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nuSTORM
neutrinos from STORed Muons

J. Pasternak,

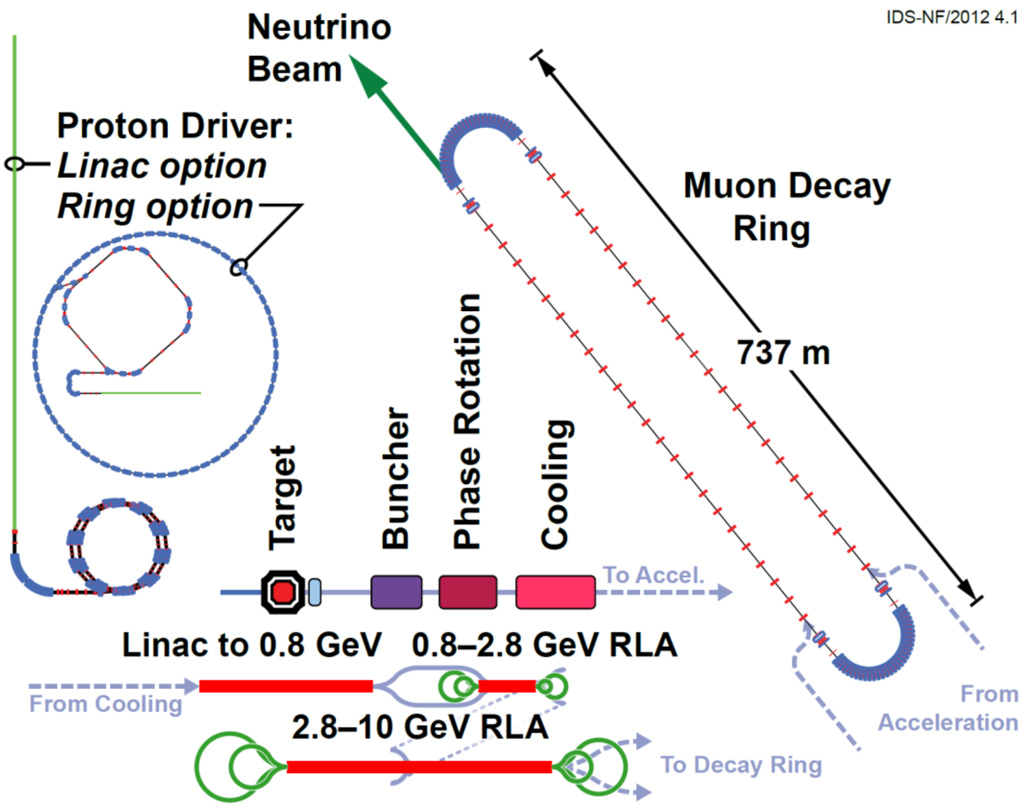
on behalf of nuSTORM study team

Padova, 03/07/18, Muon Collider Workshop

Outline

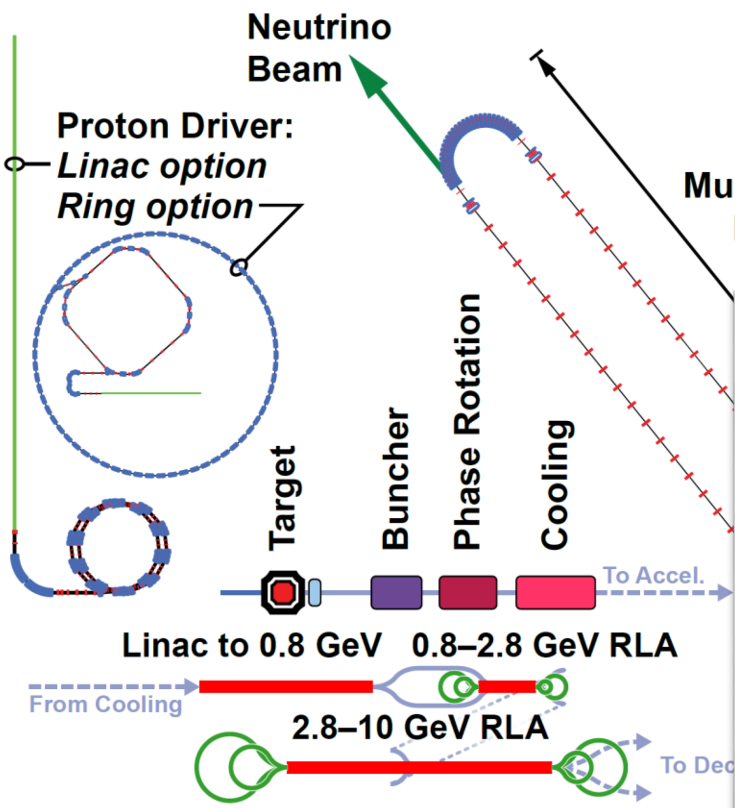
- Origin
- Motivation
- FODO design for nuSTORM (FNAL)
- Advanced FFA concept
- FFA design
- Siting at CERN
- Summary and future plans

Origin – the Neutrino Factory



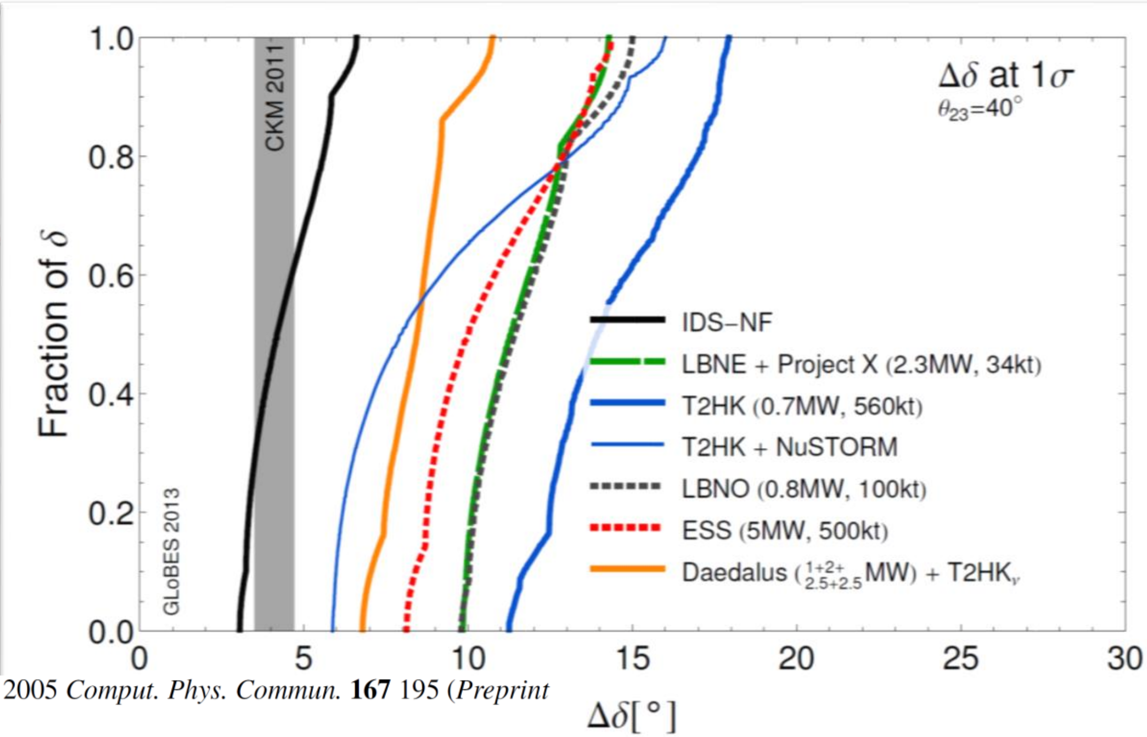
- Neutrino Factory can perform a precision measurement of neutrino oscillation parameters.
  - The most precise measurement of leptonic CP violation

Origin – the Neutrino Factory



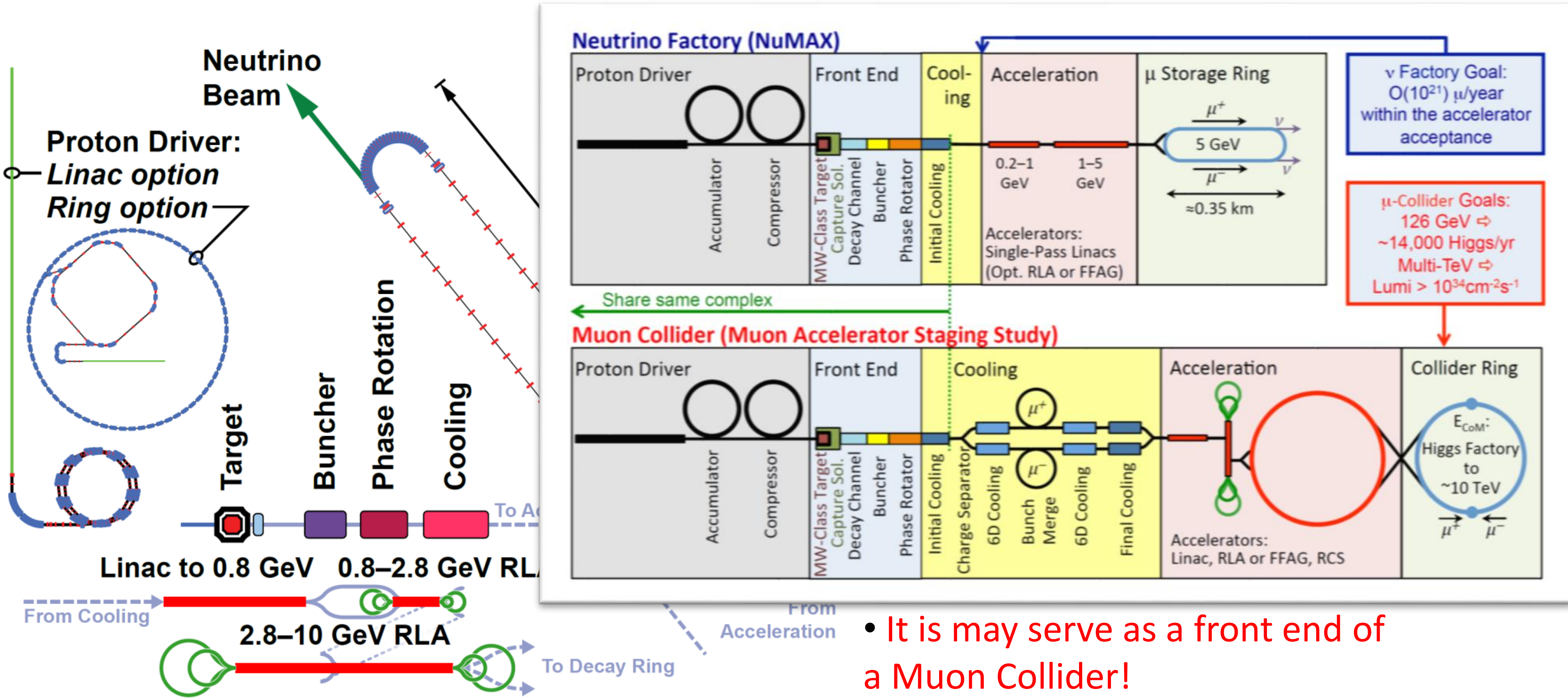
IDS-NF/2012 4.1

- Neutrino Factory can perform a precision measurement of neutrino oscillation parameters.
  - The most precise measurement of leptonic CP violation



