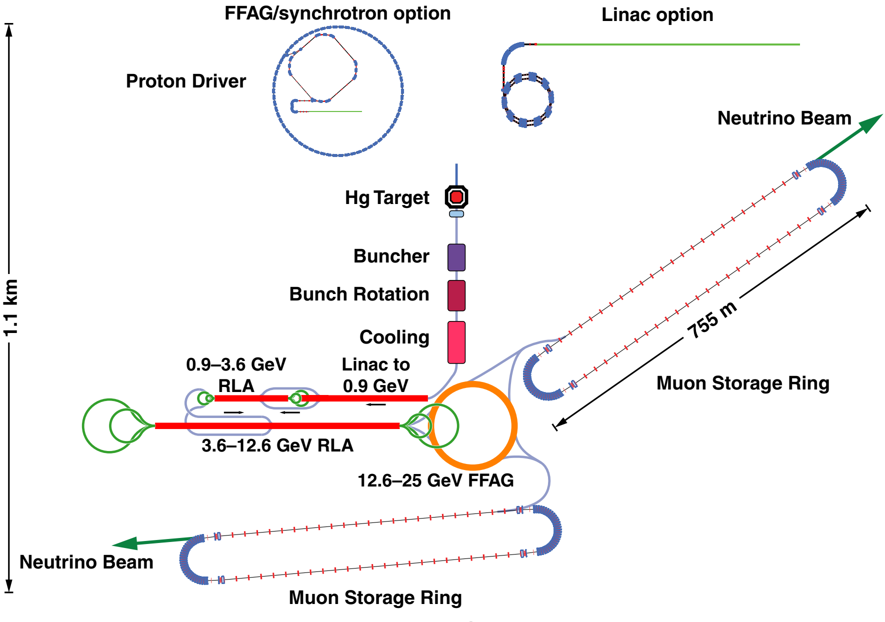
Mauro Mezzetto
Istituto Nazionale di Fisica Nucleare, Sezione di Padova

““Future experiments (III): Neutrino Factories."

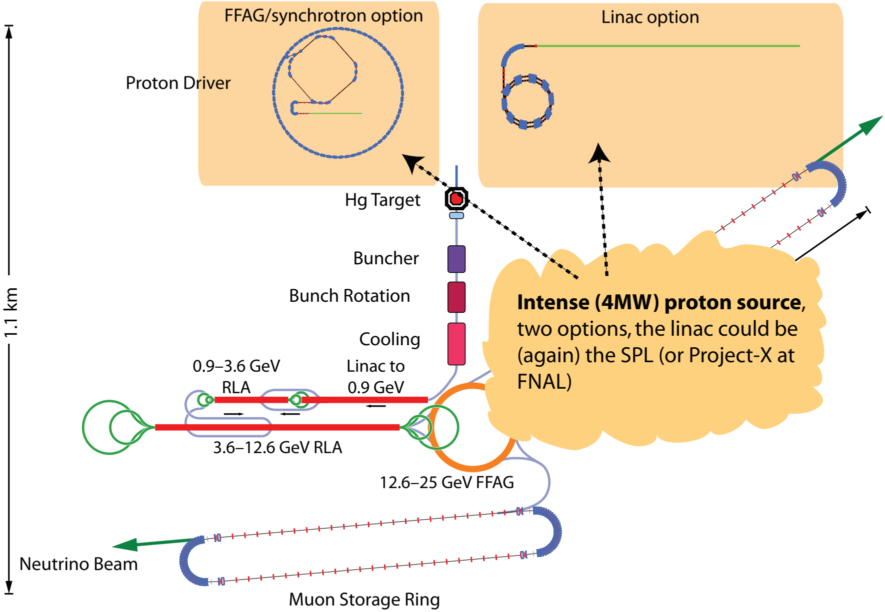
- The machine
- The demonstrators
- The physics
- Comparison among different facilities

I borrowed slides from:
Ken Long talk at Neutrino Telescopes 2011
Steve Geer lesson at INSS 2010
JJ Gomez Cadenas lessons at INSS 2009

Layout of a Neutrino Factory

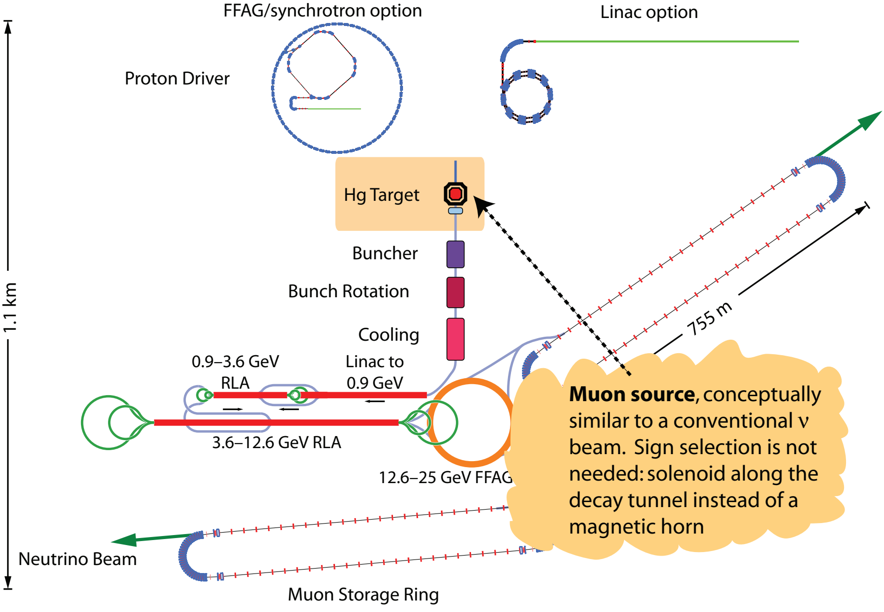


Layout of a Neutrino Factory



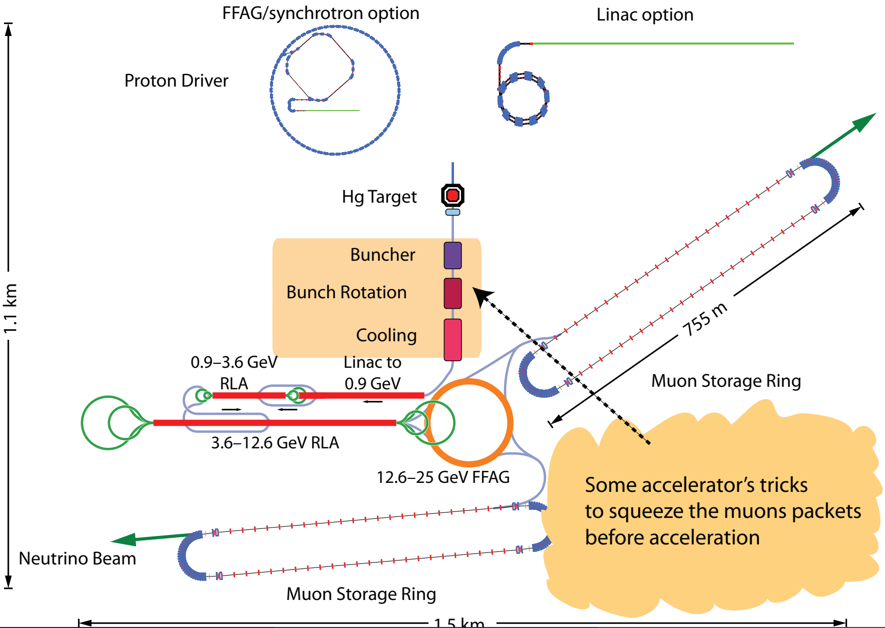
Intense (4MW) proton source, two options, the linac could be (again) the SPL (or Project-X at FNAL)

Layout of a Neutrino Factory



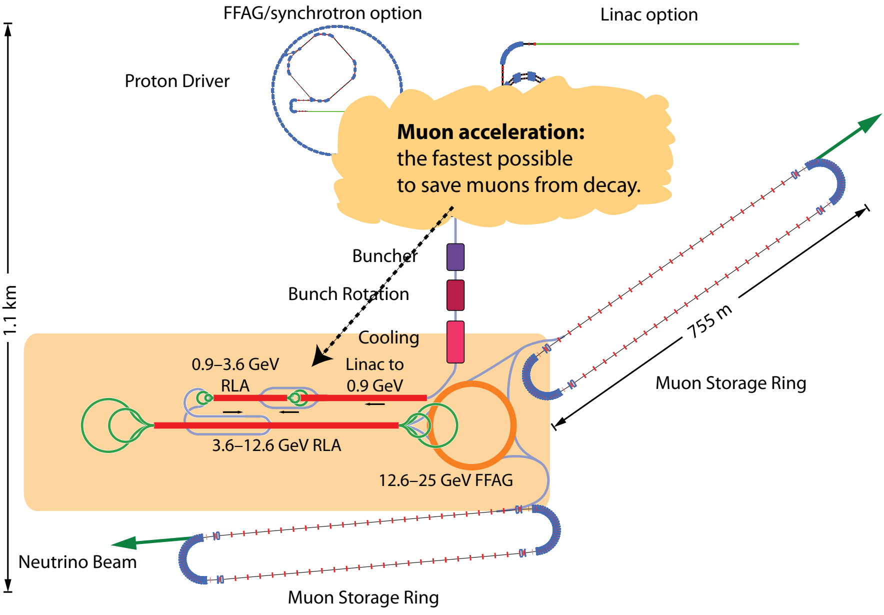
Muon source, conceptually similar to a conventional ν beam. Sign selection is not needed: solenoid along the decay tunnel instead of a magnetic horn

Layout of a Neutrino Factory



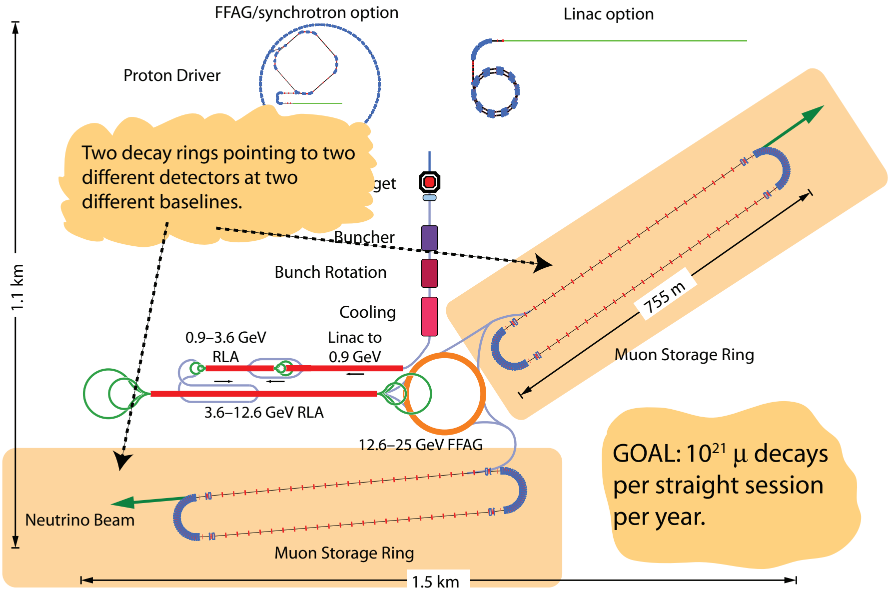
Some accelerator's tricks
to squeeze the muons packets
before acceleration

Layout of a Neutrino Factory



Muon acceleration:
the fastest possible
to save muons from decay.

Layout of a Neutrino Factory

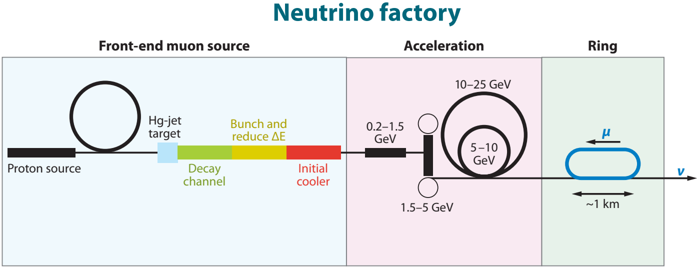


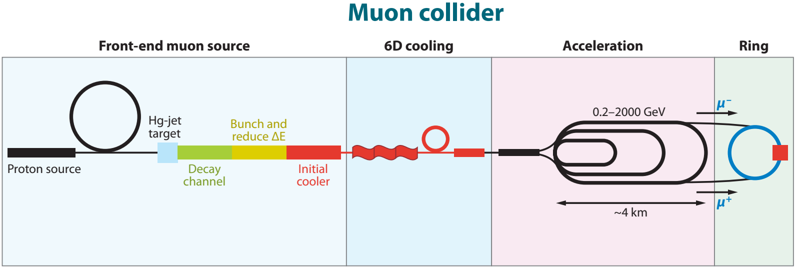
Two decay rings pointing to two different detectors at two different baselines.

