The International Design Study for the Neutrino Factory

K. Long, 23 July, 2010

on behalf of the IDS-NF collaboration

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

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ift
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ИНСТИТУТ ЯДЕРНЫХ ИССЛЕДОВАНИЙ РОССИЙСКОЙ АКАДЕМИИ НАУК INSTITUTE FOR NUCLEAR RESEARCH OF RUSSIAN ACADEMY OF SCIENCES
THE UNIVERSITY OF WARWICK
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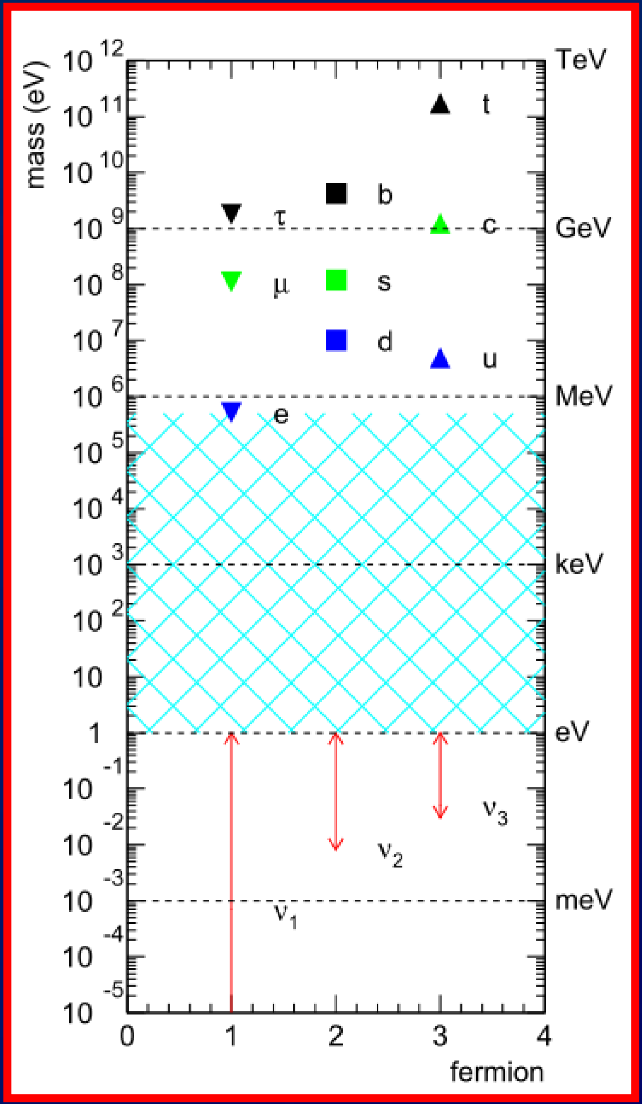
Neutrino Factory:

Prologue

- Neutrino oscillations, an established phenomenon
  - → Neutrino mass is not zero and neutrinos mix
    - i.e. Standard Model is incomplete
  - → Either:
    - Majorana neutrino: a new state of matter; or
    - New physics:
      - To distinguish Dirac neutrino from Dirac anti-neutrino



- Phenomenological description:
  - Mixing of mass states → flavour states
    - Potentially yields additional source of CP violation

- Observations:
  - Neutrino mixing pattern substantially different to that of the quarks
  - Neutrino masses are tiny

- Why?

A. De Gouvea

Standard neutrino Model (SνM):

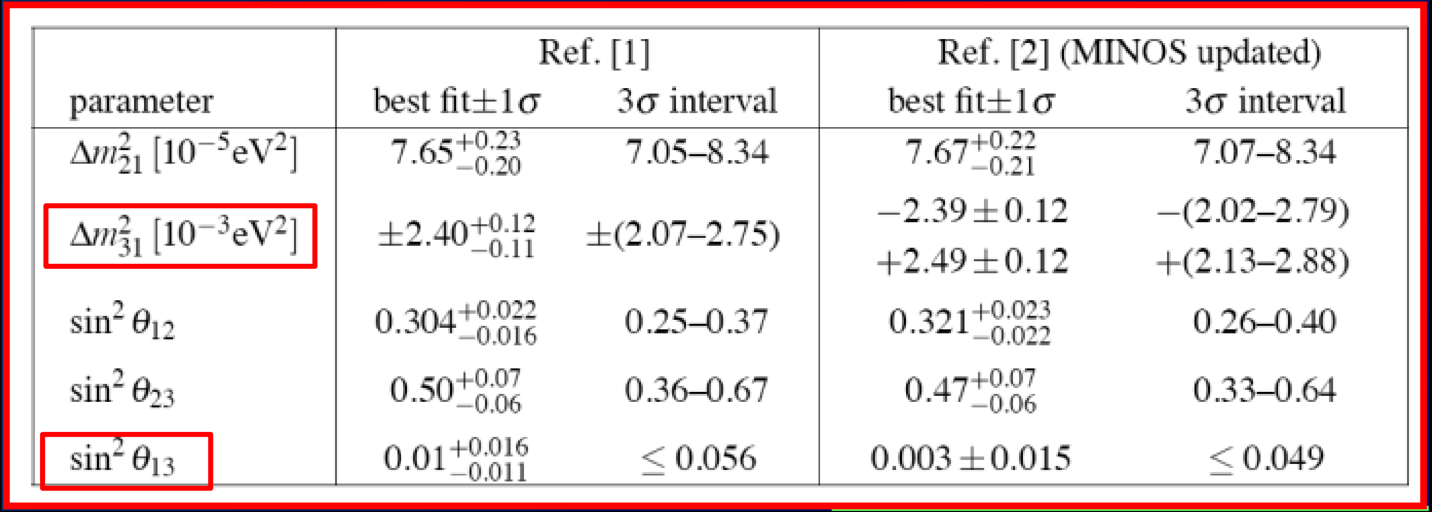
- **Phenomenological description:**

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

$$\Delta m^2_{21}=m^2_2-m^2_1>0$$

$$\Delta m^2_{31}=m^2_3-m^2_1$$

$$\left|\Delta m^2_{31}\right|\gg\Delta m^2_{21}$$



	Ref. [1]		Ref. [2] (MINOS updated)	
parameter	best fit$\pm1\sigma$	3σ interval	best fit$\pm1\sigma$	3σ interval
Δm^2_{21} [10^{-5}eV^2]	$7.65^{+0.23}_{-0.20}$	7.05–8.34	$7.67^{+0.22}_{-0.21}$	7.07–8.34
$\boxed{\Delta m^2_{31}\ [10^{-3}\mathrm{eV}^2]}$	$\pm2.40^{+0.12}_{-0.11}$	$\pm$(2.07–2.75)	-2.39 ± 0.12 $+2.49\pm0.12$	$-$(2.02–2.79) $+$(2.13–2.88)
$\sin^2\theta_{12}$	$0.304^{+0.022}_{-0.016}$	0.25–0.37	$0.321^{+0.023}_{-0.022}$	0.26–0.40
$\sin^2\theta_{23}$	$0.50^{+0.07}_{-0.06}$	0.36–0.67	$0.47^{+0.07}_{-0.06}$	0.33–0.64
$\boxed{\sin^2\theta_{13}}$	$0.01^{+0.016}_{-0.011}$	≤0.056	0.003 ± 0.015	≤0.049

[1] Schwetz, Tortola and Valle, arXiv:0808.2016

[2] Gonzalez-Garcia and Maltoni, arXiv:0704.1800

from A. de Gouvea, CERN 01Oct09

The experimentalists' contribution:

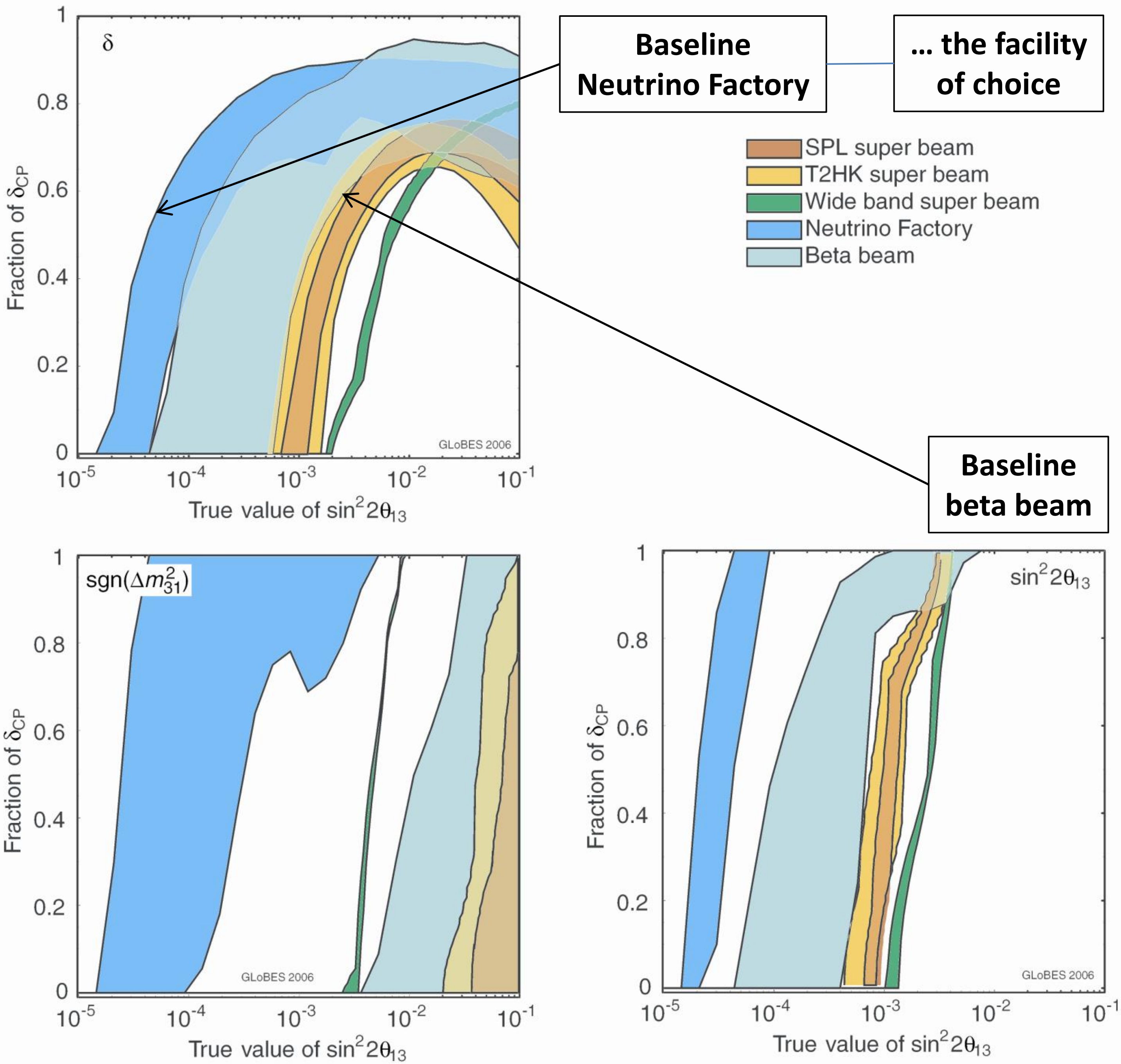
- Discovery:
  - Search for leptonic CP violation
  - Determine mass hierarchy
  - Investigate discrete symmetries
- Measure mixing parameters with a precision sufficient to:
  - Determine structure of theory:
    - Ultimate theory must unify quarks and leptons:
      - Quark and lepton mixing parameters must be related
- Therefore, seek to:
  - Determine neutrino-mixing parameters with a precision approaching that of the quark-mixing parameters

$$\begin{tikzcd}
P(\nu_\alpha \to \nu_\beta) \arrow[r, leftrightarrow, dashed, "CP"] \arrow[d, leftrightarrow, dashed, "T"'] \arrow[dr, leftrightarrow, dashed, "CPT"'] & P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) \arrow[d, leftrightarrow, dashed, "T"] \\
P(\nu_\beta \to \nu_\alpha) \arrow[r, leftrightarrow, dashed, "CP"'] & P(\bar{\nu}_\beta \to \bar{\nu}_\alpha)
\end{tikzcd}$$

Precision-era facility must address:

- Mass hierarchy
- CP violation
- θ_{13}
- θ_{12}, θ_{23}, Δm_{31}^2, Δm_{21}^2
- More over:
  - Is θ_{23} maximal?
  - Is θ_{13} zero?
  - Beyond the SνM:
    - NSIs
    - MVNs
    - Sterile neutrinos

- ISS reports:
  - Physics Report: Rept.Prog.Phys.72:106201,2009;
  - Accelerator Report: JINST 4:P07001,2009;
  - Detector Report: JINST 4:T05001,2009.



