First results using the TrackFit in the Muon Chambers to identify muons

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Introduction

- Idea:
  - Incorporate the muon system in the tracking and use it for the muon ID → Fit tracks (Rec/Track/Best) with hits from muon chambers. Also use probability for a muon to have reached stations where we find hits.
  - Extrapolators allow us to define FOI: field opened more flexible. Will get hits within $5\sigma$.

$$\sigma = \sqrt{S_{\text{ext}}^2 + \left(\frac{\text{padsize}}{\sqrt{12}}\right)^2}$$

- $S_{\text{ext}}$ being error given by extrapolator (momentum, slope dependent).

- Main purpose of method is getting a momentum independent Muon ID tool depending in few parameters.
- Use of tools already available in tracking.
Introduction

- Method of calibration:
  - Version of DaVinci v19r11. Some modifications done in packages from tracking:
    - Tr/TrackFitEvent
    - Tr/TrackFitter
  - Build distributions both from $\chi^2$ fit and *arrival probability*. Use different momentum ranges.
    - Use inclusive $J/\Psi \rightarrow \mu\mu$ for **muons**.
    - Use $\Lambda_b \rightarrow \Lambda(p\pi)J/\Psi(\mu\mu)$ for **non muons**.
      * Always use tracks within detector acceptance

- Will test method also with $B_s \rightarrow \mu\mu$ in SR with $B \rightarrow hh$ background
How to get $\chi^2$

**Muons**
- Get track from Track/Best linked to a muon and coming from $J/\Psi$.
- Just select long tracks in detector acceptance!
- Get hits in 4 last stations coming from our muon and being within 5 sigmas
- Fit track using these hits
- Get $\chi^2$

**Non muons**
- Get Track/Best tracks, not linked to a muon and not decaying to a muon either.
- Just select long/downstream tracks in acceptance!
- Get hits in 4 last stations within 5 sigmas. Keep closest hit to extrapolation per station
- Fit track using these hits
- Get $\chi^2$
How to get $\chi^2$. Efficiency in stations vs # of $\sigma$

Open window of $n$ sigmas in each station and check percentage of times muon hit is inside!

Enough with 5 sigmas!
How to get $\chi^2$. 0 and 1 hits percentage in m/nmuons

**New feature** introduced: fit of tracks only with 1 or 2 hits from muon chambers -> Possibility to save muons also with less than 3 hits. Will keep only those with 2 hits or more,

<table>
<thead>
<tr>
<th>Momentum bin</th>
<th>Momentum range (GeV)</th>
<th>0 hits</th>
<th>1 hit</th>
<th>&gt;1 hit</th>
<th>0 hits</th>
<th>1 hit</th>
<th>&gt;1 hit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3 – 6</td>
<td>0.43</td>
<td>2.46</td>
<td>97.11</td>
<td>73.19</td>
<td>20.88</td>
<td>5.93</td>
</tr>
<tr>
<td>2</td>
<td>6 – 10</td>
<td>0.29</td>
<td>0.37</td>
<td>99.34</td>
<td>73.30</td>
<td>20.93</td>
<td>5.77</td>
</tr>
<tr>
<td>3</td>
<td>10 – 15</td>
<td>0.21</td>
<td>0.26</td>
<td>99.54</td>
<td>69.23</td>
<td>23.93</td>
<td>6.84</td>
</tr>
<tr>
<td>4</td>
<td>15 – 20</td>
<td>0.36</td>
<td>0.22</td>
<td>99.42</td>
<td>66.14</td>
<td>26.42</td>
<td>7.44</td>
</tr>
<tr>
<td>5</td>
<td>20 – 25</td>
<td>0.27</td>
<td>0.34</td>
<td>99.39</td>
<td>61.56</td>
<td>30.56</td>
<td>7.88</td>
</tr>
<tr>
<td>6</td>
<td>&gt;25</td>
<td>0.21</td>
<td>0.15</td>
<td>99.64</td>
<td>70.08</td>
<td>25.88</td>
<td>4.04</td>
</tr>
</tbody>
</table>
How to get $\chi^2$. Distr. for muons and nmuons

