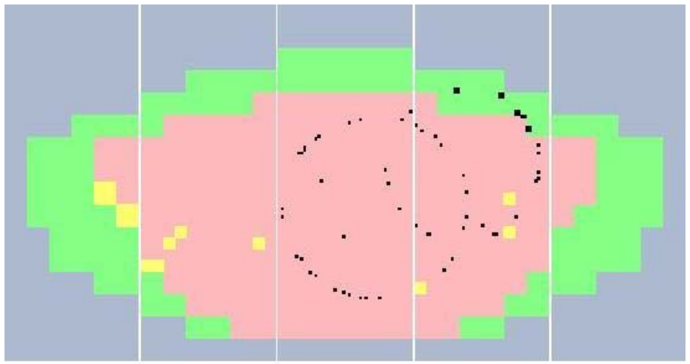
RICH-related data analysis, and its use for physics

Peter Križan

University of Ljubljana and J. Stefan Institute



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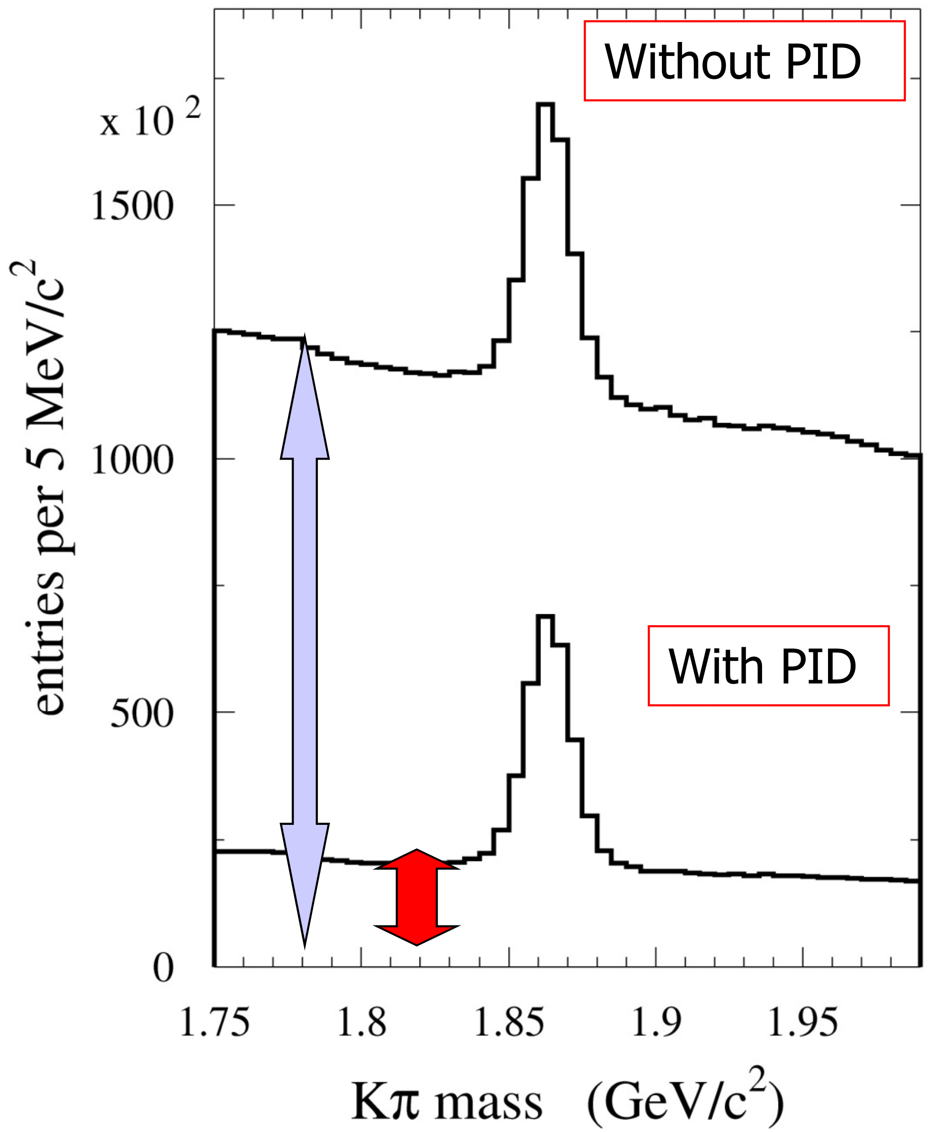
Summary

Mostly covering topics presented at this workshop

Why particle ID?

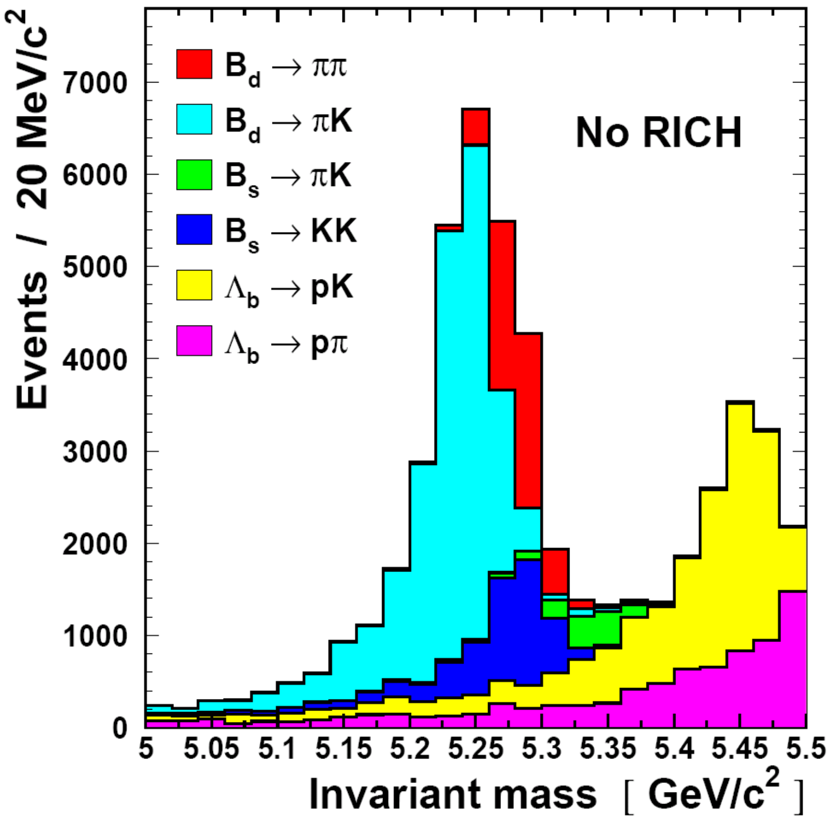


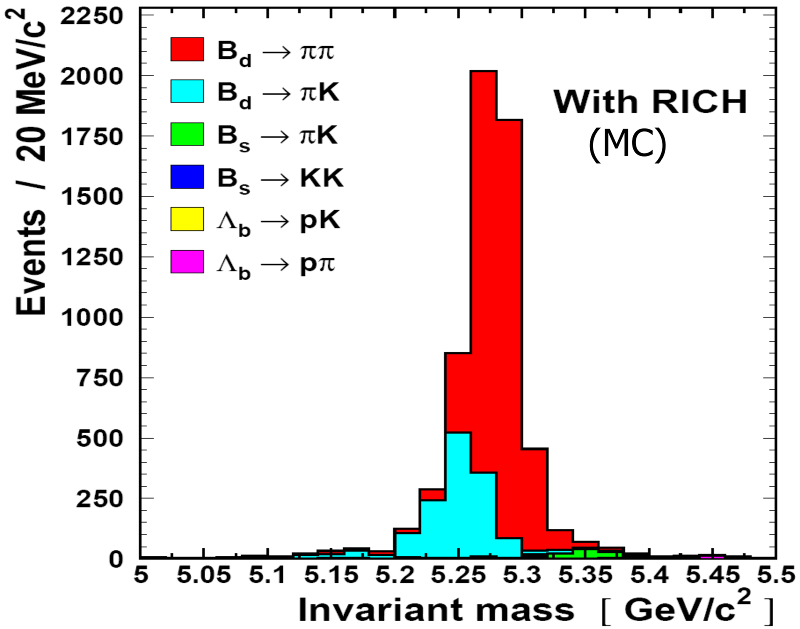
Example 1: B factory

Particle identification reduces the fraction of wrong Kπ combinations (combinatorial background) by ~5x

Why particle ID?

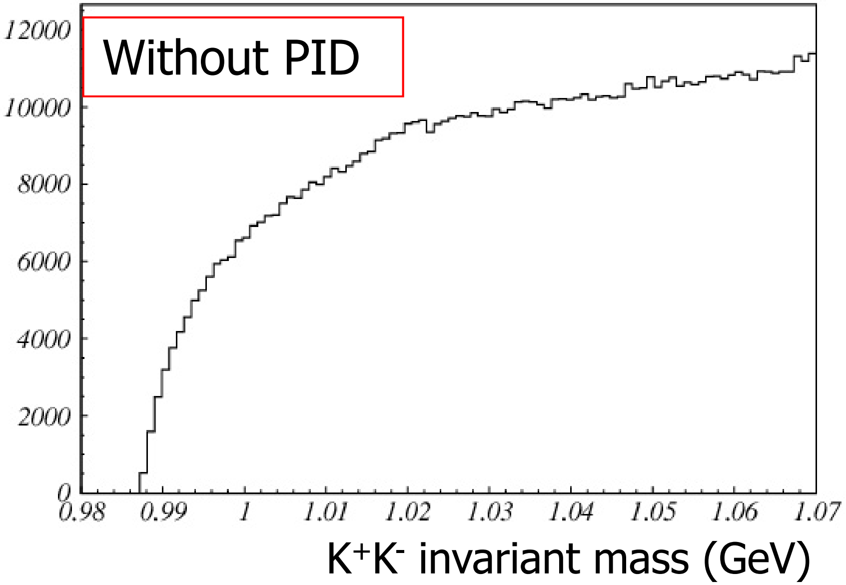
Example 3: LHCb

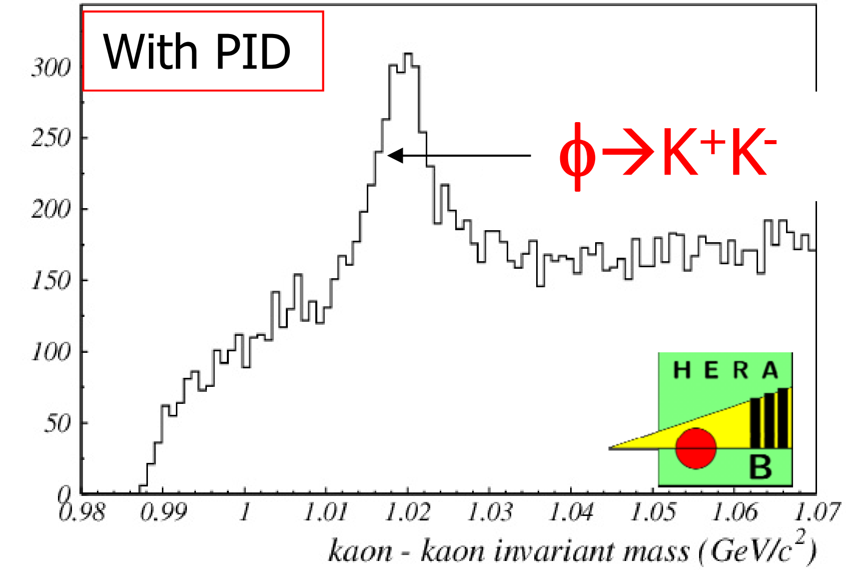




Need to distinguish $B_d \to \pi\pi$ from other similar topology 2-body decays and to distinguish B from anti-B using K tag.

Why particle ID?





Example 2: HERA-B

K^+K^- invariant mass.

The inclusive $\phi \to K^+K^-$ decay only becomes visible after particle identification is taken into account.

Why particle ID?

PID is also needed in:

•General purpose LHC experiments: final states with electrons and muons

•Searches for exotic states of matter (quark-gluon plasma)

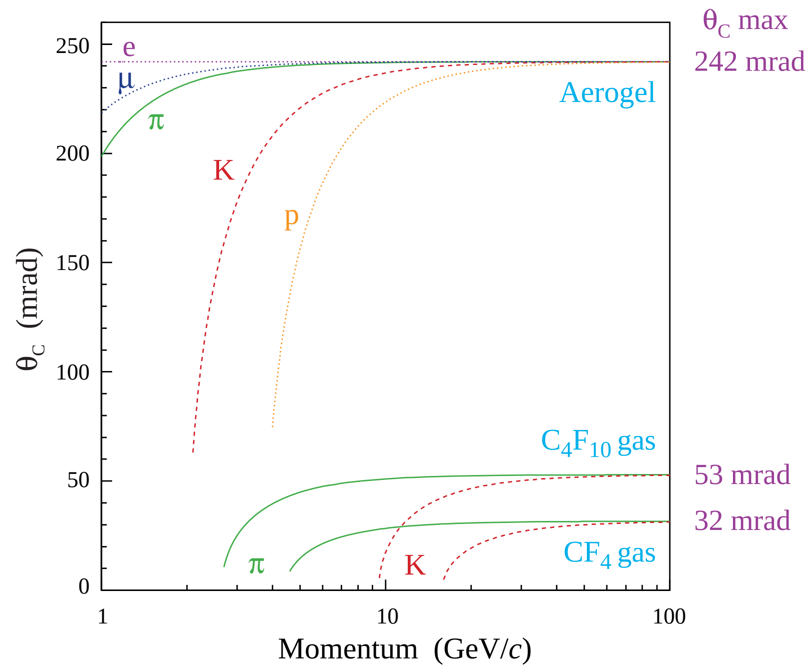
•Spectroscopy and searches for exotic hadronic states

•Studies of fragmentation functions

•Identification of neutrino flavour in neutrino mixing experiments

Cherenkov detectors

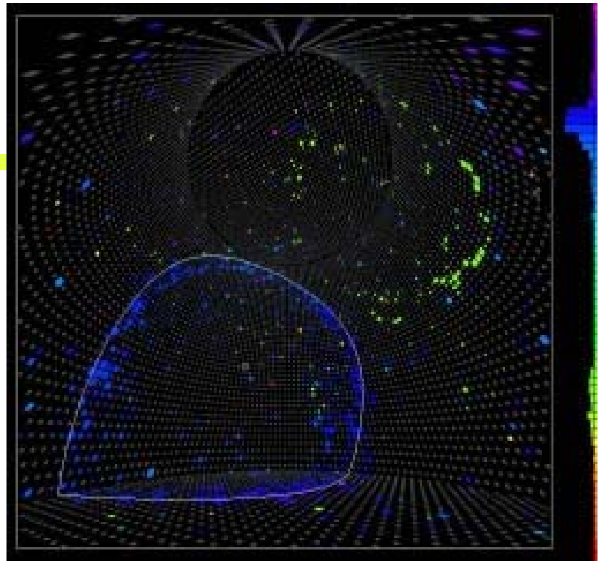
Provide particle identification over huge kinematic regions



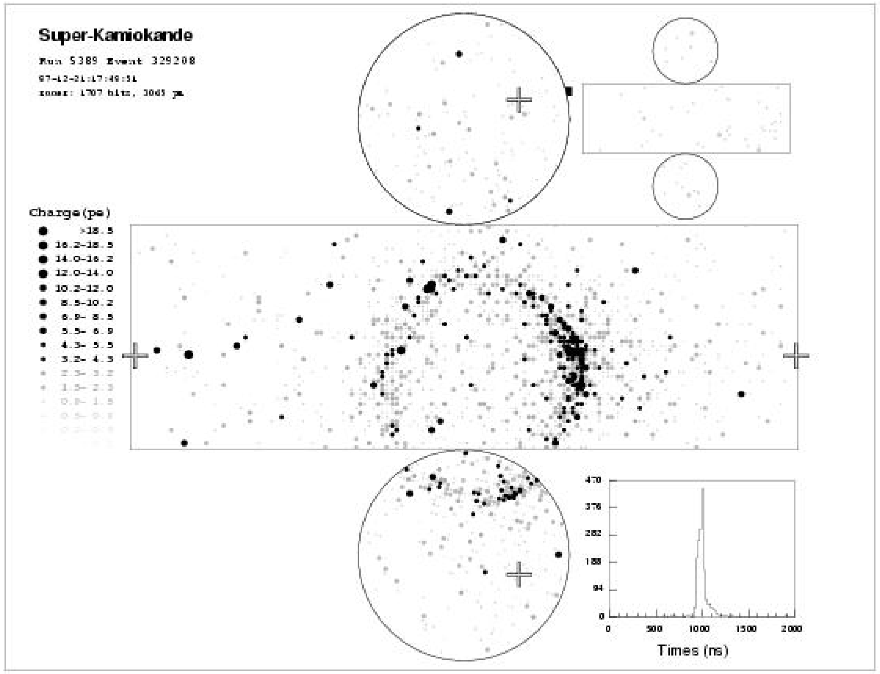
Provide a detector medium for neutrinos

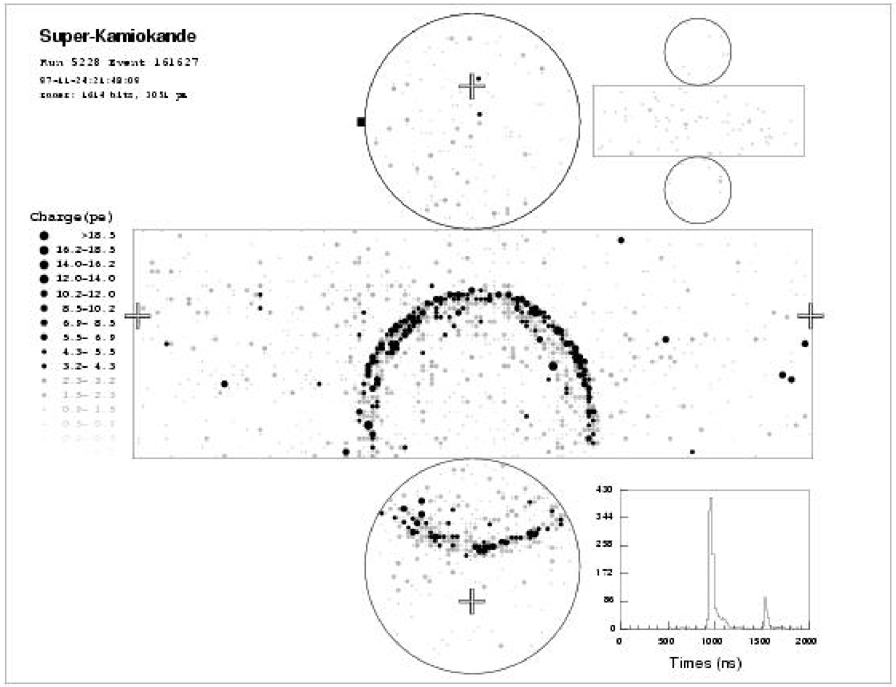
Two out of three recent Nobel Prizes in particle physics got essential experimental support from Cherenkov detectors

