Charged Particle Identification & TOP

The Inn at Virginia Tech and Skelton Conference Center

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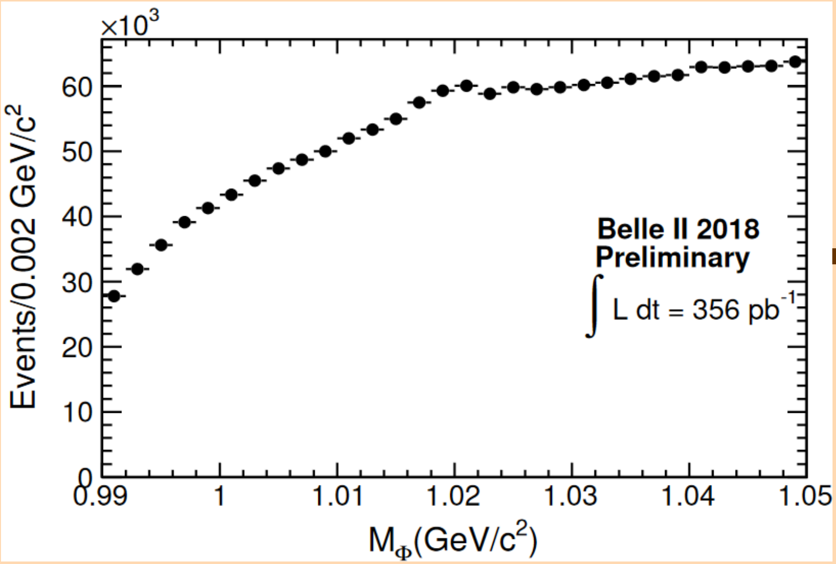
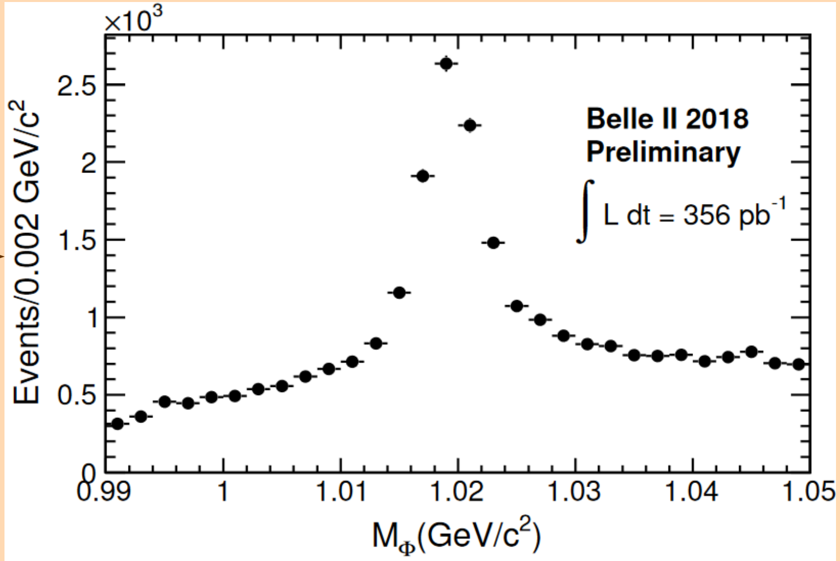
- Charged Particle IDentification (PID) is a **crucial aspect of most particle physics experiments**, in addition to tracking and calorimetry.
- Good PID information is necessary **to isolate hadronic final states and reduce backgrounds** to enable stringent requirements for rare decay channels.

For Example: Searching for ϕ meson decays to K^+K^-:

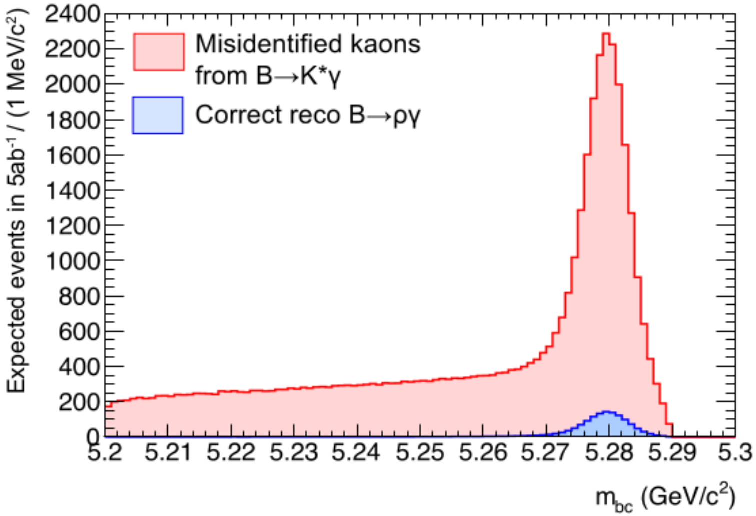


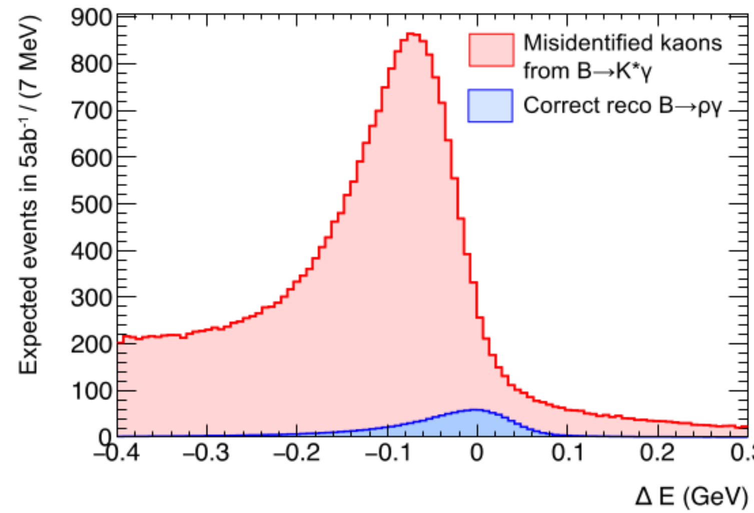


$\phi \to K^+K^-$ decay barely show up as a peak in the invariant mass distribution on a background of false combinations…

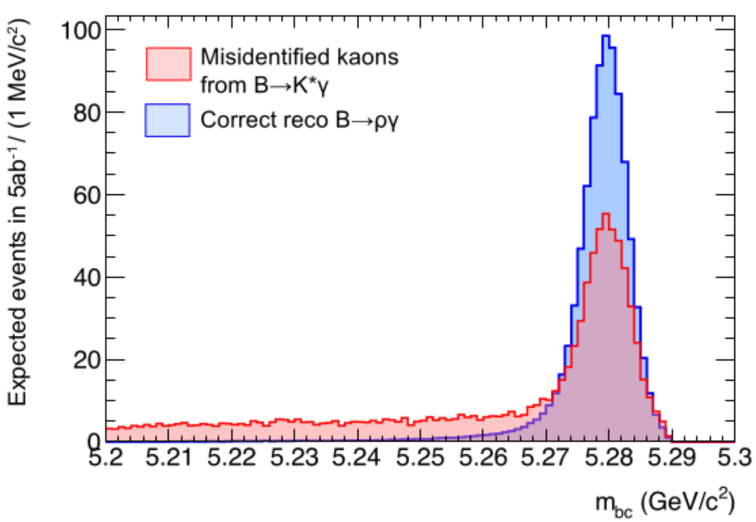
… until particle identification criteria are taken into account

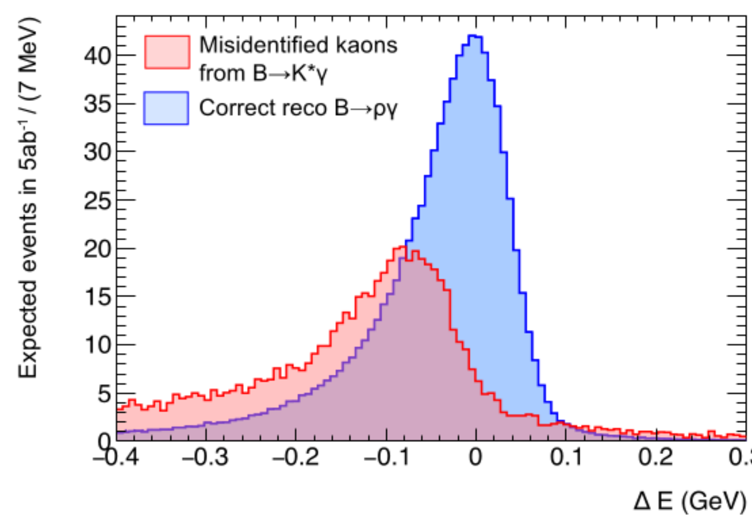
- Example : searching for **$B \to \rho^0[\pi^+\pi^-]\gamma$** [BF ~ 10^{-7}] (sig); **$B \to K^{*0}[K^+\pi^-]\gamma$** [BF ~ 10^{-5}] (bkg)





Without PID selection criteria.



