Imperial College London

K. Long; 10 August, 2011

The Neutrino Factory

Contents:

- Sensitivity and precision
- Muon accelerators for particle physics
- Conclusions

The Neutrino Factory

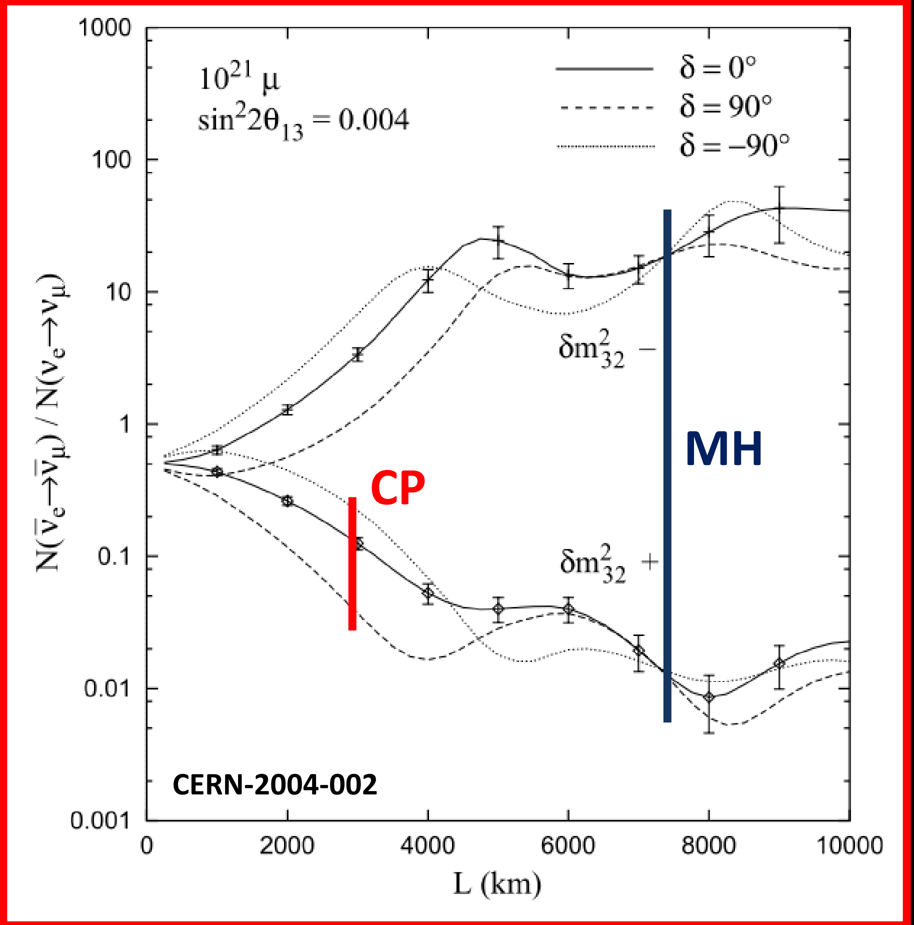
Sensitivity and precision

The Neutrino Factory:

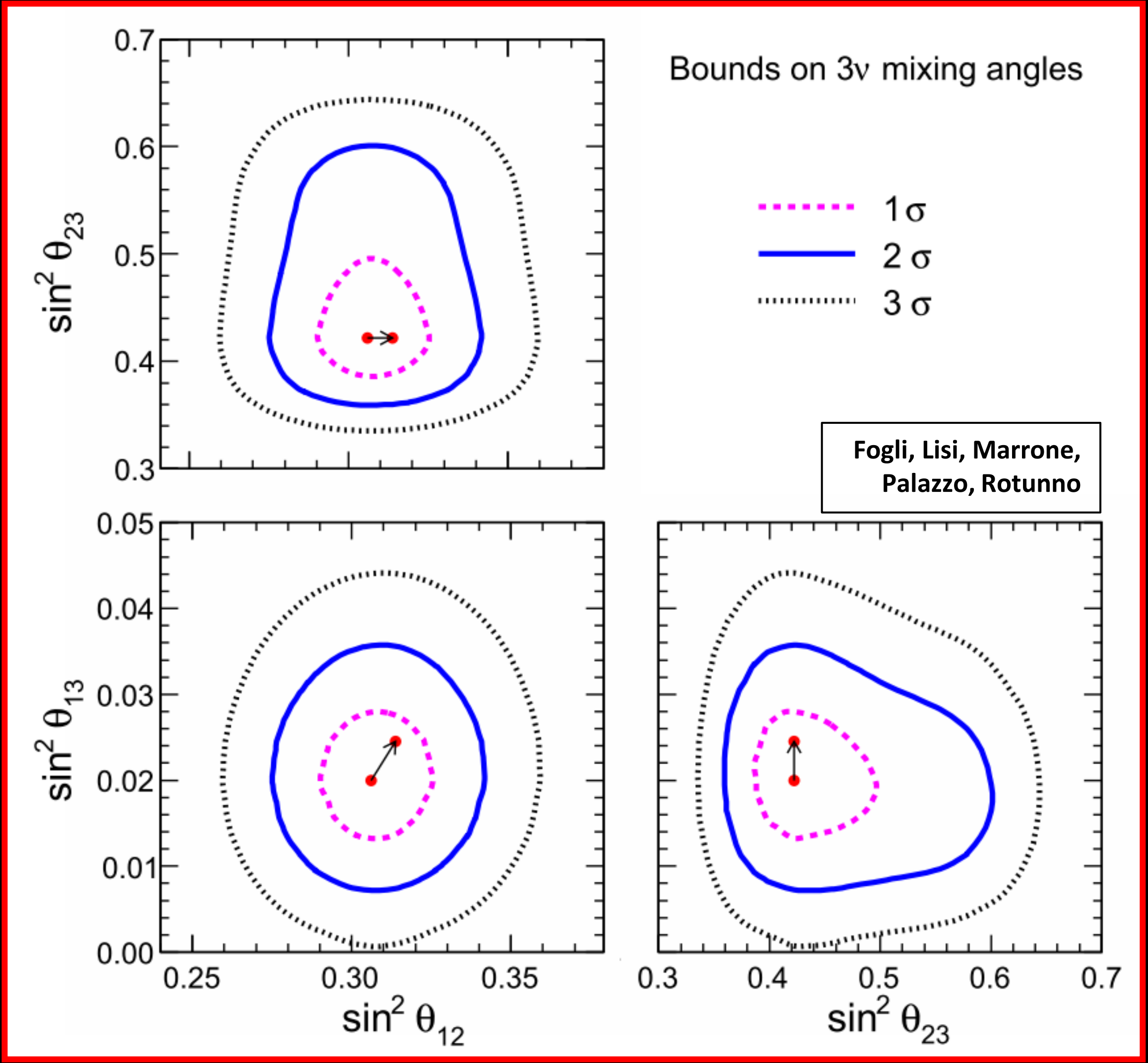
- **Multiplicity of channels**

Stored $\mu^- \to e^- \nu_\mu \bar{\nu}_e$	
Disappearance	Appearance
$\bar{\nu}_e \to \bar{\nu}_e \to e^+$	$\bar{\nu}_e \to \bar{\nu}_\mu \to \mu^+$ $\bar{\nu}_e \to \bar{\nu}_\tau \to \tau^+$
$\nu_\mu \to \nu_\mu \to \mu^-$	$\nu_\mu \to \nu_e \to e^-$ $\nu_\mu \to \nu_\tau \to \tau^-$