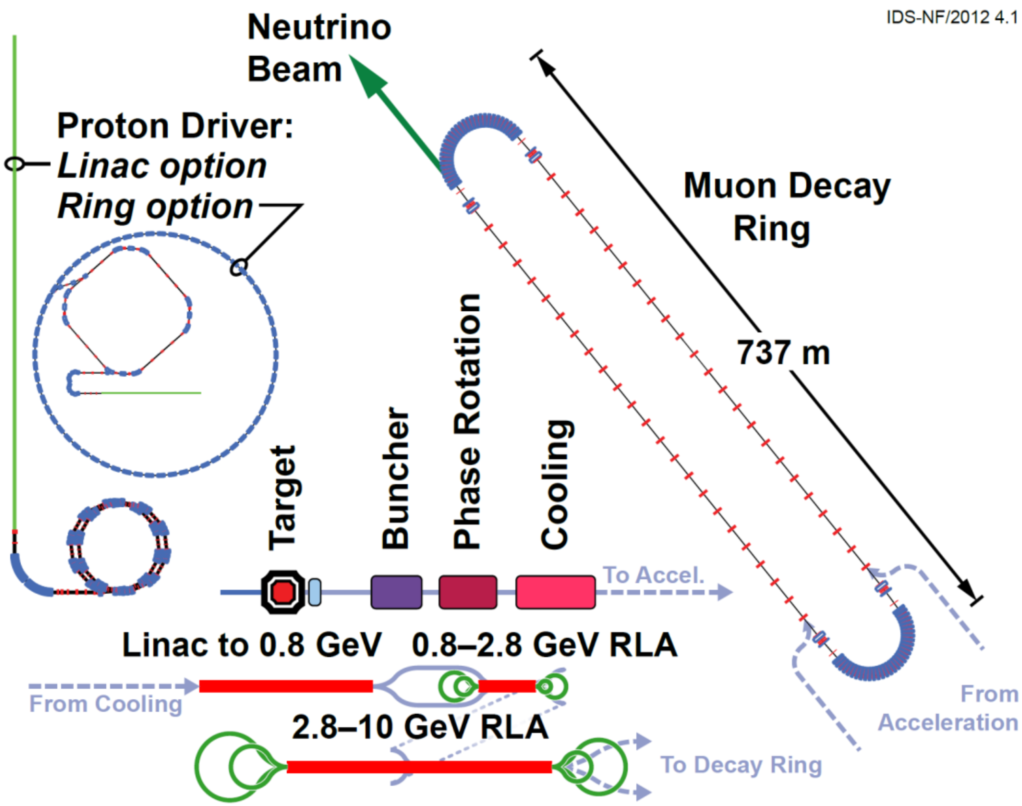
Huber P, Lindner M and Winter W 2005 *Comput. Phys. Commun.* **167** 195 (*Preprint* hep-ph/0407333)

Origin – the Neutrino Factory



- It is may serve as a front end of a Muon Collider!

Origin – the Neutrino Factory



- Challenges include:

-high power proton driver,

-high power target

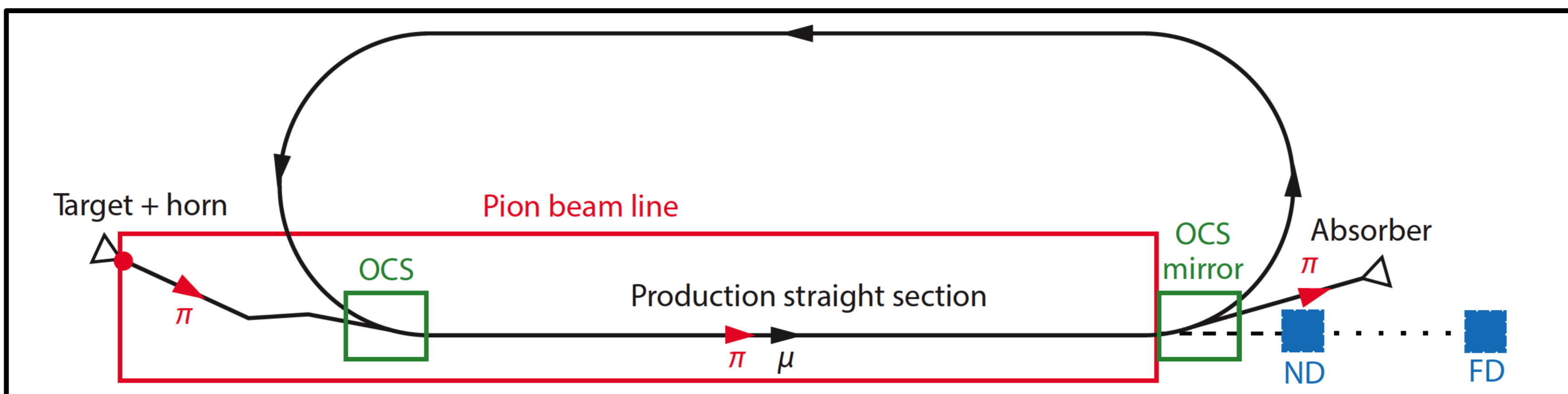
-ionization cooling,

-muon acceleration.

- Based on essentially new accelerator facilities so hard to realize in a near future using existing lab structures.

Origin - Idea

- nuSTORM (`NeUtrinos from STORed Muons') is a facility based on a low-energy muon decay ring.
- Can use existing proton driver (like SPS at CERN)
- Conventional pion production and capture (horn)
  - Quadrupole pion-transport channel to decay ring
  - Direct injection of pions into the decay ring to form circulating muon beam subsequently used as a source of neutrinos



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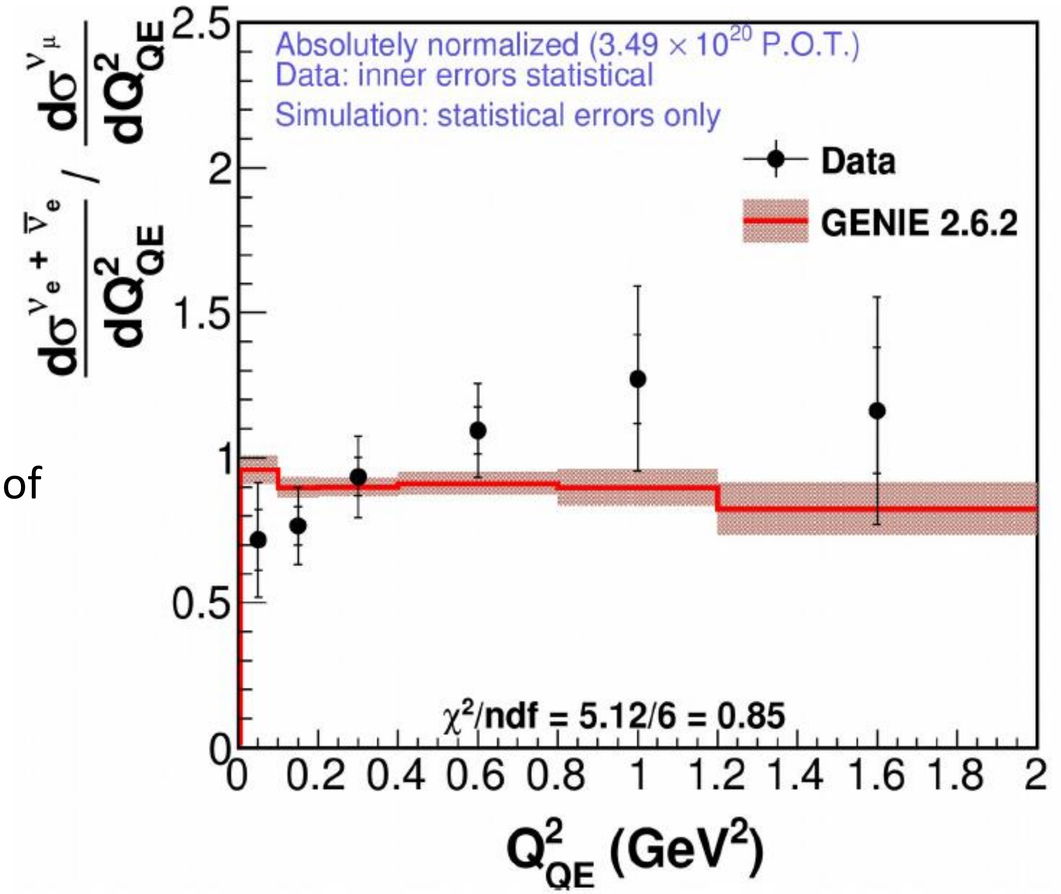
nuSTORM - Motivation

- Neutrino interaction physics – can measure neutrino cross sections precisely

J. Morfin, First discussion of nuSTORM in the context of the Physics Beyond Colliders workshop, IC, 16/02/17



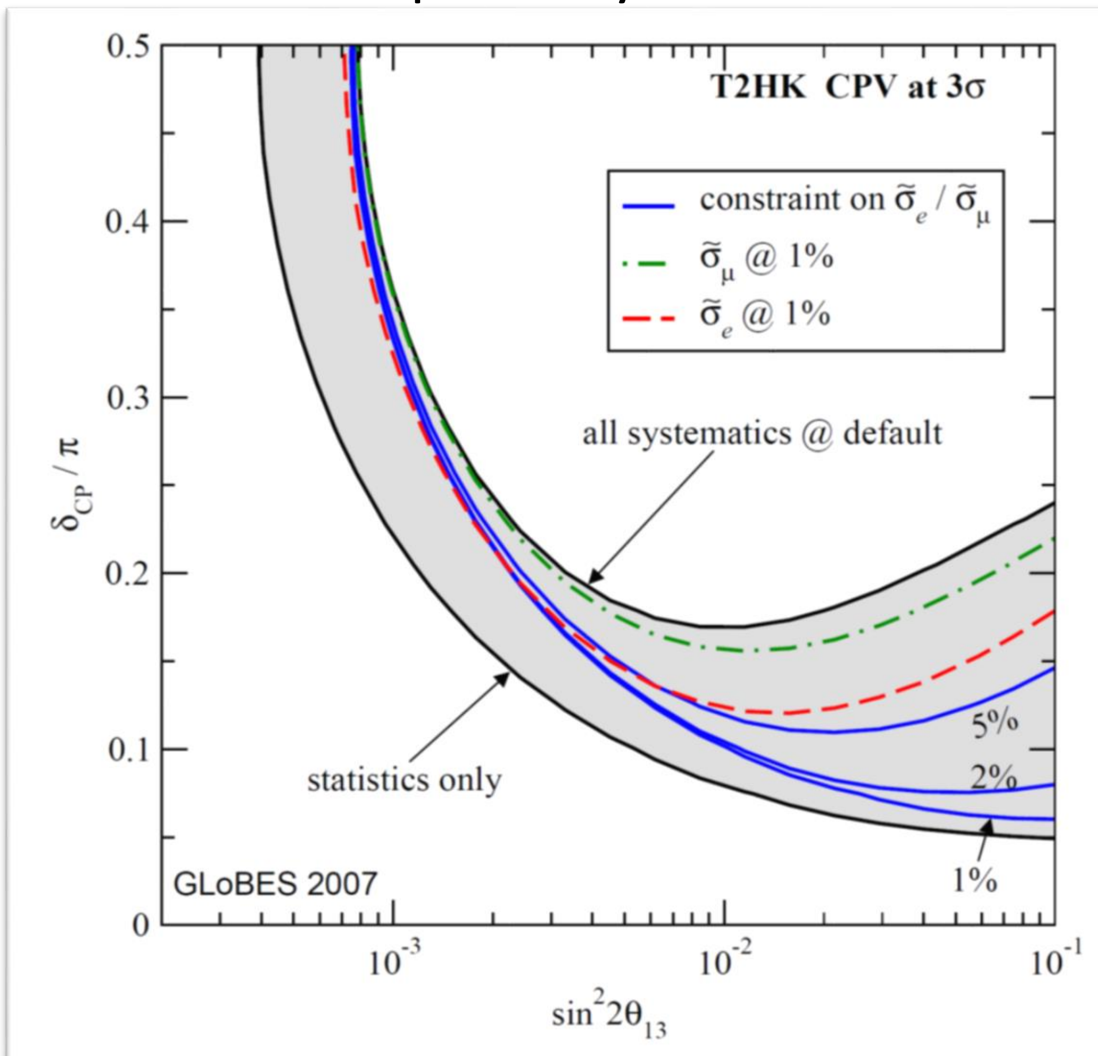
Uncertainty on ratio of $\nu_e - \nu_\mu$ cross sections

