Transverse muon polarization in $K^+ \to \mu^+ \nu_\mu \gamma$: scanning over the Dalitz plot

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We study the potential of the measurement of the transverse muon polarization P_T in the $K \rightarrow \mu\nu_{\mu}\gamma$ decay with the sensitivity of $\delta P_T \sim 10^{-4}$. It is shown that the forthcoming experiment can measure the contribution of the electromagnetic final state interactions to P_T that gives a possibility to unambiguously determine the signs of the sum of the kaon form factors F_V and F_A even without fixing their difference. We also estimate the sensitivity of this experiment to the new physics, which could give rise to T-violation: multi-Higgs doublet models, supersymmetric extensions of the Standard Model, left-right symmetric model and leptoquark models.

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I. INTRODUCTION

In spite of remarkable progress in study of CPviolation phenomena in both K and B sectors it remains an interesting issue. The Standard Model (SM) successfully describes existing experimental data by a single phase of the CKM matrix, although it is hard to believe that this phase is the only source of CP-violation. For example, the baryon asymmetry of the Universe can not be explained by the CKM phase only and at least one additional source of the CP-violation is required.

A good place to look for new CP-violating phases is a measurement of processes where the SM CP-violation is vanishing or very suppressed while additional or alternative sources of CP-violation can produce a sizable effect. Such interesting observables are the electric dipole moment of neutron which is extremely small in the SM, and the transverse lepton polarization in three-body decays of kaons and B-mesons [1–3].

In this paper, we study the T-odd muon polarization in the decay $K^+ \to \mu^+ \nu_\mu \gamma$ ($K_{\mu 2\gamma}$). Namely, we investigate the possibility to measure the vector and axialvector kaon form factors, F_V and F_A , from the T-odd muon polarization emerging due to the electromagnetic final state interactions (FSI). Also we analyze potential contributions to P_T from various extensions of the SM. In this study we focus on the Dalitz plot region where $K_{\mu 2\gamma}$ events have a large angle between photon and muon momenta. This is the region, where T-odd muon polarization exhibits the best sensitivity to F_V and F_A . Moreover, we found that in this region the ratio of the possible contribution to P_T from new physics and FSI contribution to P_T becomes the largest. Hence, the analysis of the $K_{\mu 2\gamma}$ events at large θ will provide the best accuracy in measurement of the relevant parameters of the new physics or the strongest constraints on them.

It is found that P_T dependence on the kaon form factors gives a possibility to unambiguously determine in $K_{\mu 2\gamma}$ decay the signs of the sum of the kaon form factors without fixing their difference. Combined with measurement of the normal muon polarization, which is very sensitive to F_V and F_A [13], this allows the values of the kaon form factors to be unambiguously extracted with 1% accuracy from this experiment. Investigating the prospects of new experiments in searching for new physics we show that, generally, they are limited mostly by the uncertainty in FSI predictions rather than by the anticipated statistical error.

The outline of the paper is as follows. In Section II we introduce the parameters describing muon transverse polarization P_T in the $K_{\mu 2\gamma}$ decay, recall the relevant formulae and estimate the expected sensitivity to P_T in forthcoming experiments. In Sec. III, an approach to determine the signs of the sum of the kaon form factors from the FSI polarization is discussed and the accuracy of this method is estimated. In Sec. IV we study the discovery potential of the P_T measurements in search for new physics. Specifically, we estimate the upper bounds on the P_T in multi-Higgs doublet models, supersymmetric extensions of the Standard Model, left-right symmetric model and leptoquark models. Sec. V contains conclusions and final remarks.

II. TRANSVERSE MUON POLARIZATION IN $K_{\mu 2\gamma}$ DECAY

A. General description

Introducing three unit vectors

$$\vec{e}_L = \frac{\vec{p}_\mu}{|\vec{p}_\mu|} , \ \vec{e}_N = \frac{\vec{p}_\mu \times (\vec{q} \times \vec{p}_\mu)}{|\vec{p}_\mu \times (\vec{q} \times \vec{p}_\mu)|} , \ \vec{e}_T = \frac{\vec{q} \times \vec{p}_\mu}{|\vec{q} \times \vec{p}_\mu|}$$

with p_{μ} and q being the four-momenta of μ^+ and γ , respectively, one can define longitudinal (P_L) , normal (P_N) and transverse (P_T) components of the muon polarization as the corresponding contributions to the squared

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matrix element of the $K_{\mu 2\gamma}$ decay,

$$|M|^2 = \rho_0 [1 + (P_L \vec{e}_L + P_N \vec{e}_N + P_T \vec{e}_T) \cdot \vec{\xi}] ,$$

with $\vec{\xi}$ being a unit vector along muon spin and ρ_0 is

$$\rho_0(x,y) = \frac{1}{2} e^2 G_F^2 |V_{us}|^2 (1-\lambda) \times \{f_{\rm IB}(x,y) + f_{\rm SD}(x,y) + f_{\rm IBSD}(x,y)\} ,$$

where the internal bremsstrahlung (IB), structure dependent (SD) and interference contributions (IBSD) are given as follows [3–5]

$$f_{\rm IB} = \frac{4m_{\mu}^2 |f_K|^2}{\lambda x^2} \left[x^2 + 2(1 - r_{\mu}) \left(1 - x - \frac{r_{\mu}}{\lambda} \right) \right], \quad (1)$$

$$f_{\rm SD} = m_K^4 x^2 \left[|F_V + F_A|^2 \frac{\lambda^2}{1 - \lambda} \left(1 - x - \frac{r_\mu}{\lambda} \right) + |F_V - F_A|^2 (y - \lambda) \right], \qquad (2)$$

$$f_{\rm IBSD} = -4m_K m_{\mu}^2 \left[\operatorname{Re}[f_K(F_V + F_A)^*] \left(1 - x - \frac{r_{\mu}}{\lambda}\right) - \operatorname{Re}[f_K(F_V - F_A)^*] \frac{1 - y + \lambda}{\lambda} \right].$$
(3)

