THE RESEARCH AND DEVELOPMENT PROGRAM TOWARDS AN ENERGY-FRONTIER MUON COLLIDER

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On Behalf of the Neutrino Factory and Muon Collider Collaboration (NFMCC), Muon Collider Task Force (MCTF), and Muon Accelerator Program (MAP)

OUTLINE

- Introduction and History
- Physics Motivation
- Conceptual Layout
- Progress and Challenges
- R&D Program
- Physics and Detector Studies

INTRODUCTION AND HISTORY

- Muons in a storage ring decay producing a beam of neutrinos $\rightarrow$ Neutrino Factory
- Colliding μ^+ and μ^- in storage ring $\rightarrow$ Muon Collider
- Muon colliders first proposed by G.I. Budker and A.N. Skrinsky in the late 1960's and early 1970's
- The necessary concept of ionization cooling was developed by Skrinsky and V.V. Parkhomchuk and expanded by D. Neuffer in the early 1980's and later by R.B. Palmer
- A Muon Collider Collaboration was formed in 1996; Neutrino Factory added in 1999 (NFMCC)
- Fermilab Muon Collider Task Force (MCTF) formed in 2006
- U.S. NFMCC and MCTF activities being merged into new national Muon Acceleration Program (MAP), hosted at Fermilab

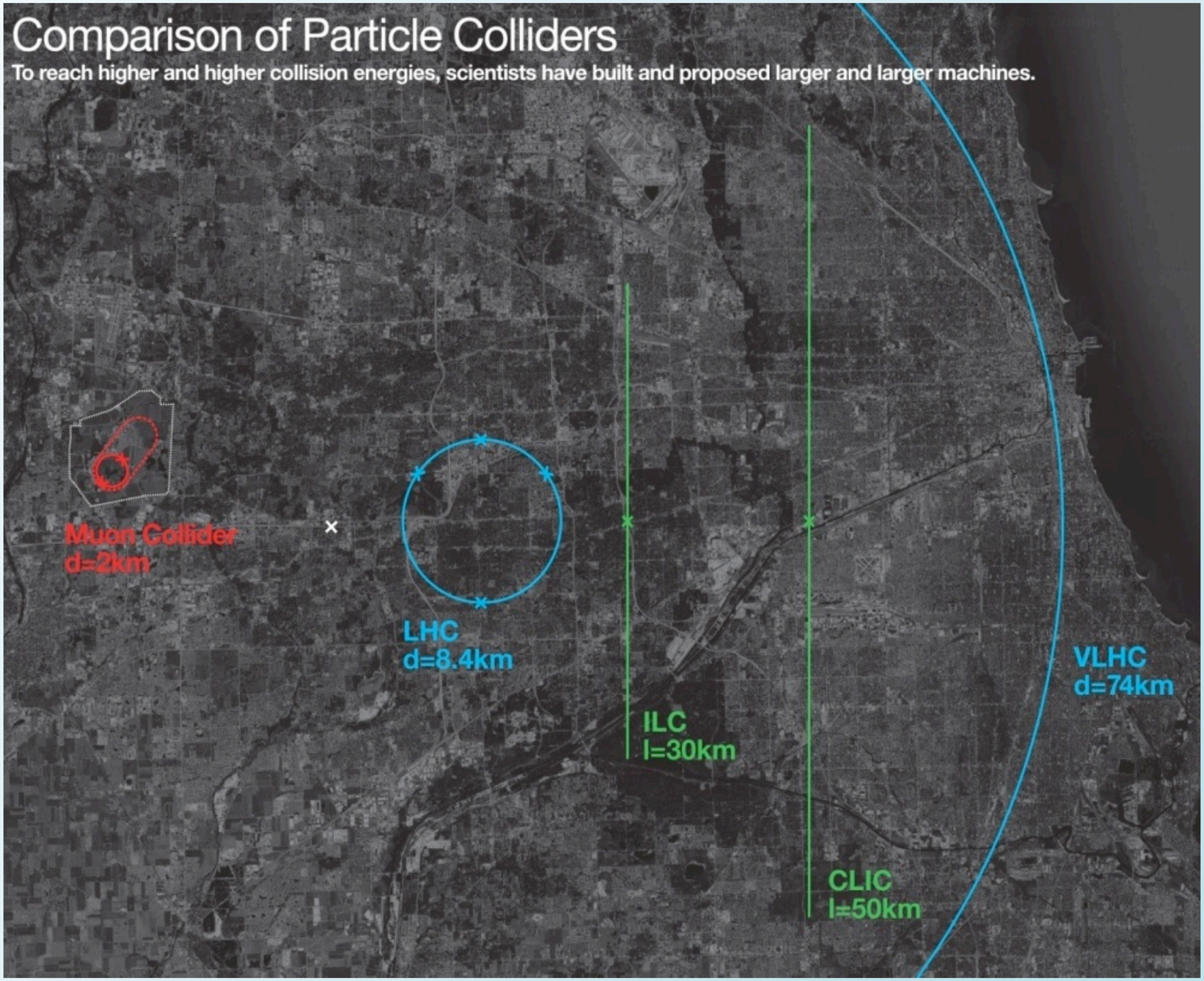
PHYSICS MOTIVATION

- Muons are fundamental particles, so same advantage as $e^{+} e^{-}$ colliders: full energy of particles in collision
- Synchrotron radiation by muons is less than for electrons by factor of $(m_e/m_\mu)^4 \approx 6\times 10^{-10}$
  - Compact, multi-pass acceleration, lower cost for RF power
  - Muon beam can have narrow energy spread
  - High energy collider can be much smaller – a ring
    - Multi-pass collisions ~ 1000 turns

Will decide energy for next lepton collider ~ 2014 based on LHC discoveries!