nuSTORM - Motivation

- Neutrino interaction physics – can measure neutrino cross sections precisely

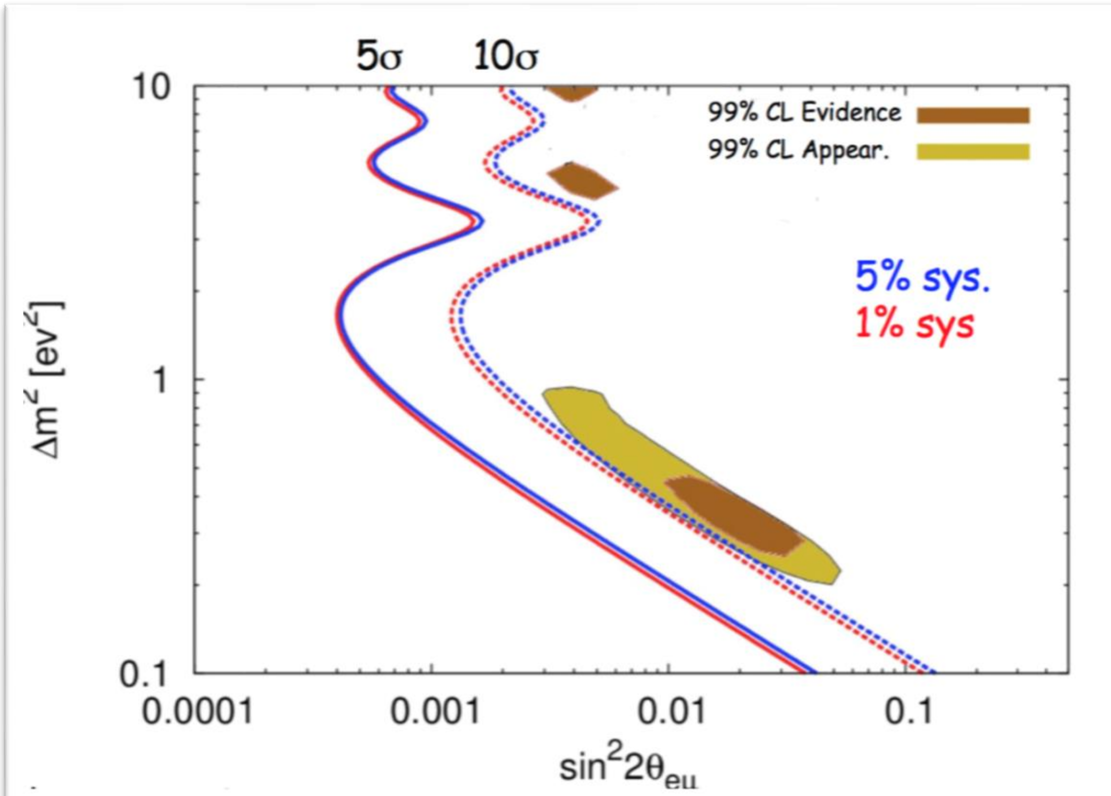
CERN-PH-TH/2007-227
VPI-IPNAS-07-09

This directly translates into the precision of neutrino oscillation experiments and in particular affects future CP violation searches .



nuSTORM - Motivation

- Neutrino interaction physics – can measure neutrino cross sections precisely
- Short baseline neutrino oscillation physics – search for sterile neutrinos



Sensitivity of nuSTORM to a sterile neutrino signal

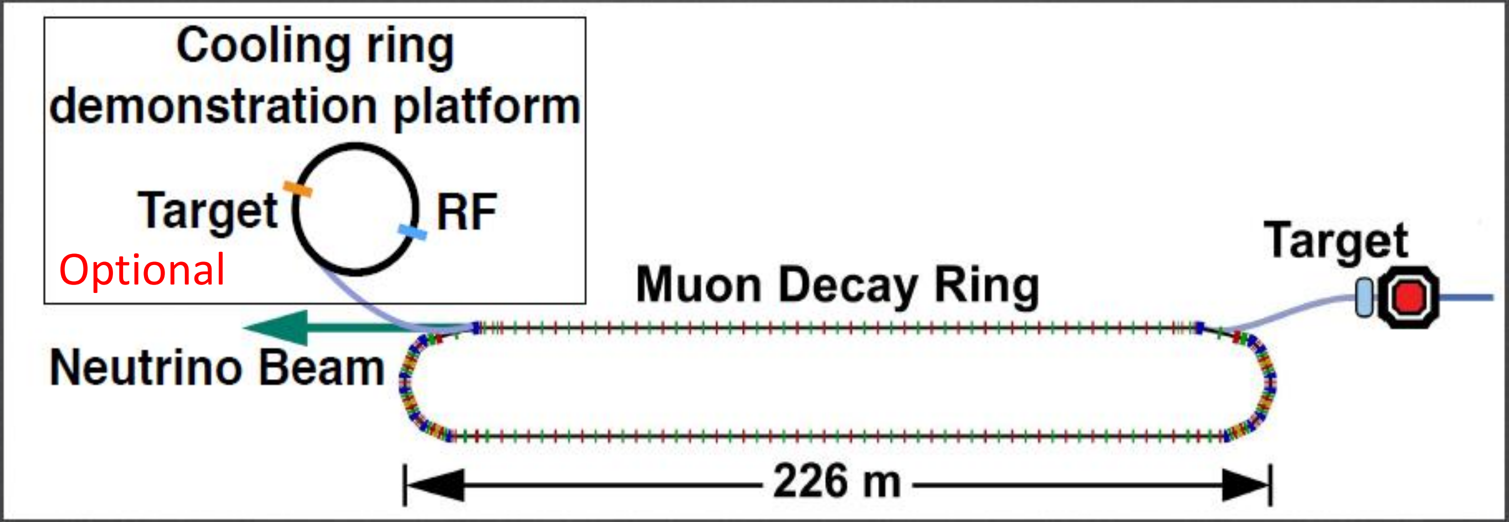
arXiv.org > hep-ex > arXiv:1805.12028, MiniBooNE Collaboration

Phys.Rev. **D89**, 071301 (2014), 1402.5250

nuSTORM - Motivation

- Neutrino interaction physics – can measure neutrino cross sections precisely
- Short baseline neutrino oscillation physics – search for sterile neutrinos
- Accelerator and Detector Technology Test Bed
  - Proof of principle for the Neutrino Factory concept
  - Muon Collider R&D platform

nuSTORM Overview

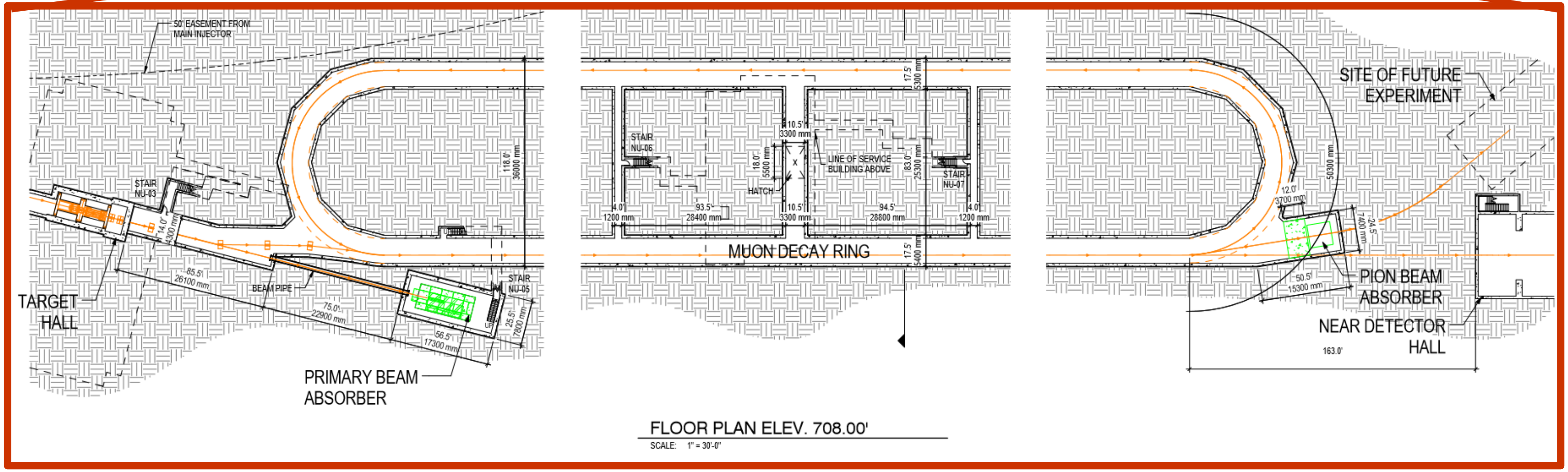


1. Facility to provide a muon beam for precision neutrino interaction physics
2. Study of sterile neutrinos
3. Accelerator & Detector technology test bed
   - Potential for intense low energy muon beam
   - Enables μ decay ring R&D (instrumentation) & technology demonstration platform
   - Provides a neutrino Detector Test Facility
   - Test bed for a new type of conventional neutrino beam

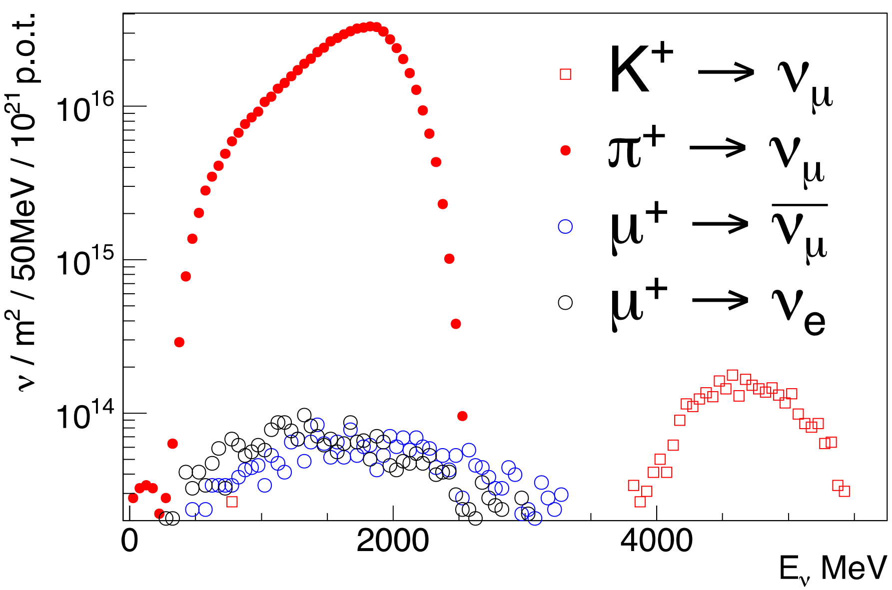
$$\mu^- \longrightarrow e^- + \bar{\nu}_e + \nu_\mu$$
$$\mu^+ \longrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$
$$\pi^- \longrightarrow \mu^- + \bar{\nu}_\mu$$
$$\pi^+ \longrightarrow \mu^+ + \nu_\mu$$

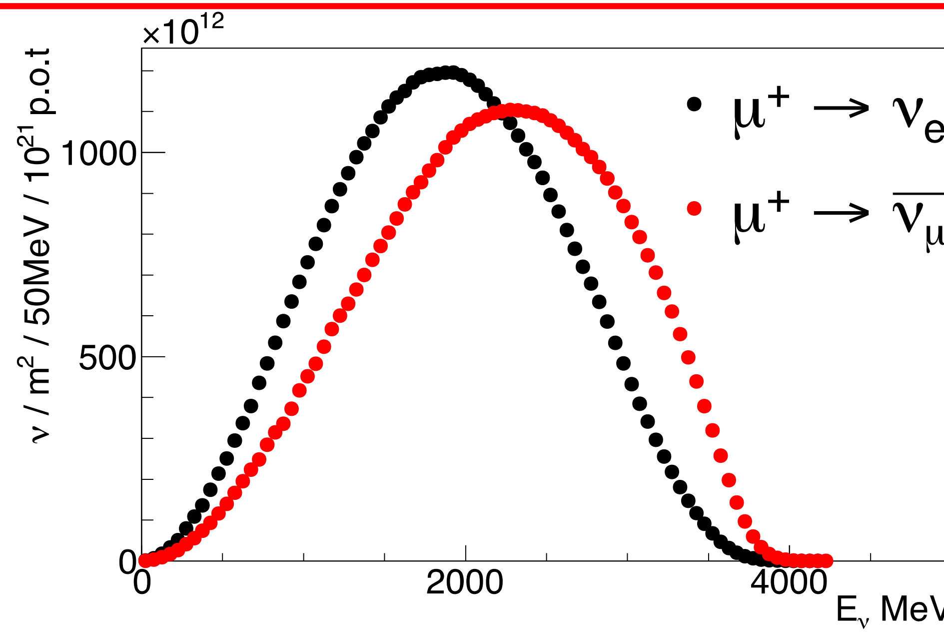
Existing Work - FNAL

- Serious proposal developed for FNAL
- FNAL taken to project definition report stage



Neutrino Flux





- Multiple channels available
- Good time separation
- Good source of electron neutrinos!

