Neutrino Factory and Muon Collider Collaboration
Introduction

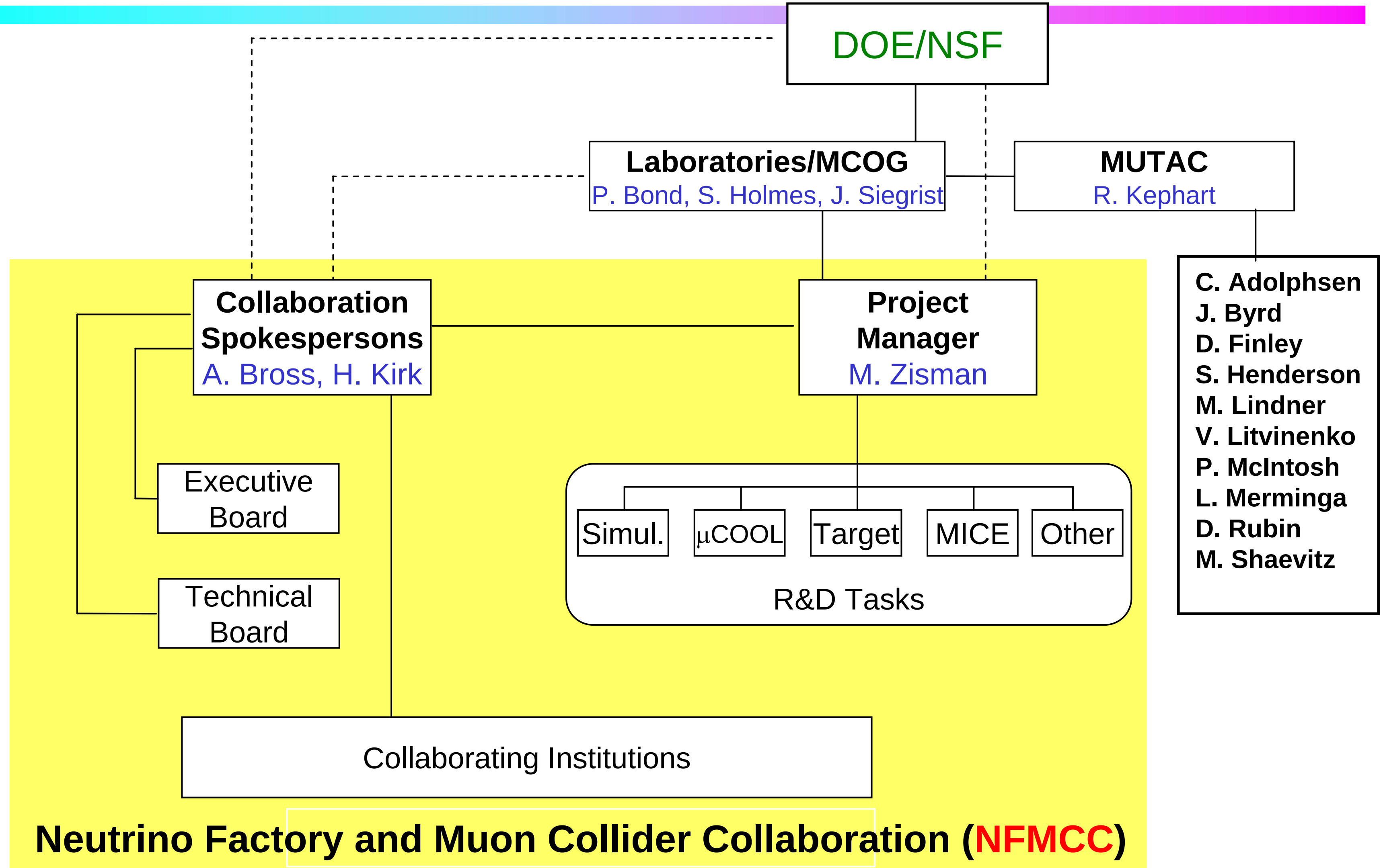
MUTAC Review
April 2007
Alan Bross

NFMCC Mission

To study and develop the theoretical tools, the software simulation tools, and to carry out R&D on the hardware that is unique to the design of Neutrino Factories and Muon Colliders

- **Extensive experimental program to verify the theoretical and simulation predictions**

Current Organization



Collaborating Institutions

US

National Labs
ANL
BNL
FNAL
LBNL
ORNL
TJNAF

Universities
Cornell
IIT
Indiana
Michigan State
Mississippi
Northern Illinois
Princeton
UC-Berkeley
UC-Davis
UC-Los Angeles
UC-Riverside
University of Chicago

International

National Labs
Budker
CERN
DESY
INFN
JINR, Dubna
KEK
RAL
TRIUMF

Universities
Karlsruhe
Imperial College
Lancaster
Max Planck
Osaka
Oxford
Pohang
Tel Aviv

Corporate Partners
Muons Inc.
Tech-X Corporation

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Scientific Program

Targetry R&D: Mercury Intense Target Experiment (MERIT)

Co-Spokespersons: Kirk McDonald, Harold Kirk

Ionization Cooling R&D: MuCool and MICE

MuCool Spokesperson: Alan Bross

US MICE Leader: Dan Kaplan

Simulations & Theory

Coordinator: Rick Fernow

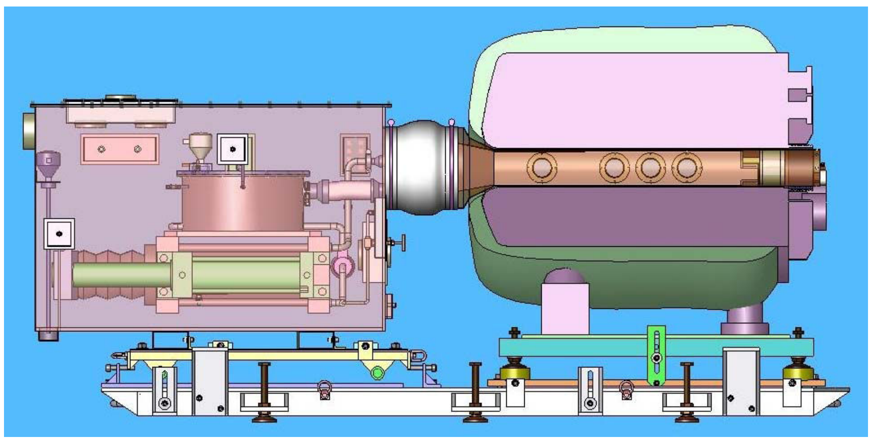
Collaborating on Electron Model for Muon Acceleration Project (EMMA)

Fermilab Muon Collider Task Force

V. Shiltsev, S. Geer

MERIT –Mercury Intense Target

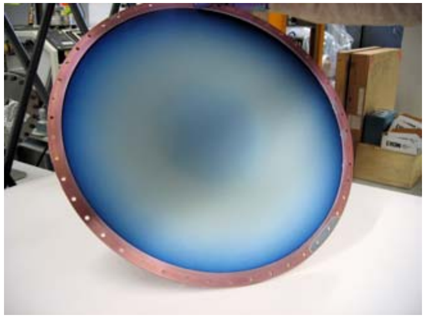
- Test of Hg-Jet target in magnetic field (15T)
- Proposal submitted to CERN April, 2004 (approved April 2005)
- Located in TT2A tunnel to ISR, in nTOF beam line
- First beam July, 2007



Muon Cooling: MuCool and MICE

Component R&D and Cooling Experiment

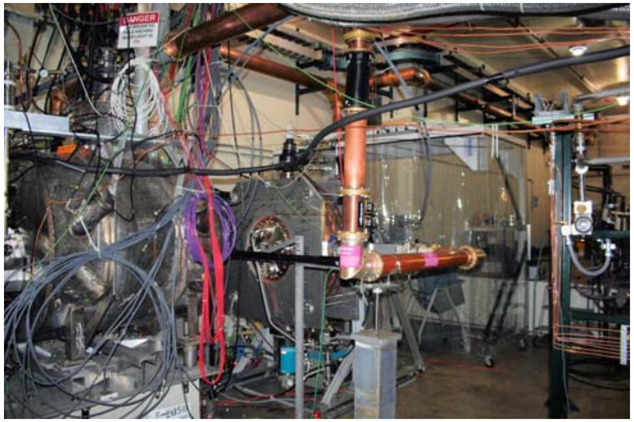
- **MuCool**
  - Component testing: RF, Absorbers, Solenoids
  - Uses Facility @Fermilab (MuCool Test Area –MTA)
  - Supports Muon Ionization Cooling Experiment (MICE)



