Istituto Nazionale di Fisica Nucleare
SEZIONE DI TORINO

Status and Result of the Belle II Particle Identification Systems

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On behalf of the Belle II collaboration

PM 2021
May 23rd 2022

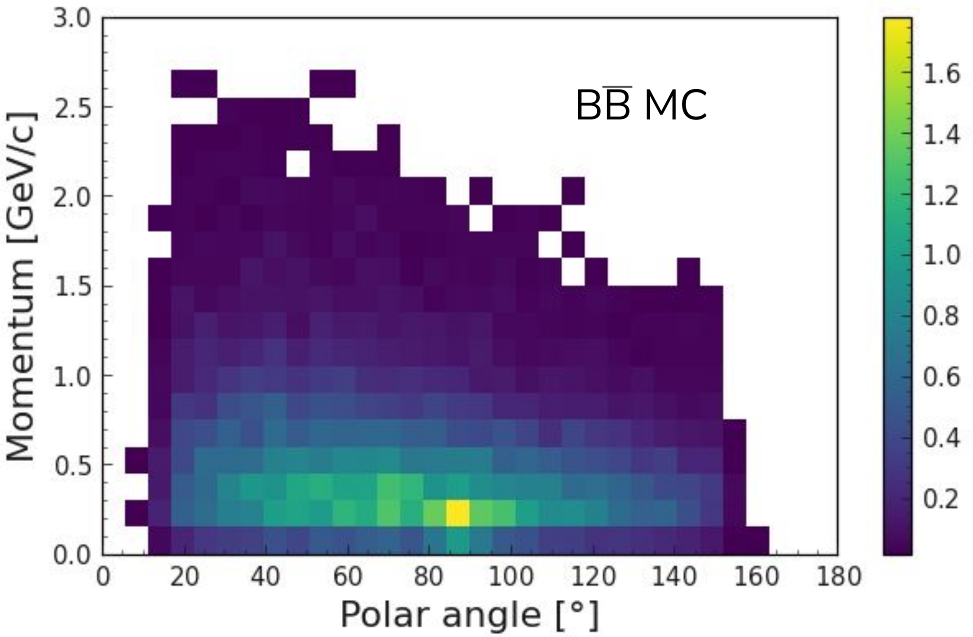
Belle II: the kinematics

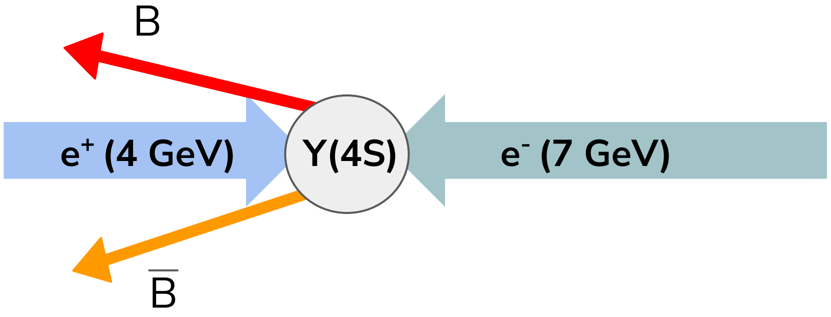
e^+e^- collisions at ~10.6 GeV

→ Asymmetric collisions

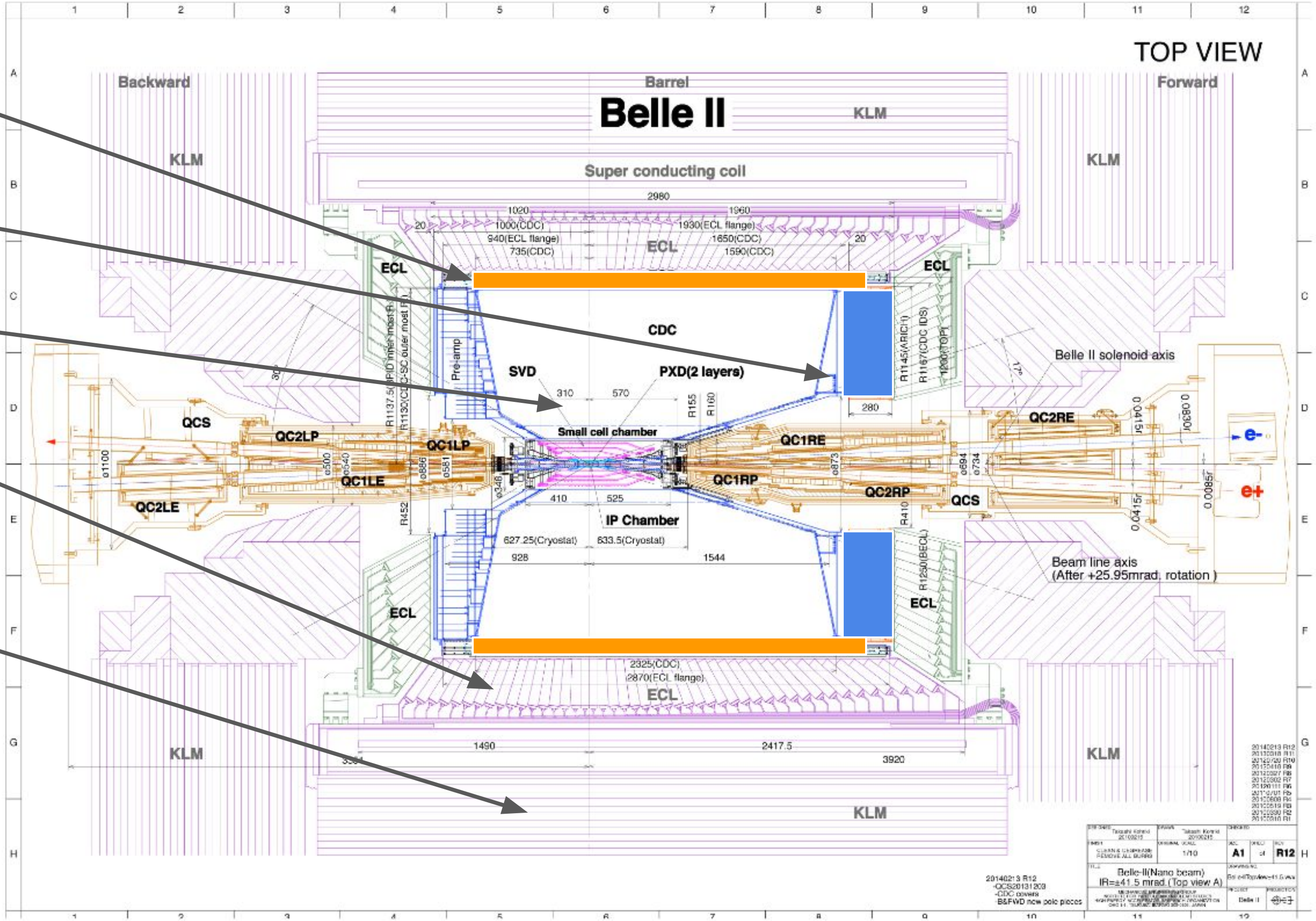
→ Focus on flavour physics: need for ID for all particle species

→ Low momentum: 50 MeV/c - 3 GeV/c





Belle II



Barrel cherenkov: TOP

Endcap Cherenkov: ARICH

dEdx: SVD + CDC

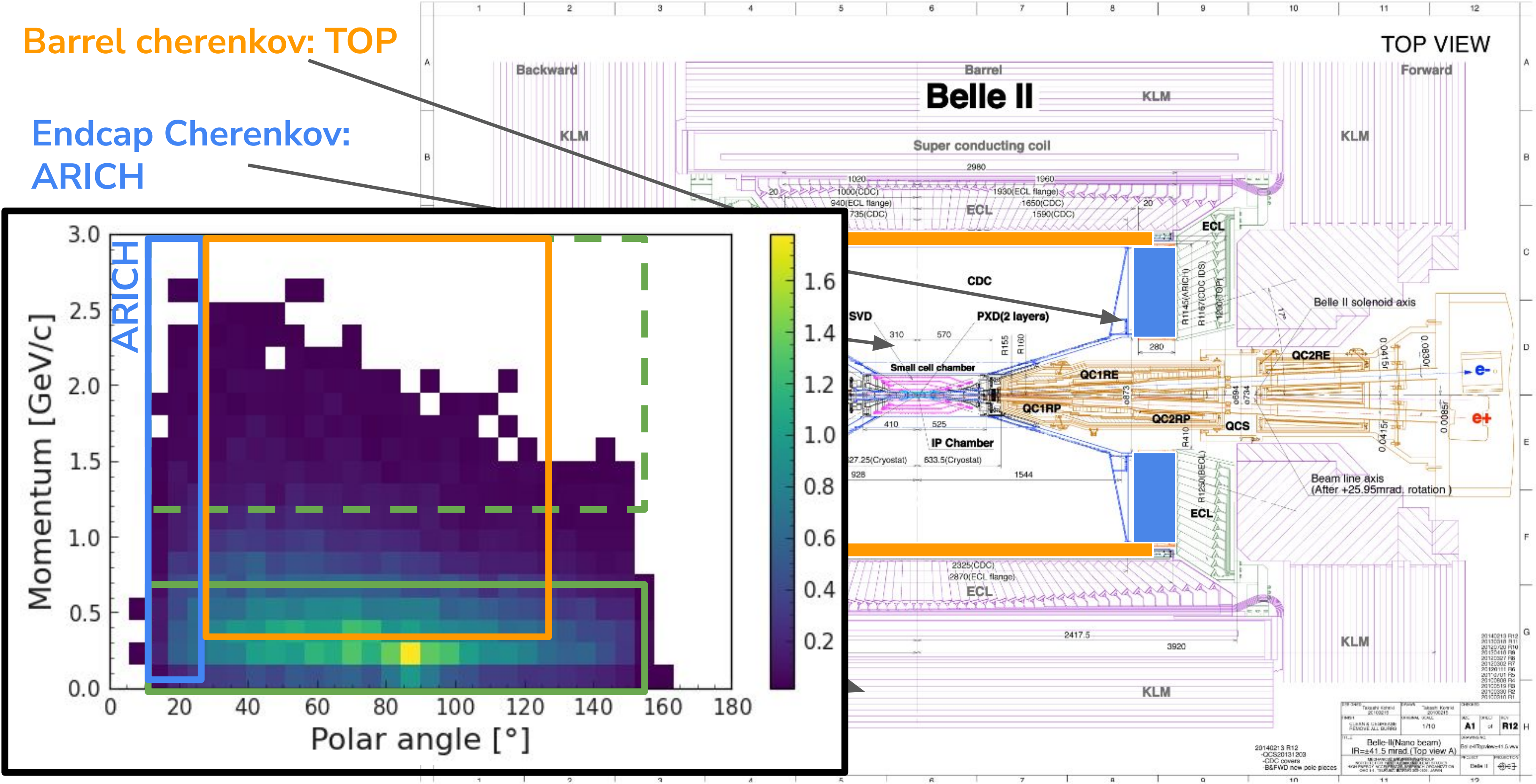
Shower shape: ECL

Pen. depth: KLM

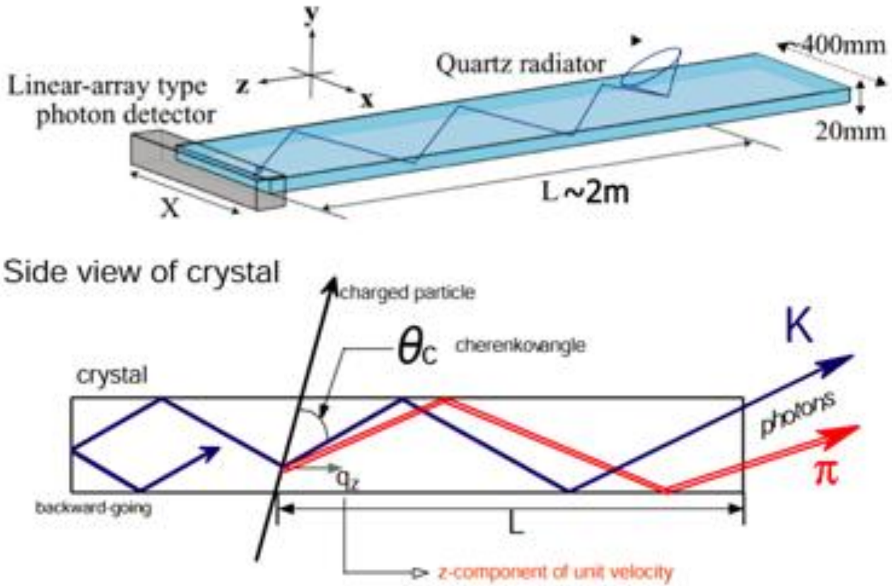
Belle II

Barrel cherenkov: TOP

Endcap Cherenkov: ARICH



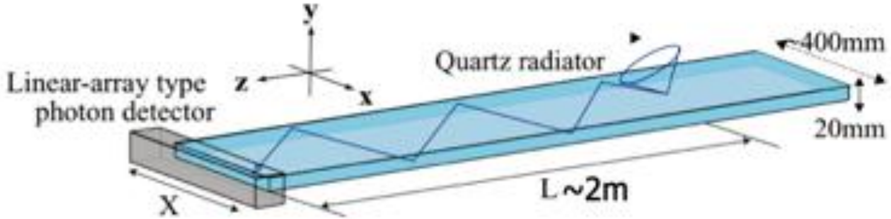
The TOP detector

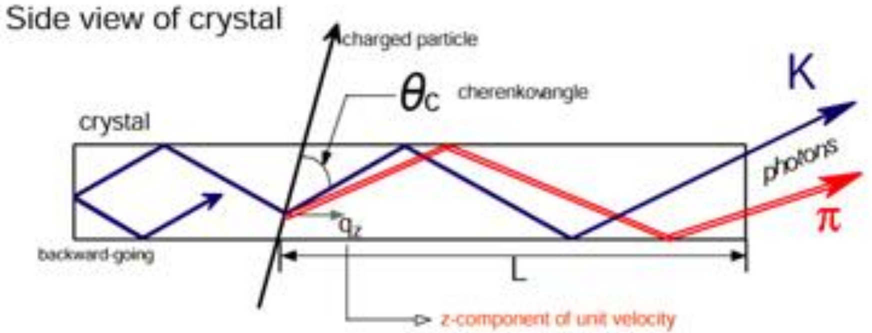


Time Of Propagation counter

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

What does the TOP measure?

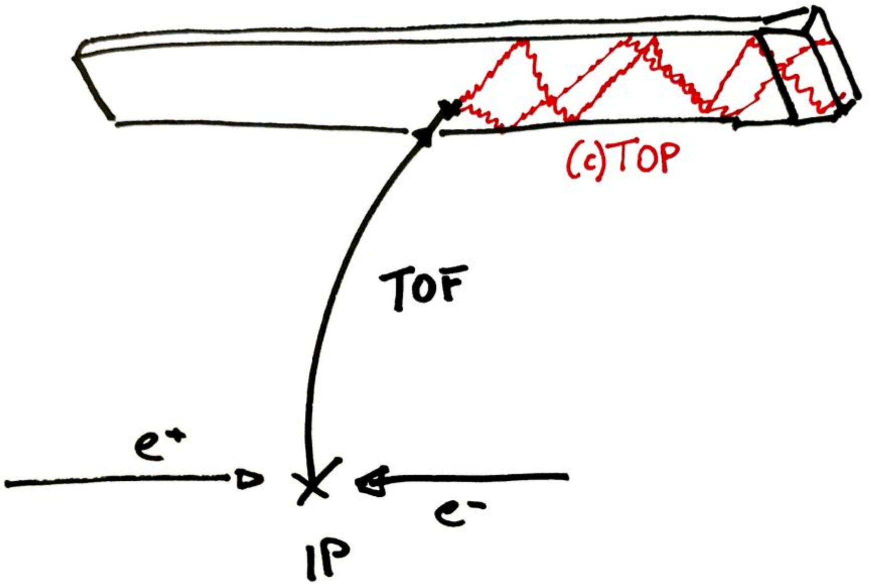




Combination the **ToF** and the **Cherenkov angle** in one single measurement

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



The TOP counter at Belle II

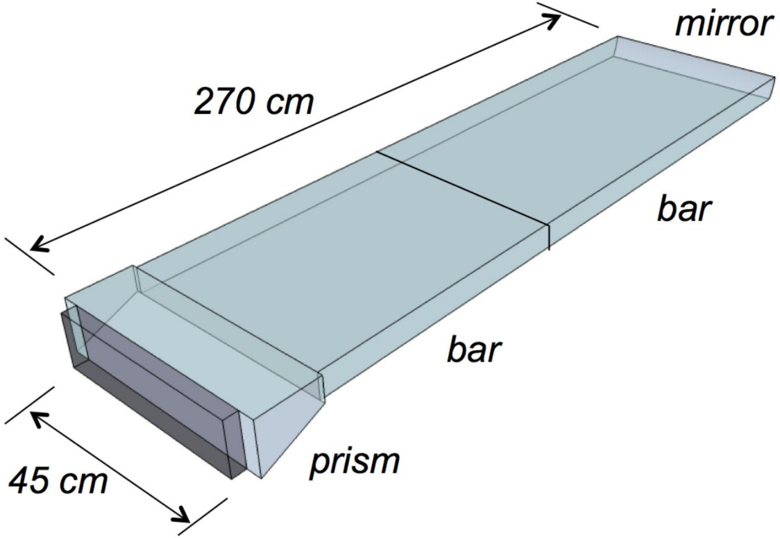
TOP implementation in Belle II:

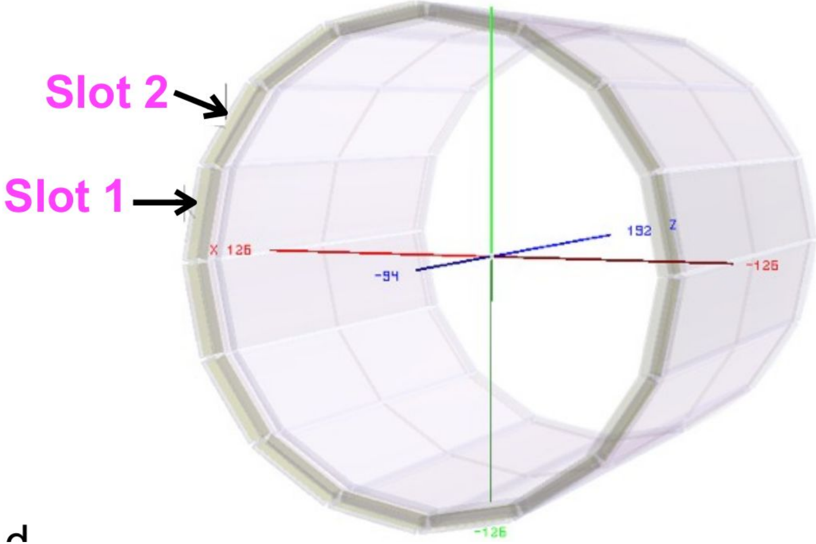
→ 16 modules (or slots) arranged around the interaction point

→ 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

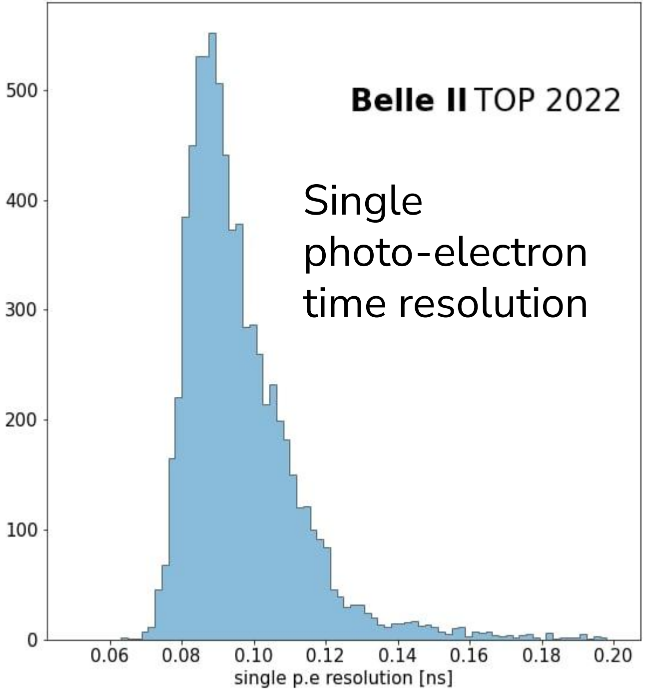
→ 2.7 GSa/s

→ 11.6 μs storage buffer

→ *Full waveform output*

→ ***28 ps resolution***

NIM A 941, 162342 (2019)



Single photo-electron time resolution

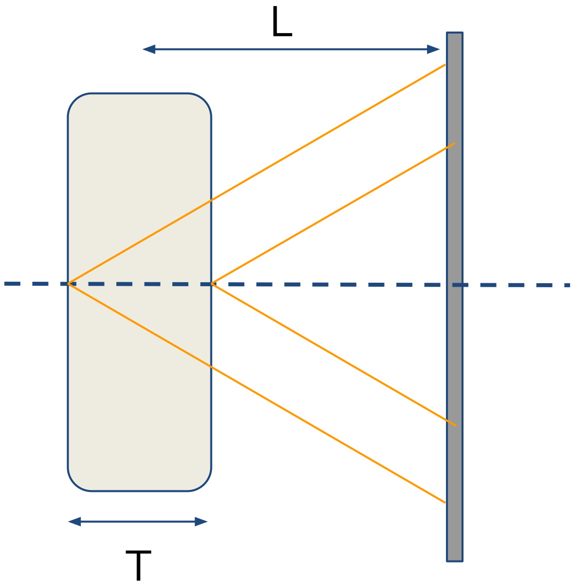
The Belle II ARICH

ARICH: proximity focus RICH

→ Aerogel wall as radiator

→ PTM plane ~ 20 cm behind the aerogel

→ PID by measuring the cherenkov angle



$$\sigma_\theta^{tot} = \frac{\overset{\propto T/L}{\sigma_\theta^{radiator}} \oplus \overset{\propto 1/L}{\sigma_\theta^{detector}} \oplus \sigma_\theta^{chrom}}{\sqrt{\underset{\propto T}{N_\gamma}}}$$

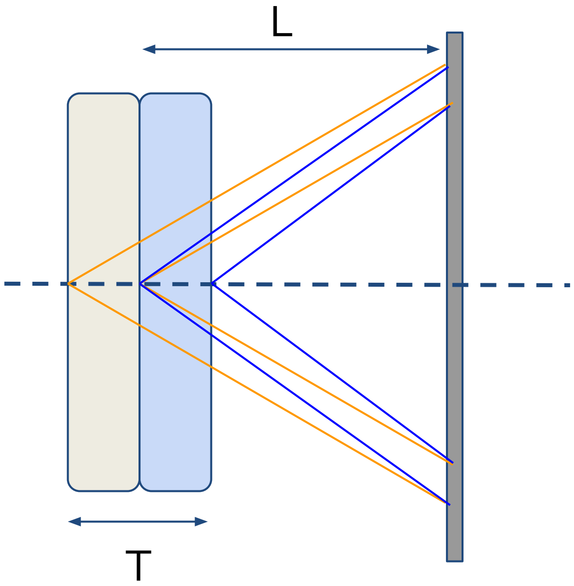
The Belle II ARICH's perks

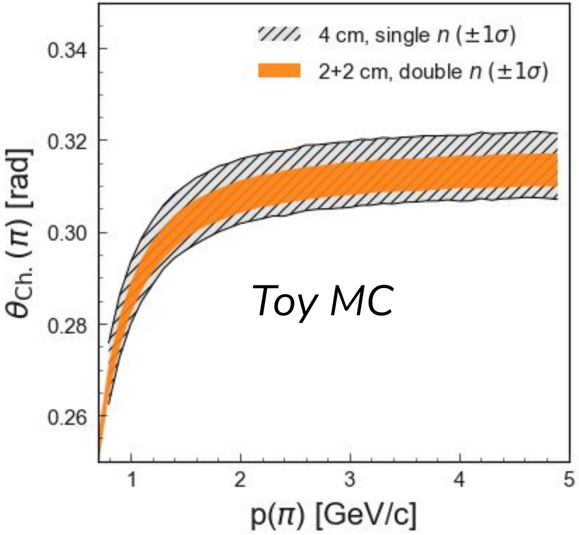
Double radiator layout

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

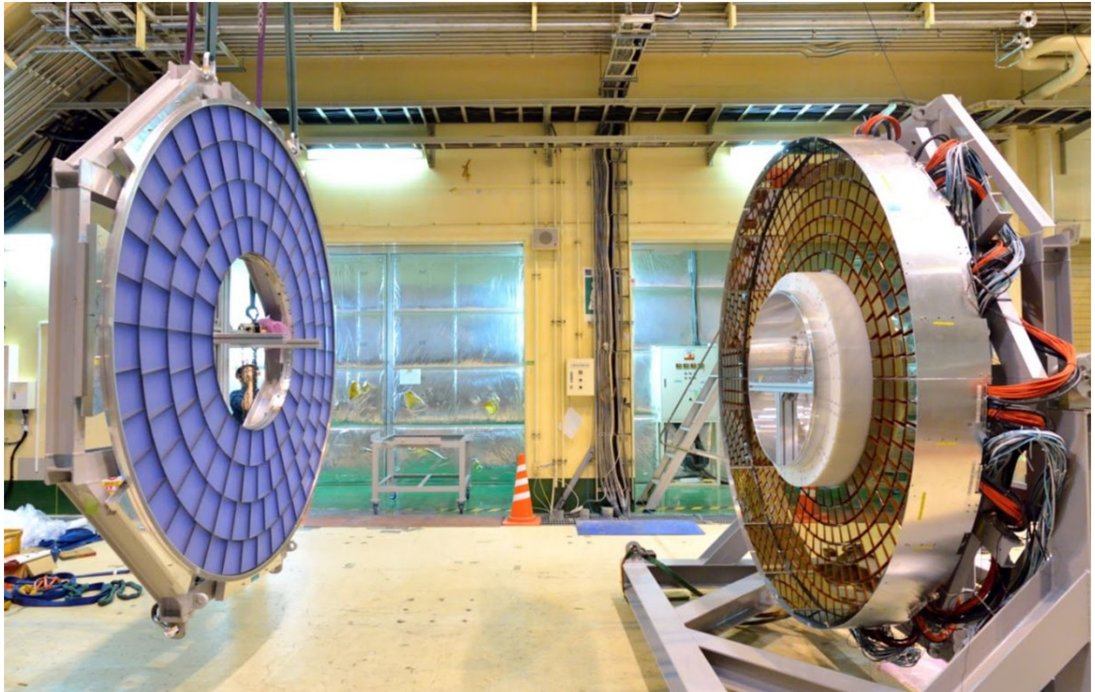
→ Tuned to have **overlapping rings**

$$\sigma_\theta^{tot} = \frac{\overset{\propto T/2L}{\overset{\downarrow}{\sigma_\theta^{radiator}}} \oplus \overset{\propto 1/L}{\overset{\downarrow}{\sigma_\theta^{detector}}} \oplus \sigma_\theta^{chrom}}{\sqrt{N_\gamma} \leftarrow \propto T}$$





