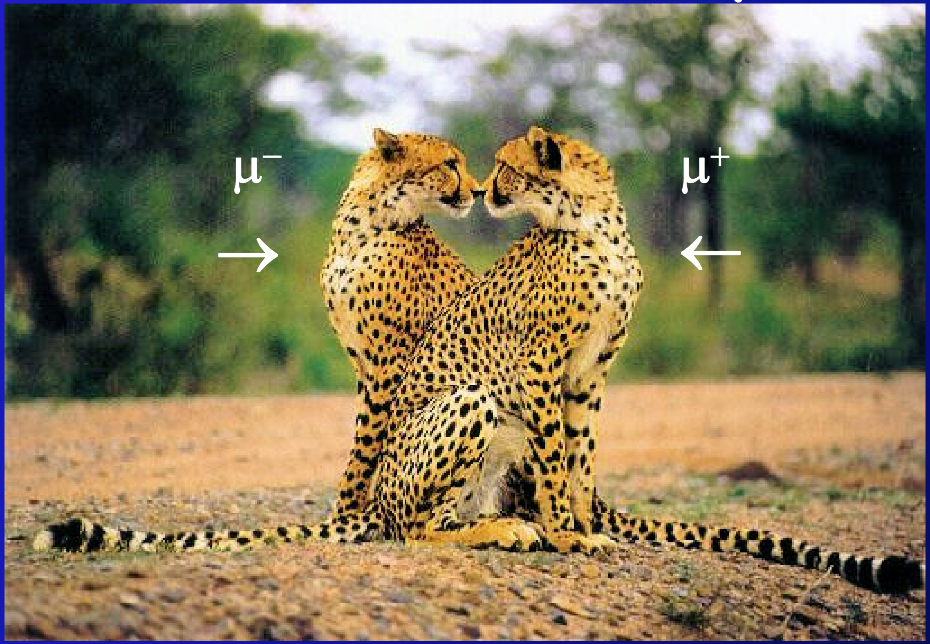
Exploring physics beyond the Standard Model with a Muon Acceleration Facility



Alan Bross
Fermilab
BEYOND 2010
Cape Town

BEYOND The Standard Model?

- **The Standard Model has been enormously successful!**
  - Already physics Beyond SM and there are many unanswered questions
  - BIG Questions
    - Birth of the Universe
    - Formation of Galaxies
    - Why we are here
- **There are two basic ways to Explore Beyond the SM**
  - Perform Very-High-Precision Measurements of accessible processes & measure small effects inconsistent with a purely SM view of the world
  - Go to Very High Energy
    - LHC
    - Next?

Outline

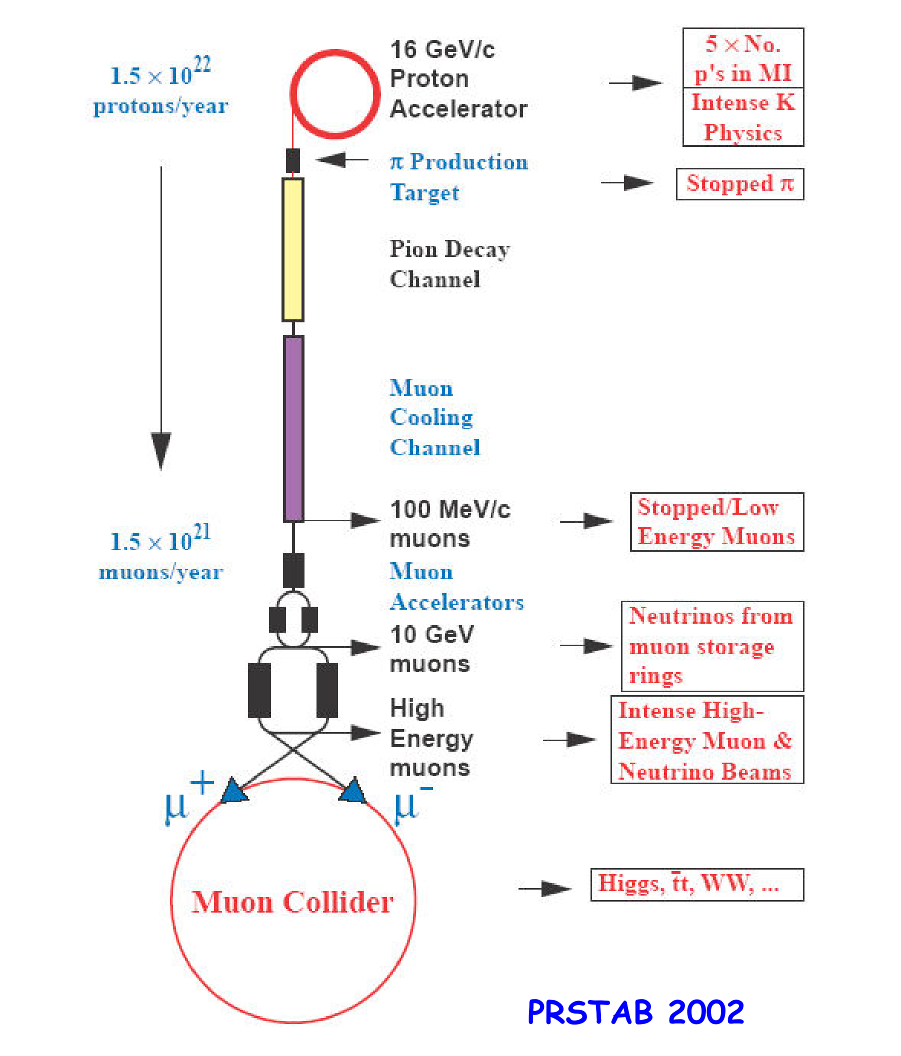
My Talk

- **Why Muon Accelerator Facilities?** ***Inspirational***
  - Physics motivation for and nature of possible future facilities based on ultra-high intensity muon beams
  - Explore the synergy between Neutrino Factory and Muon Collider facilities both from the point of view of the physics program and the accelerator complex
- **Neutrino Factory and Muon Collider Fundamentals**
- **What technologies are crucially central to making the above a reality.** ***Technical R&D Overview***
- **Path to Realization**
- **I hope to give you Overview of our activities but will have to leave out many technical details**
  - http://www.cap.bnl.gov/mumu/
  - https://mctf.fnal.gov/

Physics in Evolution

What we might do at a Muon Accelerator Facility

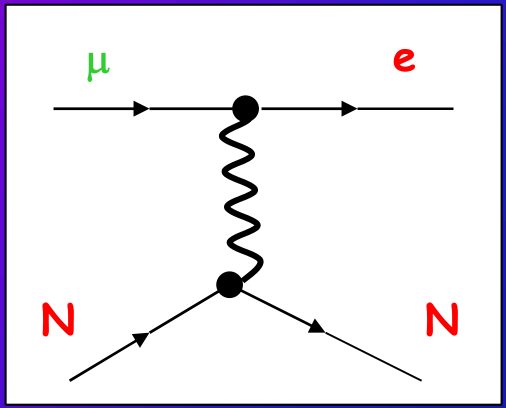
Evolution of a Physics Program



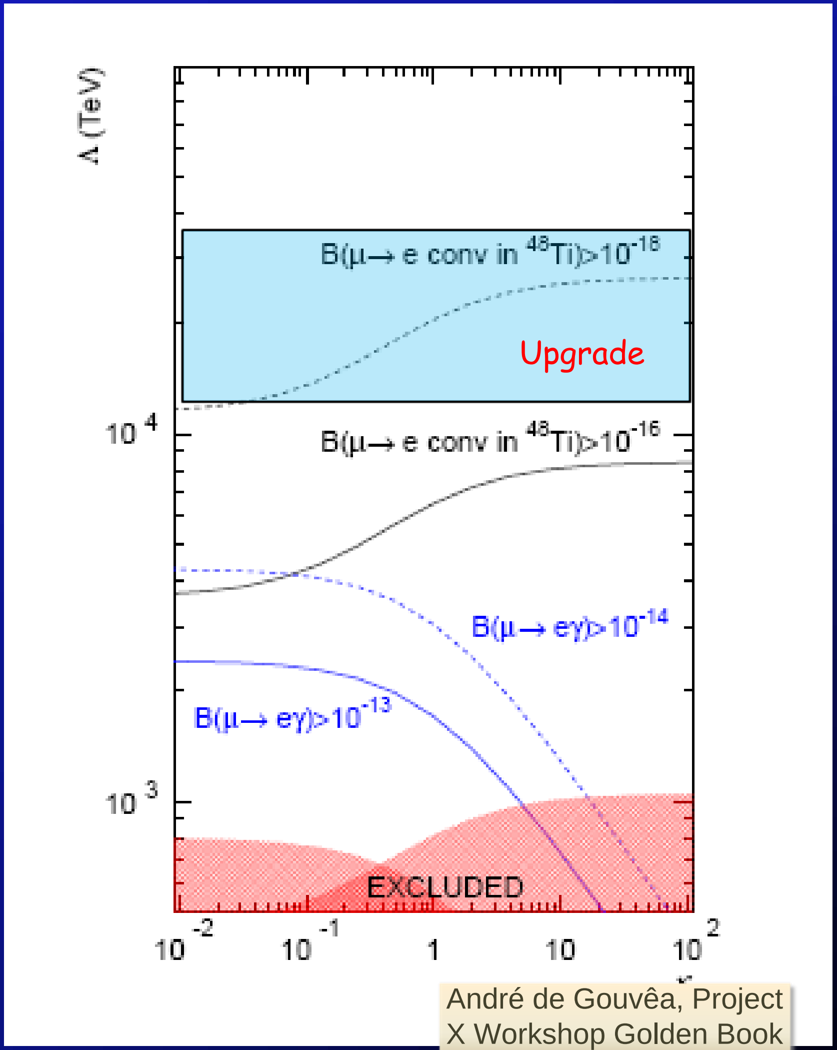
From Snowmass 96

- A μ source providing 1-2 X 10^{21} μ/yr supports a rich physics program:
- Intense Low-energy muon physics (LFV)
  - $\mu \rightarrow e$ conversion experiment
- Neutrino Factory
  - Low Energy 4 GeV
  - High Energy 25 GeV
- Energy Frontier Muon Collider
  - 1.5 - 4 TeV+
    - With maybe a lower E_{com} machine (Higgs, Z') first.

Low-Energy Muon Physics: $\mu \rightarrow e$ conversion



- **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}
- **Mass Reach to ≈4 X 10^4 TeV**



André de Gouvêa, Project X Workshop Golden Book

The Neutrino Factory

Well-understood neutrino source:

μ Decay Ring:

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

$$\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$$

S. Geer, Phys. Rev. **D57** (1998) 6989*

- Flavor content fully known
- "*Absolute*" Flux Determination is possible
  - Beam current, polarization, Near Detector semi & purely leptonic event rates
- Tremendous control of systematic uncertainties with well designed near detector(s)

*Bross et al., NIM **A332**, (1993)

Neutrino Factory – μ Decay Rings

$\mu^+ \to e^+ \nu_e \overline{\nu}_\mu$	$\mu^- \to e^- \overline{\nu}_e \nu_\mu$	
$\overline{\nu}_\mu \to \bar{\nu}_\mu$	$\nu_\mu \to \nu_\mu$	disappearance
$\overline{\nu}_\mu \to \bar{\nu}_e$	$\nu_\mu \to \nu_e$	appearance (challenging)
$\overline{\nu}_\mu \to \bar{\nu}_\tau$	$\nu_\mu \to \nu_\tau$	appearance (atm. oscillation)
$\nu_e \to \nu_e$	$\bar{\nu}_e \to \bar{\nu}_e$	disappearance
$\nu_e \to \nu_\mu$	$\bar{\nu}_e \to \bar{\nu}_\mu$	appearance: "golden" channel
$\nu_e \to \nu_\tau$	$\bar{\nu}_e \to \bar{\nu}_\tau$	appearance: "silver" channel

- **'Reference' Neutrino Factory:**
  - $\geq 10^{21}$ useful decays/yr; exposure '5 plus 5' years
- **Two baselines (≈7500 km & ≈4000 km)**
  - 50 kT magnetised iron detector (MIND) with MINOS performance – Golden Channel Detector
  - Backgrounds (for golden channel):
    - Sign of μ mis-ID'd
    - Charm decays
  - $E_{res} \sim 0.15 * E_\nu$

"Golden" → Sign of μ observed in detector opposite to that stored in decay ring

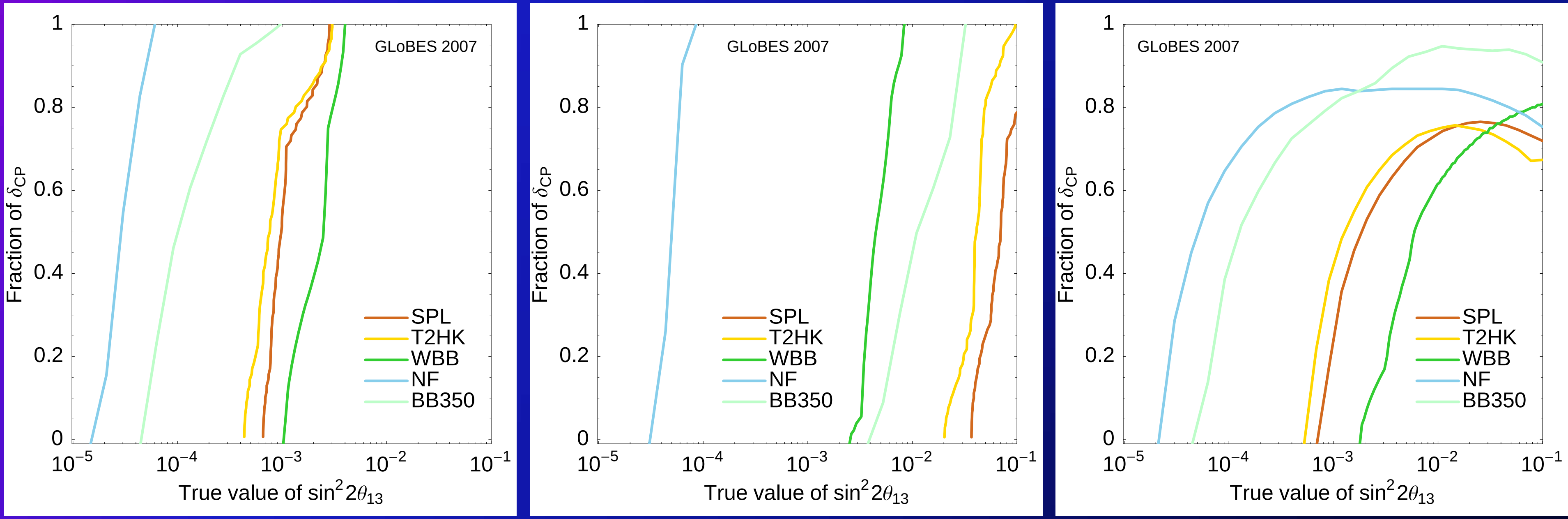
$\mu^+ \to \nu_e \Rightarrow \nu_\mu n \to \mu^- p$