50 cm ∅ Be RF window

MuCool Test Area

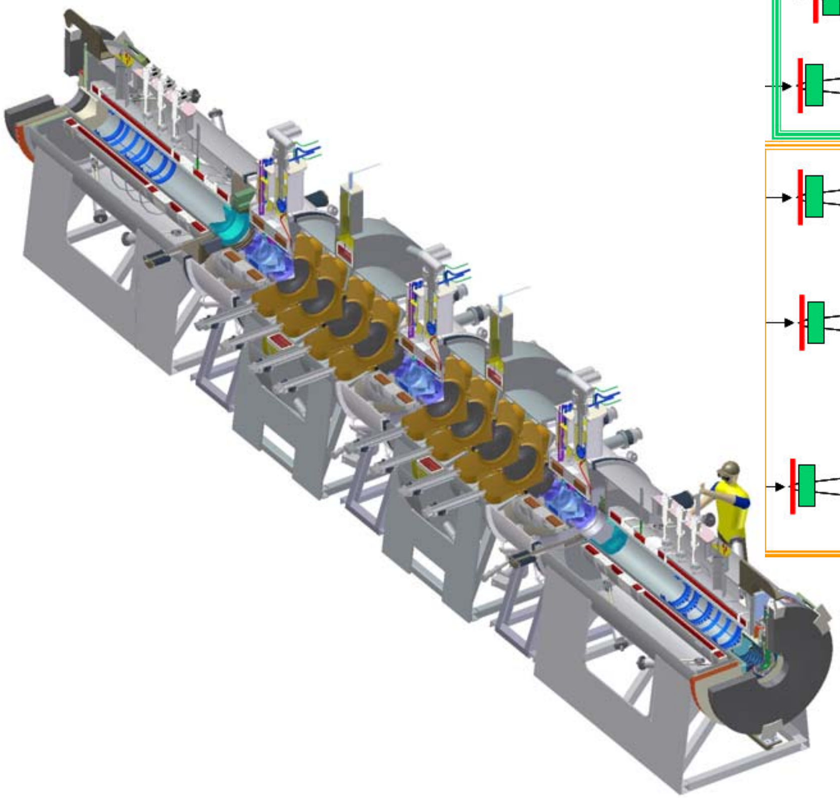
MuCool
201 MHz RF Testing

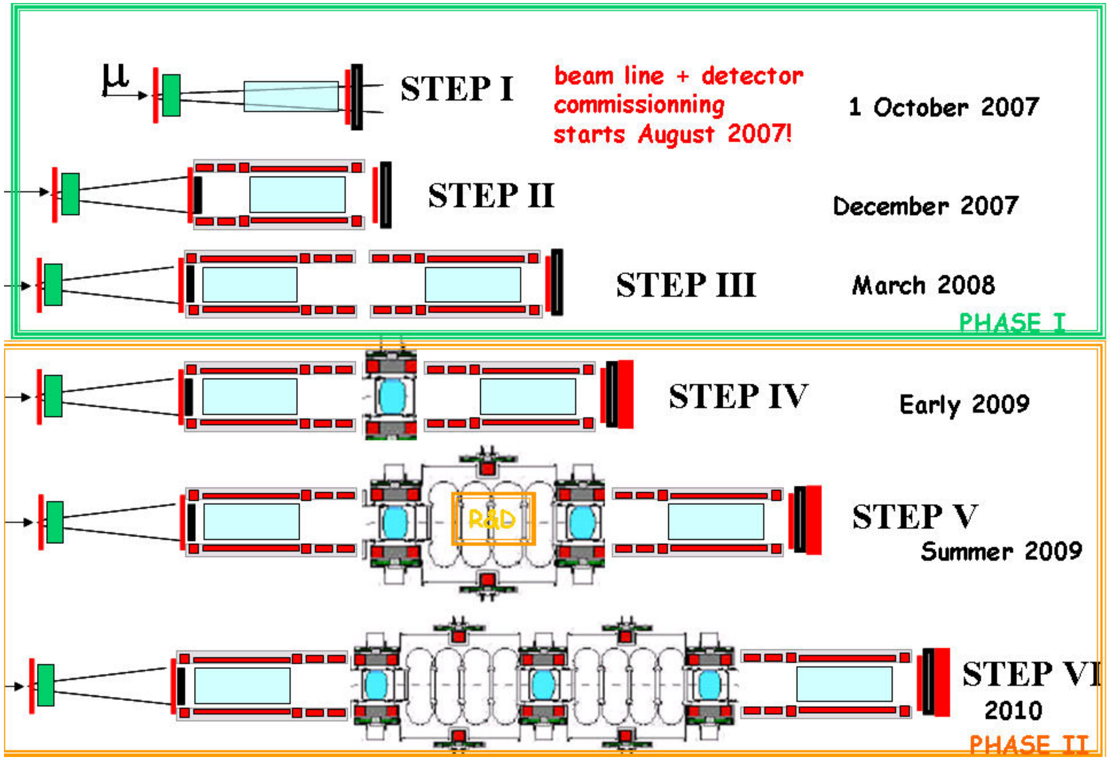


MuCool
LH_2 Absorber
Body

Muon Ionization Cooling Experiment (MICE)

MICE
Measurement of Muon Cooling
Emittance Measurement @ 10^{-3}
First Beam August 2007





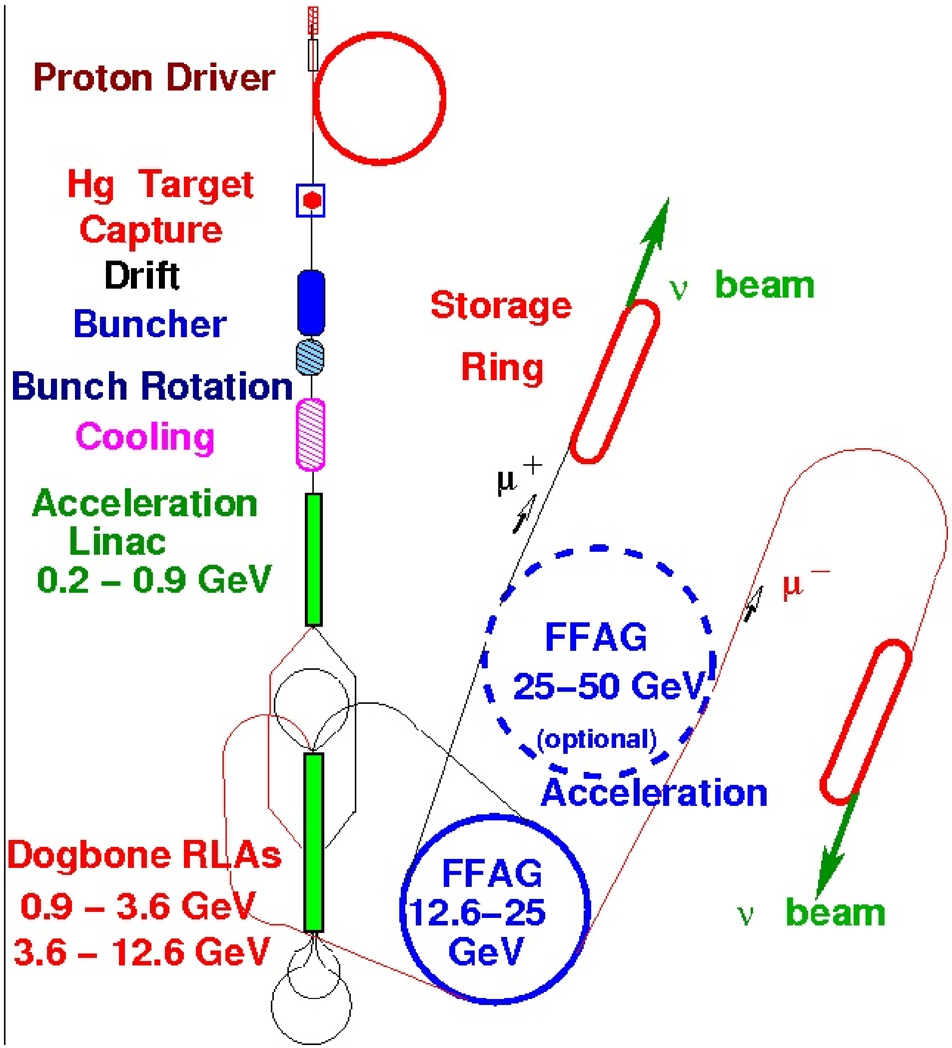
Design Studies

- Very Productive Period for the Collaboration
  - Strong participation in the International Scoping Study of a Future Neutrino Factory and Super-beam facility (ISS)
    - Super Beams
    - Beta-Beam Facility
    - Neutrino Factory

