PID capabilities (for charged hadrons)

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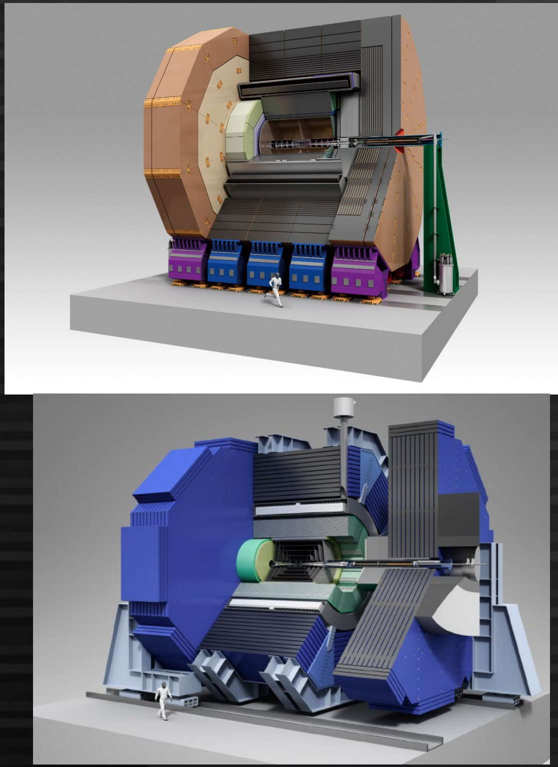
Most of the ideas/pictures taken by talks of
ECFA WG3: Topical workshop on calorimetry, PID and photodetectors
on May 3-4 at CERN

Particle ID: a missing piece?

- Particle flow detectors are designed for
  - Impact parameter resolution with vertex detector for b/c tagging etc.
  - Momentum resolution (for Higgs recoil etc.) and track separation (for tau etc.) with precise tracking
  - Jet energy resolution with Particle Flow Algorithm
    - Highly-granular calorimetry and magnet outside HCAL
  - Lepton ID using shower shape, track-cluster ratio and ECAL/HCAL ratio
- But hadronic Particle ID function is less considered
  → adding new power to our detectors



Contents of this talk

1. Why do we need (or prefer to have) Particle ID?
   - Strange tagging
   - Helping b/c tagging / jet charge
   - Jet energy reconstruction
2. Detector technologies for (hadron) particle ID
   - dE/dx (in TPC and others)
   - Time-of-flight: Silicon, Scintillator, RPC
   - (Ring-imaging) Cherenkov
   - Transition radiation

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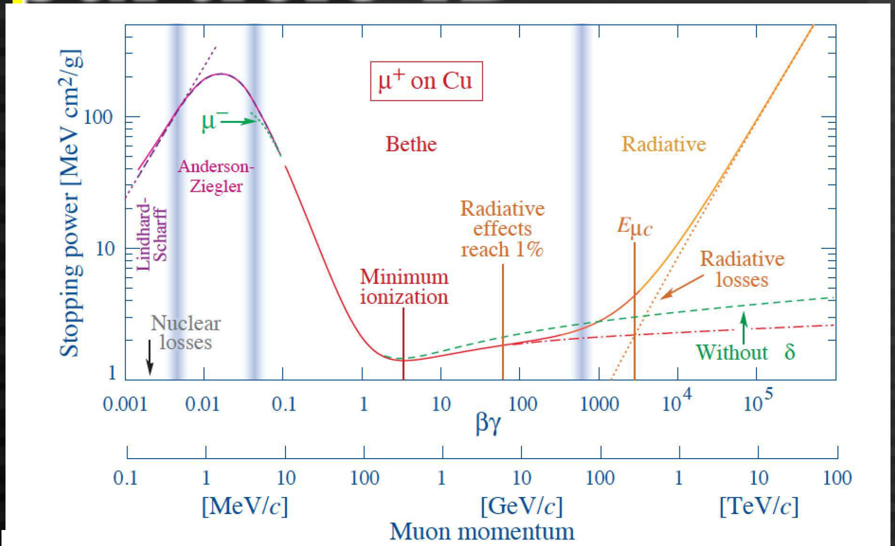
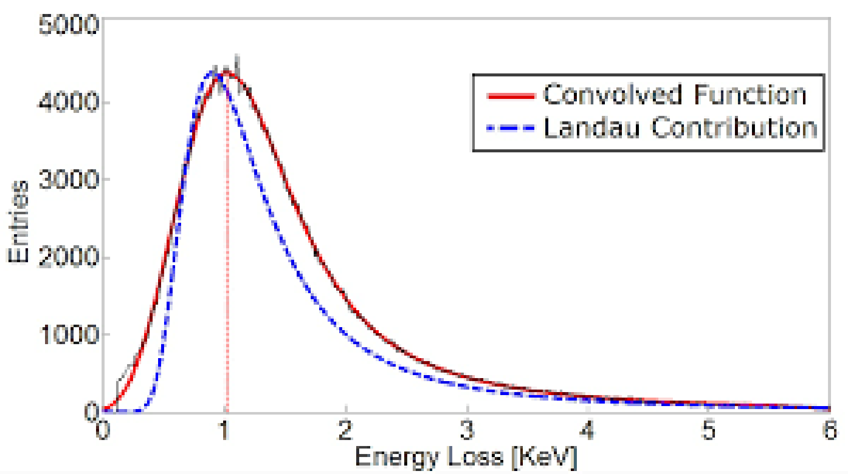
dE/dx measurement for particle ID

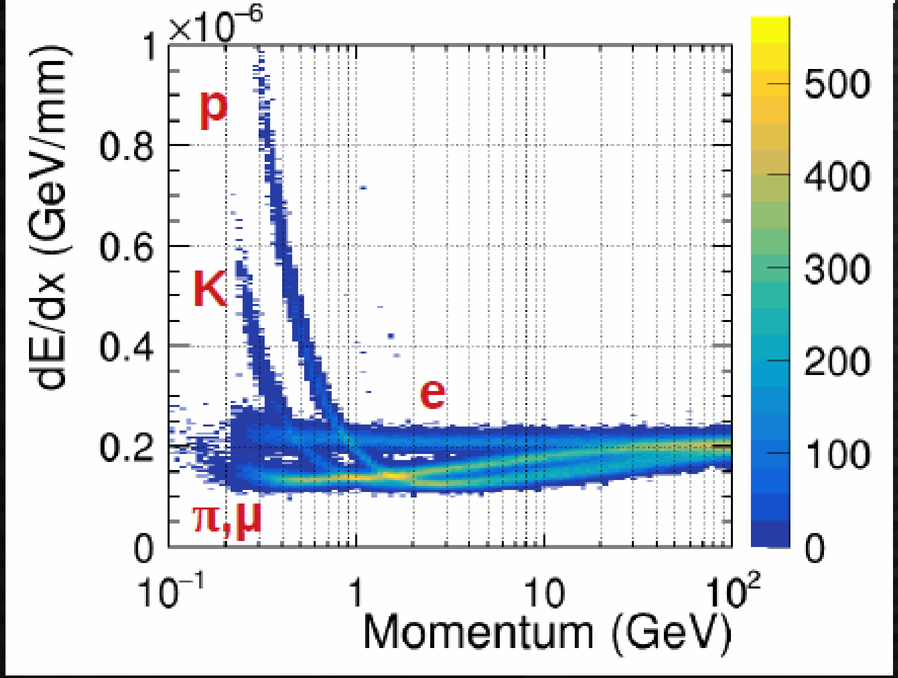
- dE/dx is a function of β, so mass can be derived with p and dE/dx
  - A few % resolution of dE/dx necessary
- dE/dx is suffered by Landau tail if averaged
  - Measuring as many points as possible to eliminate off-center fraction is essential → gas tracking is an optimal solution





