Imperial College London

Science & Technology Facilities Council

νSTORM

K. Long; 19 October 2018

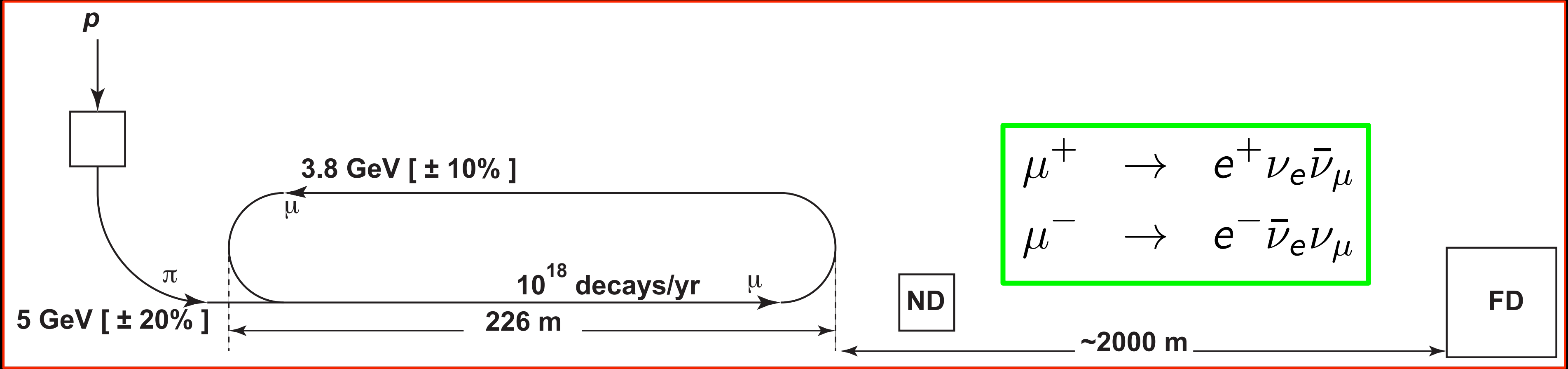
Contents

- What is nuSTORM?
- Why study neutrino interactions?
- nuSTORM for neutrino scattering
- nuSTORM & CERN Physics Beyond Colliders study
- The benefit of nuSTORM
- Conclusions

nuSTORM

What is nuSTORM?

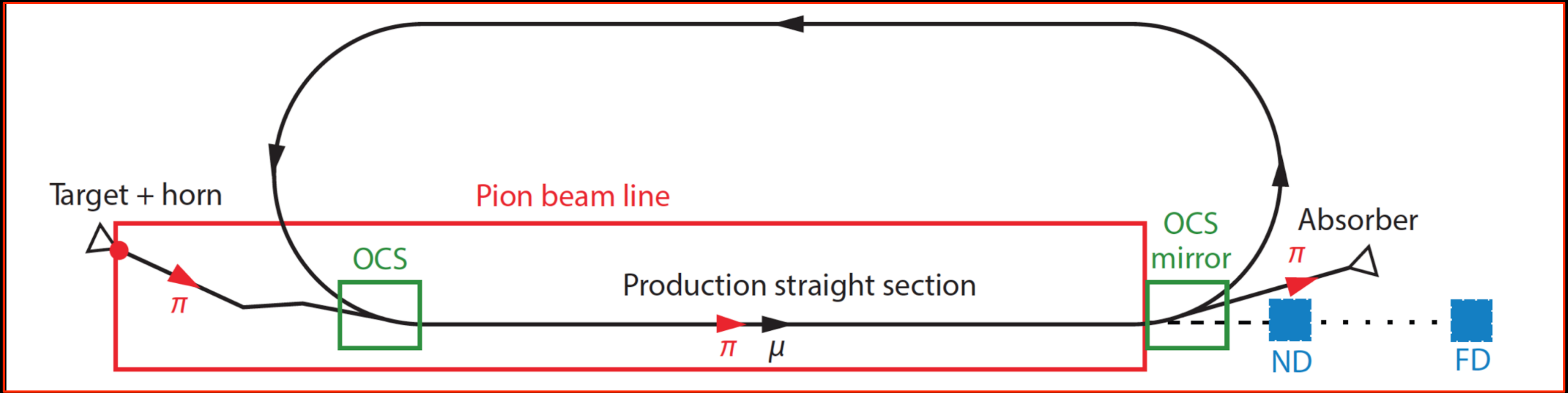
Neutrinos from stored muons



- **Scientific objectives:**
  1. **%-level ($\nu_e N$) cross sections**
     - **Double differential**
  2. **Sterile neutrino search**
     - **Beyond Fermilab SBN**

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

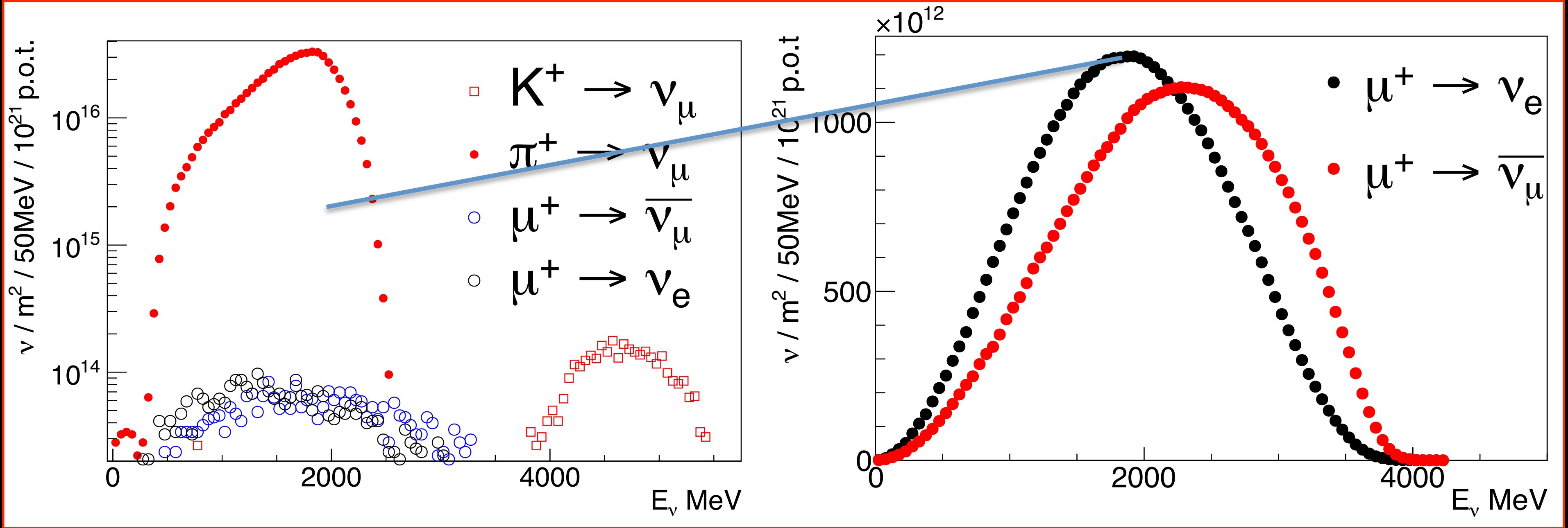
nuSTORM overview



- **Fast extraction at >~ 100 GeV**
- **Conventional pion production and capture (horn)**
  - **Quadrupole pion-transport channel to decay ring**