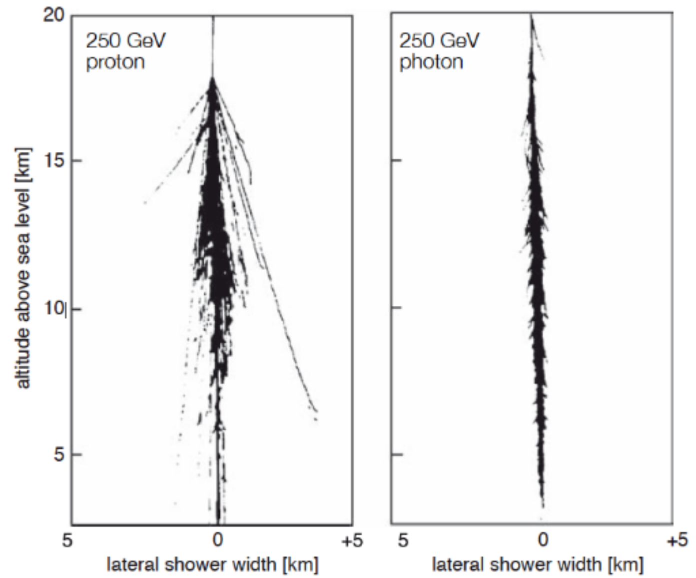


With PID selection criteria.

- In B factories, PID criteria is also important to enable B meson flavour-tagging techniques.
- Good charged particle identification is required up to about 4 GeV/c.

Final state charged particles (e, μ, π, K and p) are identified :

(1) the way they **interact:**

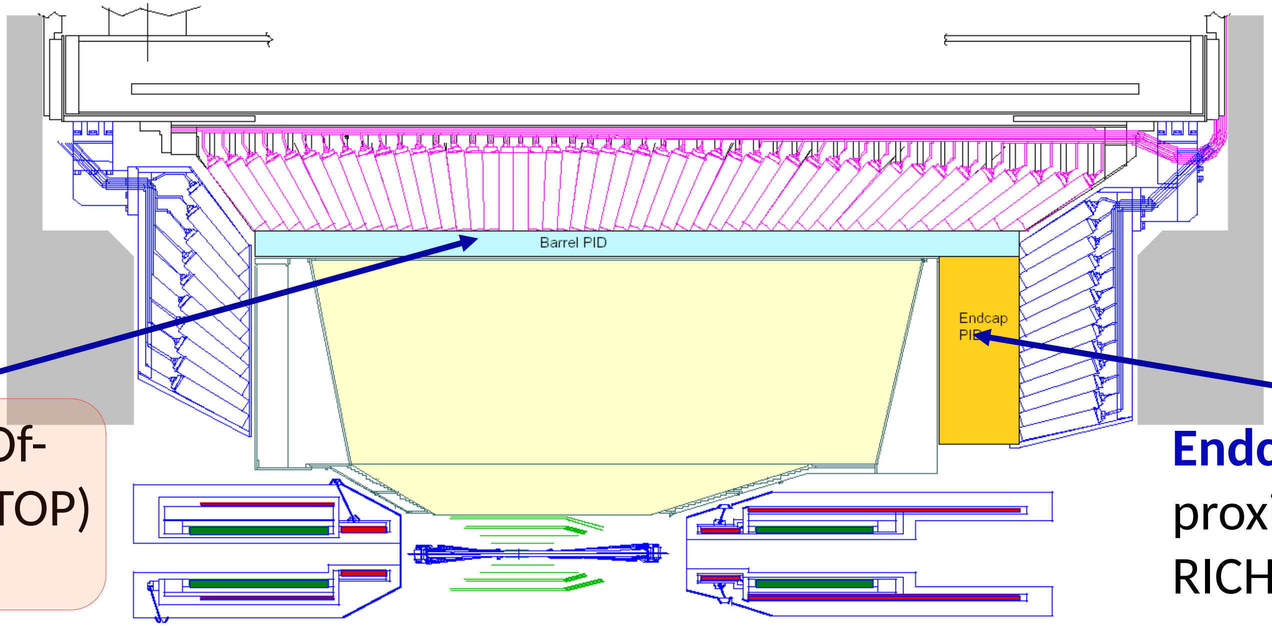


(details in Ewan's talk for **ECL** and Leo's talk for **KLM**)

(2) Determining their **mass :** from the relation between **momentum** and **velocity**,

$$p = \gamma m v$$

- (p is known - radius of curvature in magnetic field) → CDC
- Measure **velocity** by:
  - Ionisation loss dE/dx → CDC (details in Roy's talk)
  - Time of Flight → included in TOP measurement
  - Cherenkov photon angle → TOP and ARICH

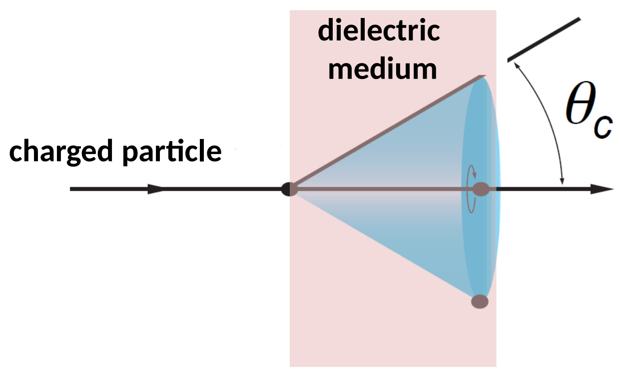


Barrel: Time-Of-Propagation (TOP) counter

Endcap: Aerogel proximity focusing RICH (ARICH)

In both region, PIDs at Belle II are ring imaging Cherenkov devices.

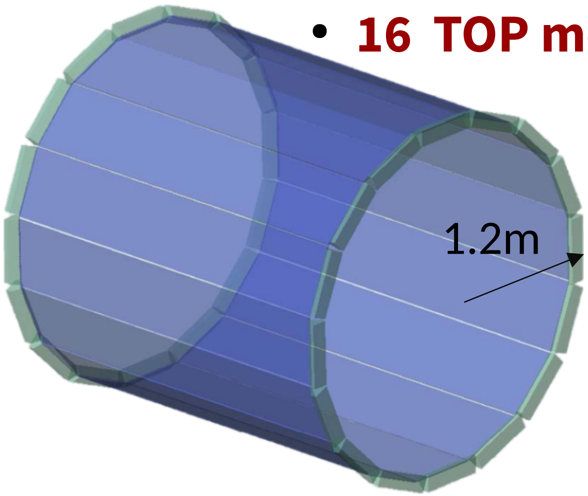
A charged track with velocity ($v = \beta c$) exceeding the speed of light (c/n) in a medium (refractive index n) emits Cherenkov light at a characteristic angle,



$$\cos\theta_c = 1/n(\lambda)\beta$$

Same momentum pions and kaons will have different velocities (β) and hence the angle of Cherenkov photons.

TOP : components



- **16 TOP modules**, arranged in a barrel shaped array with inner radius ~ 1.2m

TOP modules consists of:

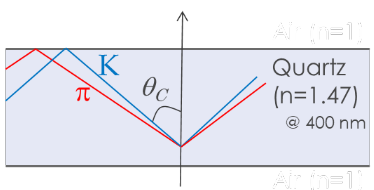
Two fused silica bars (each 45×125×2 cm^3) → Radiator to generate Cherenkov photons.

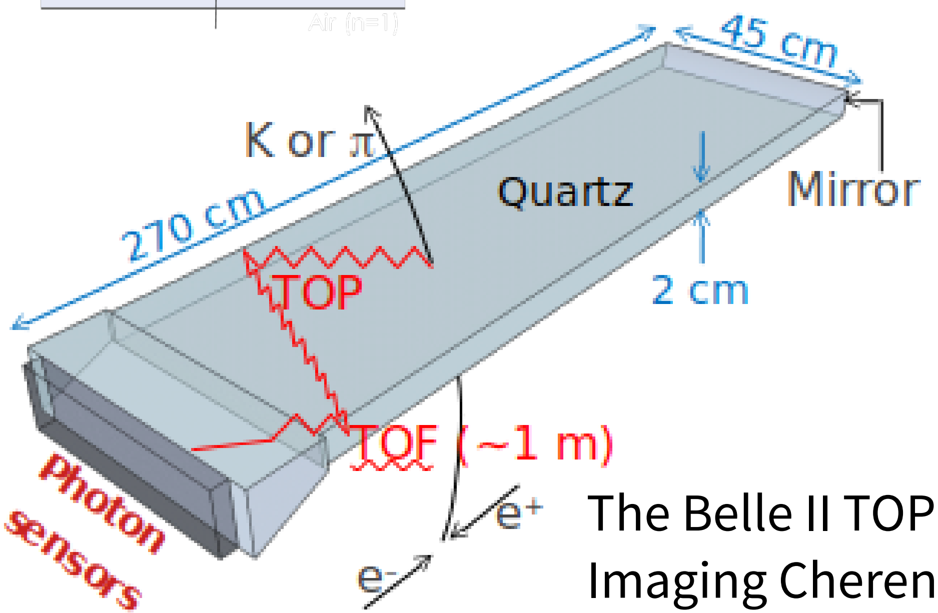
Mirror (45×10×2 cm^3) → focuses the emitted photons to the sensor plane

Expansion volume (45.6×10×2cm^3 → 45.6×10×5.1cm^3) to expand the image and improve resolution.