Neutrino detection and identification: Supekamiokande



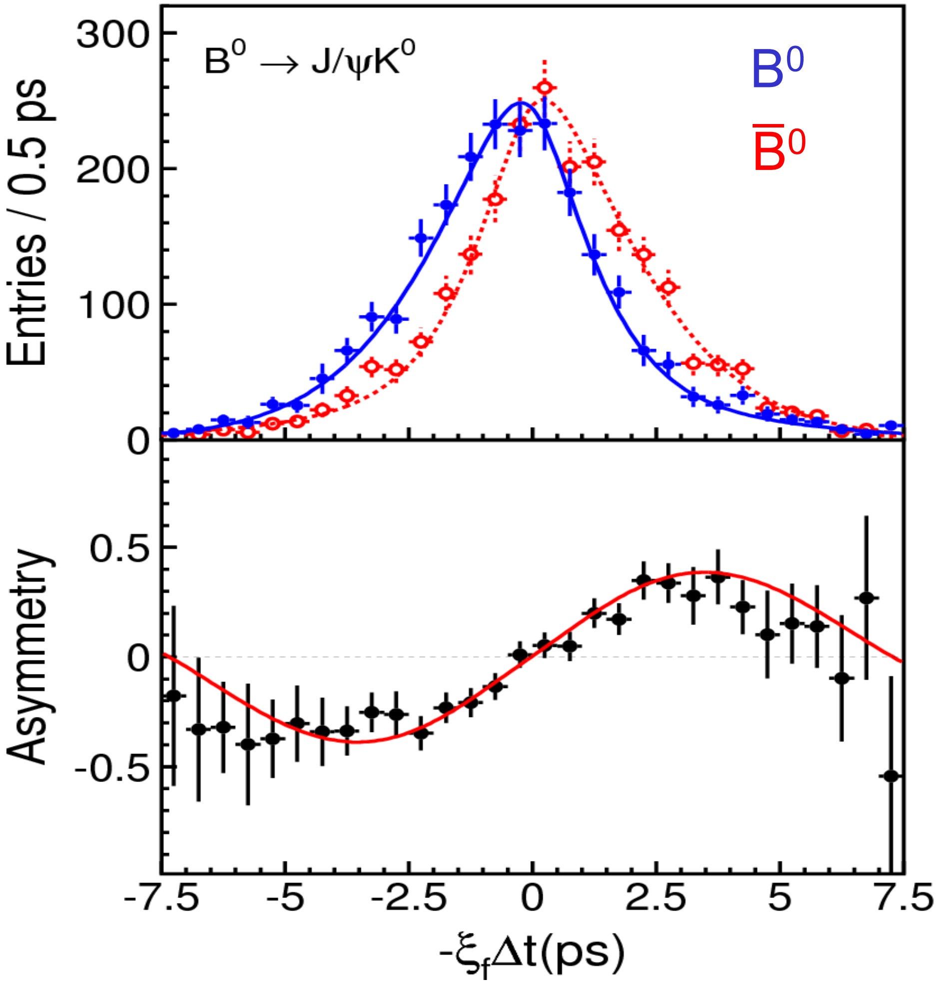
Muon-electron discrimination based on the patterns at the sensor walls.





Cherenkov detectors in flavour physics

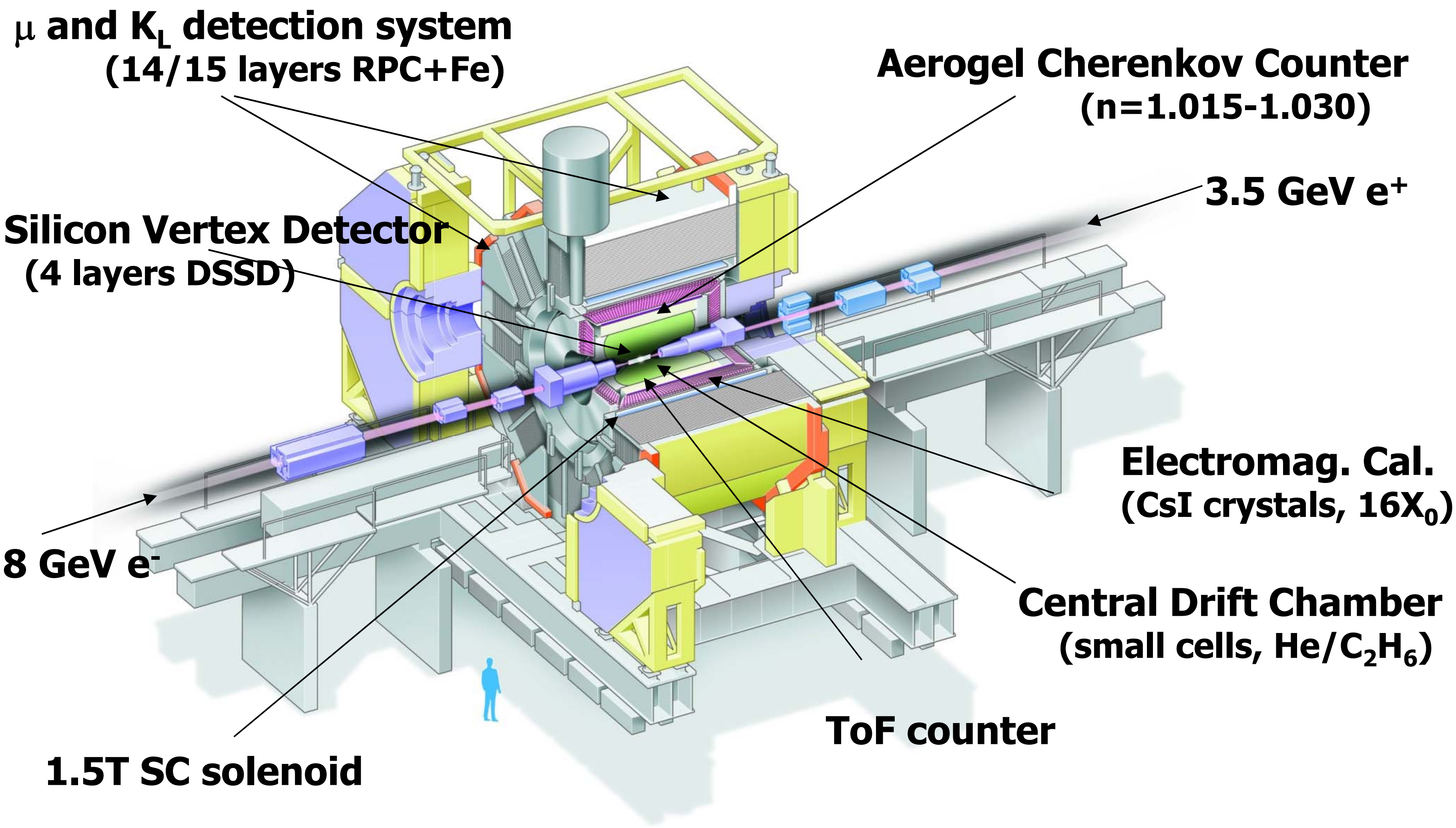
Particle identification at B factories (Belle and BaBar): was essential for the observation of CP violation in the B meson system.



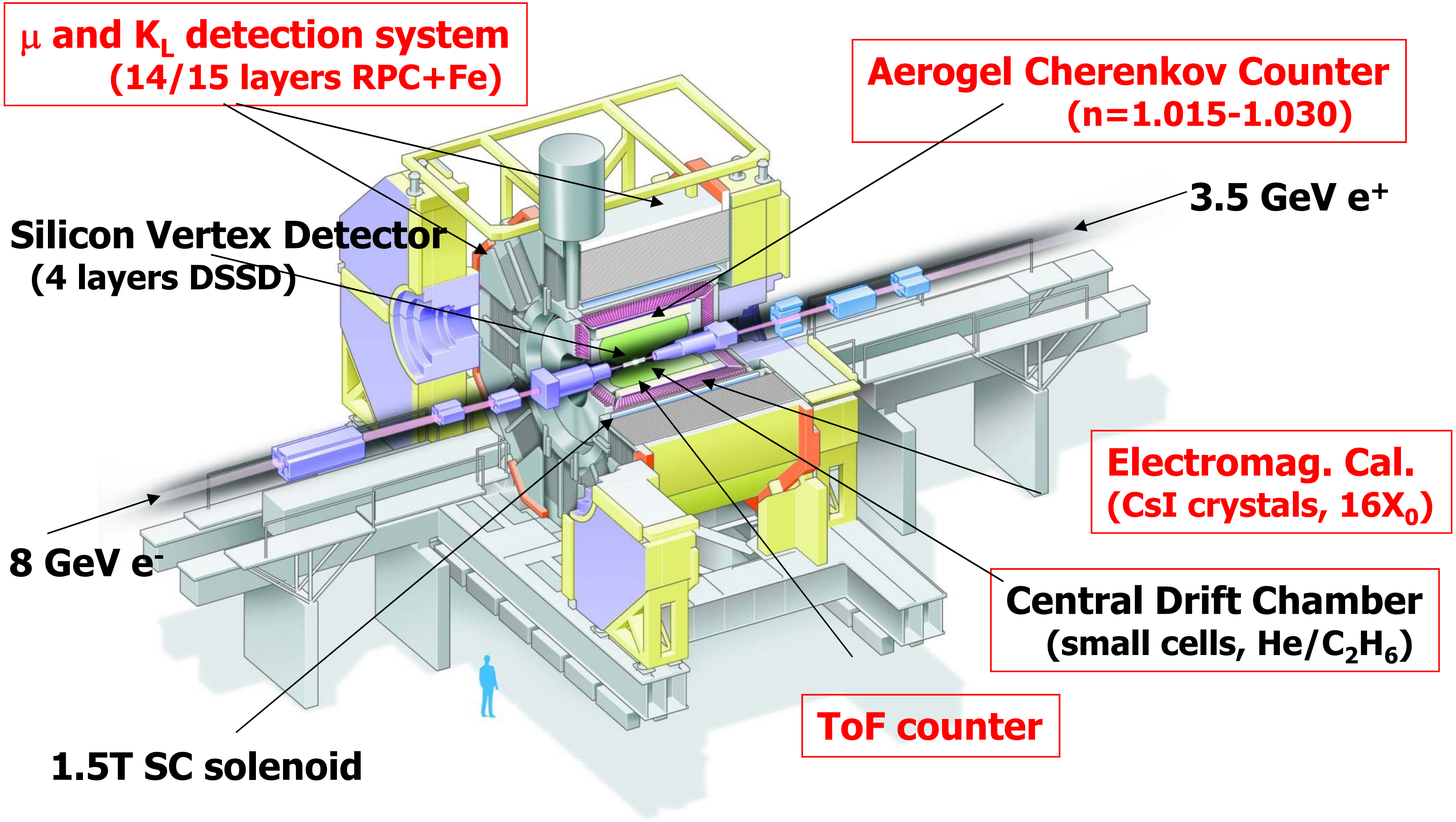
B^0 and its anti-particle decay differently to the same final state $J/\psi\ K^0$

Flavour of the B: from decay products of the other B, charge of the kaon, electron, muon

Example: Belle

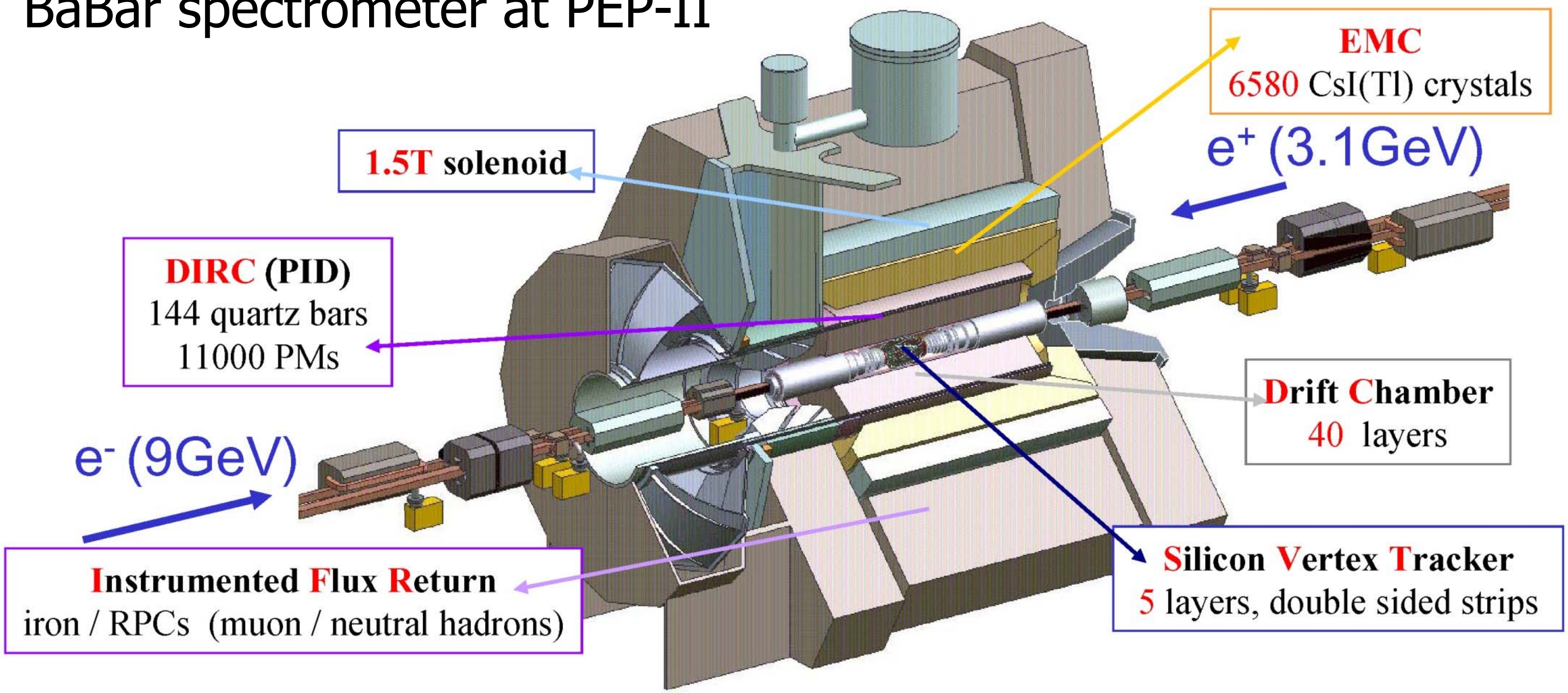


Particle identification systems in Belle



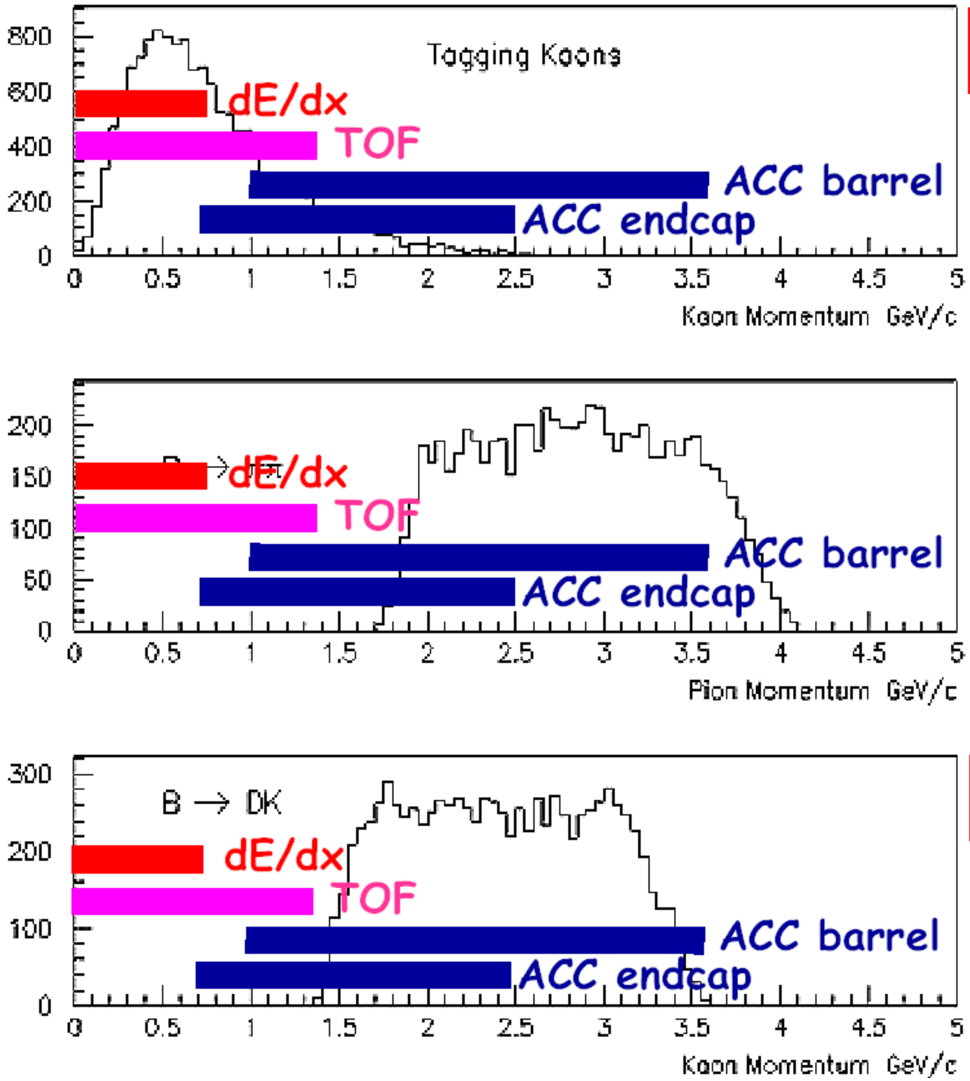
DIRC - detector of internally reflected Cherenkov light