Belle II ARICH structure



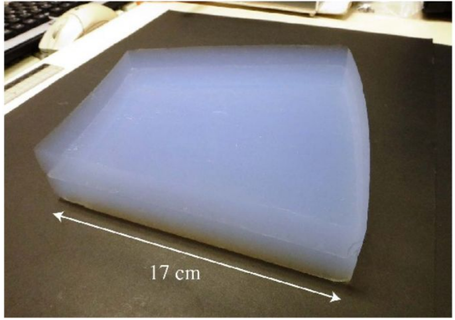
Belle II ARICH structure

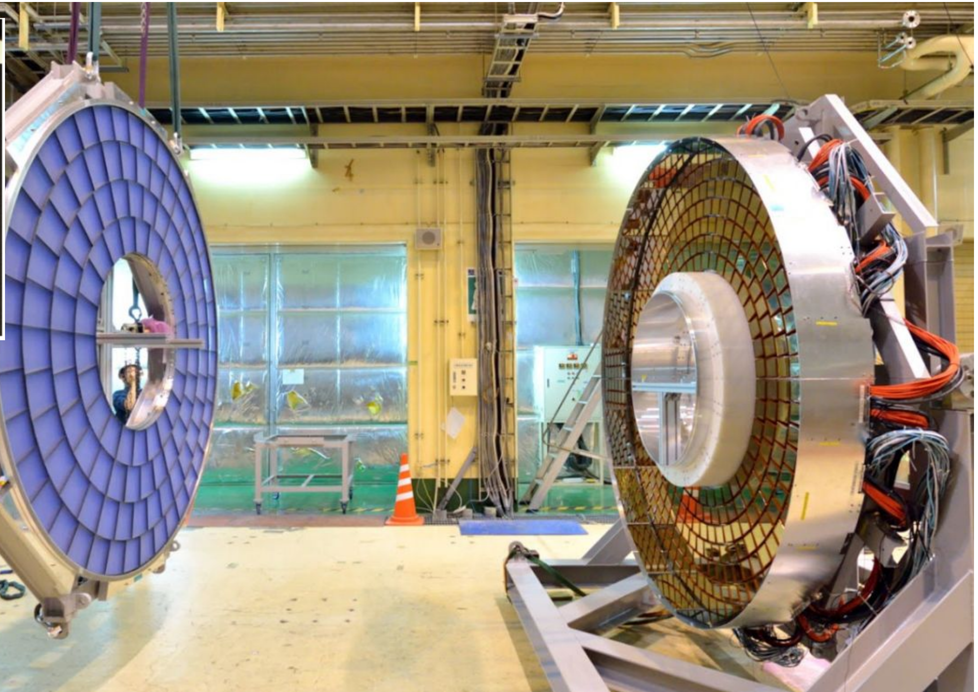
Hydrophobic Aerogel

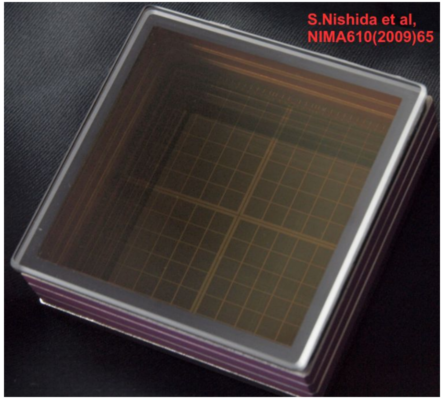
→ 17x17 cm, 2cm thick
→ Trans. length > 30 mm at 300 nm
→ $n_1 = 1.045$, $n_2 = 1.055$

Hamamatsu Hybrid Avalanche Photo Detector (HAPD)