MCPPMT: At the exit window of the prism, two rows of sixteen fast multi-anode photon detectors are mounted.

$\cos\theta_c = 1/n\beta$



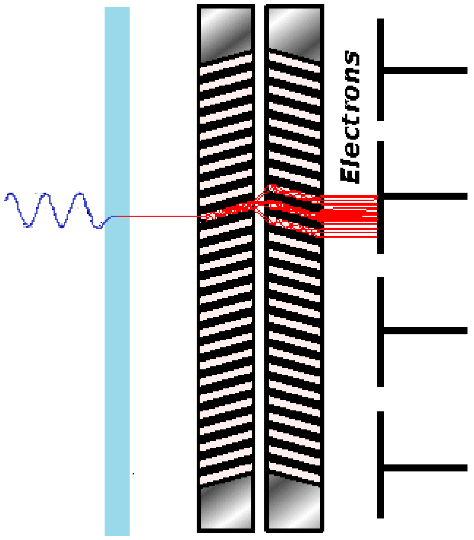


Cherenkov photons emitted in the quartz radiator from the charged track → total internal reflection → registered at the end of the bar by a fast position sensitive detector of single photons.

θ_c is reconstructed from: hit position (x,y) in the photo detector plane and time of propagation

The Belle II TOP detector is the first detector combining the Ring Imaging Cherenkov technique with fast time resolution.

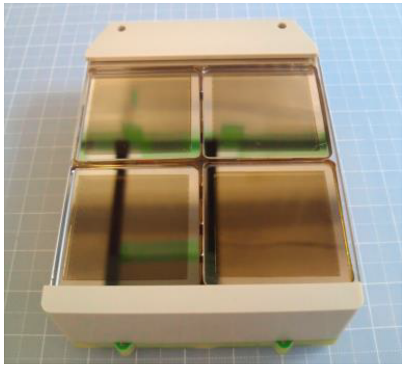
- A micro-channel plate (MCP) photomultiplier tube (PMT) provides a good time response.
- Transit time spread ~ 30 – 35 ps (required is <50ps)

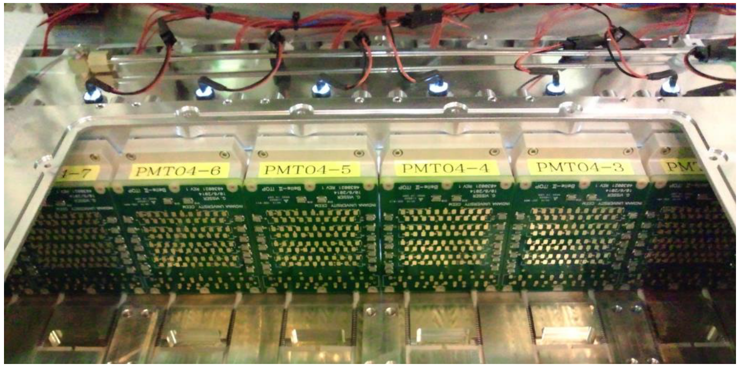


<u>Characterstics</u>

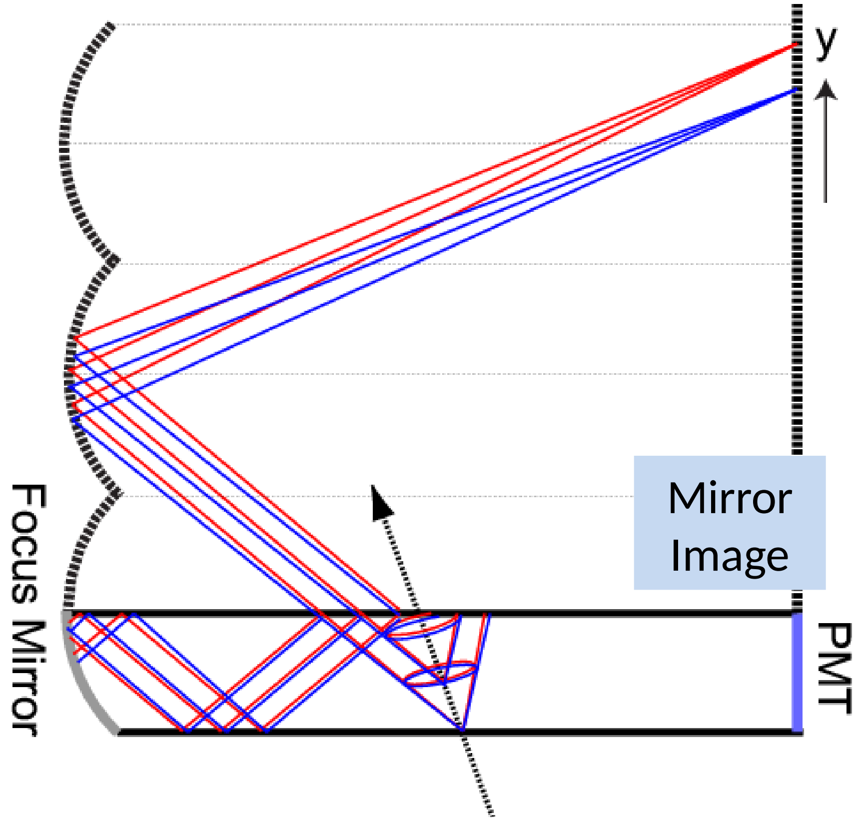
Overall size : $27.5 \times 27.5 \times 15.6$ mm^3
Photo cathode : Multi-alkali (23×23 mm^2)
MCP width: 400 μm, pore: 10 μm and bias angle: 13 degrees
Anode 22 x 22 mm^2 (divided into 4 x 4 pads)
Dimensions of each pad: 5.275 x 5.275 mm^2 with gap 0.3mm

Quantum efficiency : >24% at 350-400nm
Gain : 2×10^6 at ~3kV
Dark-rate : 5kHz for 16 anodes

