

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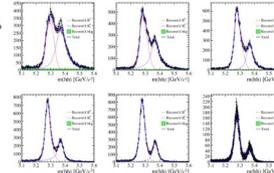
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# Motivation for time-of-flight particle ID at the future Higgs factory

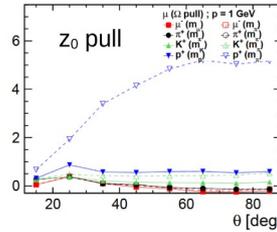
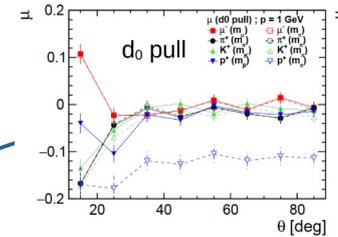
- Flavour physics
- Improved vertex reconstruction using refitted tracks
- Contribution to the kaon mass measurement
- Higgs Yukawa couplings
- $A_{FB}$
- And so on...

## Indicators vs. PID efficiency

- Scan of the hh invariant mass vs. PID efficiency
- Examples shown here:  
PID efficiency 50%, 70%, 80%, 90%, 95%, 100%
- Indicators:  
• Mean values of the mass peaks form the fits
- Can make plots of Indicators vs. PID efficiency



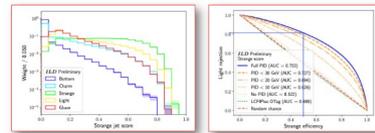
Shanzhen Chen link



Yasser Radkhorrani

## Impact of PID on Strange Tagging

- Use a Recurrent Neural Net tagger for classifying jet-flavour, train on full (ILD<sup>7</sup>) simulation ( $Z \rightarrow inv$ )( $H \rightarrow qq$ ) samples and include per-jet level inputs & variables on the 10 leading particles in each jet, including PDG-based PID  $\rightarrow$  general validity!

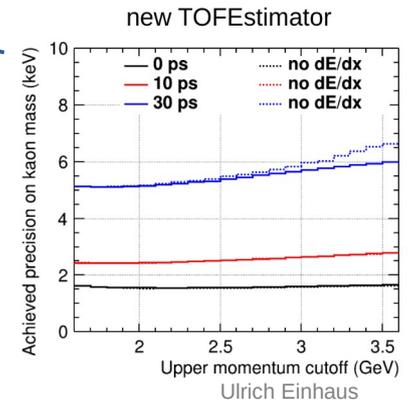


Good discrimination of s-jets from u/d- and g-jets

@50% s-jet tagging efficiency, >80% u/d-jet rejection with Full PID

<sup>7</sup> ILD = multipurpose International Large Detector concept @ the International Linear Collider  
July 09, 2022 V.M. Cairo

