



Electromagnetic calorimeter of Belle II

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(For Belle II calorimeter team)

- SuperKEKB and Belle II
- Belle II calorimeter
- Energy reconstruction
- Calorimeter performance
- Beam background
- Time resolution
- Photon/hadron separation
- Summary



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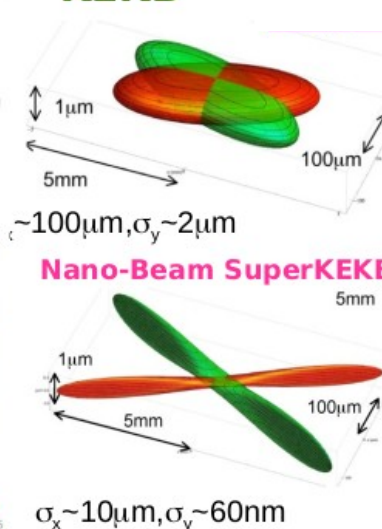
Belle II



Super KEKB

Grey is recycled, coloured is new

KEKB



$e^-(7\text{GeV}) - e^+(4\text{GeV})$ collider

Target luminosity $6 \cdot 10^{35} \text{ cm}^{-2}\text{s}^{-1}$

Achived luminosity **$5.3 \cdot 10^{34} \text{ cm}^{-2}\text{s}^{-1}$**
(World Record)

Accumulated luminosity $\sim 914 \text{ fb}^{-1}$

Beam currents 2.6 A **(3.6 A)**
Large beam background

Almost entirely new machine!

EM Calorimeter:
CsI(Tl), waveform sampling electronics

KL and muon detector:
Resistive Plate Counter (barrel outer layers)
Scintillator + WLSF + MPPC (end-caps, inner 2 barrel layers)

electrons (7GeV)

Central Drift Chamber
Smaller cell size, long lever arm

Vertex Detector
2 layers Si Pixels (DEPFET) +
4 layers Si double-sided strip DSSD

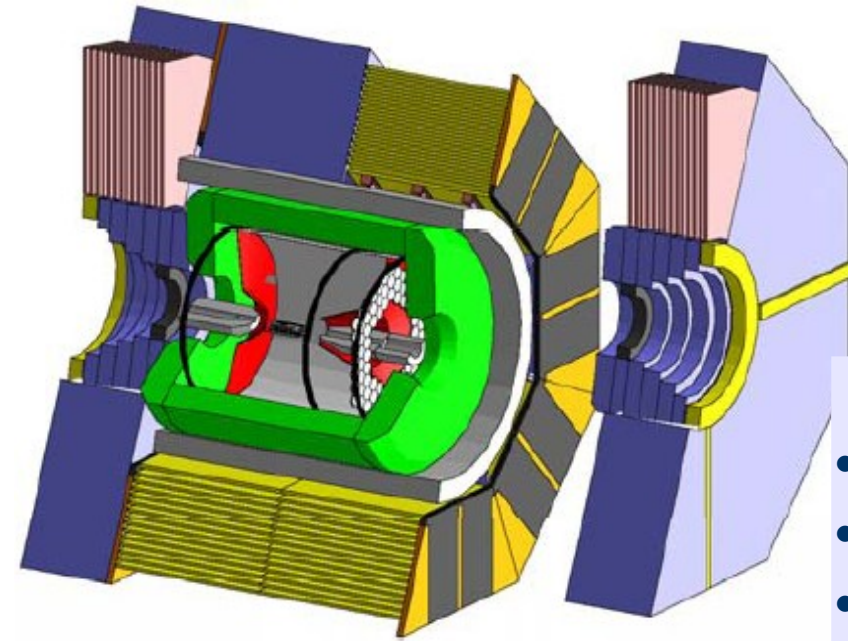
positrons (4GeV)

Particle Identification
Time-of-Propagation counter (barrel)
Prox. focusing Aerogel RICH (forward)

+ New software, improved tracking, ...
+ Optimization for low multiplicity trigger
+ Improved simulation, generators and GRID

- Study of rare decays of B^- , D^- mesons and τ .
- Measurement of CP violation parameters
- Search for new physics

Belle II calorimeter



- Measurement energy, time and angles of the photons
(30 MeV - 7 GeV)
- Electron identification
- Hadrons identification
- Neutral trigger
- On-line luminosity measurement

- Total 8736 counters.
- Barrel 6624
- Forward end cap 1152
- Backward end cap 960

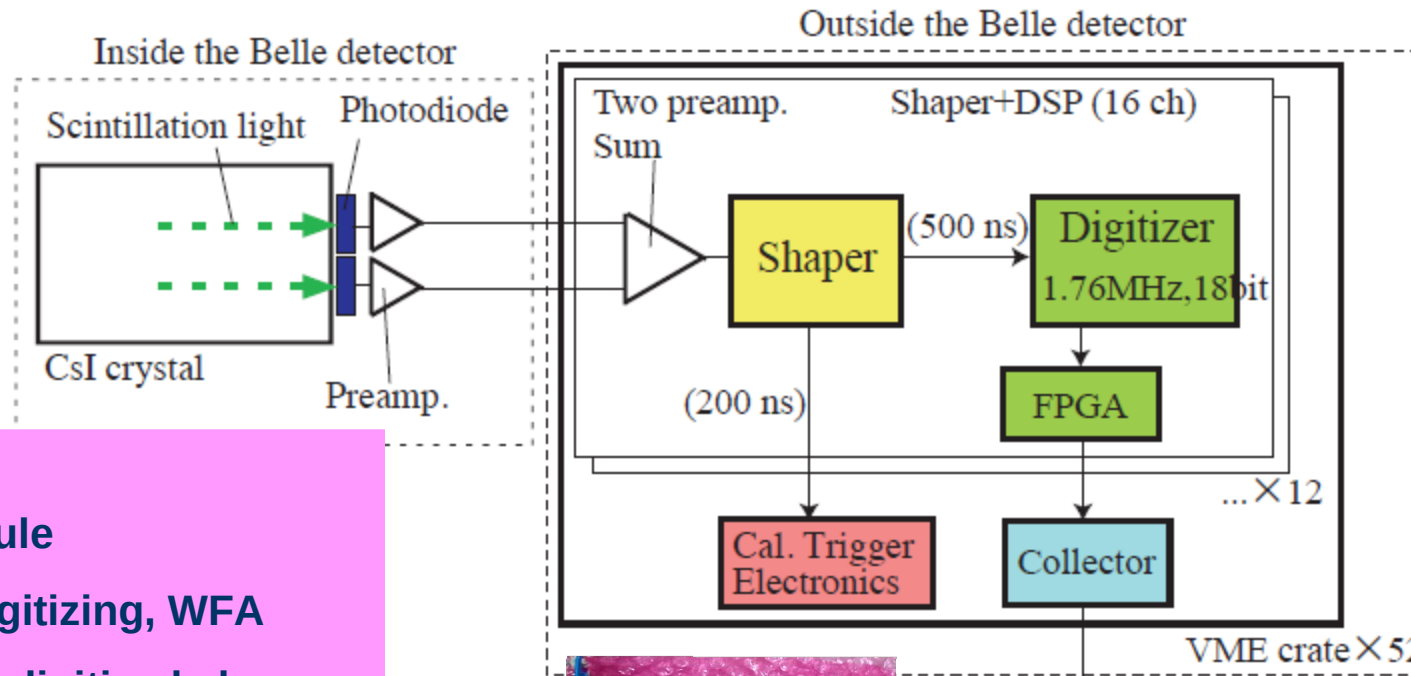
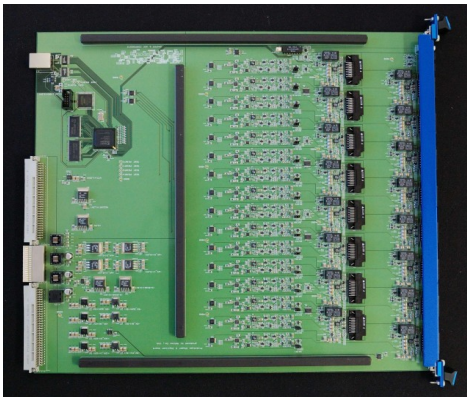
Counter:

- 30cm long CsI(Tl) (16.1X0)
- 2x 2cm² PIN diodes
- 2 preamplifiers



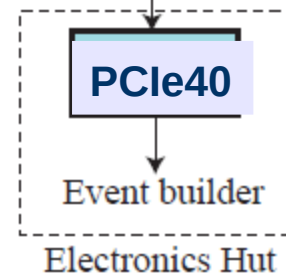
- Crystals, PINs and preamplifiers are kept from Belle calorimeter
- Belle calorimeter have been working for more than 20 years – all counters are alive!
- Shaping and digitizing electronics have been upgraded

Belle II calorimeter electronics



- 9U VME module
- 16 channels/per module
- Shaping (~500 ns), digitizing, WFA
- Output A, T, Q or/and digitized shape
- Fast sum signal for trigger

- Storage and loading of the coefficient arrays to the shaper-dsp-modules.
- Getting of the trigger and collection of data from shapers, packing and sending data to DAQ.
- Test pulses generation.