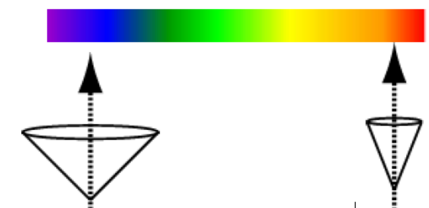




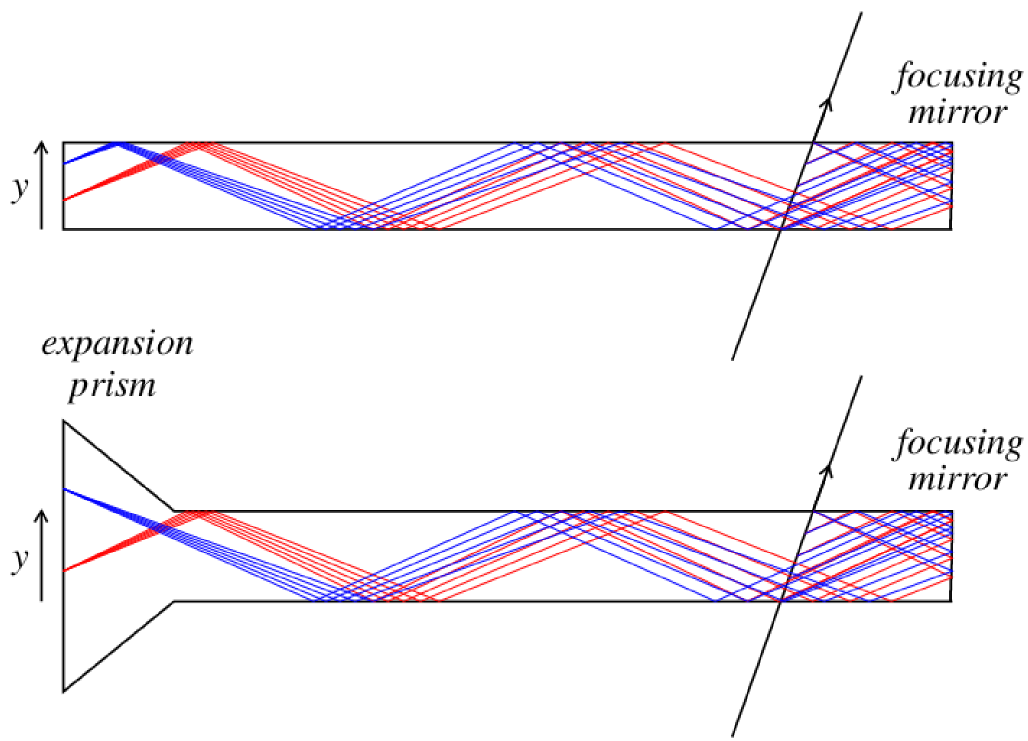
TOP : need of mirror



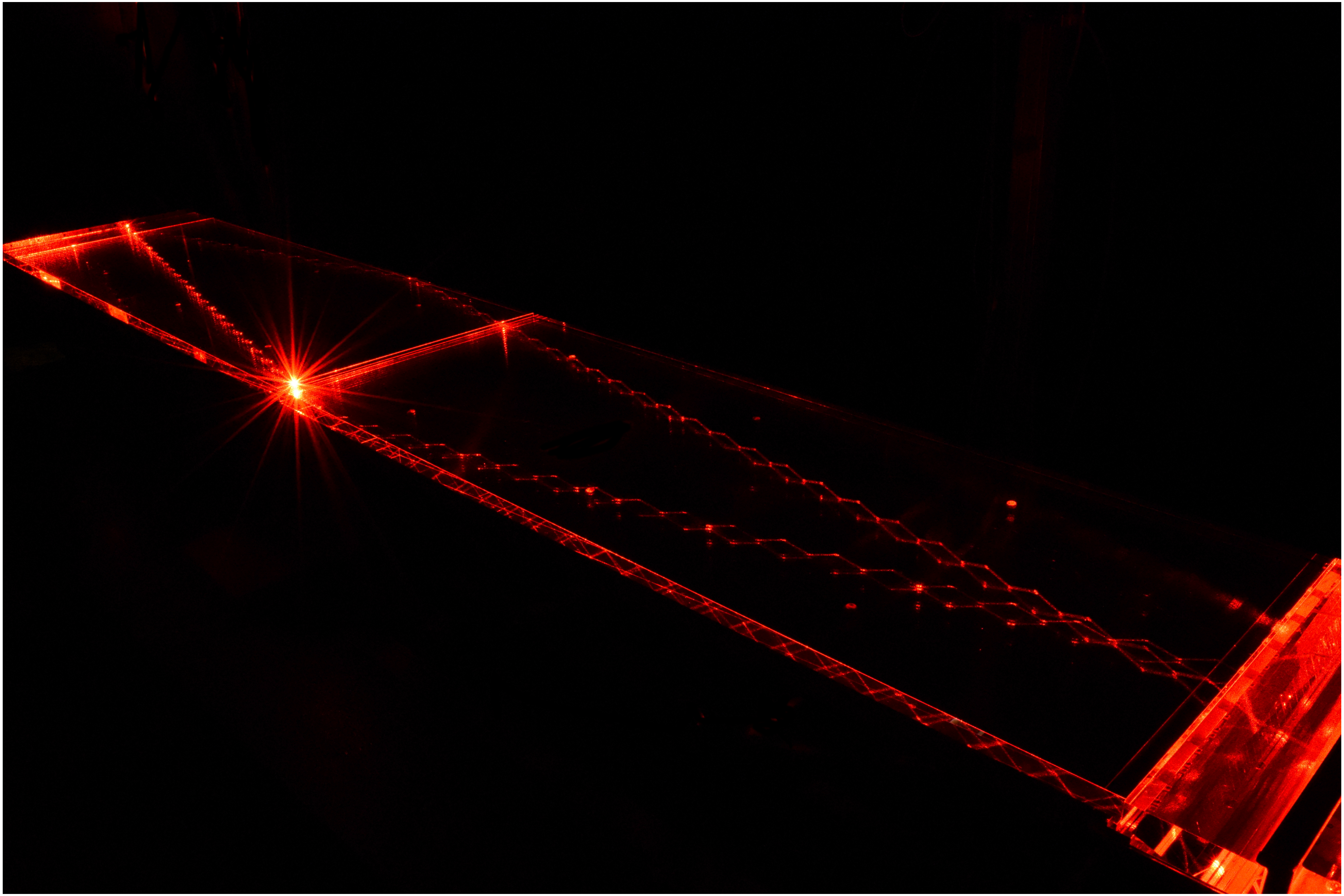
- parallel rays get focused to a single point → removes bar thickness
- non-parallel rays are focused to different points →
  - o K/π separation
  - o allows to correct for chromatic dispersion.



$$\theta_c(\lambda) = \cos^{-1}\left(\frac{1}{n(\lambda)\beta}\right)$$



Laser beam inside a TOP module



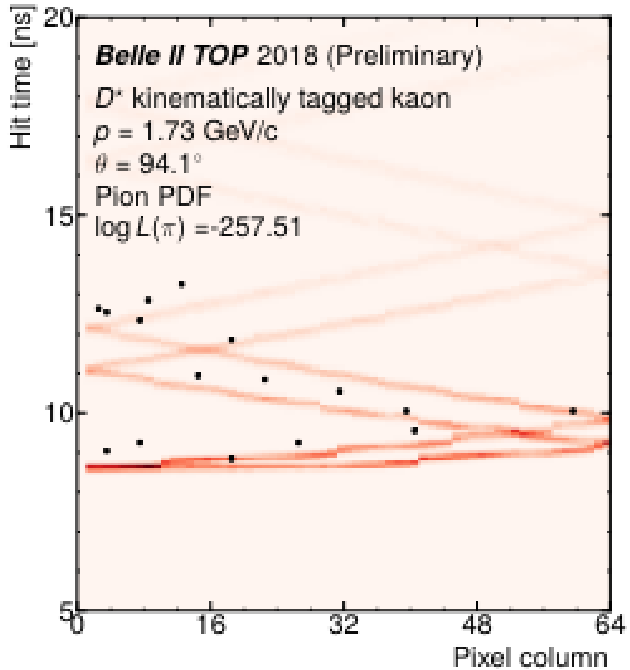
- K/π PID efficiency and fake-rate can be studied from the decay $D^{*+} \rightarrow D^0 (K^- \pi^+) \pi^+$.
- Slow pions (π^+) can be used to tag D^0, which is finally used to identify **K** and **π**.
- This can be helpful in getting K/π PID efficiency/fake rate without using MC truth information (also valid for data case).

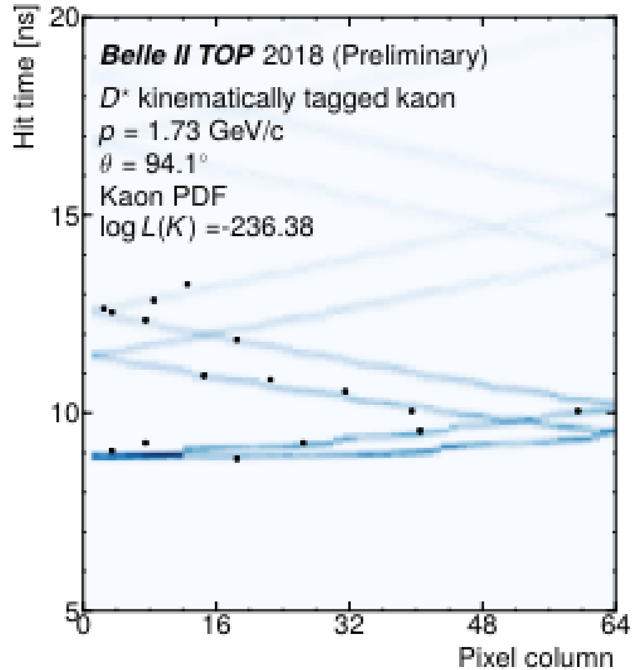
- Charged tracks are required to originate from near the interaction region.
- Two opposite sign track with kaon and pion mass hypothesis are combined to reconstruct a D^0 candidate.
- Another charged track (slow pion) is added to reconstruct D^{*+}.
- K-identification efficiency (and π mis-identification rate) are calculated by applying a criteria on ΔM (mass-difference between D^{*+} and D^0) and fitting $M[D^0]$ distribution.

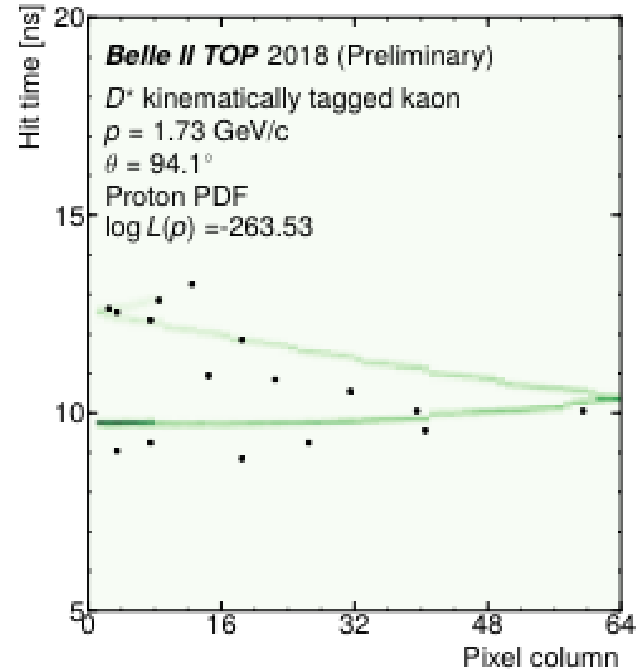
$$\epsilon_K = \frac{\text{number of } K \text{ tracks identified as } K}{\text{number of } K \text{ tracks}} \qquad f_\pi = \frac{\text{number of } \pi \text{ tracks identified as } K}{\text{number of } \pi \text{ tracks}}$$

