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On behalf of «OKA» collaboration (IHEP-INR-JINR)

Study of radiative kaon decay $K^+ \to \pi^0 e^+ \nu\gamma$ using OKA detector

The talk layout

- OKA detector
- Ke3 and Ke3γ decays selection
- Background suppression
- Results
- Conclusions

Radiative $K^+ \to \pi^0 e^+ \nu\gamma$ decay

The matrix element for $K \to \pi^0 e\nu\gamma$ has general structure

$$T = \frac{G_F}{\sqrt{2}} e V_{us} \varepsilon^\mu(q) \Big\{ (V_{\mu\nu} - A_{\mu\nu}) \overline{u}(p_\nu) \gamma^\nu (1-\gamma_5) v(p_l) \qquad (1)$$

$$+ \frac{F_\nu}{2 p_l q} \overline{u}(p_\nu) \gamma^\nu (1-\gamma_5)(m_l - \not{p}_l - \not{q}) \gamma_\mu v(p_l) \Big\} \equiv \epsilon^\mu A_\mu .$$

First term of the matrix element describes Bremsstrahlung of kaon and direct emission(Fig.1a The lepton Bremsstrahlung is presented by second part of Eq(1) and (Fig.1b).

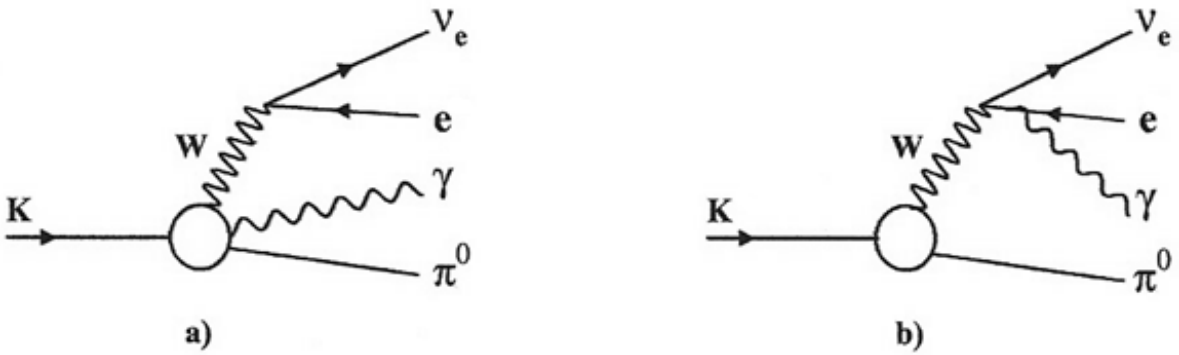

Figure 1: *Diagrammatic repressentation of the $K_{l3\gamma}$ amplitude.*

Radiative $K^+ \to \pi^0 e^+ \nu\gamma$ decay

The radiative $K^+ \to \pi^0 e^+ \nu\gamma$ decay allow as to perform quantitative tests CHPT, thanks to theoretical developments over the past couple of decades as well as recent and ongoing high-statistics experimental studies.

The first complete analysis within CHPT to $O(p^4)$ order was performed by Bijinens et al. [Nucl. Phys. B396 (1993) 81]. Recently, the CHPT analysis was revisited and extended to $O(p^6)$ Kubis et al. [Eur Phys. J. C50 (2007) 557].

$K^+ \to \pi^0 e^+ \nu\gamma$ decay is one of kaon decays where new physics beyond Standard model can be probed. This decay is especially interesting as it is sensitive to T-odd contributions. According to CPT theorem, observation of T violation is equivalent to observation of CP-violating effects.

OKA: search for T-violation in K^+ decays

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

$$\xi_{\pi e\gamma} = \frac{1}{M_K^3} p_\gamma \cdot [p_\pi \times p_e] \qquad (2)$$

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

$$A_\xi = \frac{N_+ - N_-}{N_+ + N_-} \qquad (3)$$

Where N_+ and N_- are number of events with $\xi > 0$ and $\xi < 0$

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$R = \Gamma(K^+ \to \pi^0 e^+ \nu\gamma) / \Gamma(K^+ \to \pi^0 e^+ \nu) = (2.56 \pm 0.16) \cdot 10^{-4}$