Here we used the standard notations $\lambda = (x + y - 1 - r_{\mu})/x$, $r_{\mu} = m_{\mu}^2/m_K^2$, and $x = 2E_{\gamma}/m_K$, $y = 2E_{\mu}/m_K$ with E_{γ} , E_{μ} being the photon and muon energies in the kaon rest frame, respectively; G_F is the Fermi constant, V_{us} is the corresponding element of the Cabibbo–Kobayashi–Maskawa (CKM) matrix and $f_K = 159.8$ MeV is the kaon decay constant. In terms of these variables the differential decay width reads

$$d\Gamma(\vec{\xi}) = \frac{m_K}{32(2\pi)^3} |M(x, y, \vec{\xi})|^2 dx \, dy$$

The transverse muon polarization P_T is determined using the partial decay width

$$P_T = \frac{d\Gamma(\vec{e}_T) - d\Gamma(-\vec{e}_T)}{d\Gamma(\vec{e}_T) + d\Gamma(-\vec{e}_T)} \equiv \frac{\rho_T}{\rho_0} .$$
(4)

This is a T-odd observable (both P_L and P_N are T-even), hence in the T-invariant theory its value equals zero at tree level. Moreover, P_T does not have tree-level contributions from the CP-violating phase in the CKM matrix. These two features make P_T a very promising observable for new CP-violating physics searches. At the same time, as will be seen in the Sec. III, analysis of loop contributions from the Standard Model (FSI) is also of a special physical interest.

B. Experimental sensitivity to P_T

For the following analysis let us estimate the level of precision which could be achieved experimentally.



FIG. 1: Branching ratio for $K_{\mu 2\gamma}$ decay for 10° wide bins in θ ; $E_{\gamma} > 20$ MeV, $E_{\mu} > 200$ MeV. Dependence of this branching ratio on the values of the F_V , F_A form factors is quite weak.

The running E246 experiment at KEK [6] dedicated for a measurement of P_T in the decay $K^+ \to \pi^0 \mu^+ \nu$ has only a limited sensitivity of about 10^{-2} to P_T in $K_{\mu 2\gamma}$ [7]. There is a proposal for a new experiment in which a statistical sensitivity $P_T \leq 10^{-4}$ in $K_{\mu 2\gamma}$ can be reached [8]. The main features of this experiment include a high resolution measurement of neutral particles from $K_{\mu3}$ and $K_{\mu2\gamma}$ decays, usage of an active muon polarimeter which provides information about stopped muons (stopping point, momentum), positron direction, and also detects photons, and a highly efficient photon veto system covering nearly 4π solid angle. This approach allows to accumulate $K_{\mu 2\gamma}$ events for all θ angles between photon and muon momenta due to efficient photon veto detector. This system eliminates $K_{\pi 2}$ decays which are the main background source at large θ .

Using parameters of the proposed detector [8] and the kaon beam intensity of about $10^7 K^+$ per second expected at the JHF [9] one can estimate the sensitivity to P_T which could be achieved in this experiment. With the analyzing power of the detector ~ 0.3 and the kinematical attenuation factor ~ 0.8, the expected sensitivity to P_T in some region \mathcal{R} of the Dalitz plot can be expressed as

$$\delta P_T(\mathcal{R}) \simeq \frac{1}{0.3 \cdot 0.8 \sqrt{N_{K_{\mu 2\gamma}}(\mathcal{R})}} , \qquad (5)$$

where $N_{K_{\mu 2\gamma}}(\mathcal{R})$ is the number of $K_{\mu 2\gamma}$ events in the region \mathcal{R} . In this experiment, the most effective suppression of background events are anticipated in the kinematic region with $E_{\gamma} > 20$ MeV, $E_{\mu} > 200$ MeV. There the number of $K_{\mu 2\gamma}$ events accumulated for one year running period is estimated to be 3×10^{10} . In what follows we adopt these cuts as well as the number of events.

The branching ratio of this decay for $E_{\gamma} > 20$ MeV and $E_{\mu} > 200$ MeV integrated over 10° wide bins in θ is presented in Fig. 1. From this plot one can estimate the sensitivity to P_T in various θ regions.

III. FSI AND PINNING DOWN THE KAON FORM FACTORS

A. Predictions and experimental data

Due to lack of understanding of the QCD low-energy structure, there is no definite prediction for the values of the F_V and F_A form factors: the calculation of them is a model dependent procedure. So, the measurement of these form factors would give a possibility to make a choice between various candidates for the correct description of the QCD low-energy limit.

The distribution of the $K_{\mu 2\gamma}$ decay width over Dalitz plot allows only the absolute values of the sum and difference of the kaon form factors to be measured, since the term f_{IBSD} (see Eq. (3)) is small. The terms with linear and quadratic dependence on F_V and F_A give the comparable contribution in some regions of the Dalitz plot that could, in principle, make it possible to measure the signs as well as the magnitudes of the form factors. Unfortunately, in the region where the linear terms grow, the dominant contribution to $K_{\mu 2\gamma}$ (internal bremsstrahlung (1), which depends only on f_K) also increases, that significantly reduces the sensitivity of Dalitz plot measurements to the kaon form factors. In practice, the situation is even worse, since only the absolute value of the sum of the kaon form factors has been measured with good accuracy in these measurements, while their difference still has only lower and upper bounds [10, 11]:

$$|F_V + F_A| = 0.165 \pm 0.013 , \qquad (6)$$

$$-0.24 < F_A - F_V < 0.04 . \tag{7}$$

Recently, both vector and axial-vector form factors have been measured in $K^+ \rightarrow \mu^+ \nu_\mu e^+ e^-$ and $K^+ \rightarrow e^+ \nu_e e^+ e^-$ decays [12]. These decays are generalizations of $K_{l2\gamma}$ for the case of a virtual photon in the final state, so the kaon form factors F_V and F_A are believed to be the same in all these processes. The combined fit for both four-body decay experiments results in

$$F_V = -0.112 \pm 0.018$$
, $F_A = -0.035 \pm 0.020$. (8)

These values are in a good agreement with $\mathcal{O}(p^4)$ predictions [4, 14] of the chiral perturbation theory (ChPT)

$$F_V = -0.096$$
, $F_A = -0.041 \pm 0.006$. (9)

B. Dependence on Q^2

It is worth to note that actually F_V and F_A are not constants, but some functions of the momentum of the lepton pair, $Q^2 \equiv (p_K - q)^2$, with p_K being kaon fourmomentum. In ChPT Q^2 -dependence emerges due to higher order corrections, which have not been calculated yet. Their magnitude can be estimated as

$$\frac{\Delta F_{V,A}}{F_{V,A}} \sim \frac{Q^2}{m_{V,A}^2} = (1-x)\frac{m_K^2}{m_{V,A}^2} \,,$$

where m_V and m_A are masses of the first strange hadronic vector (K^*) and axial-vector (K_1) resonances, respectively. This estimate implies corrections as large as 25%, hence the experimental data on $K_{l2\gamma}$ should be fitted with at least two additional parameters, that generally decreases the chances to determine F_V and F_A in $K_{l2\gamma}$ experiments.