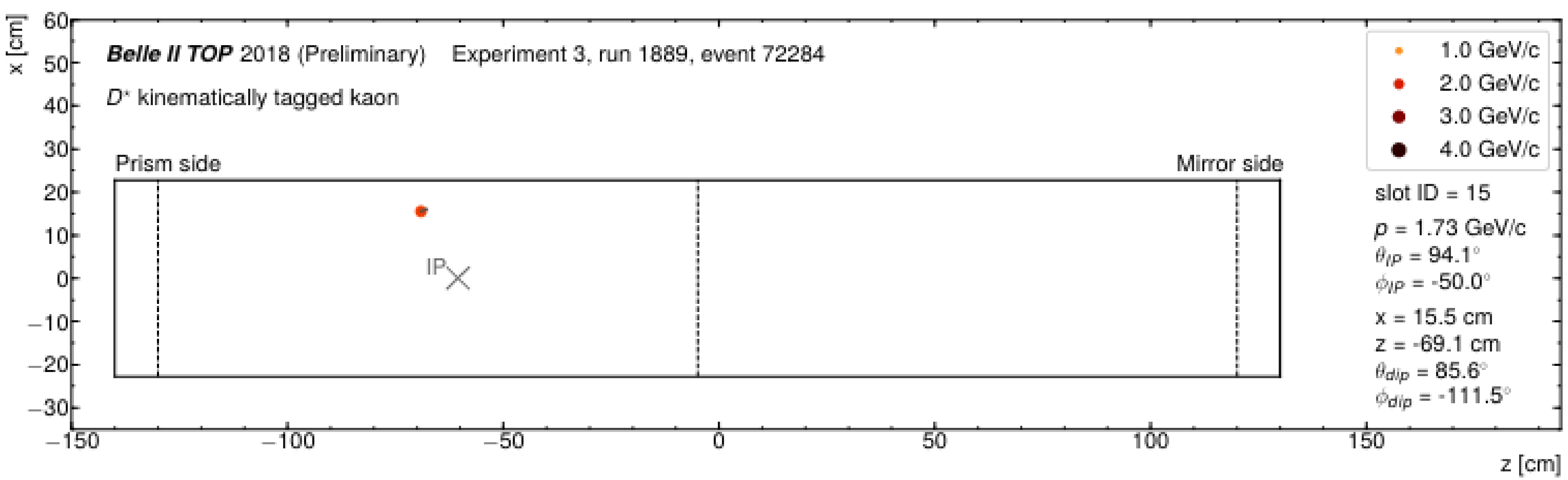
- Results presented here are based on 71.2 fb^{-1} data collected during 2019 and 2020.

D* Kinematically tagged Kaon in TOP









- Information from each PID system is analyzed independently to determine a likelihood for each charged particle hypothesis.

$$L_i = \prod_{detector} L_i^{detector} \qquad i = \{e, \mu, \pi, K, p \text{ and } d\}$$

Global ID

- Basf2 variables : **`electronID, muonID, pionID, kaonID, protonID, DeuteronID`**

$$R_i^G = \frac{L_i}{\sum_i L_i}$$

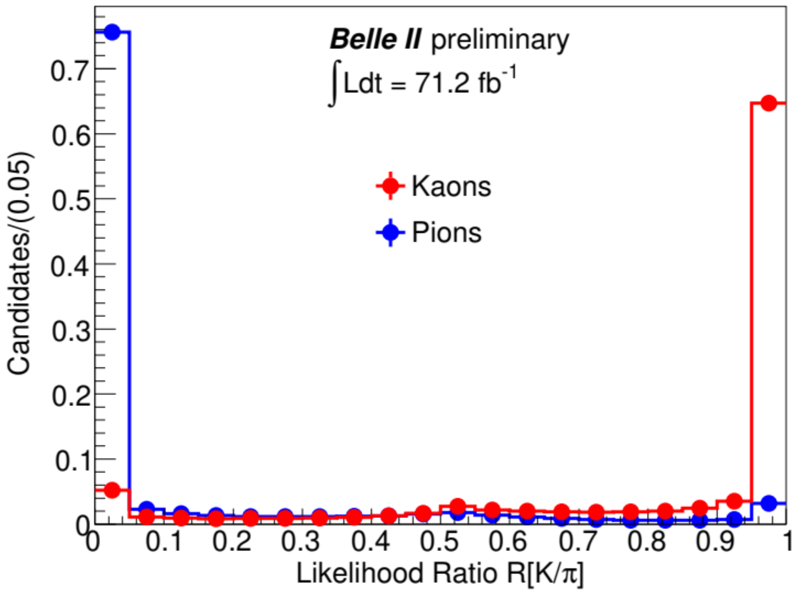
Binary ID

- Basf2 variables : **`pidPairProbabilityExpert(pdgCodeHyp, pdgCodeTest, detectorList)`**

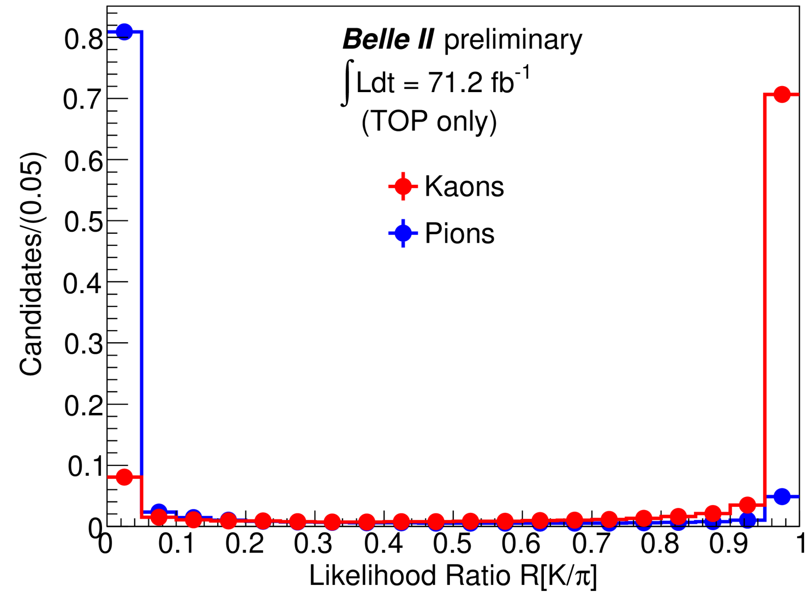
$$R(\alpha:\beta) = \frac{L_\alpha}{L_\alpha + L_\beta}$$

For example the criteria on R(K:π)>0.5 would mean that the charged tracks resembles more like K than a π

All sub-detectors



TOP only



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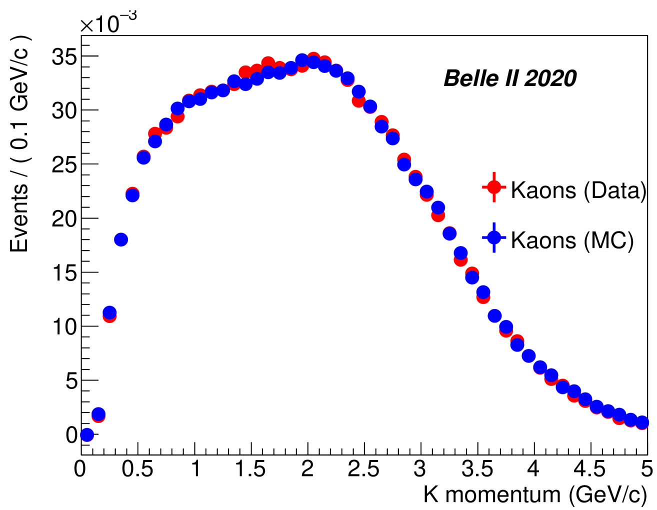
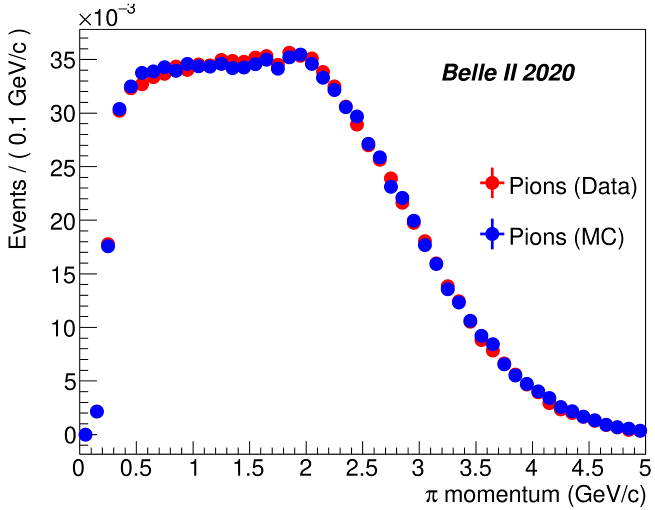
$$R(\alpha:\beta)=\frac{L_\alpha}{L_\alpha+L_\beta}$$

For example the criteria on R(K:π)>0.5 would mean that the charged tracks resembles more like K than a π

