Slide 0

Session: T12 Detector R&D and Data Handling

Time: 20 minutes (16+4)

Audience: mostly ATLAS people

	Overview of ATLAS Upgrades projects for HL-LHC *Audimax, Universität Hamburg*	*Ludovico Pontecorvo* 16:45 - 17:05
17:00	**ATLAS ITk Pixel Detector Overview** *Audimax, Universität Hamburg*	*Michele Weber* 17:05 - 17:25
	The ATLAS ITk Strip Detector System for the Phase-II LHC Upgrade *Audimax, Universität Hamburg*	*Dominique Anderson Trischuk* 17:25 - 17:45
	The Silicon Vertex Detector of the Belle II Experiment *Audimax, Universität Hamburg*	*Yo Sato* 17:45 - 18:05
18:00	**Development of the time-of-flight particle identification for future Higgs factories** *Audimax, Universität Hamburg*	*Bohdan Dudar* 18:05 - 18:25
	Overview of the ATLAS High-Granularity Timing Detector: project status and results *Audimax, Universität Hamburg*	*Pablo Fernandez Martinez* 18:25 - 18:45
	The LHCb VELO detector: design, operation and first results *Audimax, Universität Hamburg*	*Alice Biolchini* 18:45 - 19:00
19:00	**Upgrade of the CMS luminosity instrumentation and the Fast Beam Condition Monitor for HL-LHC** *Audimax, Universität Hamburg*	*Alexey Shevelev* 19:00 - 19:15

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

EPS-HEP2023 conference

T12 Detector R&D and Data Handling

21 August 2023

Bohdan Dudar[1,2], Ulrich Einhaus[1], Jenny List[1], Konrad Helms[1,3], Frank Gaede[1]

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HELMHOLTZ

UHH

CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

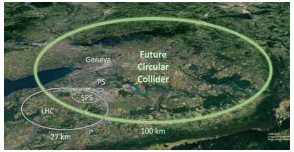
ILD

FTX

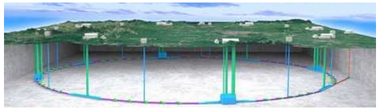
DESY.

Future Higgs factory candidates

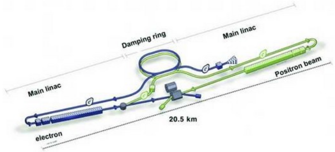
FCC-ee



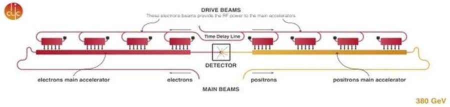
CEPC



ILC



CLIC



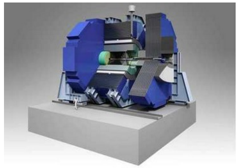
. . .

CCC,
CERC,
ReLiC,
ERLC, …

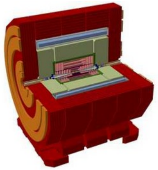
Detector concepts

Main tracker	*Fully Si tracker* TOF (?)	*Drift chamber* dN/dx + TOF (?)	*TPC* dE/dx + TOF (?)

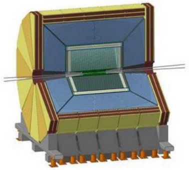
SiD



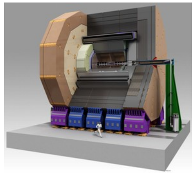
CLICdp



IDEA

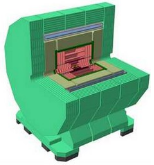


ILD

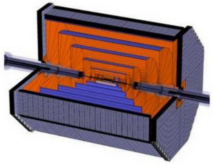


In this study we use ILD

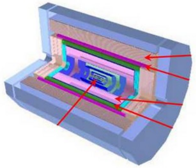
CLD



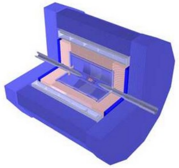
FST



CEPC 4th concept

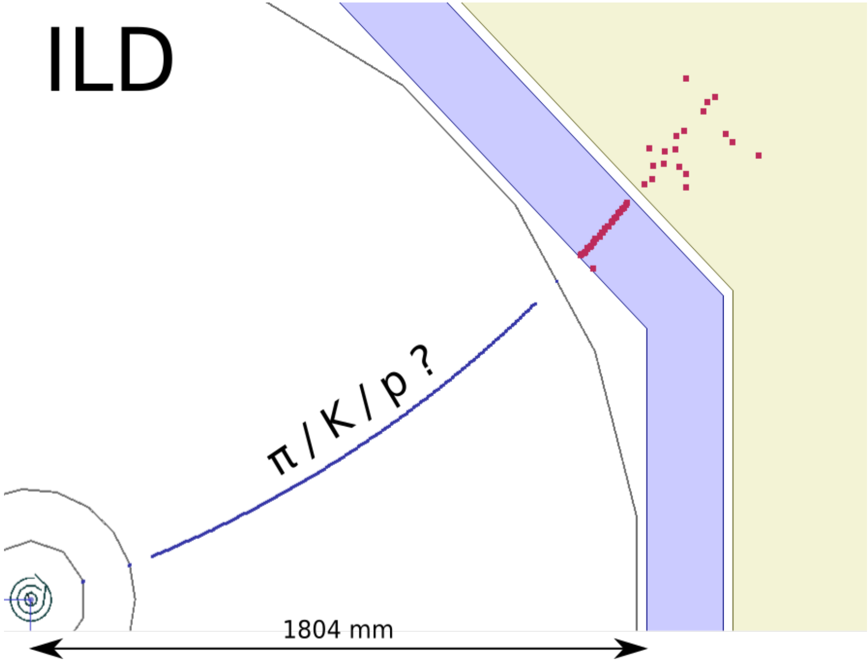


CEPC Baseline

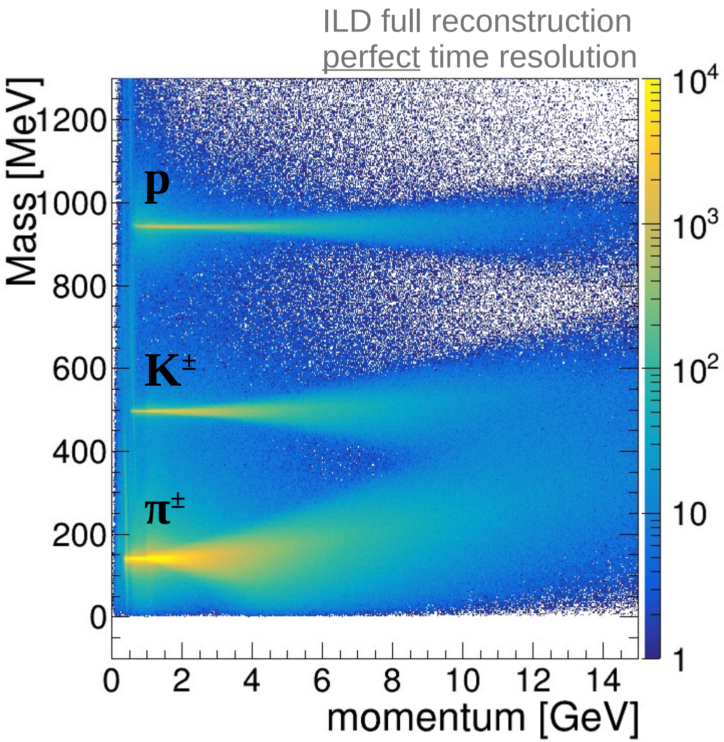


Would future detectors benefit from the time-of-flight particle identification?