BaBar spectrometer at PEP-II



PID coverage of kaon/pion spectra in Belle

BELLE

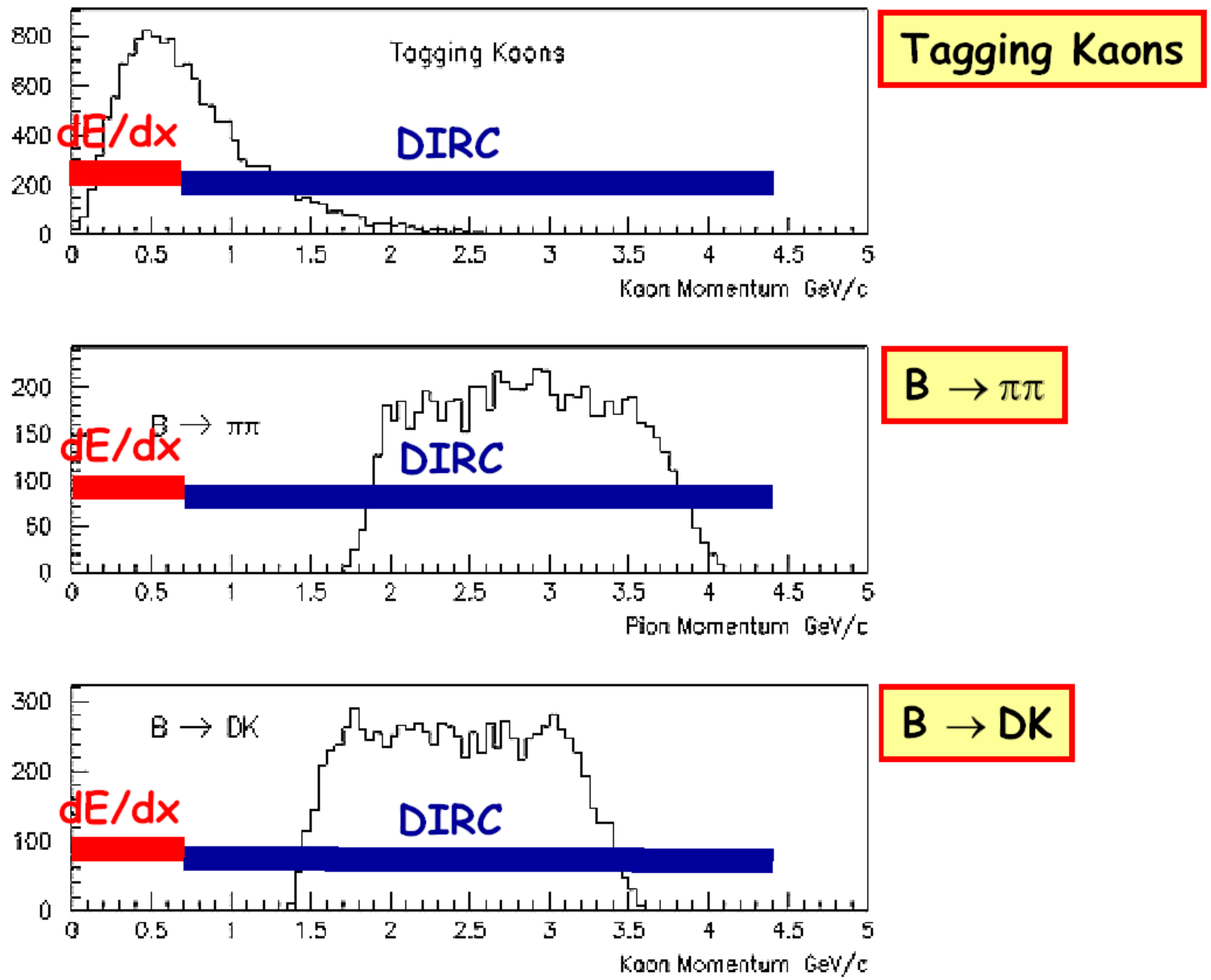


Tagging Kaons

B → ππ

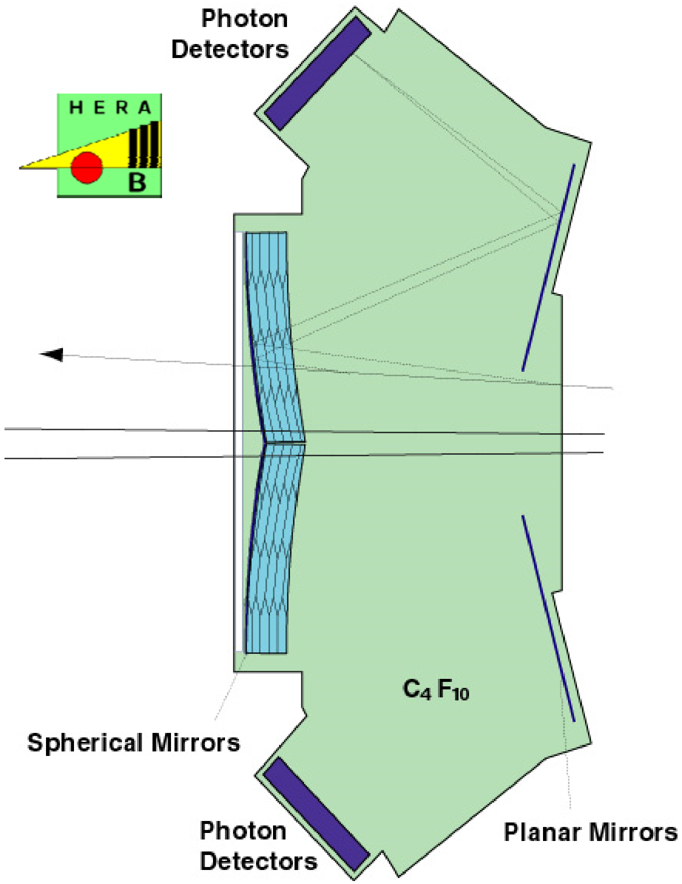
B → DK

PID coverage of kaon/pion spectra in BaBar

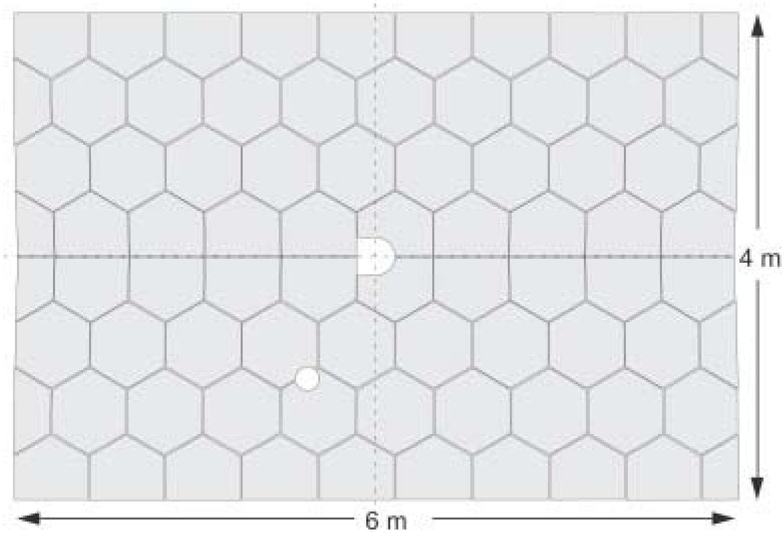


Calibration and alignment

Mirror alignment



Gas based RICHes: large mirrors → segments → relative alignment

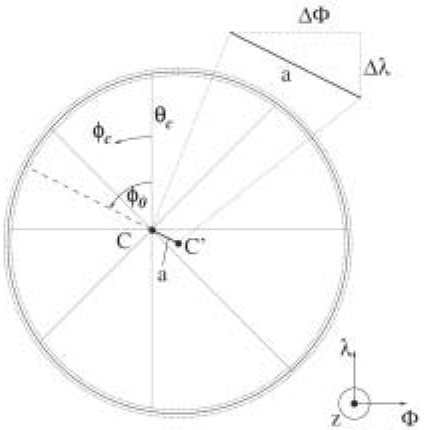


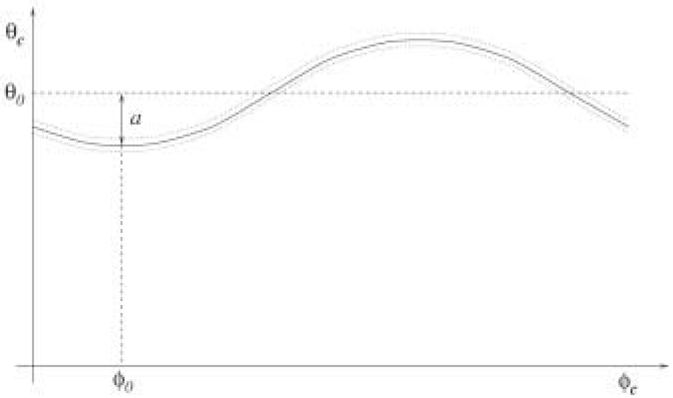
- Spherical mirror: 80 hexagonal segments
- Planar mirrors: 2x 18 rectangular segments

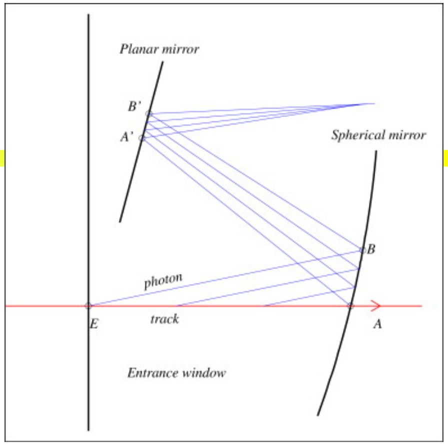
Aligning pairs of spherical and planar segments by using unambiguous photons.

Mirror alignment

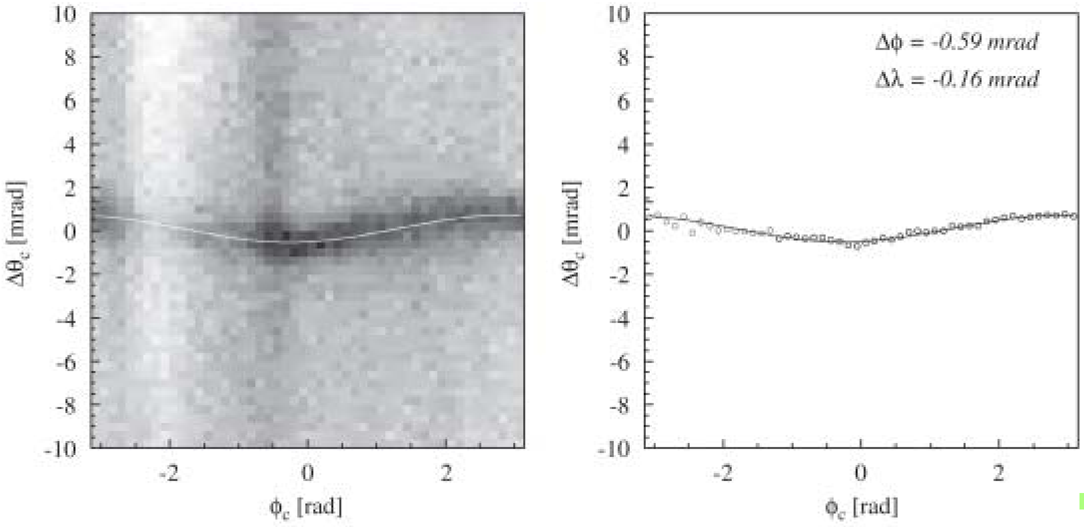
Misalignment: Cherenkov angle depends on the azimuthal angle around the track



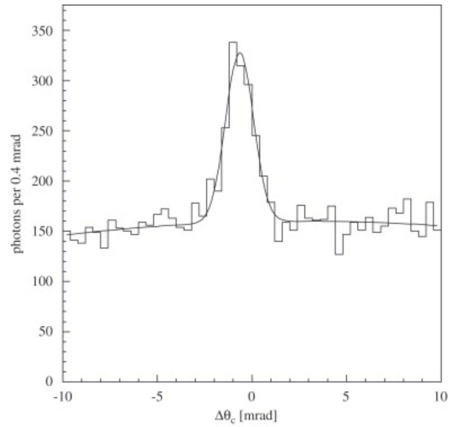




Use unambiguos photons.



mirrors 34 14



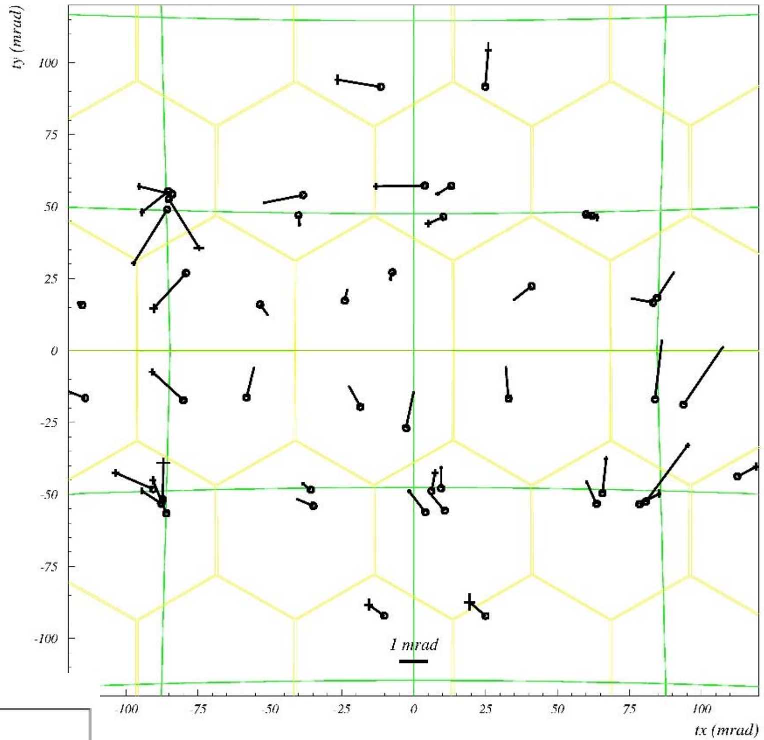
Slice in phi_c

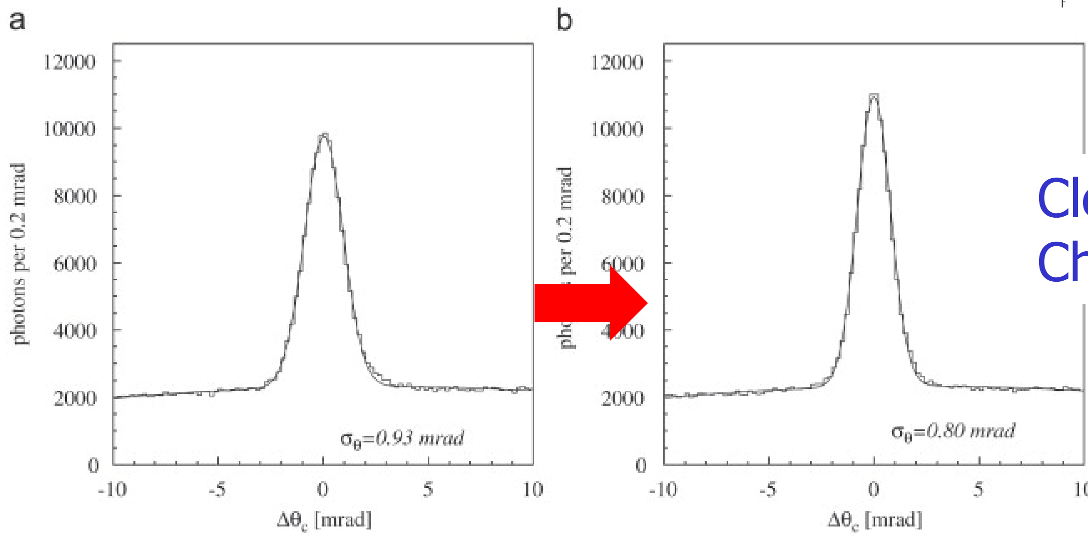
Mirror alignment

Initial mirror system alignment: with optical methods, theodolite.

Alignment with data: tells you the ultimate truth…

Combine all alignment data for all (possible) pairs of segments → solve a system of linear equations





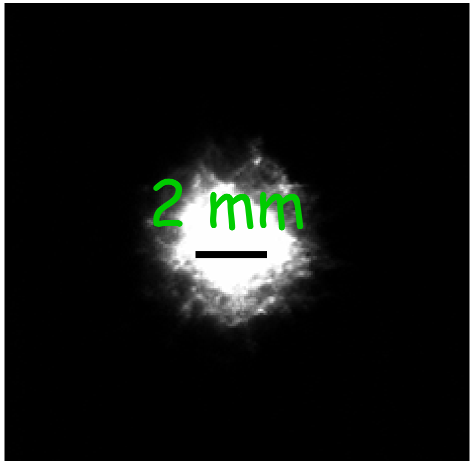
Clear improvement in Cherenkov angle resolution

→NIMA 586 (2008) 174

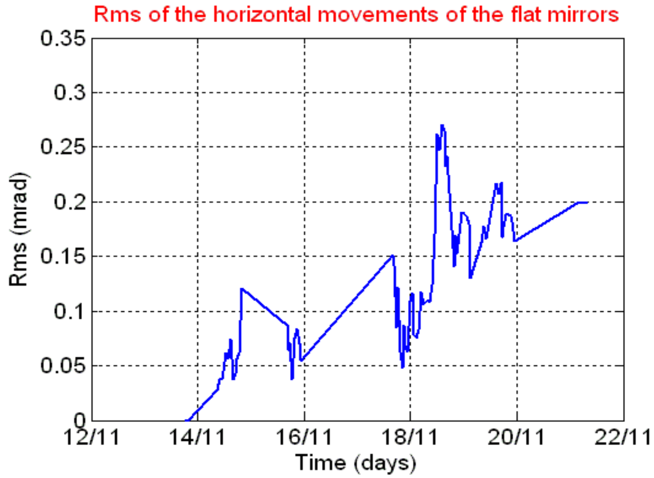
LHCb initial alignment

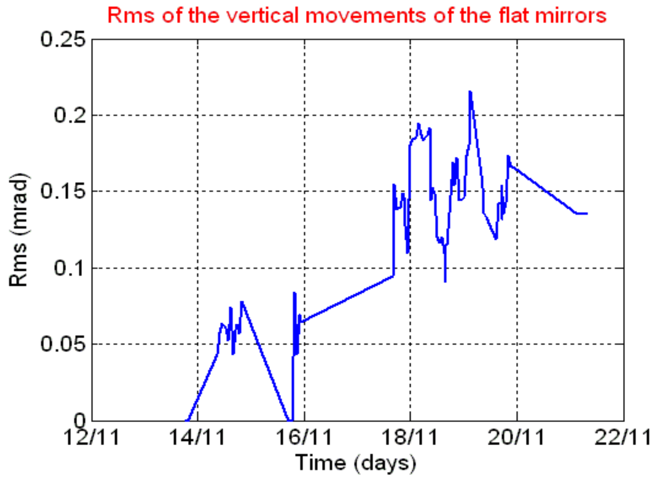
A. Papanestis (RICH2007)

Initial mirror alignment
(50 μrad)

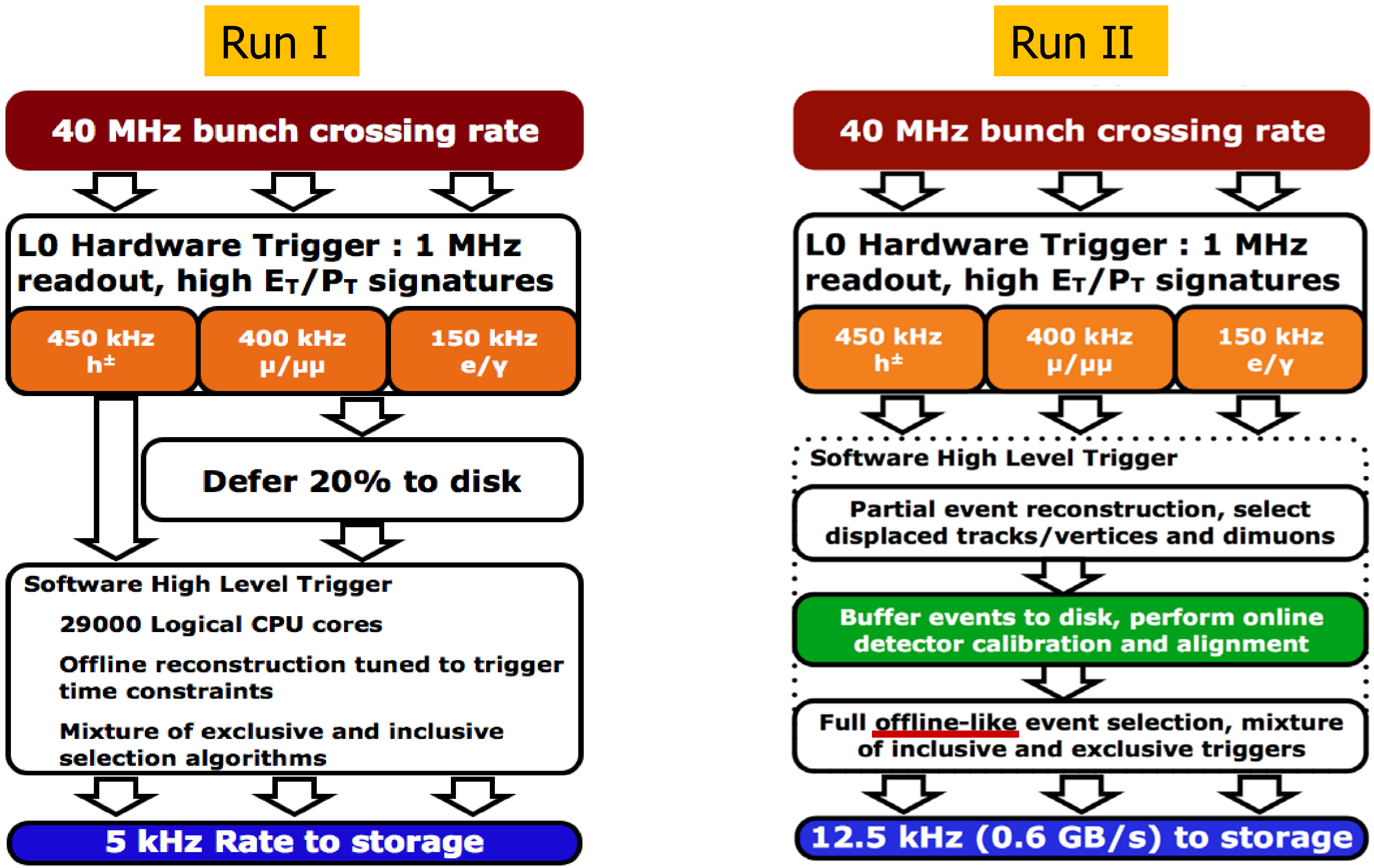


Mirror movement during transport and installation





New LHCb Trigger: need online detector calibration



→ Talk by Antonis Papanestis

LHCb calibration

Key points to monitor - All time-dependent!

Cherenkov angle

– RICH mirrors / detector planes alignment

– Tracking system alignment

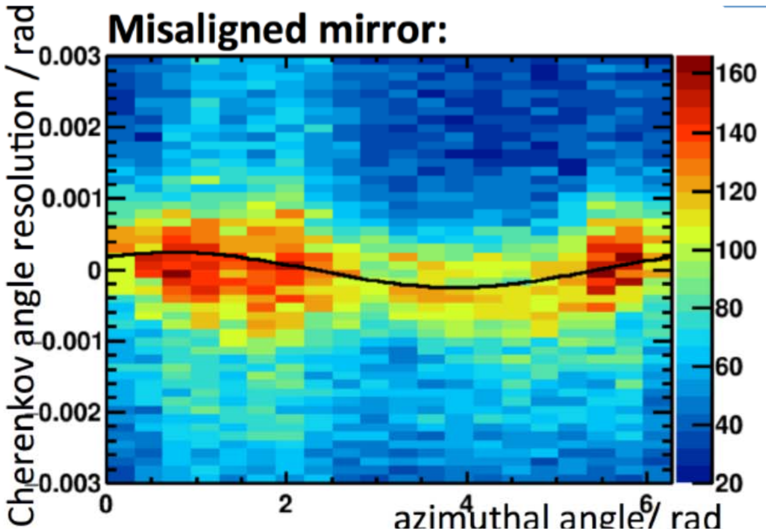
– HPD image calibration

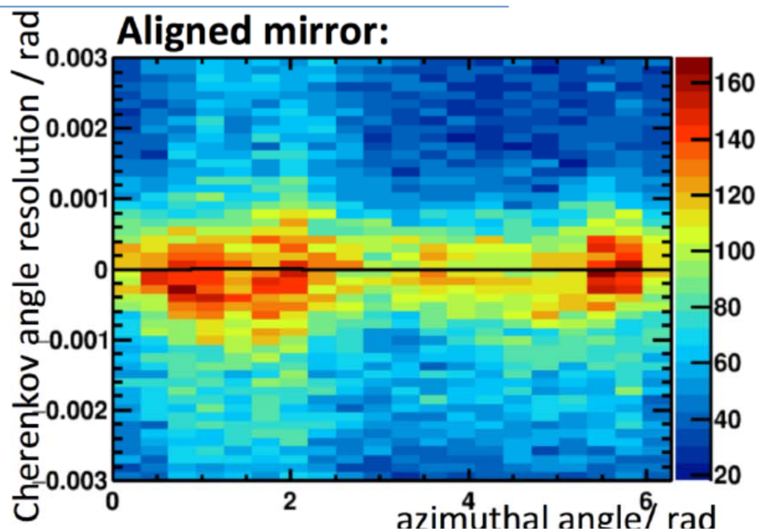
– Refractive index (Cherenkov angle)

Number of photons

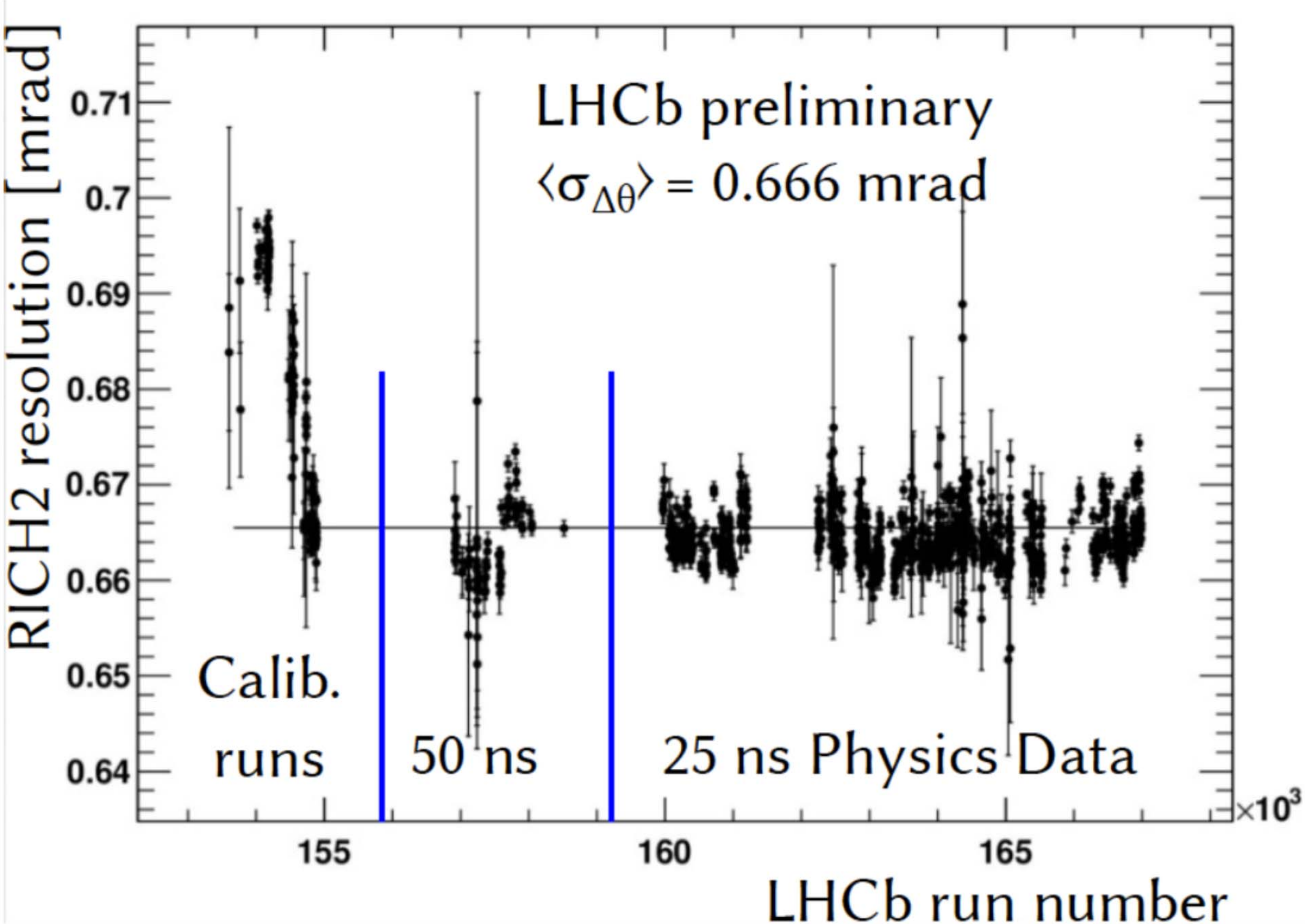
– Refractive index

→ Talk by Jibo He





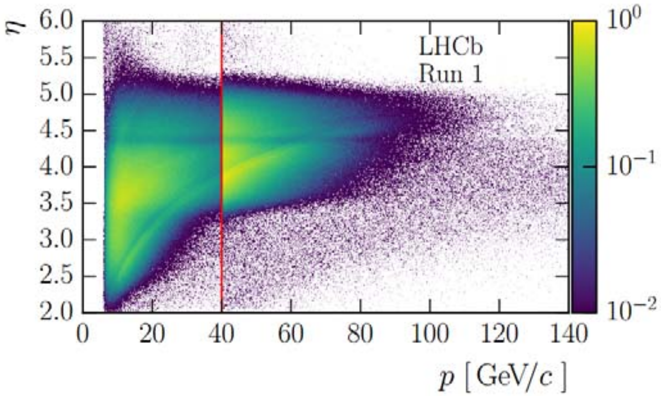
Resolution stability: RICH2

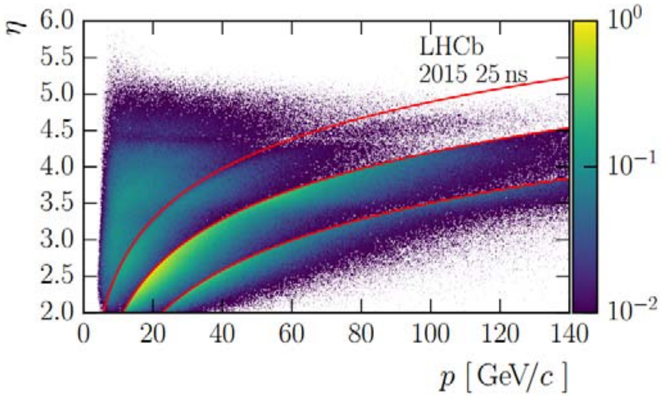


Calibration sample

- Collect pure samples of known-ID particles
- There is a main trigger line for each particle and possibly another one for cross-checks and systematic studies

Species	Low $p - p_T$	High p and p_T
$e^{\pm}$	—	$J/\psi \to e^+e^-$
$\mu^{\pm}$	$D_s^+ \to \mu^+\mu^-\pi^+$	$J/\psi \to \mu^+\mu^-$
$\pi^{\pm}$	$K_S^0 \to \pi^+\pi^-$	$D^* \to D^0(K^-\pi^+)\pi^+$
$K^{\pm}$	$D_s^+ \to K^+K^-\pi^+$	$D^* \to D^0(K^-\pi^+)\pi^+$
$p^{\pm}$	$\Lambda^0 \to p\pi^-$	$\Lambda^0 \to p\pi^-$, $\Lambda_c^+ \to pK^-\pi^+$



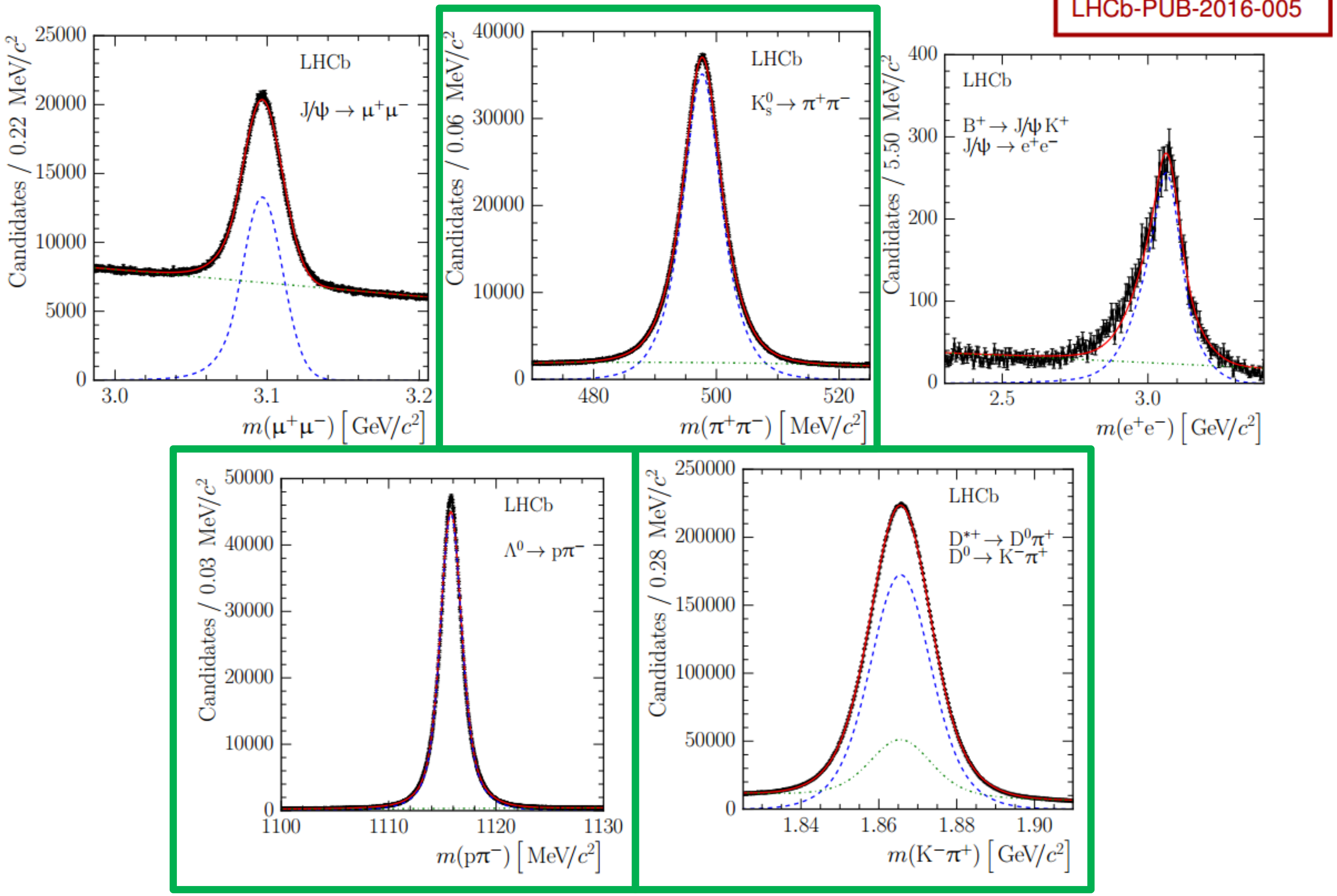


New selections designed to improve the kinematic coverage

→ Talk by Antonis Papanestis

Mass distributions of PID samples

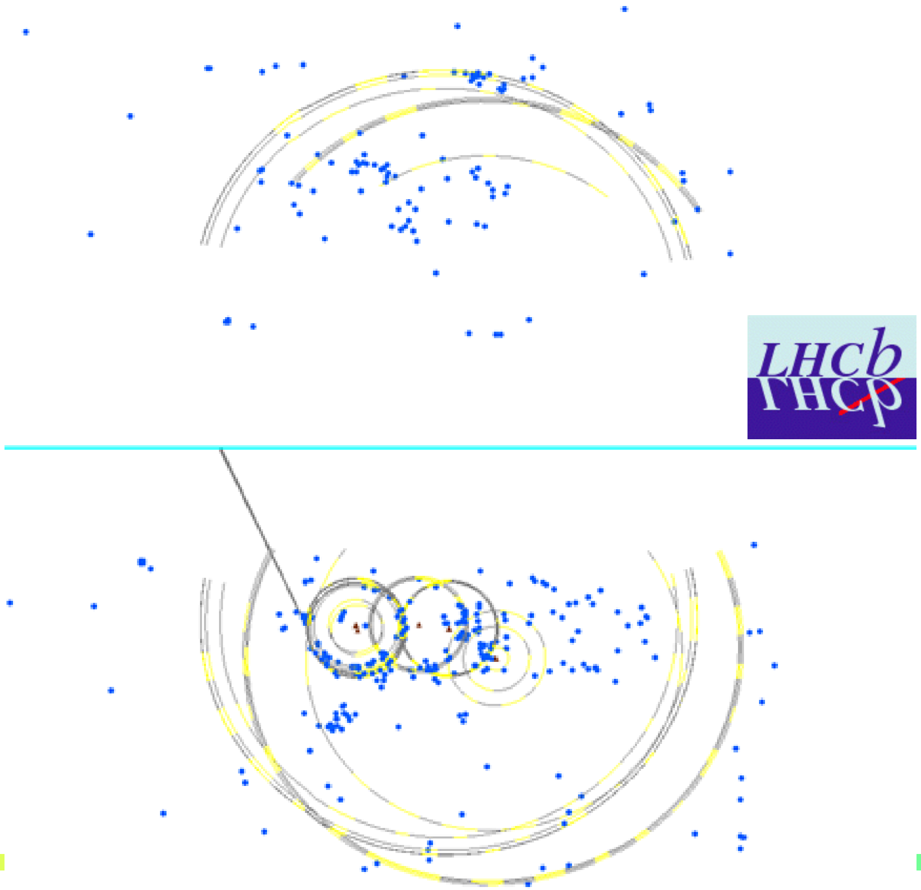
LHCb-PUB-2016-005



→ Talk by Antonis Papanestis

Reconstruction and likelihood calculation

- Track based (global and local likelihood)
- Track based ring search (no time → backup slides)
- Stand-alone ring search



