Recent results on kaon physics from OKA experiment

V. Obraztsov, SRC "Kurchatov Institute" - IHEP, Protvino
On behalf of the «OKA» collaboration (IHEP-INR-JINR)

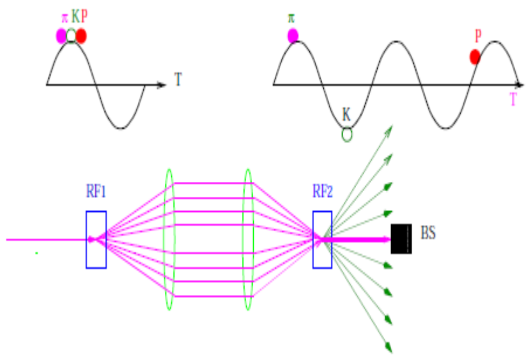
" The 7-th international conference on particle physics and astrophysics",
Moscow, 22.10-25.10 2024

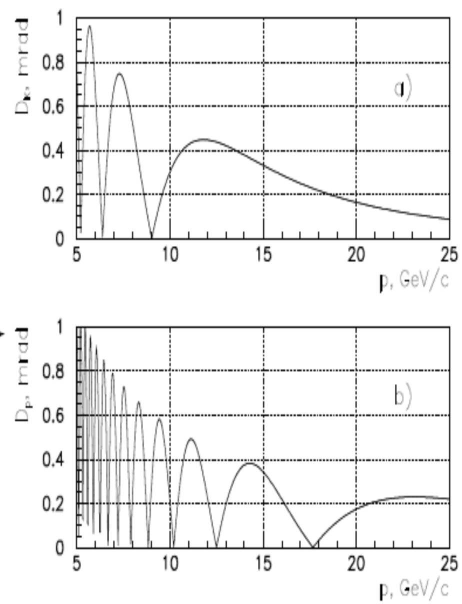
The talk layout

- OKA beam, detector
- Search for the ALP in the $K^+ \to \pi^+\pi^0 a$ decay
- $K^+ \to \mu^+\nu\gamma$, measurement of $F_V - F_A$
- $K^+ \to e^+\nu\pi^0\gamma$, $K^+ \to \mu^+\nu\pi^0\gamma$, χPT $O(p^4)$, search for T(CP) violation
- $K^+ \to \pi^+\pi^+\pi^-\gamma$, $\pi^+\pi^0\pi^0\gamma$ test of χPT

OKA: The experiment with RF-separated $K^{\pm}$ beam @U-70

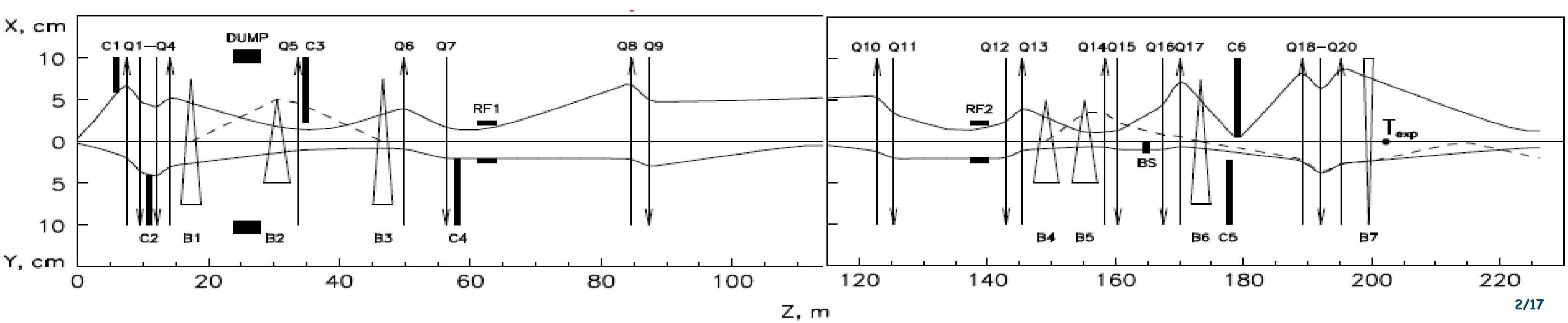
RF separation with Panofsky scheme is realised. It uses two SC RF deflectors. Sophisticated cryogenic system, built at IHEP provides superfluid He for cavities cooling.



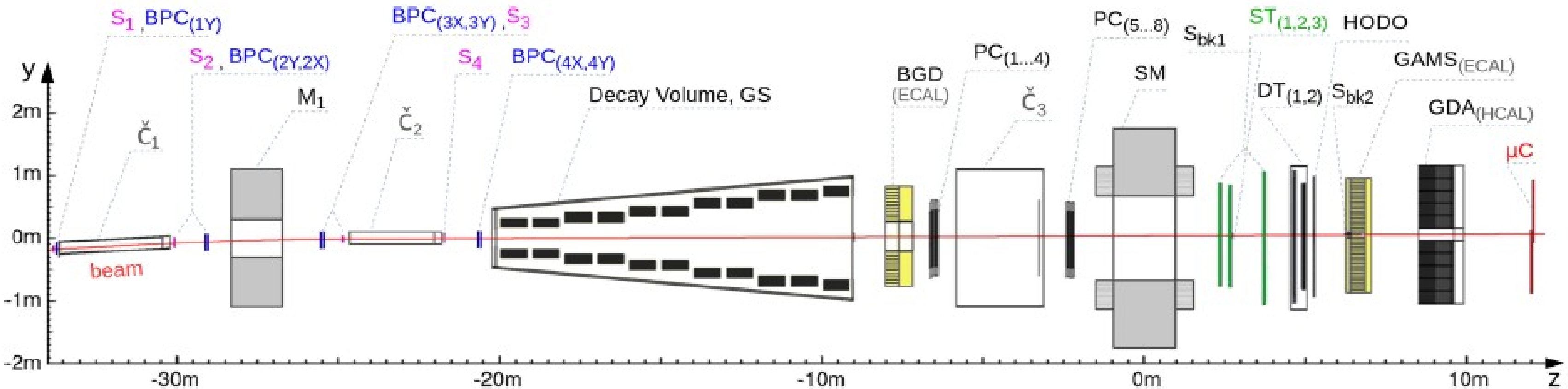


Operating frequency,(S-band)	2865 MHz
Wavelength, λ	~10.5 cm
Effective deflector length	2.74 m
Number of cells/deflector	104
Mean deflecting field	~1(0.6) MV/m
Working temperature	1.8 K

Main beam parameters :	
Primary proton beam energy	50 GeV
Primary proton beam intensity	$7\cdot10^{12}$ ppp
Secondary beam momentum	17.7 GeV
Length of the beam line	~200m
K^+ intensity at the end	$\sim 0.5\cdot10^6$
K^+ in the beam	~ 13%



OKA detector



1. Beam spectrometer: 1mm pitch BPC ~1500 channels; Sc and $\check{C}$ counters
2. Decay volume with Veto system:
   L=11m; Veto: 670 Lead-Scintillator sandwiches 20* (5mm Sc+1.5 mmPb), WLS readout
3. PC's, ST'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, BGD EM cal. ~ 4000 LG.
7. Muon identification: GDA-100 HCAL + 4 muon counters (μC) behind
8. For some runs Cu target inside decay volume was used: Ø=8 cm, t=2mm and C3 big Cerenkov counter

Main triggers $S_1 \cdot S_2 \cdot S_3 \cdot \overline{C}_1 \cdot C_2 \cdot \overline{S}_{bk} \cdot (\Sigma_{GAMS} > 2.5\,GeV) \cup (2 \leqslant MH \leqslant 4)$