Baseline Neutrino Factory

… the facility of choice

Baseline beta beam

- Motivation; timescale and risk
- IDS-NF Neutrino Factory baseline
- Status of the study
  - Accelerator facility
    - Neutrino detectors: see A. Laing's talk in 'track 13'
- Opportunities and conclusions

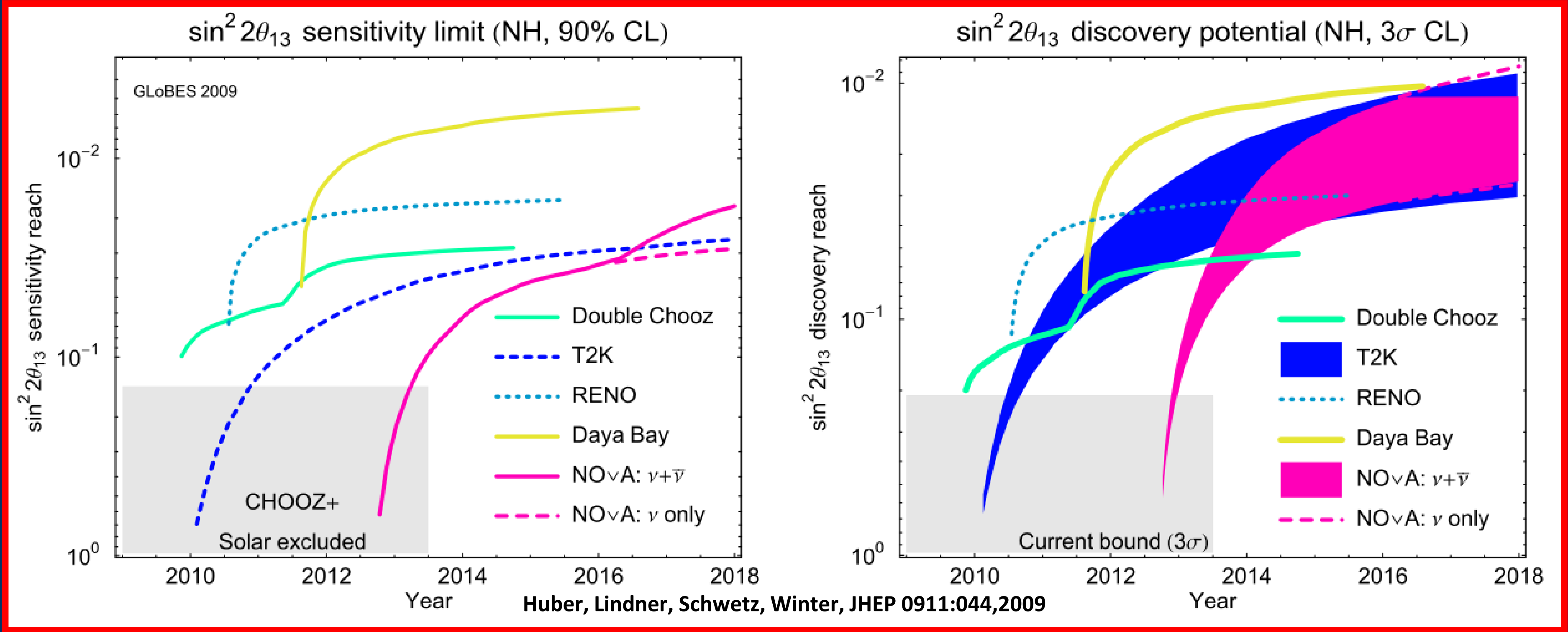
Related presentations:
A. Laing: 'Detectors for CP violation at the Neutrino Factory'. (track 13, Saturday 24Jul10, 12:20);
Y. Karadzhov: 'Status of MICE, the international Muon Ionisation Cooling Experiment', poster;
V.Verguilov: 'Measurement of emittance reduction in MICE', poster;
M.Bonesini: 'The MICE particle identification system', poster.

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, NOvA

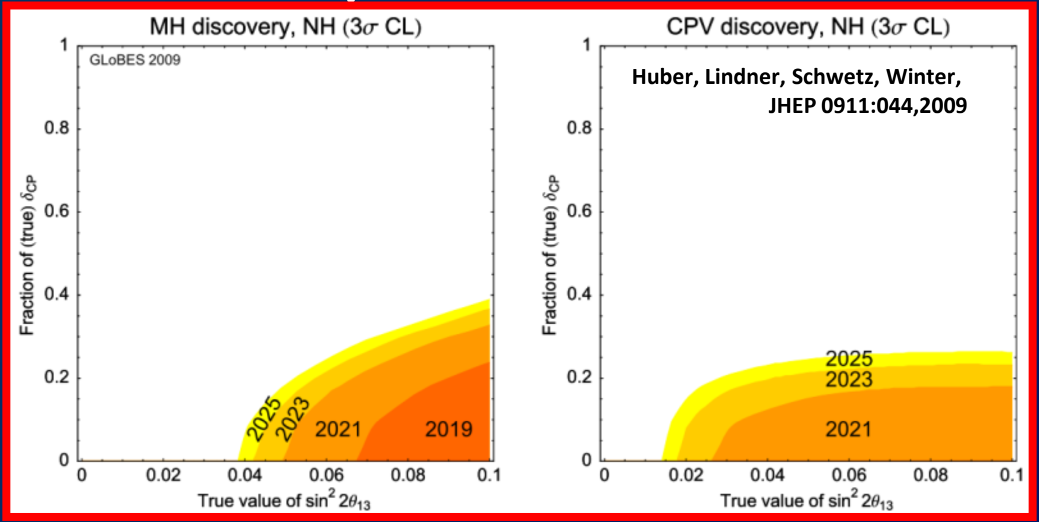


Huber, Lindner, Schwetz, Winter, JHEP 0911:044,2009

- ‘Sensitivity plateau’ of ~10^{-2} reached around 2016

Potential/risk of incremental upgrade:

- Power upgrade to increase performance of T2K and NOνA:

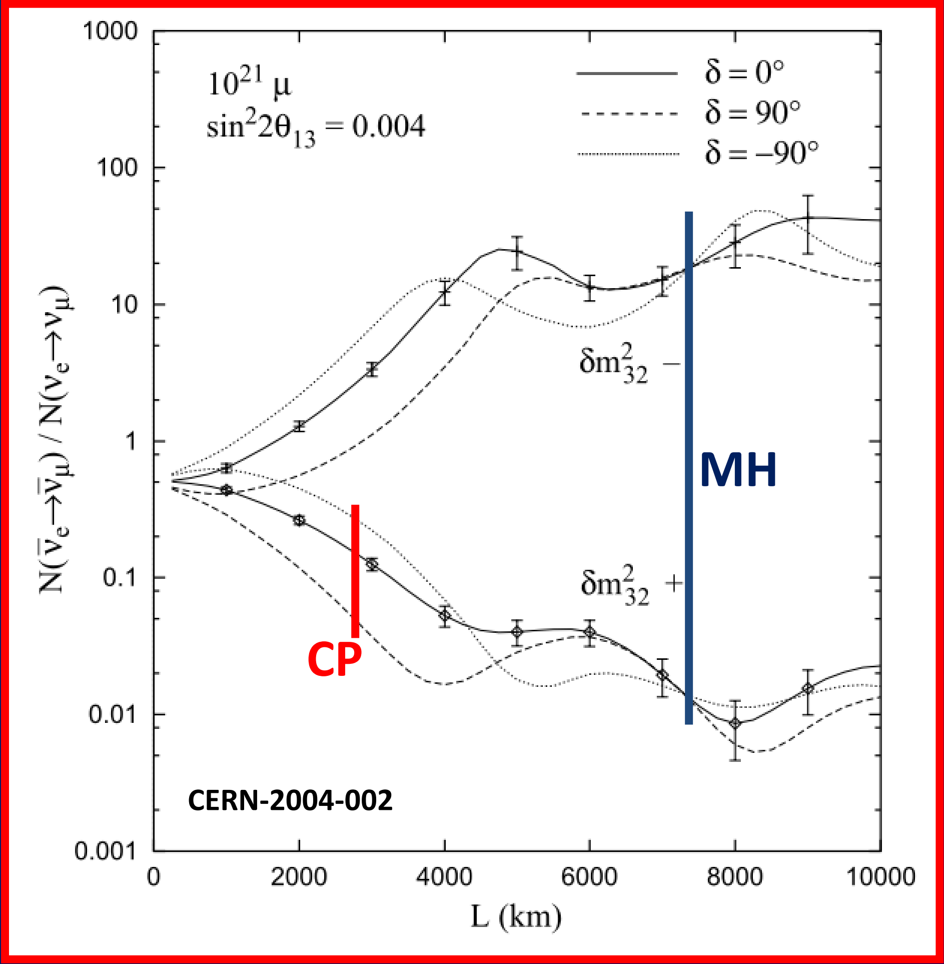


Huber, Lindner, Schwetz, Winter, JHEP 0911:044,2009

- 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 ~10^{-2}
    - 70—75% of (δ)parameter space uncovered ($\sin^2 2\theta_{13}$ > ~ 10^{-2})
      - No δ-sensitivity for $\sin^2 2\theta_{13}$ smaller than ~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
    - (Large) high-energy ν_e ($\bar{\nu}_e$) flux
      - Optimise event rate at fixed *L/E*
      - Optimise MH sensitivity
      - Optimise CP sensitivity

