Detector R&D Towards a 10 TeV Muon Collider

Ben Rosser

University of Chicago

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Significant community interest in muon colliders emerged during Snowmass, European Strategy processes:

- Colliding fundamental particles (like electrons) with much less synchrotron radiation (like protons) offers **compact, efficient way** to reach high energies.
- Muons are unstable: **many challenges**, lots of accelerator and detector R&D needed!

Work is underway on both areas, both in the US and internationally:

- CERN has formed the **International Muon Collider Collaboration** to coordinate activities.
- Informal organization created in the US (pending outcome of P5).
- US Muon Collider R&D Coordination Panel formed to provide input to P5 for both accelerator and detector needs.

This talk:

- Brief outline of **detector** R&D efforts.
- Overview of updated 10 TeV detector concept.
- Preliminary performance results.
- Opportunities for future R&D.
The Case for 10 TeV

- $\sqrt{s} = 10 \text{ TeV}$ $\mu^+\mu^-$ **approximately comparable** to 100 TeV $pp$ collider:
  - Can nail down shape of the Higgs potential, achieve strong Higgs precision (2206.08326).
  - $5\sigma$ discovery potential for some minimal WIMP dark matter models at correct thermal target.
- Muon colliders **become VBF colliders**: notion of "electroweak PDF" emerges.
  - $s$-channel interactions (dashed lines) fall with $\sqrt{s}$; electroweak interactions become dominant.

![Graph showing single Higgs production](image)

M. Forslund, P. Meade (10.1007/JHEP08(2022)185)
Accelerators and Beam Induced Background

- Main muon collider challenges: accelerator related:
  - Targetry; alternatives to liquid mercury.
  - 6D ionization cooling to focus beam.
  - Fast ramping magnets for acceleration.
  - Neutrino radiation mitigation.
  - Work underway on all these areas.

- Machine-detector interface extremely important:
  - Decaying muons: large beam-induced background (BIB) in our detectors.
  - Only two bunches, collisions at $O(10 \mu s)$.
  - Need accelerator/detector experts to collaborate!

**Tentative target parameters Scaled from MAP parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>3 TeV</th>
<th>10 TeV</th>
<th>14 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L$</td>
<td>$10^{34}$ cm$^{-2}$s$^{-1}$</td>
<td>1.8</td>
<td>20</td>
<td>40</td>
</tr>
<tr>
<td>$N$</td>
<td>$10^{12}$</td>
<td>2.2</td>
<td>1.8</td>
<td>1.8</td>
</tr>
<tr>
<td>$f_r$</td>
<td>Hz</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>$P_{\text{beam}}$</td>
<td>MW</td>
<td>5.3</td>
<td>14.4</td>
<td>20</td>
</tr>
<tr>
<td>$C$</td>
<td>km</td>
<td>4.5</td>
<td>10</td>
<td>14</td>
</tr>
<tr>
<td>$\langle B \rangle$</td>
<td>T</td>
<td>7</td>
<td>10.5</td>
<td>10.5</td>
</tr>
<tr>
<td>$\varepsilon_L$</td>
<td>MeV m</td>
<td>7.5</td>
<td>7.5</td>
<td>7.5</td>
</tr>
<tr>
<td>$\sigma_t/E$</td>
<td>%</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>$\sigma_z$</td>
<td>mm</td>
<td>5</td>
<td>1.5</td>
<td>1.07</td>
</tr>
<tr>
<td>$\beta$</td>
<td>mm</td>
<td>5</td>
<td>1.5</td>
<td>1.07</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>$\mu$m</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>$\sigma_{x,y}$</td>
<td>$\mu$m</td>
<td>3.0</td>
<td>0.9</td>
<td>0.63</td>
</tr>
</tbody>
</table>

Comparison: CLIC at 3 TeV: 28 MW

IMCC, 2201.07895
Existing Detector Design

- Existing detector concept **based on CLIC** with addition of **shielding nozzles** to reduce BIB.

  **hadronic calorimeter**
  - 60 layers of 19-mm steel absorber + plastic scintillating tiles;
  - 30x30 mm² cell size;
  - 7.5 $\lambda_I$.

  **electromagnetic calorimeter**
  - 40 layers of 1.9-mm W absorber + silicon pad sensors;
  - 5x5 mm² cell granularity;
  - 22 $X_0 + 1 \lambda_I$.