Energy Loss by 12 GeV Protons in 5.6 um silicon

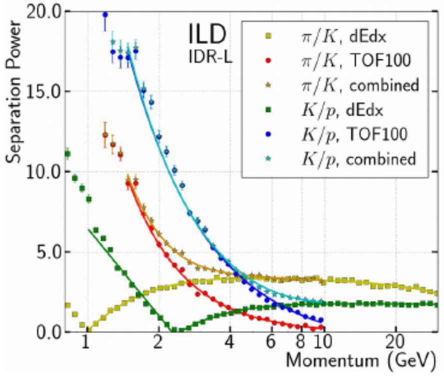
dE/dx at ILD TPC



Performance of dE/dx with TPC (and others)

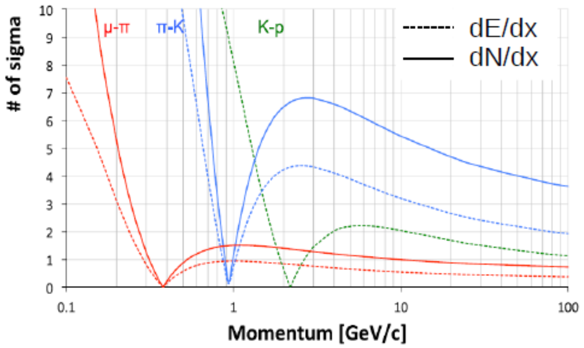
- dE/dx (energy deposit) vs dN/dx (counting cluster)
  - dN/dx seems to give better results (because of truncation of high-edep tail) but requires precise spatial resolution (eg. pixel TPC with silicon readout)
  - More intelligent reconstruction (using both energy and cluster information) possible? (Maybe ML?)
- dE/dx at front layers of ECAL can also be explored?
  - Hadrons are mostly track-like

TPC: dE/dx (dN/dx?)
ECal: TOF



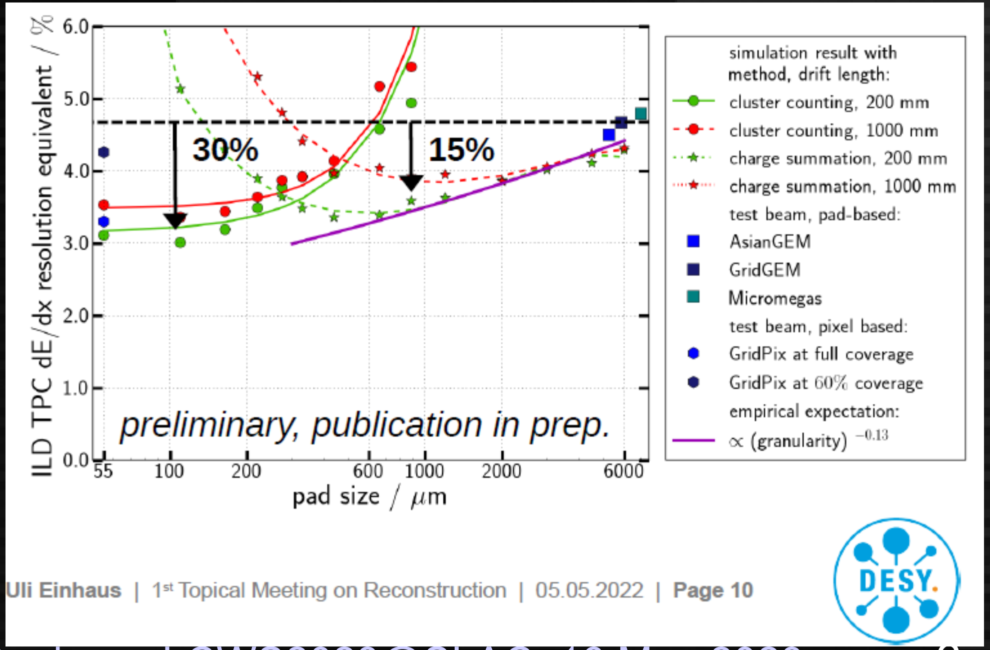
[ILD IDR 2020
https://arxiv.org/abs/2003.01116]

DC: dE/dx or dN/dx



[IDEA, FCC-ee CDR 2019
https://doi.org/10.1140/epjst/e2019-900045-4]

Separation power:
dE/dx PID has insensitive momentum region due to the overlap of stopping power



preliminary, publication in prep.

