Imperial College London

K. Long,
29 November, 2013

Neutrinos from stored muon beams:

Acknowledgements:

- **Many thanks to those who provided information or material:**
  - **And in particular the International Design Study for the Neutrino Factory (the IDS-NF), EUROnu, MICE and nuSTORM collaborations**

International Design Study for the
Neutrino Factory

IDS-NF-020

Interim Design Report

The IDS-NF collaboration

136 authors, 48 Institutes:

Bulgaria	University of Sofia
France	IPHC Strasbourg
Germany	MPI Heidelberg, MPI Munich, Fakultät für Physik und Astronomie Würzburg
India	HCRI Allahabad, Inst. of Math. Sci. Chennai, SINP Kolkata, TIFR Mumbai
Italy	Milano Bicocca, Universita di Napoli Federico II, Universita di Padova and INFN Padova, Sezione INFN Roma Tre
Japan	Kyoto University RRI, University of Osaka, Tokyo Metropolitan University
Spain	UAM and IFT Madrid, UV/CSIC and IFIC Valencia
Russia	INRR Moscow
Switzerland	CERN, University of Geneva
UK	Brunel University, Daresbury Laboratory, Glasgow University, Imperial College London, IPPP Durham, Oxford University, Rutherford Appleton Laboratory, Sheffield University, Warwick University
USA	Brookhaven National Laboratory, Fermi National Laboratory, Jefferson Laboratory, Laurence Berkeley National Laboratory, University of Mississippi, Michigan State University, Muons Inc., Northwestern University, Oak Ridge National Laboratory, Princeton University, University of California at Riverside, Stony Brook University, University of South Carolina, Virginia Polytechnique Institute, University of California at Los Angeles

https://www.ids-nf.org/wiki/FrontPage/Documentation/IDR

Contents:

Neutrinos from stored muon beams:

Neutrinos; physics beyond the Standard Model

Standard Model:

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix} \quad \begin{pmatrix} e^+ \\ \bar{\nu}_e \end{pmatrix}$$

$$\begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix} \quad \begin{pmatrix} \mu^+ \\ \bar{\nu}_\mu \end{pmatrix}$$

$$\begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix} \quad \begin{pmatrix} \tau^+ \\ \bar{\nu}_\tau \end{pmatrix}$$

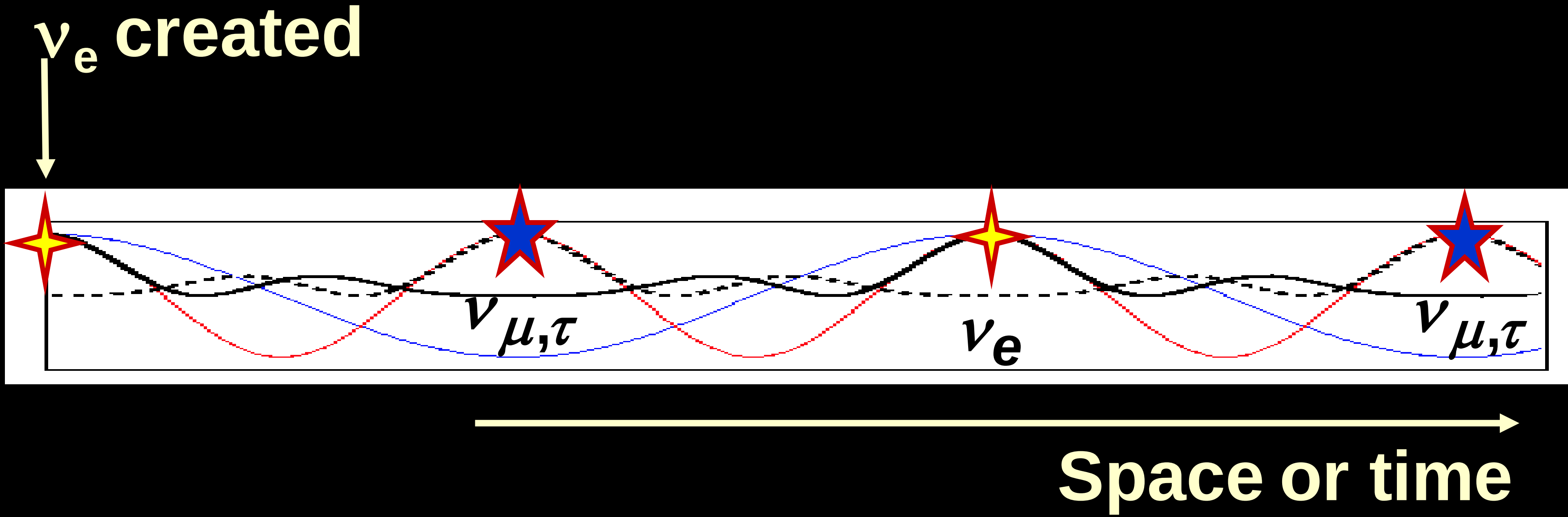
The Standard Model neutrino was:

- *Massless*
- Chargeless
- Helicity eigenstate

Extend SM to include neutrino mass:

- Massive neutrino *NOT* helicity eigenstate, and …
  - since neutrino has no conserved quantum numbers
    - (except, perhaps, a global lepton number)

  quantum mechanics implies neutrinos will mix
- Mixing among three neutrino states:
  - Admits possibility that CP-invariance may be violated in neutrino mixing
    - Exciting opportunity for discovery!



A window on the unknown:

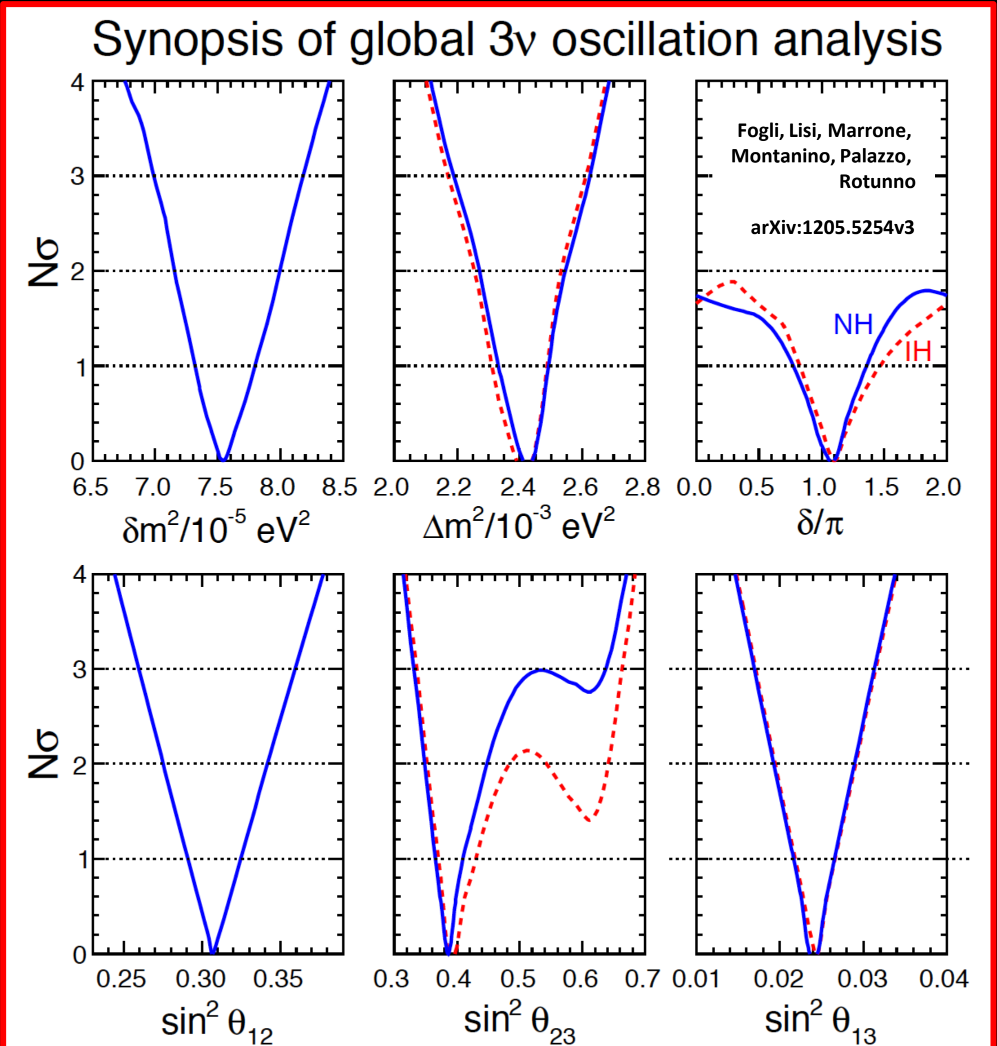
- Neutrino masses are tiny compared to those of the other fermions:
  - Hint that neutrino masses do not arise from the same mechanism?
  - Related to physics at very high mass scales as in “see-saw models”?
- If Standard Model Lagrangian is treated as an effective theory:
  - Dimensional analysis [Weinberg] indicates that:
    - Majorana mass term for neutrinos is first term beyond the Standard Model Lagrangian
- Fundamental questions:
  - What is the nature of the neutrino, Majorana or Dirac?
  - What is the absolute neutrino-mass scale?
  - Is CP-invariance violated in neutrino oscillations?
  - Is the neutrino-mass spectrum normal or inverted?
  - Is the neutrino-mixing matrix unitary?
  - Are there sterile neutrinos?
  - Is there a connection between quark and lepton flavour?

Neutrinos from stored muon beams:

Standard Neutrino Model

Standard Neutrino Model:

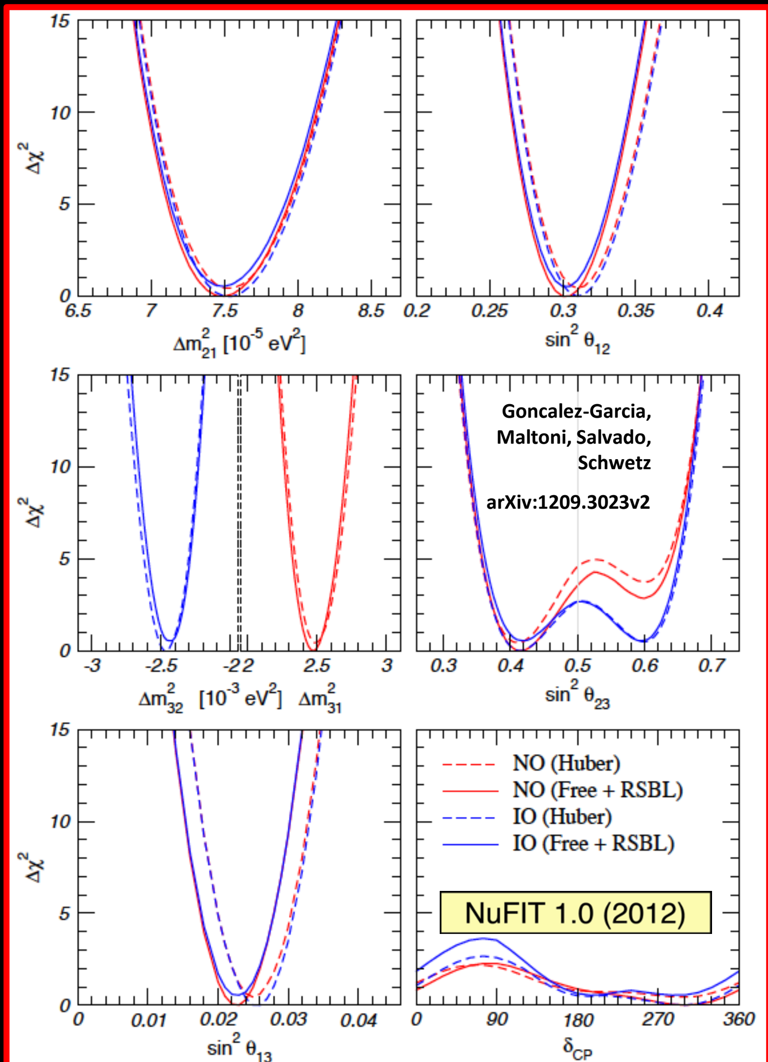
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12}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



- **Exciting new data!**
- **Discovery of leptonic CP-violation is possible**
- **Increases motivation for precision determination of the parameters and search for "non-standard effects"**

Standard Neutrino Model:

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



- Exciting new data!
- Discovery of leptonic CP-violation is possible
- Increases motivation for precision determination of the parameters and search for "non-standard effects"

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, …

	Appearance
	$\nu_\alpha \to \nu_\beta \quad \bar{\nu}_\alpha \to \bar{\nu}_\beta$
CPT:	$P(\nu_\alpha \to \nu_\beta) = P(\bar{\nu}_\beta \to \bar{\nu}_\alpha)$; $P(\nu_\alpha \to \nu_\alpha) = P(\bar{\nu}_\alpha \to \bar{\nu}_\alpha)$
CPiV:	$\frac{P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)}{P(\nu_\alpha \to \nu_\beta) + P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)}$
MH:	$P(\nu_\alpha \to \nu_\beta)$; $P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$ $[P(\nu_\alpha \to \nu_\alpha)]$
$(\theta - \frac{\pi}{4})$:	$P(\nu_\alpha \to \nu_\beta)$; $P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$ and $P(\nu_\alpha \to \nu_\alpha)$

Neutrinos from stored muon beams:

Searching for CP-invariance violation

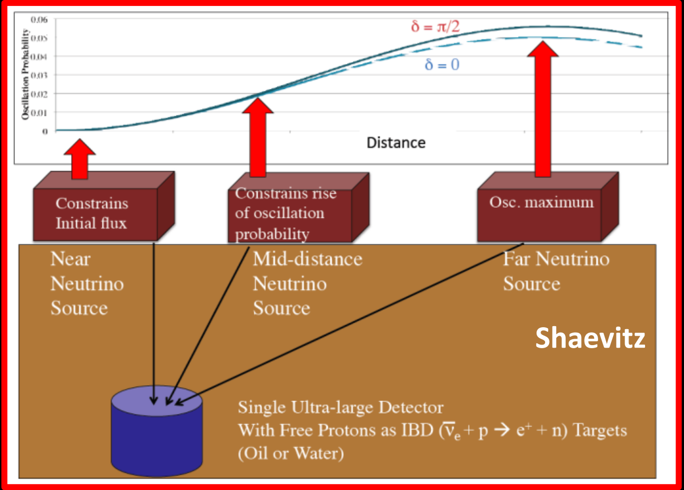
Option thumbnails:

- Conventional super-beams:
  - Wide-band, long baseline: e.g. LBNE, LBNO
    - <E_μ> ~ 2—3 GeV; matched to LAr or Fe calorimeter;
    - Long-baseline allows observation of first and second maximum
    - Near detector exploited to reduce systematic errors
  - Narrow-band, short baseline: e.g. T2HK, SPL
    - <E_μ> ~ 0.5 GeV; matched to H_20 Cherenkov;
    - Short-baseline allows observation of first maximum
    - Near detector exploited to reduce systematic errors

- Neutrino Factory: IDS-NF baseline E_μ=10 GeV;
  - Uniquely well known flux (flavour content and energy spectrum);
  - Baseline 1500—2500 km
  - Requires a magnetised detector
  - Identified by EUROnu as the facility for the high-precision programme

CPiV:

- Two options:
  - Exploit *L/E* spectrum:
    - DAEδALUS:
      - Pion/muon decay at rest
      - $\nu_\mu \rightarrow \nu_e$
      - No "matter effect contamination"
      - Measurement of δ—assumes SνM



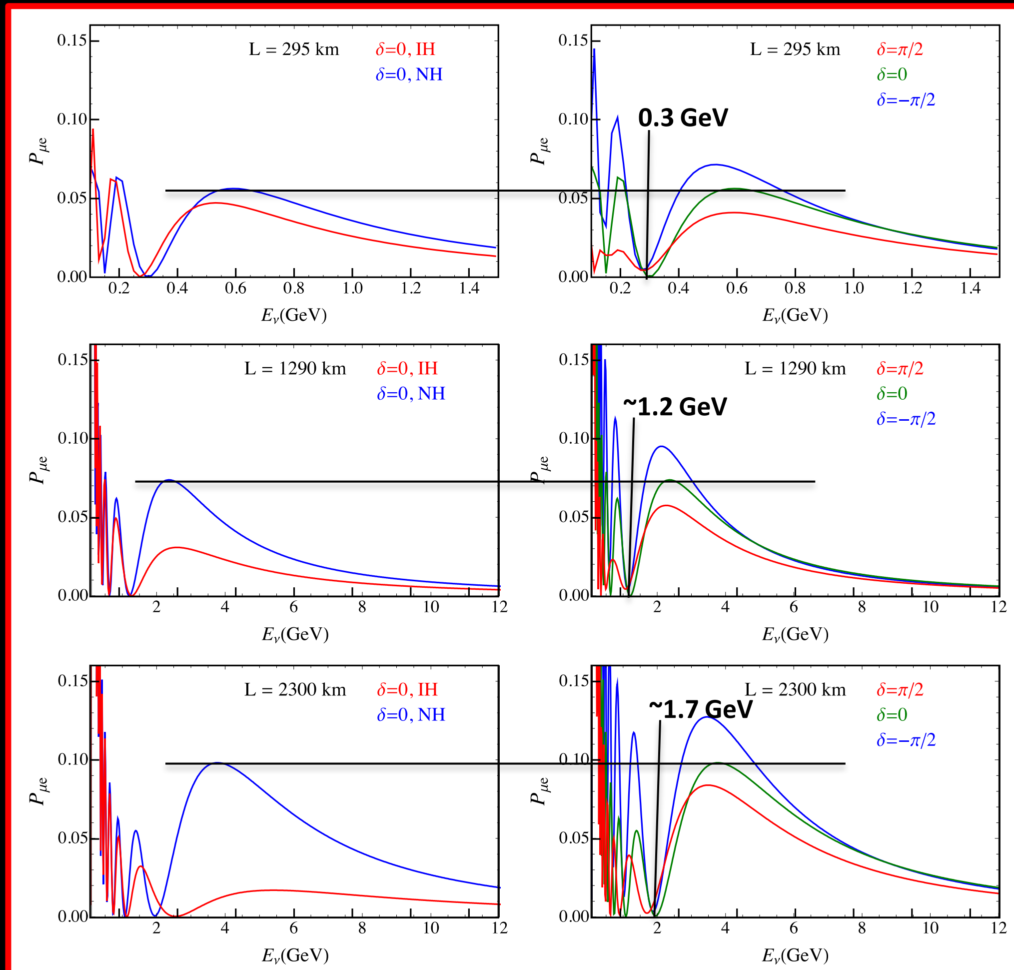
  - Measure asymmetry:

$$\frac{P(\nu_\alpha \rightarrow \nu_\beta) - P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta)}{P(\nu_\alpha \rightarrow \nu_\beta) + P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta)} \propto \frac{1}{\sin 2\theta_{13}}$$

