NEUTRINO FACTORIES

Realization & Physics Potential

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(October 19, 2001)

Why Neutrino Experiments ?

- Over the last decade an incredible discovery has emerged in particle physics: Neutrinos have tiny (sub-eV) masses.

- We don't know what new beyond-the-Standard-Model physics is responsible for the tiny masses, but it's bound to be something exciting.

- The long-term goal for the neutrino program is to answer the question:

  What new physics is responsible for sub-eV neutrino masses ?

Which Neutrino Measurements ?

- We don't know exactly what we need to do to pin down the physics responsible for neutrino masses, but there is a broad consensus that the first steps for the accelerator-based neutrino program are:
  - Measure the unknown mixing angle θ_{13} (is it non-zero) ?
  - Determine the pattern of neutrino masses (mass hierarchy)
  - Find or constrain CP violation in the neutrino sector (measure or constrain the CP phase δ)

- The less clear longer-term steps may involve finding more neutrino surprises, will probably involve guidance from other experimental results (LHC, CLV, neutrinoless $\beta\beta$ …), & will almost certainly involve precision neutrino parameter measurements:
  - Do any of the parameters have special values ?
  - Suggestive relationships between parameters ?
  - Is 3 flavor mixing the whole story ?

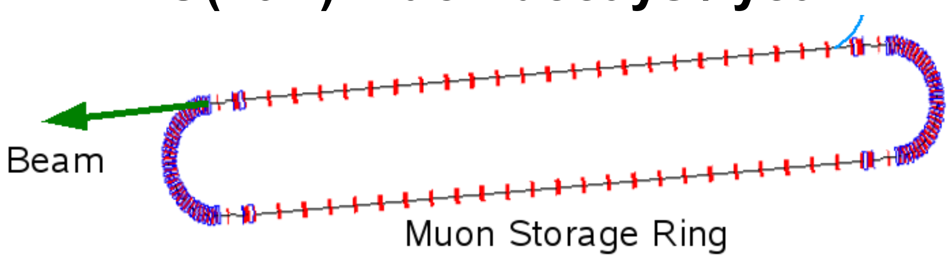
WE NEED CLUES

A New Type of Neutrino Beam

- A Neutrino Factory would provide a new type of neutrino beam, made from muon decays (c.f. charged pion decays for conventional neutrino beams.

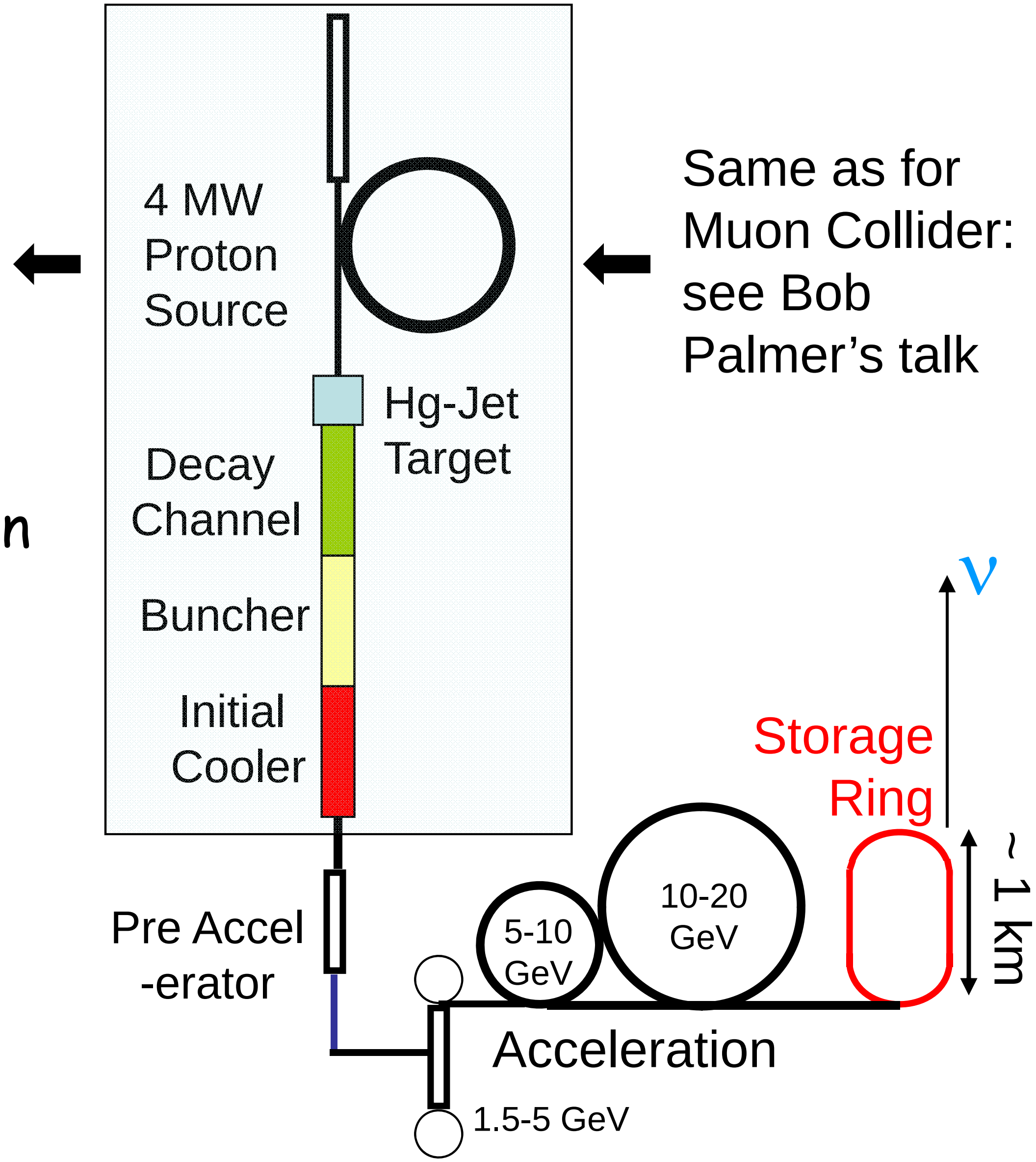
- Since muons live 100 longer than charged pions, to be efficient a linear muon decay channel would have to be tens of km long, hence:

O(10^{21}) muon decays / year



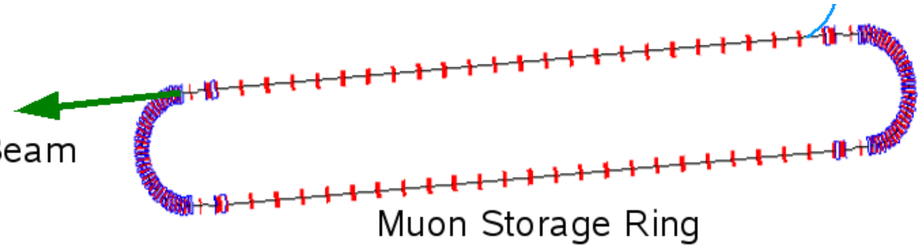
Neutrino Factory Schematic

- Proton Source
  - Beam power ≥ 4MW
  - E ≥ few GeV
  - Short bunches (≤ 3ns)
- Target, capture & decay
  - Create $\pi^{\pm}$, decay into $\mu^{\pm}$
- Bunching & Phase Rotation
  - Capture into bunches
  - Reduce ΔE
- Cooling (cost effective but not mandatory)
  - Use Ionization Cooling to reduce transverse emittance to fit within an accelerator



Beam Properties

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



- 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.

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

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

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

Key Experimental Signature

- Measuring the transitions $\nu_e \leftrightarrow \nu_\mu$ is crucial for the future neutrino oscillation program.

- With a conventional neutrino beam this means measuring $\nu_\mu \rightarrow \nu_e$ oscillations, and hence ν_e appearance. With a NF we can measure $\nu_e \rightarrow \nu_\mu$ oscillations & hence ν_e appearance $\rightarrow$ very low backgrounds

$$\mu^+ \rightarrow e^+ \, \nu_e \, \bar{\nu}_\mu \xrightarrow{CC} \mu^+$$

$$\nu_e \downarrow \quad \nu_\mu \xrightarrow[CC]{} \mu^-$$

$\nu_e \rightarrow \nu_\mu$ 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 $\longrightarrow$ background-free $\nu_e \rightarrow \nu_\mu$ oscillations with probabilities of $O(10^{-4})$ can be measured !

