Imperial College London

K. Long,
25 February 2013

Neutrino Factory and nuSTORM

"Snowmass Preparatory mini-Workshop on Frontier Capabilities: Accelerator Technology Test Beds and Test Beams."

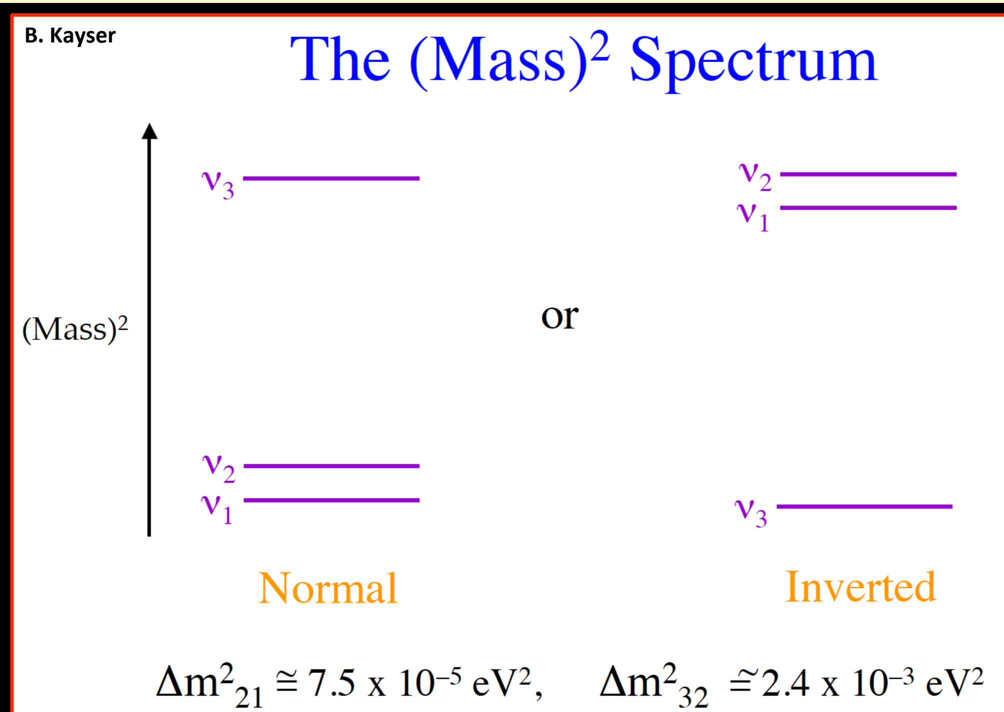
Contents:

- Neutrino Factory
- nuSTORM
- Elements of a staged programme

Standard Neutrino Model:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$\times \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$



- Three mass states linked to three flavour states via *unitary* mixing matrix;
- Additional, *sterile*, states conceivable:
  - Would imply:
    - 3-neutrino mixing matrix not unitary

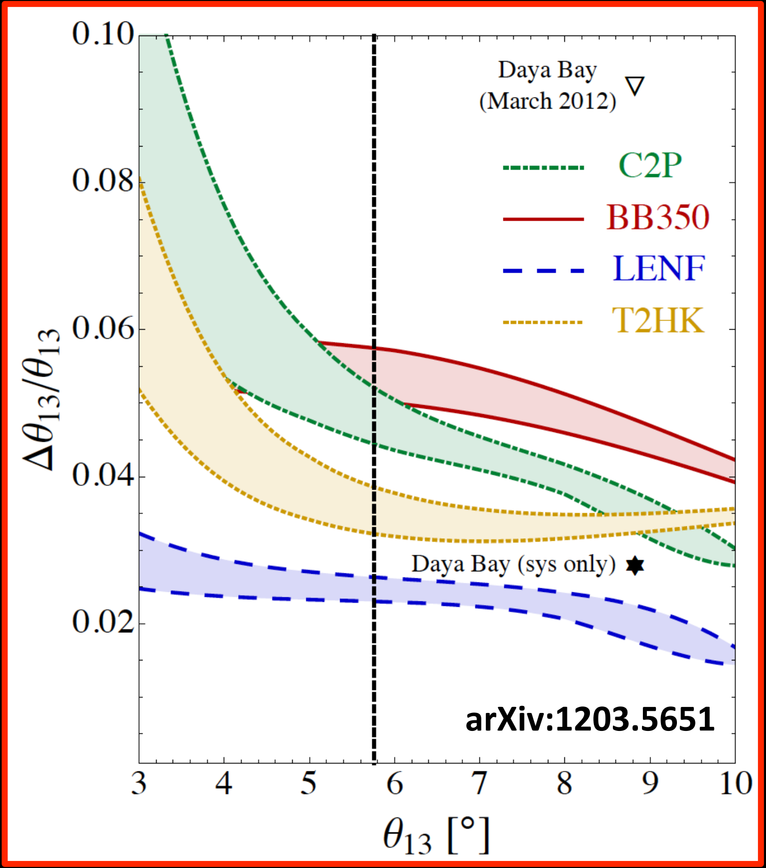
Neutrino Factory and nuSTORM:

Neutrino Factory

The SνM measurement programme:

- Looking beyond MINOS, T2K, NOνA, DChooz, Daya Bay, Reno, …
  - θ_{13} will be very well known

- Therefore future programme must:
  - Complete the "Standard Neutrino Model" (SνM):
    - Determine the mass hierarchy
    - Search for (and discover?) leptonic CP-invariance violation
  - Establish the SνM as the correct description of nature:
    - Determine precisely the degree to which θ_{23} differs from $\pi/4$
    - Determine θ_{13} precisely
    - Determine θ_{12} precisely
  - Search for deviations from the SνM:
    - Test the unitarity of the neutrino mixing matrix
    - Search for sterile neutrinos, non-standard interactions, …



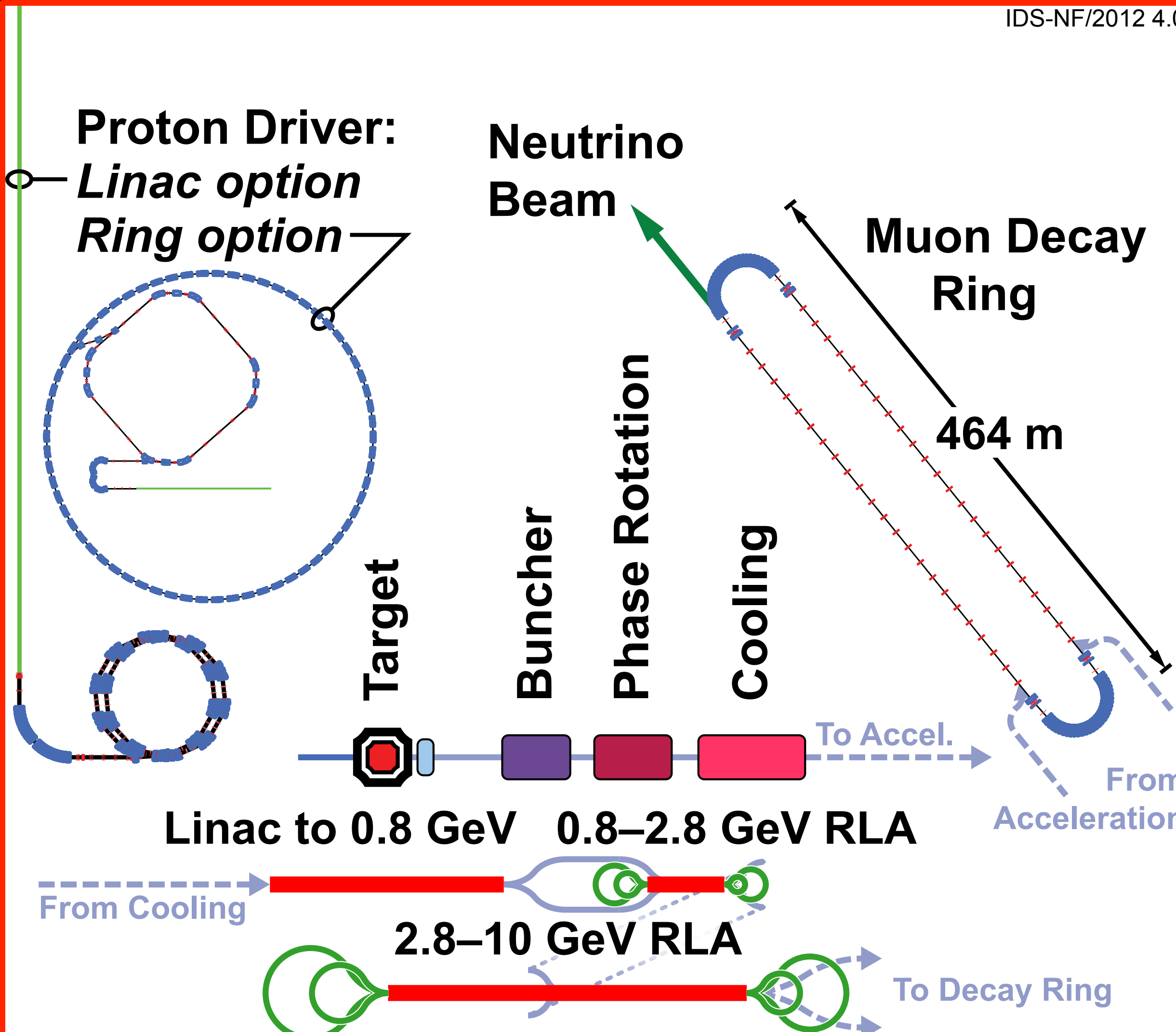
Neutrino Factory:

- Optimise discovery potential for CP and MH:
  - Requirements:
    - Large ν_e ($\bar{\nu}_e$) flux
      - Detailed study of sub-leading effects
- Unique:
  - (Large) high-energy ν_e ($\bar{\nu}_e$) flux
    - Optimise event rate at fixed *L/E*
    - Optimise MH sensitivity
    - Optimise CP sensitivity

Stored $\mu^- \to e^- \nu_\mu \bar{\nu}_e$	
Disappearance	**Appearance**
$\bar{\nu}_e \to \bar{\nu}_e \to e^+$	$\bar{\nu}_e \to \bar{\nu}_\mu \to \mu^+$ $\bar{\nu}_e \to \bar{\nu}_\tau \to \tau^+$
$\nu_\mu \to \nu_\mu \to \mu^-$	$\nu_\mu \to \nu_e \to e^-$ $\nu_\mu \to \nu_\tau \to \tau^-$

All channels available at the Neutrino Factory

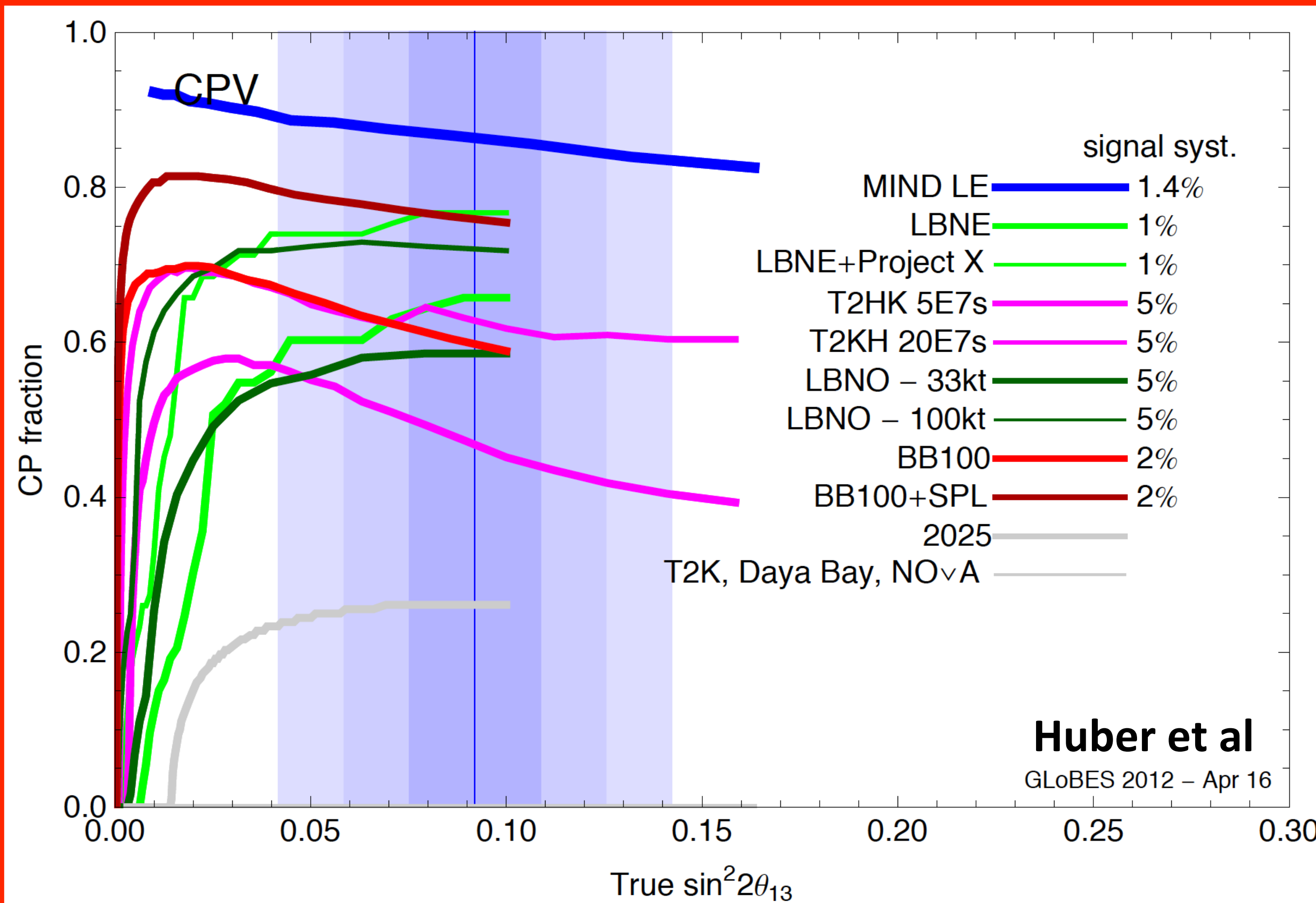
	Value
Accelerator facility	
Muon total energy	10 GeV
Production straight muon decays in 10^7 s	10^{21}
Maximum RMS angular divergence of muons in production straight	$0.1/\gamma$
Distance to intermediate baseline detector	1 500–2 500 km



P. Coloma, P. Huber et al, IDS-NF#8:
https://www.ids-nf.org/wiki/GLA-2012-04-18/Agenda

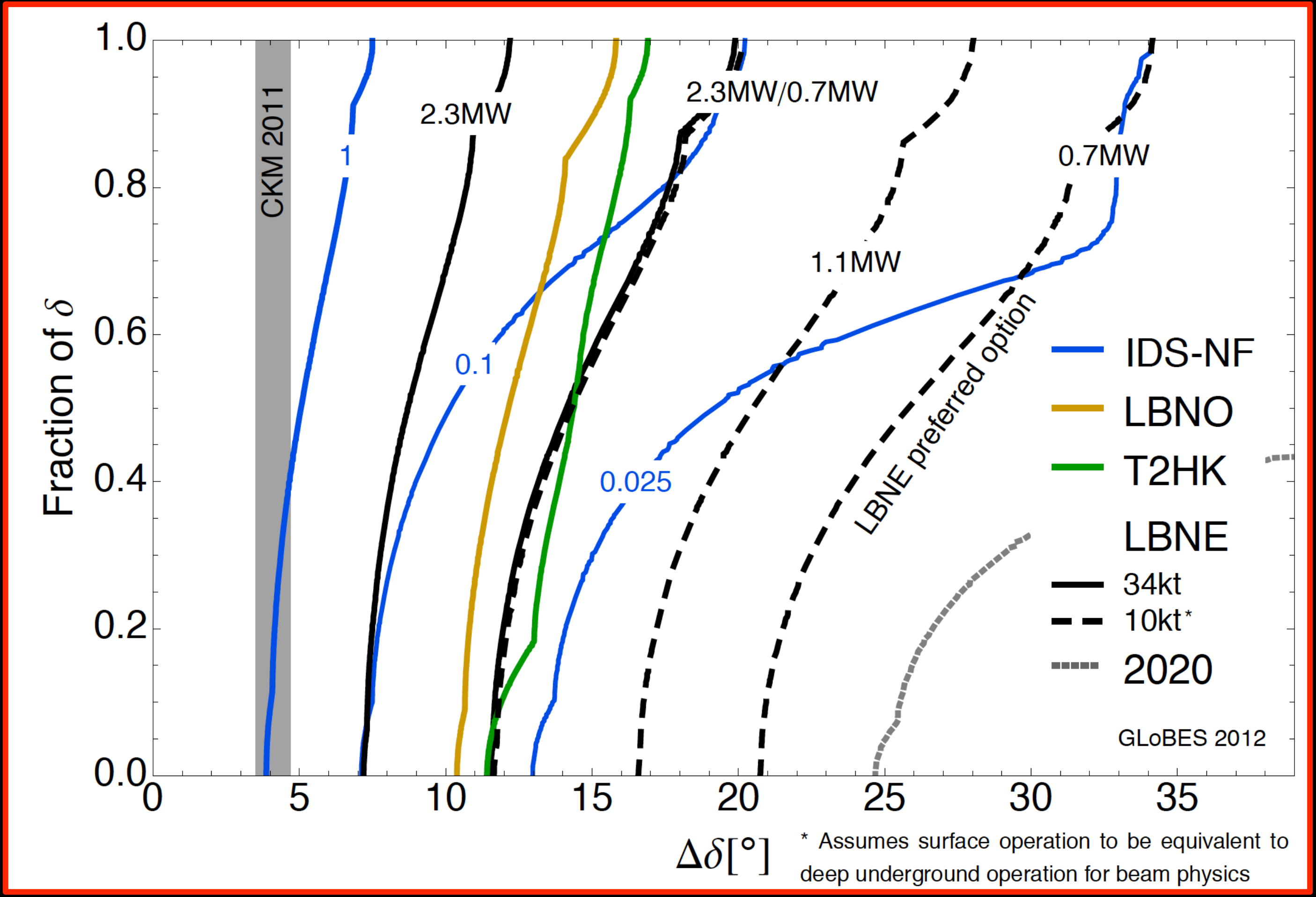
Discovery reach:

- Discovery reach at 3σ:
  - Neutrino Factory: 85—90%
  - Beta beam and SPL: 70—80%
  - Super beam: 60—75%



Coloma, Huber, Kopp, Winter
arXiv:1209.5973

Comparison:



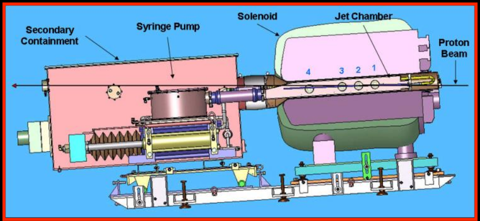
- **Benefit of luminosity:**
  - **Solid blue lines show effect on precision of scaling luminosity from baseline 10^{21} decays per year**
  - **Potential for definition of staged upgrade programme**

Accelerator challenges:

- Proton driver:
  - 4 MW; 5 < Ep < 15 GeV; bunch length 1—3 ns
  - Linac (CERN, FNAL) and ring (RAL, JPARC) options: Progress: costing based on SPL
- Pion-production target:
  - Baseline: liquid mercury jet
  - Options: powder jet or solid
  - Progress: particle shielding, magnetic lattice
- Muon front end:
  - Chicane (new) to remove secondary hadrons:
    - Bent solenoid transport & beryllium absorber
  - Buncher & rotator:
    - Progress: lattice revision in response to engineering study
  - Cooling:
    - Baseline: solenoid transport, LiH absorber
    - Options: bucked coils or high-pressure H2
    - Progress: lattice revision in response to engineering study
- Rapid acceleration:
  - Two options considered for acceleration to 10 GeV:
    - Linac, RLA I and RLA II;
    - Linac, RLA I and FFAG
  - Choice based on cost and performance estimates

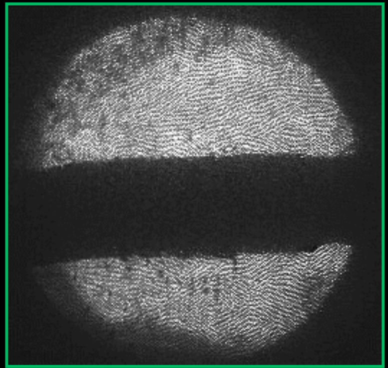
- Proton driver:
  - Development of high-power, pulsed proton source
    - FETS; PIXIE; [R&D programme outlined by Prebys]
      - Large charge, very short bunches
- Pion-production target:
  - MERIT experiment at CERN proved principle of mercury jet target
    - Need to distinguish pre-construction development from proof of principle
- Muon front end:
  - MuCool programme at FNAL:
    - Study of effect of magnetic field on high-gradient, warm, copper cavities;
    - Critical programme
  - MICE experiment at RAL:
    - Proof of principle of ionization-cooling technique
    - Critical programme
  - RF power sources (e.g. Diacrode) at LANL:
    - Some work at LANL, however, cost driver for the Neutrino Factory
      - Deserves more attention
- Rapid acceleration:
  - EMMA experiment at DL:
    - Proof of principal of non-scaling FFAG technique;
      - Novel technology allows circular acceleration without magnet ramp
  - Superconducting, 201 MHz resonators at Cornell:
    - Some work at Cornell, however, significant part of cost of muon acceleration
      - Deserves more attention

Baseline target: proof of principle: MERIT:

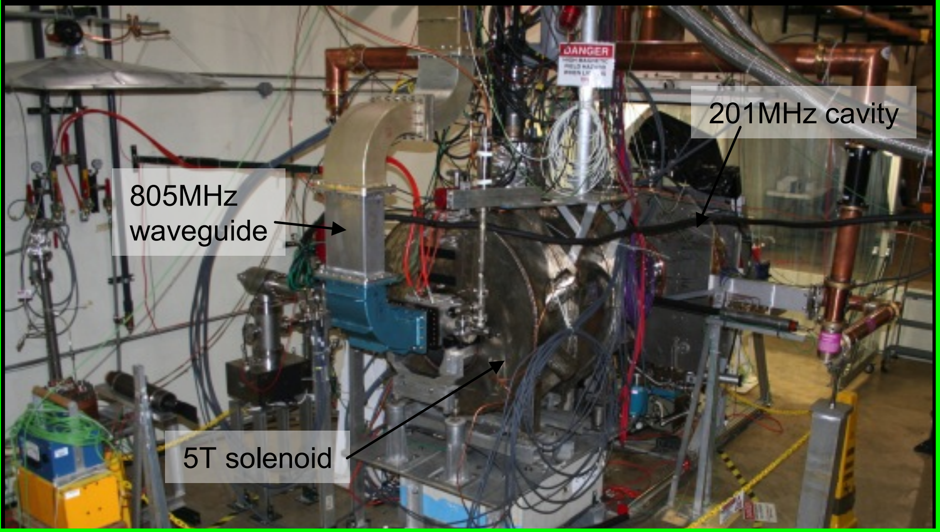


- 'Disruption length': 28 cm
- 'Refill' time: 14 ms
  - Corresponds to 70 Hz
- Hence:
  - Demonstrated operation at:
    - 60 kJ × 70 Hz = 8 MW

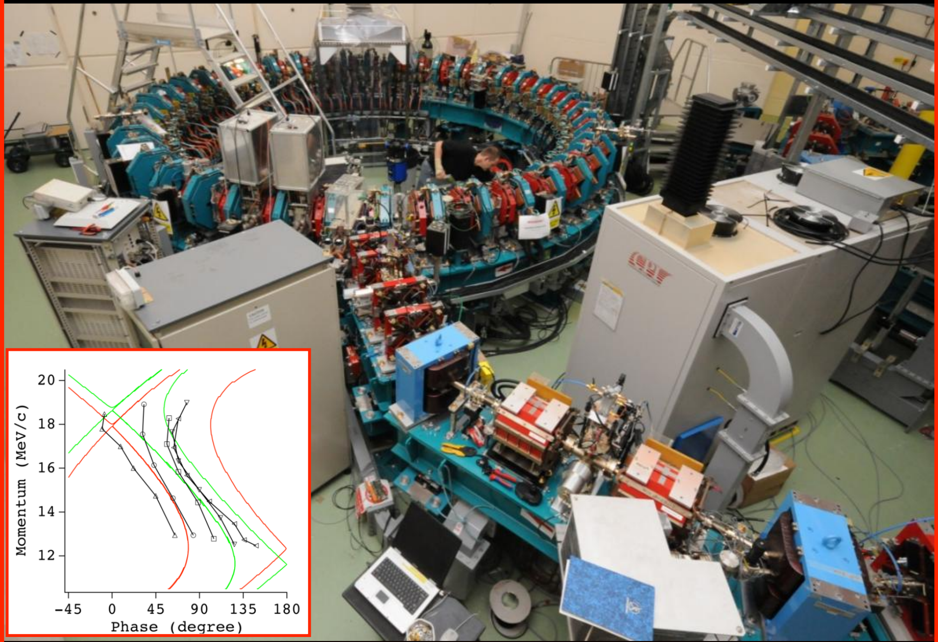
- 20 m/s liquid Hg jet in 15 T B field
- Exposed to CERN PS proton beam:
  - Beam pulse energy = 115 kJ
  - Reached 30 tera protons at 24 GeV



