K. Long, 14 June, 2010

Steps towards the
Neutrino Factory

Imperial College
London

Acknowledgements:

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

Софийски университет "Св. Климент Охридски"
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ИНСТИТУТ ЯДЕРНЫХ ИССЛЕДОВАНИЙ РОССИЙСКОЙ АКАДЕМИИ НАУК
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PRINCETON UNIVERSITY
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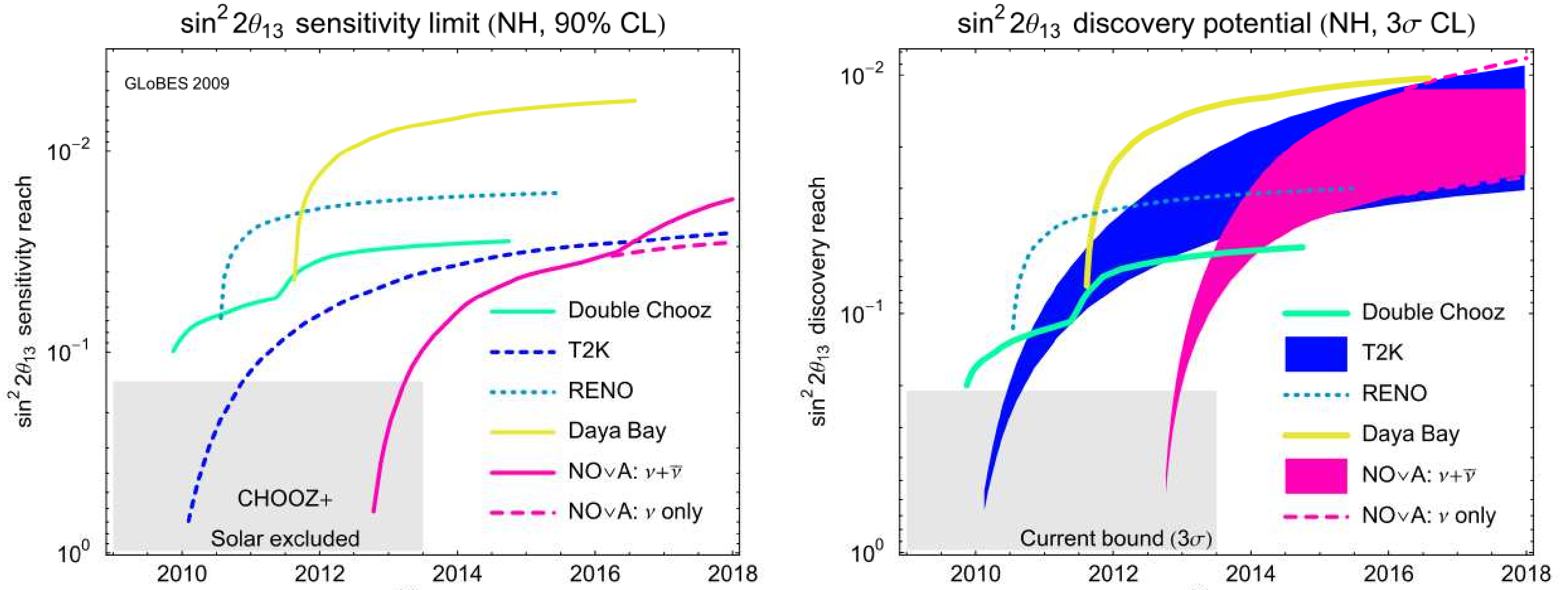
- Motivation; timescale and risk
- IDS-NF Neutrino Factory baseline
- Status of the study
  - Accelerator facility
  - Neutrino detectors
- Opportunities and conclusions

Steps towards the **Neutrino Factory:**

Timescale and risk [of incremental approach]

Discovery of non-leading oscillations:

- **Present, and near future, experiments that seek to measure θ_{13}:**
  - **Reactor: D-Chooz; Daya Bay; Reno**
  - **Long-baseline: T2K, NOνA**



$\sin^2 2\theta_{13}$ sensitivity limit (NH, 90% CL)

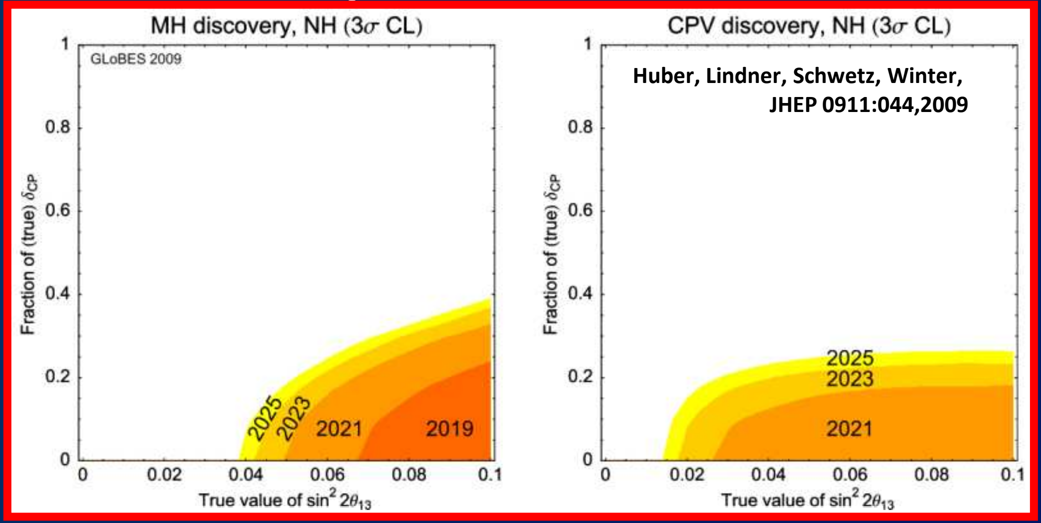
$\sin^2 2\theta_{13}$ discovery potential (NH, 3σ CL)

Huber, Lindner, Schwetz, Winter, JHEP 0911:044,2009

- **'Sensitivity plateau' of ~10^{-2} reached around 2016**

Potential/risk of incremental upgrade:

- Power upgrade to increase performance of T2K and NOνA:



Huber, Lindner, Schwetz, Winter, JHEP 0911:044,2009

- Upgraded facilities:
  - Some sensitivity to MH and δ:
    - Over 25—30% of (δ)parameter space:
      - So long as $\sin^2 2\theta_{13}$ larger than $\sim 10^{-2}$
    - 70—75% of (δ)parameter space uncovered ($\sin^2 2\theta_{13} > \sim 10^{-2}$)
      - No δ-sensitivity for $\sin^2 2\theta_{13}$ smaller than $\sim 10^{-2}$
- Opportunity:
  - Establish facility with discovery potential over close to the full parameter space and down to very small $\sin^2 2\theta_{13}$:
    - With, in addition, the best possible:
      - Precision on the SνM parameters
      - Flexibility in the study of physics beyond the SνM

Risk avoidance: the Neutrino Factory:

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

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

All channels potentially available at the Neutrino Factory

Risk avoidance: the Neutrino Factory:

- 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*

Rate ∝ flux × cross section

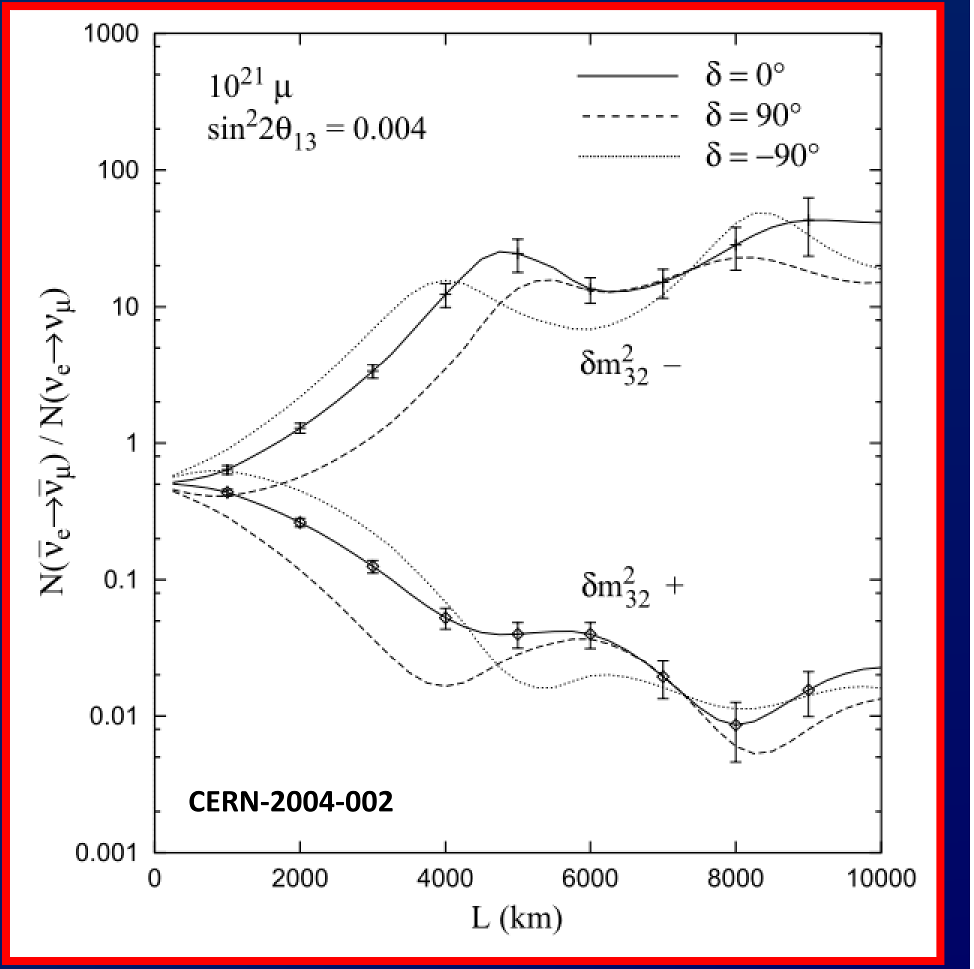
- o $\boldsymbol{\Phi} \propto \frac{1}{\gamma^2} \times \frac{1}{L^2} \propto \frac{E_\mu^2}{L^2}$
- o $\boldsymbol{\sigma} \propto E_\nu$ [for $E_\nu > \mathbf{10}$ GeV]
- o For μ decay: E_ν scales with E_μ

$$\therefore \text{Rate} \propto \frac{E_\mu^3}{L^2}$$

$$\text{i.e. for fixed } \left[\frac{L}{E_\mu}\right]^{-1} \text{; Rate} \propto E_\mu$$

Risk avoidance: the Neutrino Factory:

- 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



CERN-2004-002

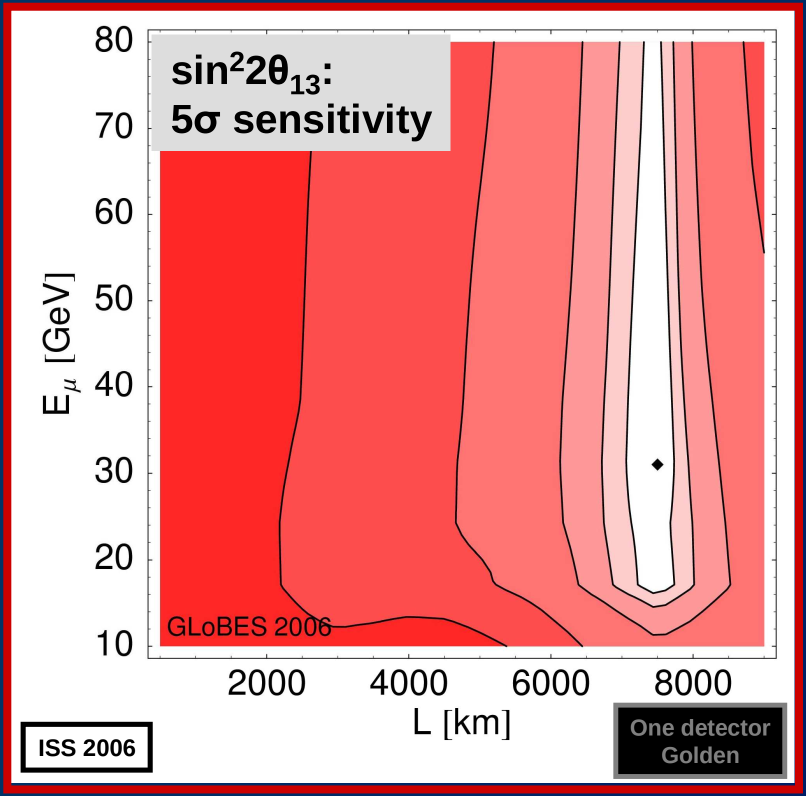
Posters: J. Kopp: IDS-NF overview
W. Winter: IDS-NF physics

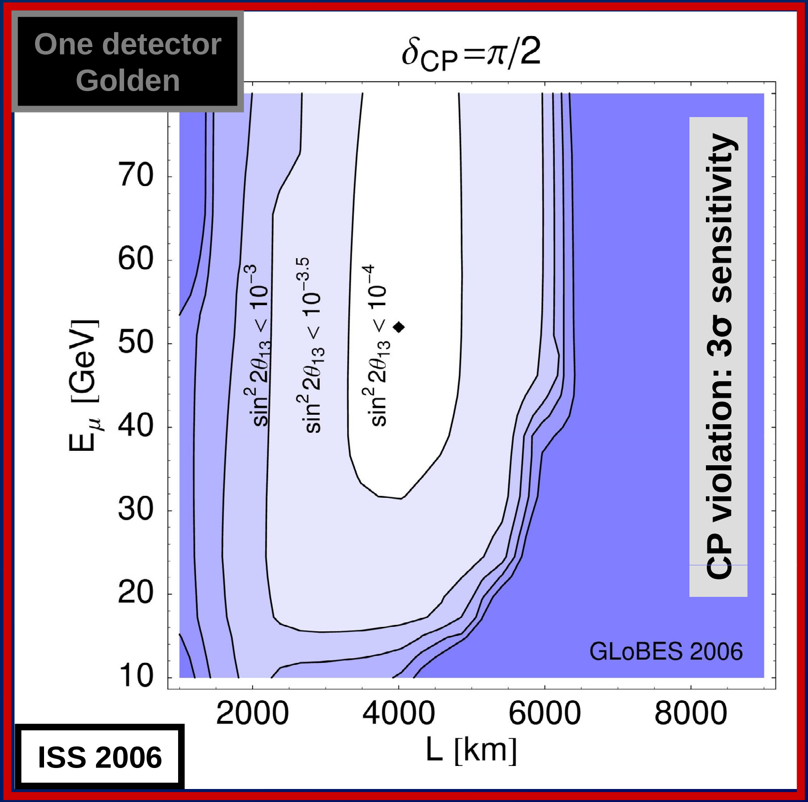
Neutrino Factory:

IDS-NF baseline; performance and optimisation

Huber, Lindner, Rolinec, Winter,
Phys.Rev.D74:073003,2006

Neutrino Factory: optimisation:



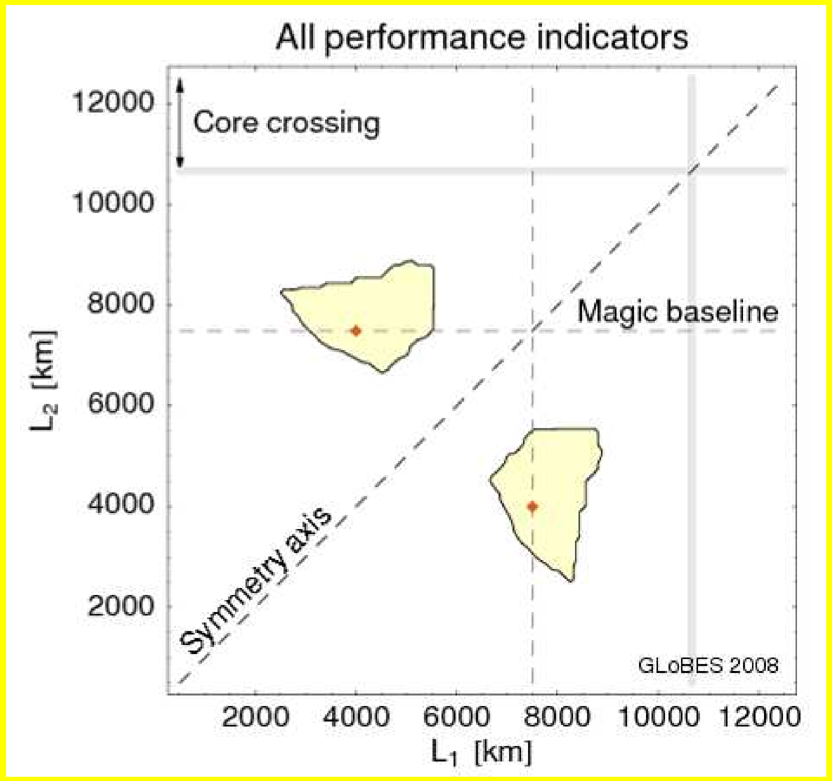


- Magic baseline (7500 km) good degeneracy solver
- Best sensitivity to CP requires baseline ~4000 km
- Stored muon energy: 25 GeV

Neutrino Factory: optimisation:

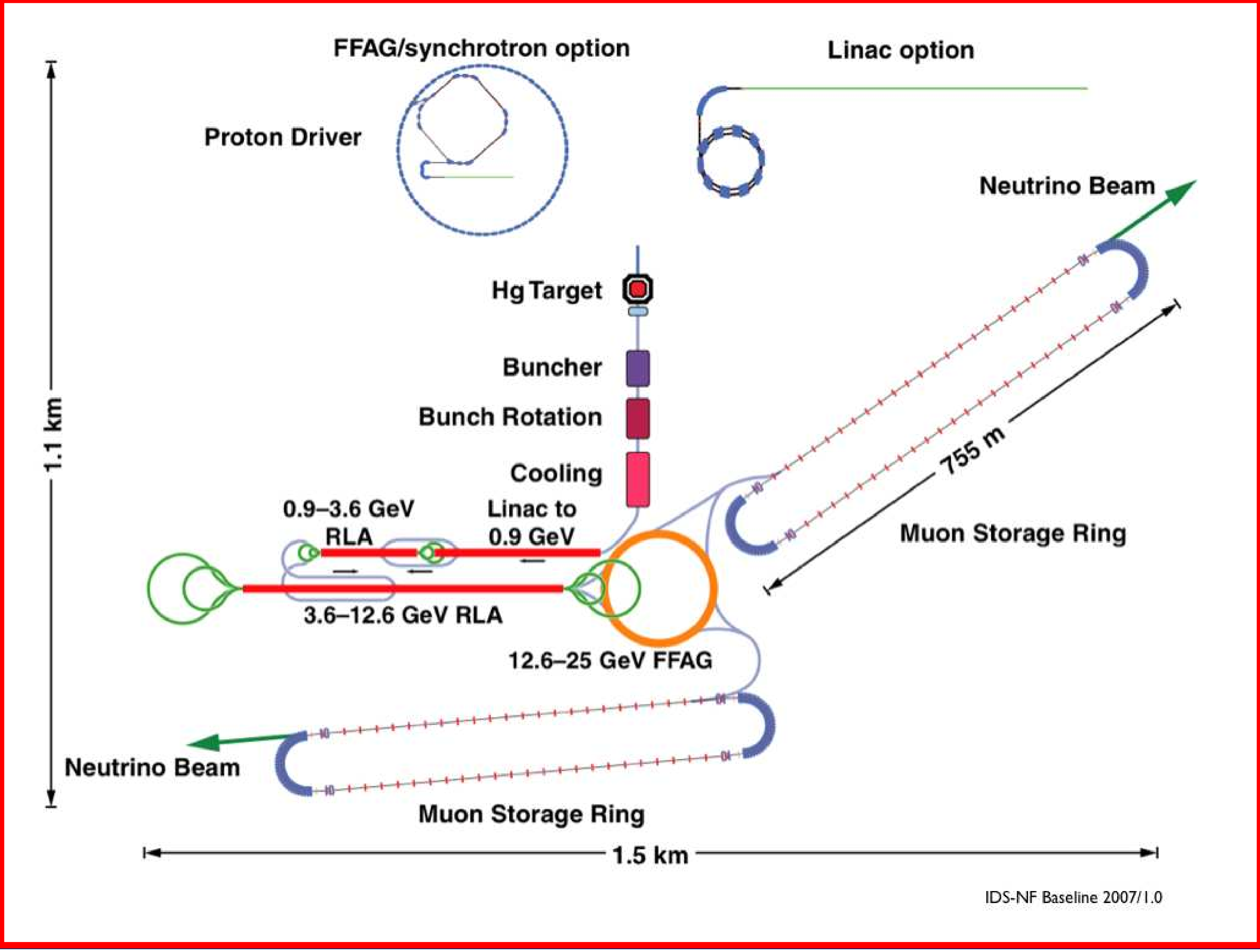
- Two detectors:
  - Compare performance of 50 kT detector at magic baseline with two 25 kT detectors

Kopp, Ota, Winter, Phys.Rev.D78:053007,2008.



- Preferred combination:
  - 2000—5000 km; good sensitivity to CP violation
  - 7000—8000 km; mass hierarchy, θ_{13}, degeneracy resolution

IDS-NF baseline: accelerator:

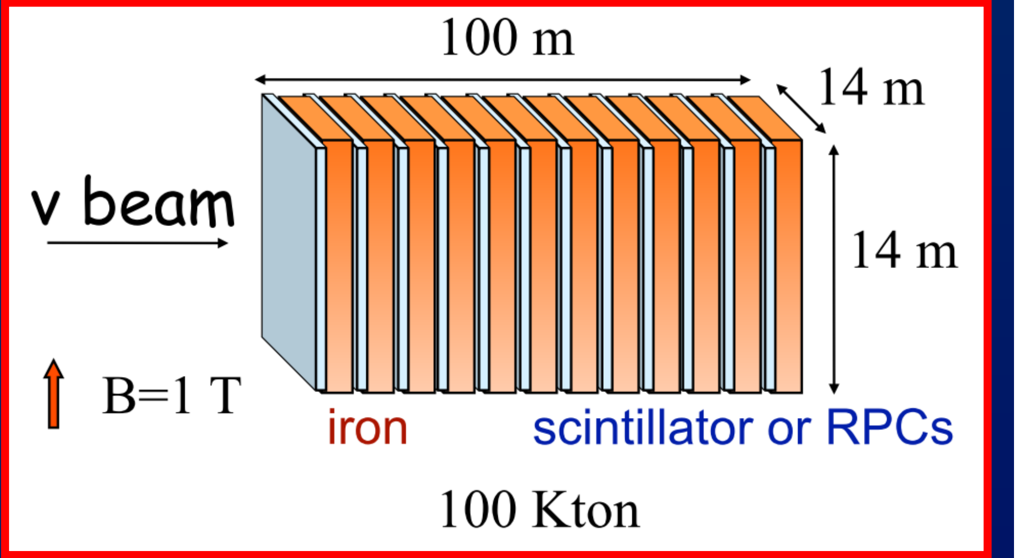


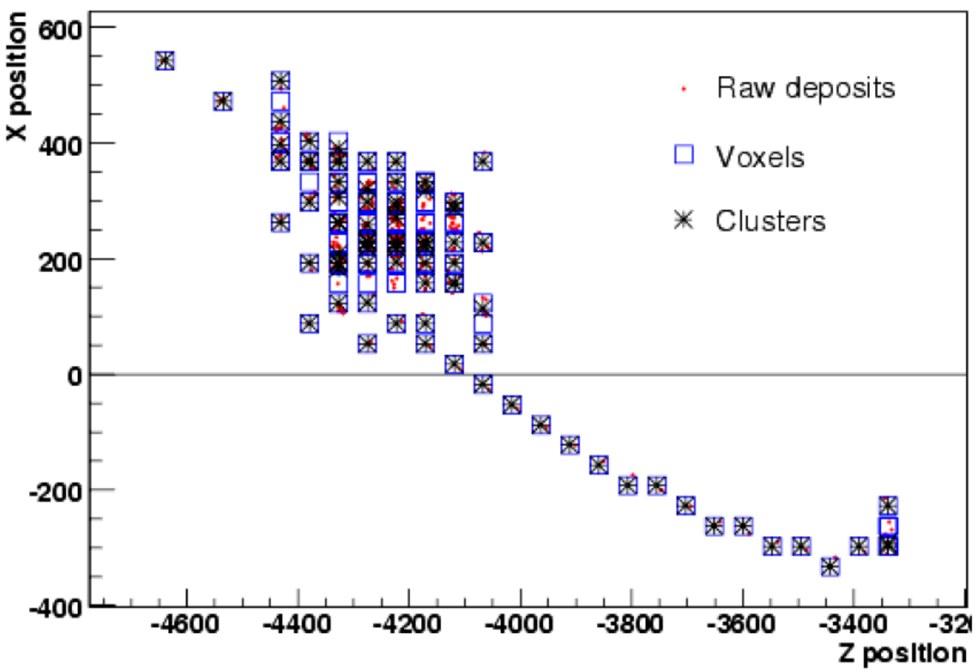
IDS-NF-002: https://www.ids-nf.org/wiki/FrontPage/Documentation?action=AttachFile&do=view&target=IDS-NF-002-v1.1.pdf

A. Cervera, A. Laing,
J. Martín-Albo, F.J.P. Soler

IDS-NF baseline: detector:

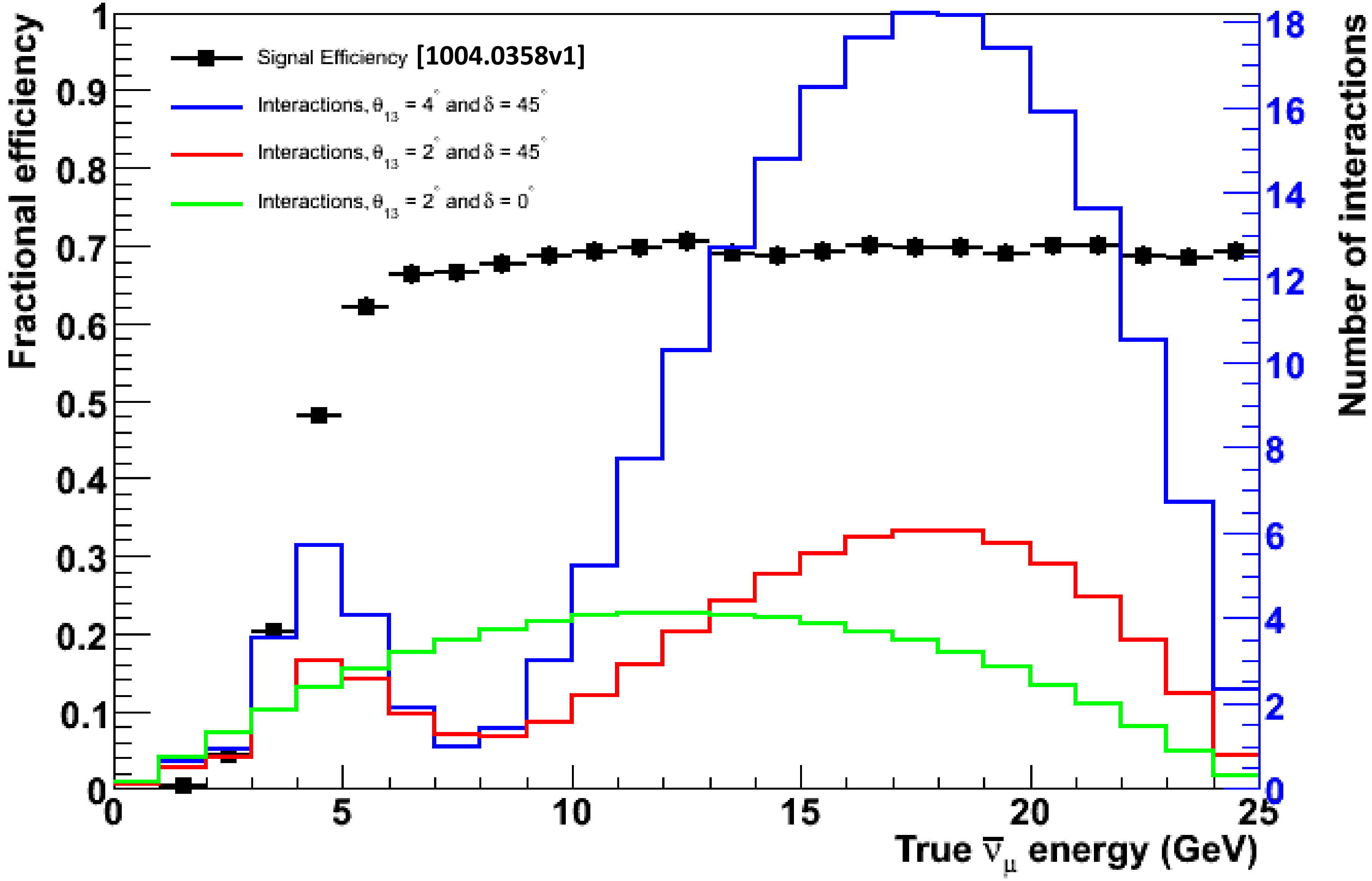
- Baseline:
  - Magnetised Iron Neutrino Detector (MIND):
    - Large (100 kTonne) mass
    - Readily magnetised
    - New analysis gives threshold at 1—2GeV
- Alternatives:
  - Totally Active Scintillator Detector (TASD);
    Liquid Argon (LAr):
    - Potential for ‘direct’ sensitivity to νe and ντ
    - Issues:
      - Magnetisation of large volume
      - Cost of large mass of TASD
      - R&D required for large mass LAr



