BINP

SND electromagnetic calorimeter time measurement and its applications

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on behalf of the SND collaboration

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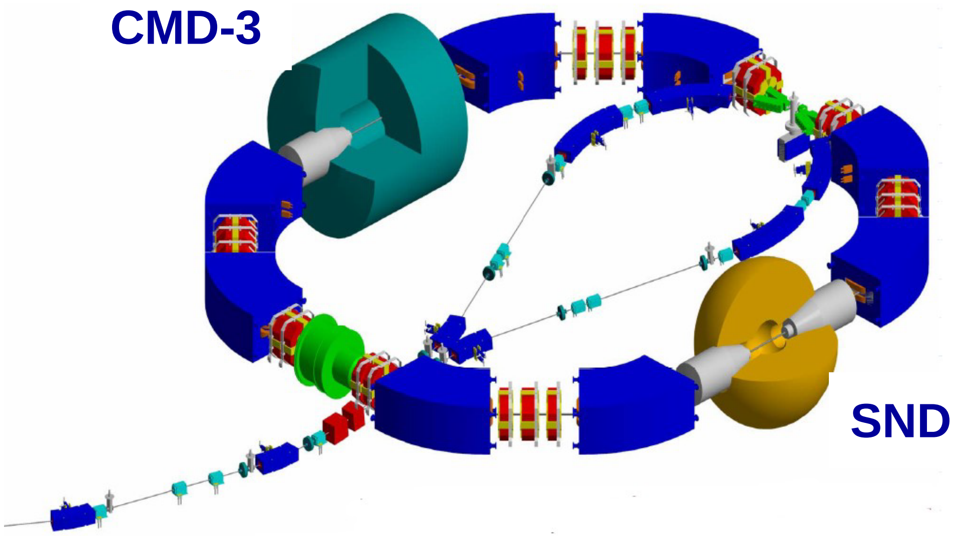
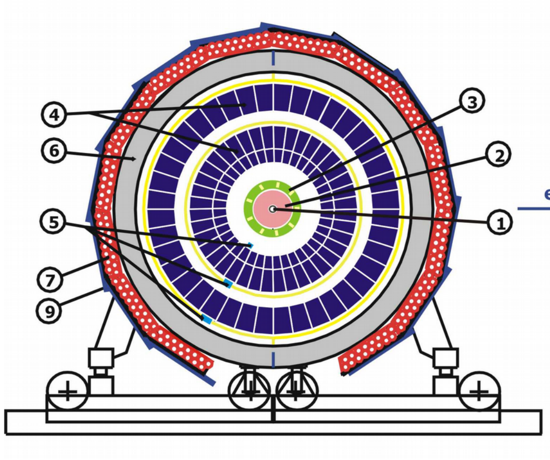
Vepp-2000 e^+e^- collider

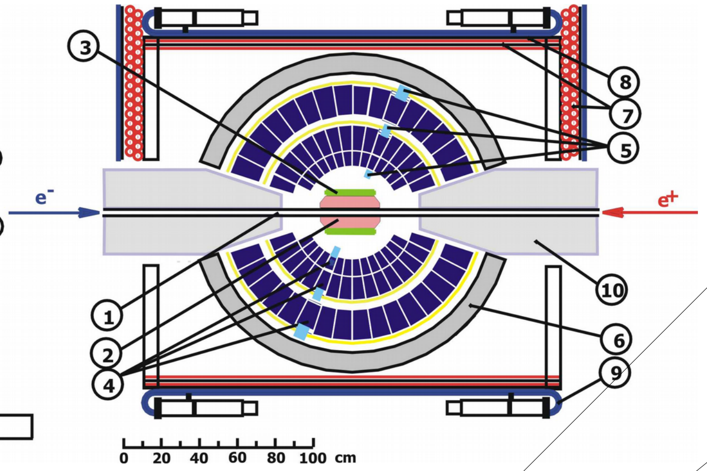
- e^+e^- collider at BINP (Novosibirsk, Russia);
- Hadronic cross section measurement experiments and e.t.c.;
- 2 interaction points: the CMD-3 and SND detectors;



- Energy range = 0.15 ÷ 1 GeV;
- Round beams concept;
- Circumference = 24.4 m;
- Luminosity = 1 x 10^{32} cm^{-2} sec^{-1} (at 1GeV);

