Istituto Nazionale di Fisica Nucleare
SEZIONE DI TORINO

PID at Belle II

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Joining EICUG/ePIC collaboration meeting
July 25th 2024

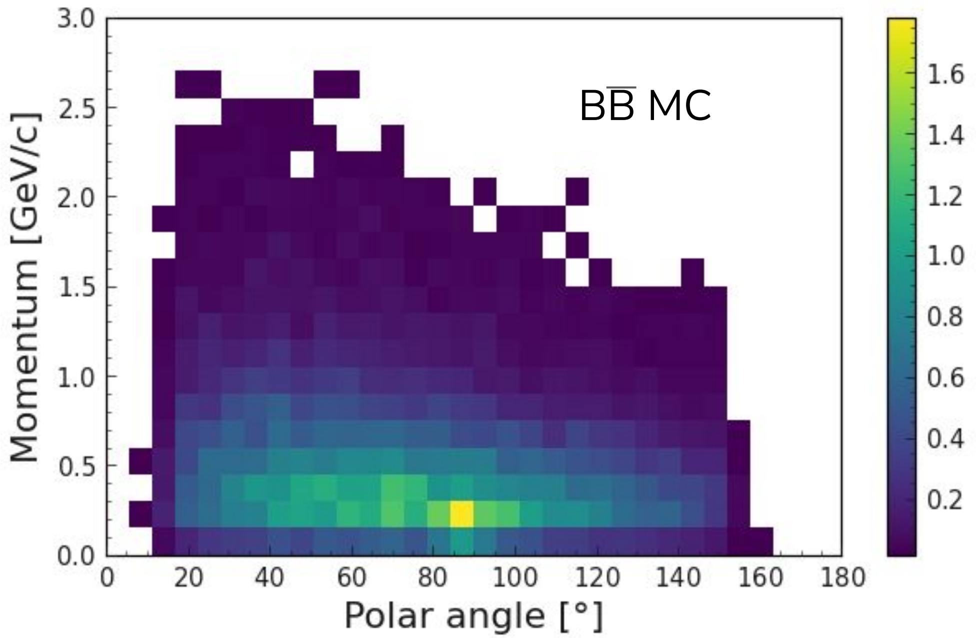
Belle II: the kinematics

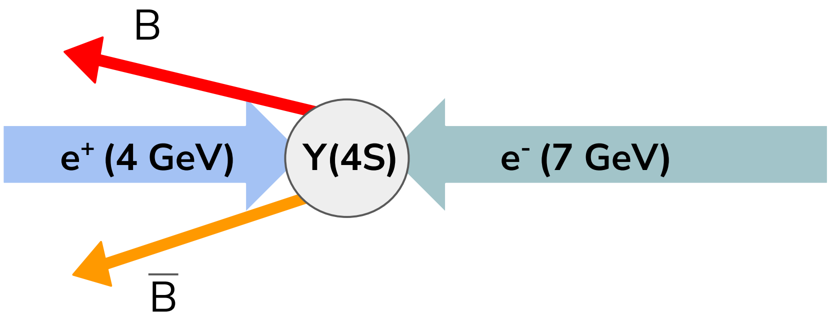
e^+e^- collisions at ~10.6 GeV

→ Asymmetric collisions

→ Focus on flavour physics: need for ID for all particle species

→ Low momentum: 50 MeV/c - 3 GeV/c





Belle II

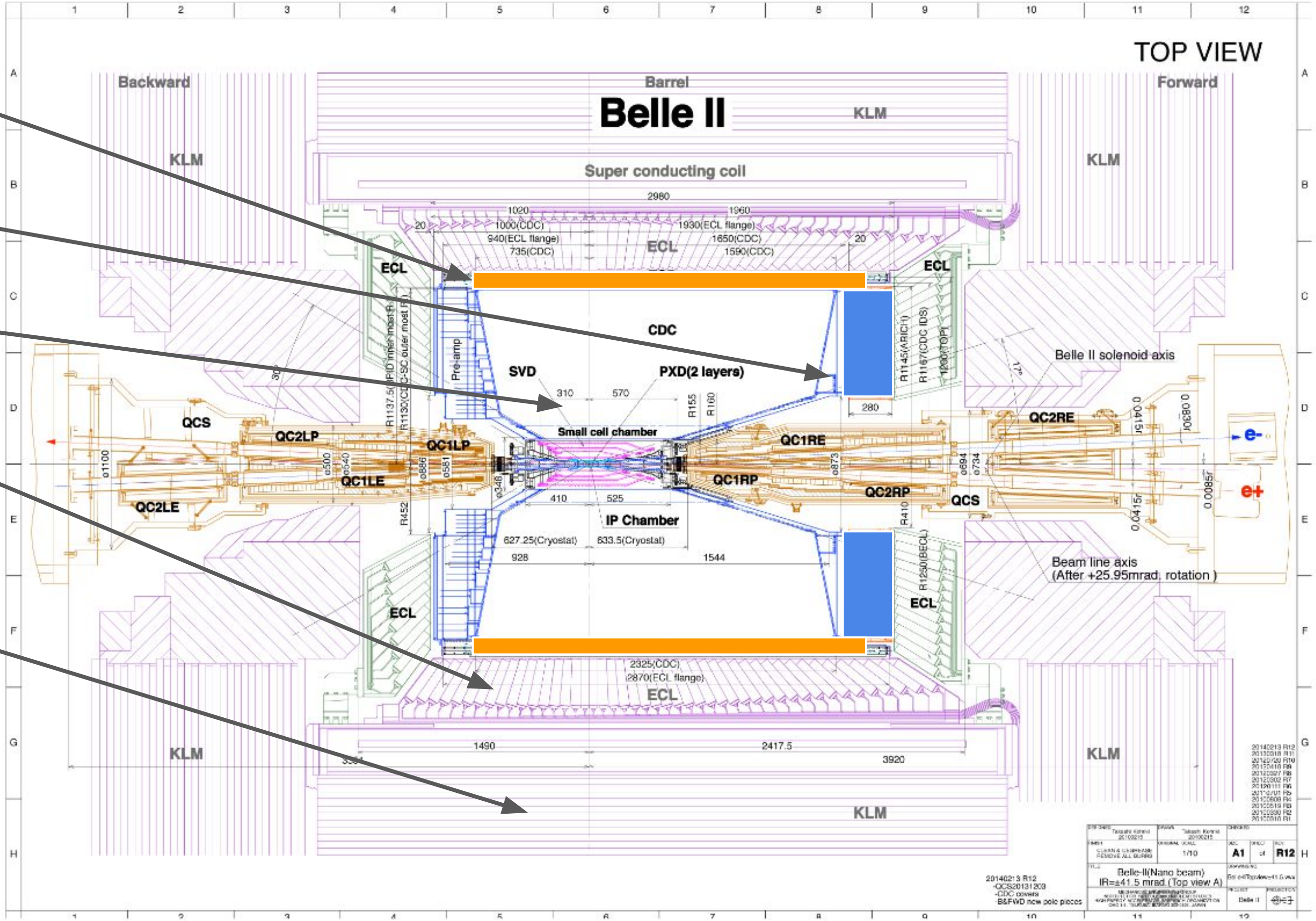
Barrel cherenkov: TOP

Endcap Cherenkov: ARICH

dEdx: SVD + CDC

Shower shape: ECL

Pen. depth: KLM



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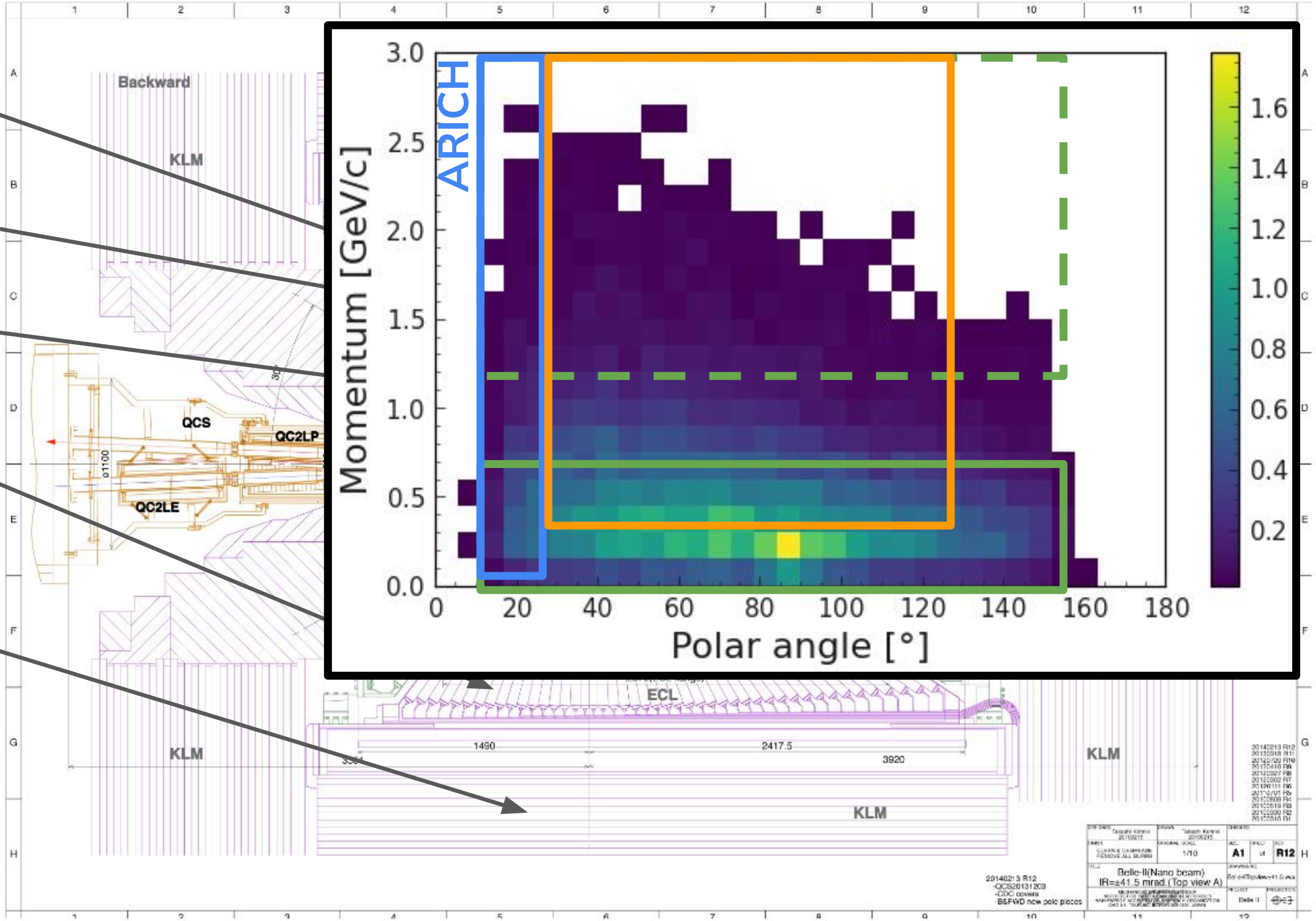


Combining information

Each sub-detector provides a likelihood value for 6 possible PID hypotheses:

