The 2020 International Workshop on the High Energy Circular Electron Positron Collider

Particle Identification at the Z factory

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Istituto Nazionale di Fisica Nucleare

Motivations

Run plan for the FCC-ee

FCC-ee phase	Run duration (yr)	$\sqrt{s}$ (GeV)	L_{int} (ab^{-1})	Event statistics
Z^0	4	88–95	150	3×10^{12} hadronic Z^0 decays
W^+W^-	2	158–192	12	3×10^8 W^+W^- pairs
Z^0H	3	240	5	10^6 Z^0H events
$t\bar{t}$	5	345–365	1.5	10^6 $t\bar{t}$ and 6×10^4 $H\nu\bar{\nu}$ events
H (optional)	3	125	21	Optional run on H resonance

M. Benedikt, A. Blondel, P. Janot, M. Mangano & F. Zimmermann - *Future Circular Colliders succeeding the LHC* - Nature Physics 16, 402–407(2020)

7×10^{11} $Z^0 \rightarrow b\bar{b}$
5×10^{11} $Z^0 \rightarrow c\bar{c}$
1×10^{11} $Z^0 \rightarrow \tau^+\tau^-$

heavy flavor physics **CP violation** **hadron spectroscopy** **flavor tagging** **τ physics**	• distinguish identical topology final states • identify charged hadron for flavor tagging • suppress combinatorics • spectroscopy studies

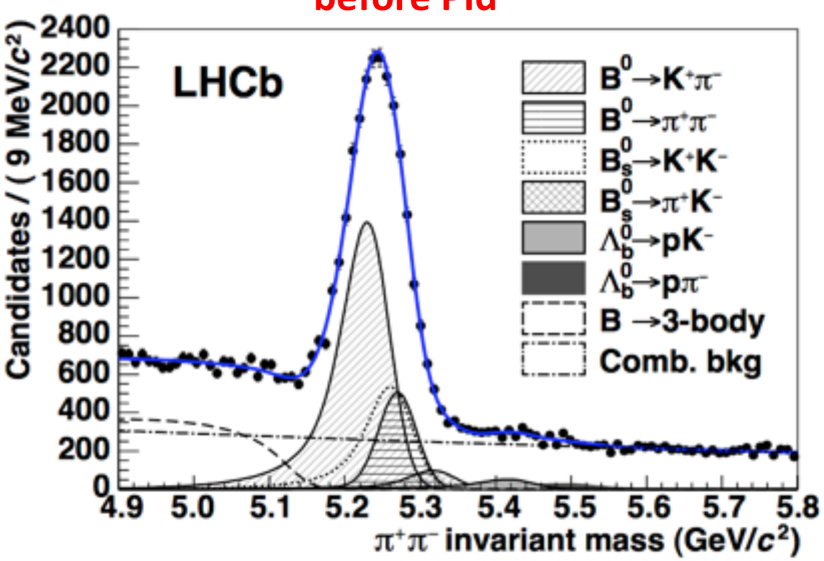
Motivations

Example: 2-prongs B-decays

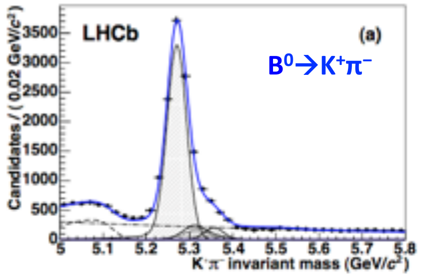
LHCb - JHEP 10 (2012) 037

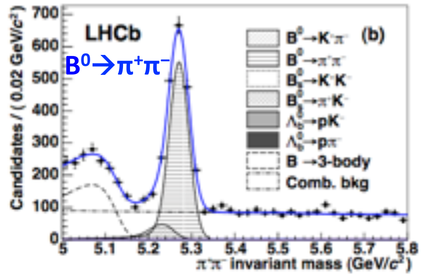
Particle identification mandatory to disentangle different final states

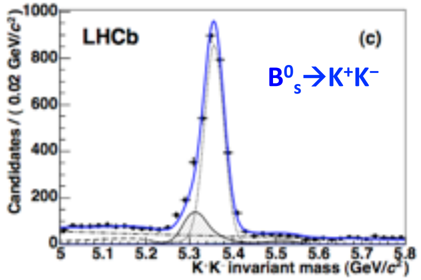
before PId

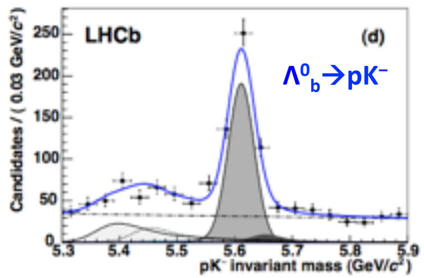


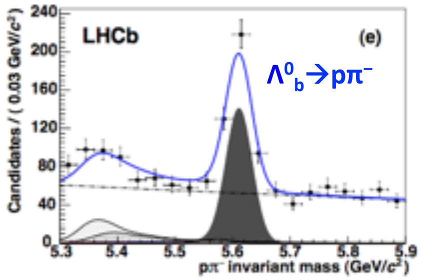
after PId









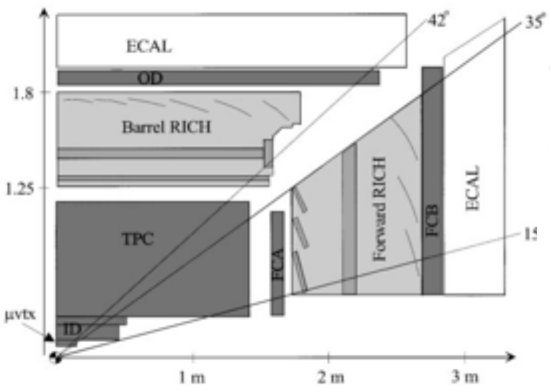


PId cut efficiencies and misidentifications

	$\pi^+\pi^-$	K^+K^-	$K^+\pi^-$	$p\pi^-$	pK^-
$B^0 \to \pi^+\pi^-$	43.1	0.33	28.6	1.53	0.13
$B^0_s \to K^+K^-$	0.05	55.0	15.4	0.05	1.63
$B^0_{(s)} \to K^+\pi^-$	1.40	4.17	67.9	0.72	0.06
$\bar{B}^0_{(s)} \to \pi^+K^-$	1.40	4.17	2.09	0.02	0.85
$\Lambda^0_b \to p\pi^-$	1.93	0.92	16.8	35.4	3.16
$\bar{\Lambda}^0_b \to \pi^+\bar{p}$	1.93	0.92	0.95	0.03	0.18
$\Lambda^0_b \to pK^-$	0.06	12.2	1.92	1.18	40.2
$\bar{\Lambda}^0_b \to K^+\bar{p}$	0.06	12.2	4.51	0.03	0.18

Some history: PId at Z^0-pole   RICH/CRID

DELPHI



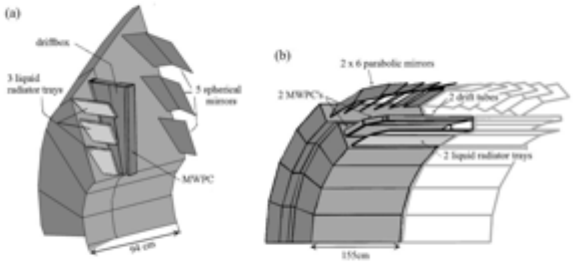
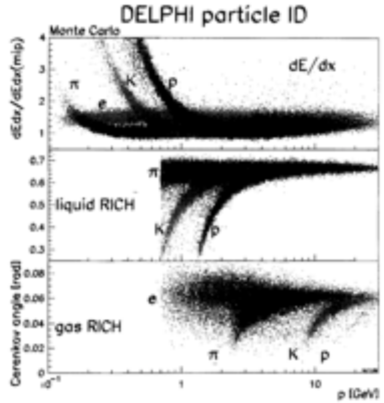


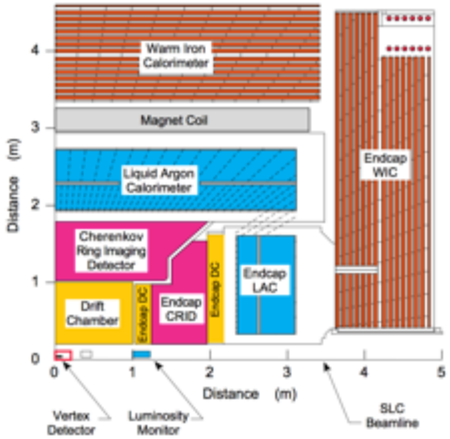
Fig. 2. Main components of the RICH detectors. (a) Forward RICH. (b) Barrel RICH.



TPC
dE/dx at 7.4%
(70% TM)

RICH combined
"standard" cut
$K^{\pm}$ efficiency 70%
contamination 30%
($p > 0.7$ GeV/c)

SLD



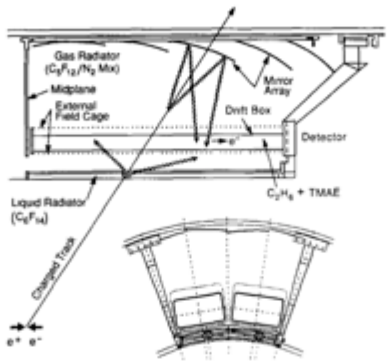
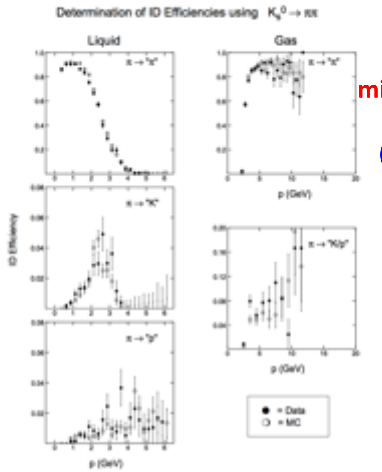
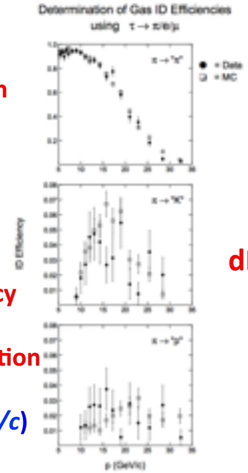


Fig. 1. Schematic of the SLD barrel CRID.