$>1$ hit $\chi^2$ distributions

Muons $\chi^2$ distribution

Non muons $\chi^2$ distribution

Still momentum dependent! Need to add mom bins in analysis.
Building $CL_{\text{ratio}}(\chi^2)$

- Building CL
  - Instead of cutting in $\chi^2$, we uniform both distributions for each momentum bin (with its integral values) and build confidence level (CL) functions and its ratio:

  $$CL_{\text{ratio}}(i, \chi^2) = \frac{CL_{\text{muons}}(i, \chi^2)}{CL_{\text{no\_muons}}(i, \chi^2)}$$

  \[i \text{ momentum bin}\]

Integral selection to ensure $CL_{\text{no\_muons}}>CL_{\text{muons}}$
Test of $CL_{ratio}(\chi^2)$ with calibration

$$CL_{ratio}(i, \chi^2) = \frac{CL_{muons}(i, \chi^2)}{CL_{no\_muons}(i, \chi^2)}$$
Test of $C_{\text{ratio}}(\chi^2)$ with calibration

- 1% mis ID -> eff in (82-96)% range
- 90% eff -> misID in (0.2-2)% range
Comparison between $\chi^2$ and distance variables

Exactly same procedure to get hits, but then use of distance instead of track fitting’s $\chi^2$.

Real distance variable more complicated than here. Use of FOI, IsMuon cut...!

$$Dist = \frac{1}{nst} \sum_{st=2}^{5} \sum_{i=x,y} \left( \frac{\text{chitpos}_i(st) - \text{extrpos}_i(st)}{\text{padsize}_i(st)} \right)^2$$

- chitpos-> closest hit to extrapolation
- extpos-> extrapolation position
- Nst-> number of st with hits in 5\sigma
How to get \textit{arr prob}

\begin{center}
\textbf{Prob vs p, angle\textunderscore min=0 mrad}
\end{center}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{prob_vs_p}
\caption{Probability vs momentum for different \textit{arr prob} functions.}
\end{figure}

\begin{align*}
P_i \text{ functions}
\end{align*}
How to get *arr prob*

*Arrival prob*: essentially probability for a muon to have reached stations where we find hits:

- We get track momentum.
- We find the probabilities it has reached stations 2, 3, 4, 5, provided it is within detector acceptance. Say they are $P_2, P_3, P_4, P_5$.
- We check which stations have hits within 5 sigmas. For a certain station $i$, if we find a hit we compute $P_i$. If we don’t, we use $(1-P_i)$.
- Example:
  Let’s assume a muon with momentum $p$ with hits only in stations 2 and 3. Probability we would use is:

$$P_2(p) \cdot P_3(p) \cdot [1 - P_4(p)] \cdot [1 - P_5(p)]$$
How to get arrival prob.  
Distr. for m and n muons

>1 hit arr prob distributions

Muons

Non muons

Muon ID with TrackFit
Test of $CL_{ratio}$ arrival prob with calibration

$CL_{ratio}(i, arr) = \frac{CL_{muons}(i, p_{arr})}{CL_{no\_muons}(i, p_{arr})}$
Test of $\text{CL}_{\text{ratio}}$ arrival prob with calibration

- $1\%$ mis ID -> eff in (90-99)$\%$ range
- 90$\%$ eff -> misID in (0.2-1)$\%$ range

Better than $\text{CL}(\chi^2)$ in every mom bin.
Combination of both still better

MuonChambers eff dependent?
Test of DLL with calibration

\[ DLL = \log[ CL_{ratio}(\chi^2) \cdot CL_{ratio}(arr)] \]
Test of DLL with calibration

Eff of muons and nmuons vs p for different dll cuts

Almost flat dependence with momentum for muons eff!

Muon ID with TrackFit
Both CLs cooperate in order to get a better discr. power!

- 1% mis ID -> eff in (93-99)% range
- 90% eff -> misID in (0.0-0.6)% range
Test of DLL with calibration

Both CLs cooperate in order to get a better discr. power!

