nuSTORM

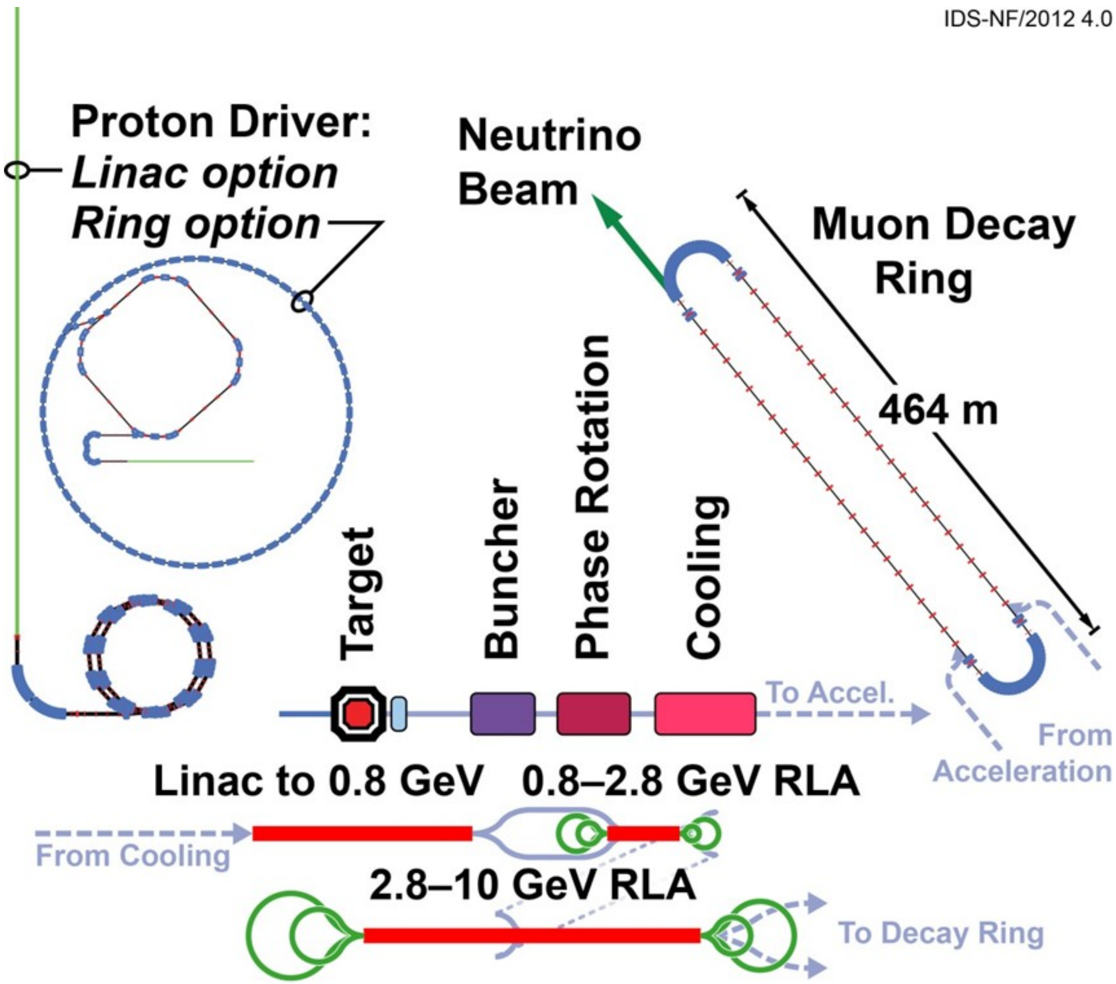
D Adey

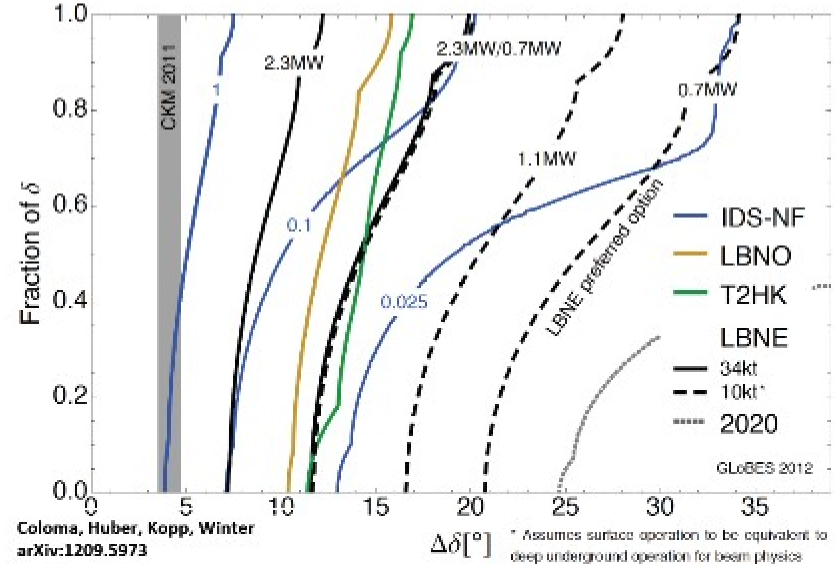
NBI 2014
Fermilab
23rd September 2014

adey@fnal.gov

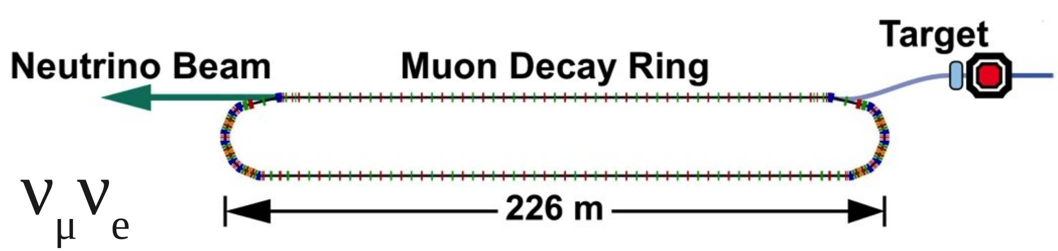
Content

- Motivations - neutrino cross-sections, sterile neutrino search, muon accelerator R&D platform
- nuSTORM – contributions from a stored muon beam
- Facility – summary and progress since proposal
- Target/Horn optimization
- Lattice design
- The future



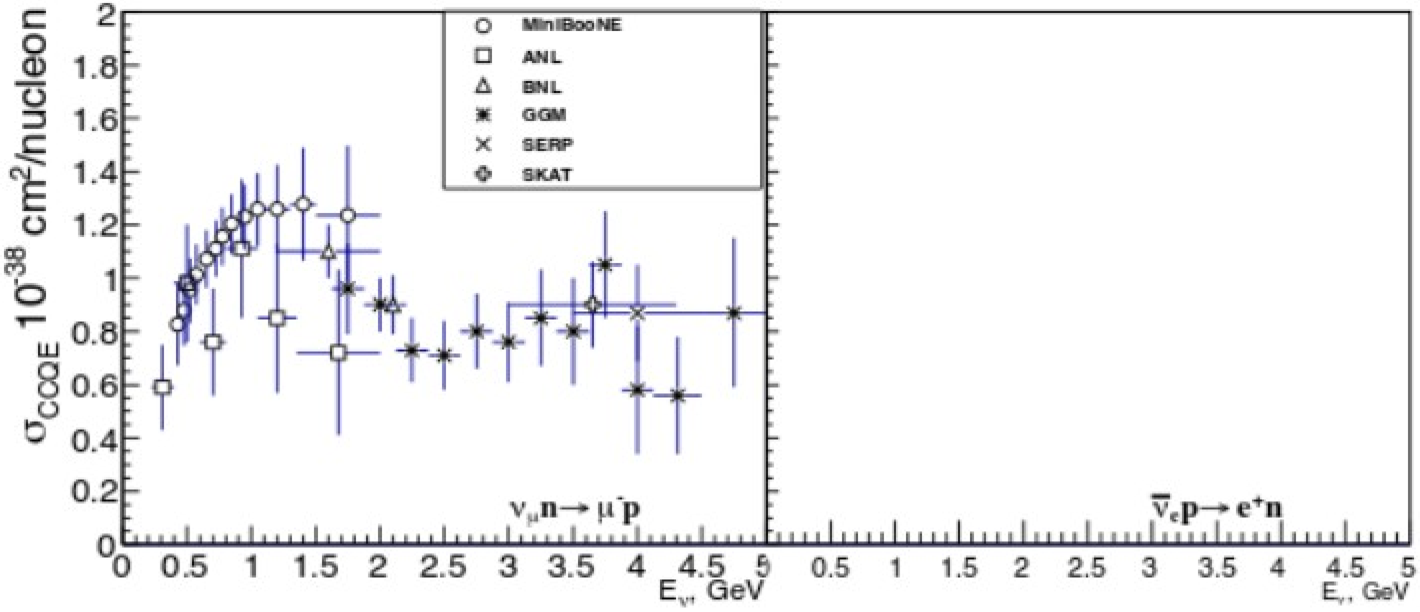


- A neutrino factory represents the best sensitivity to current experimental goals, but is technologically challenging and not immediately viable
- R&D is established and on-going as part of MAP and international collaborators

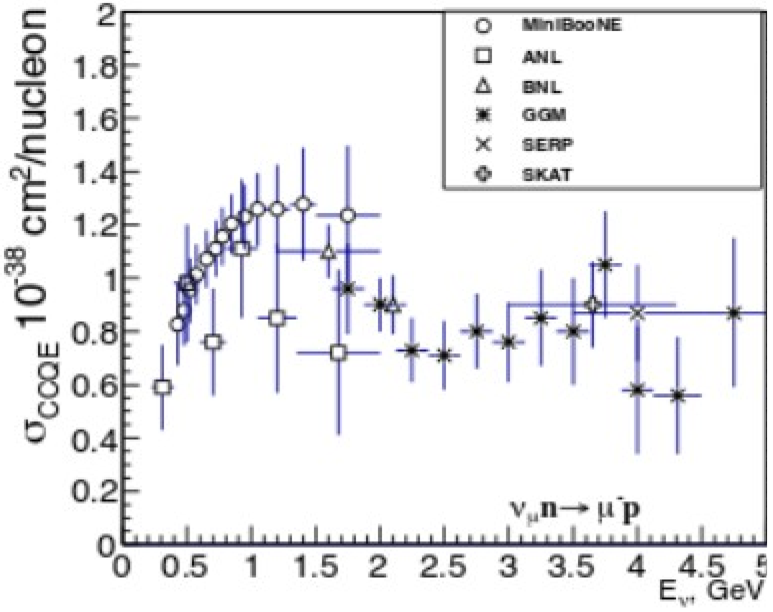


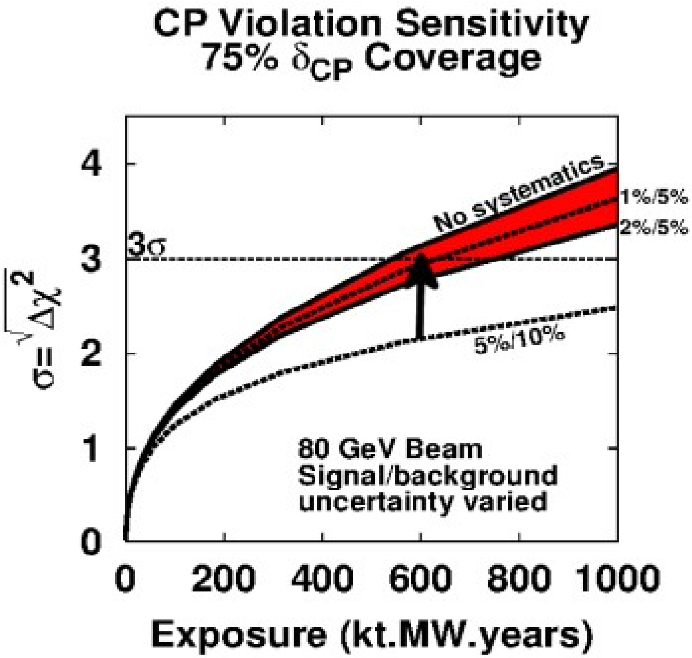
- Muon and electron neutrino beam can be produced from a stored muon beam using existing technology

Motivations



- Deficit in electron neutrino cross section measurements at accelerator energy regimes
- Existing measurements affecting by, amongst other things, flux precision
- Muon decay offers opportunities to explore much of this





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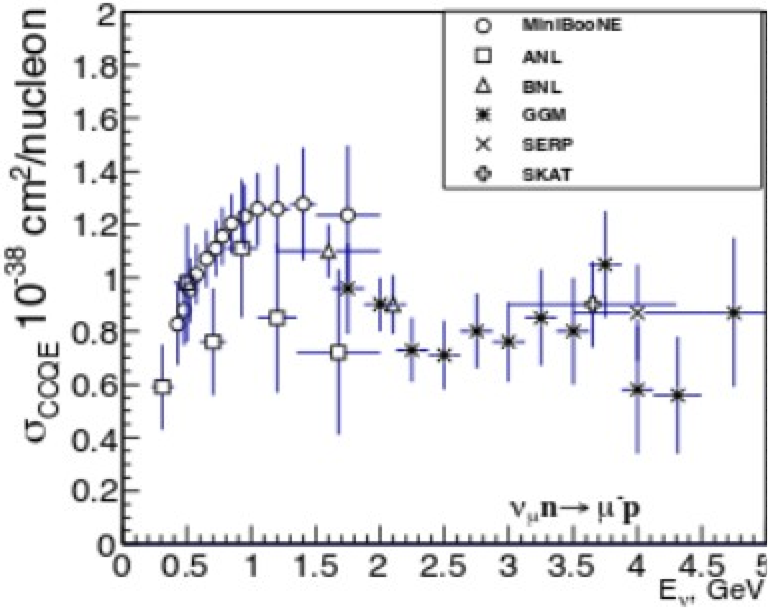