Spherical Neutral Detector

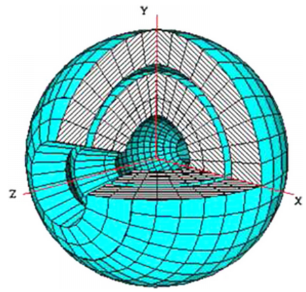


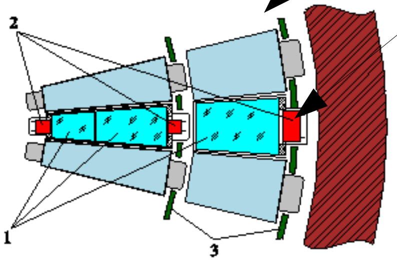


1. Beam pipe
2. Tracking system
3. Cherenkov counter
4. **Electromagnetic calorimeter crystals (NaI (Tl)) (EMC)**
5. **Phototriods**
6. Iron muon absorber

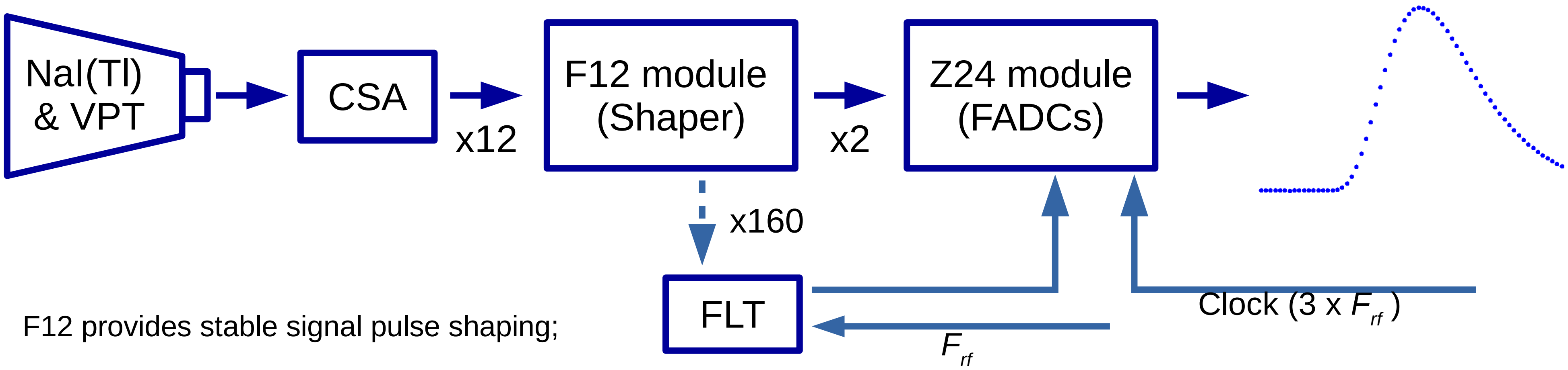
7-9. Muon detector

10. Focusing solenoids





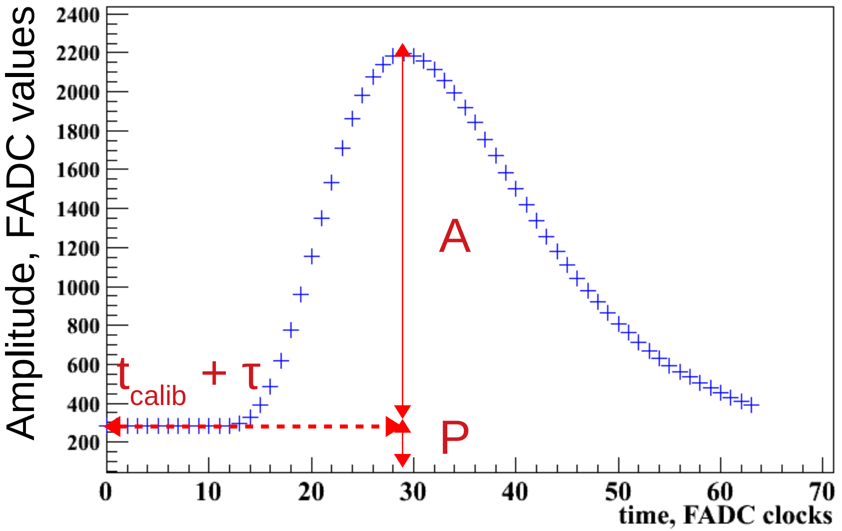
The EMC spectrometric channel



- F12 provides stable signal pulse shaping;
- FLT and FADC clock signals are synchronized with the beam revolution frequency (F_{rf} = 12.3 MHz);
- **New digitizing module (Z24)***:
  - System-on-Chip Xilinx Zynq-7000 & 6 FLASH ADCs (4 channels, 12 bit, 40 MBPS);
  - In use for data taking since ~ 09.2018;
  - Produces the digitized signal oscillogram that can be processed to **reconstruct signal arrival time and energy deposition.**
- We process oscillograms on an online-farm and store them for offline re-processing.