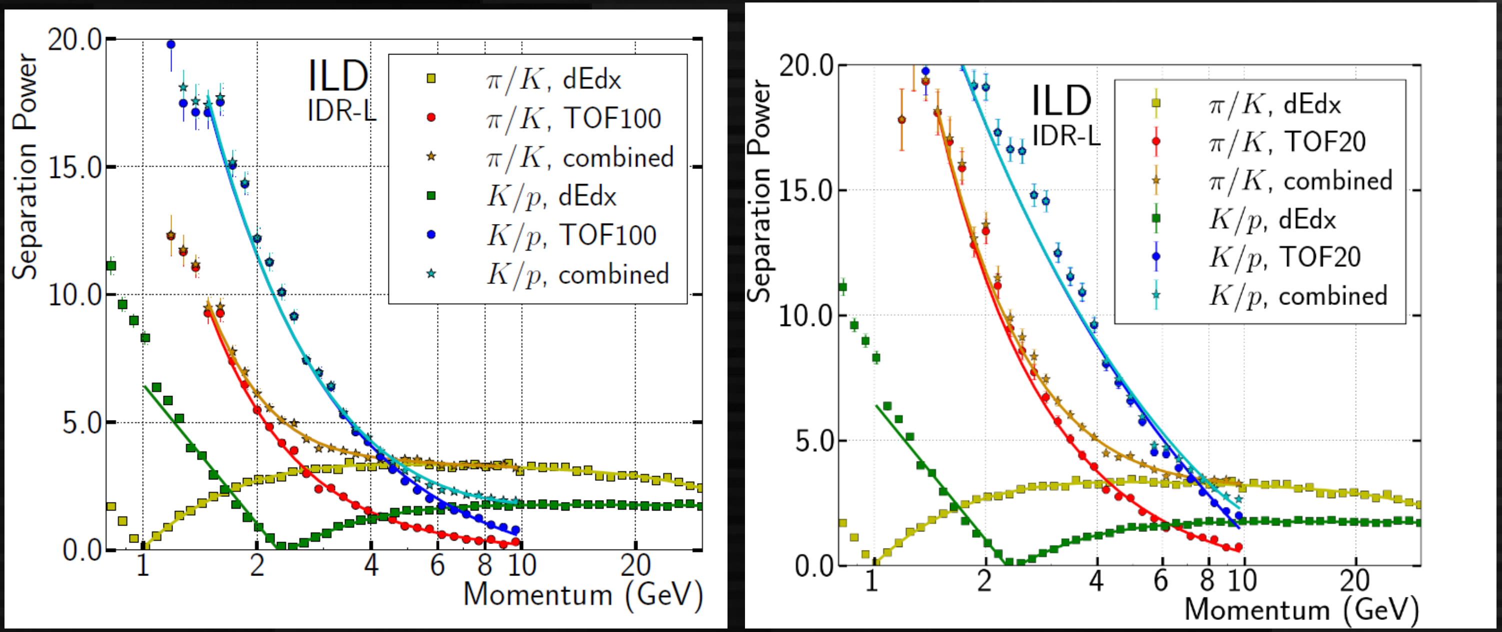
Uli Einhaus | 1st Topical Meeting on Reconstruction | 05.05.2022 | **Page 10**

Time-of-flight: necessary timing resolution

- <100 psec timing is necessary for pi/K/p separation of 5-10 GeV
  - Most of tracks inside jets covered
  - But usually high-energy tracks are more important
  - Precise calculation of track length
- Relatively easy to cover dE/dx gap at 1-2 GeV
  - But clear advantage on dE/dx for higher energy
- Target: O(10 psec)

Time difference @2m lever arm

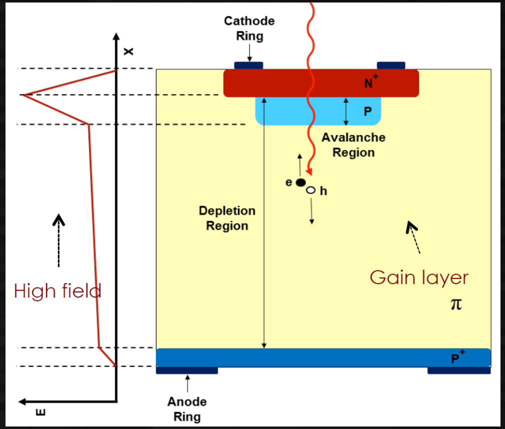
Energy	β (π)	β (K)	β (p)	Δt (π/K)	Δt (K/p)
5 GeV	0.9996	0.9951	0.9822	30 ps	88 ps
10 GeV	0.9999	0.9988	0.9956	7 ps	21 ps

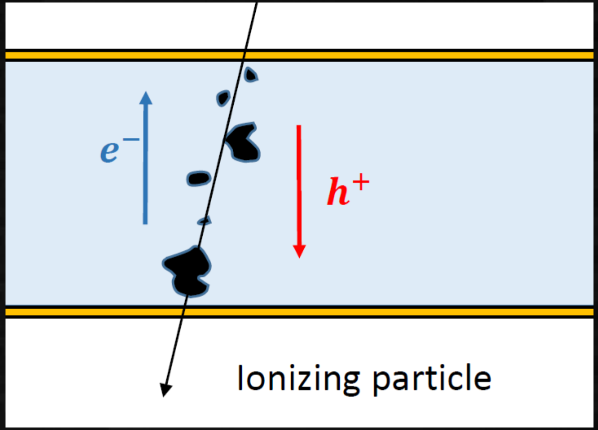


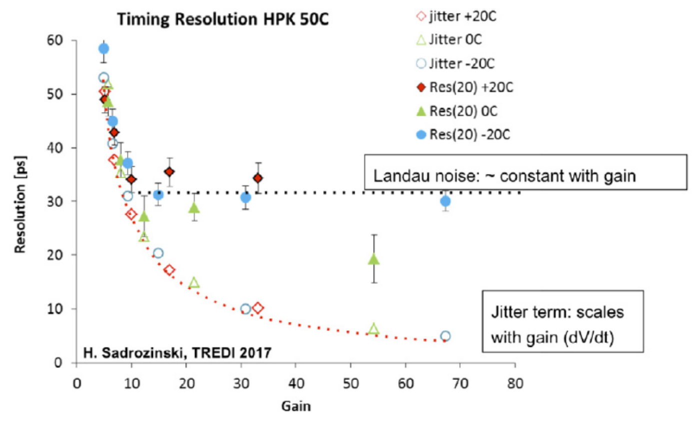
Separation power of hadron ID at ILD by dE/dx and ToF
Timing with ECAL assumed; track-like hits of first 10 layers averaged

ToF technologies: silicon sensors

LGAD (Low Gain Avalanche Detector)
Silicon sensor with linear (10-100) gain
Time resolution limited by Landau fluctuation



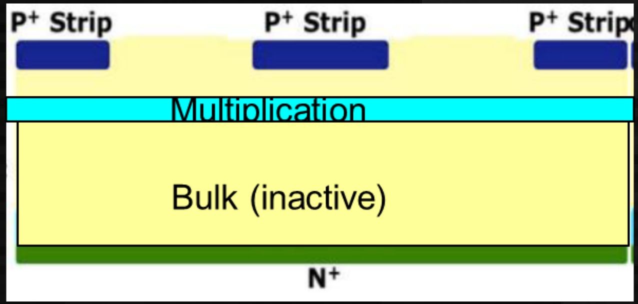




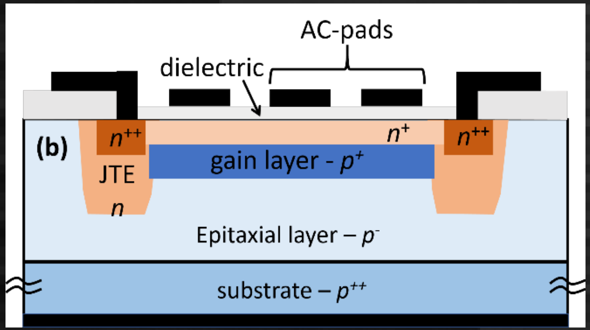
To be used for HL-LHC
(ATLAS HGTD / CMS MTD)
1-2 mm cells realize
~30 psec timing resolution

Various LGAD structures proposed for improvement

- AC-LGAD: reducing inactive region between cells
  Suitable for tracking detectors (strips/pixels)
- Inverse LGAD: gain flatness and thinner active layer
- Monolithic LGAD: smaller noise to reduce jitter



Inverse LGAD (single sided)



AC-LGAD

SPAD (Single Photon Avalanche Diode)
Geiger-mode detector similar to SiPM

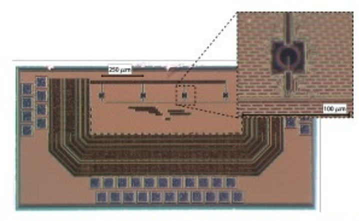


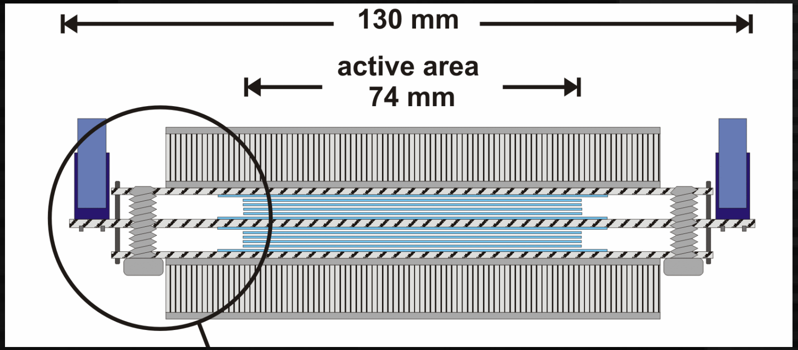
FIG. 1: Micrograph of the implemented chip embedding 25 μm diameter SPADs with integrated pixel circuit [20].

Monolithic SPAD
demonstrated < 10 psec
MIP timing resolution

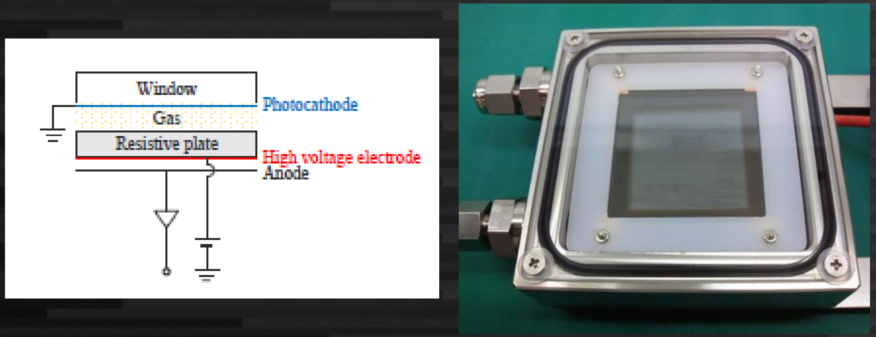
ToF technologies: photon, RPC, others

NIMA 824, 92-95

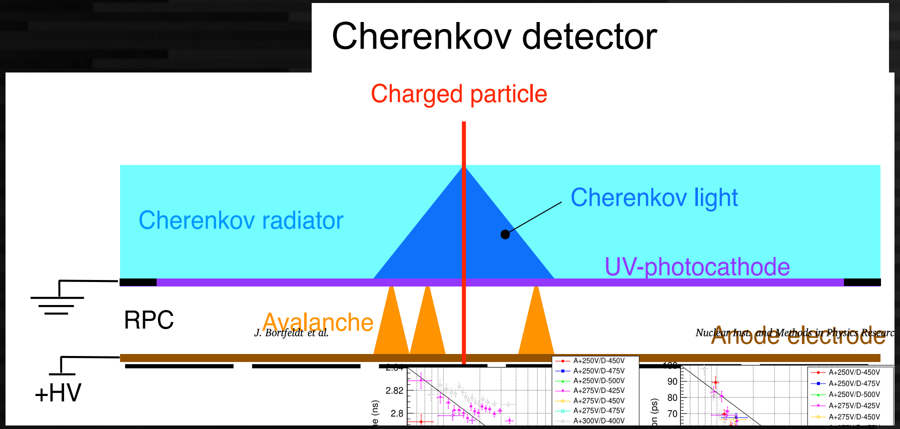
MEG2 timing counter
(Plastic scintillator + 6 SiPMs)
40 psec achieved



ALICE ToF detector using multi-gap RPC
~50 psec for MIP achieved



Gas photomultiplier (GasPM)
with single photon timing
of 25 psec demonstrated
Combination with Cherenkov
detector being studied



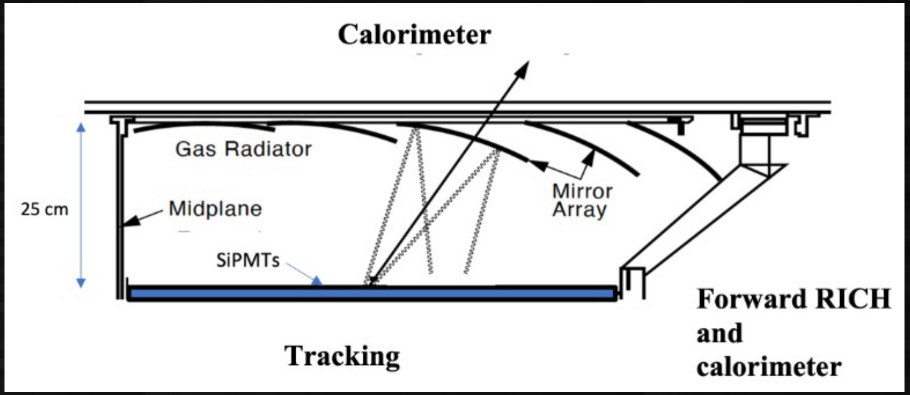
Various technology realizes ~50 psec timing
resolution with possibly lower cost than silicon
(but somewhat more complicated treatment
such as temperature control, gas flow etc. needed)

ToF in Calorimeter or tracker/pre-shower?

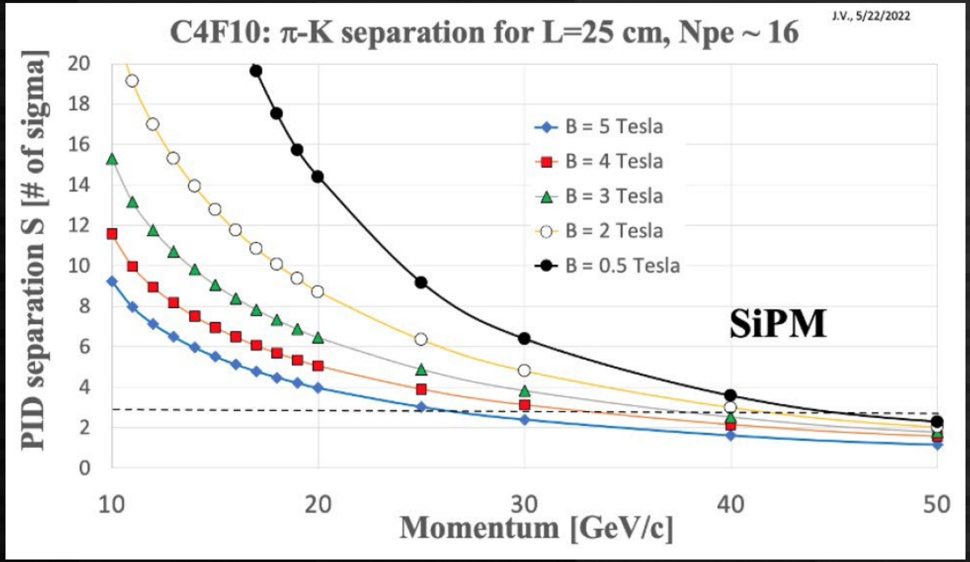
- ToF in trackers (silicon: AC-LGAD/SPAD etc.)
  - Small number of layers with ultimate timing resolution
    - Requirement on heat dissipation somewhat looser than calorimeters
    - Fewer layers → lower cost
  - Charged particles only (not available for neutral particles and PFA improvements)
  - Measuring mass of heavy BSM (long-lived particles etc.)
- ToF in calorimeters (partially or fully replaced)
  - Improving resolution by averaging many particles in shower (not single MIP)
    - Tracking inside calorimeter required – or inclusively done by Machine Learning?
  - High density readout: electronics more difficult
    - Heat dissipation is said to be square of timing resolution of electronics
    - Moderate timing resolution (eg. 100 psec/MIP) still helps thanks to the averaging
  - Further usage: PFA improvement, secondary photon etc.

Cherenkov detectors etc.

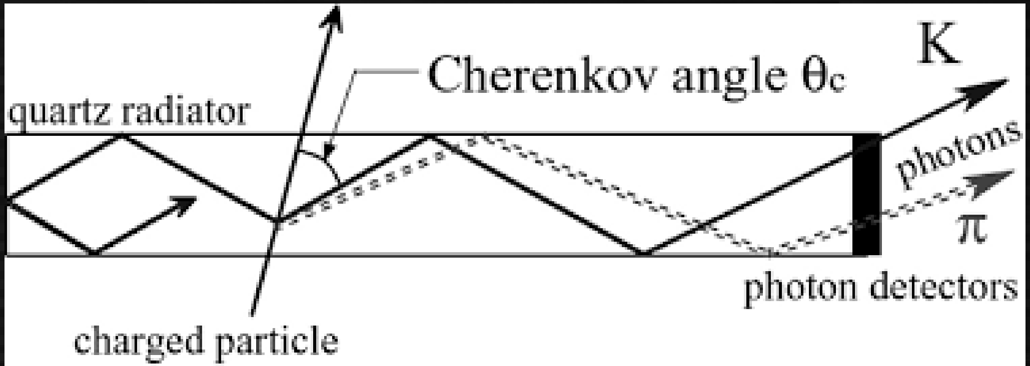
RICH: Traditional method of particle ID



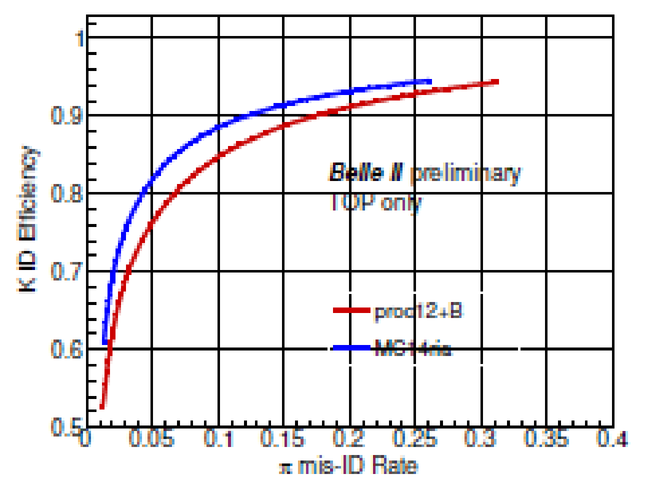
Dedicated PID ring-imaging Cherenkov detector to be placed between tracker and calorimeter



3 sigma pi/K separation up to 25 GeV/c is expected by design study



Belle-II Time of Propagation counter position and timing readout by MCP-PMT

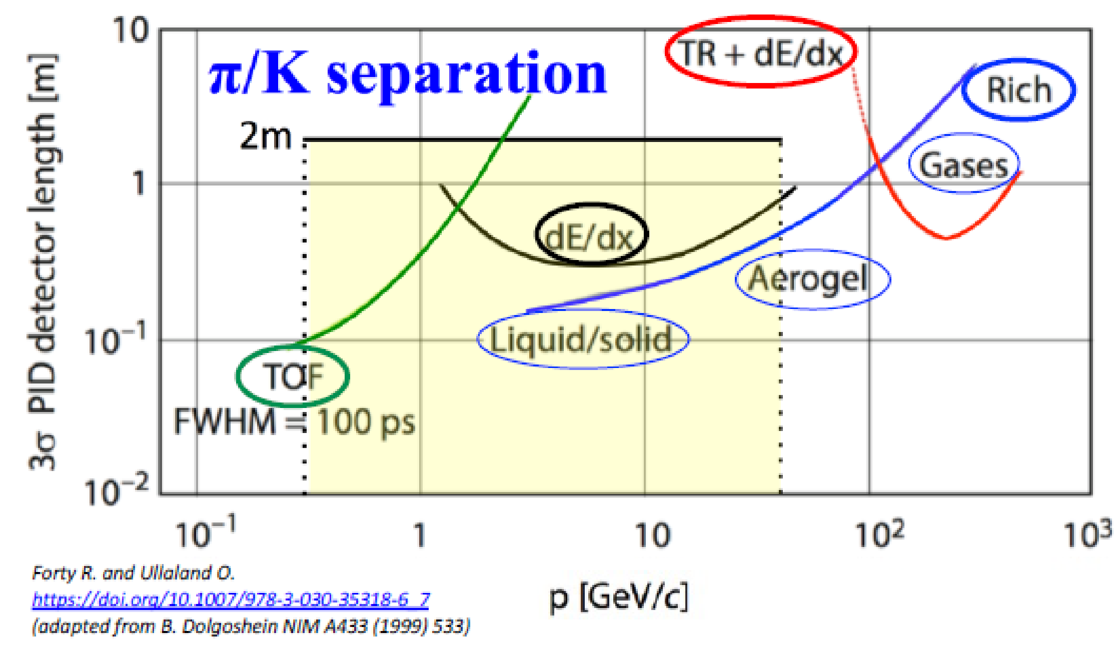


Powerful enough for Belle-II momentum range

https://docs.belle2.org/record/2733/

Probable PID performance

- Low energy: ToF is the most powerful choice (up to a few GeV)
  - Most of the tracks in jets are this energy range but less important for quark flavor tagging (due to gluon contamination)
- dE/dx: powerful up to 10-20 GeV
  - ILD already has TPC: no upgrade needed (pixel preferred though)
- RICH: strong for high-p range
  - Additional space and material before calorimeter is acceptable?
- Transition Radiation (eg. ATLAS)
  - No real consideration, but possible for highest p range?



Forty R. and Ullaland O.
https://doi.org/10.1007/978-3-030-35318-6_7
(adapted from B. Dolgoshein NIM A433 (1999) 533)

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    - Strange tagging
    - Helping b/c tagging / jet charge
    - Jet energy reconstruction

More detailed discussion by U. Einhaus at
https://indico.cern.ch/event/1256374/contributions/5338875/

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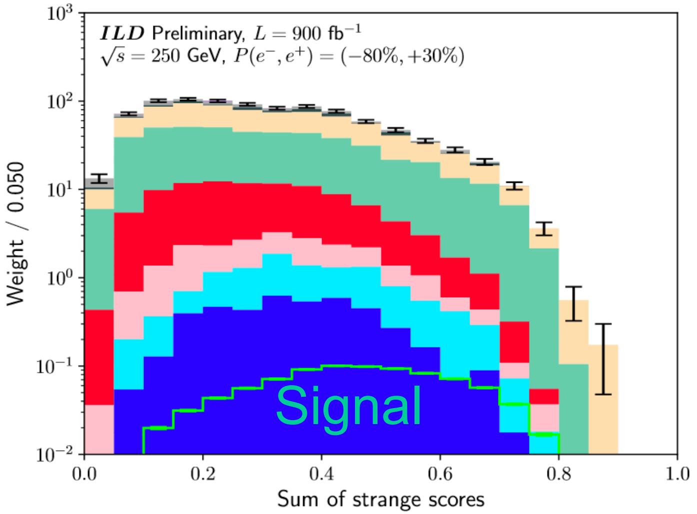
    - dE/dx (in TPC and others)
    - Time-of-flight: Silicon, Scintillator, RPC
    - (Ring-imaging) Cherenkov
    - Transition radiation

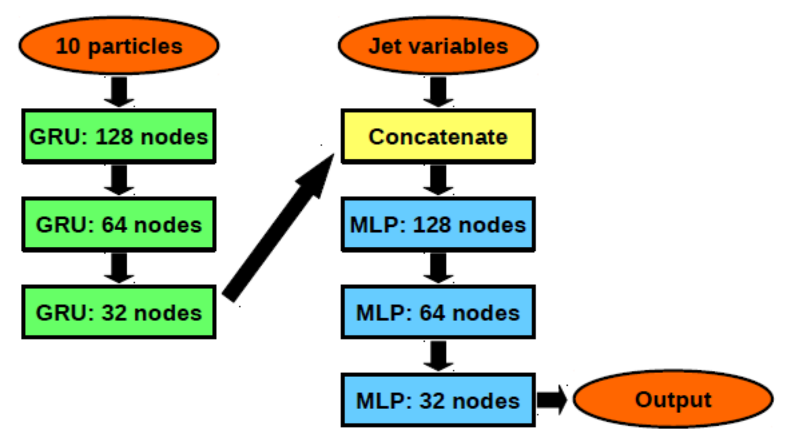
Strange quark tagging: physics case

- Strange quark usually gives leading strange mesons (kaons etc.) → pi/K/p separation (to reject pi/p) is essential
  - But usually for high-energy tracks
- Physics cases for strange quarks:
  - Higgs to ss (Br 10^{-4} but possible enhancement with BSM)
  - e^+e^- to ss (SM form factors and BSM like Z')
    - Charge ID is important to see A_{FB} etc.
- More direct use of kaons
  - B physics (by identifying full or partial decay chain)
  - Tau decay to strange

Recent physics studies

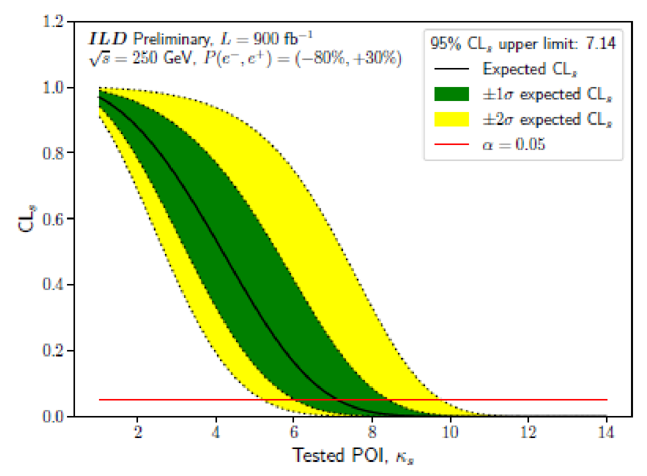
H → ss (arXiv:2203.07535)