$A(\xi) = -0.022 \pm 0.024$

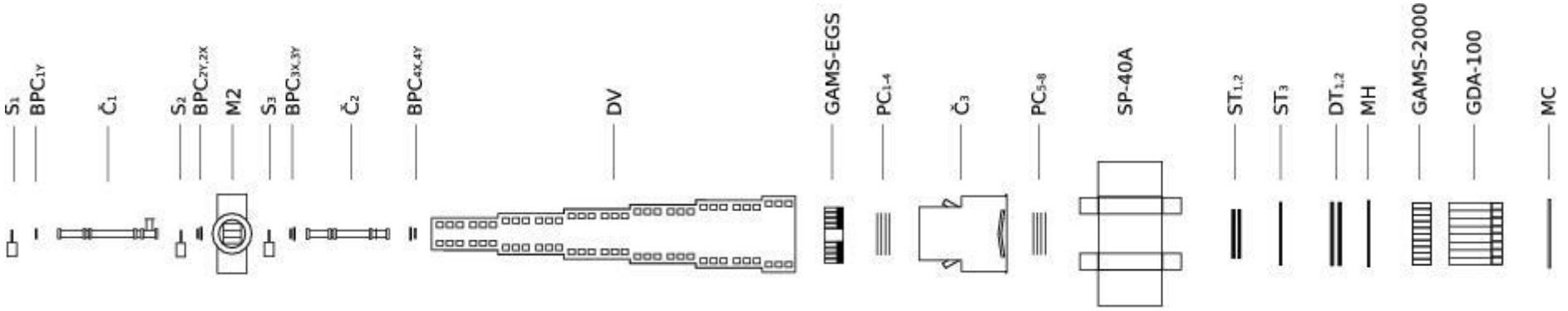
IHEP PS U-70

U-70 ring

IHEP Protvino

OKA collaboration operate at IHEP PS U-70 in Protvino, Moscow region.
Detector is located in positive RF-separated beam with 12.5% of K-meson.

OKA detector

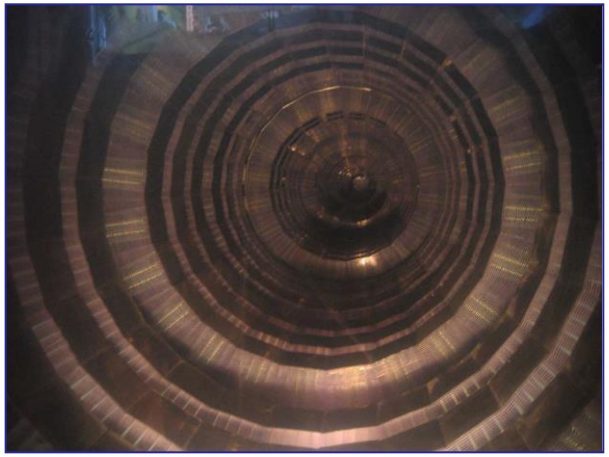


$$Trg = S_1 \cdot S_2 \cdot S_3 \cdot \check{C}_1 \cdot \bar{\check{C}}_2 \cdot \bar{S}_{bk} \cdot (\Sigma_{GAMS} > \text{Mip})$$

1. Beam spectrometer: 1mm pitch PC, ~1500 channels; Cherenkov counters
2. Decay volume with Veto system:
   11m; Veto: 670 Lead-Scintillator sandwiches 20* (5mm Sc+1.5 mmPb), WLS readout
3. PC's and DT's for magnetic spectrometer:
   ~5000 ch. PC (2 mm pitch) + 1300 DT (1 and 3 cm)
4. Pad(Matrix) Hodoscope ~300 ch. WLS+SiPM readout
5. Magnet: aperture 200*140 cm^2
6. Gamma detectors: GAMS2000, EHS-backward EM cal. ~ 4000 LG.
7. Muon identification: GDA-100 HCAL+ 4 muon trigger counters behind

