# Calibration and Commissioning of the Time Of Propagation PID Detector at the Belle II Experiment

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on behalf of the Belle II TOP Group

"14th Pisa Meeting on Advanced Detector"
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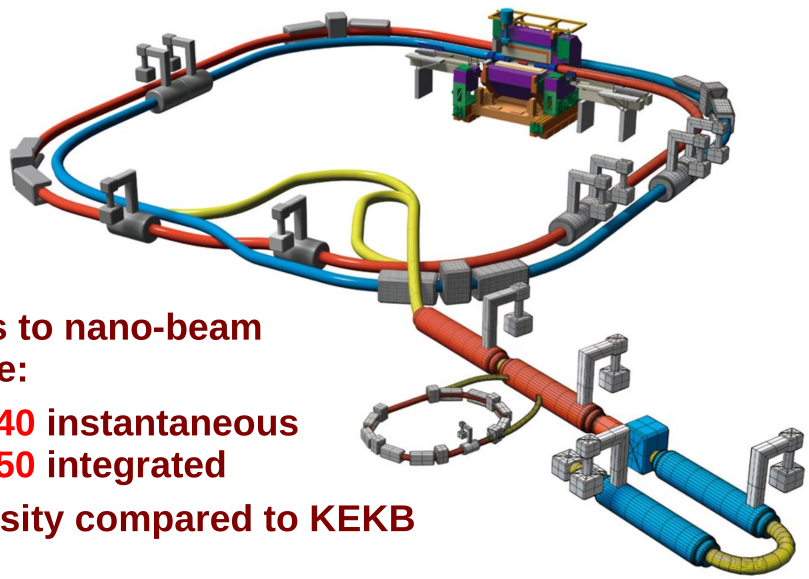
# The SuperKEKB $e^+e^-$ Collider

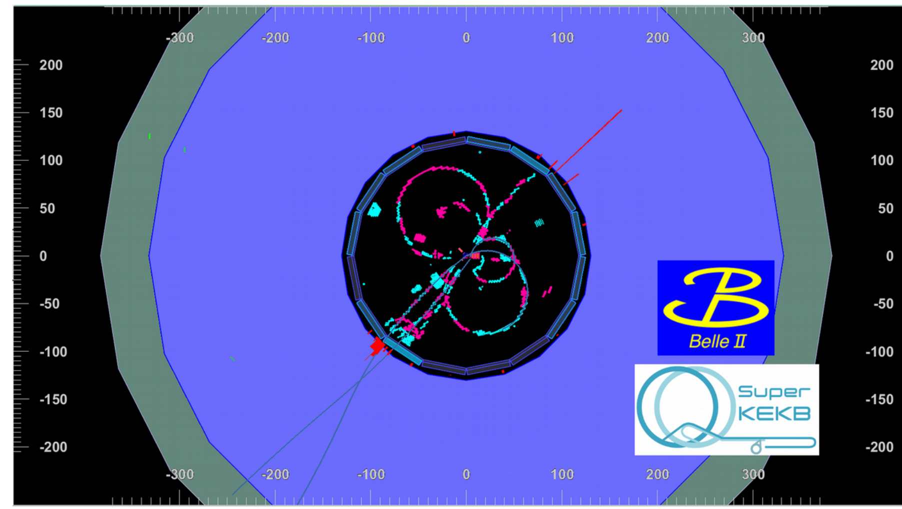
The SuperKEKB $e^+e^-$ Collider will operate at a CM energy corresponding (or close to) the mass of the Υ(4S) resonance:

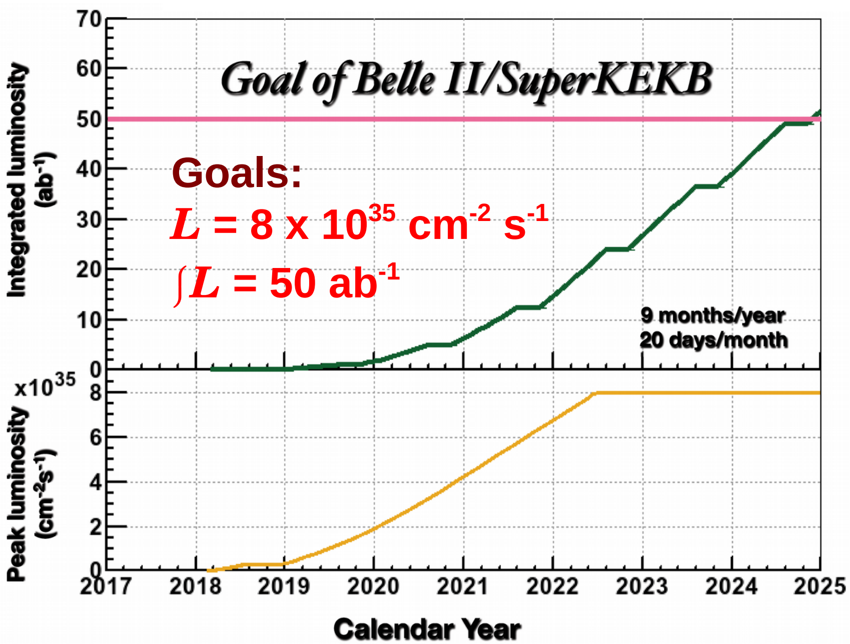


**Thanks to nano-beam scheme:**

**x40 instantaneous**
**x50 integrated**

**luminosity compared to KEKB**




**First collisions delivered on April 26th!**

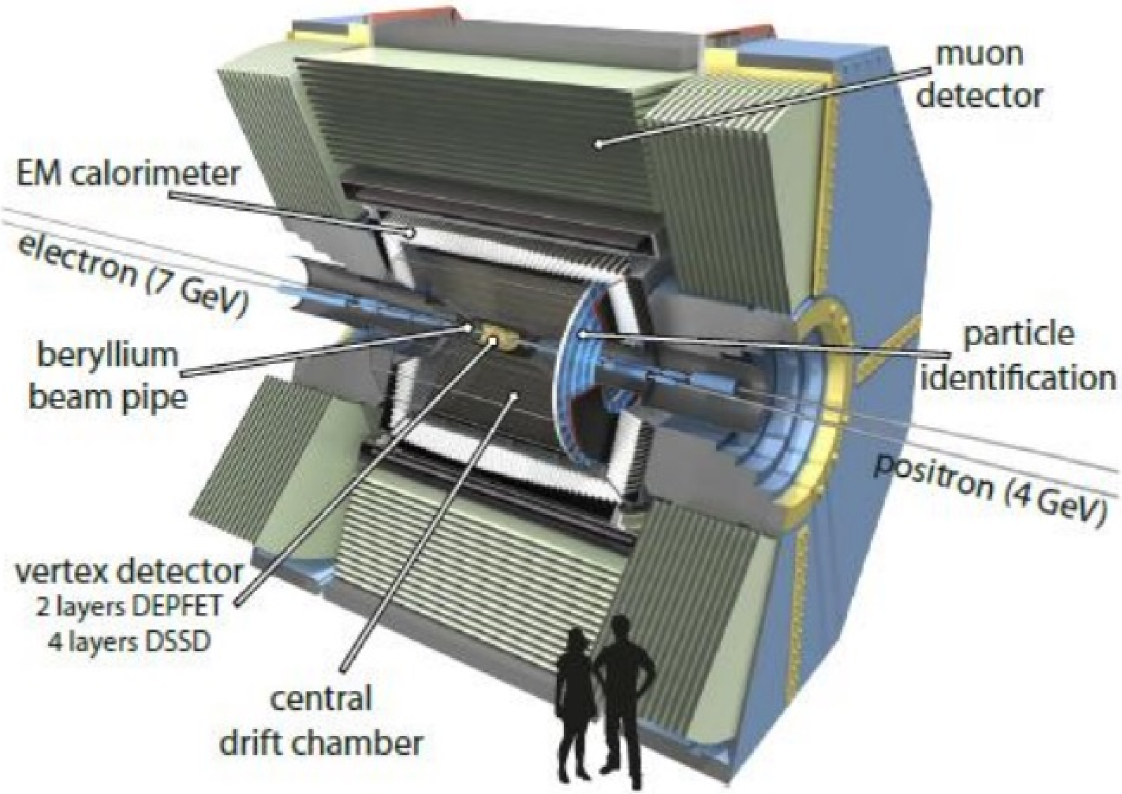
# The Belle II Detector

- Extensive upgrade of Belle in all areas;
- Vast Physics Programme: search for New Physics in B-, D-mesons, $\tau$ decays, exotic particles, Dark Sector, … ;
- Need to cope with much harsher machine background conditions;
- Particle IDentification is one of the fundamental ingredients of the program;

Target K-$\pi$ separation:

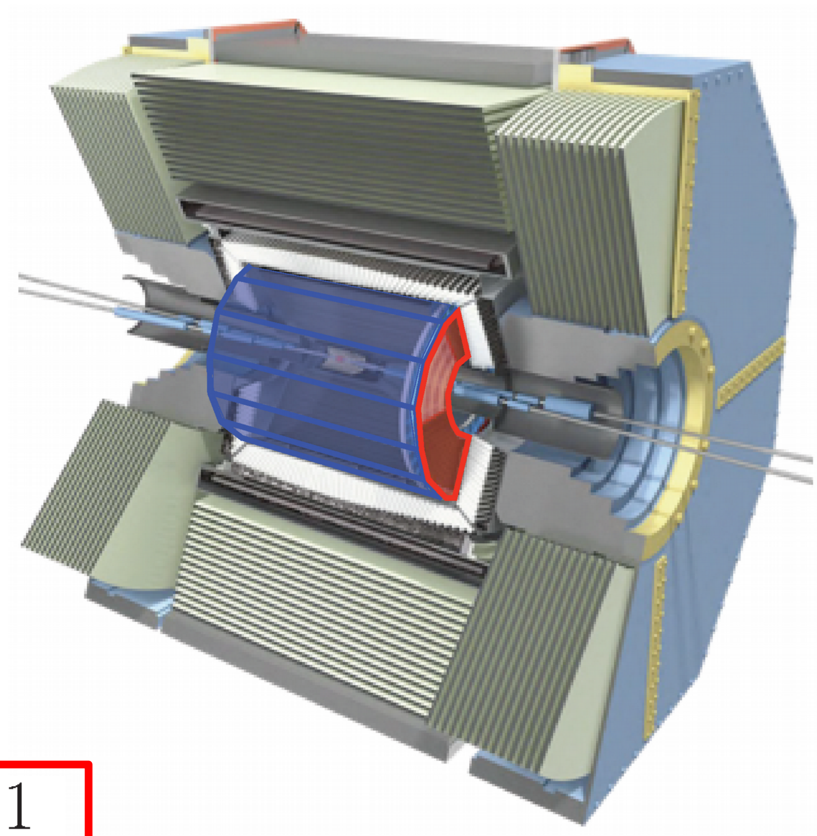
K($\pi$) efficiency > 95%
$\pi$(K) mis-ID rate < 5%

up to p = 4 GeV



# Hadron PID at Belle II

- At low momentum, this is mostly provided by the dE/dx measurement of the Central Drift Chamber (resolution ~5%);
- Two sub-detectors cover the high momentum part of the spectrum:
  - Barrel region: TOP;
  - Endcap region: ARICH;
- Common concept: measure the velocity β of the candidate particle from the Cherenkov cone of light emitted when passing through a medium:

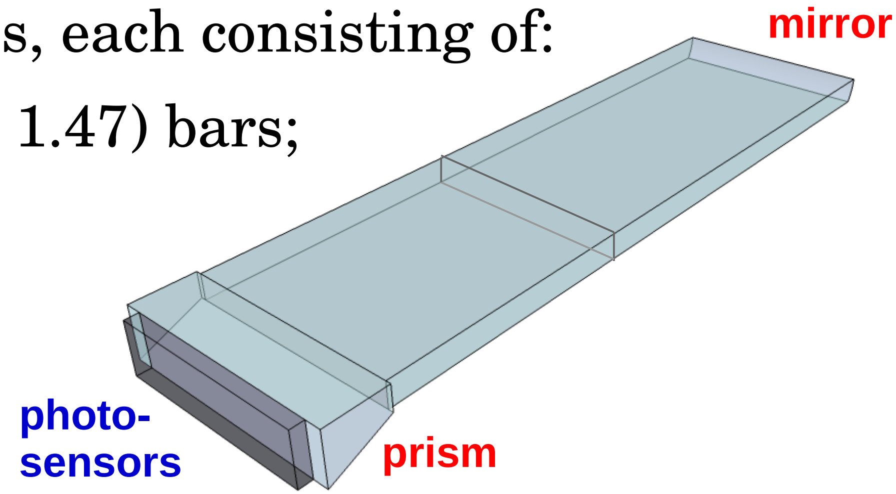


$$\cos\theta_C = \frac{1}{n\beta}$$

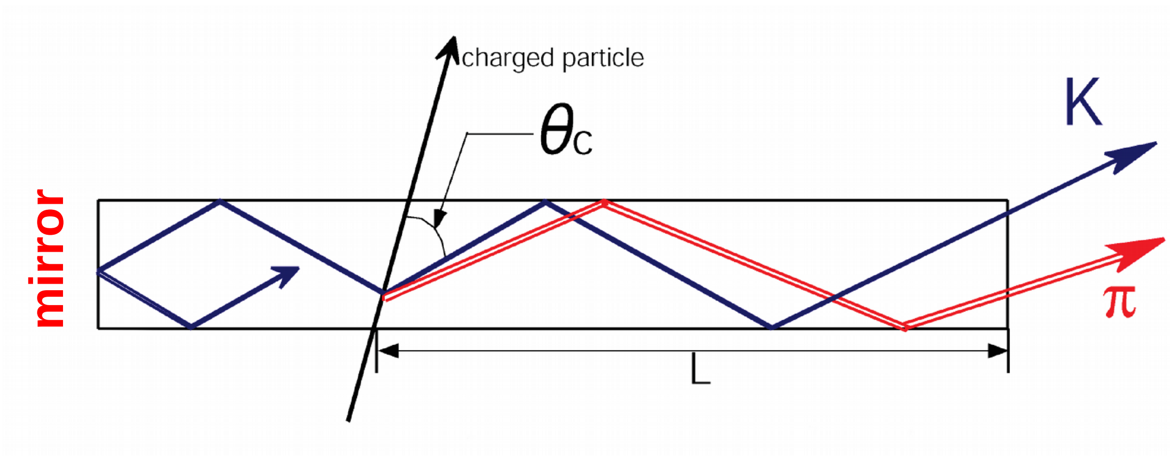
- Complement this with the momentum measured by the tracking devices and extract the most likely mass.

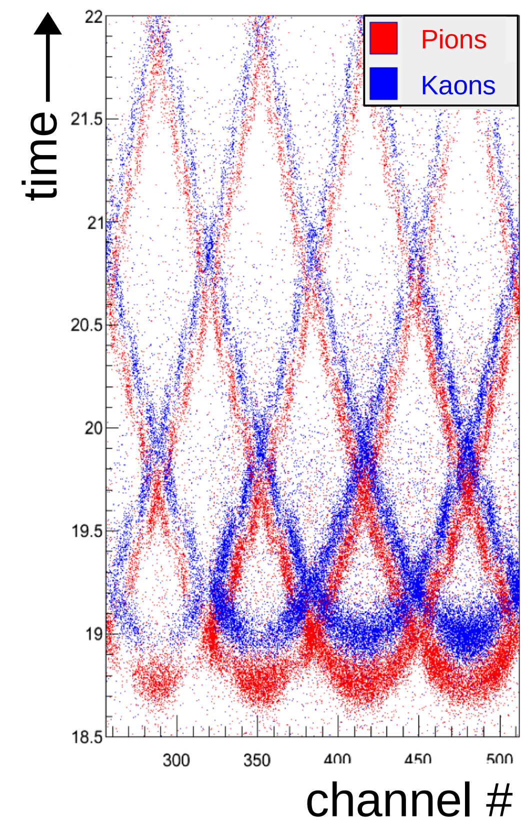
# Time Of Propagation Counter

- The TOP counter consists of 16 modules, each consisting of:
  - 2 x (135cm * 45cm * 2cm) quartz (n = 1.47) bars;
  - a small expansion prism at one end;
  - a focusing mirror at the other;