Neutrino Factory Studies

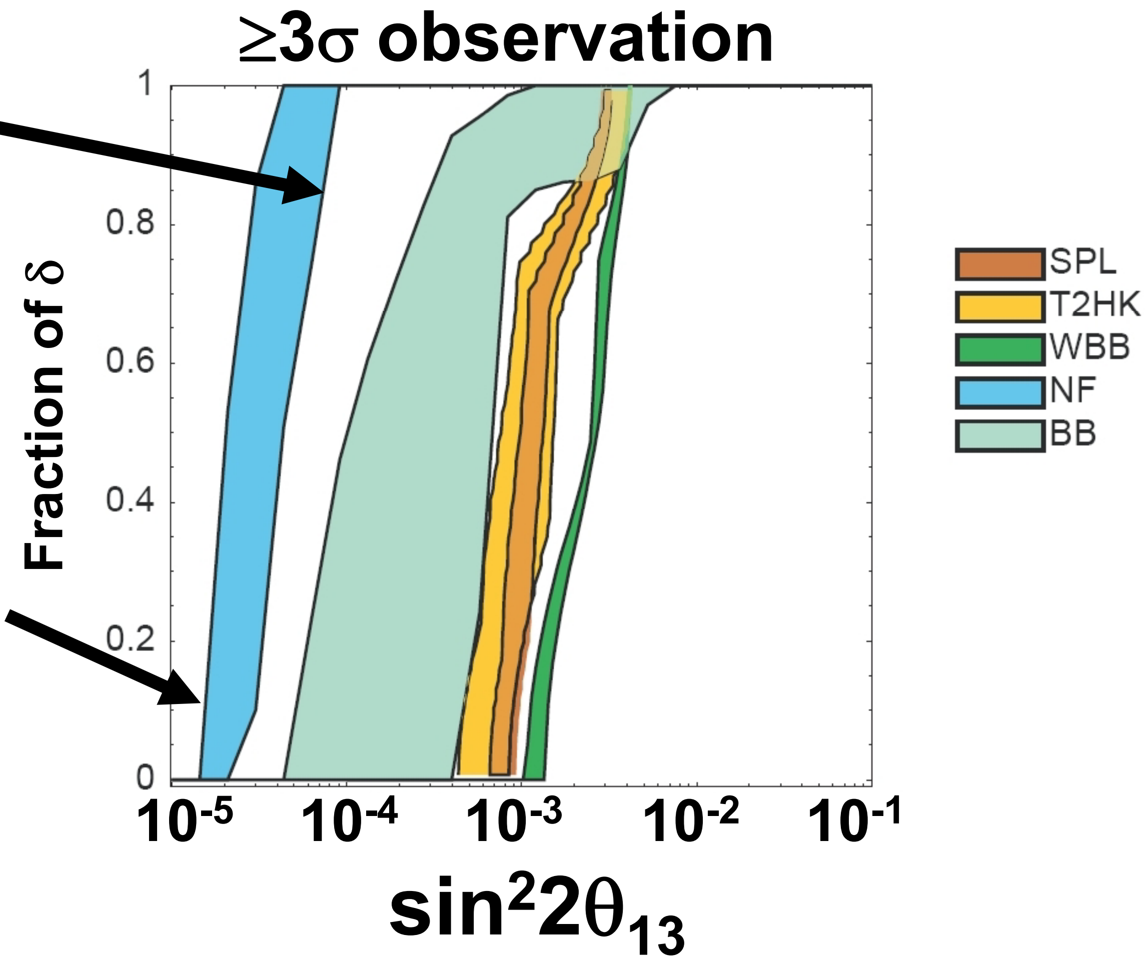
- Over the last decade a series of design studies have developed the NF concept:
  - First Generation - "Feasibility":
    - Feasibility Study 1 (FNAL 2000)
    - Japanese Study 1 (2001)
    - CERN Study (2004)
  - Second Generation – performance & cost-reduction:
    - Study 2 (BNL 2001): performance
    - Studies 2a & 2b (2005): cost
  - Third Generation – International:
    - International Scoping Study: selected 25 GeV NF (RAL 2006) (MOST RECENT COMPLETED STUDY)
    - International Design Study: seeks to deliver a Reference Design report by ~2011 (ONGOING STUDY)
    - Low Energy NF (NEW DEVELOPMENT)

International Scoping Study Reports

- **Physics report : Rep. Prog. Phys**
- **Accelerator report: JINST 4:P07001,2009**
- **Detector: JINST 4:T05001,2009**

ISS Physics Results: θ_{13} Sensitivity

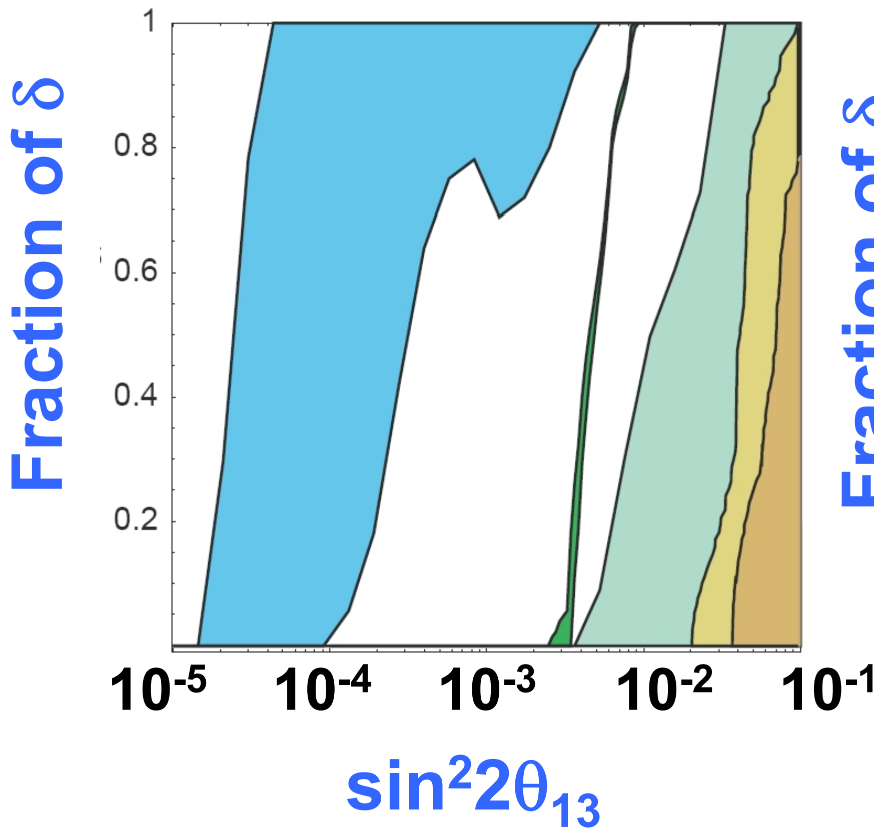
- "Conservative" NF (right edges in plots)
  - 10^{21} muon decays/yr
  - 4 years x 50 KT
  - E = 50 GeV
  - L = 4000 km
- "Optimized" NF (left edges in plots)
  - 10^{21} muon decays/yr
  - 5 years x 50 KT x 2
  - E = 20 GeV
  - L = 4000 & 7500 km



