Neutrino Factory and Muon Collider R&D in the US

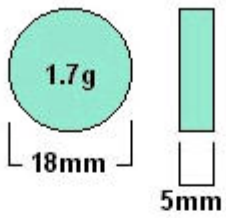
"Two Mints in One?

Fermilab

Two Mints?

- It has been said that a Neutrino Factory is not cost-effective unless it leads to a Muon Collider and &
- You Need a Neutrino Factory to get you to a Muon Collider
  - Corollary – NF comes for free (almost)
    - More Later
- What are the parameters?

"Two Mints in One?"

Certs	
	
Formal name	Certs Classic Mints
Classification	Breath mint
Description	Breath mint
Form	Modified disc
Volume	1.3cm³ (approx.)
Mass	1.7g (approx.)
Density	1.3g/cm³ (approx.)
Ingredients	Sugar, corn syrup, partially hydrogenated cottonseed oil†, flavor (with soy lecithin)†, magnesium stearate, copper gluconate†, color. († = ingredient of Retsyn)

Nutrition Information	Per mint: Calories 5, Fat 0g, Sodium 0g, Carbohydrates 2g, Sugars 2g, Protein 0g.
Active Ingredients	None
Flavors	Cinnamon, Mixed Fruit, Peppermint, Spearmint, Wintergreen
Sugar Free?	No
Manufacturer	Cadbury-Schweppes
Year introduced	1956
Slogans / Taglines	The Right Amount Of Mint
Related products	Certs Cool Mint Drops, Certs Powerful Mints
Hazards	food coloring

- Even a breath mint has a parameter list

What similarities are there between the parameter lists for a Neutrino Factory and for a Muon Collider?

A Bit of History

Since the late 1990s, the Neutrino Factory and Muon Collider Collaboration (a.k.a. Muon Collaboration) has pursued an active R&D program that has focused on muon production, capture and acceleration. (Out-growth of Snowmass 96 work on 4TeV $\mu^+\mu^-$ Collider.) Initially the physics emphasis was on muon colliders (both a Higgs Factory and an energy frontier machine). By 2000 the focus of the collaboration had shifted to studying the feasibility of a Neutrino Factory. Recently new ideas in muon ionization cooling have reinvigorated the collaboration's efforts on the investigation of energy frontier muon colliders. I will:

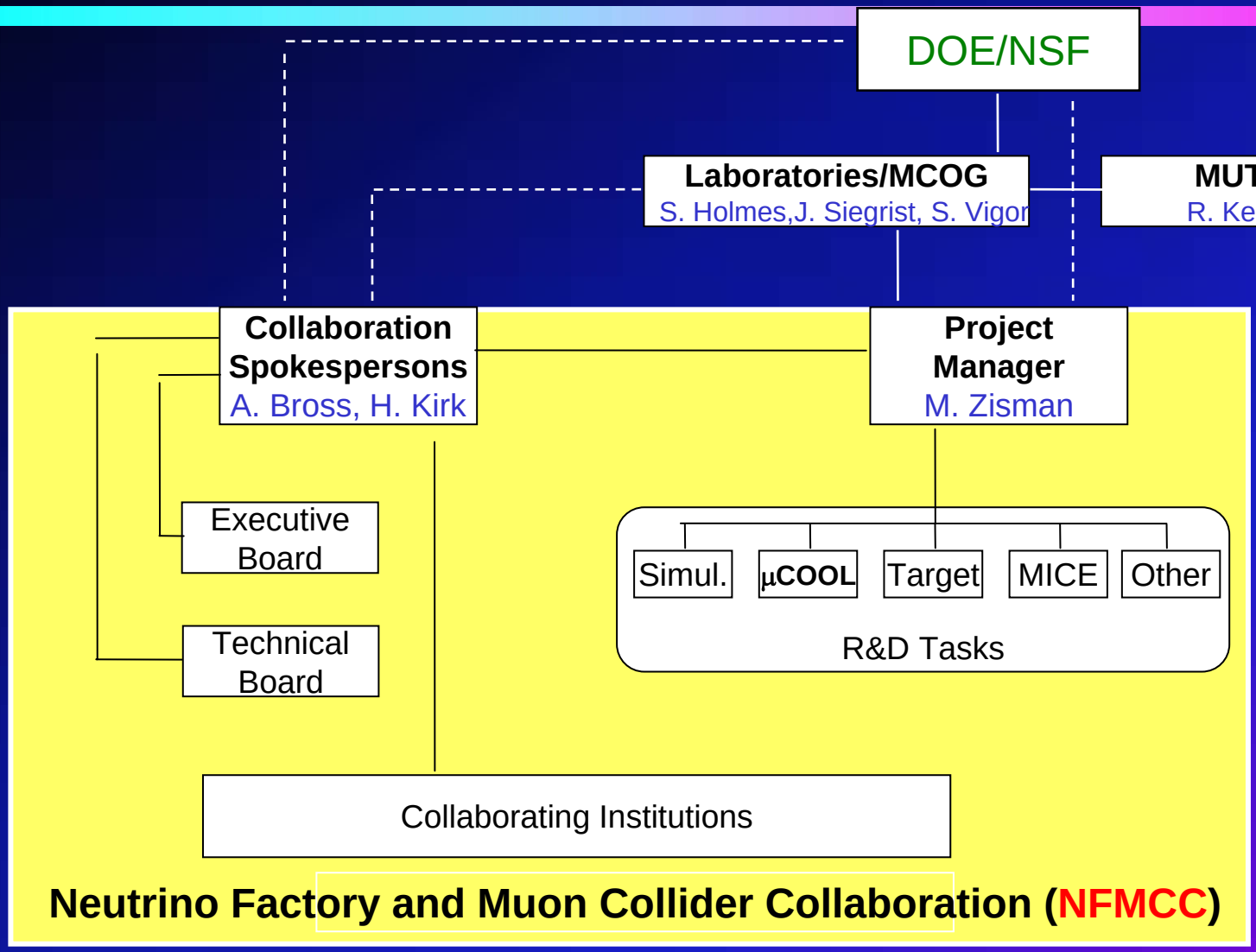
1. Review the physics motivation for our activities
2. Describe Collaboration's program
3. Explore the synergy between Neutrino Factory and Muon Collider facilities both from the point of view of the physics program and the accelerator complex

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
- Argonne
- BNL
- Fermilab
- LBNL
- Oak Ridge
- Thomas Jefferson

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

International

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

Universities
- Karlsruhe
- Imperial College
- Lancaster
- Osaka
- Oxford
- Pohang
- Tel Aviv

Corporate Partners

- Muons Inc.
- Tech-X Corporation

Core Program

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

Spokesperson: Kirk McDonald

Project Manager: Harold Kirk

Ionization Cooling R&D: MuCool and MICE

MuCool Spokesperson: Alan Bross

US MICE Leader: Dan Kaplan

Simulations & Theory

Coordinator: Rick Fernow

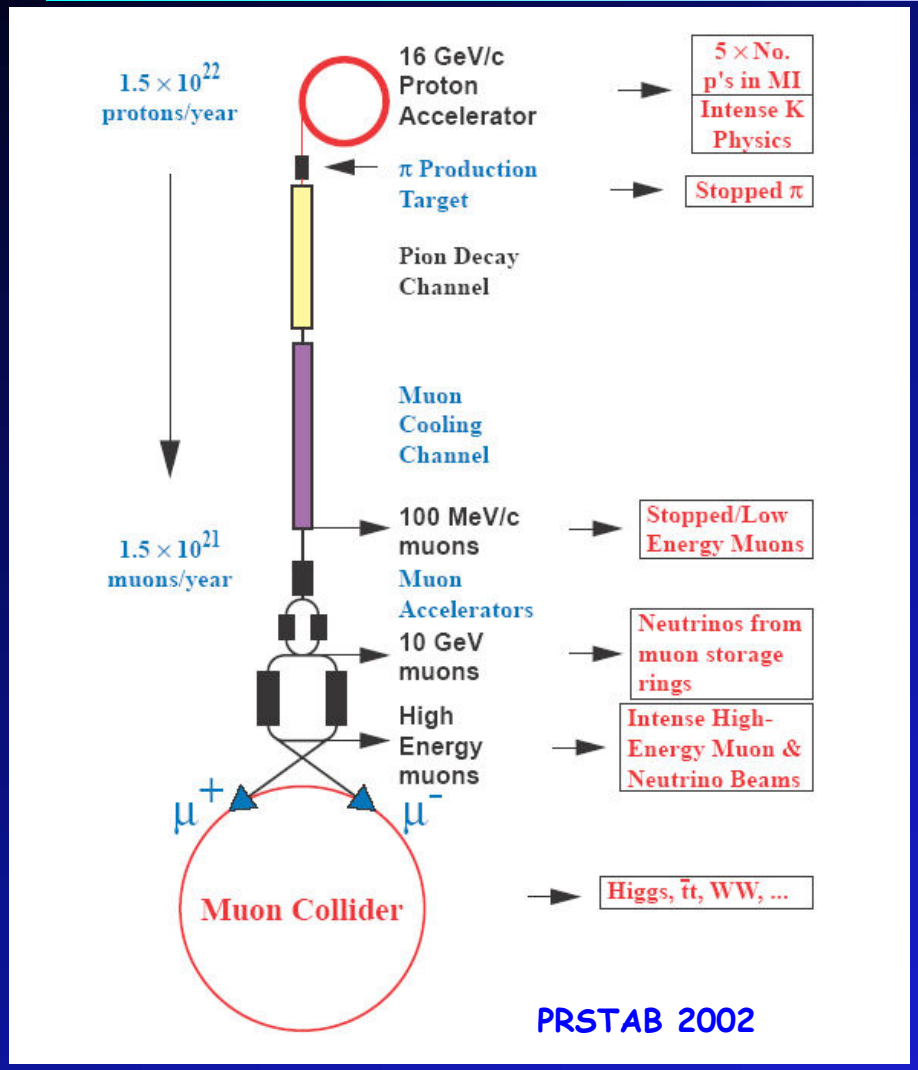
Muon Collider Task Force*

*@ Fermilab

Physics Motivation

Is Muon Production, Capture and Acceleration R&D worth the investment?

Evolution of a Physics Program

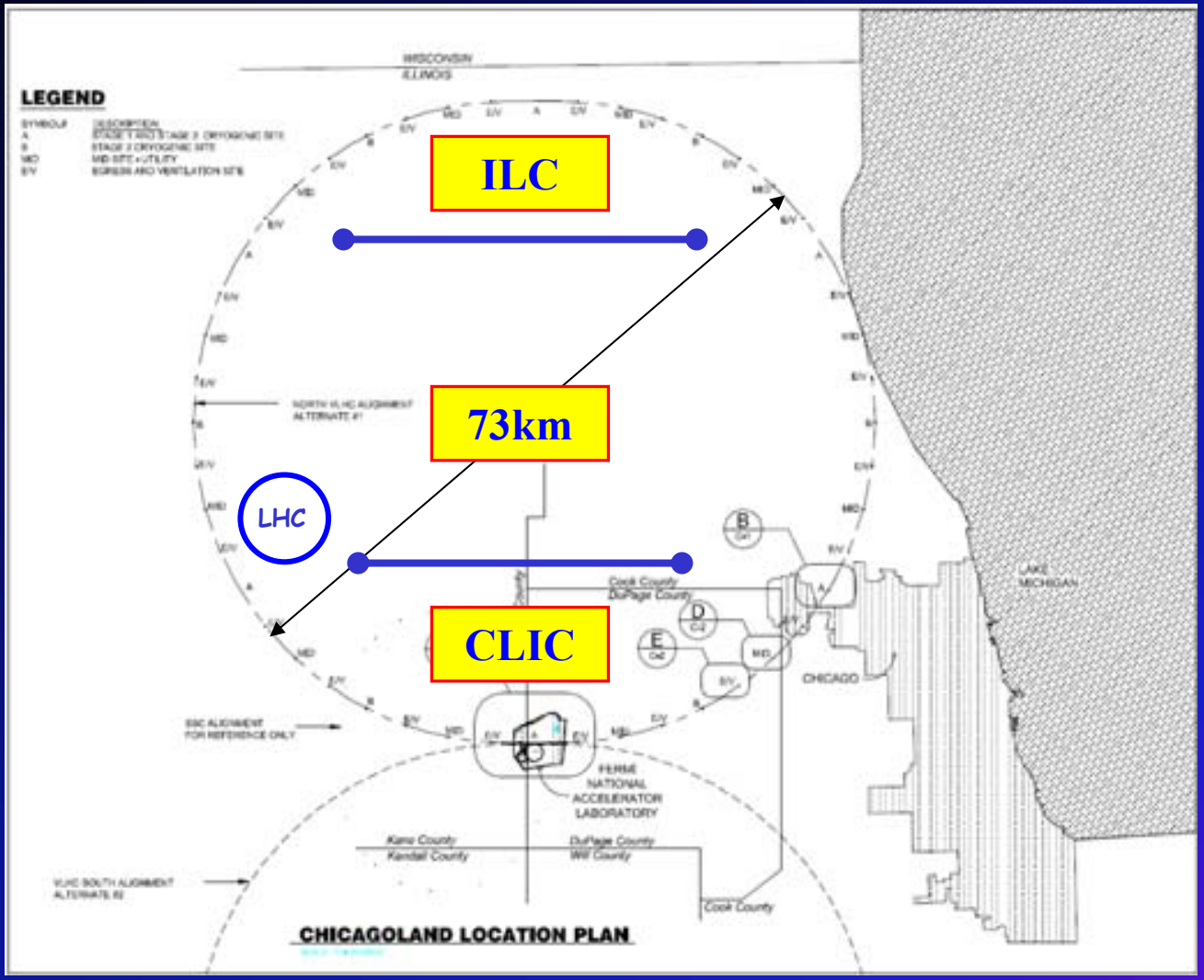


From Snowmass 96

1. Intense Low-energy muon physics
   - μ e conversion experiment
2. Neutrino Factory
   - High Energy 10-20 GeV
   - Low Energy 4 GeV
3. Energy Frontier Muon Collider
   - 1.5 - 4 TeV+

OK, 3 Mints in One

Footprint and the Energy Frontier



The VLHC is the largest machine to be seriously considered to date

- Stage 1 – 40 TeV
  - > 2 TeV mass reach
- Stage 2 – 200 TeV
  - > 10 TeV

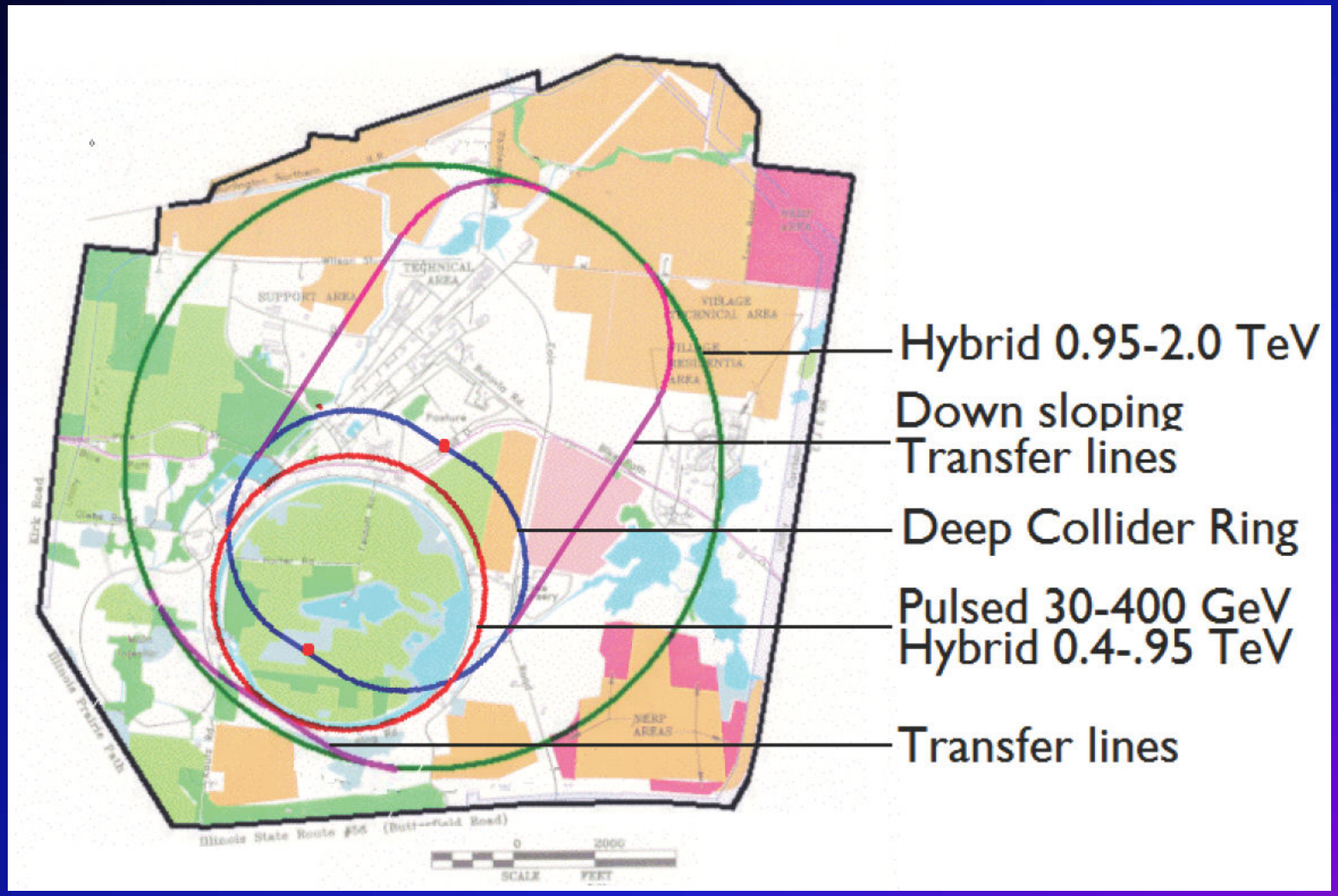
ILC

0.5

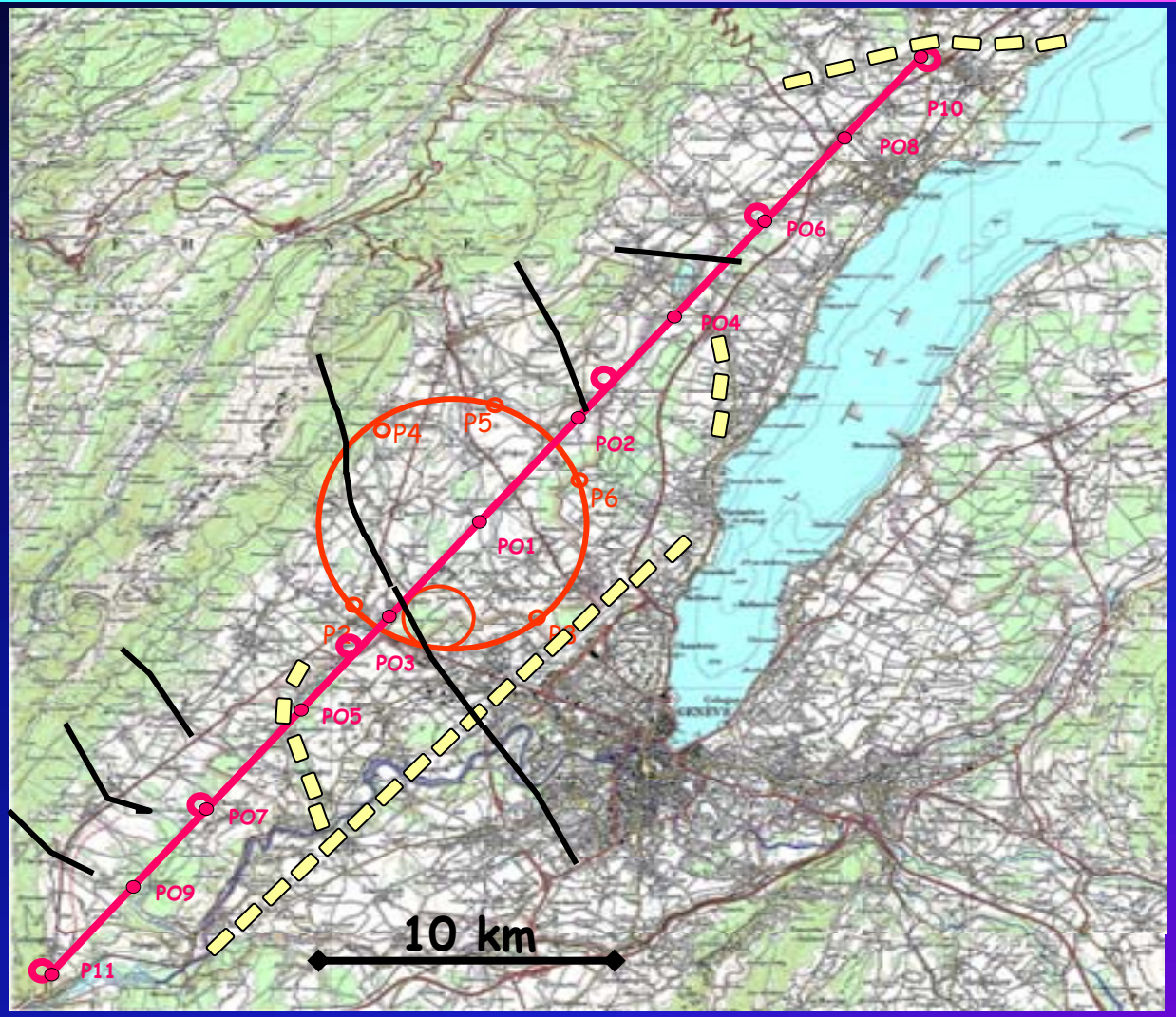
CLIC

3+ TeV

4 TeV COM Muon Collider



CLIC at CERN



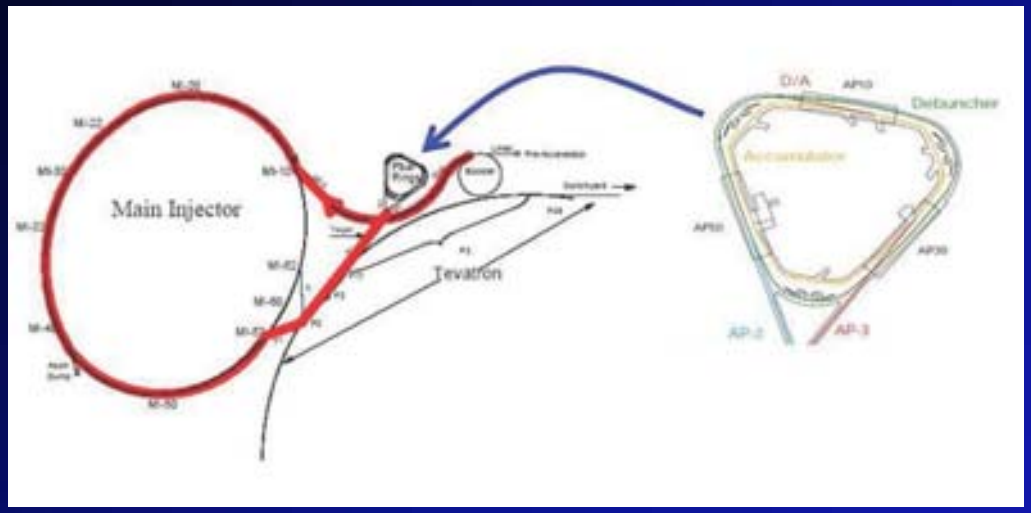
Muon Collider Parameter Lists

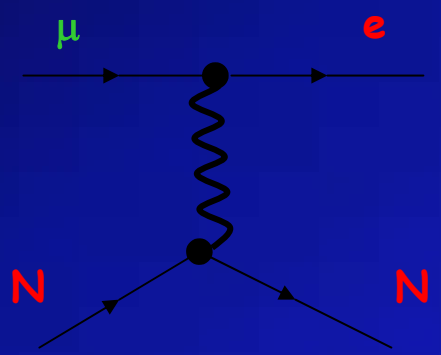
Collider Parameters

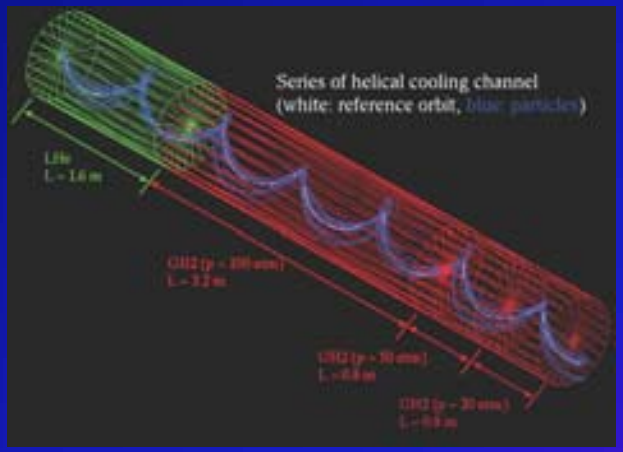
	This Paper	Snowmass	Extrapolation	
C of m Energy	1.5	4	8	TeV
Luminosity	1	4	8	10^{34} cm^{2}sec^{-1}
Beam-beam Tune Shift	0.1	0.1	0.1	
Muons/bunch	2	2	2	10^{12}
Ring <bending field>	5.2	5.18	10.36	T
Ring circumference	3	8.1	8.1	km
Beta at IP $= \sigma_z$	10	3	3	mm
rms momentum spread	0.1	0.12	0.06	%
Muon Beam Power	7.5	9	9	MW
Required depth for ν rad (1)	13	135	540	m
Muon survival (2)	0.07	0.07	0.07	
Repetition Rate	12	6	3	Hz
Proton Driver power	$\approx$4	$\approx$ 1.8	$\approx$ 0.8	MW
Trans Emittance	25	25	25	pi mm mrad
Long Emittance	72,000	72,000	72,000	pi mm mrad