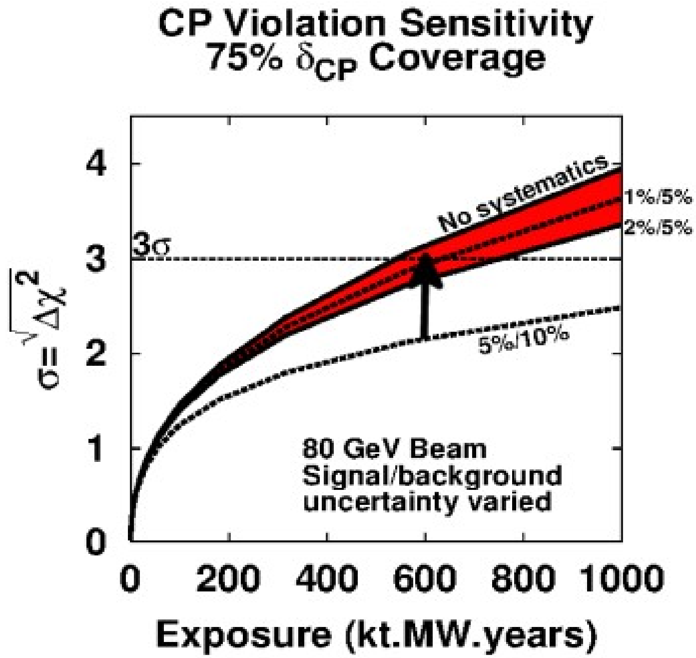

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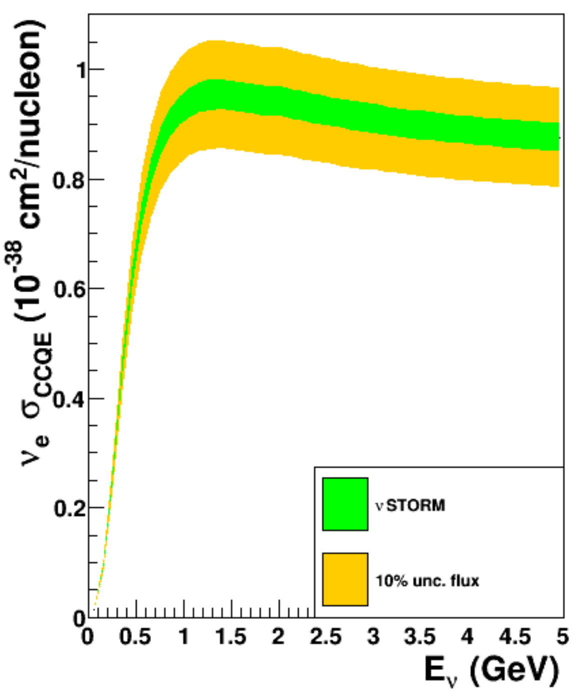
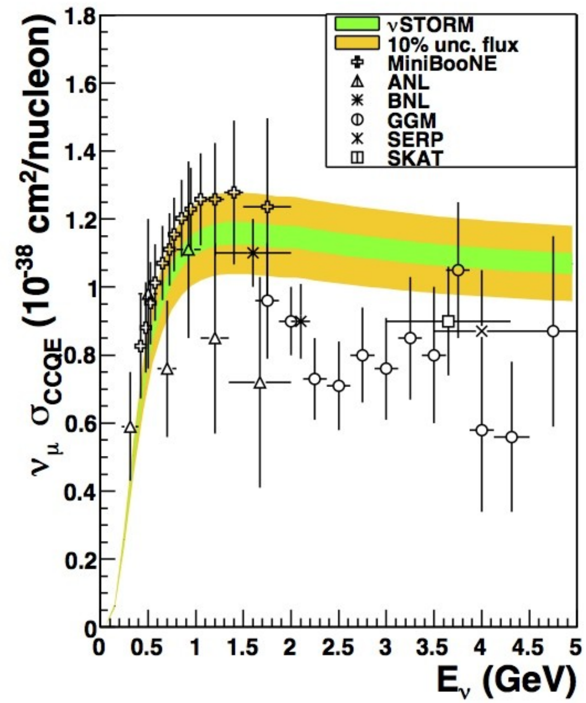
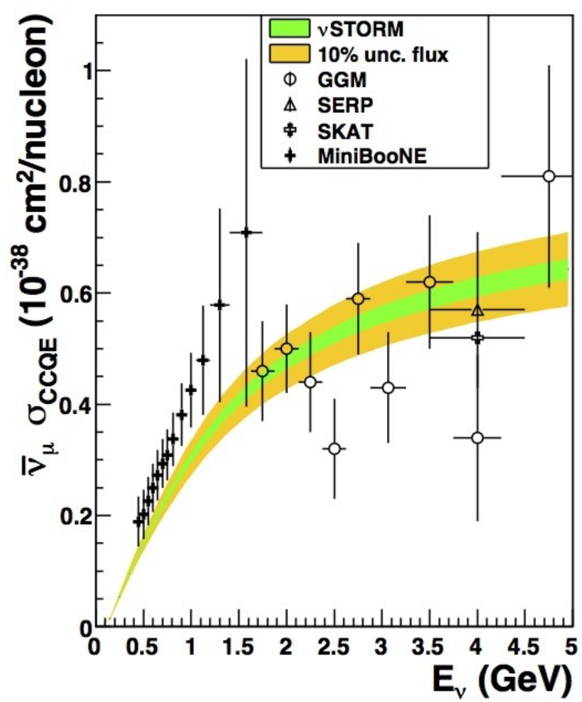
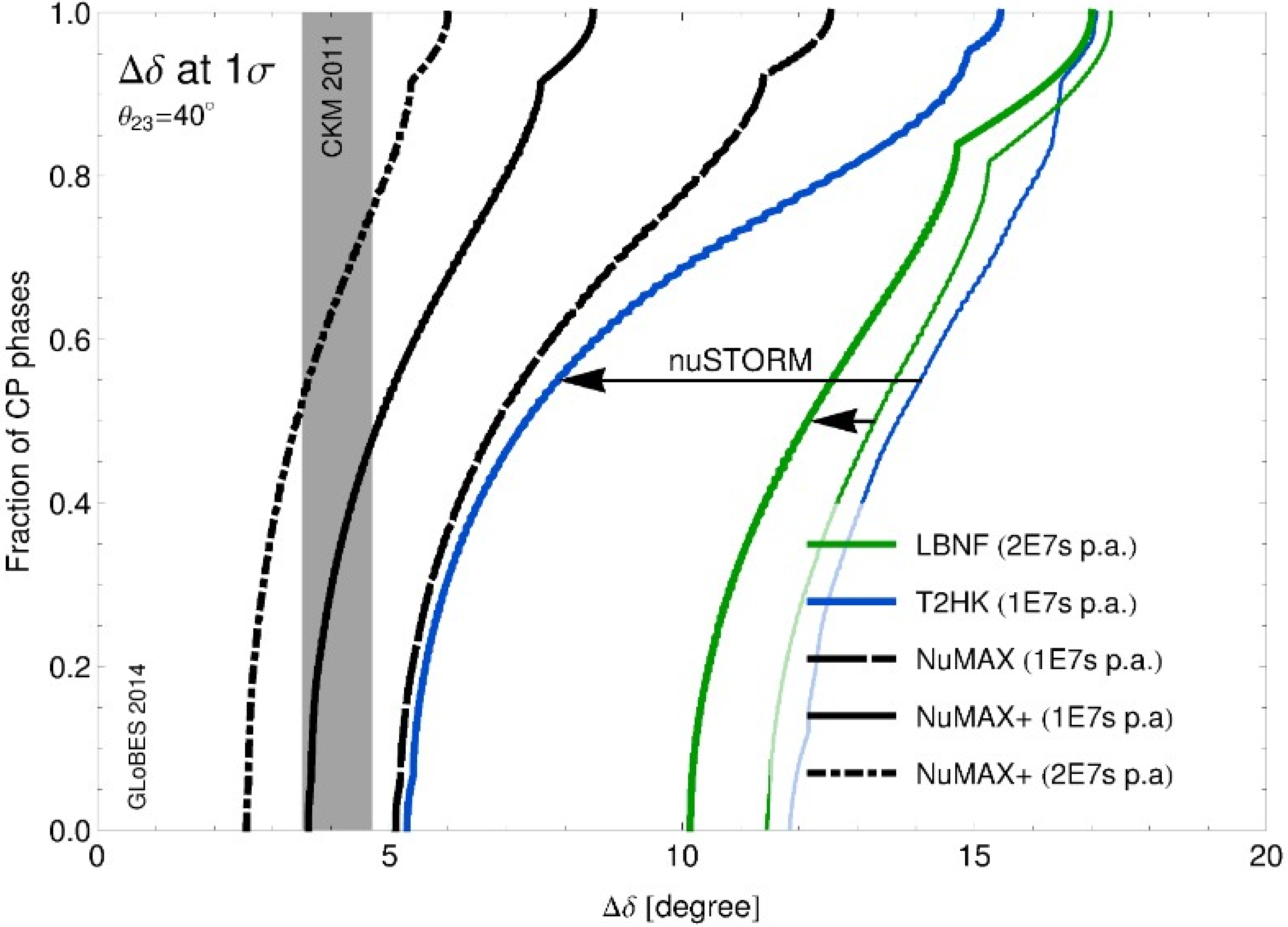
nuSTORM contribution







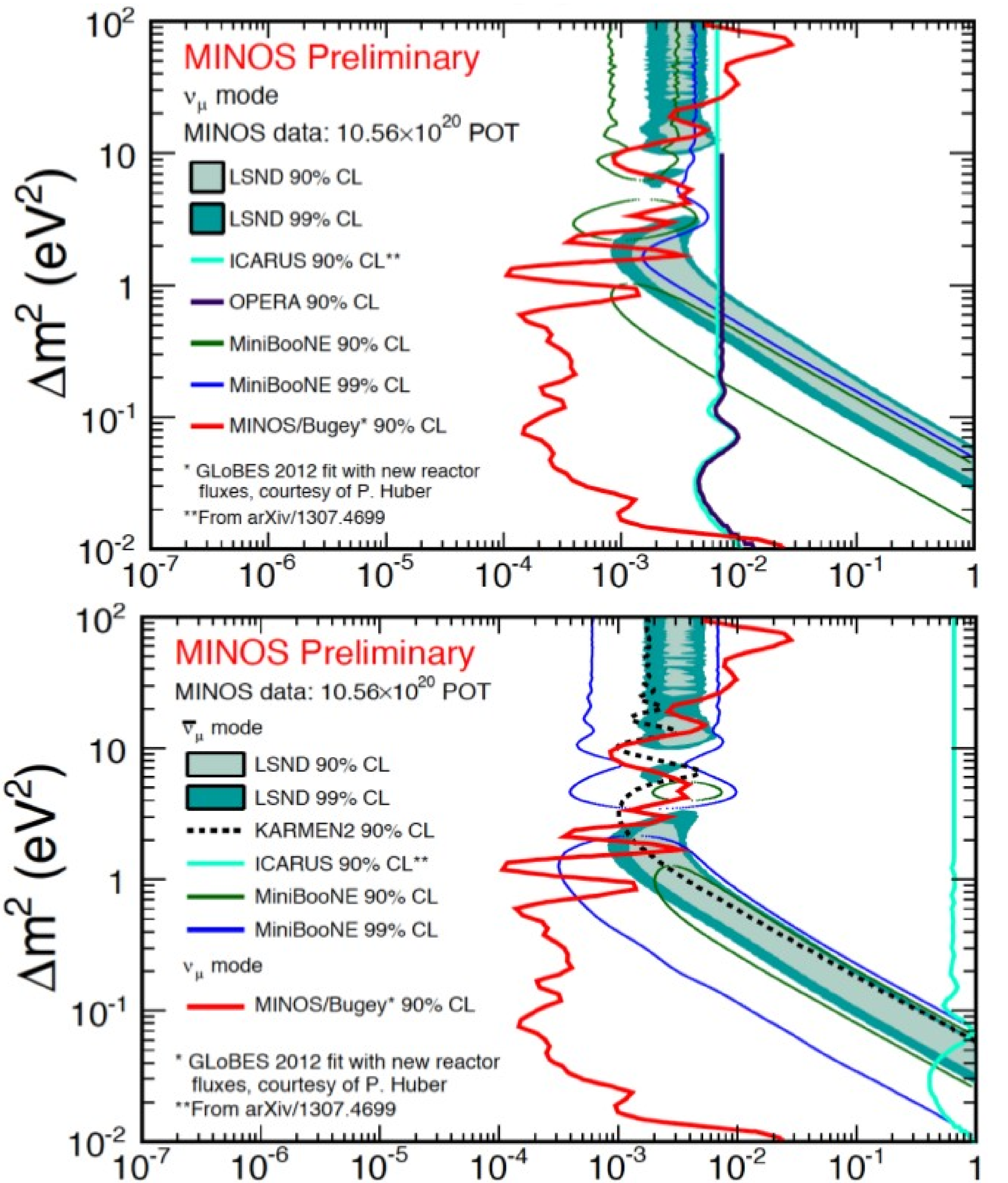
• To achieve states aims of 75% CP coverage at 3σ, systemic precision of ~1% is required
• nuSTORM can contribute significantly in constraining cross component input to systematic errors



Sterile Neutrinos

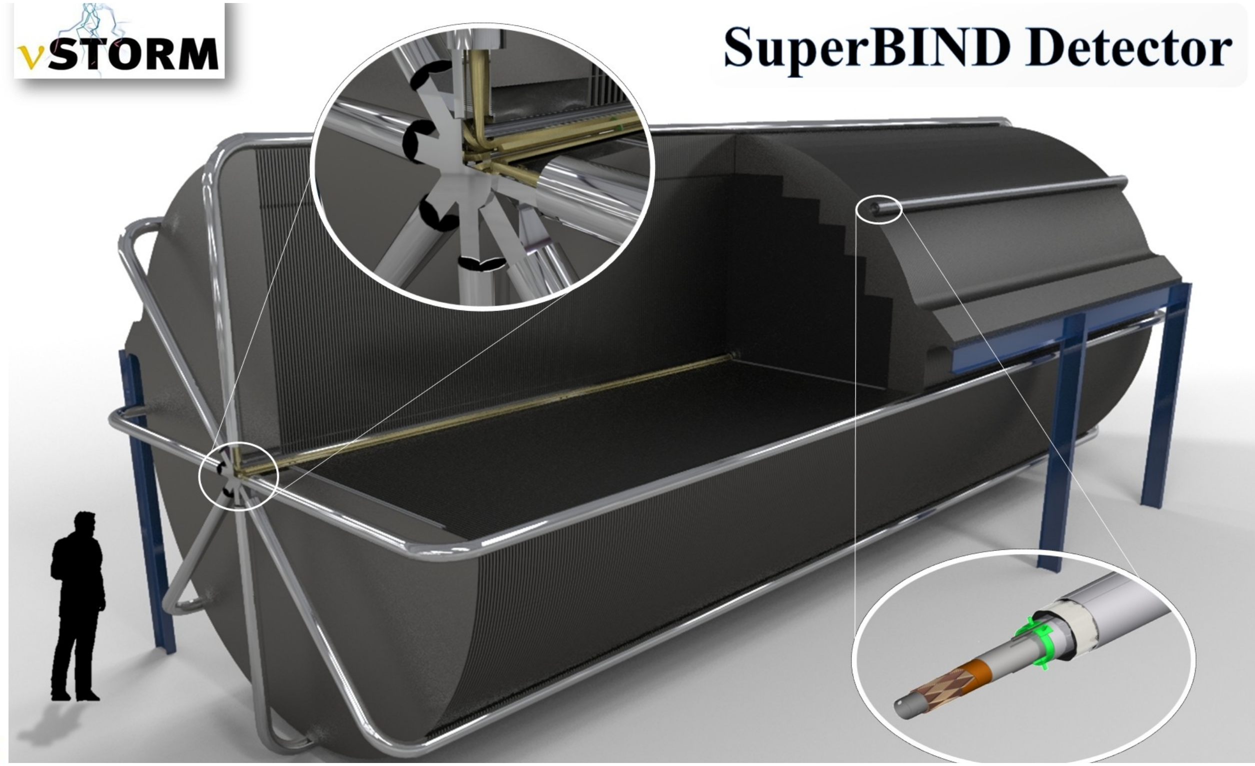
- Gallium: 2.7σ evidence for ν_e disappearance
- LSND: 3.8σ evidence for ν_e appearance
- MiniBooNE: 3.8σ evidence for ν_e and ν_e appearance
- Reactor: 3σ evidence for ν_e appearance
- Combined cosmology covers 4 DOF
- New limits from MINOS

Something definitive required

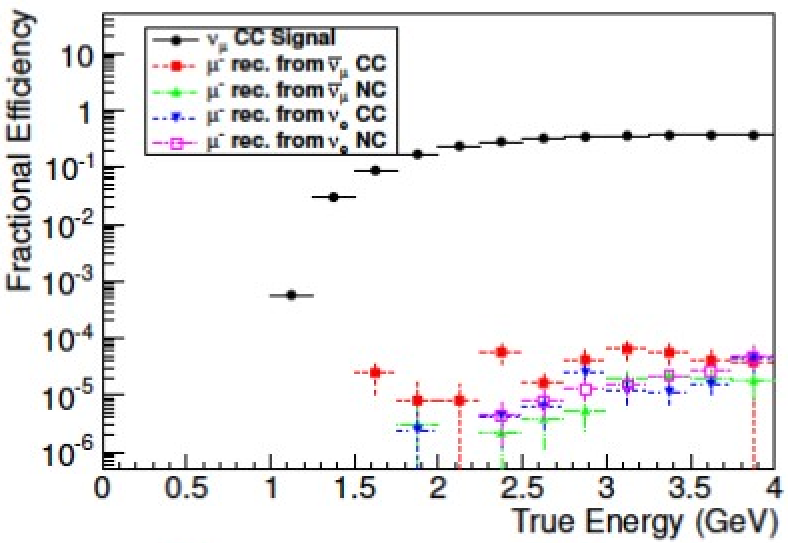


- Far detector – 2km
- 1.3kTon magnetized iron sampling calorimeter
- Superconducting transmission line

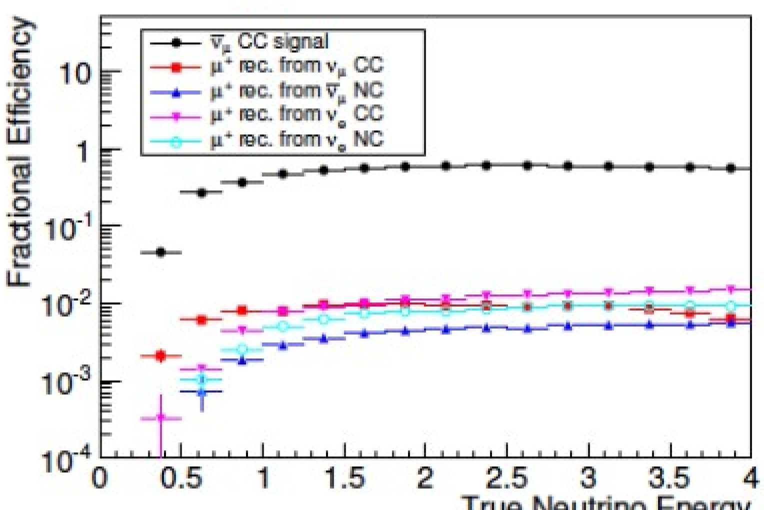
SuperBIND Detector



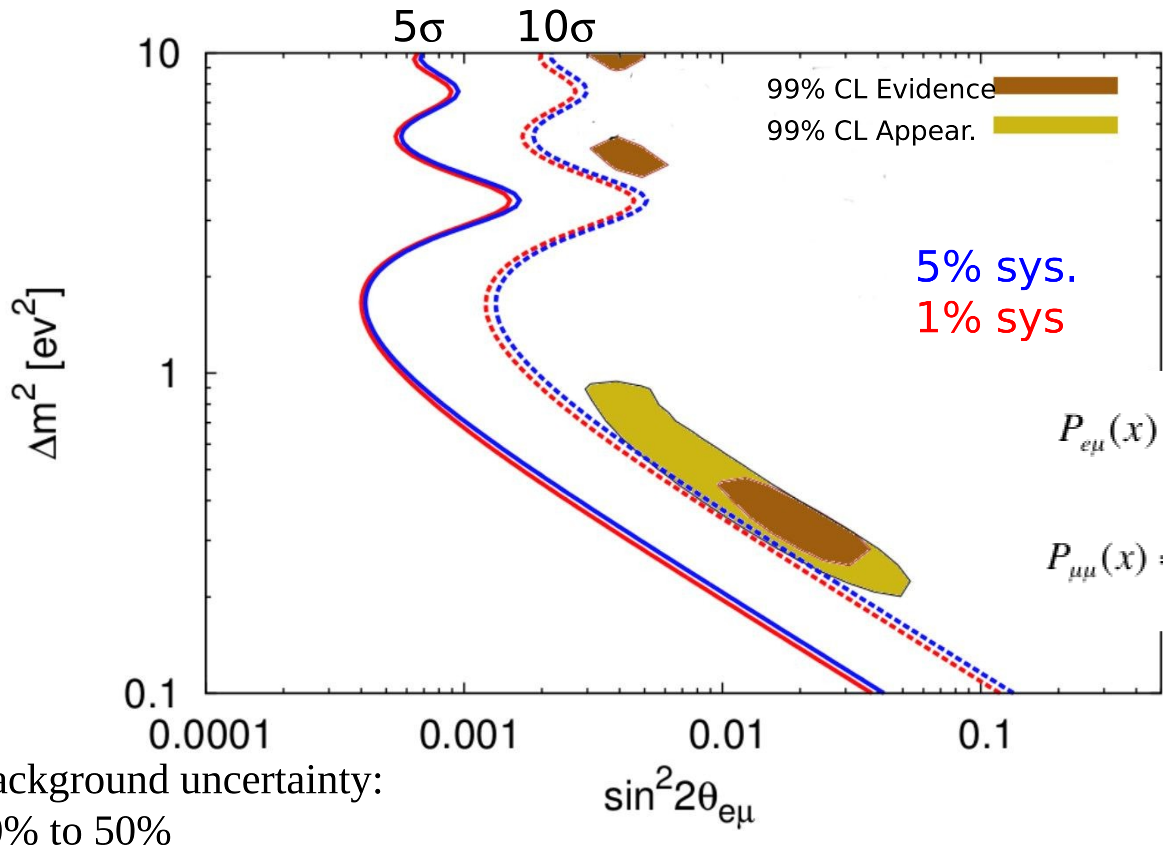
Appearance efficiencies



Disappearance efficiencies



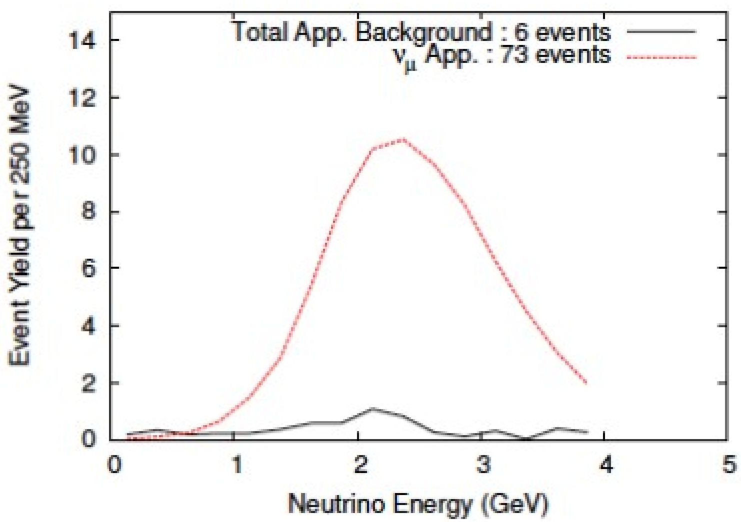
Sterile neutrino sensitivities

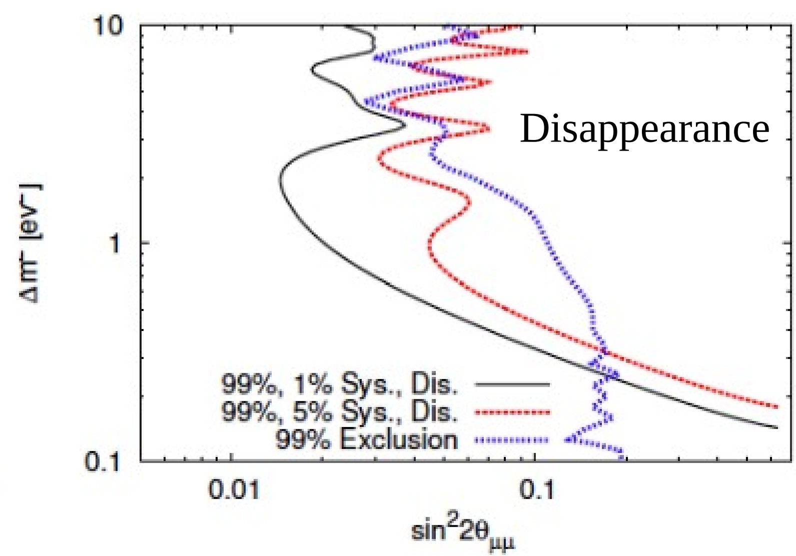


$$P_{e\mu}(x) = 4|U_{e4}|^2|U_{\mu 4}|^2 \sin^2\left(\frac{m_{14}^2 x}{4E}\right) \equiv \sin^2(2\theta_{e\mu})\sin^2\left(\frac{m_{14}^2 x}{4E}\right)$$

$$P_{\mu\mu}(x) = 4|U_{\mu 4}|^2\left(1-|U_{\mu 4}|^2\right)\sin^2\left(\frac{m_{14}^2 x}{4E}\right) \equiv \sin^2(2\theta_{\mu\mu})\sin^2\left(\frac{m_{14}^2 x}{4E}\right)$$

