THE INTERNATIONAL DESIGN STUDY
FOR THE NEUTRINO FACTORY

Final Results from IDS-NF Study

NUFACT14 Workshop, Glasgow

on behalf of the IDS-NF Collaboration

Paul Soler, 26 August 2014

University of Glasgow

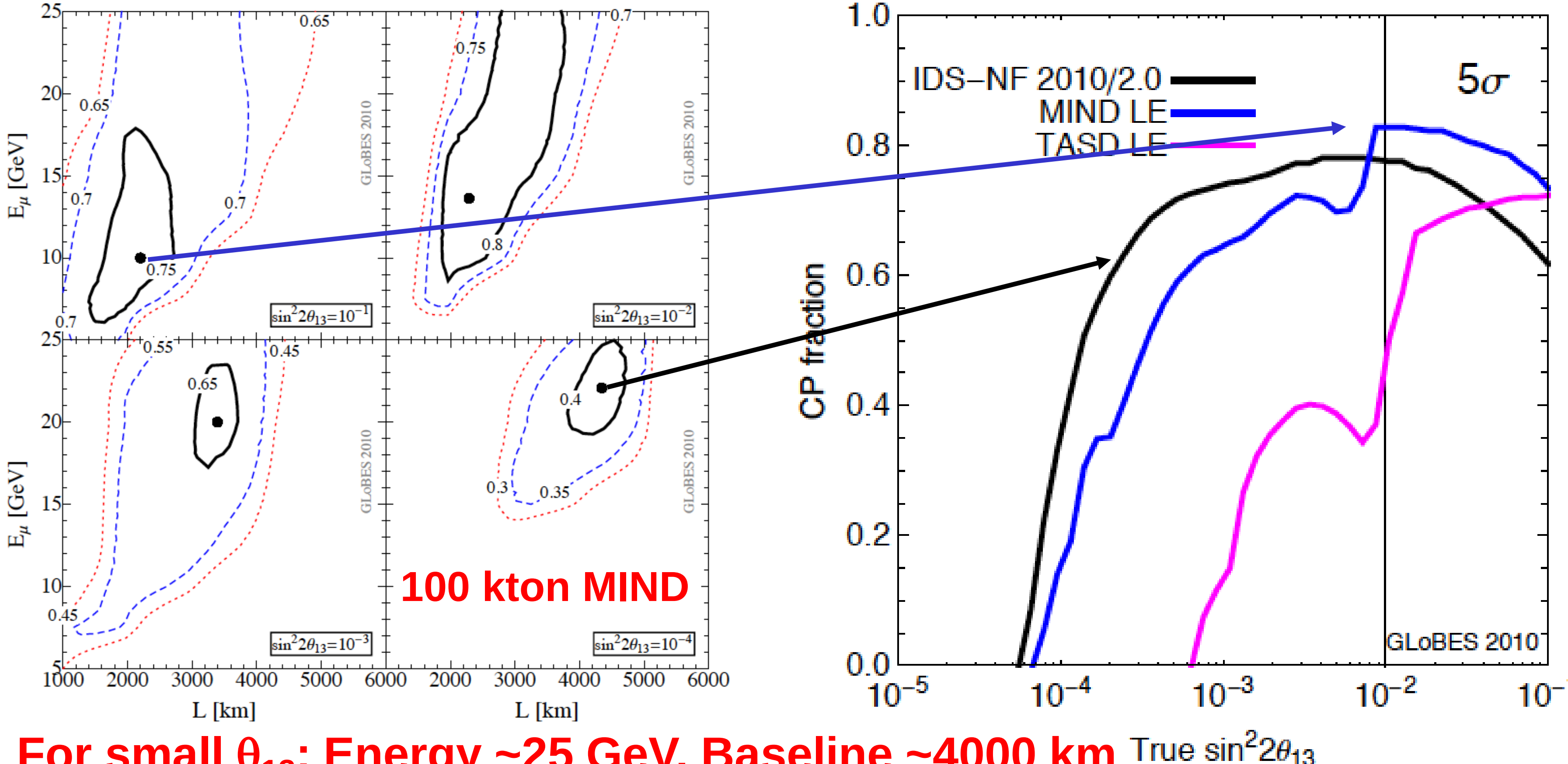
International Design Study

- 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

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

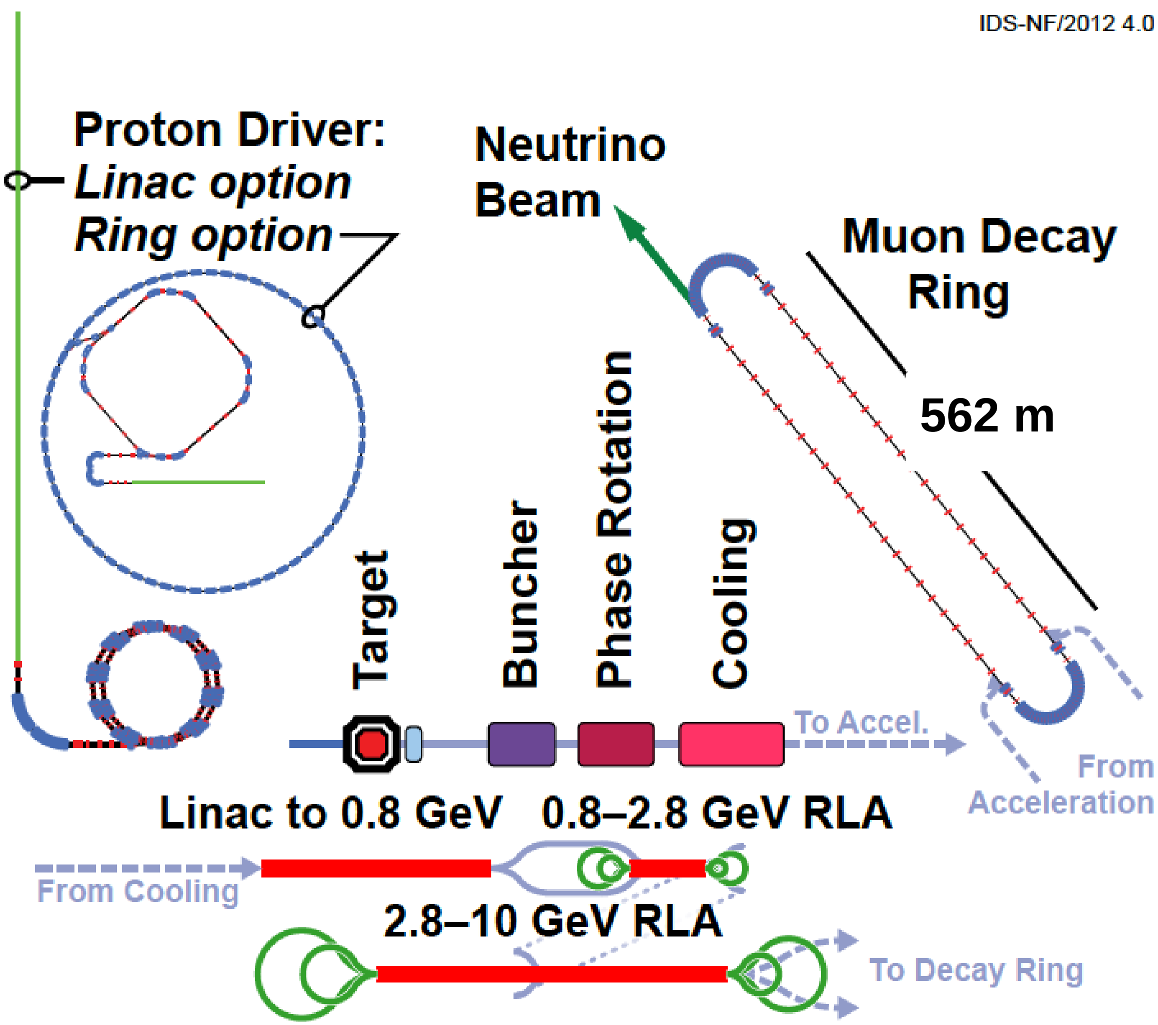
Contours of CP coverage



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

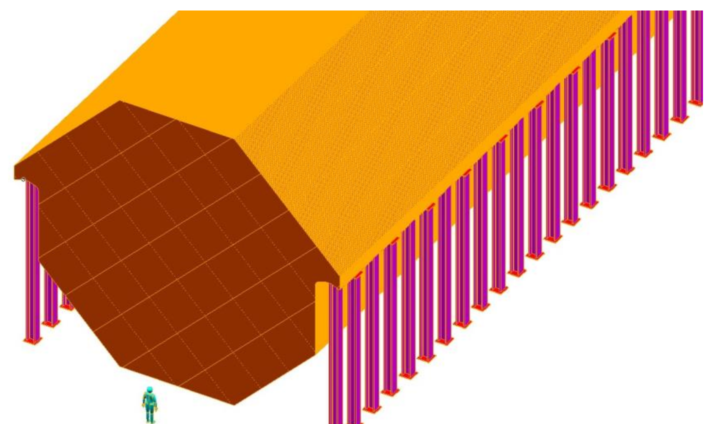
For large θ_{13}: Energy 10 GeV, Baseline ~2000 km

