Results on kaon physics from OKA setup @ U-70 synchrotron

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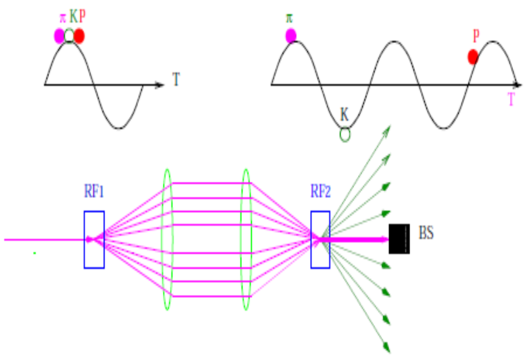
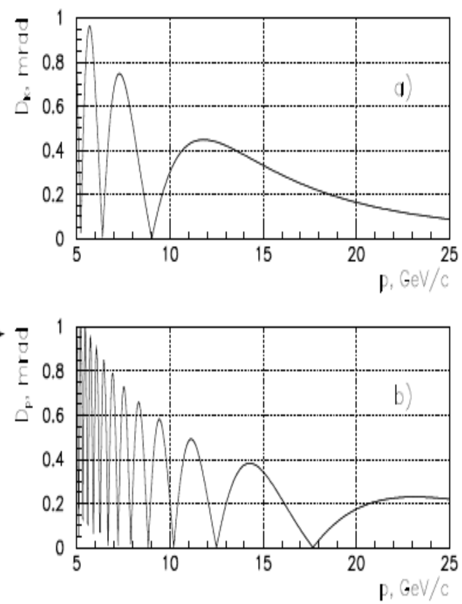
The talk layout

- OKA beam, detector, data
- Ke3 decay formfactors
- Kμ3γ decay study (Ke3γ reported at QUARKS-2016)
- Search for ν_H in Kμ2 decay
- $K^+ A \rightarrow K^+ \pi^0 A$
- Conclusions

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, presented by CERN. Sophisticated cryogenic system, built at IHEP provides superfluid He for cavities cooling.