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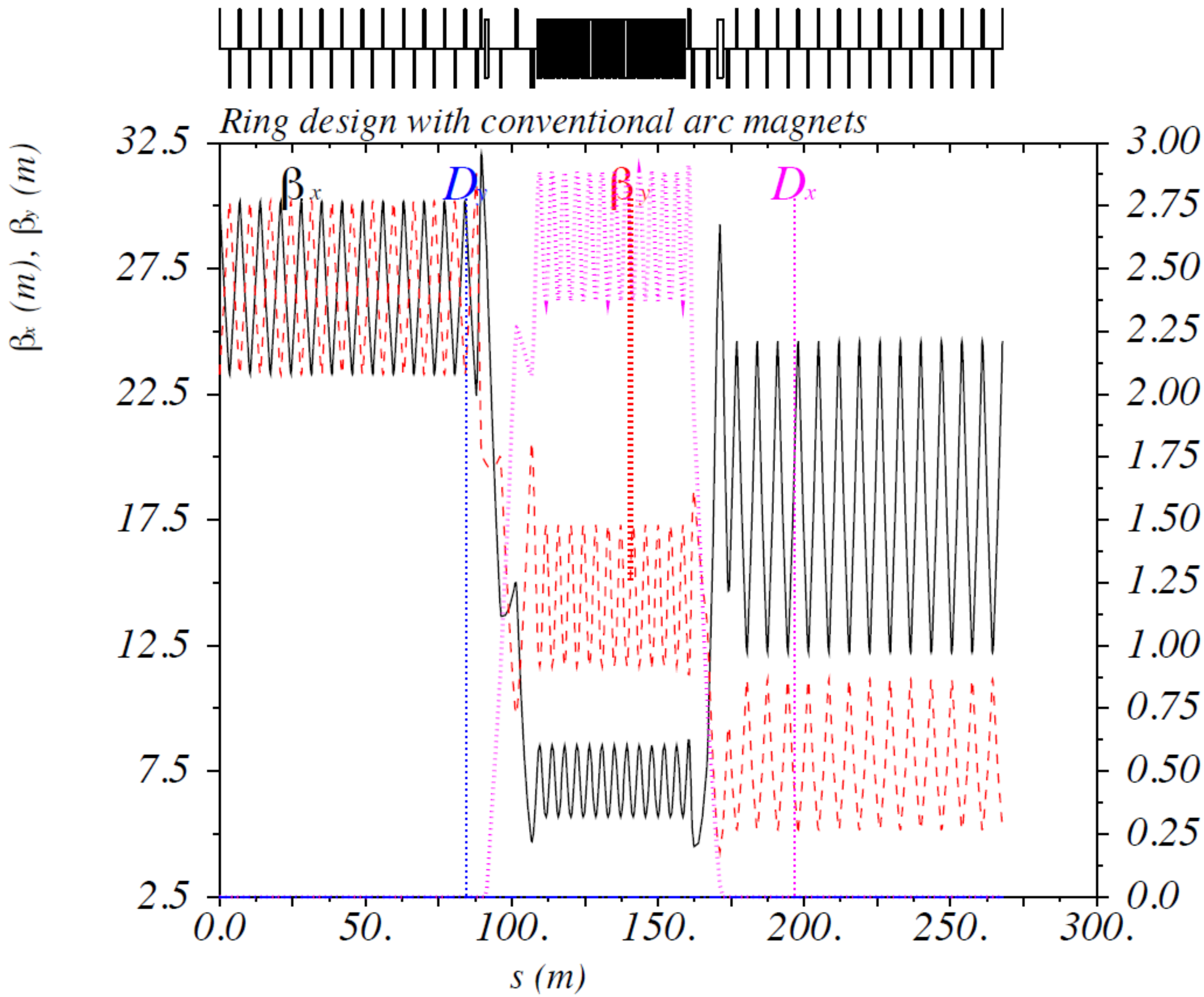
FODO design, A. Liu

Parameters	Values (units)
Central momentum $P_{0,\mu}$	3800 (MeV/c)
Circumference	535.9 (m)
Arc length	86.39 (m)
Straight length	181.56 (m)
(ν_x, ν_y)	(6.23, 7.21)
$(d\nu_x/d\delta, d\nu_y/d\delta)$	(-3.11,-12.73)

- Based on separated function AG lattice, well known technology
- Partial chromaticity correction with sextupoles was studied

FODO design, A. Liu



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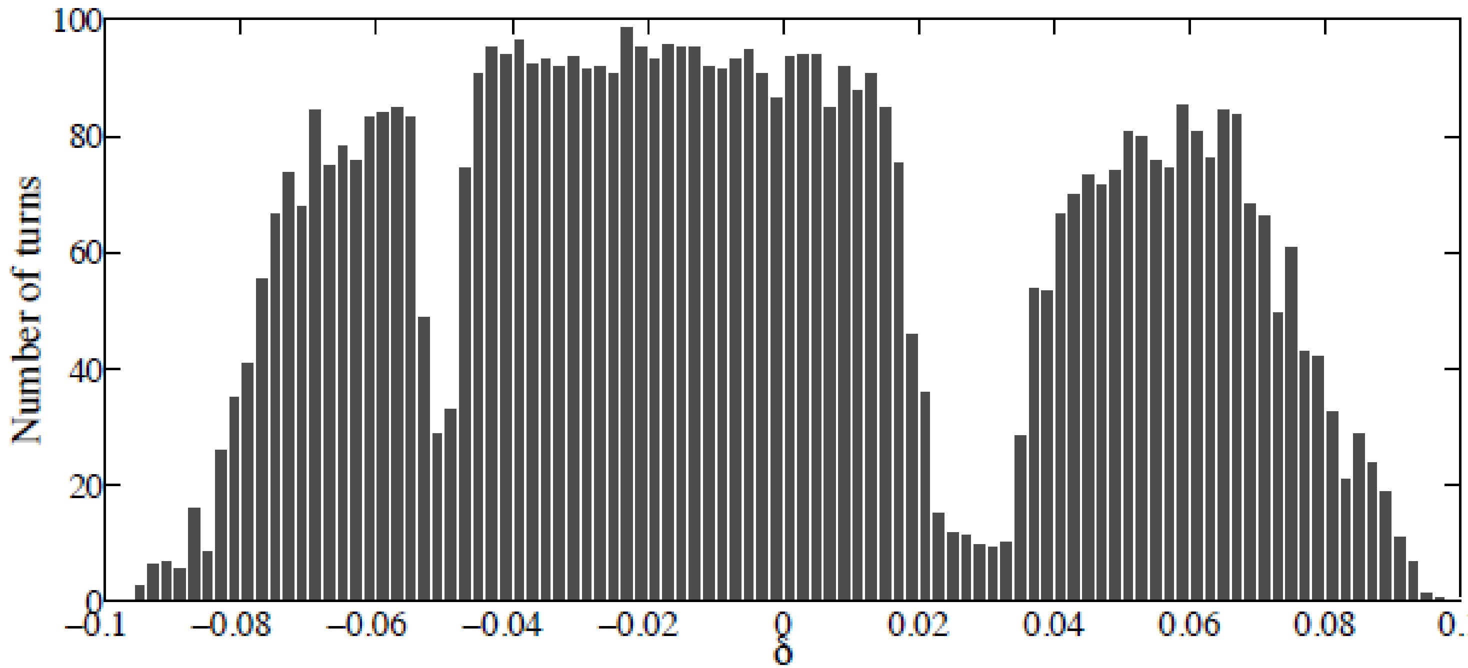
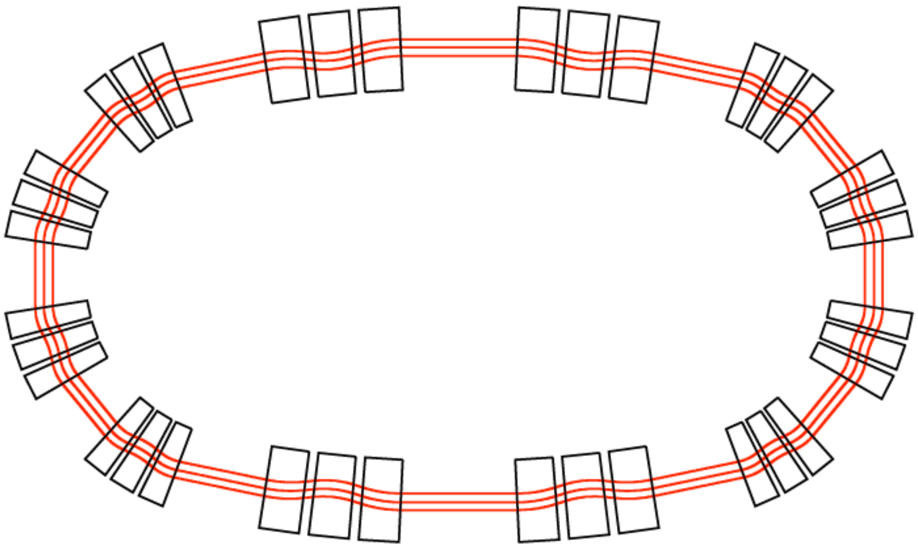
Losses in the FODO (w/o sextupoles)

