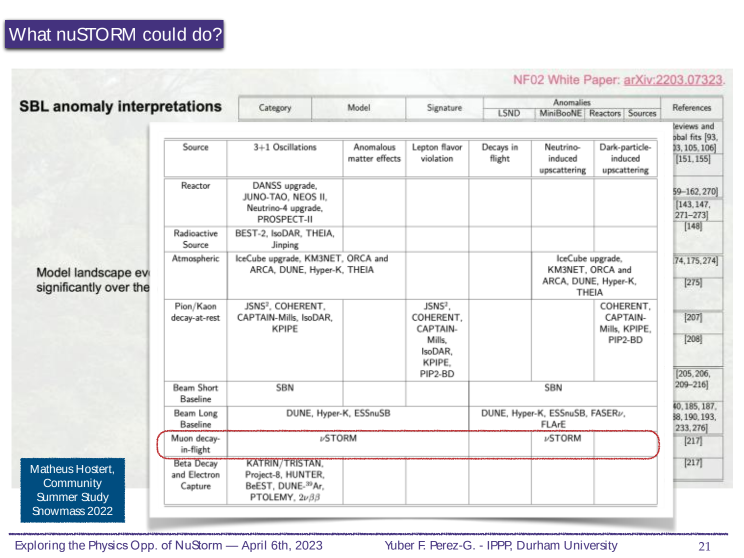




Y.F. Perez-Gonzalez

BSM opportunities ("beyond steriles")





- ✤ Unique combination of flavours should help in constraining the $g_A^{\nu e}$, $g_V^{\nu e}$ SM couplings

- ✤ There is a vast landscape of BSM models trying to explain different phenomena, like the short baseline anomalies.

- ✤ Large flux, low backgrounds and low systematics make nuSTORM the best place to constrain many possible BSM models.

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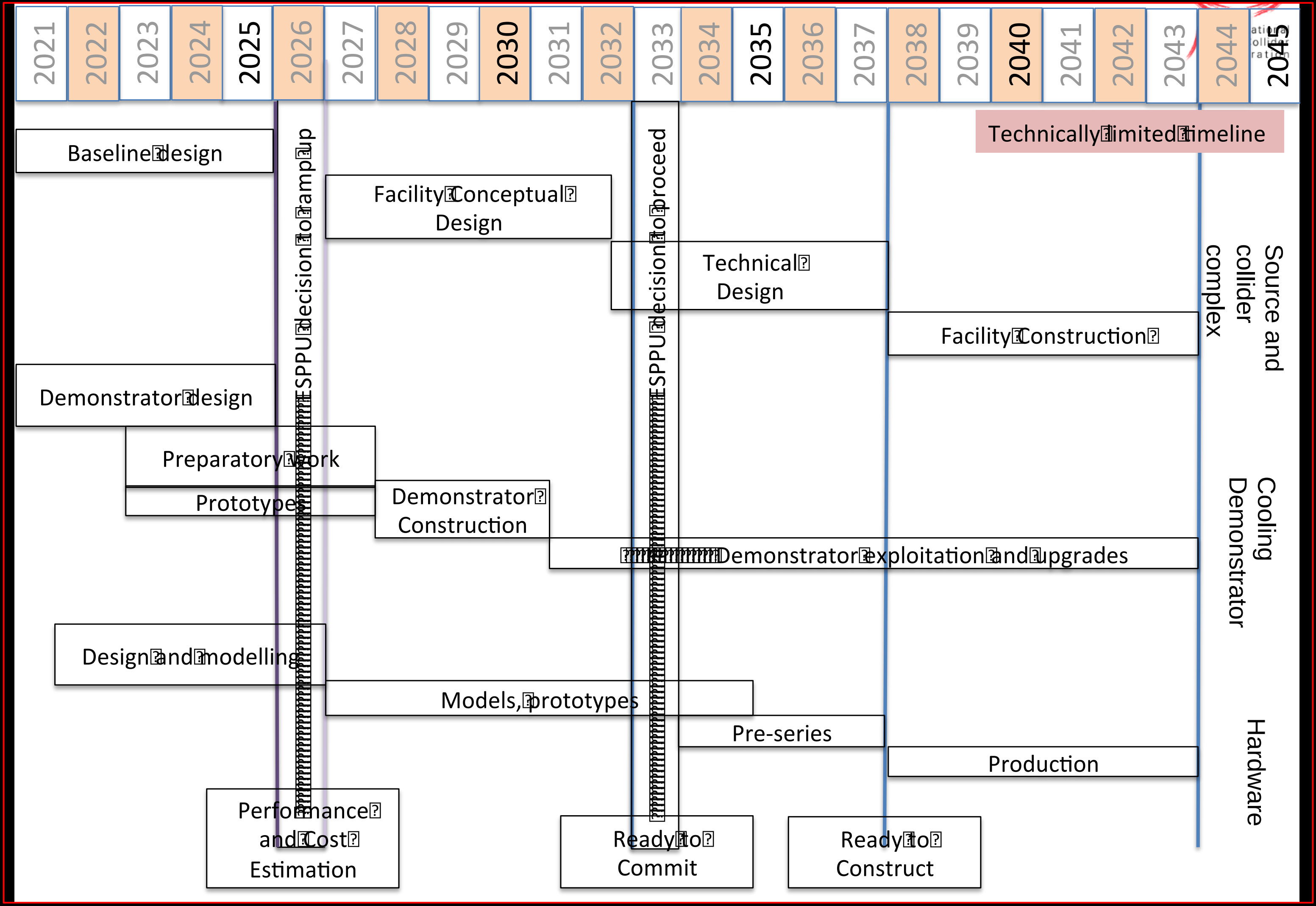
Recordings: part 1 MhE^W=!6, part 2 S33$$fP5 (auto-delete in 15 days, i.e. on ~ 21 April)