Background uncertainty:
10% to 50%





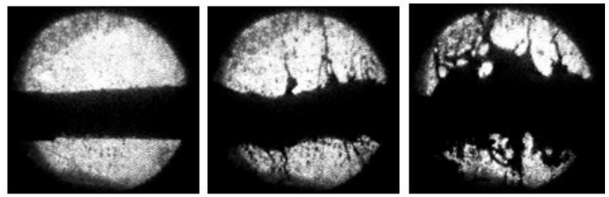
Available physics

$\mu^+ \to e^+ \nu_e \overline{\nu}_\mu$	$\mu^- \to e^- \overline{\nu}_e \nu_\mu$	
$\overline{\nu}_\mu \to \bar{\nu}_\mu$	$\nu_\mu \to \nu_\mu$	disappearance
$\overline{\nu}_\mu \to \bar{\nu}_e$	$\nu_\mu \to \nu_e$	appearance (challenging)
$\overline{\nu}_\mu \to \bar{\nu}_\tau$	$\nu_\mu \to \nu_\tau$	appearance (atm. oscillation)
$\nu_e \to \nu_e$	$\bar{\nu}_e \to \bar{\nu}_e$	disappearance
$\nu_e \to \nu_\mu$	$\bar{\nu}_e \to \bar{\nu}_\mu$	appearance: “golden” channel
$\nu_e \to \nu_\tau$	$\bar{\nu}_e \to \bar{\nu}_\tau$	appearance: “silver” channel

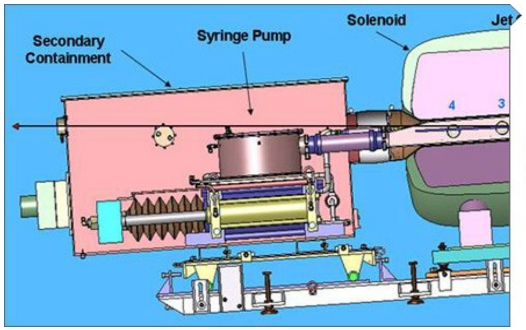
Charged and neutral current processes
Measurement of ne induced resonance production
Nuclear effects
Semi-exclusive & exclusive processes
Measurement of Ks0, L & L-bar production
New physics & exotic processes
Test of nm - ne universality
Heavy n
eV-scale pseudo-scalar penetrating particles

ν_e and ν_e-bar x-section measurements -
A UNIQUE contribution from nuSTORM
Essentially no existing data
p0 production in n interactions
Coherent and quasi-exclusive single p0 production
Charged p & K production
Coherent and quasi-exclusive single p+ production
Multi-nucleon final states
ν-e scattering
ν-Nucleon neutral current scattering
Measurement of NC to CC ratio

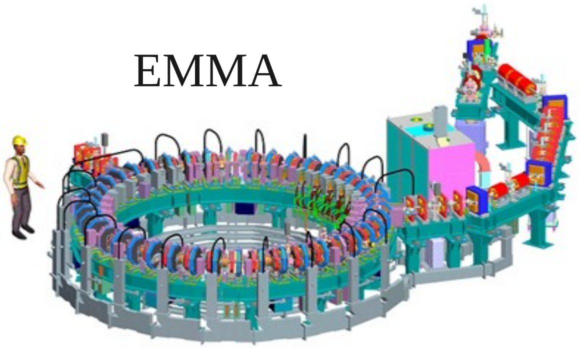
Muon Accelerator Technology



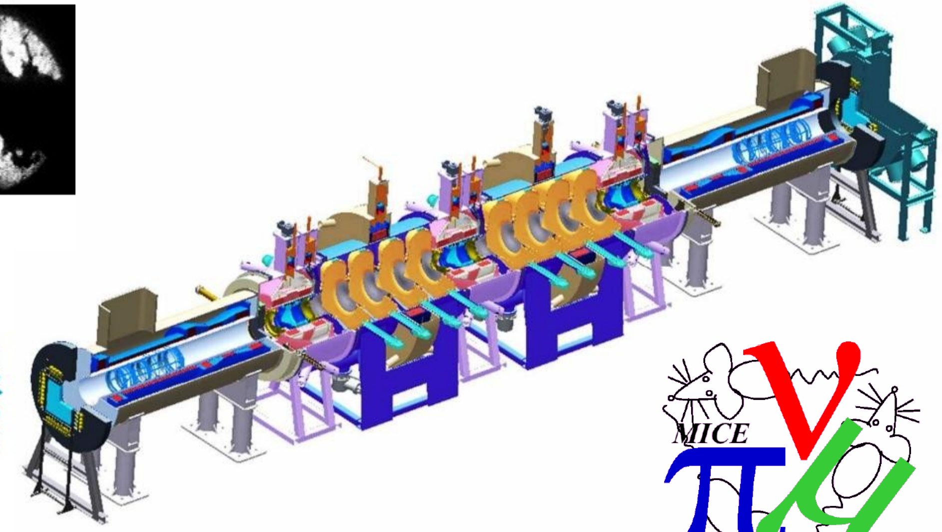
a) b) c)



MERIT

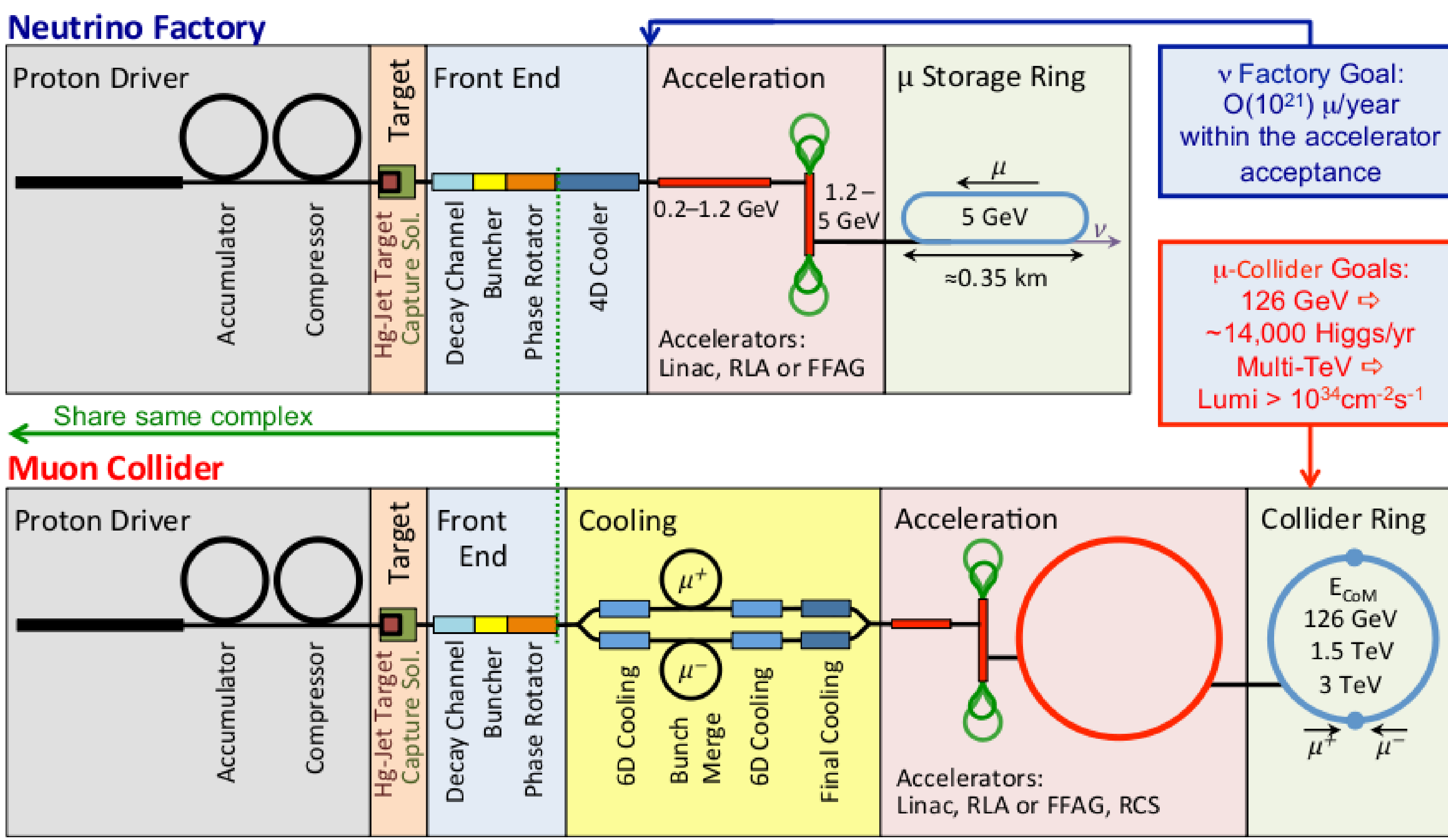


EMMA



Muon-based accelerators and neutrino beams require extensive R&D.

A muon storage ring provides R&D staging platform alongside physics studies



Neutrinos from Stored Muons

- Dipole chicane gives momentum and sign selection
- Stored beams can be measured to great accuracy using standard beam diagnostics – neutrino flux precision
- Muon decay beams are flavor precise and generate high statistics electron neutrinos

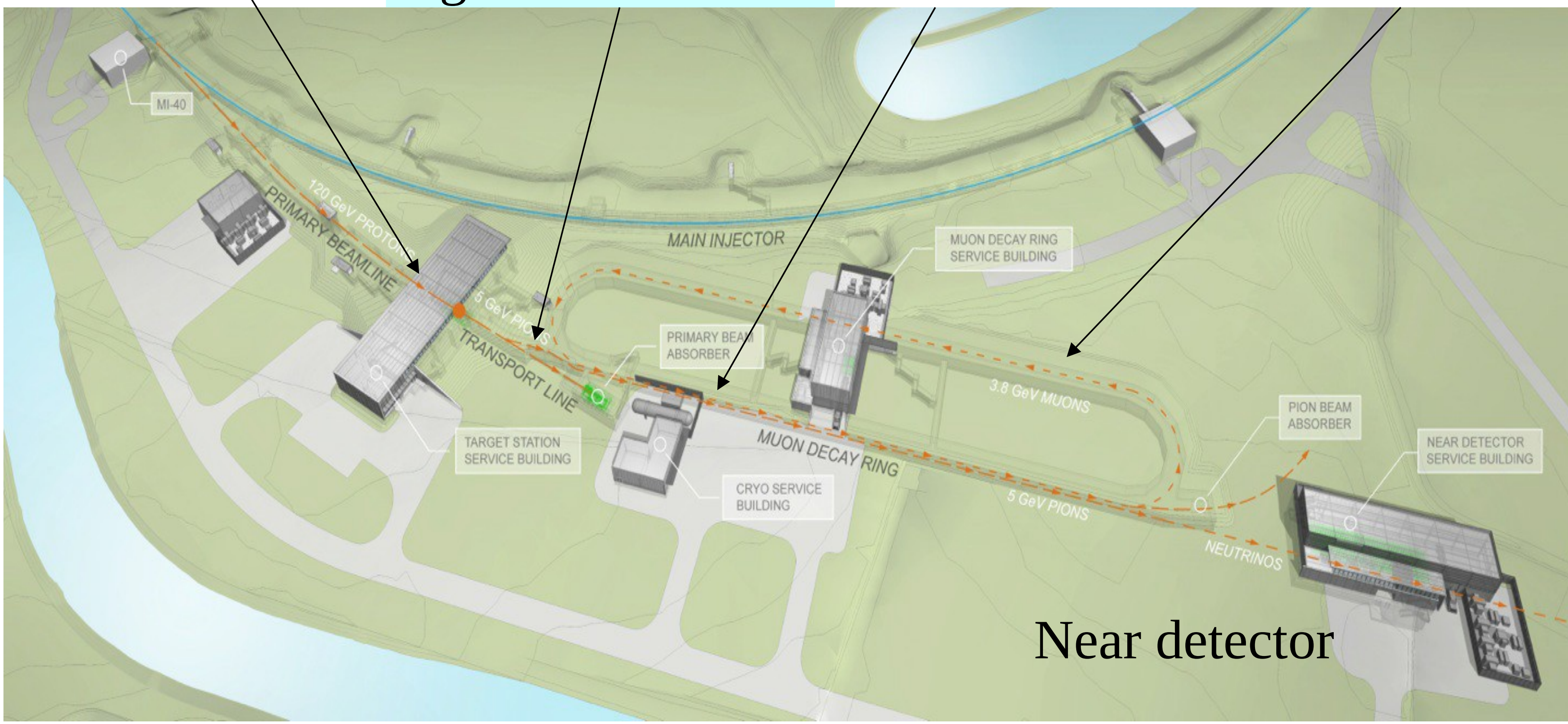
νSTORM

Protons on Target
Horn collection

Pion transport through dipoles – momentum and sign selection

Pions injecting into ring decay into muons

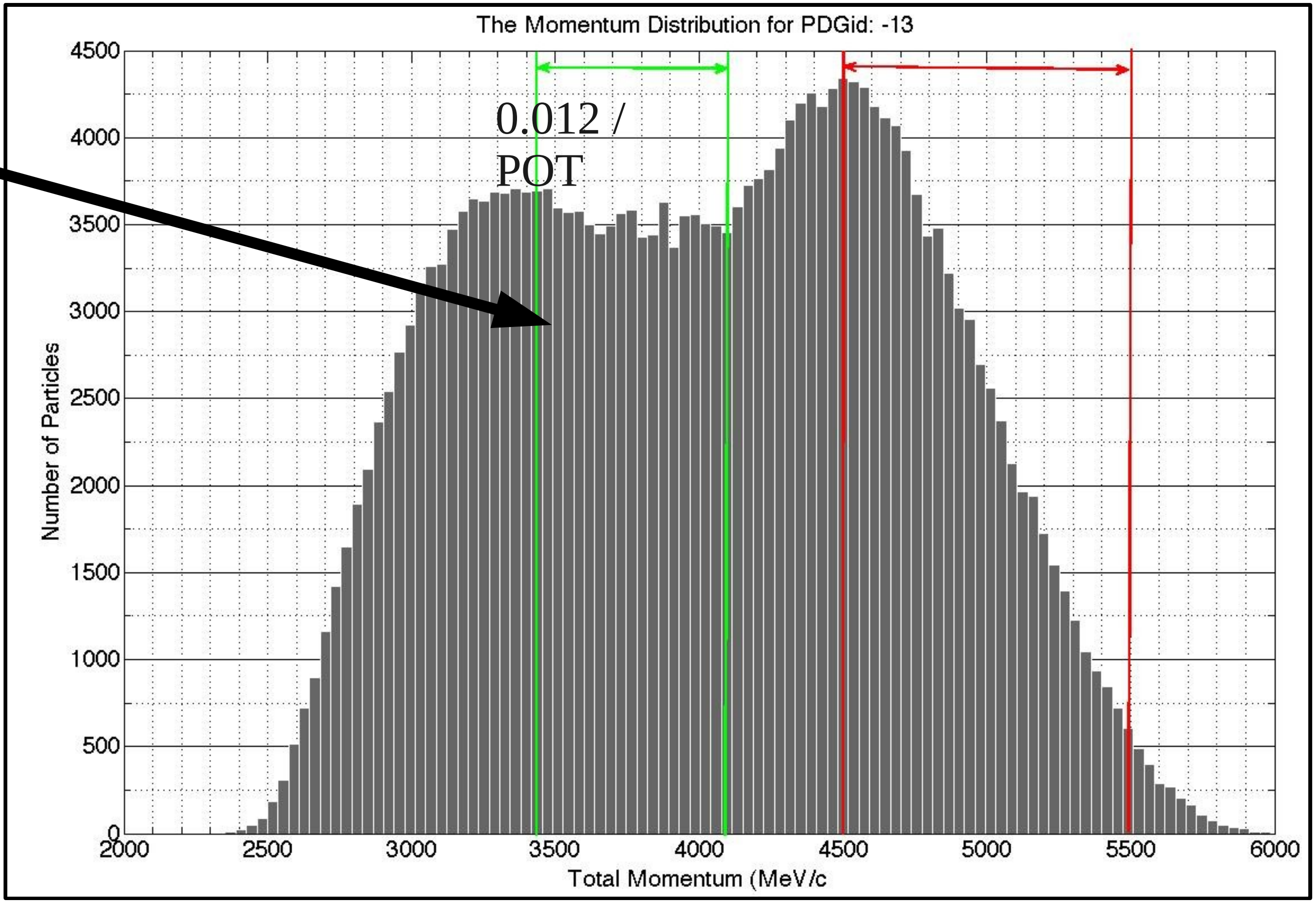
Stored muons decay with direction neutrino beam