- **Optimise discovery potential for CP and MH**
  - Requirements:
    - Large ν_e ($\bar{\nu}_e$) flux
      - Detailed study of sub-leading effects
    - (Large) high-energy ν_e ($\bar{\nu}_e$) flux
      - Optimise event rate at fixed *L/E*
      - Optimise MH sensitivity
      - Optimise CP sensitivity



θ_{13}:



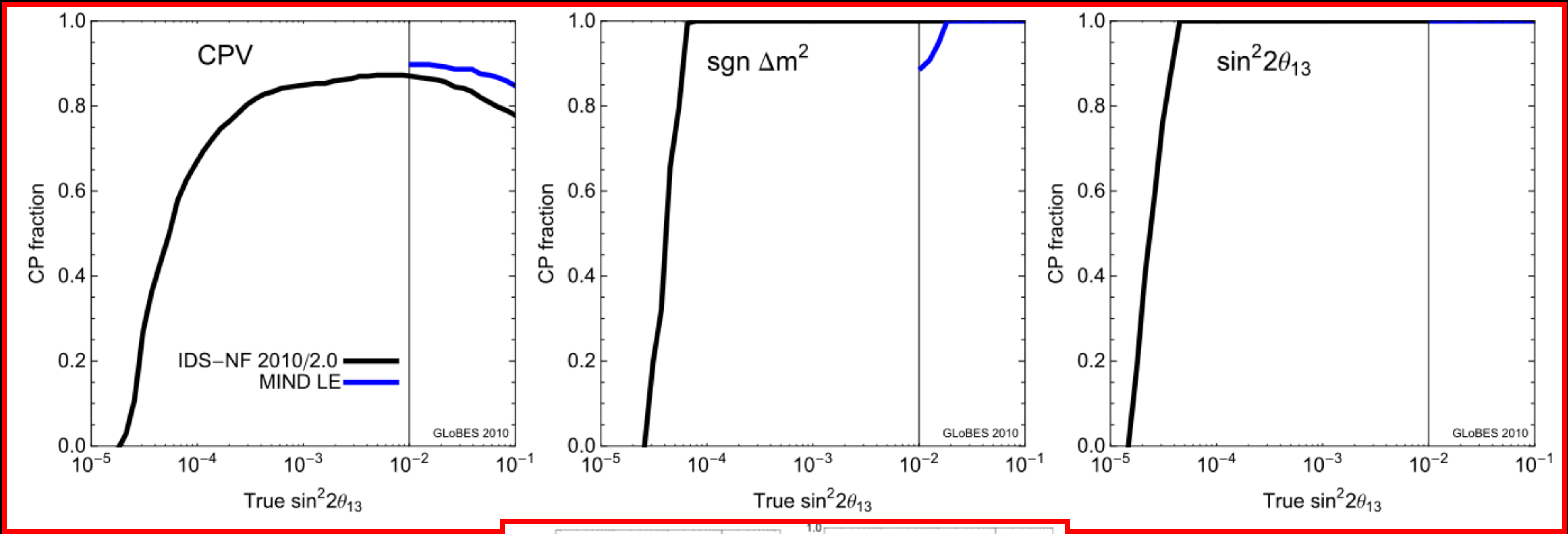
- **Global analysis of oscillation data, including recent T2K and MINOS data, indicate evidence for $\theta_{13} > 0$ at 3σ**

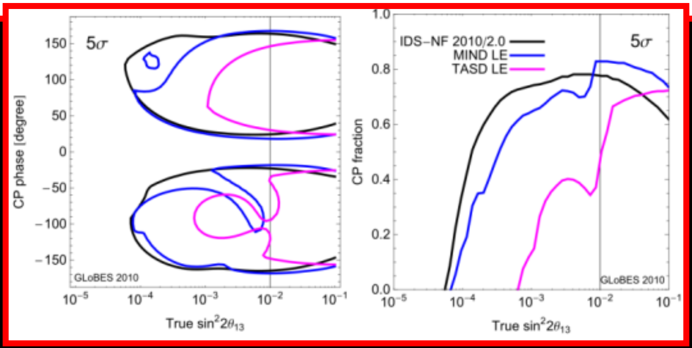
- **Exciting new data!**
- **If confirmed, makes discovery of CP possible:**
  - **Almost certainly at Neutrino Factory**
  - **Increases motivation for precision determination of parameters and search for "non-standard effects"**

Neutrino Factory performance:

- Discovery reach at 3σ extends down to $\sin^2 2\theta_{13} \sim 5 \times 10^{-5}$
  – Should θ_{13} to be shown to be > 0 before start of Neutrino Factory project:
    - Re-optimisation of baseline:
      – 10 GeV muon energy serving a single 100 kTon MIND at a baseline of 2000 km