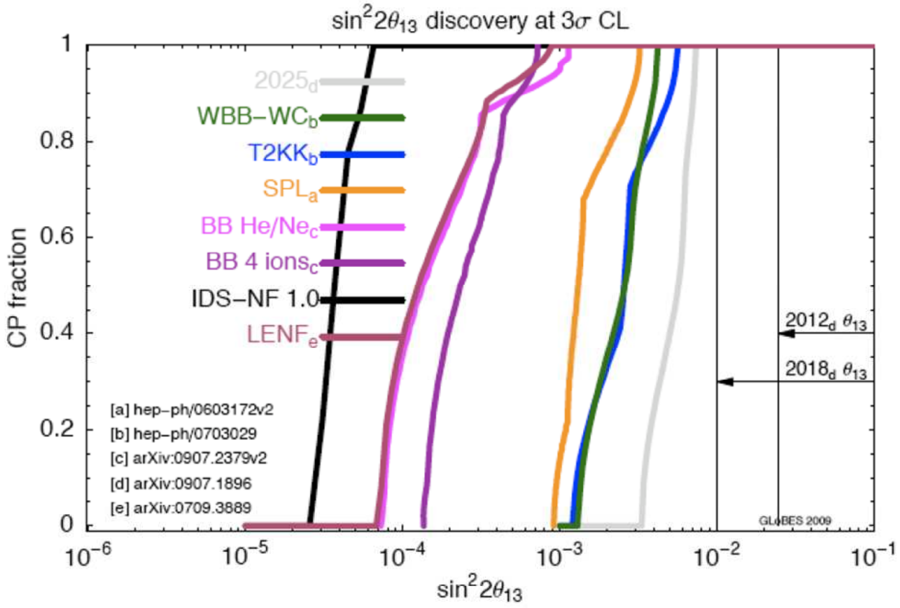


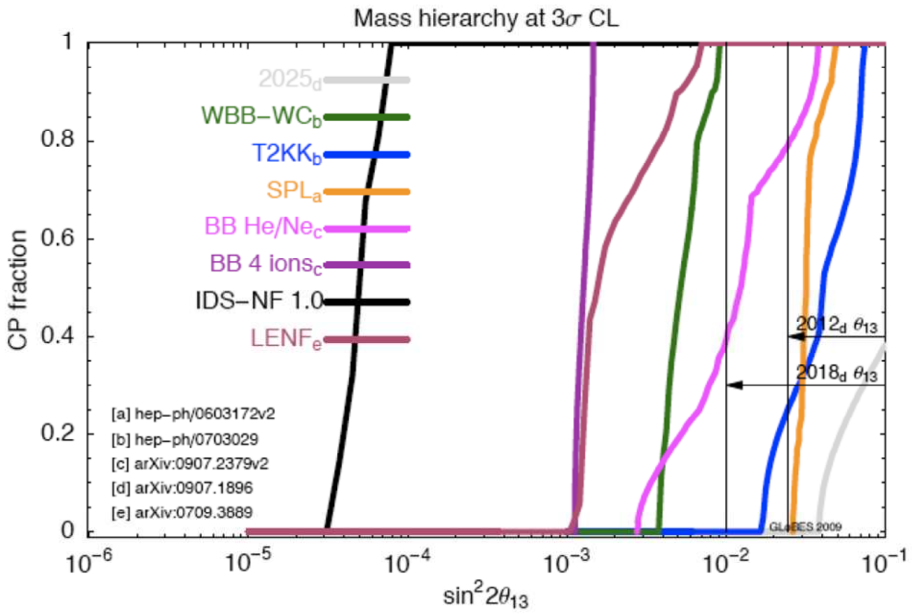
IDS-NF baseline: performance:

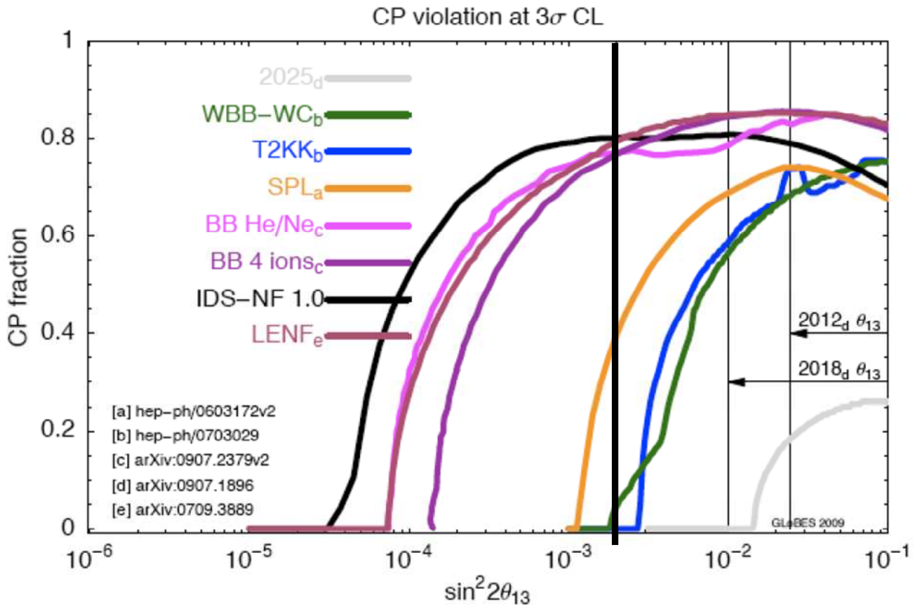
A. Laing



IDS-NF baseline performance:



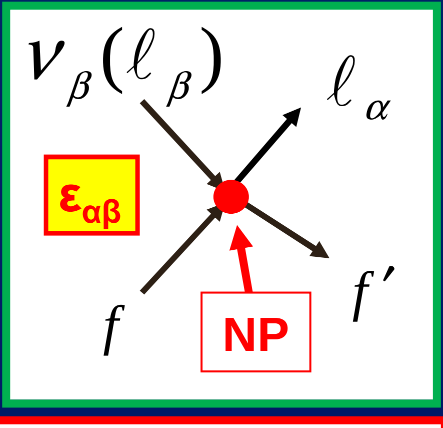




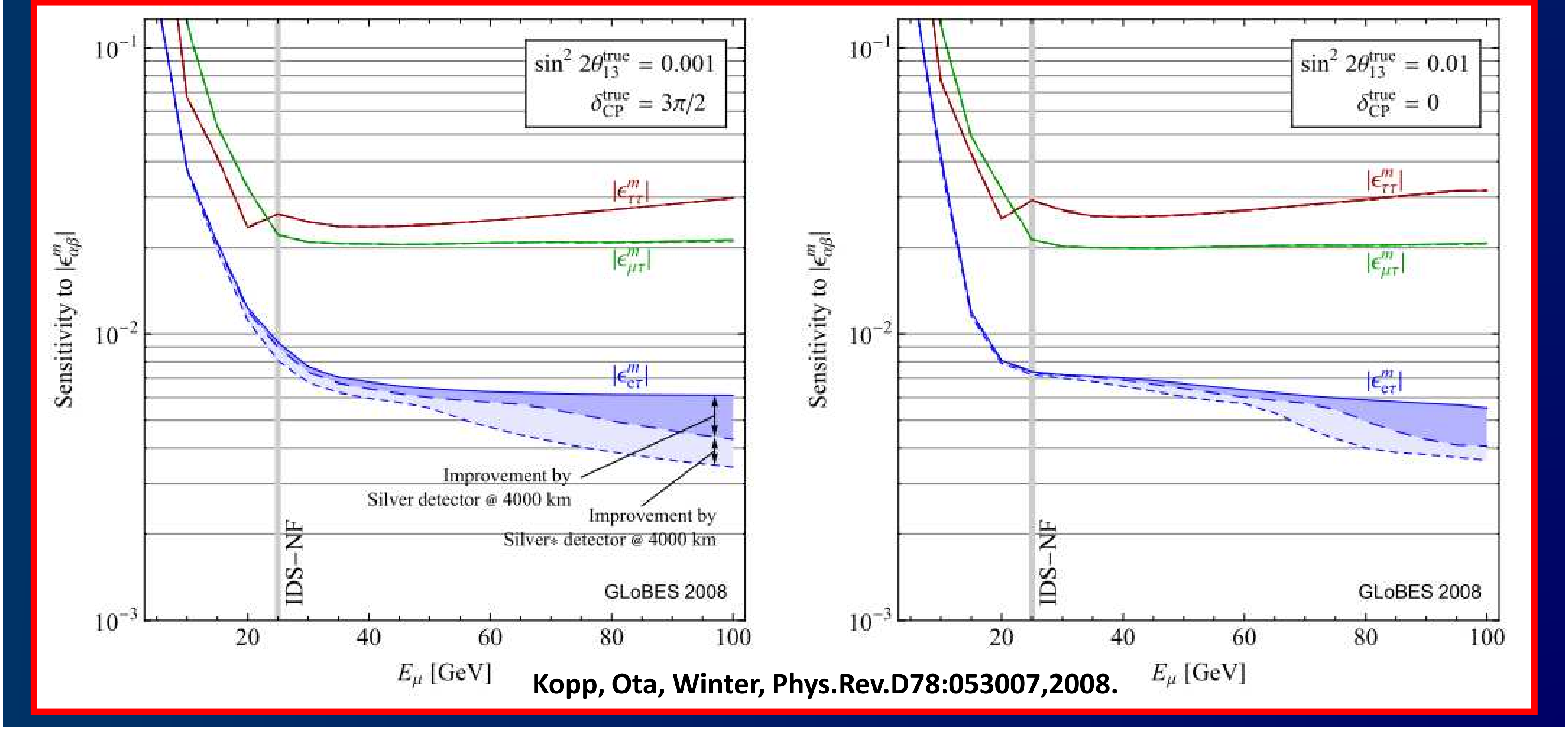
- Neutrino Factory outperforms other options:
  - – Larger discovery reach
- Competitors (large θ_{13}):
  - – Beta beam:
    - But requires large Ne flux, high-γ, and/or 4-ions
  - – Low energy Neutrino Factory:
    - See later, but, reduced redundancy/flexibility

EUROnu: 1005.3146v1

IDS-NF baseline: performance:

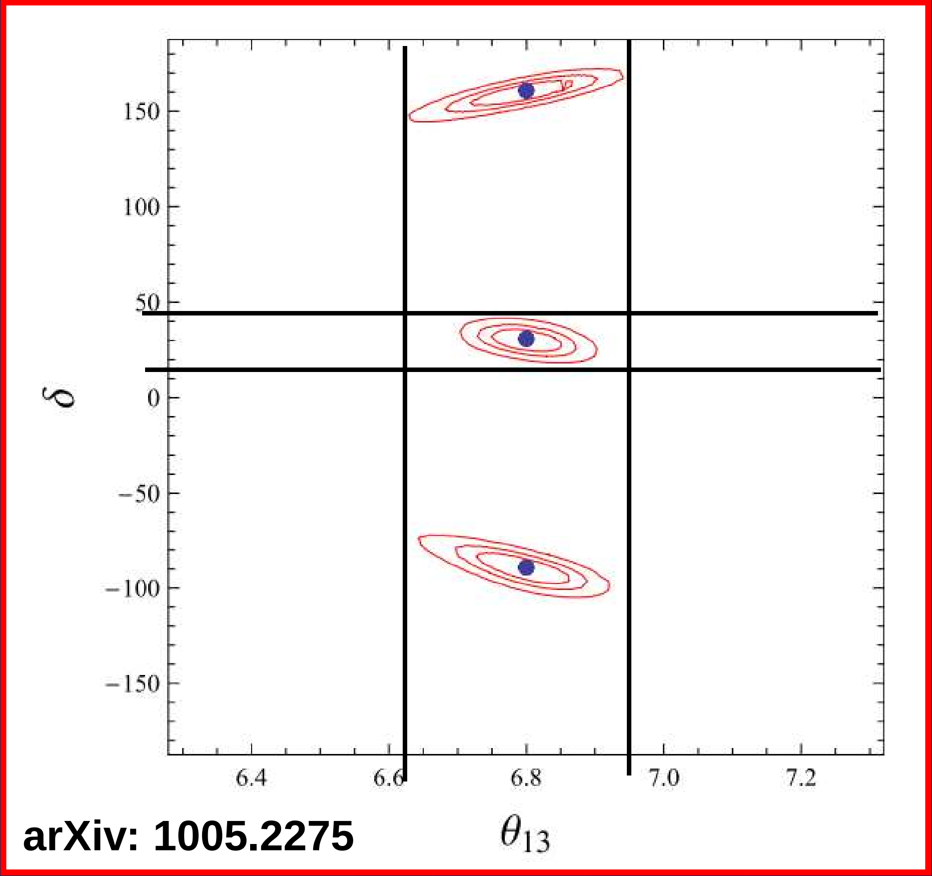


- Physics beyond the SvM:
  - – Example: on-standard interactions
    - Excellent performance for E_μ = 25 GeV (IDS-NF baseline)

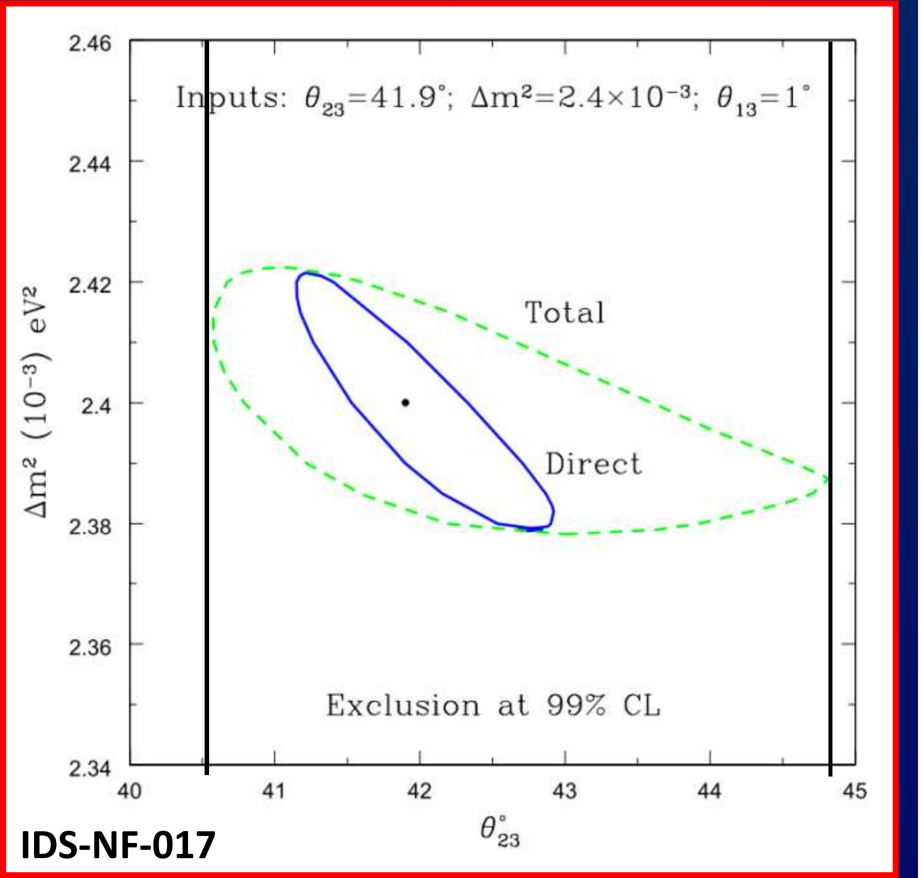


Kopp, Ota, Winter, Phys.Rev.D78:053007,2008.

