THE INTERNATIONAL DESIGN STUDY FOR THE NEUTRINO FACTORY

A final report of the International Design Study for a Neutrino Factory

NUFACT13 Workshop, IHEP, Beijing

on behalf of the IDS-NF Collaboration

Paul Soler, 24 August 2013

University of Glasgow

Neutrino Factory Design Studies

"A journey of a thousand leagues begins with the first step"

Lao Tsu, "Tao te Ching", ~600 BC

- Long journey of "design studies"
  - S. Geer: Phys Rev D57, 6989 (1998) – birth of modern neutrino factory
  - 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)
  - ECFA/CERN Study: CERN-2004-002; ECFA-04-230
  - International Scoping Study: JINST 4 P07001 (2009) & T05001 (2009), Rept. Prog. Phys. 72 (2009) 106201
  - International Design Study: launched 2008, ongoing

International Design Study

- International Design Study for a Neutrino Factory (IDS-NF)
  - Principal objective: deliver Reference Design Report by 2013
    - Physics performance of the Neutrino Factory
    - Specification of each of the accelerator, diagnostic and detector systems that make up the facility
    - Schedule and cost of the Neutrino Factory accelerator, diagnostics, and detector systems.
  - Co-sponsored by EU through EUROnu
  - Web site: **https://www.ids-nf.org/wiki/FrontPage**
- Interim Design Report: IDS-NF-020 **arXiv:1112.2853** delivered 2011
- EUROnu reports: http://prst-ab.aps.org/speced/EURONU
- Reference Design Report that itemises facility, accelerator and detector performance and physics reach will be published by the end of the year

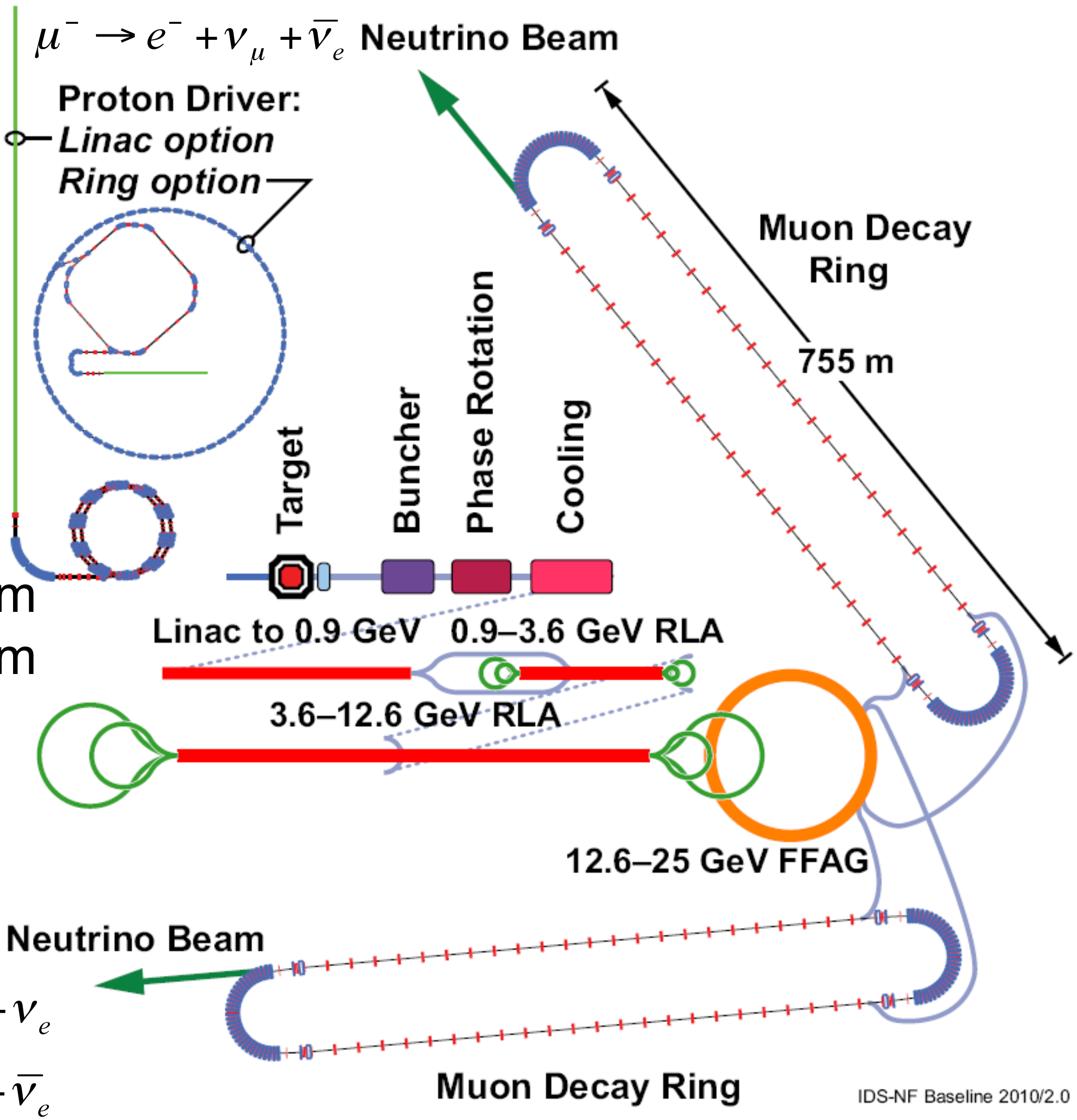
Optimisation of Neutrino Factory

- Before θ_{13} discovery, baseline design for a Neutrino Factory had two storage rings and energy was 25 GeV (v2.0)
- Two different detectors at two different baselines to reduce ambiguities in θ_{13} vs δ fits
- One baseline was ~4000 km and the other was ~7500 km (magic baseline).

arXiv:1112.2853

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

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



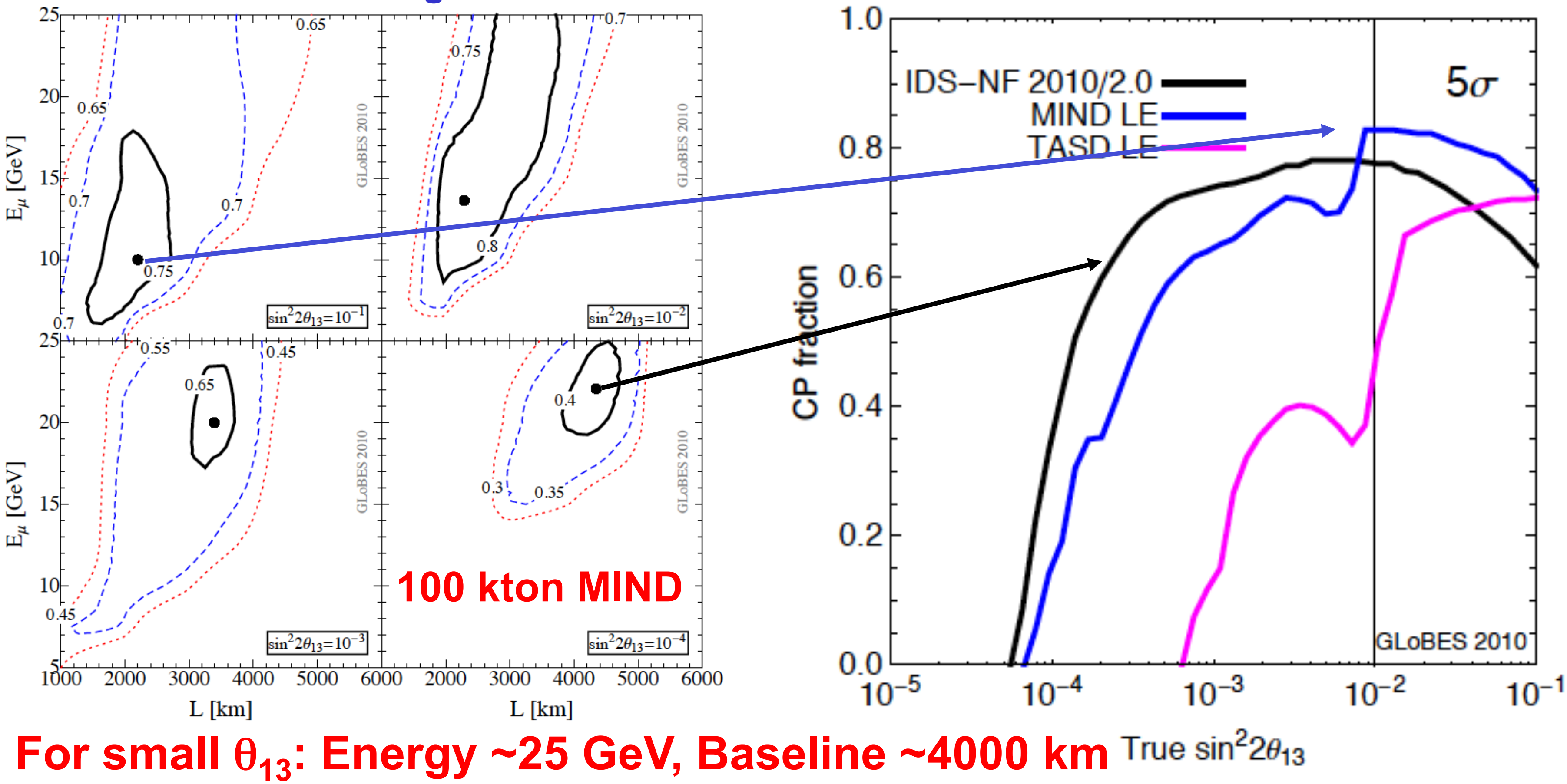
$$\mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e$$

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

Optimisation of Neutrino Factory

- Optimisation for high θ_{13}: only one baseline

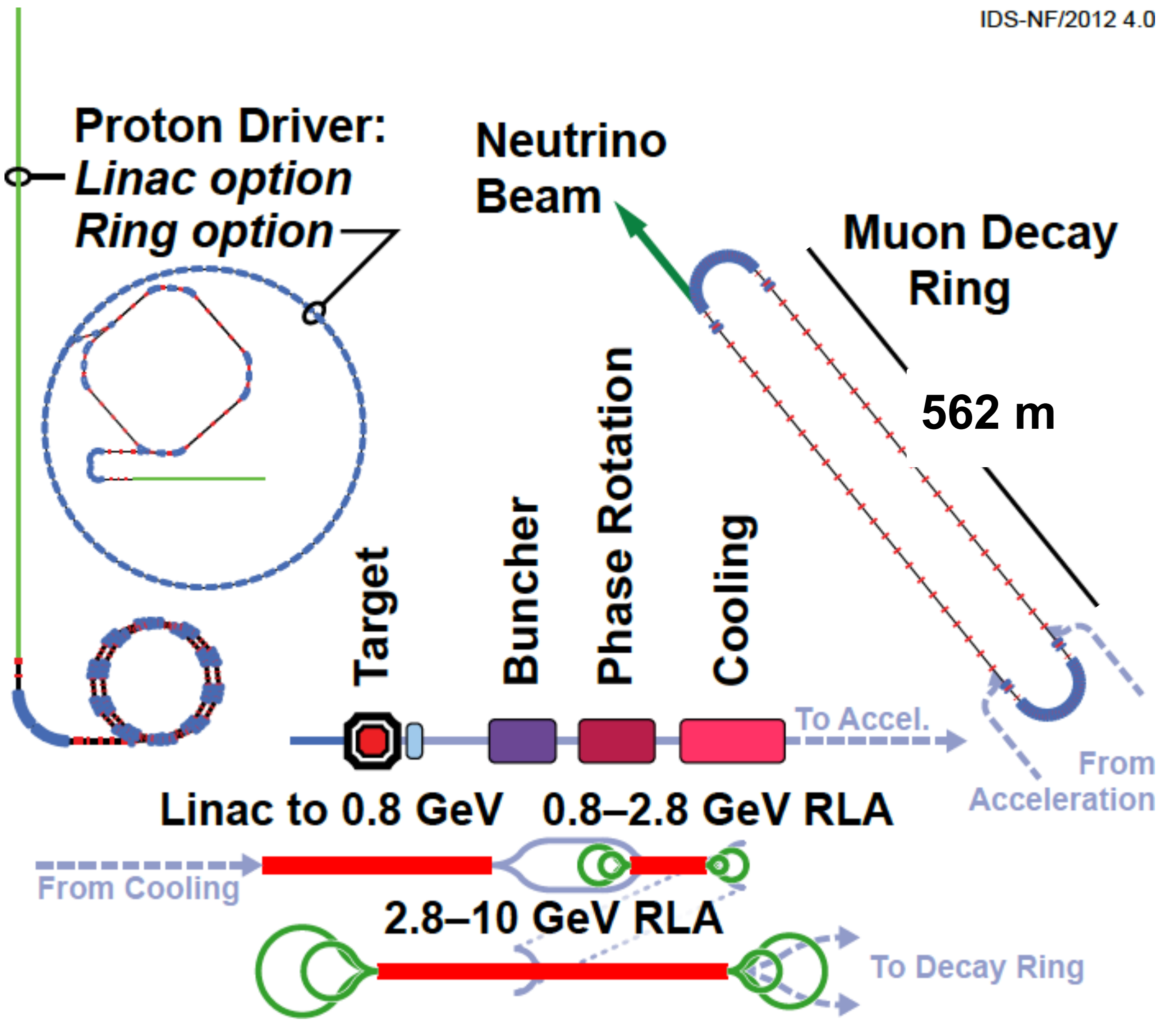
Contours of CP coverage



For small θ_{13}: Energy ~25 GeV, Baseline ~4000 km

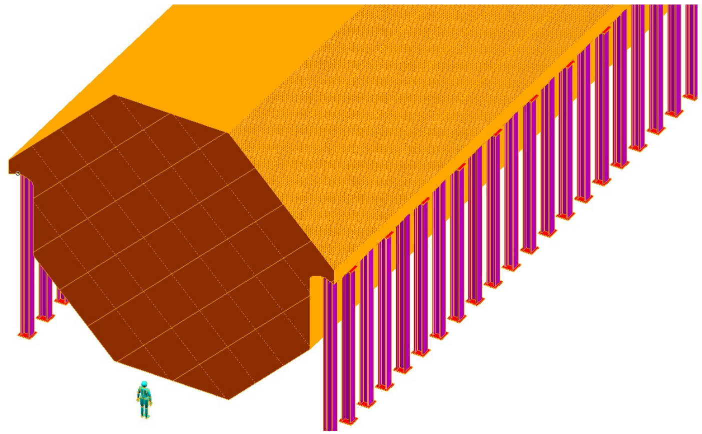
For large θ_{13}: Energy 10 GeV, Baseline ~2000 km