GOAL: 10^{21} μ decays per straight session per year.

Neutrino Factory as a first stage of a Muon Collider

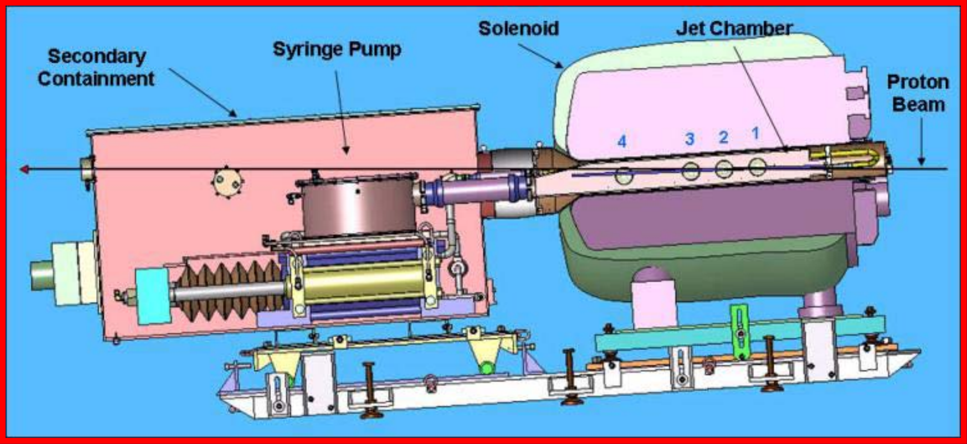
From S. Geer, Ann.Rev.Nucl.Part.Sci.59:347-365,2009.





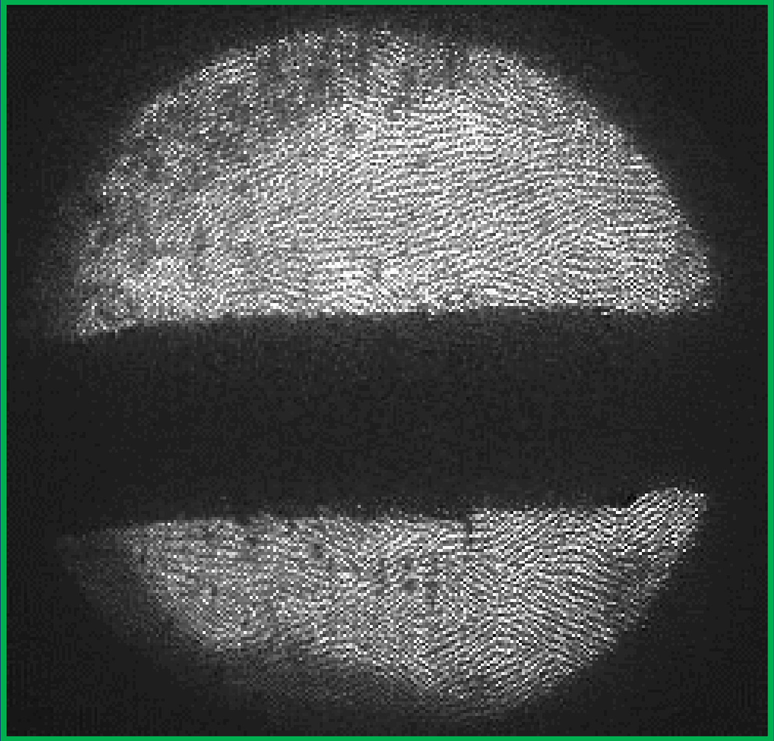
Baseline target: proof of principle: MERIT:

IPAC10: WEPE078



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

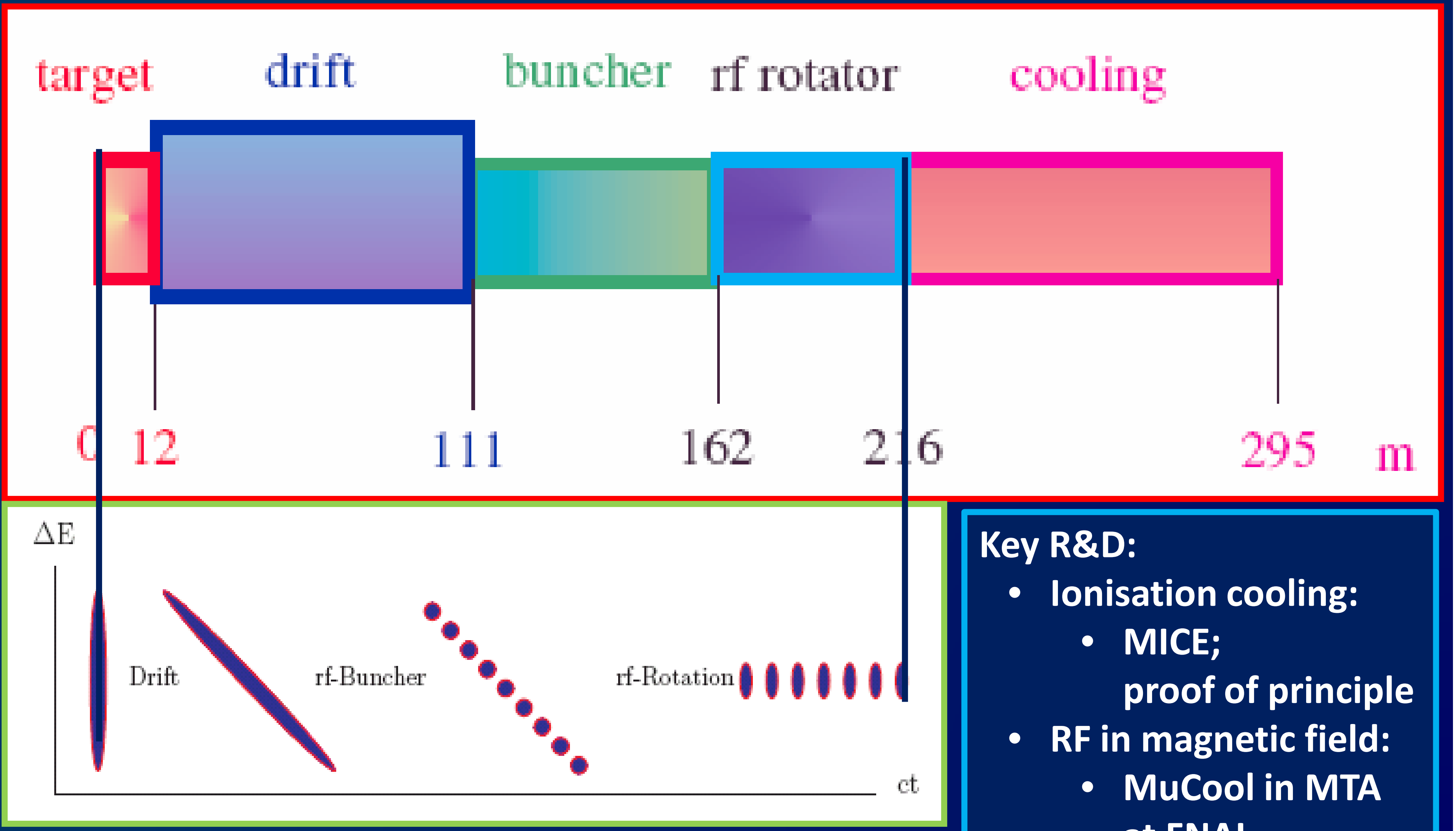
- 20 m/s liquid Hg jet in 15 T B field
- Exposed to CERN PS proton beam:
  - Beam pulse energy = 115 kJ
  - Reached 30 tera protons at 24 GeV



Neuffer, Rogers

Muon front-end:

IPAC10: WEPE050, WEPE051, WEPE068, WEPE074, WEPE076

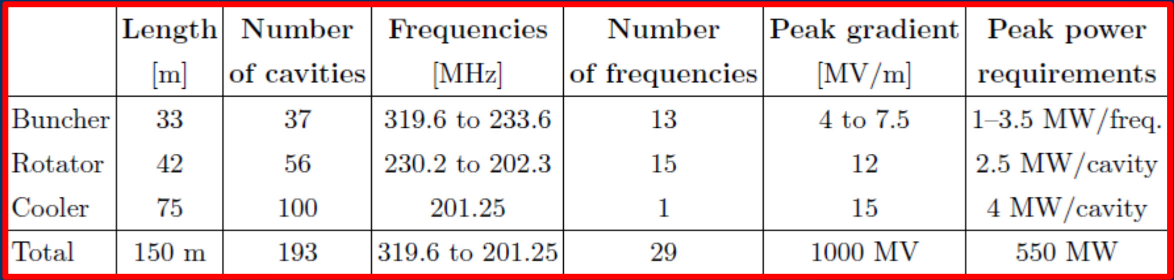


Key R&D:
- Ionisation cooling:
  - MICE;
    proof of principle
- RF in magnetic field:
  - MuCool in MTA
    at FNAL

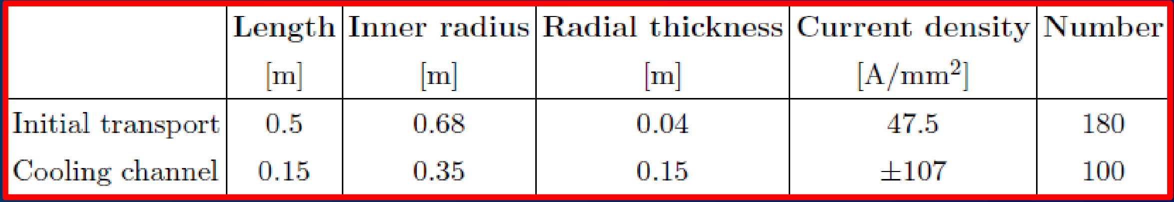
Neuffer, Rogers

Muon front-end:

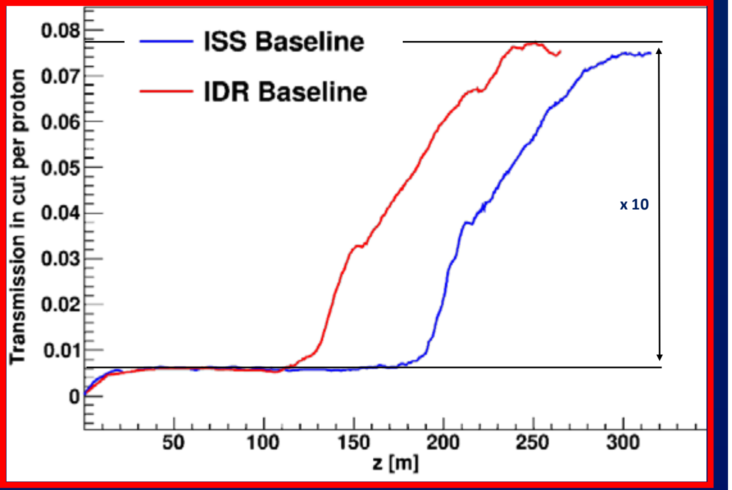
- Optimised bunching, phase-rotator, and ionisation-cooling lattice is reduced