→ 63x63 mm, 4.9mm pixel.
→ QE ~ 28% at 380 nm
→ Gain = $4\text{x}10^4$



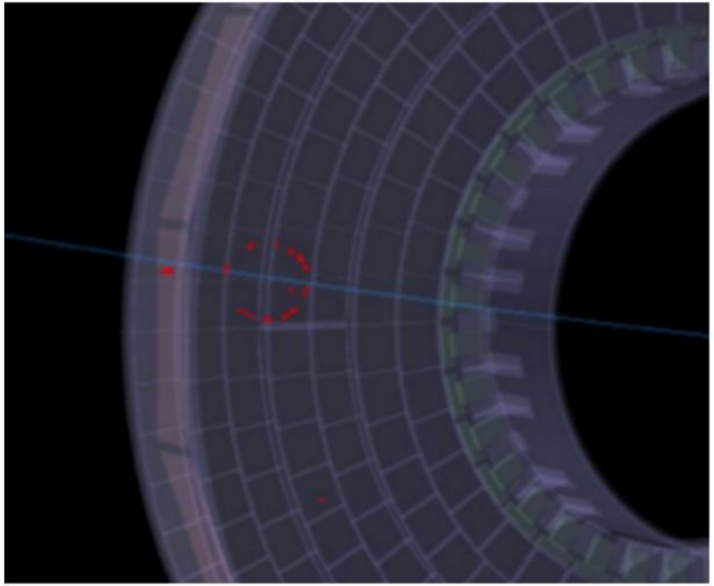


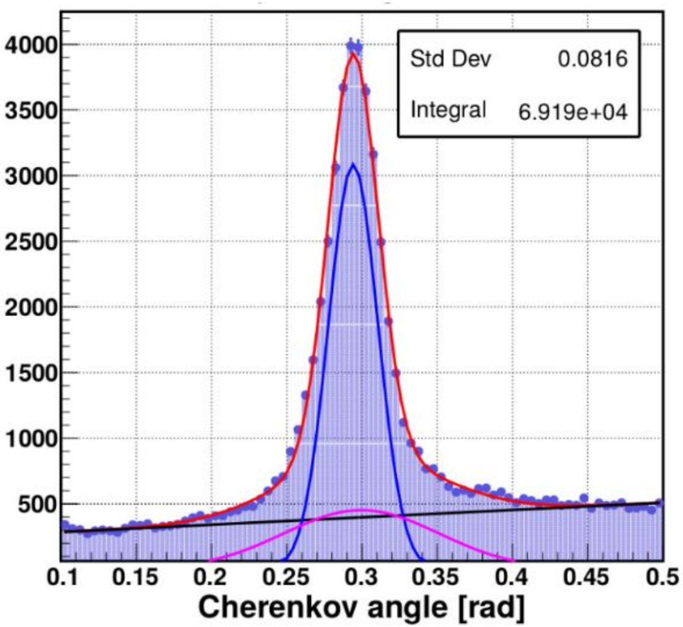

S.Nishida et al, NIMA610(2009)65

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**



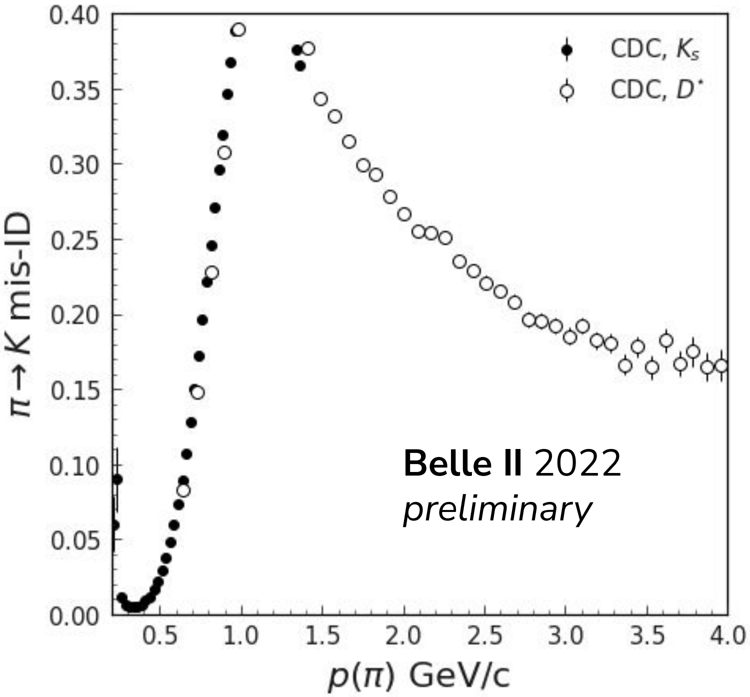


The impact of TOP and ARICH

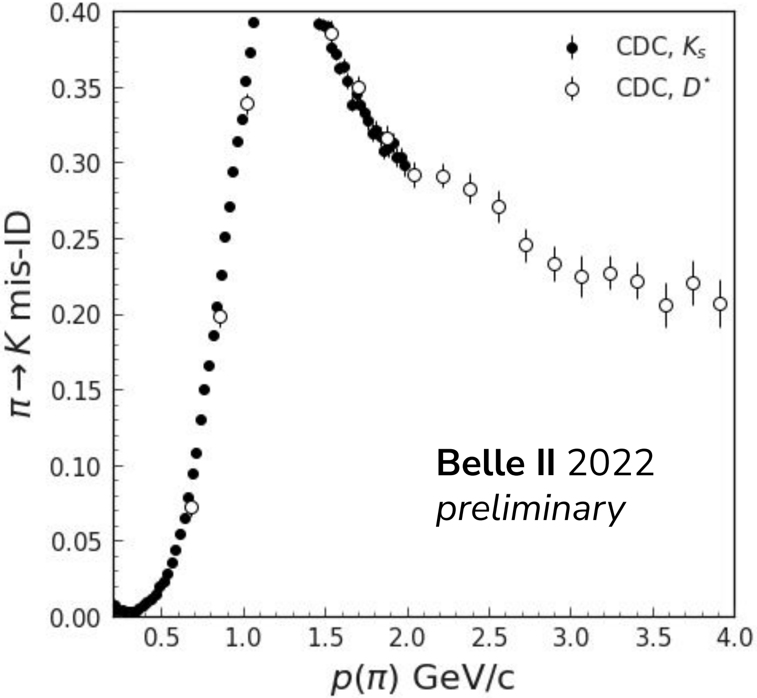
π → K mis-identification probability in collision data

- 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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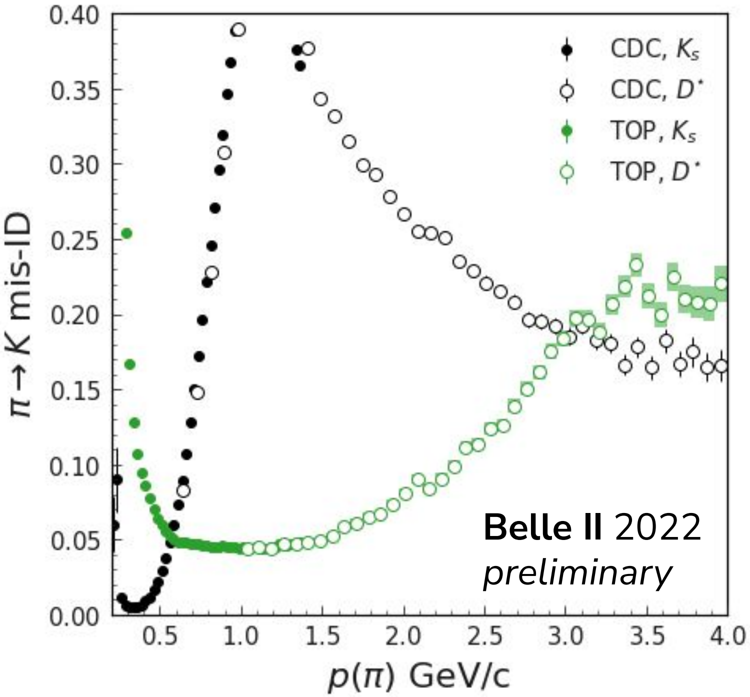
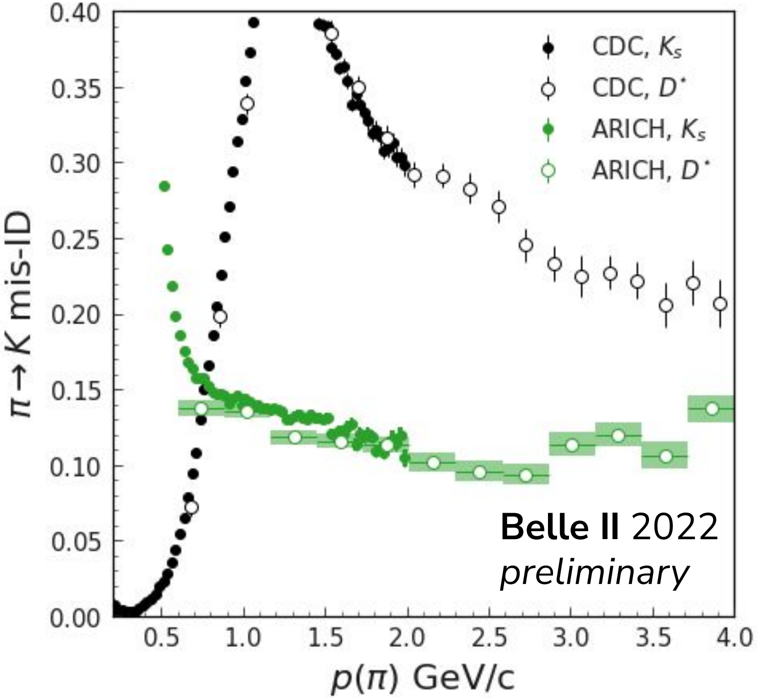


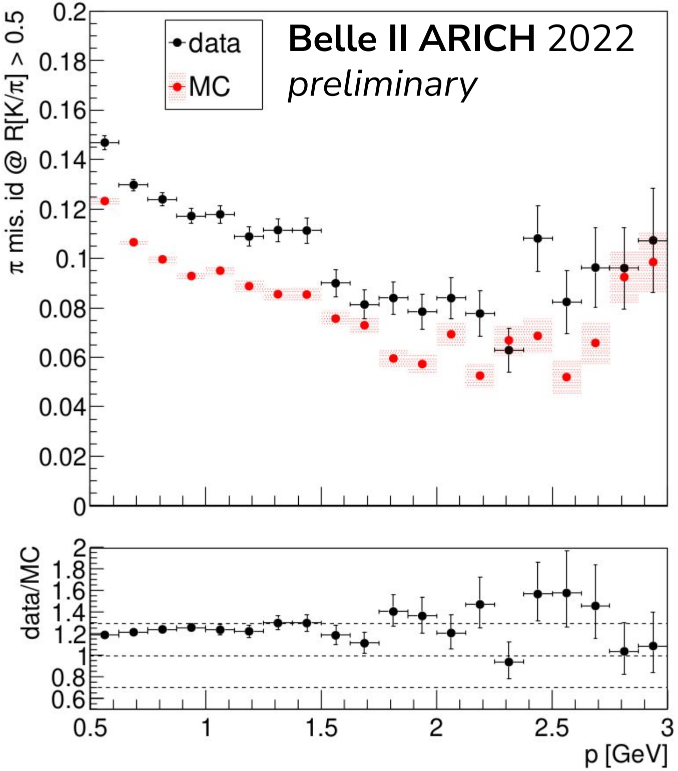
in ARICH acceptance

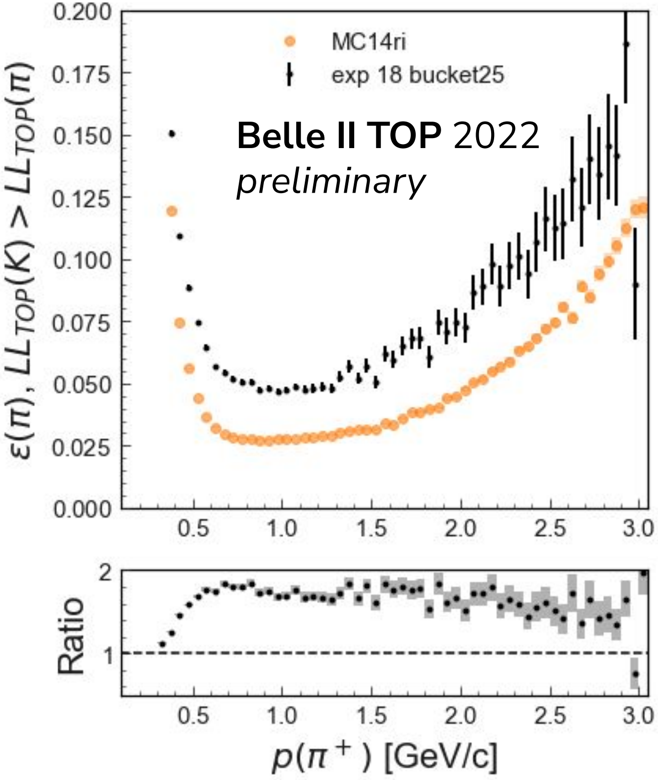


Expectations VS reality

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

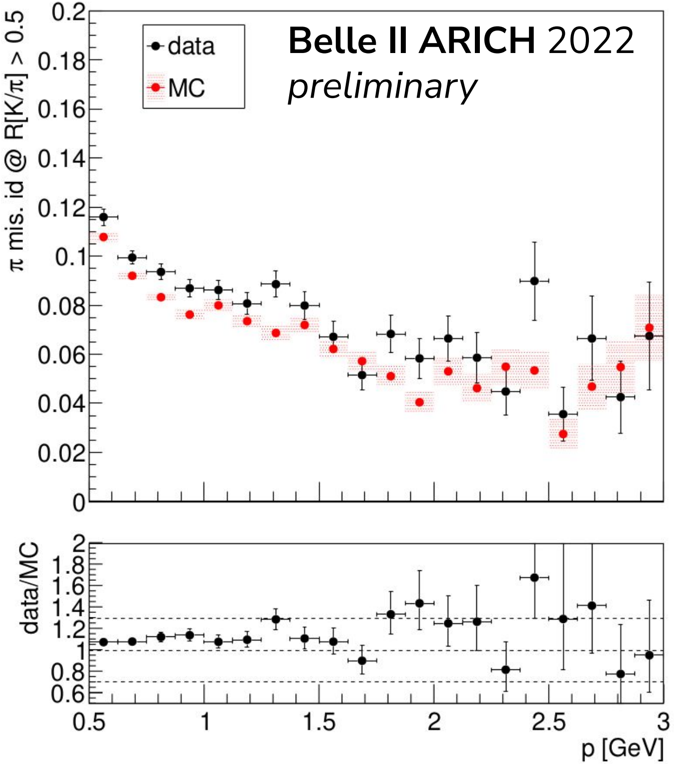
- Many lessons learned so far!





