$K^+ \to \pi^0\mu^+\nu\gamma$ and $K^+ \to \pi^0e^+\nu\gamma$ decays: recent results from the «OKA» experiment

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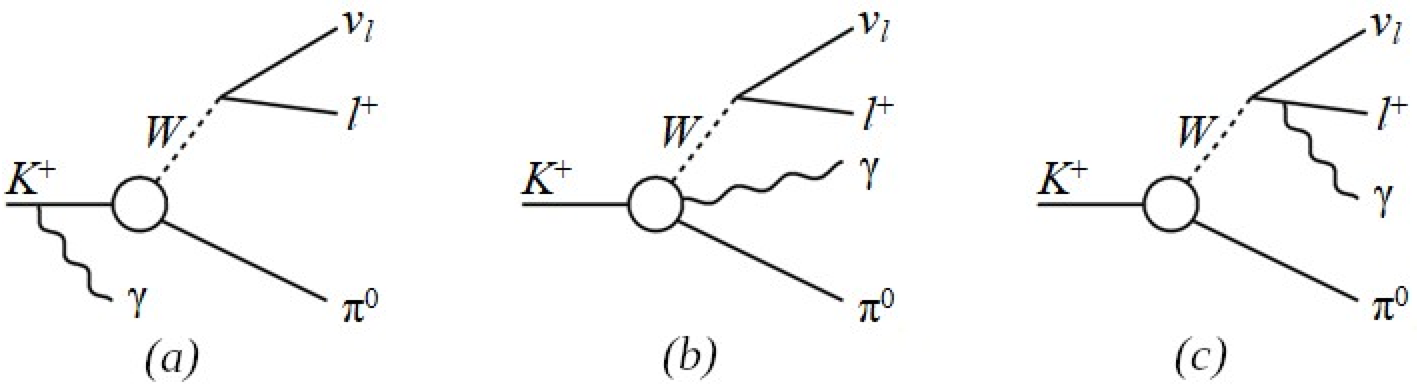
AYSS-2023
JINR, Dubna, Russia
30.X – 03.XI, 2023

$K^+ \to \pi^0\mu^+\nu\gamma$ and $K^+ \to \pi^0 e^+\nu\gamma$ radiative decays

The matrix element for this decay has general structure:

$$T = \frac{G_f}{\sqrt{2}} e V_{us} \epsilon^{\alpha}(q) \left\{ (V_{\alpha\beta} - A_{\alpha\beta}) \bar{u}(p_\nu)\gamma^\beta(1-\gamma^5)v(p_l) + \frac{F_\beta}{2p_l q}\bar{u}(p_\nu)\gamma^\beta(1-\gamma^5)(m_l - \hat{p}_l - \hat{q})\gamma_\alpha v(p_l) \right\}.$$

First term of the T describes the bremsstrahlung of kaon and the direct emission, (a, b). The lepton bremsstrahlung presented by the second part of T and (c).



Diagrams describing $K^+ \to \pi^0 l^+ \nu\gamma$.

$K^+ \to \pi^0 l^+ \nu\gamma$ decays: motivation

$K^+ \to \pi^0 l^+ \nu\gamma$ decays are among those kaon decays where new physics beyond Standard Model can be probed. These decays are especially interesting as they are sensitive to T-odd contributions. According to CPT theorem, observation of T-violation is equivalent to observation of CP-violating effects.

Second, precise tests of ChPT.

Third, it is interesting to test lepton universality:

$$\frac{Br(K_{\mu 3\gamma})}{Br(K_{e3\gamma})}.$$

$K^+ \to \pi^0 l^+ \nu\gamma$: important observables

Important experimental observable used in CP-violation searches is the T-odd correlation for $K^+ \to \pi^0 \mu^+ \nu\gamma$ decay defined as:

$$\xi_{\pi l \gamma} = \frac{1}{M_K^3} \vec{p}_\gamma \cdot [\vec{p}_\pi \times \vec{p}_l].$$

To establish the presence of nonzero triple-product correlations, one construct a T-odd asymmetry of the form:

$$A_\xi = \frac{N_+ - N_-}{N_+ + N_-},$$

$N_{+}(_{-})$ – number of events with ξ >(<) 0.

