nuSTORM: variations on a theme

D Adey
on behalf of nuSTORM

NuFact 2014, Glasgow UK
28th August 2014

adey@fnal.gov

Content

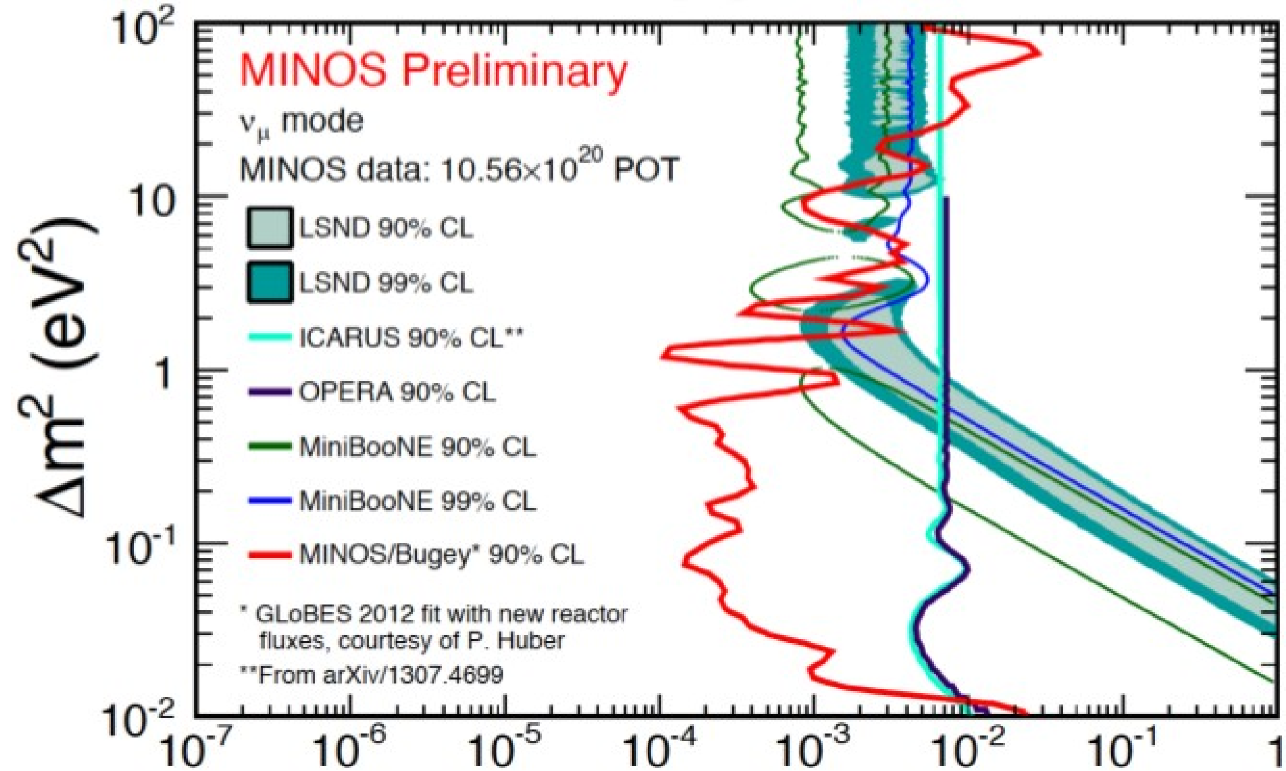
- nuSTORM motivations
- A neutrinos from stored muons concept
- Flux calculations and uncertainties
- Pion-decay flux
- Off-axis flux
- Physics studies
- Thanks to A Bross, A Liu, R Bayes, P Soler, D Neuffer, E Santos, JB Lagrange, J Morfin, C Tunnel, P Huber

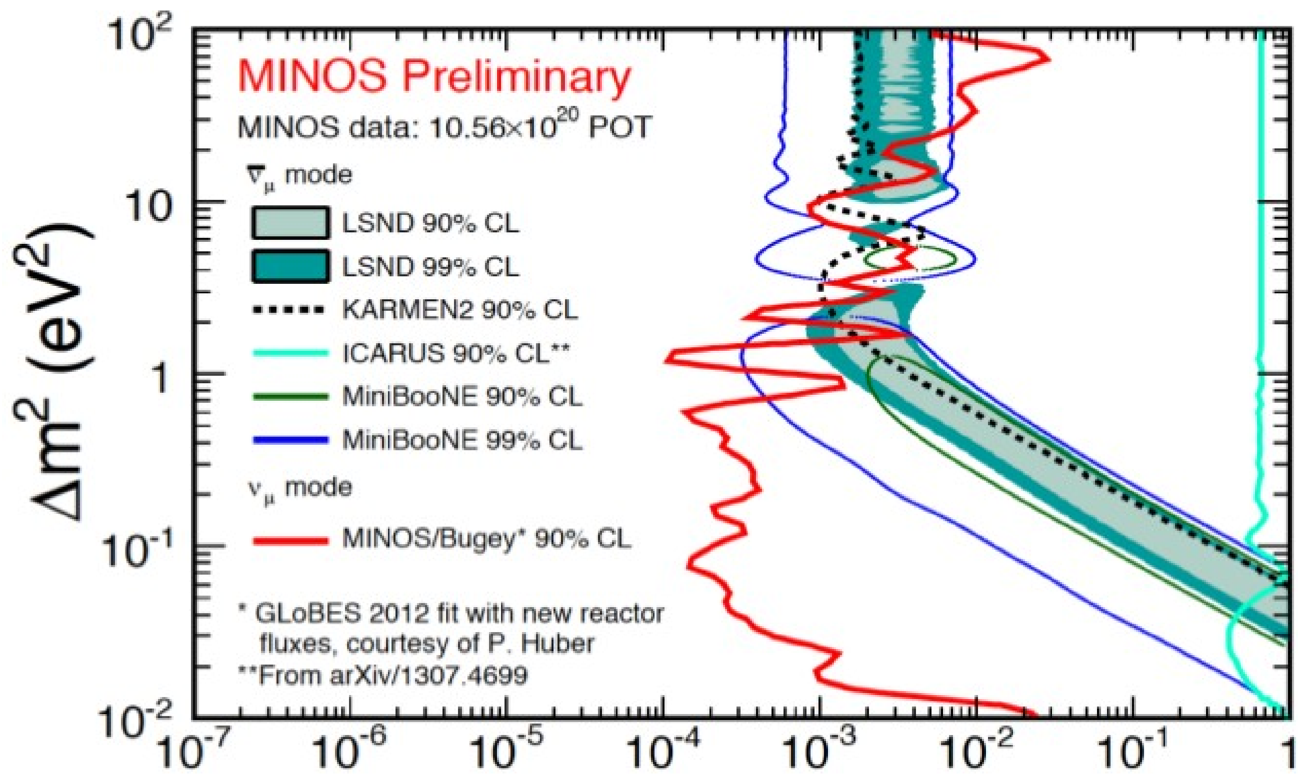
Motivations

Sterile Neutrinos

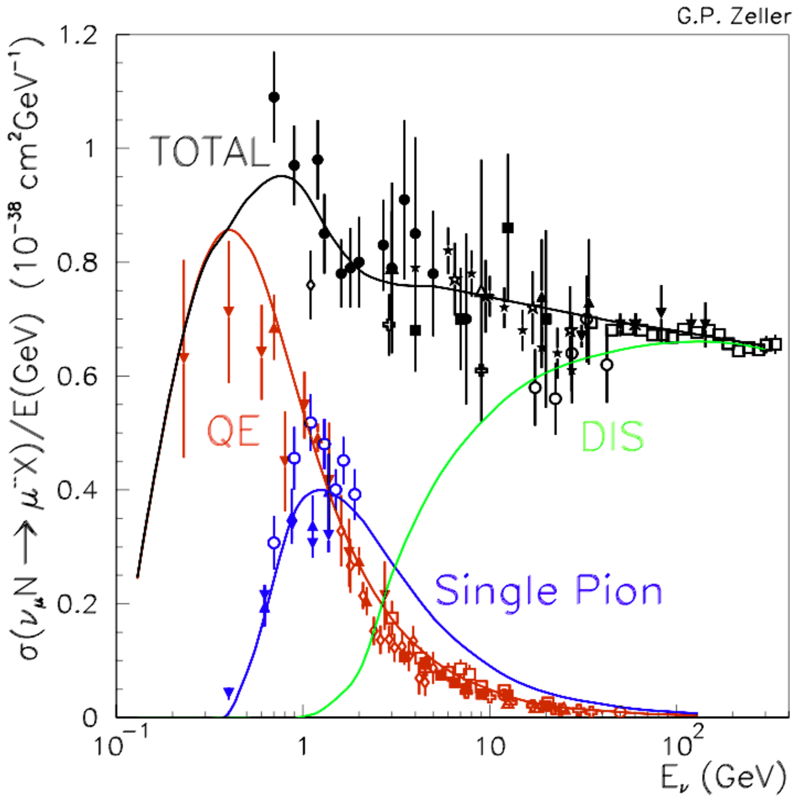
- Gallium: 2.7σ evidence for ν_e disappearance
- LSND: 3.8σ evidence for ν_e appearance
- MiniBooNE: 3.8σ evidence for ν_e and ν_e appearance
- Reactor: 3σ evidence for ν_e appearance
- Combined cosmology covers 4 DOF
- New limits from MINOS

Something definitive required

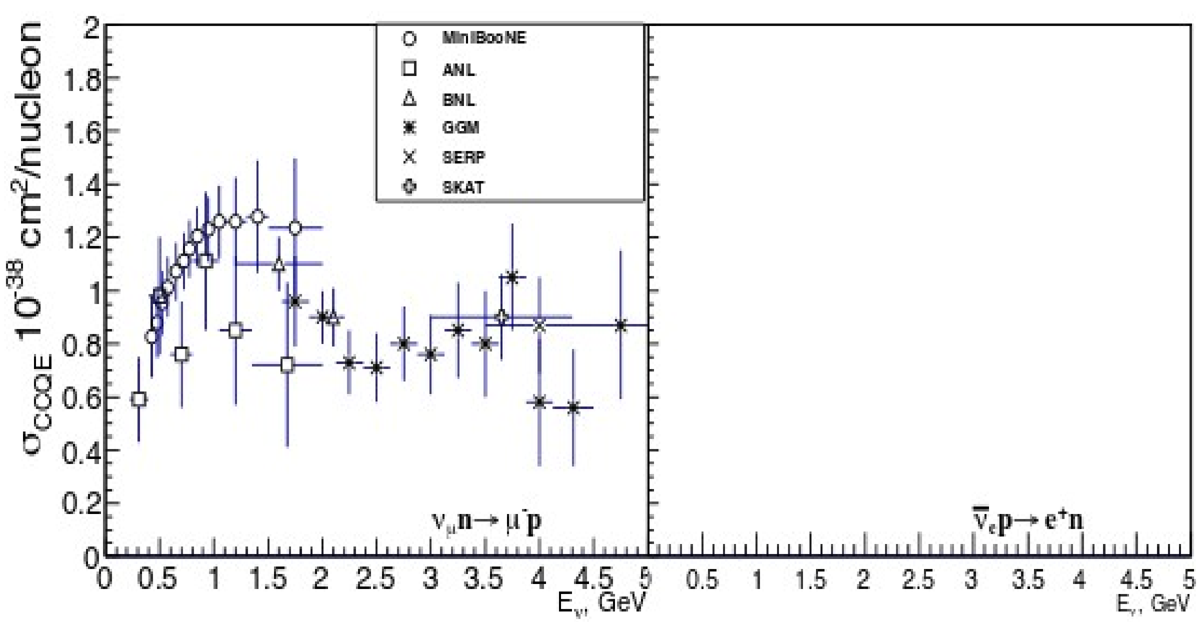


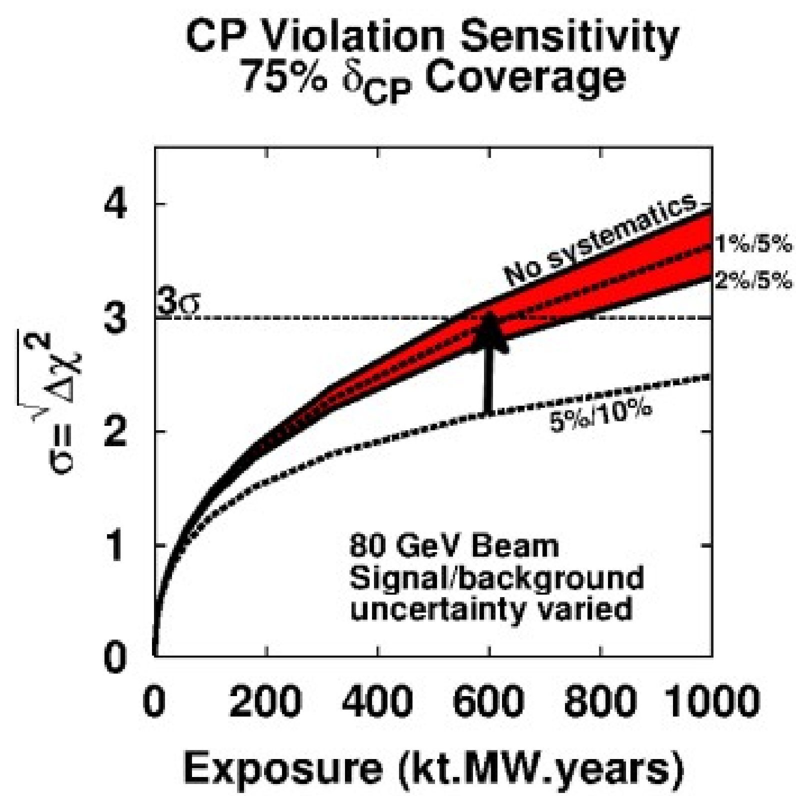


Cross Sections

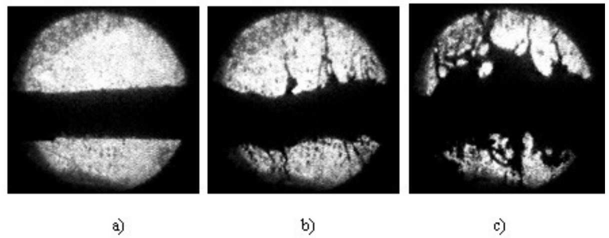


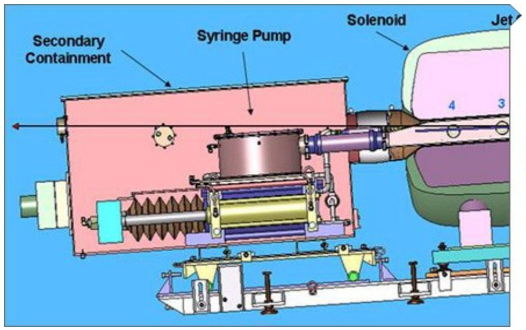
- Deficit in electron neutrino cross section measurements at accelerator energy regimes
- Neutrino / anti-neutrino cross section ratios vital for CP sensitivity
- Existing measurements affected by flux precision – future experiments will require ~1% total error to achieve CP coverage aims
- Muon decay offers opportunities to explore all of this