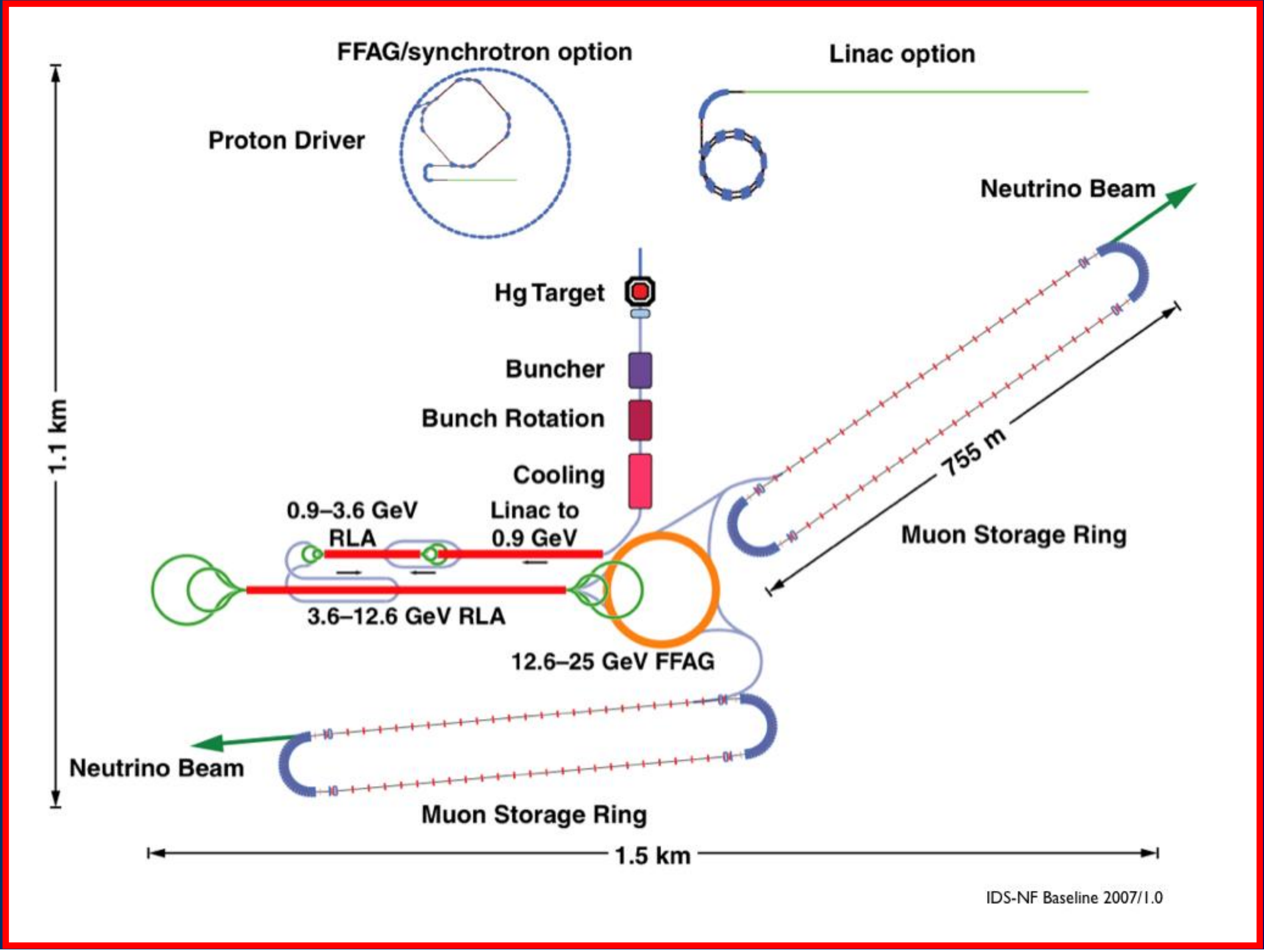


CERN-2004-002

Neutrino Factory:

IDS-NF baseline; performance and optimisation

IDS-NF baseline: accelerator:

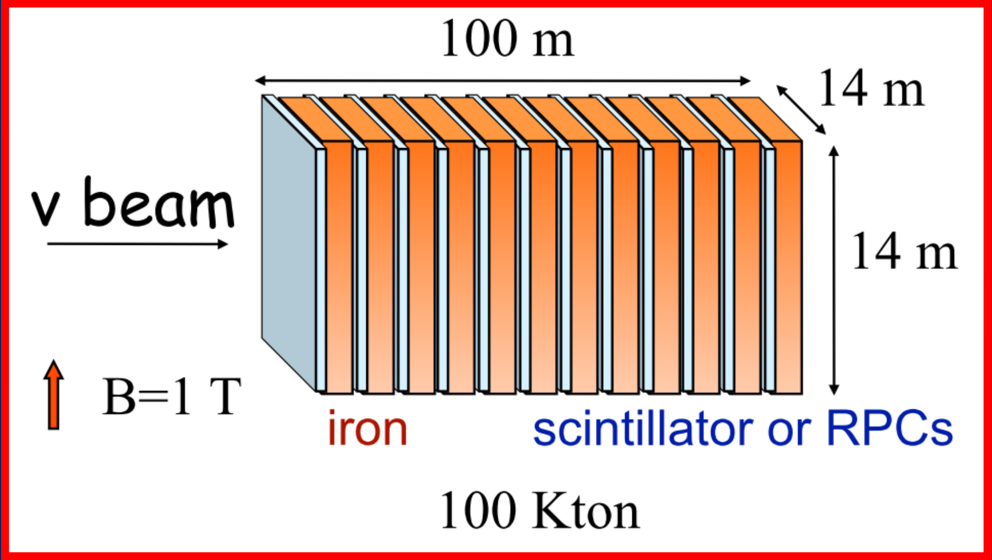


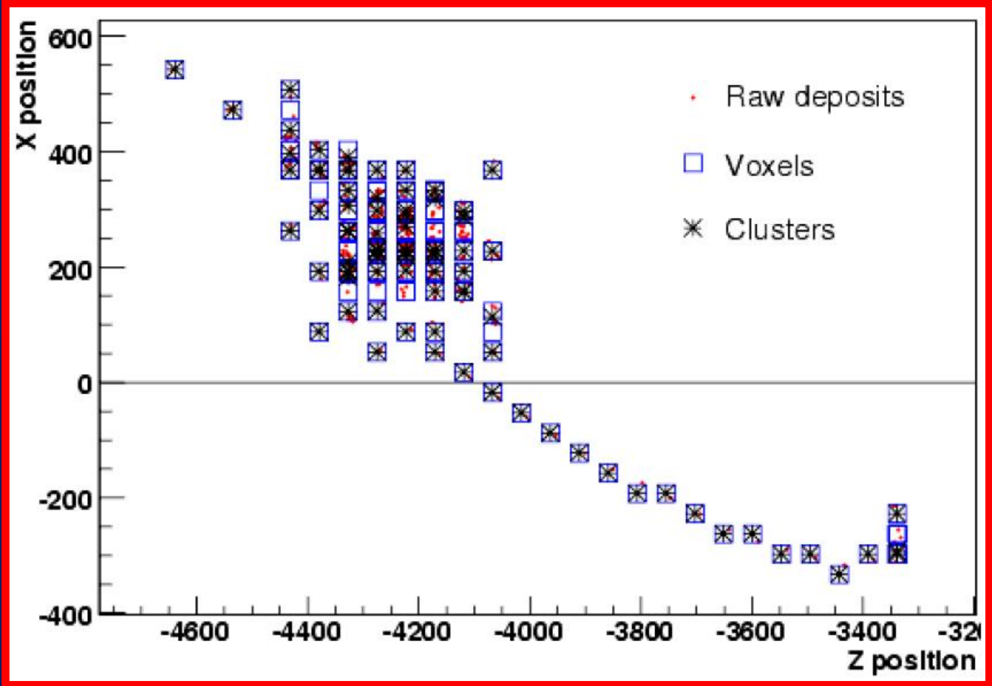
IDS-NF-002: https://www.ids-nf.org/wiki/FrontPage/Documentation?action=AttachFile&do=view&target=IDS-NF-002-v1.1.pdf

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 ν_e and ν_τ
    - Issues:
      - Magnetisation of large volume
      - Cost of large mass of TASD
      - R&D required for large mass LAr

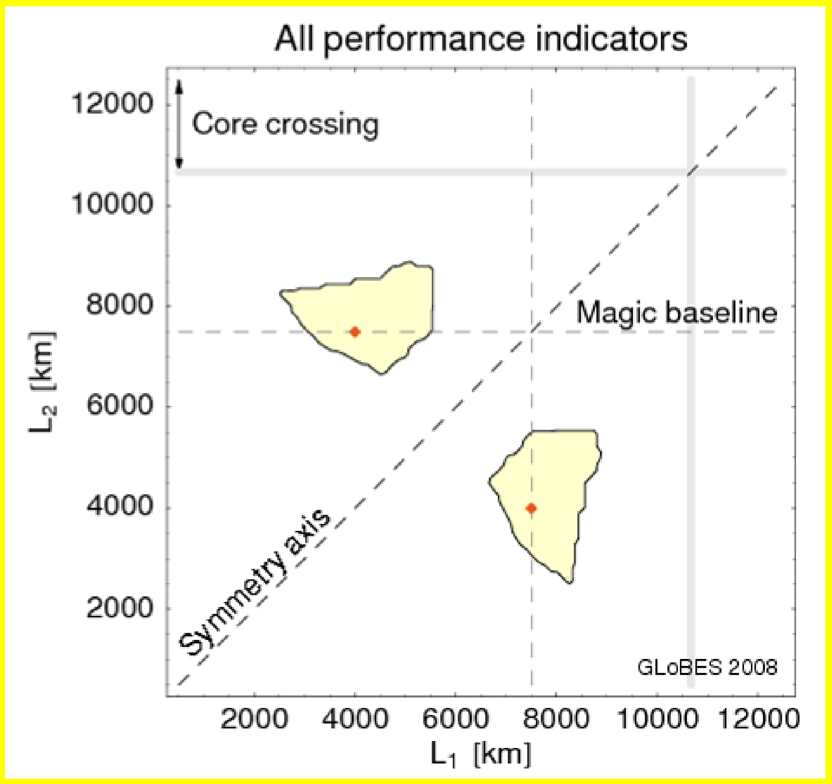




Neutrino Factory: optimisation:

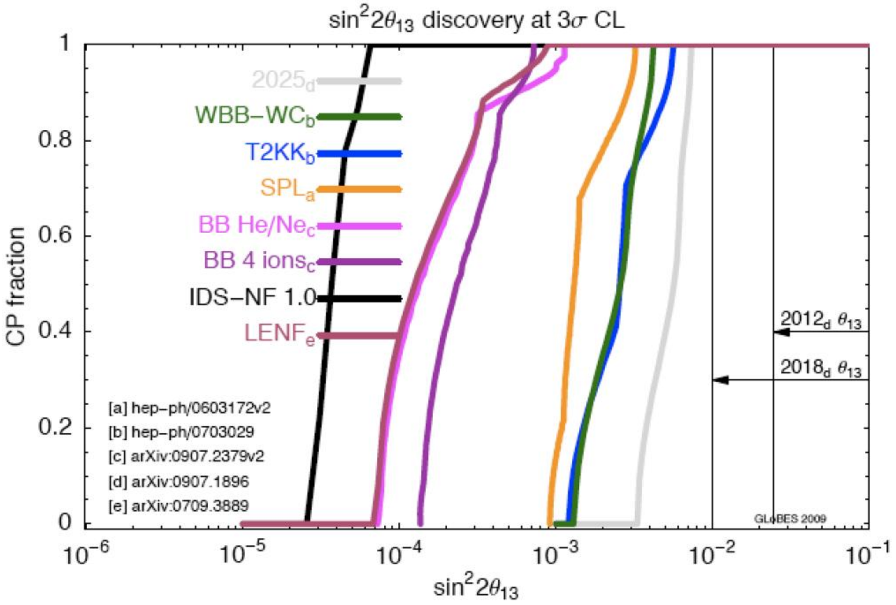
- Two detectors:
  - Compare performance of 50 kT detector at magic baseline with two 25 kT detectors

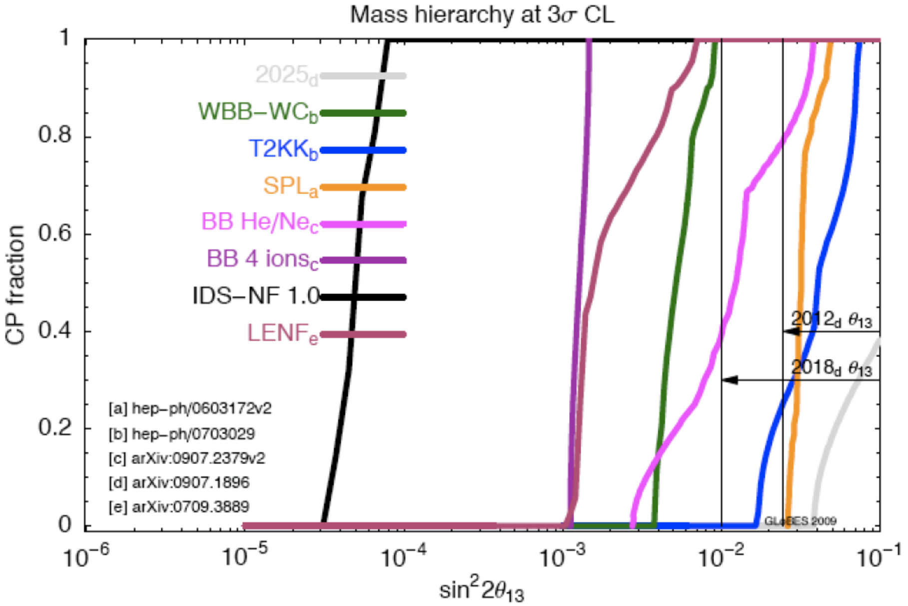
Kopp, Ota, Winter, Phys.Rev.D78:053007,2008.