IHEP PS U-70

IHEP

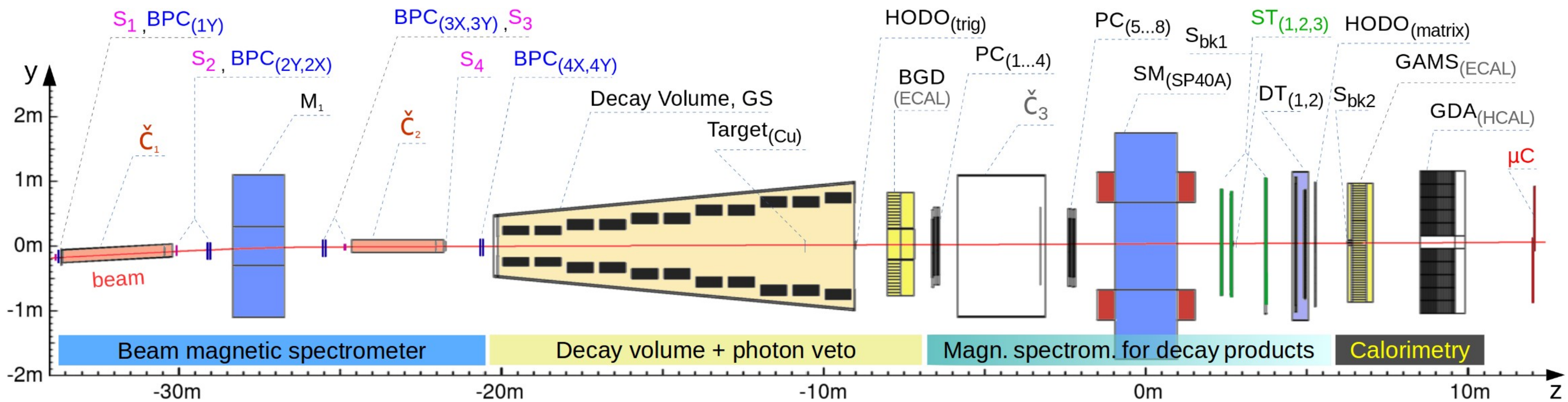
U-70 ring

The OKA collaboration operates at the IHEP Protvino U-70 Proton Synchrotron.

Detector is located in positive RF-separated beam with 12.5% of *K*-meson

17.7 GeV/c $3 \cdot 10^5$ kaons per 2 sec U-70 spill. Separation is provided by two SC deflectors cooled by superfluid He.

OKA detector



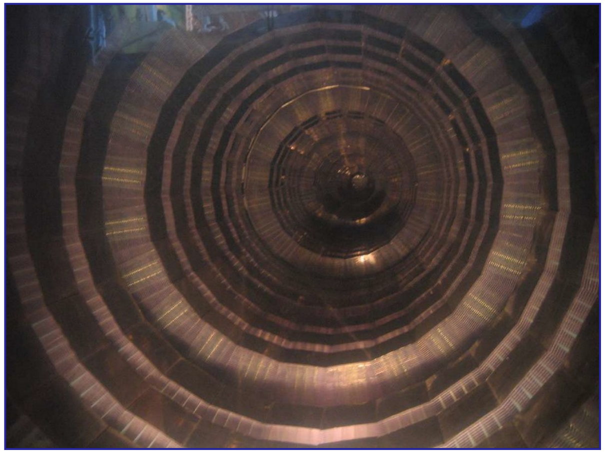
$$Trg = S_1 \cdot S_2 \cdot S_3 \cdot S_4 \cdot \bar{\check{C}}_1 \cdot \check{C}_2 \cdot \bar{S}_{bk} \cdot (E_{GAMS} > 2.5GeV)$$

$S_1 - S_4$ are scintillating counters; $\check{C}_1$, $\check{C}_2$ – Cherenkov counters ($\check{C}_1$ sees pions, $\check{C}_2$ pions and kaons); S_{bk} – two scintillation counters on the beam axis after the magnet to suppress undecayed particles.