Neutrino Factory Baseline



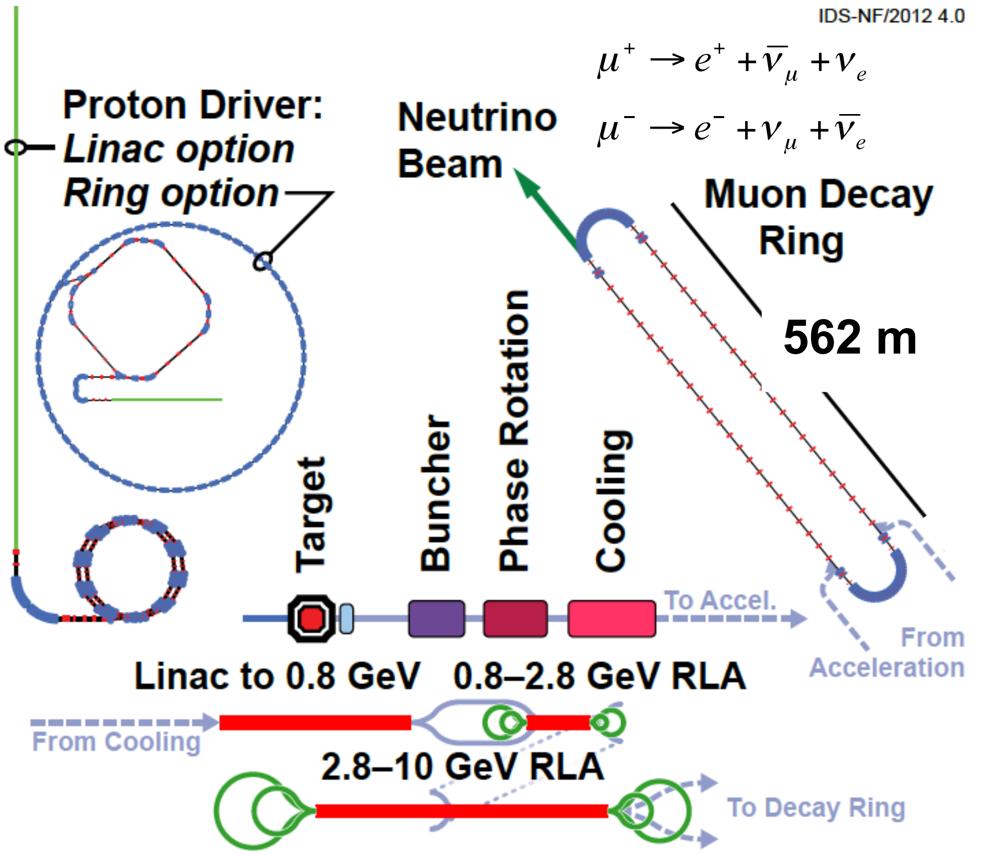
Baseline reviewed last year: from 25 GeV to 10 GeV muons (v4.0), one storage ring with detector at 2000 km, due to large θ_{13} results

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

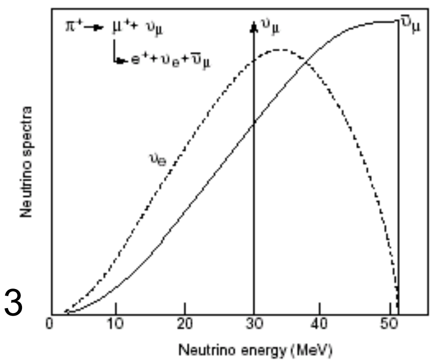


Neutrino Factory Baseline

- 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



Neutrino spectra calculable to high accuracy

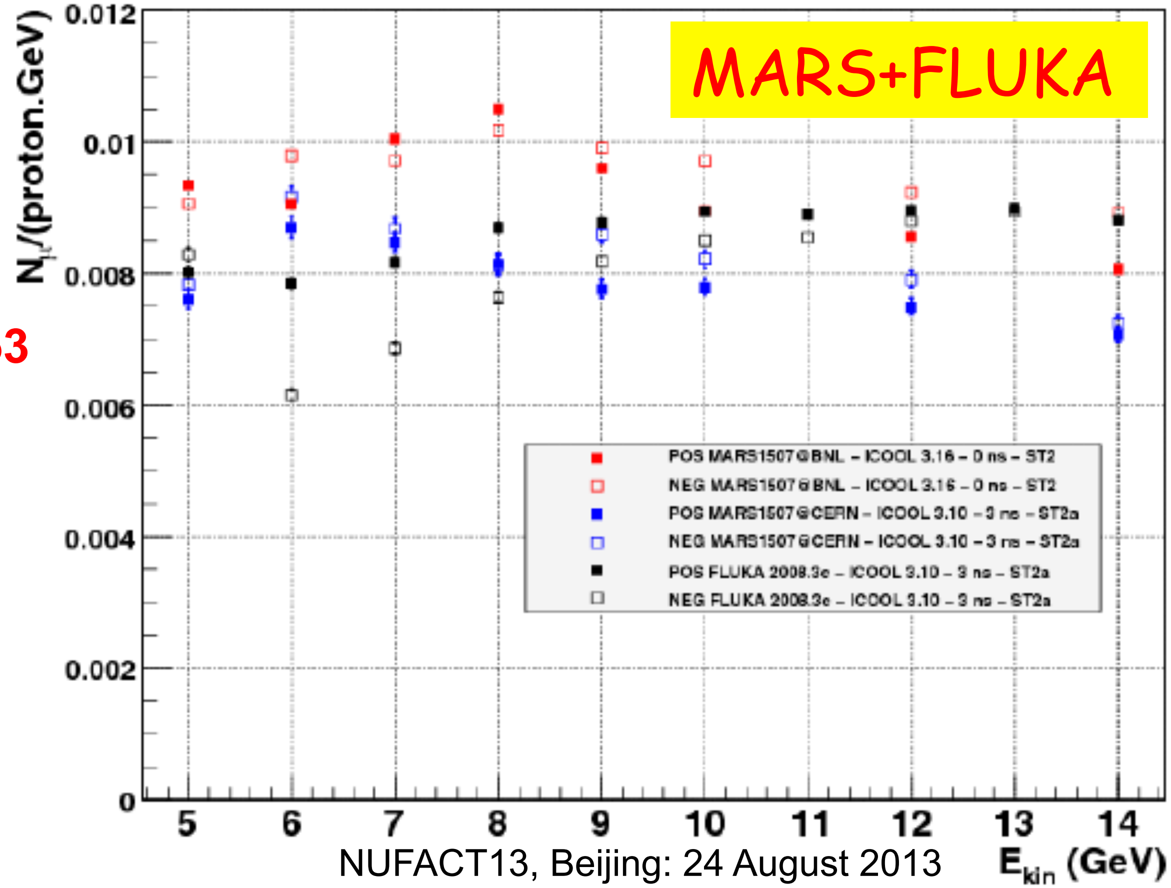


Optimum energy proton driver

- 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:

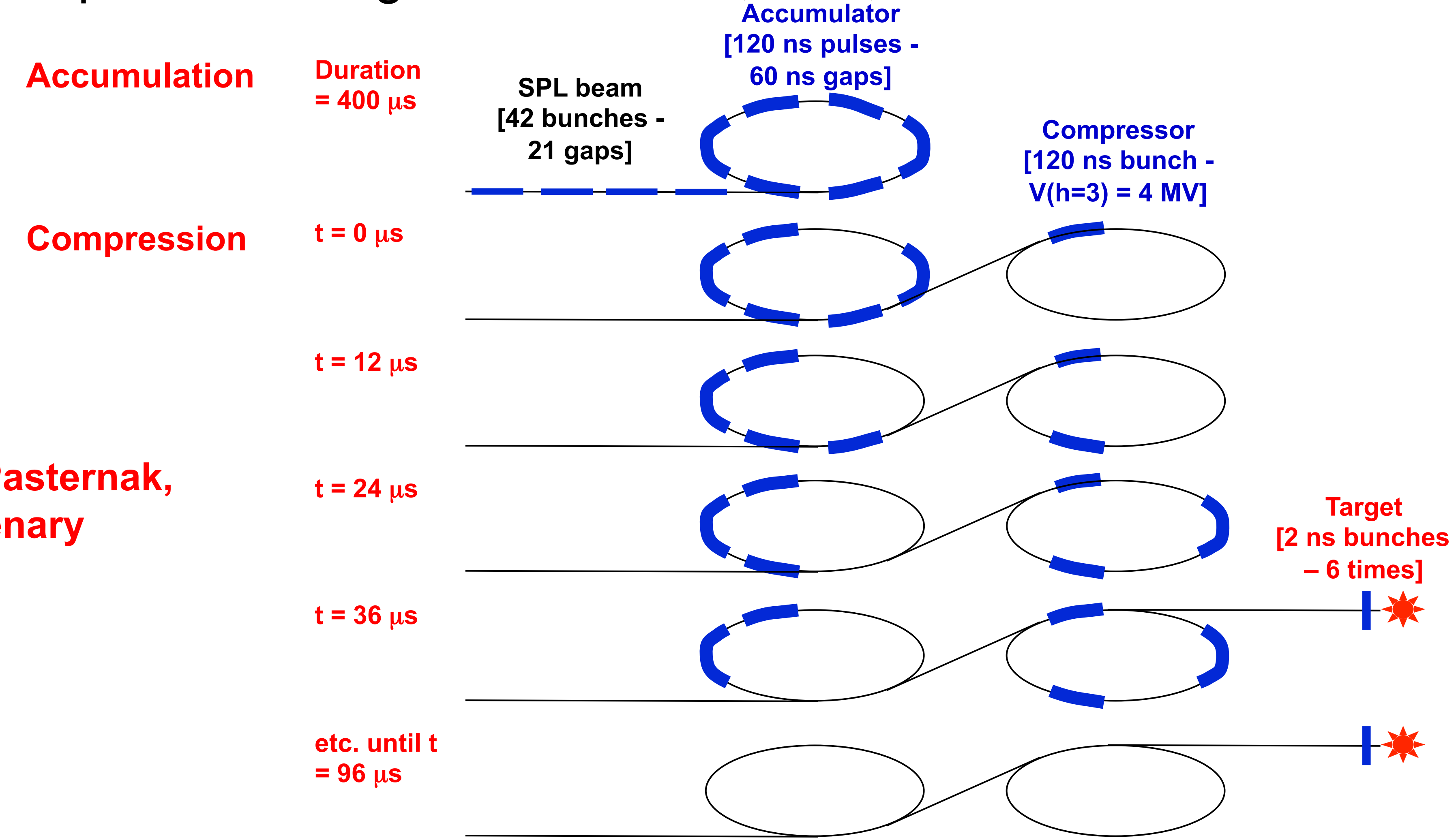
  arXiv:1112.2853

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	$< 5\ \mu$m
β^* at target	≥ 30 cm

- Choice is regional decision
  - LINAC based (SPL) proton driver at CERN
  - Synchrotron(s)/FFAG based proton driver (green field solution) – studied at RAL.
  - Project X LINAC based solution at Fermilab.

Proton Driver (SPL)

- Superconducting Proton LINAC, SPL, at CERN: 5 GeV

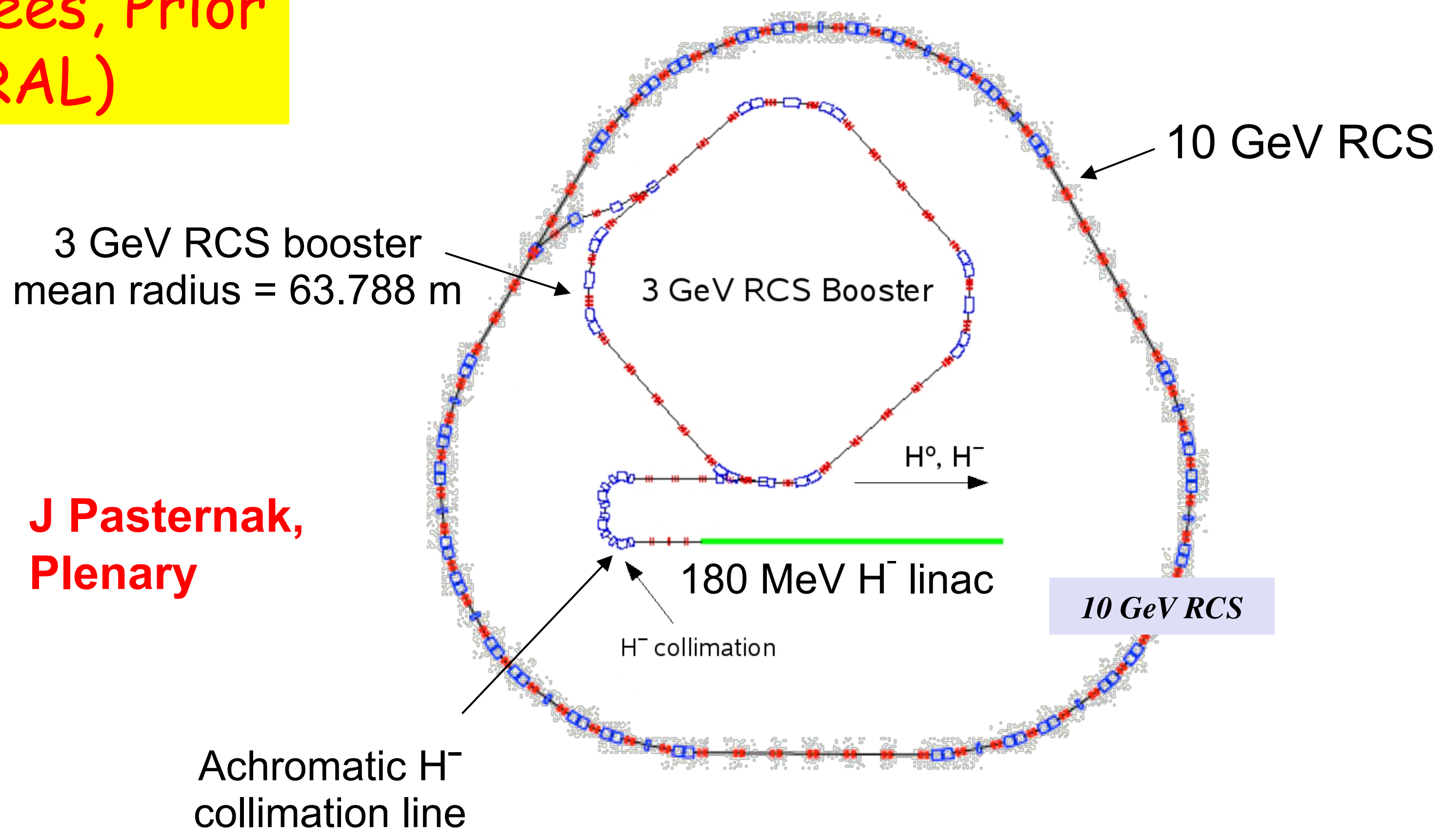


J Pasternak, Plenary

Proton Driver (RCS)