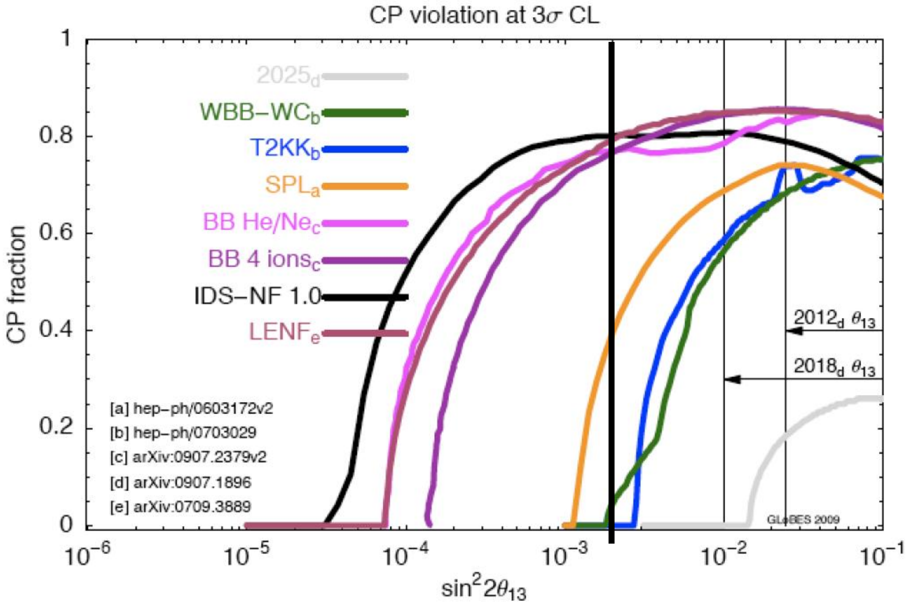


- Preferred combination:
  - 2000—5000 km; good sensitivity to CP violation
  - 7000—8000 km; mass hierarchy, θ_{13}, degeneracy resolution

IDS-NF baseline performance:





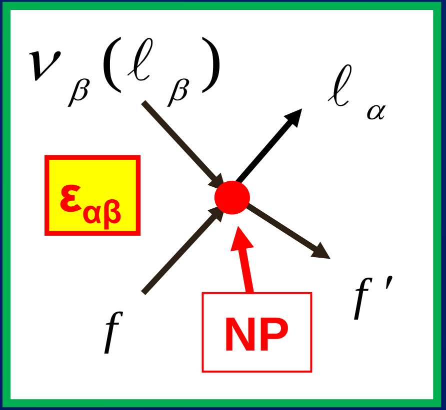


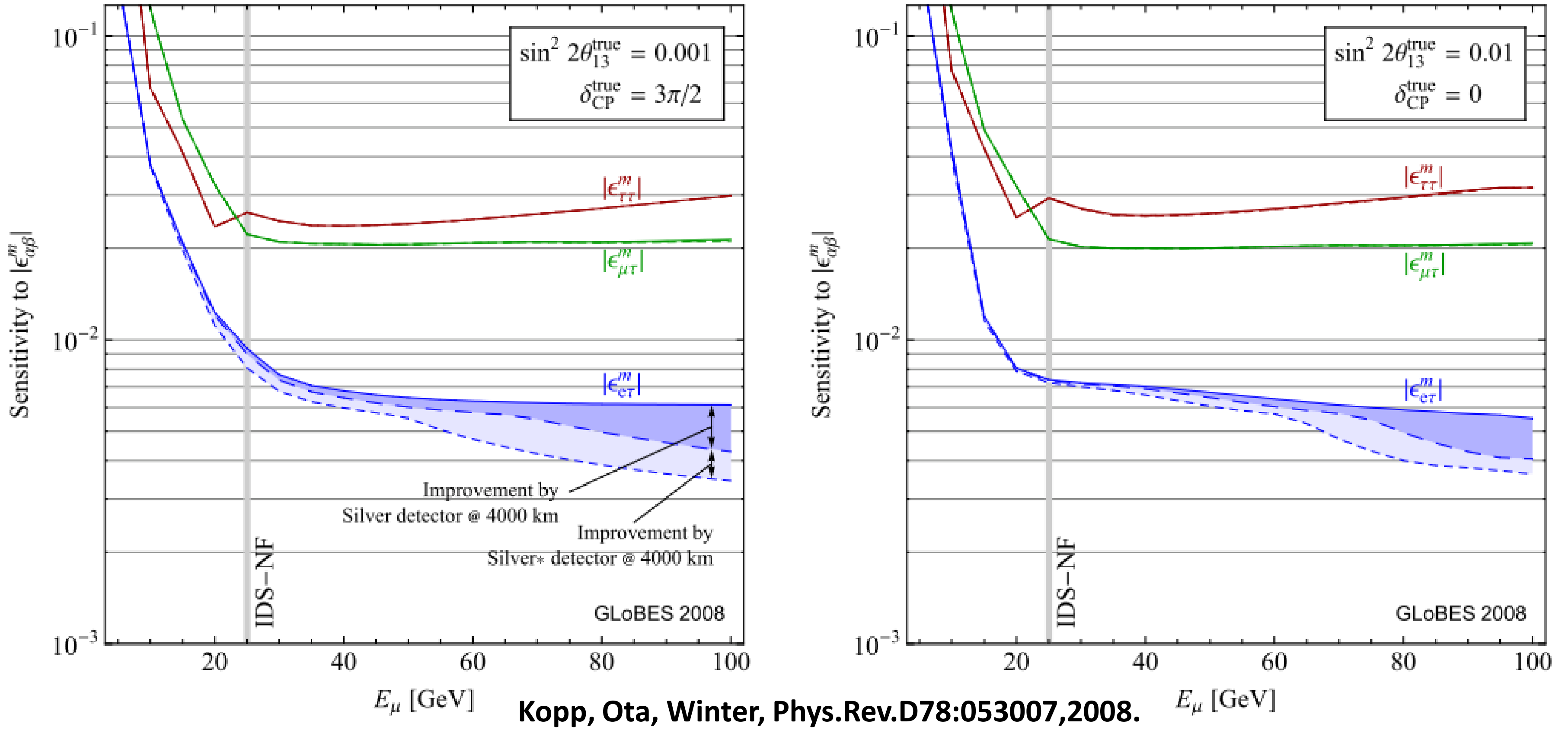
- **Neutrino Factory outperforms other options:**
  - **Larger discovery reach**
- **Alternative/option (large θ_{13}):**
  - **Beta beam:**
    - **But requires large Ne flux, high-γ, and/or 4-ions**
  - **Low energy Neutrino Factory:**
    - **Below tau threshold: reduced redundancy/flexibility**

EUROnu: arXiv: 1005.3146v1

IDS-NF baseline: performance:

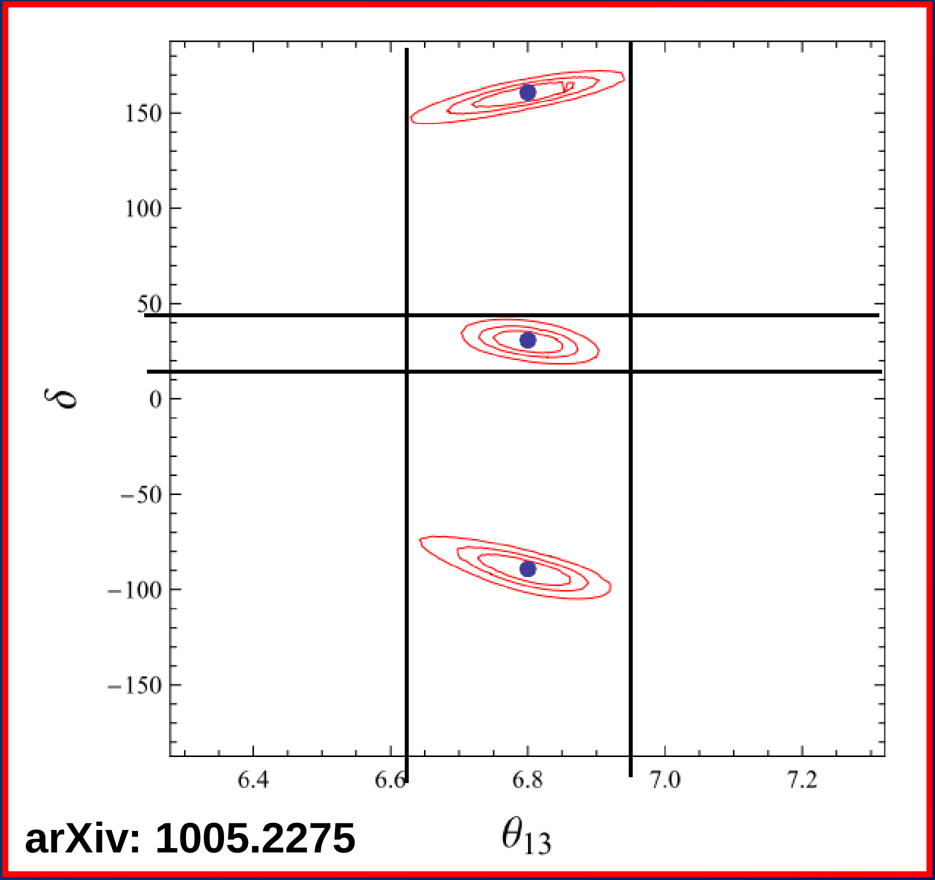
- Physics beyond the SνM:
  - – Example: on-standard interactions
    - Excellent performance for E_μ = 25 GeV (IDS-NF baseline)



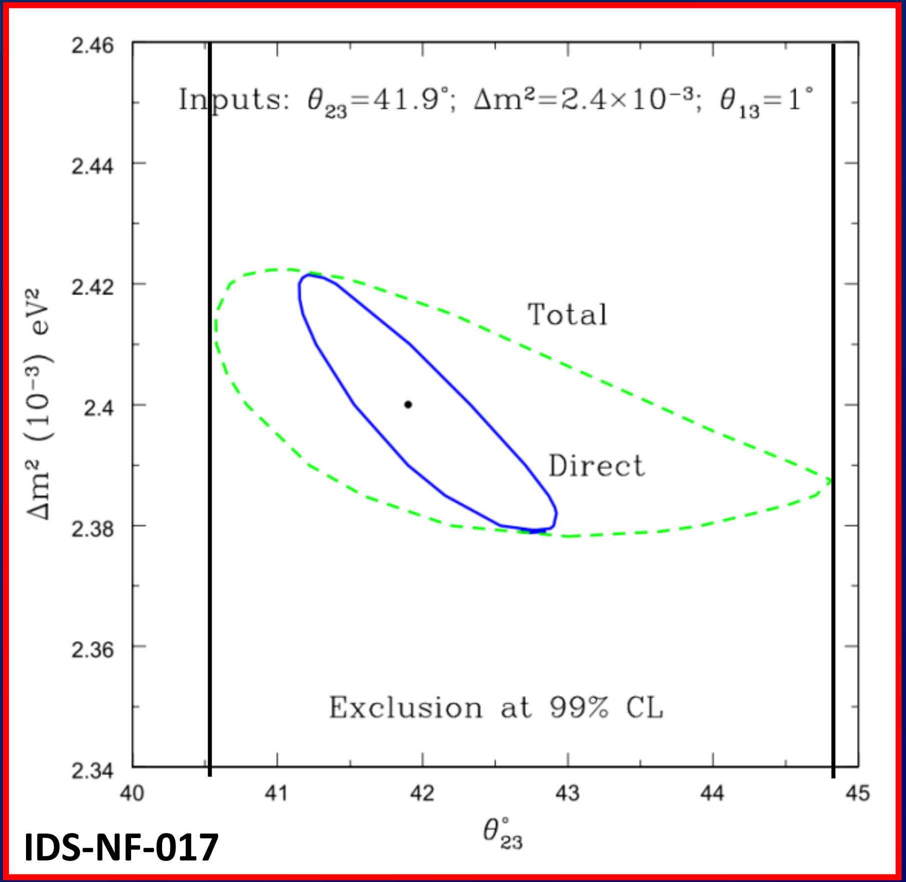


Kopp, Ota, Winter, Phys.Rev.D78:053007,2008.