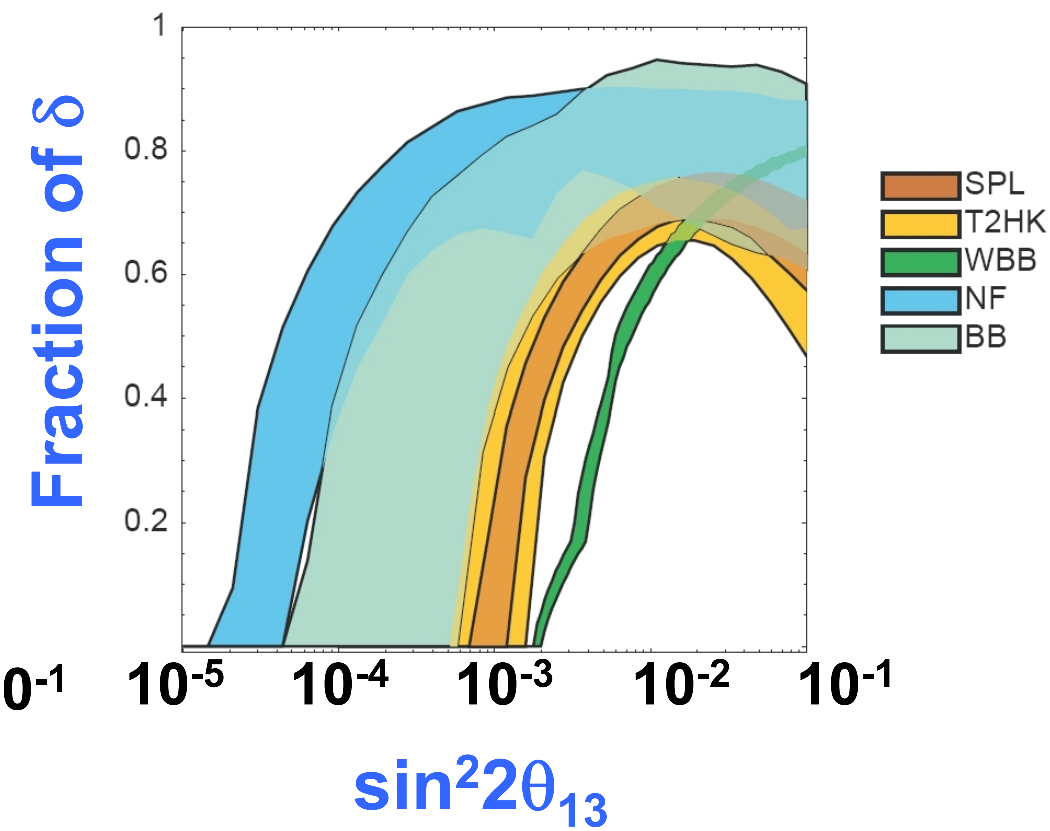
Even if θ_{13} = 0 at some high mass scale, radiative corrections are likely to make it larger than the limiting NF sensitivity

ISS Physics Results: Mass Hierarchy

Mass Hierarchy determined at ≥3σ



CPV established at ≥3σ



If θ_{13} is small, an ~20-25 GeV Neutrino Factory provides exquisite sensitivity that goes well beyond the capability of conventional neutrino beams

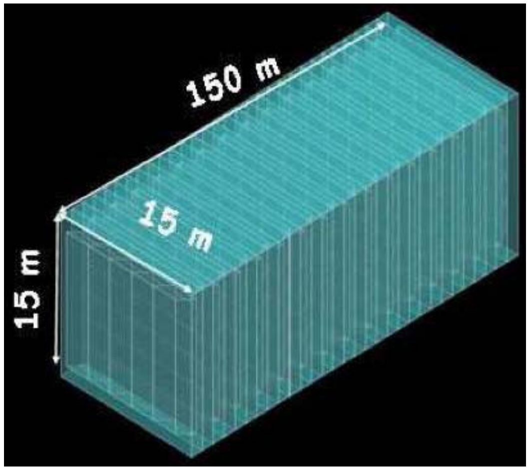
What if θ_{13} Large ?

Geer, Mena, & Pascoli, Phys. Rev. D75, 093001, (2007); Bross, Ellis, Geer, Mena,& Pascoli, Phys. Rev. D77, 093012 (2008)
Phys. Rev. Special Topics AB, Ankenbrandt, Bogacz, Bross, Geer, Johnstone, Neuffer, Popovic – in press

- New ideas on how to affordably magnetize a very large low Z fully active detector have opened the possibility of a low energy NF, ideal it θ_{13} is "large"

- 4 GeV NF design simulated → 1.4×10^{21} useful decays/year of each sign

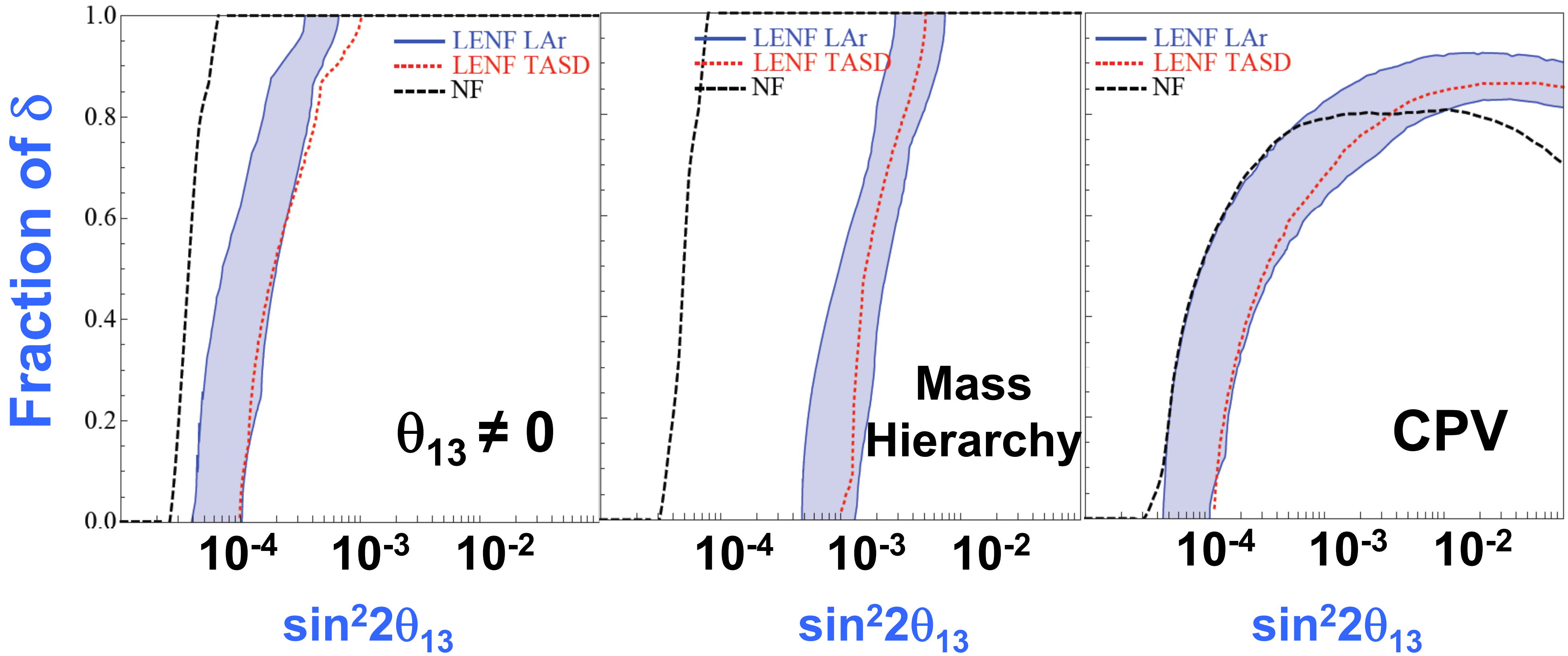
- For present physics studies, assume:
  - 4.5 GeV NF
  - 1.4×10^{21} useful decays/year of each sign
  - background level of 10^{-3}
  - 20KT detector (Fid. Mass)
  - 10 year run
  - L = 1280 km (FNAL-Homestake)



Totally Active Scintillator Detector
15m long scintillators
triangular cross-section
(base=3cm, ht=1.5cm)
B = 0.5 T