$\pi^{\pm}$ efficiency
≈ 80%
misidentification
5-12%
($p < 8$ GeV/c)

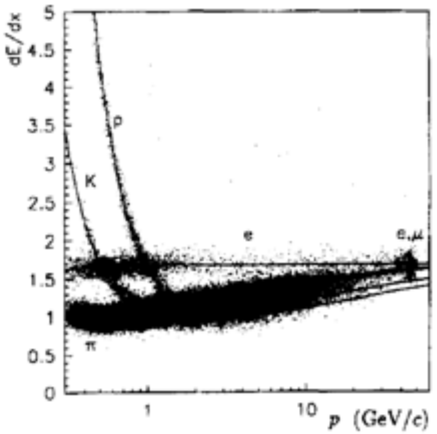


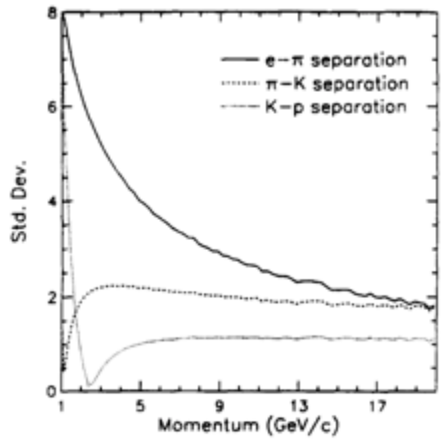
$\pi^{\pm}$ efficiency
≈ 90%
misidentification
≈ 8%
($p < 30$ GeV/c)

Drift
Chamber
dE/dx at 6.4%
(70% TM)

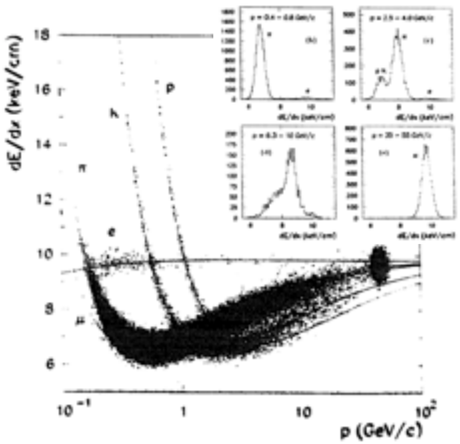
Some history: PId at Z^0-pole dE/dx

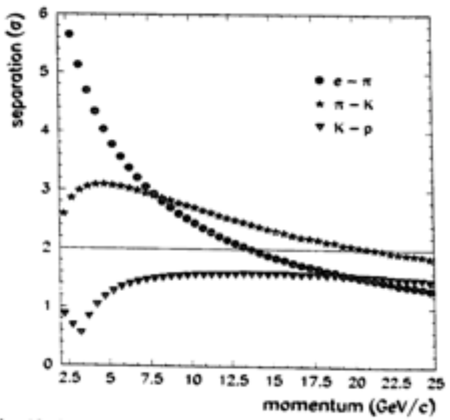
ALEPH





OPAL





TPC

two-sided truncated mean:
discard lowest 8% and largest 40%

$$\frac{\sigma_{dE/dx}}{(dE/dx)} = 1.19 N^{-0.5} (dx/w_0)^{-0.4} \left[(dE/dx) / (dE/dx)_{mip} \right]^{-0.4}$$

$$\frac{\sigma_{dE/dx}}{(dE/dx)} = 4.5\%$$

Drift Chamber (4 bar)

hit quality cuts and truncated mean:
discard largest 30%

$$\frac{\sigma_{dE/dx}}{(dE/dx)} \propto N^{-0.43}$$

$$\frac{\sigma_{dE/dx}}{(dE/dx)} = 3.1\% \text{ (dimuons)}, \; 3.8\% \text{ (m.i.p.)}$$

Some history: PId at Z^0-pole (LEP + SLC)

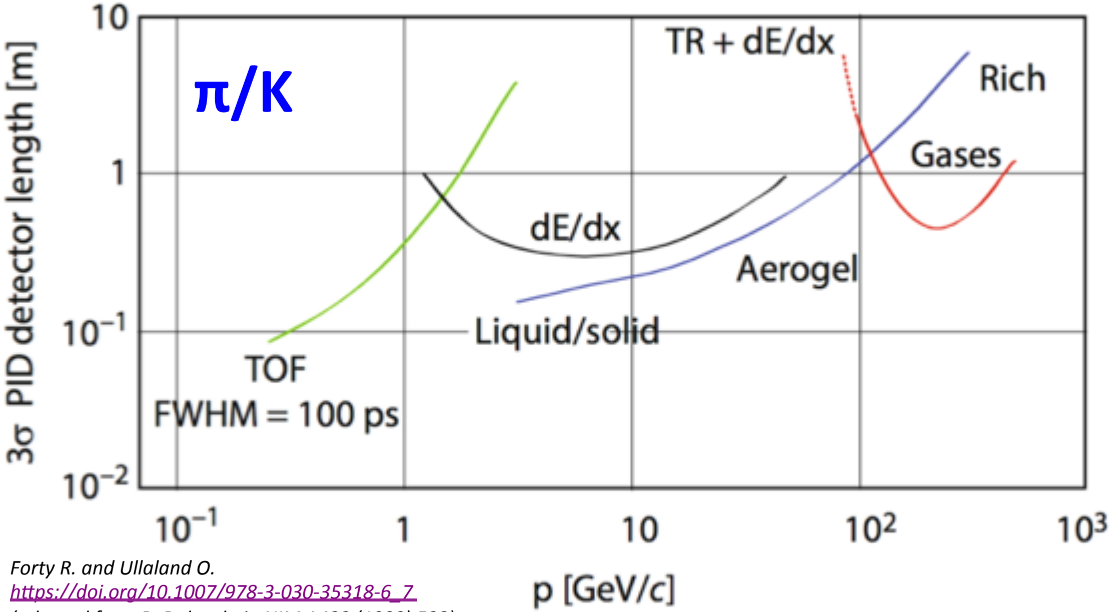
Comments:

- Č Ring Imaging
    - limited performance in this range of momenta (efficiency 80%, contamination 30%, misidentification 10%)
    - very complex system (mechanics, hydraulics, gas, temperature, photoconverter...) hard to maintain
    - large extrapolating distance between tracking and e.m. calorimeter ($\mathcal{O}$[m], cost of calo, magnet, ...)
    - not negligible amount of material in terms of X_0 in front of calorimeter (pre-showering)
    - loss of hermeticity (for 10^{12} Z^0, need control of acceptance at 10^{-5} level)

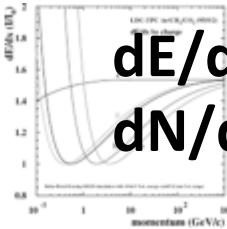
- dE/dx
    - byproduct of gaseous tracking
    - stringent stability requirements
      - HV (gas gain); gas (composition, density, temperature, pollutants, ...); electronic gain equalization
    - quality cuts and corrections
      - saturation; attachment; cross-talk; multiple hits; gas gain; space charge
    - truncated mean
      - measurements reduced to 50%-70%
    - despite the wealth of LEP/SLC physics results, only marginal PId performance ($\sigma \approx$ 5-7% at normal pressure)

Not the whole history: alternative technologies today

$$\frac{m^2}{p^2} = \frac{1}{\gamma^2 - 1} = \frac{1-\beta^2}{\beta^2}$$



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

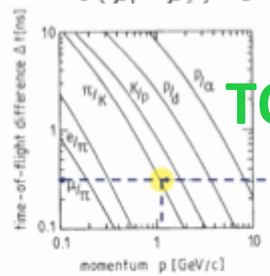


dE/dx
dN/dx

$$-\frac{dE}{dx} = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\ln\frac{2m_ec^2\beta^2\gamma^2T_{max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$

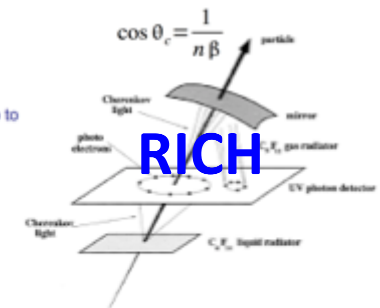
$$N_{cluster} = \int_0^L \frac{1}{w(x)}\frac{dE}{dx}dx \qquad T_{max} = \frac{2m_ec^2\beta^2\gamma^2}{1 + \frac{2\gamma m_e}{M} + \left(\frac{m_e}{M}\right)^2}$$

$$\Delta t = \frac{L}{c}\left(\frac{1}{\beta_1} - \frac{1}{\beta_2}\right) = \frac{L}{c}\left(\sqrt{1+m_1^2c^2/p^2} - \sqrt{1+m_2^2c^2/p^2}\right) \approx \frac{Lc}{2p^2}\left(m_1^2 - m_2^2\right)$$