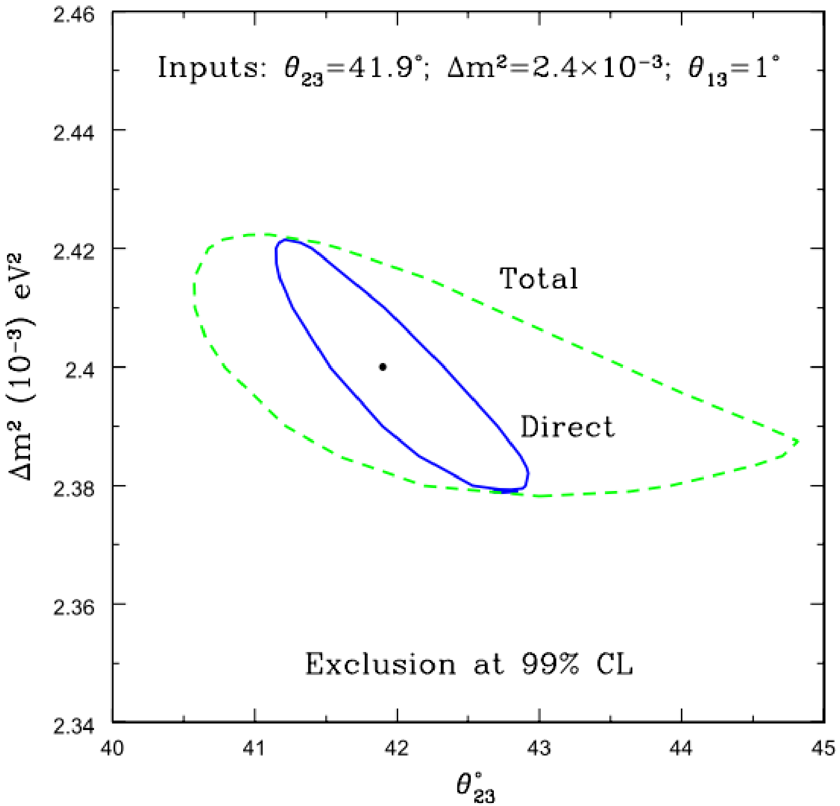
      gives excellent performance



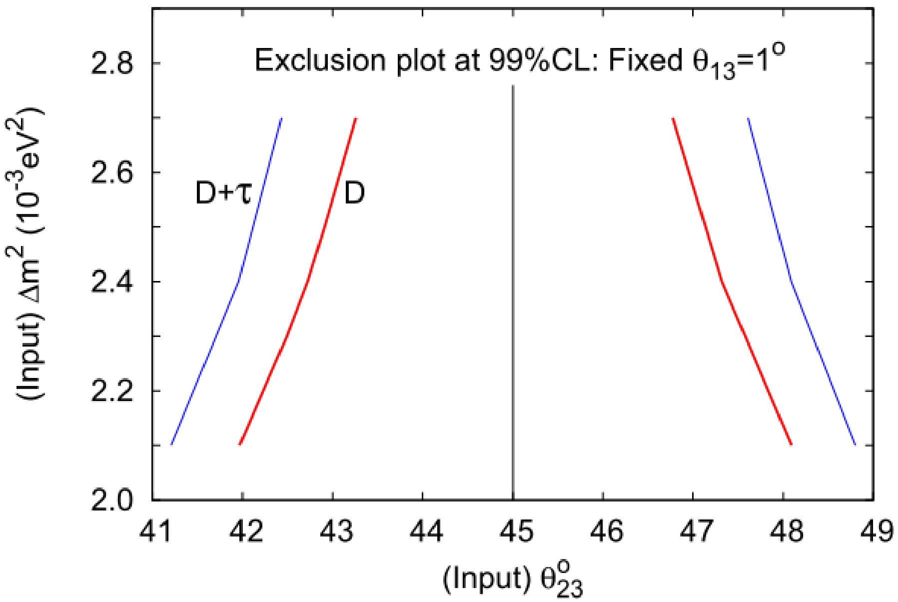


Neutrino Factory performance:

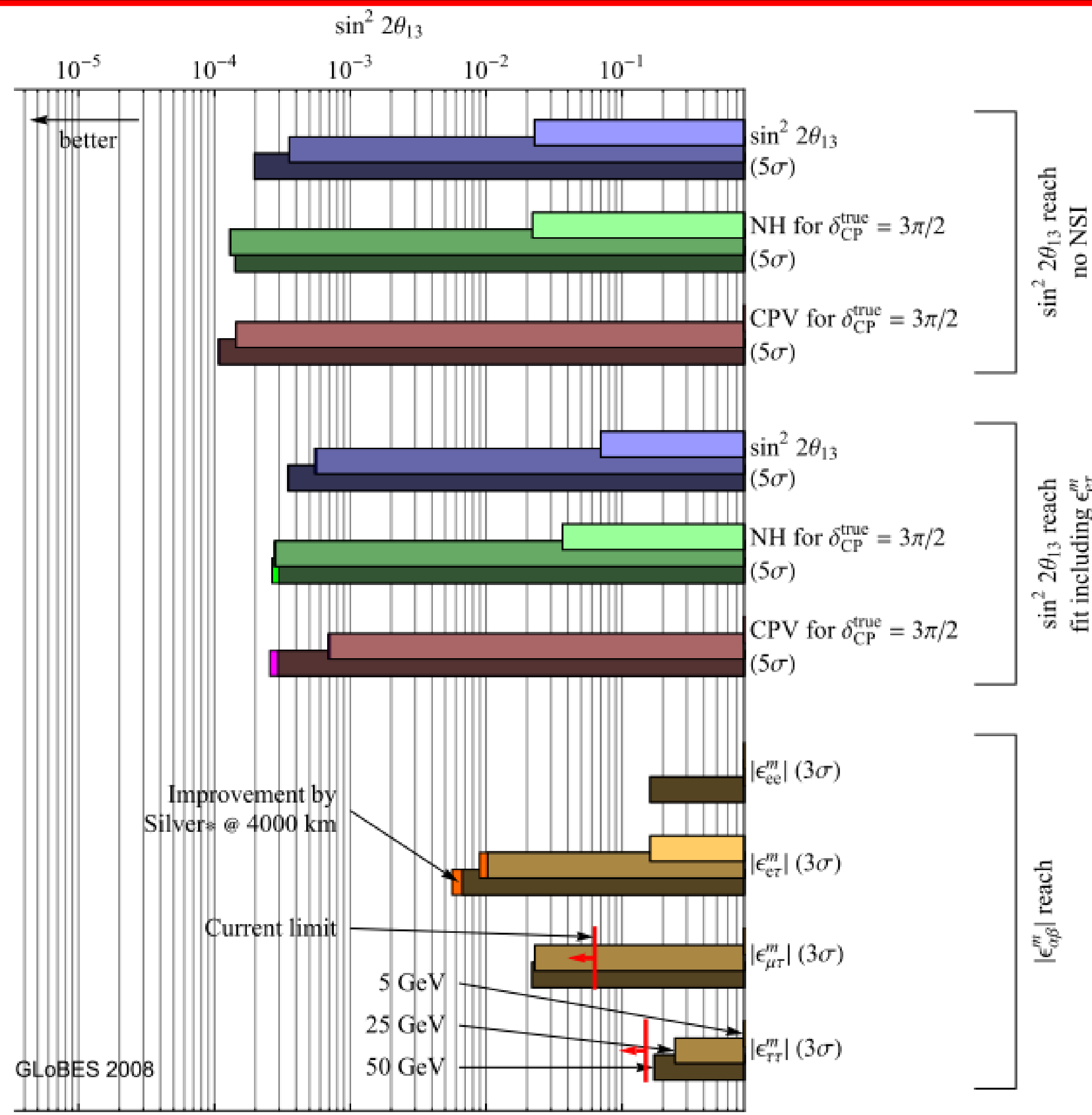
- **Precision:**
  - Determination of deviation of θ_{23} from $\pi/4$:
    - Uncertainty ~ $\pm 4^o$ at 99% C.L.