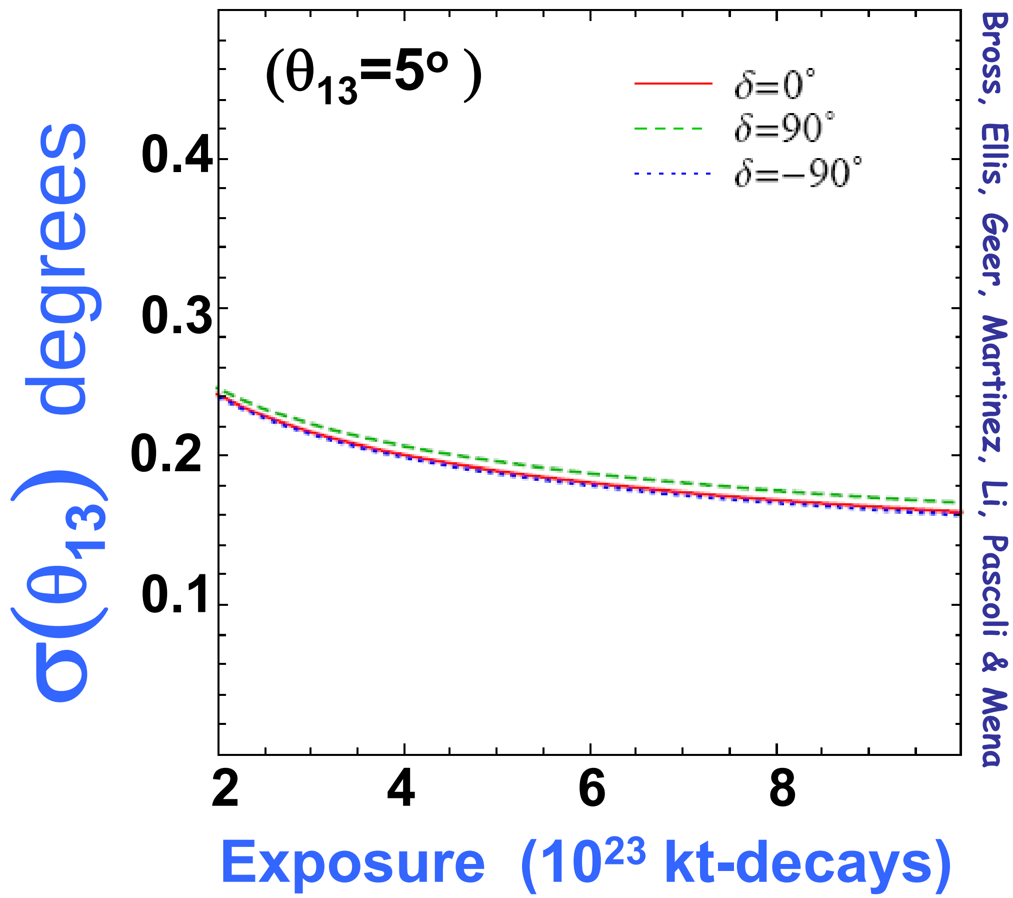
3σ Discovery Potential

Bross, Ellis, Geer, Martinez, Li, Pascoli & Mena



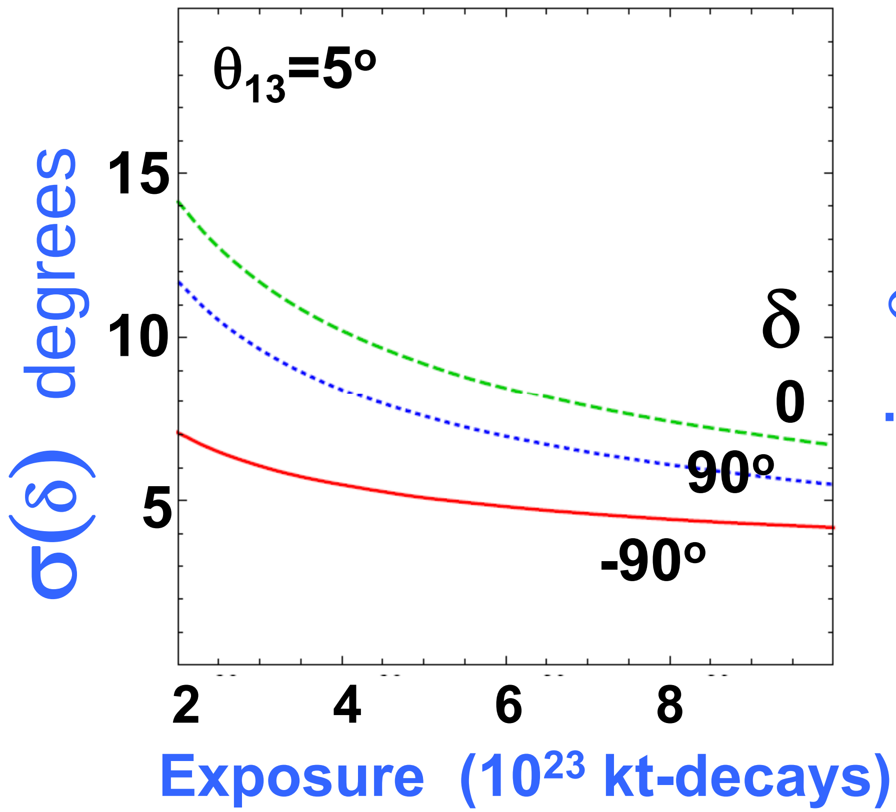
- A Low Energy NF with a FNAL – Homestake baseline has discovery sensitivity down to $\sin^2 2\theta_{13} = O(10^{-3} - 10^{-4})$!

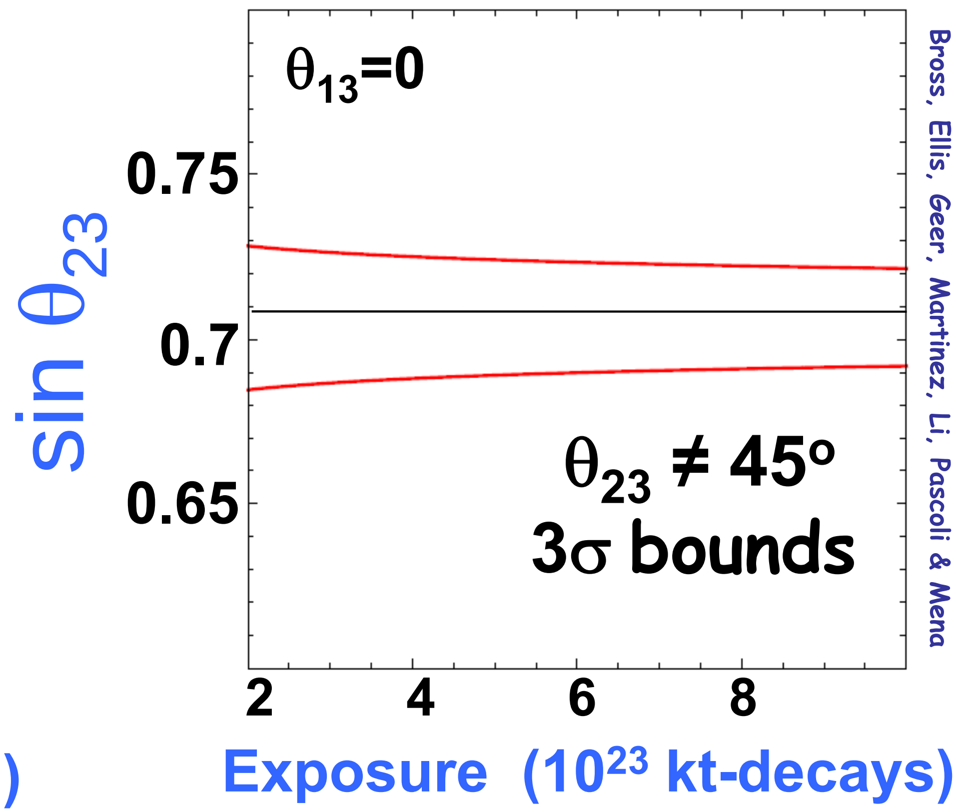
Low Energy NF Precision



If θ_{13} is "large", a low energy NF would enable precision measurements

Low Energy NF Precision





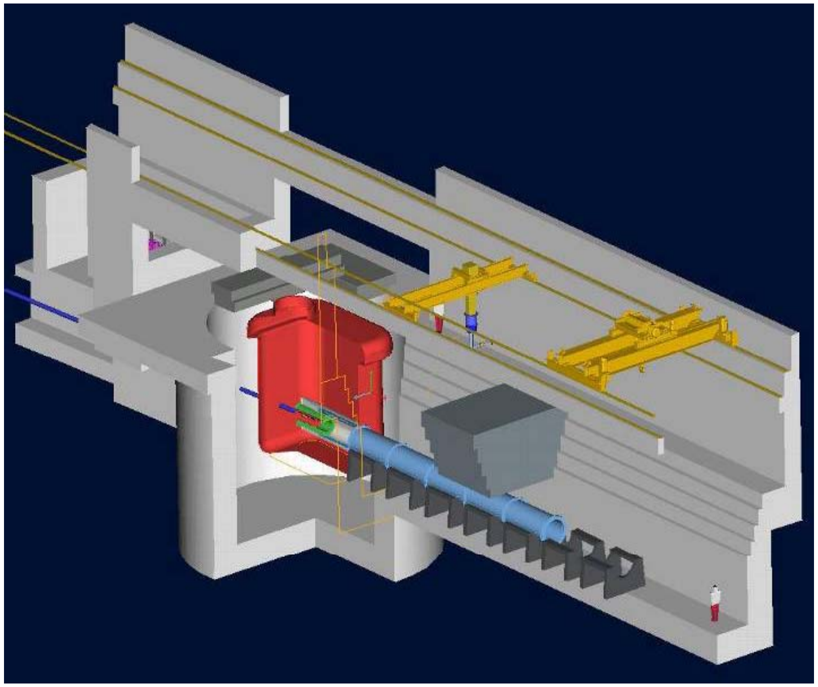
Neutrino Factory R&D

- Neutrino Factory R&D pursued since 1997.
- Since, in our present designs, the Neutrino Factory and Muon Collider have common front ends (up to & including the initial cooling channel), much of the R&D is in common.
- See Bob Palmer's Muon Collider talk for proton requirements, target, bunching & phase rotation, and cooling design and R&D.
- Key experiments:

  MERIT: Target demonstration – complete
  MuCool: RF in mag. fields – critical, ongoing
  MICE: Cooling channel systems test, ongoing
  EMMA: Promising new acceleration scheme test, in preparation

Targetry

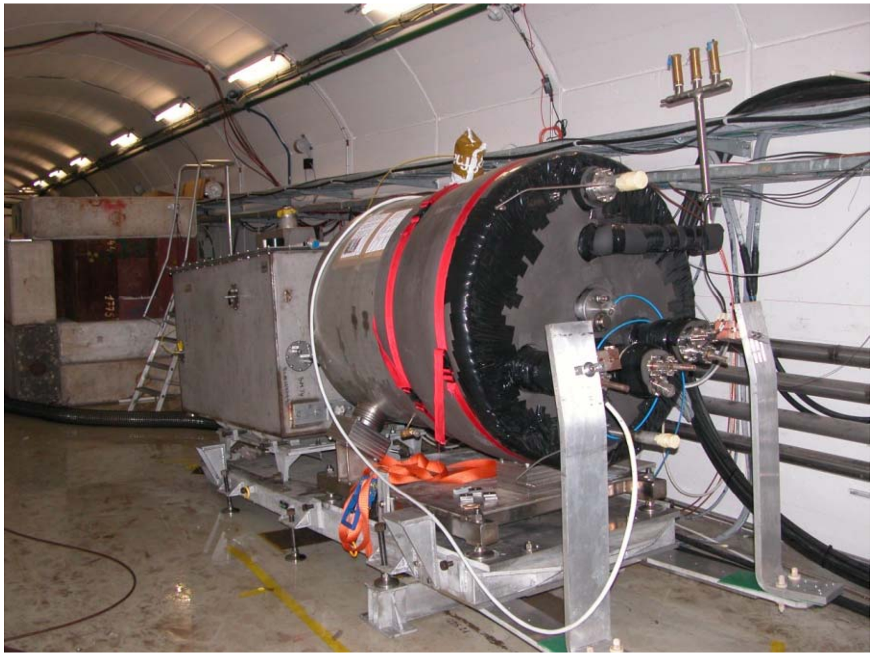
- Need proton beam power of 4MW & short bunches (≤3ns)
- Optimum proton beam energy = 10 ± 5 GeV (ISS study) but at fixed power muon yield drops slowly with energy - lose ~30% for E=120 GeV (Mokhov)
- A 4MW target station design study was part of "Neutrino Factory Study 1" in 2000 → ORNL/TM2001/124
- Facility studied was 49m long = target hall & decay channel, shielding, solenoids, remote handling & target systems.
- Target: liquid Hg jet inside 20T solenoid, identified as one of the main Neutrino Factory challenges requiring proof-of-principle demonstration.

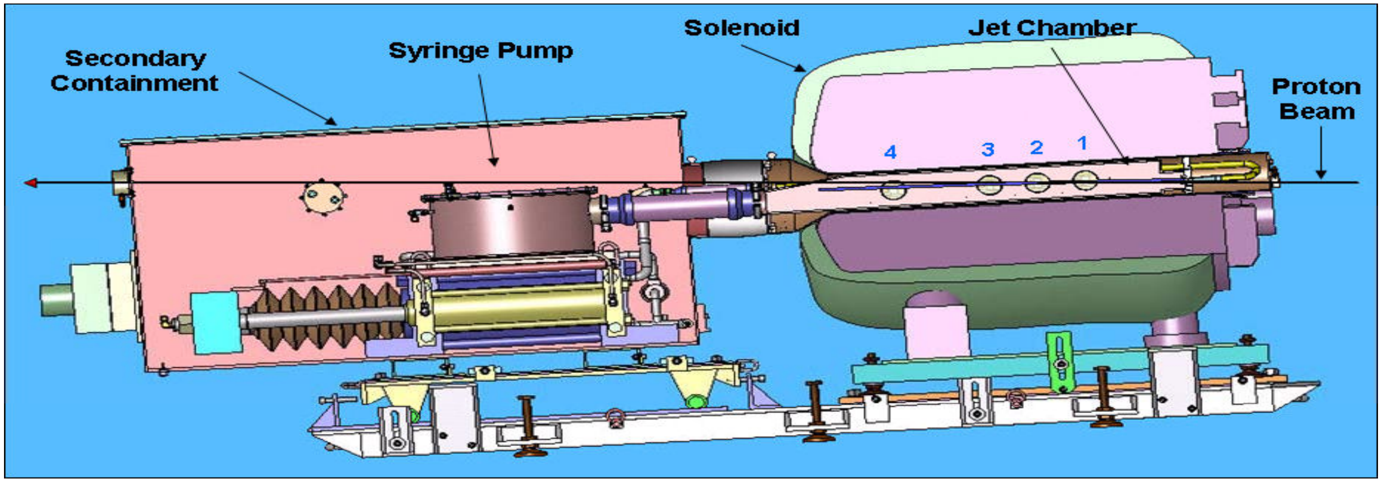


4MW Target Station Design

The MERIT Experiment at CERN

- The MERIT experiment was designed as proof-of-principle demonstration of a liquid Hg jet target in high-field solenoid.
- In Fall 2007 MERIT ran at the CERN PS and successfully demonstrated a liquid Hg jet injected into a 15T solenoid, & hit with a suitably intense beam (115 KJ / pulse !).

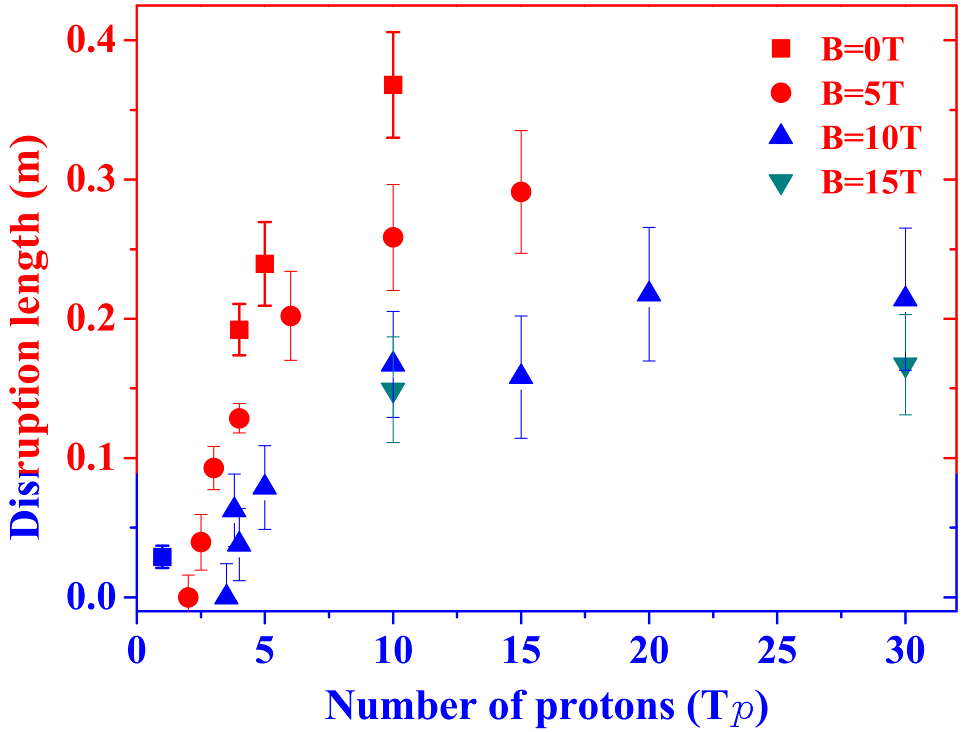


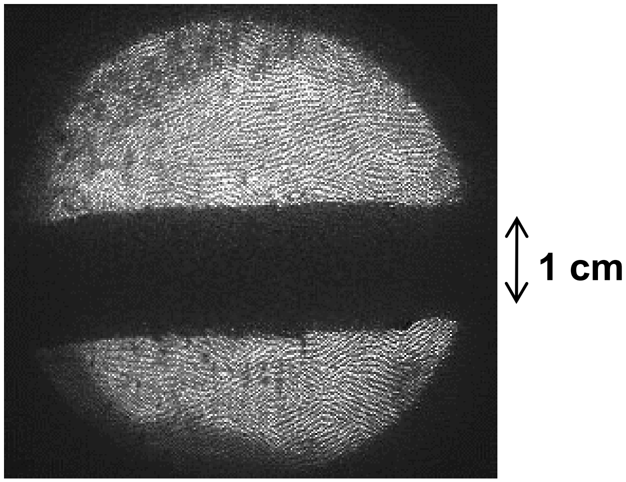


MERcury
Intense
Target

MERIT RESULTS

- Jet disrupted on a ms timescale (disruption length <28 cm ~ 2 int. lengths. The jet was observed to re-establish itself after 15ms … before the next beam pulse arrives → rep. rate 70Hz.
- Preliminary analysis suggests this target technology is good for beams up >8 MW !



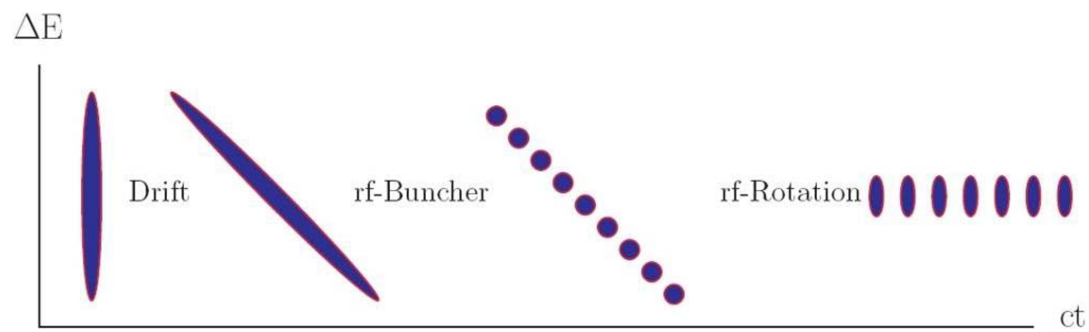


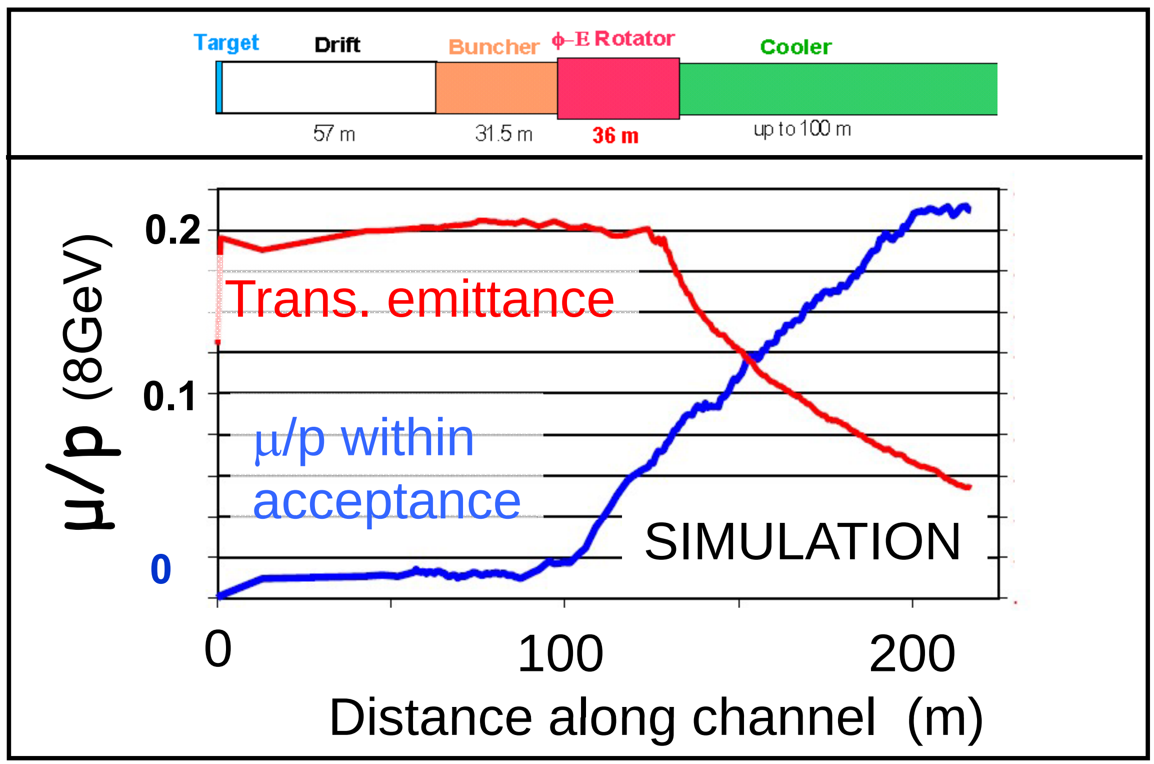
Hg jet in a 15T solenoid observed with a high-speed camera

Bunching, Phase Rotation & Cooling

- After drifting down a 57m long pion decay channel, the muons have developed a time-energy correlation. A clever arrangement of RF cavities captures the muons in bunches & then reduces their energy spread.

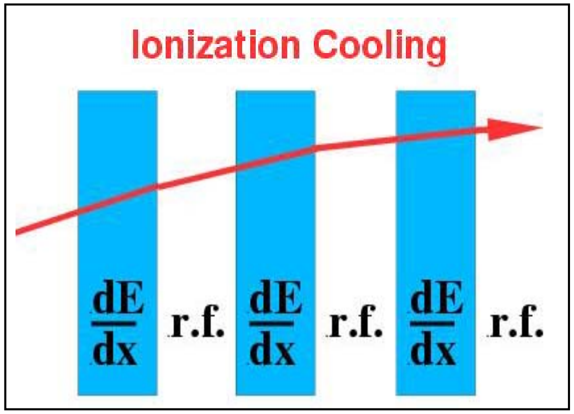
- An ionization cooling channel reduces trans. phase space of the muon population to fit within the accelerator acceptance.