- Dipole chicane provides sign and momentum selection of pions
- Stored beam allows for instrumentation and characterization of beam
- Current, momentum, divergence, size, position

- Produces flavor-known beam with high statistics electron neutrinos, with a flux known to better than 1%

Stored Muon Acceptance

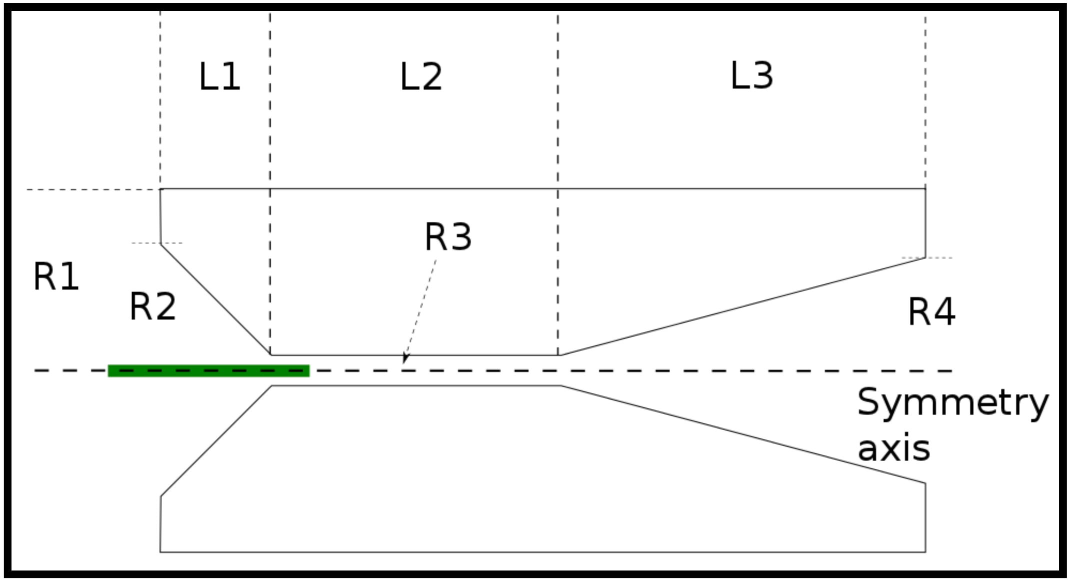


- Primary goal is to maximize muons within the acceptance of the ring – 3.8GeV +- 10%
- Large number of free parameters around the target/horn – target material, length, position, horn current, inner/outer radius etc.
- Some are independently chosen – target
- Simulating the full production lattice for the entire parameter space computationally prohibitive

material	momentum (GeV/c)	±15%	±10%	±5%	target length (cm)	density (g/cm^3)	σ_b (mm)
Carbon	3	0.085	0.056	0.028	27.3	3.52	0.15
Carbon	5	0.099	0.067	0.033	32.2	3.52	0.15
Inconel	3	0.131	0.087	0.044	19.2	8.43	0.15
Inconel	5	0.136	0.091	0.045	27.0	8.43	0.15
Tantalum	3	0.164	0.109	0.054	15.3	16.6	0.15
Tantalum	5	0.161	0.107	0.053	21.3	16.6	0.15
Gold	3	0.177	0.118	0.059	18.0	19.32	0.15
Gold	5	0.171	0.112	0.056	20.0	19.32	0.15
Gold	5	0.143	0.094	0.047	20.0	19.32	1.
Graphite	5	0.085	0.057	0.028	95.0	1.789	0.15
Graphite	5	0.096	0.064	0.032	95.0	1.789	1.

Horn optimization

Initial horn: NuMI design



Model the horn field from the parameters for random initial individuals

Track the particles and calculate the outputs

Select the best individuals and produce the offspring

After set number of generations, or the population ceases to improve, finish the process

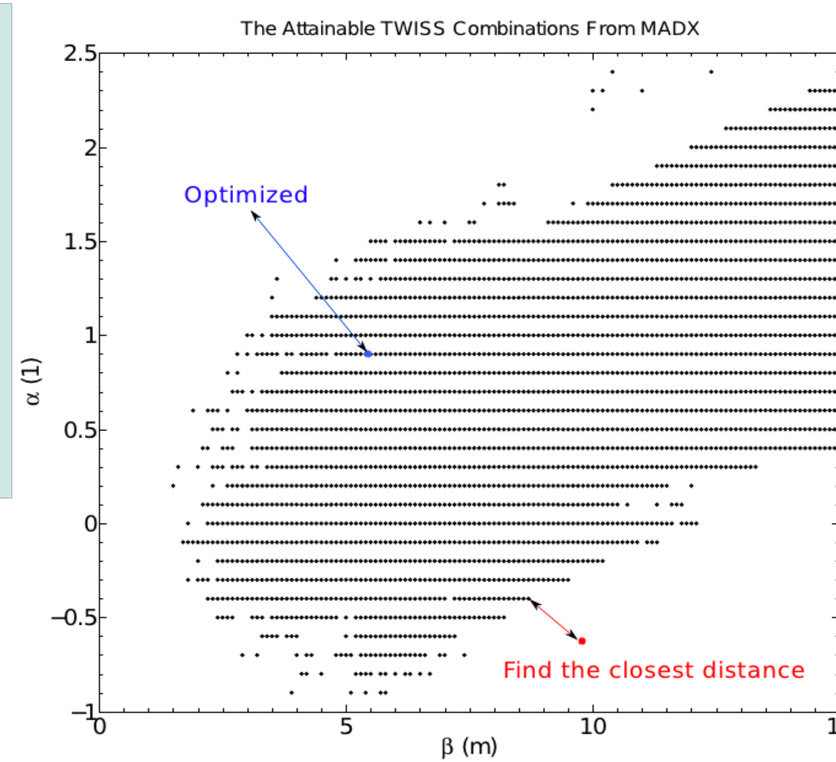
- Multi-Objective Genetic Algorithm treats each parameter as a "gene"
- The genes are initially randomized to produce individuals, and then each generation iterates selecting on the best individuals
- Outputs of merit are number of muons in the momentum acceptance; pions within the acceptance phase space

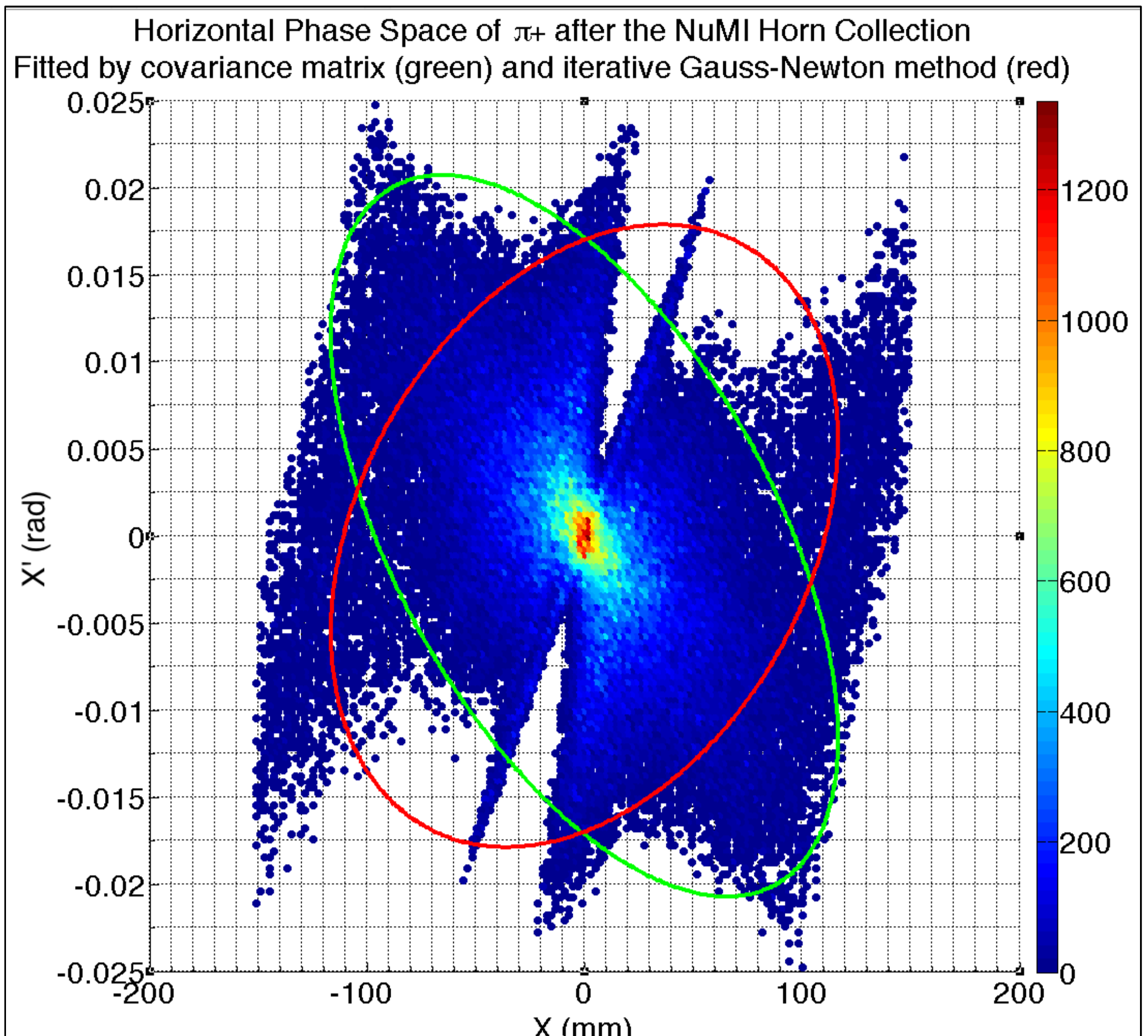
Generate pions from target/horn → Measure pions within acceptance

Fit once to produce covariance matrix + solve transfer lattice

Track pions through transfer line to measure acceptance

Calculate muons at end of decay straight from pions at beginning





- Tracking through the pion transfer line is done with G4Beamline
- Lattice was solved using MadX
- Input covariance matrix to MadX found by fitting the distribution of pions produced at the horn
- Allows calculation of pion transfer line acceptance

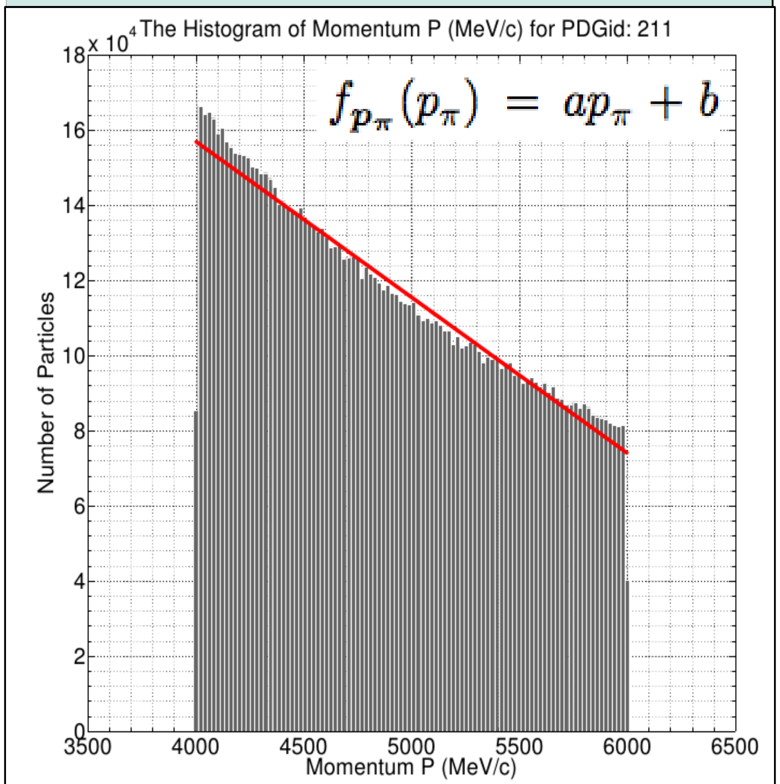
Generate pions from target/horn → Measure pions within acceptance

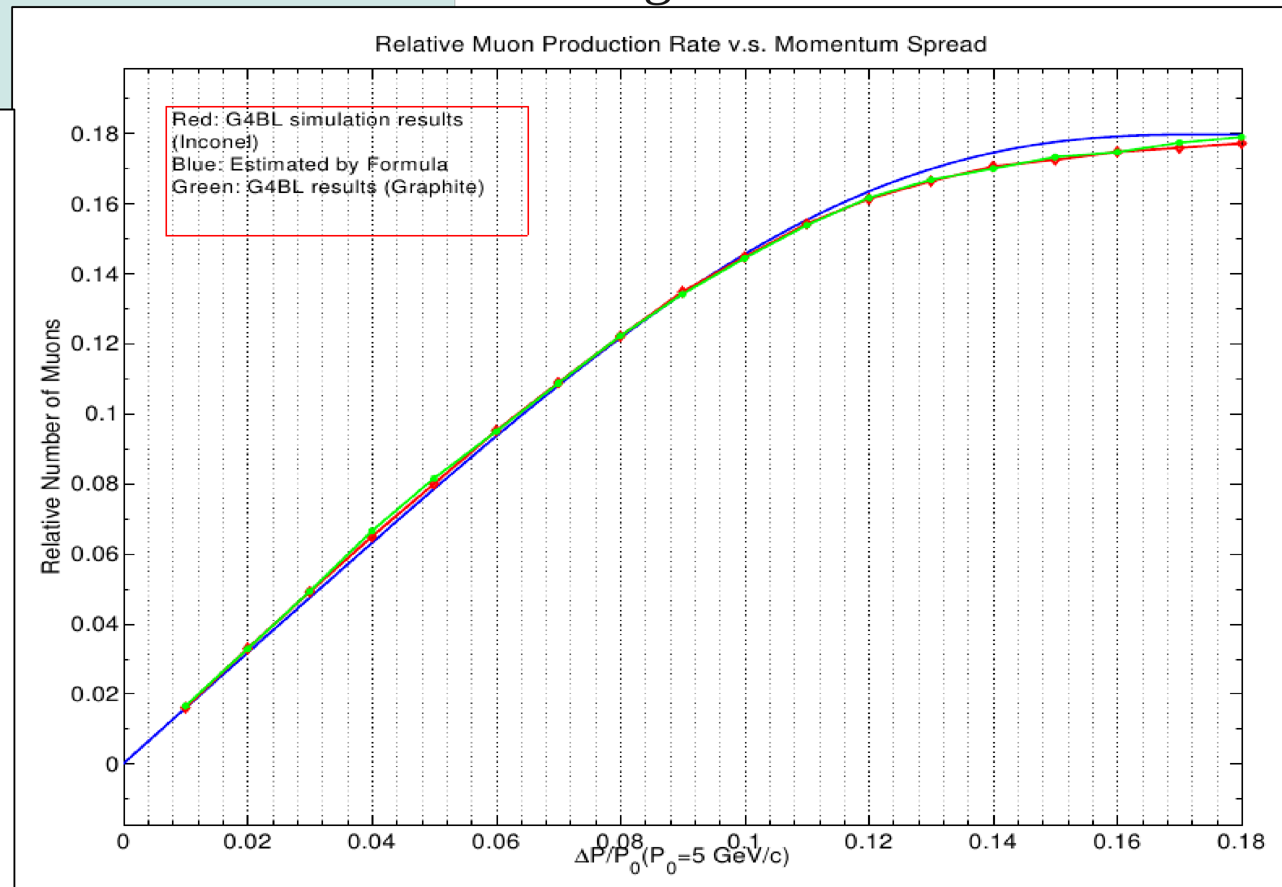
Fit once to produce covariance matrix + solve transfer lattice

Track pions through transfer line to measure acceptance

Calculate muons at end of decay straight from pions at beginning

- Number of muons within the momentum acceptance of the ring is calculated based on the pion momentum distribution at the start of the injections straight





$$N_{\mu,\text{end}}(m) = 1.78 \times 10^3 N_0 \left[1 \times 10^4 m a + \ln\left(\frac{1+m}{1-m}\right) b\right] \text{P}_{\text{trans}}(m)\text{P}_\Phi$$

$$N_{\mu,\text{end}}(0.18) \sim 8.82 \times 10^2 N_0 \left[1.8 \times 10^3 a + 0.36 b\right]$$