Global likelihood PID algorithm

Take all pixels hit *and* all tracks *and* all radiators, and maximize

$$L = L\left(n_{pixel}, \Sigma\, e_{pixel,track}, b_{pixel} \right)$$

1. Assume all particles to be pions (or seed from previous reconstruction). Estimate background parameter b_{pixel}
2. Calculate likelihood of given pixel distribution
3. Iterate

- change PID hypothesis for one track at a time
- recalculate likelihood
- choose change, that had biggest (positive) impact
- assign new PID to that track until no positive change is found

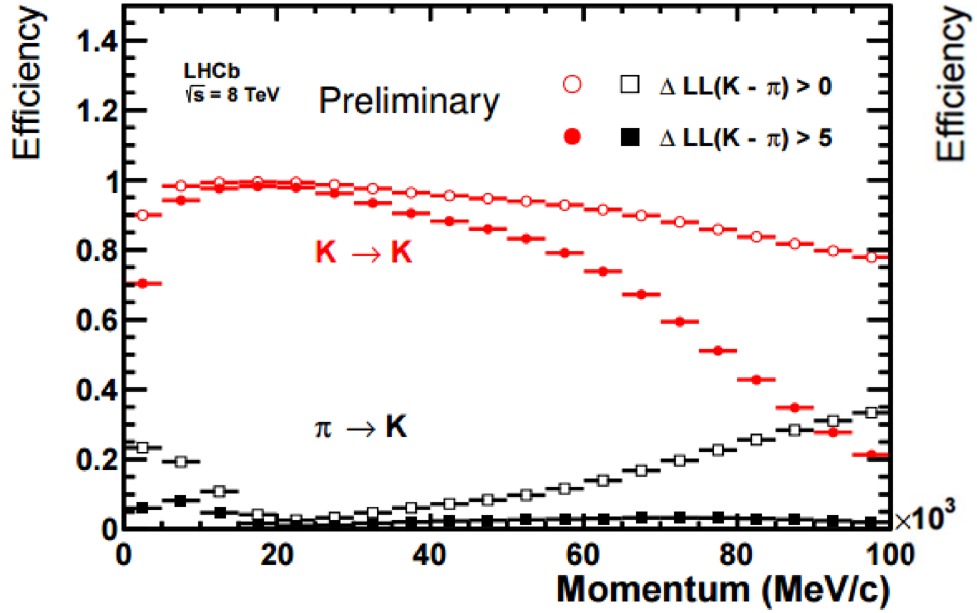
With improved PID hypotheses, background estimate can be updated, and next iteration can start (2nd is usually final).

The best you can do when most of the hits come from reconstructed tracks. → R. Forty, NIMA 433 (1999) 257-261

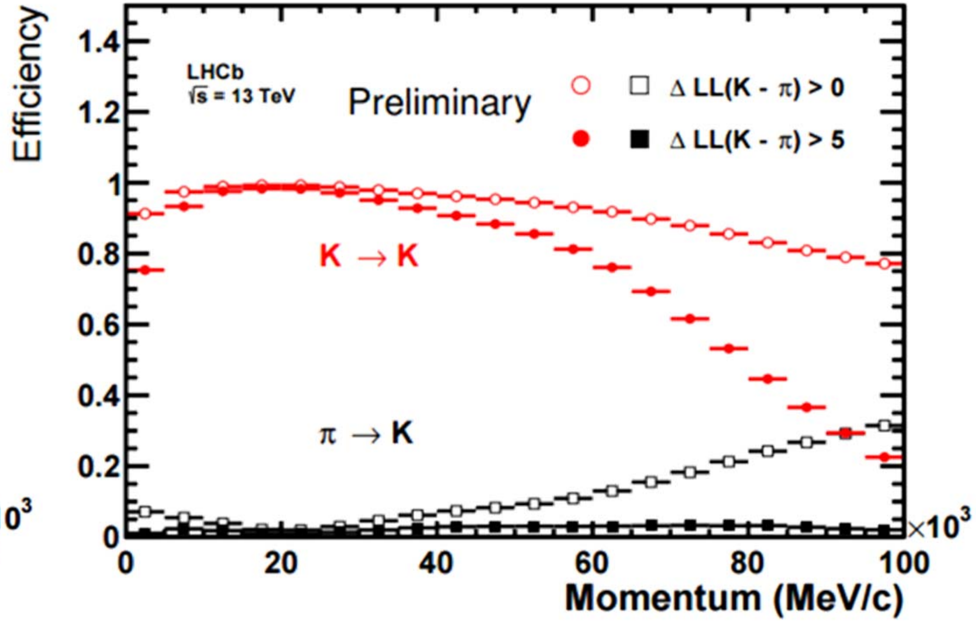
LHCb RICHes: performance

Comparison between:

Run I

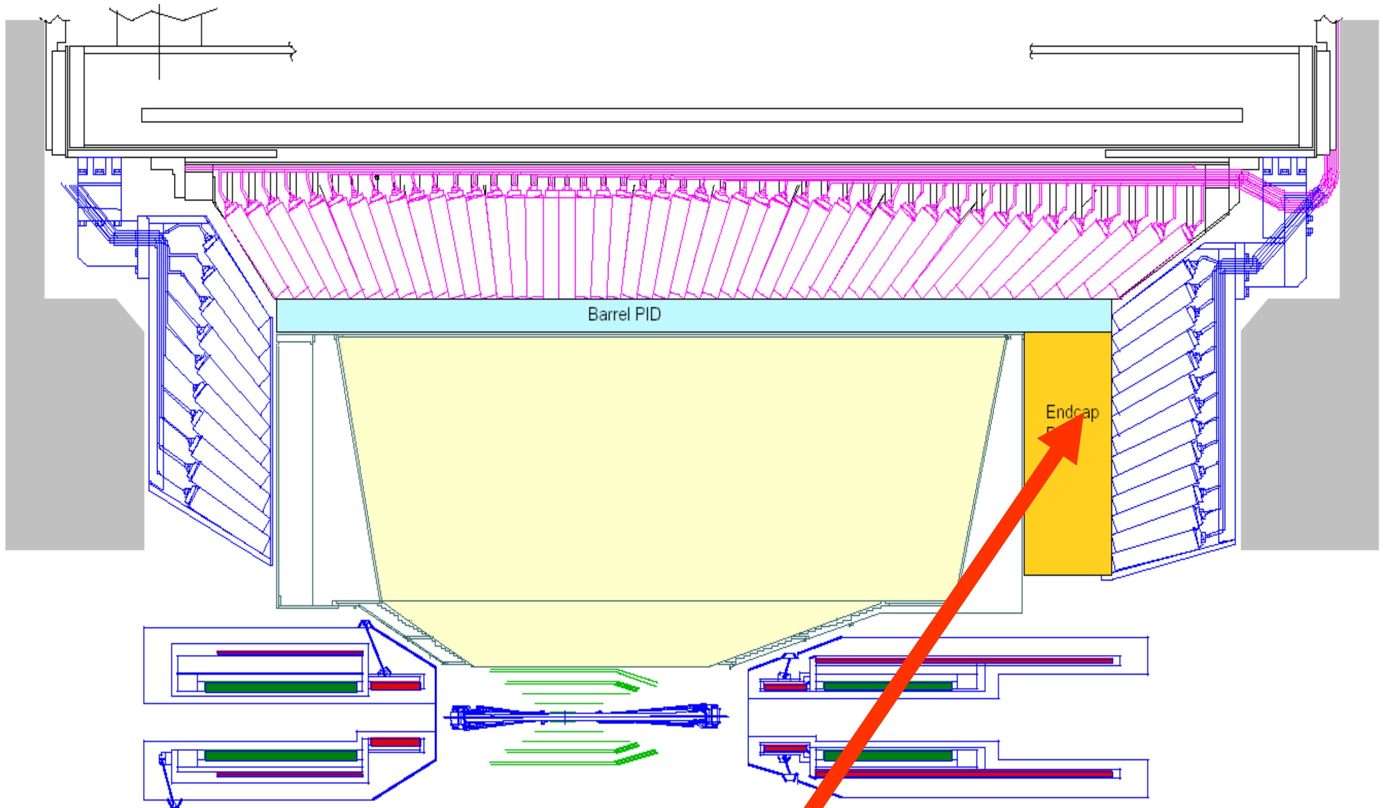


Run II (2015)



→ Talk by Antonis Papanestis

Belle II PID system



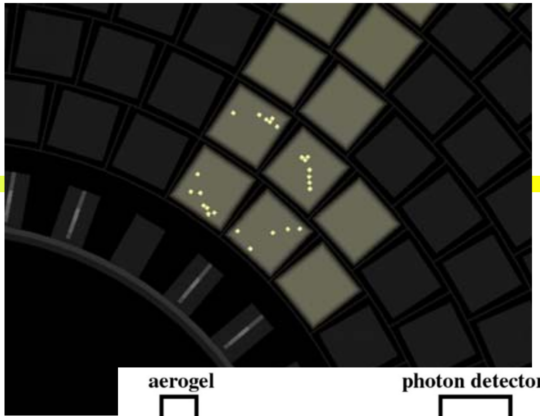
Two new particle ID devices, both RICHes:

Barrel: Time-of-propagation counter (TOP) counter

Endcap: proximity focusing RICH

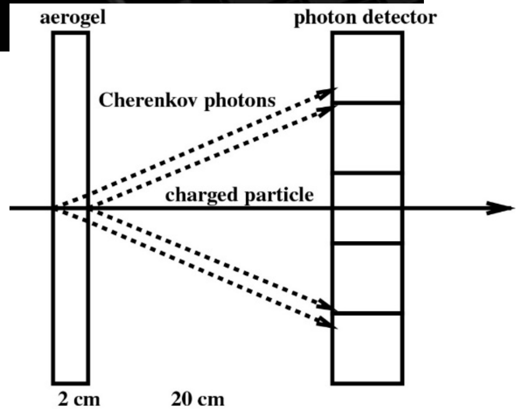
→ Talk by Rok Pestotnik

Aerogel RICH of Belle II



Lower track densities, no overlap of rings

→ track based local likelihood calculation



- reconstructed tracks are extrapolated from the tracking chamber to the ARICH volume.
- construct likelihood function for 6 particle type hypotheses for each track (independently)

For each particle hypothesis h

$$\ln\mathcal{L}^h = -N^h + \sum_{\text{hit } i}\left[n_i^h + \ln(1 - e^{-n_i^h})\right]$$

N^h: Expected total number of hits

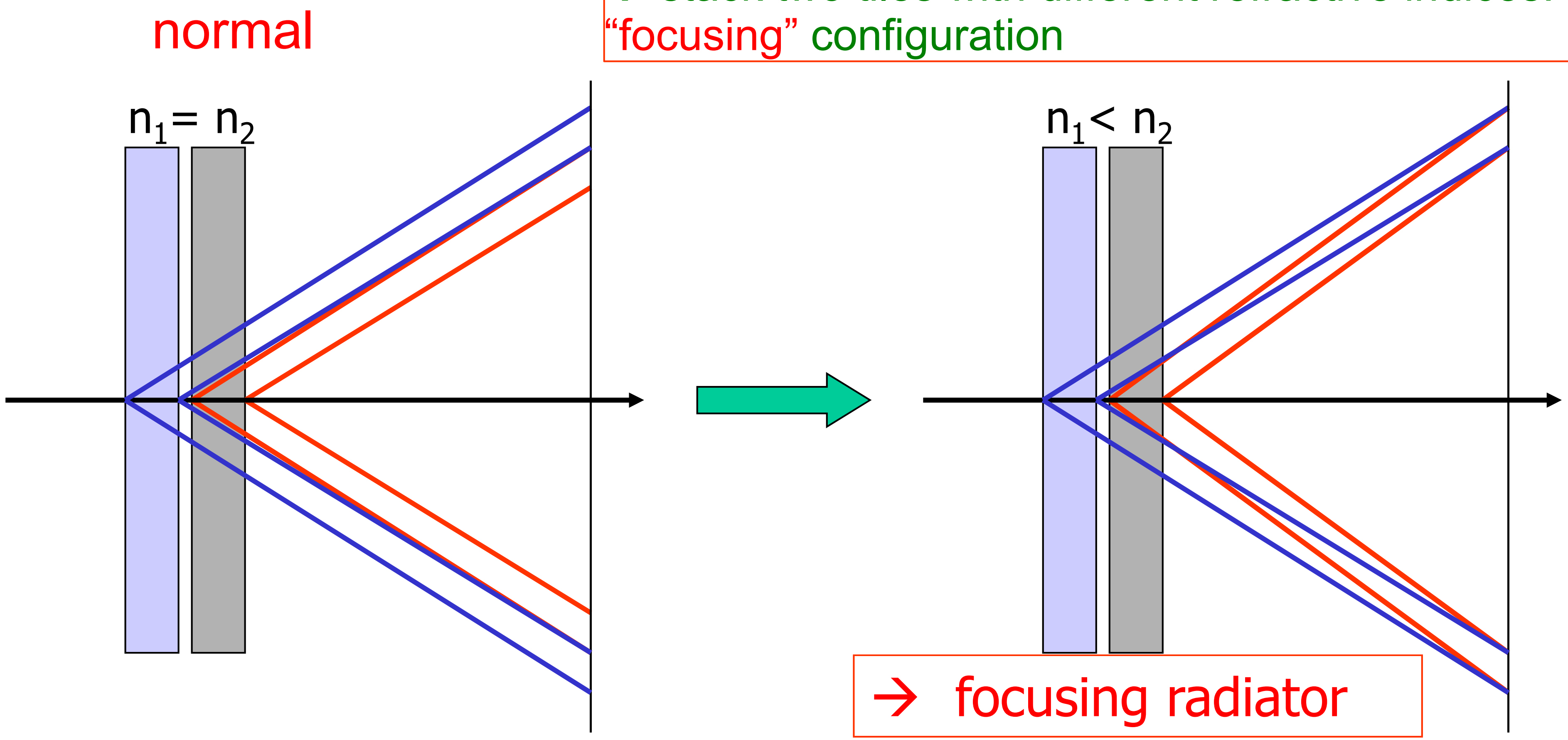
n_i^h: Expected number of hits on pixel i

→ Talk by Luka Šantelj

Radiator with multiple refractive indices

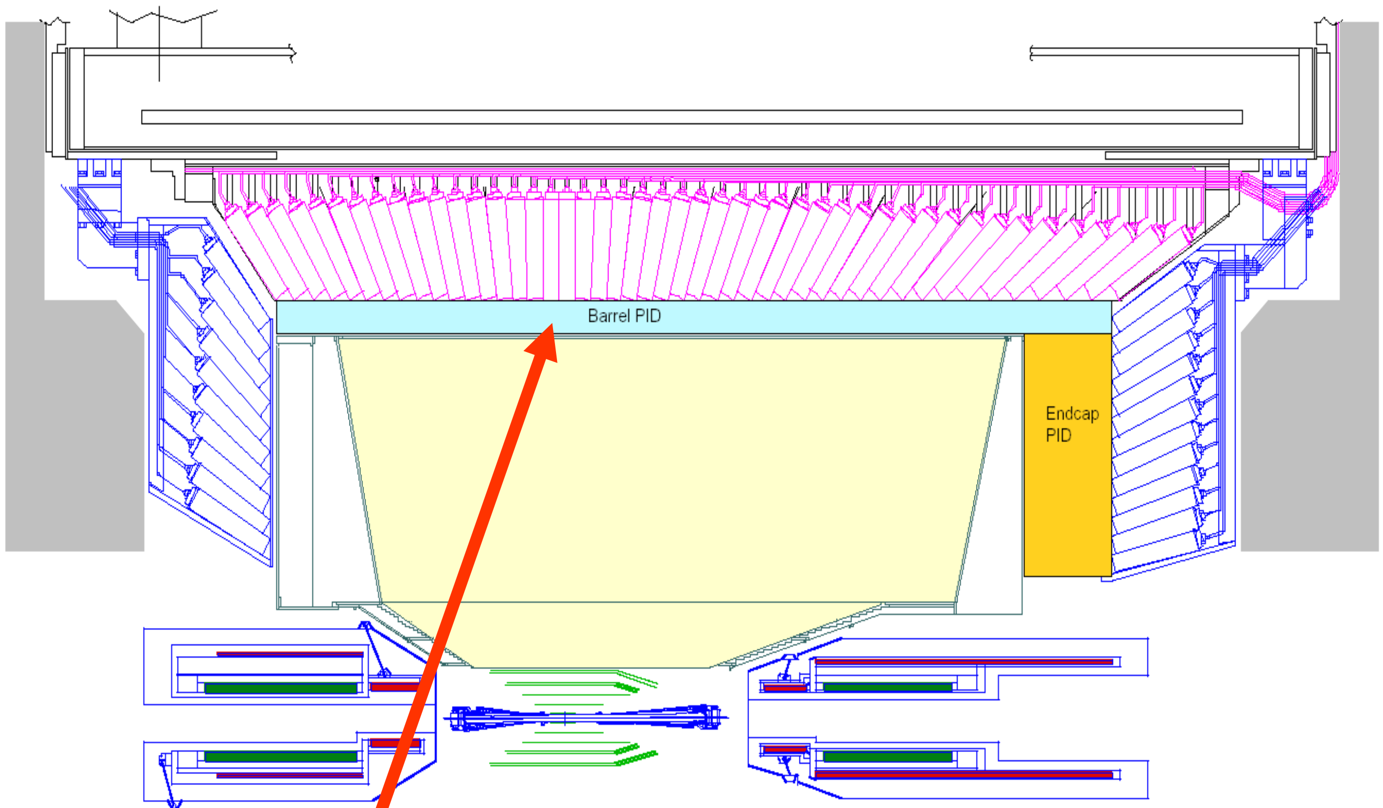
How to increase the number of photons without degrading the resolution?

