Advanced Neutrino Sources

(Neutrino Factories and Beta Beams)

Experiments at advanced neutrino sources would be designed to go beyond the planned few-sigma discoveries (θ_{13}, mass hierarchy, CPV) and make precision measurements of the oscillation parameters, and precisely test the 3-flavor mixing framework. If θ_{13} is small, they may also have to make the initial few-sigma discoveries.

- Design
- R&D Status
- Remaining R&D Needed
- Cost and Illustrative Schedule Information

Appendix: Physics reach

INTRODUCTION: ADVANCED NEUTRINO SOURCES

• Neutrino Factories (NF) & Beta Beams (BB) produce ν beams by storing unstable particles in a ring with long straight sections:

NF

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

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

BB Examples

$${}^{18}_{10}Ne \to {}^{18}_{9}F\, e^+ \nu_e$$

$${}^{6}_{2}He \to {}^{6}_{3}Li\, e^- \bar{\nu}_e$$

• The stored beam properties & decay kinematics are well known → uncertainties on neutrino flux & spectra are small → **PRECISION**

• Initial beams are flavor "pure" (BB) or "tagged" by final lepton charge (NF) → **PRECISION**

• The NF has the additional advantages of very low background rates (wrong-sign muon signature) & a wealth of information (to obtain oscillation parameters can measure and simultaneously fit 6 spectra with μ^+ & 6 spectra with μ^- stored) → **PRECISION**.

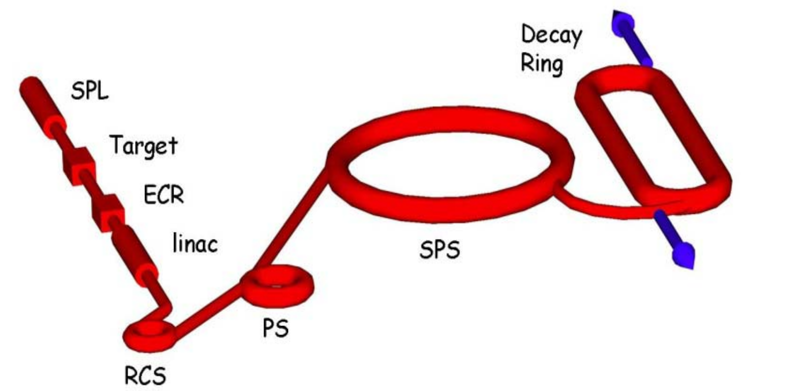
BETA BEAMS

- Need beta-decaying ion sources for ν_e & anti-ν_e

- Accelerate to high energy ($E_\nu \leq 2\gamma Q$ with Q~few MeV) & need fast ramp

- Store in decay ring

- Would also like conventional ν_μ beam with same L/E

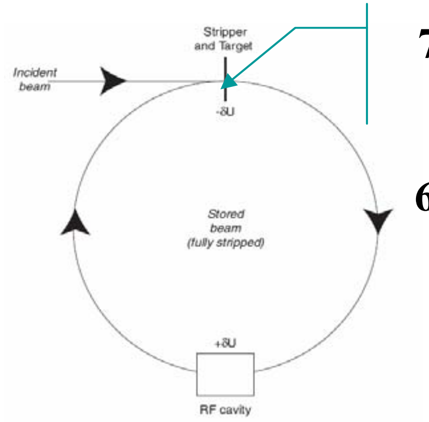


Eurisol at CERN: Ion choice: ^6He and ^{18}Ne

CERN EXAMPLE

EURISOL+SPS
$\gamma \leq 150$ (^6He) or 250 (^{18}Ne)
Ring length ~ 6km
Beam → Frejus (L=130km)

^7Li
^6Li



$^7Li(d,p)$
^8Li
$^6Li(^3He,n)^8B$

Alternative Ion Source using ring with gas-jet target & ionization cooling
(C. Rubbia et al., NIM A 568 (2006) 475–487)

FNAL BETA BEAM SCENARIO

ILLUSTRATIVE SCENARIO

- Proton Source = Project X
- New ion source: ^{8}Li and ^{8}B
  - Target
  - ECR to strip & bunch
- Ion Acceleration
  - New Linac → ~100 MeV/u
  - New Synchrotron→~500 MeV/u
  - Booster → γ = few
  - MI → final energy
- New decay ring (circum= ~3 Km)

EXAMPLE

	γ	$\langle E_\nu \rangle$	τ_0 (rest)
^{8}Li	60	1.0 GeV	0.84s
^{8}B	101	1.7 GeV	0.77s
Baseline	L~300km		

R&D ISSUES

General

- ^{8}B production (sticks to target)
- High freq. ECR source (to deal with intensities)

Fermilab specific

- Accumulator ring design
- Decay ring design
- Detailed study of intensity limitations due to e.g. activation of machines (estimate 1 W/m from decay in Booster for 10^{19} decays/yr in straight).
- Detailed study of RF required manipulations

NOTE: Following the 2004 APS Neutrino Study recommendation with limited U.S. resources, have not invested in BB R&D→ No FNAL BB Feasibility Study.

NEUTRINO FACTORY DESIGN STUDIES

In the U.S. (with international partners) we have been investing in NF R&D for the last decade (NF idea proposed in 1997) → component development, systems testing, & 4 generations of design studies:

- **First Generation "Feasibility" Studies:**
  Feasibility Study 1 (FNAL 2000)
  Japanese Study 1 (2001)
  CERN Study (2004)