- ✓ 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



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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

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ISIS

Overview of nuSTORM accelerator design

J. Pasternak,
on behalf of nuSTORM study team

22/09/2022, CERN, Geneva

Recruitment:
P. Jurj (ex MICE)
Hope in post "next week"

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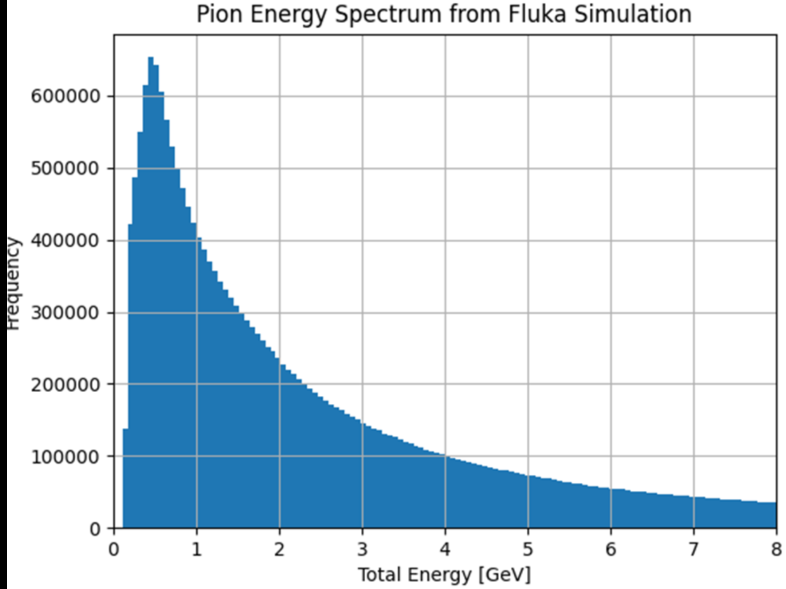
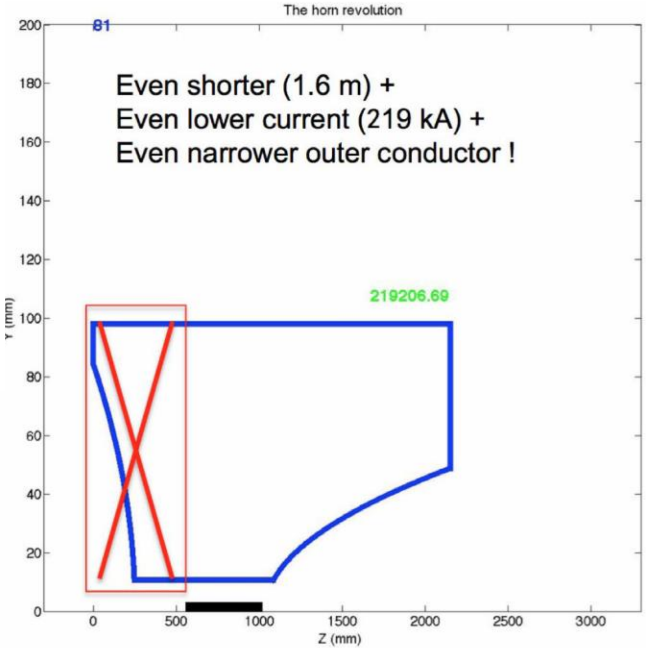
Science & Technology Facilities Council ISIS

