Development of the time-of-flight particle identification for future Higgs factories

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Detectors for Future Facilities, R&D, novel techniques

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Motivation for time-of-flight particle ID at the future Higgs factory

- Flavour physics
- Improved vertex reconstruction using refitted tracks
- Contribution to the kaon mass measurement
- Higgs Yukawa couplings
- $A_{FB}$
- And so on...

![Motivation Diagram](image-url)
Time-of-flight particle ID is great complementary tool to $dE/dx$ ($dN/dx$) in gaseous detectors
And is only available particle identification tool for fully Si detector designs
Basic principle

E.g. LGADs Si sensors
time resolution < 50 ps

\[ \beta = \frac{\ell_{\text{track}}}{c \cdot \text{TOF}} \]

\[ m = \frac{p}{\beta} \sqrt{1 - \beta^2} \]
Extraction of the separation power
Barrel region / perfect time resolution of the closest ECAL hit

\[
\text{Sep.Power} = \frac{|\mu_1 - \mu_2|}{\sqrt{0.5(\sigma_1^2 + \sigma_2^2)}}
\]
Separation power vs time-of-flight resolution

Impossible to identify even with ideal time resolution per particle

TOF pID momentum region is limited by other factors than TOF, e.g. track length

No reason to push for “femtosecond” timing detectors

10 ps resolution per particle is sufficient

Sep.Power = \[ \frac{|\mu_1 - \mu_2|}{\sqrt{0.5(\sigma_1^2 + \sigma_2^2)}} \]
Track length impact

Helix approximation (bad)

\[ \ell_{\text{track}} = \frac{|\varphi_{\text{end}} - \varphi_{\text{start}}|}{|\Omega|} \sqrt{1 + \tan^2 \lambda} \]

Iterate hit-by-hit (good)

\[ \ell_{\text{track}} = \sum_{i=0}^{n} \ell_i = \sum_{i=0}^{n} \sqrt{\left( \frac{\varphi_{i+1} - \varphi_i}{\Omega_i} \right)^2 + (z_{i+1} - z_i)^2} \]

Considerable improvement in the endcap!

Plots use TPC with 220 radial hits

Large number of track hits is important for track length measurement
Realistic implementations inside a detector

Detector design has constraints:
• precise timing $\rightarrow$ higher power consumption
• higher power consumption $\rightarrow$ more money
• higher power consumption $\rightarrow$ more space & material for active cooling

What about synchronization across a large detector?
• Clock jitter between electronic elements?
• Precision of determining $t_{EVENT}$?
Comparison of three realistic scenarios

1\textsuperscript{st} ECAL layer with LGADs (~30 ps hit time resolution)

\[
\text{TOF} = t_{\text{hit}} - \frac{|\vec{r}_{\text{hit}} - \vec{r}_{\text{track}}|}{c}; \quad \Delta \text{TOF} = \Delta t_{\text{hit}}
\]

10 ECAL layers with conventional Si sensors (~100 ps hit time resolution)

\[
\text{TOF} = \frac{1}{N_{\text{hits}}} \sum_{i=1}^{N_{\text{hits}}} \left( t_i - \frac{|\vec{r}_{i} - \vec{r}_{\text{track}}|}{c} \right); \quad \Delta \text{TOF} = \frac{\Delta t_{\text{hit}}}{\sqrt{N_{\text{hits}}}}
\]

Silicon external tracker (SET) (~50 ps hit time resolution)

\[
\text{TOF} = \frac{t_{\text{front strip}} + t_{\text{back strip}}}{2}; \quad \Delta \text{TOF} = \frac{\Delta t_{\text{hit}}}{\sqrt{2}}
\]
Comparison of three realistic scenarios

Time-of-flight resolution per particle is roughly the same for all realistic options.

Combining many hits give:

$$\sigma_{\text{TOF}} \sim \frac{\sigma_{\text{hit}}}{\sqrt{n}}$$

Need a more realistic digitization simulation (energy/threshold effects on hit time resolution)
Time-of-flight using many hits

Each hit has:
\[ x, y, z, t, E \]

ECAL shower

Very smart algorithm ( ) = time-of-flight

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Many analyses are ongoing...

Flavor tagging

- Jets are bundles of hadrons originated by quarks and gluons.
- Flavor tagging is the algorithm which classify the quark (b/c/u/g).
- In the TOF, the flavor tagging algorithm is based on the Boosted Decision Trees, which is a traditional ML.

Purpose of this study
- Improve the performance of the flavor tagging by introducing deep-learning techniques.
- Combine vertex finding and flavor tagging in single CNN architecture.
- Incorporate hadron charge to enhance the separation.
Summary

- Time-of-flight particle ID is being recognized as a valuable tool for future Higgs factory detectors

- Time-of-flight particle ID is intrinsically limited at higher momentum by non time-of-flight parameters, e.g. track length, momentum

- Many hits can be combined in various ways to achieve good time resolution per particle. Follow up work is ongoing to show this with realistic simulation of the digitizer response
Back up: math for TOF algorithm

\[ \ell_{\text{track}} = \sum_{i=0}^{n} \ell_i = \sum_{i=0}^{n} \sqrt{\left( \frac{\varphi_{i+1} - \varphi_i}{\Omega_i} \right)^2 + (z_{i+1} - z_i)^2} \]

\[ \beta = \frac{\ell_{\text{track}}}{c \cdot \text{TOF}} \]

\[ p_i = e^{\frac{|B_z|}{\Omega_i}} \sqrt{1 + \tan^2 \lambda_i} \]

\[ p = \sqrt{\langle p^2 \rangle_{HM}} = \sqrt{\sum_{i=0}^{n} \frac{\ell_i}{p_i^2} / \sum_{i=0}^{n} \frac{\ell_i}{p_i^2}} \]

\[ m = \frac{p}{\beta} \sqrt{1 - \beta^2} \]

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arXiv:2107.02031
Back up: new track length results for the barrel