→ stack two tiles with different refractive indices: "focusing" configuration



→NIM A548 (2005) 383, NIMA 565 (2006) 457

Belle II PID systems – side view

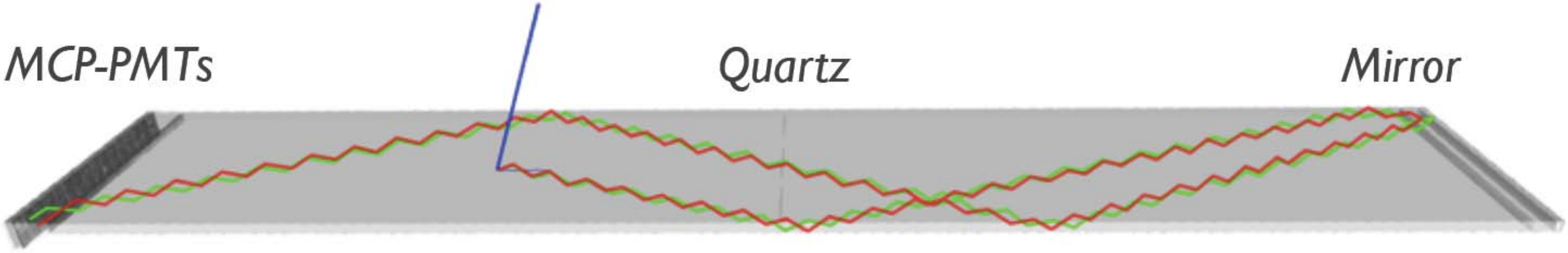


Two new particle ID devices, both RICHes:

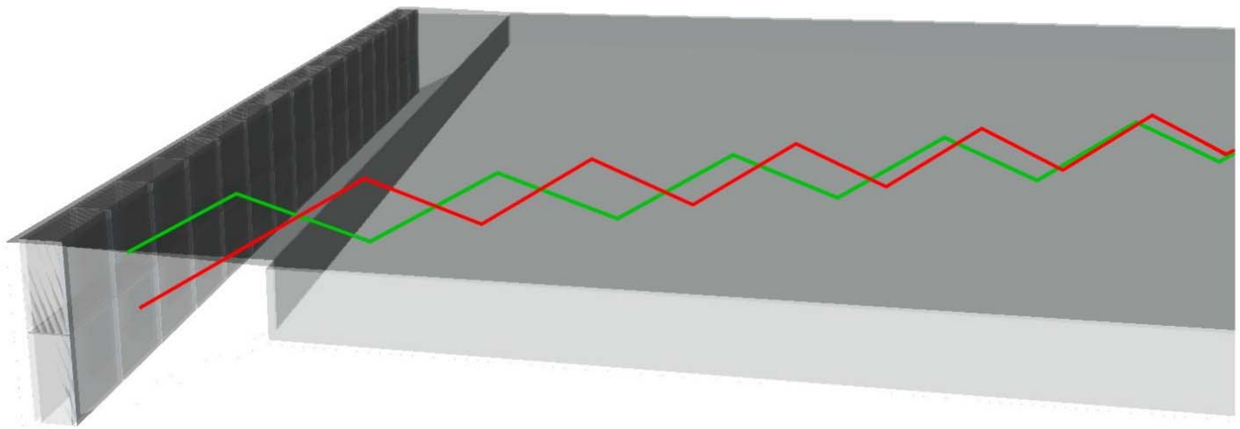
Barrel: time-of-propagation (TOP) counter

Endcap: proximity focusing RICH

Barrel PID: Time of propagation (TOP) counter



Example of Cherenkov-photon paths for 2 GeV/c $\pi^{\pm}$ and $K^{\pm}$.

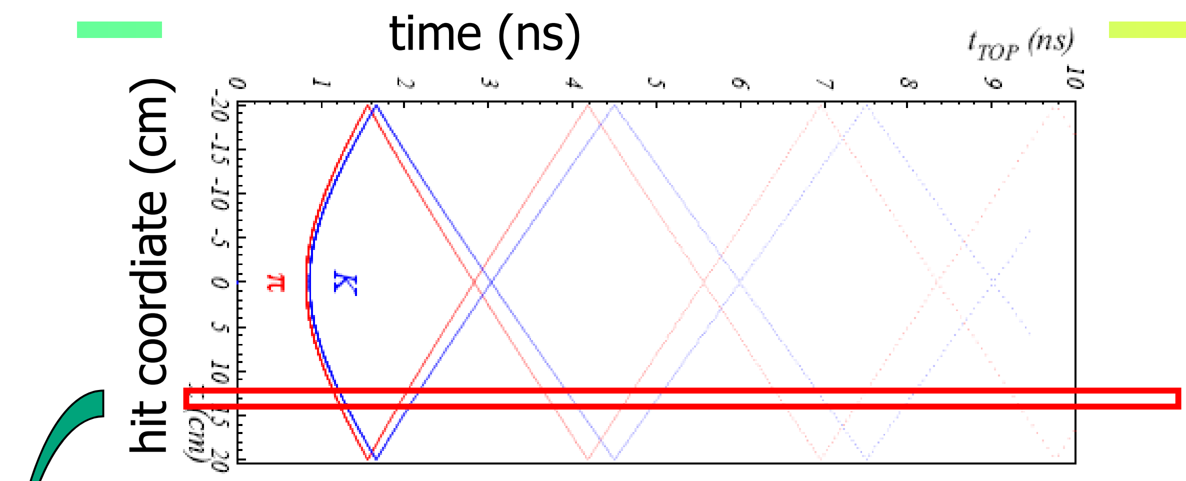


Similar to DIRC, but instead of two coordinates measure:

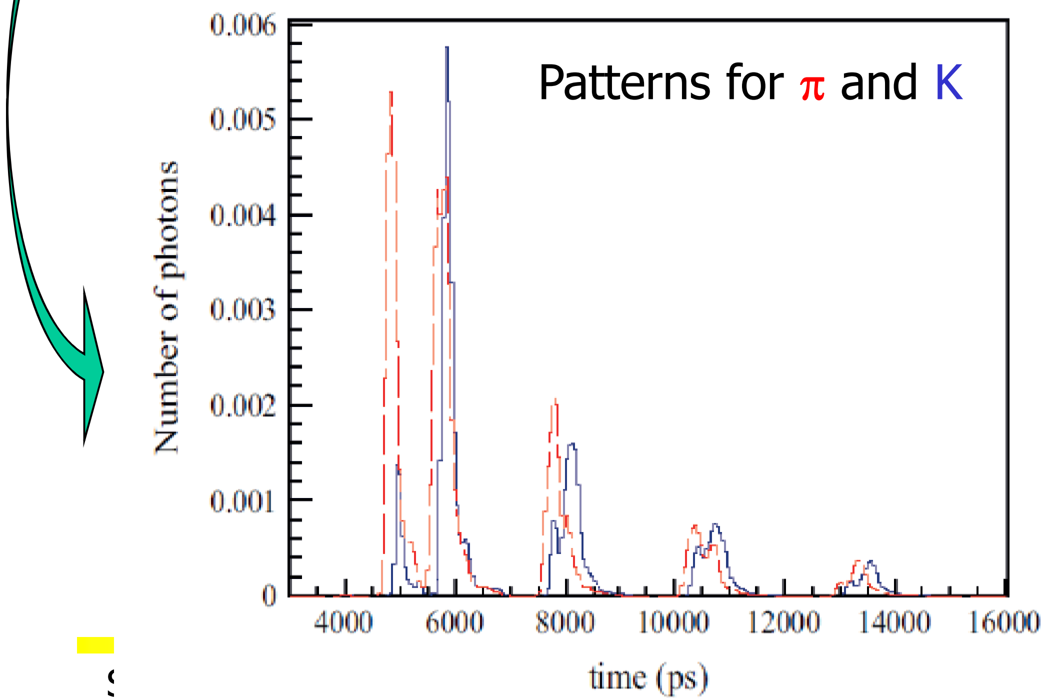
- One (or two coordinates) with a few mm precision
- Time-of-arrival with excellent time resolution

→ Talk by J. Fast

TOP image



Pattern in the coordinate-time space ('ring') of a pion and kaon hitting a quartz bar



Time distribution of signals recorded by one of the PMT channels: different for π and K (~shifted in time)

TOP: likelihood construction

For a given mass hypothesis $h = e, \mu, \pi, K, p$:

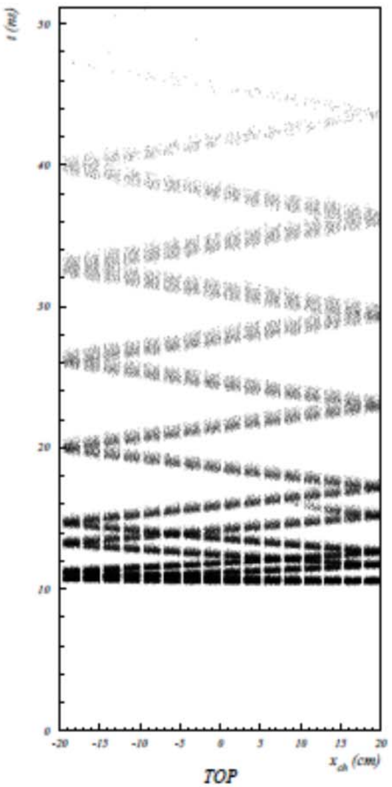
$$\log \mathcal{L}_h = \sum_{i=1}^{N} \log\left(\frac{S_h(x_i, t_i) + B(x_i, t_i)}{N_e}\right) + \log P_N(N_e)$$

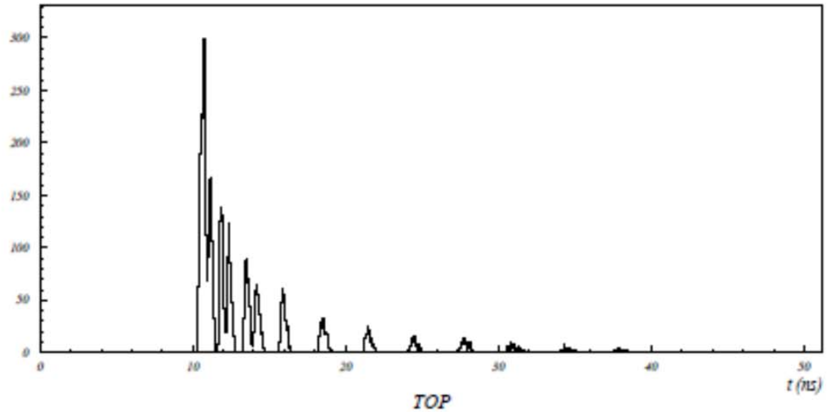
- N ... number of detected photons
- $N_e = N_h + N_B$ ... expected number of photons
- $S_h(x, t)$ ... signal distribution for mass hypothesis h
- $B(x, t)$ ... distribution of background photons
- $P_N(N_e)$ ... Poisson probability of mean N_e to obtain N photons

Distributions normalized as:

$$\sum_{j=1}^{n_{ch}} \int_0^{t_m} S(x_j, t)dt = N_h, \qquad \sum_{j=1}^{n_{ch}} \int_0^{t_m} B(x_j, t)dt = N_B$$

TOP: likelihood construction II



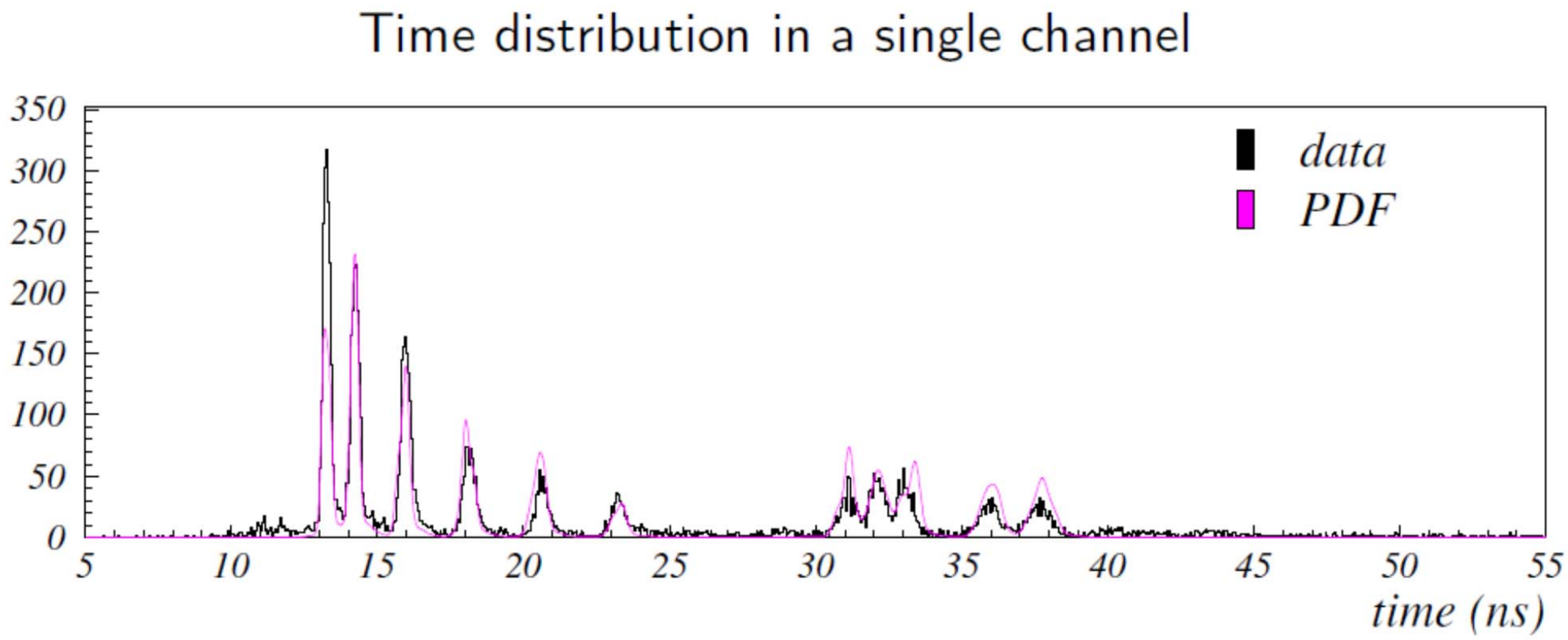


$$S_h(x_j, t) = \sum_{k=1}^{m_j} n_{kj} g(t - t_{kj}; \sigma_{kj})$$

- n_{kj} … number of photons in the k-th peak
- t_{kj} … position of the k-th peak
- σ_{kj} … width of the k-th peak
- $g(t - t_{kj}; \sigma_{kj})$ … normalized Gaussian

The name of the game: find analytic expressions!

TOP: likelihood construction III



Analytic expression can be derived in spite of the complexity of the problem!