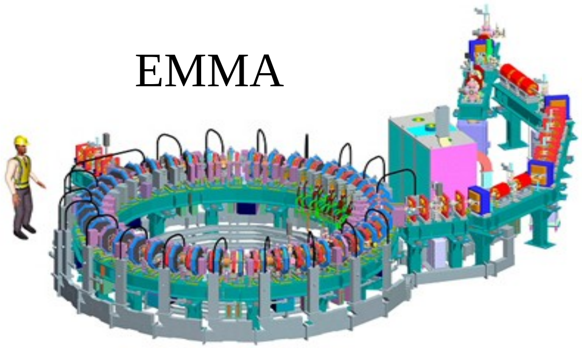
Muon Accelerator Technology

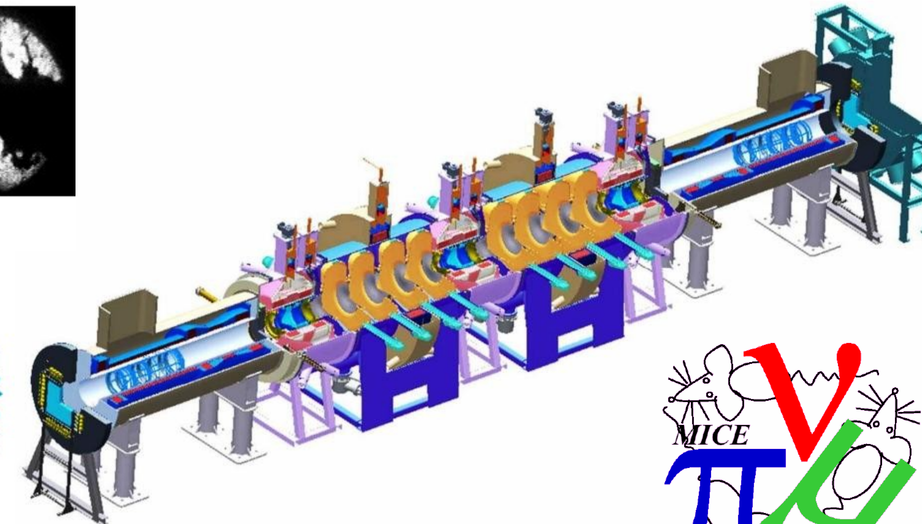




MERIT

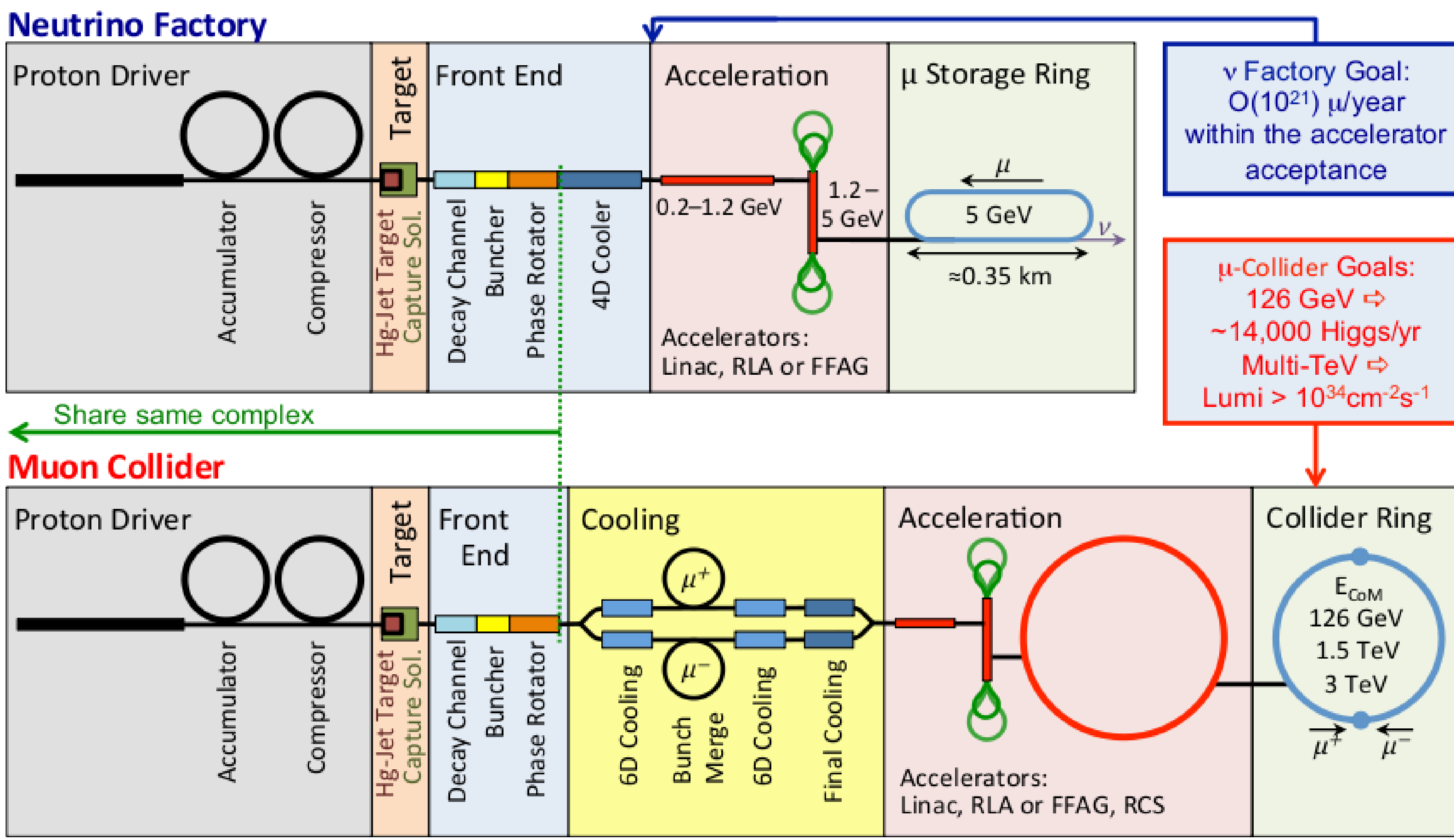
EMMA



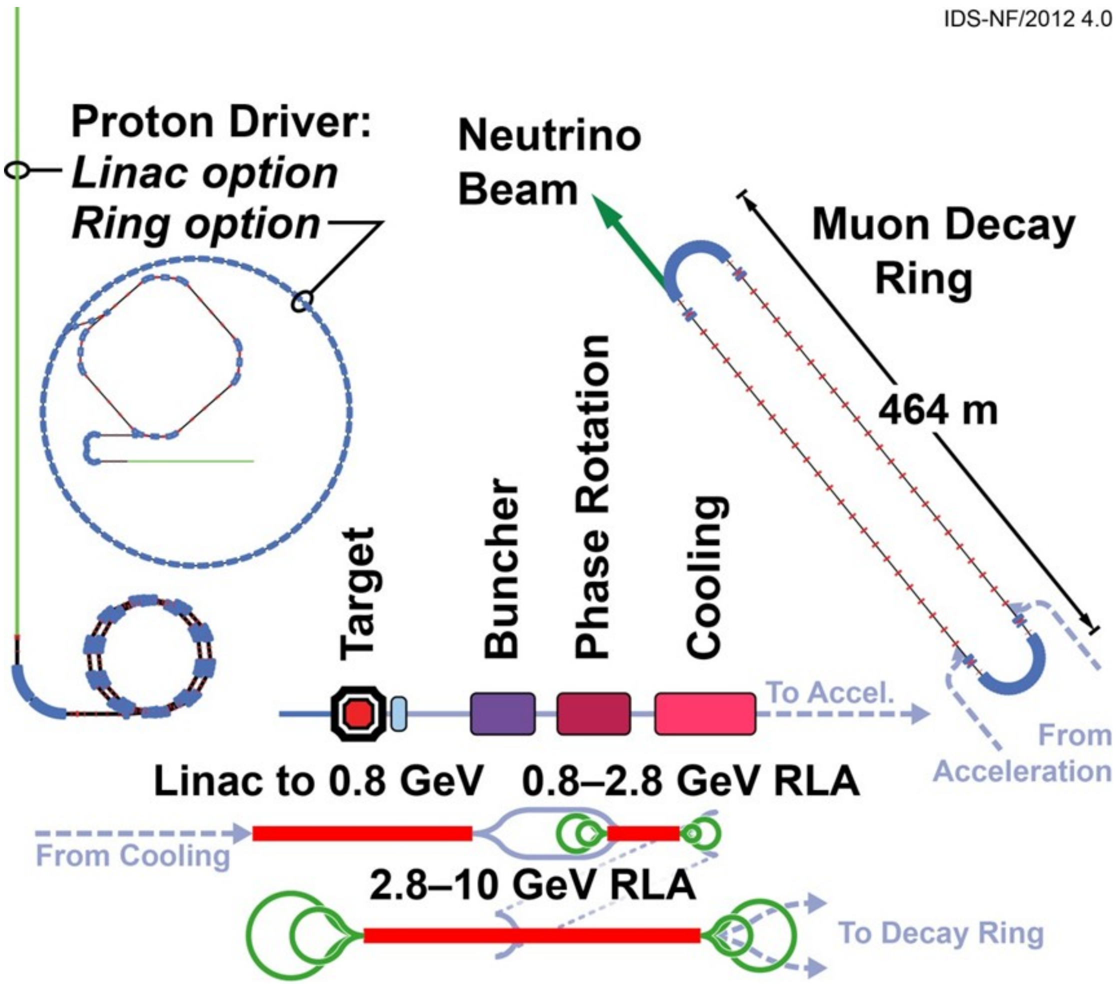


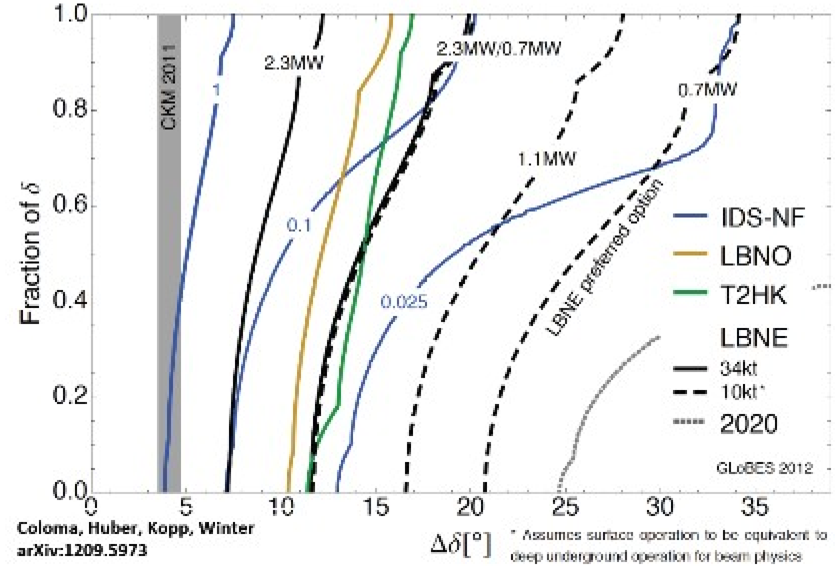
Muon-based accelerators and neutrino beams require extensive R&D.

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

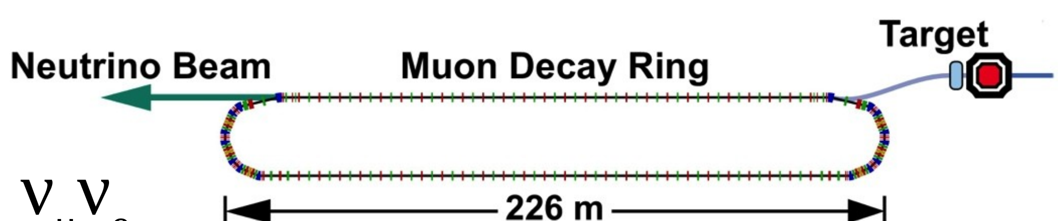


Neutrinos from Stored Muons





- 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



$\nu_\mu \nu_e$

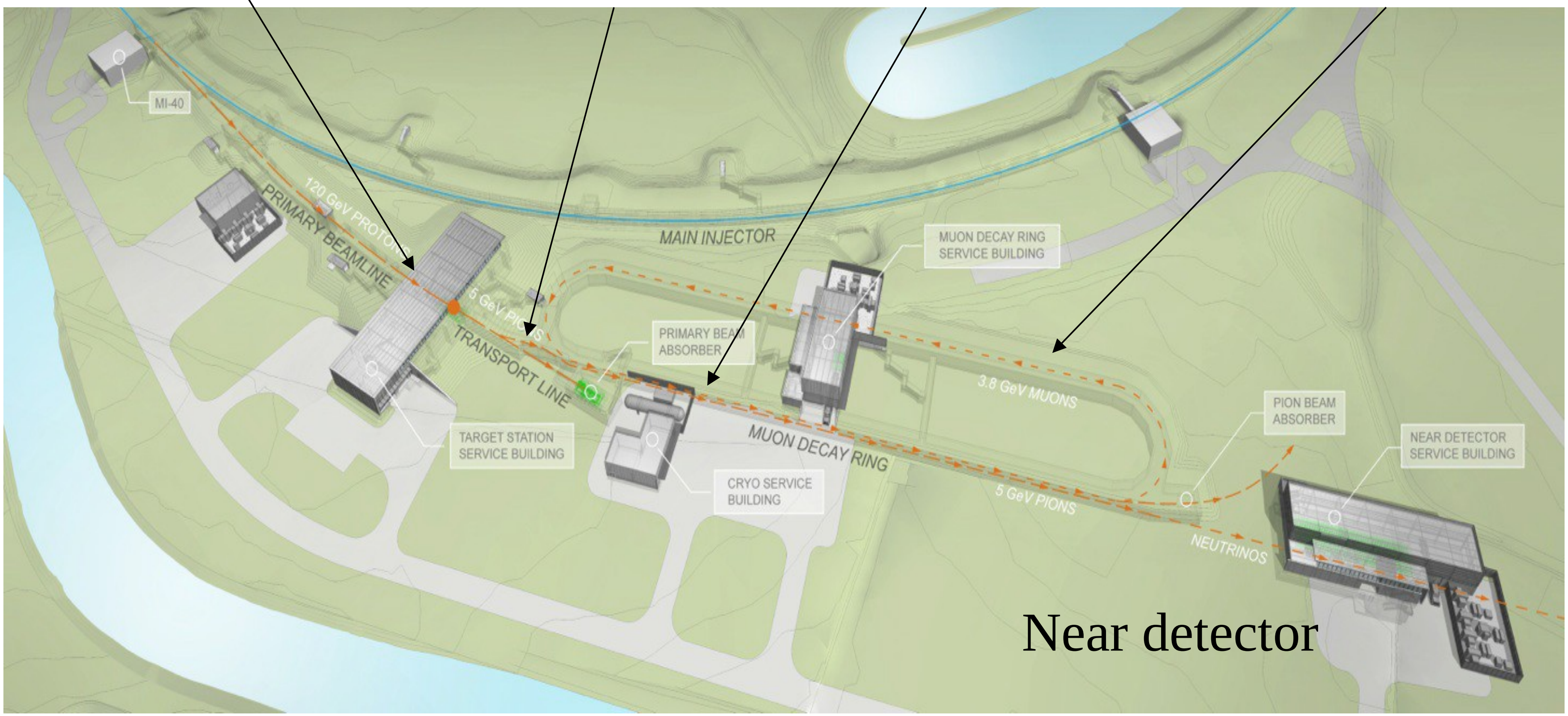
- Muon and electron neutrino beam can be produced from a stored muon beam using existing technology νSTORM

Protons on Target
Horn collection

Pion transport through dipoles – momentum and sign selection

Pions injected into ring decay into muons

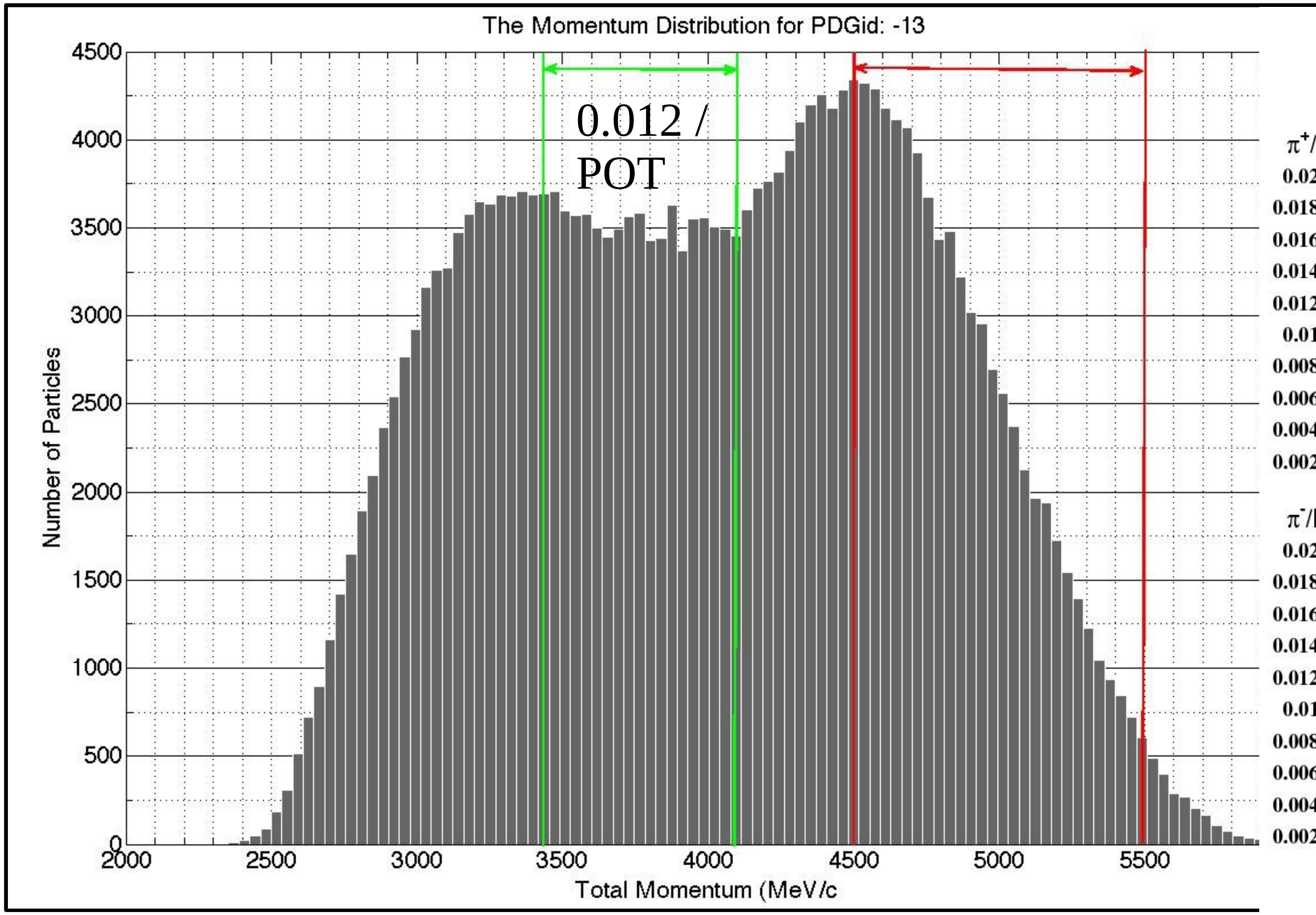
Stored muons decay into directed neutrino beam