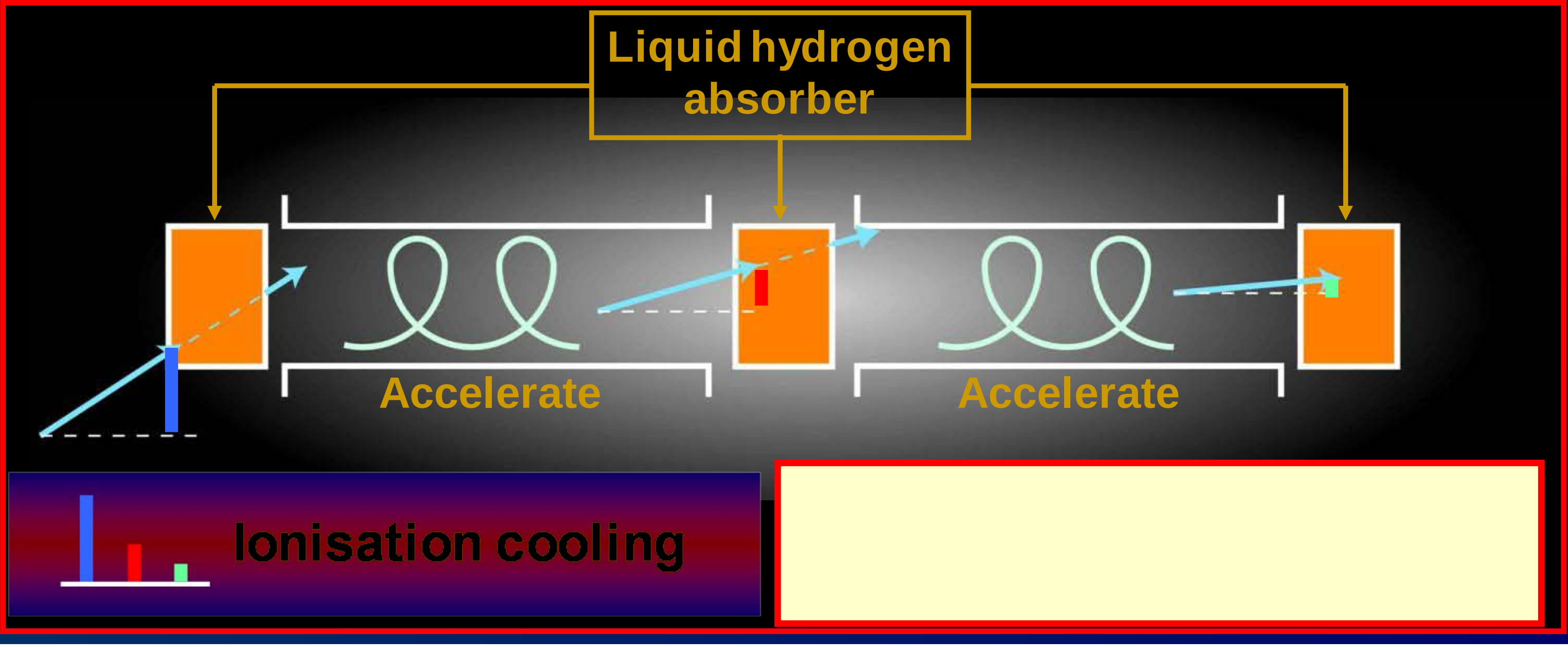


	Length [m]	Number of cavities	Frequencies [MHz]	Number of frequencies	Peak gradient [MV/m]	Peak power requirements
Buncher	33	37	319.6 to 233.6	13	4 to 7.5	1–3.5 MW/freq.
Rotator	42	56	230.2 to 202.3	15	12	2.5 MW/cavity
Cooler	75	100	201.25	1	15	4 MW/cavity
Total	150 m	193	319.6 to 201.25	29	1000 MV	550 MW

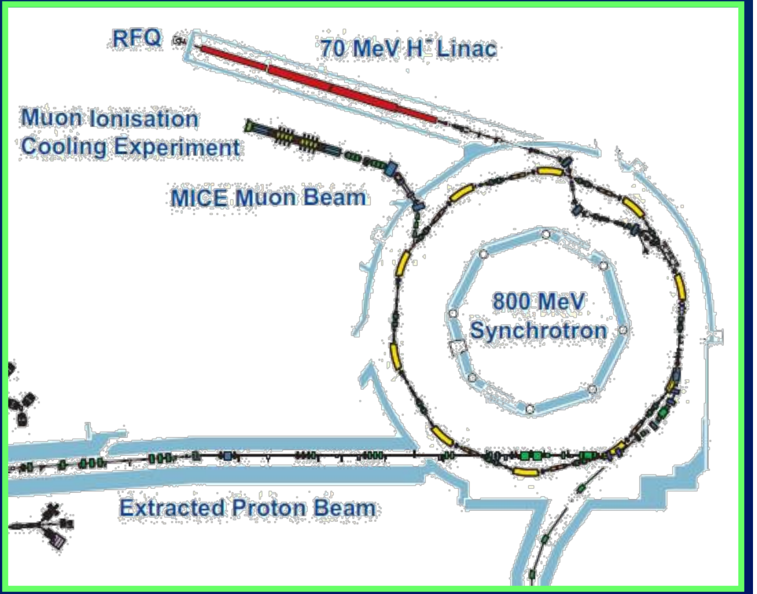


	Length [m]	Inner radius [m]	Radial thickness [m]	Current density [A/mm^2]	Number
Initial transport	0.5	0.68	0.04	47.5	180
Cooling channel	0.15	0.35	0.15	±107	100



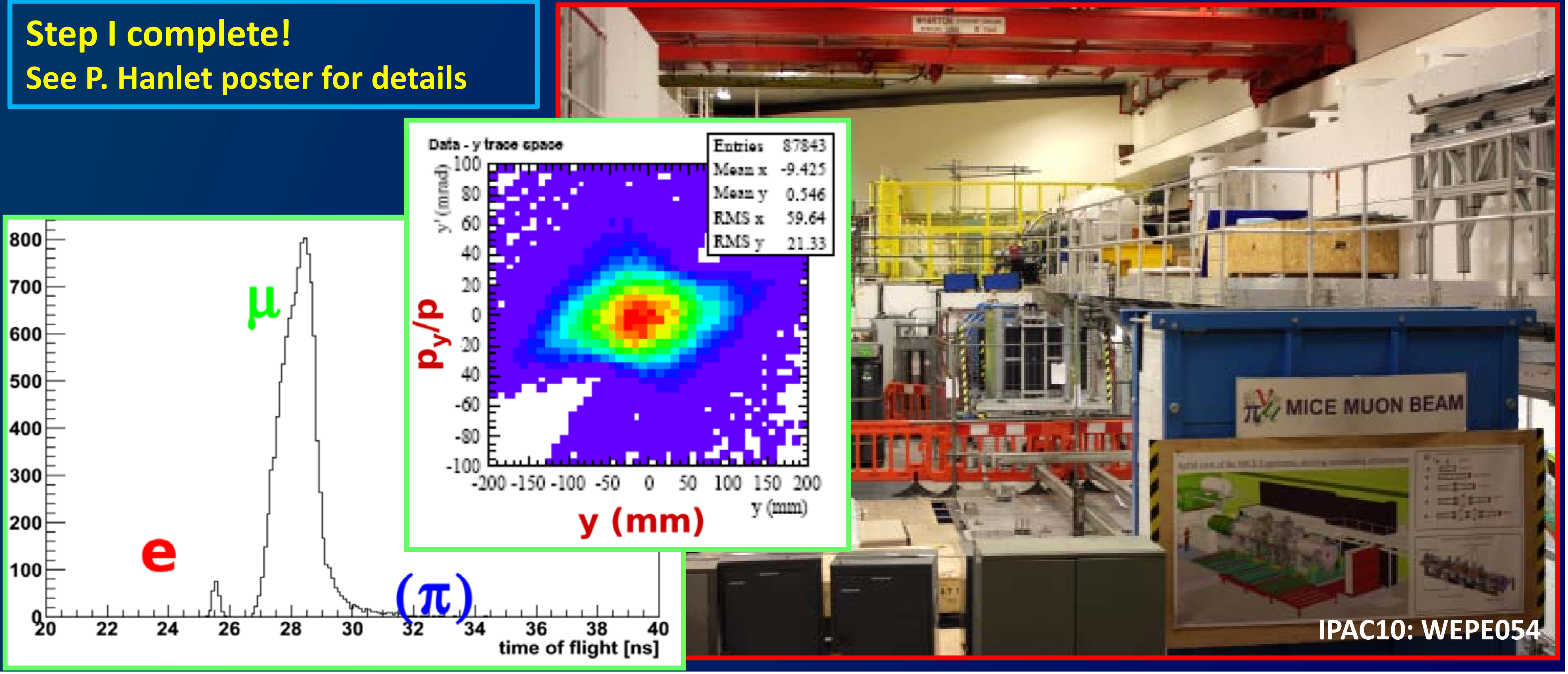


- **MICE: proof of principle:**
  - Design, build, commission and operate a realistic section of cooling channel
  - Measure its performance in a variety of modes of operation and beam conditions
    - Results will allow Neutrino Factory complex to be optimised



Step I complete!

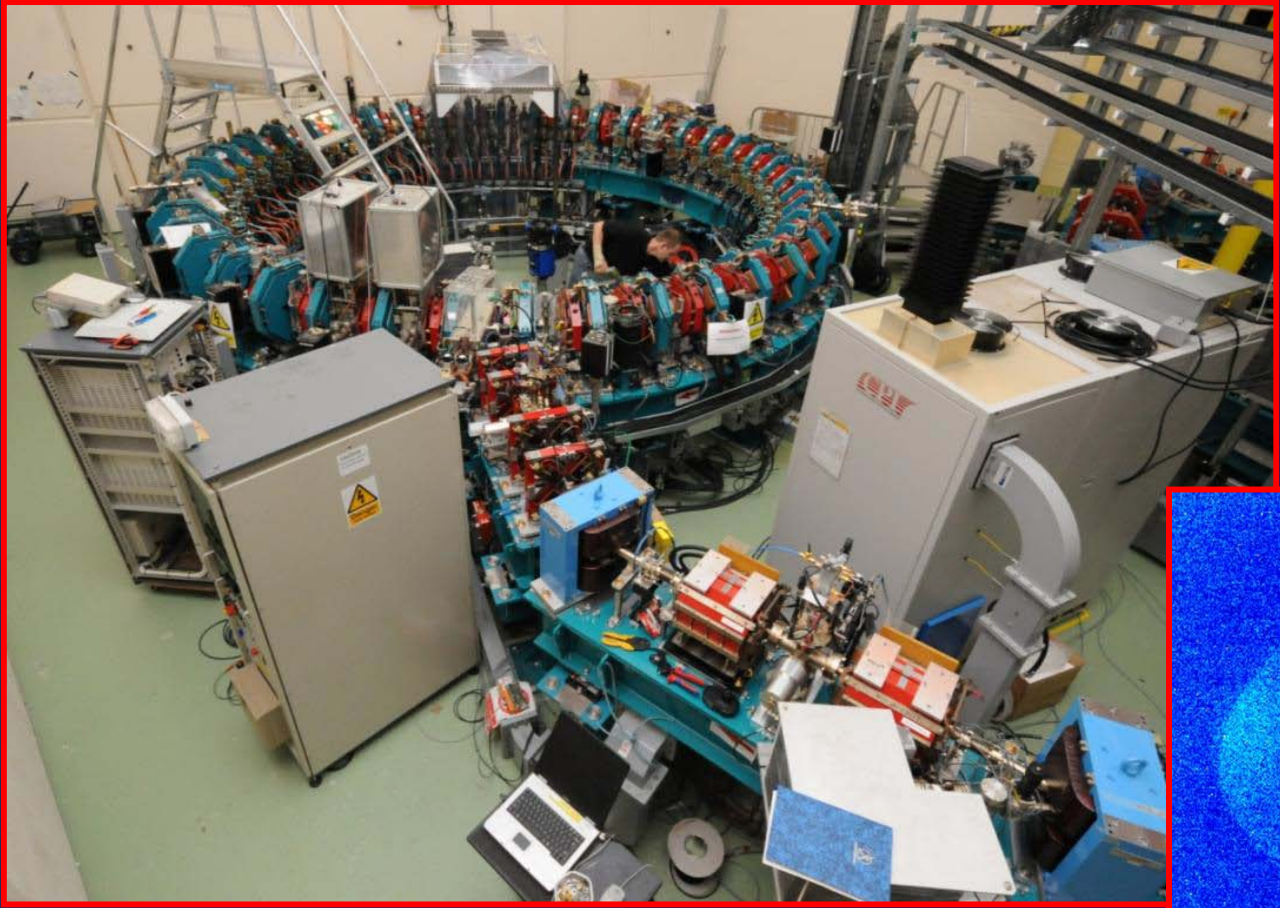
See P. Hanlet poster for details



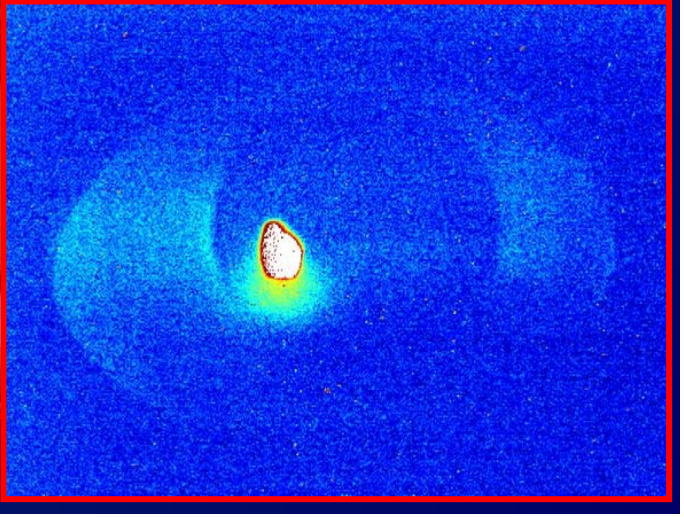
IPAC10: WEPE054

Muon acceleration: proof of principle:

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



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



Beam Properties - 1

- Neutrino Factories produce n beams by storing muons in a ring with long straight sections → O(10^{21}) muon decays/year

- Muon decays produce a beam consisting of 50% $\nu_e(\bar{\nu}_e)$ & 50% $\bar{\nu}_\mu(\nu_\mu)$

$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu \Rightarrow 50\% \nu_e + 50\% \bar{\nu}_\mu$$

$$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu \Rightarrow 50\% \bar{\nu}_e + 50\% \nu_\mu$$

- Advantages c.f. conventional neutrino beams:

- well known beam flux & spectra (low systematic uncertainties)

- can search for $\nu_e \rightarrow \nu_\mu$ oscillations with very low backgrounds (wrong-sign muon signature)

- can measure spectra for events tagged by right-sign muons, wrong-sign muons, electrons, τ^+, τ^-, or no leptons; and do all this when there are positive muons stored and when there are negative muons stored → a wealth of information.

