Potential (AC)-LGAD Applications for the Muon Collider

Sergo Jindariani (Fermilab)
A.Apresyan, C.Pena, D.Stratakis, S.Xie (Fermilab), K.Nakamura (KEK)
On behalf of IMCC and US Muon Collider R&D Coordination Group

More comprehensive talk on Muon Collider detector needs in Simone Pagan-Griso’s talk in Thursday’s plenary

CPAD’2024, Knoxville, TN

The Path to 10 TeV (excerpts from the 2023 P5 report)

- The proposed program aligns **with the long-term ambition of hosting a major international collider facility in the US, leading the global effort** to understand the fundamental nature of the universe.

- In particular, **a muon collider** presents an attractive option both for technological innovation and for bringing energy frontier colliders back to the US.

- Although **we do not know if a muon collider is ultimately feasible**, the road toward it leads from current Fermilab strengths and capabilities to **a series of proton beam improvements and neutrino beam facilities**, ...

- At the end of the path is an unparalleled global facility on US soil. **This is our Muon Shot.**

The Machine Concept at ~10 TeV

- The goal is to get to **10 TeV center-of-mass** energy with L ~ 10^{35} cm^{-2} s^{-1} (driven by the Higgs physics requirements)
- **Staging in energy** (e.g. 3→10 TeV) or **in luminosity** (a la LHC→HL-LHC) are possible

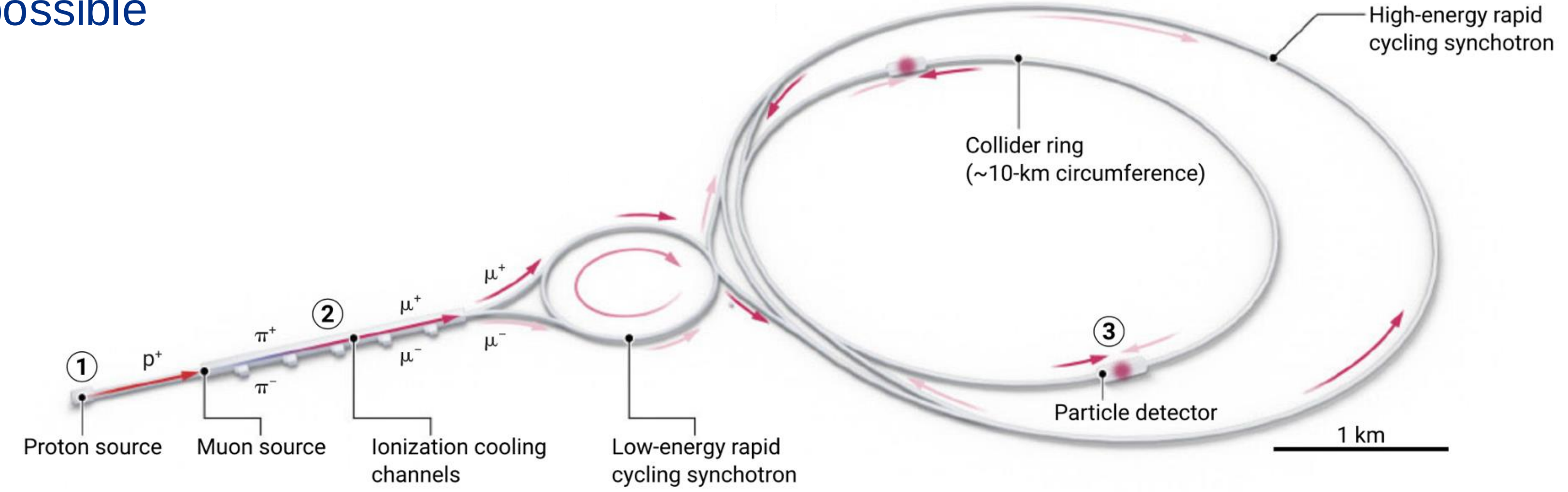


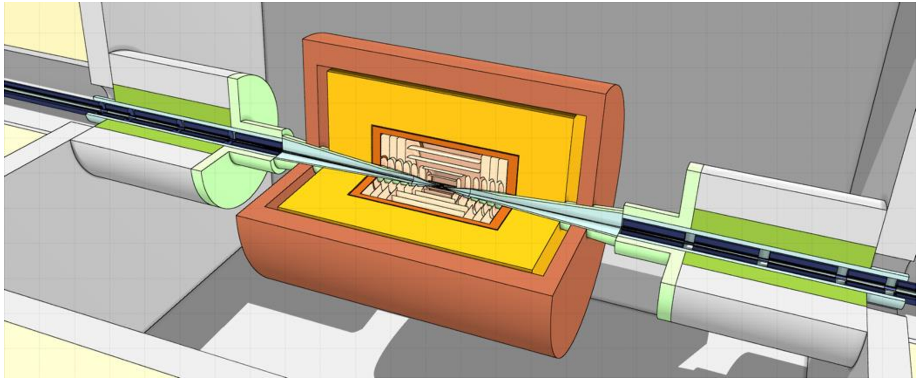
Image courtesy of A. Fisher and the Science magazine

Fermilab

More in Kiley Kennedy’s talk on Th

Why Specialized Detectors?

- Unique challenge of Muon Collider detectors – beam induced background (BIB)
- Most of the energy in the detector is from muon decays that eventually result in a high rate of particles reaching the detector → need special detectors to suppress it



Why Specialized Detectors?

