

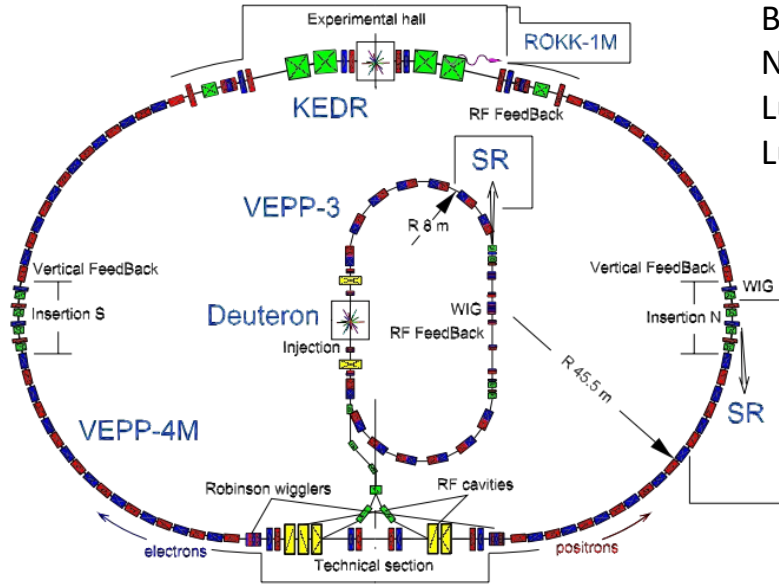
The energy resolution of the KEDR Liquid Krypton Electromagnetic Calorimeter

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With participation of institutes: *Budker INP, IHEP Protvino,
INFN Milano, INFN Pavia, INFN Bologna and BNL Upton NY*

VEPP-4M e+e- collider and KEDR (in operation since 2004...)



Beam energy	1 – 5 GeV
Number of bunches	2 x 2
Luminosity at 1.5 GeV	$2 \cdot 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$
Luminosity at 5.0 GeV	$2 \cdot 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$

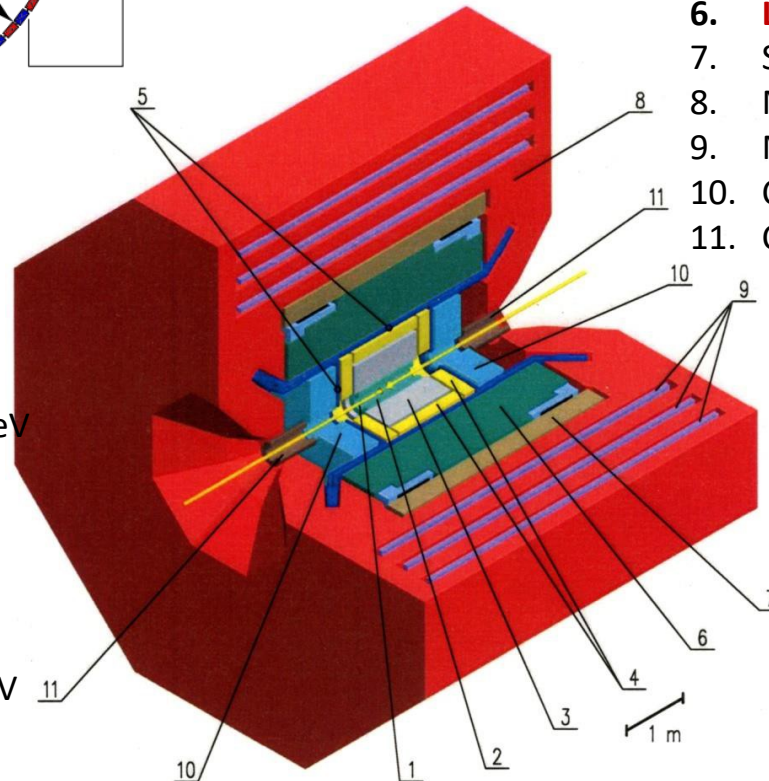
1. Vacuum chamber
2. Vertex detector
3. Drift chamber
4. Aerogel counters
5. ToF counters
6. **Liquid krypton calorimeter**
7. Superconducting coil
8. Magnet yoke
9. Muon tubes
10. CsI Calorimeter
11. Compensating s/c solenoid

Wide Physics Program:

- High precision measurement of particle masses; J/ψ and Υ -families, D-mesons, τ -lepton
- Rare J/ψ decays
- R- measurements in the region $2E=2-7 \text{ GeV}$
- Two photon physics

Beam energy measurement:

- Resonant depolarization method
- Instant measurement accuracy 1-3 keV
- Energy interpolation accuracy 10-30 keV



Introduction (why LKr was chosen?)

Liquid Ar and Xe were widely used for calorimetry in particle physics

Some examples: ATLAS (LAr), MEG and CMD-3 (Lxe)

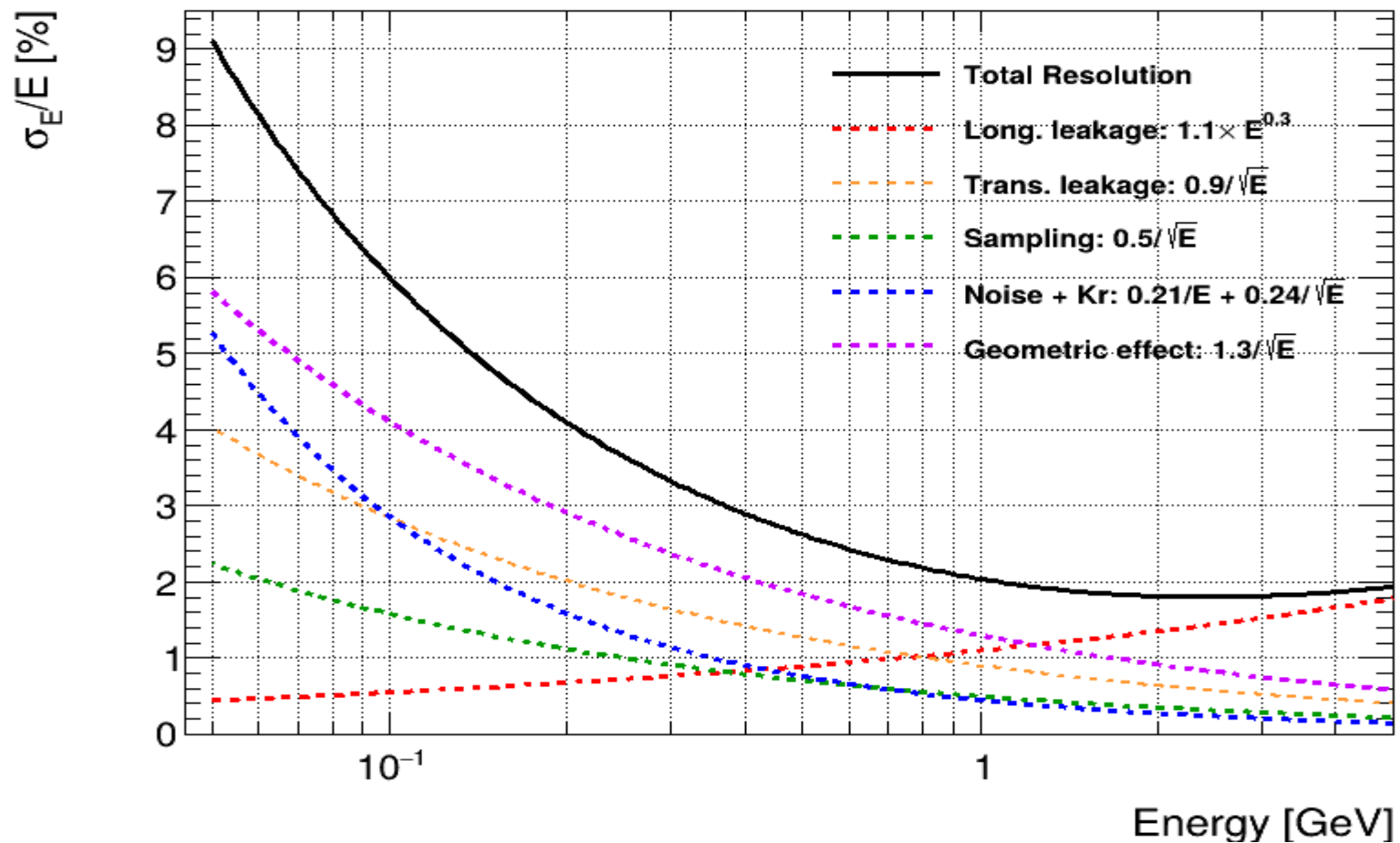
- Ease of calibration (no intrinsic amplification, uniformity)
- Stability
- High level of segmentation
- Radiation hardness

	Ar	Kr	Xe
T boiling, K	87.1	119.6	164.9
T smelting, K	83.6	115.8	161.9
ρ liquid/ ρ gas	784	641	519
V_{dr} , mm/ μ s at 1 kV/cm	1.8	2.4	2.2
W, eV/pair	24.4	18.3	15.6
dE/dx, MeV/cm	2.3	3.4	3.9

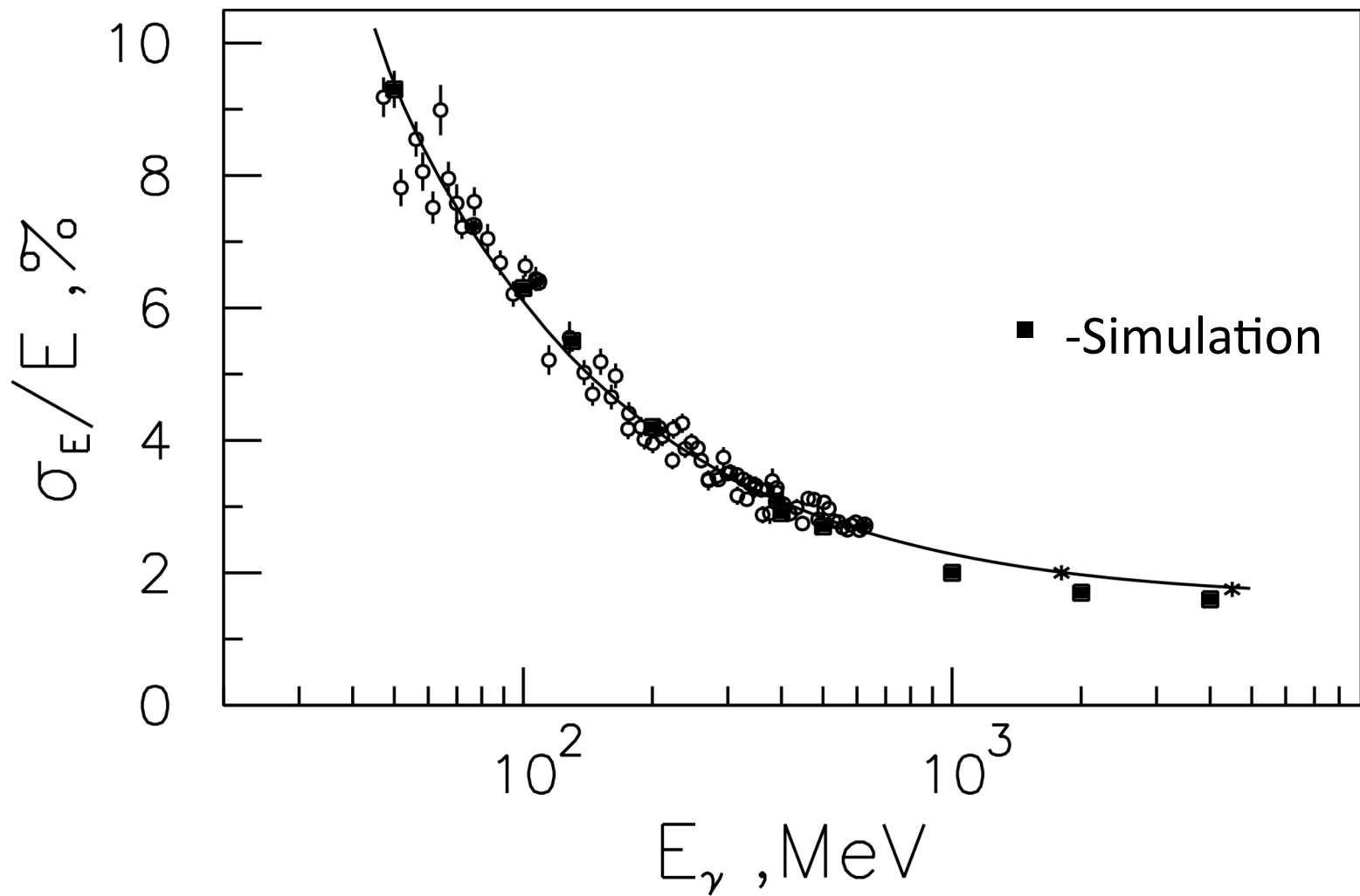
Natural krypton contains β -radioactive isotope ^{85}Kr with the spectrum edge energy of 0.67 MeV. For this reason, **liquid krypton was never considered unsuitable for calorimetry!**

Experiments with prototypes based on liquid krypton (0.5 tons) at the Budker INP (Novosibirsk) in 1990s, showed that the energy resolution can be comparable to that of crystal calorimeters. **Krypton is much more accessible and significantly cheaper (by 10 times) than xenon and CsI crystal**

As a result of the experiments with the prototypes, the LKr calorimeter for the KEDR experiment was designed and built and LKr was used in some other projects....



Contributions to the energy resolution of the LKr calorimeter



The energy resolution of the LKr calorimeter prototype (0.5 tons)

KEDR Liquid Krypton Calorimeter (quasi-homogeneous)

Main parameters:

$$V_{\text{LKr}} = 11 \text{ m}^3$$

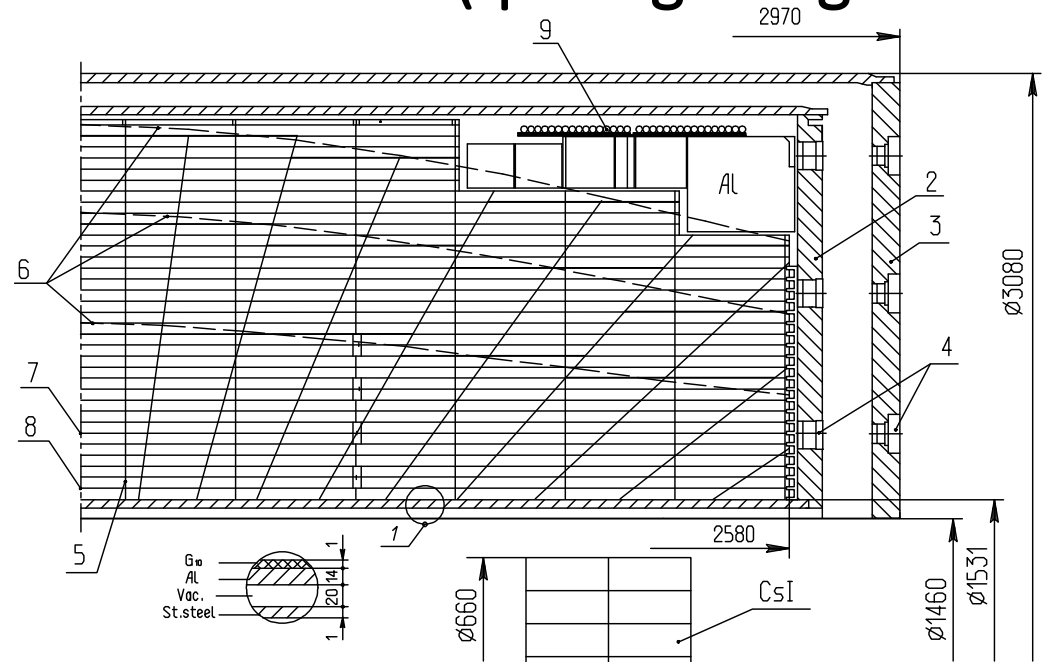
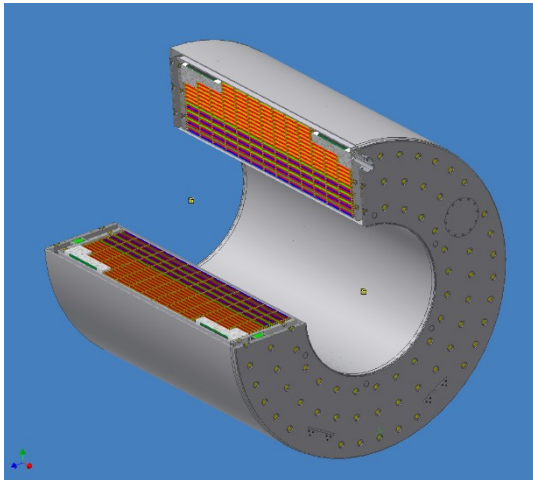
$$M_{\text{LKr}} = 27 \text{ tons}$$

$$\text{Calorimeter thickness} = 14.8 X_0$$

$$\text{Entrance wall thickness} = 0.22 X_0$$

$$\text{Electrodes number: } 35$$

$$\text{Electrodes total thickness} = 0.33 X_0$$



Inner $\varnothing$ of electrode system: 1533 mm

Outer $\varnothing$ of electrode system : 2894 mm

Length of electrode system : 2600 mm

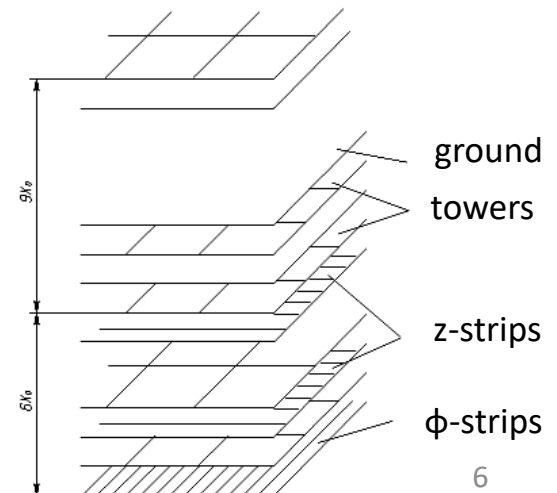
Anode-cathode gap: 19.46 mm

Electrode thickness: 0.54 mm of G10

Working HV: 1 kV

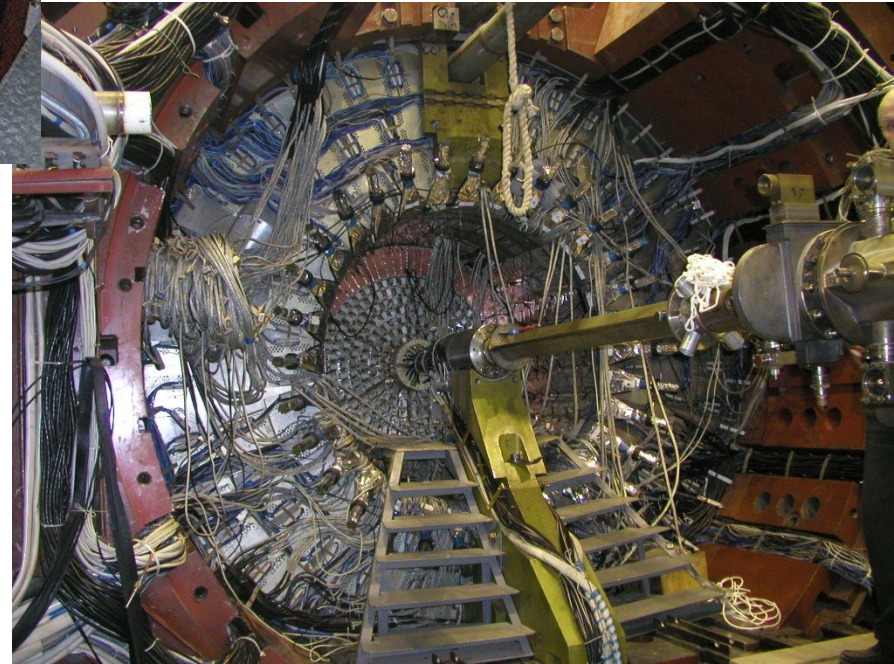
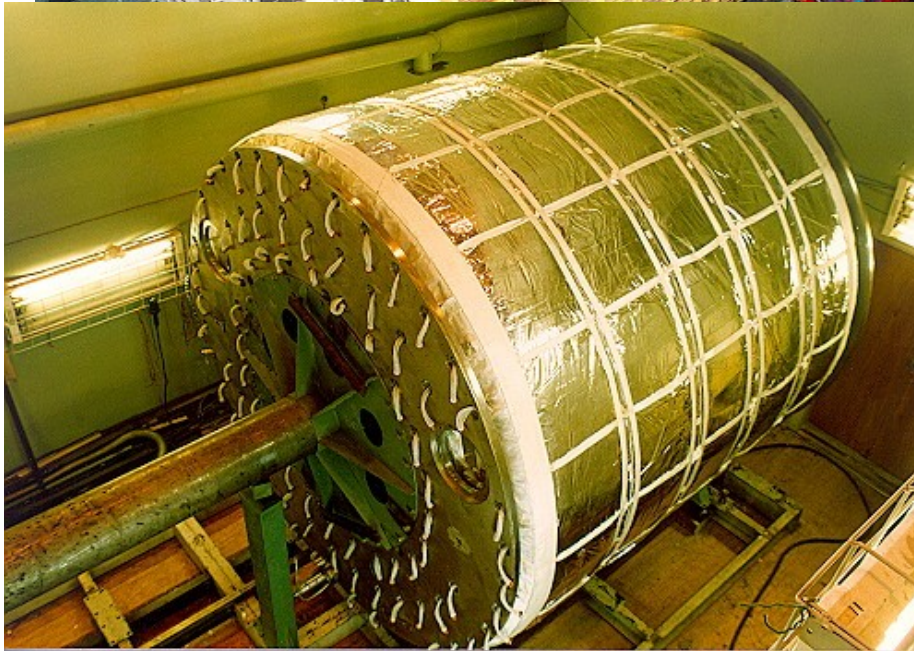
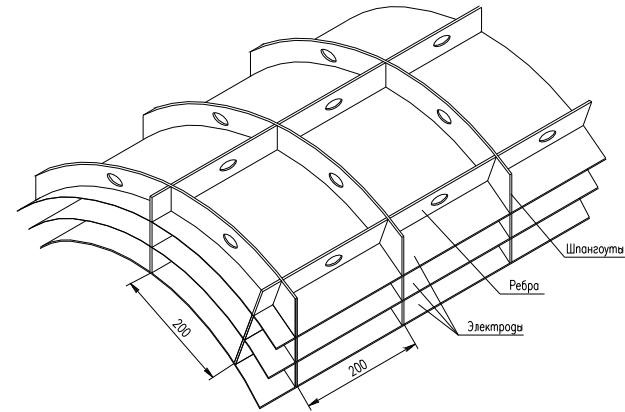
Number of towers: 2304

Number of strips: 4936



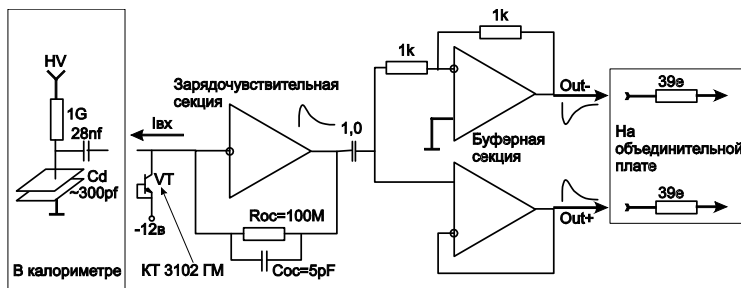
The electrode system has three layers of towers in the radius, the grounded electrodes of the first layers are divided into strips (4 strip layers for ϕ angle measurement and 4 for Θ).

Liquid Krypton Calorimeter assembly



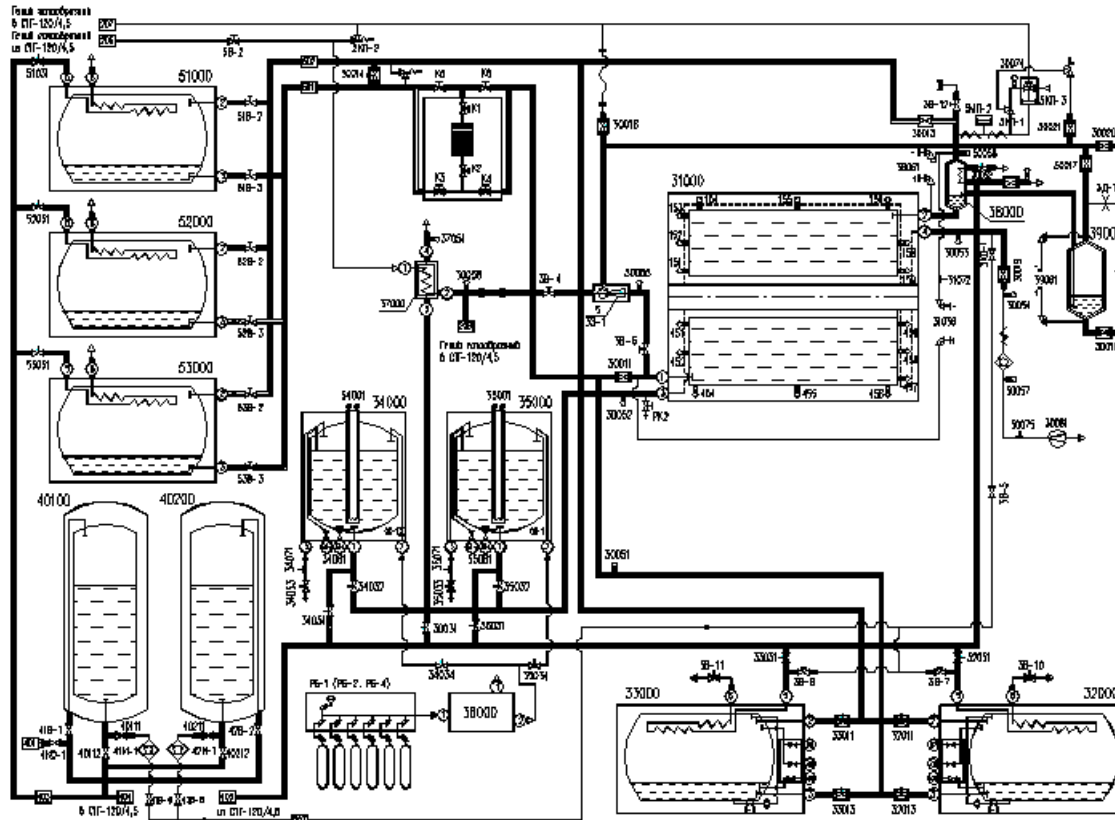
- Charge sensitive preamplifier based on FET NJ1800D (designed by V.Radeka and P.Manfredy)
- RC-2CR pulse shaper ($\tau = 1.5 \mu\text{s}$ for towers, $\tau = 5.2 \mu\text{s}$ for strips)
- Peak ADC (12-bit)

Preamplifier



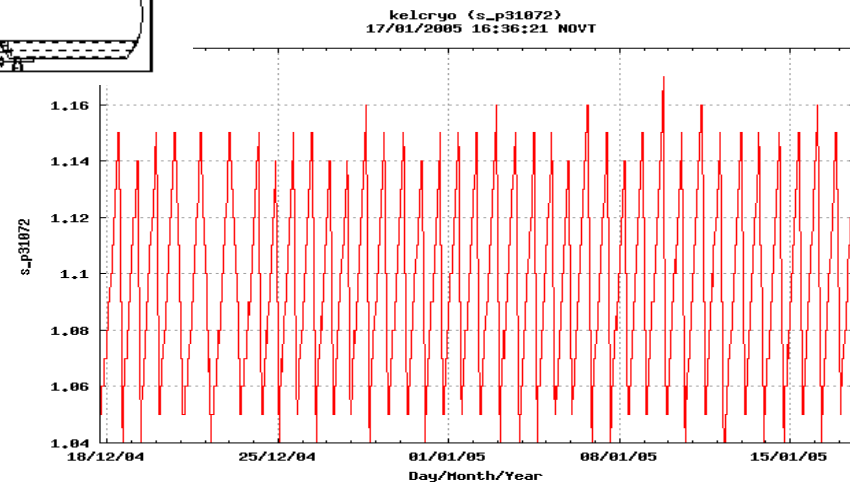
The diagram shows a two-stage amplifier circuit. The first stage is an inverting amplifier with a transformer-coupled input. The input signal is connected to the primary of a transformer. The secondary of the transformer is connected to a 1n8 capacitor, which is in series with a 27k resistor. The output of this stage is connected to the input of the second stage, which is a non-inverting amplifier. The second stage has a 750pF capacitor in series with its input, followed by a 2.14k resistor connected to ground. The output of the second stage is connected to a 1.5V supply and a 5k1 resistor. The circuit is powered by a 1.5V supply.

Cryogenic system



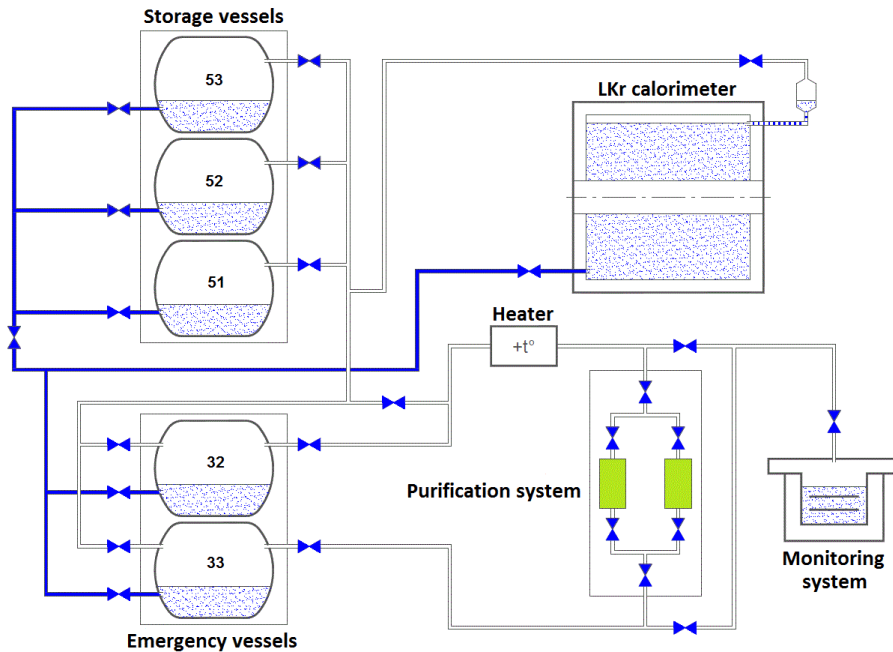
Once a day, the calorimeter is cooled with liquid nitrogen. The range of the pressure variation in the calorimeter is about 0.1 atm, which corresponds to a 1 K change in the temperature of liquid krypton.

$$\frac{1}{T} \frac{dA_{\text{mip}}}{dT} = -1.3 \pm 0.2 \% / \text{K}; \quad \frac{1}{T} \frac{dA_{\gamma}}{dT} = -0.40 \pm 0.05 \% / \text{K};$$

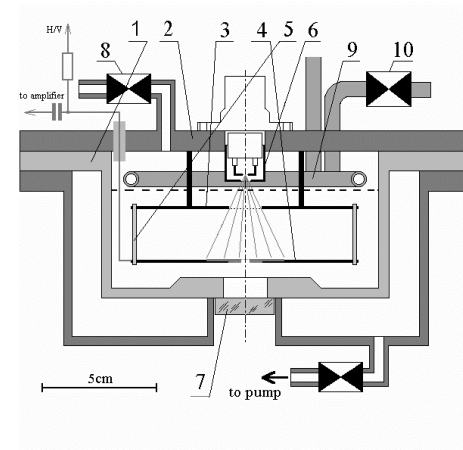


Krypton Purification

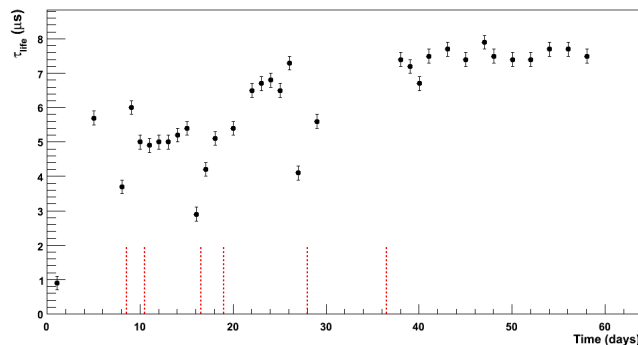
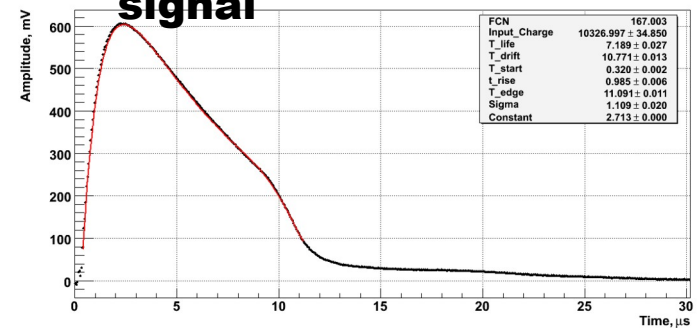
The UTOA-40/A industrial purifier with two large cartridges is used for krypton purification. The purification system could only operate with gaseous krypton at room temperature.



Purity monitor

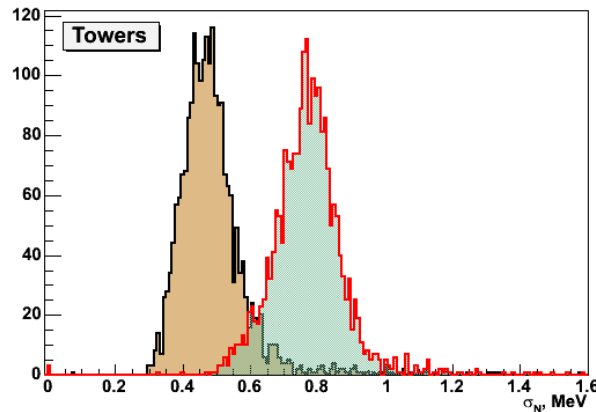


Purity monitor signal

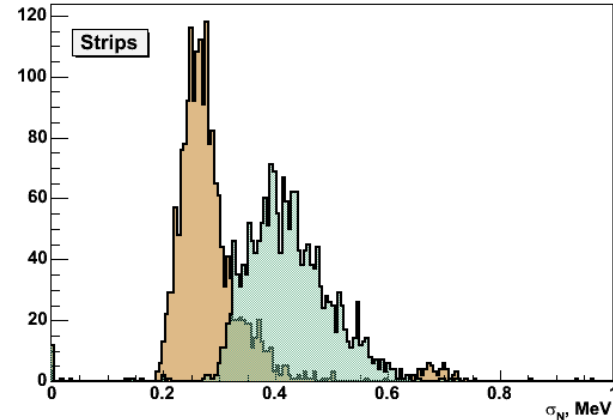


Electronics Noise and Radioactivity

Distributions of measured noise in the calorimeter electronics channels.
Transparent histograms — HV on; solid histograms — HV off.

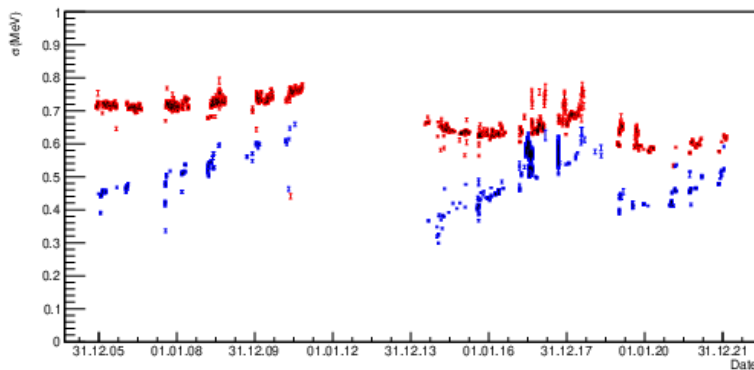


N = 0.5 MeV; N+R = 0.8 MeV; R = 0.6 MeV

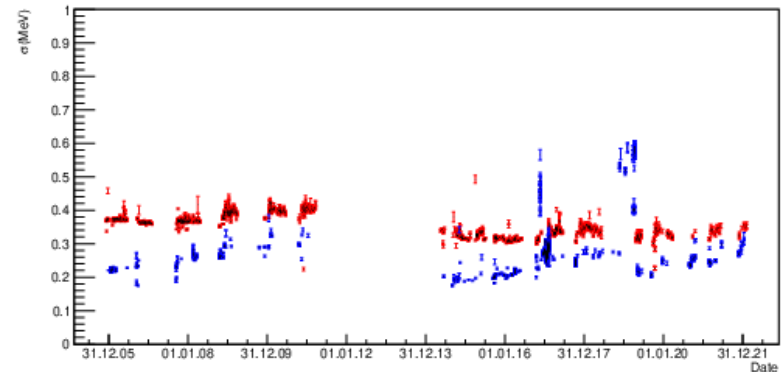


N = 0.3 MeV; N+R = 0.4 MeV; R = 0.3 MeV

Time dependence of the mean noise in the calorimeter electronics.
Red points — total noise. Blue points — intrinsic electronics noise.



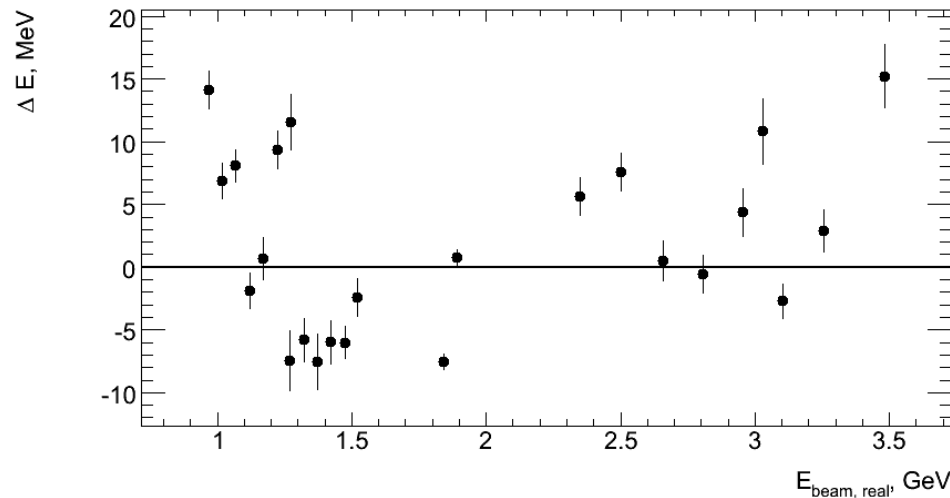
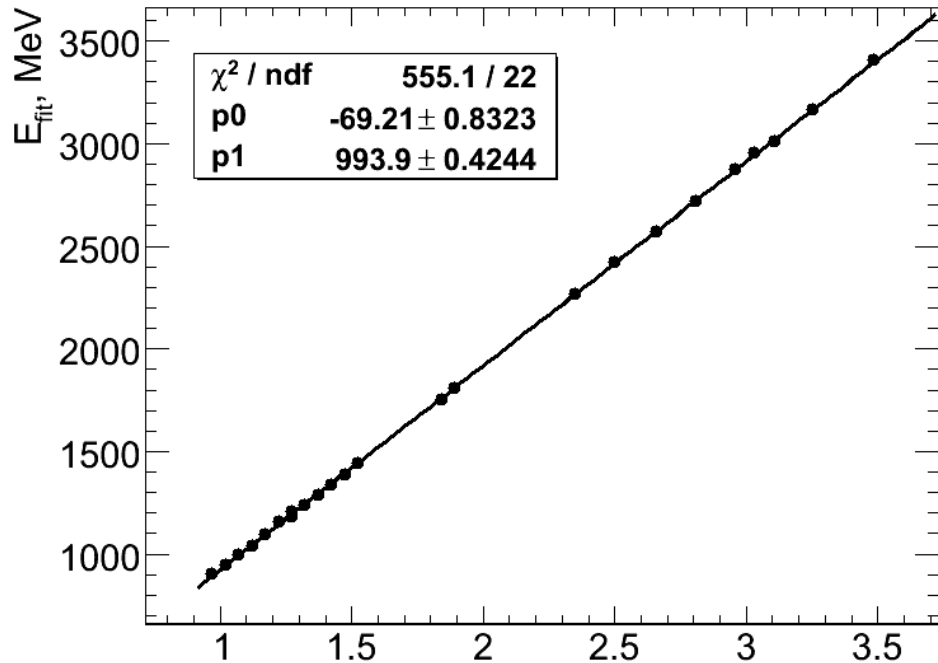
Towers



Strips

Good agreement with design!

Linearity and Long-term stability



KEDR has performed a series of experiments in 2015-2022 to measure the R value (the ratio of the hadron production cross section to the muon pair production cross section) over a wide energy range from 1.84 GeV to 7.0 GeV.

These experiments provide an opportunity to study the linearity and long-term stability of the calorimeter response over a wide range of cluster energies using electron-positron scattering events.

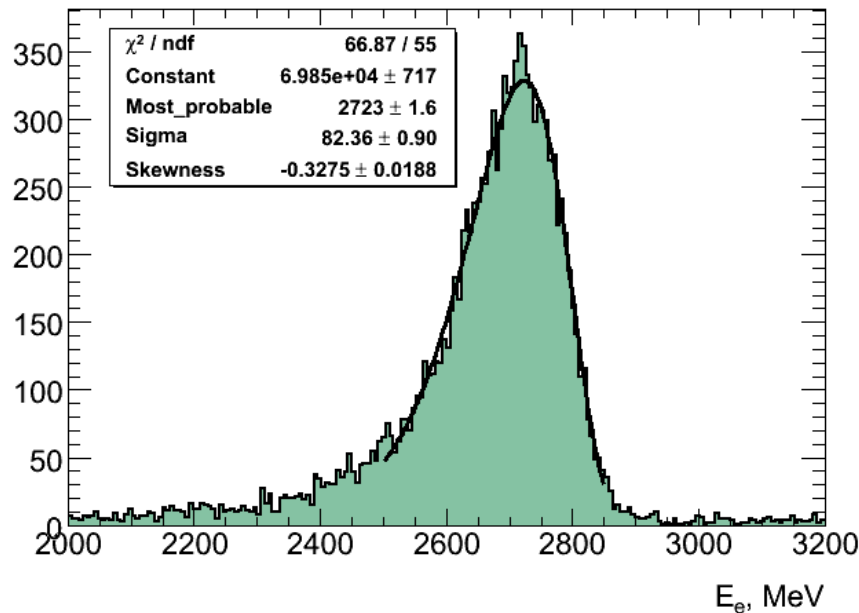
The dependence of the cluster energy in the LKr calorimeter on the beam energy in the collider is shown, as well as the deviation from the linear fit.

Linearity <1%

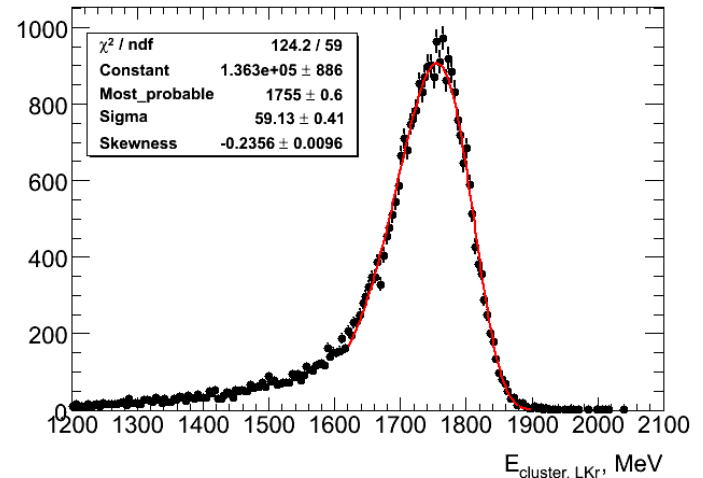
Calorimeter Energy Resolution

The energy resolution for $e^+e^- \rightarrow e^+e^-$ events

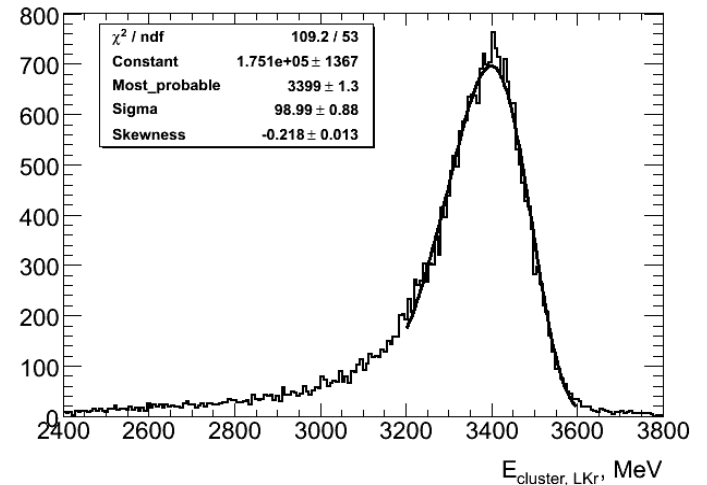
$E_{\text{beam}} = 2.7 \text{ GeV}$ $\sigma E/E = (3.02 \pm 0.03)\%$



$E_{\text{beam}} = 1.75 \text{ GeV}$ $\sigma E/E = (3.36 \pm 0.02)\%$



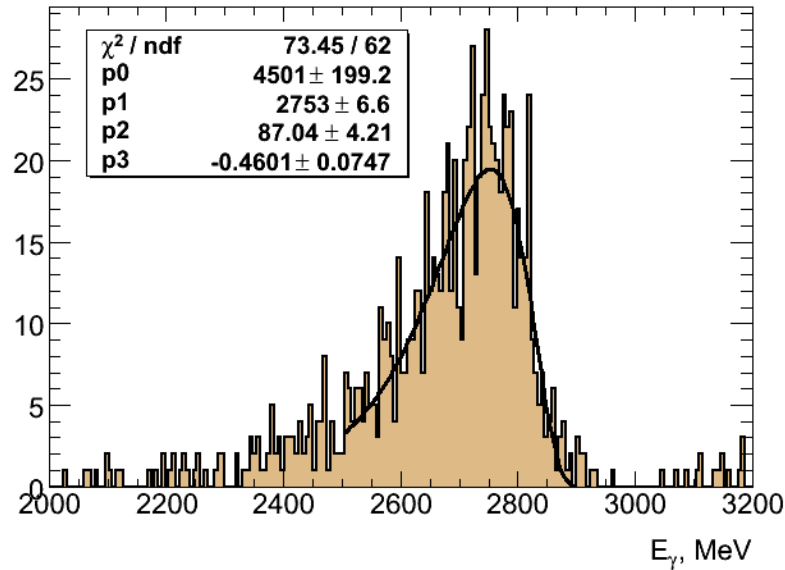
$E_{\text{beam}} = 3.4 \text{ GeV}$ $\sigma E/E = (2.91 \pm 0.03)\%$



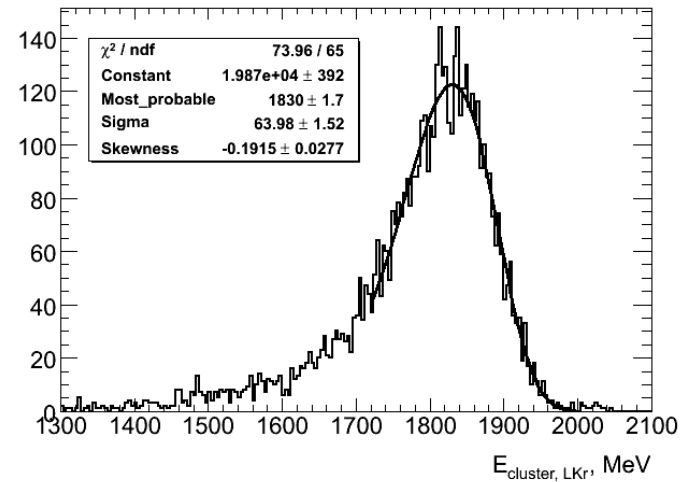
Calorimeter Energy Resolution

The same for photons in $e^+e^- \rightarrow \gamma\gamma$ events.

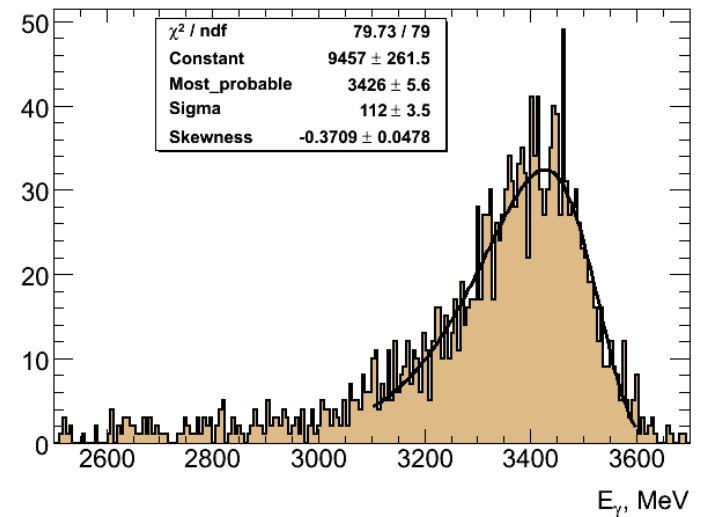
$E_{\text{beam}} = 2.7 \text{ GeV}$ $\sigma E/E = (3.16 \pm 0.15)\%$



$E_{\text{beam}} = 1.8 \text{ GeV}$ $\sigma E/E = (3.50 \pm 0.08)\%$



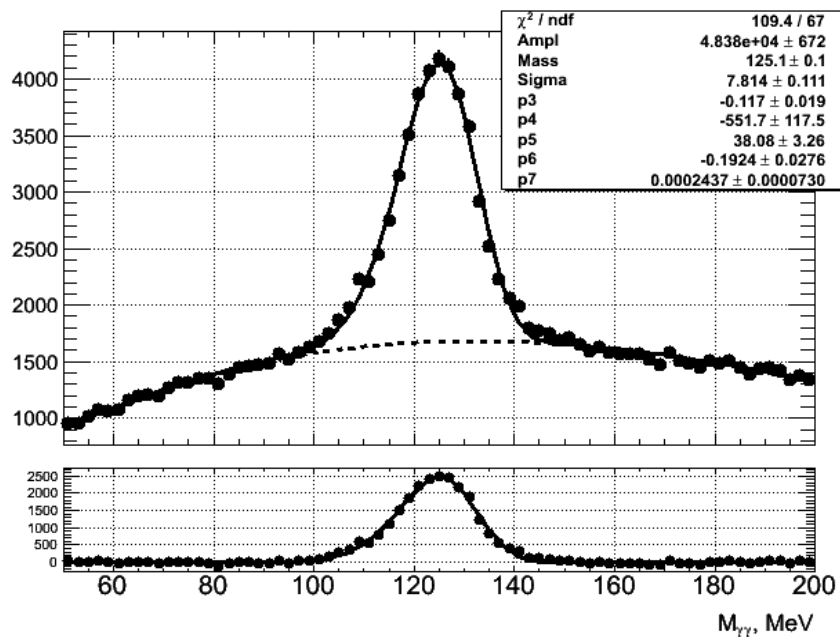
$E_{\text{beam}} = 3.4 \text{ GeV}$ $\sigma E/E = (3.27 \pm 0.10)\%$



Invariant mass of two photons

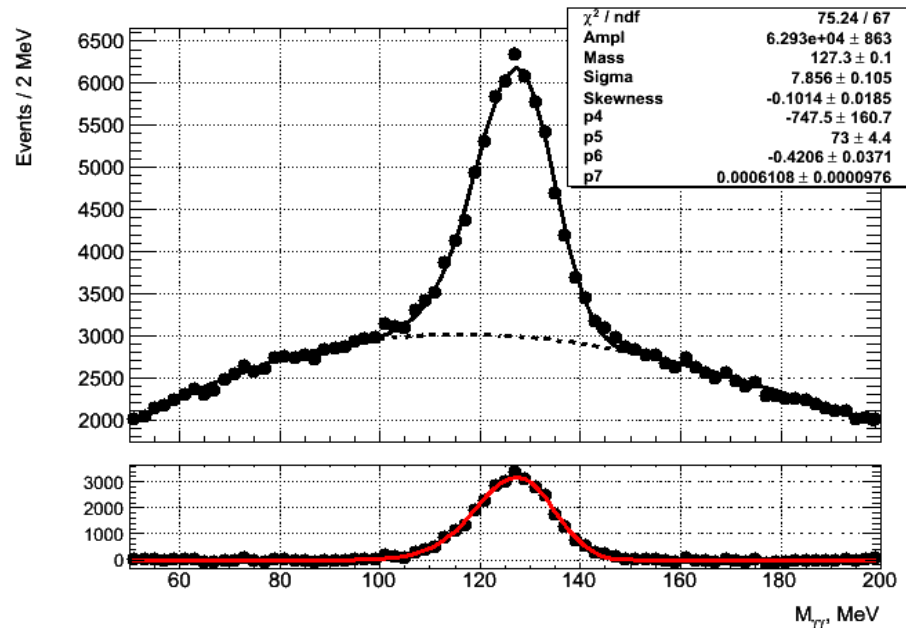
The peak from π^0 decay.

Experimental data at the $\Psi(2S)$ peak.



$$\sigma_M/M = (6.24 \pm 0.09)\%$$

MC

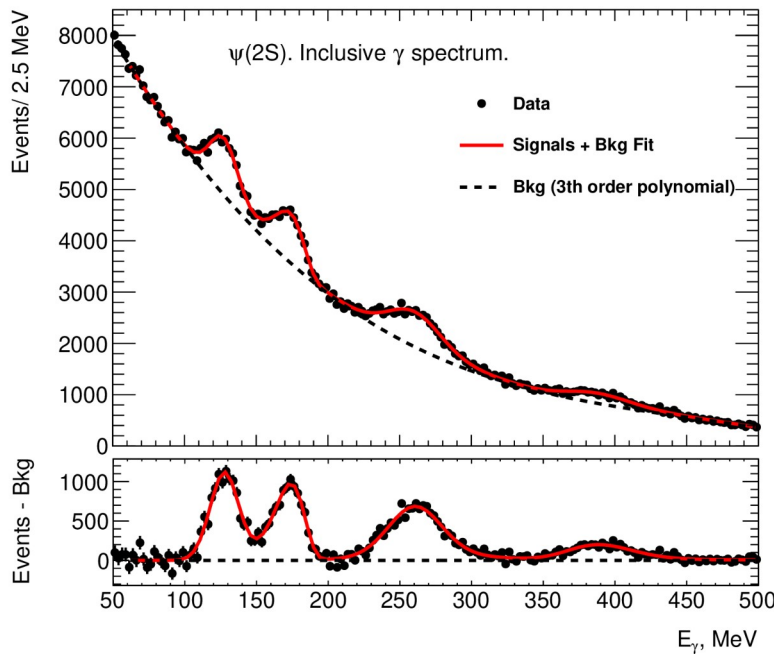


$$\sigma_M/M = (6.17 \pm 0.12)\%$$

Energy Resolution at Low Energies.

Radiative transitions $\Psi' \rightarrow \gamma \chi_{c0,1,2}$

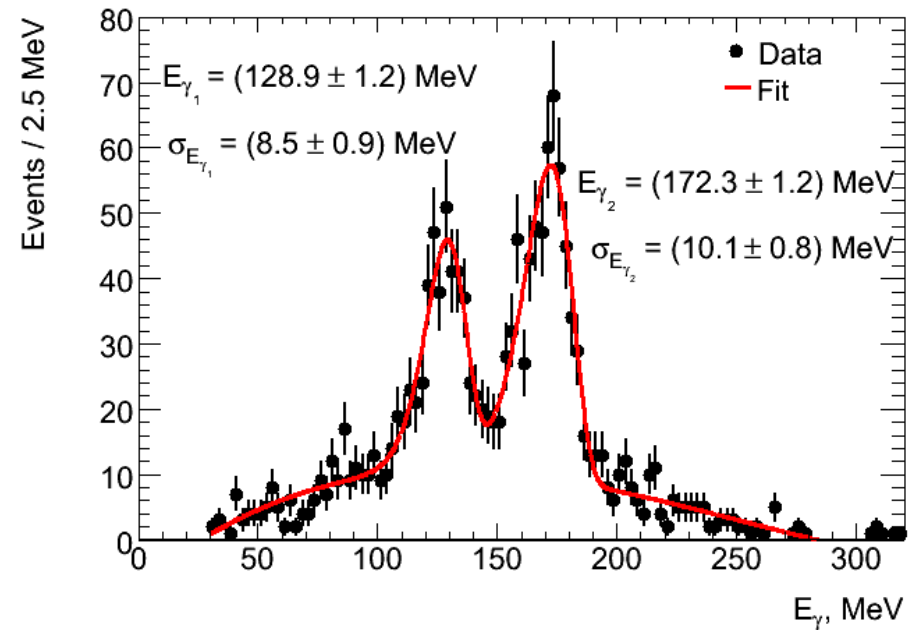
Inclusive photon spectrum. Photons from π^0 decays are excluded. Fit: third-order polynomial + three asymmetric Gaussians + $BW \times \omega^3 \times$ asymmetric Gaussian for $\Psi' \rightarrow \gamma \chi_{c0}$.



E_γ	128 MeV	171 MeV	261 MeV
σ_E/E	$(7.7 \pm 0.4)\%$	$(6.1 \pm 0.3)\%$	$(6.4 \pm 0.3)\%$

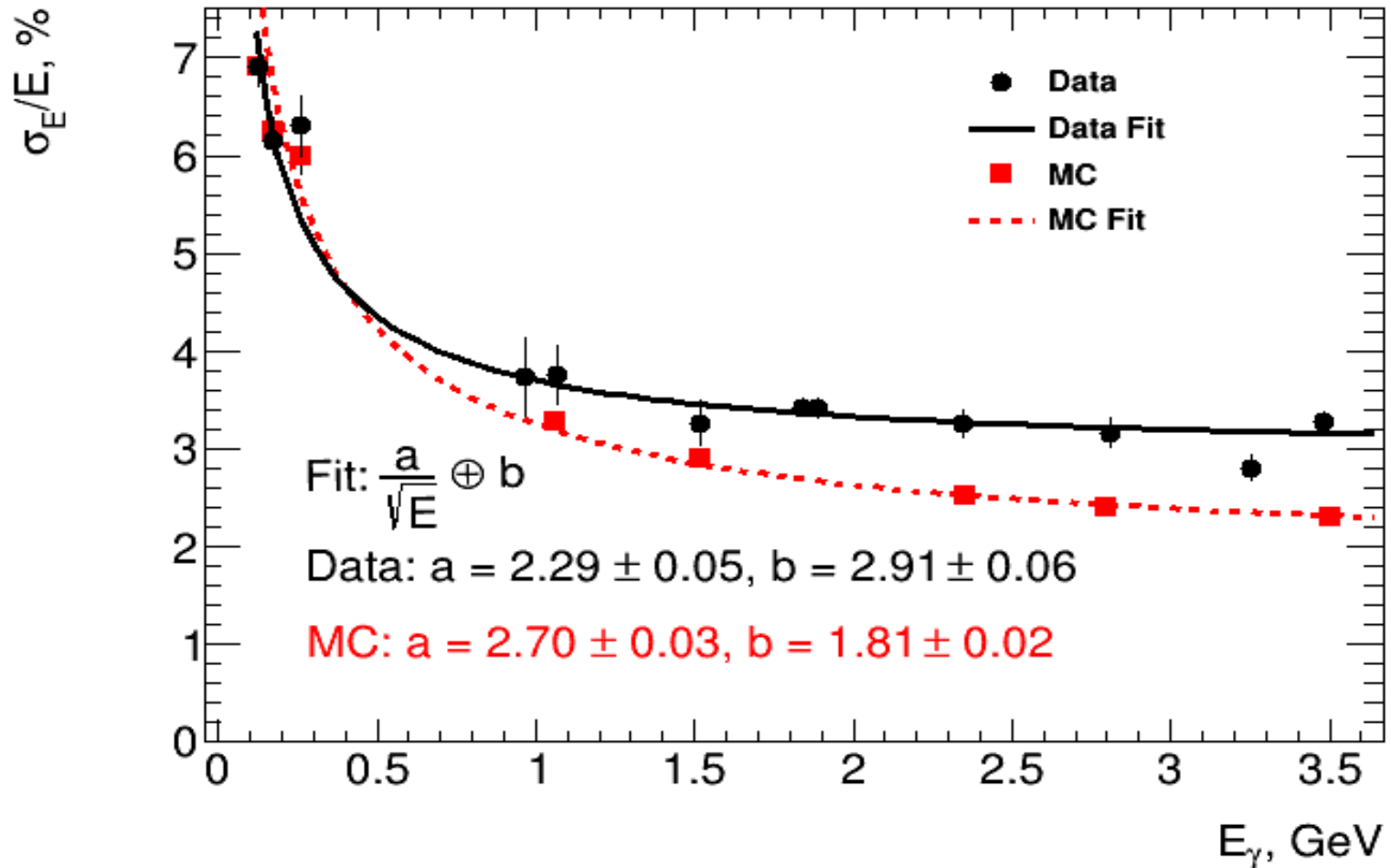
Cascade radiative transitions

$\Psi' \rightarrow \gamma \chi_{c1,2} \rightarrow \gamma \gamma J/\psi \rightarrow \gamma \gamma l^+ l^-$

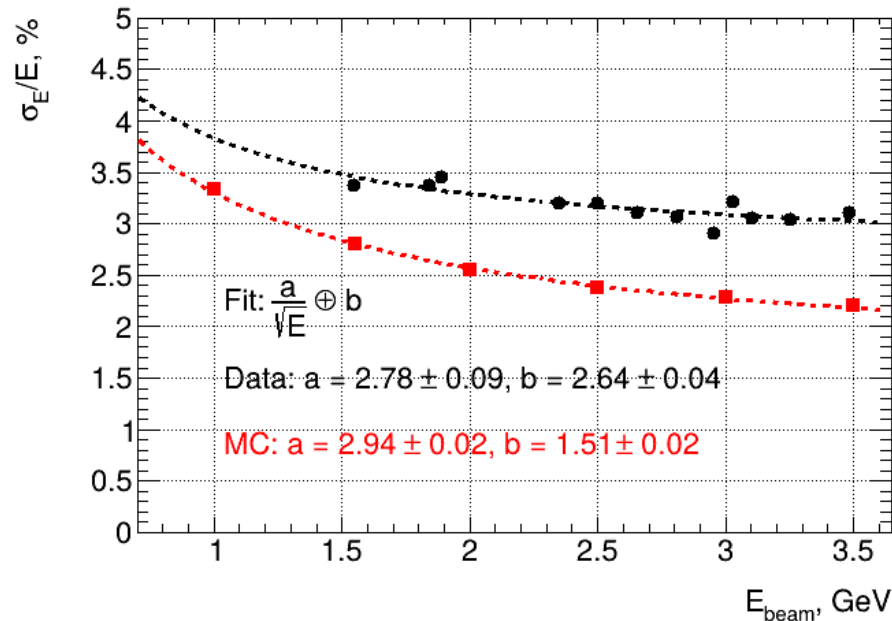


E_γ	128 MeV	171 MeV
σ_E/E	$(6.6 \pm 0.7)\%$	$(5.9 \pm 0.5)\%$

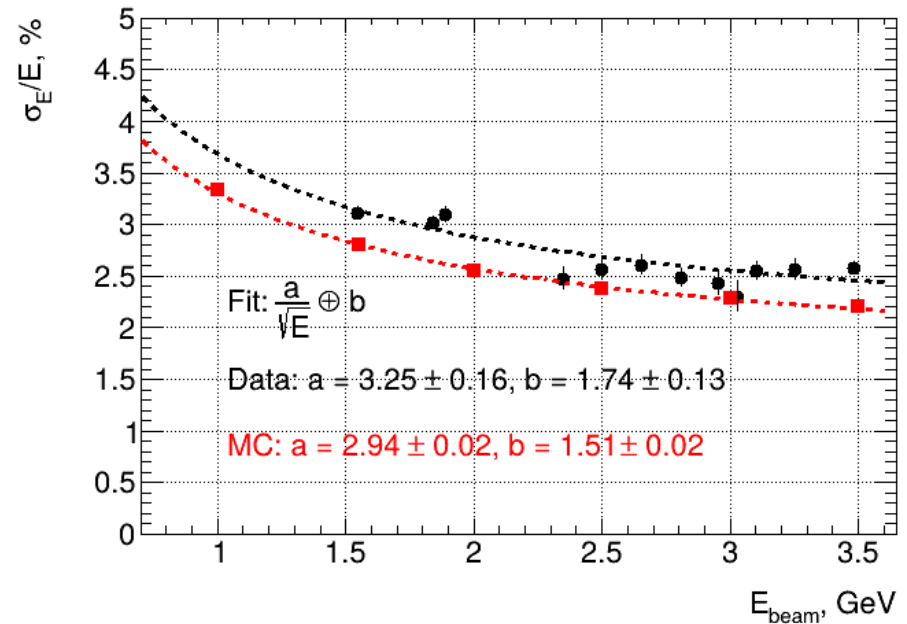
Energy Resolution. Photons



Energy Resolution. Electrons

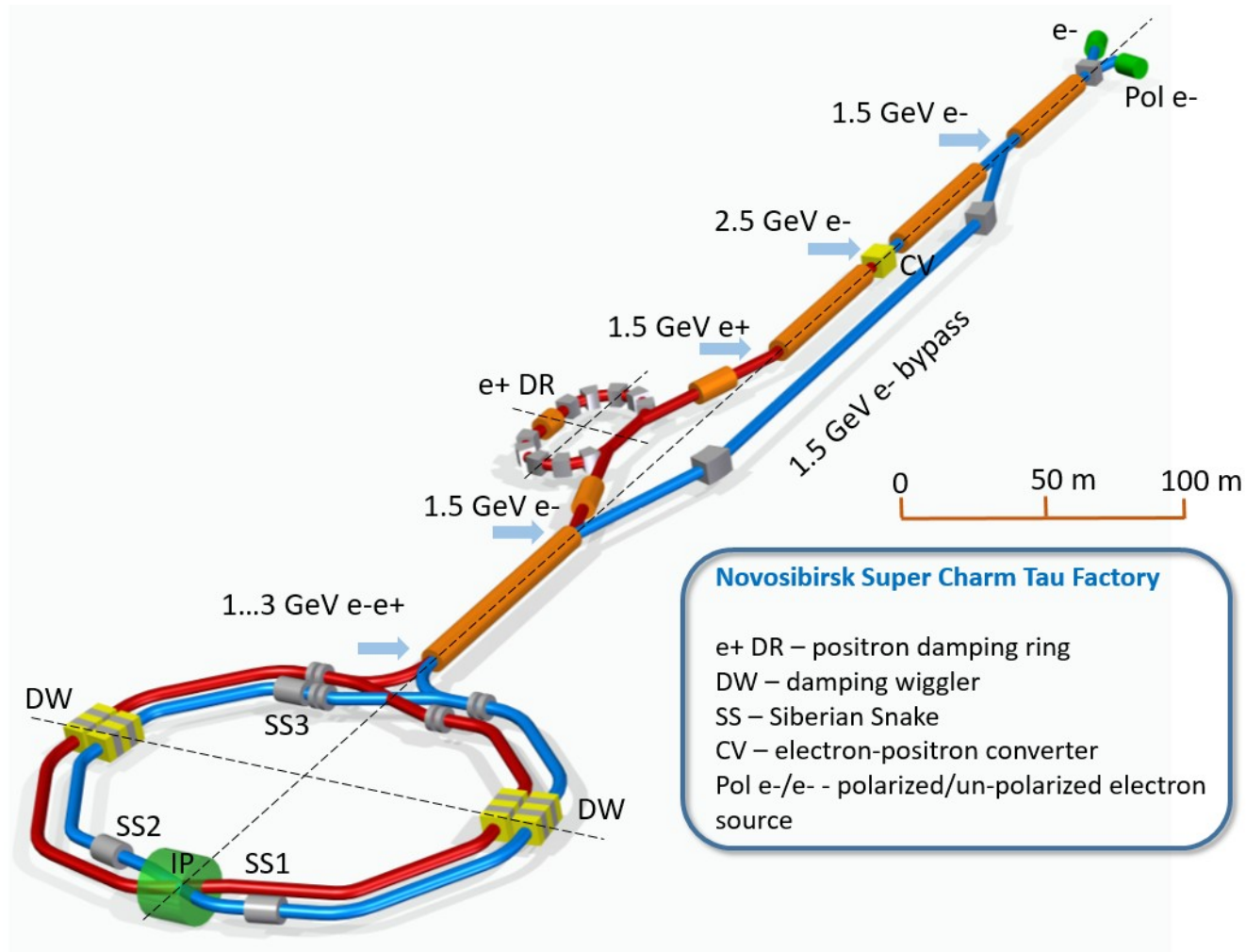


Only the electronics calibration with a pulse generator and normalization to the MIP amplitude are used for cluster reconstruction.

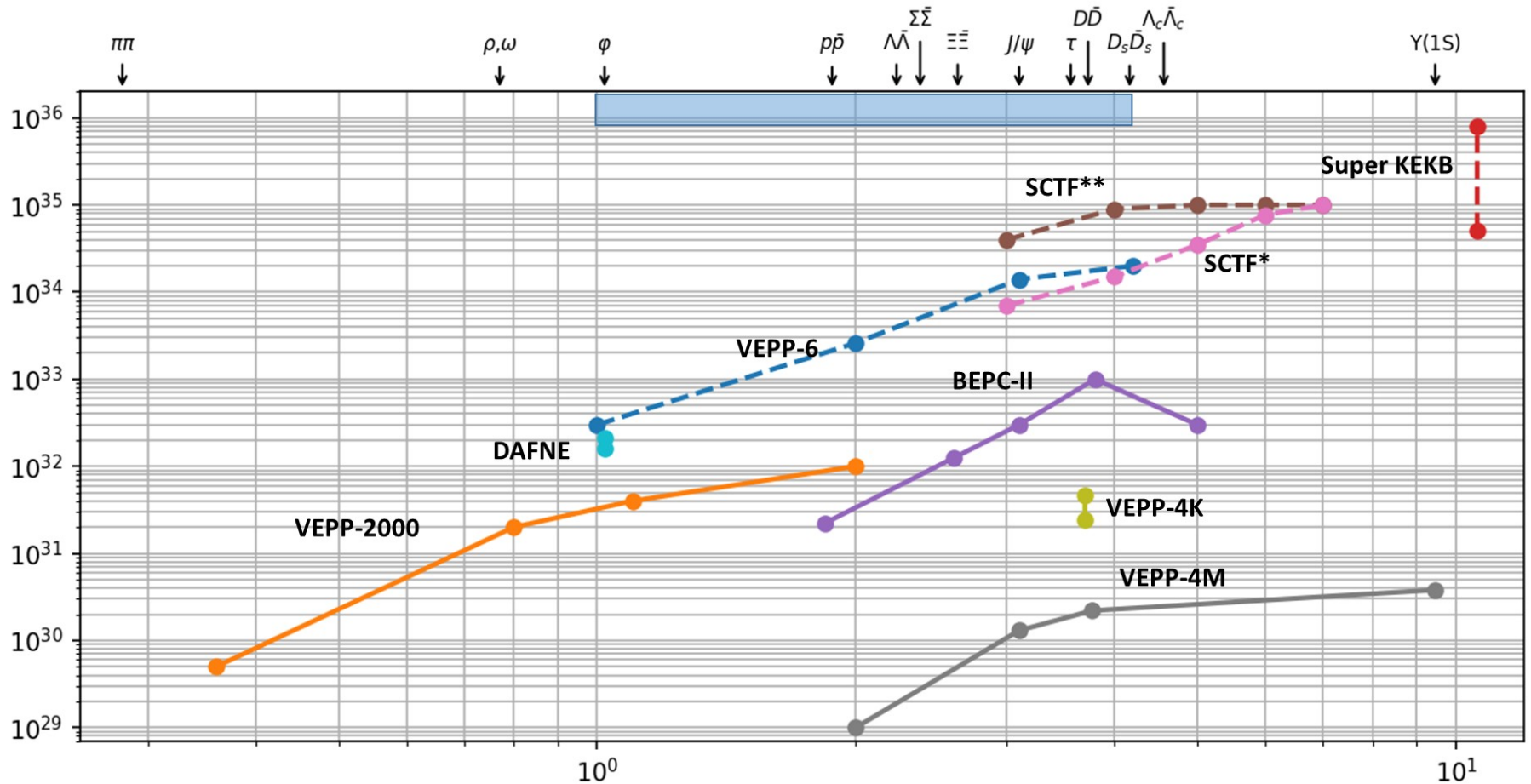


The resolution is evaluated over a limited region of the calorimeter, whose channels are calibrated by the same pulse generator.

The new collider VEPP-6 now under consideration at Budker INP (simplified version of SCTF)



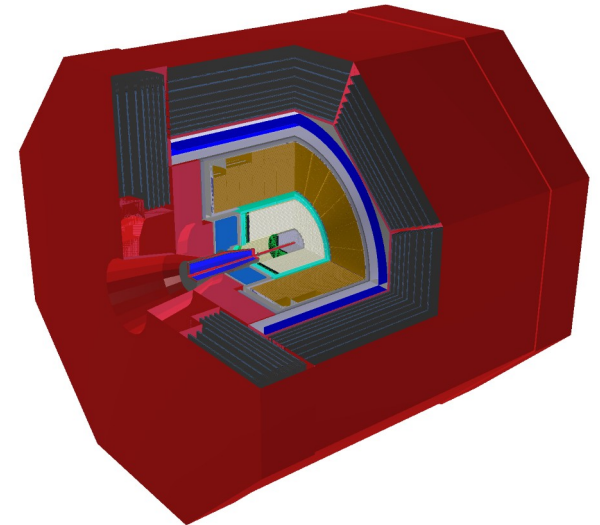
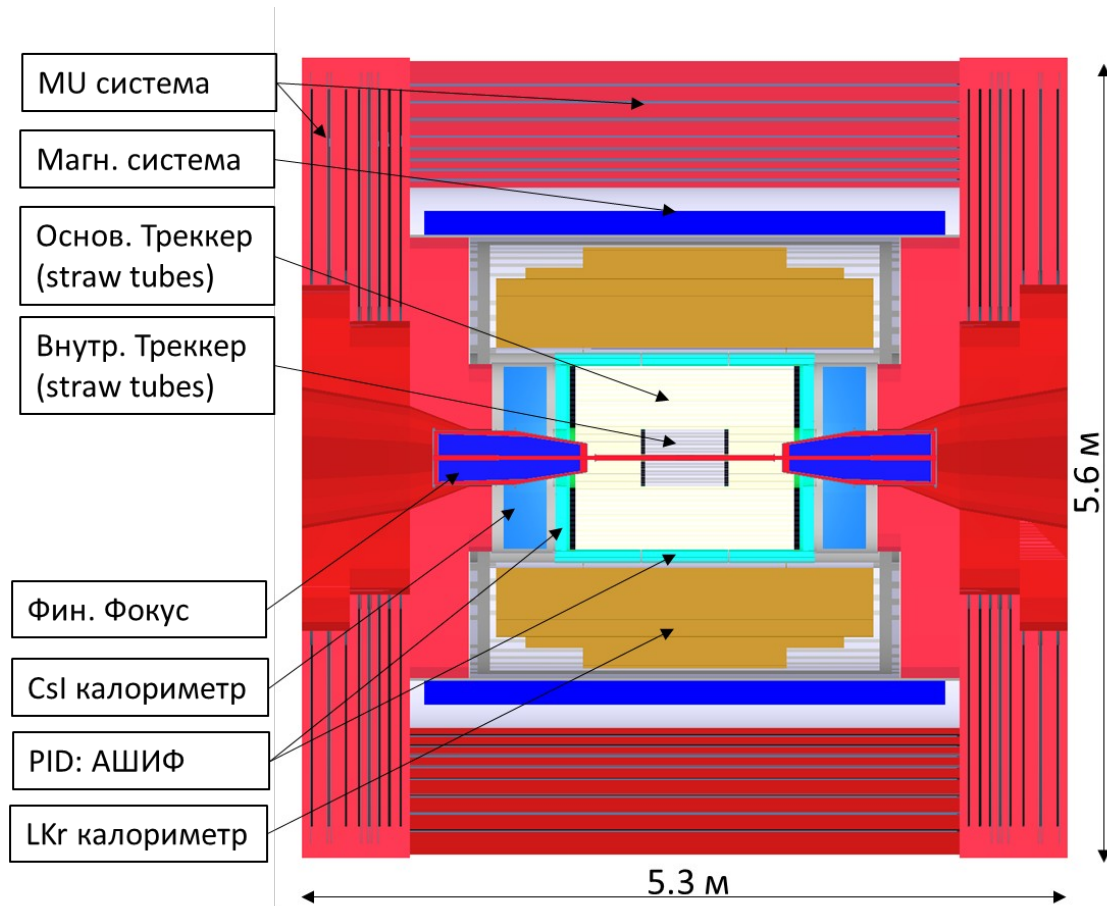
Colliders at a glance



Good synergy with STCF, BEPS-II and VEPP-2000

Detector concept for VEPP-6

New life for LKr calorimeter!

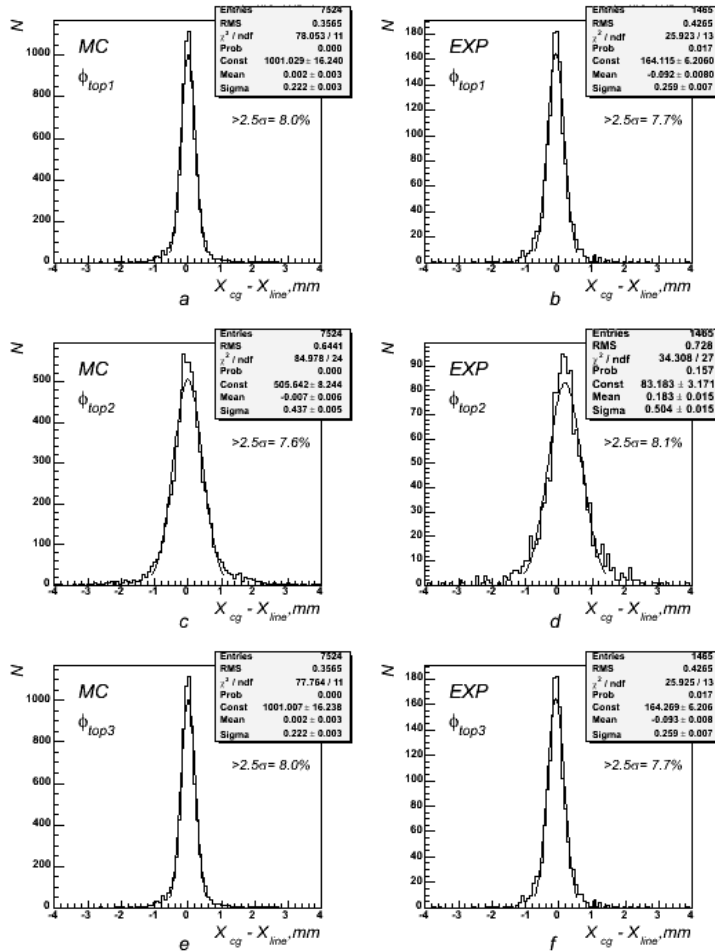


Conclusion

- Stable operation with excellent performance of the KEDR LKr calorimeter during 20 years (good choice!)
- Wide physics program with KEDR detector was realized (LKr calorimeter is the key subsystem!)
- New collider VEPP-6 -> new life for LKr calorimeter

BACK-up slides

Spatial Resolution for MIPs



Spatial resolution for MIPs was measured using data obtained with cosmic-ray events. The distributions of the difference between the cluster coordinates in a coordinate layer and the reconstructed track coordinate are shown for three layers of ϕ -strips.

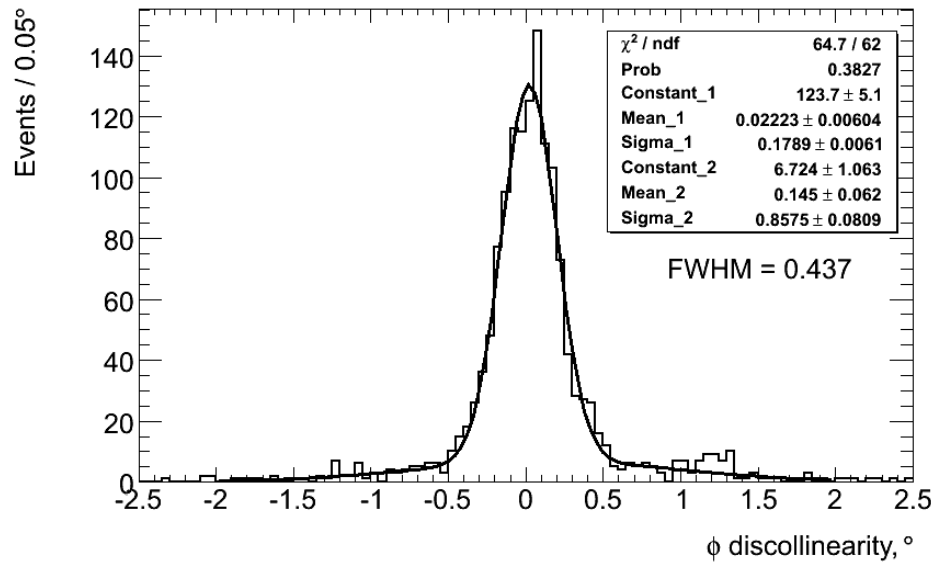
Resolution for the $\phi 2$ layer:

$$\sigma_{MC} = 0.437 \cdot \sqrt{3/2} = 0.535 \text{ mm} \pm 0.015$$

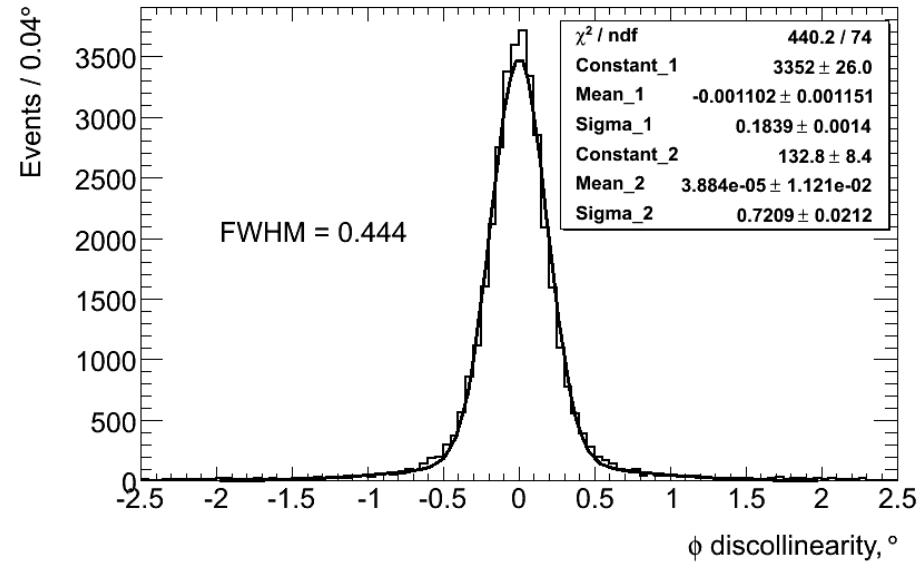
$$\sigma_{exp} = 0.504 \cdot \sqrt{3/2} = 0.618 \text{ mm} \pm 0.019$$

Spatial Resolution for Photons

Distribution of the acollinearity angle of photon clusters in the LKr calorimeter for $e^+e^- \rightarrow \gamma\gamma$ events. Ebeam = 3.5 GeV



Experiment



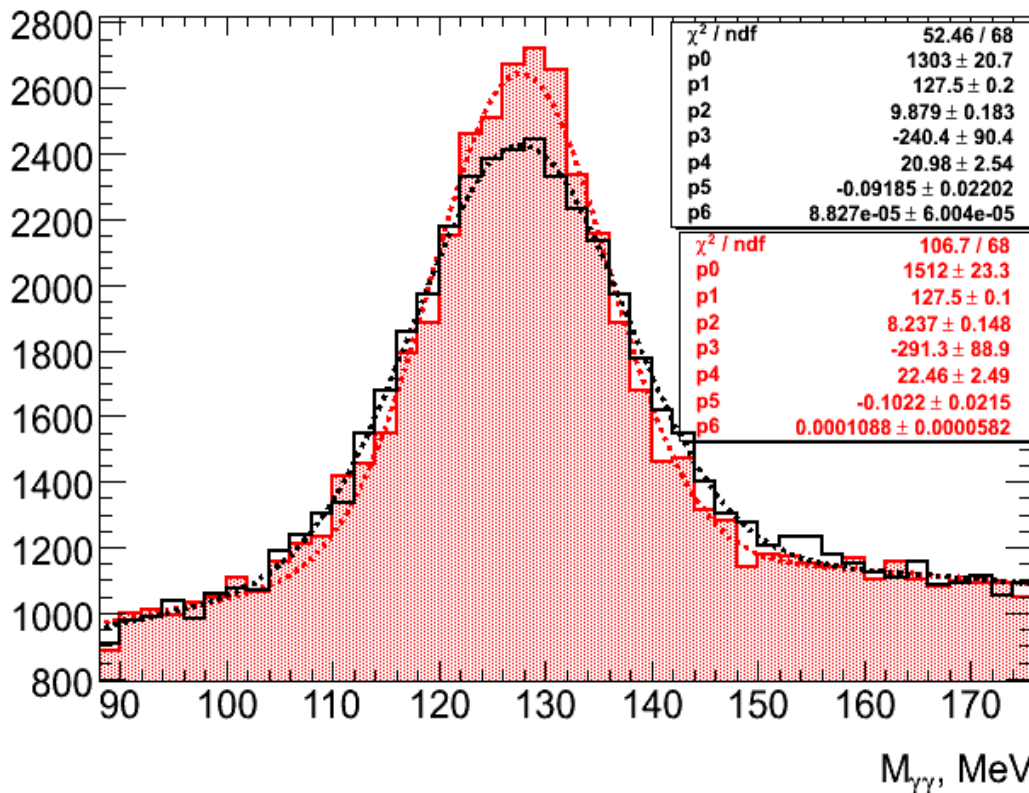
MC

$$\sigma_{\phi} \approx 0.13^{\circ} \Rightarrow \sigma \approx 1.8 \text{ mm}$$

Spatial Resolution for Photons

π^0 mass resolution.

Experimental data collected at the J/ψ peak. The transparent (**black**) histogram shows the invariant mass determined using the photon-cluster coordinate obtained from the towers only. **Red** — the cluster coordinate is determined from the strips.



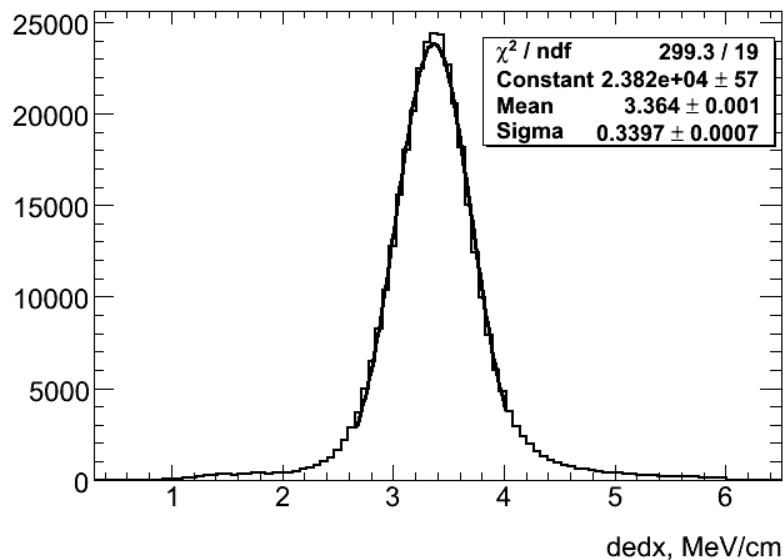
$$\sigma_M/M = (7.75 \pm 0.12)\% \quad \text{Towers}$$

$$\sigma_M/M = (6.46 \pm 0.12)\% \quad \text{Strips}$$

dE/dx Measurement

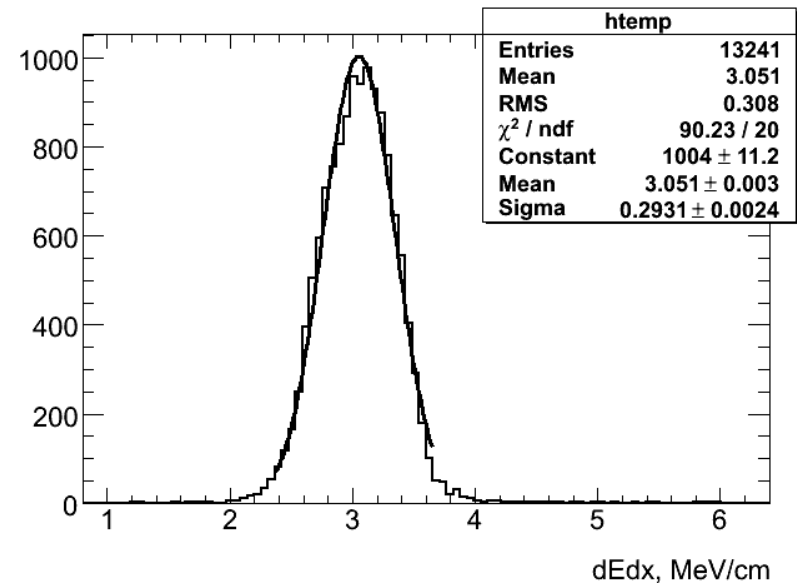
The presence of 8 strip layers in the calorimeter electrode system makes it possible to measure ionization losses for MIPs.

Distribution of the truncated-mean ionization losses of cosmic muons in the strips.



$$\sigma_{\text{dEdx}}/\text{dEdx} = 10.1\%$$

MC



$$\sigma_{\text{dEdx}}/\text{dEdx} = 9.6\%$$

Conclusion

The KEDR liquid krypton calorimeter has been used in experiments for 20 years. During this time, it has proven to be a reliable, stable, unpretentious instrument with good performance.

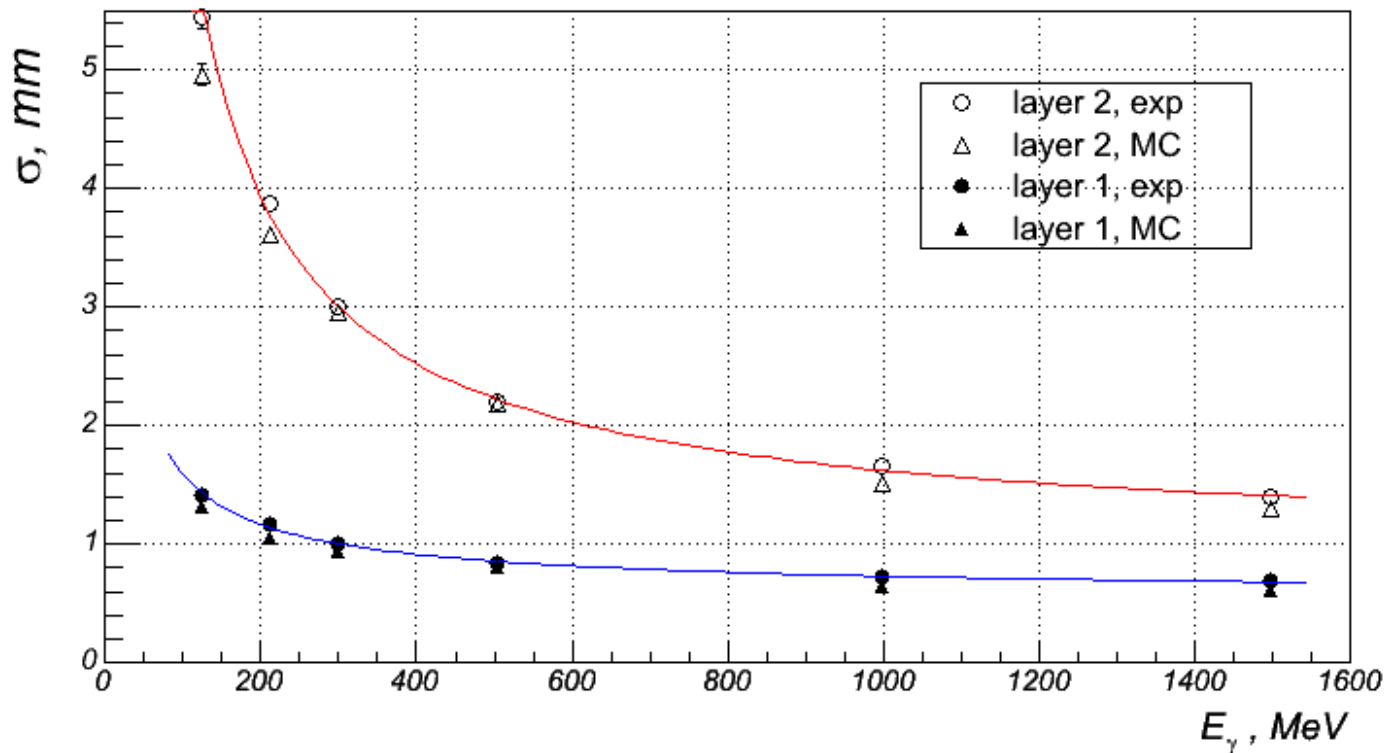
Wide physics program was realized with KEDR detector:

- High precision measurement of particle masses; J/ψ -families, D-mesons, τ -lepton
- Rare J/ψ decays
- R- measurements in the region $2E=2-7$ GeV
- Two photon physics

Particle masses of Υ -families and rare decays **are currently measured with a goal to improve PDG data**

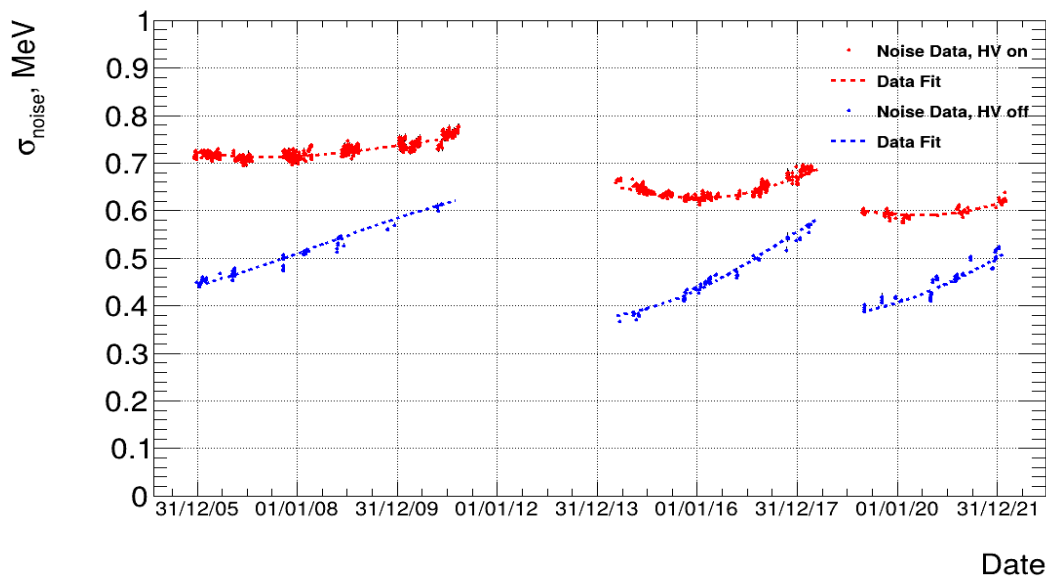
Spatial Resolution for Photons

Photon spatial resolution was measured directly in an experiment with a calorimeter prototype in a tagged-photon beam. The dependence of spatial resolution on photon energy is shown for two strip layers. The first layer is the layer in which the photon conversion occurred. The second layer is the layer immediately following it. The strip width is 1 cm.



Electronics Noise and Radioactivity

Tower channels



Mean noise of a spectrometric electronics channel with HV on (red points) and off (blue points).

Joint fit of the data with analytical functions for electronics noise (blue curve) and radioactivity. The red curve shows their sum in quadrature.

Fixed parameters:

$T_{dr} = 9 \mu s$, $\tau_{rc-2cr} = 1.5 \mu s$, ^{85}Kr activity = 300 Hz/cm³.

Free parameters:

Tower capacitance: C_d [pF]

Tower volume: V_{LKr} [liters]

Electron lifetime: τ_l^i [μs] = $T_{const} + T_0^i \cdot \exp(-t/\tau_d^i)$,
i — time-interval index.

Decay time constant of ^{85}Kr : τ_{85} [months].

Fit result:

$C_d = 341.0 \pm 0.3$ pF; $V_{LKr} = 3.19 \pm 0.02$ l;

$T_{const} = 1.17 \pm 0.01 \mu s$

$\tau_{85} = 240.1 \pm 0.4$ months.

$T_0^1 = 3.70 \pm 0.01 \mu s$; $\tau_d^1 = 31.23 \pm 0.01$ months

$T_0^2 = 13.78 \pm 0.01 \mu s$; $\tau_d^2 = 16.66 \pm 0.02$ months

$T_0^3 = 10.76 \pm 0.07 \mu s$; $\tau_d^3 = 18.17 \pm 0.01$ months

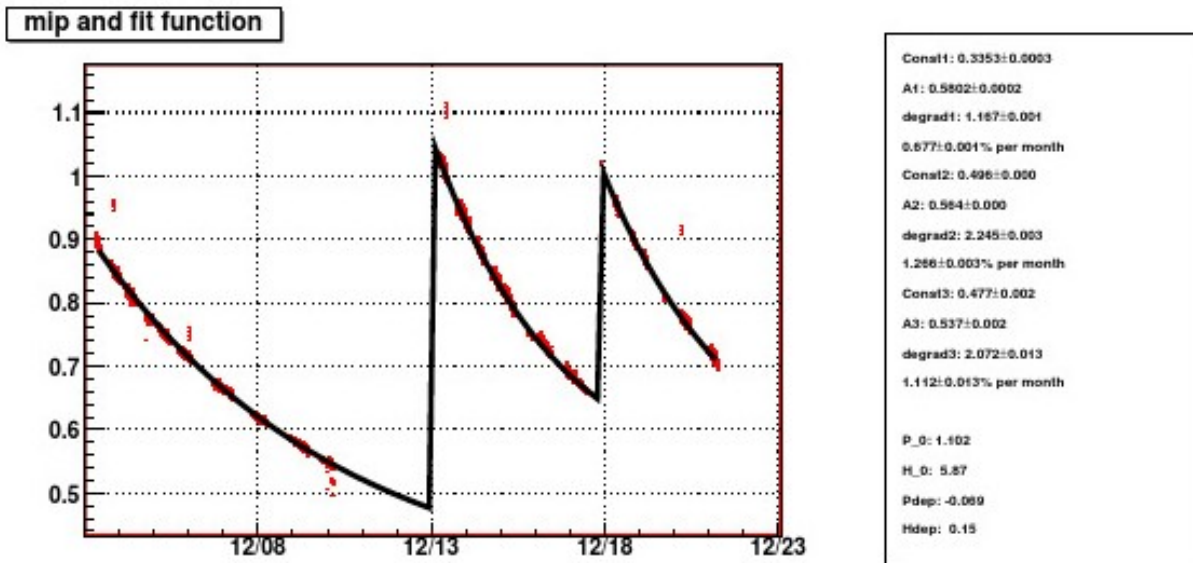
Half-life: $T_{1/2} = \tau_{85} \cdot \ln 2 = 166.4 \pm 0.3$ months =

13.86 $\pm$ 0.03 years

Krypton Purification

The LKr calorimeter does not have a system to permanently purify the krypton from electronegative impurities. Therefore, the signal amplitude in the calorimeter decreases with time. When the amplitude falls below a certain level, the krypton was completely purified during a technical shutdown.

Amplitude of M.I.P. as a function of time (2003 - 2023)



Reconstruction of events in the LKr calorimeter takes this time dependence of the amplitude into account. All signals are normalized to the average amplitude of the minimum ionizing particle.