In $K^+ \rightarrow l^+ \nu_l e^+ e^-$ both vector and axial-vector form factors get additional dependence on the non-zero q^2 that also increases the bias in the corresponding fitting procedure. In Ref. [12] experimental data was fitted assuming constant form factors and form factors depending on Q^2 and q^2

$$F_{V,A}(Q^2, q^2) = \frac{F_{V,A}}{(1 - q^2/m_{\rho}^2)(1 - Q^2/m_{V,A}^2)}, \quad (10)$$

with m_{ρ} being mass of ρ meson. This dependence appears in the approximation of dominance of the contribution of lowest lying resonances [14]. The experimental data favors the dependence (10) over the constant $F_{V,A}$, though the accuracy achieved in this experiment did not allow definite confirmation or rejection of Q^2 -, q^2 -dependence.

The determination of the Q^2 -dependence of the form factors may be done in future experiments. In particular, analysis of the P_N muon polarization in $K_{\mu 2\gamma}$ decays can improve knowledge about the $F_{V,A}$ behavior for sure [13]. However, at present, the unknown Q^2 -dependence imports some uncertainty into predictions for muon asymmetry to be measured in future experiments. This concerns FSI contribution as well as possible contribution from new physics, since both are functions of the kaon form factors.

To avoid all these difficulties one can try to find a physical observable which strongly depends on F_V and F_A and can be measured with an accuracy sufficient to distinguish the signs of kaon form factors in the $K_{\mu 2\gamma}$ decay. This implies that: (i) the observable we are interested in should exhibit linear dependence on F_V and F_A in some region of the Dalitz plot; (ii) in this region the differential partial width should be sufficiently large; (iii) the Q^2 -corrections in this region should be small enough to unambiguously determine the sign of the kaon form factors.

Below we consider the transverse muon polarization calculated in the framework of the Standard Model as a physical observable, which pins down the signs of kaon form factors in $K_{\mu 2\gamma}$ decay.

C. Final state interactions

In the framework of the Standard Model, the contribution to P_T emerges only at loop levels due to the FSI. This contribution has been recently calculated [15] at one-loop level. The expression for $\rho_T^{SM}(x, y)$ can be read out from Ref. [15] after changing the definitions of the form factors: $F_V^{[15]} \to -m_K F_V$ and $F_A^{[15]} \to m_K F_A$. The asymmetry is positive at any relevant (x, y) and its absolute value ranges from zero to 1.5×10^{-3} . The Dalitz plot distribution of P_T for several values of the form factors satisfying (6), (7) is presented in Fig. 2.

D. Experimental prospects for determination of the form factors

The transverse muon polarization emerging from the FSI exhibits the behavior we are looking for to pin down the signs of the kaon form factors. Indeed, the muon transverse polarization is sensitive to the signs of F_V and F_A , especially at large angles θ between photon and muon momenta.

To illustrate this point we present the P_T values integrated over 10°-intervals as a function of θ in Fig. 3. The value of P_T associated with a bin $\theta_1 < \theta < \theta_2$ is determined as

$$P_T(\theta_1 < \theta < \theta_2) = \frac{\int\limits_{\text{cuts, } \theta_1 < \theta < \theta_2} \rho_T \, dx \, dy}{\int\limits_{\text{cuts, } \theta_1 < \theta < \theta_2} \rho_0 \, dx \, dy} , \qquad (11)$$

where the additional relevant cuts are $E_{\gamma} > 20$ MeV, $E_{\mu} > 200$ MeV. We evaluate P_T for four different sets of the form factors corresponding to the boundaries of the allowed intervals (6), (7). One can see that the predictions for P_T differ significantly, and in the region of large angles, $\theta > 120^{\circ}$, the sign of $F_V + F_A$ can be unambiguously determined from the P_T analysis only. Suppression of $K_{\pi 2}$ decays becomes less efficient at very large θ angles because of low efficiency of the detection of low energy photons from asymmetrical π^0 decays, so we adopt the region $120^{\circ} < \theta < 160^{\circ}$ as the realistic region with the best sensitivity to the kaon form factors. The difference between the P_T values increases with θ and reaches its maximum value at $\theta \sim 150^{\circ}$, as seen from Fig. 3. Although the differential $K_{\mu 2\gamma}$ branching ratio decreases at large θ , its value is still reasonable at large θ , see Figure 1. The fraction of the $K_{\mu 2\gamma}$ events within $120^{\circ} < \theta < 160^{\circ}$ is about 7%. By making use of Eq. (5), the statistical sensitivity to P_T in this Dalitz plot region is estimated to be

$$\delta P_T(120^\circ < \theta < 160^\circ) \sim 1.0 \times 10^{-4}$$
, 1σ level. (12)

To unambiguously determine the sign of $F_V + F_A$ without any additional data on the difference of the form factors one has to be able to distinguish the P_T values with $F_V + F_A = 0.165$, $F_A - F_V = -0.24$ and $F_V + F_A = -0.165$, $F_A - F_V = 0.04$ (the two closest lines in Fig. 3). For these two sets of the form factors, the difference between P_T values in the region $120^\circ < \theta < 160^\circ$ is 1.6×10^{-4} , that allows determination of the sign of the sum of the form factors at the level of 1.6 σ . Note, there is no usual degeneracy related to the signs of the sum of the form factors, that provides a possibility to pin down the sign of the sum without fixing the difference.

