Search for the light invisible axion-like particle in the $K^+ \to \pi^0\pi^+a$ decay on the «OKA» setup

Ilia Tiurin
Institute for High Energy Physics, Protvino, Russia
«OKA» collaboration (IHEP, INR, JINR)

MISP 2024
Voronovo, Russia
04.III, 2024

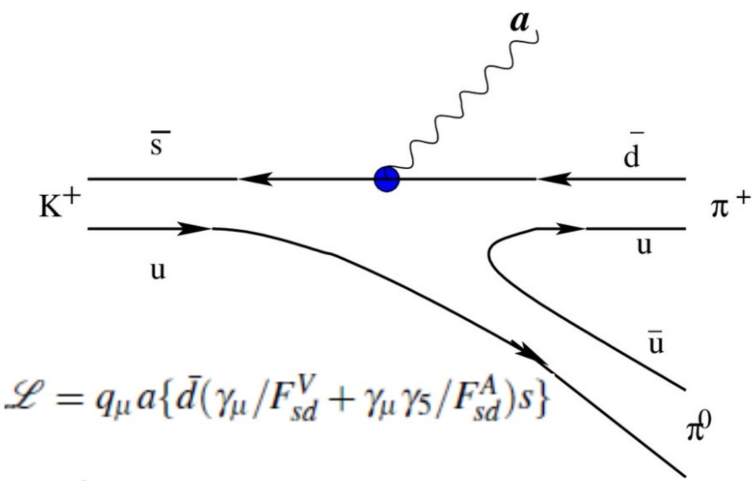
Introduction

The QCD Axion is a hypothetical pseudoscalar particle, that was intoduced to solve the strong CP problem (Peccei-Quinn, 1977) [1].

It’s properties are described by the decay constant f_a , related to the scale of Peccei-Quinn (PQ) symmetry breaking scale Λ_{PQ}: $f_a = \Lambda_{PQ}/4\pi$.

The QCD axion mass $m_a \sim m_\pi f_\pi/f_a$. It decays to two photons, the decay time is

$$\tau^a \sim 2^8 \pi^3 f_a^2/(\alpha m_a^3).$$



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

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

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

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

If axion is a candidate to Dark Matter Particle: $\tau^a \sim 13.8$ Gyr and $m_a < 10$ eV.

Axion also has couplings to quark currents, in particular to the *sd* flavour changing neutral current (*FCNC*). There is a vector and axial vector coupling (left picture), where q_μ – axion 4-momentum, F^A and F^V – effective constants, with $F^{A/V} = 2f_a/C^{A/V}$ being model-dependent constants.

Introduction

Due to parity conservation in QCD the decay $K^+ \to \pi^0\pi^+ a$ is sensitive to the axial-vector coupling while much better constrained decay $K^+ \to \pi^+ a$ tests the vector coupling [2].

A more general models of axion-like particles (ALP) consider cases in which the axion mass is not set by QCD dynamics only, but by some other mechanism. These models have two free parameters: m_a and f_a. Then there is much softer limit on axion mass: $m_{ALP} < 1\ GeV/c^2$ [3].

The only result on the axion search in $K^+ \to \pi^0\pi^+ a$ a decay mentioned in PDG [4] is that of BNL-787 [5]. Better upper limits can be extracted from ISTRA+ paper [6], devoted to the search for pseudoscalar sgoldstino. The result is ~ Br < 10^{-5} at 90% C.L.

We assume, that the ALP has sufficiently long life-time and decays outside the detector. In our study we rely on [3, 7] where the phenomenology of the $K^+ \to \pi^0\pi^+ a$ decay are considered in detailes.