- Hardware options: 4 MW operation
  - Option with a Rapid Cycling Synchrotron (RCS)

Rees, Prior (RAL)



J Pasternak, Plenary

Proton Driver (RCS)

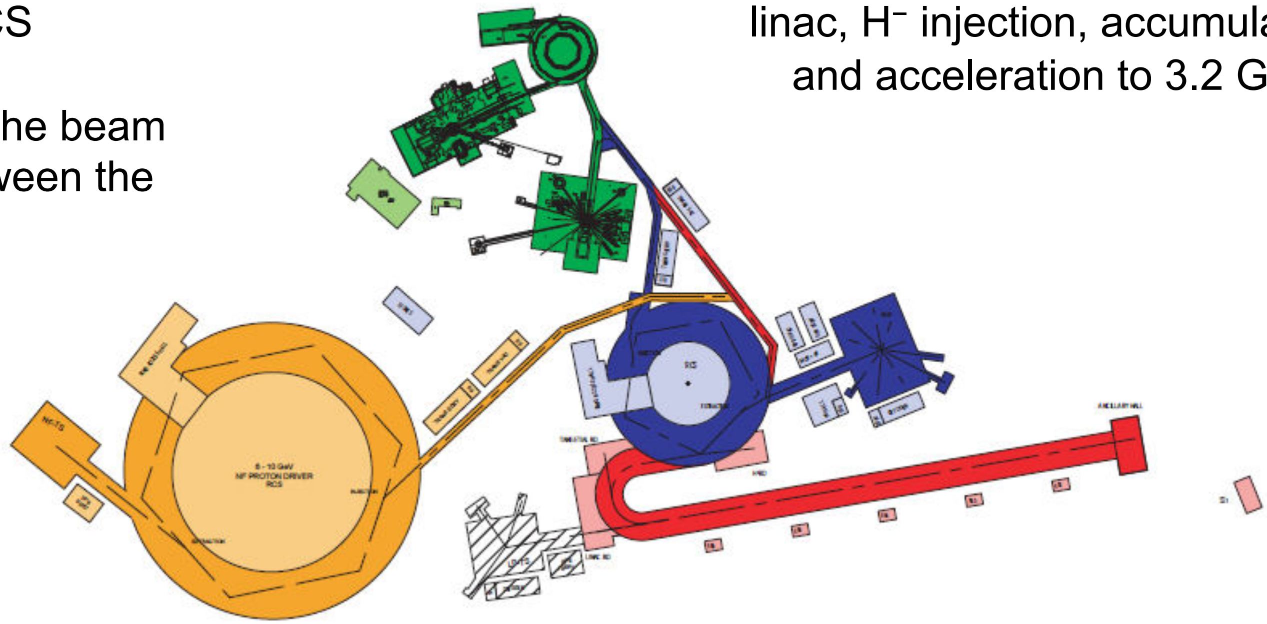
❑ Solution found around ISIS upgrade at RAL

- Based on MW ISIS upgrade with 800 MeV Linac and 3.2 (≈ 3.3) GeV RCS

- Assumes a sharing of the beam power at 3.2 GeV between the two facilities

- Requires additional RCS machine in order to meet the power and energy needs of the Neutrino Factory

- Both facilities can have the same ion source, RFQ, chopper, linac, H^- injection, accumulation and acceleration to 3.2 GeV



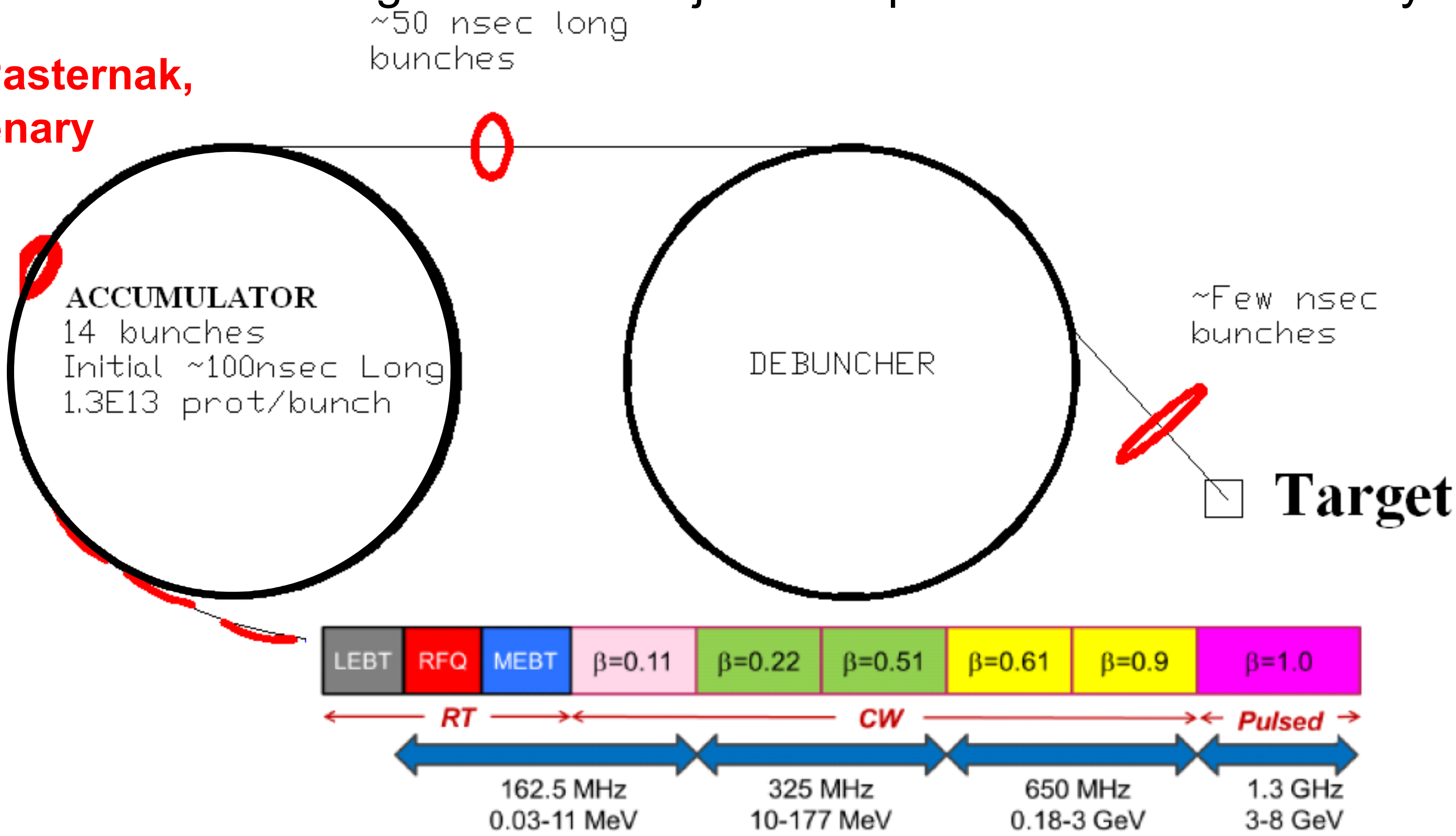
J Pasternak, Plenary

- Options for the bunch compression to 1 – 3 ns RMS bunch length:
  - adiabatic compression in the RCS
  - ‘fast phase rotation’ in the RCS
  - ‘fast phase rotation’ in a dedicated compressor ring

Proton Driver (Project X)

- Hardware options: 1-4 MW operation from 3-8 GeV
  - Staging of Project X facility at Fermilab
  - Final configuration of Project X required for neutrino factory

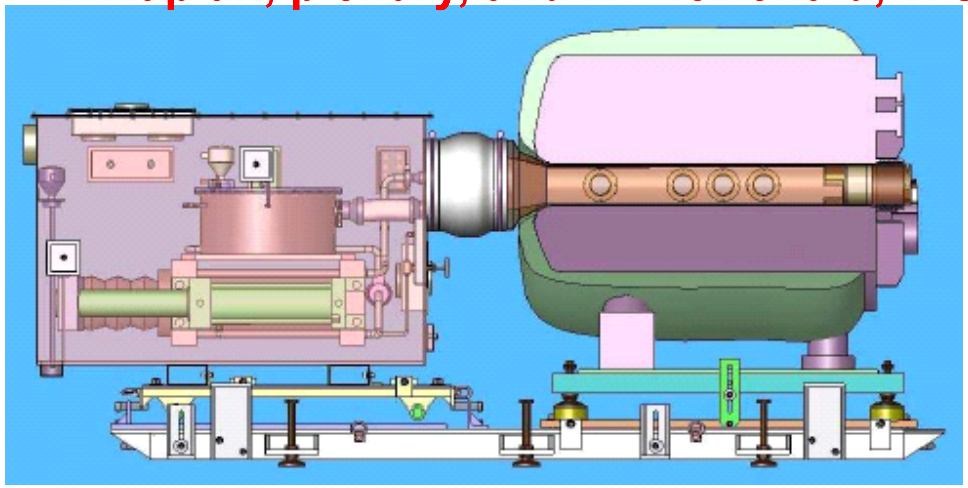
J Pasternak, Plenary

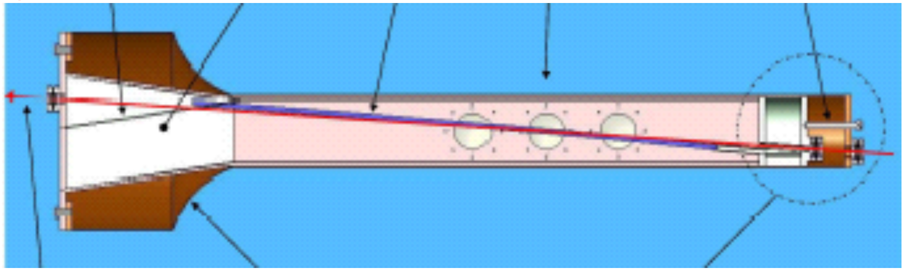


Target R&D: MERIT

- MERIT experiment tested Hg jet in 15-T solenoid
  - 24 GeV proton beam from CERN PS: experiment ran 2007

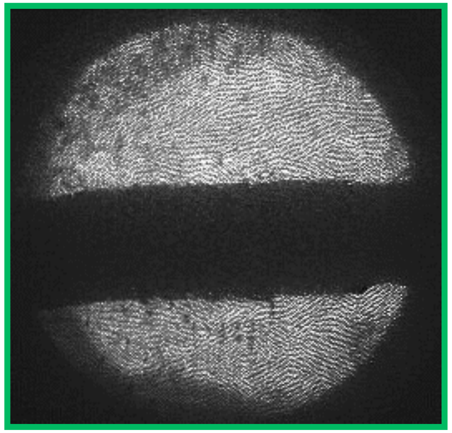
D Kaplan, plenary, and K. McDonald, WG3

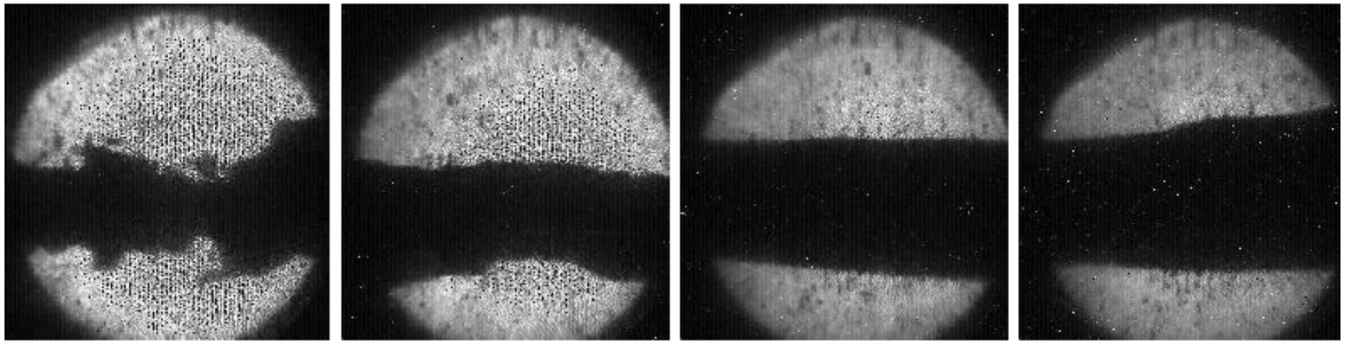




MERIT experiment showed proof-of-principle of Hg jet system in magnetic field – rated up to 8 MW