- 1% mis ID -> eff in (93-99)% range
- 90% eff -> misID in (0.0-0.6)% range
How to get *arr prob* (variation)

- *Arrival prob*: essentially probability for a muon to have reached stations where we find hits. Try this to be less MWPC efficiency dependent:
  - We get track momentum.
  - We find the probabilities it has reached stations 2,3,4,5, provided it is within detector acceptance. Say they are \(P_2, P_3, P_4, P_5\).
  - We check which stations have hits within 5 sigmas. For a certain station \(i\), if we find a hit we compute \(P_i\). If we don’t, we use \((1-P_i)\). Given all probabilities per stations, we suppress the smallest value.
  - Example:
    Let’s assume a muon with momentum \(p\) with hits only in stations 2 and 3. Probability we would use is:

\[
P_2(p) \cdot P_3(p) \cdot [1 - P_5(p)]
\]

provided the smallest prob per station is

\[
[1 - P_4(p)]
\]
Test of $CL_{ratio}$ $arr\ p$ and DLL with calibration ($var$)

Needs to be checked up to what point this $arr\ prob$ definition is more “robust”!
Test method with $B_s \rightarrow \mu \mu$ in SR

**Muons**
- Get muon from $B_s$ linked to Track/Best. We run in SR selection.
- Just select long tracks in detector acceptance!
- Get hits in 4 last stations coming from our muon and being within 5 sigmas
- Fit track using these hits
- Get $\chi^2$

**Non muons**
- Get Track/Best tracks, not linked to a muon and coming from a $B$. In principle refuse also decays in flight.
- Just select long/downstream tracks in acceptance!
- Get hits in 4 last stations within 5 sigmas. Keep closest hit to extrapolation per station
- Fit track using these hits
- Get $\chi^2$

Use of $B \rightarrow hh$ as background because of same mom range than $B_s \rightarrow \mu \mu$.

Still need to study decays in flight!
Test method with $B_s \to \mu\mu$ in SR

Eff vs MisID -> CLS=dll_chi2,SAMPLES=[bsmumu,bhh_wodcf]

Non muons without decays in flight!

Again more discriminative power from arr prob. Both together works better.
Future plans

- Check $B \rightarrow hh$ background including *selected* decays in flight.
- Get both muons and non muons set from $bb$ inclusive and use it to test all these methods. Use also non muons set for $B_s \rightarrow \mu\mu$ background.
- Check MWPC efficiency dependence of this method.
- Incorporate our method to MuonID official package.
Summary

- Incorporate muons system to tracking and use it for MuonID.
- New selection of relevant hits for muonID by using $5\sigma$ as FOI. Checked to be enough.
- Use 2 variables to discriminate: $\chi^2$ (from track fit) and $arr\ prob$. Build $CL_{ratio}(\chi^2)$ and $CL_{ratio}(P_{arr})$ distribution for each momentum bin with calibration. Get DLL value from them. Also cut for tracks with less than 2 hits!
- First tests with calibration done. DLL works better than each CL by itself. Efficiency of method for muons flat in momentum for different cuts.
  - 90% eff -> misID in (0.0-0.6)% range.
- Result for $B_s\rightarrow\mu\mu$ in SR using $B\rightarrow hh$ as background.
  - 99% eff vs .3% misID, without decays in flight
Backup
Efficiency in stations vs momentum and # of $\sigma$ - Zoom

- Also check any possible momentum and/or station bias

Small dependance with $p$ at small momentum for all stations. Over 95% in every case.
5σ/FOI – x coordinate

Reg 1 2 3 4

ST 2 2 1 0 3 4 5

Muon ID with TrackFit
5σ/FOI – y coordinate

Muon ID with TrackFit
Arrive probability: $\eta$ vs $p$
0 and 1 hits percentage in m $(B_s \to \mu\mu \text{ SR}) / \text{nm} (B \to hh)$

Repeat same table as before, now not momentum bins needed. Separate background w/wo decays in flight!

<table>
<thead>
<tr>
<th>$B_s \to \mu\mu$ MUONS (%)</th>
<th>$B \to hh$ NON MUONS (%) (without decays in flight)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 hits</td>
<td>1 hit</td>
</tr>
<tr>
<td>0.27</td>
<td>0.40</td>
</tr>
</tbody>
</table>