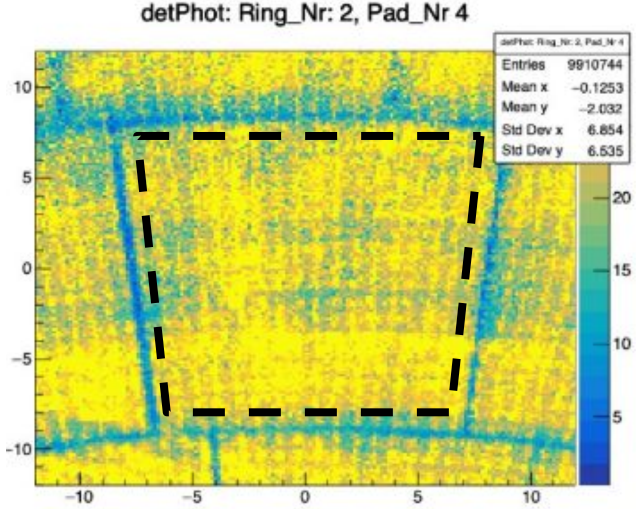
Lessons learned: ARICH tile alignment

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



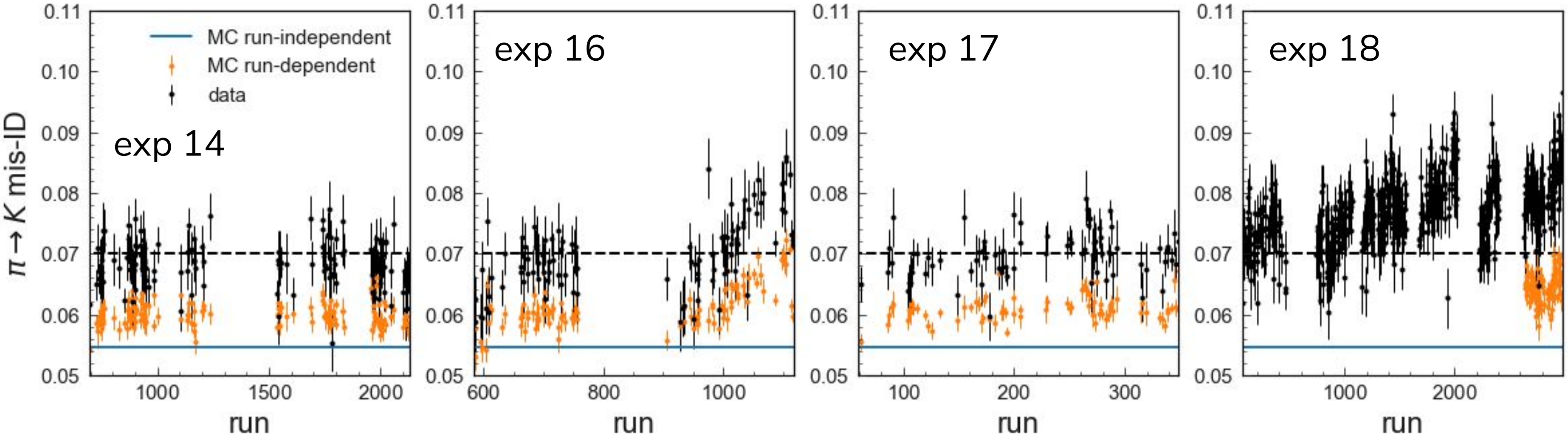
Removing tracks extrapolated in the edges

- 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

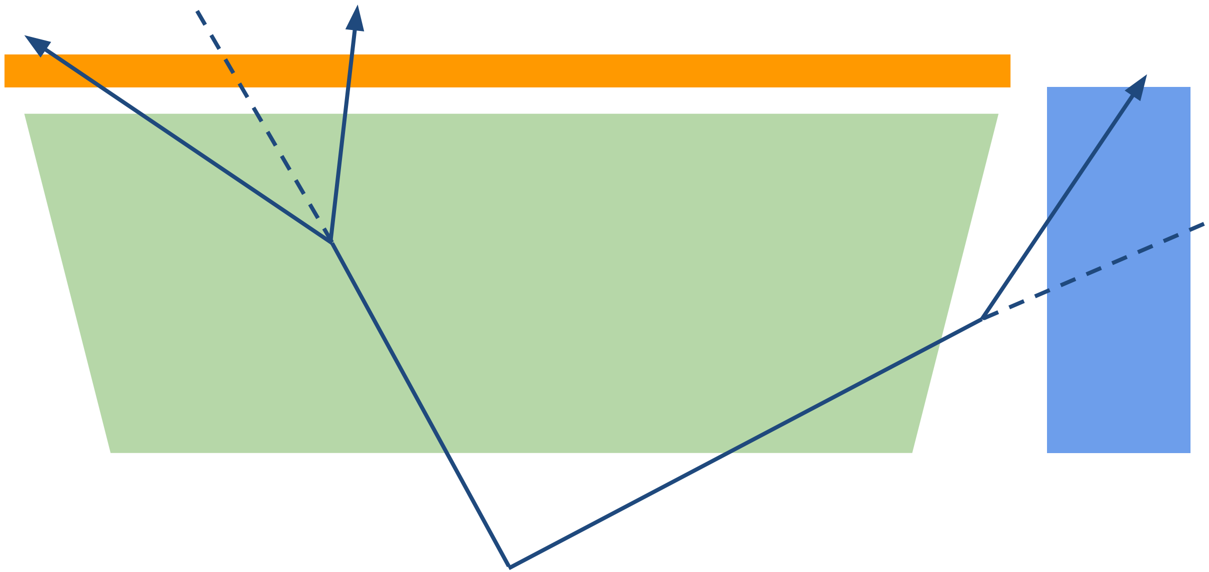


Residual discrepancy is under investigation.

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**

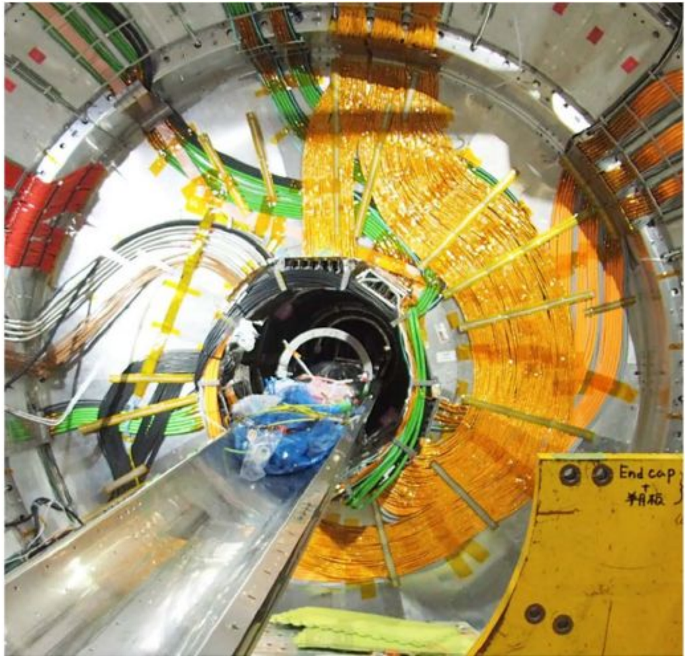


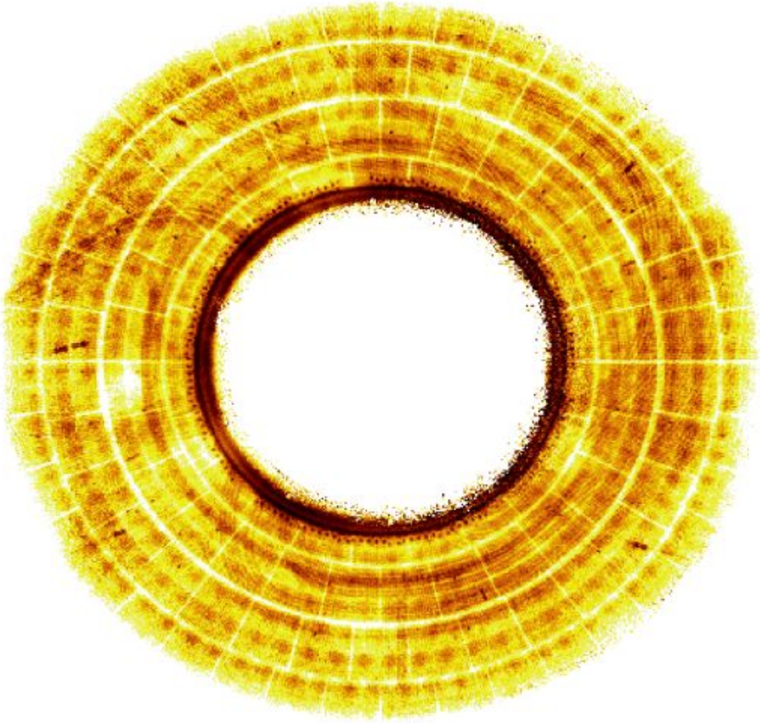
Lessons learned: hard scattering in ARICH

