The TOP counter and determination of bunch-crossing time at Belle II

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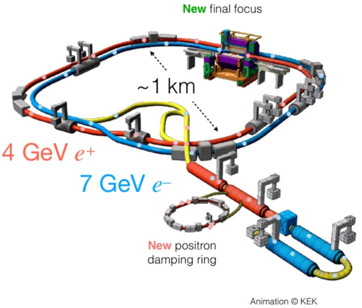
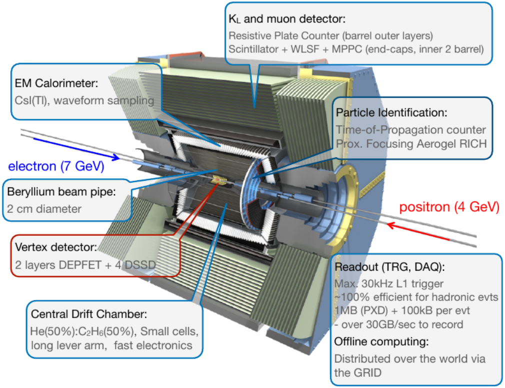
RICH 2022

Belle II experiment: 2nd generation "Super B Factory"





SuperKEKB accelerator

- upgraded KEKB
  $\rightarrow$ nano-beam optics
- target luminosity: 30 $\times$ KEKB

Belle II detector

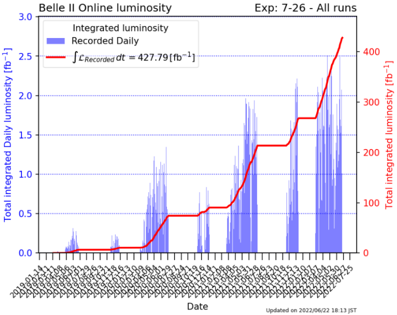
- general purpose spectrometer
- vertexing, tracking, neutral's detection, PID

Belle II at work

- Recorded 428 fb^{-1} since 2019
  - eqiv. to BaBar or 1/2 Belle

  $\rightarrow$ ~1% of final goal
- Luminosity world record of $4.7 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

  $\rightarrow$ still an order of magnitude to go
- Now in long shutdown for several upgrades, restart at fall 2023



Physics program

- B, charm and tau physics, complementary to LHCb
- Searches in dark sector

$\rightarrow$ 11 physics papers already published or submitted to journals

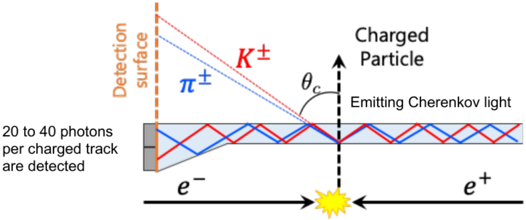
Particle identification at Belle II

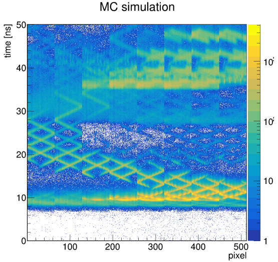
- Almost any detector component involved
  - SVD and CDC: energy losses (dE/dx)
  - TOP: Cherenkov imaging in barrel region
  - ARICH: Cherenkov imaging in forward region
  - ECL: energy deposits
  - KLM: penetrating power (trajectory length)

  mostly hadron ID   mostly lepton ID
- All these components provide log likelihoods for e, μ, π, K, p, d
- Combined by summing over detector components:
  - $\log \mathcal{L}_h = \sum_{\rm det} \log \mathcal{L}_h^{\rm det}, \;\; h = \{e, \mu, \pi, K, p, d\}$
- Particle selection with either
  - binary PID: $P_{h/h'} = \frac{\mathcal{L}_h}{\mathcal{L}_h + \mathcal{L}_{h'}}$
  - global PID: $P_h = \frac{\mathcal{L}_h}{\sum_{h'} \mathcal{L}_{h'}}$

SVD	silicon vertex detector
CDC	central drift chamber
TOP	time-of-propagation counter
ARICH	proximity focusing aerogel RICH
ECL	electromagnetic calorimeter
KLM	K_L and muon detector

TOP counter: principle of operation



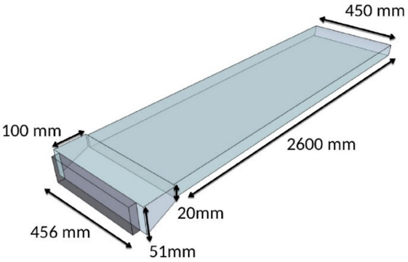


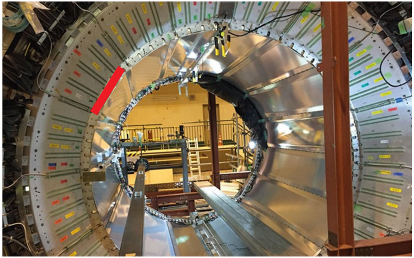
- Cherenkov photons transported to the photon sensors by means of total internal reflections (DIRC)
- Two dimensional information about the Cherenkov ring by measuring the time-of-arrival and the position of photons at photon sensors.
- Time-of-arrival is measured relative to the e^+e^- collision time $\rightarrow$ includes time-of-flight of the particle.

time-of-flight measurement combined with Cherenkov ring imaging

Belle II TOP

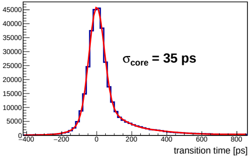
- Hadron ID in the barrel region ($32^0 < \theta < 120^0$)
- 16 modules at $R = 120$ cm
- Quartz optics of a module
  - 2.6 m long quartz plate, 2 cm × 45 cm in cross-section
  - spherical mirror at forward side
  - expansion prism at backward side

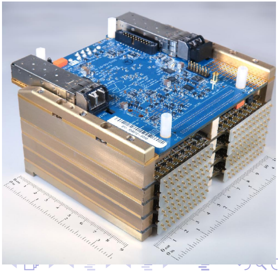




Belle II TOP

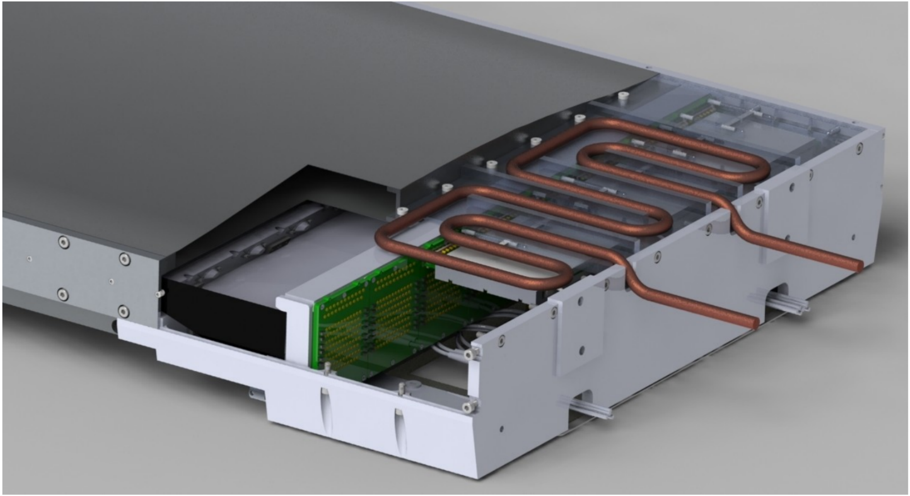
- Photon sensors → talk by Okubo-san on Friday
  - Hamamatsu MCP-PMT's,
    4×4 channels, 5.5 mm pixel size
  - 2 rows of 16 PMT's per module (512 pixels)
  - single photon sensitivity
  - excellent time resolution
  - works in magnetic field
- Front-end electronics
  - waveform sampling with 2.7 Gs/sec
  - custom designed ASIC with 11 μs long analog ring buffer for storing waveforms
    → running continuously
  - 8 channels/ASIC
  - 16 ASIC's/boardstack (=128 channels)
  - digitization and feature extraction (50% CFD)
  - data sent-out by optical link





TOP module

4 boardstacks per module



Time calibration of Belle II TOP

Done in four steps

- time-base of wave-sampling electronics
  - double-pulses injected into ASIC channels
  - precision < 50 ps
- time alignment of channels within module
  - laser pulses injected into a module
  - precision < 50 ps
- time alignment of modules
  - collision data (dimuon events)
  - precision < 10 ps

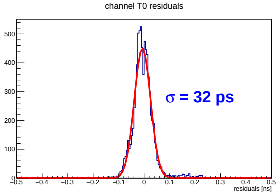
$\rightarrow$ these three found very stable in time

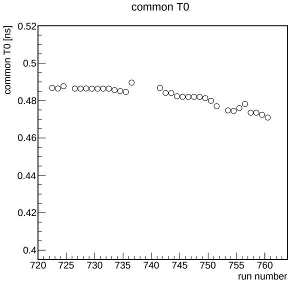
- relative to collision time (common T0)
  - collision data (dimuon events)
  - precision < 10 ps

$\rightarrow$ varies from run to run

time alignment of channels

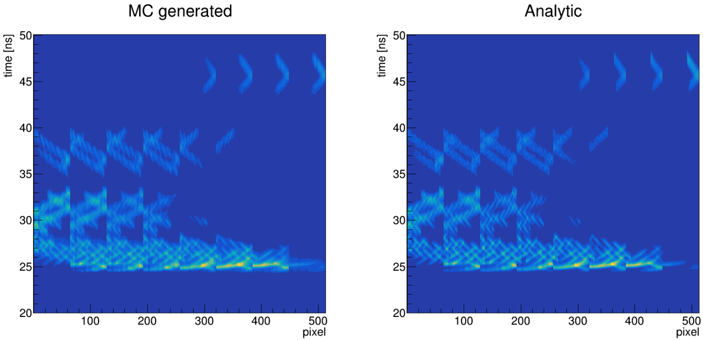
x-check with collision data





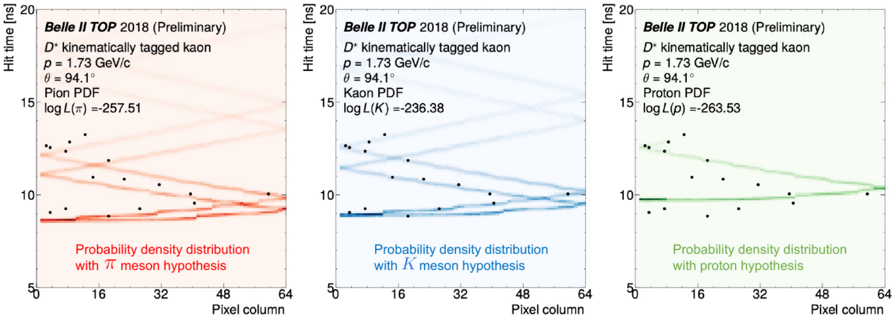
Particle identification with TOP

- Extended likelihood method with analytically constructed PDF's to determine log likelihoods of e, μ, π, K, p, d
- PDF in a single channel described with a sum of Gaussian distr.
  - positions, widths and normalizations determined analytically according to particle impact position, angles, momentum and mass
- Method presented at RICH2010 (NIM A 639 (2011) 252-255)

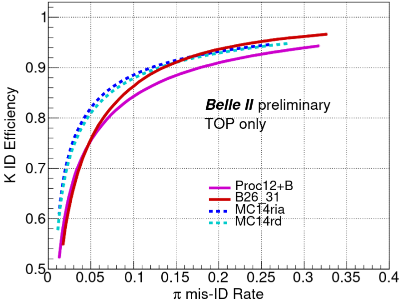


An example from collision data

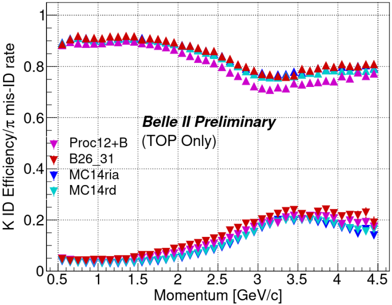
- Kinematically tagged kaon from $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$ decay



PID performance: with $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$

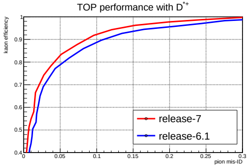


$\mathcal{L}_K > \mathcal{L}_\pi$



reprocessing	year	K effi at 10% π fake
proc9	2019	80%
proc10	2020	82%
proc11/12	2021	84%
proc13	2022	86%
(proc14)	(2023)	$\sim$90%

test on small dataset

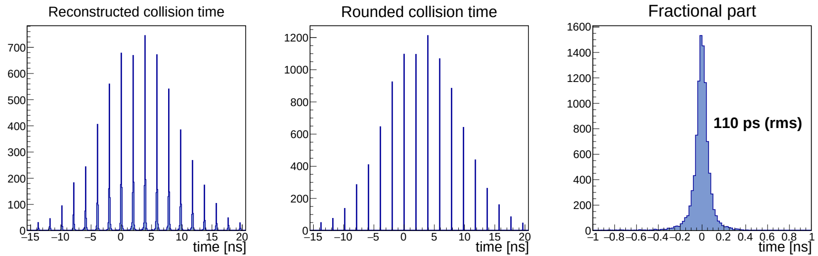


Determination of bunch-crossing time

- Start for photon time-of-arrival measurements is given by L1 trigger
- L1 trigger not precise enough:
  - time jitter $\sim$8 ns
  - required precision < 25 ps
- Required precision can be achieved by identifying bunch-crossing of the collision in off-line processing
- SuperKEKB:
  - bunch length of 6 mm $\rightarrow$ 14 ps spread in collision time
  - RF clock of 508 MHz $\rightarrow$ 2 ns bucket spacing
  - 5120 RF buckets per beam revolution