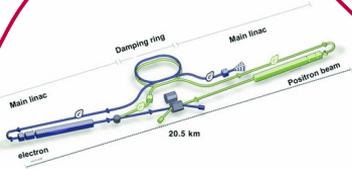
Valentina Cairo 2203.07535



Ulrich Einhaus

# Higgs factory candidates

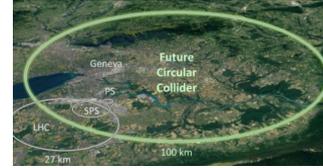
## ILC



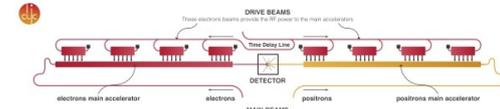
## CEPC



## FCC-ee

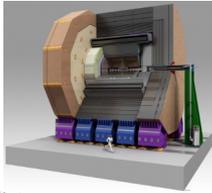


## CLIC

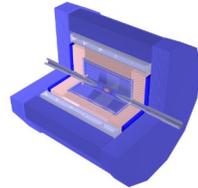


# Detector concepts

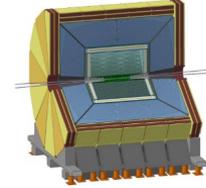
## ILD



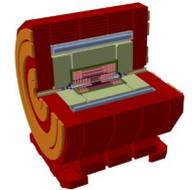
## CEPC Baseline



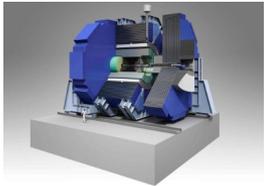
## IDEA



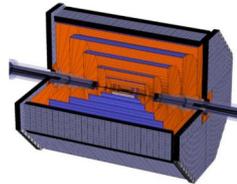
## CLICdp



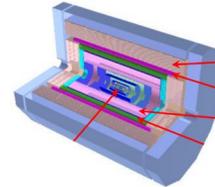
## SiD



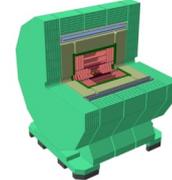
## FST



## CEPC 4<sup>th</sup> concept

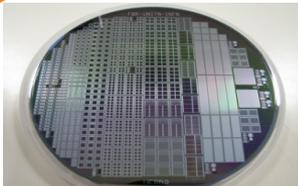


## CLD

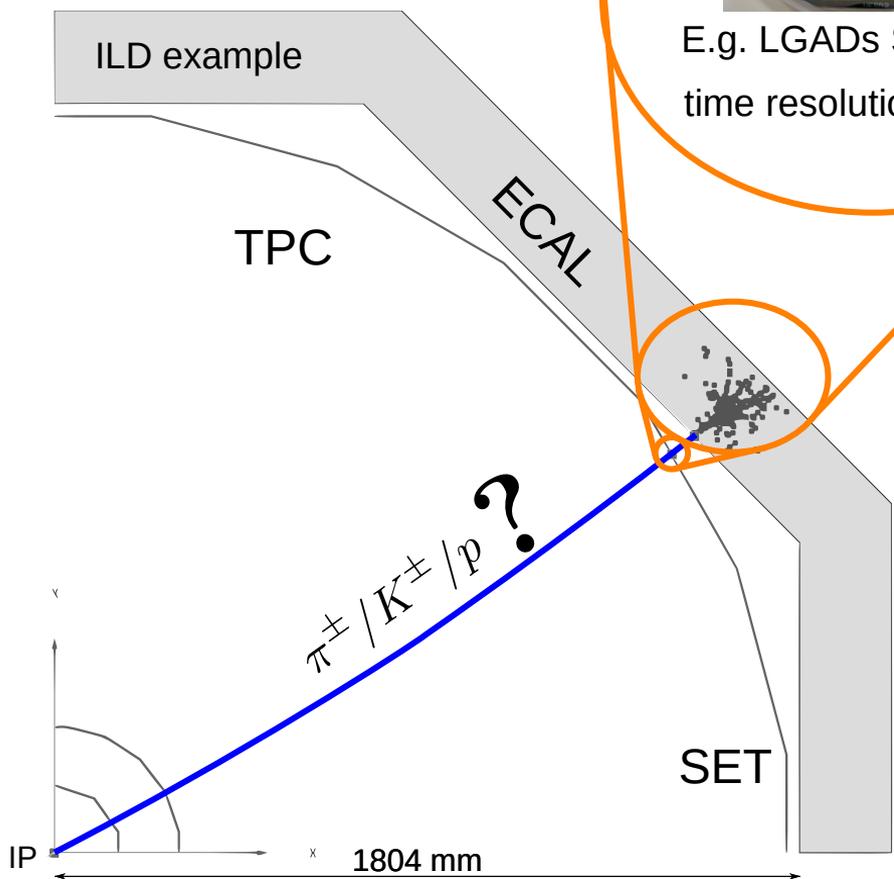


Time-of-flight particle ID is great complementary tool to  $dE/dx$  ( $dN/dx$ ) in gaseous detectors  
And is only available particle identification tool for fully Si detector designs