A MUON COLLIDER IS COMPACT

A 4 TeV muon collider would fit on the Fermilab site



PHYSICS MOTIVATION

$\sqrt{s}$ < 500 GeV:

- Threshold regions

  top pairs

  EW boson pairs

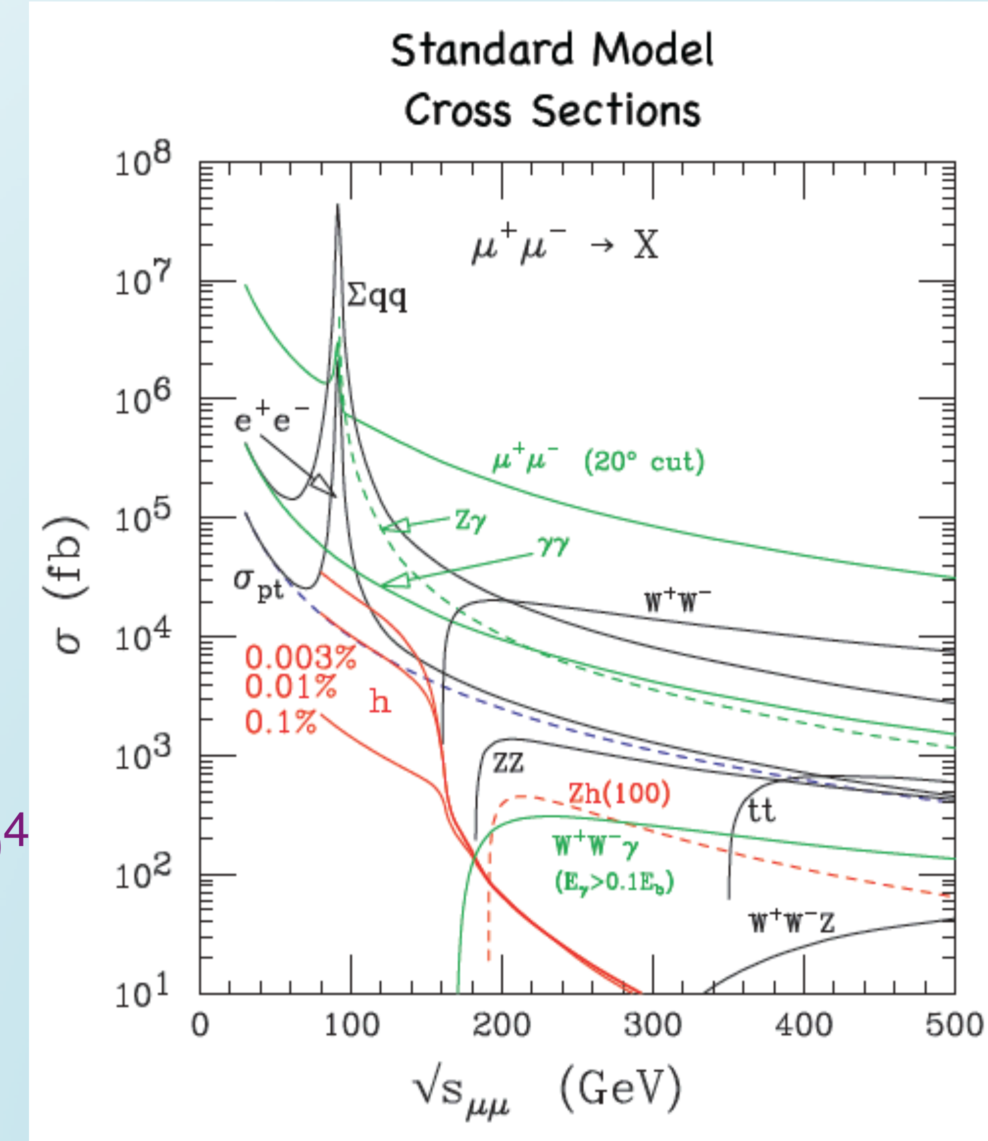
  Zh production

- Enhanced *s*-channel production for Higgs-like particles

  Proportional to $(m_\mu/m_e)^2 \sim 4 \times 10^4$

  Narrow energy spread – resolve nearly degenerate states

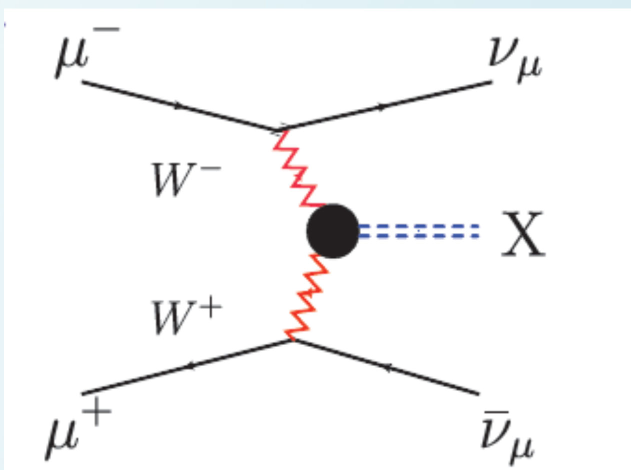
  Could be important for H^0, A^0



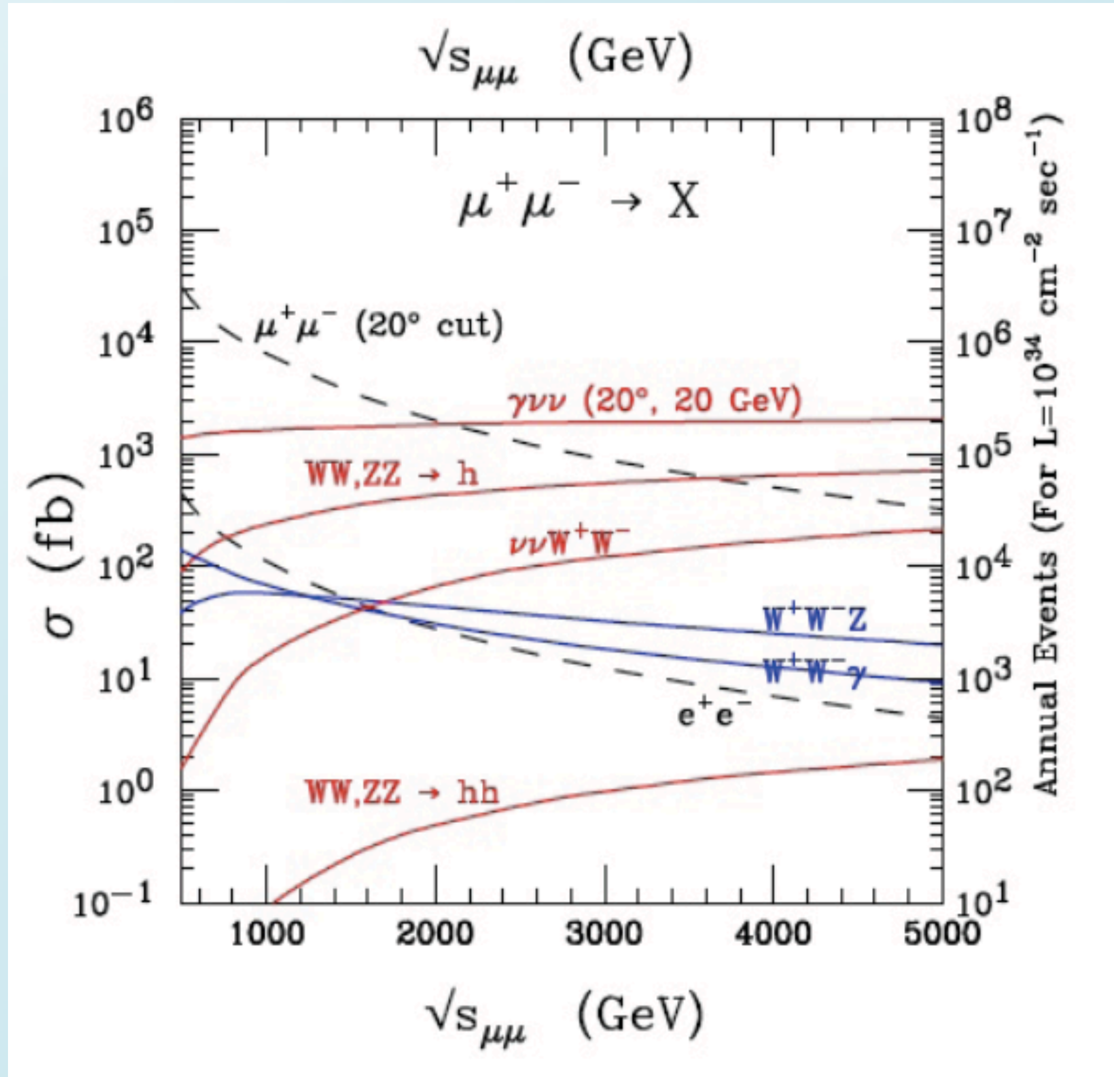
PHYSICS MOTIVATION

