Particle ID in Belle II
ARICH and TOP

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Spring B2SKW, KEK
06/26/2019

What to Expect

- What is Particle Identification?
- Techniques for charged particle identification
- Dedicated charged PID subdetectors in Belle II
  - ARICH
  - TOP

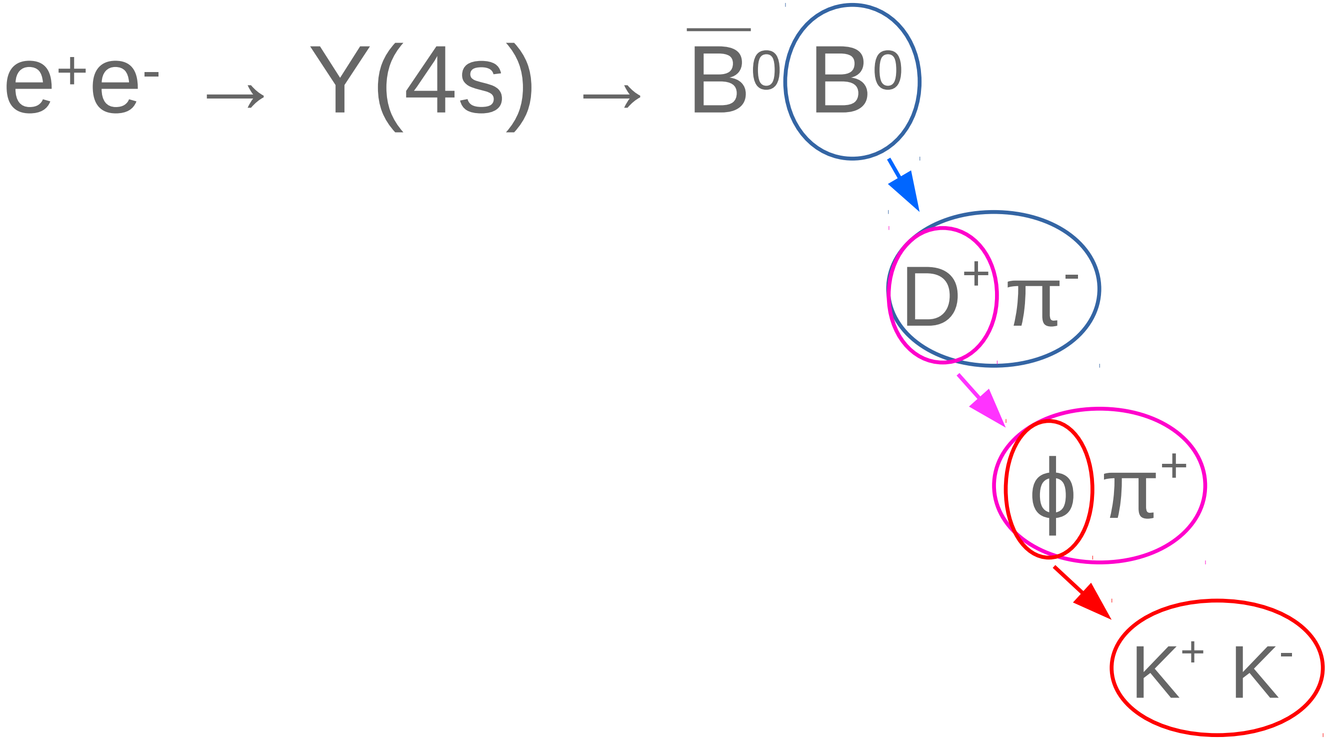
- Heavily borrowing from the excellent lectures by Umberto Tamponi

Recap: Particle Detection

- PDG: thousands of known particles and their various decays
- But in detectors: $e^{\pm}$, $\mu^{\pm}$, γ, $\pi^{\pm}$, $K^{\pm}$, K_L^0 , $p^{\pm}$, n, (ν)
  - Charged particles: **momentum** from bending radius in B-field
    → light "tracking" detectors (non-destructive measurements)
  - Kinetic **energy** from stopping particles in material
    → heavy "calorimeters" (destructive measurement)
- What else can we measure?

Why Particle Identification?

- In flavour physics, we are often interested in reconstructing the whole decay chain of a specific event
  - Aim to reconstruct all final state particles: identify species



$e^+e^- \rightarrow Y(4s) \rightarrow \overline{B}{}^0 B^0$

$D^+ \pi^-$

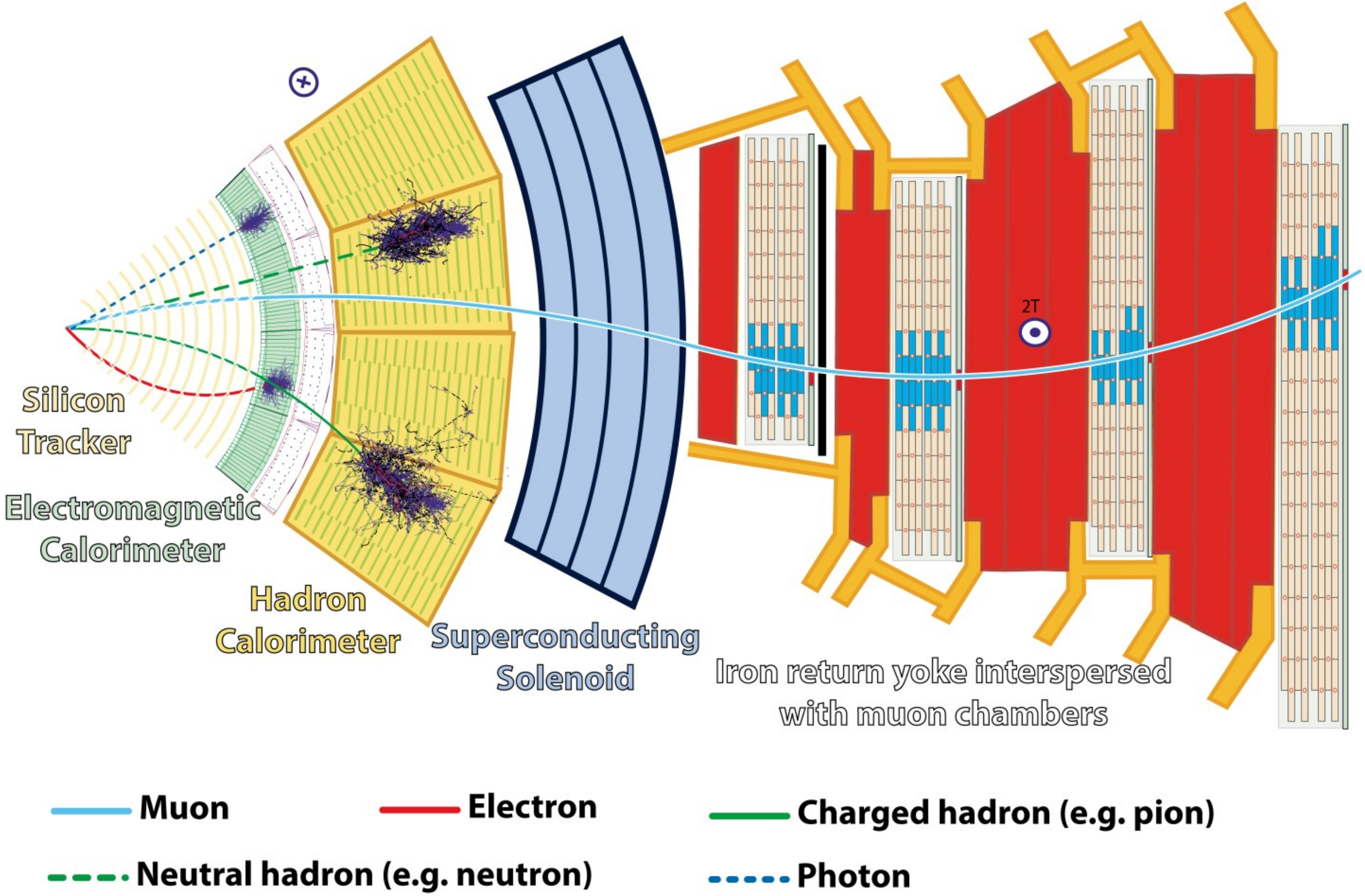
$\phi \pi^+$

$K^+ K^-$

Particle Identification

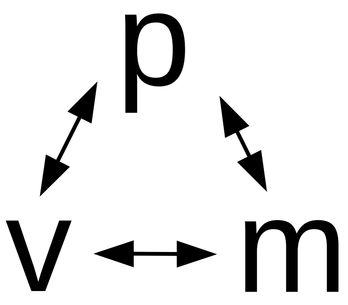
- Some final state particles are easily identified by “unique” behaviour
  - Photons, Electrons (see M. Milesi’s talk)
  - High-momentum muons (p>GeV) (see A. Martini’s talk)
- Some behave very similarly
  - Charged hadrons, low-momentum muons
  - Neutral hadro ns
- The goal is always to construct a **likelihood** for a detected particle being of a given species.
  - Likelihoods of various detectors can be combined into a global PID likelihood (see U. Tamponi’s talk)

Particle Behaviour



Distinguishing Charged Hadrons

- Particle identification == measuring a particle's rest mass
  - $\pi^\pm$: 140MeV
  - $K^\pm$: 494MeV
  - $p^\pm$: 938MeV
  - $\mu^\pm$: 106MeV
- Momentum is known already
  - Do we have a handle on the particle velocity?



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

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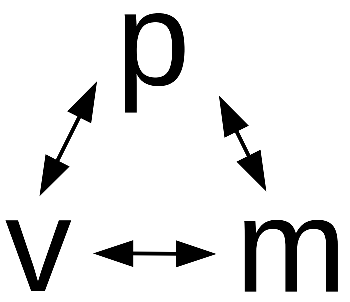
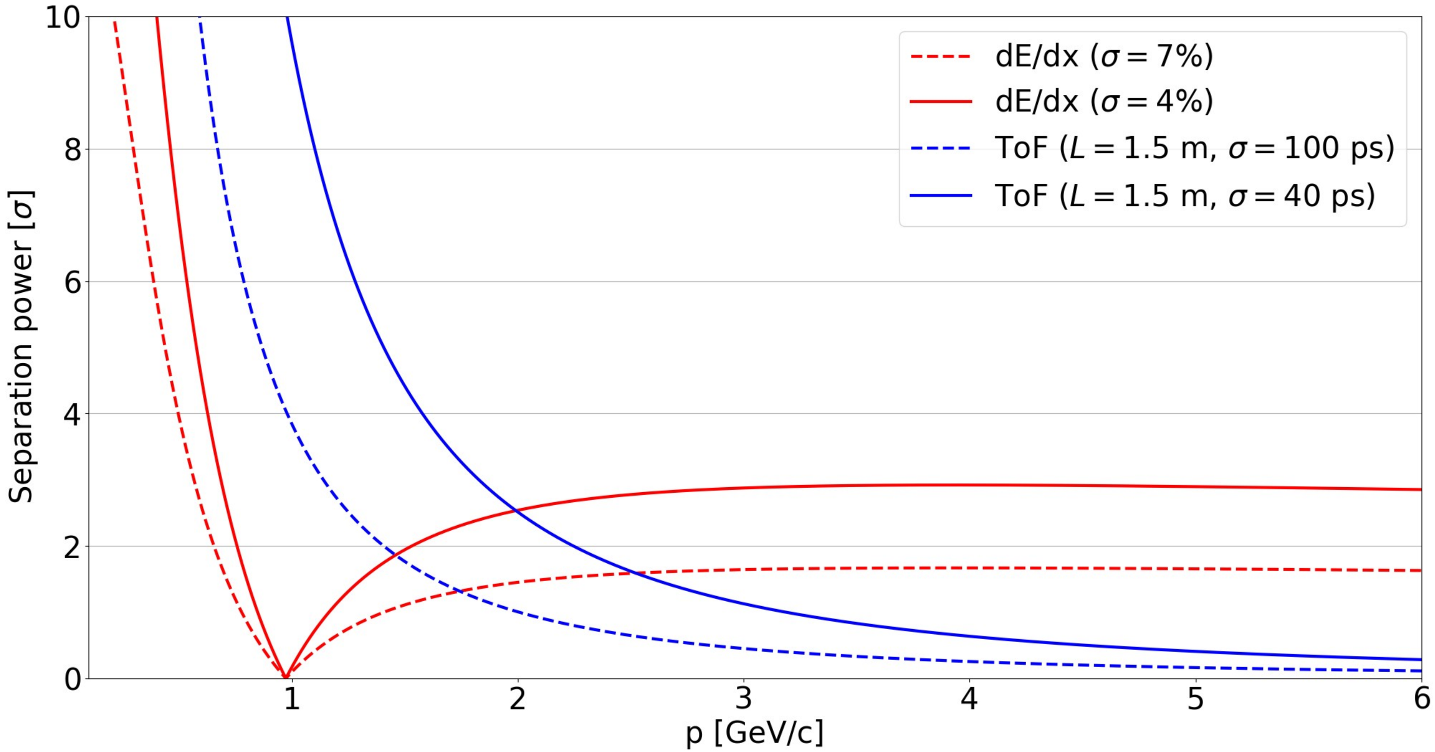


$$\beta\gamma = \frac{p}{m}$$

- Specific energy loss: dE/dx
- Time of flight (ToF)
- Cherenkov techniques

K/π Separation: dE/dx and ToF

- dE/dx resolution limited by fundamental physics
- ToF depends on detector time resolution and lever arm
- Clearly need something else for higher momenta

