Detector Performances Studies at Muon Collider

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for
Motivation

Muon Collider offers the potential precision measurements on Higgs couplings including Higgs potential via trilinear and quadrilinear coupling

\[ V = \frac{1}{2} m_h^2 h^2 + (1 + k_3) \lambda_{h h h}^{SM} v h^3 + (1 + k_4) \lambda_{h h h h}^{SM} h^4 \]

**Trilinear coupling, \( k_3 \)**
- \( \sqrt{s} = 10 \text{ TeV}, \mathcal{L} \sim 10^{35} \text{cm}^{-2} \text{s}^{-1} \)
- 10 ab\(^{-1} \)

\( k_3 \) sensitivity \( \sim 3\% \)

Best sensitivity \( \sim 5\% \) FCC combined (arXiv:1905.03764)

**Quadrilinear coupling, \( k_4 \)**
- \( \sqrt{s} = 14 \text{ TeV}, \mathcal{L} \sim 10^{35} \text{cm}^{-2} \text{s}^{-1} \)
- 20 ab\(^{-1} \)

\( k_4 \) sensitivity *few* \( 10\% \)

FCC-hh in a optimistic scenario 30 ab\(^{-1} \)
\( \lambda_4 = \in [\sim - 4, \sim + 16] @ 68\% \text{ C. L.} \) (arXiv:1905.03764)
Motivation cont’d

Muon Collider could be an efficient discovery machine!
Full collision energy available for particle production
But sufficient luminosity is required…

14 TeV lepton collisions are comparable to 100 TeV proton collisions

The luminosity per beam power is about constant in linear colliders, It can increase in muon colliders
What is different for a muon collider detector?

• Muon decay… just a back of the envelope calculation:
  beam 0.75 TeV $\lambda = 4.8 \times 10^6$ m, with $2 \times 10^{12} \mu/$bunch $\Rightarrow 4.1 \times 10^5$ decay per meter of lattice

• Muon induced background is critical for
  - Magnets, they need to be protected
  - Detector, the performance depends on the rate of background particles arriving to each subdetector and the number and the distribution of particles at the detector depends on the lattice

Electromagnetic showers induced by electrons and photons interacting with the machine components generate hadrons, secondary muons and electrons and photons.

Muon Accelerator Program, MAP (https://map.fnal.gov)
Beam-induced background simulation

MAP developed a realistic simulation of beam-induced backgrounds in the detector:

• implements a model of the tunnel ±200 m from the interaction point, with realistic geometry, materials distribution, machine lattice elements and magnetic fields, the experimental hall and the machine-detector interface (MDI);

• Secondary and tertiary particles from muon decay are simulated with MARS15 then transported to the detector

For each collider energy the machine elements, the MDI and IP have to be properly designed and optimized.

In particular, the two tungsten nozzles, cladded with a 5-cm layer of borated polyethylene, play a crucial role in background mitigation inside the detector.
Beam-induced background properties for 750 GeV $\mu^\pm$ beams

Contributions from $\mu$ decays $|z| > 25$ m become negligible for all background species but Bethe-Heitler muons.

- **Photons**: $\langle P_y \rangle = 1.7$ MeV
- **Electrons**: $\langle P_e \rangle = 6.0$ MeV
- **Charged hadrons**: $\langle P_{\text{ch. had.}} \rangle = 460$ MeV

Secondary and tertiary particles have low momentum.
Beam-induced background properties for 750 GeV $\mu^-$ beam

Time information are crucial to reduce the beam-induced background

New detectors generations are needed
Detector Response Simulation

- A detailed simulation of the potential detector is necessary to assess the achievable precision of future physics measurements
- Making use of the simulation/reconstruction tools previously developed within the MAP program based on the ILCroot package: supports signal + MARS background merging