Neutrino Factory Baseline



Baseline reviewed 2012: 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

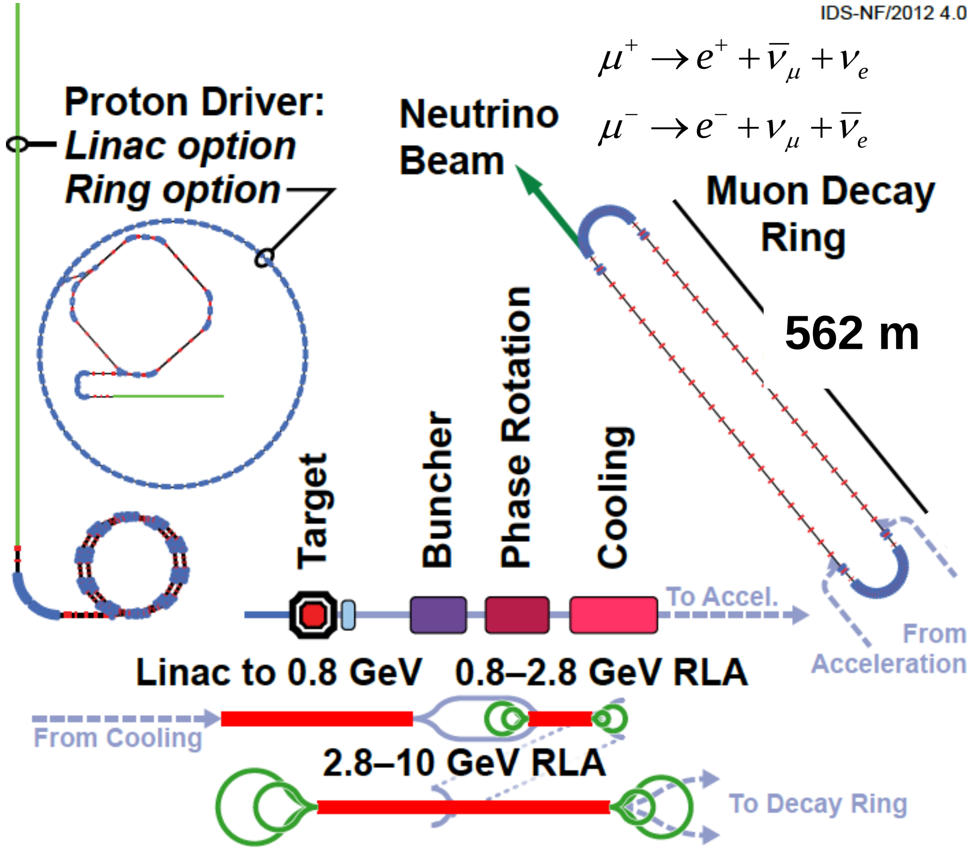


Neutrino Factory Baseline

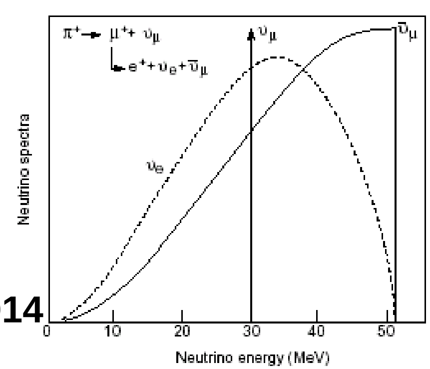
- Proton driver
  - Proton beam ~8 GeV on target
- Target, capture and decay
  - Create π, decay into μ (MERIT)
- Bunching and phase rotation
  - Reduce ΔE of bunch
- Ionization Cooling
  - Reduce transverse emittance (MICE)
- Acceleration
  - 120 MeV→ 10 GeV with RLAs
  - FFAG option now not favoured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

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

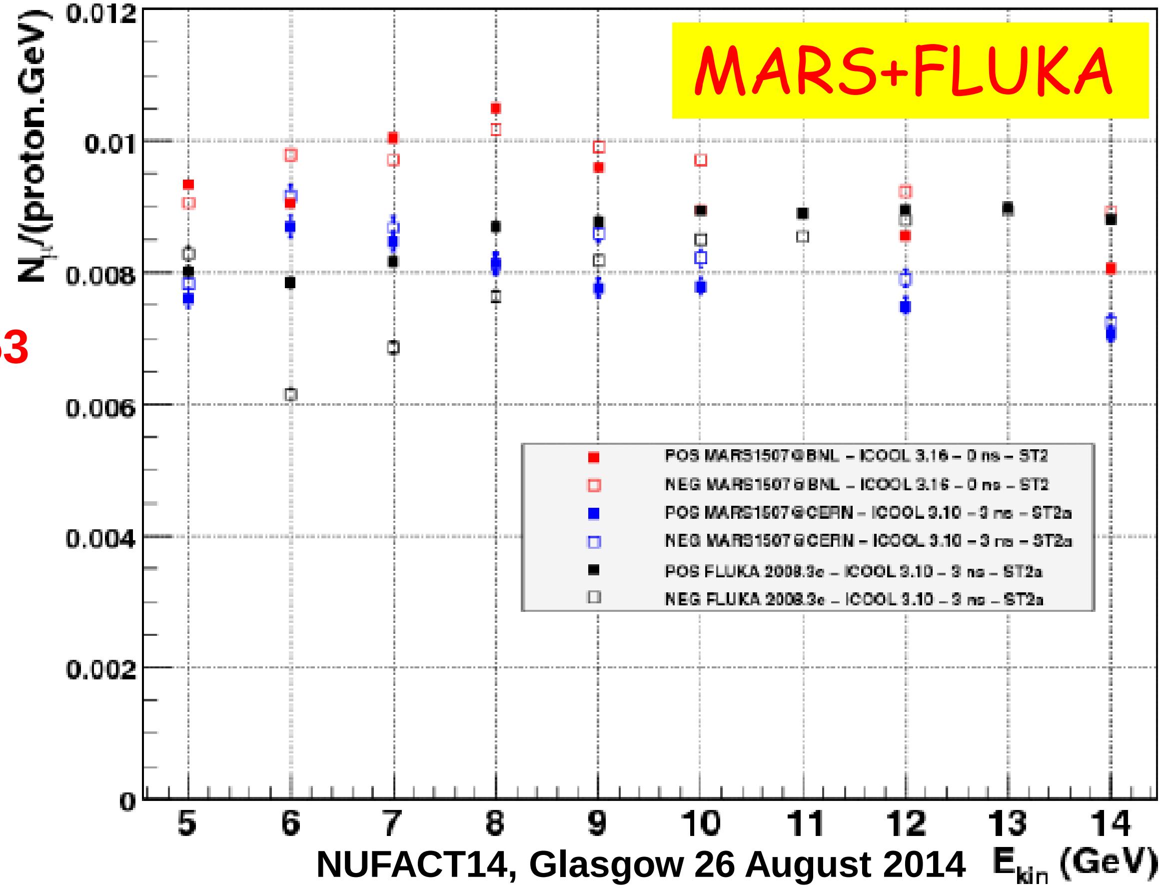


Optimum energy proton driver

- 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:

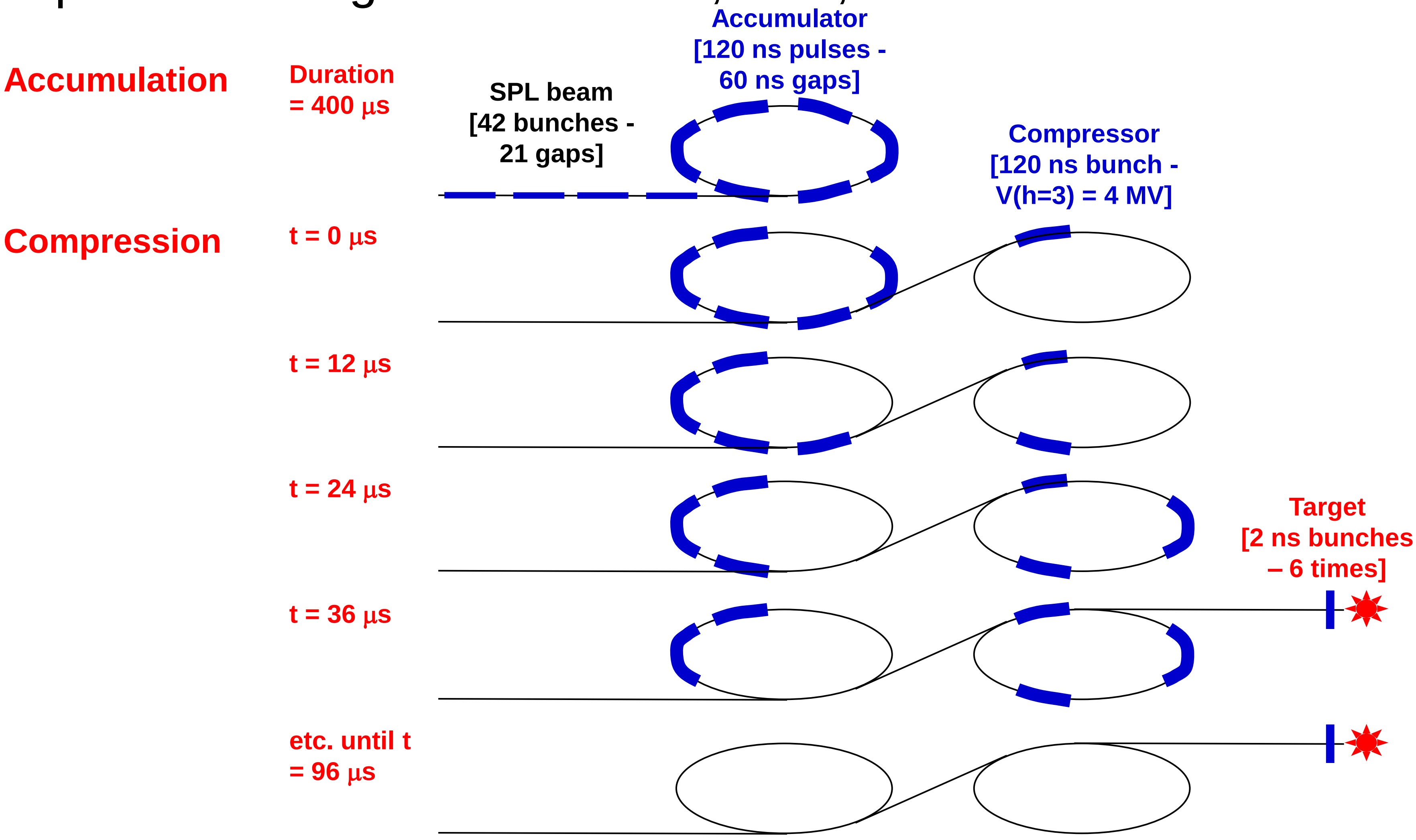
arXiv:1112.2853

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

Proton Driver (SPL)