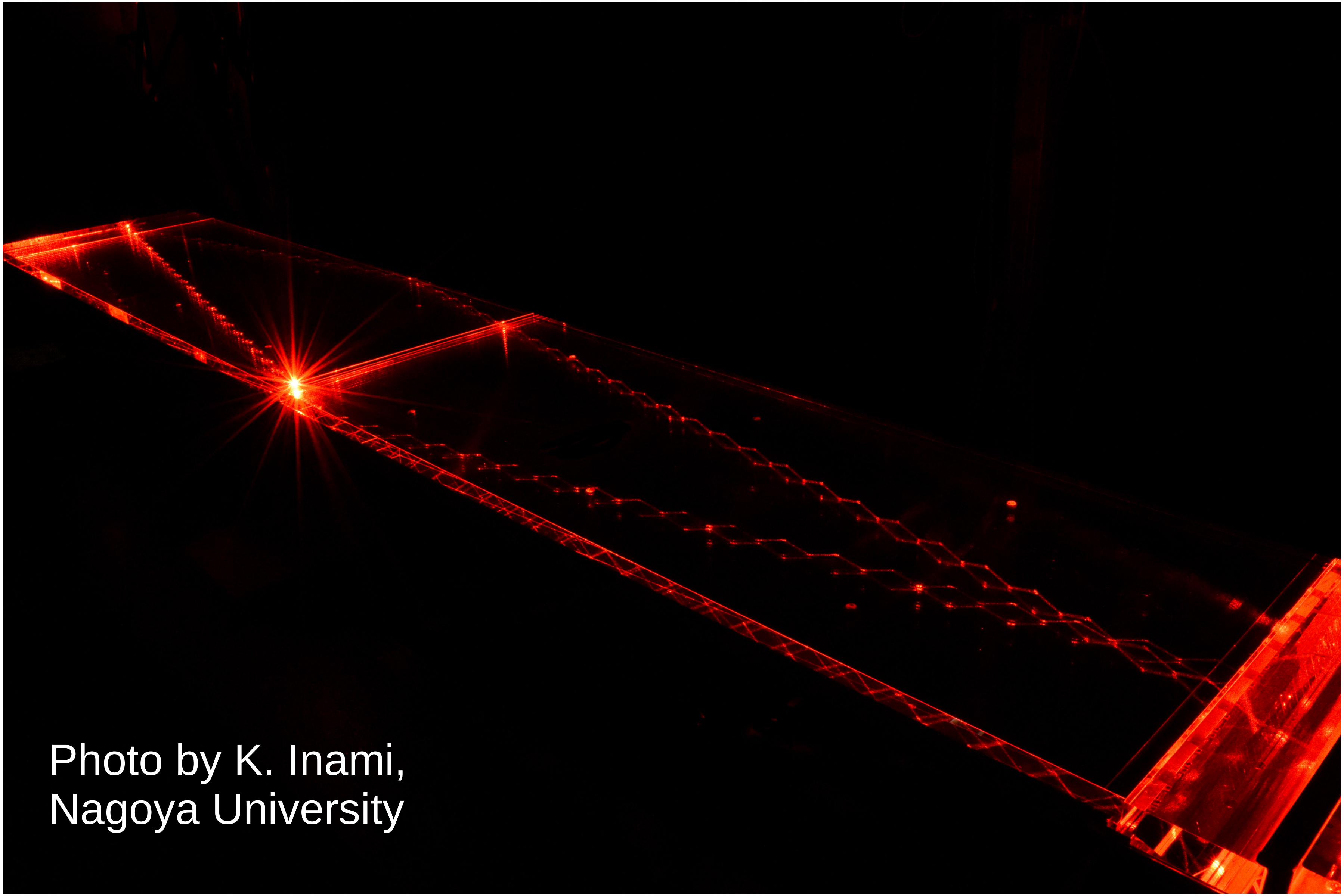

- Principle of the measurement:




- Crucial requirement: resolution on the time of arrival of the Cherenkov photons must be within 100 ps.

# Time Of Propagation Counter



# The Photo-Sensor

- A charged particle produces O(100) photons in a TOP module;
- Requirement for the photo-sensor:
  - operate in single photon regime;
  - good Quantum Efficiency (QE);
  - cope with magnetic field and backgrounds;
  - excellent time resolution;

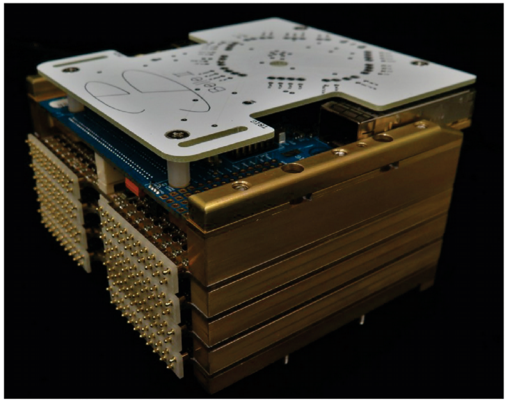

- Our choice: Micro Channel Plate (MCP) PMT, developed and built by Hamamatsu Photonics;
- 32 MCP-PMT's (4x4 channels each) instrument one TOP module;
- NaKSbCs photocathode (average QE 29.3% at $\lambda = 360$ nm);
- Transit Time Spread (TTS) < 40ps;
- Recent intense R&D activity to extend the lifetime of the sensors (some will be replaced in ~2 years).

For more information, see K. Inami's poster

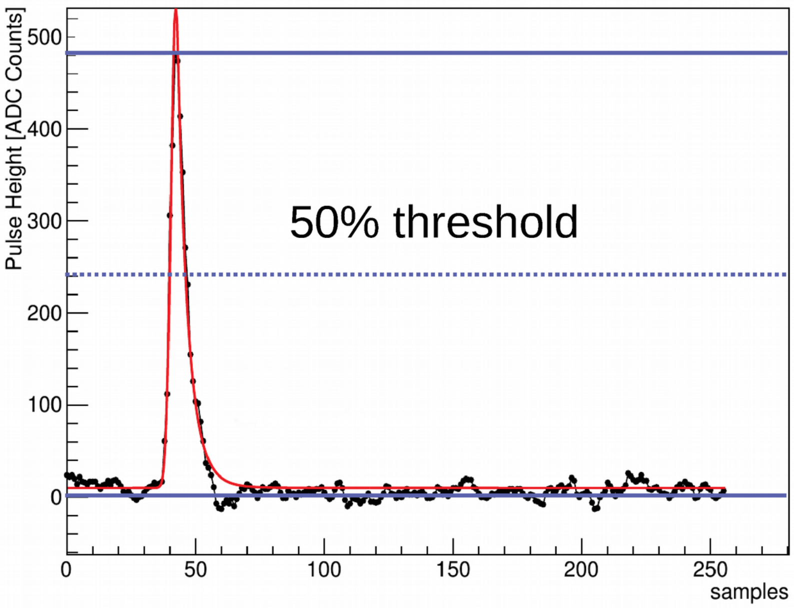
# Read-out Electronics

- Very stringent requirements:
  - 30 kHz trigger rate;
  - no deadtime;
  - low power consumption;
  - ~500 MHz bandwidth;
  - excellent time resolution;
- The output of each electronics channel is sampled at 2.7GHz, with 12 bit resolution;
- No way we can transfer 265 Tbit/s, Feature Extraction (and pedestal subtraction) must be performed online.

Fundamental FEE unit: the "boardstack"

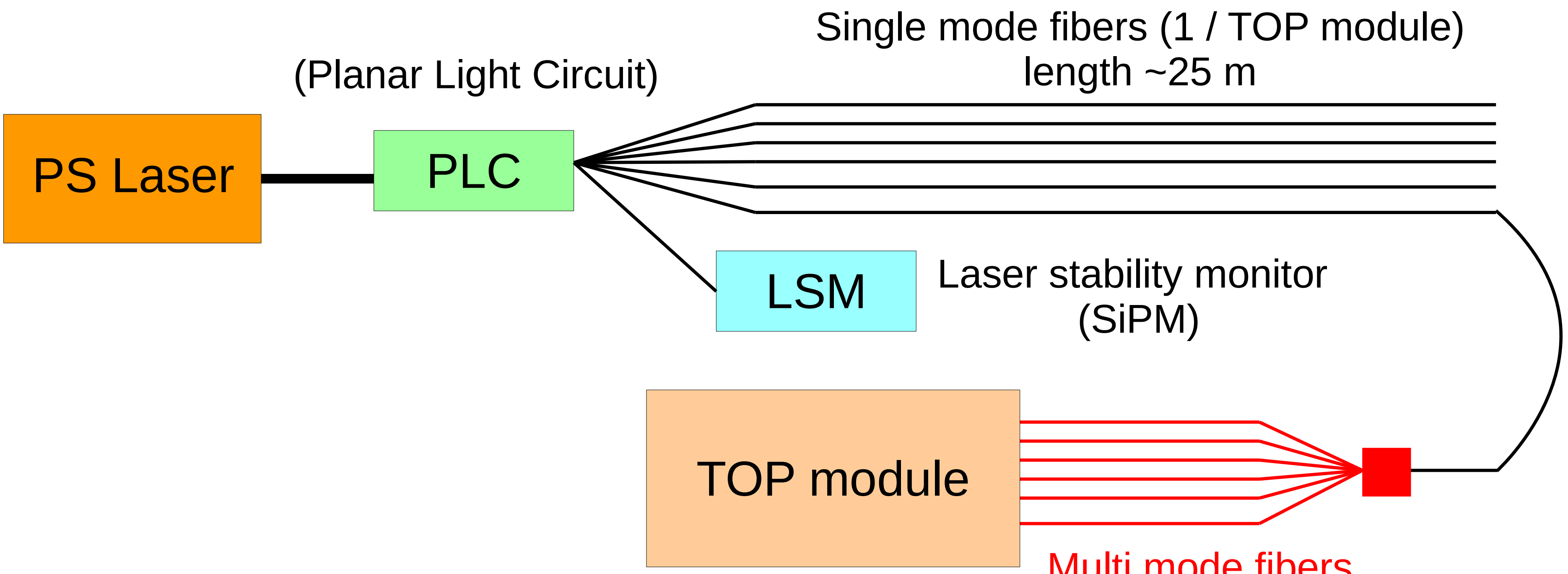


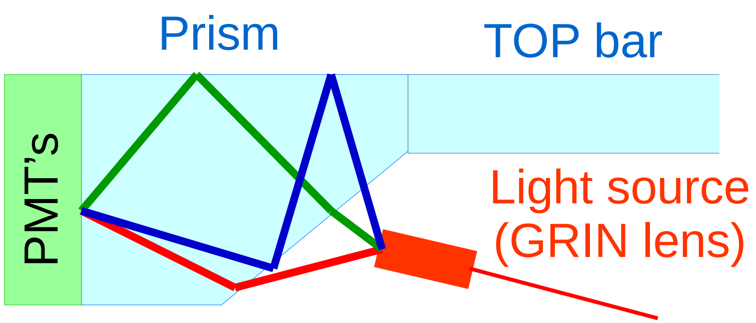
Each boardstack reads out 1/4 of a TOP module (128 channels)