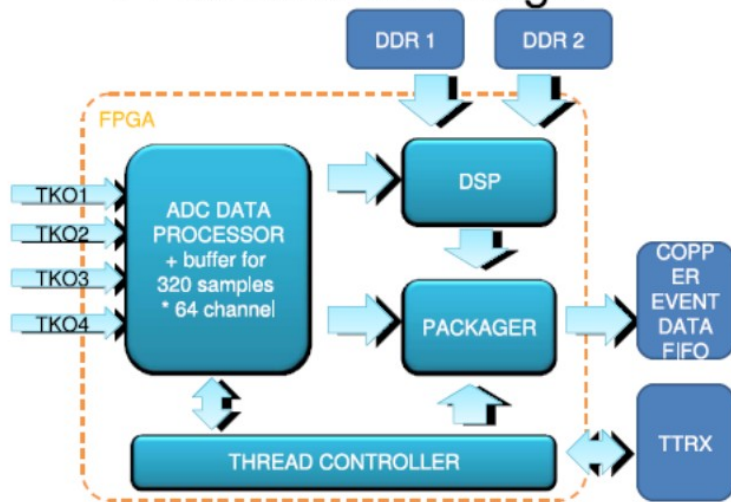


Fit algorithm in FPGA

Trigger → fit 16 points to response function taking correlations into account

- Result: Amplitude(18 bits), Time(12 bits), Quality of fit (4 bits)
- For some fraction of data both input and output information are sent to DAQ

FPGA overall design

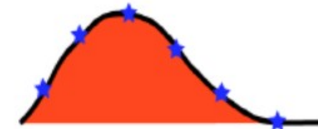


Algorithm details

$$\chi^2(A, p, t_0) = \sum_{i,j} (y_i - Af(t_i - t_0) - p) S_{ij}^{-1} (y_j - Af(t_j - t_0) - p) \rightarrow \min$$

$$S_{ij} = \overline{(y_i - \bar{y})(y_j - \bar{y})}$$

$f(t)$ — counter response



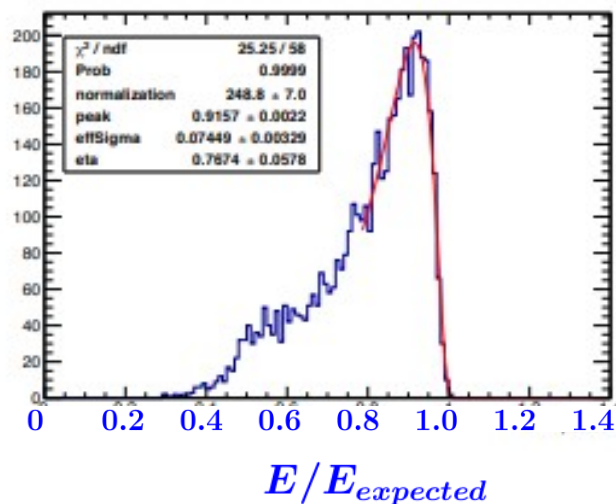
$$Af(t_i - t_1 - \Delta t) = Af(t_i - t_1) - A\Delta t f'(t_i - t_1) = Af(t_i - t_1) + Bf'(t_i - t_1)$$

where t_1 — initial time (trigger time)

$$\begin{cases} \sum_{i,j} f_i S_{ij}^{-1} (y_j - Af_j - Bf'_j - p) = 0 \\ \sum_{i,j} f'_i S_{ij}^{-1} (y_j - Af_j - Bf'_j - p) = 0 \\ \sum_{i,j} S_{ij}^{-1} (y_j - Af_j - Bf'_j - p) = 0 \end{cases} \Rightarrow \begin{cases} A = \sum_i \alpha_i y_i \\ B = \sum_i \beta_i y_i \Rightarrow \Delta t = -B/A \\ p = \sum_i \gamma_i y_i \end{cases}$$

- Algorithm can handle more than 40 kHz of the trigger rate with 100% occupancy (30 kHz is expected for design luminosity)

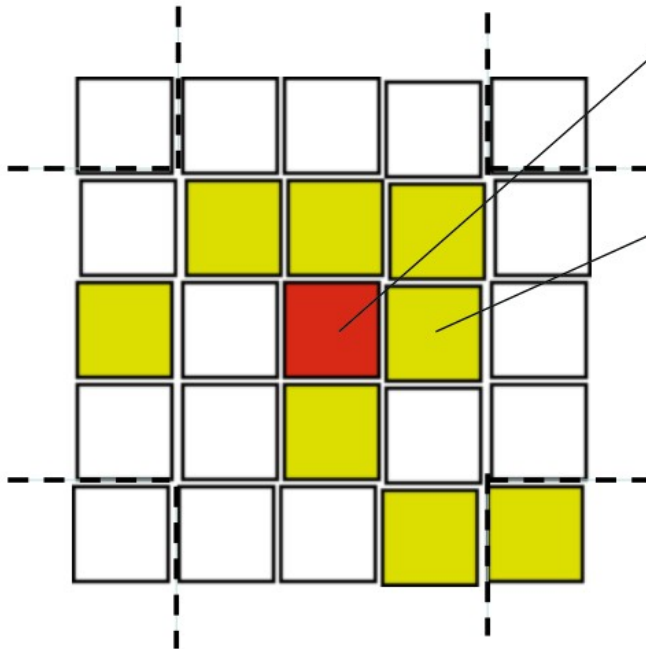
Gamma-gamma calibration



Energy response of individual crystals is calibrated using $e^+e^- \rightarrow \gamma\gamma$ events.

- the most-energetic crystal in the shower is considered.
- right edge of the distribution doesn't depend on inactive material in front of Calorimeter.
- Accuracy is better 0.5%
- Calibration constants have changed by an average of 2.5% since 2020. Decrease in light output is due to radiation damage.