    - Large θ_{13} makes discovery conceivable, *but*:
      - Places premium on the control of systematic uncertainties

P. Coloma

MH and CPiV at LBL experiments:

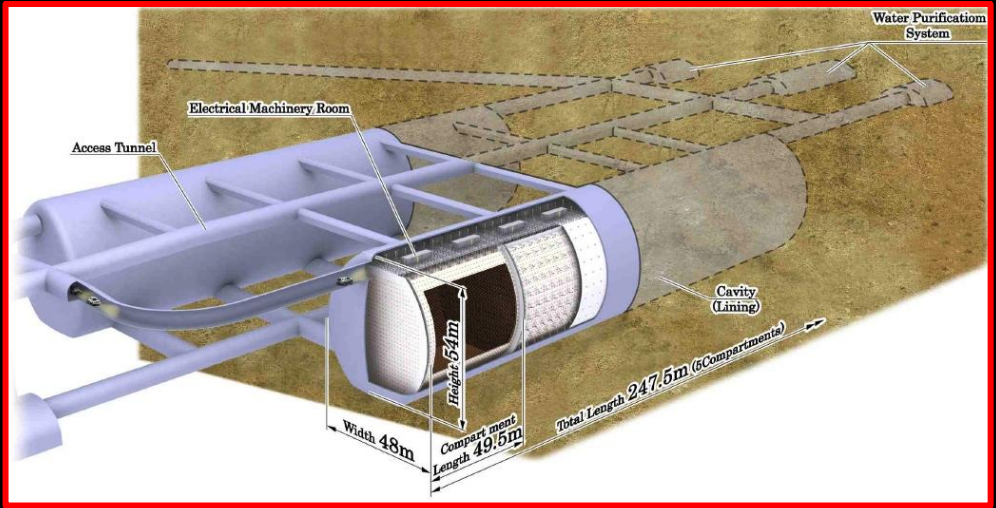


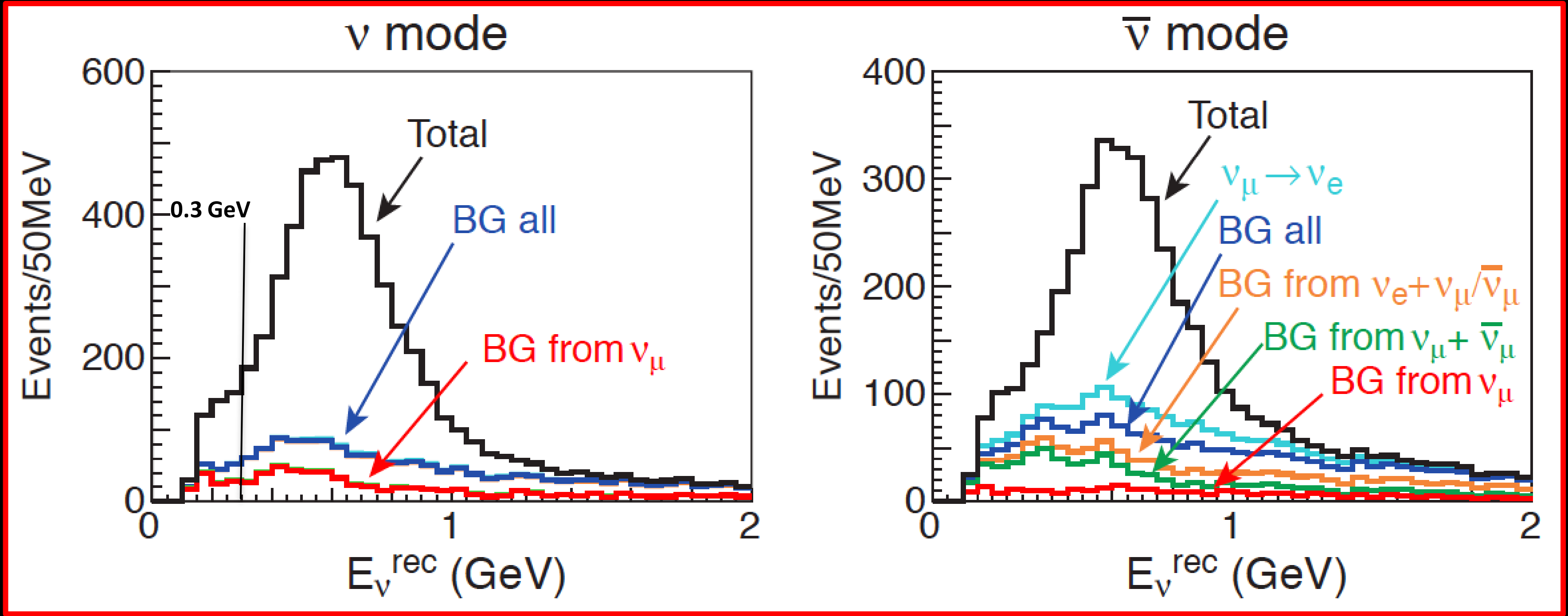
- **Mass hierarchy and CPiV modulate oscillation probability:**
  - **Need to measure as a function of *L/E* [measure *E* spectrum]**
- **MH sensitivity grows with *L* [matter effect]**
- **CPiV modulation grows with *L/E* [but, measure *E* spectrum]**

arXiv:1109.3262

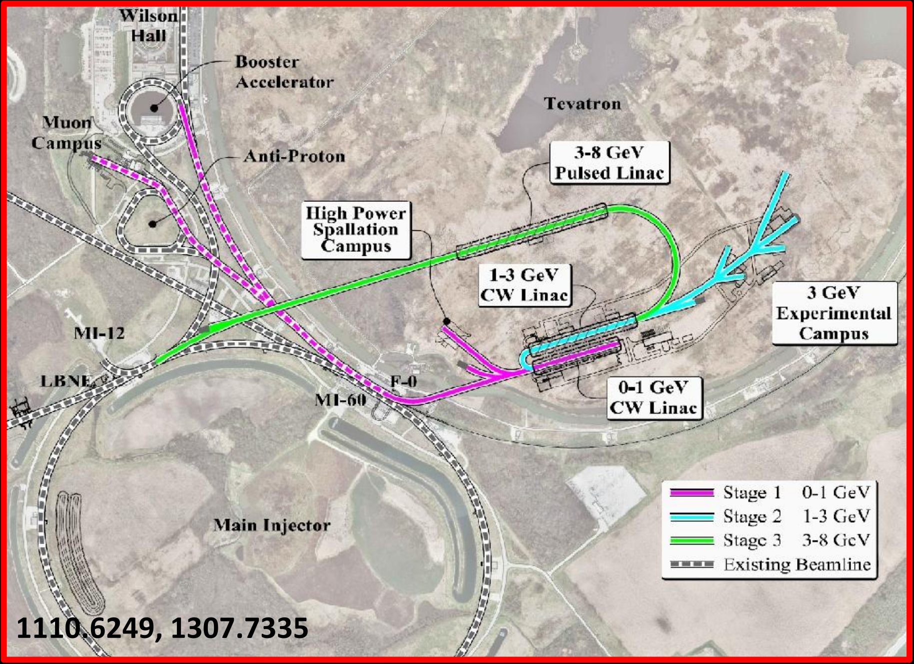
T2 Hyper-Kamiokande:

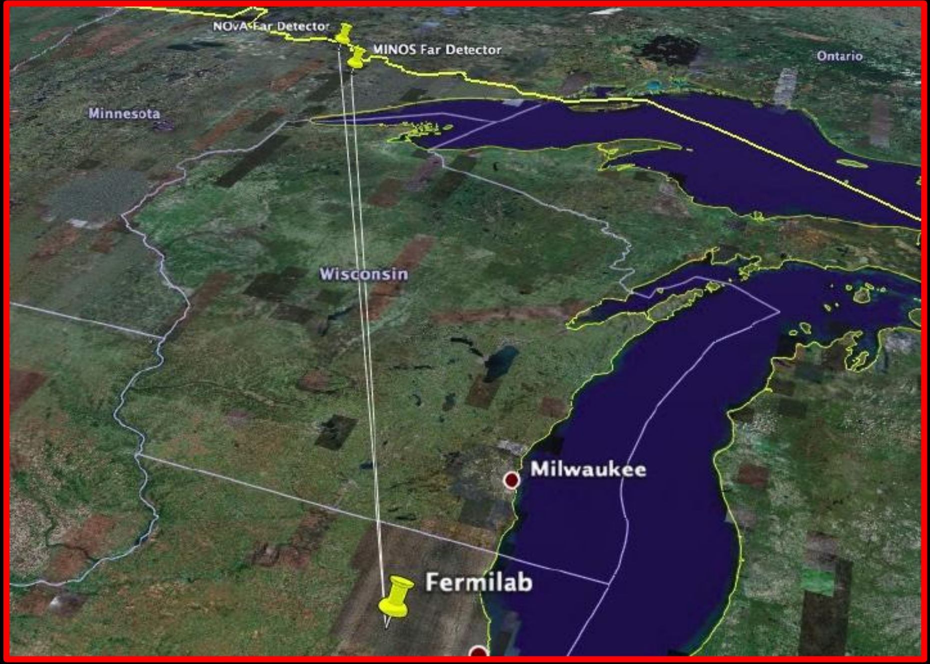
- Source:
  - JPARC neutrino beam: upgrade path to 1.66 MW
- Detector: water Cherenkov
  - Fiducial mass: 560 kTonne
  - Site:
    - 2.5° off axis;
    - Baseline ~290 km

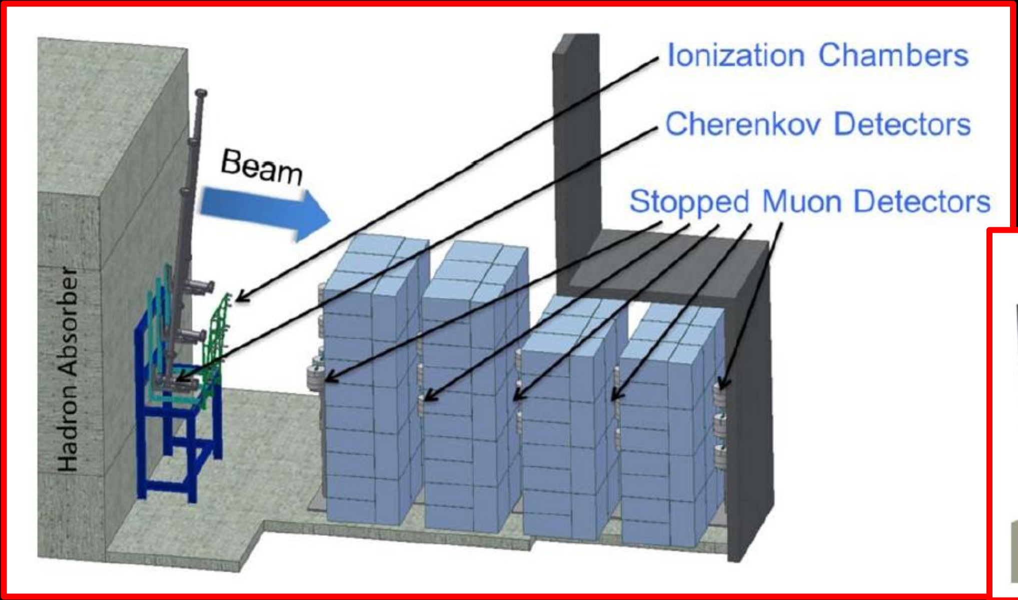




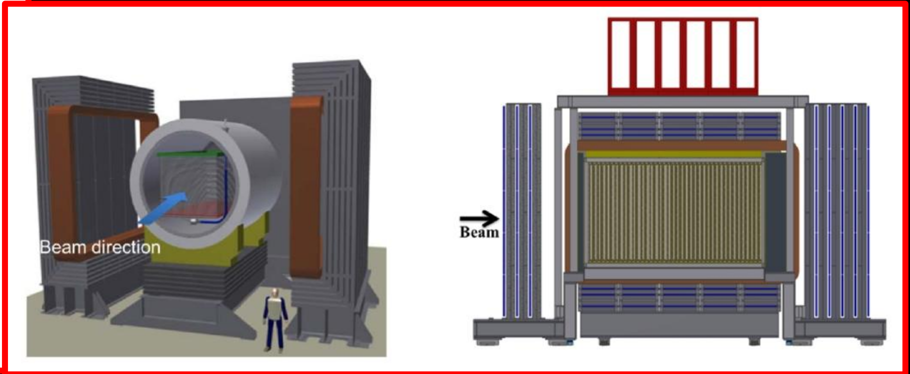
Long-Baseline Neutrino Experiment:





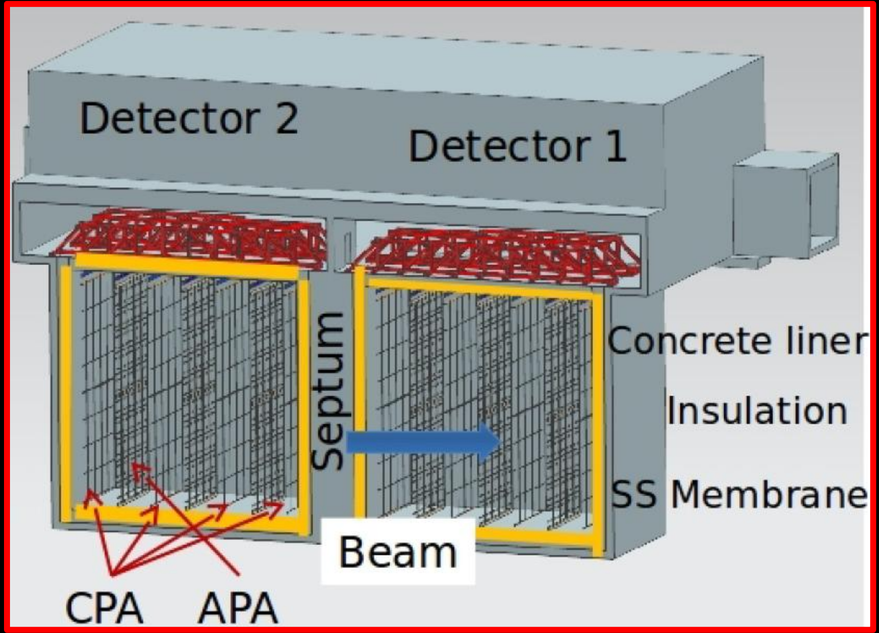


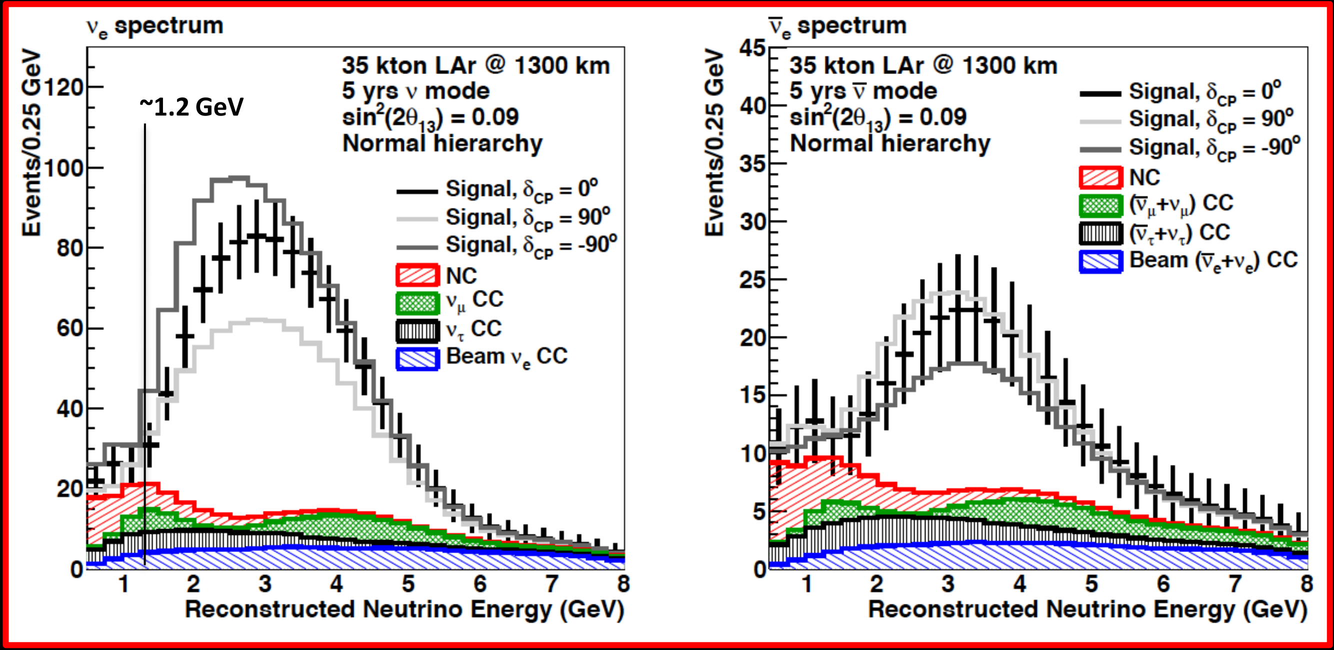
- Near detector options:
  - HiResMnu
  - Lar TPC