# The Laser Calibration System

- Important tool for calibrating the relative timing of the channels and monitoring the performance of the whole system:




A PMT pixel can be reached by different light paths (with different times)

# TOP Calibration Overview

**Time Base Calibration**

Ensure the linearity of time digitization: performed by measuring the interval of double charge pulses across the sampling range

**Local $T_0$ Calibration**

Align in time all channels within a module, using the laser calibration system

**Module $T_0$ Calibration**

Align in time all modules of the TOP counter, using cosmics and collision data

**Geometrical Alignment**

Determine the actual position of each TOP module in the common reference frame using collision (cosmic) data

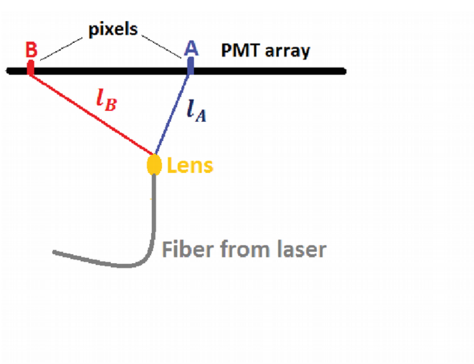
**Common $T_0$ Calibration**

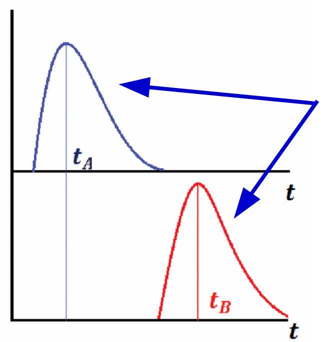
Align in time with the other Belle II subdetectors

**GOAL: uncertainty < 100 ps on the single detected photons**

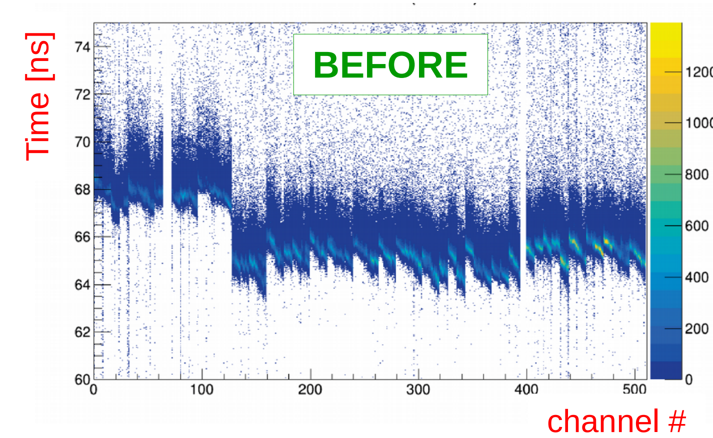
# Local $T_0$ Calibration

- Quite complicated procedure, different light sources and photon paths give contributions to every channels: many details to take care of!
- Effectively need fine tuning for all 8192 channels of TOP;

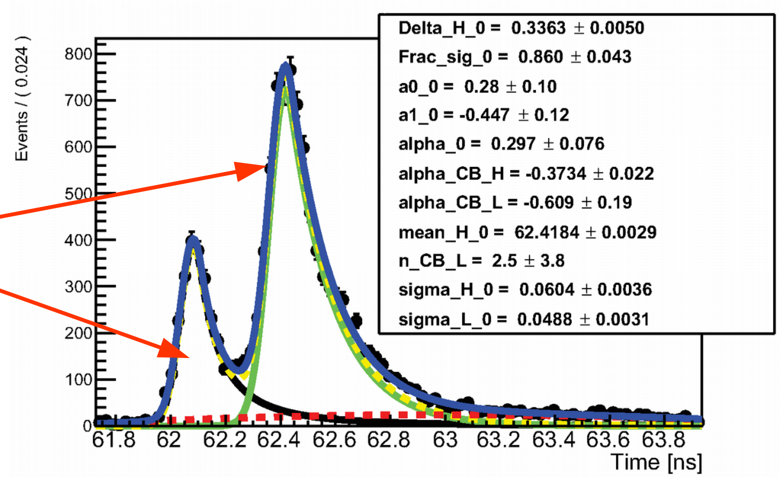


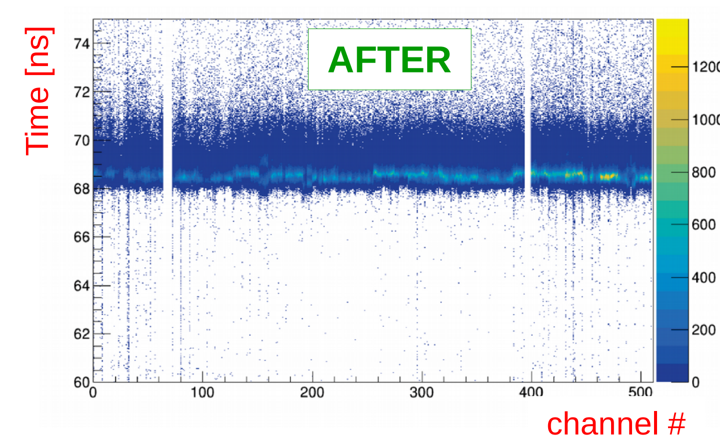




Different propagation times from one source to different channels




Contributions from two different sources to the same channel

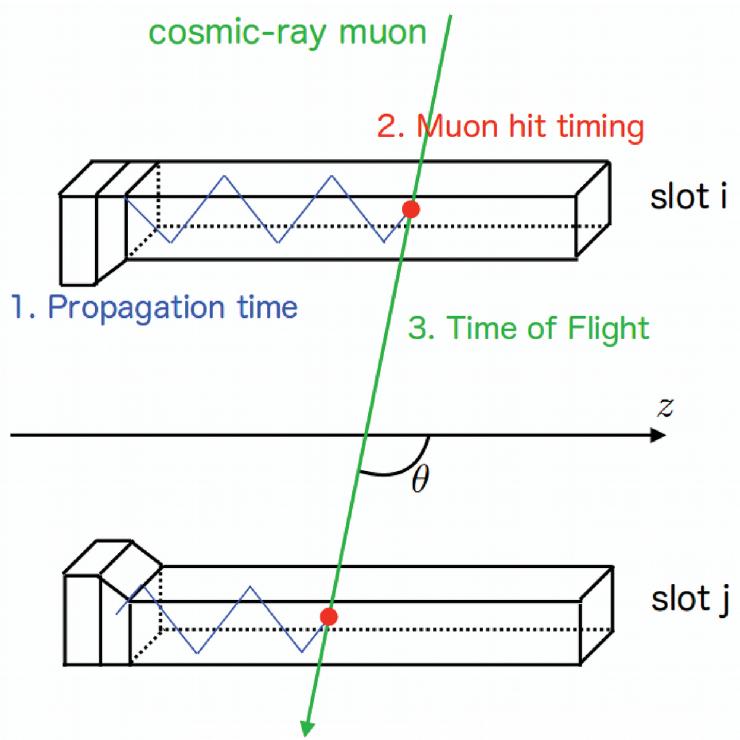



- Current status: precision ~100 ps (but still margin for improvement!).

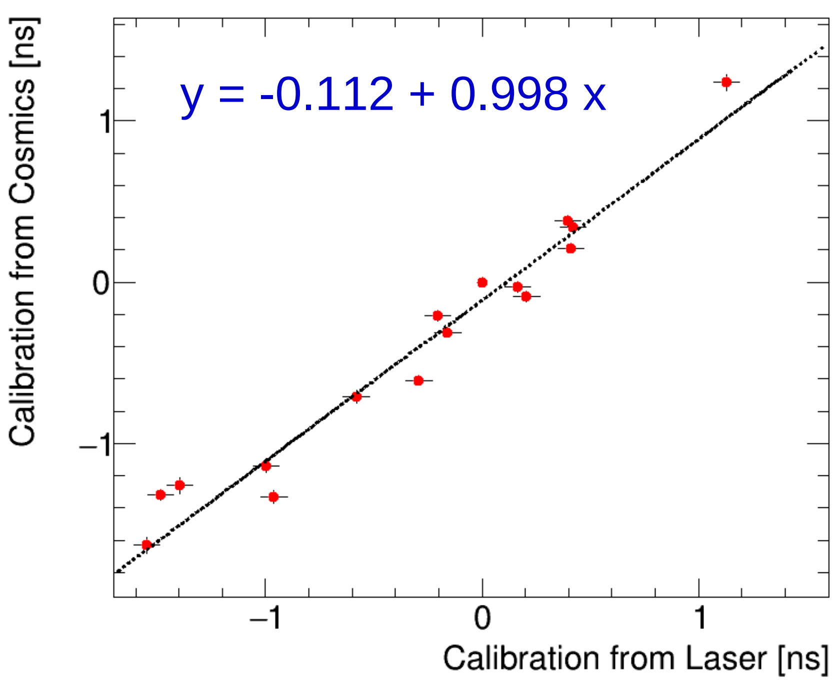
# Module $T_0$ Calibration

- Idea: use cosmic events to align in time all TOP modules:



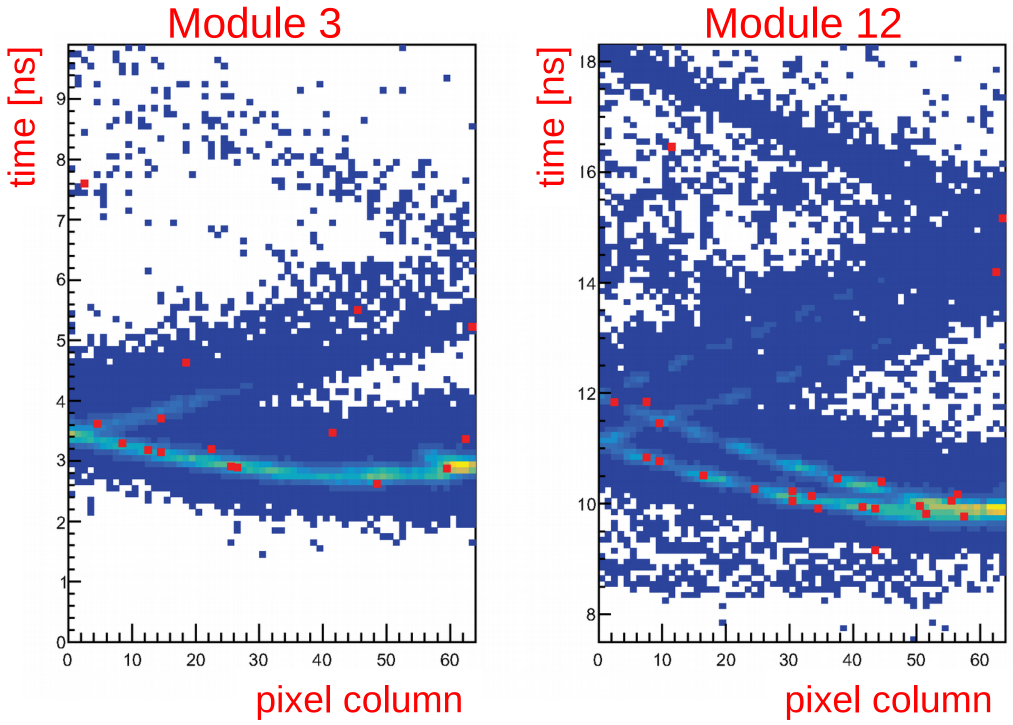

- Compare photon detection times for cosmic rays that hit two different modules, taking into account time of flight and different propagation times;
- Minimize a $\chi^2$ to find the best calibration constants (one module taken as reference);

- Crosscheck with laser system (uncertainty from uniformity of fiber lengths) shows excellent consistency!

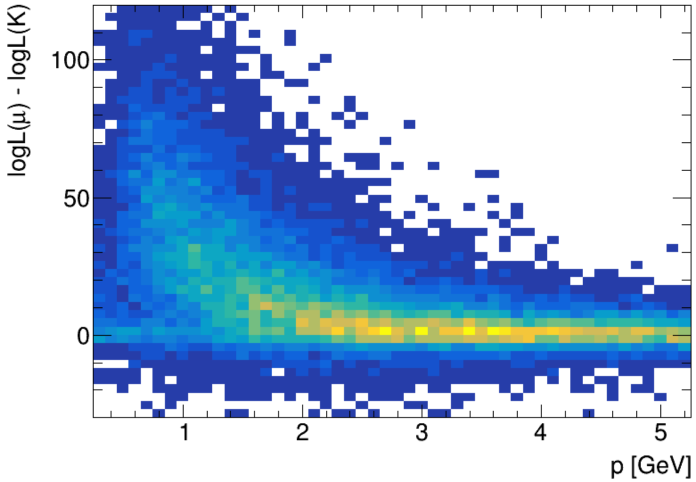


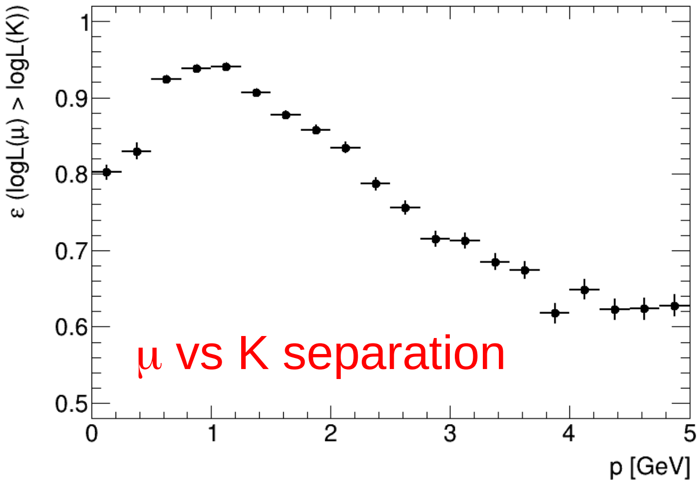
# Cosmic Ray Run

- TOP joined the Global Cosmic Runs with other Belle II subdetectors since last Summer (>50M events recorded);
- Debugging opportunity + first performance assessment:




Points: detected photons
Colored bands: pdf



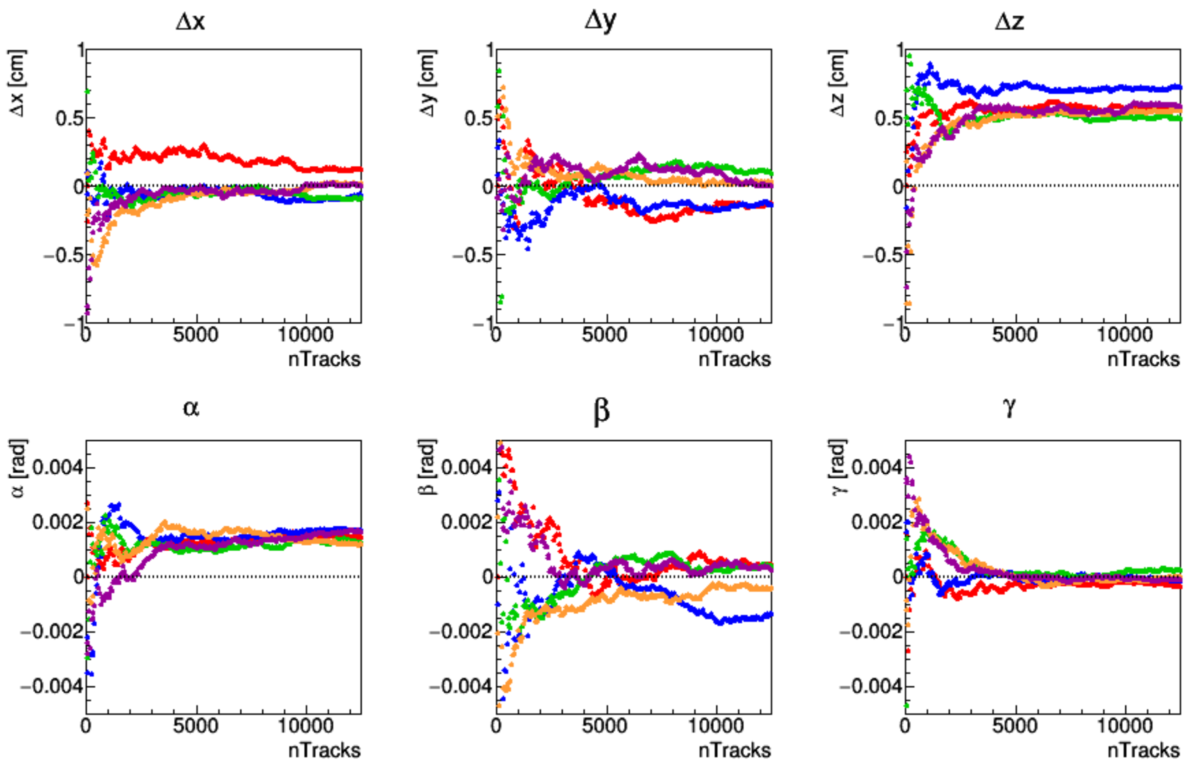




Very reasonable performance, despite calibration being still far from perfect!