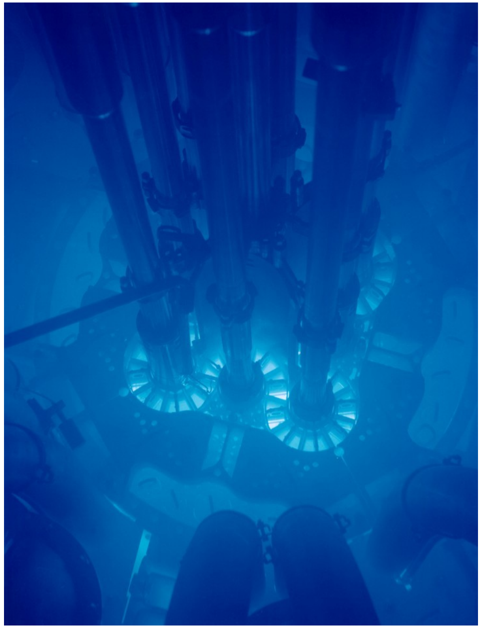


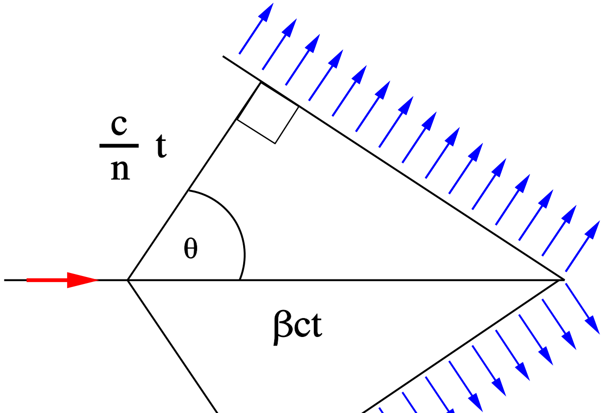
Cherenkov Radiation: Basics

- Charged particle moving through a dielectric medium with velocity > the propagation speed of light in the medium will radiate photons along the way
  - Velocity threshold effect
  - (n.b.: Interestingly, this is radiation from constant motion)
- Photons are emitted at a fixed angle depending on refractive index n and particle velocity v:

$$\cos(\theta) = \frac{c'}{v} = \frac{1}{n\beta}$$

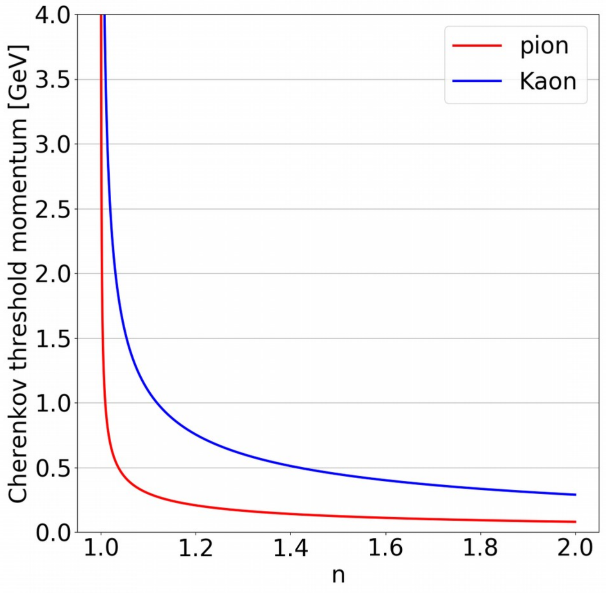
- Emission spectrum is ~1/E: mostly in optical range

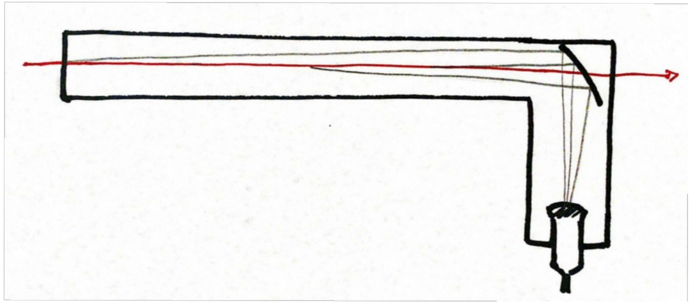




Cherenkov: Threshold Counters

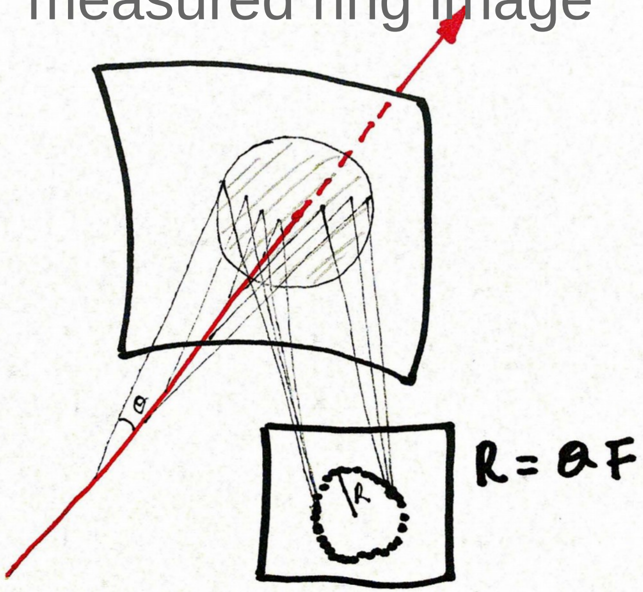
- Free choice of radiator medium
  (just needs to be transparent, non-scintillating, dielectric):
  - Gases (easily adjust n with pressure)
  - Aerogels, Crystals
- Simple decision: Cherenkov photons detected or not?
  - Not using angular information
- Simple detector design:
  - Volume of radiator medium
  - Single photo detector
  - (Mirror)

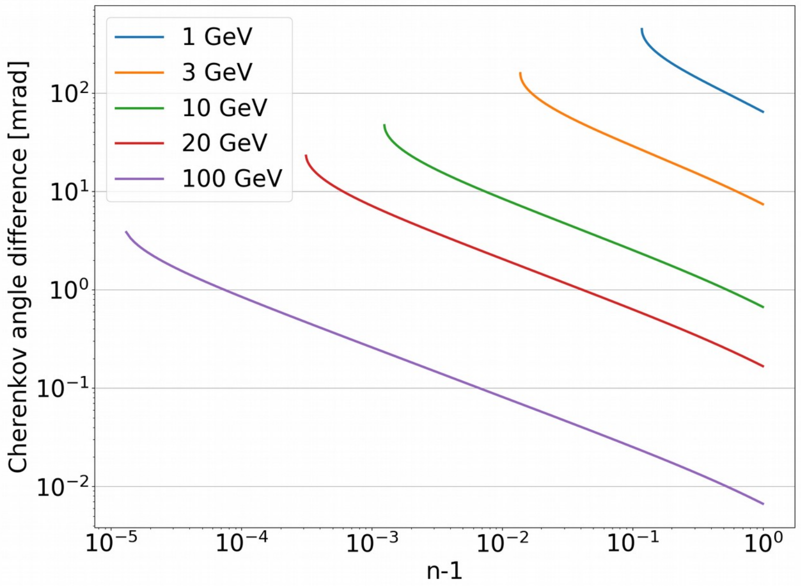




Ring Imaging Cherenkov (RICH)

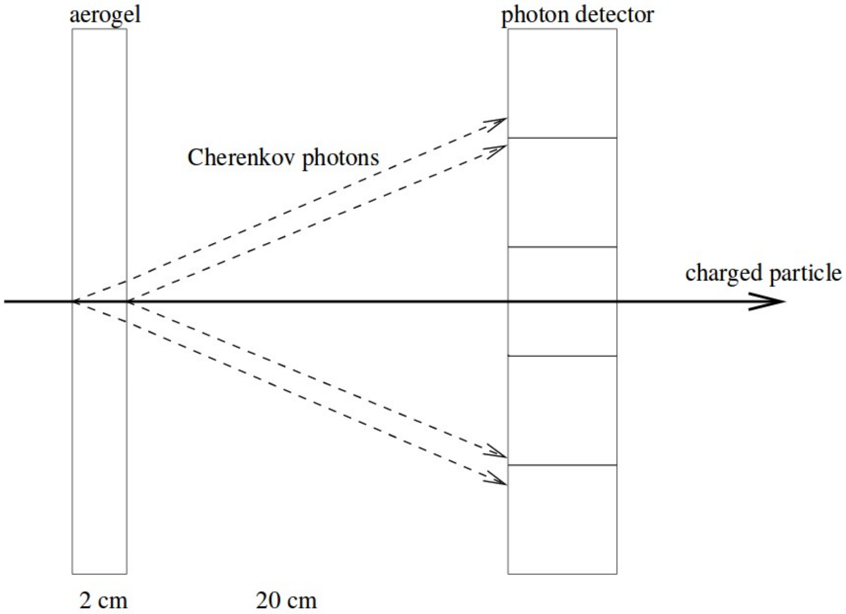
- Disc of Cherenkov photons becomes a ring after focusing
  - Radius of projected Cherenkov ring is a direct measure of the Cherenkov opening angle and thus particle velocity
- Now need imaging readout (many PMTs, pixelated detectors)
  - Reconstruction now depends angular resolution on the measured ring image



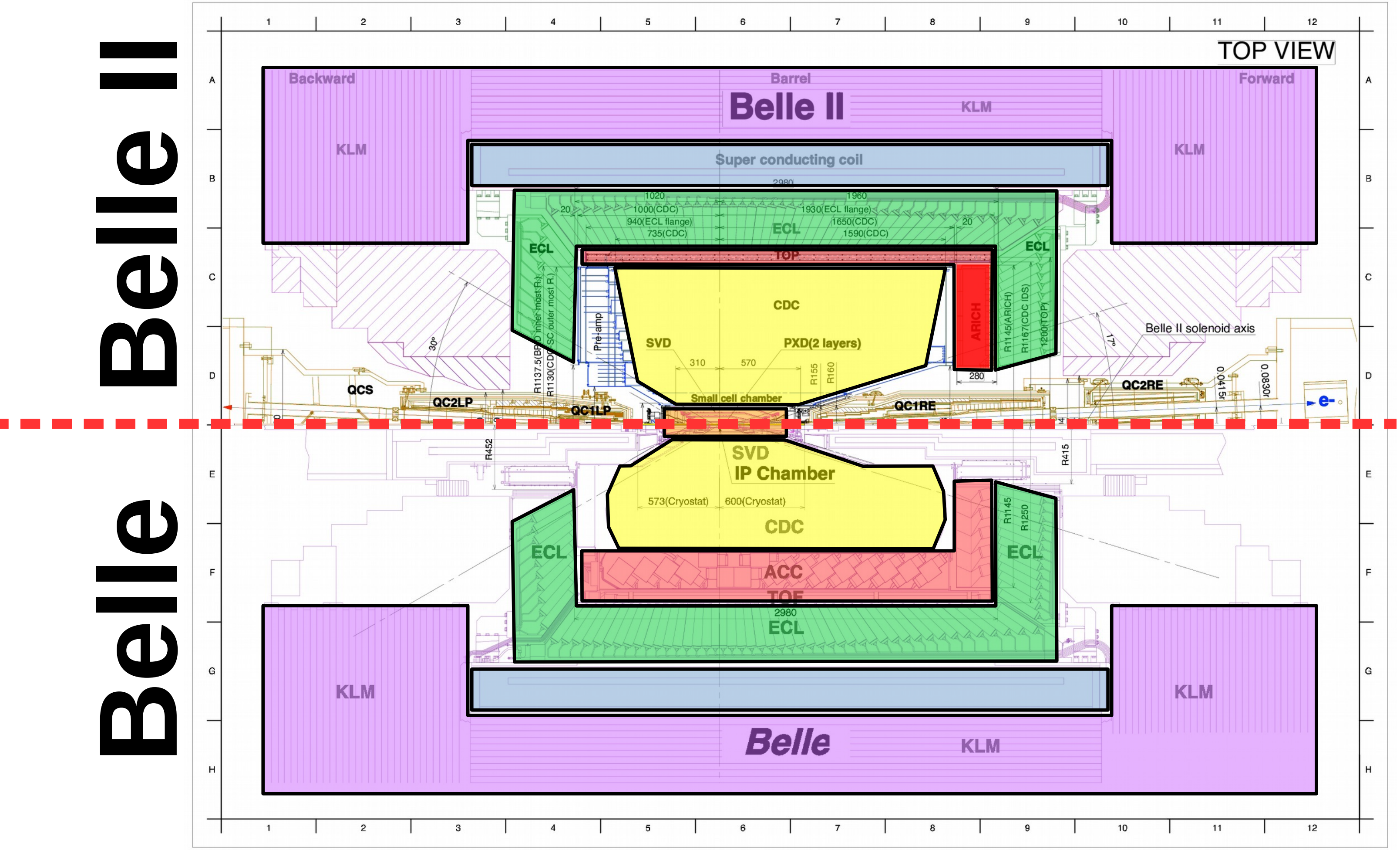


RICH: Proximity Focusing

- Gas RICH not suited for 4π detectors (especially barrel region), how can we make this smaller?
  - B-factories: momentum range <5GeV
- Don’t need a focusing mirror if radiator is thin enough
  - Needs more light yield, larger opening angle → higher n radiator → Aerogel
- Drawbacks:
  - Rings can get distorted into ellipses depending on track angle
  - Radiator thickness adds on to angular resolution



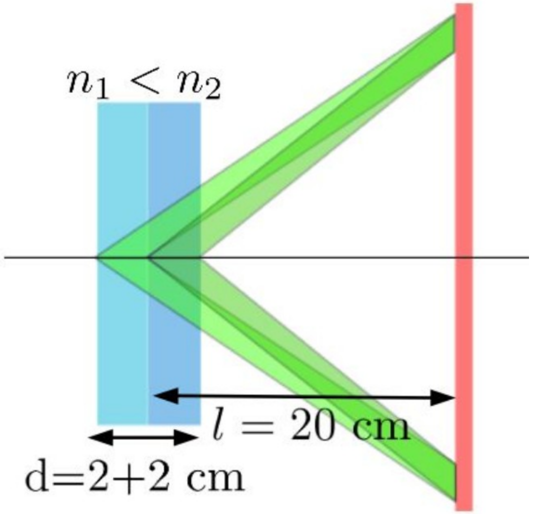
ARICH: Belle II Endcap PID

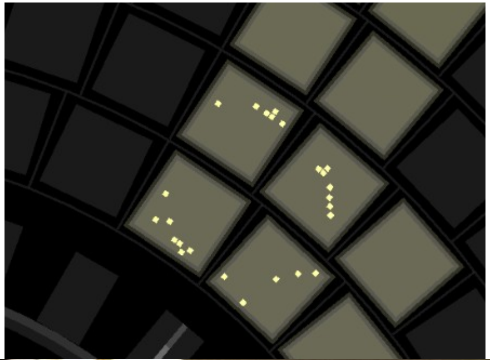


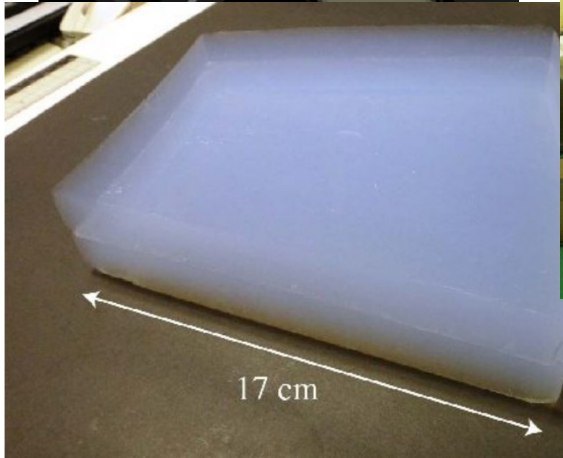
- 🟪 K_L/Muon System
- 🟦 Magnet Coil
- 🟩 EM Calorimeter
- 🟥 π/K Identification
- 🟨 Drift Chamber
- 🟧 Silicon Tracking