* NIMA v.824 (2016), pp. 362-364

Digitized signal pulse properties

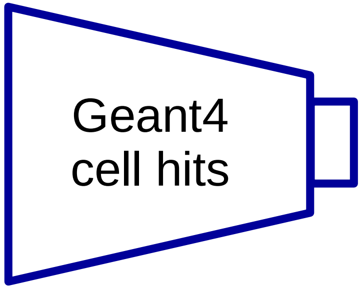


Typical signal waveform from an EMC channel.

- We expect the signal waveform to be stable for each EMC channel and use **a special calibration procedure*** to retrieve it;
- 64 samples;
- Sampling period = 27.12 ns;
- 1 FADC value = ~ 0.25 MeV;
- Maximum sample value = 4095 (FADC);
- Typical pedestal values:
  - P = 280 ÷ 350 (FADC);
  - σ_P = 1 ÷ 5 (FADC);

* NIMA v.936 (2019) pp.117-118

EMC channel response simulation



Each EMC crystal is divided into sensitive cells.
Cell hit information:

$t_i = (t_{prestep} + t_{poststep}) / 2$ - cell hit time

E_i - energy deposition in this cell

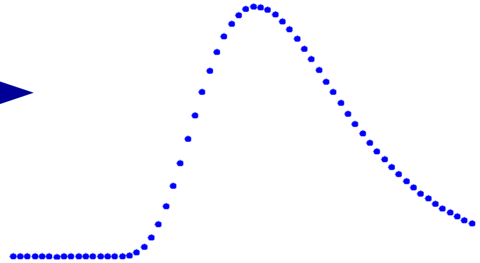
(x,y,z) - cell center

For each triggered EMC counter:

$$U_i = [k_{chan} \sum_j (E_j * F_{shape}(i - t_j - t_{shift})) + P + P_{noise}]$$

i – signal sample index, j — cell hit index

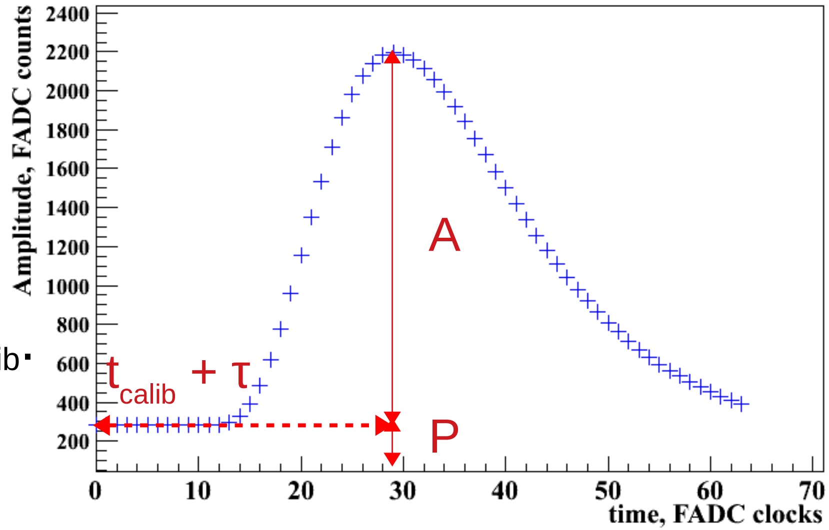
k_{chan} - coefficient for MeV to FADC value conversion



Signal pulse processing

- Fit the EMC digitized signal with U(t) to extract:
  - A – the signal amplitude
  - P – the signal pedestal
  - τ – the signal arrival time with respect to *F(t)* – the calibrated signal shape in an EMC channel with the maximum at t_{calib}.
- Two algorithms (work in progress!):
  - Based on the linearization *;
  - Based on the correlation function.

$$U(t) = A \cdot F(t-\tau) + P$$



* JINST v.12 (2017) p. C07043

The linearization algorithm

- Based on the algorithm for the Belle II calorimeter electronics *;
- Minimizes the function

$$\chi^2 = (y_i - A \cdot F(t_i - \tau) - P) \cdot S_{ij}^{-1} \cdot (y_i - A \cdot F(t_j - \tau) - P)$$