1. Beam spectrometer: PC’s;
2. Decay volume with Veto system;
3. PC’s and DT’s for magnetic spectrometer;
4. Magnet;
5. Matrix hodoscope: SiPM;
6. Gamma detectors: GAMS-2000;
7. Muon identification: HCAL + μC;

Decay Volume with Veto system

DV: 11m;
Veto: 670 Lead-Scintillator sandwiches 20×(5mm Sc + 1.5mm Pb), WLS readout.



Inside

Veto system

$K^+ \to \pi^0\mu^+\nu\gamma$ experimental status

Contrary to the $K_{e3\gamma}$ decay, where high statistics (OKA, NA62) measurements are available, $K_{\mu3\gamma}$ decay is poorly known.

$\Gamma(K^+ \to \pi^0\mu^+\nu_\mu\gamma)/\Gamma_{total}$ — Γ_{19}/Γ

VALUE (10^{-5})	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
$\mathbf{1.25 \pm 0.25}$ OUR AVERAGE							
$1.10 \pm 0.32 \pm 0.05$		23	[1] ADLER	2010	B787		$30 < E_\gamma < 60$ MeV
$1.46 \pm 0.22 \pm 0.32$		153	[2] TCHIKILEV	2007	ISTR	-	$30 < E_\gamma < 60$ MeV
• • We do not use the following data for averages, fits, limits, etc. • •							
$2.4 \pm 0.5 \pm 0.6$		125	SHIMIZU	2006	K470	+	$E_\gamma > 30$ MeV; $\Theta_{\mu\gamma} > 20^\circ$
<6.1	90	0	LJUNG	1973	HLBC	+	$E(\gamma) > 30$ MeV

[1] Value obtained from B($K^+ \to \pi^0\mu^+\nu_\mu\gamma$) = $(2.51 \pm 0.74 \pm 0.12) \times 10^{-5}$ obtained in the kinematic region $E_\gamma > 20$ MeV, and then theoretical $K_{\mu3\gamma}$ spectrum has been used. Also B($K^+ \to \pi^0\mu^+\nu_\mu\gamma$) = $(1.58 \pm 0.46 \pm 0.08) \times 10^{-5}$, for $E_\gamma > 30$ MeV and $\theta_{\mu\gamma} > 20^\circ$, was determined.

[2] Obtained from measuring B($K_{\mu3\gamma}$) / B($K_{\mu3}$) and using PDG 2002 value B($K_{\mu3}$) = 3.27%. B($K_{\mu3\gamma}$) = $(8.82 \pm 0.94 \pm 0.86) \times 10^{-5}$ is obtained for 5 MeV $< E_\gamma <$ 30 MeV.

$K^+ \to \pi^0 l^+ \nu\gamma$ theoretical status

	Br ($K_{\mu 3\gamma}$)	A_ξ ($K_{\mu 3\gamma}$)	Br ($K_{e3\gamma}$)	A_ξ ($K_{e3\gamma}$)
Bijnens et al.	1.9×10^{-5}	—	2.8×10^{-4}	—
Braguta et al.	2.15×10^{-5}	1.14×10^{-4}	3.18×10^{-4}	-0.59×10^{-4}
Khriplovich et al.	1.81×10^{-5}	2.38×10^{-4}	2.72×10^{-4}	-0.93×10^{-4}

Theoretical calculations for $K_{e3\gamma}$ branching. The following cuts in the kaon rest frame are used: $E^* \geq 30$ MeV, $\theta_{l\gamma} \geq 20^\circ$, where E^* is the photon energy. Theoretical errors were not specified by autors.

$K_{l3\gamma}$ decays: background

K_{l3} is used as normalization channel. Two main observables for signal and normalization events are used: reconstructed mass $M(K_{l3\gamma}) = M(l^+, \pi^0, \nu, \gamma)$, where all missing momentum is attributed to ν and $M_\nu = 0$ is assumed and a similar observable $M(K_{l3}) = M(l^+, \pi^0, \nu)$.