# Basic principle

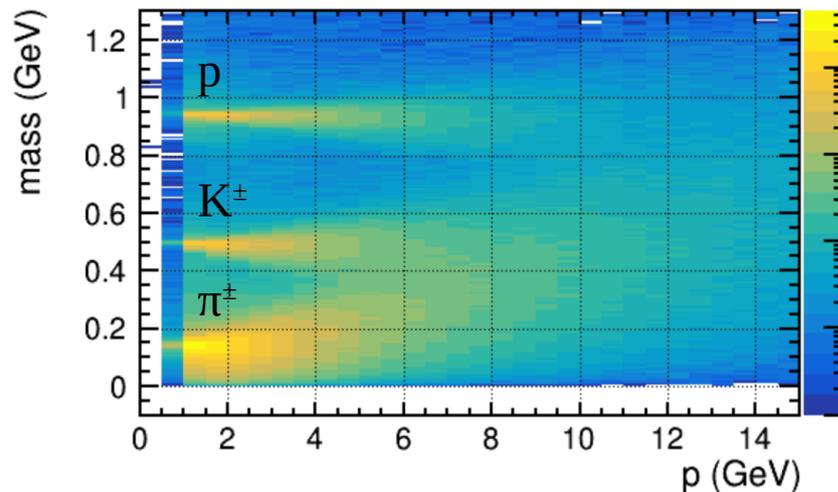


E.g. LGADs Si sensors  
time resolution < 50 ps



$$\beta = \frac{l_{\text{track}}}{c \cdot \text{TOF}}$$

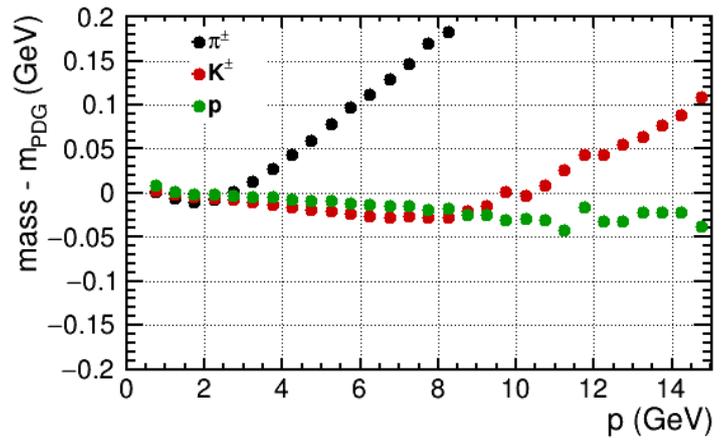
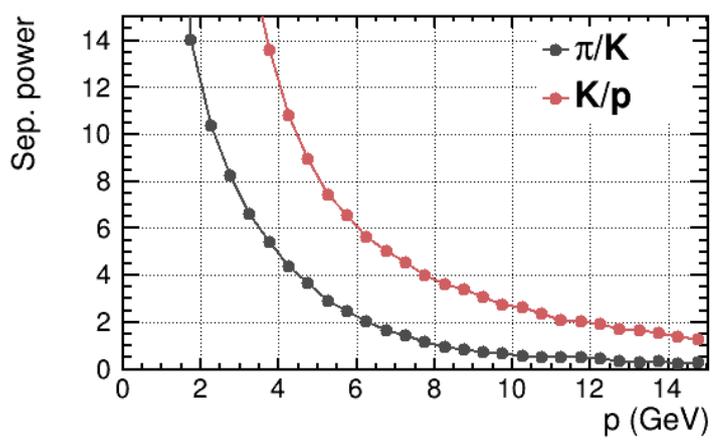
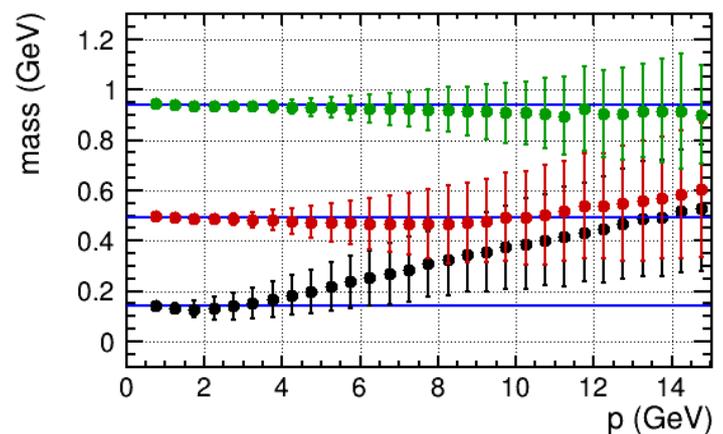
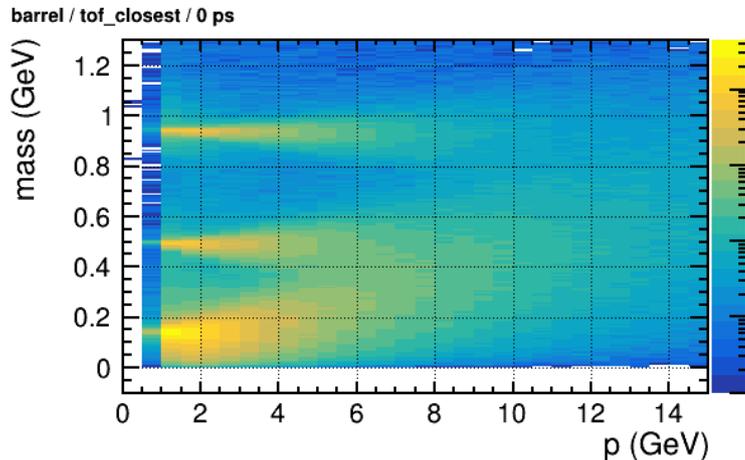
$$m = \frac{p}{\beta} \sqrt{1 - \beta^2}$$