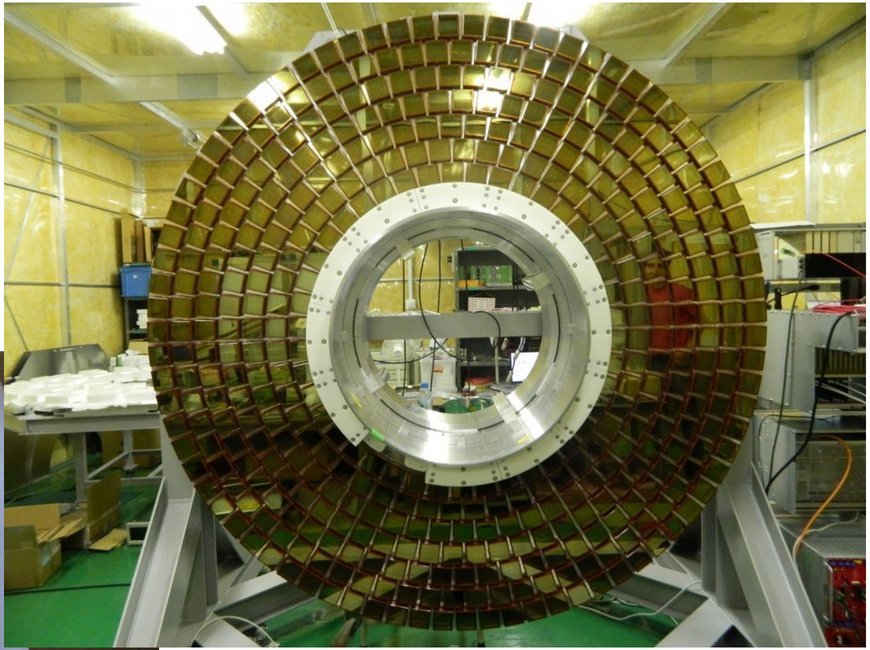
ARICH: Belle II Endcap PID

- Special trick: use two stacked layers of Aerogel with slightly different n to double the lightyield
- Large single photon sensitive are with ~mm spatial resolution: Hybrid APD sensors



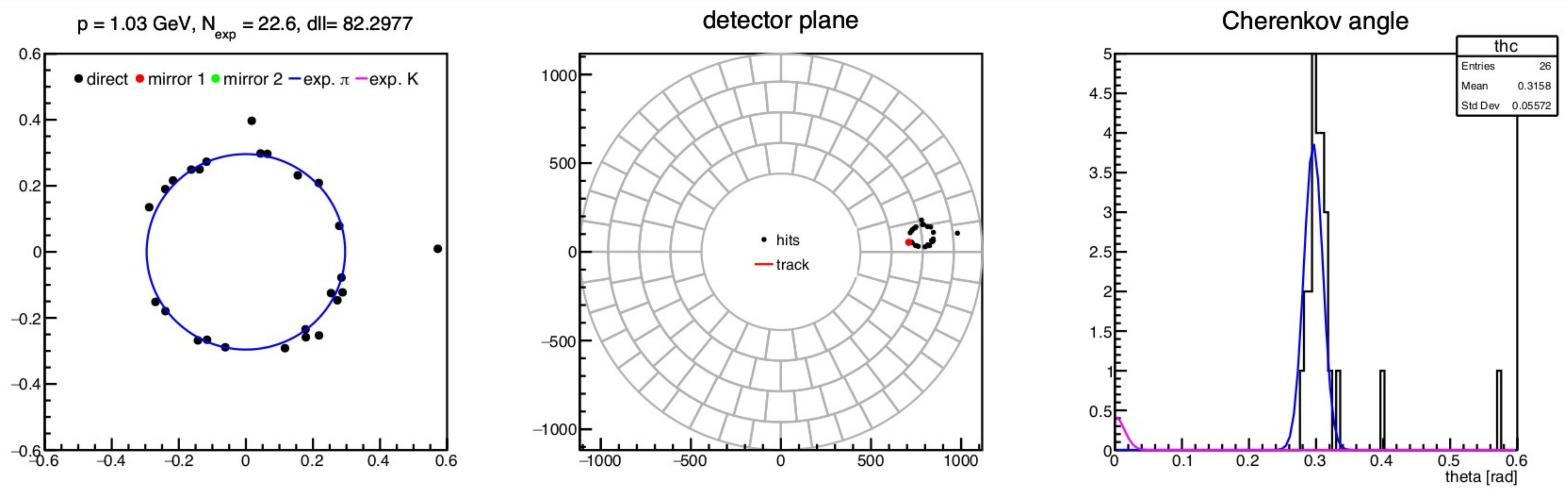






ARICH: Ring Image p=1.03GeV

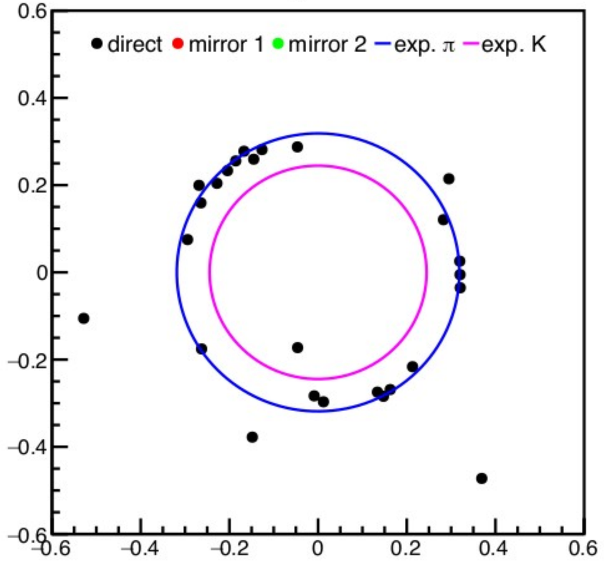
- Cherenkov threshold effect: Kaon would not radiate at all



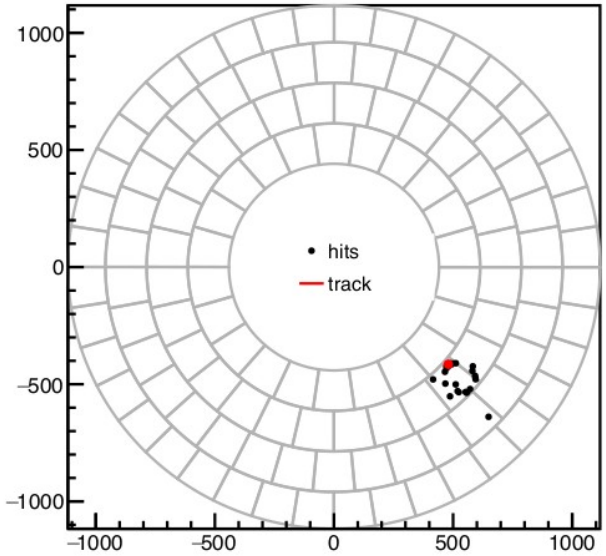
ARICH: Ring Image p=2.26GeV

- Large difference in Cherenkov angles → easy PID

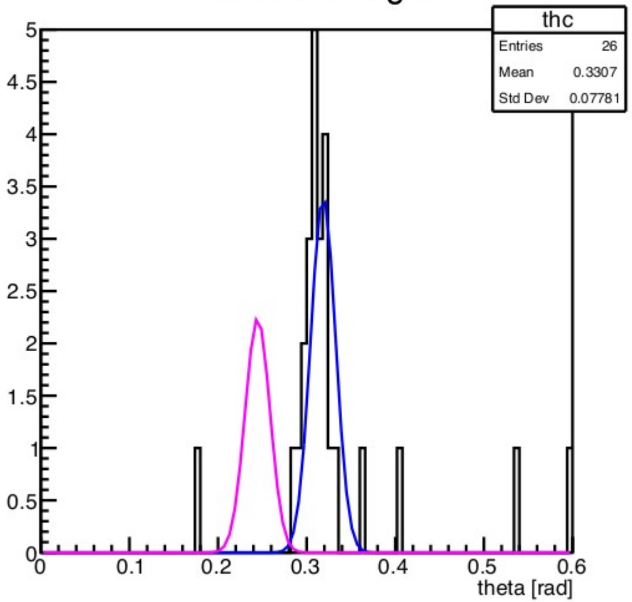
p = 2.26 GeV, N_{exp} = 19.9, dll= 56.7993



detector plane

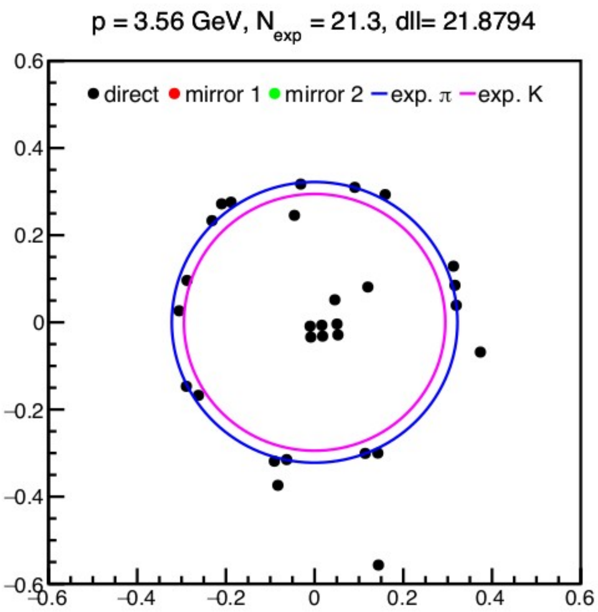


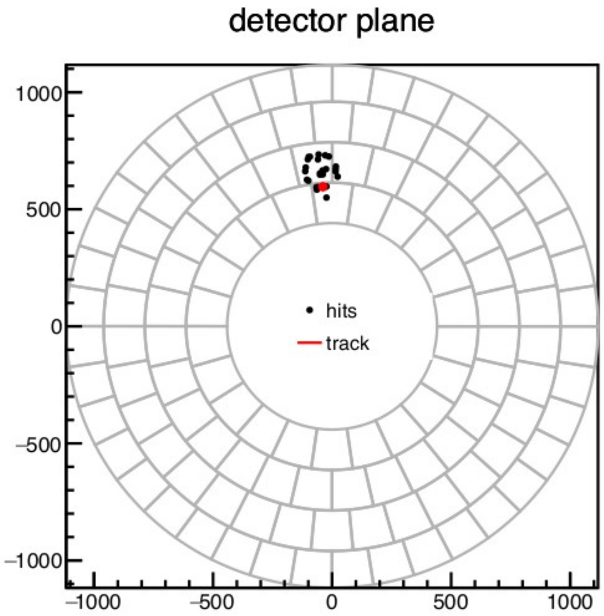
Cherenkov angle

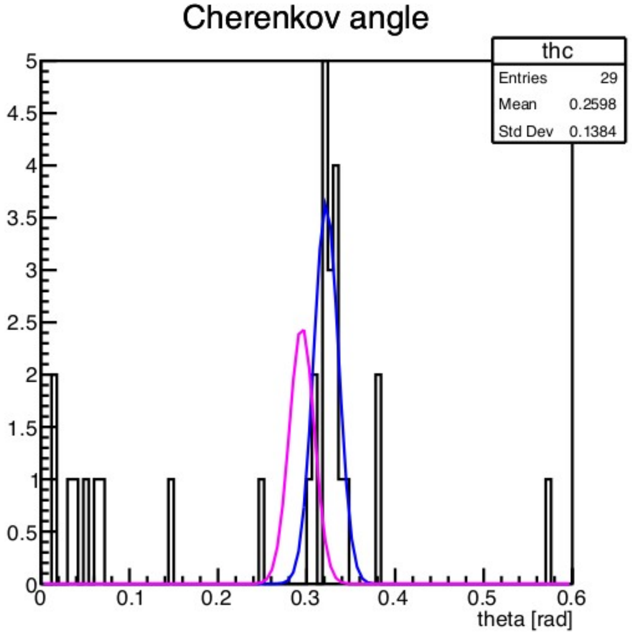


ARICH: Ring Image p=3.56GeV

- Not so easy anymore. Clearly more likely a pion than a Kaon, but how much exactly likely?