1) $K^+ \rightarrow l^+\nu\pi^0$ with an extra photon. The main source of extra photons is lepton interaction in the detector;

2) $K^+ \rightarrow \pi^+\pi^0\pi^0$ where one of the π^0 photon is not detected and π^+ is misidentified as a l^+;

3) $K^+ \rightarrow \pi^+\pi^0$ with a "fake photon" and π^+ misidentified as a l^+. The fake photons can come from π^+n interactions in the gamma detector and from accidentals;

4) $K^+ \rightarrow \pi^+\pi^0\gamma$ when π^+ is misidentified as a l^+;

5) $K^+ \rightarrow \pi^0\pi^0 l^+\nu$ when one γ is lost.

All these background sources are included in MC calculations.

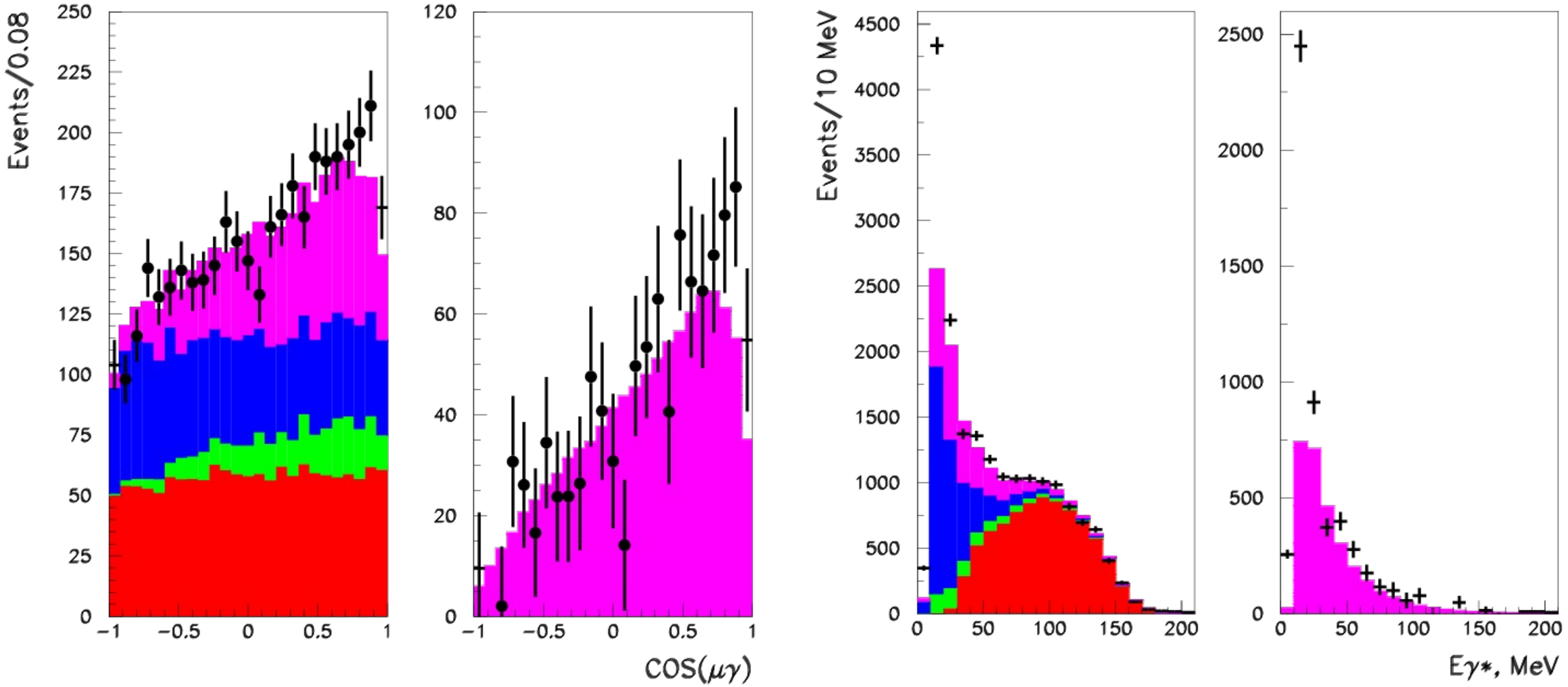
In $K_{\mu 3\gamma}$ decays backgrounds 1, 2 and 4 are dominated.