Prescaled triggers $S_1 \cdot S_2 \cdot S_3 \cdot C_1 \cdot C_2 \cdot S_{bk}/10$ $\quad S_1 \cdot S_2 \cdot S_3 \cdot C_1 \cdot C_2 \cdot S_{bk} \cdot \mu C\ /4$

Run's in 2010-2013, 2016, 2018 $N_K \sim 5 \times 10^{10}$

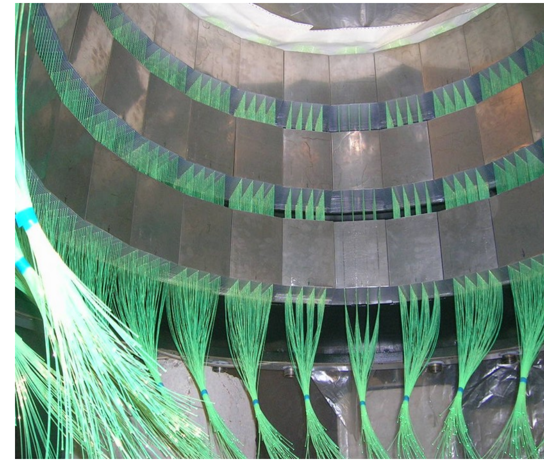
Main directions of the data analysis:

$K^+ \to e^+ \nu \pi^0$, $K^+ \to \mu^+ \nu_S$, K^+ Cu $\to K^+ \pi^0$ Cu , $K^+ \to \pi^+ \pi^0 a$, $K^+ \to \mu^+ \nu \gamma$, $K^+ \to e^+ \nu \pi^0 \gamma$, $K^+ \to \mu^+ \nu \pi^0 \gamma$, $K^+ \to \pi^+ \pi^+ \pi^- \gamma$, $K^+ \to \pi^+ \pi^0 \pi^0 \gamma$

«OKA» setup

General view of the OKA setup

ST, DT chambers, Matrix Hodoscope, ECAL



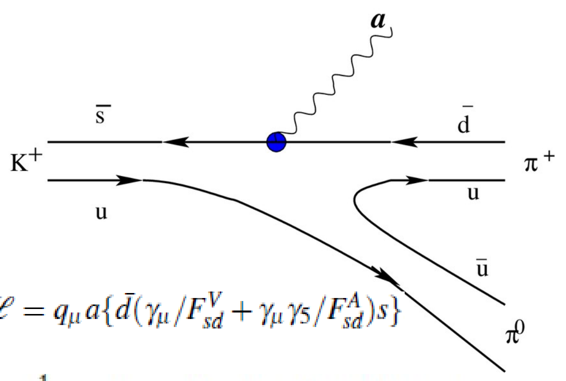
Decay volume Veto System

RF deflector in the beamline

Liquid He lines

Tail of the beam line

Search for the ALP in $K^+ \to \pi^+\pi^0 a$ decay



$$\mathscr{L} = q_\mu a\{\bar{d}(\gamma_\mu/F^V_{sd} + \gamma_\mu\gamma_5/F^A_{sd})s\}$$

$$-\frac{1}{\sqrt{2}}\langle\pi^+(p_2)\pi^0(p_3)|\,\bar{s}\gamma^\mu\gamma^5 d\,|K^+(p)\rangle \;=$$

$$\langle(\pi^+(p_2)\pi^-(p_3))_{I=1}|\,\bar{s}\gamma^\mu\gamma^5 u\,|K^+(p)\rangle \;=$$

$$\frac{-i}{M}(F(p_2+p_3)^\mu + G(p_2-p_3)^\mu + Rp_1^\mu)$$

F,G,R from $K^+ \to \pi^+\pi^- l\nu$ (Kl4)

The QCD Axion is a hypothetical pseudoscalar particle, invented to solve the strong CP problem. It's properties are described by the decay constant f_a , related to Peccei-Quinn symmetry braking scale Λ_{PQ} : $f_a = \Lambda_{PQ}/4\pi$. The QCD axion mass $m_a = m_\pi f_\pi / f_a$.

$a \to \gamma\gamma$; $\tau_a = 2^8\pi^3 f_a^2/(\alpha m_a^3)$. If axion is dark matter $\to \tau_a \geq 13.8$ Gyr $\to m_a \leq 10$ eV.

For axion-like particles (ALP) m_{ALP} is not set by QCD only $\to$ two free parameters:

m_{ALP} , f_{ALP} $m_{ALP} < 1$ GeV.

Axion may have vector and/or axial couplings to quark currents, in particular to sd FCNC

P-conservation $\to$ vector $K^+ \to \pi^+ a$ axial $K^+ \to \pi^+\pi^0 a$

$$\mathscr{L} = q_\mu a\{\bar{d}(\gamma_\mu/F^V_{sd} + \gamma_\mu\gamma_5/F^A_{sd})s\}$$

We assume that the axion decays outside the setup.

Start from 3.65 10^9 events Common cuts for $K^+ \to \pi^+\pi^0 a$ and $K^+ \to \pi^+\pi^0$

- 1 beam track , 1 secondary track $\theta >$ 4 mrad , vertex matching CDA < 1.25 cm.
- no extra track segments behind the SM magnet
- vertex inside the DV .
- $17.0 < p_{beam} < 18.6$ GeV
- number of showers in GAMS or BGD not associated with track = 2
- π^0 identification $|m_{\gamma\gamma} - m_{\pi 0}| < 15$ MeV

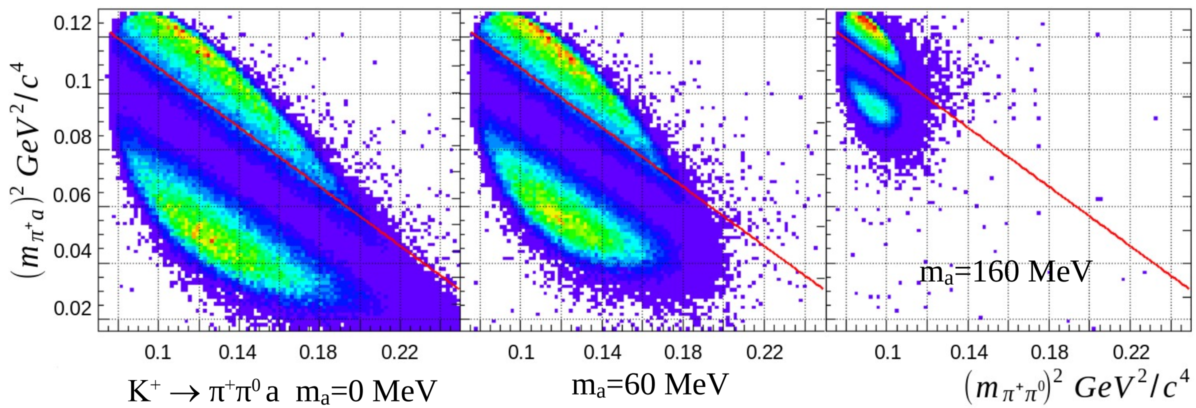
After selections 44.5 10^6 $K^+ \to \pi^+\pi^0$

Search for the axion in $K^+ \to \pi^+\pi^0 a$ decay

In order to disentangle $K^+ \to \pi^+\pi^0 a$ from $K^+ \to \pi^+\pi^0(\gamma)$, $K^+ \to \pi^+\pi^0\pi^0$, $K^+ \to e^+\nu\pi^0$, $K^+ \to \mu^+\nu\pi^0$

