Energy calibration and data processing of the LXe/CsI-combined calorimeter of the CMD-3 detector

A. Semenov, B. Shwartz, T. Kuznetsov on behalf of the CMD-3 calorimeter group

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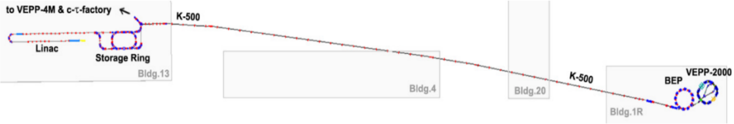
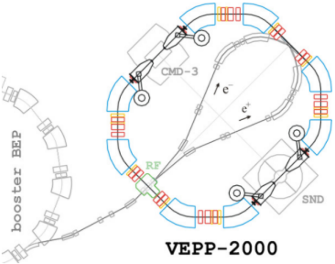
Introduction

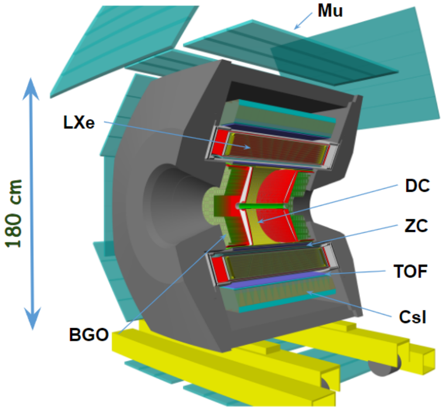
Physics program of the symmetric electron-positron collider VEPP-2000 includes high-precision measurements of the $e^+ e^- \to \textit{hadrons}$ cross-sections in the energy range from the production threshold to $2\,\mathrm{GeV}$.



The high collider luminosity (up to $1 \times 10^{32}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$) is provided by a special feature that involves using the round beam cross section concept.



CMD-3 detector



Magnetic field: 1.3 T

Track reconstruction:

$$\sigma_{\rho\phi} \approx 100\,\mu\text{m}$$
$$\sigma_z \approx 2\text{–}3\,\text{mm}$$

$\sigma_p/p \approx \sqrt{(4.4p[GeV])^2 + 0.62\%}$

Combined EM-calorimeter:

Barrel: 5.3 X_0 *LXe* + 8.1 X_0 *CsI* = 13.5 X_0

End caps: 14.4 X_0 *BGO*

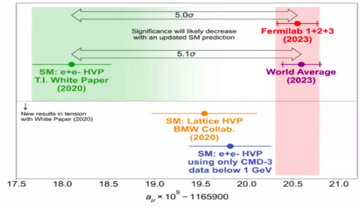
TOF: $\sigma_t \approx 1\,\text{ns}$

Compact multipurpose detector comprising magnetic spectrometry with high resolution calorimetry.
The barrel calorimeter is **outside** the magnetic field.

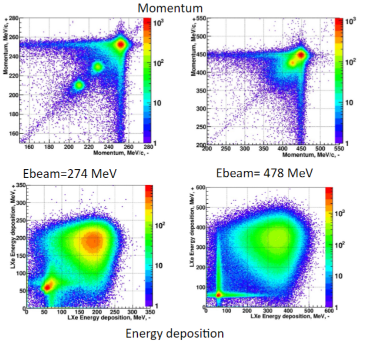
Motivation

1. Accurate measurement of photon energy and coordinate improves the resolution for determining the neutral hadrons mass (π^0 and η), thereby improving the cross-section measurement of neutral processes.
2. Particle identification.

The recent result of the CMD-3 collaboration



Measurement of the $e^+ e^- \to \pi^+\pi^-$ cross section from threshold to 1.2 GeV with the CMD-3 detector https://arxiv.org/pdf/2302.08834



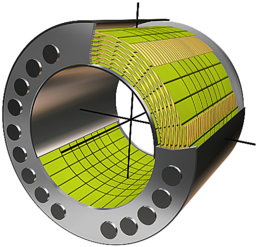
Two collinear tracks

<u>Precise calibration is extremely important for hadronic cross sections measurement as well as for reducing systematic uncertainties.</u>

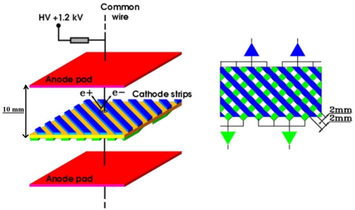
Barrel calorimeter

LXe calorimeter

Calorimeter sketch



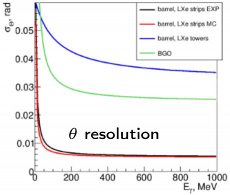
Layer structure



Strip width is 2 mm

Alternating 8 anode and 7 cathode cylindrical layers. The anodes are divided to 264 cells (33 by azimuth angle and 8 along Z-axis). The cathode layers have orthogonal strips on the both sides (2112 strips). The total thickness is $5.4X_0$.

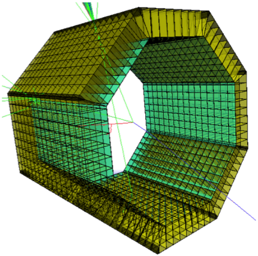
Property	LXe	LKr	LAr
Atomic number (Z)	54	36	18
Atomic mass (A)	131.29	83.8	39.95
Density, g/cm^3	2.95	2.42	1.40
Rad. Len. X_0, cm	2.87	4.7	14.0
Moliere radius, cm	5.22	5.86	9.04
dE/dx, MeV/cm	3.71	3.28	2.11



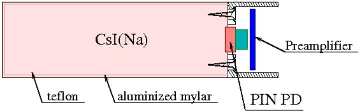
Barrel calorimeter

CsI calorimeter

Calorimeter sketch



Crystal structure

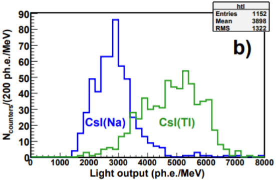


$6 \times 6 \times 15\,\mathrm{cm}^3$

Hamamatsu PIN PD

The calorimeter consists of 1152 scintillation crystals compiled to the 8 octants. Around 60% of the crystals are doped by Tl and the rest by Na. The total thickness is $8.1X_0$.

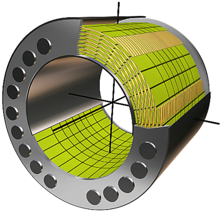
Property	CsI(Tl)	CsI(Na)
Density, g/cm^3	4.51	
Rad. Len. X_0, cm	1.86	
Moliere radius, cm	3.57	
dE/dx, MeV/cm	5.6	
λ_{max}, nm	560	420
τ, ns	1000	600
L, ph/MeV	45000	30000



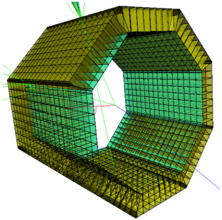
Barrel calorimeter

Overview

LXe calorimeter



CsI calorimeter

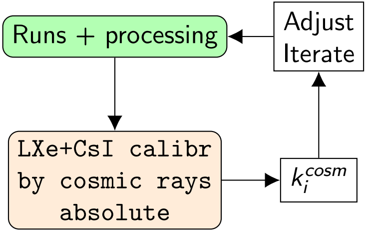


Type	BGO	LXe	CsI
Structure	680 crystals	264 towers 2112 strips	1152 crystals $6 \times 6 \times 15\,\mathrm{cm}^3$
X_0	14.4	5.4	8.1
θ	0.3-0.8 2.34-2.84	0.8-2.34	
σ_E/E	$\frac{2.4\%}{\sqrt{E/GeV}} \oplus 2.3\%$	$\frac{3.4\%}{\sqrt{E/GeV}} \oplus 2\%$	
σ_θ	$28\,\mathrm{mrad}$	$6\,\mathrm{mrad}$ by strips $40\,\mathrm{mrad}$ by towers	

Energy calibration

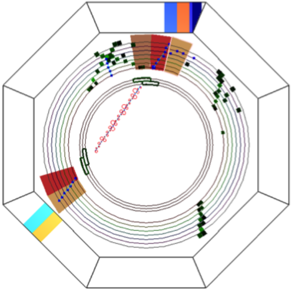
Description

Energy in a channel $E = k \cdot (A - p)$, where A — ADC amplitude, p — ADC piedestal and k — conversion factor.
Assuming that $\frac{dE}{dx}$ of the cosmic muons (MIP) does not depend on the position of the channel, measure $E_{ch}/D_{ch} = \varepsilon$,
$\varepsilon^{mc}_{CsI,LXe} = 0.604, 0.3725 MeV/mm$



k^{cosm}_{i}

$$k^{cosm} = \varepsilon^{mc}_{peak} / \varepsilon^{exp}_{peak}$$



The calibration requires 1000 events per channel →
LXe – 3 hours, CsI – 2 days.

Energy calibration

Description

Approx energy deposition for one particle $E^{\mu}_{dep} \approx 90\,\mathrm{MeV}$ in the case of transverse flight (relative to the beam).

Preselection:

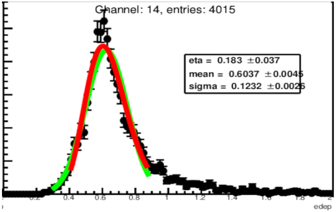
- $DCNTracks < 2$
- $LXeEnergy < 300\,\mathrm{MeV}$
- $CsIEnergy < 300\,\mathrm{MeV}$
- $LXeNClus < 3$
- $CsINClus < 4$

Selection:

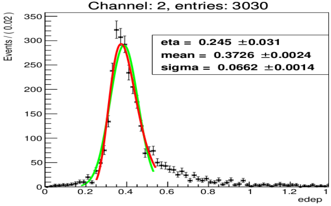
- $NLXeTrk \geq 2 \cdot NDC$
- $E_{CsIhit} > 30\,\mathrm{MeV}$
- $Dist_{CsIhit} > 40\,\mathrm{mm}$
- $E_{LXehit} > 5\,\mathrm{MeV}$
- $Dist_{LXehit} > 5\,\mathrm{mm}$

The precise calorimeter geometry description was made. The distances into the both calorimeters were measured by strip track. The track from LXe was extended for CsI.

CsI channel



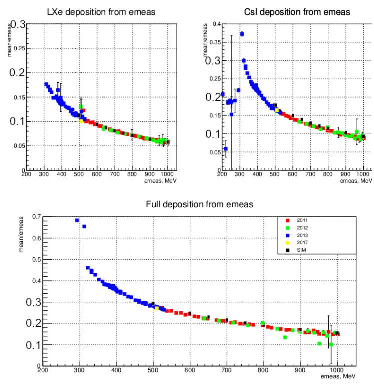
LXe channel



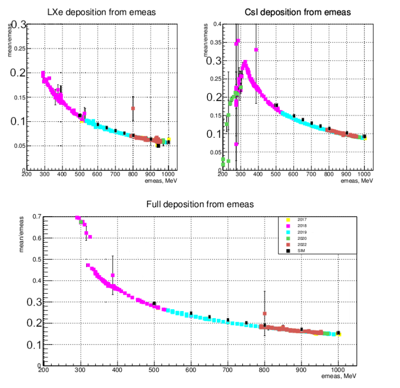
Energy calibration

Final results

Select $e^+ e^- \to MIP^+ MIP^-$ events $\to$ fit energy deposition $\to$ get distribution mode



2011—2013 before upgrade



2017—2022 after upgrade

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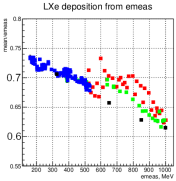
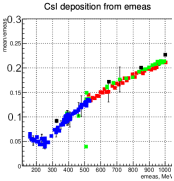
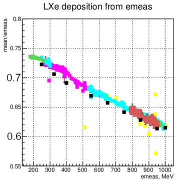
Energy calibration

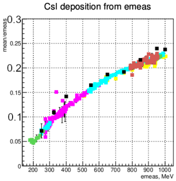
Final results

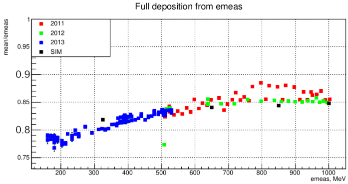
Select $e^+ e^- \to e^+ e^-$ events $\to$ fit energy deposition $\to$ get distribution mode

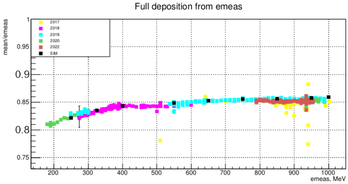










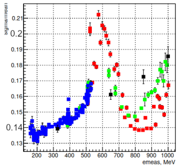


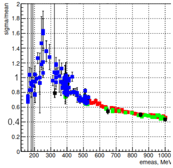
2011—2013 before upgrade 2017—2022 after upgrade

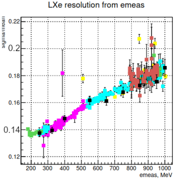
Energy calibration

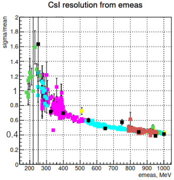
Final results

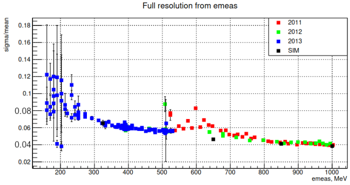
Select $e^+e^- \to e^+e^-$ events $\to$ fit energy deposition $\to$ get resolution

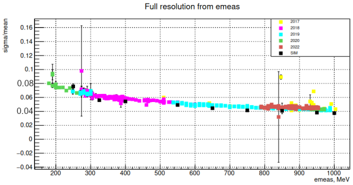










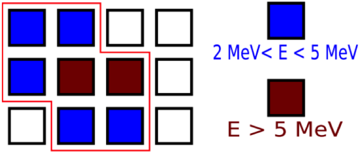


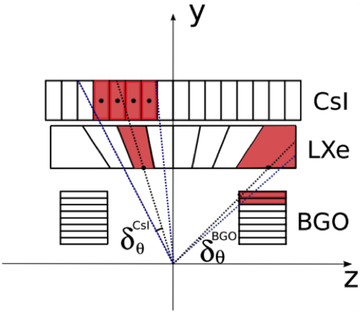
2011—2013 before upgrade 2017—2022 after upgrade

Clusters reconstruction

Standard procedure

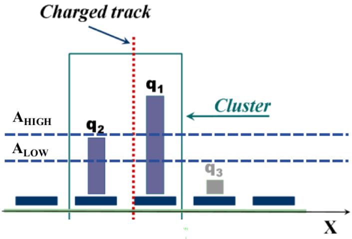
LXe or CsI cluster

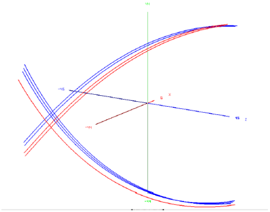




Add all CsI clusters and crystals with E>2MeV within 0.2 rad around towers
Also $\delta_\theta^{BGO} = 0.05$ rad, $\delta_\varphi^{BGO} = 0.1$ rad

Strip cluster



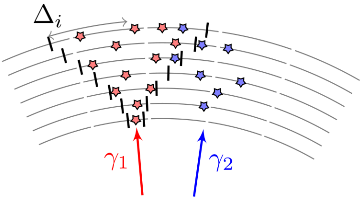


Blue — first layer, red — second layer

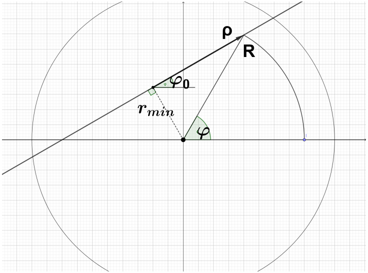
Photon separation

Preview

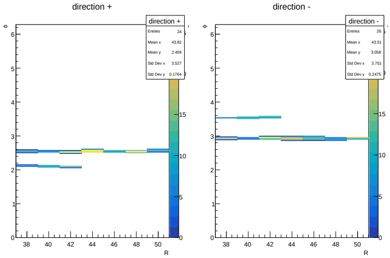
The tower angle size is 0.2*rad*. To separate two photons the angle distance must be more than 0.4*rad*.
In process $\pi^0 \to \gamma\,\gamma$ the overlapping is obtained for E_{π^0} above $\approx 600\,\mathrm{MeV}$.



Parametrization



Filtering and clusterization



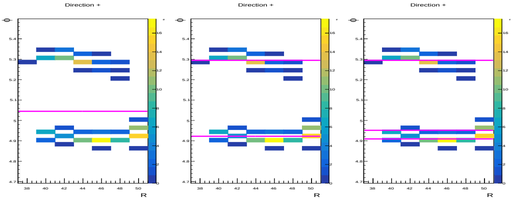
$$\phi(R) \approx [\varphi_0 \pm tg(\theta)] + [r_{min} \pm Z_0] \cdot \frac{1}{R} + O(\frac{1}{R^2})$$