$K_{\mu 3\gamma}$ event selection

General criteria (all one track events): good quality beam with proper momentum, vertex within decay volume, good quality secondary track with reasonable χ^2 etc.

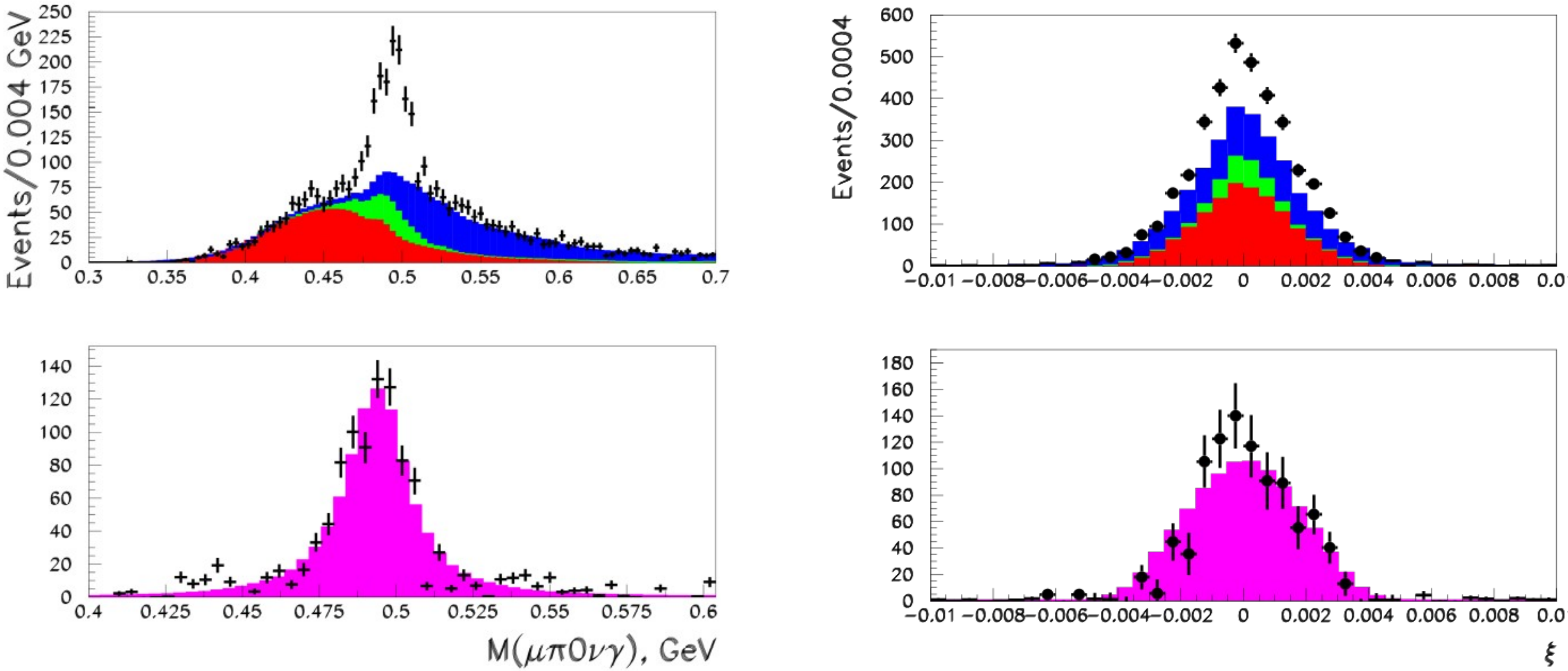
Cut	$K_{\mu 3}$ | $K_{\mu 3\gamma}$
• Muon compatible signal in GAMS, HCal and μC	++
• 2 e/m showers in GAMS with $E_\gamma > 0.6$ GeV	+−
• 3 e/m showers in GAMS with $E_\gamma > 0.6$ GeV	−+
• $\|M_{\gamma\gamma} - M_{\pi 0}\| < 20$ MeV (best combination for $K_{\mu 3\gamma}$)	++
• Missing energy > 0.5 GeV	++
• No amplitude overflow in GAMS counters	++
• The position of radiative photon at GAMS surface is not near beam hole nor at the boudary	−+
• Total energy in Veto and BGD is below threshold	++
• Number of additional track segments after spectrometer magnet is zero	++
• $K_{\mu 3}$ special: $\cos(\mu^+\pi^0)$ in rest frame > −0.95. Effective against $K^+ \to \pi^+\pi^0$ bkg	+−
• $K_{\mu 3\gamma}$ special: missing mass $MM(\pi^+\pi^0) < 0.12$ GeV. Effective against $K^+ \to \pi^+\pi^0\pi^0$ bkg	−+