Mint 1

Low-Energy Muon Physics
μ to e conversion - *Mu2e*





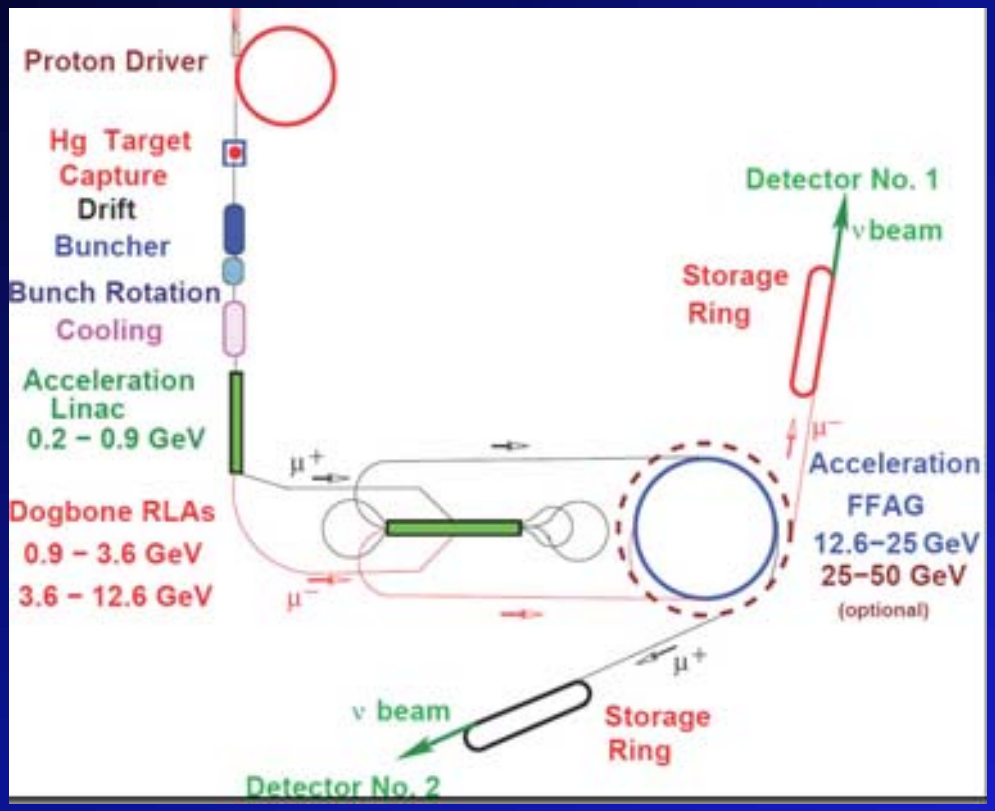


- Sensitive tests of Lepton Flavor Violation (LFV)
  - In SM occurs via ν mixing
    - Rate well below what is experimentally accessible
  - Places stringent constraints on physics beyond SM
    - Supersymmetry
      - Predictions at 10^{-15}
- Requirement – Intense low energy μ beam
  - Cooling improves stopping efficiency in target of experiment
  - Test bed for Muon Ionization Cooling for NF and MC with intense μ beam

Mint 2

Neutrino Factories

Preliminary Design From the International Scoping Study



- Why a Neutrino Factory?
  - Neutrino Mixing has been observed
    - They have Mass
  - Physics beyond SM
    - Very Rich Experimental Program
- Want Very Intense ν beam with well-understood systematics

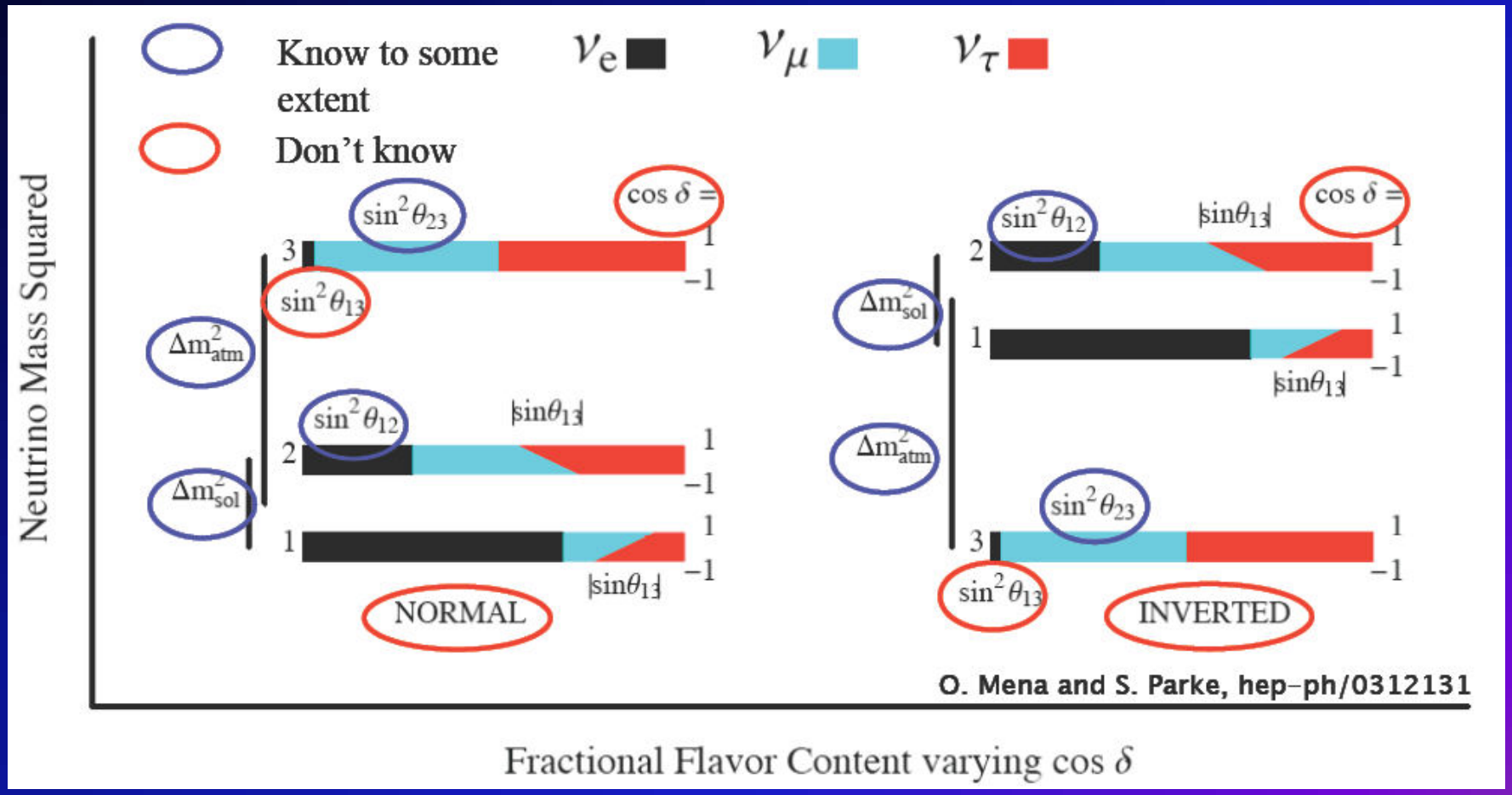
Neutrino Physics – The Big Questions

- Did neutrinos play a role in birth of the universe?
- Did neutrinos play a role in Galaxy Formation?
- What is the origin of neutrino mass?
- 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?

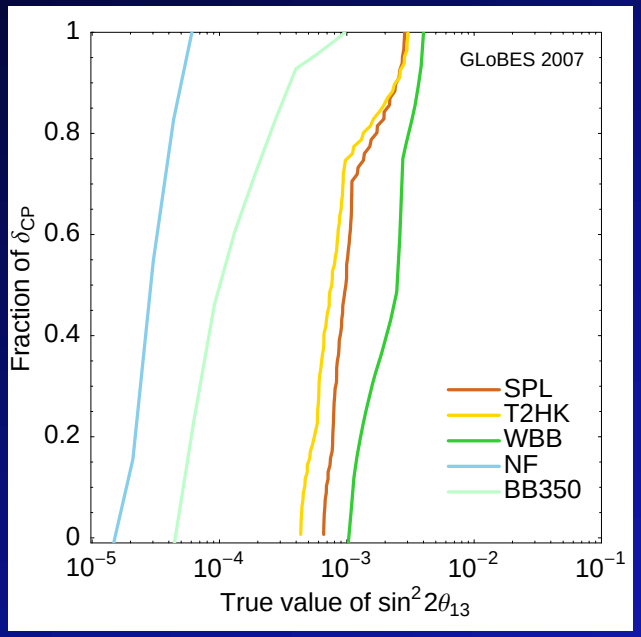
3 ν Mixing Model



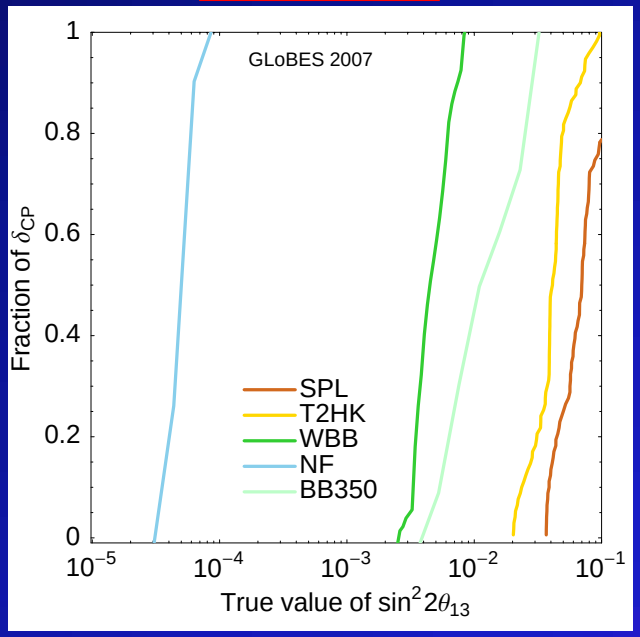
ISS – NF Physics Reach

- What we do know is that the NF gives the best Physics Reach
  - NF ≡ PRECISION

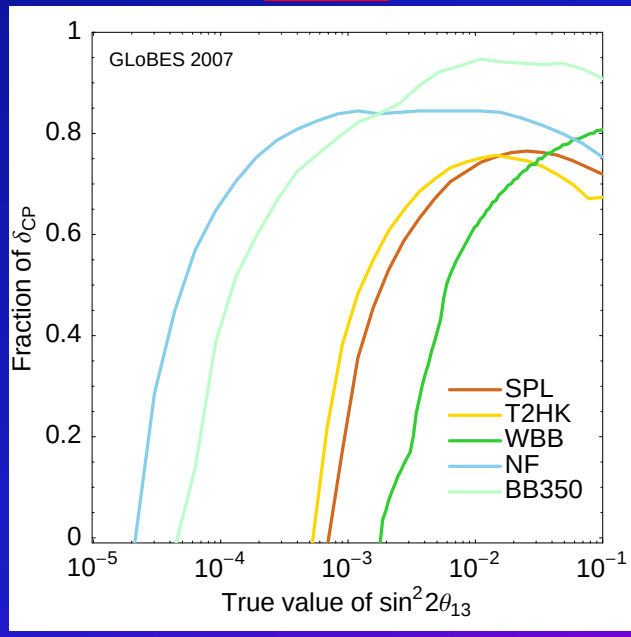
$\sin^2 2\theta_{13}$



Hierarchy



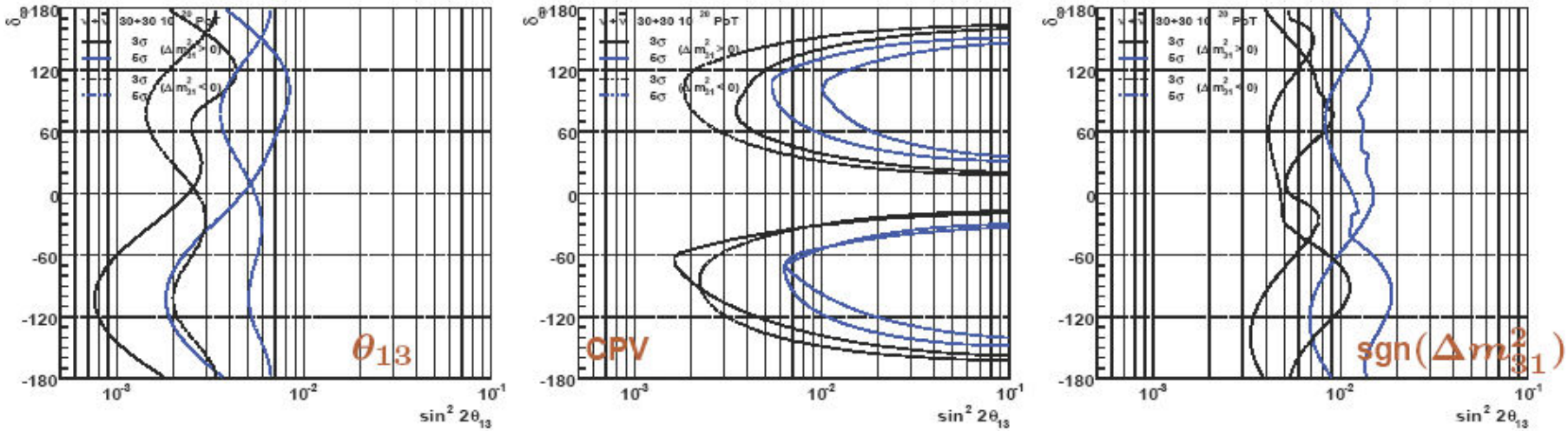
δ *CP*



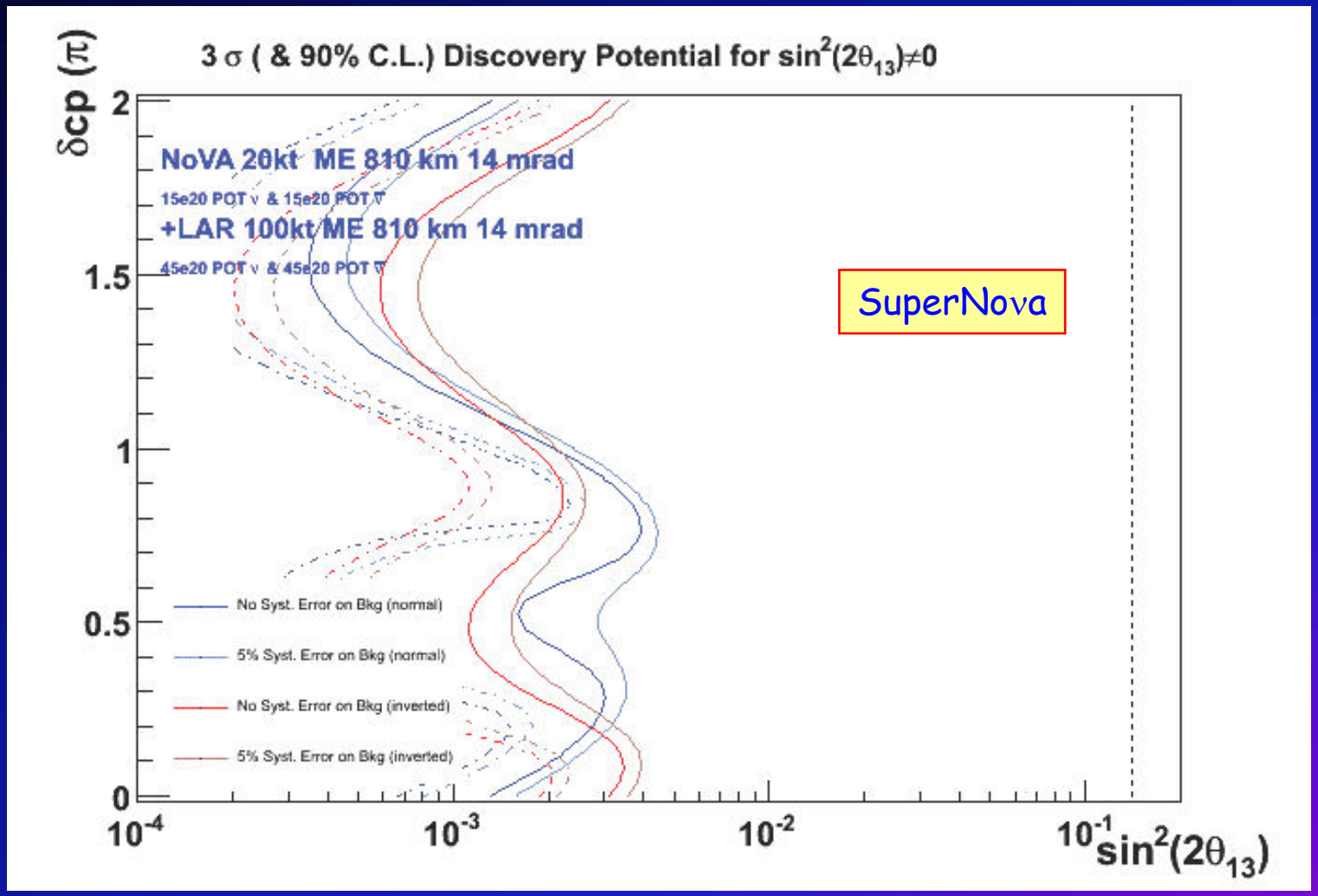
SPL: 4MW, 1MT H_2OC, 130 km BL
T2HK: 4 MW, 1MT H_2OC, 295 km BL
WBB: 2MW, 1MT H_2OC, 1300 km BL

NF: 4MW, 100KT MIND, 4000 & 7500 BL
BB350: γ=350, 1MT H_2OC, 730 km BL

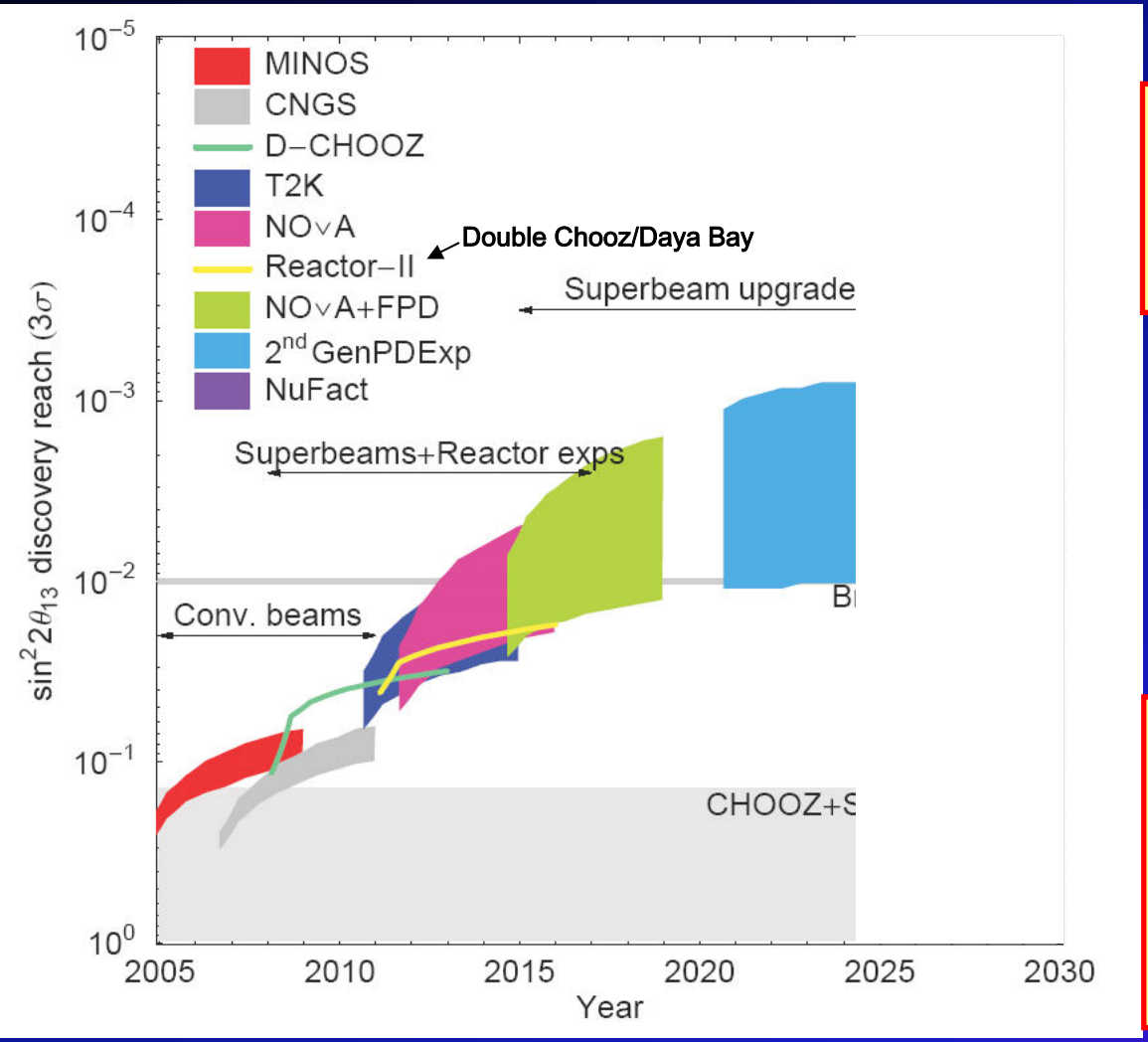
Discovery potential (— 5σ —3σ). **LAr. 100 kT**, 1.2 MW, 6yrs:



Fermilab-BNL WBB Study
Low-Energy WBB to DUSEL


3 σ (& 90% C.L.) Discovery Potential for sin²(2θ13)≠0
δcp (π)
NoVA 20kt ME 810 km 14 mrad
15e20 POT ν & 15e20 POT ν̄
+LAR 100kt ME 810 km 14 mrad
45e20 POT ν & 45e20 POT ν̄
SuperNova
No Syst. Error on Bkg (normal)
5% Syst. Error on Bkg (normal)
No Syst. Error on Bkg (inverted)
5% Syst. Error on Bkg (inverted)
2
1.5
1
0.5
0
10⁻⁴
10⁻³
10⁻²
10⁻¹
sin²(2θ13)

Neutrino Factory
To Build or Not to Build



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

Mint 3

Muon Collider - Motivation

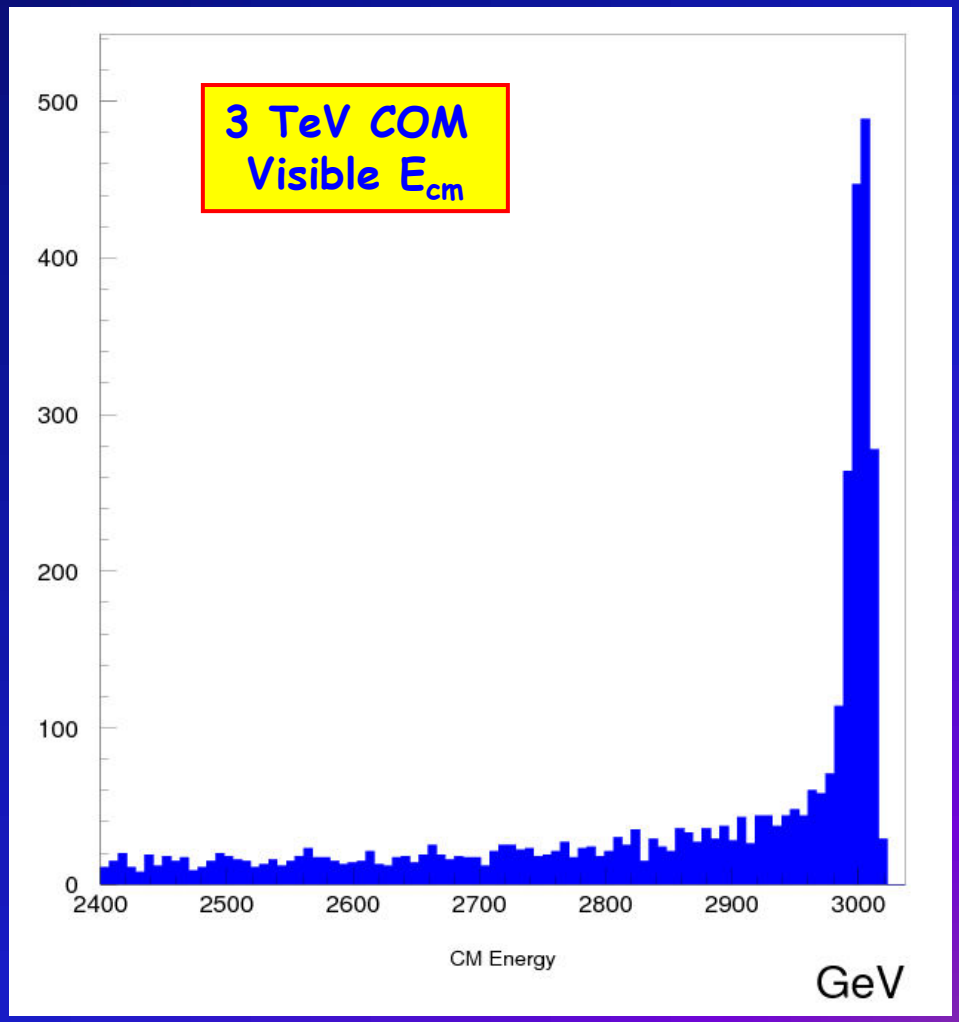
Reach Multi-TeV Lepton-Lepton Collisions at High Luminosity