$\sqrt{s} > 500$ GeV:

- Fusion processes increasingly dominate *s*-channel processes
- Probing reach addresses all major outstanding questions

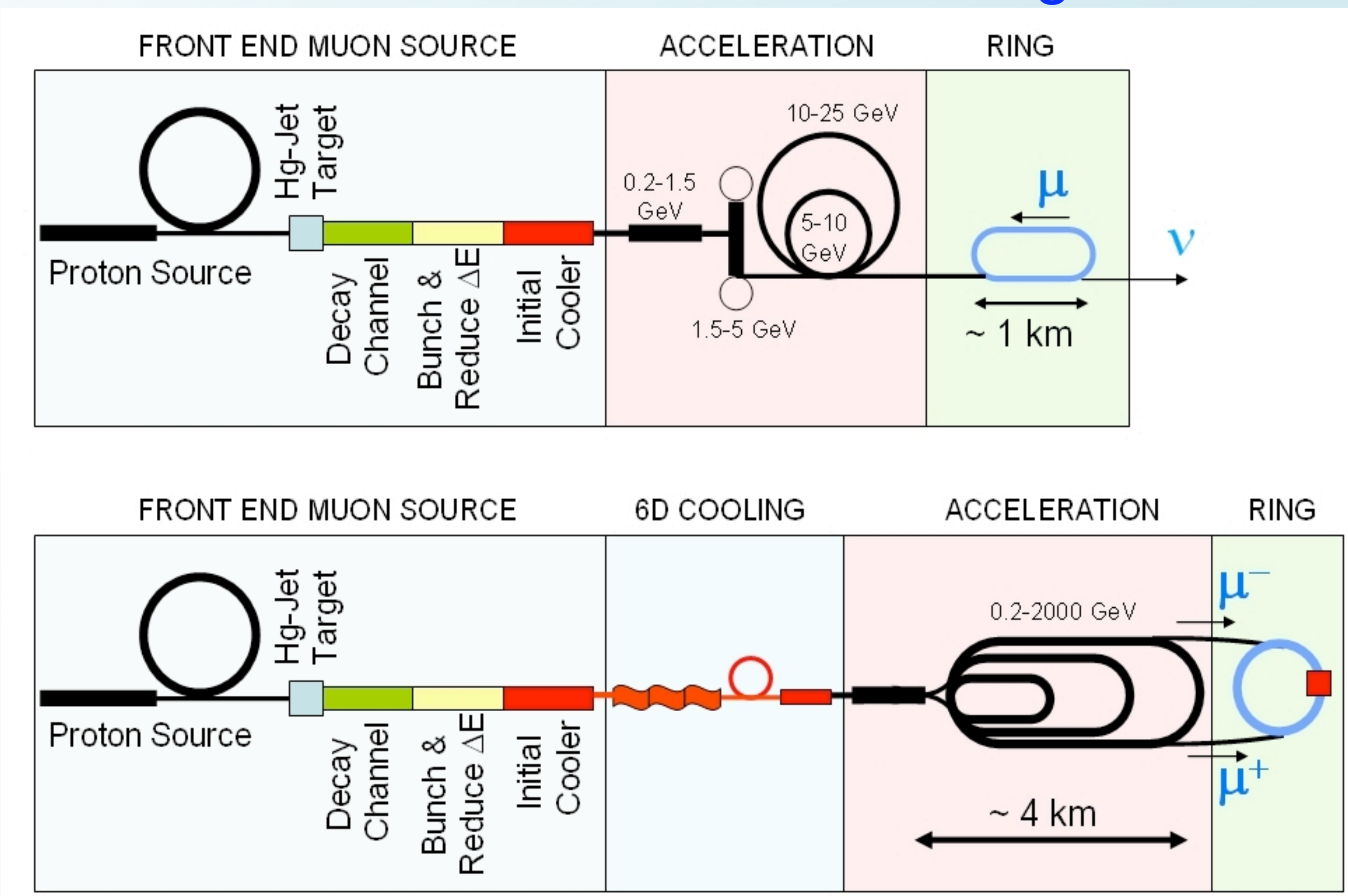


$$\sigma(s) = C \ln\left(\frac{s}{M_X^2}\right) + \ldots$$



SCHEMATIC LAYOUT

Same front-end design for Neutrino Factory and Muon Collider in current baseline design



NEUTRINO FACTORY

MUON COLLIDER

10^{21} μ's per year within acceptance

CONCEPTUAL LAYOUT

Muon Collider Conceptual Layout

Project X
Accelerate hydrogen ions to 8 GeV using SRF technology.

