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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HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

UHH

CLUSTER OF EXCELLENCE QUANTUM UNIVERSE

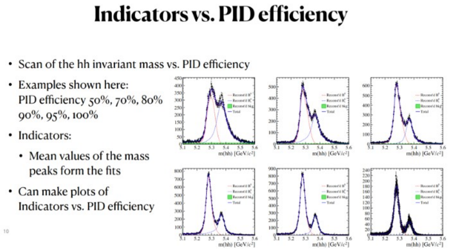
ILD

FTX

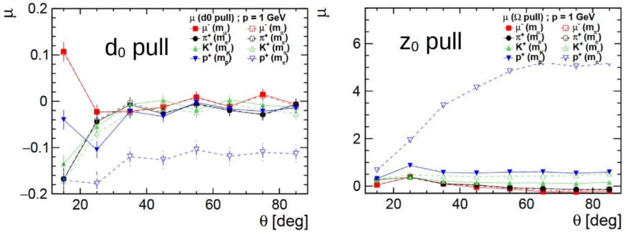
DESY.

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

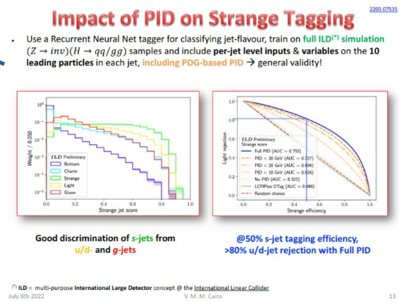
- Flavour physics
- Improved vertex reconstruction using refitted tracks
- Contribution to the kaon mass measurement
- Higgs Yukawa couplings
- A_{FB}
- And so on...



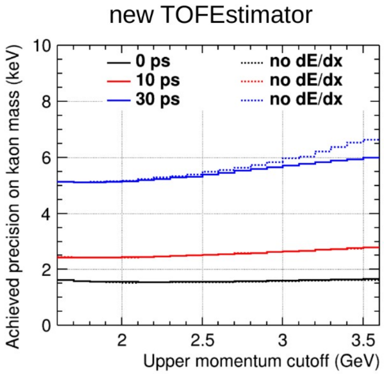
Shanzhen Chen link



Yasser Radkhorrami



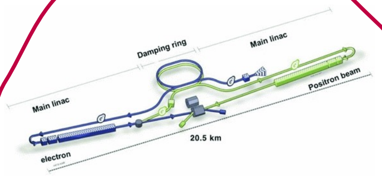
Valentina Cairo 2203.07535



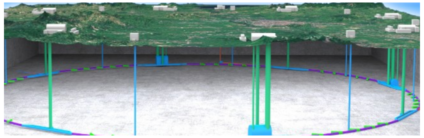
Ulrich Einhaus

Higgs factory candidates

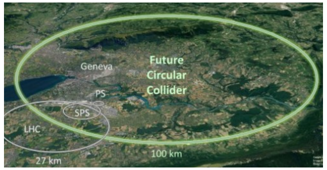
ILC



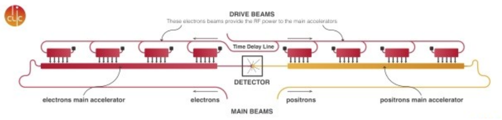
CEPC



FCC-ee



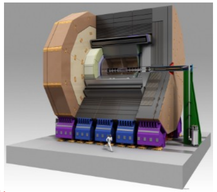
CLIC



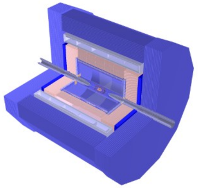
I use ILD full simulation as an example case