If the difference between the form factors is measured with better precision than in Eq. (7) one has to compare the situations with equal $F_A - F_V$ and different signs of the sum of the form factors, that gives the difference in P_T values in the same region ($120^\circ < \theta < 160^\circ$) of ($2.6 \div$ 3.6) × 10^{-4} depending on the precise value of $F_A - F_V$. Then the statistical sensitivity (12) allows to determine the signs at the level of $3 \div 4 \sigma$.

So, measurement of P_T allows signs of the form factors to be distinguished. It is worth to note in passing, that at large θ the main contribution to the P_T (FSI) comes from the Dalitz plot region x > 0.4, where the uncertainty associated with the momentum of the lepton pair Q^2 is $\lesssim 15\%$. This uncertainty is small enough to be neglected, because it is significantly less than the difference in P_T for the form factors of different signs, see Fig. 3.

Recently we found [13] that the normal muon polarization P_N is extremely sensitive to the values of the form factors. Since measurement of P_T pins down the sign of the form factors, it will provide a possibility of an independent cross-check of the results from measurement of P_N in the future experiment [8], which will determine F_V and F_A with accuracy as high as 1% [13] basing only on its own experimental data.

IV. NEW PHYSICS

A. Standard parameterization

For a general investigation of possible contribution of some new CP-violating sources to the transverse muon polarization in $K_{\mu 2\gamma}$ we first introduce the most general four-fermion interaction

$$\begin{aligned} \mathcal{L} &= -\frac{G_F}{\sqrt{2}} V_{us}^* \bar{s} \gamma^{\alpha} (1-\gamma_5) u \cdot \bar{\nu} \gamma_{\alpha} (1-\gamma_5) \mu \\ &+ G_V \bar{s} \gamma^{\alpha} u \cdot \bar{\nu} \gamma_{\alpha} (1-\gamma_5) \mu + G_A \bar{s} \gamma^{\alpha} \gamma_5 u \cdot \bar{\nu} \gamma_{\alpha} (1-\gamma_5) \mu \\ &+ G_S \bar{s} u \cdot \bar{\nu} (1+\gamma_5) \mu + G_P \bar{s} \gamma_5 u \cdot \bar{\nu} (1+\gamma_5) \mu + \text{h.c.} , \end{aligned}$$

where G_S , G_P , G_V , and G_A , arising from new physics, denote scalar, pseudoscalar, vector, and axial-vector coupling constants, respectively. Their contribution to $K_{\mu 2\gamma}$ decay amplitude may be taken into account by the redefinition of the usual kaon form factors as follows,

$$f_K \rightarrow f_K (1 + \Delta_P + \Delta_A),$$

$$F_V \rightarrow F_V (1 + \Delta_V),$$

$$F_A \rightarrow F_A (1 - \Delta_A),$$

with

$$\Delta_{(P,A,V)} = \frac{\sqrt{2}}{G_F V_{us}^*} \left(\frac{G_P B_0}{m_\mu}, G_A, G_V\right) \,.$$

The constant B_0 is related to quark condensate as $\langle 0|\bar{q}q|0\rangle = -\frac{1}{2}B_0f_{\pi^0}^2$ and may be evaluated from the



FIG. 2: P_T distribution for different $F_V + F_A$ and $F_A - F_V$ values. The imposed cuts $E_{\gamma} > 20$ MeV, $E_{\mu} > 200$ MeV and the region $120^{\circ} < \theta < 160^{\circ}$ are also shown.

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FIG. 3: P_T (FSI) asymmetry for 10° wide bins in θ . Upper region corresponds to negative $F_V + F_A$ and lower one — to positive.

masses of kaon and quarks, $B_0=M_{K^0}^2/(m_d+m_s)\approx 2$ GeV. The scalar type interaction G_S does not con-

tribute to $K_{\mu 2\gamma}$ decay because of parity, and will not be considered below. Note, however, that it contributes to the transverse muon polarization in the $K \to \pi^0 \mu \nu_{\mu}$ $(K_{\mu 3})$ decays (while the pseudoscalar interaction G_P does not).

The imaginary parts of the new coupling constants are responsible for CP-violation and could give rise to the tree-level contributions to the muon polarization [3–5],

$$p_T(x,y) = -2e^2 G_F^2 |V_{us}|^2 m_K^2 m_\mu \frac{1-\lambda}{\lambda} \sqrt{\lambda y - \lambda^2 - r_\mu}$$
$$\times \left\{ \operatorname{Im}[f_K (F_V + F_A)^*] \frac{\lambda}{1-\lambda} \times \left(1 - x - \frac{r_\mu}{\lambda}\right) + \operatorname{Im}[f_K (F_V - F_A)^*] \right\}.$$

It is convenient to rewrite $P_T(x, y)$ as

$$P_T(x,y) = P_T^V(x,y) + P_T^A(x,y)$$

with

$$P_T^V(x,y) = \sigma_V(x,y) \operatorname{Im}(\Delta_A + \Delta_V), P_T^A(x,y) = [\sigma_V(x,y) - \sigma_A(x,y)] \operatorname{Im}(\Delta_P), \quad (13)$$

where

$$\sigma_V(x,y) = 2e^2 G_F^2 |V_{us}|^2 m_K^2 m_\mu f_K F_V \\ \times \frac{\sqrt{\lambda y - \lambda^2 - r_\mu}}{\rho_0(x,y)} \left[\frac{\lambda - 1}{\lambda} - \left(1 - x - \frac{r_\mu}{\lambda} \right) \right] ,$$

$$\sigma_A(x,y) = 2e^2 G_F^2 |V_{us}|^2 m_K^2 m_\mu f_K F_A \\ \times \frac{\sqrt{\lambda y - \lambda^2 - r_\mu}}{\rho_0(x,y)} \left[\frac{\lambda - 1}{\lambda} + \left(1 - x - \frac{r_\mu}{\lambda} \right) \right] \,.$$

B. Distribution over the Dalitz plot

To illustrate the sensitivity of the transverse muon polarization to new physics we adopt the experimental values (8) for the kaon form factors and plot the integrated over 10° θ -intervals P_T values as a function of θ (see the definition (11)) in Fig. 5. The distribution of P_T^V and P_T^A over the Dalitz plot are completely determined by the functions $\sigma_V(x, y)$ and $[\sigma_V(x, y) - \sigma_A(x, y)]$, presented in Fig. 4. Indeed, the values of new *CP*-violating coupling constants provide only the normalization factors, see Eqs. (13). To understand the general behavior we present P_T^V and P_T^A values for 10° wide bins in θ at $\operatorname{Im}(\Delta_V + \Delta_A) = \operatorname{Im}(\Delta_P) = 1$ in Fig. 6.

