Time-of-flight particle identification at future Higgs factories

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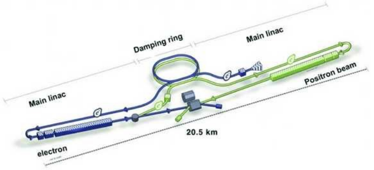
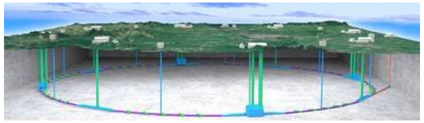
Future Higgs factory candidates

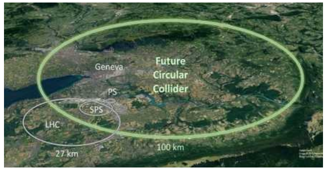
ILC



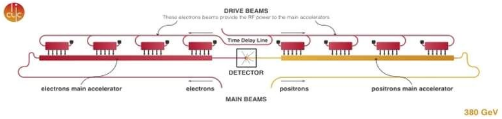
CEPC



FCC-ee



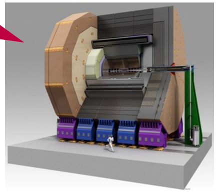
CLIC



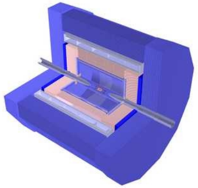
Detector concepts

This study is done using ILD

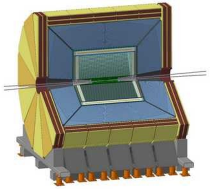
ILD



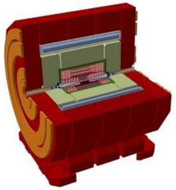
CEPC Baseline



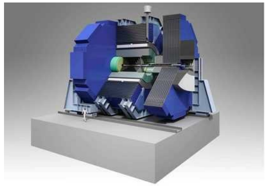
IDEA



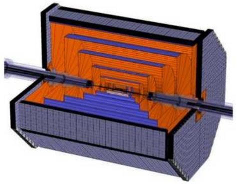
CLICdp



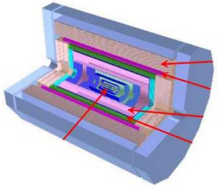
SiD



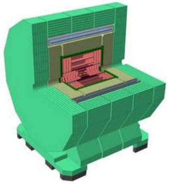
FST



CEPC 4th concept

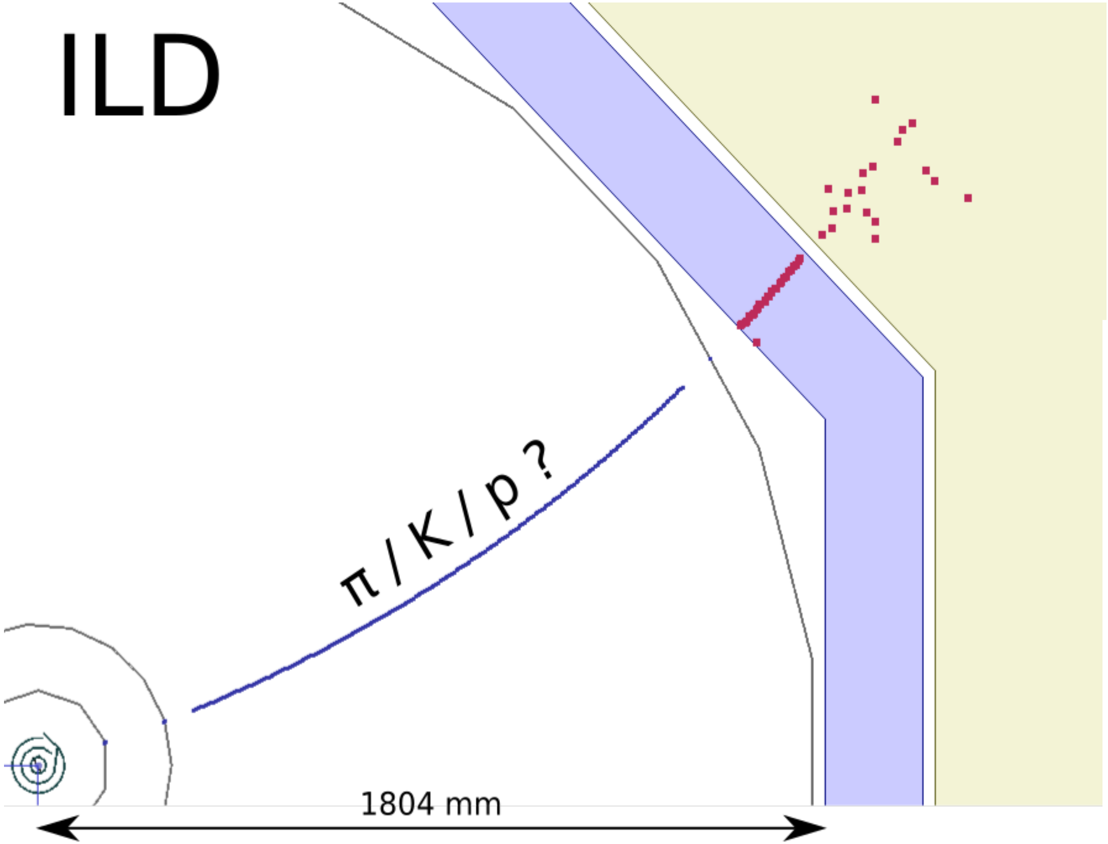


CLD

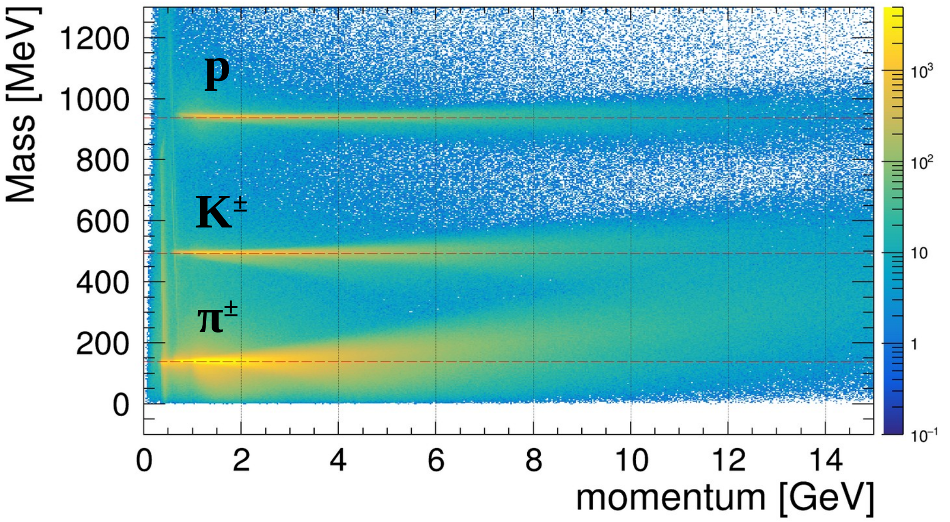


Time-of-flight particle ID is great complementary tool to dE/dx (dN/dx) in gaseous detectors
And is only available particle identification tool for fully Si detector designs

How does time-of-flight particle identification work?