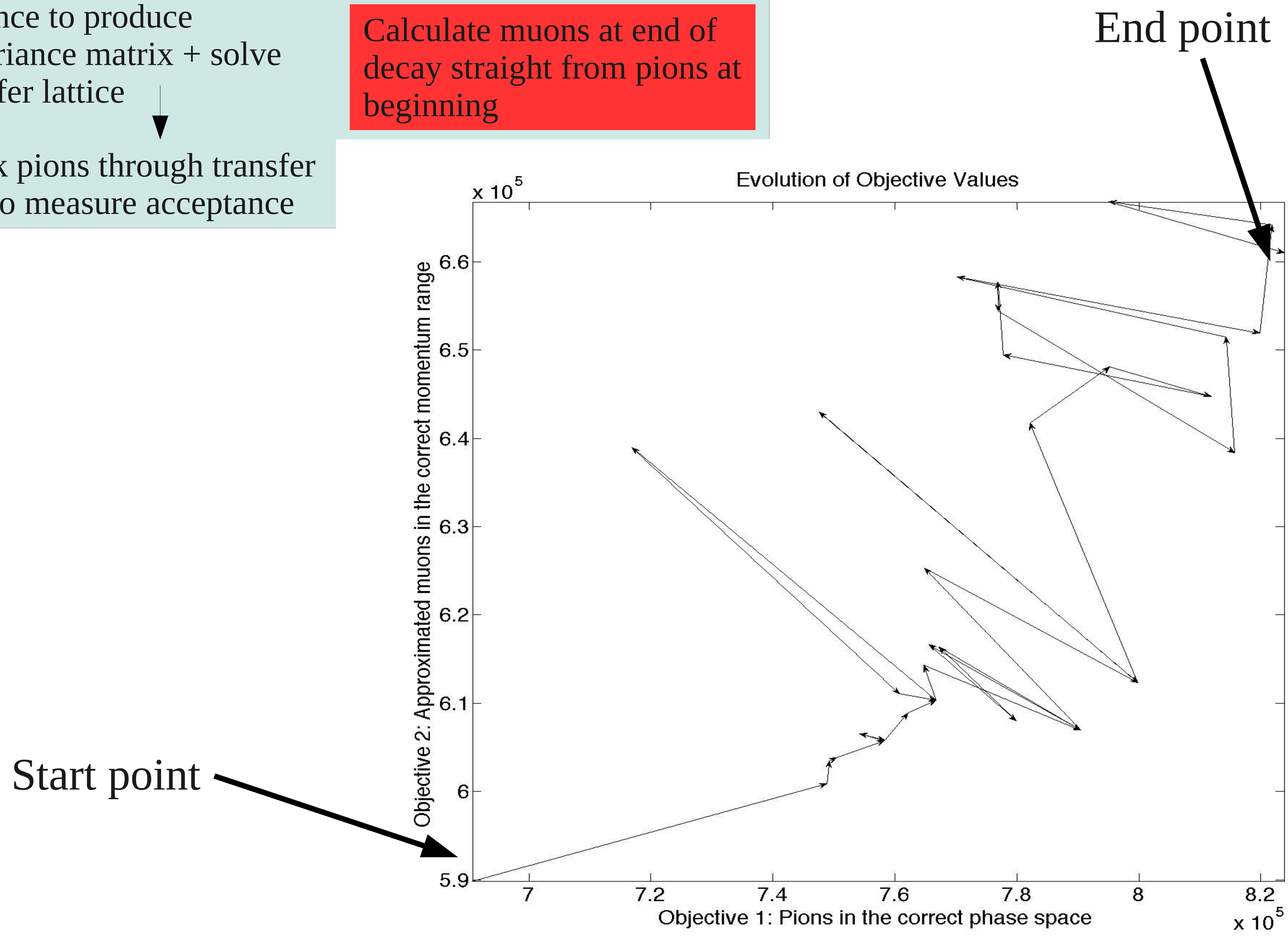
Generate pions from target/horn

Measure pions within acceptance

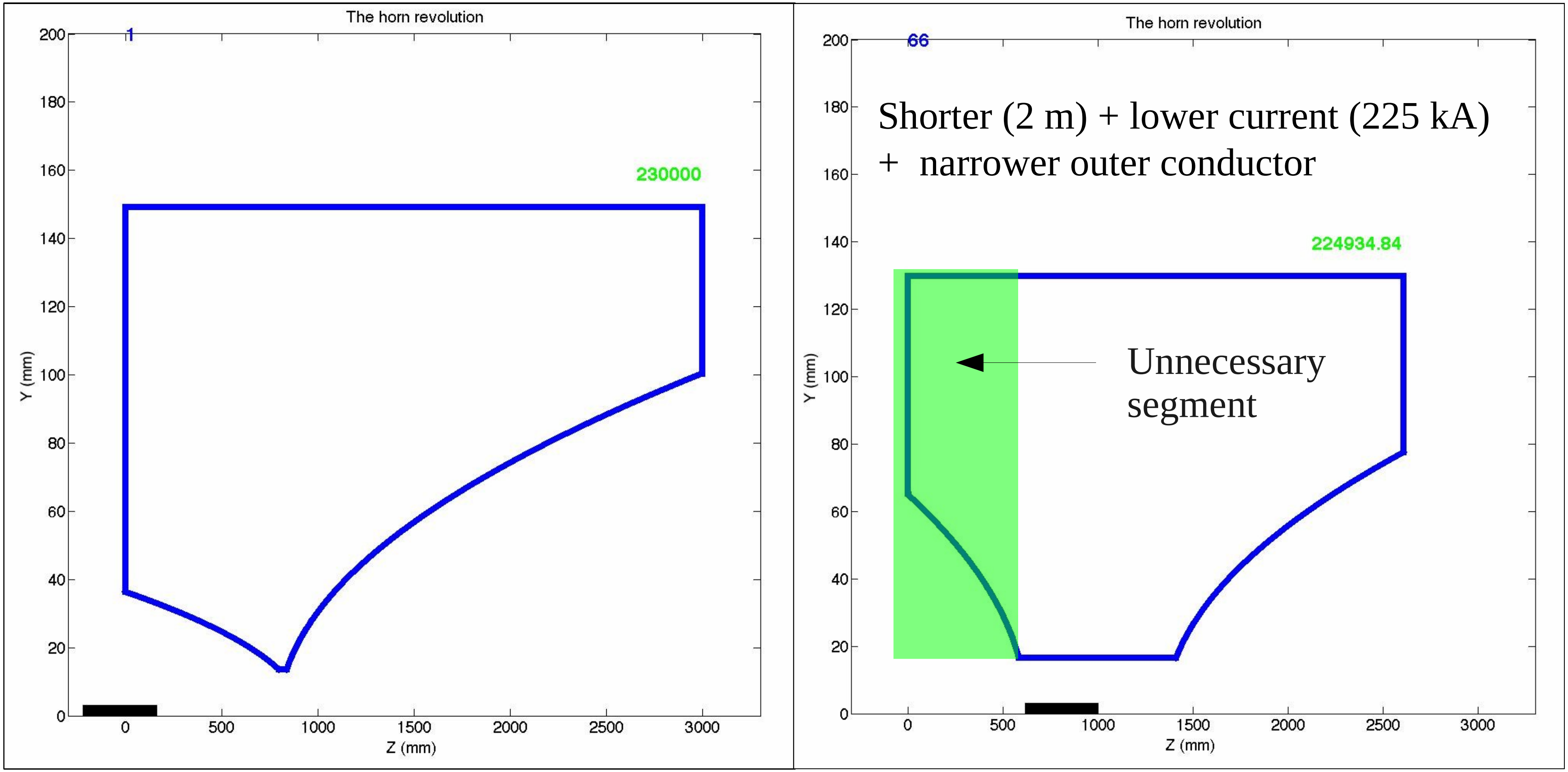
Fit once to produce covariance matrix + solve transfer lattice

Calculate muons at end of decay straight from pions at beginning

Track pions through transfer line to measure acceptance

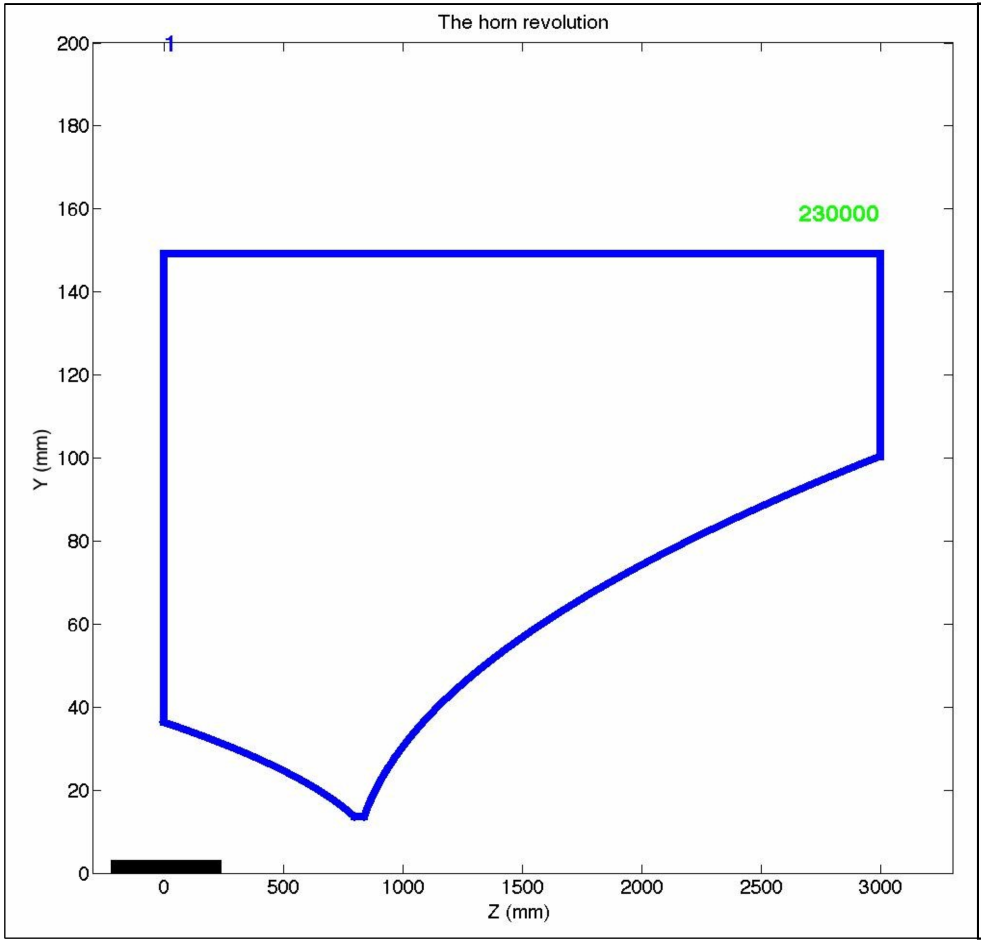


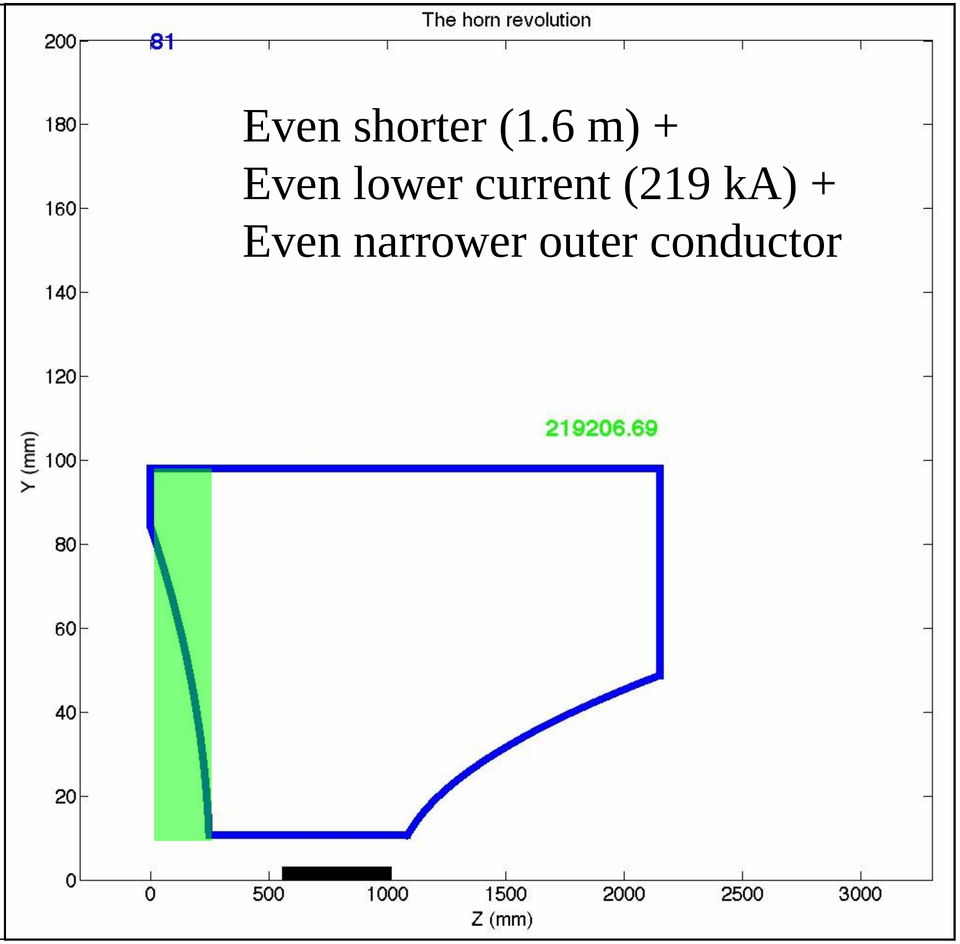
Inconel - 2.5 interaction lengths



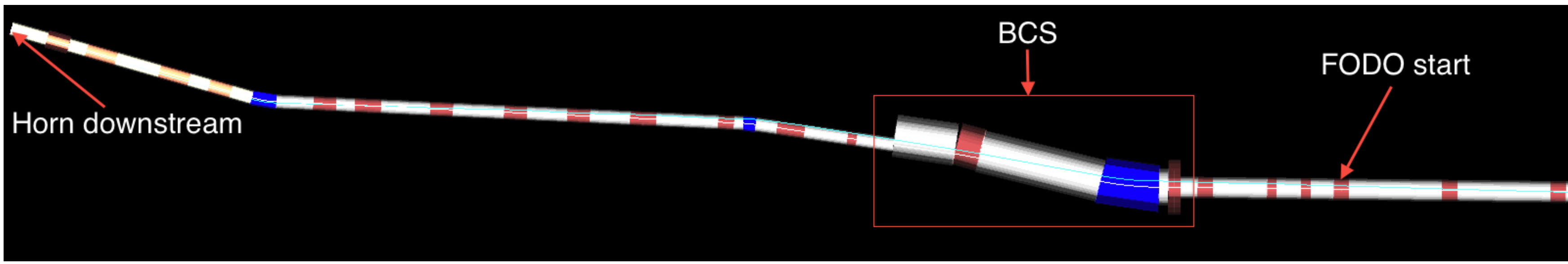
Nμ increased by 14%
Nπ increased by 18%
Pion beamline re-matched and π+ re-tracked
μ+ in both 2000 μm and 3.8±10% GeV/c increased by 8.3%

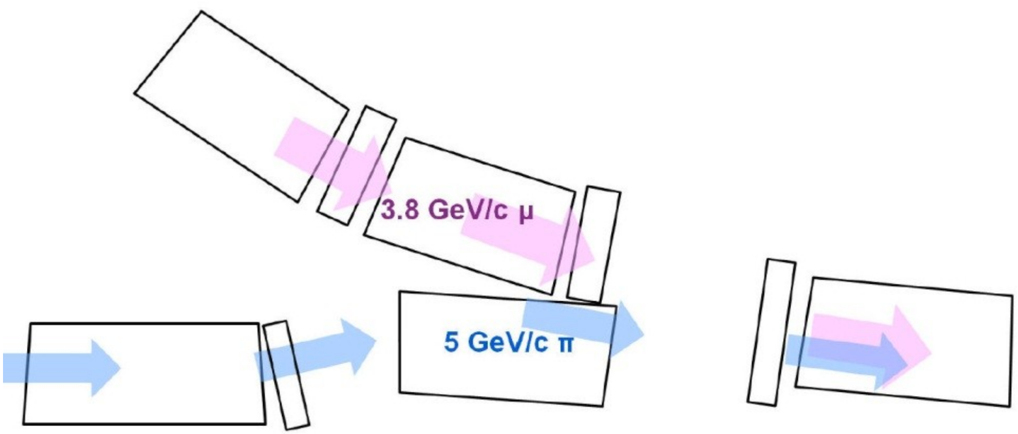
Inconel - 3 interaction lengths

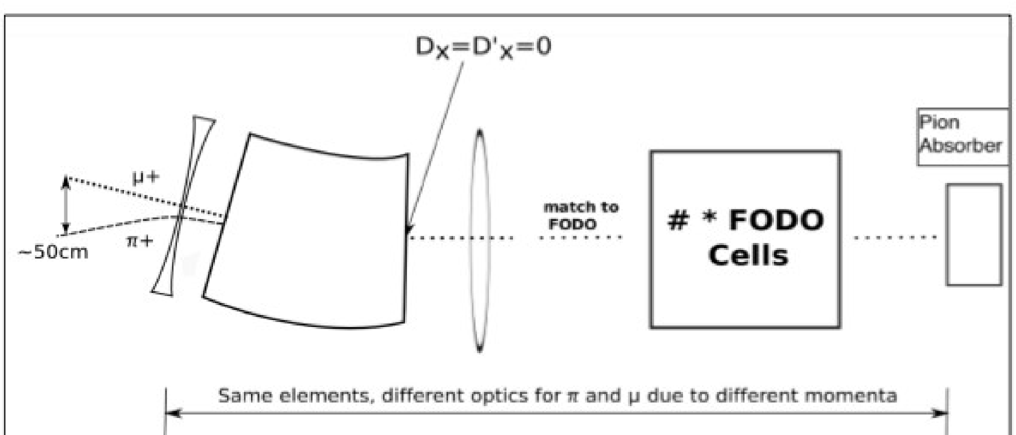




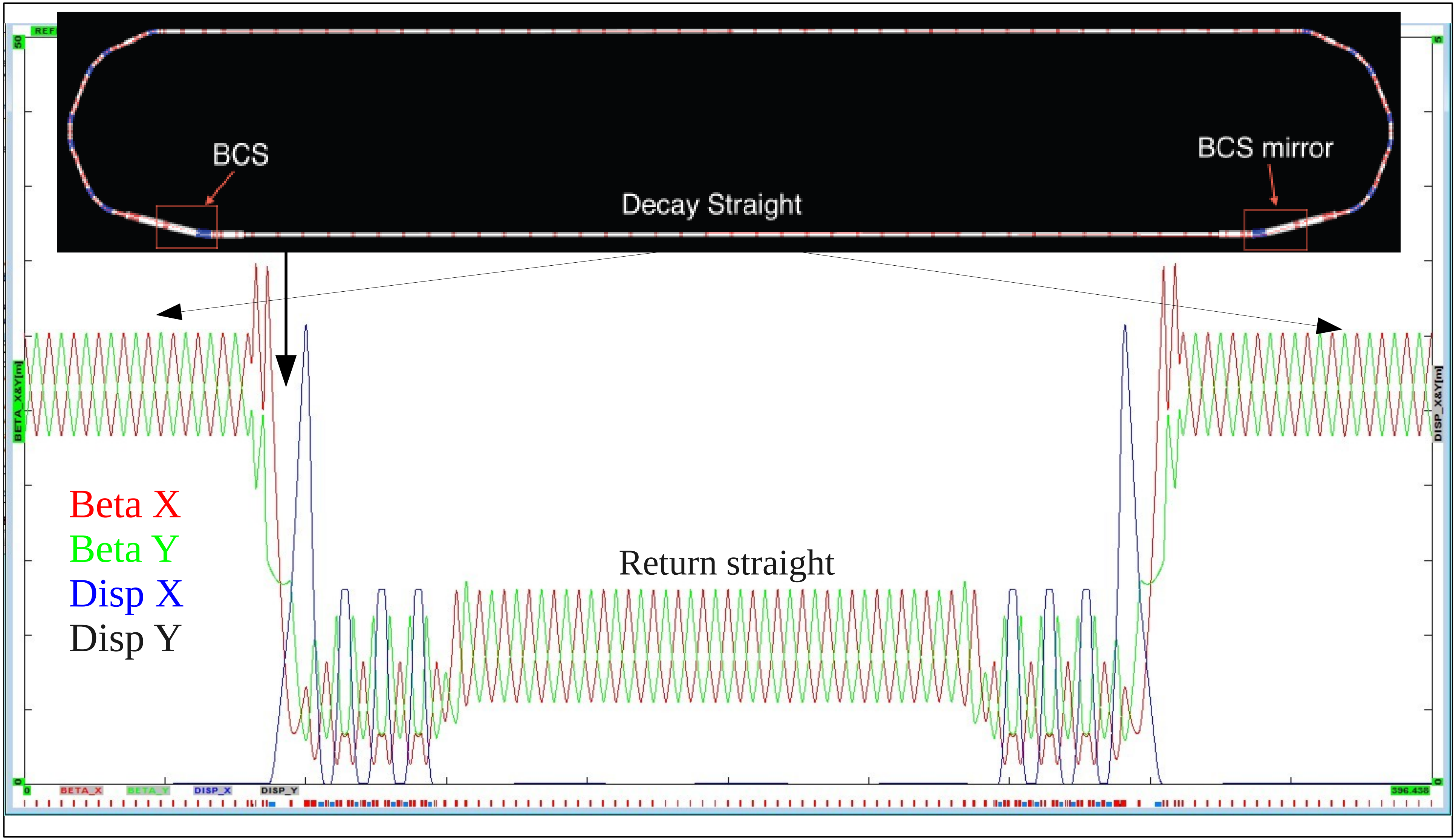
Nμ and Nπ increased by ~20% (If just changing the target length: ~5%)
Pion beamline re-matched and π+ re-tracked
μ+ in both 2000 μm and 3.8±10% GeV/c increased by ~16%