The Collaboration's Focus was NF

  - Exciting New developments in Muon Collider Design and Simulation
    - Complete cooling scenario for a Muon Collider
      - All cooling components have been simulated
    - Low-emittance Muon Collider

Neutrino Factory – ISS Preliminary Design



- Proton Driver
- Target, Capture, Decay (MERIT)
  - $\pi \to \mu$
- Bunching, Phase Rotation
  - Reduce ΔE
- Cooling (MICE)
- Acceleration (EMMA)
  - 103 MeV $\to$ 25 & 50* GeV
- Storage/Decay ring

*Still under study

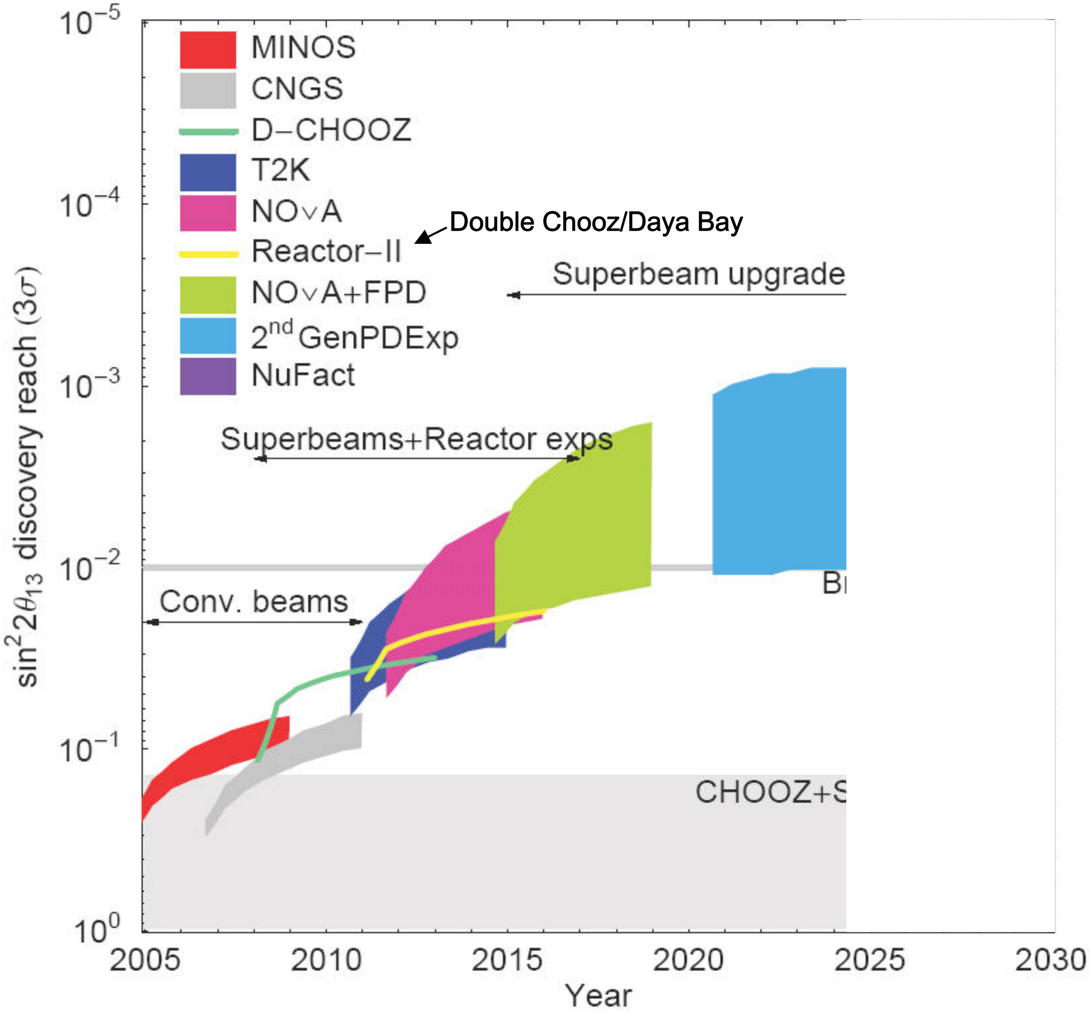
The Big Neutrino Questions

- What is the origin of neutrino mass?
- Did neutrinos play a role in our existence?
  - Galaxy Formation
- Did neutrinos play a role in birth of the universe?
- Are neutrinos telling us something about unification of matter and/or forces?
- Will neutrinos give us more surprises?

Big questions ≡ tough questions to answer

Is a Neutrino Factory needed in order to answer these questions?