Long-Baseline Neutrino Experiment:

- Source:
  - FNAL MI: 700 kW
  - Project X: 2.3 MW [upgrade]
- Detector: LAr TPC
  - Fiducial mass: 10 kTonne
    - Upgrade to 34 kTonne
  - Site: SURF
    - On axis; upgrade u/g 4850 ft
    - Baseline 1300 km



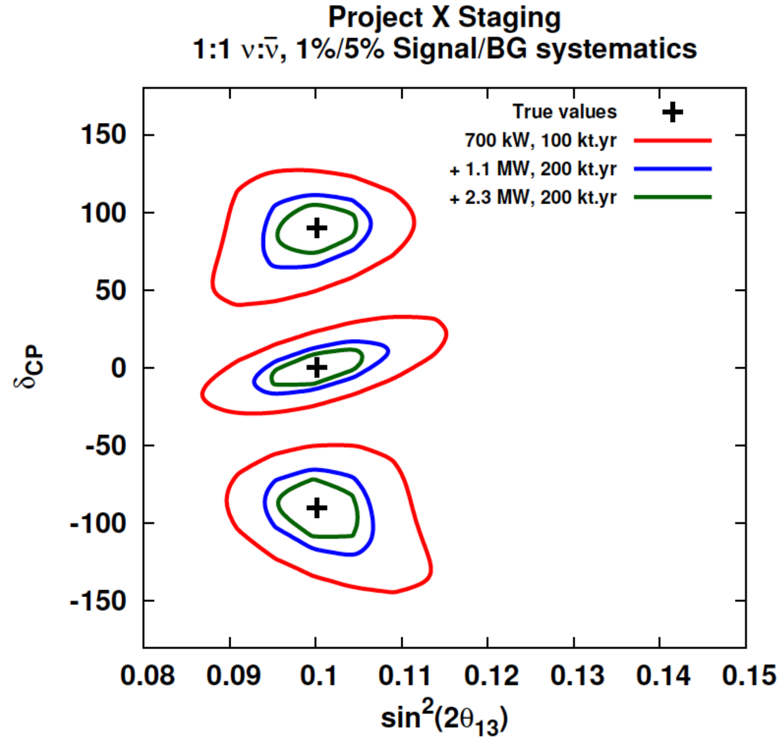


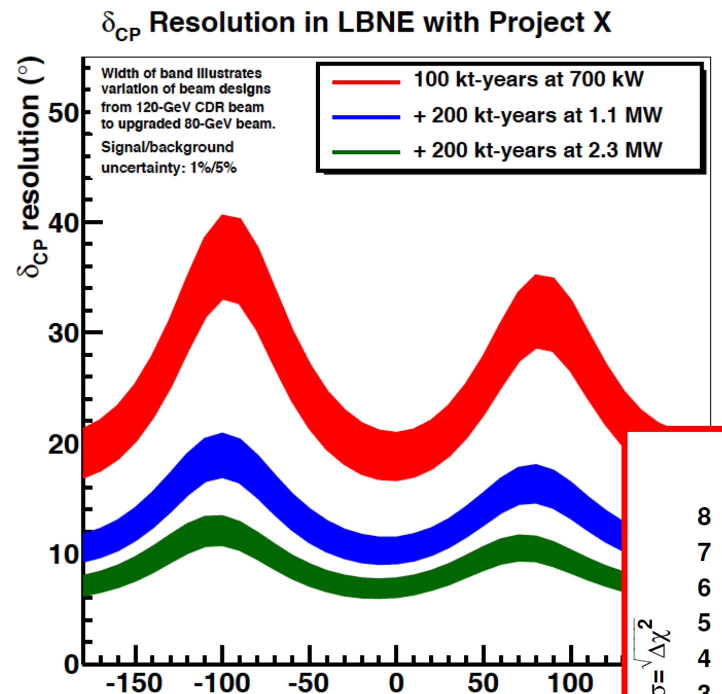
arXiv:1307.7335

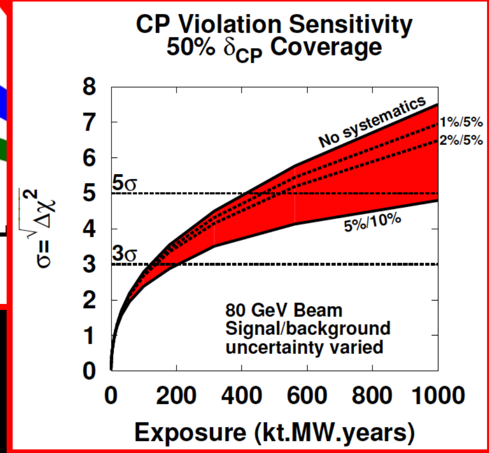
Long-Baseline Neutrino Experiment:

- Systematic uncertainties:
  - Signal: 1%
  - Background: 5%

Systematic uncertainty	Sensitivity	Required Exposure
0 (statistical only)	3 σ, 50% δ_{cp}	100 kt.MW.yr
0 (statistical only)	5 σ, 50% δ_{cp}	400 kt.MW.yr
1%/5% (Sig/bkgd)	3 σ, 50% δ_{cp}	100 kt.MW.yr
1%/5% (Sig/bkgd)	5 σ, 50% δ_{cp}	450 kt.MW.yr
2%/5% (Sig/bkgd)	3 σ, 50% δ_{cp}	120 kt.MW.yr
2%/5% (Sig/bkgd)	5 σ, 50% δ_{cp}	500 kt.MW.yr
5%/10% (no near ν det.)	3 σ, 50% δ_{cp}	200 kt.MW.yr







arXiv:1307.7335

Controlling systematics: near detector:

Flavor	Technique	Relative abundance	Absolute normalization	Relative flux $\Phi(E_\nu)$	Detector requirements
ν_μ	$\nu_\mu e^- \to \nu_\mu e^-$	1.00	2.5%	$\sim 5\%$	e ID θ_e Resolution e^-/e^+ Separation
ν_μ	$\nu_\mu e^- \to \mu^- \nu_e$	1.00	3%		μ ID θ_μ Resolution 2-Track (μ+X) Resolution μ energy scale
ν_μ	$\nu_\mu n \to \mu^- p$ $Q^2 \to 0$	1.00	$3-5\%$	$5-10\%$	D target p Angular & Energy resolution Back-Subtraction
$\bar{\nu}_\mu$	$\bar{\nu}_\mu p \to \mu^+ n$ $Q^2 \to 0$	0.70	5%	10%	H target Back-Subtraction
ν_μ	Low-ν_0	1.00		2.0%	μ^- vs μ^+ E_μ-Scale Low-E_{Had} Resolution
$\bar{\nu}_\mu$	Low-ν_0	0.70		2.0%	μ^- vs μ^+ E_μ-Scale Low-E_{Had} Resolution
$\nu_e/\bar{\nu}_e$	Low-ν_0	0.01	1-3%	2.0%	e^-/e^+ Separation (K_L^0)

Experiment	NC/CC (π^0) Events	Beam-ν_e Events	Syst.Error	Comment
BNL E734 [87]	235	418	20%	No ND
BNL E776(89)(NBB) [88]	10	9	20%	No ND
BNL E776 (WBB)	95	40	14%	No ND
MiniBooNE (>450MeV) [89]	140	250	9%	No ND
NOMAD	<300	5500	< 5%	No ND
MINOS [90]	111	12	3.8%	ND–FD

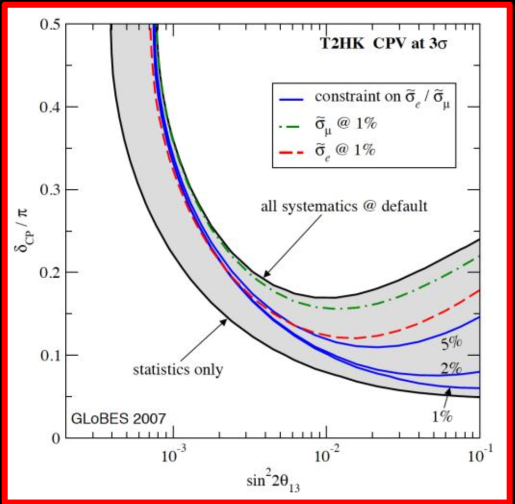
- **High-resolution near detector and detailed programme of measurement essential to meet specified systematic uncertainties**
- **Effects such as nuclear/final-state interactions must also be controlled at the %-level**

arXiv:1307.7335

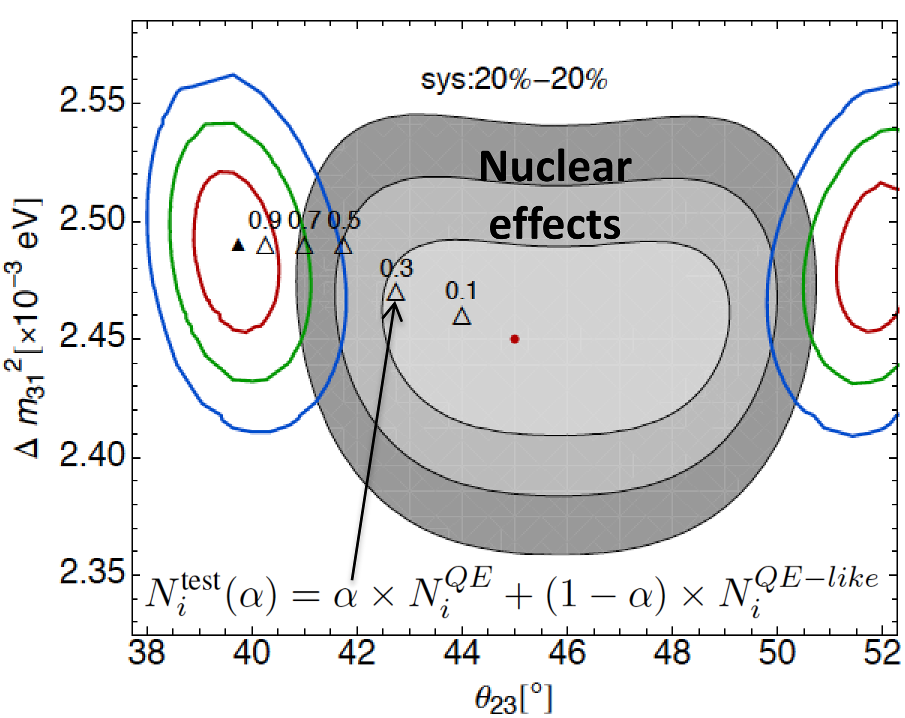
Neutrinos from stored muon beams:

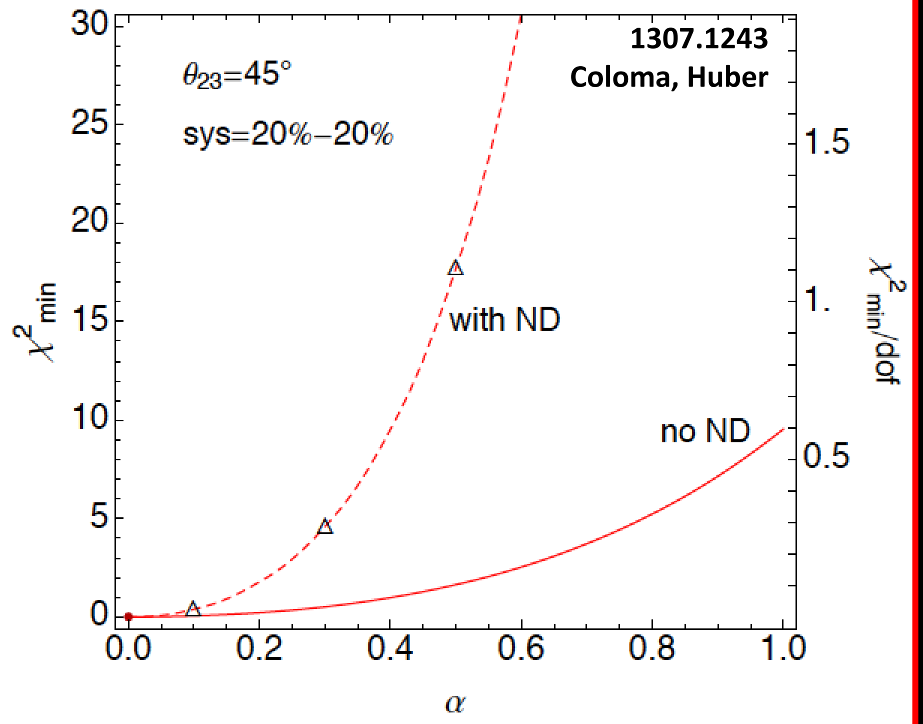
Neutrinos from stored muon beams

Limiting systematics in the LBL programme:



- **NBB + H2O Cherenkov:**
  - **Clearly limited by cross section uncertainties**
- **WBB + LAr TPC:**
  - **Critical point: ν_e appearance in ν_μ beam:**
    - **Convolution of flux × cross section × nucl. effect**
    - **Precision limited by deconvolution**





Cross section measurement performance:

- **Existing experiments:**
  - Sets the goal

Experiment	Systematic uncertainty (%) Detector	Monte Carlo	Other	Sub-total	Flux	Total
MiniBooNE NCE ($E_\nu \sim 1$ GeV)	15.6	6.4		16.9	6.7	18.1
MiniBooNE CCQE ν_μ ($E_\nu \in 0.2-3.0$ GeV)	3.2	15.7		16.1	6.9	17.5
MiniBooNE CCQE ν_e ($E_\nu \in 0.2-3.0$ GeV)	14.6	8.5		16.1	9.8	19.5
MiniBooNE CCπ^0 ν_μ ($E_\nu \in 0.5-2.0$ GeV)	5.8	14.4		15.6	10.5	18.7
MiniBooNE QE$\frac{d^2\sigma}{dT_\mu d\cos\theta_\mu}$ ($E_\nu \in 0.5-2.0$ GeV)	4.6	4.4		6.4	8.7	10.7
T2K Inclusive ν_μ CC ($E_\nu \sim 1$ GeV)	0.7–12	0.4–9		1.3–15	10.9	10.9–18.6
Minerva $\bar{\nu}_\mu$ CCQE ($Q^2 < 1.2$ GeV^2)	8.9–15.6	2.8	2–6	9.6–17	12	15.3–20.8
LSND $\bar{\nu}_\mu p \to \mu^+ n$ 0.1GeV	5	12		13	15	20

- **Performance of HiResMnu:**

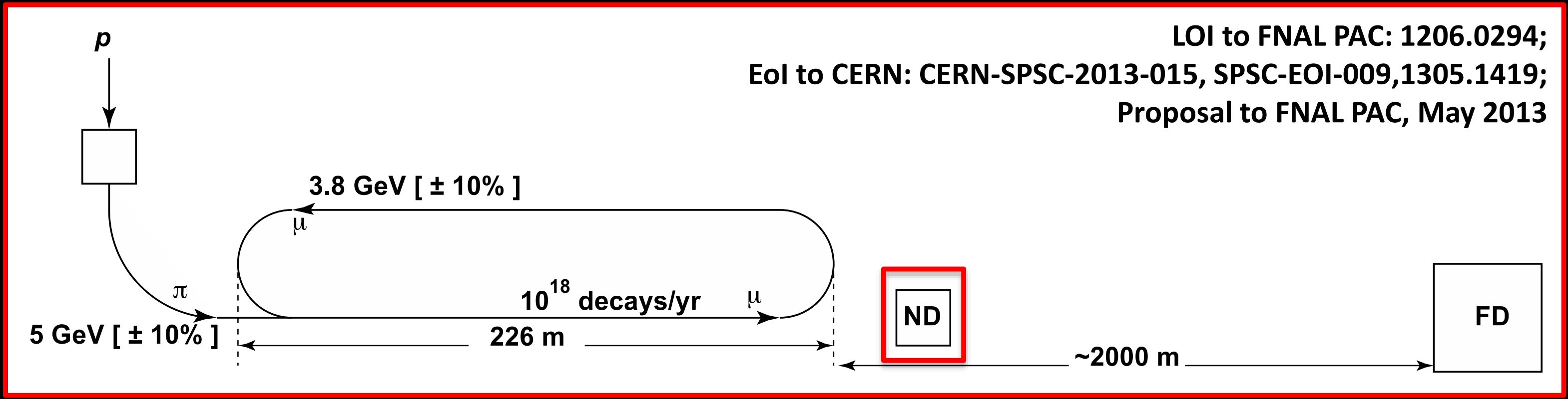
Detector	Types of Errors	Contribution (%)
HiResMν	Reconstruction	0.8
	Background	2.1
	FSI error	1.5
	Total	2.9