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

Neutrino Factory:

Accelerator facility:

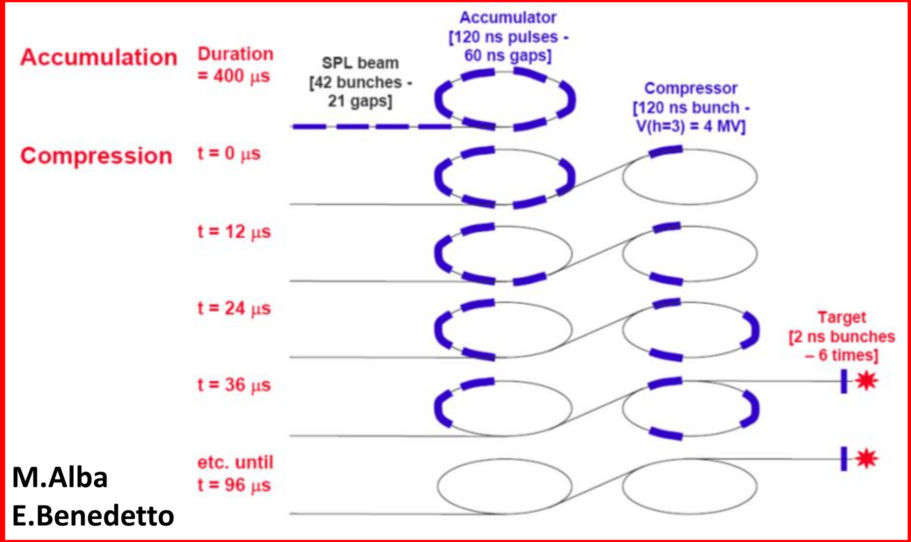
[Neutrino Factory detectors: see A. Lang's talk in 'track 13'

Proton driver:

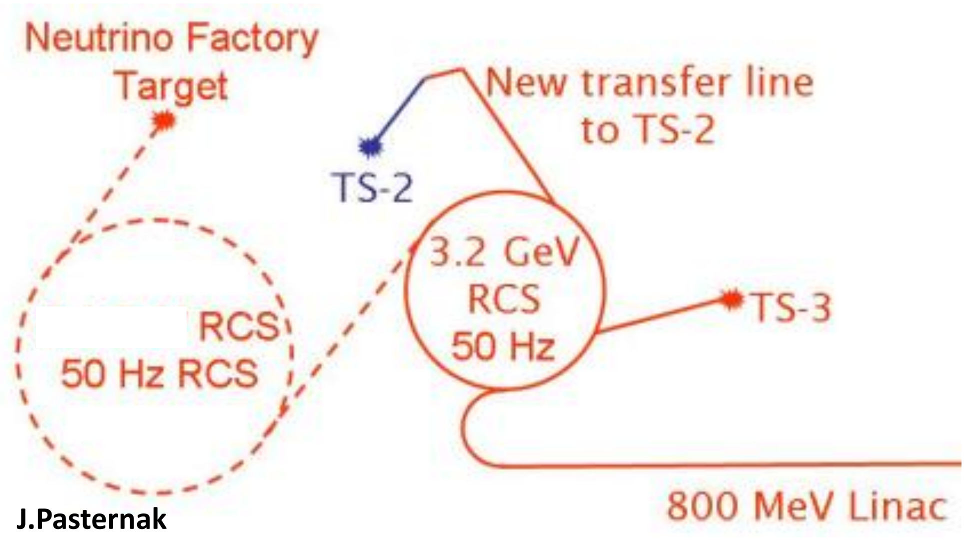
IPAC10: THPD074,
MOPEC049,
WEPE098

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

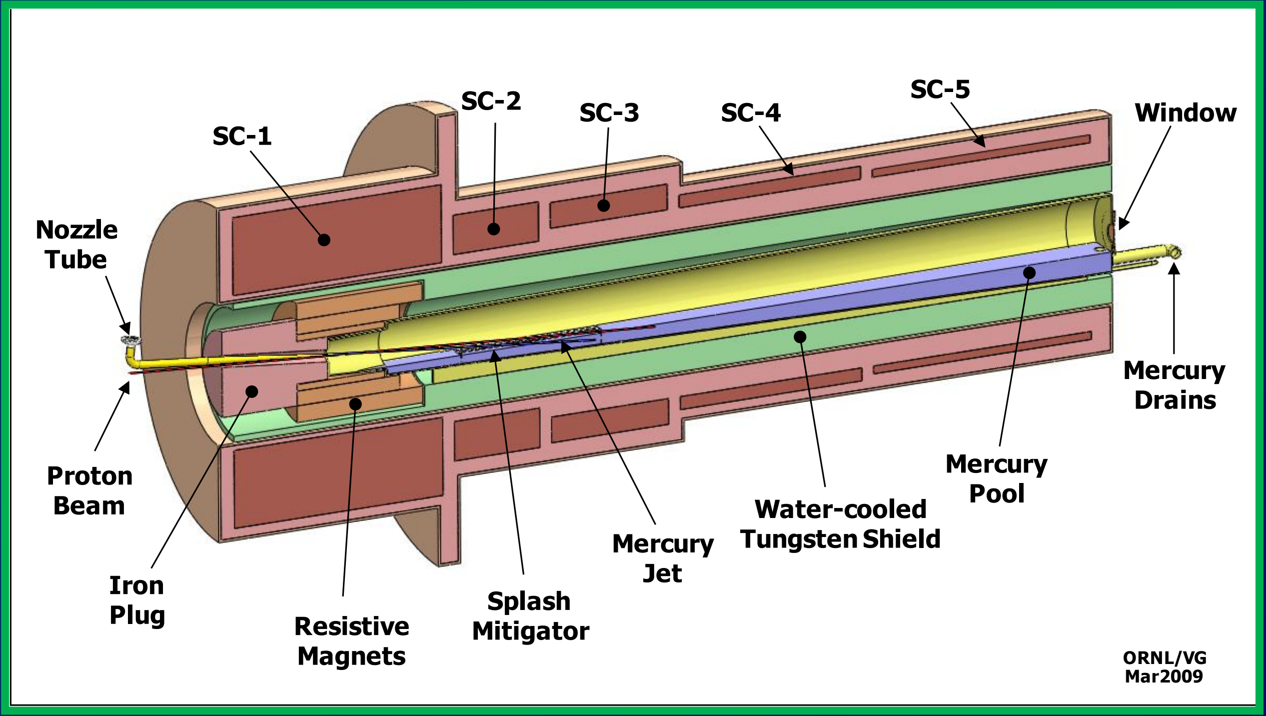


J.Pasternak

Target/capture:

IPAC10: WEPE101, THPEC092

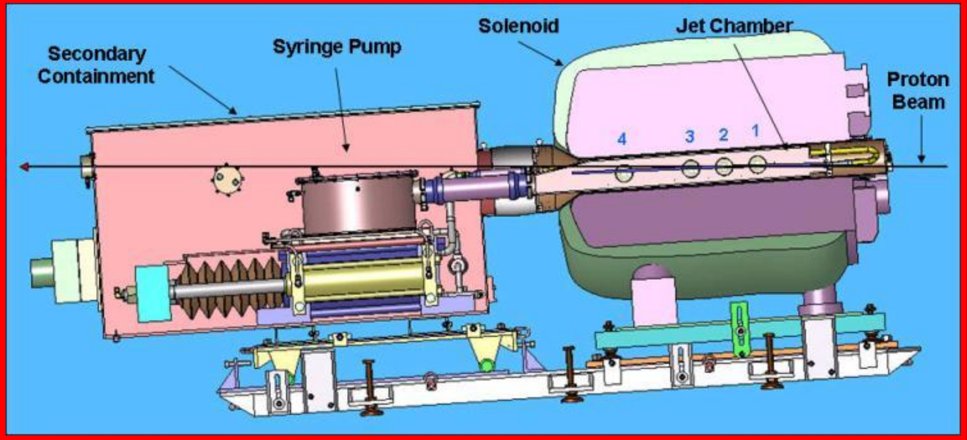
Parameter	*Value*	*Comment*
Jet velocity	20 m/s	Reformation of jet
Field at i/p	20 T	Pion collection
Field at exit of capture	1.75 T	Pion focusing



- **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

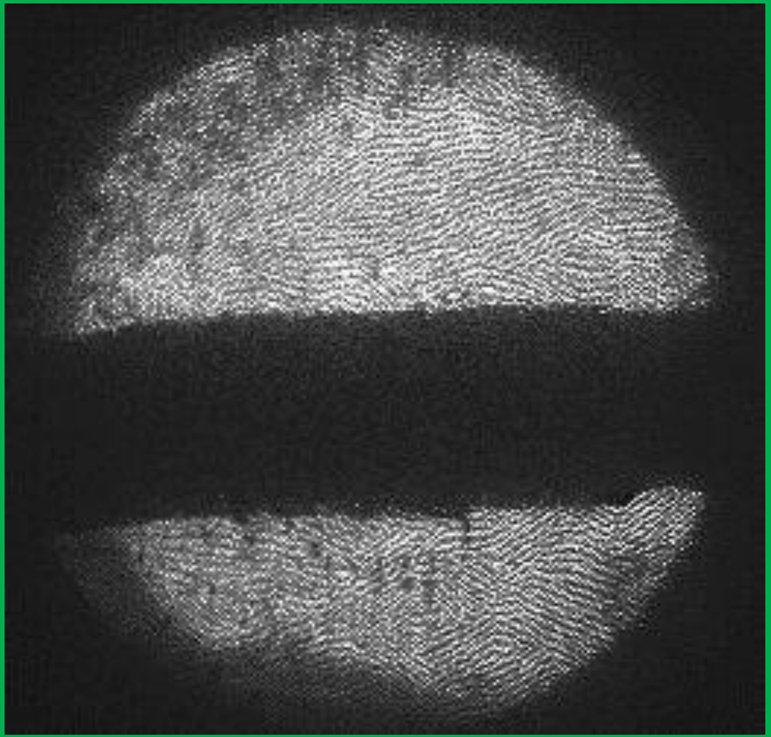
Baseline target: proof of principal: MERIT:

IPAC10: WEPE078



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

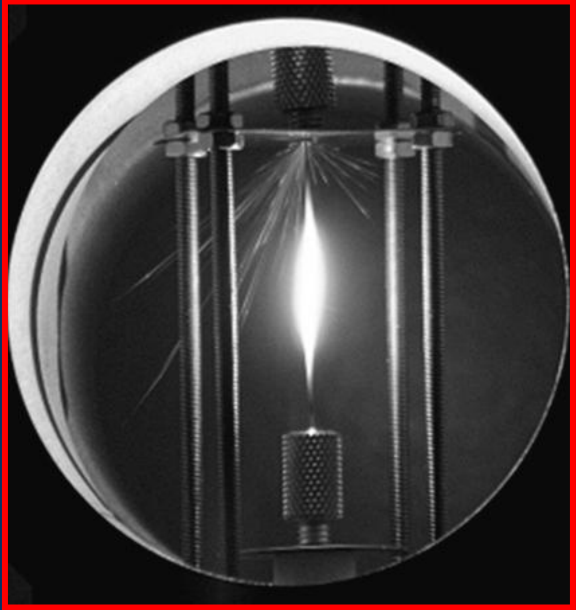
- 20 m/s liquid Hg jet in 15 T B field
- Exposed to CERN PS proton beam:
  - Beam pulse energy = 115 kJ
  - Reached 30 tera protons at 24 GeV