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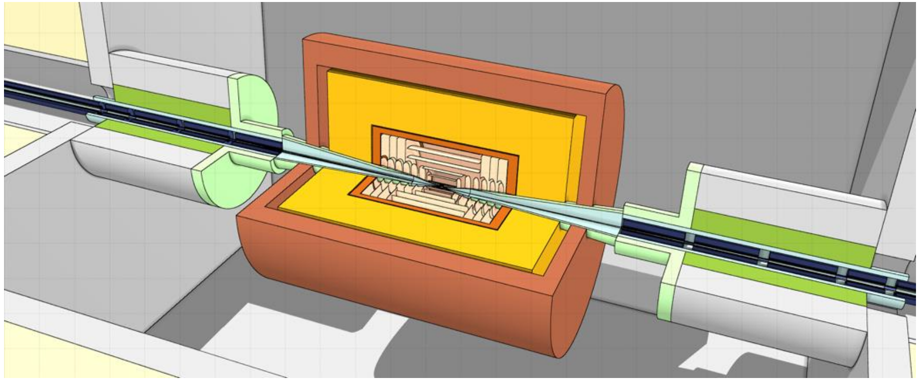
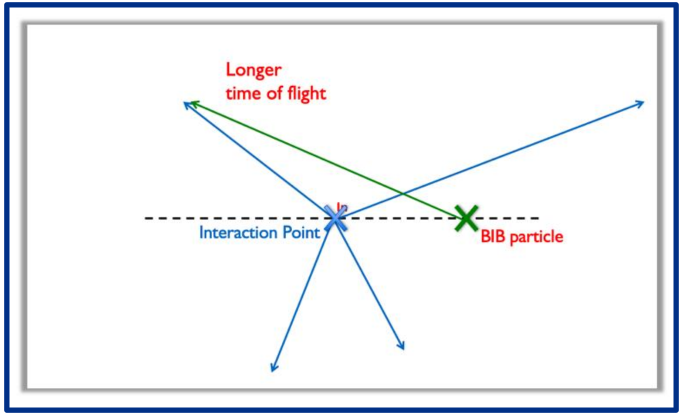
- Unique feature/challenge of Muon Collider detectors – beam induced background (BIB)
- Most of the energy in the detector is from muon decays that eventually result in a high rate of particles reaching the detector → need special detectors to suppress it
- Most of the BIB arrives out of time – precision timing coupled with high spatial resolution is a strong handle
- Significant radiation doses – detectors need to be rad-hard
- Natural next steps in evolution of LHC detectors, significantly more relaxed that FCC-hh