Compressor Ring
Reduce size of beam.

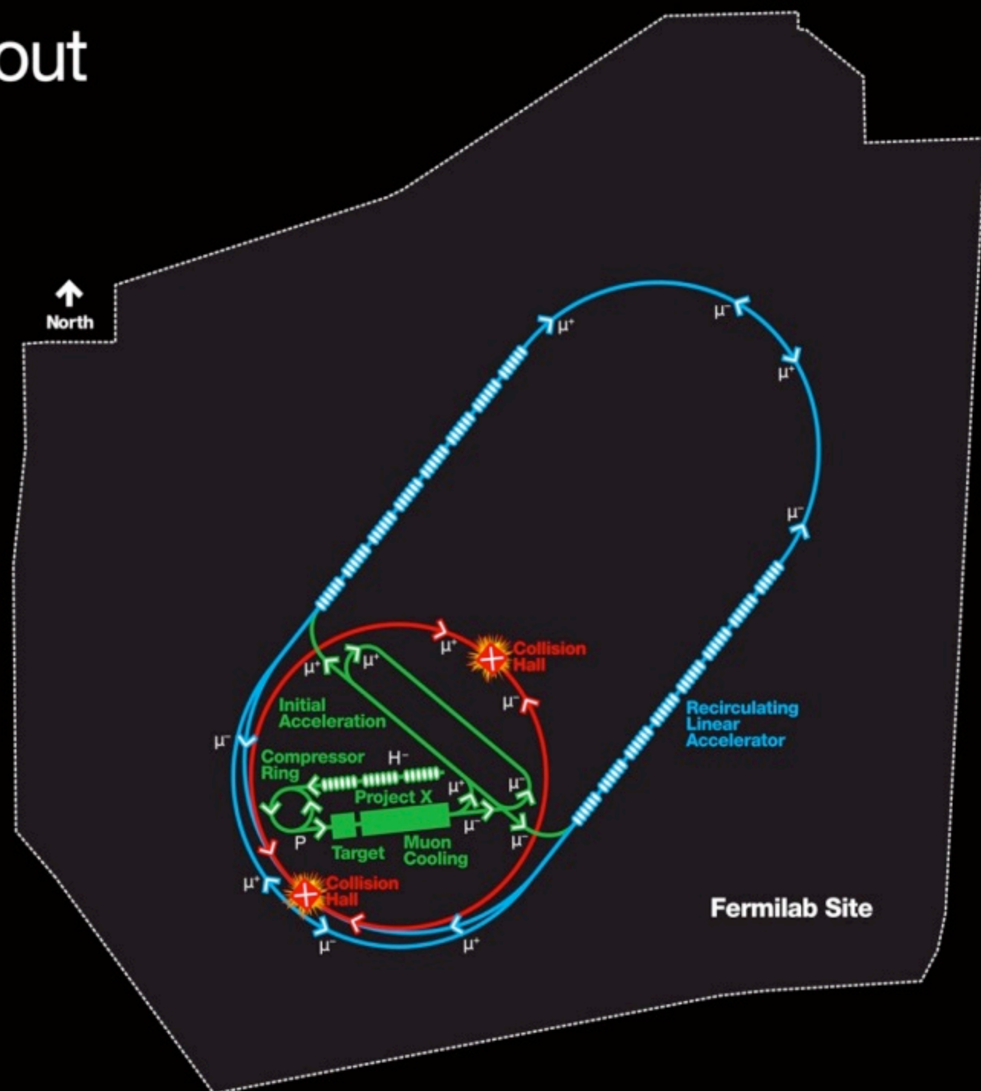
Target
Collisions lead to muons with energy of about 200 MeV.

Muon Capture and Cooling
Capture, bunch and cool muons to create a tight beam.

Initial Acceleration
In a dozen turns, accelerate muons to 20 GeV.

Recirculating Linear Accelerator
In a number of turns, accelerate muons up to 2 TeV using SRF technology.

Collider Ring
Bring positive and negative muons into collision at two locations 100 meters underground.



EXAMPLE 1.5 TeV MUON COLLIDER SCENARIOS

	LEMC	HEMC
Avg. luminosity (10^{34} cm^{-2} s^{-1})	2.7	1
Avg. bending field (T)	10	8
Proton driver repetition rate (Hz)	65	15
β^* (cm)	0.5	1
Muons per bunch (10^{11})	1	20
Muon bunches in collider (each ring)	10	1
Norm. Transv. Emittance (µm)	2.1	25
Norm. Long. Emittance (m)	0.35	0.07
Energy spread (%)	1	0.1

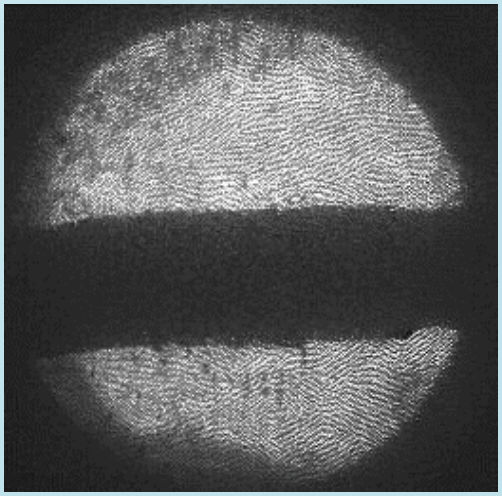
Low-emittance muon collider (LEMC); high-emittance muon collider (HEMC)

PROGRESS AND FUTURE R&D

- Proton Source
  - Upgraded Project-X (4 MW, 1–3 ns bunch length)
  - See R. Tschirhart talk "Project-X at Fermilab"

- Target
  - MERIT Experiment at CERN PS
  - Mercury jet in a 15 T solenoid

1 cm ↕



Measured disruption length = 28 cm

PROGRESS AND FUTURE R&D

- Decay, Bunching and Phase Rotation
  - Muons come from decay of pions produced in target, so large emittances and energy spreads
  - Front end captures pions produced from target, bunches the muons, and reduces the energy spread
  - Decay and capture uses Neutrino Factory Feasibility Study 2 solenoid channel
  - Neuffer 12-bunch scheme for bunching and phase rotation suitable for either Neutrino Factory or Muon Collider
  - Further R&D needed to make realistic