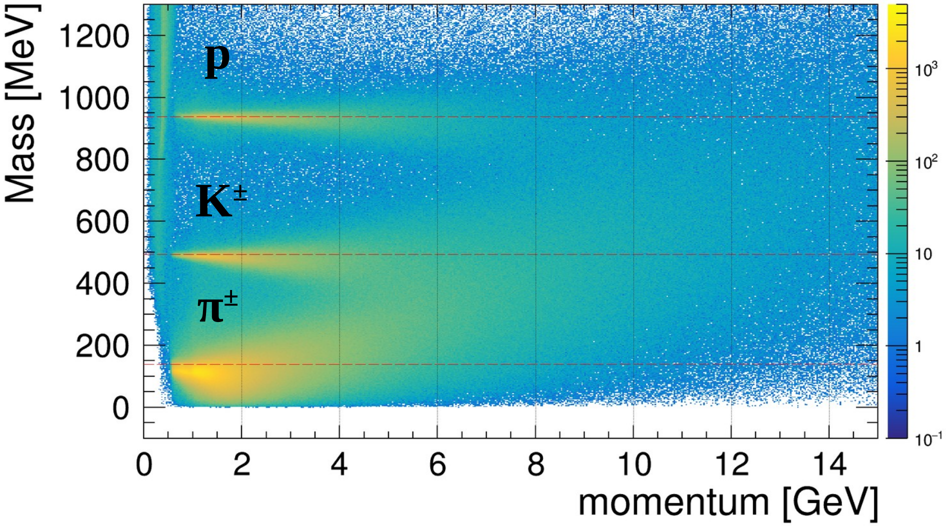
$$m = p\sqrt{\frac{c^2\mathrm{TOF}^2}{\ell^2_{\mathrm{track}}} - 1}$$



Impact of track length reconstruction

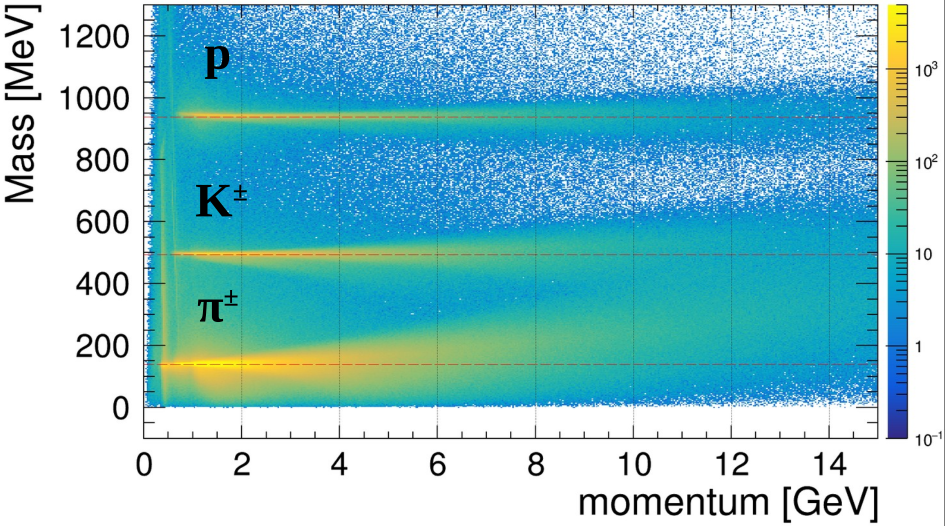
2020

$$\ell_{\text{track}} = \frac{\varphi_{\text{IP}} - \varphi_{\text{ECAL}}}{\Omega_{\text{IP}}}\sqrt{1+\tan^2\lambda_{\text{IP}}}$$



2023

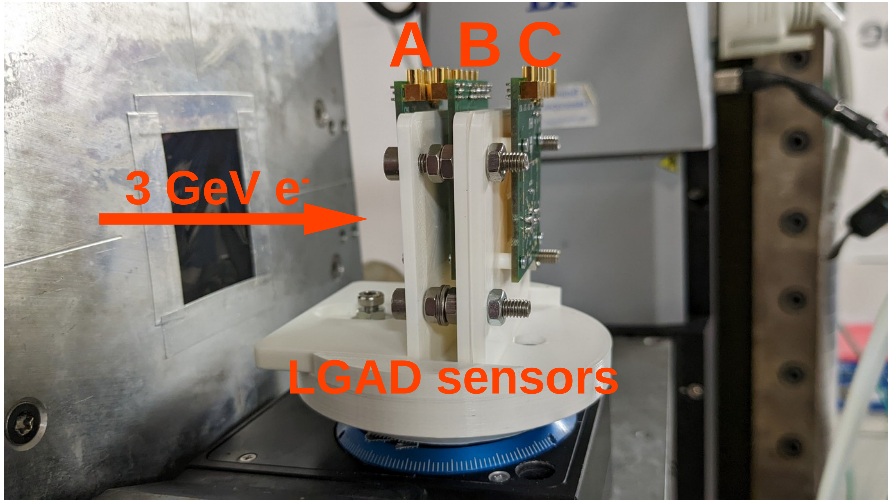
$$\ell_{\text{track}} = \sum_{i}^{N_{\text{hits}}} \ell_i = \sum_{i}^{N_{\text{hits}}} \frac{|z_{i+1} - z_i|}{|\tan\lambda_i|}\sqrt{1+\tan^2\lambda_i}$$