Sizable material budget in front of ARICH

→ CDC backplane, inner tracker cables…

→ Clearly seen mapping the impact points of electrons with associated photons

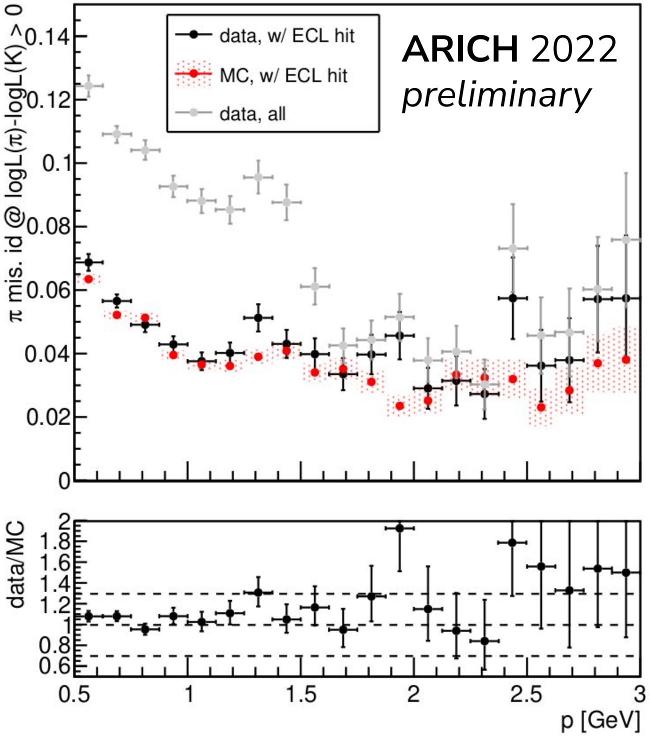


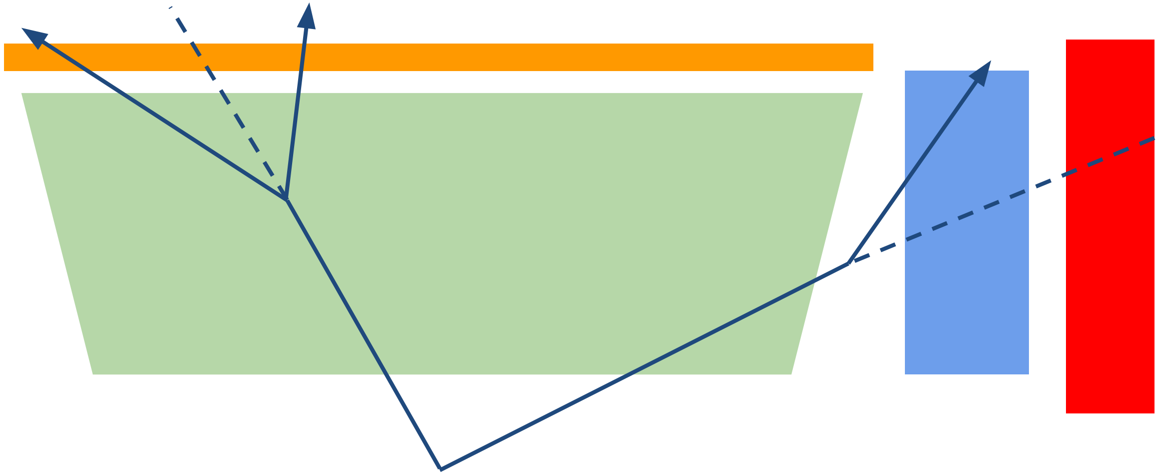


Mitigating material scattering

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…





Summary

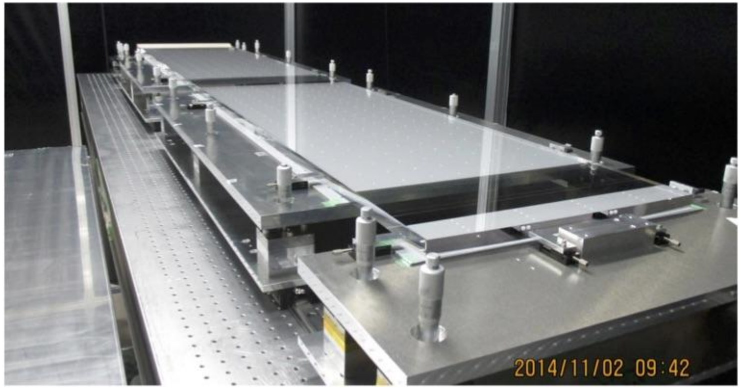
TOP and ARICH are two innovative Cherenkov detectors

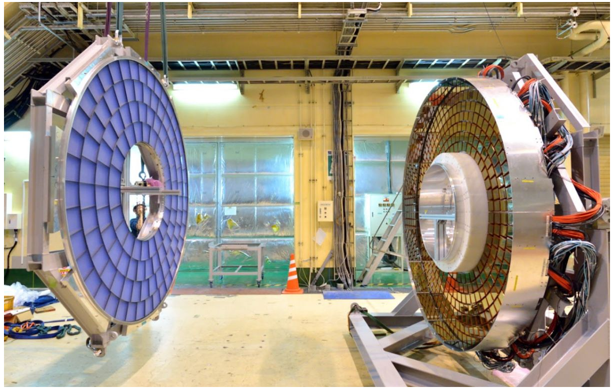
3 years into the operations, observed performance are getting close to expectations

- Tile alignment is the main culprit for ARICH
- TOP still under investigation, but large effect of the background simulation has been found

Belle II is entering the Long Shutdown 1

- Partial replacement of the TOP PMTs to prevent aging
- Fully understand TOP and ARICH performance

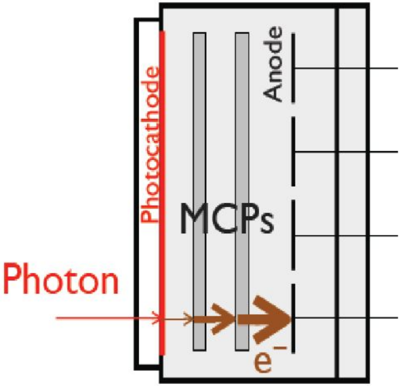


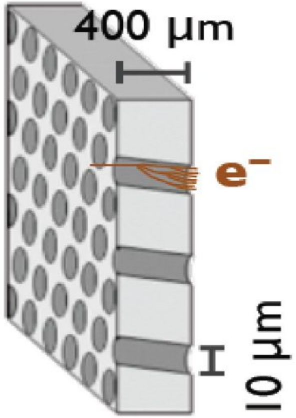


Backup

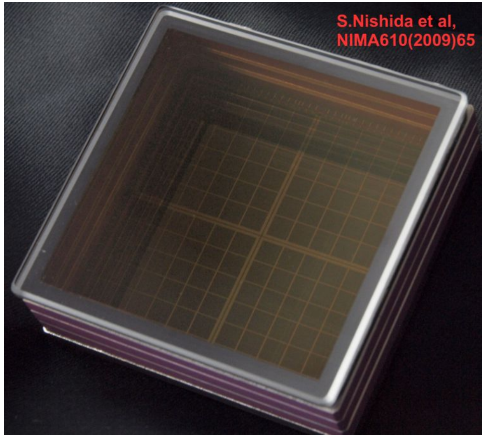
TOP sensors

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**





ARICH sensors



S.Nishida et al, NIMA610(2009)65

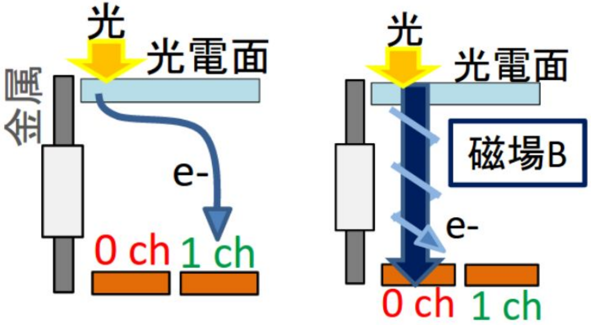
Hamamatsu Hybrid Avalanche Photo Detector (HAPD)

→ 63x63 mm, 4.9mm pixel.