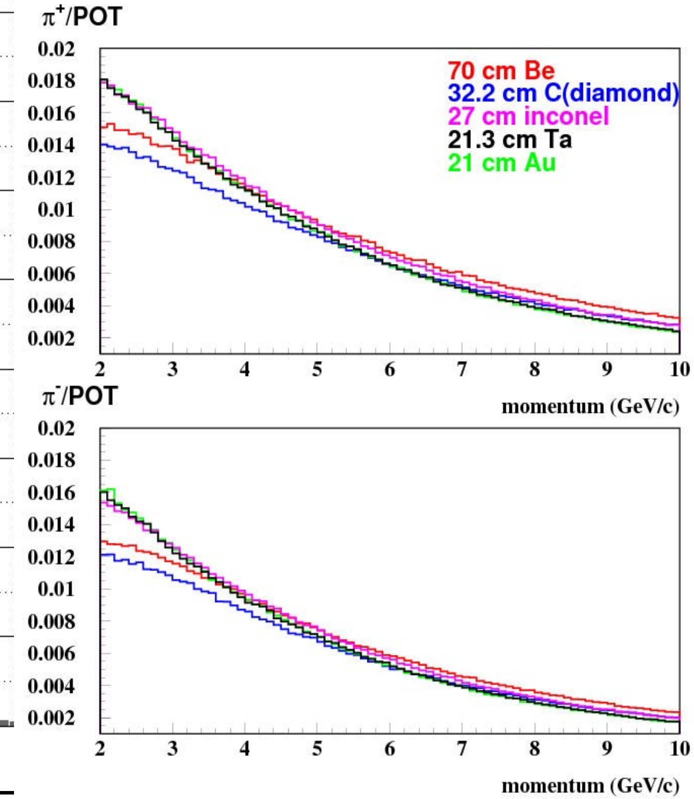


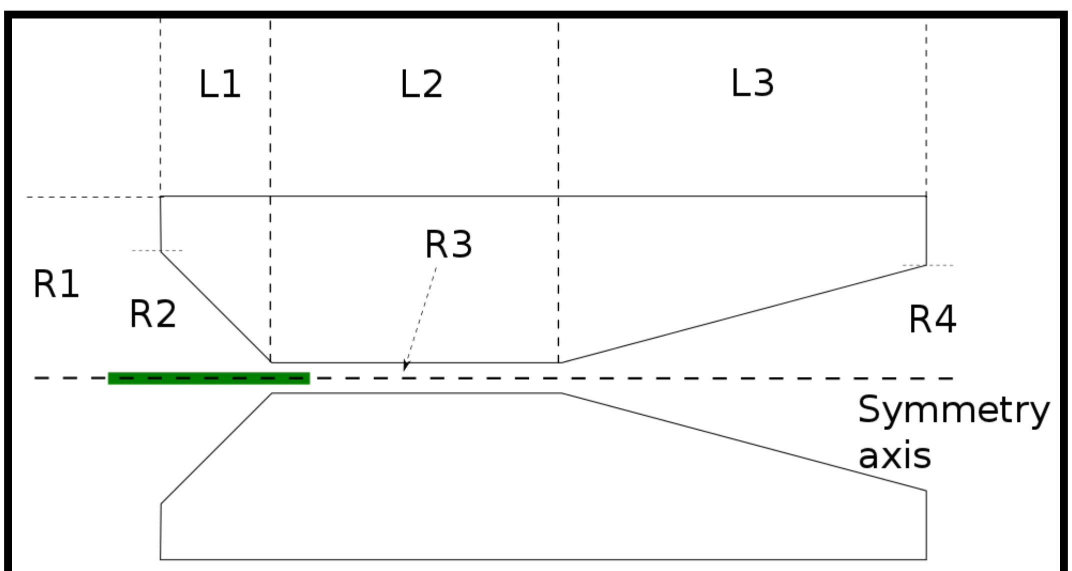
- Dipole chicane provides sign and momentum selection of pions
- Stored beam allows for instrumentation and characterization of beam
- Current, momentum, divergence, size, position

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

Beam optimization

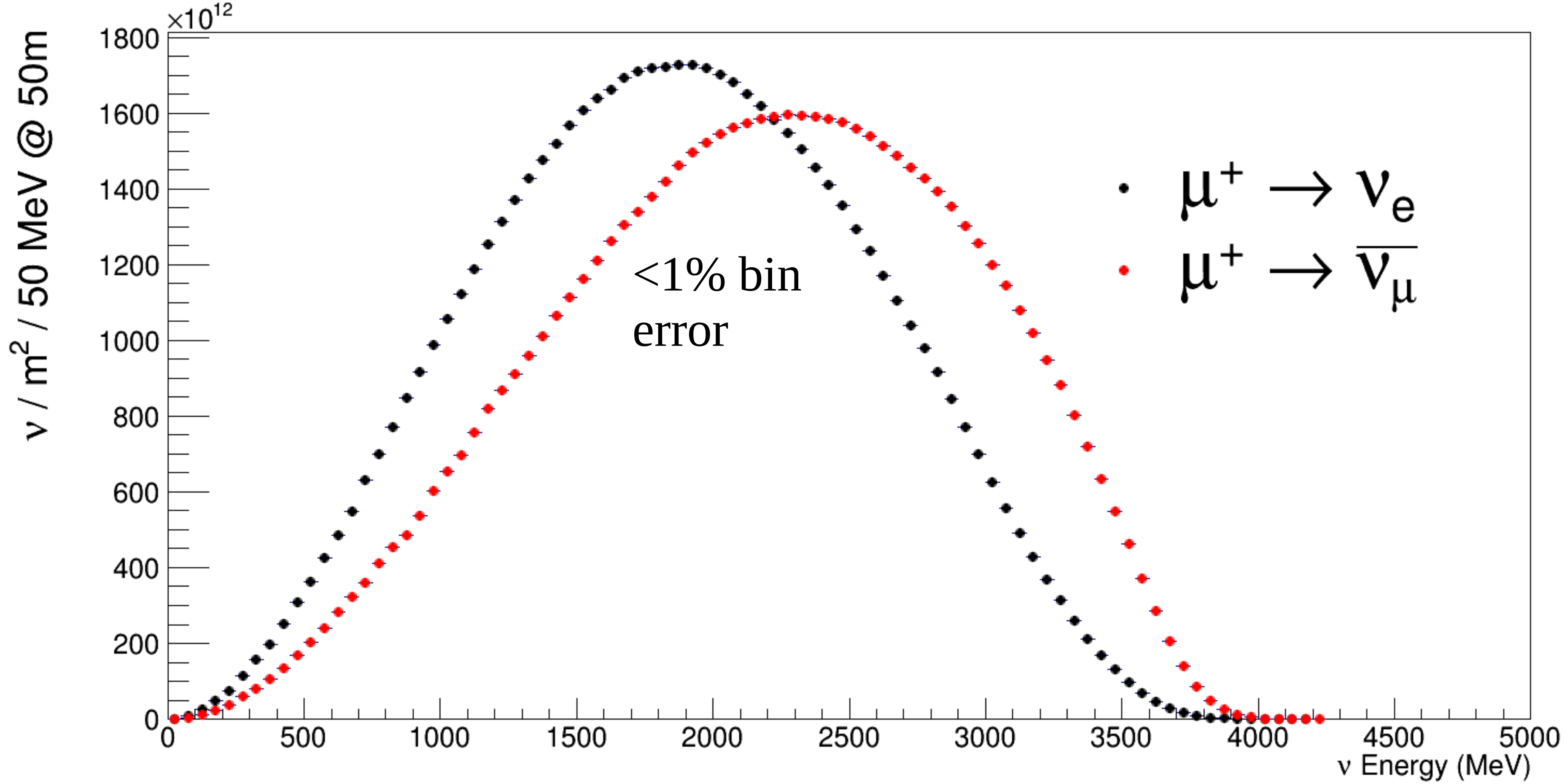






- Horn optimized to maximize muons stored in the ring by maximizing two functions (pions in phase space; muons in momentum acceptance) in GA
- FODO decay ring - See D Neuffer talk
- FFAG options – see JB Lagrange talk

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 amplification with horn optimization

<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

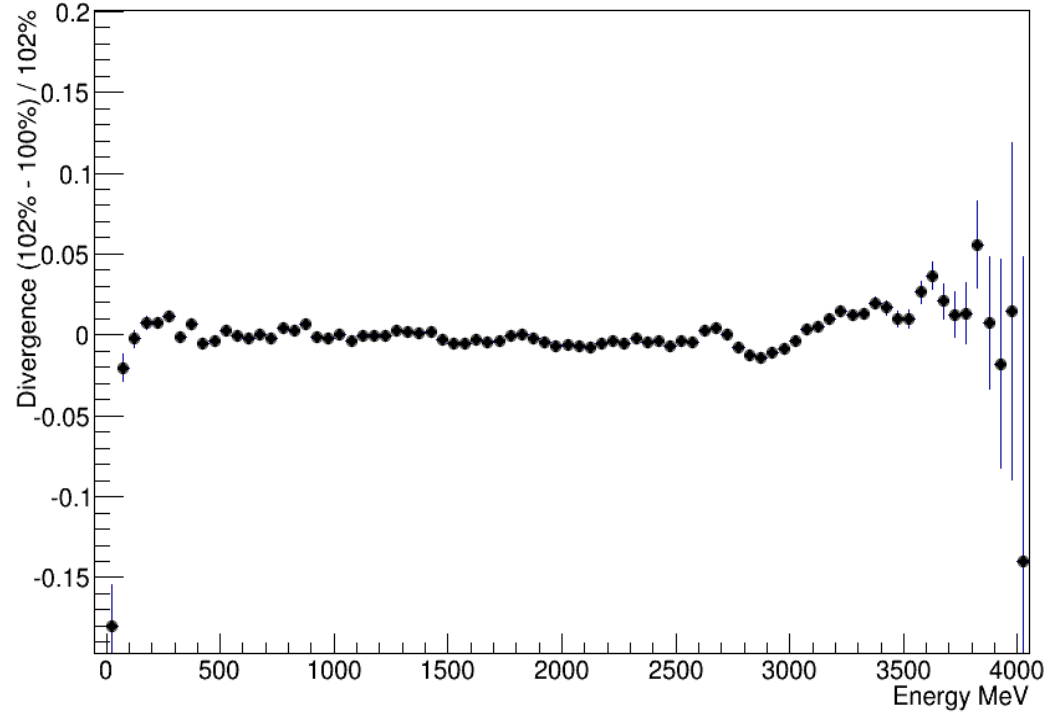
Beam diagnostics

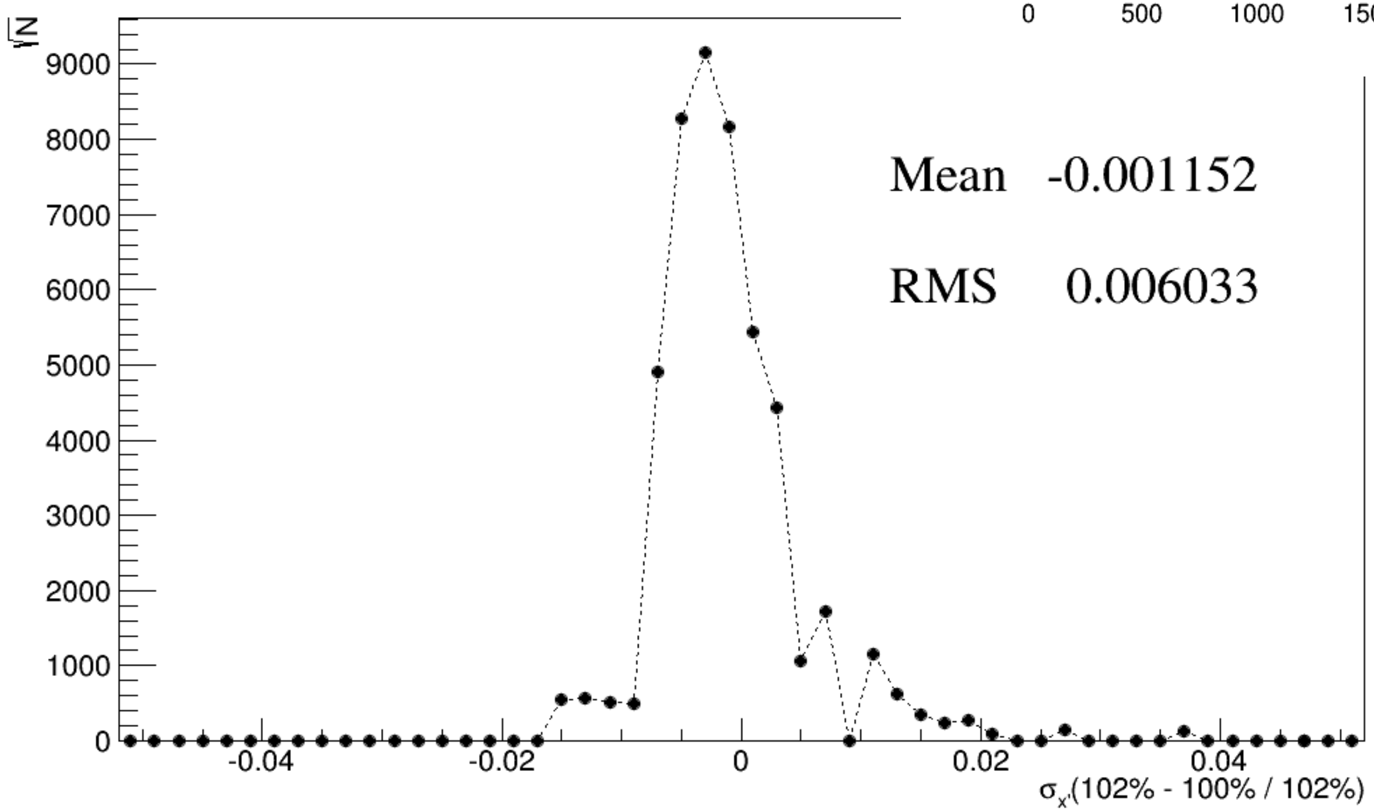
Quantity	Planned Detectors	Comment
Intensity	Beam Current Transformer	0.1% resolution realistic
Beam Position	Button BPM	1 cm resolution expected
Beam Profile	Scintillating screens	Destructive, 1 cm resolution
Energy	Polarimeter	
Energy Spread	Beam Profile measurement in Arcs	order of 0.1% resolution
Beam loss	Ionization or Diamond Detectors	