- Results MERIT: Hg jet (v=20 m/s) target operated at 8 MW in 15 T field



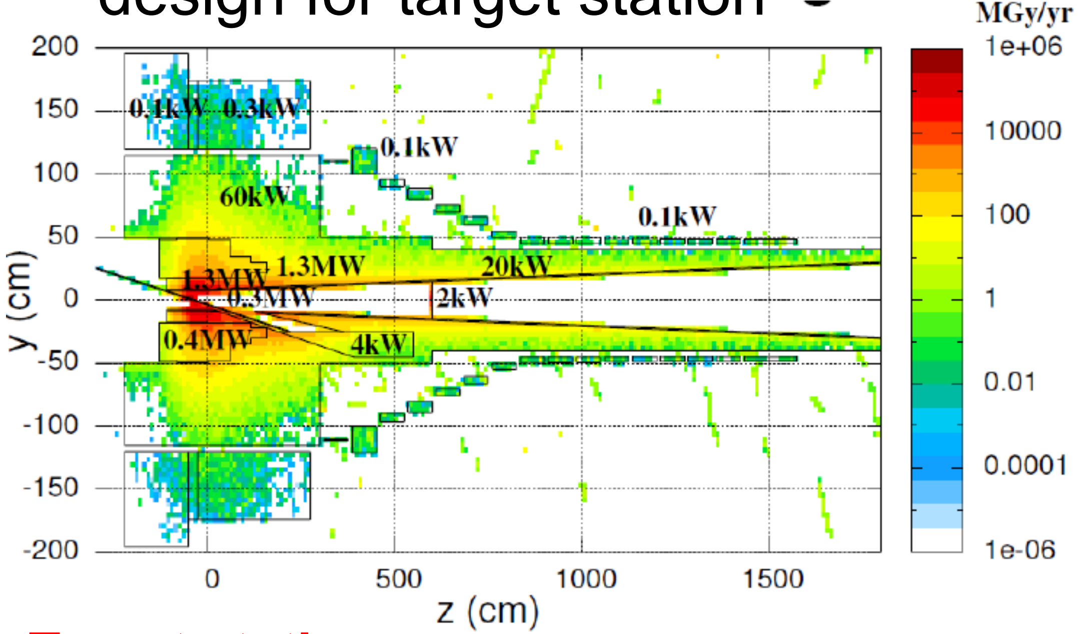


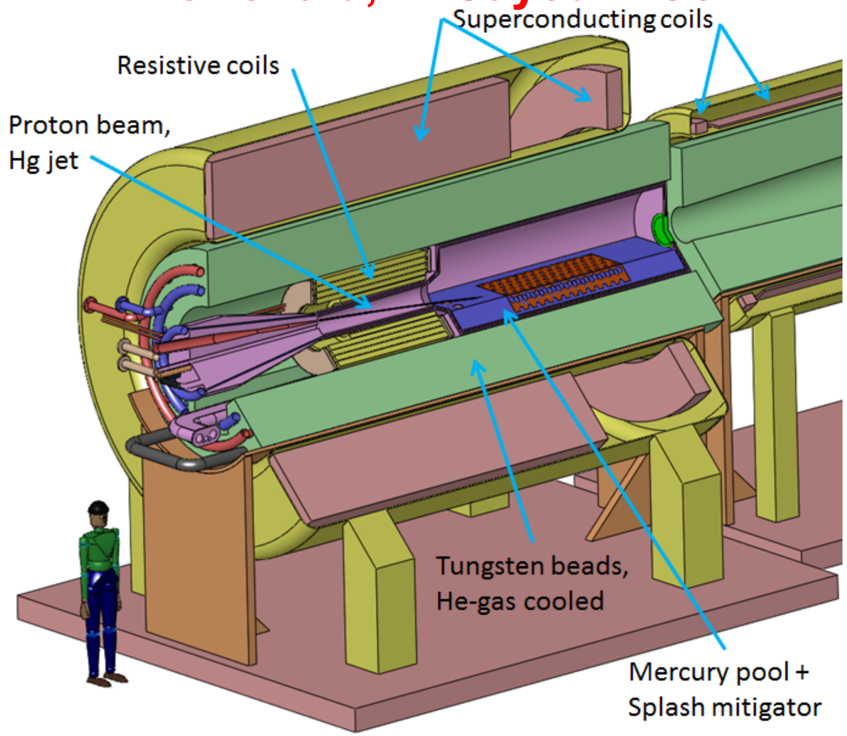
0T 5 T 10 T 15 T

Target

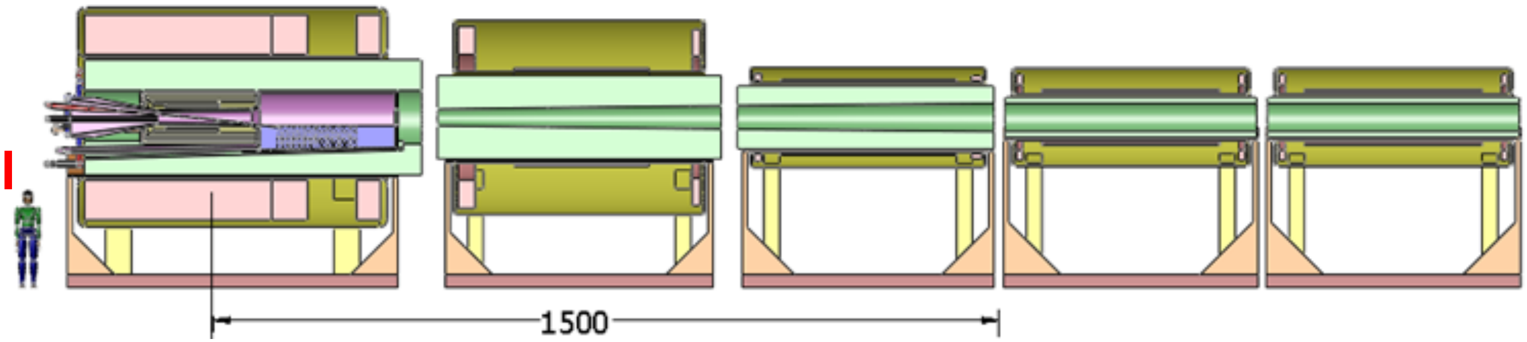
- Had to increase radiation shielding in solenoid surrounding new design for target station

K. McDonald, H. Sayed WG3





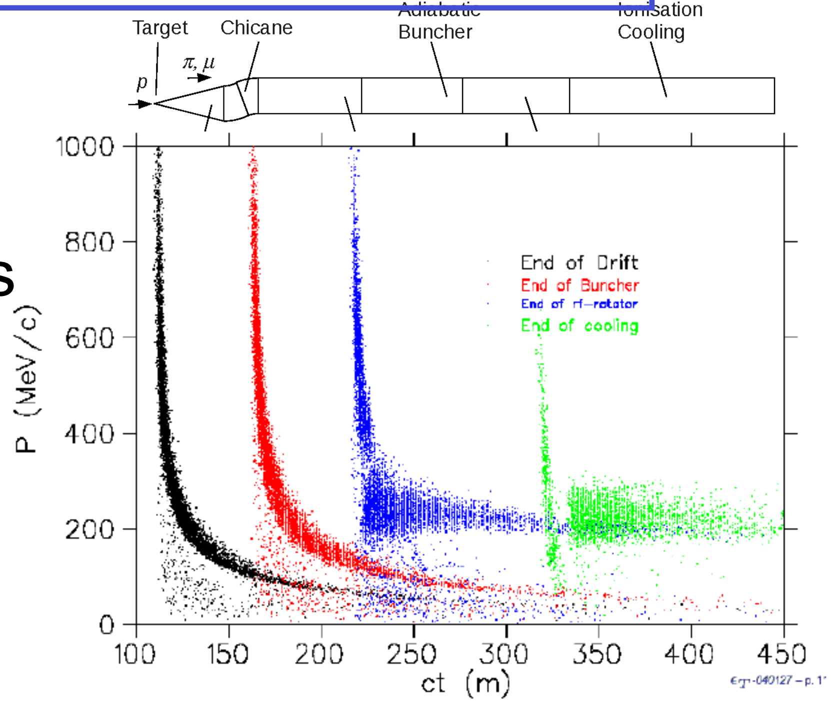
Target station and start of decay channel

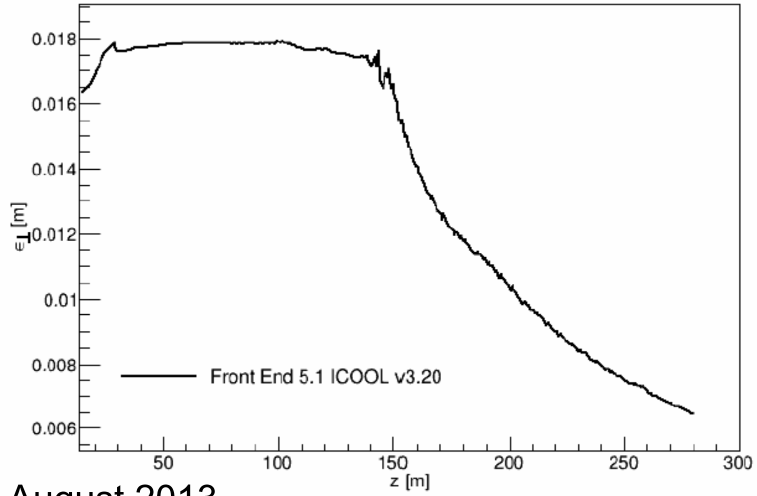


Muon Front End

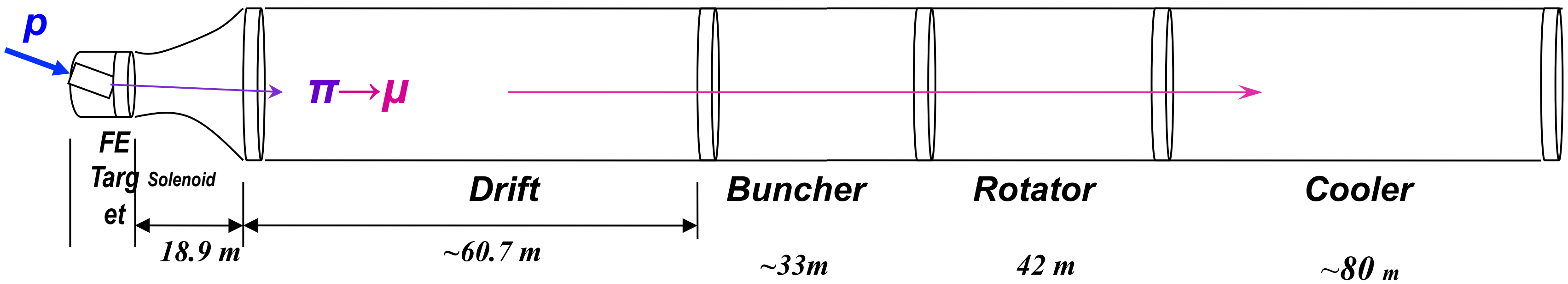
D. Neuffer, WG3

- Adiabatic B-field taper from Hg target to longitudinal drift
- Added chicane to remove protons
- Drift in ~1.5 T, ~60 m solenoid
- Adiabatically bring on RF voltage to bunch beam
- Phase rotation using variable frequencies
  - High energy front sees -ve E-field
  - Low energy tail sees +ve E-field
  - End up with smaller energy spread
- Ionisation Cooling
  - Try to reduce transverse beam size
  - Prototyped by MICE

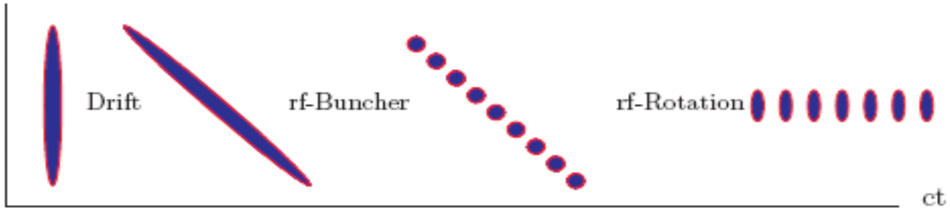




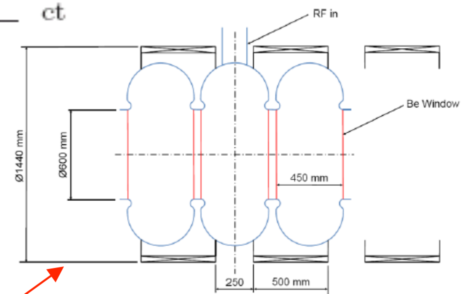
Muon Front End

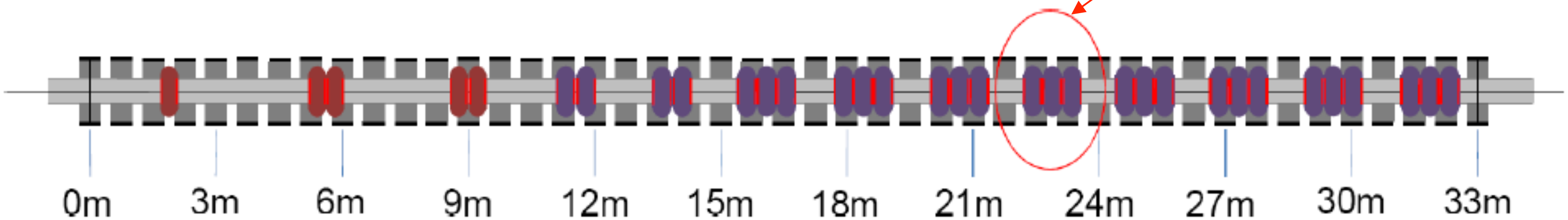


D. Neuffer, WG3

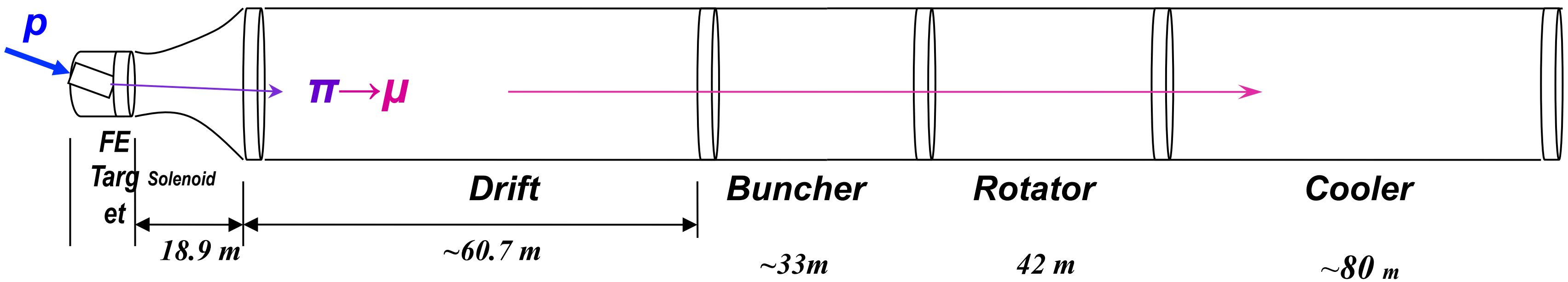


- Buncher:
  - 33 normal conducting RF cavities
  - RF frequency: 320-232 MHz
  - Gradient: 3.4-9.7 MV/m