Detector concepts

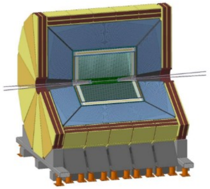
ILD



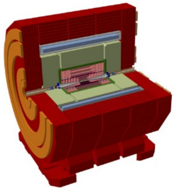
CEPC Baseline



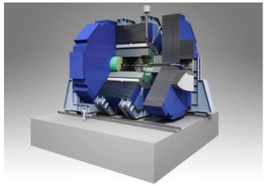
IDEA



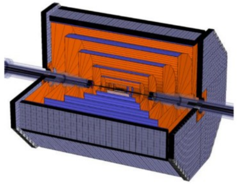
CLICdp



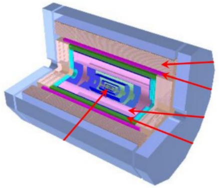
SiD



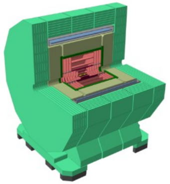
FST



CEPC 4th concept

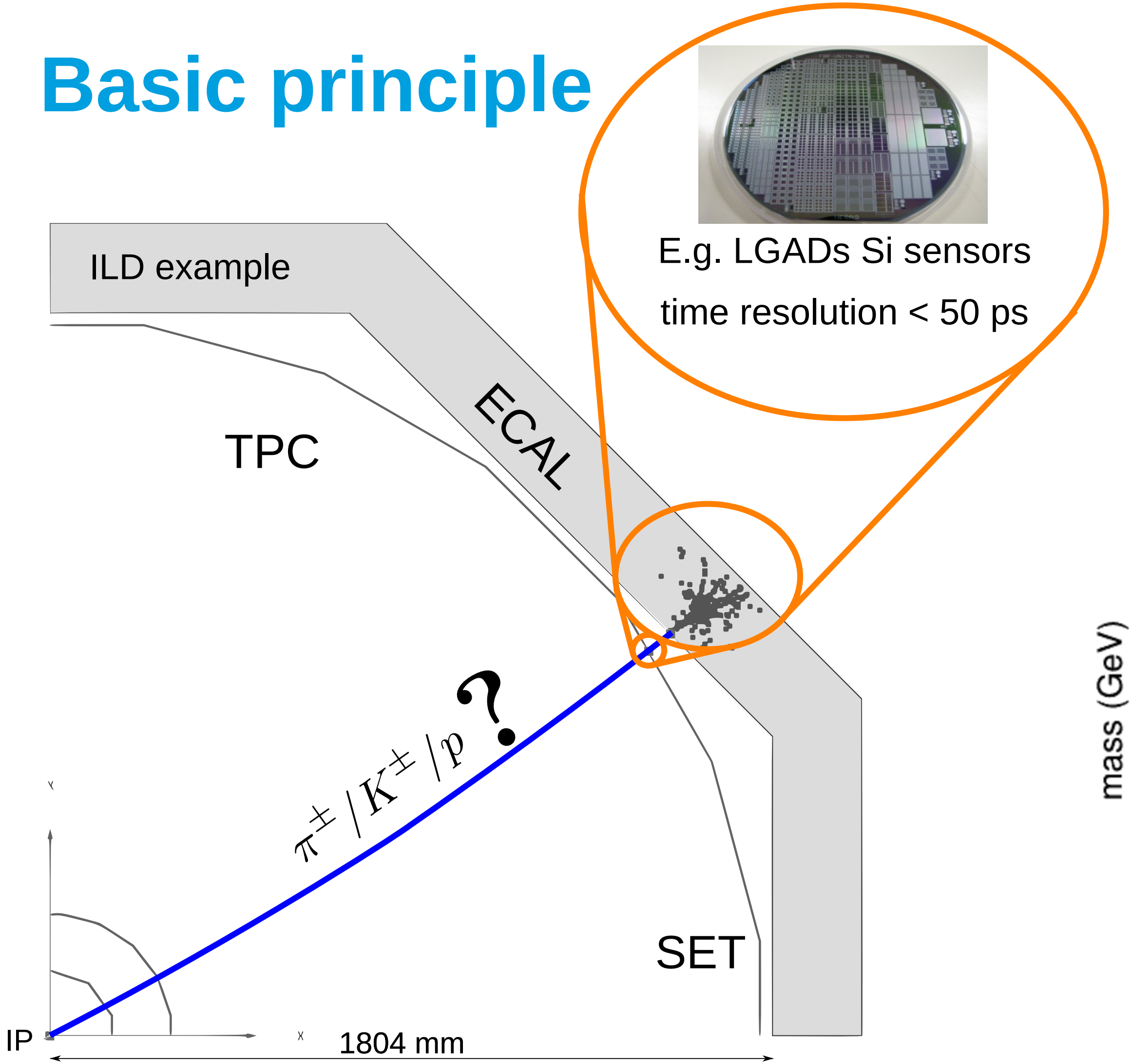


CLD



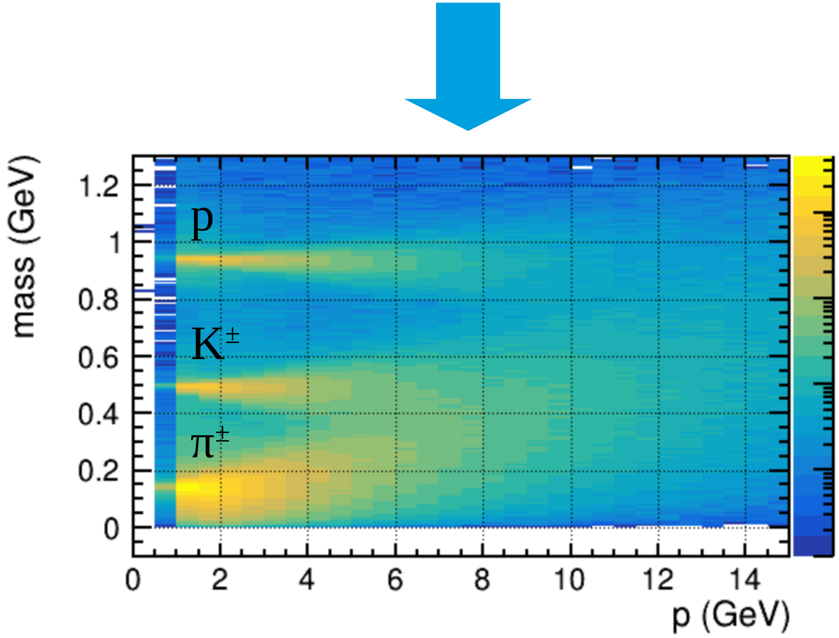
Time-of-flight particle ID is great complementary tool to dE/dx (dN/dx) in gaseous detectors
And is only available particle identification tool for fully Si detector designs