10 particles
GRU: 128 nodes
GRU: 64 nodes
GRU: 32 nodes

Jet variables
Concatenate
MLP: 128 nodes
MLP: 64 nodes
MLP: 32 nodes
Output



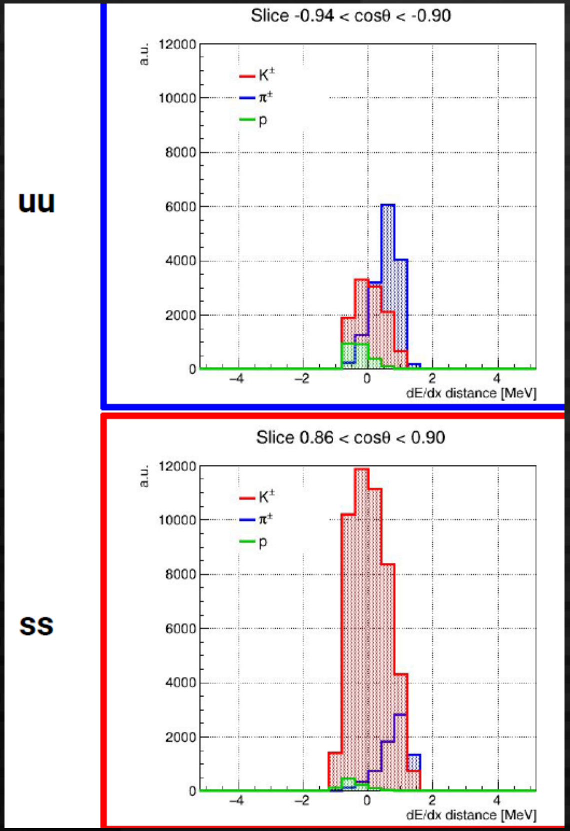
DNN-based reconstruction
with ILD PID and LCFIPlus
b/c tagging outputs combined

Kappa_s ~ 7 possible to probe

possibility to improve with
eg. RICH added to the detector

e^+e^- → ss (ongoing work)

Y. Okugawa

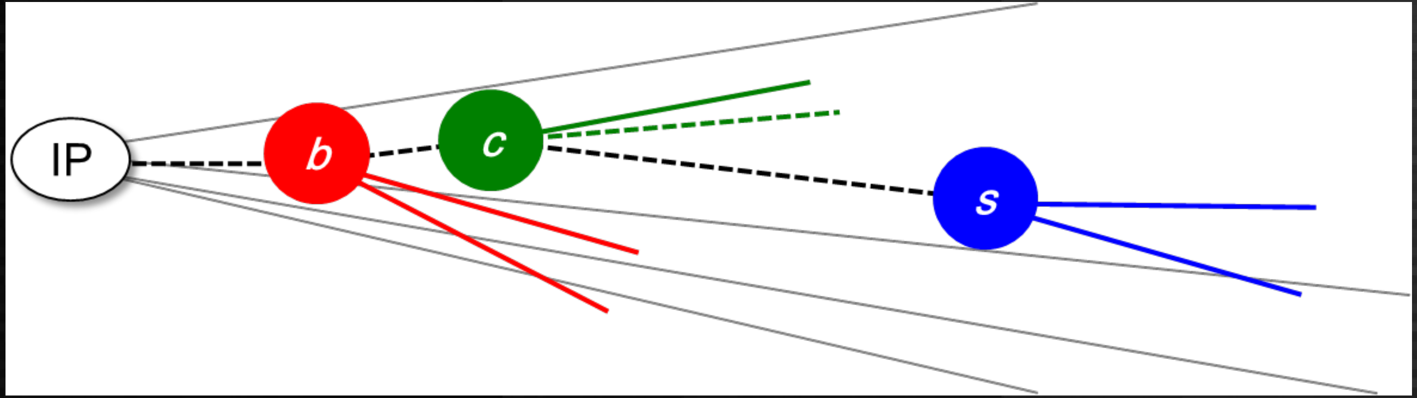


Leading tracks in ss is mostly kaons
(while significant kaons in uu also…)

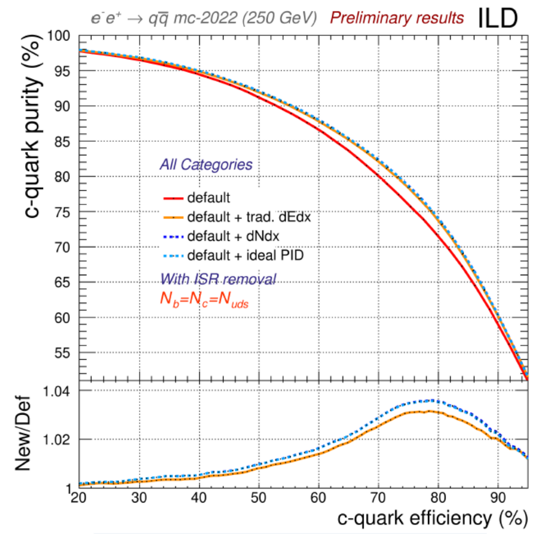
b/c tagging using strange tag?

Need care about FCCee results done with Delphes simulation
Material effect can be significant for flavor tagging.

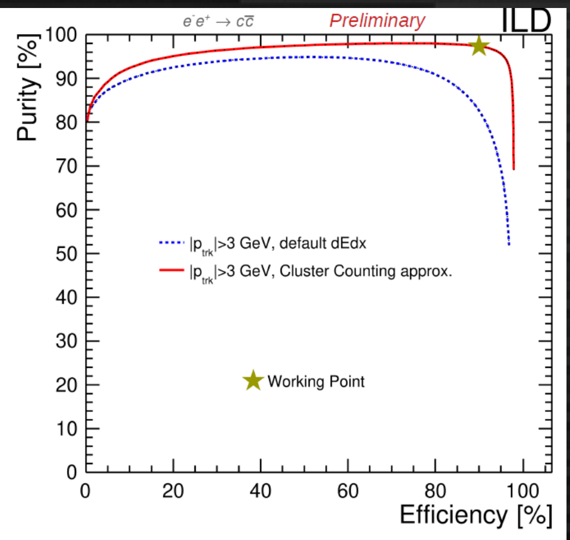
- Decay chain of b/c hadron includes strange hadron – mostly kaons
  - Trace of kaons from secondary vertices strengthen the probability of b/c hadrons
  - Charge of kaon is essential to b/c charge



- Effect of having kaons in b/c tagging
  - Traditional algorithm (LCFIPlus)
    - Implementation by J. P. Márquez (dE/dx or dN/dx only) → right plots
  - DNN-based – to be done
- b/c tagging is essential for many physics including Higgs self-coupling