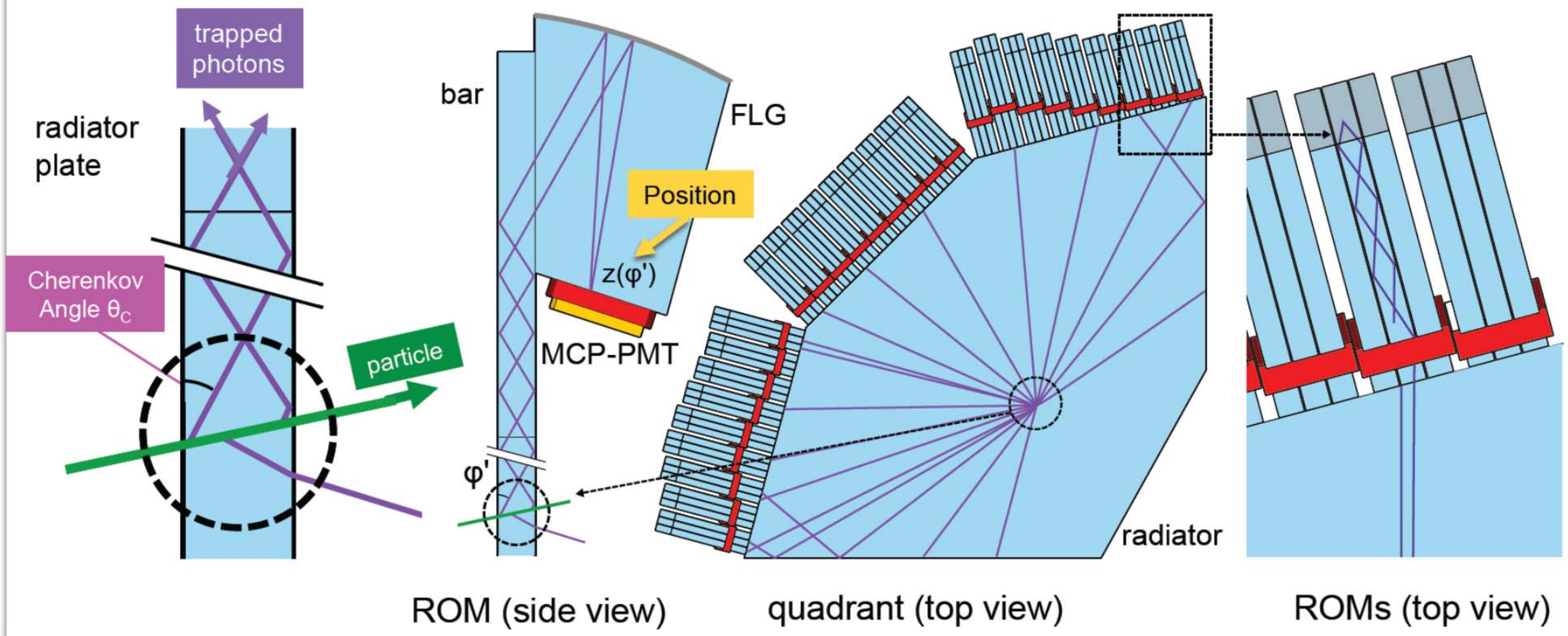
→M. Starič at RICH2010 (NIM A 639 (2011) 252-255)

This likelihood calculation is also employed in TOP calibration/alignment

→talk by M. Starič yesterday

Reconstruction: PANDA Disc DIRC

Disc DIRC: Optical concept and analytic photon reconstruction



Analytic reconstruction formula:

$$z(\varphi') = z(\varphi, \alpha_{FEL}) = z\left(\arctan\left(\frac{\tan\varphi}{\cos\alpha_{FLG}}\right)\right)$$

→ Talk by Michael Dueren

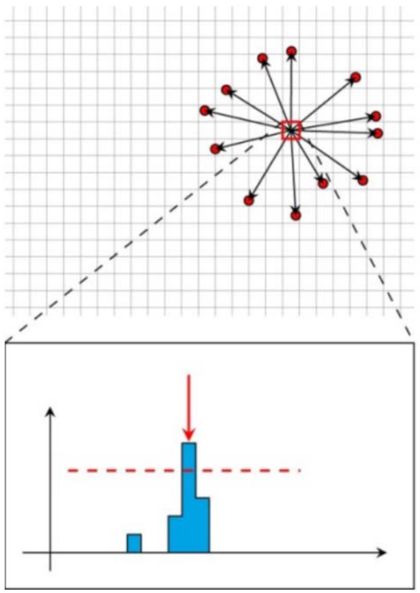
Stand-alone ring seach

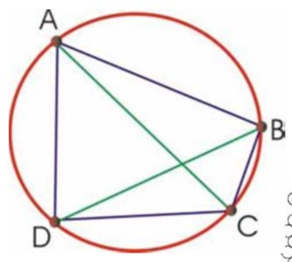
Hough transform: e.g. when looking for saturated rings (unknown parameters x_c, y_c of the ring)

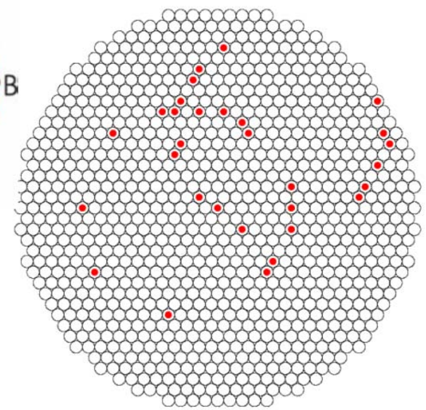
→ used in CBM

Two algorithms (Histogram and Almagest) adopted to running at a GPU farm for triggering in NA62

→ talk by M. Fiorini







Physics impact

- LHCb
- NA62
- ALICE
- Belle II
- PANDA
- GlueX and CLAS12

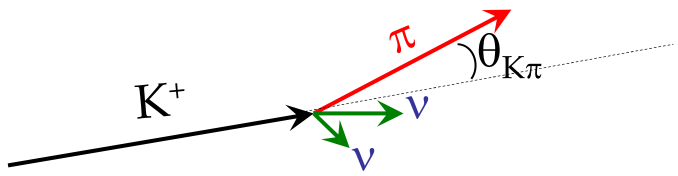
- Neutrino and astroparticle physics experiments: to be covered today and tomorrow

NA62 - Experimental principles

- Goal → 10% precision Branching Ratio measurement
- $O(100)$ $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ events in ~ three years of data taking

Very challenging experiment

Weak signal signature



$m^2_{miss} = (P_K - P_\pi)^2$

→ Statistics
- BR(SM) ~ 8.4 x 10^{-11}
- Acceptance: 10%
- K decays: 10^{13}

- Main background:

  $K^+ \rightarrow \mu^+ \nu$ ($K_{\mu 2}$) BR = 63.4%
- Rejection factor at least 10^{-12}
  - Kinematics : $10^{-4} \div 10^{-5}$
  - Veto for muons ~10^{-5}
  - Particle Identification:

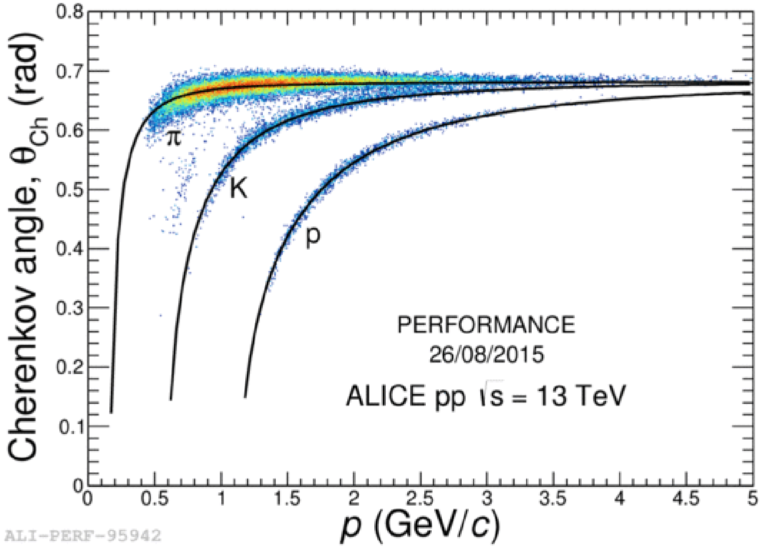
    μ suppression < 10^{-2} → **RICH**

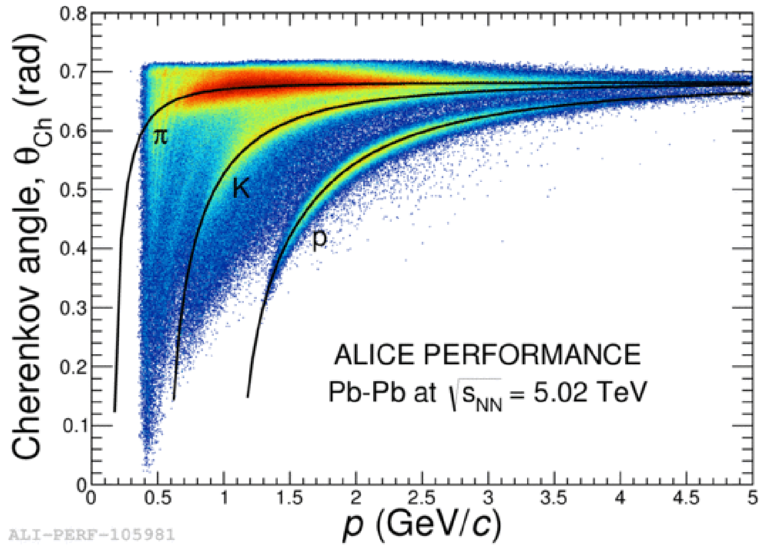
Huge background

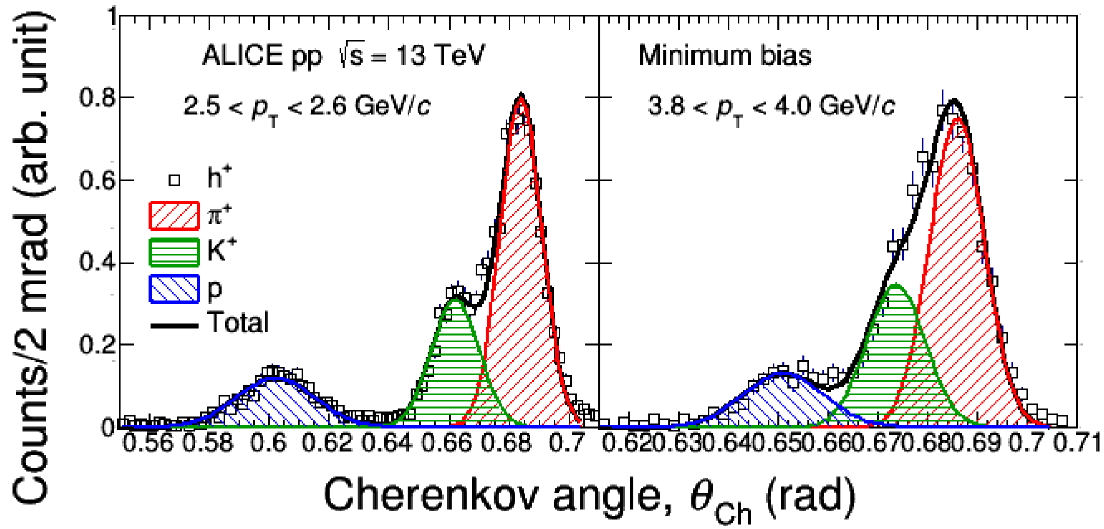
Decay	BR
$\mu^+\nu$ ($K_{\mu 2}$)	63.5%
$\pi^+\pi^0$ ($K_{\pi 2}$)	20.7%
$\pi^+\pi^+\pi^-$	5.6%
$\pi^0 e^+ \nu$ (K_{e3})	5.1%
$\pi^0 \mu^+ \nu$ ($K_{\mu 3}$)	3.3%

→ Talk by Giuseppina Anzivino

ALICE: PID performance on pp $\sqrt{s}$ =13 TeV and Pb-Pb $\sqrt{s_{NN}}$ =5.02 TeV







→ Talks by De Cataldo, G. Volpe

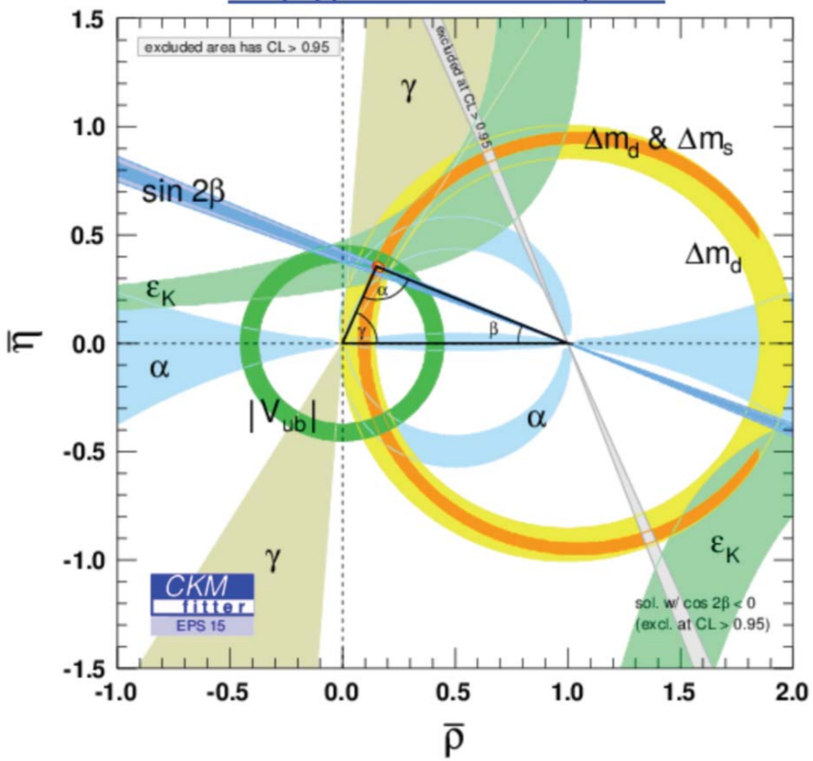
RICH detectors in LHCb

RICHes at LHCb are an absolutely vital part of the experiment.

Incredible harvest over the last few years, impossible to summarize all – so just a few examples, where RICHes are clearly indispensable

- Angle $\gamma \setminus \phi_3$
- Two-body charmless decays

http://ckmfitter.in2p3.fr



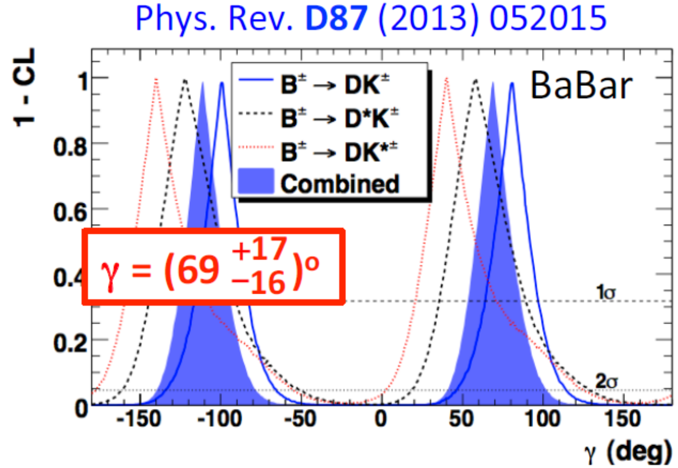
Experimental status for γ

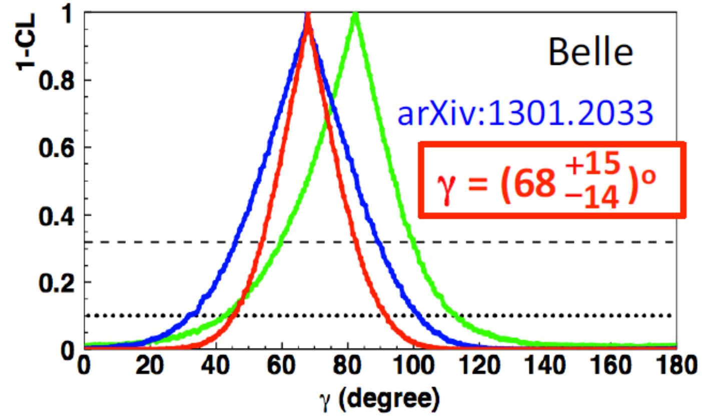
- New combination of all available measurements from LHCb

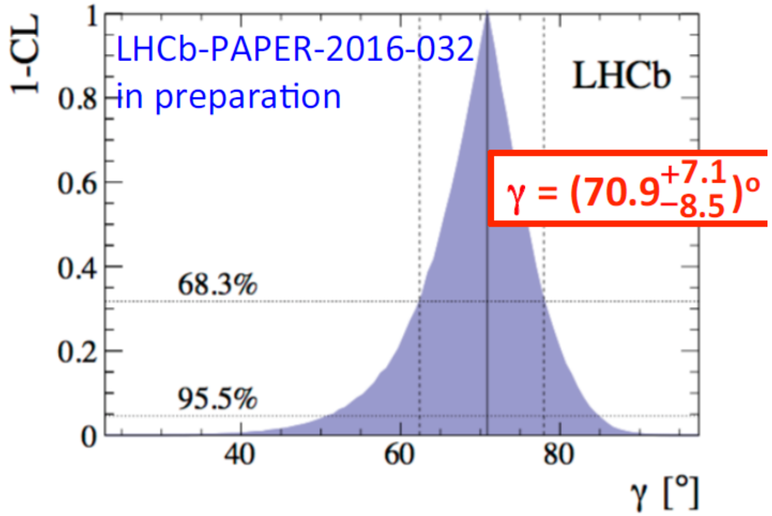
LHCb measurements used in the combination

B decay	D decay	Method
$B^+ \to Dh^+$	$D \to h^+h^-$	GLW/ADS
$B^+ \to Dh^+$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS
$B^+ \to Dh^+$	$D \to h^+h^-\pi^0$	GLW/ADS
$B^+ \to DK^+$	$D \to K^0_S h^+h^-$	GGSZ
$B^+ \to DK^+$	$D \to K^0_S K^+\pi^-$	GLS
$B^+ \to Dh^+\pi^-\pi^+$	$D \to h^+h^-$	GLW/ADS
$B^0 \to DK^{*0}$	$D \to K^+\pi^-$	ADS
$B^0 \to DK^+\pi^-$	$D \to h^+h^-$	GLW-Dalitz
$B^0 \to DK^{*0}$	$D \to K^0_S\pi^+\pi^-$	GGSZ
$B^0_s \to D^\mp_s K^\pm$	$D^+_s \to h^+h^-\pi^+$	TD

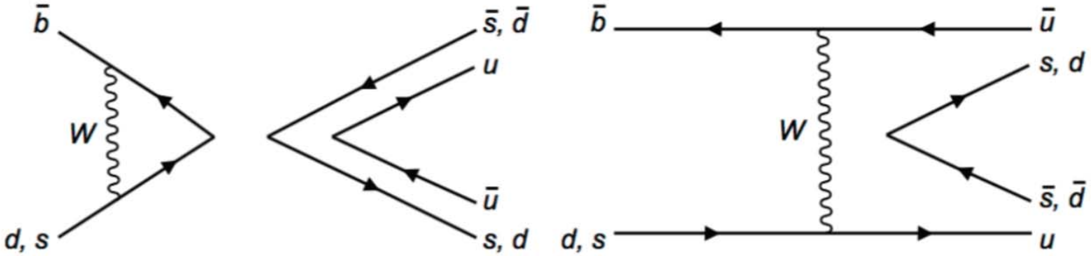
- Significantly more precise than previous results from the *B*-factories and the Tevatron