→ electron, muon, pion, kaon, proton, deuteron

→ The likelihood values are calculated comparing the observed signal with the expectation for each particle hypothesis (based in MC, data template, or analytic models)

→ If particle is out-of-acceptance, LogL = 0 for all hypotheses

$$\mathcal{L}_\alpha^d = \mathcal{L}^d(\mathbf{x}|\alpha)$$

Likelihood for hypothesis α from detector *d* that observed **x** hits

$$\mathcal{L}(\mathbf{x}|i) = \exp\left(\sum_d^{d\in D} \log\mathcal{L}^d(\mathbf{x}|i)\right)$$

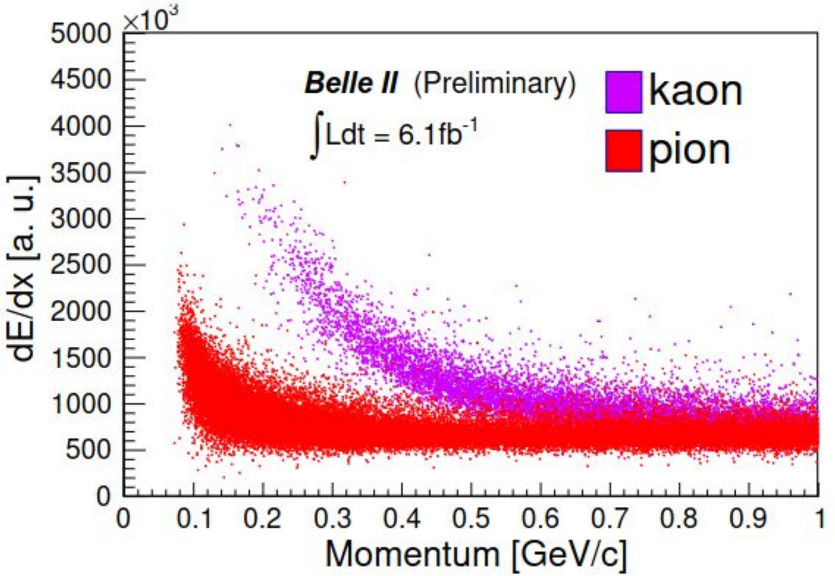
Likelihood for hypothesis α from all detectors

$$P(A_i|\mathbf{x}) = \frac{P(\mathbf{x}|A_i)\cdot P(A_i)}{\sum_j P(\mathbf{x}|A_j)P(A_j)} \quad \Rightarrow P(i|\mathbf{x}) = \frac{\mathcal{L}_i}{\sum_j \mathcal{L}_j}$$

PID probability

Silicon tracker

→ PDF is templated directly from data using tagged p, K, protons



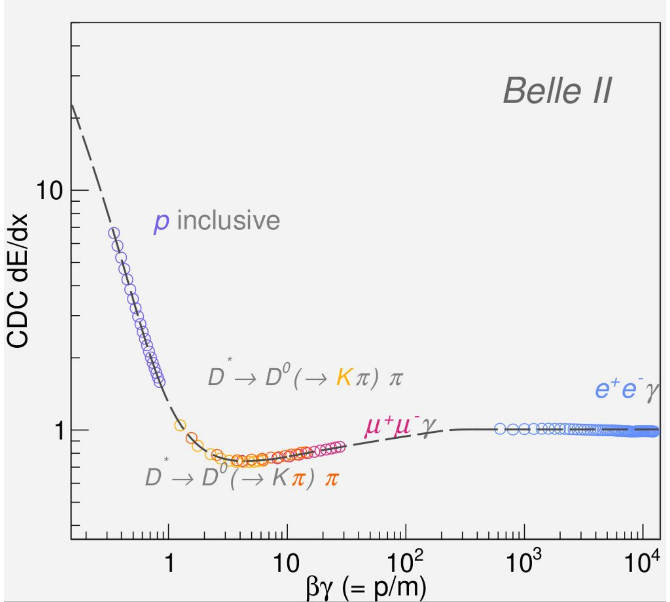
$$\mathcal{L}_{\alpha}^{\mathrm{SVD}}(\mathrm{d}E/\mathrm{d}x,\ p) = \prod_i \mathcal{P}_{\alpha}[(\mathrm{d}E/\mathrm{d}x)_i, p]$$

Silicon tracker

→ PDF is templated directly from data using tagged p, K, protons

Drift chamber

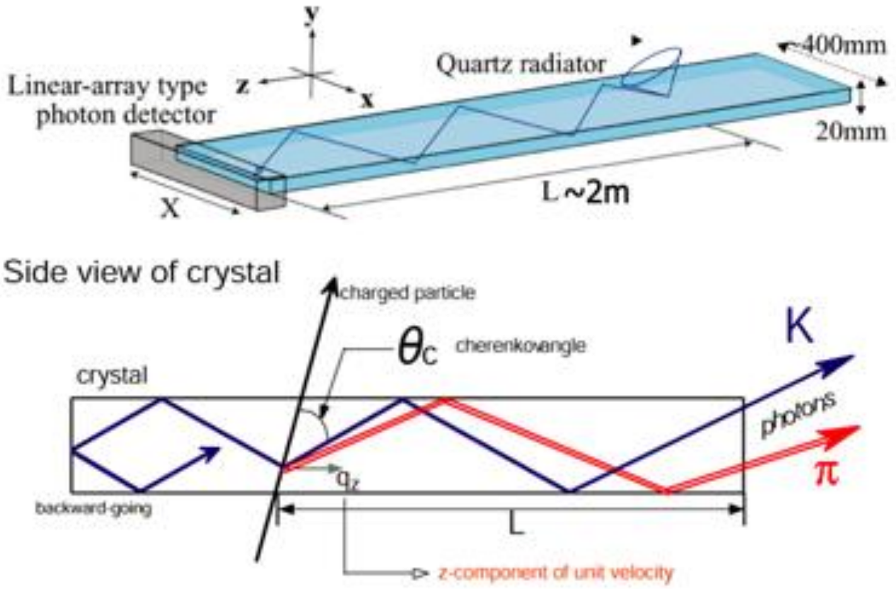
→ Calculate the expected dE/dx after running several data-driven calibrations



$$\chi_\alpha = \frac{(\mathrm{d}E/\mathrm{d}x)_{\mathrm{meas}} - (\mathrm{d}E/\mathrm{d}x)_{\mathrm{pred}}}{\sigma_{\mathrm{pred}}}$$

$$\mathcal{L}_\alpha^{\mathrm{CDC}} = \exp\left(-\frac{\chi_\alpha^2}{2}\right)$$

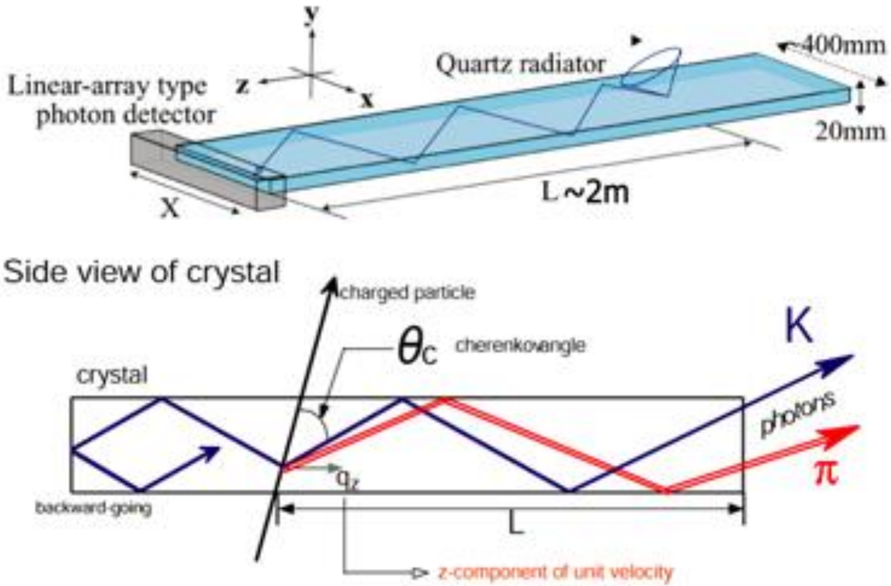
Time-of-Propagation



Time Of Propagation counter

- Long and thin fused silica radiators
- Cherenkov angle is function of the time spent by the photons in it
- Mostly PID by timing

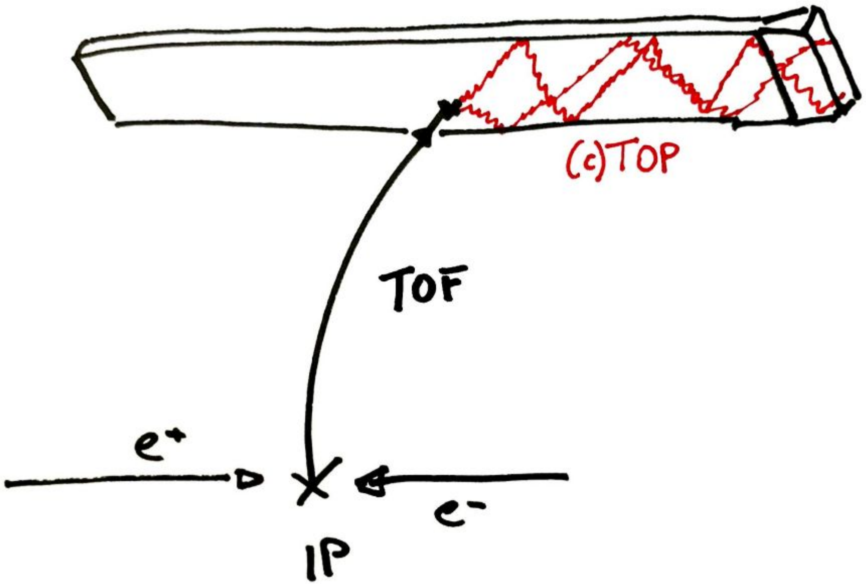
Time-of-Propagation



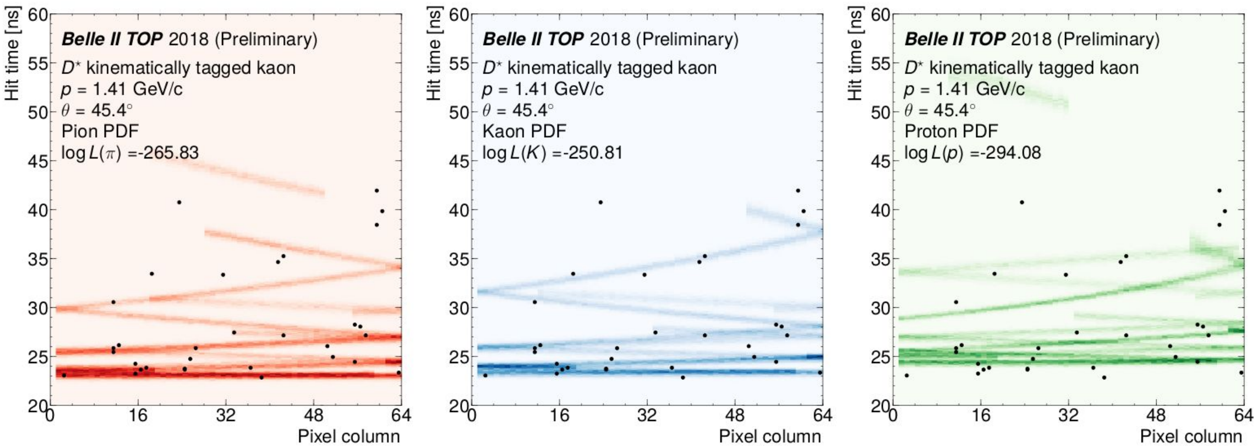
Combination the **ToF** and the **Cherenkov angle** in one single measurement

Time Of Propagation counter

- Long and thin fused silica radiators
- Cherenkov angle is function of the time spent by the photons in it
- Mostly PID by timing



Time-of-Propagation



1.41 GeV

mirror-facing event

$$\mathcal{L}_\alpha^{\mathrm{TOP}} = \exp\left[\sum_{i=1}^{N} \log\left(\frac{N_\alpha S_\alpha(c_i,t_i) + N_B B(c_i,t_i)}{N_\alpha + N_B}\right) + \log P_N(N_\alpha + N_B)\right]$$

Dual aerogel proximity RICH

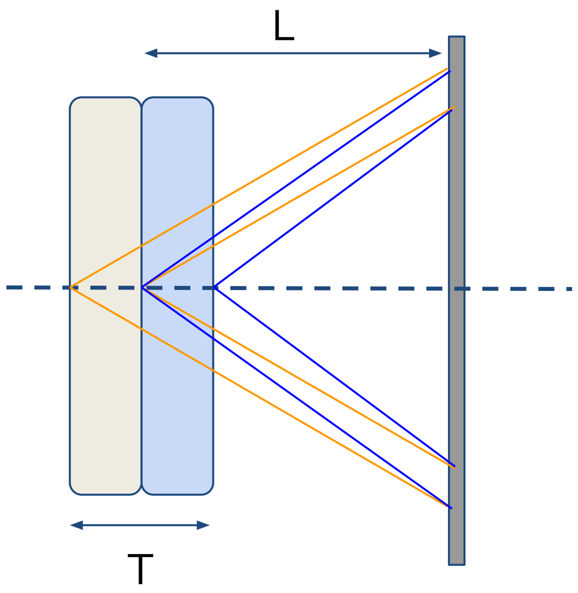
Dual radiator (but another kind of)

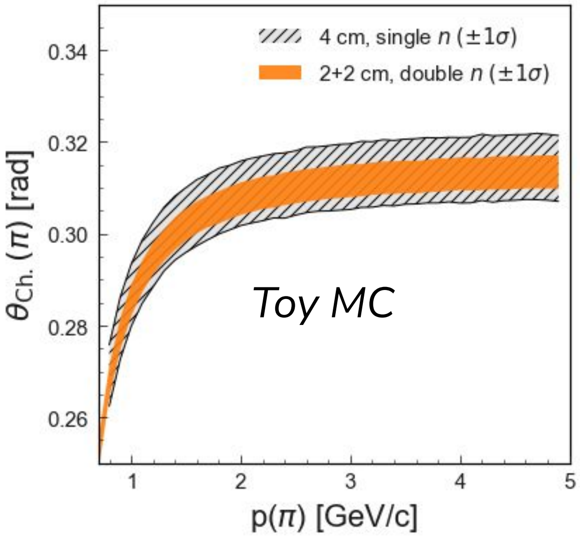
→ Two thin (2 cm) layers with different refractive index

→ Tuned to have **overlapping rings**

$$\sigma_\theta^{tot} = \frac{\sigma_\theta^{radiator} \oplus \sigma_\theta^{detector} \oplus \sigma_\theta^{chrom}}{\sqrt{N_\gamma}}$$

∝T/2L (radiator), **∝1/L** (detector), **∝T** (N_γ)

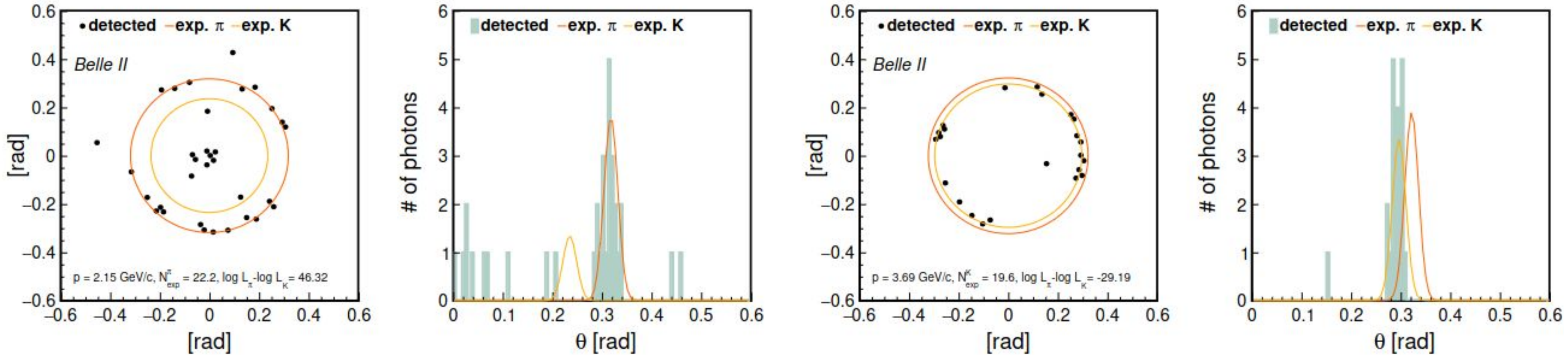




Dual aerogel proximity RICH

Dual radiator (but another kind of)

→ Two thin (2 cm) layers with different refractive index
→ Tuned to have **overlapping rings**
→ Reconstruction: count the number of hints in the expected ring



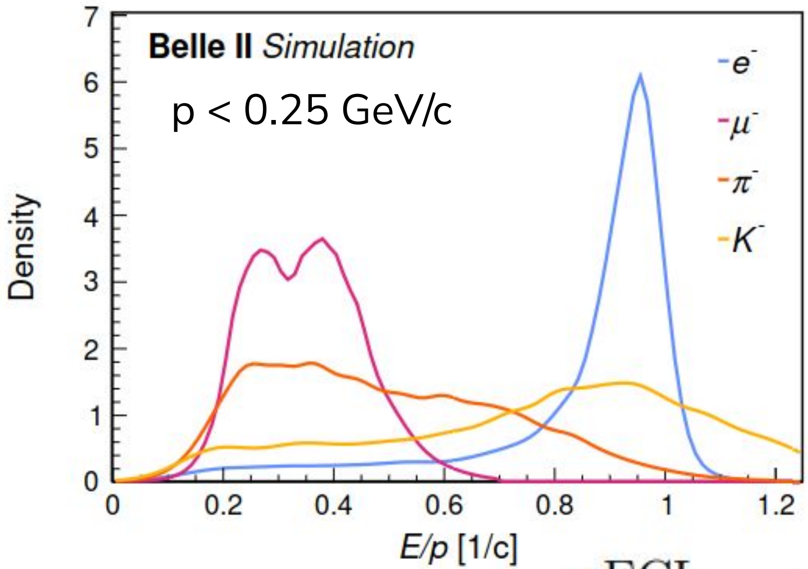
$$\mathcal{L}_\alpha^{\mathrm{ARICH}} = \exp\left[-N_\alpha + \sum_{k=1}^{N}\left(n_{\alpha,k} + \log(1 - e^{-n_{\alpha,k}})\right)\right]$$

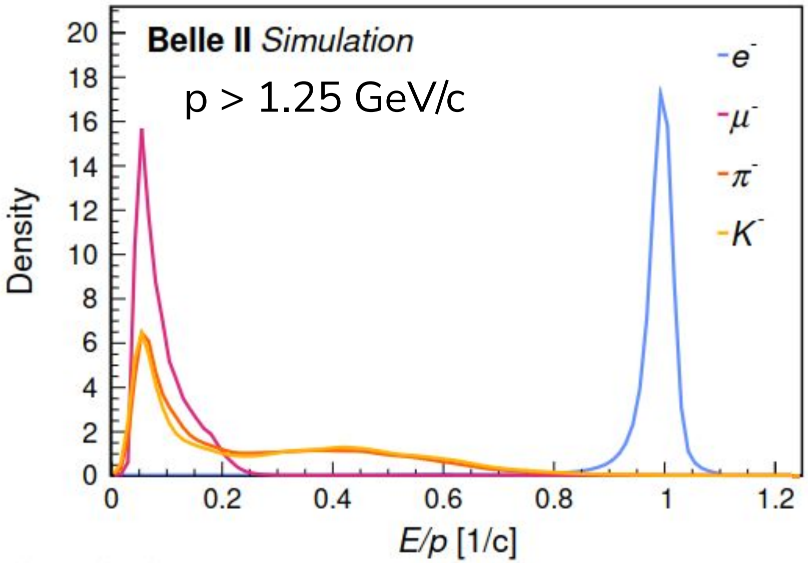
Calorimeter and K_L system

Electromagnetic calorimeter

→ Use the E/p ratio, PDF templated from MC.

→ More recently: combine all shower shape variables into a BDT

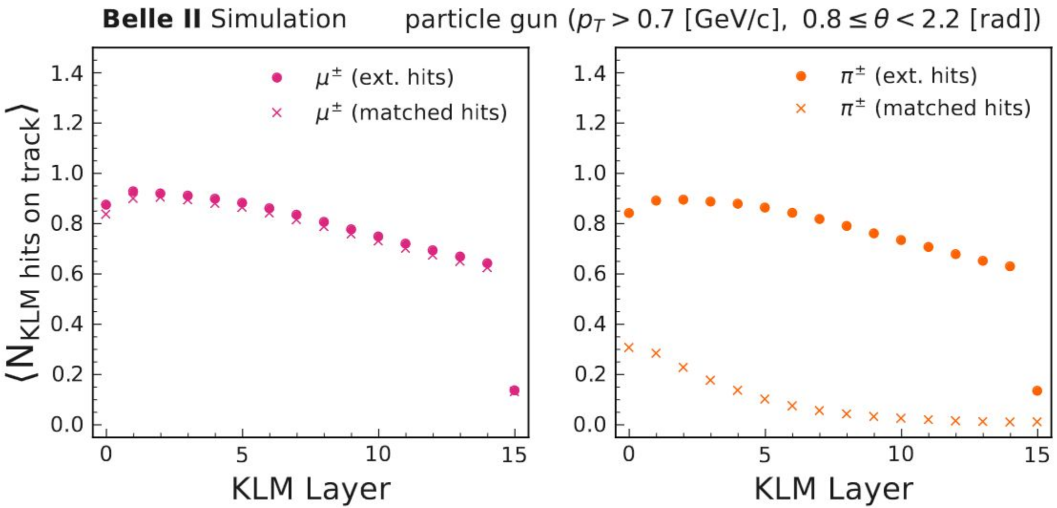




$$\mathcal{L}_{\alpha}^{\mathrm{ECL}} = \mathcal{P}_{\alpha}(E/p)$$

KLM (instrumented return yoke)

→ use the penetration depth in the iron plates, accounting for the scintillator efficiency



$$\mathcal{L}_{\alpha}^{\mathrm{KLM,L}} = \prod_{k=1}^{N_{\mathrm{ext}}} \mathcal{L}_{\alpha,k}^{\mathrm{L}}$$

$$\mathcal{L}_{\alpha,k}^{\mathrm{L}} = p_{\alpha,k} \quad \text{if hit}$$

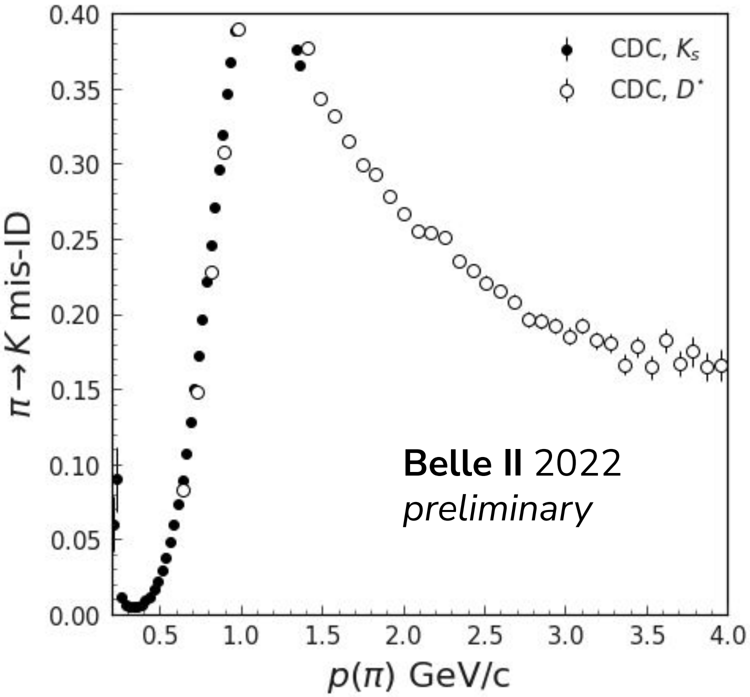
$$\mathcal{L}_{\alpha,k}^{\mathrm{L}} = (1 - p_{\alpha,k}\varepsilon_k) \quad \text{if not hit}$$

The impact of TOP and ARICH

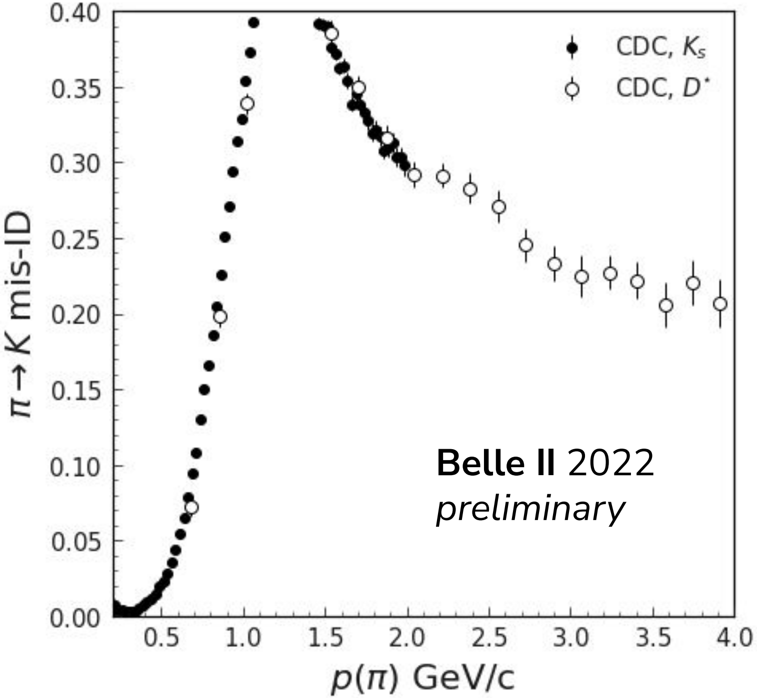
π → K mis-identification probability in collision data

- True pions tagged in D and K_s decays
- Ask for LL(K) > LL(π)

in TOP acceptance



in ARICH acceptance



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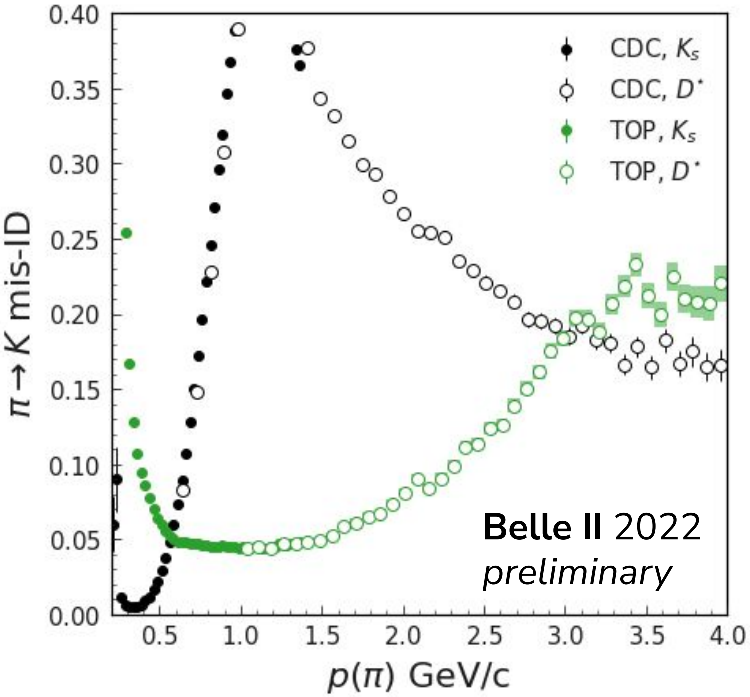
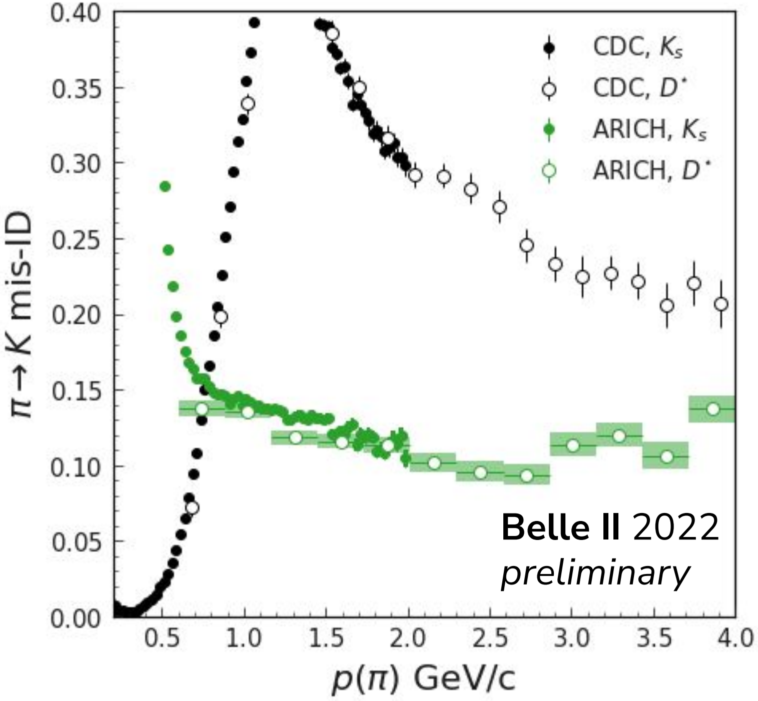
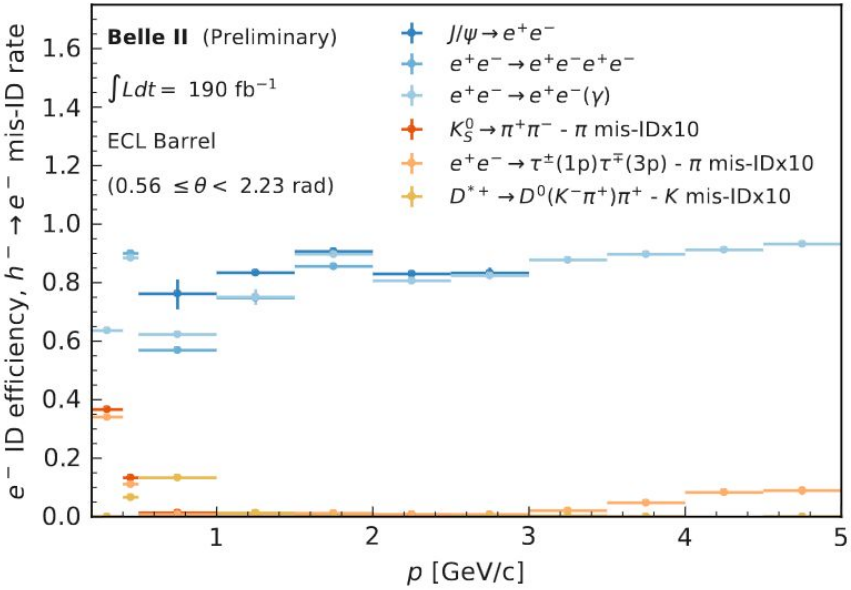


in ARICH acceptance



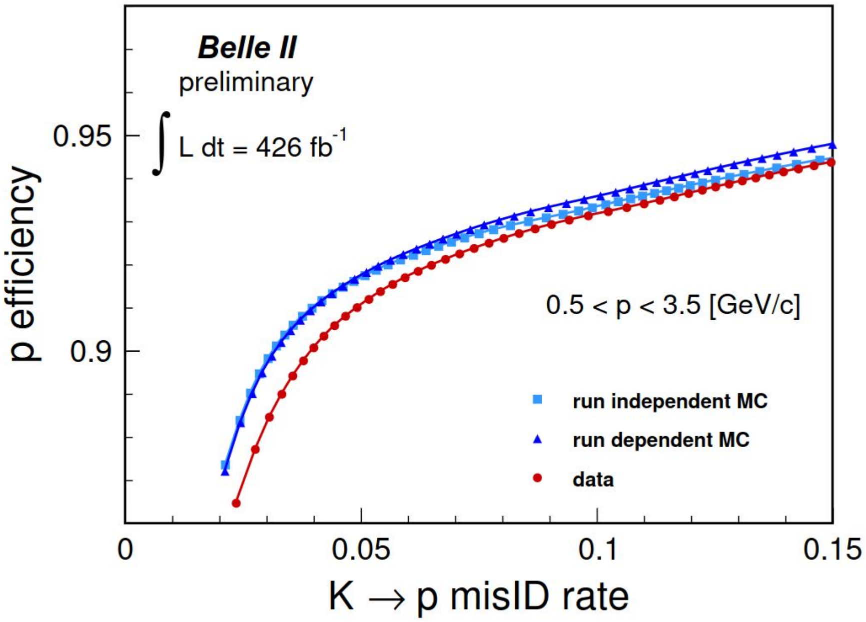
Global performance

Electron-pion separation



(c) eID > 0.9 selection.

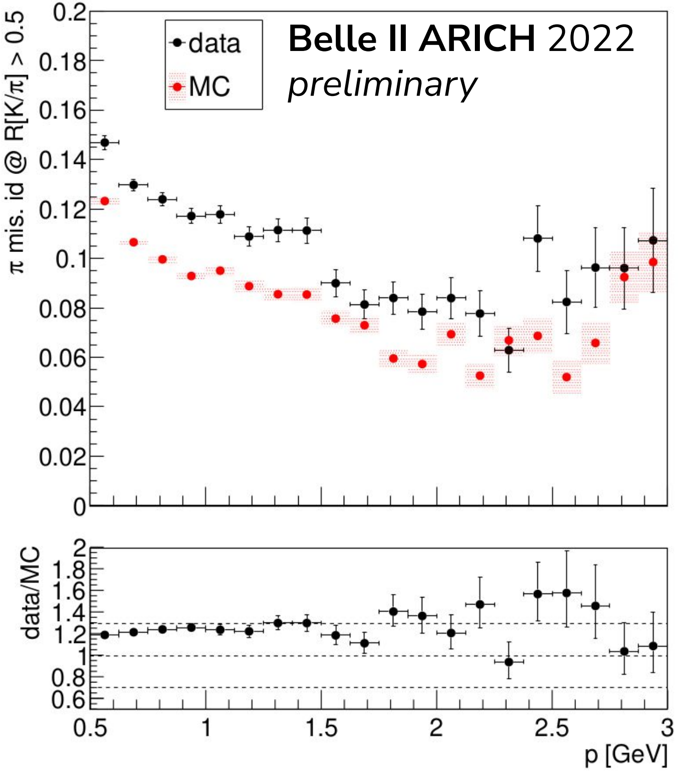
Kaon-proton separation

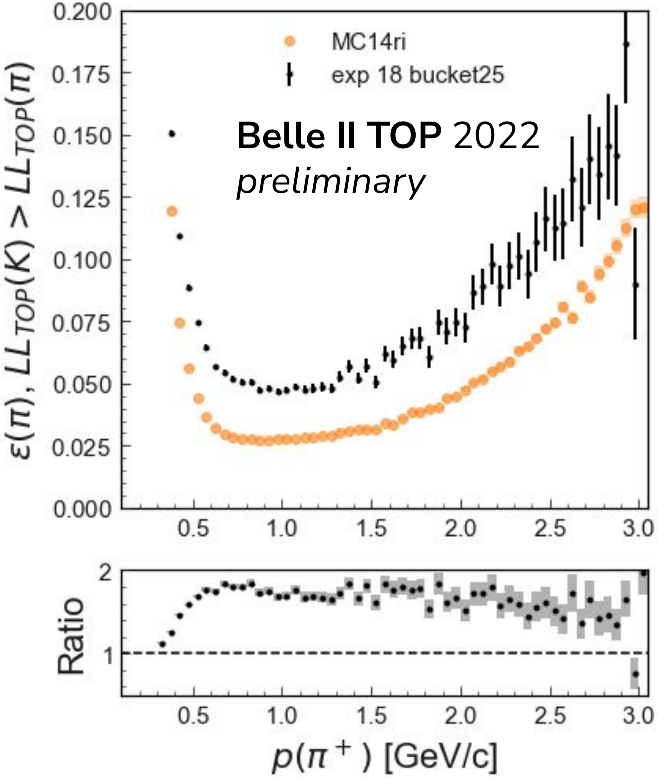


Expectations VS reality

Performance observed in data still don’t match with (optimistic) MC

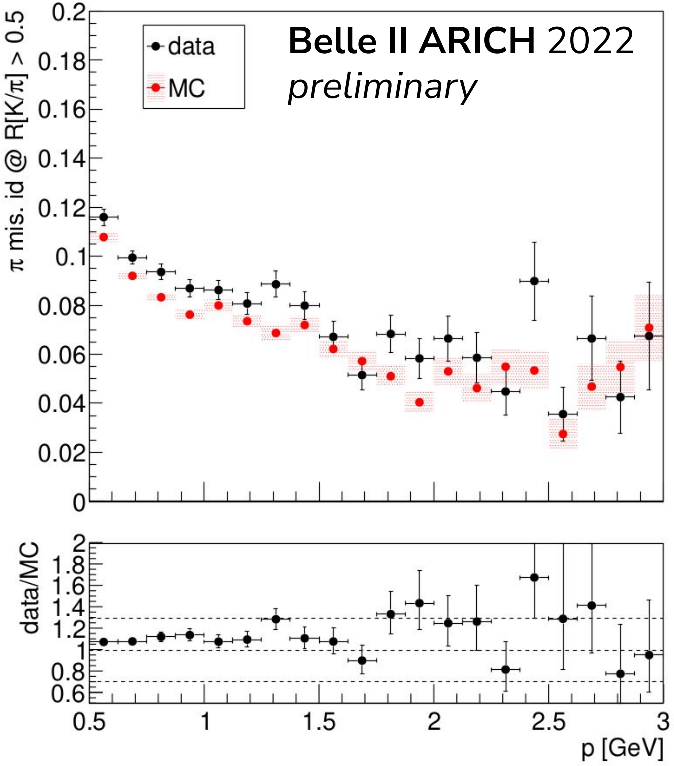
- Many lessons learned so far!





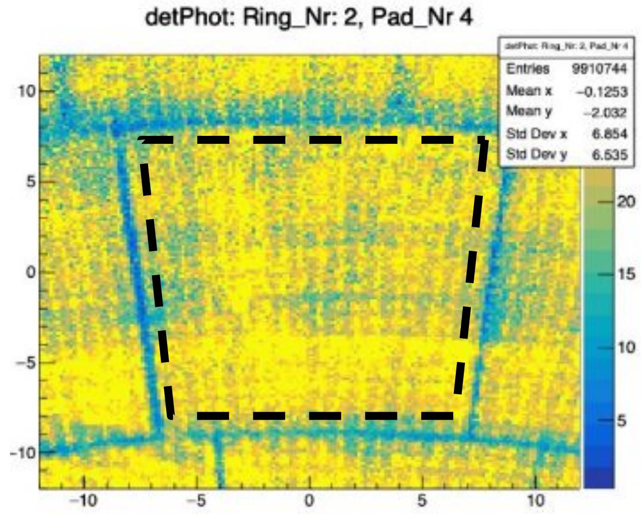
Lessons learned: ARICH tile alignment

Aerogel tile edges are responsible for most of the disagreement in ARICH



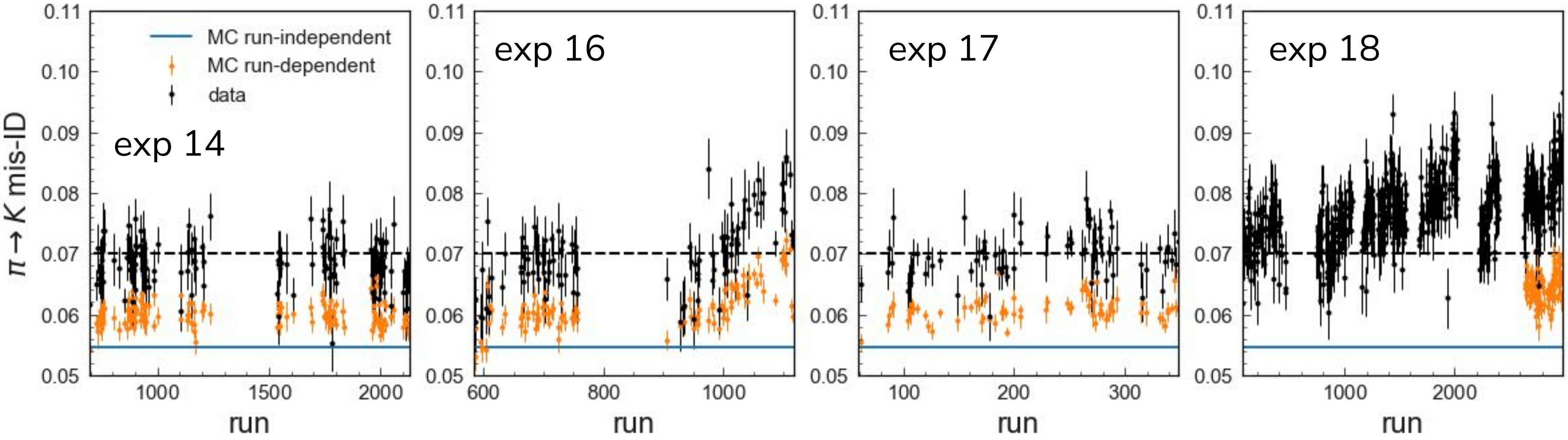
Removing tracks extrapolated in the edges

- Improves PID (expected) reducing acceptance
- Improves data/MC (not expected)
  - Work towards better tile alignment



Lessons learned: background effects on TOP

For TOP, half of the data/MC disagreement is recovered with more realistic simulation
→ Actual dead/hot channel maps form data
→ Backgrounds from random triggers instead of simulation

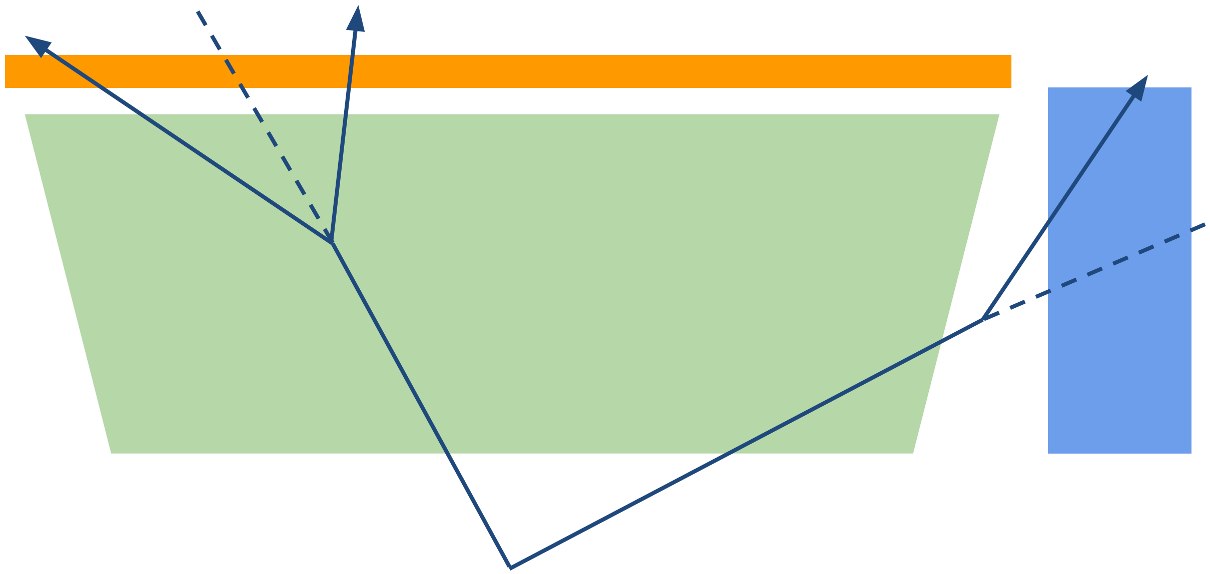


Residual discrepancy is under investigation.

Lessons learned: extrapolating is dangerous

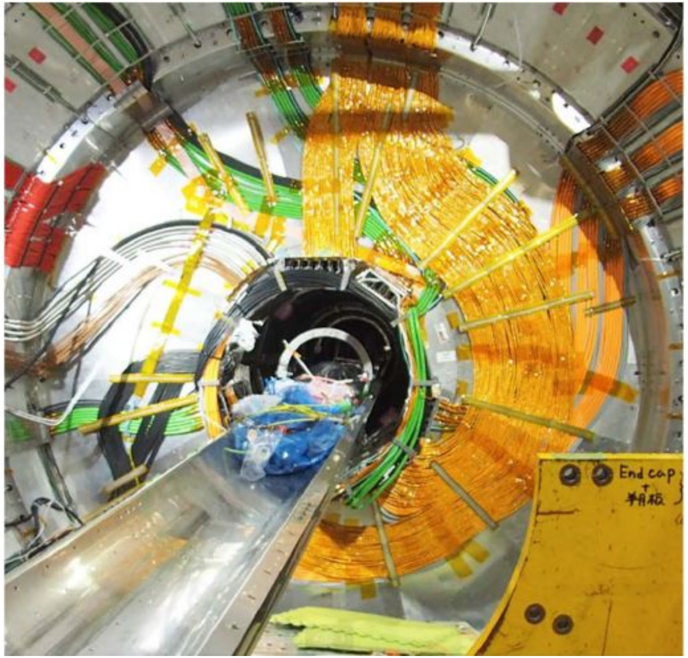
Both TOP and ARICH are outside the tracking volume

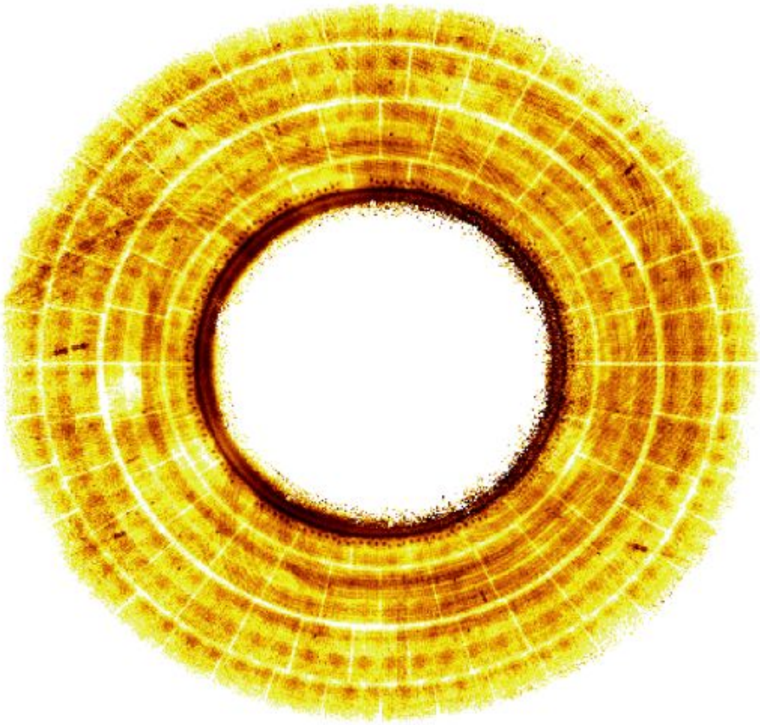
- Rely on track extrapolation
- Decays-in-flight and hard scattering lead to wrong extrapolation
- **Significant PID degradation from hard-scattering**



Lessons learned: hard scattering in ARICH

Sizable material budget in front of ARICH
→ CDC backplane, inner tracker cables...
→ Clearly seen mapping the impact points of electrons with associated photons

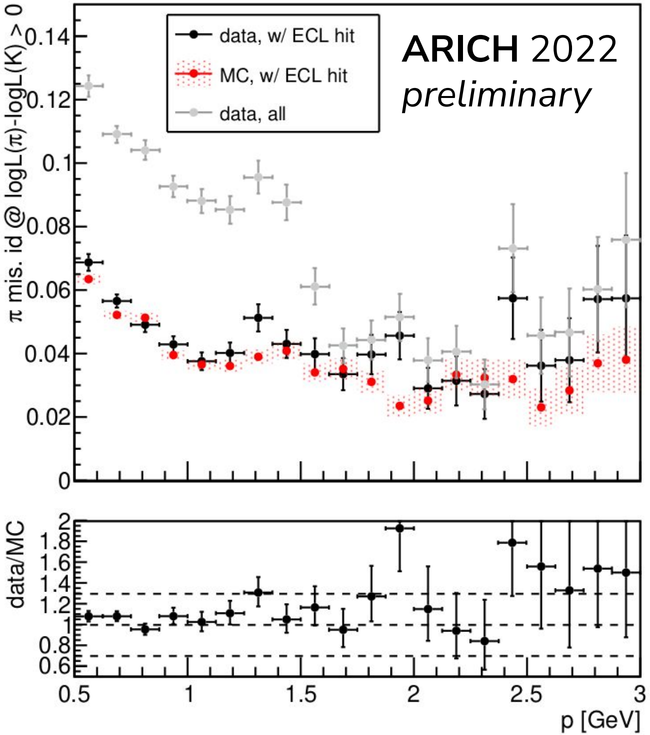


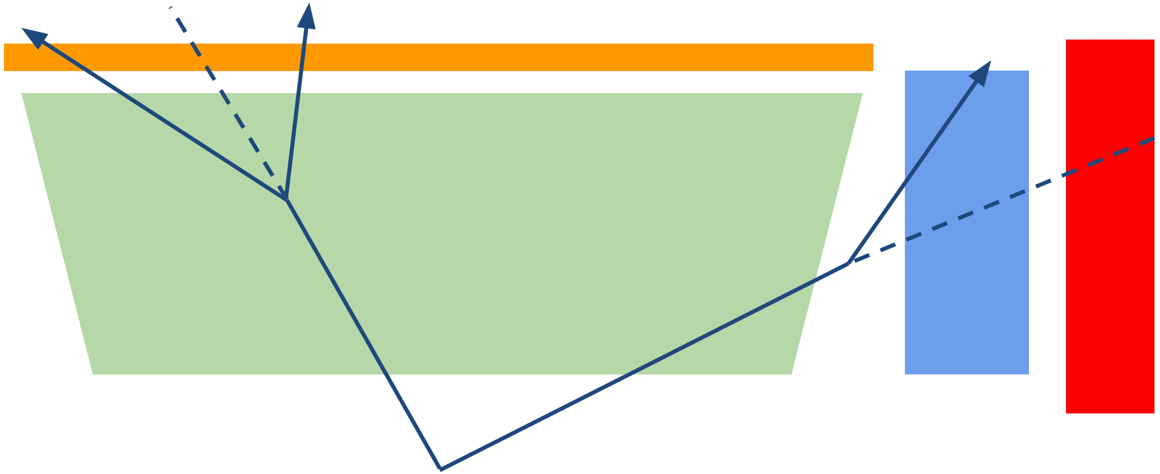


Mitigating material scattering

Use the Calorimenter behind ARICH and TOP to remove bad extrapolations

- Require a cluster matched with the track
- Powerful tool, but introduced correlation between subdetectors…





User's end-point

INFN

We save only the LogL values in the mDST

- ~20% of raw data are always available for extra studies

Particle identification probabilities are calculated on-fly by the analysis libraries

- Users can choose which type or probability (global, binary, ternary…)
- Users can choose which detectors are to be used

```
electronID, muonID, pionID, kaonID, protonID, deuteronID

pidPairChargedBDTScore(pdgCodeHyp, pdgCodeTest)
```

"Expert" variables

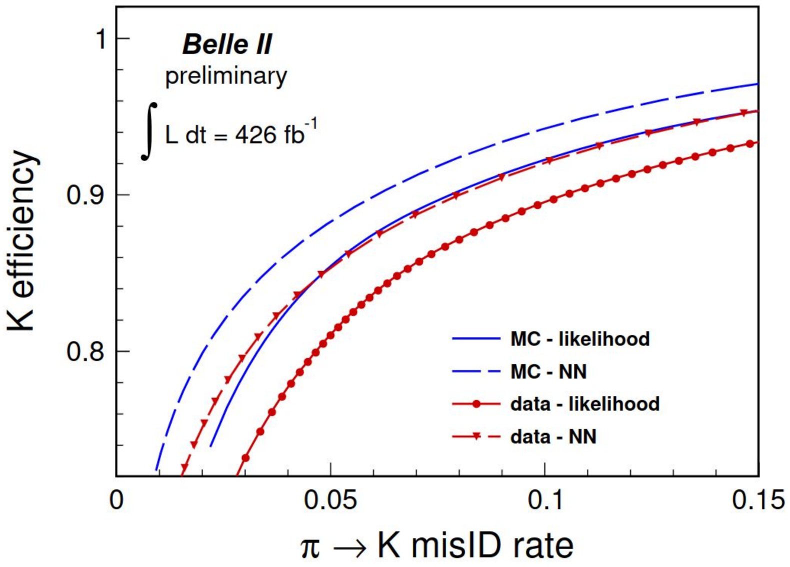
```
pidLogLikelihoodValueExpert(pdgCode, detectorList)

pidDeltaLogLikelihoodValueExpert(pdgCode1, pdgCode2, detectorList)

pidPairProbabilityExpert(pdgCodeHyp, pdgCodeTest, detectorList)

pidProbabilityExpert(pdgCodeHyp, detectorList)
```

Future developments

Pure Log-likelihood combination SHOULD be the best estimator if:

- All LL are well defined
- There are no correlations between detectors

Beam background level, tracking, pre-showering in the PID detectors and backsplash from calorimeter are correlating the PID detector response.



If one trains a NN to combine the Log-Likelihoods, performance are improved

Backup

The TOP counter at Belle II

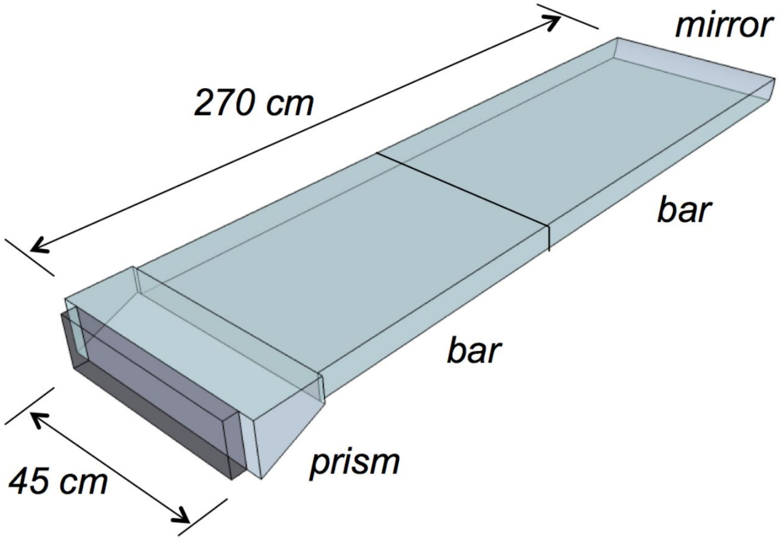
TOP implementation in Belle II:

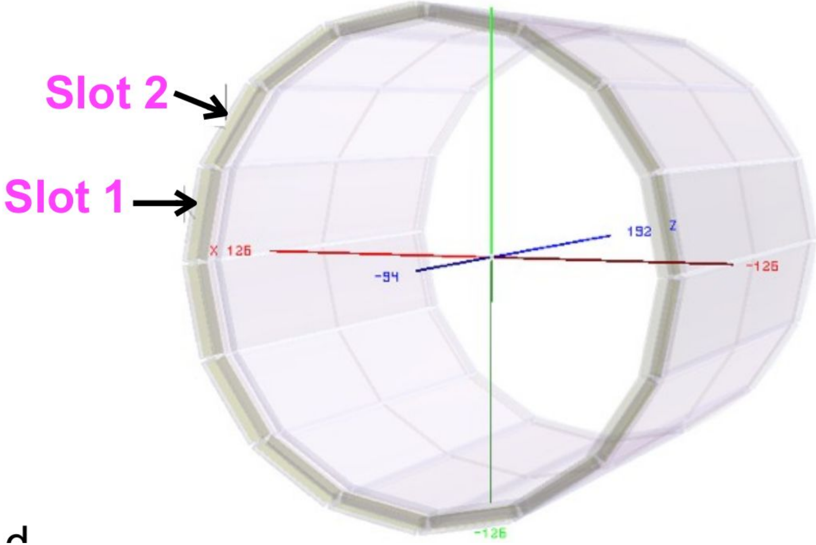
→ 16 modules (or slots) arranged around the interaction point

→ Each module is made of two identical bars of fused silica glued together

→ Backward side: expansion prism, PMTs and readout

→ Forward side: spherical mirror



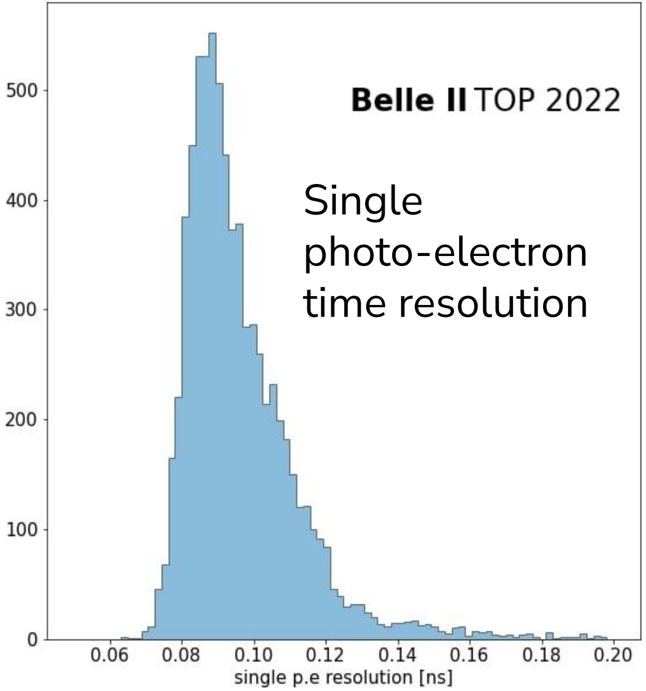


TOP: readout and its performance

Hamamatsu MCP-MPTs
→ 23x23 mm, 5 mm pixel
→ NaKSbCs photocathode; QE ≥ 24% (28% on average) at 380 nm
→ 55% collection efficiency
→ Gain = 10^5 – 10^6
→ **Transient time spread < 40 ps**
NIM A, 766, p. 163-166. (2014)

Readoud: IRSX Scope-on-a-chip
→ 8 channel waveform digitizer
→ 500 MHz Bandwidth
→ 2.7 GSa/s
→ 11.6 μs storage buffer
→ *Full waveform output*
→ ***28 ps resolution***

NIM A 941, 162342 (2019)



TOP sensors

Hamamatsu MCP-MPTs
→ 23x23 mm, 5 mm pixel
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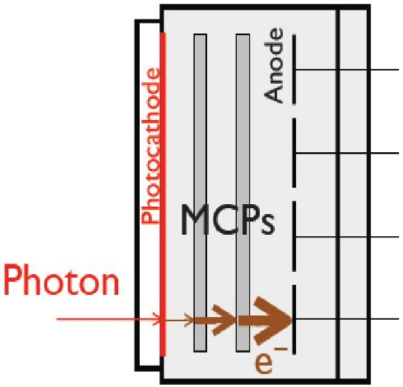
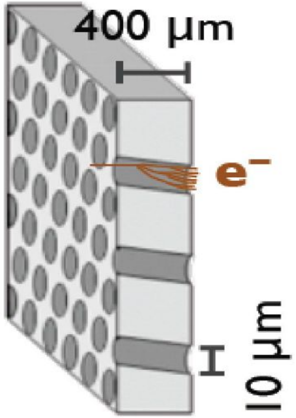
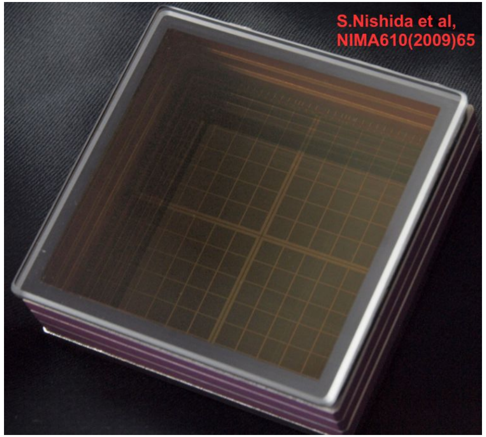




ARICH sensors



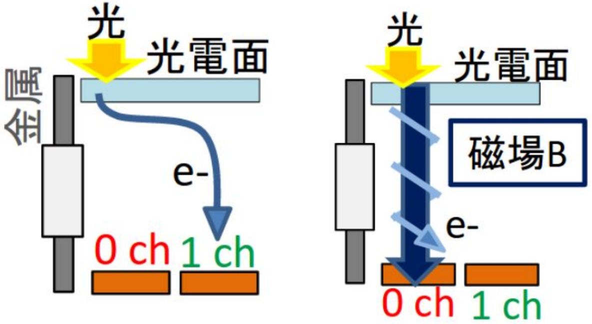
Hamamatsu Hybrid Avalanche Photo Detector (HAPD)

→ 63x63 mm, 4.9mm pixel.

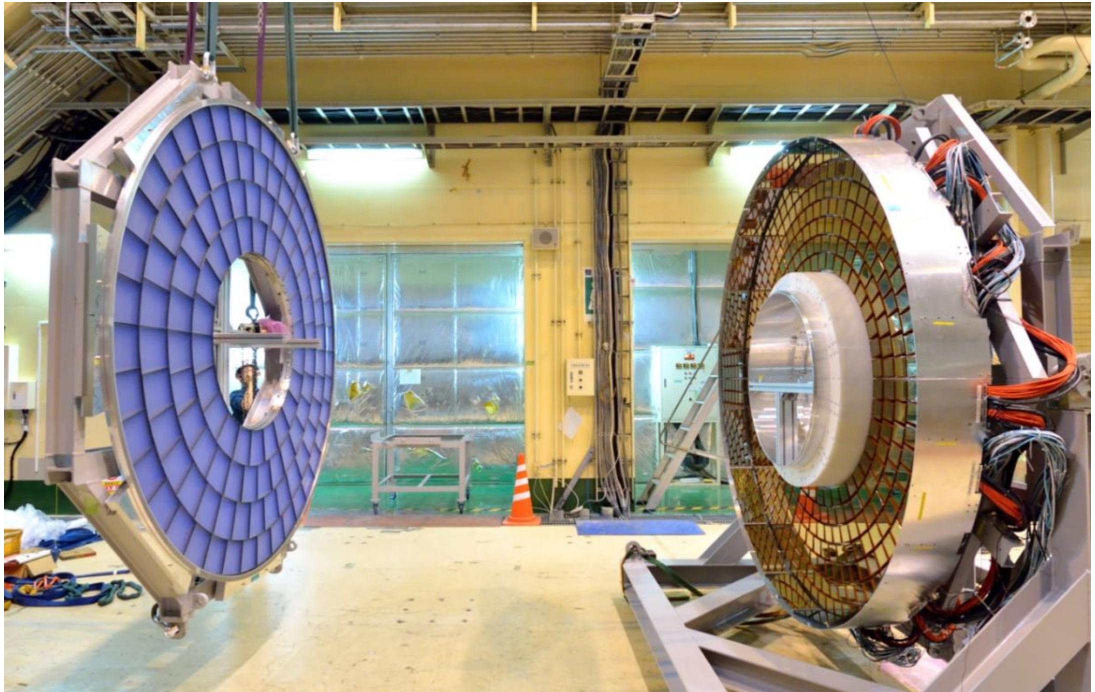
→ NaKSbCs photocathode; QE ≥ 24%
(28% on average) at 380 nm

→ Gain = Signal gain = $4x10^4$ by
Hybrid amplification process.
Operation in 1.5 T magnetic field

Enhancement in the magnetic field



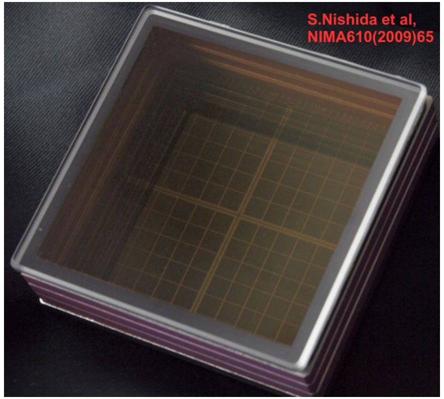
Belle II ARICH structure

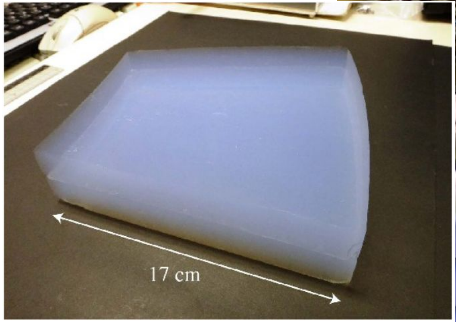


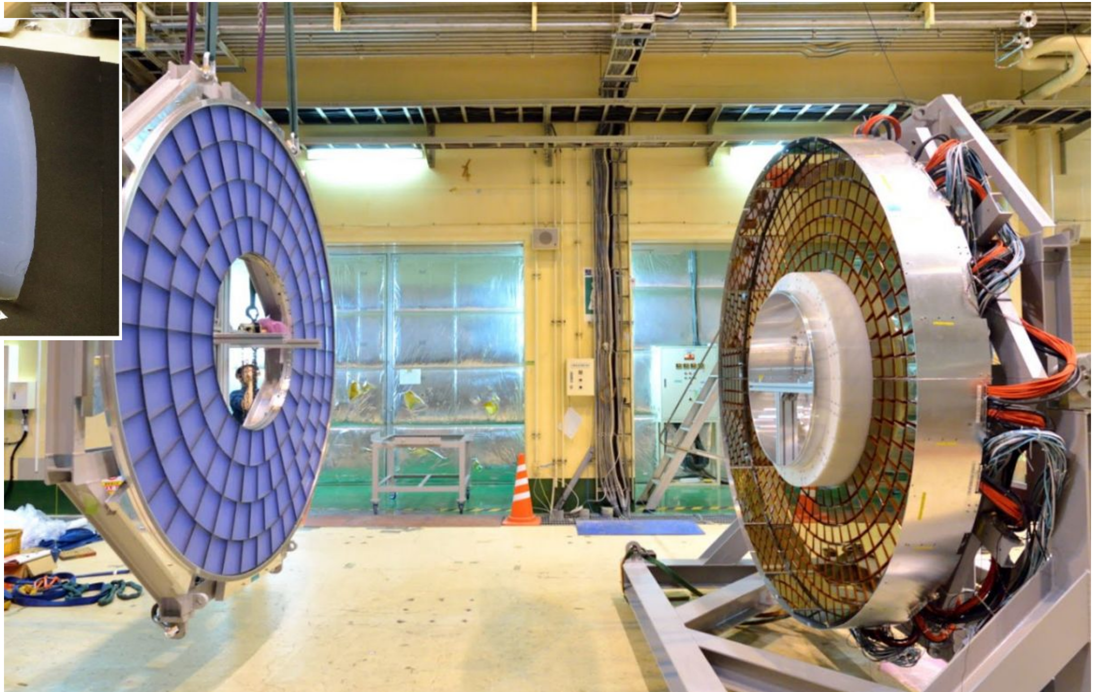
Belle II ARICH structure

Hydrophobic Aerogel
→ 17x17 cm, 2cm thick
→ Trans. length > 30 mm at 300 nm
→ $n_1 = 1.045$, $n_2 = 1.055$

Hamamatsu Hybrid Avalanche Photo Detector (HAPD)
→ 63x63 mm, 4.9mm pixel.
→ QE ~ 28% at 380 nm
→ Gain = 4×10^4



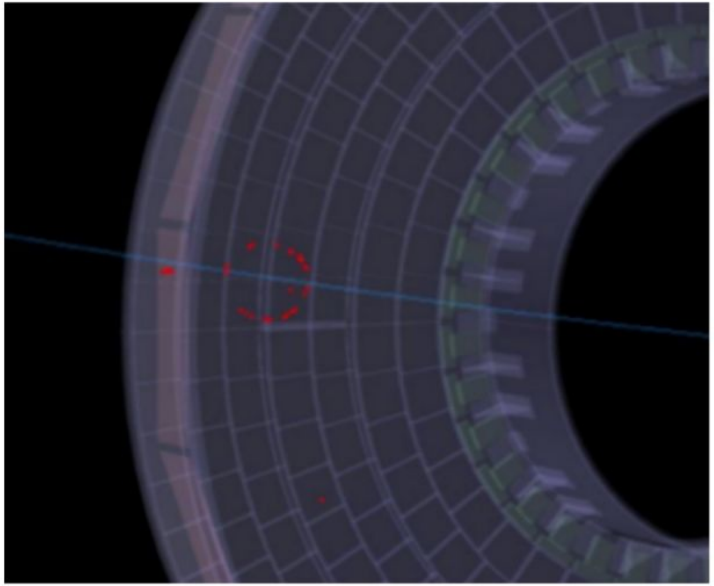


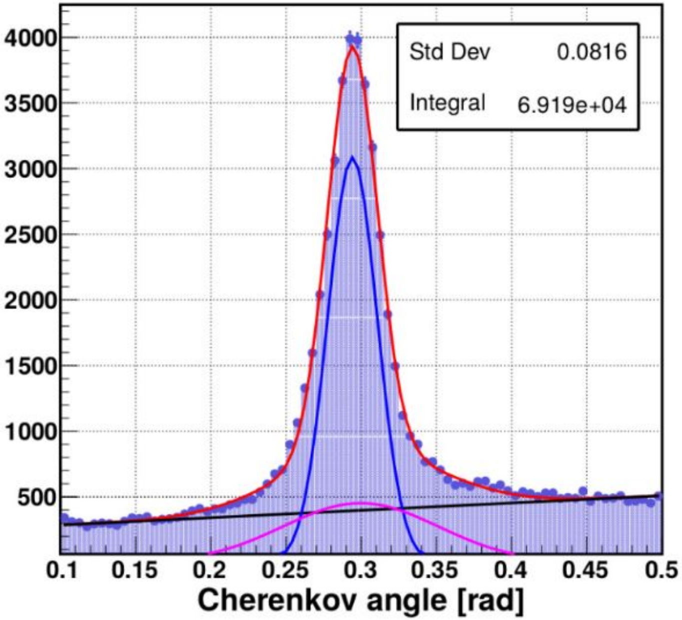


See Rok's poster for more info!
https://agenda.infn.it/event/22092/contributions/167676/

Belle II ARICH: low-level performance

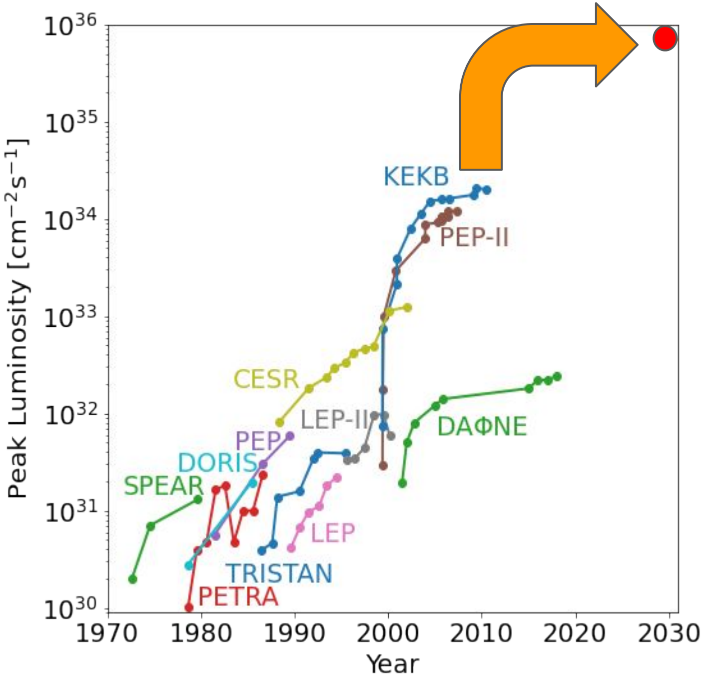
Cherenkov angle resolution from bhabha events: **14 mrad**





Super-KEKB and the nanobeam scheme

Belle II goal: collect 50 ab^{-1} (~50x Belle data)
Super-KEKB goal: >30x KEKB luminosity



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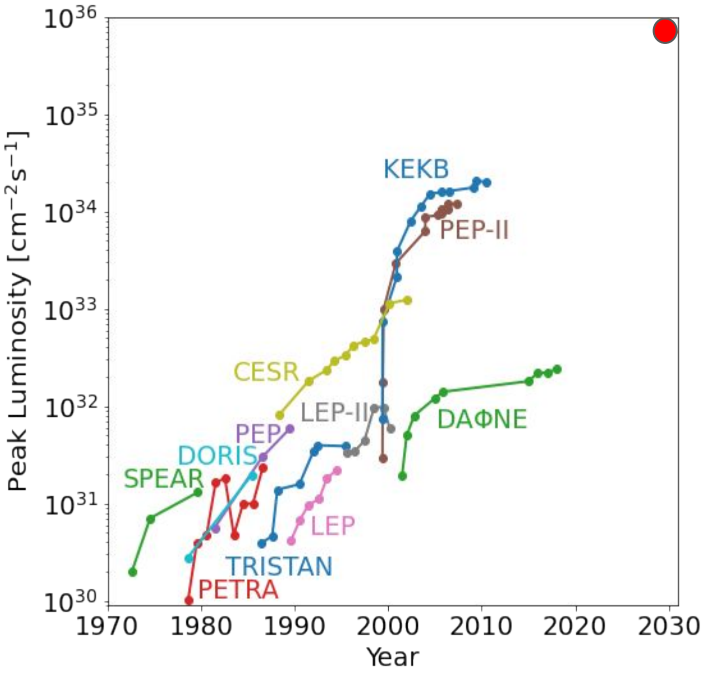


Beam aspect ratio (flat beam ~ 1-2%)

Beam currents

$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_\pm\xi_{y\pm}}{\beta_y^*}\right)\left(\frac{R_L}{R_{\xi_{y\pm}}}\right)$$

Vertical β function at IP

Geometrical corrections

Brute force:

- Current 2 x larger

Nanobeam scheme:

- β_y* 20 x smaller
- Vertical beam size ~ 50 nm

Belle II VS Belle, a matter of backgrounds

[P.Lewis et al, NIM A 914, 69-144 (2019)]

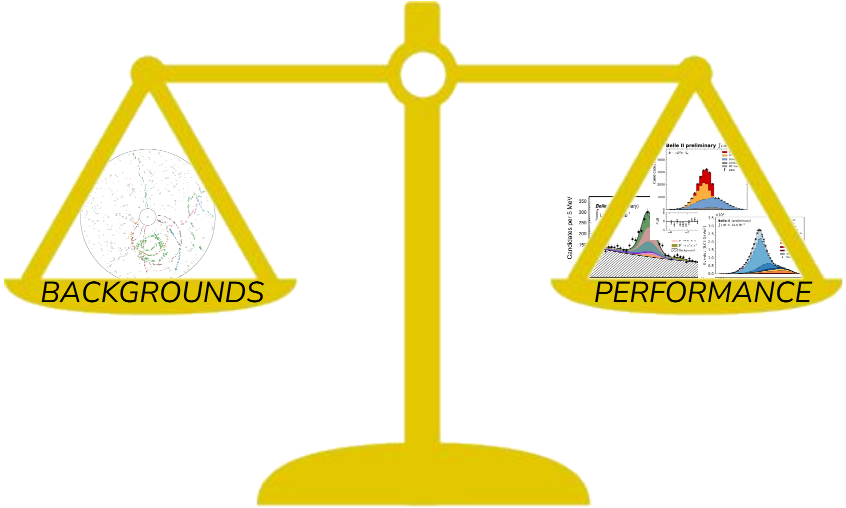
Single beam backgrounds:

- Touschek ∝ $I^2 \sigma_y^{-1} n_b^{-1}$ ⬆
- Beam Gas ∝ I ⬆
- Synchrotron radiation ∝ I ⬆

Luminosity backgrounds:

- Radiative Bhabha ∝ L ⬆
- Two-photon ∝ L ⬆
- Injection ⬄

Belle II is designed to perform as well as or better than Belle with much higher backgrounds!



Belle II performance VS Belle, in broad strokes

Tracking *[Comp. Phys. Comm. 259 (2021) 107610 (Monte Carlo only), in preparation (data)]*

- Better resolution at both low and high p_t
- Better efficiency at low p_t
- 2x better vertexing and decay time resolution

Full event reconstruction *[Comput. Softw. Big Sci* **3,** 6 (2019)*]*

- Better purity and efficiency

Neutrals *[paper in preparation]*

- Better algorithms and electronics
- (Currently) only enough to compensate the increased backgrounds

Particle identification *[paper in preparation]*

- Better algorithms and new detectors (working on NN-based approaches)
- (Currently) only enough to compensate the increased backgrounds