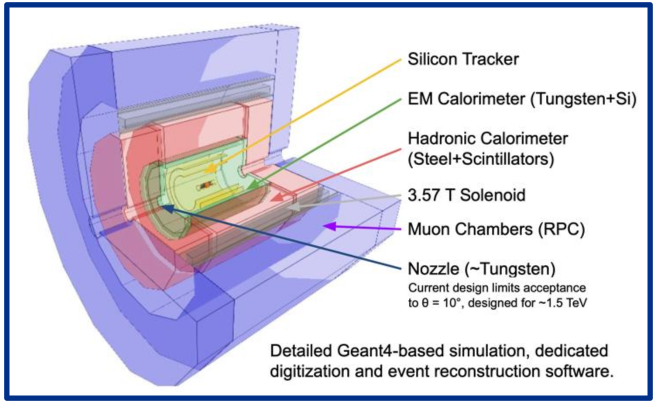




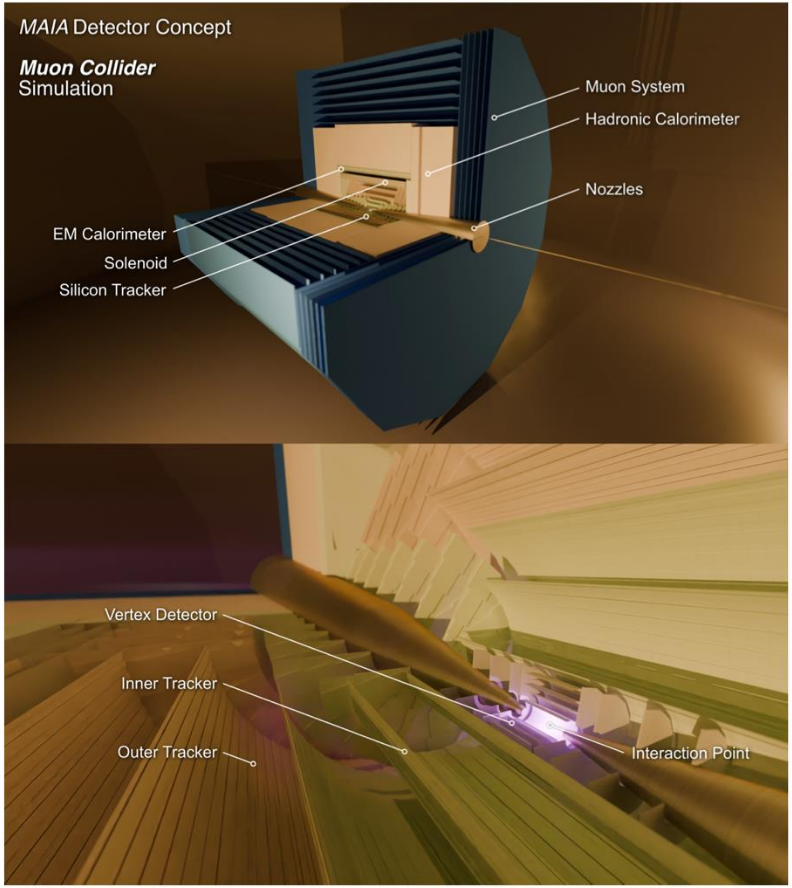
Detector Designs

Two concepts for 10 TeV detector (MAIA and MUSIC) developed since last year

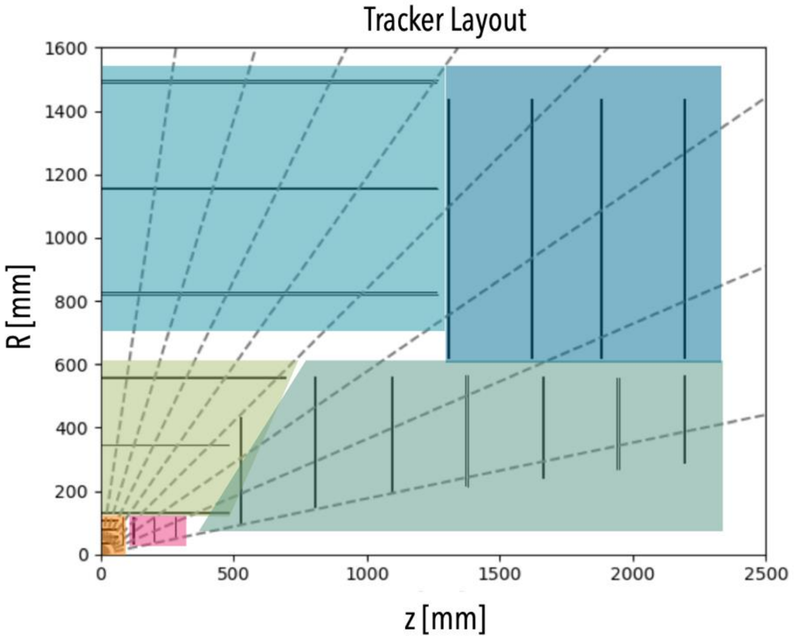
More in Ben Rosser's talk



The 3 TeV design stemming from CLIC has been extensively studied for Snowmass



4D Tracker



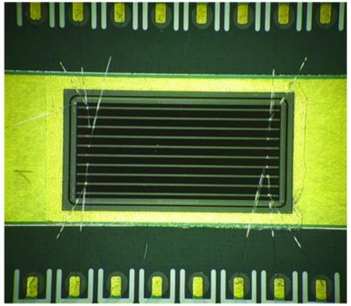
	Vertex Detector	Inner Tracker	Outer Tracker
Sensor Type	pixels	macropixels	microstrips
Layers, Barrel (Endcap)	4 (4)	3 (7)	3 (4)
Cell Size	$25\mu m \times 25\mu m$	$50\mu m \times 1mm$	$50\mu m \times 10mm$
Sensor Thickness	$50\mu m$	$100\mu mm$	$100\mu mm$
Time Resolution	30ps	60ps	60ps
Spatial Resolution	$5\mu m \times 5\mu m$	$7\mu m \times 90\mu m$	$7\mu m \times 90\mu m$

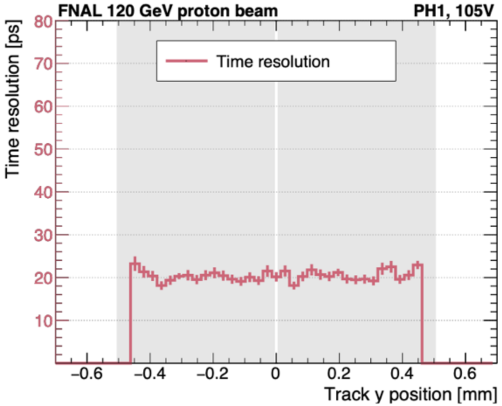
- Occupancy per layer with 1% target directly translates into feature size and timing resolution
- With (micro-)strips it may be more difficult to achieve target timing resolution – requires more studies and optimization

More in Artur Apresyan's talk

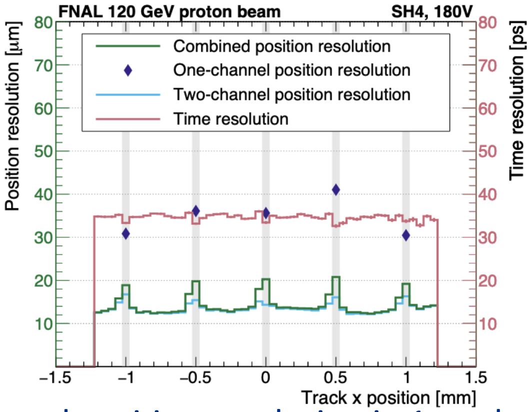
Comparing to LGAD Performance

- Active R&D to extend and improve LGAD technology
  - Improve performance by providing 100% fill factor
  - Excellent position and time resolution
    - Signal sharing allows for improved position resolution
- Large scale prototypes: 1- and 2-cm long strip sensors manufactured
  - 20 ps time resolution for pixels, 30 ps and ~15 μm achieved