Photon separation

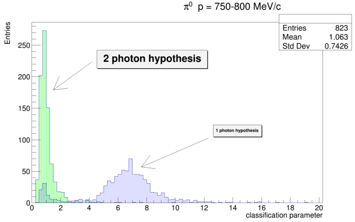
Approach

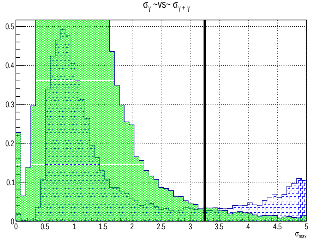
Minimizing of

$$J_N = \sum_i a_i \cdot \min\left(|\phi_i - \phi_0(R_i)|, \ldots |\phi_i - \phi_{N-1}(R_i)|\right)^2.$$



Classification parameter: $\sigma_N = \sqrt{J_N / \sum_i a_i} \approx \alpha R_M$.



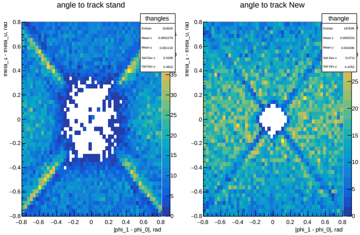


Energy of the LXe tower is divided by fraction of the strip amplitudes.

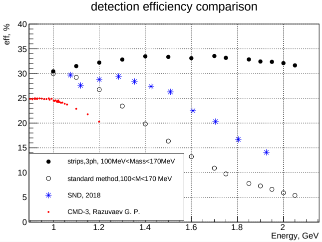
Photon separation

Results

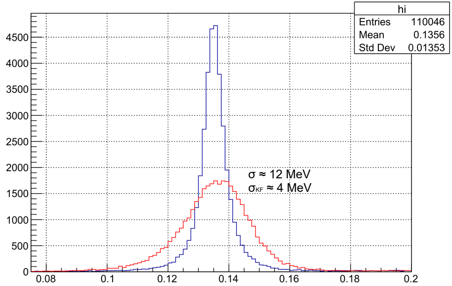
Improve angle reconstruction



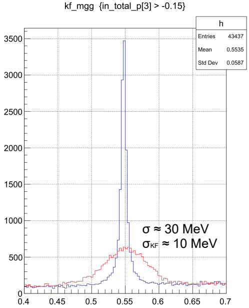
Improve eff for $e^+ e^- \to \pi^0 \gamma$



Kinfit for π^0 mass reco



Kinfit for η mass reco



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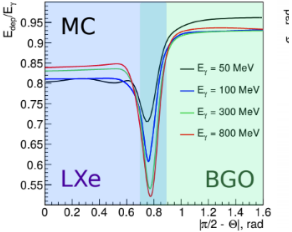
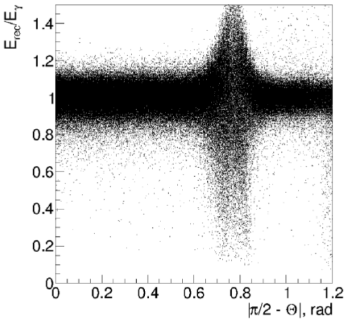
Photon energy calculation

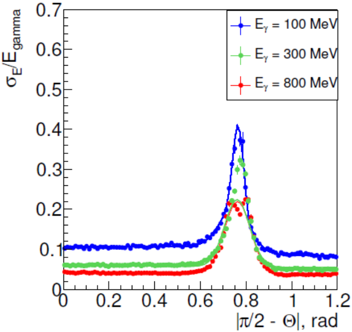
Standard procedure

1. Using the simulation get a function: $E^{dep} = f(E_\gamma, \theta)$
2. Invert function (numerical) and get energy: $E_\gamma = f^{-1}(E_{dep}, \theta)$

Shower leackage correction







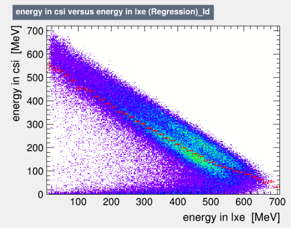
Photon energy calculation

Preview of ML method

A large number of photon parameters are recorded.

- Energy depostion in calorimeters (x3)
- Angles (x2)
- Radius on conversation (x1)

The idea is to use MLP to fit and search for hidden dependencies.



For the initial task, consider the barrel calorimeter parameters only: $E_{LXe}, E_{CsI}, \rho_{conv}, \theta, \phi$.