# Extraction of the separation power

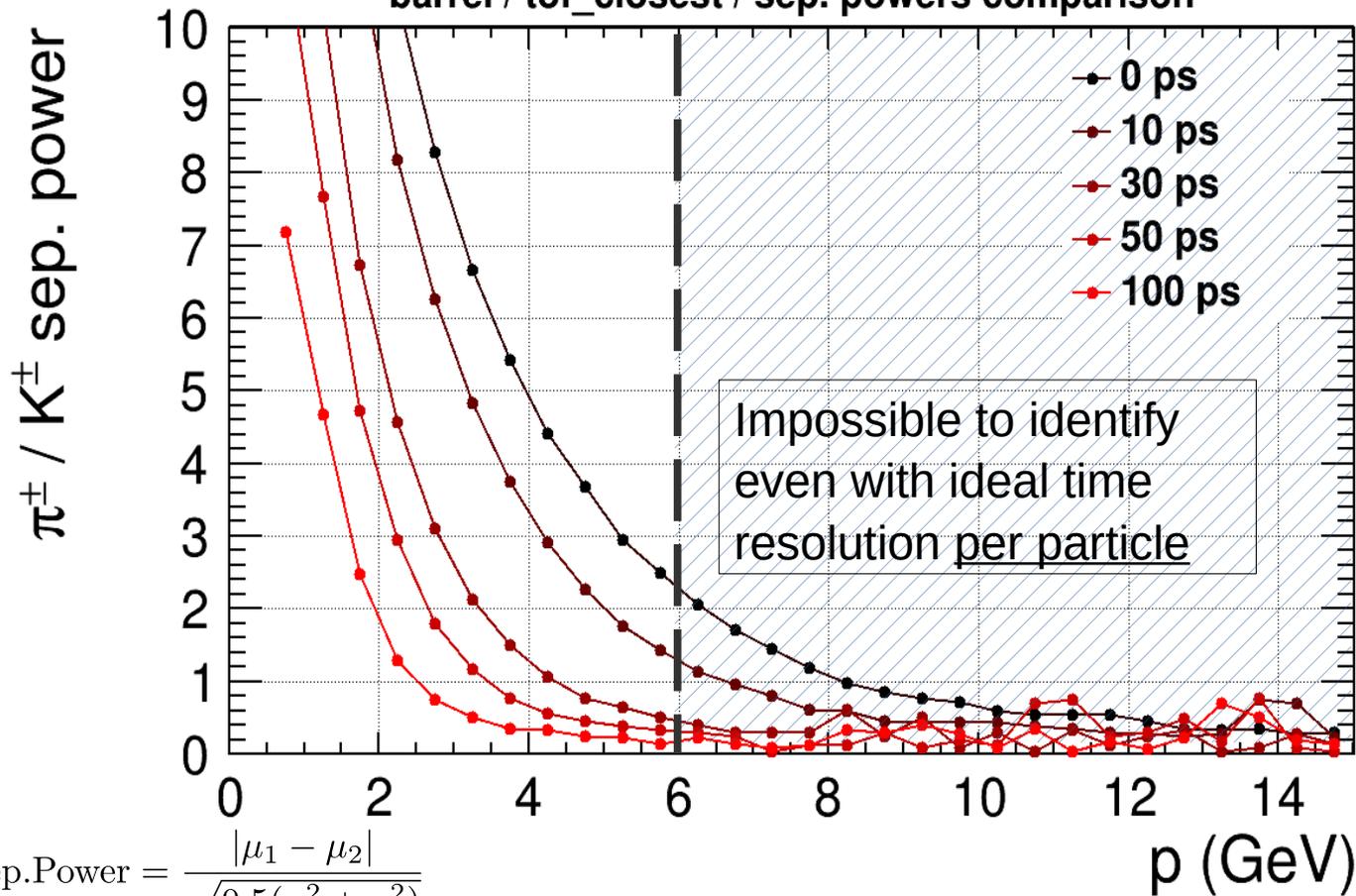
Barrel region / perfect time resolution of the closest ECAL hit

$$\text{Sep. Power} = \frac{|\mu_1 - \mu_2|}{\sqrt{0.5(\sigma_1^2 + \sigma_2^2)}}$$



