Measurement of $K^+ \rightarrow \mu^+ \nu_\mu \gamma$ decay form factors in OKA experiment

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$K \rightarrow \mu \nu \gamma$ decay

**IB** - inner bremsstrahlung, where photon is emitted from the charged particle in the initial or final state

**SD** - structure-dependent radiative decay, which involves the emission of a photon from the intermediate states in the transition

**INT** - possible interference of **IB** and **SD**

### Differential cross section in K-meson rest frame

$$\frac{d\Gamma_{K\mu\nu\gamma}}{dx dy} = A_{IB}f_{IB}(x, y)$$

$$+ A_{SD}[(F_V + F_A)^2 f_{SD+}(x, y) + (F_V - F_A)^2 f_{SD-}(x, y)]$$

$$- A_{INT}[(F_V + F_A)f_{INT+}(x, y) + (F_V - F_A)f_{INT-}(x, y)]$$

where $x = 2E_\gamma/m_K$, $y = 2E_\mu/m_K$, c.m.s.

In lower order of $\chi PT$ $O(p^4)$, $F_V = 0.0945$, $F_A = 0.0425$ and $F_V - F_A = 0.052$

We will measure $F_V - F_A$ difference that connects with **INT**- and **SD**-. First measurement of this difference was made by **ISTRAT+** (Phys.Lett. B695 (2011) 59-66)

$F_V - F_A = 0.21 \pm 0.04\,(stat.) \pm 0.04\,(syst.)$
\[ K \to \mu \nu_\mu \gamma \text{ decay matrix} \]

Contribution of SD- to \( F_V - F_A \) is \(~20\) times lower
Main backgrounds

\(K^+ \rightarrow \mu^+ \nu_\mu \pi^0\) (K\(\mu\)3) with 1\(\gamma\) lost from \(\pi^0 \rightarrow \gamma \gamma\) (Br = 3.353%)

\(K^+ \rightarrow \pi^+ \pi^0\) (K2\(\pi\)) with 1\(\gamma\) lost from \(\pi^0 \rightarrow \gamma \gamma\) and \(\pi\) misidentification (Br = 20.66%)

\(K^+ \rightarrow \mu^+ \nu_\mu\) with 1\(\gamma\) background (Br = 63.55%)

\(K^+ \rightarrow \pi^+ \pi^- \pi^+\) (K3\(\pi\)) with 1\(\gamma\) background and \(\pi\) misidentification (Br = 5.58%)

Biggest background to INT- comes from K\(\mu\)3

\(K \rightarrow \mu \nu_\mu \pi^0\)

\(K \rightarrow \mu \nu_\mu \gamma\)

\(K \rightarrow \pi^+ \pi^0\)
OKA setup

Beam spectrometer, Decay volume (DV) with Veto system, Main magnetic spectrometer, 2 Gamma detectors (GAMS-2000, EGS), Muon identification (hadron calorimeter GDA-100 and MC), Matrix Hodoscope (MH).

1) Muon - beam $\times C_1 \times C_2 \times \overline{BK} \times MC$
2) Kaon - beam $\times C_1 \times C_2 \times \overline{BK}$
3) GAMS - beam $\times C_1 \times C_2 \times \overline{BK} \times E_{GAMS}$
4) 2 – 4 tracks - beam $\times C_1 \times C_2 \times \overline{BK} \times MH$

OKA beam is a RF-separated secondary beam of $70 GeV$ Proton Accelerator of IHEP, Protvino. Beam has up to 20% of kaons with momentum $17.7 GeV/c$ during analyzed Run 14 (November 2012).

Event selection

- GAMS trigger
- 1 Kaon beam track
- 1 secondary Muon
- 1 shower in GAMS > 1GeV
- Decay vertex inside decay volume DV
Method of $K \rightarrow \mu\nu\gamma$ decay selection

1. All x-y kinematical region was divided into x-stripes with width $\Delta x = 0.05$.

Next steps were applied for each X-stripe:
2. Apply a cut $Y_{min} < Y < Y_{max}$ in signal region and fill $\cos\theta_{\mu\gamma}$ plot. $\theta_{\mu\gamma}$ - angle between $\mu$ and $\gamma$ in c.m.s.
3. Put a cut on $\cos\theta_{\mu\gamma}$ to reject background.
4. Fill $M_K$ plot.
5. For the first iteration IB term was used only (Green color).
6. Simultaneous fit of all 3 histograms with MINUIT.

For correct estimation of statistical error $\sigma_{exp}$ the errors of $M_K$ histogram fit were used.
The cuts on $Y$ for signal in 10 $X$-stripes.
Simultaneous fit has a good agreement with $1.3 < \chi^2 / NDF < 1.7$
For each X-stripe we have experimental event number $N_{Data}$ from data fitting and IB event number $N_{IB}$ from MC. Then we plot $N_{Data}/N_{IB}$ as a function of $X$. For IB only we would have $N_{Data}/N_{IB} = 1$. For small $X$ IB is dominated and INT- is negligible. For large $X$ we see that $N_{Data}$ also contains negative interference term. We fit $N_{Data}/N_{IB}$ distribution with which is a sum of IB and INT-

$$p_{signal} = p0 \times (1 + p1 \times f \left( \frac{N_{INT-}}{N_{IB}} \right))$$

$p1 = F_v - F_A$

The result of fit

$$F_v - F_A = 0.134 \pm 0.021$$

The total number of selected $K \to \mu \nu \nu$ decay events is $\sim 100K$. 