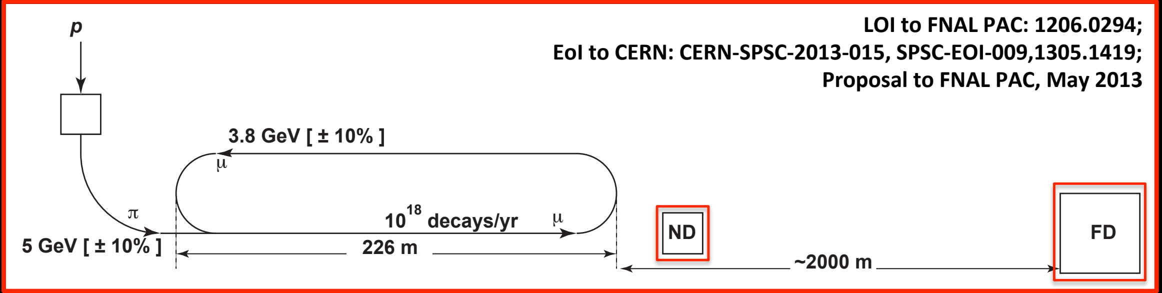
10.1146/annurev-nucl-102014-021930

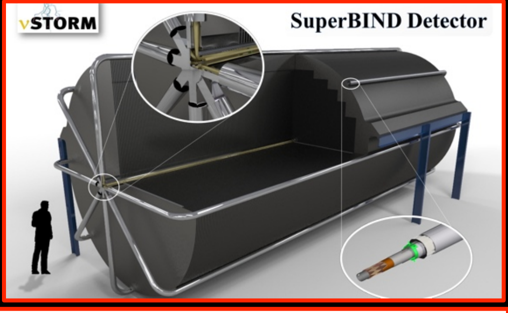
Neutrino flux

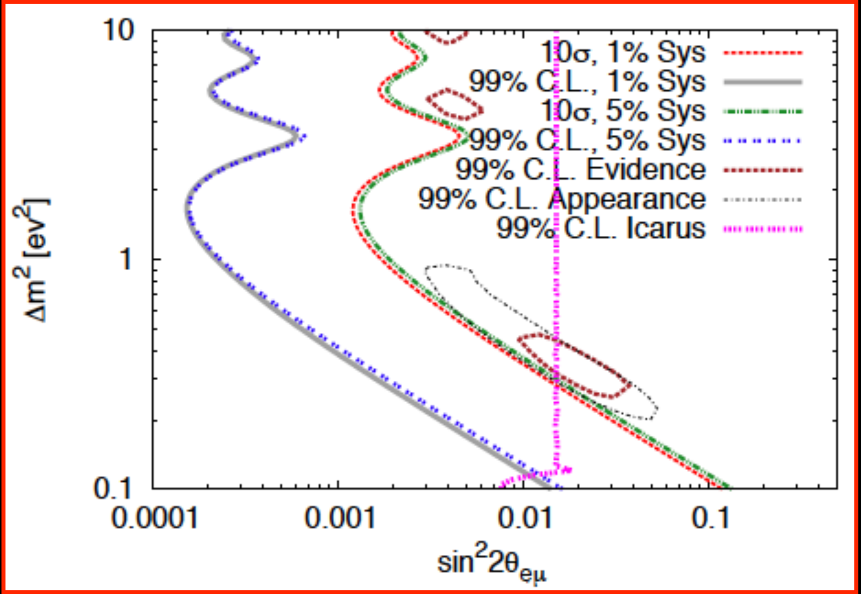


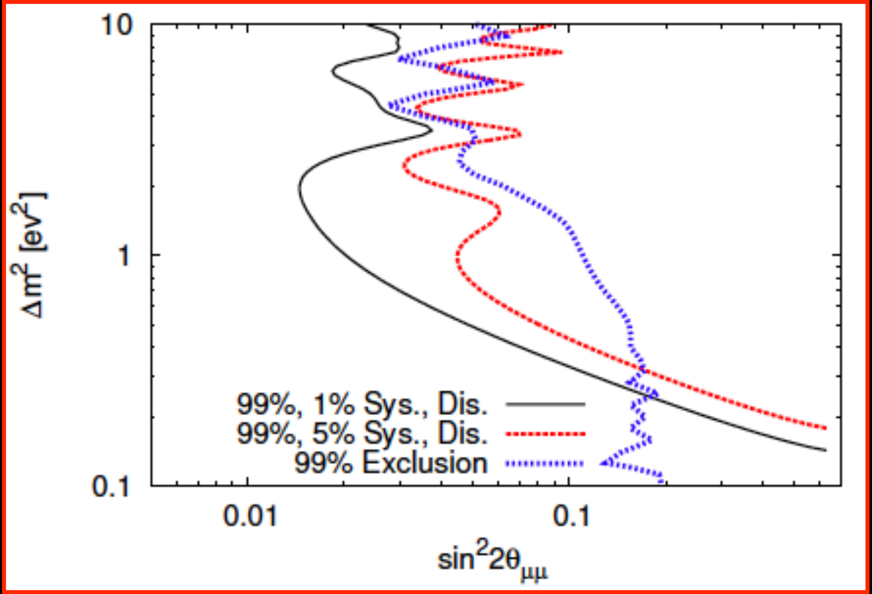
- ν_μ flash:
  - Pion: 6.3×10^{16} m^{-2} at 50m
  - Kaon: 3.8×10^{14} m^{-2} at 50m
    - Well separated from pion neutrinos
- ν_e and $\overline{\nu_\mu}$ from muon decay:
  - ~10 times as many ν_e as, e.g. J-PARC beam
  - Flavour composition, energy spectrum
    - Use for energy calibration

Sterile neutrino search @ FNAL









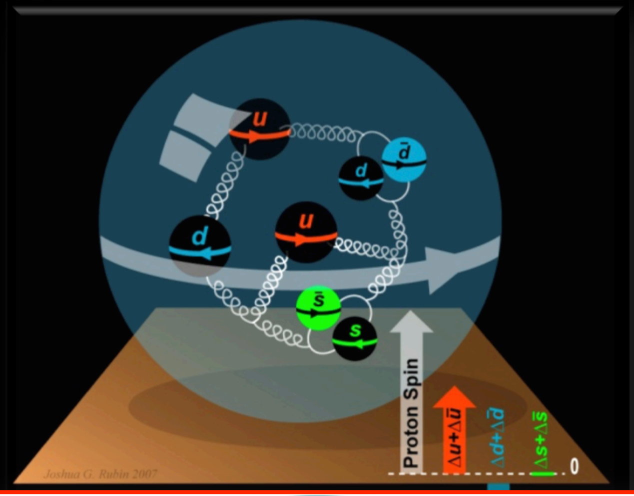
Adey et al., PRD 89 (2014) 071301

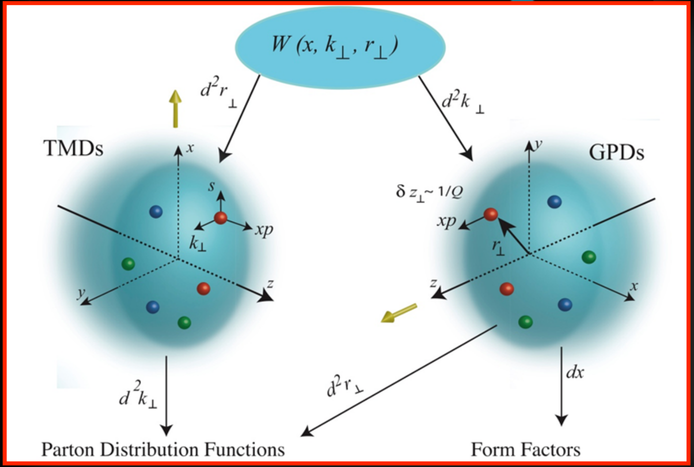
nuSTORM

Why study neutrino interactions?

To understand the nucleon and the nucleus

- Neutrino unique probe: weak and chiral:
  - Sensitive to flavour/isospin and 100% polarised
- How could neutrino scattering help?
  - Nucleon (e.g.):
    - Spin puzzle
  - Nucleus (e.g.):
    - Multi-nucleon correlations
    - Precise determination of:
      - Model parameters or, better,
      - Theoretical (ab initio) description
- Can the neutrino's unique properties compete with the rate in, e.g. electron scattering?
  - Measure weak charge directly; rate and Q^2 dependence:
    - For e^- rely on interference with photon, 10^{-6}-level asymmetry
  - To be studied!
- Benefit of nuSTORM:
  - Precise flux and energy distribution

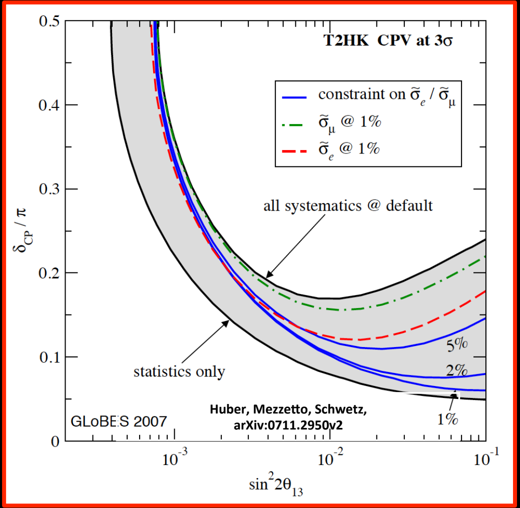




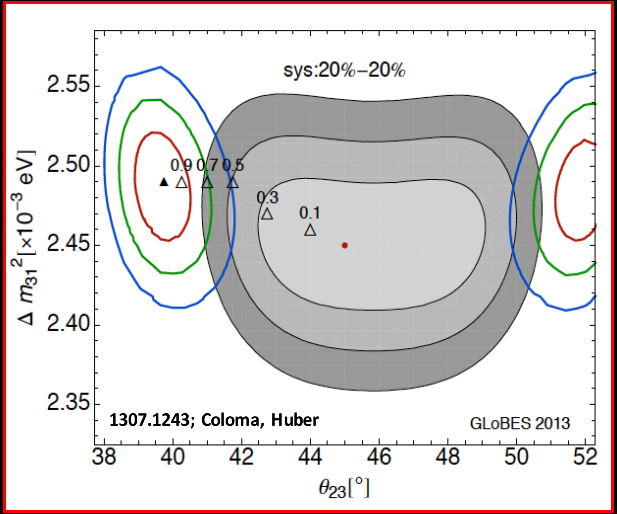
Search for CPiV in lbl oscillations

- Seek to measure asymmetry:
  - $P(\nu_\mu \succ \nu_e) - P(\bar{\nu}_\mu \succ \bar{\nu}_e)$
- Event rates, convolution of:
  - Flux, cross sections, detector mass, efficiency, *E*-scale
    - Measurements at %-level required
  - Theoretical description:
    - Initial state momentum, nuclear excitations, final-state effects

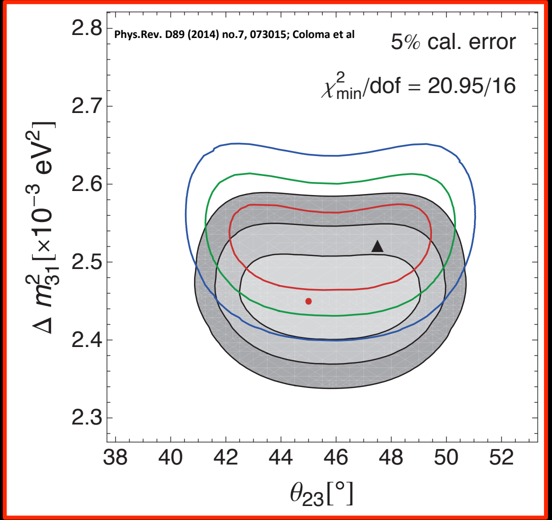
Systematic uncertainty and/or bias



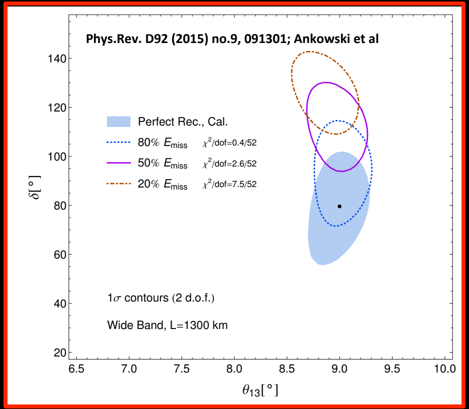
Uncertainty
(cross section and ratio)



Event mis-classification



Energy scale mis-calibration



Missing energy (neutrons)

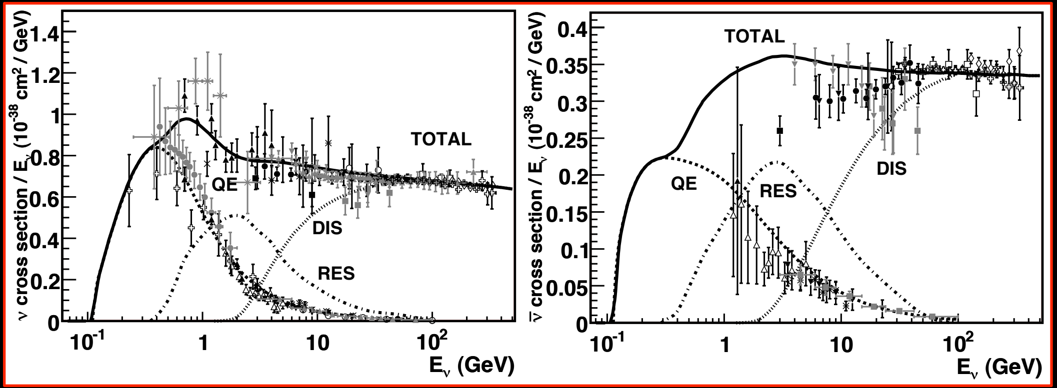
Search for CPiV in lbl oscillations

- Seek to measure asymmetry:
  - $P(\nu_\mu \succ \nu_e) - P(\bar{\nu}_\mu \succ \bar{\nu}_e)$
- Event rates convolution of:
  - Flux, cross sections, detector mass, efficiency, *E*-scale
    - Measurements at %-level required
  - Theoretical description:
    - Initial state momentum, nuclear excitations, final-state effects
- Lack of knowledge of cross-sections leads to:
  - Systematic uncertainties; and
  - Biases; pernicious if ν and $\bar{\nu}$ differ

