Designing a Muon Collider Detector

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On behalf of the Muon Collider Physics and Detector Group
Muon Colliders

- Provides a powerful and versatile tool for HEP explorations
  - Colliding elementary particles
  - Less synchrotron radiation than e+e- – can use circular accelerators
  - Luminosity per energy consumed
  - Path to very high energy collisions
- The 2020 Update of the European Strategy for Particle Physics recommended to “investigate the possibility to have bright muon beams”
- International Muon Collider Collaboration (IMCC) established, hosted by CERN
- Resurgence of interest in Muon Colliders within Snowmass
  - Expertise in the US from the Muon Accelerator Program (MAP)
Dramatic improvement in Higgs coupling precision with respect to HL-LHC

New physics reach similar or better than 100 TeV proton-proton machine

arXiv:2103.14043

arXiv:1901.06150
Beam Induced Background

- Beam background identified as one of the main challenges
- Main Source of Beam Induced Background (BIB) are beam muon decays
- Muons decay with an average lifetime of $2.2 \cdot 10^{-6}$ seconds at rest, at $\sqrt{s} = 3$ TeV they live for about $3.1 \cdot 10^{-2}$ seconds
  - beam 1.5 TeV $\lambda = 9.3 \times 10^6$ m, with $2 \times 10^{12} \mu$/bunch $\Rightarrow 2 \times 10^5$ decay per meter of lattice.

<table>
<thead>
<tr>
<th>beam energy [GeV]</th>
<th>62.5</th>
<th>750</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu$ decay length [m]</td>
<td>$3.9 \times 10^5$</td>
<td>$4.7 \times 10^6$</td>
</tr>
<tr>
<td>$\mu$ decays/m per beam</td>
<td>$5.1 \times 10^6$</td>
<td>$4.3 \times 10^5$</td>
</tr>
<tr>
<td>photons ($E_{\text{ph.}}^{\text{kin}} &gt; 0.2$ MeV)</td>
<td>$3.4 \times 10^8$</td>
<td>$1.6 \times 10^8$</td>
</tr>
<tr>
<td>neutrons ($E_{\text{n}}^{\text{kin}} &gt; 0.1$ MeV)</td>
<td>$4.6 \times 10^7$</td>
<td>$4.8 \times 10^7$</td>
</tr>
<tr>
<td>electrons ($E_{\text{el.}}^{\text{kin}} &gt; 0.2$ MeV)</td>
<td>$2.6 \times 10^6$</td>
<td>$1.5 \times 10^6$</td>
</tr>
<tr>
<td>charged hadrons ($E_{\text{ch. had.}}^{\text{kin}} &gt; 1$ MeV)</td>
<td>$2.2 \times 10^4$</td>
<td>$6.2 \times 10^4$</td>
</tr>
<tr>
<td>muons ($E_{\text{mu.}}^{\text{kin}} &gt; 1$ MeV)</td>
<td>$2.5 \times 10^3$</td>
<td>$2.7 \times 10^3$</td>
</tr>
</tbody>
</table>
Detector

**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.

**tracking system**
- **Vertex Detector:**
  - double-sensor layers (4 barrel cylinders and 4+4 endcap disks);
  - 25x25 \( \mu \text{m}^2 \) pixel Si sensors.
- **Inner Tracker:**
  - 3 barrel layers and 7+7 endcap disks;
  - 50 \( \mu \text{m} \times 1 \text{ mm} \) macro-pixel Si sensors.
- **Outer Tracker:**
  - 3 barrel layers and 4+4 endcap disks;
  - 50 \( \mu \text{m} \times 10 \text{ mm} \) micro-strip Si sensors.