# Geometrical Alignment

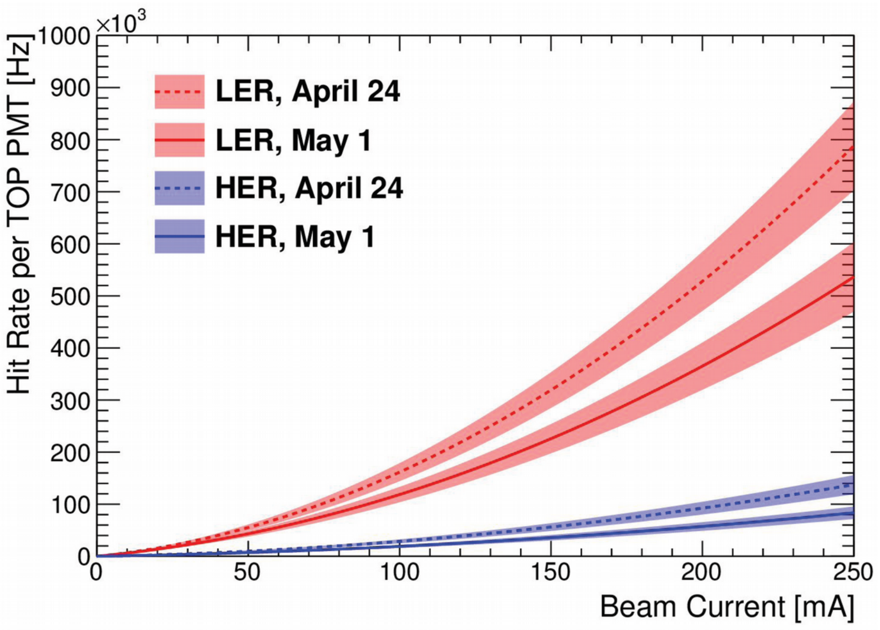
- Still missing: precise determination of actual position of TOP modules;
- Strategy: select a sample of muons, and iteratively maximize the Likelihood $L_\mu$ varying the shifts Δx, Δy, Δz and rotation angles α, β, γ about the three coordinate axes;
- With $e^+e^- \rightarrow \mu^+\mu^-$ events, can get a precision of ~0.3 mm on the shifts and 0.3 mrad on the rotation angles;
- Tested the procedure on cosmic data (some biases are expected).

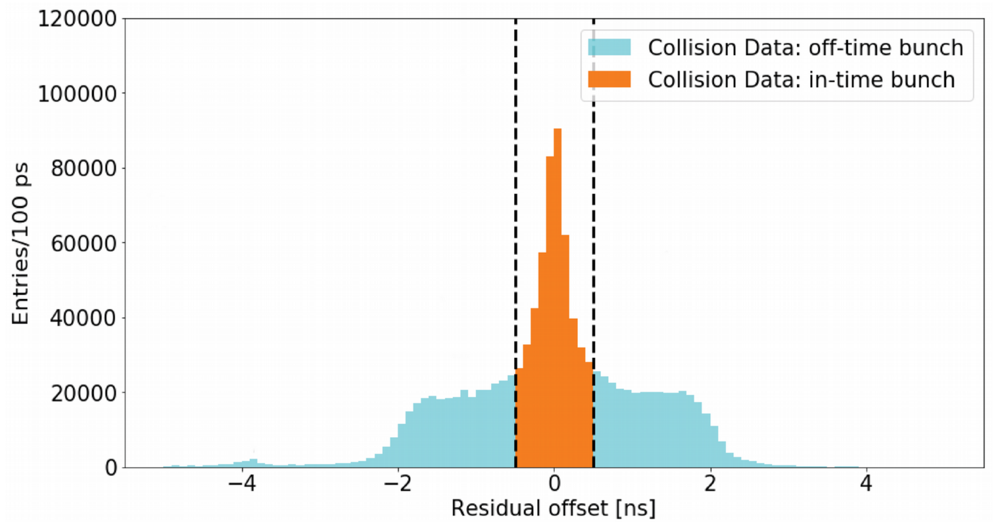
Alignment on 5 independent samples of cosmic data.
Very preliminary!



# First Collision Events

- $e^+e^-$ data taking started 1 month ago;
- TOP stably included in DAQ, should have no problem coping with the expected rates this year;
- Hit rates give a robust measurement of (gradually improving) beam background conditions;
- We can use two-track events to determine the event $T_0$ and align with the other subdetectors;
- Cannot show PID performance on collision data yet: we need to reprocess the data with final calibrations… and collect large samples of $K_S$, $D^*$, $\Lambda$, …



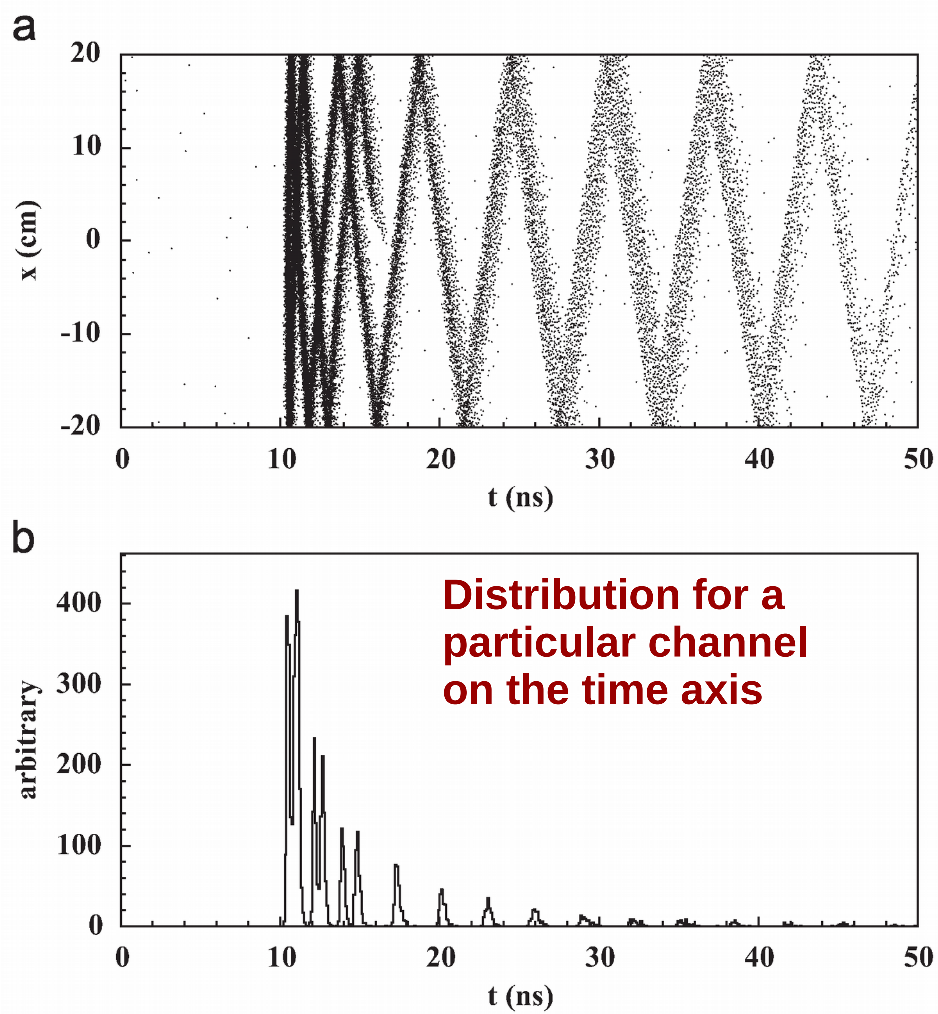
# Conclusions

- The TOP Counter is a novel PID detector, which will play a major role in the Belle II Physics Programme;
- Its construction was completed in May 2016 and now TOP is stably taking data with the other subdetectors;
- The calibration of the TOP Counter is a complex procedure, our target is a time resolution of < 100 ps for single photon detection;
- Preliminary results based on calibration pulses, laser, and cosmic data give a resolution of ~150 ps: not yet our goal, but we are getting there;
- We expect to have the first measurement of the TOP PID performance on collision data in a timescale of a few weeks!

# Backup Slides

# PID Likelihood

Expected 2D pattern for a charged track hitting a TOP Module




M. Staric et al. NIM A 595, 252-255 (2008)

The expected 2D distribution of the photon hits associated to a charged particle depends on its:

- species (π, K, …);
- momentum;
- position of impact point on the quartz bar;
- angles of impact;

For each track hitting a TOP module we expect ~25 photon hits.

TOP PID is performed comparing the distribution of those hits with the expected pattern for different particle hypotheses.