# Separation power vs time-of-flight resolution

barrel / tof\_closest / sep. powers comparison



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

Impossible to identify even with ideal time resolution per particle

$$\text{Sep. Power} = \frac{|\mu_1 - \mu_2|}{\sqrt{0.5(\sigma_1^2 + \sigma_2^2)}}$$

# Track length impact

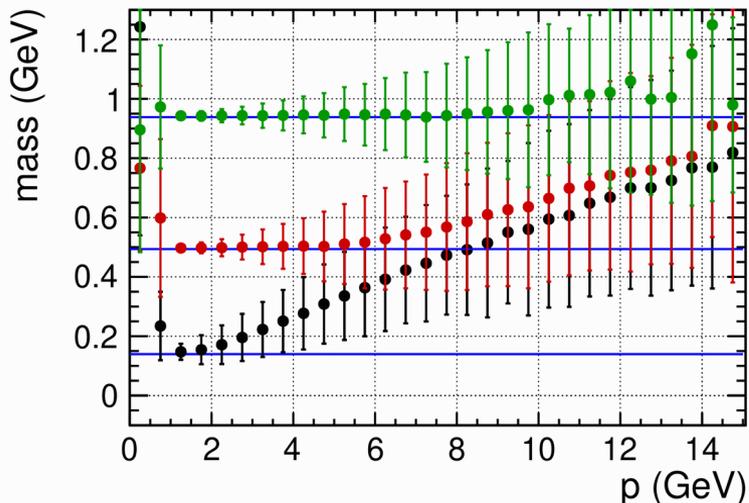
Helix approximation (bad)

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

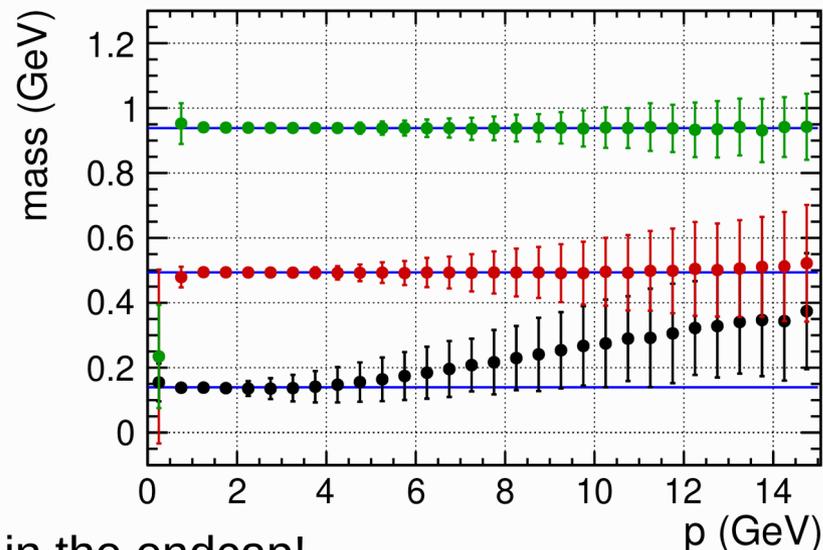
Iterate hit-by-hit (good)

$$l_{\text{track}} = \sum_{i=0}^n l_i = \sum_{i=0}^n \sqrt{\left(\frac{\varphi_{i+1} - \varphi_i}{\Omega_i}\right)^2 + (z_{i+1} - z_i)^2}$$

OLD track length / 0 ps / endcap



NEW track length / 0 ps / endcap

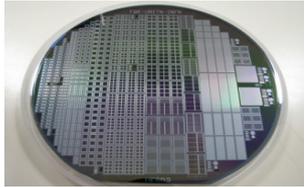


Considerable improvement in the endcap!

