Optimization of K/π separation using timing information with ILD simulation

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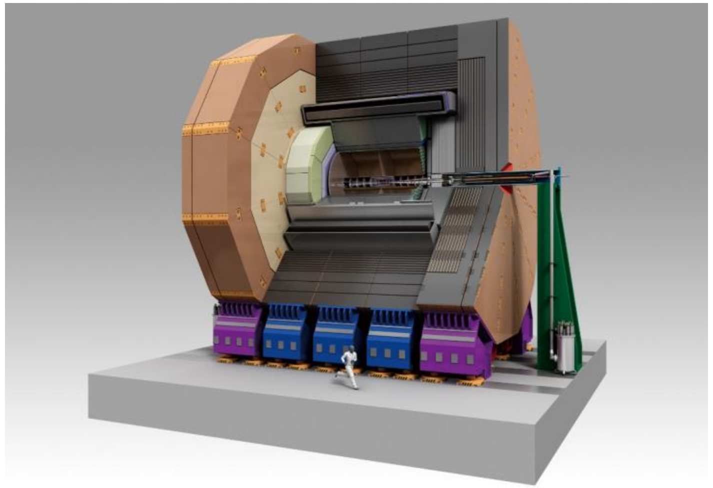
ILD and ECAL

ILD (International Large Detector)

- Tracking detector : TPC + sillicon
- Particle ID @TPC
  - → energy loss (dE/dx) and momentum

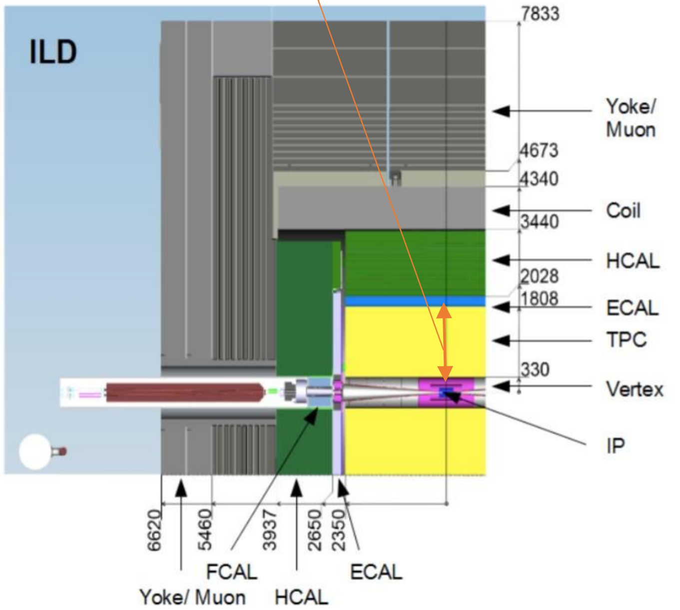
SiW-ECAL

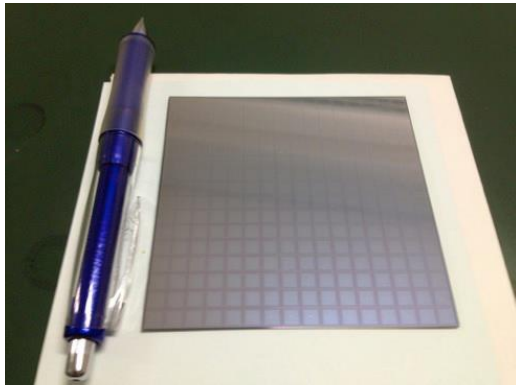
- Sandwich calorimeter (30 layers)
- Detection layers: Si
  (Pixel size : $5 \times 5\ mm^2$)
- Absorption layers: Tungsten
  (inner: 2.1 mm thick, outer: 4.2 mm thick)
- 24 radiation length in total



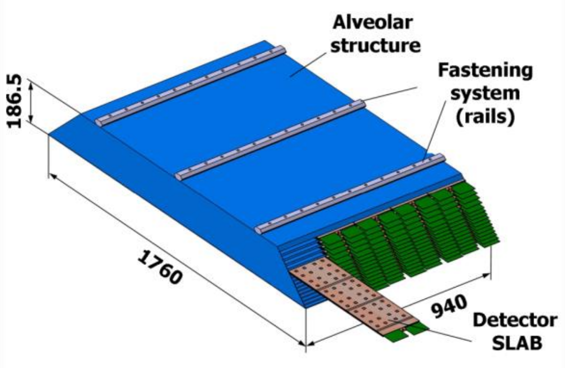
ILD

Distances of from IP to ECAL : 1.8 m





5.5 mm x 256 pixels,
9 x 9 cm / sensor



ECAL

Particle ID and Time resolution

Particle ID of hadrons

- There exists momentum ranges where we can't identify particle only by dE/dx and momentum.
- Better separation power can be obtained by adding Time-of-Flight (ToF).
- Possible to separate π/K/p up to $3\sim5$ GeV by 50 ps ToF with dE/dx at TPC

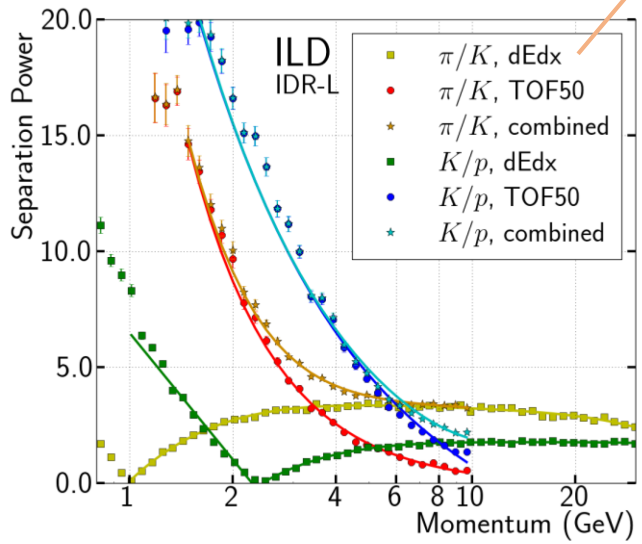
LGAD (Low Gain Avalanche Detector)

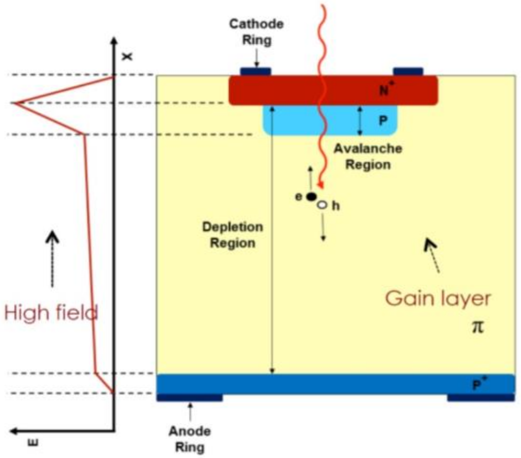
- A silicon sensor with avalanche amplification mechanism
- Higher timing resolution
  - 26 ps timing resolution achieved (study of ATLAS group)

(Final) target of this study

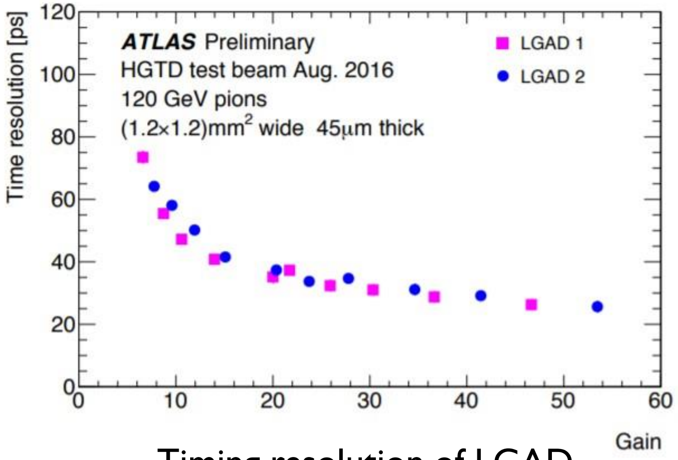
- How LGAD contributes to time resolution and particle identification when it is used as part of ECAL?
- Which ECAL layers (inner/middle/outer) should be replaced with LGAD for PID?

Timing resolution : 50 ps





Structure of LGAD



Timing resolution of LGAD
(ATLAS group)

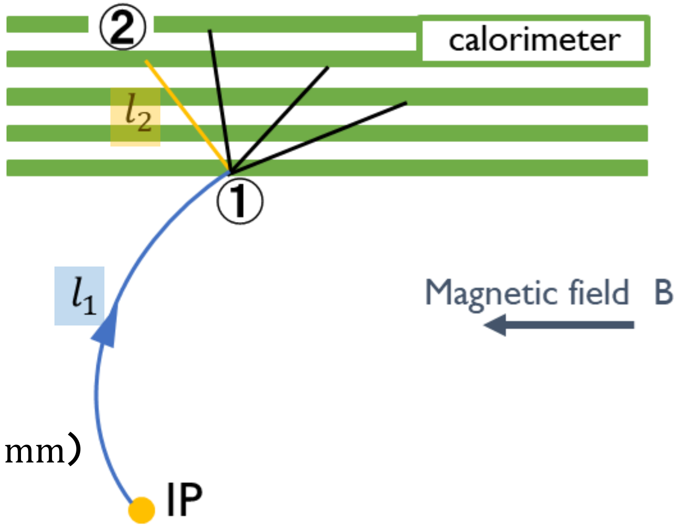
Calculation method of mass: path length

Path length of charged particle

IP → ①	Spiral orbit l_1	and
① → ②	straight line l_2	

- Hits with $l_2 > 400$ mm were cut

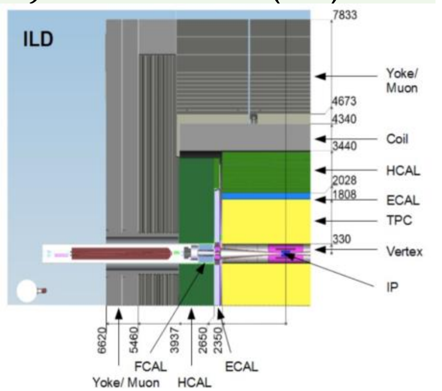
（Thickness of calorimeter is about 200 mm）



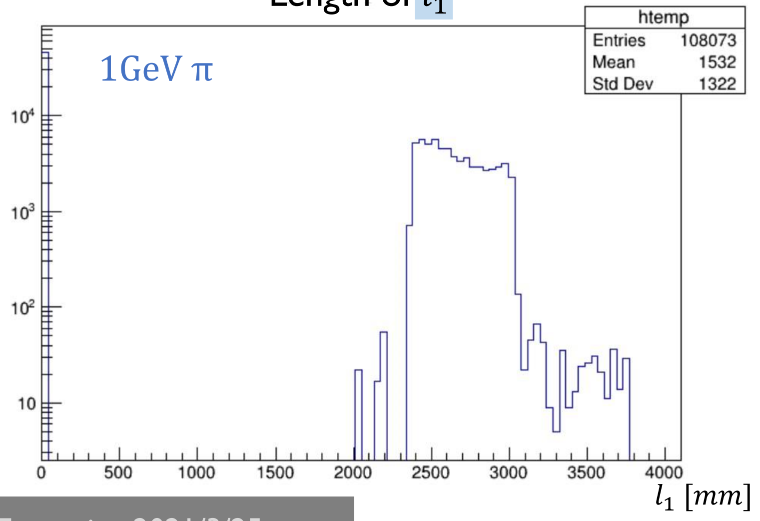
Data

- ➢ single particle of PDG=211 (π^+) and PDG=321(K^+)
- ➢ ILD detector simulation
- ➢ ILC soft : v01-19-04
- ➢ Energy

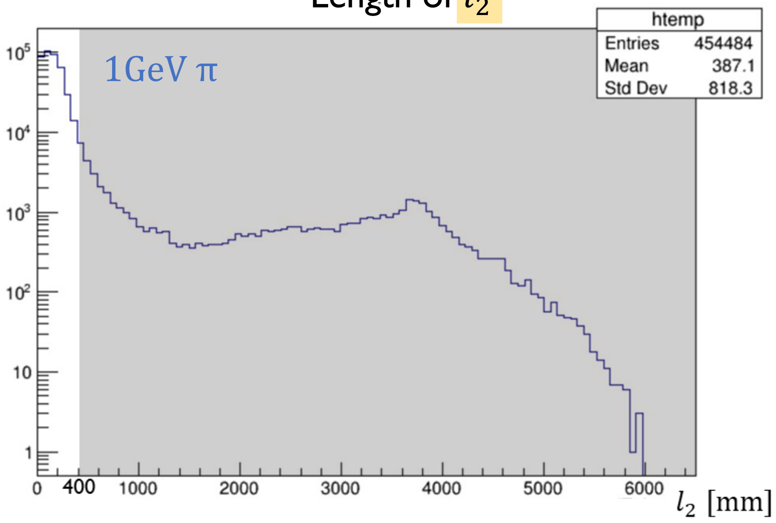
  1 , 2 , 5 , 10 GeV
- ➢ 10,000 events each



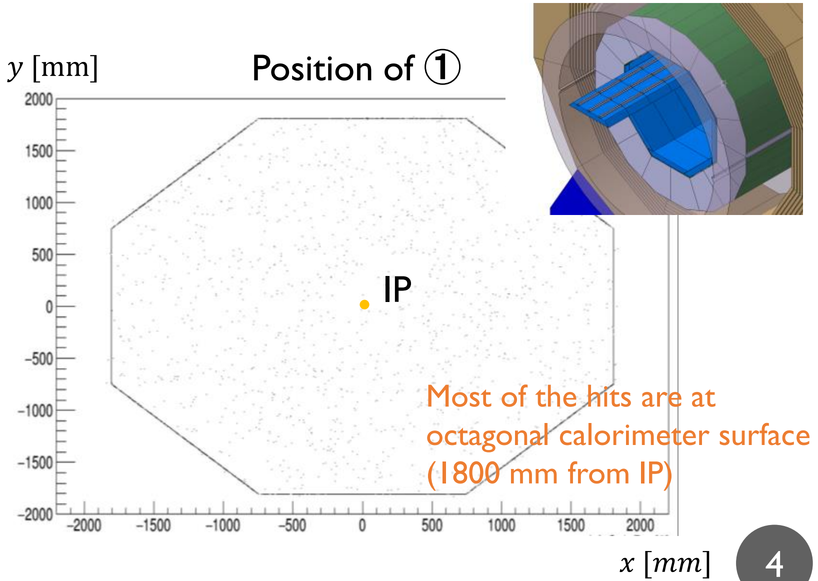
Length of l_1



Length of l_2



Position of ①



Most of the hits are at octagonal calorimeter surface (1800 mm from IP)

Calculation method of mass

- ➢ t_2 is smeared with Gaussian → timing resolution of calorimeter

$\overline{t_1}$: Mean time at ①

time of flight from IP to ① $t_1 = t_2 - \frac{l_2}{c}$

Calculate mean of t_1 within range

of t_1 with maximum number of entries $\pm$3bin

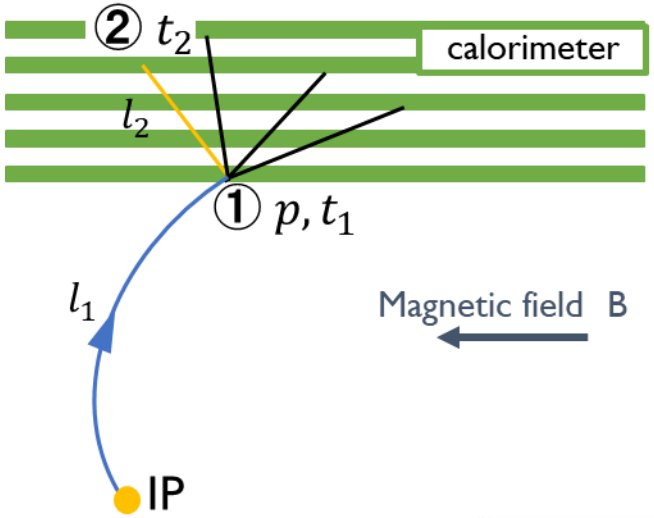
$$\overline{t_1} = \frac{\sum n \cdot t_1}{\sum n}$$