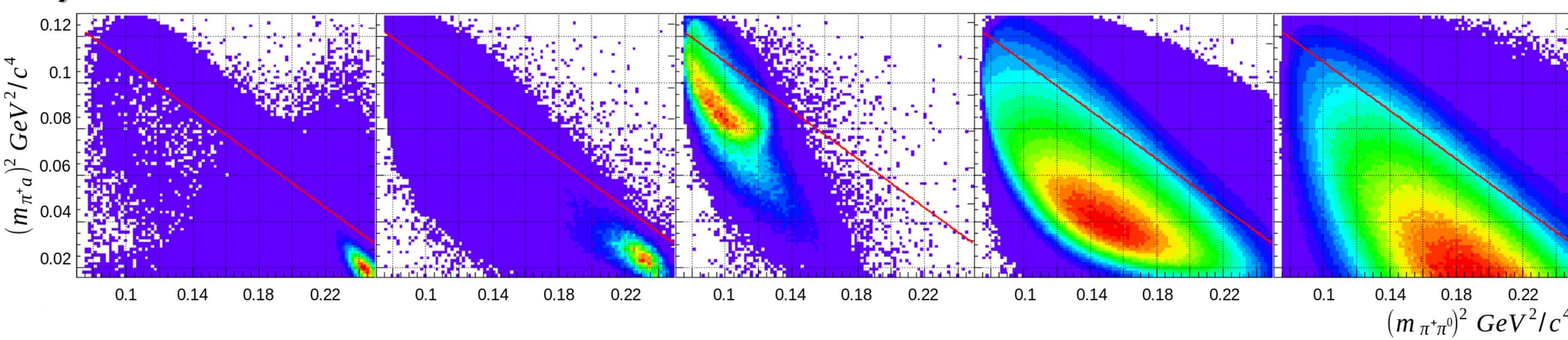
- $E_{mis} = E_{K+} - E_{\pi+} - E_{\pi 0} > 2.8$ GeV — Cut on missing energy
- $P^*_{\pi+} < 150\ MeV$, $P^*_{\pi 0} < 189\ MeV$ — Cuts on the momenta of pions in the K^+ rest frame againsts $K^+ \to \pi^+\pi^0$
- No signal in muon counters μC — to suppress $K^+ \to \mu^+\nu\pi^0$
- $E/p \leq 0.83$ — E- the energy of the shower, assosiated with the track, againsts $K^+ \to e^+\nu\pi^0$
- track is identified as π^+ in GAMS or in GDA-100
- $E_{GS} < 100$ MeV — the cut on the energy in the guard system - against $K^+ \to \pi^+\pi^0\pi^0$

a)



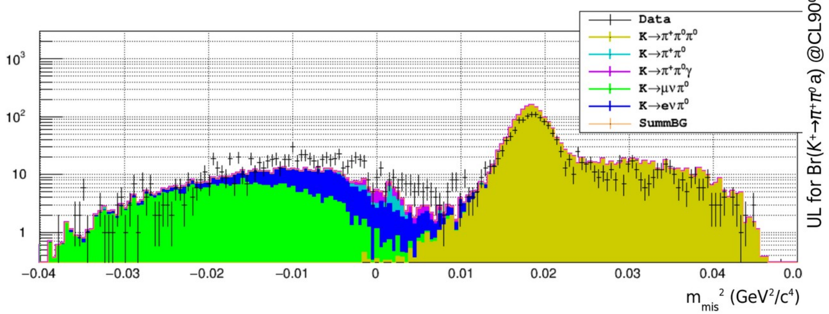
$K^+ \to \pi^+\pi^0 a$ m_a=0 MeV m_a=60 MeV

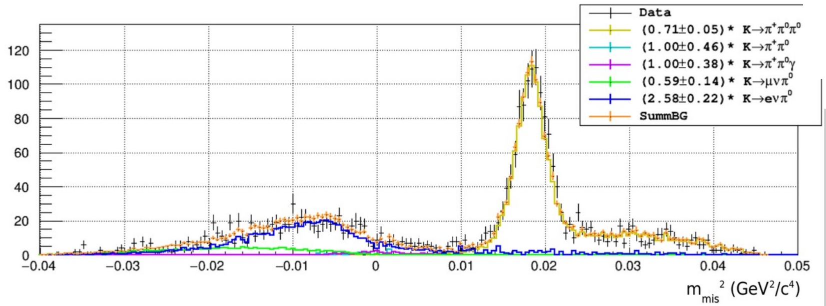
b)

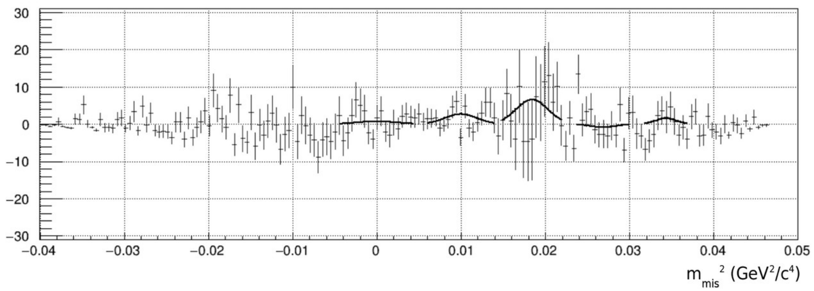


$K^+ \to \pi^+\pi^0$ $K^+ \to \pi^+\pi^0\gamma$ $K^+ \to \pi^+\pi^0\pi^0$ $K^+ \to \mu^+\nu\pi^0$ $K^+ \to e^+\nu\pi^0$

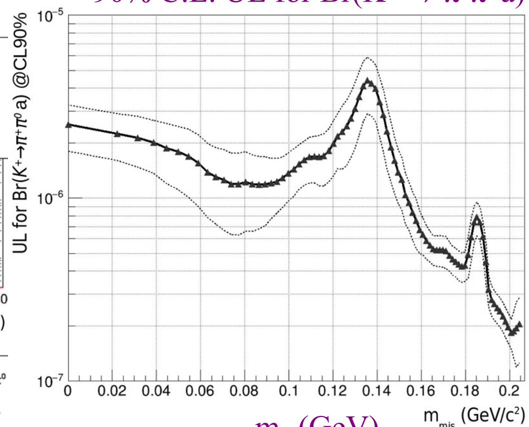
Search for the axion in $K^+ \to \pi^+\pi^0 a$ decay





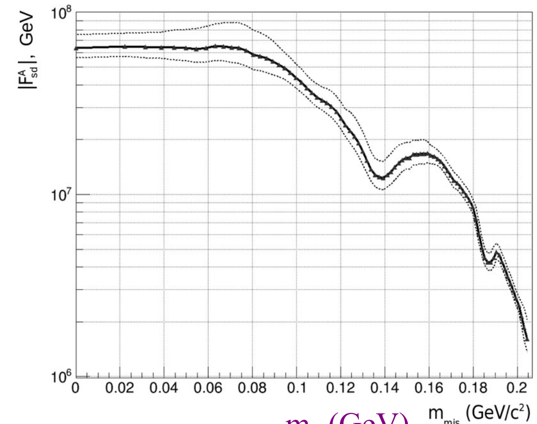


90% C.L. UL for $Br(K^+ \to \pi^+\pi^0 a)$



m_a (GeV)

LL for F^A_{sd} (GeV)



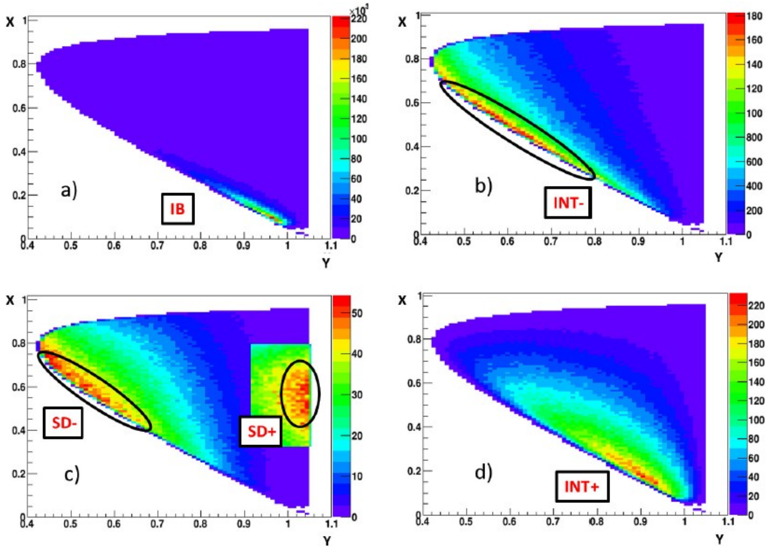
m_a (GeV)

The obtained Lower Limit $F^A_{sd} > 6.5 \cdot 10^7$ GeV for axion mass below 70 MeV , is the best among the HEP experiments: Phys. Rev. D **102** 015023 (2020).