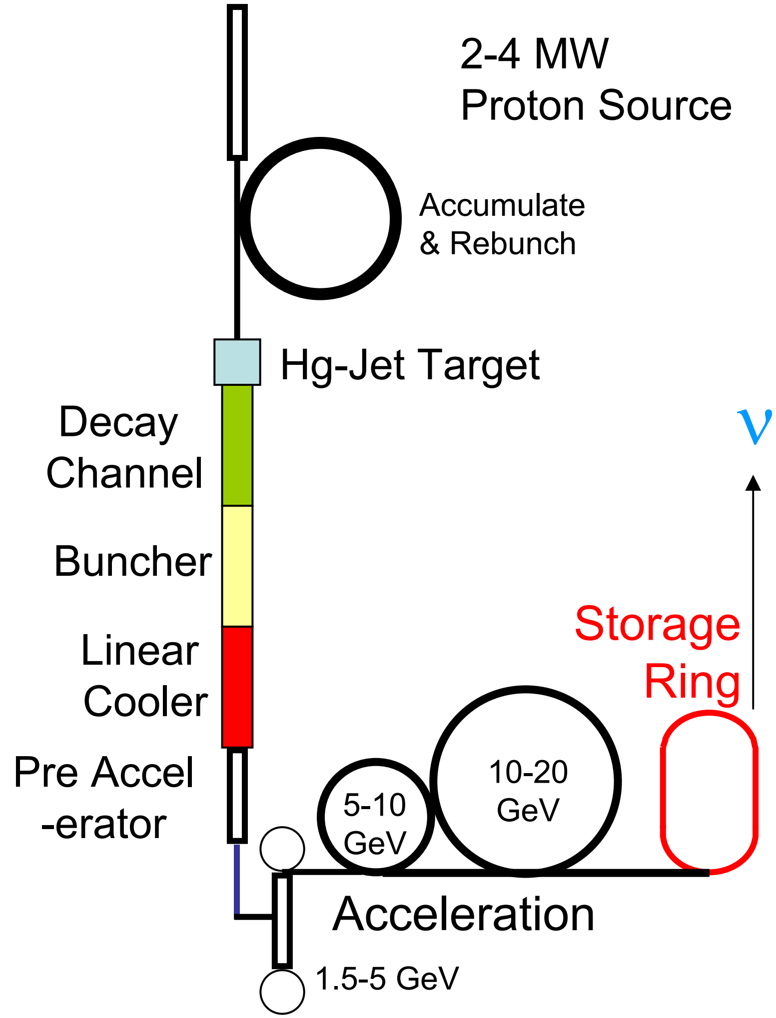
- **Second Generation "Performance & Cost-Reduction" Studies:**
  Study 2 (BNL 2001): performance
  Studies 2a & 2b (2001-6): cost effectiveness

- **Third Generation "International" Study:**
  International Scoping Study (RAL 2006): International baseline design

- **Fourth Generation Study:**
  International Design Study: ZDR by ~2010, RDR by ~2012)

NEUTRINO FACTORY INGREDIENTS

- Proton Source
  - primary beam on production target
- Target, Capture, and Decay
  - create π; decay into μ
- Bunching & Phase Rotation
  - reduce ΔE of bunch
- Cooling
  - reduce transverse emittance
- Acceleration
  - 130 MeV $\rightarrow E_{NF}$
- Storage Ring
  - store for 500 turns; long straight section



US Design schematic: 20 GeV NF
(Phys. Rev. ST Accel. Beams 9, 011001 (2006))

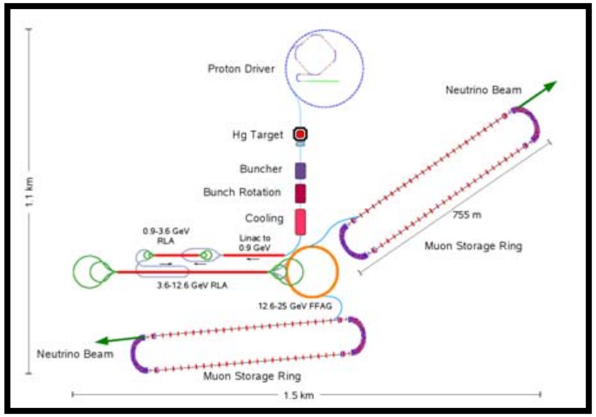
NEUTRINO FACTORY: ISS DESIGN

- **International Neutrino Factory design study** sponsored by RAL

– Participation & leadership from Europe, U.S., & Japan.

– Selected 25 GeV NF design similar to Study 2b 20 GeV design

– Report: RAL-TR-2007-23

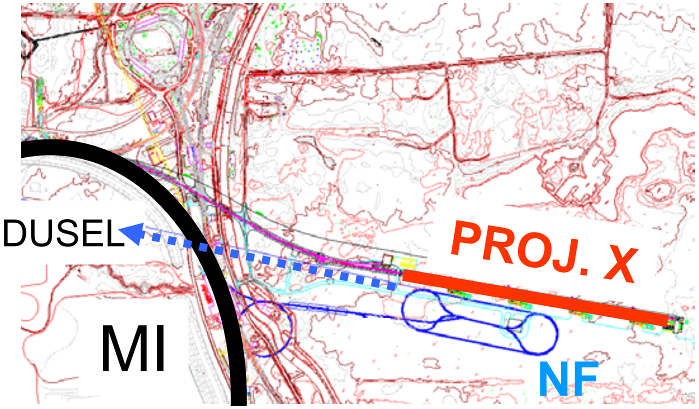


NEUTRINO FACTORY: 4 GeV DESIGN

- **During the ISS a new concept emerged for a NF detector that can measure the muon charge from low energy neutrino interactions.**

– 4 GeV NF combines strengths of Wide Band Beam (spanning several oscillations) & NF → outstanding perf-ormance for **both large & small θ_{13}**

– Cheaper (less acceleration) & matched to FNAL–DUSEL baseline



on the FNAL Site

PROTON SOURCE REQUIREMENTS

- **Need beam power (at least 2MW) and short bunches (3ns).**

- Optimum beam energy = 10 ± 5 GeV (ISS study) but at fixed power, muon yield drops slowly with energy - lose ~30% for E=120 GeV (Mokhov)

- **Project X is well suited to drive a NF. To get ≥2MW use either:**

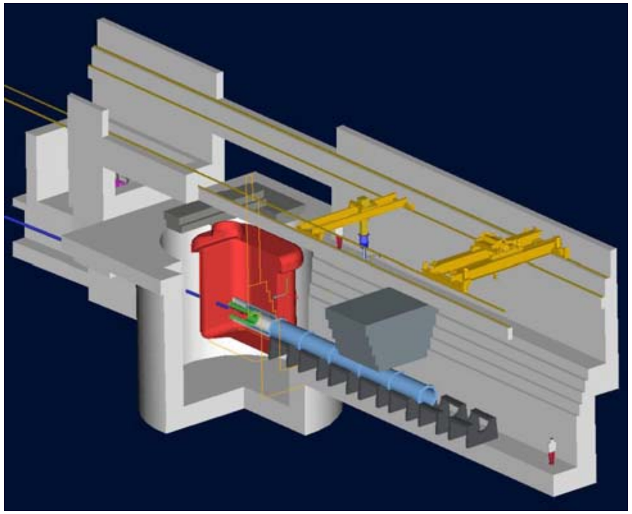
  (i) Project X + MI (50 GeV, say) + new 50 GeV rebunching ring, or
  (ii) Upgraded Project X (2MW at 8 GeV) + new 8 GeV rebunching ring.