Comparing Figs. 5 and 6 one can realize that while both FSI and new-physics contributions are peaked at large θ , the slope is steeper in the former case:

$$\frac{P_T^V(\theta \sim 150^\circ)}{P_T^V(\theta \sim 20^\circ)} \simeq 20 , \qquad \frac{P_T^A(\theta \sim 150^\circ)}{P_T^A(\theta \sim 20^\circ)} \simeq 35 , \quad (14)$$

$$\frac{P_T^{FSI}(\theta \sim 150^\circ)}{P_T^{FSI}(\theta \sim 20^\circ)} \simeq 4.5 . \tag{15}$$

This shows that the sensitivity to new physics increases the region of Dalitz plot with large θ angles. Indeed, the best way to distinguish FSI and new-physics contributions is to compare the θ -dependence and P_T averaged over the large angles, $\theta = 120^{\circ} \div 160^{\circ}$. For this range we obtain

$$P_T^V(120^\circ < \theta < 160^\circ) = 0.14 \cdot \operatorname{Im}(\Delta_V + \Delta_A) , (16)$$

$$P_T^A(120^\circ < \theta < 160^\circ) = 0.15 \cdot \operatorname{Im}(\Delta_P) .$$
(17)

Taking into account the expected experimental sensitivity (12) one may hope to detect effects of new physics leading to $\text{Im}(\Delta_V + \Delta_A)$ or $\text{Im} \Delta_P$ as small as 0.7×10^{-3} at 1 σ level.

In the estimation of the sensitivity presented above we neglected the contribution to P_T from the FSI. This is possible if one reduces the uncertainty in the prediction

of P_T^{FSI} to values smaller than δP_T . To this end careful determination of the F_A and F_V form factors from other experiments is needed. For example, from $K \to l\nu_l e^+ e^-$, see Eq. (8), or from the measurement of the normal muon polarization P_N in $K_{\mu 2\gamma}$ decay, which is also a very sensitive to the form factors observable [13]. Simultaneous measurement of both P_N and P_T in one experiment with the same statistical sensitivity provides good opportunity for accurate determination of F_A and F_V from P_N and, therefore, precise calculation of the FSI contribution to measured P_T and clear separation the non-SM P_T from physics background.

The values of Δ_V , Δ_A and Δ_P are completely determined by the physics beyond the Standard Model. Below we consider several extensions of the SM and present the corresponding bounds on Δ_V , Δ_A and Δ_P from existing experimental data.

C. Two-Higgs-doublet models with suppressed FCNC

In a general two-Higgs doublet (2HD) model [1] upand down-type quarks, as well as leptons, couple to both two-Higgs doublets. The up- and down-type quark mass matrices cannot be diagonalized simultaneously, that is the reason for flavor changing neutral current to be induced at tree level. The relevant terms read [5]

$$\mathcal{L}_{^{2}\mathrm{HD}} = \frac{zm_{\mu}}{4M_{H}^{2}} \bar{s} \sum_{i} [\tilde{\xi}_{i2}^{D*} V_{ui}^{*} (1-\gamma_{5}) - \tilde{\xi}_{i1}^{U*} V_{is}^{*} (1+\gamma_{5})] u \\ \times \bar{\nu} (1+\gamma_{5}) \mu \quad (18)$$

where M_H is the mass of charged Higgs boson, zm_{l_i} are coupling constants of charged Higgs boson and corresponding leptons and $\tilde{\xi}_{ij}^{U,D}$ are mixing matrices parameterizing up- and down-type quark interactions with the lightest neutral Higgs boson. This interaction results in the muon transverse polarization

$$P_T = -[\sigma_V - \sigma_A] \frac{B_0 z}{2\sqrt{2}G_F M_H^2 |V_{us}|} \sum_i \operatorname{Im}[V_{is}^* \tilde{\xi}_{i1}^U + V_{ui}^* \tilde{\xi}_{i2}^{D*}] .$$
(19)

The measurement of the $b \rightarrow s\gamma$ gives $M_H > 315 \text{ GeV}$ [16], perturbativity bound (see, e.g., [17]) implies $z < 2 \text{ GeV}^{-1}$ and, if the only relevant terms in Eq. (19) are $\tilde{\xi}_{11}^U$ and $\tilde{\xi}_{22}^D$, neutral kaon system constrains them to be $\lesssim 10^{-2} \sqrt{M_H/\text{GeV}}$ [5]. With account of Eq. (17) this favors the limit

$$\begin{aligned} P_T(120^\circ < \theta < 160^\circ) &| \lesssim 3 \times 10^{-2} \left(\frac{315 \text{ GeV}}{M_H}\right)^{3/2} \\ &\times \left(\frac{z}{2 \text{ GeV}^{-1}}\right) \left(\frac{\text{Im}[\tilde{\xi}_{11}^U + \tilde{\xi}_{22}^{D*}]}{10^{-2}}\right) \,. \end{aligned}$$

It is more than 300 times larger than the expected experimental sensitivity to P_T [8]. Note, that without special

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FIG. 4: Distribution of σ_V and $[\sigma_V - \sigma_A]$ over the Dalitz plot.



FIG. 5: FSI contribution to P_T for 10° wide bins in θ ; the kaon form factors are equal to the measured values (8).

fine-tuning between $\text{Im}[\tilde{\xi}_{11}^U]$ and $\text{Im}[\tilde{\xi}_{22}^{D*}]$, the strongest limit on P_T comes from the search for transverse muon polarization in $K \to \pi^0 \mu \nu$ decay [21], since the interaction (18) generally provides both G_P and G_S of the same order [18] (see Sec. IV A). This yields

$$|P_T(120^\circ < \theta < 160^\circ)| \lesssim 3 \times 10^{-3}$$

at 95% CL.

On the other hand, depending on the structure of the mixing matrices $\tilde{\xi}^U$, $\tilde{\xi}^D$, the lower bound on P_T in 2HD model can be as large as 0.1.

D. Three-Higgs-doublet models

In these models three different Higgs doublets (h_u, h_d, h_l) couple to up-, down-type quarks and leptons, respec-



FIG. 6: P_T for 10° wide bins in θ at $\text{Im}(\Delta_V + \Delta_A) = \text{Im}(\Delta_P) = 1$; the kaon form factors are equal to the measured values (8).

tively. The relevant interaction between SM fermions and charged Higgs bosons for $K_{\mu 2\gamma}$ decay reads

$$\mathcal{L} = \frac{\sqrt{G_F}}{\sqrt[4]{2}} \sum_{i=1}^{2} \left\{ h_i^+ [\alpha_i \bar{u} V M_d (1+\gamma_5) d + \beta_i \bar{u} M_u V (1-\gamma_5) d + \gamma_i \bar{\nu} M_l (1+\gamma_5) e] \right\} + h.c. ,$$
(20)

where V is the CKM matrix, M_d , M_u and M_l are diagonal down-type quark, up-type quark and lepton mass matrices, respectively, and α_i , β_i and γ_i (i = 1, 2) are complex mixing parameters in Higgs sector. This interaction results in [18]

$$P_T = -[\sigma_V - \sigma_A] \left(\frac{m_K^2}{m_1^2} - \frac{m_K^2}{m_2^2} \right) \\ \times \left(\operatorname{Im} \gamma_1 \alpha_1^* - \frac{m_u}{m_s} \operatorname{Im} \gamma_1 \beta_1^* \right)$$
(21)

where m_i are the masses of charged Higgs bosons. The current experimental constraints on the parameters of the theory (see, e.g., Ref. [19] for a collection of relevant formulae) give the same order bound on P_T as from [21] for P_T in $K \to \pi^0 \mu \nu$ decay (as far as G_P and G_S emerging from Lagrangian (20) are generally of the same order),

$$|P_T(120^\circ < \theta < 160^\circ)| \lesssim 3 \times 10^{-3}$$
, 95% CL.

This upper limit is about 30 times larger than the expected sensitivity of the new experiment.

E. Supersymmetric models with R-parity

In the minimal supersymmetric extension of the Standard Model (MSSM) the relevant four-fermion interactions emerge due to W-boson and charged Higgs boson exchanges with couplings being enhanced by squarkgluino loops.

Right-handed current interaction is generated by the diagram with gluino, stop and sbottom particles running in the loop with left-right mass insertions both for stop and sbottom. This gives rise to the effective interaction [20]

$$\begin{aligned} \mathcal{L}_{I} &= -C \frac{G_{F}}{\sqrt{2}} \bar{s} \gamma^{\alpha} \left(1 + \gamma_{5} \right) u \cdot \bar{\nu} \gamma_{\alpha} \left(1 - \gamma_{5} \right) \mu + \text{h.c.} , (22) \\ C &= I_{0} \frac{m_{t} m_{b} \left(A_{t} - \mu \cot \beta \right) \left(A_{b} - \mu \tan \beta \right)}{M_{\tilde{g}}^{4}} \\ &\times \frac{\alpha_{s} [M_{\text{SUSY}}]}{36 \pi} V_{31}^{U_{\text{R}}} V_{32}^{D_{\text{R}}*} V_{33}^{SCKM*} , \end{aligned}$$

where A_t and A_b are the soft supersymmetry breaking trilinear terms for stops and sbottoms, μ is Higgs superfield mixing parameter, $\tan \beta$ is the ratio of the two Higgs vacuum expectation values, $M_{\tilde{g}}$ is gluino mass, $V^{U_{\rm R}}$ and $V^{D_{\rm R}}$ are the rotations in the generation space between up-type right-handed squarks and down-type right-handed squarks and corresponding quark partners, respectively; V^{SCKM} is the super CKM matrix associated with W-squark-squark couplings, and I_0 is given by the integral

$$I_0 = \int_0^1 dz_1 \int_0^{1-z_1} \frac{24z_1 z_2}{\left(1 + \left(\frac{m_{\tilde{t}}^2}{M_{\tilde{g}}^2} - 1\right) z_1 + \left(\frac{m_{\tilde{b}}^2}{M_{\tilde{g}}^2} - 1\right) z_2\right)^2}$$

For W-boson exchange, the interaction (22) provides the

polarization

$$P_{T_W} = -\sigma_V I_0 \frac{m_t m_b (A_t - \mu \cot \beta) (A_b - \mu \tan \beta)}{M_{\tilde{g}}^4} \\ \times \frac{\alpha_s [M_{\text{SUSY}}]}{18\pi} \frac{\text{Im}[V_{31}^{U_{\text{R}}} V_{32}^{D_{\text{R}}*} V_{33}^{SCKM*}]}{|V_{us}|} .$$
(23)

Current experimental constraints on the parameters of the theory [11] leads to

$$|P_{T_W}(120^\circ < \theta < 160^\circ)| \lesssim 0.8 \times 10^{-3}$$
, (24)

where we set $m_{\tilde{t}} = m_{\tilde{b}} = M_{\tilde{g}}/2$, $\tan \beta \simeq 50$, $M_{\tilde{g}} \simeq A_b \simeq \mu \simeq A_t \simeq 500 \text{GeV}$, and $\text{Im}[V_{31}^{U_{\text{R}}} V_{32}^{D_{\text{R}}*} V_{33}^{SCKM*}] \simeq 0.5$.