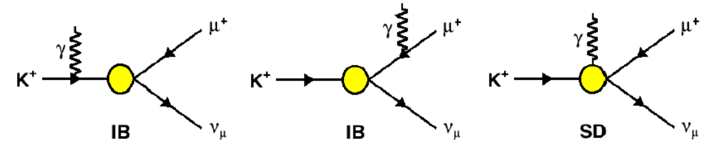
Process	F^V_{ij} (GeV)		F^A_{ij} (GeV)
$K^+ \to \pi^+\pi^0 a$	$\cdots$	BNL E-787	1.7×10^7
$\Lambda \to na$(decay)	6.9×10^6		5.0×10^6
$\Sigma^+ \to pa$	6.7×10^6		2.3×10^6
$\Xi^- \to \Sigma^- a$	1.0×10^7		1.3×10^7
$\Xi^0 \to \Sigma^0 a$	1.6×10^7		$\mathbf{2.0 \times 10^7}$
K-$\bar{K}$ (Δm_K)	$5.1 \times 10^{5\dagger}$		2.0×10^6
(ϵ_K)	$0.9 \times 10^{6\dagger}$		$\mathbf{4.4 \times 10^7}$

Supernova bound: In the neutron stars(NS) n, p, e, Λ coexist. $\Lambda \to n\,a$ new cooling mechanism of NS. Maximum during few seconds after SN explosion, when protoneutron star reaches T~ 0.1 MeV
SN1987A $F^A_{sd}, F^V_{sd} > 10^9$ GeV Model dependent !

Study of the $K^+ \to \mu^+ \nu \gamma$ decay



$$x = \frac{2E_\gamma^{cm}}{m_K};\ y = \frac{2E_\mu^{cm}}{m_K}$$

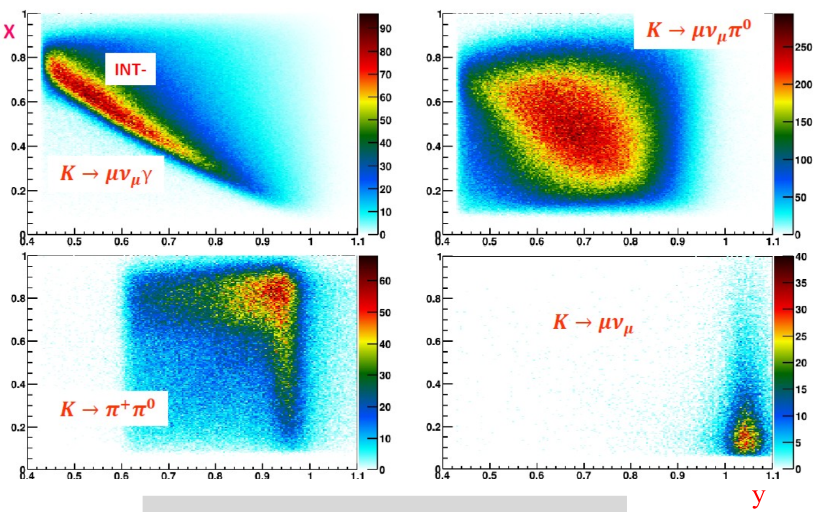


$$\frac{d\Gamma}{dxdy} = A_{IB} f_{IB}(x,y) + A_{SD}[(F_V+F_A)^2 f_{SD^+}(x,y) + (F_V-F_A)^2 f_{SD^-}(x,y)]$$
$$- A_{INT}[(F_V+F_A) f_{INT^+}(x,y) + (F_V-F_A) f_{INT^-}(x,y)]$$

$$f_{IB}(x,y) = \left[\frac{1-y+r}{x^2(x+y-1-r)}\right] \times \left[x^2 + 2(1-x)(1-r) - \frac{2xr(1-r)}{x+y-1-r}\right]$$
$$f_{SD^+}(x,y) = [x+y-1-r][(1-x)(1-y)+r]$$
$$f_{SD^-}(x,y) = [1-y+r][(x+y-1)(1-x)-r]$$
$$f_{INT^+}(x,y) = \left[\frac{1-y+r}{x(x+y-1-r)}\right] \times [(1-x)(1-x-y)+r]$$
$$f_{INT^-}(x,y) = \left[\frac{1-y+r}{x(x+y-1-r)}\right] \times [x^2-(1-x)(1-x-y)-r]$$

$$x = \frac{2E_\gamma^{cm}}{m_K};\ y = \frac{2E_\mu^{cm}}{m_K}$$

$$A_{IB} = \frac{\alpha}{2\pi}\Gamma_{K\mu 2}\frac{1}{(1-r)^2};\quad A_{SD} = \frac{\alpha}{2\pi}\Gamma_{K\mu 2}\frac{1}{4r(1-r)^2}\left(\frac{m_K}{f_K}\right)^2;\quad A_{INT} = \frac{\alpha}{2\pi}\Gamma_{K\mu 2}\frac{1}{(1-r)^2}\frac{m_K}{f_K};\quad r = \frac{m_\mu}{m_K}$$



Main background sources

$$\chi PTO(p^4):\quad F_V = \frac{\sqrt{2}M_K}{8\pi^2 F_\pi} = 0.096;\quad F_A = \frac{4\sqrt{2}M_K}{F_\pi}(L_9^r + L_{10}^r) = 0.042;\quad F_V - F_A = 0.054$$

$$\chi PTO(p^6):\quad F_V = F_V(0)(1+\lambda(1-x));\quad F_V(0) = 0.082;\quad \lambda = 0.4;\quad F_A = 0.034$$

VALUE	CL%	EVTS	DOCUMENT ID		TECN	CHG
−0.21 ±0.06		22K	DUK	2011	ISTR	-
• • • We do not use the following data for averages, fits, limits, etc. • • •						
−0.24 to 0.04	90	2588	ADLER	2000B	B787	+
−2.2 to 0.6	90		DEMIDOV	1990	XEBC	
−2.5 to 0.3	90		AKIBA	1985	SPEC	

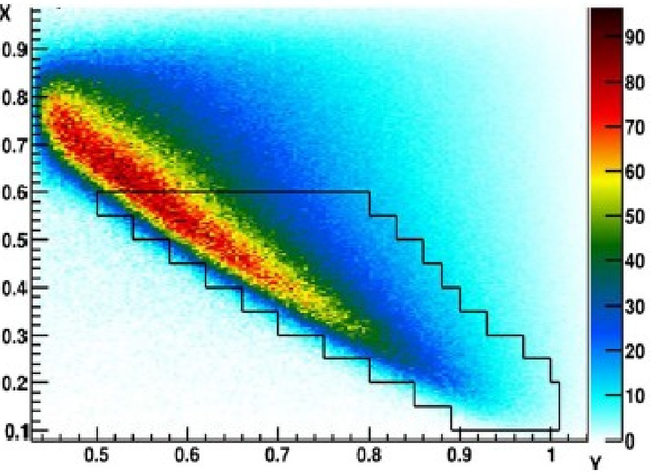
References:

DUK	2011	PL B695 59	Extraction of Kaon Formfactors from $K^- \to \mu\nu\gamma$ Decay at ISTRA+ Setup
ADLER	2000B	PRL 85 2256	Measurement of Structure-Dependent $K^+ \to \mu^+\nu_\mu\gamma$ Decay
DEMIDOV	1990	SJNP 52 1006	Measurement of the $K^+ \to \mu^+\nu\gamma$ Decay Probability
AKIBA	1985	PR D32 2911	A Study of the Radiative Decay $K^+ \to \mu^+\nu_\mu\gamma$

$K^+ \to \mu^+ \nu \gamma$ selection and analysis

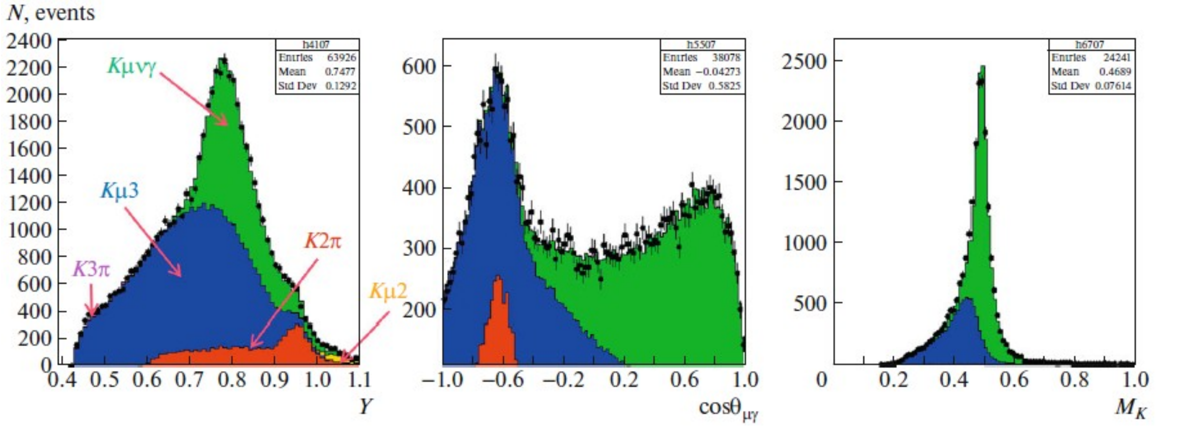
- 1 beam K^+ track
- 1 secondary track identified as μ in GAMS, GDA-100 and MC
- Decay vertex inside DV
- 1 e.m. shower in GAMS with E >1GeV not associated with charged track
- $E_{GS} < 10$ MeV ; $E_{EGS} < 100$ MeV

- <u>Fit procedure</u>
- x,y region is devided into strips Δx=0.05 (~12 MeV)
- plot y-disribution; select cuts $\{y_{min}, y_{max}\}$; plot $\cos\theta^*_{\mu\gamma}$; select $\cos_{min}$ cut; Plot M_K
- Simultaneous fit of the 3 histograms, parameters- N_{sig}, N_{bkg} both signal(IB) and background shapes are taken from MC
- to correctly estimate errors, fit only M_K – plot with initial parameters of the simultaneous fit



Geant3 MC: 22M sig. , 624M bkg.
only IB term in signal

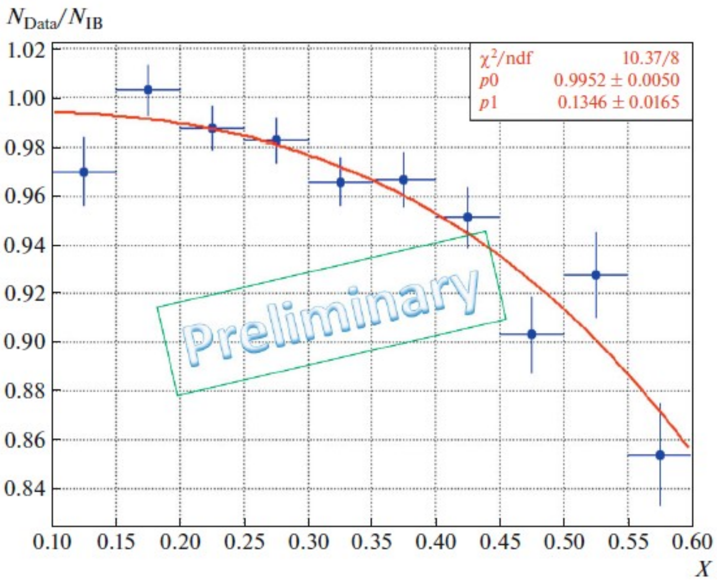
From the fits, in total 144115±380 signal events 25 < E^*_γ < 150 MeV



Strip #6 (0.35<x<0.4)

$$M_K^2 = (p_\mu + p_\nu + p_\gamma)^2$$
$$\vec{p}_\nu = \vec{p}_K - \vec{p}_\mu - \vec{p}_\gamma \ ; \ E_\nu = |\vec{p}_\nu|$$

$K^+ \to \mu^+ \nu \gamma$ decay, Fv-Fa extraction



N_{DATA} / N_{IB} ratio as a function of x(blue points)

Red line is the result of the fit with $p_{sig}(x)=p0(1+p1\cdot\phi_{INT-}(x)/\phi_{IB}(x))$
p0 is the normalization p0=0.9952 ± 0.005 ; p1=Fv-Fa=0.135±0.017
$\phi_{INT-}(x)$- x-distribution of reconstructed MC-signal weighted events
$w_{INT-}=(M_K/F_K)\ f_{INT-}(x_{true},y_{true})$; $\phi_{IB}(x)$- the same with $w_{IB\_}= f_{IB}(x_{true},y_{true})$

Systematics

- Non-ideal description of signal and background by MC: $1.3<\chi^2/NDF<1.7$

Stat. errors in each bin of N_{DATA}/N_{IB}-plot scaled with $\sqrt{(\chi^2/NDF)}$. New value Fv-Fa=0.138±0.026 (nominal 0.134±0.021) $\to \sigma_{shape}$ =0.012

- Width of -x- strips: Fv-Fa calculation repeated for 2 different values of width Δx=0.035, Δx=0.07 (nominal 0.05) $\to \sigma_{\Delta x}$ =0.008
- The fit range in x (number of -x- strips): remove one or two bins on the left(right) edge. $\to \sigma_x$ =0.005
- -y- limit in the strips: instead of maximizing $S/\sqrt{(S+B)}$ use FWHM from the signal MC $\to \sigma_y$ =0.005
- Effect of INT+ : INT+ term is added to N_{DATA} / N_{IB} fit. The BNL E787 value |Fv+Fa|= 0.165±0.013 is used (±0.178) $\to \sigma_{INT+}$=0.018

$\to \sigma_{SYS}$ =0.024

$K^+ \to \mu^+ \nu \gamma$ decay Fv-Fa

"OKA" $F_V\text{-}F_A = 0.135 \pm 0.017_{stat} \pm 0.024_{syst}$

χPT O(p^4) $F_V = \frac{\sqrt{2} M_K}{8\pi^2 F_\pi} = 0.096$; $F_A = \frac{4\sqrt{2} M_K}{F_\pi}(L_9^r + L_{10}^r) = 0.042$

$F_V\text{-}F_A = 0.054$ 2.8 σ difference

Lattice calcullations: $F_V\text{-}F_A = (0.083 \pm 0.013) - (0.019 \pm 0.012) \cdot x_\gamma$ Phys. Rev. D 103, 014502 (2021) (1.8σ)