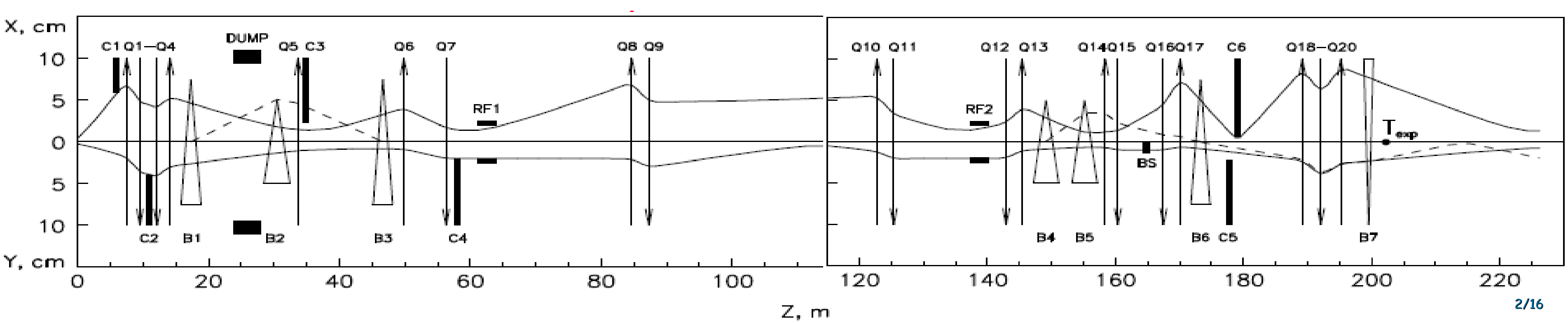




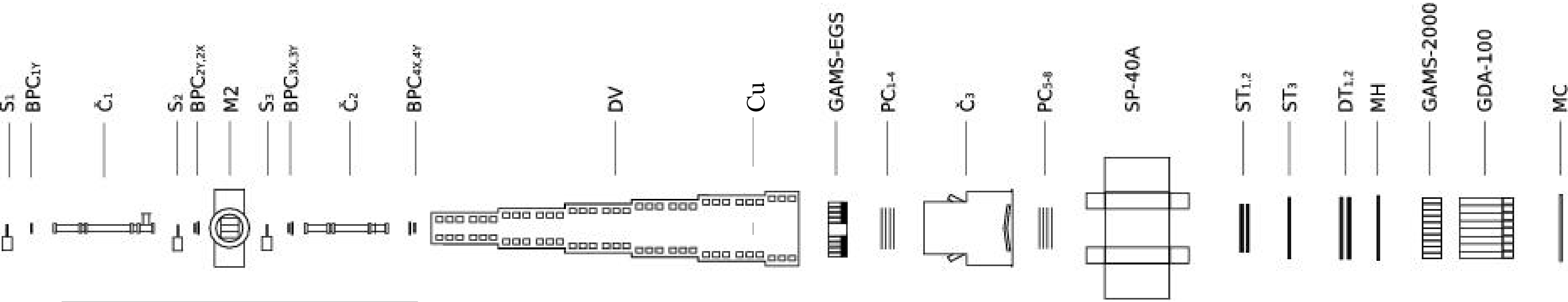
Operating frequency,(S-band)	2865 MHz
Wavelength, λ	~10.5 cm
Effective deflector length	2.74 m
Number of cells/deflector	104
Mean deflecting field	~1 MV/m
Working temperature	1.8 K

Main beam parameters :

Primary proton beam energy	50-65 GeV
Primary proton beam intensity	10^{13} ppp
Secondary beam momentum	12.5 or 18 GeV
Length of the beam line	~200m
K^{+} intensity at the end	~ 10^{6}
K^{+} in the beam	up to 20%



OKA detector



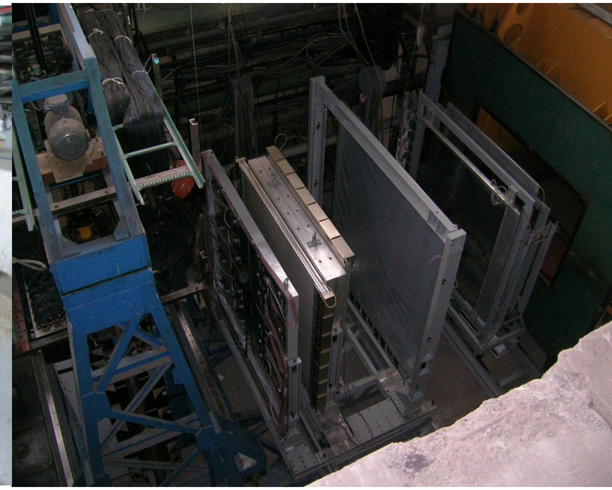
The main trigger $Trg = S_1 \cdot S_2 \cdot S_3 \cdot \check{C}_1 \cdot \bar{\check{C}}_2 \cdot \bar{S}_{bk} \cdot (\Sigma_{GAMS} > \mathrm{Mip})$

Prescaled triggers $S_1 \cdot S_2 \cdot S_3 \cdot C_1 \cdot \bar{C}_2 \cdot \bar{S}_{bk} \cdot MC\ /4$ $S_1 \cdot S_2 \cdot S_3 \cdot C_1 \cdot \bar{C}_2 \cdot \bar{S}_{bk}/10$

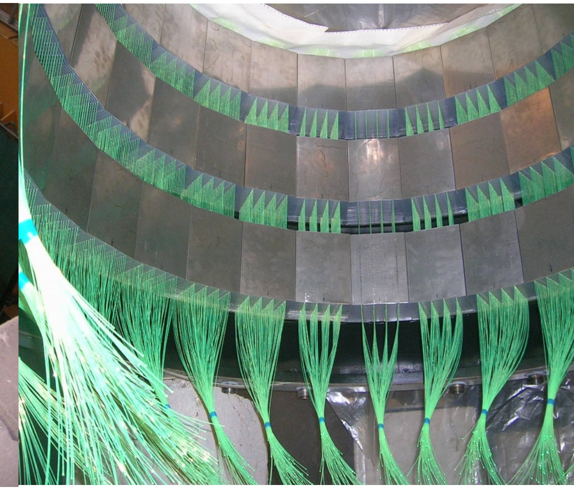
1. Beam spectrometer: 1mm pitch PC, ~1500 channels; Sc and $\check{C}$ counters
2. Decay volume with Veto system:
L=11m; Veto: 670 Lead-Scintillator sandwiches 20* (5mm Sc+1.5 mmPb), WLS readout
3. PC's and DT's for magnetic spectrometer:
~5000 ch. PC (2 mm pitch) + 1300 DT (1 and 3 cm)
4. Pad(Matrix) Hodoscope ~300 ch. WLS+SiPM readout
5. Magnet: aperture 200*140 cm^2
6. Gamma detectors: GAMS2000, EHS-backward EM cal. ~ 4000 LG.
7. Muon identification: GDA-100 HCAL+ 4 muon counters behind
8. For some runs Cu target inside decay volume was used: Ø=8 cm, t=2mm