IHEP PS U-70

IHEP

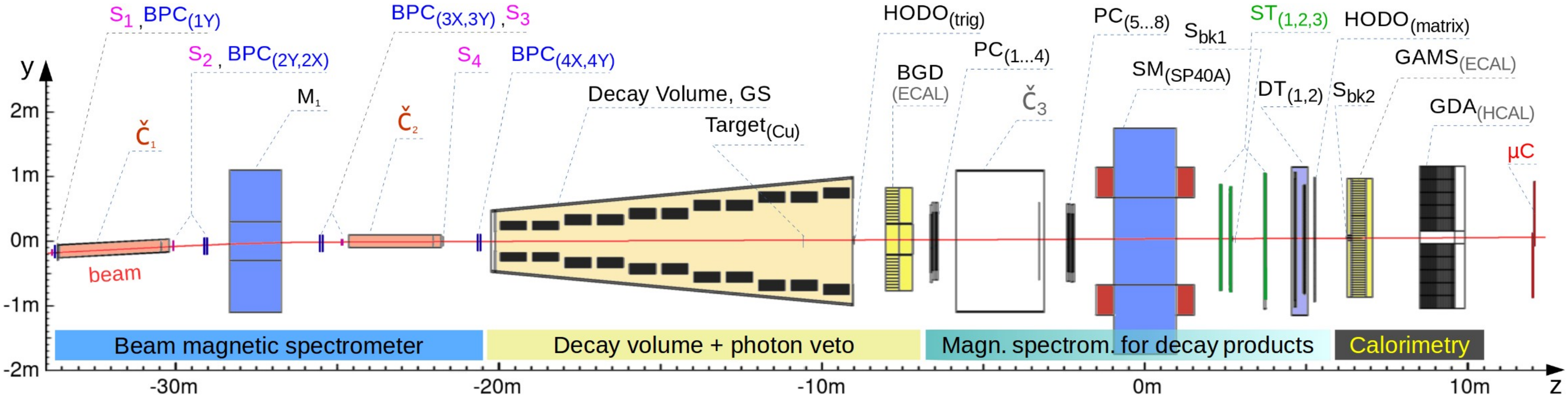
U-70 ring

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

Detector is located in positive RF-separated beam [8] with 12.5% of *K*-meson

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

OKA detector



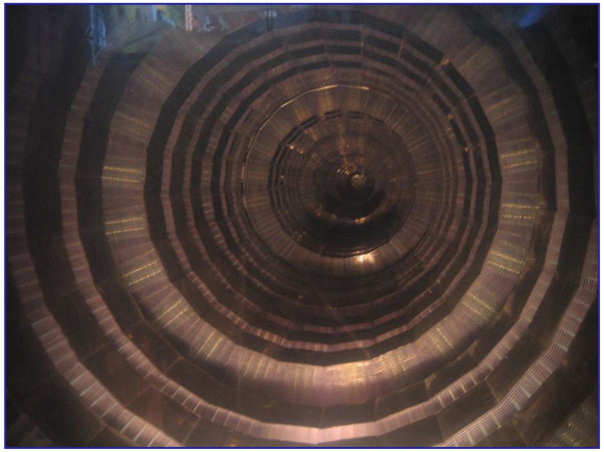
$$Trg = S_1 \cdot S_2 \cdot S_3 \cdot S_4 \cdot \bar{\check{C}}_1 \cdot \check{C}_2 \cdot \bar{S}_{bk} \cdot (E_{GAMS} > 2.5GeV)$$

$S_1 - S_4$ 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. GDA (HCAL) and 8. Muon counters μC;
More about OKA setup can be found in [9–11].

Decay Volume with Veto system

DV: 11m, 15m^3;
Filled with Helium;
Veto: 670 Lead-Scintillator sandwiches 20×(5mm Sc + 1.5mm Pb), WLS readout.



Inside

Veto system

Event selection

The 3.65×10^9 events with kaon decays are logged, 8×10^8 events are reconstructed with a single charged particle in the final state.

Single beam track, single secondary track with the decay angle > 4 mrad and with the vertex matching distance (CDA) below 12.5mm. A moderate chi-square cut for the charged track quality is applied.

Absence of extra track segments behind SM magnet.