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

Small Footprint - Could Fit on Existing Laboratory Site

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



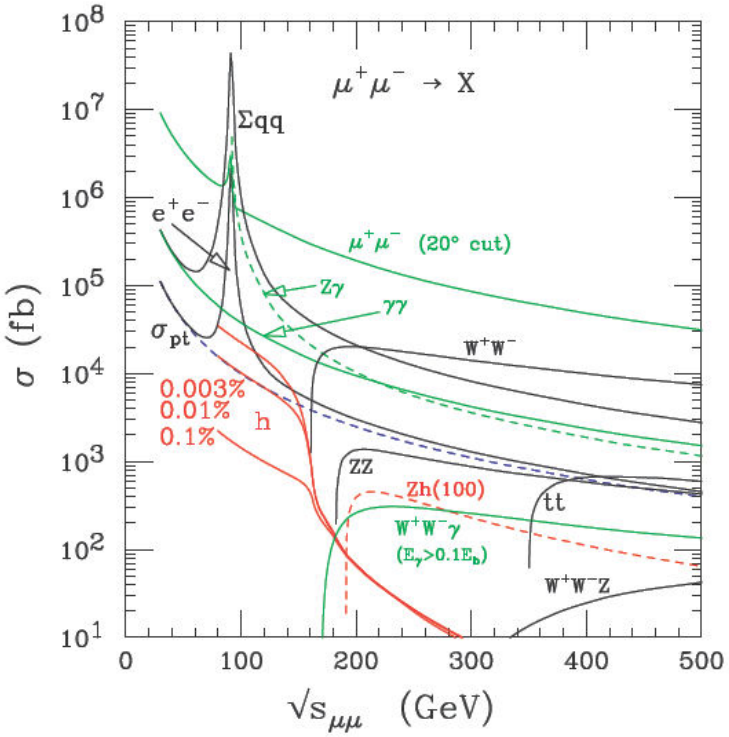
S-channel Coupling to Higgs

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

      $m(h) = 110$ GeV : Γ = 2.8 MeV
      $m(h) = 120$ GeV : Γ = 3.6 MeV
      $m(h) = 130$ GeV : Γ = 5.0 MeV
      $m(h) = 140$ GeV : Γ = 8.1 MeV
      $m(h) = 150$ GeV : Γ = 17 MeV
      $m(h) = 160$ GeV : Γ = 72 MeV



Higgs Γ

Fine energy resolution (ΔE/E) is possible for muon colliders

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

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

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

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

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

h

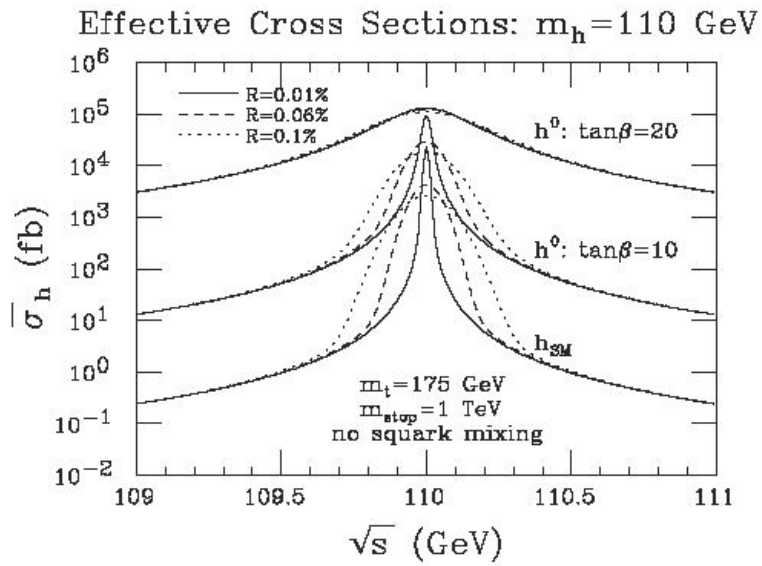
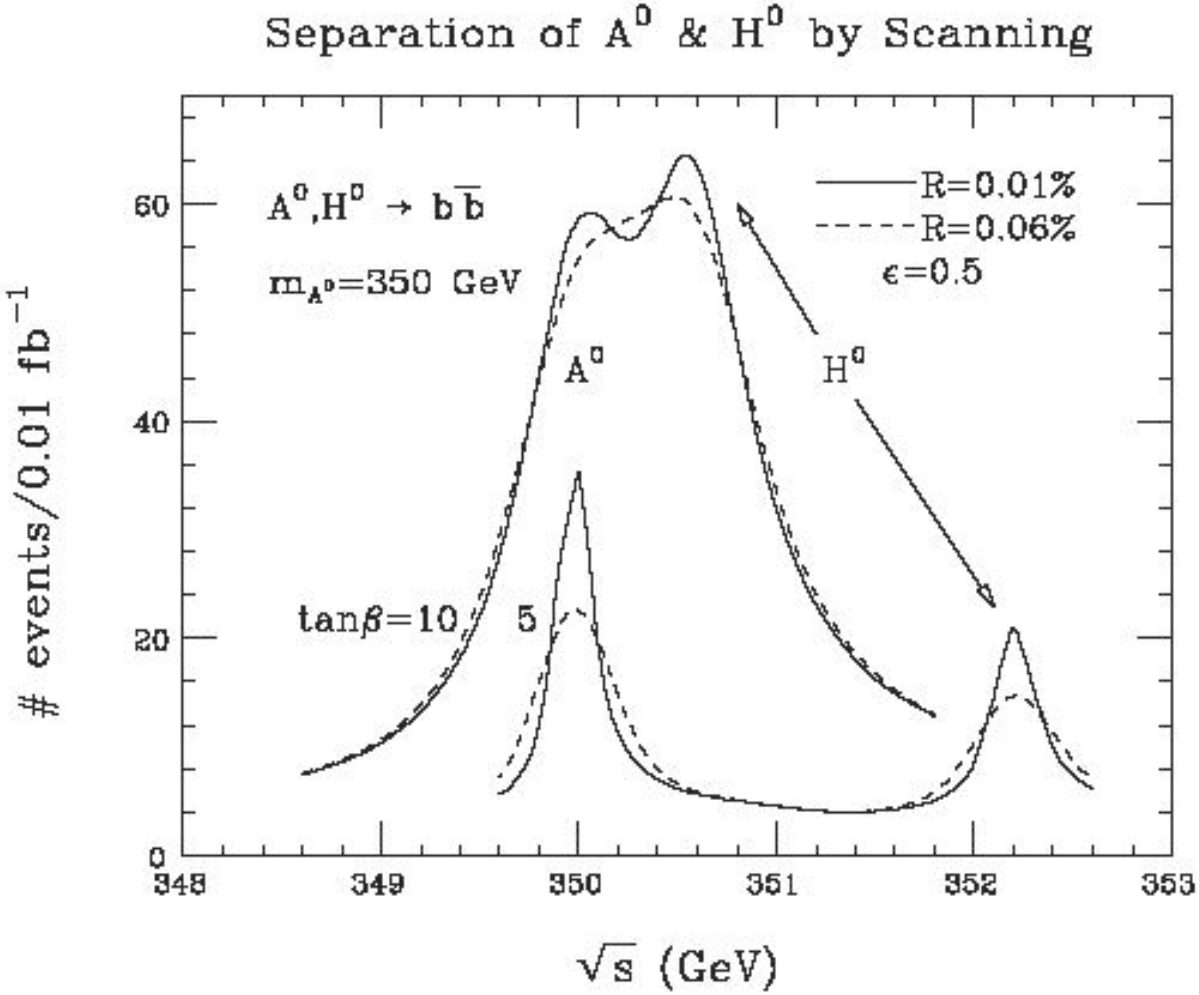


Figure 7: The effective cross section, $\overline{\sigma}_h$, obtained after convoluting σ_h with the Gaussian distributions for $R = 0.01\%$, $R = 0.06\%$, and $R = 0.1\%$, is plotted as a function of $\sqrt{s}$ taking $m_h = 110$ GeV. Results are displayed in the cases: h_{SM}, h^0 with $\tan\beta = 10$, 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.

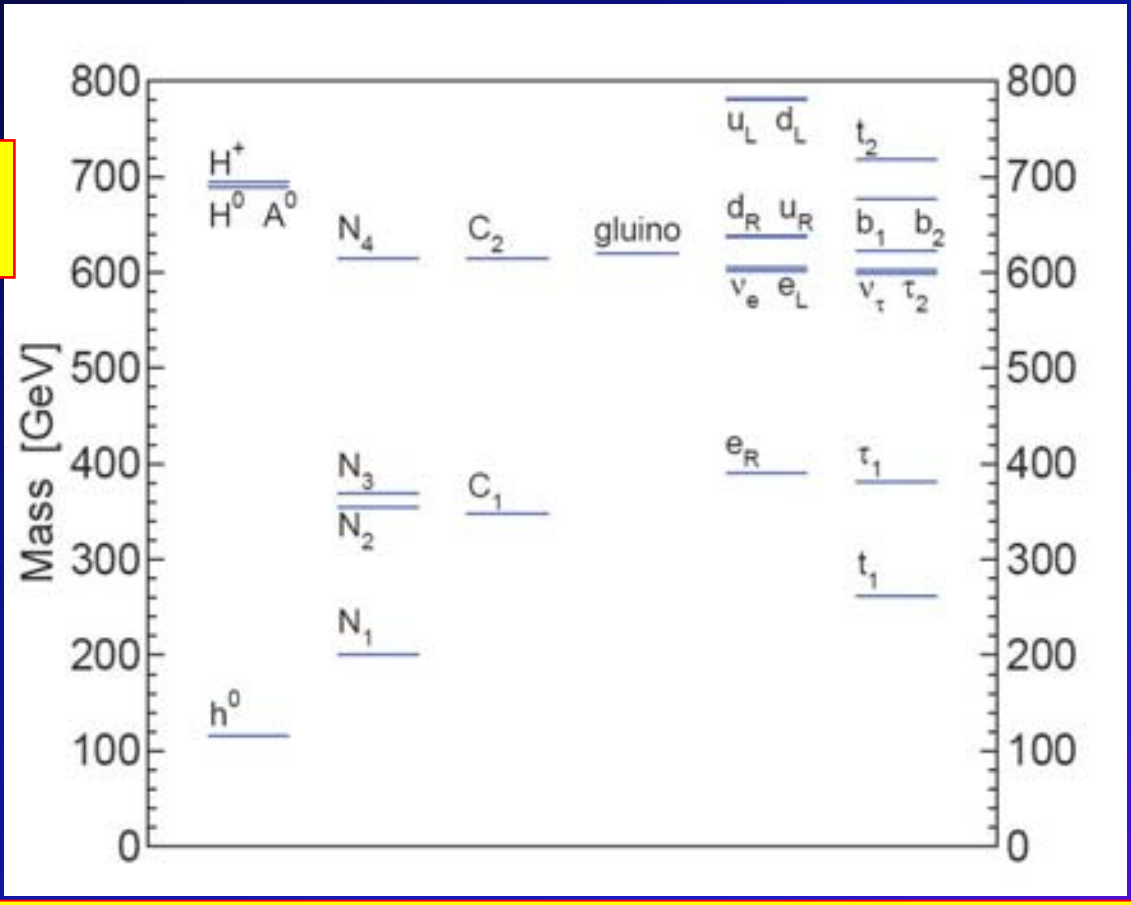
MC Physics - Resolving degenerate Higgs



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

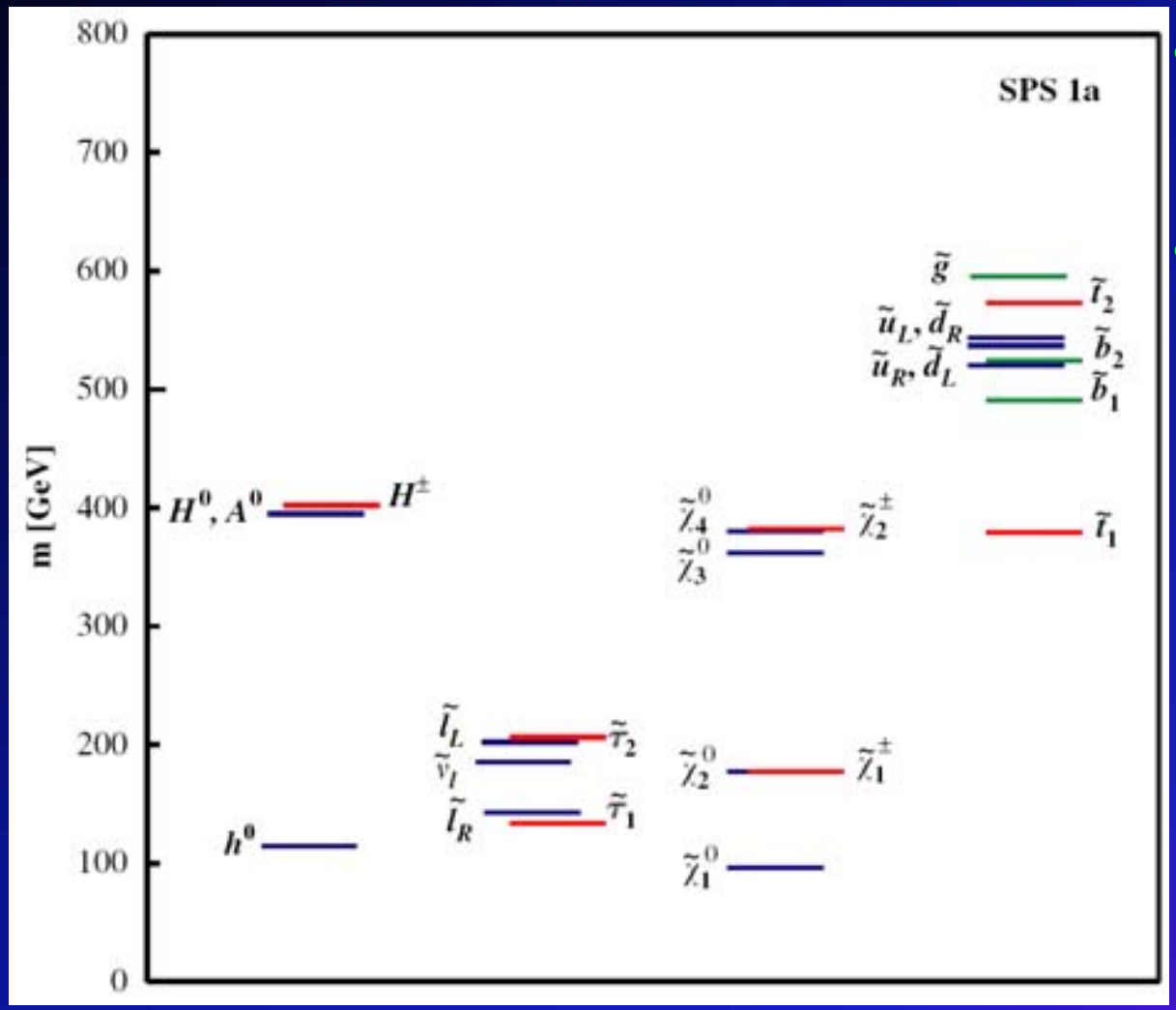
Limitations of a 500 GeV Lepton Collider?
High-Mass SUSY

Stephen Martin
hep-ph/0703097
March, 2007



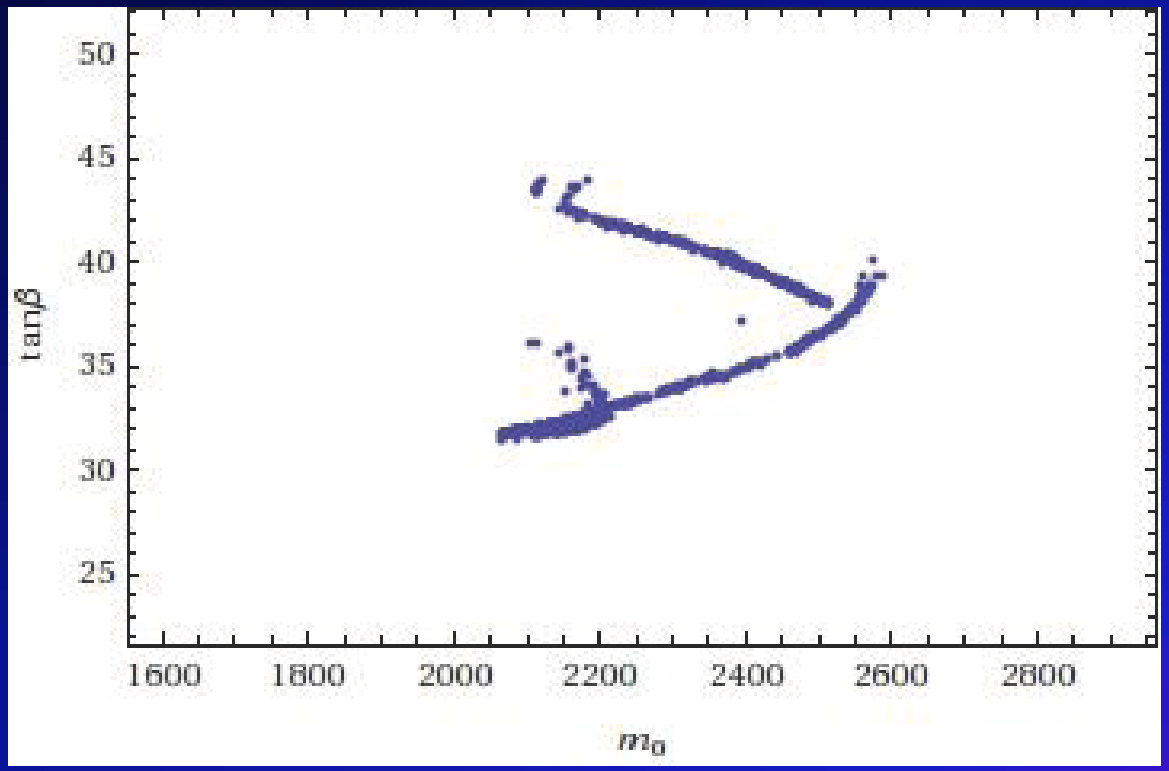
A typical sample "compressed" Higgs and superpartner mass spectrum with $\Omega_{DM}h^2 = 0.11$ (WMAP)
An unfortunate feature, quite common to this scenario for dark matter, is that no visible superpartners would be within reach of a linear collider with $\sqrt{s} = 500$ GeV

All is not Lost for the ILC – Snowmass Points and Slope - SPS1a



- As Jack Gunion has said, "This is a Highly-Tuned Solution
- mSUGRA
  - m_0, $m_{1/2}$, A_0, $\tan\beta$, μ .
    - scalar mass
    - gaugino mass
    - trilinear coupling
    - ratio of Higgs vev
    - SUSY Higgs parameter sign

But the Parameter Space is LARGE



- One particular fit in Yang Bai's analysis: https://mctf.fnal.gov/Members/sgeer/muoncolliderbai.pdf
- Contraints
  - Cosmological DM density
  - $g_\mu - 2$
  - LEP and TeV Higgs mass
  - LSP mass

SPS1a – Snowmass Point Spread 1a?

Key Ingredients of the Facilities

Let's Stick to the Last Two Mints

Needs Common to NF and MC Facility

- Proton Driver
  - Primary beam on production target
- Target, Capture, and Decay
  - Create π's; decay into μ's
- Phase Rotation
  - Reduce ΔE of bunch
- Cooling
  - Reduce emittance of the muons
    - Cost-effective for NF
    - Essential for MC
- Acceleration
  - Accelerate the Muons
- Storage Ring
  - Store for ~1000 turns

But there are Key Differences

Neutrino Factory

- Cooling
  - Reduce transverse emittance
    - $\varepsilon_\perp$ ~ 25 mm
- Acceleration
  - Accelerate to 20-40 GeV
    - May as low as 5-7 GeV
- Storage Ring
  - No intersecting beams

Muon Collider

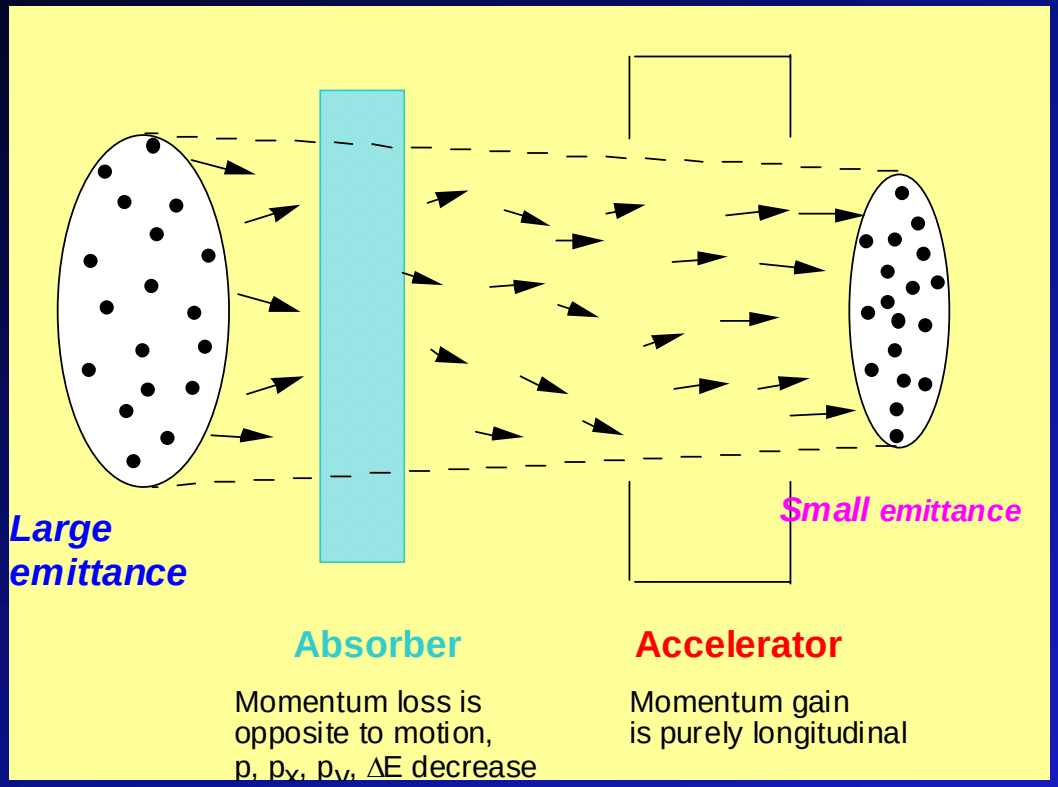
- Bunch Merging
- Cooling
  - Reduce 6D emittance
    - $\varepsilon_\perp$ ~ 3-25 μm
    - ε_L ~ 70 mm
- Acceleration
  - Accelerate to 1-2 TeV
- Storage Ring
  - Intersecting beams

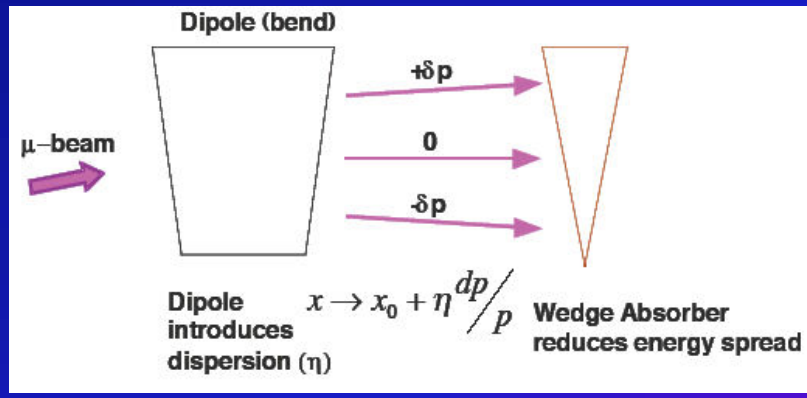
Key R&D Issues

- High Power Targetry – NF & MC *(MERIT Experiment)*
- Initial Cooling – NF & MC *(MICE (4D Cooling))*
- 200 MHz RF - NF & MC *(MuCool and Muon's Inc)*
  - Investigate Gas-Filled RF cavities
  - Investigate RF cavities in presence of high magnetic fields
  - Obtain high accelerating gradients (~15MV/m)
- Intense 6D Cooling – MC
  - RFOFO "Guggenheim"
  - Helical Channel Cooling *(MANX Proposal)*
  - Parametric Resonance Ionization Cooling
- Bunch Recombination
- Acceleration– A cost driver for both NF & MC, but in very different ways
  - FFAG's – *(EMMA Demonstration)*
  - Multi-turn RLA's – a BIG cost reducer
  - RCS for MC
- Storage Ring(s) – NF & MC
- Theoretical Studies NF & MC
  - Analytic Calculations
  - Lattice Designs
  - Numeric Simulations

Note: Almost all R&D Issues for a NF are currently under theoretically and experimentally study