The charged Higgs boson exchange enhanced by gluonstop-sbottom loops gives rise to the effective interaction [20]

$$\begin{aligned} \mathcal{L}_{II} = & -C_1 \frac{G_F}{\sqrt{2}} \bar{s} \left(1 + \gamma_5\right) u \cdot \bar{\nu} \left(1 + \gamma_5\right) \mu \\ & -C_2 \frac{G_F}{\sqrt{2}} \bar{s} \left(1 - \gamma_5\right) u \cdot \bar{\nu} \left(1 + \gamma_5\right) \mu + \text{h.c.} , \\ C_1 = & \frac{\alpha_s [M_{\text{SUSY}}]}{3\pi} I_1 \frac{m_t m_\mu \tan\beta}{M_{H^+}^2} \frac{A_t \cot\beta + \mu}{M_{\tilde{g}}} V_{31}^{U_R} V_{32}^{D_L*} V_{33}^{H*} \\ C_2 = & \frac{\alpha_s [M_{\text{SUSY}}]}{3\pi} I_1 \frac{m_b m_\mu \tan\beta}{M_{H^+}^2} \frac{A_b \tan\beta + \mu}{M_{\tilde{g}}} V_{31}^{U_L} V_{32}^{D_R*} V_{33}^{H*} \\ I_1 = & \int_0^1 dz_1 \int_0^{1-z_1} \frac{2}{1 + \left(\frac{m_{\tilde{t}}^2}{M_{\tilde{g}}^2} - 1\right) z_1 + \left(\frac{m_{\tilde{b}}^2}{M_{\tilde{g}}^2} - 1\right) z_2} , \end{aligned}$$

where V^H is the mixing in the coupling between charged Higgs and up-type right-handed and down-type lefthanded squarks, $V^{U_{\rm L}}$ and $V^{D_{\rm L}}$ are the rotations in the generation space between up-type left-handed squarks and down-type left-handed squarks and corresponding quark partners, respectively. This results in

$$P_{T_{H}} = -(\sigma_{V} - \sigma_{A}) \frac{\alpha_{s}[M_{\text{SUSY}}]}{3\pi} I_{1} \frac{B_{0}m_{t}\tan\beta}{M_{H^{+}}^{2}} \frac{A_{t}\cot\beta + \mu}{M_{\tilde{g}}} \\ \times \frac{\text{Im}[V_{31}^{U_{R}}V_{32}^{D_{L}*}V_{33}^{H*}]}{|V_{us}|} \\ - (\sigma_{V} - \sigma_{A}) \frac{\alpha_{s}[M_{\text{SUSY}}]}{3\pi} I_{1} \frac{B_{0}m_{b}\tan\beta}{M_{H^{+}}^{2}} \frac{A_{b}\tan\beta + \mu}{M_{\tilde{g}}} \\ \times \frac{\text{Im}[V_{31}^{U_{L}}V_{32}^{D_{R}*}V_{33}^{H*}]}{|V_{us}|} .$$
(25)

With the estimate $\text{Im}[V_{31}^{U_{\text{R}}}V_{32}^{D_{\text{L}}*}V_{33}^{H*}] \simeq 0.5$ and $\text{Im}[V_{31}^{U_{\text{L}}}V_{32}^{D_{\text{R}}*}V_{33}^{H*}] \simeq 0.5$ and the same settings as listed below Eq. (24) both terms in Eq. (25) are of the order 10^{-2} .

So, P_{T_W} and P_{T_H} are 10 and 100 times larger, respectively, than the expected experimental sensitivity.

Note in passing, that without a special cancellation associated with light superpartners, charge Higgs boson gives large contribution to $b \to s\gamma$. This yields the bound $M_H > 315$ GeV [16], which decreases the upper limit on P_{T_H} by an order of magnitude.

F. Supersymmetric models without R-parity

In this section we consider the supersymmetric extensions of the Standard Model with the violation of the R-parity and the lepton number. The relevant superpotential is given by

$$\mathcal{W}_{\rm RV} = \frac{1}{2} \lambda_{ijk} L_i L_j E_k^c + \lambda_{ijk}' L_i Q_j D_k^c$$

with L_i and E_i^c being the chiral superfields of lepton doublets and singlets, and Q_i , D_i^c denote chiral superfields of quark doublets and down-type singlets, respectively. In this model the contribution to $K_{\mu 2\gamma}$ decay arises due to the interaction

$$\mathcal{L}_{\rm RV} = -\frac{\lambda_{2i2}^* \lambda_{i12}'}{4M_{\tilde{e}_{\rm L_i}}^2} \bar{s}(1-\gamma_5) u \cdot \bar{\nu}(1+\gamma_5) \mu ,$$

where $M_{\tilde{e}_{L_i}}$ are masses of the left-handed sleptons. The resulting transverse muon polarization reads [5]

$$P_T = (\sigma_V - \sigma_A) \operatorname{Im}[\lambda_{2i2}^* \lambda_{i12}'] \frac{B_0}{m_\mu |V_{us}|} \frac{1}{2\sqrt{2}G_F M_{\tilde{e}_{L_i}}^2}.$$
(26)

The strongest relevant experimental limit on the parameters of the model comes from the measurement of $K_L \rightarrow \bar{\mu}\mu$ decay rate [22], and one can obtain from Eqs. (17), (26)

$$|P_T(120^{\circ} < \theta < 160^{\circ})| \lesssim 1.5 \times 10^{-5} \qquad (27)$$
$$\times \left(\left(\frac{\text{Im}[\lambda_{212}^* \lambda_{112}']}{3.8 \times 10^{-7}} \right) \left(\frac{M_{\tilde{\nu}_1}}{M_{\tilde{e}_{L_1}}} \right)^2 + \left(\frac{\text{Im}[\lambda_{232}^* \lambda_{312}']}{3.8 \times 10^{-7}} \right) \left(\frac{M_{\tilde{\nu}_3}}{M_{\tilde{e}_{L_3}}} \right)^2 \right)$$

with $M_{\bar{\nu}_i}$ being sneutrino masses. This contribution (27) is obviously too small to be detected. Note in passing that in models with relevant hierarchy in slepton sector or in models with some cancellation of the sparticle contributions to $K_L \to \bar{\mu}\mu$ decay, one could expect P_T in $K_{\mu 2\gamma}$ at the level of 10^{-3} .