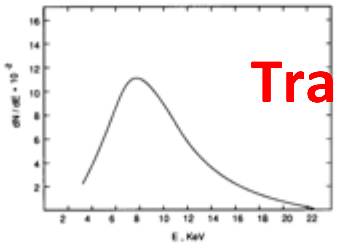


TOF

$$\cos\theta_c = \frac{1}{n\beta}$$



RICH



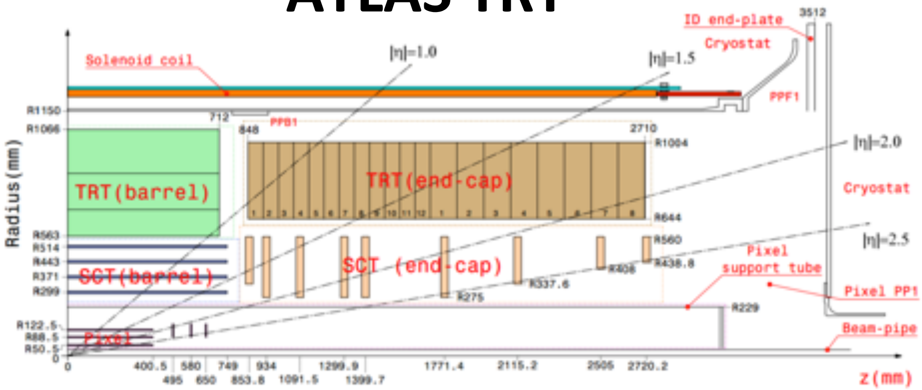
Trans. Rad.

$$W = \frac{1}{3}\alpha\hbar\omega_p\gamma$$

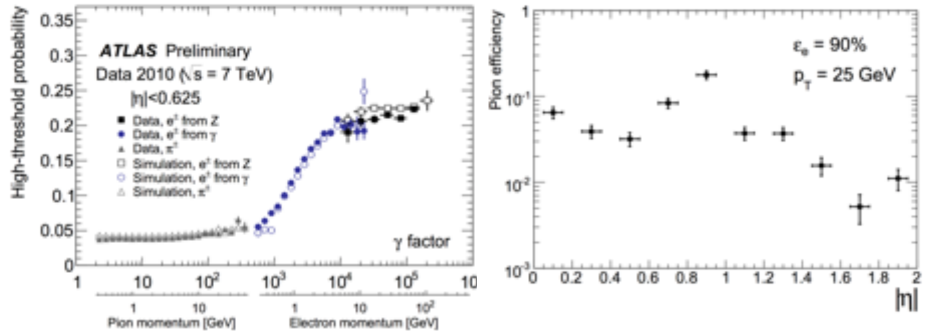
$$\omega_p = \sqrt{\frac{N_e e^2}{\epsilon_0 m_e}} \qquad \hbar\omega_p = 20\,eV$$

Transition Radiation Detectors

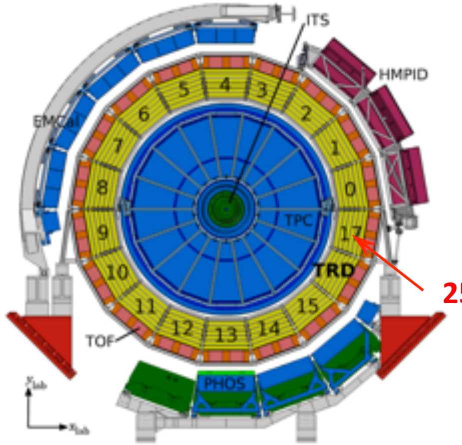
ATLAS TRT

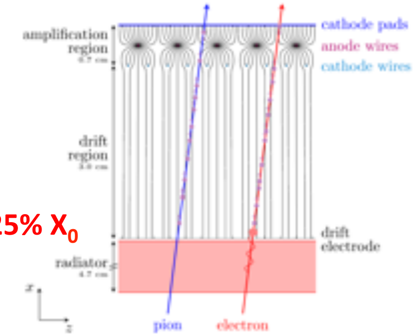


380,000 straw 4 mm dia. (Xe/CO2/O2) in polyethylene foam

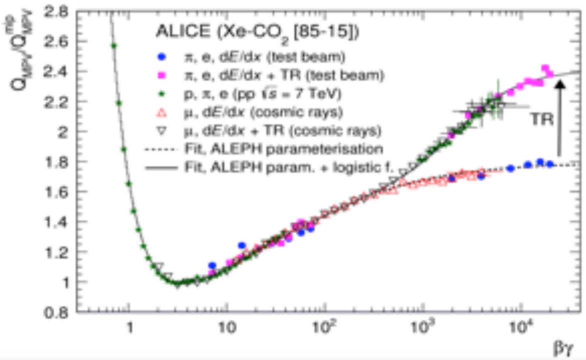


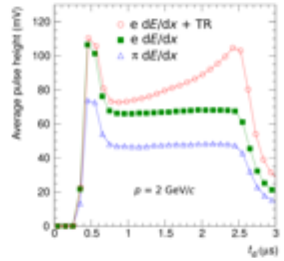
ALICE TRT

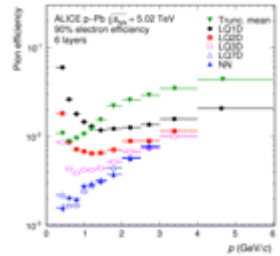




1,200,000 drift chamber channels (Xe/CO2) in foam and fibers



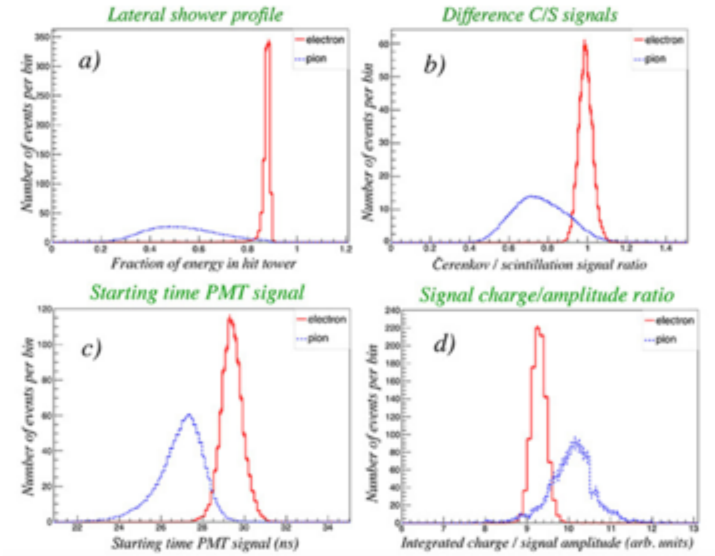




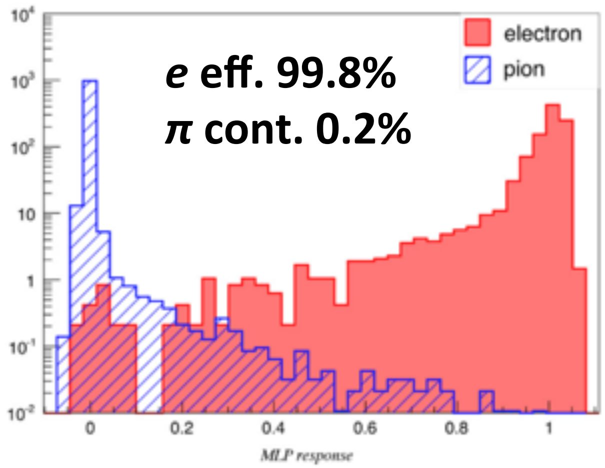
Transition Radiation Detectors

Comments:

- Good **e/π separation** devices (**2.5 σ, ATLAS – 3.5 σ, ALICE**) valid for γ > 1000
- **No hadron separation** (pi, K, p)
- **Transverse dimension order of 0.5 m for 25% X_0 (ALICE)**



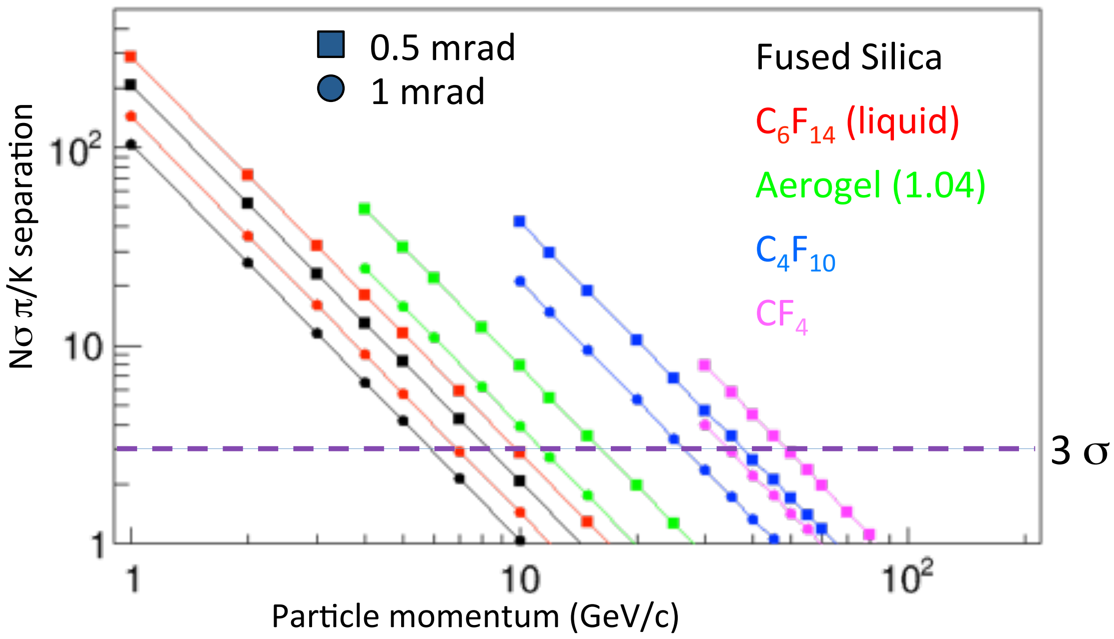
60 GeV/c



e/π separation
in DREAM (RD52)
based on
4 estimators
derived by the
C and S signals