Basic principle



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

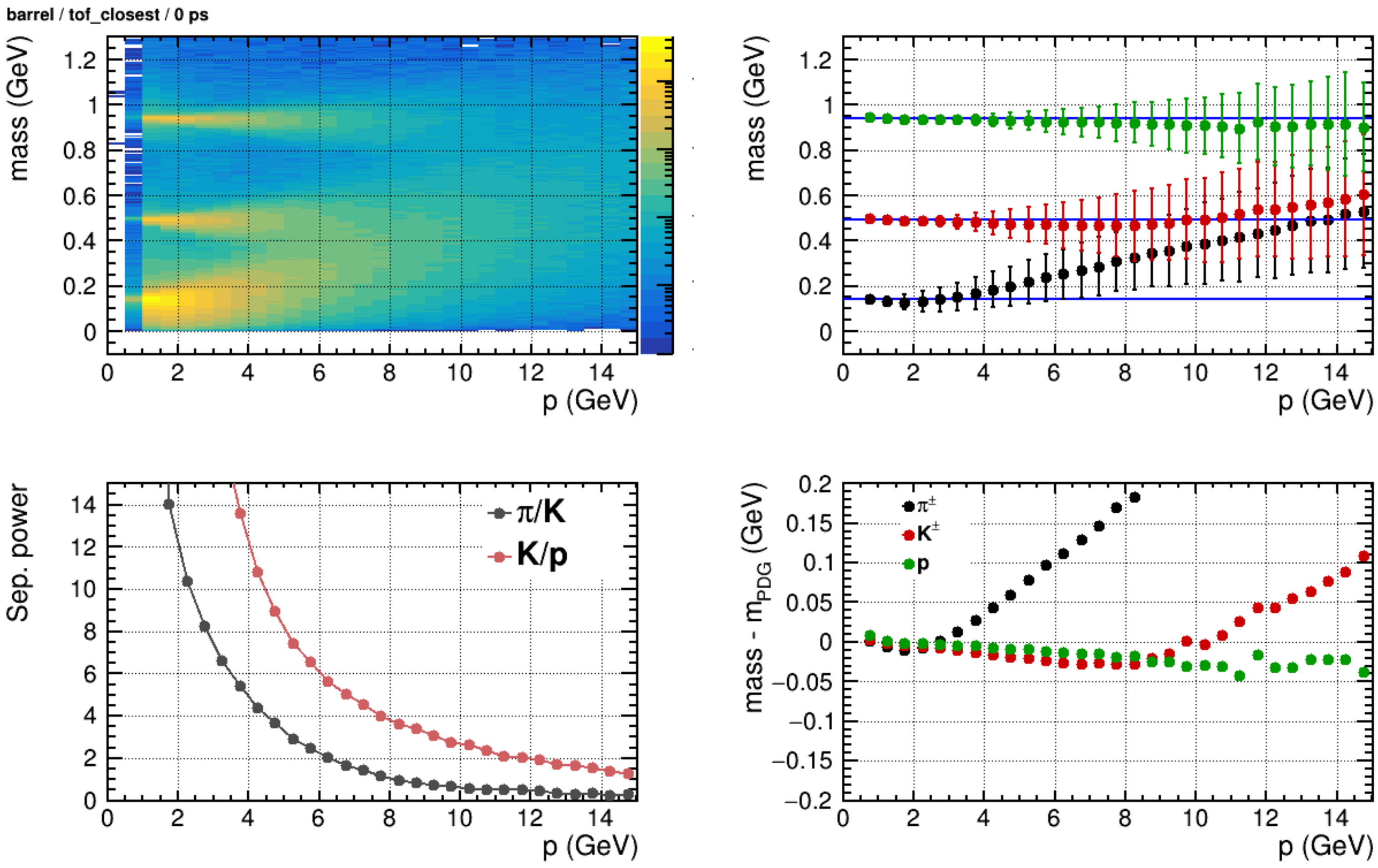
$$m = \frac{p}{\beta}\sqrt{1-\beta^2}$$



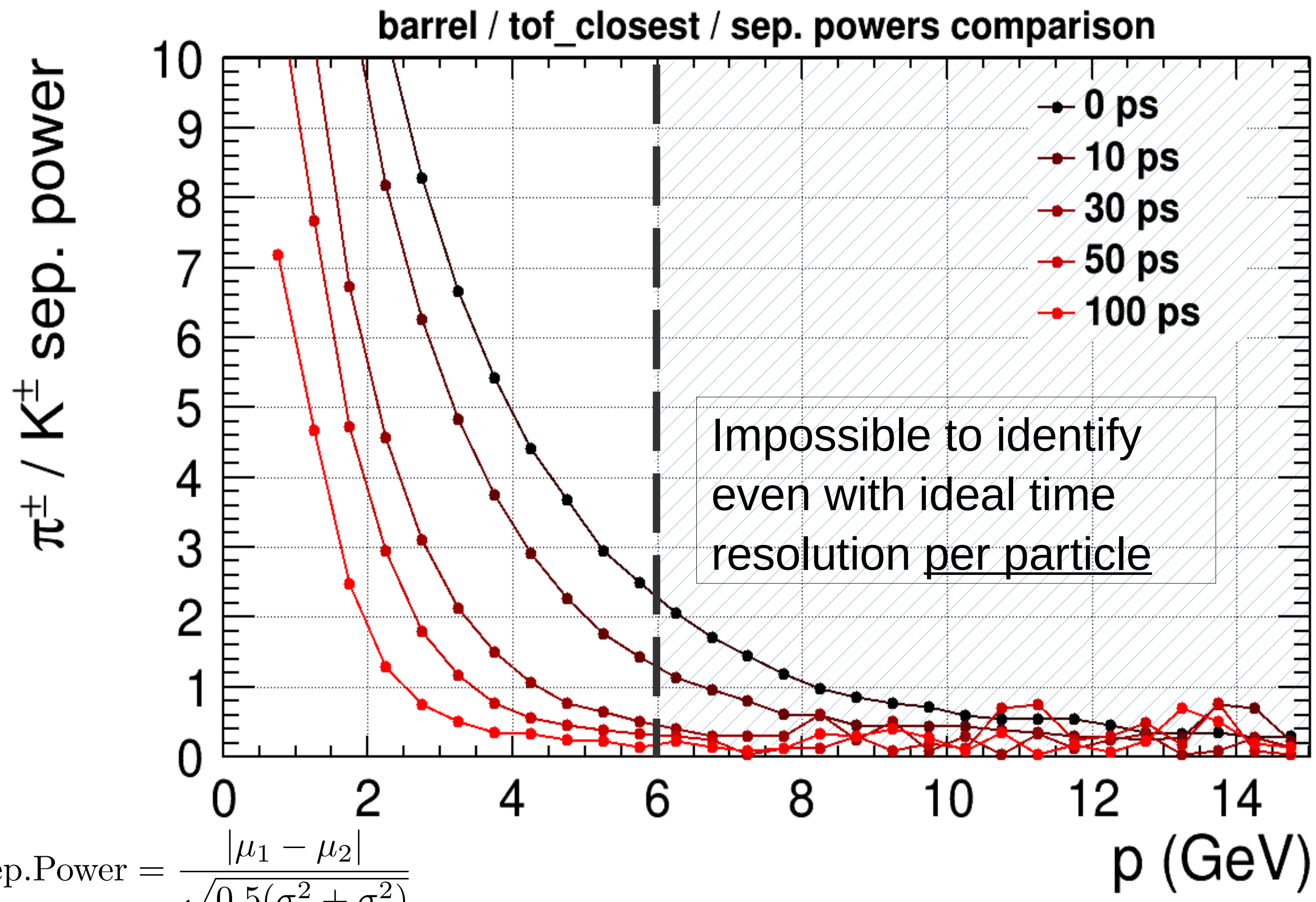
Extraction of the separation power

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



