

Time-of-flight particle identification at future Higgs factories

DPG conference, session: T 48.5

21 March 2023

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HELMHOLTZ

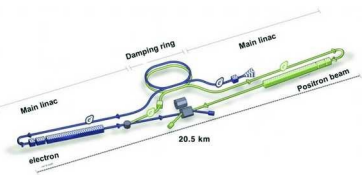


CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

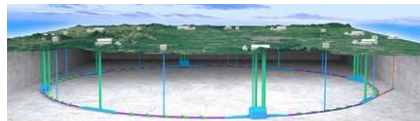


Future Higgs factory candidates

ILC



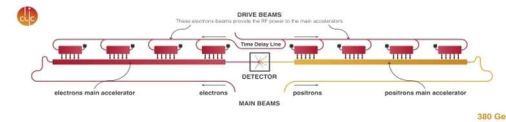
CEPC



FCC-ee



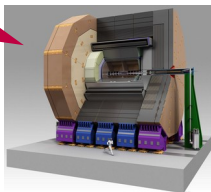
CLIC



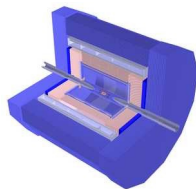
Detector concepts

This study is done using ILD

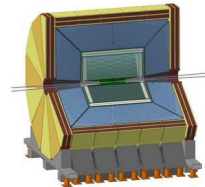
ILD



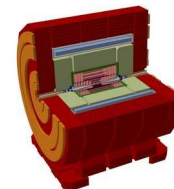
CEPC Baseline



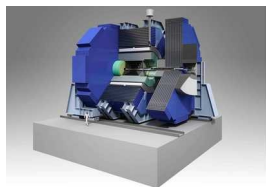
IDEA



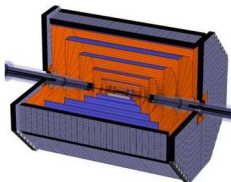
CLICdp



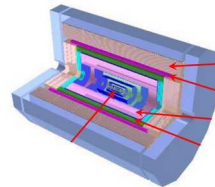
SiD



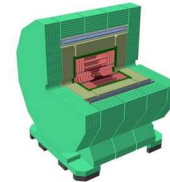
FST



CEPC 4th concept

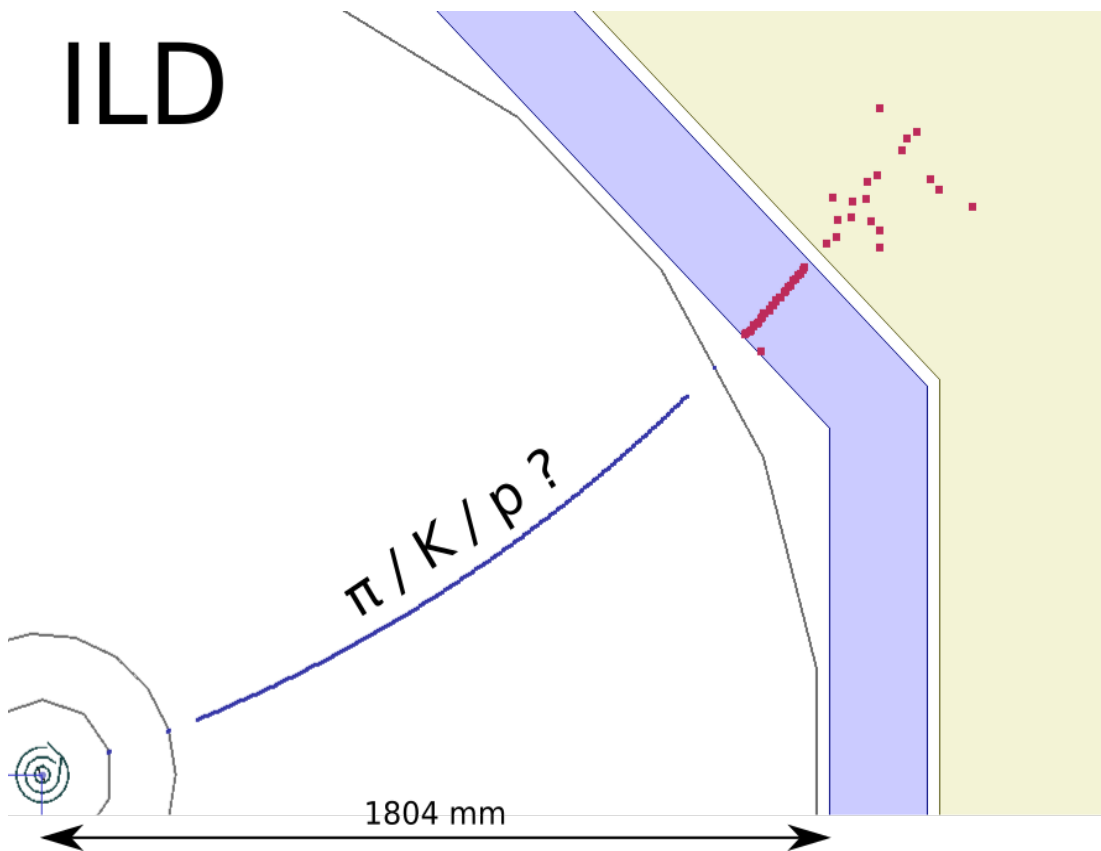


CLD

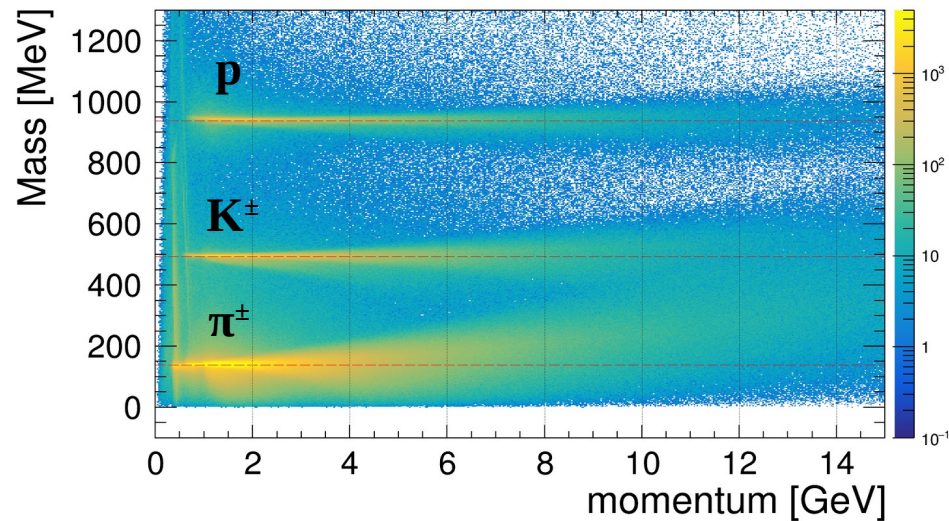


Time-of-flight particle ID is great complementary tool to dE/dx (dN/dx) in gaseous detectors
And is only available particle identification tool for fully Si detector designs

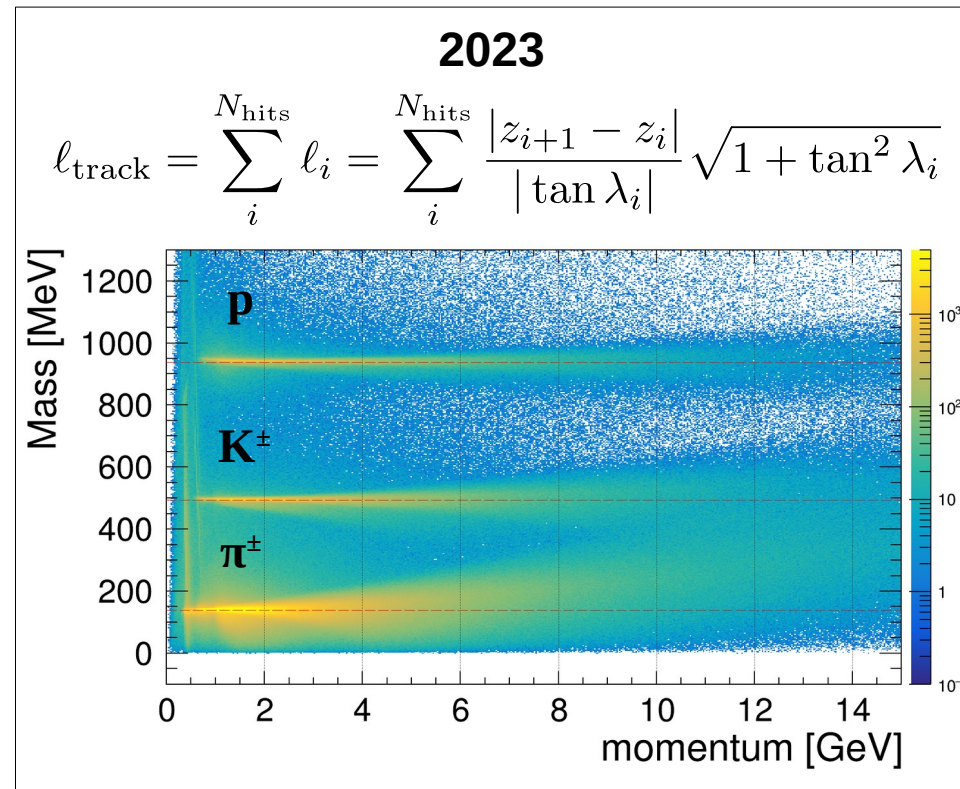
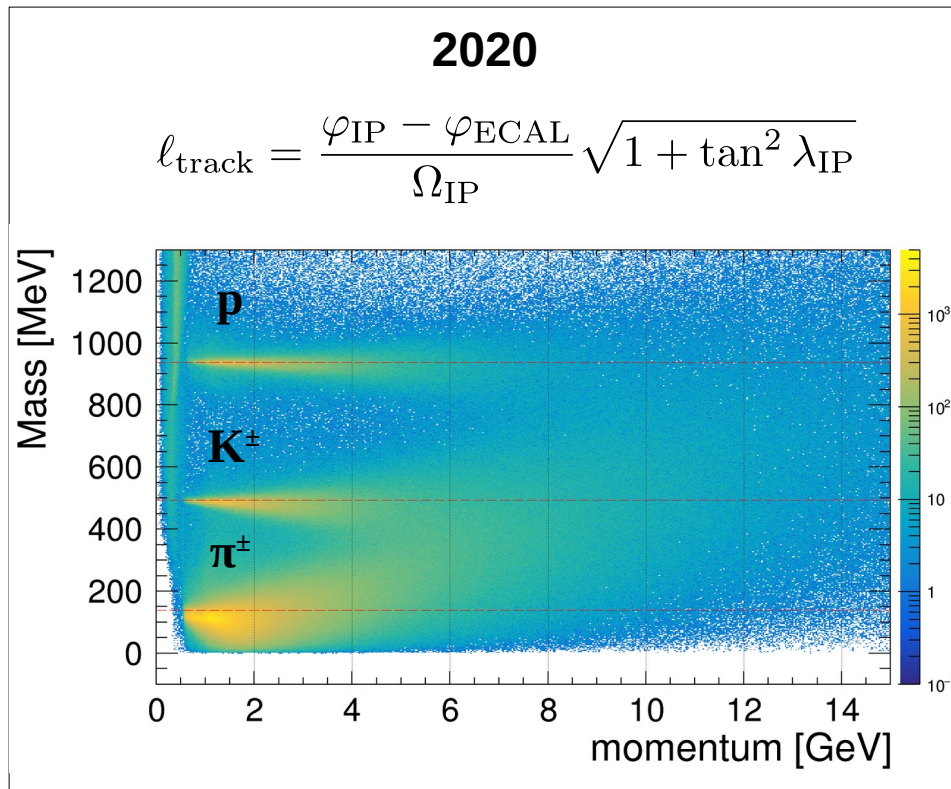
How does time-of-flight particle identification work?



$$m = p \sqrt{\frac{c^2 \text{TOF}^2}{\ell_{\text{track}}^2} - 1}$$



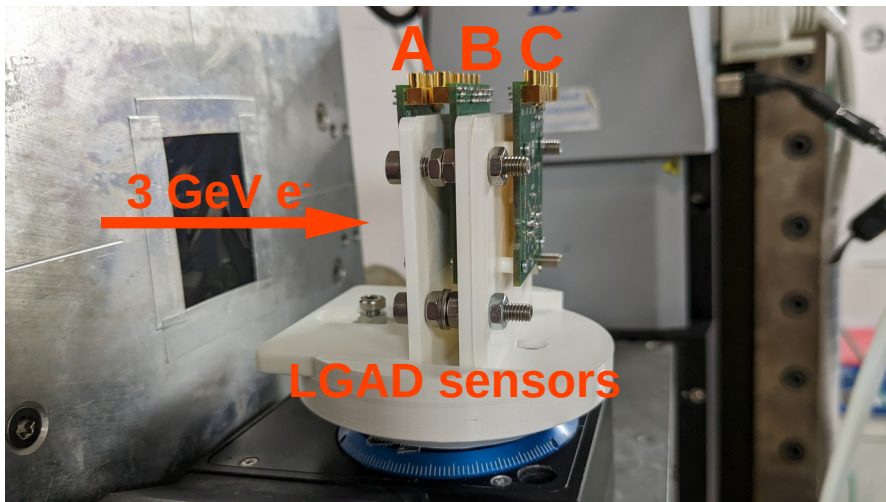
Impact of track length reconstruction



- ❖ Track length reconstruction is not trivial
- ❖ Track length is also a limiting factor
- ❖ Track length in fully Si trackers might be challenging?

plots assume perfect time resolution
and use ILD TPC with 220 radial hits

Time resolution of the LGADs: test beam measurements



$$\Delta t_{AB} = t_A - t_B$$

$$\Delta t_{CB} = t_C - t_B$$

$$\Delta t_{CA} = t_C - t_A$$



$$\sigma_{AB}^2 = \sigma_A^2 + \sigma_B^2$$

$$\sigma_{CB}^2 = \sigma_C^2 + \sigma_B^2$$

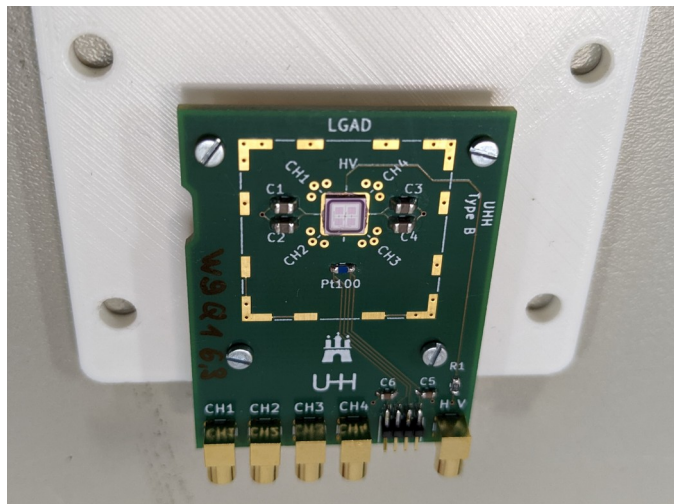
$$\sigma_{CA}^2 = \sigma_C^2 + \sigma_A^2$$



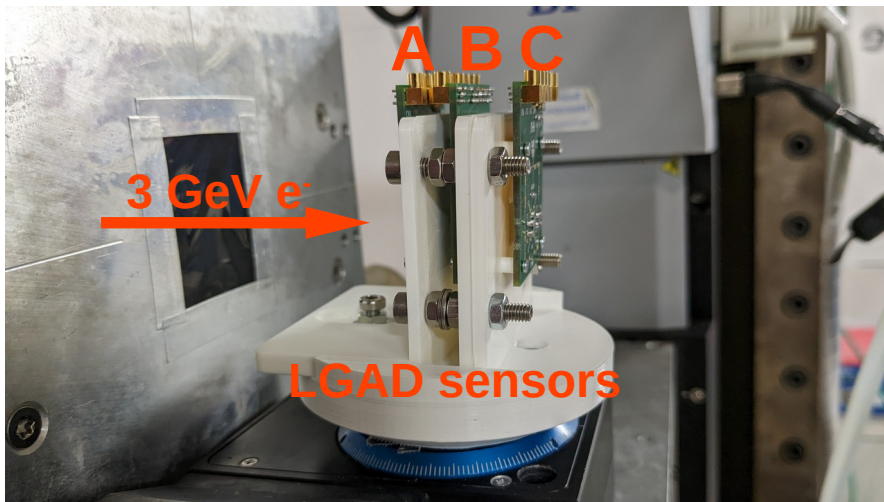
$$\sigma_A^2 = \frac{\sigma_{AB}^2 + \sigma_{CA}^2 - \sigma_{CB}^2}{2}$$

$$\sigma_B^2 = \frac{\sigma_{AB}^2 + \sigma_{CB}^2 - \sigma_{CA}^2}{2}$$

$$\sigma_C^2 = \frac{\sigma_{CA}^2 + \sigma_{CB}^2 - \sigma_{AB}^2}{2}$$



Time resolution of the LGADs: test beam measurements



$$\Delta t_{AB} = t_A - t_B$$

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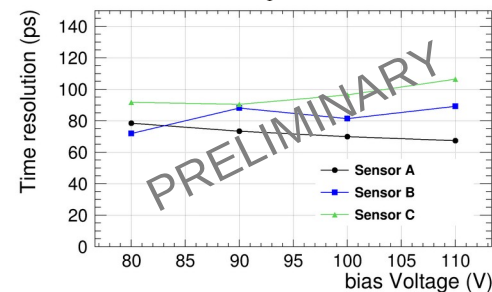
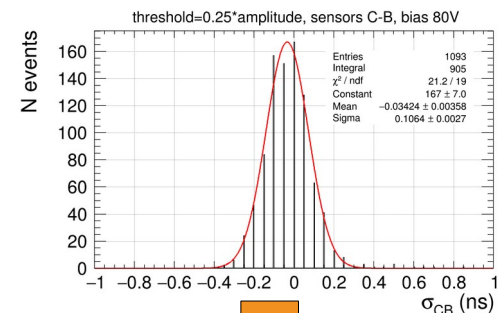
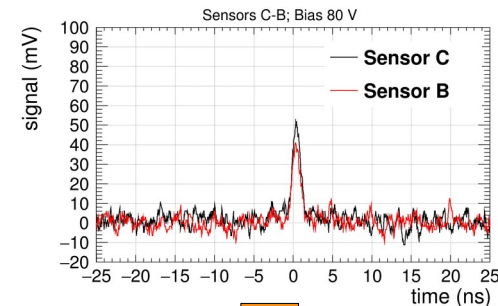
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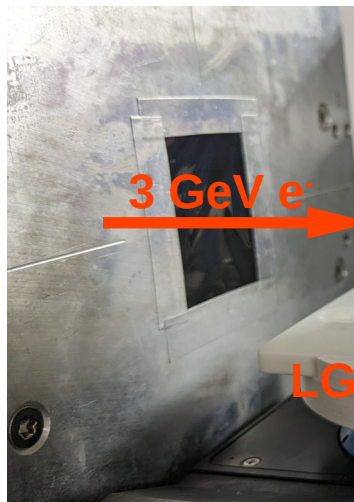
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Time resolution of the LGADs: test beam measurements



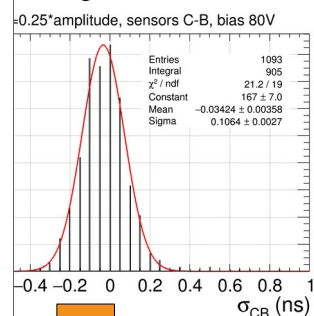
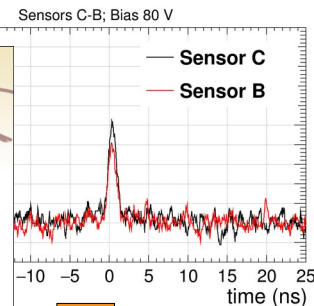
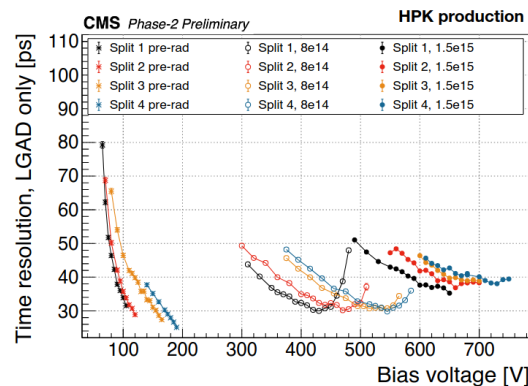
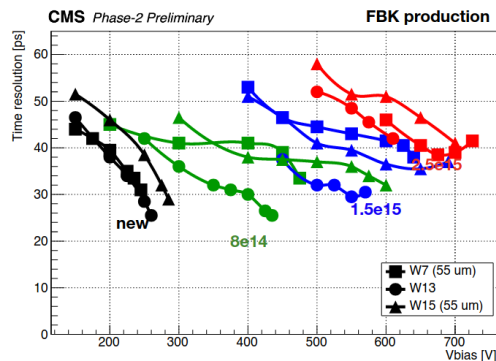
Timing resolution performances

Sensor performances are benchmarked using very fast low noise electronics

→ results might be different with the ETL ASIC

Measurements performed with **Beta-source setups** based on **Sr90 sources** in Torino and at Fermilab

Most performing prototypes can reach a **timing resolution <40 ps** up to fluences of **$2.5 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$**



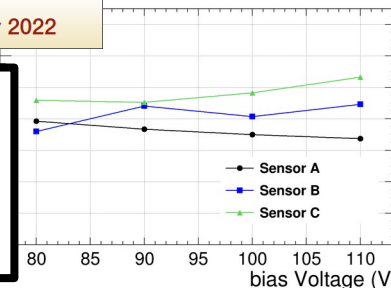
Marta Tornago

ICHEP 2022 Bologna

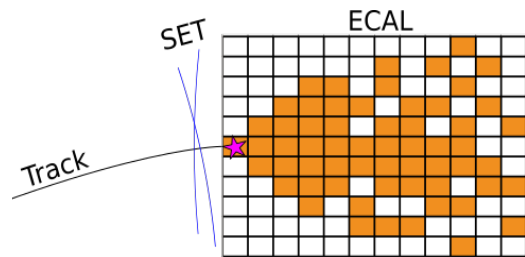
7th July 2022

We have measured 80 ps time resolution
CMS/ATLAS: < 40 ps is achievable

ICHEP link



Timing implementation in the ILD



Placement:

Dedicated ECAL
timing layer (LGADs)

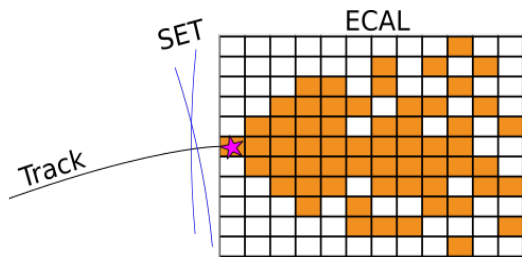
Hit time resolution:

~ 30 ps

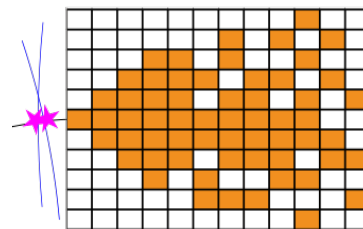
TOF resolution:

~ 30 ps

Timing implementation in the ILD



Dedicated ECAL
timing layer (LGADs)



Two Si strips of external
tracker (LGADs?)

Hit time resolution:

~ 30 ps

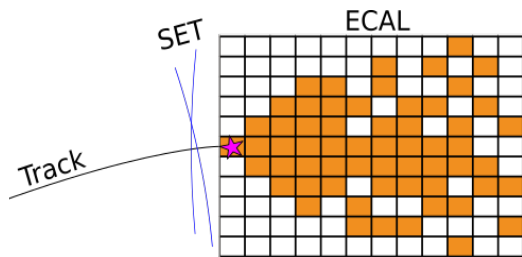
~ 50 ps

TOF resolution:

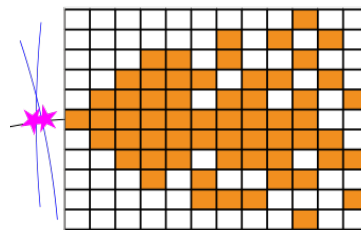
~ 30 ps

~ ? ps

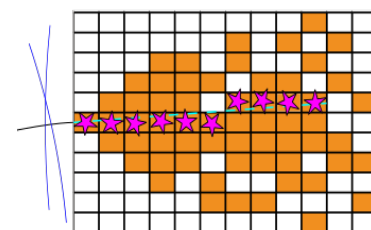
Timing implementation in the ILD



Dedicated ECAL
timing layer (LGADs)



Two Si strips of external
tracker (LGADs?)



10 ECAL layers
(not LGADs)

Hit time resolution:

~ 30 ps

~ 50 ps

~ 100 ps

TOF resolution:

~ 30 ps

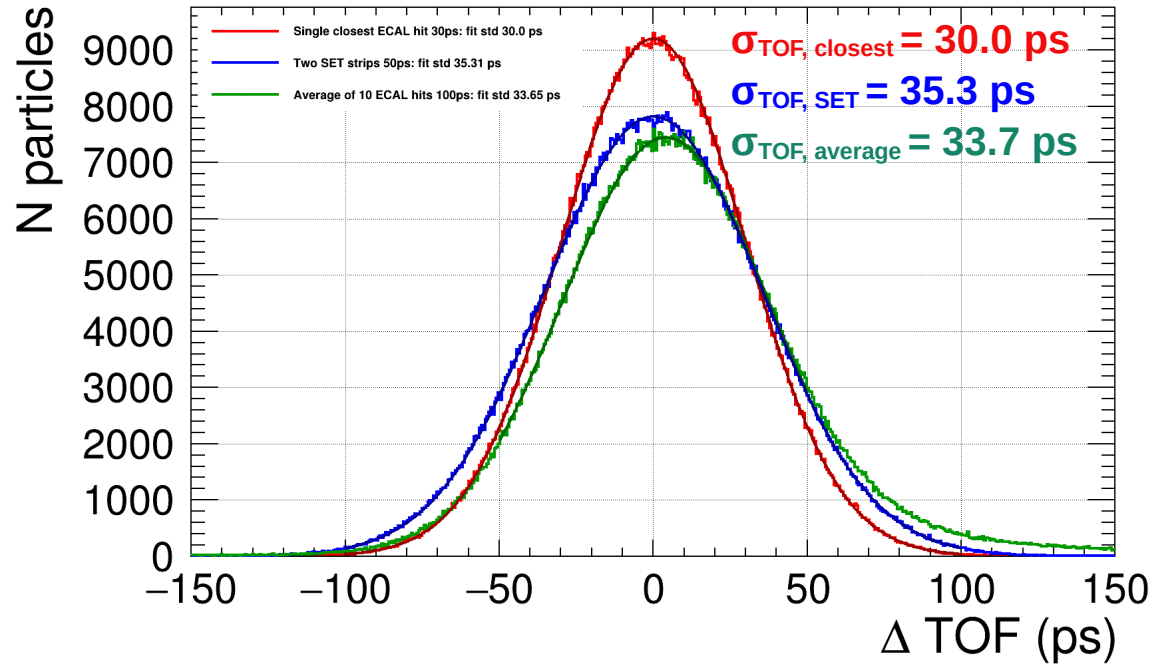
~ ? ps

~ ? ps

LGADs in the detector:

- high power consumption
- active cooling
- space& material budget
- not good

Timing implementation in the ILD

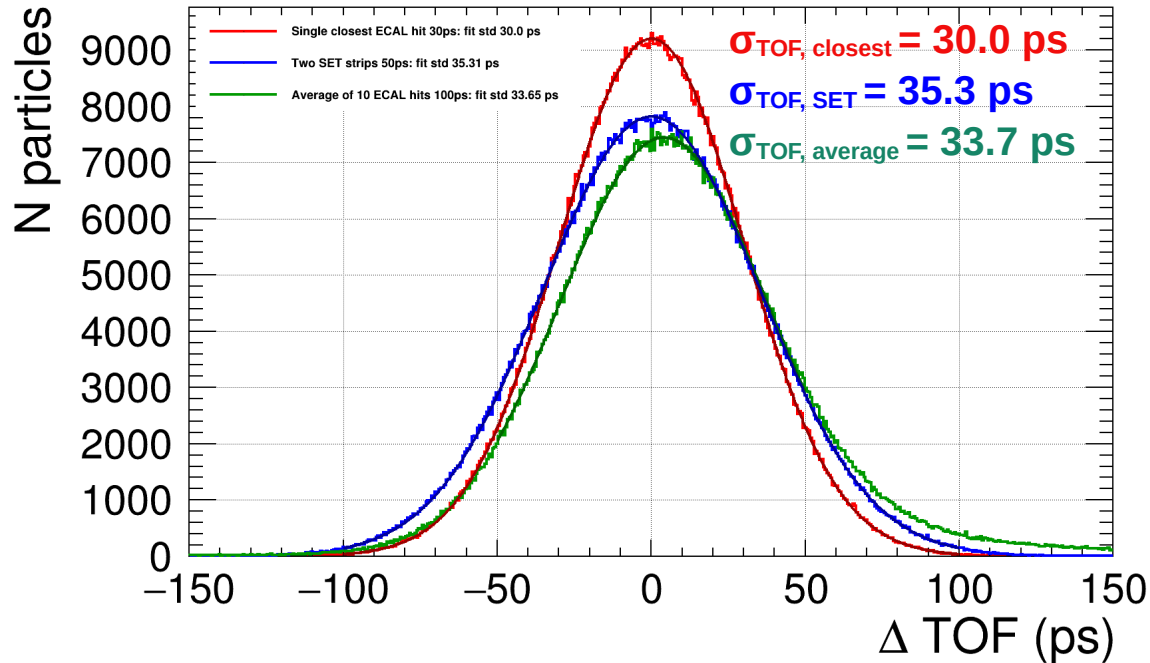


TOF resolution behaves as an average of independent measurements:

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

- ❖ Rule of thumb: more hits $\rightarrow$ better
- ❖ No significant^(back up) deterioration (10 hits)
- ❖ Deterioration due to shower development might appear using more hits (?)

Timing implementation in the ILD



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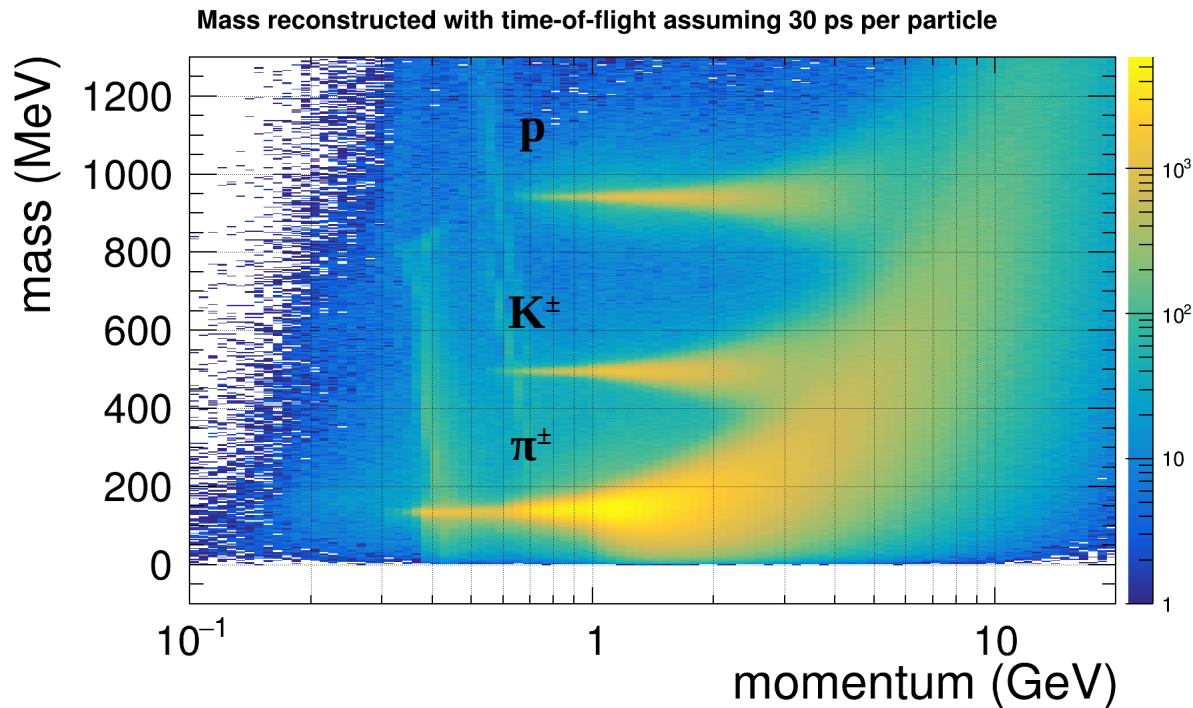
- ❖ Rule of thumb: more hits $\rightarrow$ better
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Be alert – time simulation is simplified:

- ❖ hit time res. = Gauss smear of the MC_{true}
- ❖ no time res. vs hit energy effects
- ❖ no threshold digitizer effects

Let's assume **30 ps TOF resolution per particle** is doable.
What does it mean in terms of the particle identification?

TOF separation power (30 ps TOF resolution)

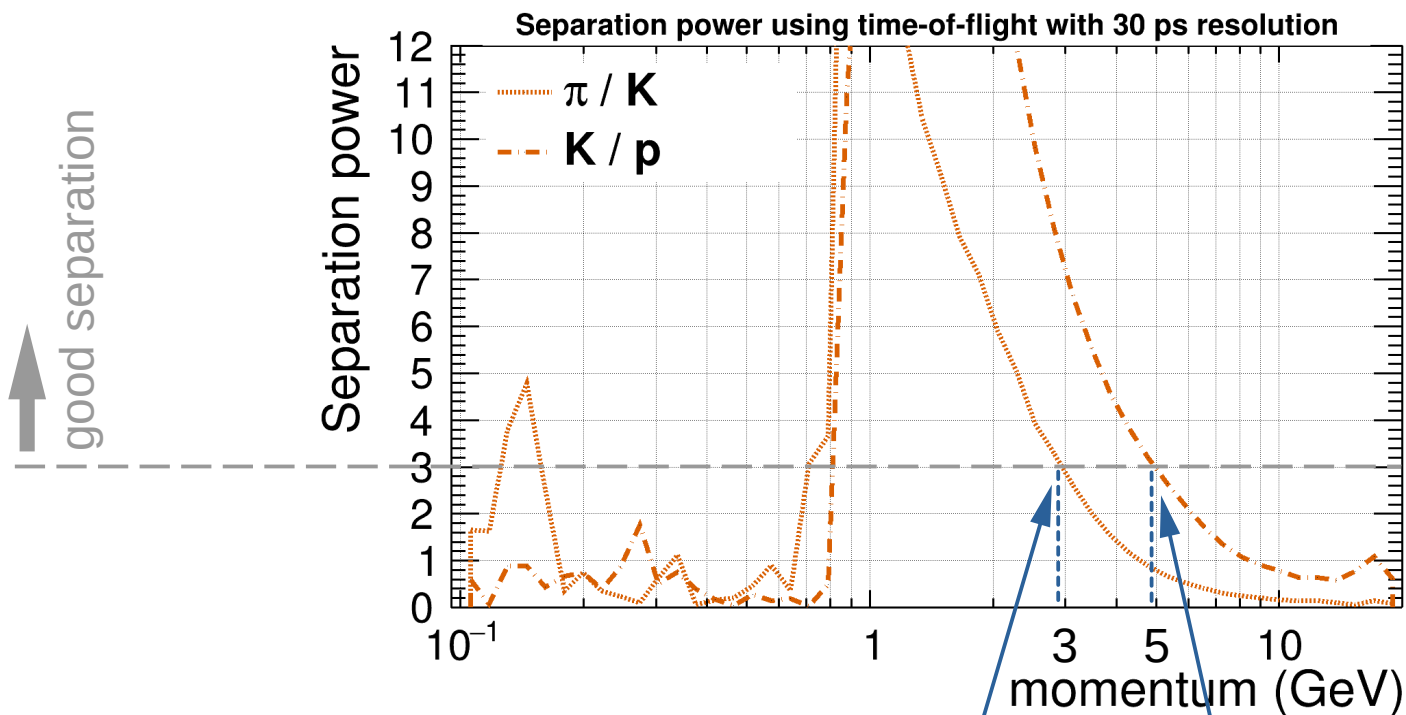


Fit each particle band in each momentum slice with a Gaussian

and define sep. power:

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

TOF separation power (30 ps TOF resolution)



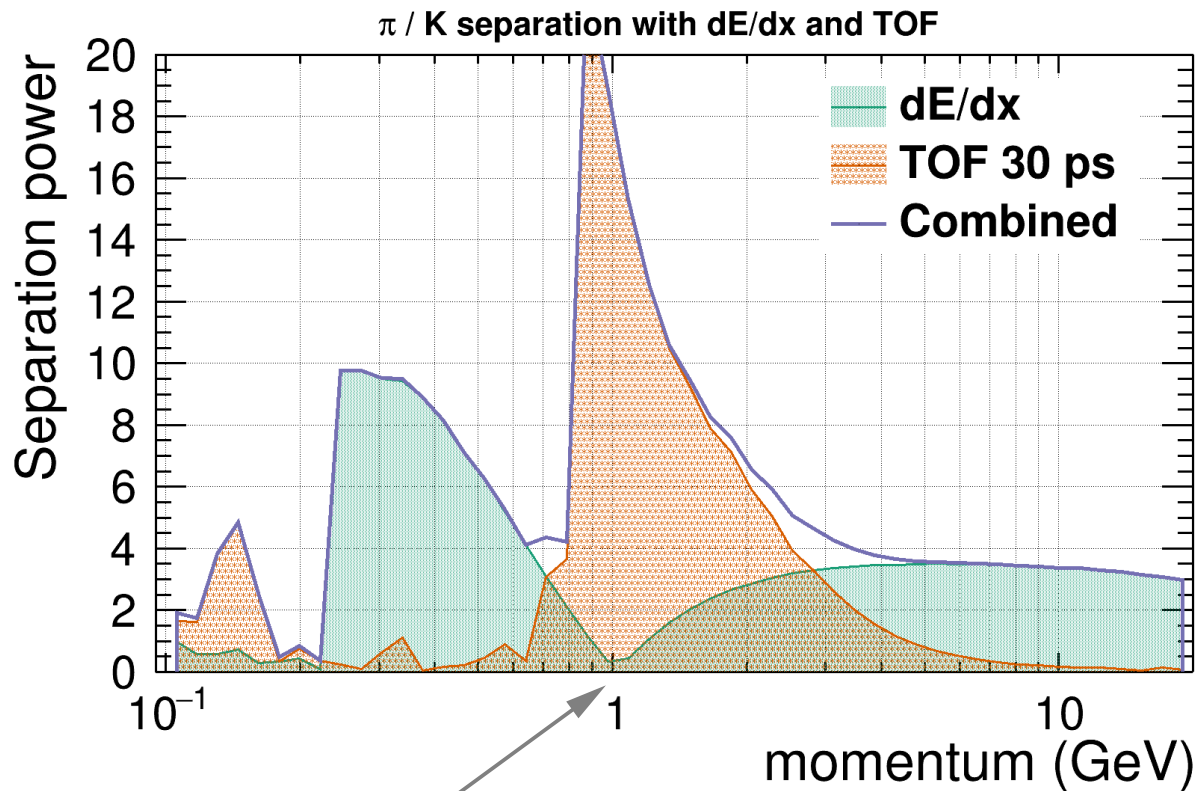
$$\text{Sep. Power} = \frac{|\mu_1 - \mu_2|}{\sqrt{0.5(\sigma_1^2 + \sigma_2^2)}}$$

TOF can provide:

- ❖ π/K separation **up to 3 GeV**
- ❖ K/p separation in **up to 5 GeV**

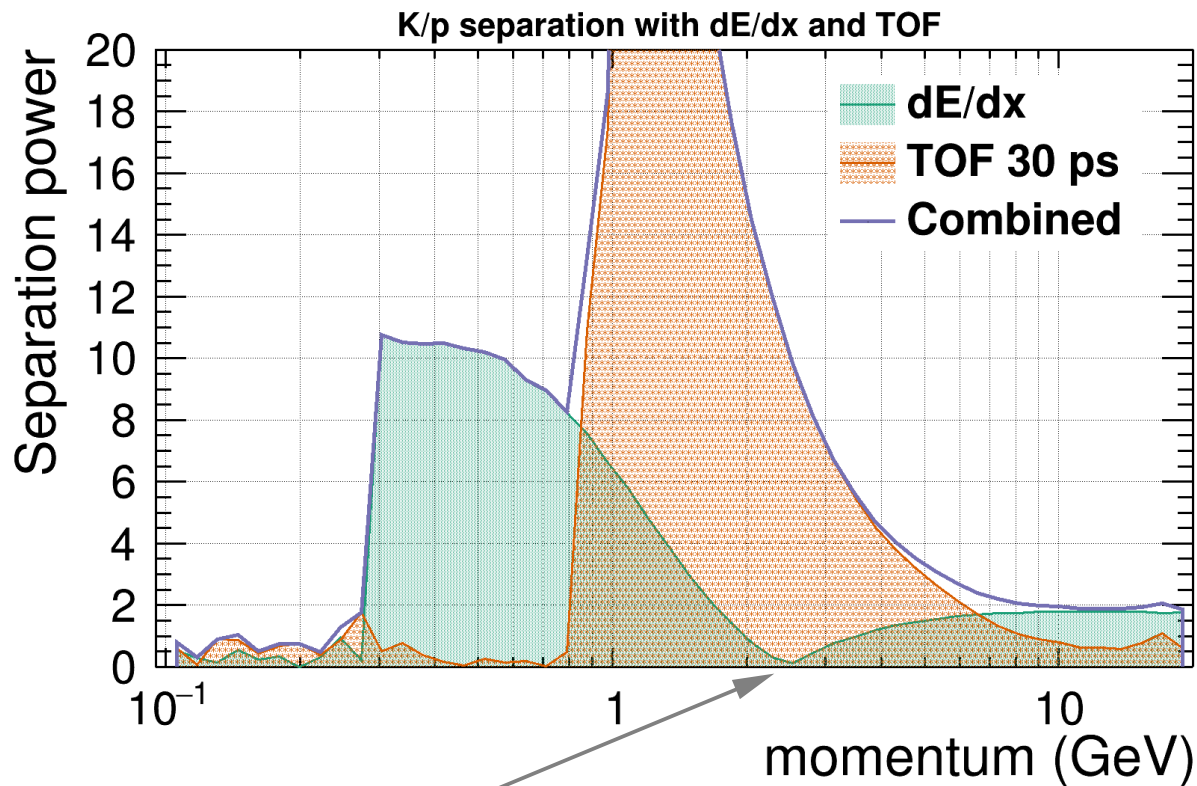
How does it interplay with dE/dx ?

π/K separation power of dE/dx + TOF (30 ps)



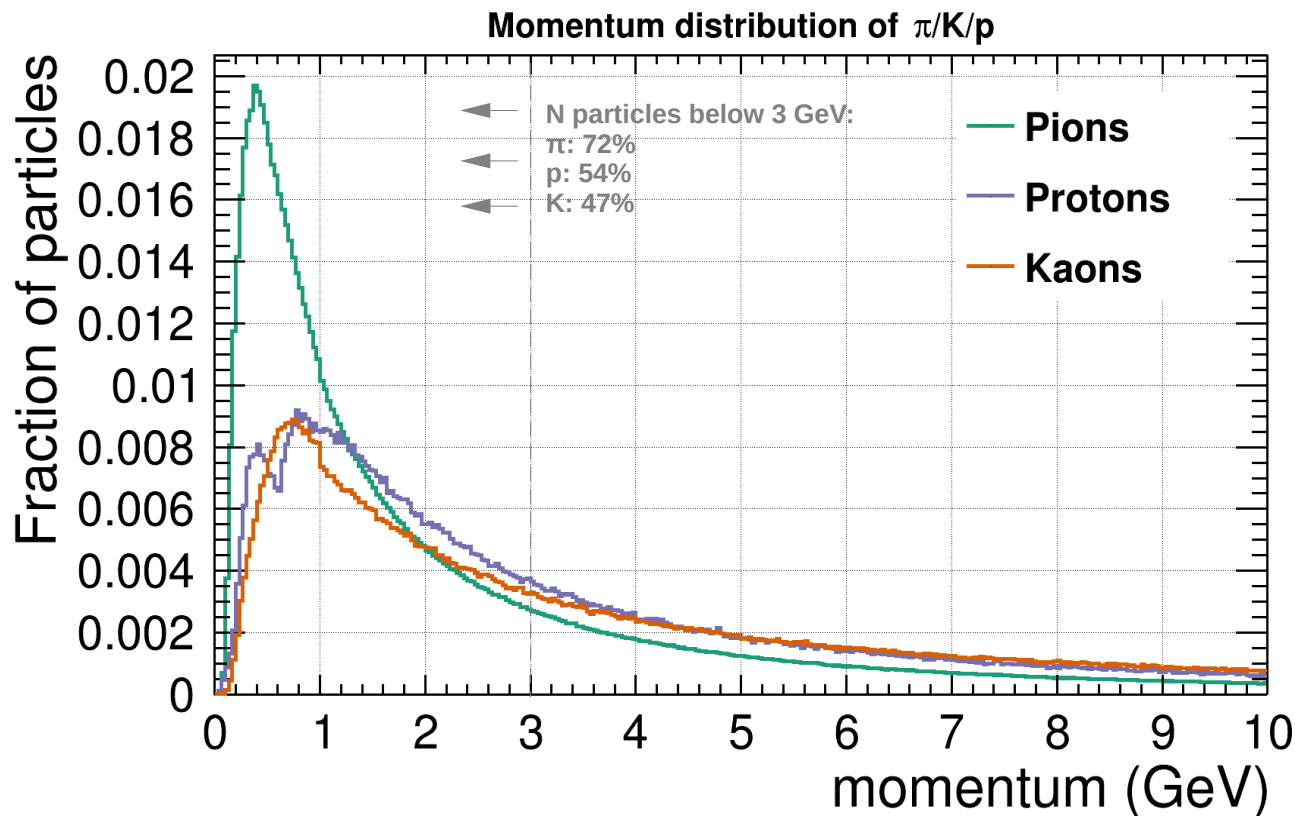
dE/dx blind spot is nicely covered by TOF

K/p separation power of dE/dx + TOF (30 ps)



dE/dx blind spot is nicely covered by TOF
How relevant is this momentum range?

Momentum distribution of $\pi/K/p$



Used MC samples:

$e^+e^- \rightarrow Z \rightarrow qq$ @ 250 GeV

$e^+e^- \rightarrow WW \rightarrow qqqq$ @ 250 GeV

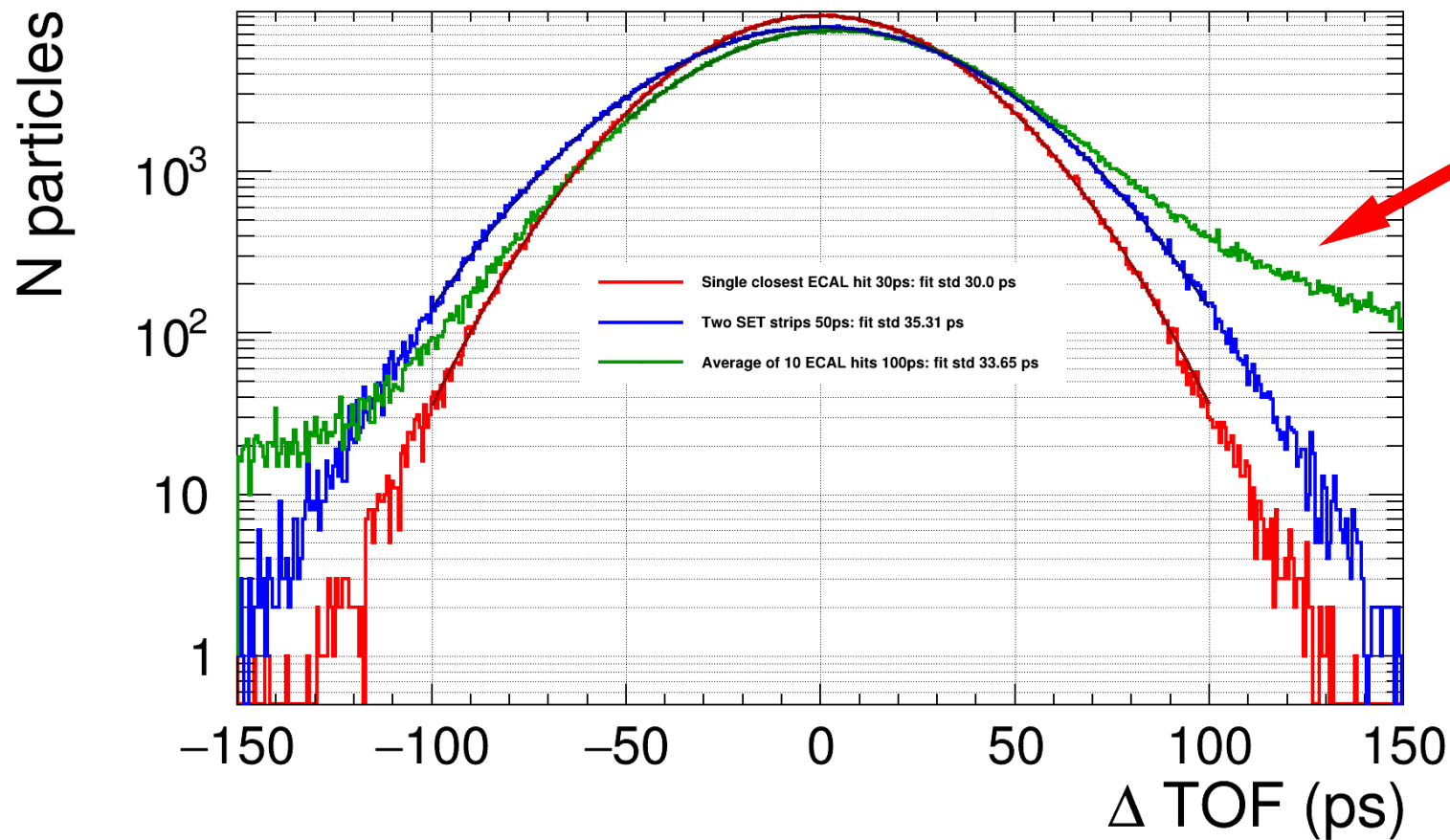
Majority of produced hadrons are at low momentum!
However, often leading particles are of most interest

Summary

- ❖ **Track length** reconstruction is not trivial and also a **limiting factor for TOF**.
Might be very **challenging with fully Si tracking**
- ❖ Dedicated ECAL timing layer or full ECAL with conventional Si sensors both viable.
A better **understanding of heat&cooling requirements** are needed
- ❖ TOF provides **π/K separation up to 3 GeV** assuming **30 ps resolution** per particle.
That is momentum range, where the majority of particles are produced
- ❖ **dE/dx** particle identification **is crucial** at future Higgs factories
and **TOF complements** it very well **by covering blind spots**

Back up

Back up: Averaging creates non-gaussian tail (not accounted in STD!)



Back up: Potential applications of time-of-flight

Potentially few applications for TOF pID:

- ❖ Kaon mass → achievable, requires involved study
- ❖ Track reconstruction → no clear transition to physics
- ❖ Vertex reconstruction → requires involved study
- ❖ Higgs studies ($H \rightarrow gg$) → requires involved study
- ❖ Flavour physics → not clear so far
- ❖ Generator tuning → not clear so far

**many little improvements to the event reconstruction
but no strong physics case so far**

- ❖ dE/dx in the ILD already covers a good momentum range of leading particles

A valuable food for thoughts for future detectors development

- ❖ Benefit of TOF for physics case at future Higgs factory?
- ❖ SiD, CLD, CLICdp (no dE/dx): track length is not trivial