Cluster reconstruction



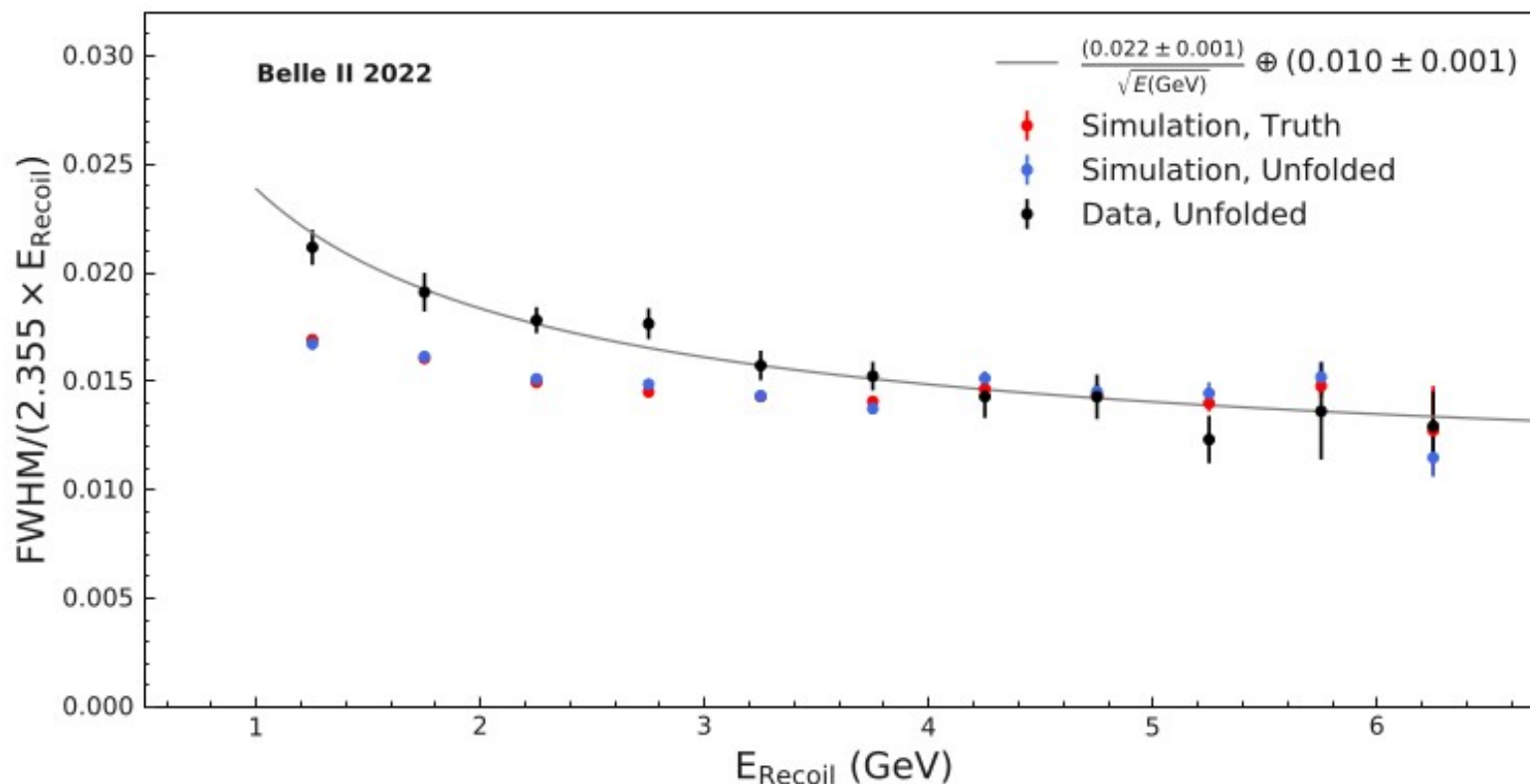
View from IP

- **Seed crystal:** Local maximum energy deposition exceeding 10 MeV
- **Belle:** hits exceeding certain threshold inside 5x5 matrix surrounding the seed crystal are considered
- **BelleII:** highest N-hits are considered among 21 crystals (5x5 matrix without corner crystals)

To get the photon energy: cluster energy is corrected by function depending on E, angles and the background level

Energy resolution

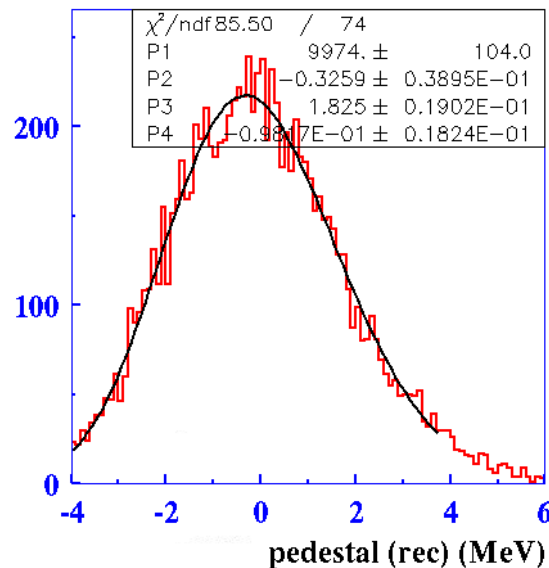
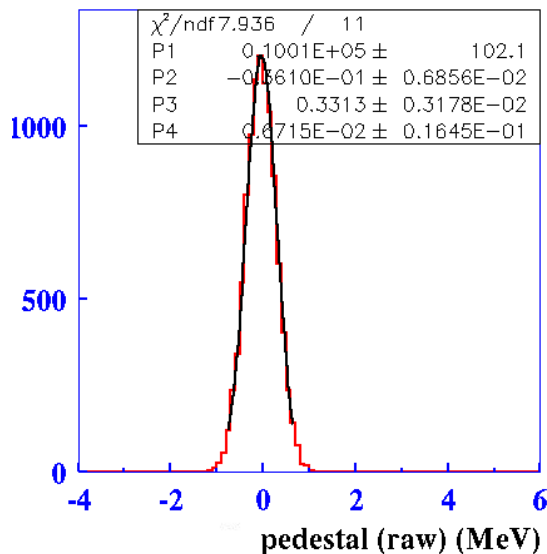
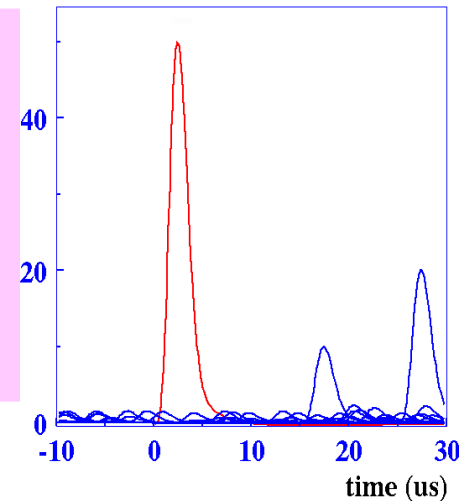
Energy resolution was studied for $e^+e^- \rightarrow \mu^+\mu^-\gamma$ events
For 1 GeV $\sigma E/E = 2.2\%$



Energy resolution

For low-energy photons, electronic noise and noise due to pulse pile-up make the dominant contribution to energy resolution.

The magnitude of the noise can be estimated by measuring the pedestal width for events recorded using a random trigger