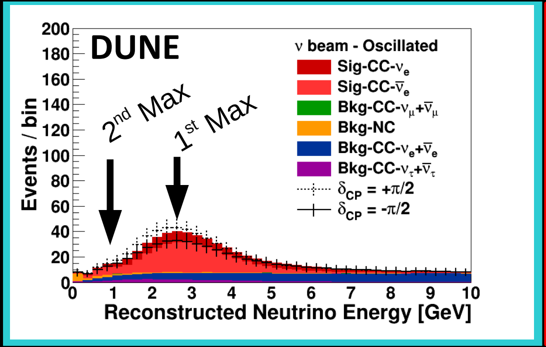
nuSTORM for neutrino scattering

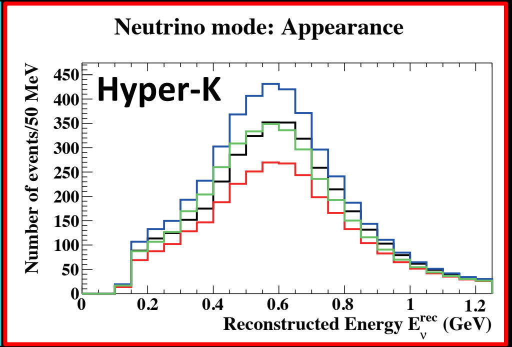
Specification: energy range

- 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_μ < 6 GeV





- So, stored muon energy range:

1 < E_μ < 6 GeV

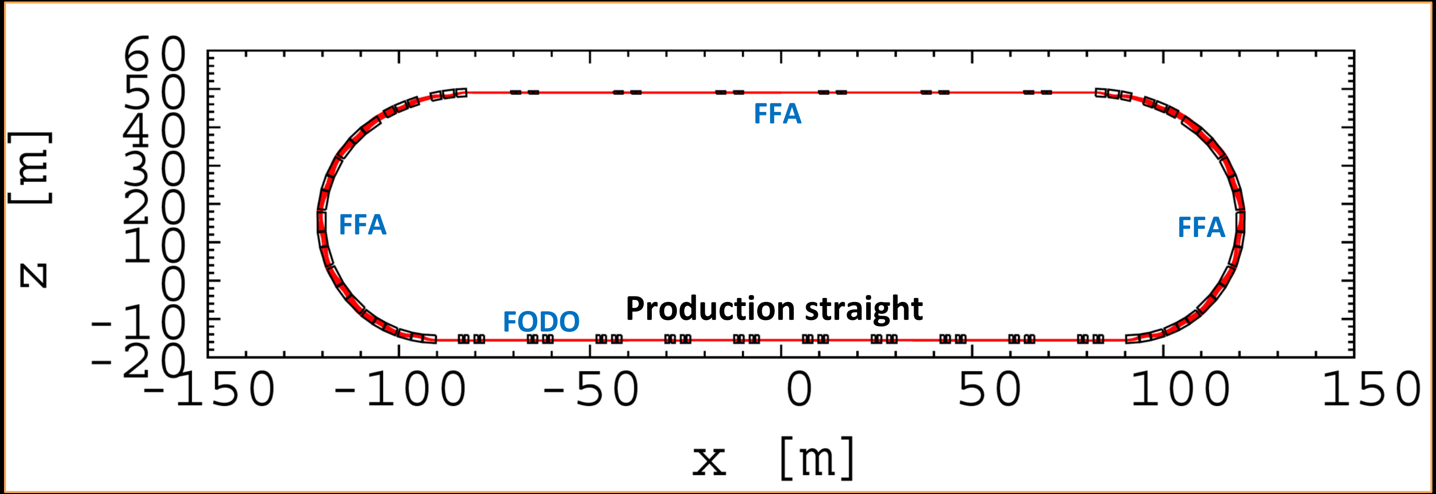
nuSTORM for νN scattering @ CERN — parameters

- New specification!
  - Requires design update:
    - $1 < E_\mu < 6$ GeV
  - Challenge for accelerator design!
  - Benefit:
    - Calibration via energy spectrum
    - Statistical 'mono-energetic beam'
- Parameter table for discussion

Parameter	Value or range	Unit	Comment
Primary proton beam Contact: M. Lamont			
Beam momentum (p)	100	GeV/c	
Total required POT	2.30E+20		
POT per year	4.00E+19		
SPS intensity	4.00E+13		
SPS cycle length	3.6	s	
Max. normalised horizontal beam emittance (1 sigma)	8	mm rad	
Max. normalised vertical beam emittance (1 sigma)	5	mm rad	
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 sigma)	2	ns	
Bunch spacing	5	ns	
Momentum spread (dp/p 1 sigma)	2.00E-04		
Main primary beam parameters on target Contact: M. Lamont			
Nominal proton beam power	156	kW	
Maximum proton beam power	240	kW	
Horizontal beta (betax)	200	m	
Vertical beta (betay)	350	m	
Horizontal divergence (1 sigma)	1	mrad	
Vertical divergence (1 sigma)	1	mrad	
Nominal horizontal and vertical beam spot size (1 sigma)	2.1	mm	
Horiz. and vert. beam-spot size min./max. (1 sigma)	1.5/2.7	mm	
nuSTORM ring, including instrumentation Contact: K. Long			
Energy (E_μ)	$1 < E_\mu < 6$	GeV	See proc. NeuTel17
Energy acceptance	10 – 20	%	
Flux			
Intensity (accuracy/resolution)	0.1/0.01	%	See [1]
Position (accuracy/resolution)	5/1	mm	See [1]
Profile (accuracy/resolution)	5/1	mm	See [1]
Tune (accuracy/resolution)		0.01/0.001	See [1]
Beam loss (accuracy/resolution)	1/0.5	%	See [1]
Momentum (accuracy/resolution)	0.5/0.1	%	See [1]
Momentum spread (accuracy/resolution)	1/0.1	%	See [1]

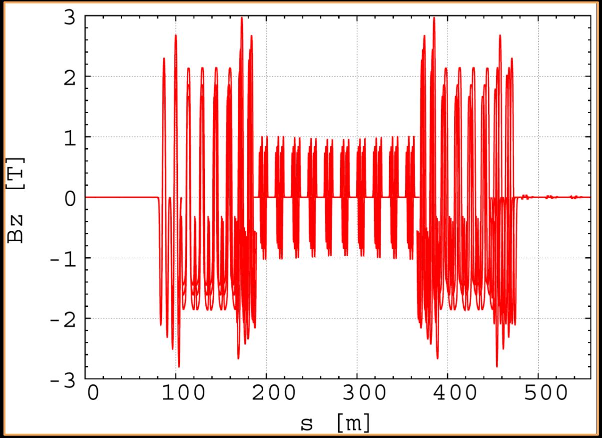
Pasternak et al;
Muon beams for particle physics, RAL, 11 October 2018

Novel Hybrid FFA solution



- **Hybrid FFA to merge benefits for superior lattice:**
  - Zero dispersion and no scallop angle (from FODO)
  - Large DA and momentum acceptance (from scaling FFA)

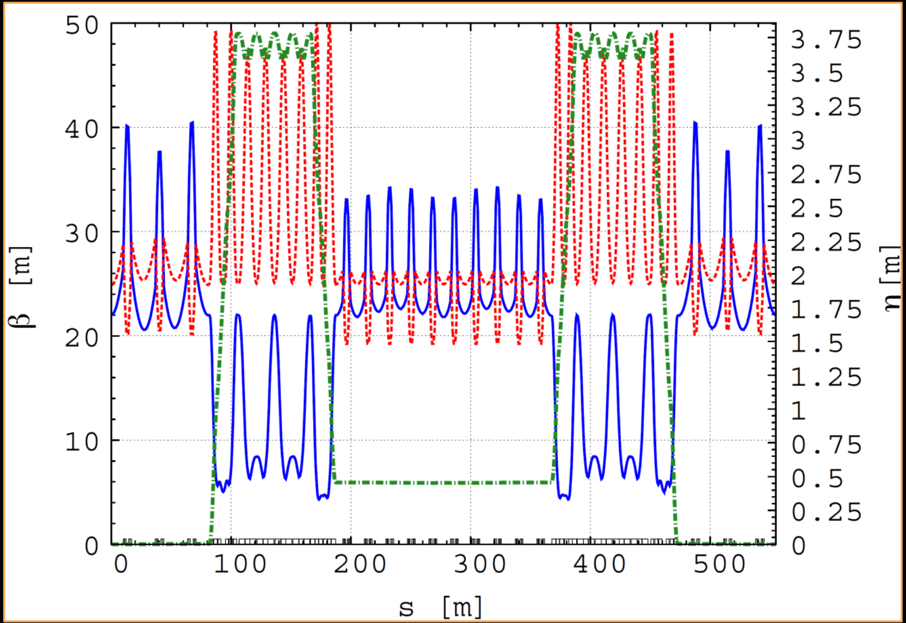
- **Lattice contains:**
  - Zero dispersion quad injection/decay straight
  - Zero-chromatic arc
  - Zero-chromatic FFA straight (can be used for experiments too)

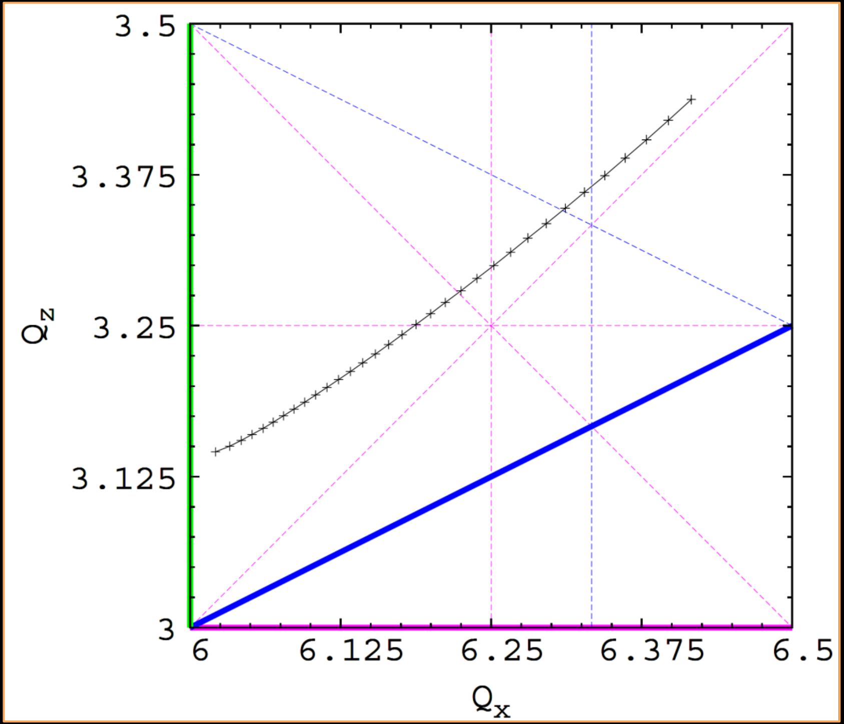


Pasternak et al;
Muon beams for particle physics, RAL, 11 October 2018

Novel Hybrid FFA solution

- **Optics incorporates sections with different optical properties:**
  - **FFA matching cells at the end of the arc**
- **Zero dispersion section maximises muon accumulation efficiency**
- **Large-momentum beam spread remains stable**