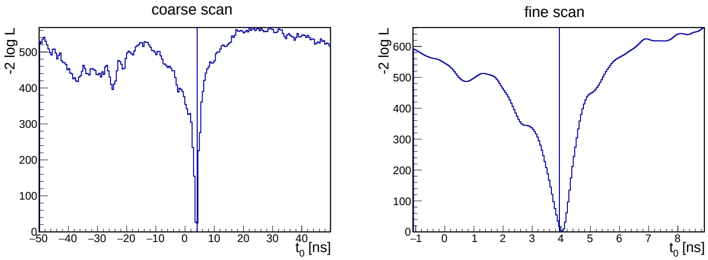
The method

- The method relies on maximizing the sum of log likelihoods of particles hitting the TOP detector against a common offset subtracted from the measured photon times
  - need at least one track in event that emits enough Cherenkov photons
  - particle identities determined from dE/dx
- The result of maximization is then rounded to the nearest RF bucket and then used to correct photon arrival times before the final log likelihoods are calculated.



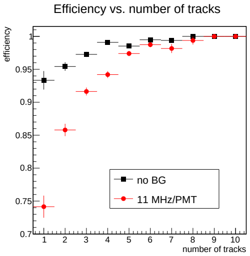
Implementation

- Minimum in $\chi^2 = -2\sum_i \log \mathcal{L}_i$ is searched by scanning a selected time region, because local minima are usually present
- Done in two steps:
  - coarse 1-dimensional scan in ± 50 ns using time-projected PDF's
  - fine scan in ± 5 ns around the result of coarse scan using full PDF's $\rightarrow$ minimum precisely determined by fitting a parabola



vertical line indicates simulated bunch-crossing time

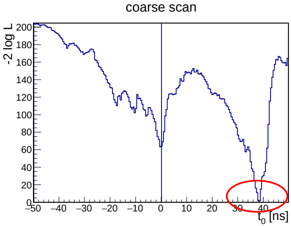
Performance

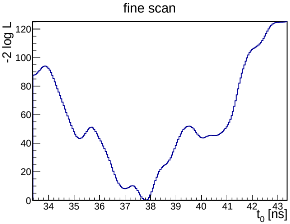


- Efficiency of finding the true bunch-crossing
  - depends on track multiplicity
  - very sensitive to beam BG

no BG	1.2 MHz/PMT	11 MHz/PMT
98.2%	97.4%	92.1%

- Inefficiency due to false minima caused by BG hits

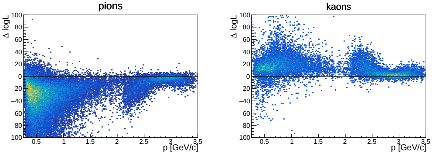




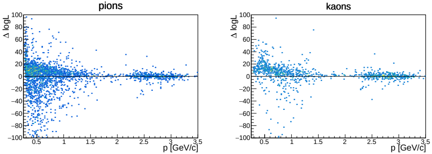
vertical line indicates simulated bunch-crossing time

Impact on PID

true bunch-crossing found

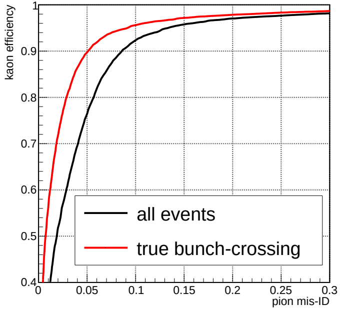


false bunch-crossing found



11 MHz/PMT beam BG

TOP only



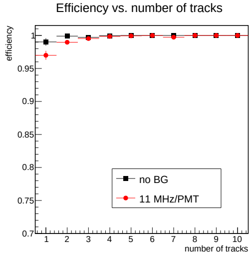
- With false bunch-crossing found:
  - likelihoods for both are more kaon-like
  - increase of pion mis-ID rather than decrease of kaon efficiency

Recent improvements

- SVD can now measure collision time with ∼1 ns precision
- Improved method:
  - instead of coarse scan use seed from SVD (to shorten the search region)
  - require reconstructed bunch-crossing to be matched with filled buckets

- Improved efficiency
  - much less dependent on track multiplicity
  - much less sensitive to beam BG

no BG	1.2 MHz/PMT	11 MHz/PMT
99.9%	99.9%	99.5%



Acceptance

- TOP likelihoods provided only if bunch-crossing is reconstructed
  - at least one track emitting sufficient number of Cherenkov photons
  - reconstructed bunch-crossing matched with filled bucket