N. Akchurin et al, NIM A735 (2014) 120

Ring Imaging Cerenkov



A. Di Mauro, 10th International Workshop on Ring Imaging Cherenkov Detectors
29 July 2018 to 4 August 2018 Russian Academy of Sciences, Moscow, Russia

Currently operating at high momenta

- **LHCb** (and upgrades)
- Na62
- ALICE HMPID

and at intermediate/low momenta

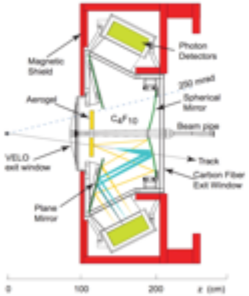
- **BELLE II** (ARICH and TOP)
- CBM
- PANDA (barrel and end-cap)
- CLAS12
- GLUEX

Focus on two illustrating examples

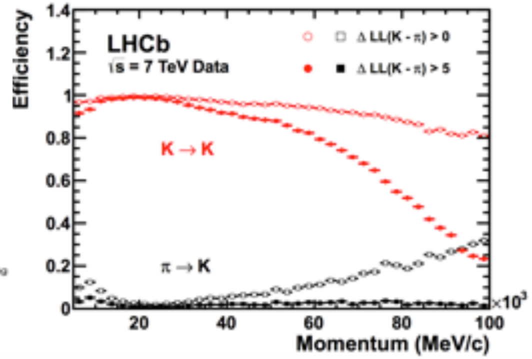
Ring Imaging Cerenkov

LHCb

RICH1

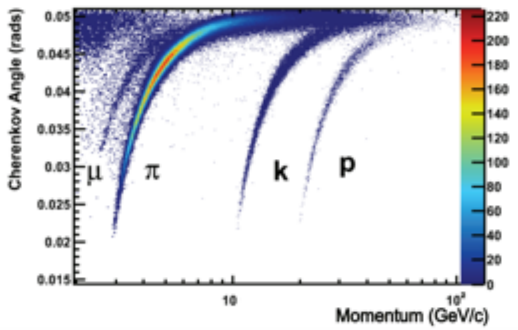


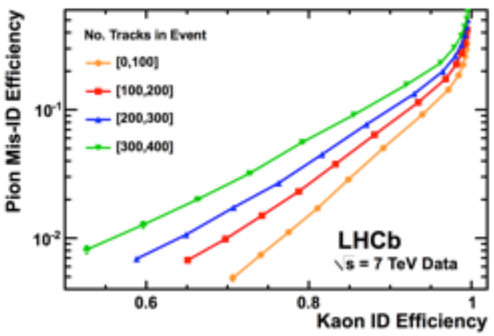
RICH2



1 – 60 GeV/c
1.4 m – 16% X_0

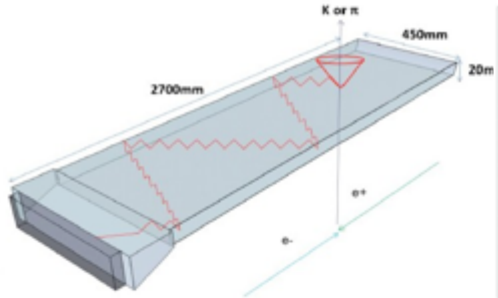
15 – 100 GeV/c
2.4 m – 45% X_0 – 16 λ





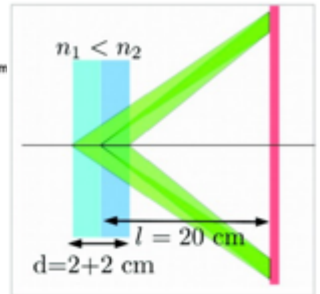
Belle II

TOP

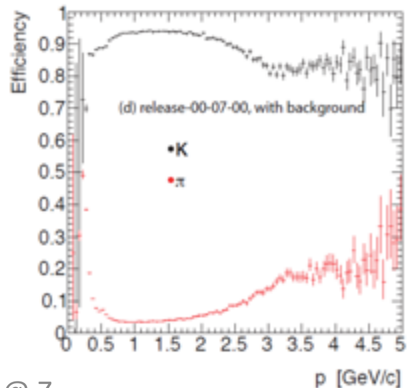


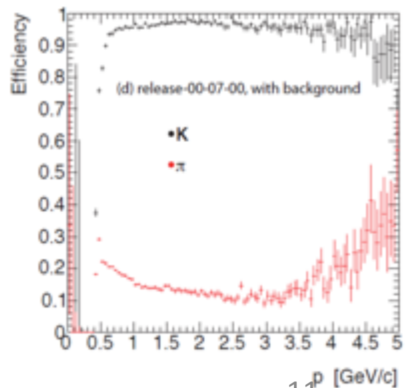
16% X_0 – ≈10 cm

ARICH



≈30 cm





RICH Detectors

Comments:

- generally very fast
- versatile, may be adapted to different configurations
- very complex system (mechanics, hydraulics, gas, temperature, photoconverter...)
- large extrapolating distance between tracking and e.m. calorimeter (except for TOP), particularly for large momenta
- not negligible amount of material in terms of X_0 (tolerable for TOP)

dE/dx and dN_{cl}/dx

$$\frac{\sigma_{dE/dx}}{(dE/dx)} = 0.41 \cdot N^{-0.43} \cdot \left(L_{track}[m] \cdot P[atm]\right)^{-0.32}$$

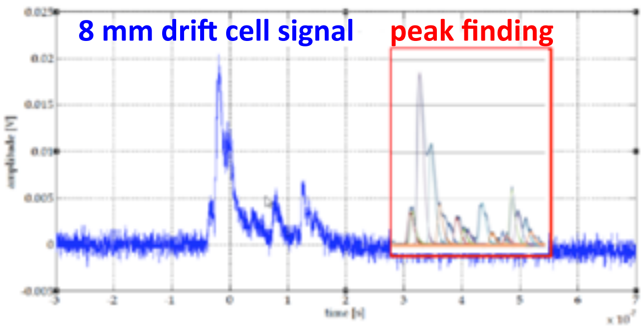
Walenta

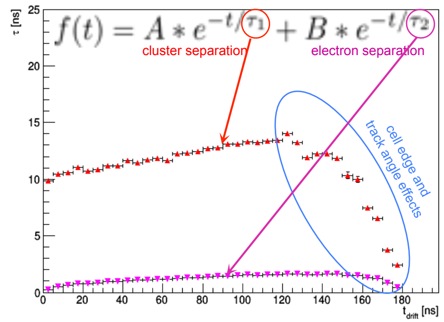
Empirical parameterization of dE/dx resolution in gas (limited by Landau fluctuations)

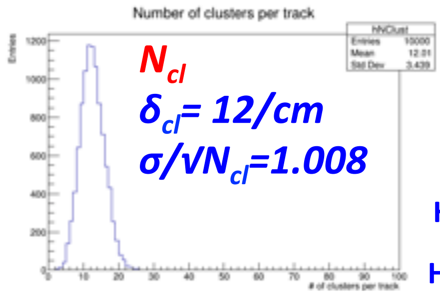
"It has been experimentally confirmed that the relativistic rise is mainly due to the increased number of the primary clusters, rather than due to the energy of clusters."

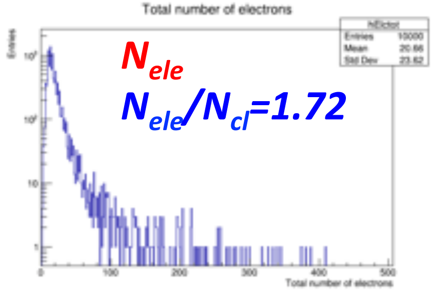
P. Reak and A.H. Walenta, IEEE Trans. Nucl. Sci. NS-27 (1980) 54

$$\frac{\sigma_{dN_{cl}/dx}}{(dN_{cl}/dx)} = \left(\delta_{cl} \cdot L_{track}\right)^{-1/2} = N_{cl}^{-1/2}$$