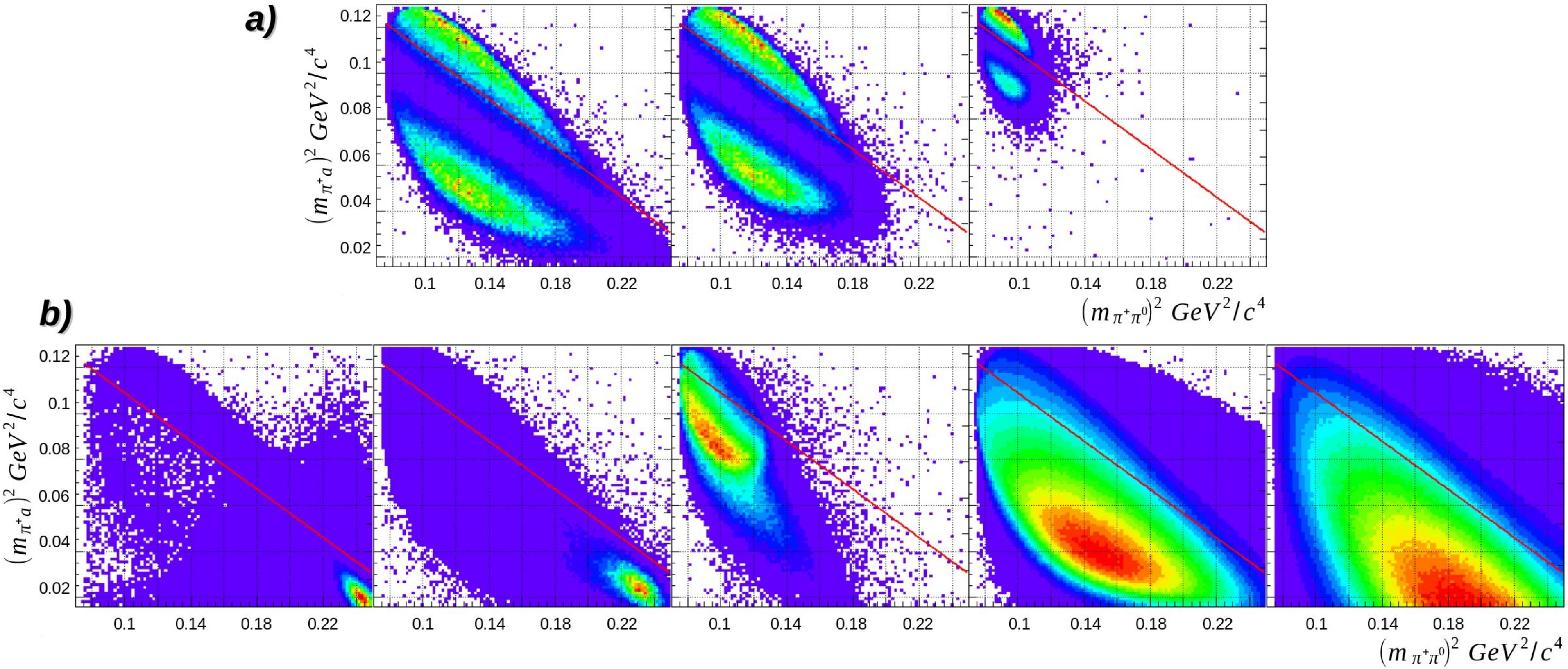
The decay vertex position is required to be inside DV.

The beam particle momentum: $17.0 < p_{beam} < 18.6$ GeV/c.

The number of showers in e/m calorimeters not assotiated with track equals 2 to select single π^0 in the final state. For this events: $|m_{\gamma\gamma} - m_{\pi 0}| < 15$ MeV/c^2.

After all selections we obtain $3 \cdot 10^7$ $K^+ \rightarrow \pi^0\pi^+$ events.

Selecting the decay of interest



The distribution of $(m_{\pi+a})^2$ vs. $(m_{\pi+\pi0})^2$ for reconstructed events of the axion (plots ***a***) for a set of masses $m_a = \{0, 60, 160\}$ MeV/c^2 and (plots **b**) for the main bkg processes ($K^+ \to \pi^+\pi^0$, $K^+ \to \pi^+\pi^0\gamma$, $K^+ \to \pi^+\pi^0\pi^0$, $K^+ \to \mu^+\nu_\mu\pi^0$, $K^+ \to e^+\nu_e\pi^0$) according to MC simulation with the matrix elements. Strong suppression of the bkg is achieved.

Selecting the decay of interest

In order to disentangle $K^+ \rightarrow \pi^0\pi^+a$ signal from its main backgrounds $K^+ \rightarrow \pi^0\pi^+$ and $K^+ \rightarrow \pi^0\pi^0\pi^+$ two kinematic cuts are applied: the missing energy $E_{mis} = (E_{K+} - E_{\pi+} - E_{\pi0}) > 2.8$ GeV; both momentum $p_{\pi0} < 150$ MeV/c, $p_{\pi+} < 189$ MeV/c in kaon rest frame.

To suppress misidentified events from $K^+ \rightarrow \mu\nu\pi^0$ a requirement of absence of signal from muon counters μC matched with the charged track is used.

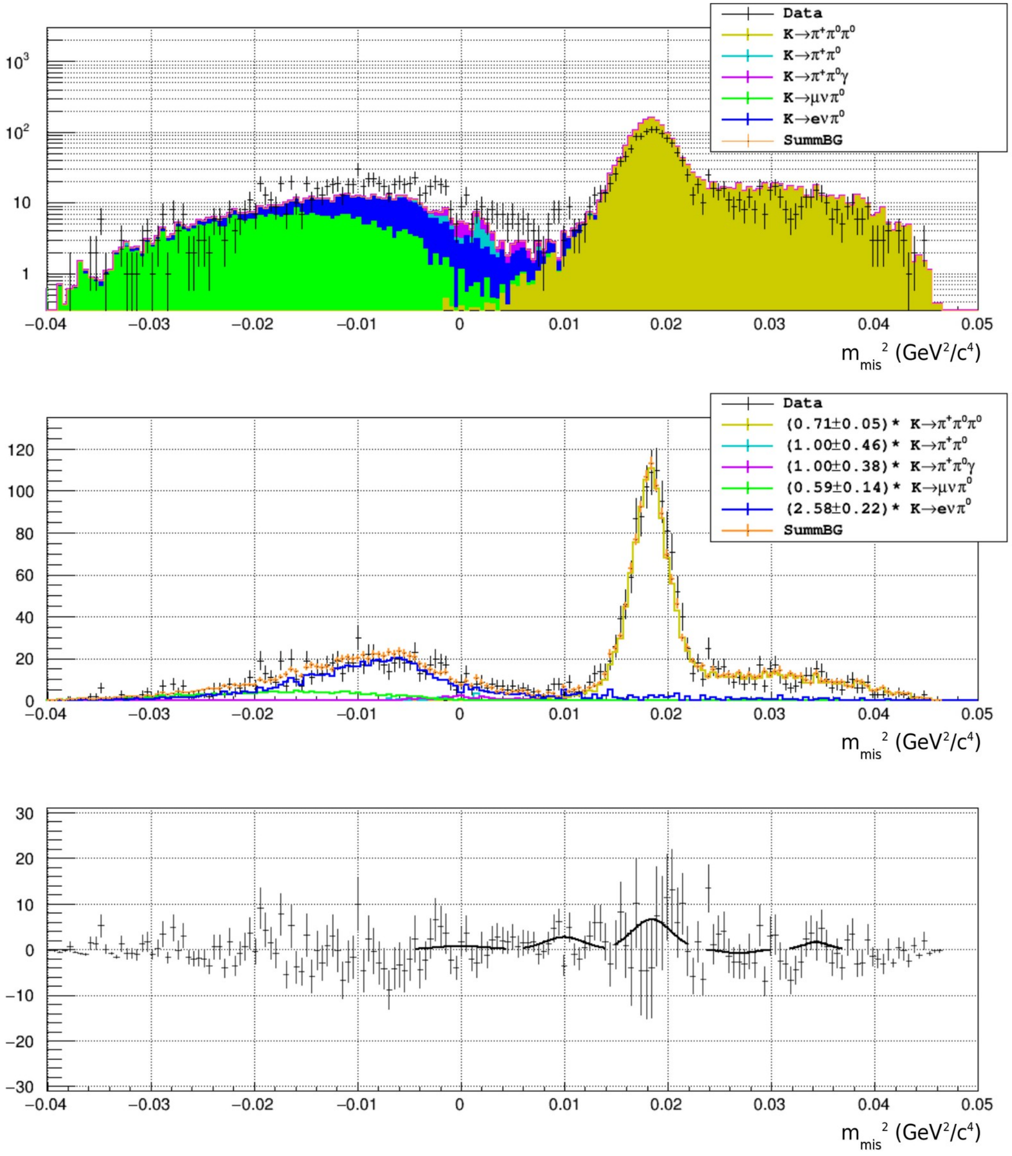
To suppress e^+ (K_{e3}) the events with $E^{cl}{}_{GAMS}/p > 0.83$ are discarded. Then, if the number of cells in the shower $N > 4$ or $E\ \ > 1.9$ GeV, the track is identified as π^+ with an “earlier” hadron shower in GAMS.

Otherwise one shower in GDA, matching the track within 22cm and with either number of cells $N_{GDA} > 4$ or with $E_{GDA}/p > 0.67$ ($N_{GDA} > 1$) is required.

This cut rejects muons and selects pions with “late” shower in GDA.