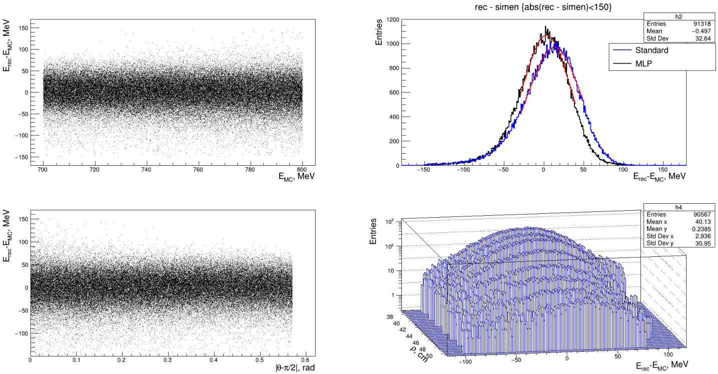
Simulate the single photon with a uniform angles distribution and uniform energy distribution in range 700–800 MeV.
Topology: $5 \to 5 \to 10 \to 5 \to 1$, actv. func: LReLU.

Photon energy

Study and test

$$\mathcal{L} = \frac{1}{2B}\sum_i^B (f(\vec{x_k};\vec{\omega}) - y_i)^2 + \frac{\lambda}{B}\sum_i^B \{\frac{1}{2K}\sum_k^K (f(\vec{x_k};\vec{\omega}) - y_k)\}^2,$$

where x — input parameters, w — NN weights, f — final function, y — answer, sum over B is a batch sum, sum over K is a sum over neighbours of i-*th* event.

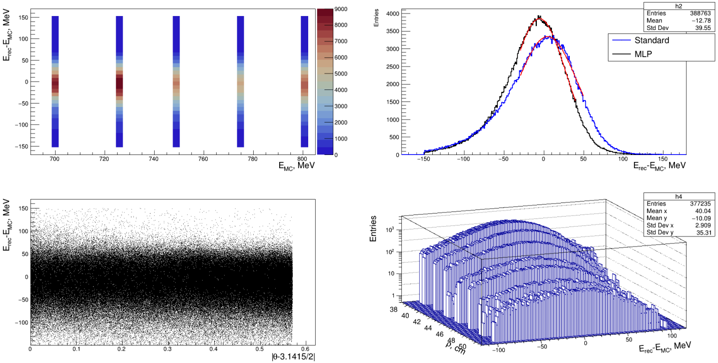


Improve: $\sigma : 33.2 \rightarrow 29.7MeV, \mu : 13.1 \rightarrow 3.2MeV$.

Photon energy

Experiment

Select events $e^+ e^- \to \gamma\,\gamma$, where we know true photon energy. Each energy points have a different statistic.

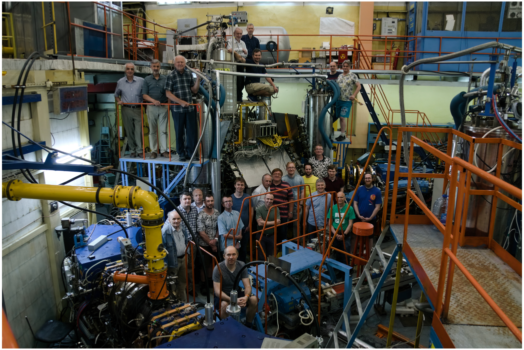


Improve: σ : 38.2 $\to$ 33.1MeV, μ : 4.5 $\to$ $-5.6MeV$.

Conclusion

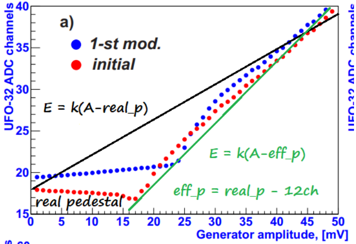
Review

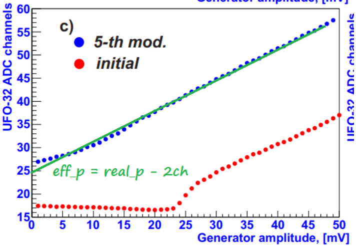
- All experimental data was calibrated
- The energy calibration precision is about $\approx 1 - 2\%$
- The procedure to separate close photons by strip system is implemented and the first results are obtained
- The photon energy reconstruction by MLP is under develop



CsI boards non-linearity

Small CsI energy deposition in old seasons



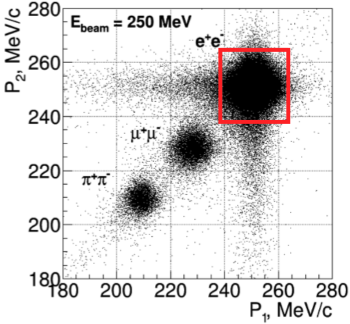


- Before the CsI boards modernisation the huge non-linearity was observed
- For old seasons (before the modernization) the effective pedestals are 12 channels lower than the measured ones.
- The new threshold for CsI clusterization is $4MeV$ for the old seasons before 2017
- Currently, a consideration of the nowday boards non-linearity is being developed (A. Erofeev)

Backup

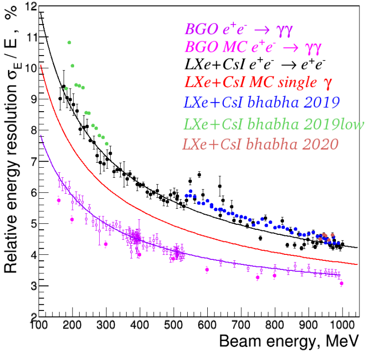
Bhabha

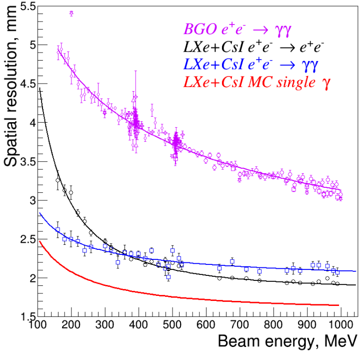
1. $E_{bgo} = 0 MeV$
2. $E_{lxe} > 10 MeV$
3. $E_{csi}/E_{lxe} < 0.5$
4. $TrackE < ebeam$
5. $|p - ebeam| > 2\sqrt{2} ebeam \cdot (0.0075 + 3.5 \cdot 10^{-5} ebeam)$
6. $|\theta_1 - \theta_2 - \pi| < 0.07$
7. $||\phi_1 - \phi_2| - \pi| < 0.07$
8. $|\theta - \pi/2| < 0.75$
9. $TrackZ < 10cm$



Backup

Calorimeter resolution

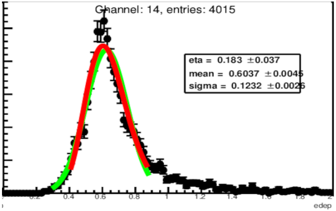




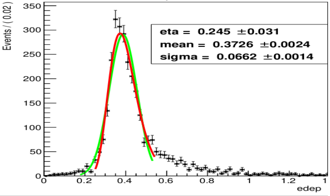
Energy calibration

Examples

CsI channel



LXe channel



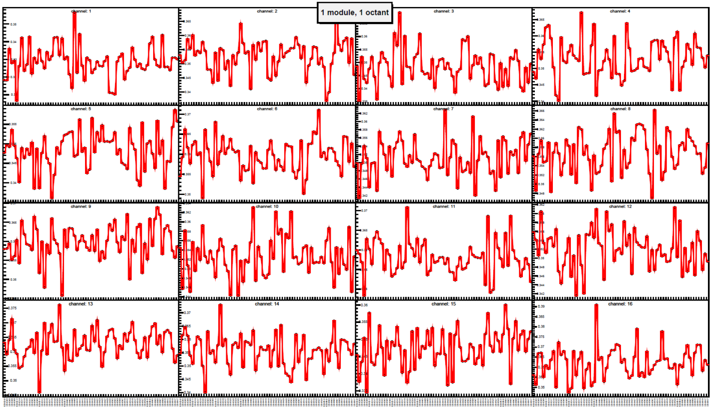
Unbinned fit:

$$f(x;\eta,\varepsilon,\sigma) = \frac{\eta}{\sqrt{2\pi}\sigma\sigma_0}\exp\left(-\frac{ln^2(1+\frac{\eta(x-\varepsilon)}{\sigma})}{2\sigma_0^2} - \frac{\sigma_0^2}{2}\right),$$

$$\sigma_0(\eta) = \frac{2}{\xi}\log\left(\frac{\xi\eta}{2} + \sqrt{1+(\frac{\xi\eta}{2})^2}\right), \xi = 2\sqrt{2\ln(2)}$$

Energy calibration

CsI stability



Energy calibration

LXe stability