IDS-NF baseline: precision; large θ_{13}:



arXiv: 1005.2275



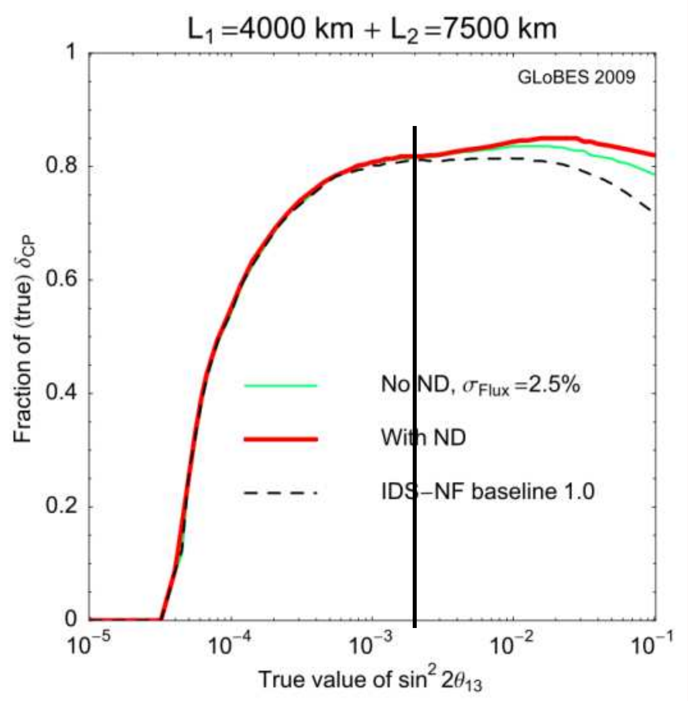
IDS-NF-017

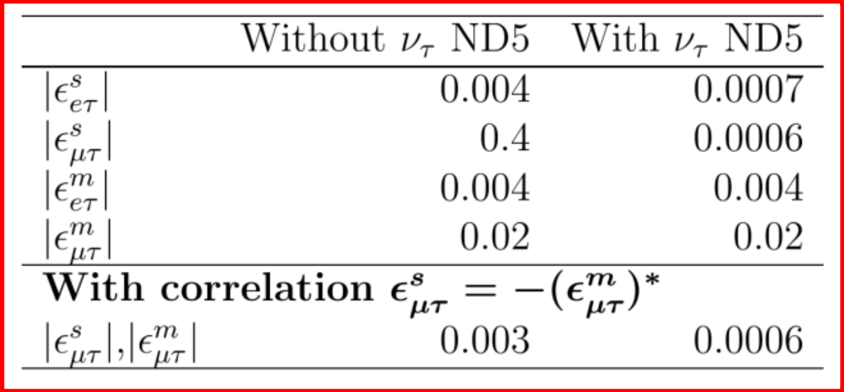
- **Precision measurement of mixing parameters:**
  - **θ_{13} measurement at < 1° level and θ_{23} at ~2° level**
  - **δ measurement at 10—15% level**
  - **Requires understanding of ν_τ component of signal**

IDS-NF optimisation; large θ_{13}:

- $\theta_{13} > 2 \times 10^{-3}$: ‘next-generation’ options comparable
  - IDS-NF baseline optimised for discovery reach
  - Near detector required to measure:
    - Flux
    - Neutrino cross sections
    - Charm production
      - Yields sensitivity to ν_τ appearance at near detector

Tang, Winter
Phys.Rev.D81:033005,2010



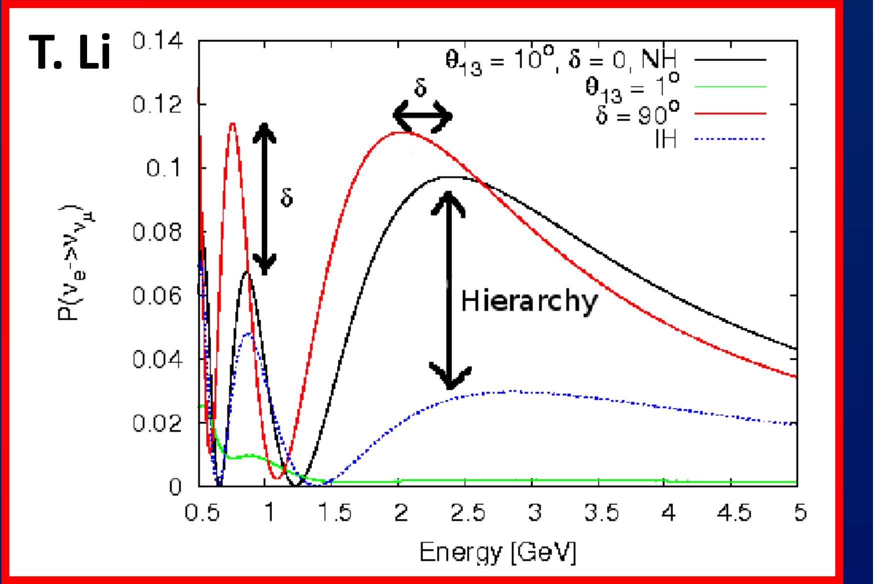


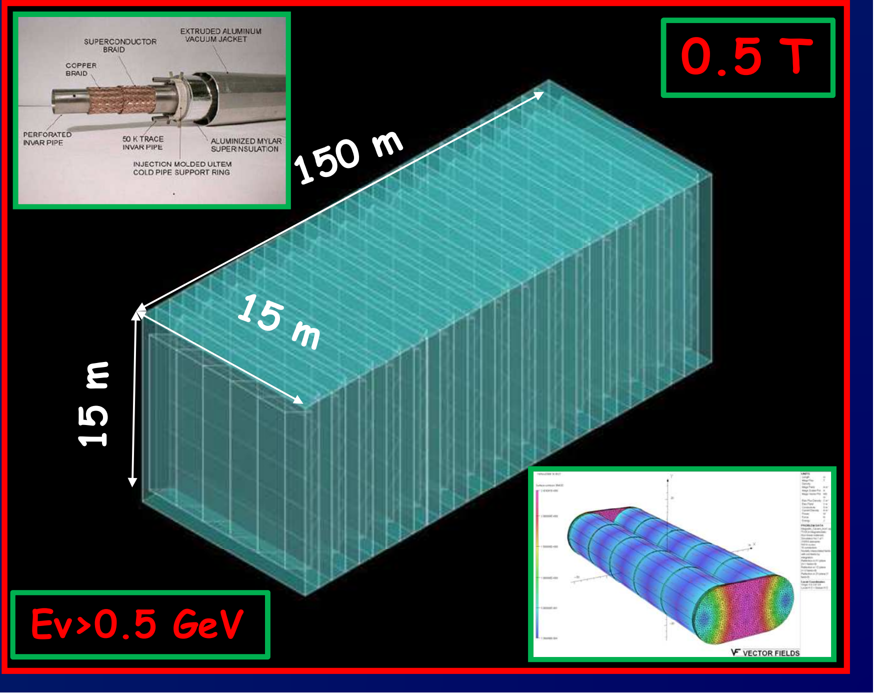
	Without ν_τ ND5	With ν_τ ND5
$\lvert\epsilon^s_{e\tau}\rvert$	0.004	0.0007
$\lvert\epsilon^s_{\mu\tau}\rvert$	0.4	0.0006
$\lvert\epsilon^m_{e\tau}\rvert$	0.004	0.004
$\lvert\epsilon^m_{\mu\tau}\rvert$	0.02	0.02
With correlation $\epsilon^s_{\mu\tau} = -(\epsilon^m_{\mu\tau})^*$		
$\lvert\epsilon^s_{\mu\tau}\rvert, \lvert\epsilon^m_{\mu\tau}\rvert$	0.003	0.0006

- Near detector will:
  - Significantly improve performance for $\theta_{13} > 2 \times 10^{-3}$;
  - Significantly improve sensitivity to NSI

Option for large θ_{13}; Low Energy NF:

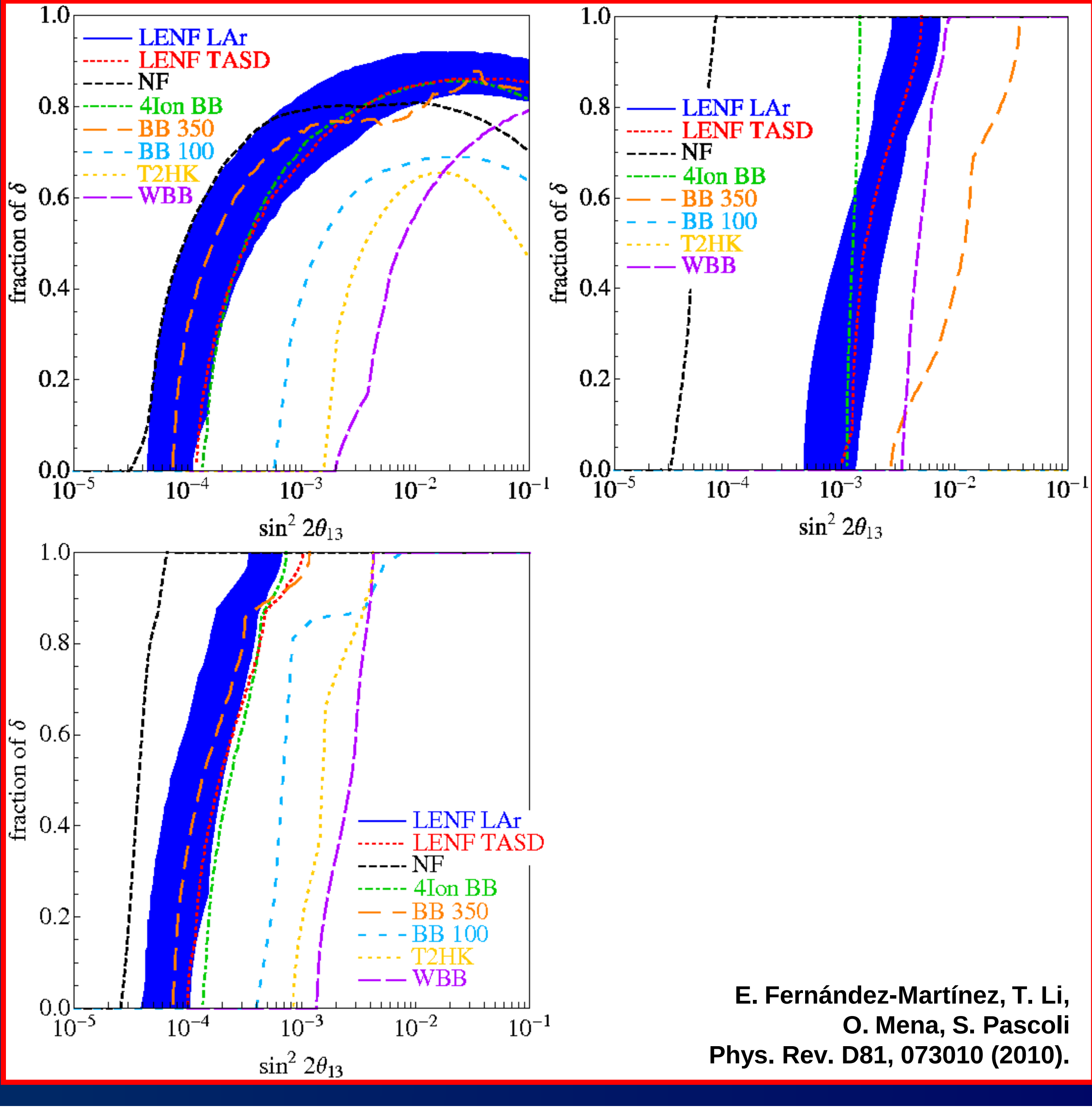
- Take advantage of large oscillation amplitude:
  - Lower muon energy to 4—8 GeV
    - Matched to baselines in the range 1500—3000 km
    - Reduced cost of muon acceleration
    - Possibly part of a staging scenario
  - Improved detector performance required:
    - Must reconstruct oscillation at low E_μ:
      - → Low energy threshold and high energy resolution
    - Requires magnetised TASD (or Liquid argon)





Low Energy Neutrino Factory; sensitivity:

Poster: T. Li: Low energy Neutrino Factory



E. Fernández-Martínez, T. Li,
O. Mena, S. Pascoli
Phys. Rev. D81, 073010 (2010).

Poster: J. Pasternak: IDS-NF accelerator facility

Neutrino Factory:

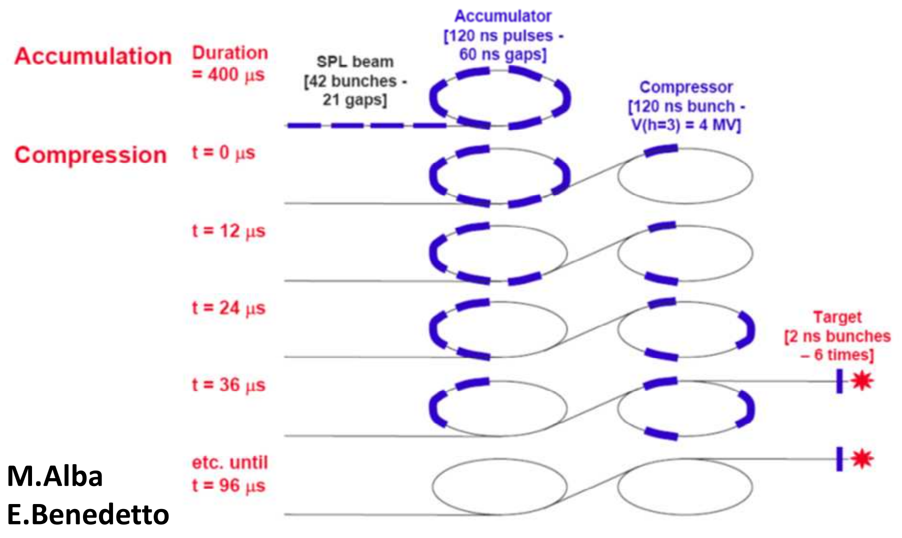
Accelerator facility:

Proton driver:

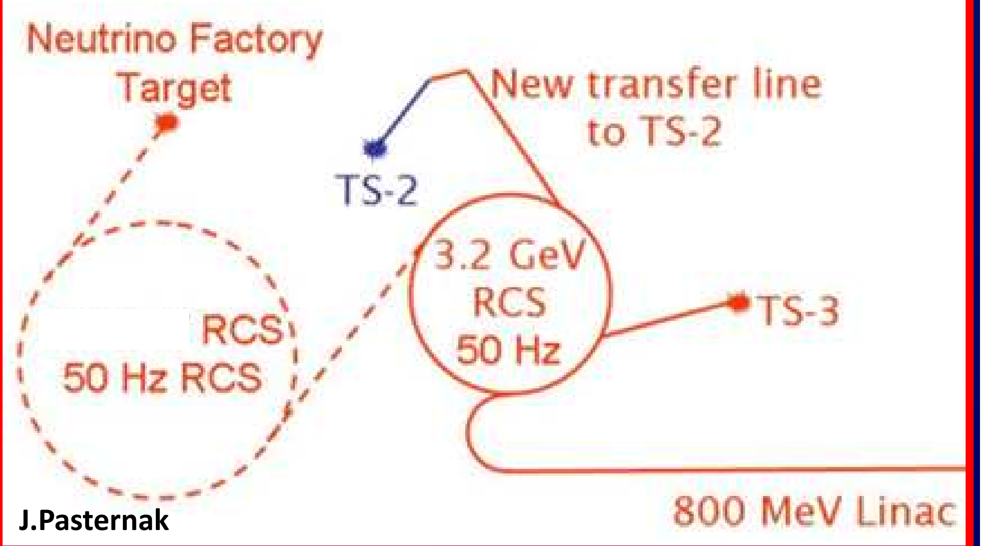
IPAC10: THPD074,
MOPEC049,
WEPE098

Parameter	***Value***	***Comment***
Beam power	4 MW	Production rate
Beam energy	5-15 GeV	Optimum pion production
Bunch length	2 ± 1 ns	Pion/muon capture

- **Challenges:**
  - **High power; short proton bunch length at ~10 GeV**
- **IDS-NF approach:**
  - **Consider two ‘generic’ options:**
    - **LINAC:**
      - **Possible development option for SPL (CERN) or Project-X (FNAL)**
      - **Requires accumulator/compressor rings**
    - **Rings:**
      - **Development option for J-PARC or RAL or possible ‘green-field’ option**
      - **Requires bunch compression**



M.Alba
E.Benedetto

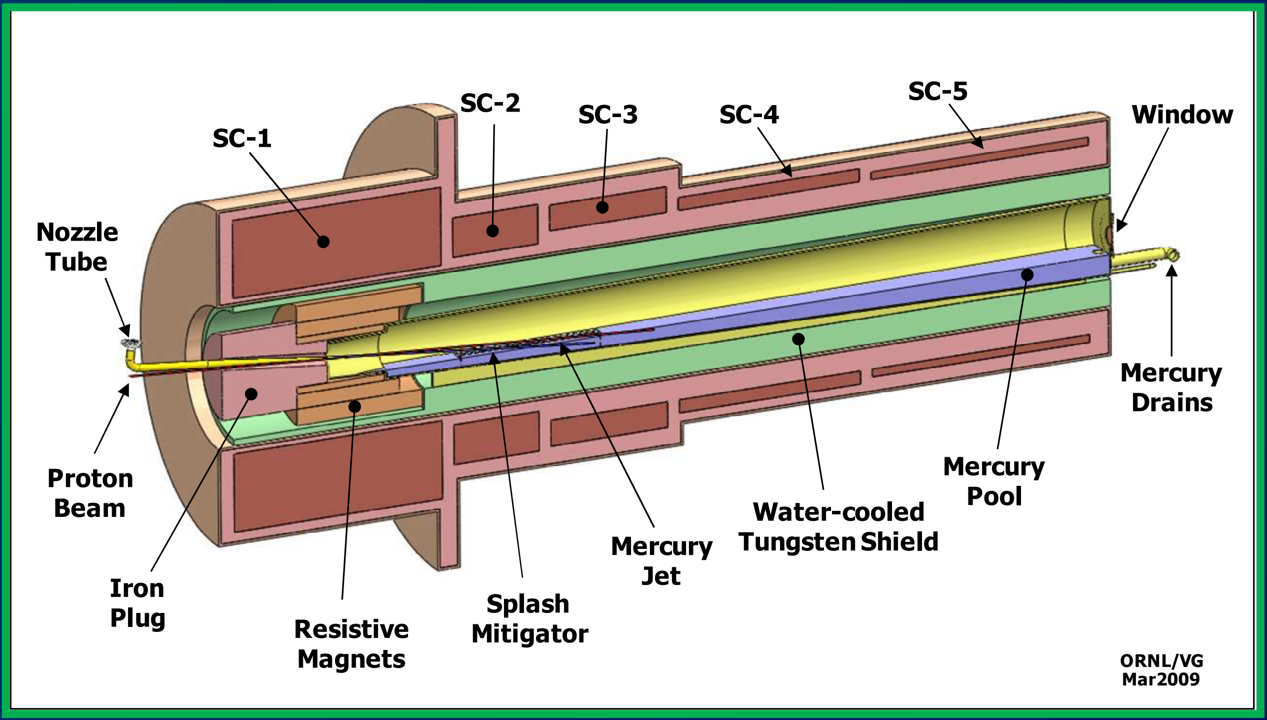


J.Pasternak

Target/capture:

IPAC10: WEPE101,
THPEC092

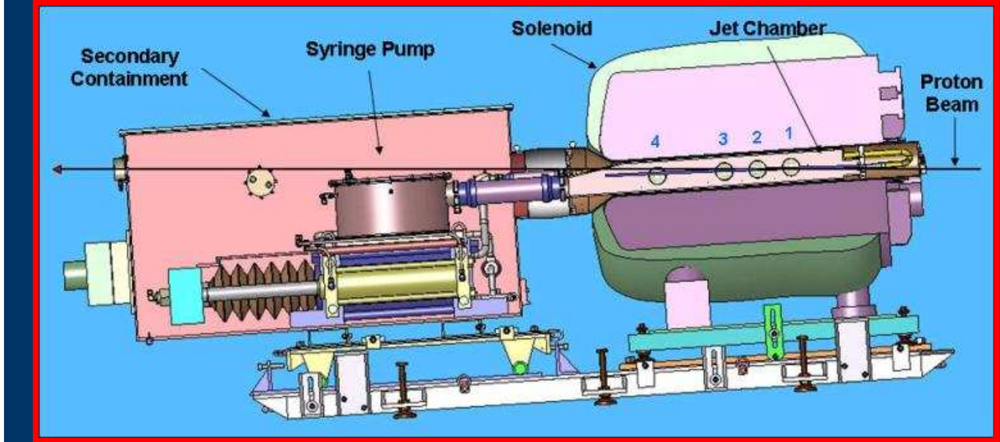
Parameter	*Value*	*Comment*
Jet velocity	20 m/s	Reformation of jet
Field at i/p	20 T	Pion collection
Field at exit of capture	1.75 T	Pion focusing



- **Baseline:**
  - Mercury jet, tapered solenoid for pion capture:
    - 20 T tapering to 1.75 T in ~13 m
- **Alternatives: [mitigation of technical risk]**
  - Tungsten bars; tungsten-powder jet

Baseline target: proof of principal: MERIT:

IPAC10: WEPE078



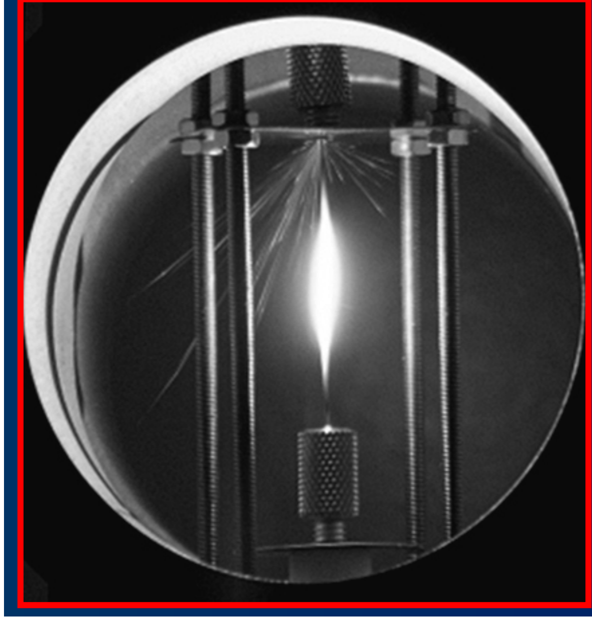
- ‘Disruption length’: 28 cm
- ‘Refill’ time: 14 ms
  - Corresponds to 70 Hz
- Hence:
  - Demonstrated operation at:
    - 115 kJ × 70 Hz = 8 MW

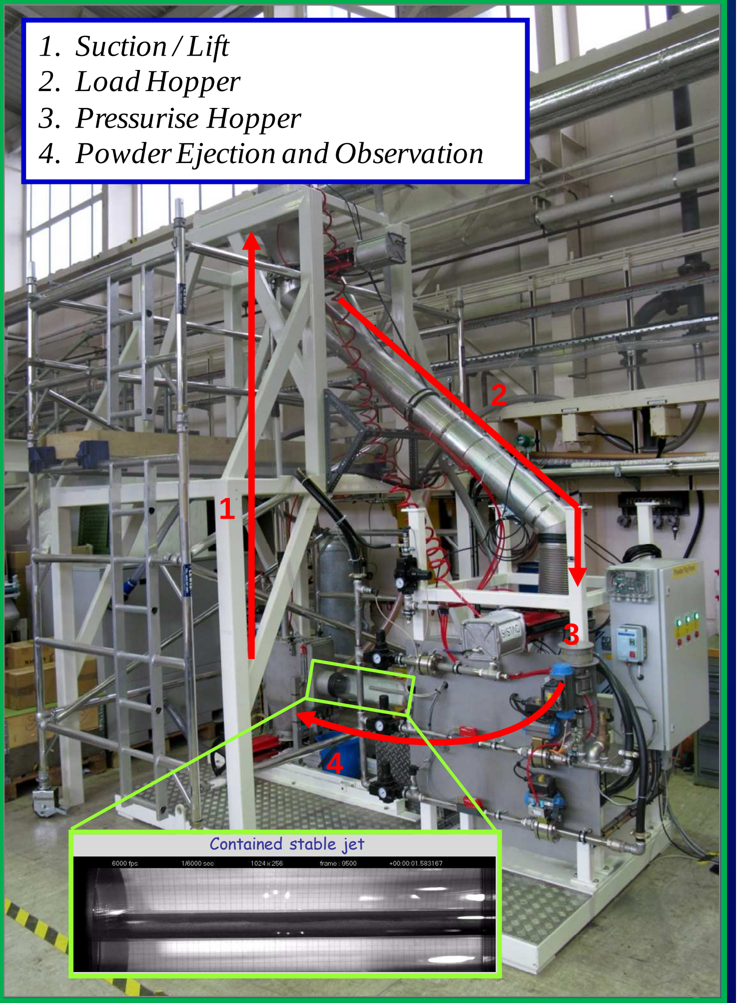
- 20 m/s liquid Hg jet in 15 T B field
- Exposed to CERN PS proton beam:
  - Beam pulse energy = 115 kJ
  - Reached 30 tera protons at 24 GeV

IPAC10: THPEC089,
THPEC091

Alternatives: solid and powder jet:

- Solid target:
  - Lifetime limitation from beam-induced shock:
    - Investigated using rapid rise-time (kicker) power supply and thin wire
  - Measurements imply:
    - 2 cm diameter tungsten rod will survive > 10 yrs
  - Proceeding to measure vibration modes to determine stress and verify models





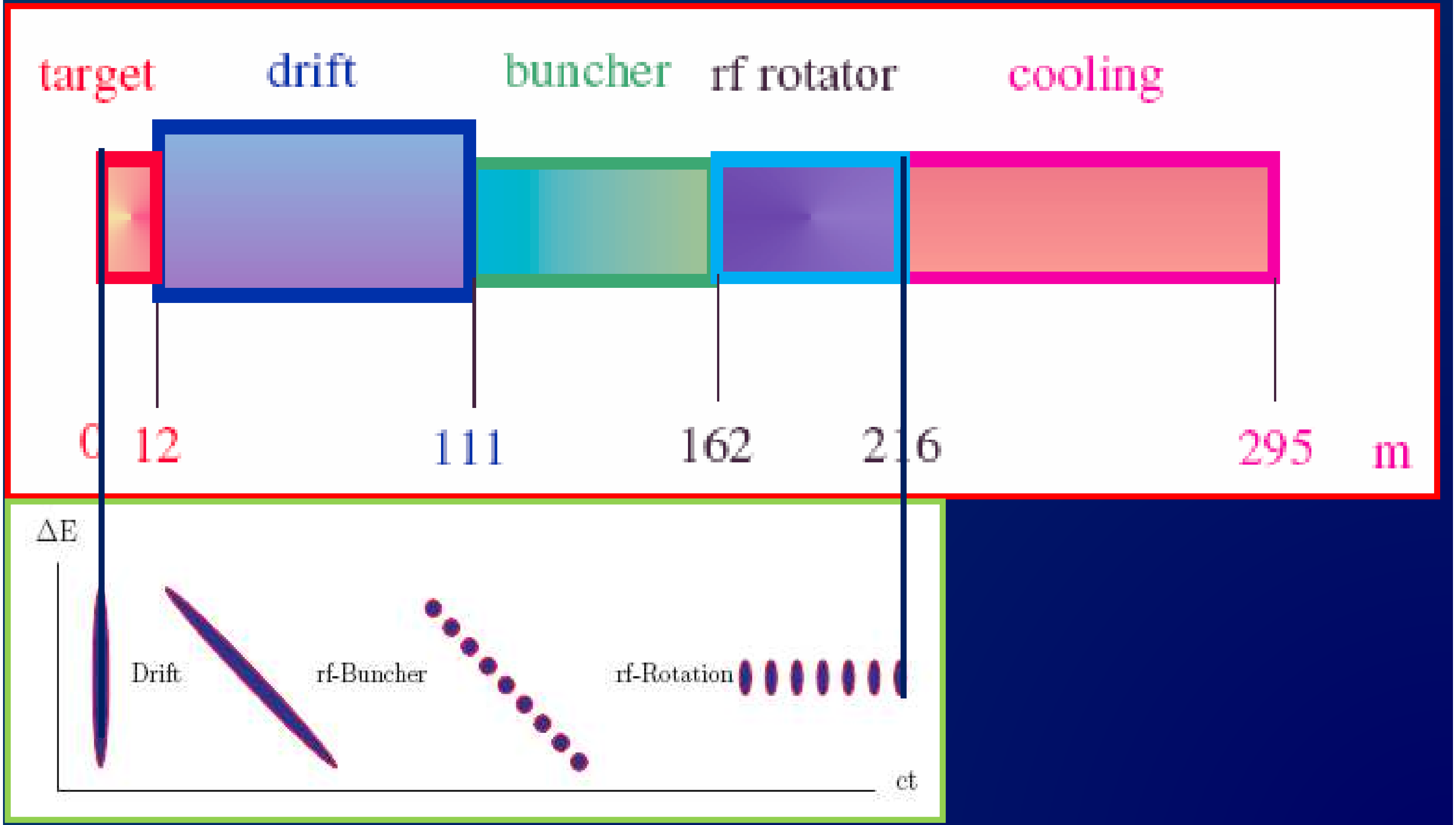
1. Suction / Lift
2. Load Hopper
3. Pressurise Hopper
4. Powder Ejection and Observation

- Tungsten-powder jet:
  - (Jet) advantage:
    - Avoids issue of shock
  - (Solid) advantage:
    - Avoids issue of Hg handling
  - ‘Bench-test’ system under evaluation
  - Proof of principal system under consideration

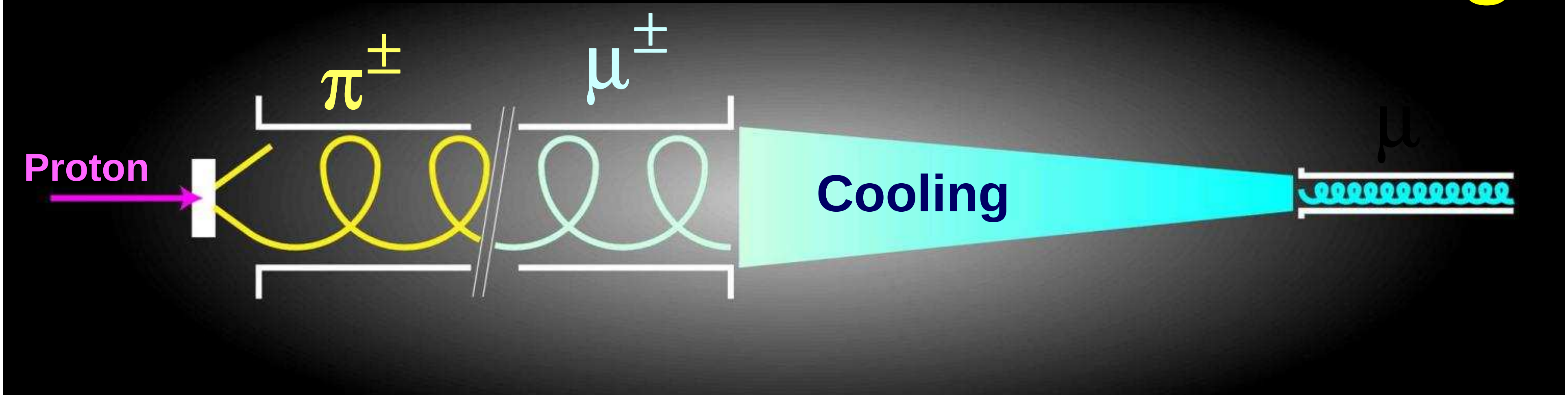
Parameter	**Value**	**Comment**
E -spread after P.R.	10%	Subsequent accel.
Freq. after P.R.	201.25 MHz	
Emittance at exit	7.4 mm rad	Subsequent accel.

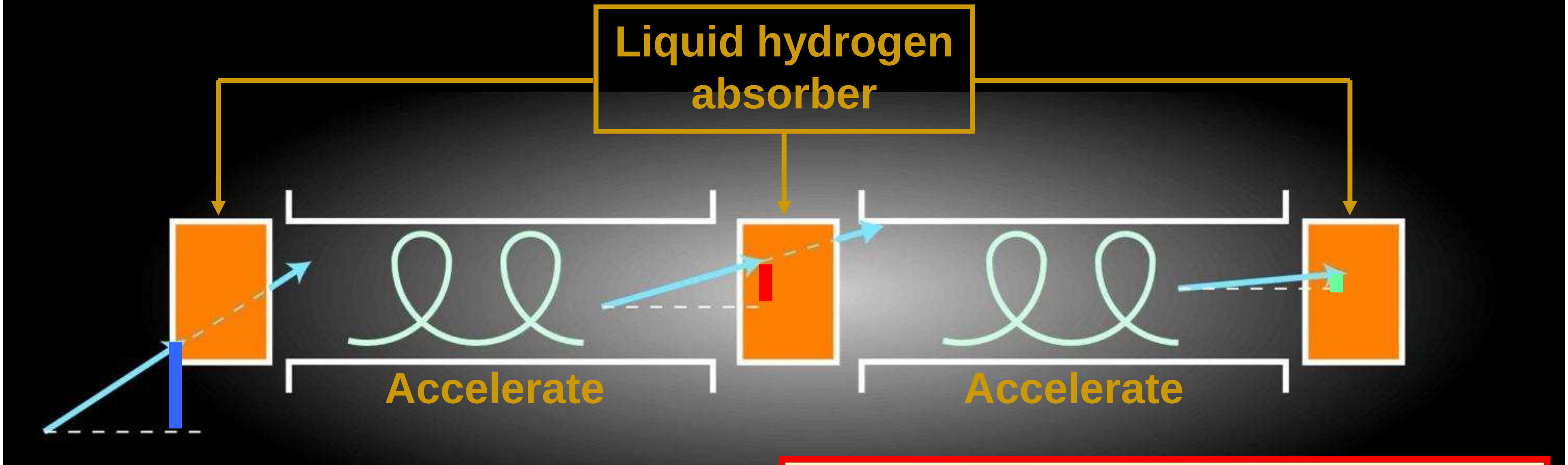
Muon front-end:

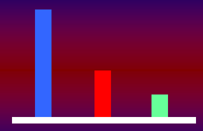
IPAC10: WEPE050, WEPE051,
WEPE068, WEPE074, WEPE076



Ionisation cooling:





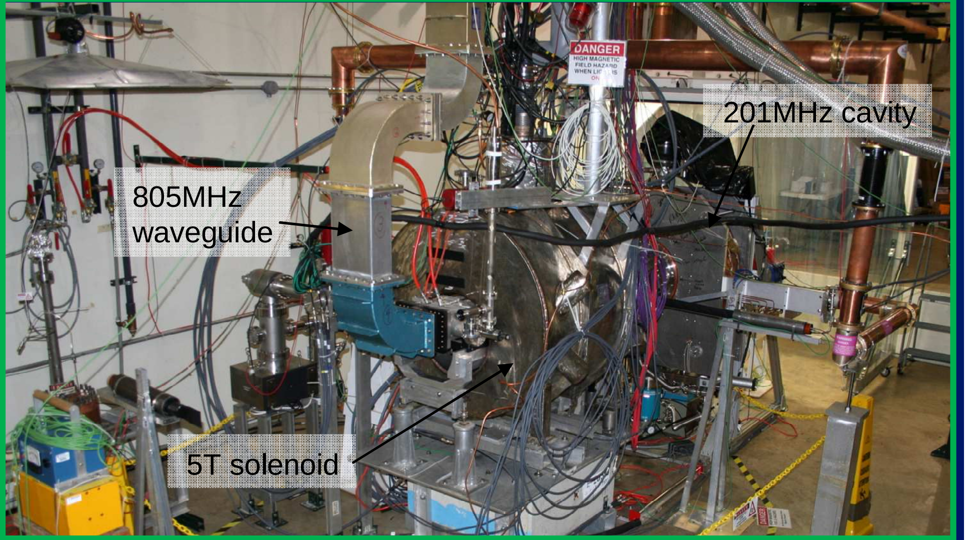


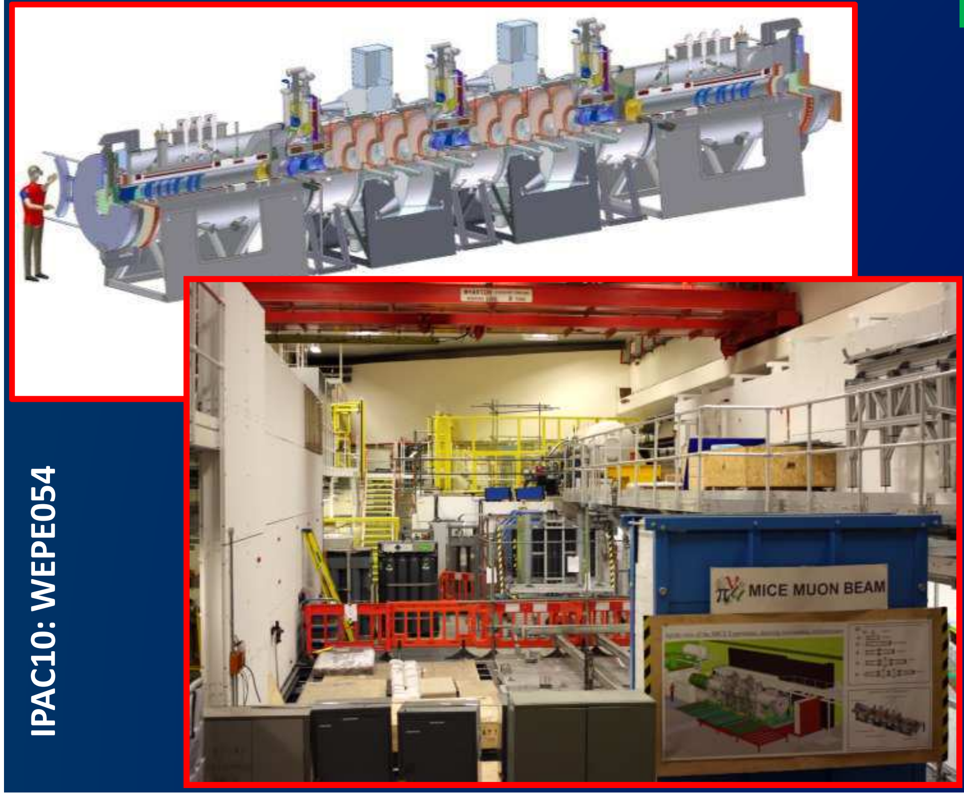
Ionisation cooling

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

Front-end R&D:

- 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





- MuCOOL: high-gradient, copper, cavities in magnetic field:
  - Study of breakdown in 805 MHz and 201 MHz cavities in magnetic field
  - Mitigation of breakdown using high-pressure (H2) gas
  - Operation of cooling channel elements with intense (1013 ppp) proton beam from FNAL booster

IPAC10: WEPE054

	E_{fin} (GeV)	*Comment*
Pre-accel. Linac	0.9	Change in γ
RLA I	3.6	Switch-yard congestion
RLA II	12.6	Switch-yard congestion
FFAG	25.0	Large acceptance, use of RF

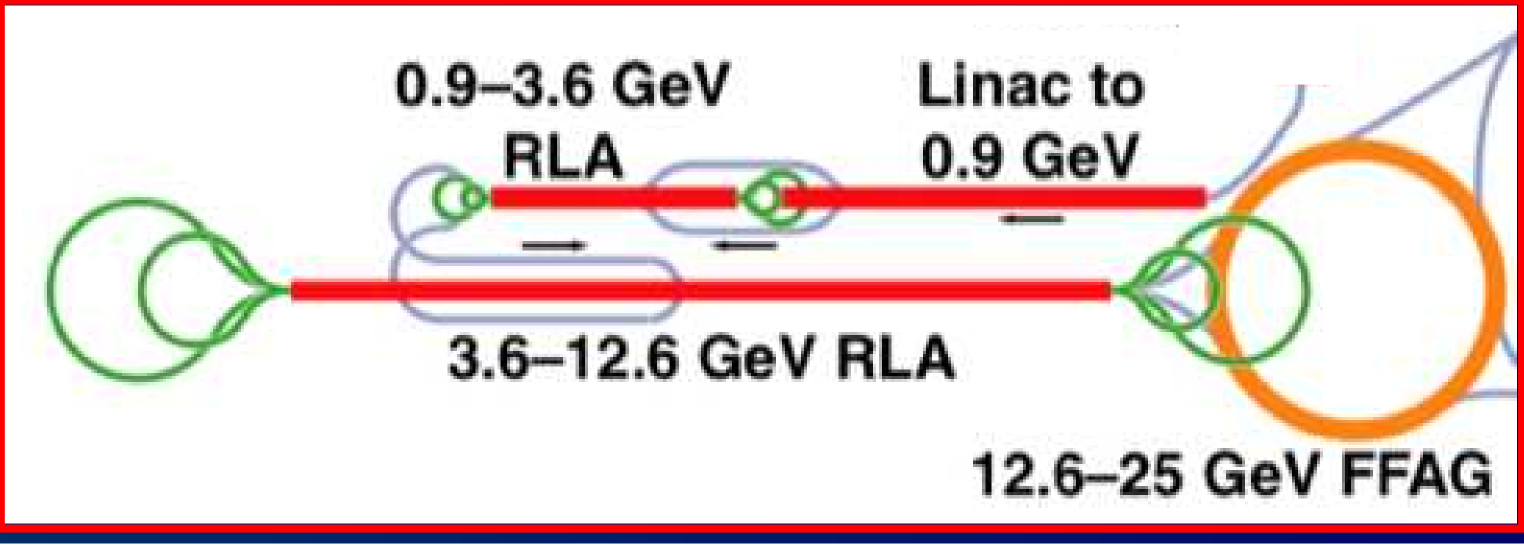
Muon acceleration:

Rapid acceleration!

- **Linac/RLAs:**
  - **Superconducting linac:**
    - **Large acceptance;**
    - **Rapidly increase γ to increase effective lifetime**
  - **Recirculating linacs (RLAs):**
    - **Continue rapid acceleration**
    - **More cost-effective use of RF**

- **Fixed Field Alternating Gradient (FFAG) accelerator:**
  - **Large aperture magnets with fixed field:**
    - **Continued rapid acceleration**
    - **Improved cost-efficiency in use of RF**
  - **Injection/extraction challenging:**
    - **Development of appropriate schemes in progress**

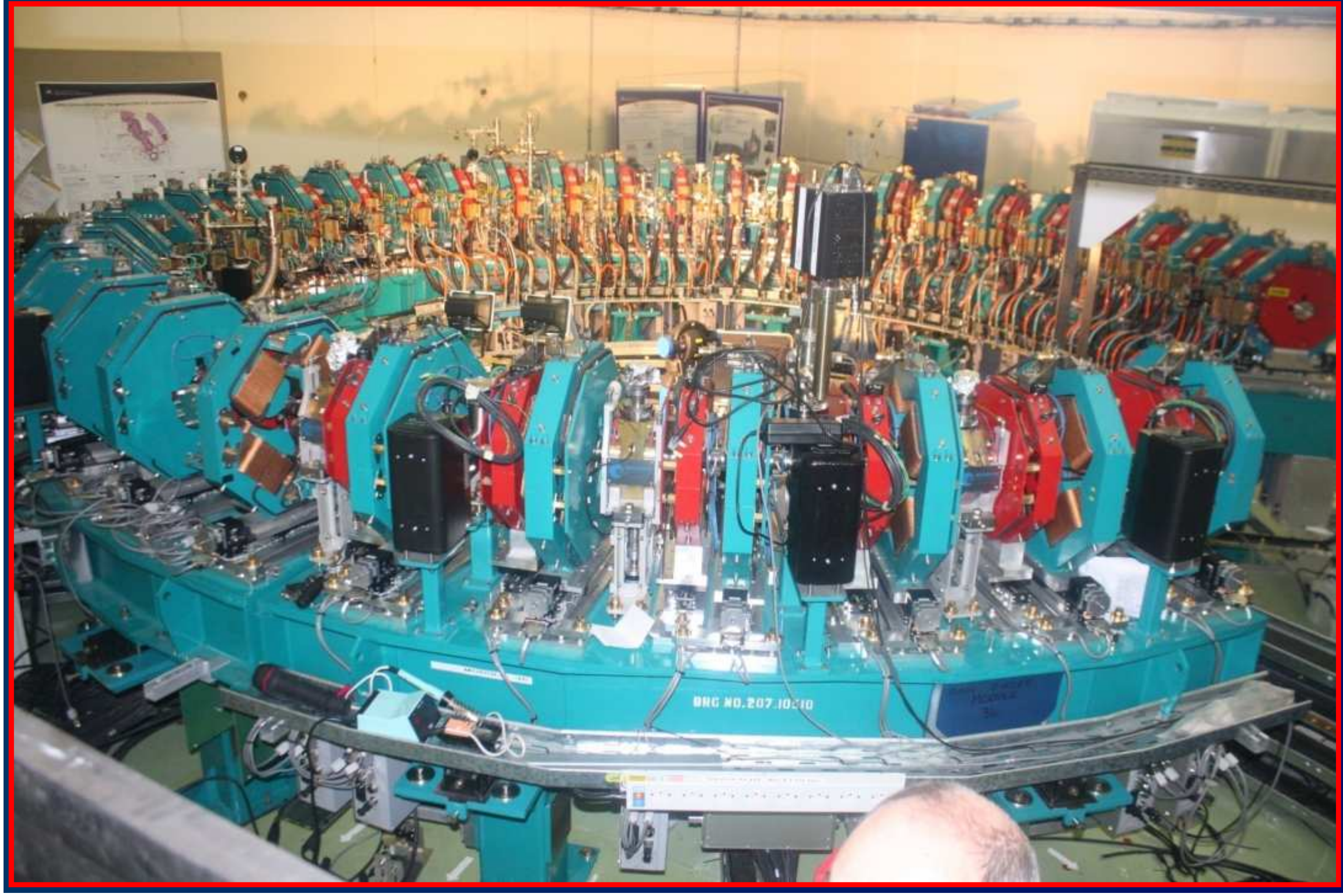
IPAC10: WEPE060, THPEB035,THPE033, THPD093



IPAC10: MOPEC043, MOPE085,WEPE057

Muon acceleration: proof of principal:

- EMMA; almost complete at Daresbury Lab.
  - Electron Model of Muon Acceleration
    - Aka:
      - Electron Model of Many Applications



- 6 of 7 sectors of EMMA have been installed;
- Commissioning of injector system and of associated diagnostics has started!
- Expect very soon
  - Installation of 7th sector; and
  - Start of commissioning of sectors 1—4

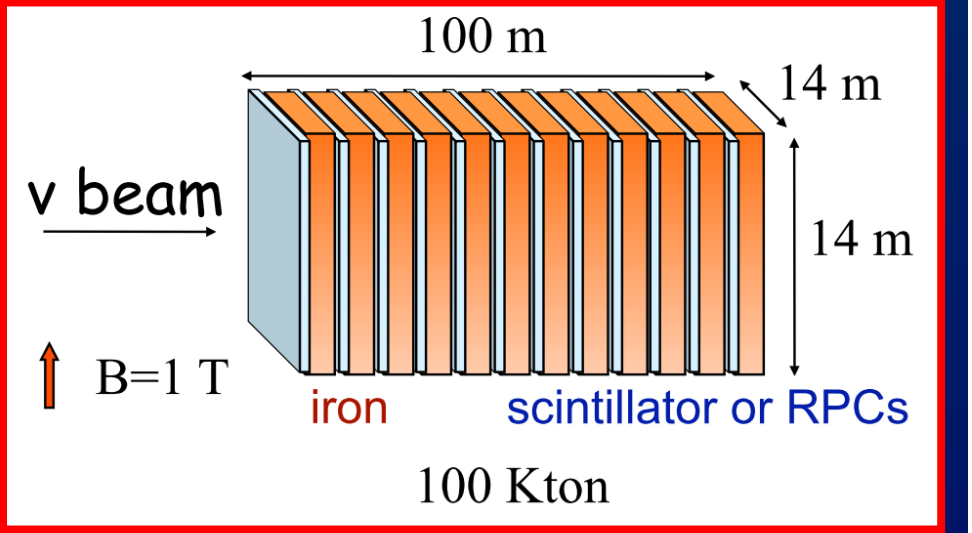
Poster: R. Tsenov: IDS-NF neutrino detectors

Neutrino Factory:

Neutrino Detectors:

MIND configuration, simulation and reconstruction:

- Iron / scintillator:
  - 4 cm / 1 cm
    - Re-optimisation in progress (see later)
  - *B* = 1 T; dipole
    - To be revised in favour of toroid (see later)



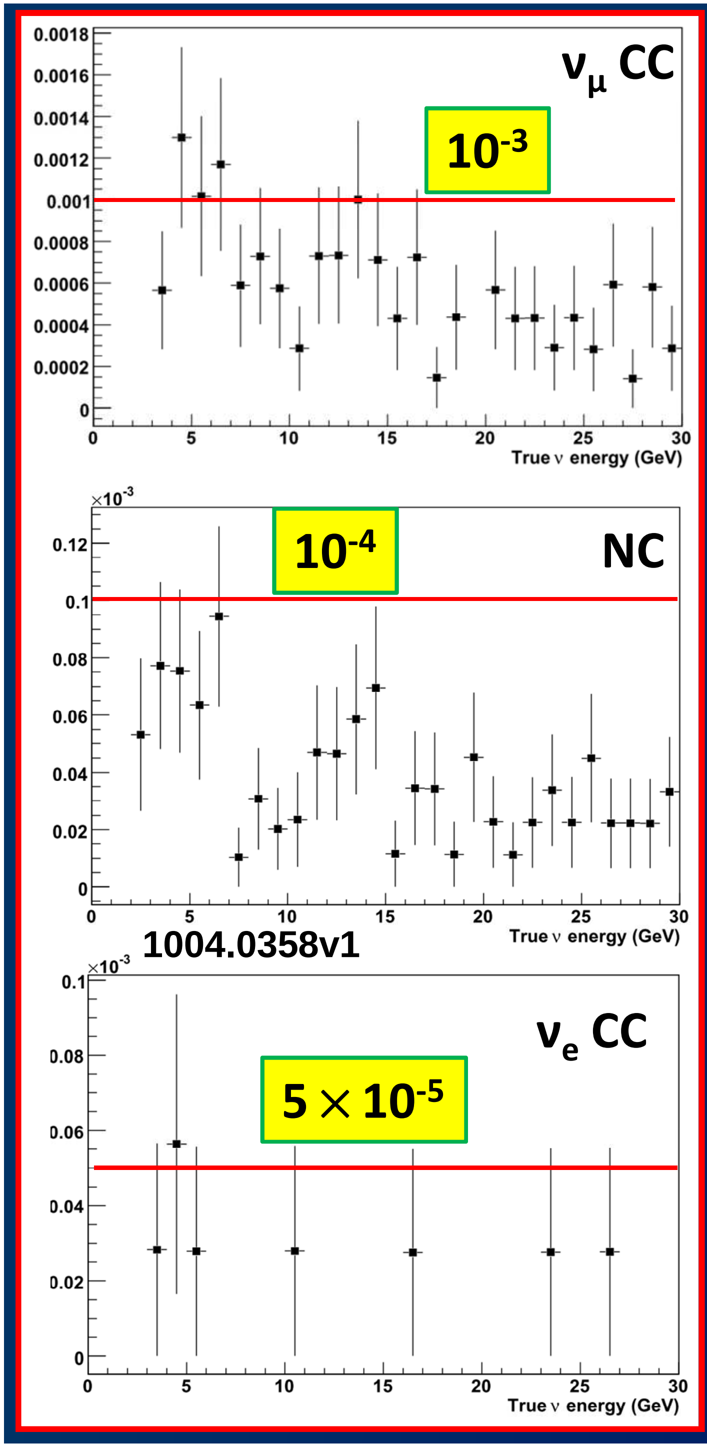
- Simulation:
  - Consider DIS (Lepto) and simulate MIND with Geant3
    - Analysis extended to include: QE, Resonance and coherent processes (see later)
- Analysis of golden channel: wrong sign muons from $\nu_e \longrightarrow \nu_\mu$
  - Digitisation to response of MIND in 'voxels'
  - Reconstruction:
    - Kalman filter if sufficiently long 'muon stub'
    - 'Cellular automaton' otherwise
  - Hadronic reconstruction:
    - Parameterisation:

$$\frac{\delta E_{had}}{E_{had}} = \frac{0.55}{\sqrt{E_{had}}} \oplus 0.03$$

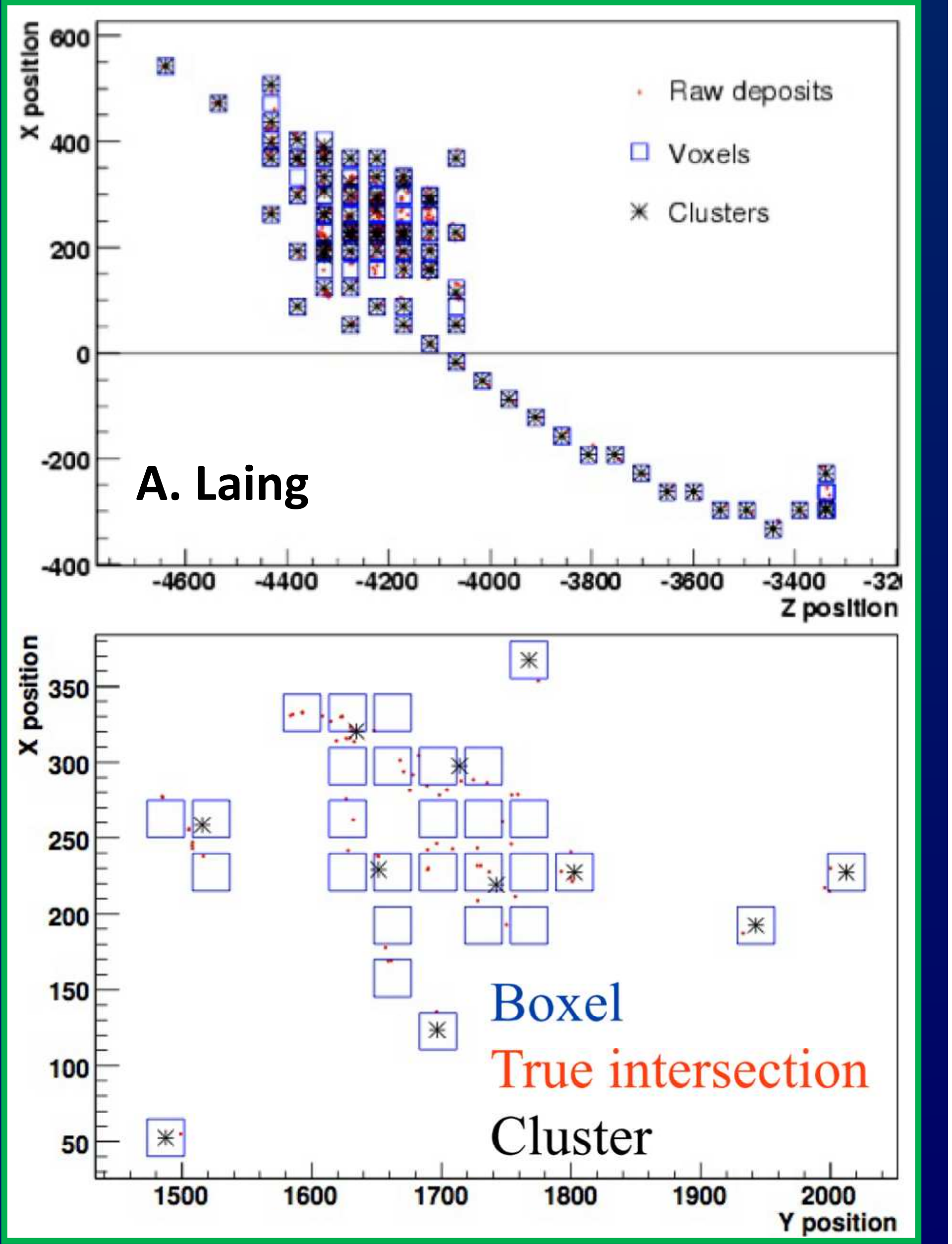
$$\delta\theta_{had} = \frac{10.4}{\sqrt{E_{had}}} \oplus \frac{10.1}{E_{had}}$$