- 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%

Physics opportunities

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

Charged and neutral current processes

Measurement of ν-e 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

eV-scale pseudo-scalar penetrating particles

p0 production in n interactions

Coherent and quasi-exclusive single p0 production

ν_e and ν_e-bar x-section measurements -

A UNIQUE contribution from nuSTORM

Essentially no existing data

Charged p & K production

Coherent and quasi-exclusive single p+ production

Multi-nucleon final states

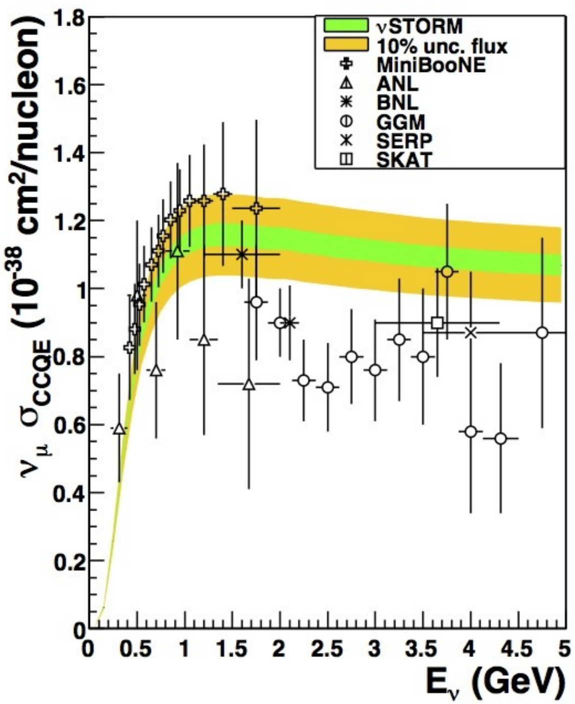
ν-e scattering

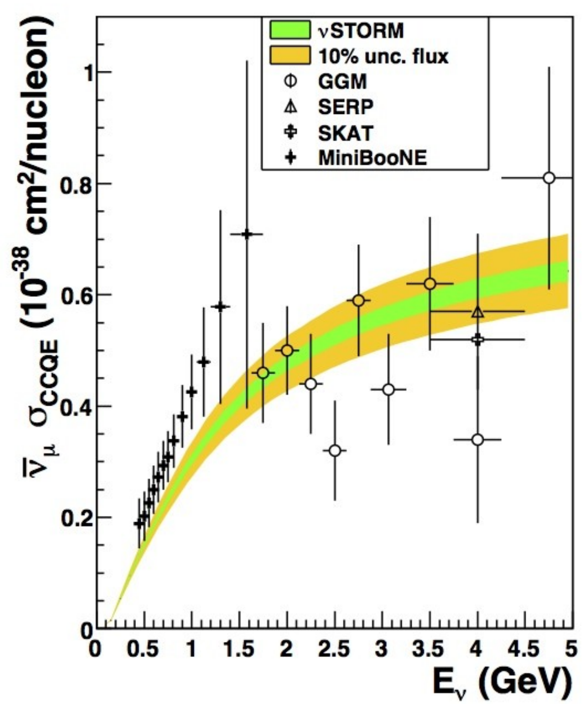
ν-Nucleon neutral current scattering

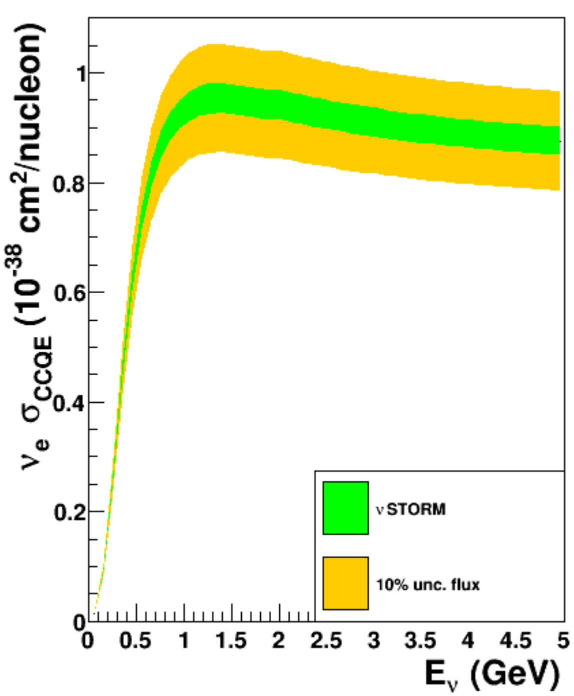
Measurement of NC to CC ratio

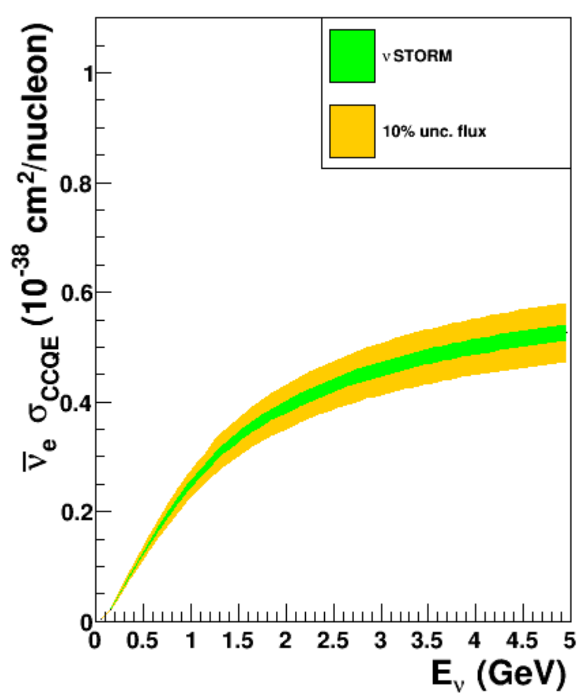
Cross section performance at a nuSTORM near detector

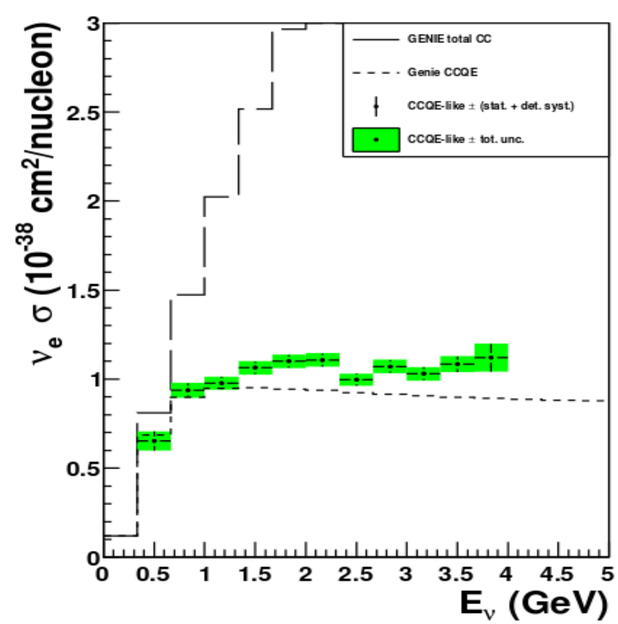
- HiResMNu detector combined with nuSTORM beam and errors
- Muon, electron + anti-neutrino cross sections measured in same experiment to high precision





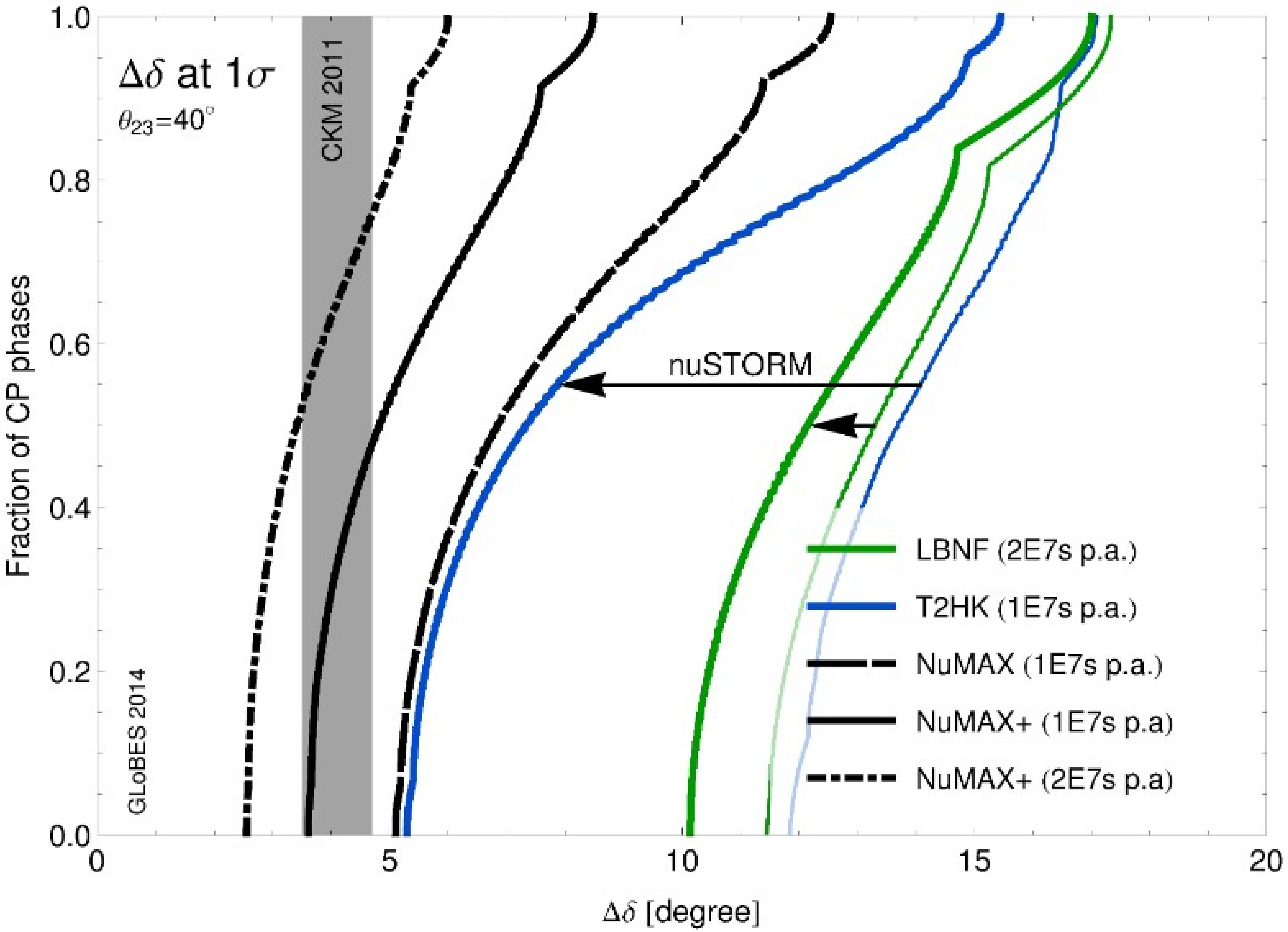






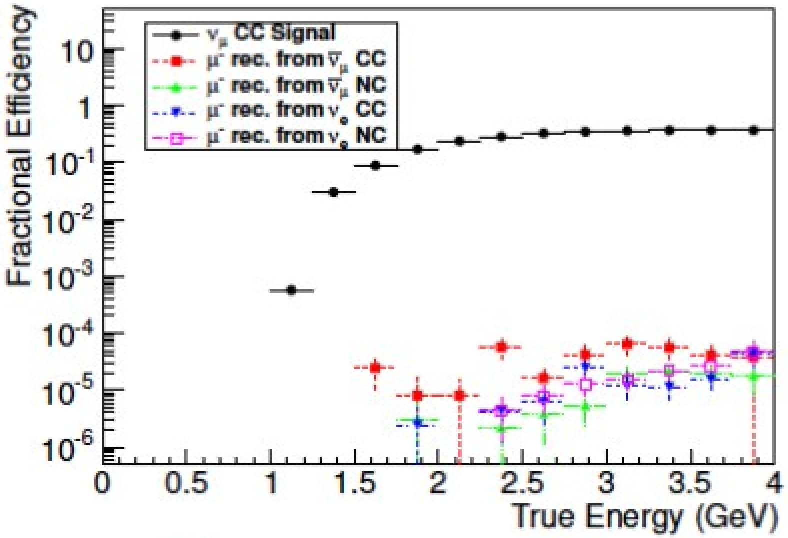
• To achieve a benchmark of 75% CP coverage at 3σ, systemic precision of ~1% is required

• nuSTORM can contribute significantly in constraining cross-section component of systematic errors

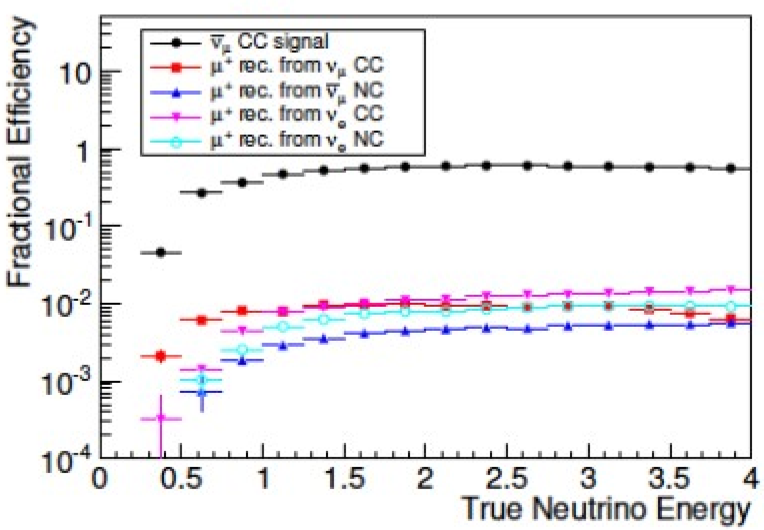


- Far detector – 2km
- 1.3kTon magnetized iron sampling calorimeter
- Superconducting transmission line