D. Indumathi and N. Sinha, Phys. Rev. D80 (2009) 113012



Sensitivity to non-standard interactions:



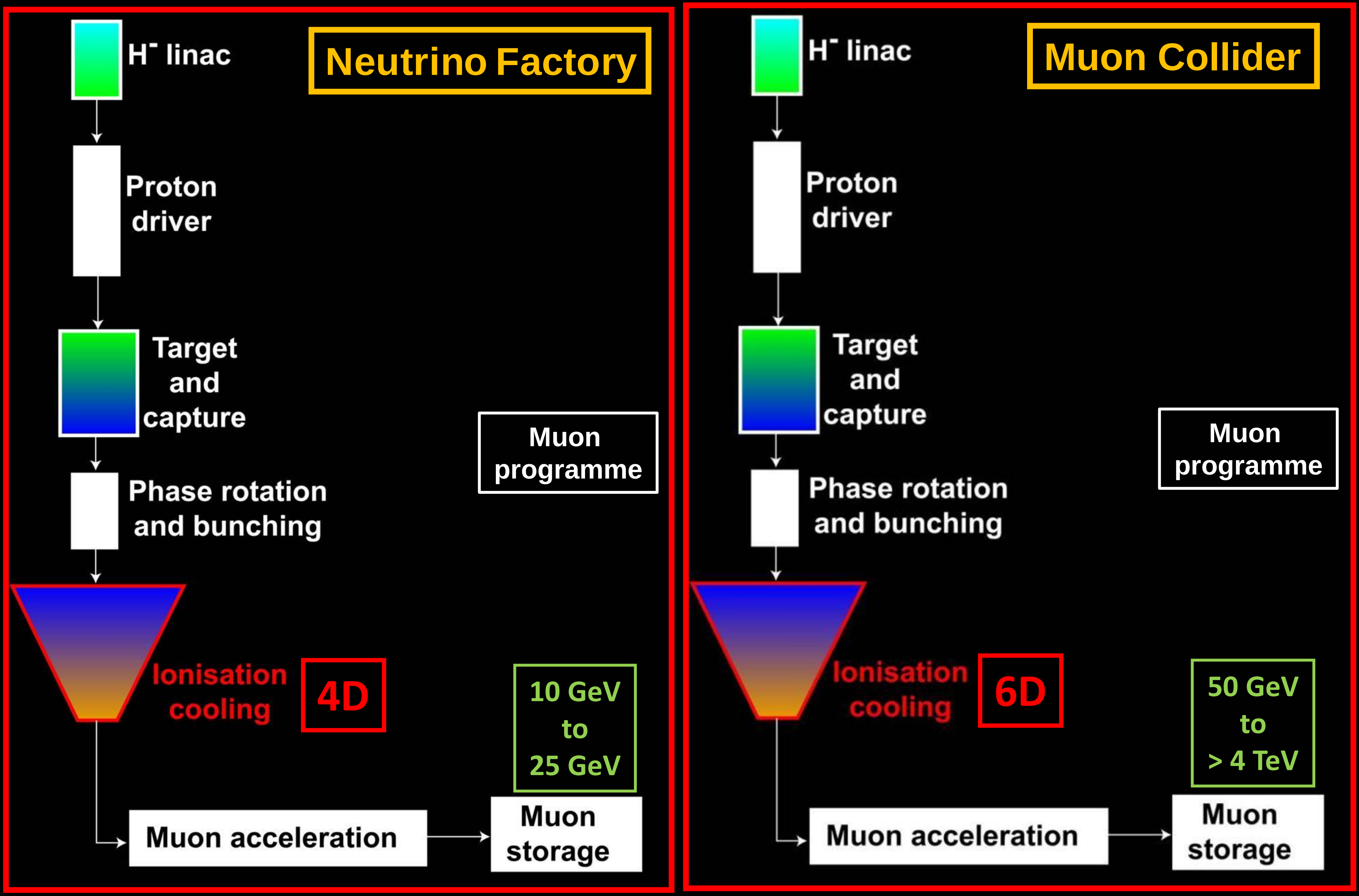
J. Kopp, T. Ota, and W. Winter, Phys. Rev. D78 (2008) 053007

The Neutrino Factory:

Muon accelerators for particle physics

Opportunities:

- **Lepton-antilepton collisions:**
  - Multi-TeV *Muon Collider* with small footprint
    - Critical issue: $L > 10^{34}$ cm^{-2}
- **Neutrino beams for study of neutrino oscillation:**
  - *Neutrino Factory* delivering high-energy ν_e & ν_μ beams
    - Critical issue: muon rate of $> 10^{14}$ s^{-1}
- **Search for charged lepton flavour violation:**
  - Intense, well controlled muon beams
    - Critical issues:
      - Extinction of signals arising from "Standard Model processes"
- **Cross section measurement and search for sterile neutrinos:**
  - Race-track muon storage ring has potential to allow:
    - Precise measurement of ν_eN cross sections
    - Study of LNSD/MiniBOONE anomolies

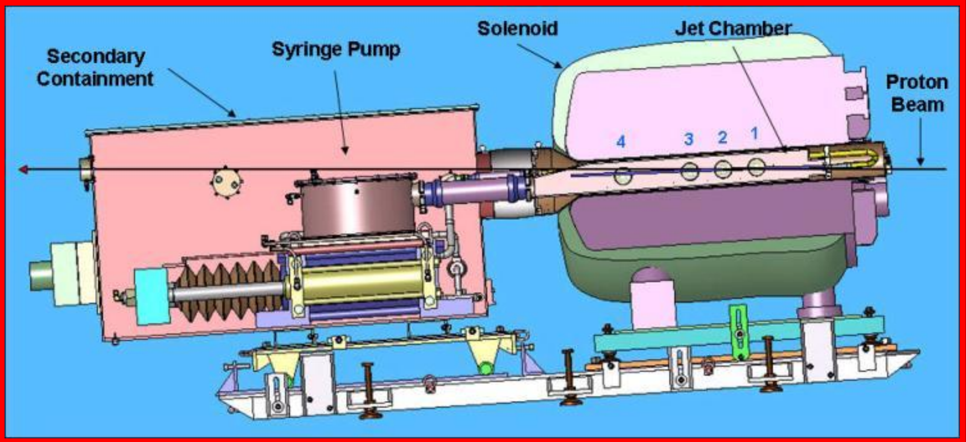

Neutrino Factory
H⁻ linac
Proton driver
Target and capture
Phase rotation and bunching
Ionisation cooling
4D
Muon acceleration
Muon storage
Muon programme
10 GeV to 25 GeV
Muon Collider
H⁻ linac
Proton driver
Target and capture
Phase rotation and bunching
Ionisation cooling
6D
Muon acceleration
Muon storage
Muon programme
50 GeV to > 4 TeV

Critical issues:

- High-power (multi-MW), pulsed, proton source
  - And particle-production target to match, MERIT
- Phase-space compression of muon beams:
  - Short muon lifetime requires novel technique:
    - Ionization cooling: proof-of-principle experiment, *MICE*
- Rapid acceleration:
  - Exploit time dilation to suppress muon decay
  - Fixed Field Alternating Gradient Acceleration
    - Novel magnet technology allows acceleration without magnet ramp
    - Proof of principle:
      - *EMMA*: under study at the Daresbury Laboratory

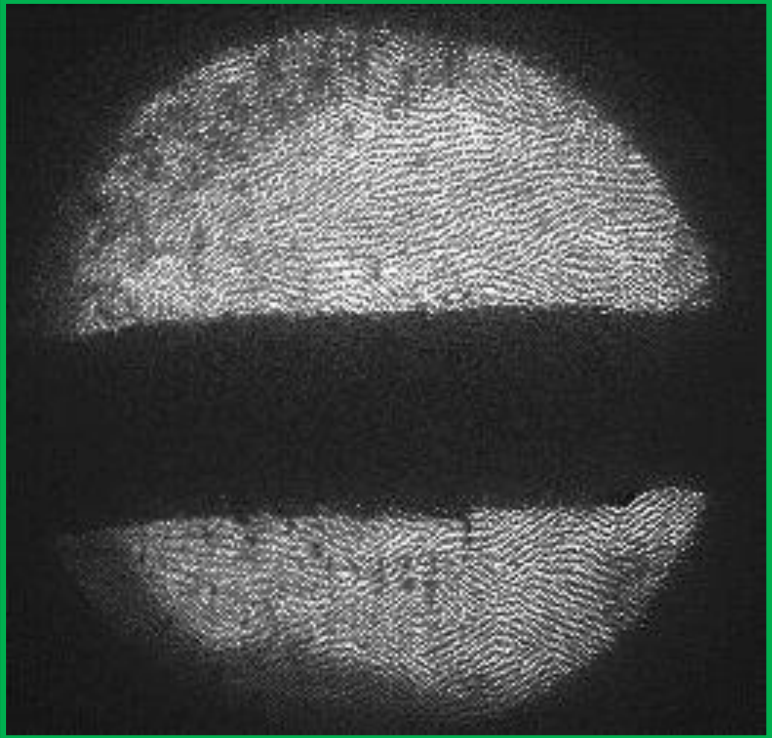
Baseline target: proof of principle: MERIT:

IPAC10: WEPE078

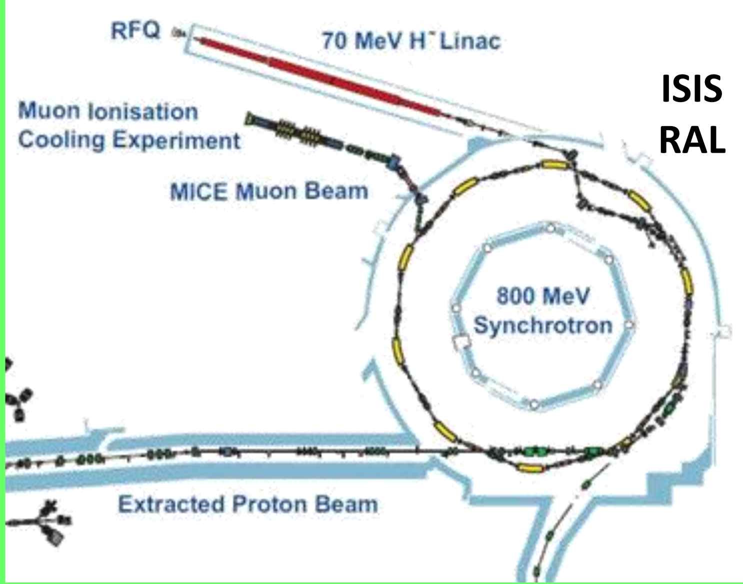


- 'Disruption length': 28 cm
- 'Refill' time: 14 ms
  - Corresponds to 70 Hz
- Hence:
  - Demonstrated operation at:
    - 60 kJ × 70 Hz = 8 MW

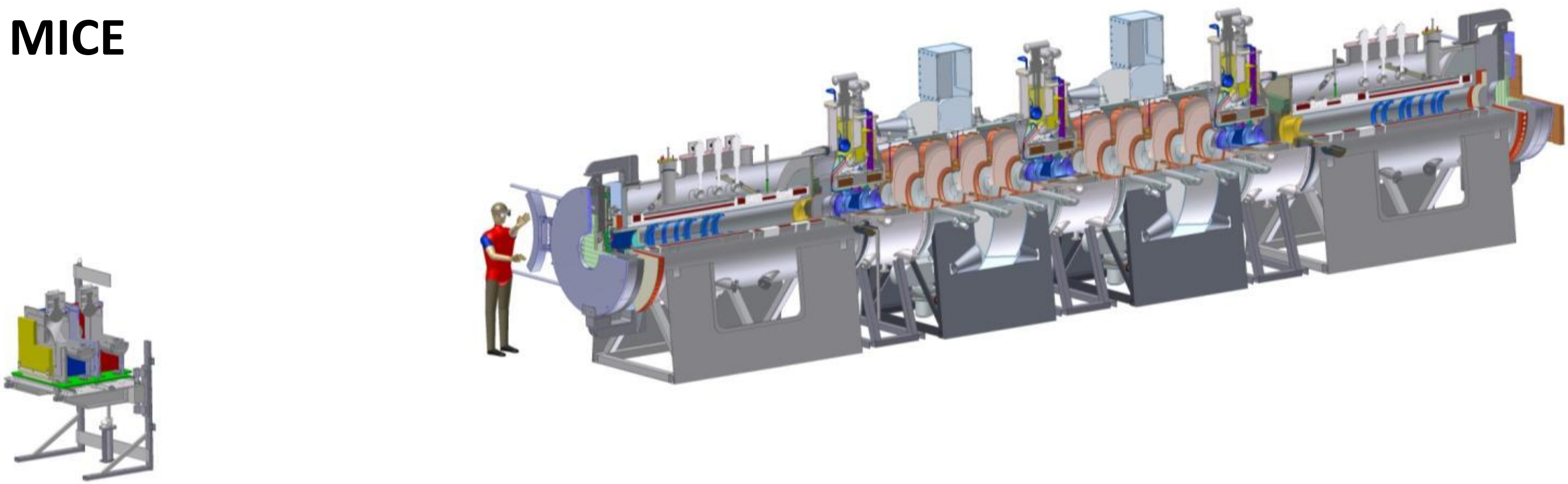
- 20 m/s liquid Hg jet in 15 T B field
- Exposed to CERN PS proton beam:
  - Beam pulse energy = 115 kJ
  - Reached 30 tera protons at 24 GeV