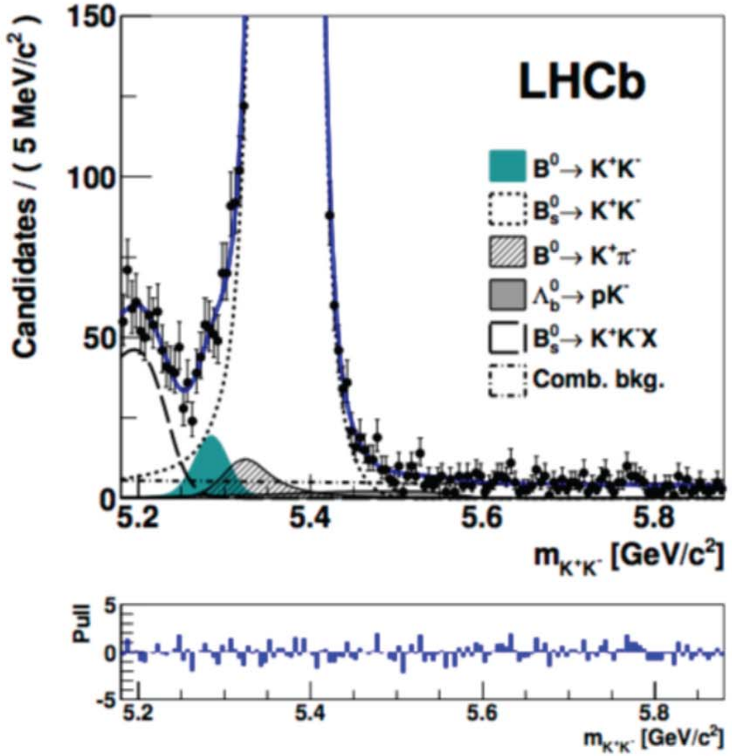






Charmless two-body B decays





- Particular class of decays that can proceed only through so-called annihilation diagrams
  - Very useful to test QCD calculations
- $B^0 \to K^+K^-$ decay observed for the first time after many years of searches
  - Significance 5.8σ

$$\mathcal{B}(B^0 \to K^+K^-) = (7.80 \pm 1.27 \pm 0.81 \pm 0.21) \times 10^{-8},$$
$$\mathcal{B}(B_s^0 \to \pi^+\pi^-) = (6.91 \pm 0.54 \pm 0.63 \pm 0.19 \pm 0.40) \times 10^{-7}$$

V. Vagnoni at ICHEP 2016.

- The $B^0 \to K^+K^-$ is the rarest B-meson decay into a fully hadronic final state ever observed

LHCb-PAPER-2016-036 in preparation

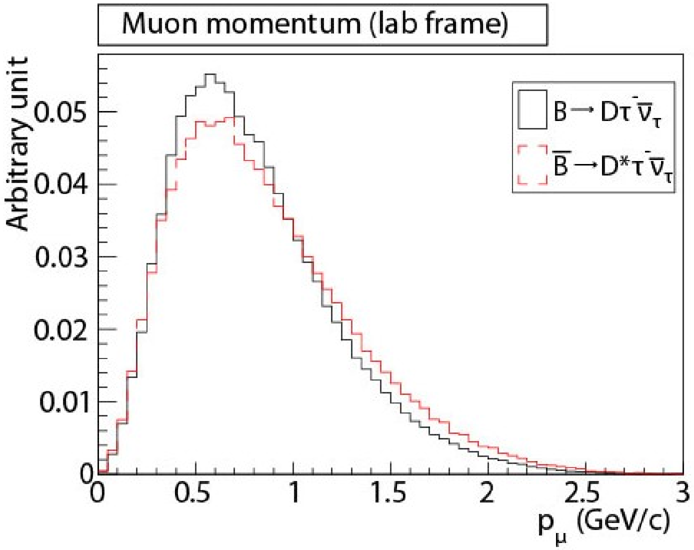
RICHes at Belle II

Again, without RICHes there is very little you can do in Belle II.

Most important: of course the pion-kaon separation up to 4 GeV/c to cover

- Few body charmless decays
- Measure $B \rightarrow \rho\,\gamma$ and discriminate it against $B \rightarrow K^*\,\gamma$
- Identify tagging kaons
- Identify low momentum muons and electrons

Hot topic: $B \rightarrow D^{(*)}\tau\nu$ decays

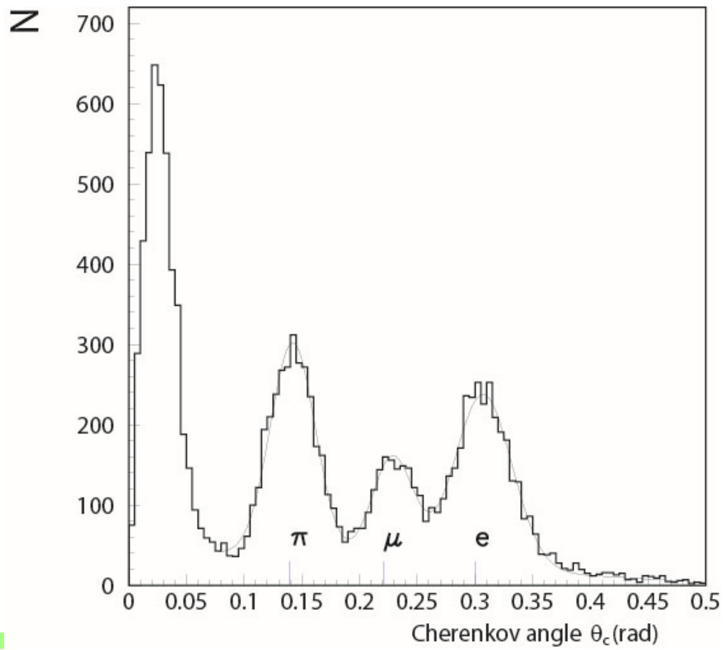


…where $\tau \rightarrow \mu\nu\nu$

→ At Belle II, a sizable fraction of muons is soft, not covered by the muon detection system

→ Identify them in a Cherenkov counter, π/μ Cher. angle difference at 0.5 GeV/c is similar as for K/π at 3 GeV/c

Example: single Cher. photons from π, μ, e in the aerogel RICH at a 0.5 GeV/c test beam; better for full rings →



Muon identification performance in a B factory / Super B factory

Standard method: RPCs in the return yoke, efficient for p > 0.7 GeV/c

efficiency

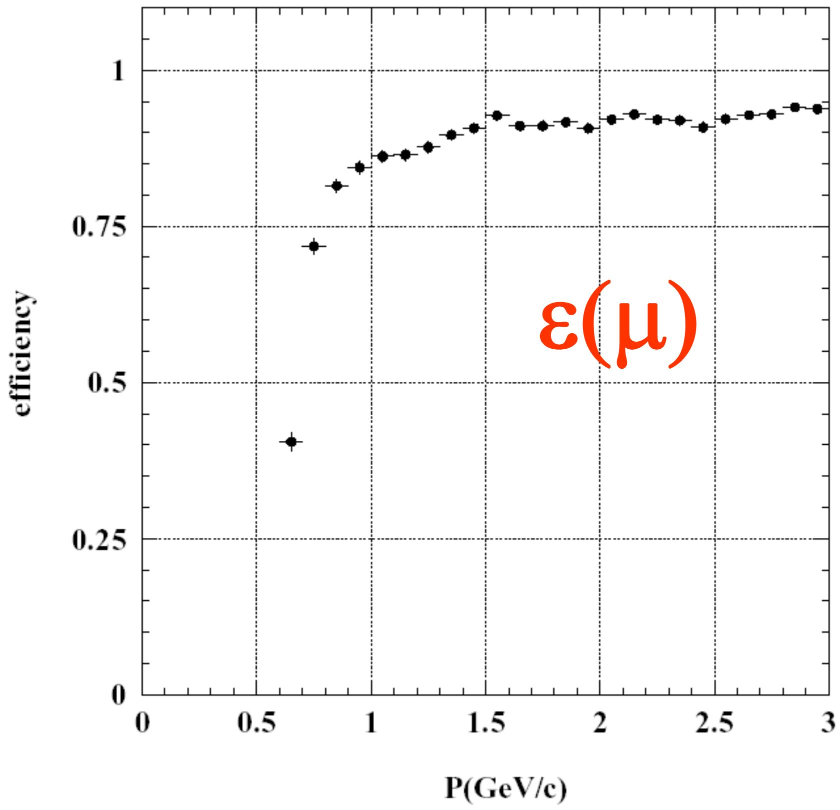


Fig. 109. Muon detection efficiency vs. momentum in KLM.

fake probability

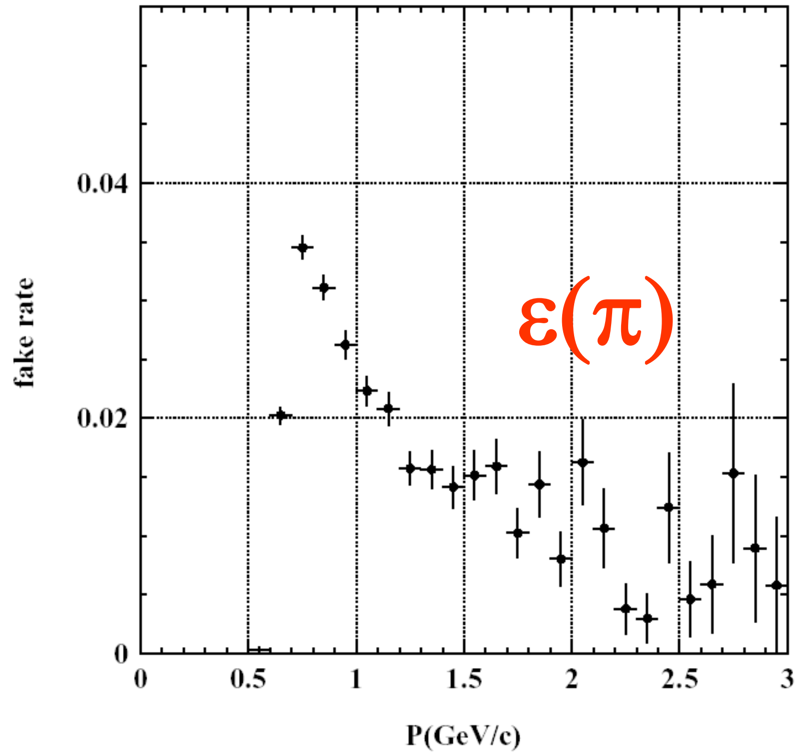


Fig. 110. Fake rate vs. momentum in KLM.

PANDA: two DIRC detectors for hadronic PID

- Barrel DIRC

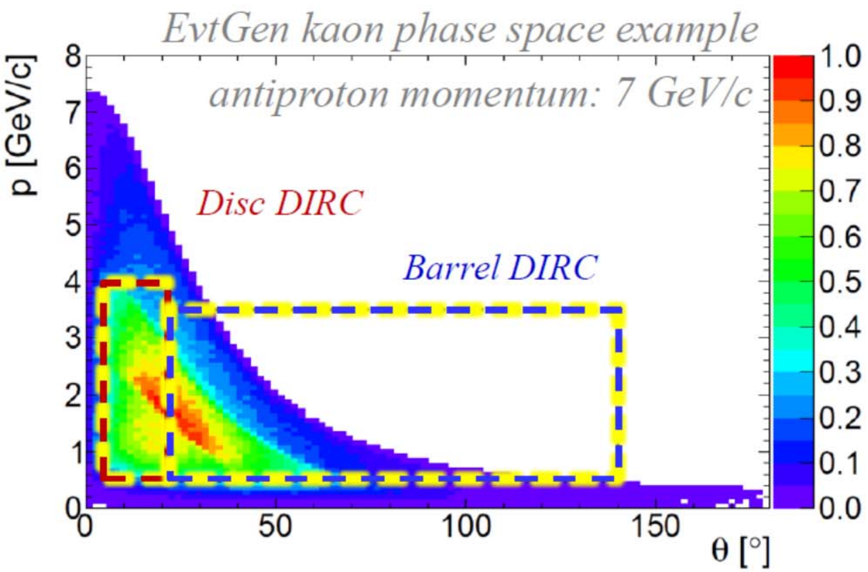
  German in-kind contribution to PANDA

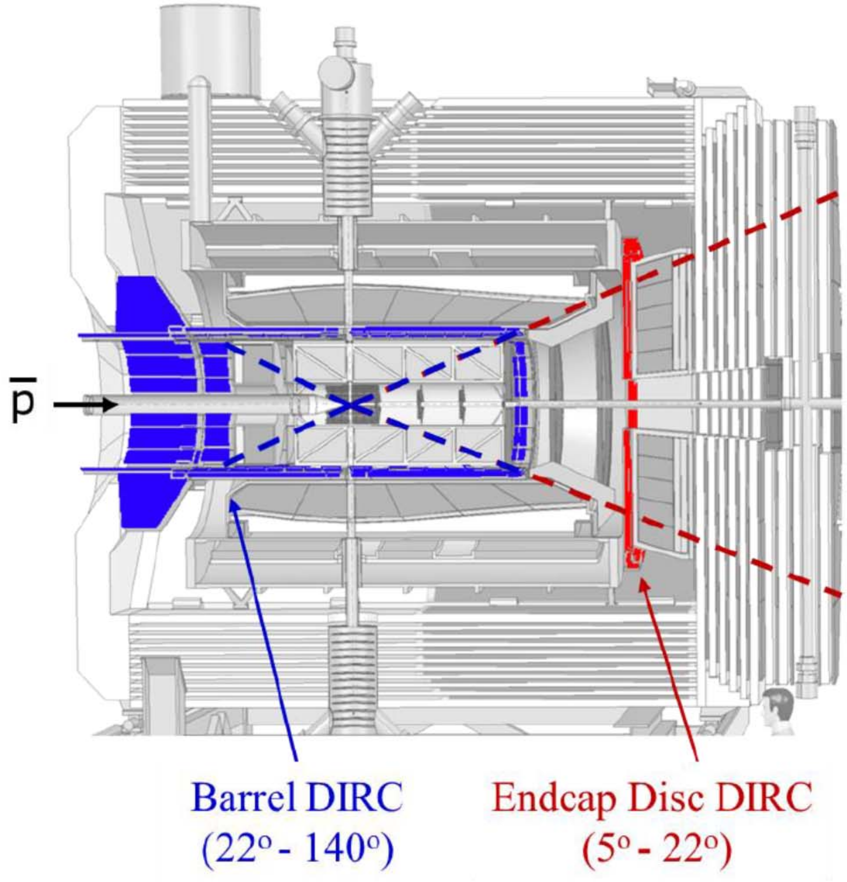
  Goal: 3 s.d. π/K separation up to 3.5 GeV/c

- Endcap Disc DIRC

  ➤ M. Dueren, Mon 16:45

  Goal: 4 s.d. π/K separation up to 4 GeV/c

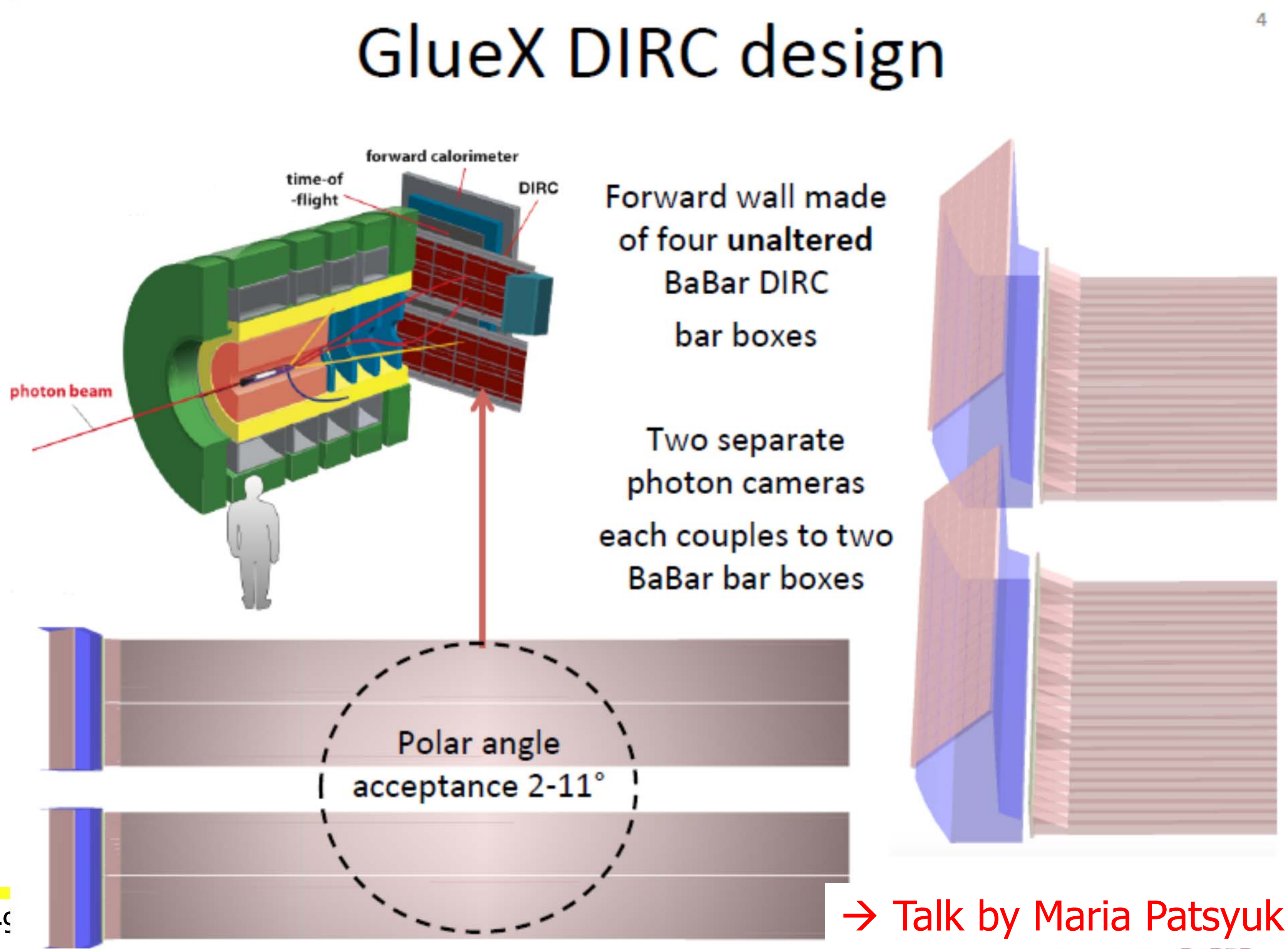




PANDA is back on track;
installation to start in 2021.

→ Talk by J. Schwiening

GlueX: complement TOF from 2 GeV/c up to 4 GeV/c



→ Talk by Maria Patsyuk

Summary

Particle identification is an essential part of several experiments, and has contributed substantially to our present understanding of elementary particles and their interactions, and will continue to have an important impact in searches for new physics.

A large variety of Cherenkov radiation based techniques has been developed for different kinematic regions and different particles.

Novel analysis methods are becoming available, and are expected to further boost the performance of Cherenkov radiation based detectors.

We are looking forward to hearing more about the progress and impact of Chernkov detection methods in neutrino and astroparticle physics experiments in the coming two days.