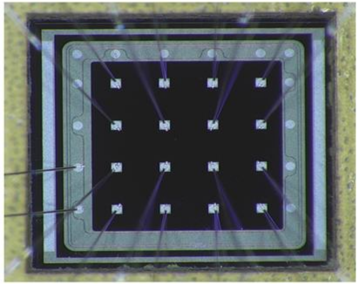




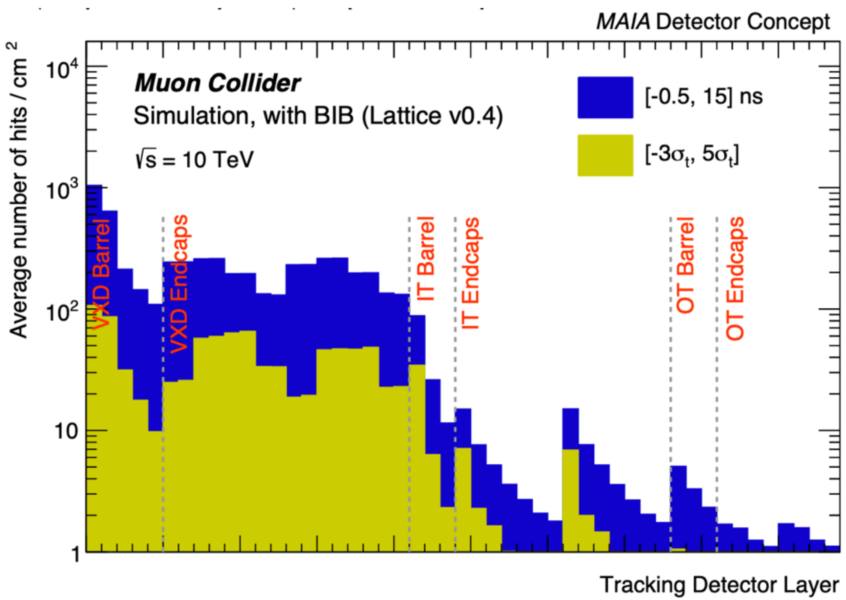
Time resolution in pixel AC-LGAD



Time and position resolution in 1-cm long strip AC-LGAD



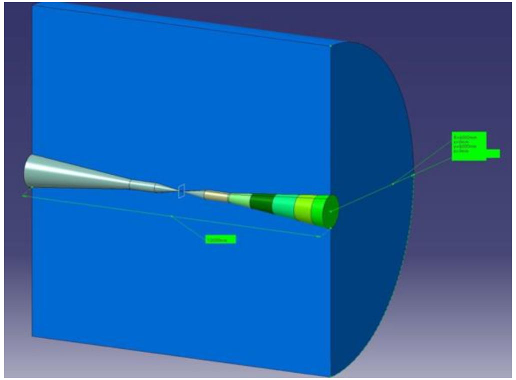
The impact of Timing



- 30-60 ps per hit resolution allows to reduce the BIB by an order of magnitude
  - Get to ~ HL-LHC like occupancies
  - Suddenly things don't look so daunting
- Naturally maps onto AC-LGAD performance projections

- Don't have a realistic digitization model
- Power consumption is a major question to be studied
- Even with timing, ~100 hits/cm^2. Data suppression is and high bandwidth transmission are important R&D directions

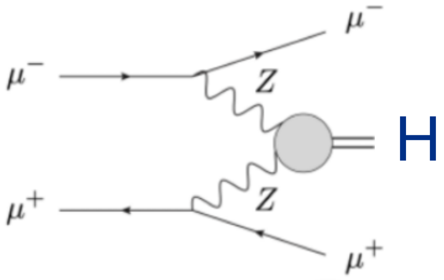
Forward Muon Tagging

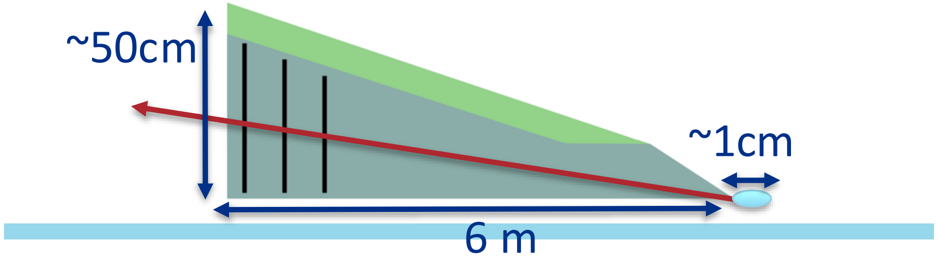


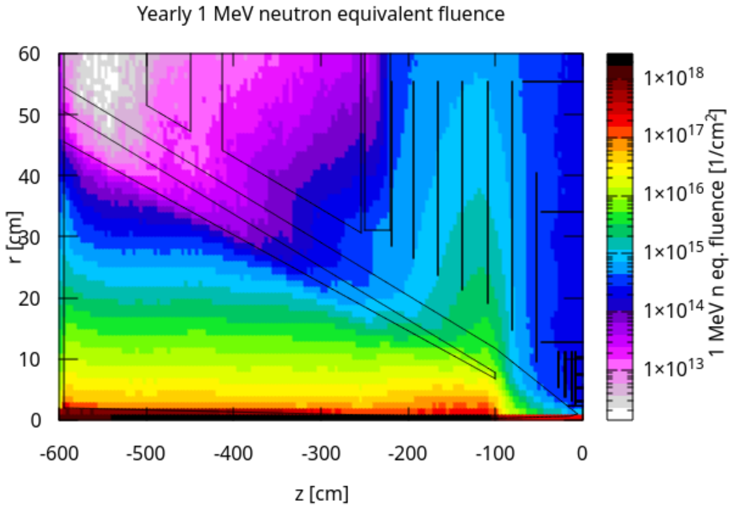
Tagging of muons in the forward region is important for physics (H→ZZ vs H→WW discrimination, Higgs width with few % precision)

- Consider layers of LGADs for the dedicated forward muon detector, interleaved with the nozzle tungsten
- Precise timing for tagging from IP and possibly muon momentum measurement