Beam Properties - 2

Consider an ensemble of negatively charged muons. In the muon rest-frame:

$$\nu_\mu : \quad \frac{d^2N}{dx\; d\Omega_{cm}} \propto \frac{2x^2}{4\pi} \left[(3-2x) + (1-2x)\, P \cos\theta_{cm} \right]$$

$$\bar{\nu}_e : \quad \frac{d^2N}{dx\; d\Omega_{cm}} \propto \frac{12x^2}{4\pi} \left[(1-x) + (1-x)\, P \cos\theta_{cm} \right]$$

For μ^+ decays
$P \rightarrow -P$

$x = 2E_\nu/m_\mu$, θ is angle between the neutrino & muon spin, P is muon polarization.

In the lab frame & forward direction ($\cos\theta_{lab} \sim 1$), $E_\nu = xE_{max} = x\,\gamma(1+\beta\cos\theta_{cm})\, m_\mu/2$,

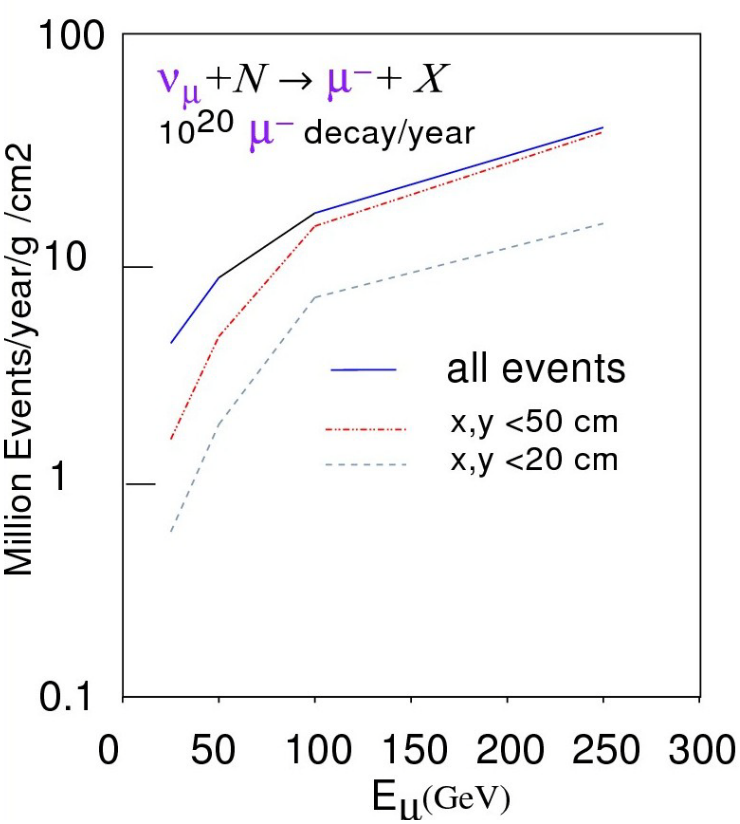
$$\nu_\mu : \quad \frac{d^2N}{dx\; d\Omega_{lab}} \propto \frac{1}{\gamma^2 (1-\beta\cos\theta_{lab})^2} \frac{2x^2}{4\pi} \left[(3-2x) + (1-2x)\, P \cos\theta_{cm} \right]$$

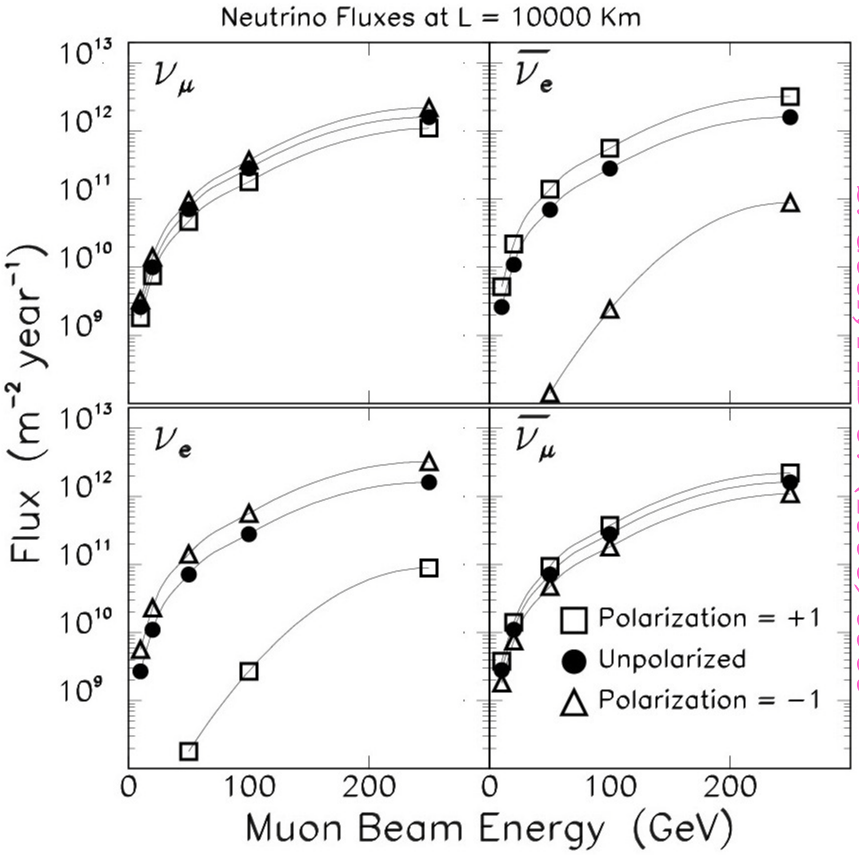
$$\bar{\nu}_e : \quad \frac{d^2N}{dx\; d\Omega_{lab}} \propto \frac{1}{\gamma^2 (1-\beta\cos\theta_{lab})^2} \frac{12x^2}{4\pi} \left[(1-x) + (1-x)\, P \cos\theta_{cm} \right]$$

Note that polarization can, in principle, be used to switch on/off the ν_e ($\bar{\nu}_e$) flux.

Beam Properties - 3

The neutrino flux provided by a Neutrino Factory is sufficient to produce millions of events/g in a near detector, and thousands of events/yr in a few kt detector on the other side of the Earth.





S. Geer, PRD 57 (1998) 6989

Key Experimental Signature

- The primary motivation for interest in neutrino factories is that they provide electron neutrinos (antineutrinos) in addition to muon anti-neutrinos (neutrinos). This enables a sensitive search for $\nu_e \rightarrow \nu_\mu$ oscillations.

$$\begin{tikzcd}
\mu^+ \arrow[r] & e^+ \, \nu_e \, \bar{\nu}_\mu \arrow[r, "\mathrm{CC}"] \arrow[d] & \mu^+ \\
& \nu_\mu \arrow[r, "\mathrm{CC}"'] & \mu^-
\end{tikzcd}$$

$\nu_e \rightarrow \nu_\mu$ oscillations at a neutrino factory result in appearance of a "wrong-sign" muon … one with opposite charge to those stored in the ring:

- Backgrounds to the detection of a wrong-sign muon are expected to be at the 10^{-4} level ⟶ background-free $\nu_e \rightarrow \nu_\mu$ oscillations with probabilities of $O(10^{-4})$ can be measured !

Oscillation Channels at a Neutrino Factory

μ^- (μ^+) decay in (ν_μ, $\overline{\nu}_e$) (($\overline{\nu}_\mu$, ν_e)).

Golden channel: search for $\nu_e \to \nu_\mu$ ($\overline{\nu}_e \to \overline{\nu}_\mu$) transitions by detecting wrong sign muons.
Default detector: 40-100 kton iron magnetized calorimeter (Minos like)

Silver channel: search for $\nu_e \to \nu_\tau$ transitions by detecting ν_τ appearance.
Ideal detectors: 4× Opera or 20 Kton LAr detector.

Oscillation Channels at a Neutrino Factory

Channel	μ charge	e charge	τ detection
$\overline{\nu}_\mu \rightarrow \overline{\nu}_e$		OK	
$\overline{\nu}_\mu \rightarrow \overline{\nu}_\mu$	OK		
$\overline{\nu}_\mu \rightarrow \overline{\nu}_\tau$			OK
$\nu_e \rightarrow \nu_e$	~OK	OK	
$\nu_e \rightarrow \nu_\mu$	OK		
$\nu_e \rightarrow \nu_\tau$			OK
	atmospherics θ_{13} CPV		degeneracies NSI

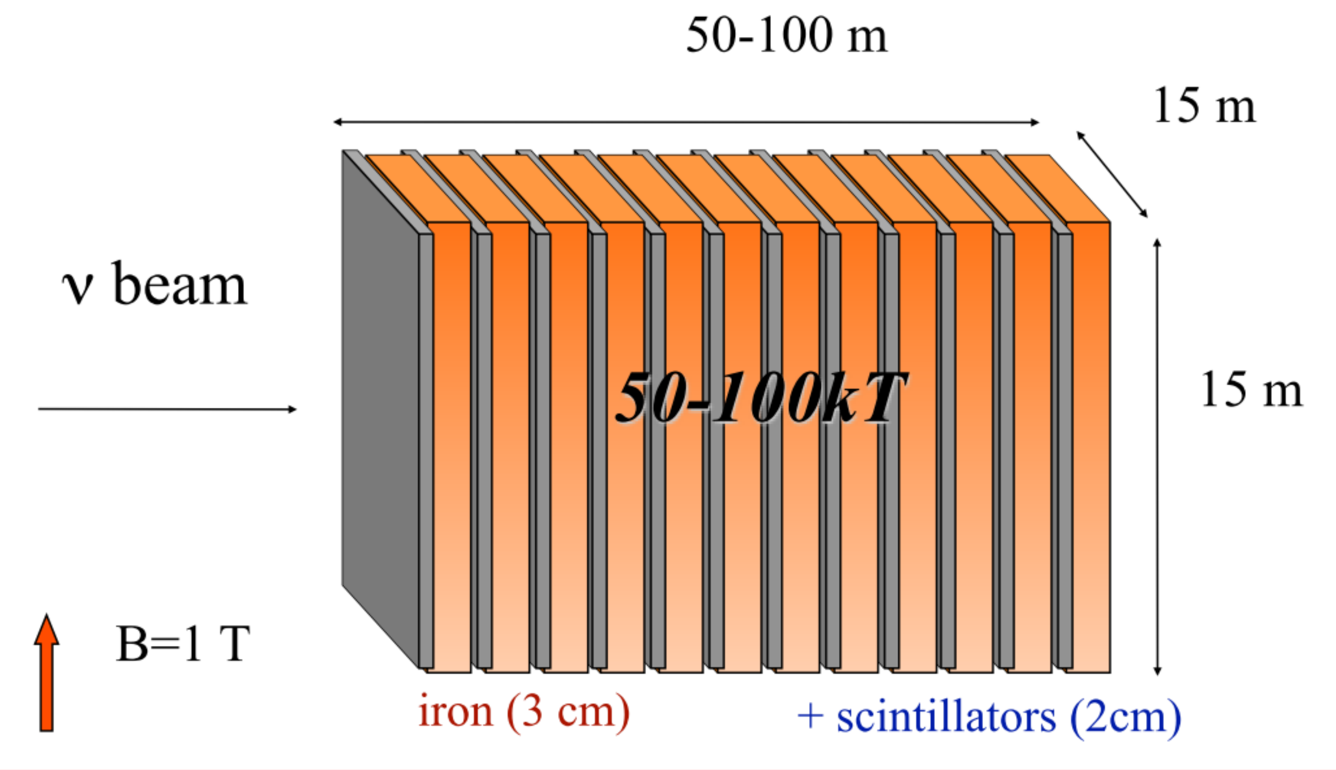
Most of the physics is done by the $\nu_\mu$channel, but from an ultimate facility you would also like to have