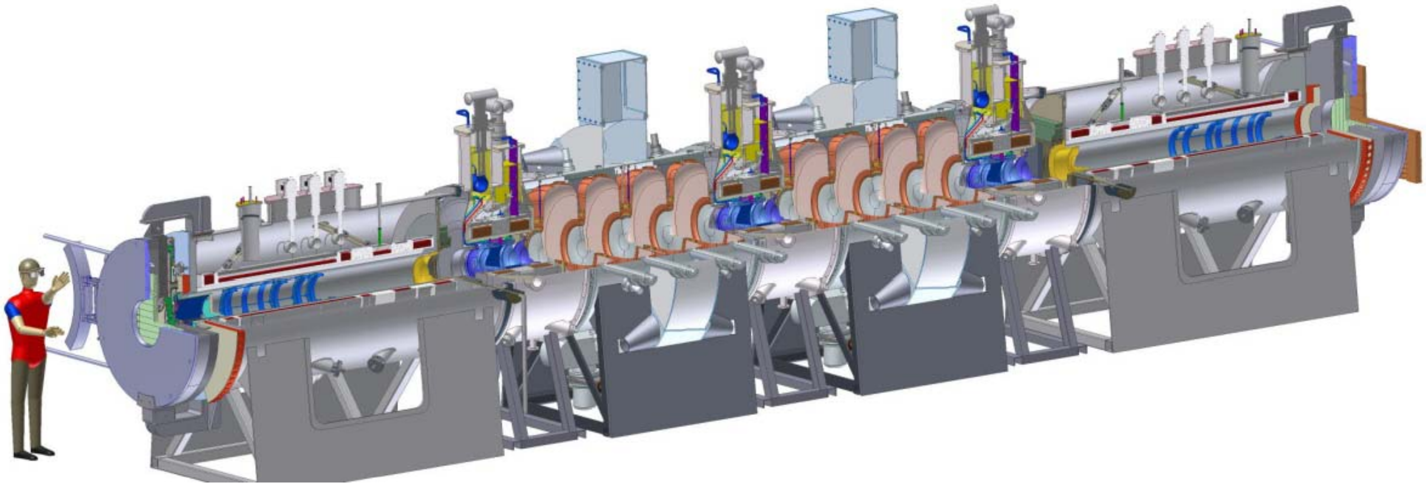




Ionization Cooling

- Must cool fast (before muons decay)
- Muons lose energy by in material (*dE/dx*). Re-accelerate in longitudinal direction → reduce transverse phase space (emittance). Coulomb scattering heats beam → low *Z* absorber. Hydrogen is best, but LiH also OK for the early part of the cooling channel.



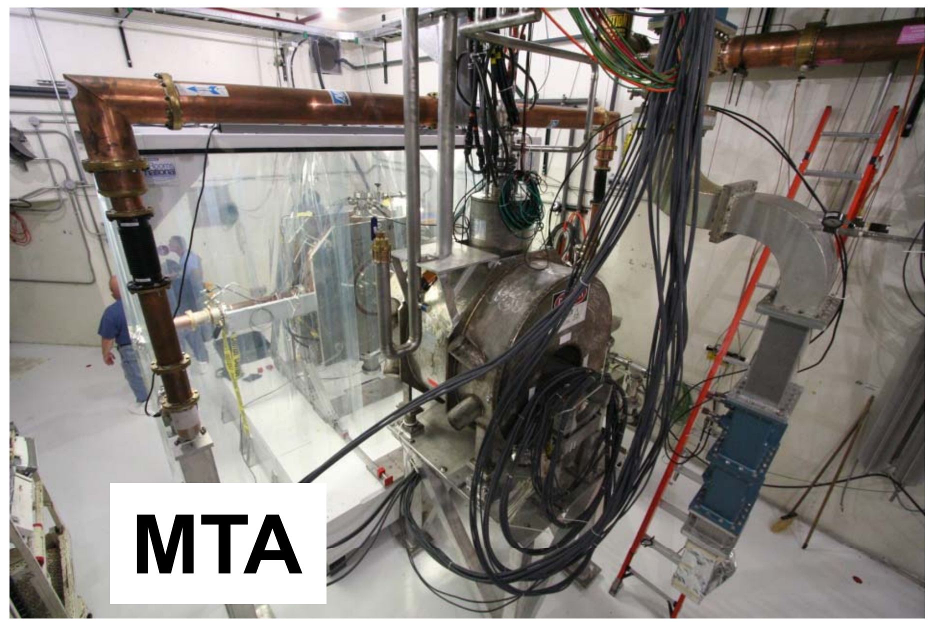


MuCool

- Developing & bench testing cooling channel components
- MuCool Test Area at end of FNAL linac is a unique facility:
  - -Liquid H2 handling
  - -RF power at 805 MHz
  - -RF power at 201 MHz
  - -5T solenoid (805 MHz fits in bore)
  - -Beam from linac (soon)

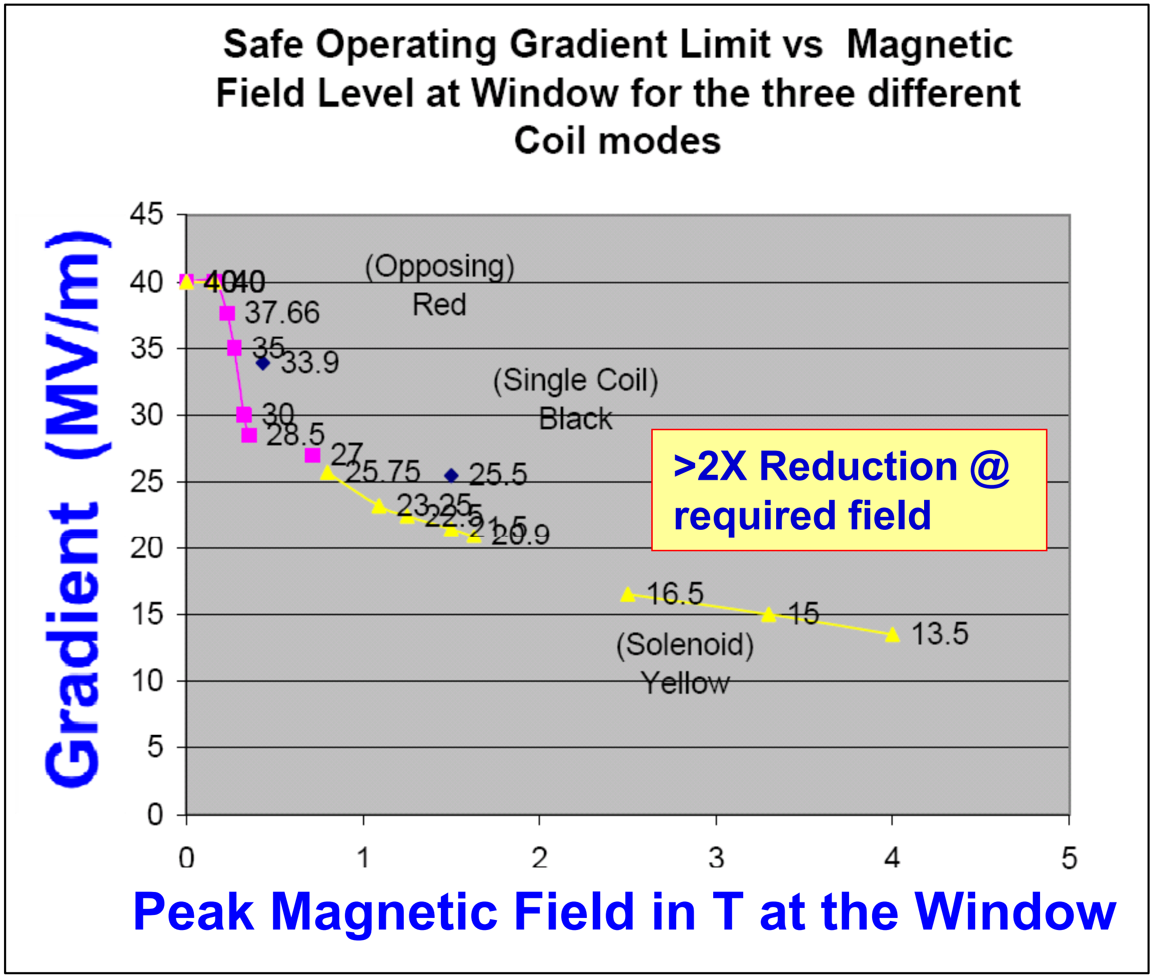
New beamline

Liq. H2 absorber



RF in Magnetic Fields

- When vac. copper cavities operate in multi Tesla co-axial mag. field, the maximum operating gradient is reduced.