Fluences at r < 10 cm are 10^{16} [1/cm^2] and represent a major challenge







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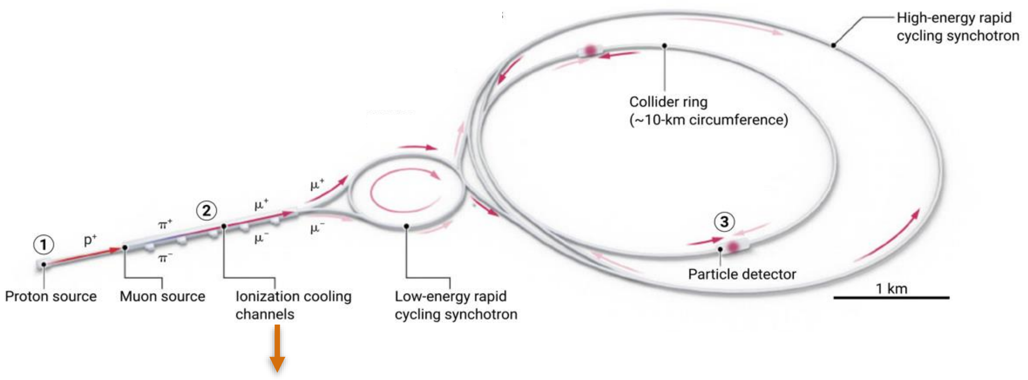
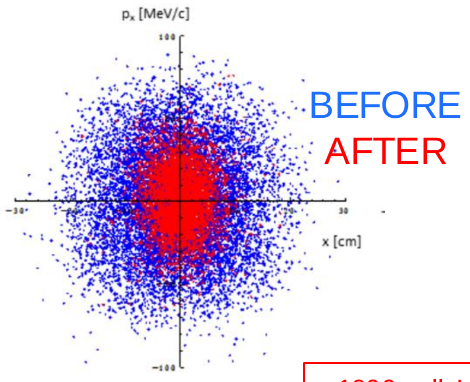
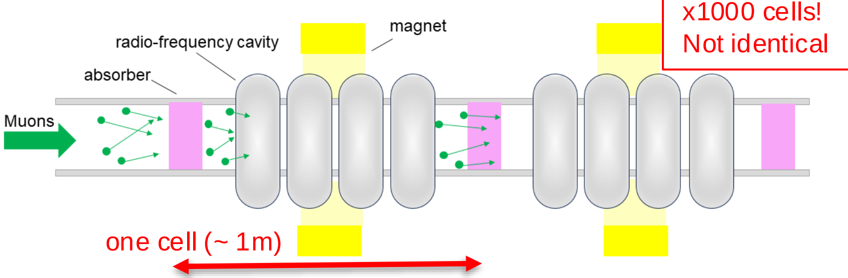
Muon cooling





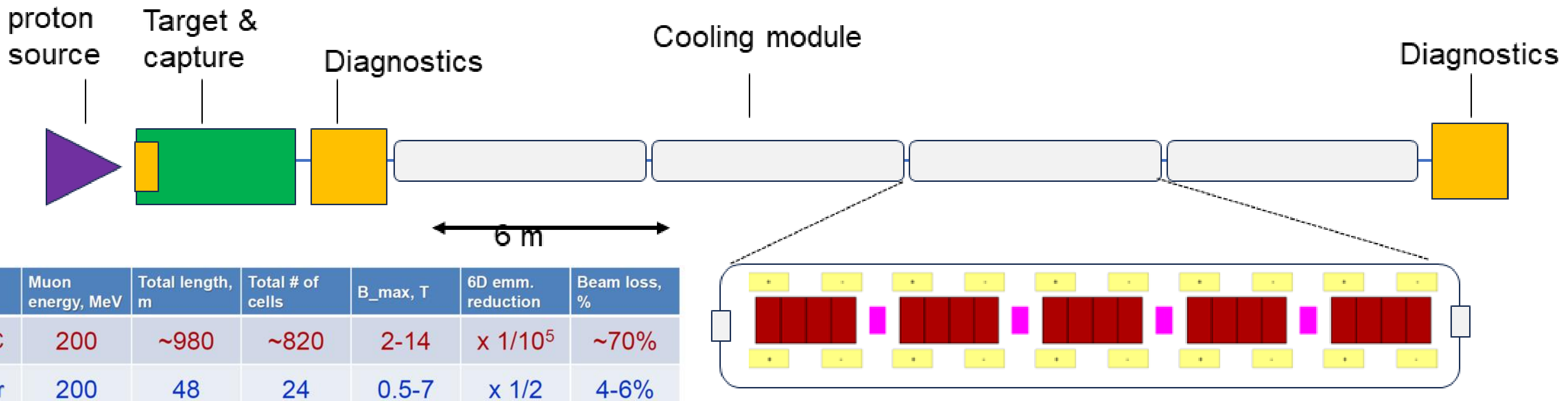


- Huge leverage on the machine design
  - Highest impact in luminosity
  - Will define the technology to build the machine

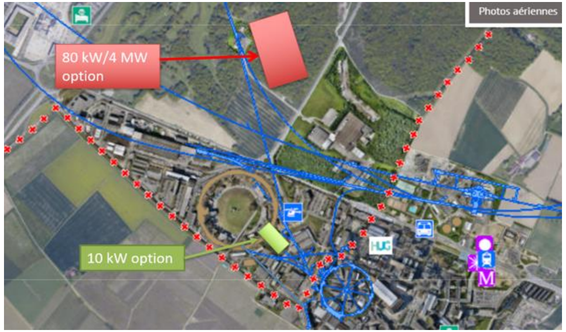
Cooling contains cells with a very compact assembly of RF cavities, high-B solenoids & absorbers

- Ionization Cooling is a key concept for the Muon Collider that needs to be demonstrated in practice in more realistic conditions than the MICE proof-of-principle demonstration