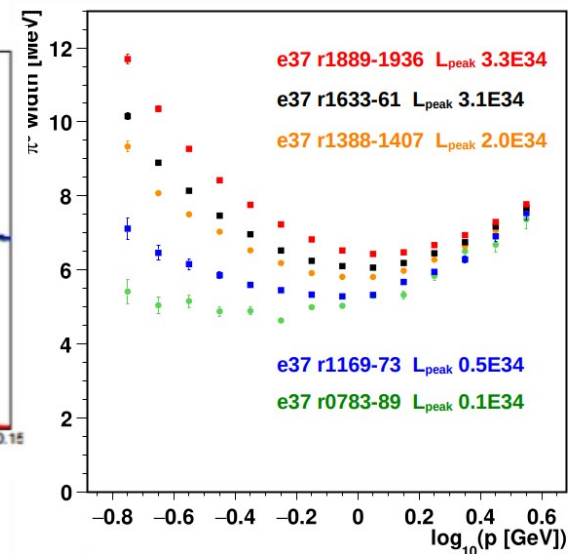
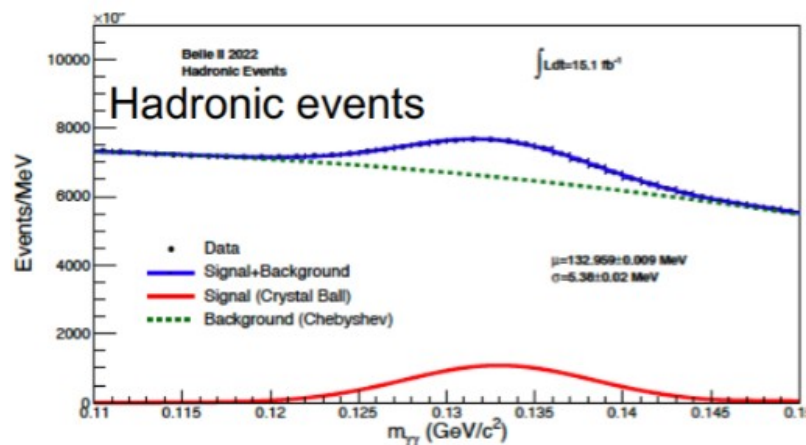
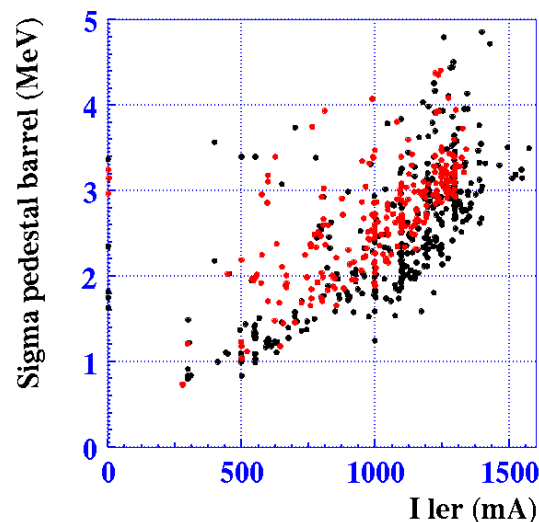


in the absence of a beam, the noise level is approximately 300 keV,

however, at high luminosity, it reaches several MeV.

π^0 mass resolution

Beam-induced background noise increases with beam current.
Pileup noise degrades mass resolution for low momenta of π^0

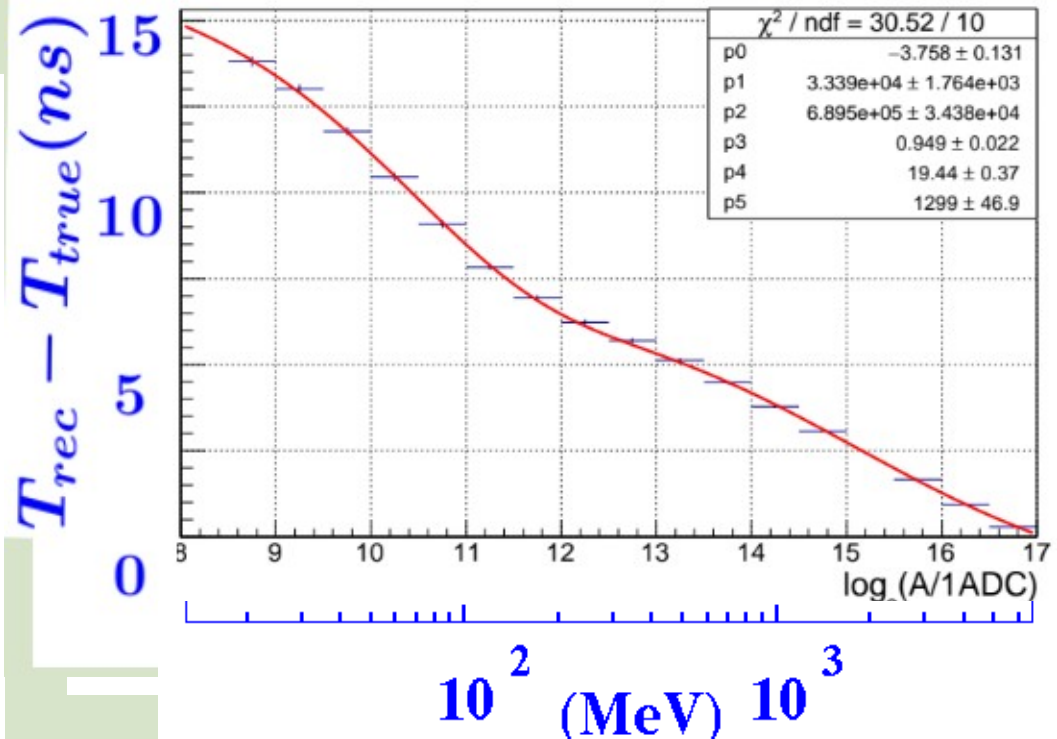
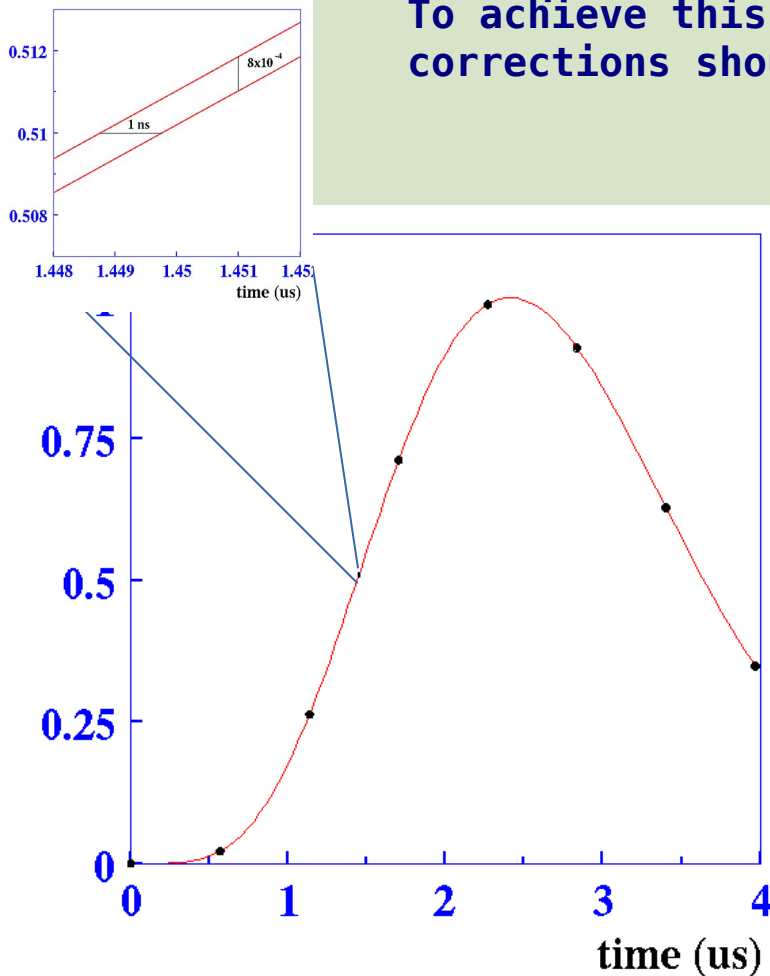


To reduce the effect of pileup noise the electronic upgrade is planned for 2032(R.Giordano talk)

Time resolution

The time is determined based on signal approximation within the FPGA.
The time resolution for energies $E > 1$ GeV is a few nanoseconds, whereas the pulse duration is few μs .