Neutrino Factory – The Physics Case

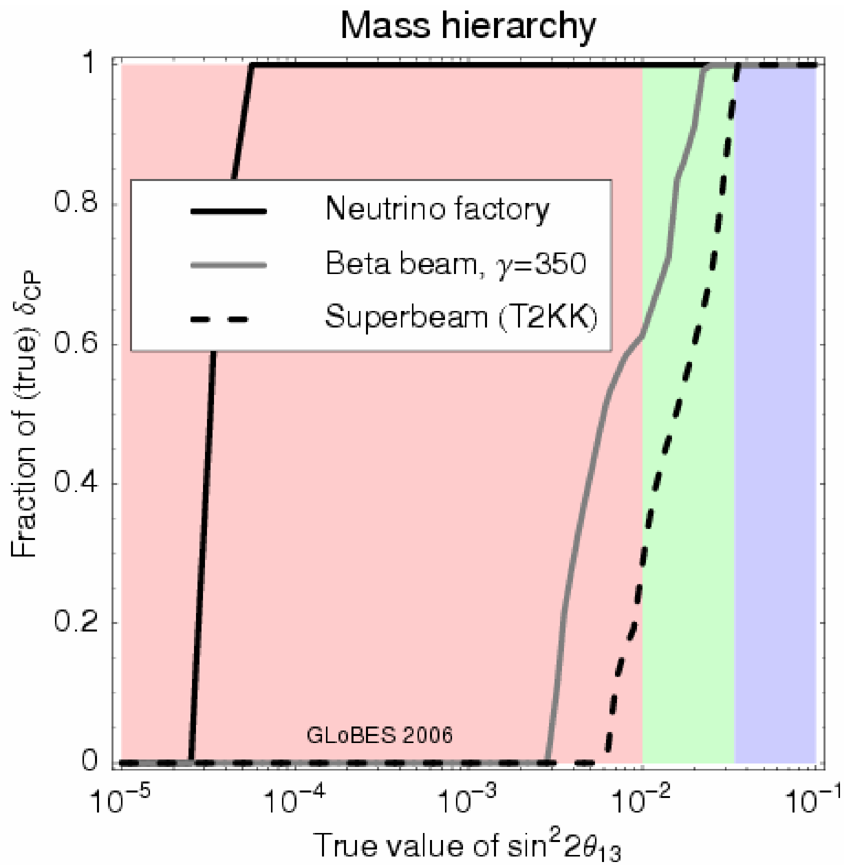


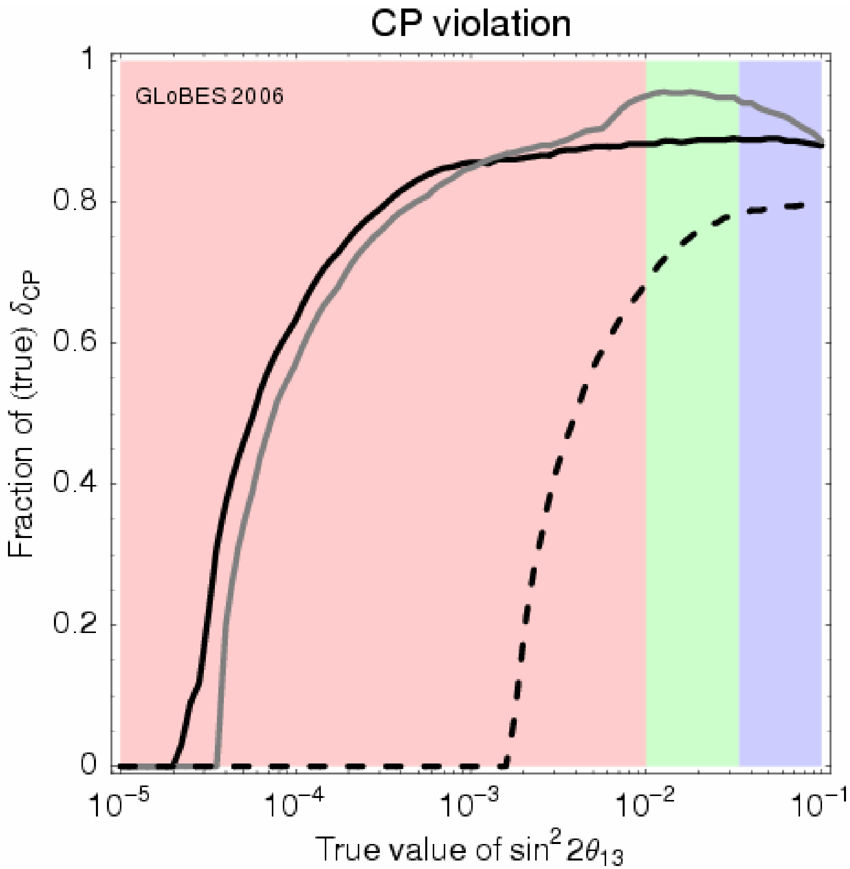
We Don't Know –
But
There is a Natural Decision Point
≈ 2012

After NOvA and T2K
If θ_{13} not seen
or
seen at 3σ
Consider Major Upgrades or New Facility

In order to make an informed decision about a New Facility and if the NF plays at role – Will need a TDR ready at this time
This defines the R&D Program

Neutrino Factory- ISS



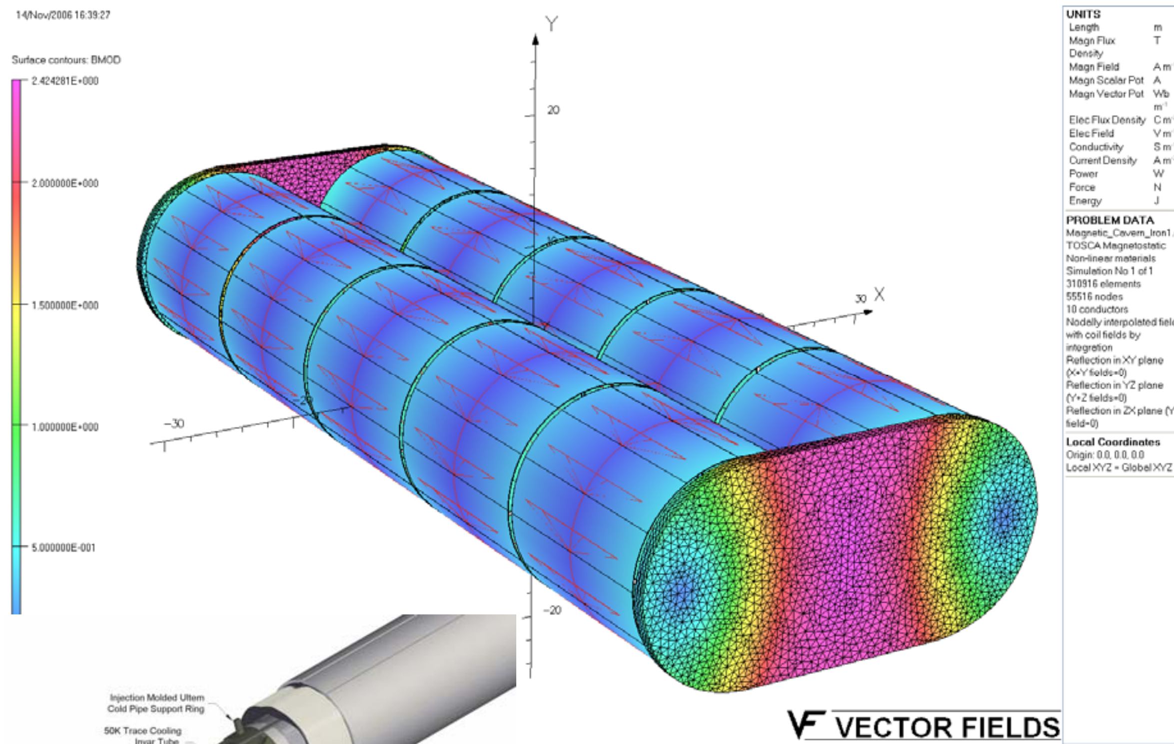


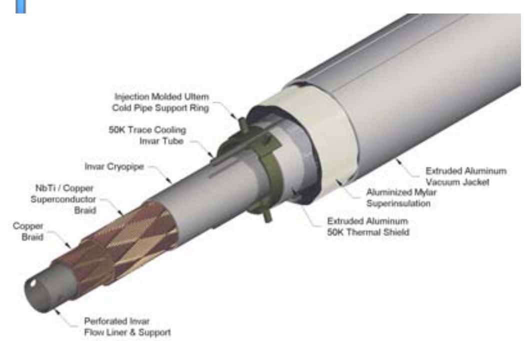
(3σ, Δm_{31}^2=0.0022 eV^2)

Best possible reach in θ_{13} for all performance indicators =Neutrino factory

Neutrino Factory Detector Design

- Totally Active Sampling Calorimeter 25kT
- 15m ∅ X 15m long -0.5T
  - Times 10!
  - Cost estimate
    - $140-680M
- New Ideas
  - High T_c SC
    - No Vacuum Insulation
  - VLHC SC transmission line
    - Technically proven
    - Might actually be affordable





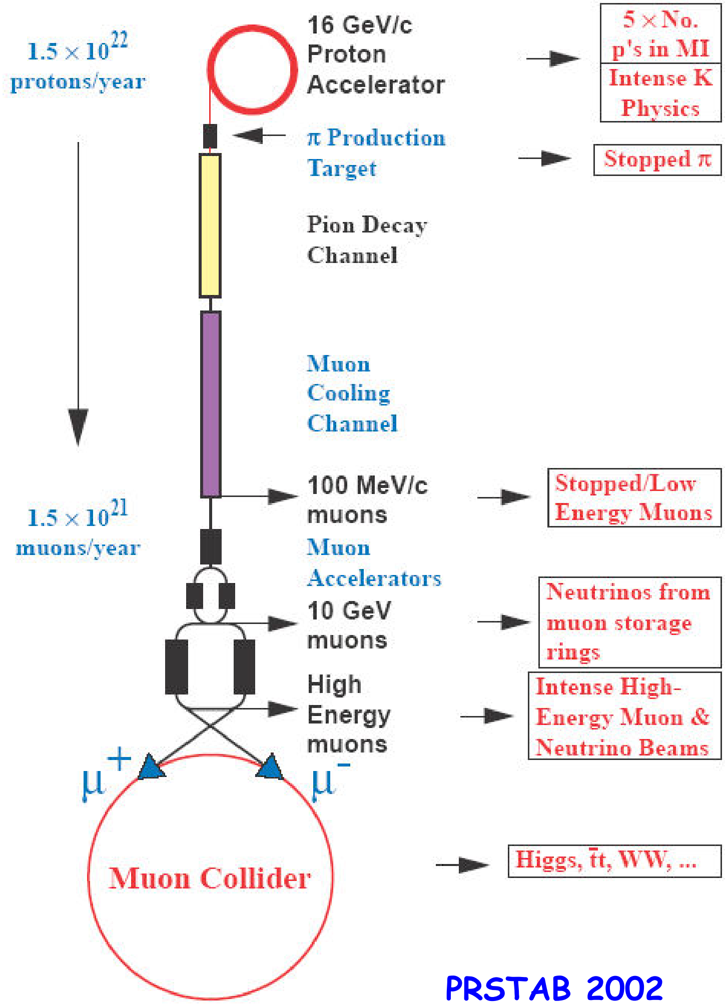
Muon Collider - Motivation

Reach Multi-TeV Lepton-Lepton Collisions at High Luminosity

Muon Colliders may have special role for precision measurements.
Small ΔE beam spread -
Precise energy scans