Decay volume with Veto System

Decay volume Veto System

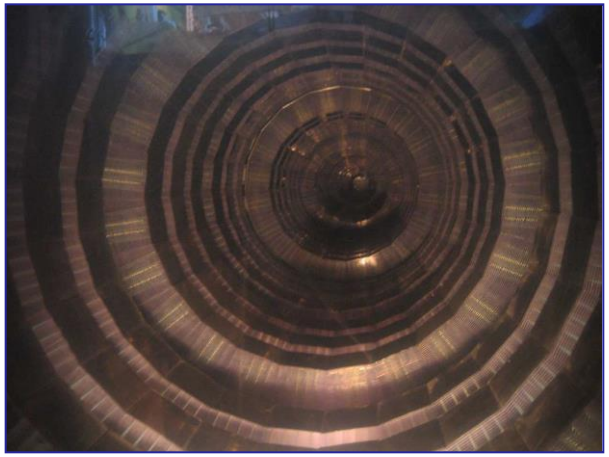


Decay volume inside view

Veto System

Decay volume with Veto System

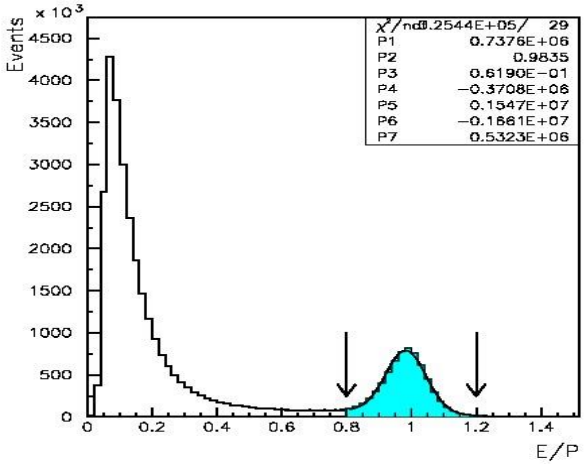
Decay volume Veto System



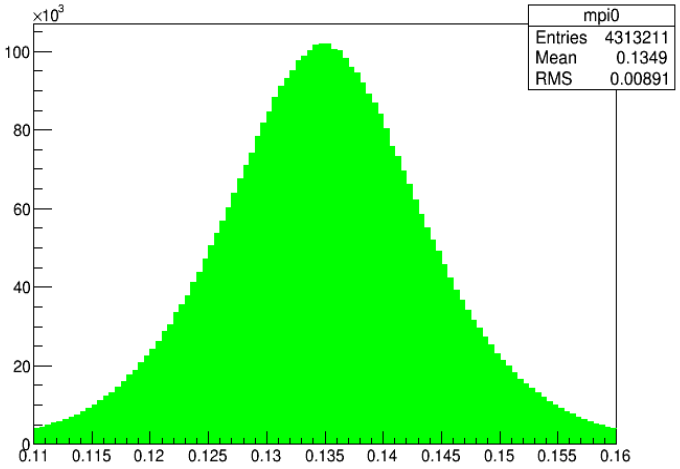
Decay volume inside view

Veto System

K_{e3} decay selection



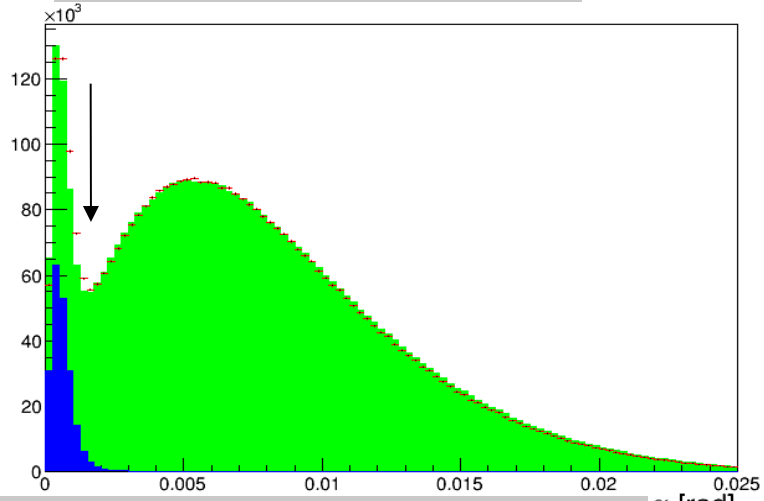
0.8 <E/P<1.2



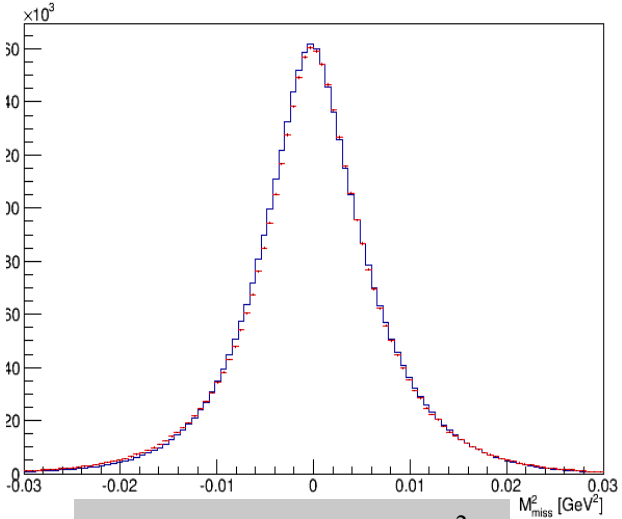
0.11 <Mγγ<0.16 GeV

1. 1 ch. track θ>2mrad point to em-shower in ECAL: (r<3cm) .8 <E/P<1.2
2. 2 extra showers (n_{cl} >3); 0.12 <Mγγ<0.15 GeV
3. α-angle between p_K and $p_{e\pi}$ α>2mrad
4. 2C -constrained fit χ^2<20

6062810 K_{e3} events with E_γ > 0.7GeV



α - angle between p_K and $p_{e\pi}$; α>2mrad



$M^2_{mis} = (p_K - p_{e\pi})^2$

$K^+ \to \pi^0 e^+ \nu\gamma$ events selection

1) One positive charged track detected in tracking system and 4 showers ($E\gamma > 0.7$GeV) detected in electromagnetic calorimeters GAMS- 2000 and EGS.

2) One shower must be associated with charged track.

3) Charged track is identified as positron.

4) Vertex situated within the decay volume.

5) The effective mass $M_{\gamma\gamma}$ for one $\gamma\gamma$ –pair is $0.12 < M_{\gamma\gamma} < 0.15$ GeV.

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Background suppression

The main background channels for the decay $K^+ \to \pi^0 e^+ \nu\gamma$ are:

1) $K^+ \to \pi^0 e^+ \nu$ with extra photon. The main source of extra photons are an interactions of positrons in the detector material.

2) $K^+ \to \pi^+ \pi^0 \pi^0$ where one π^0 photons not detected and π^+ decays to $e^+ \nu$ or misidentified as positron.

3) $K^+ \to \pi^+ \pi^0$ with fake photon and π^+ decayed or misidentified as positron. Fake photon clusters can come from π^+ hadron interaction in the detector, external bremsstrahlung, accidentals. All these sources are included in our MC calculations.

4) $K^+ \to \pi^+ \pi^0 \gamma$ when π^+ decays or is miss-identified as an positron.