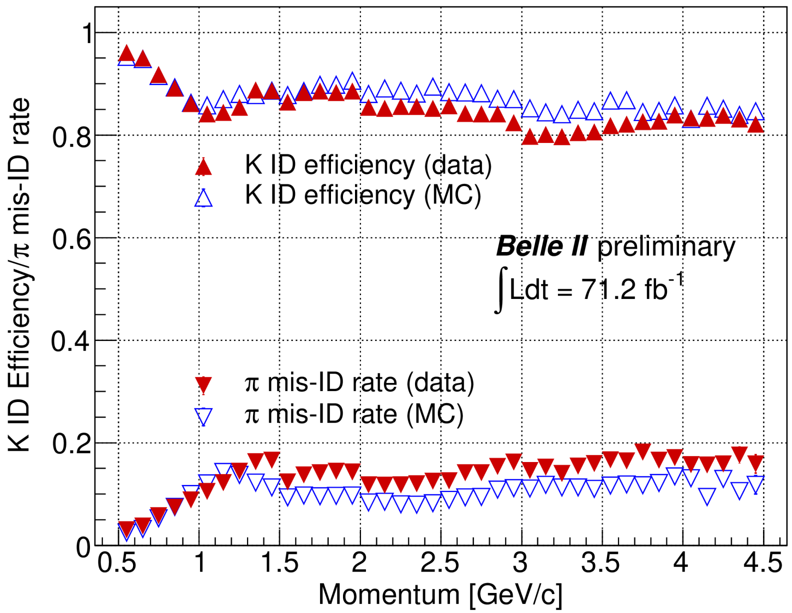
- Momentum distribution of the K and π sample:



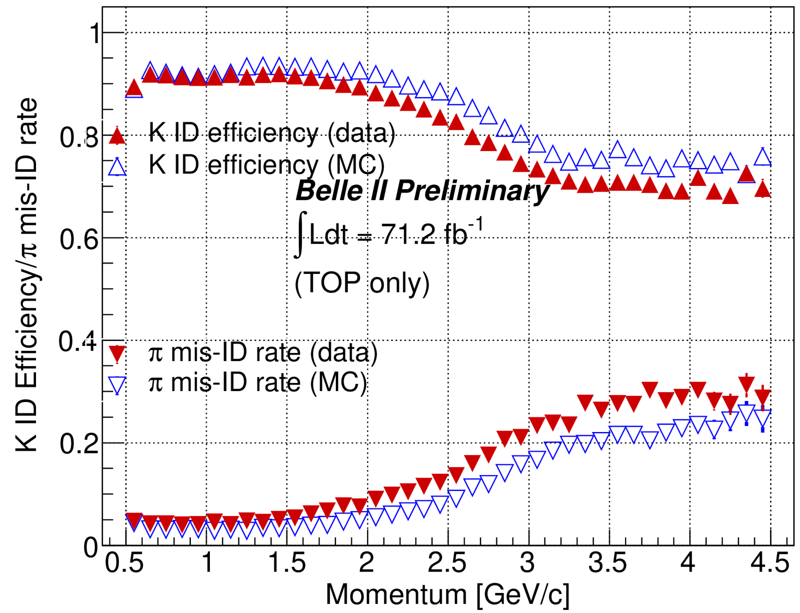


- Data-MC comparison for K-eff. and π mis-ID rate for R[K/π] > 0.5 w.r.t. momenta

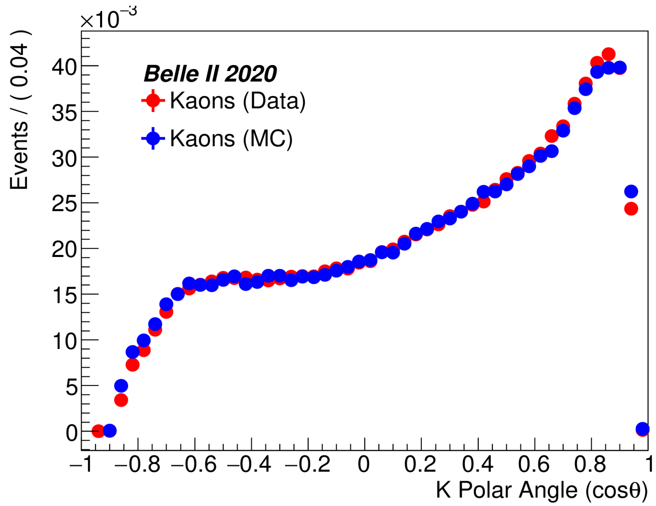
All sub-detectors

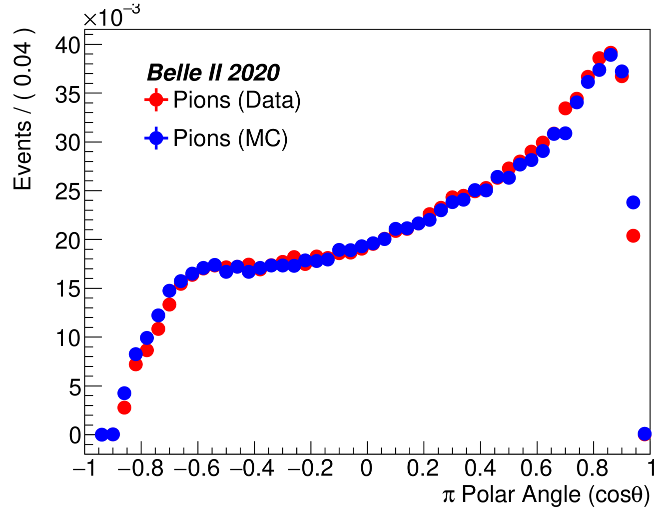


TOP only



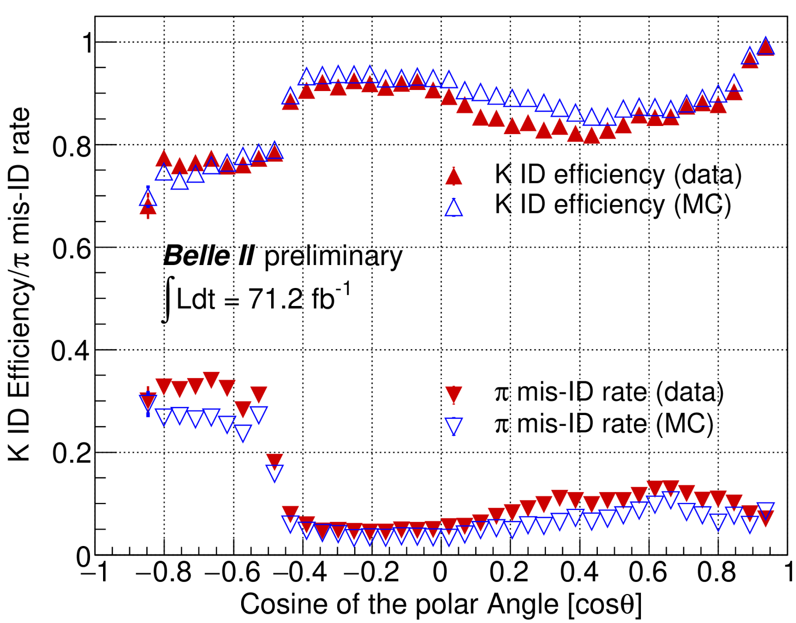
- Polar angle distribution of the K and π sample:



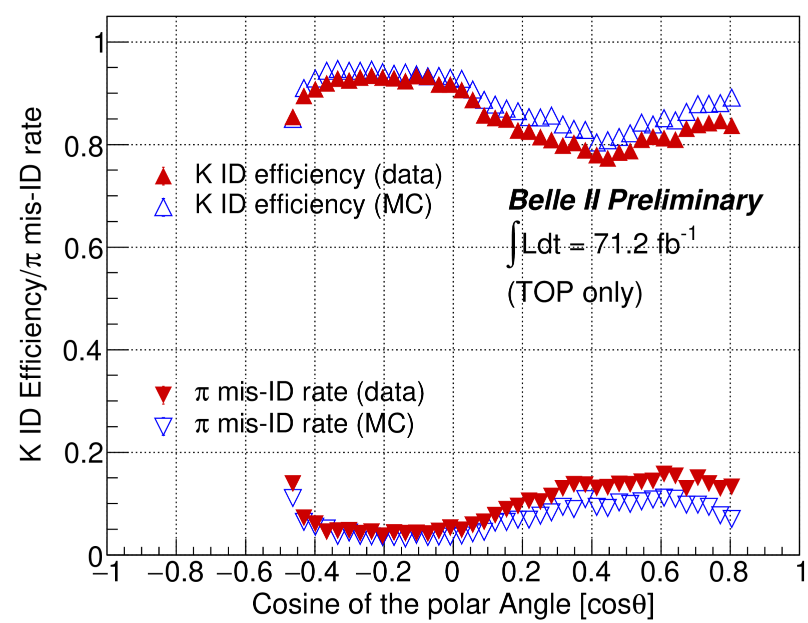


- Data-MC comparison for K-eff. and π mis-ID rate for R[K/π] > 0.5 w.r.t. polar angle.