$K_{\mu3\gamma}$ event selection



In kaon rest frame. Left: distribution of cos($\mu\gamma$), right: energy of odd gamma distribution. Magenta – MC $K_{\mu3\gamma}$ signal, red – MC bkg from $K_{\pi+\pi0\pi0}$, green – MC bkg from $K_{\pi+\pi0\gamma}$, blue – MC bkg from $K_{\mu3}$.

$K_{\mu 3\gamma}$ event selection



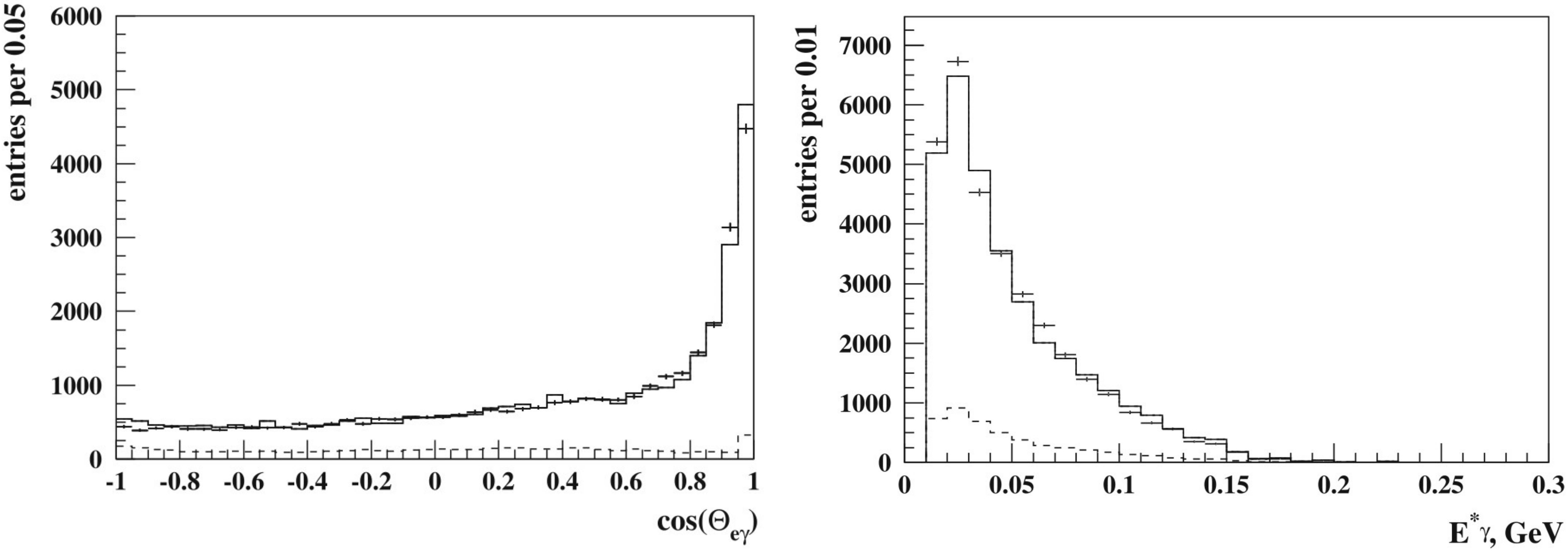
Left − $K_{\mu 3\gamma}$ invariant mass distribution. Right − ξ distribution. Top − with bkg, bottom − bkg substracted. Magenta – MC $K_{\mu 3\gamma}$ signal, red – MC bkg from $K_{\pi+\pi0\pi0}$, green – MC bkg from $K_{\pi+\pi0\gamma}$, blue – MC bkg from $K_{\mu 3}$.