The measured value is in a reasonable agreement with ISTRA+ result: $F_V\text{-}F_A = 0.21 \pm 0.04_{stat} \pm 0.04_{syst}$ (1.17 σ)

And with a (model dependent) result of BNL E865 ($K^+ \to \mu^+ \nu e^+ e^- + \mu^+ \nu e^+ e^-$) $F_V\text{-}F_A = 0.077 \pm 0.026$ (1.47 σ)

Expect doubling of the statistics by the end of 2024

$K^+ \to \pi^0 \mu \nu \gamma$ (Kμ3γ)

This decay complements Ke3γ much better studied by OKA and NA62. OKA publications: JETP Lett. v.116 No 9 (2022), EPJ C(2021) 81.
K^+μ3γ was first seen by ISTRA+ and KEK K470 in 2006 and later by BNL E787 in 2010.
For K^0 was discovered by NA48 in 1998 and later improved by KTeV in 2005
There are calculations of Branching and T-odd asymmetry: $\xi = \vec{p}_\gamma \cdot (\vec{p}_l \times \vec{p}_\pi)/m_K^3$ $\qquad A_\xi = \frac{N_{\xi>0} - N_{\xi<0}}{N_{\xi>0} + N_{\xi<0}}$

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

VALUE (10^{-5})	CL%	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1.25 ± 0.25 OUR AVERAGE							
1.10 ±0.32 ±0.05		23	[1] ADLER	2010	B787		$30 < E_\gamma < 60$ MeV
1.46 ±0.22 ±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 ±0.5 ±0.6		125	SHIMIZU	2006	K470	+	$E_\gamma > 30$ MeV; $\Theta_{\mu\gamma} > 20°$
<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 ±0.74 ±0.12) $\times 10^{-5}$ obtained in the kinematic region $E_\gamma > 20$ MeV, and then theoretical $K_{\mu 3\gamma}$ spectrum has been used. Also B($K^+ \to \pi^0 \mu^+ \nu_\mu \gamma$) = (1.58 ±0.46 ±0.08) $\times 10^{-5}$, for $E_\gamma > 30$ MeV and $\theta_{\mu\gamma} > 20°$, was determined.

[2] Obtained from measuring B($K_{\mu 3\gamma}$) / B($K_{\mu 3}$) and using PDG 2002 value B($K_{\mu 3}$) = 3.27%. B($K_{\mu 3\gamma}$) = (8.82 ±0.94 ±0.86) $\times 10^{-5}$ is obtained for 5 MeV $< E_\gamma <$ 30 MeV.

Kl3γ theory, experiment E^*_γ>30 MeV $\theta_{\mu\gamma}$>20°	Br Kμ3γ x10^5	Br Ke3γ x10^4	A_ξ Kμ3γ QED FSI	A_ξ Ke3γ QED FSI
Bijnens et al. (1993) χPT O(p^6)	1.9	2.8		
Braguta et al. (2002) χPT O(p^4)	2.15	3.18	1.14x10^{-4}	-0.59 x10^{-4}
Khriplovich, Rudenko (2011)	1.81± 0.2	2.72 ± 0.1	2.38 x 10^{-4}	-0.30 x 10^{-4}
NA62		3.087± 0.037		< 8.6 x 10^{-3}
OKA	**2.0±0.1**	**2.98± 0.094**	**< 0.1**	**< 13 x 10^{-3}**

From Braguta et al. (2003) for NP Kμ3γ :

$A_\xi = -(3.6\cdot 10^{-3}\,\mathrm{Im}(g_S) + 1.2\cdot 10^{-2}\,\mathrm{Im}(g_P) + 1.0\cdot 10^{-2}\,\mathrm{Im}(g_V + g_a))$

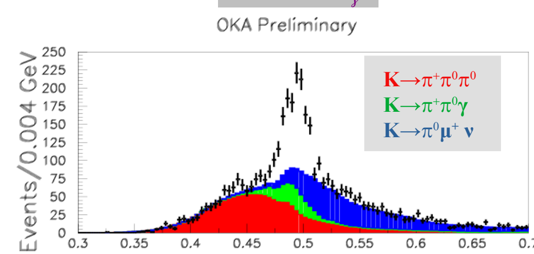
Sensitivity of Ke3γ to NP is not as good :

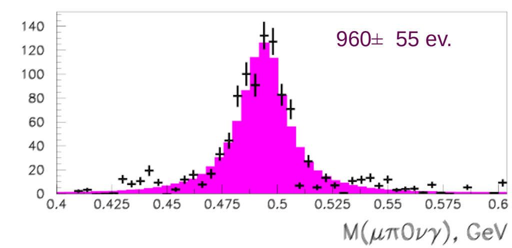
$A_\xi = -(2.9\cdot 10^{-6}\,\mathrm{Im}(g_S) + 3.7\cdot 10^{-5}\,\mathrm{Im}(g_P) + 3.0\cdot 10^{-3}\,\mathrm{Im}(g_V + g_a))$

Event selection

- 1 beam K^+ track
- 1 secondary track identified as μ in GAMS, GDA-100 and μC
- Decay vertex inside DV
- 3 e.m. shower in GAMS with E > 0.6GeV not ass. with track
- π^0 identification $|m_{\gamma\gamma} - m_{\pi 0}| <$ 15 MeV (best combination)
- $E_{miss} > 0.5$ GeV
- The position of radiative photon at GAMS surface is not near beam hole nor at the boudary
- $E_{GS} < 10$ MeV ; $E_{EGS} < 100$ MeV
- Number of additional track segments after spectrometer magnet is zero
- Miss-mass $(P_K - P_{\pi+} - P_{\pi 0})^2 < 0.014\ GeV^2$ (against $K \to \pi^+\pi^0\pi^0$ bkg)

$30\ MeV < E^*_\gamma$





$K \to \pi \mu\nu \gamma$ decay study (Preliminary)

Branching : The decay $K \to \mu^+ \nu \pi^0$ is used for the normalisation

$Br(K\mu3\gamma)/Br(K\mu3) = (4.5 \pm 0.25\ (stat)) \cdot 10^{-4}$, $30\ MeV < E^*_\gamma < 60\ MeV$

Using PDG value: Br(Kμ3) = 3.352%:

$Br(K\mu3\gamma) = (1.49 \pm 0.085\ (stat)) \cdot 10^{-5}$, $30\ MeV < E^*_\gamma < 60\ MeV$

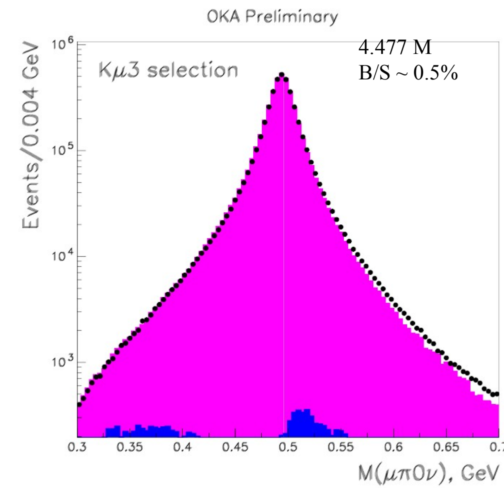
in agreement with ISTRA+ measurement, but statistical error is 3 times smaller.