TARGET STATION

- A 4MW target station design study was part of "Neutrino Factory Study 1" in 2000 → ORNL/TM-2001/124

- Facility studied was 49m long = target hall & decay channel, shielding, solenoids, remote handling & target systems.

- Target: liquid Hg jet inside 20T solenoid.

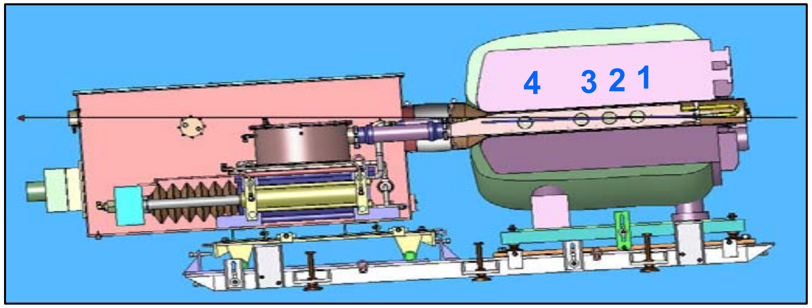


4MW Target Station Design

HOT NEWS: MERIT RESULTS

NF Studies 1 & 2 identified the target technology (a liquid Hg jet injected into a 20T solenoid) as the one of the most challenging parts of a NF → target R&D program.

- In Fall 2007 the target R&D culminated in the MERIT expt which successfully demonstrated a liquid Hg jet injected into a 15T solenoid, & hit with a suitably intense beam from the CERN PS (115 KJ / pulse !)



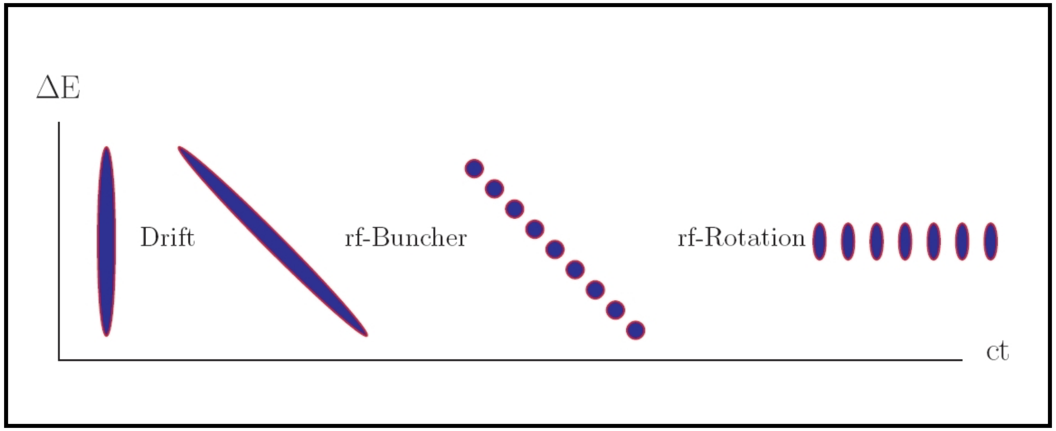
MERIT EXPERIMENT

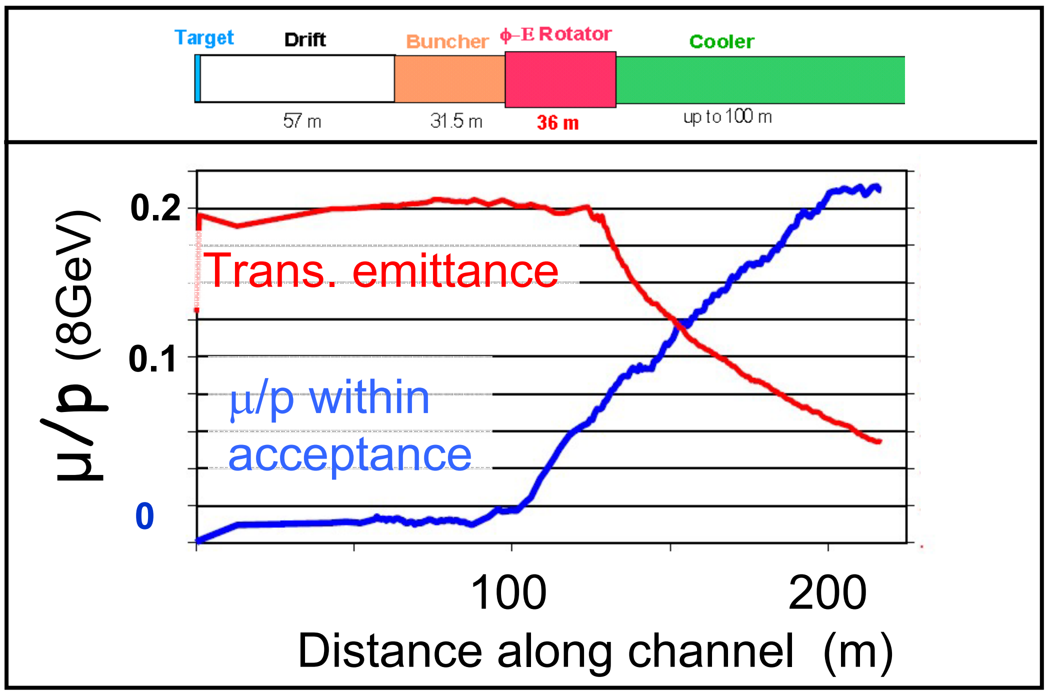
- The jet is disrupted, but this happens on a ms timescale (disruption length <28 cm ~ 2 int. lengths. The jet was observed to re-establish itself after 15ms … before the next beam pulse arrives.

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

Preliminary analysis suggests this target technology is good for beams up to 8 MW !

BUNCHING, PHASE ROTATION, COOLING





A clever arrangement of RF cavities bunches the muons & reduces their energy spread.