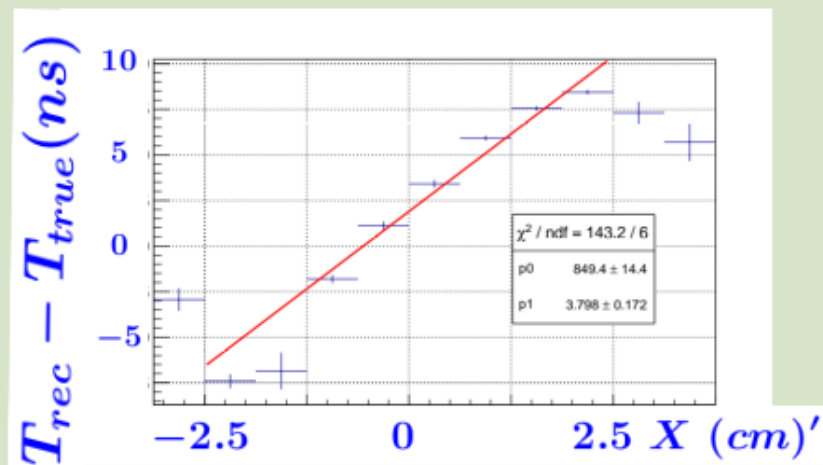
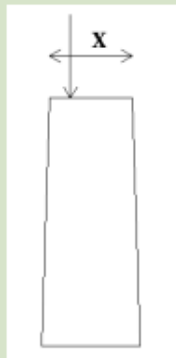
To achieve this resolution, a number of corrections should be applied:



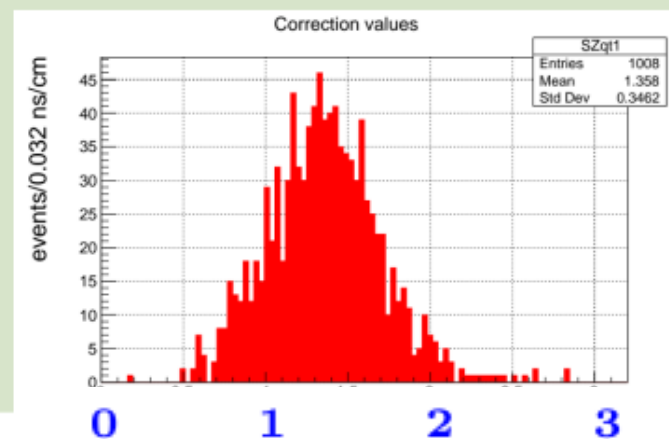
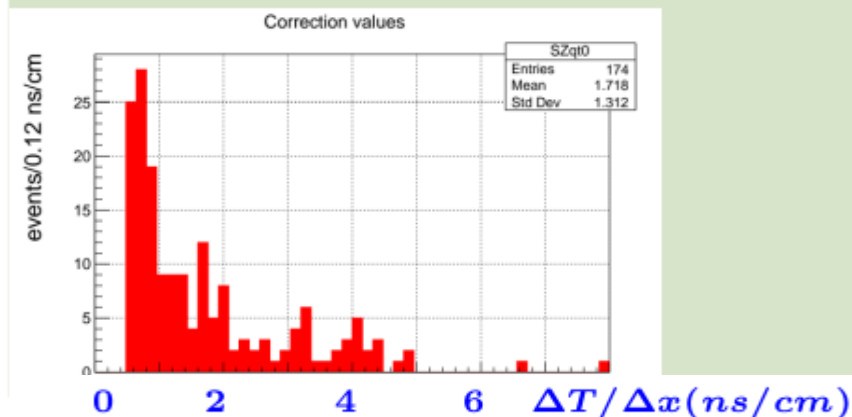
Time walk corrections (obtained on $e^+e^-\gamma$)

Time resolution

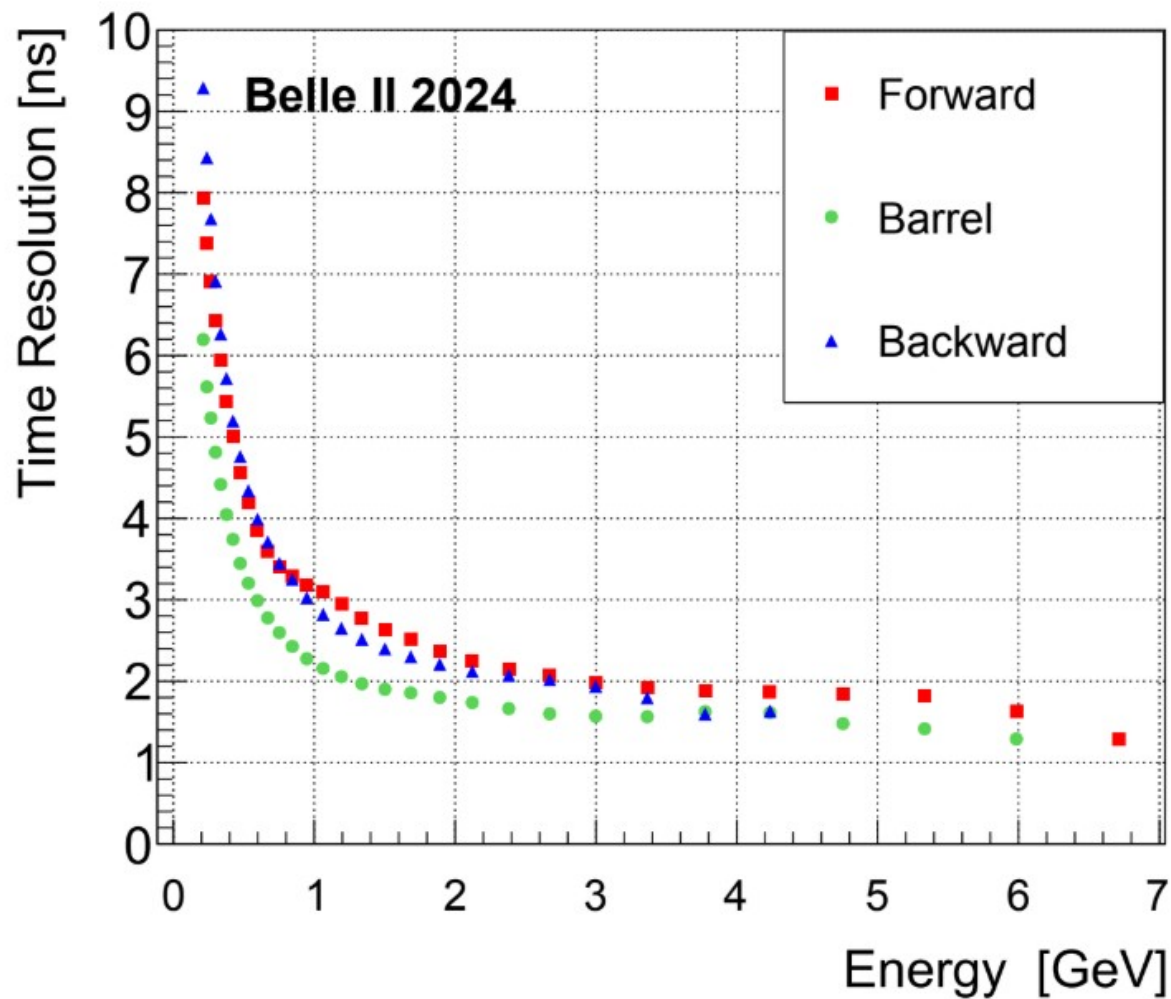
-For some crystals dependence of the time on the transverse Shower position



Coefficient depends on producer. We have about 6000 x-ls Amcrys, 2000 x-ls SICAS, and ~1000 x-ls SaintGobain. Most of Saint Gobain crystals have the essential dependence



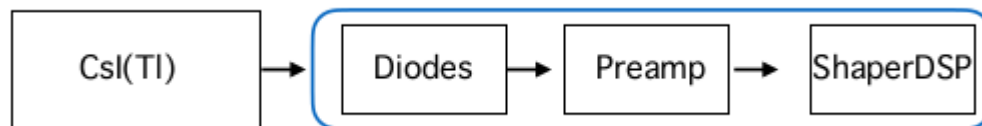
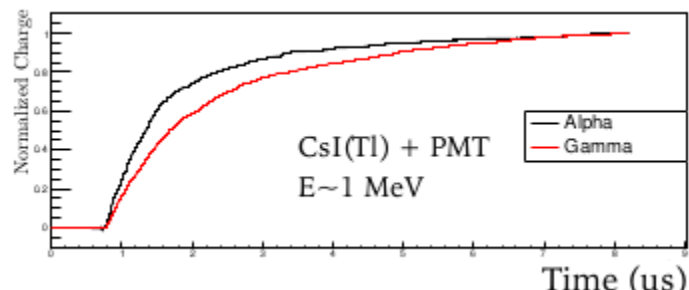
Time resolution