All sub-detectors

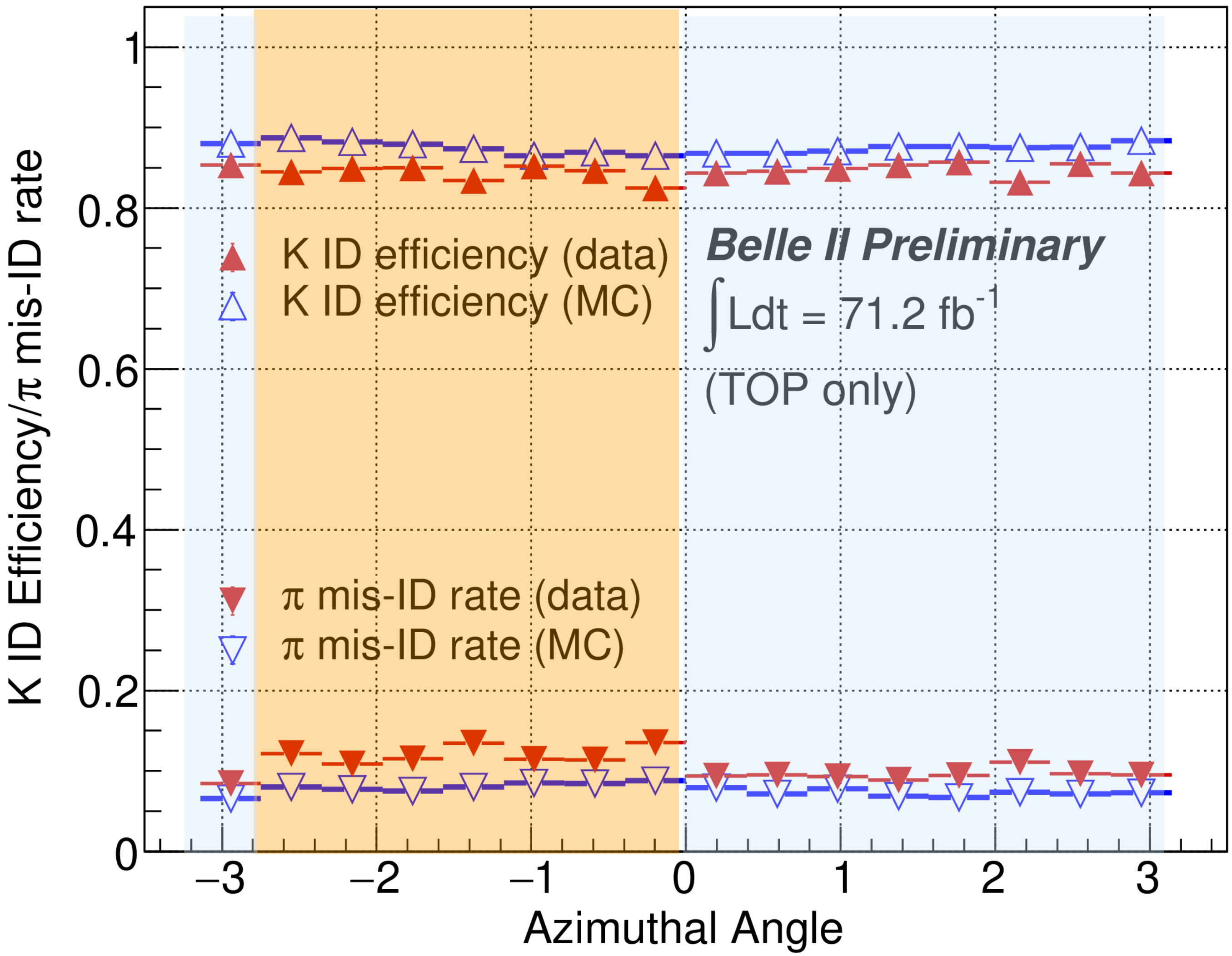


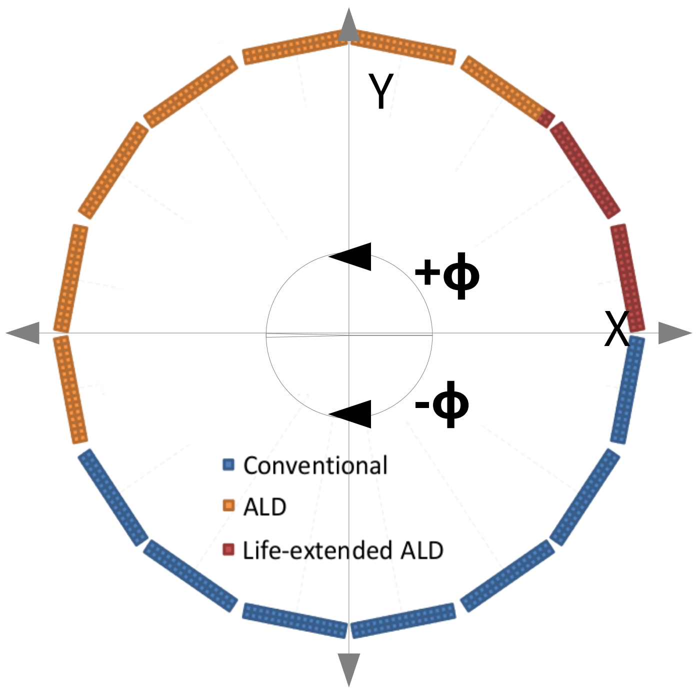
TOP only



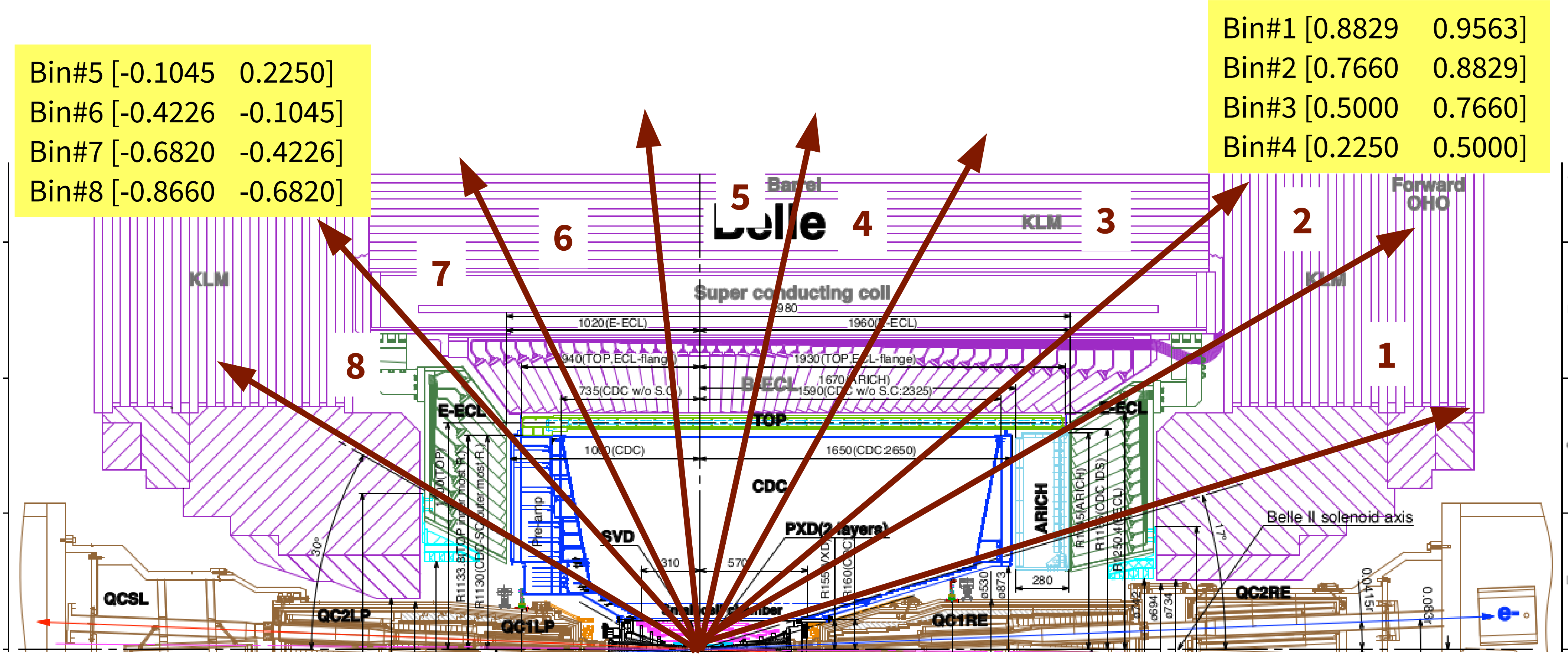
PID performance as a function of azimuthal angle

- Data-MC comparison for K-eff. and π mis-ID rate (TOP only) for R[K/π] > 0.5 w.r.t. azimuthal angle.