Target and horn simulations



- 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)

Horn geometry (Tupri005, IPAC'14)



Pion beam line simulation in BDSIM

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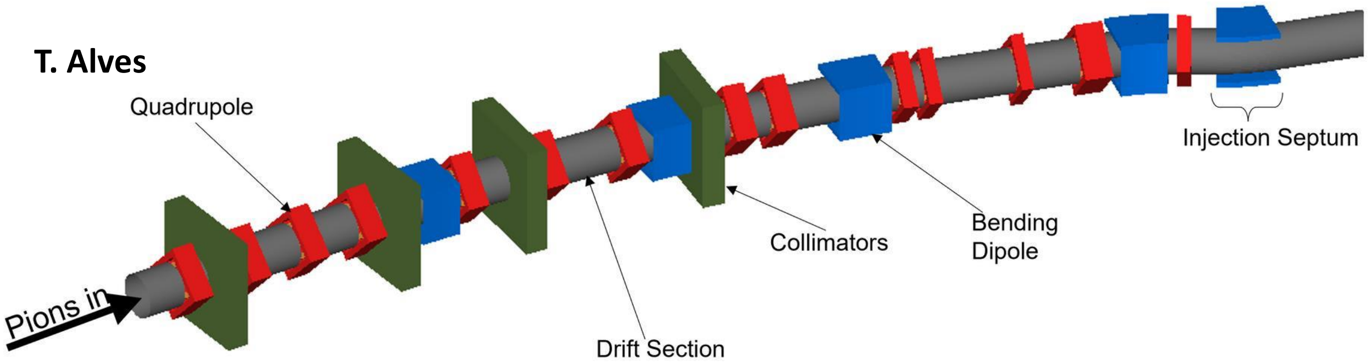
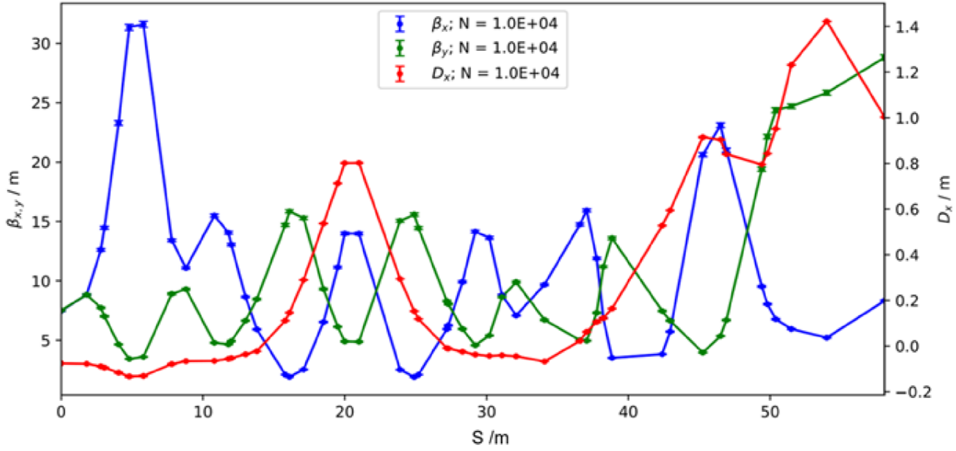
T. Alves