Ionization Cooling Demonstrator



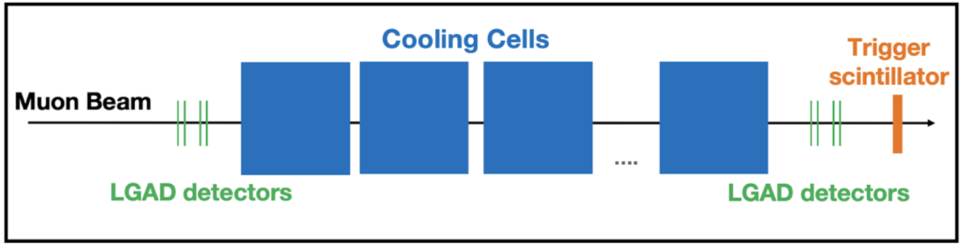
	Muon energy, MeV	Total length, m	Total # of cells	B_max, T	6D emm. reduction	Beam loss, %
Full scale MC	200	~980	~820	2-14	x $1/10^5$	~70%
Demonstrator	200	48	24	0.5-7	x 1/2	4-6%



Need to have advanced demonstrator design in 3-5 years for the mid-term P5 “collider panel”

Demonstrator Instrumentation

- For smaller muon bunch intensities will need to use particle physics instrumentation
- Need to measure 6D phase space distribution (x,y,z,px,py,pz)=(x,y,px,py,t,E) of the beam



- Precise parameters tbd in the next few years:
  - Approximately: RMS beam size ~10mm, RMS pT ~ 10 MeV, RMS time ~100 ps
  - Need few % precision on these parameters
- May need a deflector cavity time→position
- Dipole field for drift: energy → position
- Starting simulation work

Conclusions

- LGADs/AC-LGADs are novel detectors that are promising candidates for various applications for the future Muon Collider

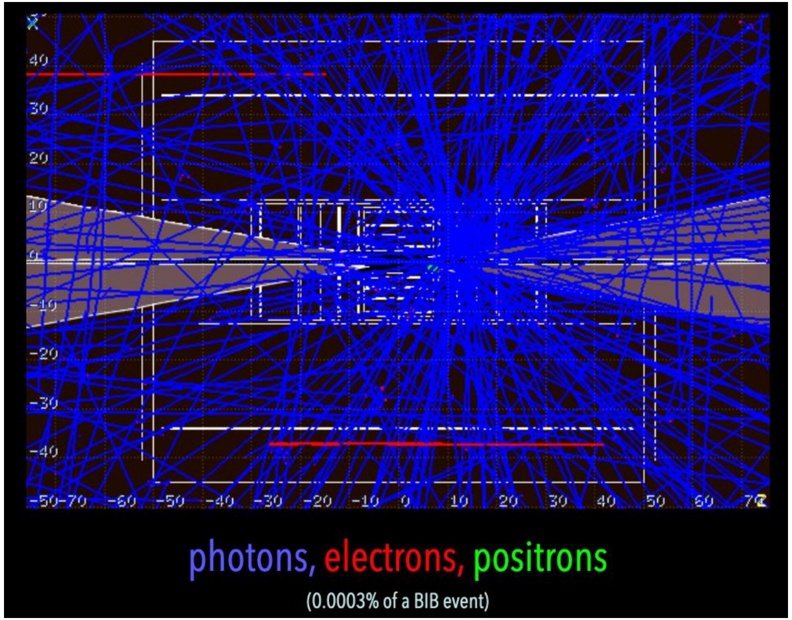
- This includes near term developments for the Ionization Cooling demonstrator as well as longer-term detector designs

- Other applications for synergistic experiments with muon beams are also possible (not covered in this presentation)

- **Continuation of a healthy LGAD R&D is necessary to develop detectors that can satisfy all specifications of the future muon collider detectors**

Extras

Why LGADs?



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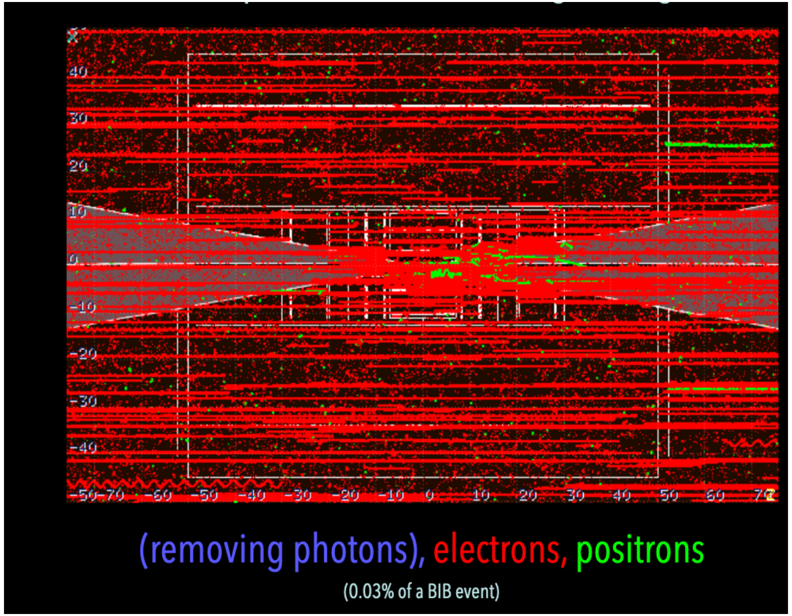
photons, electrons, positrons
(0.0003% of a BIB event)