- Full control of degeneracies
- Unitarity of the mixing matrix
- Redundance, cross checks and surprises
- CPT
- NSI

Magnetised Iron Neutrino Detector (MIND):

Cervera, Laing,
Martin-Albo, Soler

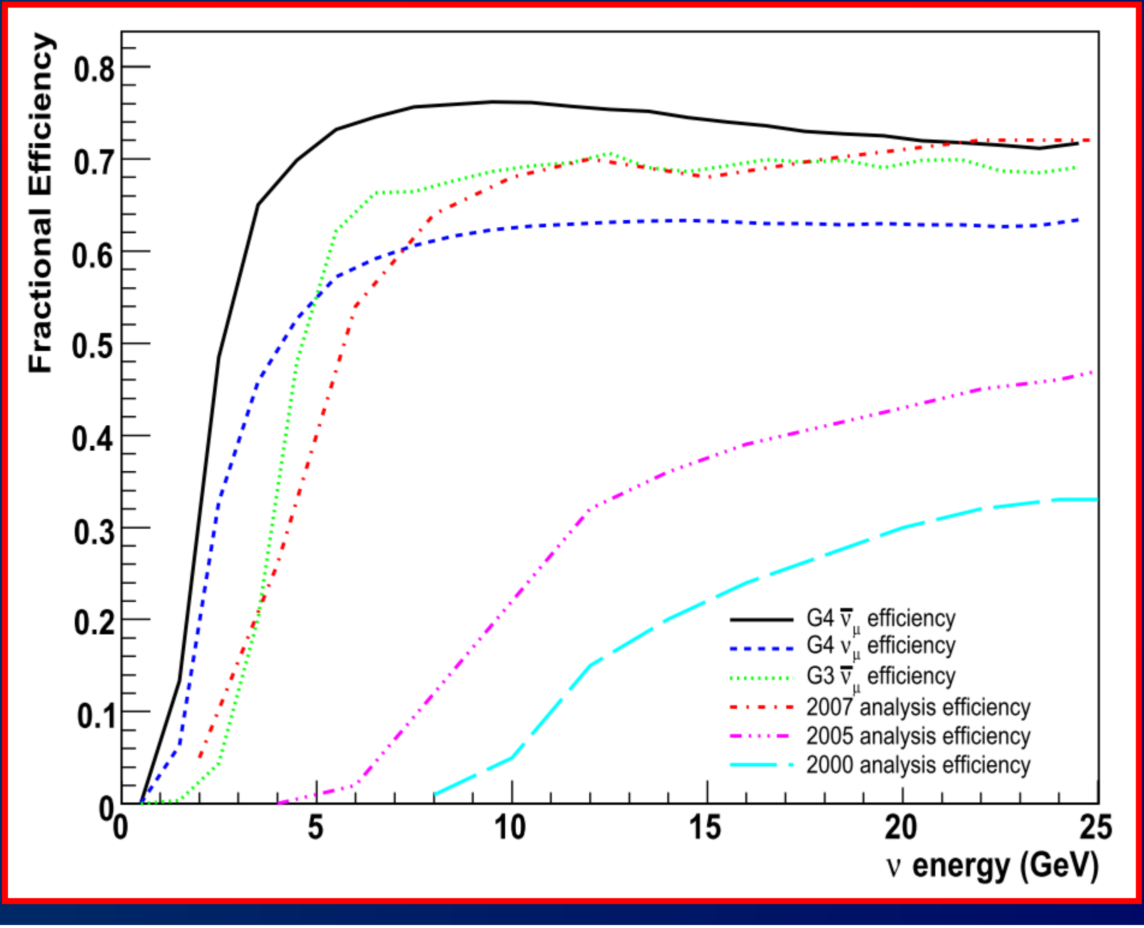
- MIND:
  - Re-optimised sampling: Fe/Sci = 3 cm/2 cm
  - Cuboid immersed in 1 T dipole field
    - More realistic field configuration in hand
  - Detector mass:
    - Intermediate detector [2000—4000 km]: 100 kT
    - Far detector [7000—8000 km]: 50 kT



Cervera, Laing,
Martin-Albo, Soler

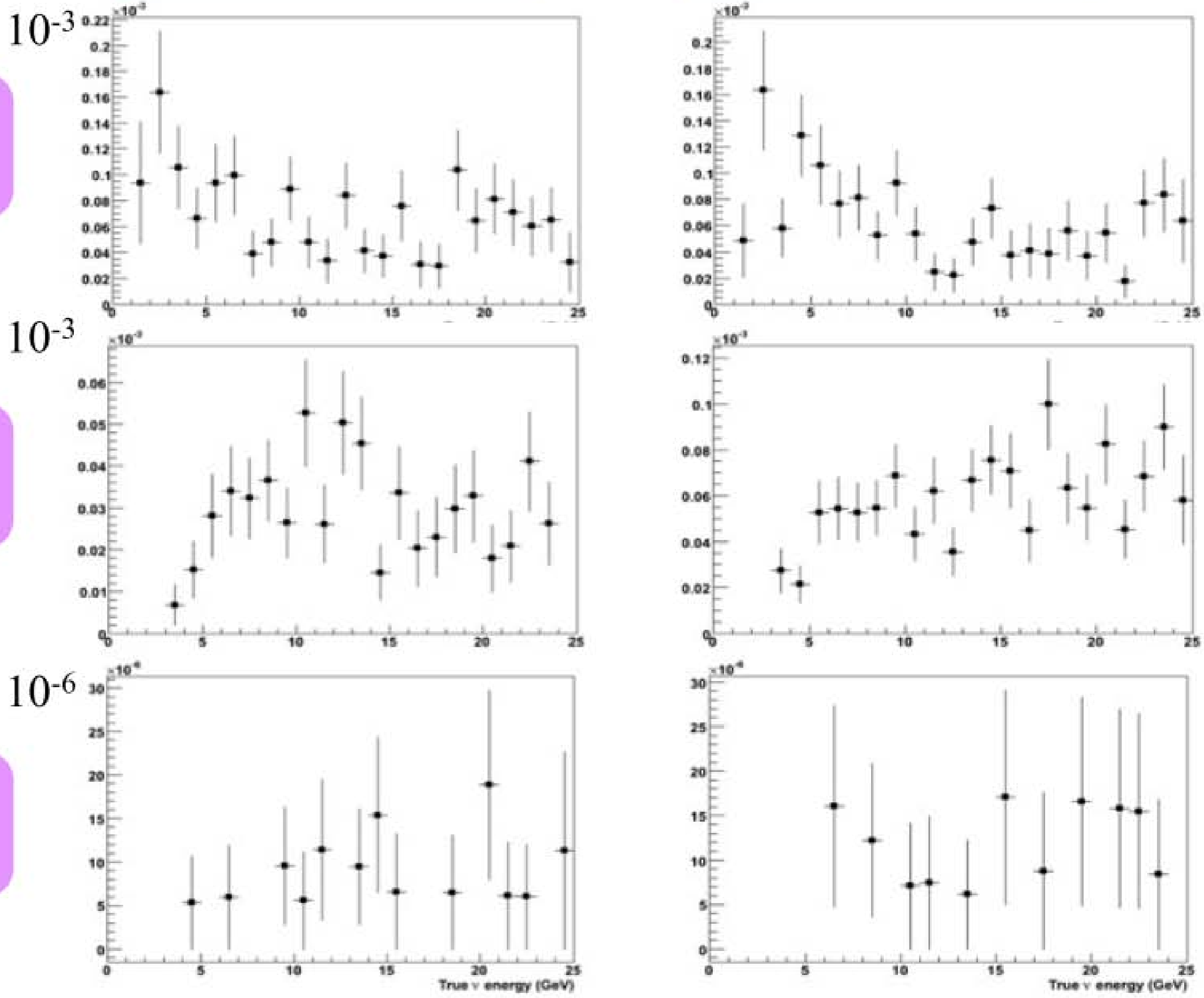
MIND: efficiency:

- Threshold: 50% of plateau at ~2.25 GeV
  - Improved by more than 2 GeV compared to start of IDS-NF [i.e. ISS Detector W/g report]



Cervera, Laing,
Martin-Albo, Soler

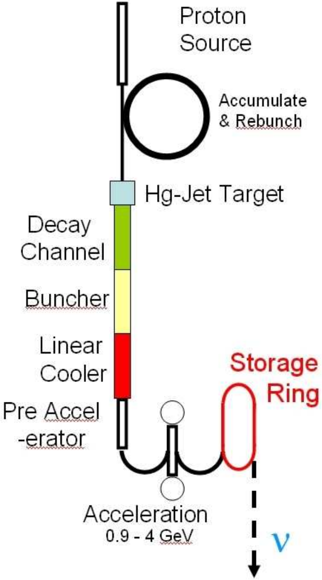
MIND: background rejection:



	μ⁻ appearance	μ⁺ appearance	
ν_μ CC			$\sim10^{-4}$
NC			$<10^{-4}$
ν_e CC			$\sim10^{-5}$

Overview of the low energy neutrino factory

- Create an intense source of $\mu^{\pm}$.
- Cool the $\mu^{\pm} \Rightarrow$ 70% increase in flux.
- Accelerate them to energies of $E_{\mu} \sim 5$ GeV.
- Inject into a storage ring where the muons decay: $\mu^{\pm} \rightarrow e^{\pm}\nu_e(\bar{\nu}_e)\bar{\nu}_{\mu}(\nu_{\mu})$
- Detect the neutrinos at a baseline of 1300 km (FNAL to DUSEL).

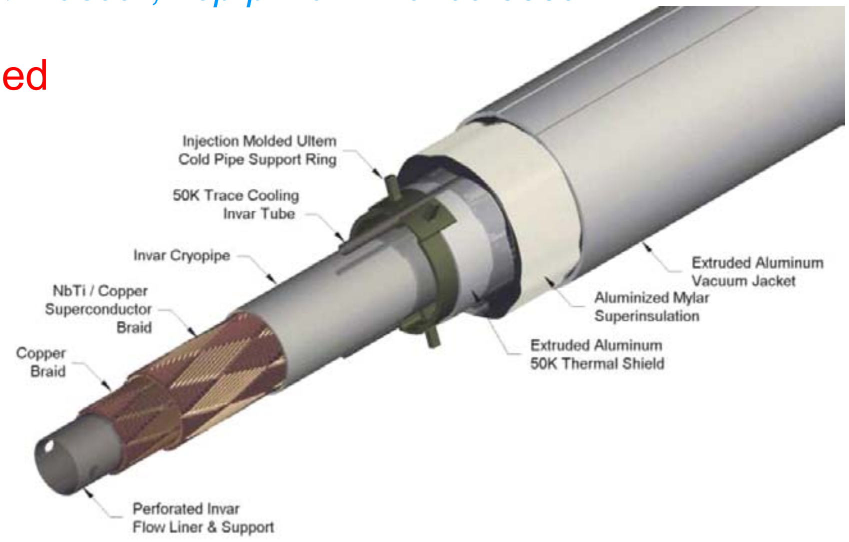


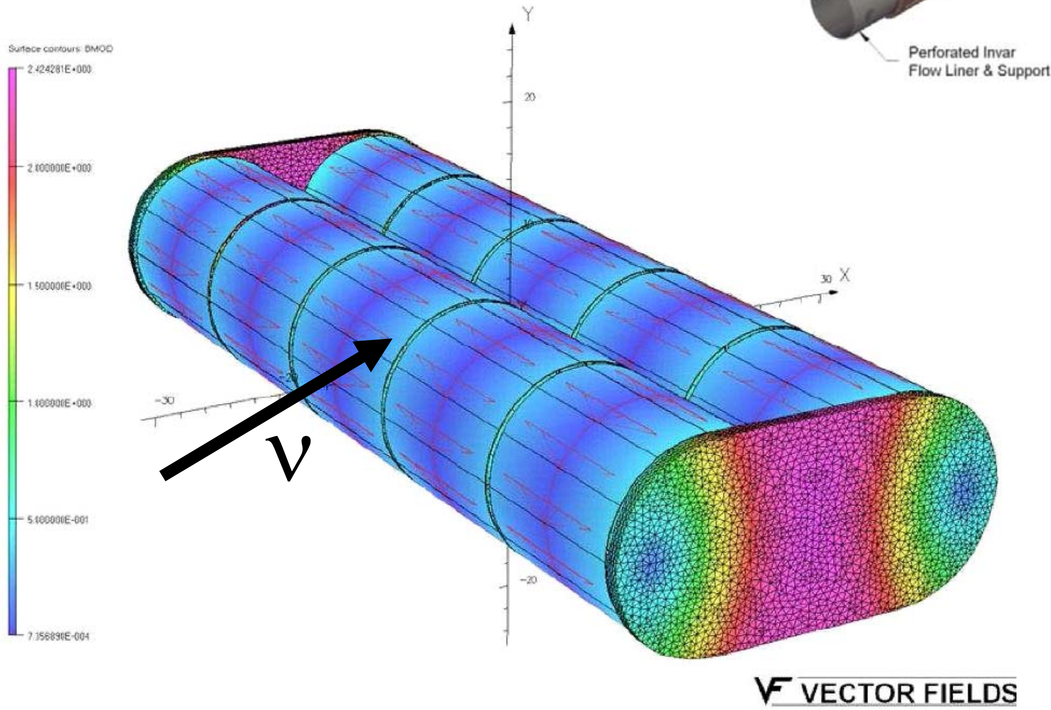
[A. Bross]

A Magnetic Hall for Large Neutrino Detectors

Bross, Ellis, Geer, Mena,& Pascoli, hep-ph arXiv:0709.3889

If we want to use a low Z detector, we need an affordable way to magnetize a large volume → Eliminate large (expensive) cryostat & vac loads by using superconducting transmission line concept developed for the VLHC – wrap it into a solenoid !

