Beyond DUNE and Hyper-Kamiokande: neutrino facilities from muon decay

Seminar, Kyoto University

29 November 2018

Paul Soler
University of Glasgow

University of Glasgow

- Nijo Castle: 1626

- University of Glasgow: 1451

4th oldest English-speaking university

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1. Physics Motivation

Neutrino mixing

- Weak eigenstates and mass eigenstates different: Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix

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

$$where\ c_{ij} = \cos\theta_{ij},\ and\ s_{ij} = \sin\theta_{ij}$$

- Three mixing angles and one CP violating phase

$$U_{PMNS} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i}|\nu_i\rangle \text{ where } \alpha = e,\mu,\tau \text{ and } i = 1,2,3$$

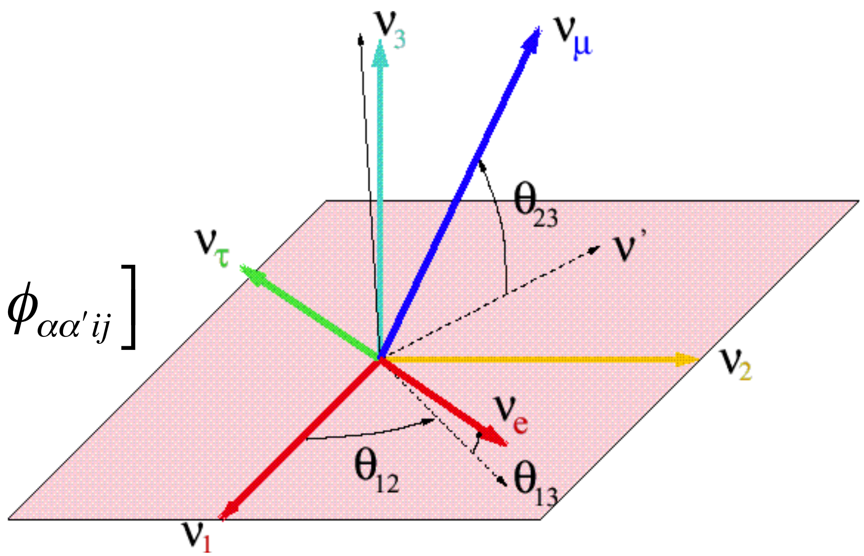
Neutrino oscillations

- Three rotations in weak and mass eigenstate space

$$|\nu_\alpha(t)\rangle = e^{i\vec{p}\cdot\vec{r}} \sum_i e^{-iE_i t} U_{\alpha i} |\nu_i\rangle$$

$$P_{\nu_\alpha \to \nu_{\alpha'}}(t) = \left|\langle \nu_{\alpha'} | \nu_\alpha(t)\rangle\right|^2 =$$

$$\sum_{i,j} \left|U_{\alpha i} U^*_{\alpha' i} U^*_{\alpha j} U_{\alpha' j}\right| \cos\left[(E_i - E_j)t - \phi_{\alpha\alpha' ij}\right]$$



$$P_{\nu_e \nu_\mu (\bar{\nu}_e \bar{\nu}_\mu)}(x) = s_{23}^2 \sin^2 2\theta_{13} \sin^2\left[\frac{\Delta m_{13}^2}{4E} x\right] + c_{23}^2 \sin^2 2\theta_{12} \sin^2\left[\frac{\Delta m_{12}^2}{4E} x\right] +$$

$$+\tilde{J} \cos\left[\pm\delta - \frac{\Delta m_{13}^2}{4E} x\right]\left(\frac{\Delta m_{12}^2}{4E} x\right) \sin\left[\frac{\Delta m_{13}^2}{4E} x\right] \quad \text{with } \tilde{J} \equiv c_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13}$$

Includes CP violation: neutrino/antineutrino oscillation difference if δ≠0

Neutrino oscillations in matter

- Resonant neutrino oscillation in matter: MSW effect
  - Discriminates between normal and inverted mass hierarchy

$$P_{\nu_e\nu_\mu(\bar{\nu}_e\bar{\nu}_\mu)}(x) = P_1 + P_2 + P_3 + P_4$$

$$P_1 = s_{23}^2 \sin^2 2\theta_{13} \left(\frac{\Delta_{13}}{B_\mp}\right)^2 \sin^2\left[\frac{B_\mp}{2}x\right]$$

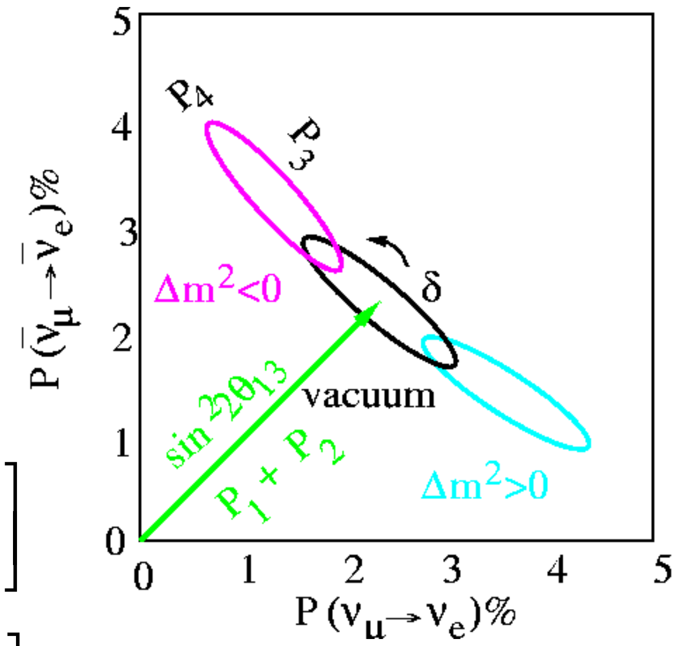
$$P_2 = c_{23}^2 \sin^2 2\theta_{12} \left(\frac{\Delta_{12}}{A}\right)^2 \sin^2\left[\frac{A}{2}x\right]$$

$$P_3 = \tilde{J}\cos\delta\cos\left[\frac{\Delta_{13}}{2}x\right]\left(\frac{\Delta_{12}}{A}\frac{\Delta_{13}}{B_\mp}\right)\sin\left[\frac{A}{2}x\right]\sin\left[\frac{B_\mp}{2}x\right]$$

$$P_4 = \pm\tilde{J}\sin\delta\sin\left[\frac{\Delta_{13}}{2}x\right]\left(\frac{\Delta_{12}}{A}\frac{\Delta_{13}}{B_\mp}\right)\sin\left[\frac{A}{2}x\right]\sin\left[\frac{B_\mp}{2}x\right]$$

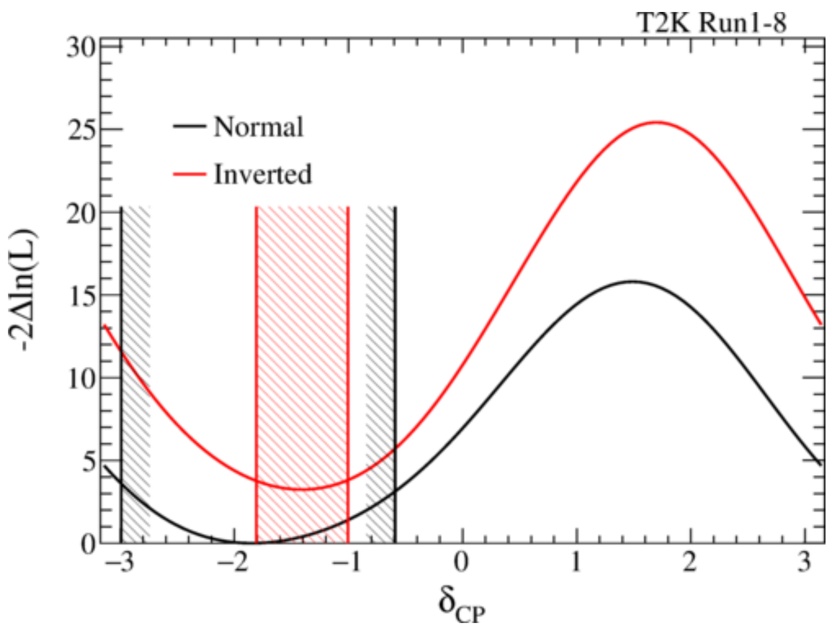
$$\Delta_{ij} \equiv \frac{\Delta m_{ij}^2}{2E} \qquad A \equiv \sqrt{2}G_F n_e \qquad \tilde{J} \equiv c_{13}\sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13}$$

with $B_\mp \equiv \sqrt{(\Delta_{13}\cos 2\theta_{13} \mp A)^2 + \Delta_{13}^2 \sin^2 2\theta_{13}} \approx |\Delta_{13} \mp A|$

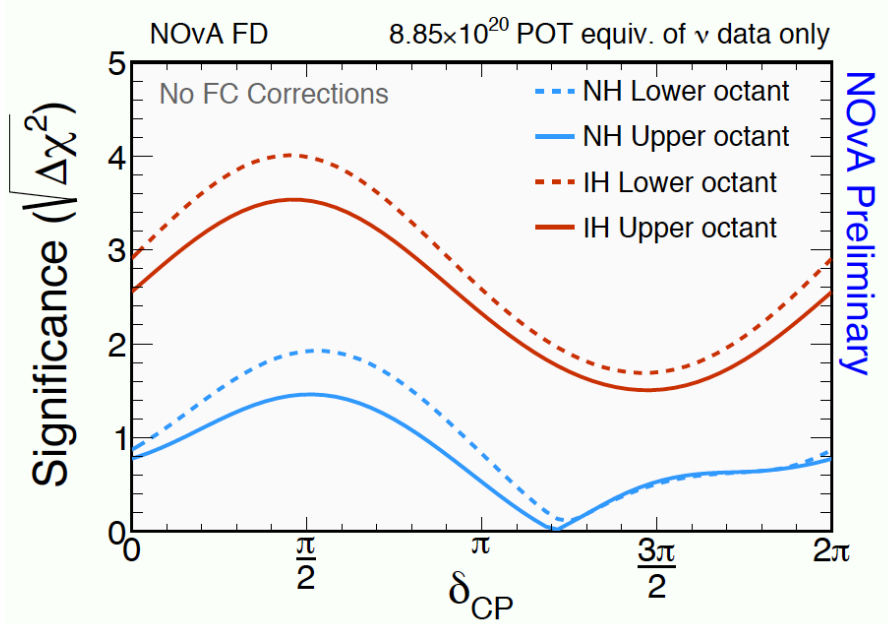


Next generation long-baseline experiments

- Main physics goals of long-baseline neutrino experiments are to observe CP violation in neutrinos and to determine neutrino mass ordering
- Both T2K and NOvA are exhibiting hints of CP violation in the neutrino sector at ~2σ level



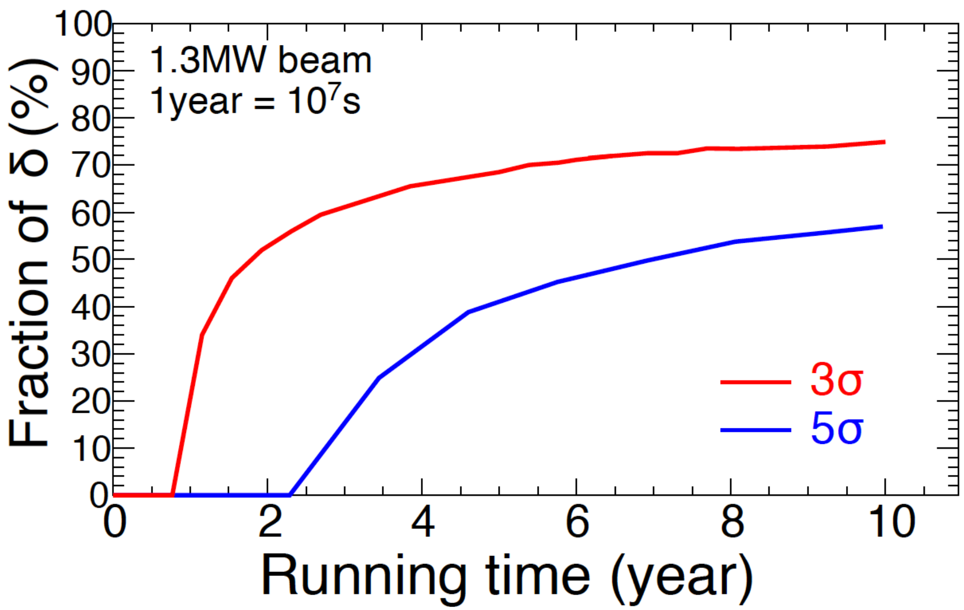
PRL, 121, 171802 (2018)

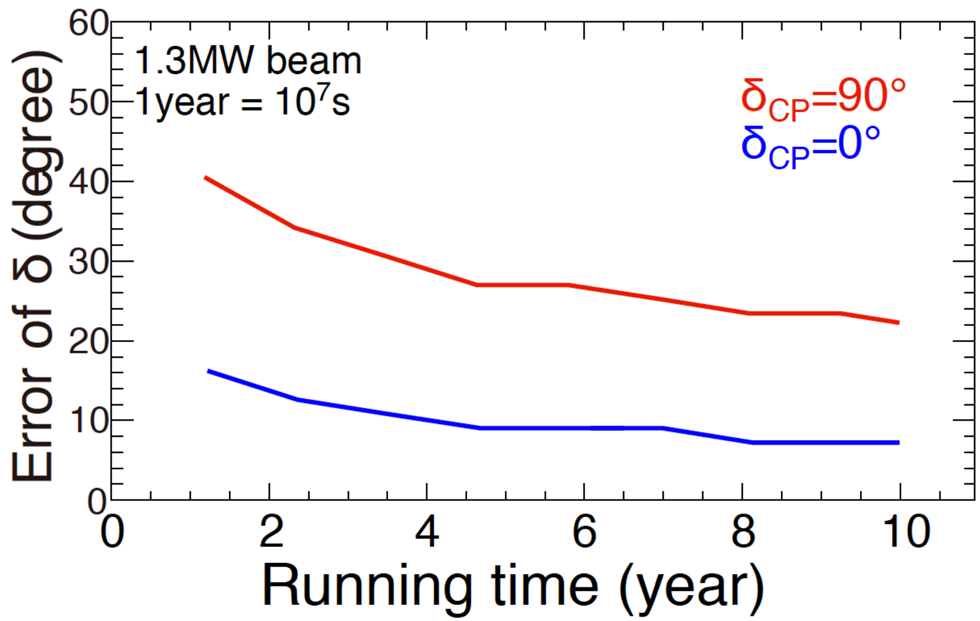


Neutrino 2018

Next generation long-baseline experiments

- Require next generation experiments for 5σ results
- Hyper-K Design Report: arXiv:1805.04163
  - CP-violation accuracy: $\Delta\delta_{CP}$~ 23^{o} after 10 years for δ_{CP}= ±90^{o}

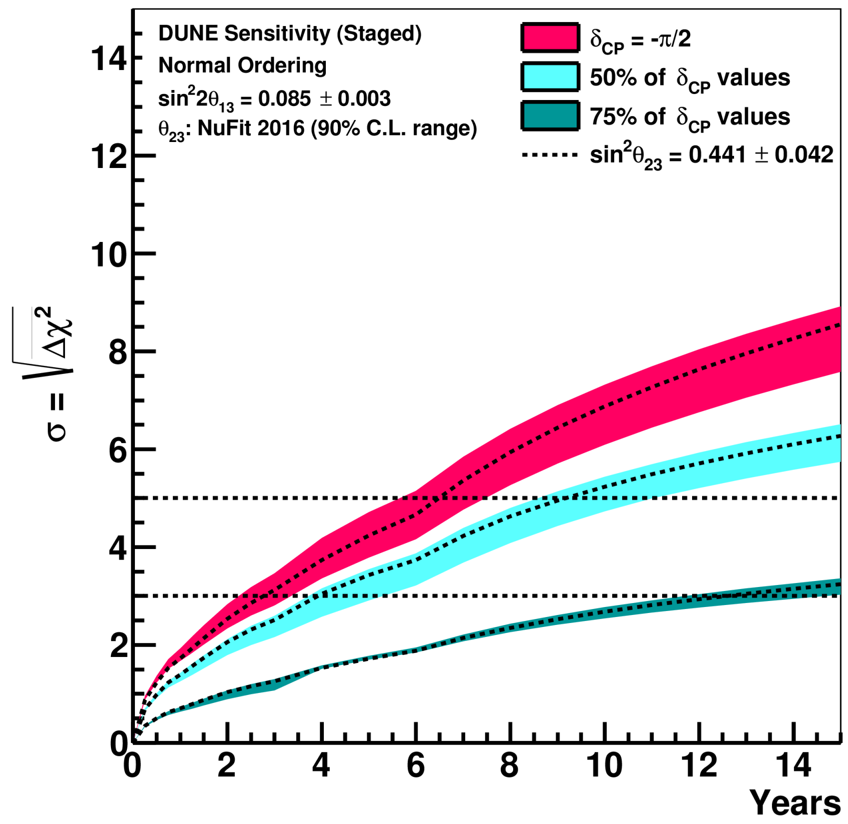




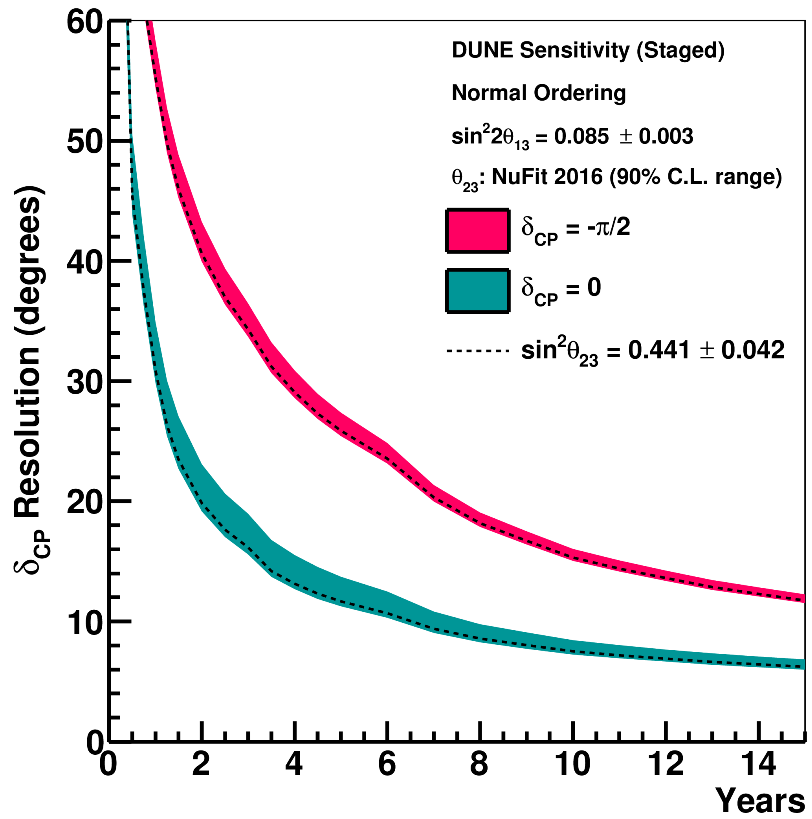
Next generation long-baseline experiments

- Require next generation experiments for 5σ results
- DUNE Interim Design Report: arXiv:1807.10334
  - CP-violation accuracy: $\Delta\delta_{CP}$~ 15^o after 10 years for δ_{CP}= ±90^o

CP Violation Sensitivity



δ_{CP} Resolution



Is discovering CP violation sufficient?

- Is discovering CP violation and determining the mass ordering sufficient or do we need more precision?
- We want to test the Standard Neutrino Model, the three-neutrino paradigm and search for new physics
- Compare PMNS mixing matrix to models:

$$U_{PMNS} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

$$\text{where } c_{ij} = \cos\theta_{ij} \text{ and } s_{ij} = \sin\theta_{ij}$$

$$U_{PMNS} = \begin{pmatrix} \sqrt{2/3} & 1/\sqrt{3} & 0 \\ -1/\sqrt{6} & 1/\sqrt{3} & 1/\sqrt{2} \\ 1/\sqrt{6} & -1/\sqrt{3} & 1/\sqrt{2} \end{pmatrix}$$

$\theta_{12}=\sin^{-1}(1/\sqrt{3})\sim 35.3^{\circ}$, $\theta_{23}=45^{\circ}$, $\theta_{13}=0$, $\delta=0$

Harrison, Perkins, Scott PLB 530 (2002), 167

Tri-bimaximal mixing: suggestive of a broken flavour symmetry

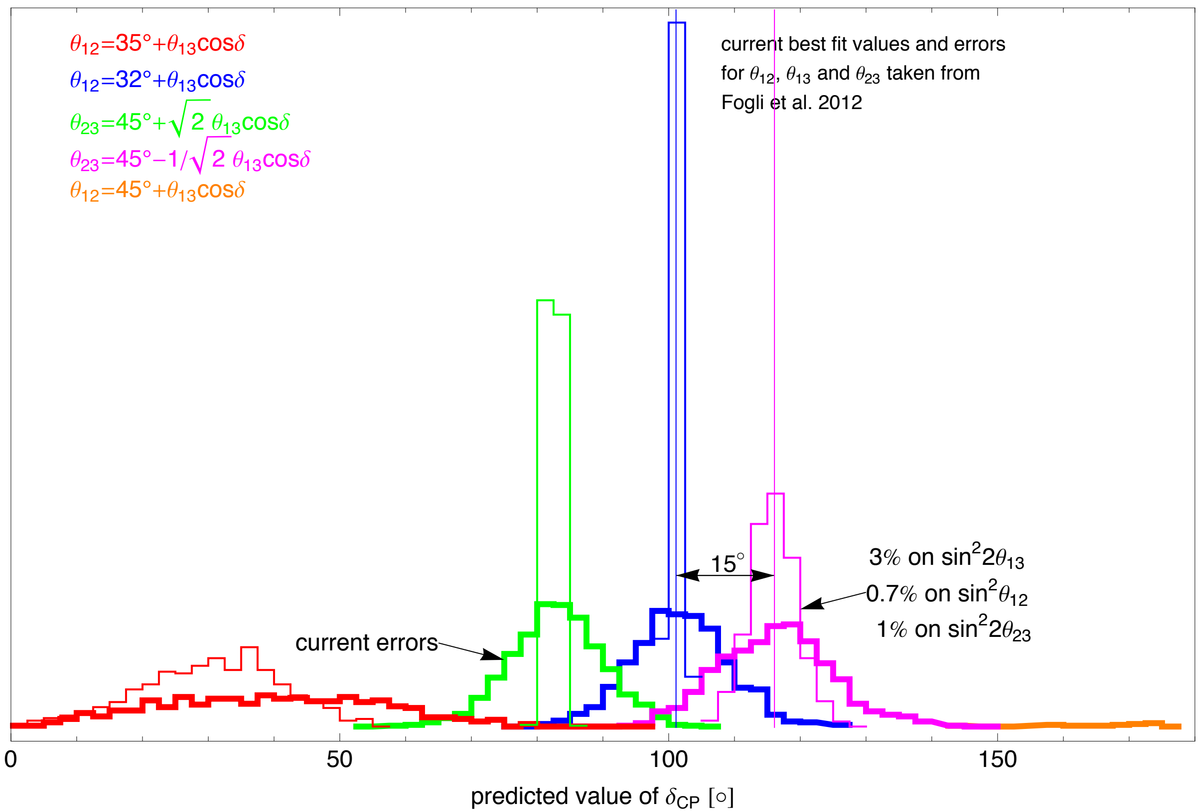
Is discovering CP violation sufficient?