International Scoping Study – Physics Reach

3σ contours shown

ISS Physics Group Report: Rept.Prog.Phys. 72:106201,2009

$Sin^2 2\theta_{13}$ | 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

Beyond Filling in the Blanks

- Determine parameters with precision sufficient to determine the structure of the underlying theory
  - Explore very large mass scale
- Beyond the SνM
  - NSI
  - Sterile ν
  - Mass Varying ν (MVN)
- Unique ν physics program at near detector(s)

$\mu^+ \to e^+ \nu_e \overline{\nu}_\mu$	$\mu^- \to e^- \overline{\nu}_e \nu_\mu$	
$\overline{\nu}_\mu \to \bar{\nu}_\mu$	$\nu_\mu \to \nu_\mu$	disappearance
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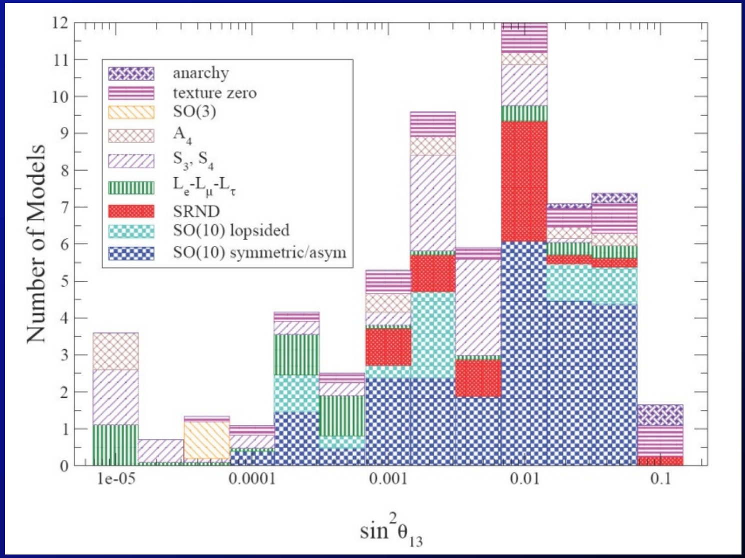
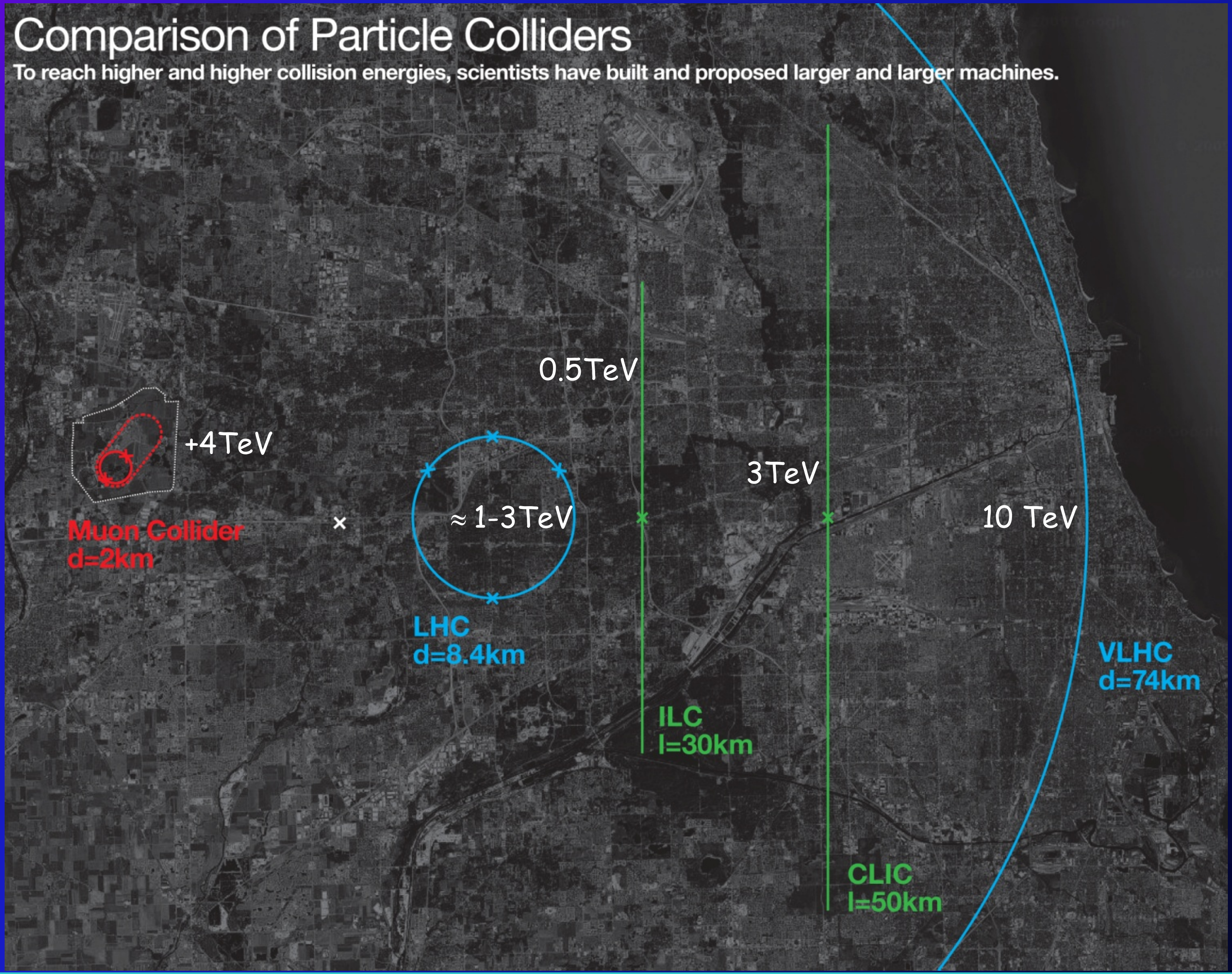


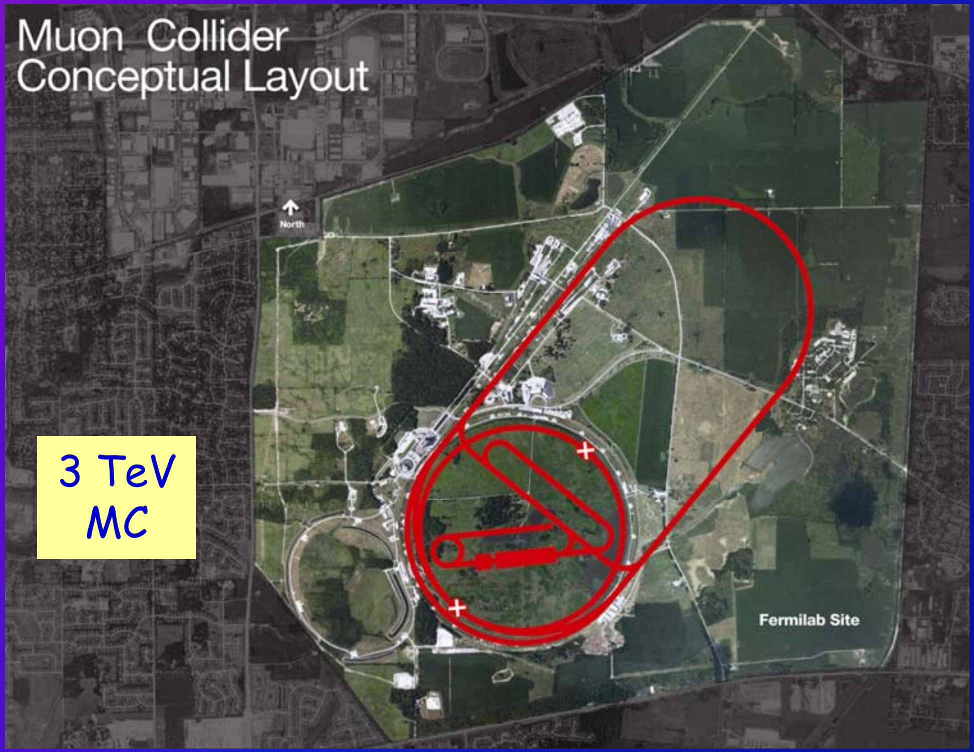
Carl Albright – arXiv:0803.4176v1

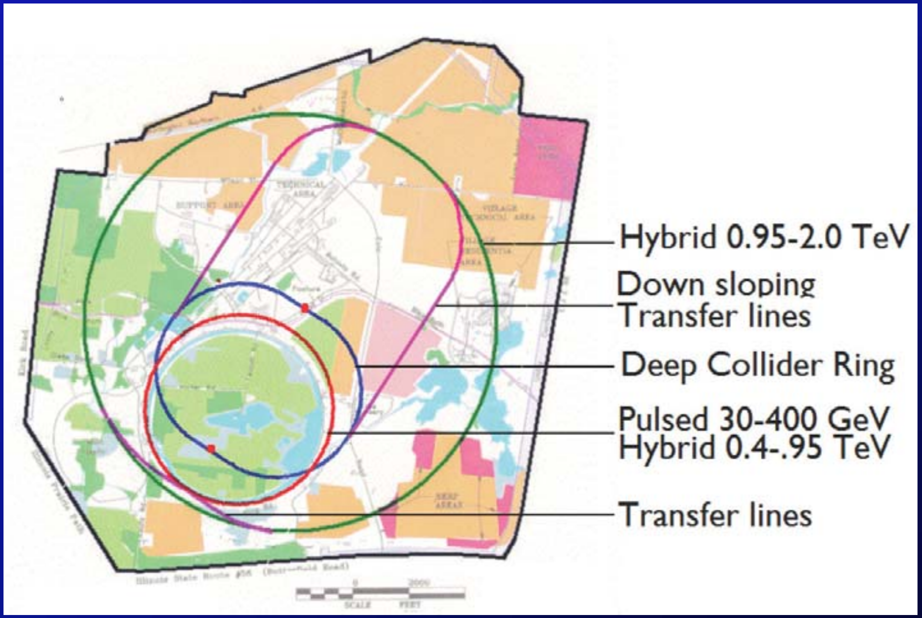
The Energy Frontier



Comparison of Particle Colliders
To reach higher and higher collision energies, scientists have built and proposed larger and larger machines.
+4TeV
Muon Collider
d=2km
≈ 1-3TeV
LHC
d=8.4km
0.5TeV
ILC
l=30km
3TeV
CLIC
l=50km
10 TeV
VLHC
d=74km

The Energy Frontier via $\mu^+ \mu^-$ Collisions





3 TeV Machine based on Recirculating Linear Accelerators & ILC SC RF

4 TeV Machine based on Rapid Cycling Synchrotron

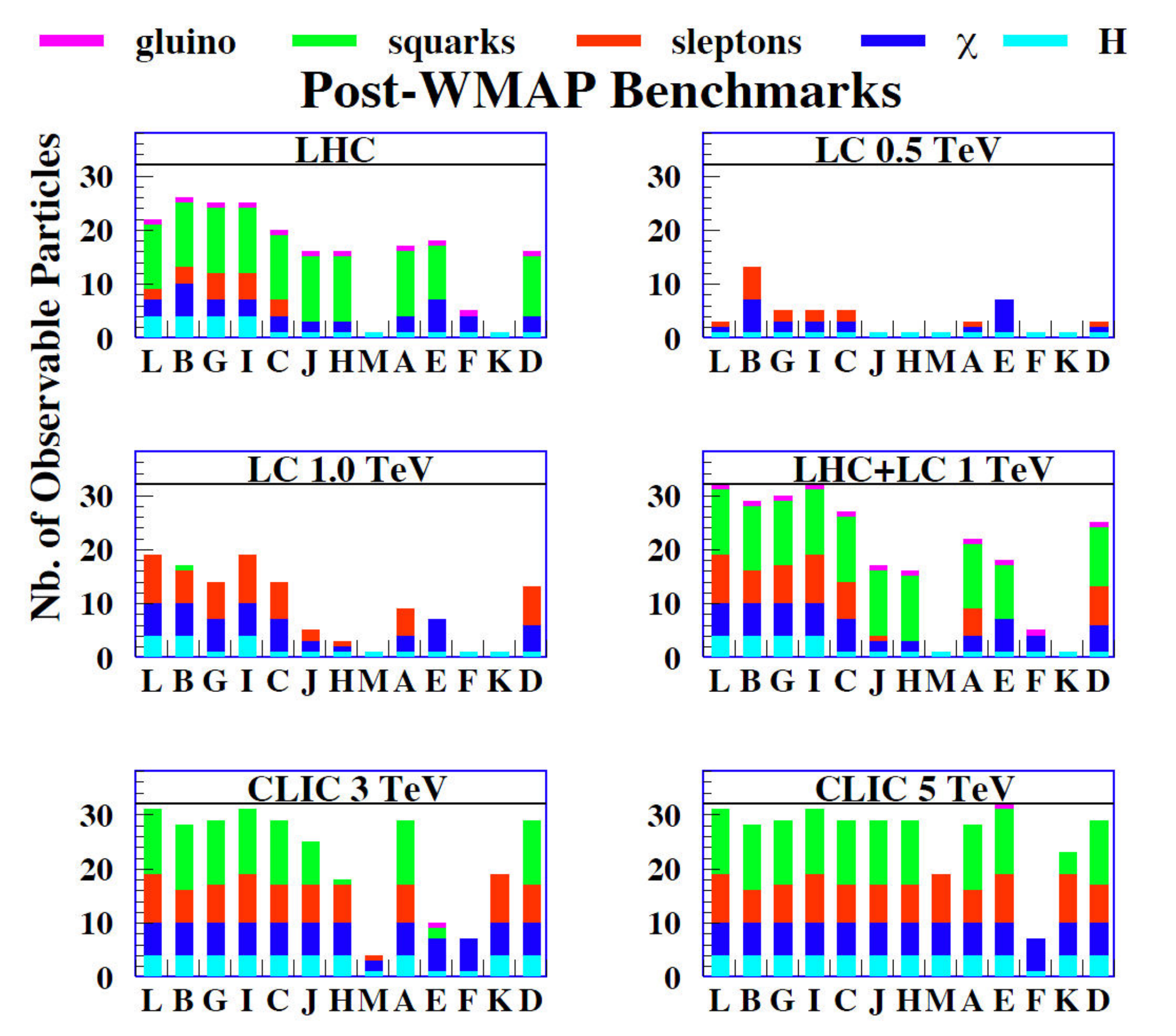
Muon Collider - Motivation

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

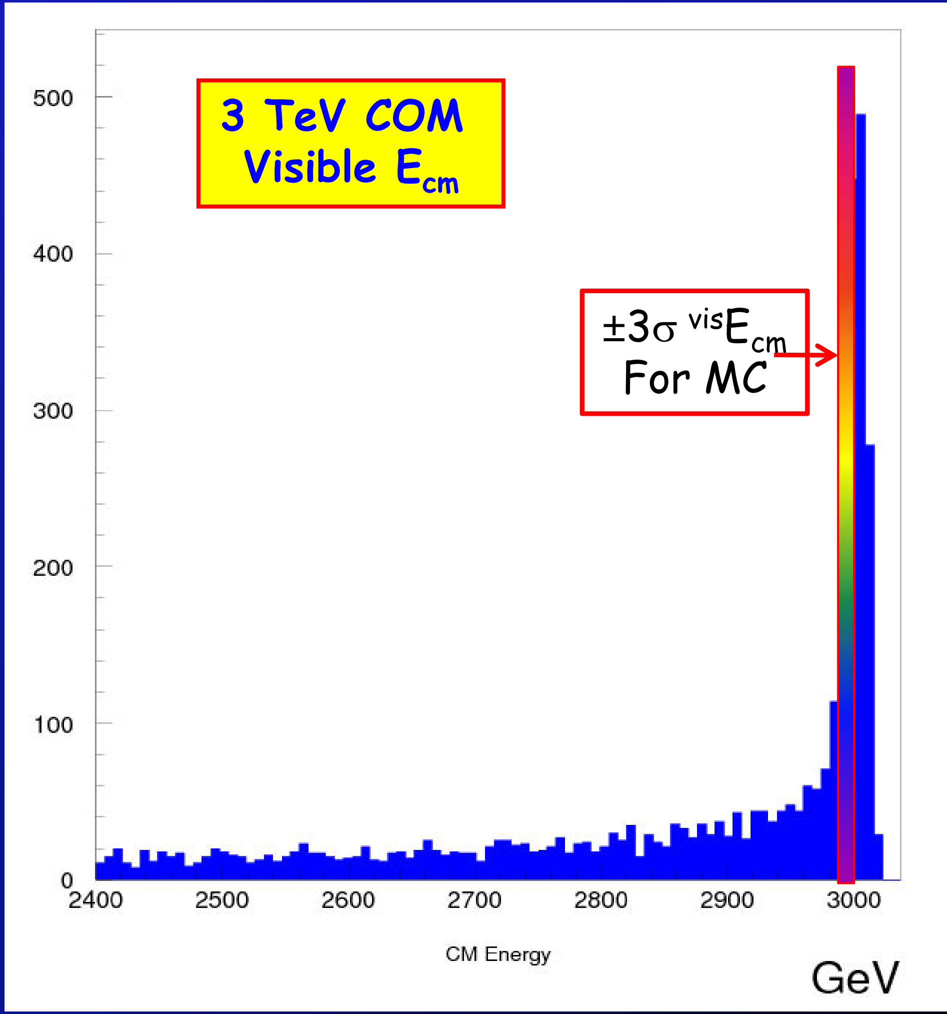
The Supersymmetric Particle Zoo



- Independent of actual supersymmetric mass scale and the reach of the ILC, the 2004 CLIC Study conclusions are still valid
  - "A Multi-TeV machine is needed for extended coverage of the mass range

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



Complexity of Colliders

	LHC	MC	CLIC
state of the art magnets	√	√	-
state of the art RF system	-	√	√
state of the art beam dynamics	-	√	√
Total # of elements	~4000	~4000	~200,000
Luminosity	>1e34	>1e34	>1e34

Key Ingredients of the Facilities

Neutrino Factory and Muon Collider

Key Technical Ingredients 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

Production of $O(10^{21})$ μ/yr

At our current level of understanding/analysis, we believe the front of the two facilities can be the same.

80% Overlap in R&D

But there are Significant Differences

Neutrino Factory

- Cooling
  - Reduce transverse emittance
    - $\varepsilon_\perp \sim 25$ mm
- Acceleration
  - Accelerate to 25 GeV
    - Maybe as low as 4-7 GeV
- Storage Ring
  - No intersecting beams

Muon Collider

- Bunch Merging
- A Great Deal of Cooling
  - Reduce 6D emittance
    - $\varepsilon_\perp \sim$ 3-25 μm
    - $\varepsilon_L \sim$ 70 mm
- Acceleration
  - Accelerate to 1-2 TeV
- Storage Ring
  - Intersecting beams

Muon Ionization Cooling

Basic Concepts

Muon Ionization Cooling - Transverse

- 2D Transverse Cooling

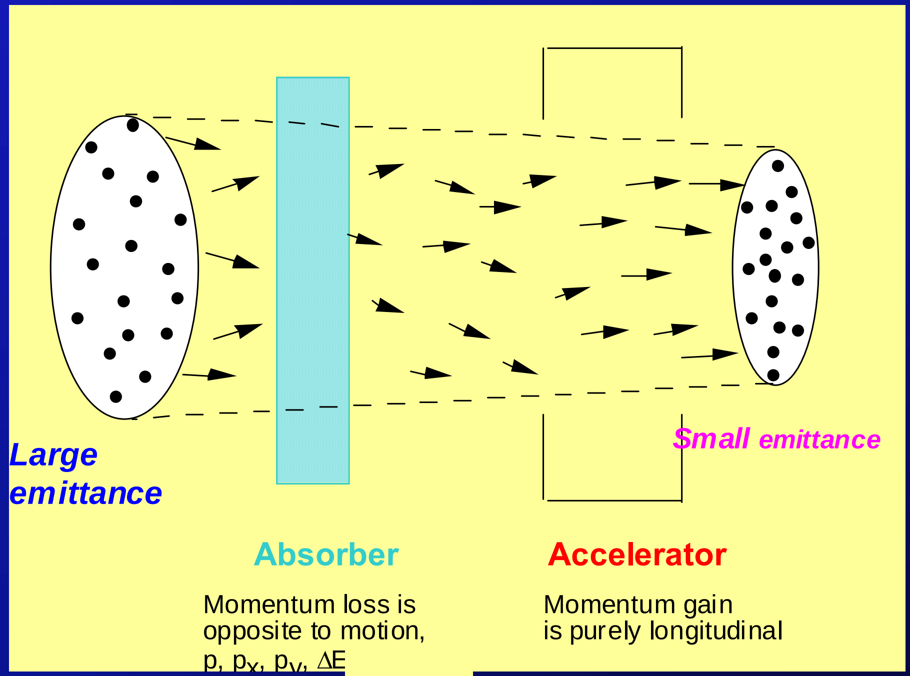
$$\frac{d\epsilon_N}{ds} = -\frac{1}{\beta^2}\frac{dE_\mu}{ds}\frac{\epsilon_N}{E_\mu} + \frac{\beta_\perp (0.014\ \mathrm{GeV})^2}{2\beta^3 E_\mu m_\mu L_R}$$

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: $M = L_R dE_\mu/ds$

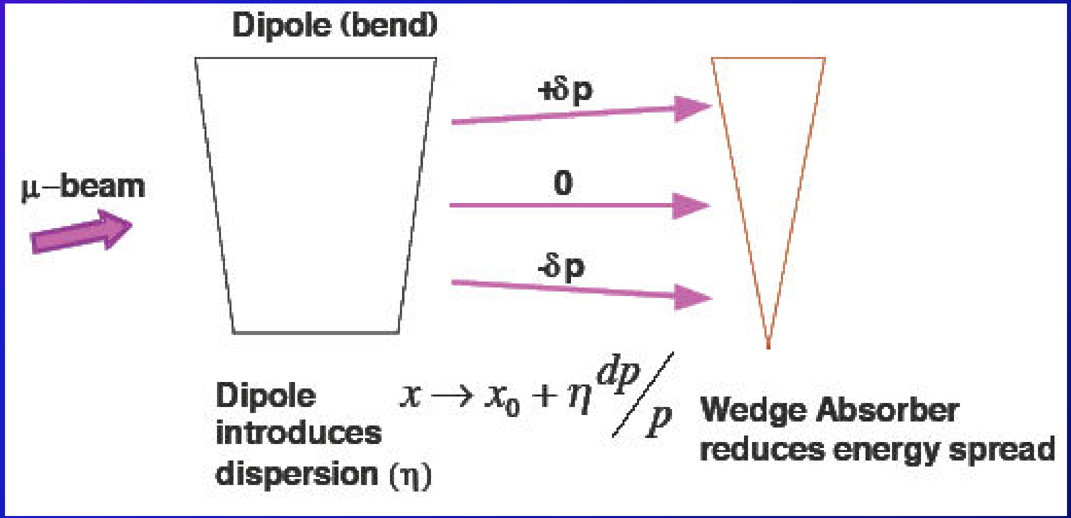
M^2 (4D cooling) for different absorbers



Material	$\langle dE/ds \rangle_{min}$ (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

Muon Ionization Cooling – Longitudinal *Emittance Exchange*



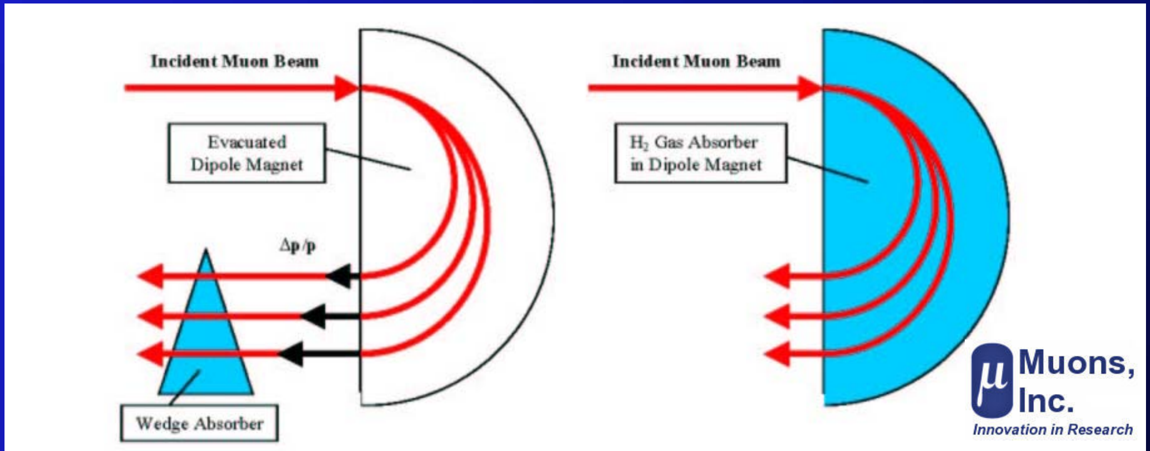
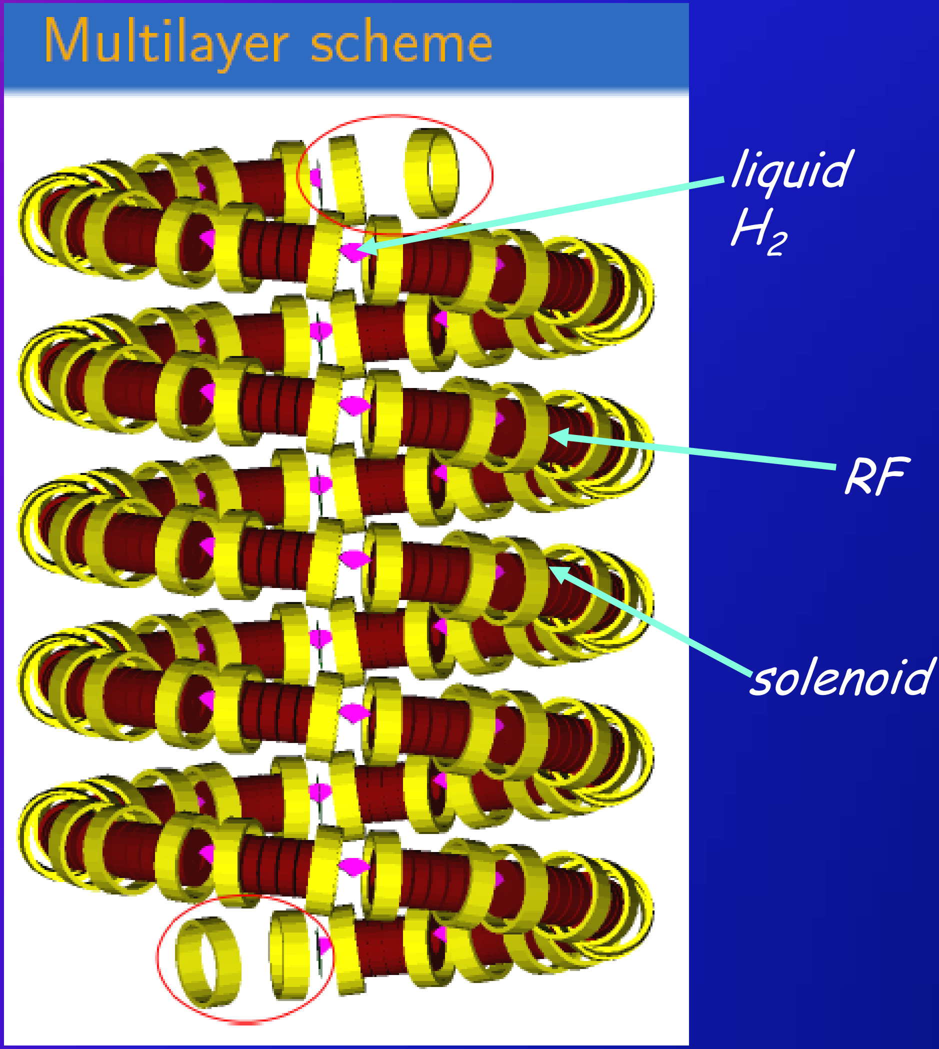
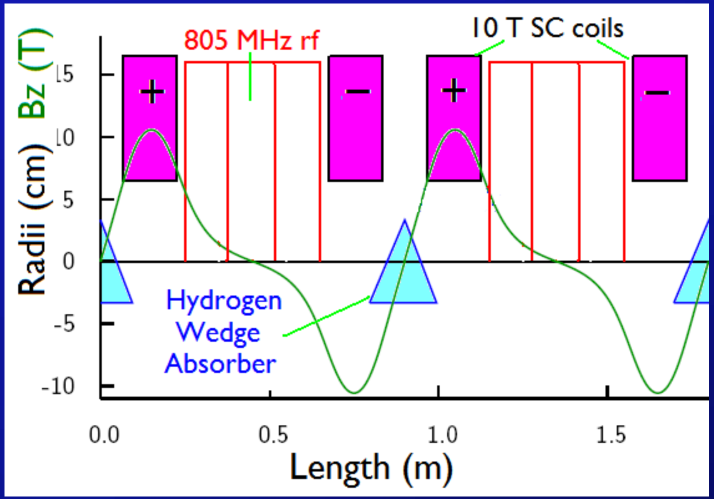


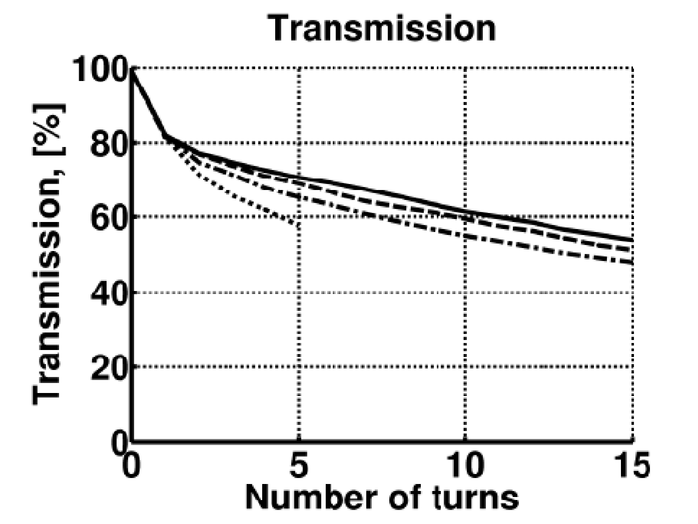
Figure 1. Use of a Wedge Absorber for Emittance Exchange

Figure 2. Use of Continuous Gaseous Absorber for Emittance Exchange

Guggenheim RFOFO - Simulations



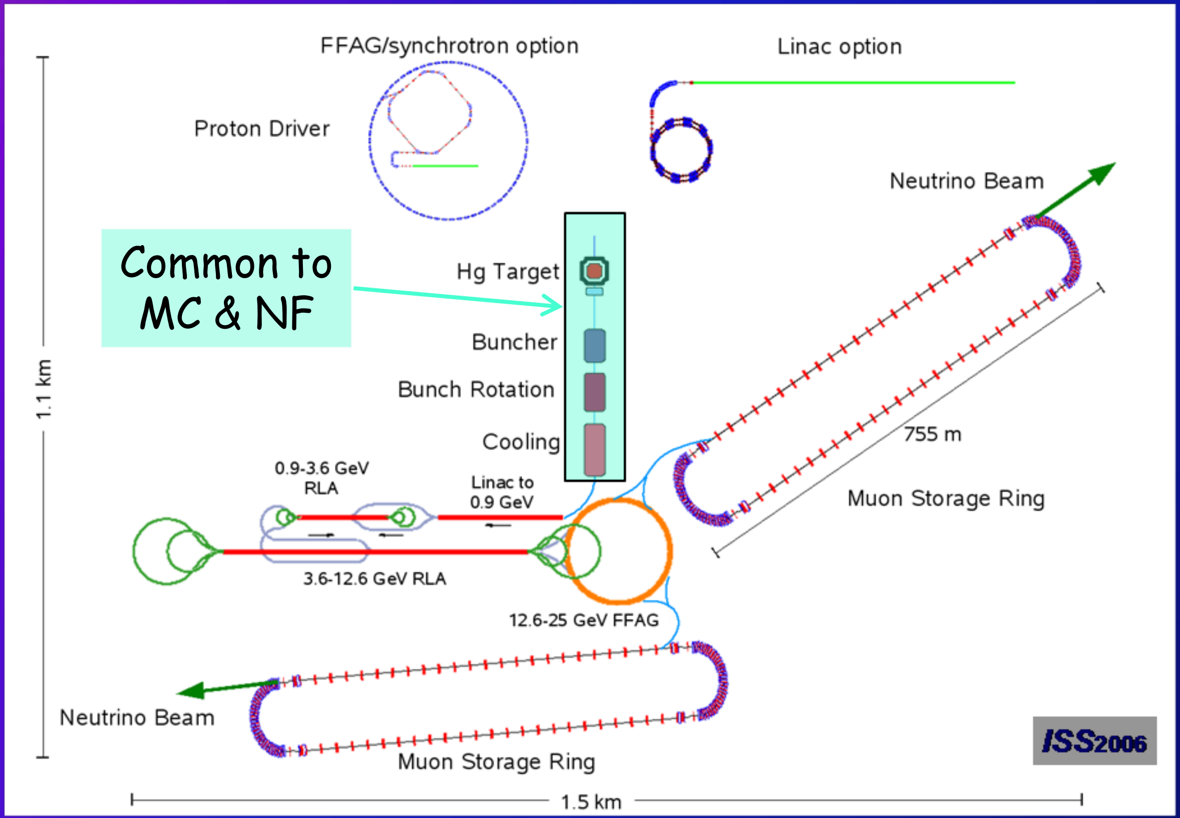




Neutrino Factory Design

Neutrino Factory Accelerator Facility

Baseline out of International Scoping Study



ISS Accelerator WG report: RAL-2007-023

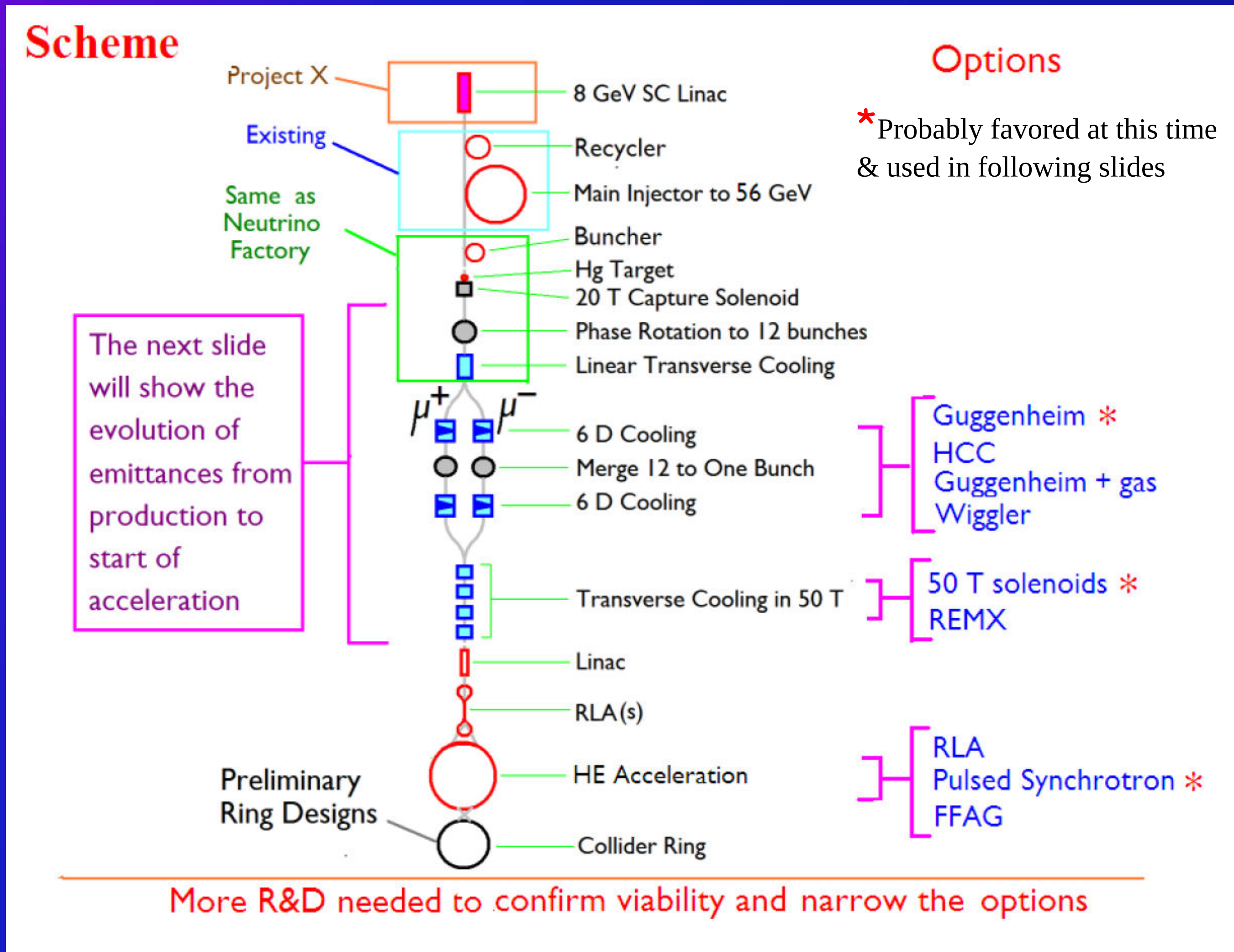
- **Proton Driver**
  - 4 MW, 2 ns bunch
- **Target, Capture, Drift ($\pi \rightarrow \mu$) & Phase Rotation**
  - Hg Jet
  - 200 MHz train
- **Cooling**
  - 30 πmm ($\perp$)
  - 150 πmm (L)
- **Acceleration**
  - 103 MeV $\rightarrow$ 25 GeV
- **Decay rings**
  - 7500 km L
  - 4000 km L
    - Baseline is race-track design
    - Triangle interesting possibility (C. Prior)

Muon Collider Design

Emphasis on Cooling

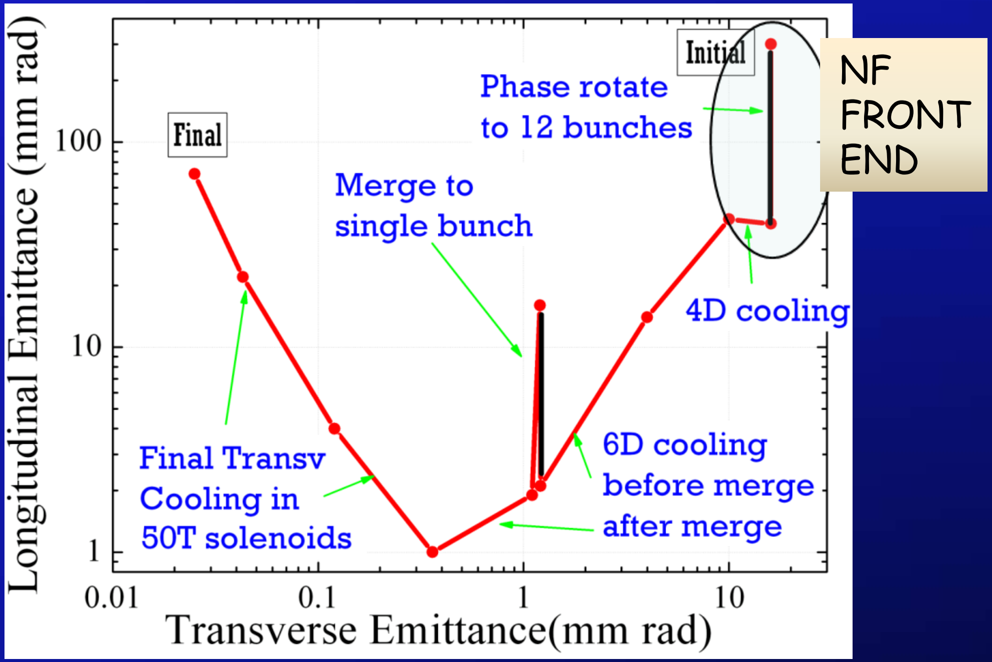
Fermilab

Muon Collider Facility



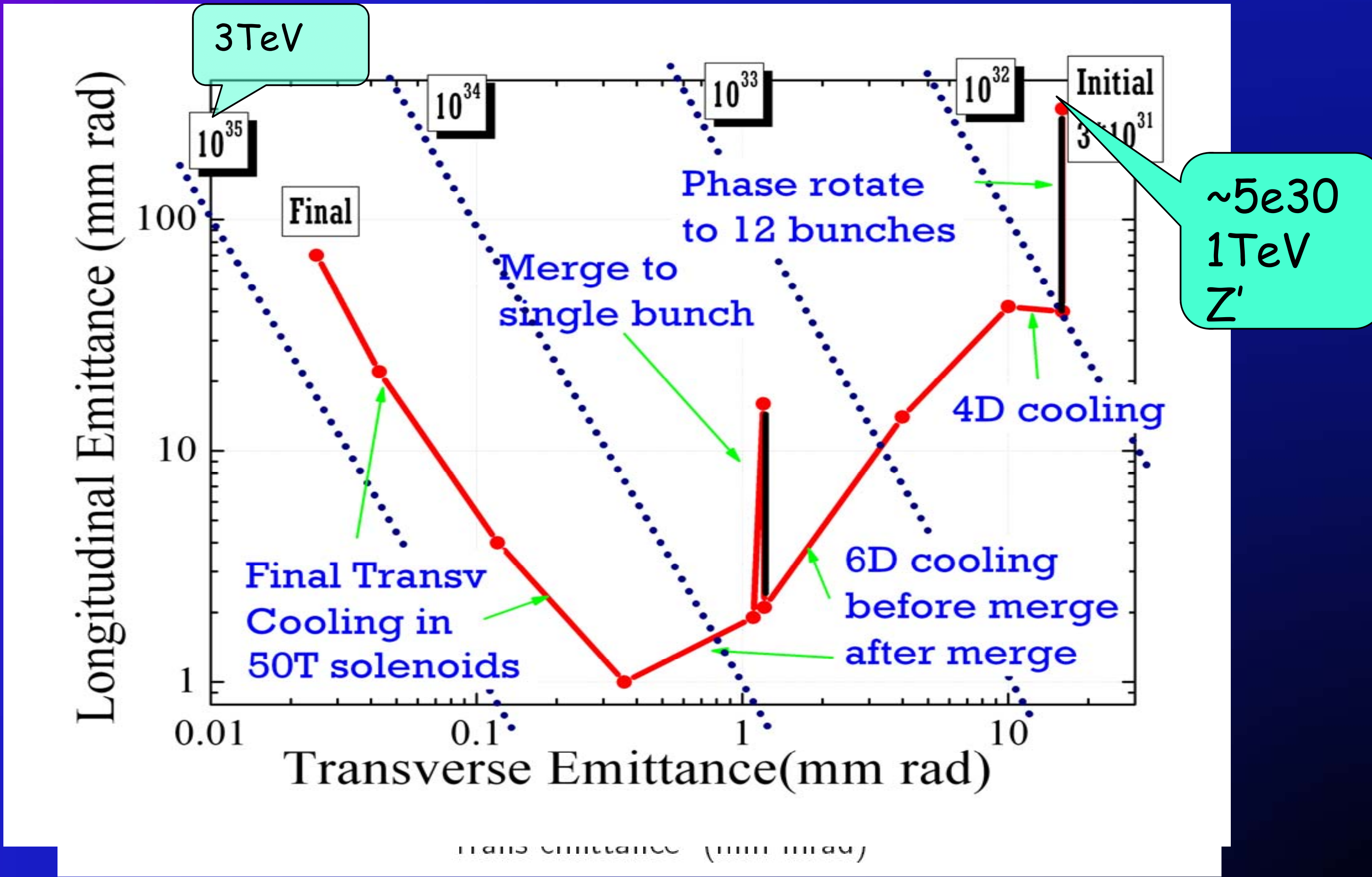
Muon Collider Design Progress

- Muon Collider designs start with a NF front-end, but require a much more ambitious cooling channel (6D cooling ~ $O(10^6)$ c.f. 4D cooling ~ $O(100)$.
- In the last 5 years concepts for a complete end-to-end self consistent cooling scheme have been developed



  - Requires beyond state-of-art components: need to be developed
  - Hardware development and further simulations need to proceed together to inform choices between alternative technologies
- Also progress on acceleration scheme & Collider ring design, but the cooling channel presently provides the main Muon Collider challenge

A Muon Collider Cooling Scenario



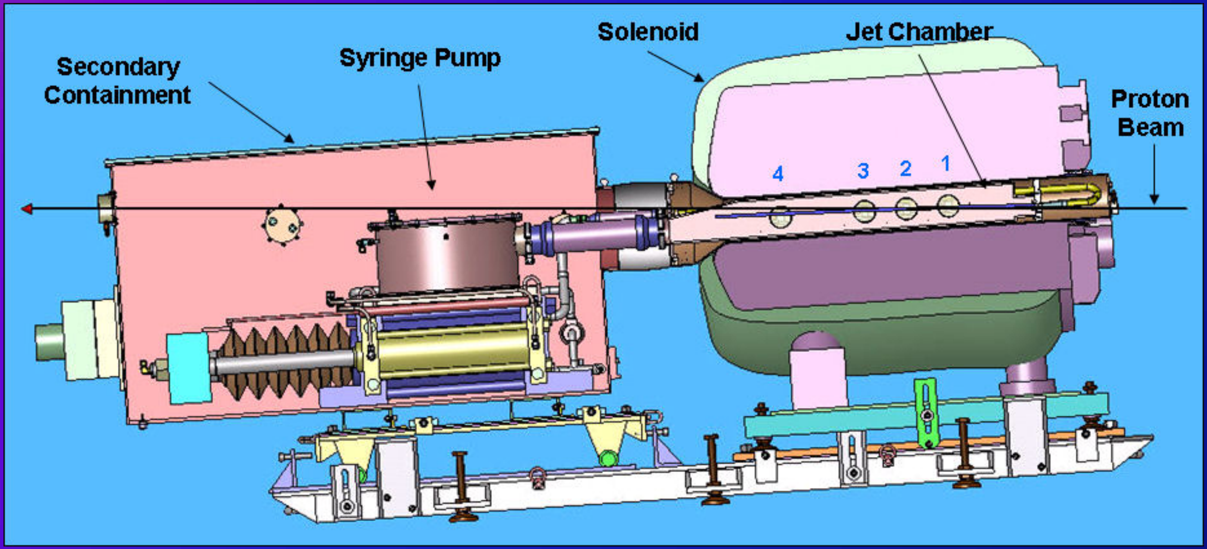
Addressing the Technological Challenges of
The Muon Collider

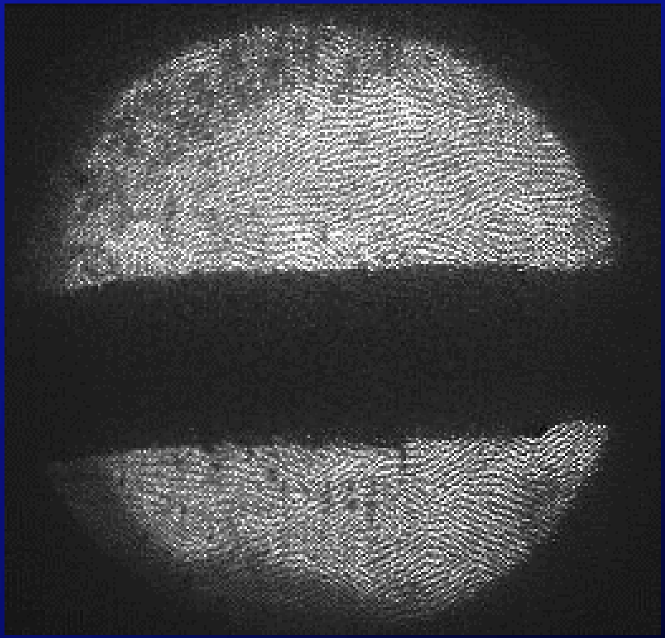
R&D Program Overview

Indicating some areas common to NF

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

MERIT
The Experiment Reached 30TP @ 24 GeV





- Experiment Completed (CERN)
  - 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

MuCool

Component R&D and Cooling Experiment

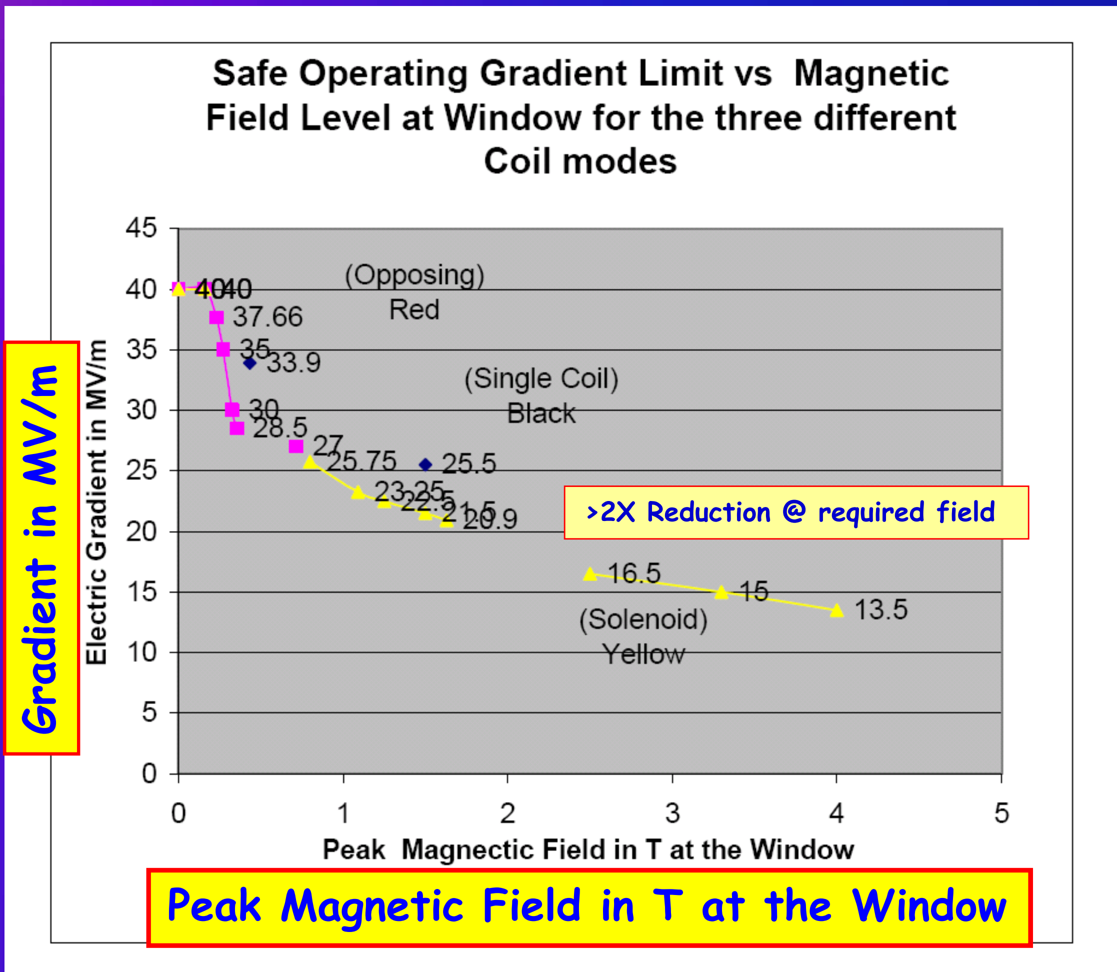
MuCool has the primary responsibility to carry out the RF Test Program

- Study the limits on Accelerating Gradient in NCRF cavities in magnetic field
- Fundamental Importance to both NF and MC – RF needed in
  - Muon capture, bunching, phase rotation
  - Muon Cooling
  - Acceleration

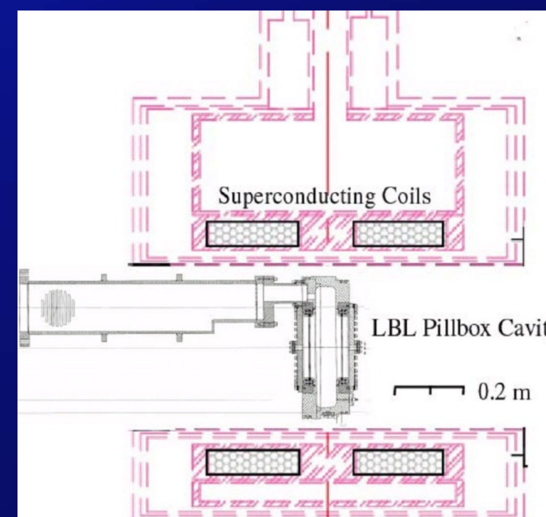
Arguably the single most critical Technical challenge for the NF & MC

The Basic Problem – B Field Effect

805 MHz Studies



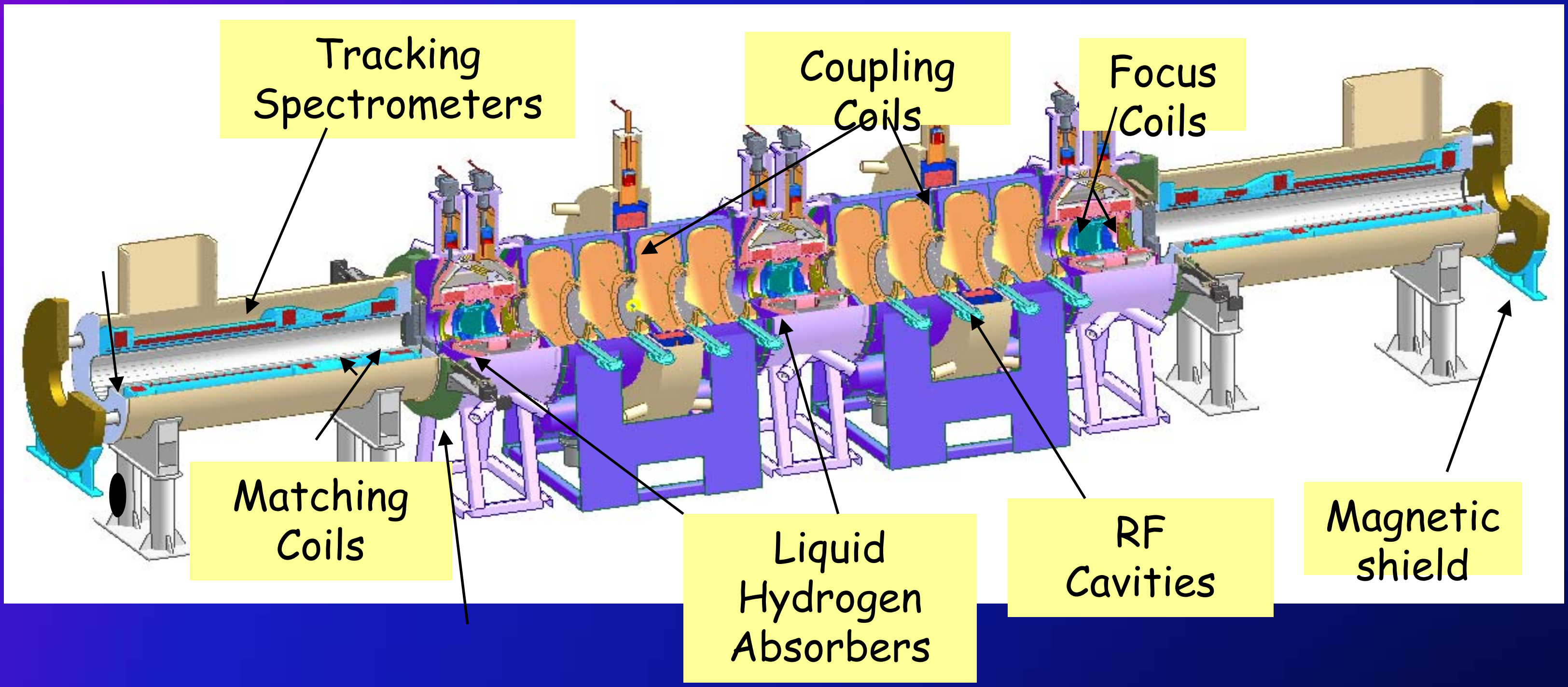
- **Data seem to follow universal curve**
  - Max stable gradient degrades quickly with B field
- **Re-measured**
  - Same results