Small Footprint -
Could Fit on Existing Laboratory Site

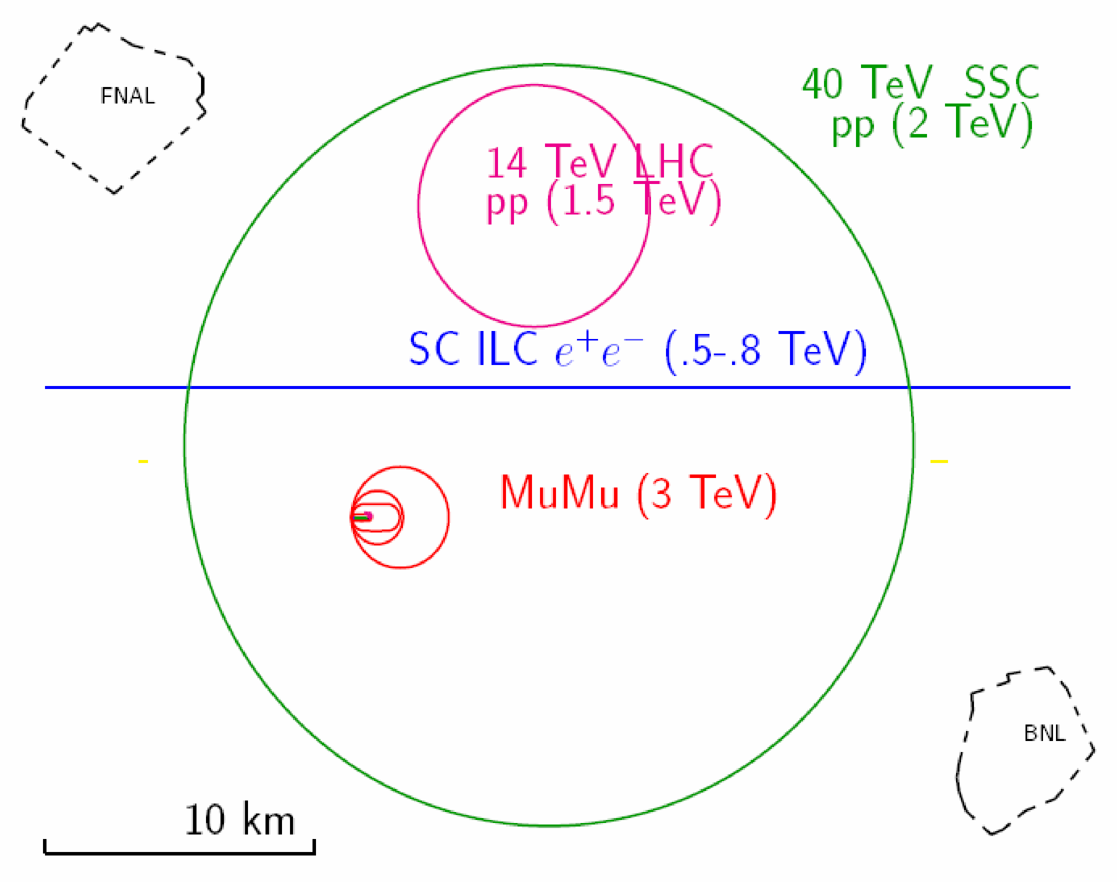
Evolution of a Physics Program



PRSTAB 2002

- Intense Low-energy muon physics
  - Intense K physics, etc
- Neutrino Factory
- Energy Frontier Muon Collider
  - 1.5 - 4 TeV

The Muon Collider Motivation – Elevator Spiel

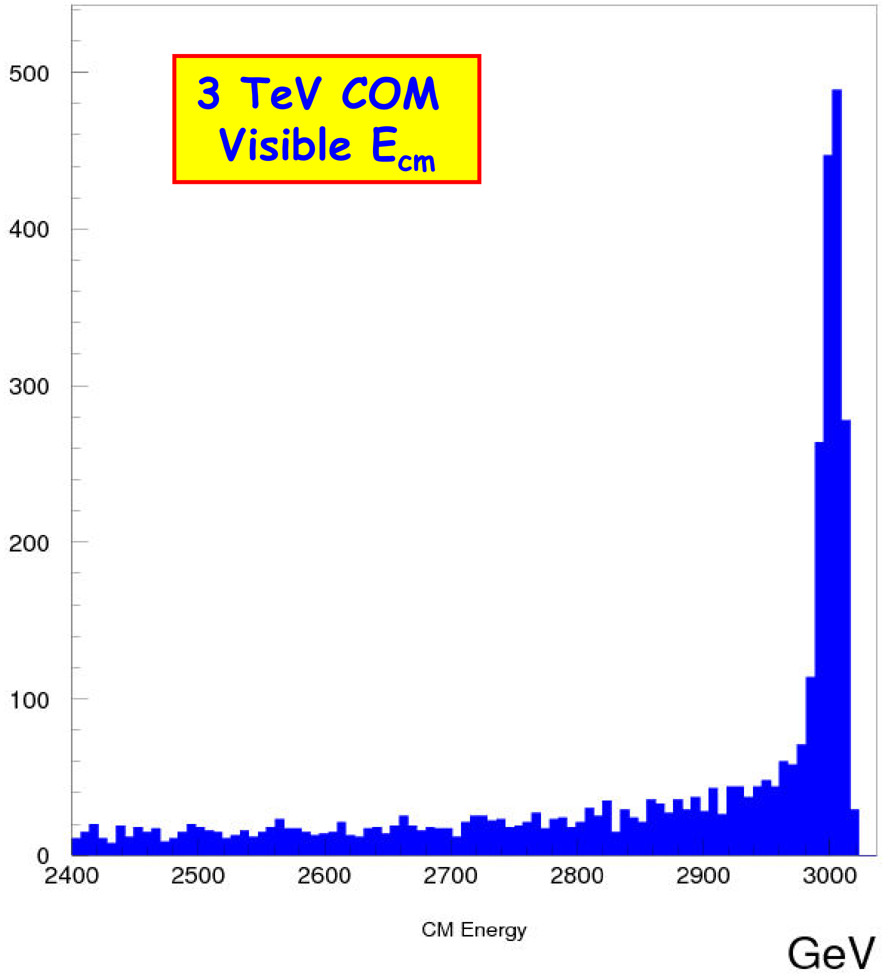


Energy Frontier Physics SMALL Footprint

PRSTAB – May 3, 2002

Muon Collider at the Energy Frontier

- Comparisons with Energy Frontier e^+e^- Collider
  - For many processes - Similar cross sections
  - Advantage in s-channel scalar production
    - Cross section enhancement of $(m_\mu/m_e)^2$
      - $\approx$ 40,000
  - Beam Polarization also possible
    - Polarization likely easier in e^+e^- machine
  - More precise energy scan capability
    - Beam energy spread and Beamstrahlhung limits precision of energy frontier (3TeV) e^+e^- machines
  - Muon Decay backgrounds in MC do have Detector implications, however



S-channel Coupling to Higgs

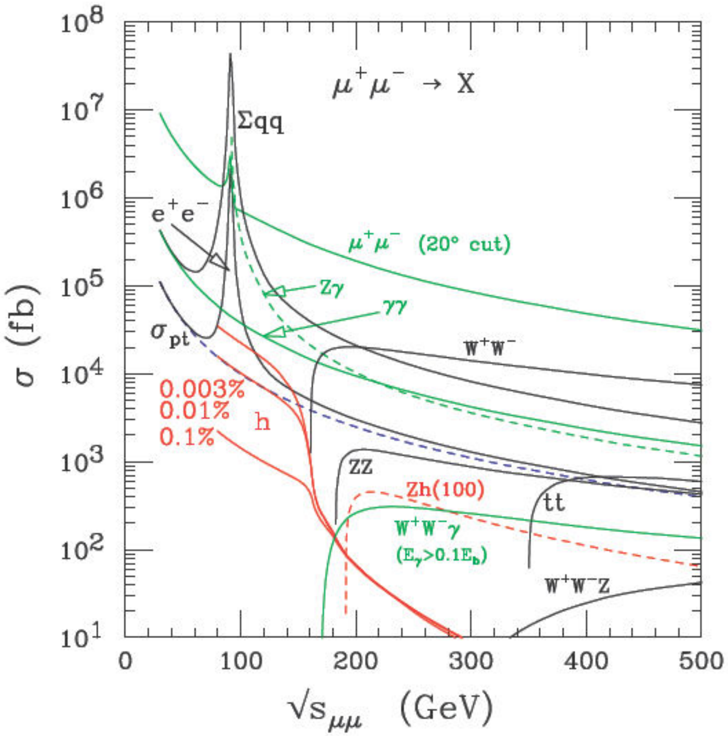
Standard Model Cross Sections

- For $\sqrt{s}$ < 500 GeV muon collider
  - threshold regions:
    - top pairs
    - electroweak boson pairs
    - Zh production
  - s-channel Higgs production:
    - coupling ∝ mass

      $$\left[\frac{m_\mu}{m_e}\right]^2 = 4.28 \times 10^4$$

    - narrow state

$$m(h) = 110 \text{ GeV}: \quad \Gamma = 2.8 \text{ MeV}$$
$$m(h) = 120 \text{ GeV}: \quad \Gamma = 3.6 \text{ MeV}$$
$$m(h) = 130 \text{ GeV}: \quad \Gamma = 5.0 \text{ MeV}$$
$$m(h) = 140 \text{ GeV}: \quad \Gamma = 8.1 \text{ MeV}$$
$$m(h) = 150 \text{ GeV}: \quad \Gamma = 17 \text{ MeV}$$
$$m(h) = 160 \text{ GeV}: \quad \Gamma = 72 \text{ MeV}$$