- What precision is required to search for mechanism behind the generation of neutrino masses?
  - In quark sector, precision around 5°
  - Flavour sum rules:

    Accuracy required ~5°

ie. deviation of mixing angles from tri-bimaximal mixing:

$$\theta_{12} - \theta_{13}\cos\delta = \sin^{-1}\left(\frac{1}{\sqrt{3}}\right)$$

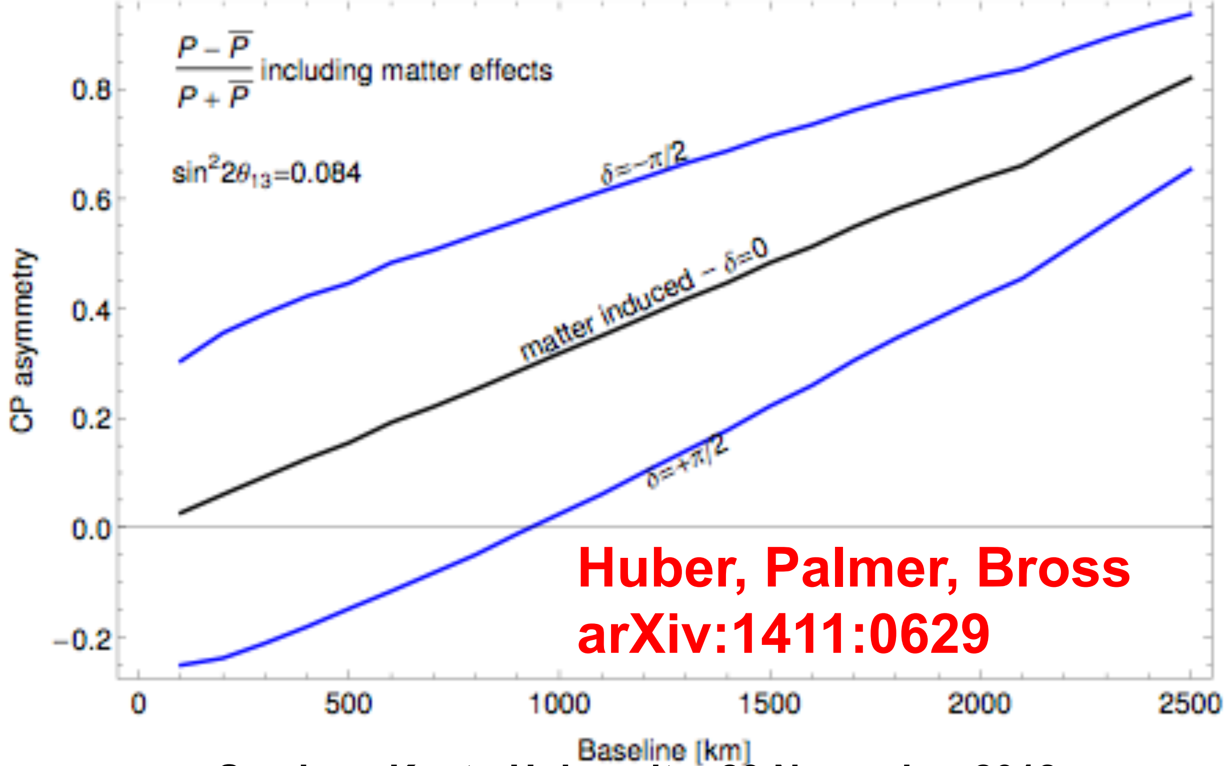


Comprehensive review: King, Luhn, Rep. Prog. Phys. 76 (2013) 056201

Precision of long-baseline experiments

- Precision requirement for CP violation:
  - For 75% of CP asymmetry coverage at 3σ: A_{CP} as low as 5%
  - Requires 1.5% measurement of $P-\overline{P}$ (~1% syst. error), but we measure rate:

$$R_{\alpha\beta}(E_{vis}) = N\int dE\Phi_\alpha(E)\sigma_\beta(E,E_{vis})\varepsilon_\beta(E)P(\nu_\alpha \to \nu_\beta, E)$$



Huber, Palmer, Bross
arXiv:1411:0629

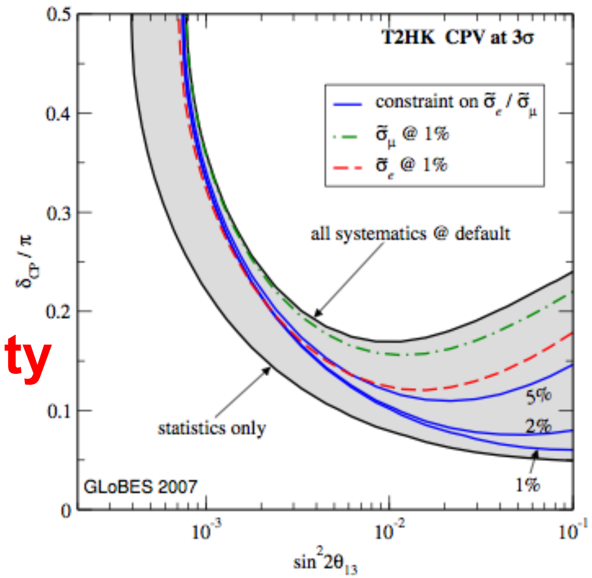
Precision of long-baseline experiments

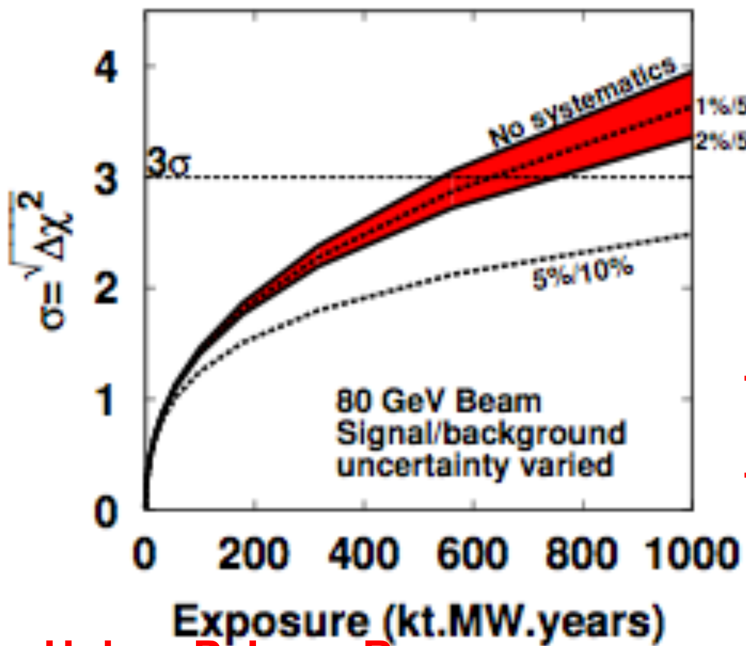
- Precision requirement for CP violation:
  - In disappearance experiment we can satisfy:

$$\frac{R_{\alpha\beta}(far)L^2}{R_{\alpha\beta}(near)} = \frac{N_{far}\Phi_\alpha\sigma_\beta\varepsilon_\beta P(\nu_\alpha \rightarrow \nu_\beta)}{N_{near}\Phi_\alpha\sigma_\alpha\varepsilon_\alpha 1} \quad \alpha = \beta$$

  - In an appearance experiment $\alpha \neq \beta$, so ν_α beam cannot measure $\sigma_\beta\varepsilon_\beta$

Huber, Mezzetto, Schwetz
arXiv:0711.2950





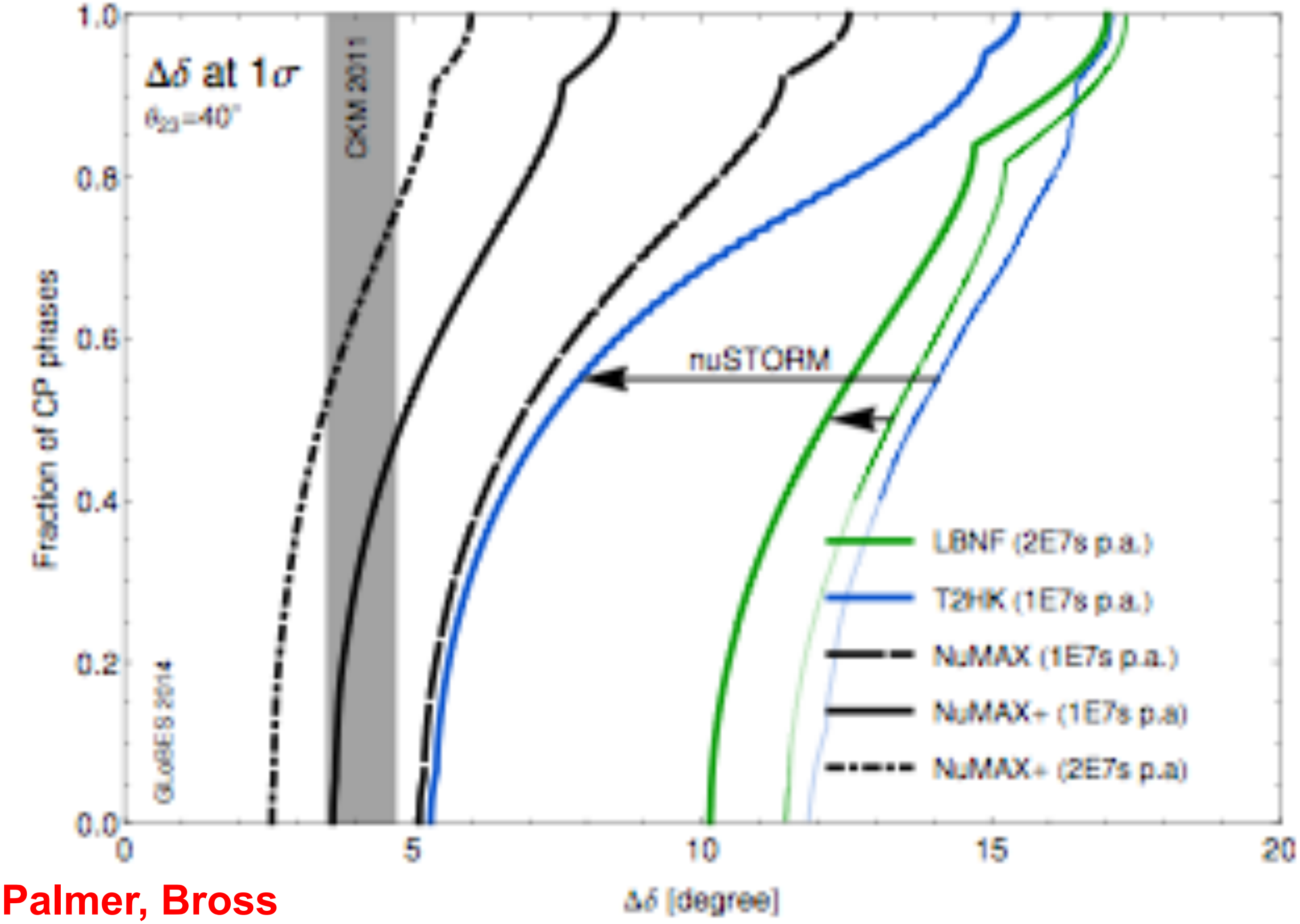
CP violation sensitivity for 75% δ_{CP} coverage at LBNE

- Syst. error on ratio $\sigma_{\nu_e}/\sigma_{\nu_\mu}$ in T2HK
- Difference in σ_{ν_μ} and σ_{ν_e} may be large

Huber, Palmer, Bross
arXiv:1411:0629

Precision of long-baseline experiments

- Influence of measurement of neutrino cross-sections with less than 1% precision (nuSTORM has that capability):



Huber, Palmer, Bross
arXiv:1411:0629

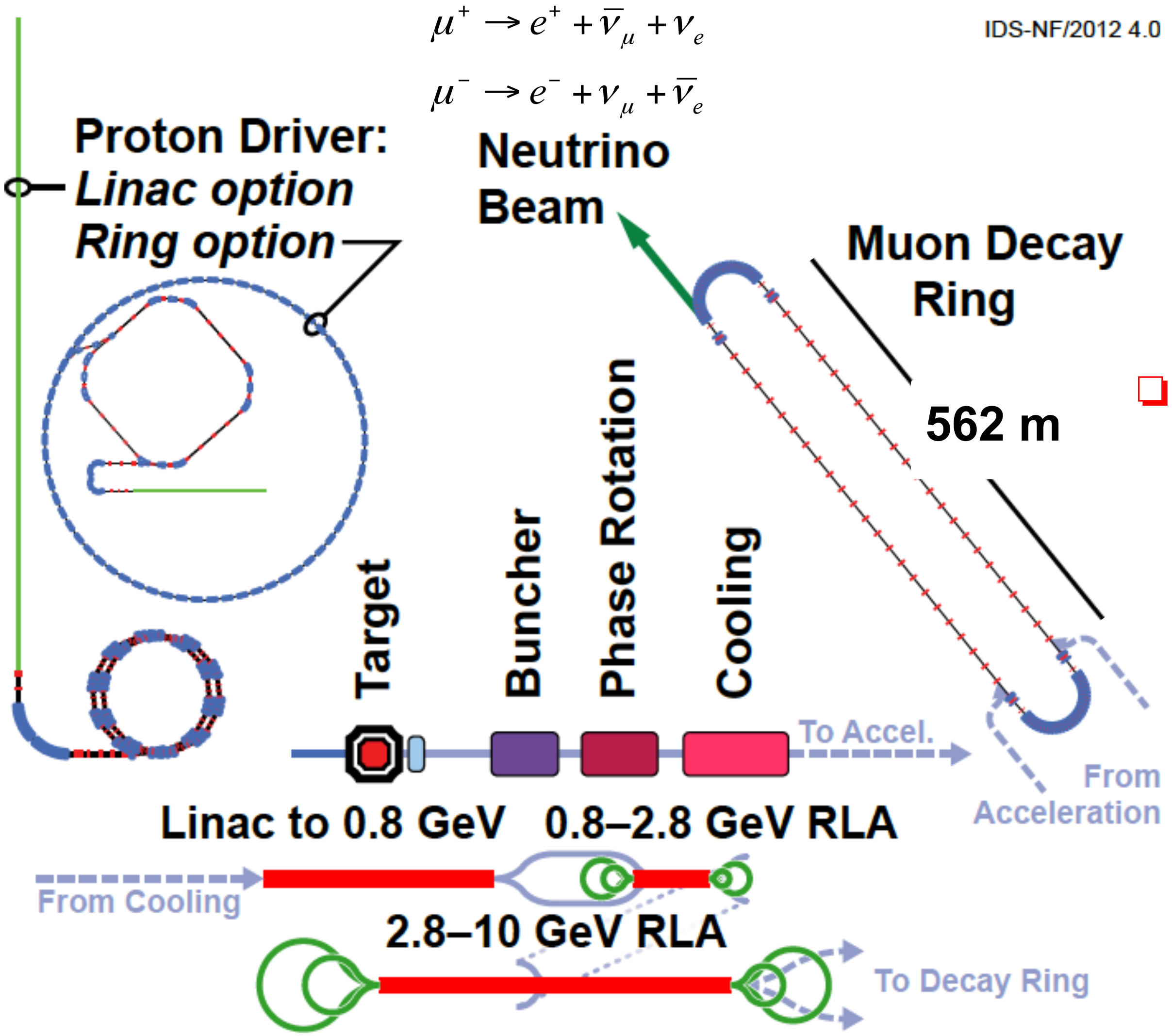
2. Neutrino Factory

Neutrino Factory Studies

- A Neutrino Factory is a neutrino beam facility from muon decay delivering 10^{21} muon decays per year
- Birth of modern Neutrino Factory:
  - S. Geer: Phys Rev D57, 6989 (1998)
- Neutrino Factory studies:
  - CERN study: CERN Yellow Report 99-02 (1999)
  - Feasibility Study I at Fermilab: Fermilab-Pub-00/108-E (2000)
  - Feasibility Study II at Brookhaven: BNL-52623 (2001)
  - Feasibility Study IIa at Brookhaven: BNL-72369 (2004)
  - International Design Study: Interim Design Report 2011 IDS-NF-020 arXiv:1102.2402
  - Muon Accelerator Staging Scenarios: launched by Muon Accelerator Programme (MAP) in USA 2013 (arXiv:1308.0494)

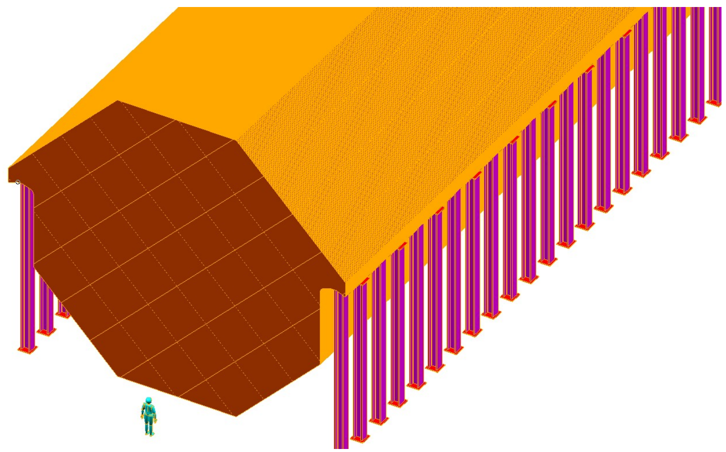
Neutrino Factory Baseline

- International Design Study for a Neutrino Factory (IDS-NF)



Baseline reviewed 2012: from 25 GeV to 10 GeV muons (v4.0), one storage ring with detector at 2000 km, after discovery that θ_{13} is large

- Magnetised Iron Neutrino Detector (MIND):
  - 100 kton at ~2000 km



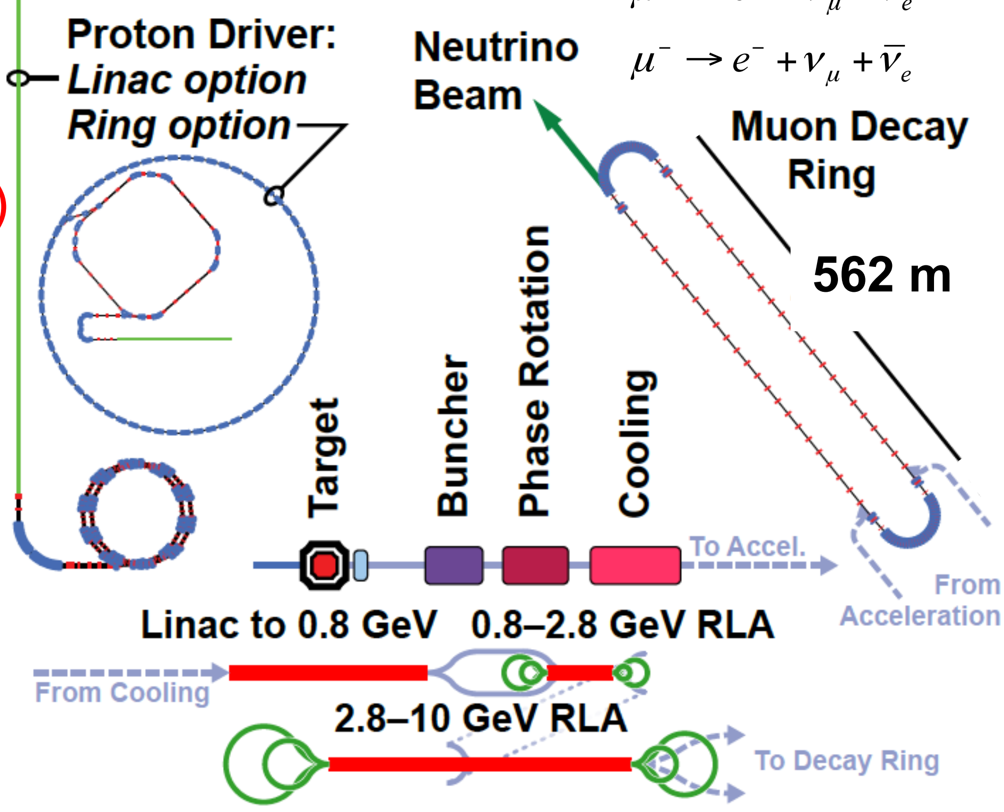
Neutrino Factory Baseline

- Proton driver
  - Proton beam ~8 GeV on target
- Target, capture and decay
  - Create π, decay into μ (MERIT)
- Bunching and phase rotation
  - Reduce ΔE of bunch
- Ionization Cooling
  - Reduce transverse emittance (MICE)
- Acceleration
  - 120 MeV→ 10 GeV with RLAs
  - FFAG option now not favoured
- Decay ring
  - Store for ~100 turns
  - Long straight sections
  - 10^{21} muons/year

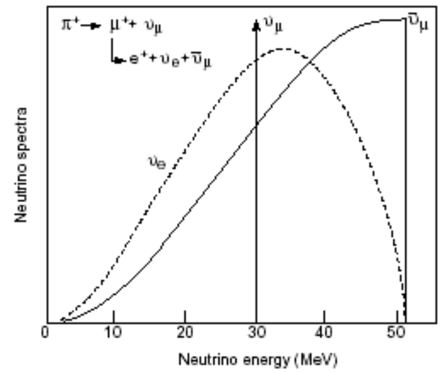
IDS-NF/2012 4.0

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

$$\mu^- \to e^- + \nu_\mu + \bar{\nu}_e$$



Neutrino spectra calculable to high accuracy

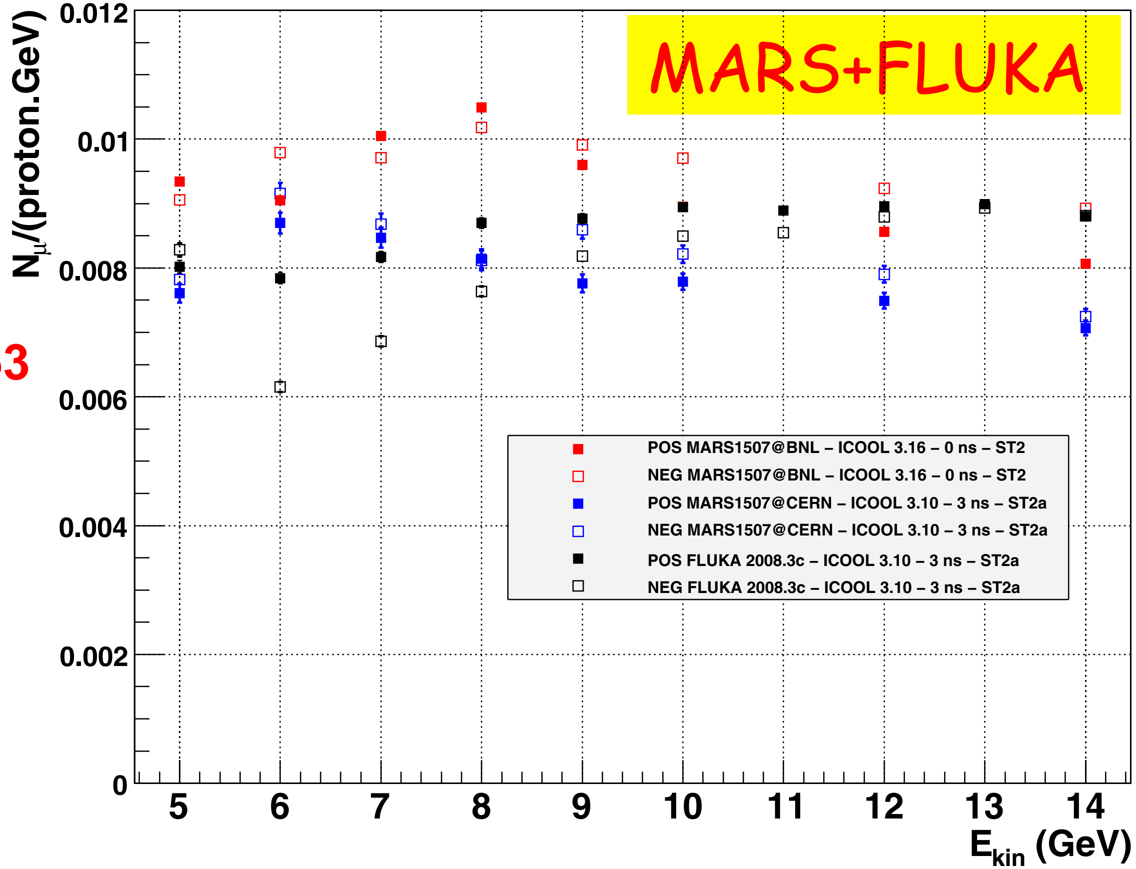


Optimum energy proton driver

- Optimum beam energy
  - Depends on choice of target
  - Optimum energy for high-Z targets around 8 GeV
  - Results validated by HARP hadron production experiment

Adopted 10 ± 5 GeV

arXiv:1112.2853



Proton Driver

- Requirements:

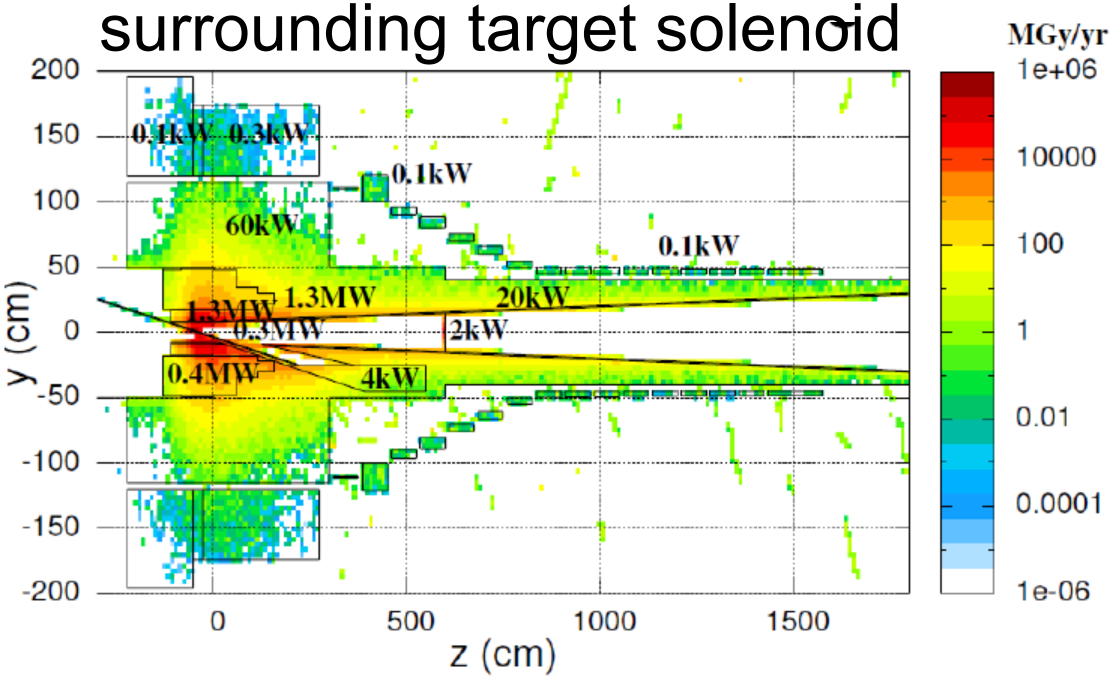
  arXiv:1112.2853

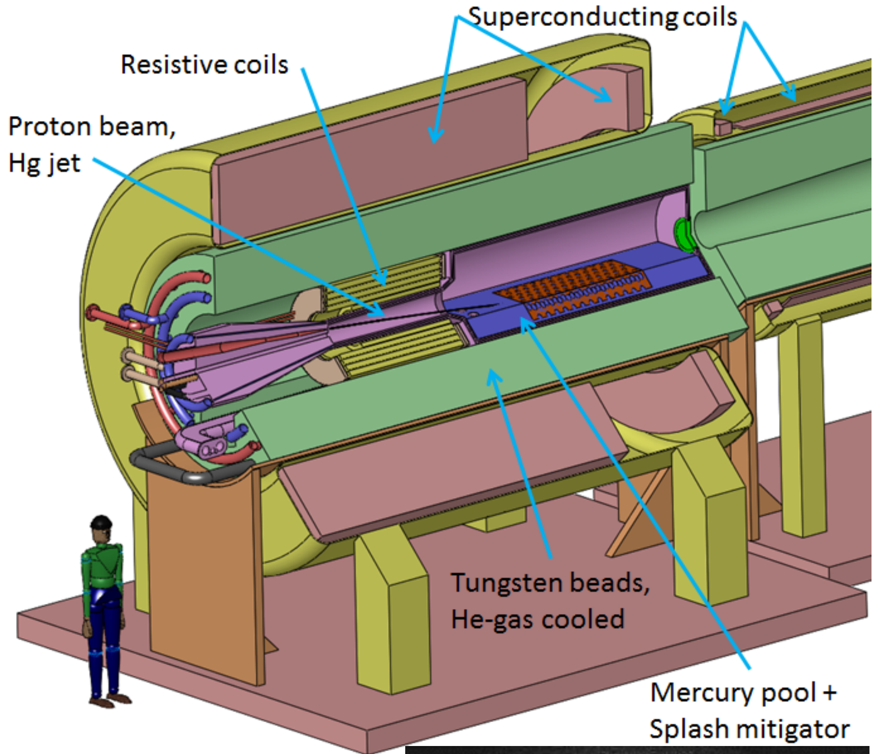
Parameter	**Value**
Kinetic energy	5–15 GeV
Average beam power	4 MW
	(3.125×10^{15} protons/s)
Repetition rate	50 Hz
Bunches per train	3
Total time for bunches	240 μs
Bunch length (rms)	1–3 ns
Beam radius	1.2 mm (rms)
Rms geometric emittance	< 5 μm
β^* at target	≥ 30 cm

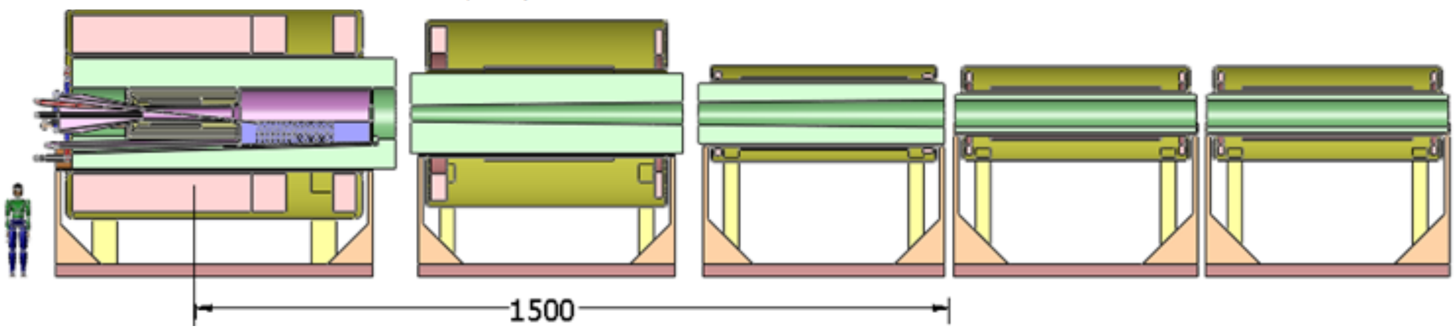
- Choice of proton driver depends on site:
  - LINAC based (SPL) proton driver at CERN
  - Synchrotron(s)/FFAG based proton driver (green field solution) – studied at RAL.
  - PIP-2 LINAC based solution at Fermilab.