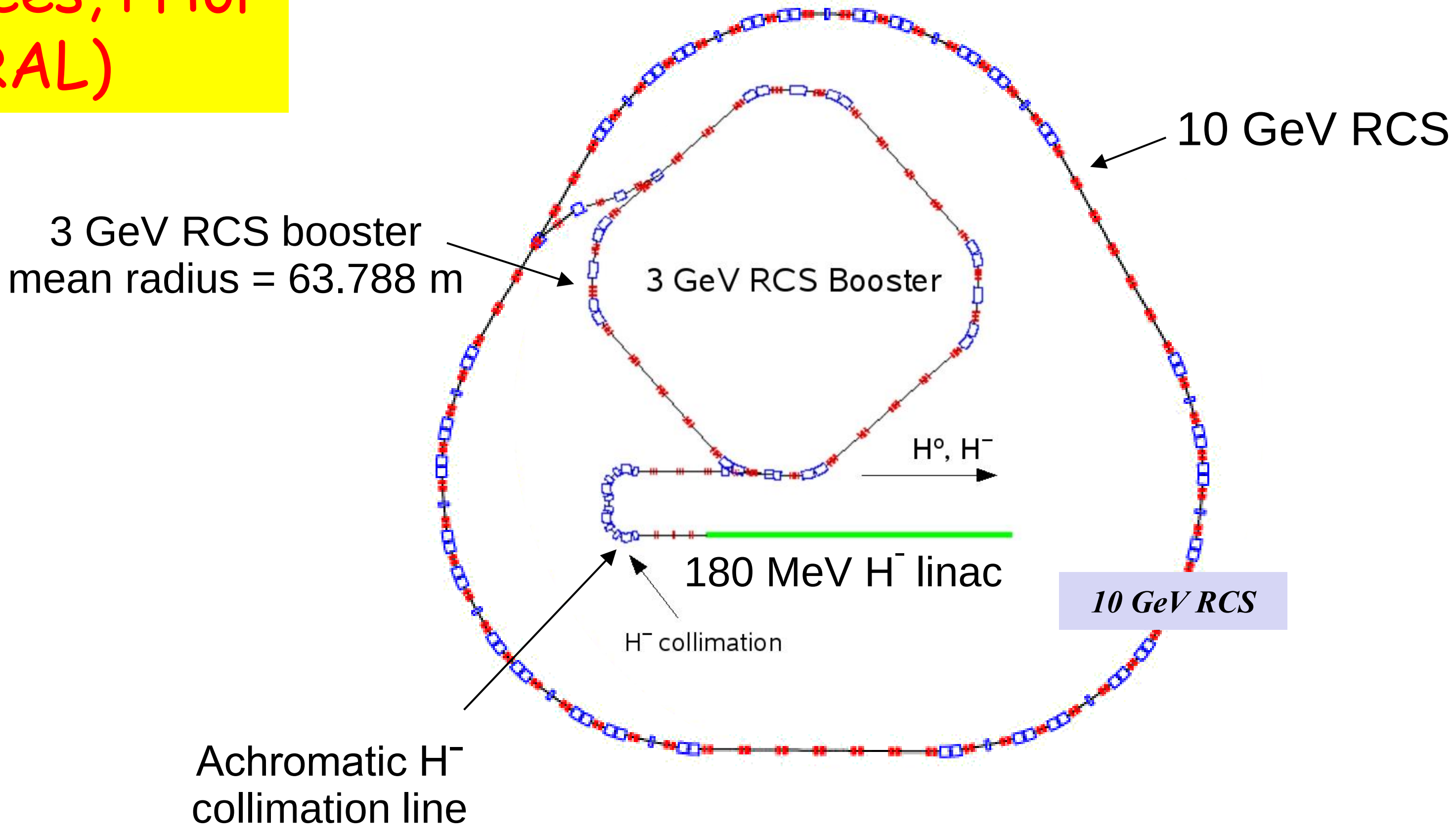
- Superconducting Proton LINAC, SPL, at CERN: 5 GeV



Proton Driver (RCS)

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

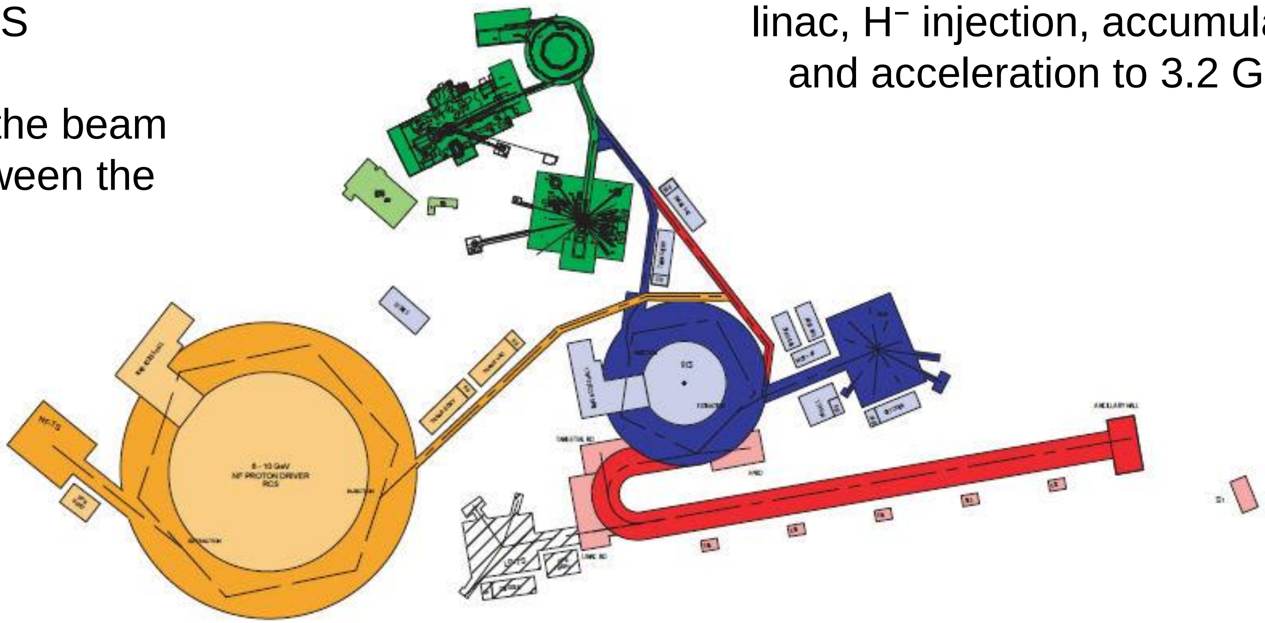
Rees, Prior (RAL)



Proton Driver (RCS)

Solution found around ISIS upgrade at RAL

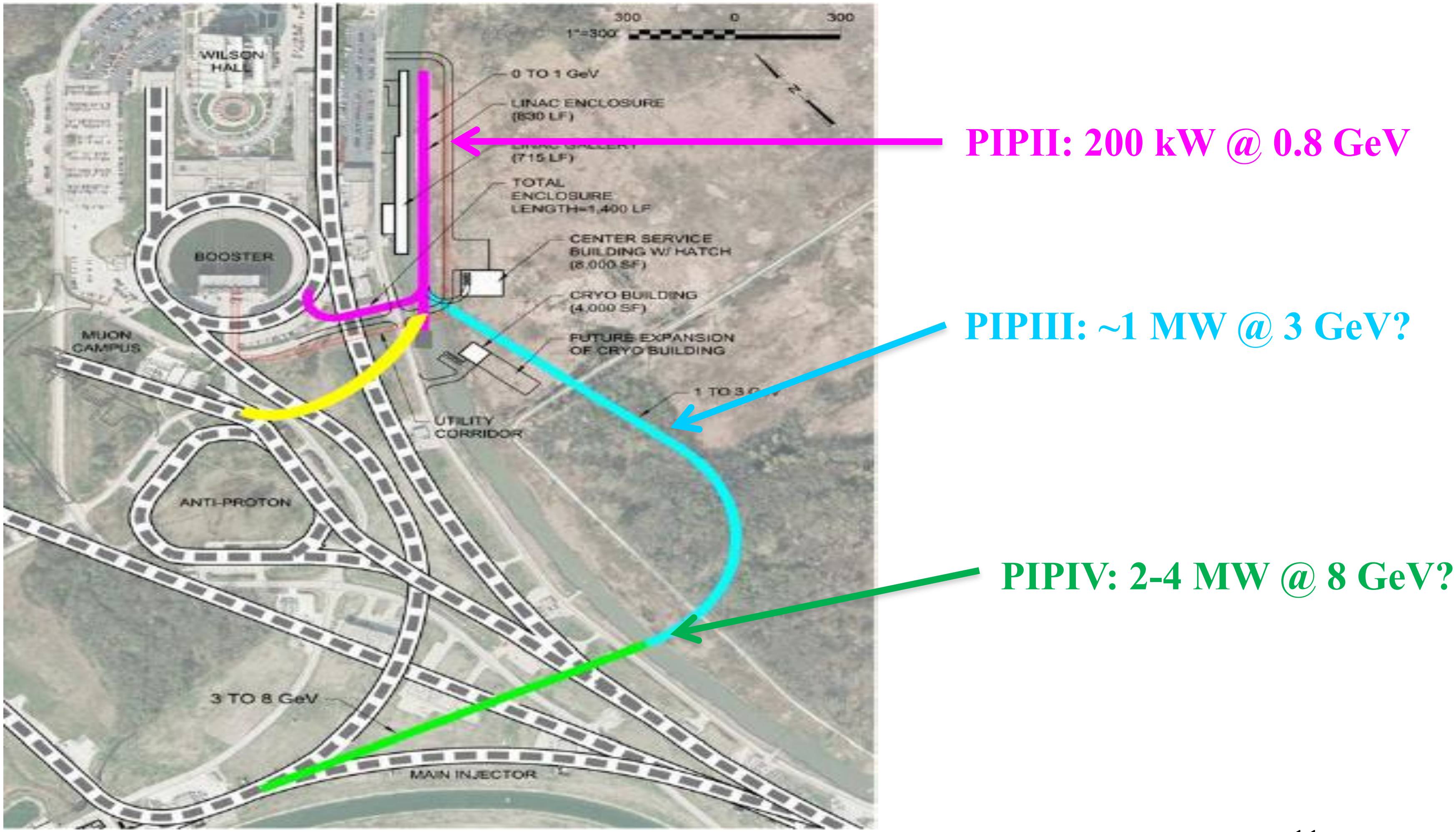
- Based on MW ISIS upgrade with 800 MeV Linac and 3.2 (≈ 3.3) GeV RCS
- Assumes a sharing of the beam power at 3.2 GeV between the two facilities
- Requires additional RCS machine in order to meet the power and energy needs of the Neutrino Factory
- Both facilities can have the same ion source, RFQ, chopper, linac, H^- injection, accumulation and acceleration to 3.2 GeV



- 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

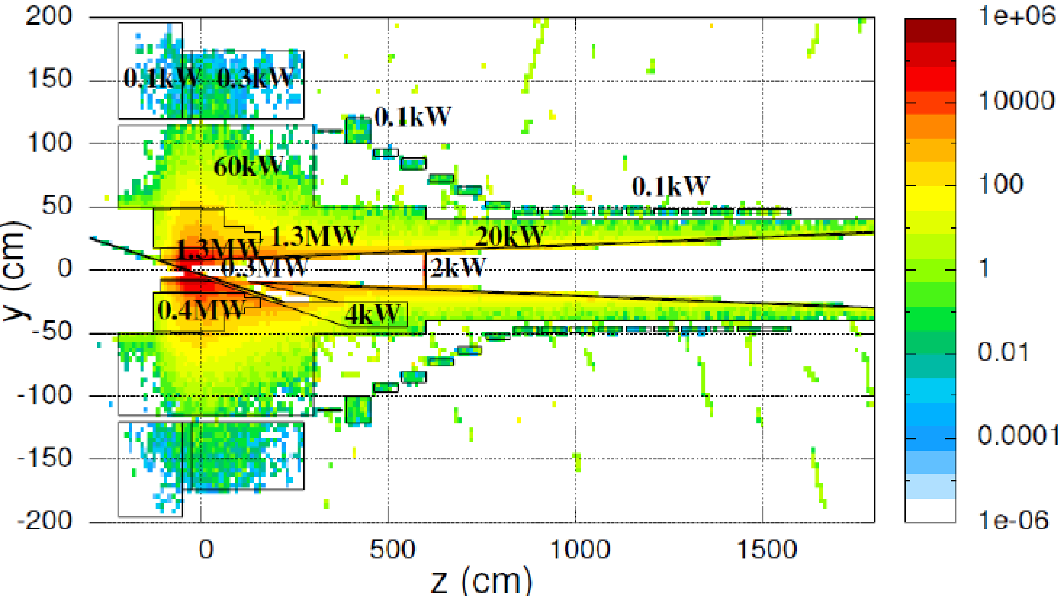
Proton Improvement Plan (PIP)