$\rightarrow$ not all events can fulfill these criteria

- Fraction of events with TOP PID

no BG	1.2 MHz/PMT	11 MHz/PMT
96.9%	95.7%	91.7%

- Fraction of tracks hitting TOP but w/o TOP PID

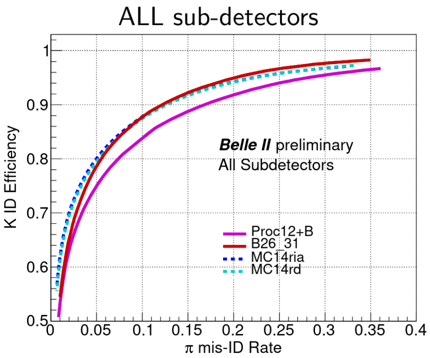
no BG	11 MHz/PMT
1.0%	4.5%

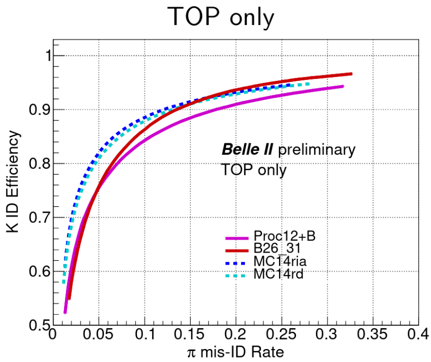
  - to be compared to 5% loss due to gaps between modules
    $\rightarrow$ poster by U. Tamponi on STOPGAP proposal
  - PID with dE/dx still available for these tracks

Conclusions

- PID performance of the Belle II TOP counter has been steadily increasing with each new software release/reprocessing since the start of data taking in 2019.
- This can be attributed particularly to the improvements in detector calibration, PDF modeling and bunch-crossing time determination.
- We are now in a long shutdown until the fall of 2023, which we are going to utilize for the replacement of conventional MCP-PMT's and malfunctioning electronic parts, as well as to prepare the front-end firmware for high-luminosity data taking.

Backup: PID performance (ROC)

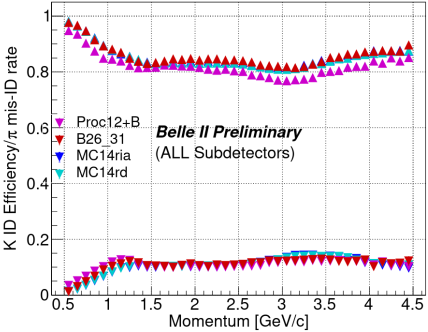




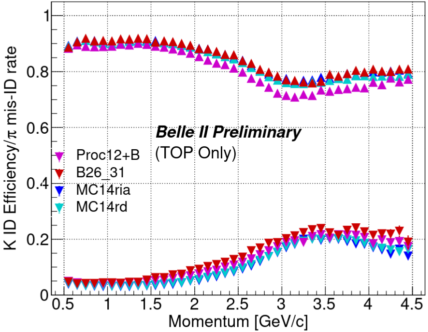
Proc12+B: software release-5 (2020)
B26_31: software release-6 (2021)

Backup: PID performance (vs. momentum)

ALL sub-detectors

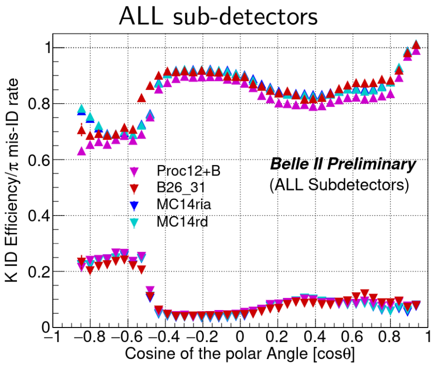


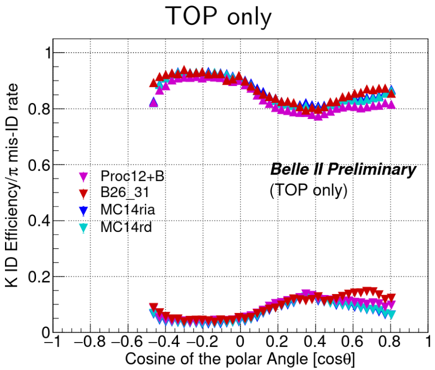
TOP only



Proc12+B: software release-5 (2020)
B26_31: software release-6 (2021)

Backup: PID performance (vs. polar angle)





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