In common with Neutrino Factory

PROGRESS AND FUTURE R&D

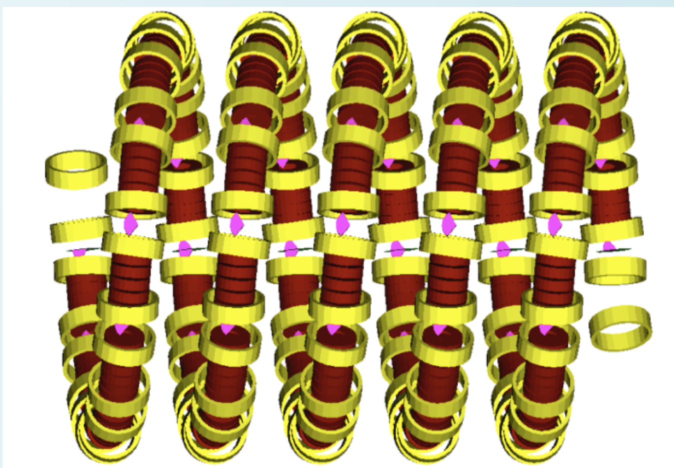
- Initial Cooling
  - Neutrino Factory Feasibility Study 2a channel (lithium hydride absorber instead of liquid hydrogen)
  - Will study using hydrogen gas absorber in place of (or in addition to) LiH

In common with Neutrino Factory

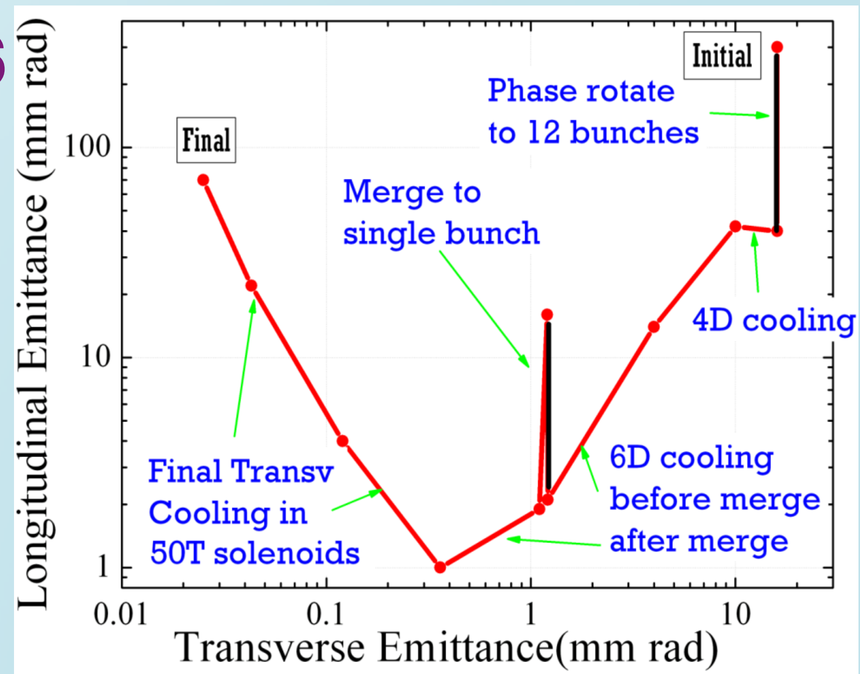
Front End: R&D on RF in magnetic field needed

PROGRESS AND FUTURE R&D

- 6-Dimensional Cooling
  - Three options: "Guggenheim" (helical RFOFO), FOFO snake, Helical Cooling Channel
  - Each has been simulated, choice in 2012
  - R&D on RF in magnetic field needed
  - Demonstration proposal 2016

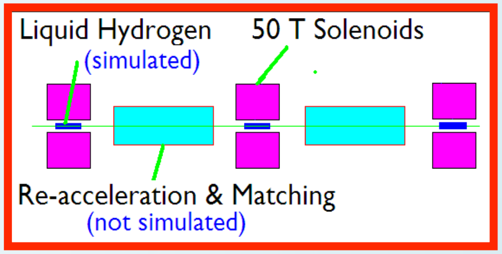


201-MHz Guggenheim Channel

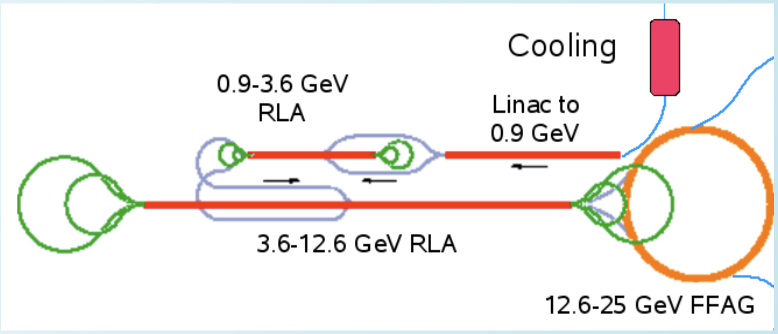


PROGRESS AND FUTURE R&D

- Final Cooling
  - ✧50-T Linear Channel – R&D on very high field magnets



- Acceleration
  - ✧Low-energy Acceleration
    - Linac followed by two dog-bone RLAs + FFAG (EMMA)
    - Techniques similar to Neutrino Factory



IDS-NF Baseline Acceleration

PROGRESS AND FUTURE R&D

- Acceleration (continued)
  - ✧ Acceleration to High Energy
    - Fast-cycling synchrotrons
    - R&D on rapid-cycling magnets ongoing

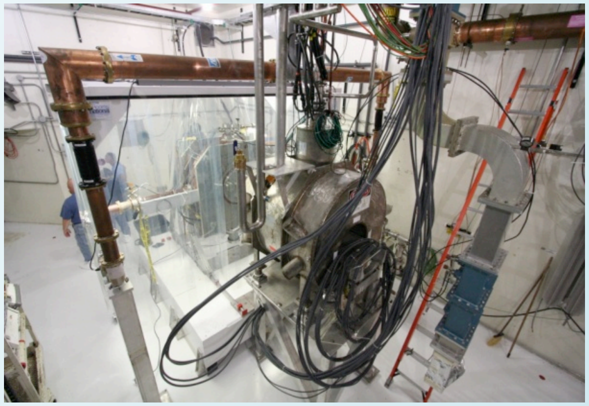
- Collider Ring
  - ✧ Good progress on lattice design, ±1.2% momentum acceptance, 4.7σ dynamic aperture (without errors)
  - ✧ Closely tied to design of detectors