Target

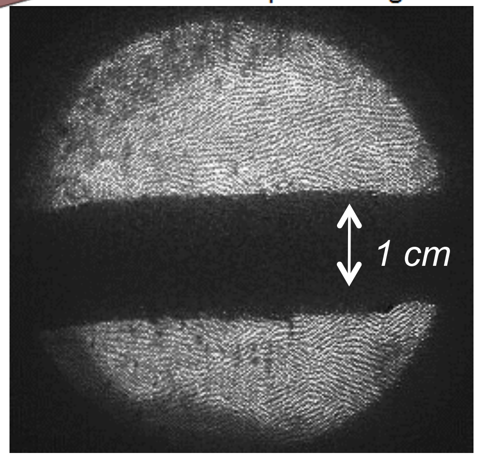
- Liquid Hg target in 20 T solenoid
- Increased radiation shielding in surrounding target solenoid







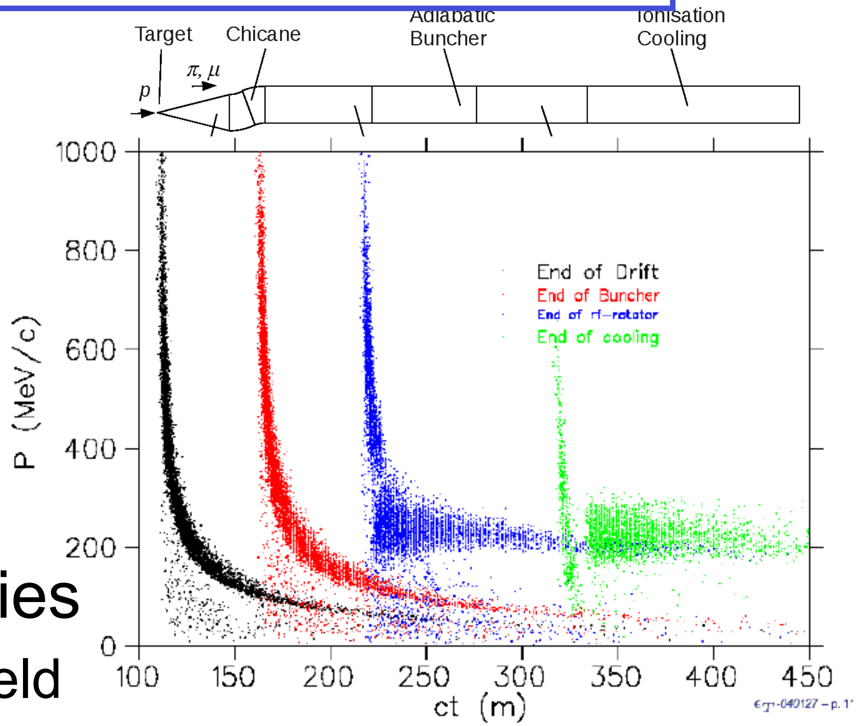
Target station & decay channel

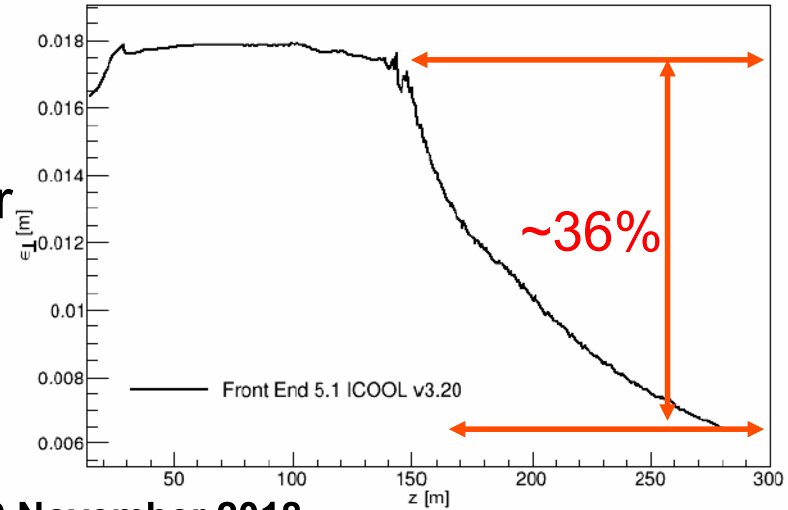


MERIT

Muon Front End

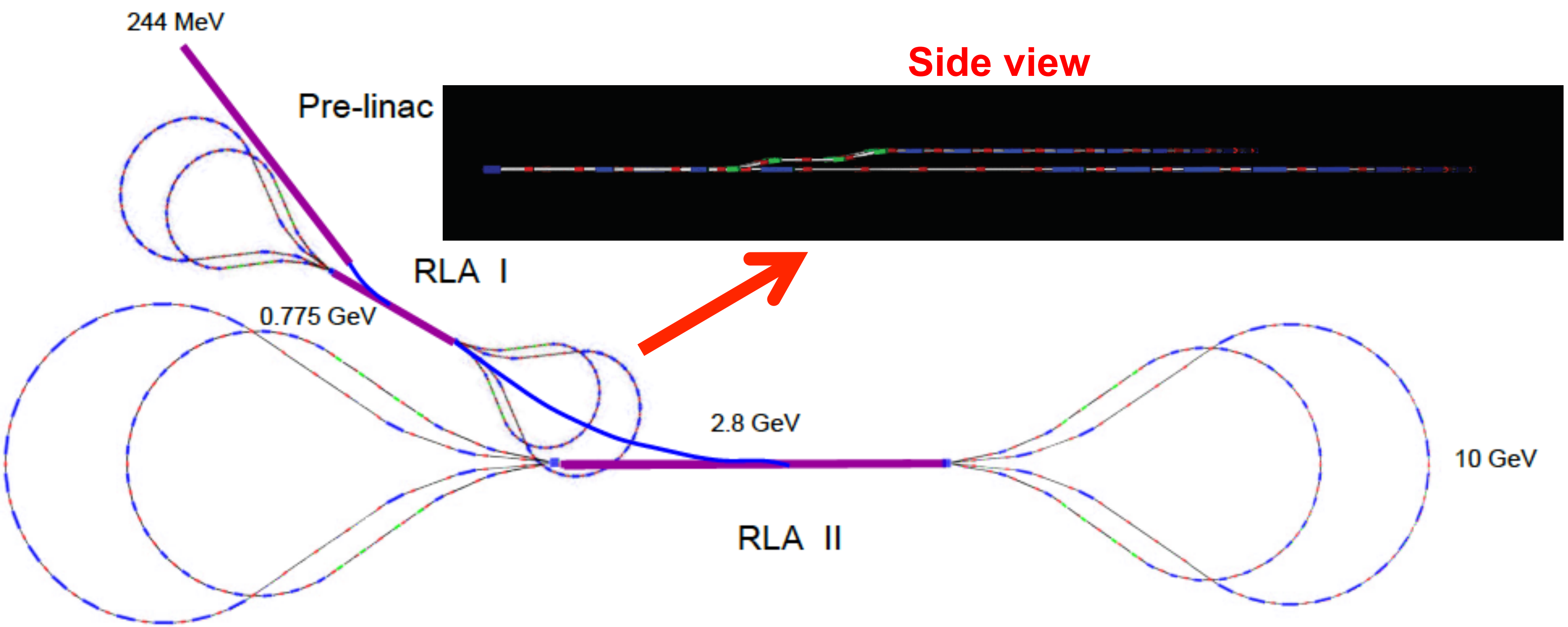
- Adiabatic B-field taper from Hg target to longitudinal drift
- Add chicane to remove protons
- Drift in ~1.5 T, ~60 m solenoid
- Adiabatically bring on RF voltage to bunch beam
- Phase rotation: variable frequencies
  - High energy front sees negative E-field
  - Low energy tail sees positive E-field
  - End up with smaller energy spread
- Ionization Cooling: MICE demonstrator
  - Reduce transverse emittance by 36%
  - Performance: 0.066 μ/proton
  - Cooling increases muon yield by ~2.2





Acceleration

- Baseline acceleration scheme at 10 GeV
  - Two “dog-bone” Recirculating Linear Accelerators (RLA)
  - First RLA up to 2.8 GeV
  - Second RLA up to 10 GeV

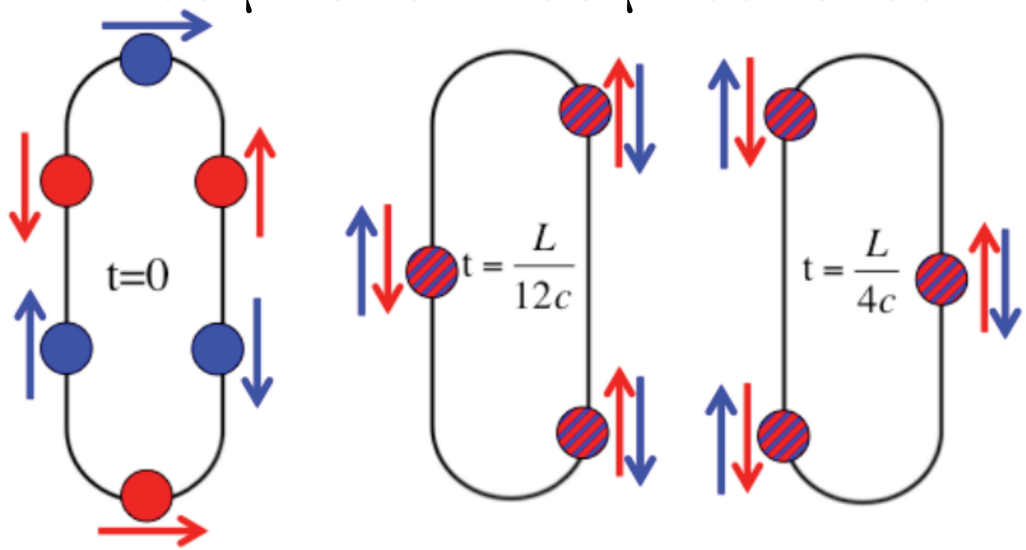


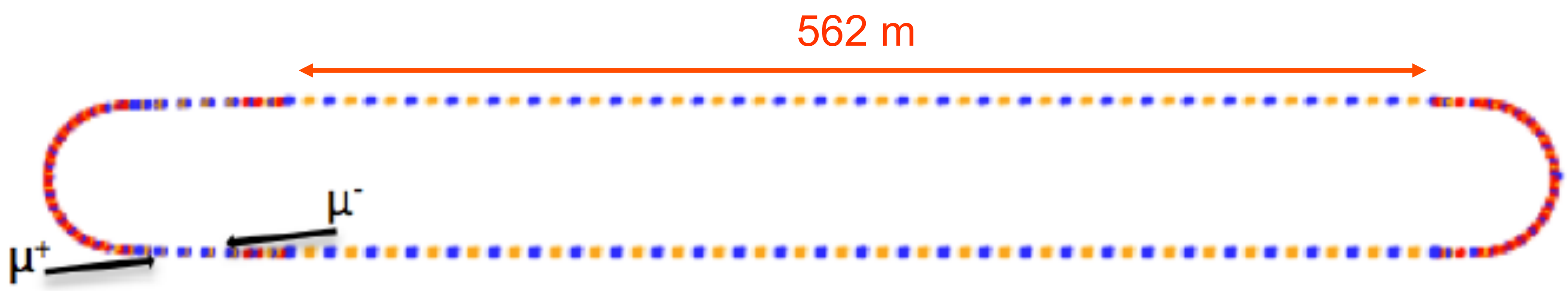
Decay Ring Geometry

- Racetrack geometry for decay ring with insertion
  - Straight: 562 m
  - Upper arc: 121 m
  - Lower arc: 113 m
  - Insertion: 46 m
  - Matching: 105 m (total)

  ➔ Circumference = 1556 m

Three μ^+ and three μ^- bunches

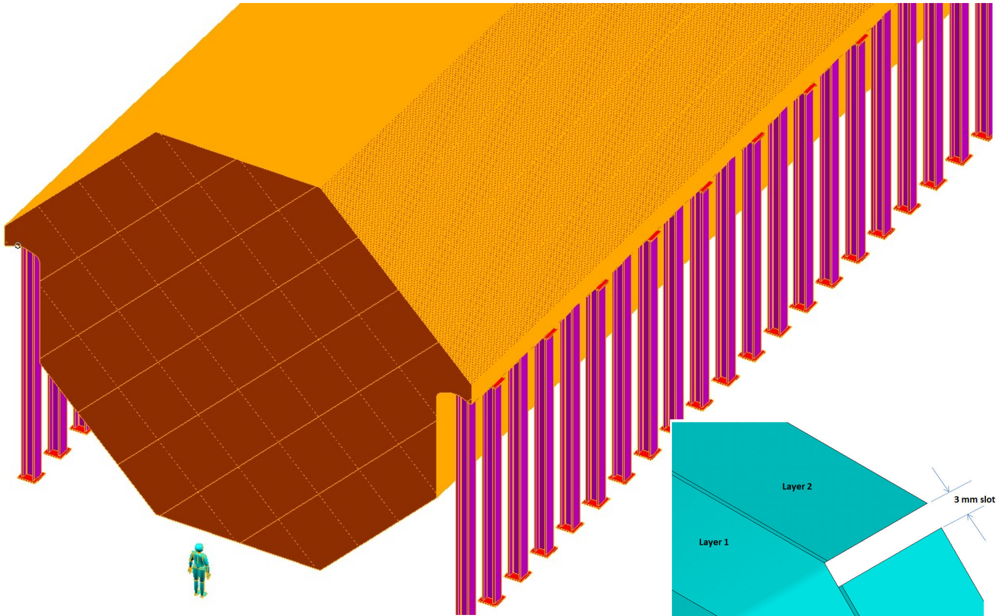




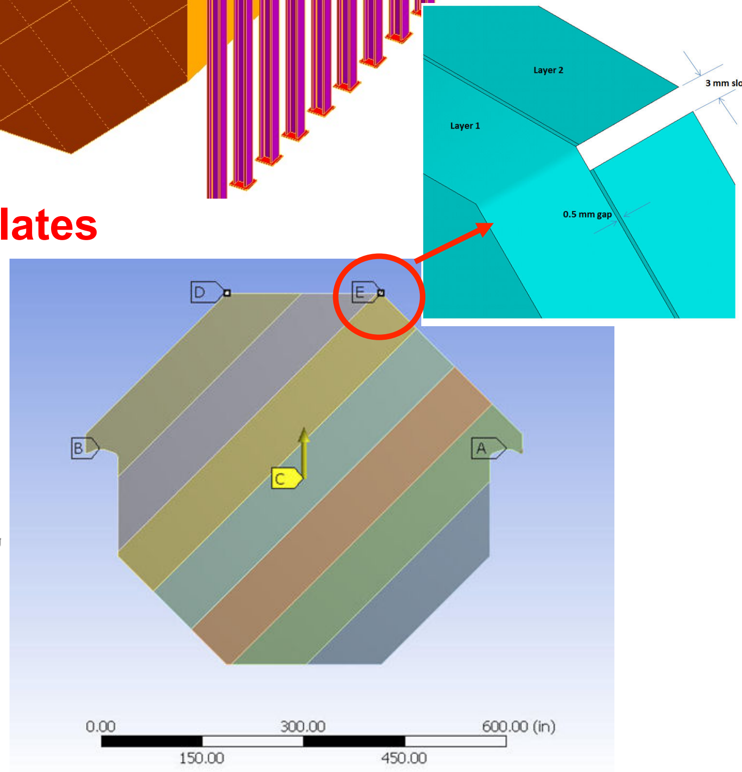
Divergence < 0.1/γ

Far Detector

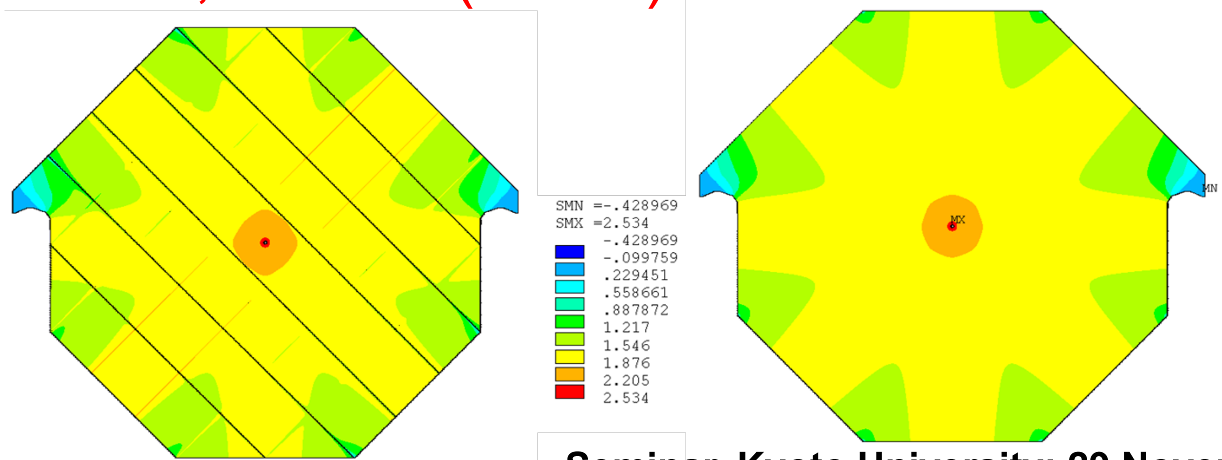
- Magnetised Iron neutrino Detector (MIND): 100 kton
- Octagonal plates and toroidal field (as in MINOS)
- Engineering metal plates
- Magnetic field delivered by 100 kA current



14mx14mx3cm plates

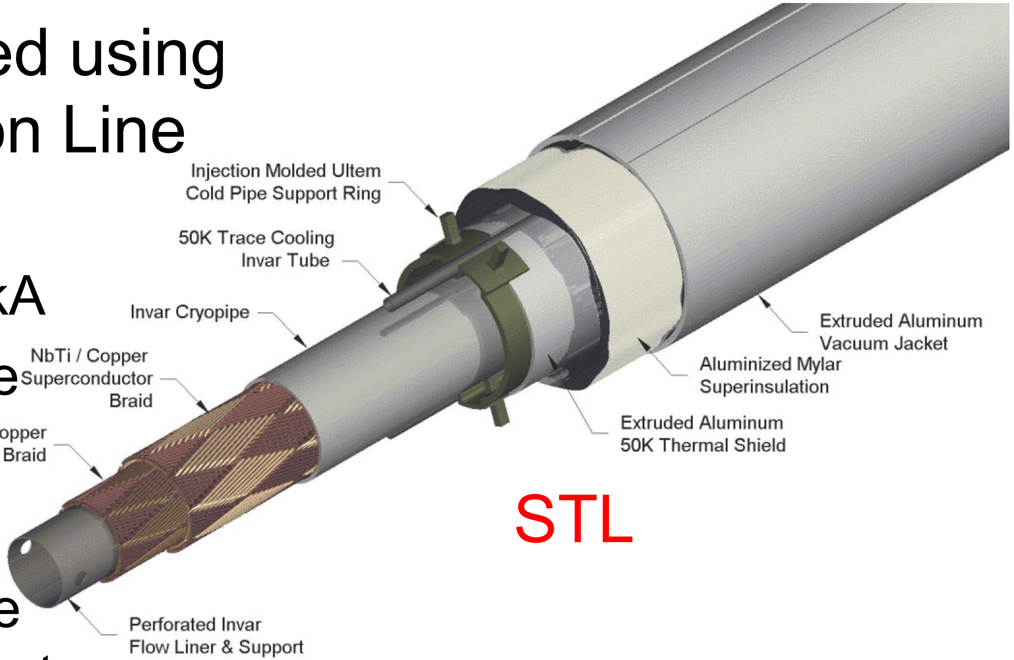


Bross, Wands (FNAL)

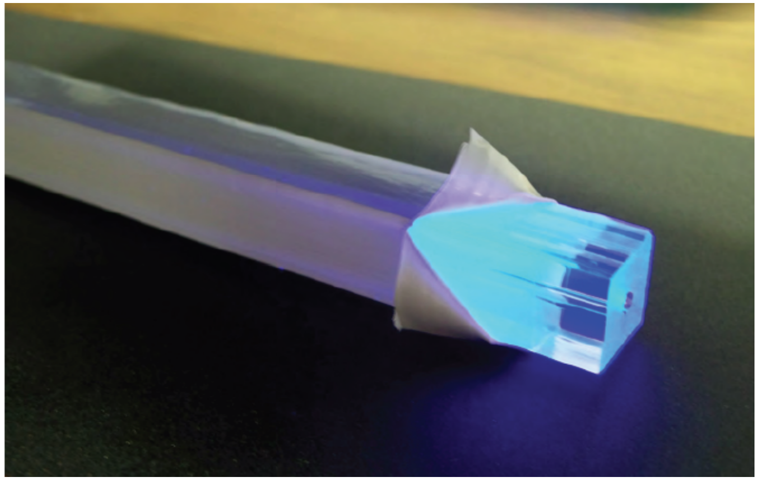


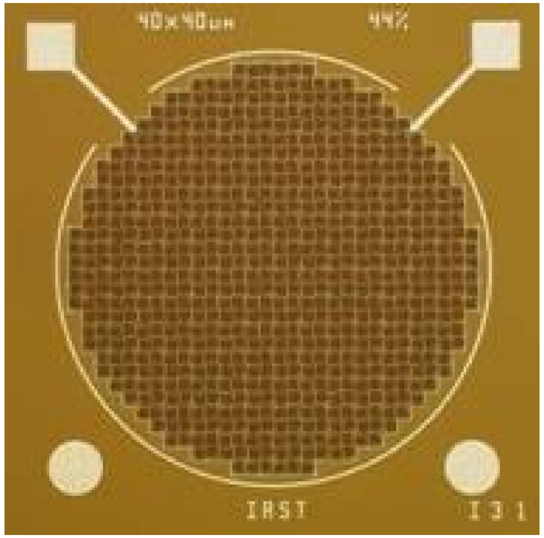
MIND magnetisation

- Magnetisation can be achieved using Superconducting Transmission Line (STL) developed for VLHC:
  - Either one 100 kA turn or 8x15 kA
  - Only need ~10 cm diameter hole
- Extruded scintillator:
  - Kuraray wavelength shifting fibre with double-ended SiPMT readout



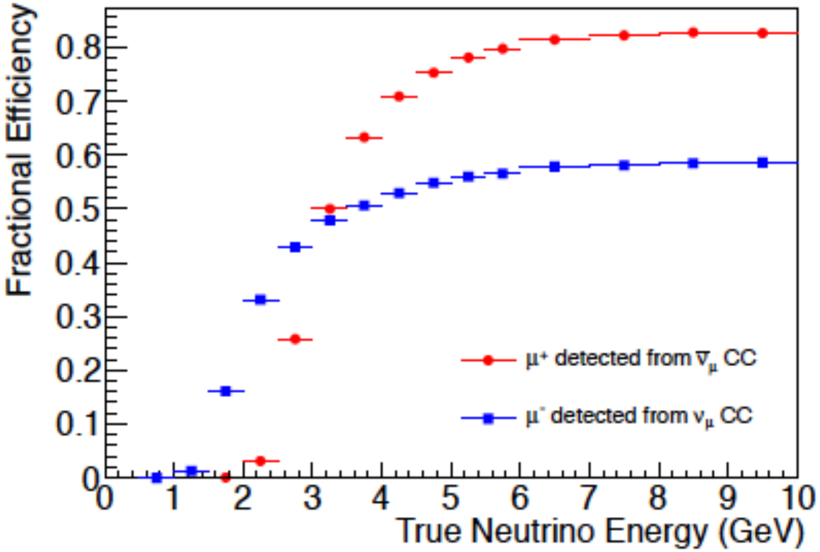
STL



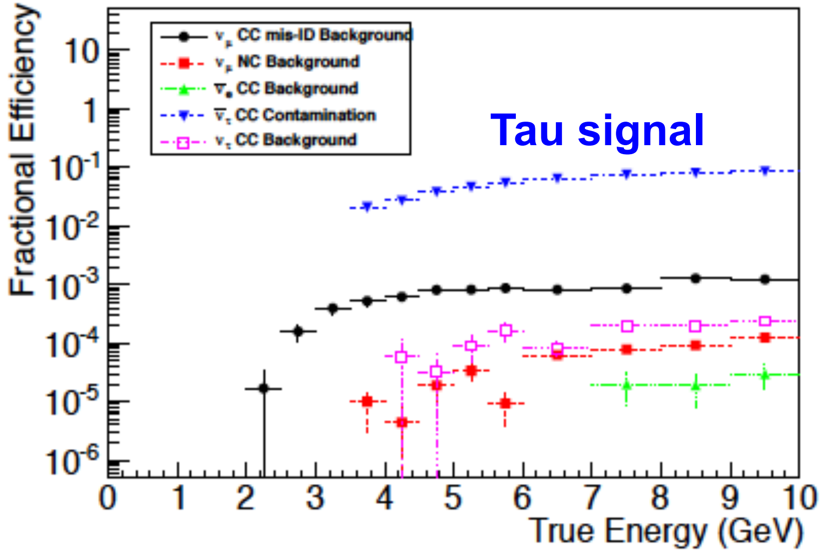


MIND efficiencies and background

BDT efficiency, focussing μ^+

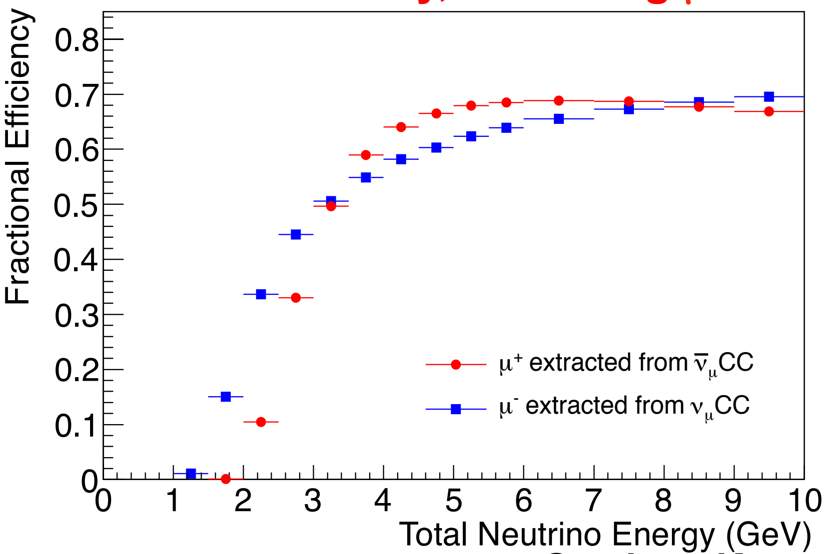


BDT background (stored μ^-, focussing μ^+)