For the comparison with theory :

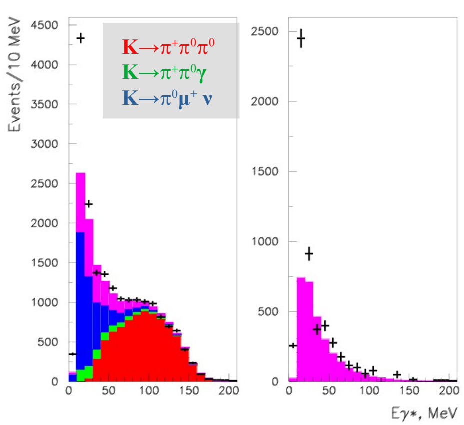
$Br(K\mu3\gamma) = (2.0 \pm 0.1\ (stat)) \cdot 10^{-5}$, $E^*_\gamma > 30\ MeV$, $\theta_{\mu\gamma} > 20^\circ$

Bijnens et al. χPT $O(p^6)$ **1.9×10^{-5}**, Braguta et al. χPT $O(p^4)$ **2.15×10^{-5}**, Khriplovich et al. **1.8×10^{-5}**

For the T-odd asymmetry the result is: **$A_\xi = -0.006 \pm 0.069$ ($A_\xi < 0.1$ 90% C.L.)**

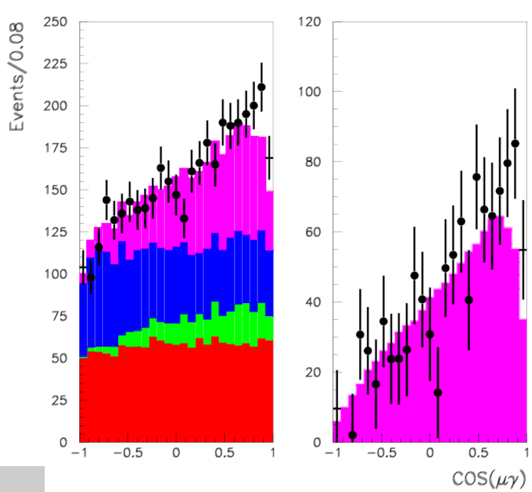


$\mu^+ \nu \pi^0$ invariant mass



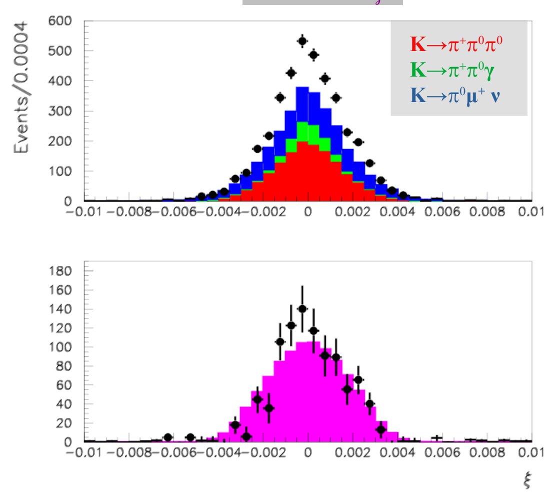
Distribution over **E*$_\gamma$** - photon energy in the kaon rest frame

$30\ MeV < E^*_\gamma$



$\cos(\theta^*_{\mu\gamma})$ distribution

$30\ MeV < E^*_\gamma$

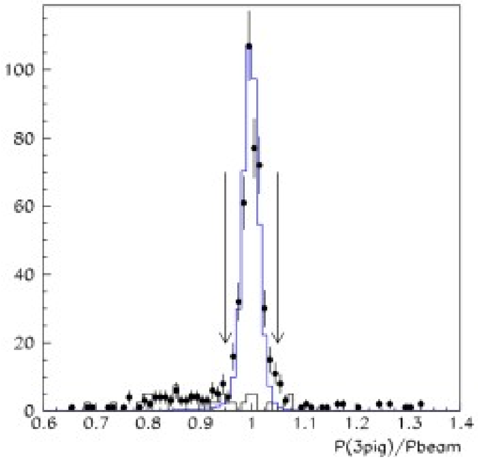


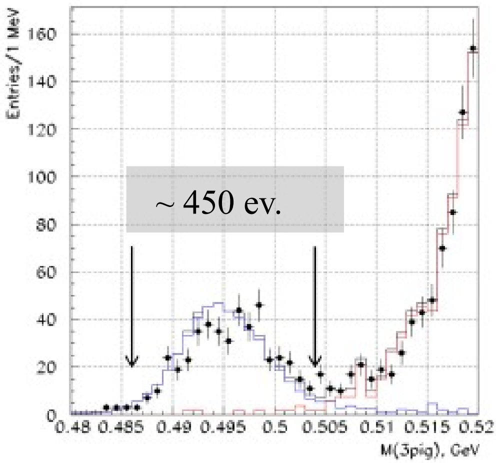
Distribution over $\xi = \vec{p}_\gamma \cdot (\vec{p}_l \times \vec{p}_\pi)/m_K^3$

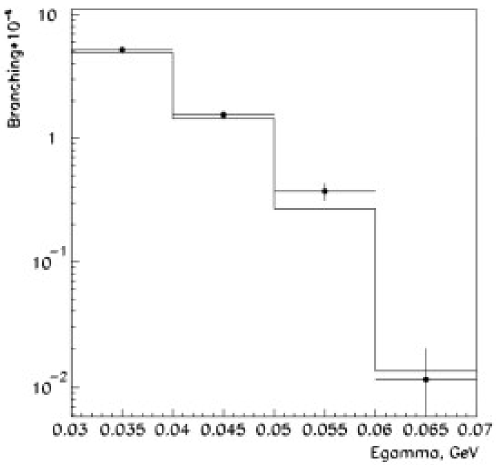
Study of the decays $K^+ \to \pi\pi\pi\,\gamma$

G. D'Ambrosio, G. Ecker, G. Isidori, H. Neufeld "The present experimental status of K3pig decays is rather meager"
χPT $O(p^4)$ "generalized bremsstrahlung"

$K^+ \to \pi^+\pi^+\pi^-\gamma$ was first found in ITEP Xenon BC В.В. Бармин и др., ЯФ 50(1989)679-682
7 ev. $E^*_\gamma \sim$ 5-10 MeV, Br. measured







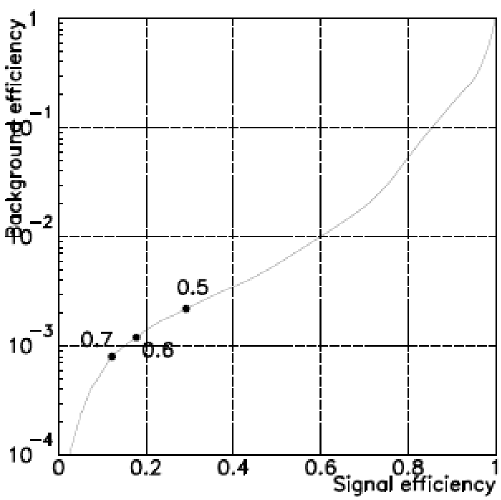
With normalization on $N(K \to 3\pi) \sim 20M$
$Br(K^+ \to \pi^+\pi^+\pi^-\gamma) = (7.1 \pm 0.4_{stat} \pm 0.3_{syst}) \cdot 10^{-6}$ $E^*_\gamma > 30$ MeV
χPT $O(p^4)$ $6.65 \cdot 10^{-6}$

Study of this decay is being continued on ~20 times higher statistics of NA62

$K^+ \to \pi^+\pi^0\pi^0\gamma$ decay   Eur.Phys.J.C 84 (2024) 4, 345

Complementary to $K^+ \to \pi^+\pi^+\pi^-\gamma$, less charged particles in the final state

$K^- \to \pi^-\pi^0\pi^0\gamma$ searched for at ISTRA В.Н. Болотов и др., Письма в ЖЭТФ, 1985 т.42, вып.9, с.390-392
5 ev. E^*_γ >10 МэВ, Br. estimated



Events selection (started from **3.6·10⁹** events)

- 1 beam K^+ track
- 1 secondary, θ>2 mrad, $\not\mu$ (μC), $\not e$ (E/p GAMS)
- Decay vertex inside DV, CDA < 1cm.
- 5 e.м. showers in GAMS E > 0.5 GeV not ass. with a track