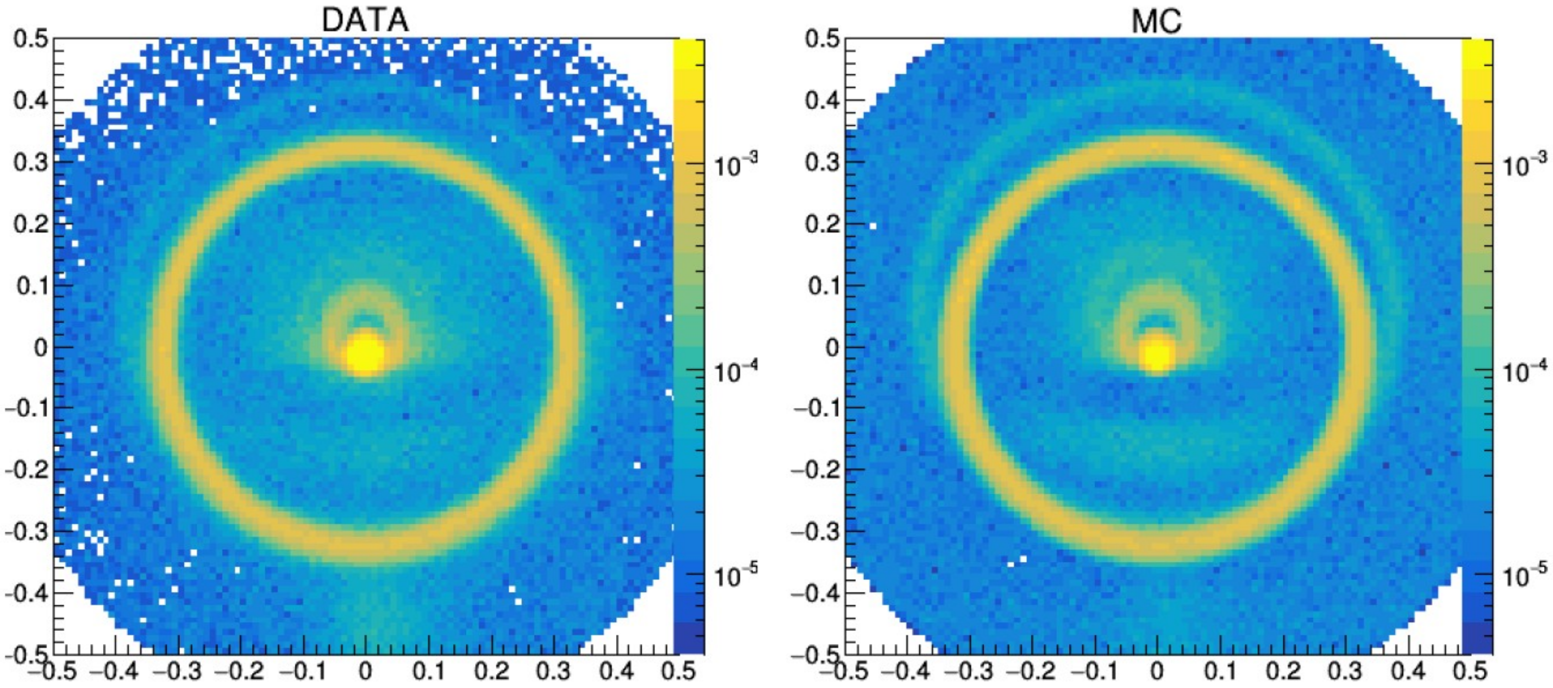






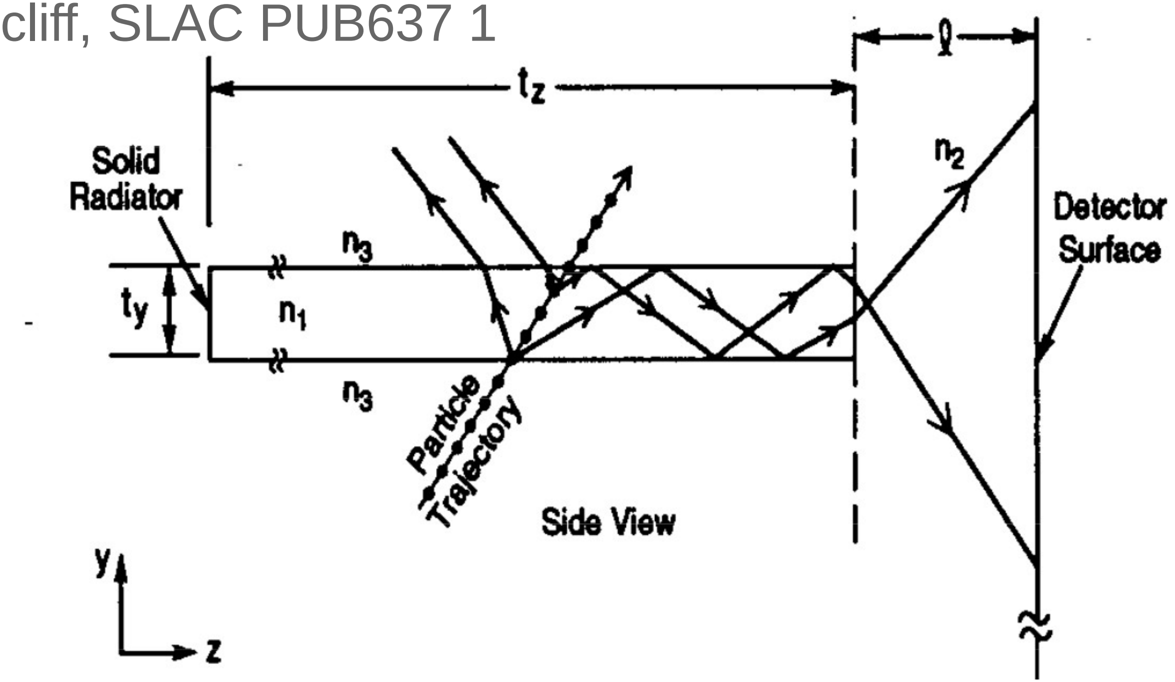
ARICH: Ring Image Likelihood

- Reconstruction not actually based on fitting the Cherenkov ring
- For each track, analytically construct a pdf of expected detected photon positions for each possible particle species
- Evaluate pdf at position of each detected photon: **likelihood** for each particle hypothesis



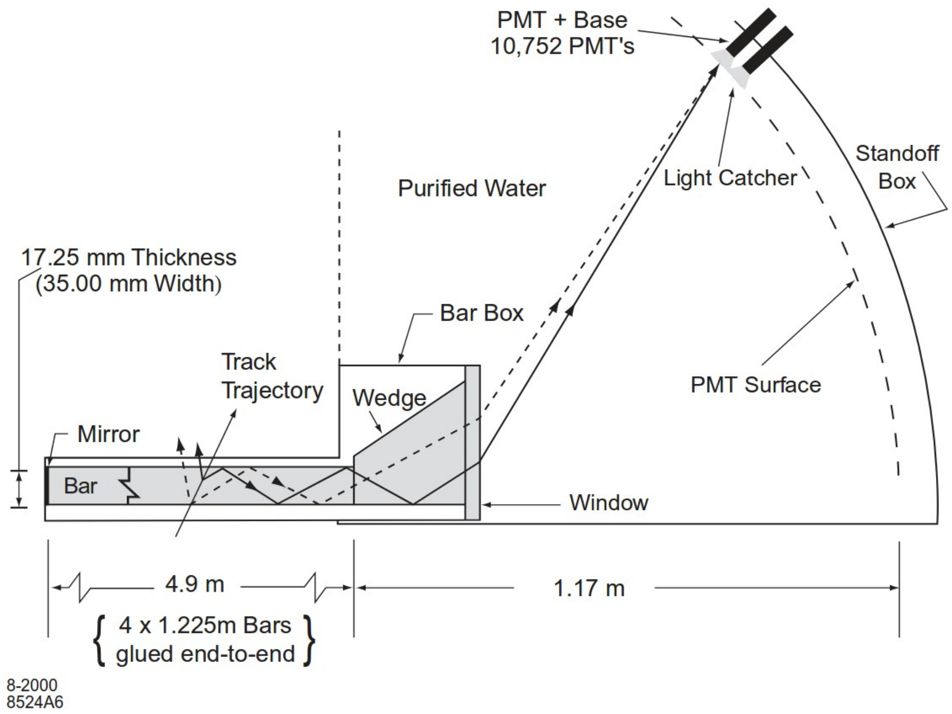
Go thinner than RICH: DIRC

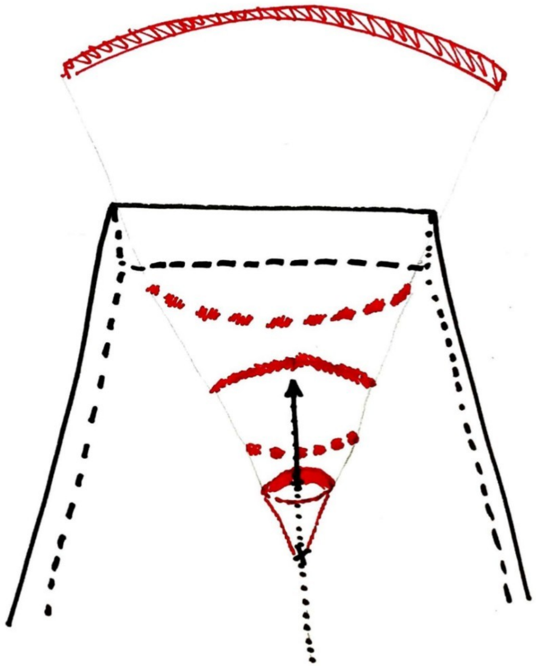
- How can we go even thinner? Capture Cherenkov photons inside of the radiator and use it as a light guide.
  - Angular information is preserved in total internal reflection
  - Needs high-n radiator (quartz) surrounded by low-n gas
- “Detector of Internally Reflected Cherenkov Light”: DIRC
  - B. Ratcliff, SLAC PUB637 1



DIRC: Realisation

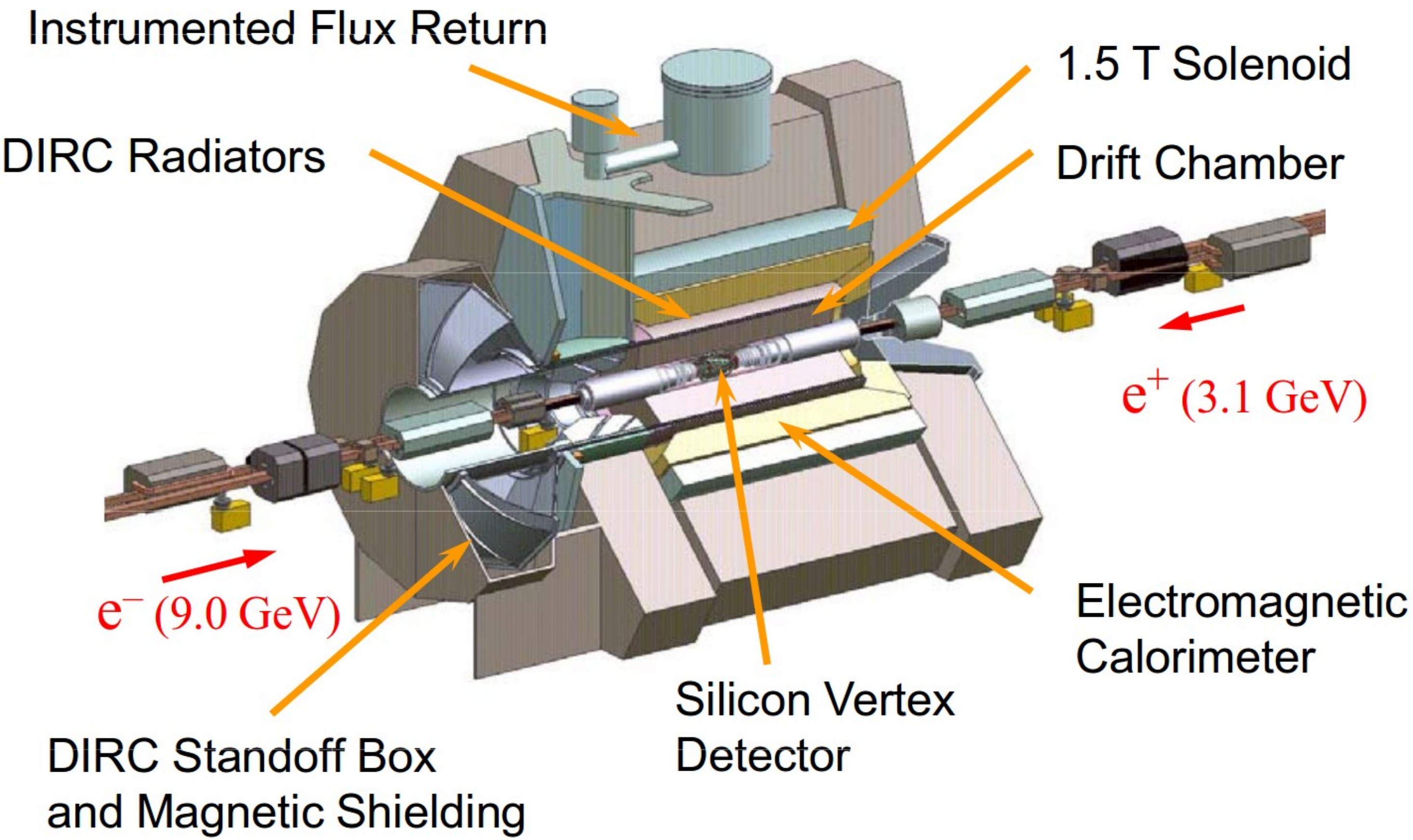
- Light guide allows to move photo sensors out of the detector barrel region
  - Quartz bar thickness is limited by minimum lightyield
- DIRC produces arcs (segments of conic sections) instead of rings
  - Arc thickness from quartz bar thickness
  - Ambiguities and reflections in the projected image can be solved in reconstruction





DIRC in BaBar

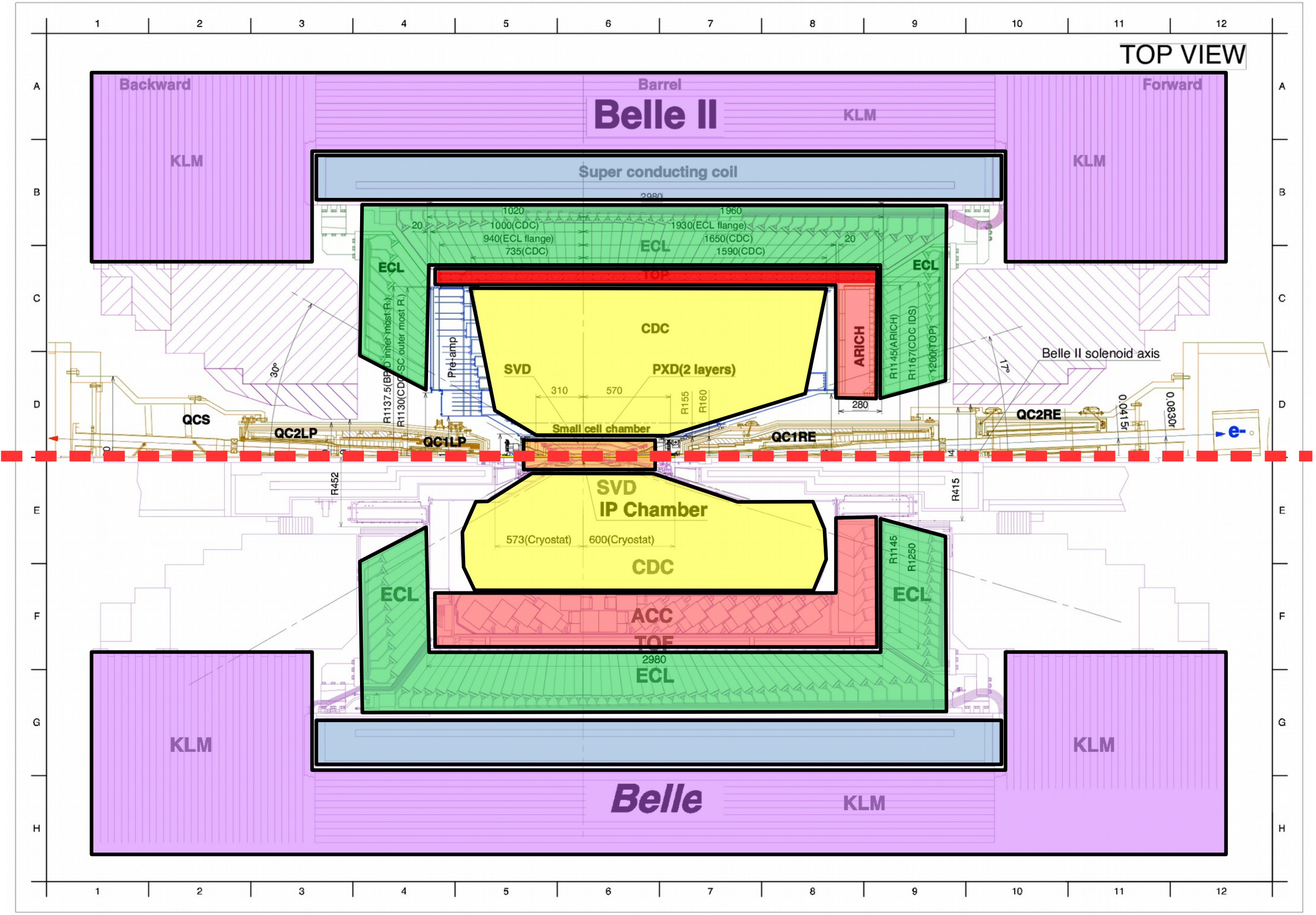
- Only DIRC ever built
  - Brilliant approach for B-factory requirements, but SOB needs a lot of space