An ionization cooling channel reduces trans. phase space, increasing useful number of muons by ×1.7 (believed cost effective c.f. increasing detector mass)

Two R&D efforts must be completed for all this to be "can build" :

- **RF in magnetic fields**
- **MICE**

Normal Conducting RF in MAGNETIC FIELDS

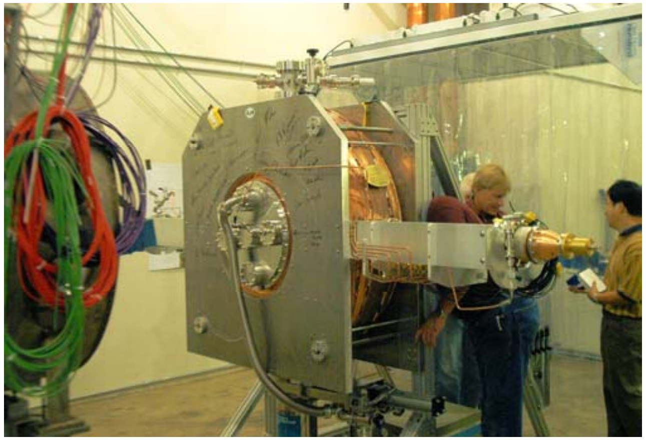
Need NCRF cavities operating in few-Tesla magnetic fields

• Could use open iris copper cavities (multi-cell 805 MHz cavity tested in few Tesla field)

• Since muons are penetrating particles, we have the option of closing the iris with a thin conducting window. At fixed peak power this doubles the gradient on-axis → **more compact channel & half the number of klystrons** !

• Two closed-cell cavity options being explored (vacuum cavities & cavities filled with high pressure H_2) . We are in the middle of the R&D needed to see if these options give the desired performance.

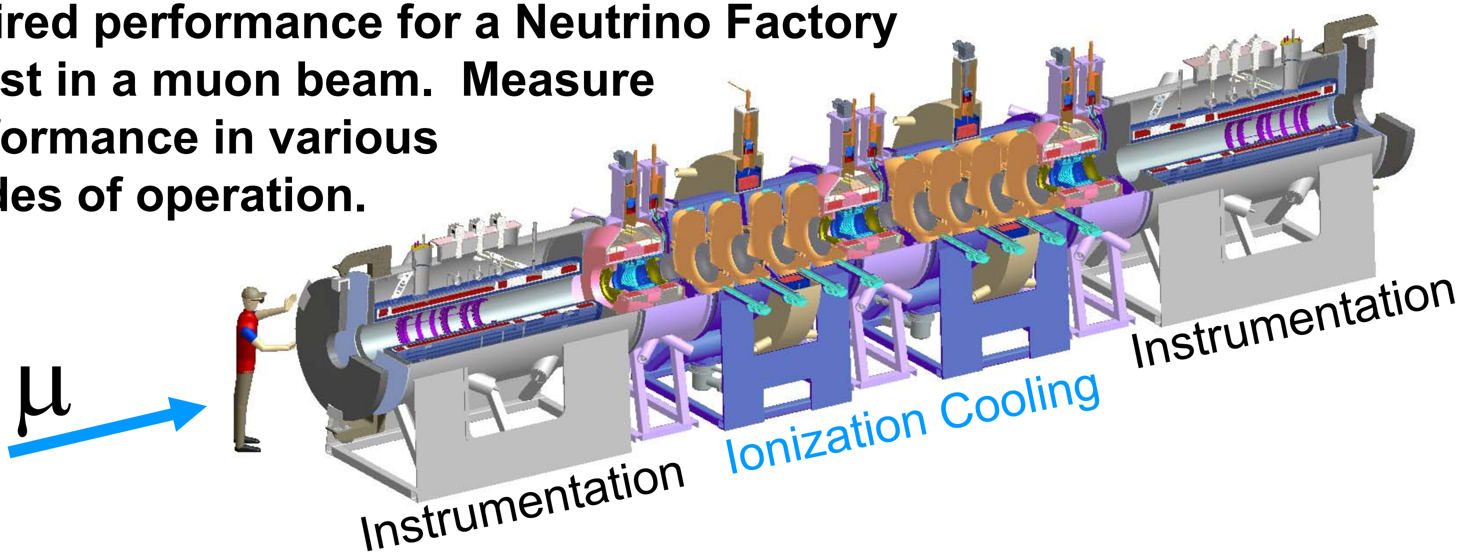
•Need to complete this R&D before locking in to the choice of RF technology.



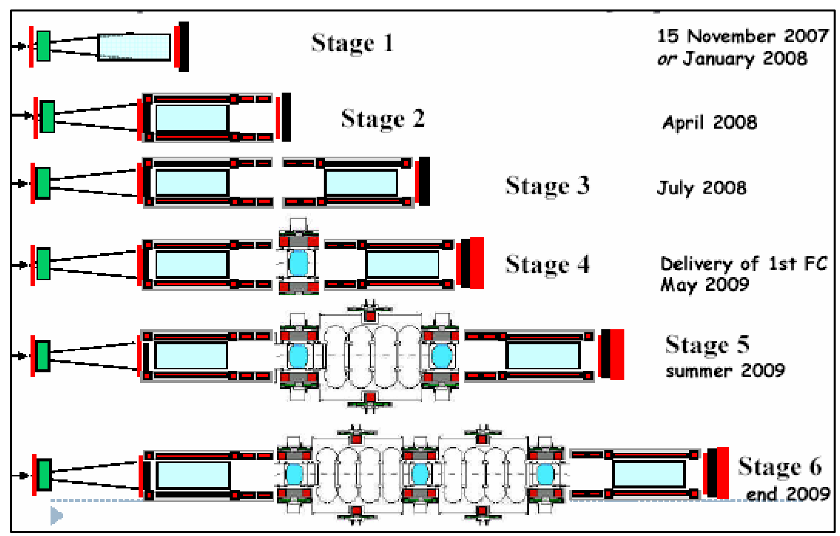
Closed-cell 201 MHz cavity processed with SCRF-type treatment (electro-polishing etc) … exceeded design gradient without any conditioning. Will be tested in appropriate magnetic field next year.

INTERNATIONAL COOLING EXPERIMENT: 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 currently being installed at a purpose-built muon beam at RAL.
- Anticipate final stage complete by ~2010



ACCELERATION

- Designs for the acceleration scheme use 201 MHz SCRF

- 201 MHz SCRF R&D at Cornell - observed substantial “Q-slope”, but achieved 11 MV/m

- 11 MV/m may be OK for 4 GeV NF (although higher gradients preferred)

201 MHz SCRF cavity at Cornell

PREACCELERATOR DESIGN

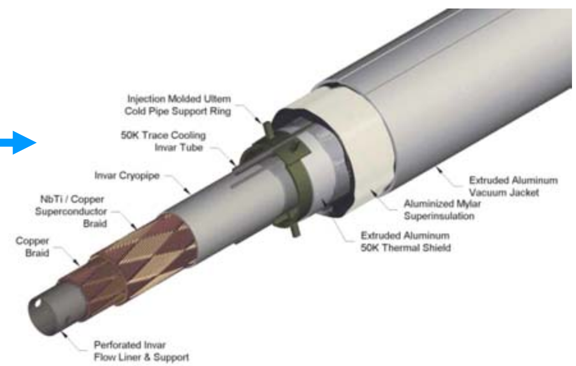
Need to continue R&D on Q-slope, demonstrate ≥11 MV/m performance can be achieved routinely for several cavities, & design and prototype the required cryo-modules.

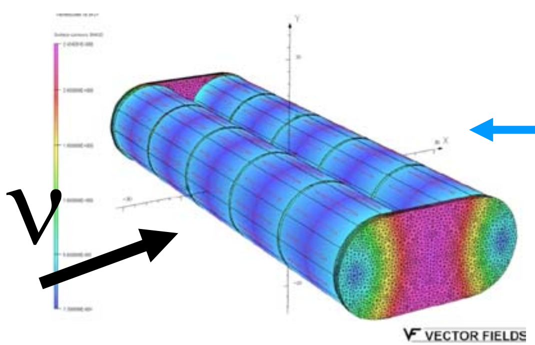
DETECTOR MAGNET

- **Detector must measure muon-sign → magnetized → Fine-grain MINOS-like detector will work for a NF with E ≥ 20 GeV.**

- **For low energy NF (e.g. 4 GeV) need affordable large volume magnet (B ~ 0.5T) so we can use a low-Z fully active detector.**

Eliminate large (expensive) cryostat & vac loads by using superconducting transmission line concept developed for the VLHC – wrap it into a solenoid !





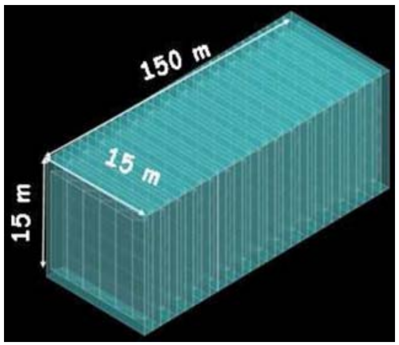
Build a magnetic cavern ($0.5T \times 34000\ m^3$). Example: two parallel solenoids with iron end-plates

- **Initial engineering study looks promising -- must prototype & test.**

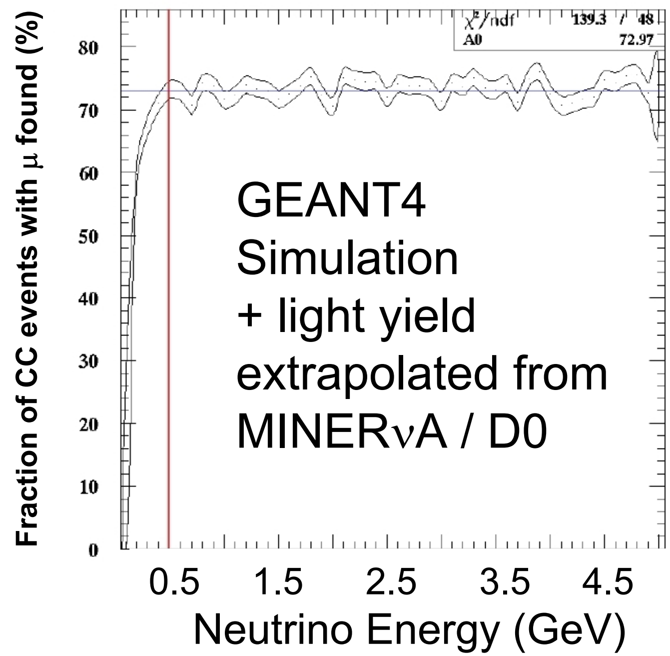
LOW ENERGY NF DETECTOR at DUSEL

- **Initial simulation study performed for a 4 GeV NF detector**

- M_{det} = 35 Kt, M_{fid} = 20 Kt,
- Vol = 15 × 15 × 150 m^3
- B = 0.5T



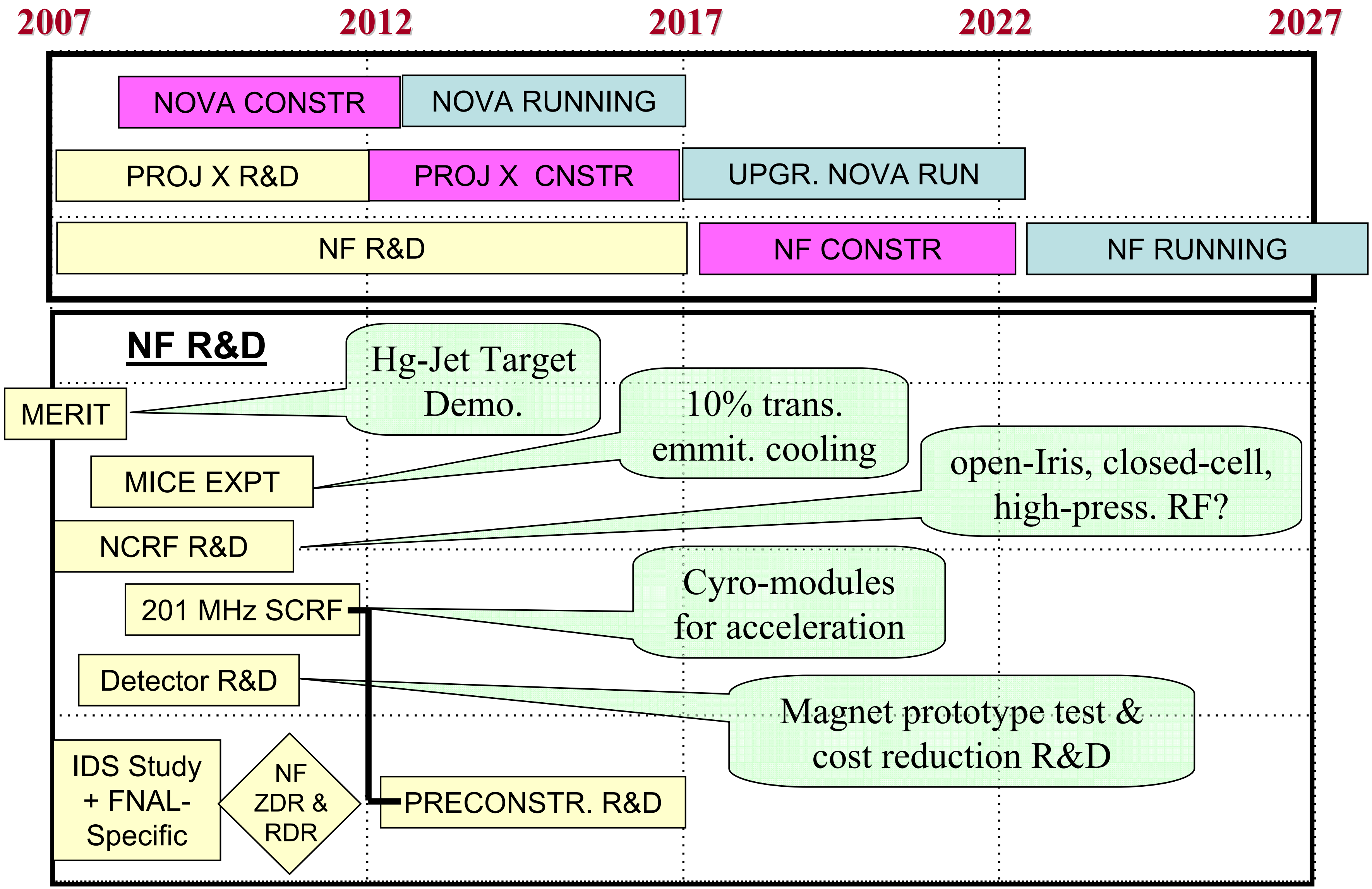
15m long scintillators
triangular cross-section
(base=3cm, ht=1.5cm)



Good muons reconstruction eff. for CC interactions with E_ν > 500 MeV/c. Muon momentum resolution better than few % below 3GeV/c, & charge mis-id rate < 10^{-4}.

- **Detector R&D needed to better understand performance & reduce cost associated with large number of channels – O(10^7)**
(Note: LAr detector may also be an option)

ILLUSTRATIVE TIMELINE



R&D SUPPORT and NF COST ESTIMATES

- **FY07/08 annual U.S. funding level for NF+Muon Collider R&D:**
  5.5M$ (SWF) + 2.4M$ (M&S)=7.9M$ (of this 2M$ is Muon Collider specific)

R&D estimates corresponding illustrative timelime

	FY09	FY10	FY11	FY12	FY13	FY14	FY15	FY16	FY17
MICE M&S	0.8	1.3	0.2	0.2					
NCRF M&S	1.0	1.0	1.0	2.0					
SCRF M&S	1.0	1.0	2.0	3.0					
DET M&S	0.1	0.2	1.0	1.0					
OTHER M&S	0.8	0.8	0.8	1.5					
M&S TOTAL	**3.7**	**4.3**	**5.0**	**7.7**					
SWF+Indir.	8.5	10.4	12.1	13.8					
TOTAL	**12.2**	**14.7**	**17.1**	**21.5**	**30**	**30**	**40**	**40**	**50**

Σ = ~10% of project cost

4 GeV NF Cost Estimate (excluding 2 MW proton source)

Start from Study 2 cost estimate scaled to account for post-study 2 improvements (ranges reflect uncertainties in scaling) →

ILC analysis suggest loading coeff = 2.07 for accelerator systems and 1.32 for CFS. Labor assumed 1.2 × M&S →

Loaded estimate = 2120 - 2670 (FY08 M$)

Unloaded estimate (M$)

Target Systems	110
Decay Channel	6
Drift, Ph. Rot, Bunch	112-186
Cooling Channel	234
Pre-Acceleration	114-180
Acceleration	108-150
Storage Ring	132
Site Utilities	66-156
TOTAL (FY08 M$)	**881-1151**

CONCLUDING REMARKS

- Sensitivity to neutrino oscillation physics motivates the development of an advanced neutrino source - see appendix

- We have a 10 year investment in NF R&D, with 3 generations of design study, R&D to develop the critical components, & two big international systems-demonstration experiments (MERIT & MICE).

- The international community is now working towards a “ZDR/RDR” by ~2010/2012. The R&D timeline & funding profile (last 2 slides) would enable the U.S. to step up to the plate and maintain our share of NF leadership, and give the U.S. a NF option that follows Project X.

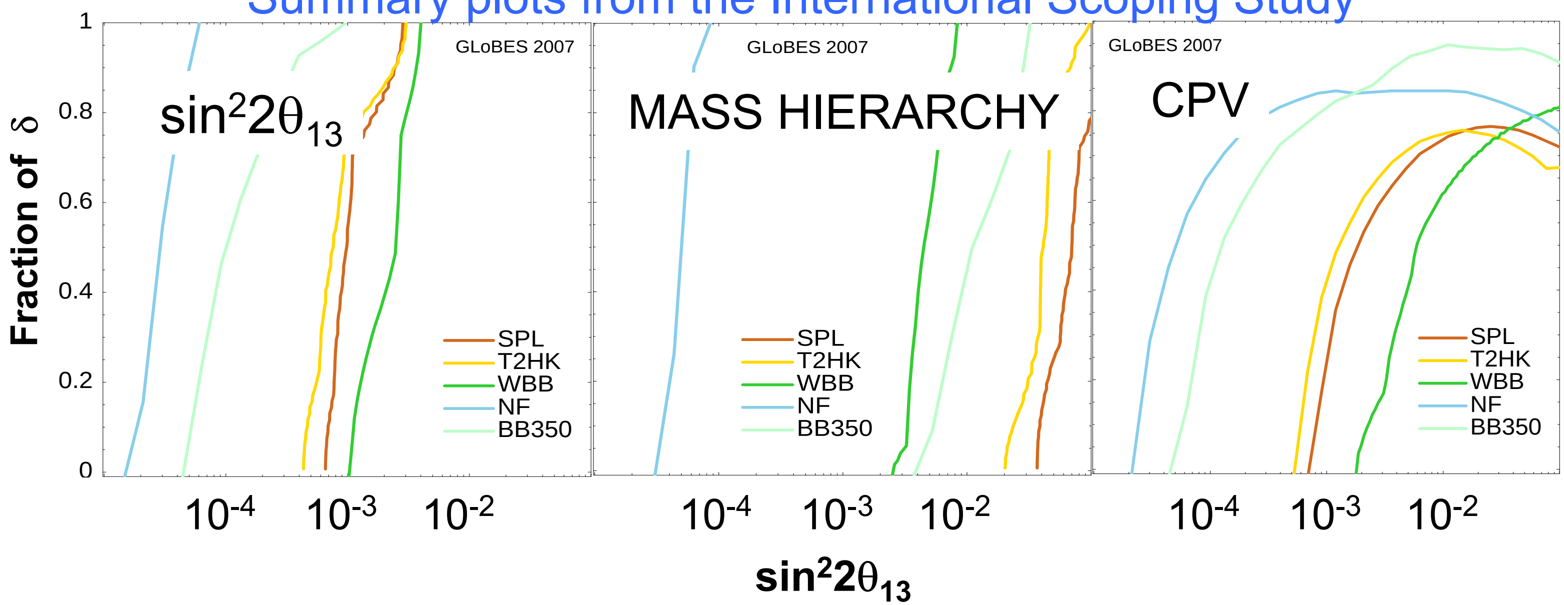
- Building a muon source for a NF is a very desirable step in establishing the technologies needed for a multi-TeV Muon Collider, and might provide a staged path to a multi-TeV lepton collider.

- BB R&D has been proceeding in Europe. Physics comparisons of BB & NF are shown in the appendix.

APPENDIX: Discovery Reach for 25 GeV NF

- **Physics reach for 25 GeV NF looks great & if θ_{13} is small may be the only option.**

Summary plots from the International Scoping Study



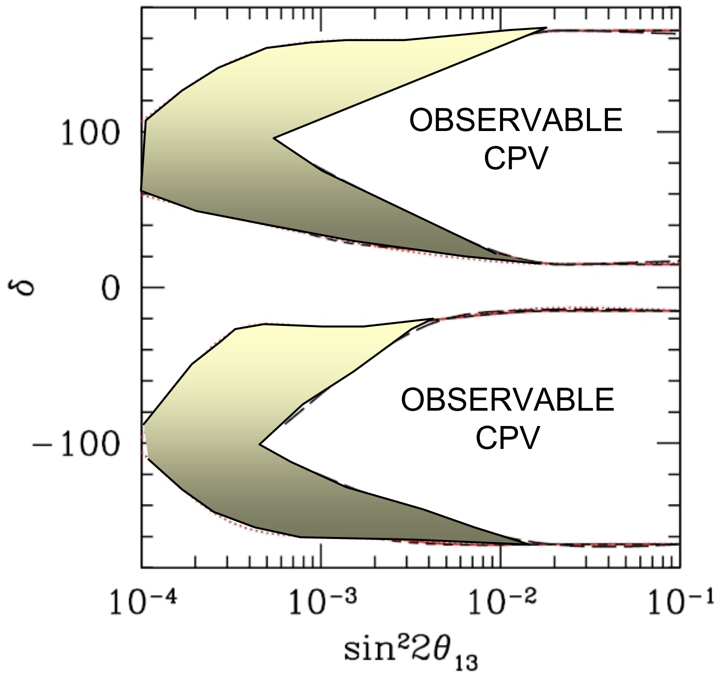
- All of these (WBB, BB, NF, T2HK) next-but-one generation neutrino experiment options are necessarily ambitious.

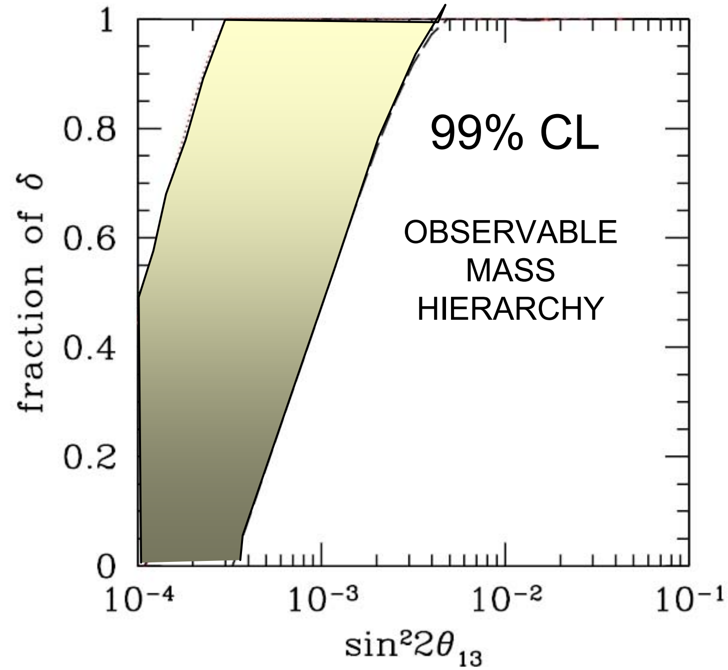
- The NF is the most sensitive option for very small θ_{13}.

- Not shown in the above plots is the low-energy NF which has great sensitivity for large (and small) θ_{13}.

APPENDIX: Discovery Reach 4 GeV NF

- **Physics reach for 4 GeV NF looks great for both large and small θ_{13}**
  - *Geer, Mena, & Pascoli, Phys. Rev. D75, 093001, (2007).*
  - *Bross, Ellis, Geer, Mena,& Pascoli, hep-ph arXiv:0709.3889*





- Bands cover range of run times (3-10y) & background levels (0 -10^{-3}).
- Combines strengths of conventional Wide Band Beam (spanning several oscillations) with low systematics of NF.
- If $\sin^2 \theta_{13}$ > few x 10^{-3} can go well beyond discovery, and make precision measurements. If θ_{13} small, have discovery reach down to $\sin^2 2\, \theta_{13}$ ~ few x 10^{-4}

APPENDIX: Statistical Precision – 4 GeV NF

Wrong-sign μ Rates at L=1280 km for normal (inverted) hierarchies & θ_{13}=8°

statistics (Kt-decays)	$\delta(^o)$	μ^+ stored (wrong-sign: μ^-)	μ^- stored (wrong-sign: μ^+)
3×10^{22} 20 Kt × 3 years	0	3340 (1600)	870 (1770)
	90	4400 (2300)	475 (1200)
	180	3400 (1660)	774 (1670)
	270	2330 (930)	1170 (2240)
1×10^{23} 20 Kt × 10 years	0	11140 (5335)	2900 (5900)
	90	14670 (7670)	1580 (4000)
	180	11340 (5530)	2580 (5570)
	270	7770 (3100)	3900 (7470)