- Pions are injected into the same ring as the muons with large aperture magnet section – no kicker.
- Dual optics for 5GeV pions and 3.6 GeV muons
- Mirrored combination section to extract surviving pions at end of decay straight



- Neutrino production straight requires minimized divergence – high beta and large magnets
- Return straight can have smaller beta to minimize magnet costs
- Decay straight – 30cm radius normal conducting 2T/m

<1% error - Beam systematics

Systematic	nuSTORM issue?
Hadron production	*Not really* – beam current will be measured although proton contamination will need to be known
Proton beam targeting	*No* – current and position of pion/muon beam will be measured
Target movement within horn	*No*
Target degradation	*No*
Horn pulse consistency	*No*
Horn degradation	*No*
Power supply issues	*No* – lattice PS will be monitored
Pion divergence	*No* – will be measured

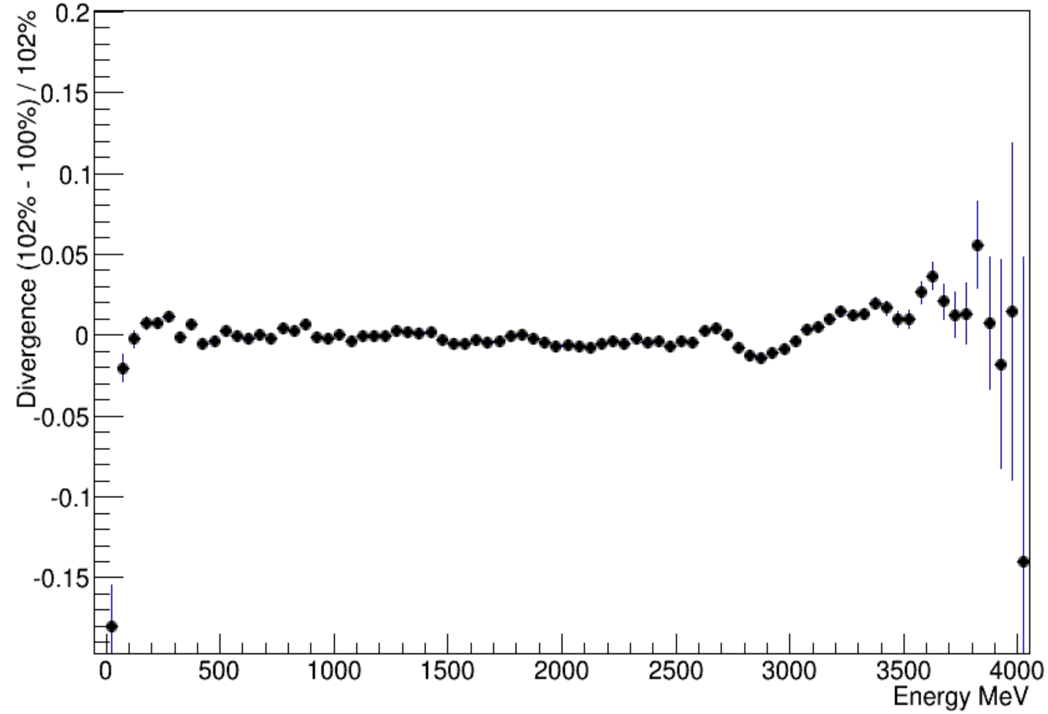
Beam diagnostics

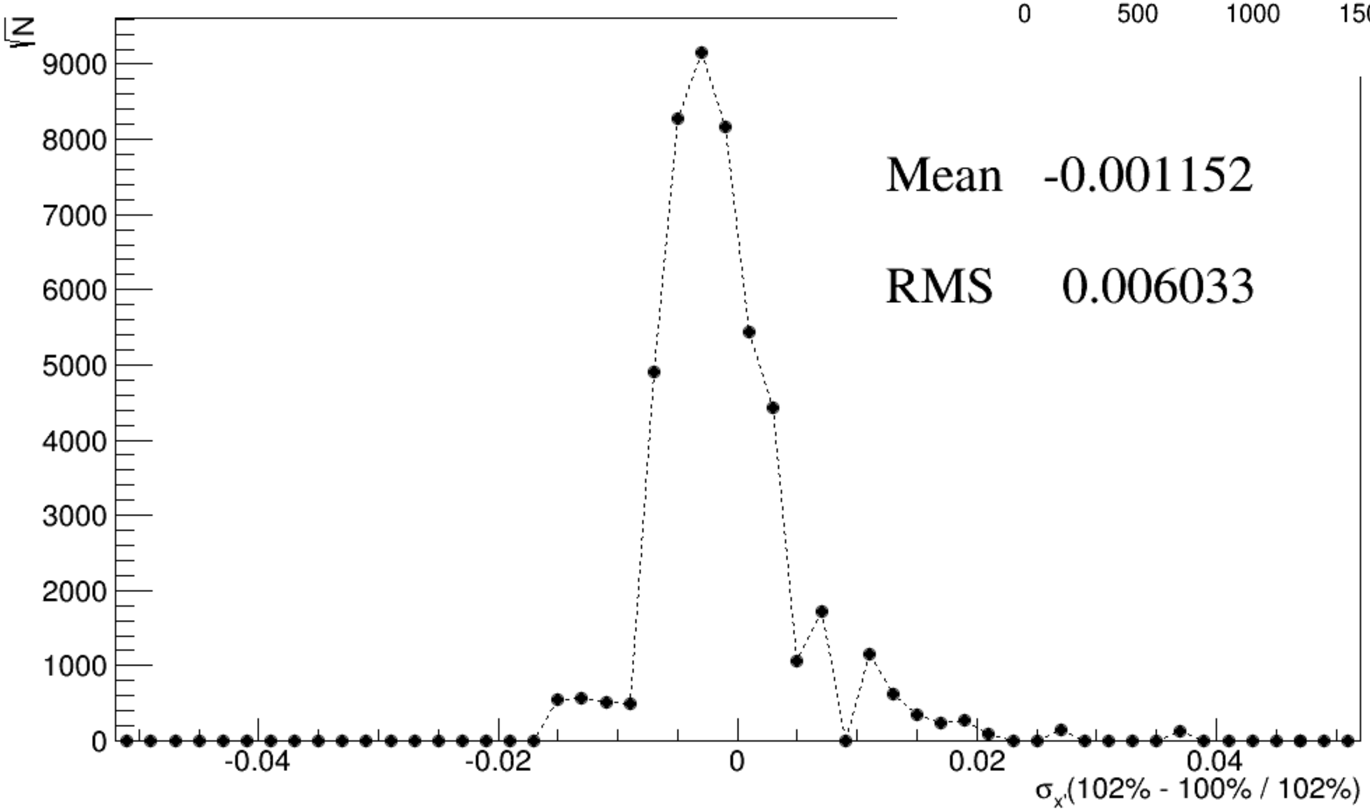
Quantity	Detector	Comment
Intensity	Beam Current Transformer	0.1% resolution
Beam Position	Button BPM	1cm resolution
Beam Profile	Scintillating Screen	1cm - Destructive
Energy	Polarimeter	
Energy Spread	Profile measurement in arcs	0.1% resolution
Beam Loss	Ionization chambers	

- Beam can be fully characterized, including destructive methods during a commissioning phase – all magnets are DC
- Magnet currents can be monitored and controlled with precision

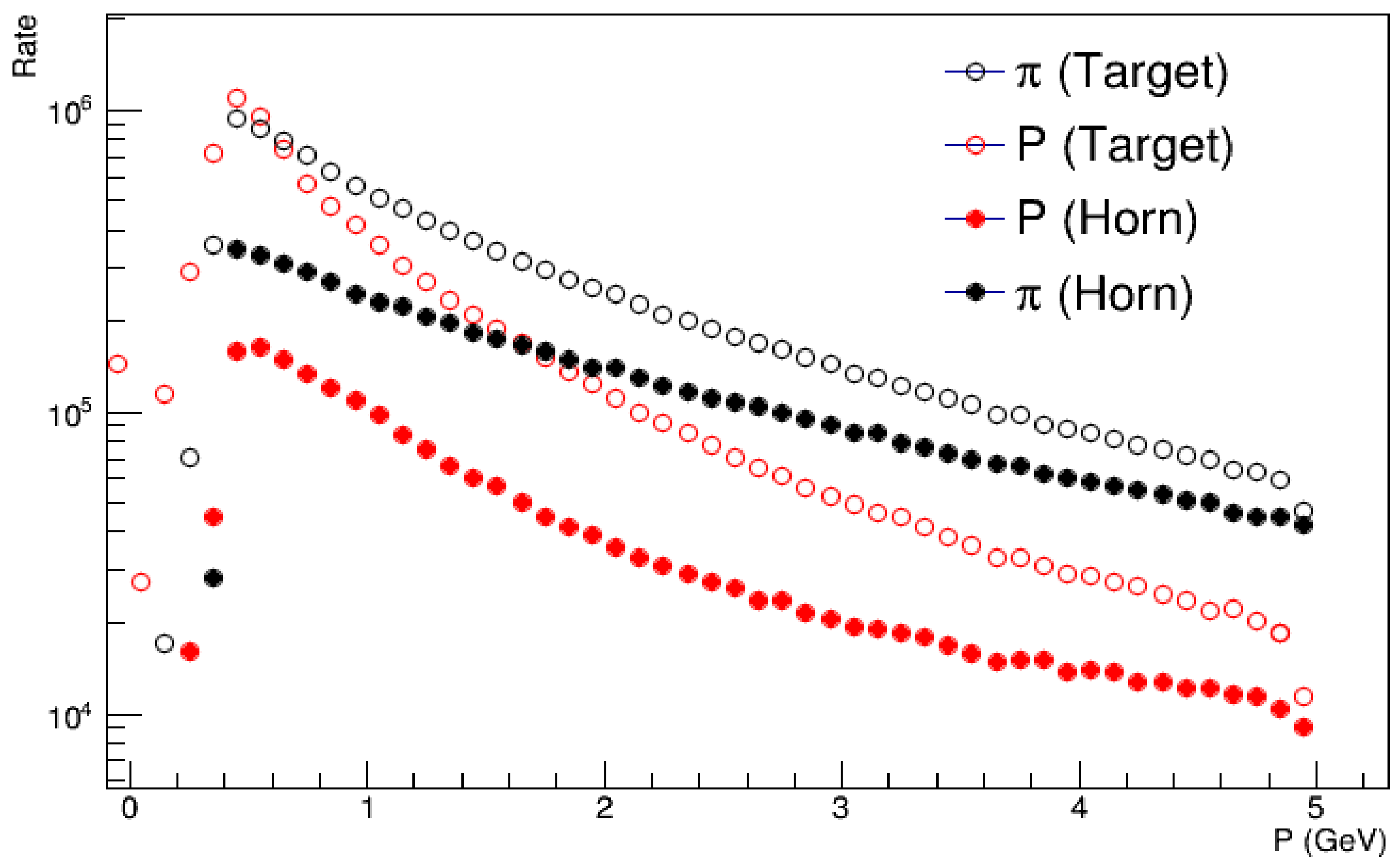
Beam divergence errors

- Muon beam re-simulated with a divergence inflated by 2%
- Resulting neutrino flux compared to nominal beam
- Less than 1% difference bin-to-bin

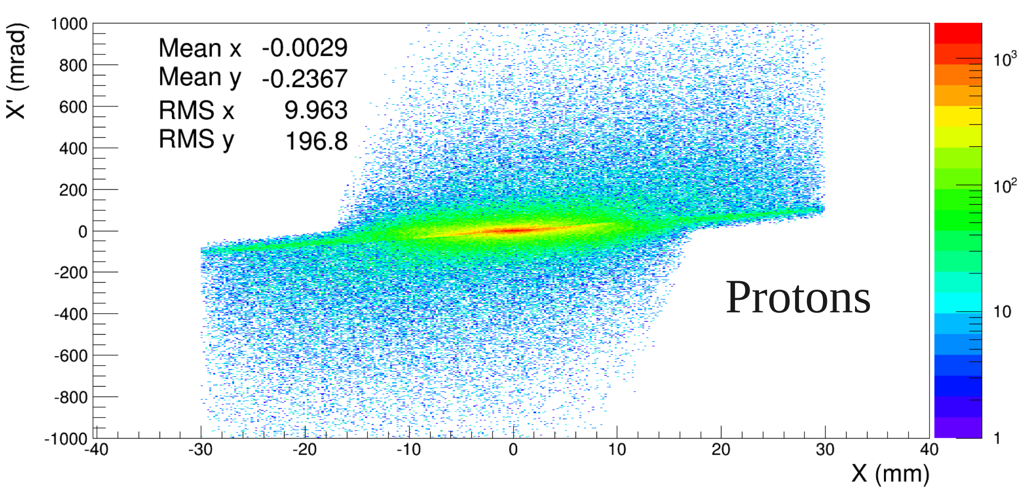


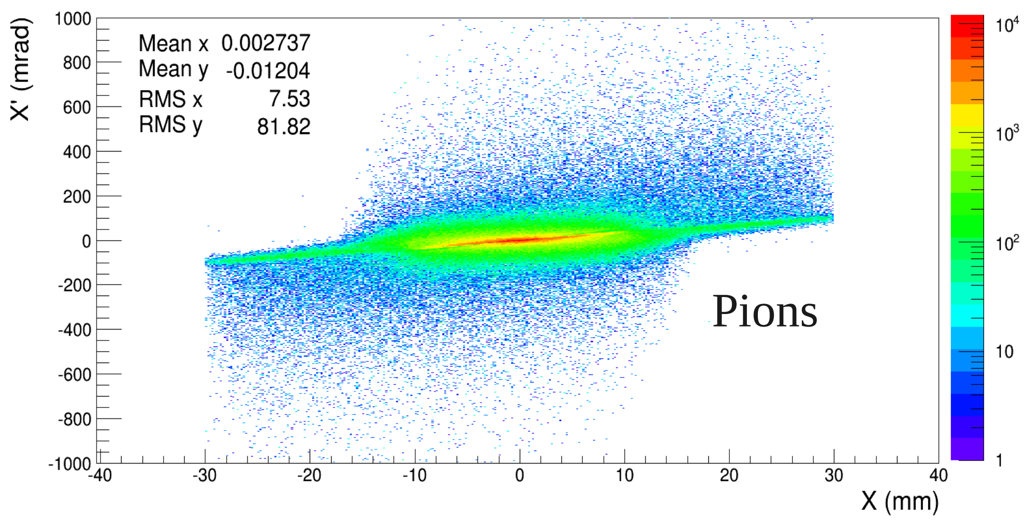


Source	Error
Intensity	0.1%
Divergence	0.6% with 2% measurement
Energy spread	0.1%



- Residual protons from primary beam within pion acceptance
- Proton contamination in the beam will inflate the current measurement in the BCTs during the first pass and the overall neutrino flux normalization
- Measurement of proton component will be required for pion decay beam at a minimum
- Possible in destructive commissioning phase