# PID Likelihood

- For each charged particle candidate we construct the extended Likelihood:

$$\log \mathscr{L}_h = \sum_{i=1}^{N} \log\left(\frac{S_h(x_i, t_i) + B(x_i, t_i)}{N_e}\right) + \log P_N(N_e)$$

$N$ : number of observed photons
$N_e$ : number of expected photons
$h$ : particle hypothesis
$S_h$ : signal distribution
$B$ : background distribution

- Restricting to a particular channel j at position $x_j$:

$$S_h(x_j, t) = \sum_{k=1}^{m_j} n_{kj} g(t - t_{kj}; \sigma_{kj})$$

$n_{kj}$ : number of expected photons in peak k
$t_{kj}$ : expected mean time of peak k
$\sigma_{kj}$ : expected width of peak k

(where the sum runs over the individual peaks of the projection on the time axis);

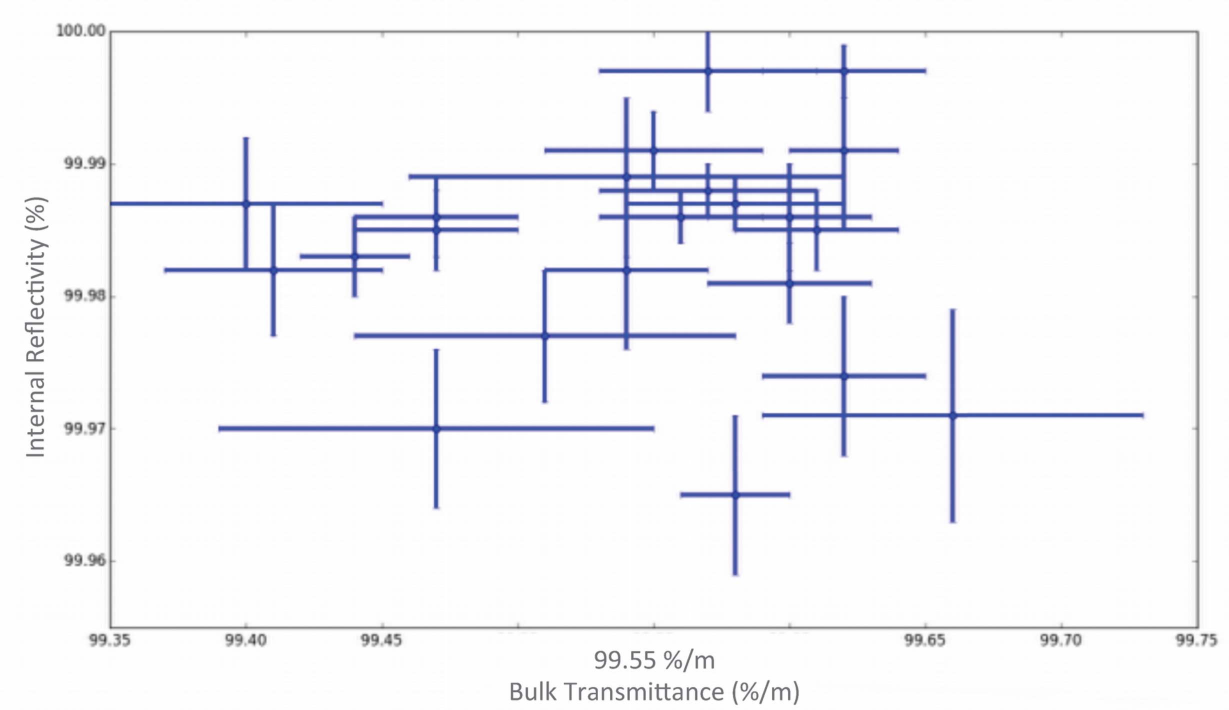
- The quantities $n_{kj}$, $t_{kj}$, $s_{kj}$ can be expressed analytically from the Cherenkov angle and the impact position and direction of the incident track.

# TOP Optics

- Stringent requirements on the quality of the TOP bars:
  - large surfaces flat to < 6.3 μm;
  - large surfaces parallel to < 4 arcsec (24 μm over 1.25 m);

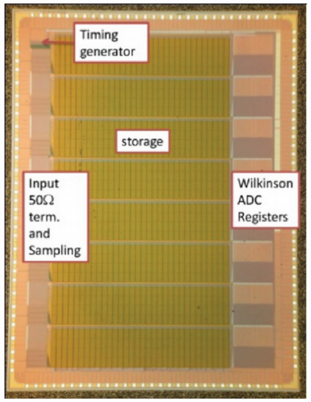
**Average Bulk Transmission:**
**(99.55 ± 0.07)%/m**

**Average Internal Reflectivity:**
**(99.984 ± 0.008)%**

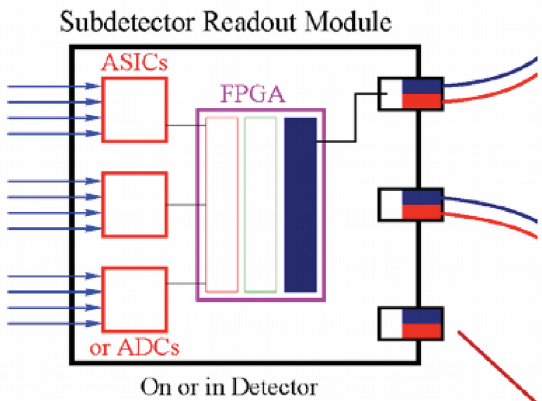


# Front End Electronics

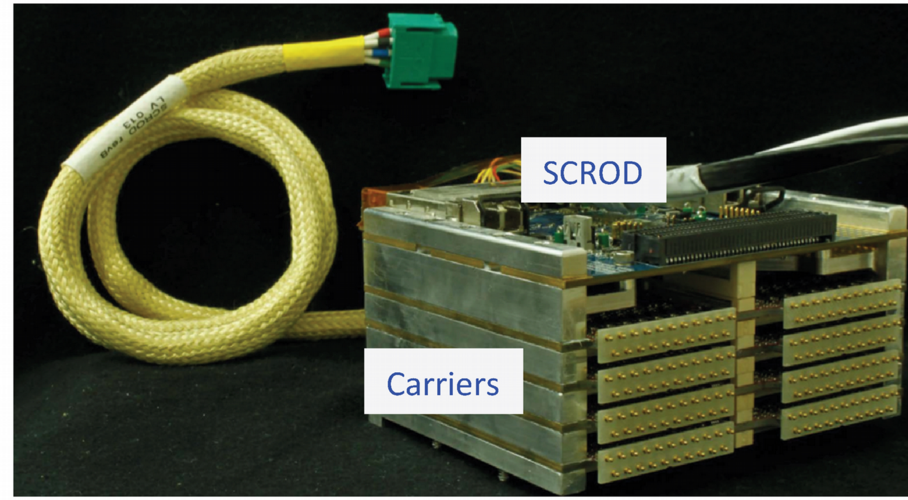
8k channel waveform sampling ASIC




Carrier boards:
4 ASICS + Xilinx FPGA

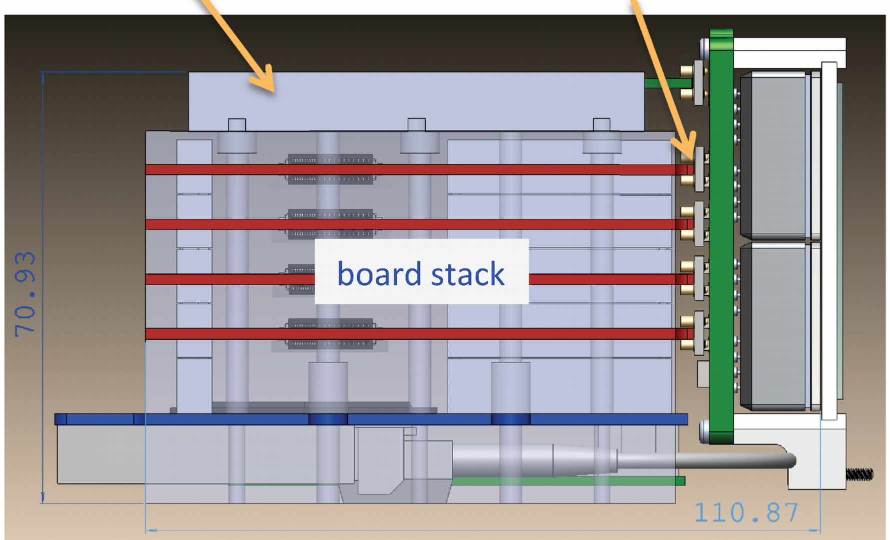



Board stack: 3 Carriers + SCROD
SCROD: master FPGA, fiber transceivers, clock, power

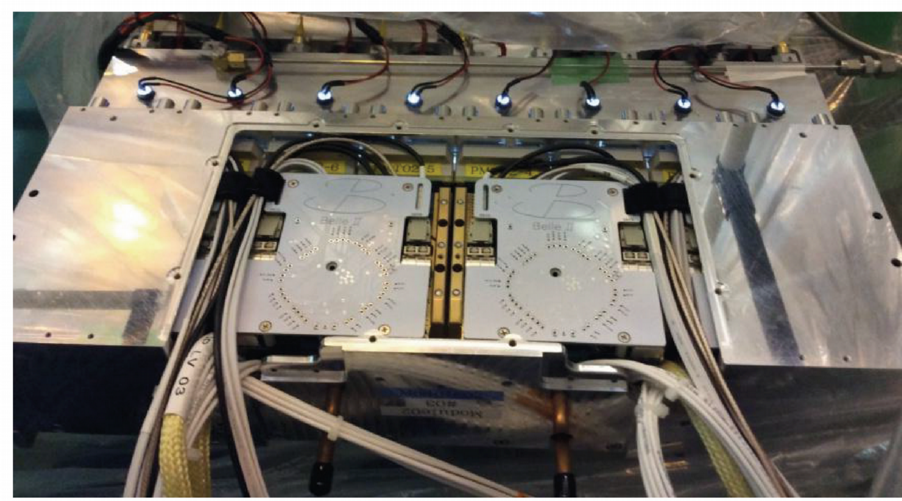



HV board (MCP-PMT power)