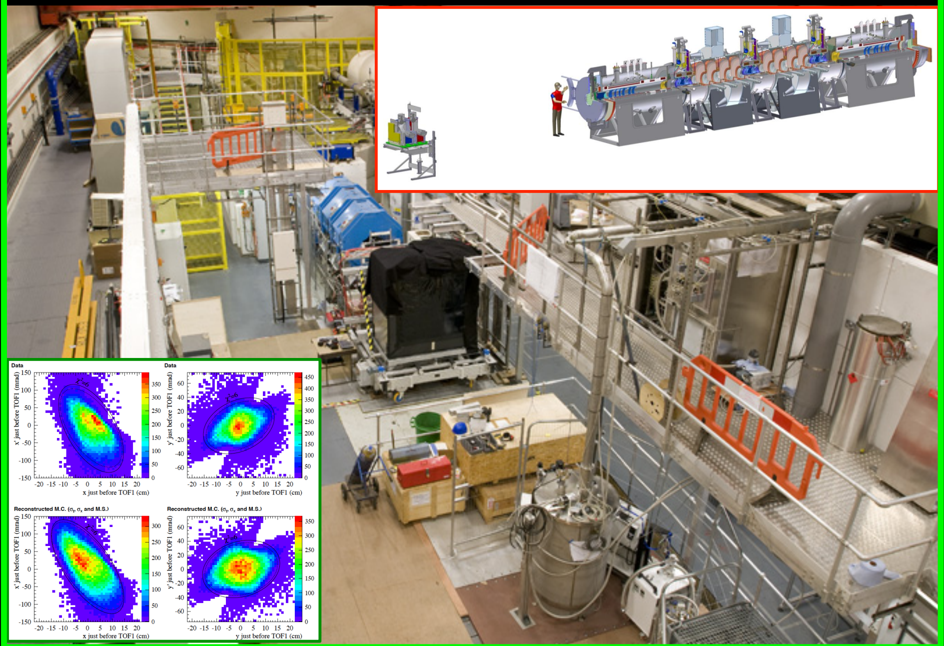
MuCool: cavities in magnetic field



Electron Model of Muon Acceleration (EMMA)



International Muon Ionization Cooling Experiment



Neutrino Factory and nuSTORM:

nuSTORM

What we need to measure:

- Present, inconclusive, information from $\nu_e \rightarrow \nu_X$ and $\nu_\mu \rightarrow \nu_X$ transitions
- Ideally, study:

Flavor Transition	CPT Conjugate
$\nu_e \rightarrow \nu_\mu$	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
$\bar{\nu}_e \rightarrow \bar{\nu}_\mu$	$\nu_\mu \rightarrow \nu_e$
$\nu_e \rightarrow \nu_{\not{e}}$	$\bar{\nu}_e \rightarrow \bar{\nu}_{\not{e}}$
$\nu_\mu \rightarrow \nu_{\not{\mu}}$	$\bar{\nu}_\mu \rightarrow \bar{\nu}_{\not{\mu}}$

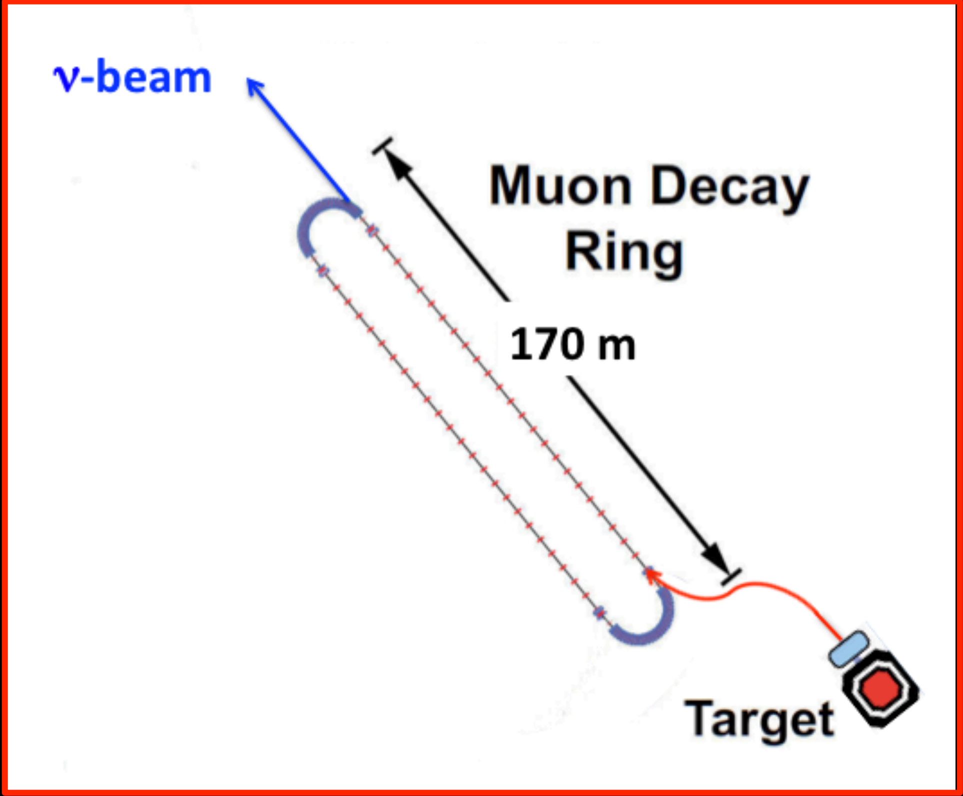
and

- Determine neutral current rate
  - oscillation to steriles will change neutral current rate
- Study $\nu_e N$ and $\nu_\mu N$ scattering
  - including hadronic final states to eliminate background uncertainties

Concept:

- Entry-level Neutrino Factory:
  - Known technology

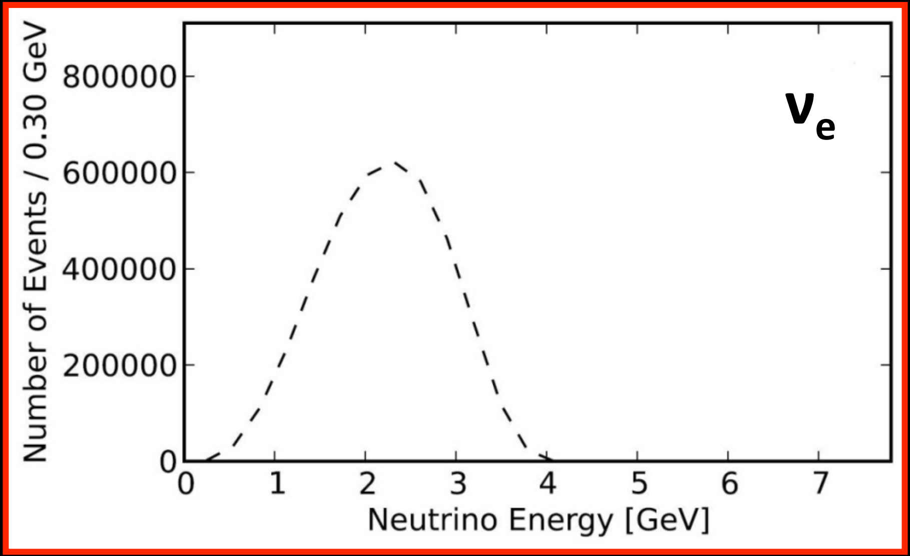
- 100 kW Target Station
  - FNAL:
    - 60 GeV protons from MI in PIP era
  - CERN:
    - 100 GeV protons from SPS post Linac4
- Target and collection:
  - "Heavy metal"
  - Optimization on-going
  - Horn collection baseline
    - Li lens has also been explored
- Collection/transport, two options:
  - Stochastic injection of π
  - Kicker with π → μ decay channel
- Decay ring
  - Large aperture FODO
  - Racetrack FFAG
- Instrumentation
  - BCTs, mag-Spec in arc, polarimeter