TECHNOLOGY DEVELOPMENT AND SYSTEM TESTS

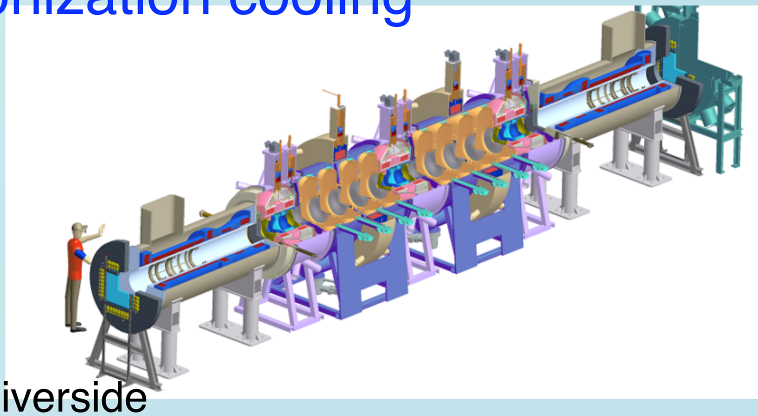
- RF Cavities in Magnetic Field
  - Copper RF cavities (normal-conducting) have been shown to break down in multi-Tesla fields at lower gradients than needed for cooling channels
  - R&D program to establish viable options (treating, high-pressure gas, atomic layer deposition, orientation of magnetic field)
- Magnet Development
  - Very high field solenoids
  - Helical solenoids
  - Very fast ramping magnets
  - HTS solenoids

TECHNOLOGY DEVELOPMENT AND SYSTEM TESTS

- MUCOOL Test Area at Fermilab
  - ✧ Ionization cooling component testing – 5-T magnet, 805- and 201-MHZ RF cavity testing, LH_2 handling, 400 MeV beam from linac



- Muon Ionization Cooling Experiment (MICE)
  - ✧ Experimental demonstration of ionization cooling
  - ✧ Under way at RAL



MUON ACCELERATOR PROGRAM (MAP)

Department of Energy
Office of Science
Washington, DC 20585

October 2, 2009

Dr. Pier Oddone
Fermi National Accelerator Laboratory
P.O. Box 500
Batavia, Illinois 60510

Dear Dr. Oddone:

Our Office believes that it is timely to mount a concerted national R&D program that addresses the technical challenges and feasibility issues relevant to the capabilities needed for future Neutrino Factory and multi-TeV Muon Collider facilities. This is consistent with the guidance we obtained from the Accelerator Science Review in December, 2008 and with the envisioned overall national strategy as articulated in the P5 Report in 2008.

The "Muon Accelerator R&D Program: A Proposal for the Next 5 Years" that was presented at the Accelerator Science Review and was submitted to our Office on December 12, 2008, was prepared jointly by the Neutrino Factory and Muon Collider Collaboration (NFMCC) and the Muon Collider Task Force (MCTF) on behalf of three "sponsoring" DOE laboratories—Brookhaven National Laboratory, Fermi National Accelerator Laboratory and Lawrence Berkeley National Laboratory. This involved:

A. Bross (NFMCC Co-spokesperson)
H. Kirk (NFMCC Co-spokesperson)
M. Zisman (NFMCC Project Manager)

S. Geer (MCTF Co-leader)
V. Shiltsev (MCTF Co-leader)

S. Vigdor (BNL, Chair MCOG)
S. Holmes (FNAL, MCOG)
J. Siegrist (LBNL, MCOG)

To proceed as a national R&D program, there needs to be a responsible and accountable program director and host laboratory that will present, defend and manage an integrated national R&D plan.

We believe that Fermilab is the natural host laboratory for this initiative because of its potential as the site of these possible facilities. So, I would like you to work with the other HEP laboratories and NFMCC and MCTF to determine what an appropriate management structure might be and who the proposed program director should be. I envision a structure and governing policy similar to LARP, but other models should be considered and proposed if believed to be more appropriate and effective. The new collaboration management should revisit the proposal previously submitted and modify it as it deems necessary. A revised proposal, incorporating the new management plan and detailed schedule and deliverables for the next 5 years, should be submitted to OHEP for review by the collaboration when it is ready.

Please let me know what the proposed management structure will be and when OHEP might expect a revised R&D plan proposal. OHEP would like to review this plan before the end of calendar year 2009, if possible.