- **Assumed performance of generic detector for evaluation of precision of cross section measurement:**

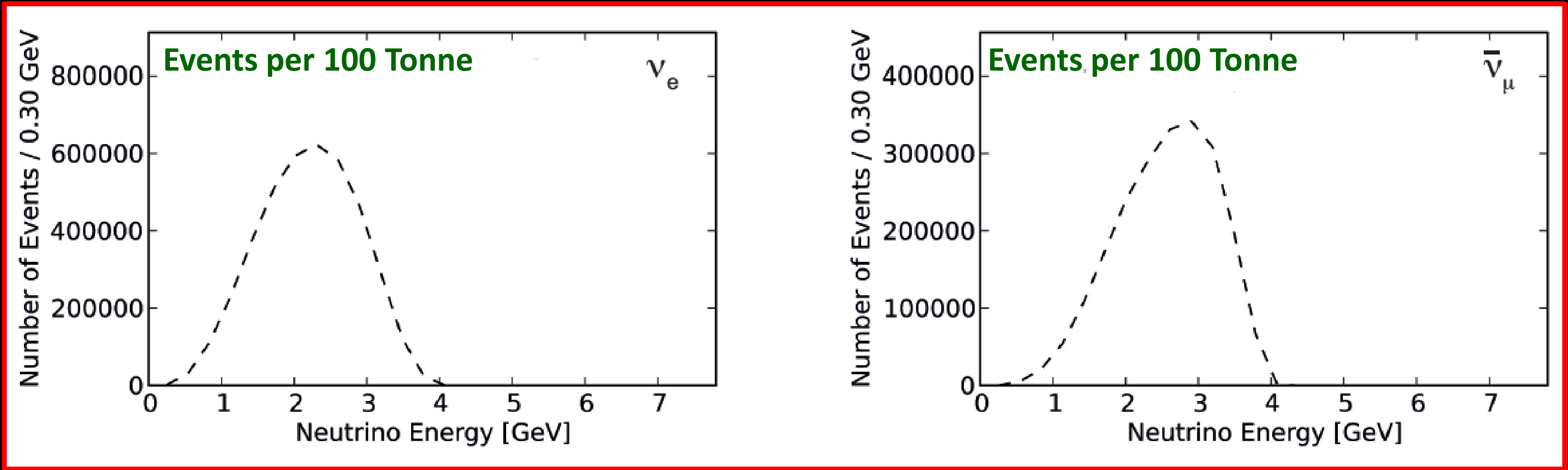
Effect	Value
Momentum resolution of contained tracks	3%
Angular resolution	3%
Minimum range for track finding	2 cm

- **Flux uncertainty varied:**
  - 1% nuSTORM specification
  - 10% typical of conventional beams for comparison

nuSTORM and cross section measurement:



- nuSTORM event rate is large:
  - Statistical precision high:
    - Can measure double-differential cross sections



Detector options:

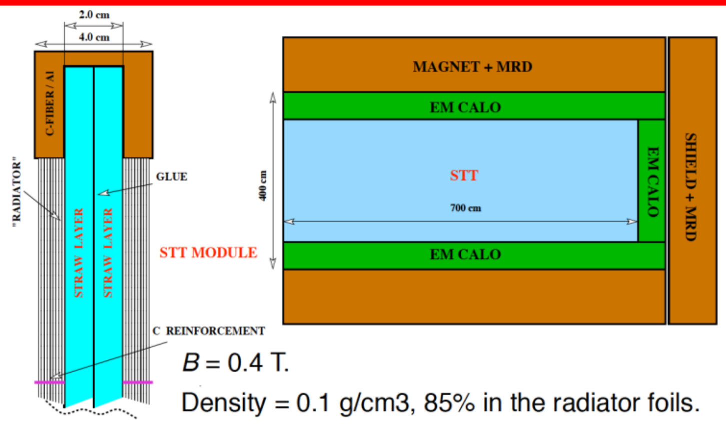


Figure 11: Schematic of the HIRESMNU concept showing the straw tube tracker (STT), the electromagnetic calorimeter (ECAL) and the magnet with the muon range detector (MRD). The STT is based upon ATLAS [174–176] and COMPASS [177, 178] trackers. Also shown is one module of the proposed straw tube tracker (STT). Interleaved with the straw tube layers are plastic foil radiators, which provide 85% of the mass of the STT. At the upstream end of the STT are layers of nuclear-target for the measurement of cross sections and the π^0s on these materials.

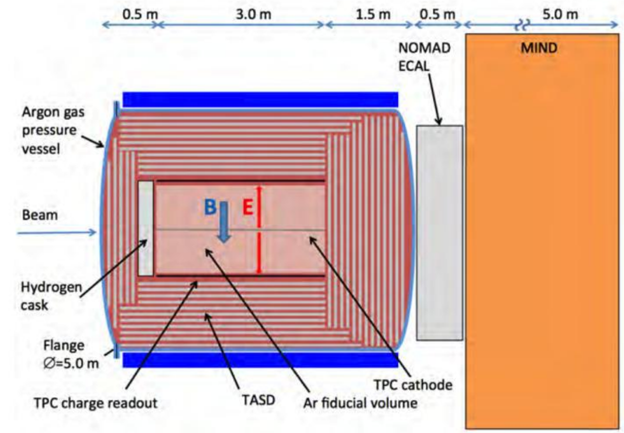
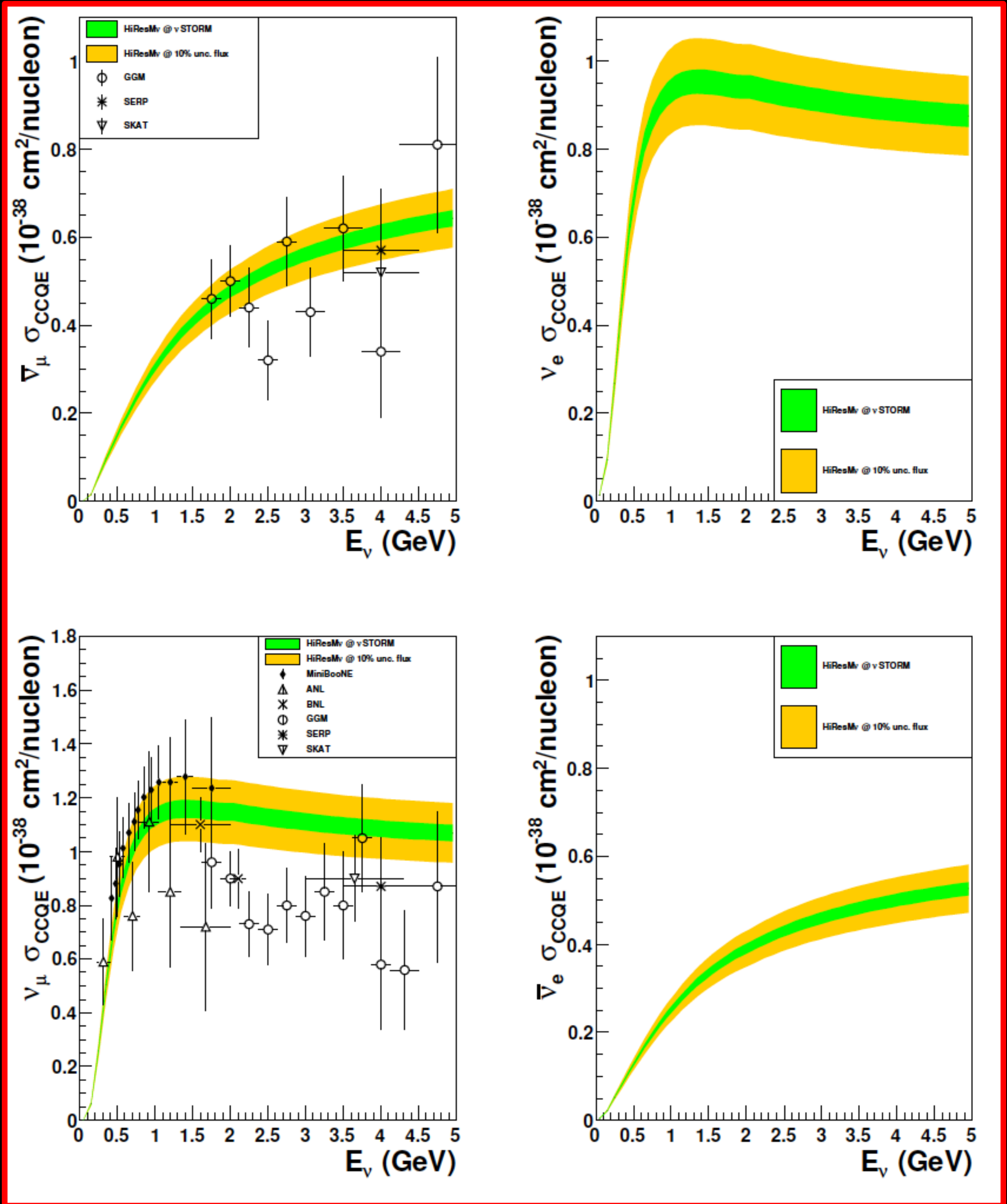


Figure 12: Schematic of the pressurized argon gas-based TPC detector. Both the TPC and scintillator calorimeter layers surrounding it are enclosed in a pressure vessel. A 0.5 T magnetic field is applied to the pressure vessel volume. Downstream of the TPC are also an electromagnetic calorimeter (ECAL) and a magnetized iron neutrino detector (MIND). The latter acts as a muon spectrometer for neutrino interactions occurring in the TPC and as an independent near detector for the sterile neutrino program.

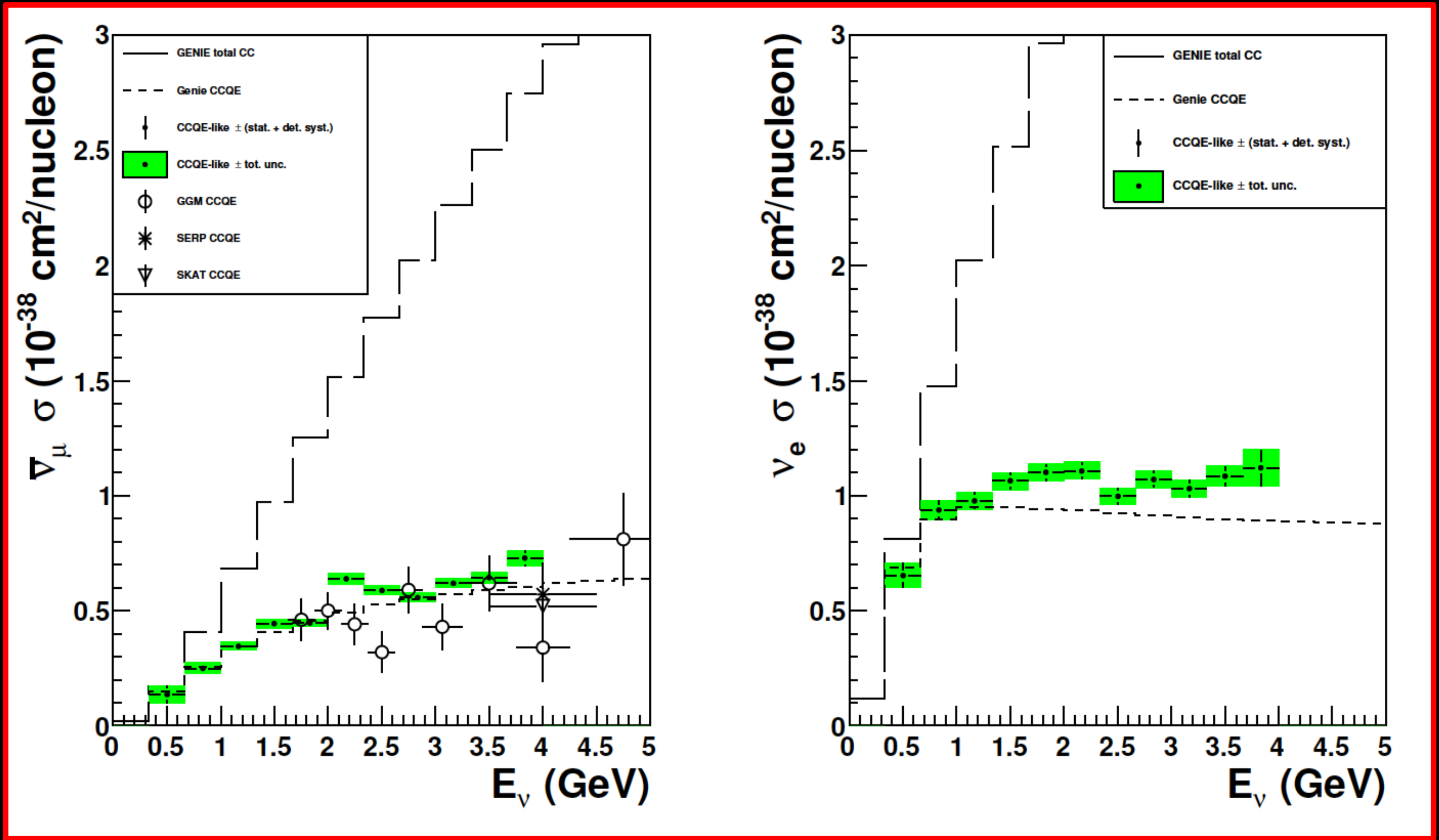
- Staged approach possible:
  - Initial measurements could exploit existing detector:
    - If at FNAL Minerva, Mini/MicroBOONE are candidates
  - Implementation of one or more dedicated detectors to make definitive measurements
- Generic study of to evaluate performance …

CCQE cross section measurement:

- Systematic uncertainties for CCQE measurement at nuSTORM:
  - Six-fold improvement in systematic uncertainty compared with “state of the art”
  - Electron-neutrino cross section measurement unique



CCQE cross section measurement:



- Simulation of "generic detector":
  - Muon-neutrino CCQE cross section measurement substantially improves "state of the art"
  - Electron-neutrino CCQE measurement *unique*
  - Evaluation of other channels has begun

Opportunity?

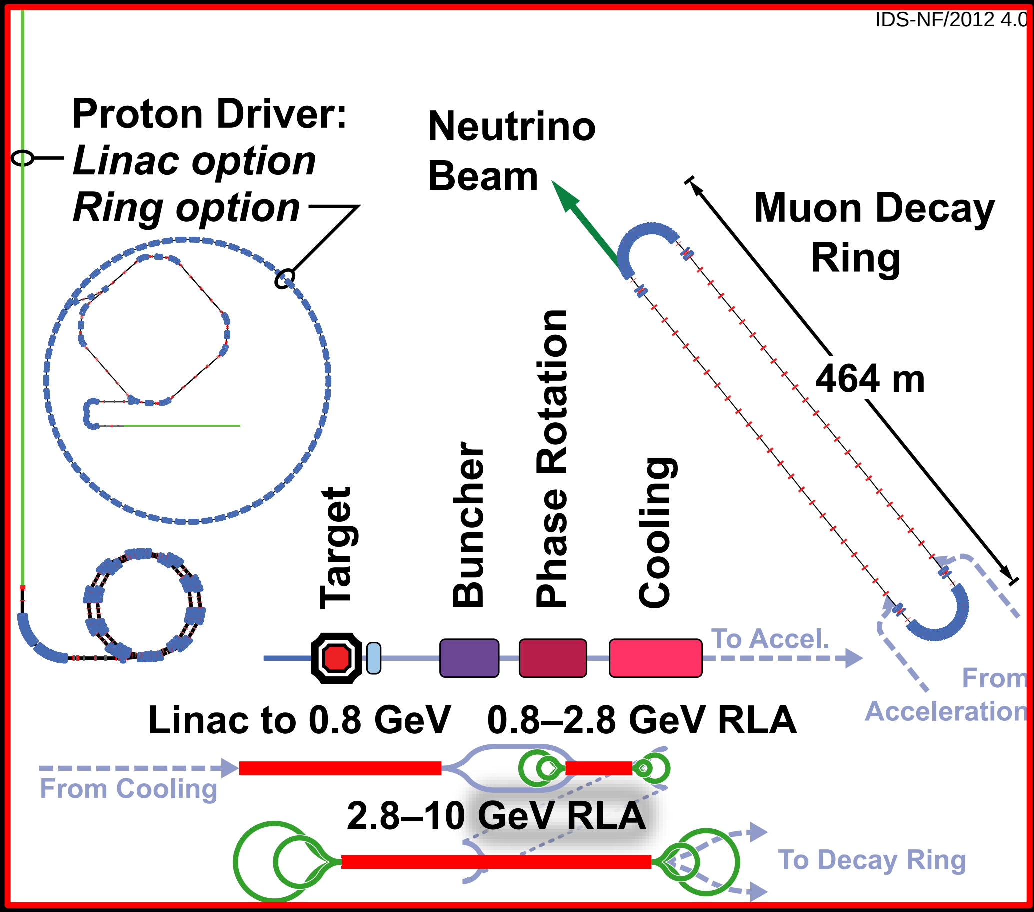
- **Is it true that *accurate measurements* of $\nu_e N$ cross sections are critical to realising the potential of the LBL programme?**
  - **If it is, nuSTORM seems to be the only way to achieve few-% precision**
- **Japanese, Canadian and UK T2K groups:**
  - **Leaders in cross section measurements using ND280**
  - **Strong contributors to oscillation analysis**
  - **Ideally placed to work together to try to answer the *in principle* question;**
    - **Potential to develop cross-section detector(s) and measurement techniques**