High-Gradient RF Operation B Field

- **Promising indications @ a Solution**
  - SCRF Processing techniques help
    - Reduce dark current
      - More advanced techniques (Atomic-Layer-Deposition) may do more
  - Cavity material properties seem to be important
    - TiN helps
      - Coupled with SCRF processing may reduce FE even more
    - Mo, Be Coatings?
    - Cavity bodies made from Be?
  - Gas-filled (H_2) cavities show promise
    - Utilize Paschen effect to stop breakdown
    - Operation with beam critical next test

Muon Ionization Cooling Experiment



- **Measure transverse (4D) Muon Ionization Cooling**
  - 10% cooling – measure to 1% (10^{-3})
- **Single-Particle Experiment**
  - Build input & output emmittance from μ ensemble

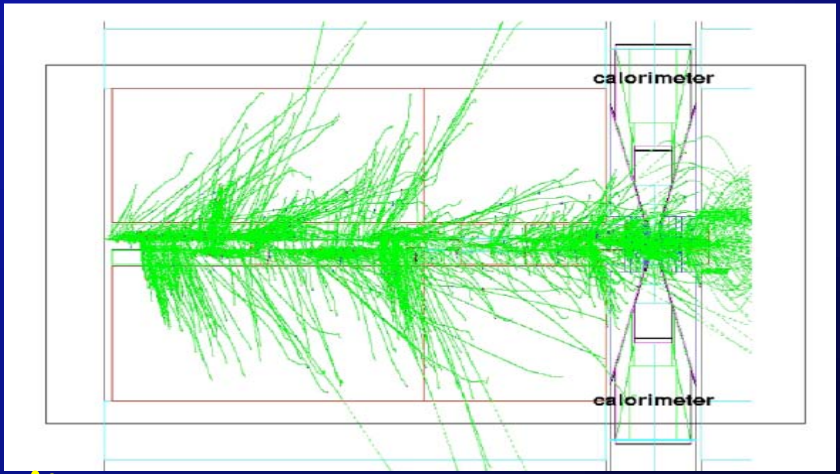
Muon Collider Machine-Detector Interface

If a Multi-TeV Muon Collider is built

Can a detector be designed that will do the physics?

Shielding Detector Backgrounds

- MC detector backgrounds studied actively 15 years ago (1996-1997). The most detailed work was done for a 2×2 TeV Collider → √s=4 TeV.
- Large background from decay electrons … decay angles O(10) mrads. Electrons stay inside beampipe for ~6m.
- Shielding strategy: sweep the electrons born further than ~6m from the IP into ~6m of shielding.



- Detailed studies show that, with careful design, this shielding strategy works extremely well.

Background Levels

- Detailed shielding design done plus background simulations using two codes (MARS & GEANT) → consistent results. Tungsten cone in forward direction with angle 20° (c.f. CLIC = 7°).
  - With modern detector technologies, perhaps angle can be reduced & tungsten can be instrumented.
- Hit densities at, r=5cm are 0.2 hits/mm2. Comparable to CLIC estimates. Also, ideas on how to further reduce hits by x100.
- SYNERGY with CLIC Detector R&D and design studies.
  - LHC Detector Technologies
- Just Completed:

Fermilab

Muon Collider Physics Workshop

Machine - Detector - Physics

November 10-12 (Tuesday-Thursday), 2009

The Way Forward

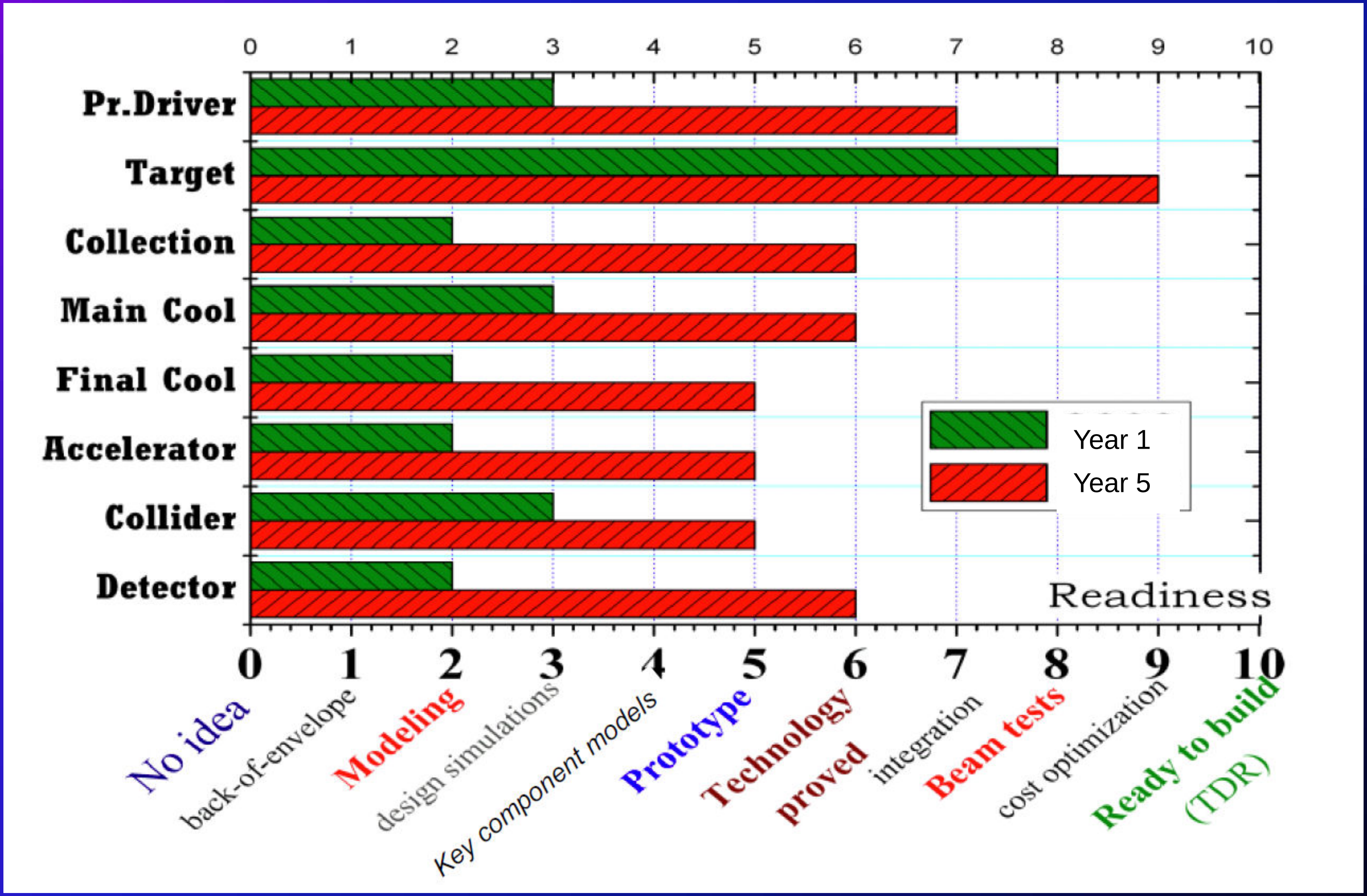
US Muon Accelerator Program

Current Guidance From DOE

- The Office of HEP at the DOE supports the concept of the 5-7 year plan
- Requests Fermilab to form a National Muon Program
  - With Strong Desire to bring in International Participation
  - & With Strong University Participation
- However, sees an increase of scope over the current program at a X2 (at least initially). Increase could start as early as FY11.
- This is consistent with Steven Chu's outlook towards science
  - Re-energize the national labs as centers of great science and innovation
  - Embrace a *degree of risk* taking in research

Muon Collider Technical Foundation after 5 Years

From Here to There



Closing Remarks

Road Map to the Future

- We believe ~2012 will be a pivotal time in HEP
  - LHC Physics Results
  - Neutrino Data from Reactor and Accelerator Experiments
    - Double Chooz Daya Bay
    - MINOS, OPERA, T2K ,NOνA
  - Major Studies for Frontier Lepton-Colliders Completed
    - ILC EDR
    - CLIC CDR
- There are likely to be many exciting results – Will point us in *Some* Direction
  - We Don't Know Which One Yet

To *"Boldly Go"* BEYOND the SM?

- **A Muon Accelerator Facility offers Unique Possibilities to Explore and Discover Physics Beyond the SM**
  - LFV experiments can obviously benefit from intense, cool muon sources
  - A Neutrino Factory may possibly be the ultimate tool to study neutrino physics
    - And is a natural step along a pathway to an Energy-Frontier Muon Collider
  - The physics case for an Energy-Frontier Lepton-Lepton Collider is compelling
    - And going towards a MC would make the cost-benefit analysis for a NF factory even more favorable

BUT

- **In the end, physics results from the LHC and the ongoing neutrino experimental program will determine how powerful the arguments will be for these facilities**
- **However, "We" have tried to make the case that the R&D SHOULD be done in order to be ready – be a credible part of the discussion – Now accepted by US DOE**

A Muon Acceleration Facility
Offers Intriguing Possibilities to
Explore Physics Beyond the SM
And
Presents Unique Capabilities difficult to
Achieve in any other way with a
Single facility

THANK YOU

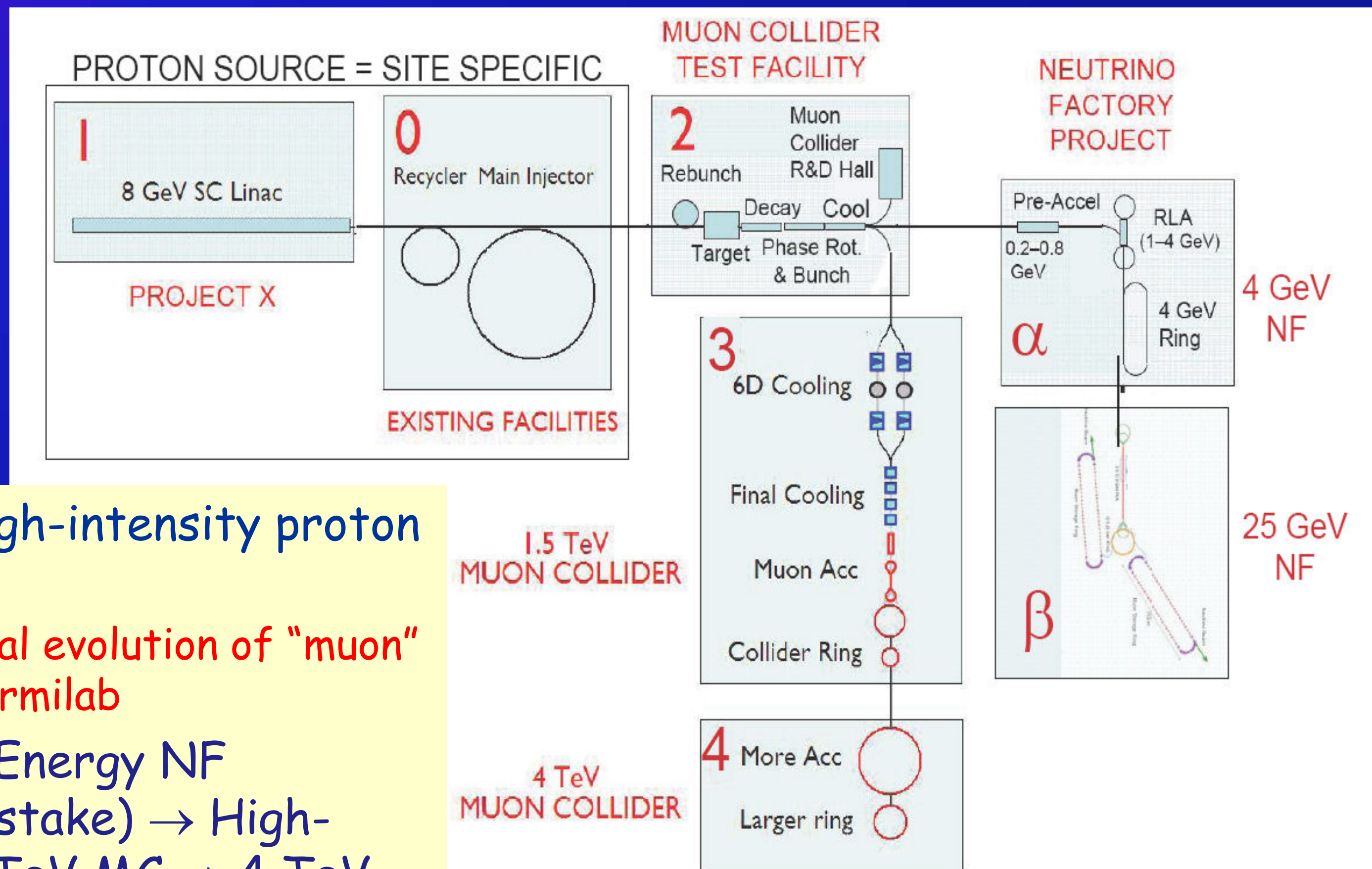
Acknowledgments

I want to thank all my colleagues in the Neutrino Factory and Muon Collider Collaboration and the Fermilab Muon Collider Task force for all the hard work and for the many conversations I have had with them on this subject.