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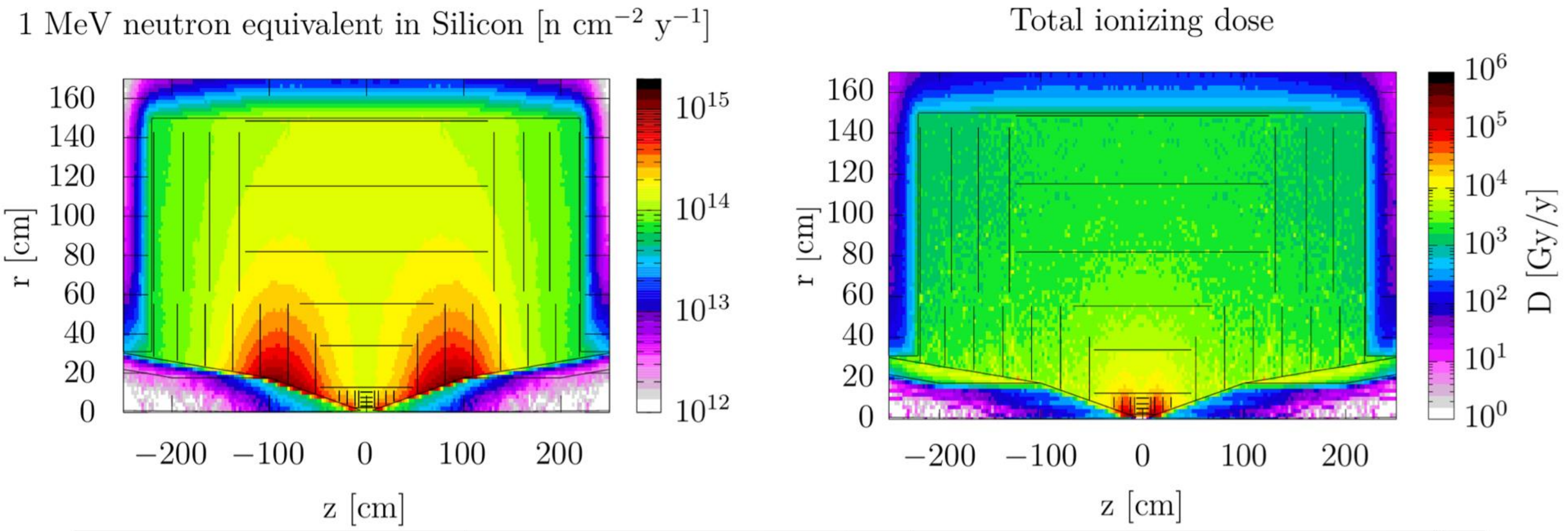
-50-70 -60 -50 -40 -30 -20 -10 0 10 20 30 40 50 60 70
(removing photons), electrons, positrons
(0.03% of a BIB event)

Detector radiation environment



	Maximum Dose (Mrad)		Maximum Fluence (1 MeV-neq/cm^2)	
	R= 22 mm	R= 1500 mm	R= 22 mm	R= 1500 mm
Muon Collider (3 TeV)	10	0.1	10^{15}	10^{14}
HL-LHC	100	0.1	10^{15}	10^{13}
Muon Collider (10 TeV)	20	0.2	3×10^{14}	10^{14}

What changed since the last P5?

- **Physics:** Strong surge of interest in Muon Colliders within the theoretical and experimental communities. Shift of emphasis in Muon Colliders from 125 GeV to 10 TeV energy [ref]
- **Accelerator Technology**:
  - Muon Accelerator Program (MAP) results completed and published, including designs of various subsystems [ref]
  - Important technological progress: multi-MW proton sources [ref], demonstration of RF in magnetic field [ref], high field solenoids [ref], good solution for neutrino flux mitigation, etc.
  - Muon Ionization Cooling Experiment (MICE) confirmed muon ionization cooling principle, results published [ref]
- **Detector technology :** Large leap in detector technologies in part from R&D done for HL-LHC upgrades. Feasibility of good quality physics established in simulation [ref]
- International Muon Collider Collaboration (IMCC) established. The process of forming US organization is ongoing.

A bit of history

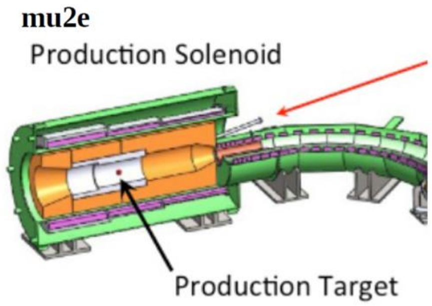
- **1960s:** First mention of Muon Colliders in the literature
- **1990s-2010:** Design studies through US institutional collaborations
- **2011-2016:** Muon Accelerator Program was approved by DOE
  - Focused on a proton-driver solution; studied 125 GeV and 1.5, 3 and 6 TeV colliders
- **2021:** Muon Colliders become part of the EU Accel. R&D Roadmap
  - International Muon Collider Collaboration (IMCC) formed, CERN currently the host lab
- **2022:** US Snowmass study reveal strong interest on Muon Colliders
  - Muon Collider Forum Report: a vision from the US perspective
- **March 2023:** Formation of the US Muon Collider R&D coordination group
  - Provide input to the P5 panel on US-based Muon Collider research
- **December 2023:** P5 Report released, with strong support for Muon Collider R&D