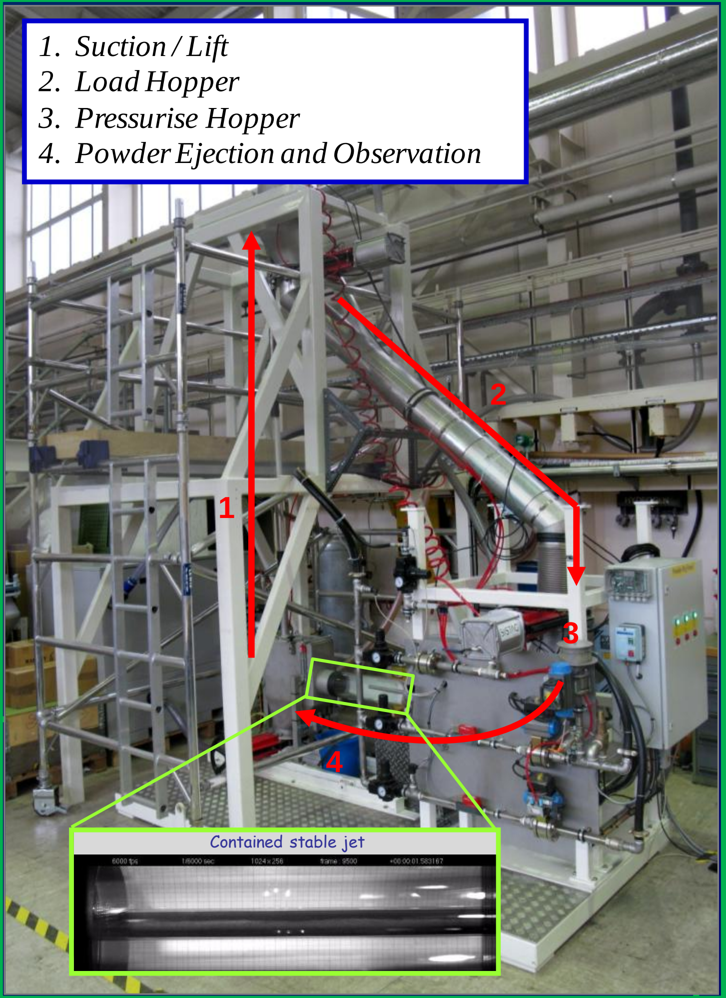


IPAC10: THPEC089,
THPEC091

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



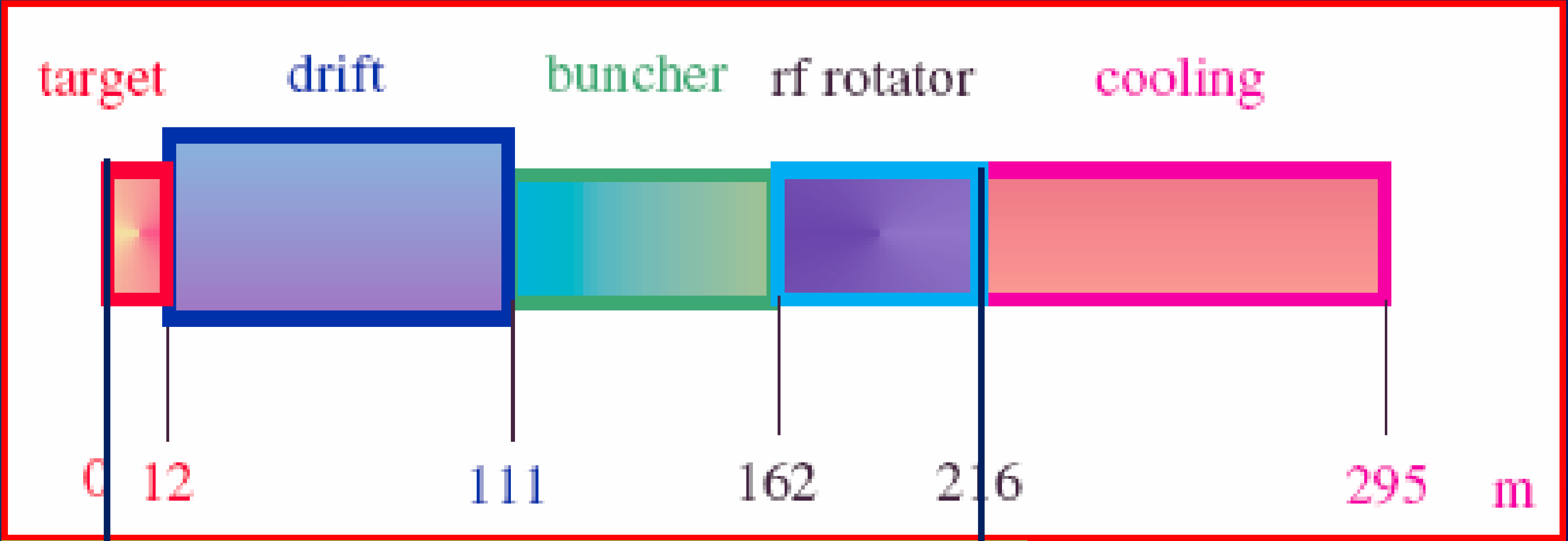


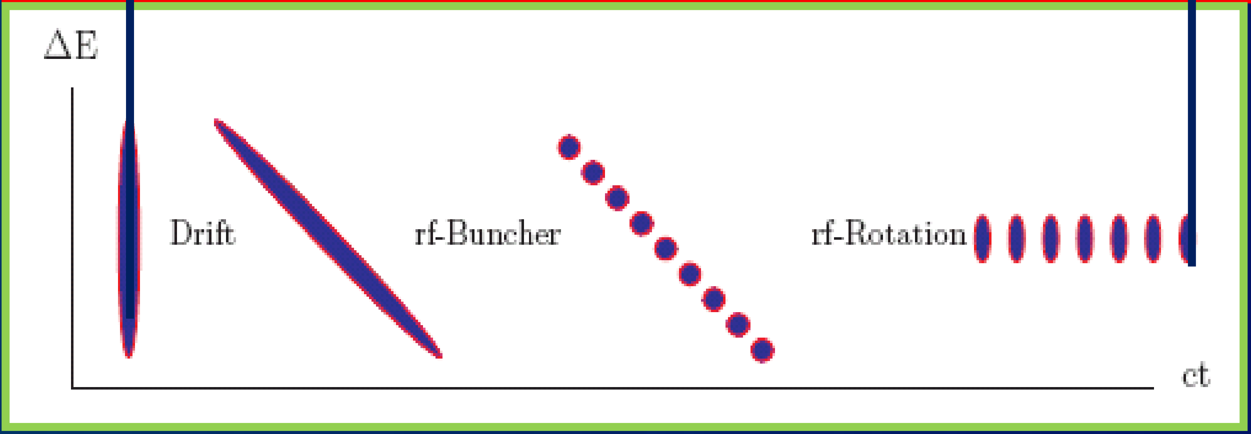
- **Tungsten-powder jet:**
  - (Jet) advantage:
    - Avoids issue of shock
  - (Solid) advantage:
    - Avoids issue of Hg handling
  - ‘Bench-test’ system under evaluation
  - Proof of principal system under consideration

Muon front-end:

IPAC10: WEPE050, WEPE051, WEPE068, WEPE074, WEPE076

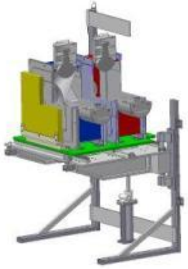
Parameter	***Value***	***Comment***
E-spread after P.R.	10%	Subsequent accel.
Freq. after P.R.	201.25 MHz	
Emittance at exit	7.4 mm rad	Subsequent accel.

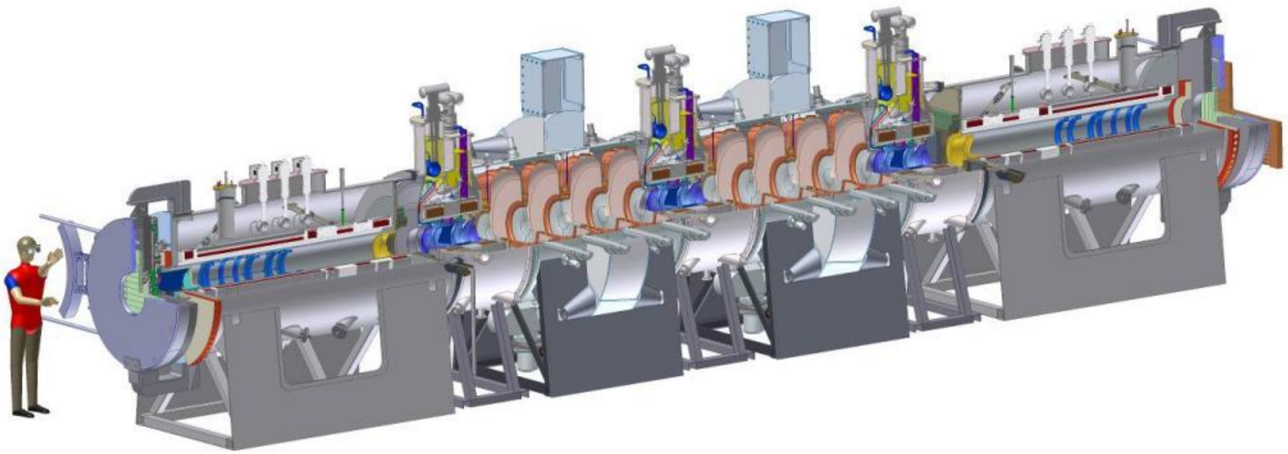


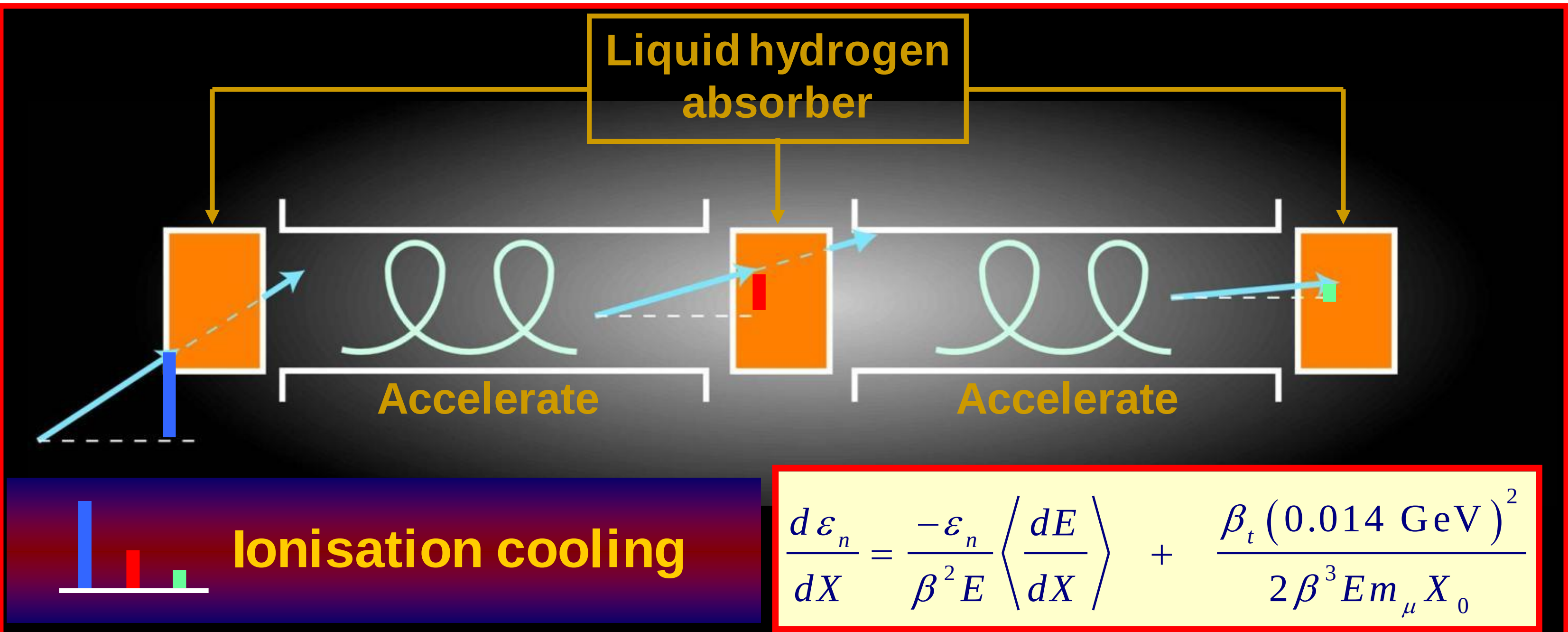


Key R&D:
- Ionisation cooling:
  - MICE; proof of principle
- RF in magnetic field:
  - MuCool: see G.Hanson’s talk