Basic idea of TOF pID



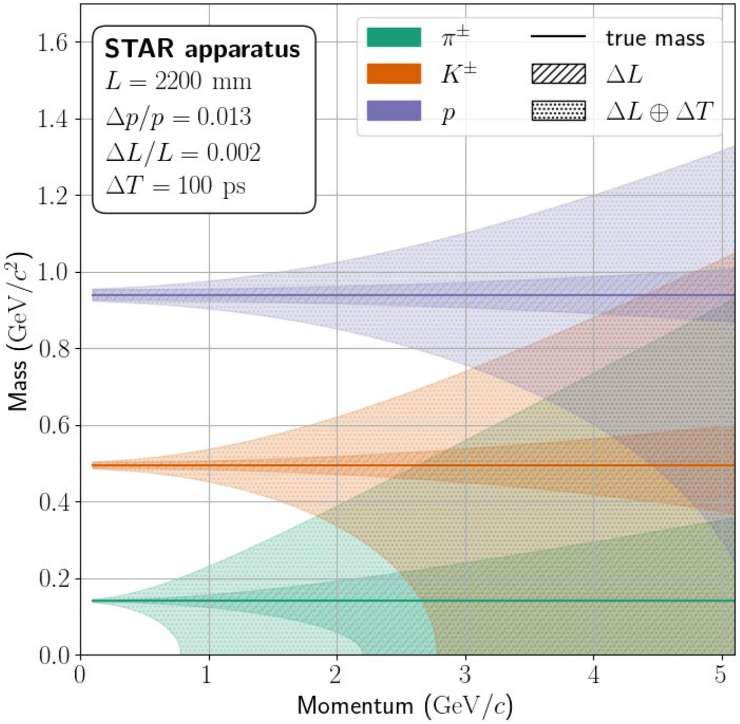
$$m = p\sqrt{\frac{c^2T^2}{L^2} - 1}$$



- Widely used by heavy-ion experiments (STAR, NA61/SHINE, ALICE)
- But new technologies (10-30 ps) bring new challenges
- Is it still relevant at CME 250 GeV?

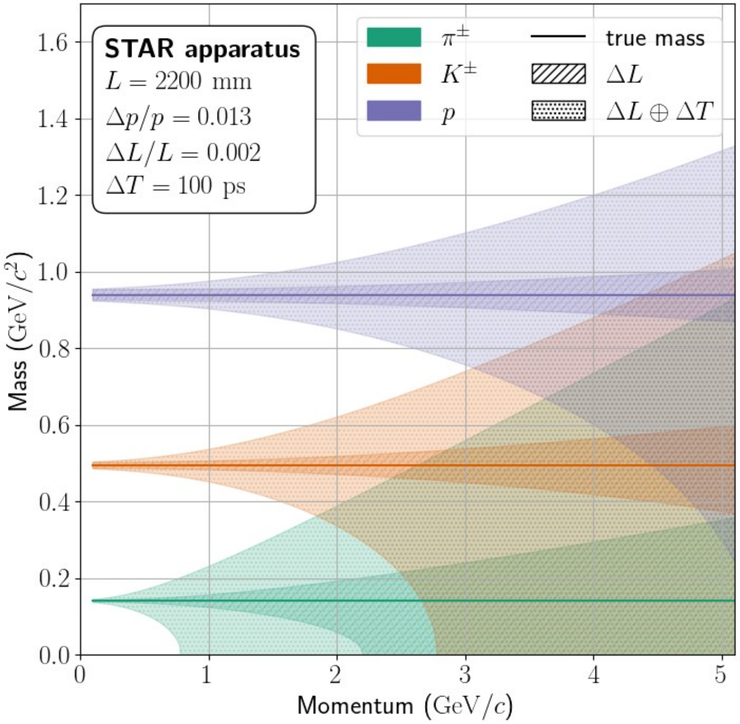
Track length resolution effects

100 ps
time res. is dominant

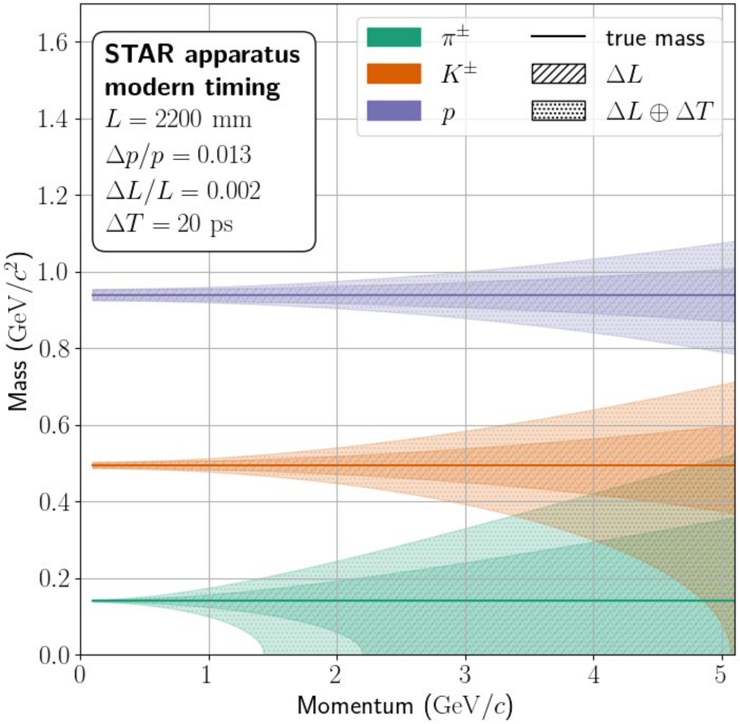


Track length resolution effects

100 ps
time res. is dominant



20 ps
trk. len. res. is non-negligible



Rule of thumb: ΔT = 10 ps ~ ΔL = 3 mm

Note: ΔL/L = 0.002 serves as an example and can be an under/over-estimation

Track length reconstruction

Equivalent formulas for perfect helix

1. $$L = \left| \frac{\varphi_{\mathrm{ECAL}} - \varphi_{\mathrm{IP}}}{\Omega_{\mathrm{IP}}} \right| \sqrt{1 + \tan^2 \lambda_{\mathrm{IP}}}$$

2. $$L = \sqrt{\left(\frac{\varphi_{\mathrm{ECAL}} - \varphi_{\mathrm{IP}}}{\Omega_{\mathrm{IP}}} \right)^2 + (z_{\mathrm{ECAL}} - z_{\mathrm{IP}})^2}$$

3. $$L = \left| \frac{z_{\mathrm{ECAL}} - z_{\mathrm{IP}}}{\tan \lambda_{\mathrm{IP}}} \right| \sqrt{1 + \tan^2 \lambda_{\mathrm{IP}}}$$

4. $$L = \sum_{i}^{N_{\mathrm{hits}}} L_i = \sum_{i}^{N_{\mathrm{hits}}} \frac{|z_{i+1} - z_i|}{|\tan \lambda_i|} \sqrt{1 + \tan^2 \lambda_i}$$