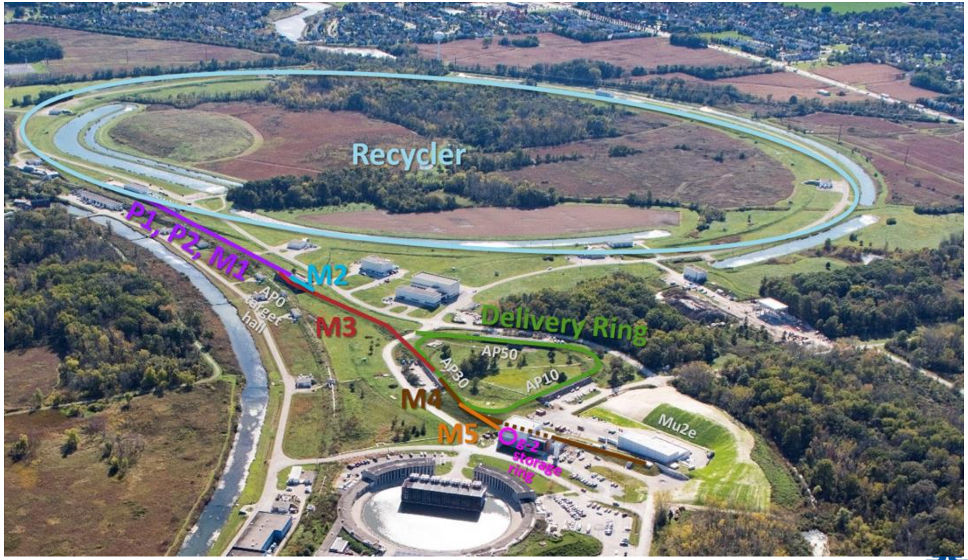
Useful References

- Useful references for this Effort:
  - Muon Smasher's Guide: Link
  - IMCC Facility overview white paper: Link
  - IMCC Simulated Performance white paper: Link
  - IMCC Promising Detector Technologies white paper: Link
  - Muon Collider Forum Report: Link

Site at Fermilab: Muon Campus

- Designed to provide beam for the Muon g-2 and Mu2e experiments
  - Capable to deliver **8 kW** beam at **8 GeV** to the Mu2e production target
  - Available tunnel space to run the demonstrator without interfering with Mu2e
  - Production target is similar to the MuC target





Excellent opportunity to examine targets under 5 T field

Muon Collider Challenges and Progress

Challenge	Progress	Future work
Multi MW proton sources with short bunches	Multi-MW proton sources have been and are being produced for spallation neutron sources and neutrino sources (SNS, ESS, J-PARC, Fermilab)	Refine design parameters, including proton acceleration to 5-10 GeV. Accumulation and compression of bunches.
Multi MW targets	Neutrino targets have matured to 1+MW. RADIATE studies of novel target materials and designs aim at 2.4MW.	Develop target design for 2 MW and short muon collider bunches. Produce a prototype in 2030s.
Production solenoid	ITER Nb3Sn central solenoid with similar specifications and rad levels produced	Study cryogenically stabilized superconducting cables and validate magnet cooling design. Investigate possibility of HTS cables.
Cooling channel solenoids	Solenoid with 30+T field now exists at NHMFL. Plans to design 40+T solenoids in place.	Extend designs to the specs of the 6D cooling channel, fabrication for the demo experiment
Ionization cooling	MICE transverse cooling results published. Longitudinal cooling via emittance exchange demonstrated at g-2.	Optimize with higher fields and gradients. Demonstrate 6D cooling with re-acceleration and focusing
RF in magnetic field	Operation of up to 50 MV/m cavity in magnetic field demonstrated, results published	Design to the specs of the 6D demo, experiment; fabrication

Muon Collider Challenges and Progress

Challenge	Progress	Future work
Fast Ramping Magnets	Demonstrated with 290 T/s up to 0.5T peak field at FNAL. Ramps up to 5000 T/s demonstrated with small magnets.	Design and demonstration work to achieve higher ramp rates (up to 1000 T/s) and peak fields of ~2T with large magnets
Very Rapid Cycling Synchrotron Dynamics	Lattice design in place for a 3 TeV accelerator ring	Develop lattice design for a 5 TeV accelerator ring
Neutrino Flux Effects	Mitigation strategies based on placing the collider ring at 200m and introducing beam wobble has been shown to achieve necessary reduction up to 10-14 TeV	Study mechanical feasibility, stability and robustness of the mover's system and impact on the accelerator and the beams
Detector shielding and rates	Demonstrated to be manageable in simulation with next generation detector technologies	Further develop and optimize 3 and 10 TeV detector concepts and MDI. Perform detector technology R&D and demonstration.
Open aperture storage ring magnets	12-15T Nb3Sn magnets have been demonstrated	Design and develop larger aperture magnets 12-16T dipoles and HTS quads
Low-beta IR collider design and dynamic aperture	Lattice design in place for a 3 TeV collider with optics and magnet parameters within existing technology limits	Develop lattice design for a 10 TeV collider

Muon Collider Synergies

Facility/Experiment	Physics Goals	Synergy
nuStorm	Short baseline neutrino program, including searches for sterile neutrino and cross section measurements	100kW proton source, muon production and collection, storage ring operation
Neutrino Factory (e.g. nuMax)	Better CP, mixing angles, mass splitting, non-standard interactions	MW class proton source, muon production and collection, 6D partial cooling and muon acceleration (up to ~5 GeV)
Dark Sector searches	Searches for particles from Dark Sectors produced in fixed target experiments using high intensity proton beam	MW class high-intensity proton beams
Charged Lepton Flavor Violation (e.g. AMF)	Searches for rare lepton flavor violating proceses (mu2e, mu2eg, mu3e, etc)	MW class proton source, muon production and collection, storage ring
Beam dump experiments	Searches for exotic particles (dark photons, Lmu-Ltau, etc) in muon beam dump experiments	100kW – MW proton source, muon production and collection, partial cooling and acceleration
Neutrinos from collider beam muon decays	DIS in neutrino-nucleus interactions, better nuclear PDF, atmospheric neutrinos FASERv like experiment with smaller flux uncertainties	Everything up to multi-TeV energy collider beams
Muon Ion Collider	A broad program addressing many fundamental questions in nuclear and particle physics	Everything up to multi-TeV energy collider beams