  **muon detectors**
  - 7-barrel, 6-endcap RPC layers interleaved in the magnet's iron yoke;
  - 30x30 mm² cell size.

  **shiedling nozzles**
  - Tungsten cones + borated polyethylene cladding.

  **tracking system**
  - **Vertex Detector:**
    - double-sensor layers (4 barrel cylinders and 4+4 endcap disks);
    - 25x25 $\mu$m² pixel Si sensors.
  - **Inner Tracker:**
    - 3 barrel layers and 7+7 endcap disks;
    - 50 $\mu$m x 1 mm macro-pixel Si sensors.
  - **Outer Tracker:**
    - 3 barrel layers and 4+4 endcap disks;
    - 50 $\mu$m x 10 mm microstrip Si sensors.

**IMCC: Muon Collider Detector (CERN)**
Existing BIB Simulation

- BIB simulations done using MARS15 and Fluka (2303.08533, 2209.01318):
  - Generally good agreement!
  - 750 GeV beam energy used for both $\sqrt{s} = 1.5, 3$ TeV.
  - Clearly see potential of timing to kill low-energy BIB.

<table>
<thead>
<tr>
<th>Simulation Source</th>
<th>MARS15</th>
<th>FLUKA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Energy [GeV]</td>
<td>62.5</td>
<td>1500</td>
</tr>
<tr>
<td>MDI Optimization</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>Muon decay length [m]</td>
<td>3.9 x 10^5</td>
<td>93.5 x 10^5</td>
</tr>
<tr>
<td>(Muon decays/m)/beam</td>
<td>51.3 x 10^5</td>
<td>2.1 x 10^5</td>
</tr>
<tr>
<td>$\gamma$/BX ($E_\gamma &gt; 0.1$ MeV)</td>
<td>170 x 10^6</td>
<td>51 x 10^6</td>
</tr>
<tr>
<td>$n$/BX ($E_n &gt; 1$ MeV)</td>
<td>65 x 10^6</td>
<td>91 x 10^6</td>
</tr>
<tr>
<td>$e^\pm$/BX ($E_e &gt; 0.1$ MeV)</td>
<td>1.3 x 10^6</td>
<td>1.1 x 10^6</td>
</tr>
<tr>
<td>$h^\pm$/BX ($E_h &gt; 0.1$ MeV)</td>
<td>0.011 x 10^6</td>
<td>0.020 x 10^6</td>
</tr>
<tr>
<td>$\mu^\pm$/BX ($E_\mu &gt; 0.1$ MeV)</td>
<td>0.0012 x 10^6</td>
<td>0.0033 x 10^6</td>
</tr>
</tbody>
</table>
Existing Performance Studies

- This 1.5/3 TeV detector design has been studied extensively during Snowmass:
  - Work based on existing designs and concepts from MAP/MICE.
  - Many results collected by the Muon Collider Forum and IMCC.
  - Potential for new R&D to surpass existing (LHC-level) reconstruction performance.
Challenges for 10 TeV Detectors

- Existing detector design shown to work, but for $\sqrt{s} = 1.5$ or 3 TeV.
- What changes at 10 TeV? Beam is more energetic, but also more relativistic:
  - BIB energy expected to be independent of $\sqrt{s}$, but there may be other differences.
  - Need 5 T magnetic field; detector size overall needs to grow with energy.
  - Thicker calorimeters to fully contain showers; higher granularity trackers at large-$r$.
- Studies underway towards different 10 TeV concepts:
  - Ranging from simple evolution of 3 TeV layout to ideas for alternate $B$ field configurations
  - Our approach: move from "CMS-like" to "ATLAS-like" magnet system.
  - Place solenoid inside the detector around the tracker; use to shield calorimeters from BIB.
  - Calorimeter layers now outside magnet, further from interactions: need to study performance.

<table>
<thead>
<tr>
<th>B</th>
<th>3.57 T</th>
<th>5 T</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness</td>
<td>344 mm</td>
<td>265 mm</td>
</tr>
<tr>
<td>R</td>
<td>3821 mm</td>
<td>1500 mm</td>
</tr>
</tbody>
</table>
10 TeV Detector Design

- Concept developed at KITP workshop at Santa Barbara in February.
- Layout implemented in DD4hep; IMCC software used for simulations over past year.