Plots use TPC with 220 radial hits

Large number of track hits is important for track length measurement

# Realistic implementations inside a detector



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

## Detector design has constraints:

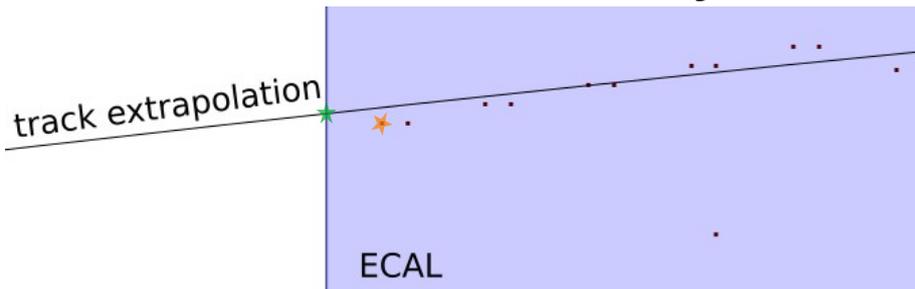
- precise timing → higher power consumption
- higher power consumption → more money
- higher power consumption → more space & material for active cooling

## What about synchronization across a large detector?

- Clock jitter between electronic elements?
- Precision of determining  $t_{\text{EVENT}}$  ?

# Comparison of three realistic scenarios

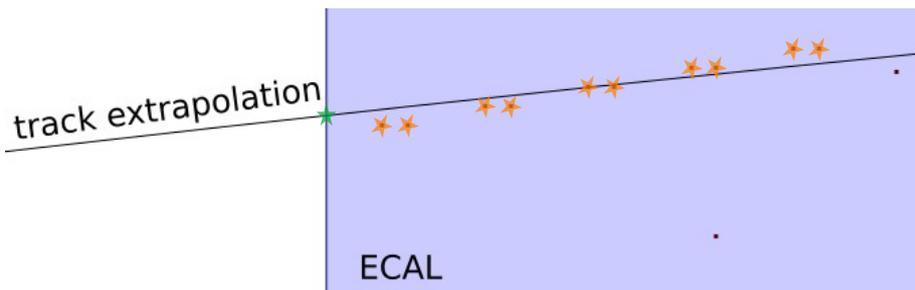
## 1<sup>st</sup> ECAL layer with LGADs (~30 ps hit time resolution)



$$\text{TOF} = t_{\text{hit}} - \frac{|\vec{r}_{\text{hit}} - \vec{r}_{\text{track}}|}{c};$$

$$\Delta\text{TOF} = \Delta t_{\text{hit}}$$

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



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

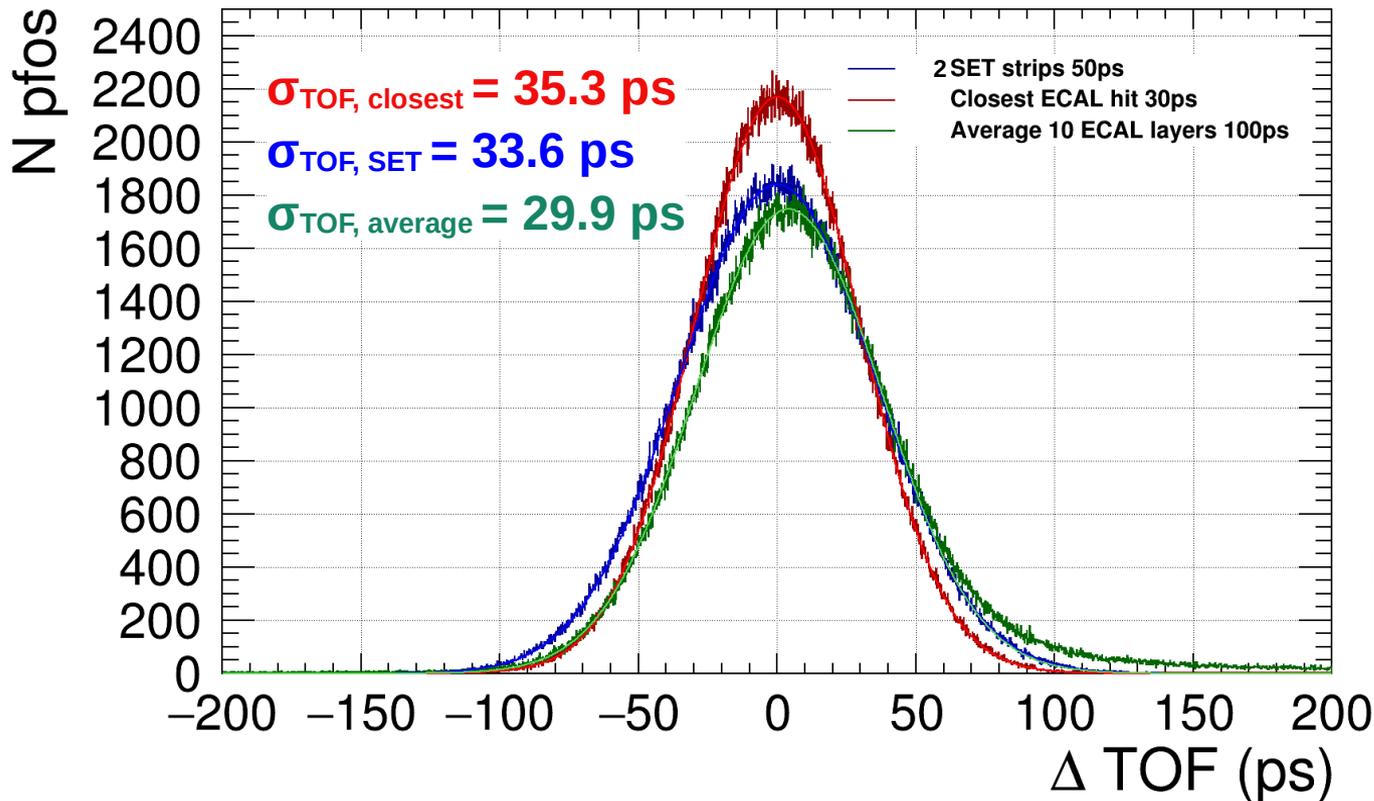
## Silicon external tracker (SET) (~50 ps hit time resolution)