TOP: Belle II Barrel PID

Belle II

Belle



K_L/Muon System

Magnet Coil

EM Calorimeter

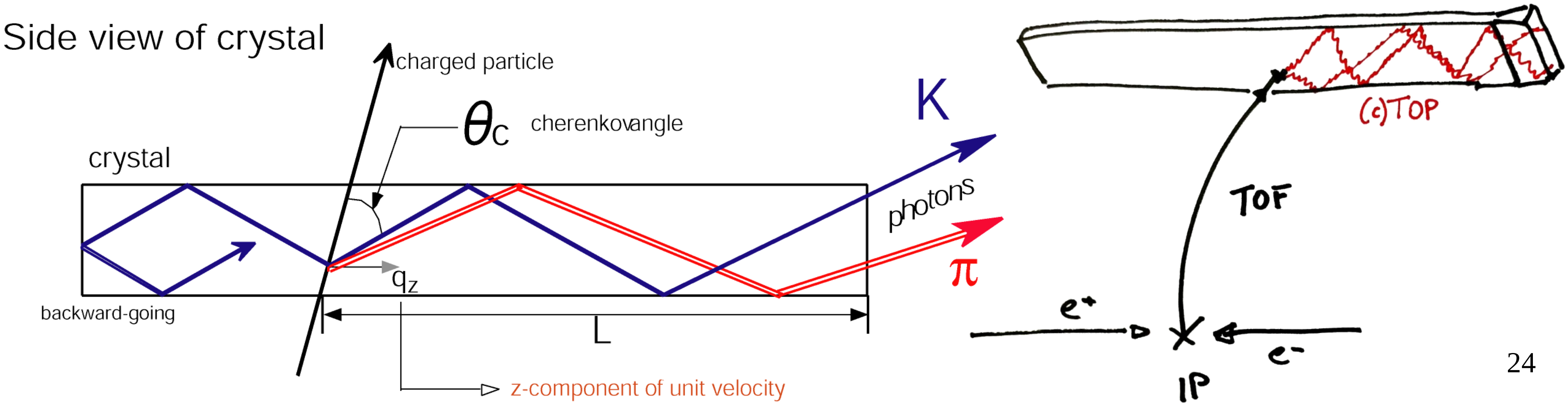
π/K Identification

Drift Chamber

Silicon Tracking

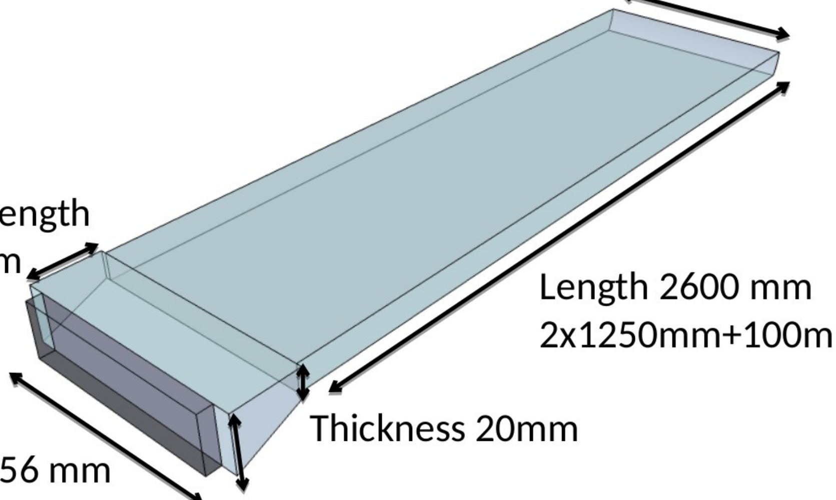
The “Time of Propagation” (TOP) Detector I

- Can we save space if we add timing to the DIRC concept?
- Instead of reconstructing the full ring image, measure time of propagation (path length) of individual Cherenkov photons.
  - Since collision timing is well known, measure ToF at the same time



The “Time of Propagation” (TOP) Detector II

- 16 quartz Cherenkov radiator bars arranged around IP
- Forward side: spherical mirror
- Backward side: small expansion prism, sensors, readout electronics



Bar/mirror width
450 mm

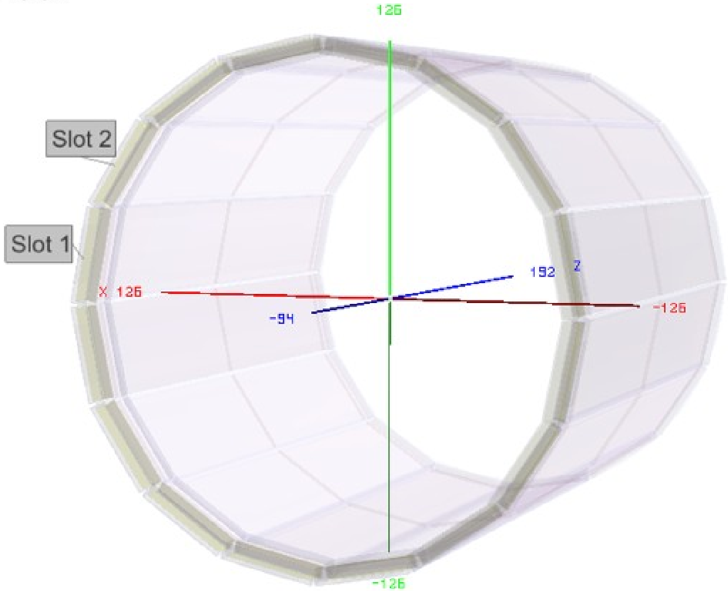
Prism length
100 mm

Length 2600 mm
2x1250mm+100mm

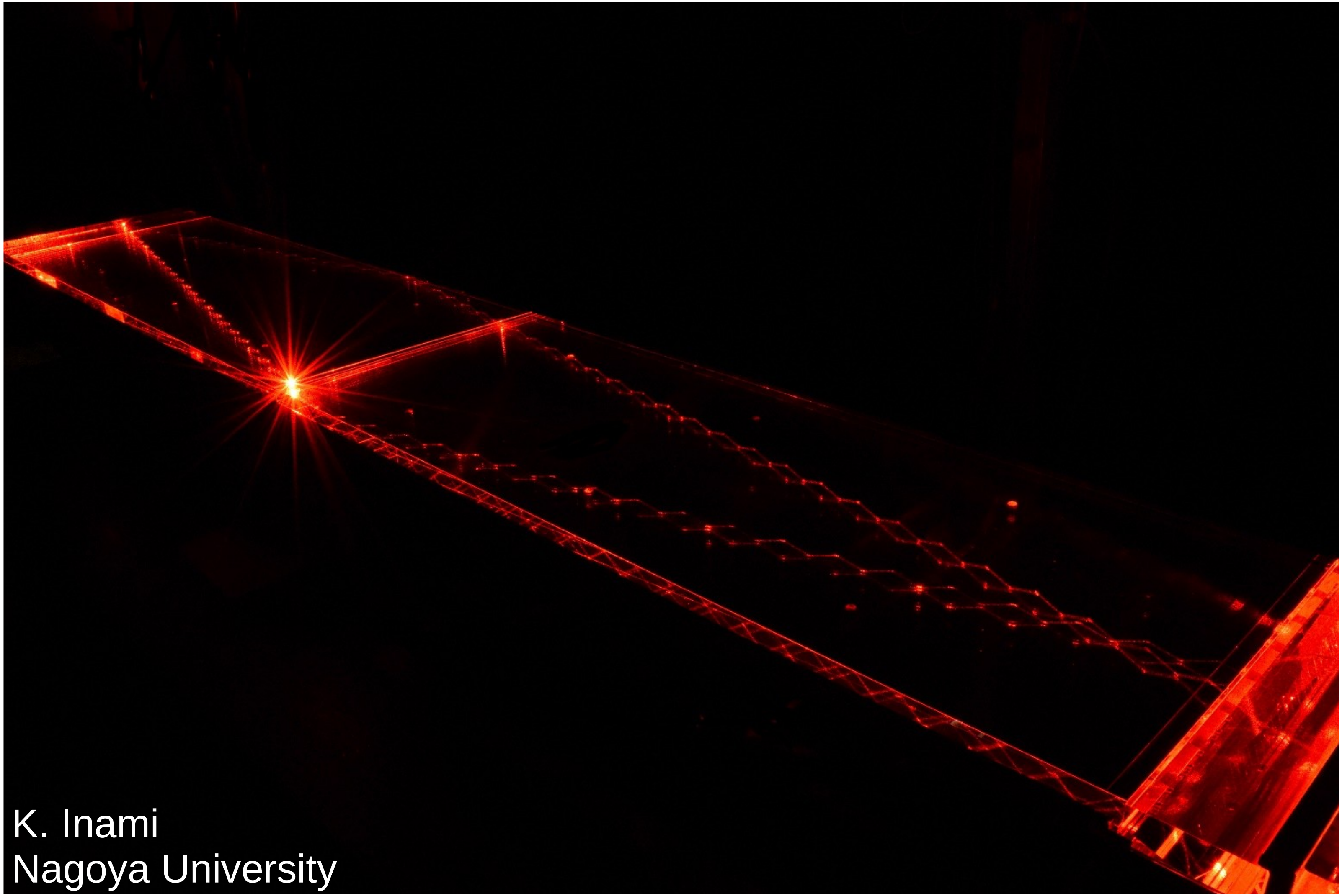
Thickness 20mm

Prism width 456 mm
MCPPMT width 444 mm

Prism height 51mm



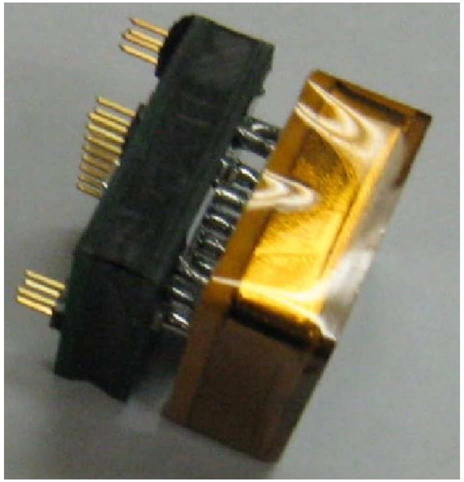
TOP: Total Internal Reflection

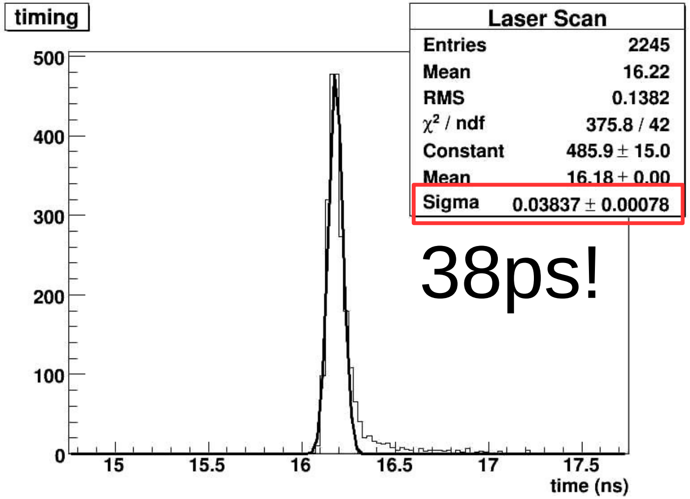


K. Inami
Nagoya University

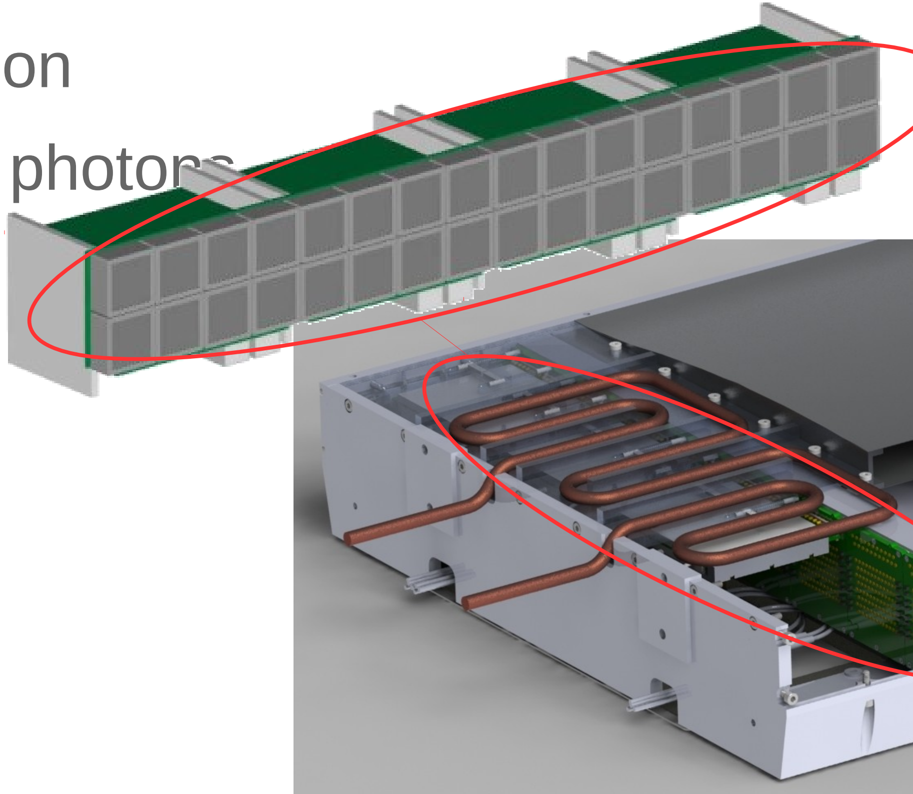
TOP Readout: Micro-Channel-Plate PMTs

- Goal: <100ps single optical photon time resolution
- Similar gain, photon efficiency as PMTs, but smaller
- (Mostly) resistant to B-fields
- Pixelated anodes for spatial resolution
- Very good time resolution for single photons



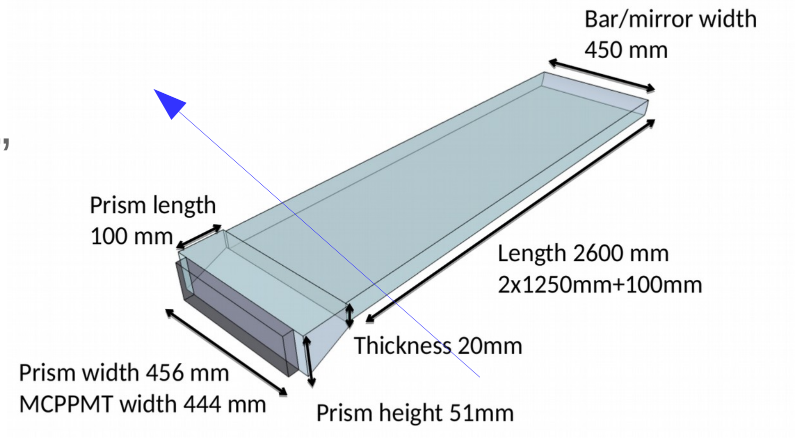


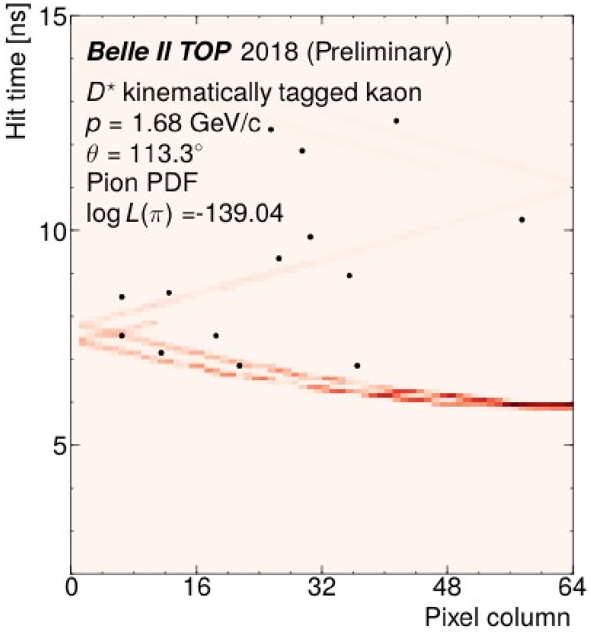
38ps!