Track length reconstruction

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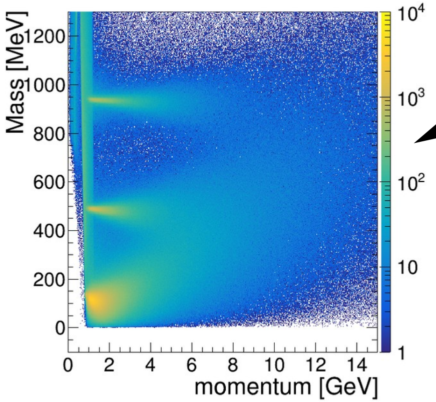
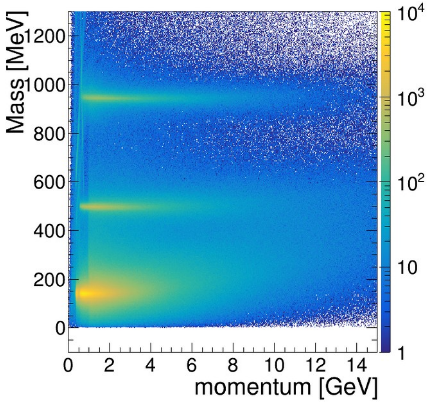
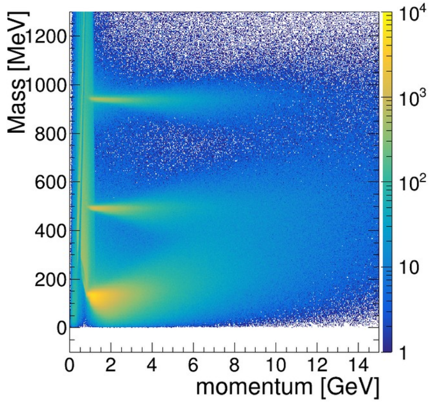
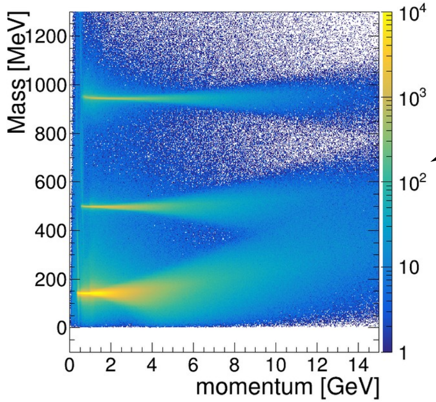


State-of-art at ILD **in 2020** before this study



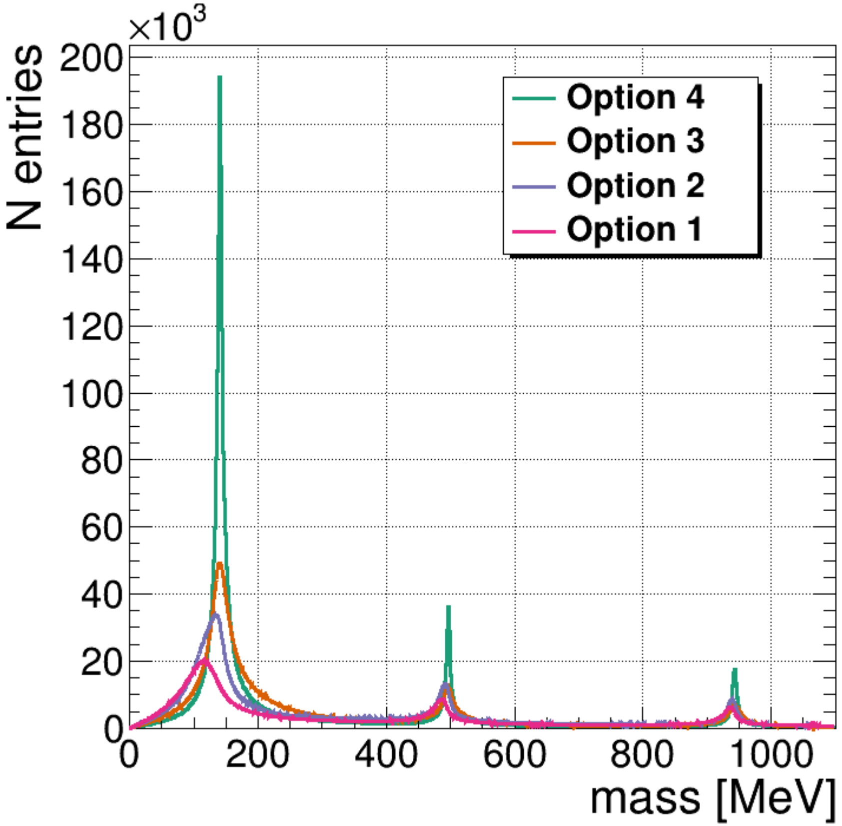




State-of-art at ILD **today**

All plots:
ILD full reconstruction
TPC – 220 radial hits
perfect time resolution

Track length reconstruction



ILD full reconstruction
TPC – 220 radial hits
perfect time resolution

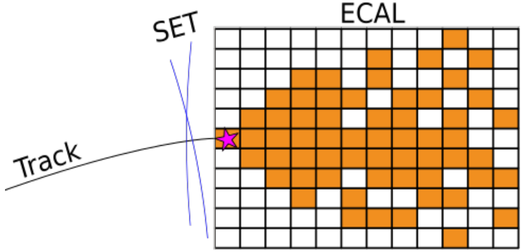
TPC is great for reconstructing the track length.
Many hits (220 in our case), thus:

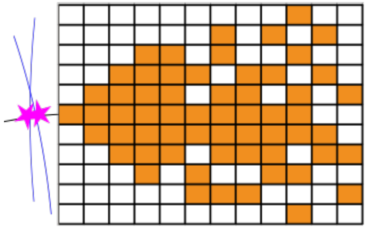
- Better track fit
- Smaller uncertainties on track parameters
- Better sensitivity to changes along the track

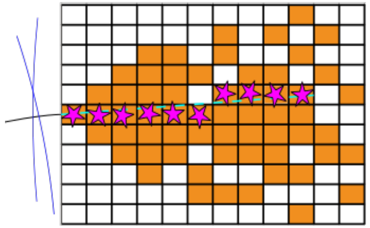
Full Si trackers might face difficulties (?)

Track length can be a limiting factor for TOF pID,
especially with extreme timing using simplified reconstruction.