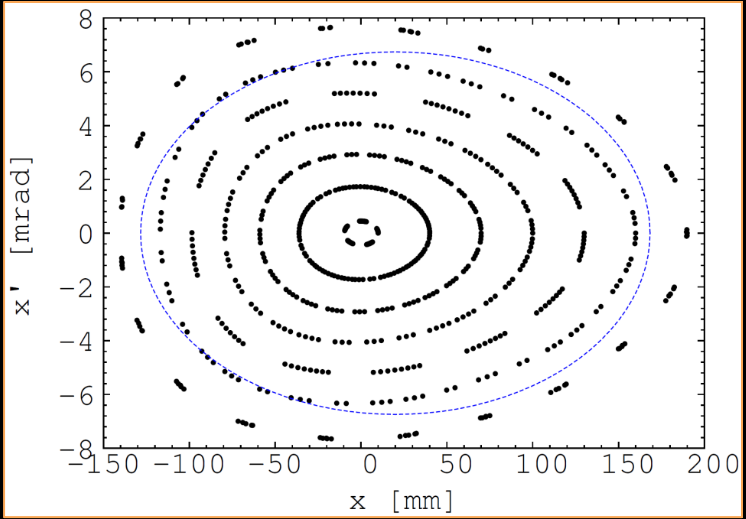


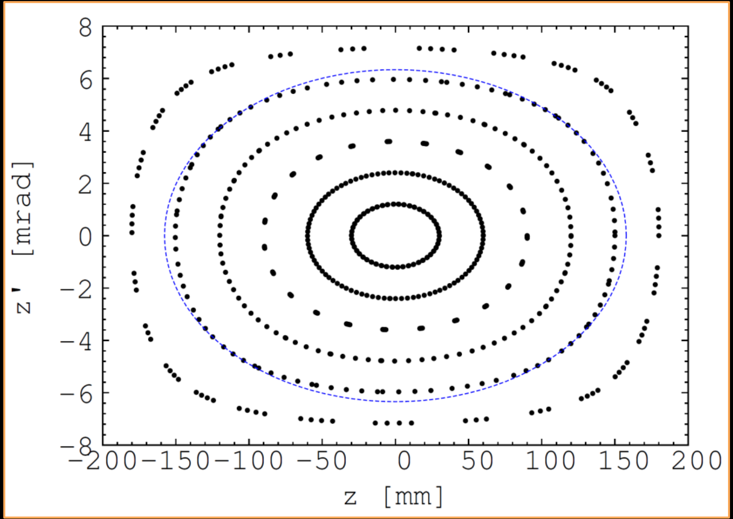


Tune spread stays between integers and half integers

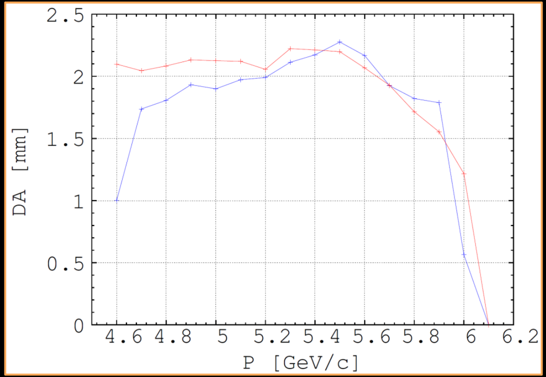
Pasternak et al;
Muon beams for particle physics, RAL, 11 October 2018

Momentum acceptance



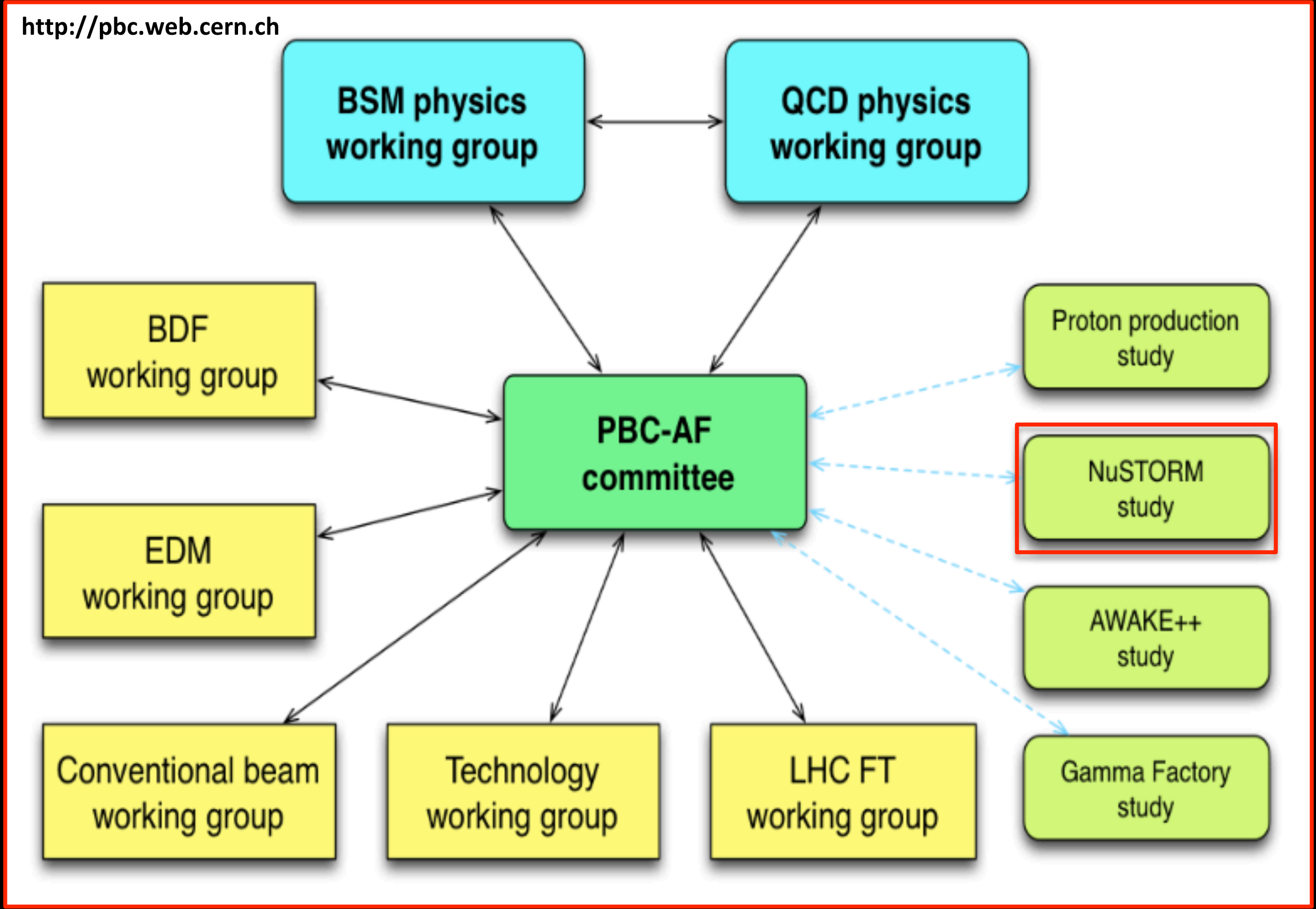


- Large dynamic aperture achieved
- DA off-momentum studied:
  - NO intermediate dips!
- Larger momentum acceptance:
  - Increased neutrino flux



nuSTORM
& CERN Physics Beyond Colliders study

Physics Beyond Colliders study group

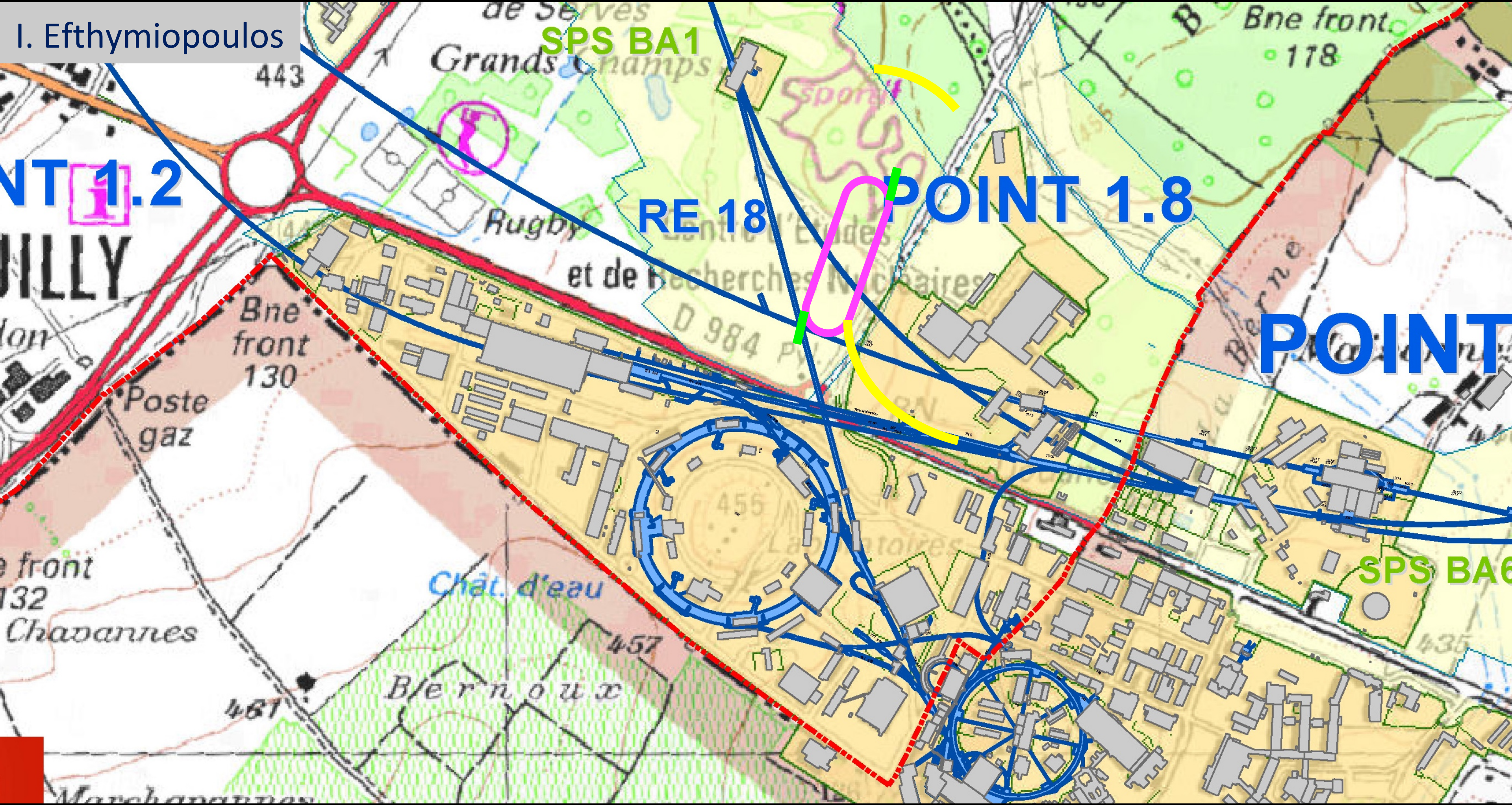


Implementation @ CERN Exploratory study

- A credible proposal for siting at CERN, including:
  - SPS requirements
  - Fast extraction, beam-line
  - Target and target complex
  - Horn
  - Siting
  - Civil engineering
  - Radio-protection implications