Muon Ionization Cooling



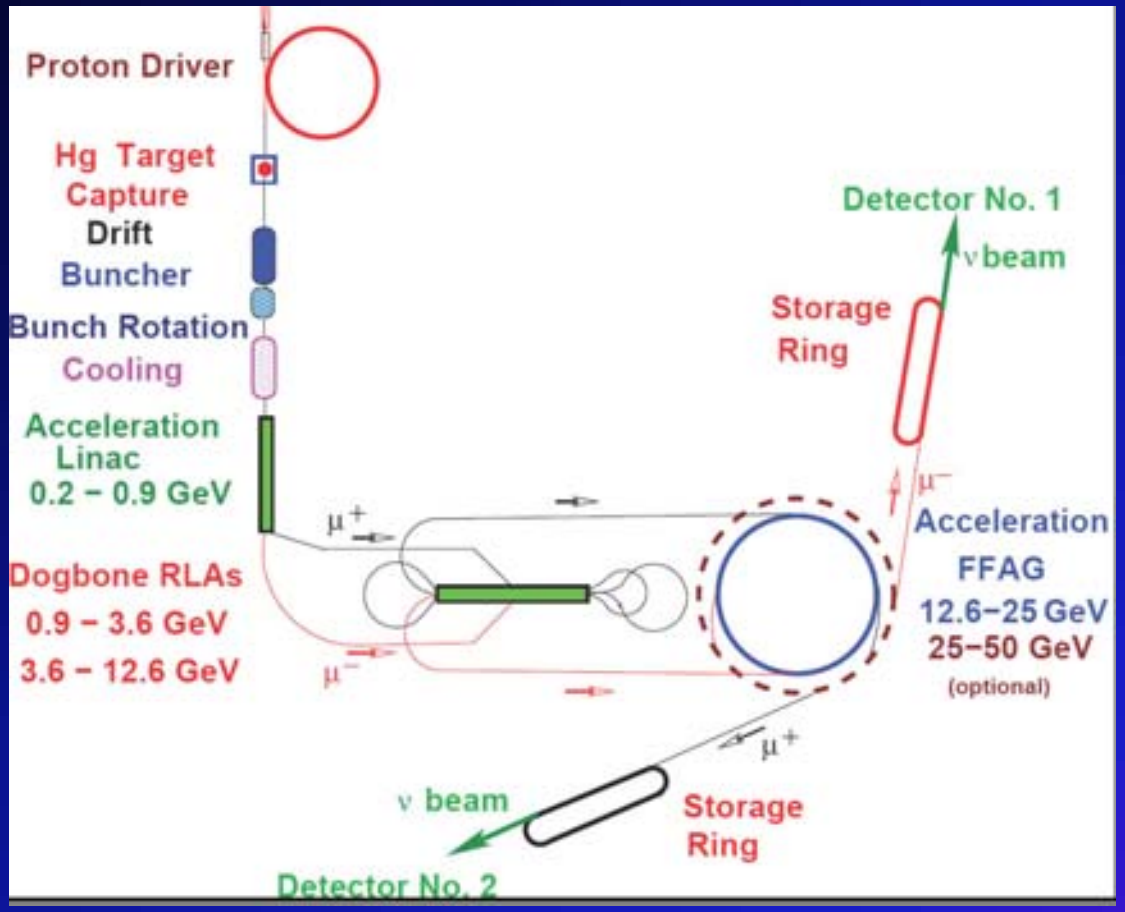


Transverse

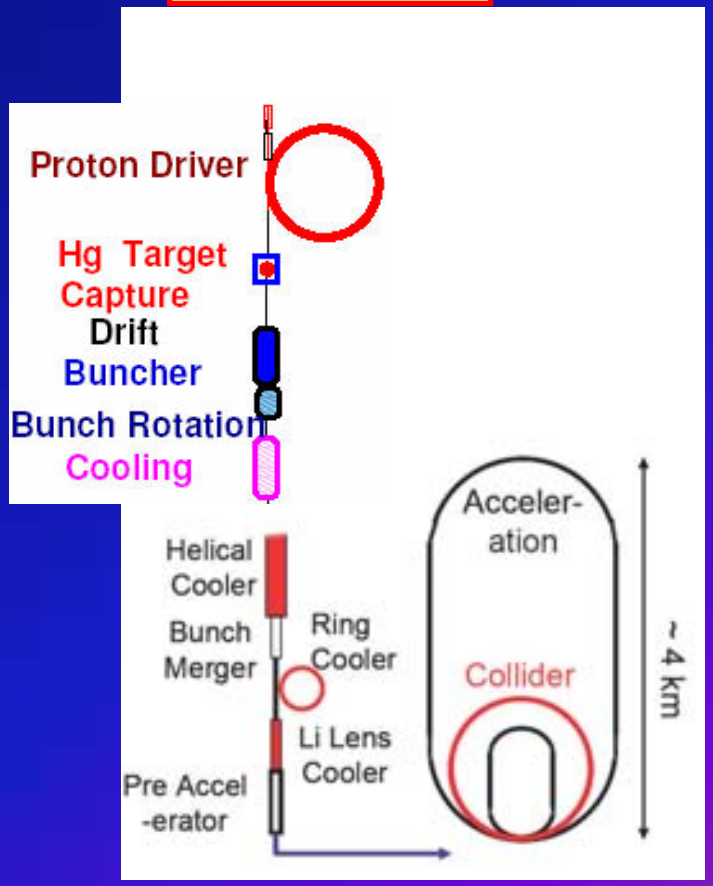
Longitudinal - Emittance Exchange

NF, Muon Collider - Synergy

Neutrino Factory –ISS Preliminary



Muon Collider



Additional Technologies Needed for a Muon Collider

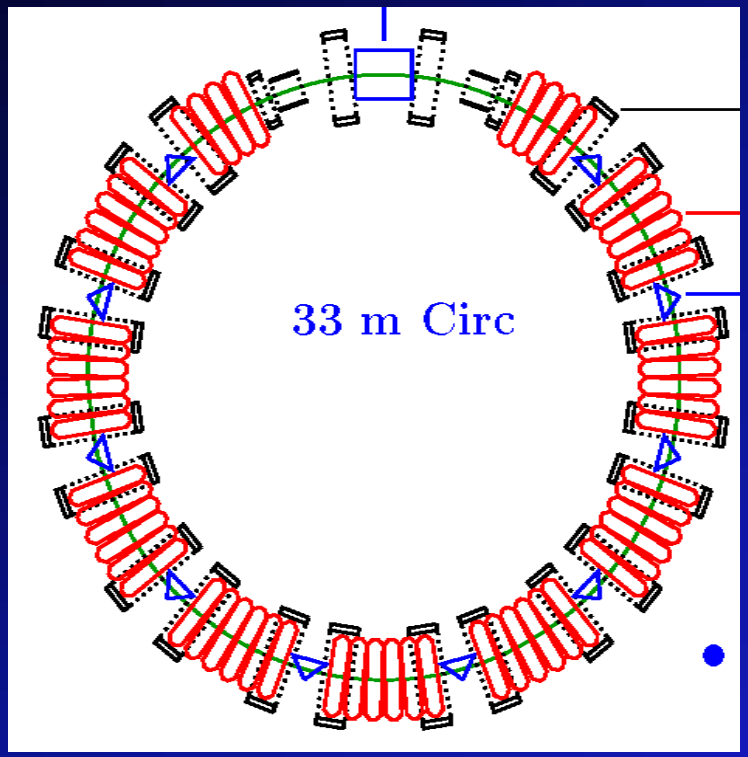
- Although a great deal of R&D has been done (or is ongoing) for a Neutrino Factory and is applicable to a MC, the Technological requirements for a Muon Collider are Much More Aggressive
  - Bunch Merging is required
  - MUCH more Cooling is required (MAKE OR BREAK FOR MC !)
    - 1000X in each transverse dimension, ≈ 10X in longitudinal

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

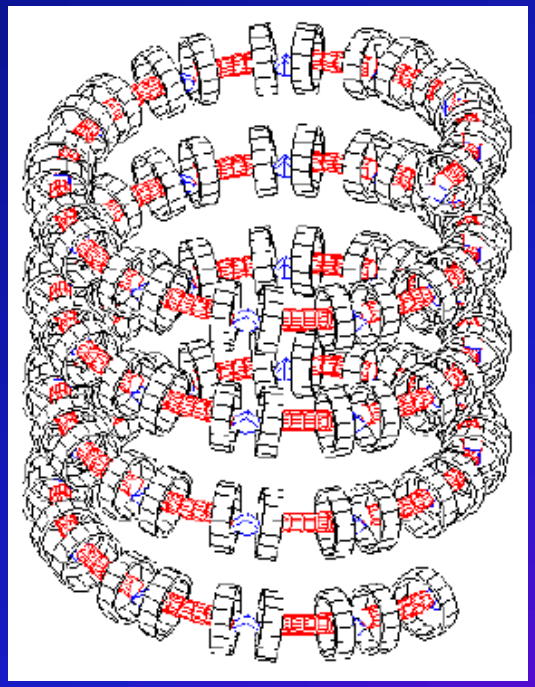
Muons Inc.
High pressure gas-filled cavities
Helical Cooling Channel
Reverse Emittance Exchange
Parametric Resonance Induced Cooling

  - 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

6 Dimensional Cooling



RFOFO Ring



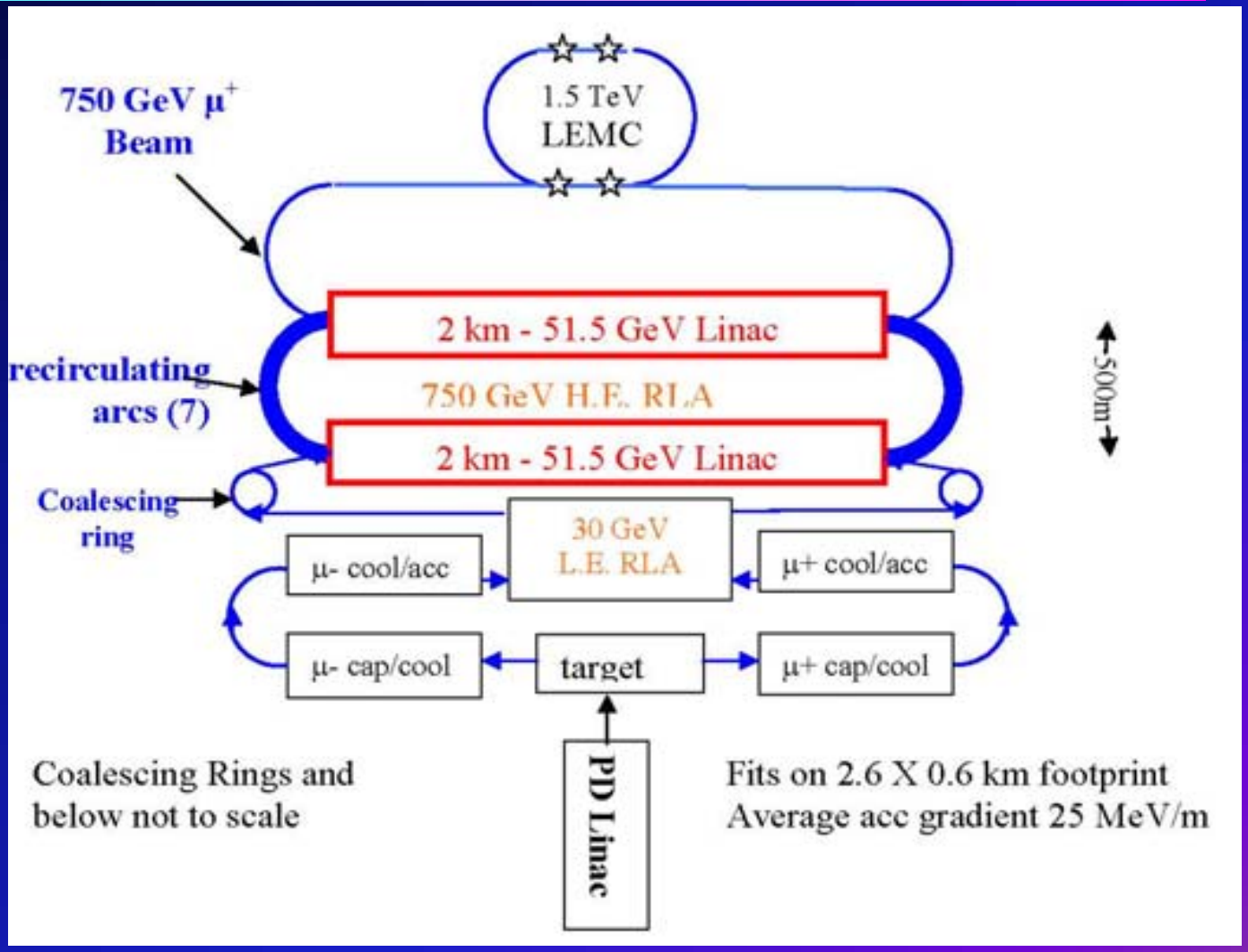
Guggenheim "Ring"

Low-Emittance Muon Collider (LEMC)

Parameter List:

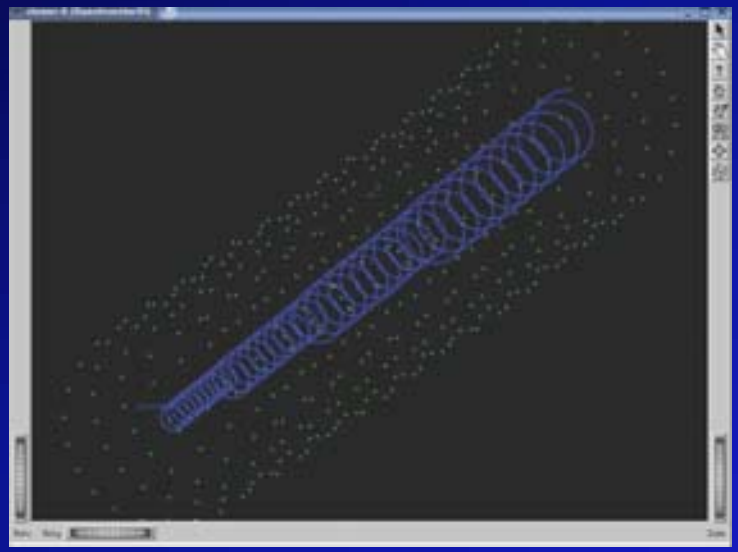
E_{cm} = 1.5 TeV
Peak $\mathcal{L}$ = 7X10^{34}
#μ's/bunch = 10^{11}
Av Dipole B = 10T
$\delta p/p$ = 1%
β^*(cm) = 0.5 (!)

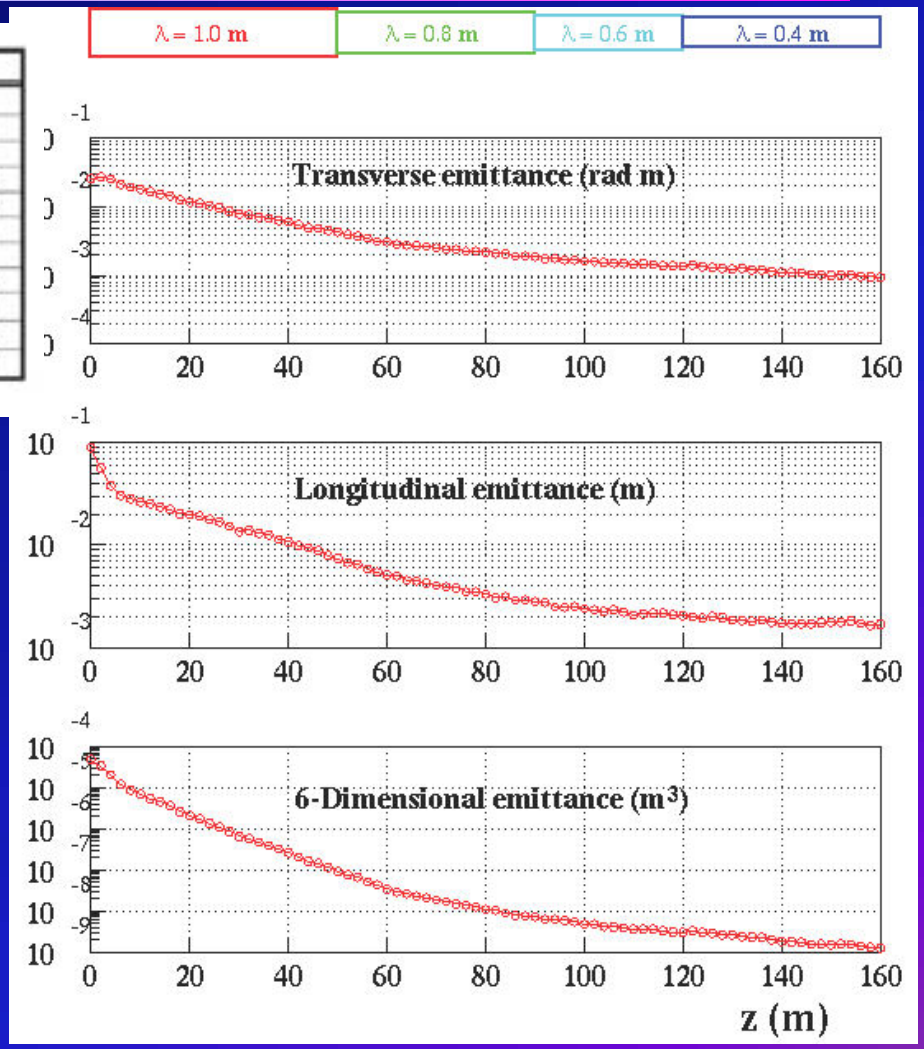
Proton driver:
E = 8 GeV
Power ≈ 1 MW



Helical Cooling Channel

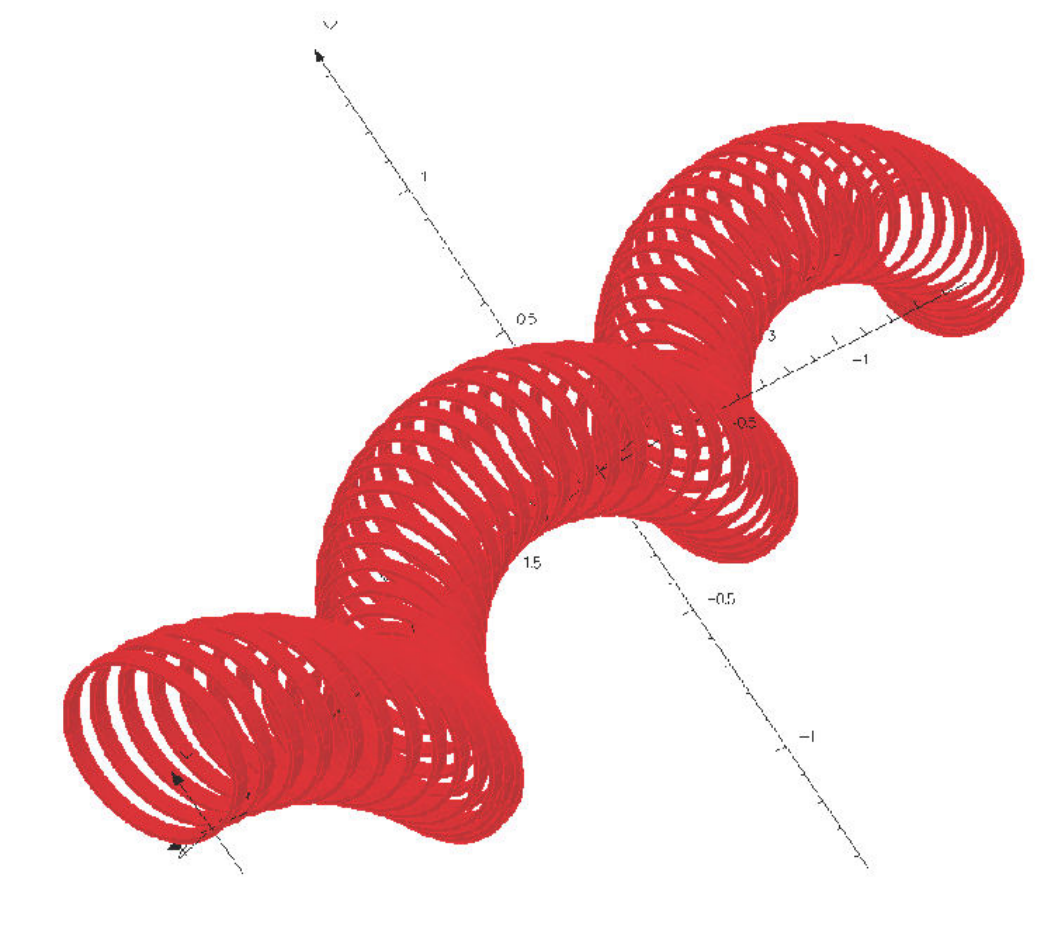
Series HCCs			Segment			
			1st	2nd	3rd	4th
L	Length	m	50	40	30	40
λ	Helix period	m	1.0	0.80	0.60	0.40
a	Reference orbit radius	m	0.16	0.13	0.095	0.064
κ	Helix pitch		1.0	1.0	1.0	1.0
B	Solenoidal component	T	-6.95	-8.68	-11.6	-17.4
b_d	Helix dipole coefficient	T	1.81	2.27	3.02	4.53
b_q	Helix quadrupole coefficient	T/m	-0.35	-0.44	-0.59	-0.88
b_s	Helix sextupole coefficient	T/m2	0.031	0.039	0.051	0.077





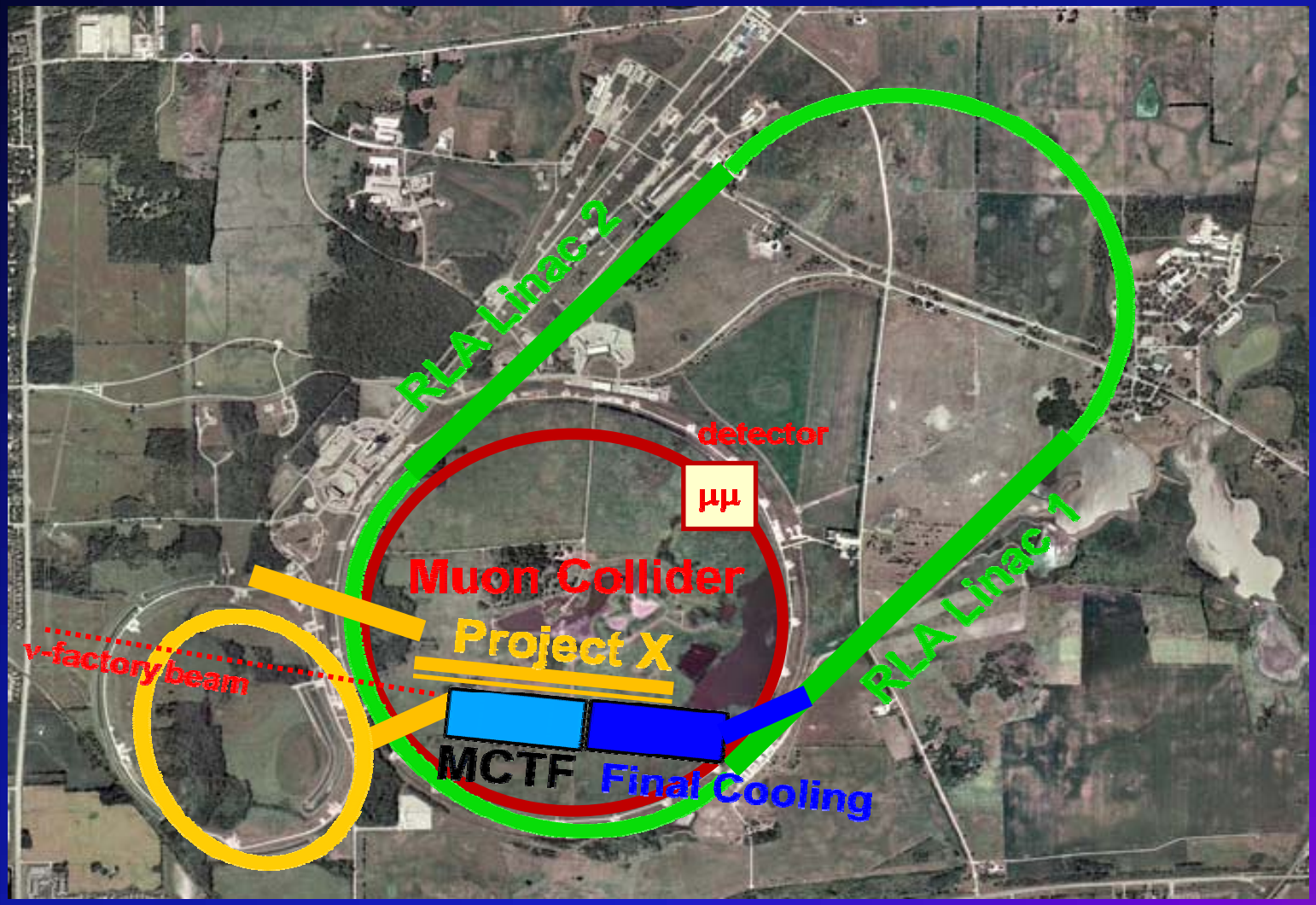
Helical Cooling Channel

- HCC
  - Solenoid + rotating dipole (Siberian Snake)
  - Can also be implemented only using solenoids



Neutrino Factory/Muon Collider and Project X

Fermilab Muon Complex - *Vision*



Scientific Program

R&D Initiatives

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)