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

P. Jurj,
R. Kamath

Demonstrator development

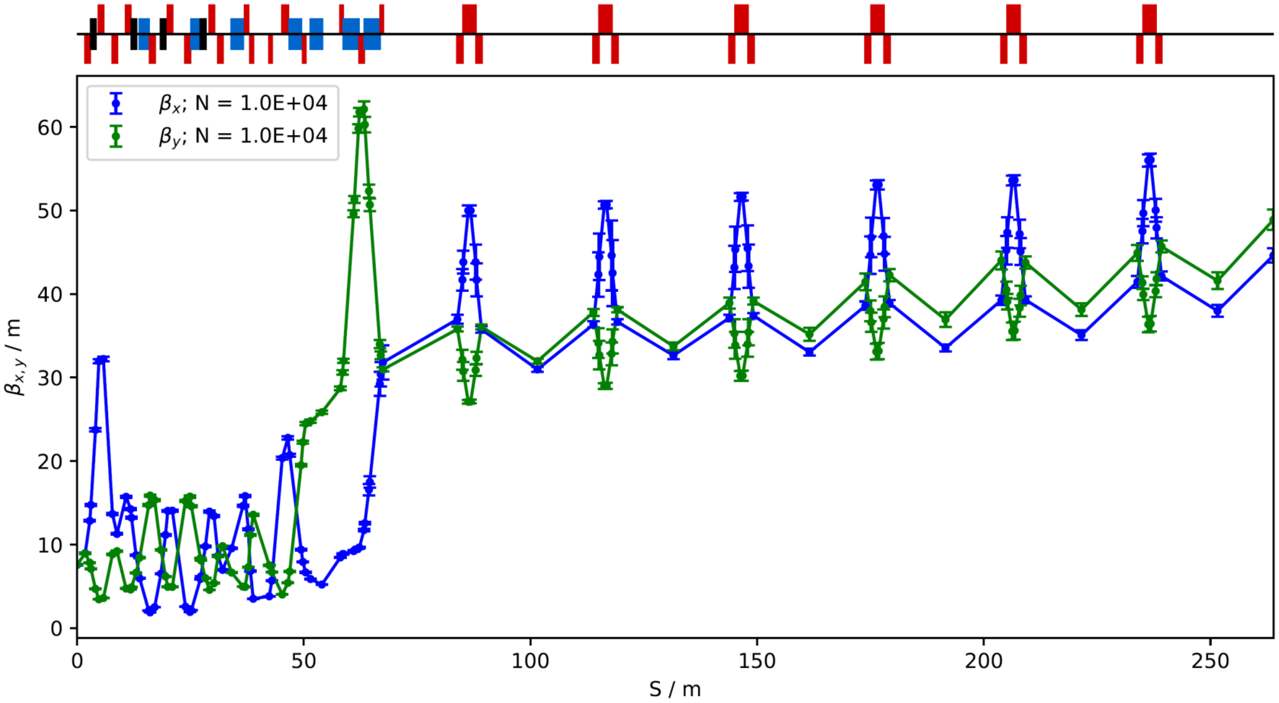
Imperial College London

T. Alves

BDSIM study extended till the end of the production straight

Science & Technology Facilities Council ISIS

P. Jurj,
R. Kamath
Demonstrator development



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

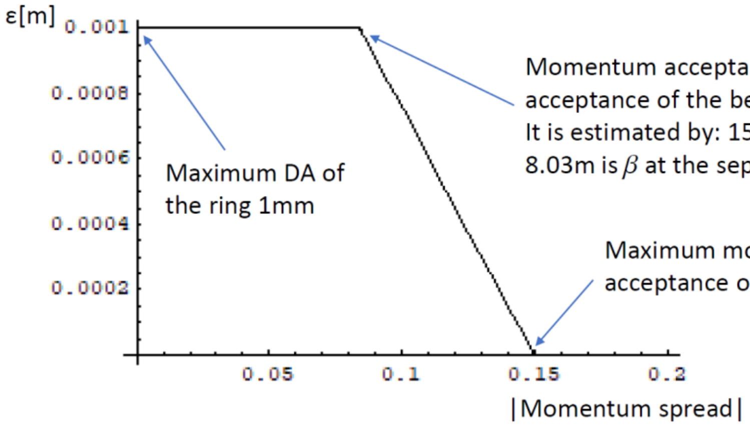
Acceptance cut at the end of the quad straight

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

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

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)



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)

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PS/SPS feeding comparison

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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

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

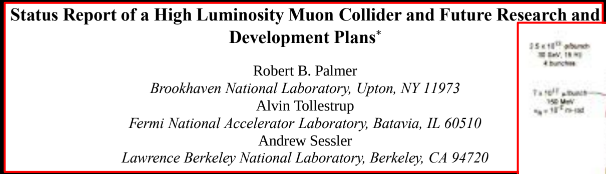
- Feasibility of executing nuSTORM at CERN:
  - Established through Physics Beyond Colliders study