In Particular I want to thank Bob Palmer, Steve, Geer, Vladimir Shiltsev and Mike Zisman

Muon Complex Evolution At Fermilab

Snowmass Update



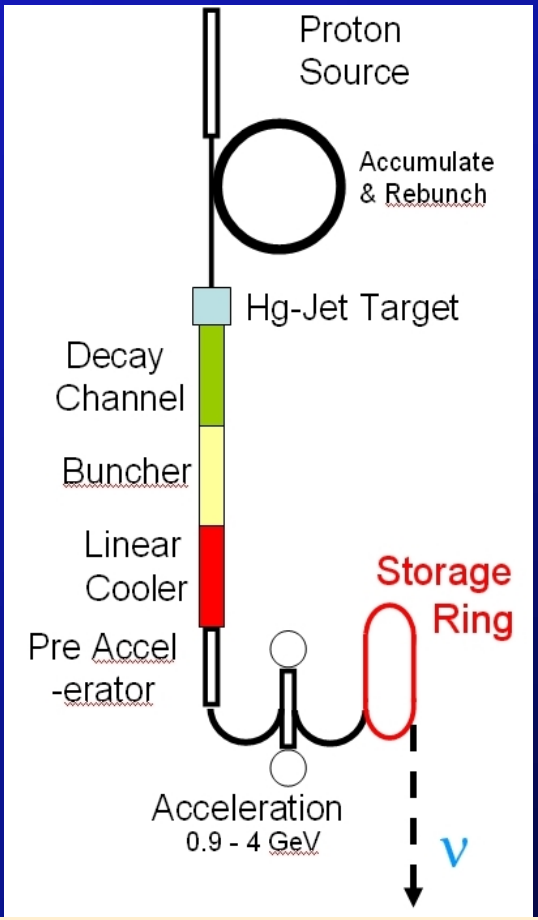
- Starting with a high-intensity proton source: Project X
  - We see a natural evolution of "muon" program for Fermilab
- Project X → Low-Energy NF (pointing to Homestake) → High-Energy NF → 1.5 TeV MC → 4 TeV MC

Fermilab

IDS Option: 4-5 GeV ν-Factory

- **Fermilab to DUSEL (South Dakota) baseline -1290km**
- **4-5 GeV muons yield appropriate L/E_ν**
- **Use a magnetized totally active scintillator detector**

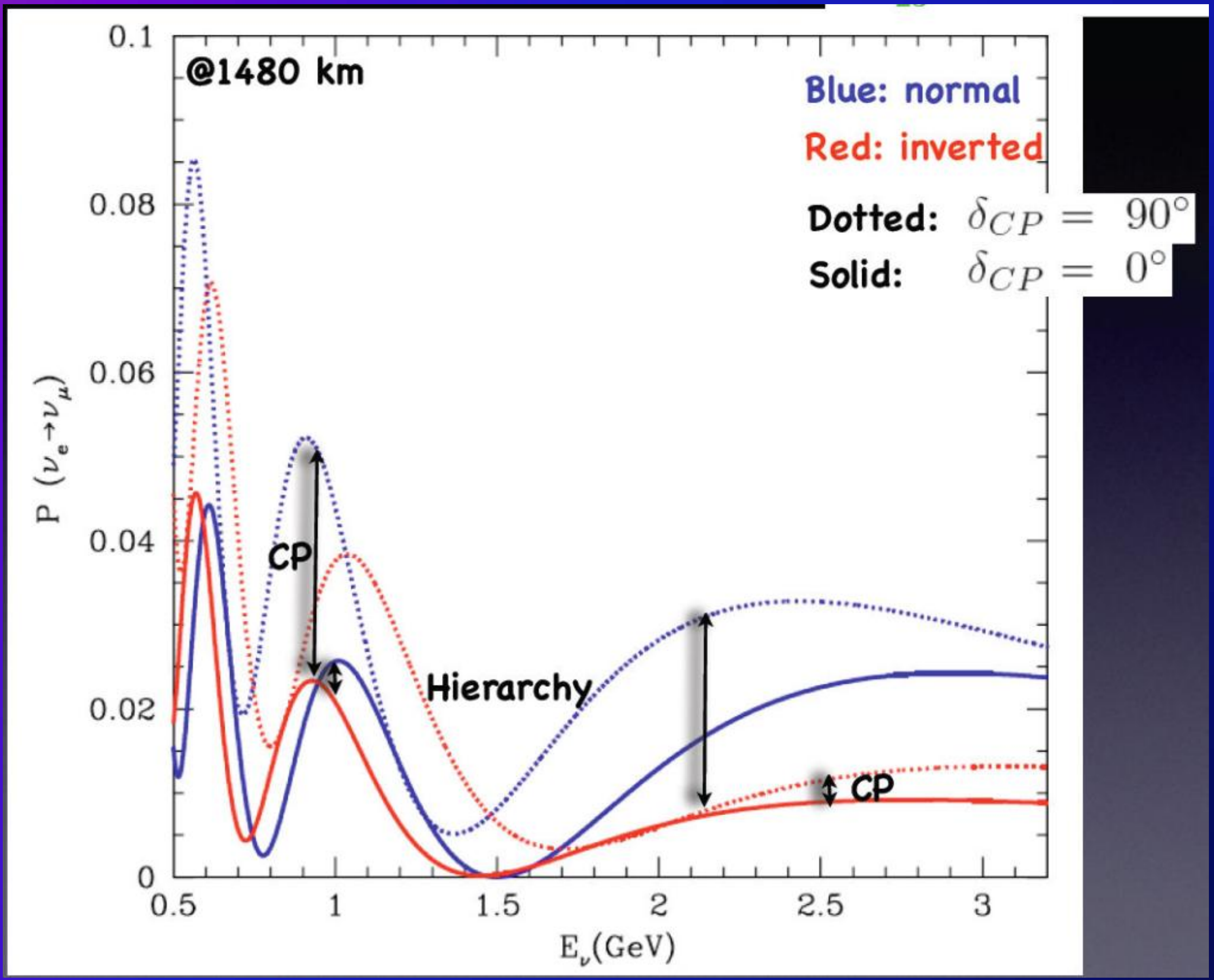
Geer, Mena, Pascoli
Phys. ReV D 75, 093001 (2007)
Bross, Ellis, Geer, Mena, Pascoli
Phys. ReV D 77, 093012 (2008)



Potentially X10 increase in Sensitivity Over Super-Beam

Ankenbrandt, Bogacz, Bross, Geer, Johnstone, Neuffer, Popovic
Fermilab-Pub-09-001-APC; Submitted to PRSTAB

$\nu_e \rightarrow \nu_\mu$ Oscillation Probability

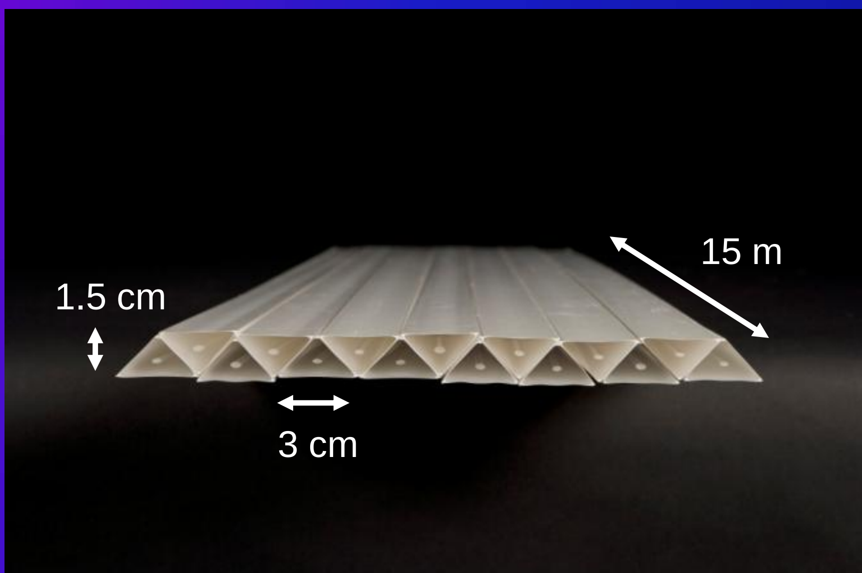


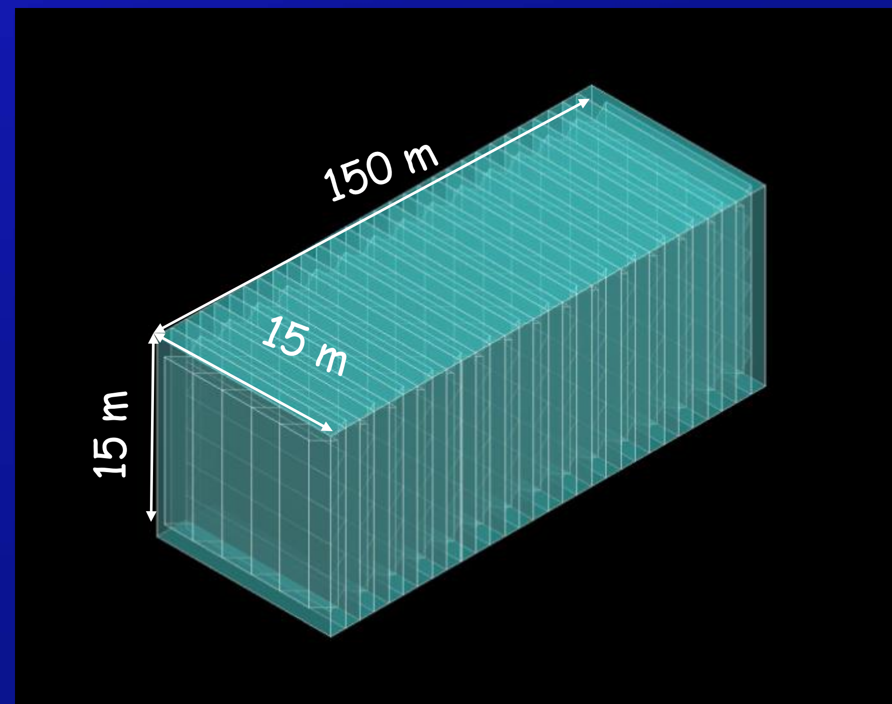
Olga Mena
NuFact08

Fine-Resolution Totally Active Segmented Detector

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

- 35 kT (total mass)
- 10,000 Modules (X and Y plane)
- Each plane contains 1000 cells
- Total: 10M channels



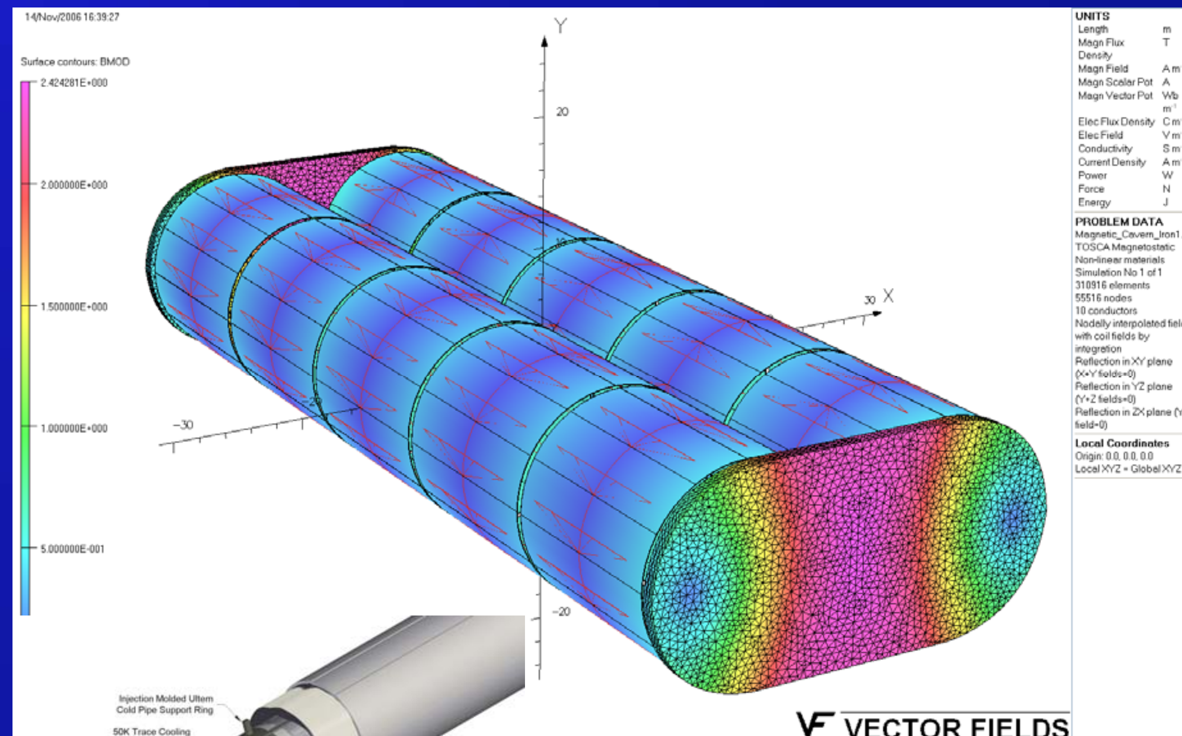


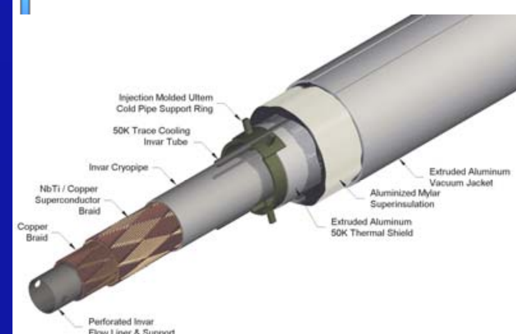
- Momenta between 100 MeV/c to 15 GeV/c
- Magnetic field considered: 0.5 T
- Reconstructed position resolution ~ 4.5 mm