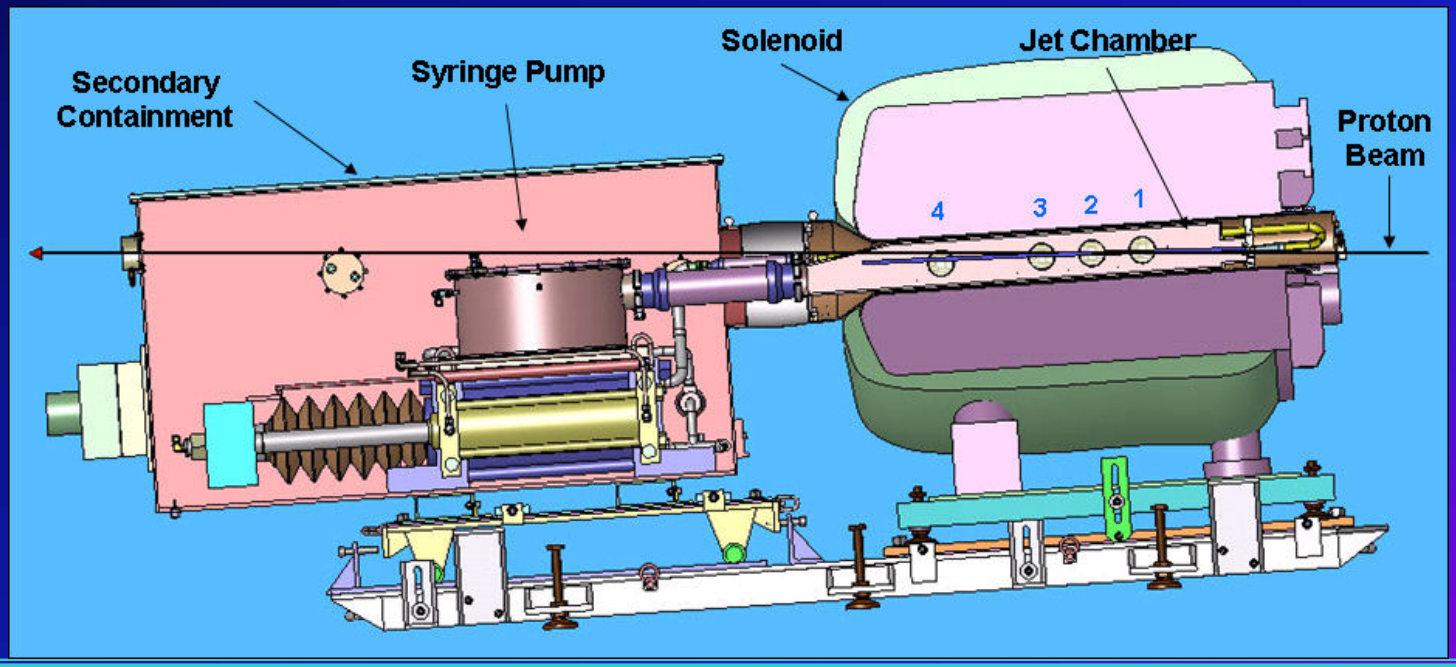
Fermilab Muon Collider Task Force

V. Shiltsev, S. Geer

MERIT

MERIT –Mercury Intense Target

- Test of Hg-Jet target in magnetic field (15T)
- Submitted to CERN April, 2004 (approved April 2005)
- Located in TT2A tunnel to ISR, in nTOF beam line
- First beam was on October 17th, 2007 (3 week run)
  - Test the principle of 50 Hz operation at 24 GeV ⇒ 4 MW



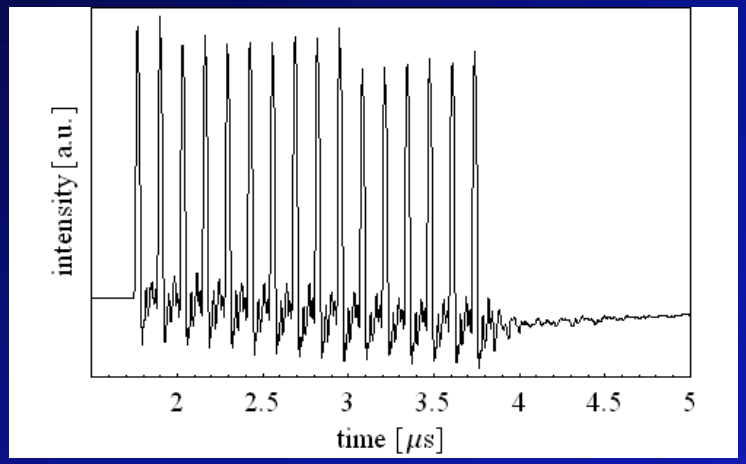
Installed in the CERN TT2a Line

Before Mating

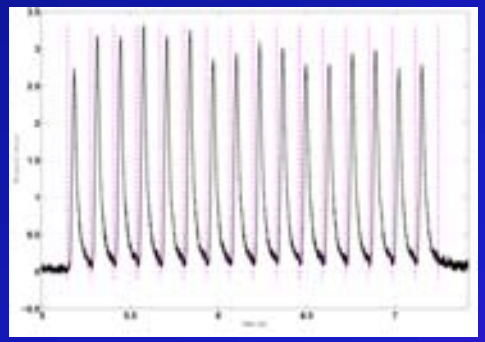
After Mating and Tilting

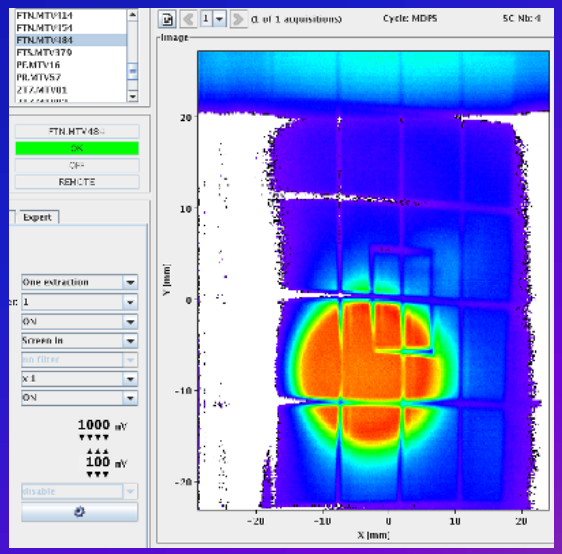
Beam instrumentation

Beam current monitor response:



Particle detector response:





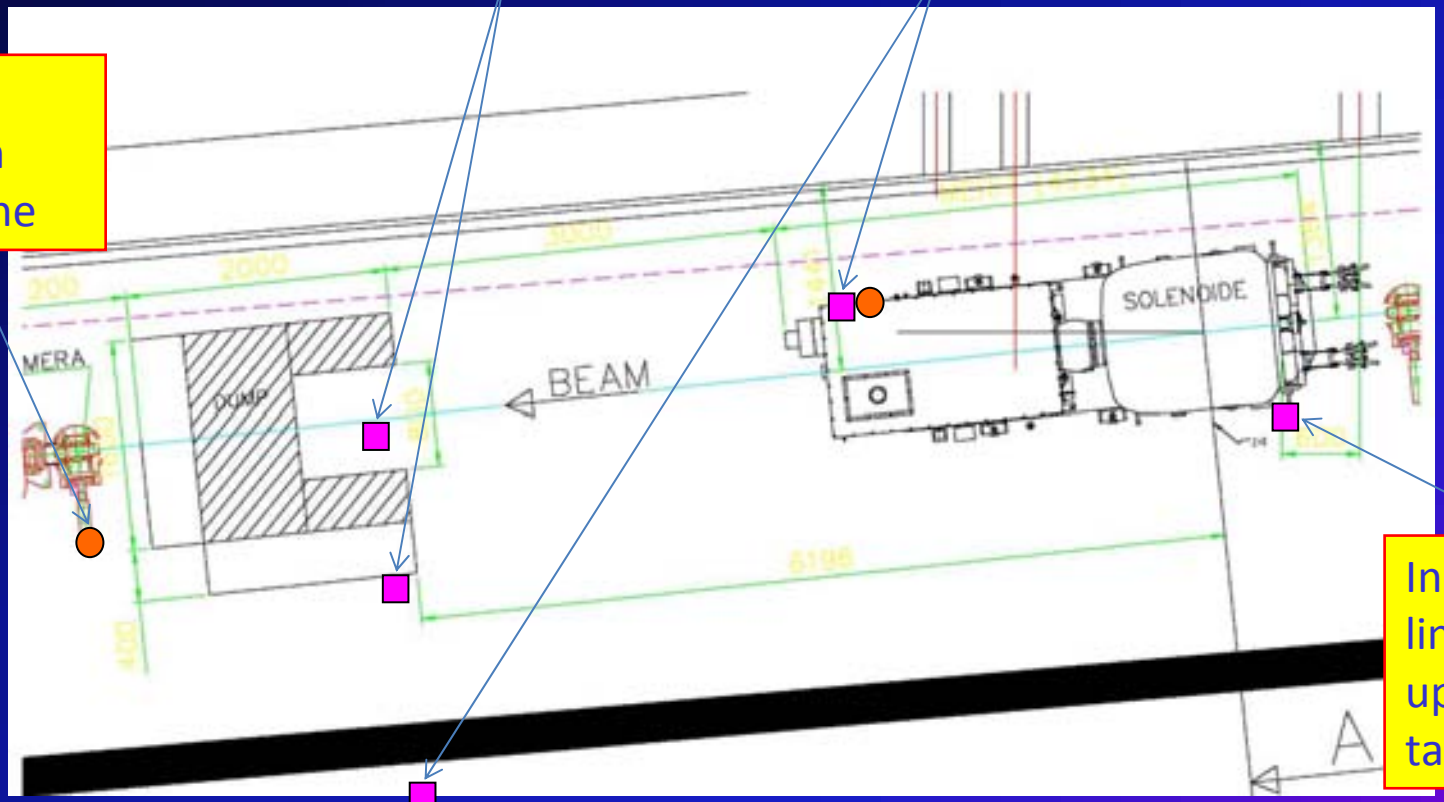
The Pump/Probe Detectors

- ACEM (Aluminum Cathode Electron Multiplier)
- Diamond

+/- 10 degrees

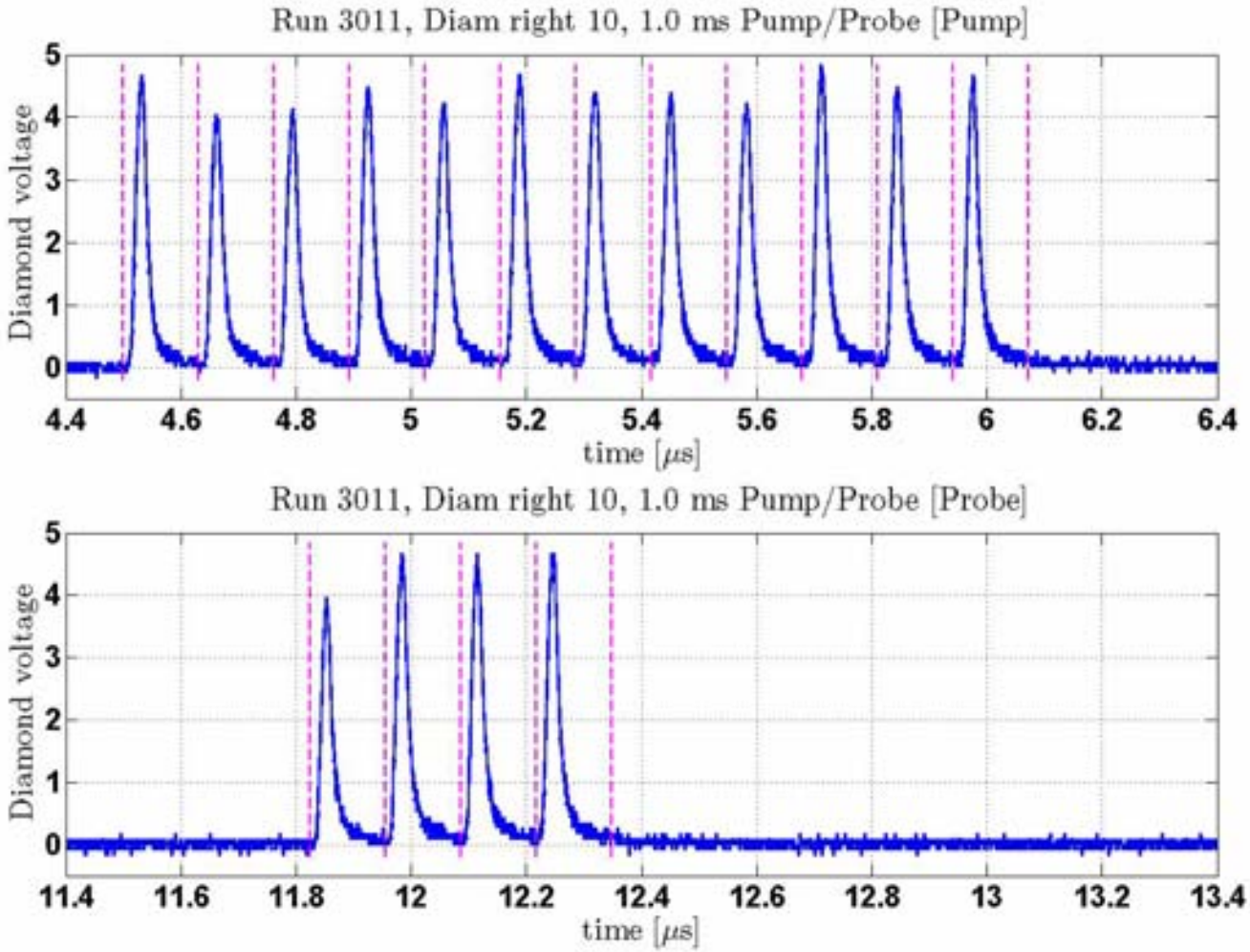
+/- 20 degrees

Behind dump in beam line

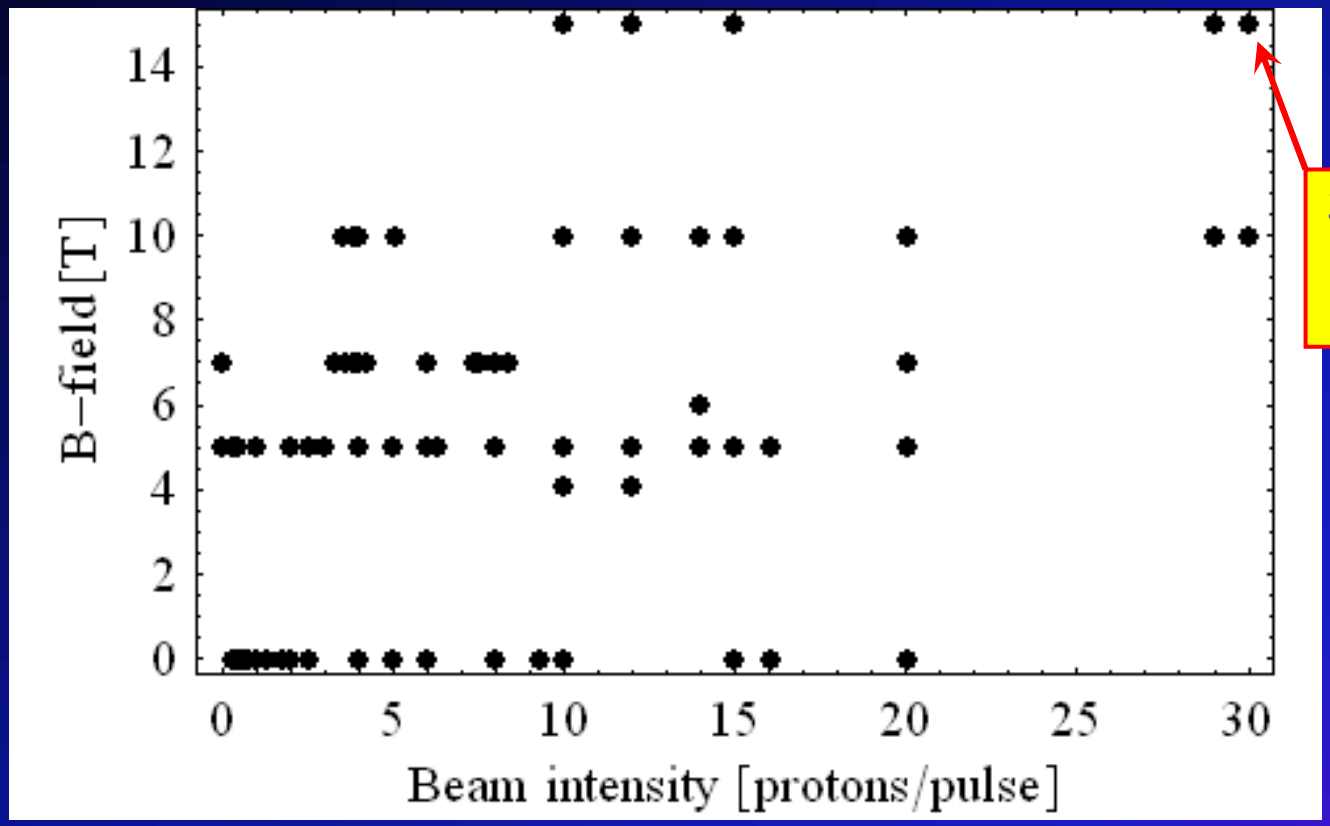


In beam line, upstream of target

A 3T Pump Pulse and a 1TP Probe Pulse with 1ms delay

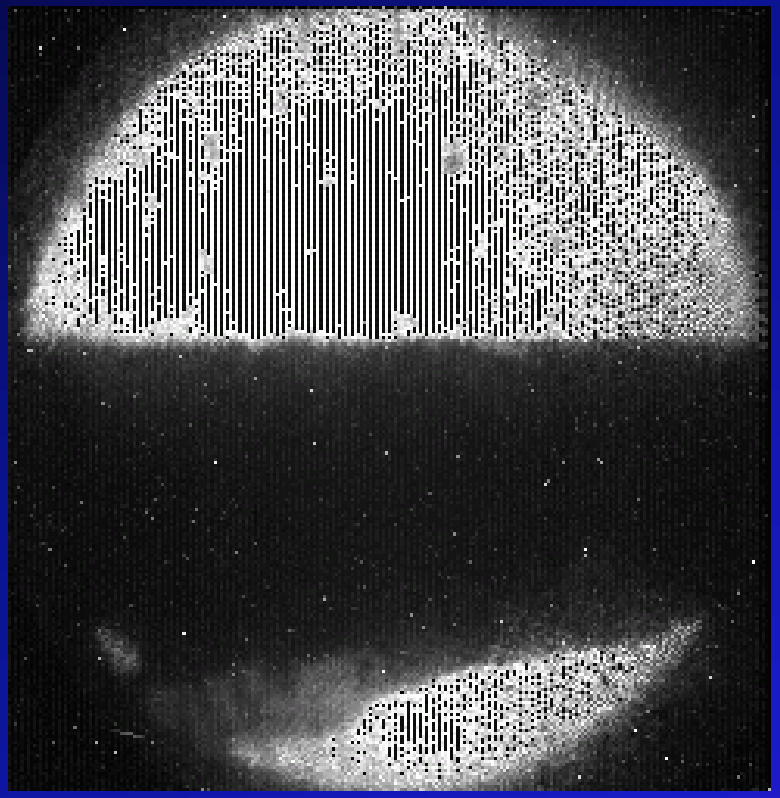


MERIT Beam Shots



30 x 10^{12} protons/pulse!!!
24 GeV
115kJ !!! a PS record

20TP 14GeV Proton Beam



Oct. 27, 2007
Solenoid Field at 10T

Viewport 2

Beam 5020, Hg 15m/s, 100μs/frame, Total 1.6ms

The 24 GeV 30TP shot

- Beam pulse energy = 115kJ
- B-field = 15T
- Jet Velocity = 20 m/s
- Measured Disruption Length = 28 cm
- Required "Refill" time is then 28cm/20m/s = 14ms
  - → Rep rate of 70Hz

→ Proton beam power at that rate is 115kJ *70 = 8MW

The MERIT Bottom Line

- The Neutrino Factory/Muon Collider target concept has been validated for 4MW 50Hz operations.
  - Tremendous work by the MERIT Team
  - And NFMCC Management wants to Thank CERN for the invaluable technical support and resources that were provided and made it possible to get the experiment on line

MuCool

Muon Cooling: MuCool and MICE

Component R&D and Cooling Experiment

- **MuCool**
  - Component testing: RF, Absorbers, Solenoids
    - With High-Intensity Proton Beam
  - 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

MuCool Program

- Mission
  - Design, prototype and test all cooling channel components (SFOFO)
    - 201 MHz RF Cavities, absorbers, SC solenoids
      - High Gradient 201 MHz Cavity operation in strong B field
  - Support MICE (cooling demonstration experiment)
  - Perform high beam-power engineering test of cooling section components

- Currently consists of 9 institutions from the US, UK and Japan

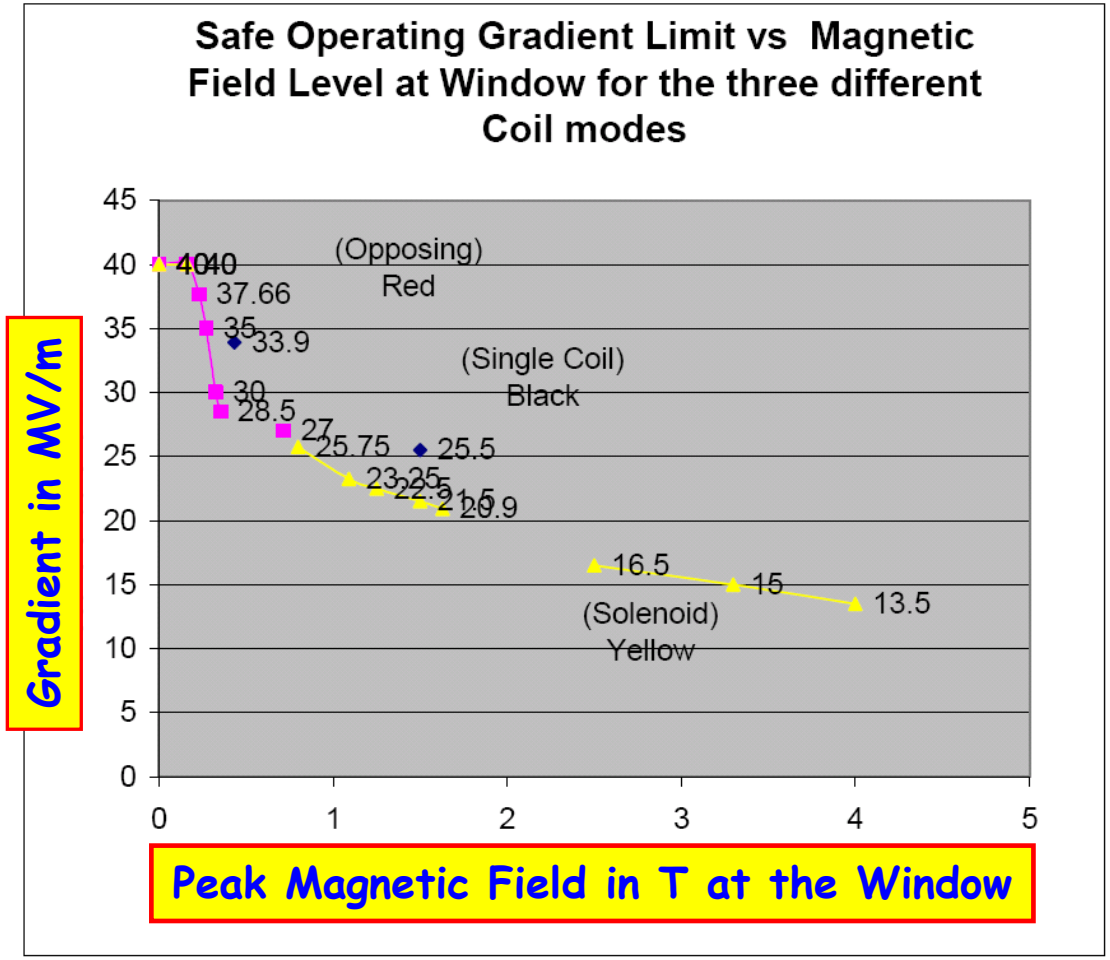
RF Development
ANL
Fermilab
IIT
JLAB
LBNL
Mississippi

Solenoids
LBNL
Mississippi

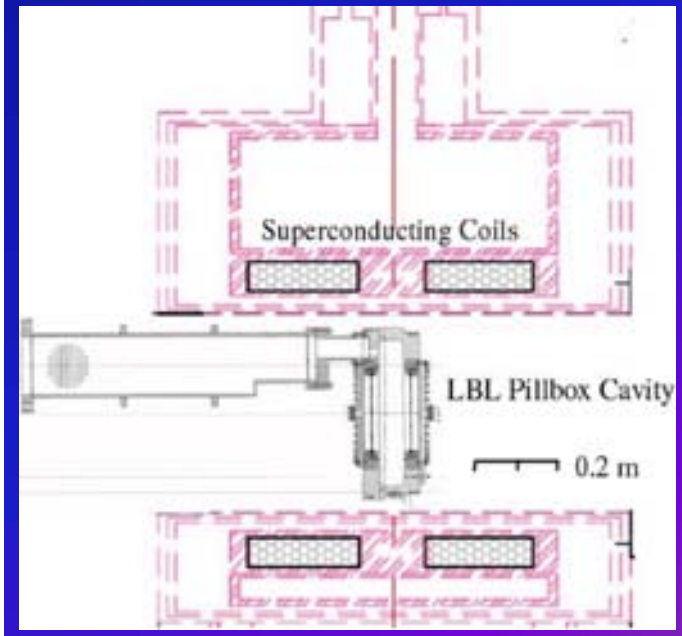
Absorber R&D
Fermilab
IIT
KEK
NIU
Mississippi
Osaka

MTA Hall

Phase I of RF Cavity Closed Cell Magnetic Field Studies (805 MHz)



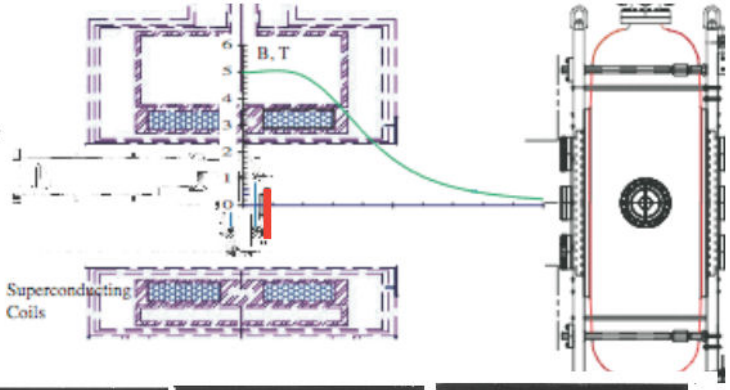
- Data seem to follow universal curve
  - Max stable gradient degrades quickly with B field
- Sparking limits max gradient
- Copper surfaces the problem



805 MHz Imaging

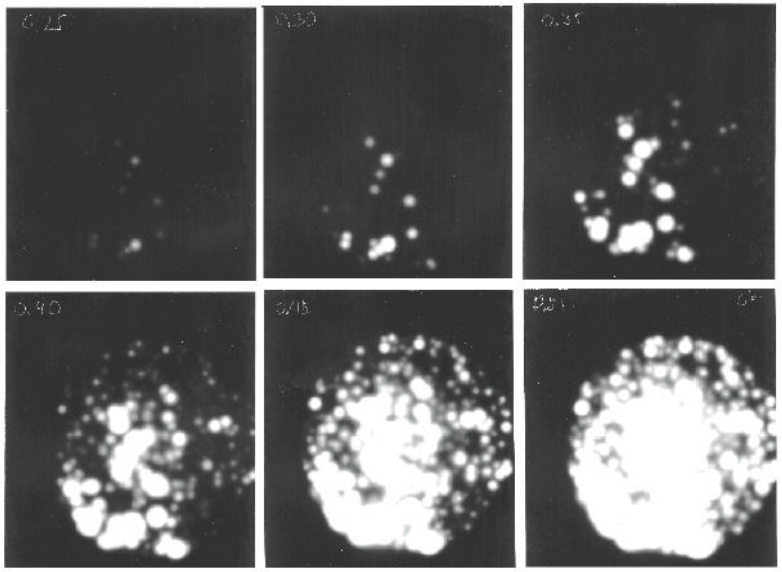
Polaroid Pictures of Field emitters

- Inserting polaroids near the window,



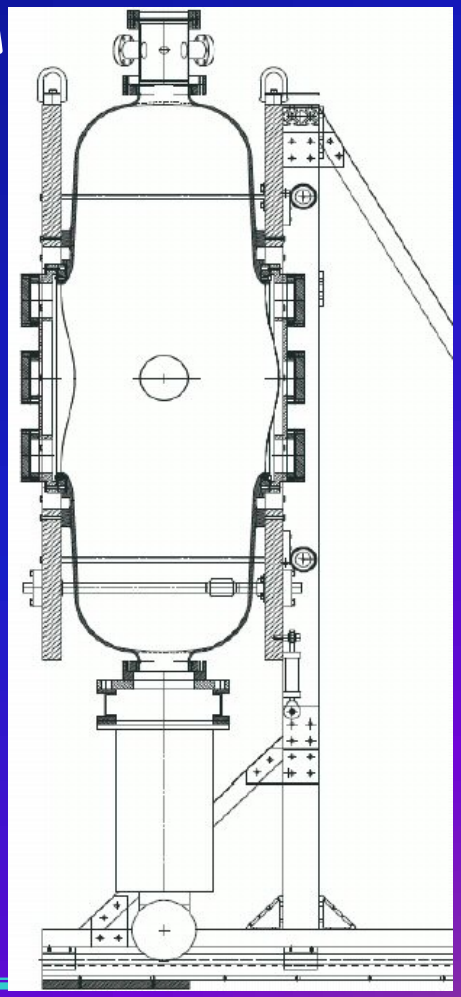
- Gives a picture of how the field emitters change with rf field.