Higgs Γ

Fine energy resolution ($\Delta E/E$) is possible for muon colliders

$$\sigma_h(\sqrt{\hat{s}}) = \frac{4\pi\Gamma(h\to\mu\mu)\,\Gamma(h\to X)}{(\hat{s}-m_h^2)^2 + m_h^2[\Gamma_h^{tot}]^2},$$

$$\sigma_{\sqrt{s}} = (7\ \mathrm{MeV})\left(\frac{R}{0.01\%}\right)\left(\frac{\sqrt{s}}{100\ \mathrm{GeV}}\right).$$

$$\overline{\sigma}_h = \frac{2\pi^2\Gamma(h\to\mu\mu)\,BF(h\to X)}{m_h^2} \times \frac{1}{\sigma_{\sqrt{s}}\sqrt{2\pi}} \qquad (\Gamma_h^{tot} \ll \sigma_{\sqrt{s}}).$$

$$\overline{\sigma}_h = \frac{4\pi BF(h\to\mu\mu)BF(h\to X)}{m_h^2} \qquad (\Gamma_h^{tot} \gg \sigma_{\sqrt{s}})$$

h

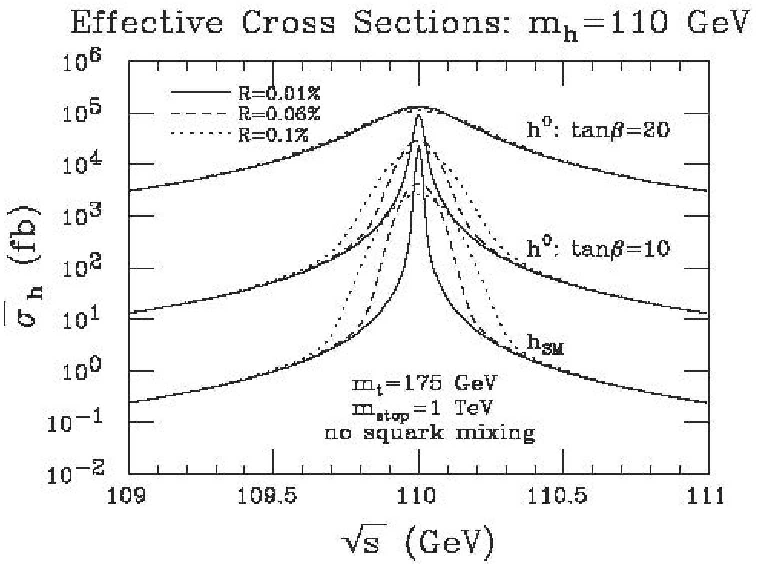
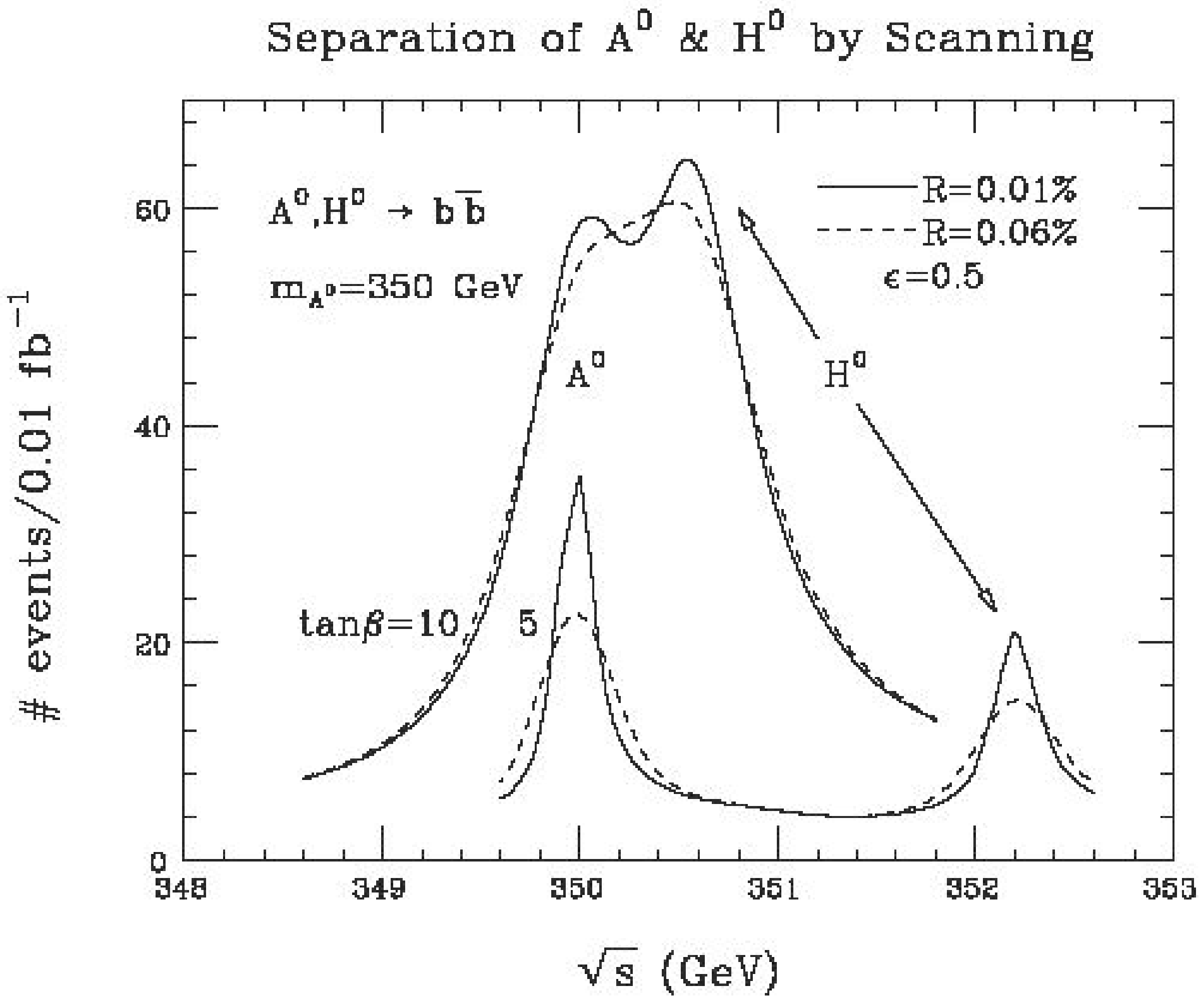


Figure 7: The effective cross section, $\overline{\sigma}_h$, obtained after convoluting σ_h with the Gaussian distributions for $R = 0.01\%$, $R = 0.06\%$, and $R = 0.1\%$, is plotted as a function of $\sqrt{s}$ taking $m_h = 110$ GeV. Results are displayed in the cases: h_{SM}, h^0 with $\tan\beta = 10$, and h^0 with $\tan\beta = 20$. In the MSSM h^0 cases, two-loop/RGE-improved radiative corrections have been included for Higgs masses, mixing angles, and self-couplings assuming $m_{\tilde{t}} =$ 1 TeV and neglecting squark mixing. The effects of bremsstrahlung are not included in this figure.