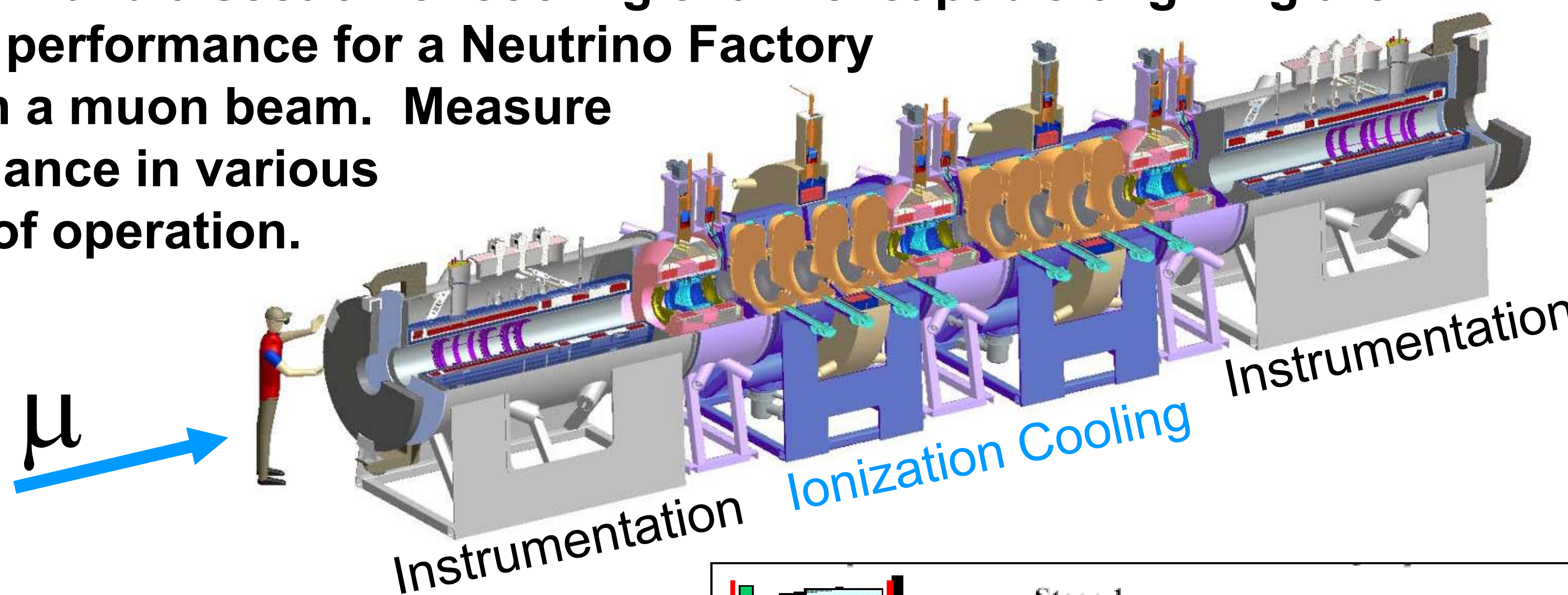


- Effect is not seen in cavities filled with high pressure hydrogen gas – possible solution (but needs to be tested in a beam – coming soon)

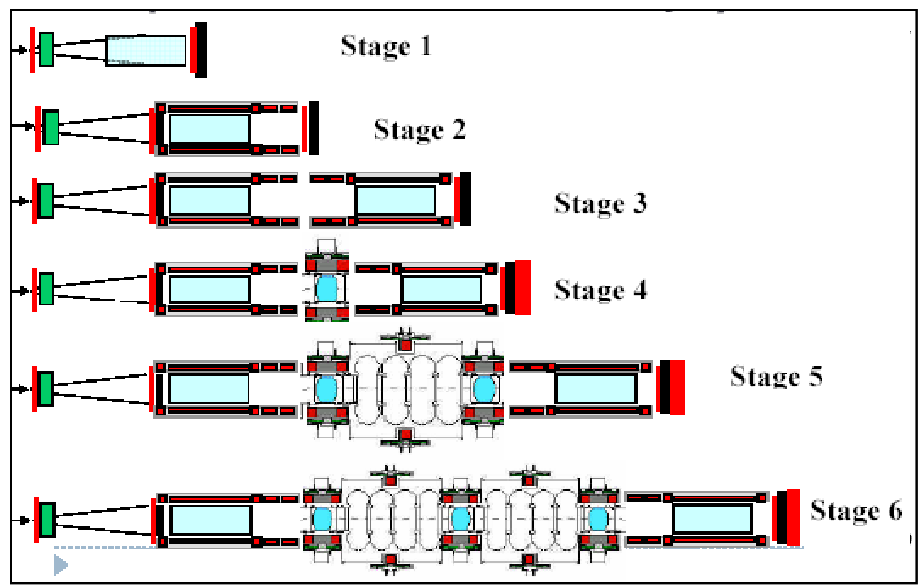
- Other possible ways to mitigate effect:
  - -special surfaces (e.g. beryllium)
  - -Surface treatment (e.g. ALD)
  - - Magnetic insulation

MICE

GOALS: Build a section of cooling channel capable of giving the desired performance for a Neutrino Factory & test in a muon beam. Measure performance in various modes of operation.

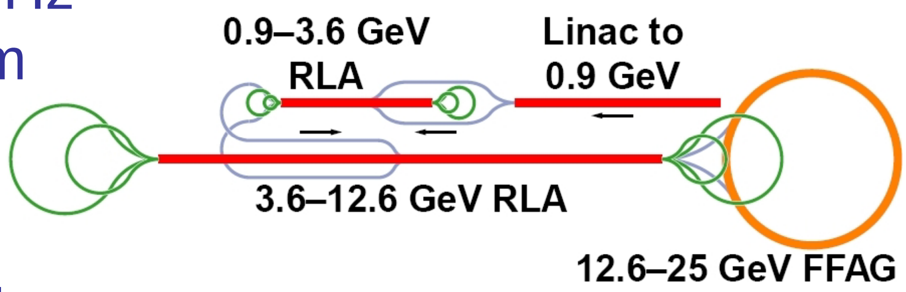


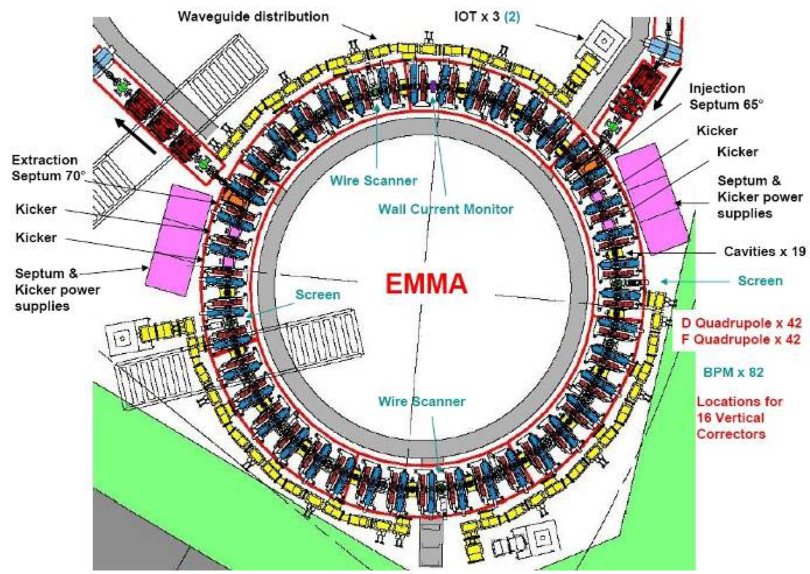
- Multi-stage experiment.
- First stage being commissioned now.
- Anticipate final stage complete by ~2011



Acceleration

- ISS Scheme
  - Pre-accelerator uses 201 MHz SCRF cavities with 17 MV/m (11 MV/m demonstrated at Cornell)
  - Non-scaling FFAG proof-of-principle R&D under prep-aration → EMMA experiment at Daresbury





- Low Energy NF
  - Pre-accelerator uses 201 MHz SCRF cavities with 12 MV/m – performance still OK
  - One RLA to get to 4 GeV

FINAL REMARKS

- International Scoping Study prepared the way for the next step – The International Design Study
- The IDS aspires to deliver a NF Reference Design Report (RDR) by 2012.
- If the community wishes, after a few more years of preconstruction R&D, neutrino factory construction could begin as early as the late 2010's
- The NF & MC front-ends are, in present designs, the same … and require a 4MW (or more) proton source providing 3ns long (or less) bunches with a rep rate of a few x 10Hz. We believe we have the target technology for this.
- Realizing a NF would mitigate many of the technical risks associated with realizing a MC

A Staged Muon Vision