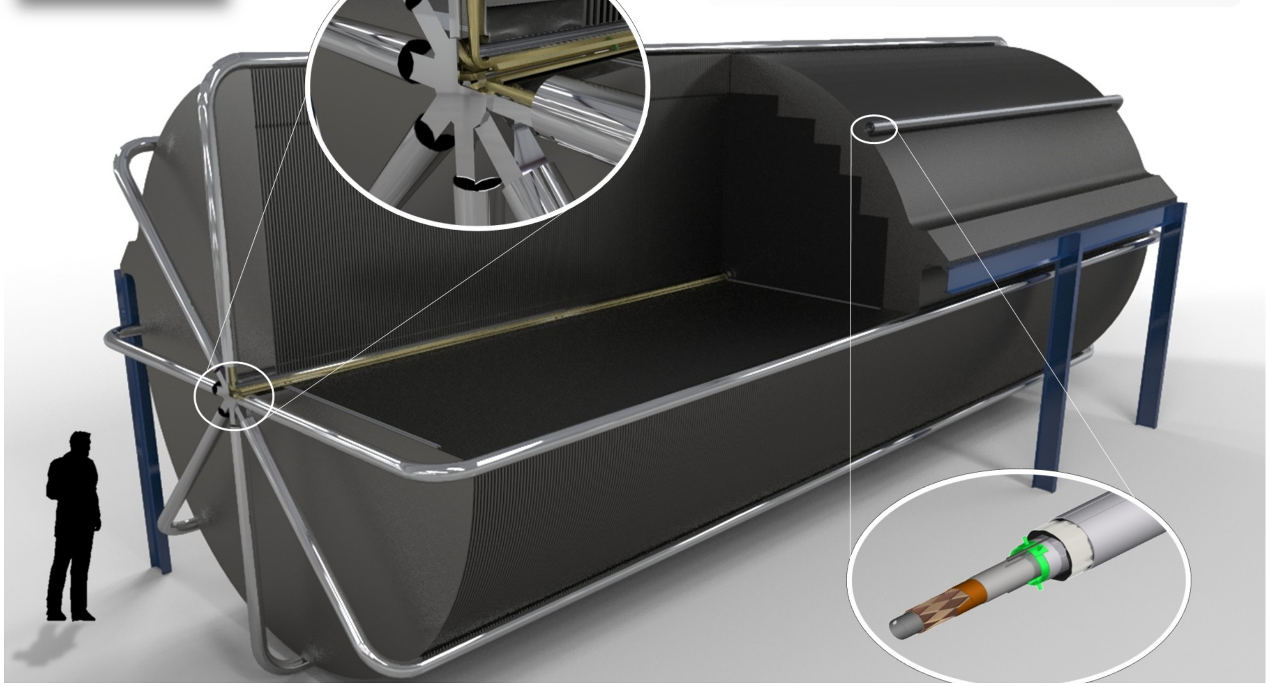
Appearance efficiencies



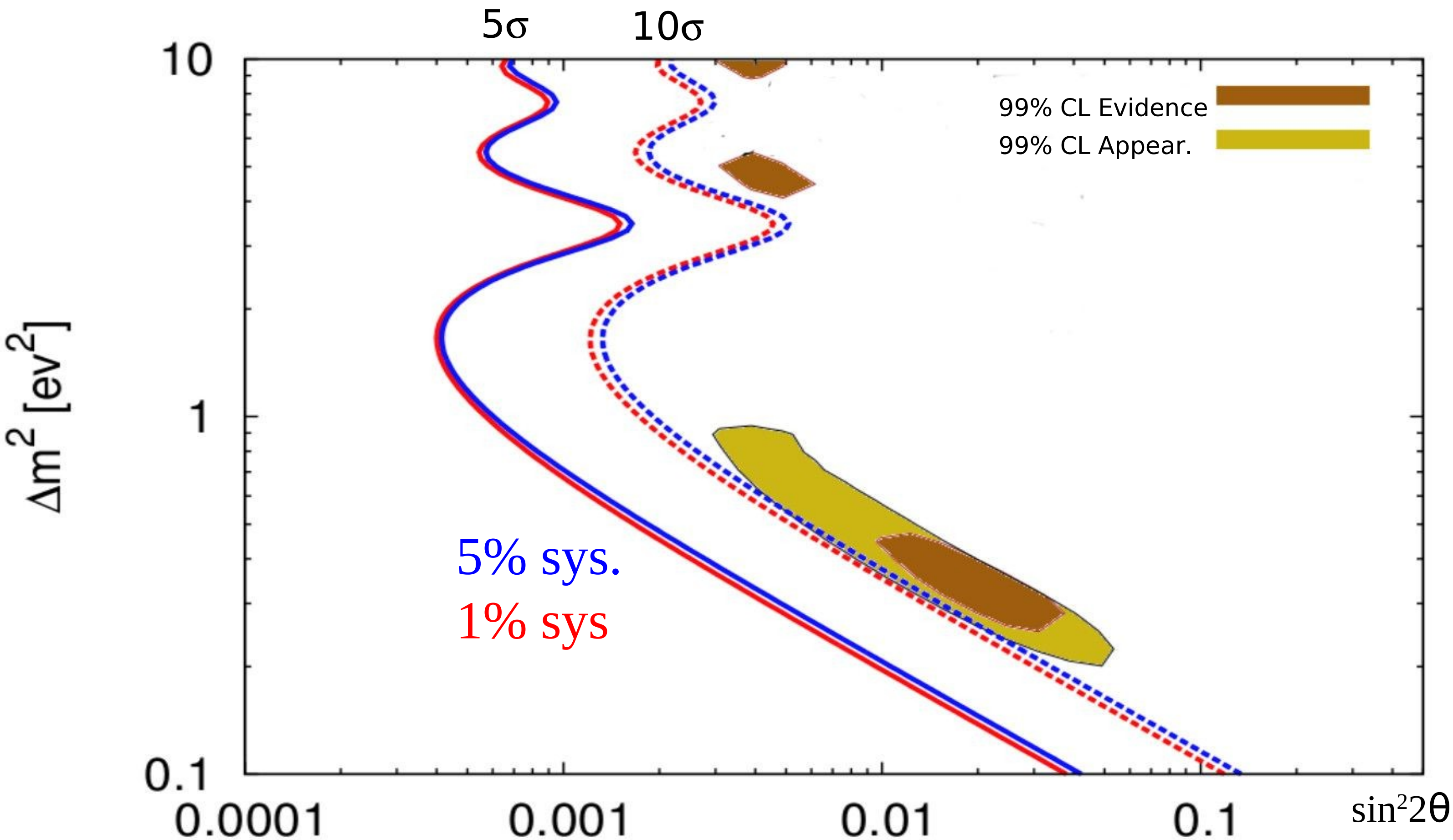
Disappearance efficiencies

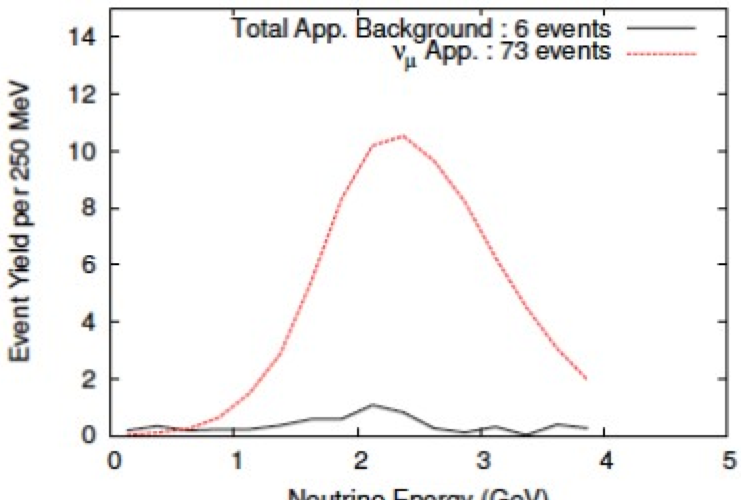


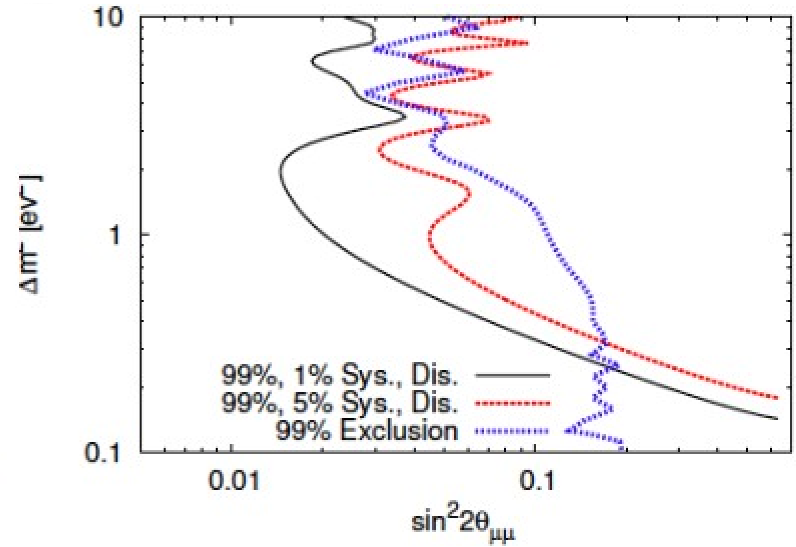
SuperBIND Detector



Sterile neutrino sensitivities







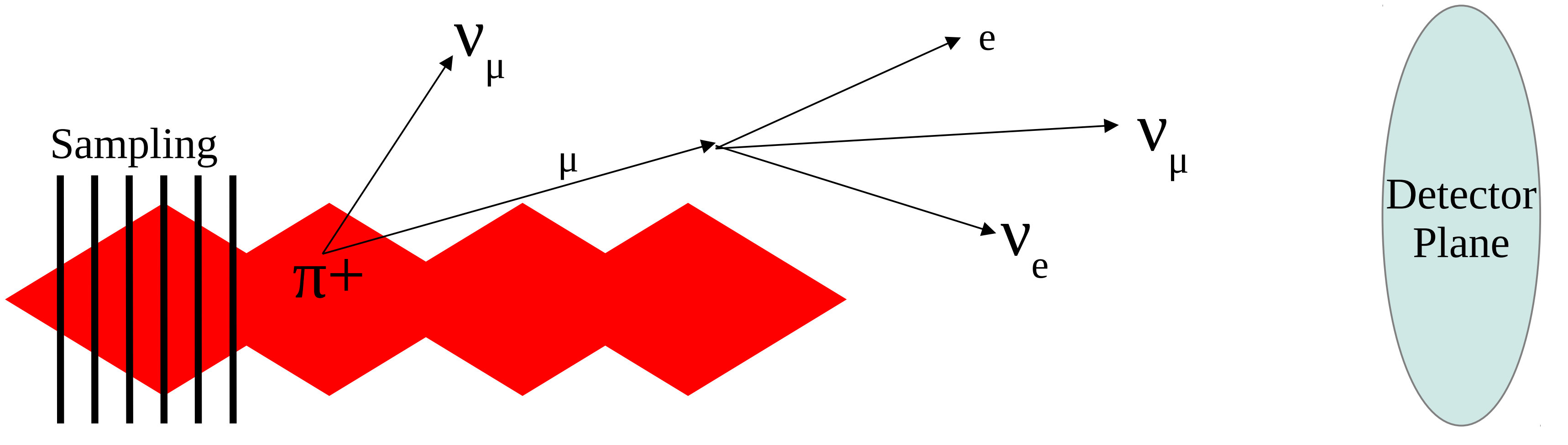
Disappearance

Hybrid neutrino factory

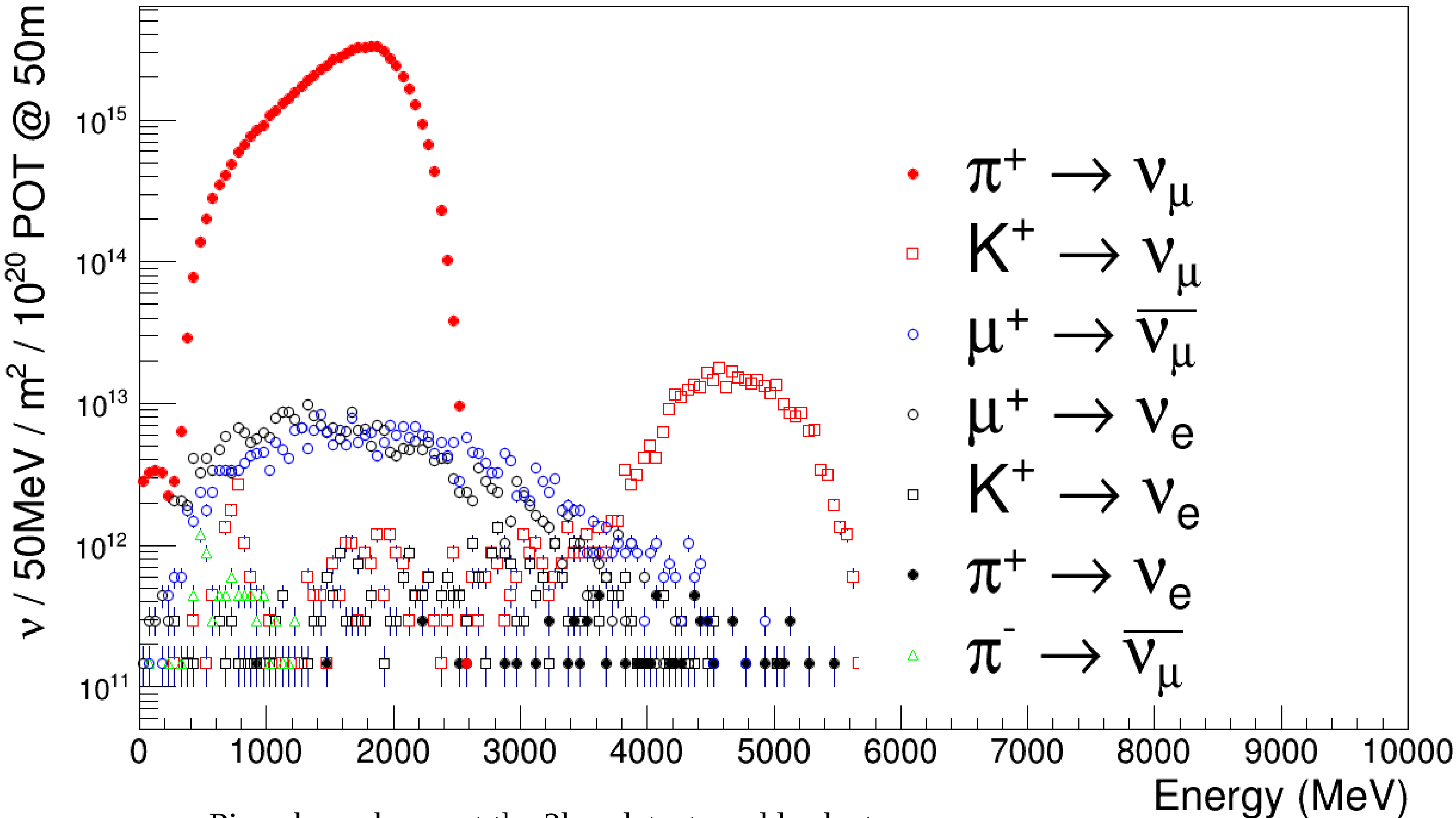
- In a neutrino factory, pions decay into muons far from storage ring to allow for emittance reduction and re-acceleration
- In nuSTORM, pions are injected into muon decay straight
- 50% pions decay in initial straight generating pion decay beam ~10x stored muon decay beam
- Sign, momentum selection, beam characterization all still present

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



Near (50 m) detector flux from pion decay

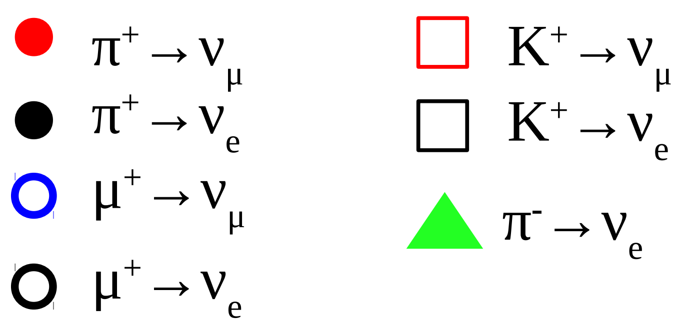


- Pion-decay beam at the 2km detector adds electron appearance channel and increased options for NC disappearance

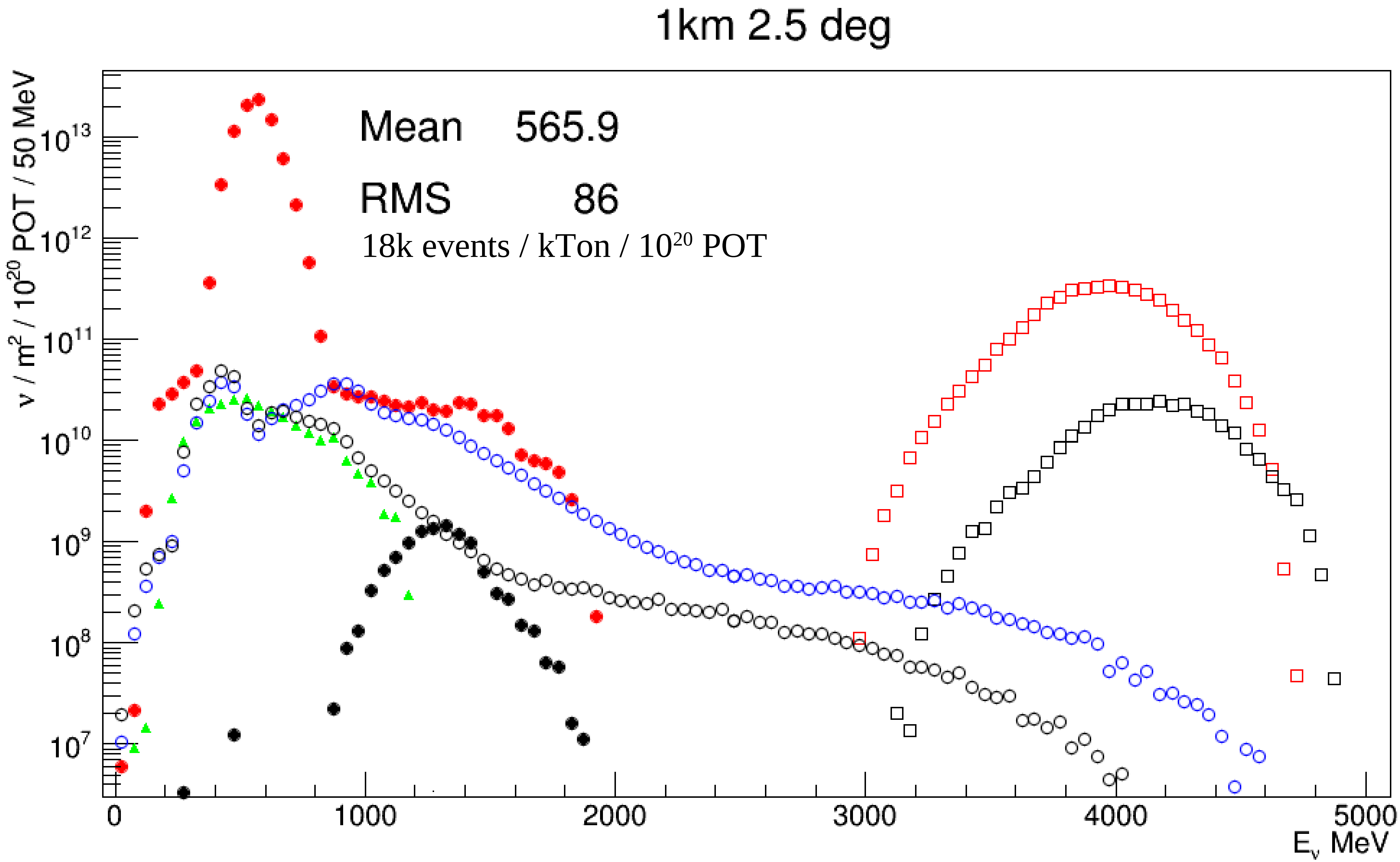
μ+ Stored		**μ- Stored**	
Channel	*Events*	*Channel*	*Events*
$\bar{\nu}_\mu$NC	1,174,710	$\bar{\nu}_e$NC	1,002,240
ν_eNC	1,817,810	ν_μNC	2,074,930
$\bar{\nu}_\mu$CC	3,030,510	$\bar{\nu}_e$CC	2,519,840
ν_eCC	5,188,050	ν_μCC	6,060,580
π+		**π-**	
ν_μNC	14,384,192	$\bar{\nu}_\mu$NC	6,986,343
ν_μCC	41,053,300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