Measuring SM Higgs width directly requires: $\Delta E/E < 0.002\%$ with an integrated lumonisity > 2 pb^{-1}

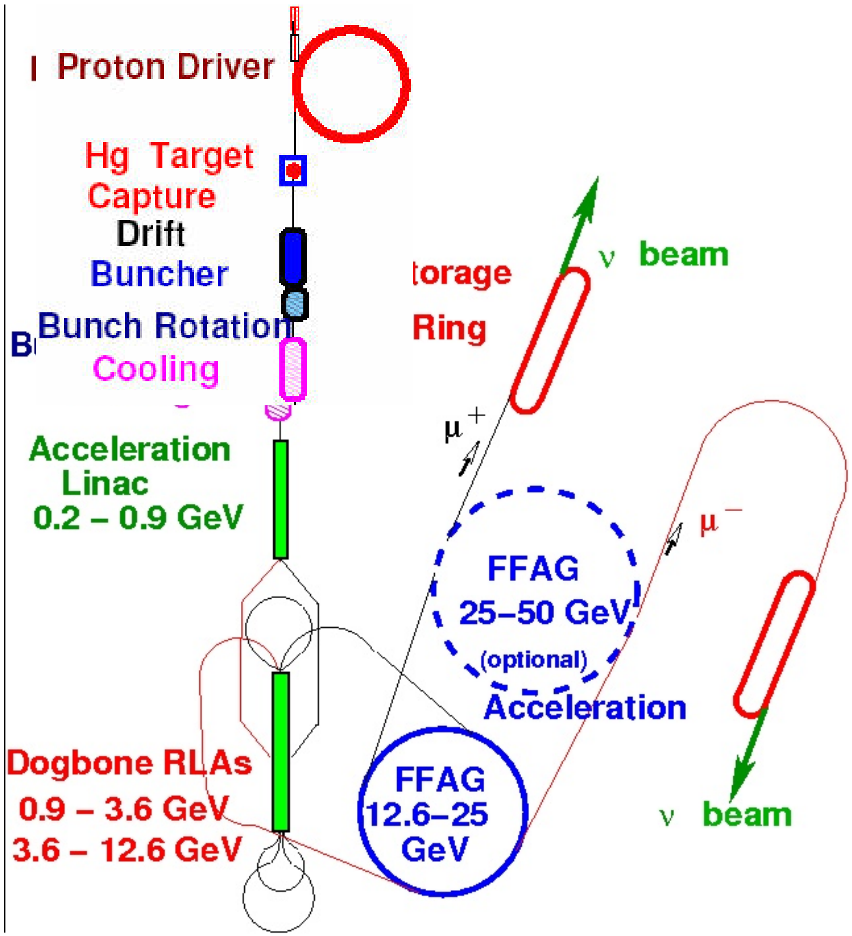
MC Physics - Resolving degenerate Higgs



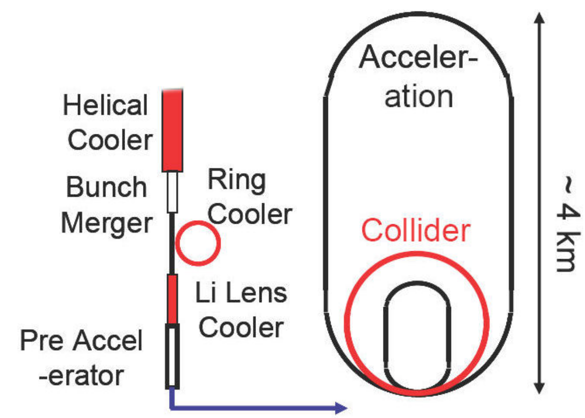
Difficult in e^+e^- machine with equivalent R ≈ 1%

Muon Collider-NF - Synergy

Neutrino Factory



Muon Collider



Enabling Technologies for Muon Collider

- Although a great deal of R&D has been done (or is ongoing) for a Neutrino Factory, the Technological requirements for a Muon Collider are Much More Aggressive
  - Bunch Merging is required
  - MUCH more Cooling is required
    - 1000X in each transverse dimension, ≈ 10X in longitudinal
  - Cooling in 6D (x,x',y,y',E,t) is required
  - Acceleration to much higher energy (20-40 GeV vs. 1.5-3 TeV)
  - Storage rings
    - Colliding beams
    - Energy loss in magnets from muon decay (electrons) is an issue

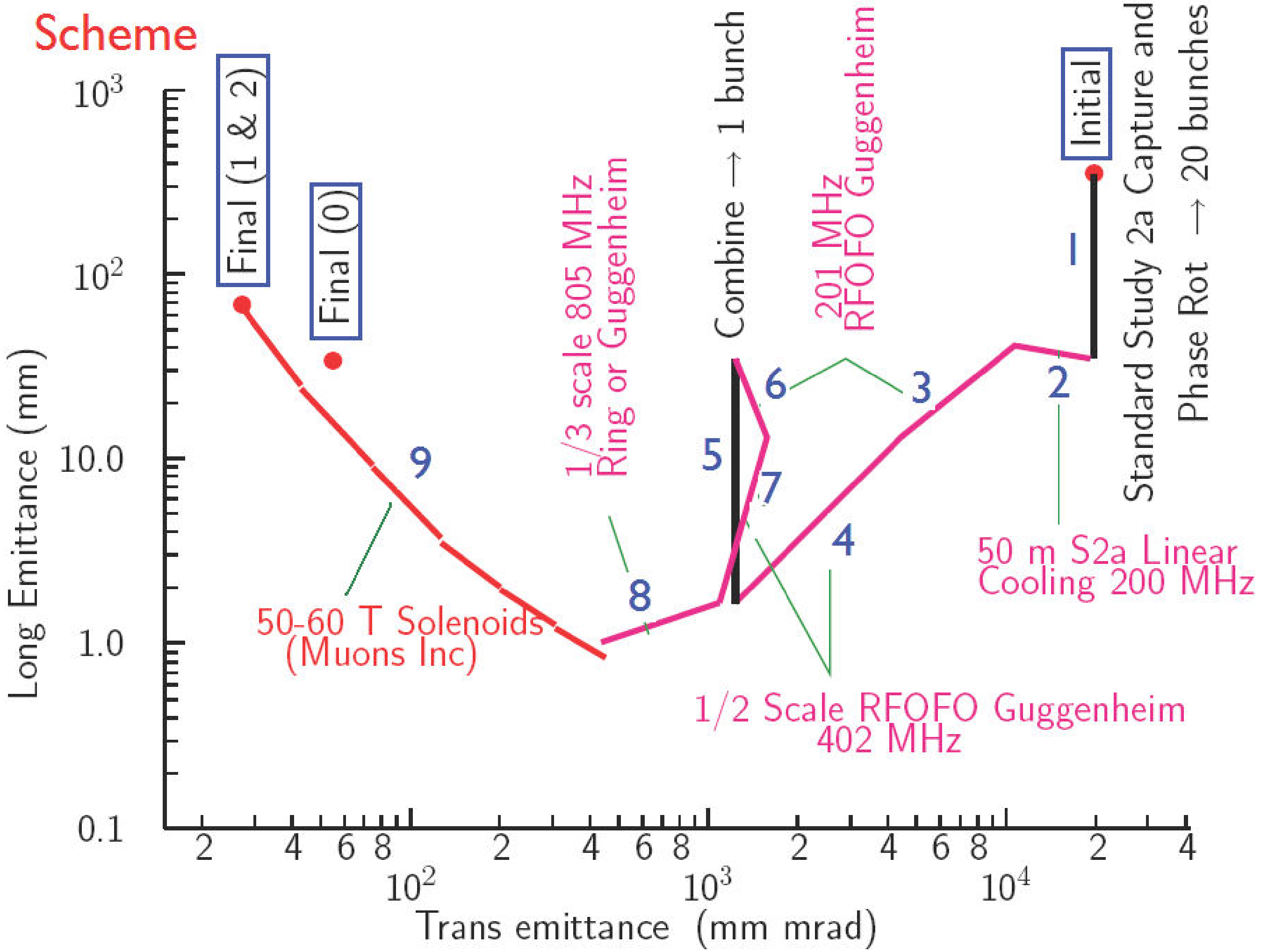
Muon Collider

- Ingredients needed in Collider cooling scenario include:
  - Longitudinal cooling by large factors …
  - Transverse cooling by very large factors
  - Final beam compression with reverse emittance exchange
  - Improvements in bunch manipulations (bunch recombination?)
  - Reacceleration and bunching from low energy

Palmer et al:
RFOFO Ring
Guggenheim
50-60T Solenoid Channel

Muons Inc.
High pressure gas-filled cavities
Helical Cooling Channel
Reverse Emittance Exchange
Parametric Resonance Induced Cooling