Muon ionisation cooling experiment

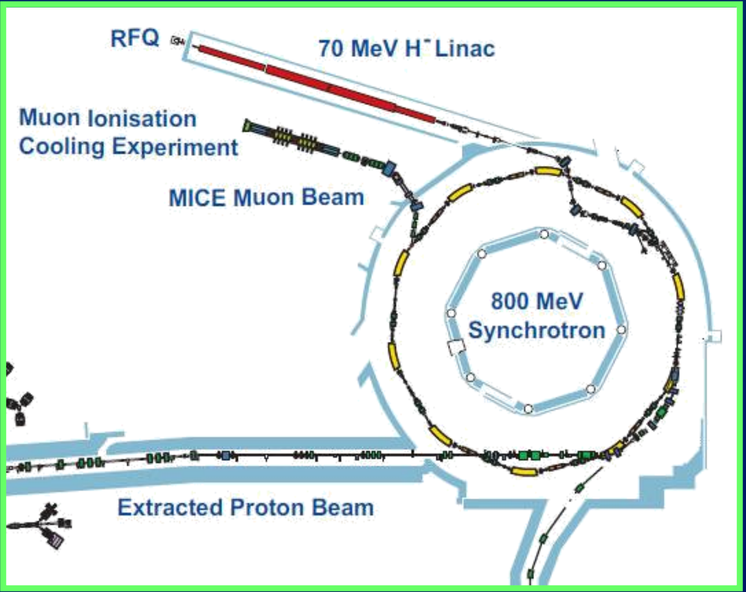






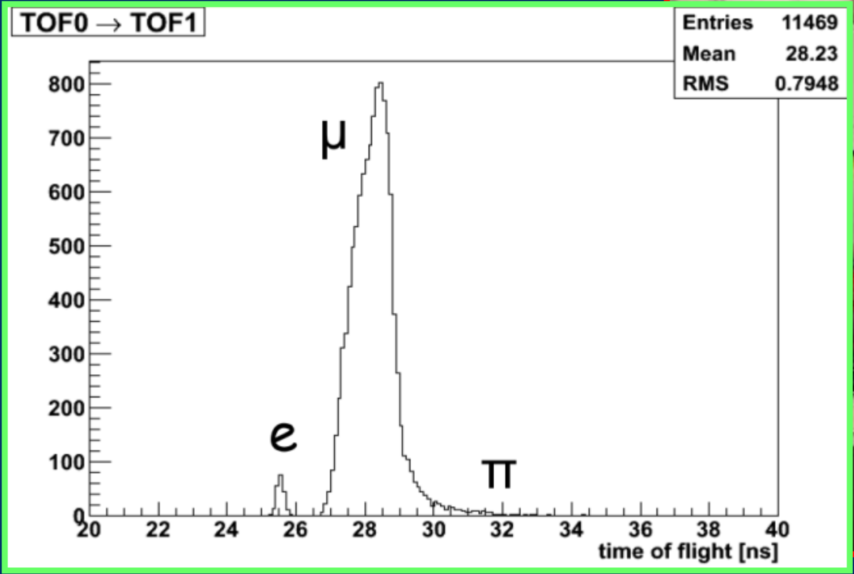
$$\frac{d\varepsilon_n}{dX} = \frac{-\varepsilon_n}{\beta^2 E}\left\langle \frac{dE}{dX} \right\rangle + \frac{\beta_t\left(0.014\ \mathrm{GeV}\right)^2}{2\beta^3 E m_\mu X_0}$$

- **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



Running for first Step well underway!

See Y.Karadzhov, V.Verguilov, and M.Bonesini posters for details



IPAC10: WEPE054

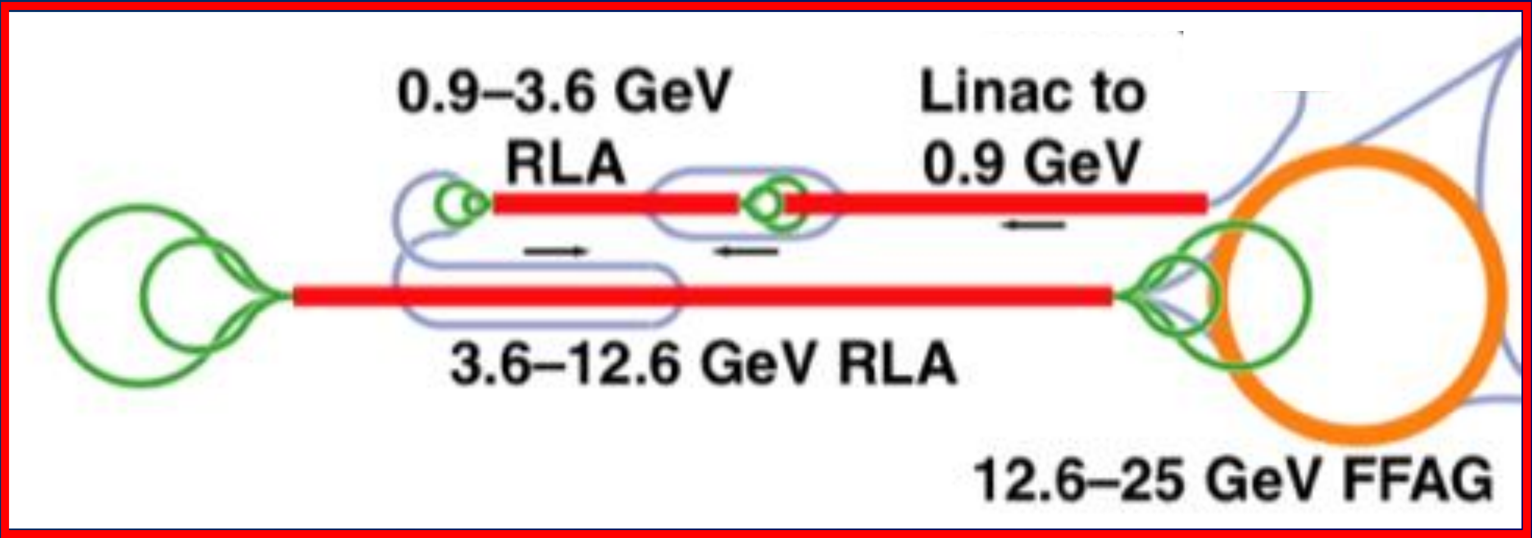
Muon acceleration:

Rapid acceleration!