- 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

Historical interlude

- 20th century:
  - ‘70s Budker, Skrinskii
  - ‘90s Palmer, Tollestrup, Sessler:
    - MCC, MCNFC, NFMCC
  - ‘99 Autin, Blondel, Ellis
    - …
- 21st century:
  - CERN MC/NF study
  - BENE, EUROnu
  - NFMCC → MAP
  - MICE
  - P5 (2013) …


Status Report of a High Luminosity Muon Collider and Future Research and Development Plans*

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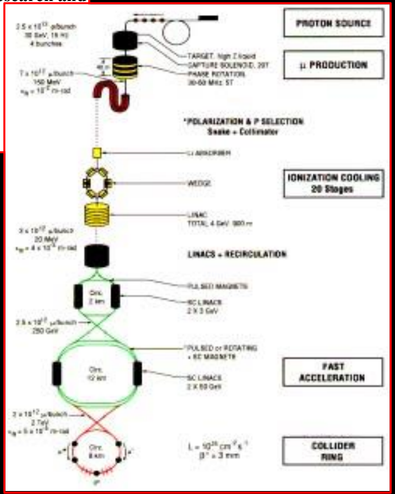
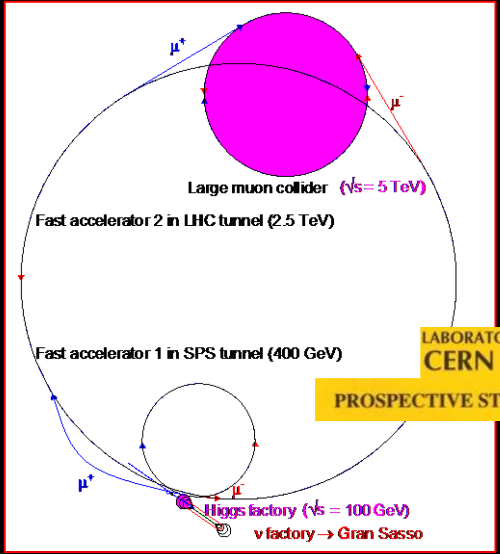
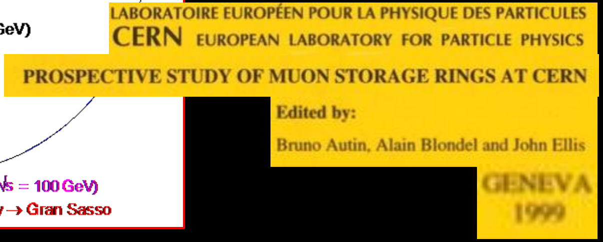
Snowmass ‘96