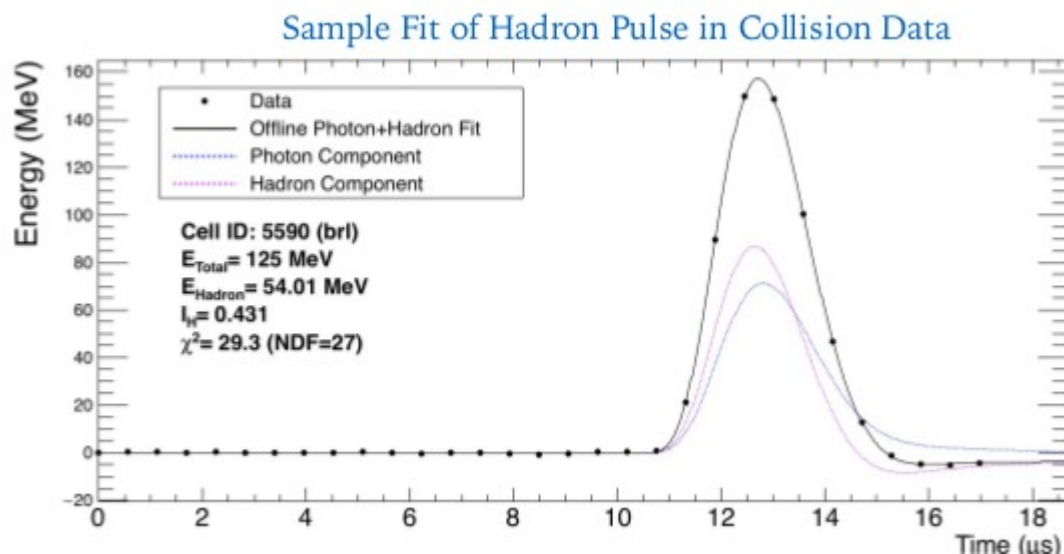
Hadron/photon separation

There is a difference in pulse shape for MIP and High density ionization

For hadron interactions we have p, nuclear fragments etc.



We can calculate the shaper response and, by analyzing the data, separate the contributions of the MIP and the hadronic component.



$$E_{\text{Total}} = E_{\text{Photon}} + E_{\text{Hadron}}$$

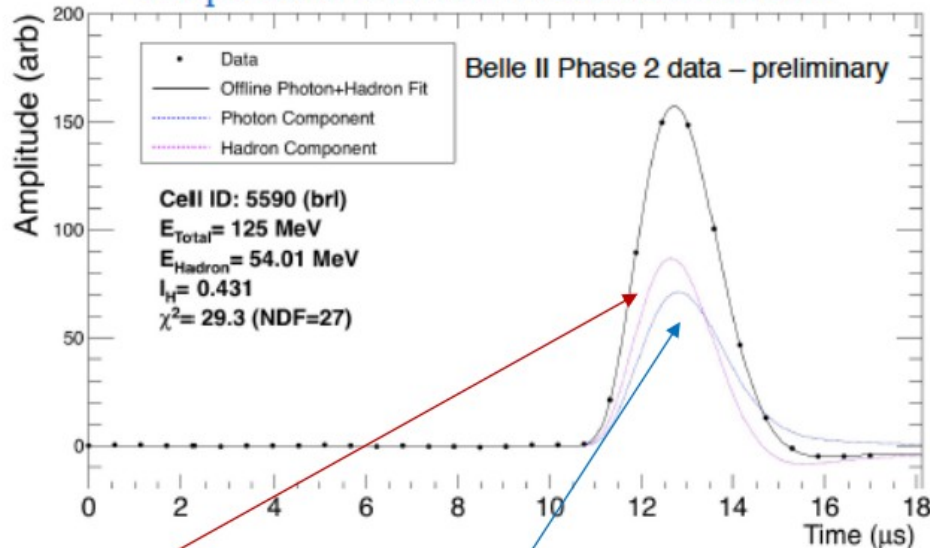
$$N_H = \frac{E_{\text{Hadron}}}{E_{\text{Total}}}$$

For hits E > 50 MeV waveforms were recorded and analyzed.

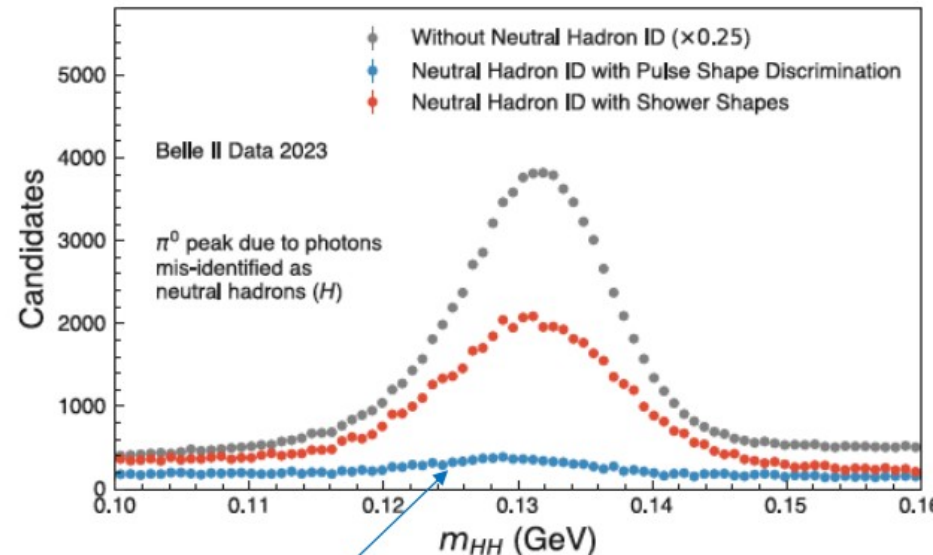
Hadron/photon separation

In Csl(T/), scintillation time evolution changes depending on dE/dX, i.e. difference between hadron and photon incidents.

Sample Fit of Hadron Pulse in Collision Data



Hadron and photon components exhibit different pulse shape



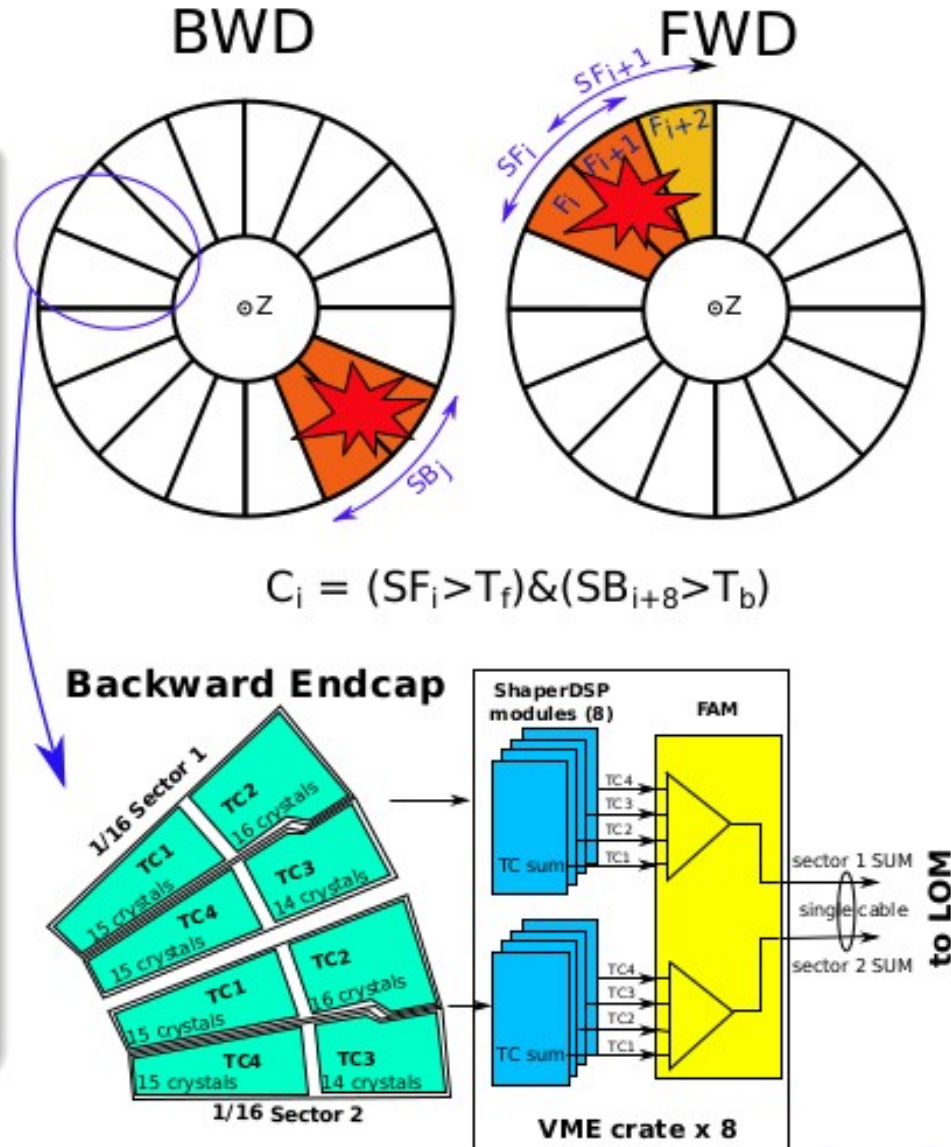
By rejecting photon-like clusters, π^0 mass peak disappears.