- Fermilab option: 1-4 MW operation from 3-8 GeV
  - Proton Improvement Plan (PIP): staging Linac facility at Fermilab

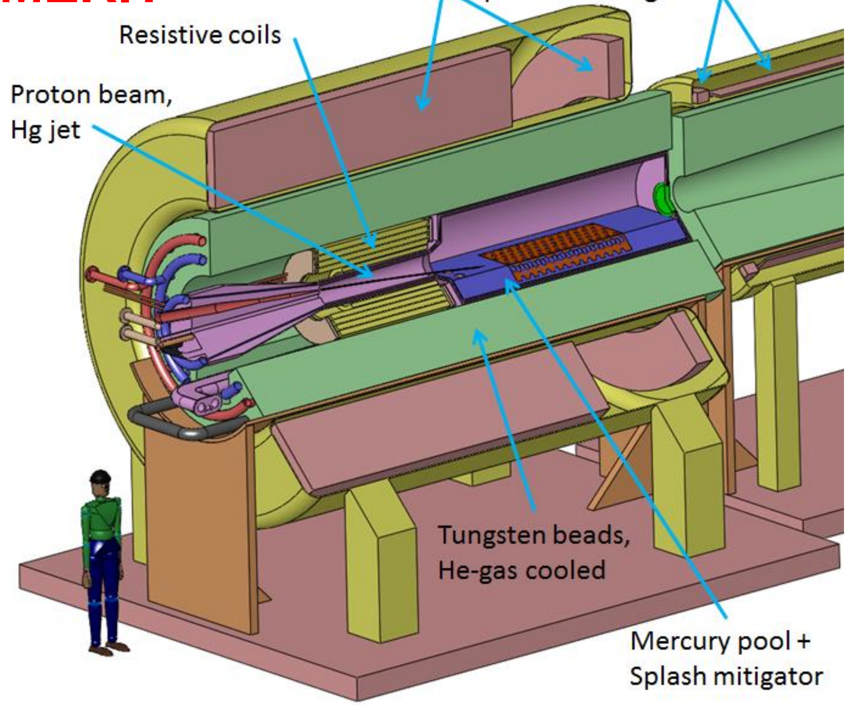


Target

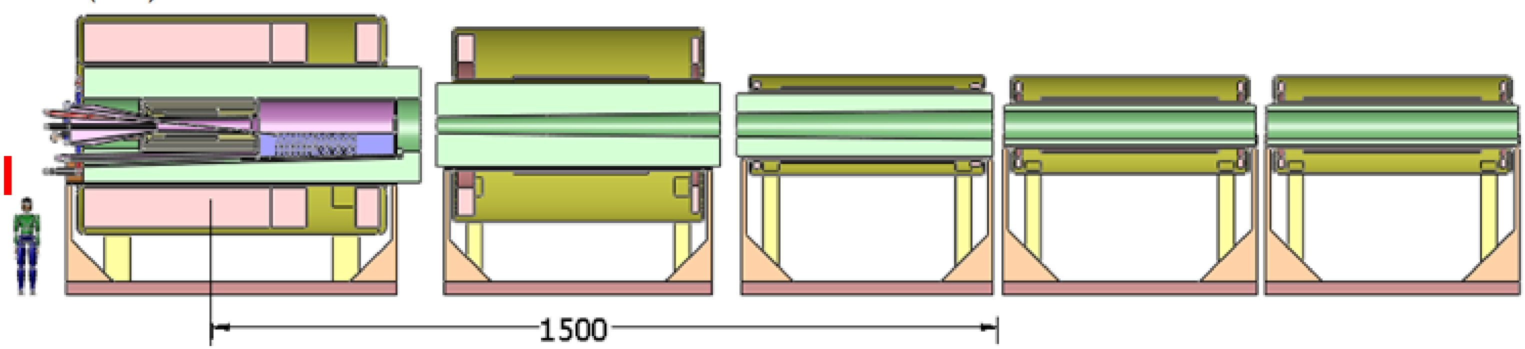
- Had to increase radiation shielding in solenoid surrounding new design for target station



Proof-of-principle: MERIT

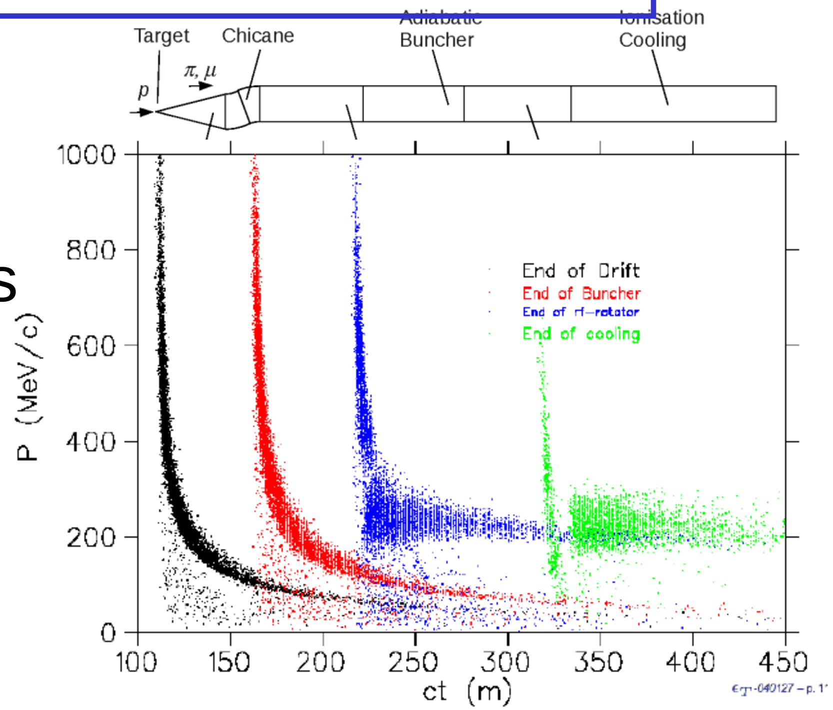


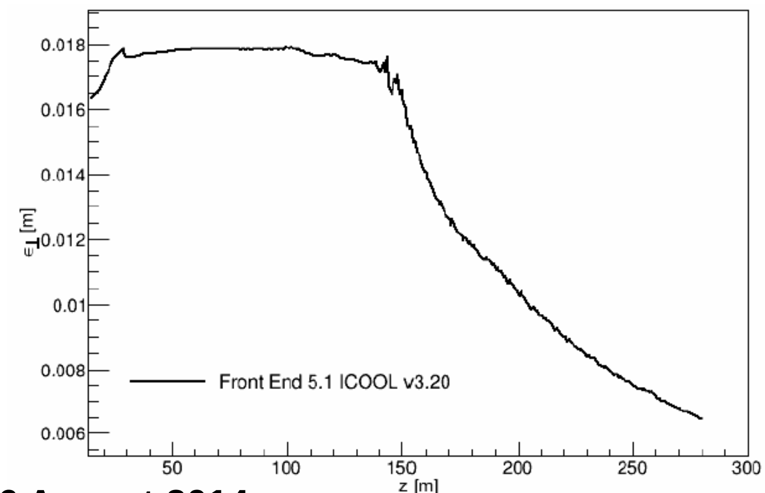
Target station and start of decay channel



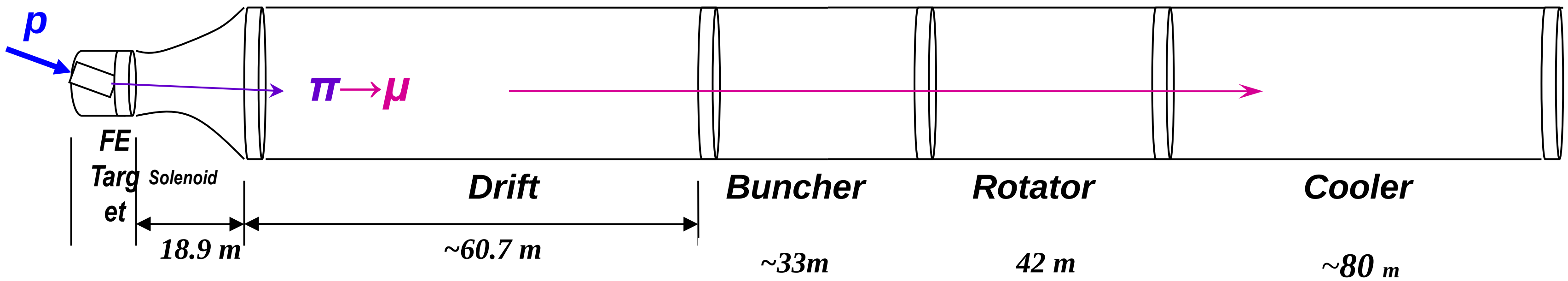
Muon Front End

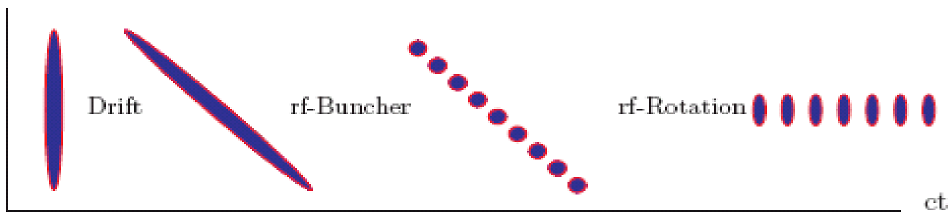
- Adiabatic B-field taper from Hg target to longitudinal drift
- Added chicane to remove protons
- Drift in ~1.5 T, ~60 m solenoid
- Adiabatically bring on RF voltage to bunch beam
- Phase rotation using variable frequencies
  - High energy front sees -ve E-field
  - Low energy tail sees +ve E-field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