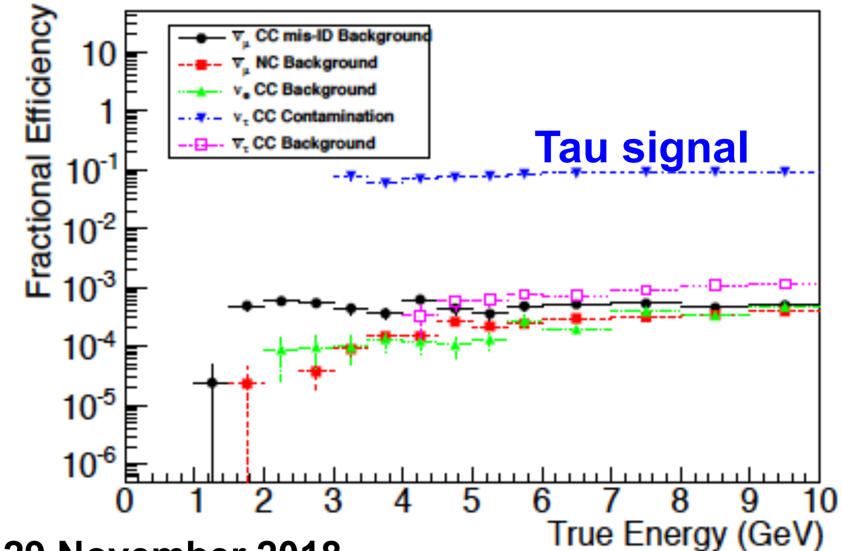


Courtesy
R. Bayes
UofG

BDT efficiency, focussing μ^-

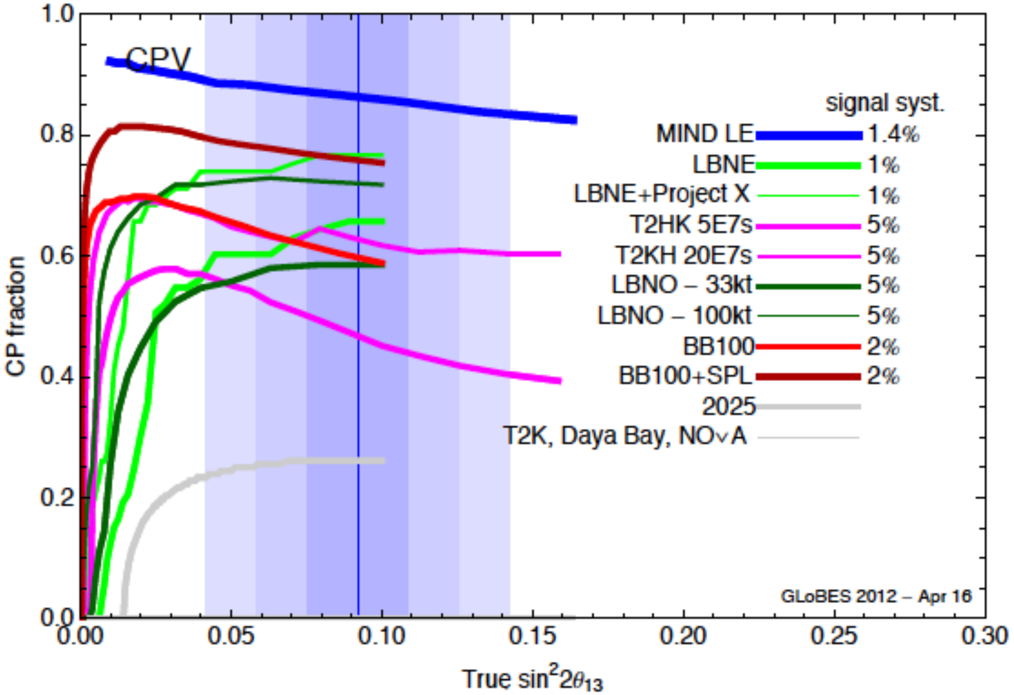


BDT background (stored μ^+, focussing μ^+)



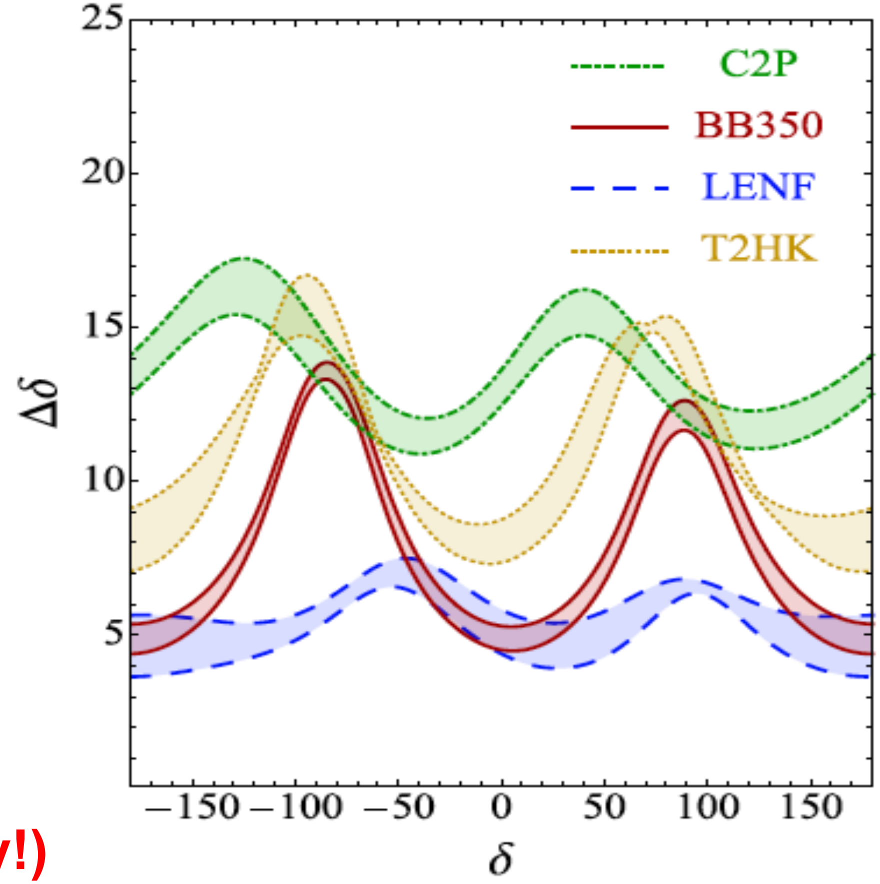
Performance 10 GeV Neutrino Factory

- Optimisation for 10 GeV Neutrino Factory, 10^{21} μ/year with 100 kton MIND at 2000 km gives best sensitivity to CP violation
- Best possible performance for a Neutrino Factory: $\Delta\delta_{CP} \sim 5^{o}$



More than 85% 5σ coverage

(ie. 85% probability of CPV discovery!)



arXiv:1203.5651

3. Neutrino Factory Staging

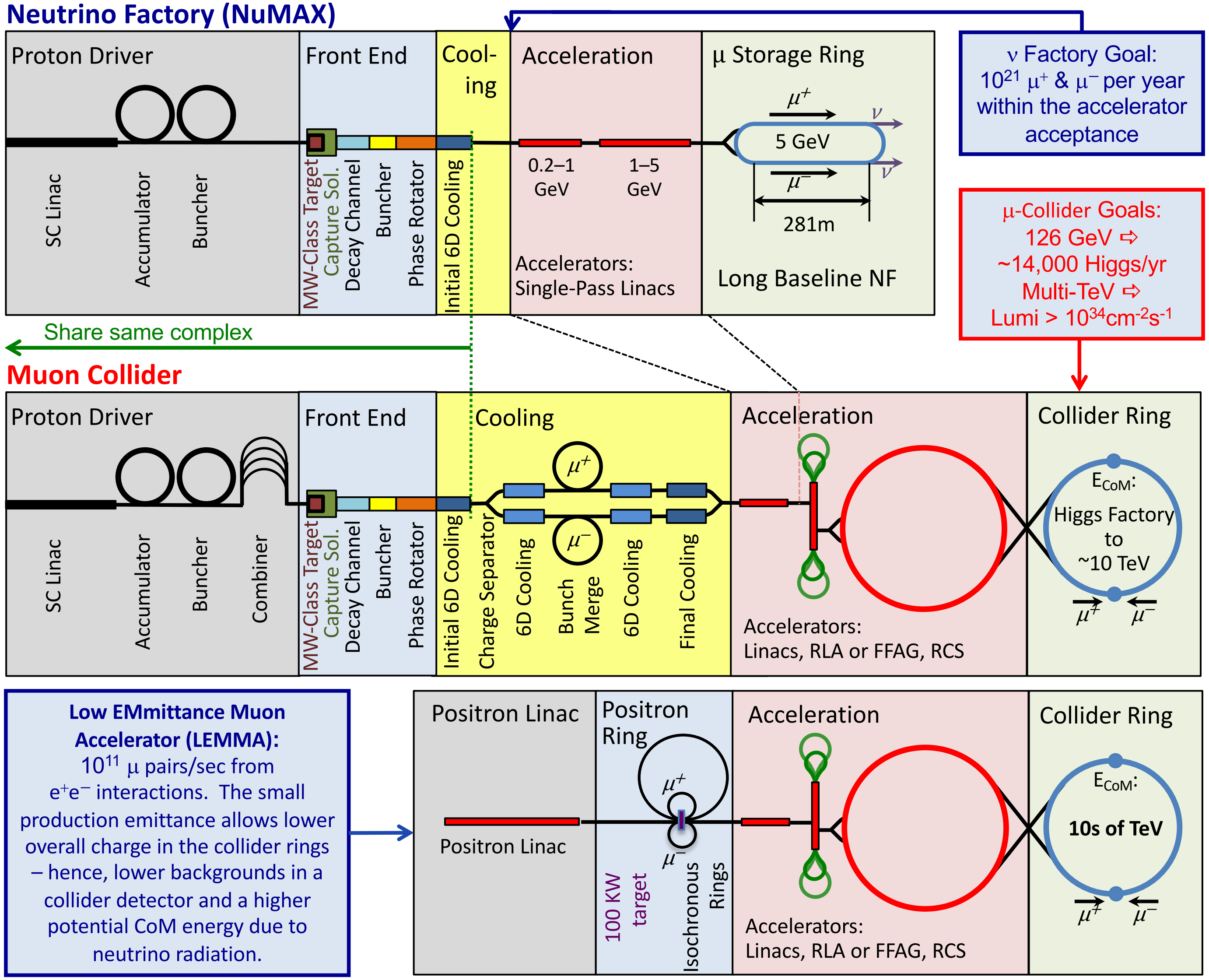
Muon Accelerator Staging Programme

- Staging Neutrino Factory allows to produce physics at each stage and spreads out cost – first step towards muon collider

arXiv:1808.01858

Staging study at FNAL: from 5 GeV Neutrino Factory to Muon Collider

LEMMA: Low Emmittance Muon Accelerator

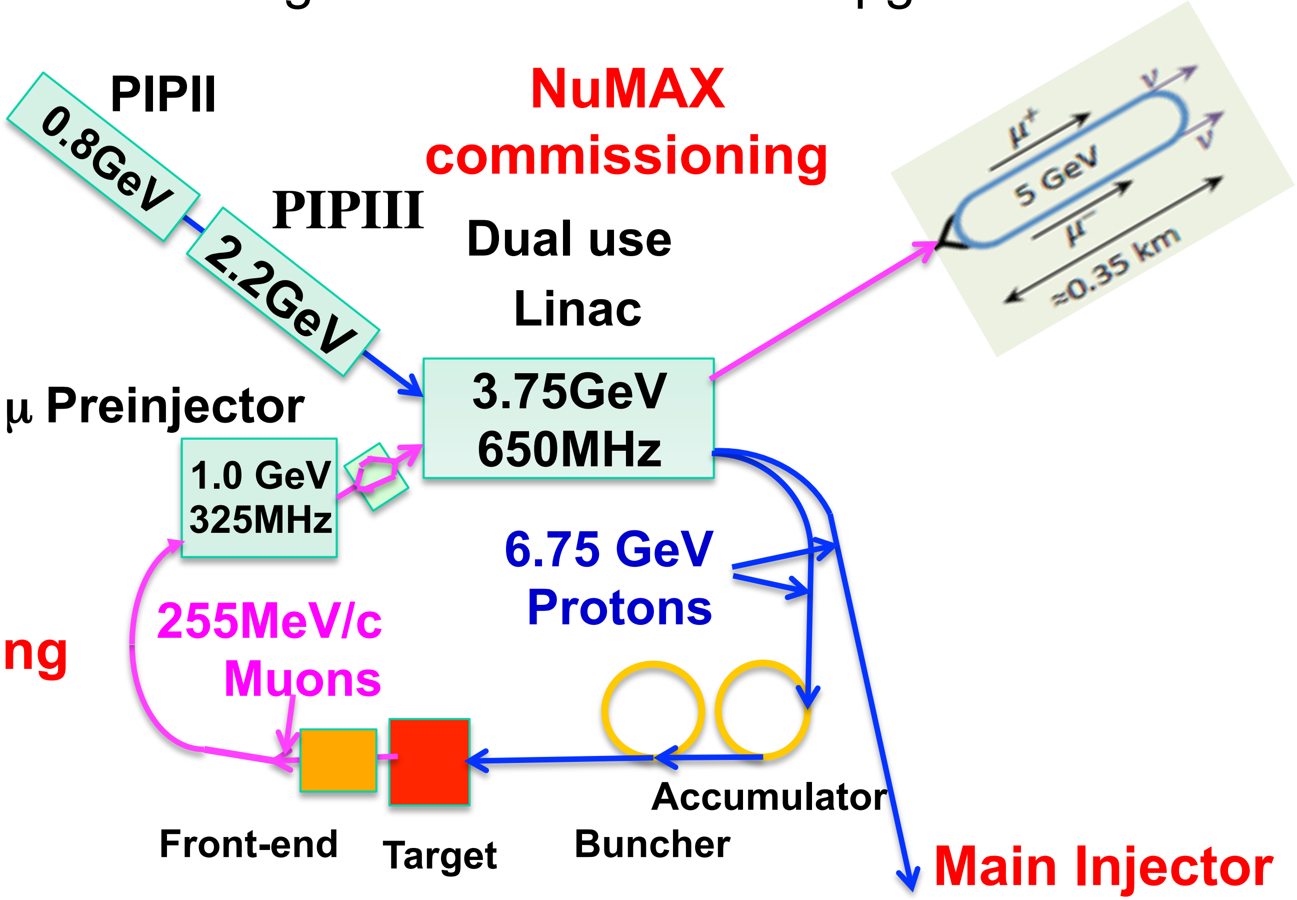


Stage 1: NuMAX commissioning

- Neutrinos from a Muon Accelerator CompleX (NuMAX)
  - Neutrino Factory with 10^{20} straight muons decays/year @ 5 GeV
  - Muon ring at 5 GeV pointing neutrino beam towards Sanford
  - A 10kT MIND or magnetized LAr detector upgraded from LBNE

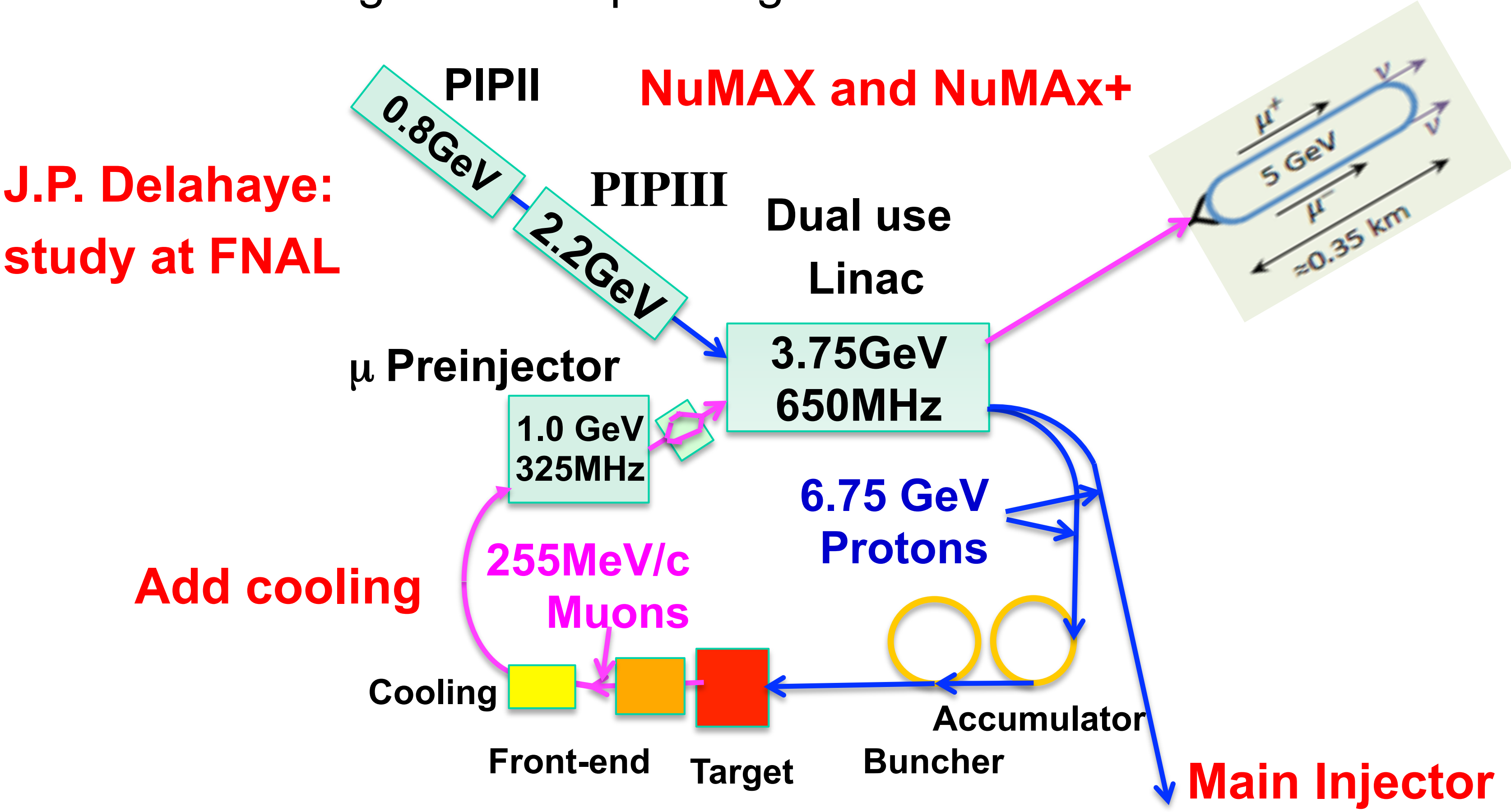
J.P. Delahaye: study at FNAL

No cooling



Stage 2: NuMAX

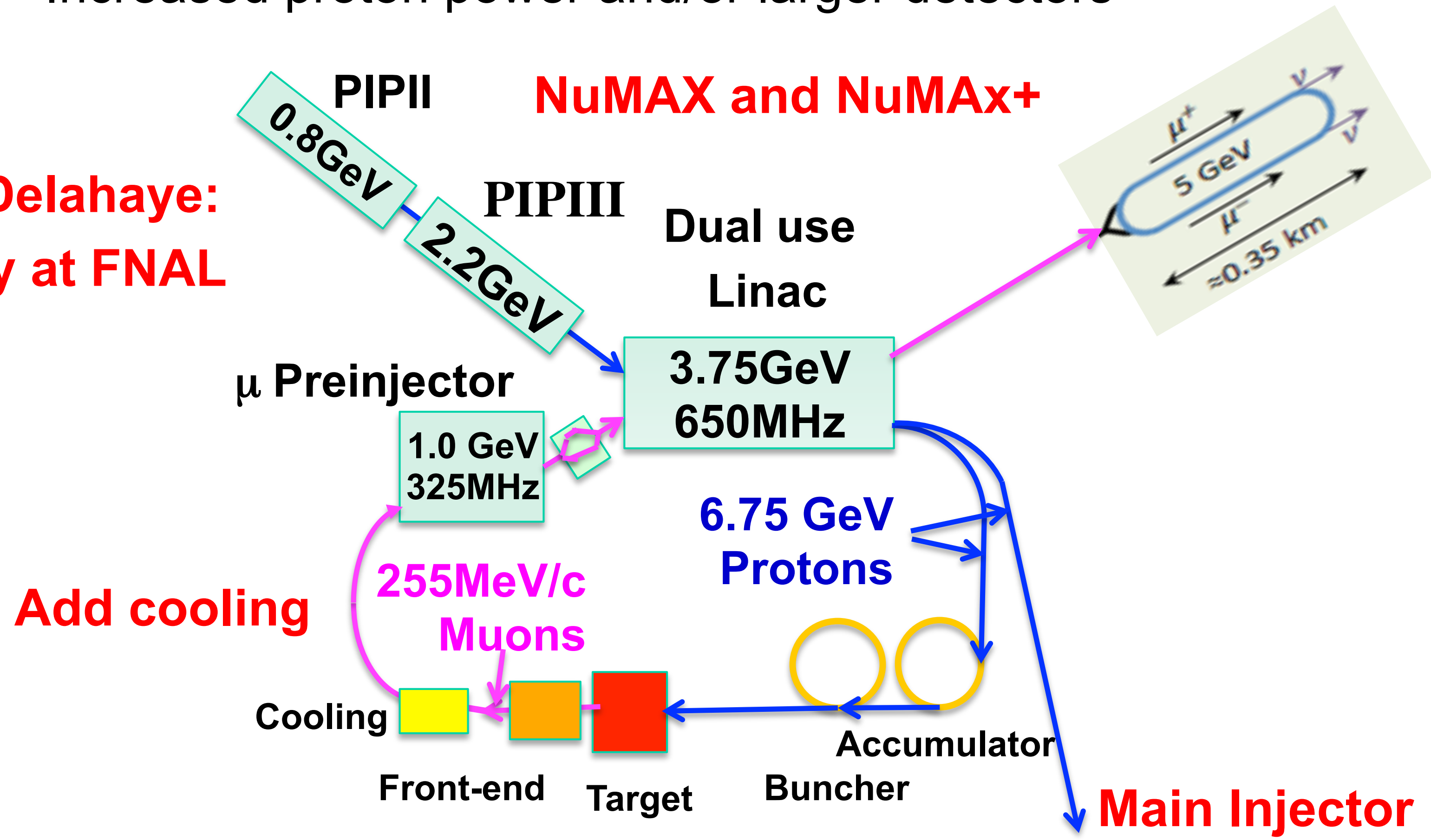
- Neutrinos from a Muon Accelerator CompleX (NuMAX)
  - Add small amount of 6D cooling
  - Neutrino Factory with 5×10^{20} straight muon decays/year @ 5 GeV
  - Muon ring at 5 GeV pointing neutrino beam towards Sanford



Stage 3: NuMAX+

- Neutrinos from a Muon Accelerator CompleX (NuMAX+)
  - Neutrino Factory with 10^{21} straight muons decays/year @ 5 GeV
  - Muon ring at 5 GeV pointing neutrino beam towards Sanford
  - Increased proton power and/or larger detectors