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

nuSTORM off-axis



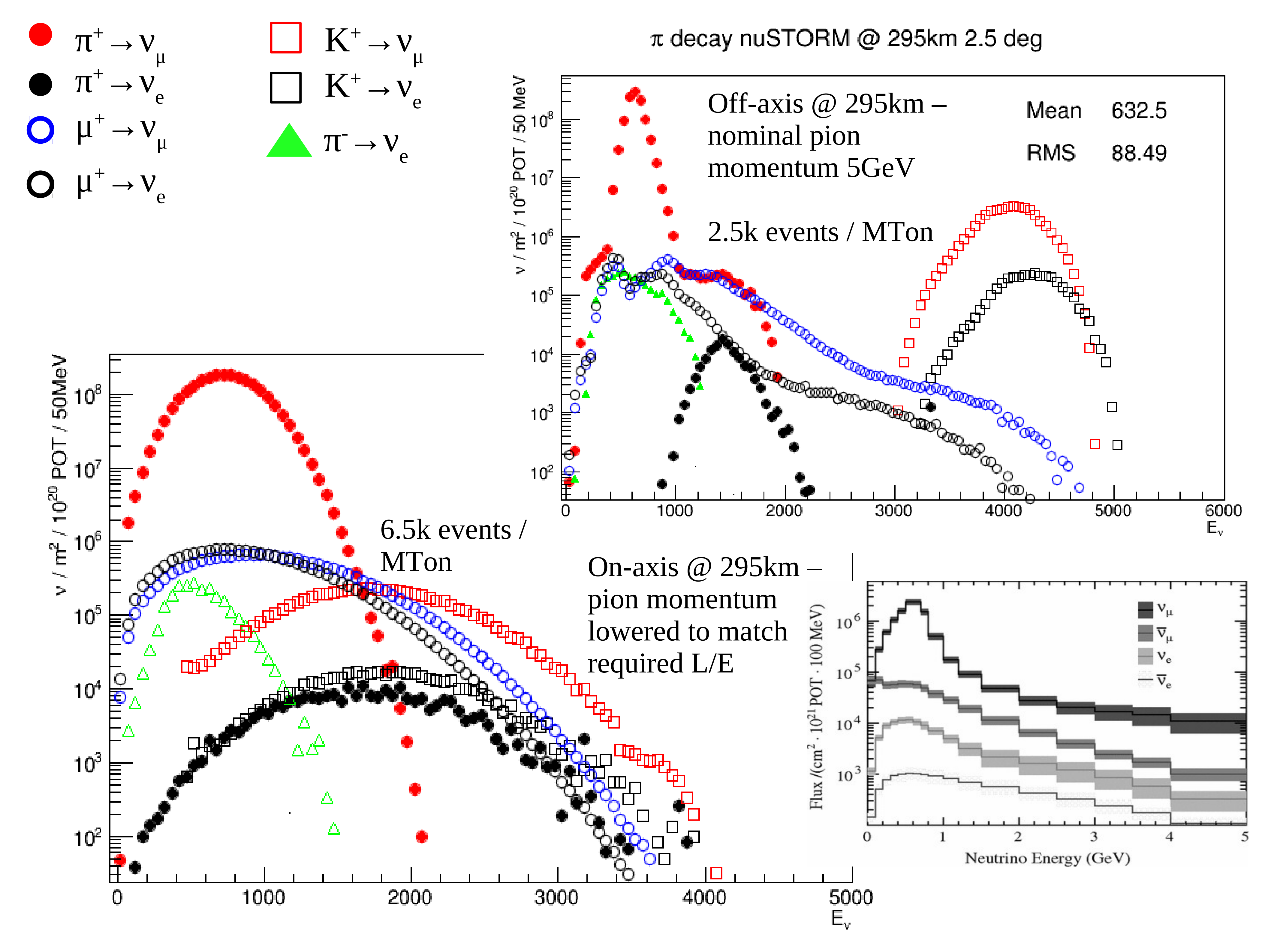
- Placing detector off-axis of the nuSTORM beam decreases energy width even further with no high energy tail
- Can be placed in the energy regime of interest to existing off-axis experiments



Summary

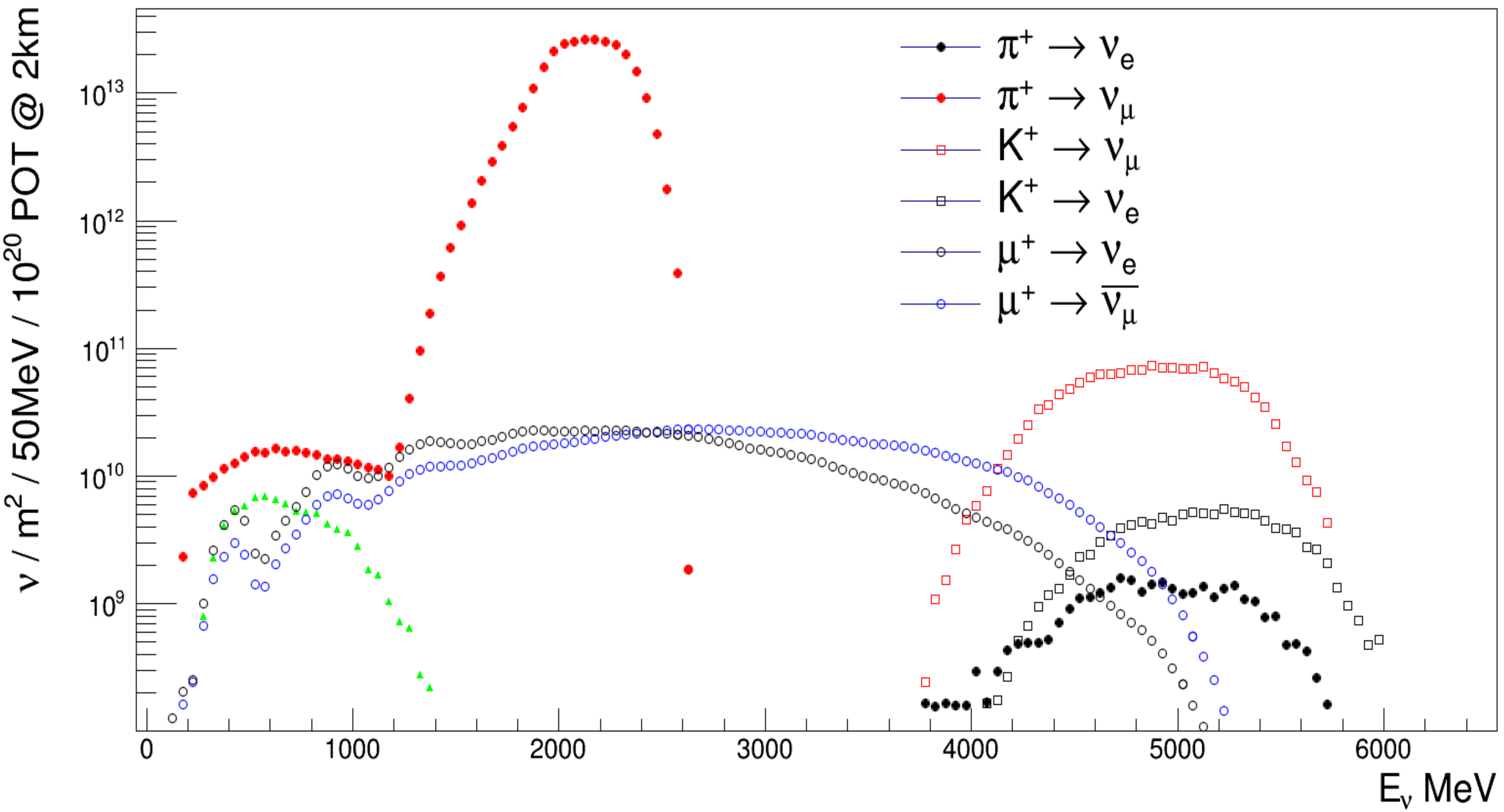
- A muon storage ring is the simplest implementation of a Neutrino Factory
- Better than 1% flux precision – measurements limited by detectors
- Neutrino beams from both muons and pions, separated in time, with very pure content
- Off-axis beam narrows beam even further to <100MeV RMS
- Ongoing work on full ring with diagnostics, near detector physics, oscillation studies
- nuSTORM provides a platform to definitively answer sterile neutrino conflicts; measure broad range of cross-sections; with possibility for conventional pion decay, long baseline, off-axis beam

Backups



$\pi^+ \rightarrow \nu_\mu$
$\pi^+ \rightarrow \nu_e$
$\mu^+ \rightarrow \nu_\mu$
$\mu^+ \rightarrow \nu_e$
$K^+ \rightarrow \nu_\mu$
$K^+ \rightarrow \nu_e$
$\pi^- \rightarrow \nu_e$
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 / m^2 / 10^{20} POT / 50 MeV
E_ν
6.5k events / MTon
ν / m^2 / 10^{20} POT / 50MeV
On-axis @ 295km – pion momentum lowered to match required L/E
Flux /(cm^2 · 10^{21}POT · 100 MeV)
Neutrino Energy (GeV)
ν_μ
$\bar{\nu}_\mu$
ν_e
$\bar{\nu}_e$

Far (2 km) detector flux from pion decay

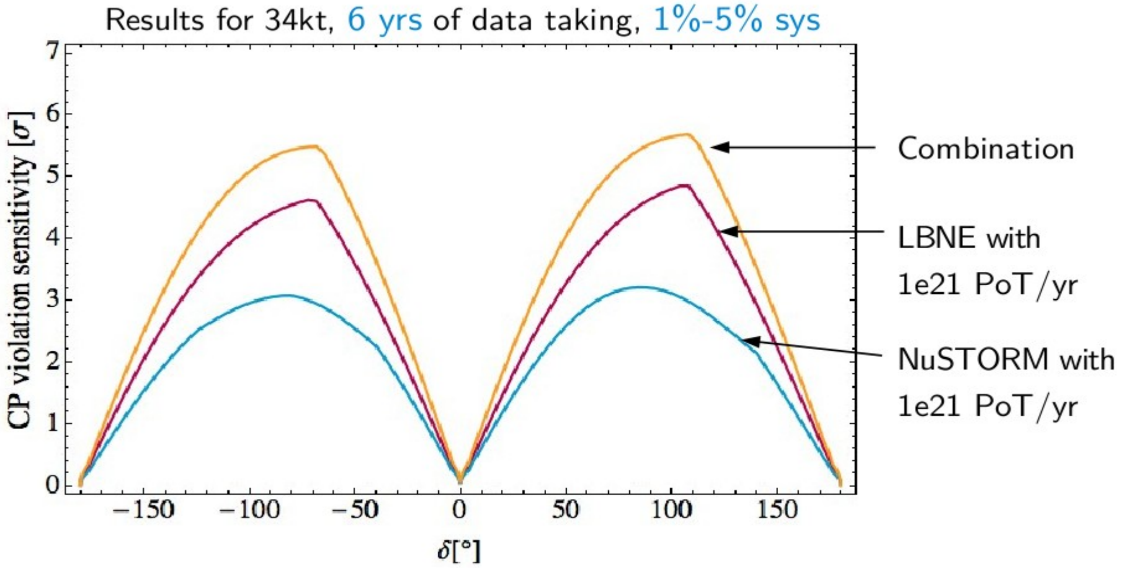


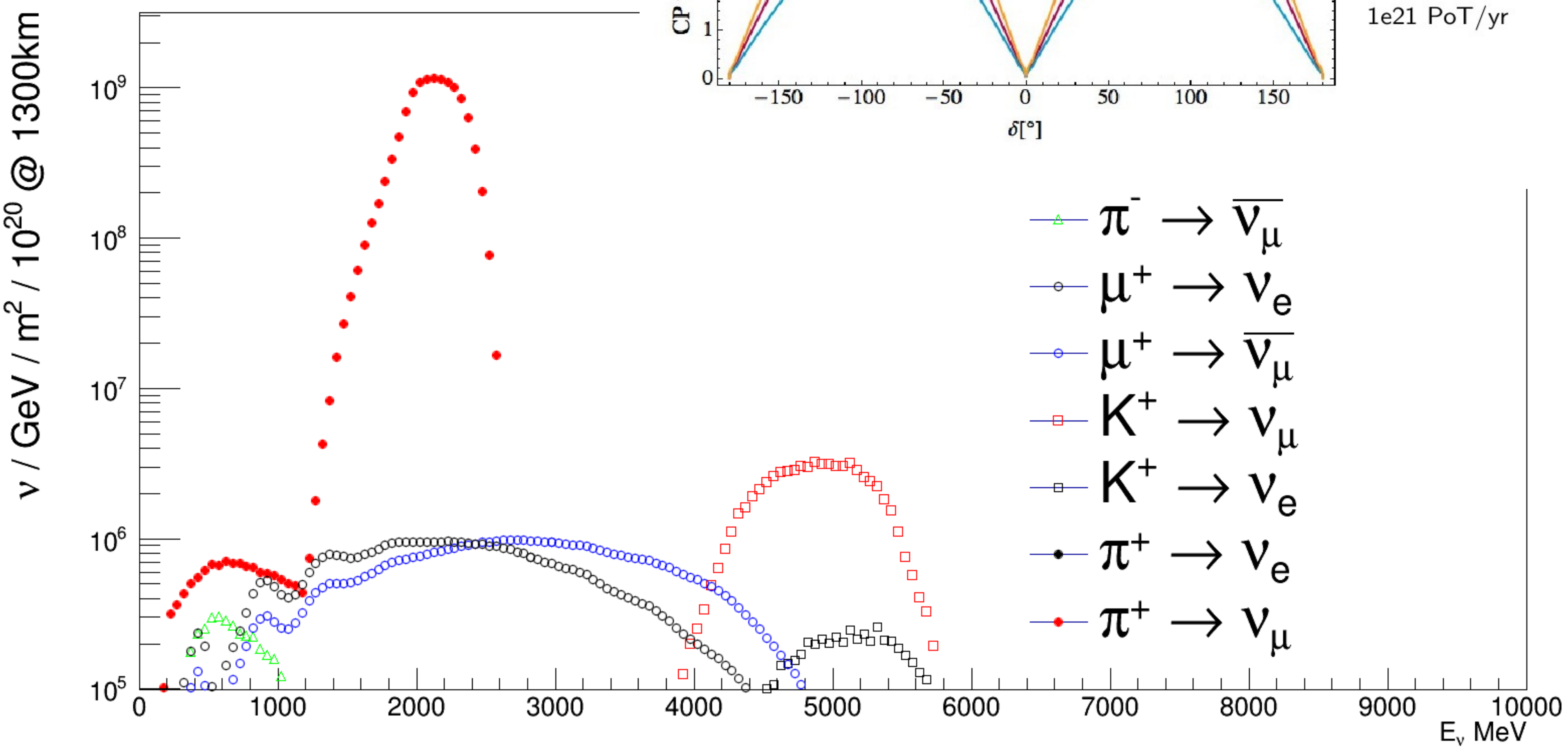
Added channels of electron neutrino appearance and NC disappearance

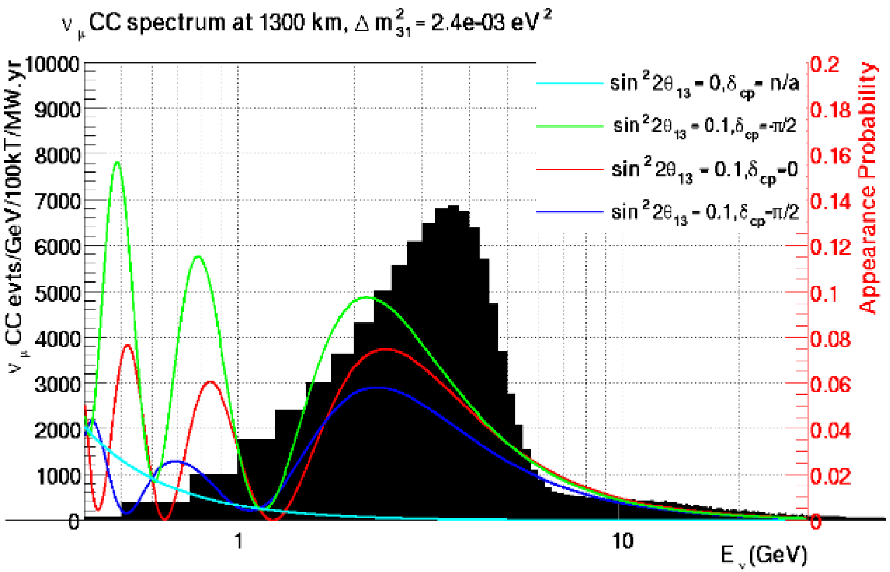
Very Far (1300 km) detector flux from pion decay

CP violation sensitivity

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



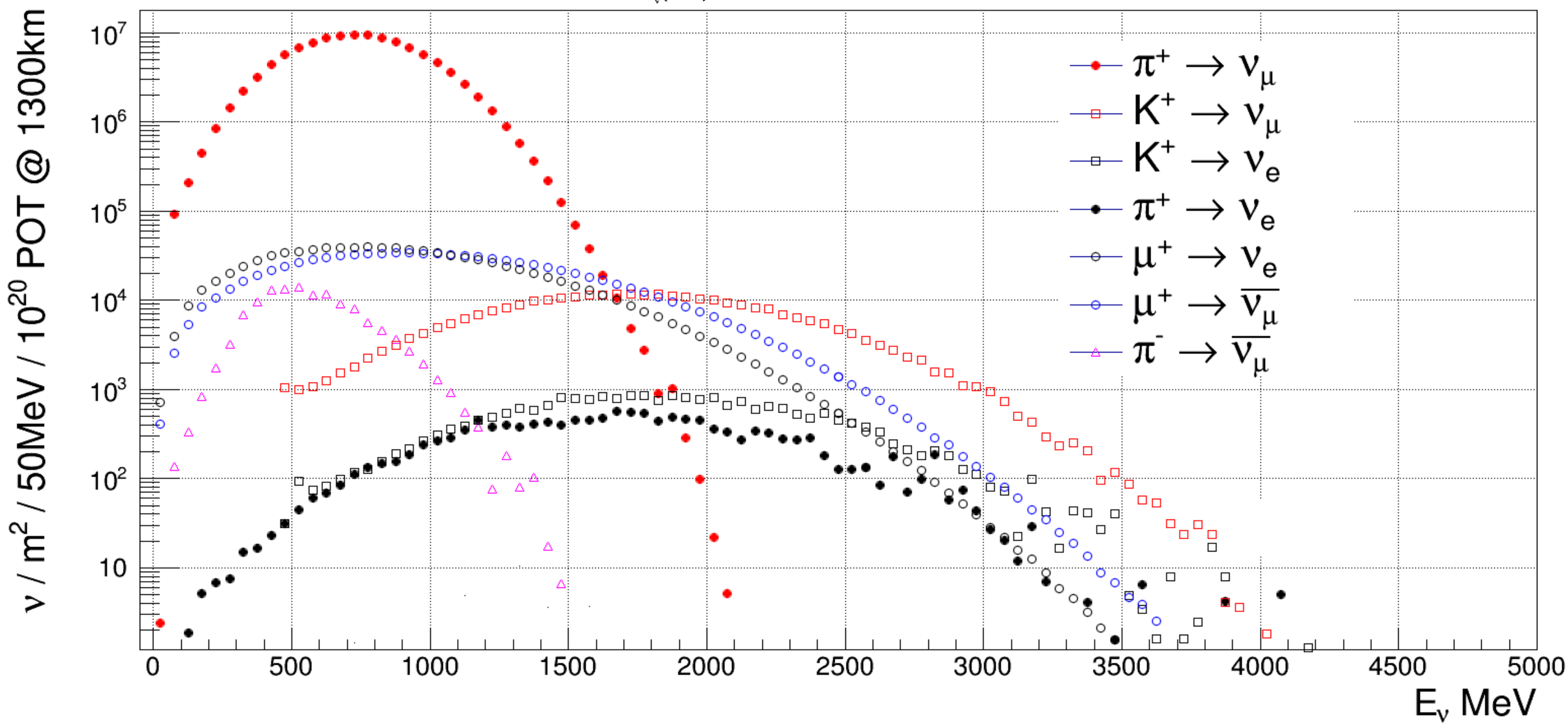


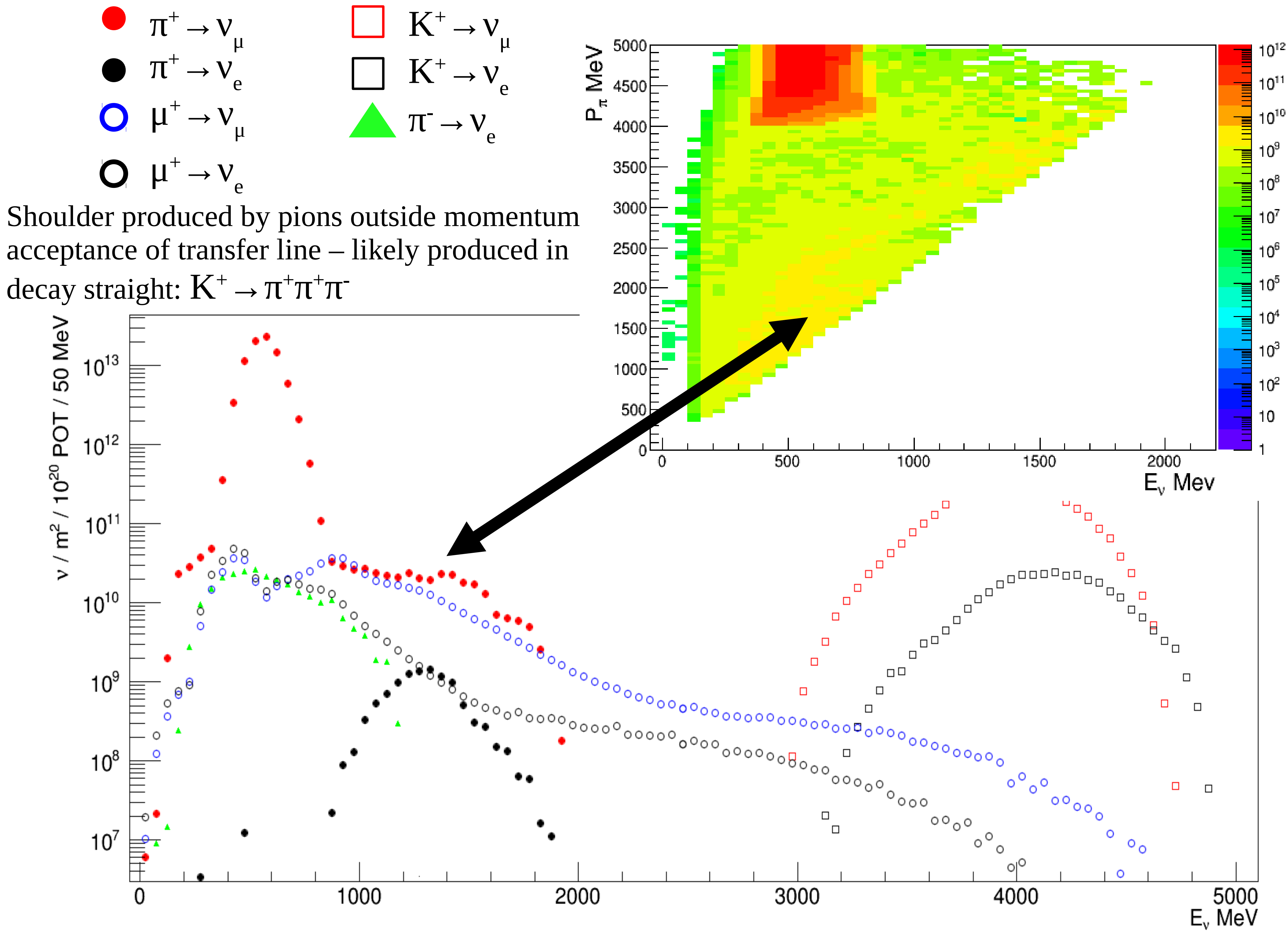


Very Far (1300 km) detector flux from pion decay – 2nd oscillation maximum

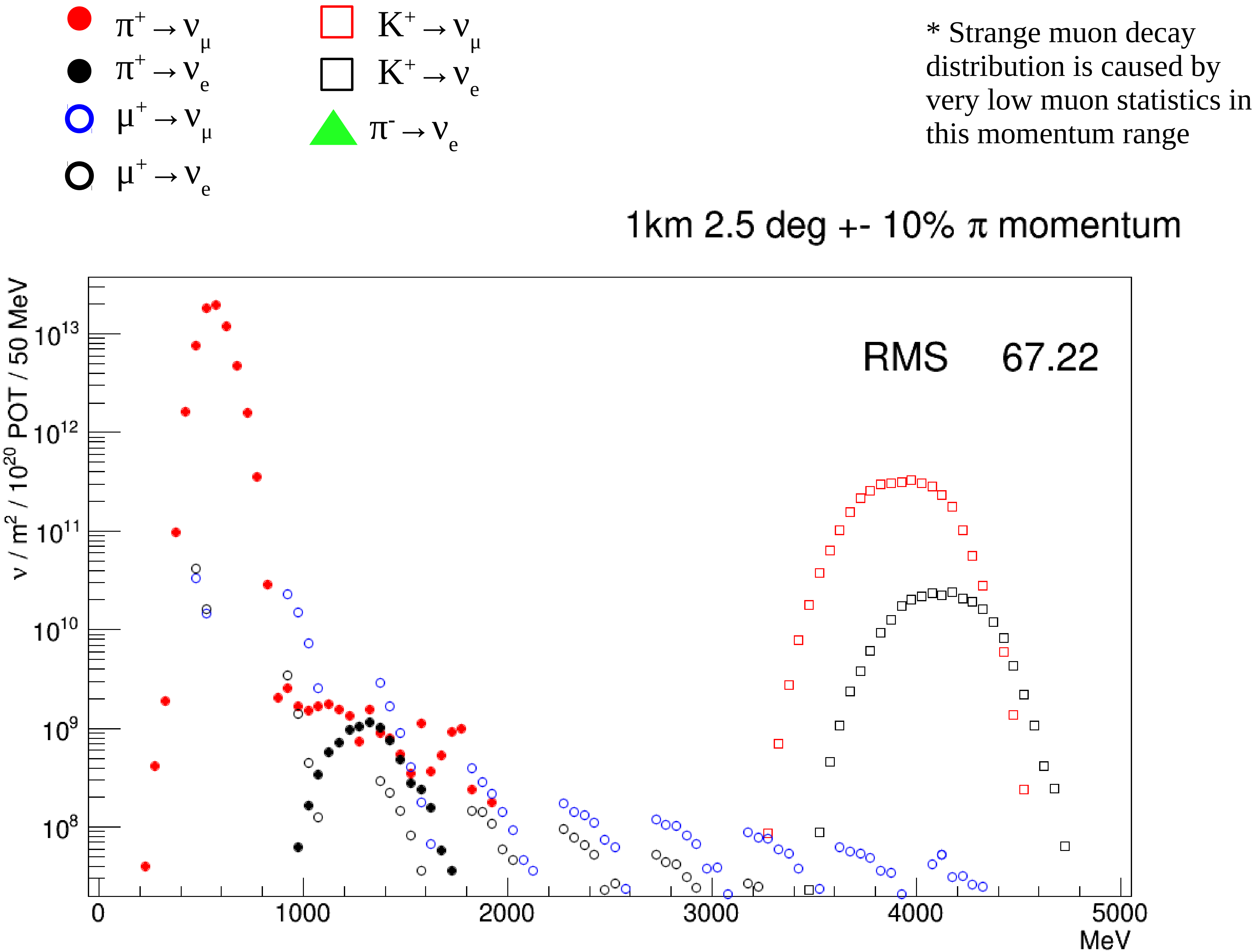
Still not an optimized pion beam, increased rate with momentum acceptance and move to pion only beam

P_π = 1.3 GeV





π+ → νμ
π+ → νe
μ+ → νμ
μ+ → νe
K+ → νμ
K+ → νe
π- → νe
Shoulder produced by pions outside momentum acceptance of transfer line – likely produced in decay straight: K+ → π+π+π-
Pπ MeV
Eν Mev
ν / m2 / 1020 POT / 50 MeV
Eν MeV



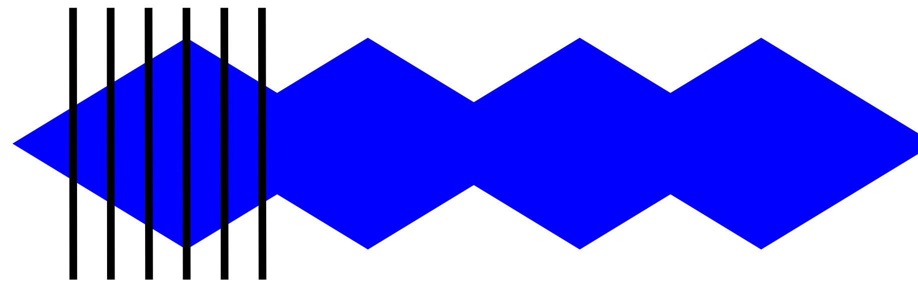
$\pi^+ \rightarrow \nu_\mu$
$\pi^+ \rightarrow \nu_e$
$\mu^+ \rightarrow \nu_\mu$
$\mu^+ \rightarrow \nu_e$
$K^+ \rightarrow \nu_\mu$
$K^+ \rightarrow \nu_e$
$\pi^- \rightarrow \nu_e$
* Strange muon decay distribution is caused by very low muon statistics in this momentum range
1km 2.5 deg +- 10% π momentum
RMS 67.22
ν / m^2 / 10^{20} POT / 50 MeV
10^8
10^9
10^{10}
10^{11}
10^{12}
10^{13}
0
1000
2000
3000
4000
5000
MeV

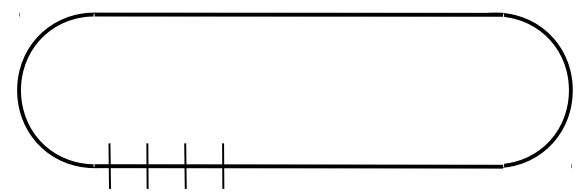
Muon beam tracking approximation

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

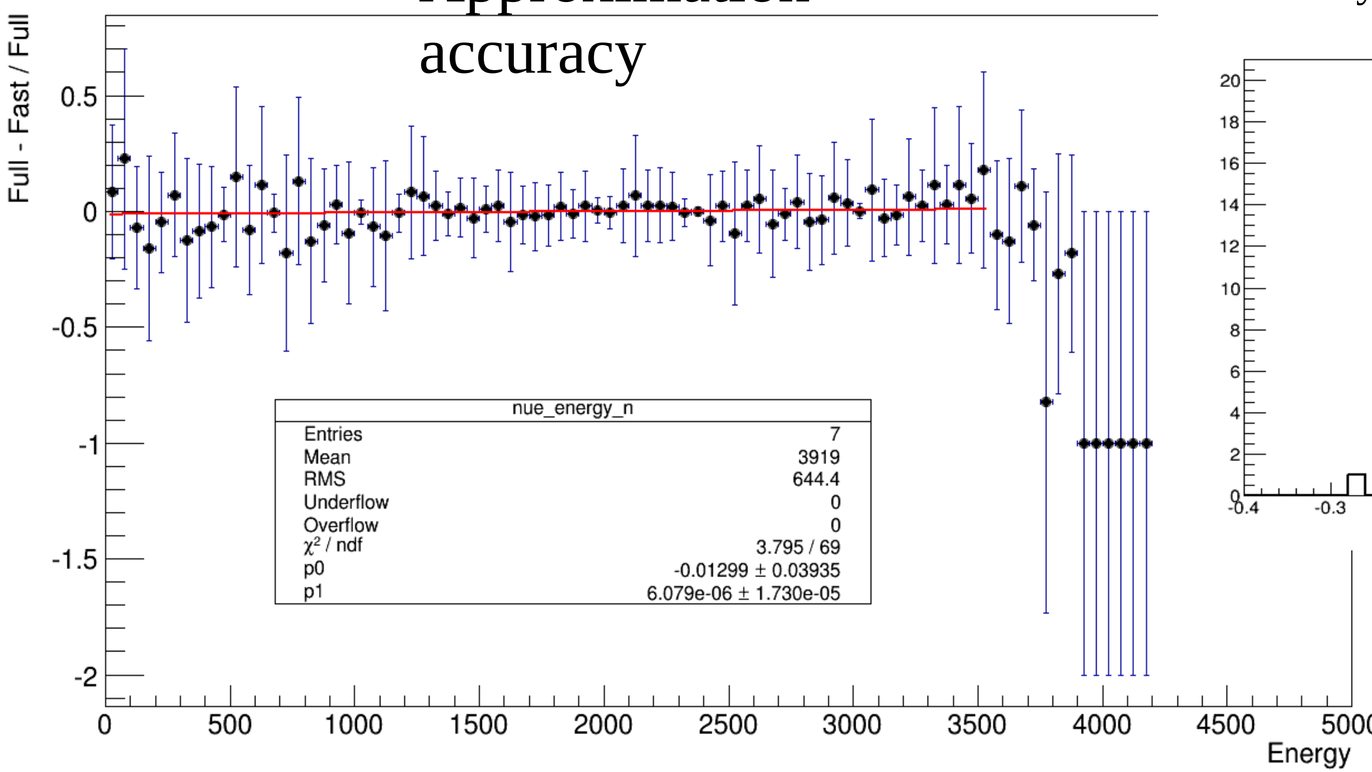
Sampling

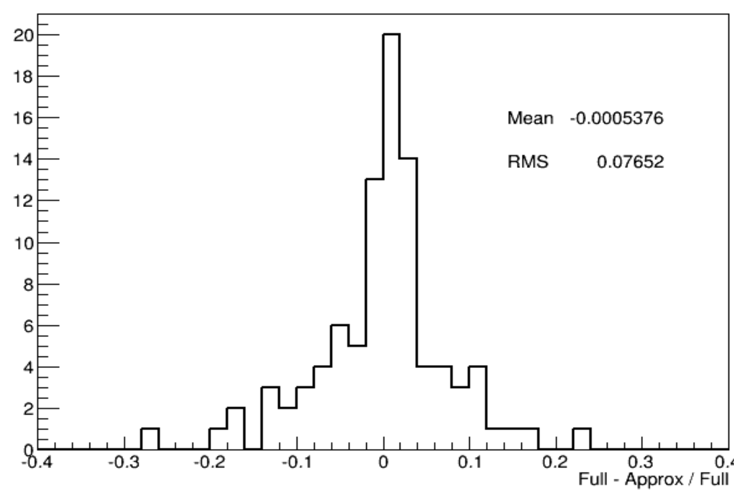




Decay points

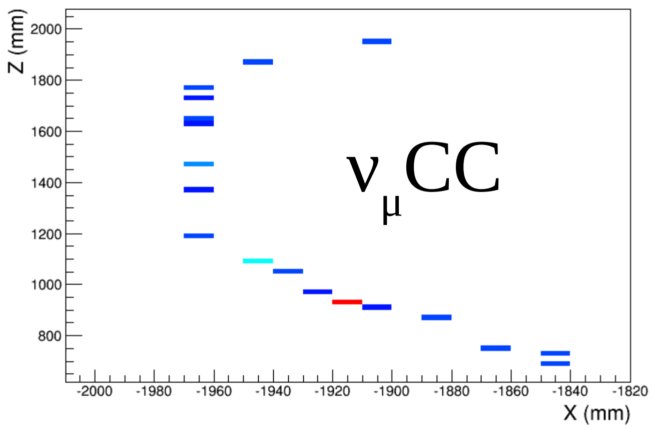
Approximation accuracy

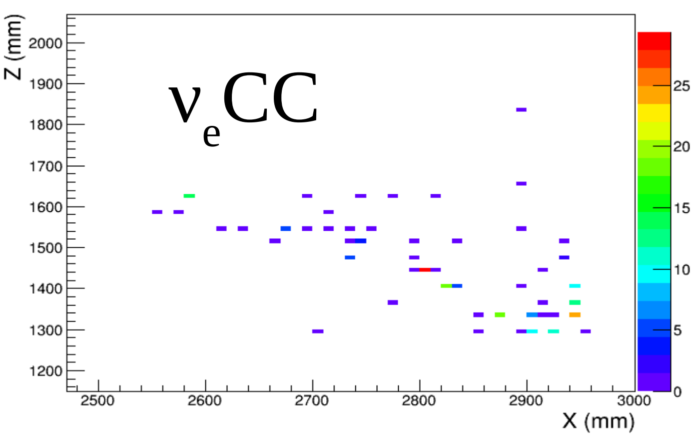


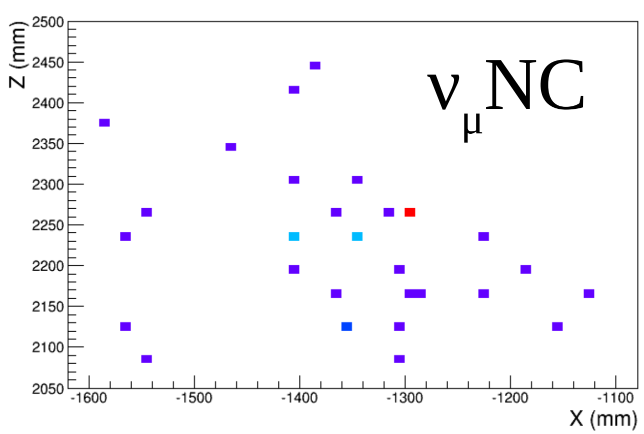


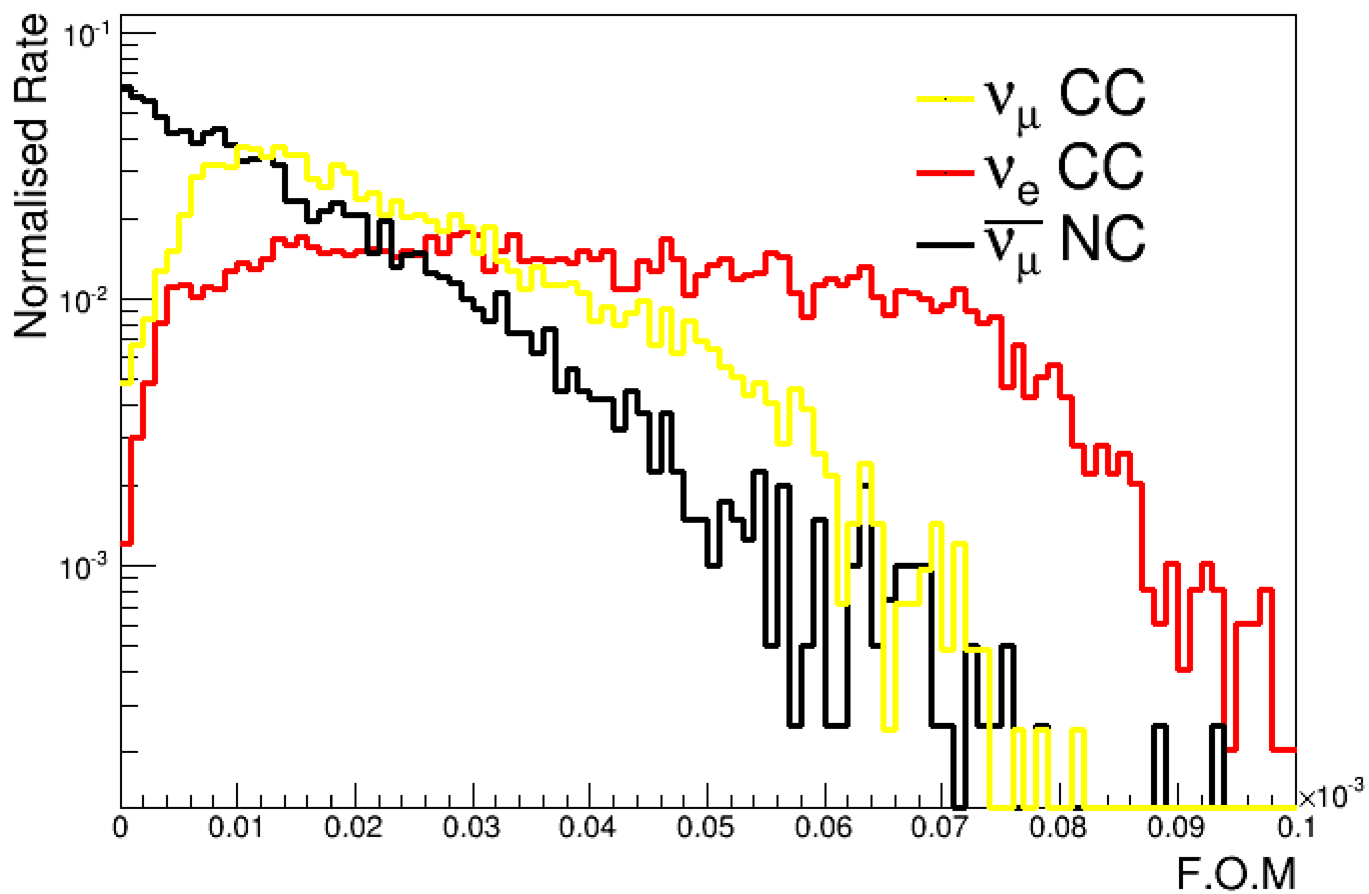
ν_e at SuperBIND

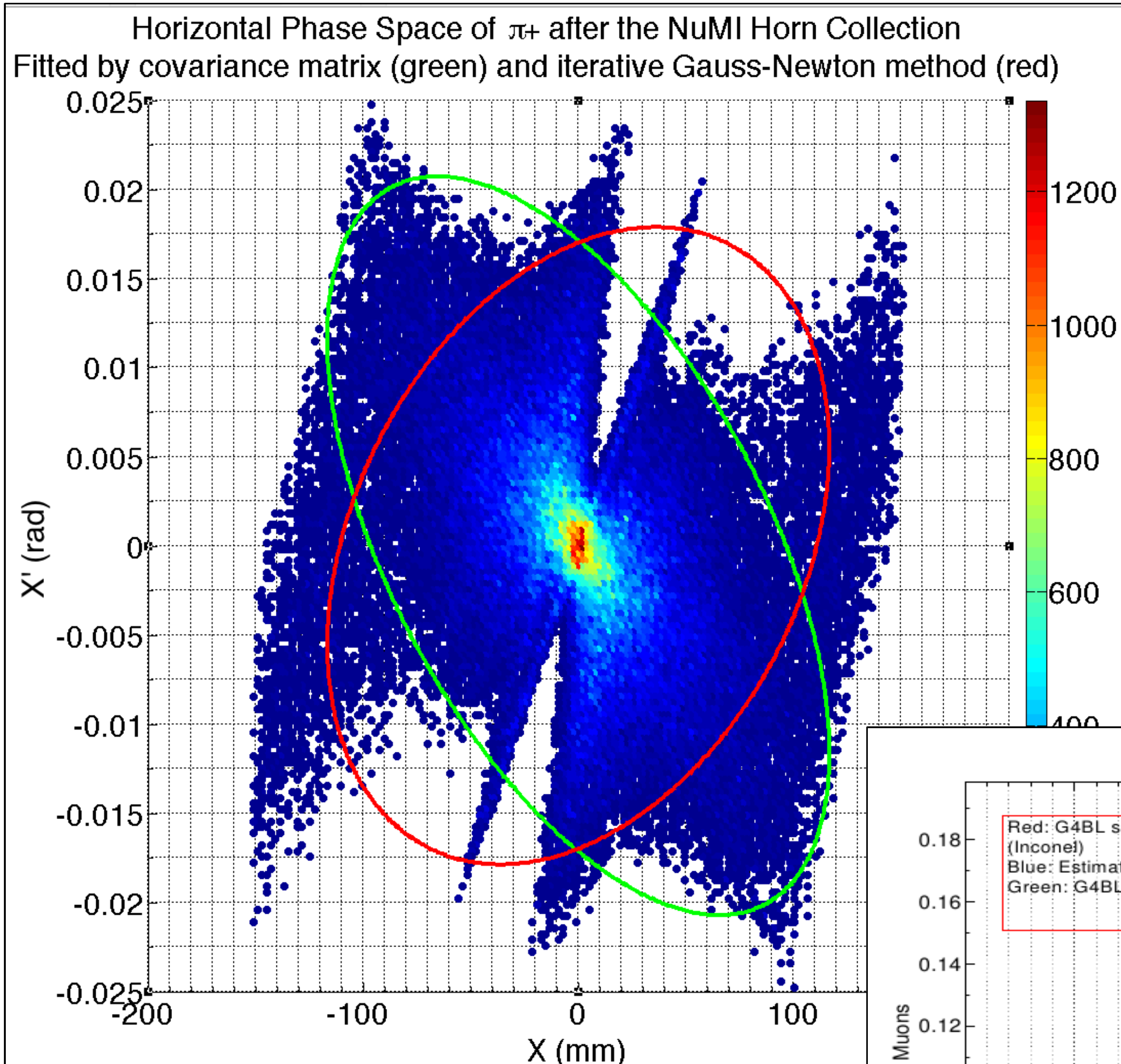
- Muon CC events are primarily identified by their range
- N_eCC and NC events are distinguished by the energy deposition density of shower – Moliere radius v. Interaction length
- Combination of variables in MVA will be necessary

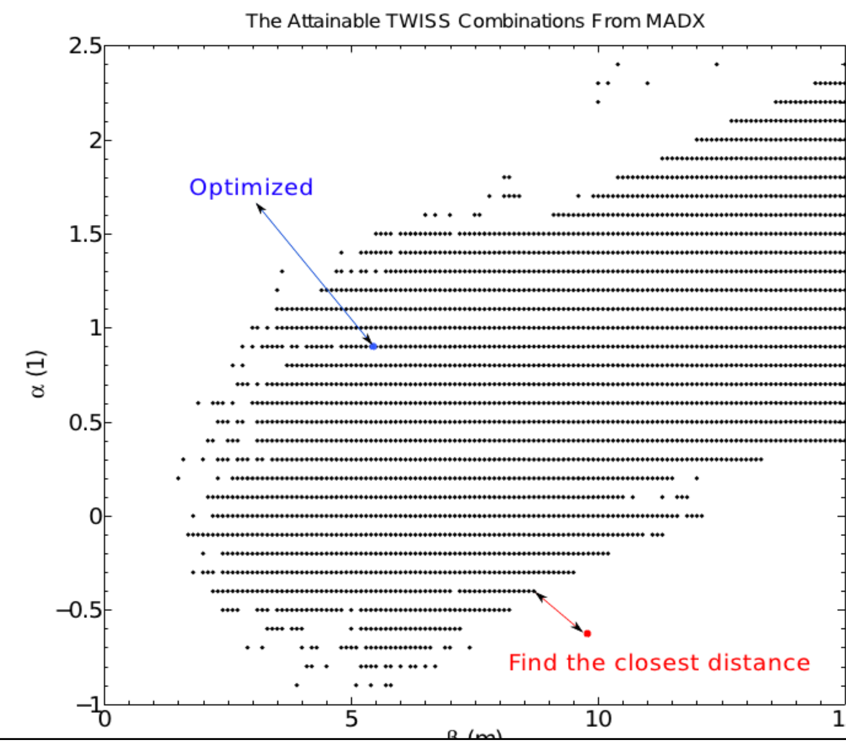


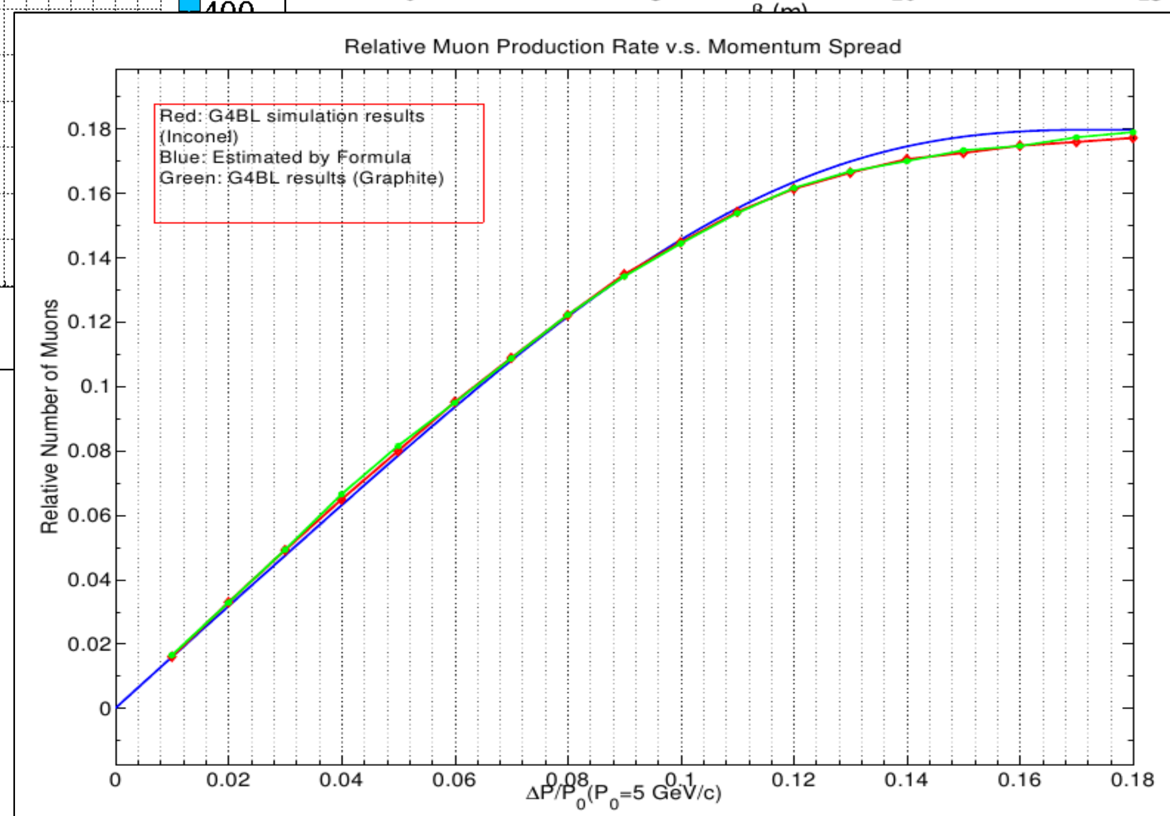












Viability of Twiss parameters for horn optimization + momentum spreads

Near detector hall