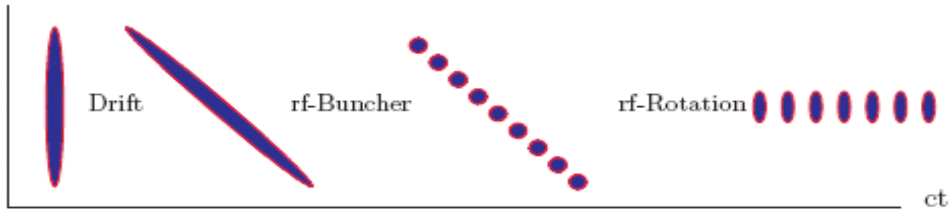


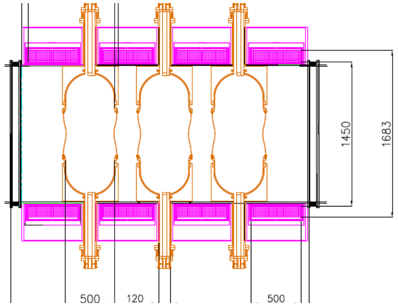


Muon Front End

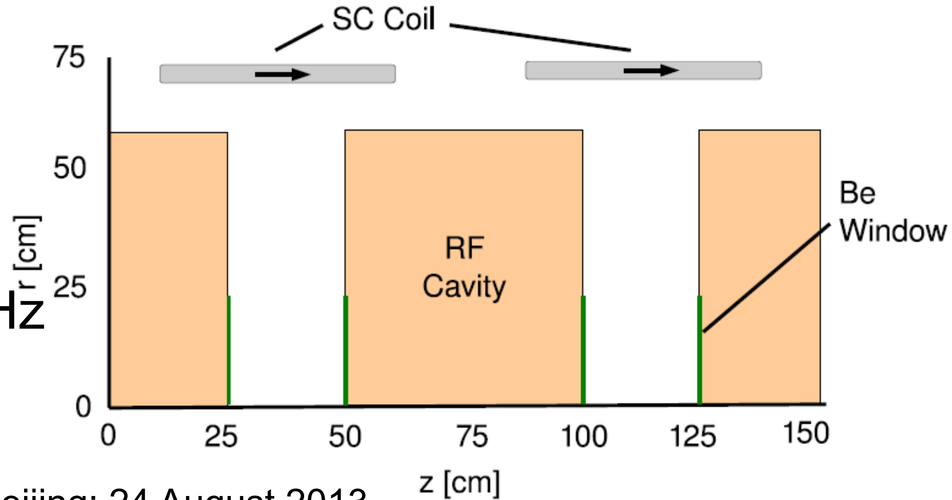


D. Neuffer, WG3

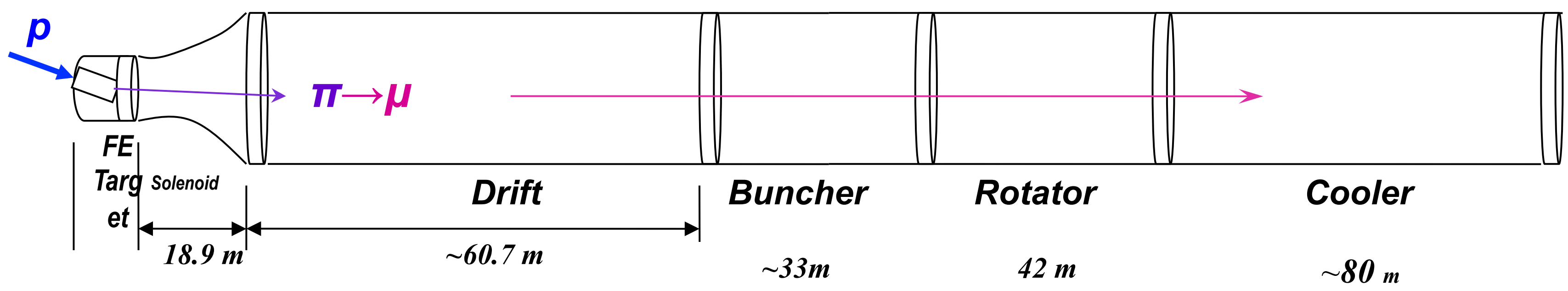




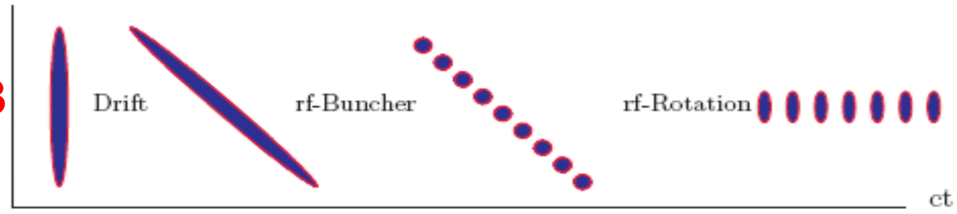
- Phase rotation:
  - 56 cells of 0.75 m length
  - Total length: 42 m
  - 56 normal conducting RF cavities with SC coils
  - RF frequency 230.2- 202.3 MHz
  - Gradient 12 MV/m

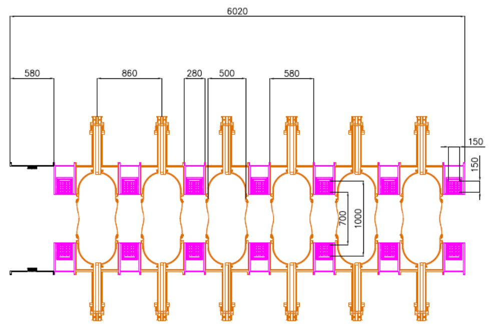


Muon Front End

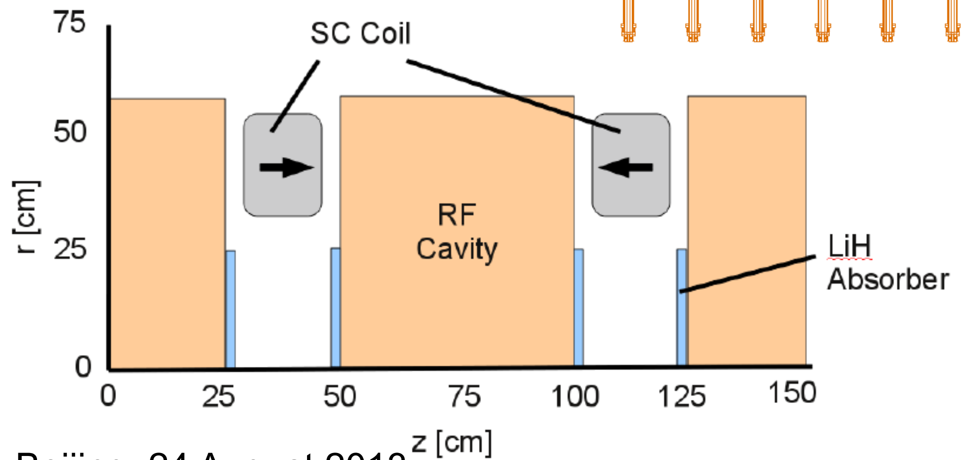


D. Neuffer, WG3
Adey, Kaplan WG3
Nugent poster

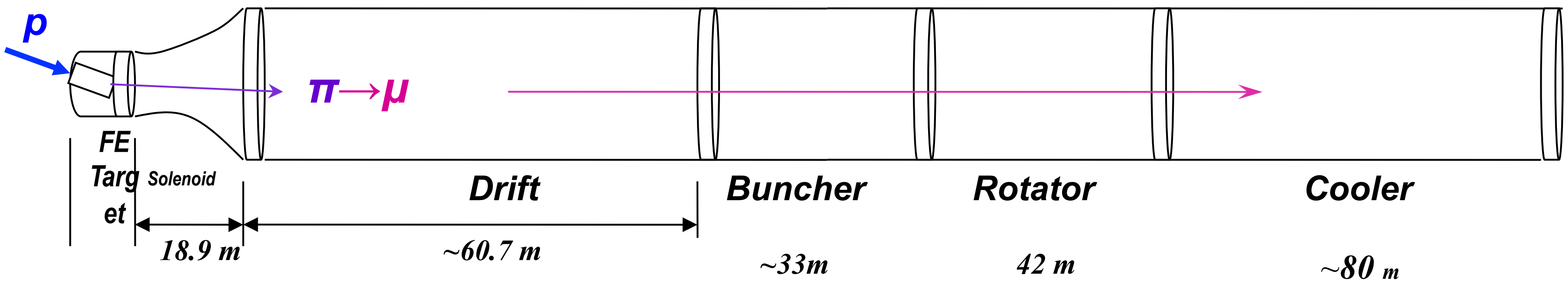




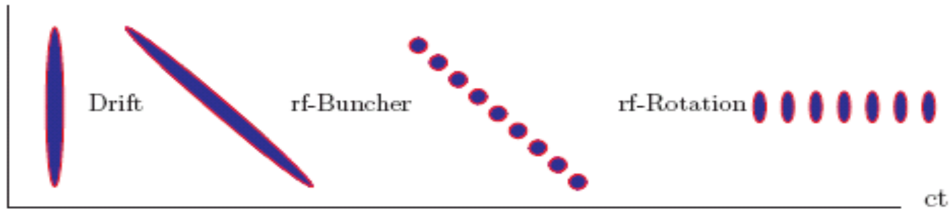
- Cooling channel: MICE demonstration
  - 100 cells of 0.75 m length ➔0.86 m
  - Total length: ~80 m
  - 100 normal conducting RF cavities with SC coils
  - RF frequency 201.25 MHz
  - Gradient 15 MV/m
  - LiH absorbers (1.1 cm)



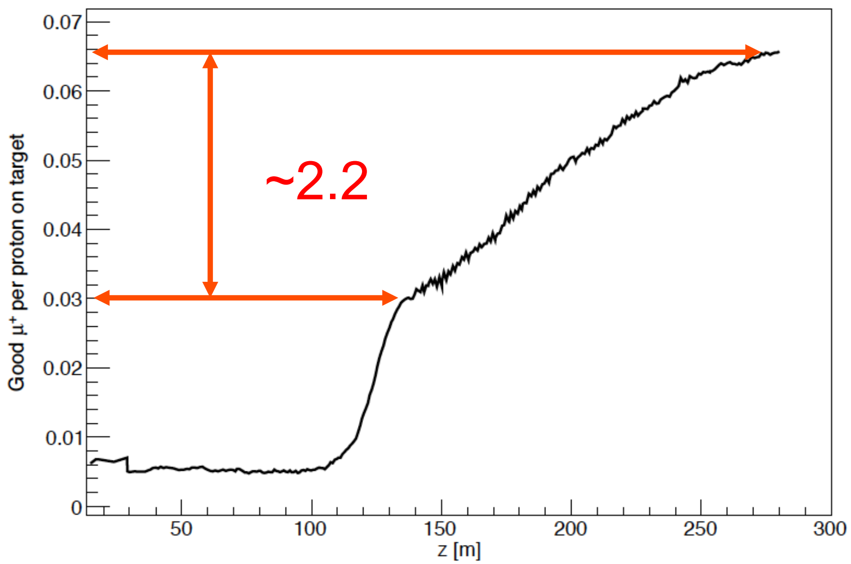
Muon Front End



D. Neuffer, WG3



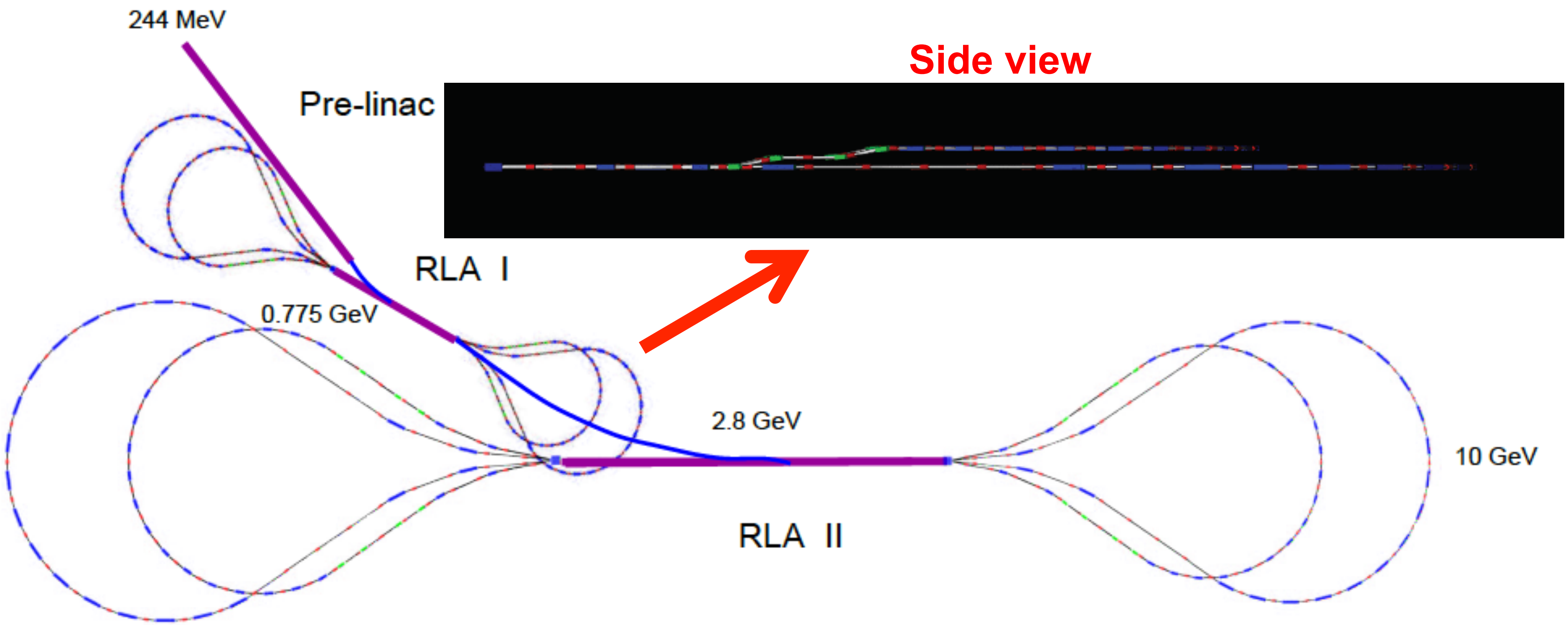
- Front end performance:
  - 0.066 μ/proton
  - Cooling increases muon yield by a factor of ~2.2
  - Cooling channel is most cost-effective way to increase yield of muons



Acceleration

- Redefined baseline after moving to 10 GeV (IDR: 25 GeV)
  - Baseline: two “dog-bone” Recirculating Linear Accelerators (RLA)
  - First RLA up to 2.8 GeV
  - Second RLA up to 10 GeV