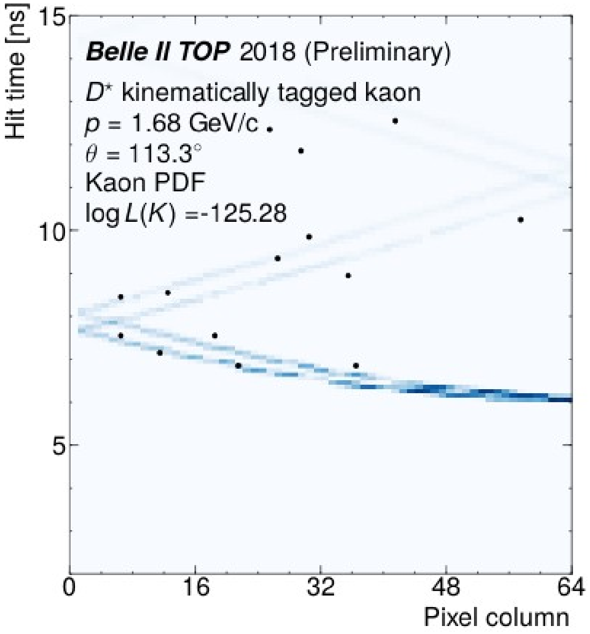


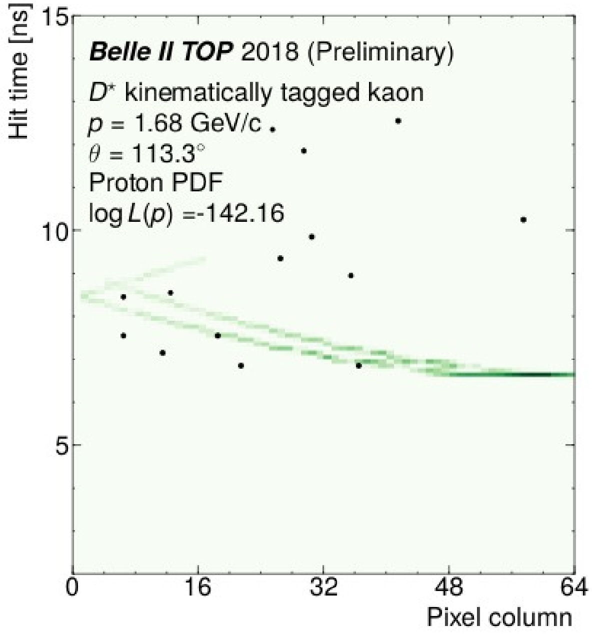
TOP “Cherenkov Rings” I

- $D^{*+} \to D^0 \pi_s^+ ; D^0 \to K^- \pi^+$ “Nature’s MC truth”
- Kaon facing prism-side of TOP bar
  - Little room for Cherenkov cone to open up
  - PDF differences dominated by ToF offset



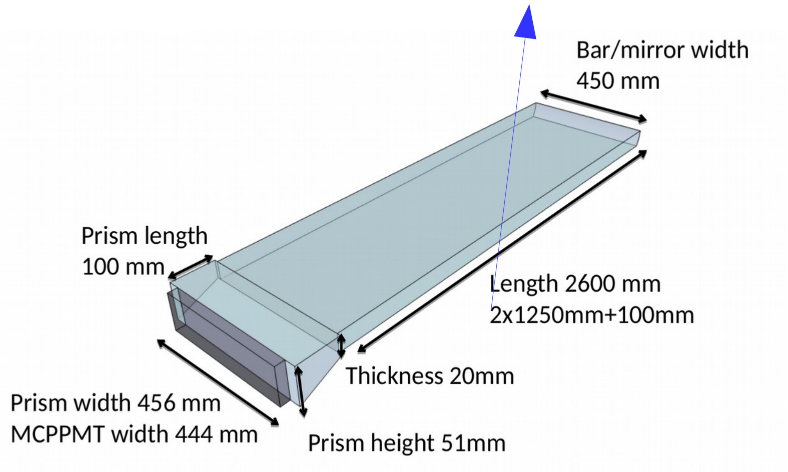


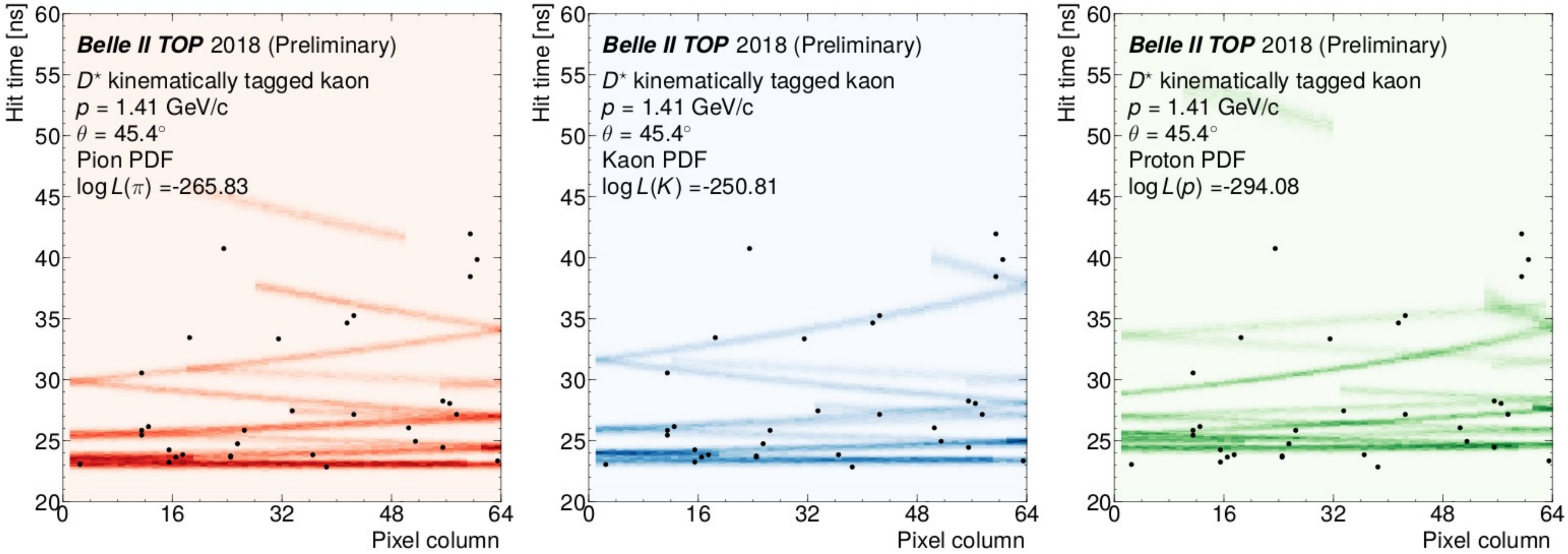




TOP "Cherenkov Rings" II

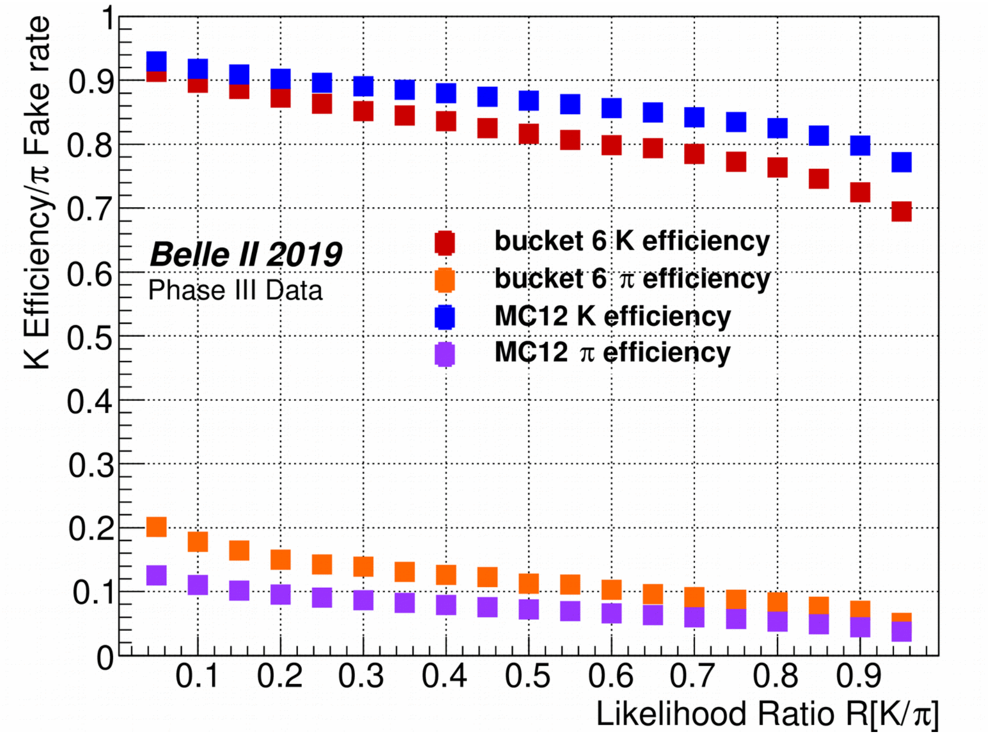
- $D^{*+} \to D^0 \pi_s^+ ; D^0 \to K^- \pi^+$ "Nature's MC truth"
- Kaon facing mirror-side of TOP bar
  - PDF differences dominated by shape