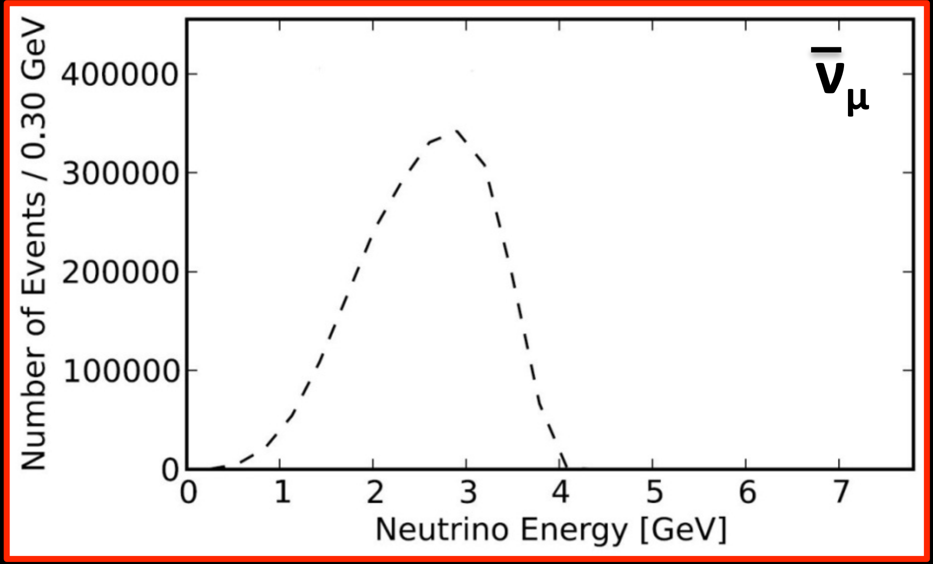


- Neutrino detectors:
  - Magnetised iron calorimeter (SuperBIND);
  - Suite of near detectors for cross-section programme

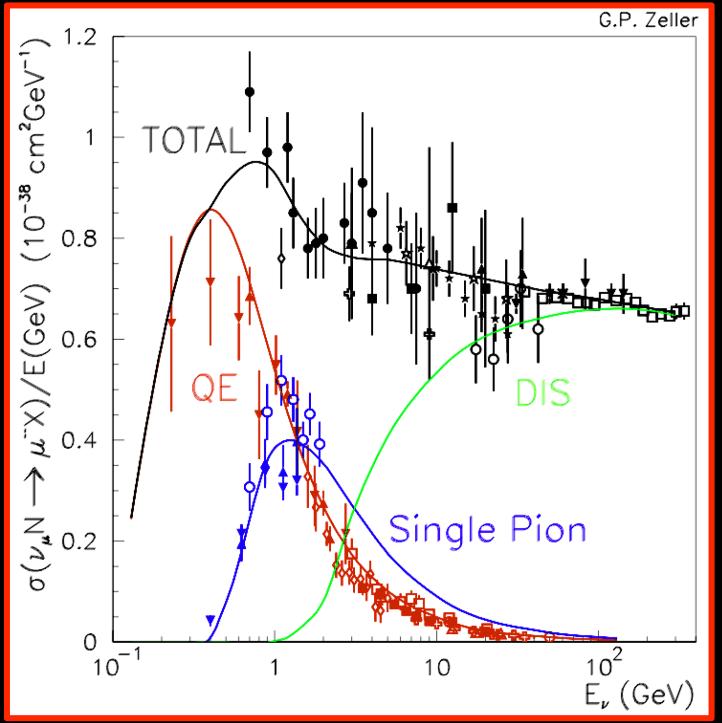
Neutrino characteristics	Fermilab	CERN
Aimed neutrino energy [GeV]	1.0 to 3.0	1.0 to 3.0
Flux measurement precision [%]	1.0	1.0
Protons on target (POT)	10^{21}	2.310^{20}
Useful μ decays [10^{18}]	1.00	$100/60 = 1.67$
Production, horn and injection		
Target (Ta) diameter/length [m], material	0.01/0.21	- / -
Pulse length [μs]	1.0	10.5
Proton energy [GeV/c]	60	100
Pion energy [GeV/c]	$5.0 \pm 10\%$	$5.0 \pm 10\%$
Horn diameter/length [m]	- / 2.0	- / -
Reflector diameter/length [m]	-	- / -
Current Horn/Reflector [kA]	300	- / -
Estimated collection efficiency	0.8	0.8
Estimated transport efficiency	0.8	0.8
Estimated injection efficiency	0.9	0.9
Acceptance [mm rad]	2.0	2.0
π/pot within momentum acceptance	0.11	$0.11 \times \frac{100}{60} = 0.187$
Length of target [m]	0.21	0.21
Distance between target and horn [m]	inside	inside
Length of horn [m]	2.0	-
Distance between horn and injection [m]	20	20
The muon storage ring		
Momentum of circulating muon beam [GeV/c]	3.8	3.8
Momentum of circulating pion beam [GeV/c]	$5.0 \pm 10\%$	$5.0 \pm 10\%$
Circumference [m]	350	350
Length of straight [m]	150	150
Ratio of Lstraight to ring circumference [Ω]	0.43	0.43
Dynamic aperture, $\mathrm{A_{dyn}}$	0.7	0.7
Acceptance [mm rad]	2.0	2.0
Decay length [m]	240	240
Fraction of π decaying in straight ($\mathrm{F_s}$)	0.41	0.41
Relative μ yield ($\mathrm{A_{dyn}} \times (\pi$ per POT$) \times \mathrm{F_s} \times \Omega$)	0.014	
Detectors		
Distance from target [m]	20/1600	300/1800-2700

nuSTORM x-section measurement potential:



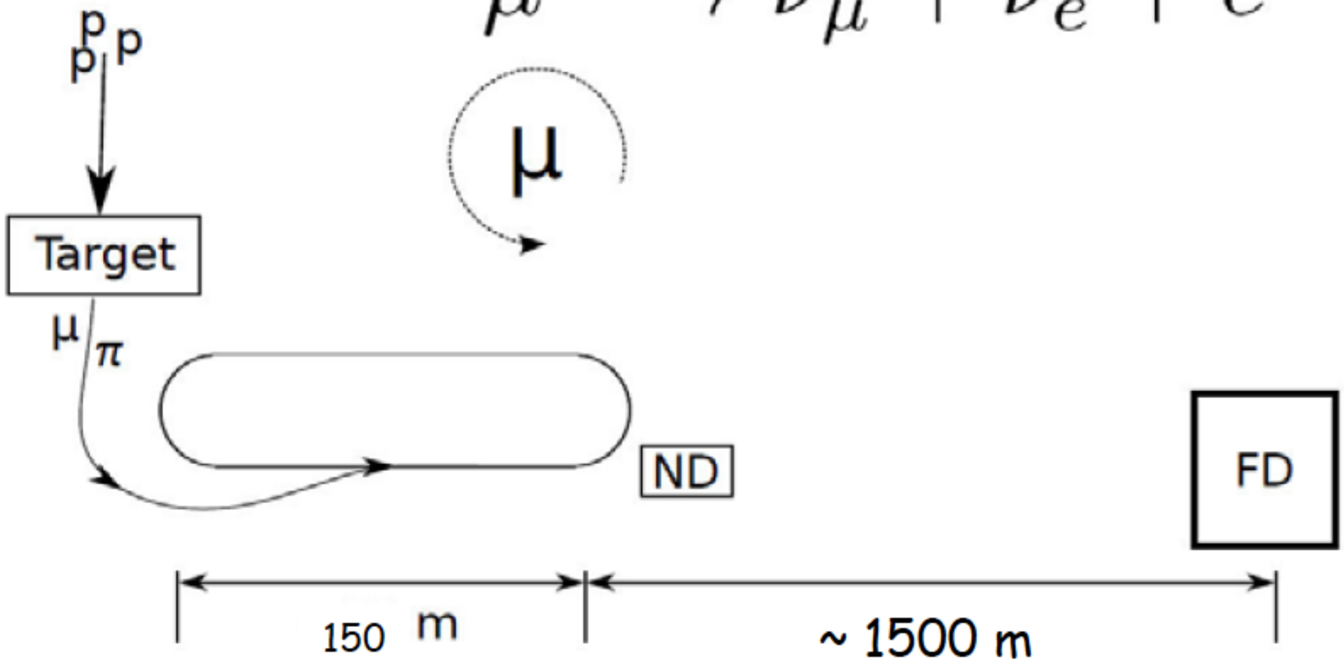


- **Above (for stored μ^+):**
  - **nuSTORM event rates/100T at near detector 50 m from straight with μ^+ stored**
- **Right:**
  - **State of the art:**
    - **Almost no ν_e measurements**



Sterile neutrino search concept:

$$\mu^+ \rightarrow \bar{\nu}_\mu + \nu_e + e^+$$

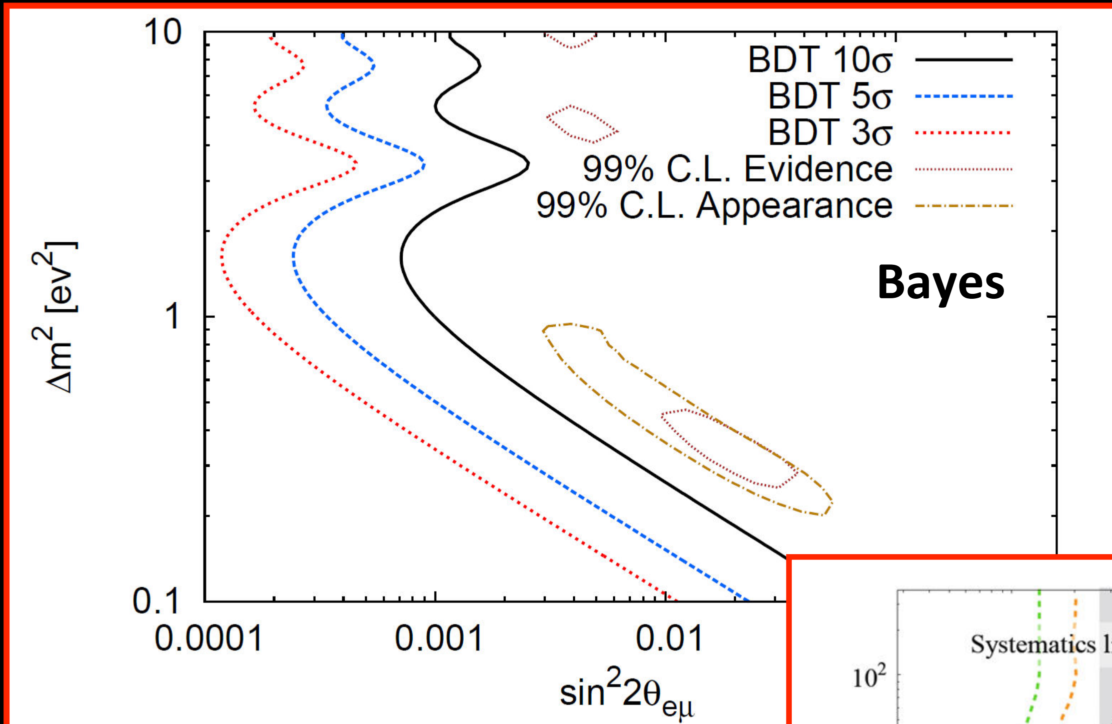


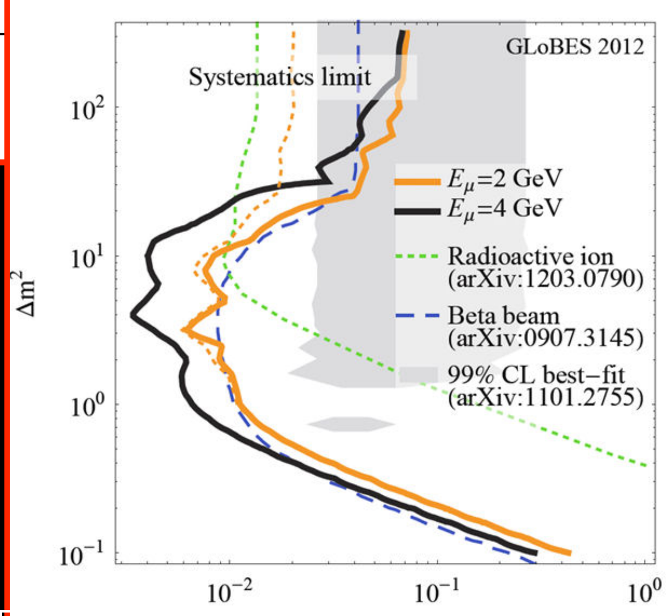
Appearance-only (though disappearance good too!)

$$Pr[e \rightarrow \mu] = 4|U_{e4}|^2|U_{\mu 4}|^2 \sin^2(\frac{\Delta m^2_{41} L}{4E})$$

LOI [Bross et al];
Fermilab proposal P-1080 &
arXiv:1206.0294

nuSTORM: performance:





Winter, disappearance

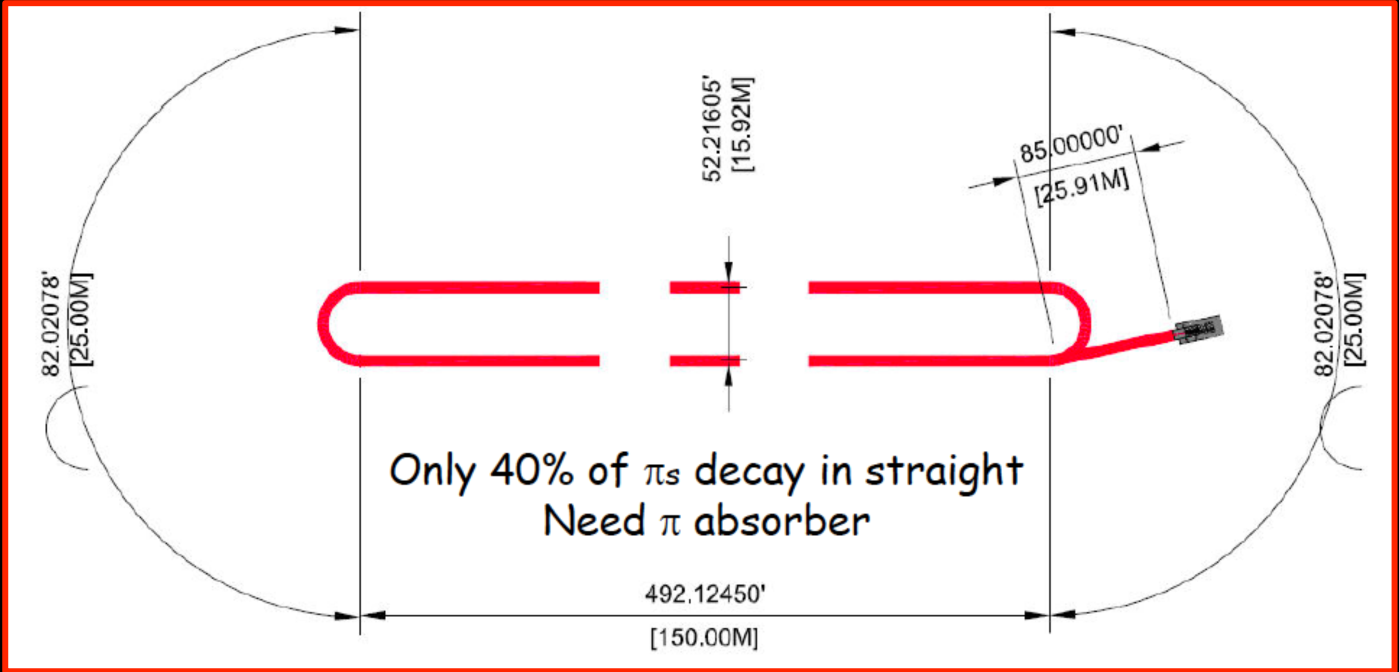
- Need either E_μ=4 GeV or 10^{19} useful muon decays/polarity to cover best-fit
- Highly competitive compared to alternatives
  (⇨ Sterile neutrino white paper)
- Can one improve on "systematics limit"?

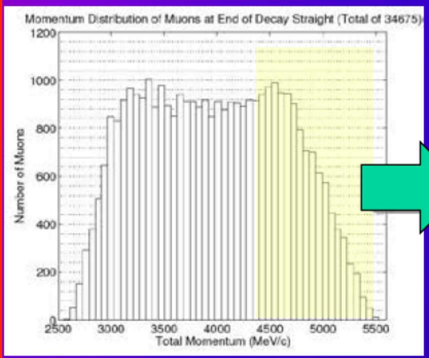
(WW, arXiv:1204.2671)

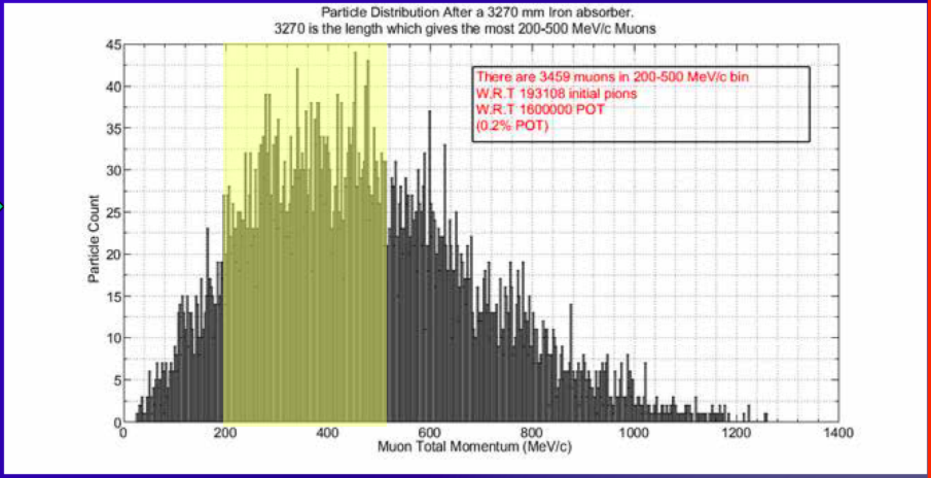
Implementation, at FNAL:

- Benefits from existing extraction tunnel;
- Ideal baseline from storage ring to D0 assembly building:
  - Space and infrastructure for SuperBIND and LAr detector;
- Space and access for near detector

Technology test-bed:







At end of straight we have a lot of πs, but also a lot of μs with 4.5 < P(GeV/c) < 5.5

After 3.27m Fe, we have ≈ 10^{10} μ/pulse in 200 < P(MeV/c) < 500

Elements of a programme

Elements of a staged programme:

- Neutrino Factory: the facility of choice for the study of neutrino oscillations:
  - Best sensitivity
  - Best precision
- But, stored muon beams have not yet been demonstrated to be capable of serving a world-class neutrino programme:
  - Require to:
    - Demonstrate (sustainable) ionization cooling:
      - MICE to Step VI
    - Demonstrate:
      - High-gradient warm RF in presence of magnetic field (MuCOOL)
      - Mastery of 201 MHz superconducting RF technology
    - Complete IDS-NF
      - Including articulation of a plausible staging scenario
  - Establish a first, realistic, scientifically first-rate neutrino experiment based on a stored muon beam
    - nuSTORM:
      - Will serve the neutrino programme by making unique $\nu_e N$ and $\nu_\mu N$ measurements;
      - Will provide decisive information on the existence of sterile neutrinos; and
      - Provide a test-bed for:
        - » 6D cooling proof of principal
        - » Storage-ring diagnostics, muon-beam handling, …