A. Bogacz, WG3



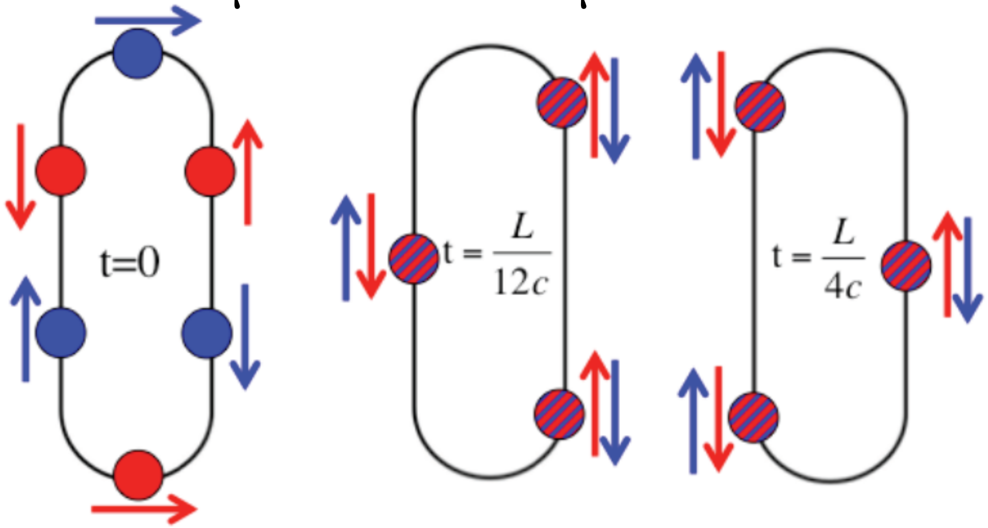
Decay Ring Geometry

- 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

A. Bogacz, WG3

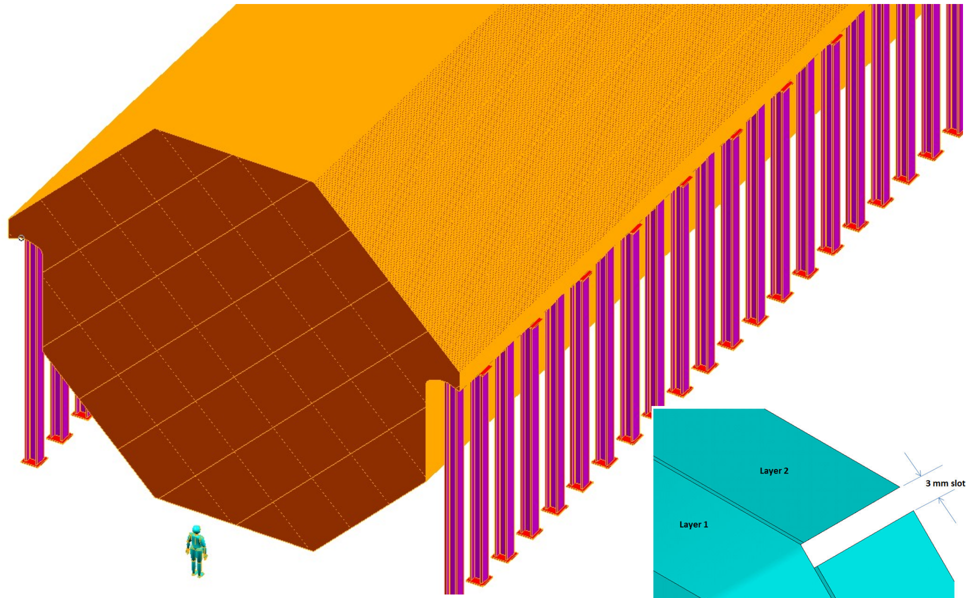
Three μ^+ and thee μ^- bunches



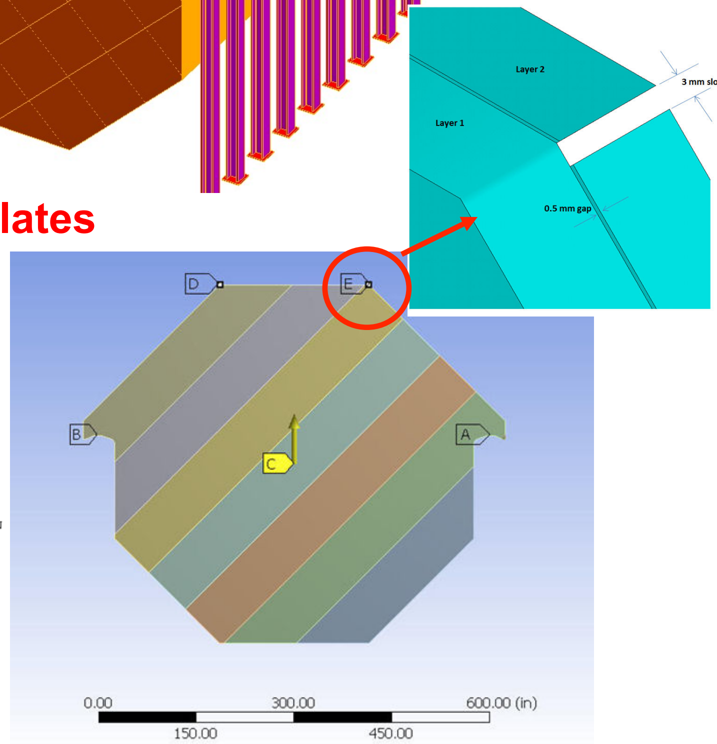
Divergence < $0.1/\gamma$

Far Detector

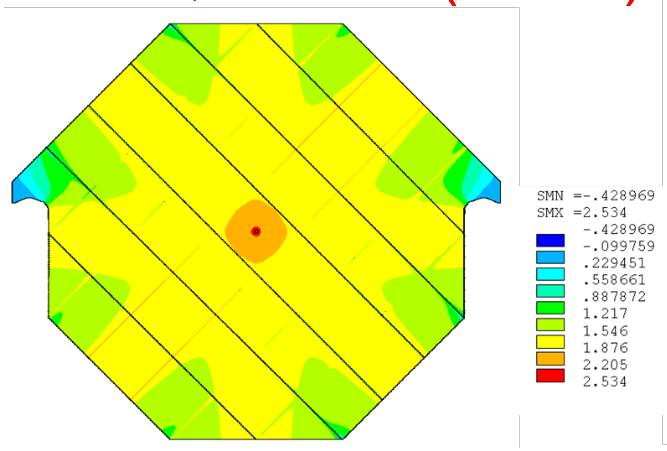
- Magnetised Iron neutrino Detector (MIND): 100 kton
- Octagonal plates and toroidal field (as in MINOS)
- Engineering metal plates
- Magnetic field delivered by 100 kA current

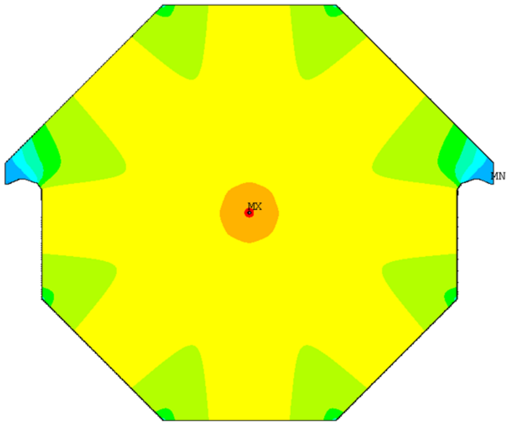


14mx14mx3cm plates



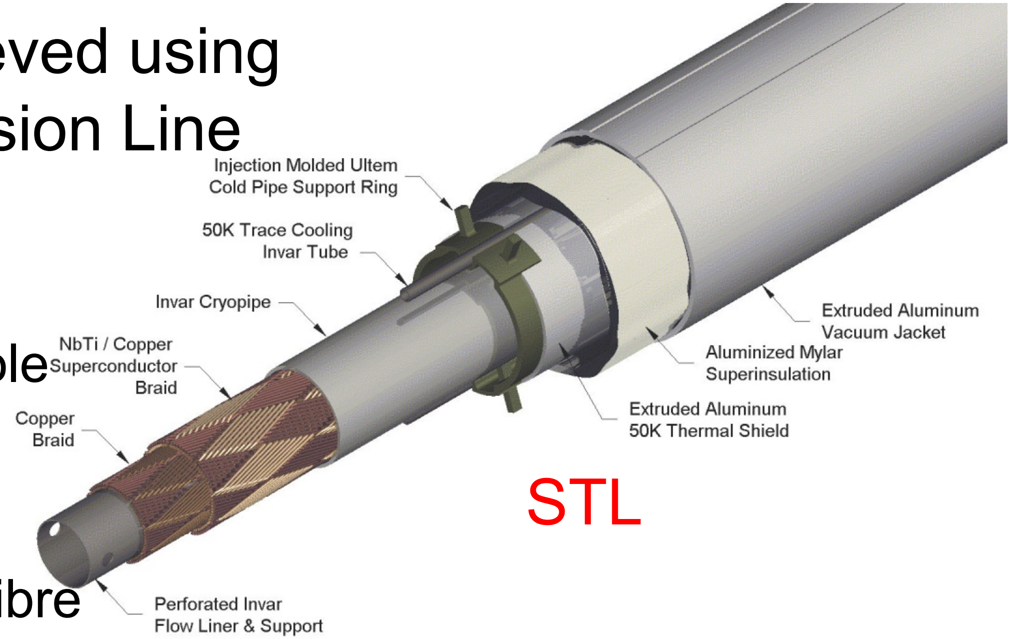
Bross, Wands (FNAL)





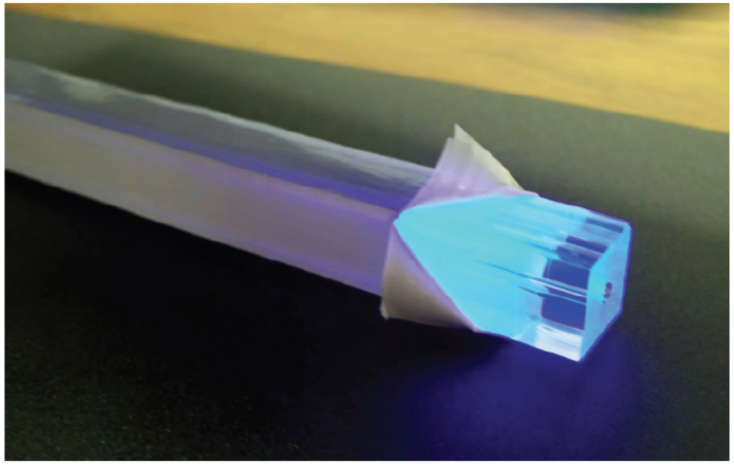
MIND magnetisation

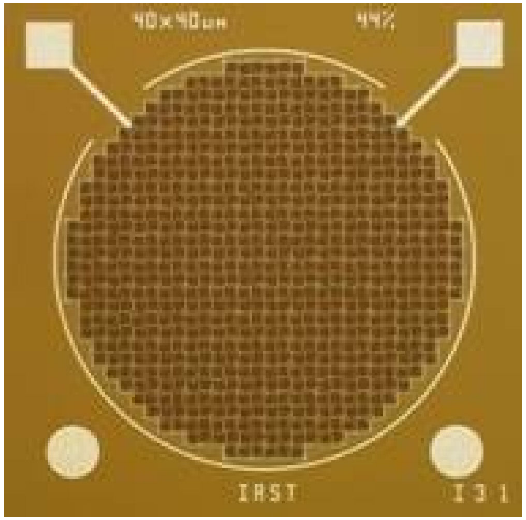
- Magnetisation can be achieved using Superconducting Transmission Line (STL) developed for VLHC:
  - Can carry 100 kA turn
  - Only need 10 cm diameter hole



STL

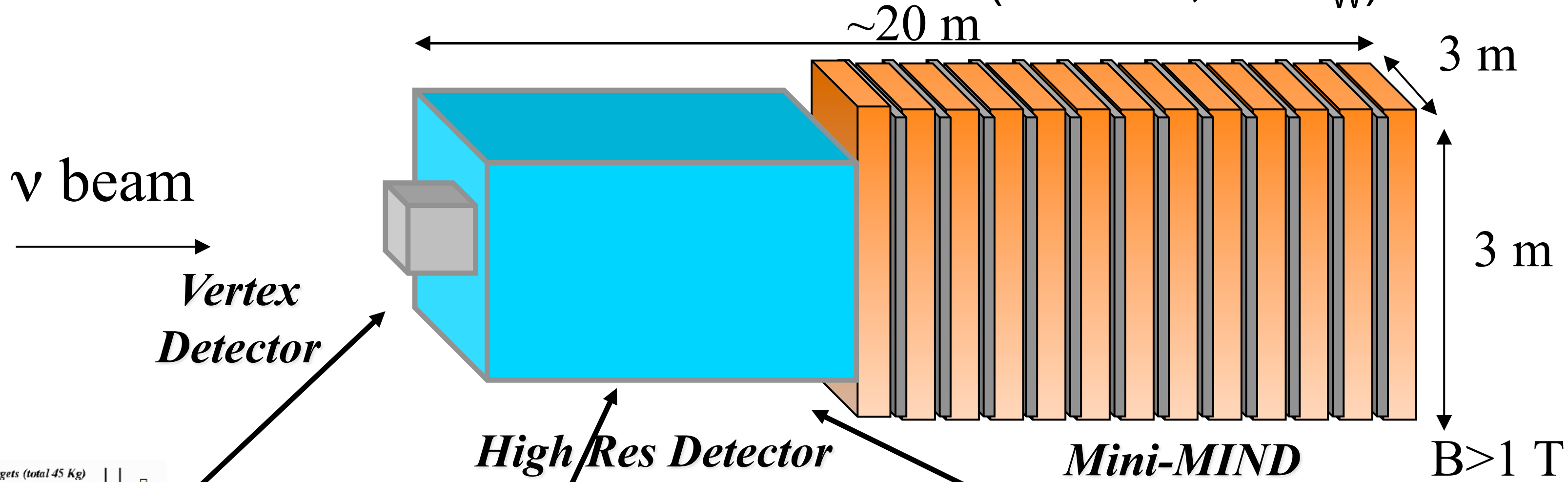
- Extruded scintillator:
  - Kuraray wavelength shifting fibre with double-ended SiPMT readout



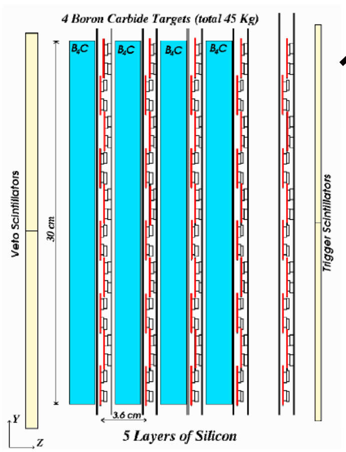


Near Detector

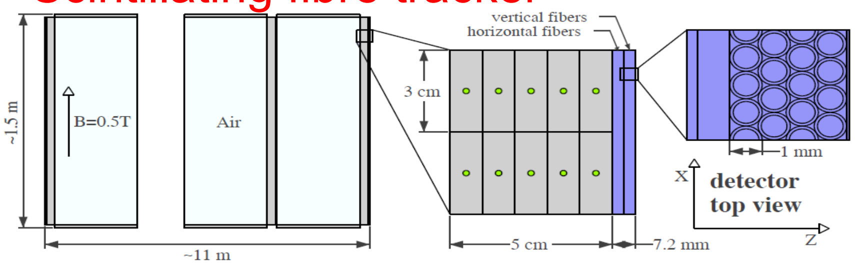
- Two near detectors required, one at each straight:
  - Neutrino flux (<1% precision) and extrapolation to far detector
  - Charm production (main background) and taus for Non Standard Interactions (NSI) searches
  - Cross-sections and other measurements (ie PDFs, $\sin^2\theta_W$)