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

Background suppression

1) $E_{miss} > 0.5GeV$, $E_{veto} < 50$ МэВ, $-2200<Z_{vx}<-950$, $E_\gamma > 0.7GeV$;

2) $|\Delta y| = |y_\gamma - y_{e+}| > 4$ cm, Δy - vertical distance in GAMS plane;

3) |x,y| of reconstructed "ν" < 100cm in GAMS-2000 plane;

4) $|M^2_{miss}(\pi^0 e^+ \gamma)| < 0.003\ GeV^2$;

5) $M_K > 0.45GeV$;

6) $4\ mrad < \theta_{e\gamma} < 40\ mrad$,

where $M^2_{miss}(\pi^0 e^+ \gamma) = (P_K - P_{\pi^o} - P_e - P_\gamma)^2$,

M_K - K meson mass recovered, mass of the $(\pi^0 e^+ \nu\gamma)$- system, assuming $m_\nu = 0$.

Background suppression

Cut	Real data	Ke3	Kπ3	Kπ2	Signal
$E_{miss} > 0.5$GeV, Z, veto	705505	418301	19869	12299	88861
$\Delta y > 4$ cm	89044	14788	13401	2167	40179
$\|x,y\|$ "v" < 100cm	60276	7817	8388	1629	31031
$M_K > 0.045$GeV	31508	4014	2796	522	23978
$\|M^2_{miss}(\pi^0 e^+ \gamma)\| < 0.003$ GeV^2	27860	3108	419	421	22568
4 mrad < $\theta_{e\gamma}$ < 40 mrad	19490	2048	262	230	16926

Table 1

Experimental data $K^+ \to \pi^0 e^+ \nu\gamma$

1) $E_{miss} > 0.5$GeV and …

2) $|\Delta y| = |y_\gamma - y_{e+}| > 4$ cm

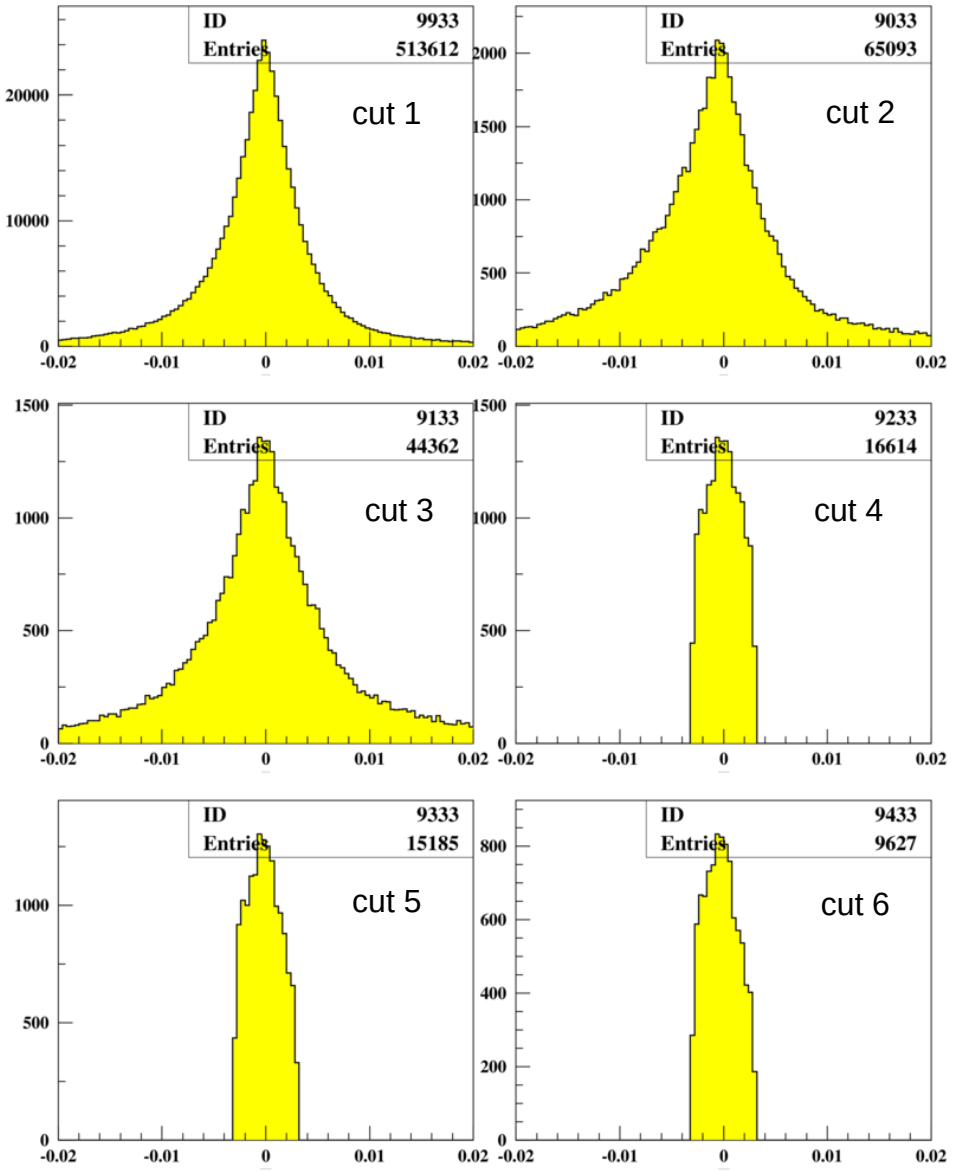
3) |x,y| in GAMS-2000 of reconstructed "ν" < 100cm