Time-of-flight reconstruction in ILD





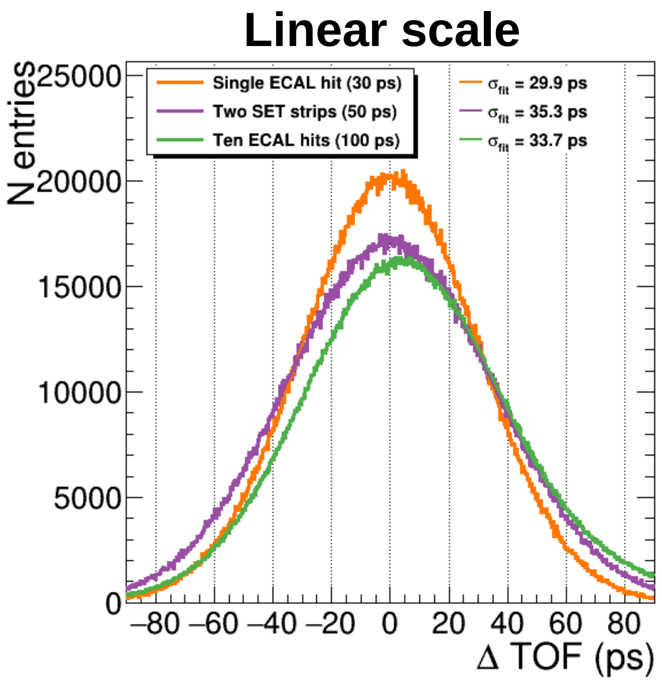


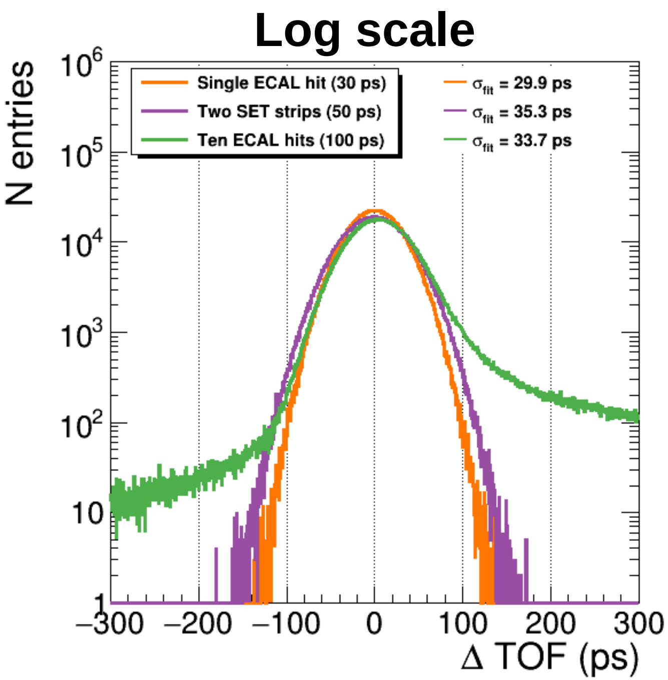
Placement:	First ECAL layer dedicated for timing	Two external tracker layers	10 ECAL layers (conservative timing)
Assumed hit time resolution:	~ 30 ps	~ 50 ps	~ 100 ps
Expected TOF resolution:	~ 30 ps	$\sim \frac{50}{\sqrt{2}}$ ps	$\sim \frac{100}{\sqrt{10}}$ ps

- Hit time reconstruction is very simplified
  (no digitization effects, only Gaussian smear of MC true time)
- Central question: what is the best way for TOF reconstruction?

Fast timing in the whole ECAL is likely not feasible:
→ high power consumption
→ requires active cooling
→ space&material budget
→ affects the particle flow

Time-of-flight reconstruction in ILD





Note: **TOF$_{true}$** is defined as: MC true time of the closest ECAL shower hit to the track position at the surface correcting for the distance assuming speed of light

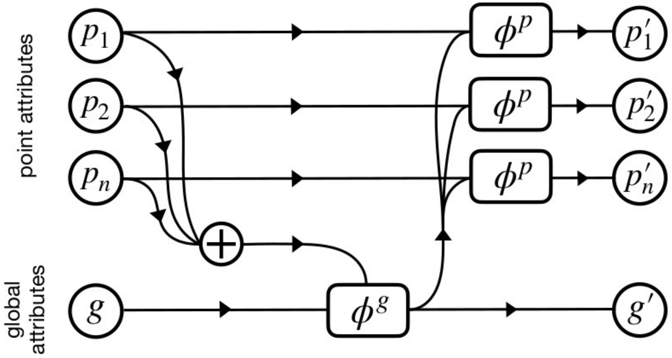
- Rule of thumb: more hits – better still holds. Using whole shower would be ideal $\left(\sigma_{\text{TOF}} \sim \frac{\sigma_{\text{hit}}}{\sqrt{n}}\right)$

  BUT

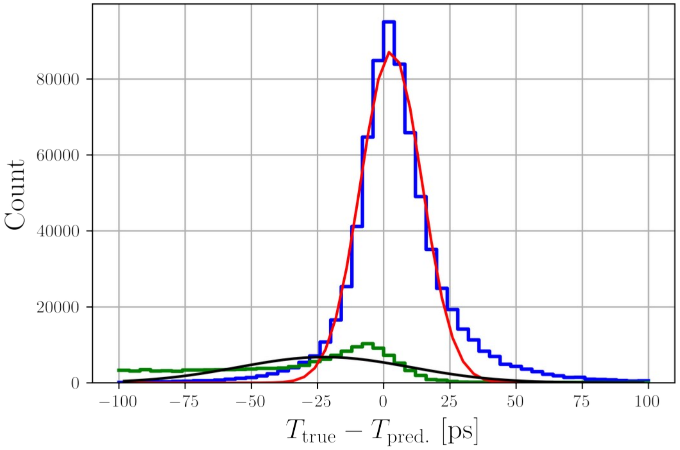
- Averaging over shower hits introduces long non-Gaussian tails (efficiency/purity loss)

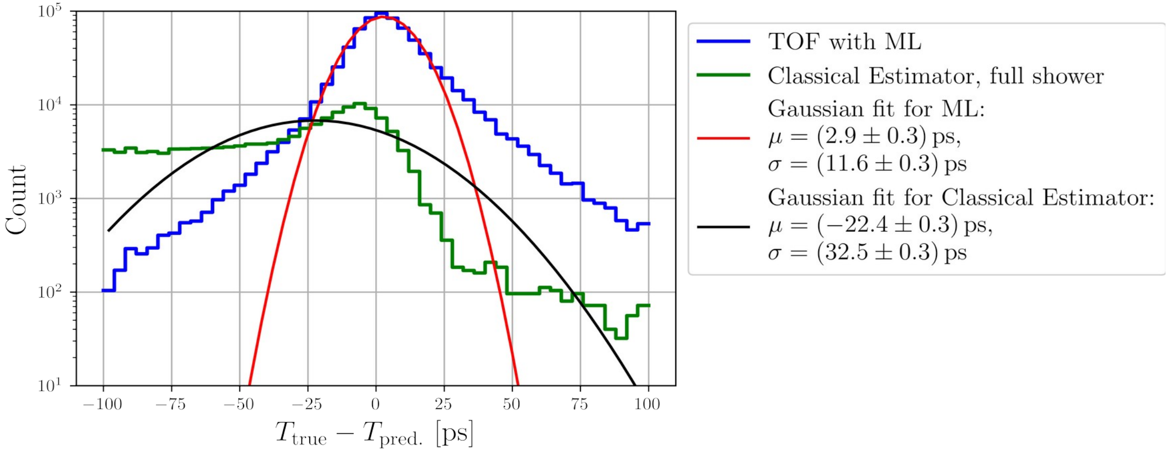
Time-of-flight reconstruction with machine learning

EPIC regression: arXiv:2301.08128



ILD ECAL:
30 layers,
5x5 mm granularity



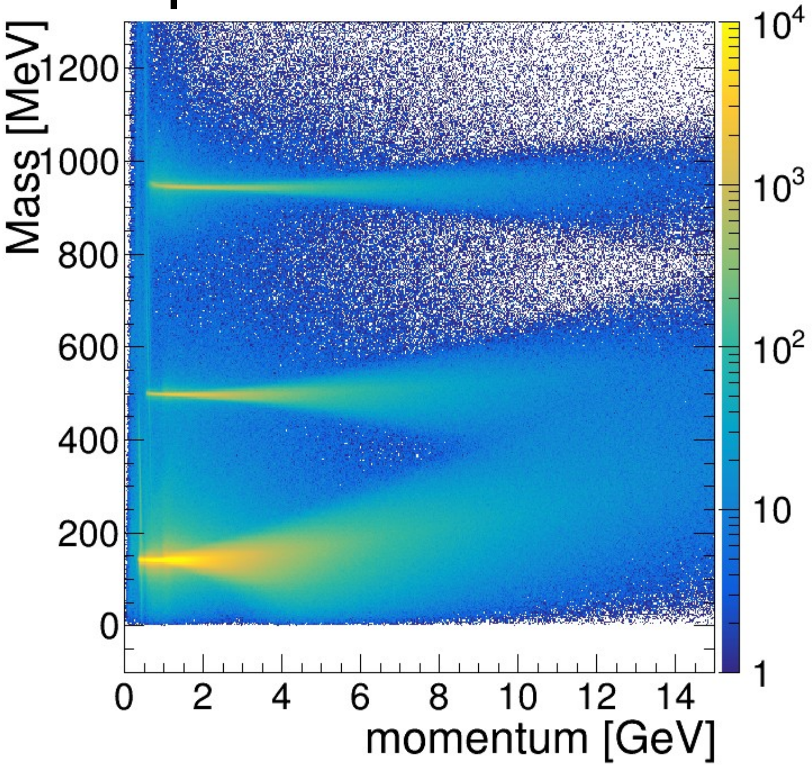


ML can utilize full shower and deduce TOF most optimally compared to the averaging.