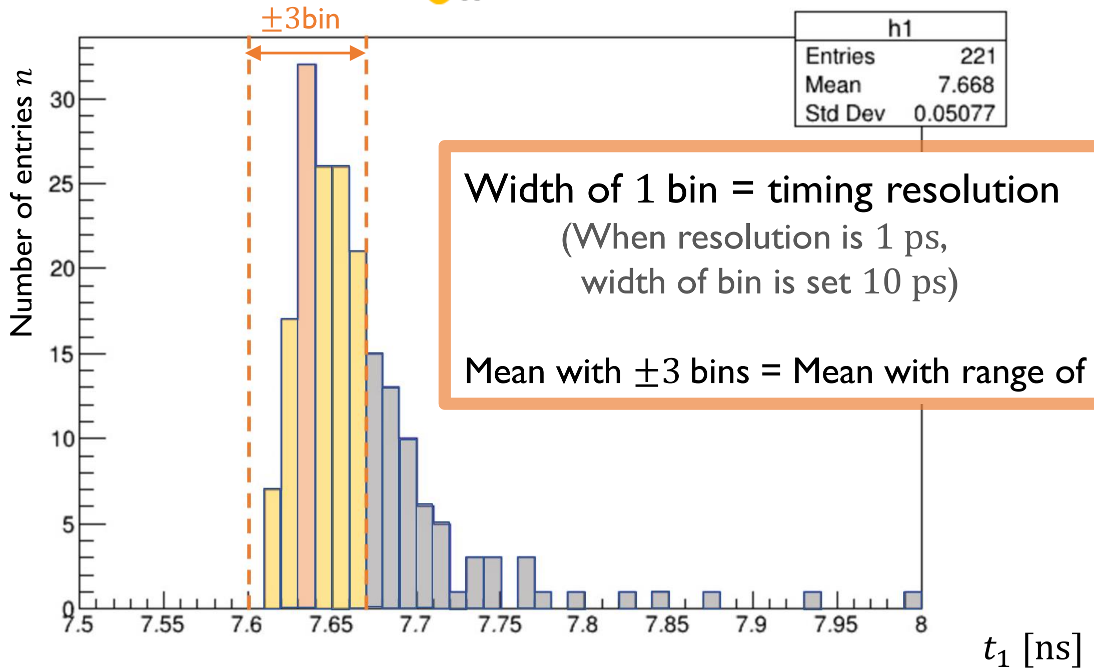
Calculation of mass

$$m = \frac{p}{\beta\gamma}$$

$$\beta = \frac{l_1}{c\overline{t_1}} \quad , \quad \gamma = \frac{1}{\sqrt{1-\beta^2}}$$

p: momentum at ①





Width of 1 bin = timing resolution

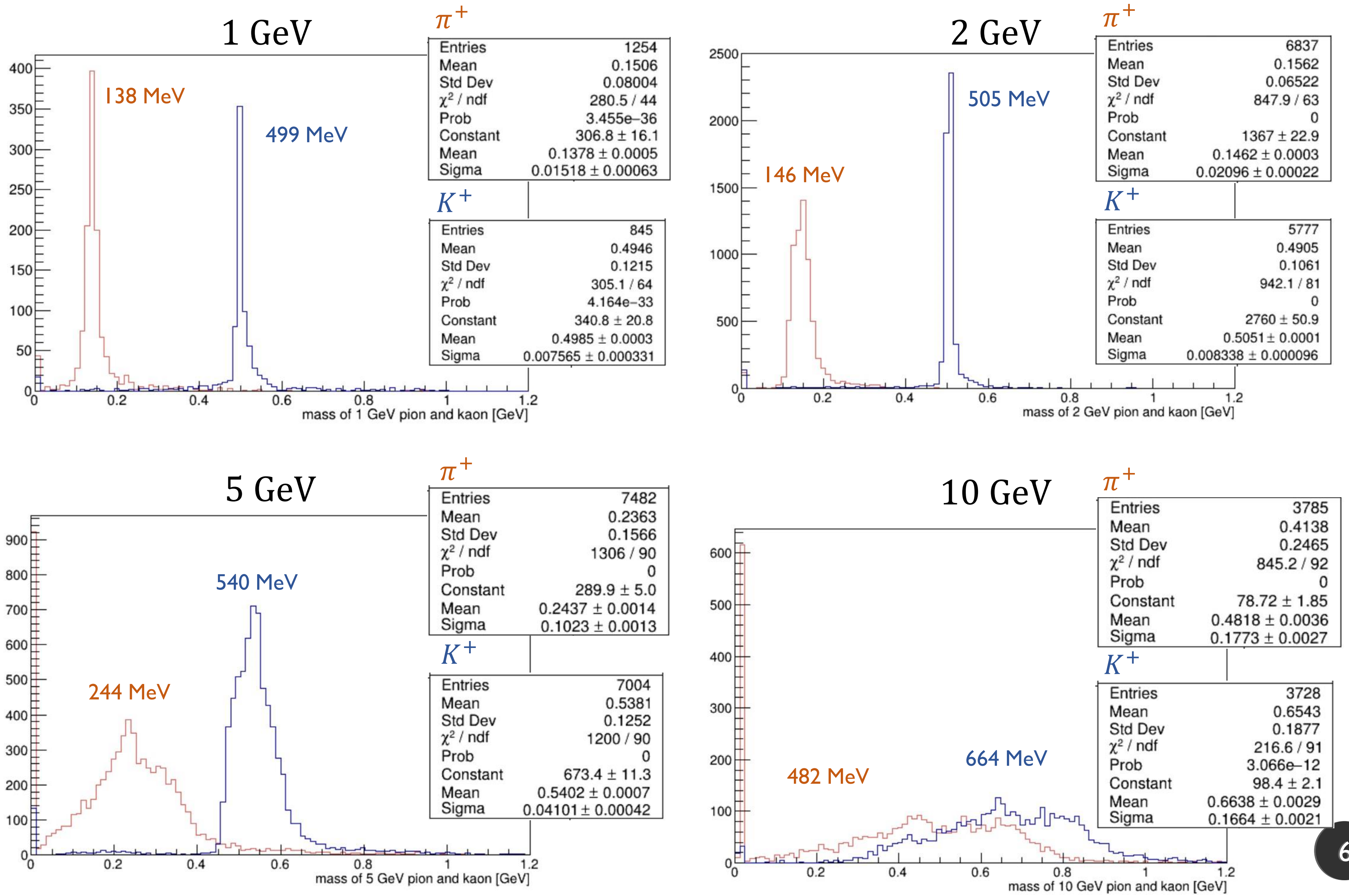
(When resolution is 1 ps, width of bin is set 10 ps)

Mean with ± 3 bins = Mean with range of $\pm 3\ \sigma$

Result: mass distribution of π^+ and K^+

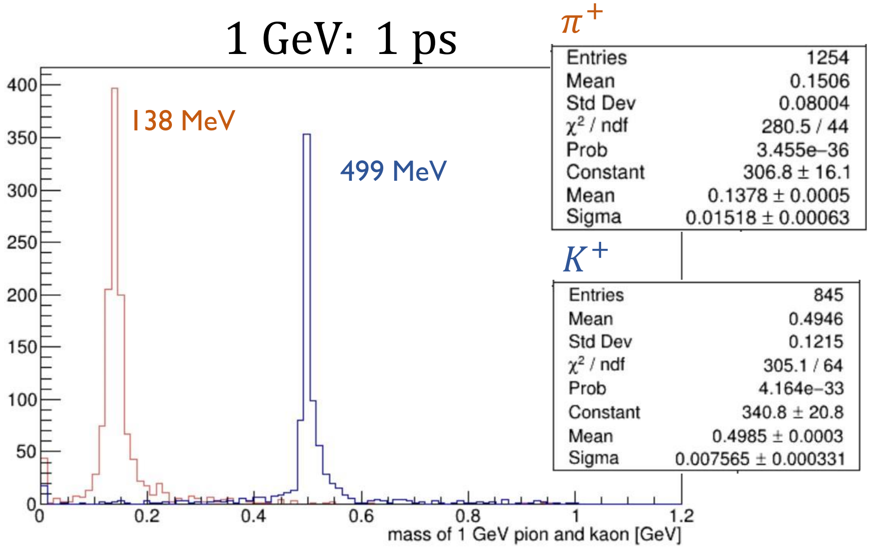
Time resolution : 1 ps

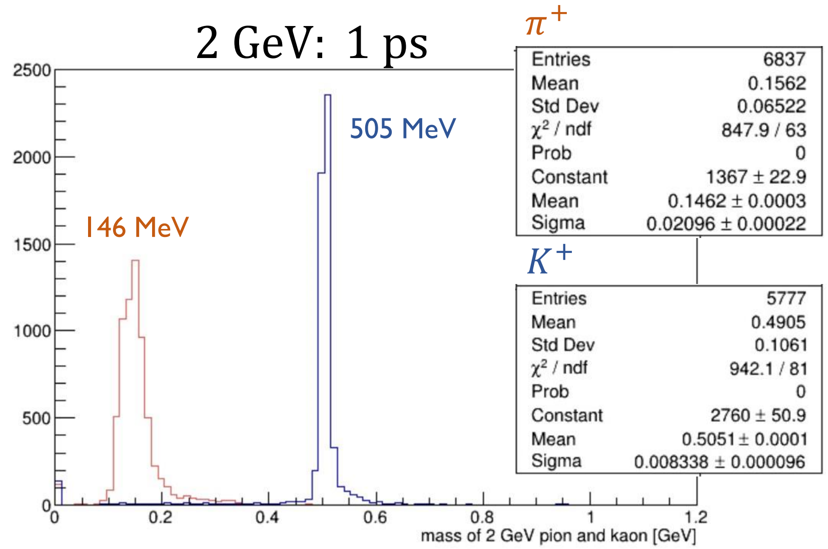
- π^+ and K^+ mass of each energy
- The peak positions are larger than the true masses at high energies (true value π^+: 139 MeV, K^+: 494 MeV)
- π^+ and K^+ can be identified up to 5 GeV if no detector timing smearing. (timing resolution: 1 ps)
- 10 GeV: bad separation



Mass distributions with timing resolutions [1, 2 GeV]

- Compare timing resolution of 1 ps and 100 ps
- The peak positions are larger than the true masses at worse timing resolution
  (true value π^+: 139 MeV
  K^+:494 MeV)

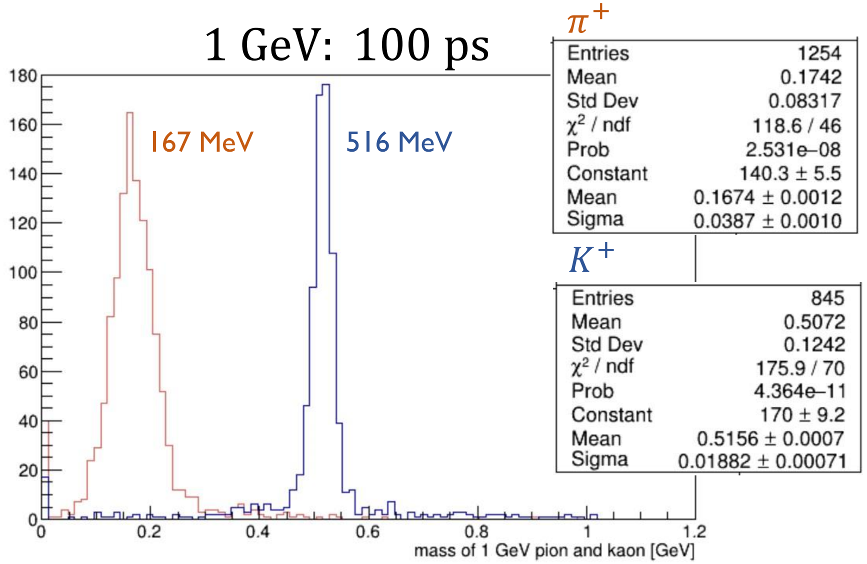


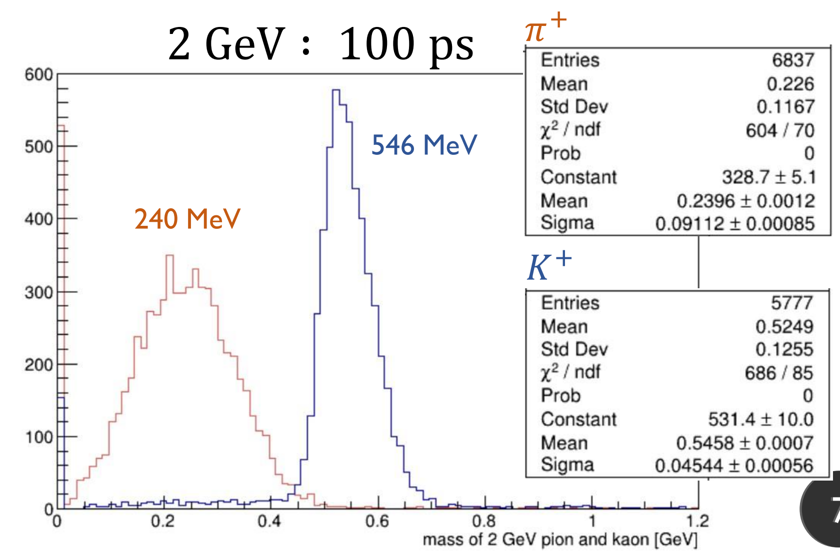


Even though timing resolution is 100 ps, π^+ and K^+ can be identified.

Assuming timing resolution 100 ps can be achieved without LGAD.

→ standard silicon sensors (with electronics update for 100 ps timing measurement) are enough to separate K/pi up to 2 GeV

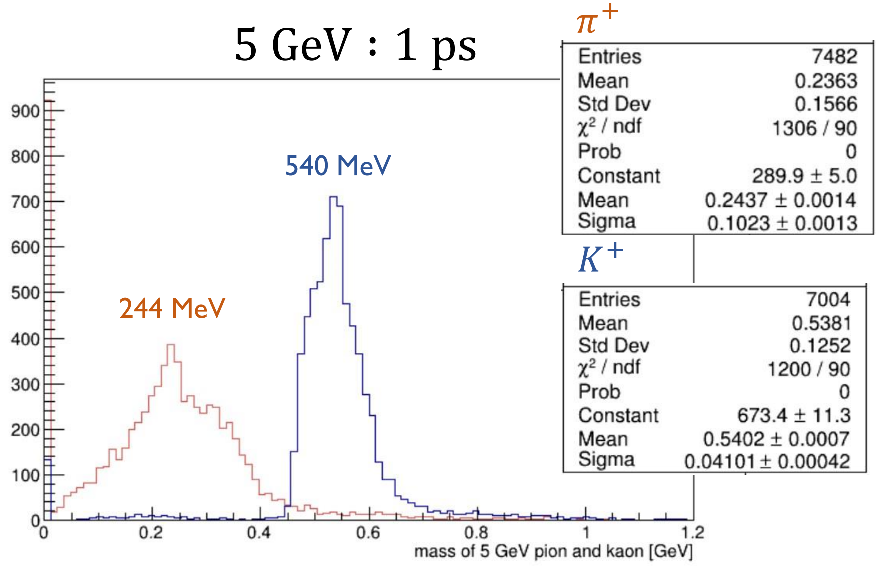


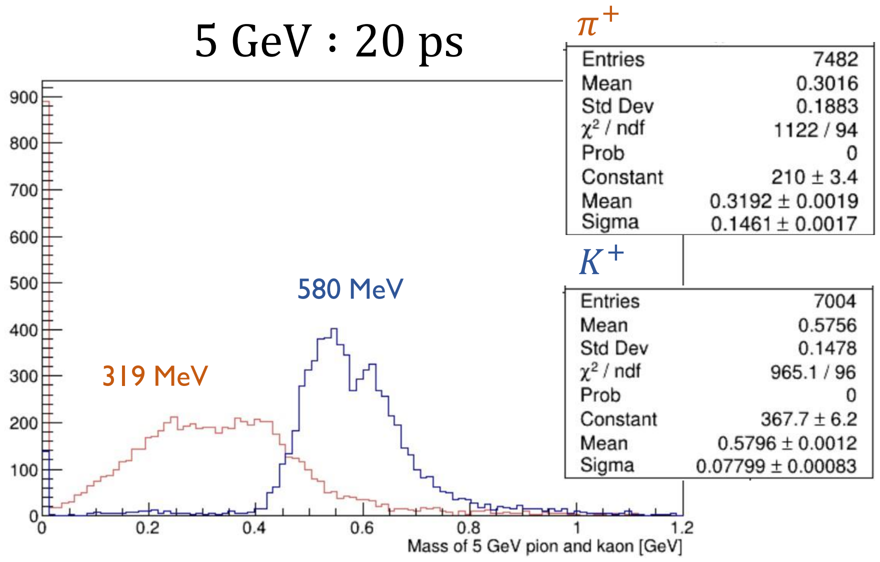


Comparison of mass distribution for timing resolutions [5 GeV]

- Compare timing resolution
  1, 20, 50 and 100 ps.

- The peak positions are larger than the true masses at worse timing resolution

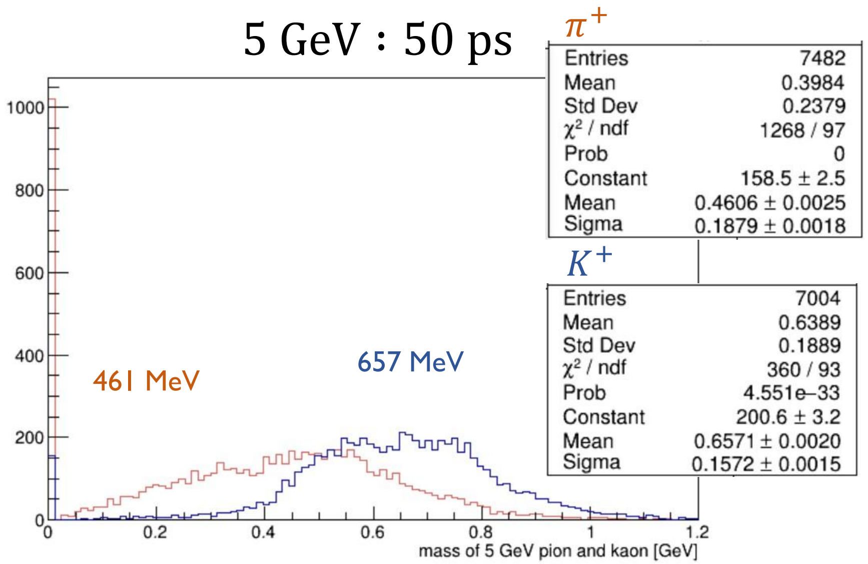


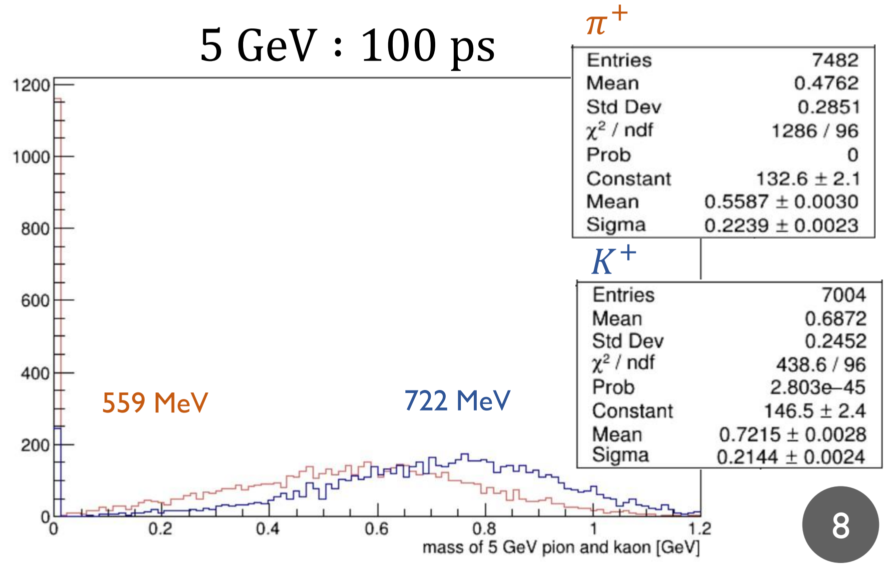


If timing resolution is better than 20 ps, π^+ and K^+ can be mostly identified.

LGAD can enable π/K separation

→ need optimization!





Timing resolution and separation power

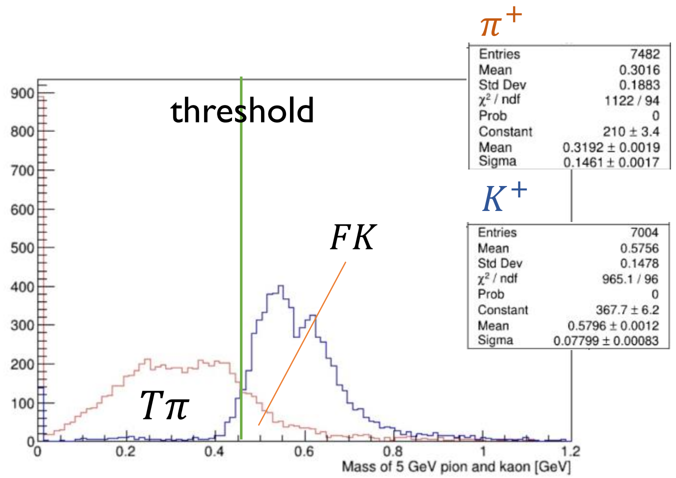
- Mass distribution of π^+（true value about 0.139 GeV）smaller than the threshold and
  K^+（true value about 0.494 GeV）larger than the threshold could be identified correctly.
- Scan the threshold to maximize "Accuracy" at each energy and timing resolution and calculate the efficiency of π^+ and K^+ with the threshold.

		true	
		π	K
prediction	π	$T\pi$	$F\pi$
	K	FK	TK

$$accuracy = \frac{T\pi + TK}{T\pi + TK + F\pi + FK}$$

$$\pi: \ Efficiency = \frac{T\pi}{T\pi + FK}$$

$$K: \ Efficiency = \frac{TK}{TK + F\pi}$$



Accuracy

accuracy	1 ps	10 ps	20 ps	50 ps	100 ps
1 GeV	96.00	95.90	96.09	96.33	96.00
2 GeV	96.71	96.49	96.43	96.17	95.63
5 GeV	94.07	93.56	88.62	72.84	66.44
10 GeV	74.10	71.02	65.11	59.46	57.98

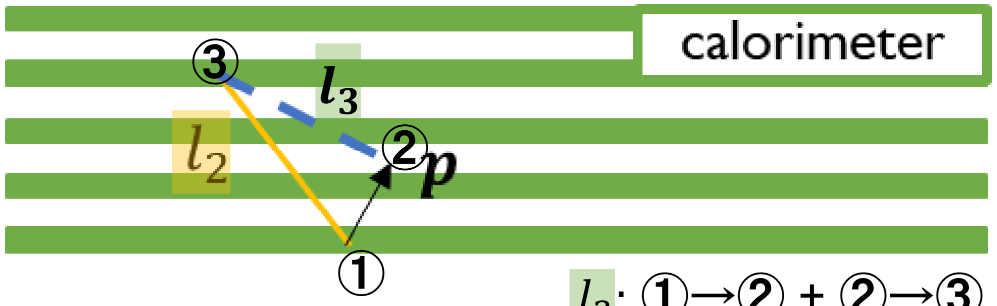
Efficiency

π	1 ps	10 ps	20 ps	50 ps	100 ps
1 GeV	97.85	98.01	97.93	97.61	97.13
2 GeV	98.96	99.08	98.82	98.64	98.42
5 GeV	92.42	92.46	84.31	64.17	65.36
10 GeV	78.15	76.72	78.23	61.19	59.78

K	1 ps	10 ps	20 ps	50 ps	100 ps
1 GeV	93.25	92.78	93.37	94.44	94.32
2 GeV	94.05	93.42	93.61	93.25	92.33
5 GeV	95.83	94.73	93.22	82.10	67.59
10 GeV	69.98	65.24	51.80	57.70	66.31

unit: %

Optimization of path length



l_3: ①→② + ②→③

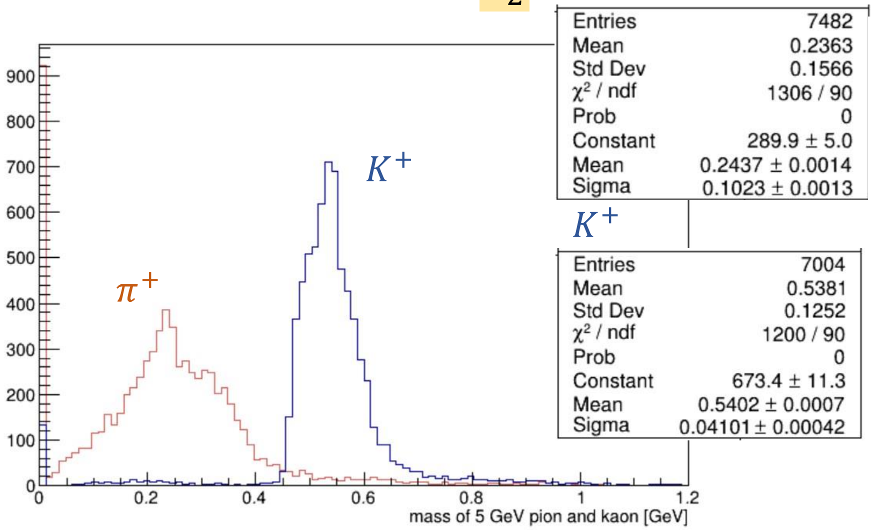
$l_{mean} = (l_2 + l_3)/2$

l_2 is underestimate as path length in calorimeter and caused tail of mass distribution.

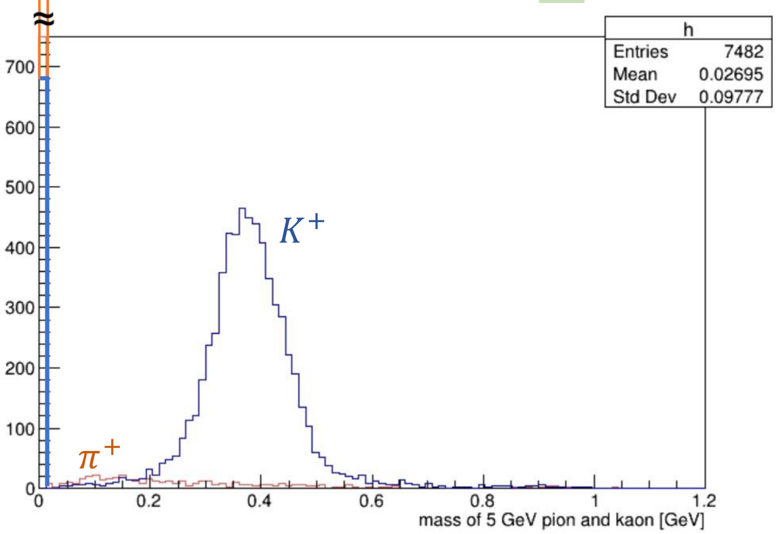
→ Calculate mass with l_3 and l_{mean}

l_3 is overestimate.

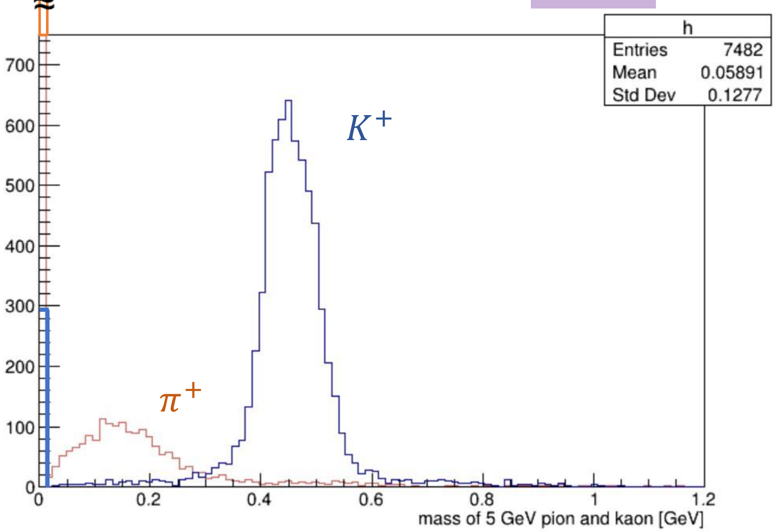
Mass calculated with l_2



←7000 Mass calculated with l_3



←5500 Mass calculated with l_{mean}



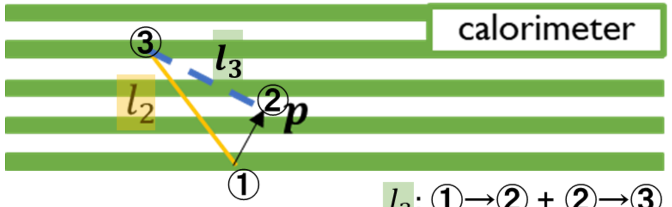
Separation power with l_{mean}

5 GeV		1 ps	10 ps	20 ps	50 ps	100 ps
π efficiency [%]	l_{mean}	95.6	92.9	90.5	76.8	69.7
	l_2	92.4	92.5	84.3	64.2	65.4
K efficiency [%]	l_{mean}	93.6	93.2	91.0	85.0	75.5
	l_2	95.8	94.7	93.2	82.1	67.6
accuracy [%]	l_{mean}	94.7	93.0	90.7	80.7	72.5
	l_2	94.1	93.6	88.6	72.8	66.4
threshold [GeV]	l_{mean}	0.27	0.27	0.33	0.38	0.44
	l_2	0.40	0.44	0.44	0.48	0.60

Improvement!

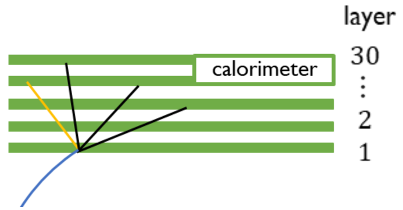
10 GeV		1 ps	10 ps	20 ps	50 ps	100 ps
π efficiency [%]	l_{mean}	82.3	81.4	65.8	56.4	72.6
	l_2	78.2	76.7	78.2	61.2	59.8
K efficiency [%]	l_{mean}	66.9	65.1	73.4	69.6	46.7
	l_2	70.0	65.2	51.8	57.7	66.3
accuracy [%]	l_{mean}	74.7	73.3	69.6	62.9	59.7
	l_2	74.1	71.0	65.1	59.5	58.0
threshold [GeV]	l_{mean}	0.05	0.05	0.09	0.39	0.86
	l_2	0.57	0.59	0.77	0.91	0.96

- Better estimation of path length leads to better K/π separation.
  - 5 GeV: Accuracy greatly improved especially at 50 and 100 ps.
  - 10 GeV: Improvement seen but smaller than 5 GeV
- More intelligent estimation of the path length using shower-shape information is desired.



l_3: ①→② + ②→③
$l_{mean} = (l_2 + l_3)/2$

Layers with different time resolution



Mass distribution calculated with l_{mean}

Set the time resolution of only certain 5 layers to 20 ps (LGAD)

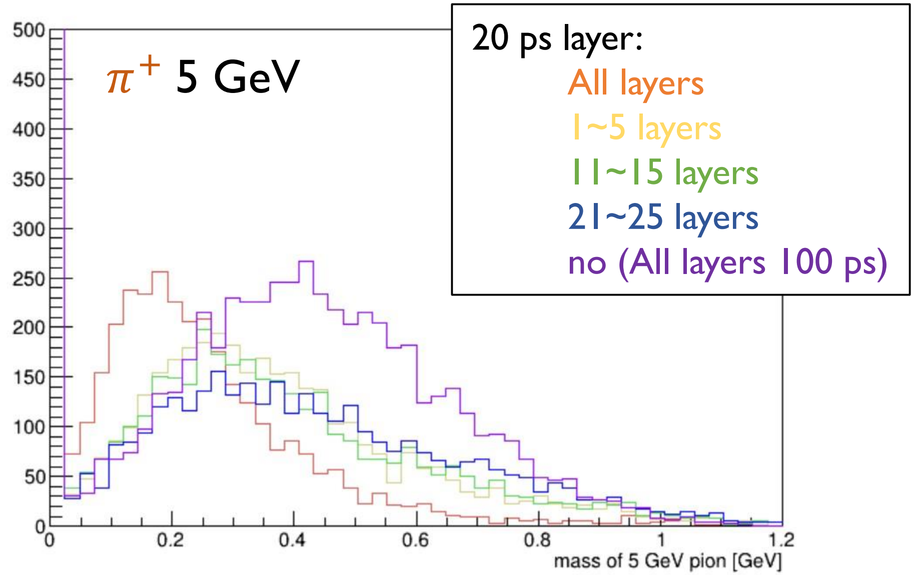
Time resolution of other layers is 100 ps (Si sensor)

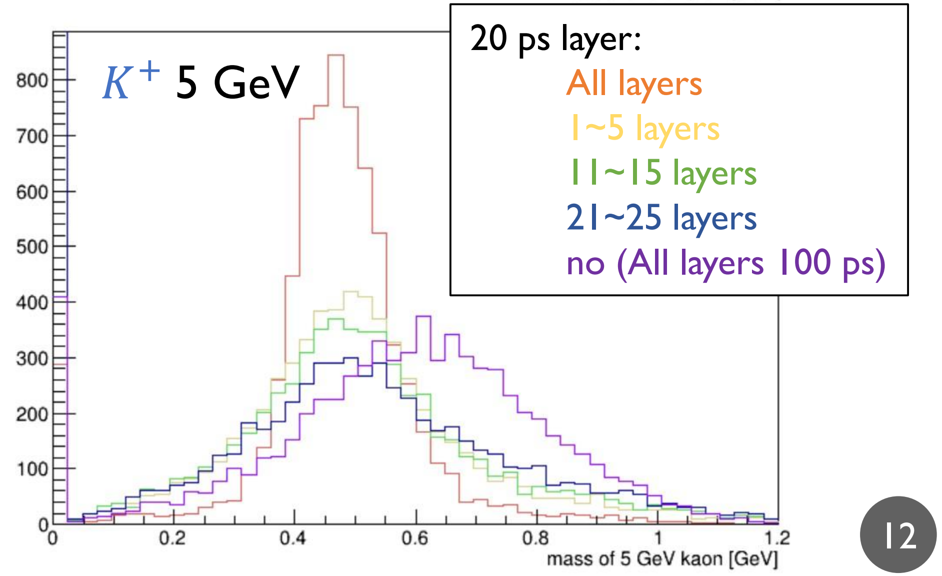
- Inner layers: less hits, but mostly track-like hits → less contamination
- Middle layers: more hits by showers → more statistics, but more contamination
- Outer layers: hits with larger position spread → may suffer from path length error

	20 ps layer	all layer	1-5 layer	11-15layer	21-25layer	no layer
5 GeV	π efficiency[%]	90.46	77.23	80.86	69.14	69.74
	K efficiency[%]	90.96	73.29	70.86	74.13	75.53
	accuracy[%]	90.7	75.32	76.03	71.55	72.54
	threshold[GeV]	0.33	0.33	0.33	0.25	0.44

With current algorithm, use of LGAD at inner or middle layers should give reasonable improvements of the separation.

Better estimation of the path length and cut on contamination may lead to different dependence → need further studies





Summary

Summary

- LGAD can improve the timing resolution of ECAL.
- Calculate π^+ and K^+ mass of each event
- Particle separate power and timing resolution
  - $1, 2\ \mathrm{GeV}$: Even though timing resolution is $100\ \mathrm{ps}, \pi^+$ and K^+ can be identified. → standard Si sensors are enough.
  - $5\ \mathrm{GeV}$: If timing resolution is better than $20\ \mathrm{ps}, \pi^+$ and K^+ can be identified mostly. → need LGAD

Next step

- Improvement of calculation method of path length at high energy

  (with possible use of deep learning)

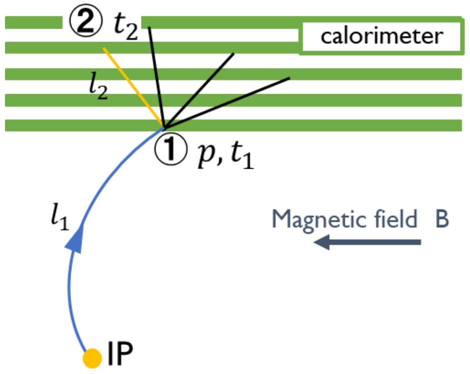
- Continue to investigate effect to the resolution and particle ID by combining LGAD with ECAL

BACKUP

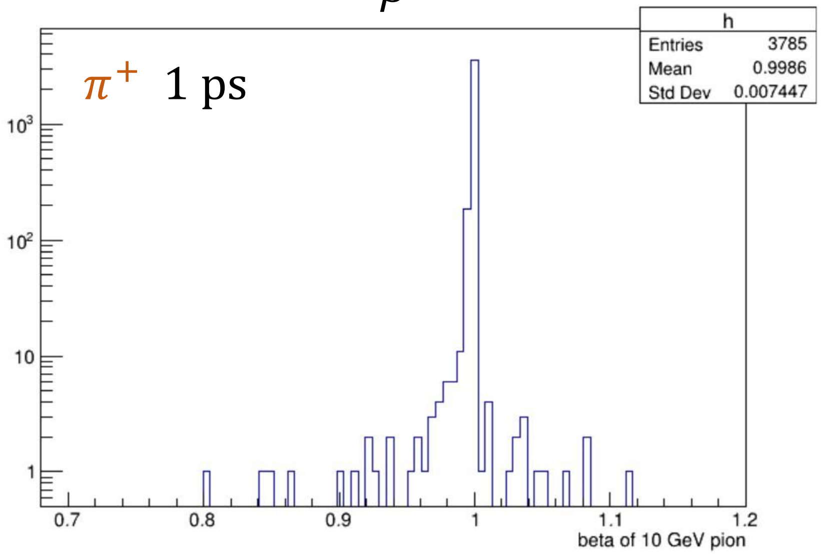
The reason why the mass distribution cannot be separated [10 GeV]

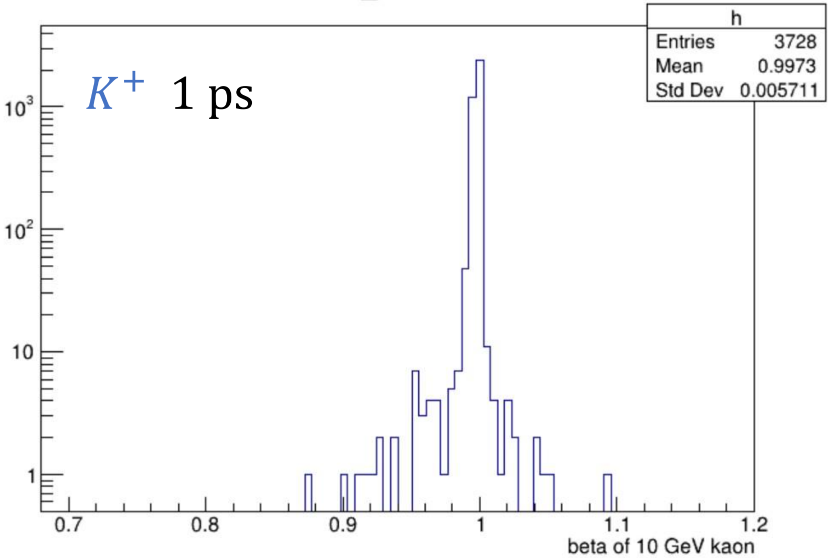
- Distribution of $\beta = \frac{l_1}{ct_1}$ is wide…
- $\pi^0 \to \gamma\gamma \to$ electromagnetic shower with many (delayed) hits

Improvement of calculation method of average value is necessary (to be done).

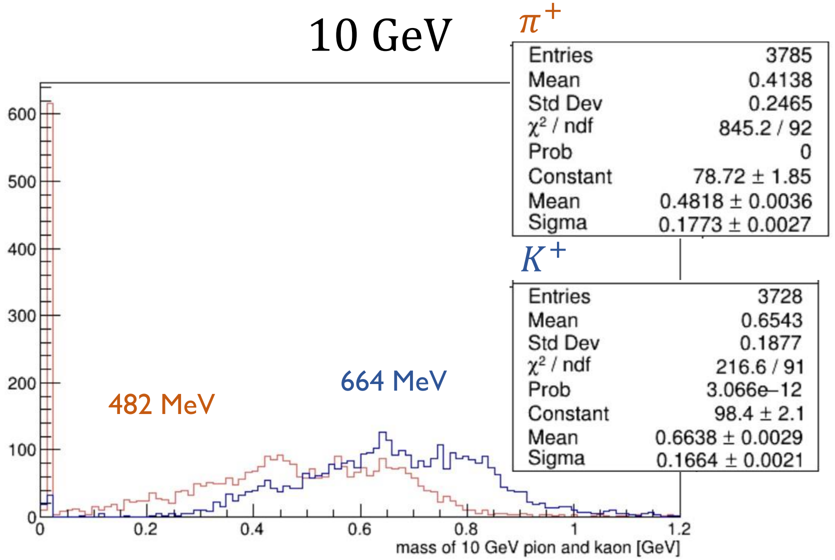


β

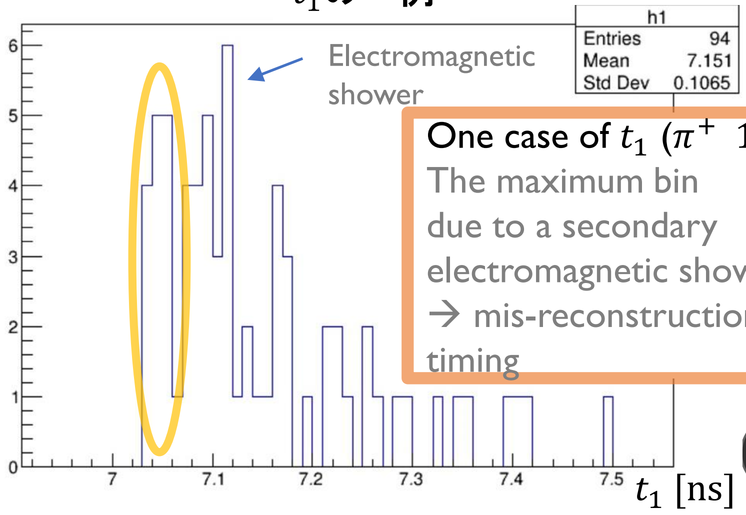




10 GeV



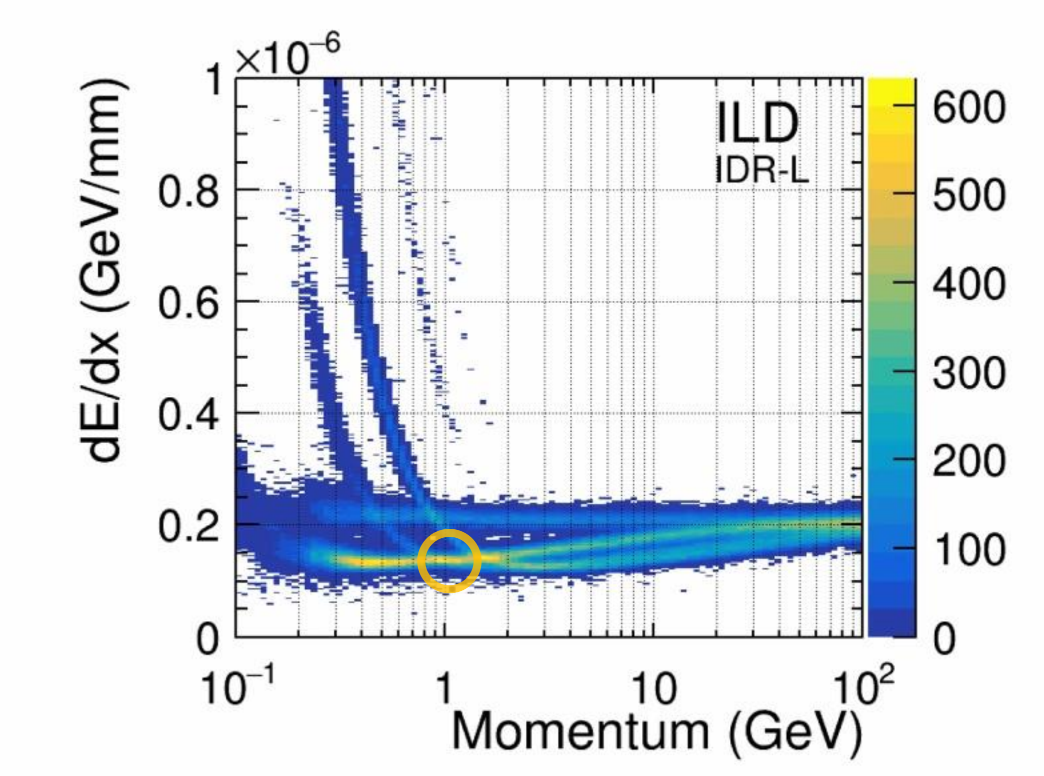
t_1の一例

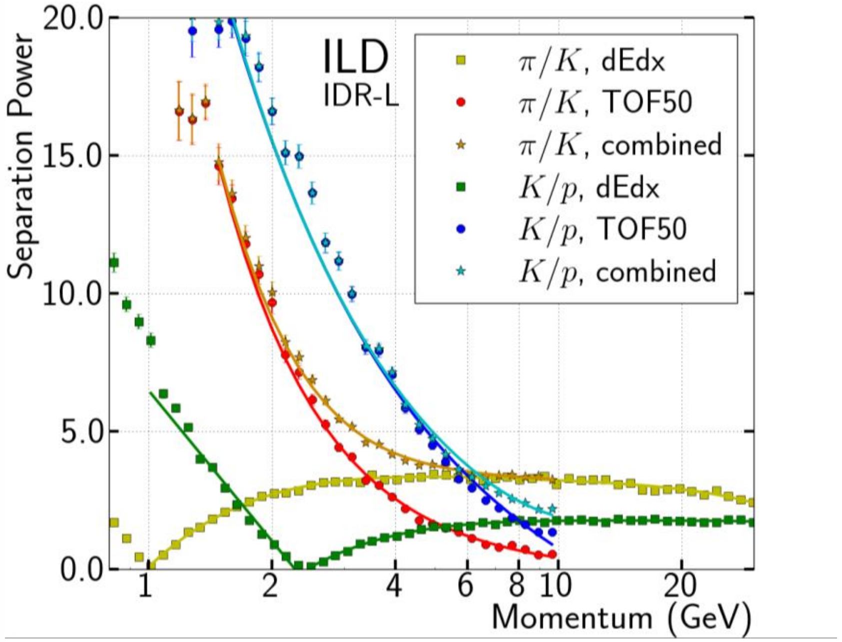


One case of t_1 (π^+ 1 ps)
The maximum bin due to a secondary electromagnetic shower → mis-reconstruction of timing

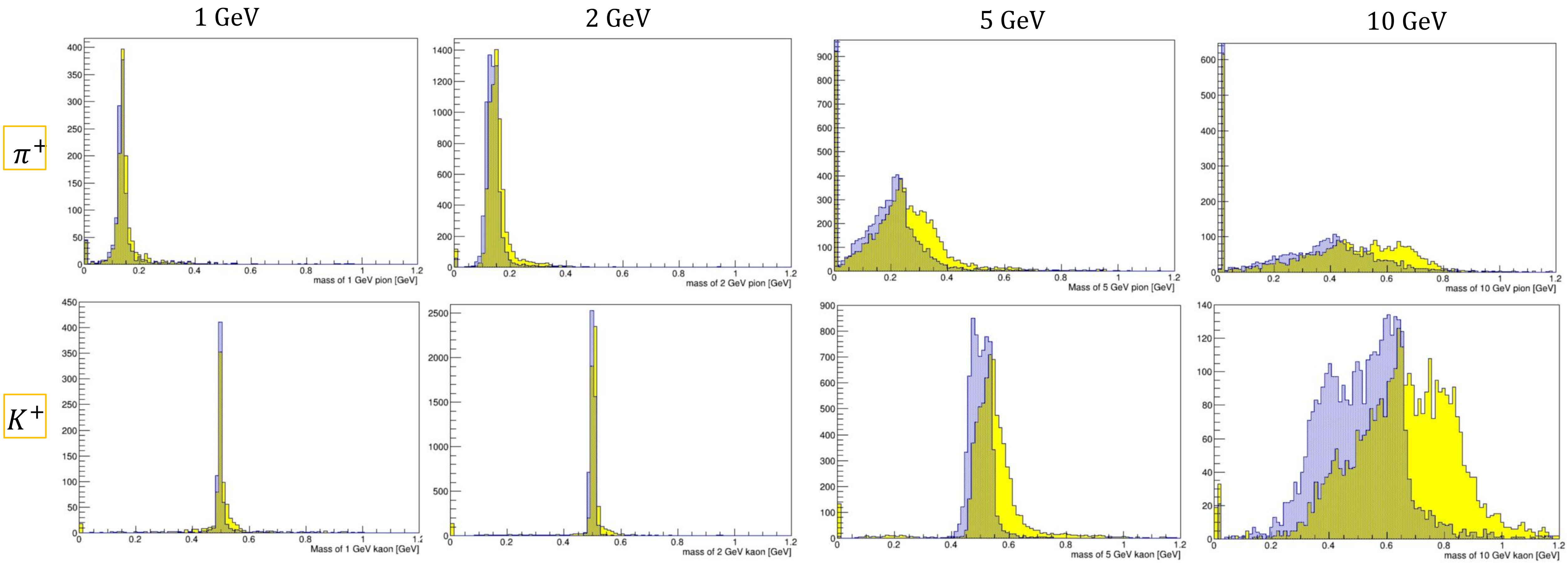
Particle separation with dE/dx

- π^+ and K^+ cannot be identified at $1\ \mathrm{GeV}$ with only $\frac{dE}{dx}$
- Better separation power can be obtained by adding ToF than only dE/dx .





Contamination of secondary particles



- Select hits directly induced by π^+ and K^+ with MC information (blue) / all hits (yellow)
- Need to think of ways to separate hits of secondary particles.

10 GeV : β and transeverse momentum

- $\beta = \frac{l_1}{t_2 c - l_2}$ vs $\cos\theta = \frac{p_z}{p}$