G. Left-right symmetric models

In models with left-right gauge symmetries $SU(2)_L \times SU(2)_R \times U(1)_{B_L}$ [23] the four-fermion interaction which contributes to $K_{\mu 2\gamma}$ decay is given by

$$\mathcal{L}_{\rm LR} = -\frac{G_F}{\sqrt{2}} \left(\frac{g_R}{g_L}\right) \xi V_{us}^{R*} \bar{s} \gamma_\mu (1+\gamma_5) u \cdot \bar{\nu} \gamma^\mu (1-\gamma_5) \mu$$

where ξ is left-right complex mixing parameter, V^R is right-handed CKM matrix and $g_{L,R}$ are coupling constants of $SU(2)_L$ and $SU(2)_R$, respectively. This interaction results [5] in

$$P_T = 2\sigma_V \frac{g_R}{g_L} \operatorname{Im}(\xi V_{us}^{R*}) .$$
 (28)

With the current experimental constraints on the parameters of the theory [24] one can obtain from Eqs. (16), (28)

$$\begin{aligned} P_T(120^\circ < \theta < 160^\circ) &| \lesssim 2 \times 10^{-3} \\ & \times \left(\frac{g_R/g_L}{1}\right) \operatorname{Im}\left[\left(\frac{\xi}{0.033}\right) \left(\frac{V_{us}^{R*}}{|V_{us}|}\right)\right], \end{aligned}$$

that is 20 times larger than the expected statistical uncertainty of P_T (12).

H. Leptoquark models

There exist two leptoquark models contributing to P_T in $K_{\mu 2\gamma}$ decay. The quantum numbers of the leptoquarks under the Standard Model group are

$$\phi_1 = \left(3, 2, \frac{7}{3}\right) , \quad \text{(Model I)} ,$$
$$\phi_2 = \left(3, 1, -\frac{2}{3}\right) , \quad \text{(Model II)}$$

and the general couplings involving these leptoquarks are given by

$$\mathcal{L}_{LQ_{I}} = \left(\frac{\lambda_{1}}{2}\bar{Q}\left(1+\gamma_{5}\right)e + \frac{\lambda_{1}'}{2}\bar{u}\left(1-\gamma_{5}\right)L\right)\phi_{1} + \text{h.c.},$$
$$\mathcal{L}_{LQ_{II}} = \left(\frac{\lambda_{2}}{2}\bar{Q}\left(1+\gamma_{5}\right)L^{c} + \frac{\lambda_{2}'}{2}\bar{u}\left(1-\gamma_{5}\right)e^{c}\right)\phi_{2} + \text{h.c.}.$$

The relevant terms read

$$\begin{aligned} \mathcal{L}_{{}_{\mathrm{LQ}_{I}}}^{K\mu\nu} &= \frac{\lambda_{1}^{22}\lambda_{1}^{\prime 1i*}}{4M_{\phi_{1}}^{2}} \bar{s} \left(1+\gamma_{5}\right) \mu \cdot \bar{\nu}_{i} \left(1+\gamma_{5}\right) u + h.c. ,\\ \mathcal{L}_{{}_{\mathrm{LQ}_{II}}}^{K\mu\nu} &= \frac{\lambda_{2}^{2i}\lambda_{2}^{\prime 12*}}{4M_{\phi_{2}}^{2}} \bar{s} \left(1+\gamma_{5}\right) \nu_{i}^{c} \cdot \bar{\mu}^{c} \left(1+\gamma_{5}\right) u + h.c. ,\end{aligned}$$

where M_{ϕ_1} are leptoquark masses, and they provide [5]

$$P_{T_I} = -(\sigma_V - \sigma_A) \operatorname{Im}[\lambda_1^{22} \lambda_1'^{1i*}] \frac{B_0}{m_\mu |V_{us}|} \frac{\sqrt{2}}{8G_F M_{\phi_1}^2} , \quad (29)$$

$$P_{T_{II}} = -\left(\sigma_V - \sigma_A\right) \operatorname{Im}[\lambda_2^{2i} \lambda_2^{\prime 12*}] \frac{B_0}{m_\mu |V_{us}|} \frac{\sqrt{2}}{8G_F M_{\phi_2}^2} \,. \tag{30}$$

With the current experimental constraints on the parameters of the models with leptoquarks, the strongest limit on P_T comes from the measurement of the P_T in $K \to \pi^0 \mu \nu$ decay [21] (supposing that G_P and G_S constants are generally of the same order in this theory), that yields

$$|P_T(120^\circ < \theta < 160^\circ)| \lesssim 3 \times 10^{-3}$$

at 95% CL. This bound is larger than the expected experimental sensitivity by a factor of 30.

V. CONCLUSIONS

The analysis presented in this paper concerns the information which could be drawn from the experiment on the measurement of the transverse muon polarization P_T in $K \to \mu\nu\gamma$ decay.

It was found that the FSI P_T distribution over the Dalitz plot is sensitive to the values of the kaon form factors. The best sensitivity is exhibited in the region of large angles θ between muon and photon. The P_T calculated in this region allows to pin down the signs of the kaon form factors in spite of the uncertainties associated with the unknown dependence of the form factors on the momentum of the lepton pair. To this end the statistics of $\geq 10^9 K_{\mu 2\gamma}$ events with large $\theta > 120^\circ$ is required.

It was recently demonstrated [13] that the normal muon polarization P_N is very sensitive to the signs and the values of the kaon form factors. Since P_N emerges at tree level, the statistics expected in the new experiment proposed at JHF allows to determine for sure the kaon form factors with a few percent accuracy. The unknown dependence of the form factors on the momentum of the lepton pair should be determined by fitting the experimental data on the P_N Dalitz plot distribution.

Finally, it was shown that possible new-physics contributions and the FSI contribution to P_T show different behavior over the Dalitz plot. In particular, at large θ the new-physics contributions to P_T grow by one and a half orders of magnitude, that suggests to consider this region as the most interesting to probe the new physics responsible for *T*-violating effects. In most cases the contribution from new physics can exceed the measurable level of P_T by one or two orders of magnitude. Moreover, extraction of form factor values from P_N allows the background contribution from FSI to the non-SM T-violating muon polarization to be determined with small uncertainty.

It is worth to note, that the signs of pion form factors F_V^{π} and F_A^{π} have not been measured yet [11]. The experimental situation there is similar to kaons, though F_V^{π} has a definite CVC prediction and the pion form factors are almost constants over the whole Dalitz plot. The FSI contributions to P_T is of the order of 10^{-4} (10^{-3}) for $\pi_{\mu 2\gamma}$ ($\pi_{e2\gamma}$) [25]. From the analysis given above, we can suggest that the measurement of the transverse lepton polarization in $\pi_{l2\gamma}$ would allow to pin down the signs of the pion form factors, if possible contributions to P_T from physics beyond the Standard Model are negligible. This issue will be considered elsewhere.

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