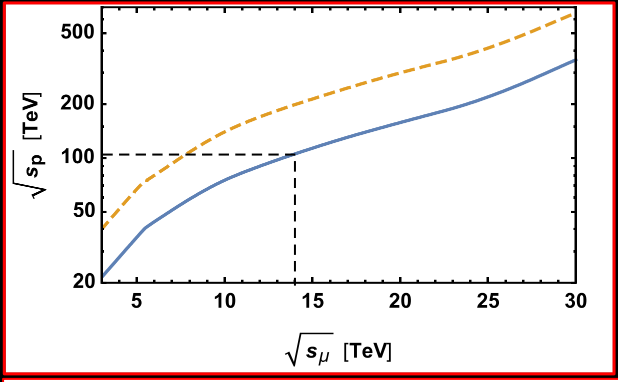


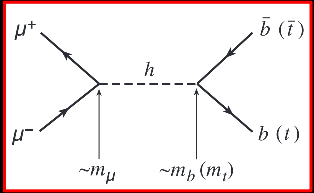

LABORATOIRE EUROPÉEN POUR LA PHYSIQUE DES PARTICULES
CERN EUROPEAN LABORATORY FOR PARTICLE PHYSICS

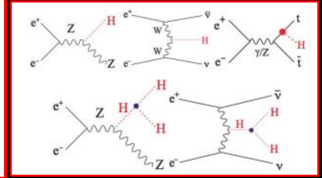
PROSPECTIVE STUDY OF MUON STORAGE RINGS AT CERN

Edited by:
Bruno Autin, Alain Blondel and John Ellis

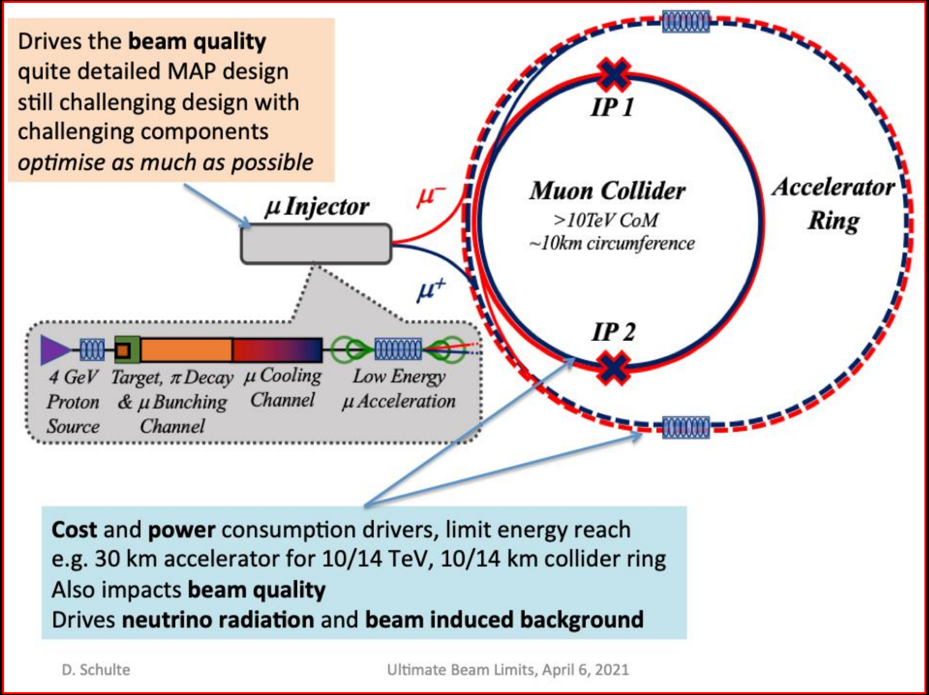
GENEVA
1999

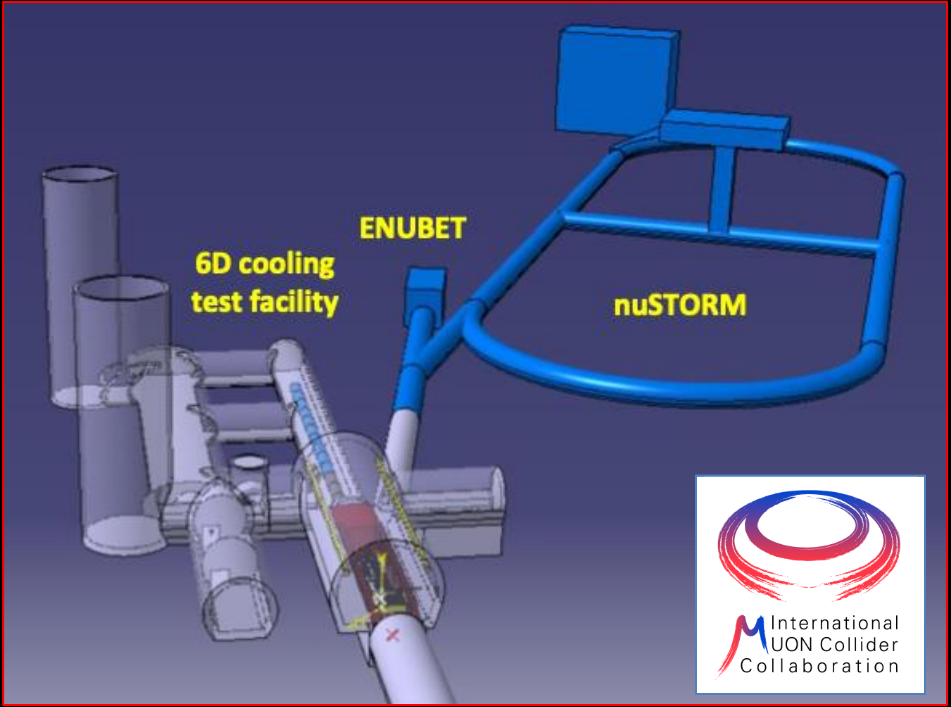






- Science case remains fantastic
- Technological R&D still ground-breaking
- ***Risks*** to programme ***remain too***
- Demonstrator is critical to the programme:
  - 6D cooling ***and*** world-leading particle physics





Thank you