$$\text{TOF} = \frac{t_{\text{front strip}} + t_{\text{back strip}}}{2};$$

$$\Delta\text{TOF} = \frac{\Delta t_{\text{hit}}}{\sqrt{2}}$$

# Comparison of three realistic scenarios

Entries 1018915



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

Combining many hits give:

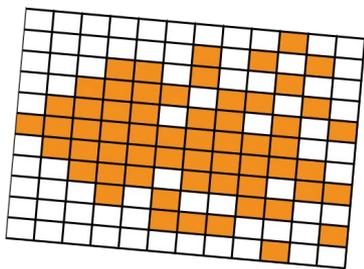
$$\sigma_{\text{TOF}} \sim \frac{\sigma_{\text{hit}}}{\sqrt{n}}$$

Need a more realistic digitization simulation (energy/threshold effects on hit time resolution)

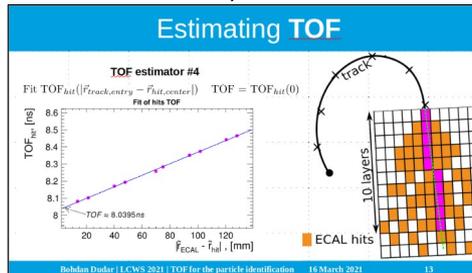
# Time-of-flight using many hits

Each **hit** has:  
x, y, z, t, E

ECAL shower



Bohdan Dudar, Ulrich Einhaus



Very smart algorithm (  ) = time-of-flight

Yuzhi Che, Manqi Ruan

6. Conclusion

- **Arbor clustering module** improves the EM (hadronic) cluster time resolution by a factor of ~1.2 (1.4)
- The cluster time resolution is proportional to the **intrinsic time resolution**.
- Cluster time resolution is inversely proportional to the  $\sqrt{N_{layer}}$ .
- **Alternative strategy**: OSV estimator could improve the EM cluster TOF resolution by a factor of ~3.

Scaling hit time resolution  
Reduced Layer number  
Current technology  
All ECAL channels  
FMV estimator  
OSV estimator  
Arbor clustering  
Perfect cluster

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Mami Kuhara, Taikan Suehara

Flavor tagging

**Flavor Tagging**

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

**Purpose on this study**

- Improve the performance of the flavor tagging by introducing deep-learning techniques.
- Combine vertex finding and flavor tagging in single DNN structure.
- Incorporate hadron charge ID to enhance the separation

**DNN (Deep Neural Network)**

- Input : 4 million events data from ILD simulation
- Output : 3 categories
- Network : 4 fully-connected layer with batch normalization and ReLU activation
- The total accuracy of DNN was about 82%.