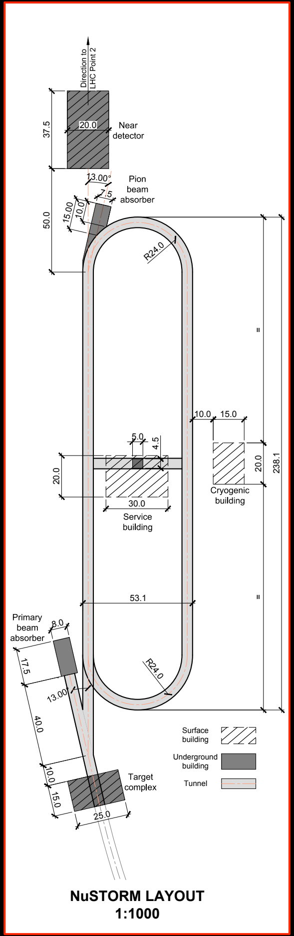
CERN
C. Ahdida, M. Calviani, J. Gall, M. Lamont, J. Osborne and others
Manchester University
R. Appleby, S. Tygier
Imperial College London
K. Long, J. Pasternak
STFC-RAL-ISIS
J-B. Lagrange

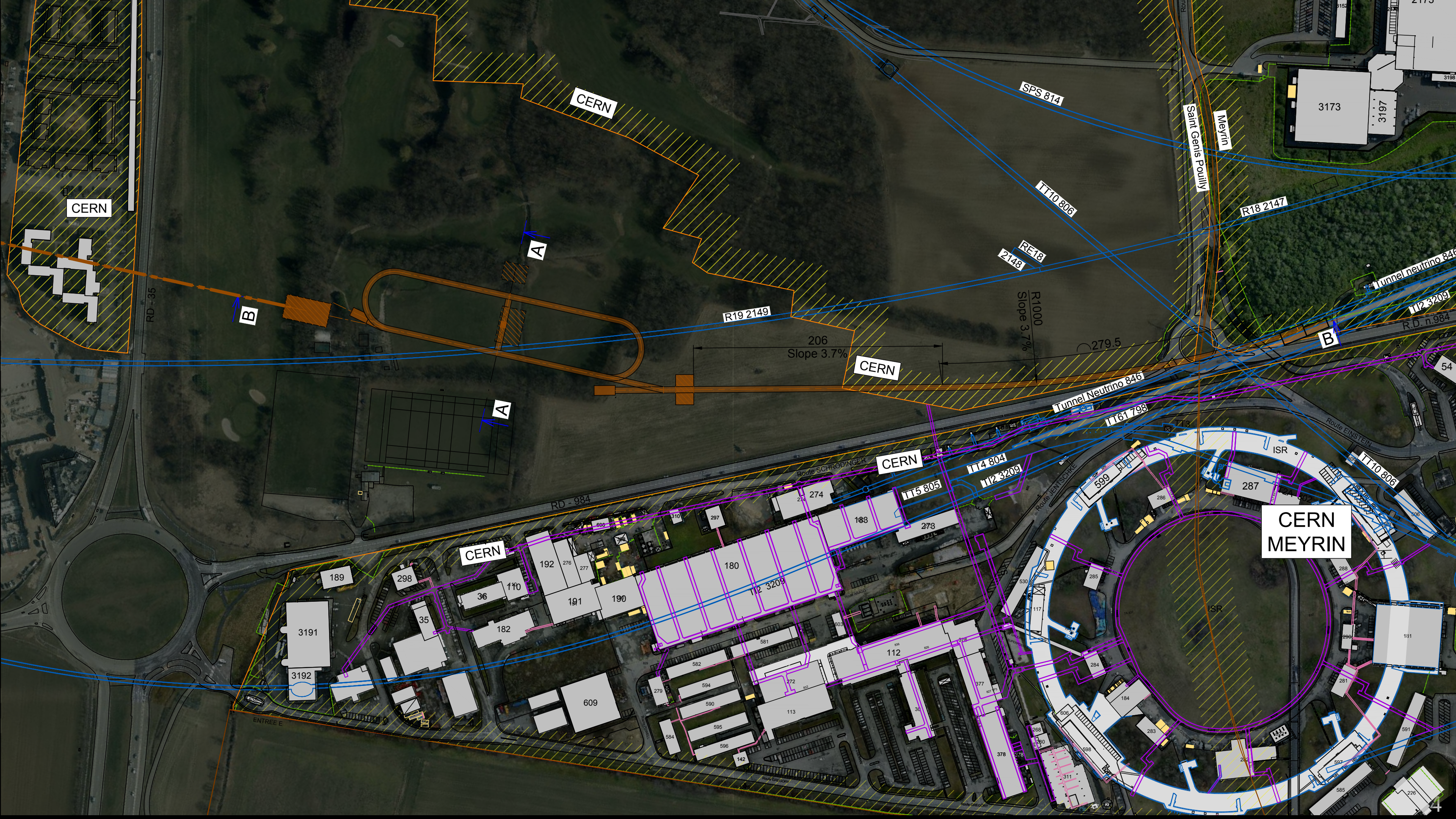
I. Efthymiopoulos



Status of study

- **Constraints:**
  - Avoid existing tunnels
  - Tunneling within molasse
- **Siting:**
  - May consider options outside present CERN footprint
- **Extraction from SPS:**
  - Fast extraction into TT61 preferred
  - Options considered for transfer line:
    - 1.6 T – easier magnets, longer
    - 1.8 T – stronger magnets, shorter
- **Target and capture:**
  - Initial ideas:
    - Prefer 'chicane' configuration used in AD
    - Similar requirements to ENUBET





CERN
CERN
SPS 814
TT10 806
Saint Genis Pouilly
Meyrin
3173
3197
R18 2147
RE18
2148
Tunnel neutrino 846
TI2 3209
R.D. n.984
A
A
B
B
RD - 35
R19 2149
206
Slope 3.7%
R1000
Slope 3.7%
279.5
CERN
Tunnel Neutrino 846
TT61 798
TT4 804
TI2 3209
TT5 805
CERN
RD - 984
CERN
ISR
287
599
CERN MEYRIN
ISR
189
298
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110
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192
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180
TI2 3209
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3192
609
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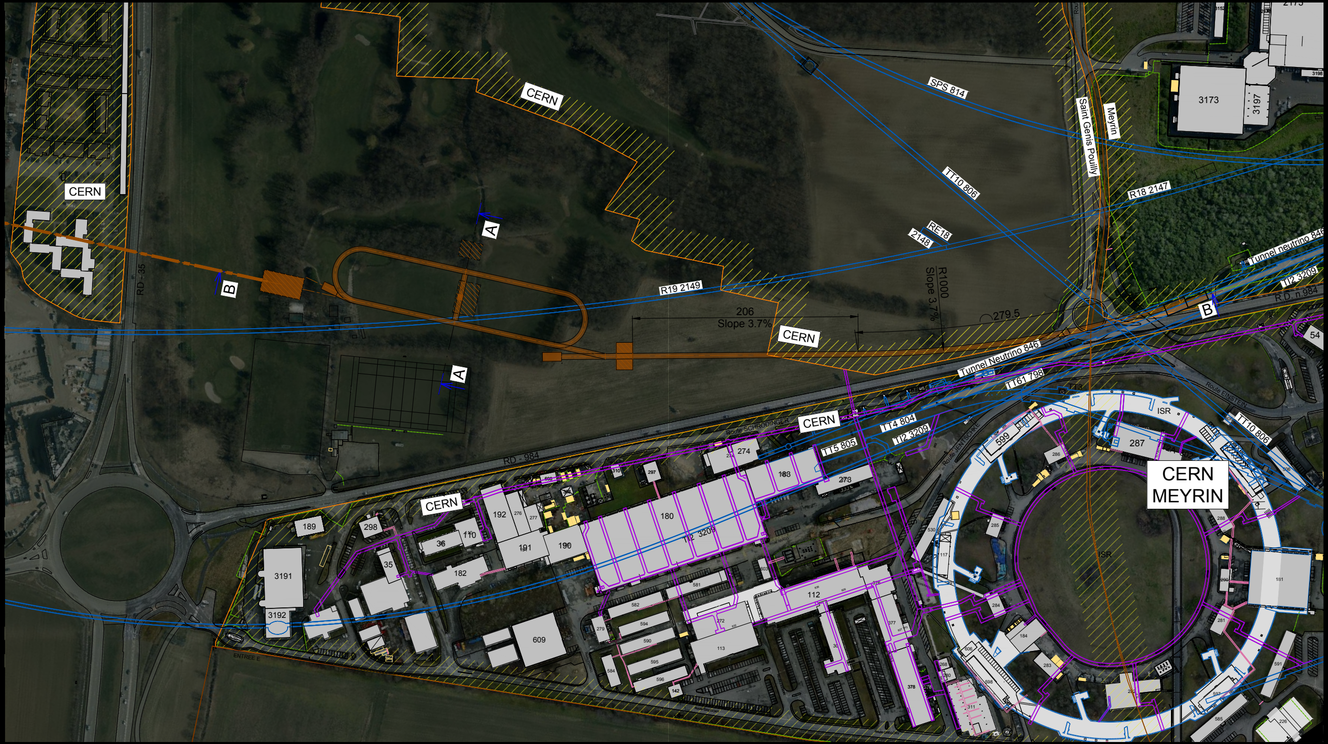
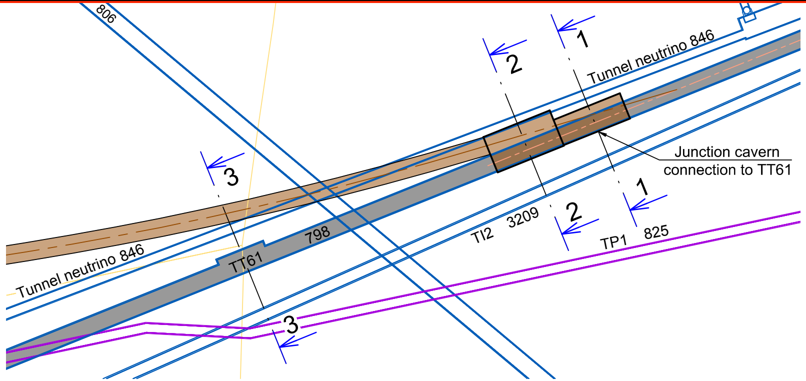