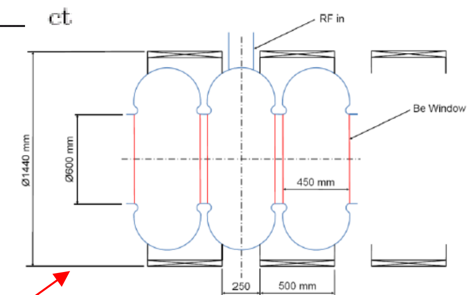


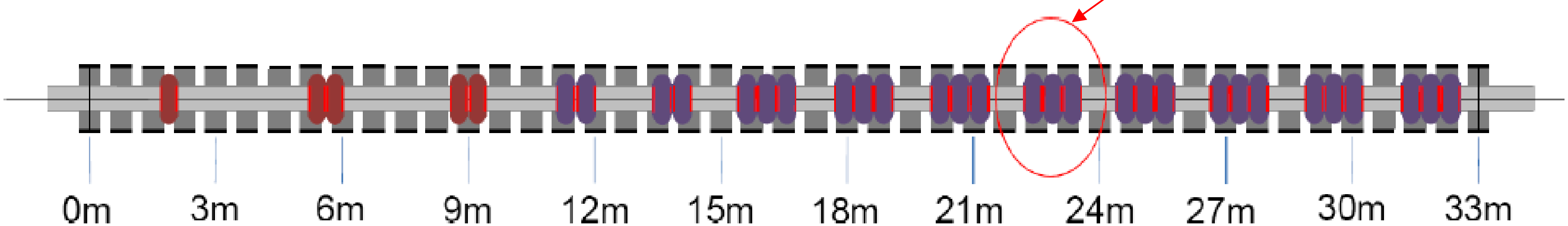
Muon Front End



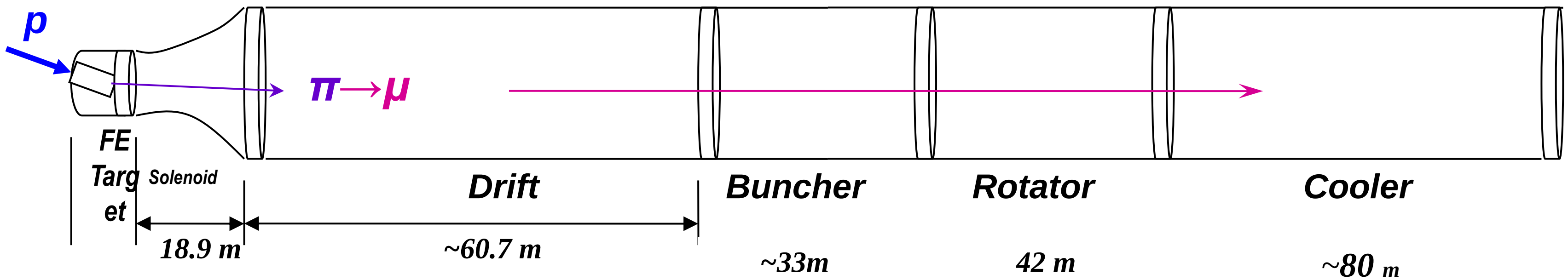


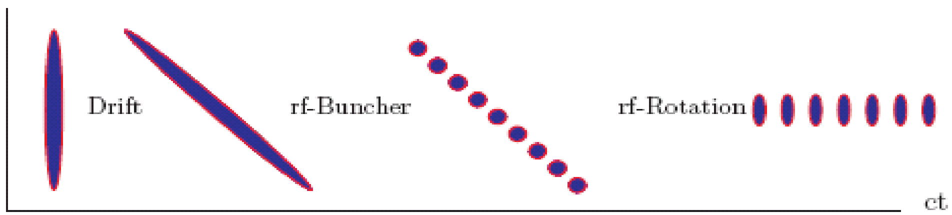
- Buncher:
  - 33 normal conducting RF cavities
  - RF frequency: 320-232 MHz
  - Gradient: 3.4-9.7 MV/m

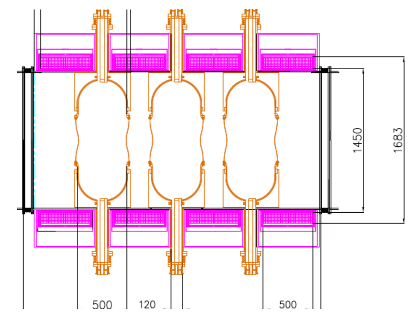




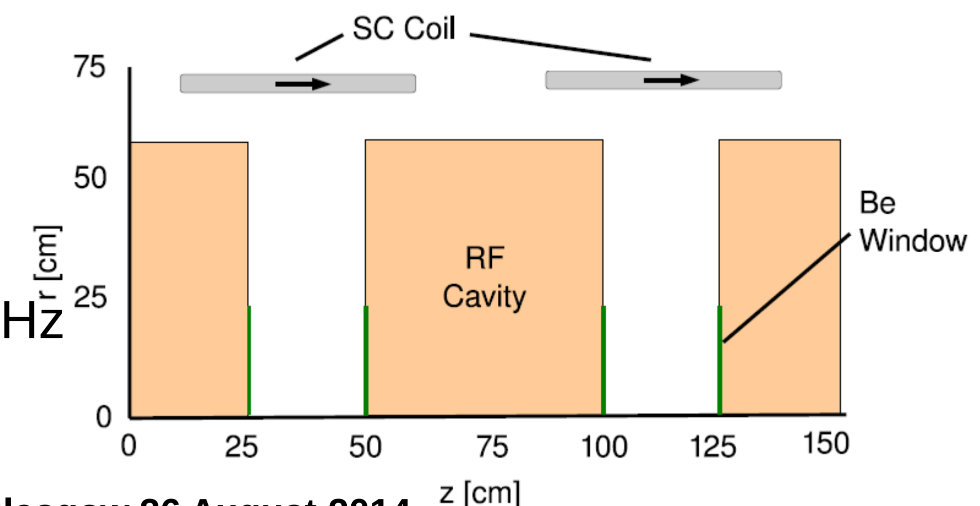
Muon Front End



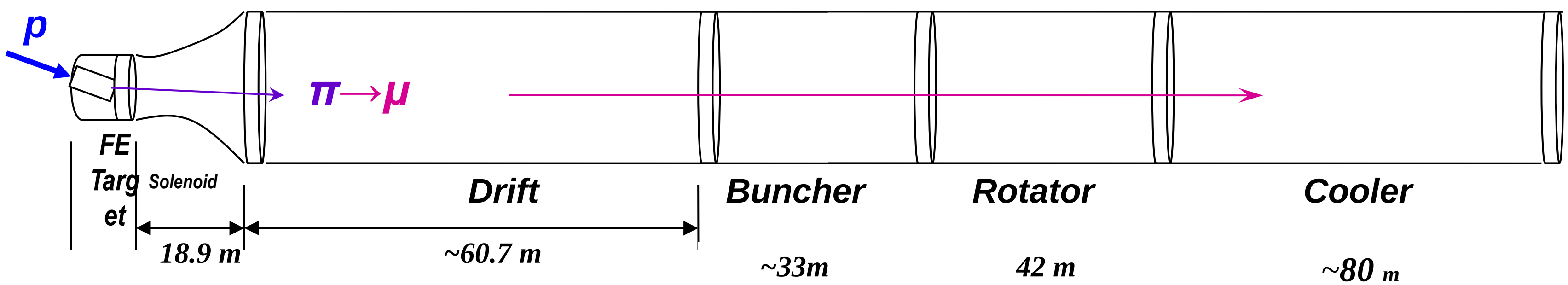


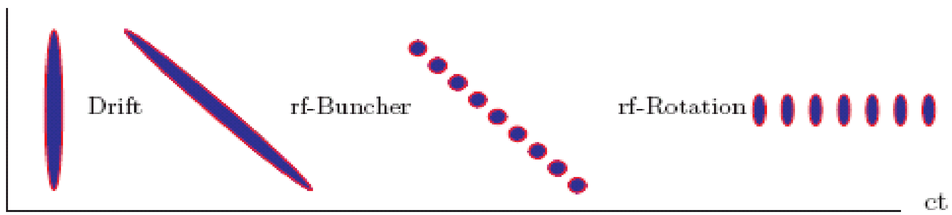


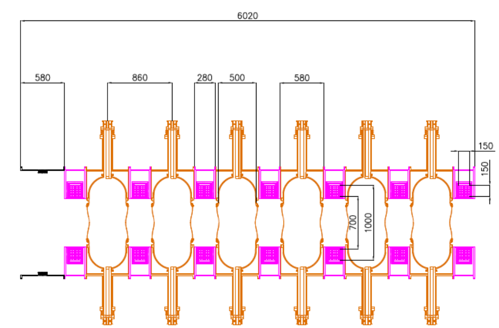
- Phase rotation:
  - 56 cells of 0.75 m length
  - Total length: 42 m
  - 56 normal conducting RF cavities with SC coils
  - RF frequency 230.2- 202.3 MHz
  - Gradient 12 MV/m



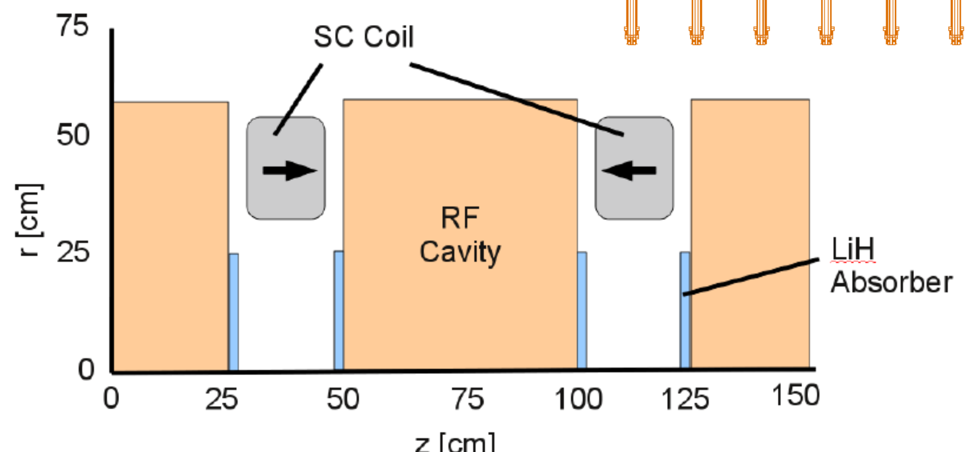
Muon Front End



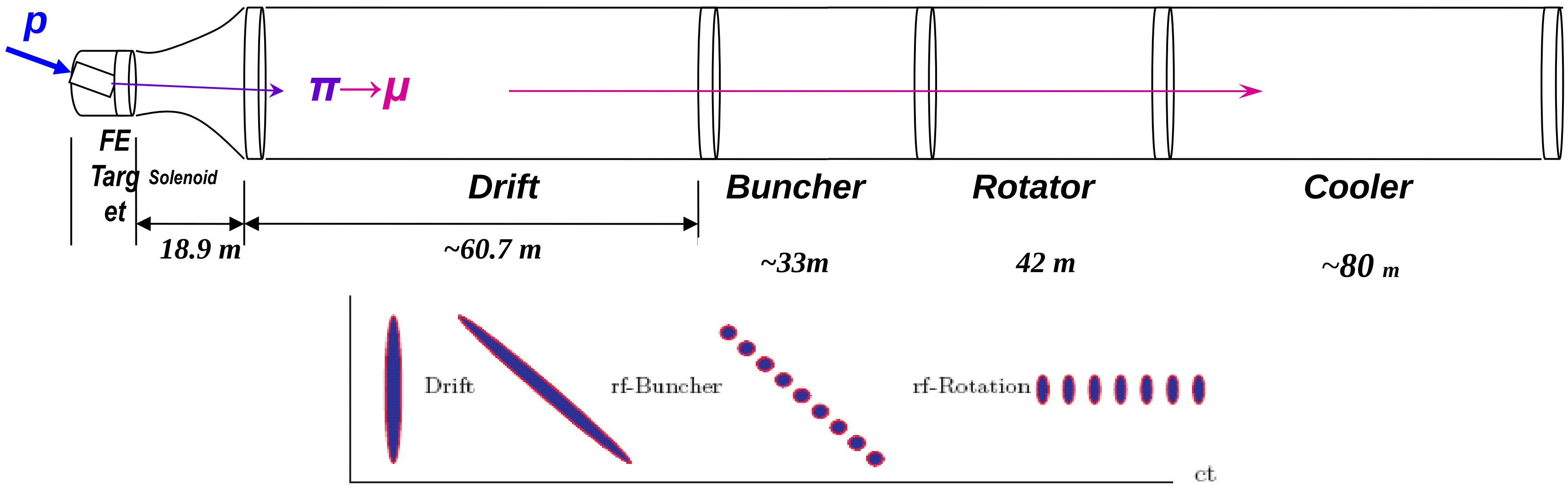




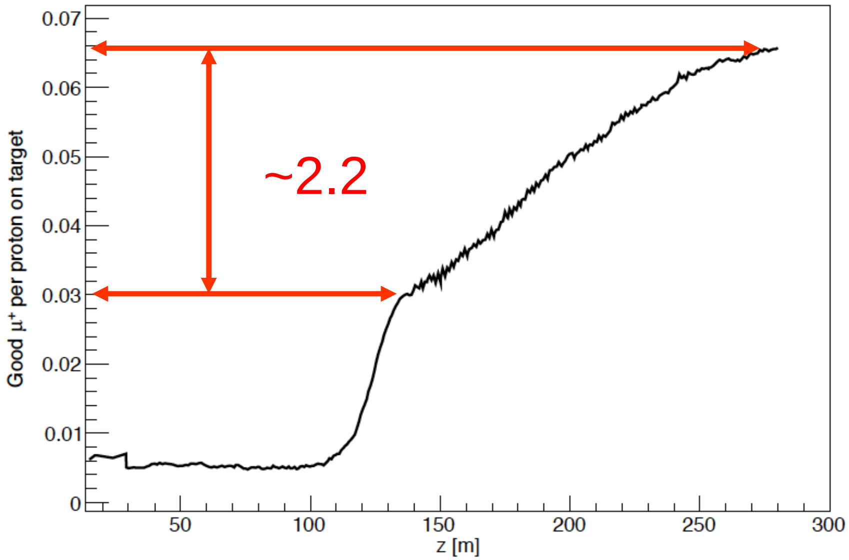
- Cooling channel: MICE demonstration
  - 100 cells of 0.75 m length ➔0.86 m
  - Total length: ~80 m
  - 100 normal conducting RF cavities with SC coils
  - RF frequency 201.25 MHz
  - Gradient 15 MV/m
  - LiH absorbers (1.1 cm)



Muon Front End

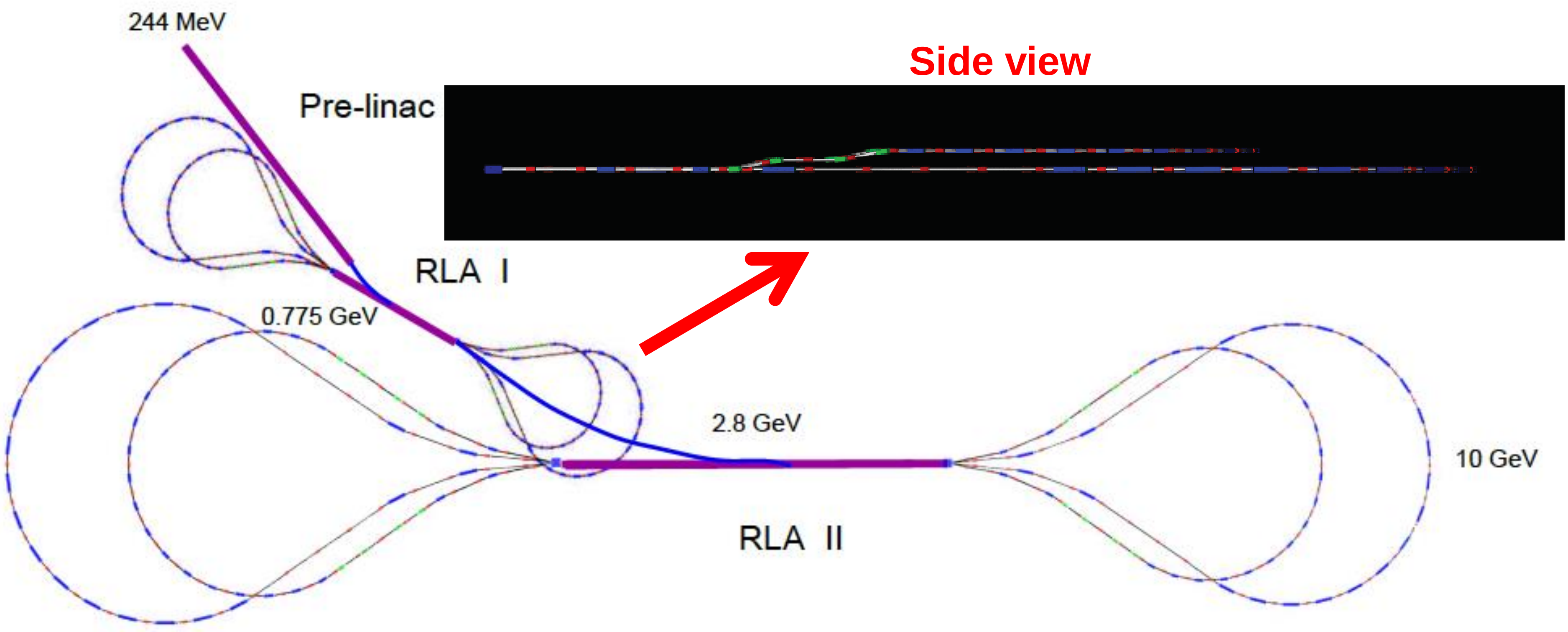


- Front end performance:
  - 0.066 μ/proton
  - Cooling increases muon yield by a factor of ~2.2
  - Cooling channel is most cost-effective way to increase yield of muons



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

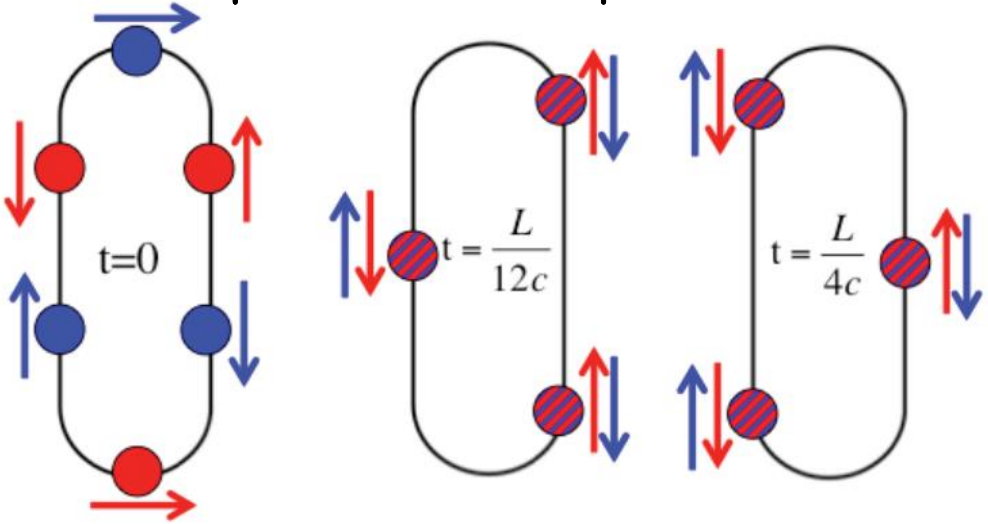


Decay Ring Geometry

- 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

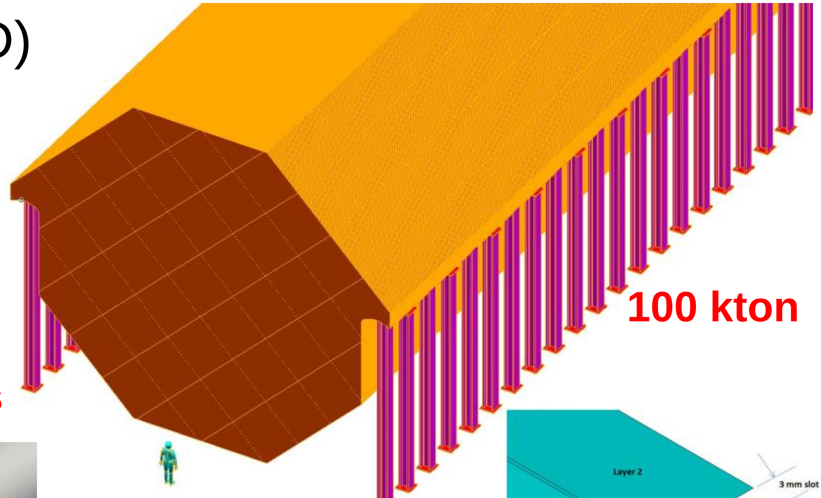
Three μ^+ and three μ^- bunches



Divergence < $0.1/\gamma$

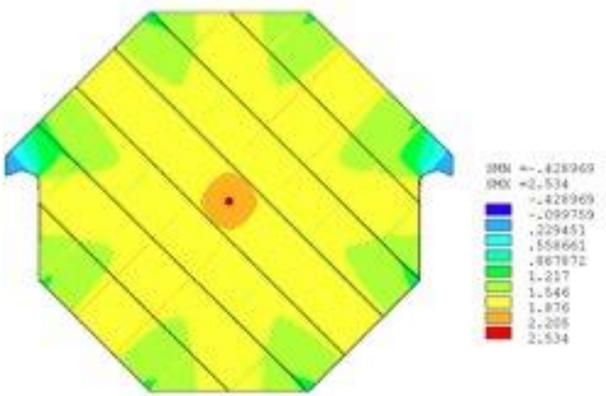
MIND Far Detector

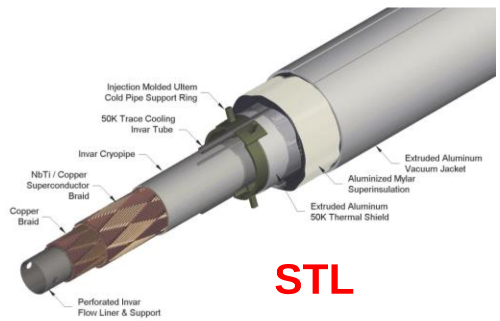
- Magnetised Iron neutrino Detector (MIND)
- Octagonal plates and toroidal field
- Magnetic field 1.2-2.2 T from 8x15 kA current delivered by Superconducting Transmission Line (STL): ~10cm hole