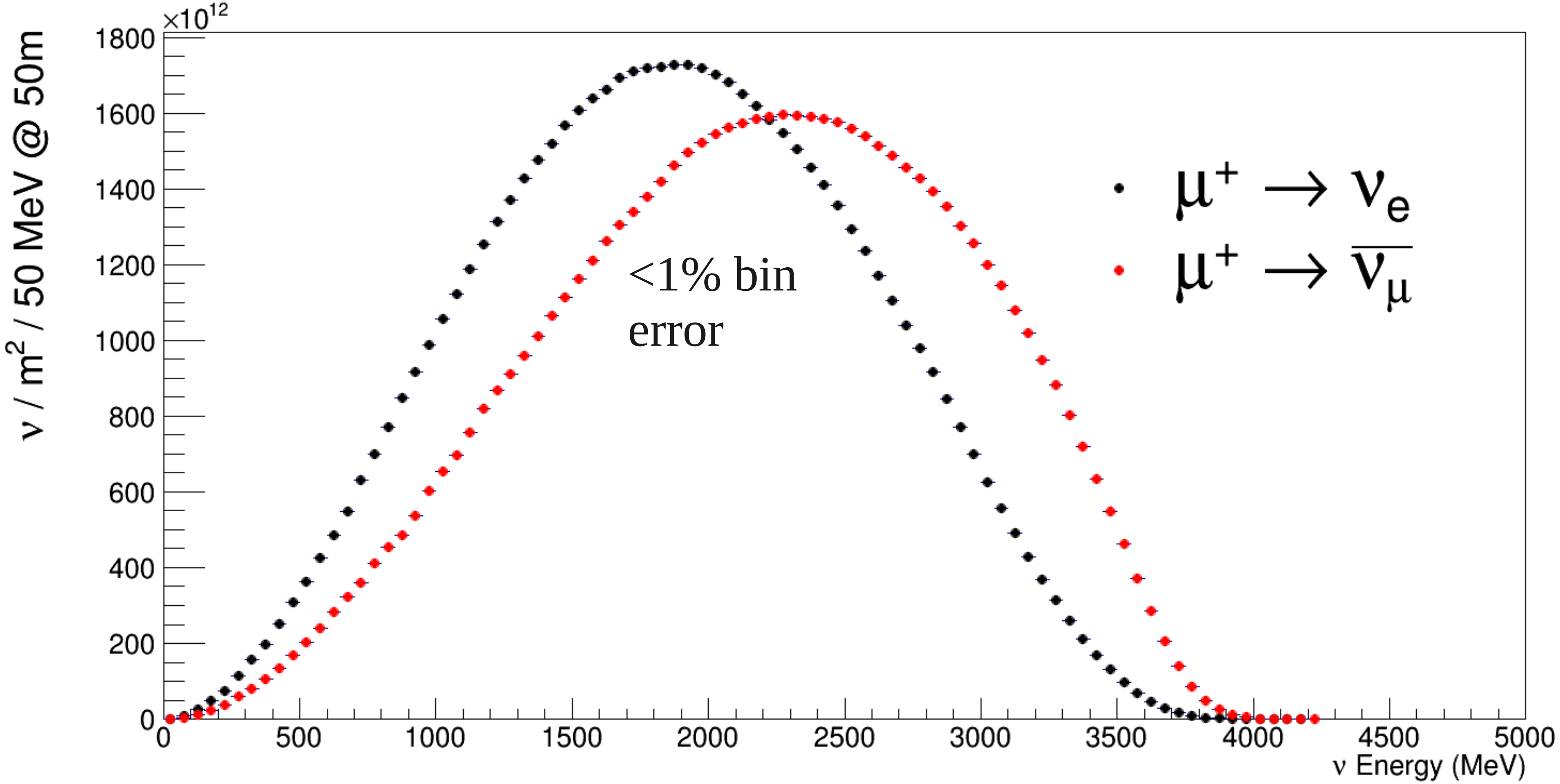




A hybrid neutrino factory

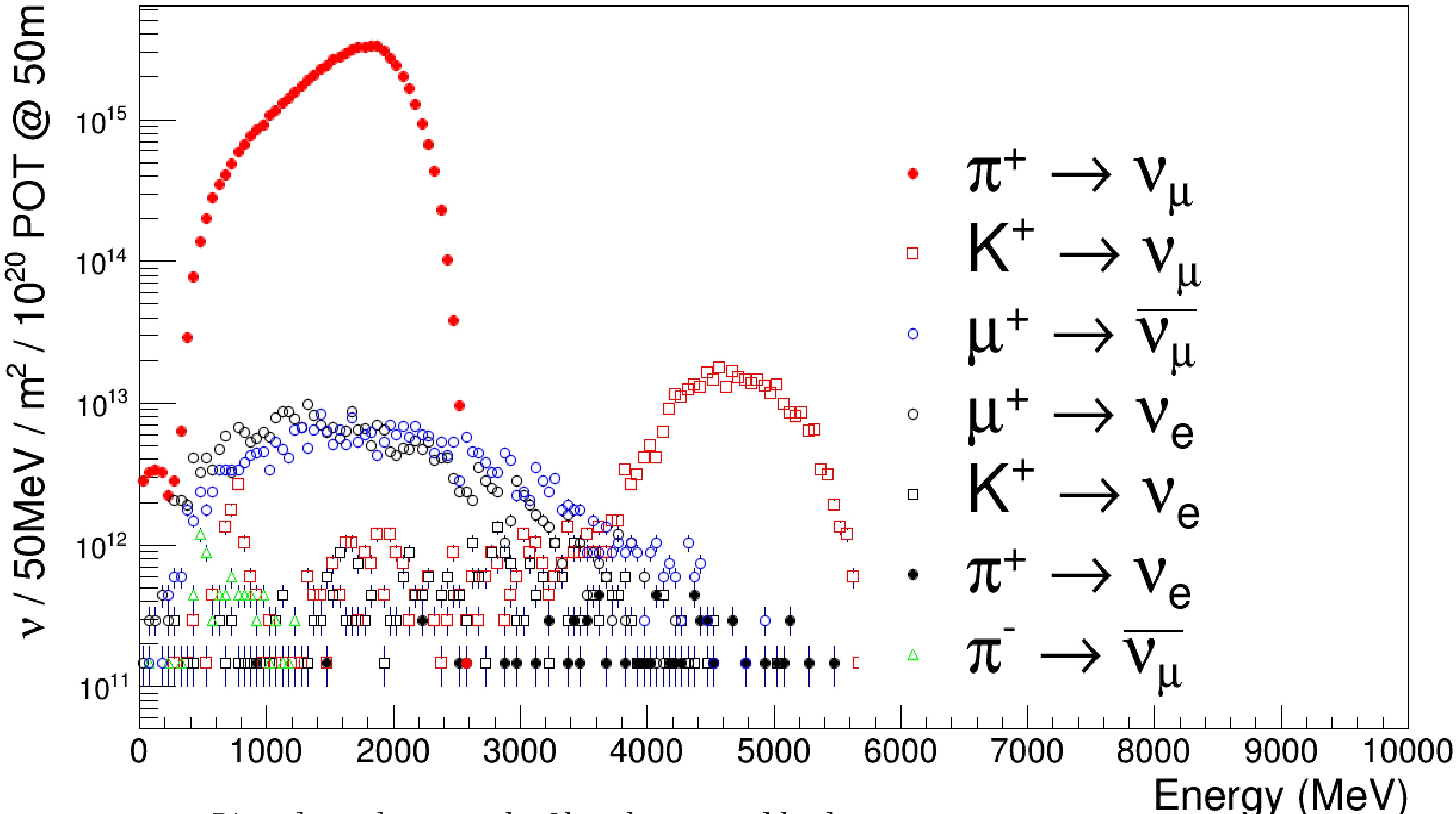
- Traditional neutrino factory design has pion decay detached from muon decay rings to include cooling and re-acceleration
- In nuSTORM, pions are injected into and decay in the muon decay straight, giving an initial pion decay flash before the decays from the stored muons
- Produces two beams – one muon decay and one pion decay 10x larger, both with <1% precision

Flux at 50 m from end of straight from muon decay



- Muon beam tracked through decay straight using G4Beamline
- Distribution used to generate decays and neutrinos sampled at 50m near detector site
- Likely flux increase with horn optimization

Near (50 m) detector flux from pion decay



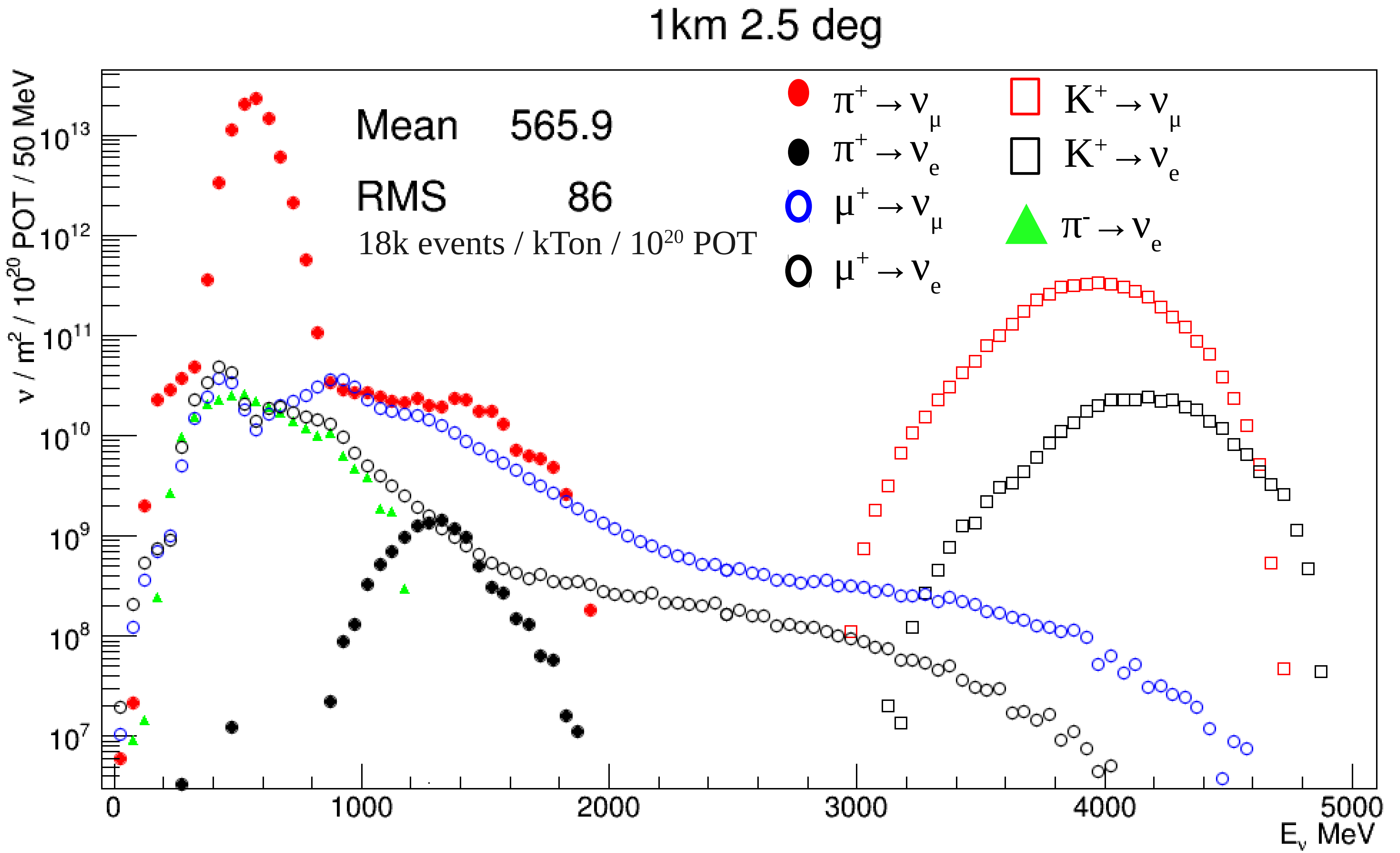
- Pion-decay beam at the 2km detector adds electron appearance channel and increased options for NC disappearance

μ+ Stored		**μ- Stored**	
Channel	*Events*	*Channel*	*Events*
ν_μNC	1,174,710	ν_eNC	1,002,240
ν_eNC	1,817,810	ν_μNC	2,074,930
ν_μCC	3,030,510	ν_eCC	2,519,840
ν_eCC	5,188,050	ν_μCC	6,060,580
π+		**π-**	
ν_μNC	14,384,192	ν_μNC	6,986,343
ν_μCC	41,053,300	ν_μCC	19,939,704

- Event rates at 50m per 100T for full exposure of 10^{21} POT

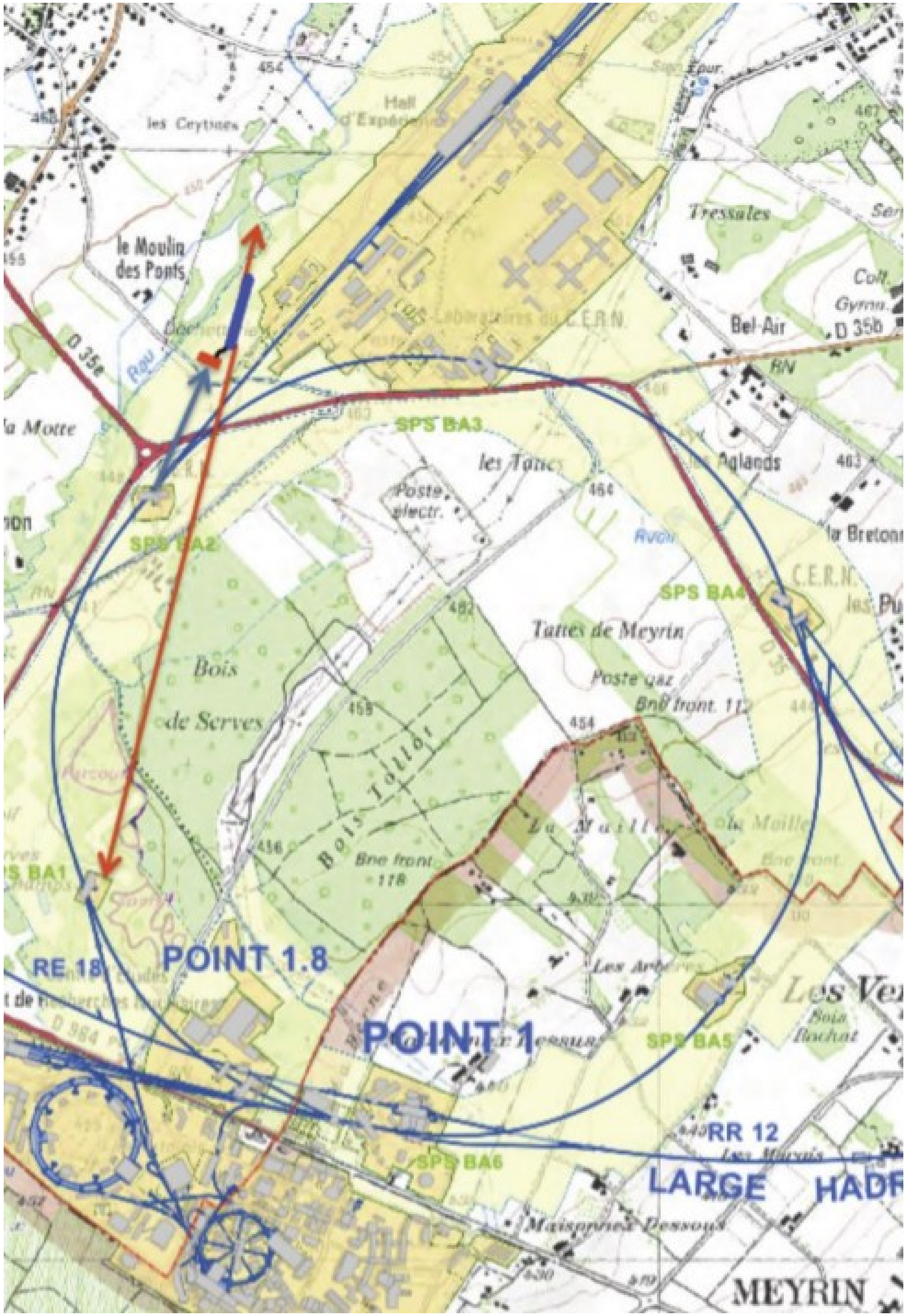
nuSTORM Off-axis

- Placing detector off-axis of the nuSTORM beam decreases energy width even further with no high energy tail
- Can be placed in the energy regime of interest to existing off-axis experiments



Future

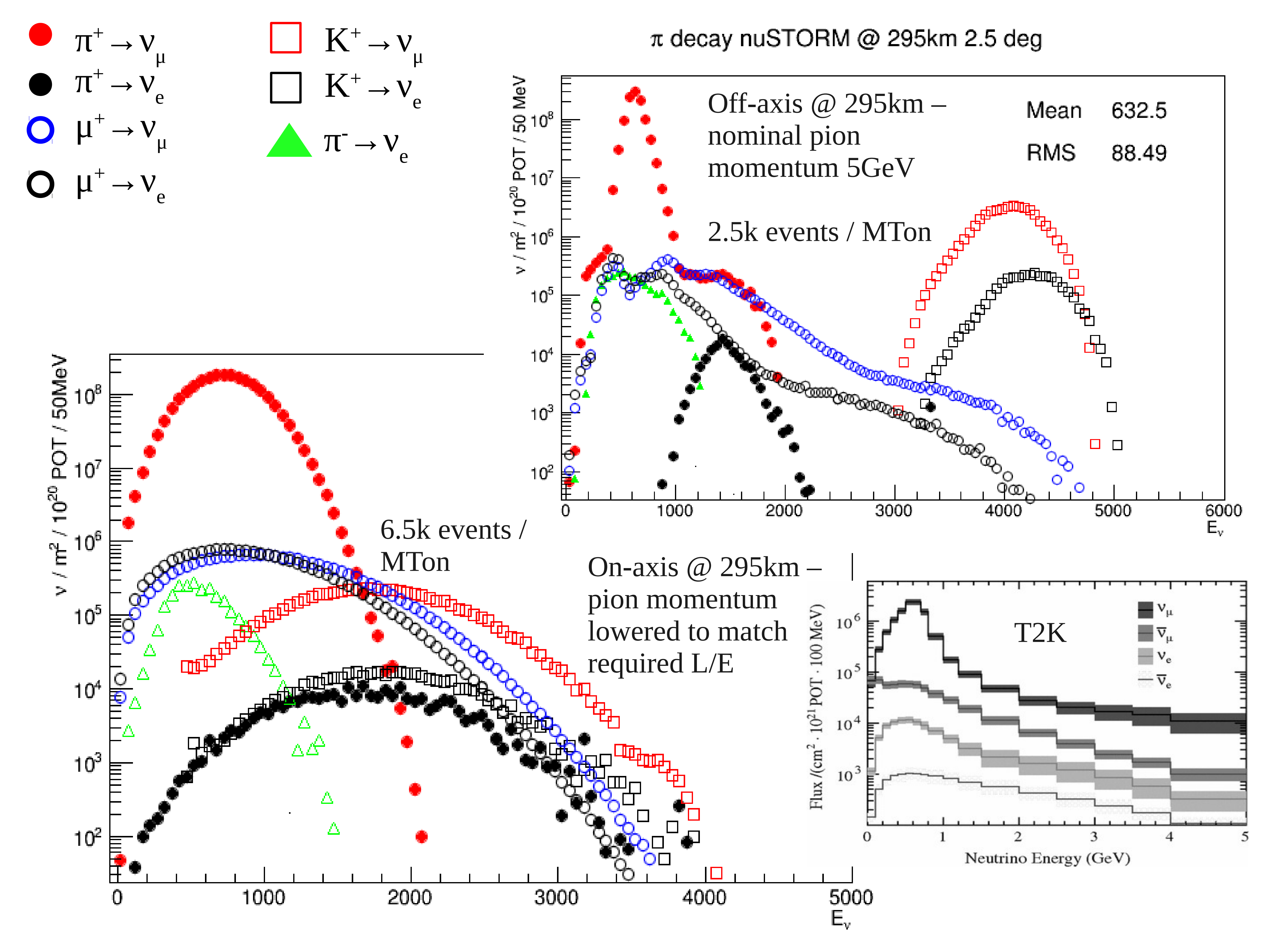
- P5 did not recommend nuSTORM be built in the US
- Expression of Intent was submitted to CERN in 2013 – facility and performance can be achieved in the same manner from SPS as from Main Injector
- Workshop planned towards the end of the year
- Work continues on facility design and physics studies, including sterile neutrinos and interaction physics in various near detector types