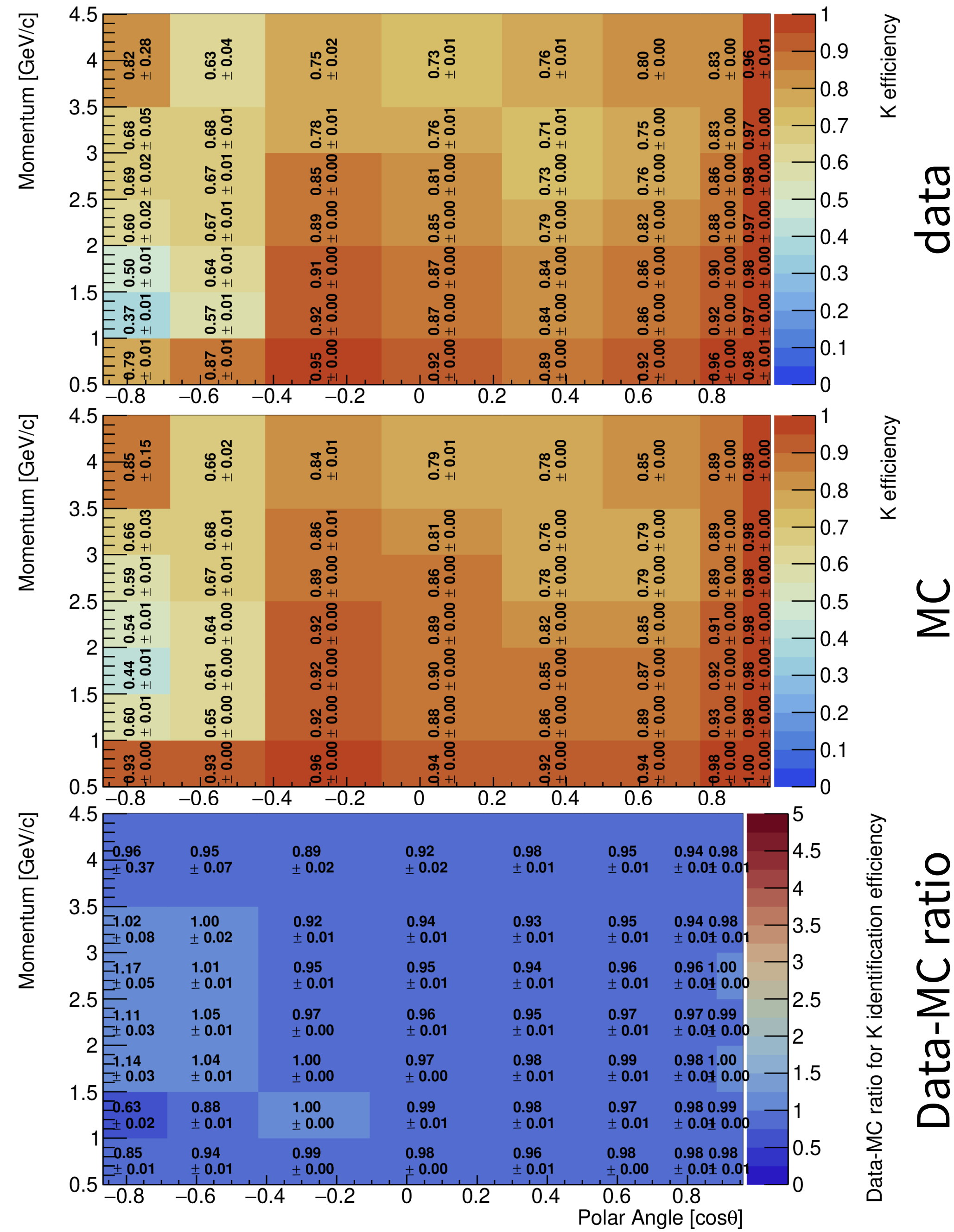




- The efficiency/fake-rate obtained from the MC sample for individual analysis needs to be corrected for the data case.
- Correction Ratio = efficiency in data/ efficiency in MC.
- These correction ratios are determined from control samples in bins of momentum and polar angles.
- For Hadron ID, the polar angle binning is decided keeping in mind the detector boundaries of ARICH, CDC and TOP

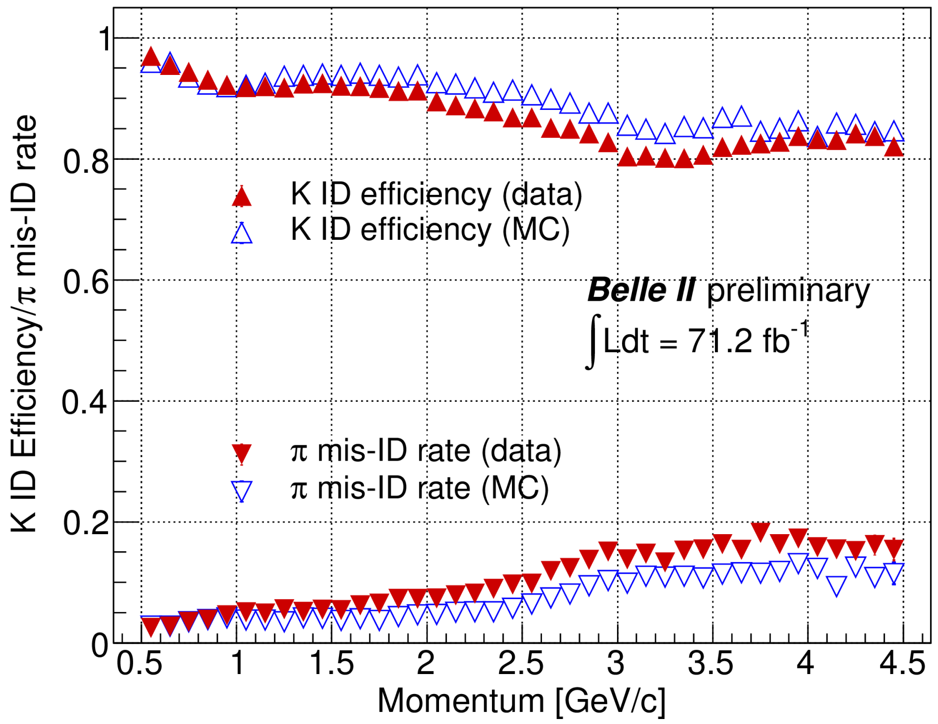


- The correction ratios (plotted here) are determined for K-eff for the requirement R[K:π] > 0.5.
- Kaon efficiency in data sample (top), in MC sample (middle) and data-MC ratio (bottom) [positive tracks].
- These corrections can be applied to the charged track (with hadron ID) according to their mometa/cos-theta distribution.
- Similarly, uncertainties on these correction factors should be included in systematic uncertainty.
- These numbers might be available in a table form, or systematic framework (in future) might be available to incorporate in any analysis.

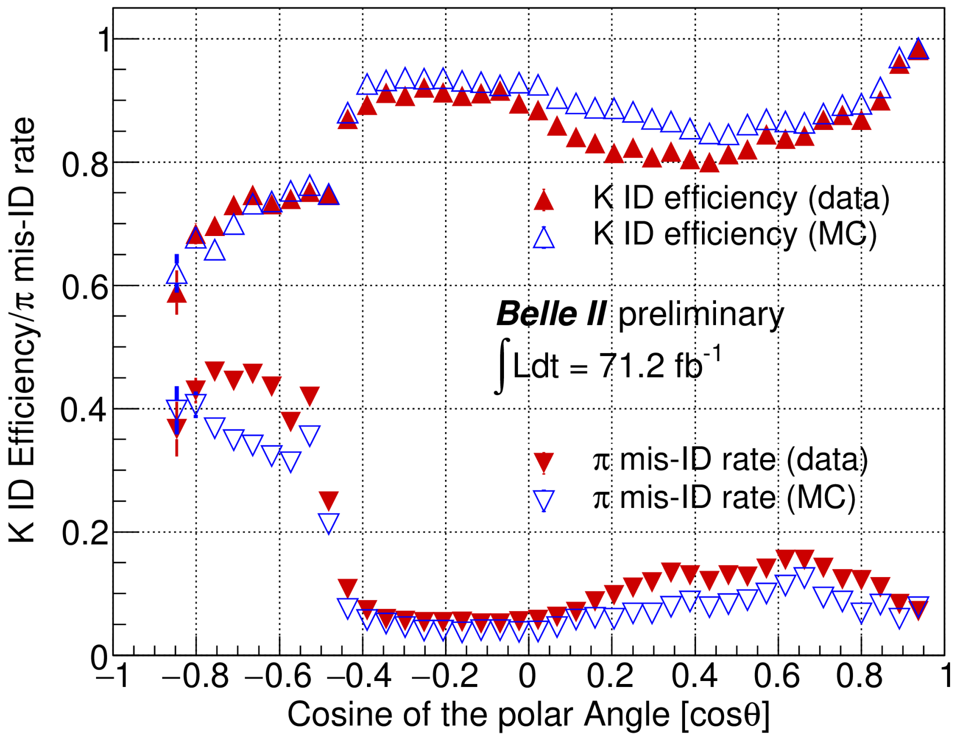


Summary

- Hadron ID (or Particle ID) is crucial for most of the analyses in Belle II. In order to achieve physics goals at Belle II, an efficient K/π separation is needed for the momentum range up to 4 GeV/c.
- The Belle II TOP detector provides the Hadron ID in the barrel region, and based on the Ring Imaging Cherenkov technique with fast time resolution.
- The TOP detector being calibrated with a data-driven method using kinematically tagged Kaons and pions from the D* sample.
- TOP currently achieves a Kaon identification of 84.6% at a mis-identification rate of 10.6% in a D* sample.
- The agreement with simulation is about 3% and is expected to improve further with larger calibration samples pending.



K-efficiency and π mis-ID rate for the PID criterion R[K/π]> 0.5 in bins of momentum for tracks, which produce atleast one hit in either the ARICH or TOP detector.



K-efficiency and π mis-ID rate for the PID criterion R[K/π]> 0.5 in bins of polar angle for tracks, which have momenta greater than 1 GeV/c

TOP : A closer look