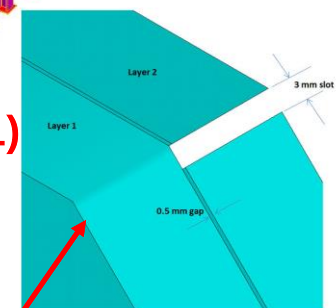
14mx14mx3cm plates

Bross, Wands (FNAL)

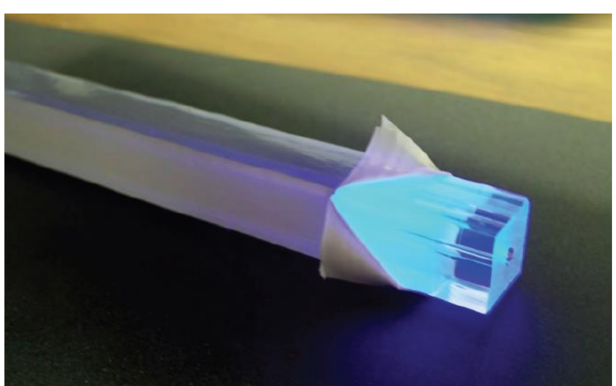


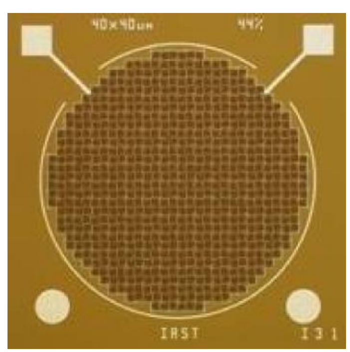


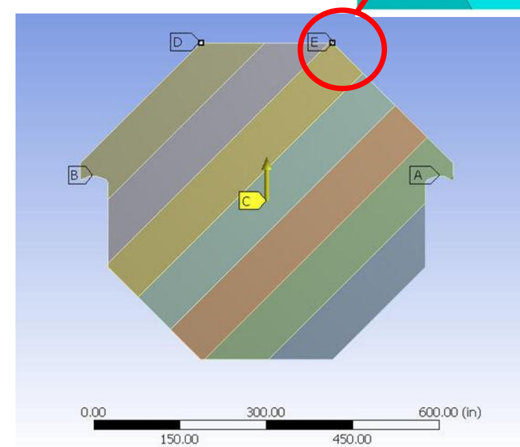
STL



- Extruded scintillator with WLS fibre and SiPMT

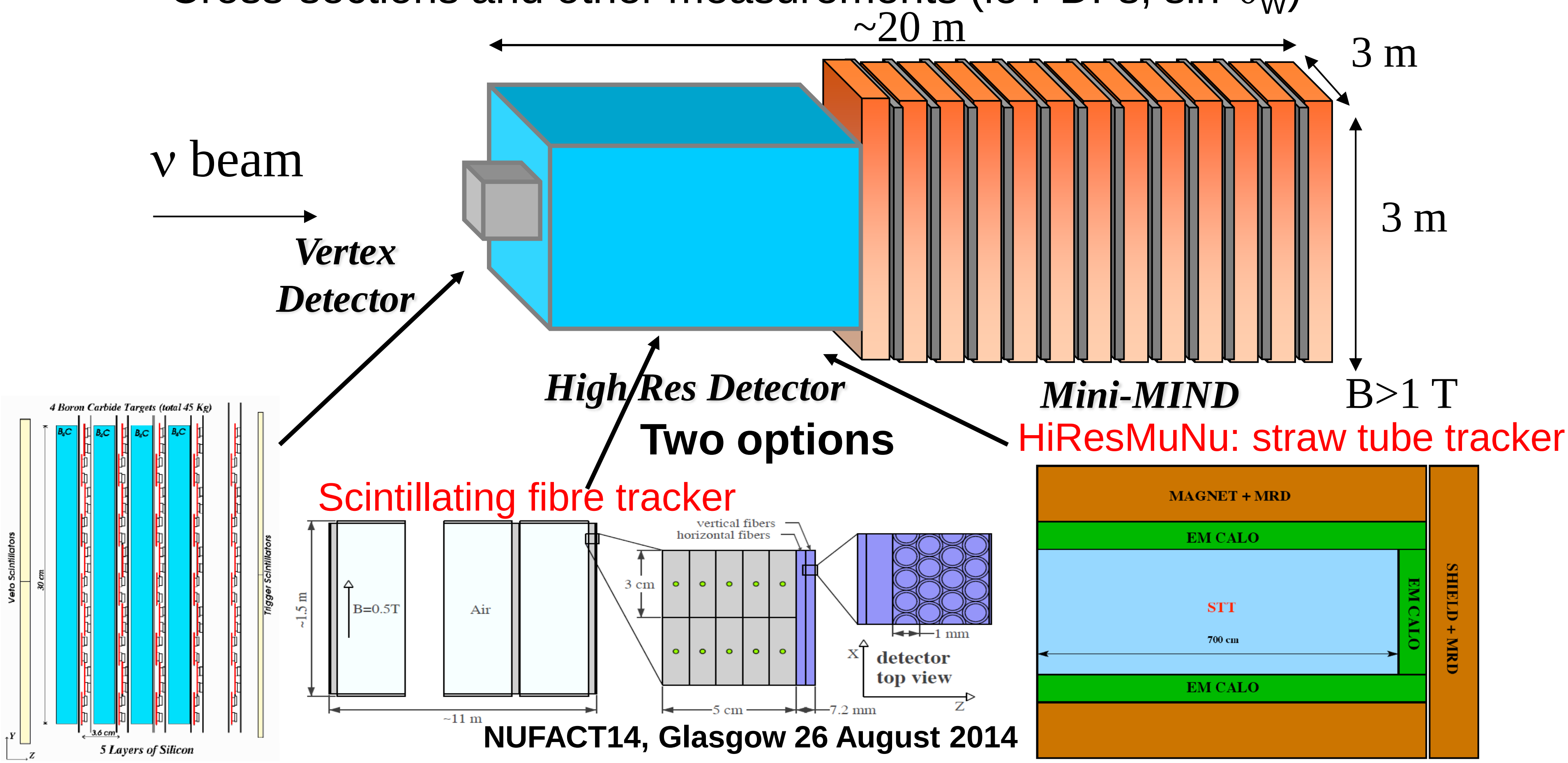






Near Detector

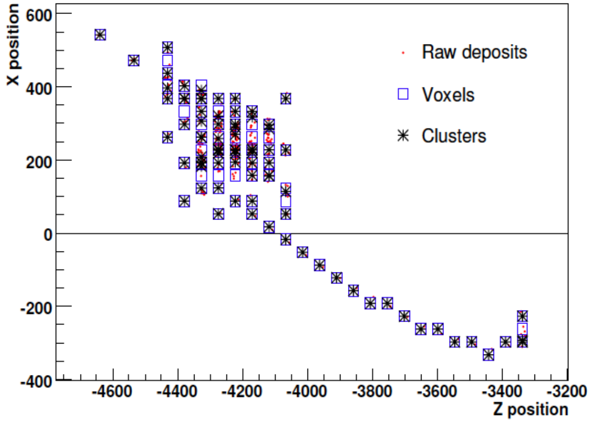
- Two near detectors required, one at each straight:
  - Neutrino flux (<1% precision) and extrapolation to far detector
  - Charm production (main background) and taus for Non Standard Interactions (NSI) searches
  - Cross-sections and other measurements (ie PDFs, $\sin^2\theta_W$)

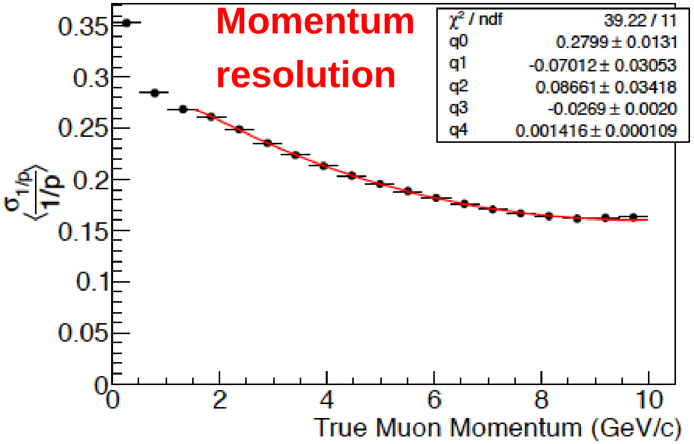


Golden Channel $\nu_e \rightarrow \nu_\mu$ analysis

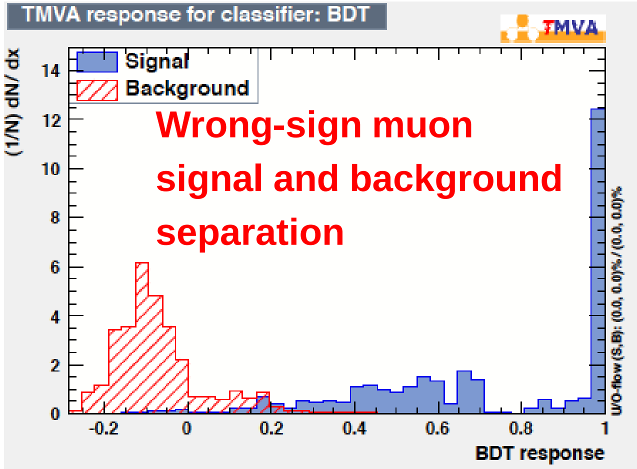
- Full simulation and reconstruction of neutrino interactions

R. Bayes

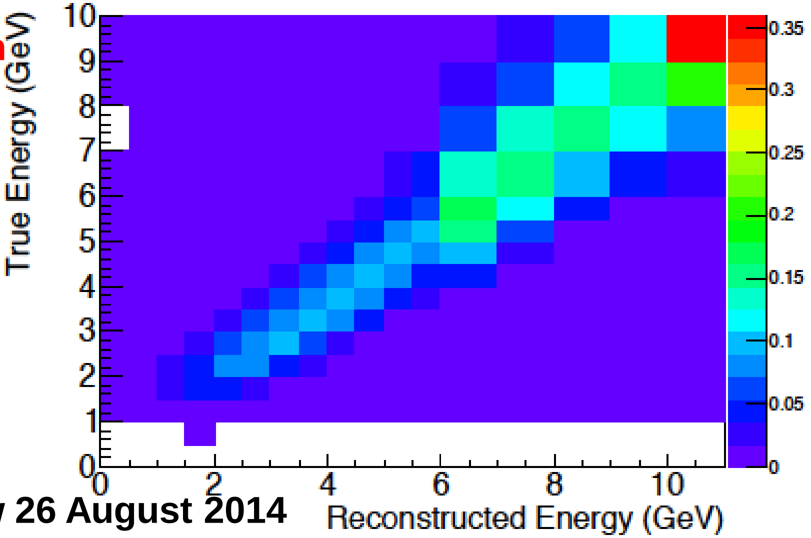




- Multi-variate analysis (MVA) with five variables, tuned for $\sin^2 2\theta_{13}$~0.1: Boosted Decision Tree (BDT) adopted