**Next step**

**GTN (Graph Transformer Network)**  
arXiv:1911.06455v2  
→ Can be deal with multiple kinds node

Node: Tracks / Vertex  
Edge: The connection between nodes

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**Many analyses are ongoing...**

# 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

$$l_{\text{track}} = \sum_{i=0}^n l_i = \sum_{i=0}^n \sqrt{\left(\frac{\varphi_{i+1} - \varphi_i}{\Omega_i}\right)^2 + (z_{i+1} - z_i)^2}$$

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

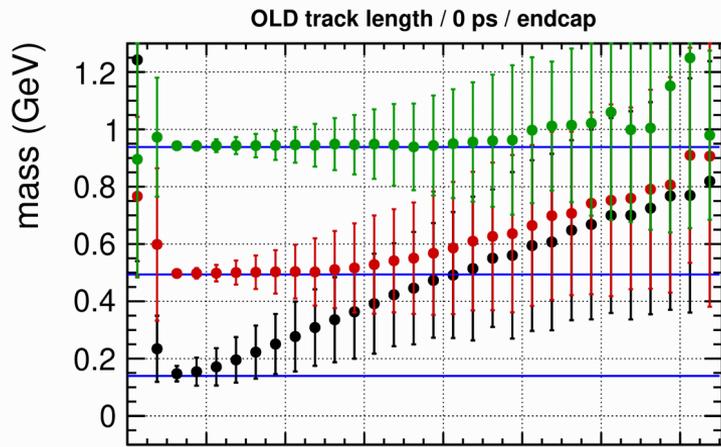
$$\beta = \frac{l_{\text{track}}}{c \cdot \text{TOF}}$$

$$p = \sqrt{\langle p^2 \rangle_{HM}} = \sqrt{\sum_{i=0}^n l_i / \sum_{i=0}^n \frac{l_i}{p_i^2}}$$

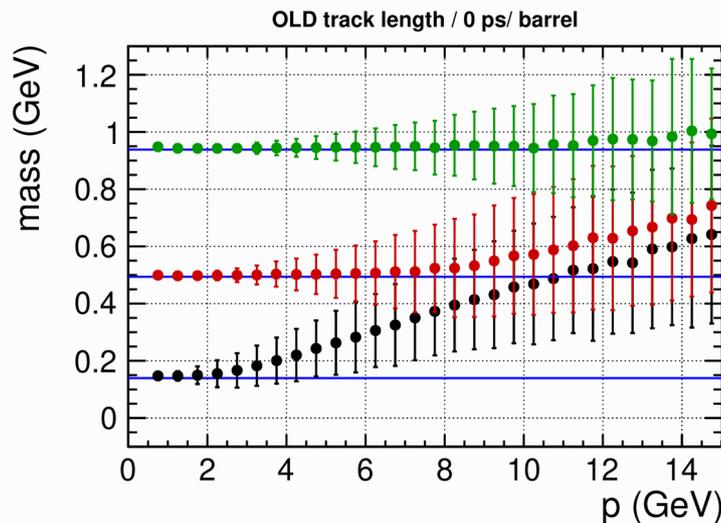
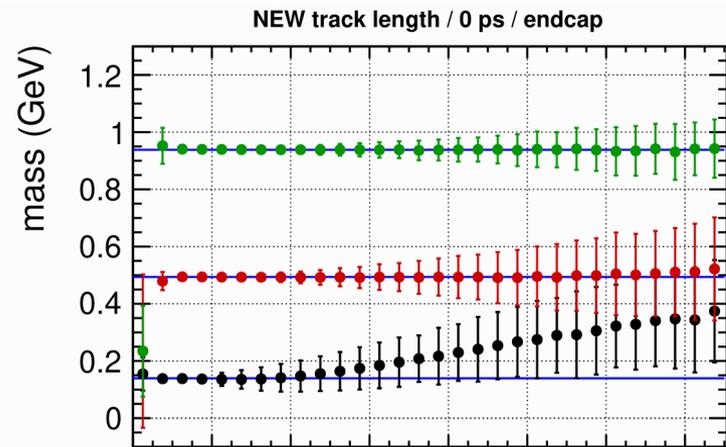
$$m = \frac{p}{\beta} \sqrt{1 - \beta^2}$$

Winfried A. Mitaroff  
[arXiv:2107.02031](https://arxiv.org/abs/2107.02031)

# Back up: new track length results for the barrel



ENDCAP



BARREL