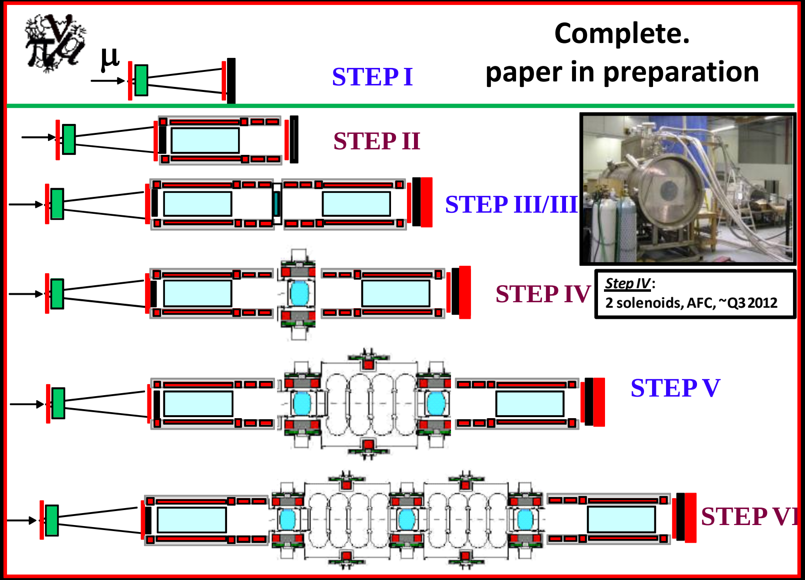
- **MICE: proof of principle:**
  - Design, build, commission and operate a realistic section of cooling channel
  - Measure its performance in a variety of modes of operation and beam conditions
    - Results will allow Neutrino Factory complex to be optimised



MICE

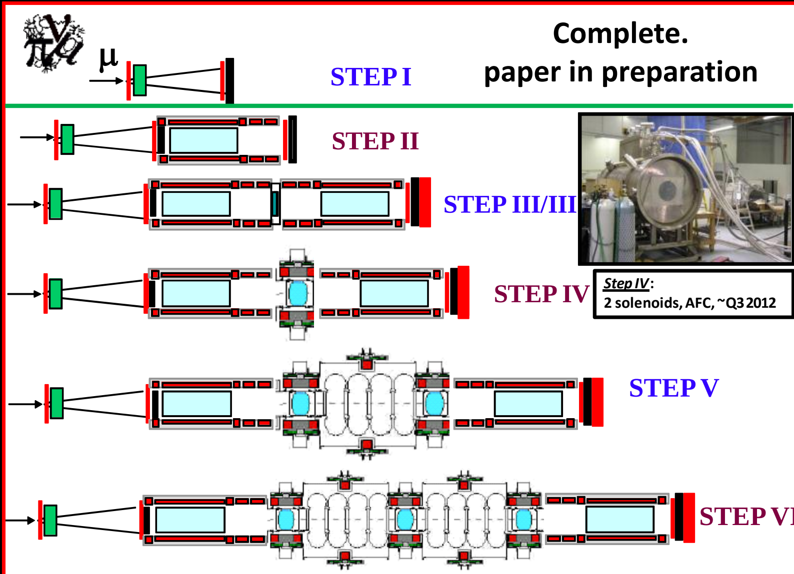


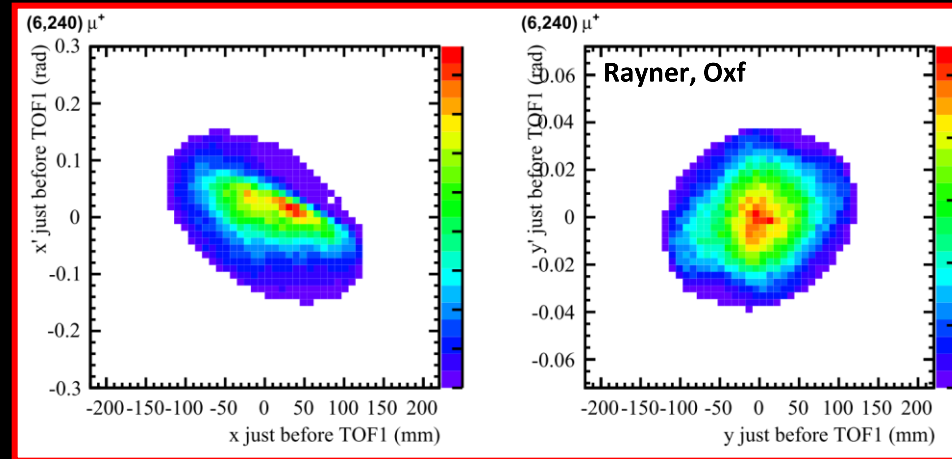
Staged implementation:



- Step I:
  - Characterization of beam complete:
    - MICE Muon Beam delivers range of momentum and emittance required by MICE
- Step IV:
  - Integration complete Q3 2012
  - Running with a variety of absorbers scheduled for 1 year
    - Break in running if ready to implement Step V
      - Implementation of Step V by Q2 2014 will allow Step V running before long ISIS shutdown [Aug14 to Feb15]
- Steps V and VI will be implemented starting at the end of Step IV data taking

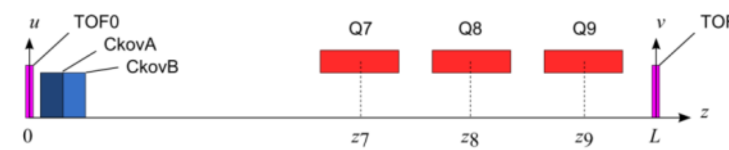
Staged implementation:





- **Step I:**
  - **Characterization of beam complete:**
    - **MICE Muon Beam delivers momentum and emittance required by MICE**

Reconstruction technique



A transfer matrix $\mathbf{M}(p_z)$ maps trace space from TOF0 to TOF1

$$\begin{pmatrix} v \\ v' \end{pmatrix} = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} \begin{pmatrix} u \\ u' \end{pmatrix}$$

$\det \mathbf{M} \equiv 1 \Rightarrow$ angles may be deduced from positions

$$\begin{pmatrix} u' \\ v' \end{pmatrix} = \frac{1}{M_{12}} \begin{pmatrix} -M_{11} & 1 \\ -1 & M_{22} \end{pmatrix} \begin{pmatrix} u \\ v \end{pmatrix}$$

Mark Rayner, for MICE — New Results from MICE

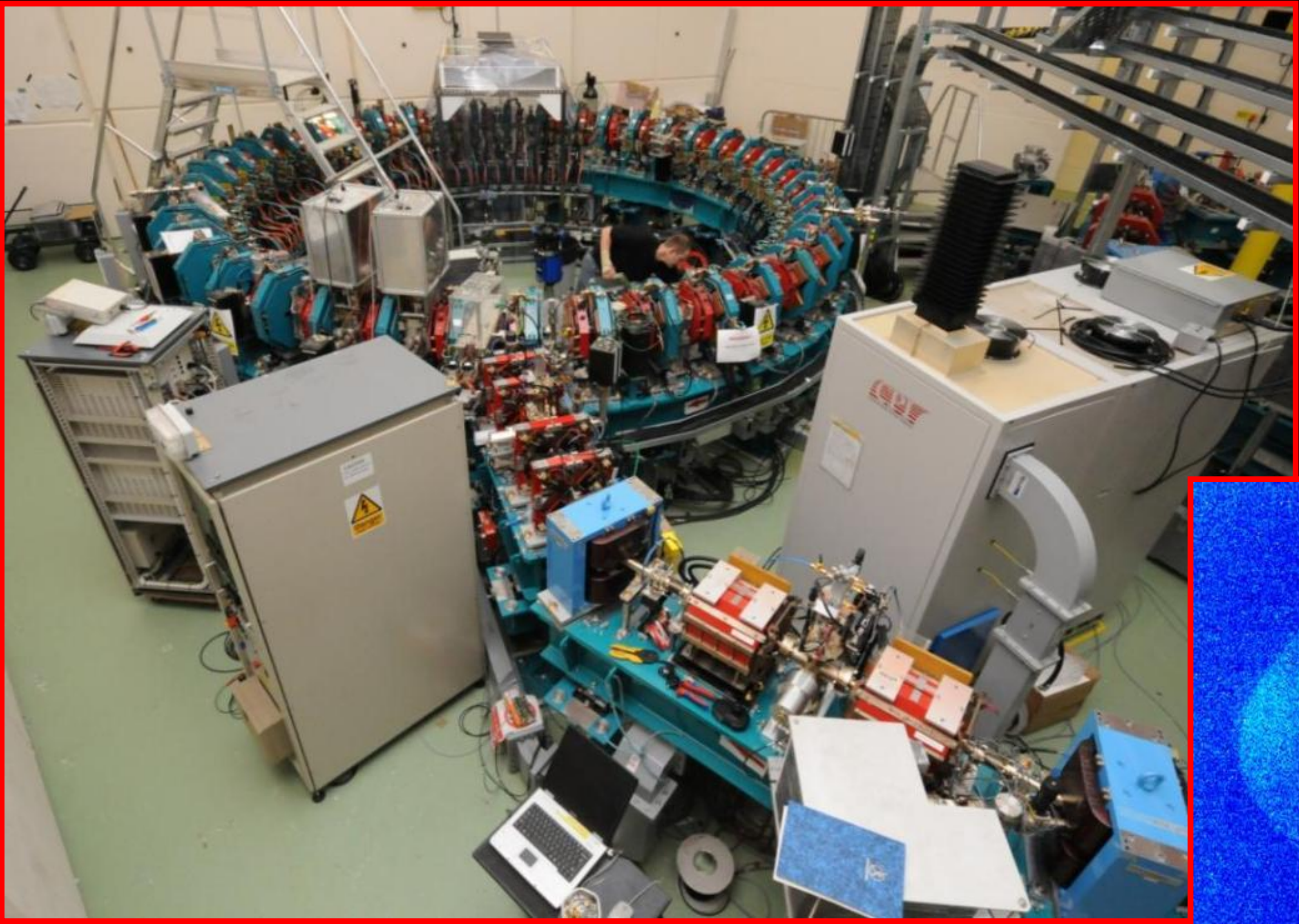
Reconstructed muon tracks/(Vms)/(3.2 ms spill)

		μ^- rate			μ^+ rate		
		P_z (MeV/c)			P_z (MeV/c)		
		140	200	240	140	200	240
ϵ_N (mm·rad)	3	4.1 ±0.2	6.3 ±0.2	4.9 ±0.2	16.8 ±1.8	33.1 ±3.2	33.0 ±2.6
	6	4.1 ±0.4	4.8 ±0.2	4.5 ±0.2	17.8 ±1.8	31.0 ±2.0	31.7 ±2.0
	10	4.6 ±0.2	5.4 ±0.2	4.4 ±0.1	21.6 ±2.2	34.0 ±2.5	26.1 ±1.5

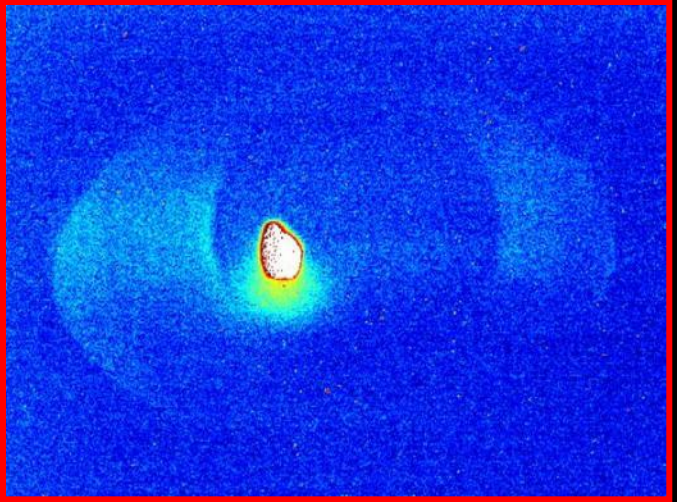
Dobbs et al (Imperial)

Muon acceleration: proof of principle:

- EMMA at the Daresbury Laboratory
  - Electron Model of Muon Acceleration
    - Aka:
      - Electron Model of Many Applications



- Installation complete;
- Commissioning underway
- First extracted beam: 15Mar11



Conclusions:

International Design Study for the

Neutrino Factory

IDS-NF-020

Interim Design Report

The IDS-NF collaboration

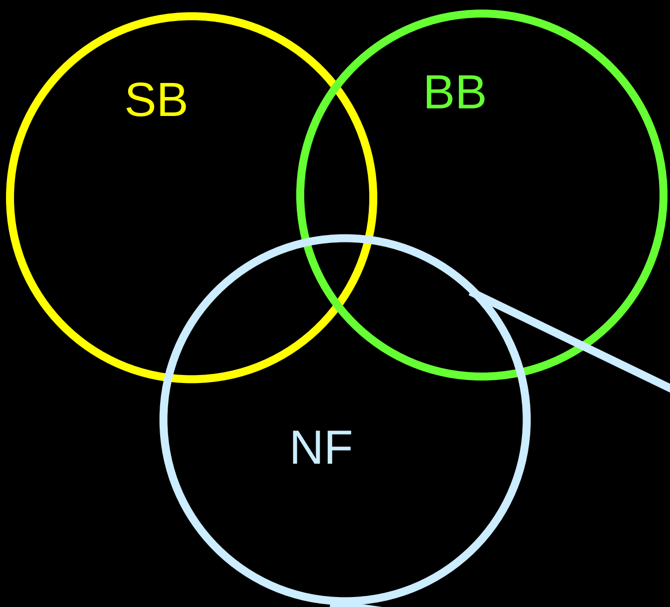
See IDS-NF site: https://www.ids-nf.org/

Bulgaria	Sofia
France	IPHC Strasbourg
Germany	MPI Heidelberg, MPI Munich, Würzburg
India	HCRI Allahabad, SINP Kolkata, TIFR Mumbai
Italy	Milano Bicocca, Napoli, Padova, Roma III
Japan	Kyoto, Osaka, Tokyo Met.
Spain	Madrid, Valencia
Russia	INRR Moscow
Switzerland	CERN, Geneva
UK	Brunel, DL, Glasgow, Imperial, IPPP Durham, Oxford, RAL, Sheffield, Warwick
USA	BNL, FNAL, JLab, LBNL, Mississippi, MSU, Muons Inc., Northwestern, ORNL, Princeton, Riverside, Stony Brook, South Carolina, Virginia Tech., UCLA

EUROnu and the IDS-NF

- **EUROnu is the European contribution to the IDS-NF**

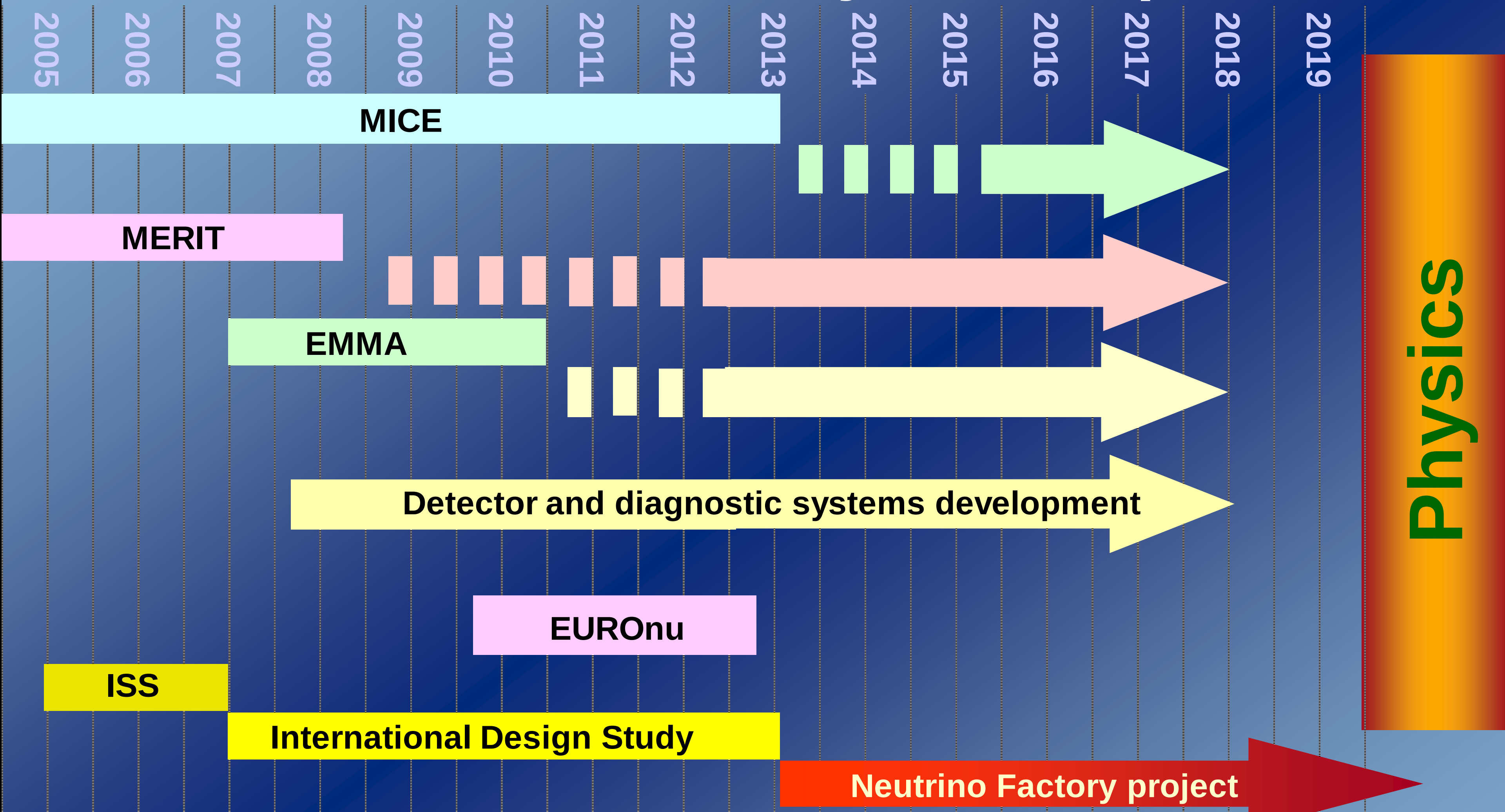
EUROnu

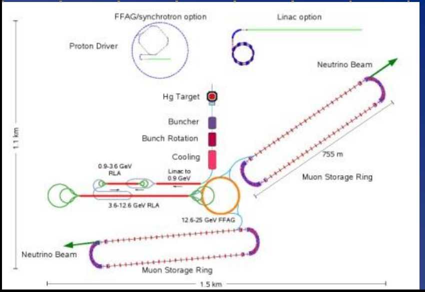


IDS-NF

- **The Americas**
  - **Canada**
  - **USA**
- **Asia**
  - **Japan**
  - **India**
  - **(in the future: China …)**
- **Europe**
  - **EUROnu**

Neutrino Factory roadmap





Conclusions:

- The Neutrino Factory:
  - Best discovery reach
  - Best precision:
    - But need to define agreed figure of merit
    - Need to assess degree to which the unique flexibility of the Neutrino Factory will allow the systematics to be controlled
  - Best sensitivity to non-standard interactions
- The International Design Study for the Neutrino Factory:
  - Collaboration energetic and ambitious!
    - IDR 2011; RDR 2012/13
  - EUROnu: encompasses and coordinates European contributions
- Baseline established and documented in the IDR
  - Alternatives to baseline retained to mitigate risks
- International hardware R&D programme
  - Addresses each of key issues in accelerator facility
    - MERIT, EMMA, MICE
- Scientific imperative:
  - Make the Neutrino Factory an option for the field!