$K_{e3\gamma}$ event selection

Cut

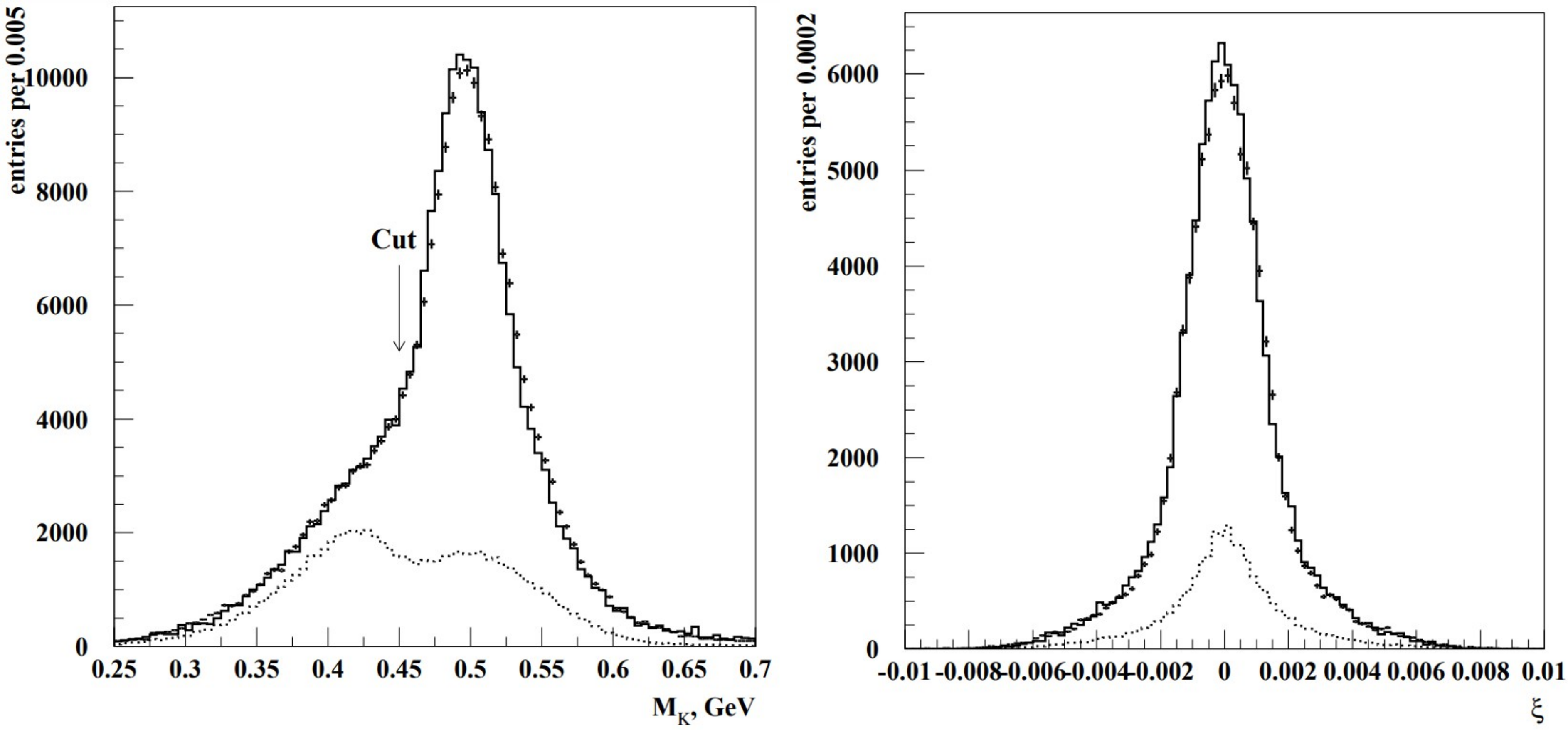
- 4 e/m showers in GAMS with $E_\gamma > 0.7$ GeV;
- One charged track is identified as e^+ with $0.8 < E/p < 1.2$;
- Missing energy > 0.5 GeV;
- No amplitude overflow in GAMS counters;
- The position of radiative photon at GAMS surface is not near beam hole nor at the boudary;
- Total energy in Veto and BGD is below threshold;
- Number of additional track segments after spectrometer magnet is zero;
- The effective mass for γ-pair $0.12 < M_{\gamma\gamma} < 0.15$ GeV;
- $\Delta y = |y_\gamma - y_e| > 3$ cm, where y is the vertical coordinate of a particle in the e/m calorimeter (the magnetic field turns charged particles in the xz-plane);
- $|x_\nu , y_\nu| < 100$ cm. The reconstructed missing momentum direction must cross the active area of the e/m calorimeter.
- The reconstructed mass of the system $M(K^+ \to e^+ \nu \pi^0 \gamma) > 0.45$GeV
- $|M^2_{miss}(\pi^0 e^+ \gamma)| = (P_K - P_{\pi^0} - P_e - P_\gamma)^2 < 0.006$ GeV^2;
- 4 mrad $< \theta_{e\gamma} <$ 80 mrad;

$K_{e3\gamma}$ event selection



In kaon rest frame. Left: distribution of cos(eγ), right: energy of odd gamma distribution. Histrogram – MC signal plus total background, MC background – dotted line histrogram.

$K_{e3\gamma}$ event selection



Left − $K_{e3\gamma}$ invariant mass distribution. Right − ξ distribution. Total background − dotted line histogram.

Preliminary results and conclusion

- We have 960 ± 55 (stat) $K_{\mu 3\gamma}$ and 19295 (101200 candidates) $K_{e3\gamma}$ signal events;

- $Br(K_{\mu 3\gamma})/Br(K_{\mu 3})$ = (4.45 ± 0.25 (stat)) × 10^{-4}, 30 < E^* < 60 MeV;
- Using PDG value $Br(K_{\mu 3})$ = 3.352%: $Br(K_{\mu 3\gamma})$ = (1.492 ± 0.085 (stat)) × 10^{-5}, which is in agreement with ISTRA+ measurement, but statistical errors is 3 times smaller;
- Theory: 1.9 × 10^{-5} (Bijinens), 2.15 × 10^{-5} (Braguta), 1.81 × 10^{-5} (Khriplovich);
- A_ξ = – 0.006 ± 0.069. Theory: 1.14 × 10^{-4} (Braguta), 2.38 × 10^{-4} (Khriplovich);

- $Br(K_{e3\gamma})/Br(K_{e3})$ = (58.7 ± 1.0 (stat) ± 1.5 (syst)) × 10^{-4}, 30 < E^* < 60 MeV and $\theta_{e\gamma} > 20^\circ$;
- Using PDG value $Br(K_{e3})$ = 5.07%: $Br(K_{e3\gamma})$ = (2.97 ± 0.13) × 10^{-4};
- Theory: 2.8 × 10^{-4} (Bijinens), 3.18 × 10^{-4} (Braguta), 2.72 × 10^{-4} (Khriplovich);
- A_ξ = (+4.4 ± 7.9 (stat) ± 1.9 (syst)) × 10^{-3}. Theory: – 0.59 × 10^{-4} (Braguta), – 0.93 × 10^{-4} (Khriplovich);

- Our results are preliminary.

Thank you for your attention!