Sincerely,

Dennis Kovar
Associate Director of Science
for High Energy Physics

cc: S. Vigdor, BNL
S. Holmes, FNAL
J. Siegrist, LBL
A. Bross (FNAL, NFMCC Co-spokesperson)
H. Kirk (BNL, NFMCC Co-spokesperson)
M. Zisman (LBNL, NFMCC Project Manager)
S. Geer (FNAL, MCTF Co-leader)
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G. Crawford, SC-25
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L. K. Len, SC-25
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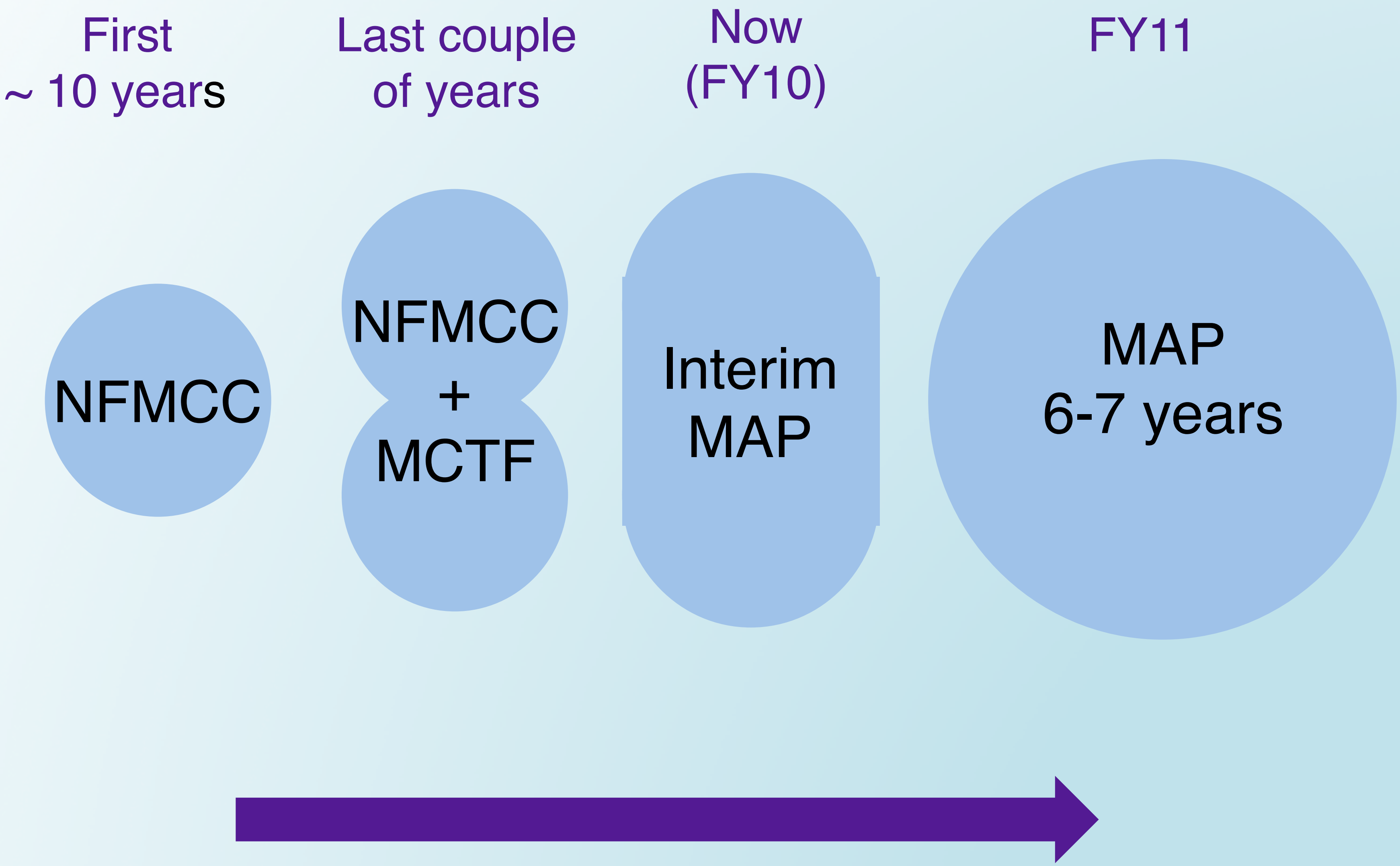
- Proposal submitted March 1, 2010
- DOE Review August 24-26, 2010
- 214 participants from 14 institutes

R&D PROGRAM DEVELOPMENT



MUON ACCELERATOR PROGRAM (MAP)

MAP deliverables:

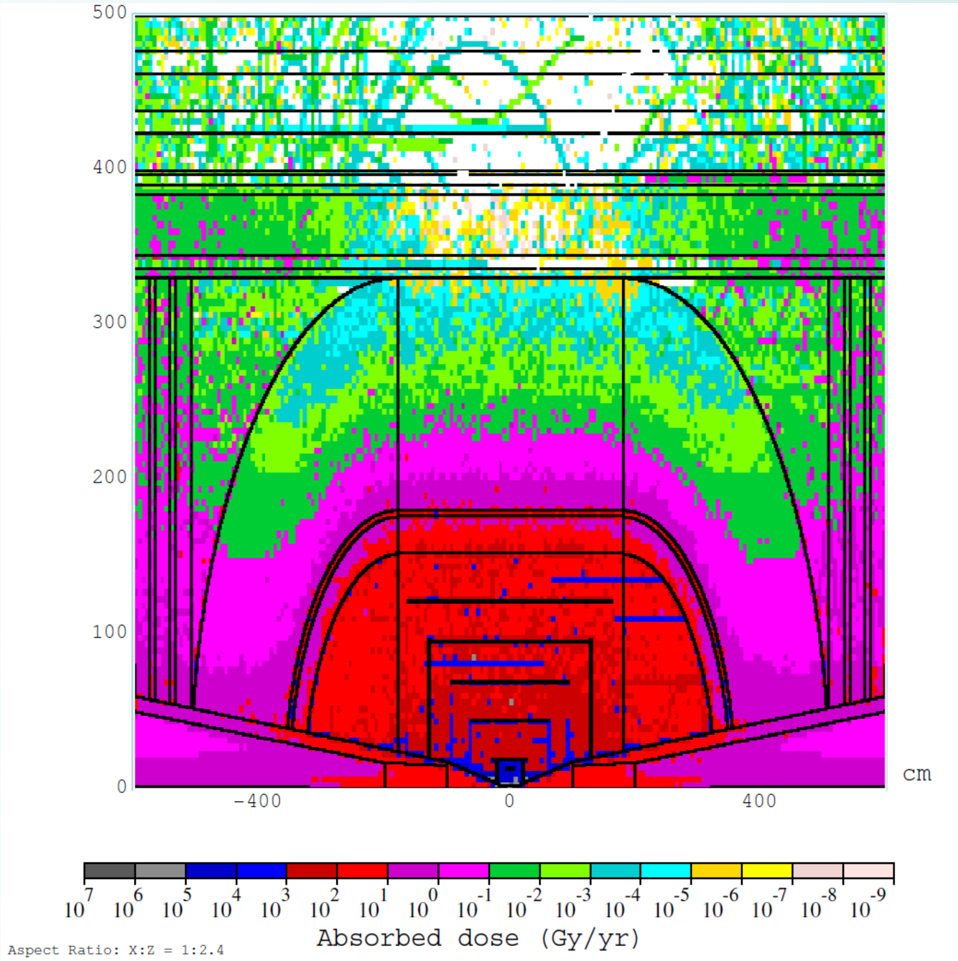
- Design Feasibility Study Report (DFSR) for a multi-TeV muon collider, including indicative cost range
- Technology development and system tests needed to inform the muon collider DFSR studies and enable down-selection
- Contributions to the International Neutrino Factory Design Study to produce a Reference Design Report by 2013

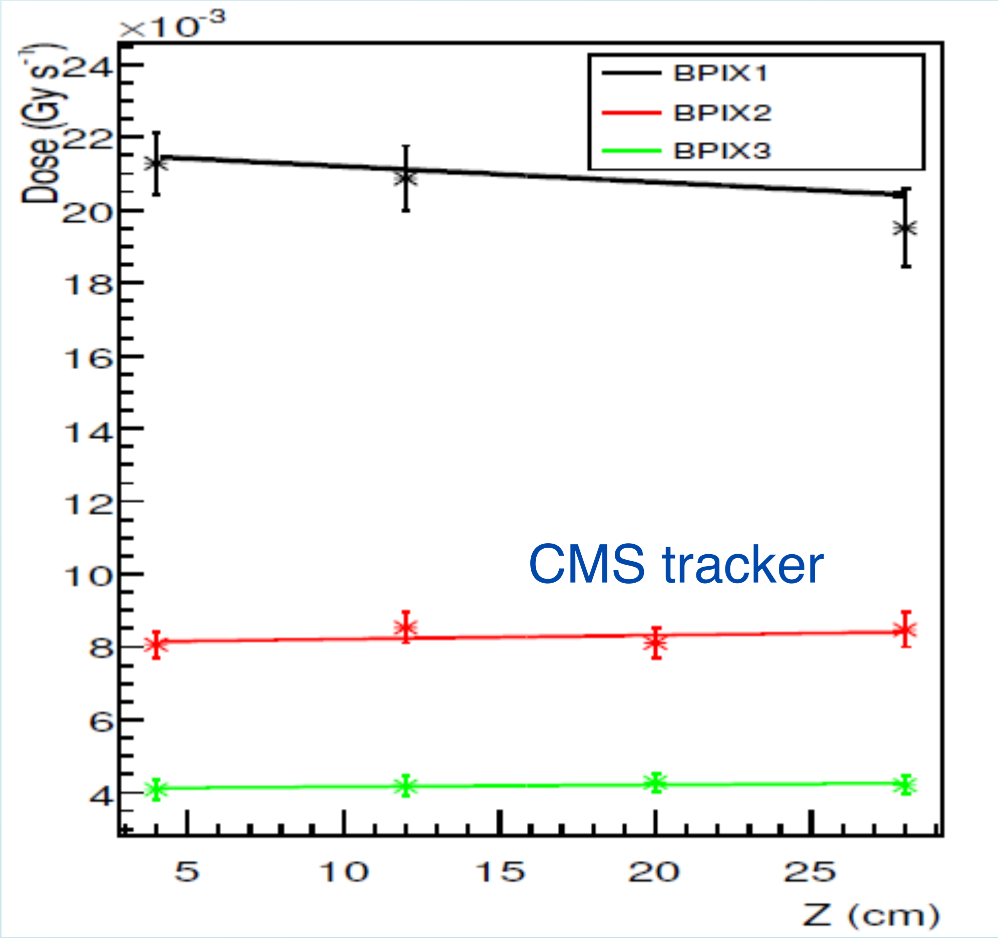
PHYSICS AND DETECTORS

- Physics and Detector studies not part of MAP – separate group forming. Kick-off workshop was held at Fermilab in November 2009; second workshop in Fall 2010
- Machine-Detector Interface group revisited background calculations, using consistent muon collider lattice, with different cone configurations
- Compared to most optimistic old 1996 configuration, peak values for backgrounds are down factor of 5-10 for all particles, except photons
- Background fluxes of particles provided as input to physics simulations

Total absorbed dose in silicon at 4 cm radius

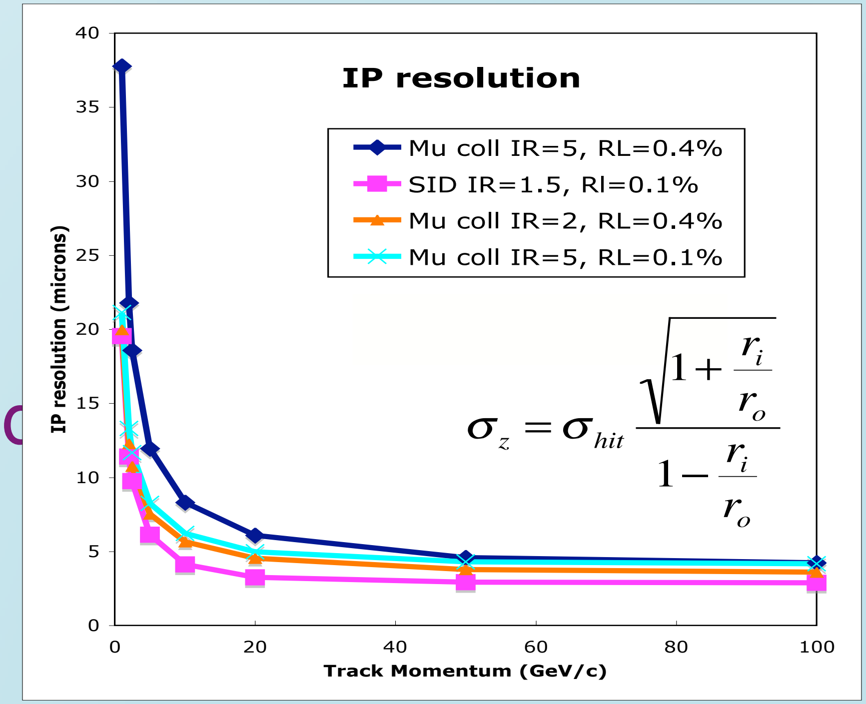
- Muon Collider: 0.1 MGy/yr
- CMS: 0.2 MGy/yr at 10^{34} cm^{-2} s^{-1}





PHYSICS AND DETECTORS

- With today's pixel detector technologies occupancies should be quite manageable in the barrel region (and easier compared to CLIC)
- Impact on precision physics of large radius of first layer of vertex detector:
  - ILC: radii of 1.5 → 6 cm
  - MC: radii of 5 → 20 cm
- Resolution factor of 2 worse for low p_T compared to ILC
- Physics implications to be studied



SUMMARY AND CONCLUSIONS

- Considerable progress on muon collider R&D
- Options delineated and encouragement from DOE to form a Muon Accelerator Program (MAP) hosted at Fermilab – proposal submitted
- Within 6-7 years we will have a Design Feasibility Study and cost range for a multi-TeV muon collider; configurations chosen and end-to-end simulation by 2014
- Plan initiated to form a national lepton collider program for physics and detectors in the US
- Decision on energy for next lepton collider depending on LHC results