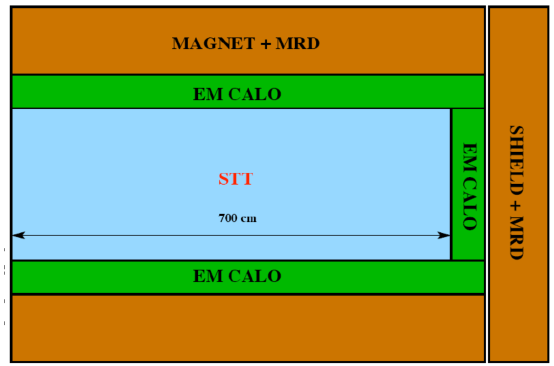
Two options



Scintillating fibre tracker



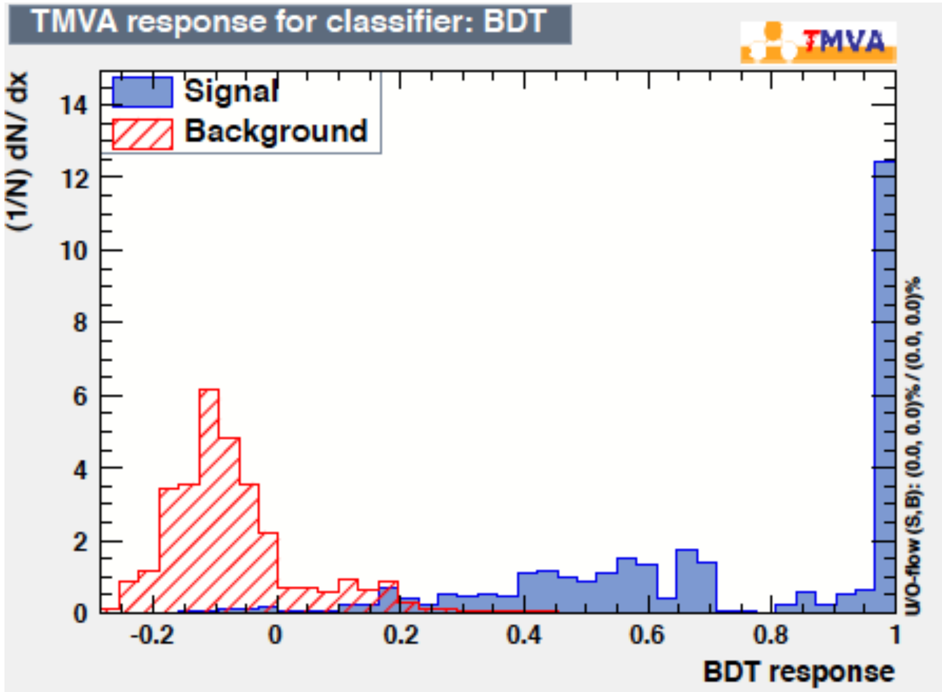
HiResMuNu: straw tube tracker

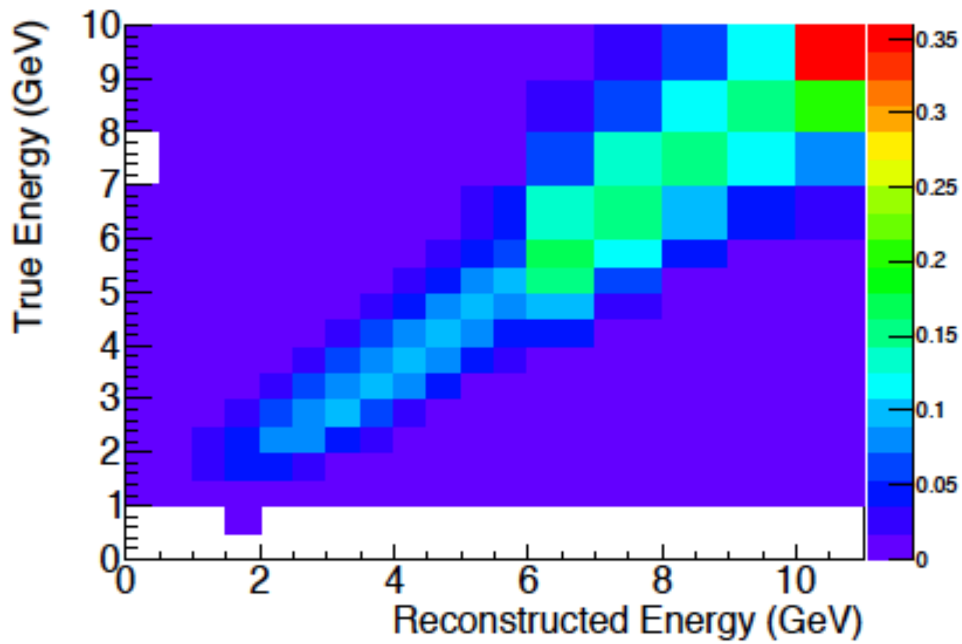


MIND analysis

- Multi-variate analysis (MVA) performed with five variables, tuned for best value of $\sin^2 2\theta_{13}$~0.1
- Boosted Decision Tree (BDT) and K-Nearest Neighbour (KNN) give best performance of MVA methods
- Migration matrices give 2D response of true vs recon energy

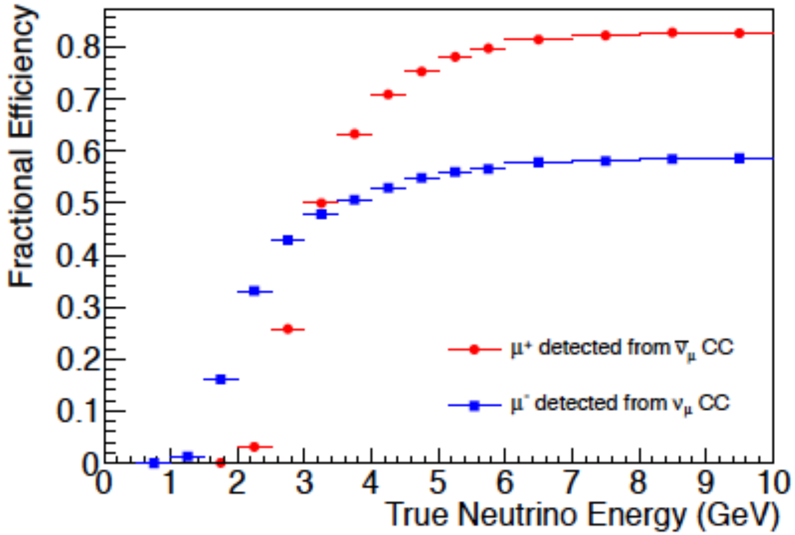
R. Bayes, WG1



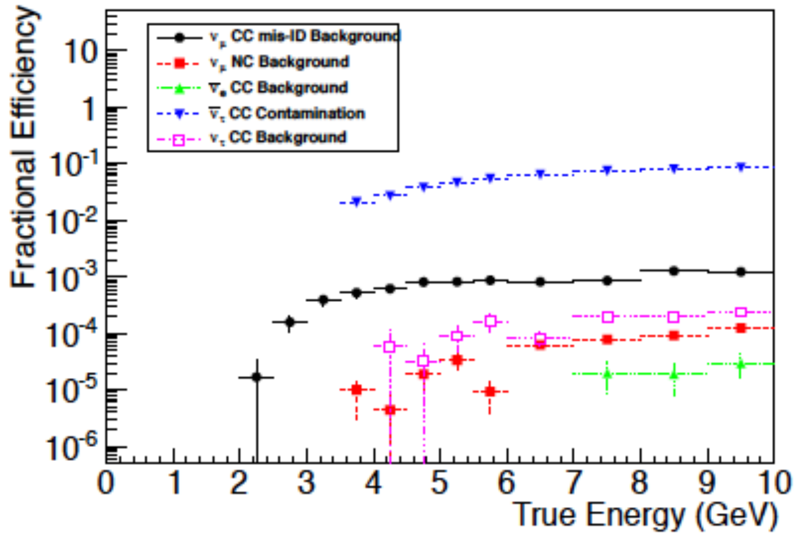


MIND efficiencies and background

BDT efficiency, focussing μ^+

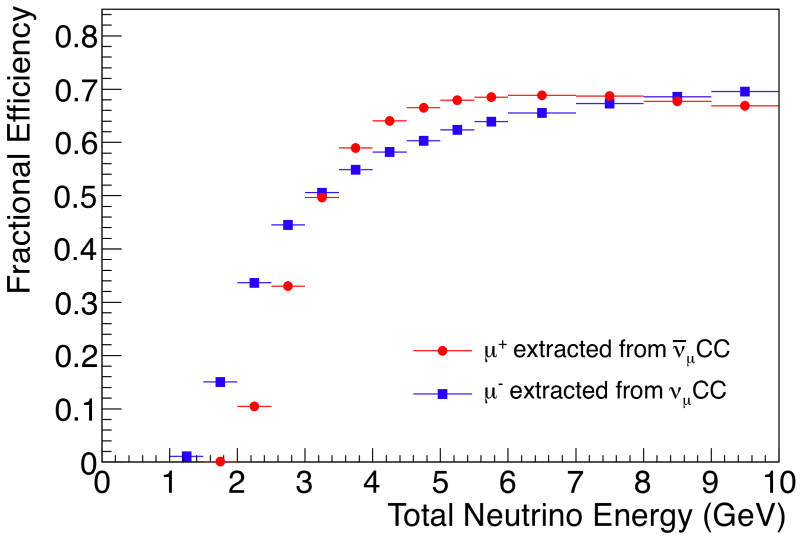


BDT background (stored μ^-, focussing μ^+)

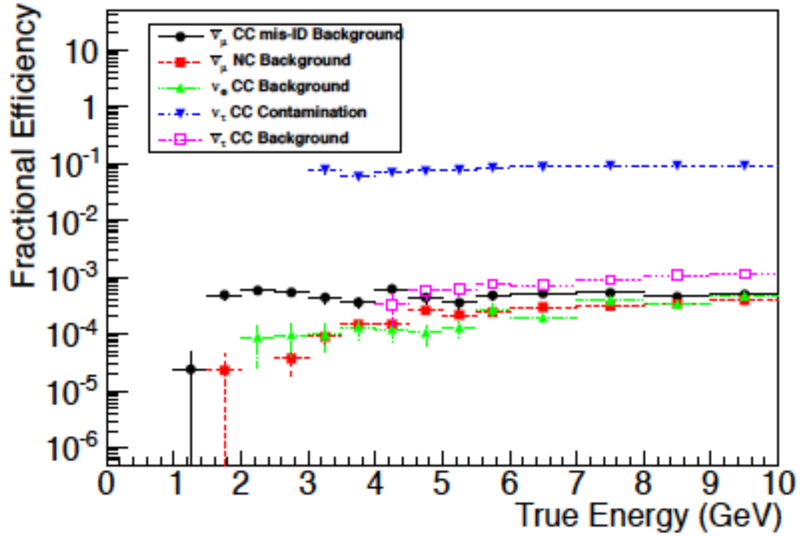


Courtesy
R. Bayes

BDT efficiency, focussing μ^-

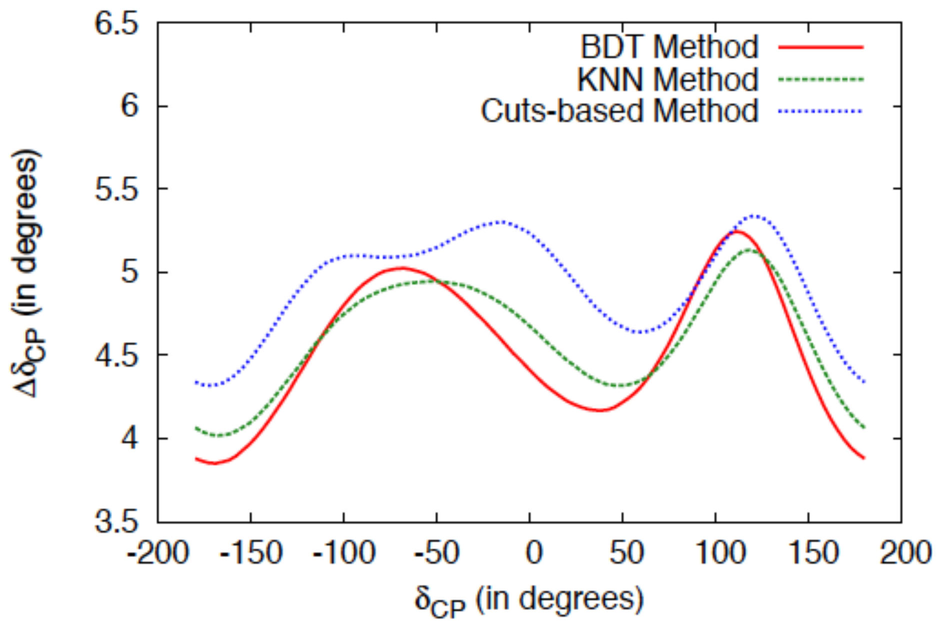


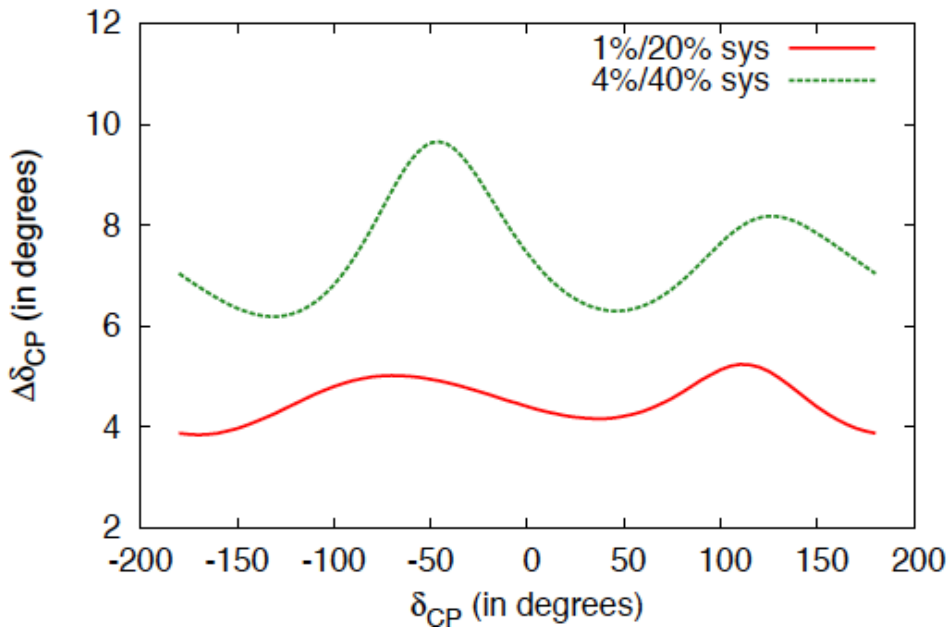
BDT background (stored μ^+, focussing μ^+)