- Reoptimized tracker: no need for double-sided vertex layers.
- Use silicon pixels for vertex, inner tracker; strips for outer tracker.
- Vertex: 30 ps timing, 5x5 $\mu$m spatial resolution.
- Inner and outer trackers: 60 ps timing, 7x90 $\mu$m spatial resolution.
Design continuing to evolve rapidly, lots of R&D still to do!

- Calorimeters: 100 ps timing resolution.
- ECAL energy resolution target: $10\%/\sqrt{E}$.
- HCAL jet energy resolution: $35\%/\sqrt{E}$.
- Optimize depth: $40 \rightarrow 50$ ECAL layers, $60 \rightarrow 75$ HCAL layers.
- Simplified muon system (no magnet yoke).
Simulating BIB at 10 TeV

- Generate **new BIB at** $\sqrt{s} = 10 \text{ TeV}$ **using Fluka**:
  - Timing, energy distribution shapes very consistent with lower-energy results.
  - **Preliminary results**: look promising, collaboration with accelerator physicists ongoing.

![Graphs showing particle distributions with energy and time axes](image)
30-60 ps timing resolution critical to reduce hit occupancy in innermost tracking layers.

Shapes agree between 1.5, 10 TeV simulations, but average number of hits 4x smaller:
- Accelerator lattice, nozzle shape have been reoptimized; this will lead to changes.
- Still investigating potential differences, but effect illustrates importance of MDI.
Slight bias in these results due to $< 1\,\text{ns}$ time window.

Relaxing the time window: higher occupancies overall but shapes more or less unchanged.
BIB in the Calorimeters

- Energy density in both calorimeters also has same shape between beam energies.
- **Order of magnitude** lower in our 10 TeV design: shows impact of solenoid shielding!
Radiation Damage

- Radiation at 10 TeV comparable to HL-LHC and previous 3 TeV muon collider studies; much lower than FCC-hh ($10^{18} \text{ MeV-n}_{eq}/\text{cm}^2$) (2209.01318, 2105.09116)

<table>
<thead>
<tr>
<th></th>
<th>Maximum Dose (Mrad)</th>
<th>Maximum Fluence (1 MeV-neq/cm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R= 22 mm</td>
<td>R= 1500 mm</td>
</tr>
<tr>
<td>Muon Collider (3 TeV)</td>
<td>10</td>
<td>0.1</td>
</tr>
<tr>
<td>HL-LHC</td>
<td>100</td>
<td>0.1</td>
</tr>
<tr>
<td>Muon Collider (10 TeV)</td>
<td>20</td>
<td>0.2</td>
</tr>
</tbody>
</table>

- Total ionizing dose

- 1 MeV neutron equivalent in Silicon [$n \text{ cm}^{-2} \text{ y}^{-1}$]
Studies underway to assess object reconstruction performance with this detector.

IMCC software based on ILCSoft/Key4HEP:

- **Common framework** for future collider R&D: shared with FCC, ILC, CLIC, C3, etc.
- Integrates many other packages; Pandora particle flow, ACTS tracking, Gaudi, etc.
- Output LCIO and EDM4hep ntuples, easy to analyze with ROOT or uproot.

Variety of signatures (electron, muon, photon, tau, pion, jet) being studied:
- Monte Carlo samples simulated using DD4hep and reconstructed with Marlin.
- During reco, BIB from Fluka can be sampled, overlaid: **computationally expensive**!
- Some **preliminary results** presented today for **tracking** and **calorimetry**.
Tracking Performance

- Track reconstruction powered by ACTS; studied using single muon samples.
- 3.5% efficiency loss from addition of BIB, but overall tracking still seems to work!
- Initial results promising, but more studies needed (especially in forward region).