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

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

Track length impact

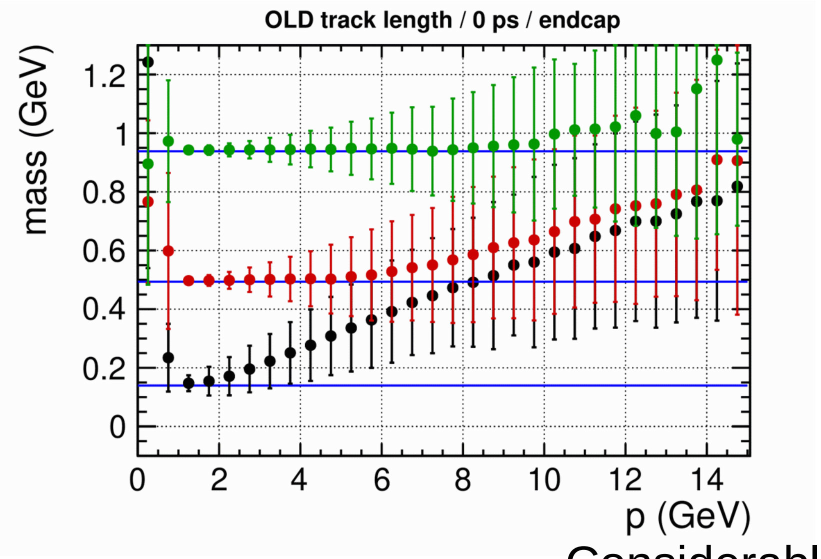
Winfried A. Mitaroff
arXiv:2107.02031

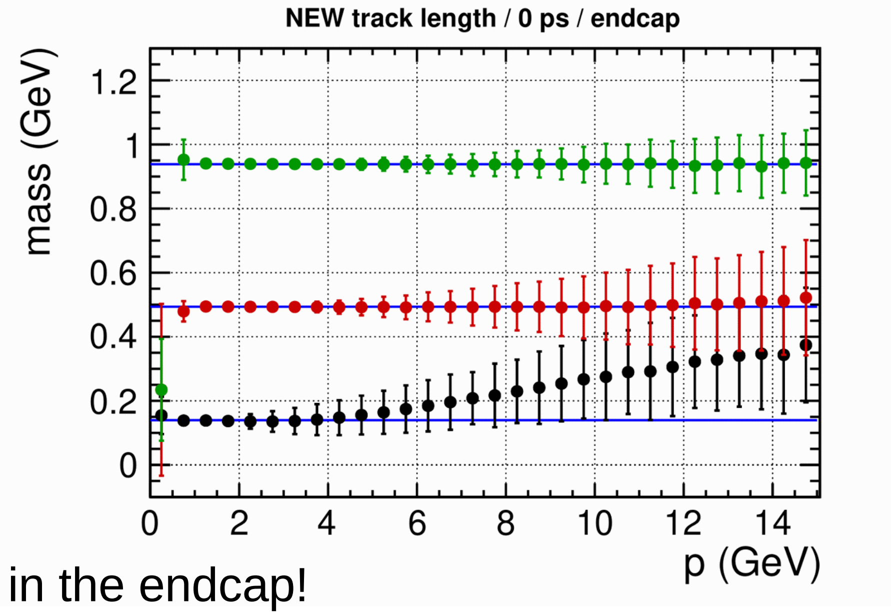
Helix approximation (bad)

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

Iterate hit-by-hit (good)

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



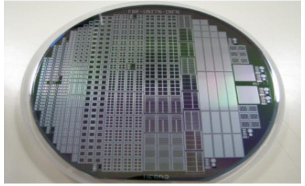


Considerable improvement in the endcap!