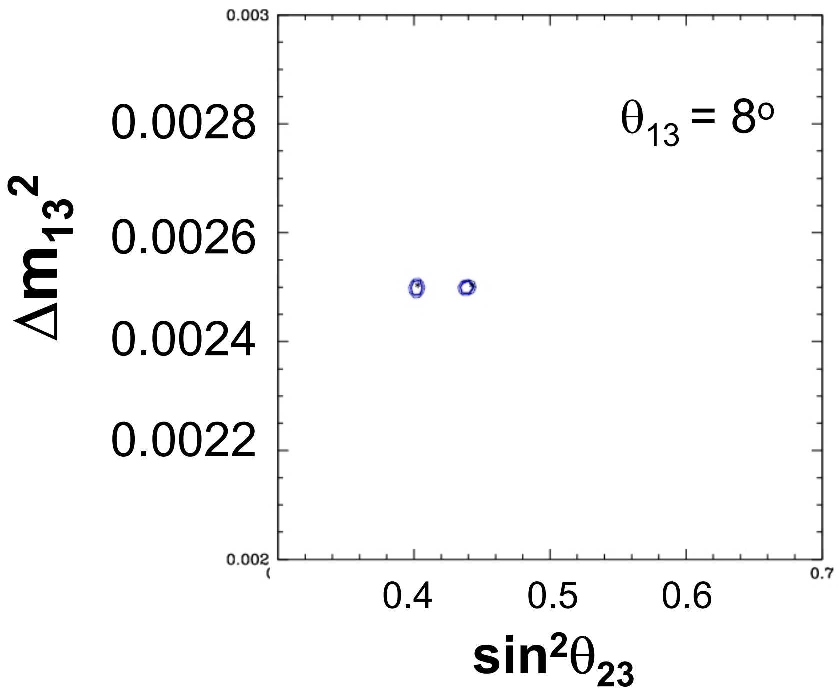
Table 2: *Wrong sign muon event rates for normal (inverted) hierarchy, assuming* $\nu_e \rightarrow \nu_\mu$ $(\bar{\nu}_e \rightarrow \bar{\nu}_\mu)$*oscillations in a 20 Kt fiducial volume detector, for a L = 1280 km baseline. We assume here* $\theta_{13} = 8^o$, *i.e.* $\sin^2 2\theta_{13} \simeq 0.076$. *We present the results for several possible values of the CP-violating phase* δ *for both the low and the high luminosity scenario.*

- If θ_{13} is large, the signal data samples in a 20 Kt NF detector would be a few $\times 10^3$ – a few $\times 10^4$.

- Backgrounds would be expected to be $\leq O(10^{-3})$ of the CC rate.

APENDIX: Precision Disappearance Measurements

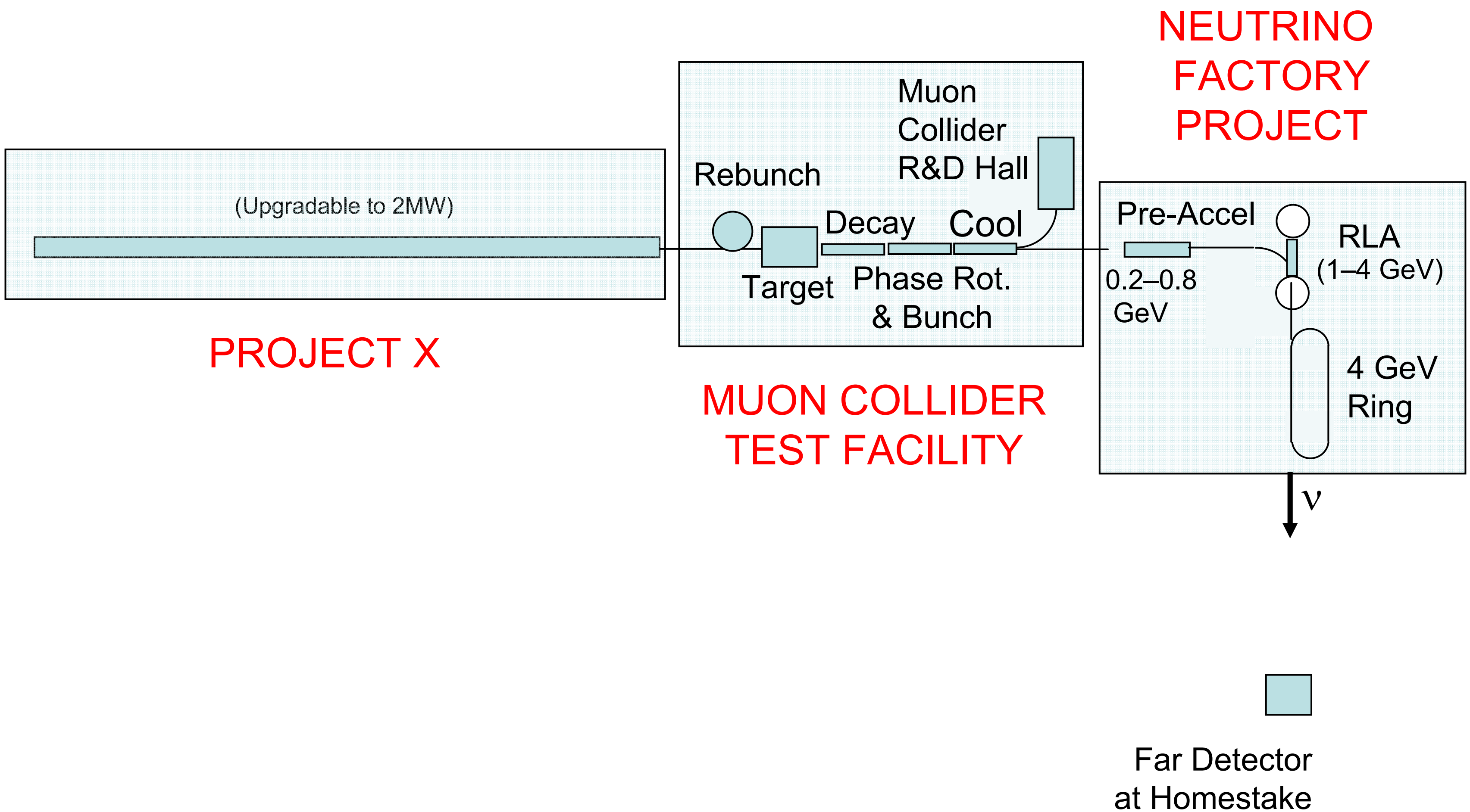
- Physics reach plots are based on the $\nu_e \rightarrow \nu_\mu$ channel. There is also the ν_μ disappearance channel, which also offers precision.



$\sigma(\Delta m_{13}^2) \sim 1\text{-}2\%$

- The Δm^2 sensitivity might be good enough to be able to determine the mass hierarchy even if $\theta_{13} = 0$! (Note: $P(\nu_\mu \rightarrow \nu_\mu)$ depends on both $|\Delta m^2_{13}|$ and $|\Delta m^2_{23}|$, & with sufficient sensitivity can determine who is larger than who).

APENDIX: Relationship between NF & Muon Collider R&D



APENDIX: Staging from NF to 1.5-4 TeV Muon Collider