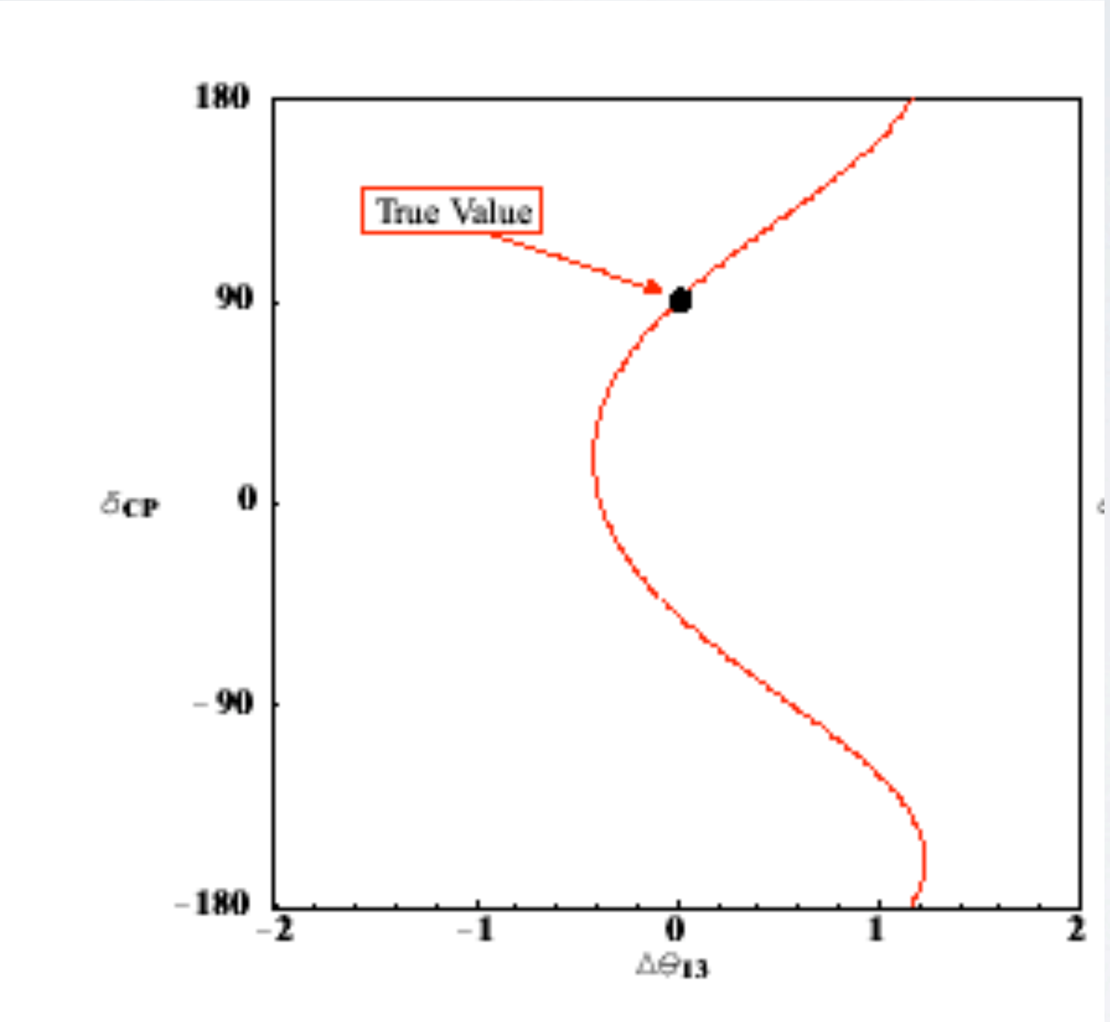




Build a magnetic cavern !

Example:
Build 10 solenoids, each 150 turns, 7.5km cable, I = 50kA, and 1m thick iron end-walls

DEGENERATE PHYSICS



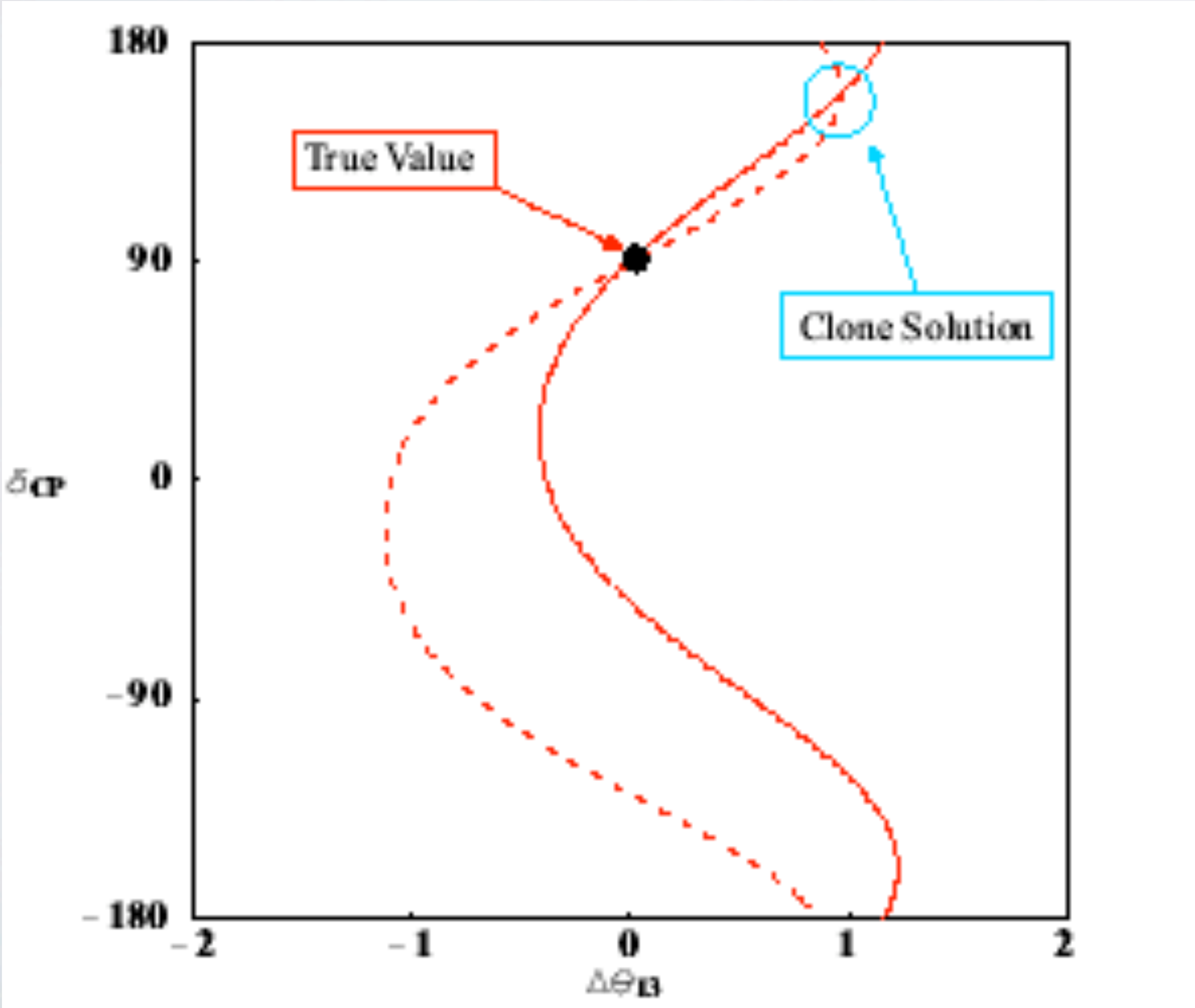
- We obtain a curve of equiprobability in the plane (θ_{13}, δ). The true solution is one of a continuous set and cannot be obtained if we fix polarity, baseline and energy.

- But one can now repeat the experiment using antineutrinos...

DEGENERATE PHYSICS

$$P_{\nu,L,E}(\bar{\theta}_{13},\bar{\delta})=\alpha_{\nu}\rightarrow\theta_{13}^{\nu}=-\frac{Y}{2X}\cos\left(\delta-\frac{\Delta_{23}L}{2}\right)\pm\left[\left(\frac{Y}{2X}\cos\left(\delta-\frac{\Delta_{23}L}{2}\right)\right)^{2}+\frac{1}{X}(\alpha_{\nu}-Z)\right]$$

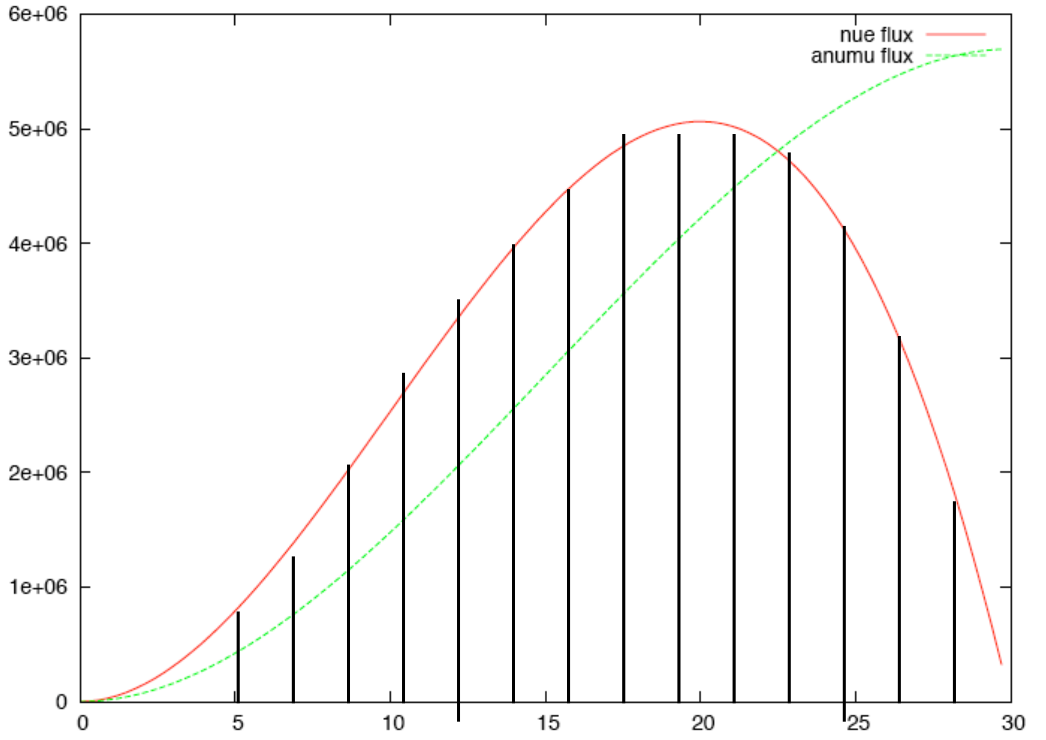
$$P_{\bar{\nu},L,E}(\bar{\theta}_{13},\bar{\delta})=\alpha_{\bar{\nu}}\rightarrow\theta_{13}^{\bar{\nu}}=-\frac{Y}{2X}\cos\left(-\delta-\frac{\Delta_{23}L}{2}\right)\pm\left[\left(\frac{Y}{2X}\cos\left(-\delta-\frac{\Delta_{23}L}{2}\right)\right)^{2}+\frac{1}{X}(\alpha_{\bar{\nu}}-Z)\right]$$