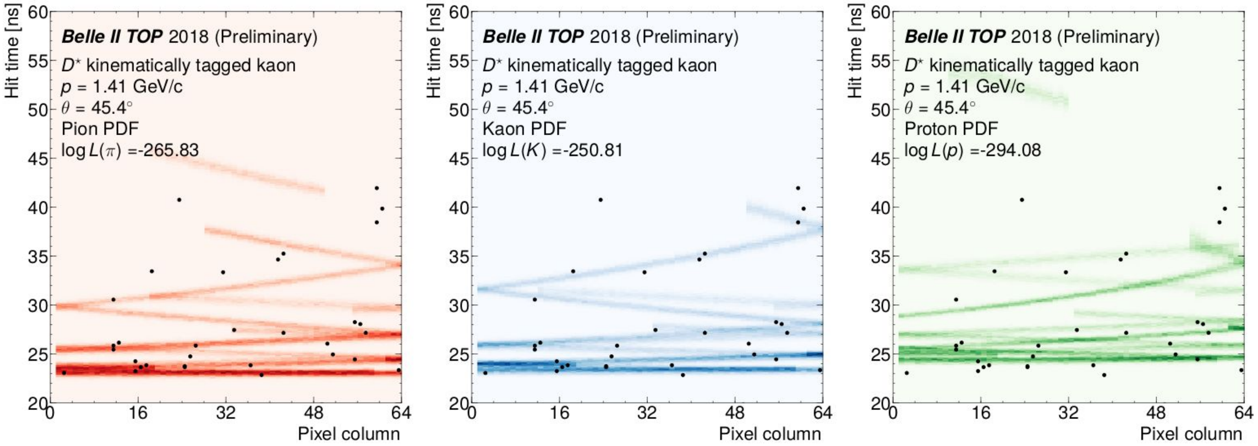
→ NaKSbCs photocathode; QE ≥ 24%
(28% on average) at 380 nm

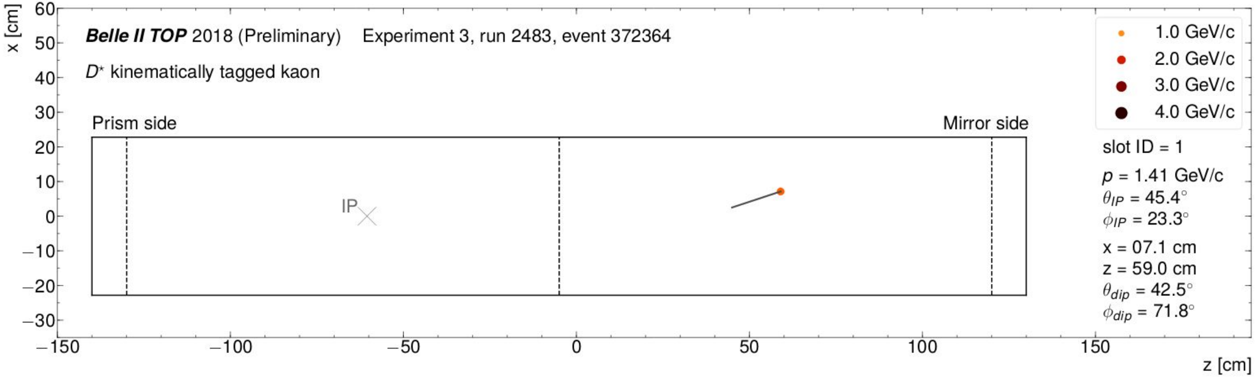
→ Gain = Signal gain = $4x10^4$ by
Hybrid amplification process.
Operation in 1.5 T magnetic field

Enhancement in the magnetic field



TOP reconstruction





1.41 GeV

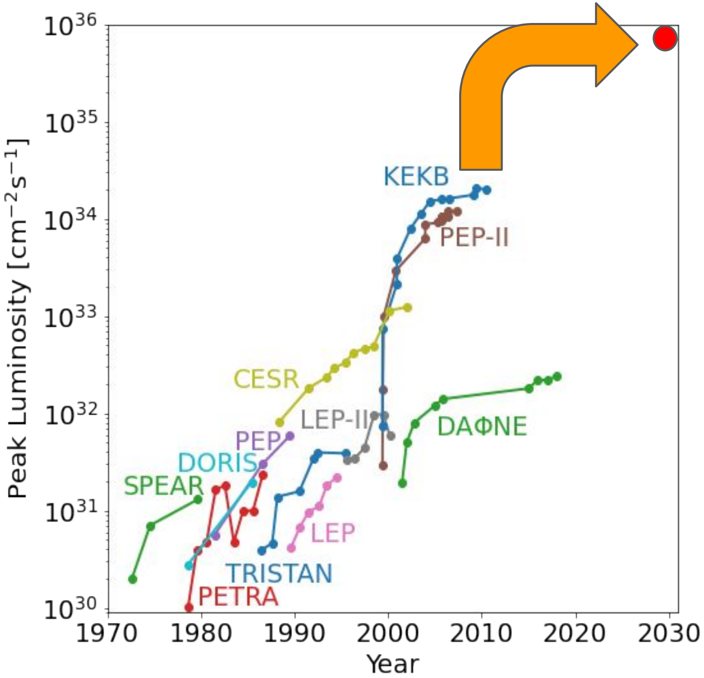
mirror-facing event

ID is dominated by the PDF shape (i.e. Cherenkov ring) rather than the global offset

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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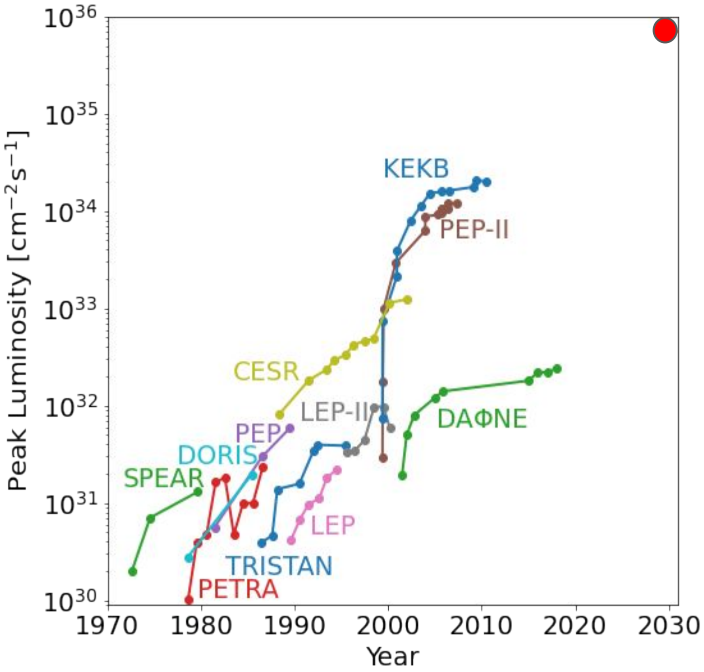


Beam aspect ratio
(flat beam ~ 1-2%)

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)]

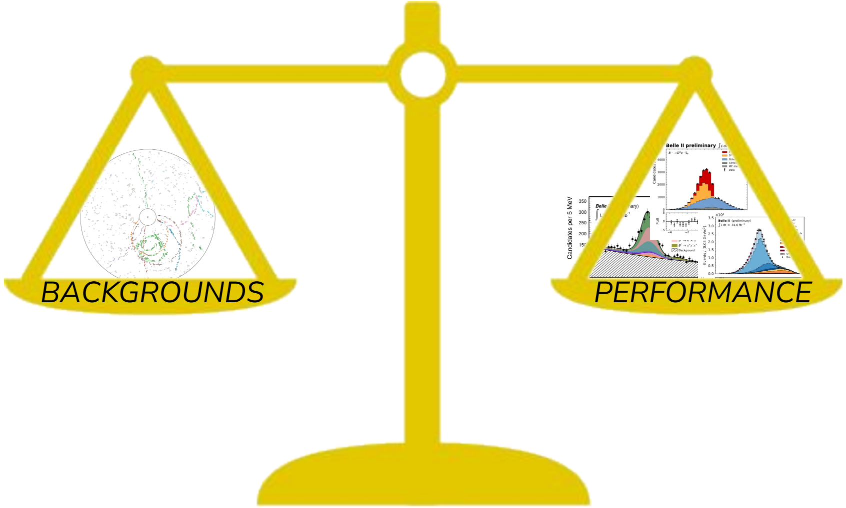
Single beam backgrounds:

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

Luminosity backgrounds:

- Radiative Bhabha $\propto L$ ⬆
- Two-photon $\propto L$ ⬆
- 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