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

10º acceptance limitation due to the nozzles + few degrees of extreme occupancy in the vertex detector.
BIB properties

Di Benedetto et al., Journal of Instrumentation 13(2018)

F. Collamati et al. 2021 JINST 16 P11009

Photons  
Electrons/positrons  
Neutrons

Muon beam 0.75 TeV

di Benedetto et al., Journal of Instrumentation 13(2018)

F. Collamati et al. 2021 JINST 16 P11009
• Low momentum particles
• Partially out-of-time with respect to the bunch crossing
• Often, not pointing to the interaction region
Radiation levels at 3 TeV comparable to HL-LHC

For comparison, FCC-hh requirements are \(~10^{18}/\text{cm}^2/\text{year}\)

Expected (FLUKA simulation) to be approximately:
- \(~10^{14-15}/\text{cm}^2/\text{y}\) in the tracker
- \(~10^{14}/\text{cm}^2/\text{y}\) in the ECAL
Tracker

- Goal: bring occupancy to <1% level. Pixel size optimized to achieve this goal
- Timing is also important, but need to be careful to not impact efficiency for slow particles
- Other requirements are not unique: low mass/power, radiation tolerance, low noise
- Total number of channels ~ 2B (similar in size to Phase-2 ATLAS/CMS).
• Precision timing is critical for reducing the number of BIB hits. Up to a factor of x3 reduction in the inner layers
• Correlation between layers (a la CMS pT module) provides additional large reduction
• Some on-detector filtering may be needed

Example R&D:
• Monolithic devices
• AC-LGADs
• 3D hybrid pixels
• Intelligent sensors
• Common challenges: services, cooling, low-power ASICS
Tracking Performance

• With some basic hit suppression and track level cuts, get good offline track efficiency and resolutions
• Active work on tracking improvements, including Kalman based algorithm
Calorimeters

- ECAL: SiW with 22 $X_0$, 5x5 mm$^2$ pads
- HCAL: Iron+Scintillator with 7.5$\lambda$
- High occupancy in the ECAL
Calorimeters (2)

- Timing and shower profile are the key
- SiW calorimeter provides excellent granularity, good resolution, high density

- Alternatives:
  - Crystals
  - Gas detectors

Example R&D:
- Better granularity
- Better timing
- Particle tracking
- dual-readout (DR) compensation
- develop fast, rad hard materials/solutions
Calorimeter Performance

Take advantage of LHC experience with pile-up suppression techniques

- In progress:
  - Particle-flow reconstruction and particle level pileup removal methods (e.g. Softkiller)
Muon Reconstruction

- Targets 100um spacial and 1ns timing resolutions
- Current design: gaseous detectors interleaved in an iron yoke
- High number of hits in the forward disks due to the BIB
- Good efficiency observed throughout the momentum and rapidity range, further improvements in progress

Future R&D directions: better timing and resolution (GEM, Micromegas, MRPC (gas issues), PicoSec…)

Very high energy muon momentum reconstruction in 10 TeV collisions remain challenging
Readout/DAQ Considerations

- Key parameter - beam crossings every 10 $\mu$s.

- Streaming approach: availability of the full event data $\rightarrow$ better trigger decision, easier maintenance, simplified design of the detector front-end...

- However, the BIB might be prohibitive for a full triggerless TDAQ scheme
Trigger/DAQ Considerations

- Data dominated by the Tracker and the ECAL

- Input data rates at 1.5 TeV (with x2 safety factor):

<table>
<thead>
<tr>
<th></th>
<th>Hit</th>
<th>On-detector filtering</th>
<th>Number of Links (20 Gbps)</th>
<th>Event Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tracker</td>
<td>32-bit</td>
<td>t-t₀ &lt; 1 ns</td>
<td>~3,000</td>
<td>30 Tb/s</td>
</tr>
<tr>
<td>Calorimeter</td>
<td>20-bit</td>
<td>t-t₀ &lt; 0.3 ns E&gt;200 KeV</td>
<td>~3,000</td>
<td>30 Tb/s</td>
</tr>
</tbody>
</table>

- Total data rate similar to HLT at HL-LHC ~ **streaming operation likely feasible.**

- Bandwidth to disk < 100 Gb/s
  - 1.5 kHz if assuming full event size
  - For comparison, rate at 10 TeV and L=10^{35} cm^{-2} s^{-1} for Higgs = 0.1Hz, VBF WW=1Hz
  - Some filtering makes sense to reduce event content
Summary and Outlook

- Presented an initial Muon Collider detector concept and the corresponding preliminary performance
- General theme – highly granular detectors with high timing resolution
- Snowmass papers in preparation (physics performance and technology R&D)

- Baseline established. Many avenues for improvements and optimization
- Committing today to a particular technology is probably premature
  - Develop further R&D efforts
  - Maintain synergies with other collider proposals