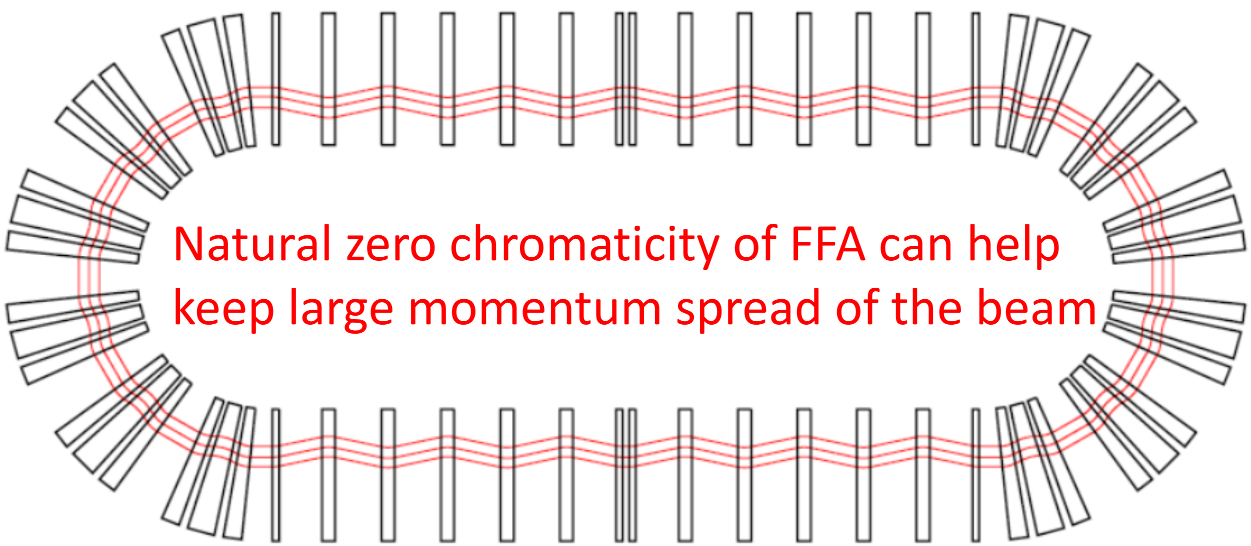


- Natural chromaticity leads to losses as a function of momentum
- Lattice errors not included
- Can we do better? Sextupolar correction was showing improvement, but,…

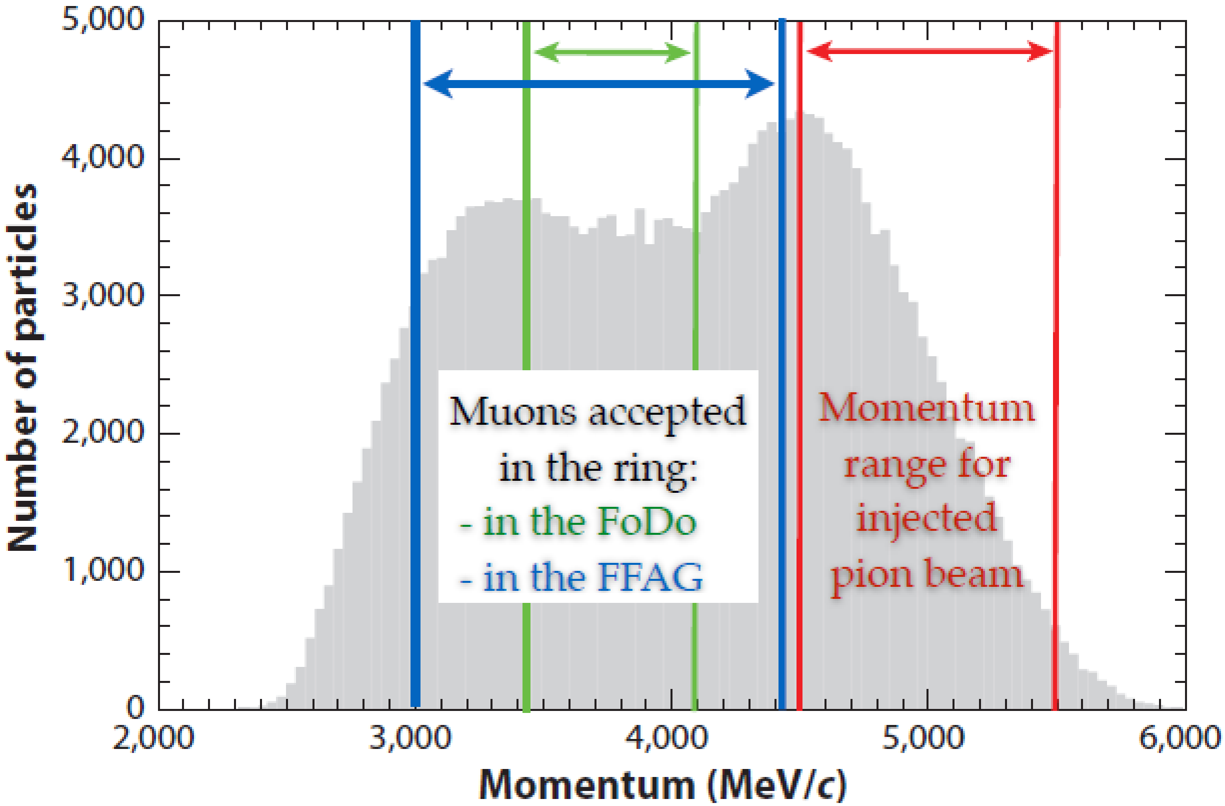
Advanced Fixed Field Alternating gradient (FFA) – can read Fixed Field Accelerator



By combining cells with different radius
or arcs with straight cells, long straight sections can be created and neutrino beam can be formed along them.



Advantage of FFA: large momentum acceptance



- FFA can accept □16% (triplet) or □19% total momentum spread.
- FODO - □9% with 58% efficiency (67% with sextupoles)

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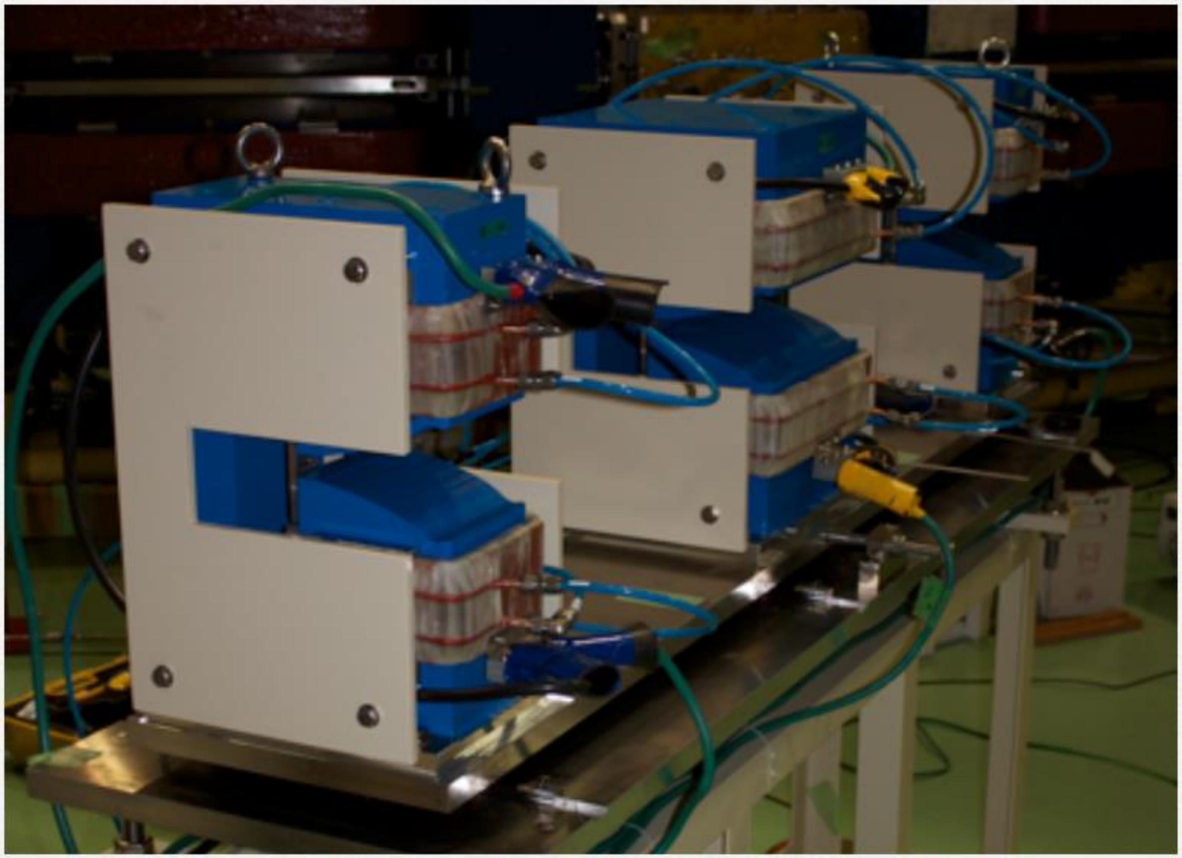
How to make straight cell?

Straight scaling FFA :

FFA cell with no overall bend.



J-B. Lagrange's thesis

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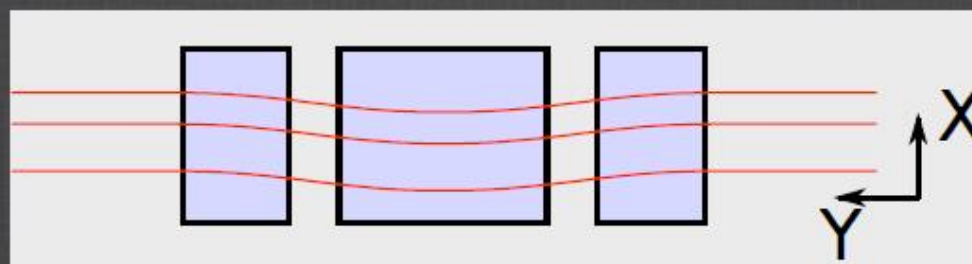
Straight FFA (principles)

Constant normalized field gradient: $m = \frac{1}{B_y}\frac{dB_y}{dx}$

$$B(X,Y) = B_0 e^{m(X-X_0)} \mathcal{F}\left(Y - (X - X_0)\tan\zeta\right)$$



Rectangular case: $\zeta = 0$

Tilted straight case: $\zeta = const.$

...however orbit scallop angle is present!

νSTORM Racetrack FFA

Constraints:

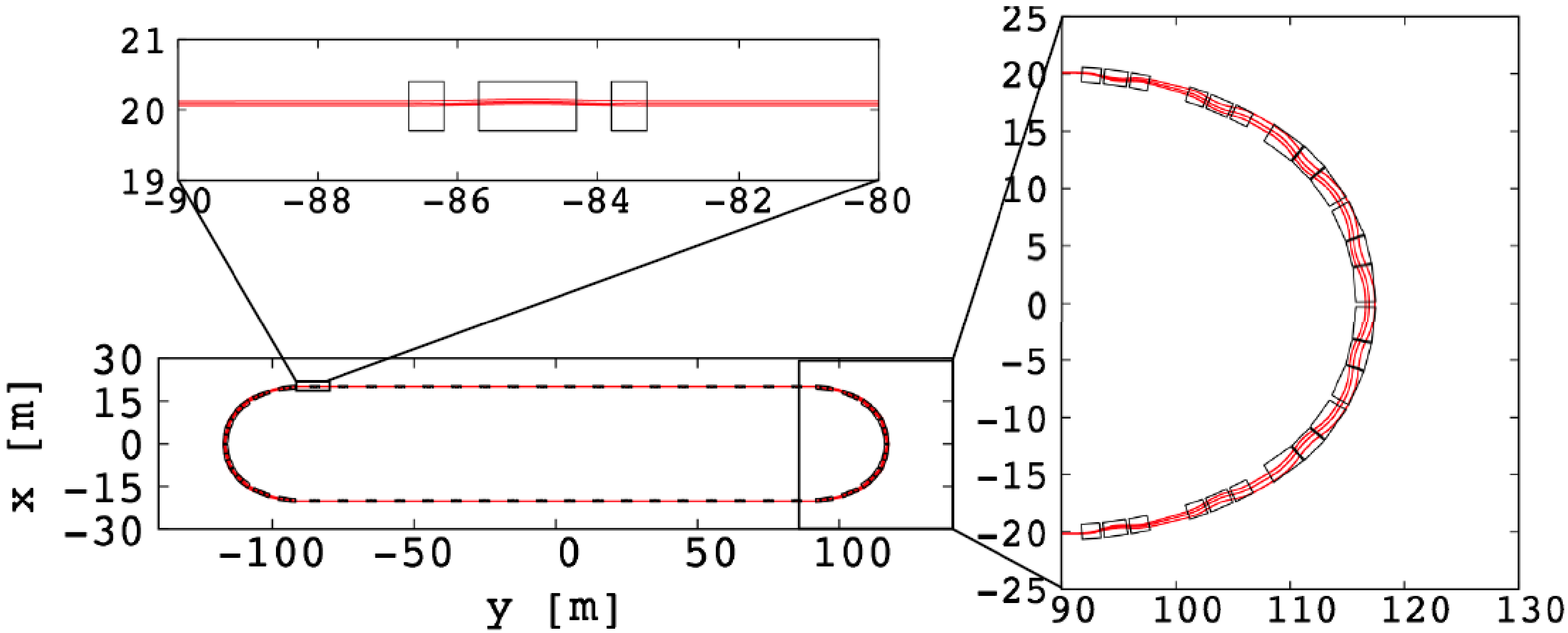
- in the straight part, the **scallop effect** must be as small as possible to collect the maximum number of neutrinos at the far detector.