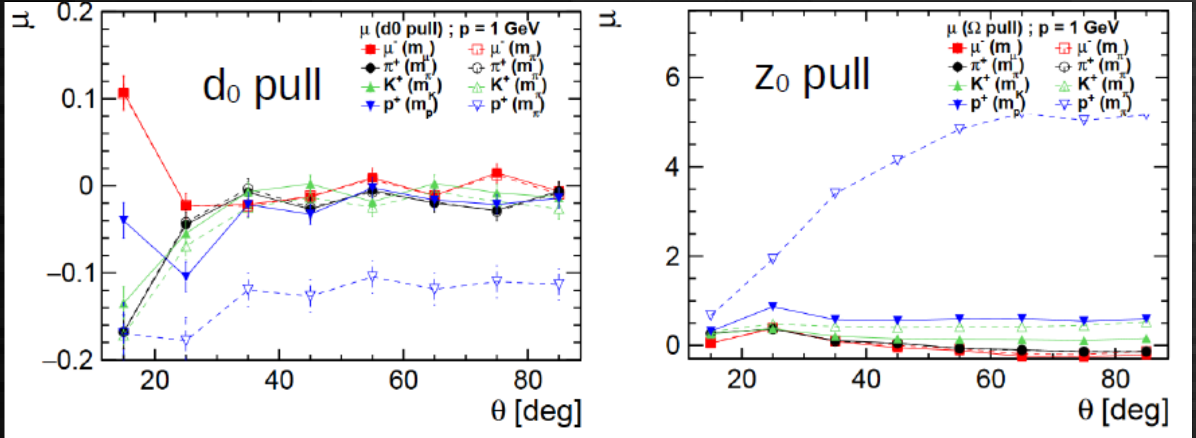


Effects in **Flavour Tagging**



Effects in **Kaon ID** for charge reco.

Effect to track/jet reconstruction



Track fitting

- Assuming mass of proton can improve impact parameter estimation
- No visible effect on vertex reconstruction seen (protons are rare anyhow)

Particle flow

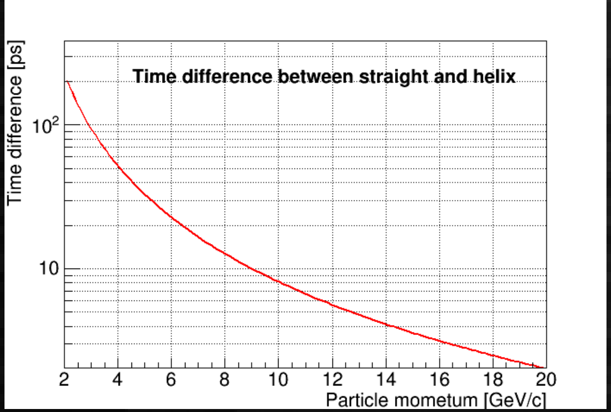
- Using correct mass for tracks than just using pion mass
  → May have some impact but probably not significant (TBC)
- More aggressively use the PID information to input to the PFA algorithm
  - Probably tried with DNN-based PID
    - Effort being started…
  - Are there any difference on calorimetric behavior of proton/kaon/pions?
  → To be investigated

Summary

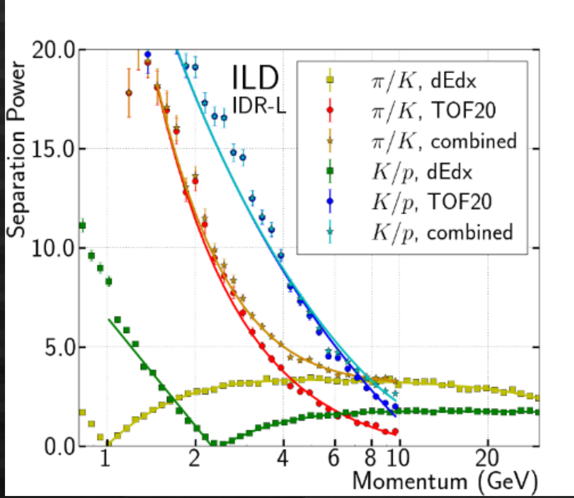
- (Hadronic) particle ID is one of remaining frontiers for HF detectors
- Several technologies for PID
  - dE/dx (dN/dx) with gaseous detectors and more
  - Time-of-flight of O(10psec)
    - Can be considered as “addition” to current detector design
  - Dedicated PID detectors (RICH or other Cherenkov, transition radiation…)
    - Significantly impacting detector design, pros/cons to be investigated carefully
- Physics cases for PID
  - Strange tagging
  - Helping b/c tagging, tracking, PFA
  - Others?

Timing for calorimetry: possible targets

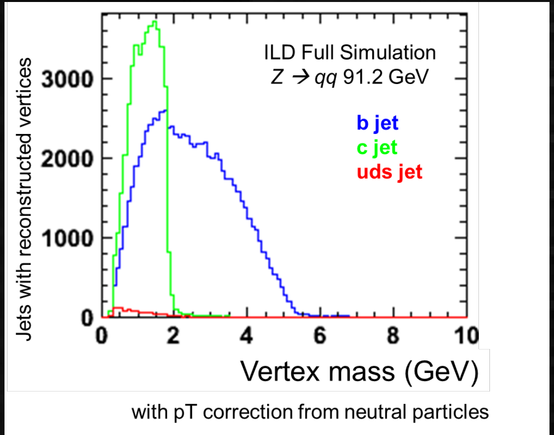
- ☐ π/K/p separation with Time-Of-Flight method
  - 30 psec (for cluster)
    Moderate performance to fill gap of dE/dx
  - A few psec (for cluster)
    up to 5-10 GeV (80-90% of jet particles)
- Track separation at PFA
  - By distance of helices and straight lines
  - ~10 psec/cluster necessary for 10 GeV track
  - Software dependent → DNN
- Secondary photon ID from b/c
  - Including photons to vertex mass → flavor ID
  - A few psec/cluster required!
  - Photons can be averaged over many hits



Timing resolution
for separation of helices



PID at ILD. 10 hits with 20 psec resolution are averaged, effective timing resolution: ~7 psec



Vertex mass of secondary tracks (only) from b/c jets

Lepton ID (e, mu, tau)

- e, mu → Basically an easy task for e+e- colliders
  - Cluster shape (mu/e/hadrons)
  - ECAL/HCAL ratio (e/others)
  - Energy leakage (mu/hadrons/others)
  - Usually 98-99% efficiency/rejection (except forward/low energy)
- Tau → less trivial but still high efficiency/purity possible
  - Leptonic decay → impact parameters usable (for moderate separation)
    - Ctau = 77 μm, shorter than b/c hadrons but still possible with a few μm reso
  - Hadronic decay → bundle of tracks/photons isolated from others
    - Tau + jets → mitigation of neighbor jet activities sometimes hard to separate

Observables at detectors

- Low-level observables
  - Tracker hits: position, energy deposit, timing
  - Calorimeter hits: position, energy deposit, timing
  - Cherenkov & transition radiation: velocity
- High-level observables
  - Track momentum, displacement (from IP), mass
  - Cluster position, direction, mass, shape (ECAL/HCAL)
- PID is