Neutrinos from stored muon beams:

Neutrino Factory

Neutrino Factory:

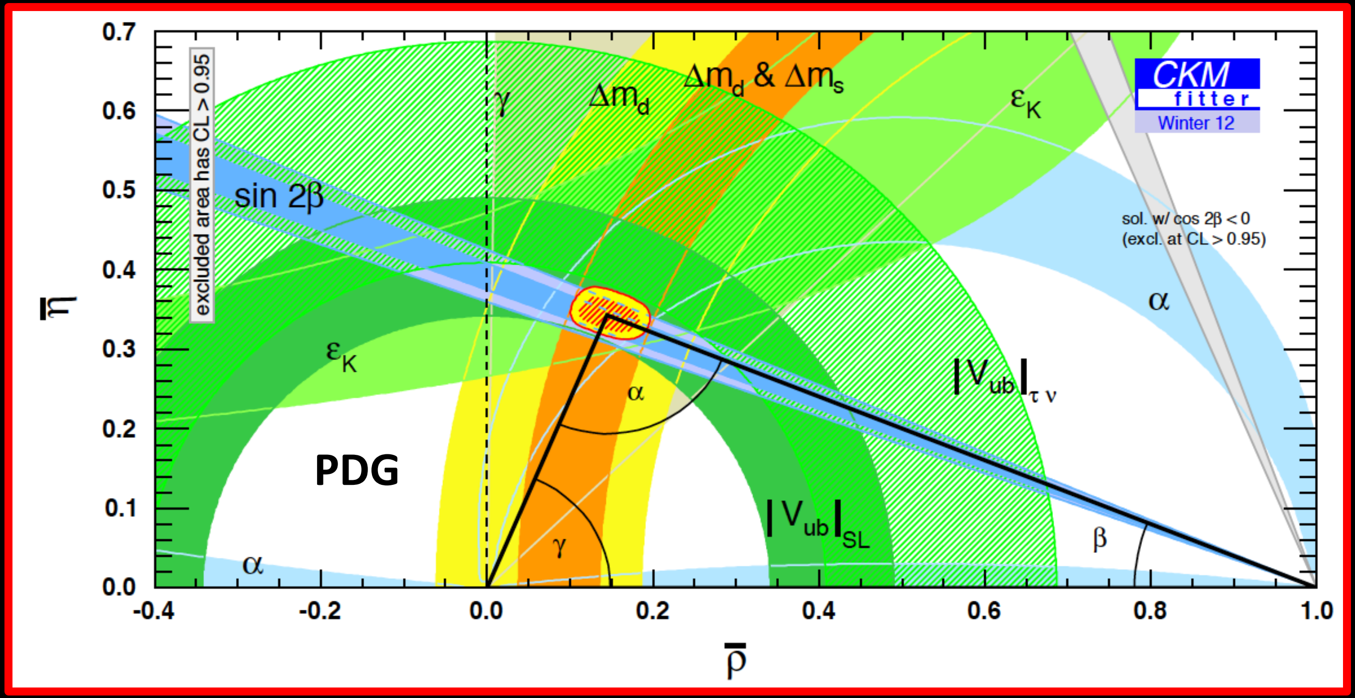
- Optimise discovery potential for CP and MH:
  - Requirements:
    - Large ν_e ($\bar{\nu}_e$) flux
      - Detailed study of sub-leading effects



- Unique:
  - (Large) high-energy ν_e ($\bar{\nu}_e$) flux
    - Optimise event rate at fixed *L/E*
    - Optimise MH sensitivity
    - Optimise CP sensitivity

The case for precision:

- What determines the goal for sensitivity and precision?
  - Sensitivity:
    - Definitive discovery!
      - Must have sensitivity of "~5σ"
      - To resolve the LSND/miniBooNE "suite of anomalies" may set the bar higher!
  - Precision:
    - Field presently led by experiment;
      - Too many, or too few, theories;
    - Goal to determine parameters with a precision comparable to that with which the quark-mixing parameters are known



arXiv:1112.2853

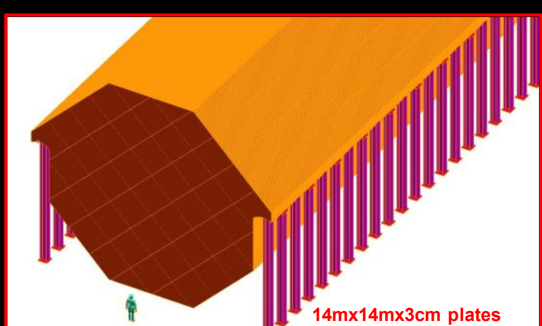
Neutrino Factory:

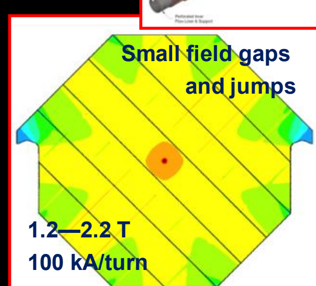
- Two approaches:
  - Optimise *L* and *E* to match detector threshold
    - IDS-NF approach:
      - 1.4% signal
      - 20% background

	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 long-baseline neutrino detector	1 500–2 500 km

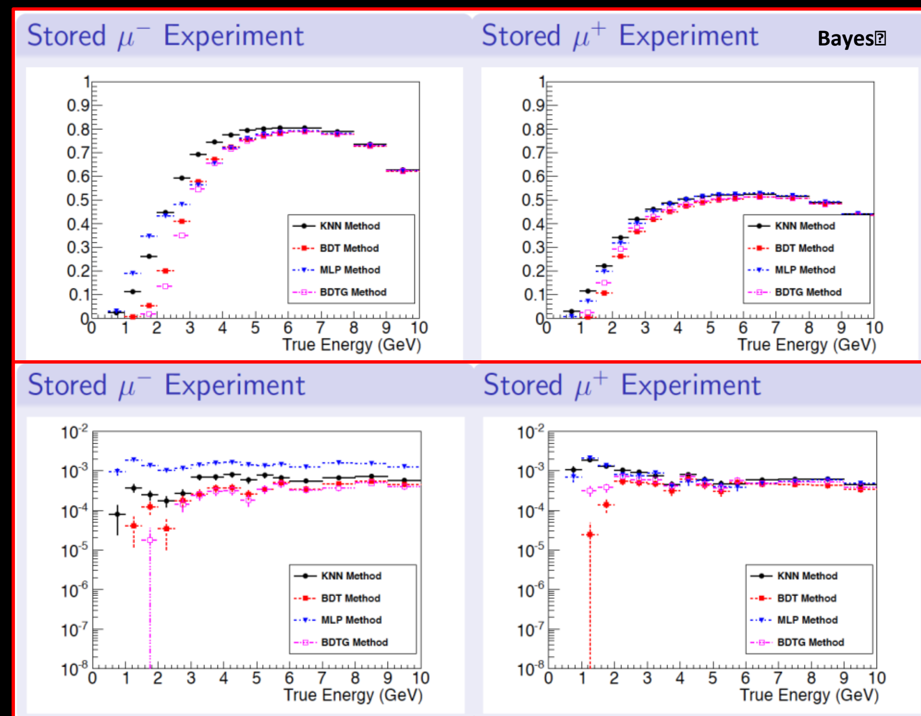
Magnetized Iron Neutrino Detector (MIND):

- IDS-NF baseline:
  - Intermediate baseline detector:
    - 100 kton at 2500—5000 km
  - Magic baseline detector:
    - 50 kton at 7000—8000 km
  - Appearance of "wrong-sign" muons
  - Toroidal magnetic field > 1 T
    - Excited with "superconducting transmission line"
  - Segmentation: 3 cm Fe + 2 cm scintillator
  - 50-100 m long
  - Octagonal shape
  - Welded double-sheet
    - Width 2m; 3mm slots between plates





Bross, Soler



arXiv:1112.2853; 1308.0494v1

Neutrino Factory:

- Two approaches:
  - Optimise *L* and *E* to match detector threshold
    - IDS-NF approach:

	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 long-baseline neutrino detector	1 500–2 500 km

  - Exploit LAr detector sited 1300 km from FNAL
    - MAP/MASS approach:

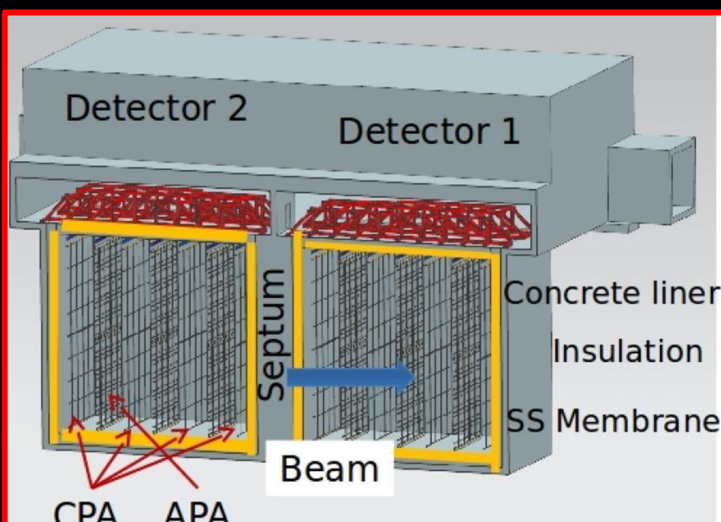
NuMAX – facility

Neutrinos from Muon Accelerators at Project X

NuMAX
- 1MW, 3GeV protons from PX stage II
- no muon cooling
- acceleration to 5GeV
- 8×10^{19} useful muons per year and polarity

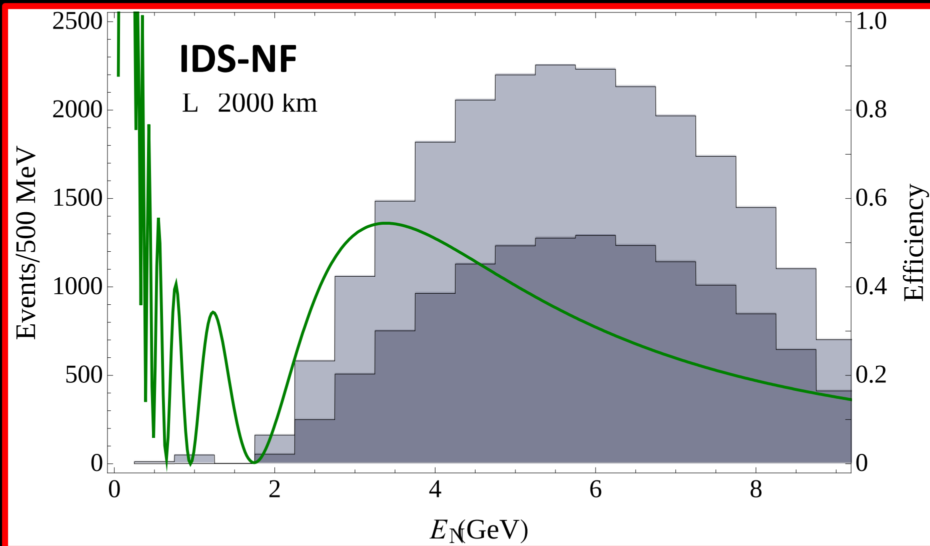
NuMAX+
- 3MW, 3GeV protons from PX stage II
- muon cooling
- acceleration to 5GeV
- 5×10^{20} useful muons per year and polarity

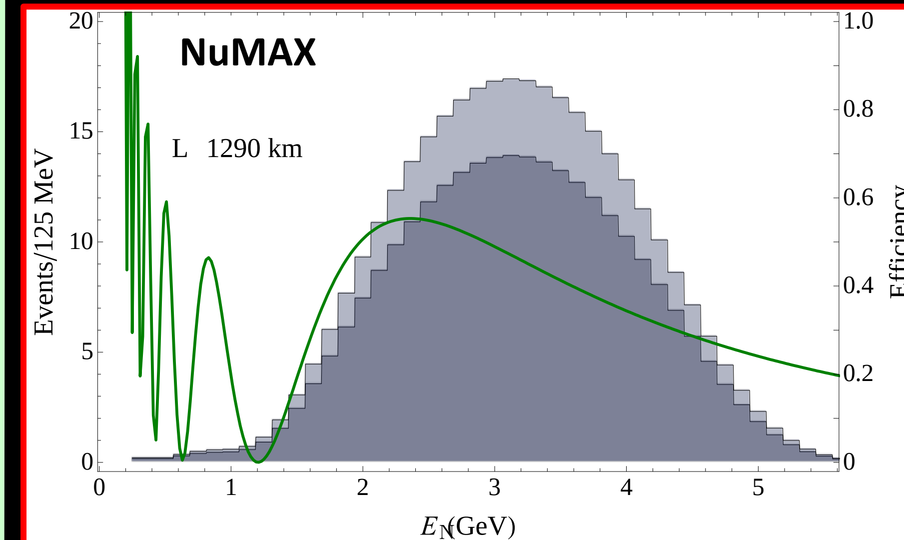
Detector at SURF, 10kt magnetized LAr – fallback
5-10 times larger magnetized iron detector

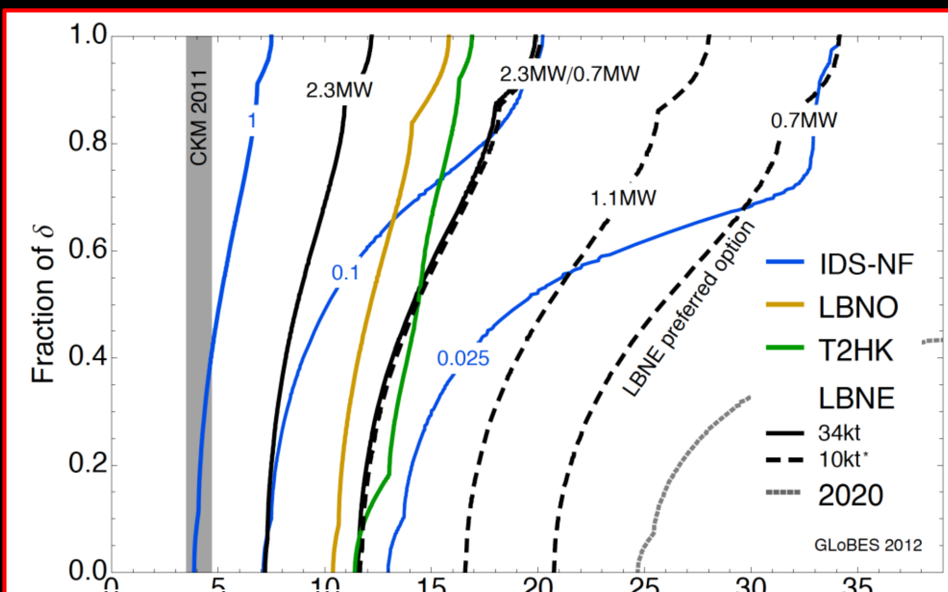


Bayes, Coloma

Neutrino Factory:

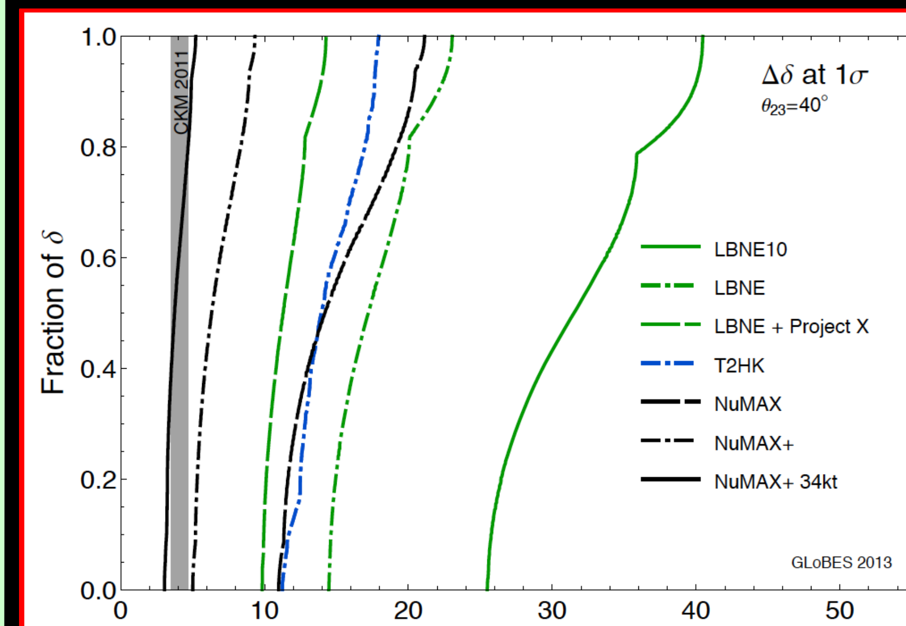






Coloma, Huber, Kopp, Winter
arXiv:1209.5973

* Assumes surface operation to be equivalent to deep underground operation for beam physics



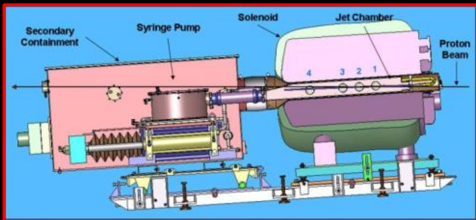
arXiv:1301.7727

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

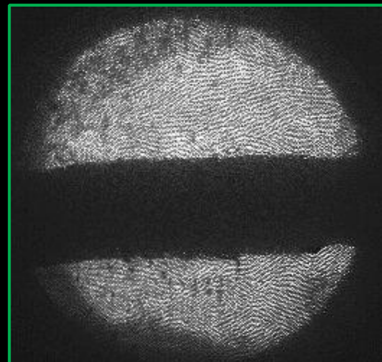
- **Proton driver:**
  - Development of high-power, pulsed proton source underway at proton labs
- **Pion-production target:**
  - MERIT experiment at CERN proved principle of mercury jet target
- **Muon front end:**
  - MuCool programme at FNAL:
    - Study of effect of magnetic field on high-gradient, warm, copper cavities;
  - MICE experiment at RAL:
    - Proof of principle of ionization-cooling technique
- **Rapid acceleration:**
  - EMMA experiment at DL:
    - Proof of principal of non-scaling FFAG technique;
      - Novel technology allows circular acceleration without magnet ramp

Baseline target: proof of principle: MERIT:

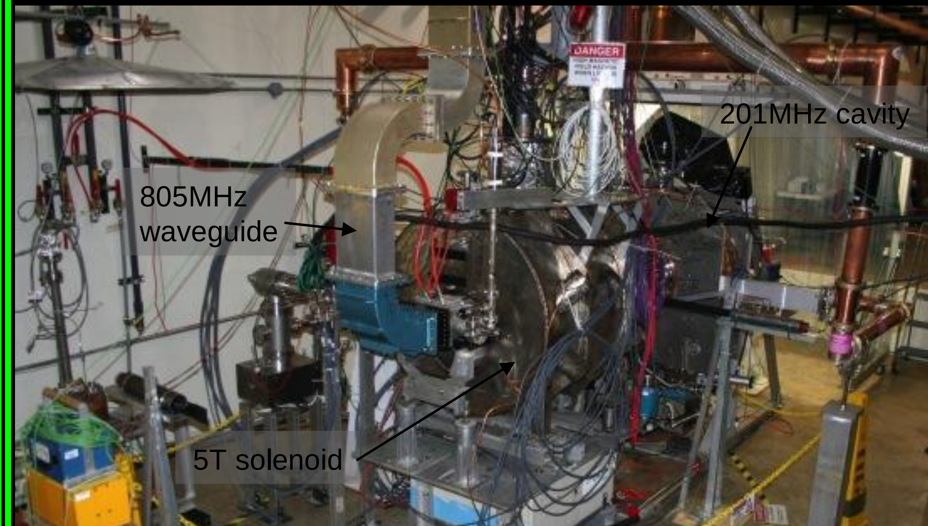


- ‘Disruption length’: 28 cm
- ‘Refill’ time: 14 ms
  - Corresponds to 70 Hz
- Hence:
  - Demonstrated operation at:
    - 60 kJ × 70 Hz = 8 MW

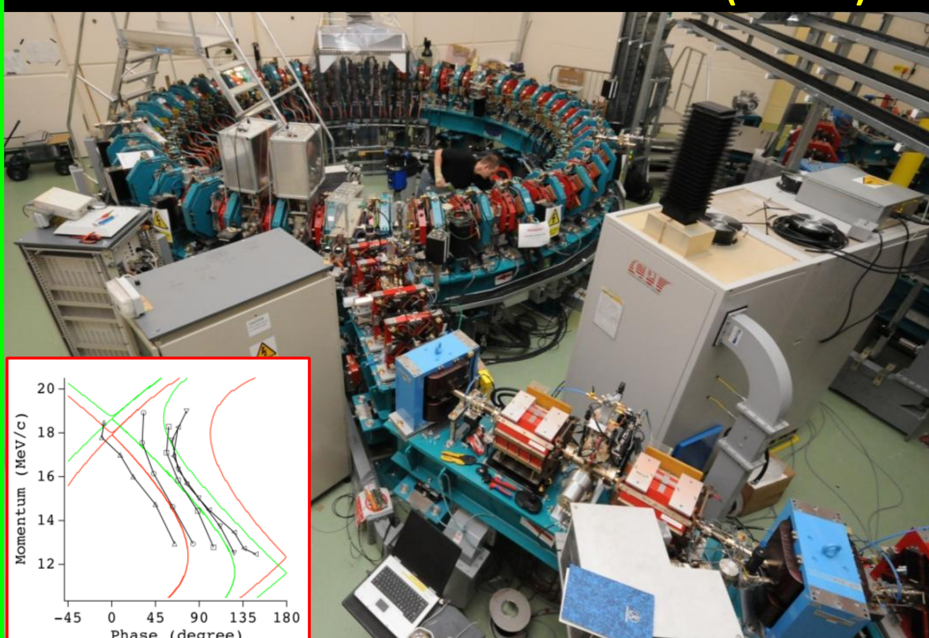
- 20 m/s liquid Hg jet in 15 T B field
- Exposed to CERN PS proton beam:
  - Beam pulse energy = 115 kJ
  - Reached 30 tera protons at 24 GeV



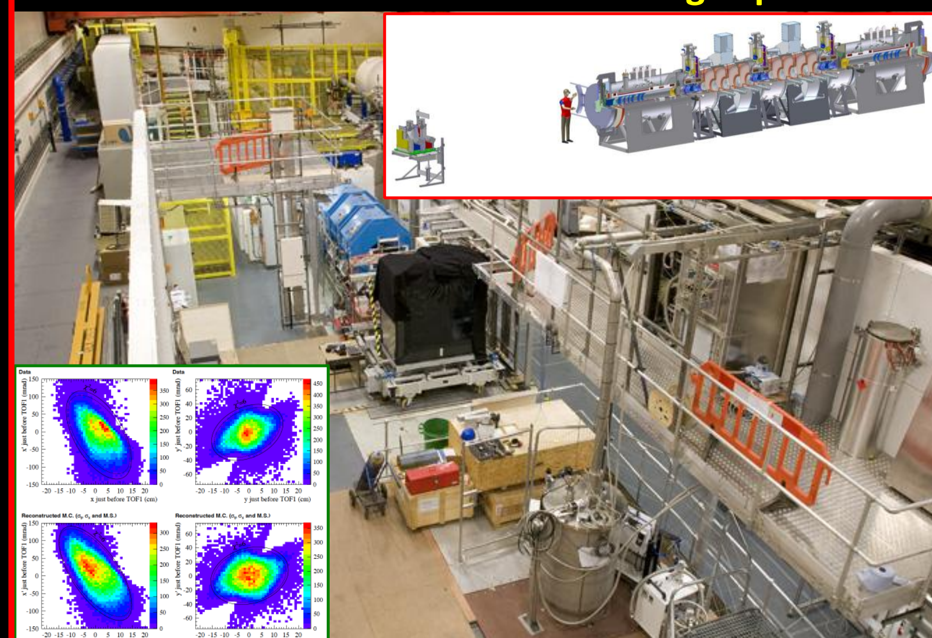
MuCool: cavities in magnetic field



Electron Model of Muon Acceleration (EMMA)



International Muon Ionization Cooling Experiment



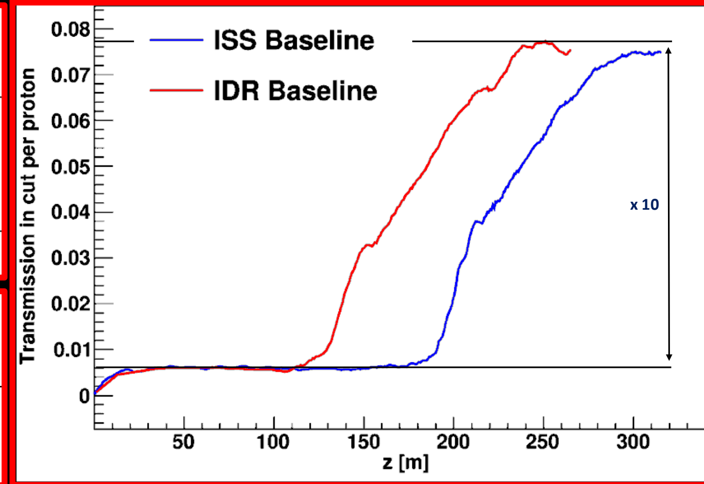
Neuffer, Rogers

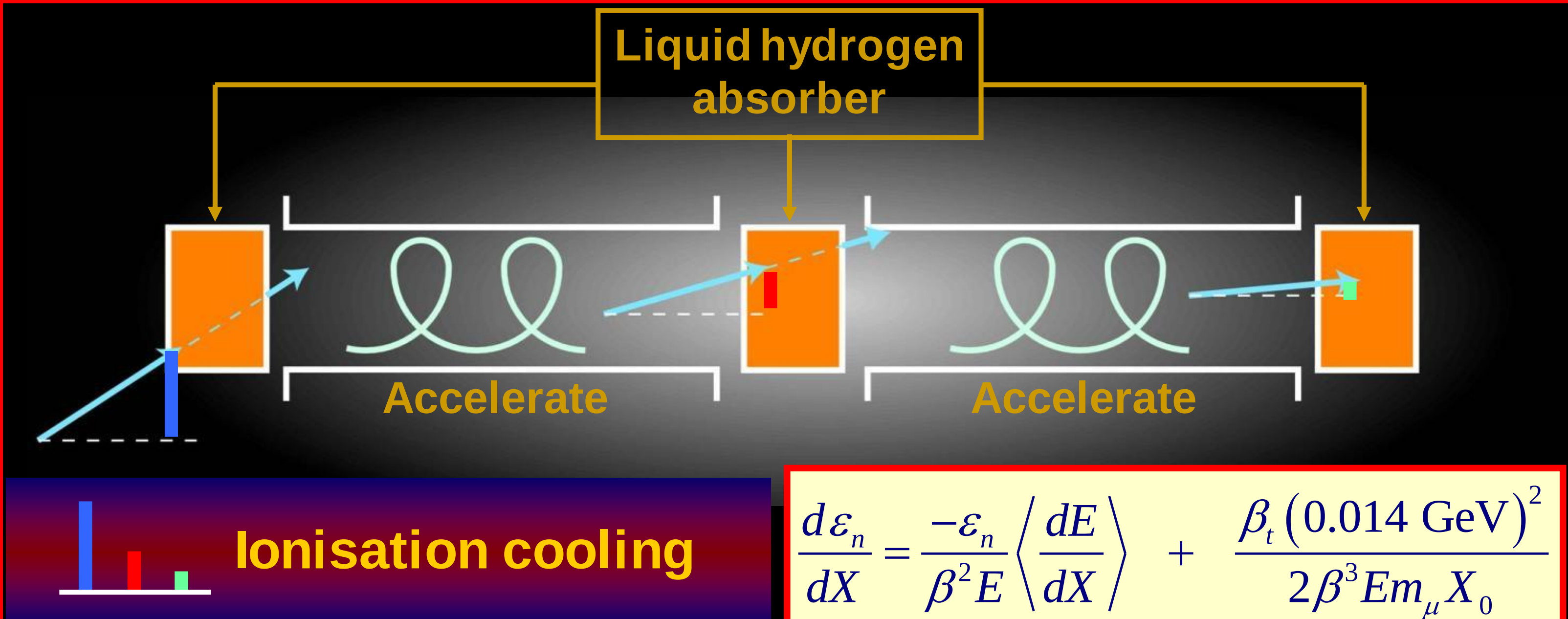
Muon front-end:

- **Optimised bunching, phase-rotator, and ionisation-cooling lattice is reduced**

	Length [m]	Number of cavities	Frequencies [MHz]	Number of frequencies	Peak gradient [MV/m]	Peak power requirements
Buncher	33	37	319.6 to 233.6	13	4 to 7.5	1–3.5 MW/freq.
Rotator	42	56	230.2 to 202.3	15	12	2.5 MW/cavity
Cooler	75	100	201.25	1	15	4 MW/cavity
Total	150 m	193	319.6 to 201.25	29	1000 MV	550 MW

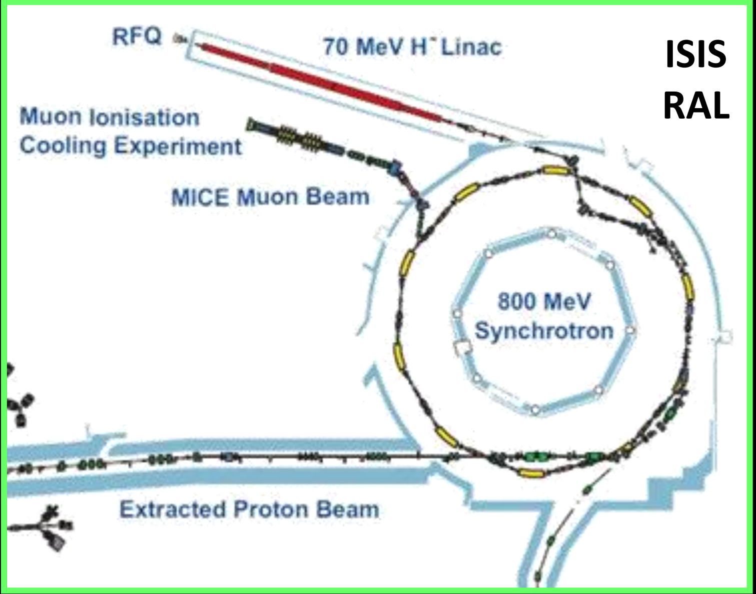
	Length [m]	Inner radius [m]	Radial thickness [m]	Current density [A/mm^2]	Number
Initial transport	0.5	0.68	0.04	47.5	180
Cooling channel	0.15	0.35	0.15	±107	100

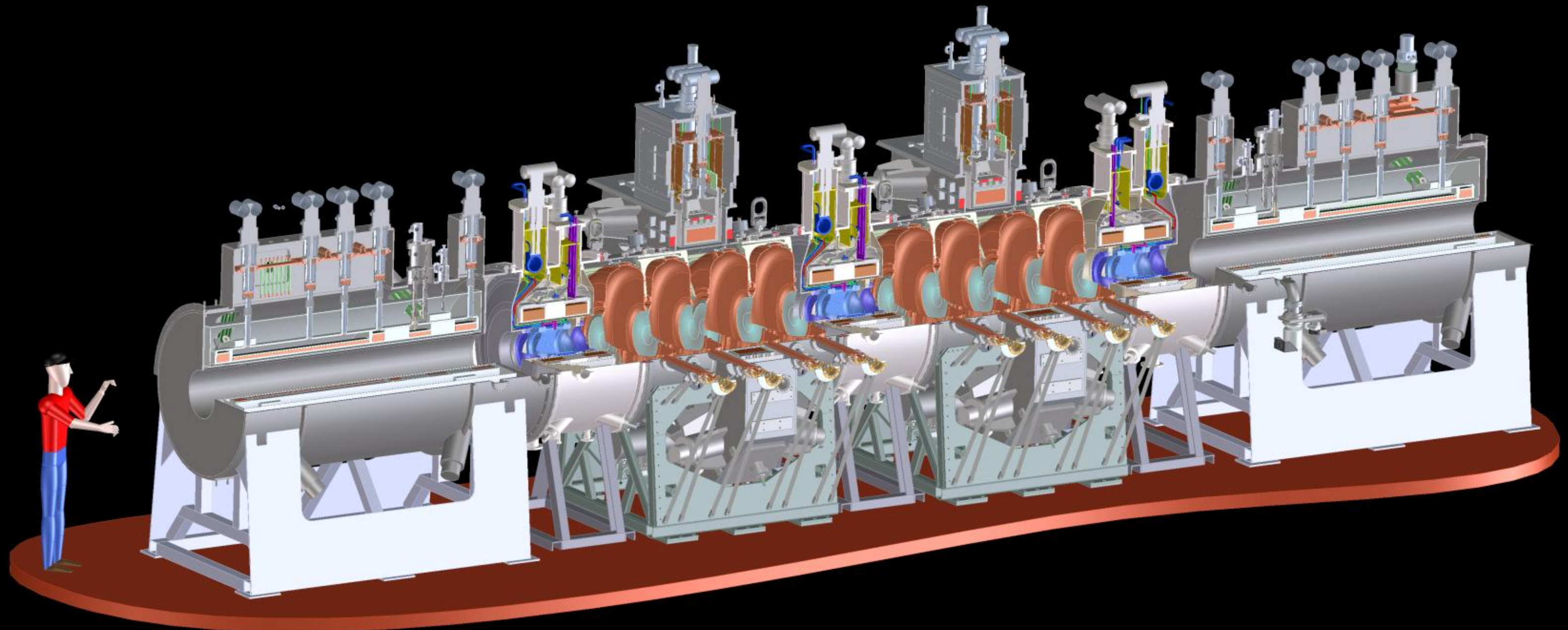




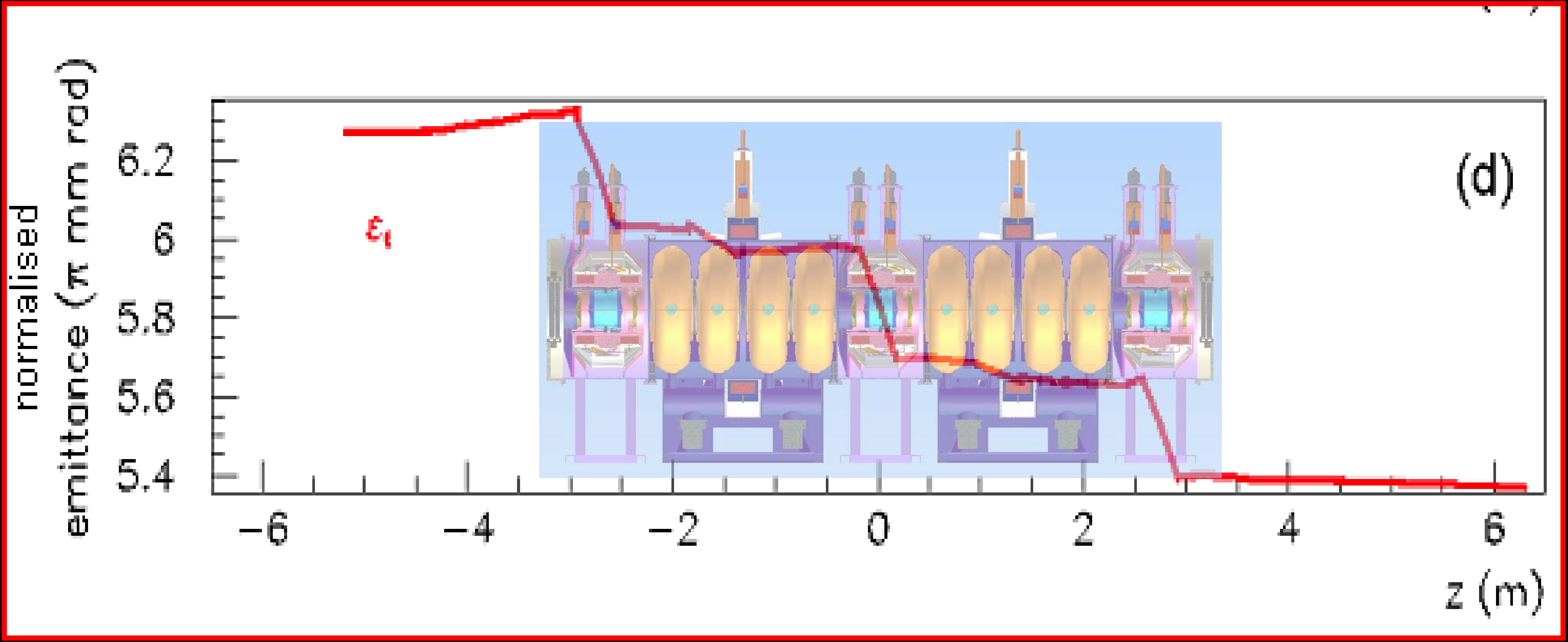
$$\frac{d\varepsilon_n}{dX} = \frac{-\varepsilon_n}{\beta^2 E}\left\langle\frac{dE}{dX}\right\rangle + \frac{\beta_t (0.014\ \mathrm{GeV})^2}{2\beta^3 E m_\mu X_0}$$

- MICE: proof of principle:
  - Design, build, commission and operate a realistic section of cooling channel
  - Measure its performance in a variety of modes of operation and beam conditions
    - Results will allow Neutrino Factory complex to be optimised





Cooling performance:



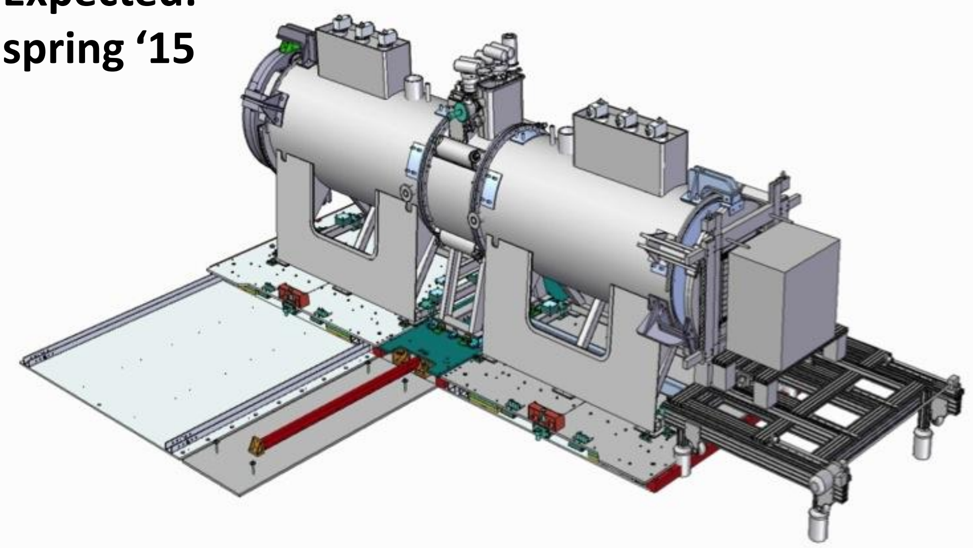
- **15% cooling in MICE channel from 5% *E* loss per absorber**

Particle-by-particle measurement, accumulate ≈ 3×10^5 muons
$\Rightarrow \Delta[\,(\varepsilon^{in} - \varepsilon^{out})/\varepsilon^{in}\,] = 10^{-3}$

MICE:



Expected: spring '15



Sub-system	Responsibility
Spectrometer solenoid #1	US
Spectrometer solenoid #2	US
Fibre tracker #1 + #2	Japan, UK, US
Focus coil #1	UK
LH_2 system A	UK
Lithium hydride	US
LH2 absorber	Japan
Diffuser	UK
Virostek plate & TOF cage assy	UK, US
Substation upgrade	UK
EMR	Geneva
(Radiation shutter	*UK)*
AFC Moving platform #1	UK
SS platforms Installation	UK
Partial Return Yoke	UK, US

- **Future programme:**
  - Step IV:
    - Construction now through March 2015
    - Running Spring 2015 for at least one year
  - Step VI: complete cooling cell:
    - Now!
      - R&D and risk management
      - Component construction
    - At end of Step IV running:
      - Complete component construction
      - Integration in MICE Hall

Neutrinos from stored muon beams:

Sterile neutrinos

What we need to measure:

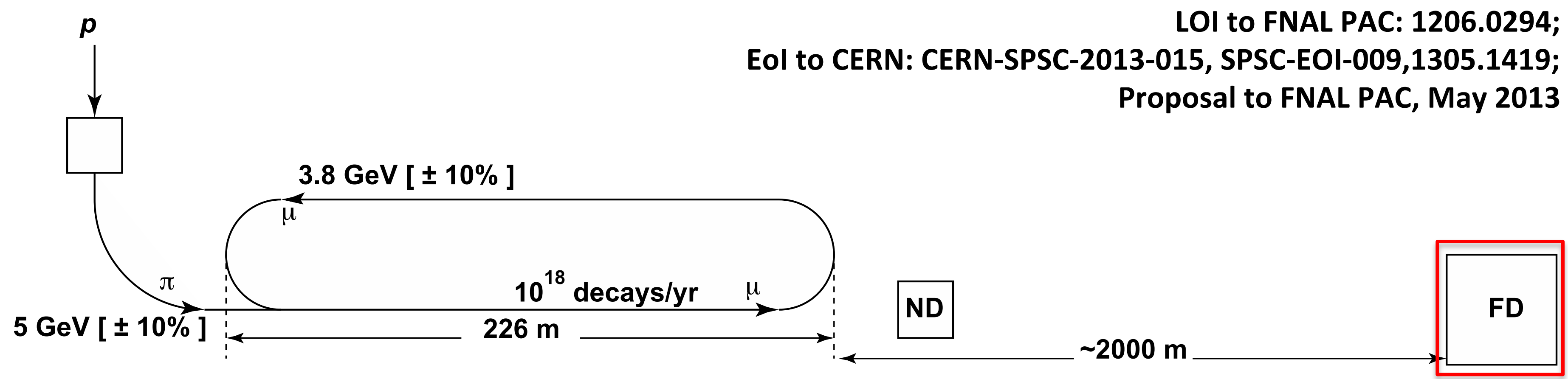
- Present, inconclusive, information from $\nu_e \rightarrow \swarrow_X$ and $\nu_\mu \rightarrow \swarrow_X$ transitions
- Ideally, study:

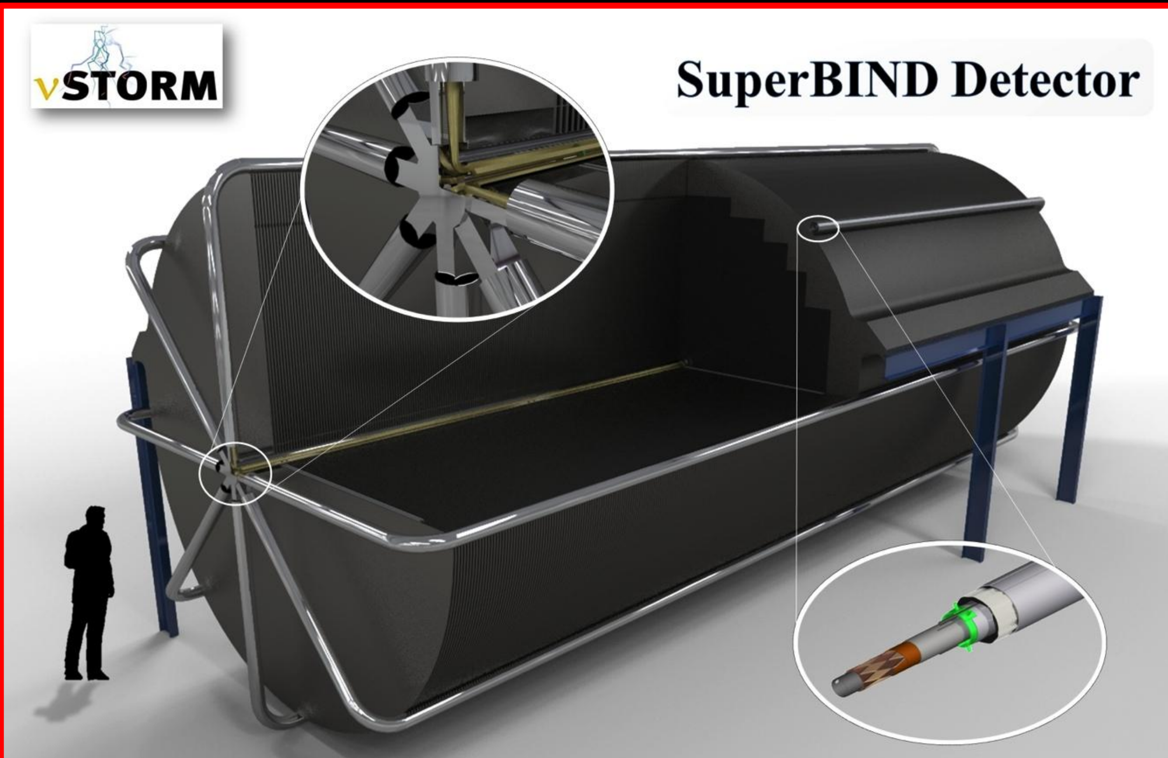
Flavor Transition	CPT Conjugate
$\nu_e \rightarrow \nu_\mu$	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
$\bar{\nu}_e \rightarrow \bar{\nu}_\mu$	$\nu_\mu \rightarrow \nu_e$
$\nu_e \rightarrow \nu_{\not{e}}$	$\bar{\nu}_e \rightarrow \bar{\nu}_{\not{e}}$
$\nu_\mu \rightarrow \nu_{\not{\mu}}$	$\bar{\nu}_\mu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

and

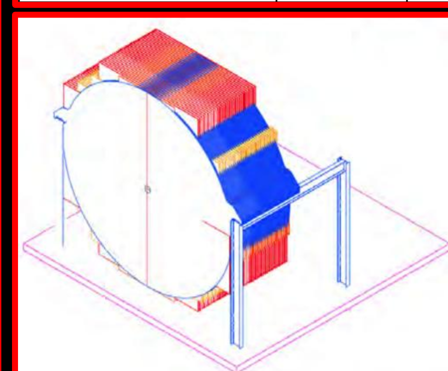
- Determine neutral current rate
  - oscillation to steriles will change neutral current rate
- Study $\nu_e N$ and $\nu_\mu N$ scattering
  - including hadronic final states to eliminate background uncertainties

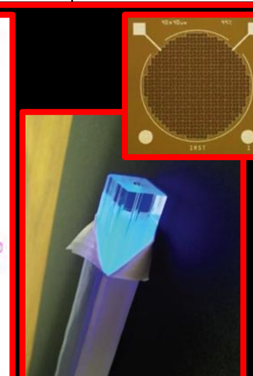
Sterile neutrino search concept:



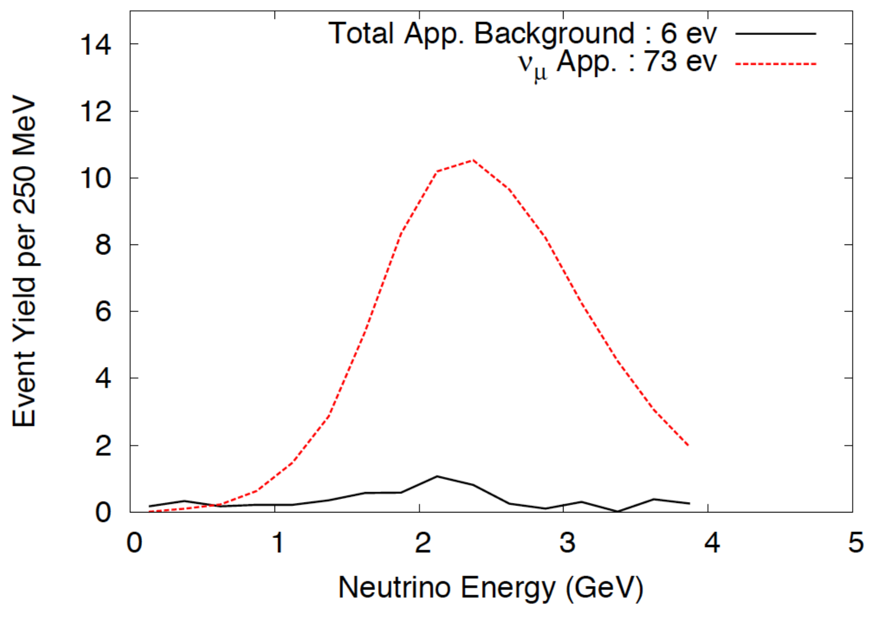


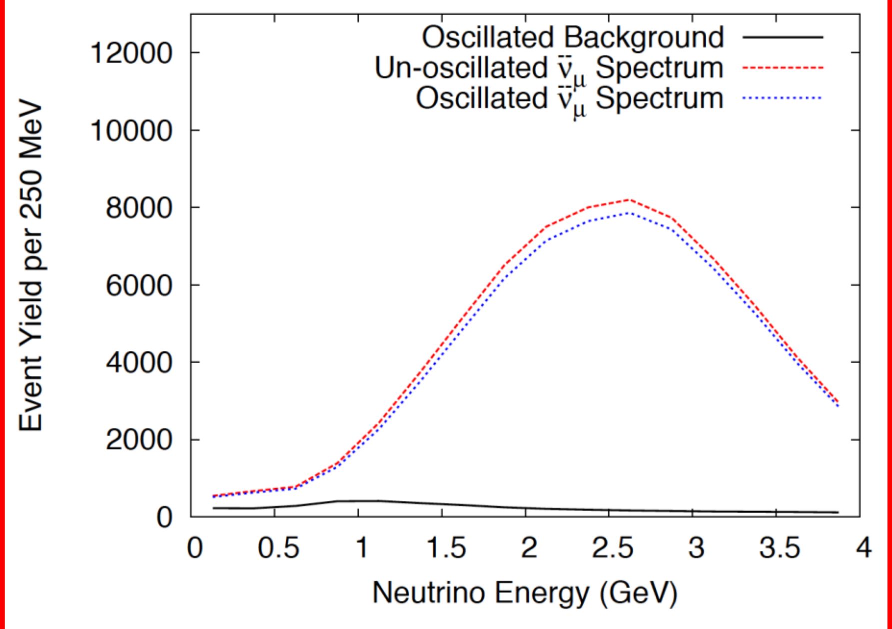
SuperBIND parameters			
Geometry:			
Circular Fe plate:	Diameter:	600.0	cm
	Thickness:	1.5	cm
Scintillator:			
Extruded rectangular bar:	Cross section:	0.75 x 2	cm^2
	Material:	Polystyrene	
	Dopants:		
	POP:	1.00	% by weight
	POPOP:	0.03	% by weight
	Coating:	15	% TiO_2 in polystyrene
Photo-detector:	SiPM		
Magnetisation:			
Toroidal field:	Stength:	2	T

