Detector needs at Muon Colliders

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Muon Collider Timeline

Goal to reach 10+ TeV. Staging at 125 GeV, ~1 TeV and 3 TeV being studied. The focus here is on a ~3 TeV detector.

Technically limited schedule
Beam Induced Background

- Beam background is one of the unique features/challenges of Muon Colliders
- Main Source of Beam Induced Background (BIB) are showers produced by electrons originating in beam muon decays
- The challenge is to separate collision particles from the BIB
Detector

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

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

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 $\mu$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 micro-strip Si sensors.

shielding nozzles
- Tungsten cones + borated polyethylene cladding.

~10 degree acceptance limitation due to the nozzles
BIB properties

Di Benedetto et al., Journal of Instrumentation13(2018)

F. Collamati et al. 2021 JINST 16 P11009

Photons

charged hadrons

electrons/positrons

neutrons

absorbed
For comparison, FCC-hh requirements are $\sim 10^{18}/\text{cm}^2/\text{year}$
Remaining BIB properties

- Low momentum particles
- Partially out-of-time with respect to the bunch crossing
- Often, not pointing to the interaction region
• Occupancy in inner layers approximately five times higher than at the LHC
• Goal: bring occupancy to <1% level. **Pixel size and timing requirements optimized to achieve this goal**
• Other requirements are not unique: **low mass/power, radiation tolerance, low noise**
• **Correlation between layers**
• **Cluster shape**

<table>
<thead>
<tr>
<th>Detector Layer</th>
<th>ITk Hit Density [mm$^{-2}$]</th>
<th>Muon Col. Hit Density [mm$^{-2}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel Layer 0</td>
<td>0.643</td>
<td>3.68</td>
</tr>
<tr>
<td>Pixel Layer 1</td>
<td>0.22</td>
<td>0.51</td>
</tr>
<tr>
<td>Strip Layer 1</td>
<td>0.003</td>
<td>0.03</td>
</tr>
</tbody>
</table>
Calorimeters

- BIB dominated by neutrals: photons (96%) and neutrons (4%).

- Ambient energy about 50 GeV per unit area (~40 GeV in HL-LHC)

  - high granularity
  - precise hit time measurement O(100ps)
  - longitudinal segmentation
  - good energy resolution $10\%/\sqrt{E}$ for photons and $35\%/\sqrt{E}$ for jets or better

- Current Design:
  - ECAL: SiW with 22 $X_0$, 5x5 mm$^2$ pads
  - HCAL: Iron+Scintillator with 7.5$\lambda$
  - Study hybrid DRO options
Muons

- Muon system is the least affected by the BIB
- Current design: gaseous detectors interleaved in an iron yoke
- Targets: 100 micron resolution and 1 ns timing
- High number of hits in the forward disks due to the BIB
  - Some technologies reaching rate limits
  - Some contain gas mixture which has a high Global Warming Potential
Readout/DAQ Considerations

- Key parameter - beam crossings every 10 μs.
- Streaming approach: availability of the full event data → better trigger decision, easier maintenance, simplified design of the detector front-end...

<table>
<thead>
<tr>
<th></th>
<th>Hit</th>
<th>On-detector filtering</th>
<th>Number of Links (20 Gbps)</th>
<th>Data Rates</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.**
- Filtering based on event properties or event content
- Bandwidth to disk < 100 Gb/s (plenty for EWK physics)

- High bandwidth and power efficient links, FPGA/GPU acceleration, advanced algorithms
Outlook

• Baseline 3 TeV design established. Many avenues for improvements
• Synergistic with other future collider detector R&D needs
• For 10 TeV the design has to be modified, work is in progress

• Snowmass overview papers:
  • https://snowmass21.org/energy/muon_forum (MuC Forum Report)
  • https://arxiv.org/abs/2203.08033 (accelerator)
  • https://arxiv.org/abs/2203.07224 (detector)
  • https://arxiv.org/abs/2203.07964 (performance)
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
Take advantage of LHC experience with pile-up suppression techniques

- In progress:
  - Particle-flow reconstruction and particle level pileup removal methods (e.g. Softkiller)
Tracker (2)

- 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.
- Other handles exist.
- 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.
### BIB as function of Energy

<table>
<thead>
<tr>
<th>beam energy [GeV]</th>
<th>MARS15</th>
<th>MARS15</th>
<th>FLUKA 1500</th>
<th>FLUKA 5000</th>
</tr>
</thead>
<tbody>
<tr>
<td>μ decay length [m]</td>
<td>3.9 x 10^6</td>
<td>46.7 x 10^5</td>
<td>46.7 x 10^5</td>
<td>93.5 x 10^5</td>
</tr>
<tr>
<td>μ decays/m per beam (for 2x10^{12} μ/bunch)</td>
<td>51.3 x 10^5</td>
<td>4.3 x 10^6</td>
<td>4.3 x 10^5</td>
<td>2.1 x 10^5</td>
</tr>
<tr>
<td>photons/BX (E_γ &gt; 0.1 MeV)</td>
<td>170 x 10^6</td>
<td>86 x 10^6</td>
<td>51 x 10^6</td>
<td>70 x 10^6</td>
</tr>
<tr>
<td>neutrons/BX (E_n &gt; 1 meV)</td>
<td>65 x 10^6</td>
<td>76 x 10^6</td>
<td>110 x 10^6</td>
<td>91 x 10^6</td>
</tr>
<tr>
<td>e^+/BX (E_e &gt; 0.1 MeV)</td>
<td>1.3 x 10^6</td>
<td>0.75 x 10^6</td>
<td>0.86 x 10^6</td>
<td>1.1 x 10^6</td>
</tr>
<tr>
<td>charged hadrons/BX (E_h &gt; 0.1 MeV)</td>
<td>0.011 x 10^6</td>
<td>0.032 x 10^6</td>
<td>0.017 x 10^6</td>
<td>0.020 x 10^6</td>
</tr>
<tr>
<td>muons/BX (E_m &gt; 0.1 MeV)</td>
<td>0.0012 x 10^6</td>
<td>0.0015 x 10^6</td>
<td>0.0031 x 10^6</td>
<td>0.0033 x 10^6</td>
</tr>
</tbody>
</table>

Approximately flat