Total energy deposition in GS below the noise threshold of 100 MeV is required to suppress events with photons escaping the acceptance of calorimeters.

Fits of the missing mass spectrum



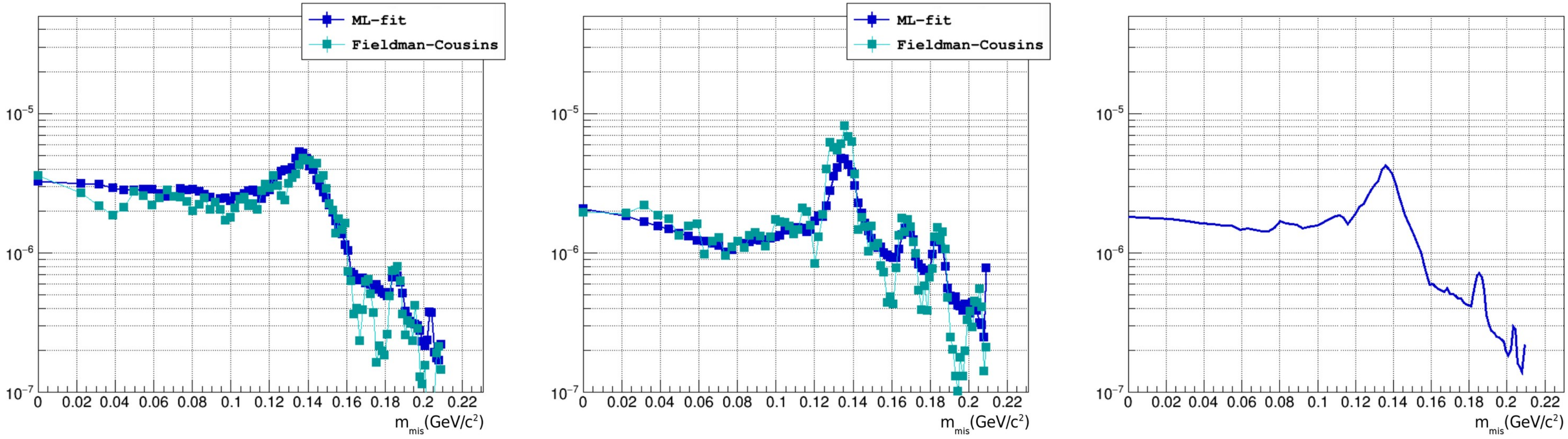
For first run!

Up: the resulting m^2_{miss}-distribution. Data – points, bkg's – colored. The stack plot is used to highlight strongly suppressed processes. The normalisation of the MC-bkg is done using the number of $K^+ \to \pi^+\pi^0$ events before the main cuts.

Middle: the result of the tuning of the relative magnitudes for the bkg processes. The corresponding scaling factors are depicted with their fit errors.

The **Bottom** plots demonstrate the difference between the experiment and the sum of the tuning bkg processes. For the illustration, the results of the signal fit are shown for five positions of m^2_{miss}.

Fits of the missing mass spectrum

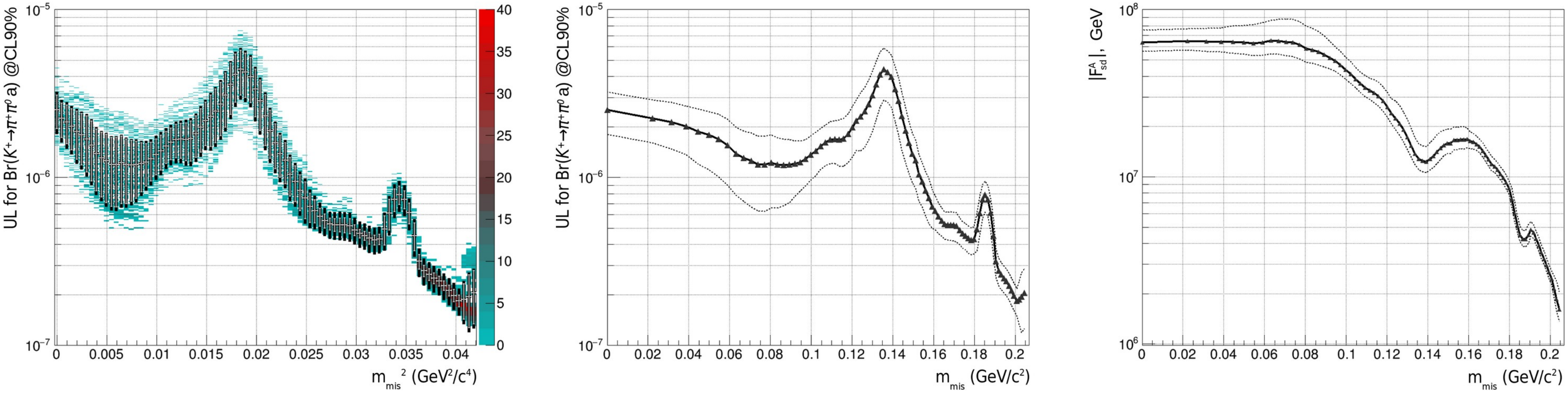


The 90% CL upper limits for the $K^+ \to \pi^+\pi^0 a$ branching for two runs (left and middle), right – for the statistical sum of two runs. The Fieldman-Cousins method [12] is used for the comparison.

The one-sided upper limit for the number of signal events corresponding to the 90% CL is constructed as $N_{UL@90\%CL} = max(N_P, 0) + 1.28\sigma_{Np}$, where N_P and σ_{Np} are evaluated from the ML fit, being the number of signal events and its error.

This approach is chosen because it allows to make a profit from the knowledge of the signal shape in contrast to the F-C method, where only central region of the signal is used. The additional profit is that the obtained parameters N_P, σ_{Np} are convinient for the statistical combination of two runs.

Branching calculations



The 90% CL upper limits for the $K^+ \to \pi^+\pi^0 a$ branching. The scatter plot (**left**) demonstates the systematics arising from variation of variables used for the selection criteria (flat distribution of 20 variables within ±1σ). The RMS of the distribution at each m^2_{miss} is indicated by gray bars superimposed over the scatter plot, while the remaining systematic errors are added quadratically and shown with black bars. **Middle** plot demonstrates the final result: the black triangles correspond to the mean value from the variation of the selection criteria, while the systematical errors are depicted with dotted lines. **Right** plot indicates the corresponding lower limit on the $|F^A_{sd}|$ parameter together with the corresponding systematic error.

Preliminary results and conclusion

- The OKA data is analyzed to search for the light ALP;
- A peak search method in the missing mass spectrum is used in analysis;
- No signal is observed, and the UL on Br’s in the mass range 0-200 MeV/c^2 are set.
- The current best UL on the Br($K^+ \rightarrow \pi^0\pi^+a$) come from the ISTRA+ [6].
- The only result on the axion search in $K^+ \rightarrow \pi^0\pi^+a$ decay mentioned in PDG [4] is that of BNL-787 experiment [5];
- Both searches were performed in the uniform phase-space distribution hypothesis, which appeared to be a rough approximation;
- Our analysis uses the realistic matrix element from [3,7] and improves the limit from ISTRA+ by a factor of 3.5-10 depending on the axion mass;
- Using the expression from [3], relating F^A_{sd} and the Br, we calculated the lower limits for $|F^a_{sd}|$. The limit is about $6.4 \cdot 10^7$ GeV for axion mass below 70 MeV/c^2, which is the best limit for $|F^a_{sd}|$ among the HEP experiments [7].

References

[1] Peccei R D, Quinn H R 1977 Phys. Rev. Lett. 38 1440-1443;

[2] Cortina Gil E at al. (NA62) 2021 JHEP03 058;

[3] Chiatto P L 2021 thesis UNIMORE/etd-10072021-091154;

[4] Workman R L et al. 2022 (Particle Data Group), Prog. Theor. Exp. Phys. 2022(8), 083C01;

[5] Adler S et al. 2001 Phys. Rev. D 63 032004;

[6] Tchikilev O G et al. 2004 Phys. Lett. B 602 149-156;

[7]Camalich J M et al. 2020 Phys. Rev. D 102 015023;

[8] A. Ageev et al., in *Proceedings of the Particle Accelerator Conference* (RuPAC, Zvenigorod, 2008), p. 282;

[9] V. Kurshetsov et al. (OKA Collab.), PoS (KAON09) 051;

[10]. A. S. Sadovsky et al., Eur. Phys. J. C **78**, 92 (2018);

[11] Donskov S V et al. 2016 Instrum. Exp. Tech. 59(4), 519-526;

[12] Feldman G J, Cousins R D 1998 Phys. Rev. D 57(7) 3872-3889;

Thank you for your attention!