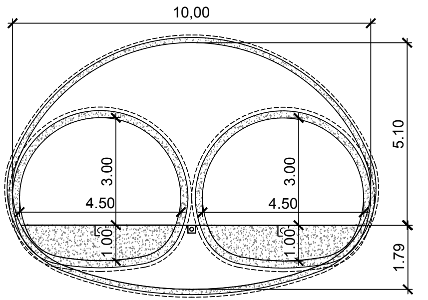
Possible far detector location for sterile neutrino search
Baseline approx. 3 km

J. Gall (CERN) et al

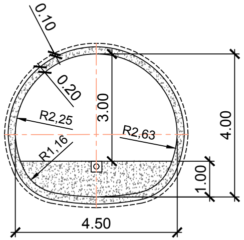
Extraction from TT61



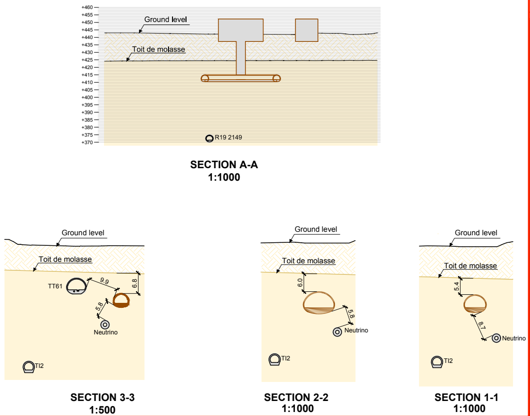
JUNCTION CAVERN - PLAN VIEW
1:1000



JUNCTION CAVERN - SECTION 2-2
1:100

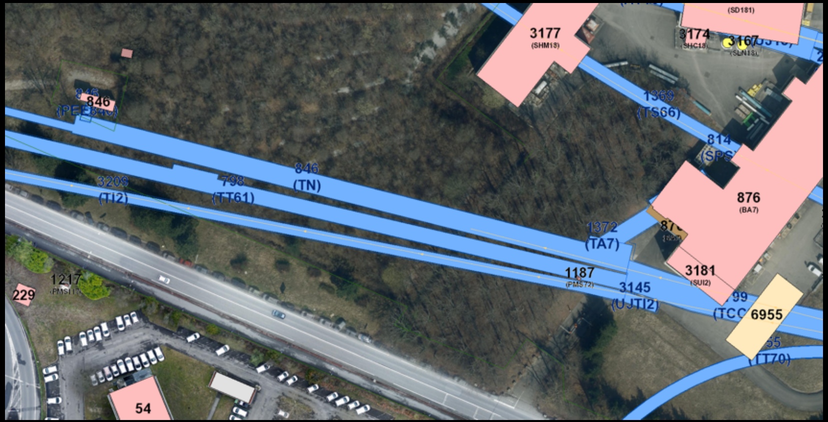


TUNNEL - TYPICAL SECTION
1:100



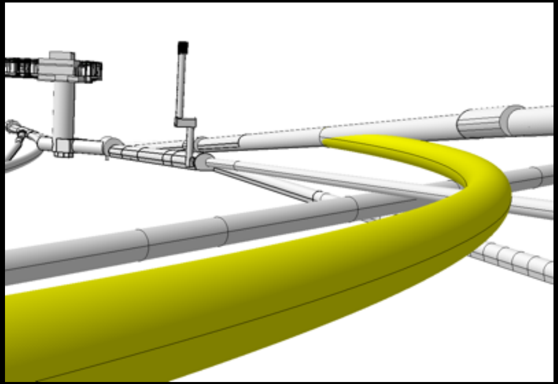
nuSTORM@CERN – SPS Extraction

- **Extraction from LSS6**
  - 100 GeV protons, large emittance beams (FT beams in SPS)
  - May need some changes to beam line equipment in this area – to be confirmed at later stage

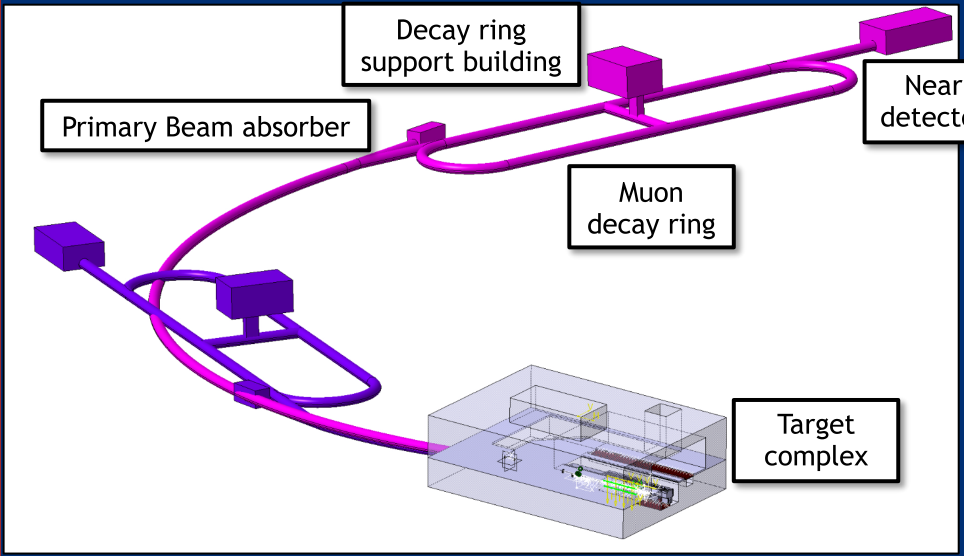


- **TT61 transfer**
  - Appeared the best location for junction cavern and transfer to new line

- **Civil Engineering to look at feasibility in detail based on parameters**
  - Minimum single plane bending radius – 300 m
  - Minimum bending radius for horizontal and vertical bending – 480 m



Target hall, detector hall, RP



Preliminary draft target complex development

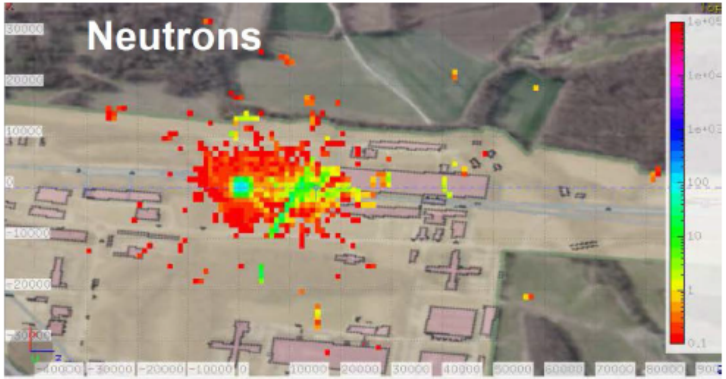


Figure 2: Top view of the ambient dose equivalent (prompt) 10 m above the ground level due to neutrons in μSv/y.

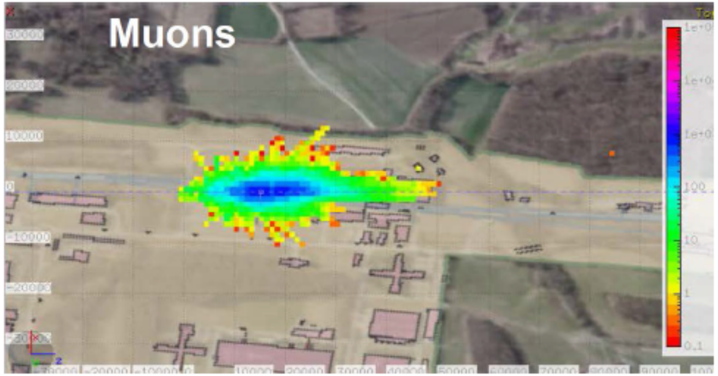


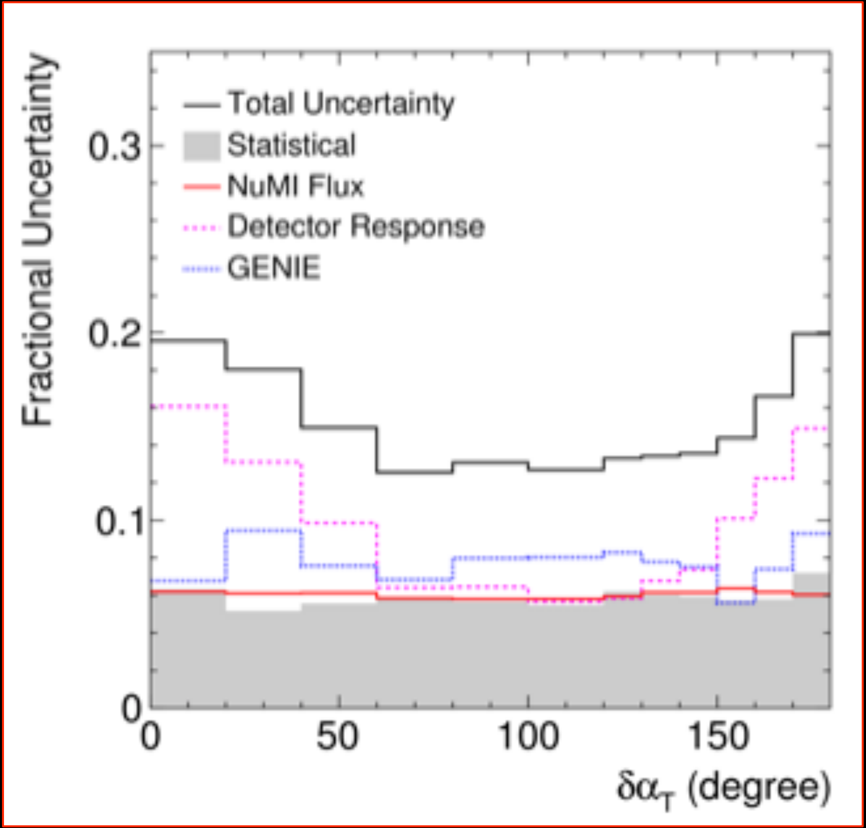
Figure 3: Top view of the ambient dose equivalent (prompt) 10 m above the ground level due to muons in μSv/y.