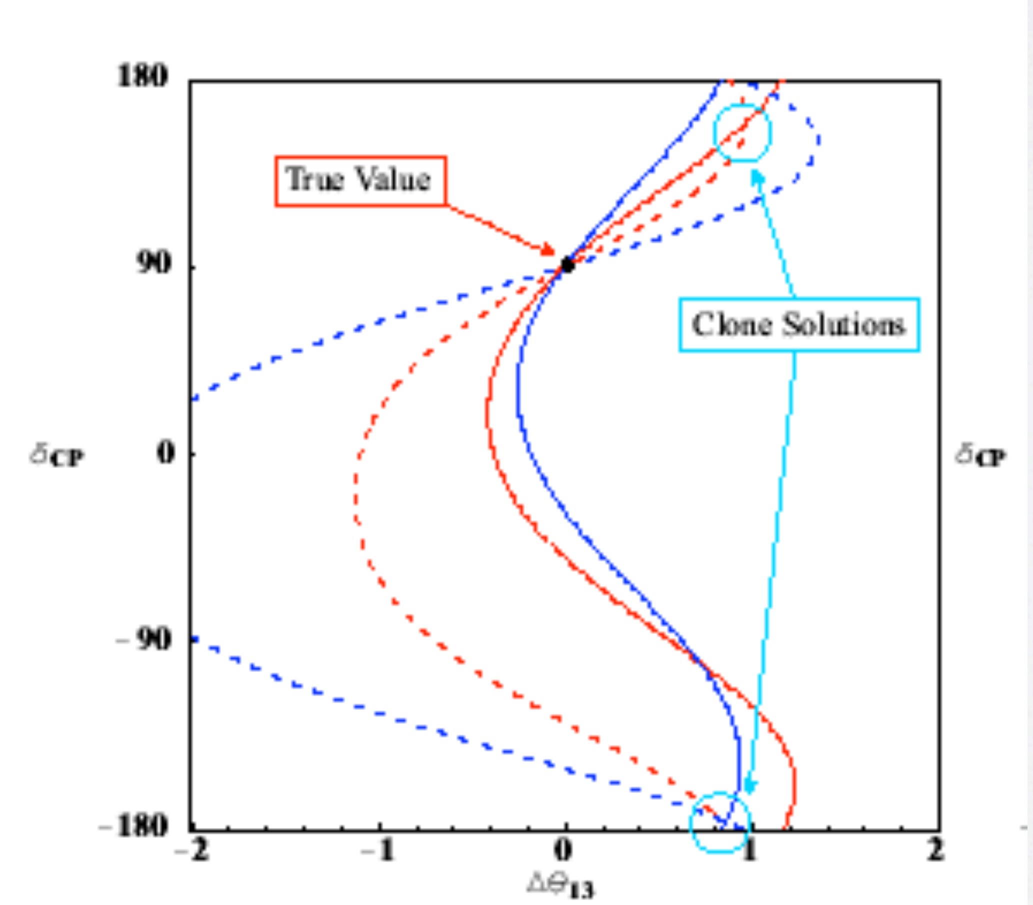


- In this case we obtain two curves which cross at the true point. But, alas, these are periodic equations. If they cross in one point, they must cross in a second point!

- Thus the outcome of the experiment is a true solution and a clone! That is we find a degeneration in the solution, which is called the intrinsic degeneracy.

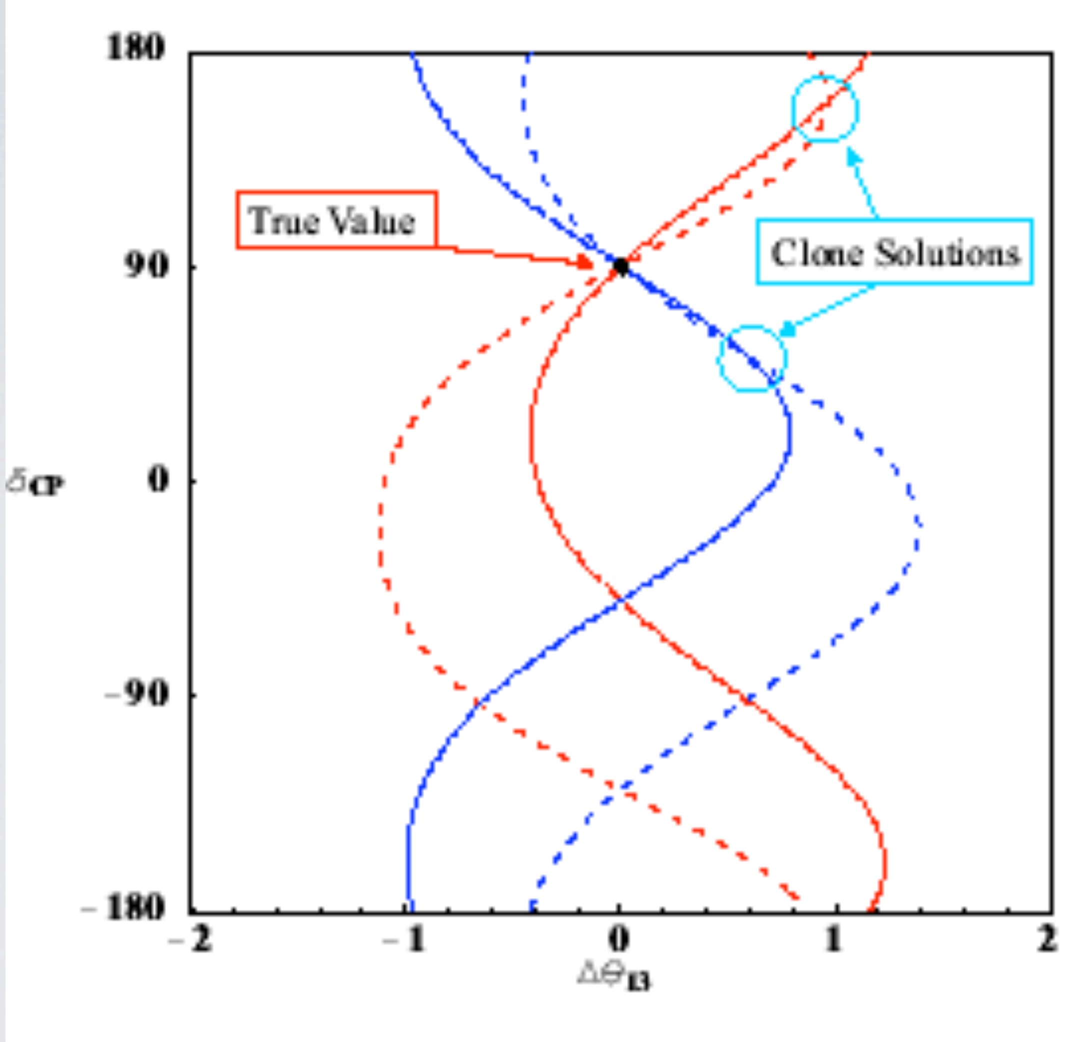
DEGENERATE PHYSICS





- Also (fortunately!) our beam is not monochromatic
- If we have good energy resolution, we can approximate our beam as a set of “monochromatic” beams.
- All monochromatic beam cross in the true point, but each one of them gives a different clone. Therefore, spectral analysis allows solving the degeneracy!

GOLDEN AND SILVER CHANNELS



- If one has a tau-capable detector then the combination of golden and silver channels, helps further the spectral analysis.

- Golden and Silver solutions cross in the true value and each one has a clone, but these are different clones! Thus one can solve the system and eliminate degeneracy.

The Magic Baseline

$$\begin{gathered} P_{\theta_{13}} = \sin^2(2\theta_{13})\sin{\theta_{23}}^2\sin^2((\hat{A}-1)\hat{\Delta})/(\hat{A}-1)^2; \\ p_{\sin\delta} = \alpha\sin(2\theta_{13})\zeta\sin\delta\sin(L\hat{\Delta})\sin(\hat{A}\hat{\Delta})\sin((1-\hat{A})\hat{\Delta})/((1-\hat{A})\hat{A}); \\ p_{\cos\delta} = \alpha\sin(2\theta_{13})\zeta\cos\delta\cos\hat{\Delta}\sin(\hat{A}\hat{\Delta})\sin(1-\hat{A}\hat{\Delta})/((1-\hat{A})\hat{A}); \\ p_{\mathrm{solar}} = \alpha^2{\cos\theta_{23}}^2\sin^2 2\theta_{12}\sin^2(\hat{A}\hat{\Delta})/\hat{A}^2; \end{gathered}$$

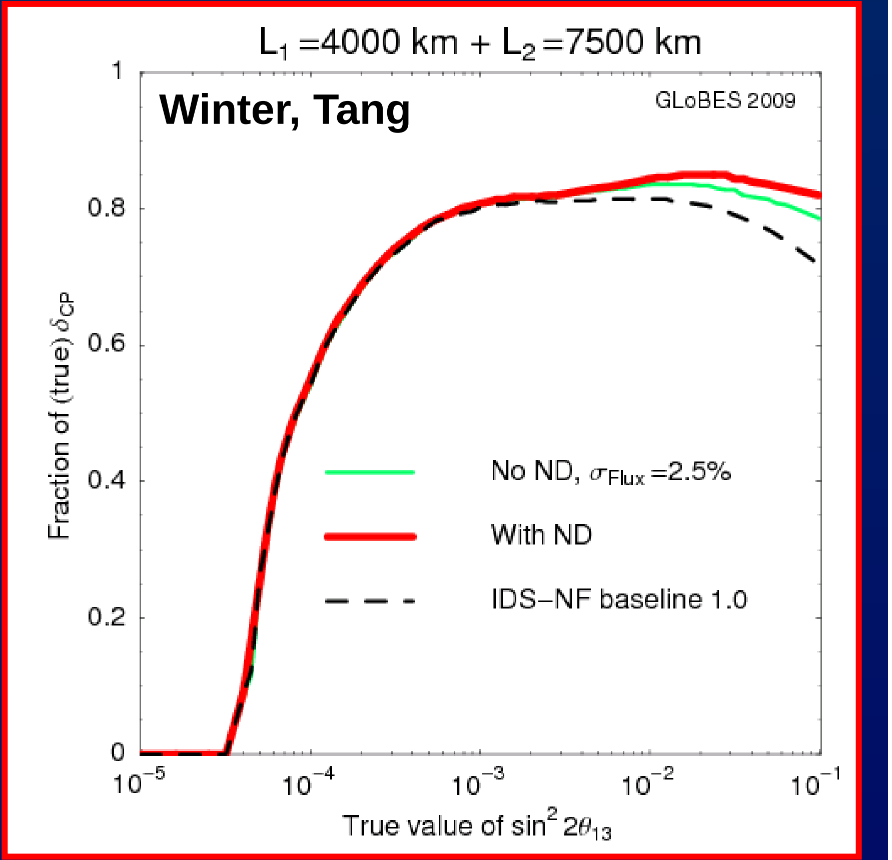
$\alpha = \mathrm{Abs}(\Delta m^2_{21}/\Delta m^2_{31})$; $\hat{\Delta} = \frac{L\Delta m^2_{31}}{4E}$ $\zeta = \cos\theta_{13}\ \sin 2\theta_{12}\sin 2\theta_{23}$ $\boldsymbol{\hat{A} = \pm a/\Delta m^2_{31}}$;
For $\rho L = \sqrt{2}\pi/G_F Y_e$ (Y_e is the electron fraction inside the earth) any δ_{CP} dependence disappears allowing $\mathrm{sign}(\Delta m^2_{23})$ effects to be measured without any degenerate solution. According to earth matter density profile, $L_{\mathrm{magic}} \simeq 7690$ km, the resonance energy for matter effects would be:

$$E_{\mathrm{res}} \equiv \frac{|\Delta m^2_{31}|\cos 2\theta_{13}}{2\sqrt{2}G_F N_e} \simeq 7\ \mathrm{GeV} \tag{1}$$

for $|\Delta m^2_{31}| = 2.4\cdot 10^{-3}\ \mathrm{eV}^2$ and $\sin^2 2\theta_{13} = 0.1$.
It is important to note that close to matter resonance, the flux of oscillated events at the detector roughly falls as a function of $1/L$ (against the $1/L^2$ fall of vacuum oscillations), which means that longer baselines might be preferred.