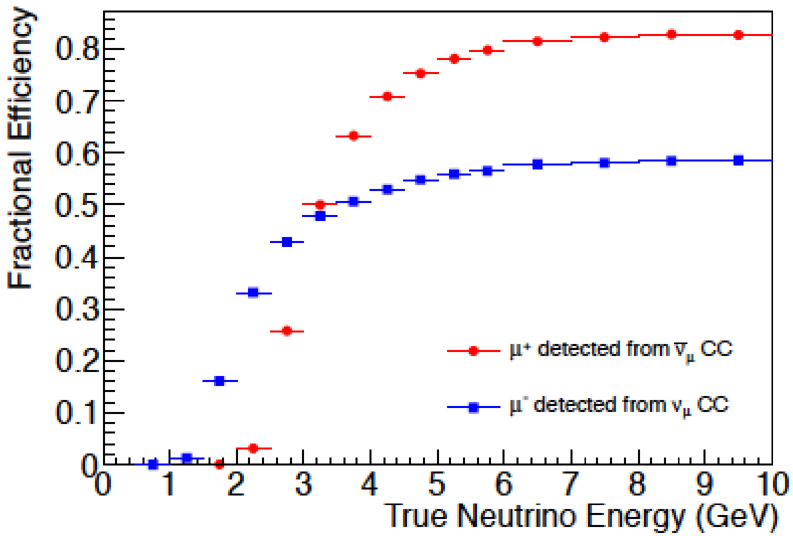
Migration matrix



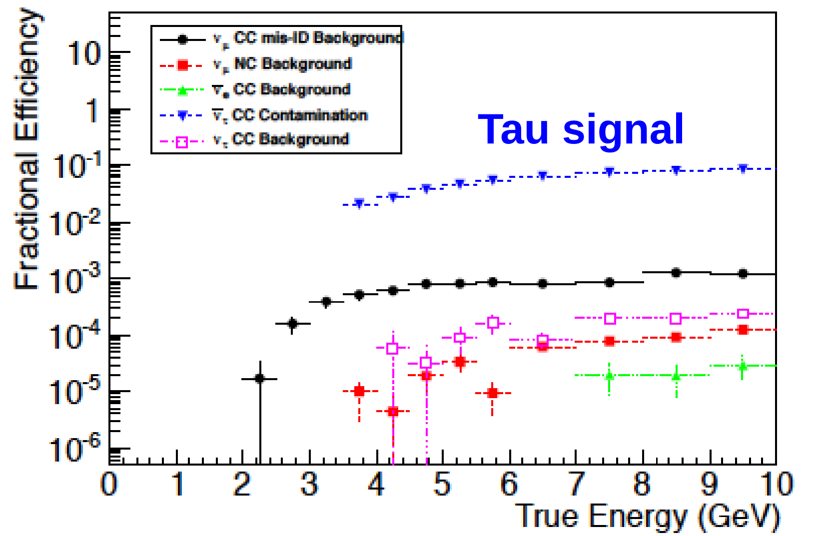
MIND efficiencies and background

R. Bayes

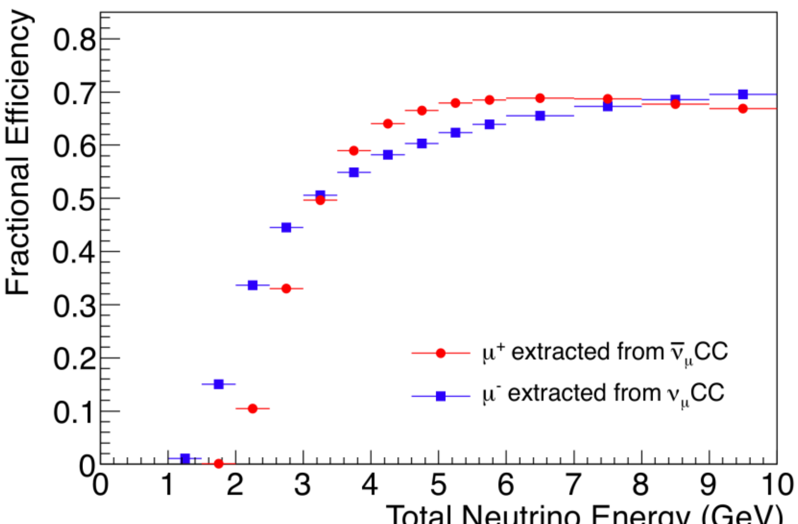
BDT efficiency, focussing μ^+



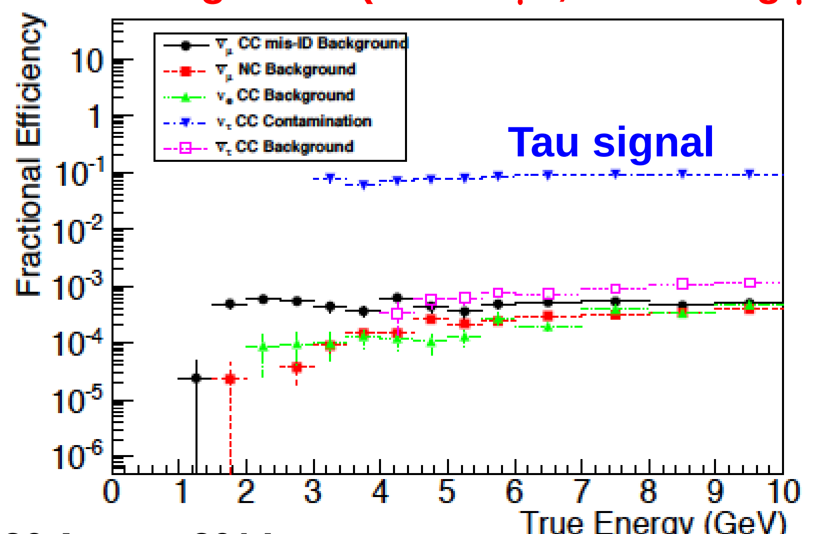
BDT background (stored μ^-, focussing μ^+)



BDT efficiency, focussing μ^-



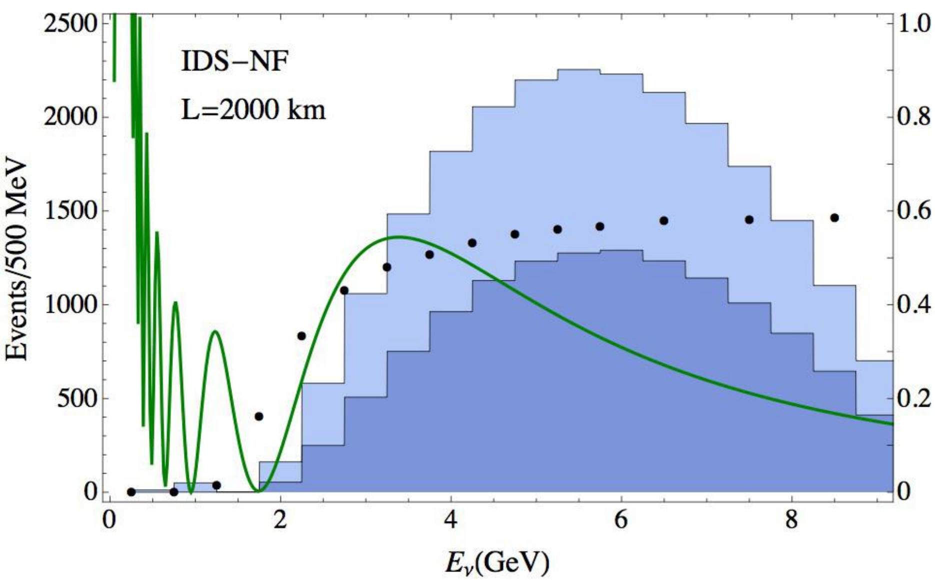
BDT background (stored μ^+, focussing μ^+)

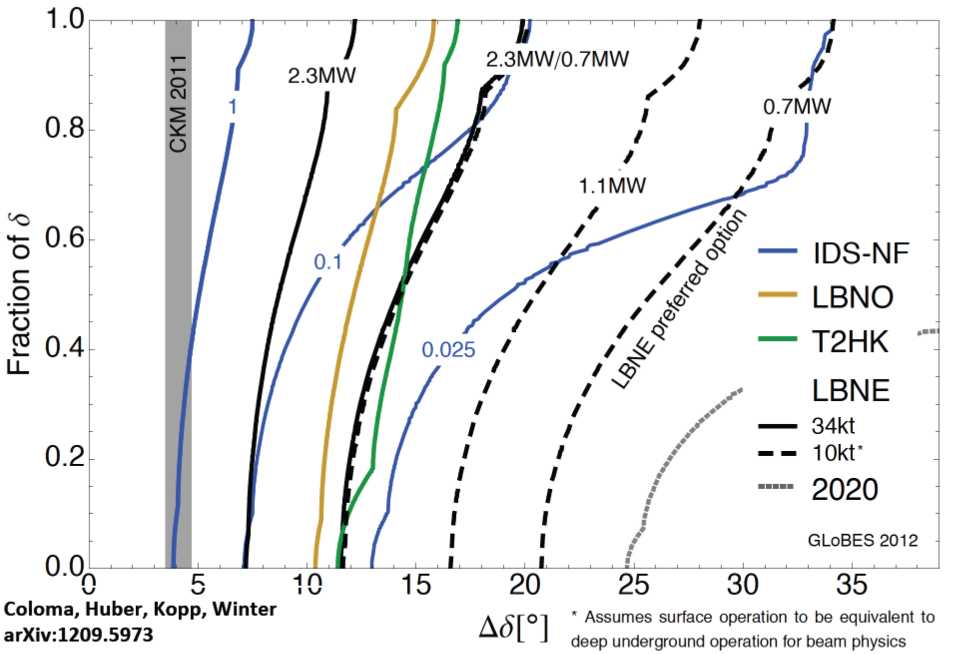


Performance 10 GeV Neutrino Factory

- Systematic errors: 1% signal and 20% background
- Results 10 GeV Neutrino Factory, 10^{21} μ/year for 10 years with 100 kton MIND at 2000 km gives best sensitivity to CP violation
- This provides best sensitivity out of all future proposed facilities

arXiv:1209.5973





CP violation 5σ coverage is 85% (ie. 85% probability of CPV discovery!)

Conclusions

- International Design Study for a Neutrino Factory (IDS-NF) has concluded its study
  - Interim Design Report delivered March 2011
  - Reference Design Report should be published by end of 2014 (it should have come out already but delayed by a number of “crises” that everyone in this room is aware of
  - It defines benchmark 10 GeV Neutrino Factory
  - Concepts for accelerator systems have been defined
  - 100 kton Magnetised Iron Neutrino Detectors (MIND)
  - Best sensitivity for CP violation of all possible future neutrino facilities
- We need to continue with international programme to have unified voice