  8.8 – 17.6 MV/m

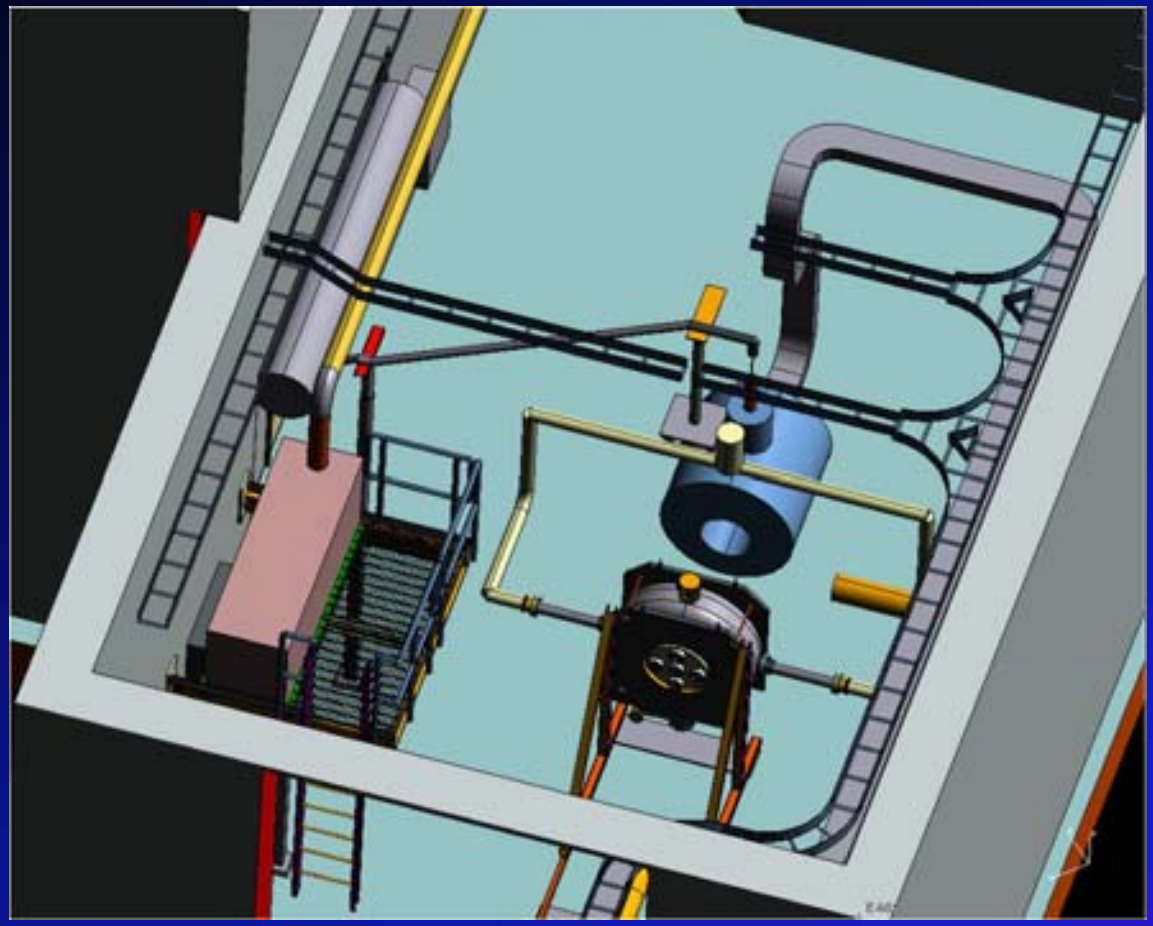


RF R&D – 201 MHz Cavity Design

- The 201 MHz Cavity has now been tested to 19MV/m at B=0 and at B= a few hundred Gauss. Design = 16MV/m

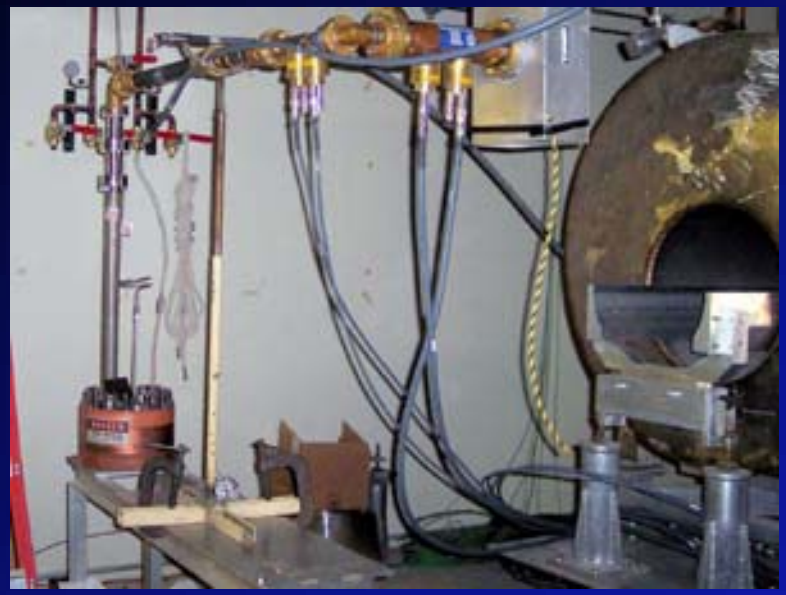


201 MHz Cavity Operation in B Field

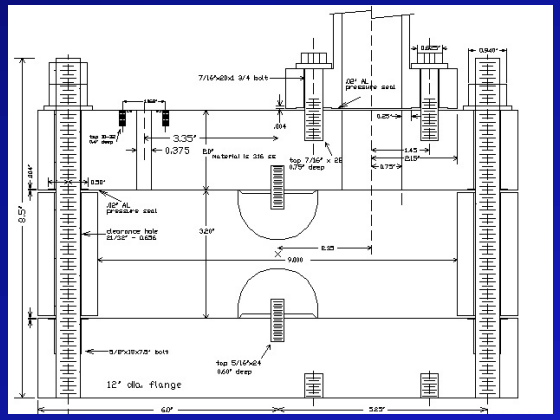


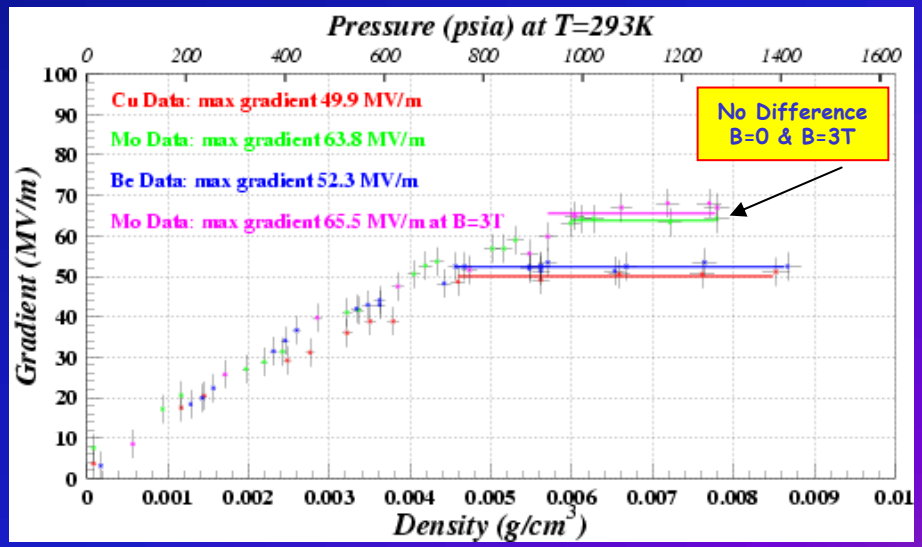
- Initial 201 MHz operation in B Field
  - Limited to few hundred Gauss
    - Using Fringe Field of 4T magnet (in blue)
- In January we will move the 201 in close proximity to our 4T magnet and will be able to operate the cavity in a max field of ≈ 1.5T

High Pressure H_2 Filled Cavity Work
Muon's Inc

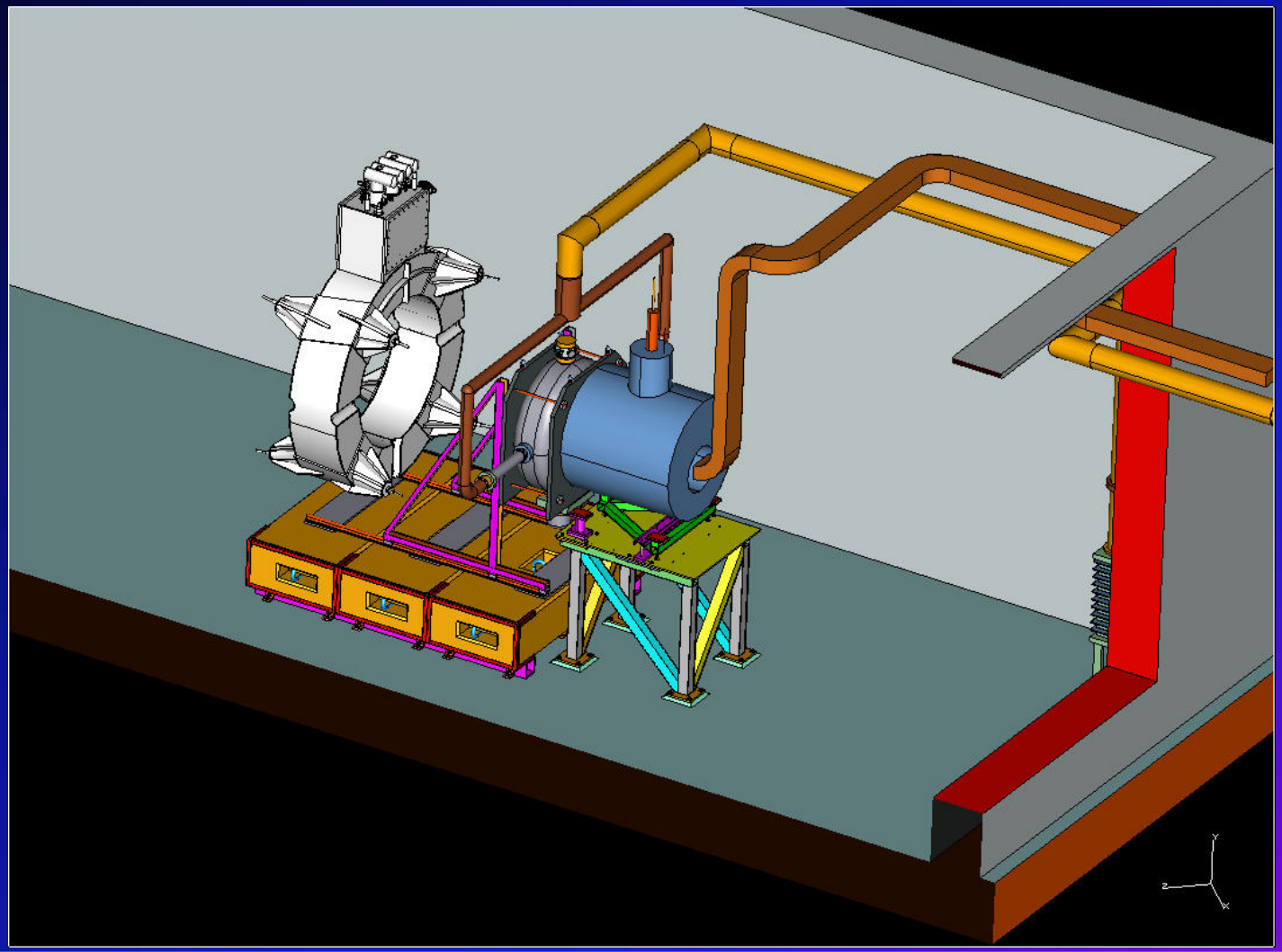


- High Pressure Test Cell
- Study breakdown properties of materials in H_2 gas
- Operation in B field
  - No degradation in M.S.O.G. up to ≈ 3.5T





Phase II - Configuration



Absorber R&D - Fundamentals

- 2D Transverse Cooling

$$\frac{d\epsilon_N}{ds} = -\frac{1}{\beta^2}\frac{dE_\mu}{ds}\frac{\epsilon_N}{E_\mu} + \frac{\beta_\perp (0.014\ \mathrm{GeV})^2}{2\beta^3 E_\mu m_\mu L_R}$$

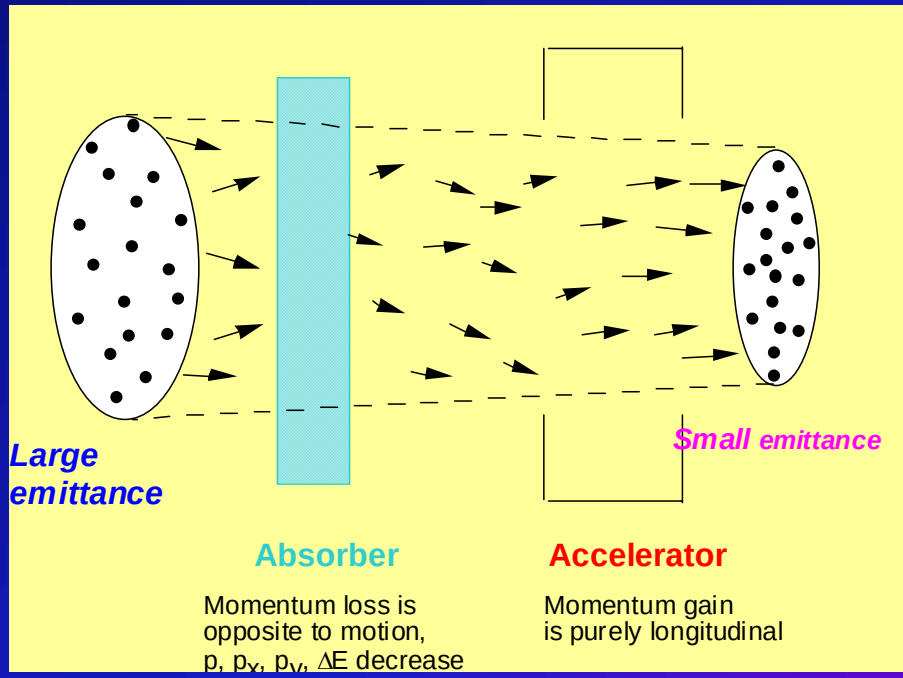
and

$$\epsilon_{N,\mathrm{min}} = \frac{\beta_\perp (14\ \mathrm{MeV})^2}{2\beta m_\mu \frac{dE_\mu}{ds} L_R}$$

- Figure of merit: $M = L_R dE_\mu/ds$

M^2 (4D cooling) for different absorbers

Material	$\langle dE/ds \rangle_{\mathrm{min}}$ (MeV g^{-1}cm^2)	L_R (g cm^{-2})	Merit
GH_2	4.103	61.28	1.03
LH_2	4.034	61.28	1
He	1.937	94.32	0.55
LiH	1.94	86.9	0.47
Li	1.639	82.76	0.30
CH_4	2.417	46.22	0.20
Be	1.594	65.19	0.18

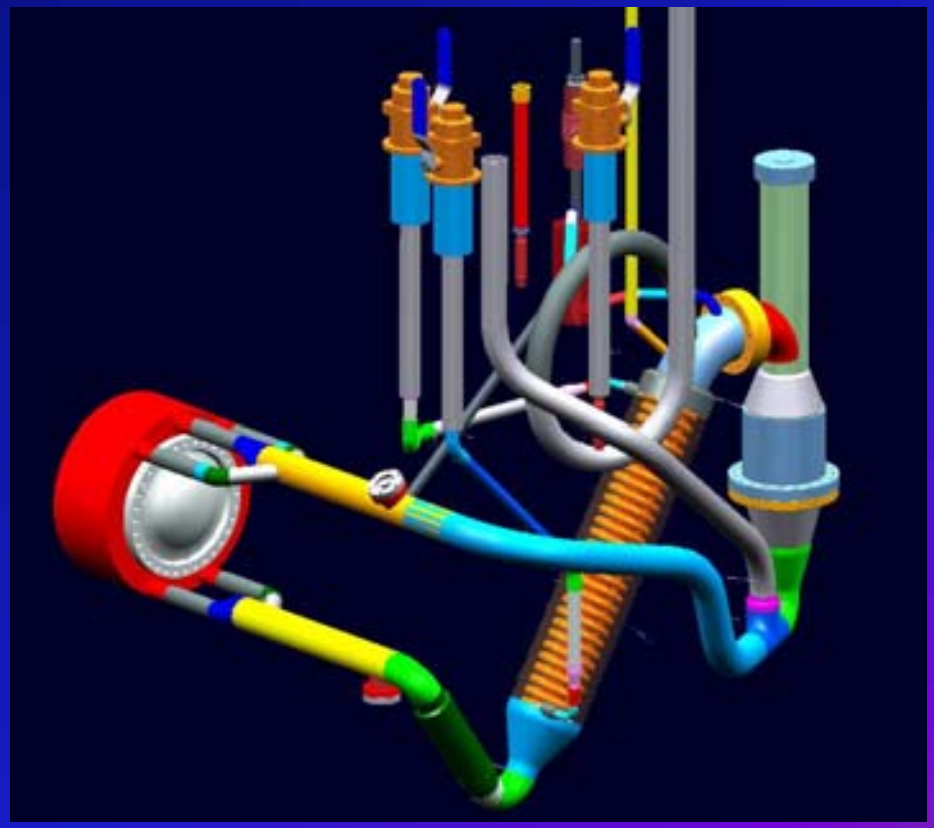


H_2 is clearly Best -
Neglecting Engineering Issues
Windows, Safety

Absorber Engineering

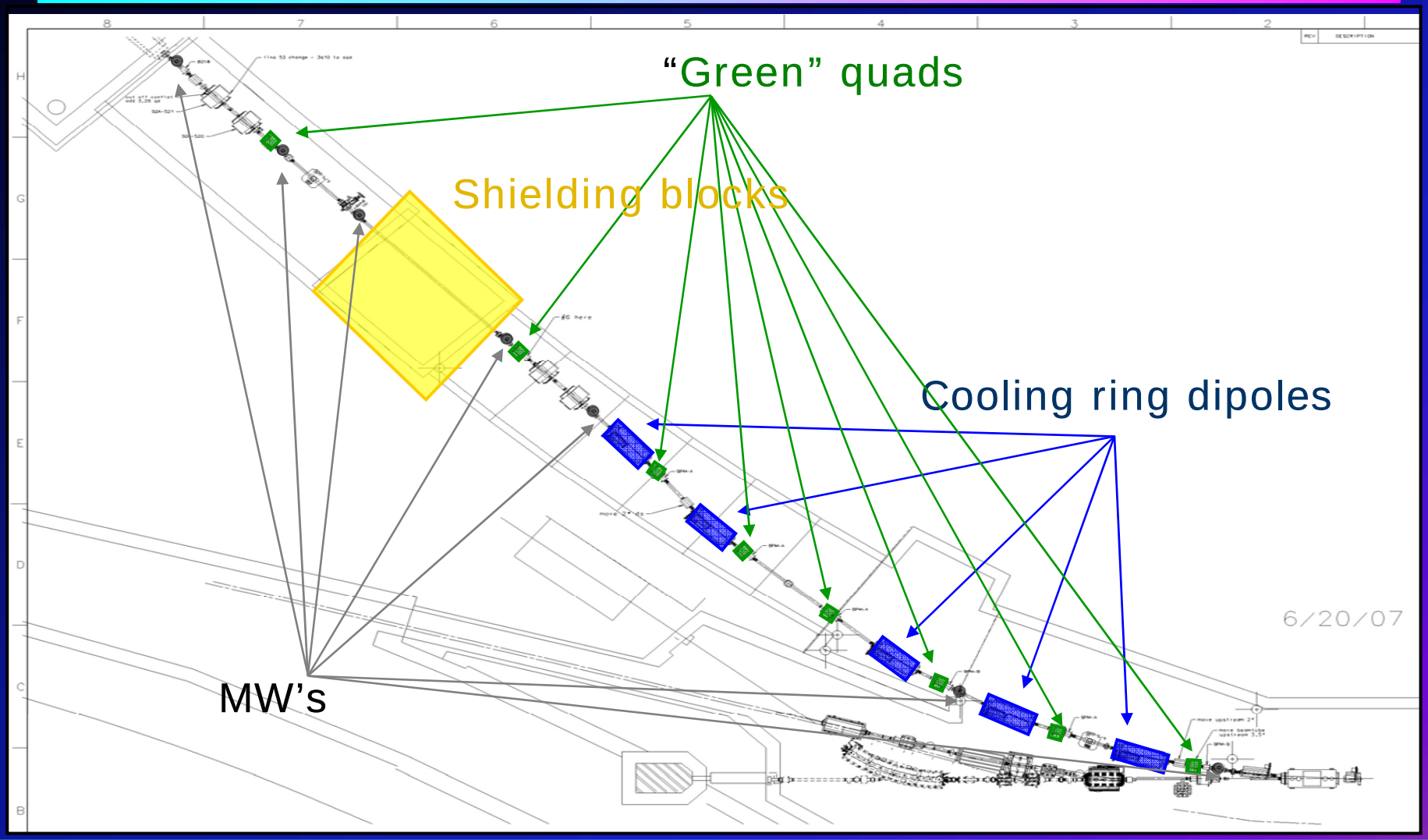
- Two LH_2 absorber designs are being studied
  - Handle the power load differently

Forced-Convection-cooled. Has internal heat exchanger (LHe) and heater – KEK System