- Detector hall taken from FNAL design
- Radio-protection (RP):
  - Evaluation based on LBNO studies
  - Requires appropriate engineering; not viewed as 'in principle problem'

The benefit of nuSTORM

Systematic uncertainties

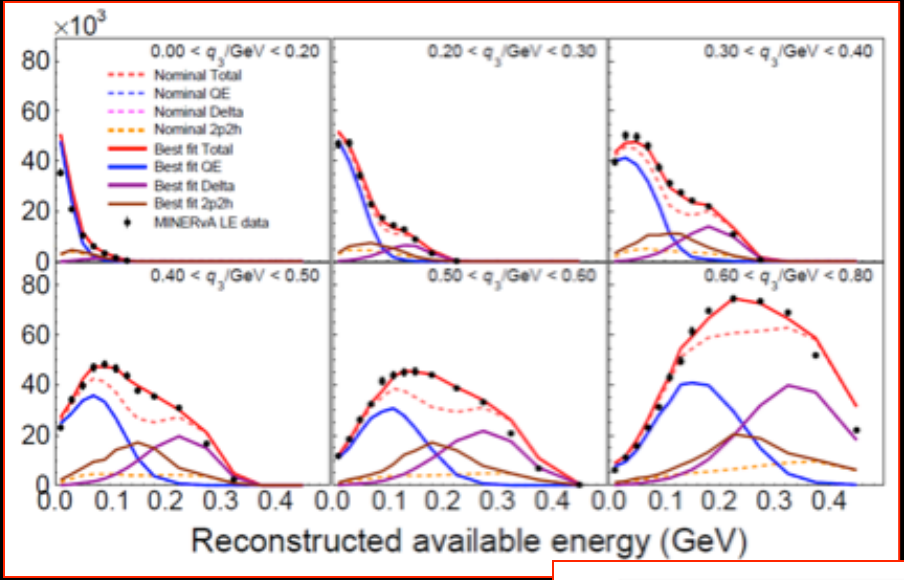
- MINERvA example:
  - Flux, detector and 'theory' contributions comparable
  - In some regions detector uncertainties dominate
- So, to exploit nuSTORM require excellent detector

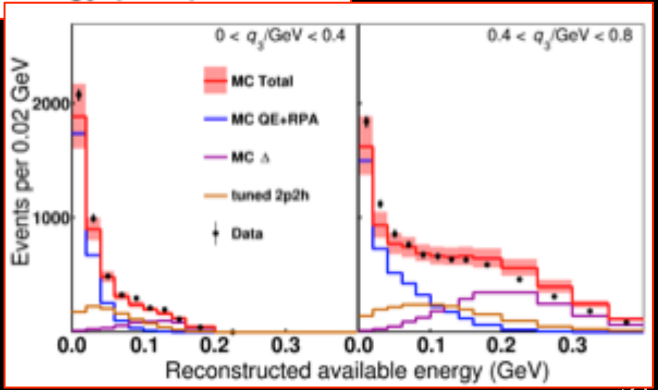


Morfin (nuSTORM w/s)

‘Where are we now?’

- ν_μ scattering rate vs available energy in bins of q_3
  - Improvements in generator (GENIE):
    - RPA, 2p2h, low-recoil fit, non-resonant pion production
  - Reproduces data
- Important:
  - Tuned generator also describes $\bar{\nu}_\mu$ samples

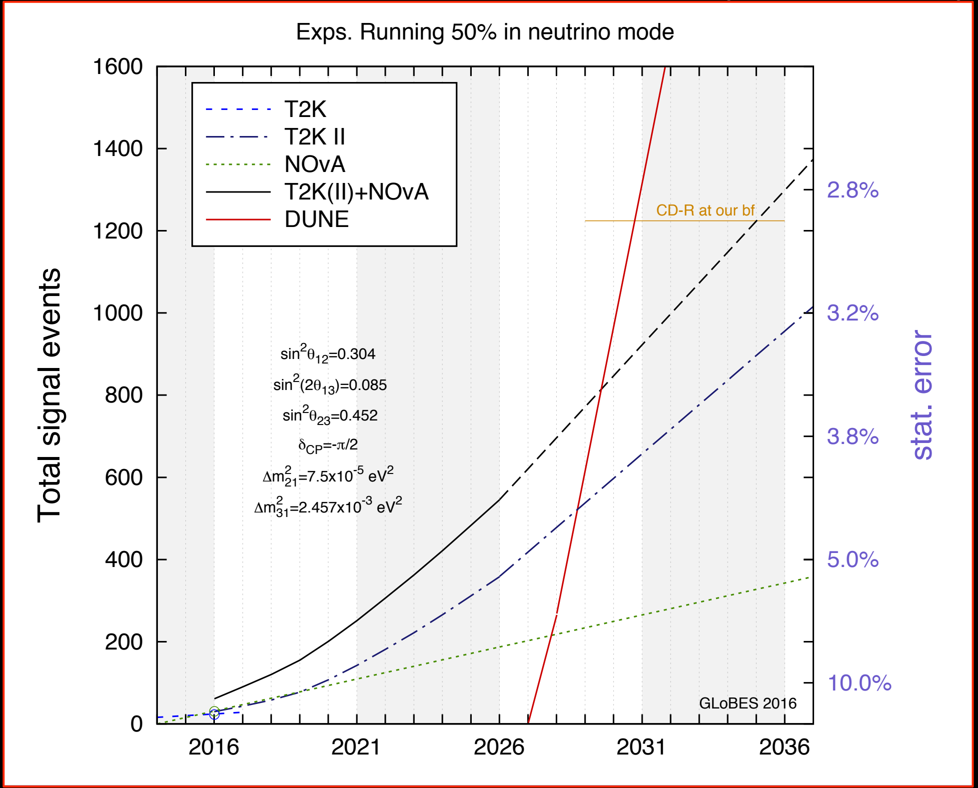




Timescales

- When could nuSTORM operate?
  - A success-orientated European strategy:
    - EPPS Update: 2020
    - Design & approval: 2023
    - Operation 2028
- At this time, DUNE and Hyper-K will be underway:
  - Near-detectors in operation:
    - Large data samples
    - Sophisticated detectors
    - ν-e scattering to determine flux
- Need to consider benefit of nuSTORM against this background

Huber (nuSTORM w/s)

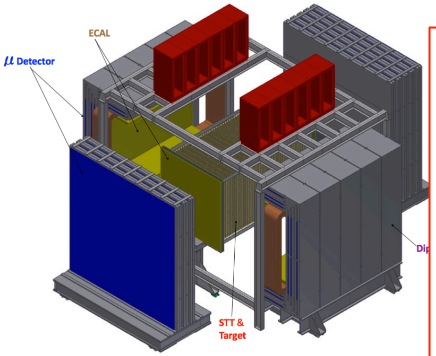


Detector options

Detectors for neutrino interactions

νSTORM

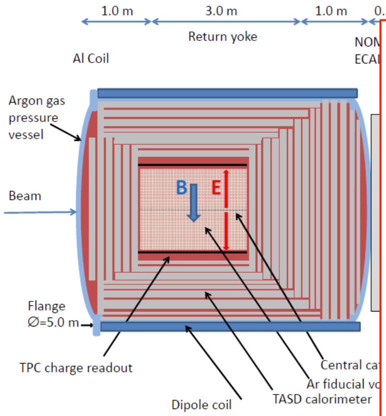
- High resolution straw-tube tracker detector:
  - HiResMuNu as was first proposed for LBNE



Detectors for neutrino interactions

νSTORM

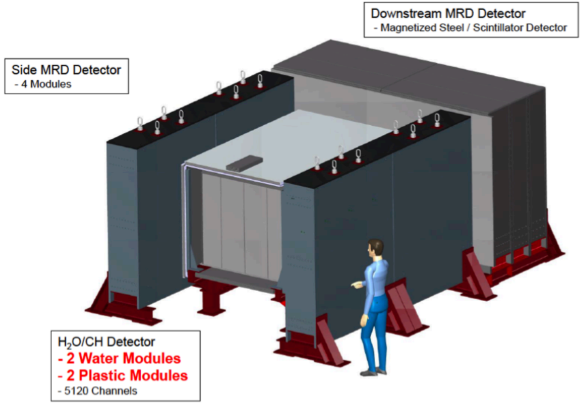
- High pressure argon gas detector:
  - Best resolution to measure nuclear effects in argon



WAGASCI/Baby MIND concept

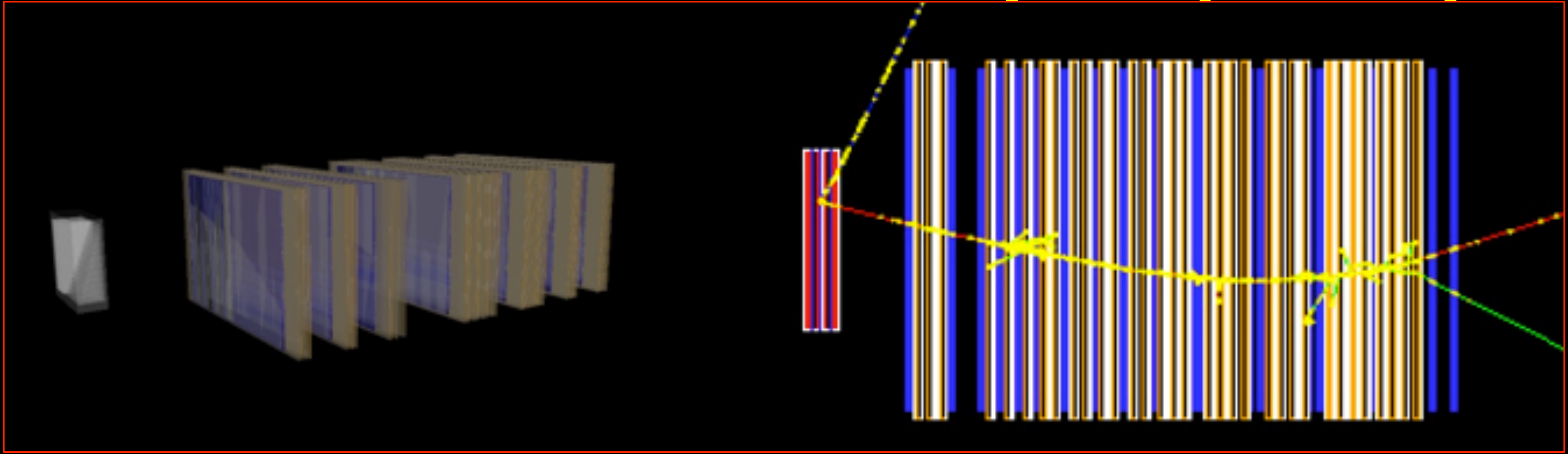
νSTORM

- Totally active scintillator, surrounded by magnetised iron spectrometers (similar to WAGASCI/Baby MIND)