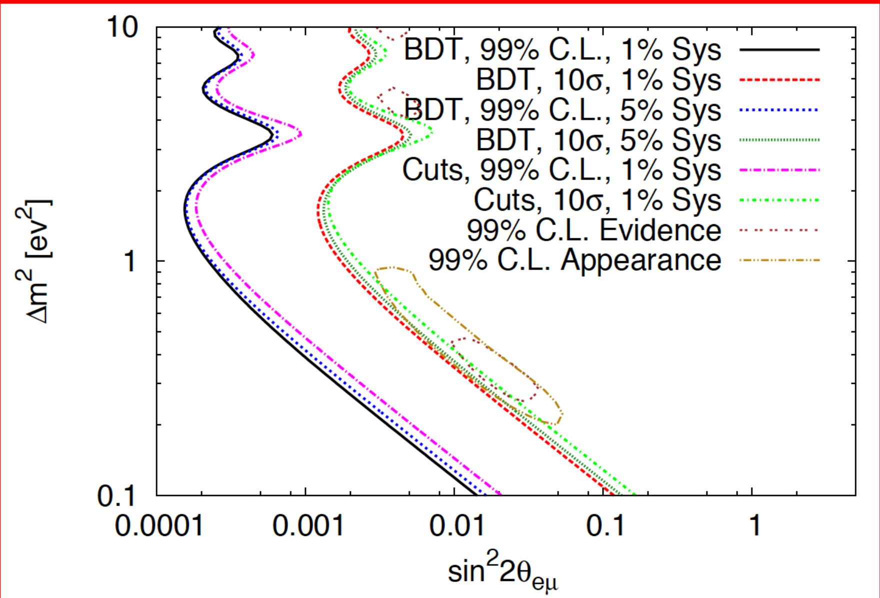


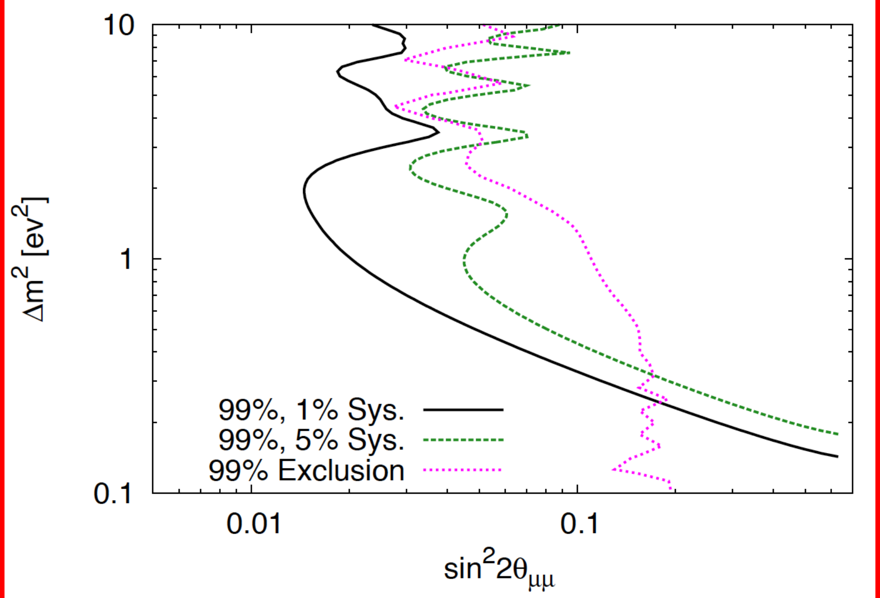


Sterile-neutrino search sensitivity:







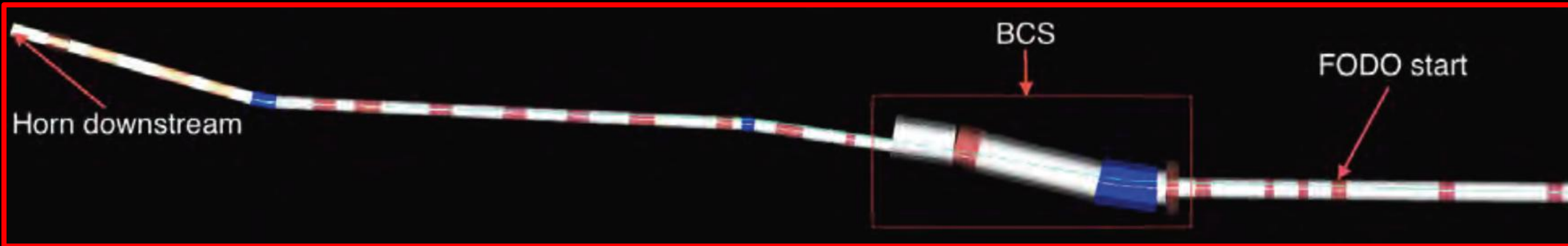


νSTORM

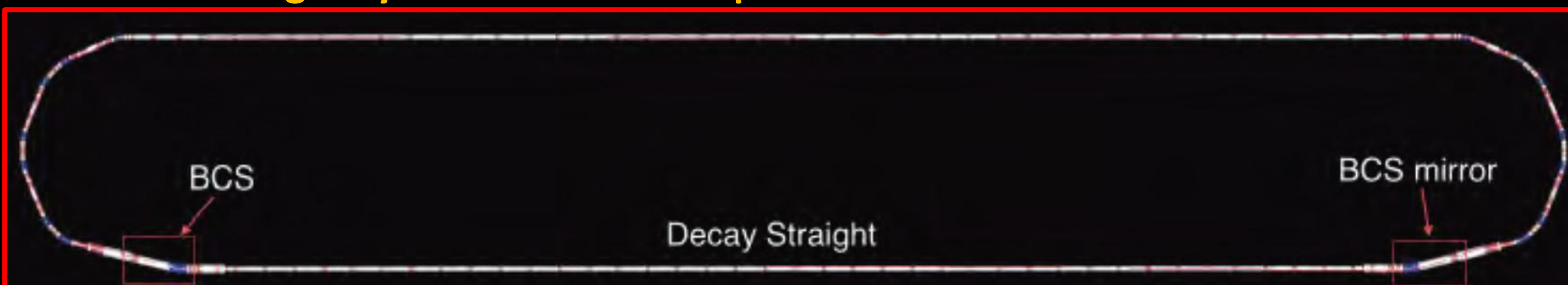
Neutrinos from stored muon beams:

nuSTORM

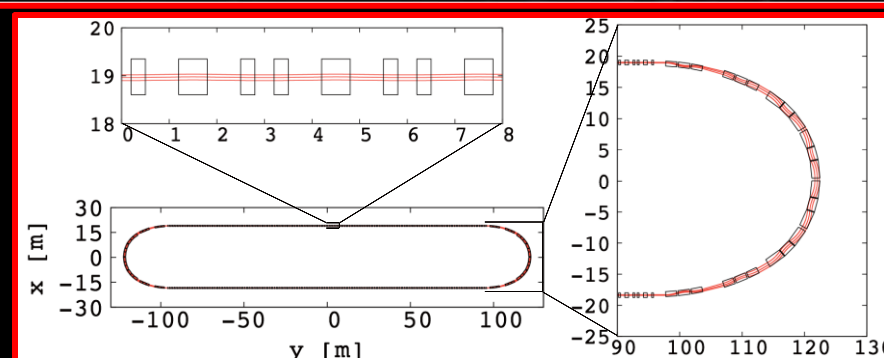
π injection and decay ring:



- Beam Combination Section (BCS) designed to deliver π-beam at start of straight
- Large aperture quad-focusing ring adopted as baseline
  - FFAG ring may be an attractive option



Parameter	FODO	FFAG with normal conducting arcs	FFAG with SC arcs
$L_{Straight}$ (m)	185	240	192
Circumference [m]	480	706	527
Dynamical acceptance A_{dyn}	0.6	0.95	0.95
Momentum acceptance	±10%	±16%	±16%
μ/POT within momentum acceptance	0.094	0.171	0.171
Fraction of μ decaying in the straight (F_S)	0.52	0.57	0.54
Ratio of $L_{Straight}$ to the ring Circ. (R)	0.39	0.34	0.36
Relative factor (A_{dyn} × μ/POT × F_S × R)	0.011	0.031	0.033



Implementation, at FNAL:

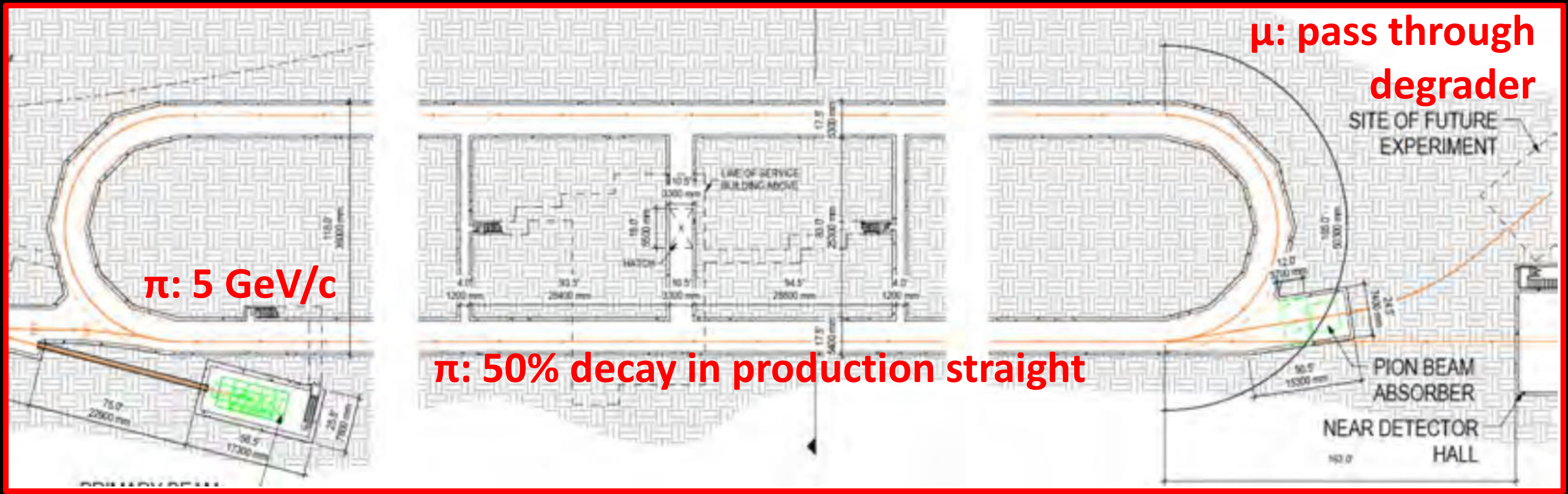
- Benefits from existing extraction tunnel;
- Ideal baseline from storage ring to D0 assembly building:
  - Space and infrastructure for SuperBIND and LAr detector;
- Space and access for near detector

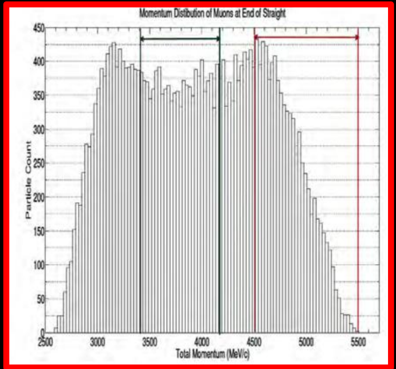
Implementation, at CERN:

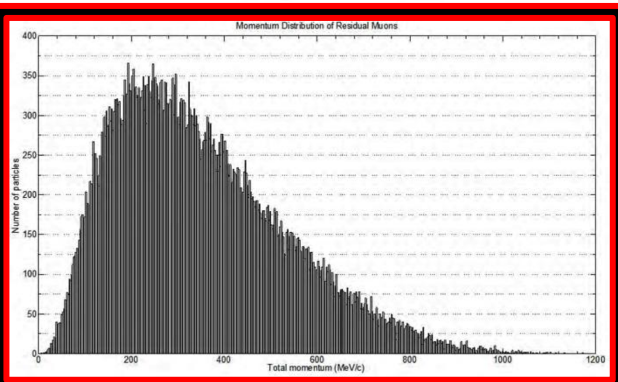
- **Principal issue:**
  - SPS spill is 10 μs:
    - Implies bend for proton or pion beam
- **Two options:**
  - NA implementation:
    - Possible exploitation of synergies with ICARUS/NESSiE
  - NA-to-WA implementation:
    - Advantage is proton/pion bend not required;
    - Longer baseline must be tuned to larger muon energy (possible)
- **Consideration just starting:**
  - EoI to include request to develop concept

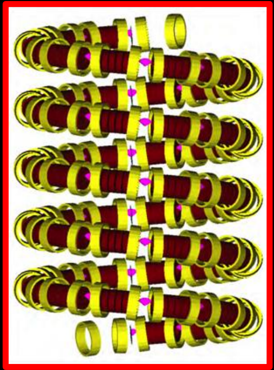
6D ionization cooling experiment:

- Reduction of 6D phase space of muon beam essential for future Muon Collider
  - MICE will provide proof of the ionization-cooling principle in 4D using a single-particle technique
- nuSTORM will provide the pulsed, high-flux muon beam required for the development of ionization cooling



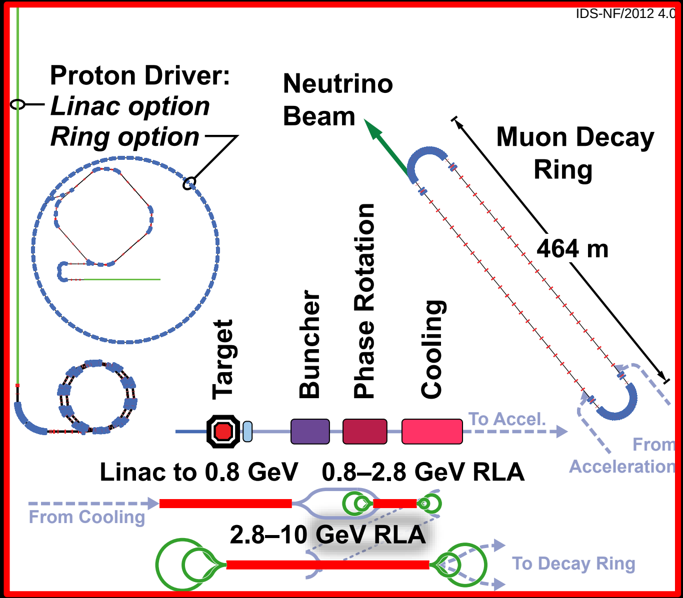


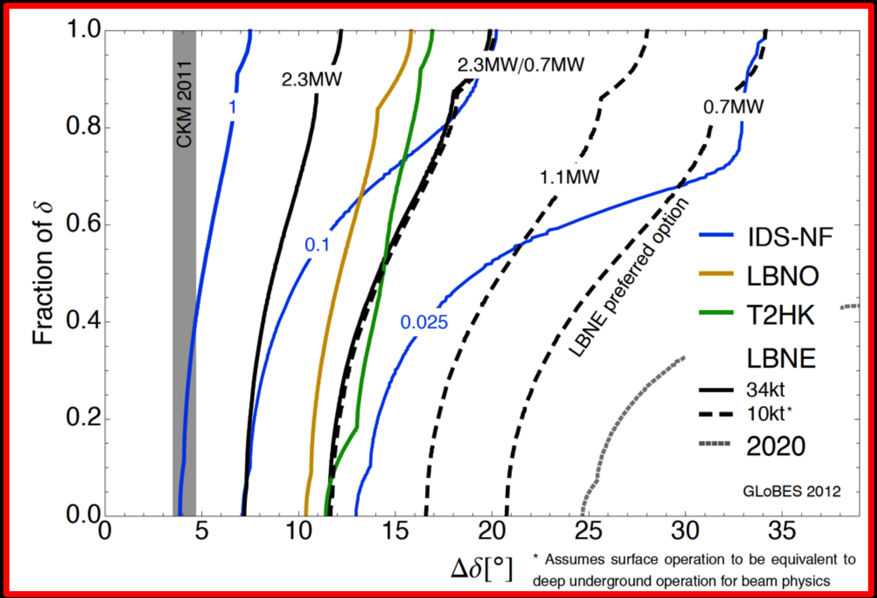




nuSTORM and muon accelerators for PP:

- Muon accelerators have the potential to:
  - Make definitive measurements of neutrino oscillations at the Neutrino Factory;
  - Provide multi-TeV lepton-antilepton collisions at the Muon Collider
- Incremental development of the Neutrino Factory programme offers exquisite sensitivity and precision:





- nuSTORM is the essential first step in the incremental progamme:
  - Can be implemented “today” using known technologies
    - For the accelerator and the detectors
  - Capable of delivering a first-rate neutrino-physics programme *and* the R&D required to prepare the subsequent step

Neutrinos from stored muon beams:

Conclusions

Conclusions [1]:

- The study of the neutrino is the study of physics beyond the Standard Model:
  - Possibly a window on extremely large mass scale
- Exciting new data; exciting opportunities:
  - Measurement of θ_{13} emphasises:
    - Discovery sensitivity for:
      - CP-invariance violation;
      - Mass hierarchy;
    - Precision measurement of neutrino oscillations
  - Sterile neutrinos situation unclear:
    - Confirmation, or discovery of sterile state, would revolutionize our field

Conclusions [2]:

- New data, new Design Studies, new accelerator R&D allow definition of powerful incremental programme encompassing:
  - Conventional super-beam experiment(s):
    - Determination of mass hierarchy;
    - Initial scan of δ_{CP} space;
      - Critical contribution: ν_e cross section measurements from nuSTORM
  - Development of the Neutrino Factory:
    - Unique; meeting the sensitivity and precision goals;
    - Mature; key issues addressed, or being addressed;
    - Incremental approach to full Neutrino Factory conceivable;
    - nuSTORM achievable, early first step that is essential for the LBL programme to meet its precision and sensitivity goals
  - Programme of sterile neutrino searches:
    - Development of existing sterile-neutrino search programme;
    - nuSTORM offers a qualitatively new technique that can address each of the channels of interest

All together a wonderful programme!

Thank you