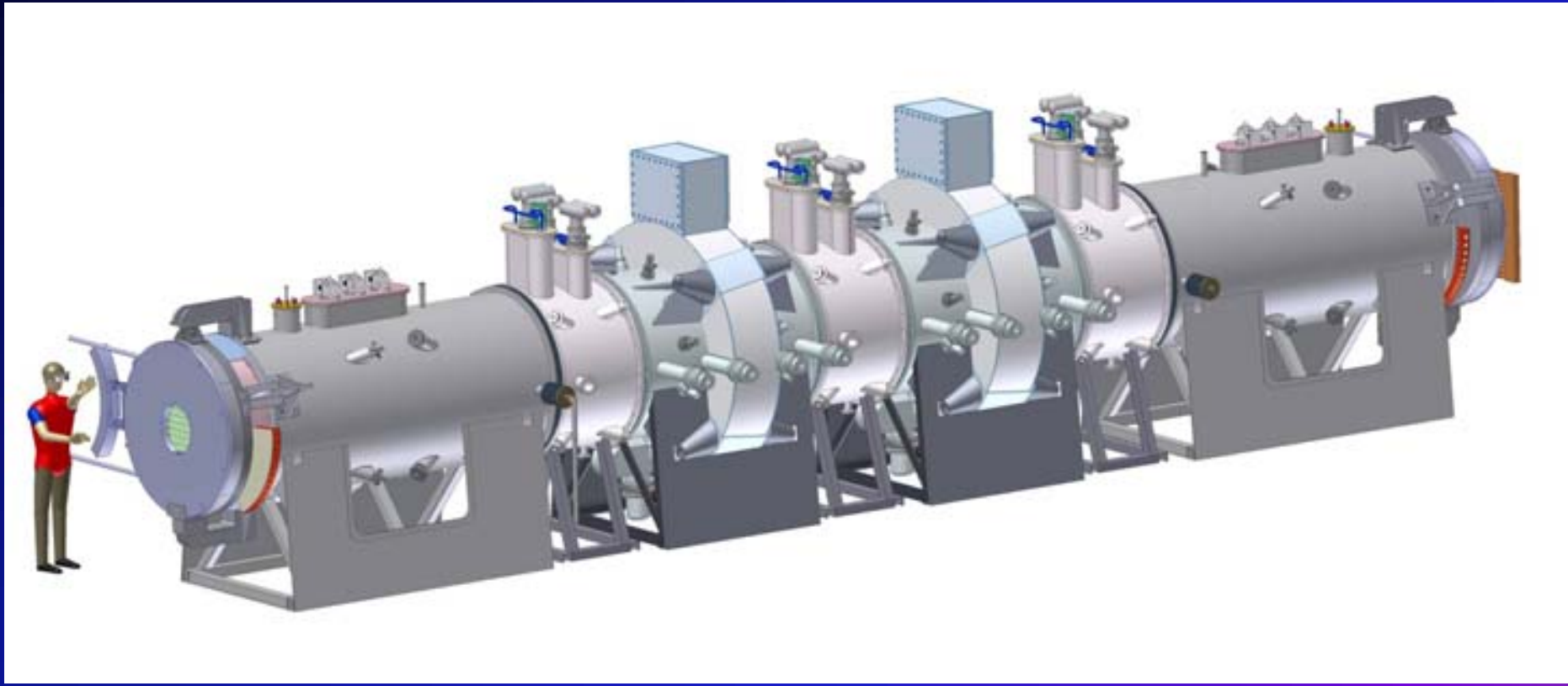
Forced-Flow with external cooling loop

MTA Beam Line



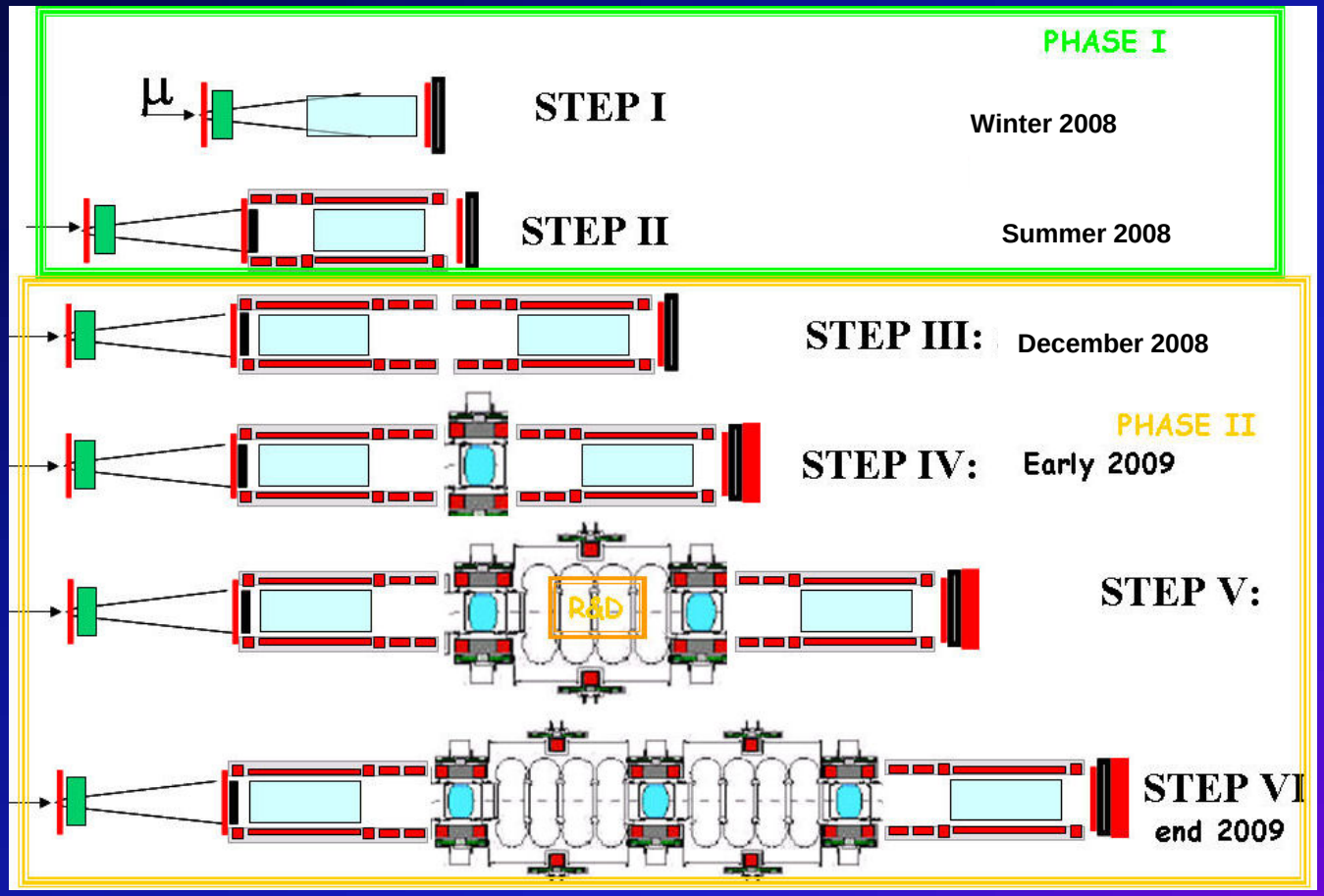
- Beam Line commissioning begins in early 2008, first tests with beam in June
- Designed to accommodate full Linac Beam
  - 1.6 X 10^{13} p/pulse @15 Hz
    - 2.4 X 10^{14} p/s
    - ≈ 600 W into 35 cm LH_2 absorber @ 400 MeV
- Will start at low intensity
  - Need Shielding upgrade (over-burden) for high-intensity

MICE

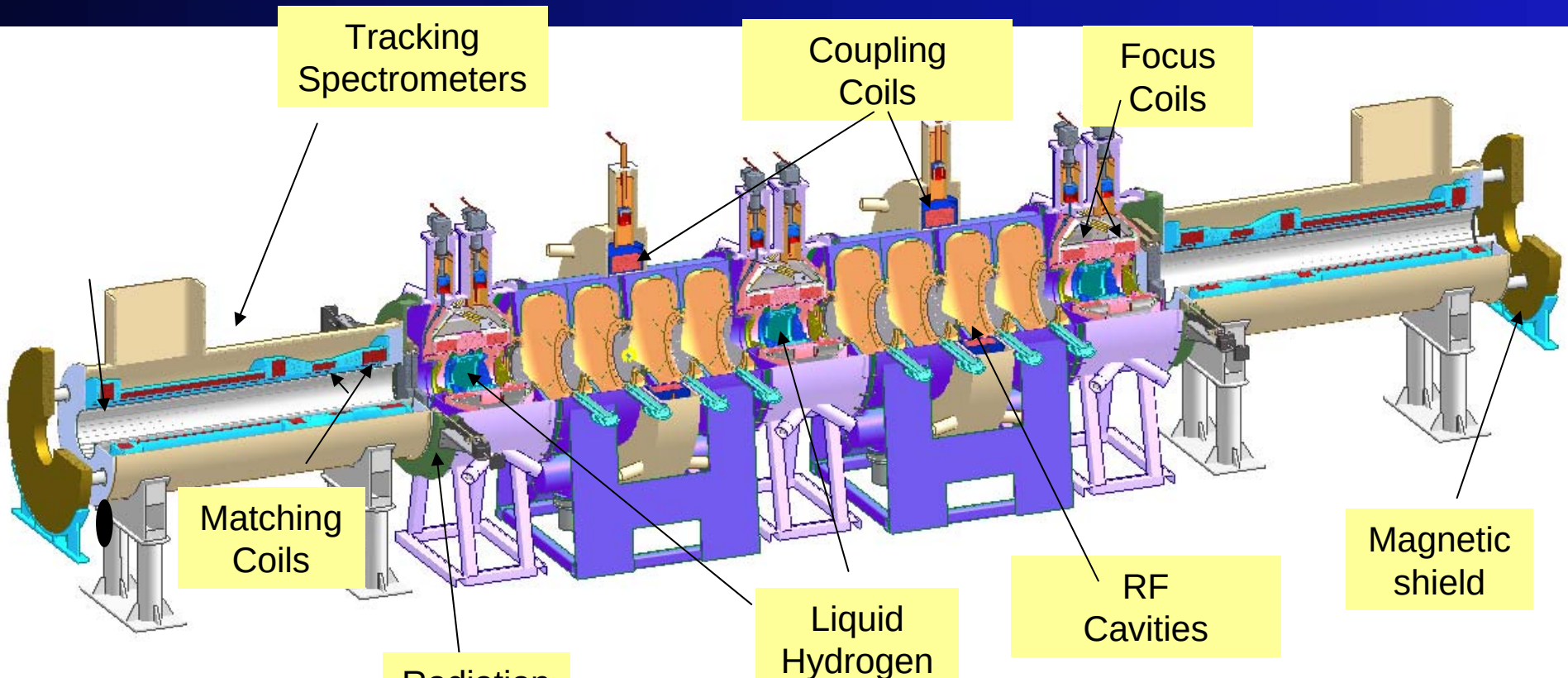


Muon Ionization Cooling Experiment (MICE)

MICE
Measurement of Muon Cooling - Emittance Measurement @ 10^{-3}



Muon Ionization Cooling Experiment MICE

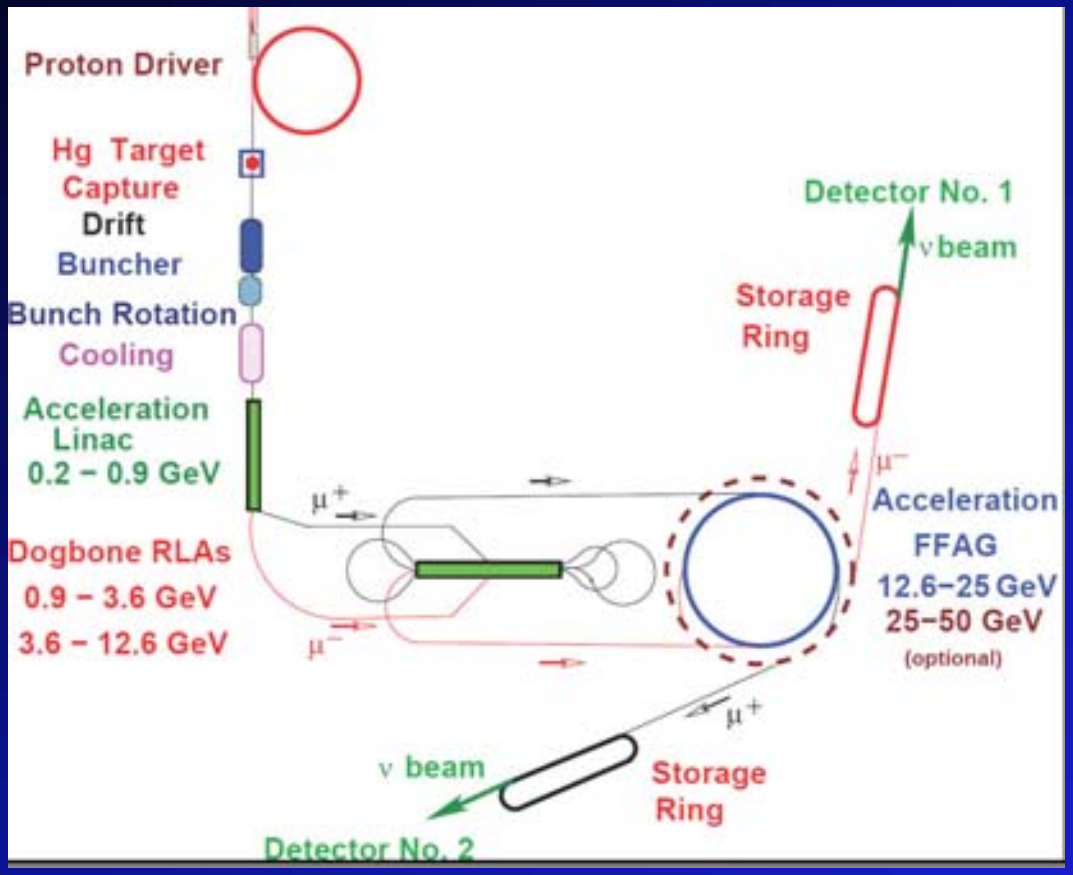


Parts is Parts

MuCool and MICE

- MuCool Collaboration interface to MICE
  - Design Optimization/develop of Study II cooling channel
    - Simulations
  - Detailed engineering
    - Full component design
    - Systems integration
    - Safety
  - RF cavity development, fabrication, and test
    - 201 MHz operation in B field
  - Absorber development, fabrication, and test
  - MuCool will prototype and test cooling hardware including MICE pieces for which the collaboration is responsible

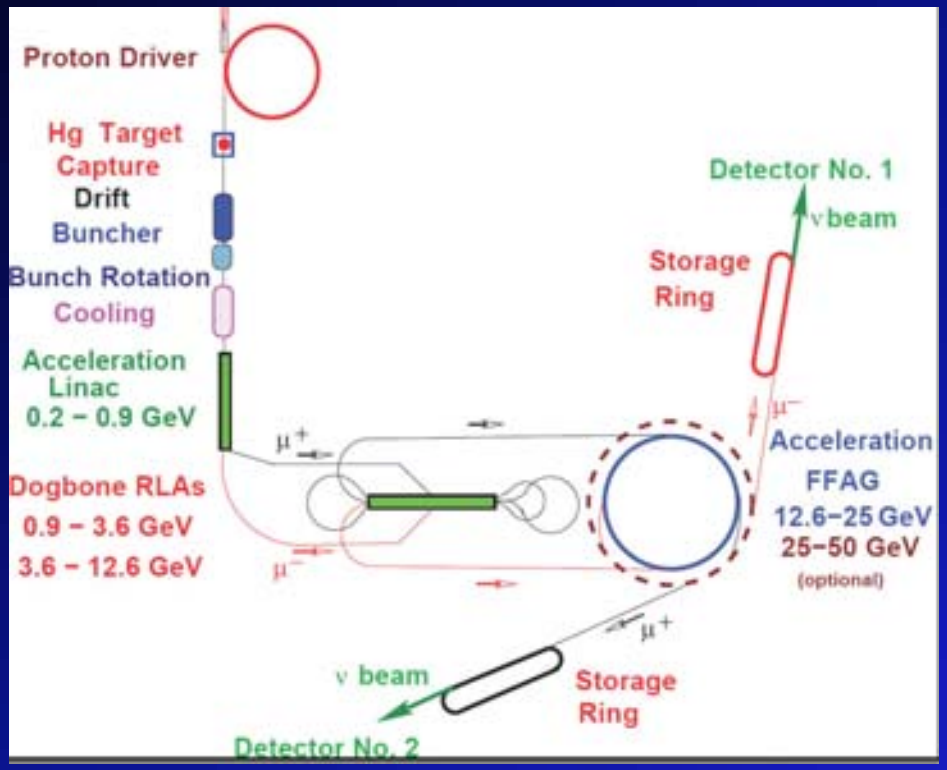
Neutrino Factory – ISS Preliminary Design

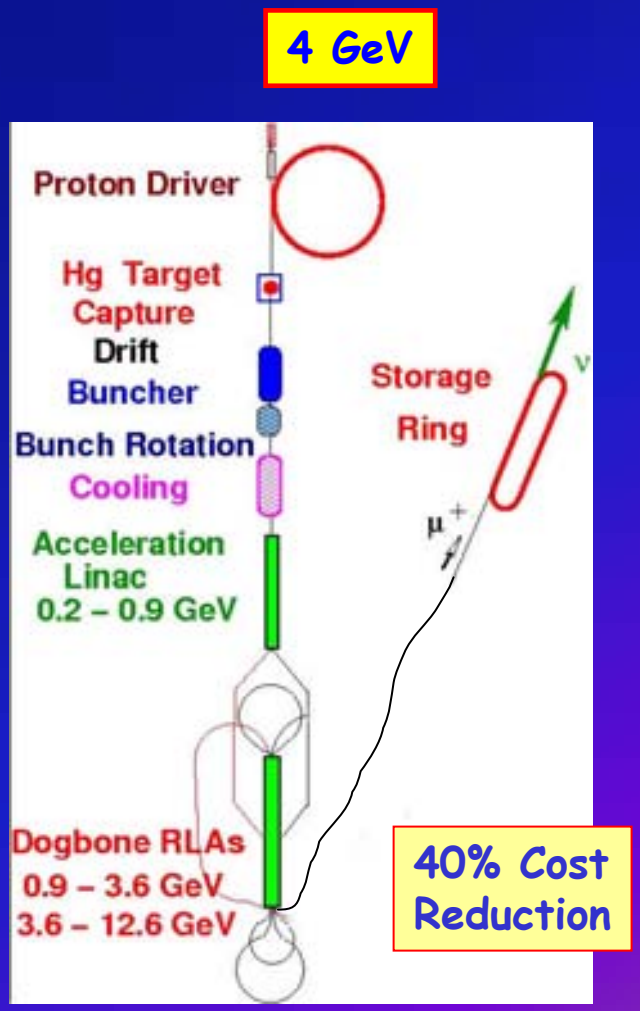


- Proton Driver
- Target, Capture, Decay
  - $\pi \rightarrow \mu$
- Bunching, Phase Rotation
  - Reduce ΔE
- Cooling
- Acceleration
  - 103 MeV $\rightarrow$ 25 & 50* GeV
- Storage/Decay ring

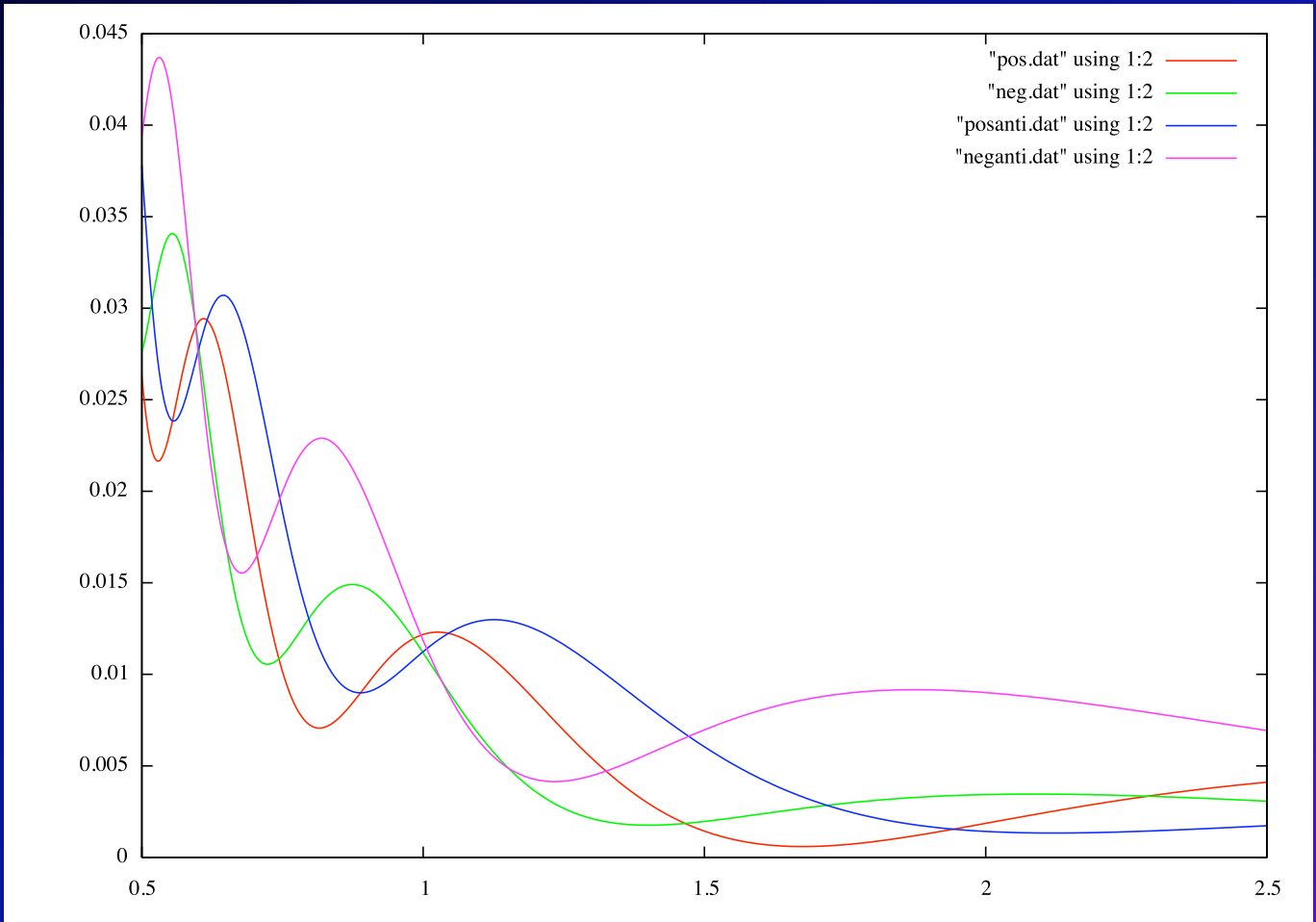
*Still under study

Low-Energy NF
Neutrino Factory Lite



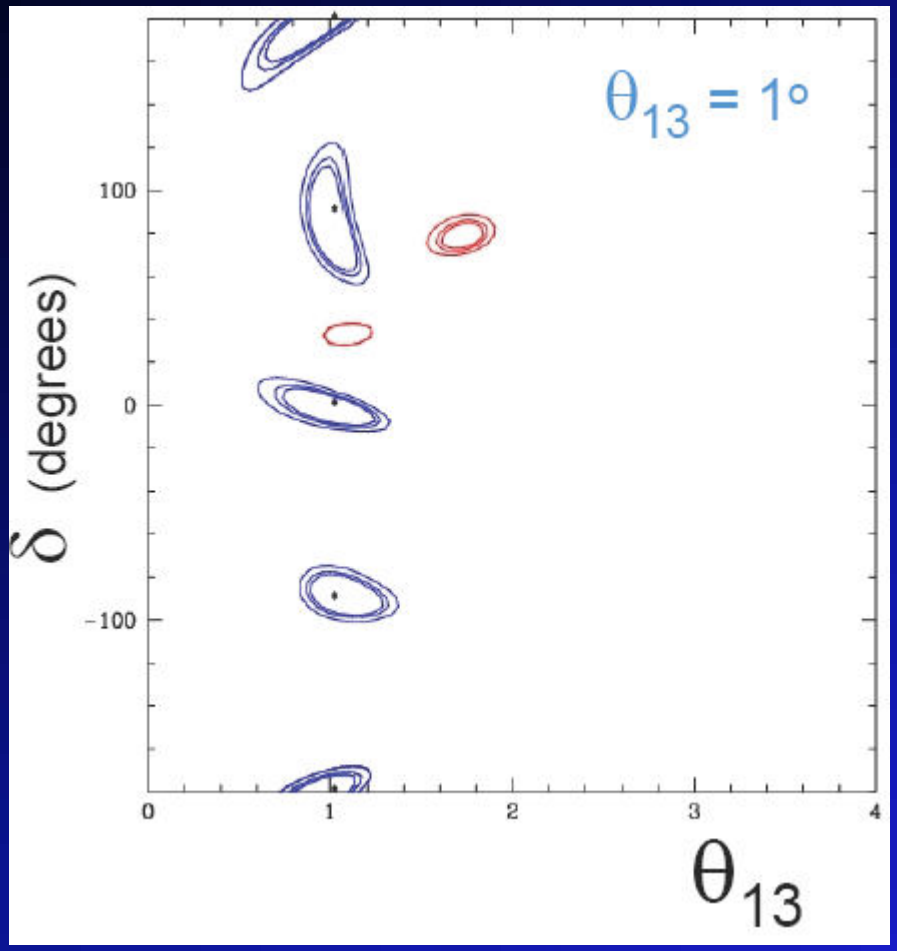


Extension of Analysis with estimated TASD σ_E



- If the TASD can fully exploit the rich oscillation pattern at low energy → 0.5 to 1.5 GeV (and go to E_ν threshold of 0.5 GeV)

Why is Low-Energy NF Interesting?