Plots use TPC with 220 radial hits

<u>Large number of track hits is important for track length measurement</u>

Realistic implementations inside a detector



E.g. LGADs Si sensors

time resolution < 50 ps

Detector design has constraints:

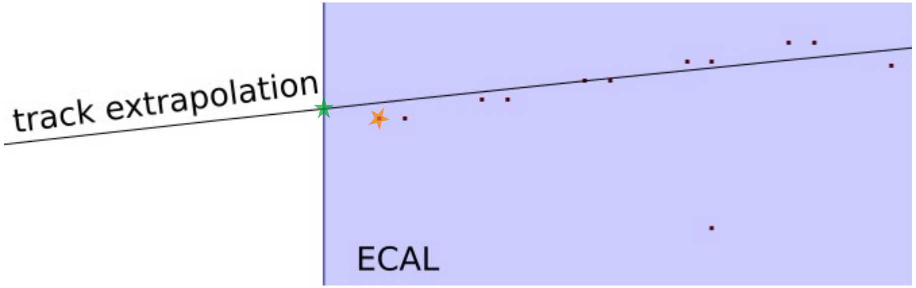
- precise timing → higher power consumption
- higher power consumption → more money
- higher power consumption → more space & material for active cooling

What about synchronization across a large detector?

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

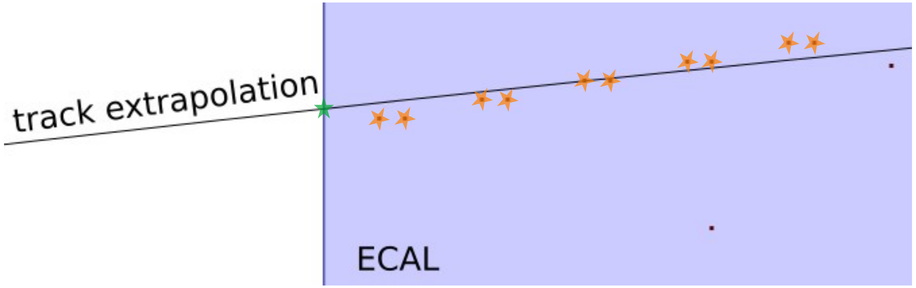
Comparison of three realistic scenarios

1st ECAL layer with LGADs (~30 ps hit time resolution)



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

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

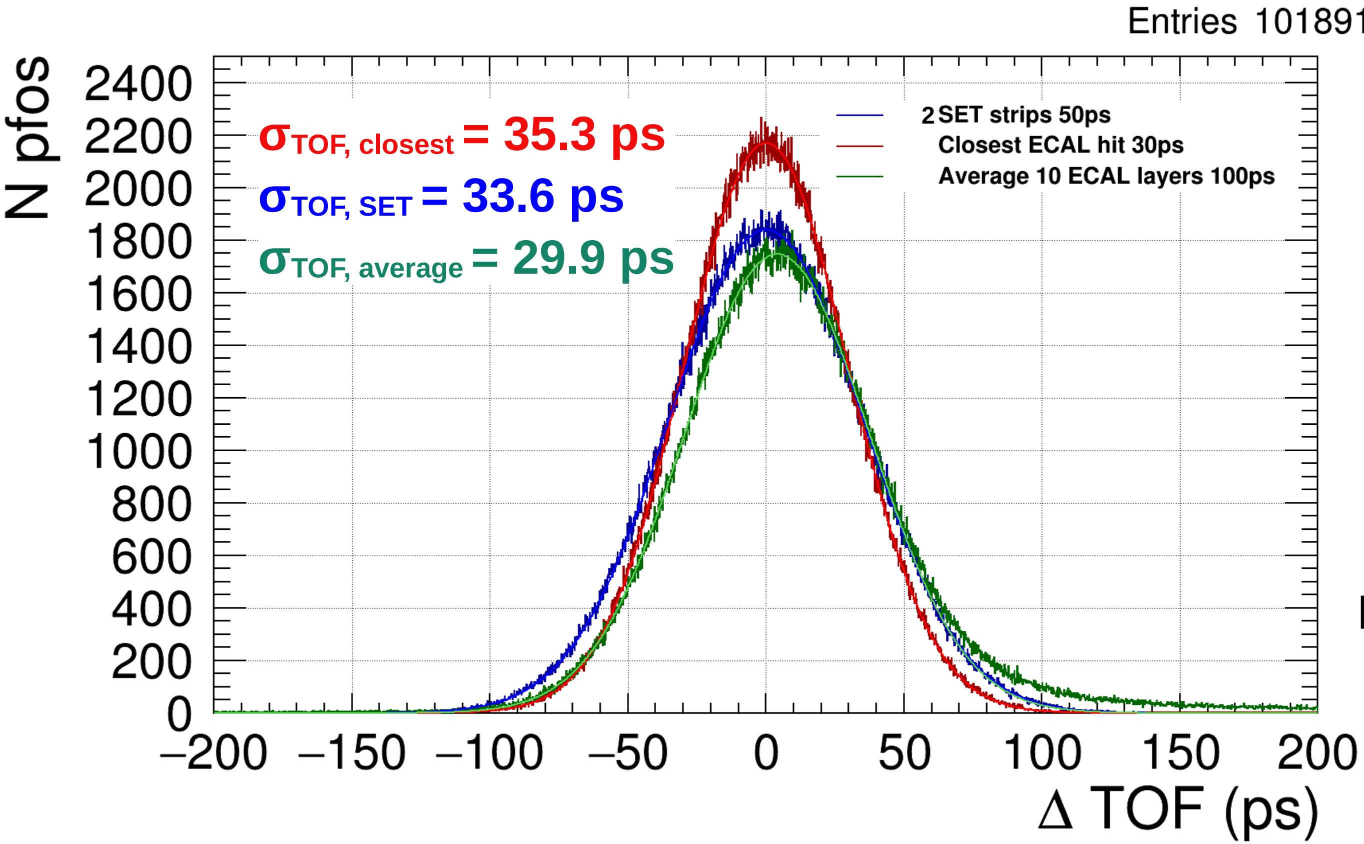


$$\mathrm{TOF} = \frac{1}{N_{\mathrm{hits}}} \sum_{i=1}^{N_{\mathrm{hits}}} \left(t_{\mathrm{i}} - \frac{|\vec{r}_{\mathrm{i}} - \vec{r}_{\mathrm{track}}|}{c} \right); \quad \Delta\mathrm{TOF} = \frac{\Delta t_{\mathrm{hit}}}{\sqrt{N_{\mathrm{hits}}}}$$

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

$$\mathrm{TOF} = \frac{t_{\mathrm{front\ strip}} + t_{\mathrm{back\ strip}}}{2}; \qquad \Delta\mathrm{TOF} = \frac{\Delta t_{\mathrm{hit}}}{\sqrt{2}}$$

Comparison of three realistic scenarios



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

Combining many hits give:

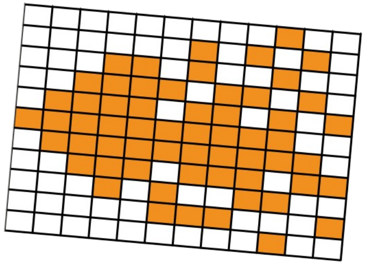
$$\sigma_{\mathrm{TOF}} \sim \frac{\sigma_{\mathrm{hit}}}{\sqrt{n}}$$

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



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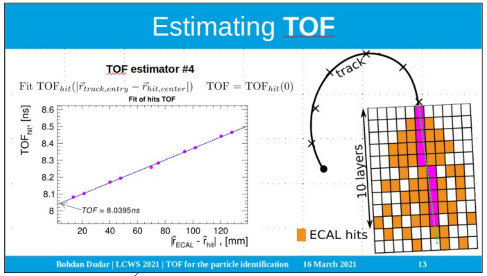
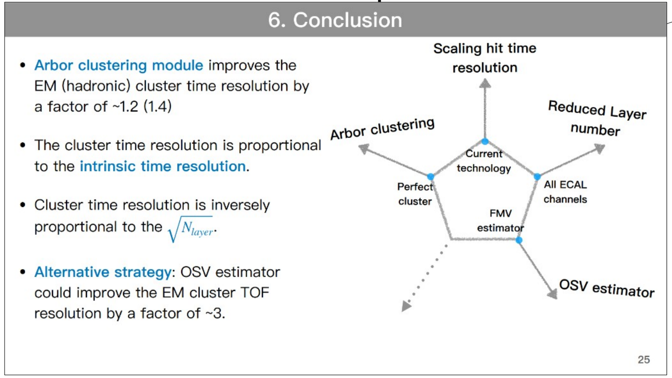