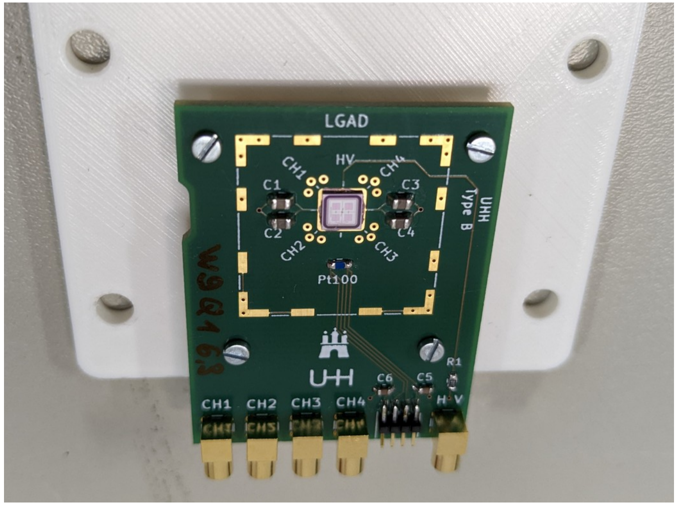


plots assume perfect time resolution

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

Time resolution of the LGADs: test beam measurements



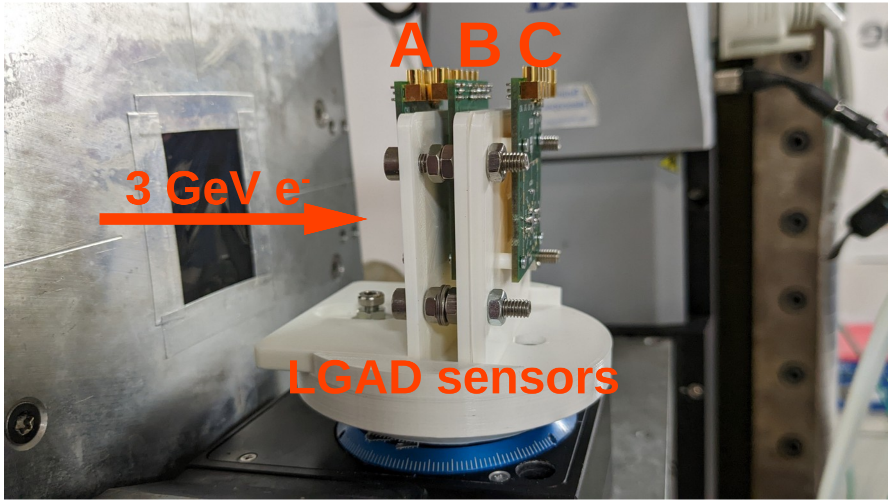


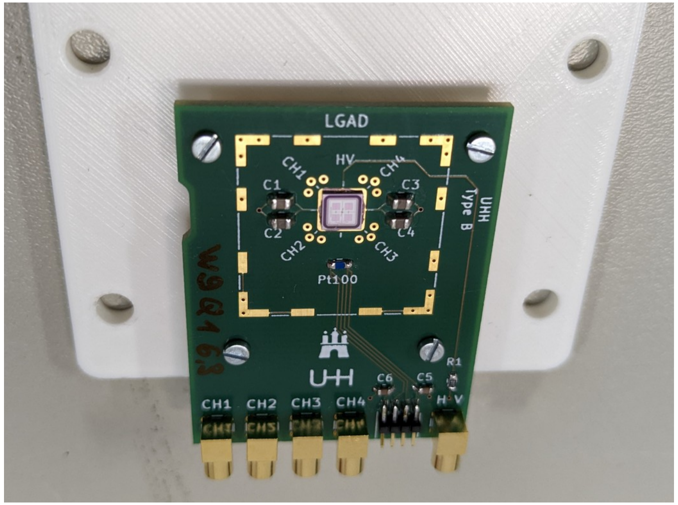
$$\Delta t_{AB} = t_A - t_B$$
$$\Delta t_{CB} = t_C - t_B$$
$$\Delta t_{CA} = t_C - t_A$$

$$\sigma^2_{AB} = \sigma^2_A + \sigma^2_B$$
$$\sigma^2_{CB} = \sigma^2_C + \sigma^2_B$$
$$\sigma^2_{CA} = \sigma^2_C + \sigma^2_A$$

$$\sigma^2_A = \frac{\sigma^2_{AB} + \sigma^2_{CA} - \sigma^2_{CB}}{2}$$
$$\sigma^2_B = \frac{\sigma^2_{AB} + \sigma^2_{CB} - \sigma^2_{CA}}{2}$$
$$\sigma^2_C = \frac{\sigma^2_{CA} + \sigma^2_{CB} - \sigma^2_{AB}}{2}$$

Time resolution of the LGADs: test beam measurements





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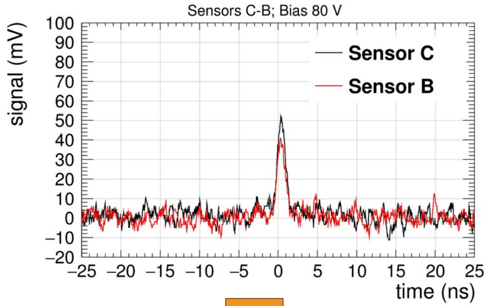