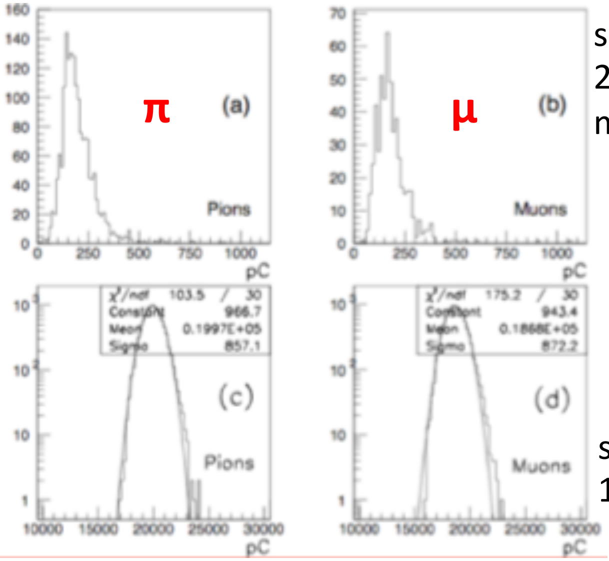


HEED simulation
1 cm
He/iC_4H_{10} - 90/10

dE/dx and dN_{cl}/dx

μ/π separation at 200 MeV/c in He/iC_4H_{10} – 95/5   100 samples 3.7 cm

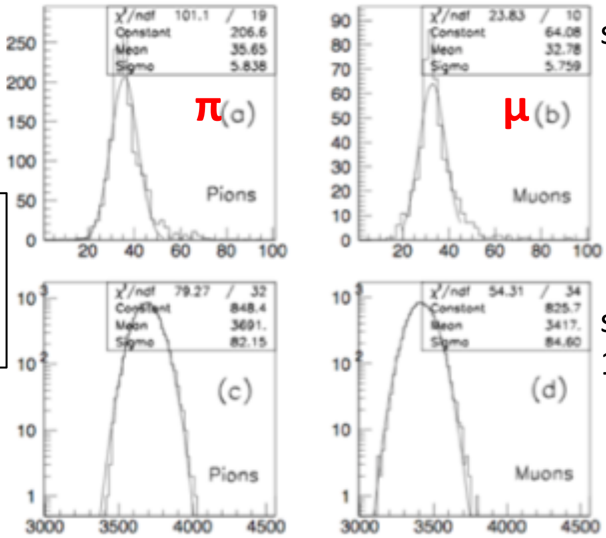
gas gain 2×10^5, 1.7 GHz – gain 10 amplifier, 2GSa/s – 1.1 GHz – 8 bit digitizer



single sample
20% truncated
mean

sum over
100 samples

test beam data



single sample

π: σ/√N$_{cl}$=0.978
μ: σ/√N$_{cl}$=1.006

sum over
100 samples

π: σ/√N$_{cl}$=1.35
μ: σ/√N$_{cl}$=1.45

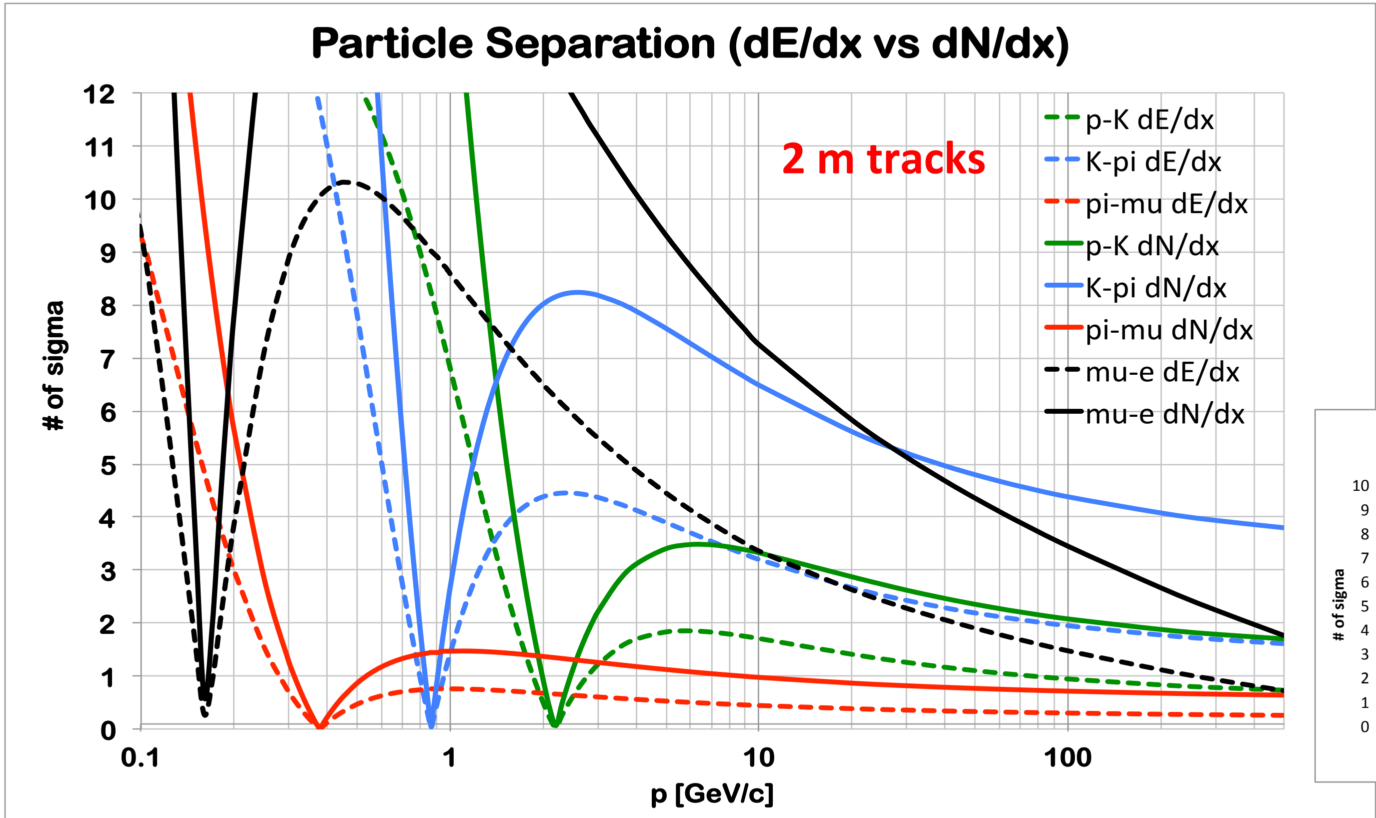
integrated charge
expected 2.0 σ separation
measured 1.4 σ separation

cluster counting
expected 5.0 σ separation
measured 3.2 σ separation

(*NIM A386 (1997) 458-469* and references therein)

dE/dx and dN_{cl}/dx

Expected from analytical calculation for IDEA Drift Chamber

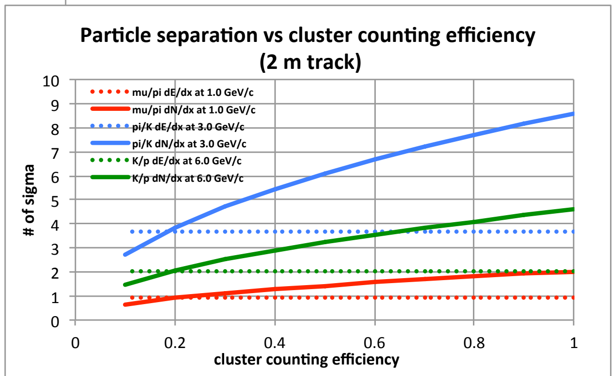


He/iC4H10 90/10

δ_{cl}=12 cm^{-1}

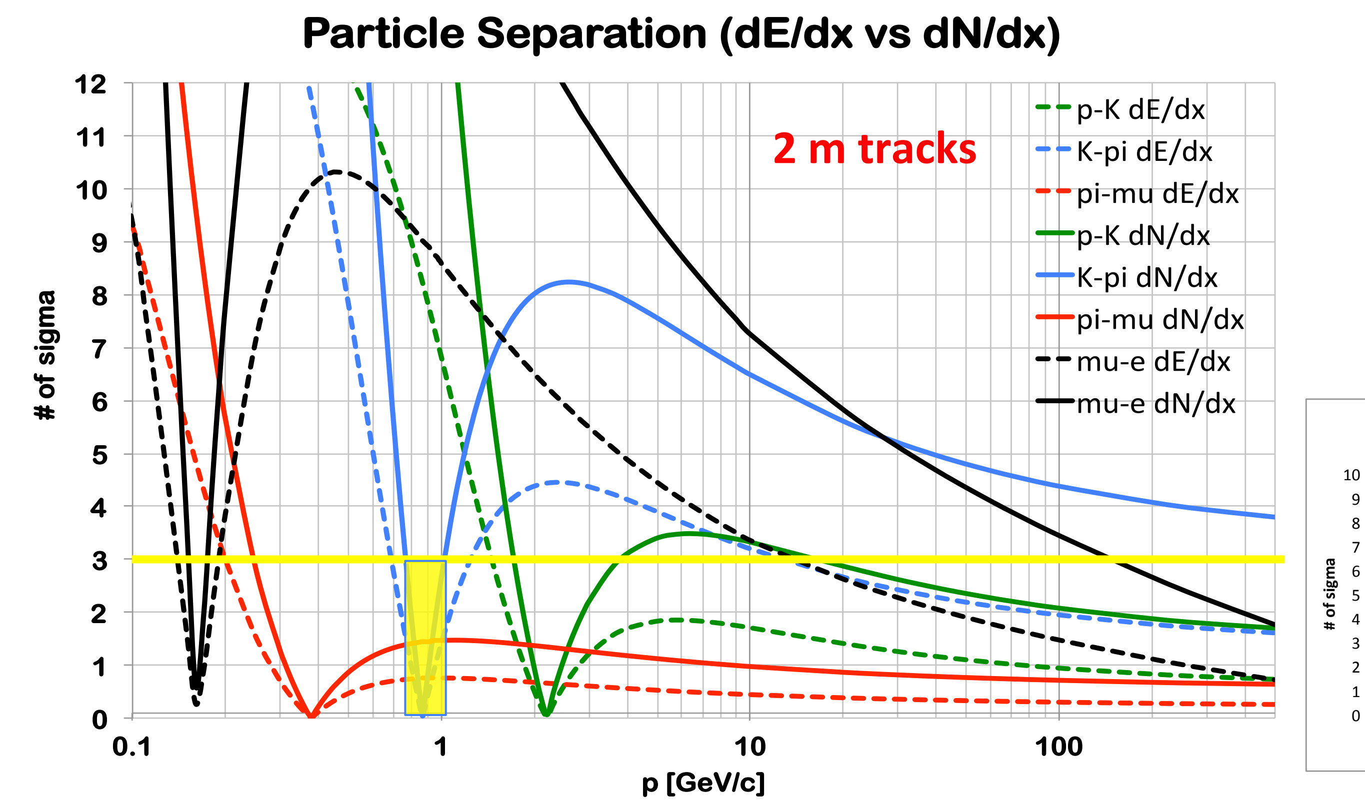
σ(dE/dx)/(dE/dx)
=4.3%

80% cluster
counting efficiency



dE/dx and dN_{cl}/dx

Expected from analytical calculation for IDEA Drift Chamber

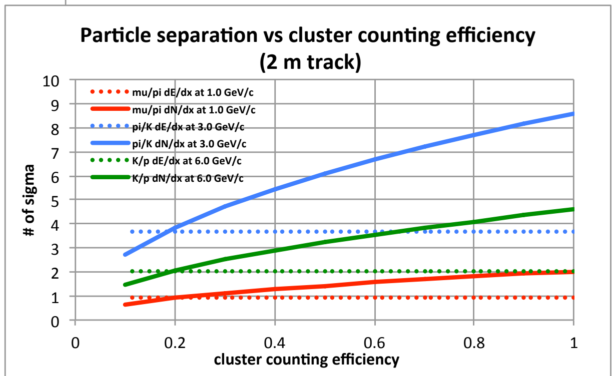


He/iC4H10 90/10

δ_{cl}=12 cm^{-1}

σ(dE/dx)/(dE/dx) =4.3%

80% cluster counting efficiency



dE/dx and dN_{cl}/dx

Expected from analytical calculation for IDEA Drift Chamber

He/iC4H10 90/10

δ_{cl}=12 cm^{-1}

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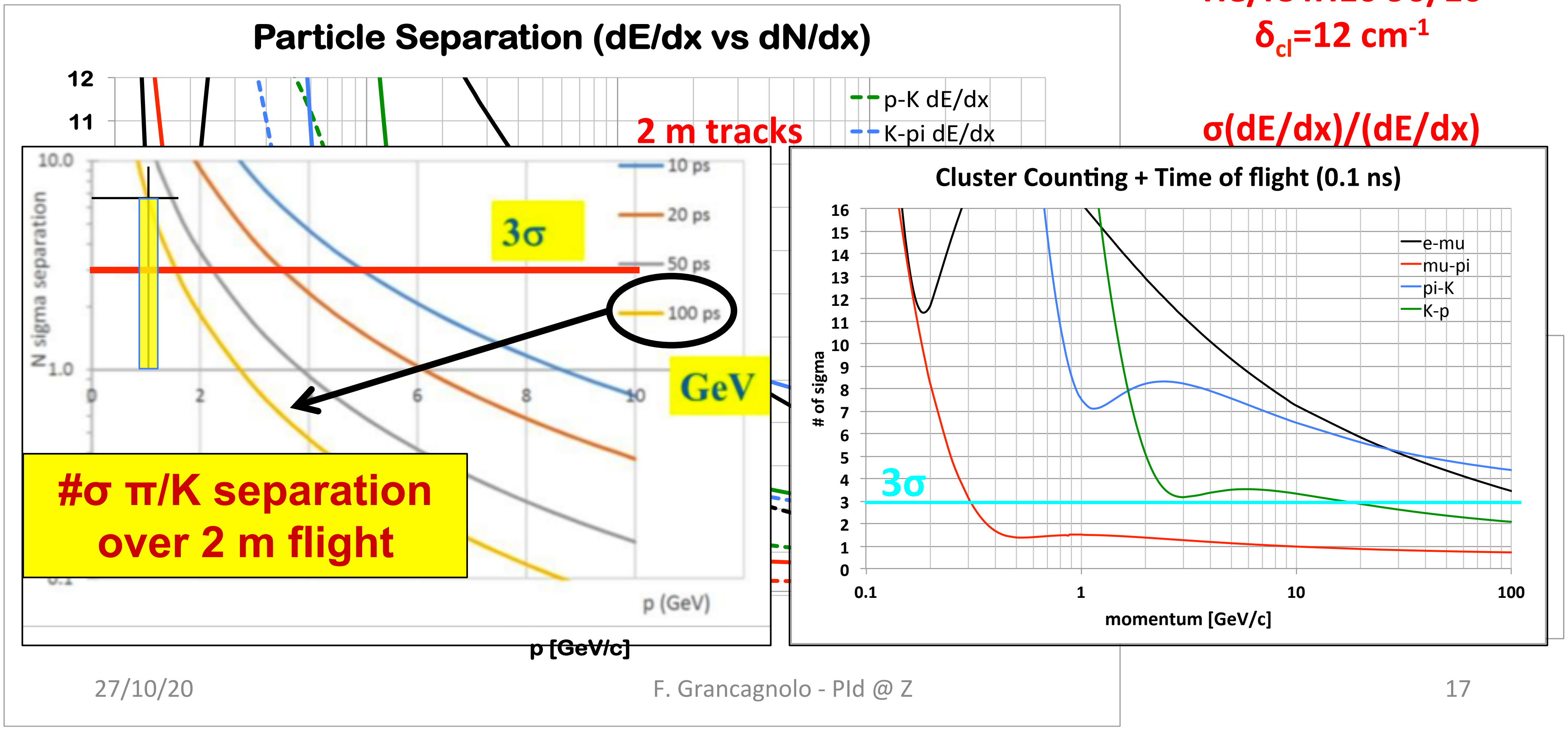


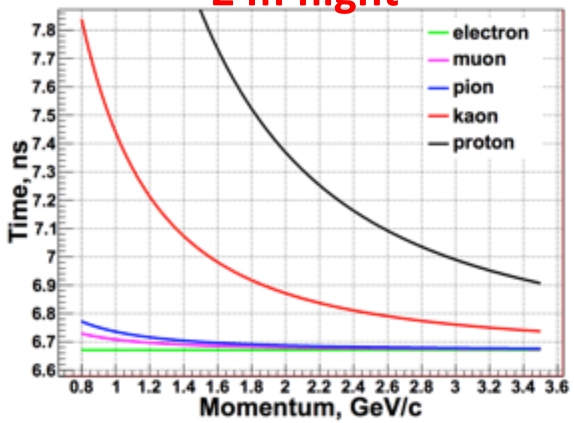
dE/dx and dN_{cl}/dx

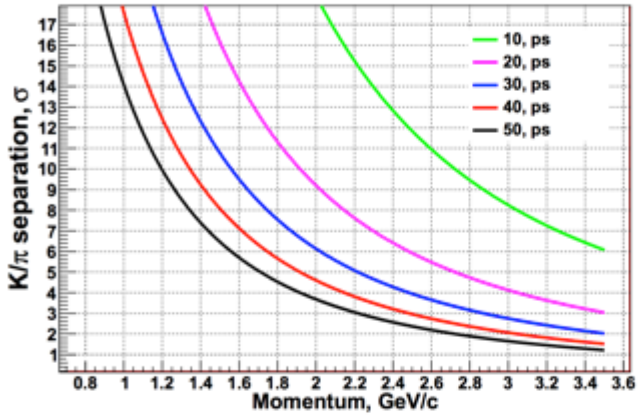
Comments:

- PID comes (almost) for free in drift chambers and TPC tracking systems.
- It suffers from blindness at the "crossing points", where additional help is needed
- **dE/dx** resolutions of around 5% are granted, provided high stability is reached on HV and gas parameters and on continuous electronics calibration. Alternatives to the truncated mean technique are highly desirable.
- **dN_{cl}/dx** resolutions are potentially a factor 2 better with respect to dE/dx. Cluster counting requires fast electronics and sophisticated counting algorithms to be fully efficient. However, given its digital nature, it is less dependent on gain stability issues.
- Techniques are currently being developed for applying cluster counting to TPC with high granularity readout. They may suffer from larger diffusion and lower counting efficiencies but present a high potential of improvement.

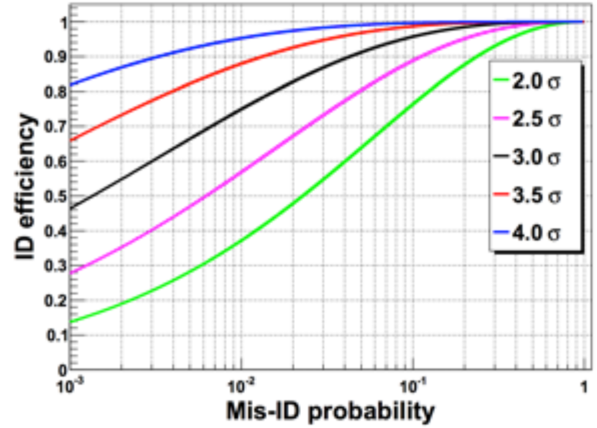
Time Of Flight Detectors

2 m flight





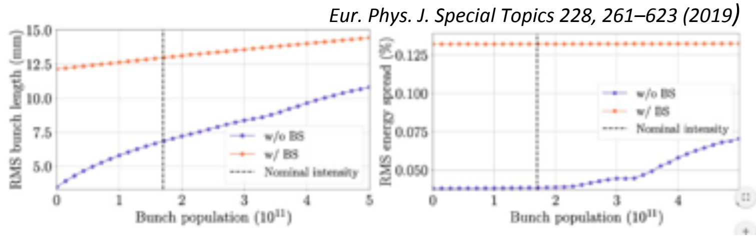
from L. Burmistrov, SuperB PhD thesis



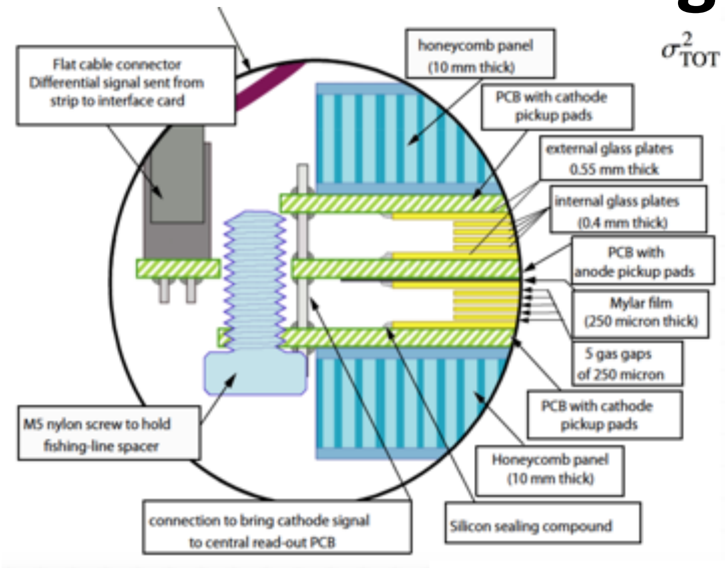
The time of flight resolution, σ_{TOF}, independently of the **intrinsic detector resolution**, σ_{det}, is made of several contributions, among which:

- ***electronics***: FE bandwidth; S/N ratio; cables length; ground connections; ambient e.m. noise, calibration, ...: hard to keep below a **few tens of ps** in a large system
- ***time of event***: σ_{t0} : assuming σ_z **= 12 mm** bunch length RMS, $\sigma_{t0} = \sigma_z/c = 40$ **ps** (track multiplicity in the event helps)
- ***track reconstruction***: uncertainty on momentum, **p**, and on the track pitch angle, **ϑ,** both imply a 2×10^{-3} relative contribution on track length which, for a 1 GeV/c K, translates in $\sigma_p = 15$ **ps** and $\sigma_\vartheta = 15$ **ps** (respectively 10 ps and 4 ps at 5 GeV/c) to be added in quadrature

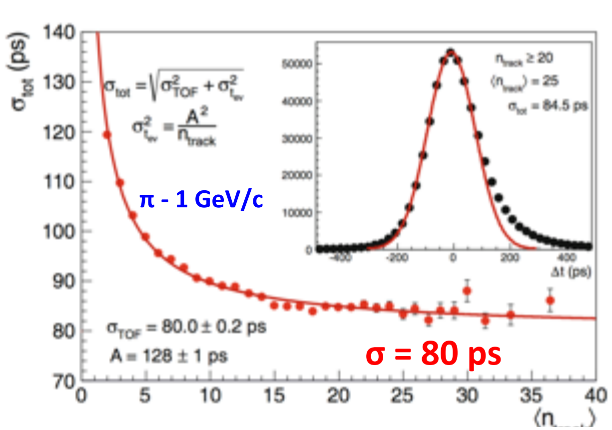
from Future Circular Collider Conceptual Design Report Volume 2
Eur. Phys. J. Special Topics 228, 261–623 (2019)



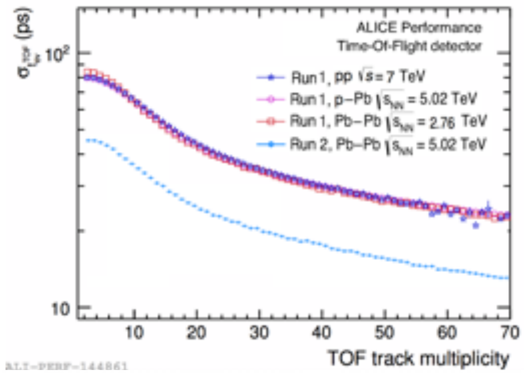
Time Of Flight Detectors: ALICE mRPC



$$\sigma^2_{TOT} = \sigma^2_{TOF} + \sigma^2_{trk} + \sigma^2_{event}$$
$$= \sigma^2_{MRPC} + 2\,\sigma^2_{TDC} + \sigma^2_{FEE} + \sigma^2_{clock} + \sigma^2_{Cal} + \sigma^2_{trk} + \sigma^2_{event}$$