- **Stochastic injection**: in the dispersion matching section, a drift length of 2.6 m is necessary to install a septum.

- to keep the ring as small as possible, **SC magnets in the arcs** are considered. **Normal conducting magnets in the straight part** are used.

- **large transverse acceptance** is needed in both planes: 1 (2) π mm.rad.

Triplet solution layout (J-B. Lagrange, JP)



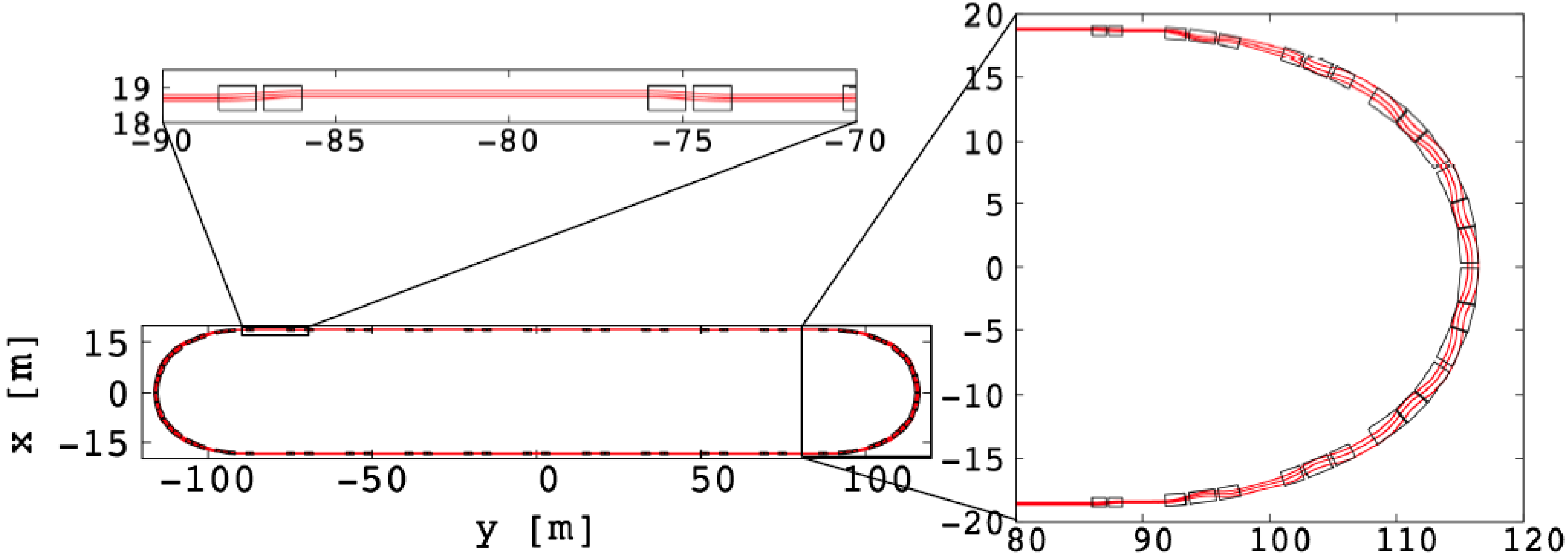
vSTORM

Triplet solution

Cell parameters

	Circular Section	Matching Section	Straight Section
Type	FDF	FDF	DFD
Cell radius/length [m]	17.6	36.2	10
Opening angle [deg]	30	15	
k-value/m-value	6.057	26.	5.5 m^{-1}
Packing factor	0.92	0.58	0.24
Maximum magnetic field [T]	2.5	3.3	1.5
horizontal excursion [m]	1.3	1.1	0.6
Full gap height [m]	0.45	0.45	0.45
Average dispersion /cell [m]	2.5	1.3	0.18
Number of cells /ring	4 × 2	4 × 2	36 × 2

Quadruplet solution
(J-B. Lagrange, JP)



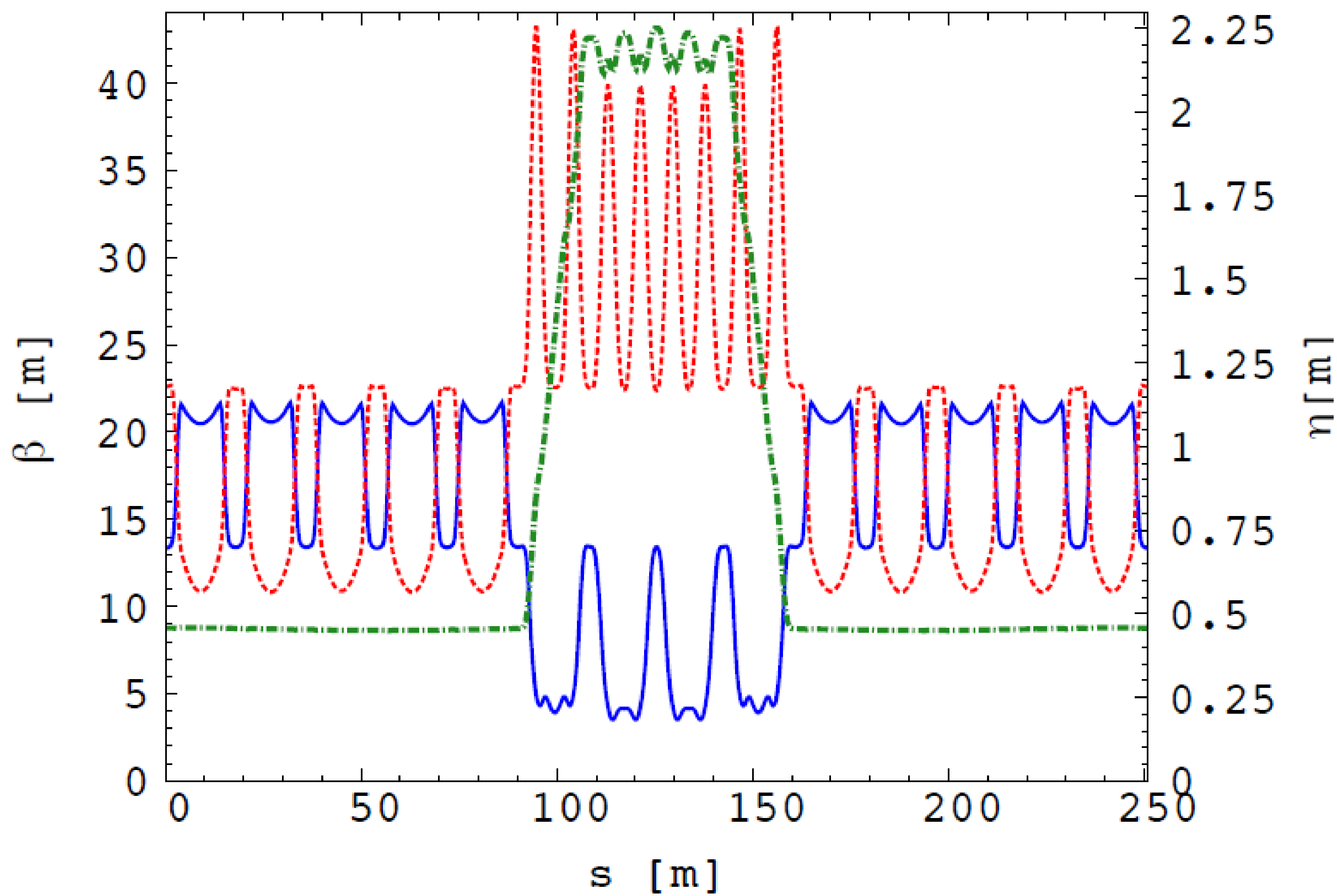
Lattice design includes three cell types
(dens arc, matching and straight ones)

Quadruplet Ring FFA parameters

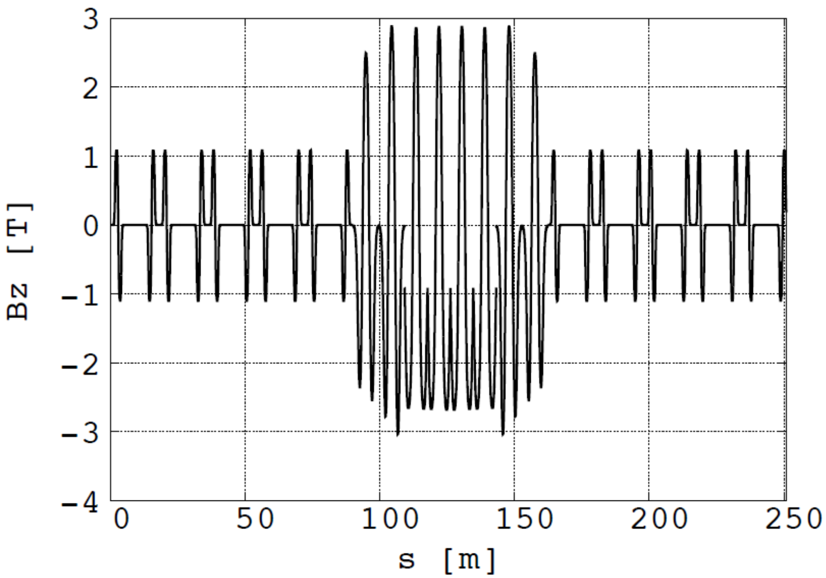
Cell parameters

	Circular Section	Matching Section	Straight Section
Type	FDF	FDF	DFFD
Cell radius/length [m]	15.8	36.1	18
Opening angle [deg]	30	15	
k-value/m-value	6.056	26.	$2.2\ m^{-1}$
Packing factor	0.92	0.58	0.24
Maximum magnetic field [T]	2.9	3.3	1.7
horizontal excursion [m]	1.4	0.9/1.3	0.7
Full gap height [m]	0.5	0.5	0.25
Average dispersion /cell [m]	2.23	1.34	0.45
Number of cells /ring	4×2	4×2	10×2