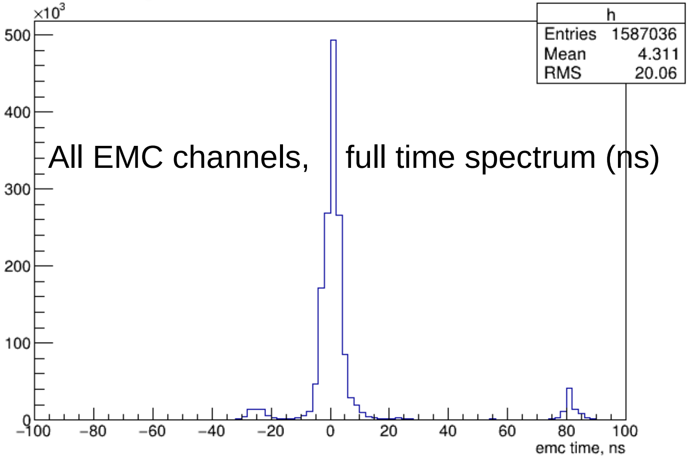
- where y_i – the sample signal magnitude at time t_i, *F(t)* – function that describes the calibrated EMC channel signal shape, S_{ij} – the noise covariance matrix;
  - *F(t)* is linearized on a time grid to calculate all needed coefficients in advance.
- For small signals we determine only **A** and **P** with fixed **τ** (linear regression).

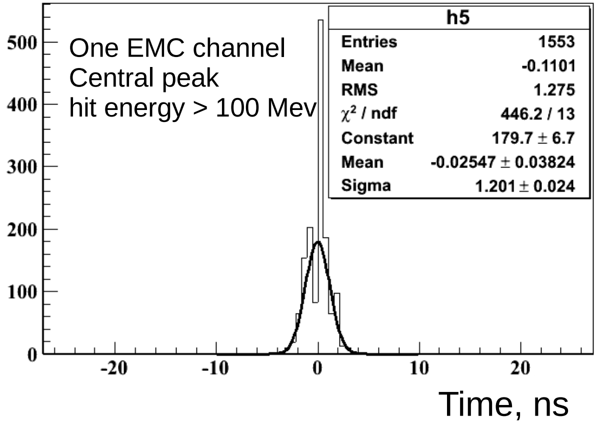
* JINST,v. 9 (2014), p. C09014

The linearization algorithm results on $e^+e^- \to e^+e^-$ events

- \+ Can process most of the signals with **A** > 50 FADC values;
- \+ Can be used on FPGA inside the digitizing module;
- \+ Relatively fast (~0.15 ms per signal);
- \- Can't process special cases (saturated and heavily shifted);
- \- The resulted time determination accuracy depends on the linearization time grid.

Total success (good signals with A > 50 FADC values)	~8%
Success for small signals (with fixed time)	~60%
Failed fit for very small signals	~30%
No fit for saturated and shifted (>7 FADC clocks) signals	~0.1%
Distorted signal shape & other problems	...





The correlation function algorithm

- **Signals are processed in 2 steps:**

Step 1 – determines the signal time shift (τ):

- Calculates the first guess for the shift (τ_0) using FFT:

$$\widehat{y_i - P}(\omega) = \exp(-i\omega\tau_0)\cdot\widehat{F}_i(\omega), \omega = \frac{2\pi}{64}$$

- Then finds the maximum of the correlation function using τ_0 as a start value:

$$\omega(\tau) = \sum_{i=0}^{i=63} (y_i - P)\cdot F(t_i - \tau)$$

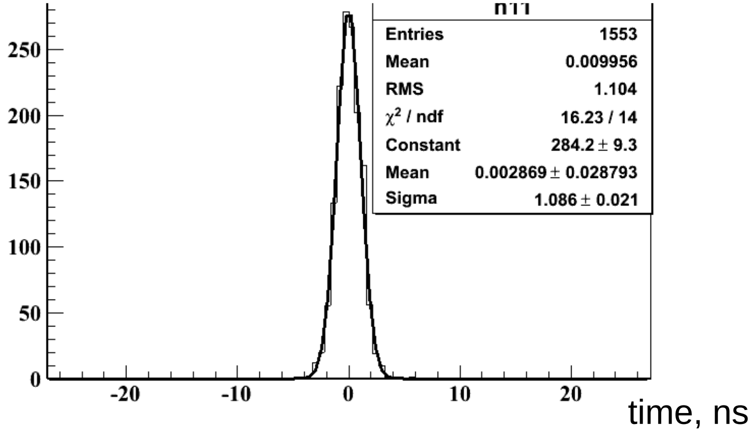
  - Minimization with the Brent's algorithm (GSL);

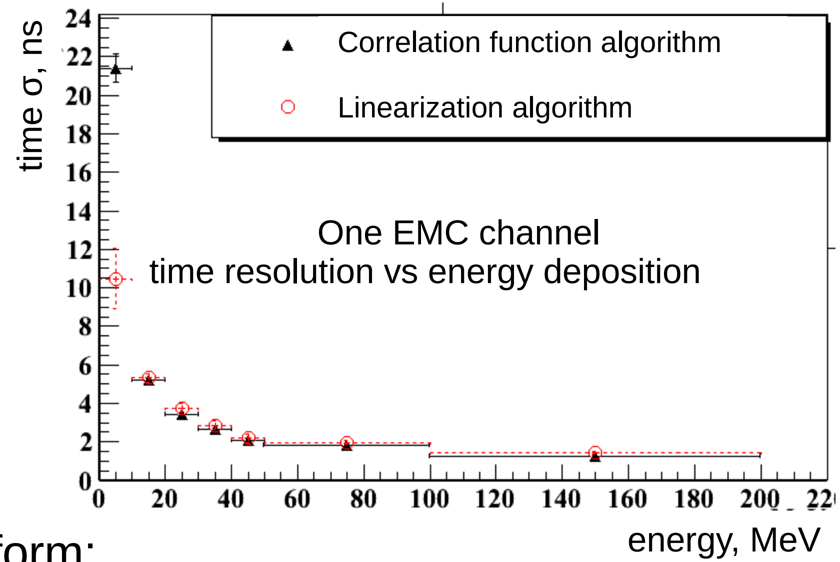
Step 2 – calculates A and P of the signal using the extracted time (linear regression).

* CHEP2019 talk

The correlation function algorithm results on $e^+e^- \to e^+e^-$ events

Time for one EMC channel
over hits with energy > 100 MeV

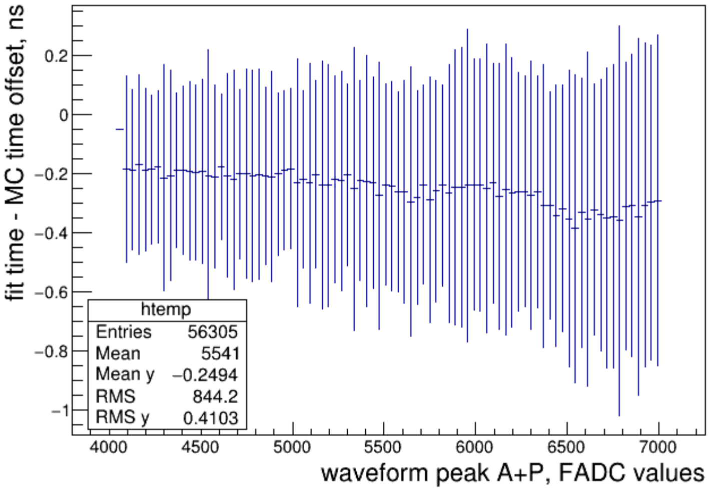


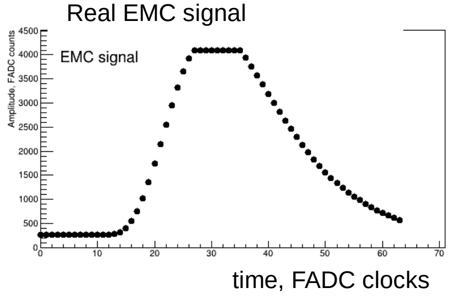


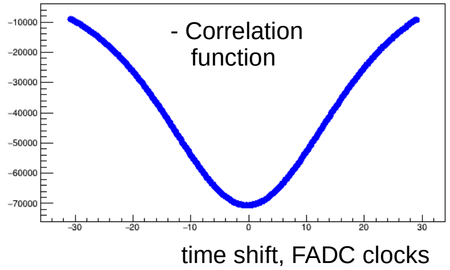
- **+** Can process almost all signals with the good waveform;
- **+** Can handle special cases: shifted and saturated signals;
- **-** Relatively slow (~1.2 ms per signal);
- **!** Bad time resolution for small amplitudes.

The correlation function algorithm: saturations

- Algorithm modifications:
  - For FFT **τ** first guess: simulates saturation on the calibrated signal waveform;
  - Determines only **A** (**P** fixed to a calibrated value) ignoring saturated samp'
- Test on MC with electronics response simulation and one fixed **τ**
  - Spread profile for difference between algorithm times and MC offset:

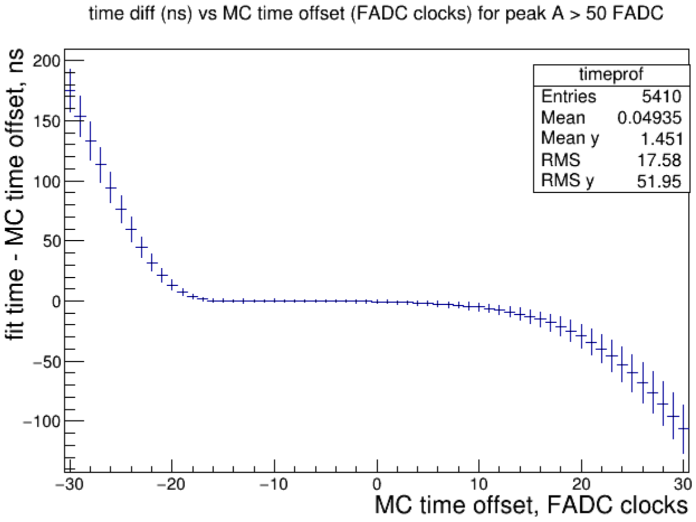


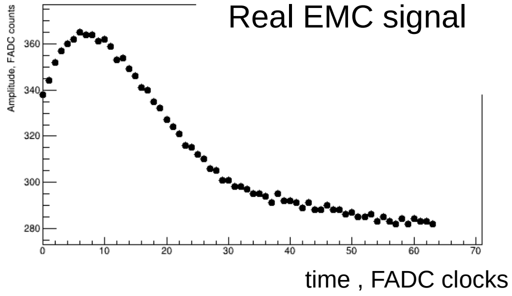


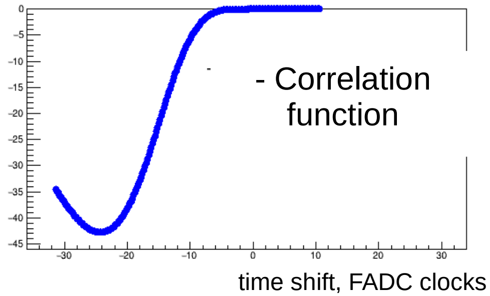


The correlation function algorithm: shifted signals

- Algorithm modifications:
  - Step 2: Determines only **A** (**P** fixed to a calibrated value).
- Test on MC with electronics response simulation and fixed τ values in range -30 ÷ +30 FADC clocks:
  - Spread profile with difference between algorithm times and MC time offset:

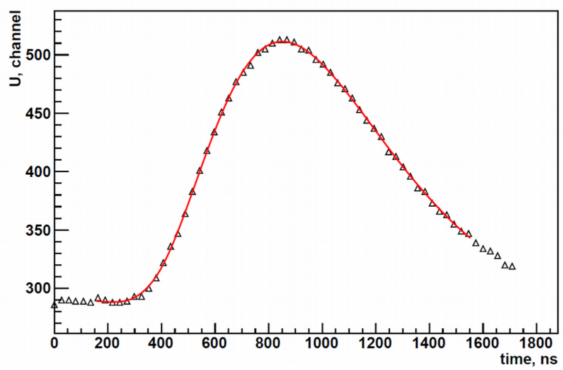






Signal waveform calibration (1)

- During data taking we calibrate the waveform using:
  1) A calibration generator:
     - Quick procedure, performed daily for monitoring:
     - For each EMC channel 100 pulses with known **A** and **τ** are used to construct an averaged pulse that is fitted with a cubic B-spline;
     - Resulted waveforms significantly differ from the waveforms obtained with 2 other procedures!
  2) Cosmic muons;
  3) e+e-→e+e- events.



* NIMA v.936 (2019) pp.117-118
CHEF2019 talk

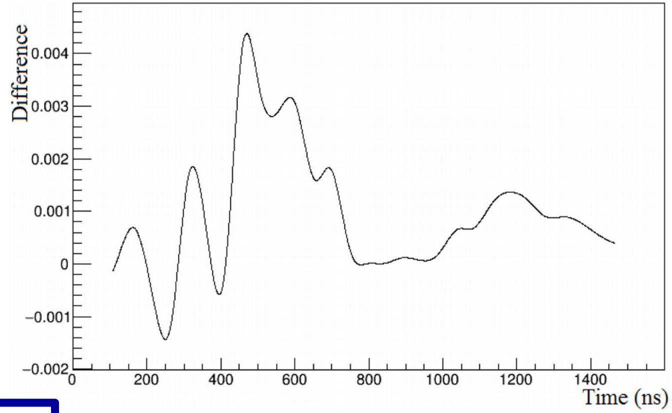
Signal waveform calibration (2)

- Calibration on cosmic muons:
  - Performed after long stops in operation or\and maintenance work;
  - Uniform time distribution: the procedure selects “the best signal” as a reference one to obtain an initial waveform;
- Calibration on $e^+e^- \to e^+e^-$ events:
  - Performed regularly on large data set;
  - Careful selection of input hits: only good strong signals from the main time peak;
  - The previous calibrated waveform or result of the cosmic calibration is used as an initial waveform.
- Iterative procedures:

Step 2. The initial waveform is used to determine A (amplitude), τ (time shift) for all selected pulses.

Step 3. Good fit results from Step 2 are used to construct an averaged pulse. Then it’s fitted by a cubic B-spline. The obtained coefficients are stored.

The waveform difference between Bhabha and cosmic calibration results (FADC values)



* NIMA v.936 (2019) pp.117-118
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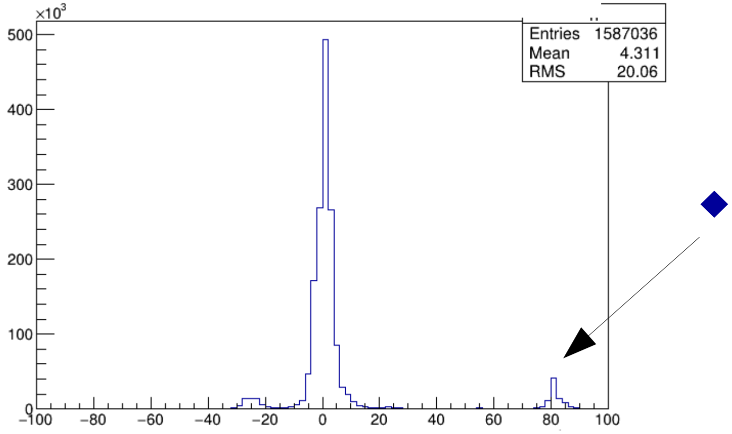
EMC time event reconstruction

- Reconstruction with EMC time was implemented in the SND software framework:
  - Result of the EMC clusterization algorithm is used to form EMC time objects;
  - New entities:
    - EMC counter time;
    - EMC event time;
    - EMC particle time.

EMC time measurement applications:

All EMC channels,
full time spectrum (ns)



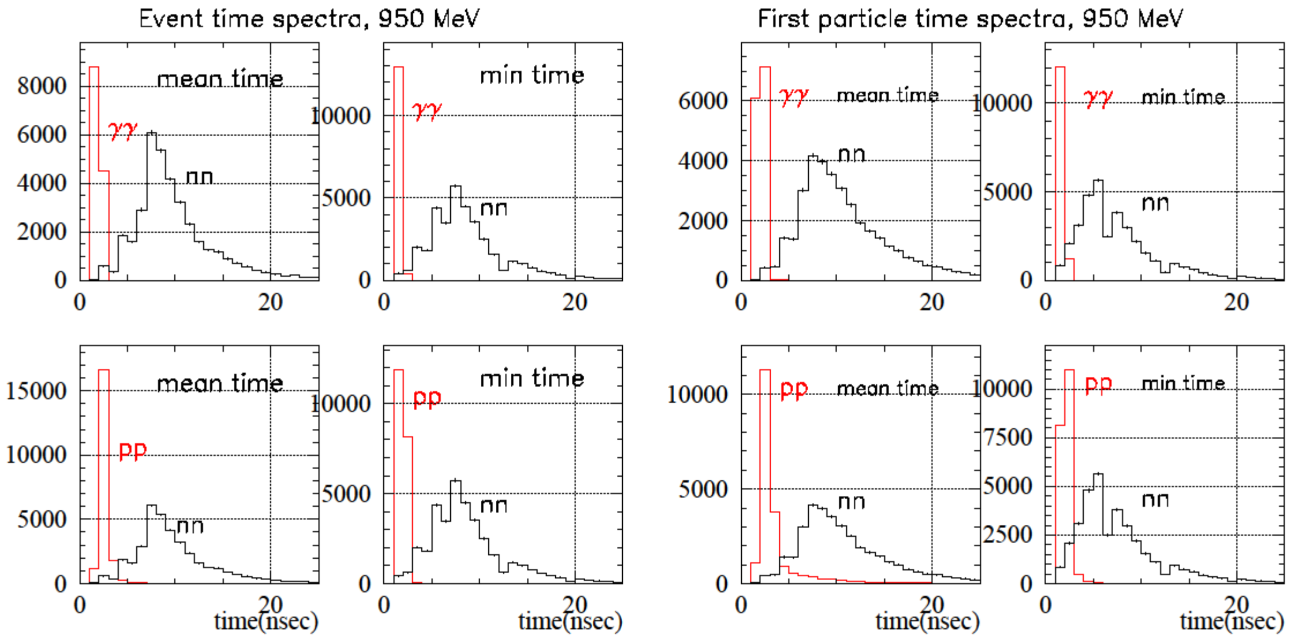
Time, ns

- Cosmic-ray background suppression (no peak on the time spectra around zero);
- Beam-induced background suppression

  (peaks at ±n*3*sampling period);
- Identification of events with long EMC response times like:

  $e^+e^- \rightarrow p\bar{p}$ $e^+e^- \rightarrow n\bar{n}$

First results on MC data

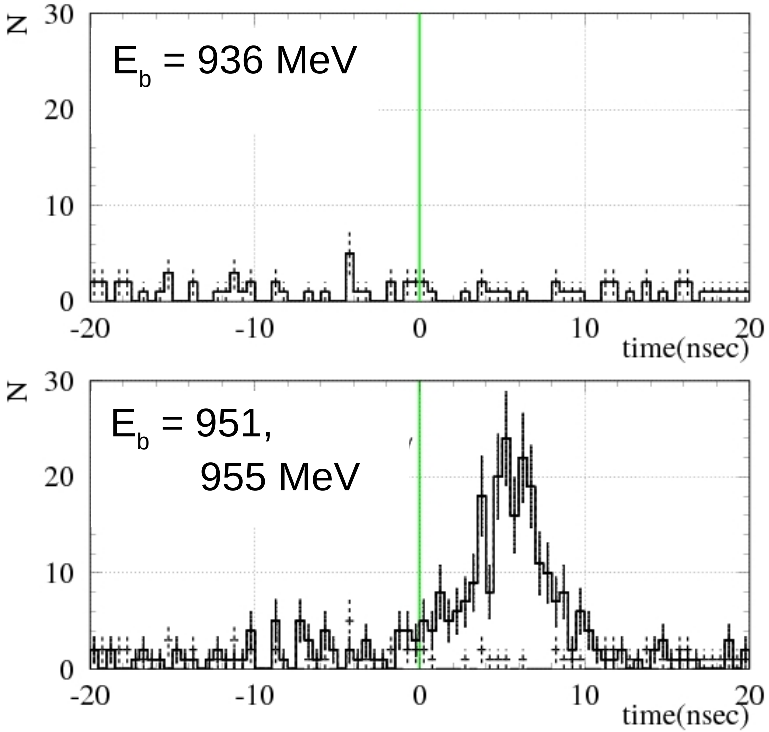


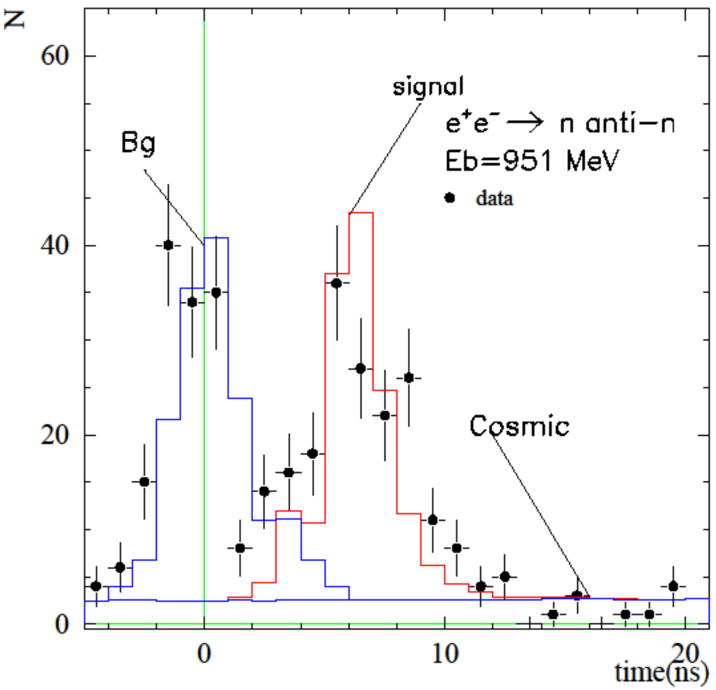
- More efficient identification of the $n\bar{n}$ events near the threshold

❄ Thanks to Sergey Serednyakov for figures!

First results, RUN 2019

- $e^+e^- \rightarrow n\bar{n}$ Time spectrum:
  - No signal below the threshold (E_b = 936 MeV):
  - Separation from background events is possible near the threshold (E_b = 951 MeV);





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Summary

- The new SND EMC electronics with FADCs is successfully used for DAQ since 2018 year;
- The new digitizer with FADCs provide us with EMC signal waveforms which we process to extract not only energy but also time information;
- We have two different algorithms for EMC signal processing which we use together to obtain the best results;
- EMC event time reconstruction and simulation of EMC channel response was implemented;
- First attempts are being made to use EMC time measurement in physics analysis.