Selection of $\pi^0\pi^0$: $(m_{\gamma1\gamma2} - m_{\pi0})^2 + (m_{\gamma3\gamma4} - m_{\pi0})^2$ (best combination)

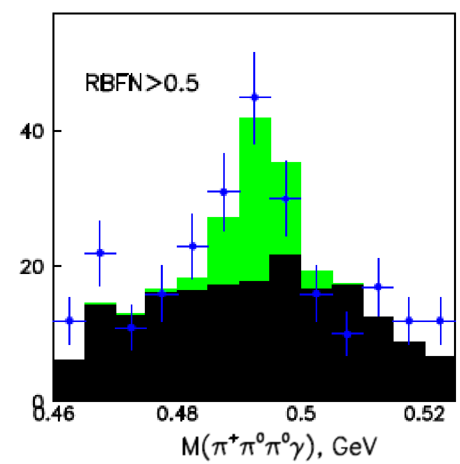
230K events, main background - $K \to \pi^+\pi^0\pi^0$ (x 5000)

Then NN (Radial Basis Function Network RFBN) is used

Input parameters for NN:

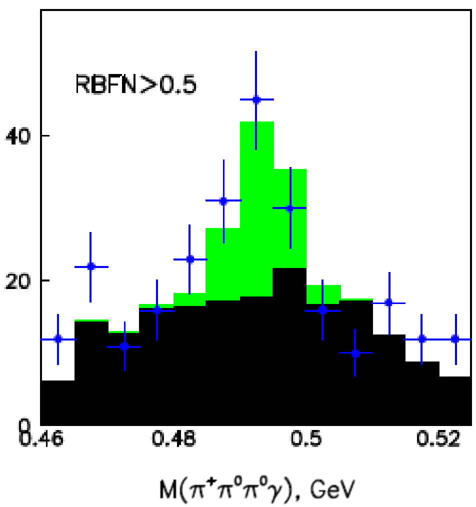
- $\Delta E = E_{\pi+} + \Sigma E_{\gamma i} - E_{beam}$
- $E_{\gamma 5}$ - energy of free (5-th) gamma
- $d_{\gamma 5}$ - distance from 5-th gamma to the track on the GAMS plane
- χ^2 of the shower shape fit for the 5-th gamma
  χ^2 of the $K^+ \to \pi^+\pi^0\pi^0$ 3C- fit
  χ^2 of the $K^+ \to \pi^+\pi^0\pi^0\gamma$ 3C- fit
- $M(\pi^+\pi^0\pi^0)$

NN performance : with RFBN>0.6 the background is suppressed by ~1000 with a signal efficiency of 0.2

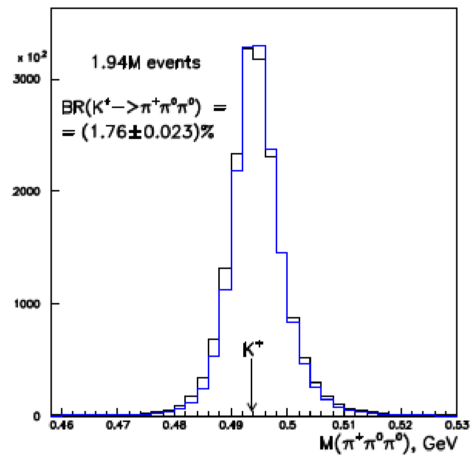


53.8 ± 13 events in the peak.
p-value of the no-signal hypothesis is $9 \cdot 10^{-5}$

Распад $K^+ \to \pi^+\pi^0\pi^0\gamma$ Eur.Phys.J.C 84 (2024) 4, 345



53.8 ± 13 ev.

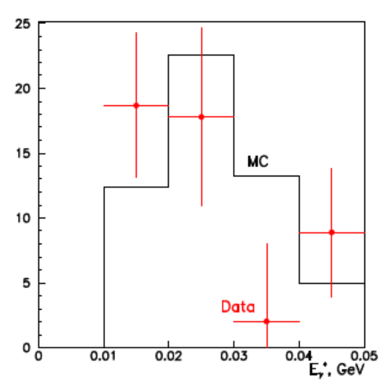


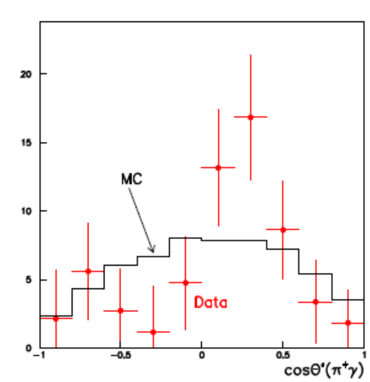
With normalization on $N(K^+ \to \pi^+\pi^0\pi^0) \sim 2M$

$Br(K^+ \to \pi^+\pi^0\pi^0\gamma) = (3.7 \pm 0.9_{stat} \pm 0.3_{syst}) \cdot 10^{-6}$ $E^*_\gamma > 10$ MeV

$Br(\chi PT\ O(p^4)) = 3.76 \cdot 10^{-6}$

The differential spectra over E^*_γ and $\cos\theta_{\pi\gamma}$ in the K^+ rest frame are also obtained





The following results have been obtained by the OKA collaboration:

✔ Search for the ALP in the decay $K^+ \to \pi^+\pi^0 a$ is performed. No signal found, 90% C.L upper limit $Br < 2.5\cdot 10^{-6} \div 2\cdot 10^{-7}$ for the ALP mass from 0 to 200 MeV. A lower limit for the F^A_{sd} - coupling constant of the axion to the axial sd current is $F^A_{sd} > 6.5\cdot 10^7$ GeV for the ALP mass below 70 MeV.

✔ The radiative decay $K^+ \to \mu^+ \nu \gamma$ is studied on statistics of ~144K events for 25 MeV < E^*_γ < 150 MeV .
A destructive interference between IB and SD- is clearly seen. The difference of the vector and axial vector constants Fv-Fa is measured:

$$F_V - F_A = 0.135 \pm 0.017_{stat} \pm 0.024_{syst}$$

which is 2.8 σ from χPT $O(p^4)$ and 1.8 σ from Lattice .

✔ The decay $K^+ \to \mu^+ \nu \pi^0 \gamma$ is studied on statistics of ~1K events for $E_\gamma > 30$ MeV region.
Branching fraction is measured:

$$Br(K\mu3\gamma) = (1.98 \pm 0.1\ (stat)) \cdot 10^{-5}$$

To be compared with χPT $O(p^4)$ $2.15 \cdot 10^{-5}$; χPT $O(p^6)$ $1.9 \cdot 10^{-5}$
An upper limit for the CP-odd asymmetry is obtained:

$$A_\xi = -0.006 \pm 0.069 \quad (A_\xi < 0.1 \ \ 90\%\ C.L.)$$

✔ The decay $K^+ \to \pi^+\pi^0\pi^0 \gamma$ is seen for the first time ~50 events with $E_\gamma > 10$ MeV.
Branching fraction is measured:

$$Br(K^+ \to \pi^+\pi^0\pi^0 \gamma) = (3.7 \pm 0.9_{stat} \pm 0.3_{syst}) \cdot 10^{-6} \quad E^*_\gamma > 10\ MeV$$

To be compared with $Br(\chi PT\ O(p^4)) = 3.76 \cdot 10^{-6}$

✔ The decay $K^+ \to e^+\nu\pi^0\pi^0\pi^0$ is searched for . No events found. $Br(K^+ \to \pi^+\pi^0\pi^0 \gamma) < 5.4 \cdot 10^{-8}$
(See talk of A. Kulik on Thursday morning session)

The work is supported by the RSCF Grant № 22-12-0051