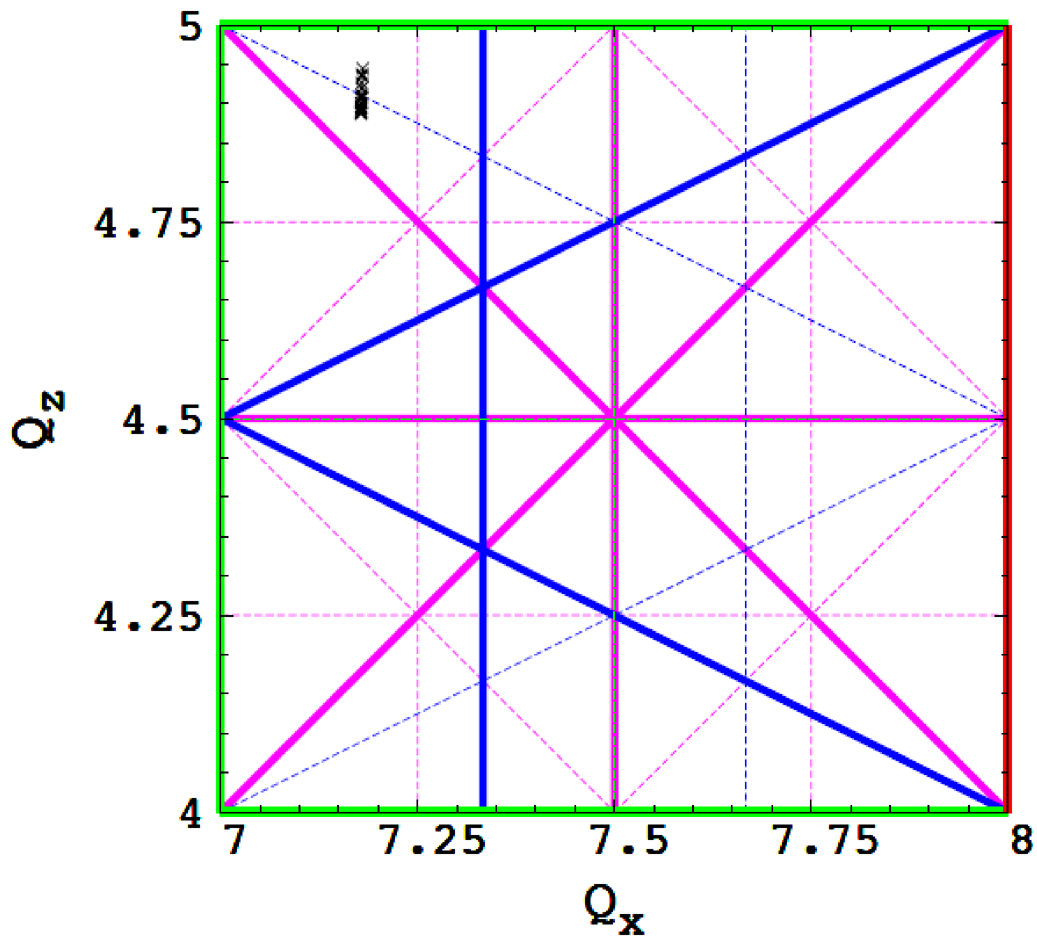
Quadruplet FFA, lattice functions



Quadruplet, lattice design



Magnetic field at the top momentum particle



Chromatic tune spread for ±19% momentum spread

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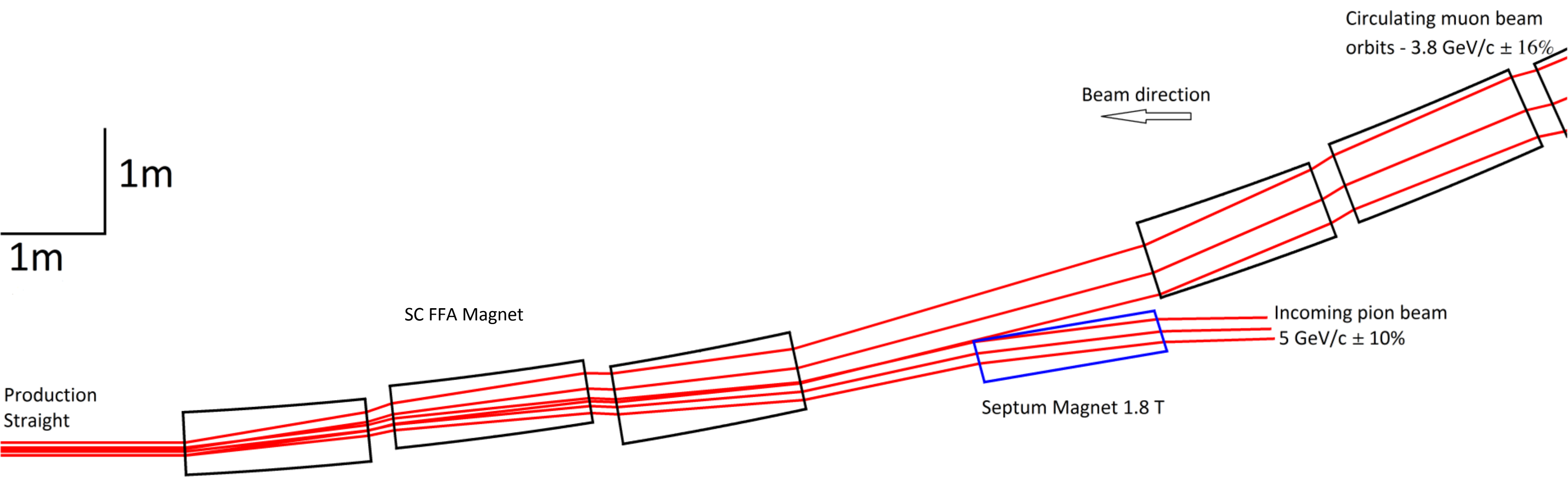
Injection section

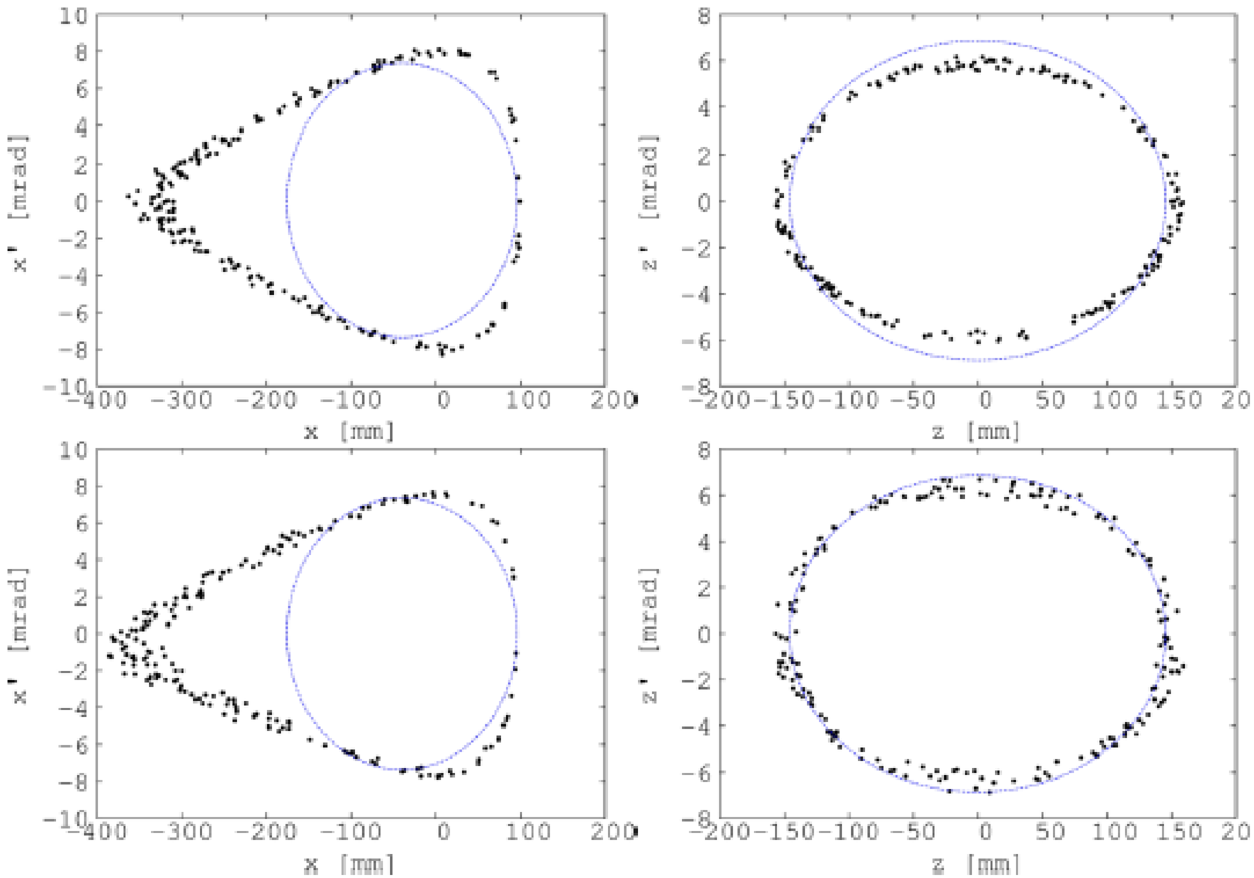


- Injection system will use septum magnet and NO kicker (stochastic injection)
- Special optics allows to introduce a sufficient straight section length

PyZgoubi vs JB's code comparison

JB

PyZgoubi



*Triplet lattice

S. Tygier,
First discussion of nuSTORM in the context of the Physics Beyond Colliders workshop, IC, 16/02/17

Very good agreement!

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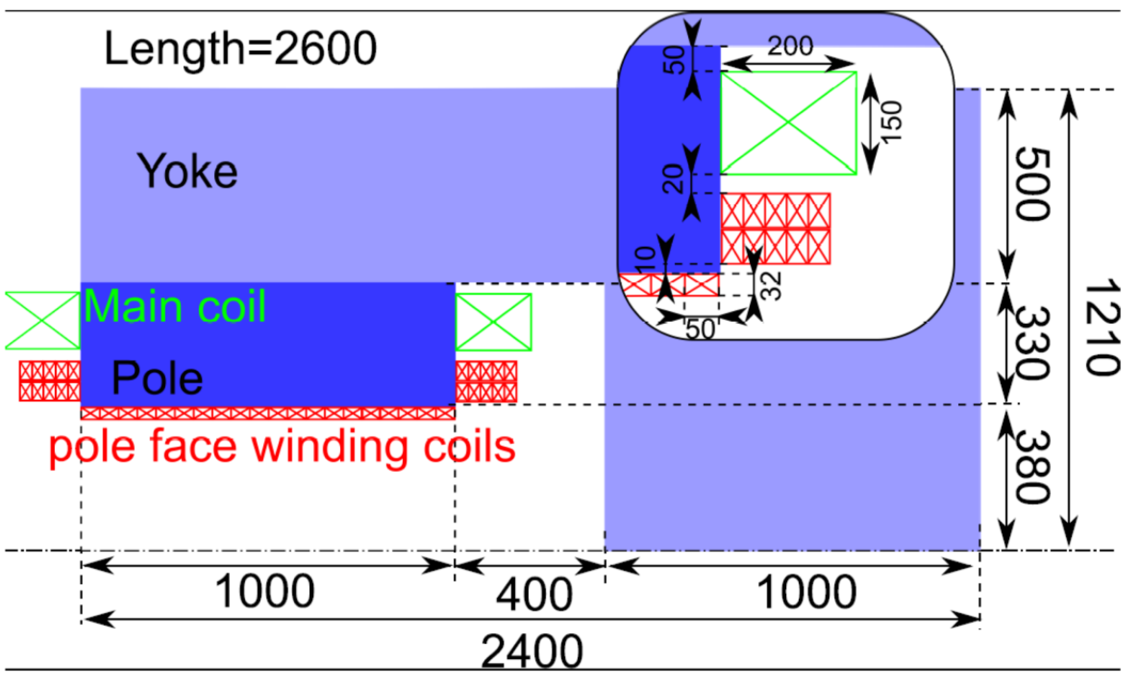
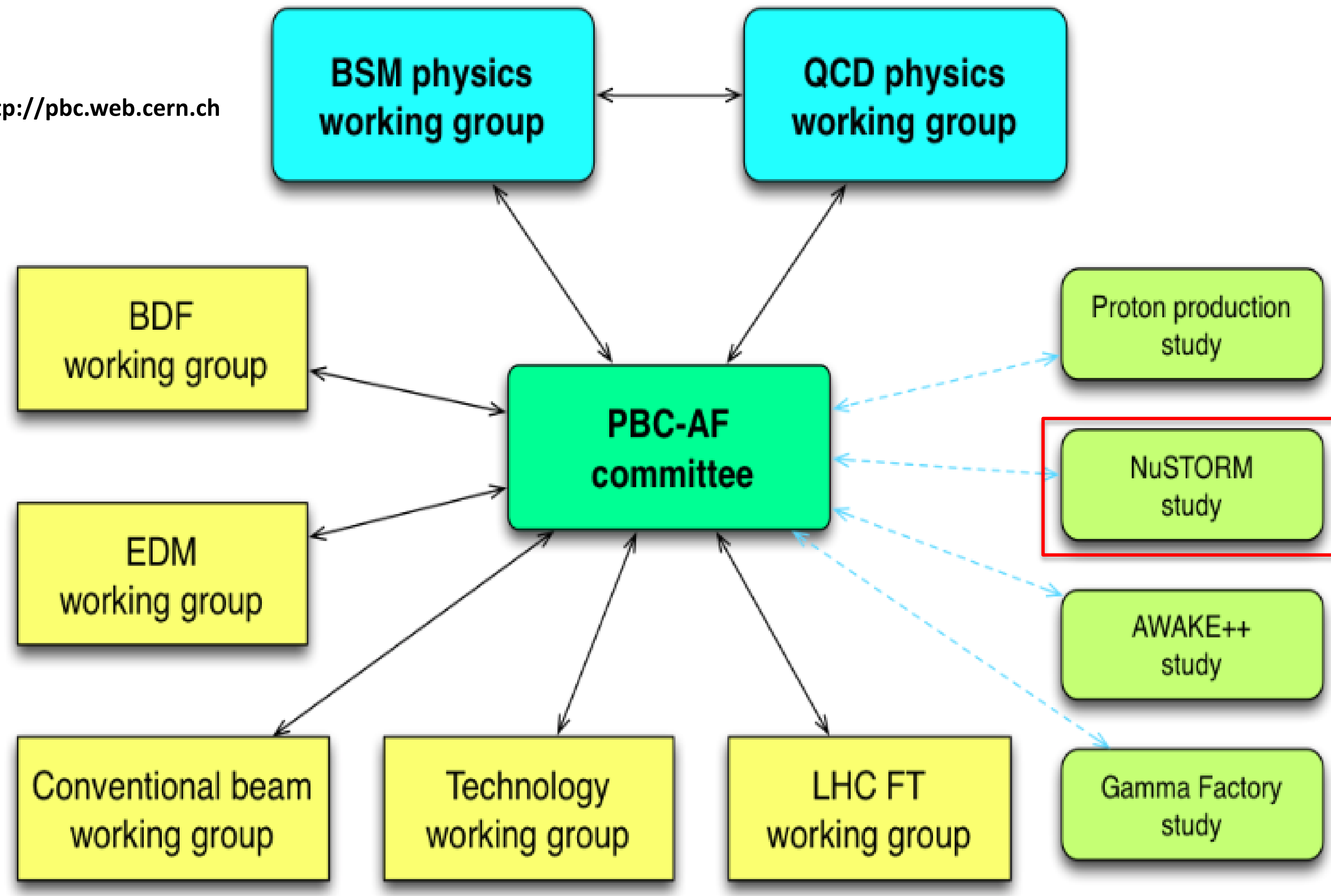
FFA arc magnet concept