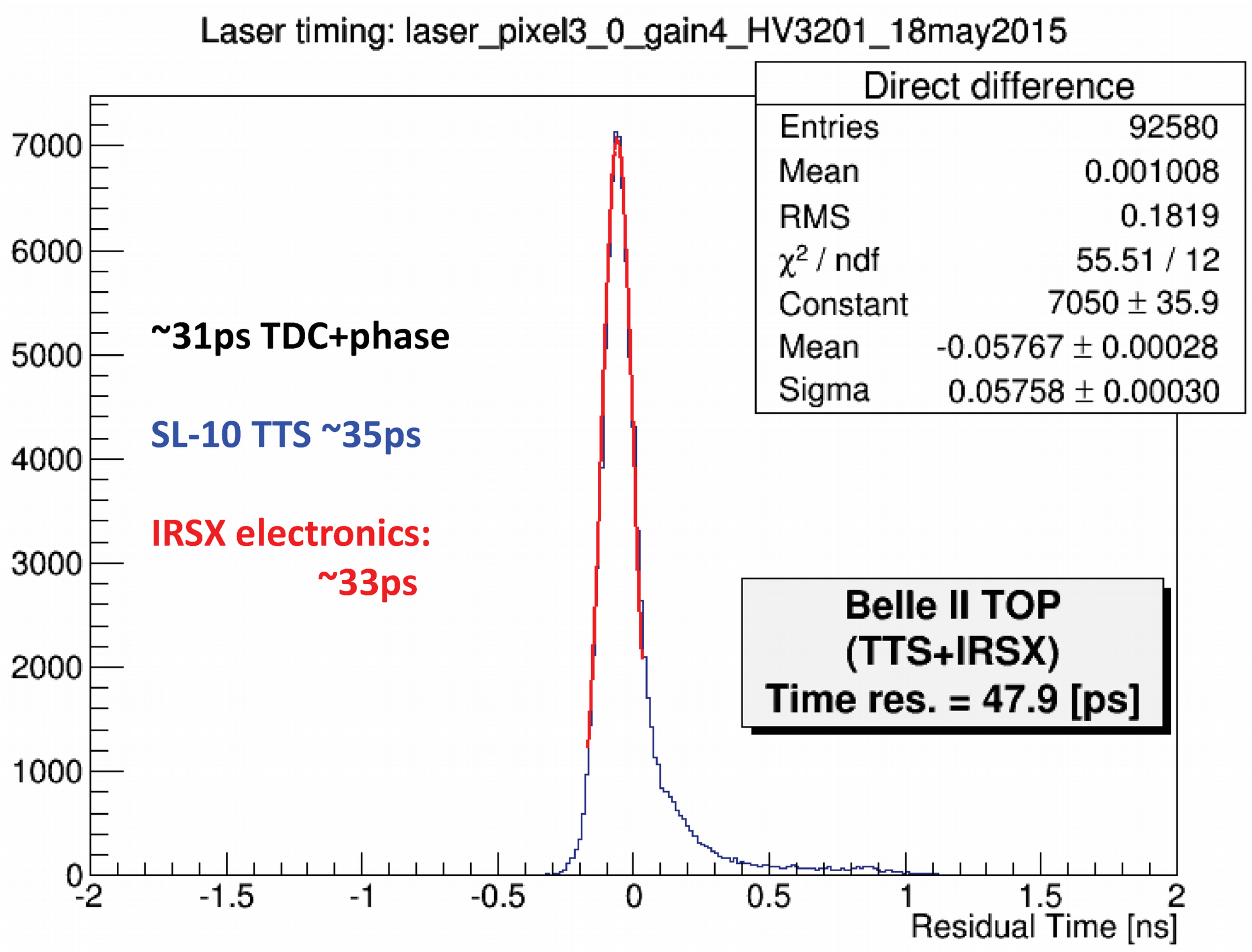
POGO pin connections to MCP-PMT modules




Four board stacks service each iTOP module

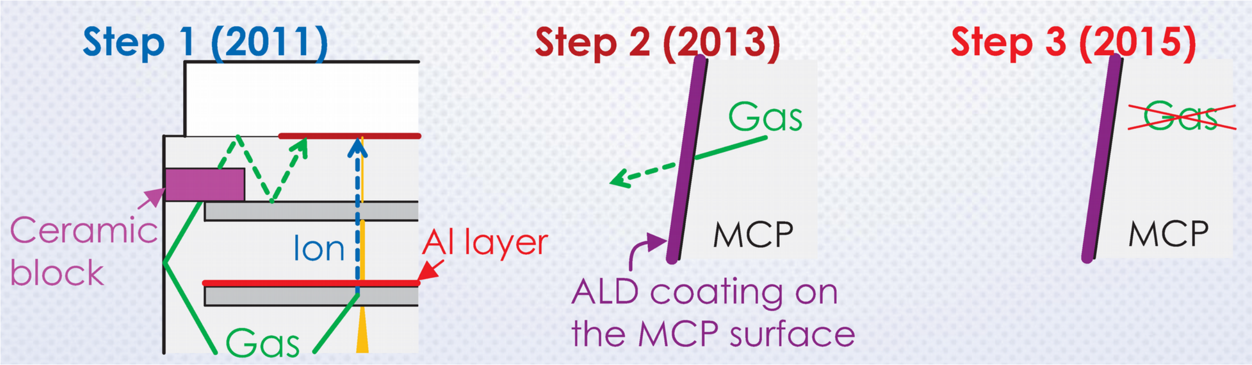


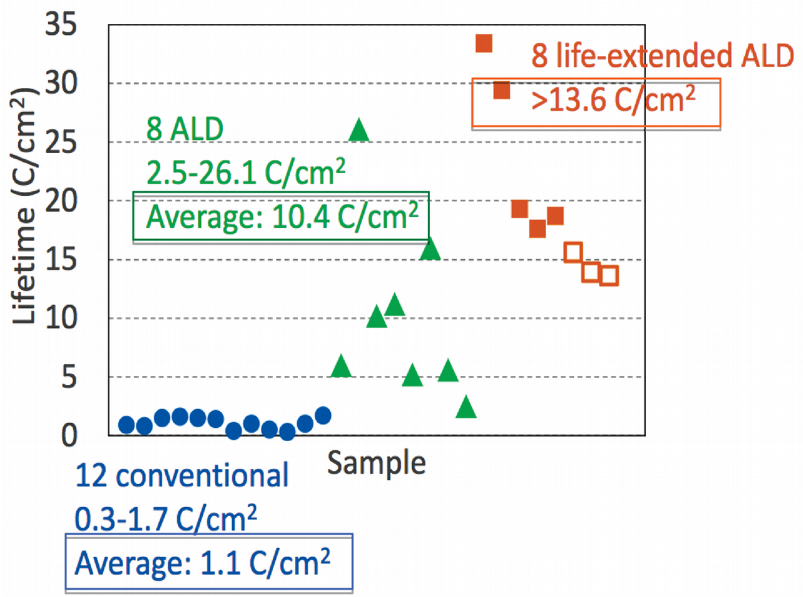
# Front End Electronics

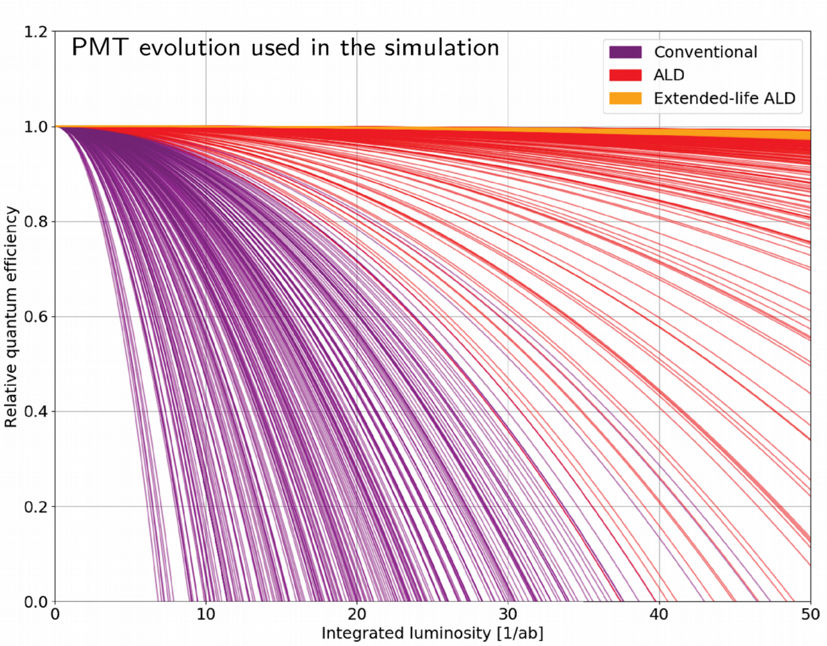


# MCP-PMT Aging

- Significant aging effect from positive ions hitting the photocathode;
- Significant improvement in the expected lifetime since beginning of construction:



# MCP-PMT Aging

- In order to keep optimal sensitivity we will have to replace ~half of the PMT's in Summer 2020;
- Benchmark channel, $B^0 \rightarrow \rho^0 \gamma$: