$K^+ \to \pi^0 \mu^+ \nu \gamma$ radiative decay: preliminary results from the «OKA» experiment

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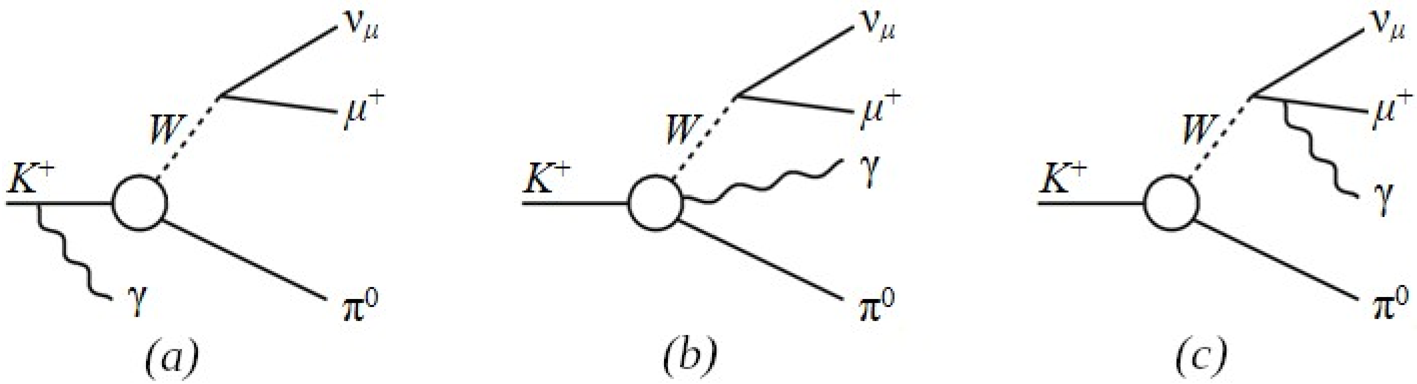
$K^+ \to \pi^0\mu^+\nu\gamma$ radiative decay

The matrix element for this decay has general structure:

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

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



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

$K^+ \to \pi^0 \mu^+ \nu\gamma$ decay: 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, it is interesting to test lepton universality:

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

Third, precise tests of ChPT.

T-violation in $K^+ \to \pi^0\mu^+\nu\gamma$ decay

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

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

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

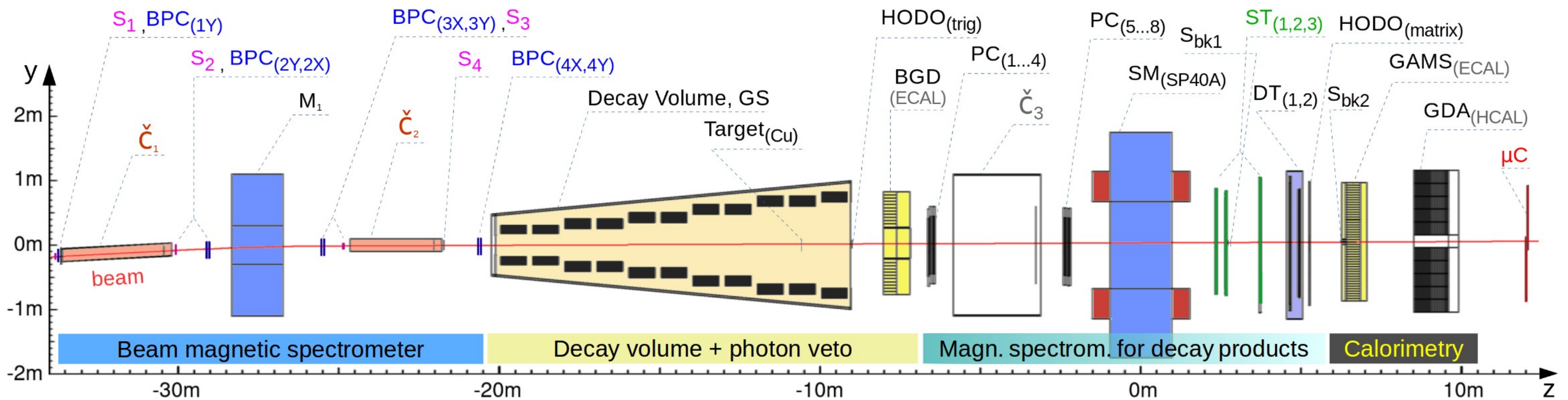
U-70 ring

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



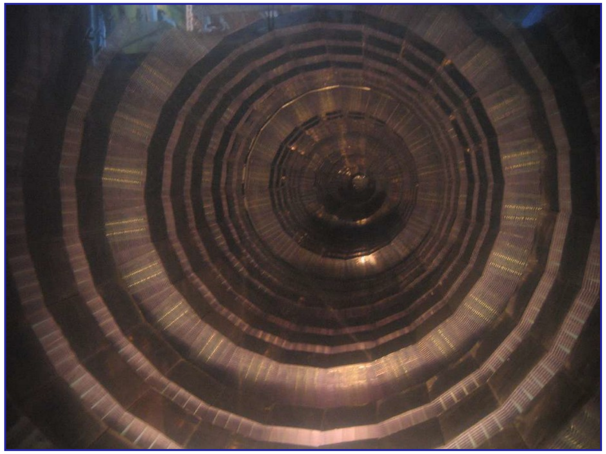
$$Trg = S_1 \cdot S_2 \cdot S_3 \cdot S_4 \cdot \bar{\check{C}}_1 \cdot \check{C}_2 \cdot \bar{S}_{bk} \cdot (E_{GAMS} > 2.5GeV)$$

$S_1 - S_4$ 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
1.25 ± 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.

Our aim is to determine the branching $K_{\mu3\gamma}$ decay with the $\leq 10\%$ accuracy.

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

	Branching ratio	A_ξ
Bijnens et al.	1.9×10^{-5}	—
Braguta et al.	2.15×10^{-5}	1.14×10^{-4}
Khriplovich et al.	1.81×10^{-5}	2.38×10^{-4}

Theoretical calculations for $K_{\mu 3\gamma}$ branching. The following cuts in the kaon rest frame are used: $E^* \geq 30$ MeV, $\theta_{\mu\gamma} \geq 20^\circ$, where E^* is the photon energy. Theoretical errors were not specified by autors.

OKA $K_{\mu3\gamma}$ measurement strategy

- $K_{\mu3}$ decay is used as normalisation channel;
- We present the ratio R = Br($K_{\mu3\gamma}$; E^*)/Br($K_{\mu3\gamma}$) for $30 < E^* < 60$ MeV, E^* is the energy of odd gamma in kaon rest frame;
- $$R = \frac{N(K_{\mu3\gamma}; E^*)}{N(K_{\mu3})} \times \frac{Eff(K_{\mu3})}{Eff(K_{\mu3\gamma}; E^*)};$$
- Two main observables for signal and normalisation events were used: reconstructed mass $M(K_{\mu3\gamma}) = M(\mu^+,\pi^0,\nu,\gamma)$ where all missing momentum is attributed to ν and $M_\nu = 0$ is assumed and the similar observable $M(K_{\mu3})=M(\mu^+,\pi^0,\nu)$;
- Background estimation for $K_{\mu3\gamma}$ and $K_{\mu3}$ and estimation of efficiency ratio $R_{eff}=Eff(K_{\mu3})/Eff(K_{\mu3\gamma}; E^*)$ were performed using MC;
- To estimate the number of signal events we adopted the ISTRA method: the distributions of background ($K^+ \to \pi^+\pi^0\pi^0$; $K_{\mu3}$; $K^+ \to \pi^+\pi^0\gamma$) as well as of signal $K_{\mu3\gamma}$ were parameterized (smoothed) using MC and the experimental distribution was fitted with four free parameters;

OKA data

In this work we use the data collected in two runs: 2012 and 2013. The configuration of OKA detector for these runs was similar but not identical. For r14 there were two periods with Cu target (2mm thick) installed, whereas in r15 no target was used. However in r15 the multichannel threshold cherenkov counter C3 was filled with helium, not air and slightly different gas mixture was used for DT. For each period of data taking a separed set of MC events was generated.

	2012			2013	total
	No tgt	tgt1	tgt2		
Live Kaons	8.257E+09	4.767E+09	2.750E+09	10.571E+09	2.634E+10
Onetrack	2.619E+08	1.441E+08	0.990E+08	2.983E+08	8.033E+08
$K_{\mu 3}$	1.475E+06	0.770E+06	0.515E+06	1.716E+06	4.477E+06

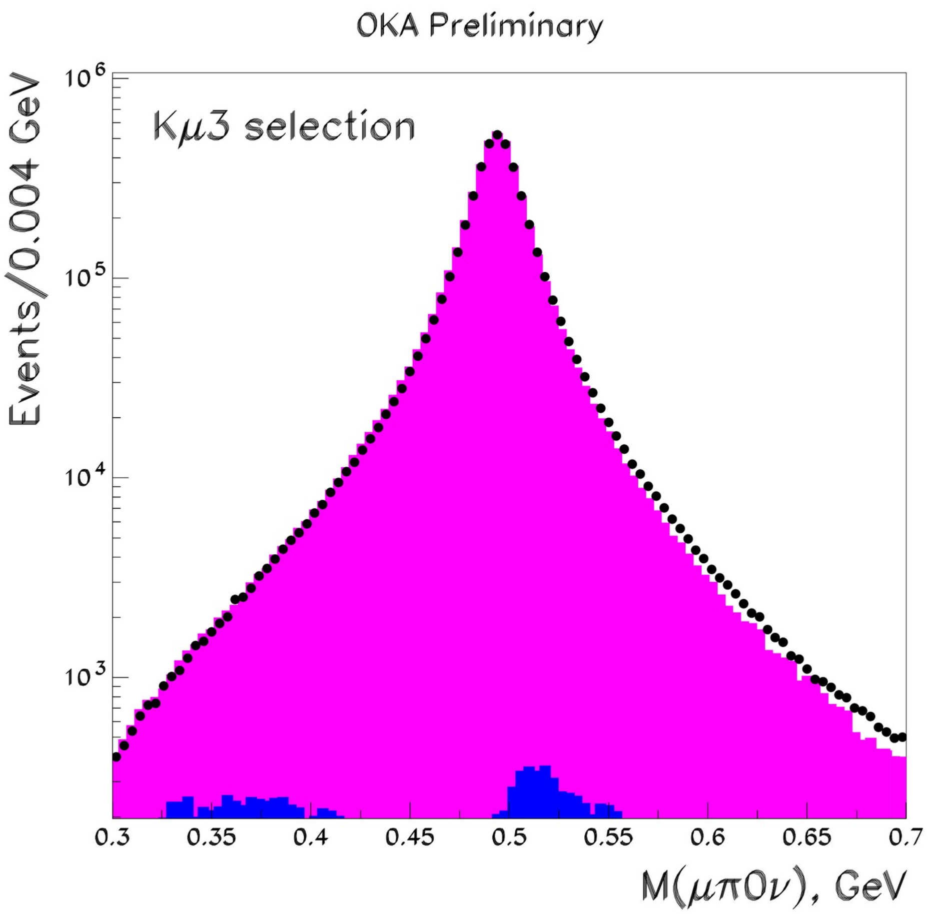
Event selection criteria

General criteria (all one track events): good beam with proper momentum, good quality 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	−+
• $\lvert M_{\gamma\gamma} - M_{\pi 0}\rvert < 20$ MeV (best combination for $K_{\mu 3\gamma}$)	++
• Missing energy > 0.5 GeV	++
• No amplitude overflow in GAMS couters	++
• 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	−+

Normalization selected events ($K_{\mu3}$)

For our method of number of signal events estimation, it is important to be sure that MC simulation provides good description for the shape of the main observable $M(K_{\mu3\gamma})$. A good description for the form of the observable $M(K_{\mu3})$ is thus necessary.

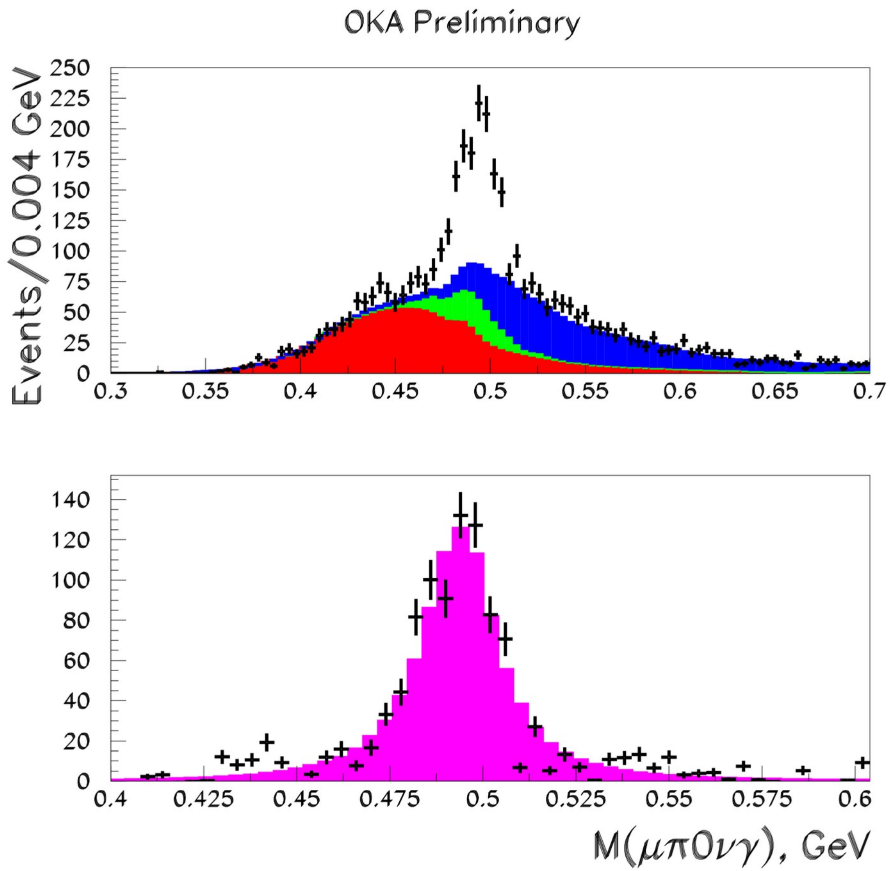


4.477M selected events. Small bkg: B/S ~ 0.5%

Signal + bkg selected events

We try three different functions to describe signal event distribution: Two Gauss with common average and different resolution, Cristall Ball function, HBOOK QUADF smoothing method. All methods give similar results, the last method was chosen as a main one. Bkg dominated by $K_{\pi^+\pi^0\pi^0}$, $K_{\mu 3}$ and $K_{\pi^+\pi^0\gamma}$. $K_{\pi^+\pi^0}$ and $K_{\mu\nu\pi^0\pi^0}$ bkg is small.

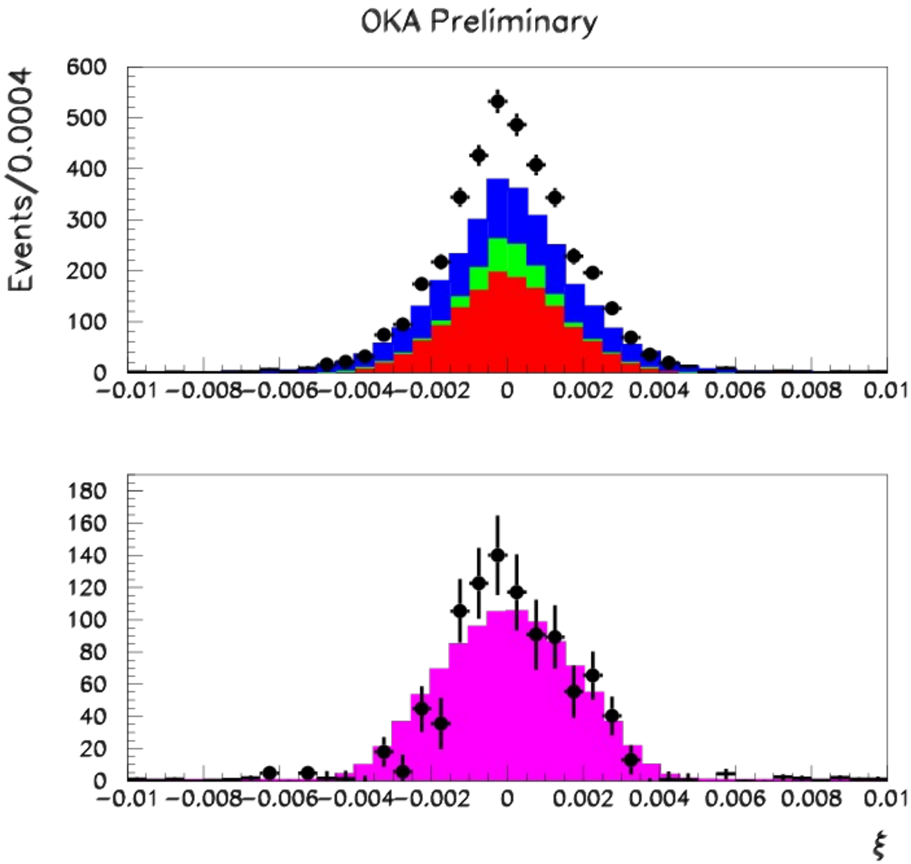
Fit gives 960 ± 55 $K_{\mu 3\gamma}$ events.



Magenta – $K_{\mu 3\gamma}$ signal, red – bkg from $K_{\pi^+\pi^0\pi^0}$, green – bkg from $K_{\pi^+\pi^0\gamma}$, blue – bkg from $K_{\mu 3}$

ξ and A_ξ

$A_\xi = -0.006 \pm 0.069$



Magenta – $K_{\mu 3\gamma}$ signal, red – bkg from $K_{\pi+\pi0\pi0}$, green – bkg from $K_{\pi+\pi0\gamma}$, blue – bkg from $K_{\mu 3}$

Preliminary results and conclusion

- The branching ratio of $K_{\mu3\gamma}$ decay relative to $K_{\mu3}$ one can be calculated as

$$\frac{Br(K_{\mu3\gamma})}{Br(K_{\mu3})} = \frac{N(K_{\mu3\gamma})}{N(K_{\mu3})} \times R_{eff},$$

- where $N(K_{\mu3\gamma})$ = 960 ± 55 (stat), $N(K_{\mu3})$ = 4.477E+06 events and R_{eff} is weighted average of $R_{eff}(i) = Eff(K_{\mu3\gamma}, i)/Eff(K_{\mu3}, i)$, i = 1...4;
- Four periods of data taking;
- The value of R_{eff}(i) varies from 2.06 − 2.07 to 2.09 − 2,11, R_{eff} = 2.073;
- We have $Br(K_{\mu3\gamma})/Br(K_{\mu3}) = (4.45 \pm 0.25\ (stat)) \times 10^{-4}$, $30 < E^* < 60$ MeV;
- Using PDG value $Br(K_{\mu3})$ = 3.352%:

  $Br(K_{\mu3\gamma}) = (1.492 \pm 0.085\ (stat)) \times 10^{-5}$, $30 < E^* < 60$ MeV, which is in agreement with ISTRA+ measurement, but statistical errors is 3 times smaller;
- Comparison with theoretical values: 1.9×10^{-5} (Bijinens), 2.15×10^{-5} (Braguta), 1.81×10^{-5} (Khriplovich);
- $A_\xi = -0.006 \pm 0.069$. Theory: 1.14×10^{-4} (Braguta), 2.38×10^{-4} (Khriplovich).

Thank you for your attention!

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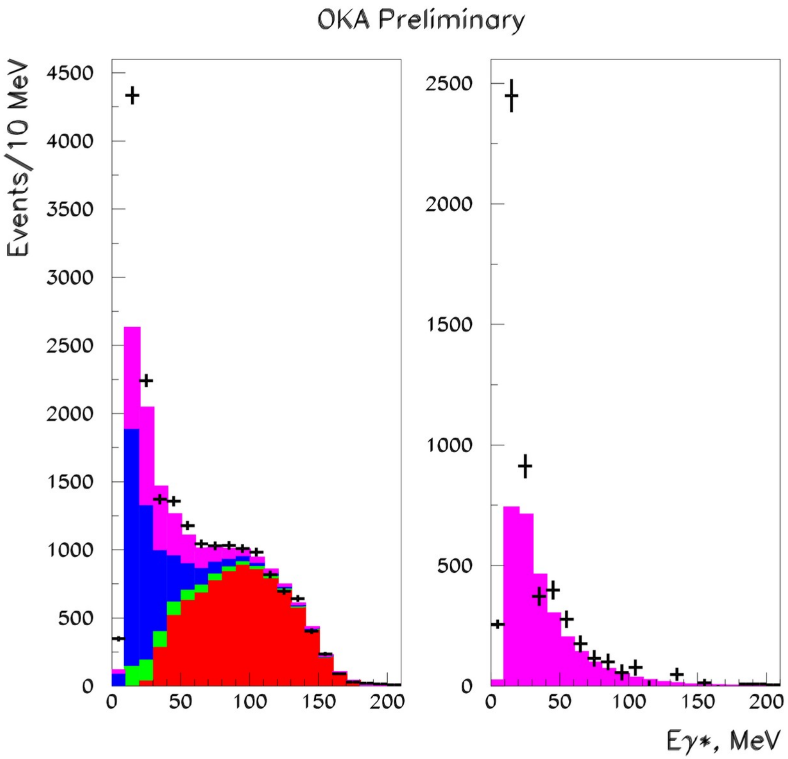
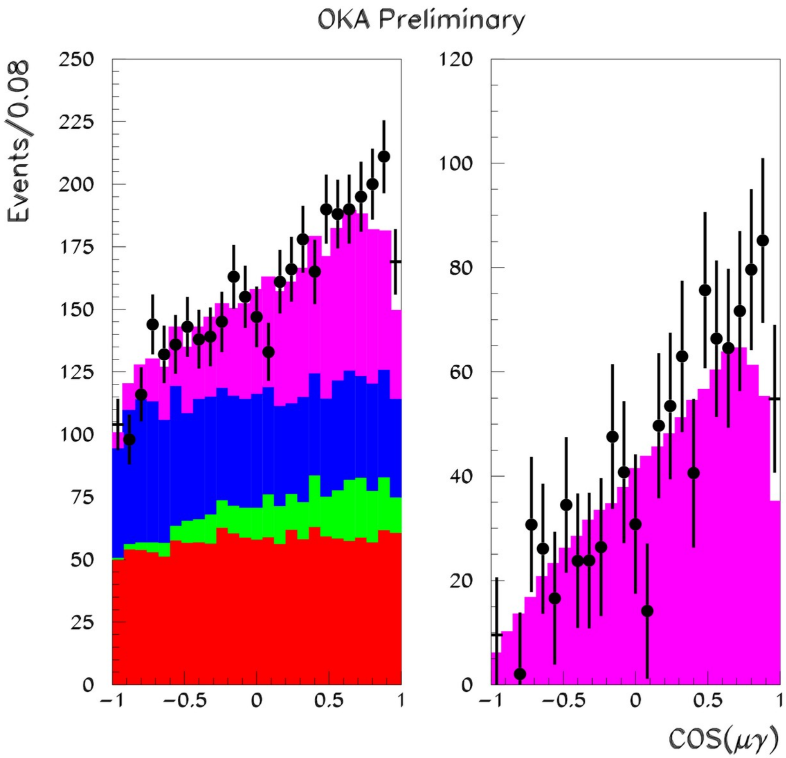
Additional slide 1





Additional slide 2