Recent results from OKA setup @ U-70 synchrotron

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

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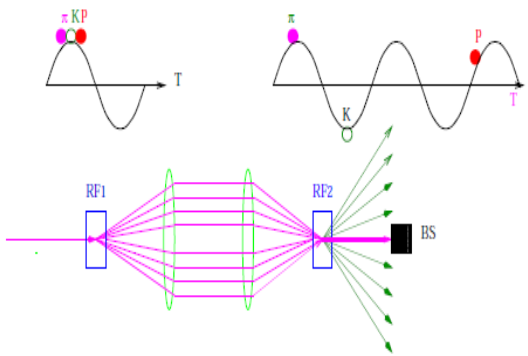
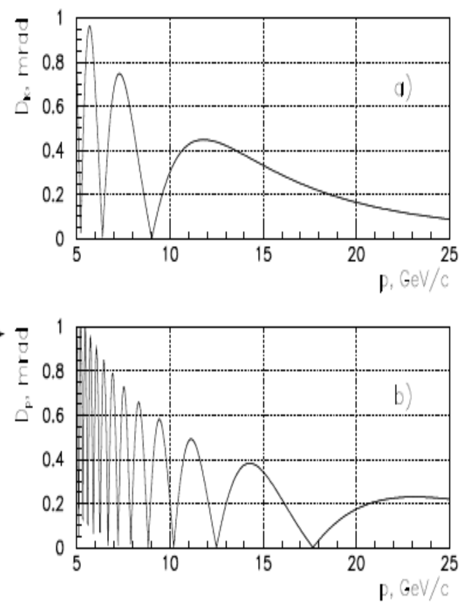
The talk layout

- OKA beam, detector, data
- Kμ2γ decay study, measurement of $F_V - F_A$
- K3πγ decay rediscovery and study

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

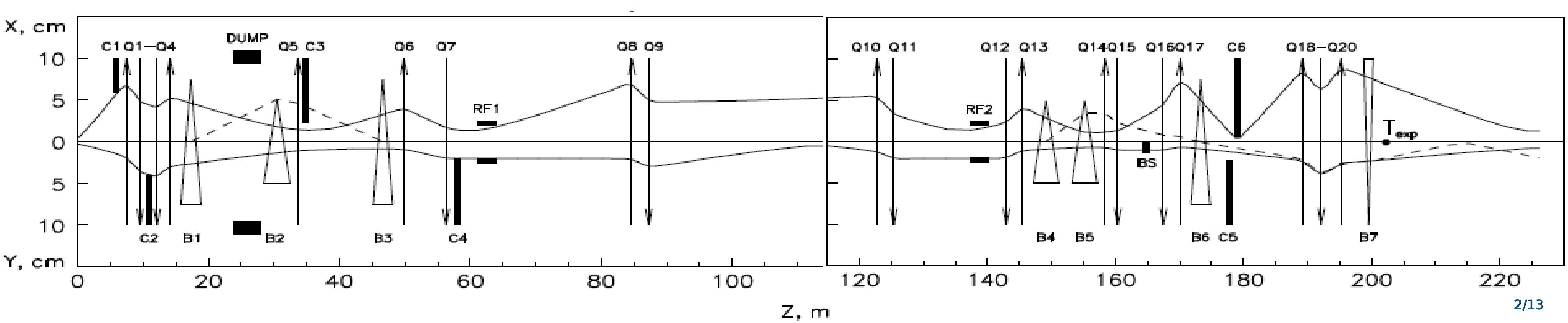
RF separation with Panofsky scheme is realised. It uses two Karlsruhe-CERN SC RF deflectors. Sophisticated cryogenic system, built at IHEP provides superfluid He for cavities cooling.