- Superferric type, 3T
- Main coil combined with distributed coils to create the FFA required field



Physics Beyond Colliders study group

http://pbc.web.cern.ch



nuSTORM team within PBC

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

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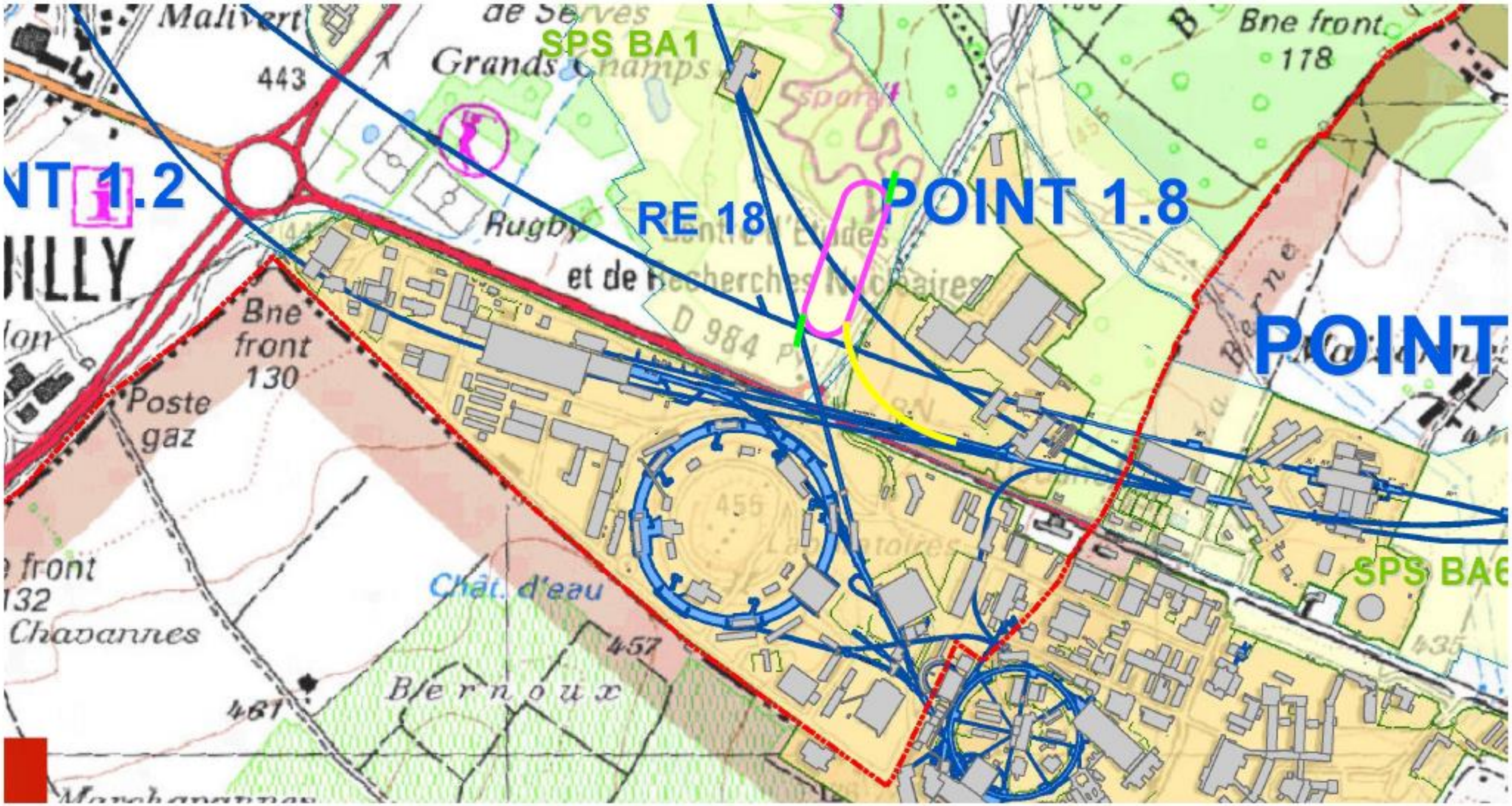
Discussions on a possible implementation of nuSTORM at CERN, I. Efthymiopoulos, PBC meeting at CERN, July 2017



A very promising option was identified!

nuSTORM @ CERN

- Initial proposal for siting at CERN to look at:
  - Muon energy range
  - SPS requirements
  - Fast extraction, beam-line
  - Siting
  - Target and target complex
  - Horn
  - Civil engineering
  - Radiation-protection implications

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CERN Physics Beyond Colliders

nuSTORM @ CERN - parameters

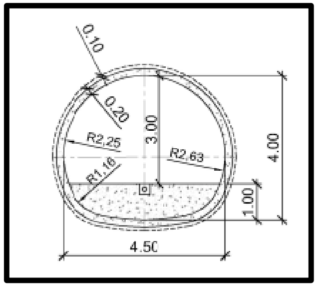
- Preliminary parameter table developed for discussion
- Now aiming at 6 GeV muons instead of 3.8 GeV -> scaled version of ring

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]

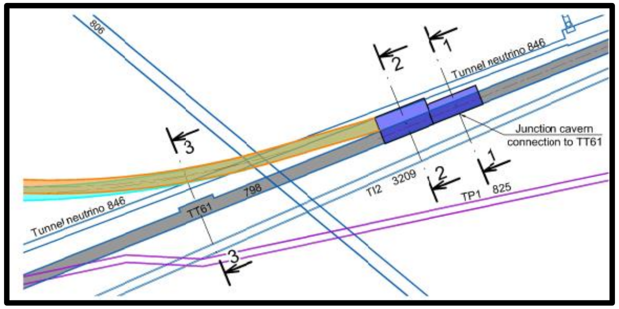
Civil Engineering - Development

- Latest options 4 and 5
- Option 4 with far target at Prevessin
- Option 5 with minimised tunnel length
- CERN Land
- Within mollase

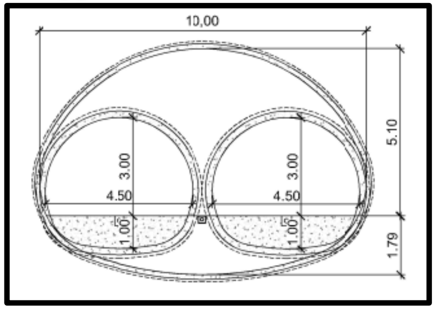
Potential far target at Prevessin



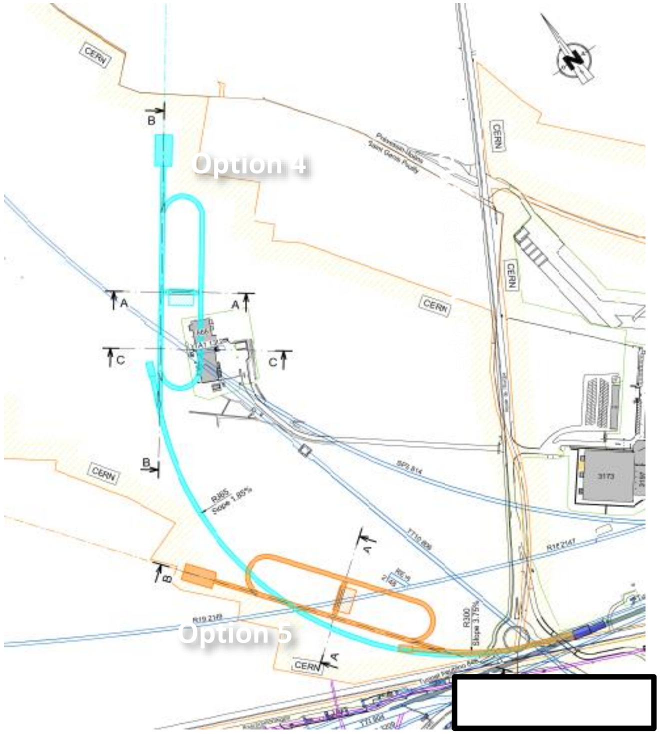
Typical section at 1-1



TT61 Extract – junction cavern



Typical section at 2-2



Plan View showing Options 4 and 5

Summary

- nuSTORM can measure neutrino interaction precisely, which can reduce systematic errors of neutrino oscillation experiments seeking CP violation signal and can contribute to the sterile neutrino search.
  - Can also serve as the R&D test bed for muon accelerators and neutrino detectors
- Solid designs exist and could be implemented straightaway (FODO or FFA)
- FFA design allows to substantially increase the ring’s momentum acceptance (and so the neutrino flux), while maintaining a very large transverse acceptance
- Siting at CERN option was identified (within PBC) and civil engineering study shows not show-stoppers. Initial review of siting issues includes:
  - Extraction
  - Beam-to-target
  - Target
  - Radiation protection
- Further design optimisation to continue within PBC and report will be submitted to the European Particle Physics Strategy Update