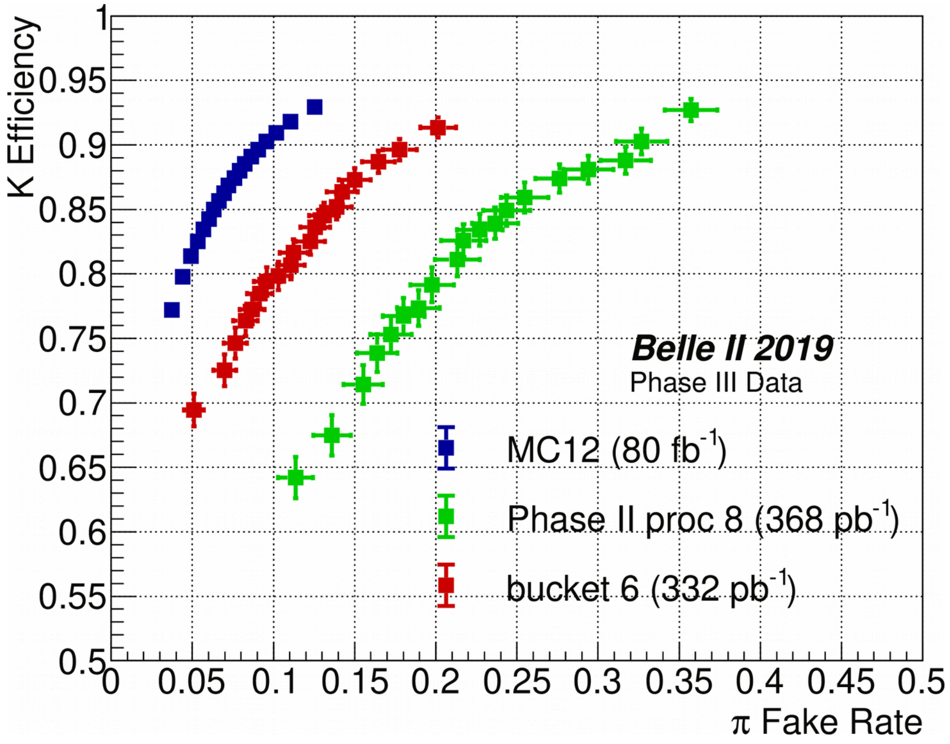


TOP PID Peformance: K-π Separation

PRELIMINARY



PRELIMINARY

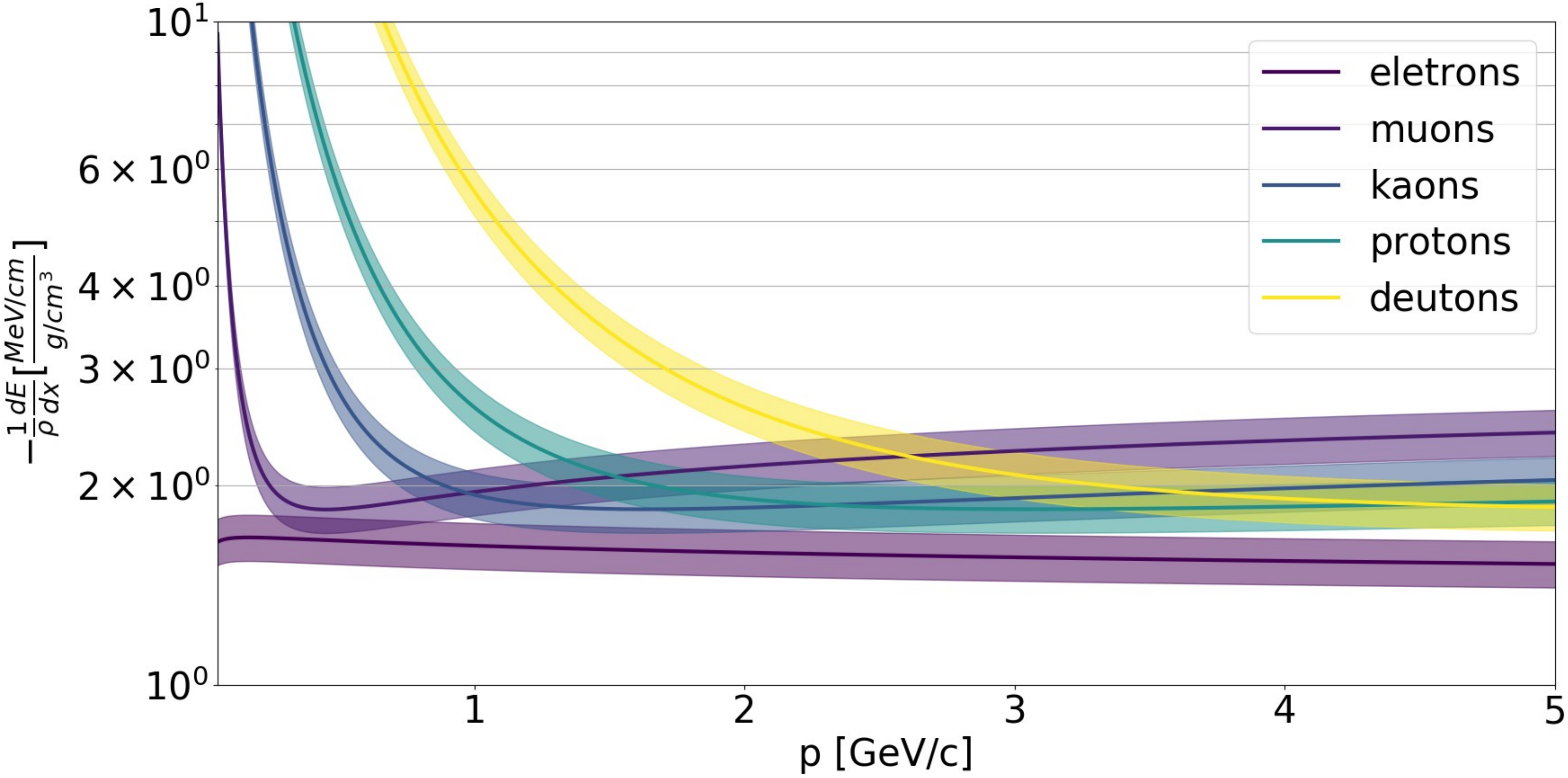


Summary

- **dE/dx and Time of Flight** techniques can work well for **low momenta**
- **Cherenkov** techniques can cover a **wider momentum range**
- Belle II Endcap: **ARICH**
  - **Aerogel** radiator (proximity focusing double layer)
  - Reconstructing Cherenkov ring image directly
- Belle II Barrel: **TOP**
  - **Quartz** radiator captures Cherenkov photons
  - Reconstructing Cherenkov angle via time of propagation of individual photons, additional Time of Flight component
- Each PID subdetector constructs a PID likelihood for a given track
  - As always: contructing the pdf is getting complicated quickly
- Umberto will explain how to **combine PID likelihoods** information of various subdetectors and how to use them in analyses

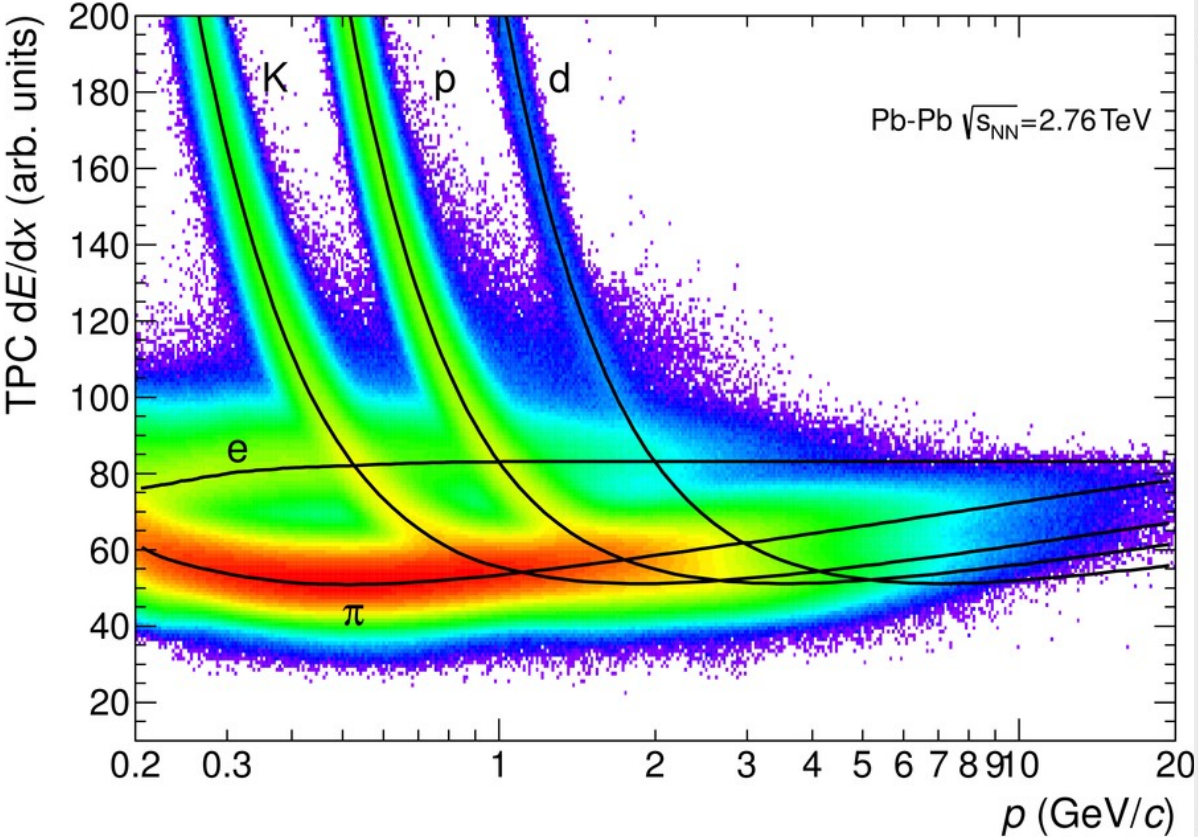
dE/dx: Specific Ionisation

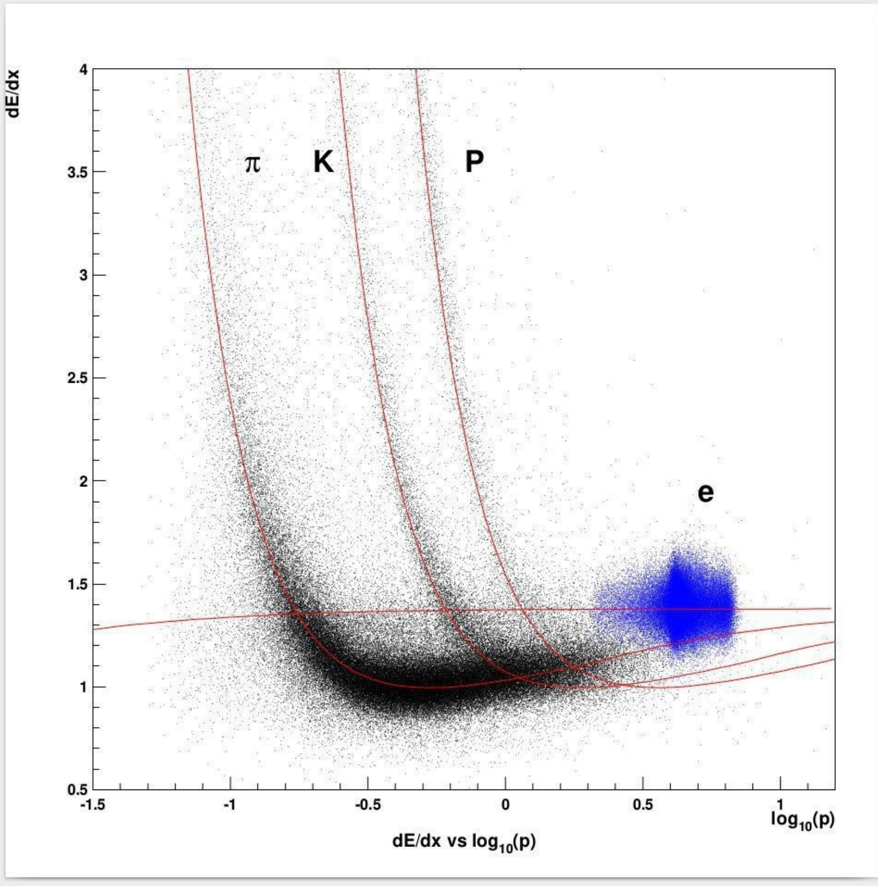
- Energy loss of charged particles in matter: Bethe-Bloch formula
- Measure ionisation from deposited charge in traversed tracking detector material (silicon diodes, gas mixture)



dE/dx: Specific Ionisation

- Some real data from ALICE and Belle I

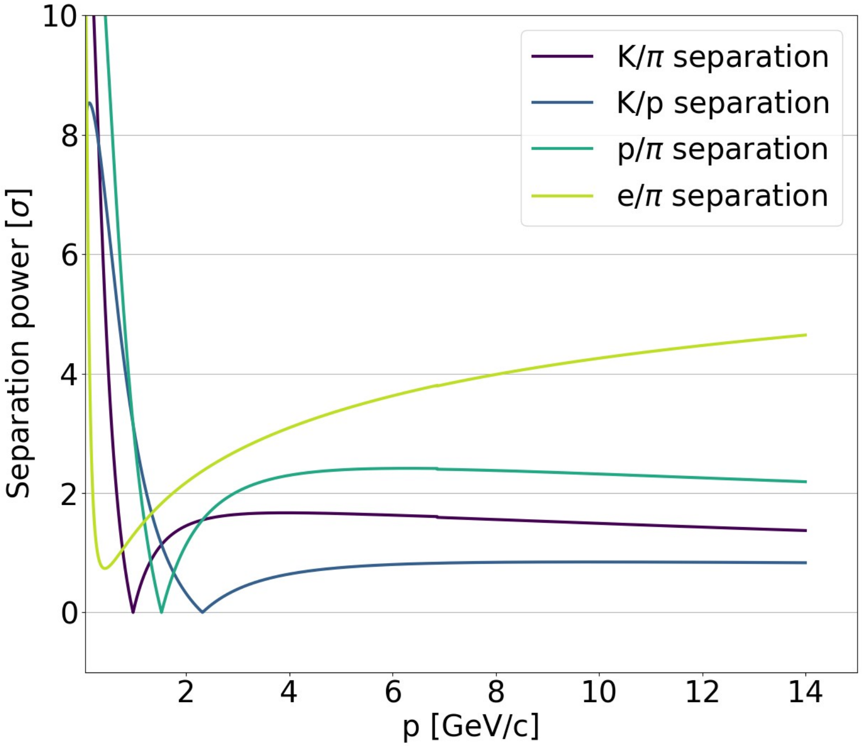


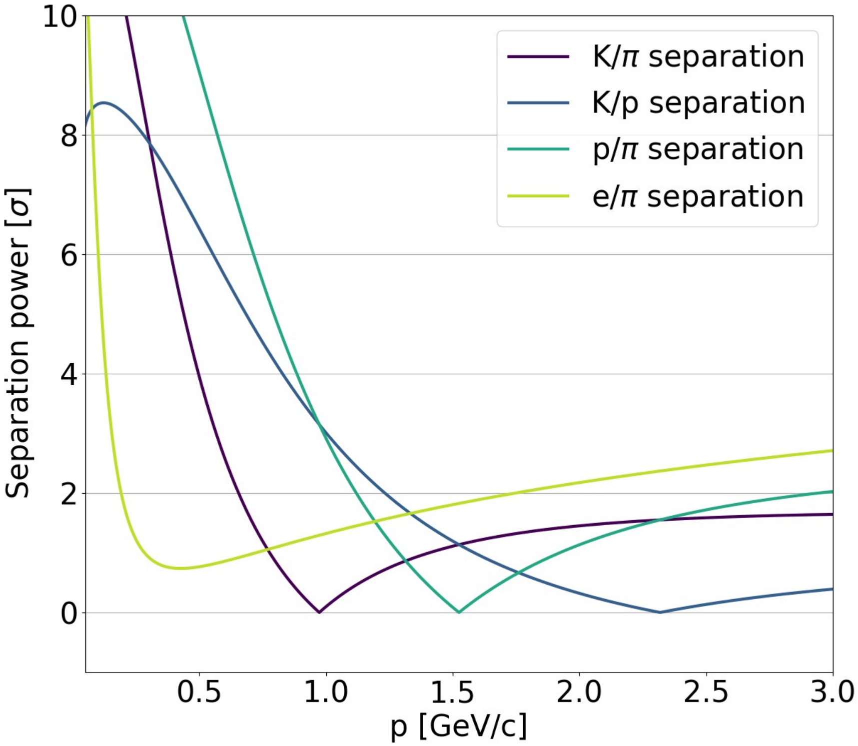


dE/dx: Separation Power

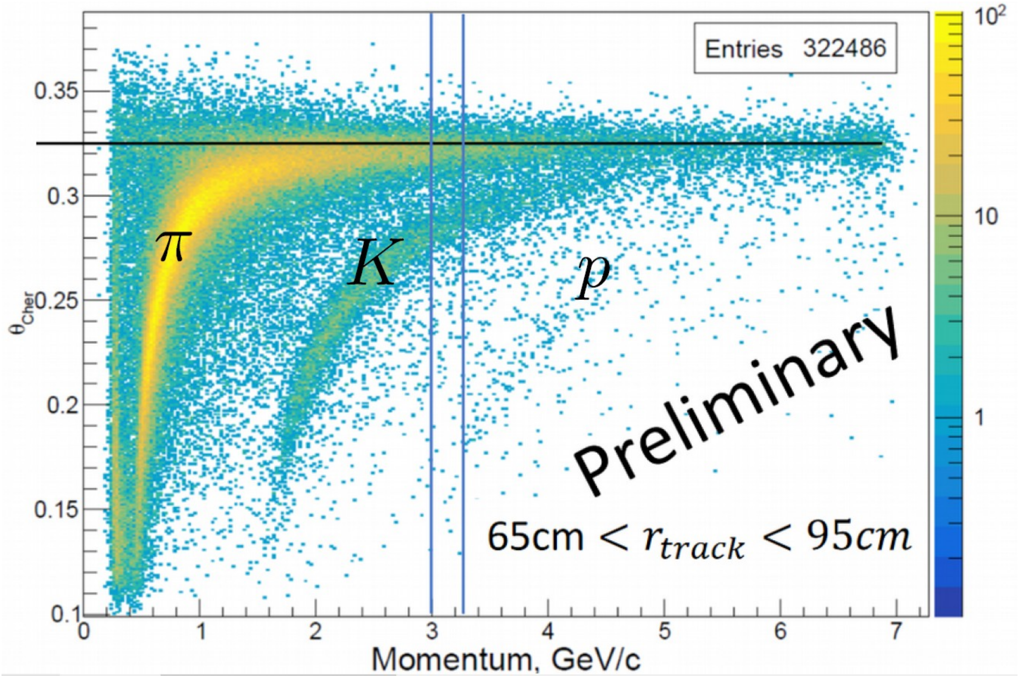
- Assuming 7% deposited energy resolution (~Belle)