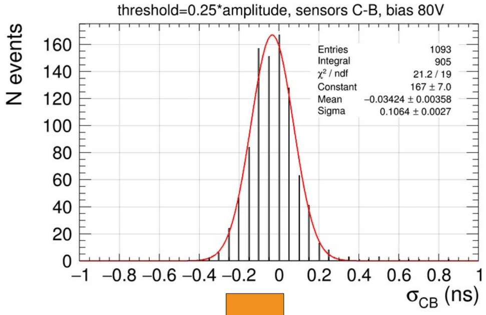

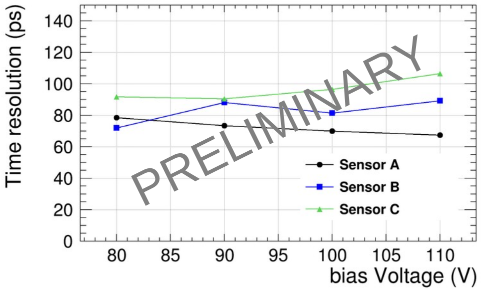

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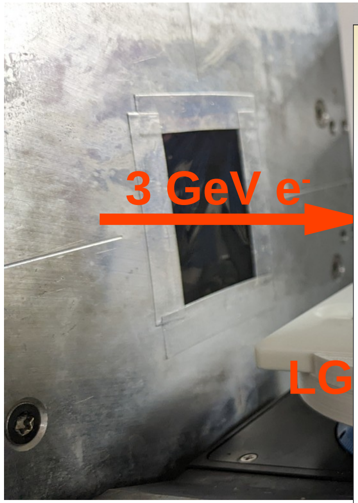
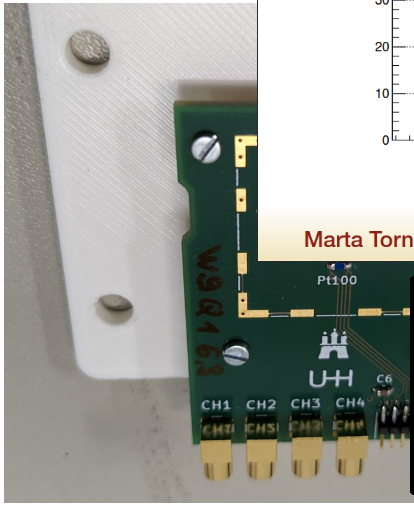
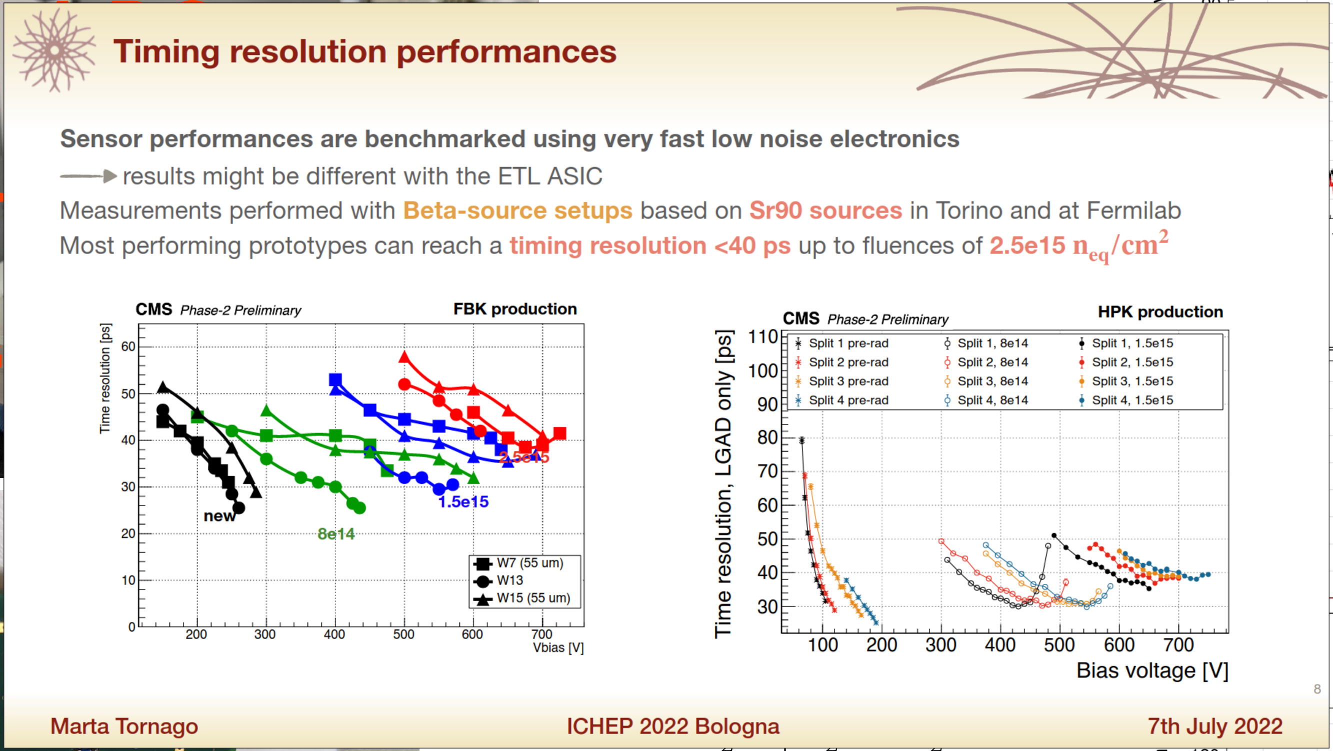
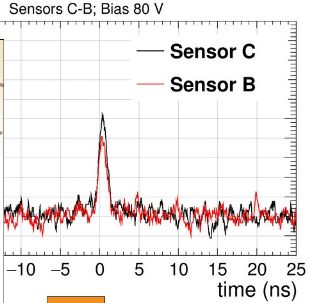
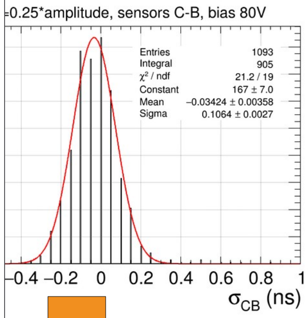
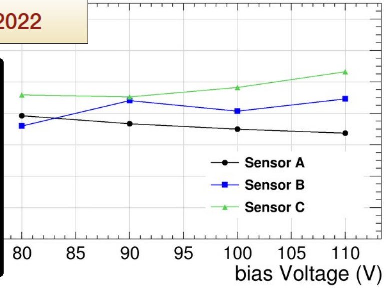










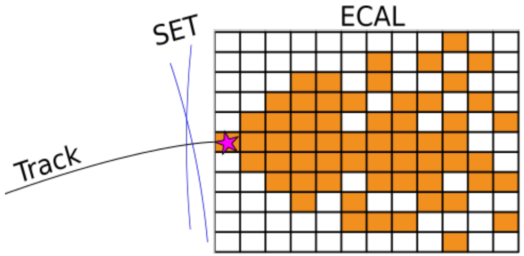


We have measured 80 ps time resolution

CMS/ATLAS: < 40 ps is achievable

ICHEP link

Timing implementation in the ILD

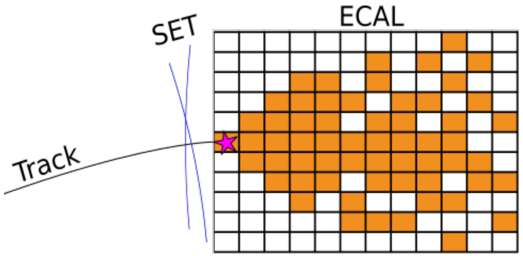


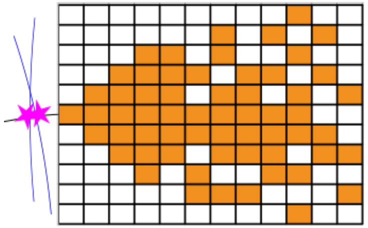
Placement: Dedicated ECAL timing layer (LGADs)