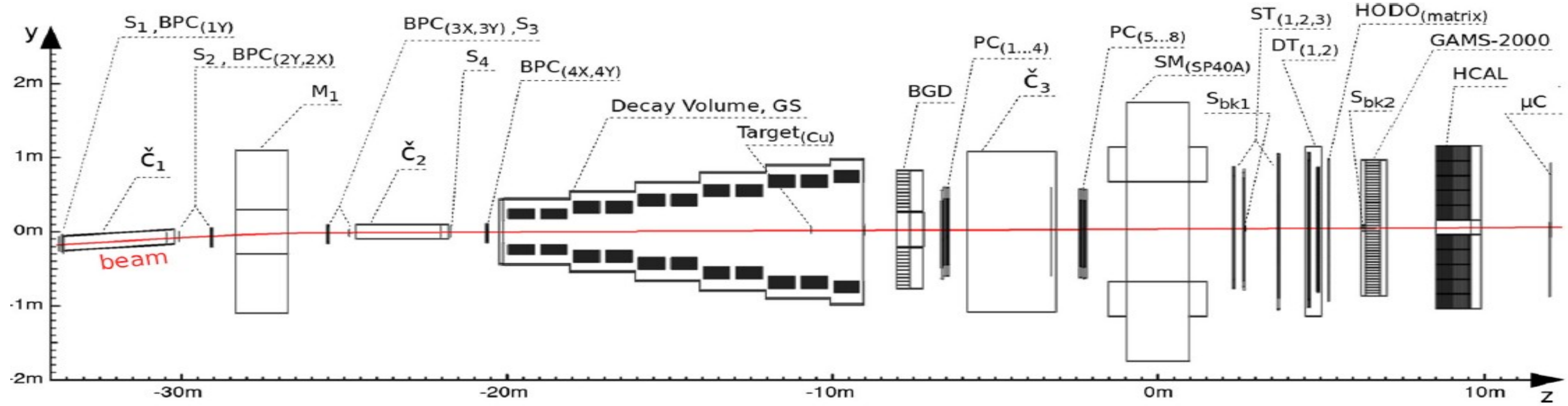


Operating frequency,(S-band)	2865 MHz
Wavelength, λ	~10.5 cm
Effective deflector length	2.74 m
Number of cells/deflector	104
Mean deflecting field	~1(0.6) MV/m
Working temperature	1.8 K

Main beam parameters :	
Primary proton beam energy	50 GeV
Primary proton beam intensity	$7x10^{12}$ ppp
Secondary beam momentum	17.7 GeV
Length of the beam line	~200m
K^+ intensity at the end	~ 10^6
K^+ in the beam	up to 20%



OKA detector



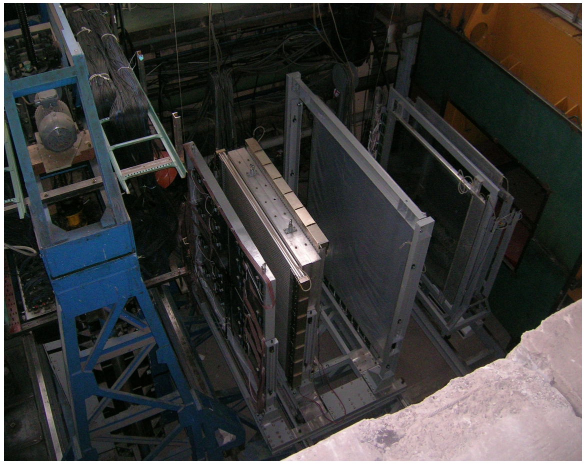
- Beam spectrometer: 1mm pitch BPC ~1500 channels; Sc and $\check{C}$ counters
- Decay volume with Veto system: L=11m; Veto: 670 Lead-Scintillator sandwiches 20* (5mm Sc+1.5 mmPb), WLS
- PC's, ST's and DT's for magnetic spectrometer: ~5000 ch. PC (2 mm pitch) + 1300 DT (1 and 3 cm)
- Pad(Matrix) Hodoscope ~300 ch. WLS+SiPM readout
- Magnet: aperture 200*140 cm^2
- Gamma detectors: GAMS2000, BGD EM cal. ~ 4000 LG.
- Muon identification: GDA-100 HCAL + 4 muon counters (μC) behind
- 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 $S_1\cdot S_2\cdot S_3\cdot \overline{C}_1\cdot C_2\cdot \overline{S}_{bk}/10$ $S_1\cdot S_2\cdot S_3\cdot \overline{C}_1\cdot C_2\cdot \overline{S}_{bk}\cdot\mu C\,/4$

«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

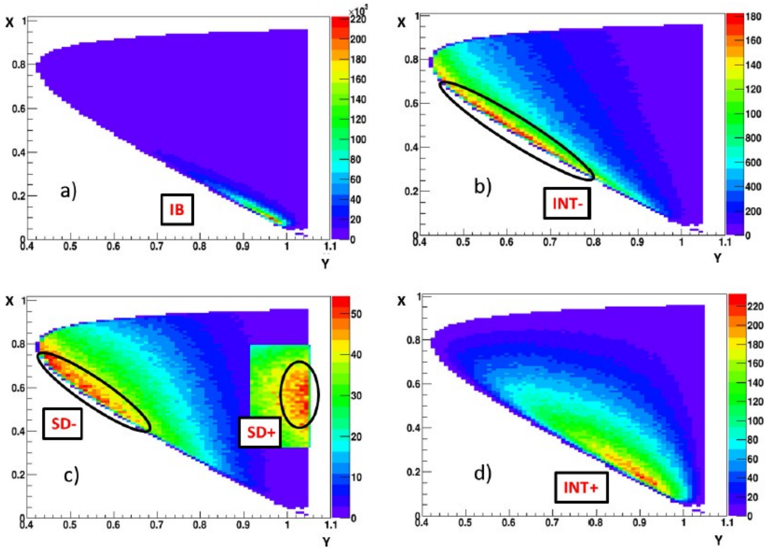
Tail of the beam line

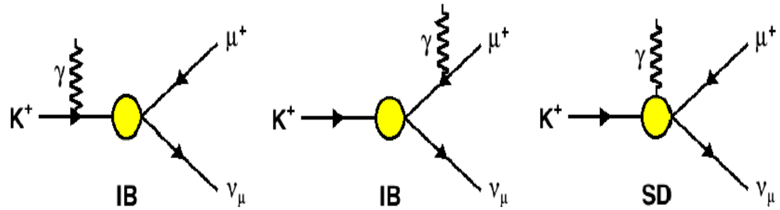
Run's in 2010-2013, 2018 $N_K \sim 5 \times 10^{10}$

<u>Main directions of the data analysis</u>:

Decays: Ke3, Kμ3, $K^+ \to \mu^+\nu_S$, Ke3γ, Kμ3γ, $K^+ \to \pi^+\pi^+\pi^- \gamma$, $K^+ \to \mu^+\nu\gamma$, $K^+ A \to K^+ \pi^0 A$

Study of the $K^+ \to \mu^+ \nu \gamma$ decay Eur.Phys.J. C79 (2019) no.7 :635



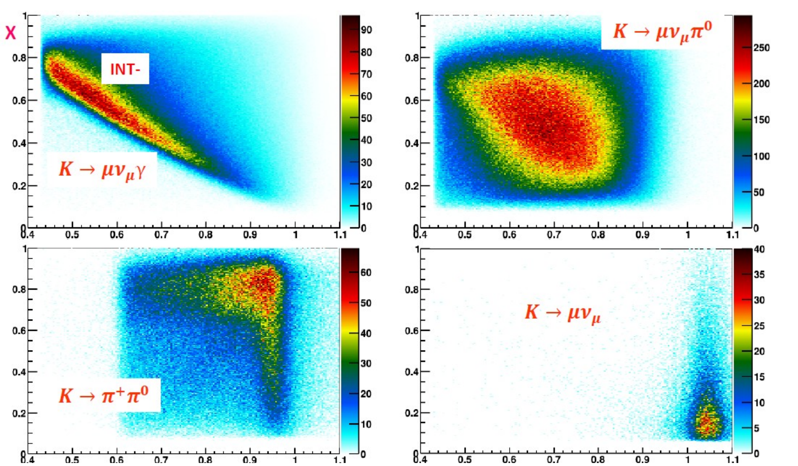


$$\frac{d\Gamma}{dxdy} = A_{IB} f_{IB}(x,y) + A_{SD}[(F_V+F_A)^2 f_{SD^+}(x,y) + (F_V-F_A)^2 f_{SD^-}(x,y)]$$
$$-A_{INT}[(F_V+F_A) f_{INT^+}(x,y) + (F_V-F_A) f_{INT^-}(x,y)]$$

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

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

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



Main background sources

$$\chi PT\, O(p^4): \quad F_V = \frac{\sqrt{2}M_K}{8\pi^2 F_\pi} = 0.096; \quad F_A = \frac{4\sqrt{2}M_K}{F_\pi}(L_9^r + L_{10}^r) = 0.042; \quad F_V - F_A = 0.054$$
$$\chi PT\, O(p^6): \quad F_V = F_V(0)(1+\lambda(1-x)); \quad F_V(0) = 0.082; \quad \lambda = 0.4; \quad F_A = 0.034$$

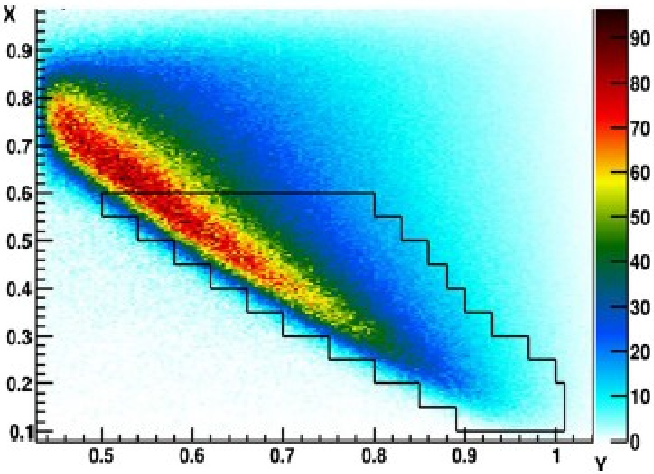
VALUE	CL%	EVTS	DOCUMENT ID		TECN
−0.21 ±0.06		22K	DUK	2011	ISTR
• • • We do not use the following data for averages, fits, limits, etc. • • •					
−0.24 to 0.04	90	2588	ADLER	2000B	B787
−2.2 to 0.6	90		DEMIDOV	1990	XEBC
−2.5 to 0.3	90		AKIBA	1985	SPEC

F_A-F_V PDGlive screenshot

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

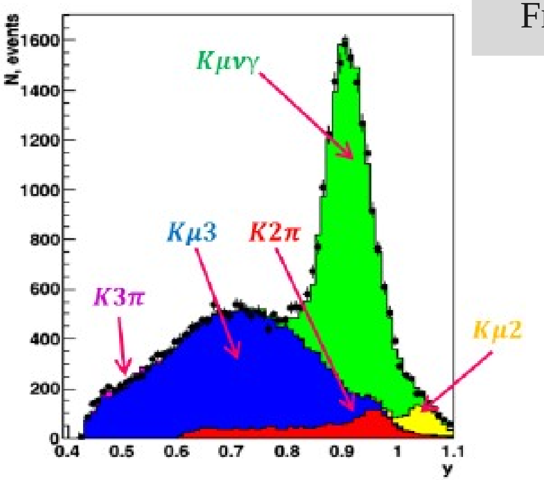
Based on half of the statistics of 2012 run, $N_K \sim 1.2 \times 10^{10}$

- 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 >1 GeV not associated with charged track
- $E_{GS} < 10$ MeV ; $E_{BGD} < 100$ MeV

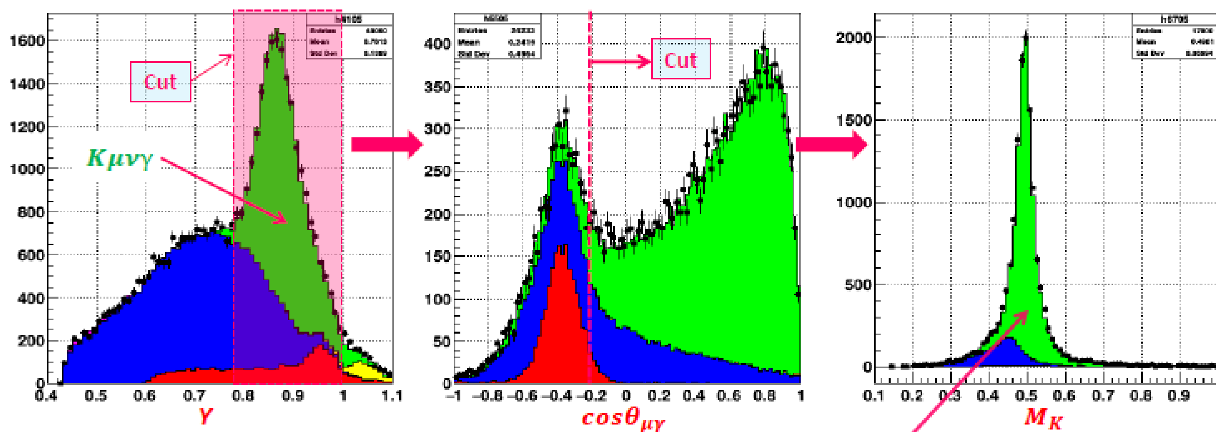


- <u>ISTRA+ procedure</u>
- x,y region is devided into strips Δx=0.05 (~12 MeV)
- plot y-disribution; select cuts $\{y_{min,}\ y_{max}\}$; plot $\cos\theta^*_{\mu\gamma}$; select $\cos_{min}$ cut; Plot M_K
- Simultaneous fit of the 3 histograms, parameters- N_{sig}, N_{bkg} , both signal(IB) and bkg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

From the fits, in total 95428±309 signal events 25 < E^*_γ < 150 MeV (ISTRA+ 22K)



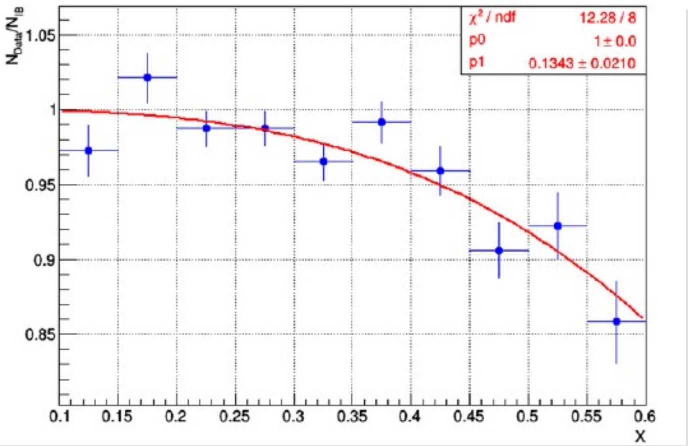
Geant3 MC: 22M sig. , 624M bkg.
only IB term in signal



Strip #3 (0.2<x<0.25)

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

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



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

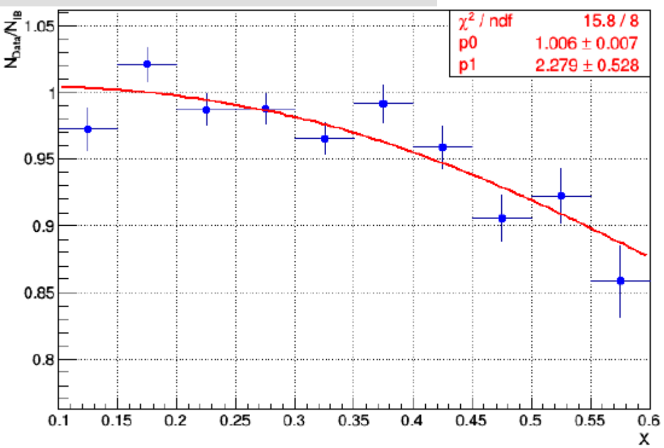
χPT $O(p^4)$ fit : F_V; F_A= const

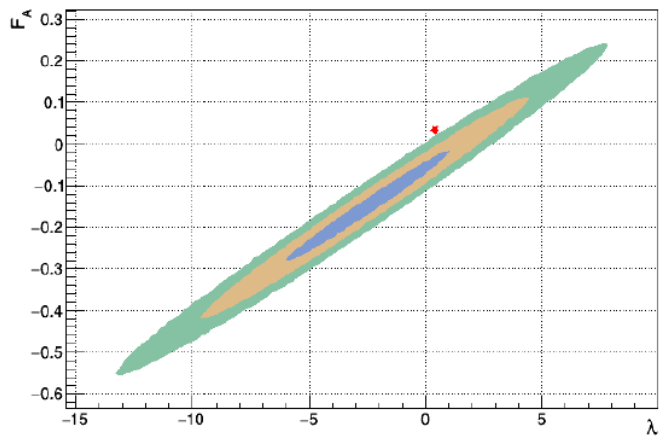
Red line is the result of the fit with $p_{sig}(x)=p0(1+p1\cdot\phi_{INT-}(x)/\phi_{IB}(x))$;

p0 is the normalization p0=1.00 ± 0.007 ; p1=Fv-Fa=0.134±0.021

$\phi_{INT-}(x)$- 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 $w_{IB}= f_{IB}(x_{true},y_{true})$





χPT $O(p^6)$ fit : $Fv=Fv(0)(1+\lambda(1-x))$; $F_V(0)=0.082$; $\lambda=0.4$; $F_A=0.034$

- Fit with fixed χPT $O(p^6)$ parameters: $\chi^2/NDF=28.0/9$
- $F_V(0)$ and F_A from χPT $O(p^6)$, λ-free parameter → $\lambda=2.28\pm0.53$; $\chi^2/NDF=15.8/8$(see the left figure)
- $F_V(0)$ from χPT $O(p^6)$, λ, F_A-free parameters → (see the correlation plot on the right figure)

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

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)
  $\rightarrow \sigma_{shape}=0.015$
- Width of -x- strips: Fv-Fa calculation repeated for 2 different values of width Δx=0.035, Δx=0.07 (nominal 0.05)
  $\rightarrow \sigma_{\Delta x}=0.011$
- The fit range in x (number of -x- strips): remove one or two bins on the left(right) edge.
  $\rightarrow \sigma_x <0.006$
- -y- limit in the strips: instead of maximizing $S/\sqrt{(S+B)}$ use FWHM from the signal MC
  $\rightarrow \sigma_y =0.008$
- 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)
  $\rightarrow \sigma_{INT+}=0.018$

$\rightarrow \sigma_{SYS}=0.027$

"OKA" $F_V\text{-}F_A = 0.134 \pm 0.021_{stat} \pm 0.027_{syst}$

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

$F_V\text{-}F_A = 0.054$ 2.3 σ difference

EχA (gauge non-local effective chiral action) S.Shim et al., Phys.Lett. B795 (2019)438-445

$F_V\text{-}F_A = 0.08$ (1.6 σ)

The measured value is in a reasonable agreement with ISTRA+ result: $F_V\text{-}F_A = 0.21 \pm 0.04_{stat} \pm 0.04_{syst}$ (1.15 σ)

And with (model dependent) result of BNL E865 ($K^+ \to \mu^+\nu e^+e^- + e^+\nu e^+e^-$) $F_V\text{-}F_A = 0.077 \pm 0.026$ (1.13 σ)

Expect tripling of the statistics by the year end

Study of the decay $K^+ \to \pi^+\pi^+\pi^- \gamma$ Eur.Phys.J. C79 (2019) no.4, 296

Based on 2 runs: 2012, 2013 analysis $N_K \sim 3.4 \times 10^{10}$

Inspired by:

[1] V.Cirigliano et al., “Kaon Decays in the Standard Model” arXiv:1107.6001 v3 [hep-ph] 14 April 2012

“The experimental status of $K^+ \to 3\pi\gamma$ is still rather meager”

[2] G. D. D’Ambrosio et al., “$K^+ \to \pi\pi\pi\gamma$ in Chiral Perturbation Theory” Z. Phys. C76(1997)301-310

a concept of “generalized bremsstrahlung”

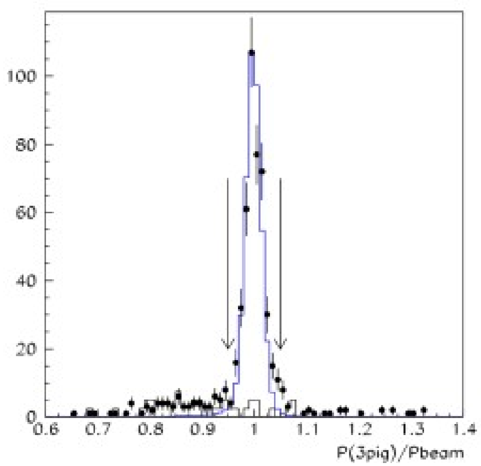
VALUE (10^{-4})	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1.04±0.31	**OUR AVERAGE**					
1.10 ±0.48	7	BARMIN	1989	XEBC		$E(\gamma) > 5$ MeV
1.0 ±0.4		STAMER	1965	EMUL	+	$E(\gamma) > 11$ MeV

Br($K^+ \to \pi^+\pi^+\pi^- \gamma$) PDGlive screenshot

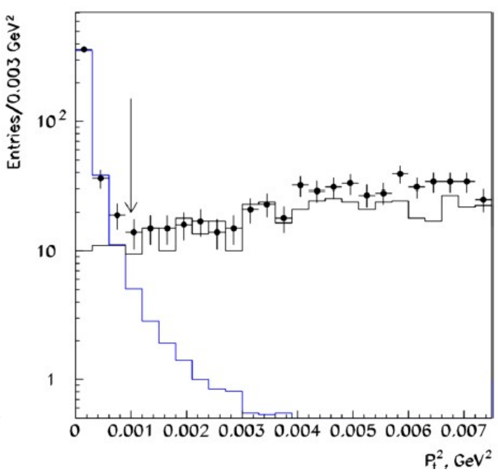
$$S_1 \cdot S_2 \cdot S_3 \cdot \overline{C_1} \cdot C_2 \cdot \overline{S_{bk}} \cdot (2 \leqslant MH \leqslant 4)$$

<u>Event selection</u>

- Beam track with measured $\vec{p}_b$
- 3 secondary charged tracs $\Sigma q_i = +$
- Decay vertex should have good χ^2 and to be inside DV
- Charged tracs not identified as electrons in GAMS-200
- One photon with E_γ > 0.5 GeV
- $M(\pi_i \gamma)$ >0.17 GeV
- $P_T^2(3\pi\gamma)$ >0.001 GeV^2
- 0.95< $|\vec{P}_{3\pi\gamma}|/|\vec{P}_{beam}|$ <1.05



$|\vec{P}_{3\pi\gamma}|/|\vec{P}_{beam}|$ after cuts

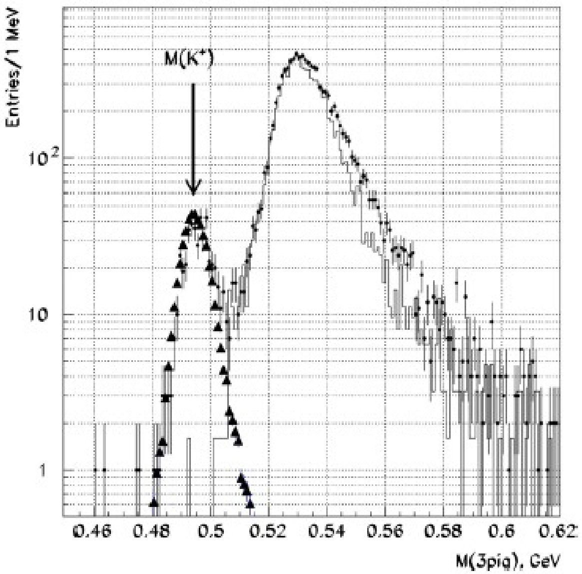


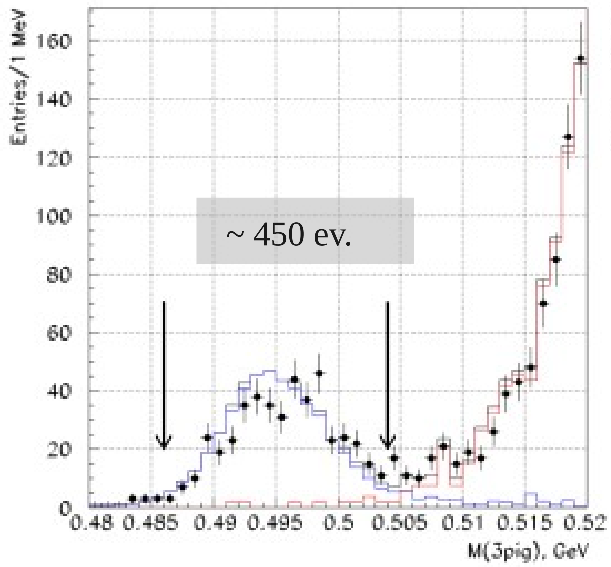
$P_T^2(3\pi\gamma)$ after cuts

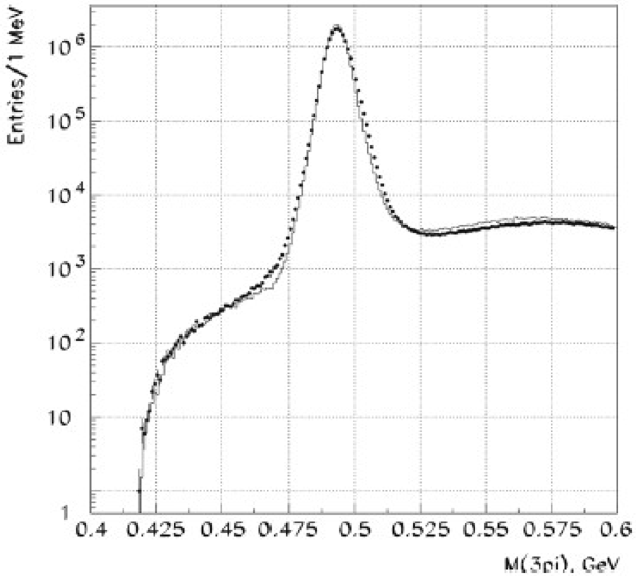
Geant3 MC:

- Bkg. $\pi^+\pi^0$, $\pi^+\pi^0\pi^0$, $\pi^+\pi^+\pi^-$, $\mu^+\nu$, $\pi^0\mu^+\nu$, $\pi^0 e^+\nu$ ~10^9 ev. mixed with Br, weights for 3 body decays → PDG $|M|^2$
- signal weight from the leading order amplitude, derived from $\pi^+\pi^+\pi^-$ [2]

Study of the decay $K^+ \to \pi^+\pi^+\pi^- \gamma$







Normalization on $N(K \to 3\pi) \sim 17$ M

$Br(K^+ \to \pi^+\pi^+\pi^- \gamma) = (7.1 \pm 0.4_{stat}) \cdot 10^{-6}$ $E^*_\gamma > 30$ МэВ

Systematics

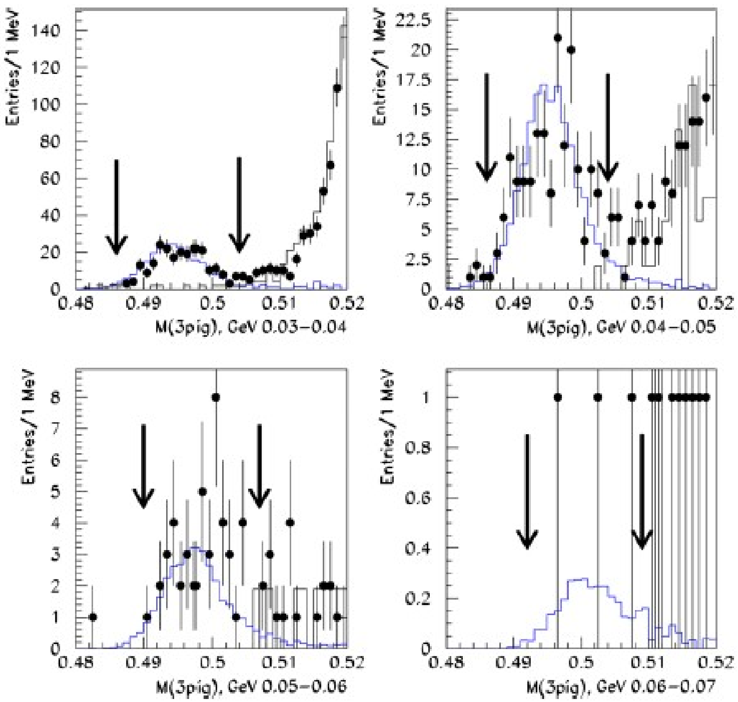
- The main source is uncertainty in the estimate of bkg in the signal region $\to \sigma_{bkg} = 0.27x10^{-6}$
- Cuts variation $\to \sigma_{cuts} = 0.1\ x10^{-6}$
- Estimate of bkg under $K \to 3\pi$ $\to \sigma_{norm} < 0.04\ x10^{-6}$

$\to \sigma_{SYS} = 0.3\ x10^{-6}$

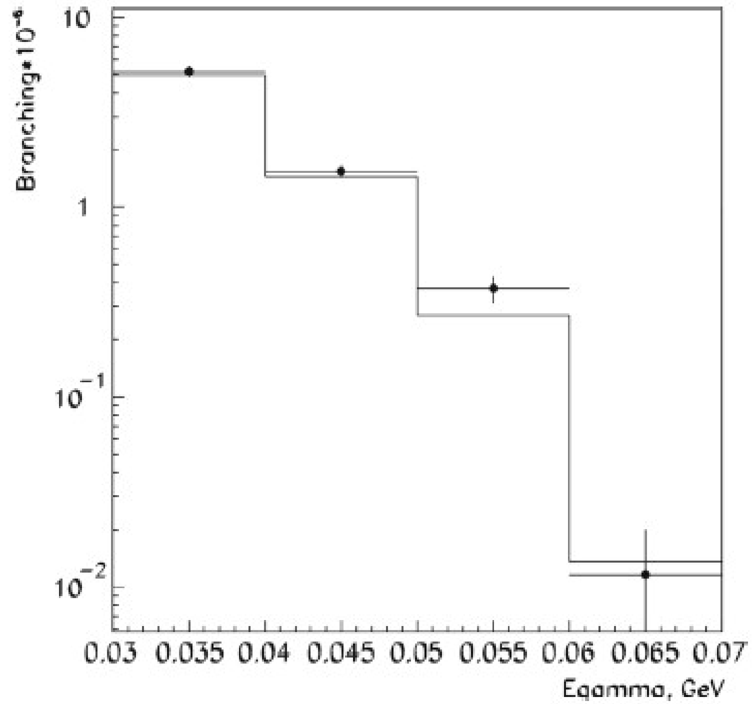
$Br(K^+ \to \pi^+\pi^+\pi^- \gamma) = (7.1 \pm 0.4_{stat} \pm 0.3_{sys}) \cdot 10^{-6}$ $E^*_\gamma > 30$ MeV

χPT $O(p^4)$ $(6.65 \pm 0.05) \cdot 10^{-6}$ [2]

Study of the decay $K^+ \to \pi^+\pi^+\pi^- \gamma$, differential branching



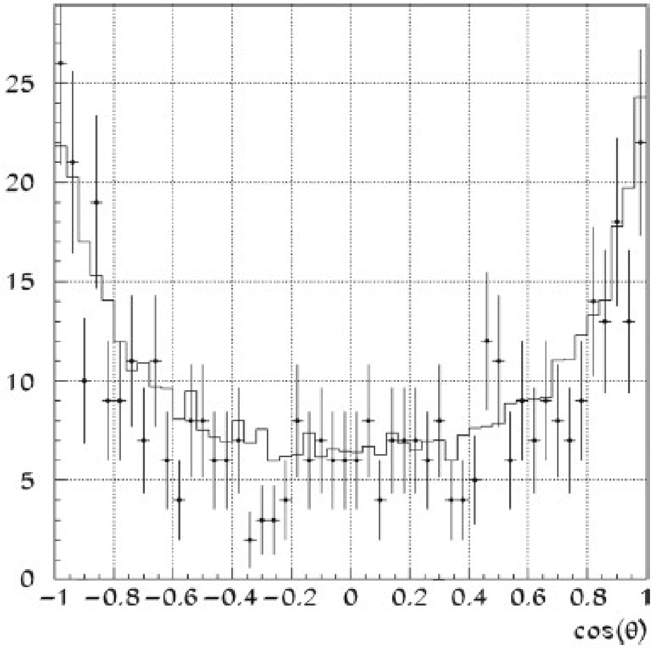
$M_{3\pi\gamma}$ in four 10 MeV bins over E^*_γ

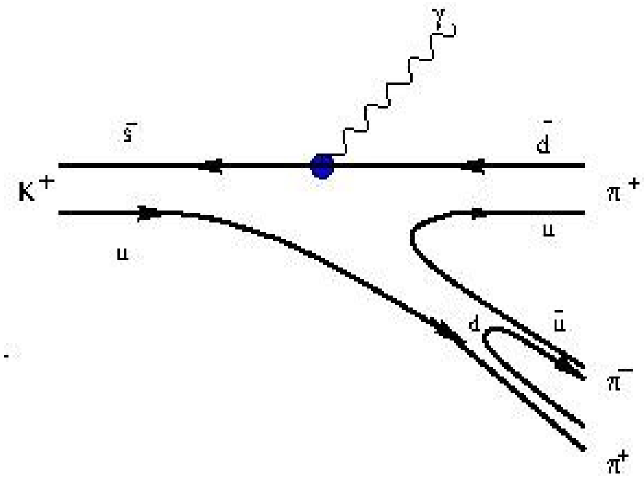


Differential $3\pi\gamma$ branching, compared with theory

Energy interval (GeV)	Branching fraction (data)	Branching fraction (CHPT [8])
0.03–0.04	$(5.17 \pm 0.34) \times 10^{-6}$	$(4.93 \pm 0.05) \times 10^{-6}$
0.04–0.05	$(1.55 \pm 0.12) \times 10^{-6}$	$(1.44 \pm 0.01) \times 10^{-6}$
0.05-0.06	$(0.35 \pm 0.05) \times 10^{-6}$	$(0.269 \pm 0.003) \times 10^{-6}$
0.06–0.07	$(0.11 \pm 0.06) \times 10^{-7}$	$(0.136 \pm 0.002) \times 10^{-7}$

In $B^+ \rightarrow K^+\pi^+\pi^- \gamma$ decay LHCb has found segnificant(~5%) up-down asymmetry of γ with respect to the hadronic system decay plane. This observable is T-odd. We perform an analogous study for $K^+ \rightarrow \pi^+\pi^+\pi^- \gamma$.





$$\cos\theta = \frac{\vec{n}_\gamma \cdot [\vec{p}_f(\pi^+) \times \vec{p}_s(\pi^+)]}{|[\vec{p}_f(\pi^+) \times \vec{p}_s(\pi^+)]|}$$ An alternative is $$\cos\theta = \frac{\vec{n}_\gamma \cdot [\vec{p}_f(\pi) \times \vec{p}_s(\pi)]}{|[\vec{p}_f(\pi) \times \vec{p}_s(\pi)]|}$$

A=(N(cosθ>0)-N(cosθ<0)/N_{tot} = -0.04(0.03) ±0.05(stat.)±0.03(syst.)

A theoretical support is needed to understand the scale of the effect in the SM and NP

Summary

<u>Several radiative decays are under study by "OKA" setup at @ U-70 synchrotron</u>

- The radiative decay $K^+ \to \mu^+ \nu \gamma$ is studied on statistics of ~95K events for 25 MeV < E^*_γ < 150 MeV .
  A destructive interference between IB and SD- is clearly seen. The difference of vector and axial constants Fv-Fa is measured:

  $F_V - F_A = 0.134 \pm 0.021_{stat} \pm 0.027_{syst}$ which is 2.3 σ from χPT $O(p^4)$ and 1.6 σ from EχA.

- The decay $K^+ \to \pi^+ \pi^+ \pi^- \gamma$ is studied on statistics of ~450 events for 30 MeV < E_γ < 70 MeV region.
  Branching fraction and differential branching fractions are measured:

  $Br(K^+ \to \pi^+\pi^+\pi^- \gamma) = (7.1 \pm 0.4_{stat} \pm 0.3_{sys}) \cdot 10^{-6}$ To be compared with χPT $O(p^4)$ $(6.65 \pm 0.05) \cdot 10^{-6}$

  An upper limit for the photon up-down asymmetry versus pion system decay plane is obtained

  $A = (N(\cos>0) - N(\cos<0))/N_{tot} = -0.04 \pm 0.05(stat.) \pm 0.03(syst.)$