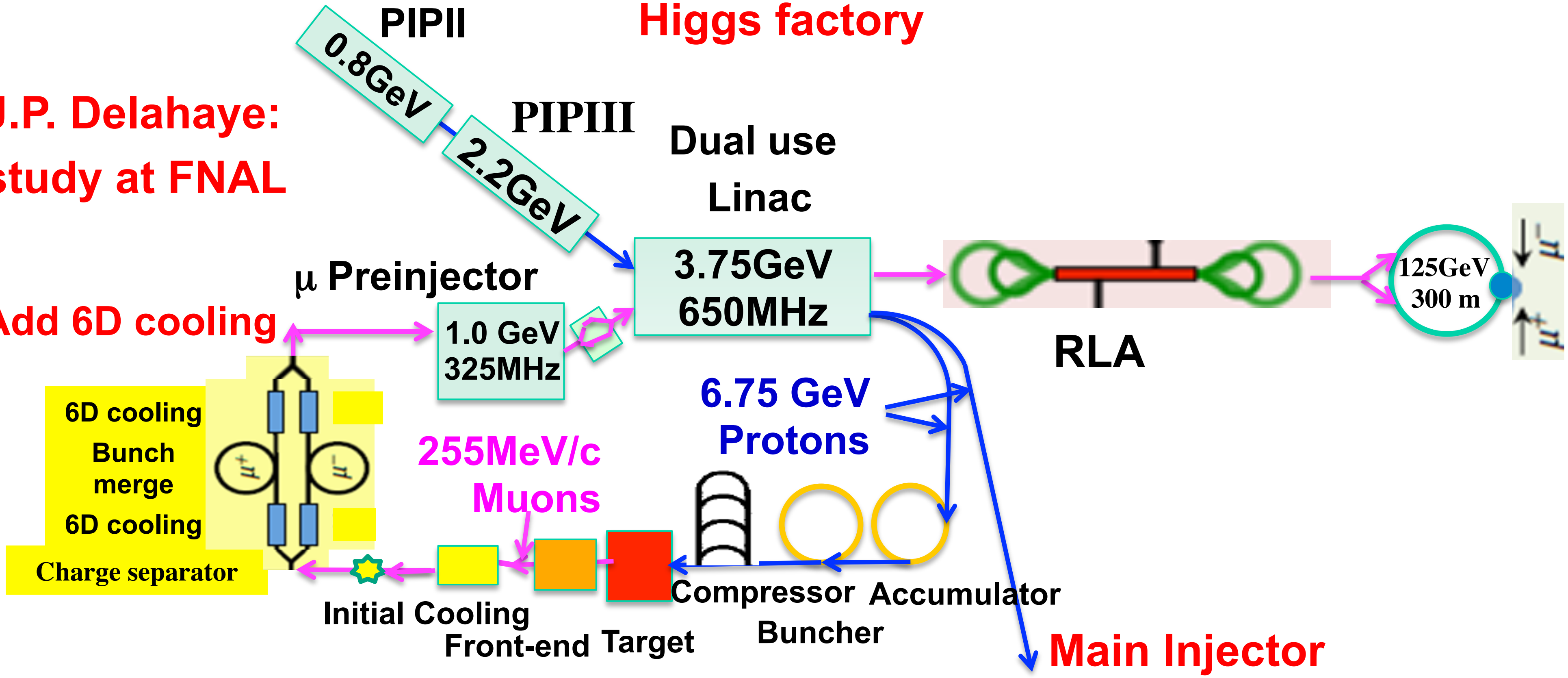
J.P. Delahaye: study at FNAL



Stage 4: Higgs Factory

- Higgs Factory: production of Higgs at 126 GeV CM
  - Collider capable of providing ~13,500 Higgs events per year with exquisite energy resolution: direct Higgs mass and width
  - Possible upgrade to a Top Factory with production of up to 60000 top particles per year

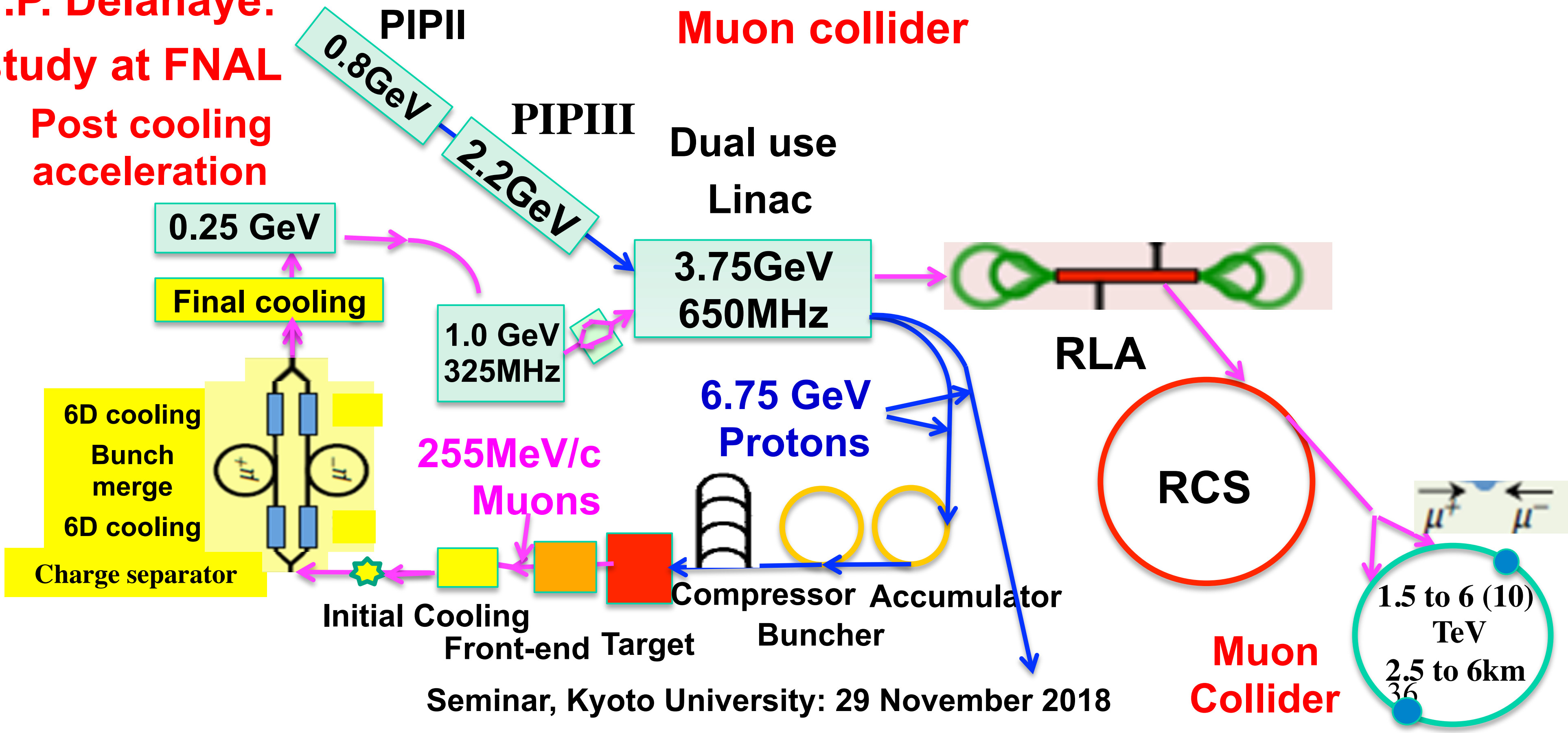
J.P. Delahaye: study at FNAL

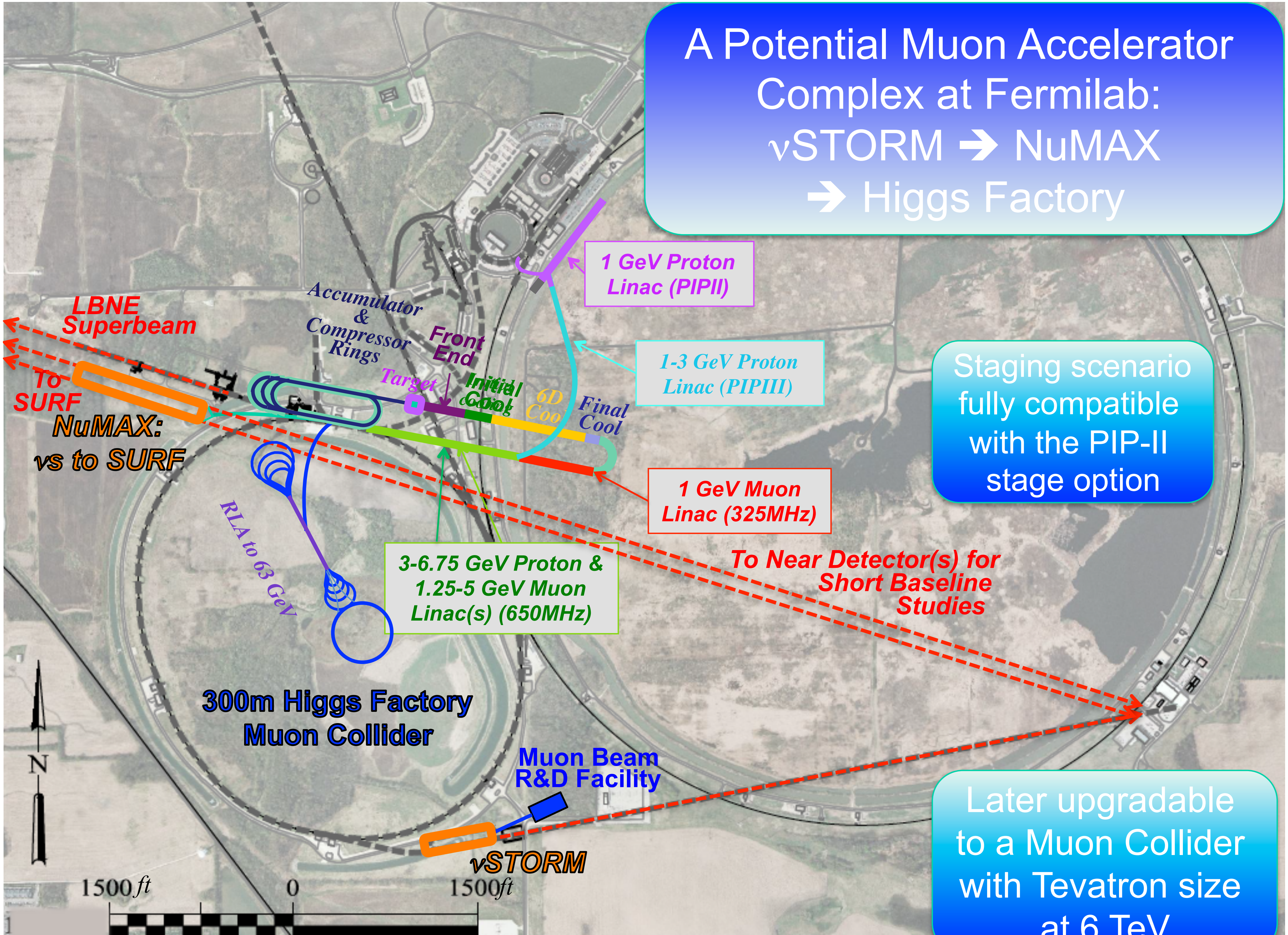


Stage 5: Muon Collider

- Multi-TeV muon collider:
  - If warranted by LHC results a muon collider can reach up to 10 TeV
  - Likely offers the best performance, least cost and power consumption of any lepton collider operating in the multi-TeV regime.

J.P. Delahaye: study at FNAL




A Potential Muon Accelerator Complex at Fermilab:
νSTORM ➔ NuMAX ➔ Higgs Factory
1 GeV Proton Linac (PIPII)
1-3 GeV Proton Linac (PIPIII)
Staging scenario fully compatible with the PIP-II stage option
LBNE Superbeam
To SURF
NuMAX: νs to SURF
Accumulator & Compressor Rings
Front End
Target
Initial Cool
Final Cool
1 GeV Muon Linac (325MHz)
3-6.75 GeV Proton & 1.25-5 GeV Muon Linac(s) (650MHz)
RLA to 63 GeV
To Near Detector(s) for Short Baseline Studies
300m Higgs Factory Muon Collider
Muon Beam R&D Facility
νSTORM
Later upgradable to a Muon Collider with Tevatron size at 6 TeV
N
1500 ft
0
1500ft
J.P.Delahaye

Staging summary

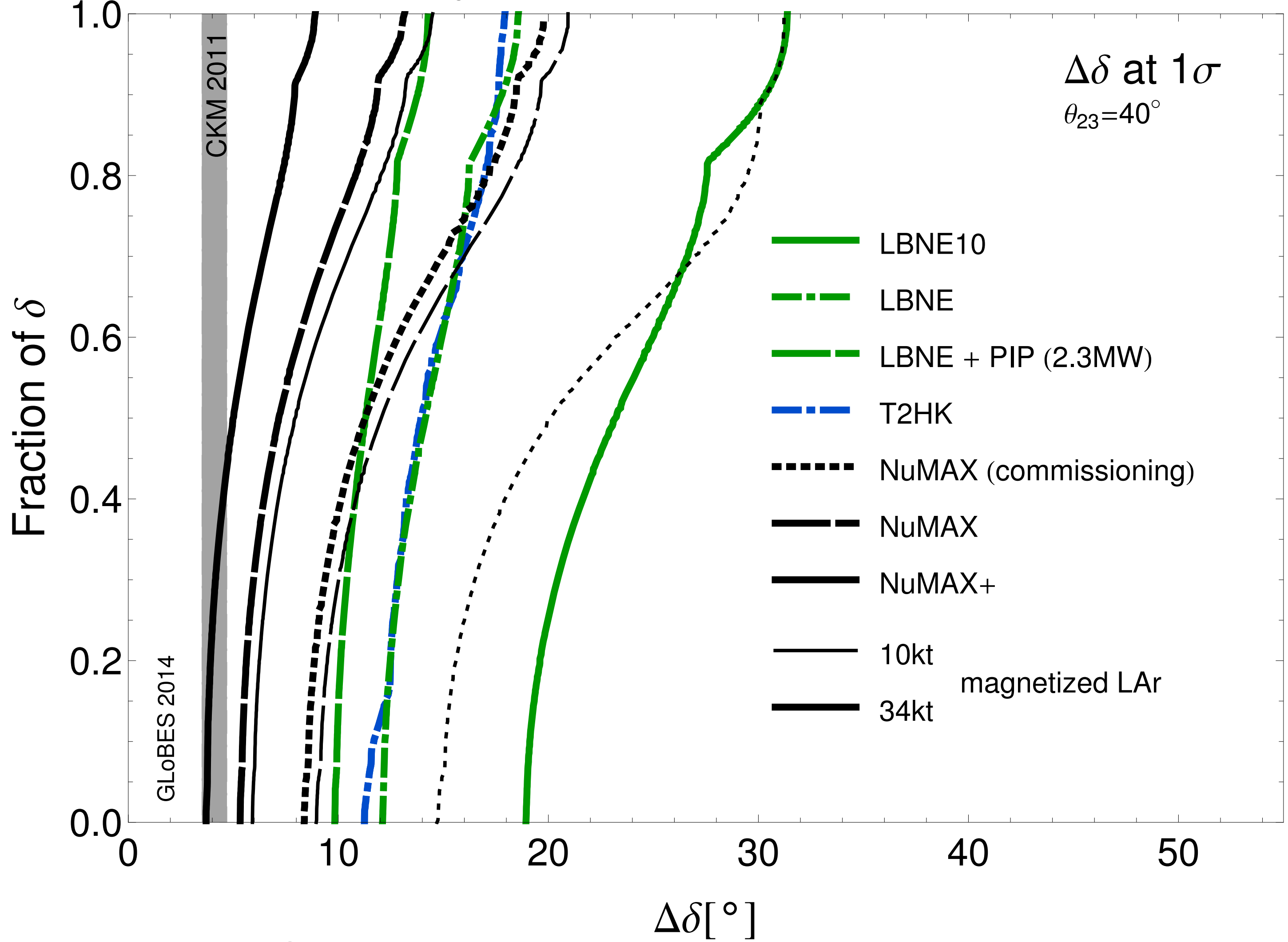
- Summary of machine parameters as a function of staging scenarios

	NuMAX Commissioning	NuMAX	NuMAX+	Higgs Fact 125 GeV	Muon Coll. 6 TeV ***
Beam energy (GeV/c)	5	5	5	62.5	3000
Cooling	No	Initial 6D	Initial 6D	6D no final	Full 6D
Proton beam power on target	1MW	1MW	2.75 MW	4 MW	1.8 MW
Proton beam energy on target	6.75 GeV	6.75 GeV	6.75 GeV	6.75 GeV	6.75 GeV
Acceleration cycle rep rate(Hz)	60	60	60	15	6
μ / cycle at front end	$1.36\ 10^{12}$	$1.36\ 10^{12}$	$3.75\ 10^{12}$	$2.6\ 10^{13}$	$2.9\ 10^{13}$
Transmission efficiency (%)	15.3	56.7	56.7	15.4	6.9
μ / bunch in ring	$3.5\ 10^{9}$	$1.3\ 10^{10}$	$3.5\ 10^{10}$	$4\ 10^{12}$	$2.0\ 10^{12}$
Bunches in ring	60	60	60	1	1
ν towards detector/year(10^7s)	$4.9\ 10^{19}$	$1.8\ 10^{20}$	$5.0\ 10^{20}$		
Higgs per year (10^7 sec)				13500	
Luminosity (10^{34} cm^{-2}s^{-1})					12

Physics performance of NuMAX

- Physics performance in terms of fraction of CP phase δ with measurement accuracy at or below Δδ

P. Huber

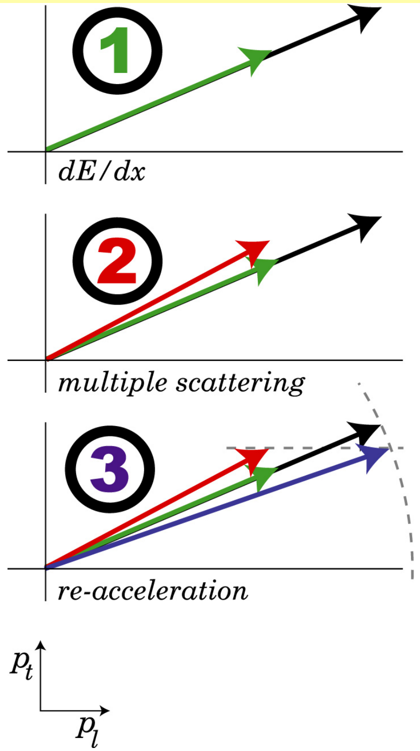


4. Muon Ionization Cooling Experiment (MICE)

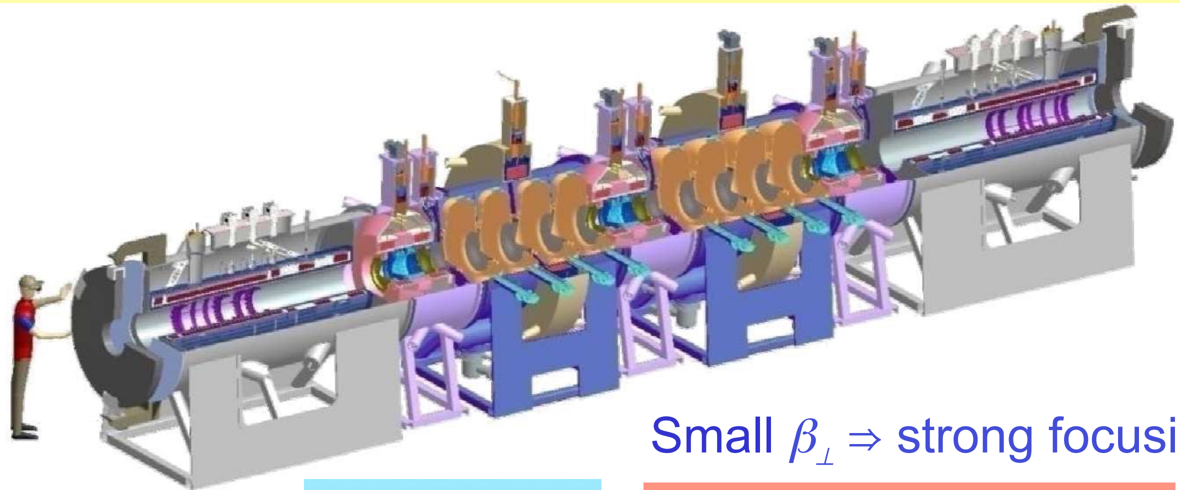
Muon Cooling

- Muon Ionization Cooling:
  - Muon Ionization Cooling is the key technology required to be able to build front-end of a Neutrino Factory and a Muon Collider (ie. stochastic cooling enabled proton-antiproton collider in 1980s)

Principle



Practice



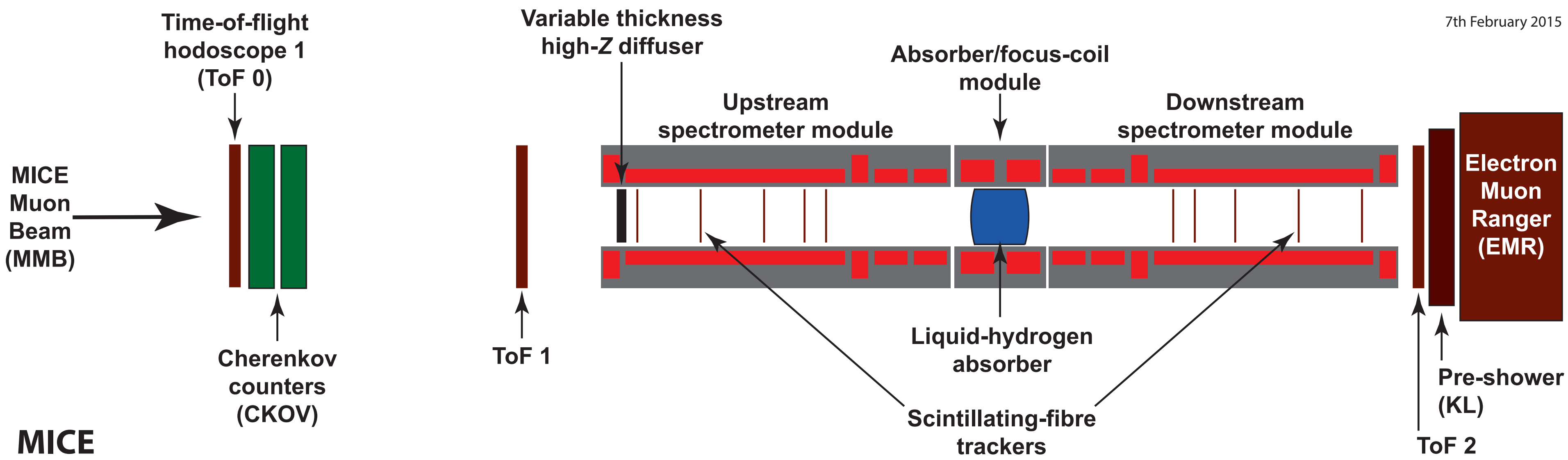
Small $\beta_\perp \Rightarrow$ strong focusing

$$\frac{d\varepsilon_T}{dz} \approx -\frac{\varepsilon_T}{E_\mu \beta^2}\frac{dE_\mu}{dz} + \frac{\beta_\perp}{2mc^2\beta^3}\frac{(13.6\,MeV)^2}{E_\mu X_0}$$

Ionization: cooling Multiple scattering: heating

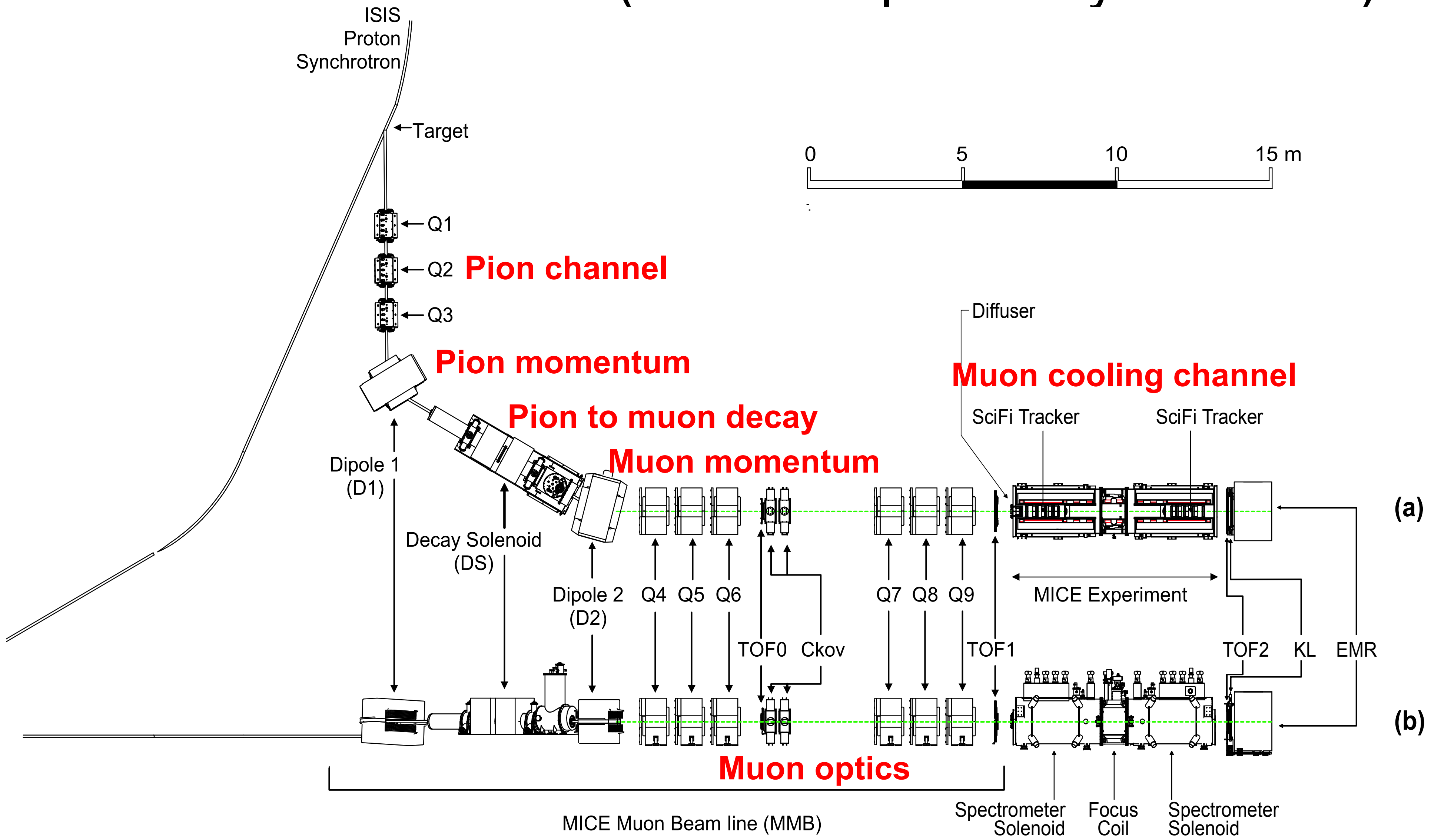
Muon Ionization Cooling Experiment

- Muon Ionization Cooling Experiment:
  - Letter of Intent: **November 2001**
  - Proposal at Rutherford Appleton Laboratory (RAL): **January 2003**
  - International collaboration built muon ionization cooling experiment at RAL