\[ \begin{array}{|c|c|}
\hline
\chi^2 / ndf & 12.28 / 8 \\
p0 & 1 \pm 0.0 \\
p1 & 0.1343 \pm 0.0210 \\
\hline
\end{array} \]

Preliminary
Since analysis is complicated and can depends on width of X-stripes, Y and angle cuts and fit procedure we try to estimate all possible systematics. Next possibilities are considered:

1) Non ideal description of signal and background in MC – $1.5 \times 10^{-2}$
2) Left and right X limits (number of points in fit) – $5 \times 10^{-4}$
3) Width of X-stripes ($\Delta x = 0.035$ and 0.07 instead 0.05) – $1 \times 10^{-2}$
4) Y limits in X-stripes (FWHM instead full signal reg.) – $8 \times 10^{-3}$
5) Possible contribution of INT+ term ($E787$) – $1.8 \times 10^{-2}$

The total systematics from 5 possible sources is $0.027$

Detail description of systematics estimation procedure are presented in Backup slides.
1) Largest statistics about **100K** events of $K \to \mu\nu\mu\nu$ has been found.

2) The negative INT–term has been selected and $F_V - F_A$ has been measured: $F_V - F_A = 0.134 \pm 0.021(\text{stat.}) \pm 0.027(\text{syst.})$

**The presented result is preliminary.**

3) The result is **2.4σ above χPT O(p4) prediction.**

   Fresh calculation in framework of the gauged nonlocal effective chiral action ($E\chi A$) gives $F_V - F_A = 0.081$ (arXiv:1810.06815 [hep-ph], Oct 16 2018).

   **Our result is 1.6σ above $E\chi A$ prediction.**

4) This result is comparable within the errors with similar analysis of ISTRA+ experiment: $F_V - F_A = 0.21 \pm 0.04(\text{stat.}) \pm 0.04(\text{syst.})$

5) **Measured stat. and syst. errors are ~2 times less than result of ISTRA+.**
Backup slides
Verification of the fit method

\[ p_1 = F_V - F_A = 0.134 \]

Measured \( p_1 = F_V - F_A = 0.134 \) value and normalization factor \( p_0 = 1 \) were used to build new \( p_{signal} \) function

\[ p_{signal} = p_0 \times (1 + p_1 \times f \left( \frac{N_{INT-}}{N_{IB}} \right)) \]

Since the \( N_{Data}/(N_{IB} + N_{INT-}) \) ratio does not depend on \( X \) the fit procedure is correct.

For additional checking the method we fit the original plot by

\[ p_{signal} = p_0 \times (1 + (0.134 + p') \times f \left( \frac{N_{INT-}}{N_{IB}} \right)) \]

As we could suppose possible additional term \( p' = 3 \times 10^{-5} \) is about zero.
Systematics
1) Non ideal forms of signal and background

For estimation of systematic error from possible non ideal description of signal and background in MC, the error of each bin was scaled by $\sqrt{\chi^2/\text{NDF}}$ factor. $\chi^2$ is obtained from simultaneous fit in each X-stripe.

New value of $F_V - F_A$ is consistent with the main one but the fit error is larger. We suppose $\sigma_{\text{form}}$ depends as $\sigma^2_{\text{fit}} = \sigma^2_{\text{form}} + \sigma^2_{\text{stat}}$ and therefore

$\sigma_{\text{stat}} = 0.021$  \[ \sigma_{\text{form}} = 0.0153 \]
Dependency $N_{\text{Data}}/N_{\text{IB}}$ on $X$ was fitted by removing points at the left (right) edge. The result points were fitted by straight line for conservative estimate of systematics. The line slope multiplied by the resolution in $X$ (from MC) gives systematic error.

Both errors are negligible.
We repeated the data analysis procedure for 2 other values of X-binning:

- $\Delta X = 0.035$, that is the worst X-resolution at maximal value of X = 0.6;
- $\Delta X = 0.07$ 2 times higher value.

$\sigma_X = 0.01$
FWHM cuts for selection of events were applied in $Y$-dependency for signal MC. Such cuts on $Y$ are stronger than those used for main data analysis.

$\sigma_X = 0.008$
5) Possible contribution of INT+ term

\[ p_{signal} = p_0 \times (1 + (F_V + F_A) \times f\left(\frac{N_{INT+}}{N_{IB}}\right) + (F_V - F_A) \times f\left(\frac{N_{INT-}}{N_{IB}}\right)) \]

Minimum of INT+ term

\[ \chi^2 / \text{ndf} = 11.86 / 8 \]

\[ p_0 = 0.9974 \pm 0.0056 \]

\[ p_1 = 0.1521 \pm 0.0211 \]

\[ p_{1_{\text{min}}} = 0.152 \]

Maximum of INT+ term

\[ \chi^2 / \text{ndf} = 12.85 / 8 \]

\[ p_0 = 1.003 \pm 0.007 \]

\[ p_1 = 0.1165 \pm 0.0210 \]

\[ p_{1_{\text{max}}} = 0.117 \]

\[ F_V + F_A \text{ value was measured by E787 experiment (Phys. Rev. Lett. 85 (2000) 2256).} \]

\[ |F_V + F_A| = 0.165 \pm 0.013 \]

2 fits were repeated with minimal and maximal value of this measured sum.

\[ \sigma_{INT+} = 0.018 \]