- The electronics of Belle II calorimeter works with high reliability.
- Calorimeter shows good energy and time resolution.
- Beam background degrades energy resolution for low photon energies
- Wave form information can be used for hadron identification

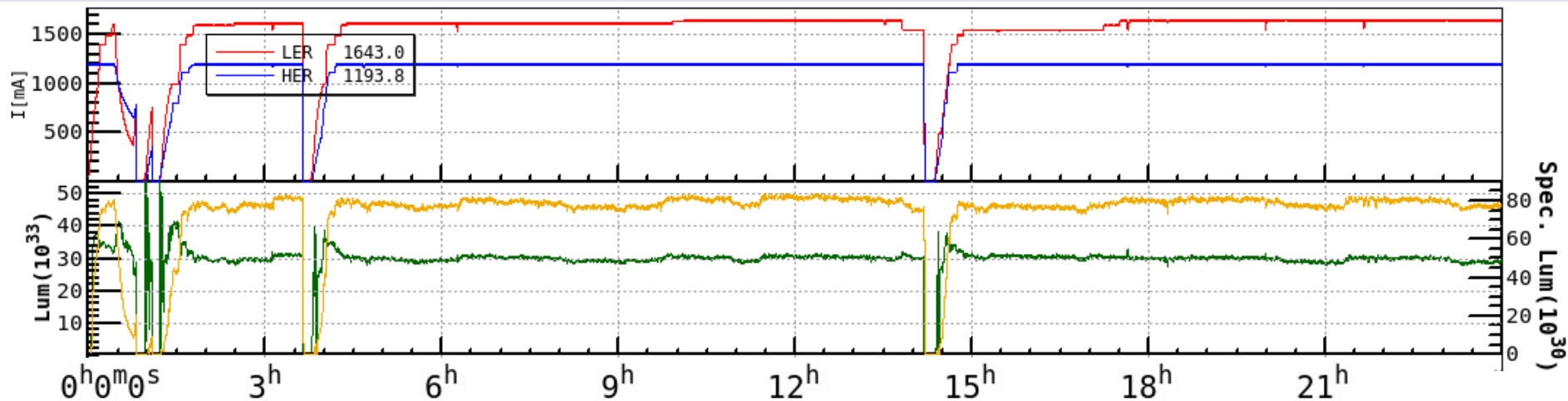
Backup

ECL luminosity monitor

- One endcap 1/16 sector (4 Trigger Cells)
- Each FAM module processes signals from 8 ShaperDSP boards (8 TC) signals and provides analog signals from two endcap sectors to LOM module
- Inner Forward Endcap sector is excluded (may be included)
- Coincidence rate of the signals in opposite sectors is counted and luminosity is calculated