A. Cervera, A. Laing,
J. Martín-Albo, F.J.P. Soler;
1004.0358v1

MIND: performance:



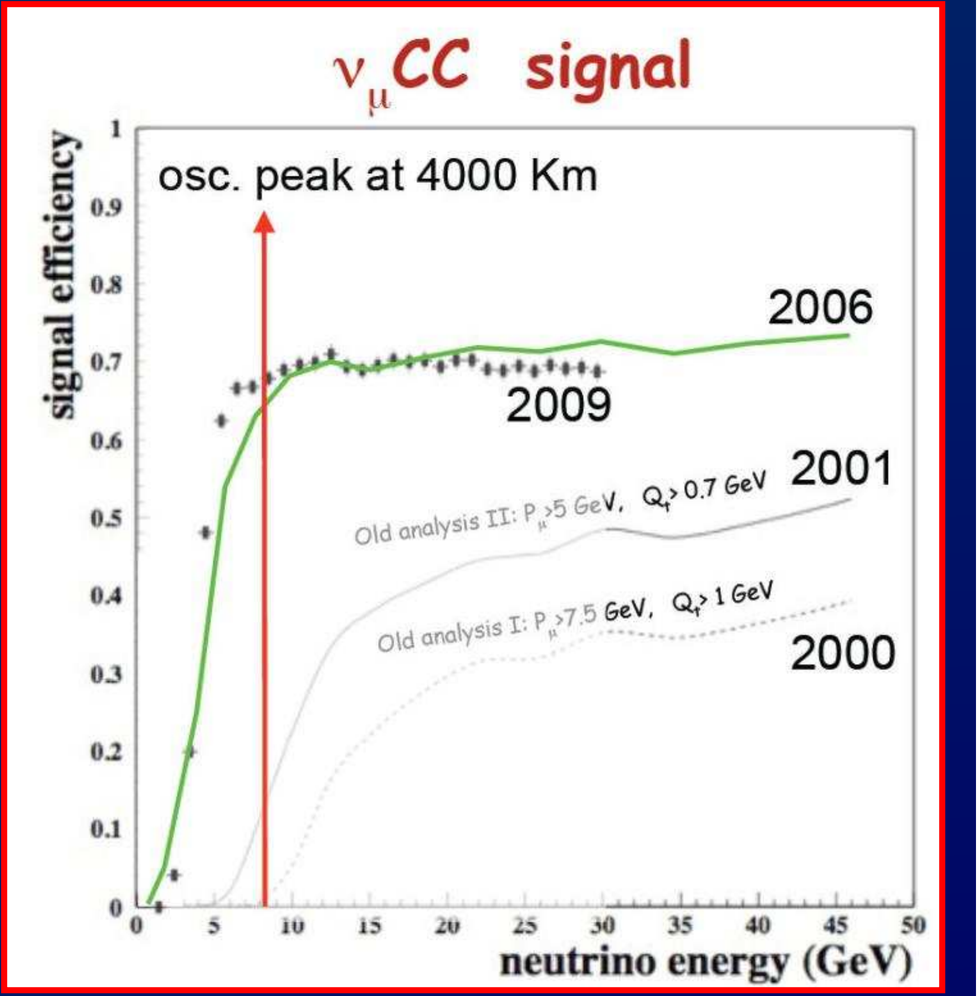
$\nu_e \rightarrow \nu_\mu$



MIND: performance:

- Neutrino Factory with baseline MIND:
  - Gives CPV discovery reach to $\theta_{13} \sim 2 \times 10^{-5}$
  - Out-performs alternative options
- Improvements:
  - In hand:
    - Re-optimisation of sampling fraction:
      - Fe:Scint = 3 cm : 2 cm
    - Full simulation of physics processes
      - NUANCE
    - Full, Geant4, simulation of MIND
      - Hadron shower

    Improves threshold by factor ~2
  - To be implemented:
    - Toroidal magnet

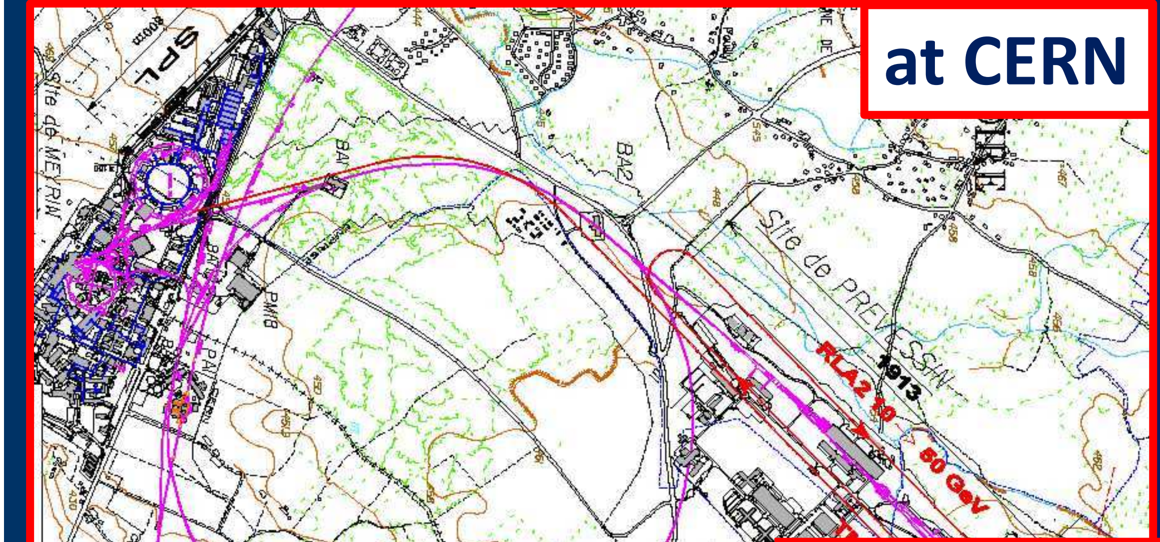


Neutrino Factory:

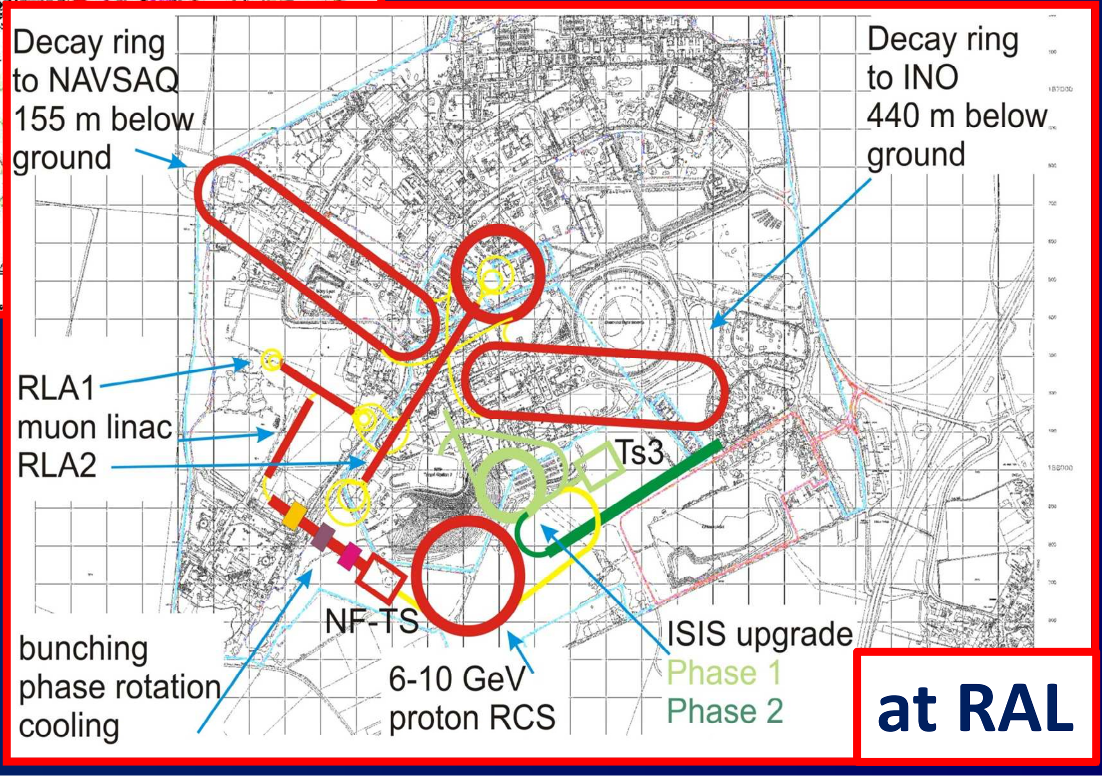
Opportunity and conclusions:

Neutrino Factory: footprint:

at CERN



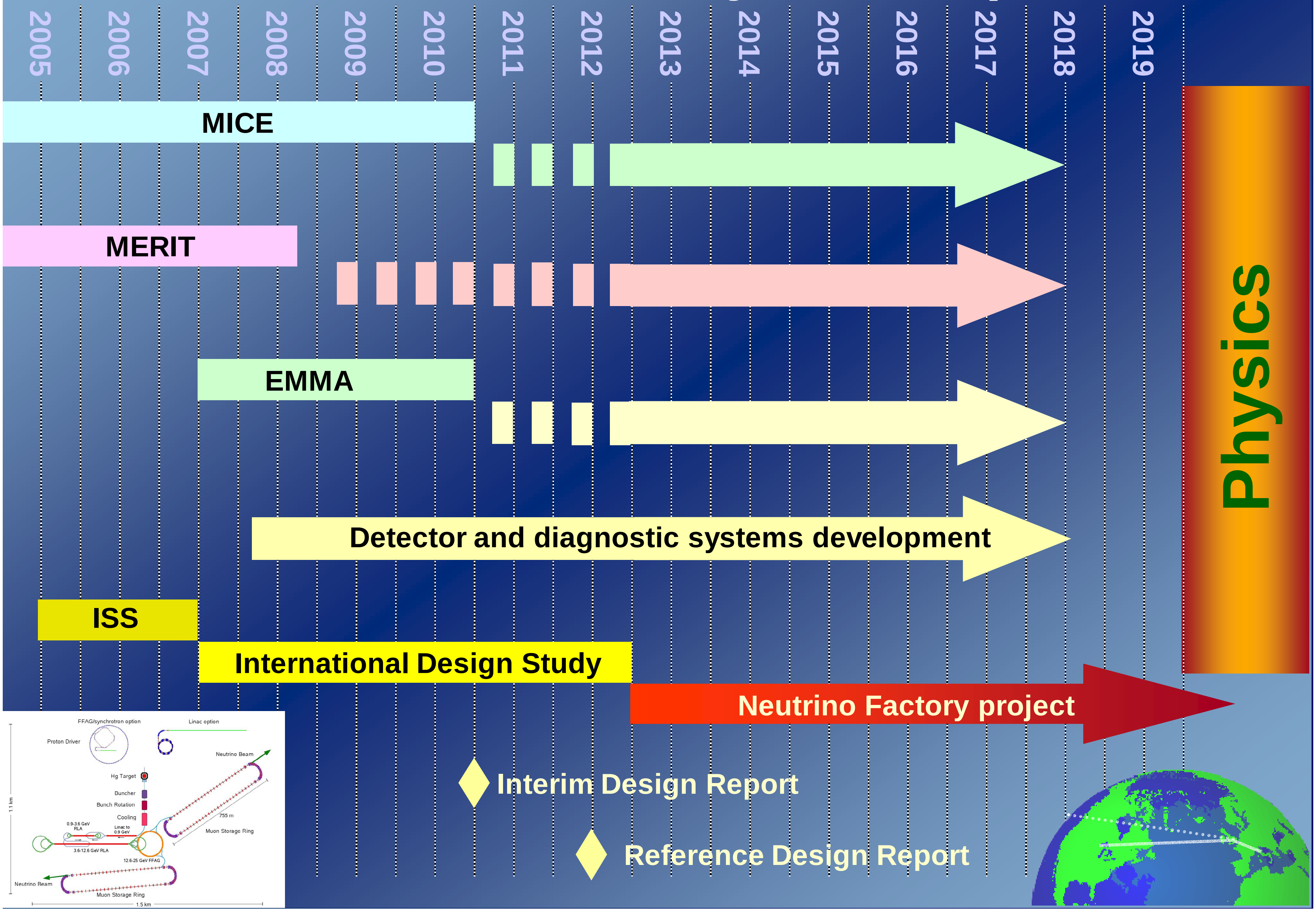
at RAL



4TeVc.o.m. Muon Collider

at FNAL

Neutrino Factory roadmap



MICE

MERIT

EMMA

Detector and diagnostic systems development

ISS

International Design Study

Neutrino Factory project

Physics

◆ **Interim Design Report**

◆ **Reference Design Report**

Conclusions:

- The Neutrino Factory, the ‘facility of choice’:
  - Best discovery reach
  - Best precision:
    - But need to define agreed figure of merit
  - Best sensitivity to non-standard interactions
- The IDS-NF baseline established and, so far, robust
  - Alternatives to the baseline, addressing particular issues (e.g., Low Energy Neutrino Factory), are under discussion
- The IDS-NF collaboration:
  - Energetic and ambitious, working towards IDR 2010/11 and RDR 2012/13:
    - EUROnu: encompasses and coordinates European contributions
- Scientific imperative:
  - Make the Neutrino Factory an option for the field!