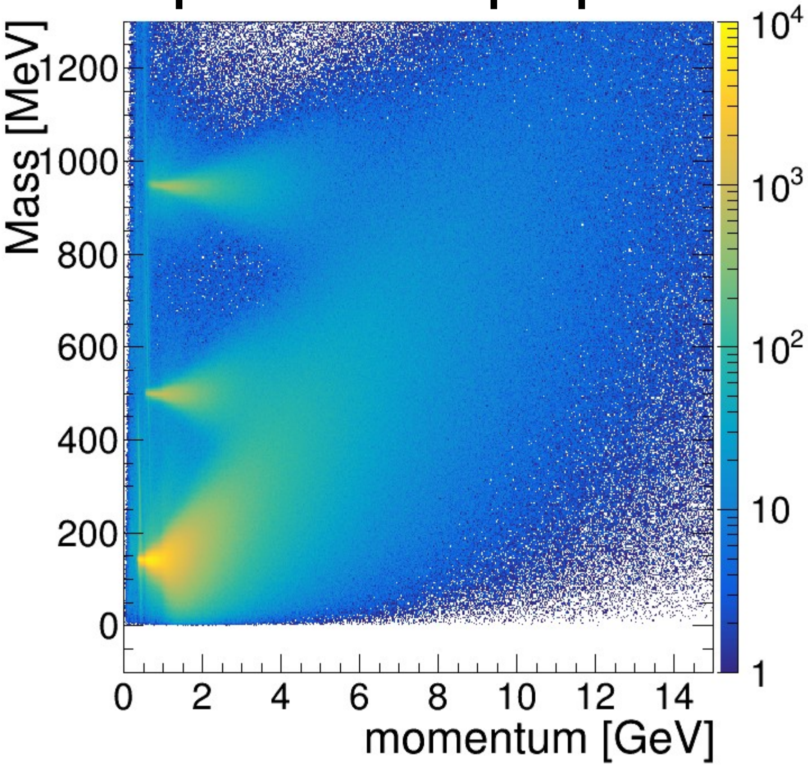
50 ps per hit → 12 ps TOF using whole shower

Time resolution effect on the pID

perfect time resolution

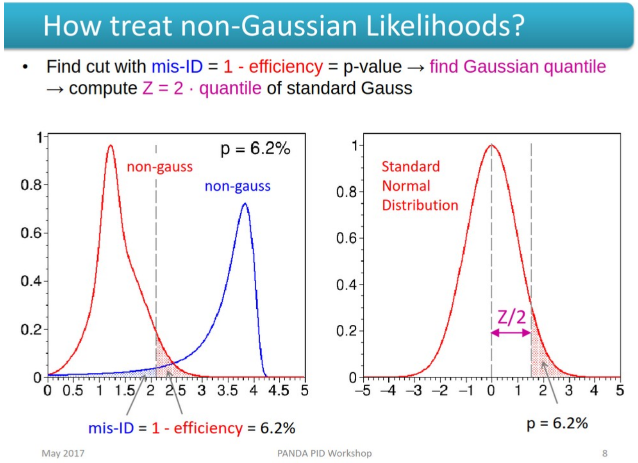


30 ps resolution per particle



Let’s quantify the separation

Separation power from p-value



General idea:

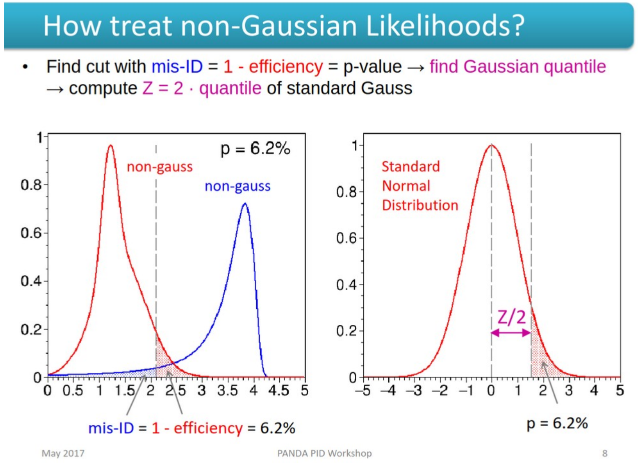
Full credit goes to K. Götzen
https://indico.gsi.de/event/7080/contributions/31950/

- Choose the cut where
  p-value = mis-id = 1 - eff

- Calculate sep. power equivalent as
  $Z = 2 \cdot \Phi^{-1}(1 - p)$

```
2*ROOT::Math::gaussian_quantile_c(p_value,1)
```

Separation power from p-value



General idea:

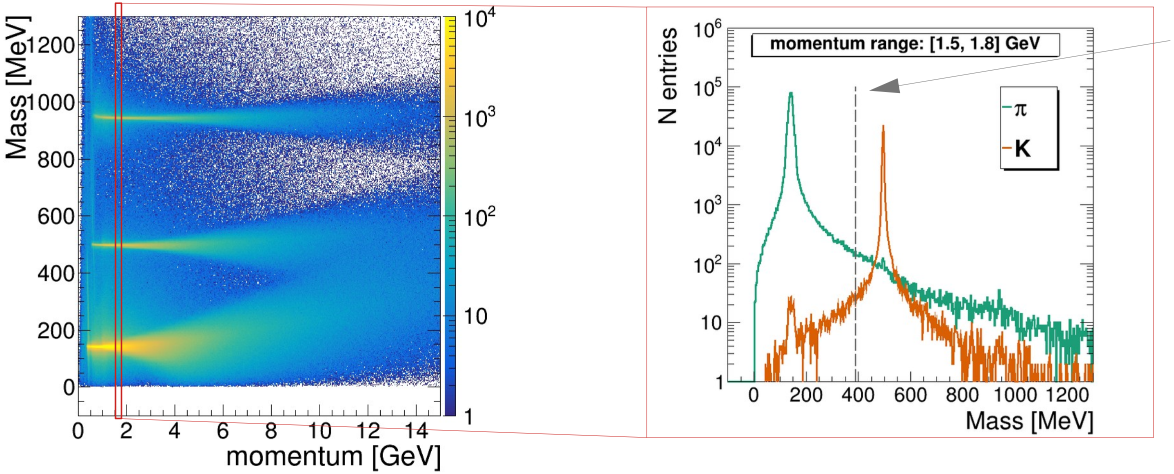
Full credit goes to K. Götzen
https://indico.gsi.de/event/7080/contributions/31950/

- Choose the cut where
  p-value = mis-id = 1 - eff

- Calculate sep. power equivalent as
  $$Z = 2 \cdot \Phi^{-1}(1 - p)$$

```
2*ROOT::Math::gaussian_quantile_c(p_value,1)
```

In our specific case:

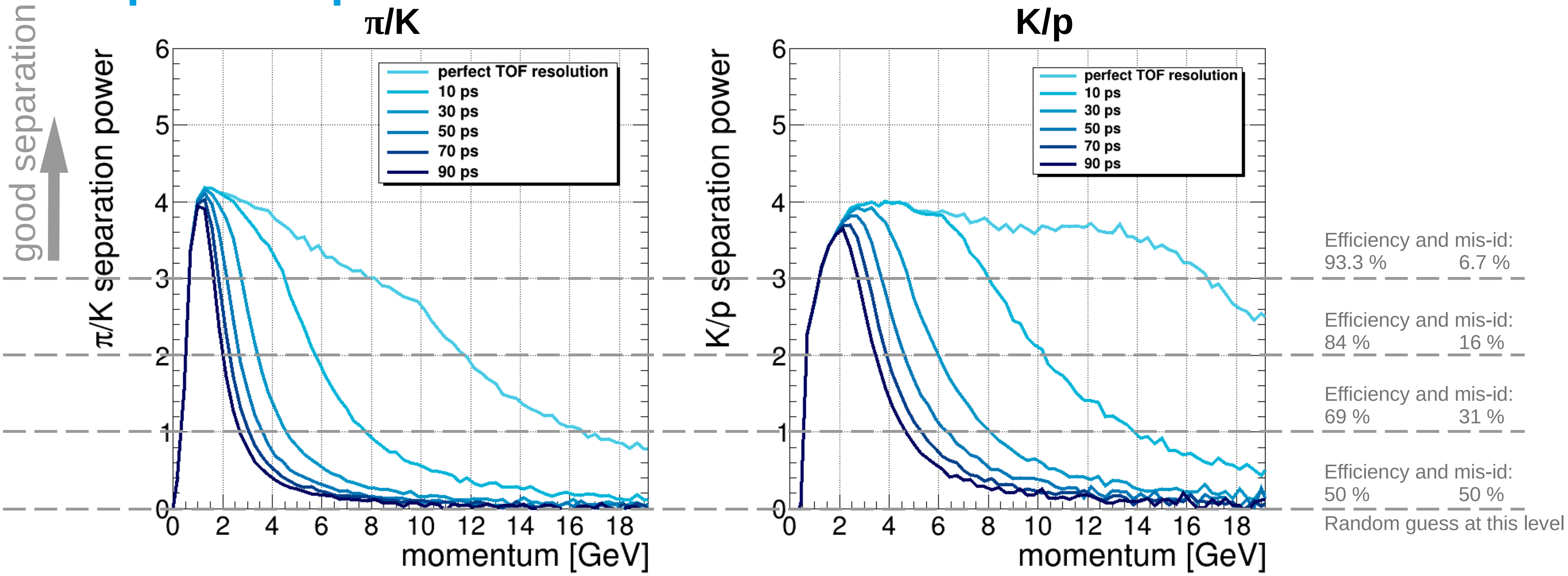


Cut chosen such that:

p-value = mis-id = 1 - eff = 2%

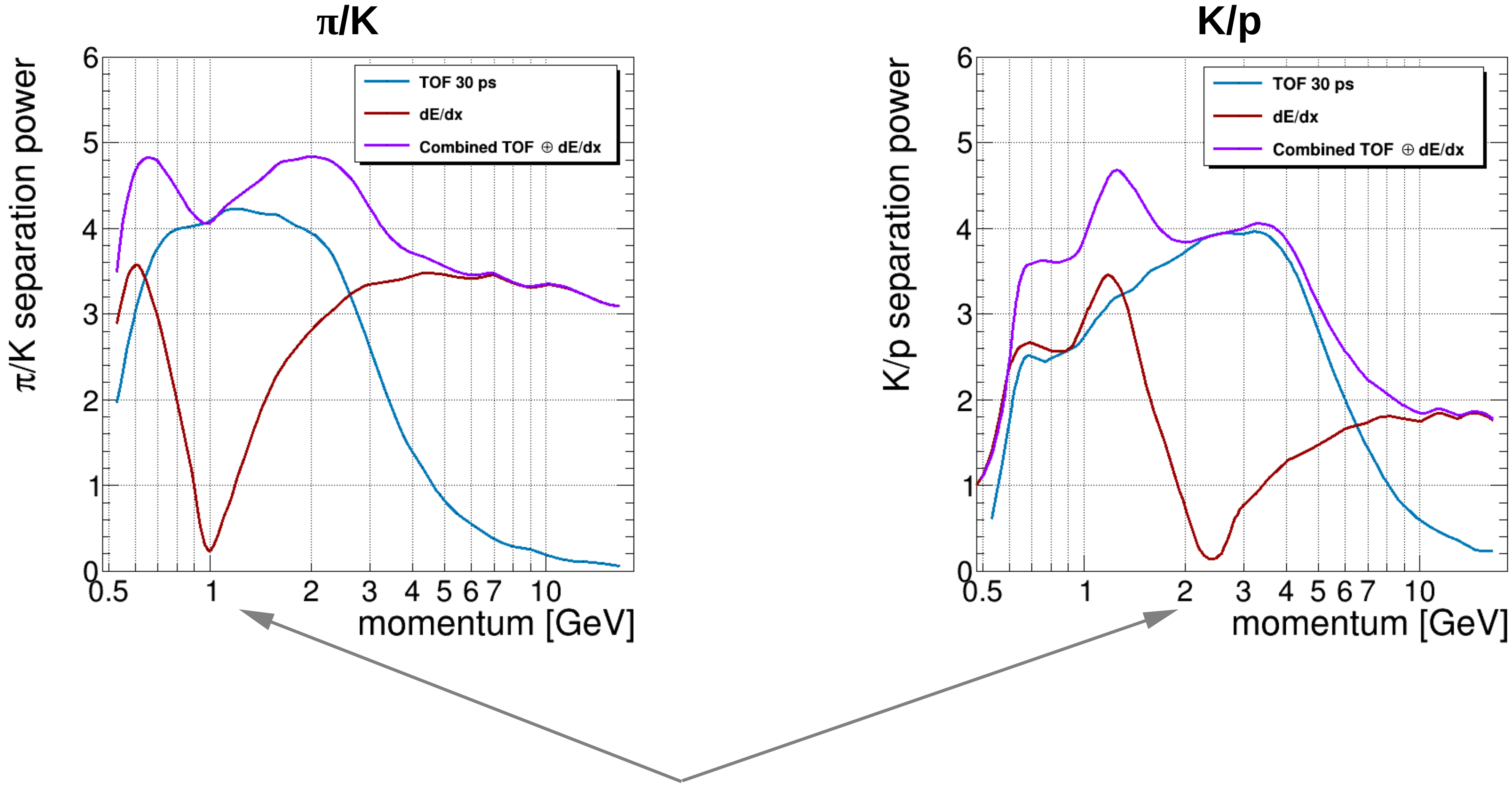
π/K sep. power (Z) = 4.17

Separation power vs TOF resolution



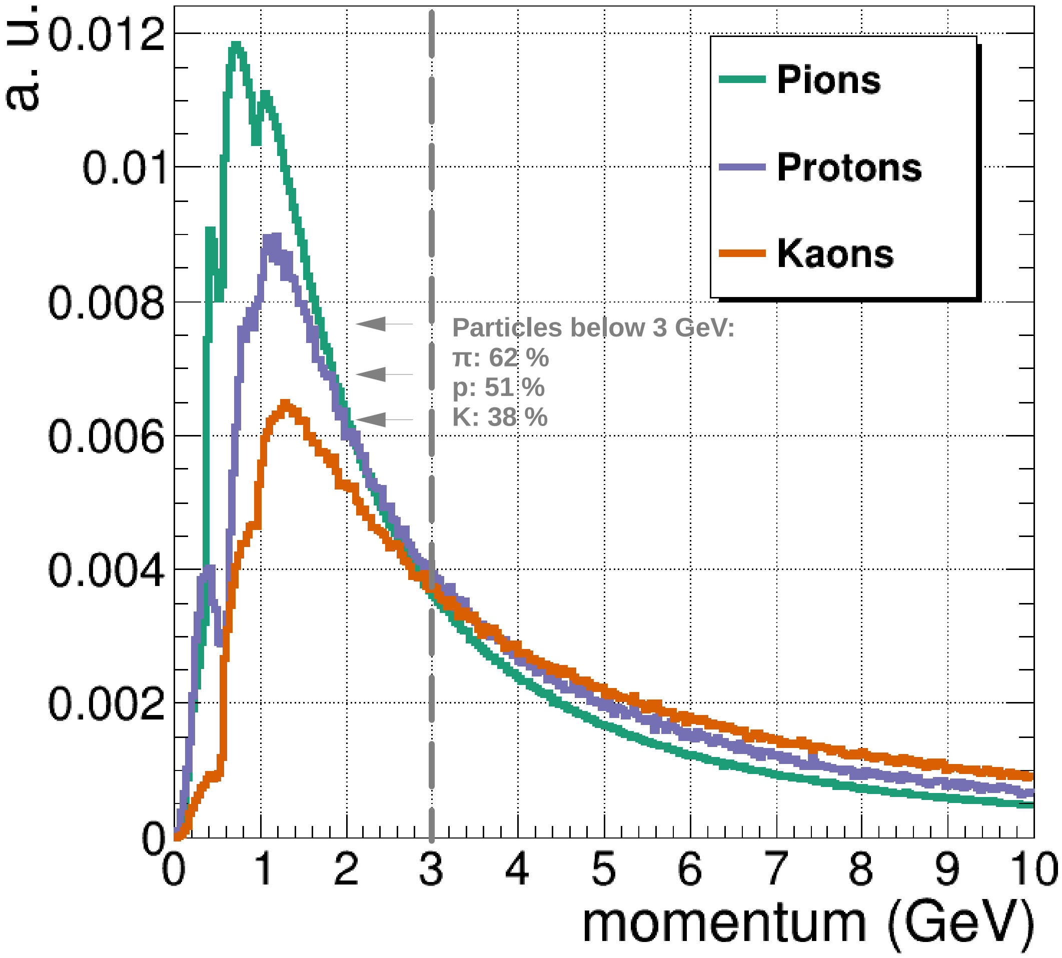
- Improving time resolution will extend the separation range
  *if not limited by other factors (track length, clock jitter, clock sync., …)
- At **30 ps** resolution per particle π/K (K/p) separation reaches **up to 3 GeV (5 GeV)**

TOF interplay with dE/dx in ILD



TOF nicely covers dE/dx blind spots

Momentum distribution of the charged hadrons



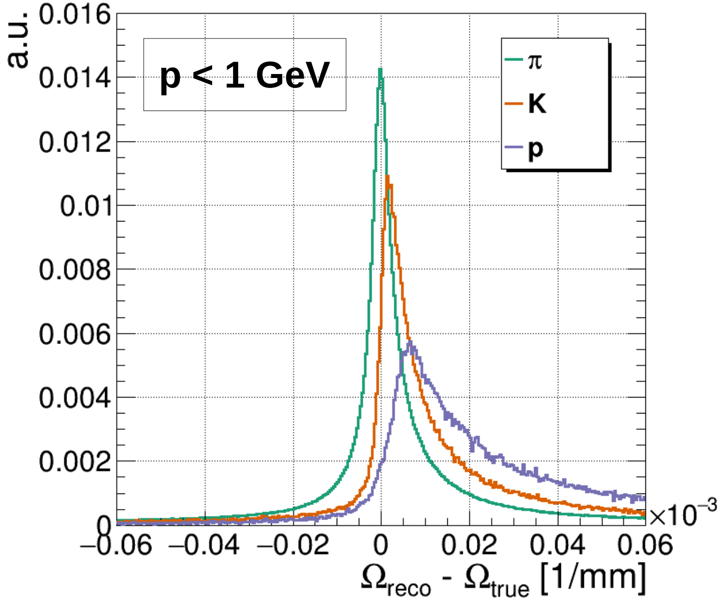
Used physics MC samples:

- $e^+e^- \rightarrow Z \rightarrow q\bar{q}$ @ 250 GeV
  Kaon-ID is important for $q/\bar{q}$ separation for A_{FB}
- $e^+e^- \rightarrow WW \rightarrow qqqq$ @ 250 GeV
  Kaon-ID is important for V_{cs},V_{cb}

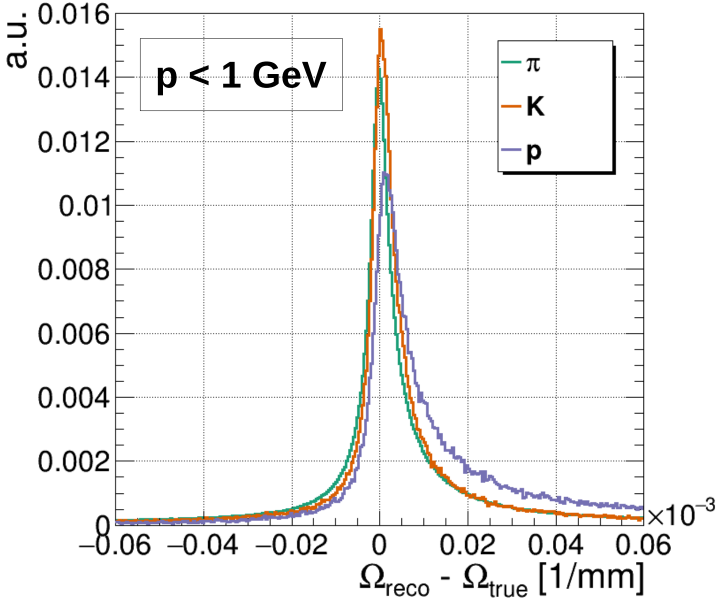
- **Good chunk of charged hadrons** that reach the ECAL is **covered by TOF**
- But, **leading particles** are often **of most interest** for physics

Use TOF to refine tracking?

track fit using π mass (default)



track fit using true mass (perfect pID)



- Reduces bias in curvature Ω (p_T) for low-momentum hadrons
- **Better track fit** in principle translates to **better vertexing**

Many other potential physics applications:

- H → bb/cc/ss/gg, A_{FB}, flavour physics, generator tuning, Kaons mass measurement
- Big landscape for further studies for quantifying the effects

Summary

- **Track length** reconstruction is not trivial and can be a **limiting factor for TOF**.
  Not clear how easy with **fully Si tracking**.

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

- **30 ps** resolution per particle provides **π/K (K/p) separation at 3σ up to 3 GeV (5 GeV)**. Can be significantly extended with better resolution.