4) $|M^2_{miss}(\pi^0 e^+ \gamma)| < 0.003$ GeV^2

5) $M_K > 0.45$GeV

6) 4 mrad < $\theta_{e\gamma}$ < 40 mrad

$$M^2_{miss}(\pi^0 e^+ \gamma) = (P_K - P_{\pi^o} - P_e - P_\gamma)^2$$



$M^2_{miss}(\pi^0 e^+ \gamma)$

Experimental data $K^+ \rightarrow \pi^0 e^+ \nu\gamma$

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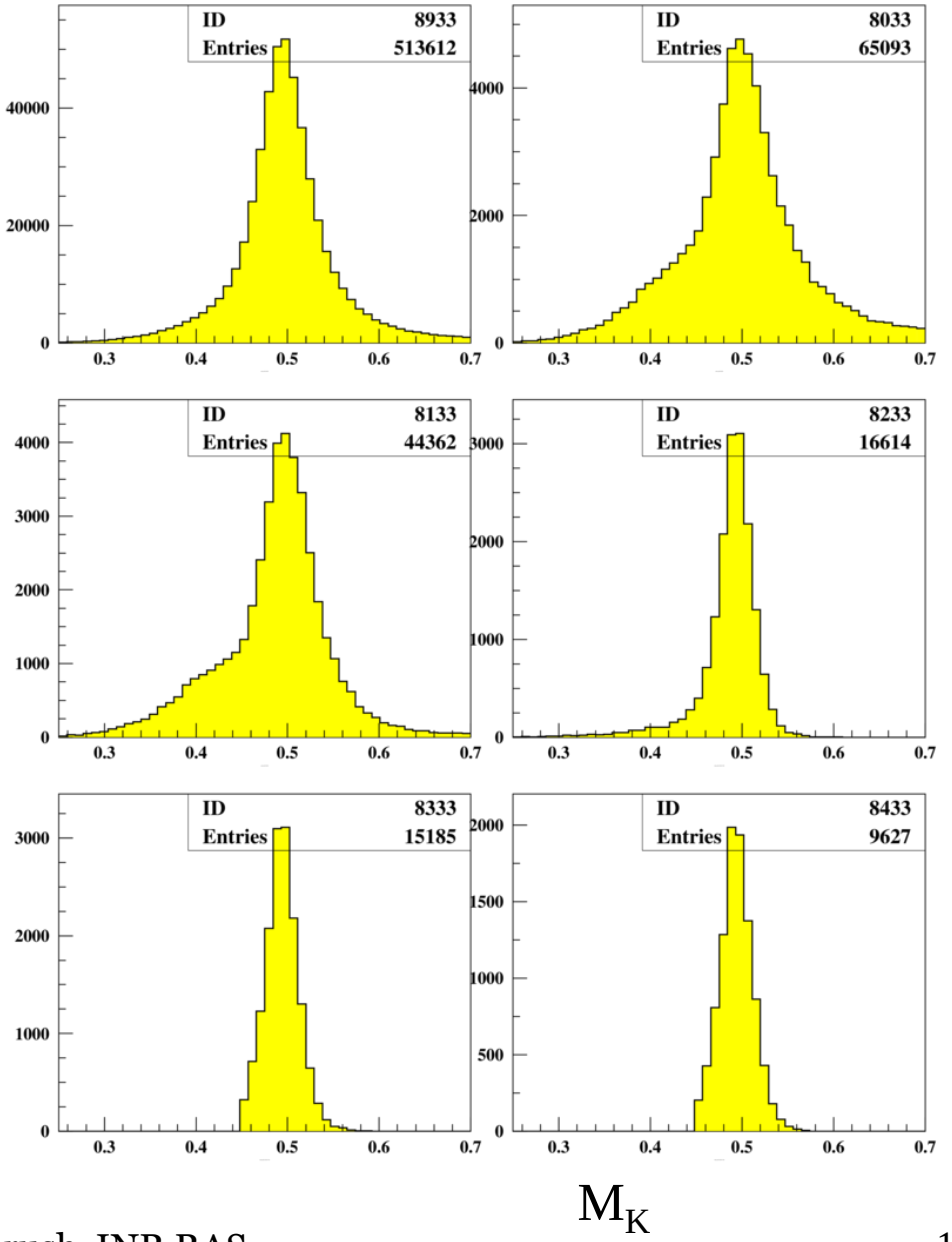
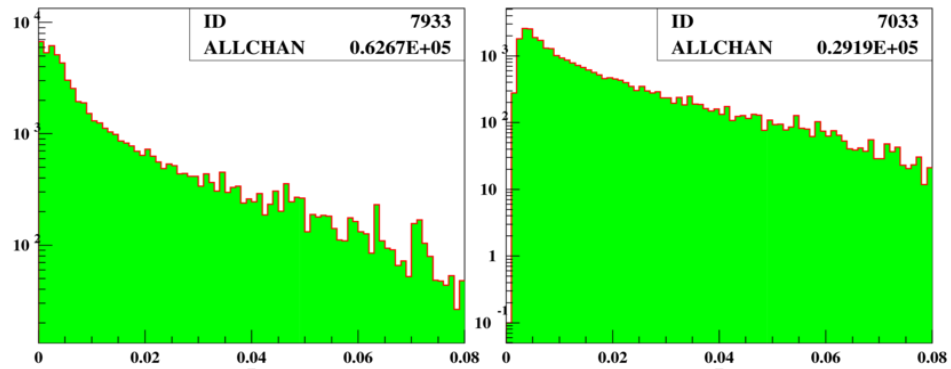
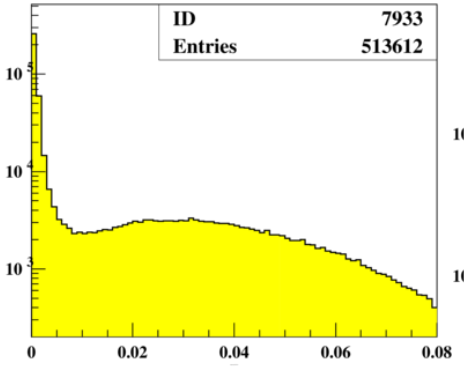