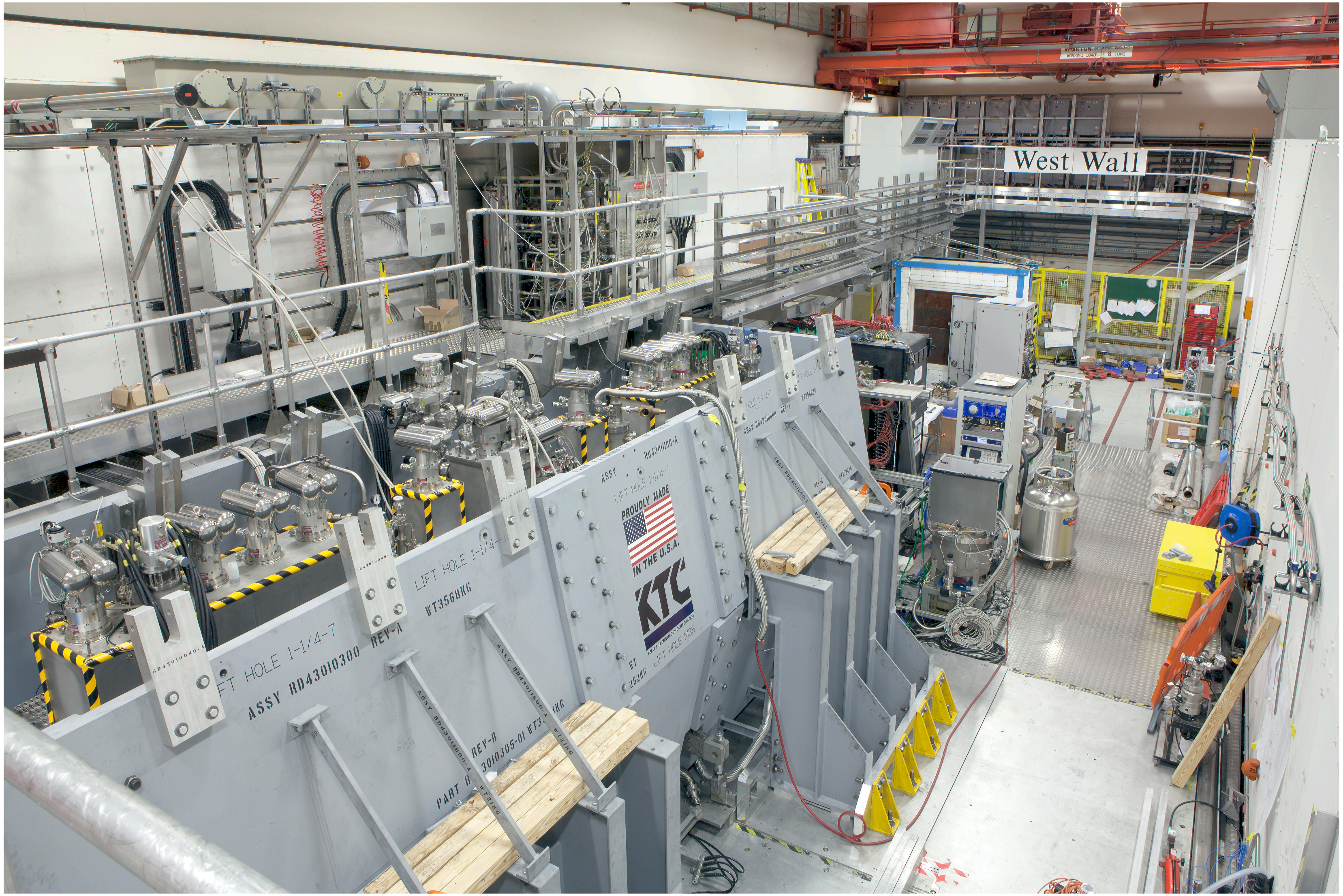
MICE Beam

- Muon beam from ISIS (800 MeV proton synchrotron)



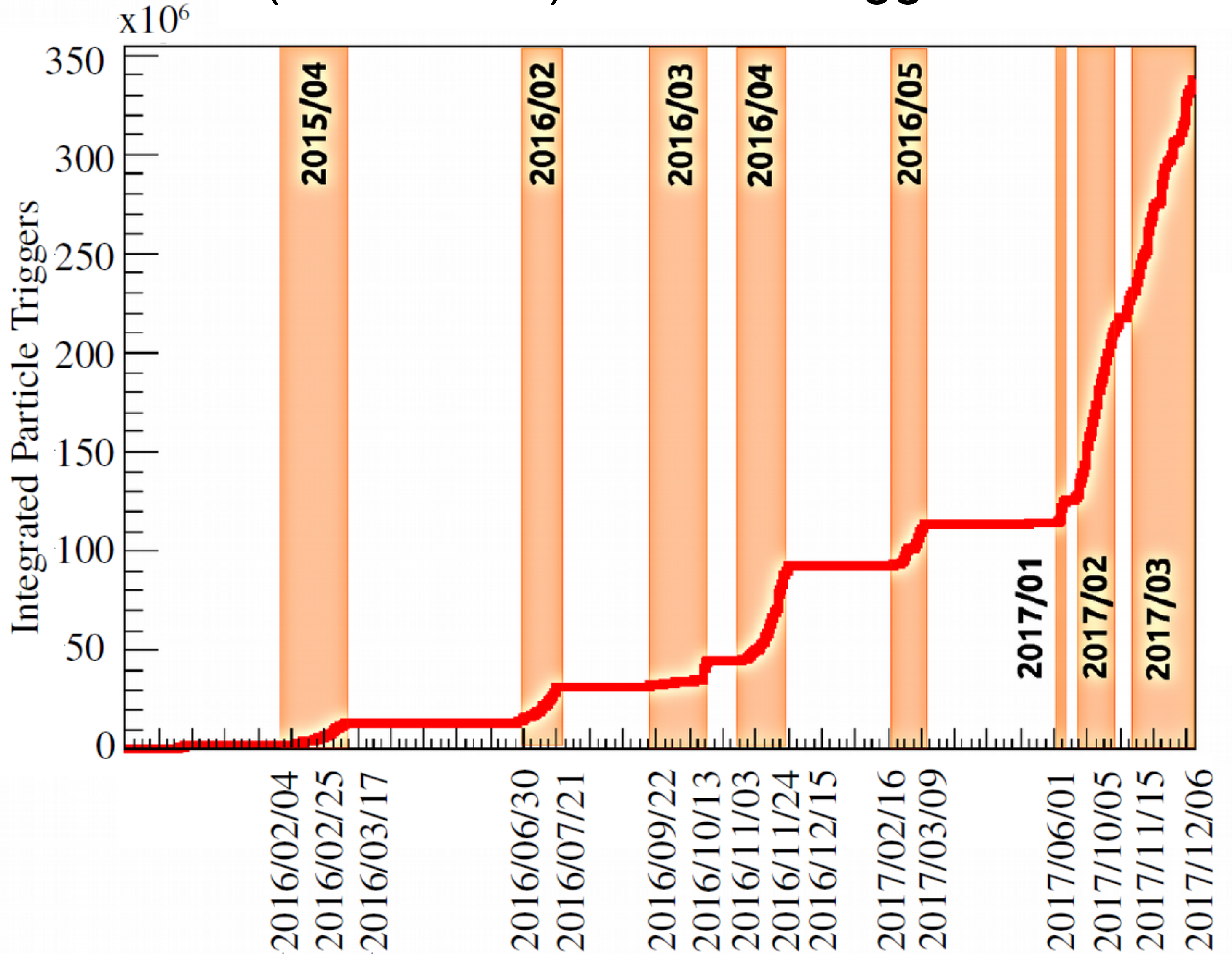
Muon Ionization Cooling Experiment

- Cooling Channel with Partial Return Yoke



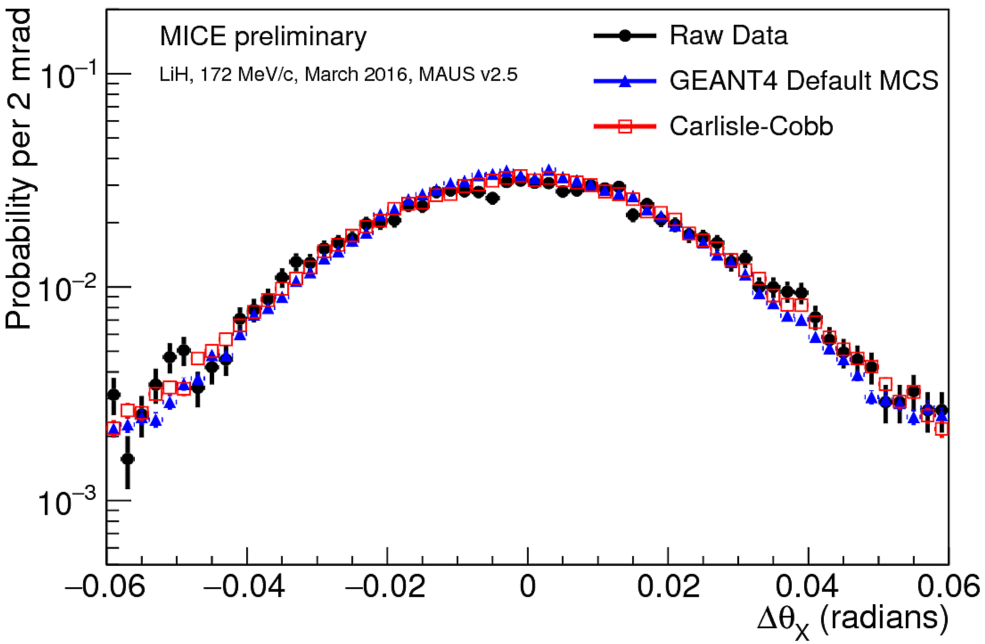
MICE Data

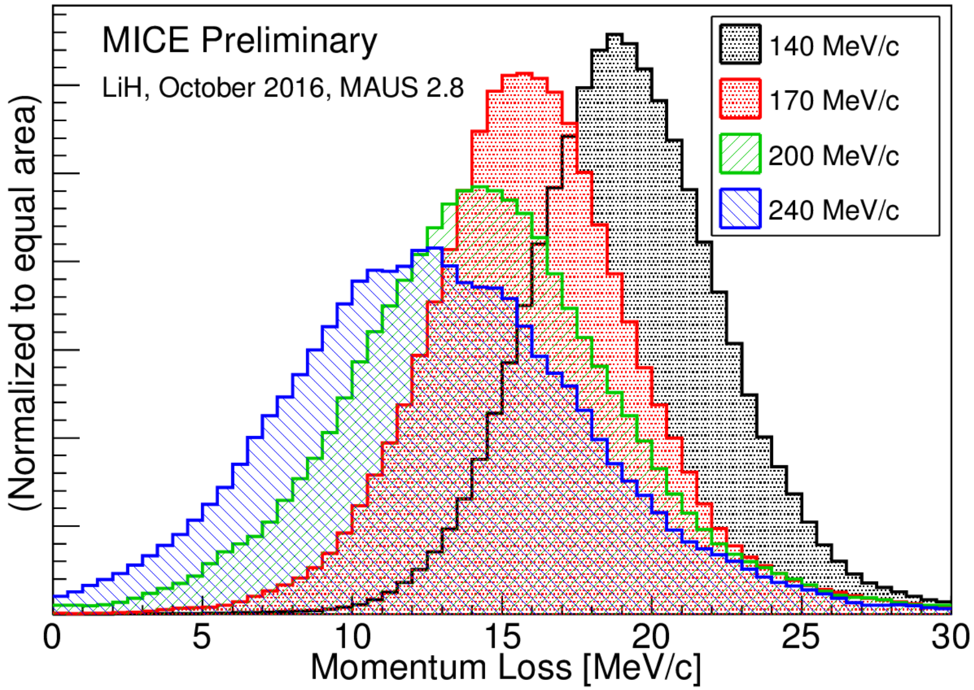
- MICE data set (2015-2017): 350x10^6 triggers



Multiple Coulomb Scattering

- First measurement of muon Multiple Coulomb Scattering in lithium hydride at 140-240 MeV/c **R. Bayes, J. Nugent**
  - Validation of Molière scattering model and Geant4
- Validation of energy loss model





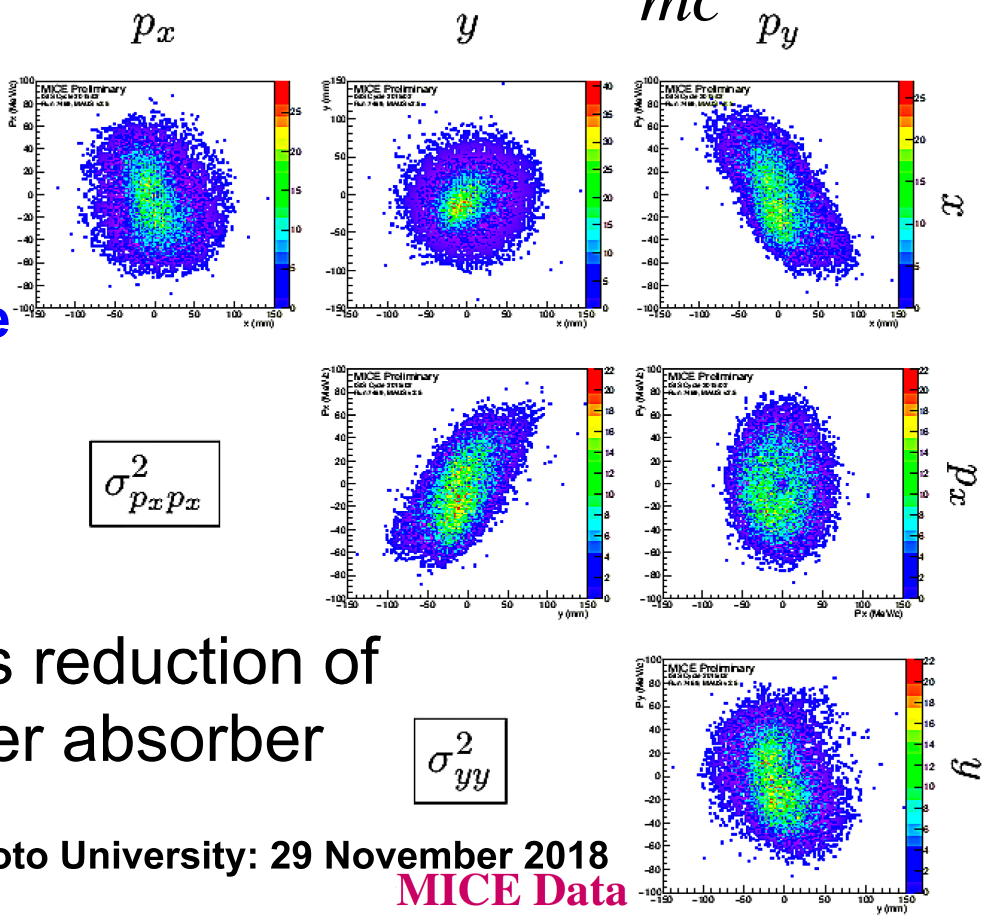
Measurement of beam emittance

- Single particle reconstruction: creates virtual beams by performing ensemble of all particles
- 4D-phase space of particles: (x, p_x, y, p_y)
- Normalised RMS transverse emittance: $\varepsilon_T = \dfrac{\sqrt[4]{|\Sigma_{4D}|}}{mc}$ 4D covariance matrix: Σ_{4D}

Ellipsoid containing
4D phase-space
RMS volume

Reconstructed phase space shows coupling of different variables for emittance calculation

σ^2_{xx} $\sigma^2_{p_x p_x}$ σ^2_{yy}



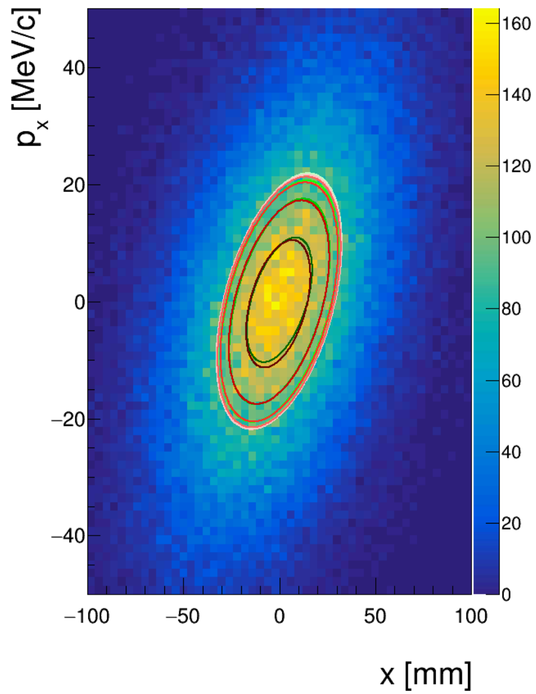
MICE Data

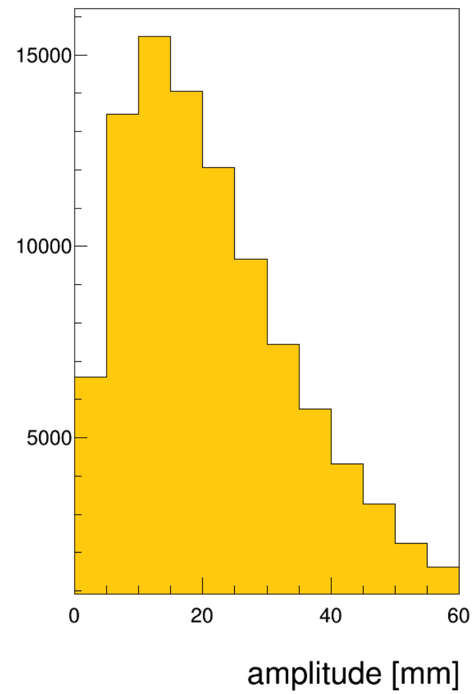
- Ionization cooling implies reduction of transverse emittance after absorber

Transverse single-particle amplitude

- Transverse single-particle amplitude:
  - Phase-space distance of muon from beam core

$$A_\perp = \varepsilon_T \mathbf{u}^T \Sigma^{-1} \mathbf{u} \quad \text{with} \quad \mathbf{v} = (x, p_x, y, p_y) \quad \text{and} \quad \mathbf{u} = \mathbf{v} - \langle \mathbf{v} \rangle$$

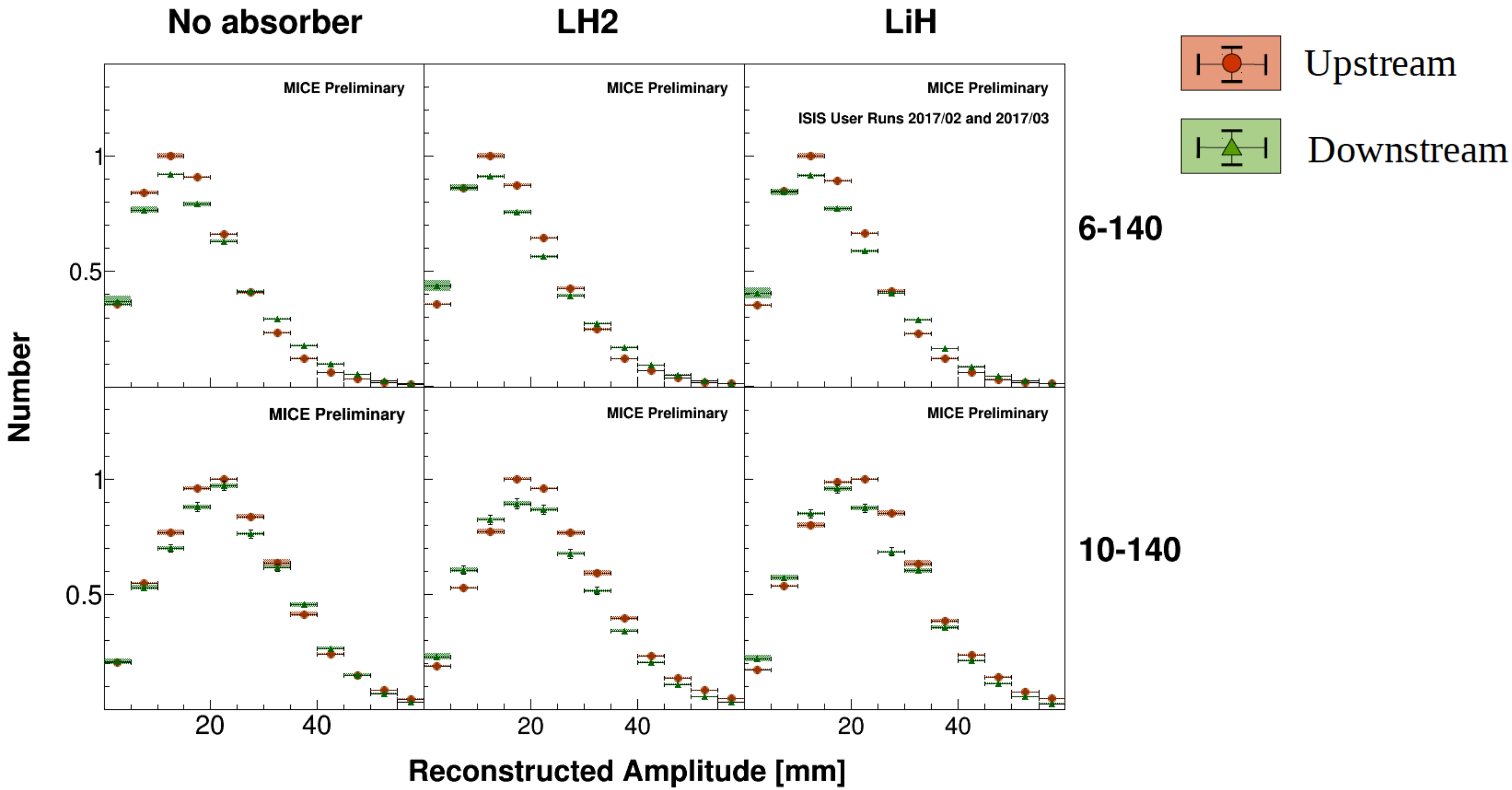




- Mean amplitude is proportional to RMS emittance
- Ionization cooling reduces amplitude in the core of the beam (higher amplitude density at low amplitudes)

Change in amplitude across absorber

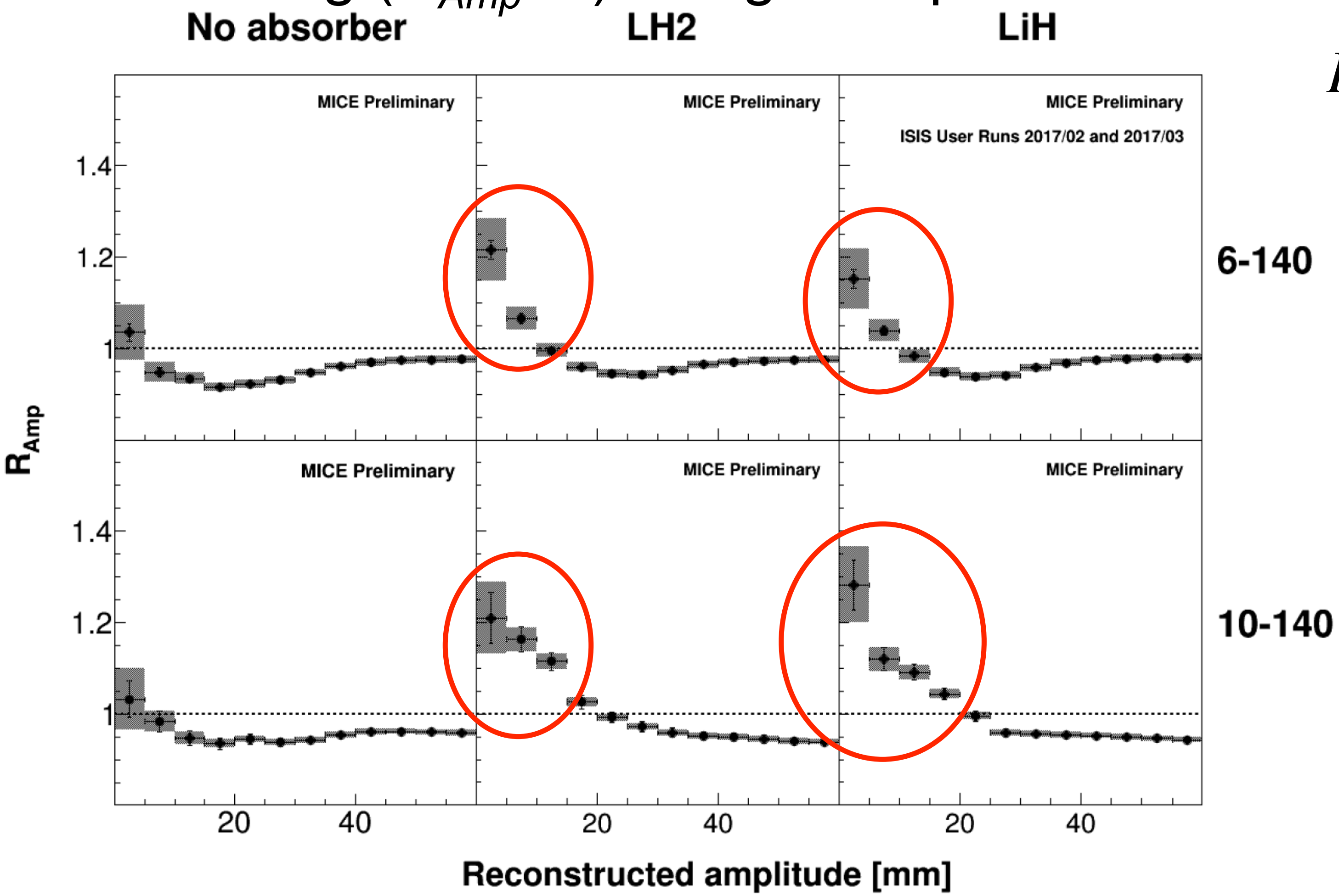
- No absorber: decrease in number of core muons
- Absorber: increase in number of core muons (cooling signal)



Ratio of cumulative core densities

- Cumulative core density increase for LH2 and LiH absorbers
- More cooling (R_{Amp}>1) at higher input emittances

$$R^N_{Amp} \equiv \frac{\sum_{n=1}^{N} A_n^{down}}{\sum_{n=1}^{N} A_n^{up}}$$



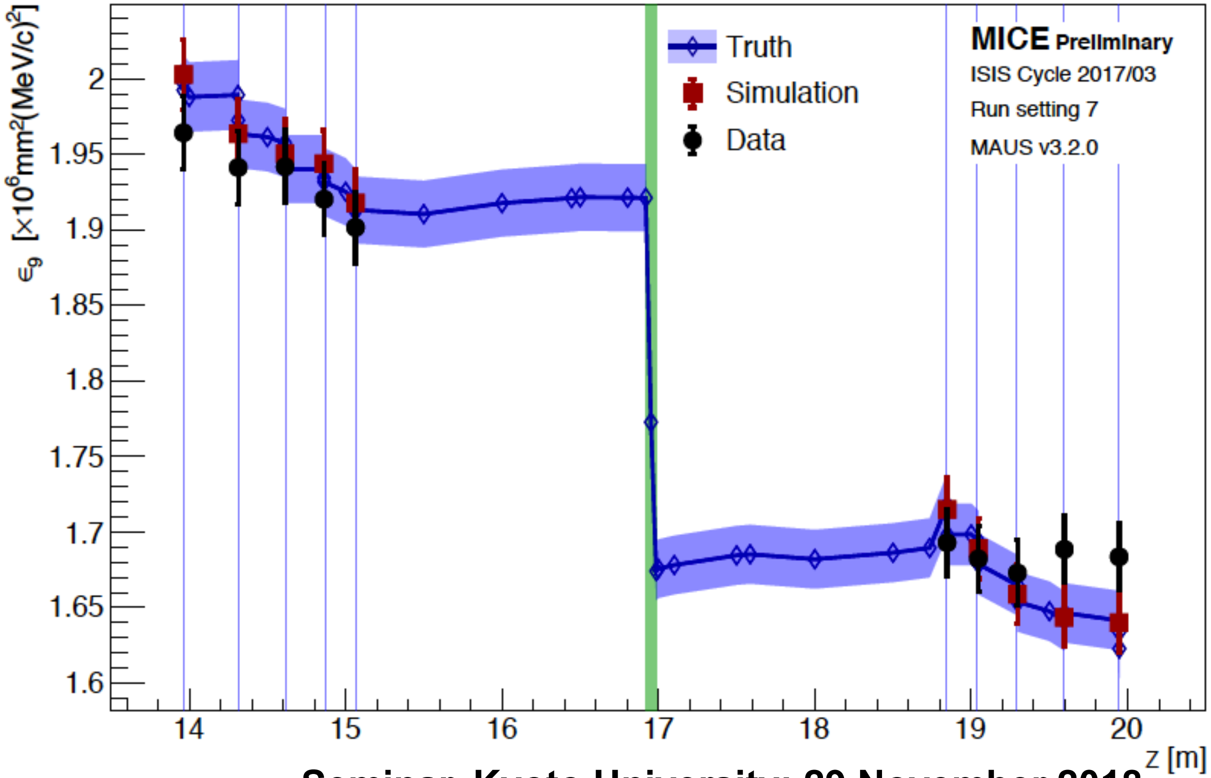
First demonstration and characterisation of ionization cooling!