MIND CP sensitivities

- Final sensitivities with 1.4% (signal) and 20% (back) systematics
- Precision in δ depends on systematic errors: neutrino factory offers best facility for controlling systematic errors

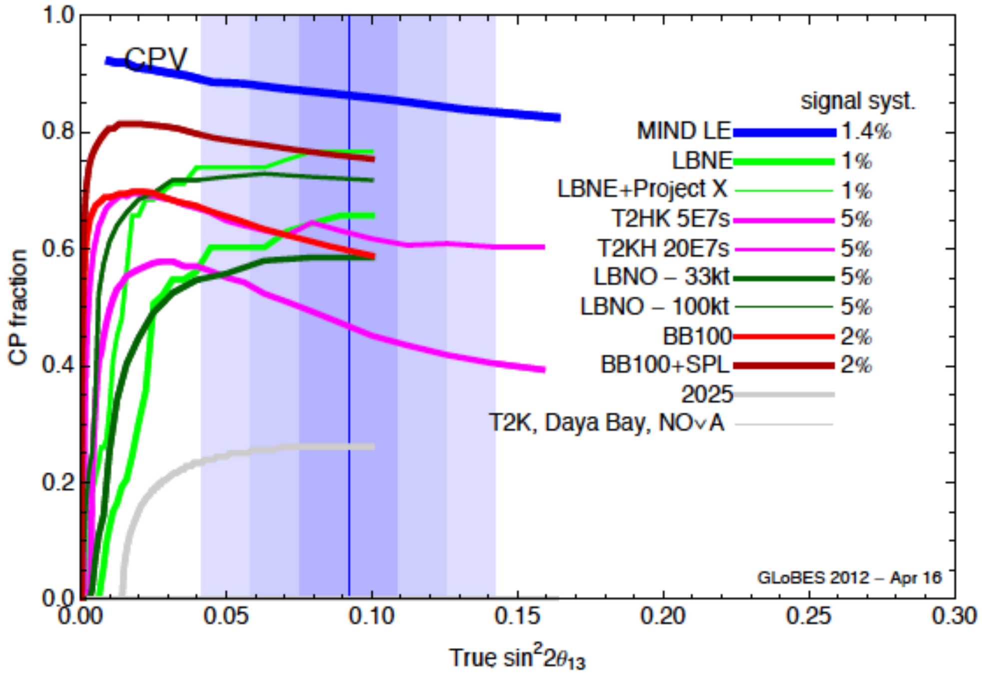




NF yields $\Delta\delta$~4°-5°, regardless of value of δ

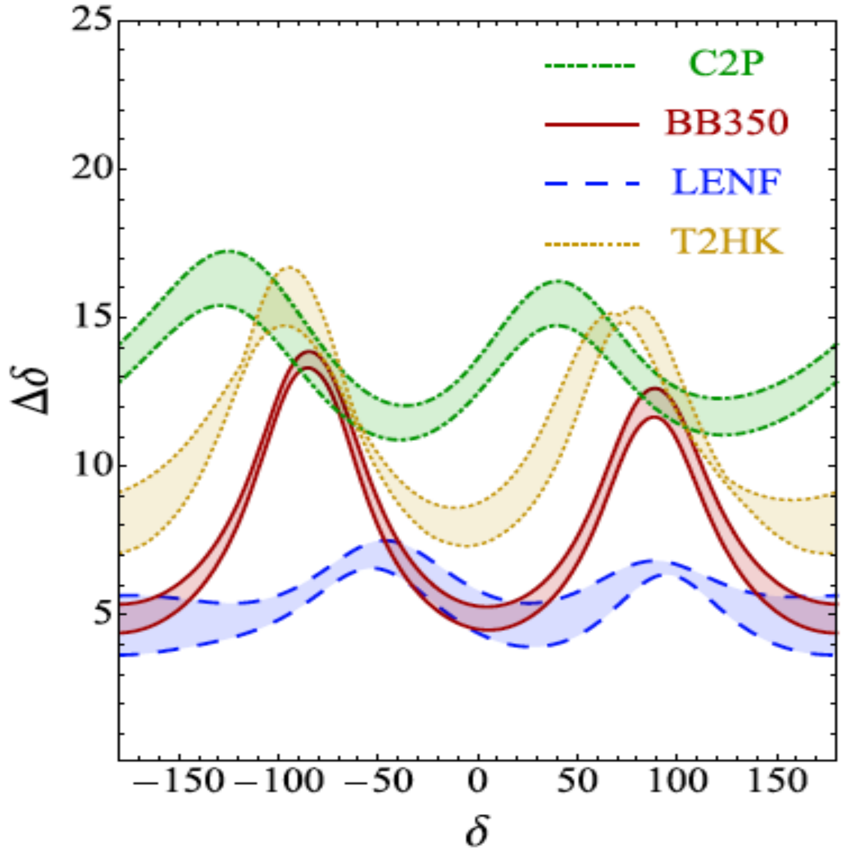
Performance 10 GeV Neutrino Factory

- Optimisation for 10 GeV Neutrino Factory with 100 kton MIND at 2000 km gives best sensitivity to CP violation



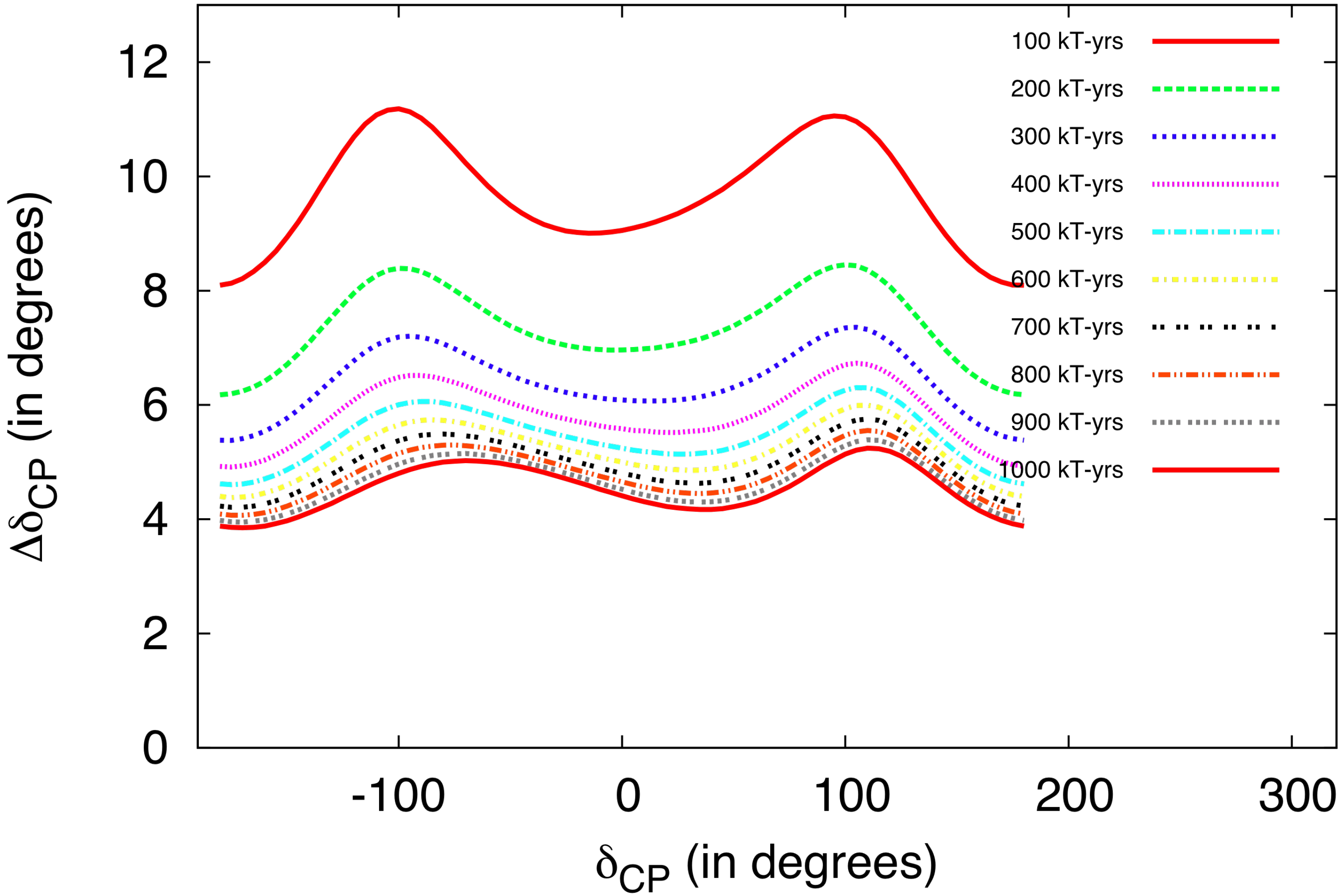
More than 85% 5σ coverage

arXiv:1203.5651



MIND CP sensitivities

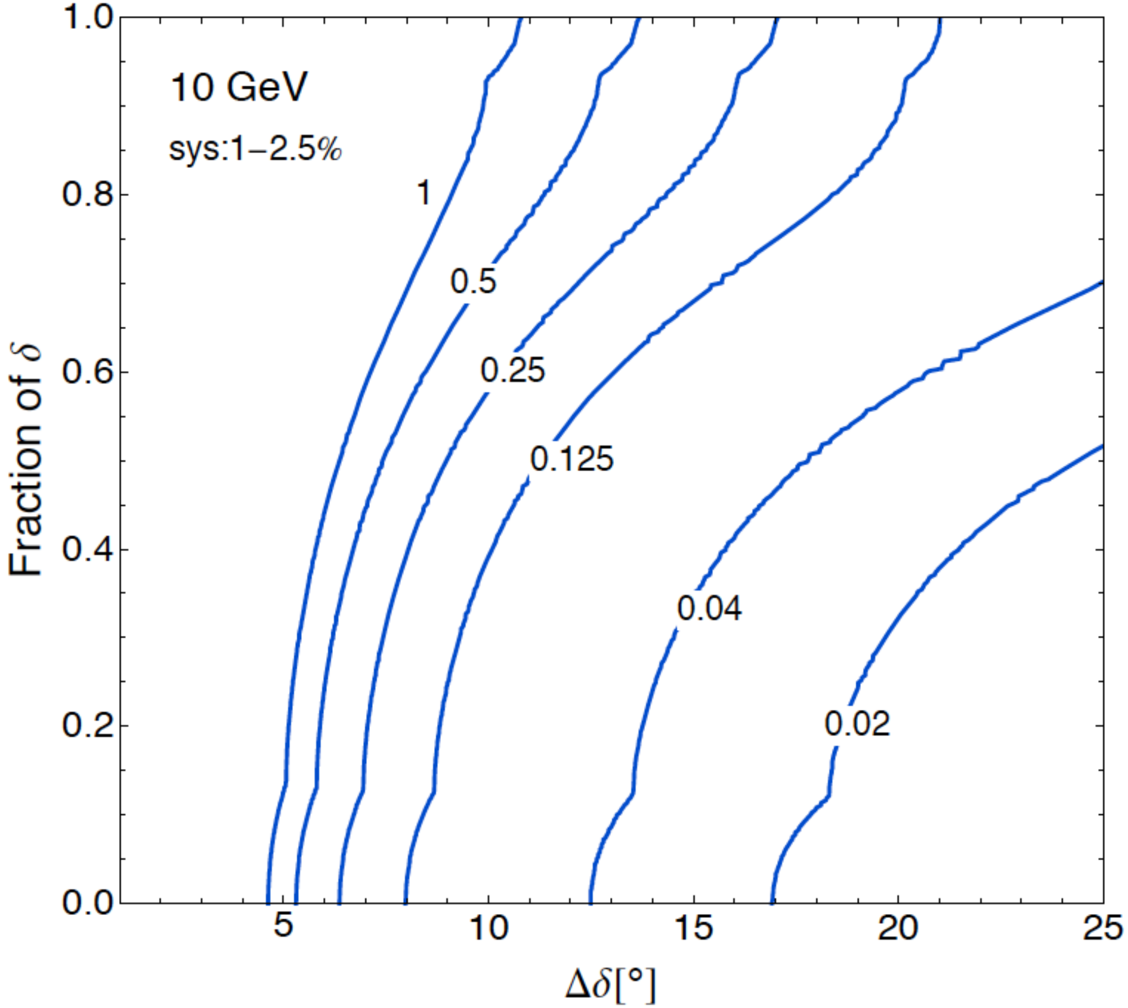
- Precision as function of exposure:



Precision moves from $\Delta\delta$~8°-11°, to $\Delta\delta$~4°-5°

MIND CP sensitivities

- CP fraction vs precision as function of exposure:



Outlook

- The International Design Study for a Neutrino Factory will not be the final word
- We have already heard about attempts (especially in the USA) to stage a Neutrino Factory and align with available projects
  - First stage could be "entry-level" neutrino factory: nuSTORM
  - Synergy with future long baseline programmes (ie. LBNE/LBNO)
  - R&D projects are essential: MERIT, MICE, MuCOOL, 6D cooling, ….
  - Future upgrade path towards a muon collider: intensity frontier gives you access to energy frontier
- We need to continue with international programme, with input from national programmes (ie. MAP) to have unified voice
- NUFACT workshops still have a significant role to play to encourage and discuss international cooperation

Conclusions

- International Design Study is about to conclude study
  - Interim Design Report delivered March 2011
  - Successful ECFA review May 2011
  - EUROnu reports being published by PR-ST AB
  - On target to produce Reference Design Report, including performance and costs by end of 2013
- Concepts for accelerator systems have been defined
- 100 kton Magnetised Iron Neutrino Detectors (MIND) at standard Neutrino Factory (10 GeV) for $\sin^2 2\theta_{13} \sim 10^{-1}$
  - Best sensitivity for CP violation of all possible future neutrino facilities
- Outlook: options for staging a Neutrino Factory are currently being considered in order to deliver physics at intermediate steps and to break up total cost over time