	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

- **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**

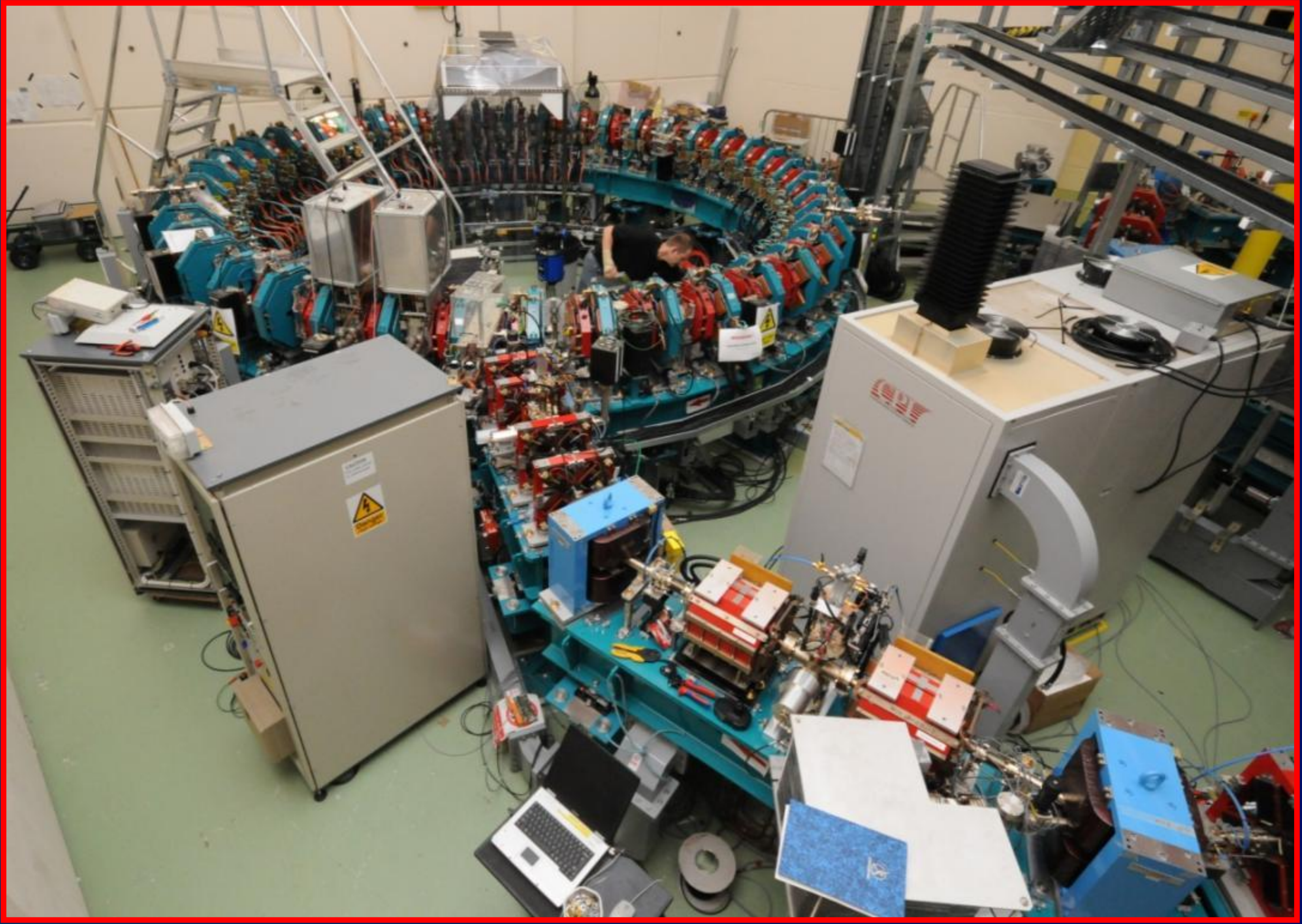


IPAC10: WEPE060, THPEB035,THPE033, THPD093

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

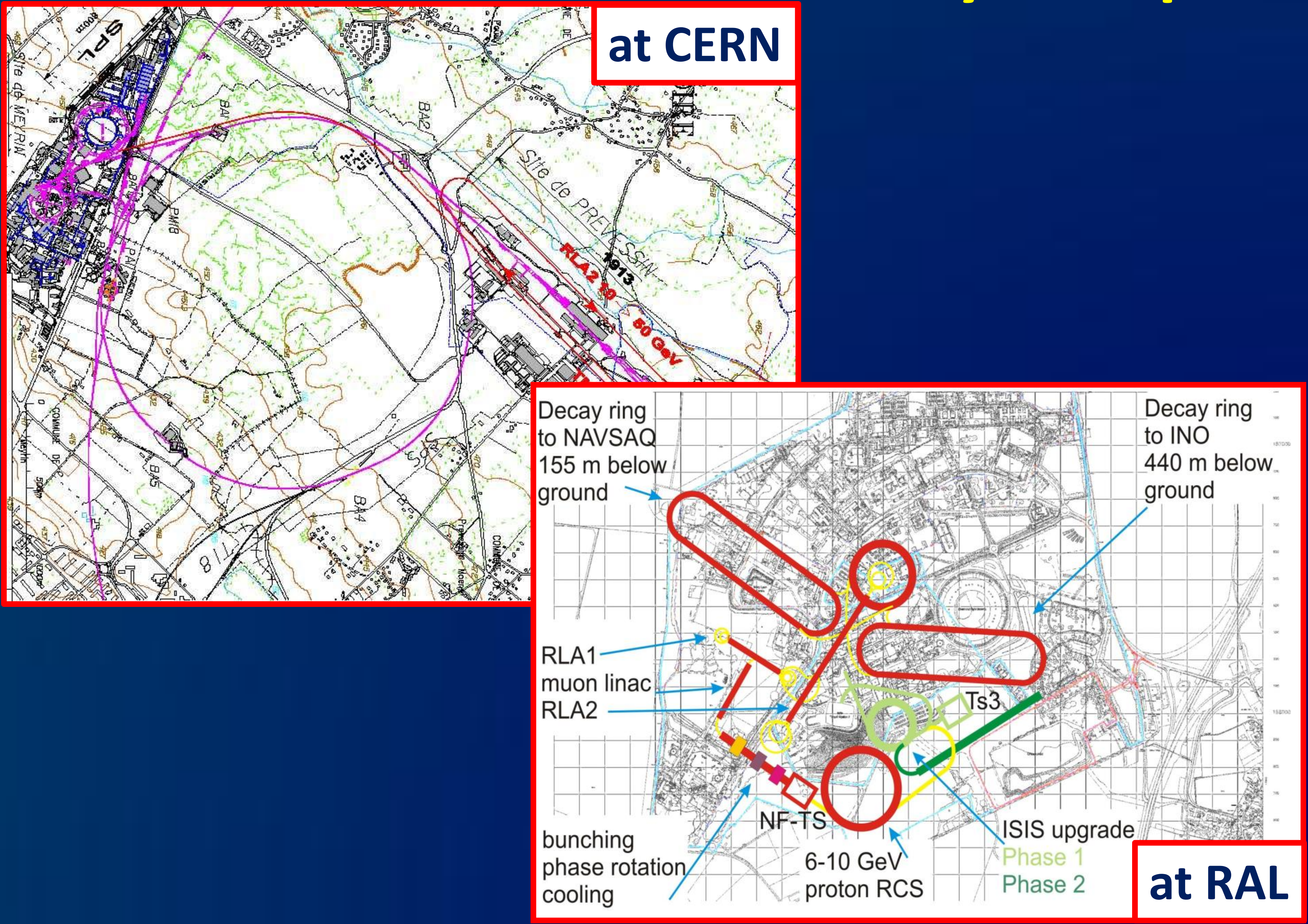


- Installation complete;
- Commissioning of injector system and of associated diagnostics and EMMA ring has started!

Neutrino Factory:

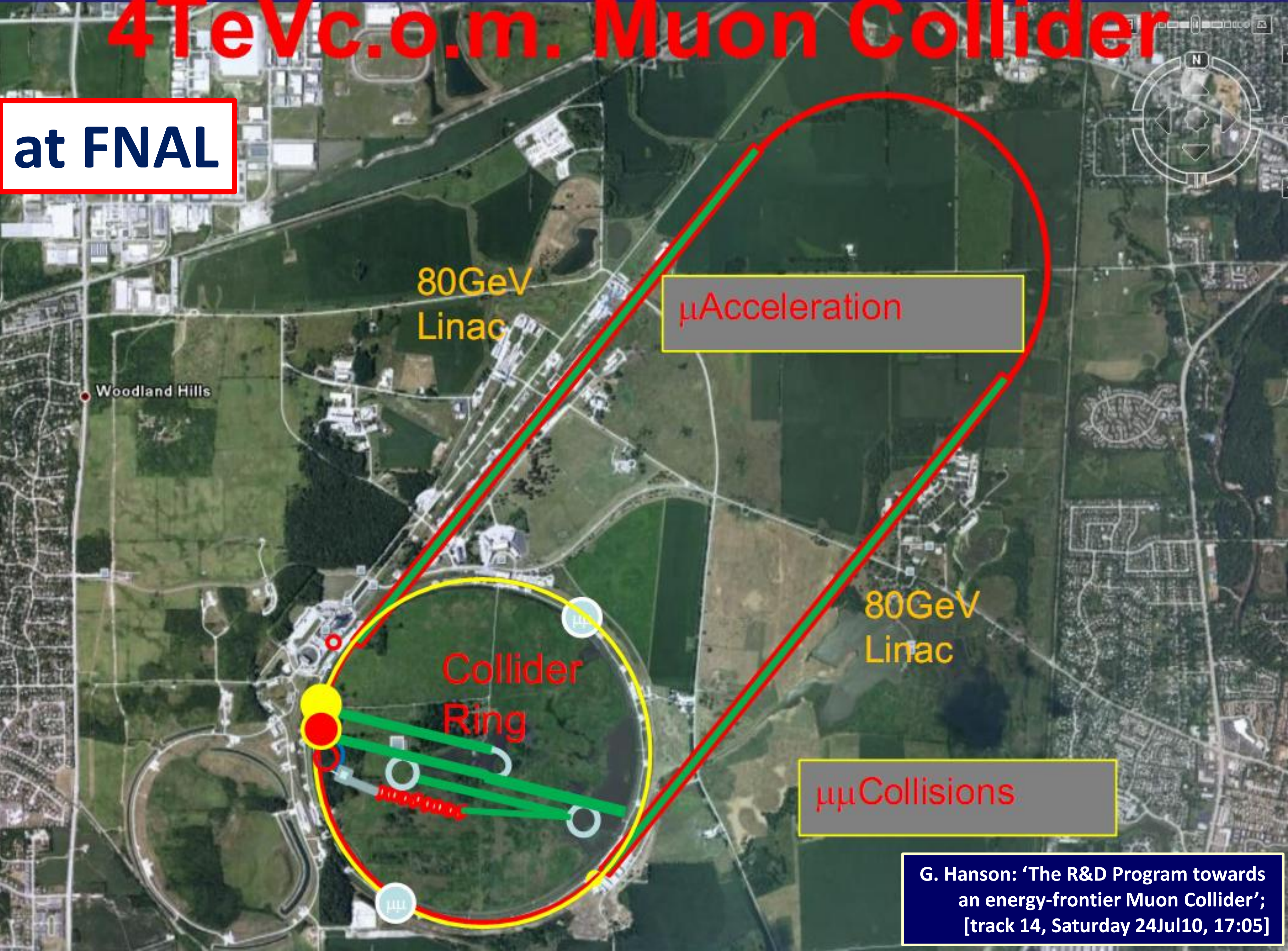
Opportunity and conclusions:

Neutrino Factory: footprint:



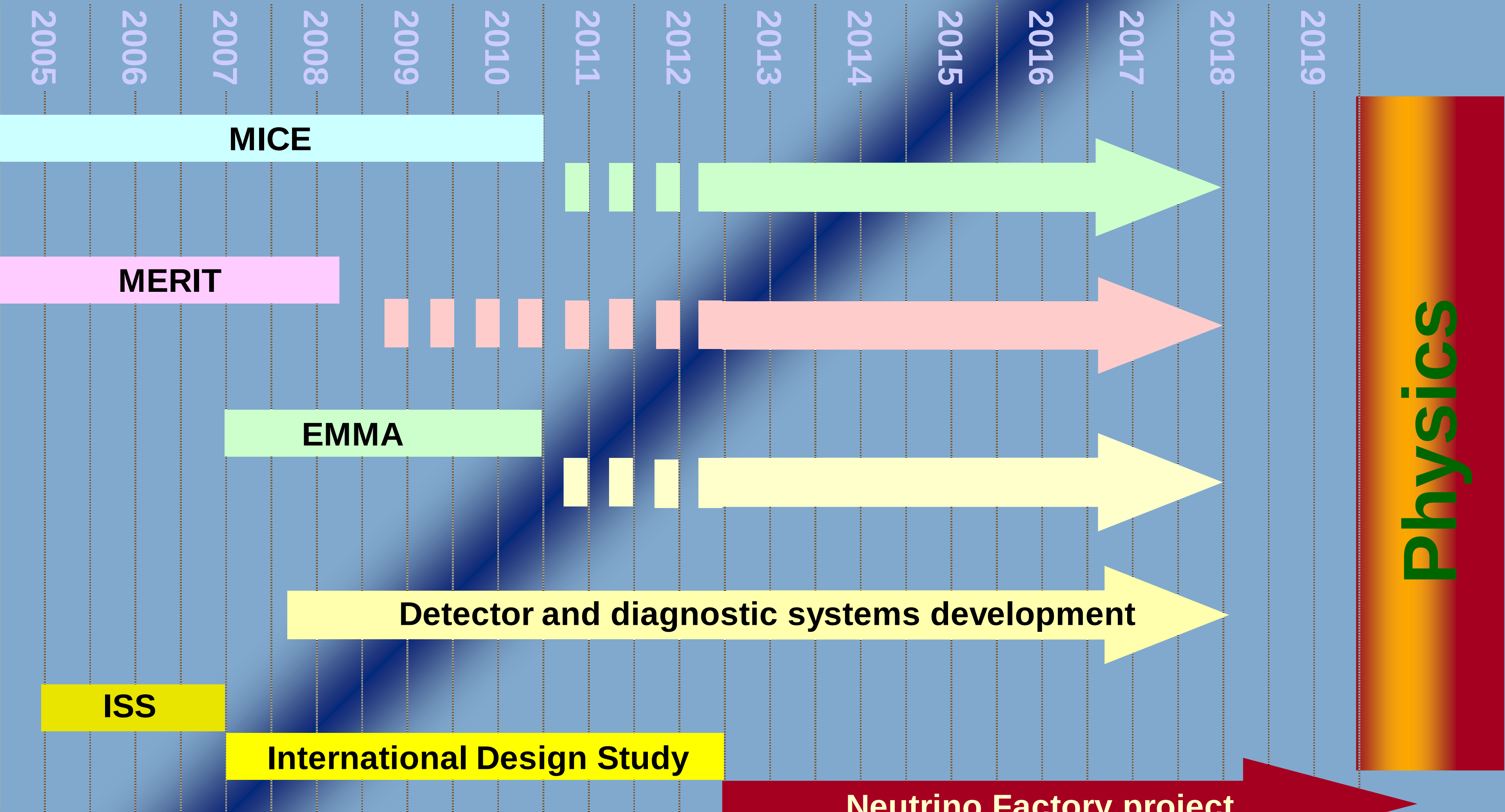
4TeVc.o.m. Muon Collider

at FNAL



G. Hanson: 'The R&D Program towards an energy-frontier Muon Collider'; [track 14, Saturday 24Jul10, 17:05]

Neutrino Factory roadmap



MICE

MERIT

EMMA

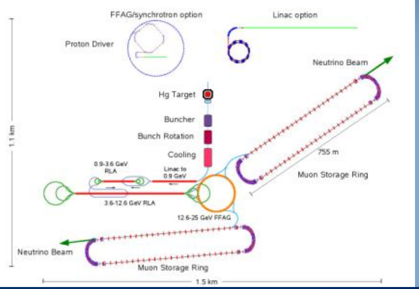
Detector and diagnostic systems development

ISS

International Design Study

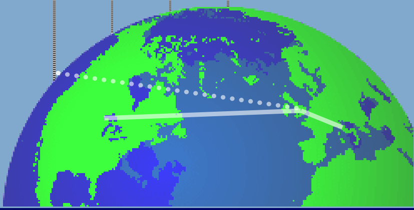
Neutrino Factory project

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!