Inherited from MAP
Tracking detectors

Verteining detector (VXD) precise tracking

\textbf{Si pixel sensors:} 20×20 \(\mu\)m pitch
\textbf{R:} 3-13 cm \textbf{L:} 42 cm
\textbf{Granularity:}
- \textbf{Barrel:} 5 layers (75 \(\mu\)m thick)
- \textbf{Endcap:} 2 × 4 disks (100 \(\mu\)m thick)

Beam pipe:
Beryllium (\textit{Be})
\textbf{thickness:} 400 \(\mu\)m

Silicon Tracker (\textit{SiT}) and Forward Tracking Detector (FTD):

\textbf{Si pixel sensors:} 50×50 \(\mu\)m pitch, \textbf{thickness:} 200 \(\mu\)m
\textbf{SiT:} \textbf{Barrel:} 5 layers \textbf{Endcap:} 2 × (4 +3) disks
\textbf{FTD:} \textbf{Endcap:} 2 × 3 disks
Tracking Performances
Assuming different time resolution for different Si detectors
Pitch 75 and 100 µm: 50 ps
Pitch 200 µm: 100 ps

A lot of background is removed
Keeping high efficiency on signal
Calorimeter detector: dual readout calorimeter for the moment

Cerenkov + scintillation light simultaneously measured -> electromagnetic and hadronic fraction of each shower determined

Beam-induced background influence also the calorimeter performances

Time can help to reduce Beam-induced background
Jet Reconstruction Performances

Use a very simple cone jet algorithm, room for a lot of improvements!

- $E_{\text{cell}}>200$ MeV
- Removal of the “average” energy as if it is underlying event
- Run a cone algorithm with R=0.5

Sample $\mu^+\mu^- \rightarrow H \rightarrow b\bar{b} + \text{background}$ @ $\sqrt{s} = 1.5$ TeV

Jet energy resolution

Resolution

$\sim 38\%$

Jet energy scale

Efficiency

- $\sim 60\%$ per jet
- $\sim 38\%$ per event

2 b-jets invariant mass (truth match)
Summary and Next Steps

- Physics reaches at muon collider strongly depend on beam-induced background which depends on beam characteristics and machine lattice in particular on the IR design.
- By using the MAP framework and simulated beam-induced background, first detector performances are assessed demonstrating that precision measurement are possible $\sqrt{s} = 1.5 \, TeV$.

arXiv:1905.03725

- New, up-to-date detector has to be designed where position, energy and time resolution have to be pushed to the limit.
- Detector and MDI have to be designed and optimized taking into account beam-induced background for center-of-mass energies: $\sqrt{s} = 3 \, TeV$, $\sqrt{s} = 6 \, TeV$, $\sqrt{s} = 14 \, TeV$, ...
  - Background diminishes with the increasing of the center-of-mass energy.
  - Physics event topology has to be studied, i.e. Higgs events become more and more forward posing new reconstruction challenges.
- Advanced reconstruction methods and analysis techniques have to be developed and applied.
BACKUP
Beam-induced background properties for 750 GeV $\mu^-$ beam

Time information are crucial to reduce the background
Tracking Performances

Vertex detector occupancy, defined as the number of hit clusters per cm$^2$ area, as a function of the detector layers. Layers from 1 to 5 correspond to the barrel layers, from the closer to the more distant from the beam pipe. Layers from 6 to 9 correspond to the endcap layers, from the closer to the more distant from the nominal interaction point. Since endcap layers are on both side with respect to the interaction point, the mean occupancy of left and right layers is shown. Occupancy with and without a time window cut ($\pm 0.5$ ns) is presented.
Di-jet mass distributions for Higgs and Z produced in 1.5-TeV muon collisions. The relative normalization of the two distributions is equal to the ratio of the expected number of events, considering the selection efficiencies and the cross sections.


\( H \rightarrow b\bar{b} \) can be reconstructed, no physics background
Polar angle distributions for single Higgs events at $\sqrt{s} = 350\text{GeV}$, $1.4\text{TeV}$ and $3\text{TeV}$, including the effects of the CLIC beamstrahlung spectrum and ISR. The distributions are normalised to unity.