Fractional emittance evolution

- Fractional emittance is phase-space volume occupied by fraction α of beam (α=9% is 1σ of 4D phase space)

$$\varepsilon_\alpha = \frac{1}{2}\left(\pi m c \varepsilon_T\right)^2 \Rightarrow \frac{\Delta\varepsilon_\alpha}{\varepsilon_\alpha} \approx \frac{2\Delta\varepsilon_T}{\varepsilon_T}$$

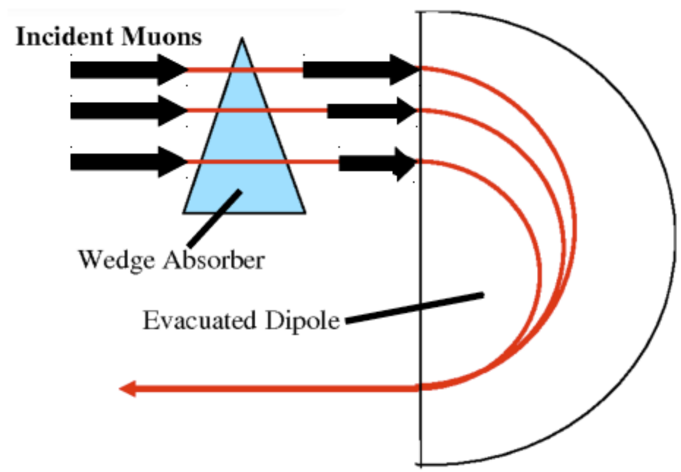
- Fractional (9%) emittance evolution 6 mm, 140 MeV/c, LiH, flip

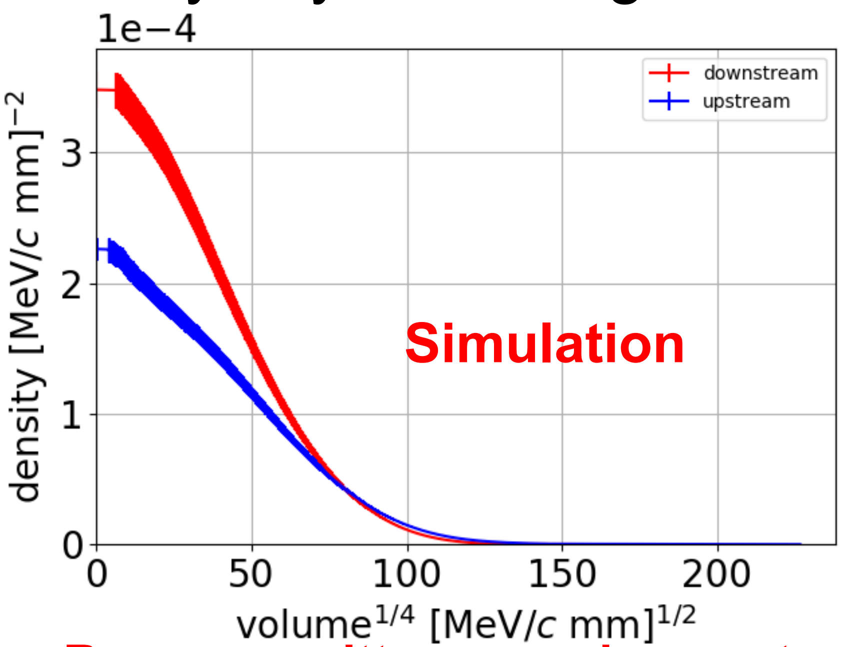


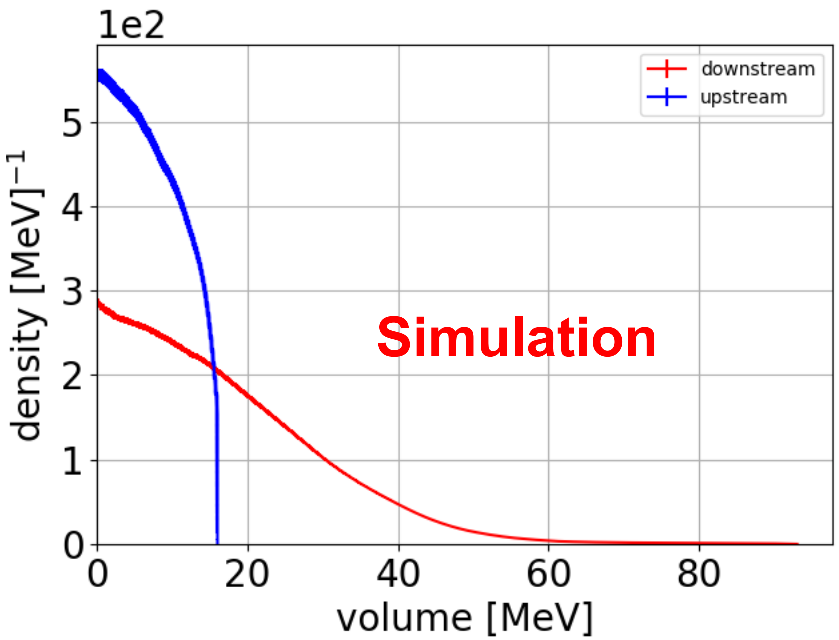
Also shows ionization cooling!

Reverse emittance exchange

- Emittance exchange: muon collider 6D cooling and g-2
- Reverse emittance exchange lengthens bunch and increases luminosity in MC
- Polyethylene wedge absorber





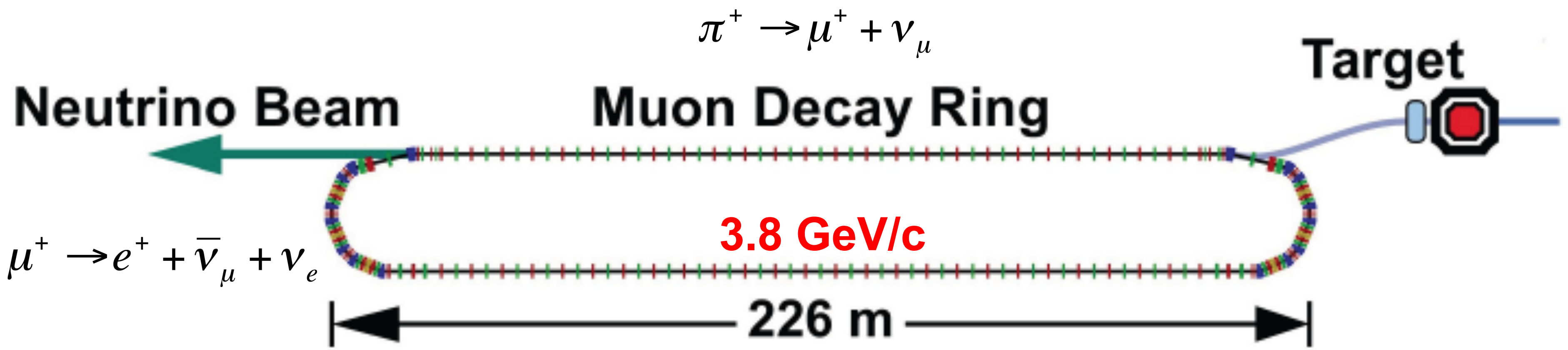


Reverse emittance exchange: transverse cooling and longitudinal heating

5. nuSTORM

nuSTORM: Neutrinos from STORed Muons

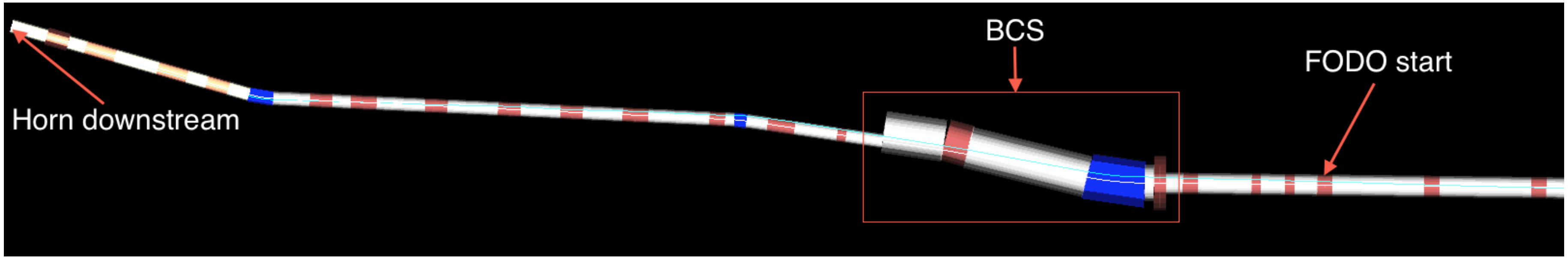
- nuSTORM: storage ring for 3.8 GeV/c muons



  - Pions of 5 Gev/c captured and injected into ring.
  - 52% of pions decay to muons before first turn: $\pi^+ \to \mu^+ + \nu_\mu$
  - For 10^{20} POT, flash of neutrinos from 8.6×10^{18} pion decays
  - Muon momentum acceptance: p = 3.8 GeV ± 10%
  - Muon decays (1 lifetime=27 orbits): $\mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e$
  - For 10^{20} POT, expect 2.6×10^{17} μ^+ decays
  - Creates hybrid beam of neutrinos from pions & muons

nuSTORM Facility

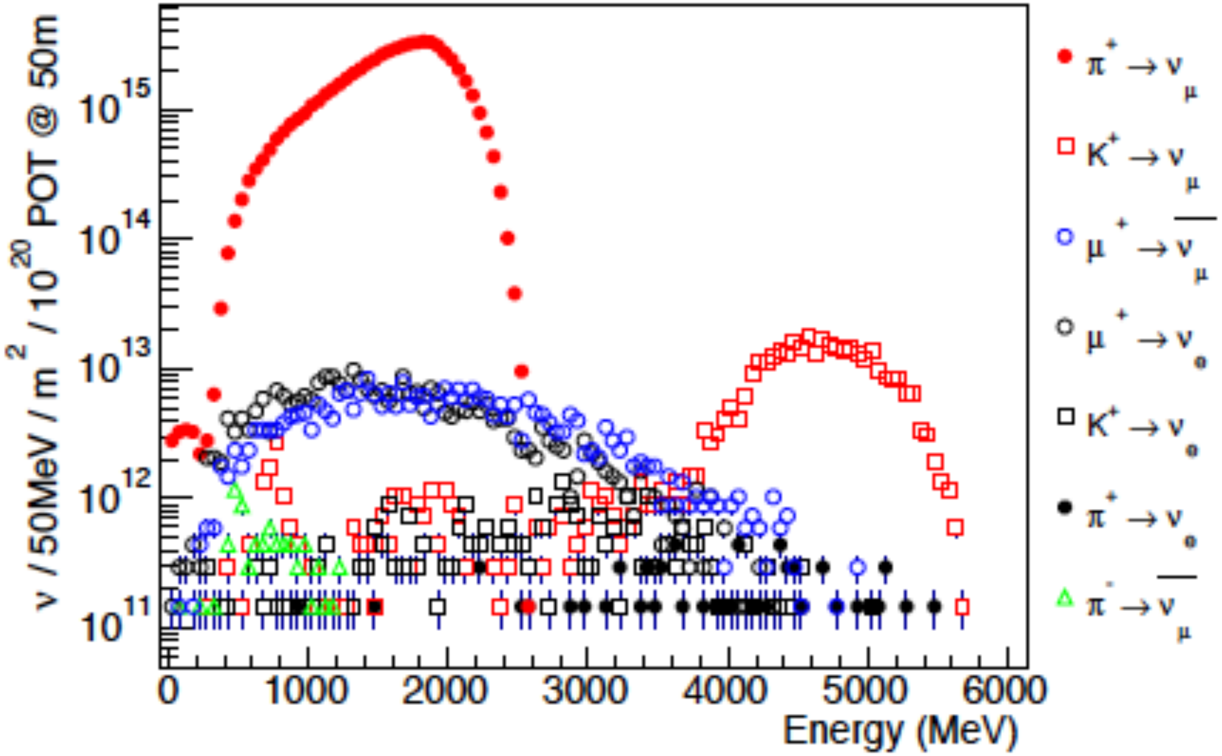
- nuSTORM facility:
  - 120 GeV protons on carbon or inconel target (100 kW)
  - NuMI-style horn for pion collection
  - Stochastic injection pions (5 GeV/c ± 10%) into storage ring: 0.09 π/POT
  - Storage ring: large aperture FODO lattice (3.8 GeV/c ± 10%) muons: 8×10^{-3} μ/POT



nuSTORM Flux

- nuSTORM flux and energy spectrum

Use muon decay neutrinos to calibrate hadron decay neutrinos?



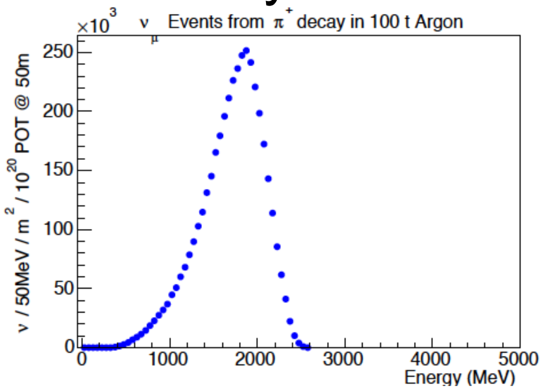
- ν_μ from pion decay $\pi^+ \rightarrow \mu^+ + \nu_\mu$ flux: 6.3×10^{16} ν/m² at 50 m
- ν_e from muon decay $\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$ flux: 3.0×10^{14} ν/m² at 50 m
- ν_μ from kaon decay $K^+ \rightarrow \mu^+ + \nu_\mu$ flux: 3.8×10^{14} ν/m² at 50 m
- Can be used for cross-section measurements and short baseline experiments

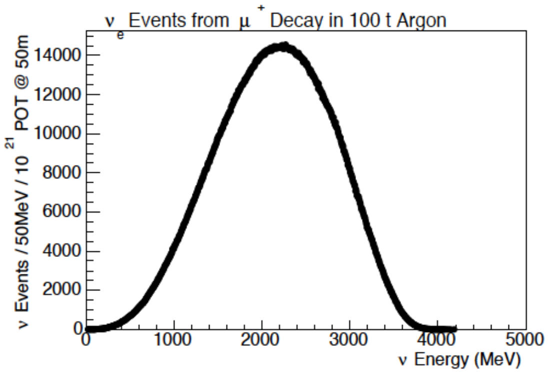
nuSTORM event rates

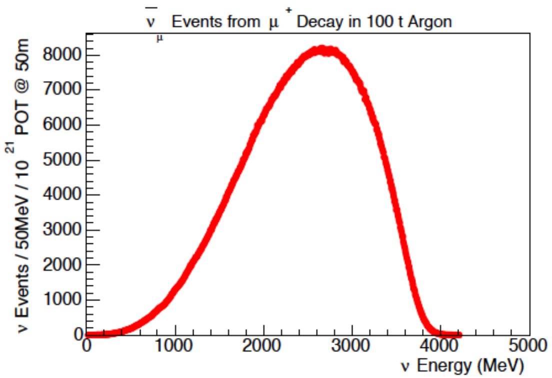
- Flux uncertainties for nuSTORM: < 1%
- Event rates per 10^{21} POT in 100 tons of Liquid Argon at 50 m

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

– Limited by detector systematics:

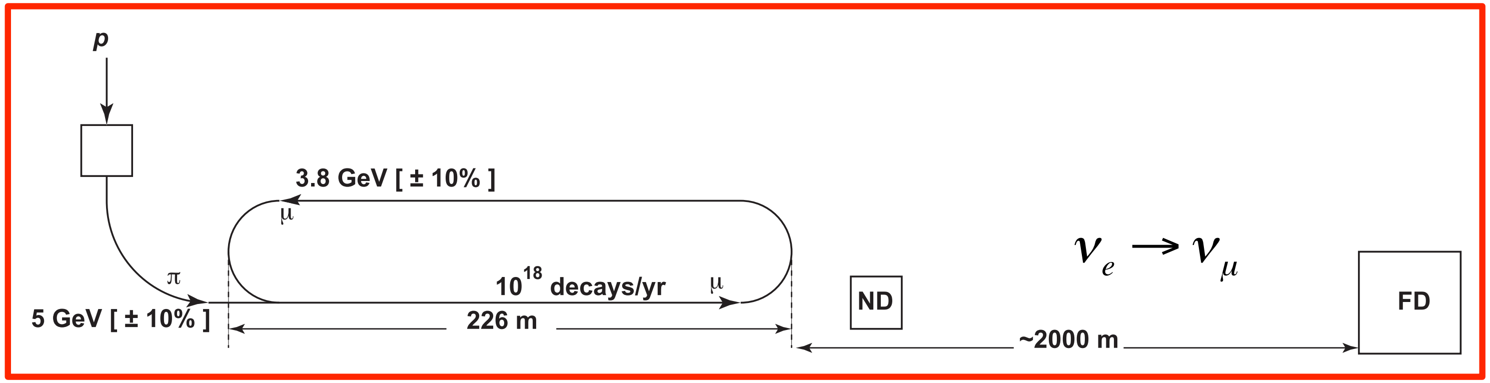




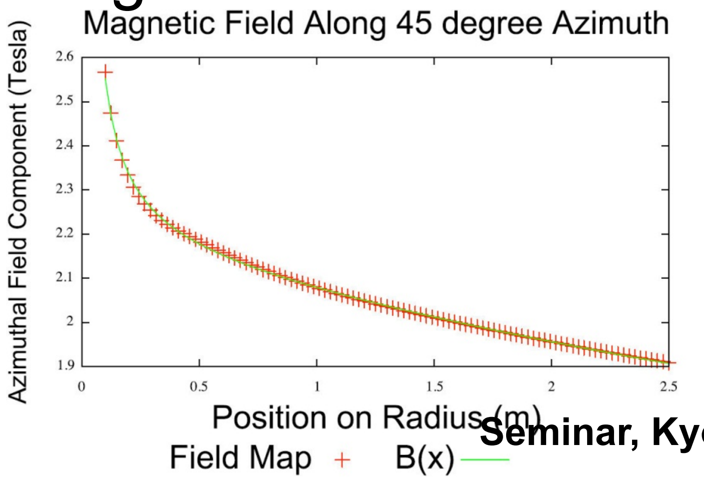


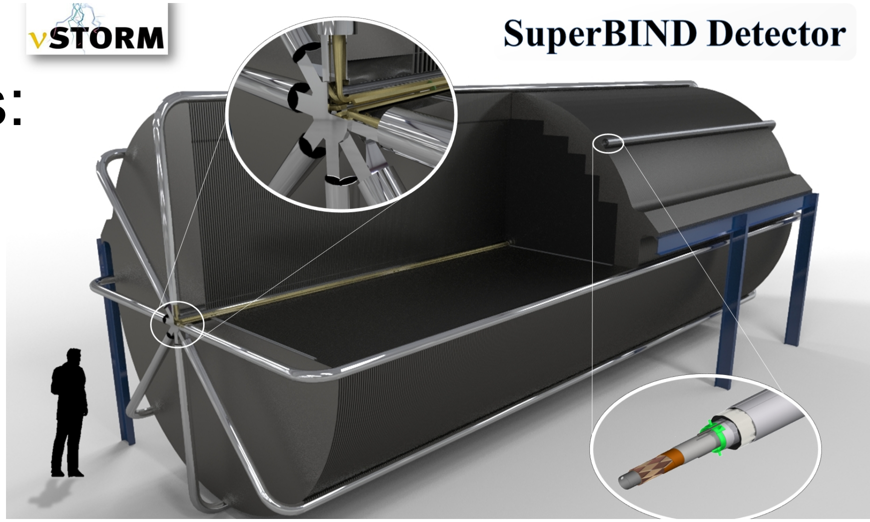
Sterile neutrino search

- Requires two magnetised detectors for neutrino oscillations:



- Super-saturated Magnetised Iron to remove wrong-sign muons: SuperBIND
- Magnetic field: 1.5-2.6 T



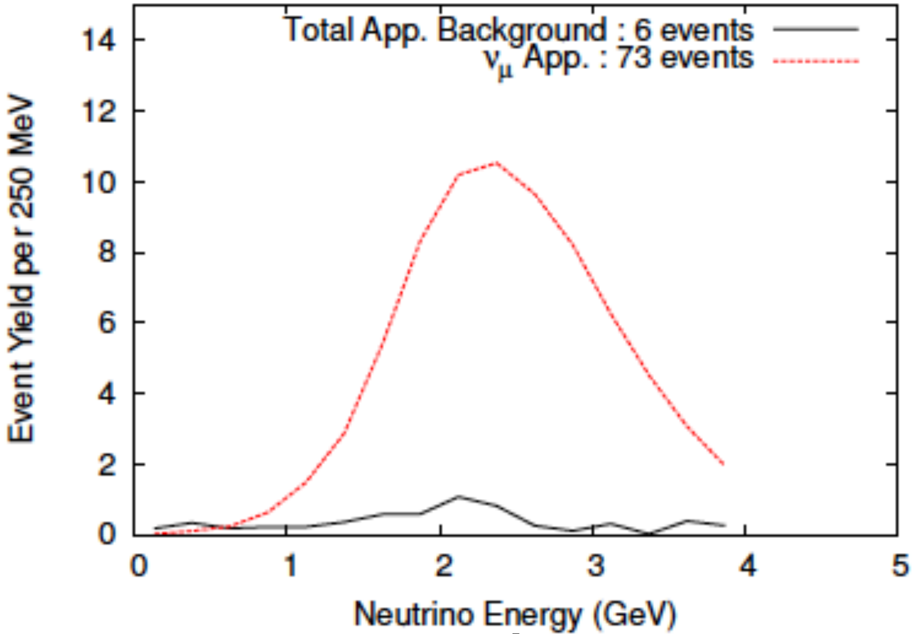


240 kA from 8 Superconducting Trasmission Lines

Sterile neutrino search

- Appearance search: **Adey et al., PRD 89 (2014) 071301**

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



With full reconstruction and efficiencies, 10^{21} POT

- Disappearance search:

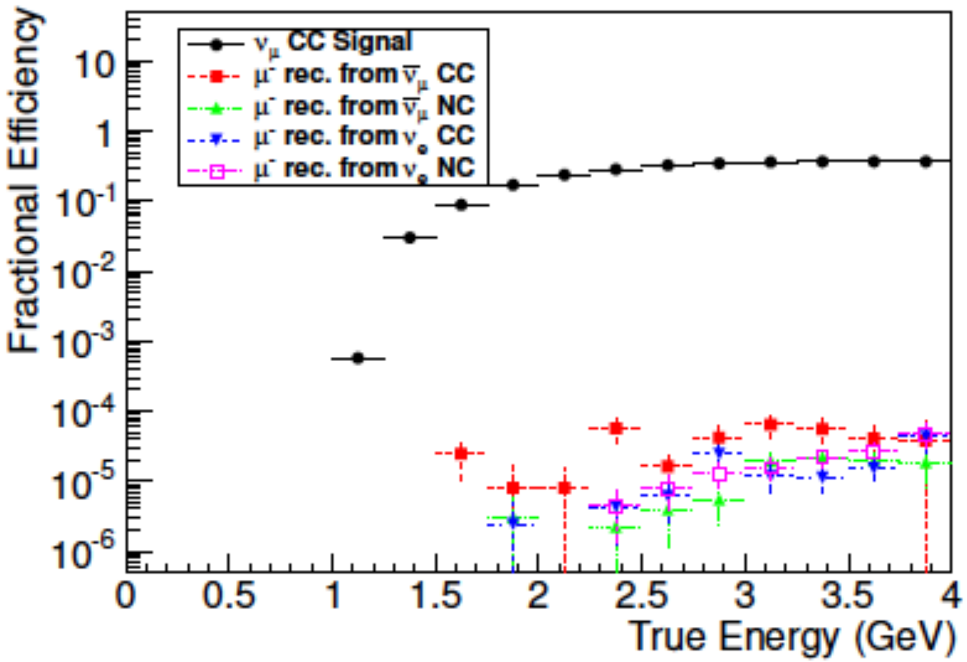
$$P_{\mu\mu}(x) = 4|U_{\mu 4}|^2 \left(1-|U_{\mu 4}|^2\right)\sin^2\left(\frac{\Delta m_{14}^2 x}{4E}\right) \equiv \sin^2(2\theta_{\mu\mu})\sin^2\left(\frac{\Delta m_{14}^2 x}{4E}\right)$$

Sterile neutrino search

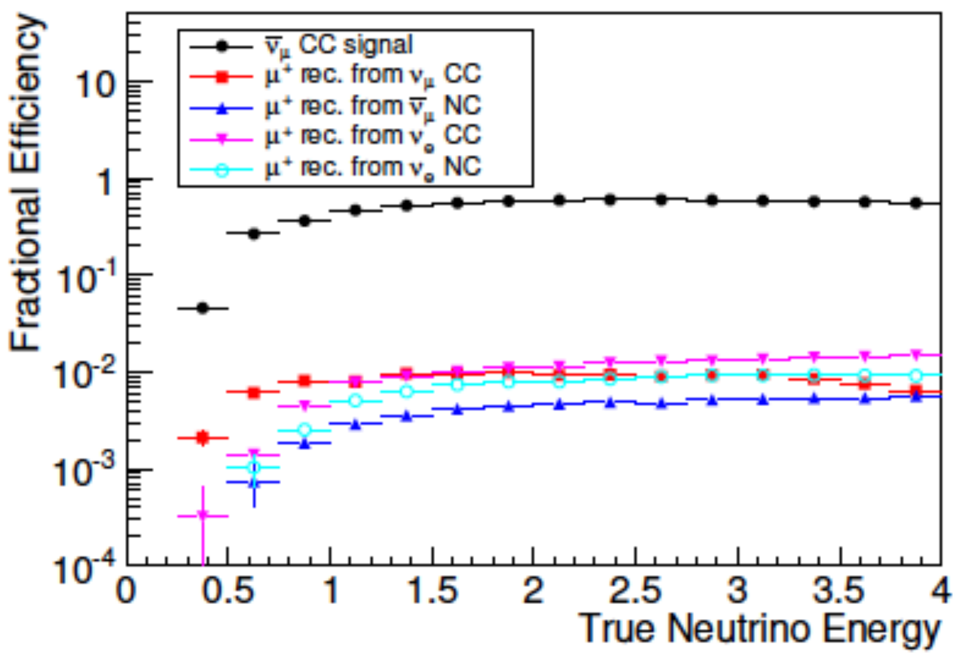
- Short-baseline oscillation search with near detector at 50 m and far detector at 2 km, 10^{21} POT exposure
- Appearance and disappearance multi-variate analyses

Adey et al., PRD 89 (2014) 071301 (Ryan Bayes' analysis)

Appearance efficiencies



Disappearance efficiencies



Sterile neutrino search

- Short-baseline oscillation search with near detector at 50 m and far detector at 2 km, 10^{21} POT exposure
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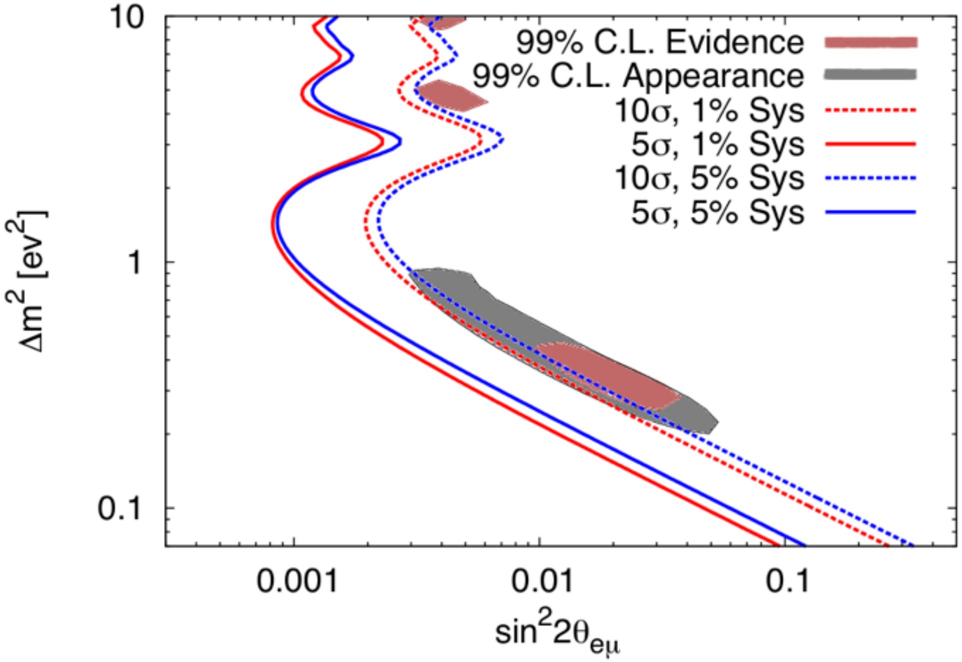
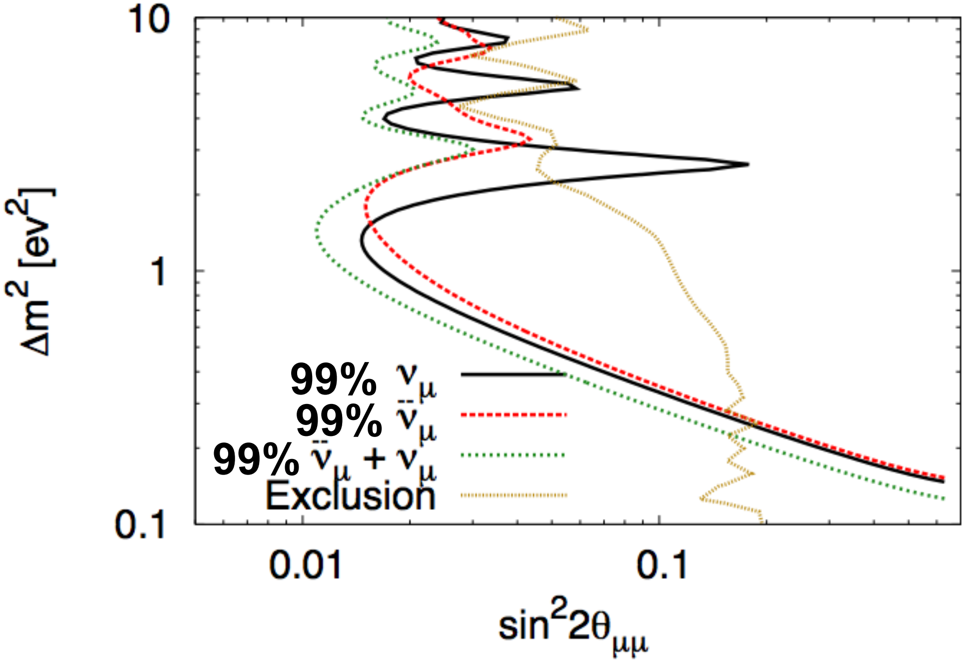
Adey et al., PRD 89 (2014) 071301 (Ryan Bayes' analysis)

Appearance sensitivity



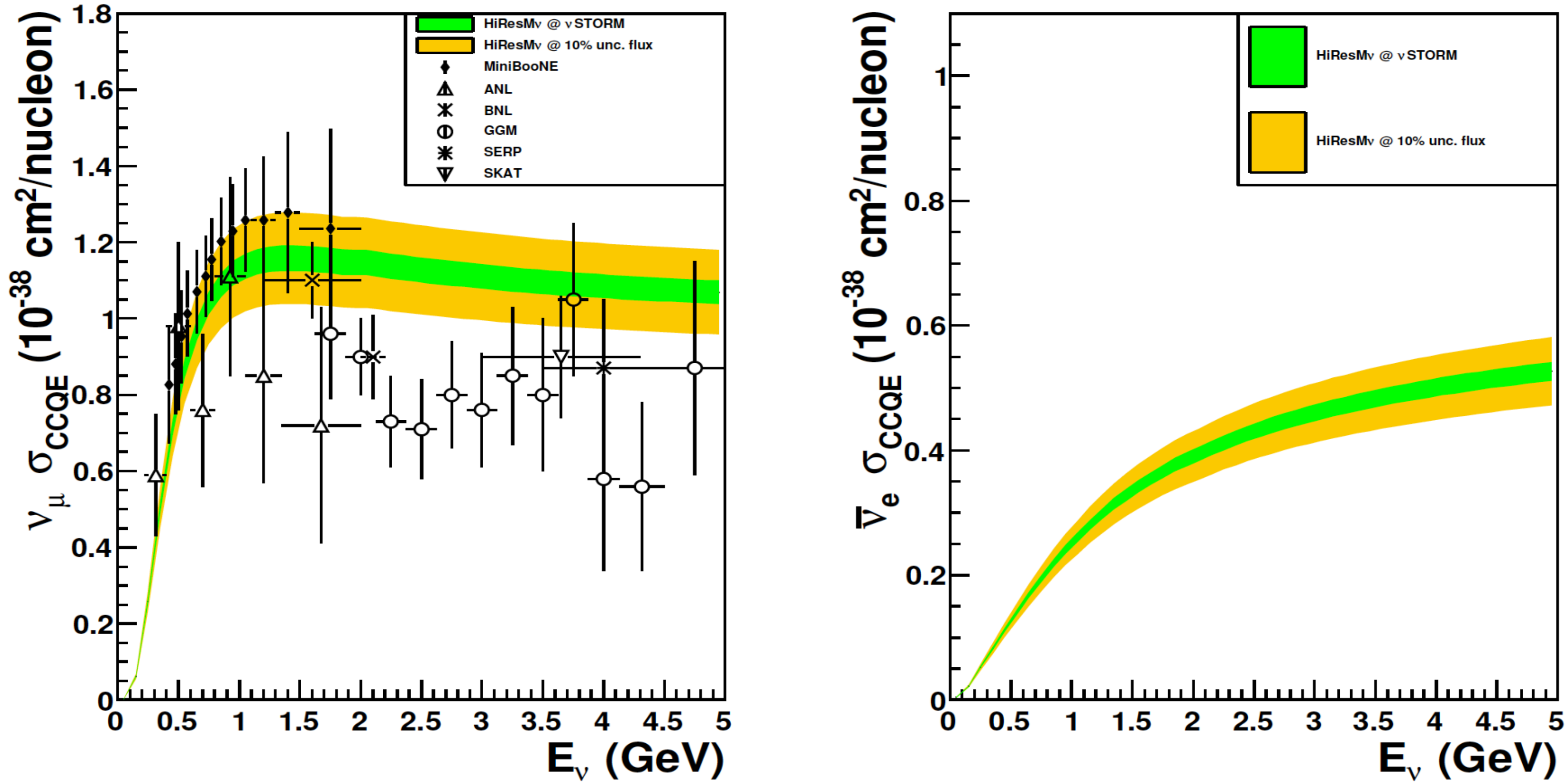
Disappearance sensitivity



After FNAL SBL programme, sterile neutrinos might not be relevant

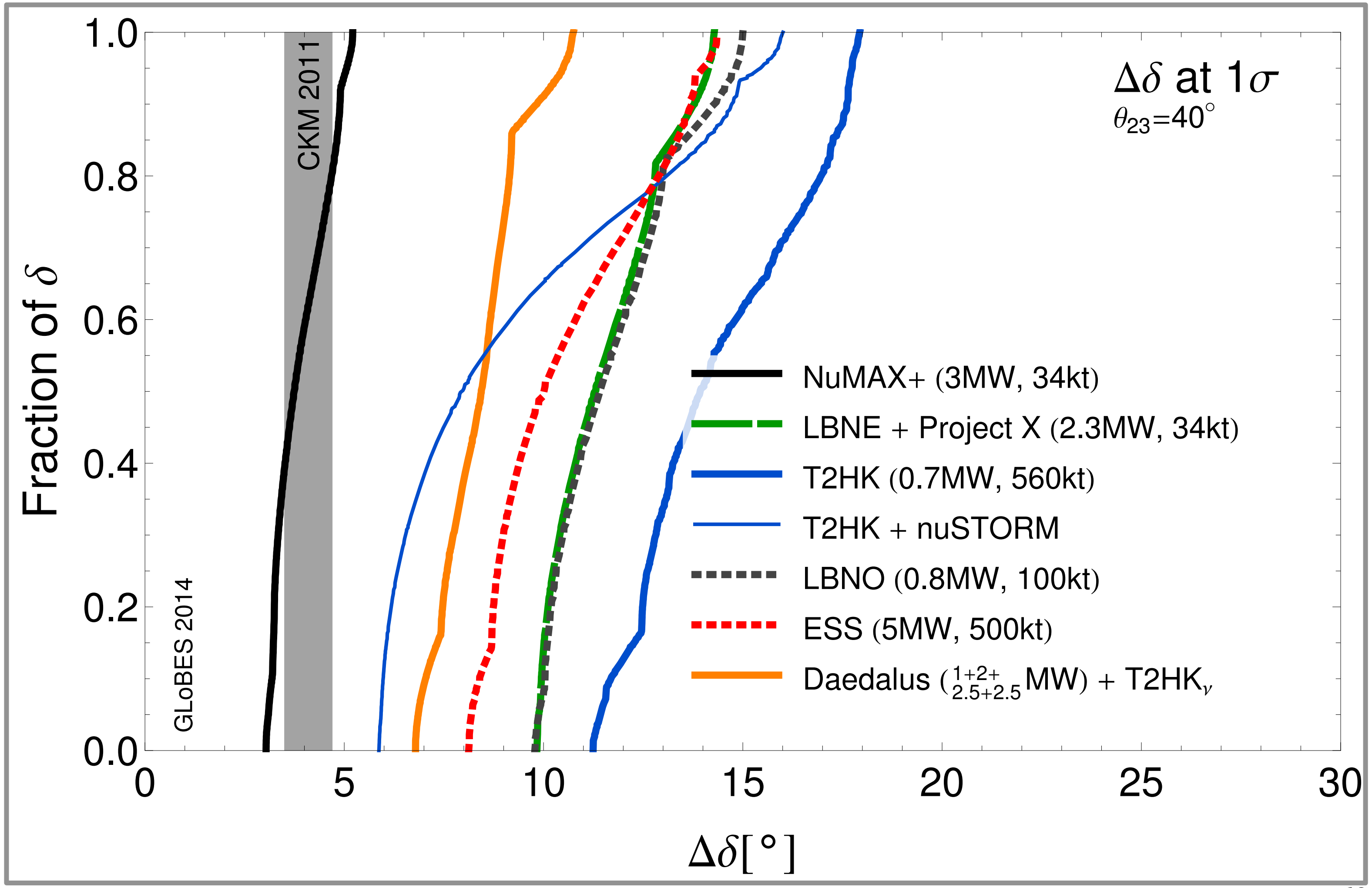
Neutrino interactions at nuSTORM

- Example of CCQE measurement errors: ~2-3%
  - Data for ν_μ and $\bar{\nu}_e$ cross-sections
  - Systematic errors completely dominated by detector



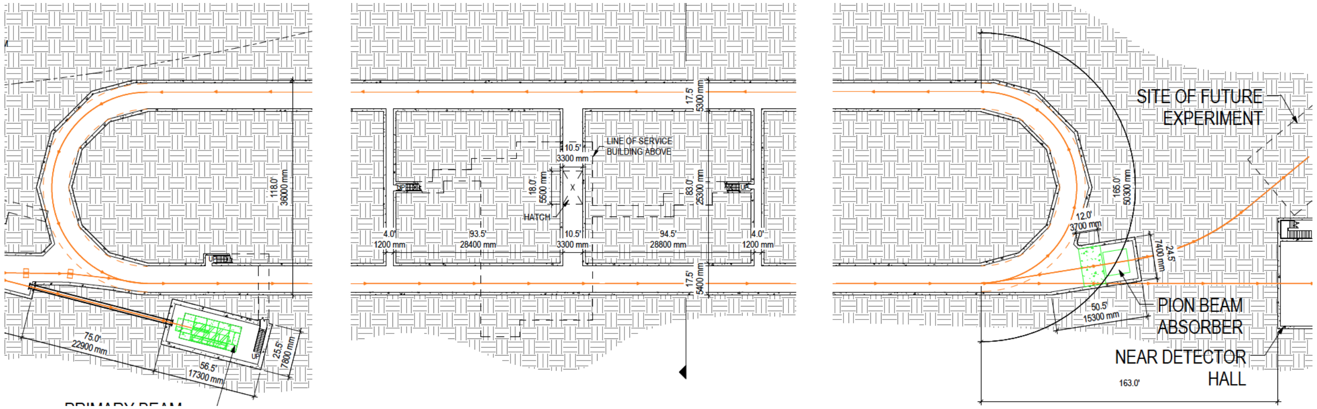
Neutrino interactions at nuSTORM

- Influence of nuSTORM cross-section measurements on DUNE and T2HK δ_{CP} measurements

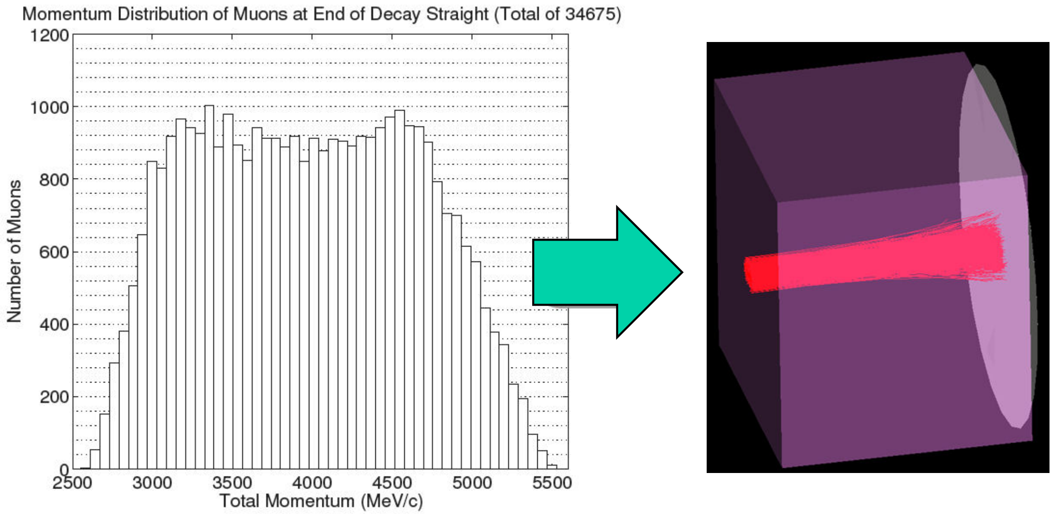


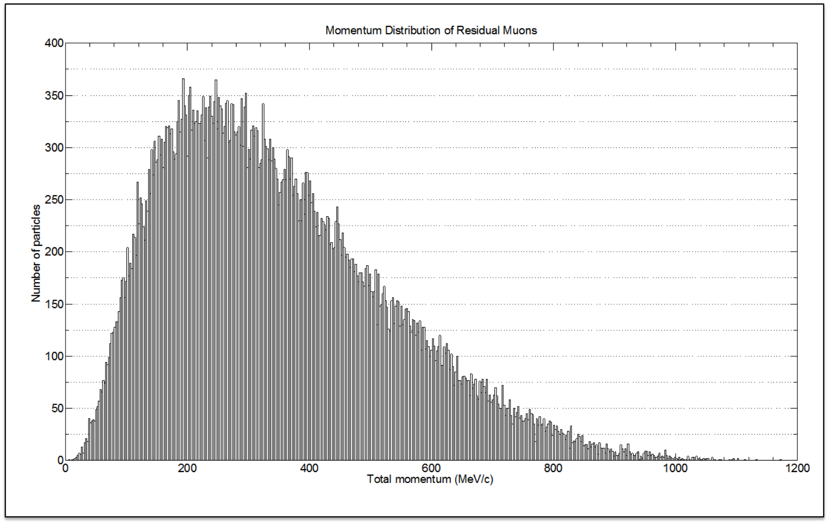
nuSTORM as 6D cooling testbed

- nuSTORM: testbed for 6D muon cooling experiment
  - At end of straight: 3.5 m iron pion absorber



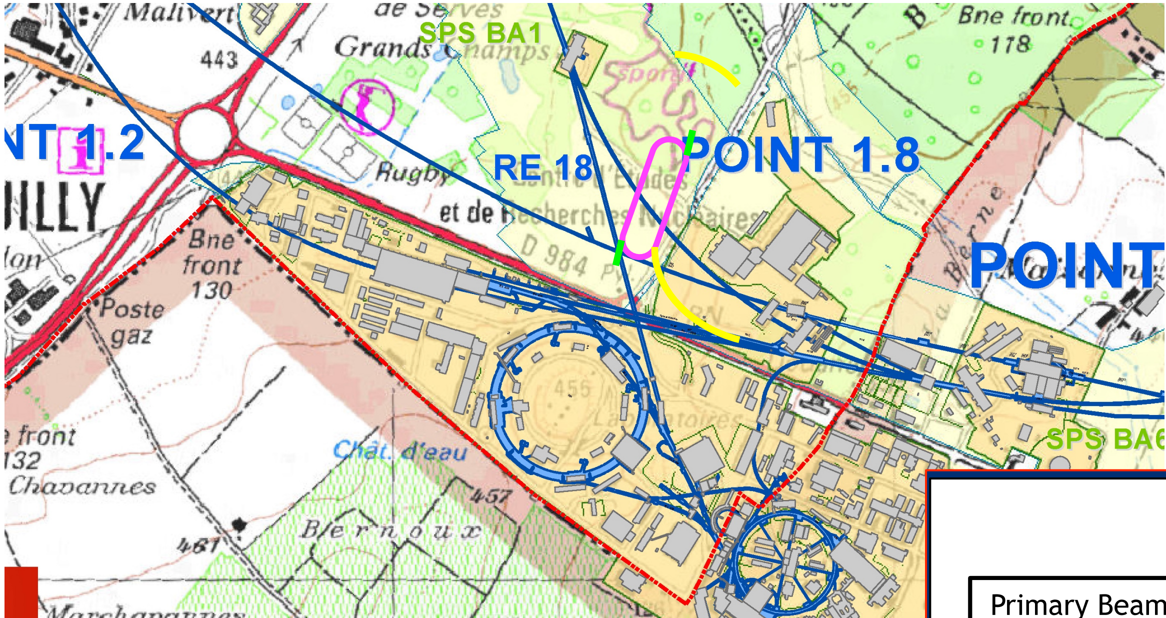
  - After absorber: 10^{10} μ/pulse between 100-300 MeV/c

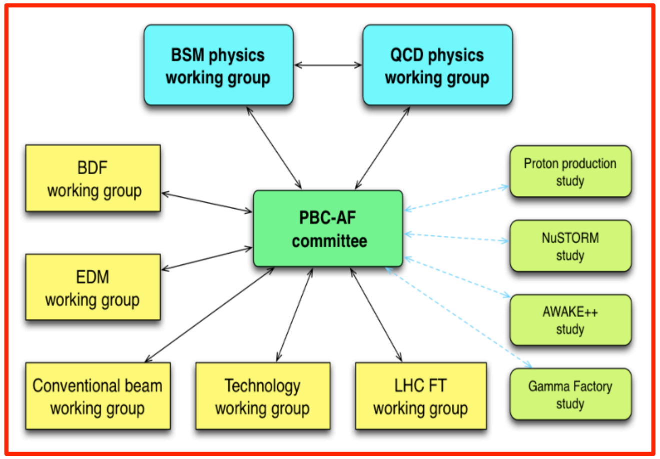


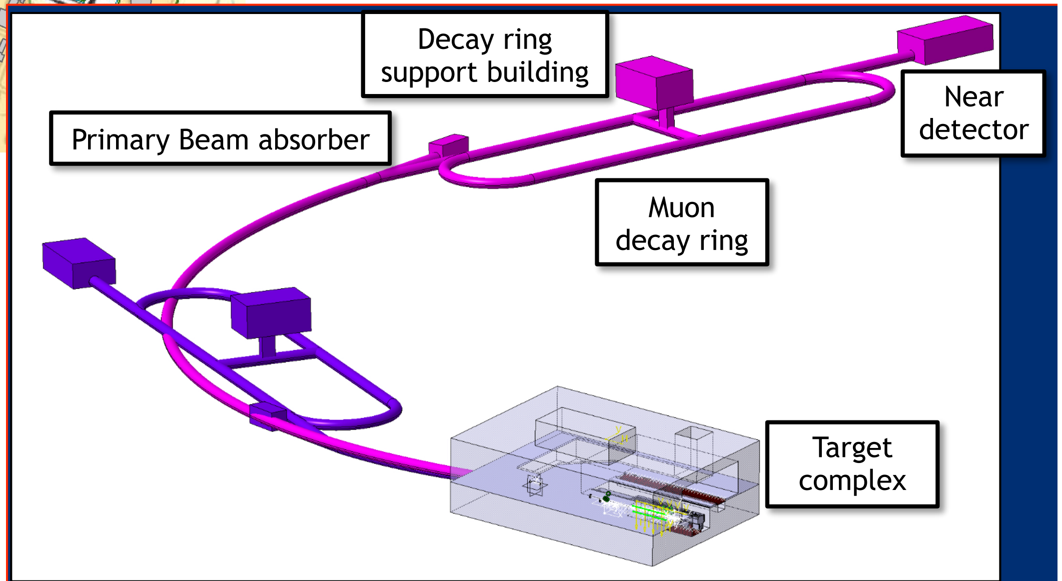


nuSTORM siting at CERN

- nuSTORM at CERN (Physics Beyond Colliders study group)







Preliminary draft target complex development

- Complementary physics programme at CERN to long-baseline experiments in Japan and USA

K. Long

Conclusions

- There is a physics case beyond Hyper-K and DUNE: test for three-neutrino paradigm and beyond Standard Model physics
- Design Study for a Neutrino Factory (IDS-NF)
  - Feasible Neutrino Factory has been designed
  - Staging of Neutrino Factory (ie. NuMAX) delivers physics at each stage
  - Provides a route to deliver high-energy muon collider
- **MICE has demonstrated muon ionization cooling for the first time: it shows that Neutrino Factory is feasible**
- NuSTORM could be first neutrino beam from muon decay
  - To be used for neutrino cross-section measurements and sterile neutrino search
  - Complementary to Hyper-K and DUNE – maximises physics impact of long-baseline experiments