Hallsjo, thesis

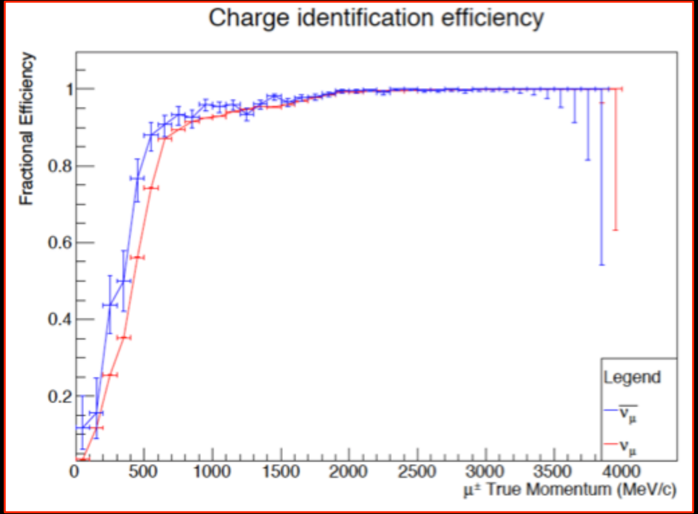
Preliminary CCQE analysis

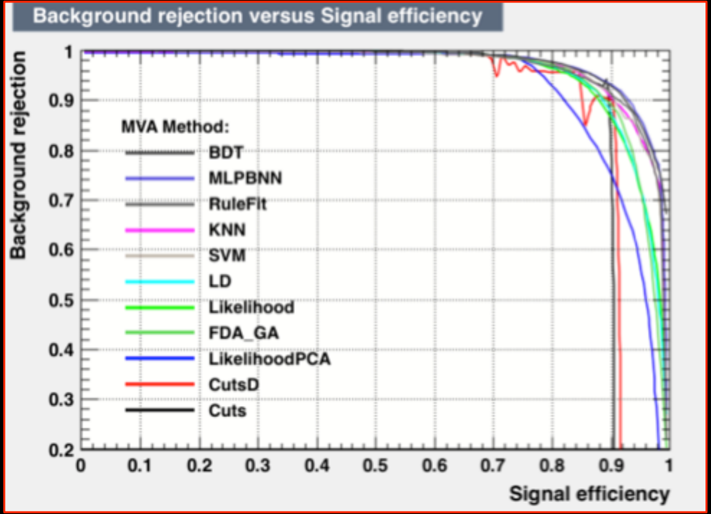


- TASD followed by BabyMIND
- Simulation with nuSTORM spectrum:
  - GENIE for event generation; and
  - GEANT4 for detector simultion

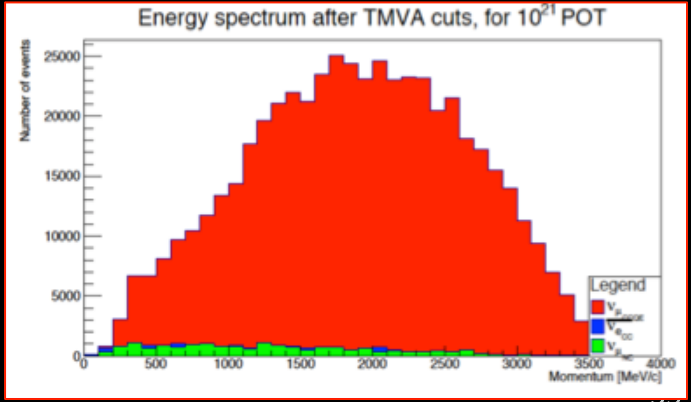
Hallsjo, thesis

CCQE performance; TASD+BabyMIND



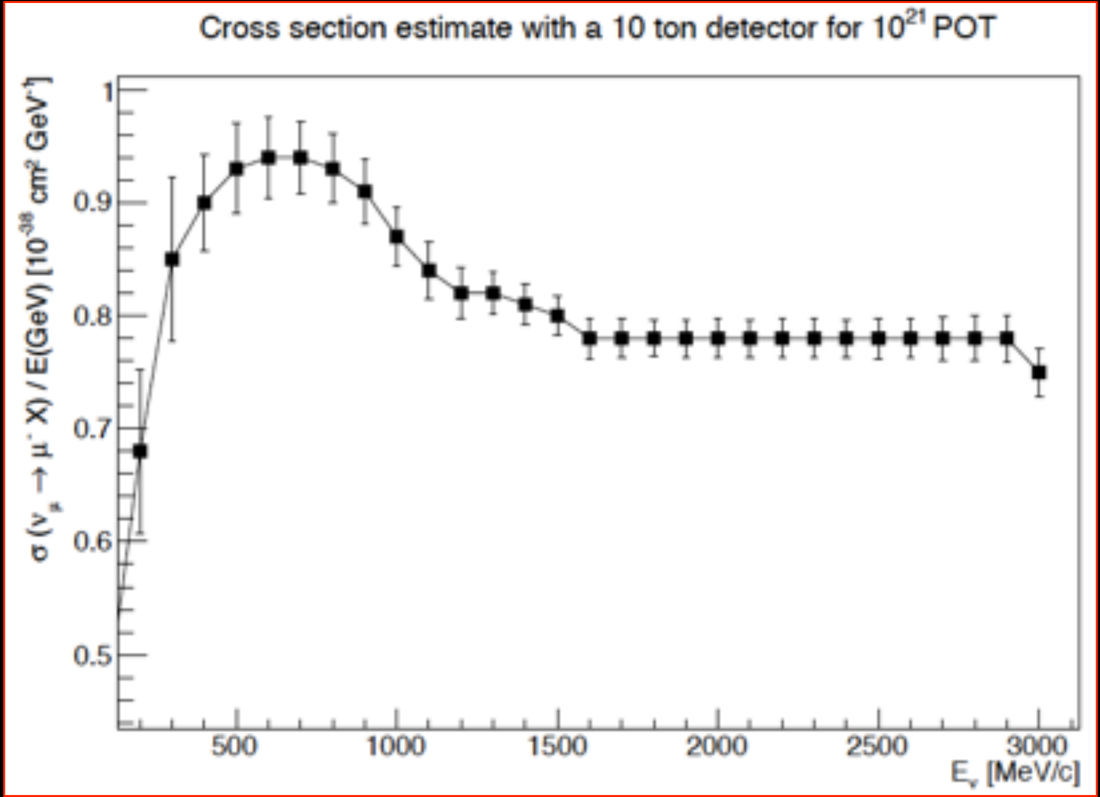


- **CCQE:**
  - Muon charge ID efficiency, background (NC) rejection vs efficiency
  - Assume 10 ton detector, 10^{21} POT
  - TMVA used to select signal



Hallsjo, thesis

CCQE performance



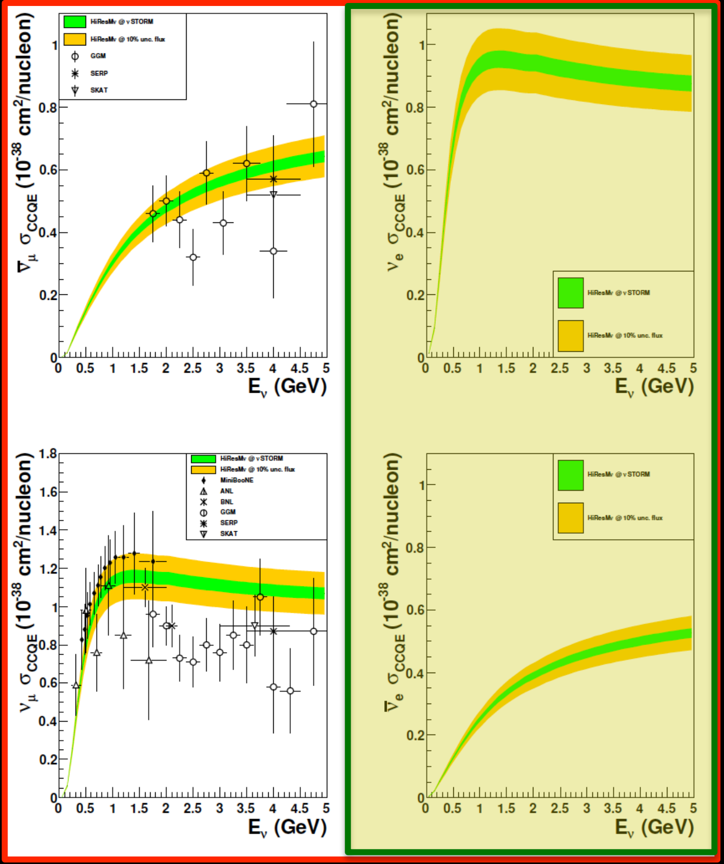
- **CCQE cross section unfolded; 10 ton, 10^{21} POT**

CCQE measurement at nuSTORM

Effect	Value
Momentum resolution of contained tracks	3%
Angular resolution	3%
Minimum range for track finding	2 cm

1% & 10% flux uncertainty

10.1103/PhysRevD.89.071301; arXiv:1305.1419



Individual ν_e measurements from T2K and MINERvA [10.1103/PhysRevLett.113.241803, 10.1103/PhysRevLett.116.081802]

- CCQE at nuSTORM:
  - Six-fold improvement in systematic uncertainty compared with (present) “state of the art”
  - Electron-neutrino cross section measurement unique
- Require to demonstrate:
  - ~<1% precision on flux

Cf/synergy with EnuBET

nuSTORM

Conclusions

Conclusions

- **nuSTORM can deliver:**
  - **νN scattering measurements with precision required to:**
    - **Serve the long- and short-baseline neutrino programmes**
    - **Provide a valuable probe for nuclear physics**

- **CERN PBC study: opportunity to define innovative programme:**
    - **nuSTORM:**
      - **Delivers critical measurement: ν_e/ν_μ *N* scattering;**
      - **Has discovery potential: sterile neutrinos;**
      - **Potential test bed for technologies/techniques required for Muon Collider**
        - » **E.g. host for 6D cooling demonstration to follow MICE**

THE END

Conclusions from nuSTORM w/s

- Seek to write:
  - Sister publication to:
    - 'Light sterile neutrino sensitivity at the nuSTORM facility', doi.org/10.1103/PhysRevD.89.071301, Phys.Rev. D89 (2014) 071301
  - Document case for and performance of scattering programme

- Fixed points, working backwards:
  - I/p to ESPPU 18Dec18
  - Presentation at Neutrino Town Meeting; CERN Globe, 23Oct18

- All are invited to participate!
  - Take i/p to ESPPU as revised EoI to CERN …
  - Email K.Long@Imperial.AC.UK