RUN 2



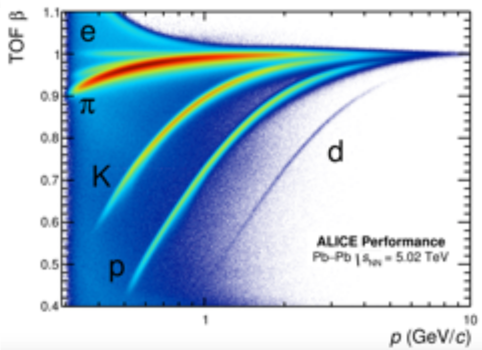
140 m²

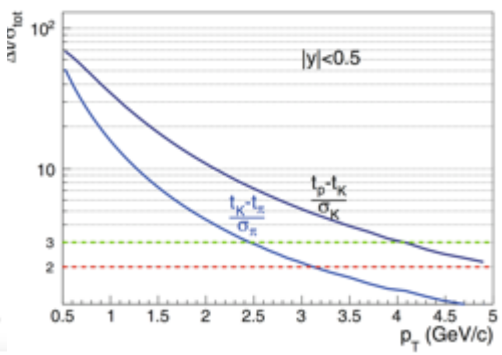
30 cm – 10% X_0

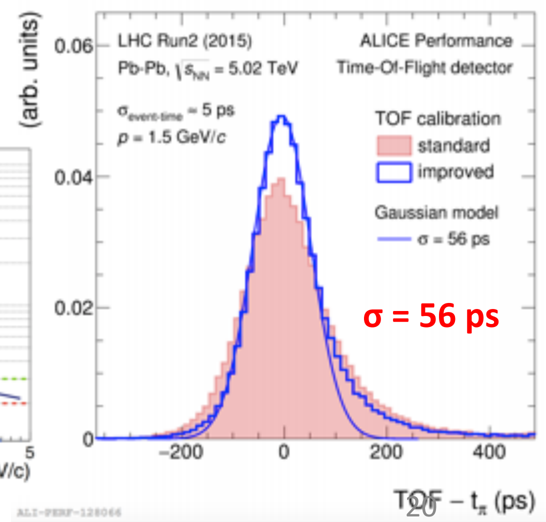
2×5 gaps 250 μm

120×7.4 cm²

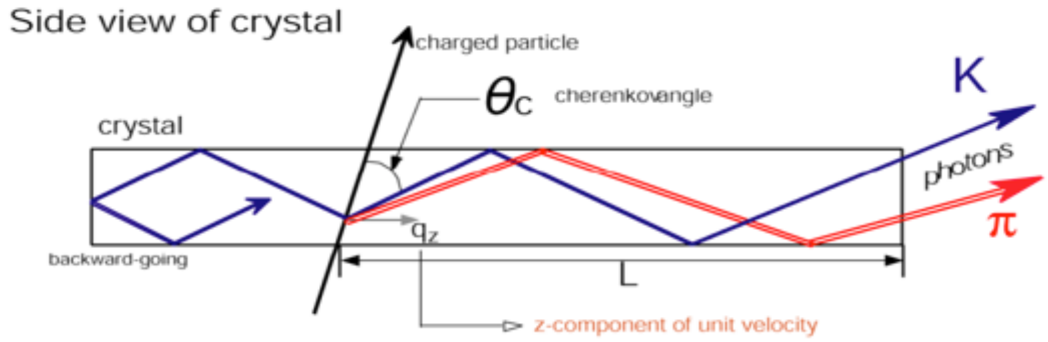
3.5×2.5 cm² pad

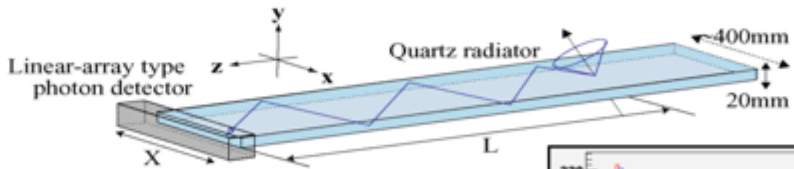


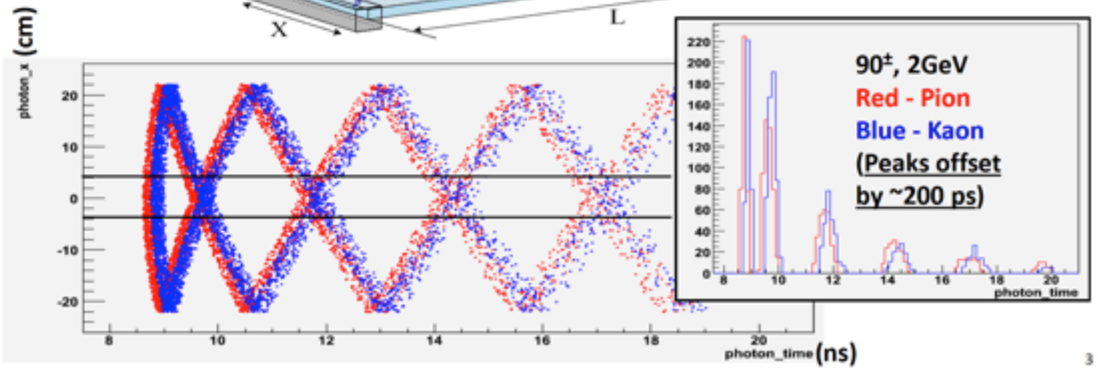


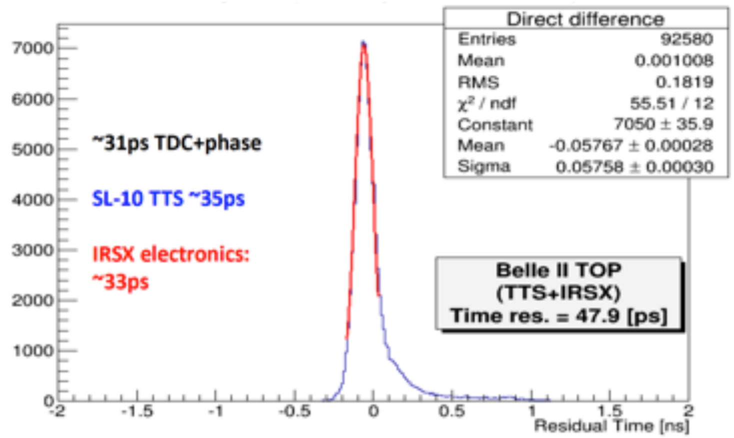


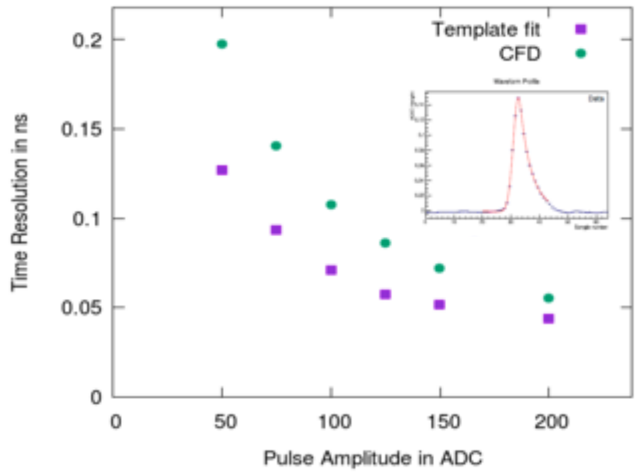
Time Of Flight Detectors: Belle II TOP





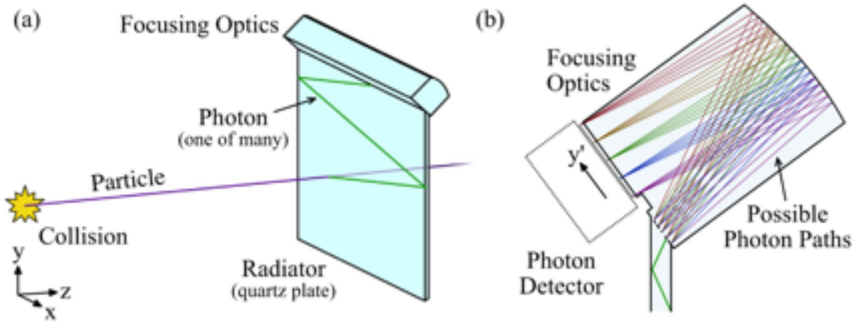




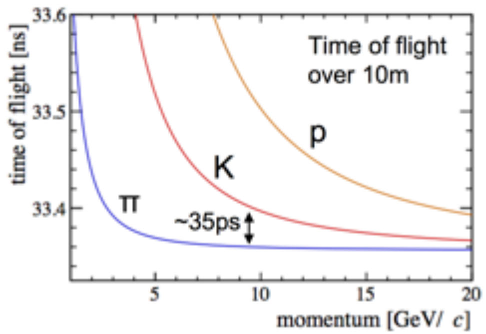


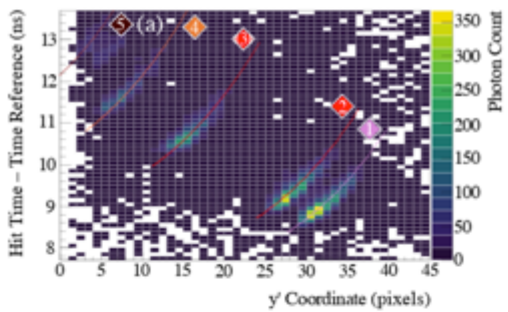
Time Of Flight Detectors: TORCH for LHCb

PANDA



Separating π/K at
10 GeV/c over 10 m
(Δ_{TOF}= 35 ps) requires
$\sigma_{TOF} \approx$ 10-15 ps.
Aim at $\sigma_{1\gamma}$=70 ps
with N_γ=30



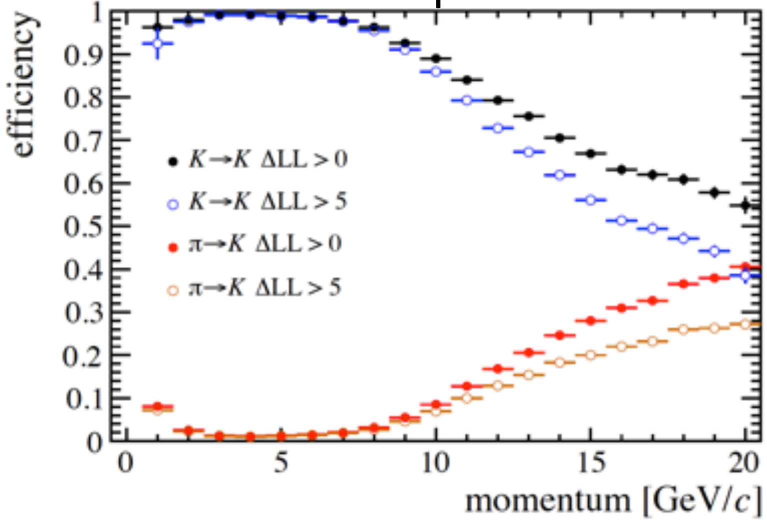


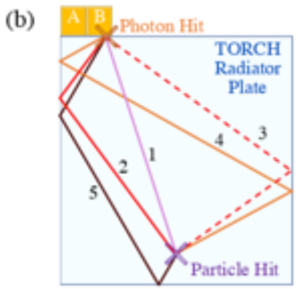
$$\sigma^2_{\mathrm{TORCH}} = \sigma^2_{\mathrm{const}} + \sigma_{\mathrm{prop}}(t_P)^2 + \sigma_{\mathrm{RO}}(N_{\mathrm{Hits}})^2$$

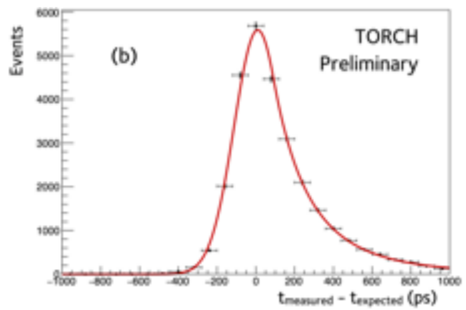
$$\sigma_{\mathrm{const}} = 33.0 \pm 7.1 \text{ ps}$$
$$\sigma_{\mathrm{prop}}(t_P) = (7.8 \pm 0.7) \times t_P \text{ ps}$$
$$\sigma_{\mathrm{RO}}(N_{\mathrm{Hits}}) = \frac{100.5 \pm 5.7}{\sqrt{N_{\mathrm{Hits}}}} \text{ ps}$$

N. Hernew @ DIRC 2019

LHCb expected







@ Z

Time Of Flight Detectors

Comments:

- **Si timing devices** have been deliberately left out of the discussion: it is premature to extrapolate from demonstrator prototypes to full systems. However, we expect great rapid progress and the first implementations in real detectors. Stay tuned.
- **mRPC** have proven their validity in several systems. They are compatible with the required resolution (50 to 100 ps) and can easily fit the space allowed between the tracker and the calorimeter, both in the barrel and in the end-caps. Their thickness in terms of radiation length is tolerable.
- **Time of propagation** of Cherenkov light represent a valid alternative to mRPC. The experience gained with the **TOP** detector in Belle II, with the **TORCH** full scale prototypes for LHCb and with the **PANDA DIRC** barrel and end-cap detectors, represent convincing evidence about the applicability of such techniques to FCC and CEPC (for a stimulating speculation see: *R. Forty, https://indico.cern.ch/event/766859/contributions/3255803/attachments/1776523/2888463/FCC-ee-TORCH.pdf*)

CONCLUSIONS

- At the Z^0 pole, with charged particle momenta ranging from a few hundred MeV/c to several tens of GeV/c, the choices for a particle identification system are limited.
- In the presence of a gaseous tracking detector, either a **TPC** or a **drift chamber**, the most natural solution is **dE/dx**. If applicable, **dN_{cl}/dx** will provide a superior discriminant power at the level of 2-3%.
- The blind region around 1 GeV/c for π/K separation can easily be covered by a modest resolution system of **TOF**. 100 ps resolution is sufficient to assure a 3σ separation over the whole momentum range in combination with **dN_{cl}/dx**.
- Good candidate for such a **TOF** system is the well established technology of the **mRPC**.
- **TOP** or **TORCH** systems also represent extremely well qualified solutions.
- **Si timing layers** can also be taken in consideration once mature, production-ready technology will be available.
- In case of a **Si tracker** as central detector, I don't have easy solutions to propose.