Jet and b-tagging at Muon Collider

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Introduction

- From MAP collaboration studies at $\sqrt{s} = 1.5$ TeV the Muon Collider Physics reach strongly depends on beam-induced background and background suppression.

- In order to probe the Physics reach of a Muon Collider we need to study the reconstruction and identification efficiencies with a full simulation.

- In this talk:
  - Jet reconstruction in calorimeter in the presence of the beam-induced background
  - b-jet tagging in the presence of the beam-induced background
Detector and background simulation

Background generated with MARS

Tracking in Nazar’s talk

Dual readout calorimeter:
lead glass towers (Cherenkov)
with scintillating fibers

Machine detector interface

Detector designed by the MAP collaboration → Full simulation with Geant4 + Digitization (ILCroot framework)
H → bb̄ and background $\sqrt{s} = 1.5$ TeV

In my previous talk (April workshop): Jet reconstruction @MC without background

Today: Jet reconstruction @MC with background

$\sqrt{s} = 1.5$ TeV
B = 3.57 T

H → bb̄ signal

Beam-induced background
The background is **diffused**

Part of the background is **asynchronous** with respect to the signal
Jet algorithm

- Jet algorithm must be optimized for the Muon Collider environment:
  - The calorimeter phase space is divided in several regions.
  - In each region the mean deposited energy $<E>$ and the standard deviation $\sigma_E$ are calculated.
  - If the cluster energy satisfies $E_{cl} - <E> > 2 \times \sigma_E$ then the cluster is used as input to the clustering but with energy $E_{cl} - <E>$
  - A cone algorithm with $R=0.5$ is used for clustering.
- For high $p_T$ the jet efficiency is ~70%: good but not optimal
- The algorithm used is rough, much room for improvements (Particle Flow, more sophisticated clustering algorithms, machine learning to separate sig. from bkg. etc.)
Jet energy measurement

Jet energy correction

The raw $p_T$ is proportional to the real $p_T$, therefore a calibration is possible.

Jet $p_T$ resolution

$\sim$30% $p_T$ resolution
Higgs invariant mass

Without beam-induced background

With beam-induced background

\[ \mu^+\mu^- \rightarrow H \rightarrow b\bar{b} \]
b-jet tagging algorithm inspired by LHCb:

1) Tracks with $p_T > 500$ MeV and impact parameter $> 0.04$ cm are selected.

2) 2-tracks vertices are formed by requiring a distance of closest approach $< 0.02$ cm and $p_T(2\text{-tracks}) > 2$ GeV.

3) 2-tracks vertices are linked if they share one track → 3-tracks vertices are formed.

$H \rightarrow b\bar{b}$

$\sqrt{s} = 1.5$ TeV

No background

$<\text{FD}> = 8.3$ cm

$H \rightarrow b\bar{b}$

$\sqrt{s} = 1.5$ TeV

Without beam-induced background
(with complete tracking)

SV-tagging efficiency ($N_{\text{tag}}/N_{\text{rec}}$)
63% similar to LHC experiments
b-jet tagging studies

Input tracks $p_T$

- Due to framework limitations, we are just able to perform a fast tracking in the presence of the beam-induced background (previous talk by Nazar).

- Inefficiencies at low track $p_T$ reduce significantly the tagging efficiency.

- In this study: a comparison between Secondary Vertices from $H \rightarrow bb$ and beam-induced background (combinatorial) is performed.

Remember that $\sqrt{s} = 1.5$ TeV is one of the most difficult cases.
b-jet tagging studies

Secondary Vertex observables

\[ \hat{t} = \frac{m(B) \cdot FD}{p} \]

Negative lifetime: negative SV projection along the jet axis (false tag)

- Beam-induced background produces fake SV
- SV-related observables show different properties between signal and beam-induced background.
- It is evident that a proper algorithm (e.g. DNN) could remove the combinatorial preserving the efficiency.
Conclusions and perspectives

● We demonstrated that it is possible to reconstruct $H \rightarrow b\bar{b}$ jets in the Muon Collider environment at $\sqrt{s} = 1.5$ TeV, with an efficiency of ~70% and an energy resolution of ~30% per jet.

● The jet reconstruction algorithm is very rough, the detector not optimized and we are not using the tracking information: much room for improvements!

● 60% b-jet tagging efficiencies, but combinatorial from beam-induced background.

● The fake SV from beam-induced background could be removed with a multivariate analysis.