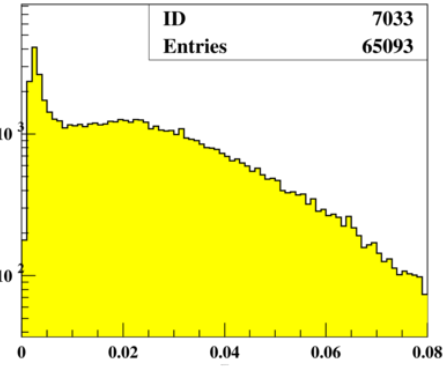
M_K

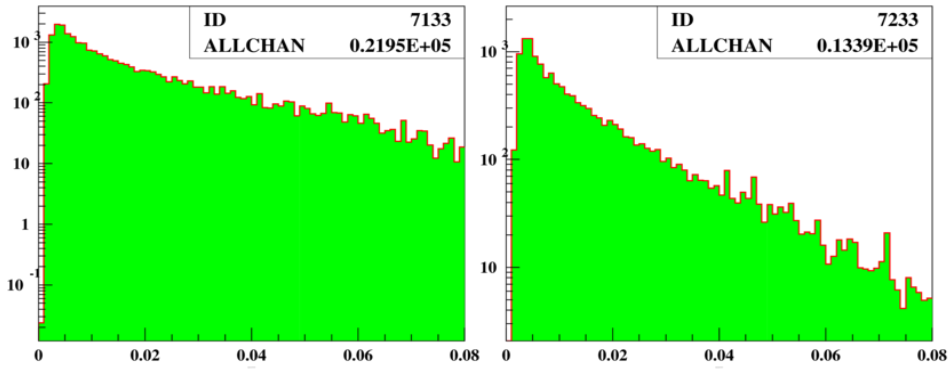
MC signal

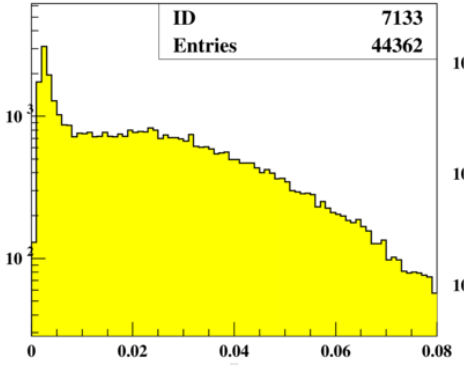
Experimental data

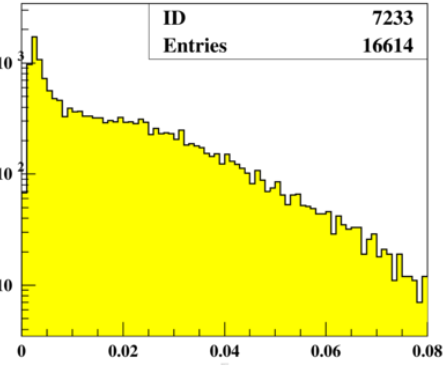


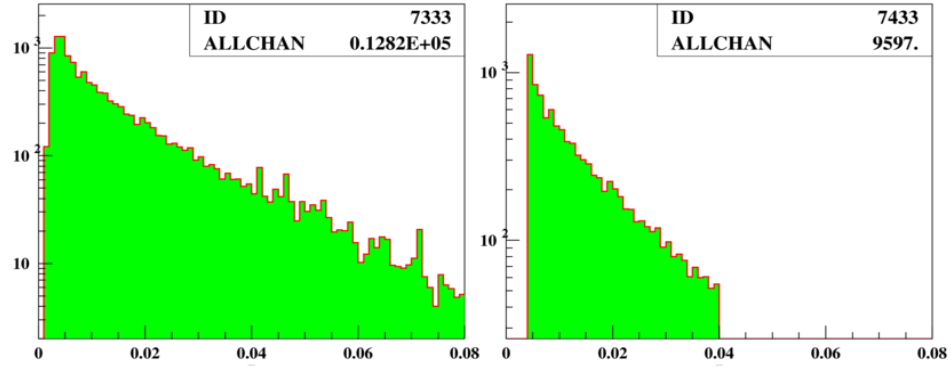


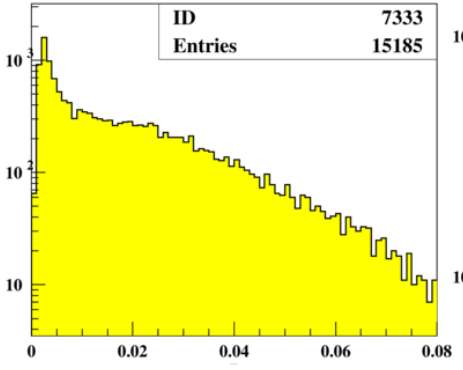


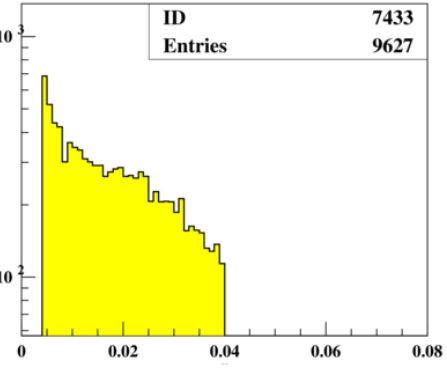




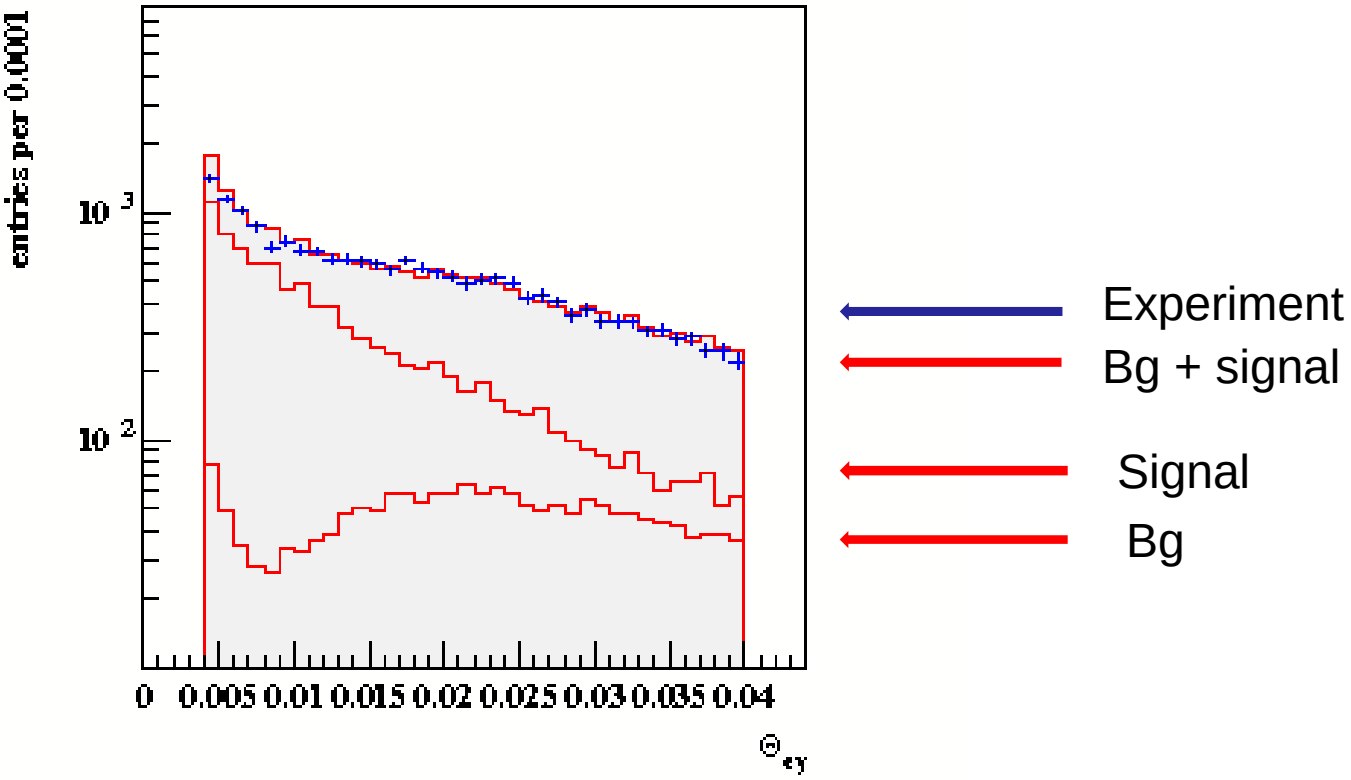








Results


entries per 0.0001
10 3
10 2
0 0.005 0.01 0.015 0.02 0.025 0.03 0.035 0.04
Θ ey
Experiment
Bg + signal
Signal
Bg

Results

For $E^*_\gamma > 10$MeV and $0.6 < \cos^*\theta < 0.9$ we have 7242 selected events with 544 background events. Comparing this after efficiency correction with ours 6062810 K_{e3} events, for the relative branching ratio we got

$$\mathbf{R=\Gamma(K^+\to\pi^0e^+\nu\gamma)\,/\,\Gamma(K^+\to\pi^0e^+\nu)=(0.58\pm0.01\pm0.02)\cdot10^{-2}}$$

Systematic errors are estimated by variation of cuts of Table 1 and using two different ways of backgrounds normalization.