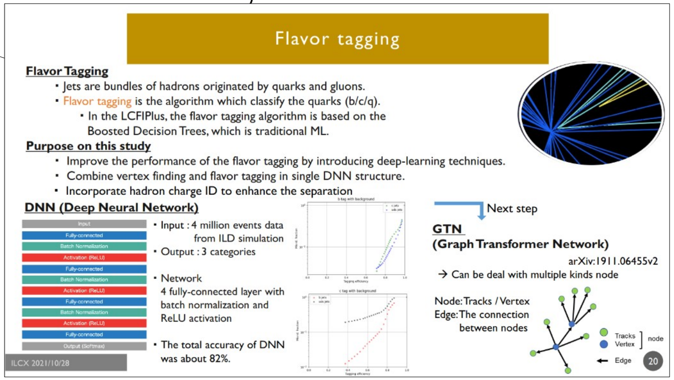
$$\text{Very smart algorithm} \left(\qquad \right) = \text{time-of-flight}$$

Yuzhi Che, Manqi Ruan



<u>Many</u> analyses are ongoing...

Mami Kuhara, Taikan Suehara



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

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

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

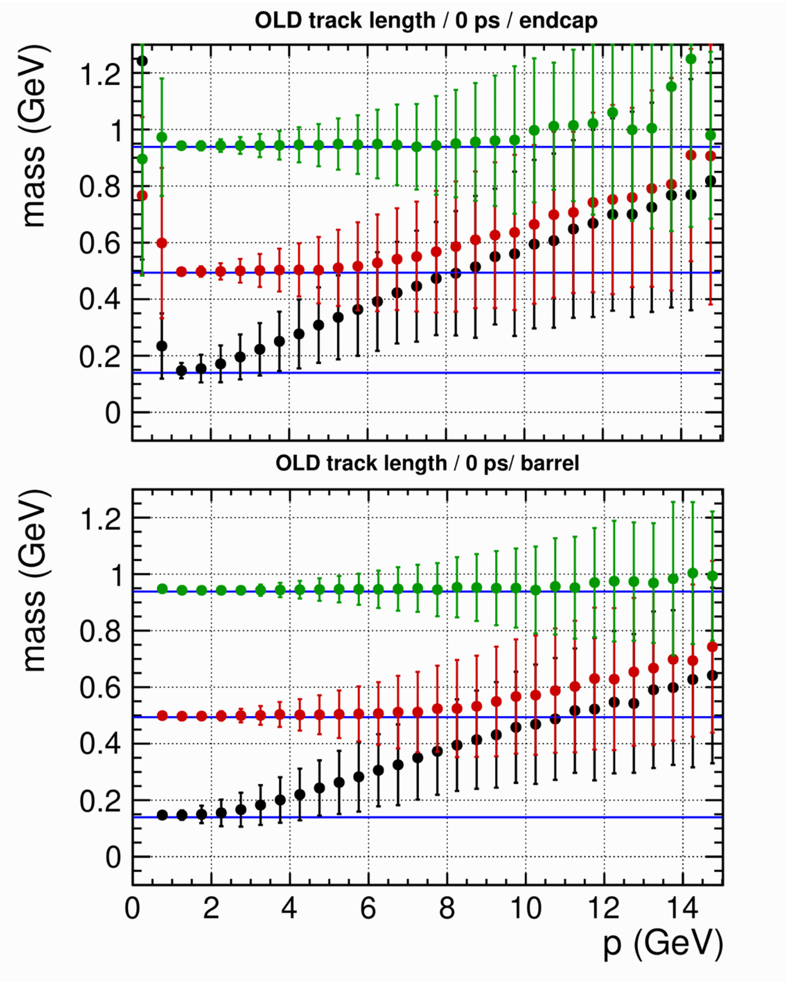
$$\beta = \frac{\ell_{\text{track}}}{c \cdot \text{TOF}}$$

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

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

Winfried A. Mitaroff
arXiv:2107.02031

Back up: new track length results for the barrel



ENDCAP

BARREL