B = 0.5T

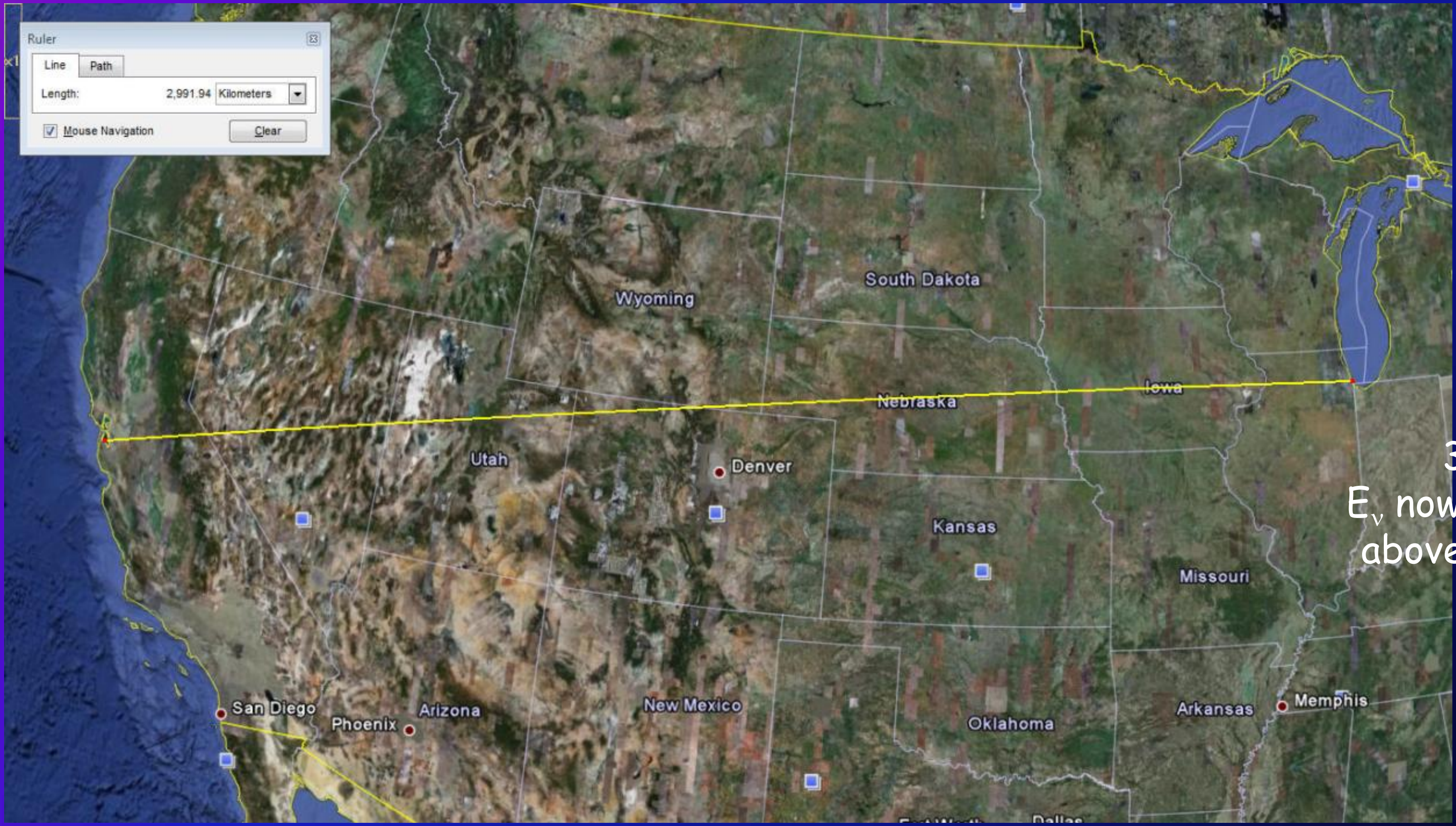
Detector Has to be Magnetized

- **Magnetized Totally Active Sampling Calorimeter 35kT**
- **Magnets**
  - 15m ∅ X 15m long -0.5T
  - Times 10!
  - Cost estimate
    - $140-680M
      - Conventional SC
- **New Idea**
  - VLHC SC transmission line
    - Technically proven
    - Might actually be affordable



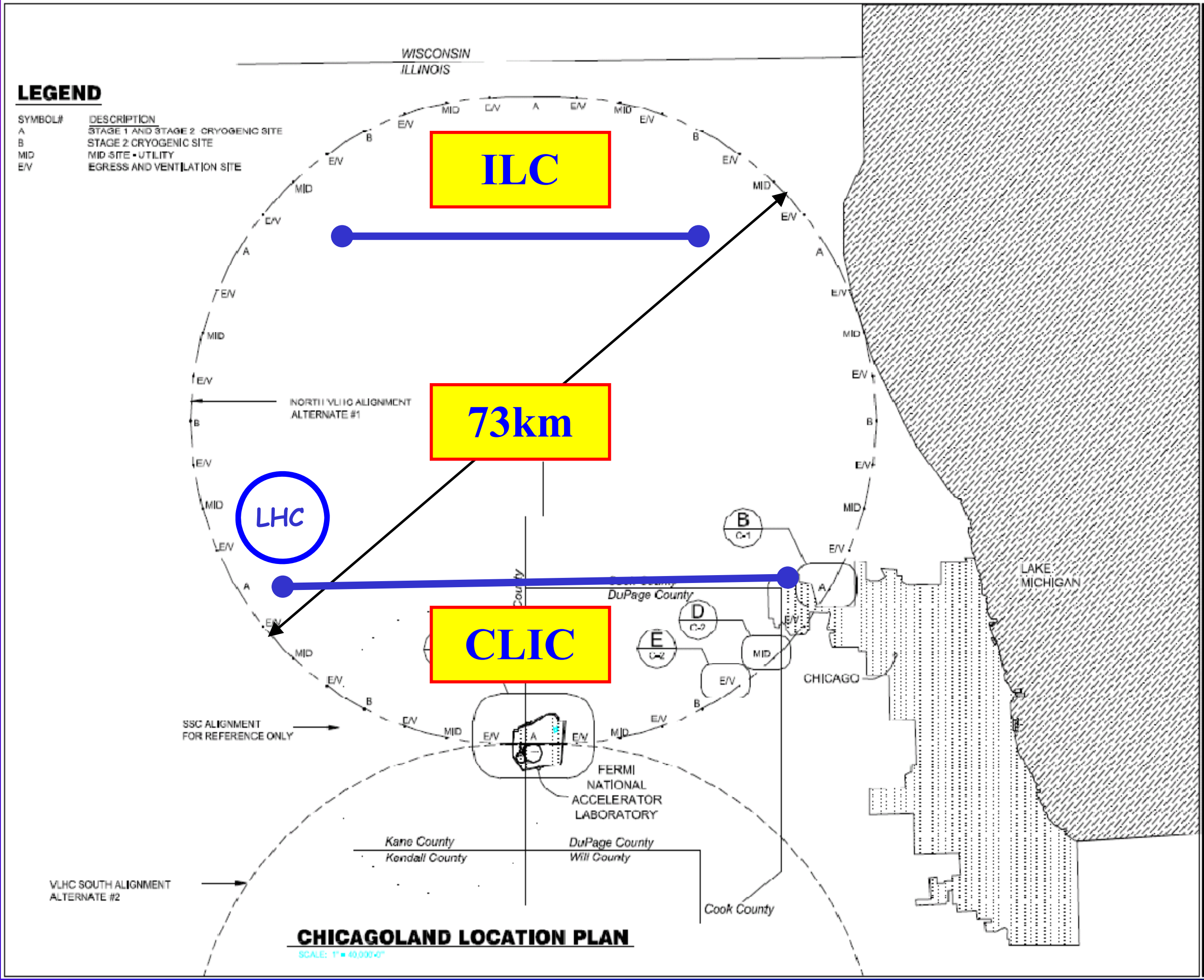


Other Baseline



3000 km
E_ν now comfortably above τ threshold

Footprint and the Energy Frontier



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

- Stage 1 – 40 TeV
- Stage 2 – 200 TeV

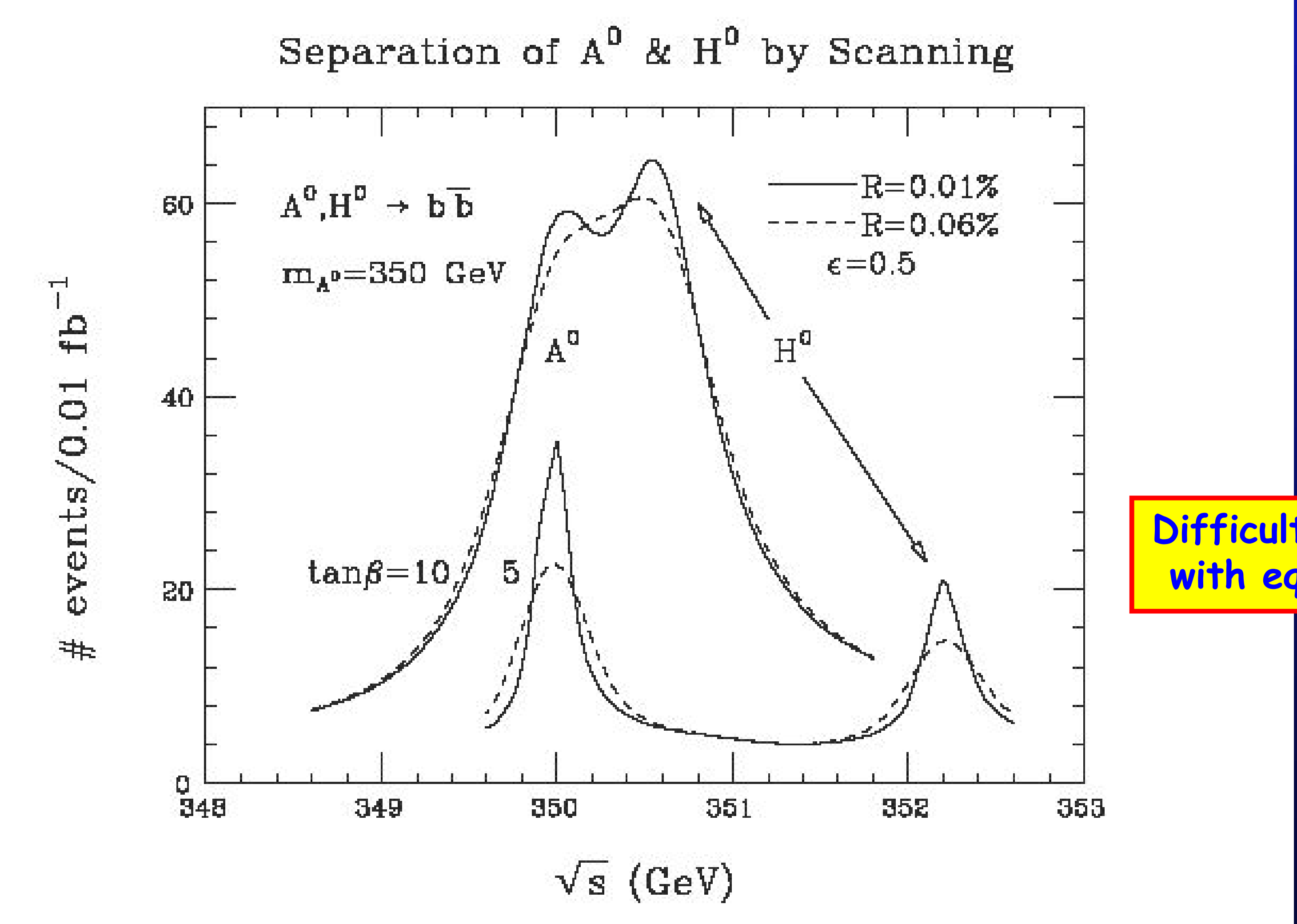
Muon Facilities are different

ILC: > 2 TeV

CLIC: 0.5 TeV

3+> 10 TeV

MC Physics - Resolving degenerate Higgs

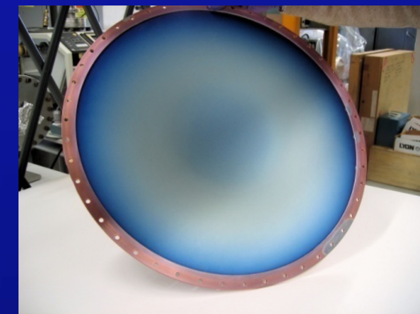


Difficult in e^+e^- machine with equivalent R ≈ 1%

MuCool

Component R&D and Cooling Experiment

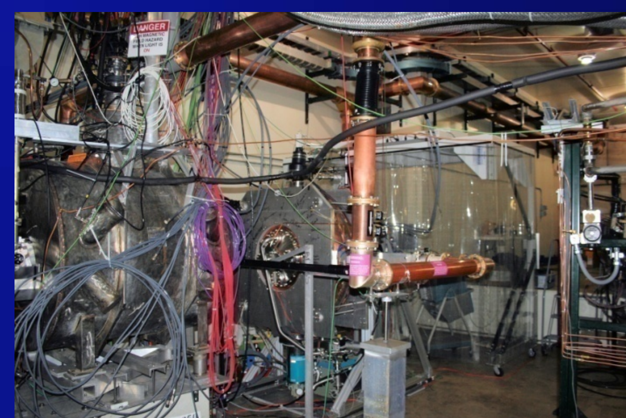
- **MuCool**
  - Component testing: RF, Absorbers, Solenoids
    - With High-Intensity Proton Beam
  - Uses Facility @Fermilab (MuCool Test Area –MTA)
  - Supports Muon Ionization Cooling Experiment (MICE)



50 cm ∅ Be RF window

MuCool Test Area

MuCool
201 MHz RF Testing



MuCool
LH_2 Absorber
Body