Near detector: motivation:

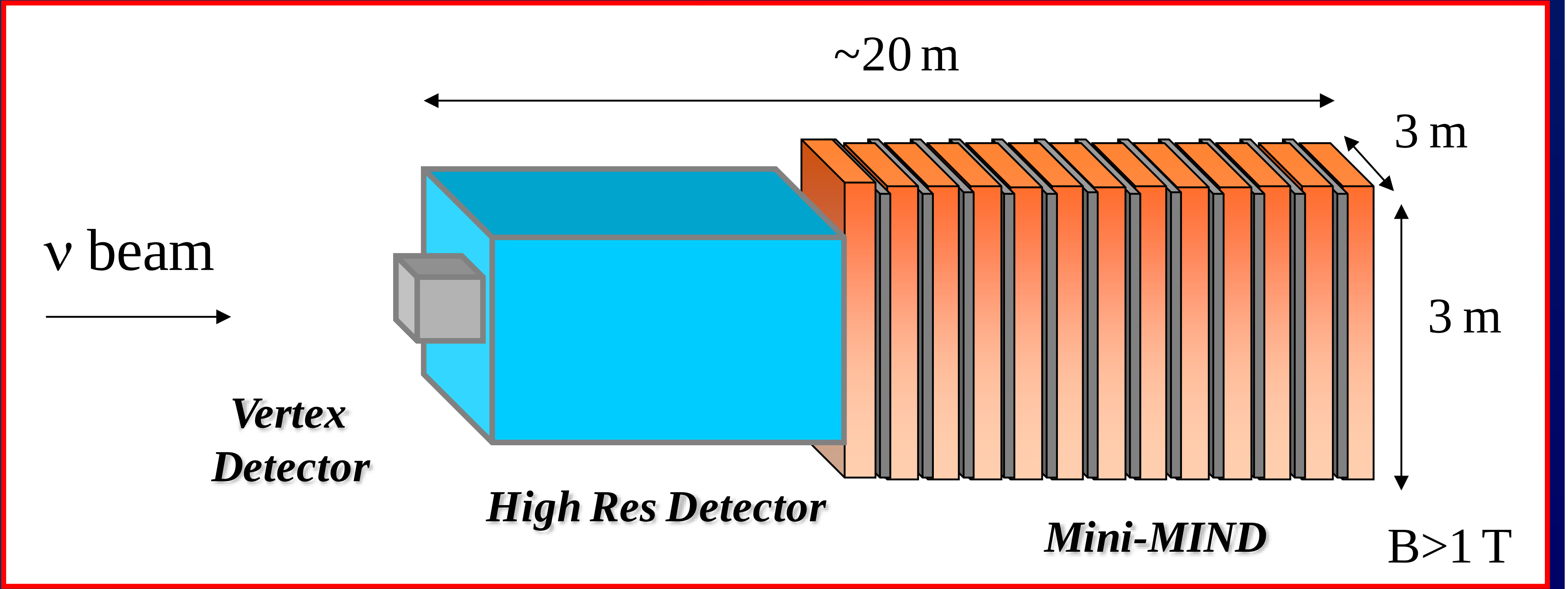
- Oscillation analysis:
  - Direct measurement of neutrino flux
  - Detailed study of charm cross sections
  - Detailed study of neutrino-nucleon scattering
    - Including deep inelastic, quasi-elastic, and resonance scattering



- Near detector physics programme:
  - Search for non-standard interactions
    - In particular, require sensitivity to taus
  - Neutrino physics:
    - Polarised (and unpolarised) structure functions
      - Determination of α_S
    - Electroweak physics: Weinberg angle
    - CP violation from D^0, $\overline{D}^0$ mixing, polarised Λ production, …

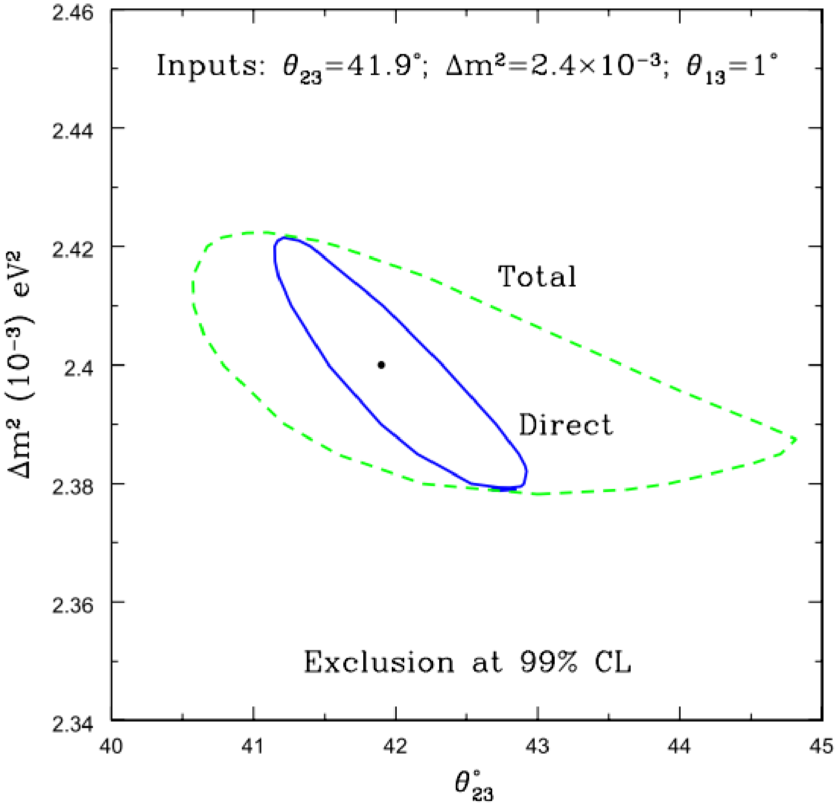
Near detector: concept:

- No near detector specified in initial IDS-NF baseline [i.e. ISS Detector W/g report]:
  - Known to be a shortcoming
- IDS-NF near detector concept (baseline 2010/2.0)

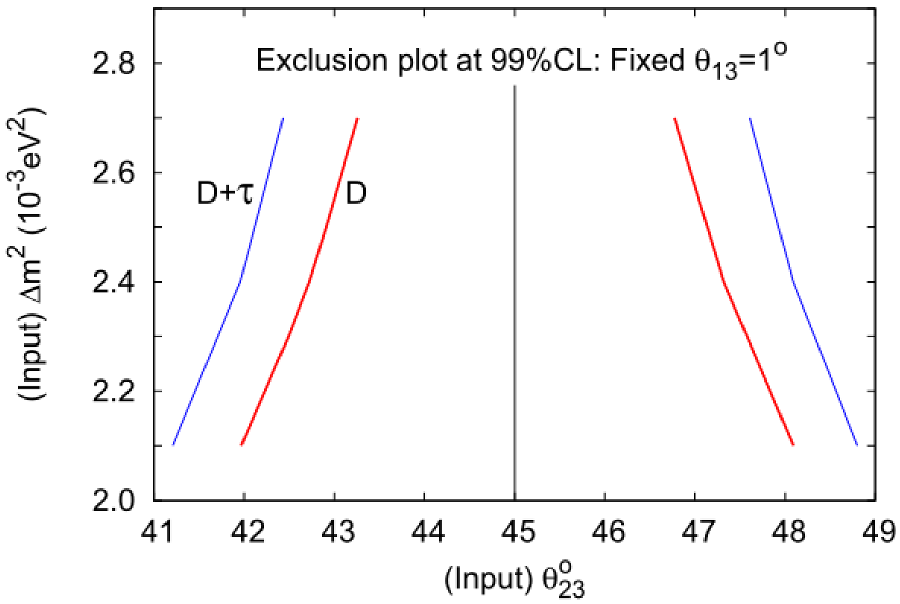


Neutrino Factory performance:

- **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 Comparison

Based to arXiv:1005.3146, the EuroNu midterm physics report

WBB: Fermilab to Dusel, 1 MW for ν running, proton energy: 120 GeV, 2 MW for $\overline{\nu}$ running (5+5 yr), 100 kton liquid argon detector, according to Barger et al, Phys. Rev. D76:053005, 2007 (hep-ph/0703029). This setup is different from the proposed LBNE experiment.

T2KK: J-Parc ν beam running at 4 MW. 270 kton WC detector at Kamioka (295 km) and 270 kton WC detector in Korea (1050 km), Barger et al, Phys. Rev. D76:053005, 2007 (hep-ph/0703029).

PS2-Slanic CERN-PS2 SuperBeam fired to 100 kton LAr detector at Slanic, as computed by A. Rubbia, arXiv:1003.1921.

SPL: Neutrino beam from CERN-SPL running at 3.5 GeV, 4 MW. 440 kton WC detector at Frejus (130 km). Campagne et al. JHEP **0704** (2007) 003 (hep-ph/0603172).

Beta Beam $\gamma = 100$ Eurisol Beta Beam to Frejus (440 kton WC detector). Campagne et al. JHEP **0704** (2007) 003 (hep-ph/0603172).

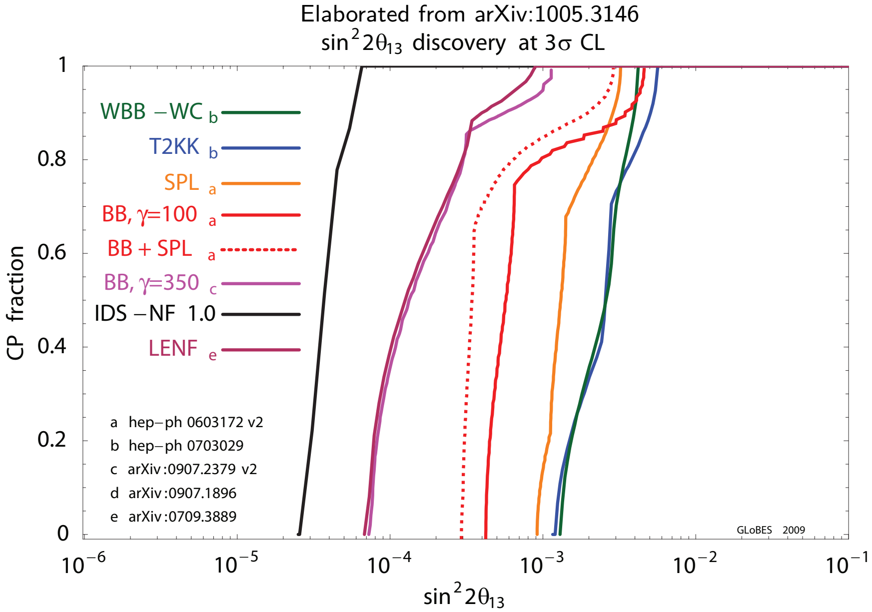
Beta Beam + SPL The combination of the above two.

Beta Beam $\gamma = 350$ Beta Beam at $\gamma = 350$, running $^6\mathrm{He}$ and $^{18}\mathrm{Ne}$ at the same decay rates as the Eurosol Beta Beam. WC detector of 500 kton at Canfranc (650 km). S. Choubey et al., JHEP 0912:020,2009 (arXiv:0907.2379)

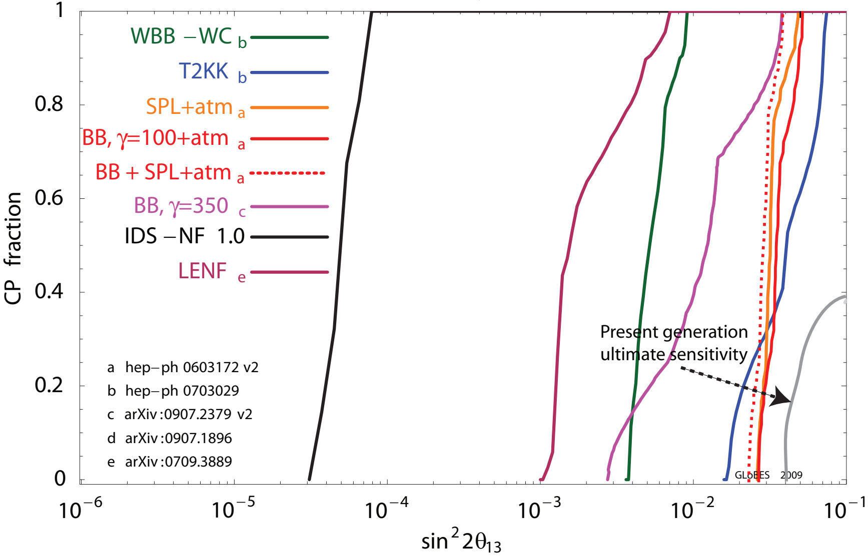
Low Energy Neutrino Factory (LENF) Neutrino Factory running at 4.12 GeV delivering 10^{21} muon decays/year for each sign, 30 kton Noνa like detector, fully magnetized (!) at 1480 km (Fermilab-Henderson mine). A. Bross et al, Phys.Rev.D77:093012,2008. (arXiv:0709.3889)

IDS 1.0 Neutrino Factory 25 GeV neutrino factory delivering $0.5 \cdot 10^{21}$ muon decays/year for each sign, a 50 kton iron magnetized detector and a 10 kton Emulsion Cloud Chamber, at 4000 km and a 50 kton iron magnetized detector at 7500 km.

Sensitivity Comparison: θ_{13}



Sensitivity Comparison: $\mathrm{sign}(\Delta m^2_{23})$



Elaborated from arXiv:1005.3146
Mass hierarchy at 3σ CL

Sensitivity Comparison: LCPV