Initial results promising, but more studies needed (especially in forward region).
Electromagnetic Calorimeter Performance

- Photon reconstruction efficiency very high even with addition of 5 T solenoid.
- Energy resolution not ideal due to high cell thresholds, but can be improved:
  - **BIB subtraction**: digitize with 50 keV thresholds, then remove average BIB when clustering.
  - Leads to **order-of-magnitude** improvement in resolution for 50 GeV photons!
Future R&D Opportunities

- **From Tuesday**: lots of overlap in detector needs for any future collider:
  - As shown in ECFA Detector Roadmap.
  - Many common needs with $e^+e^-$, $pp$: work can benefit multiple projects!
- **Some areas of particular importance:**
  - **Timing** critical for BIB reduction.
  - Dedicated **forward detectors** for muon tagging: distinguish VBF processes.
  - **Nozzle optimization** and mechanics.
  - Radiation hardened readout electronics with **on-detector intelligence**.
  - **Solenoid design**: need to develop and retain expertise for high-field magnets (discussed in RDC10 on Thursday).
10 TeV detector R&D for a muon collider is underway, but there’s still lots to do!
- Have gone from design concept to simulations and studies in less than a year.
- Plan to write a paper describing this initial design soon.
- Collaboration between **accelerator and detector** experts critical in studying muon colliders.

This effort has been a joint effort with contributions by many people, including:
- Federico Meloni, Thomas Madlener, Priscilla Pani (DESY); Daniele Calzolari (CERN).
- Tova Holmes, Larry Lee, Ben Johnson, Micah Hillman, Adam Vendrasco (Tennessee).
- Sergo Jindariani, Kevin Pedro, (FNAL); Rose Powers (Yale).
- Simone Pagan Griso (LBNL); Isobel Ojalvo, Junjia Zhang (Princeton).

Thanks for your attention!
Backup
### Accelerator R&D Needs

<table>
<thead>
<tr>
<th>Target</th>
<th>Status</th>
<th>Notes</th>
<th>Future work</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse compression</td>
<td>1-3 ns</td>
<td>SPS does O(1) ns</td>
<td>Need higher intensity. O(30) ns loses only factor 2 in the produced muons.</td>
</tr>
<tr>
<td></td>
<td>O(1) ns</td>
<td></td>
<td>Refine design, including proton acceleration. Accumulation and compression of bunches.</td>
</tr>
<tr>
<td>High-power targets</td>
<td>2 MW</td>
<td>2 MW</td>
<td>Available for neutrino and spallation neutrons. Aim for 4 MW to have margin.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Develop target design for 2 MW, O(1) ns bunches create larger thermal shocks. Prototype in 2030s.</td>
</tr>
<tr>
<td>Cooling solenoids</td>
<td>50 T</td>
<td>30-40 T</td>
<td>30 T leads to a factor 2 worse transverse emittance with respect to design.</td>
</tr>
<tr>
<td>RF in magnetic field</td>
<td>&gt;50 MV/m</td>
<td>65 MV/m</td>
<td>MUCOOL published results. Requires test in non-uniform B.</td>
</tr>
<tr>
<td>6D cooling</td>
<td>$10^4$</td>
<td>0.9 (1 cell)</td>
<td>MICE result (no re-acceleration). Emittance exchange demonstrated at g-2.</td>
</tr>
<tr>
<td>RCS dynamics</td>
<td>-</td>
<td>-</td>
<td>Simulation. 3 TeV lattice design in place.</td>
</tr>
<tr>
<td>Rapid cycling magnets</td>
<td>2 T/ms</td>
<td>2.5 T/ms</td>
<td>Normal conducting magnets.</td>
</tr>
<tr>
<td></td>
<td>2 T peak</td>
<td>1.81 T peak</td>
<td>HTS demonstrated 12 T/ms, 0.24 T peak.</td>
</tr>
<tr>
<td>Ring magnets aperture</td>
<td>20 T</td>
<td>12-15 T (Nb3Sn)</td>
<td>Need HTS or revise design to lower fields.</td>
</tr>
<tr>
<td></td>
<td>quads</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Collider dynamics</td>
<td>-</td>
<td>-</td>
<td>3 TeV lattice in place with existing technology.</td>
</tr>
<tr>
<td>Neutrino radiation</td>
<td>10 $\mu$Sv/year</td>
<td>-</td>
<td>3 TeV ok with 200 m deep tunnel. 10 TeV requires a mover system.</td>
</tr>
<tr>
<td>Detector shielding</td>
<td>Negligible</td>
<td>LHC-level</td>
<td>Simulation based on next-gen detectors.</td>
</tr>
</tbody>
</table>
ECFA Roadmap

- ECFA roadmap tables for **electronics** and **integration**; again emphasizing commonality between needs for future facilities.