Theoretical prediction for R from CHPT is $R = 0.56\cdot10^{-2}$

For T-odd asymmetry we got:

$$\mathbf{A_\xi = -\,0.009\pm0.012}$$

Theoretical prediction in Standard Model is $\mathbf{A_\xi} = -0.59\cdot10^{-4}$.

Results

N_{ev}	$R_{exp} \cdot 10^{-2}$	Reference
6698	0.58 ± 0.01 ± 0.02	This work
1456	0.48 ± 0.02 ± 0.03	ISTRA+
82	0.46 ± 0.08	XEBC
192	0.56 ± 0.04	ISTRA
13	0.76 ± 0.28	HLBC

Table 2

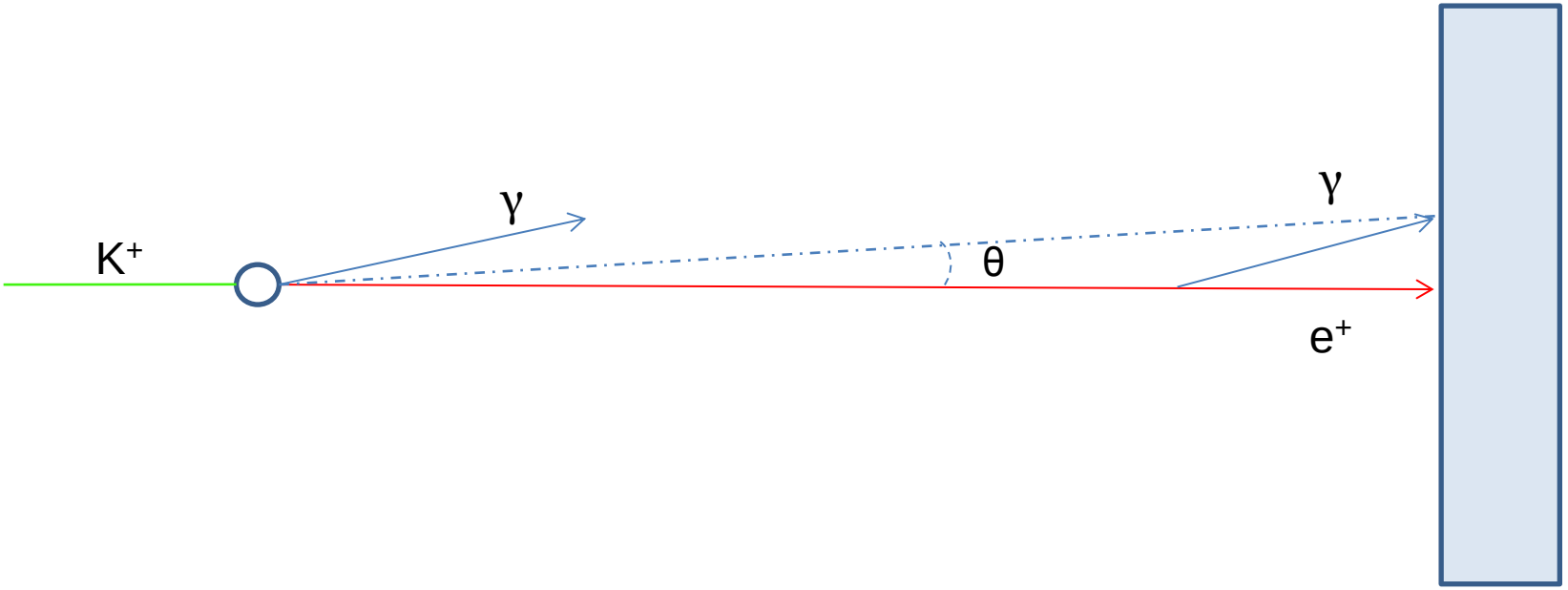
Summary

1) OKA collaboration, operating at IHEP Protvino U-70 PS in RF-separated beam, has accumulated large statistics of K^+ decays.

2) **$K^+ \to \pi^0 e^+ \nu\gamma$** decay signal is extracted with a low background.

3) **$R = \Gamma(K^+ \to \pi^0 e^+ \nu\gamma) / \Gamma(K^+ \to \pi^0 e^+ \nu) = (0.58 \pm 0.01 \pm 0.02) \cdot 10^{-2}$**
for the region $E^*_\gamma > 10$ MeV and $0.6 < \cos^*\theta_{e\gamma} < 0.9$ at statistic 6698 events.

4) Asymmetry in the T-odd variable ξ **$A(\xi) = -0.009 \pm 0.012$**
for the region $E^*_\gamma > 10$ MeV and $0.6 < \cos^*\theta_{e\gamma} < 0.9$

Next step – to measure SD terms.

K_{e3} background