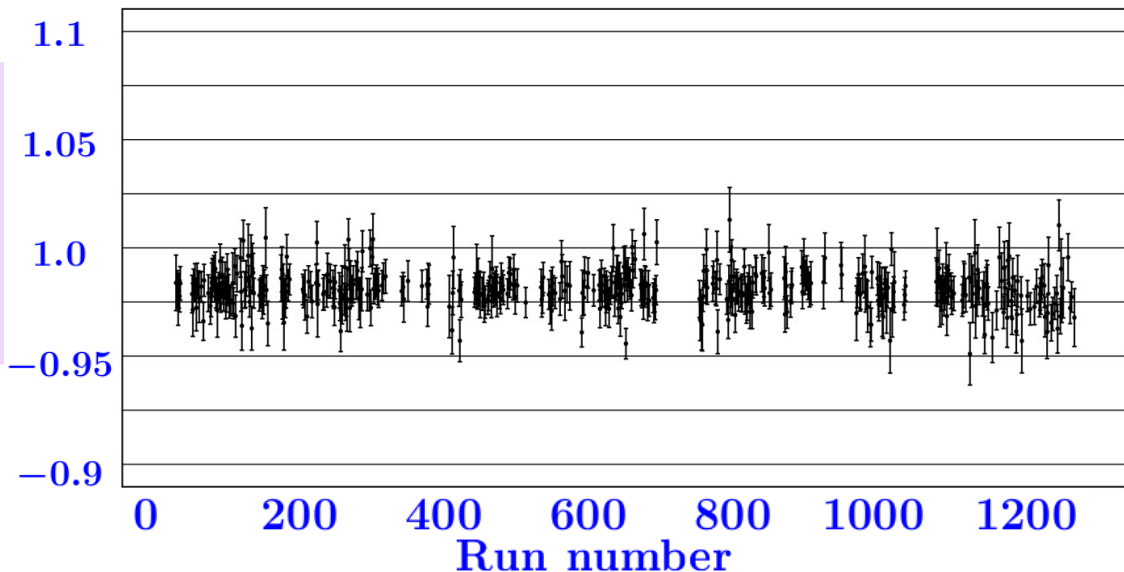


On-line Luminosity measurement

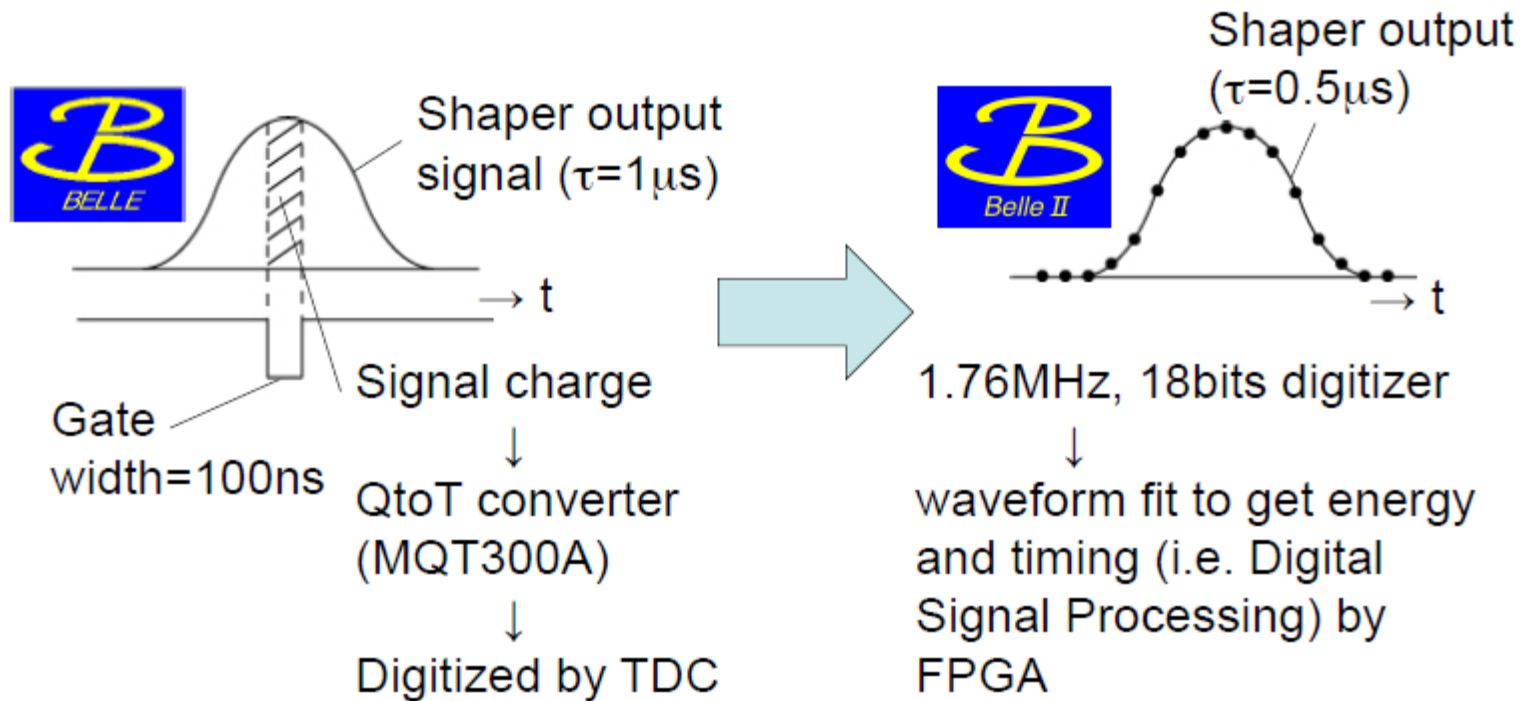


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On-line Offline luminosities are the same with accuracy of 2% and provides stability 0.5%.

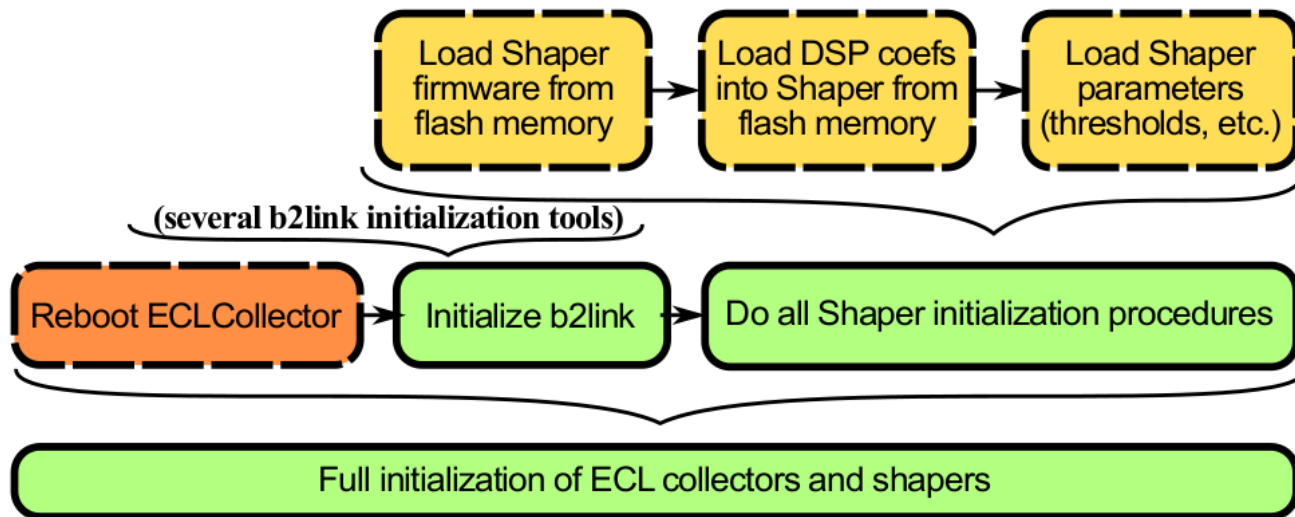


Readout electronics change



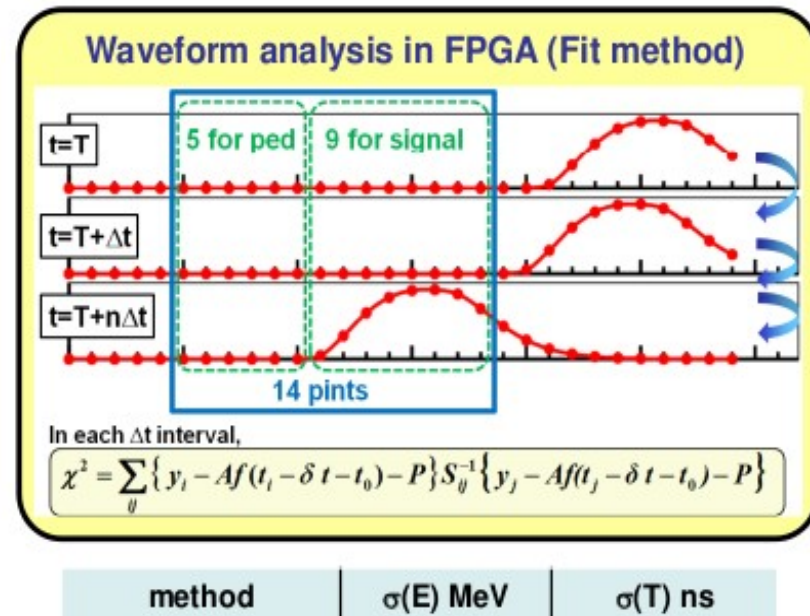
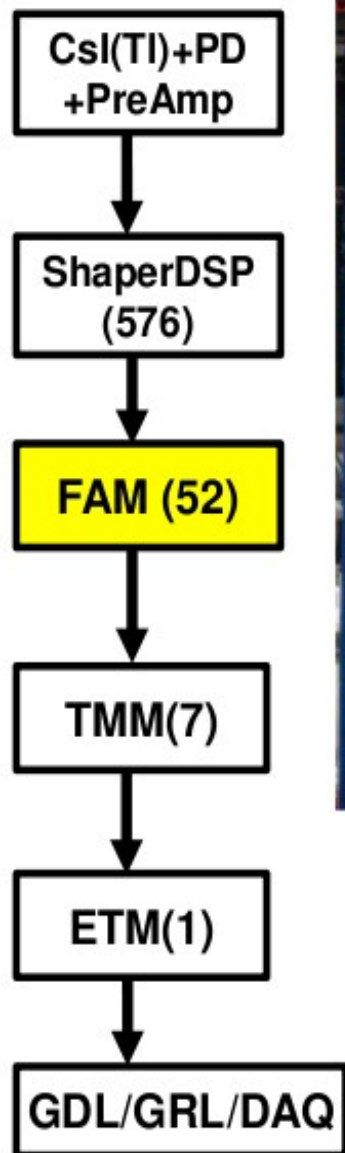
Calorimeter DAQ

- Calorimeter DAQ includes 576 ShaperDSP modules, 52 collectrs and 5 servers.
- The configuration includes ~80 000 parameters.
- Also we need about 1 500 000 coefficients for ShaperDSP algorithm
- The slow control system was developed for quick configuration and initialization of the Calorimeter DAQ
- The Data Quality Monitor continuesly provides histograms for shifters



Full initialization takes ~1 minute.

FAM (FADC Analog Module)



Trigger signals in FAM are digitized and A and T are calculated each time clock.

The digitized data are sent to TMM and ETM, where the decision is taken based on the event energy deposition, and event pattern.