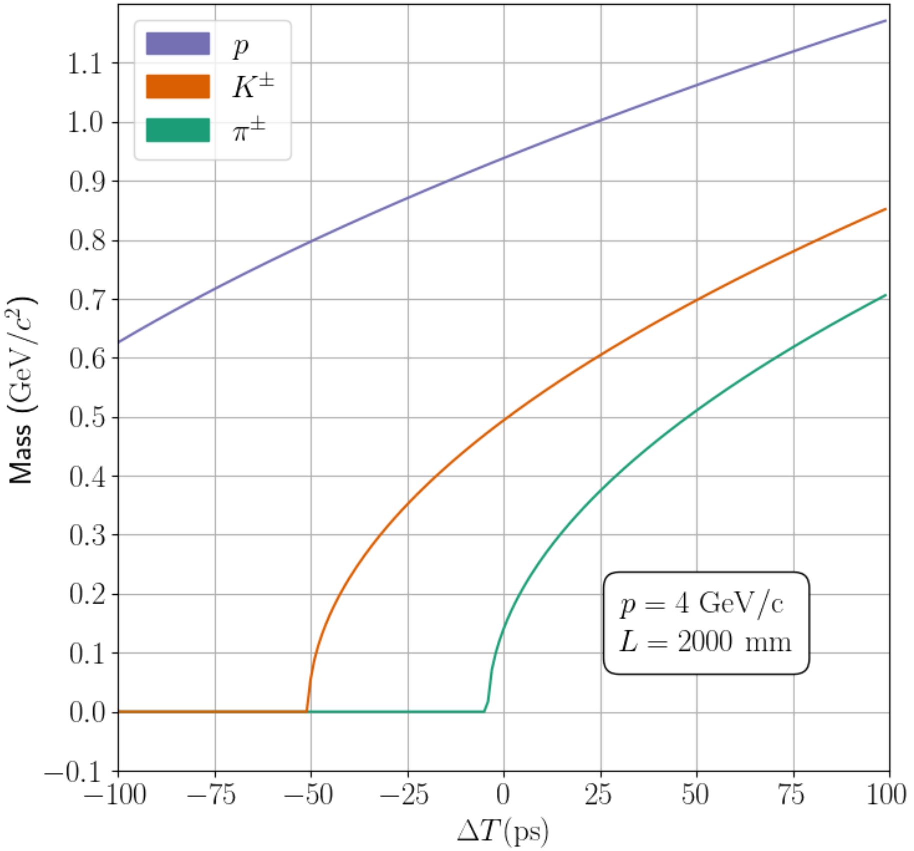
- **TOF nicely complements** the **blind spots** of already existing pID tools such as **dE/dx**, and extends momentum coverage.

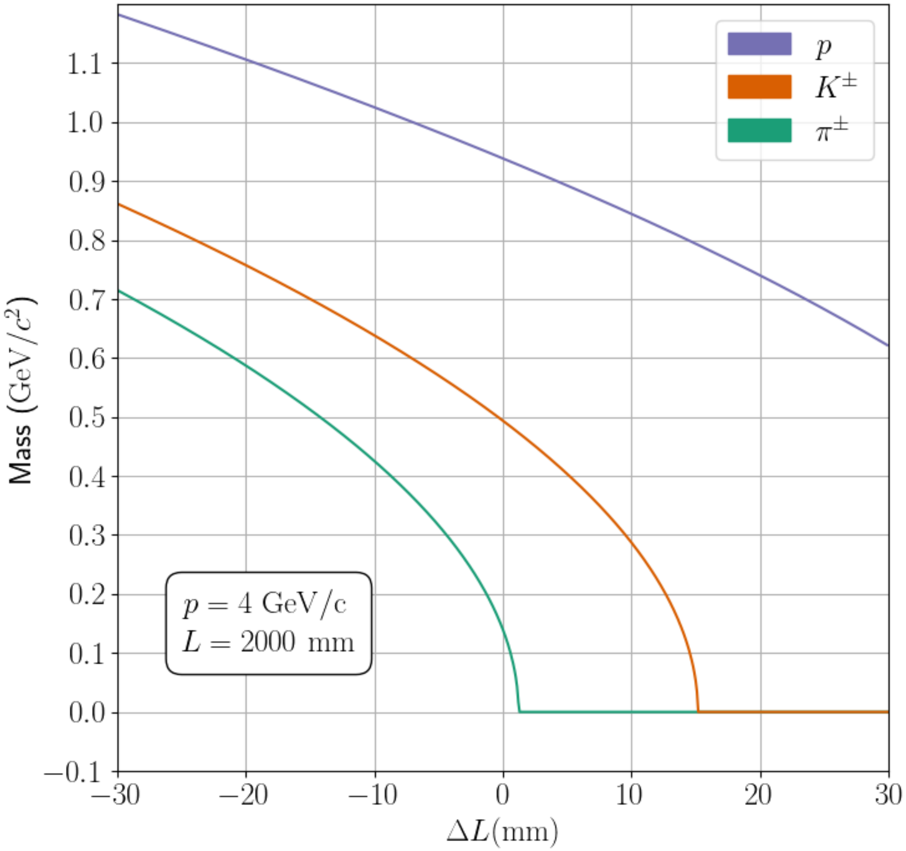
- Exact physics applications are still to be studied.
  Mild event reconstruction improvement can be achieved.

Back up

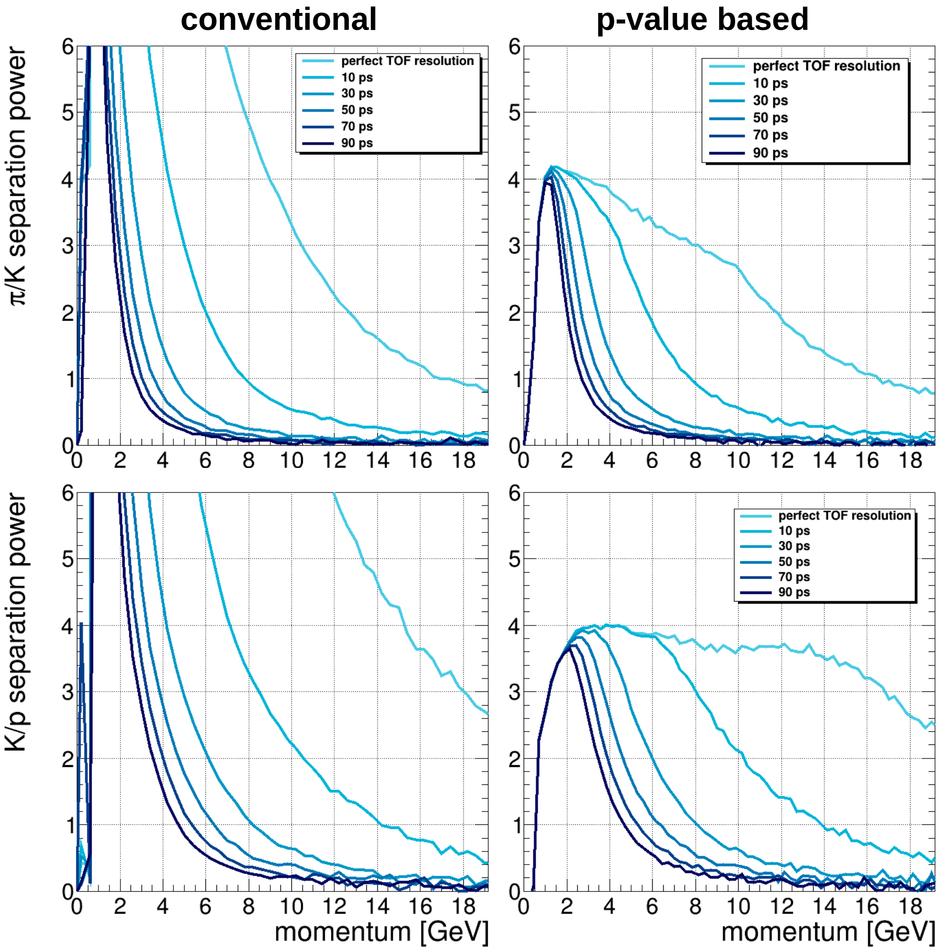
TOF reconstructed mass vs bias of TOF or track length

Rule of thumb: ΔT = 10 ps ~ ΔL = 3 mm





Conventional separation power comparison



Conventional sep. power
(gauss fit) is a bad estimator

- overestimates the performance
- fit is unstable with low statistics (requires less binning)
- Incapable of dealing with non-Gaussian tails
- Incapable of dealing with particle miss-match
- Usually one doesn't check the fit quality in every slice and hopes everything works "ok"

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

p-value sep. power
(presented in this study)

- More stable with low statistics (nothing is fitted)
- Works nice with ANY shapes even non-Gaussian
- Translates to efficiency and mis-id by definition