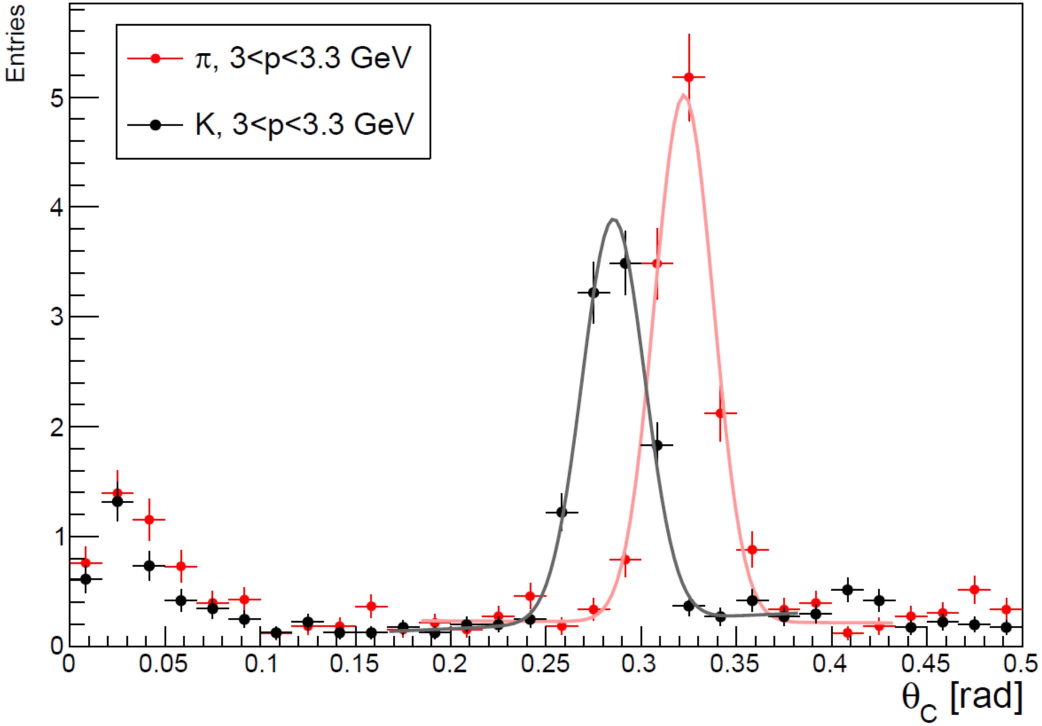
  → works great for low momenta, very mediocre above ~GeV





ARICH: Separation





ToF: Concept

- Time of flight

Measure signal time difference between two detectors with good time resolution [start and stop counter]

- Typical detectors:

  Scintillation counter + photodetector

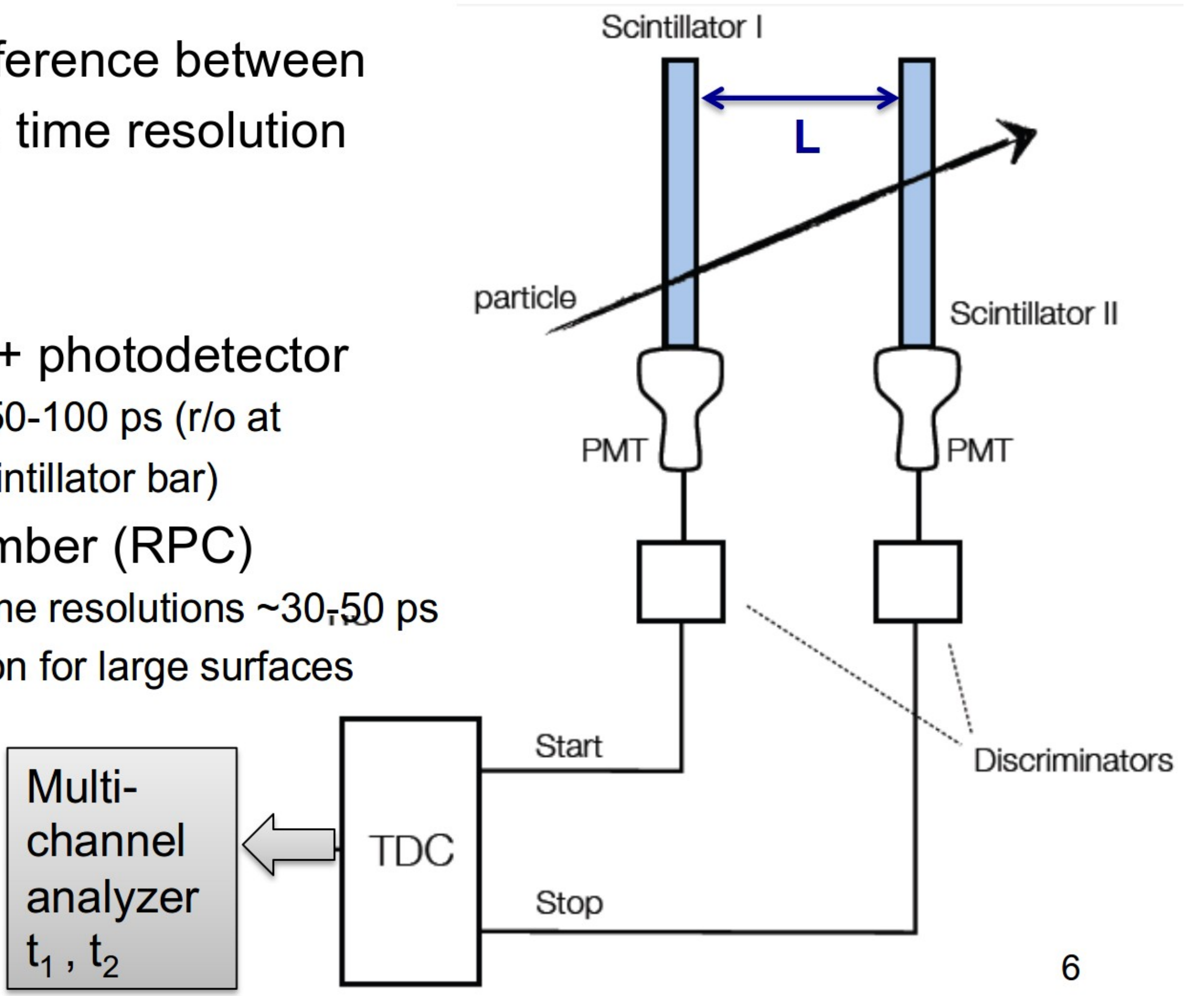
    time resolutions ~50-100 ps (r/o at both ends of the scintillator bar)

  Resistive Plate Chamber (RPC)

    not sensitive to B, time resolutions ~30-50 ps

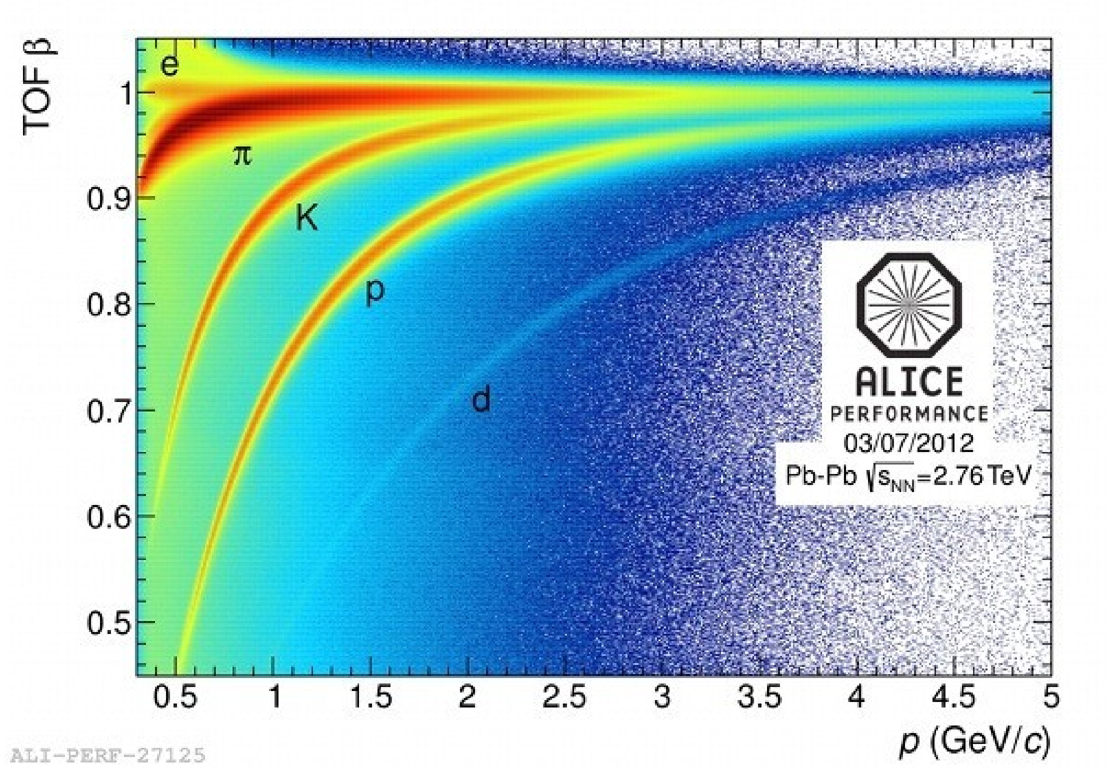
    cost effective solution for large surfaces

$$\Delta t = t_2 - t_1 = \frac{L}{c\beta}$$



ToF: Data

- Real data from ALICE and Belle



ALI-PERF-27125

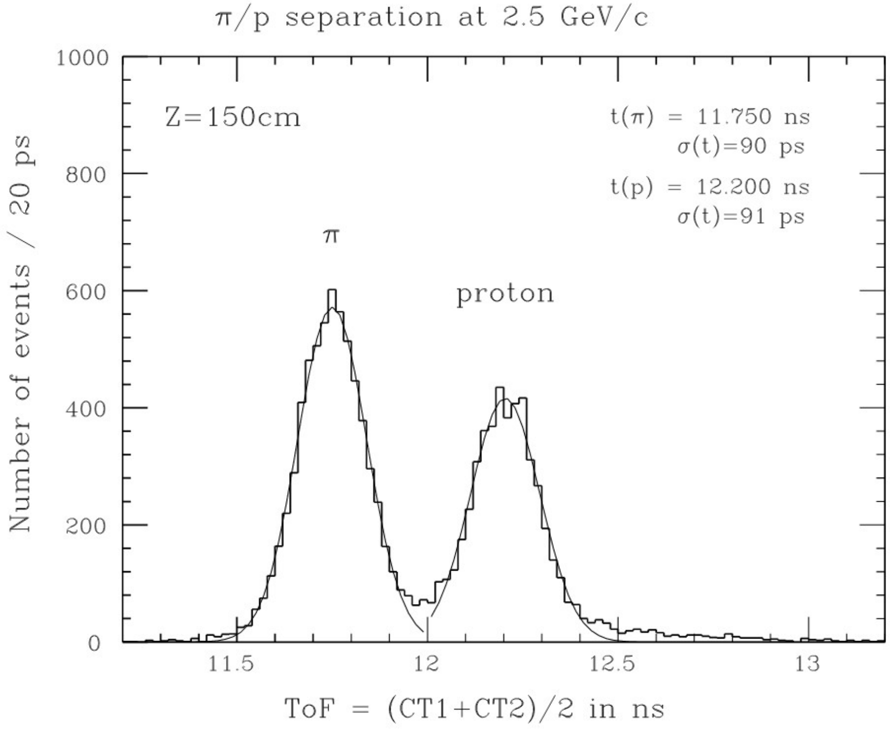


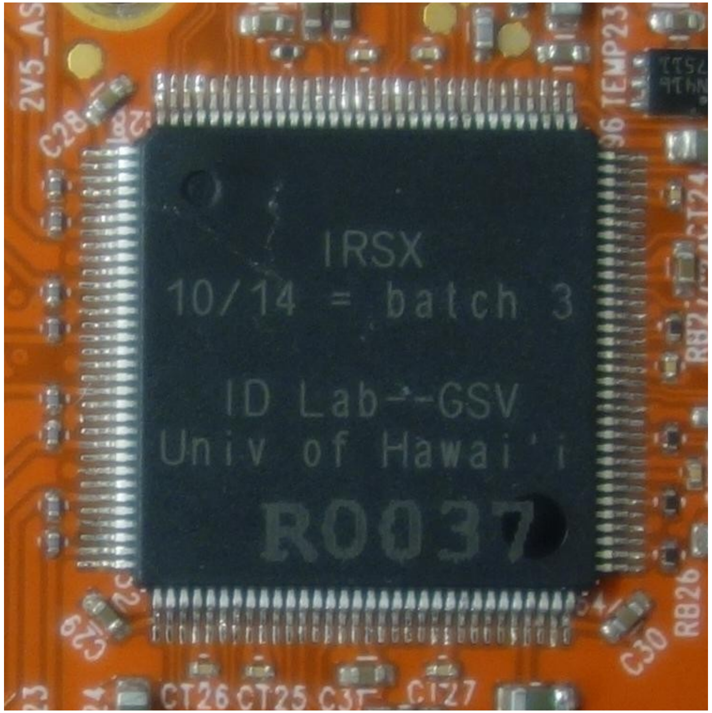
Fig. 62. π/p separation at 2.5 GeV/c.

TOP Readout: Electronics

- Reads MCP-PMT signals
- Time resolution <50ps
  - ~GSa/s sampling
  - ~500MHz bandwidth
- 8192 channels
- Affordable
- Low power
- Small form factor
- Online data processing
- etc. etc.

Readout: Electronics

- "Oscilloscope on a Chip": IRSX ASIC
  - Designed by IDLAB, UH (Prof. Gary Varner)
- Operated at 2.7GSa/s in TOP
  - ~600MHz analog bandwidth
  - 32k analog buffer cells (~10us)
  - 12 bit digitisation w/o deadtime
- Power budget ~600mW/ch
  - ASIC: ~125mW/ch
  - Preamp: ~150mW/ch
  - FPGAs: ~300mW/ch



Online Data Reduction

- Whole TOP stores 22×10^{12} samples every second
- Only digitise relevant ASIC samples
  - Based on global trigger, local channel triggers
- Apply all raw data conditioning in frontend
  - Pedestal subtraction
  - Time base calibrations
- Extract waveform features in frontend
  - Photon timing, pulse shape parameters
- Write out only feature parameters
- Powerful frontend processing: 320 FPGAs, 640 ARM cores
  - Based on Xilinx Zynq SoCs

Feature Extraction in TOP

- Constant fraction discrimination
- Template fit to photon pulses
  - Computationally complex, possible on Zynq DSPs?
  - but only needed for low amplitude hits