Summary

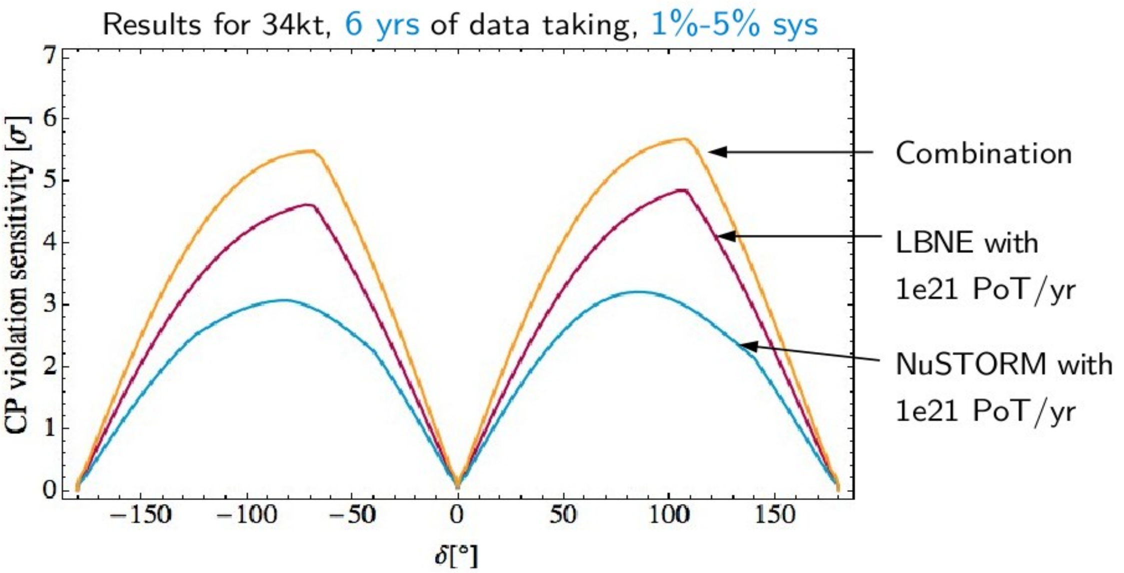
- Cross section measurements essential for limited systematics of future experiments can be resolved by a muon decay beam
- Sterile neutrino conflicts can be resolved at the same facility
- nuSTORM flux is optimized by target, horn, transfer and storage ring studies
- Flux precision is expected at <1%
- Muon-decay and pion-decay narrow band beams with sign-selection and high precision available in the same experiment
- Thanks to R Bayes, A Bross, P Coloma, P Huber, JB Lagrange, J Pasternak, A Liu, D Neuffer, E Santos, P Soler, C Tunnel

Backups

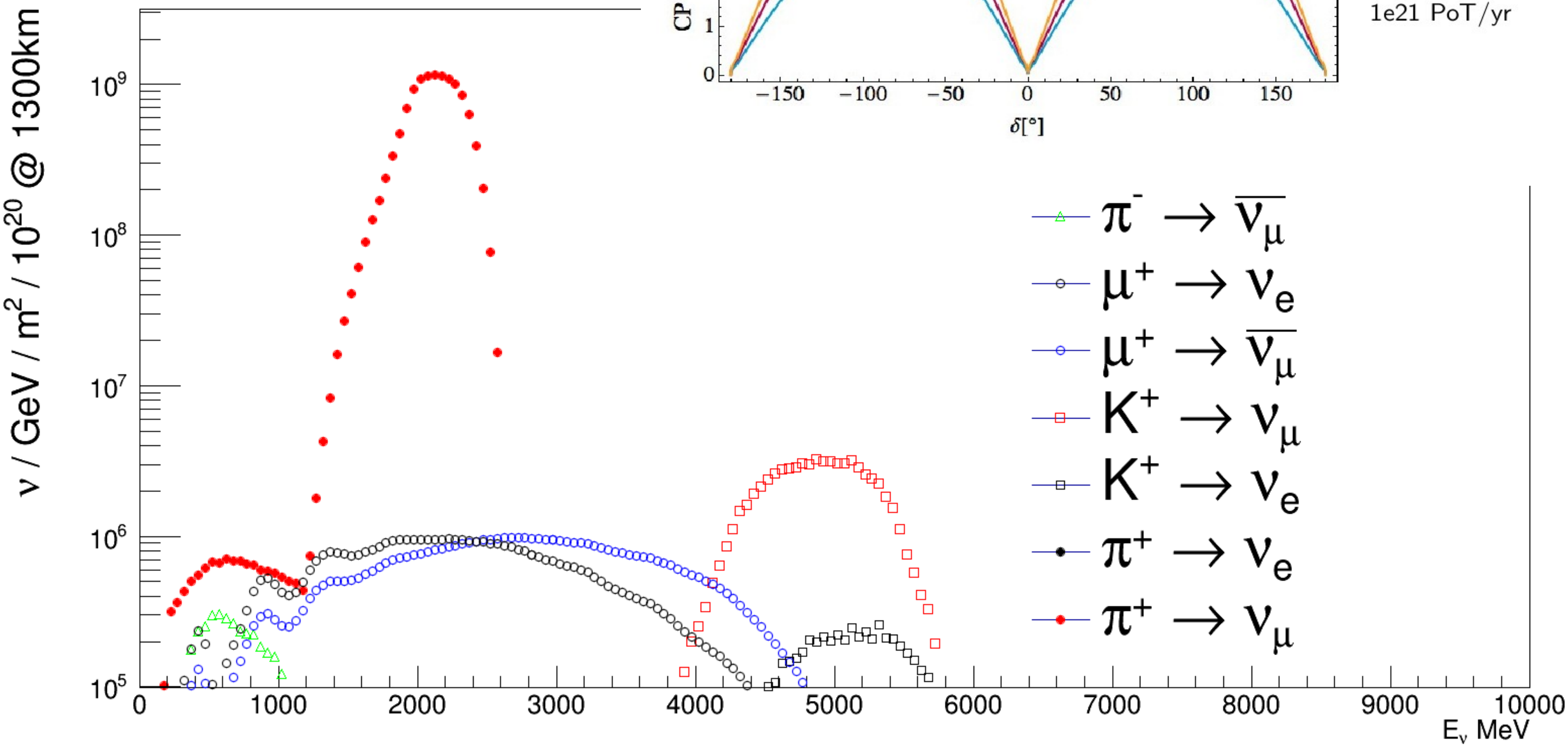

π+ → νμ
π+ → νe
μ+ → νμ
μ+ → νe
K+ → νμ
K+ → νe
π- → νe
π decay nuSTORM @ 295km 2.5 deg
Off-axis @ 295km – nominal pion momentum 5GeV
Mean 632.5
RMS 88.49
2.5k events / MTon
ν / m² / 10²⁰ POT / 50 MeV
Eν
6.5k events / MTon
On-axis @ 295km – pion momentum lowered to match required L/E
ν / m² / 10²⁰ POT / 50MeV
T2K
Flux /(cm² · 10²¹ POT · 100 MeV)
Neutrino Energy (GeV)

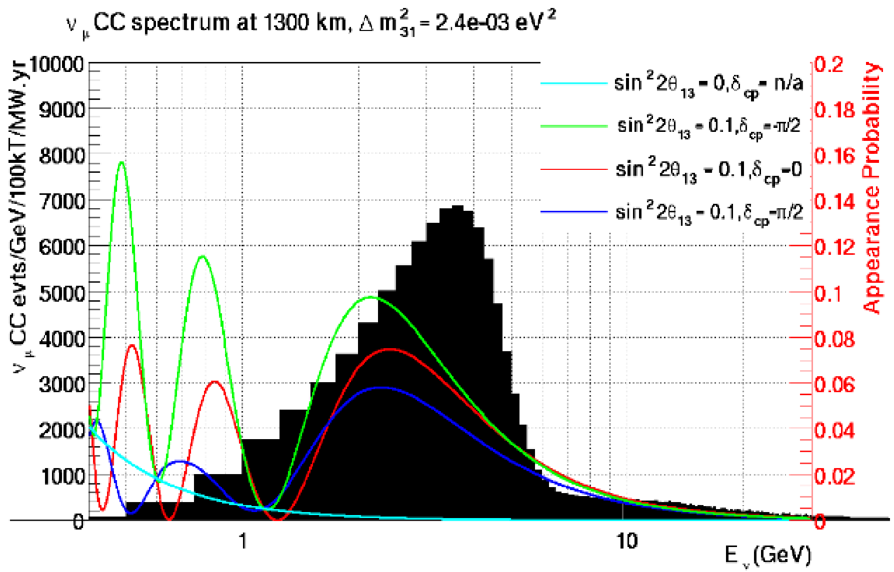
Very Far (1300 km) detector flux from pion decay

CP violation sensitivity



- nuSTORM long-baseline contribution to CP only – does **NOT** include contribution to cross-section systematic

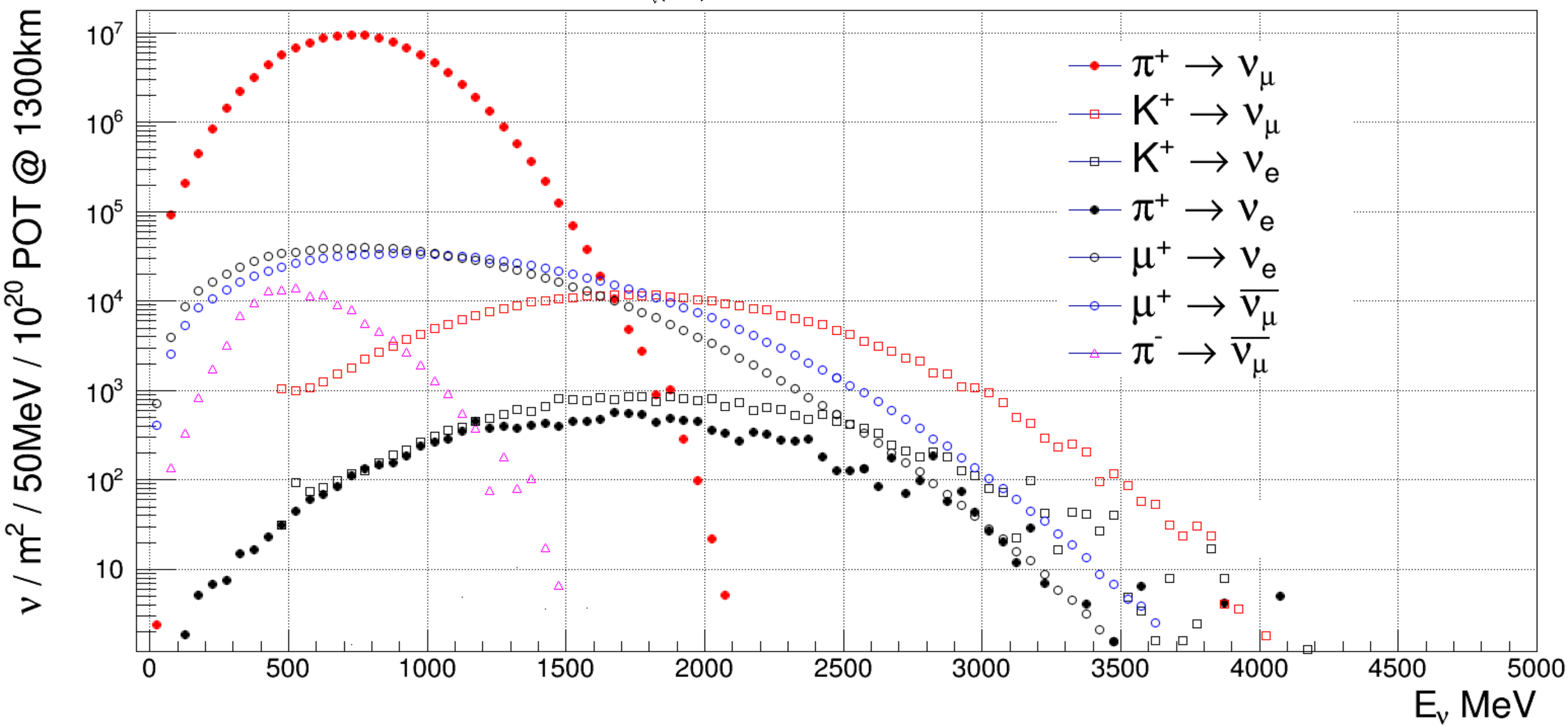




Very Far (1300 km) detector flux from pion decay – 2nd oscillation maximum

Still not an optimized pion beam, increased rate with momentum acceptance and move to pion only beam

P_π = 1.3 GeV

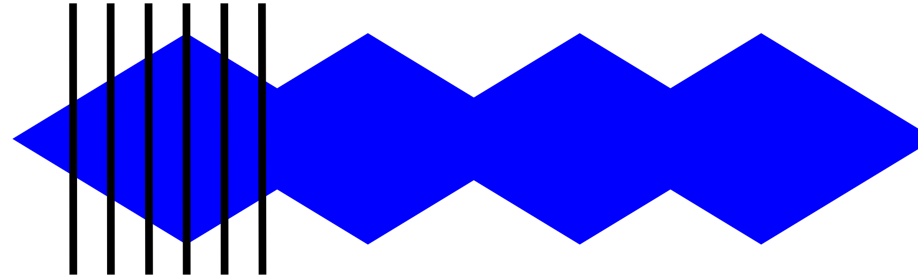


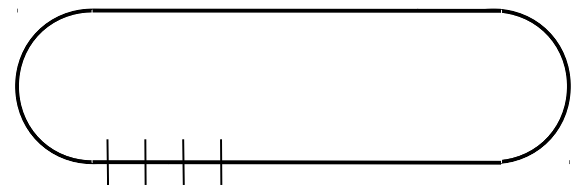
Muon beam tracking approximation

Full Geant tracking of muon beam through decay lattice is computationally intensive.

Beam was sampled a) with a single FODO cell b) over the entire straight and this sample used at decay points along the straight

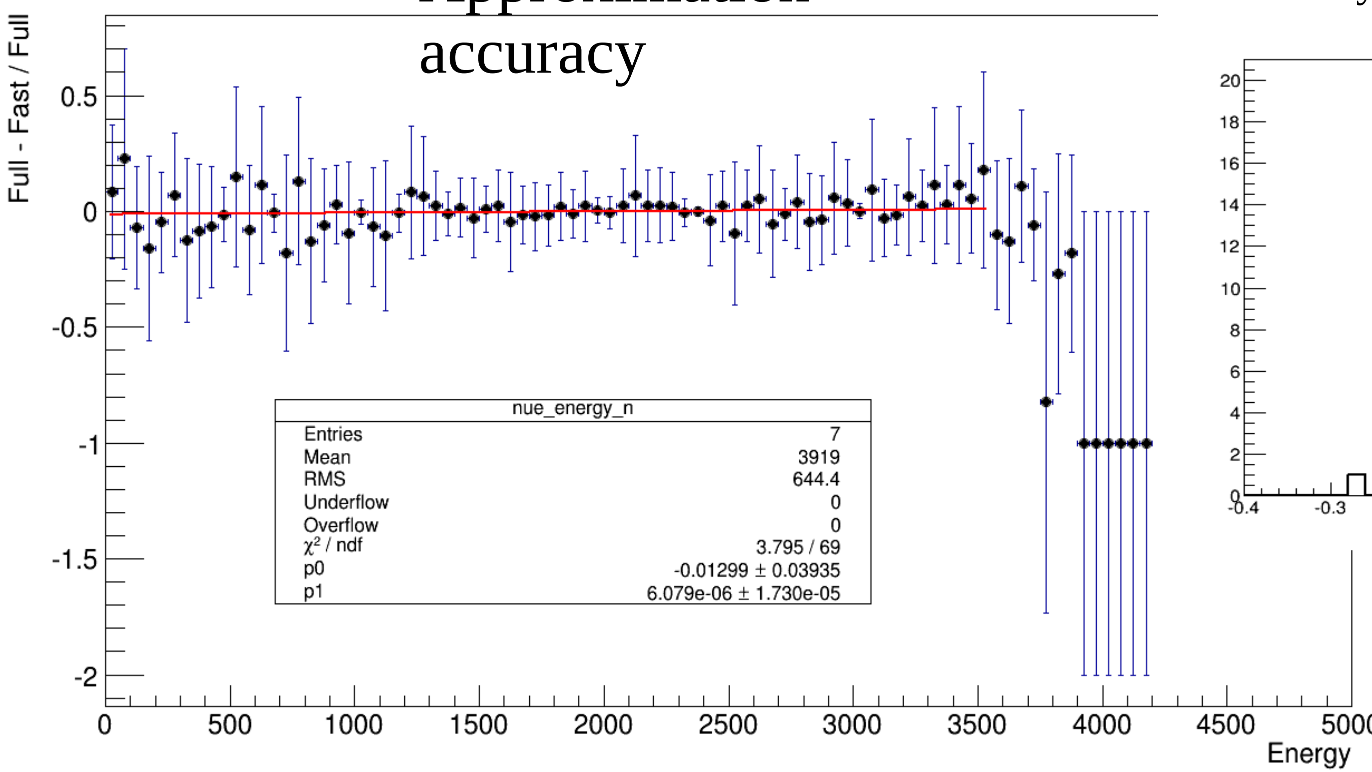
Sampling

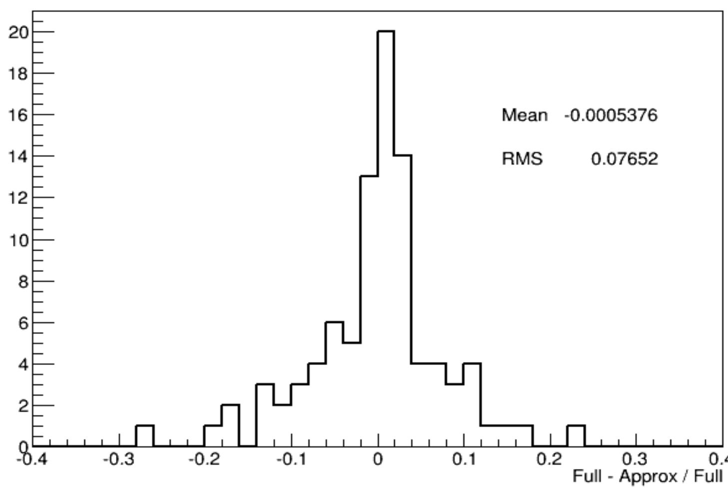




Decay points

Approximation accuracy





π decay simulation method

- MARS simulation of target and horn
- Particles produced and captured in horn tracked through transport line and into decay straight using G4Beamline
- Resulting neutrinos measured at sampling plane 50m from end of decay straight (near detector hall)
- For long baselines, position and divergence of each beam particle (pion, muon, kaon) to calculate flux of each channel at detector location
- Scaled to 10^{20} POT – full exposure 10^{21} POT