The Belle II TOP PID detector

Roberto Mussa
INFN Torino

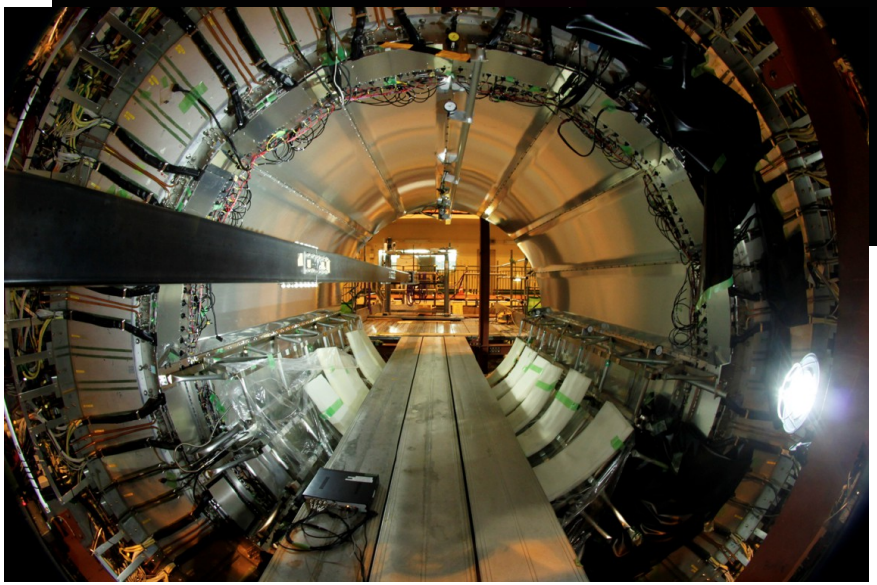
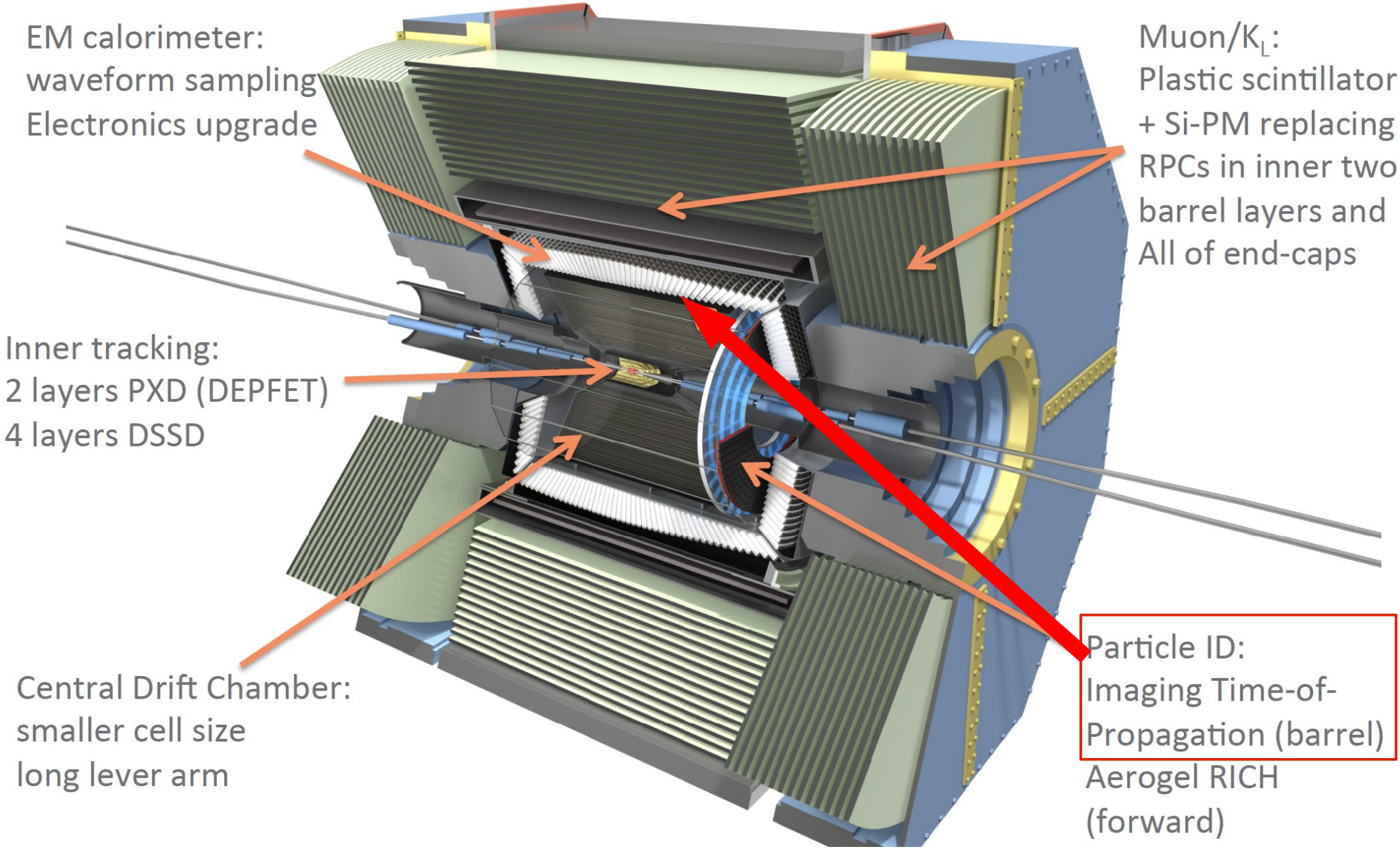


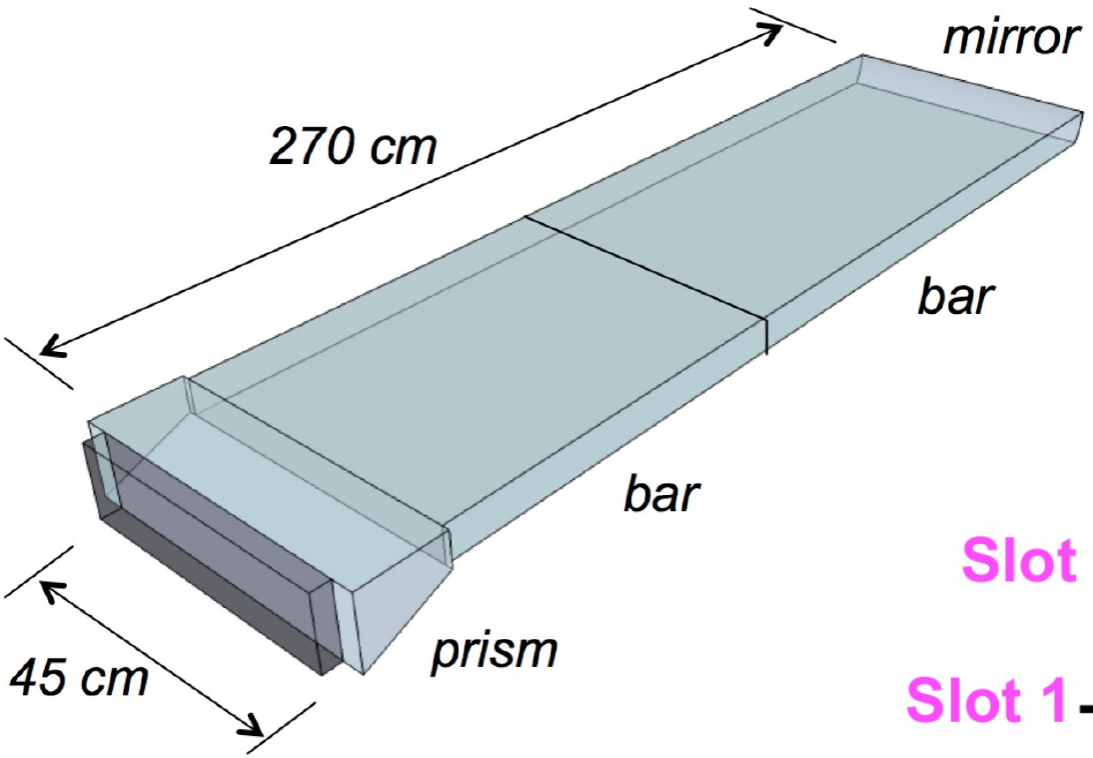
Photo by K.Inami, Nagoya U

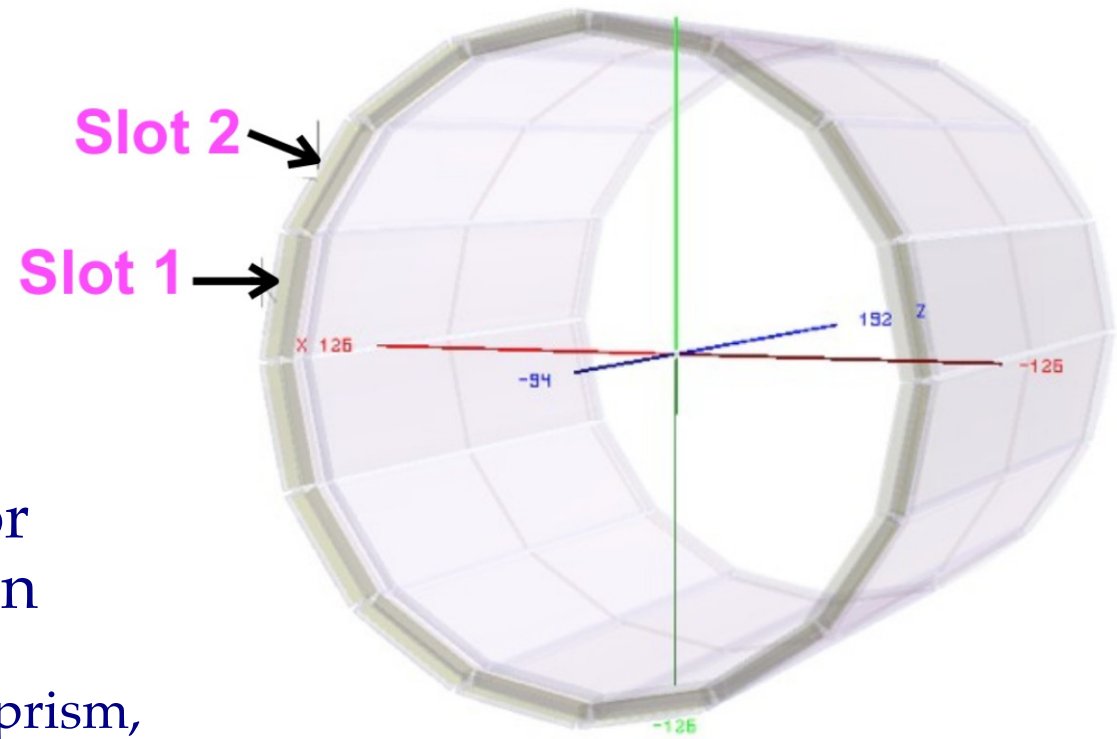
FCC-ee Workshop CERN, 9/1/19

Belle II Detector



TOP detector geometry





16 quartz Cherenkov radiator bars arranged in barrel region

- Forward side: spherical mirror
- Backward side: small expansion prism, sensors, readout electronics

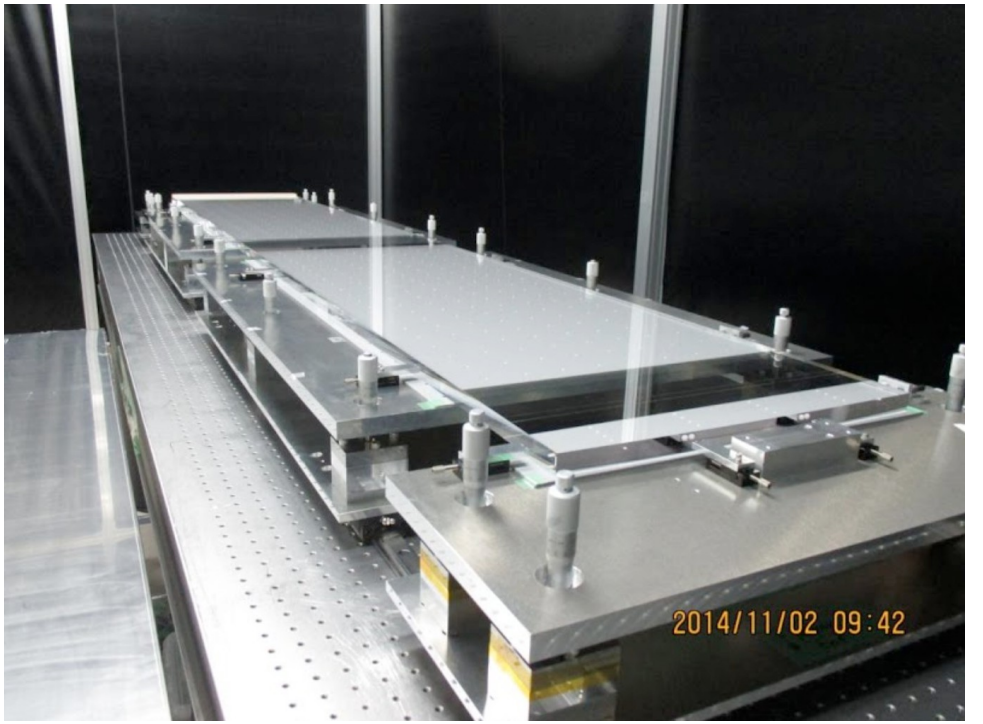
TOP optics

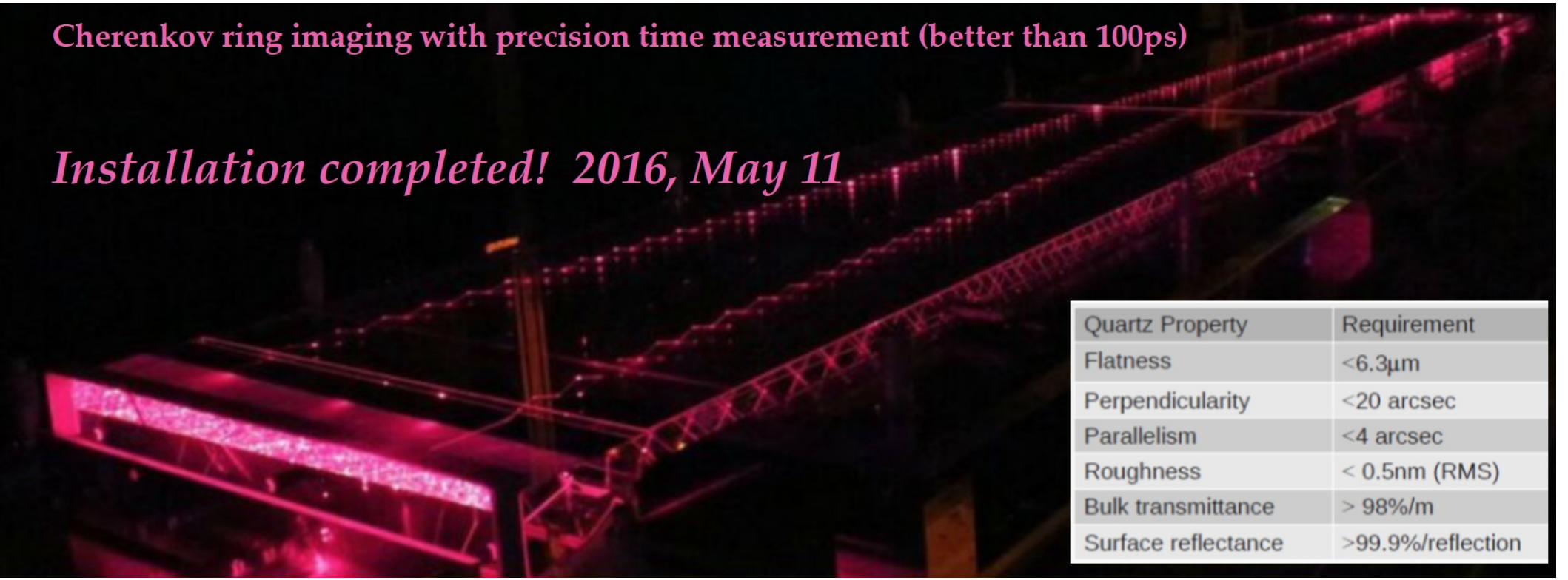
Quartz bars: 1250x450x20 mm^3

Mirrors: 100x450x20 mm^3

Prisms: 100x456x20 mm^3 at bar face, expanding to 456x50 mm^2 at PMT

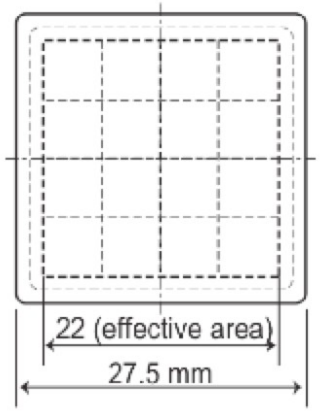
Material: Corning 7980





Quartz Property	Requirement
Flatness	<6.3μm
Perpendicularity	<20 arcsec
Parallelism	<4 arcsec
Roughness	< 0.5nm (RMS)
Bulk transmittance	> 98%/m
Surface reflectance	>99.9%/reflection

TOP sensors: Hamamatsu MCPPMTs



MCPPMT: Microchannel plate PMT

Developed in collaboration with U. Nagoya

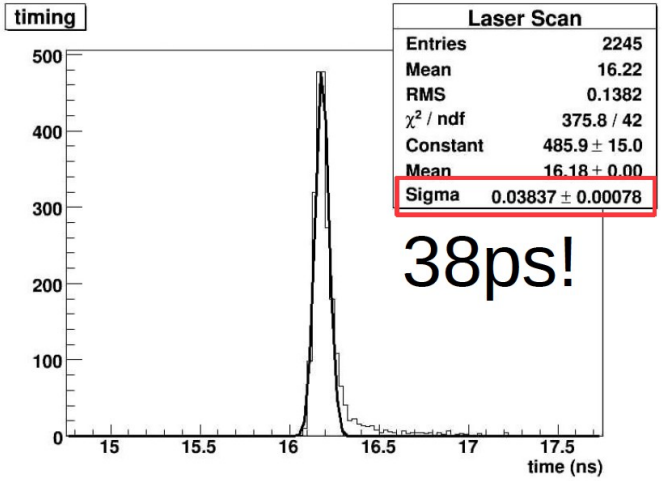
~70% active area; 55% collection efficiency

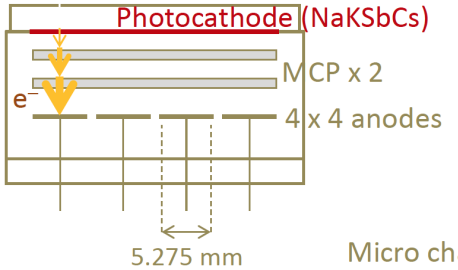
NaKSbCs photocathode

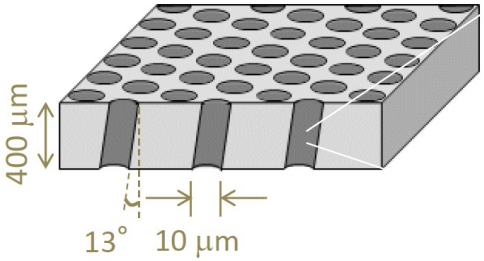
QE > 24% (average 28%) at 380 nm

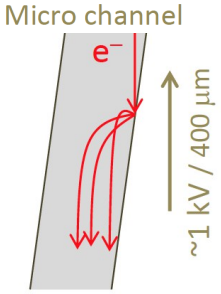
HV = 2.1-3.5 kV; Gain from 105 to 106

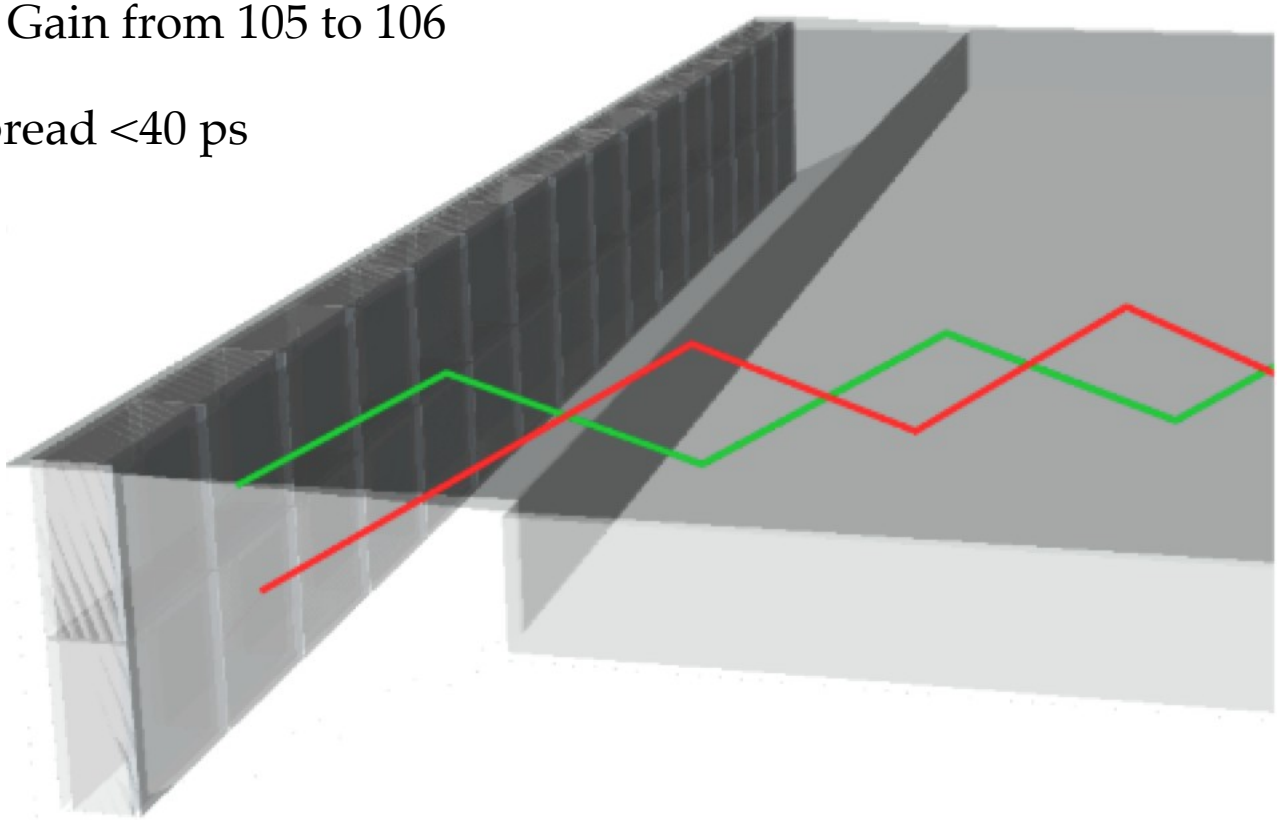
Transient time spread <40 ps











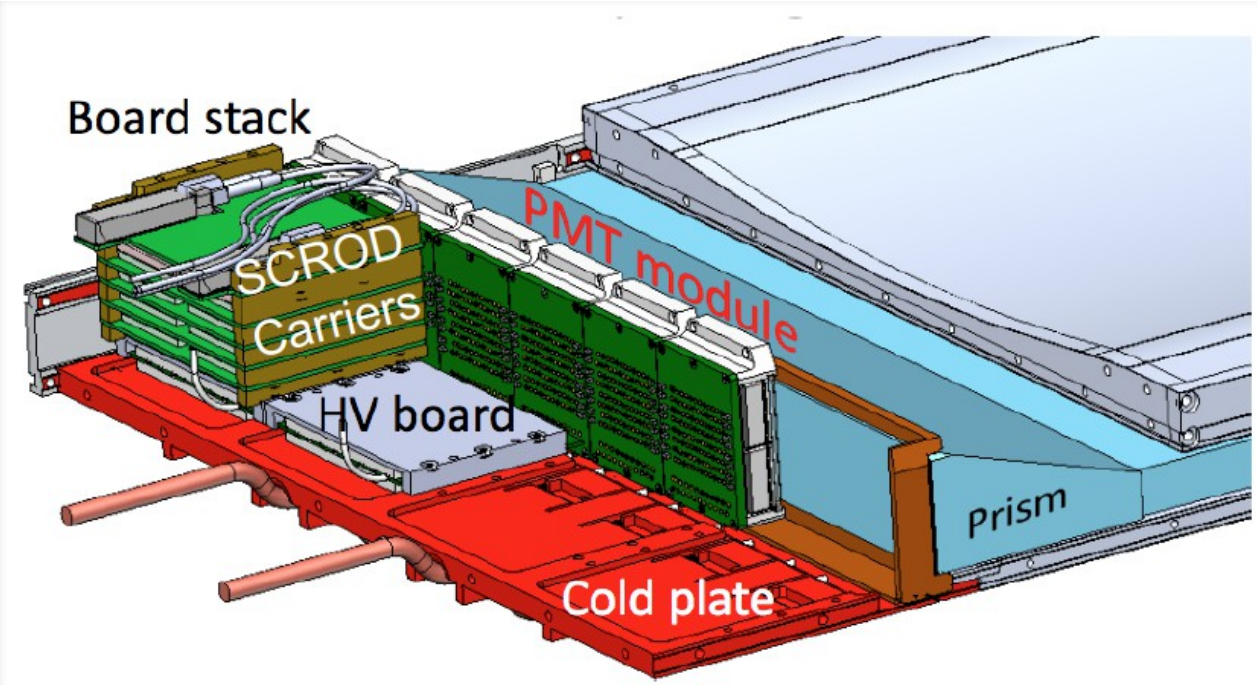
TOP Front-end Electronics

ArXiV:1804.10782

Based on IRSX chip
(developed at UH Manoa)

2 x  = 

- 8 ch. 12-bit waveform digitizer
- ~600 MHz analog bandwidth
- 2.7 GSa/s
- 11.6 μs storage buffer (32k)
- Full waveform output



Online processing
(via Xilinx Zinq FPGAs)
Raw ASIC output ~ 265 Tbit/s!

Pedestal subtraction

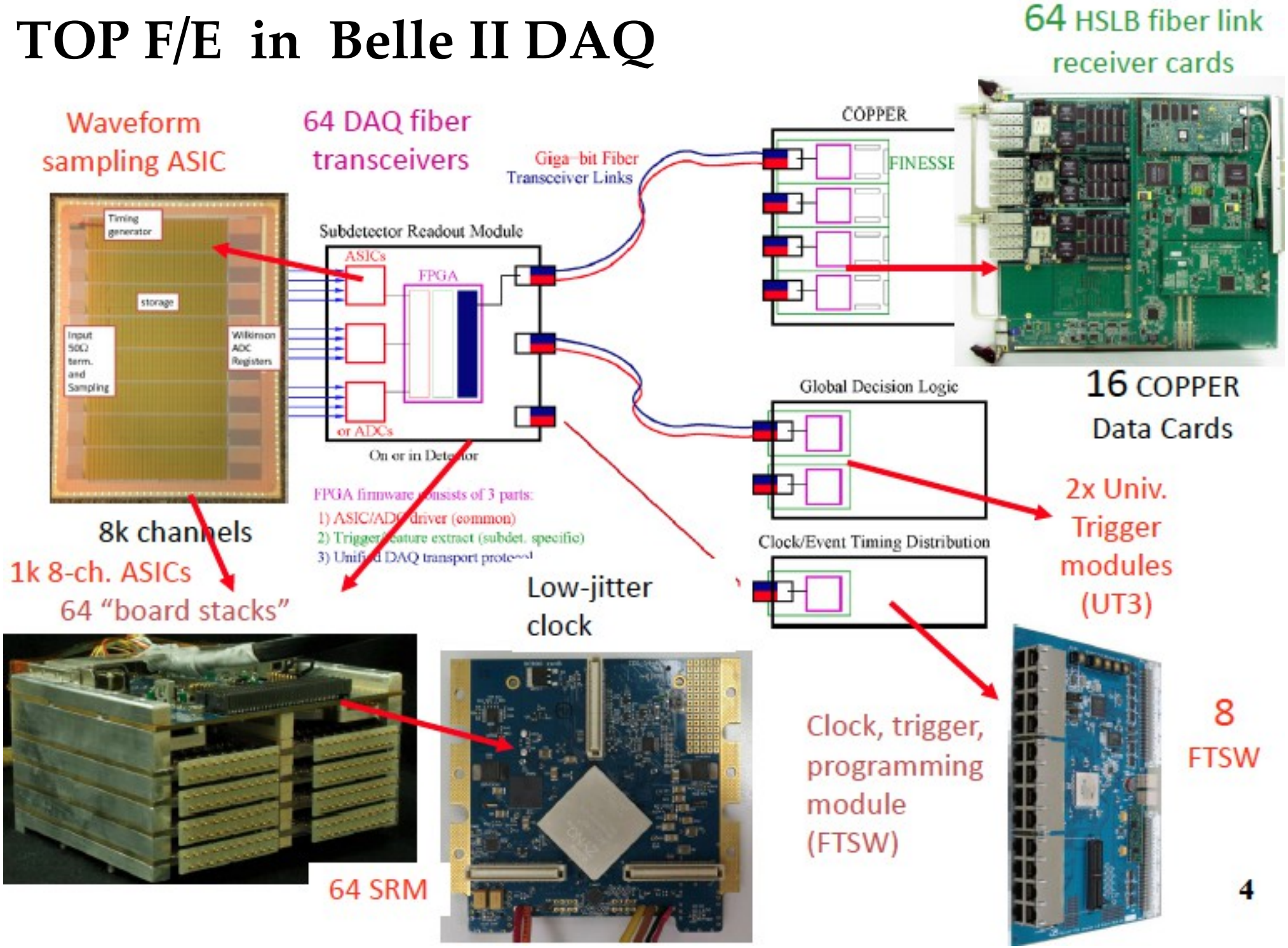
Waveform analysis

Feature extraction

Power budget:

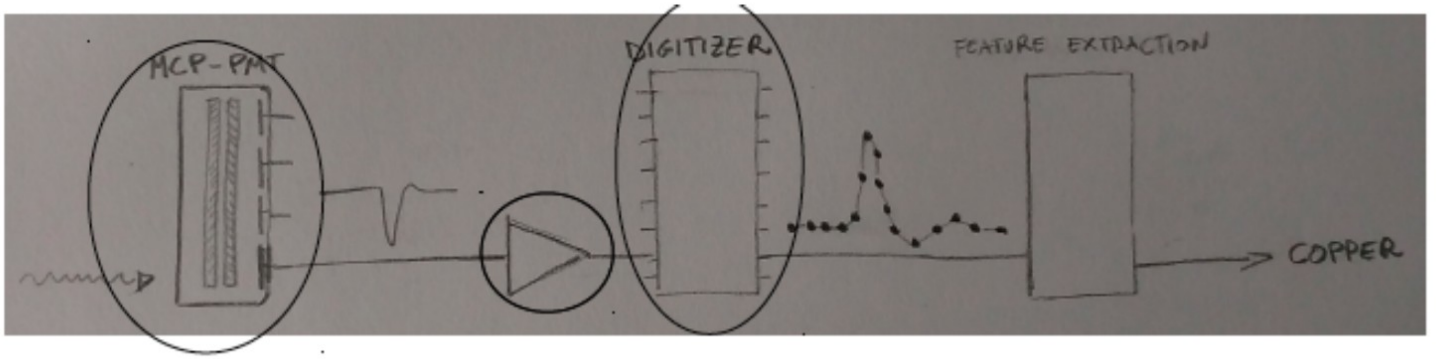
ASIC : 125 mW/ch
Preamp : 150 mW/ch
FPGA: 300 mW/ch

TOP F/E in Belle II DAQ



TOP time calibration : overview

What we have to calibrate



Photon detection
→ PMT Transient time

Fast amplifier
→ Transient time

Digitization of the waveform
→ sampling bin size

$$T_{photon} = t_{digit} + T^0_{channel} + T^0_{module}$$

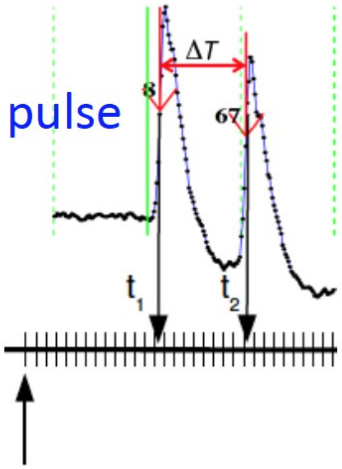
+ PMT channel gain

Time base calibration (TBC)
Calibration of the bin size of the digitizer

Local T0
Synchronization of the channels within a single quartz bar

Module T0
Synchronization of the modules one with the others

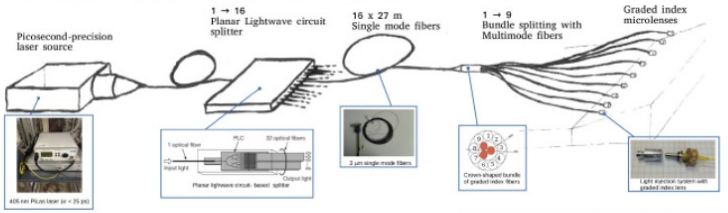
Double cal pulse



SST clock (KEKB clock-based)
Sample 0

Laser pulse calibration

To synchronize the channels within a single module we flash them with a laser pulse



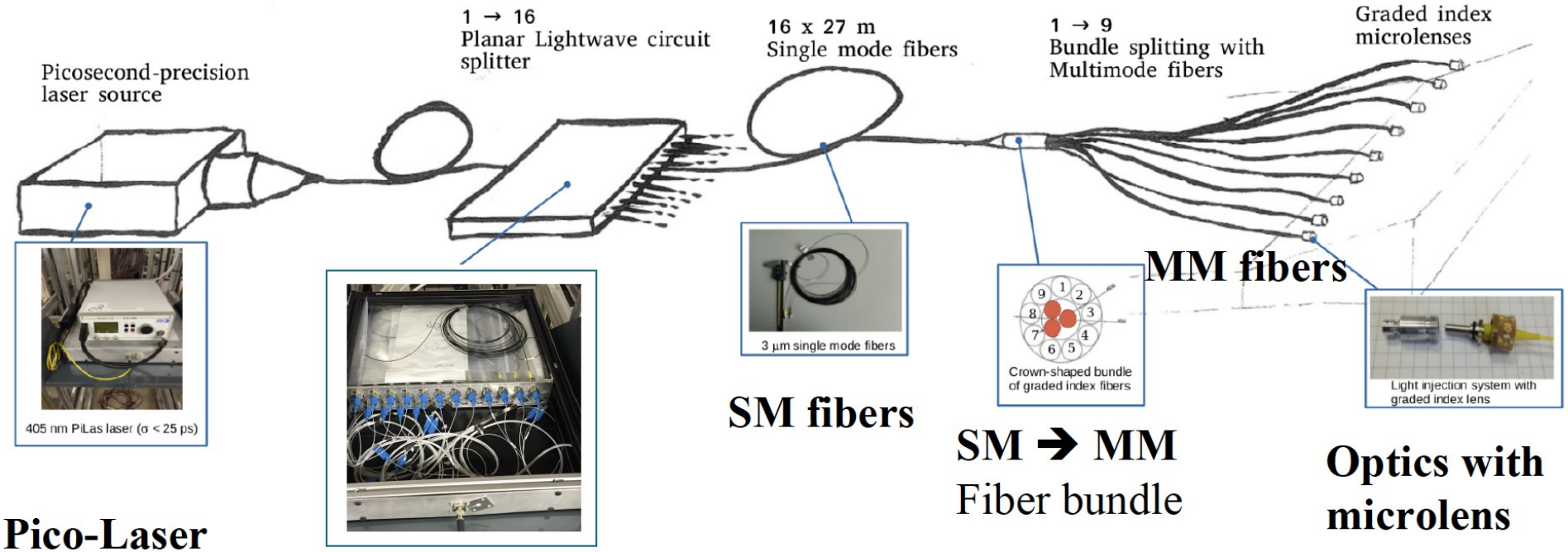
Alignment

$$\chi^2 \equiv -2\sum^{n} \log \mathcal{L}^{(i)}_{\mu}(\hat{p}) = \min,$$

$$\hat{p} \equiv (\Delta x, \Delta y, \Delta z, \alpha, \beta, \gamma, t_0)$$

TOP time calibration : light distribution system

Designed and built by INFN and Univ.Torino and Padova



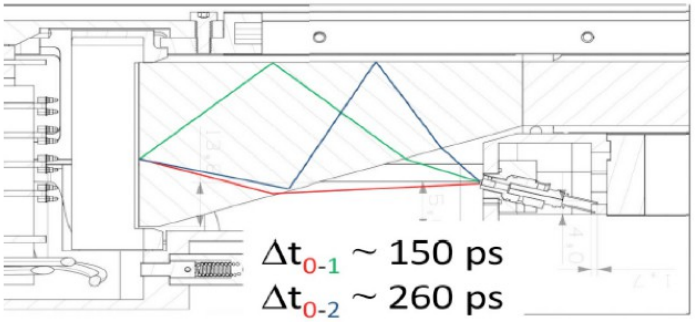
Pico-Laser
(pulsed light to simulate Čherenkov light)

Planar Lightwave circuit
(demultiplex of SM fiber)

(to increase the numerical aperture and reach all the PMT channels)

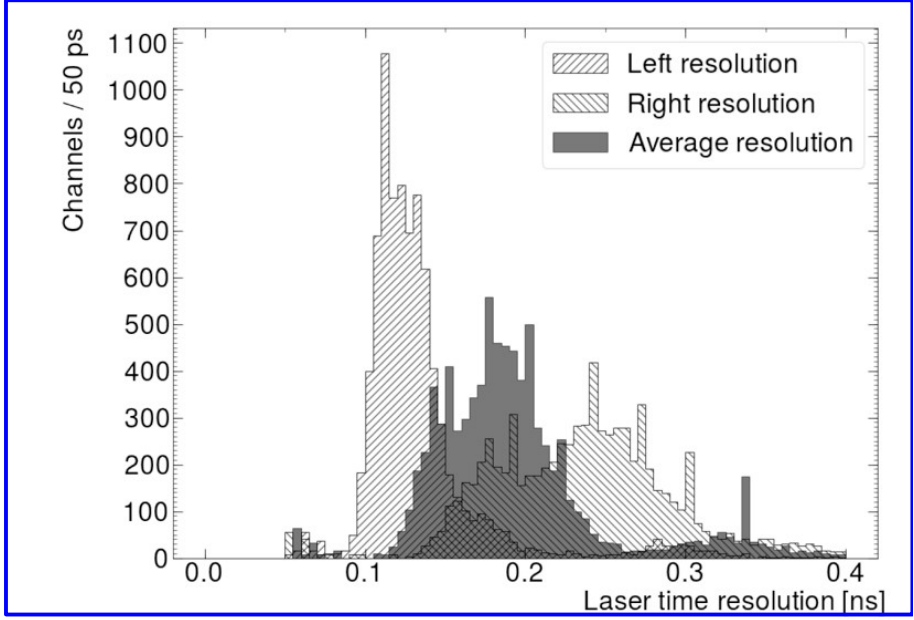
The challenge:
- 512 pixels per module
- 9 light sources per module

- Laser peak is a combination of 2 or 3 PDFs with the same width: 0,1,2 reflections.



Results: laser calibration

Distribution of rising (left) edge and trailing (right) edge time resolutions



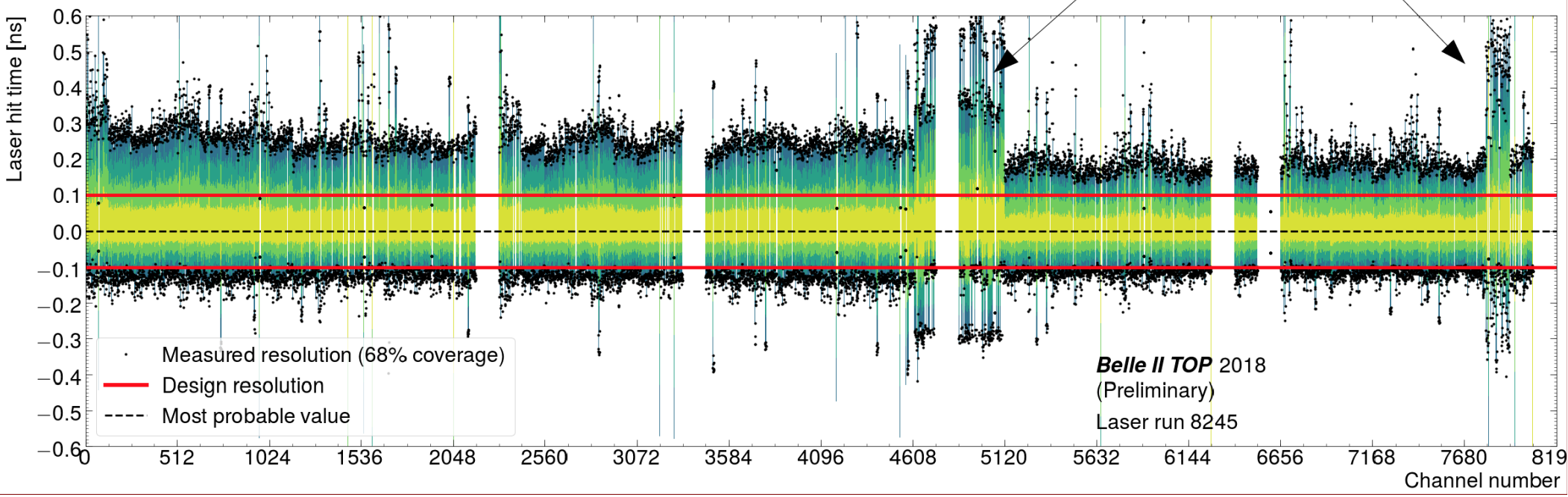
Synthetic summary of multigaussian fits on all pixels (16x512) of the TOP detector

Example of one laser run

→ Color: PDF distribution

→ Points: 68% quantiles

Single modules with temporarly issues



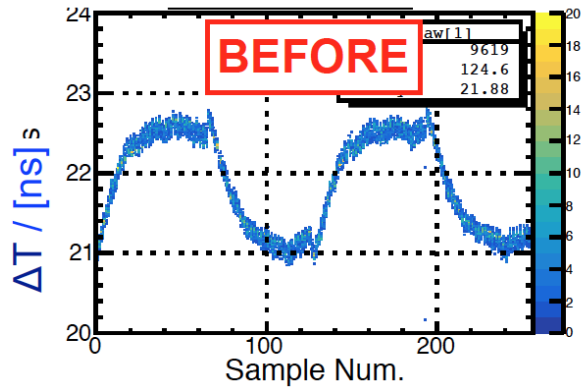
TOP time calibration : overview

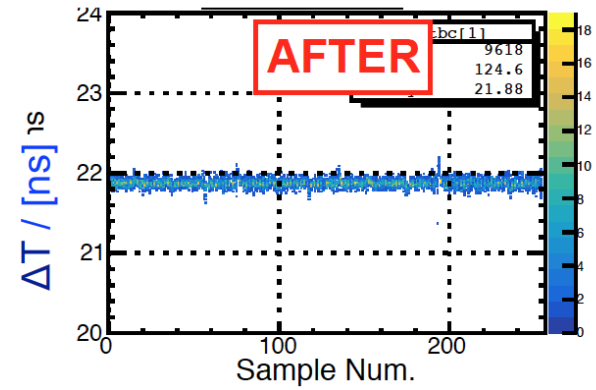
Time Base Calibration

- Ensure the linearity of time digitization

After TBC calibration

timing resolution of electronics	<	30 ps

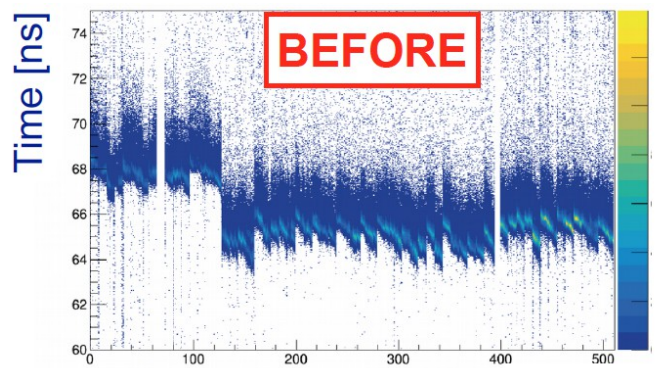


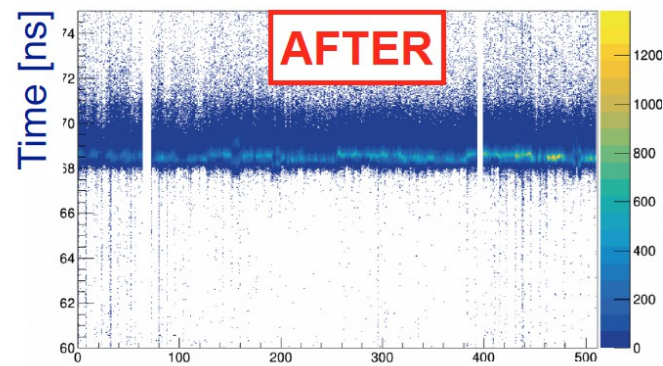


Local T_0 Calibration

- Align in time all channels within a module.

Current status: precision ~100 ps (but still margin for improvement!)





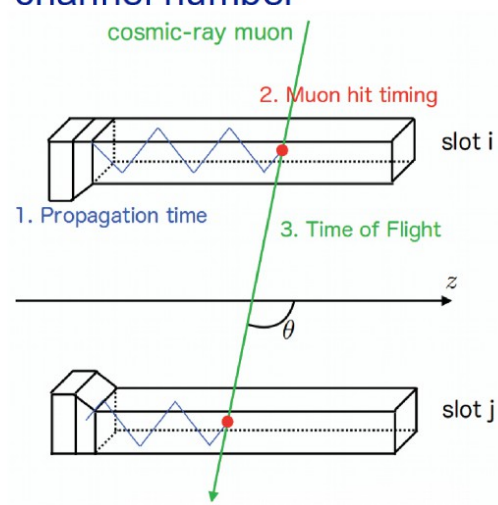
channel number

channel number

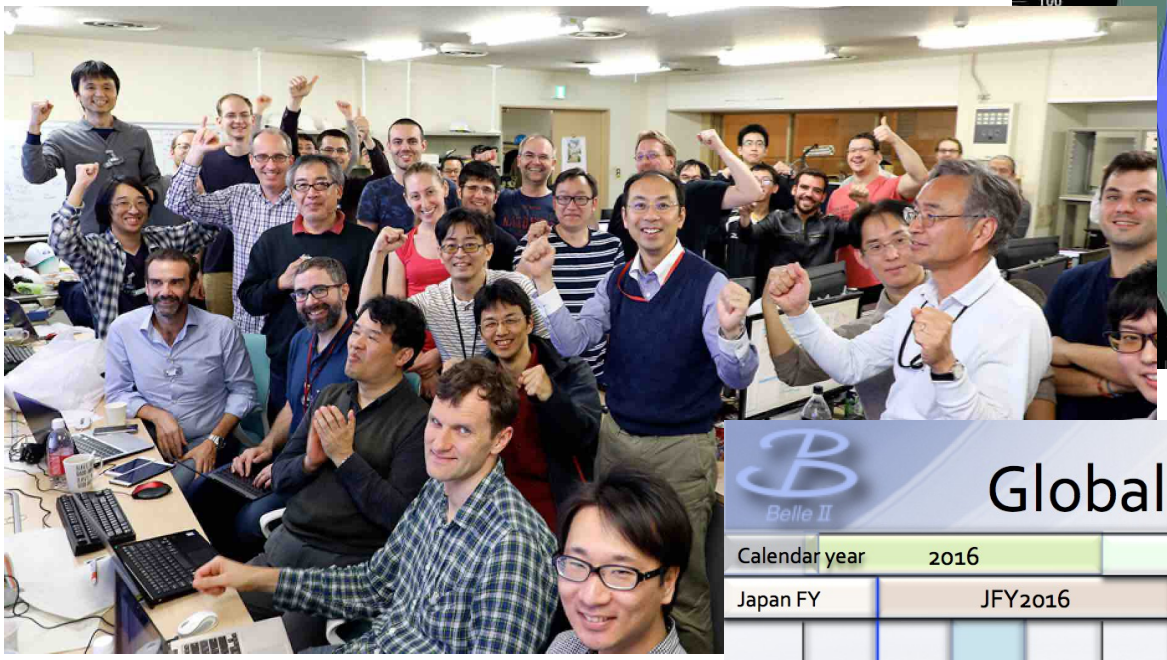
Module T_0 Calibration

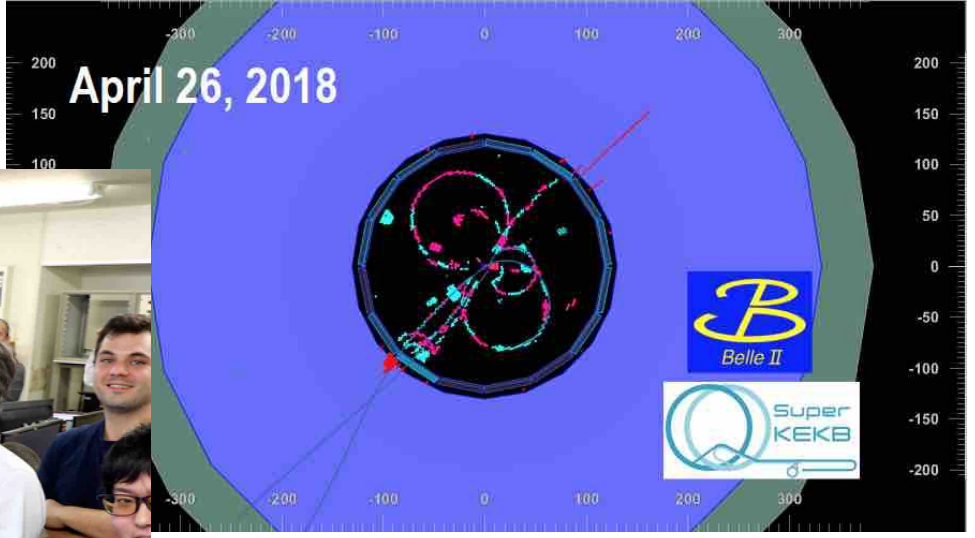
- Align in time all modules of the iTOP counter.

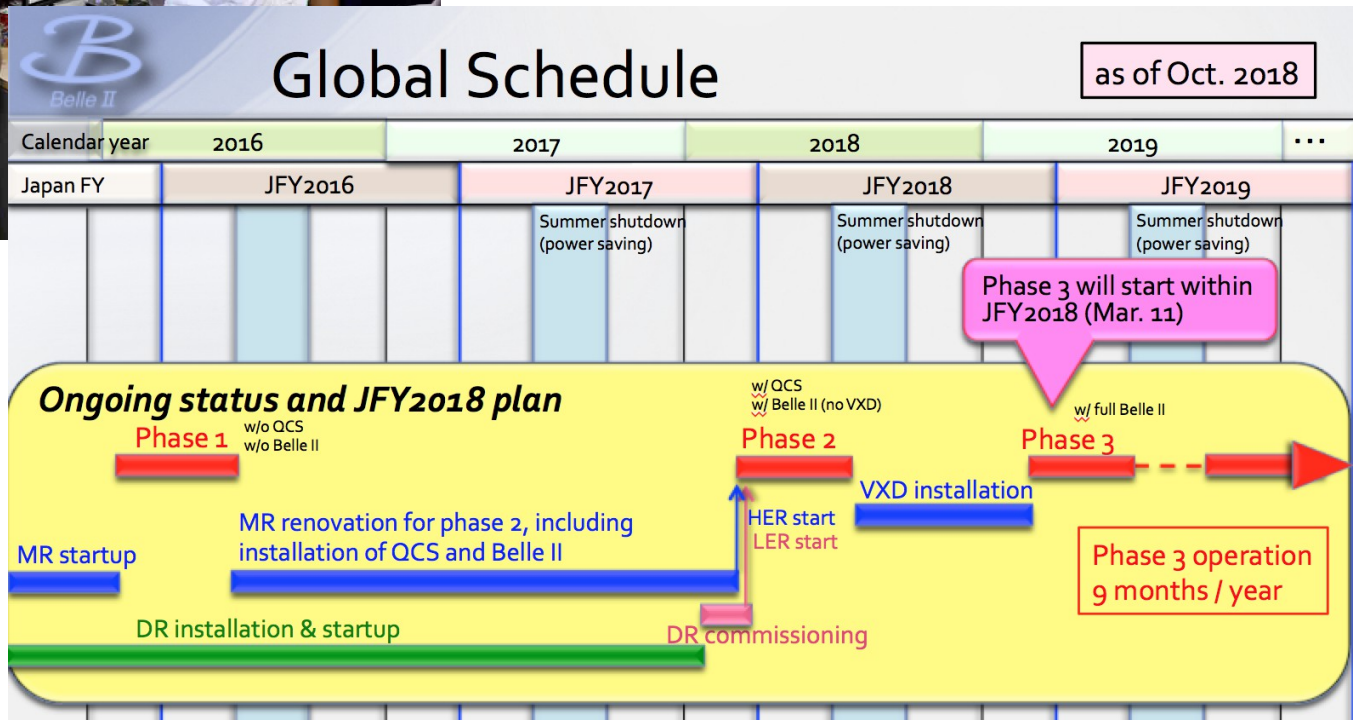
Will be improved by geometrical allignment



BelleII first collisions







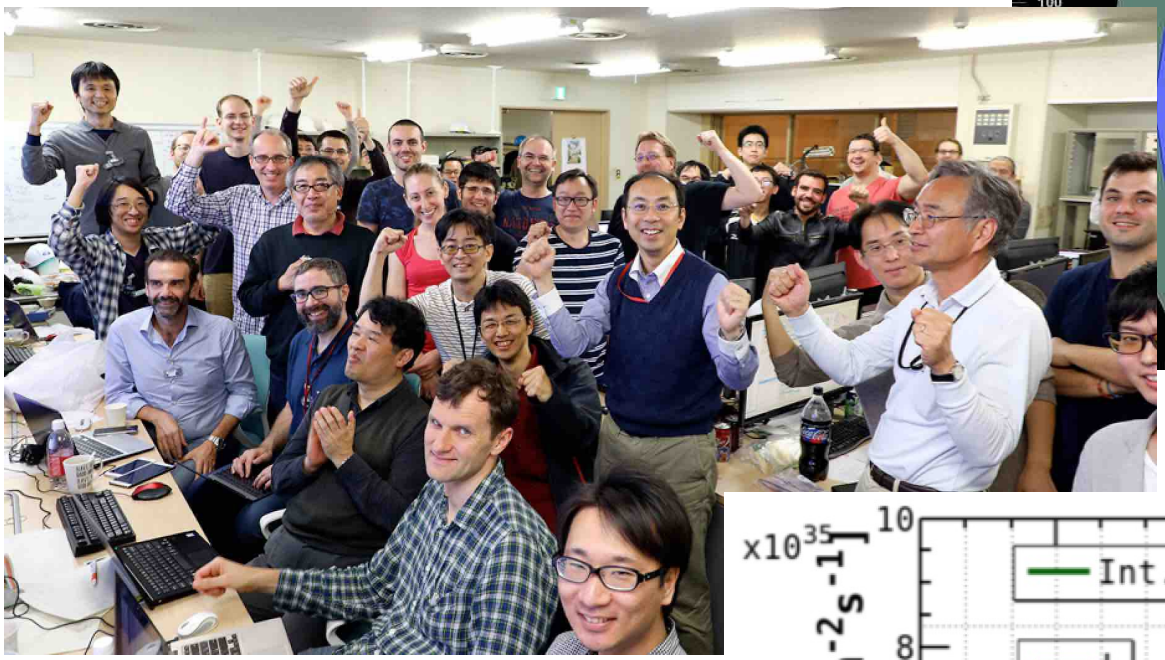
Phase II physics run:
Apr 26 to July 17, 2018
(without vertex detector)

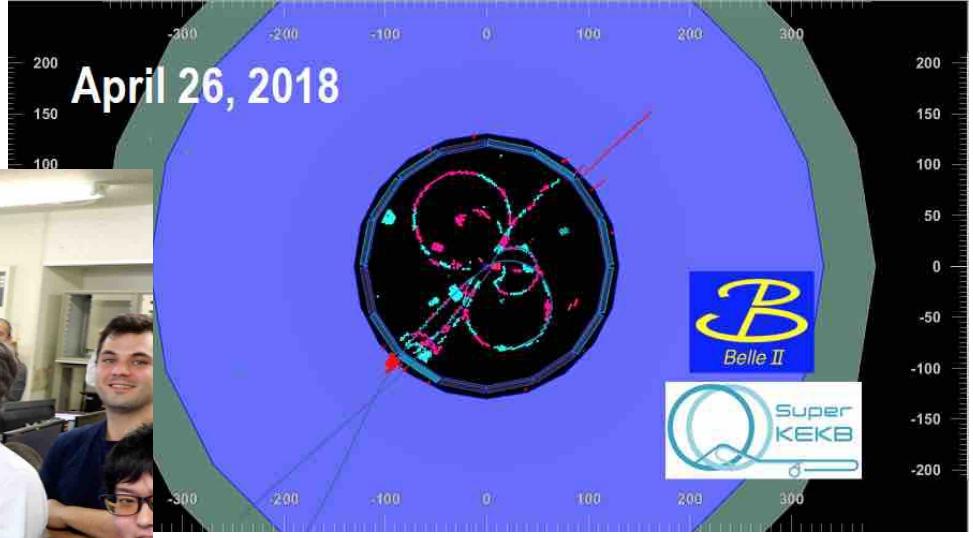
- $L_{peak} = 0.55\ 10^{34}\ cm^{-2}\ s^{-1}$
- $Ldt = 0.5\ fb^{-1}$ @ Y(4S)

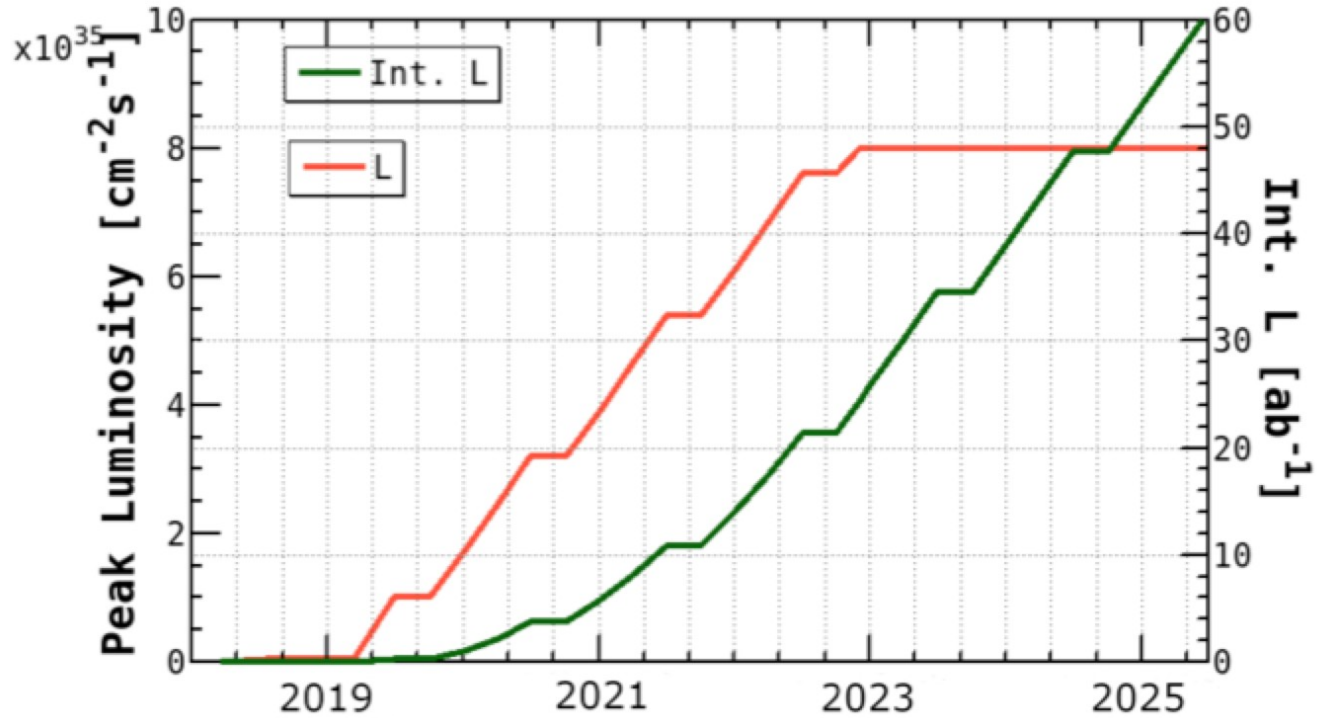
TOP commissioning results:

- Uptime > 90%
- Active channels = 97.5%
- First PID tests on collisions

BelleII first collisions







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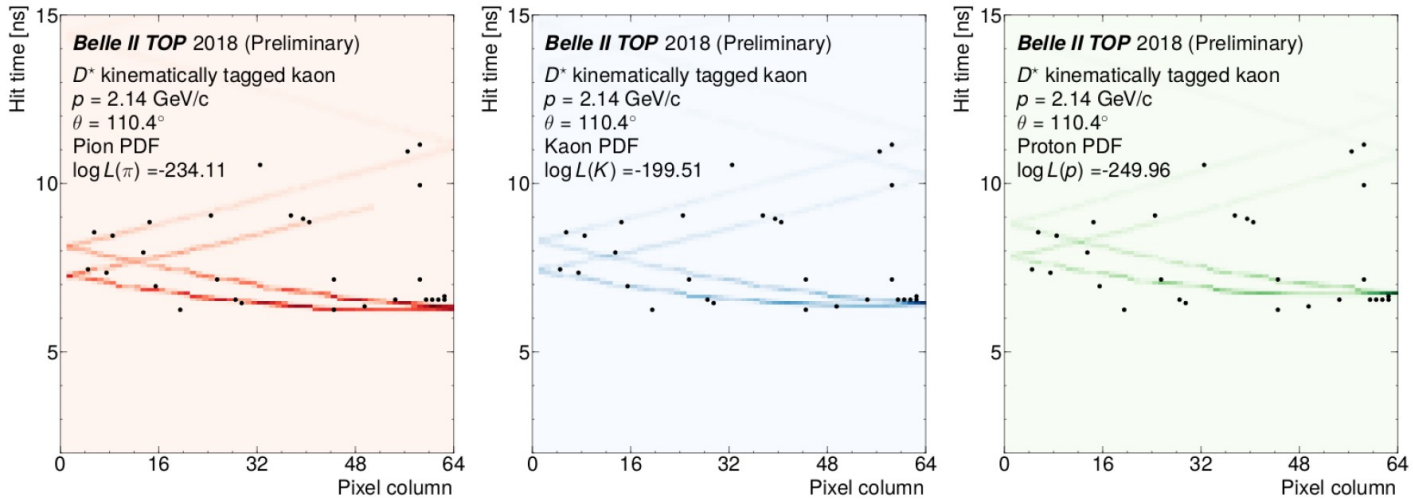
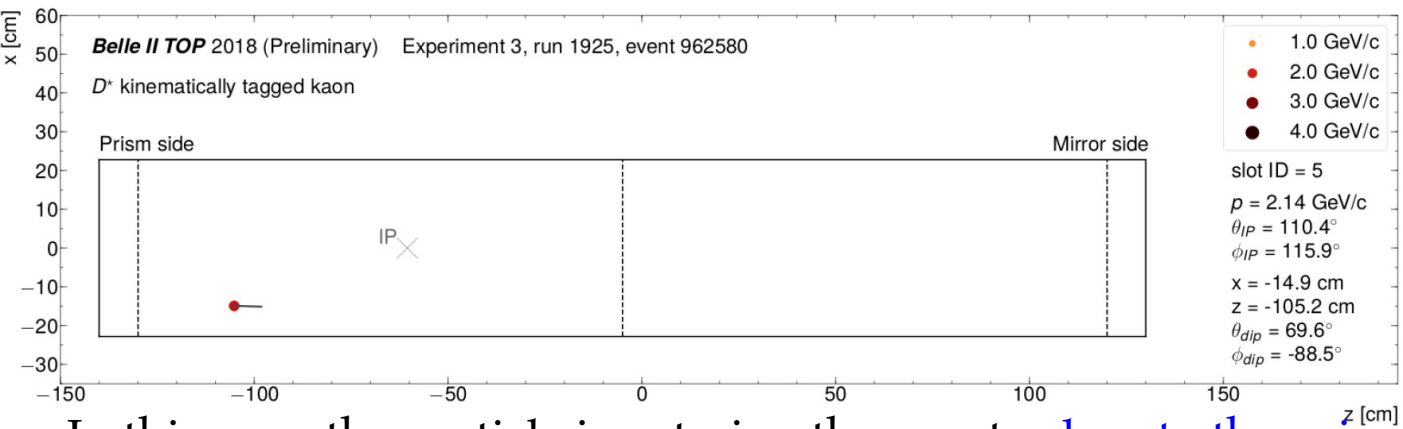
First results: TOP working principle

Every black dot is a photon on the PMT pixel array. Caustics are formed by the Cerenkov light cone, after many reflections, on this array.





2.14 GeV

prism-facing event

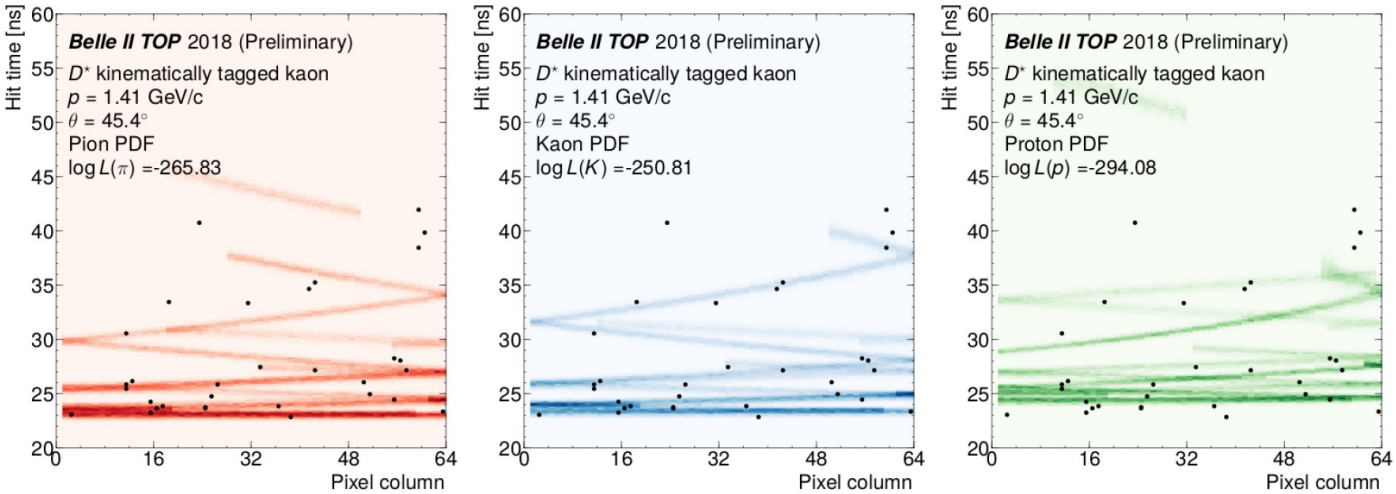
Little room for the Cherenkov cone to open up

ID is dominated by the PDF shift (i.e. ToF) rather than the shape difference

In this case, the particle is entering the quartz close to the prism, and all light directly reaches the PMT array after few reflections. The TOP is mostly measuring the time of flight from the interaction vertex to the quartz.

First results: TOP working principle

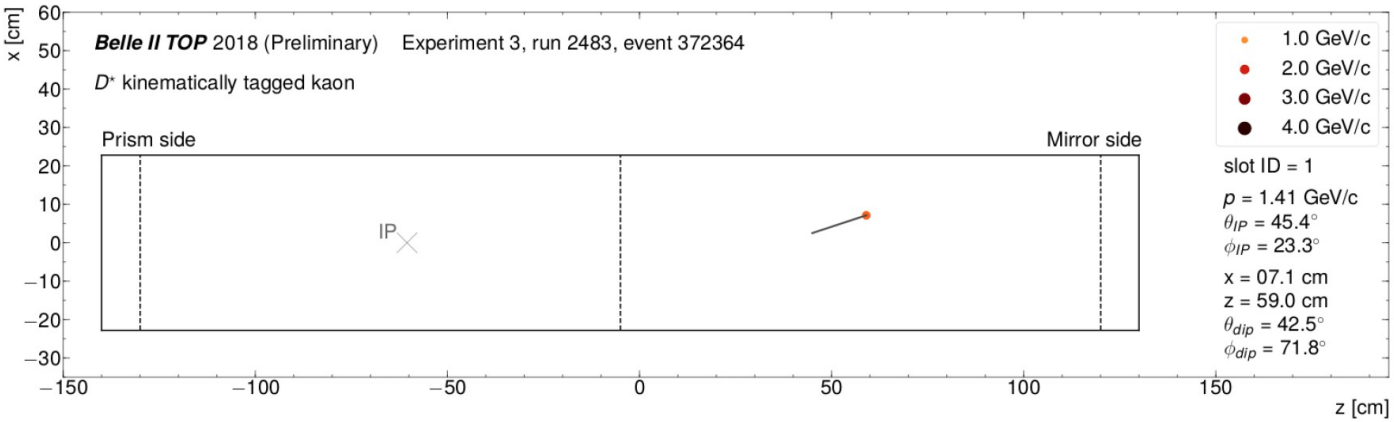
Every black dot is a photon on the PMT pixel array. Caustics are formed by the Cerenkov light cone, after many reflections, on this array.



1.41 GeV

mirror-facing event

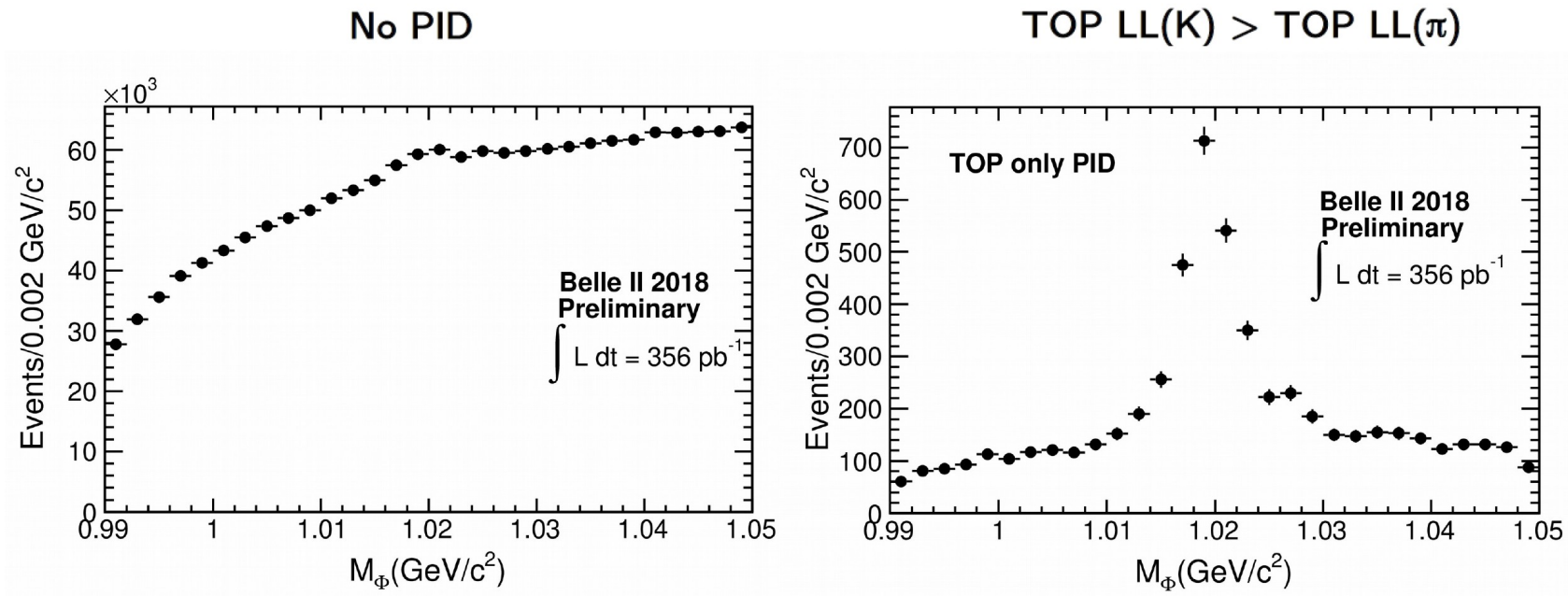
ID is dominated by the PDF shape (i.e. Cherenkov ring) rather than the global offset



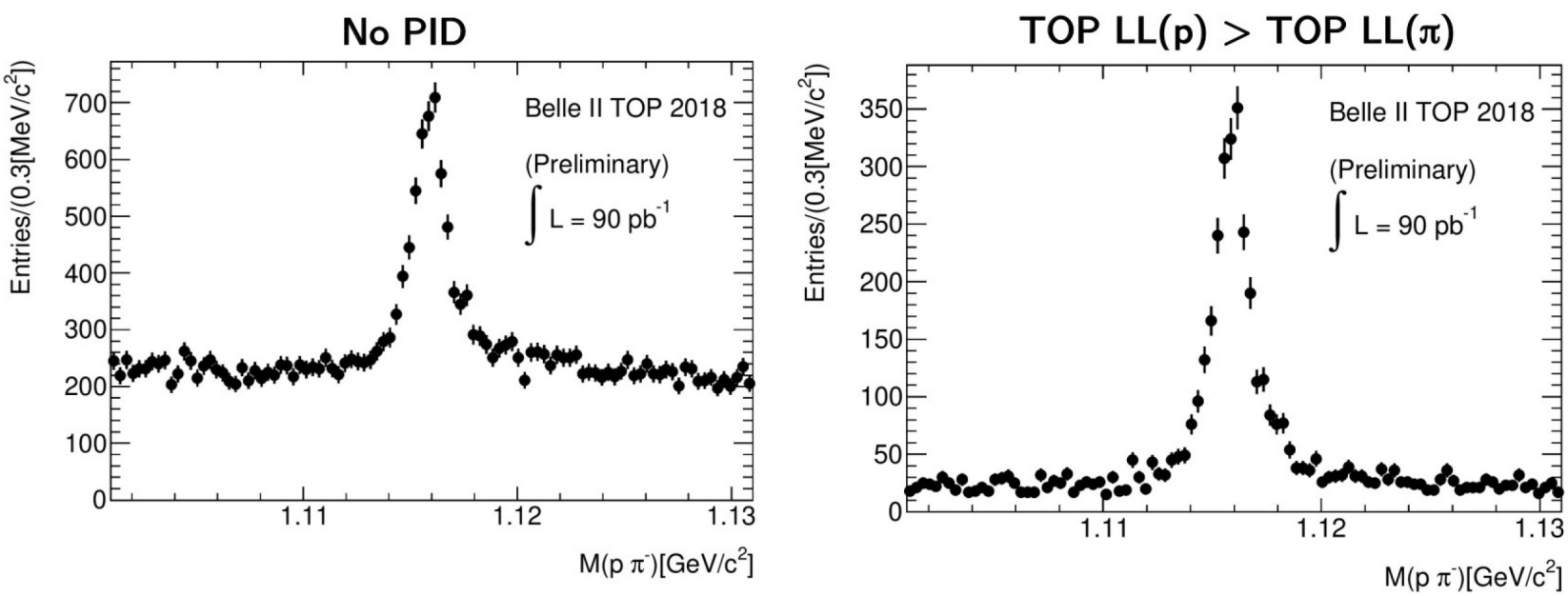
In this case, the particle is entering the quartz close to the mirror, and all photons reach the PMT array after many reflections. The TOP is mostly measuring the time of propagation of light inside the quartz.

TOP Preliminary results on πK and πp discrimination

$\Phi \rightarrow K^+K^-$
With both K in TOP acceptance



$\Lambda \rightarrow \pi p$
With proton candidate in TOP acceptance



Preliminary Results: PID performance vs momentum

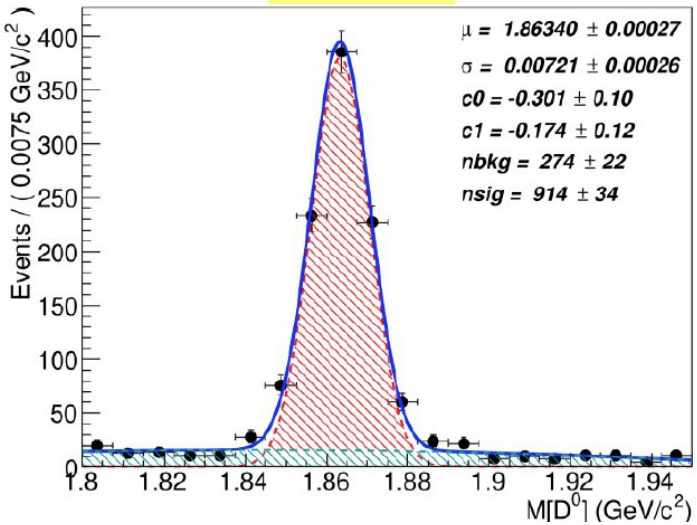
Process:
$D^{*+} \rightarrow D^0(K^+\pi^-)\ \pi^+$

Data set:
Ldt = 355 pb^{-1}
914±34 candidates

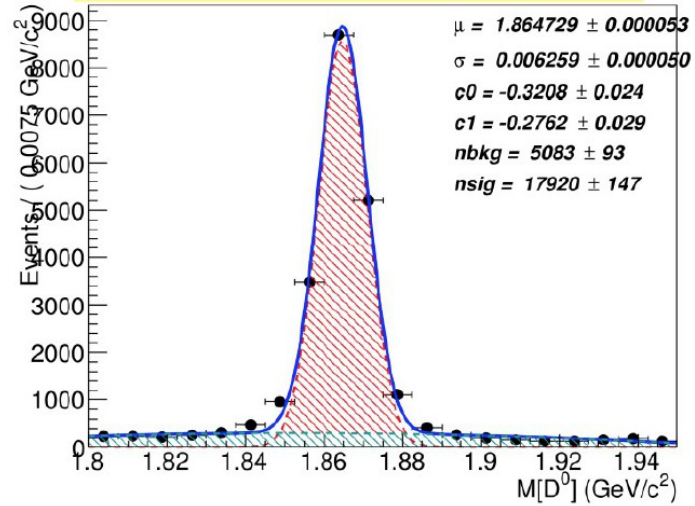
P*>2.5 GeV
$|\Delta M-145.43|<1.5$ MeV

TOP performance
10-20% worse than MC expectation

Prod 6

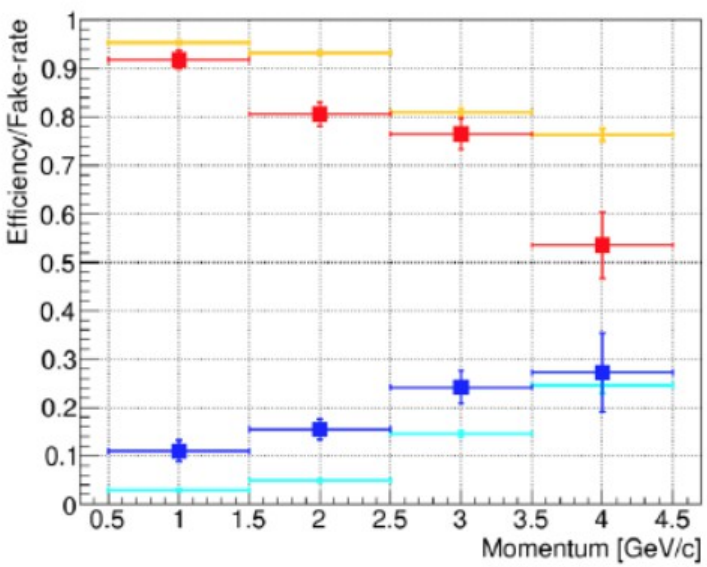


~5 fb^{-1} Phase II $\Upsilon(4S)$ MC

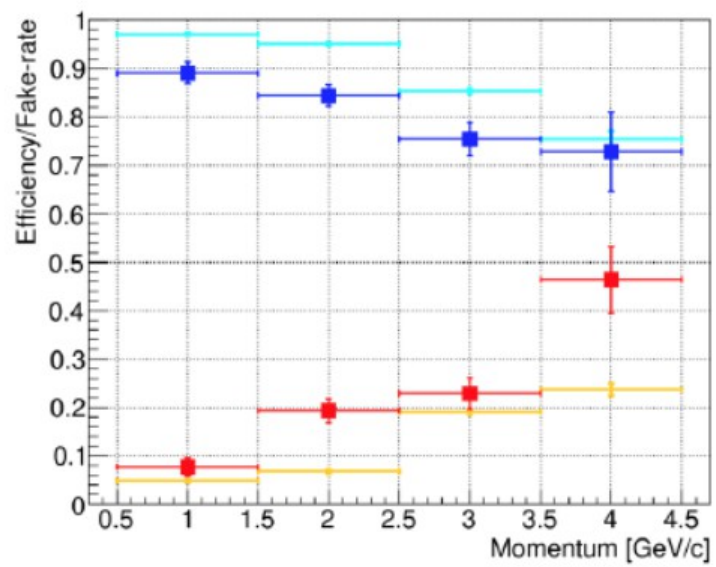


TOP only PID

K-eff [Data] K-eff [MC]
π-fake [Data] π-fake [MC]



π-eff [Data] π-eff [MC]
K-fake [Data] K-fake [MC]



Where to work to improve PID performance

Core level improvements:

- We achieved a core time resolution of 120 ps with laser calibrations, pixel by pixel distributions are not yet well reproduced by MC;

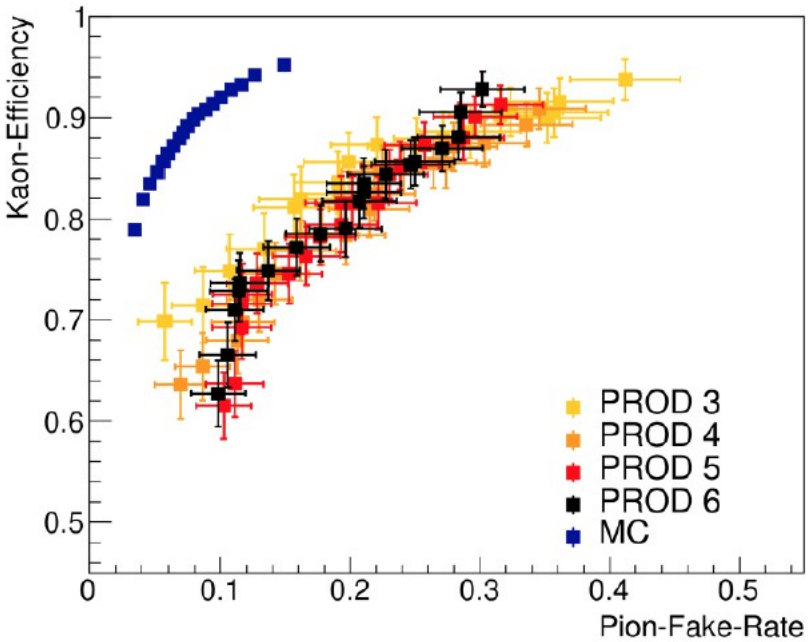
- Still debugging firmware and optimizing ASIC operational parameters.

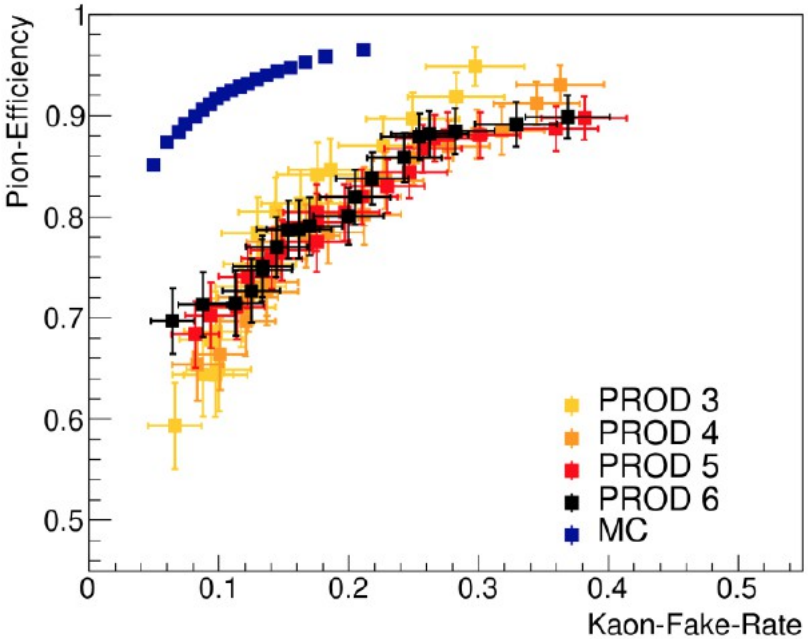
- We have residual non-linearities in the time base calibration which can explain the higher time resolution and PID performance degradation. New calibration algorithms are being prepared.

- Geometrical alignment is currently limited by the available statistics

High level analysis:

- Performance metrics show that TOP working principle and PID performance are OK, but still worse than MC expectations. Software algorithms still need full debugging.





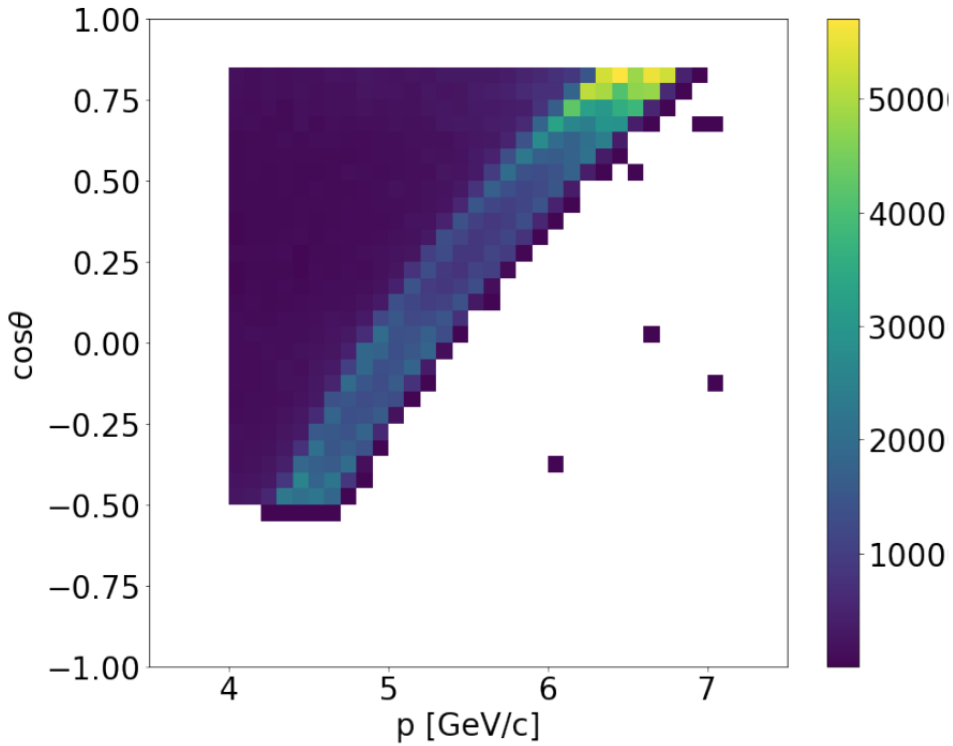
Future prospects with dimuons

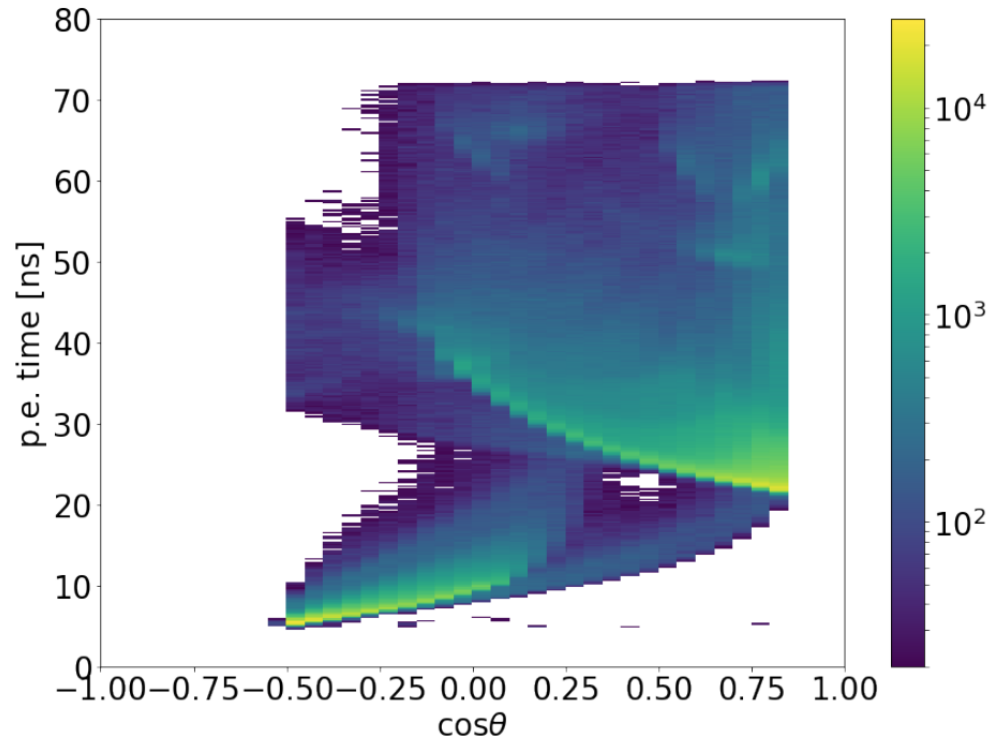
iTOP resolution estimation
Global performances

Preliminary study to estimate extra-time resolution from MC di-muon events

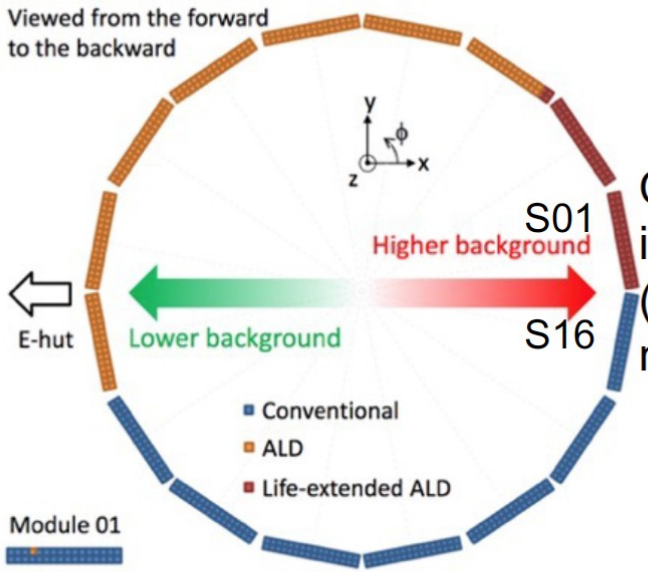
Convolution between MC PDF and Gaussian MC Data PDF

Muon-pairs events are generated in all permitted kinematic and acceptance areas and involve globally all TOP modules

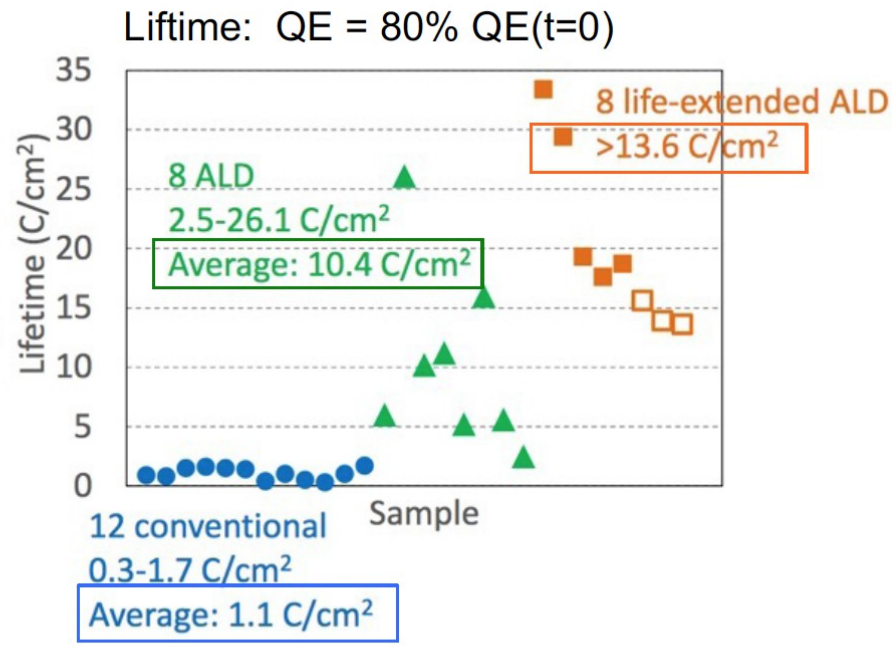




MCPPMT aging



Conventional MCP-PMT inside 7 modules (tot 224 PMT) must be replaced in 2020



Photon background levels are a major concern for the MCPPMT performance: the first batch of devices will surely NOT STAND operation at high luminosity.

Atomic Layer Deposition (developed recently by Hamamatsu) will allow to increase sensors' lifetime by ~10x

9/16 modules are equipped with ALD PMTs

The high backgrounds observed in Phase II, rescaled even at 10^{35}, raise even more concerns. Mitigation strategies are being studied

1 MHz/PMT at 5 10^5 gain ➔ 1 C/cm² @ 50 ab^{-1}

4÷8 MHz/PMT ➔ 1 C/cm² @ 12÷6 ab^{-1}

Integrated luminosity at the summer shutdown

2019: 0.18-0.33 C/cm² (2 ab^{-1})
2020: 0.72-1.33 C/cm² (8 ab^{-1})
2021: 1.52-2.82 C/cm² (17 ab^{-1})
2022: 2.69-4.98 C/cm² (30 ab–1)
2023: 3.76-6.97 C/cm² (42 ab–1)

Replace conventional MCP-PMT.

Summary

TOP has been stably taking data during the first period of data taking at Y(4S) energy (phase II): it will play a major role in Belle II physics program

We performed the first measurements of TOP PID performance with hadrons from e+e- collisions

TOP is positively reducing the expected backgrounds, but ....

In order to achieve the desired time resolution , we need to improve:
- the time base calibration for all sampling windows
- the relative timing of each pixel in each quartz bar (laser calibration)
- the alignment of all quartz bars with the inner tracking chambers

Firmware development will allow to further improve performance

Standard MCPPMTs will be replaced with life extended ALD PMTs to cope with expected sensor aging at high luminosity

THANK YOU !