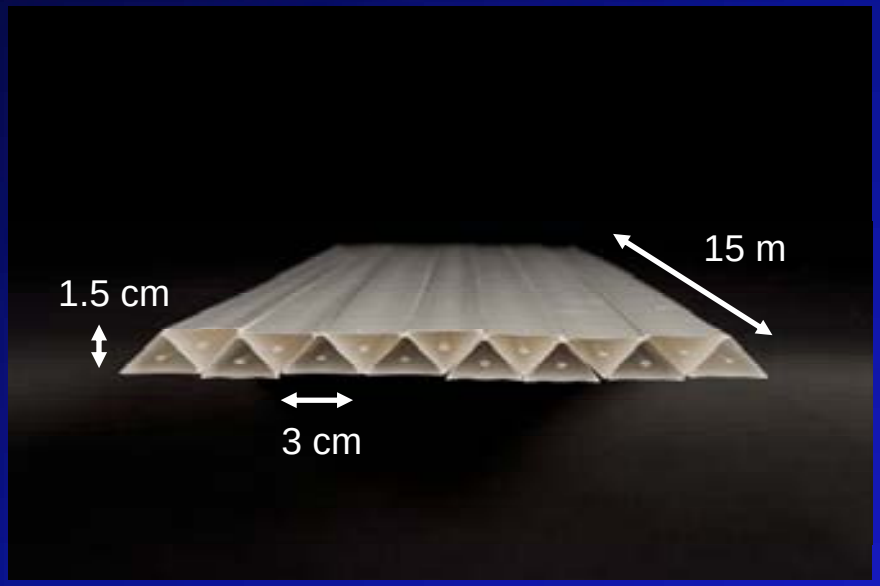
- Choose NF Energy ~ 4 GeV
- This is motivated by the realization that for baselines O(1000km), if θ_{13} is not very "small", the oscillation pattern is extremely rich below ~4 GeV.
  - **Requires "Special" Detector**
- Fitting $\nu_e \rightarrow \nu_\mu$ and $\nu_e \rightarrow \nu_\mu$ rates for 3 energy bins
  - **CP Violation phase δ can be determined with 95% CL precision of 20°, if $\sin^2 2\theta_{13} > 0.001$ ($\theta_{13} > 0.9°$)**
  - **Mass hierarchy determined for all δ, if $\sin^2 2\theta_{13} > 0.01$ ($\theta_{13} > 3°$)**

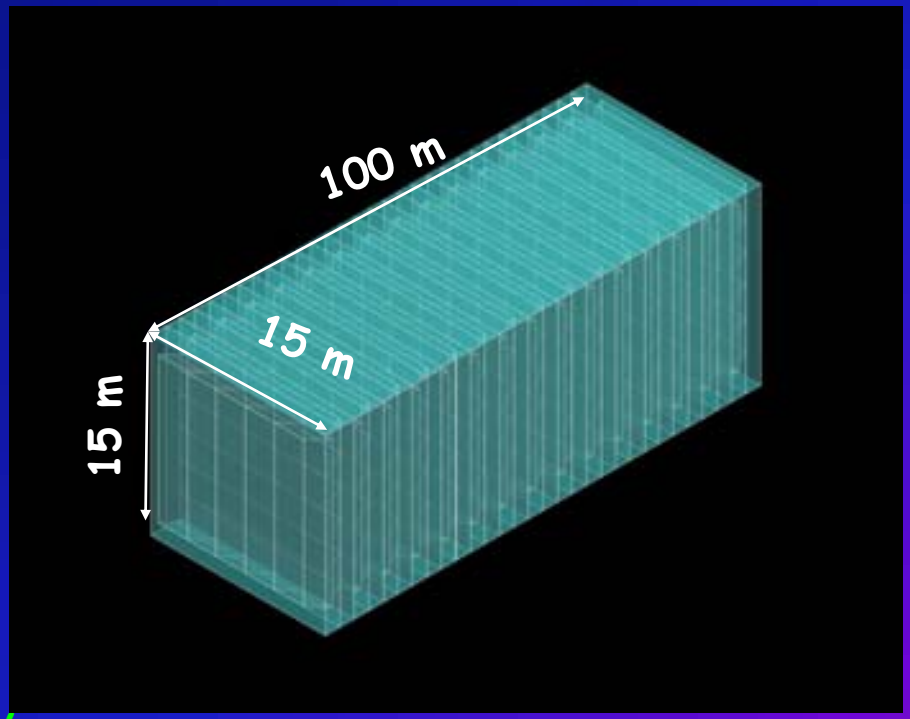
Fit $\nu_e \rightarrow \nu\mu$ & $\nu_e \rightarrow \nu_\mu$ rates (90%, 95%, 99% CL Contours)

"Special" Detector – Fine-Resolution Totally Active Segmented Detector

Simulation of a Totally Active Scintillating Detector (TASD) using Nova and Minerva concepts with Geant4

- 3333 Modules (X and Y plane)
- Each plane contains 1000 slabs
- Total: 6.7M channels

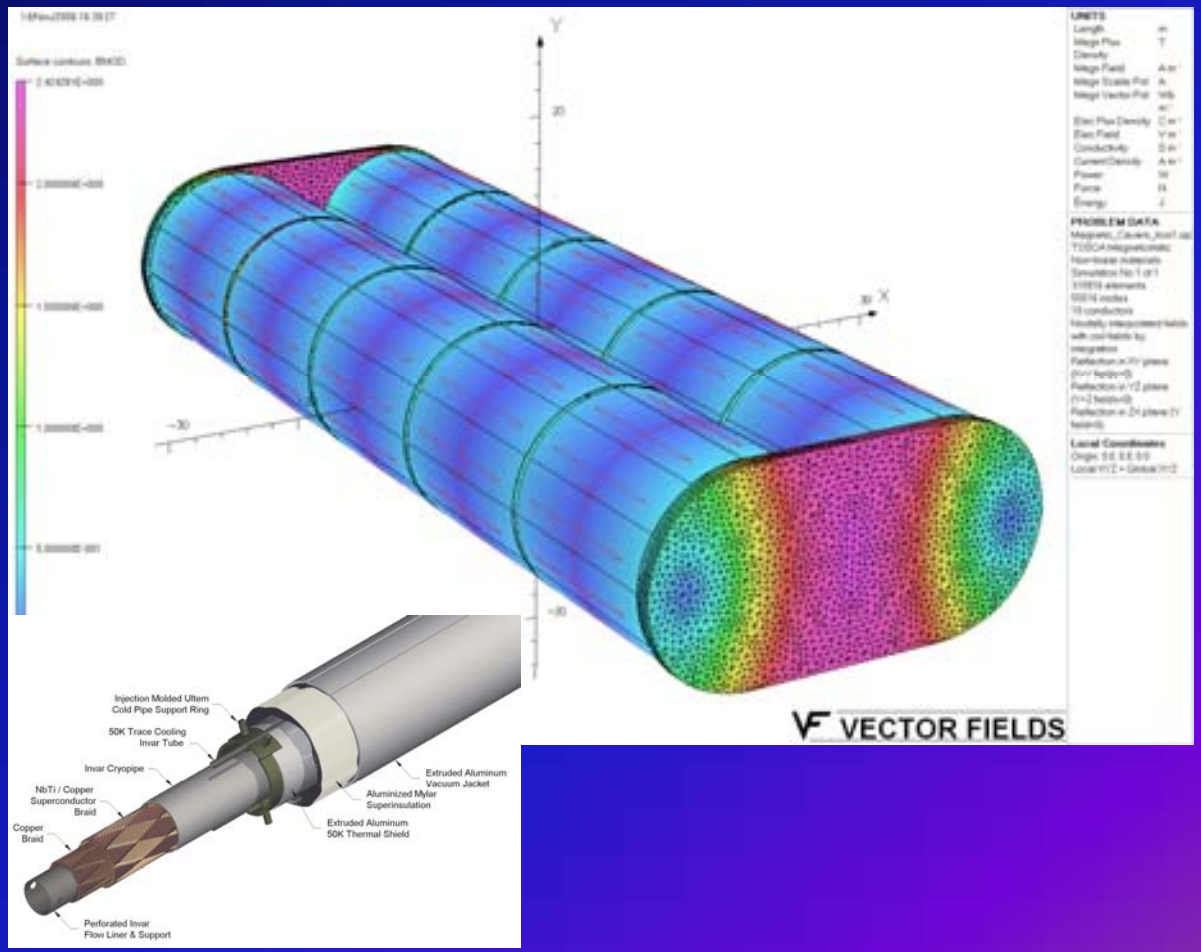




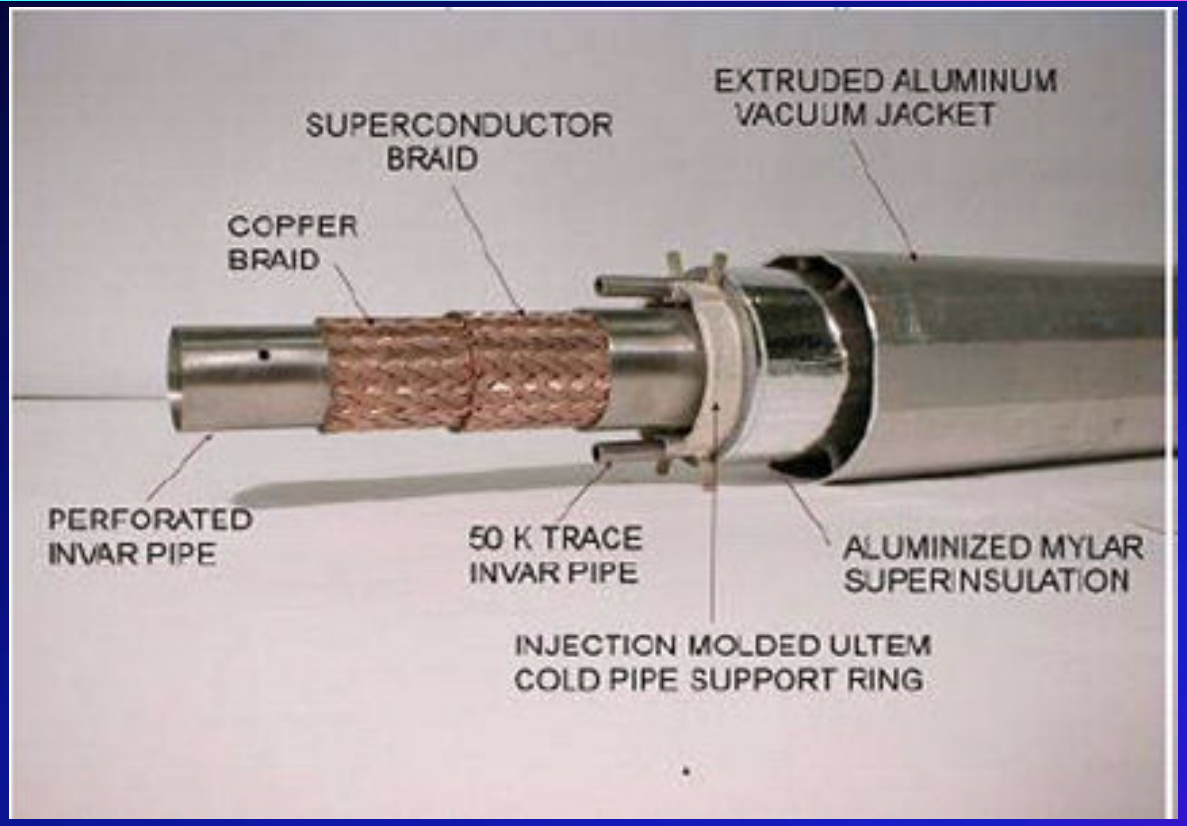
- Momenta between 100 MeV/c to 15 GeV/c
- Magnetic field considered: 0.5 T
- Reconstructed position resolution ~ 4.5 mm

"Special" Detector Has to be Magnetized

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



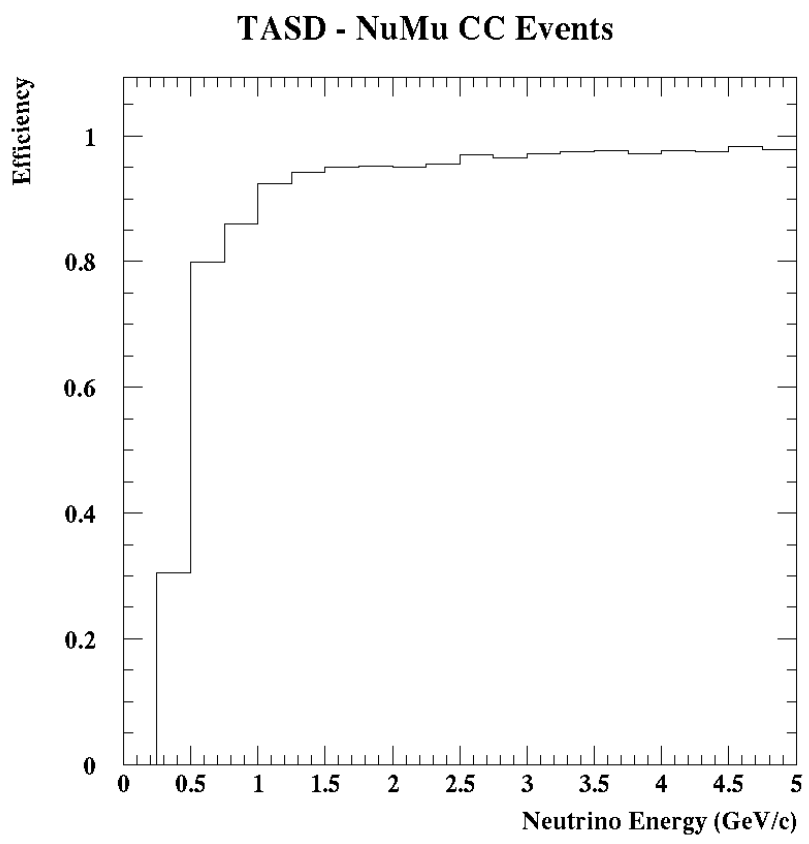
Superconducting Transmission Line makes this concept possible *(affordable)*



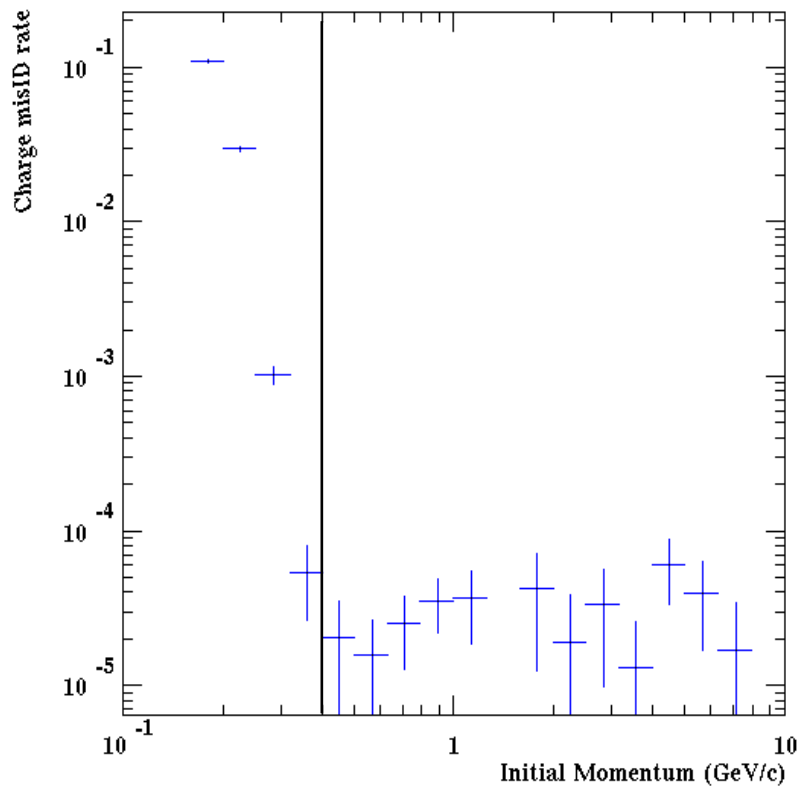
- SCTL not a "concept" – prototyped, tested and costed for the VLHC Project at Fermilab

TASD Performance

ν Event Reconstruction Efficiency



Muon charge mis-ID rate



Fermilab Muon Collider Task Force

MCTF

Fermilab

Muon Collider Task Force

Muon Collider
Advanced Accelerator R&D Proposal

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JLAB:
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ANL:
J.Norem

TASK FORCE
35 members
MUONS INC.
5 collaborators
BNL
6 collaborators
LBNL
4 collaborators
ANL
1 collaborator
JLAB
5 collaborators

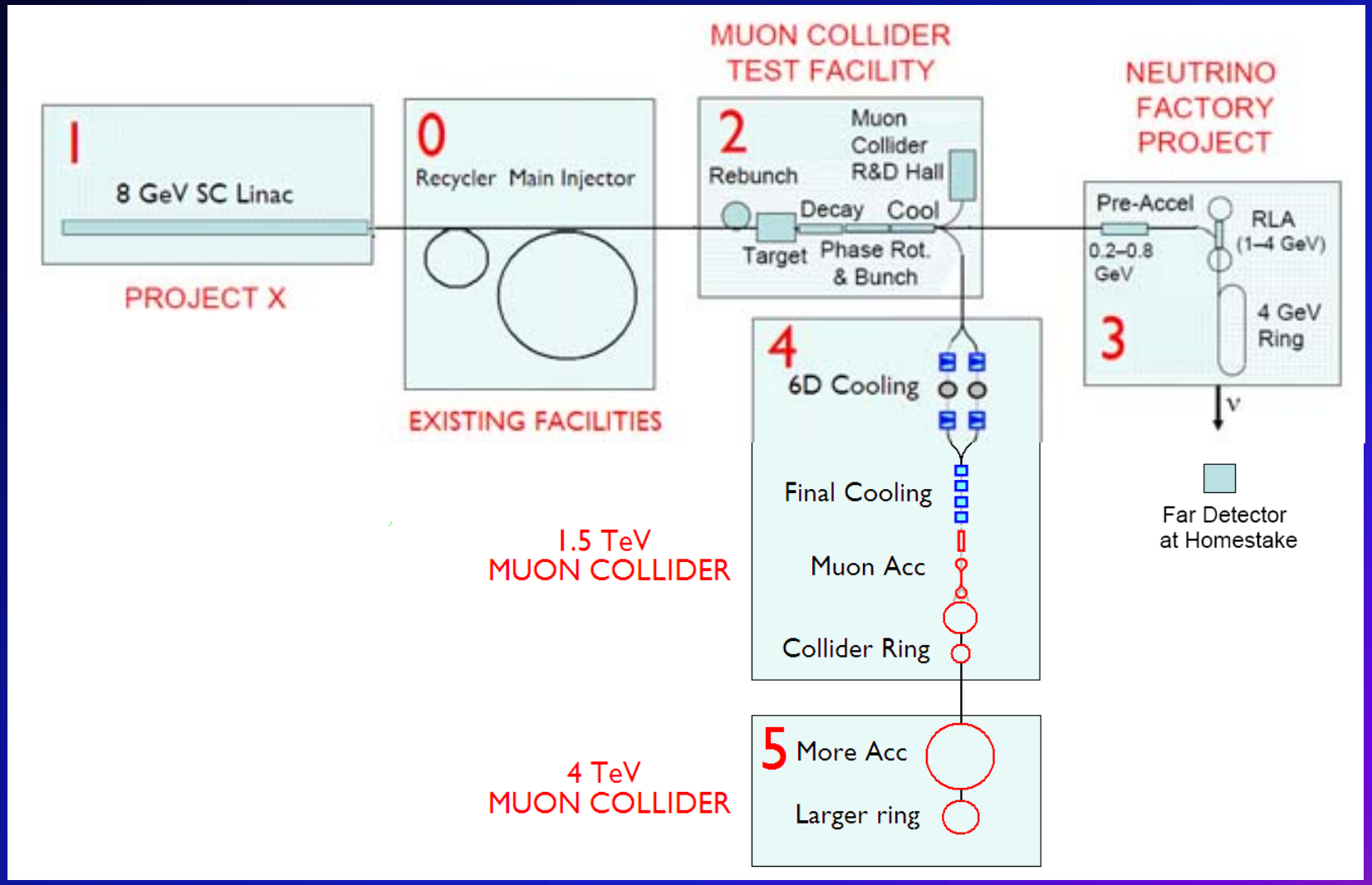
Proposed MCTF Activities

- **Collider Design and Simulations to establish the muon cooling requirements.**
  - Take a fresh look at the overall Muon Collider scheme. In addition to establishing the ionization cooling requirements, we will also identify the remaining muon source and collider design and performance issues.
- **Component Development**
  - We will develop and bench test the components needed for the 6D cooling channel.
- **Beam Tests and Experiments**
  - We will perform beam tests of the components. For that we will build a proton beam line for high-intensity tests of LiH absorbers and pressurized RF cavities. Later, we will design and build a muon production, collection and transport system. 250-300 MeV/c muons will be used in the 6D ionization cooling demonstration experiment.

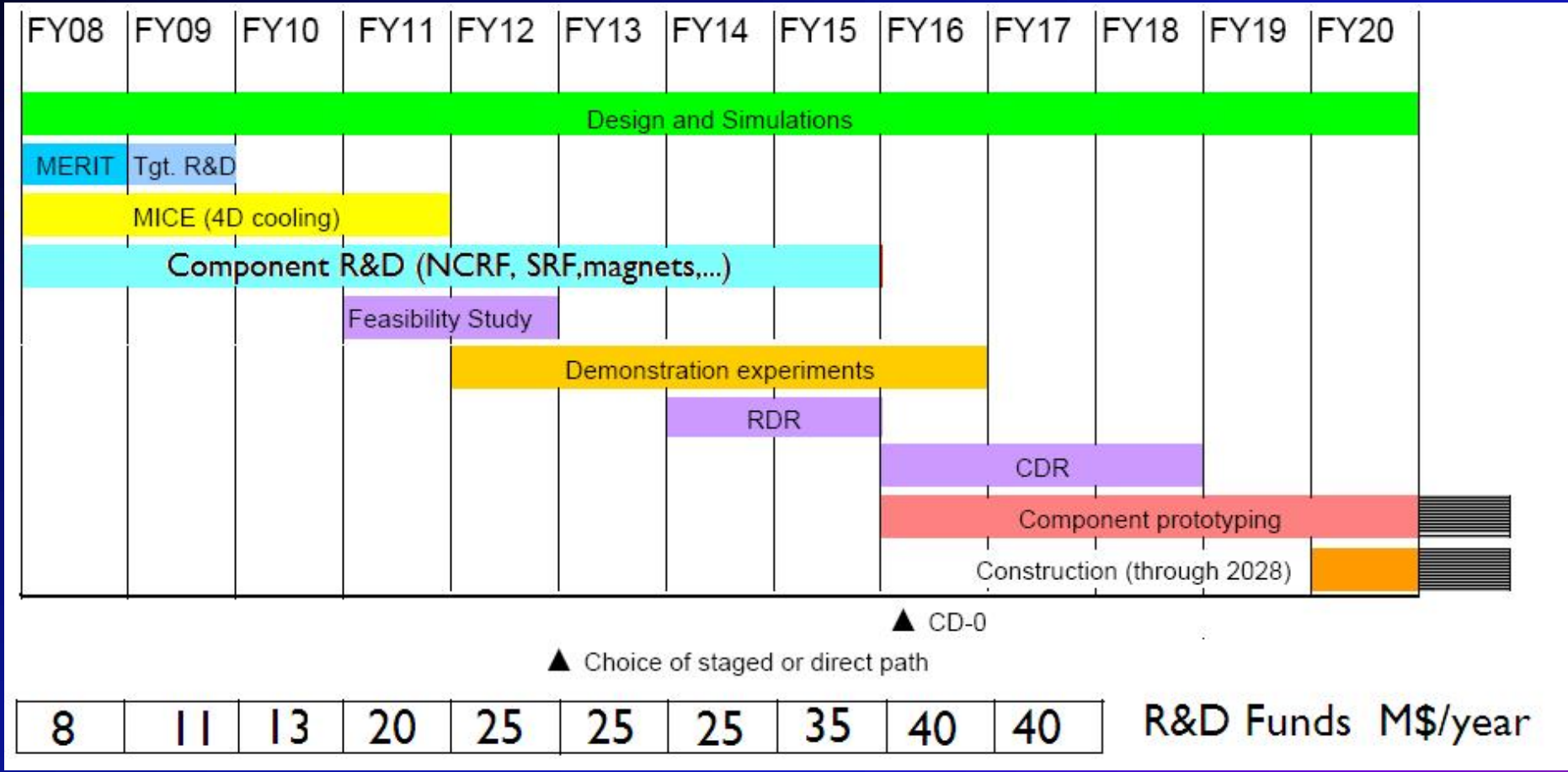
The Way Forward?

Muon Complex Vision

Muon Complex Evolution



Timeline and Funding Request
To Deliver IDS RDR & MC FS



2012 is shaping up to be Interesting

- In the end, physics from the LHC and the ongoing neutrino experimental program (2Chooz, Daya Bay, Nova, T2K) will determine how powerful the arguments will be for these facilities
  - vs. some other Energy Frontier Machine and Upgrades to ongoing ν experimental programs (incremental approach) for the ν sector
- However, the NF presents the most precise method to fully measure the physics in the neutrino sector (at an acceptable cost?) AND
- The energy reach and physics potential of a Muon Collider competes favorable with all machine complexes currently under study
  - Has definite siting advantages
  - Cost T.B.D. – The R&D must first be done!
    - MuCool, MERIT and MICE a GOOD START!

$2\frac{1}{2}$ Questions

- Does the HEP community want the Muon Collider to be a CREDIBLE option for a new facility and on what time scale?
  - We (NFMCC) have set a goal of 2012
    - Expanded theoretical and simulation studies backed by experiments (6D Cooling, Intense Cooling, m Production and Capture). Report – "Snowmass 12"
    - (HEPAP 1997)
      - The Subpanel recommends that an expanded program of R&D be carried out on a muon collider, involving both simulation and experiments. This R&D program should have central project management, involve both laboratory and university groups, and have the aim of resolving the question of whether this machine is feasible to build and operate for exploring the high-energy frontier
- What effort/resources are needed to achieve this goal?
  - Fermilab Steering Committee Report
    - Muon Collider Feasibility: 5-7 Year Effort
      - A rough comparison with the U.S. ILC development intensity prior to the International Technology Recommendation Panel decision would indicate the need for a minimum of $20M annually and 100 FTE of appropriate skills in the U.S.