A Muon Collider Cooling Scenario

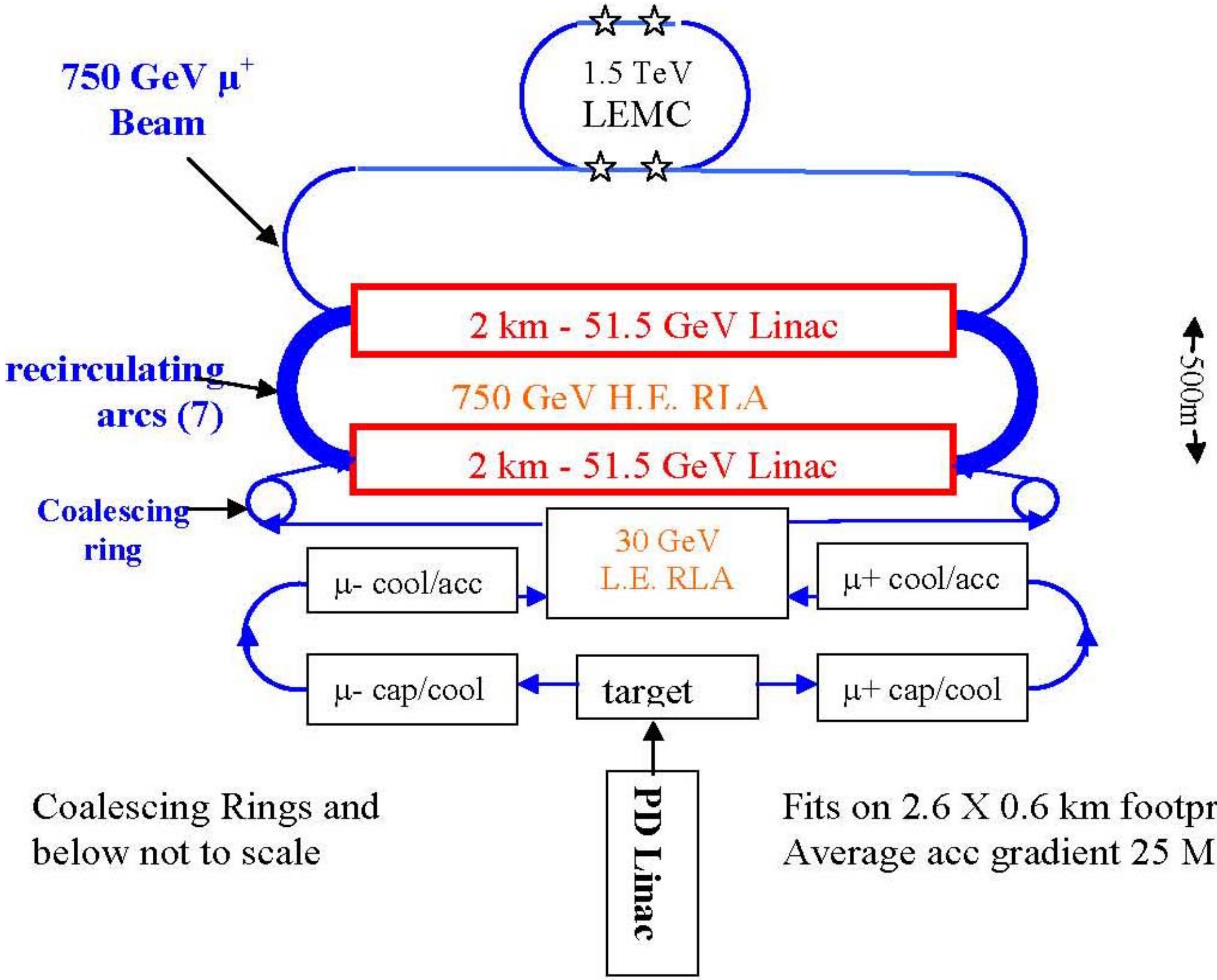


Low-Emittance Muon Collider (LEMC)

Parameter List:

E_{cm} = 1.5 TeV
Peak $\mathcal{L}$ = 7×10^{34}
#μ's/bunch = 10^{11}
Av Dipole B = 10T
δp/p = 1%
β^*(cm) = 0.5 (!)

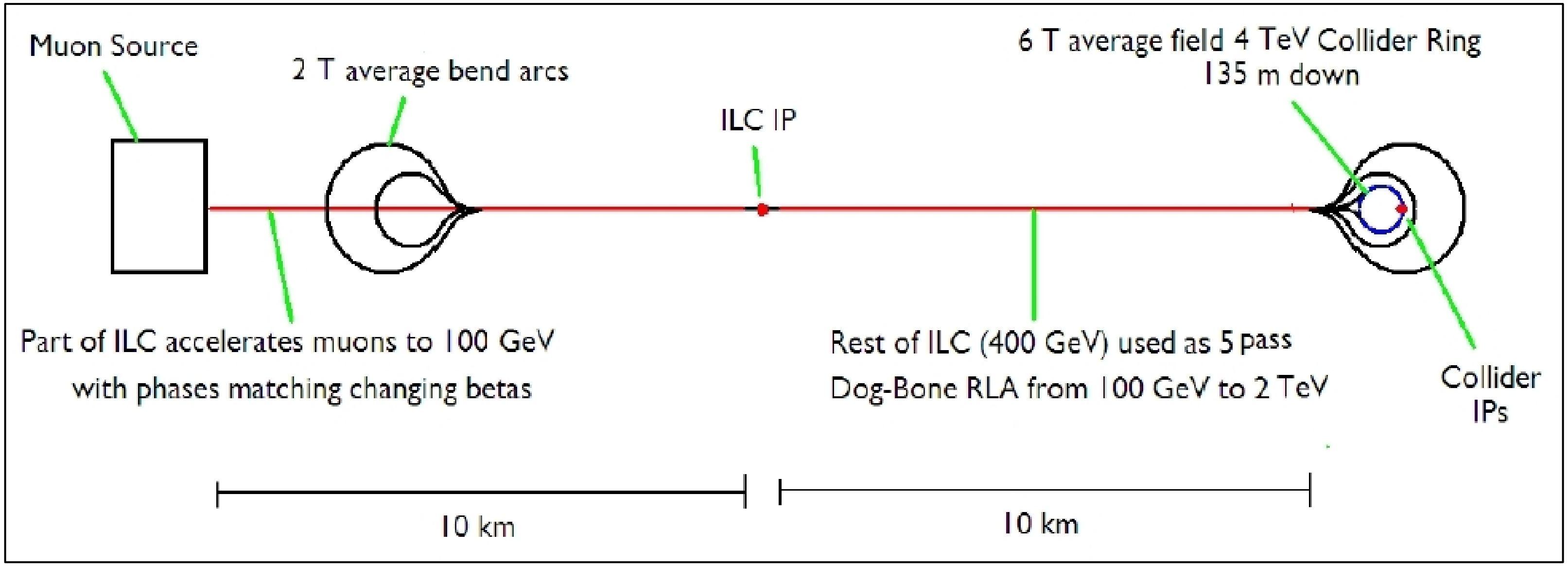
Proton driver:
E = 8 GeV
Power ≈ 1 MW



Coalescing Rings and below not to scale

Fits on 2.6 X 0.6 km footprint
Average acc gradient 25 MeV/m

An ILC Upgrade?



In this schematic we see the real power of the Muon Collider concept. A 2x2 TeV machine based on a 500 GeV linac.

Conclusions

The Collaboration has entered a very exciting phase

- Neutrino Factory
  - Compelling case for a precision neutrino program
    - With present assumptions Neutrino Factory out-performs other options. However, more is needed before concluding this is the right path
      - What the on-going Neutrino Physics program tells us
      - Process must include cost and schedule considerations
        - International Design Study
- Muon Collider
  - New concepts improve the prospects for a multi-TeV Muon Collider
    - LEMC concept – HCC/REMEX/PIC (Muons Inc.)
  - Front-end is the same (similar) as for a Neutrino Factory
  - First complete cooling scenario has emerged
    - Palmer Scheme

The Way Forward

- Technical Progress
  - MERIT and MICE will be taking data in the near future and will address some of the fundamental technical issues in high-power targetry and muon cooling
- Expanded Emphasis on MC
  - New ideas in Muon Cooling have led to a renewed interest in Muon Collider studies with very exciting prospects
    - Creation of the Fermilab Muon Collider Task Force (MCTF) is a positive step
- Resource Limitations
  - The collaboration is still funding limited and progress in a number of areas is considerably slower than is technically possible
  - Expansion of our activities into new initiatives is extremely constrained