Hit time resolution: ~ 30 ps

TOF resolution: ~ 30 ps

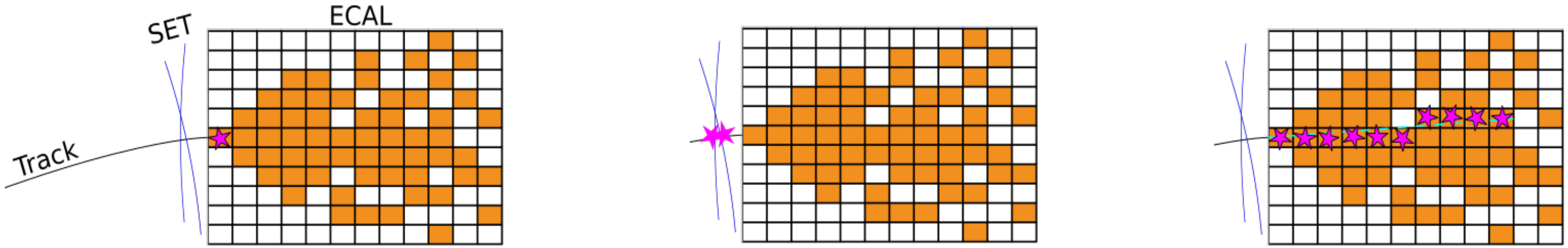
Timing implementation in the ILD





Placement:	Dedicated ECAL timing layer (LGADs)	Two Si strips of external tracker (LGADs?)
Hit time resolution:	~ 30 ps	~ 50 ps
TOF resolution:	~ 30 ps	~ ? ps

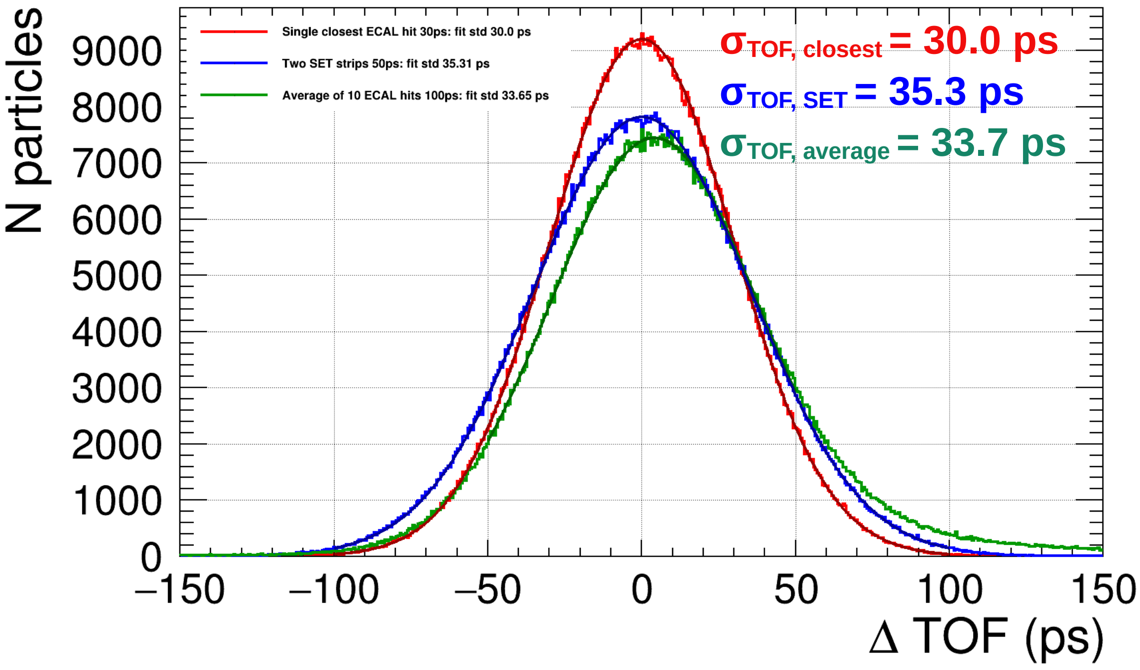
Timing implementation in the ILD



Placement:	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

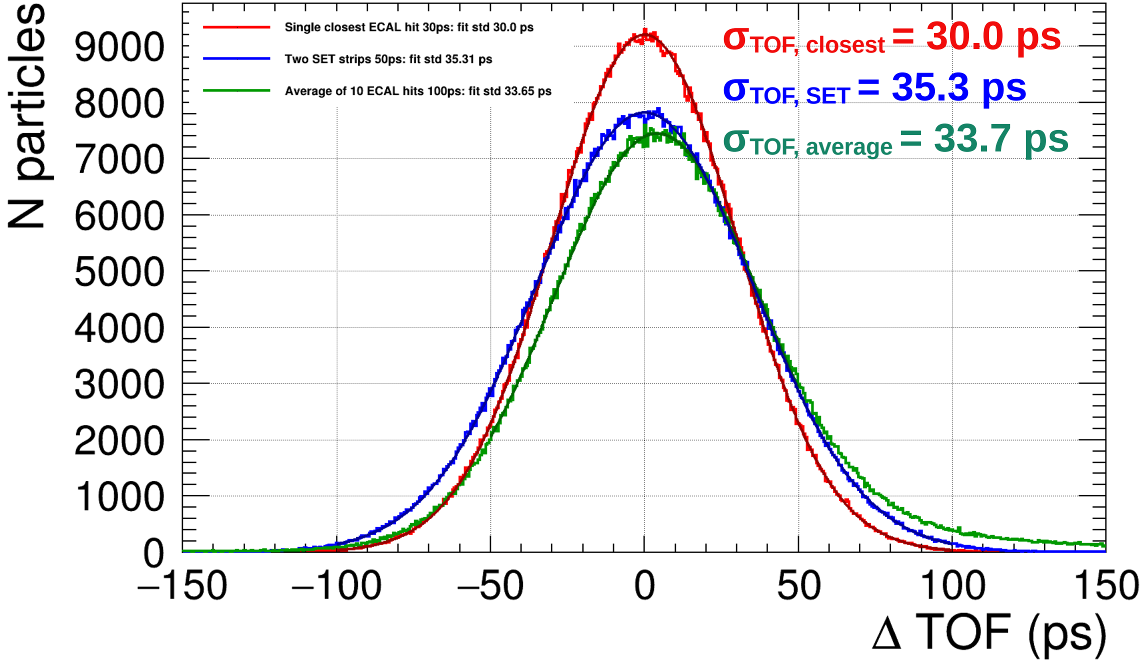


TOF resolution behaves as an average of independent measurements:

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

- Rule of thumb: more hits → 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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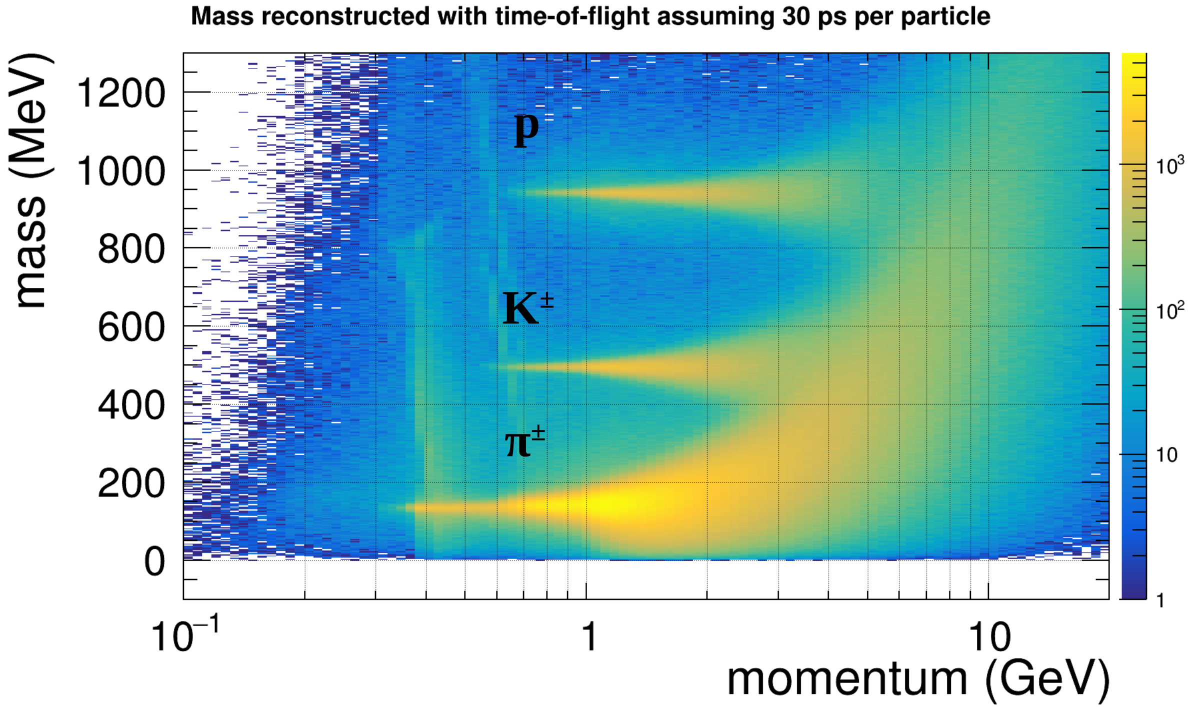
Be alert – time simulation is simplified:

- 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?

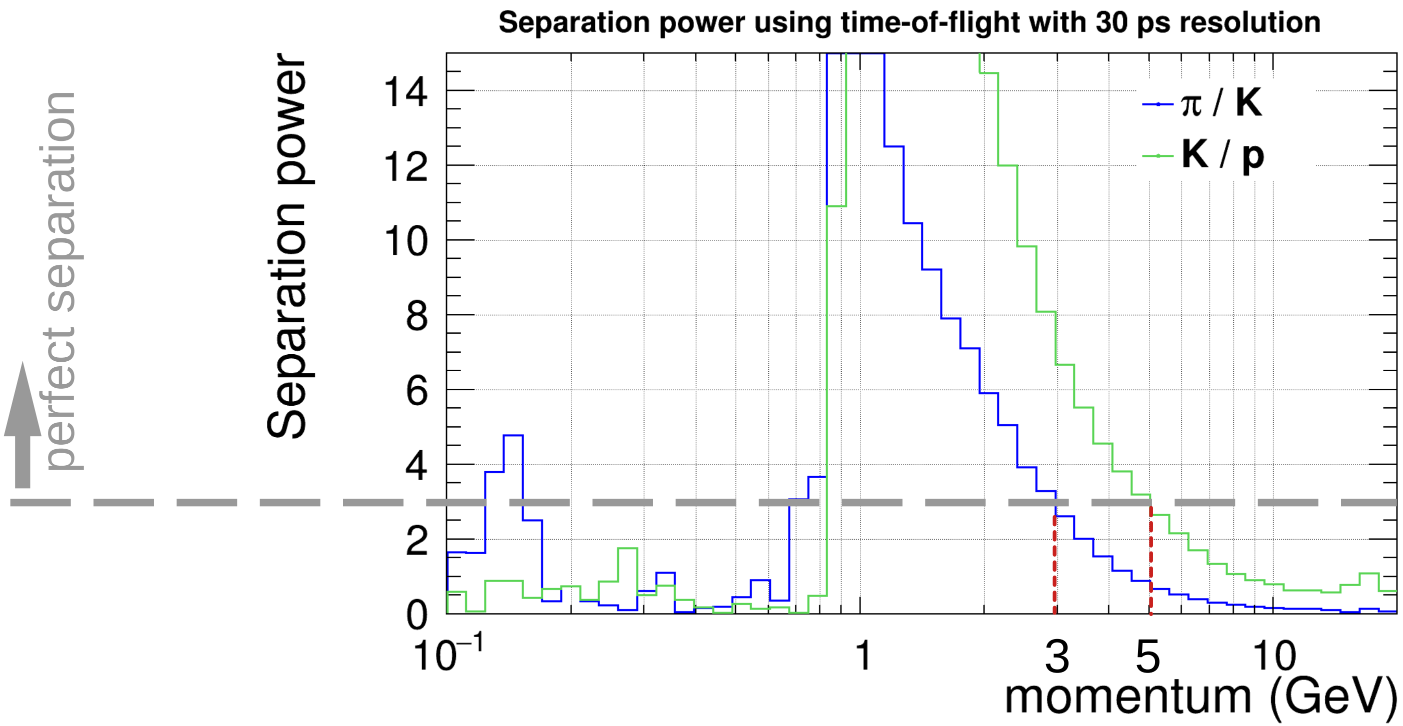
TOF separation power (30 ps TOF resolution)



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)



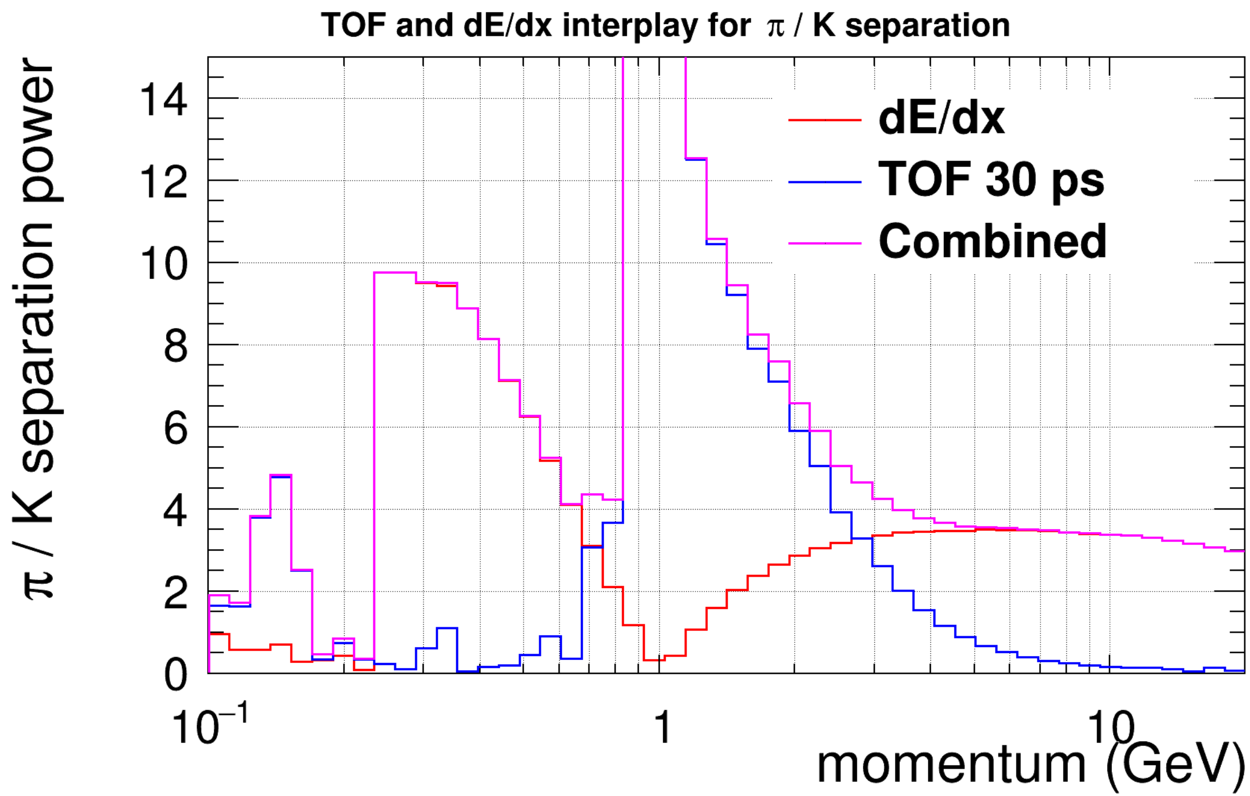
$$\text{Sep.Power} = \frac{|\mu_1 - \mu_2|}{\sqrt{0.5(\sigma_1^2 + \sigma_2^2)}}$$

TOF can provide:

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

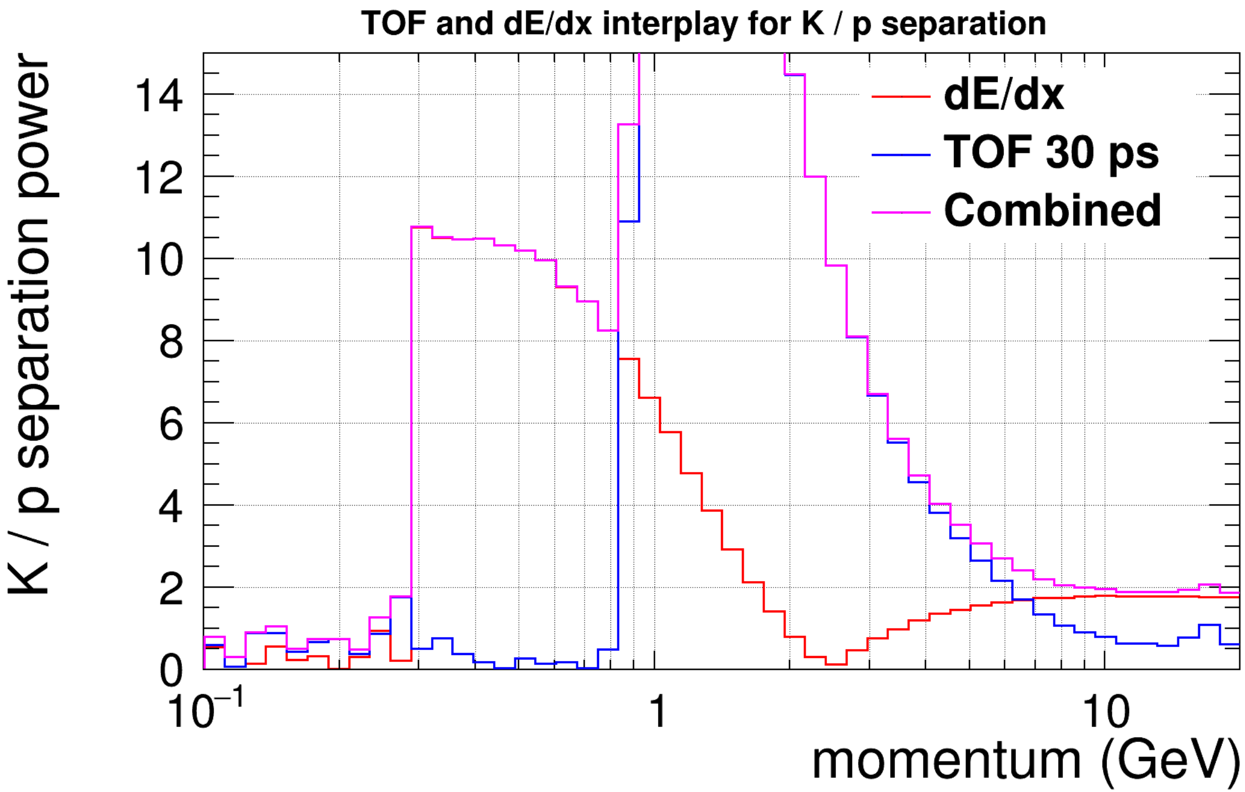
How does it interplay with dE/dx?

Separation power of dE/dx + TOF (30 ps)



TOF nicely complements dE/dx in the blind spot where Bethe-Bloch curves intersect

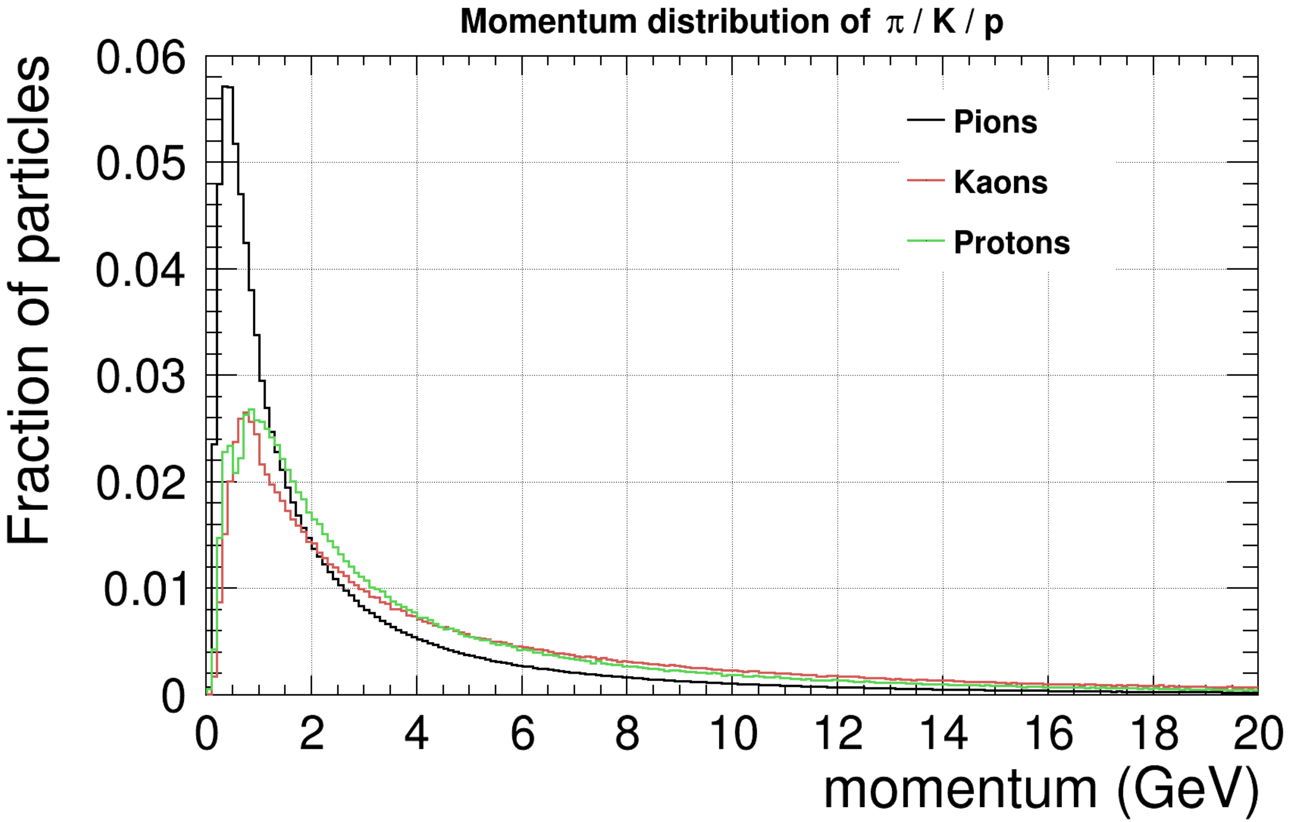
Separation power of dE/dx + TOF (30 ps)



TOF nicely complements dE/dx in the blind spot where Bethe-Bloch curves intersect

How relevant is this momentum range?

Momentum distribution of π/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, usually 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**

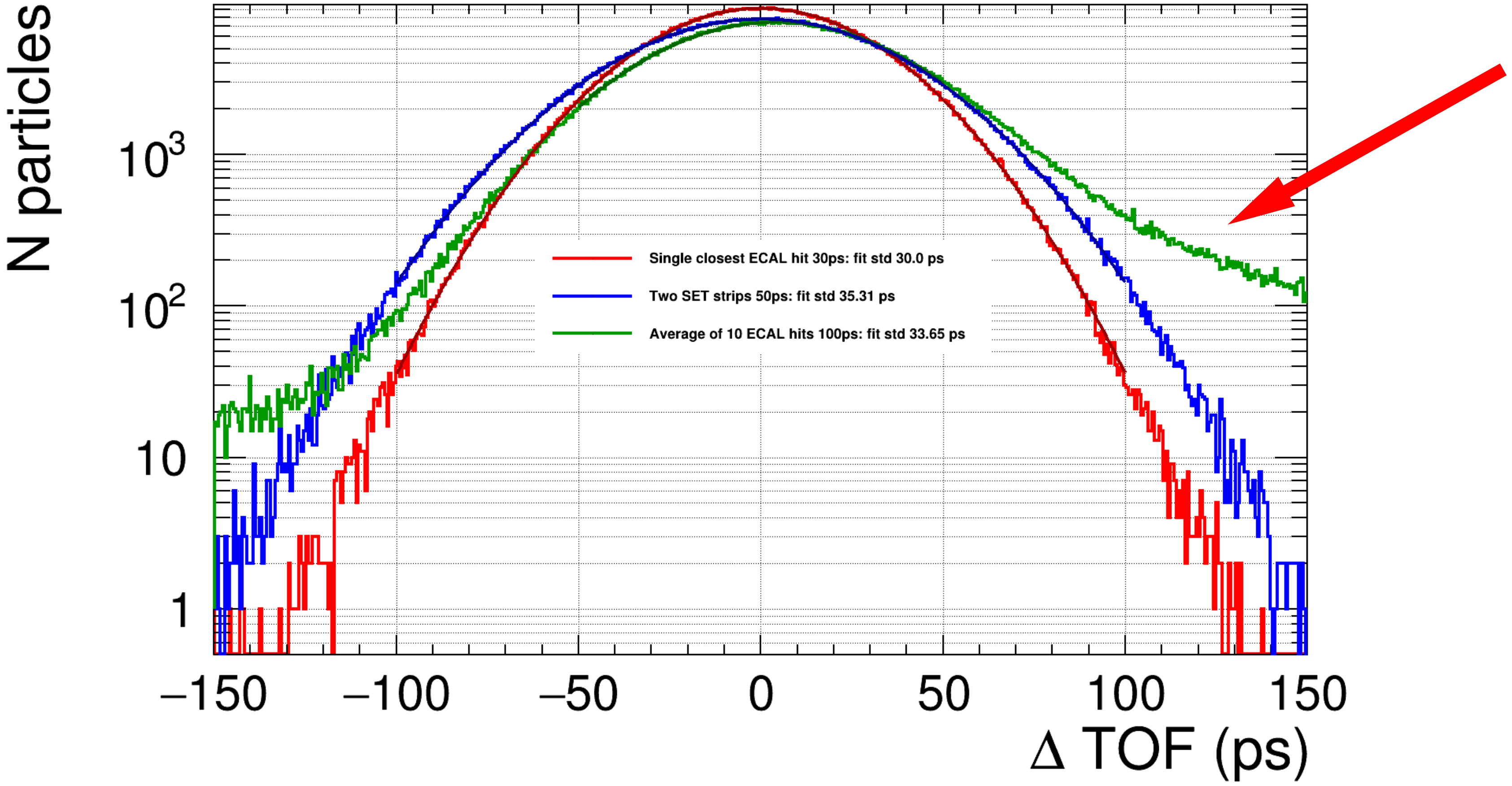
- Dedicated ECAL timing layer or full ECAL with conventional Si sensors both viable.
  A better **understanding of heat&cooling requirements** are needed

- 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→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