● Since we are able to perform just a “fast tracking” with ILCroot (in the presence of the beam-induced background) we are moving these studies to the ILCSoft framework (next talk by Donatella).
Backup slides
Introduction

• The Standard Model is greatly confirmed at LHC energies.

• But many sectors of the SM are poorly known or unexplored, as example:
  
  → Higgs interaction with light fermions.
  
  → Higgs self-interaction.
  
  → Top-quark interaction with gauge bosons and Higgs known at 10% level.
Introduction

- HL-LHC prospects on Yukawa coupling

If $\Lambda_{NP}$ is the New Physics energy scale, the precision that should be achieved to probe it is:

$$\frac{\Delta k}{k} = \frac{5\%}{\Lambda_{NP}^2}$$

- If $\Lambda_{NP} = 10$ TeV then 0.05% precision is needed.

- The Higgs sector can be the portal for New Physics.

- Muon Collider is an ideal machine to study it.
Higgs production at Muon Collider

- Main Higgs production channels at Muon Collider generated with Pythia 8.
- Comparison with CLIC results (ISR included) to cross check our Monte Carlo cross sections. [https://arxiv.org/pdf/1608.07538.pdf](https://arxiv.org/pdf/1608.07538.pdf)
- Cross sections are compatible apart from small differences.
- WW fusion dominates at multi-TeV energies.

### √s = 350 GeV

<table>
<thead>
<tr>
<th>Process</th>
<th>σ [fb] @ CLIC</th>
<th>σ [fb] @ Muon Collider</th>
</tr>
</thead>
<tbody>
<tr>
<td>l⁺l⁻ → HZ</td>
<td>133</td>
<td>136</td>
</tr>
<tr>
<td>l⁺l⁻ → l⁺l⁻ H (ZZ fusion)</td>
<td>7</td>
<td>3.3</td>
</tr>
<tr>
<td>l⁺l⁻ → νl⁺ν⁻ H (WW fusion)</td>
<td>34</td>
<td>32</td>
</tr>
</tbody>
</table>

### √s = 1.4 TeV

<table>
<thead>
<tr>
<th>Process</th>
<th>σ [fb] @ CLIC</th>
<th>σ [fb] @ Muon Collider</th>
</tr>
</thead>
<tbody>
<tr>
<td>l⁺l⁻ → HZ</td>
<td>8</td>
<td>7.3</td>
</tr>
<tr>
<td>l⁺l⁻ → l⁺l⁻ H (ZZ fusion)</td>
<td>28</td>
<td>30</td>
</tr>
<tr>
<td>l⁺l⁻ → νl⁺ν⁻ H (WW fusion)</td>
<td>276</td>
<td>294</td>
</tr>
</tbody>
</table>

### √s = 3 TeV

<table>
<thead>
<tr>
<th>Process</th>
<th>σ [fb] @ CLIC</th>
<th>σ [fb] @ Muon Collider</th>
</tr>
</thead>
<tbody>
<tr>
<td>l⁺l⁻ → HZ</td>
<td>2</td>
<td>1.48</td>
</tr>
<tr>
<td>l⁺l⁻ → l⁺l⁻ H (ZZ fusion)</td>
<td>48</td>
<td>51.4</td>
</tr>
<tr>
<td>l⁺l⁻ → νl⁺ν⁻ H (WW fusion)</td>
<td>477</td>
<td>500</td>
</tr>
</tbody>
</table>
H → b̅b at Muon Collider

- H → b̅b has the highest branching ratio:
  - Coupling with b
  - Coupling with μ (Higgs Factory)
  - Coupling with W (multi-TeV)

- We chose this channel to test our full detector simulation.

- At multi-TeV → Physics backgrounds are orders of magnitude smaller than signal.

- BUT beam-induced background is the real issue.

### Processes with 2 b-quarks in the final state

<table>
<thead>
<tr>
<th>Process</th>
<th>σ [pb] @ 125 GeV</th>
<th>σ [pb] @ 1.5 TeV</th>
<th>σ [pb] @ 10 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>μ μ → γ* / Z → b̅b</td>
<td>19</td>
<td>0.046</td>
<td>0.0014</td>
</tr>
<tr>
<td>μ μ → γ* / Z γ* / Z → b̅b + X</td>
<td>0.11</td>
<td>0.029</td>
<td>0.0013</td>
</tr>
<tr>
<td>μ μ → γ* / Z γ → b̅b + γ</td>
<td>23</td>
<td>0.12</td>
<td>0.0034</td>
</tr>
<tr>
<td>μ μ → H → b̅b (s-channel)</td>
<td>40</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>μ μ → HZ → b̅b + X</td>
<td>-</td>
<td>0.004</td>
<td>~0.0001</td>
</tr>
<tr>
<td>μ μ → μ μ H(→ b̅b) (ZZ fusion)</td>
<td>-</td>
<td>0.018</td>
<td>0.055</td>
</tr>
<tr>
<td>μ μ → γ γ μ μ H(→ b̅b) (WW fusion)</td>
<td>-</td>
<td>0.18</td>
<td>0.54</td>
</tr>
</tbody>
</table>
$H \rightarrow b\bar{b}$ at $\sqrt{s} = 1.5$ TeV

WW fusion is the main production channel: 2 neutrinos in association

In my previous talk:
Jet reconstruction @MC without background


No background here
H → b¯b reconstruction at $\sqrt{s} = 125$ GeV

- Jets are reconstructed using Particle Flow inputs (tracks and isolated clusters) and a Cone clustering with $R = 2.0$
- Jet Energy corrections are applied
- 1000 events generated
- Measured distributions plotted

$p_T > 10$ GeV
$|\eta| < 1.5$  $\rightarrow$ Higgs selection efficiency $= 78\%$

Jet pseudorapidity

Jet transverse momentum [GeV]

Jets are back-to-back
H → b¯b mass distribution at \( \sqrt{s} = 125 \) GeV

- Higgs mass peak resolution → 15%
- Excellent result for distinguish it from Z → bb and not-resonant backgrounds
H → b̅b reconstruction at √s = 1.5 TeV

- Jets are reconstructed using Particle Flow inputs (tracks and isolated clusters) and a Cone clustering with R = 1.0
- 500 events generated

\[ p_T > 10 \text{ GeV} \]
\[ |\eta| < 1.5 \]

Higgs selection efficiency = 76%
Almost identical to Higgs Factory

Jets are NOT back-to-back
→ Leptons are produced in association with the Higgs
H → b¯b mass distribution at √s = 1.5 TeV

- Higgs mass peak resolution = 30%
- Worst resolution with respect to Higgs Factory case (15%)
- Improvements under study:
  - B field
  - Jet radius
  - Particle Flow inputs
b-tagging $\sqrt{s} = 125$ GeV vs $\sqrt{s} = 1.5$ TeV

SV invariant mass [GeV]

SV-tagging efficiency (125 GeV) = 63%

$H \rightarrow b\bar{b}$ $\sqrt{s} = 125$ GeV

$\langle FD \rangle = 5.6$ cm

$H \rightarrow b\bar{b}$ $\sqrt{s} = 1.5$ TeV

$\langle FD \rangle = 8.3$ cm

SV flight distance [cm]

SV invariant mass [GeV]

SV-tagging efficiency (1.5 TeV) = 69%

Jets are more boosted $\rightarrow$ higher flight distance

Improved tagging efficiency at 1.5 TeV
Effects of the beam-induced background

• We understood the Higgs reconstruction @ Muon Collider in the absence of beam-induced background
  ▶️ Jets reconstruction
  ▾ b-tagging

• What can be the effect of the beam induced background?
  ▶ A significant amount can be removed with detector-level requirements
  ▶ Random hits assigned to signal tracks and calorimeter clusters → momentum degradation
  ▶ Fake tracks and calorimeter clusters → to be removed with the jet clustering (anti-kt?)
  ▶ Use Regions of Interest algorithms for reconstruction, as proposed for HL-LHC.
Computational challenge

- The effects of the beam-induced background are impossible to predict without a full detector simulation of signal + background as it is now.

  - Simulation of 1 background event
    ~ 1200 hours
    ~ 20 GB RAM
    ~ 60 GB hard disk
  - Simulation of 1000 signal events
    ~ 90 hours
    ~ 10 GB hard disk
  - Merging of 1 signal event with 1 background event
    ~ 100 hours

Applying physical cuts before the simulation is impossible

We have to face challenges

- Software debugging and optimization
- Parallelization
- Grid

Tests done on Intel(R) Xeon(R) CPU E5-2665 0 @ 2.40GHz (8x)
b-tagging

Input tracks $IP$ vs $\phi$

H→bb

background
b-tagging

Input tracks IP vs $p_T$

H → bb

background