«OKA» setup

General view of the OKA setup



ST, DT chambers, Matrix Hodoscope, ECAL

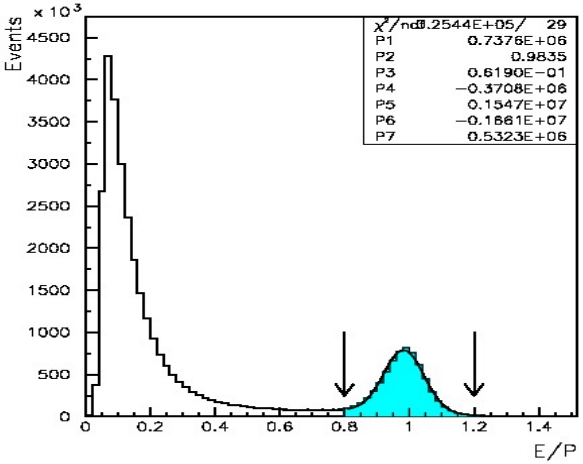


Decay volume Veto System

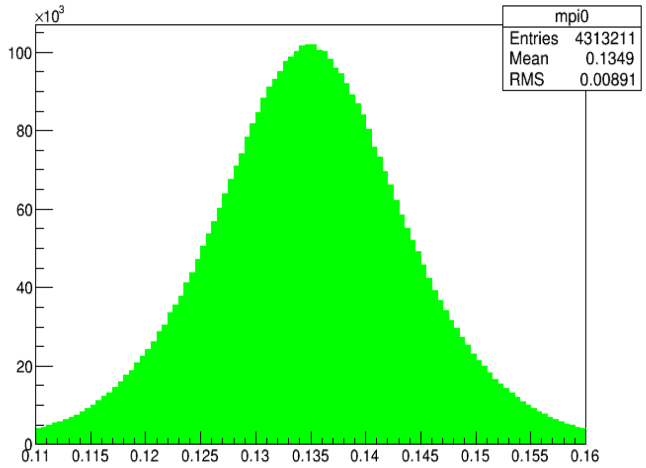
Statistics

	Nov2010	Nov2011	Nov2012	Apr2013	Total
Beam Energy	12.5 ;17.7	17.7	12.5 ; 17.7	17.7	
Live Kaons, 10^9	6.2	5.1	17.4	12.2	40.9
K2pi, 10^6	15.2	15.5	61	42	134
Ke3, 10^6	2.5	2.0	8.1	~5	~17

$K^+ \to \pi^0 e^+ \nu$ (Ke3) decay selection

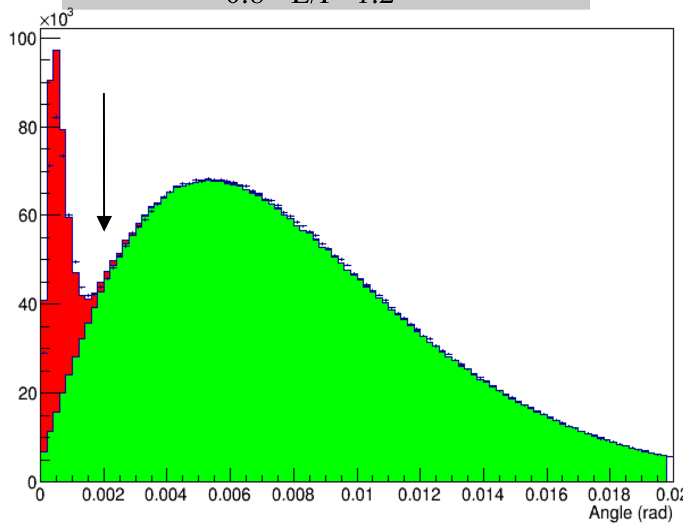


0.8 <E/P<1.2

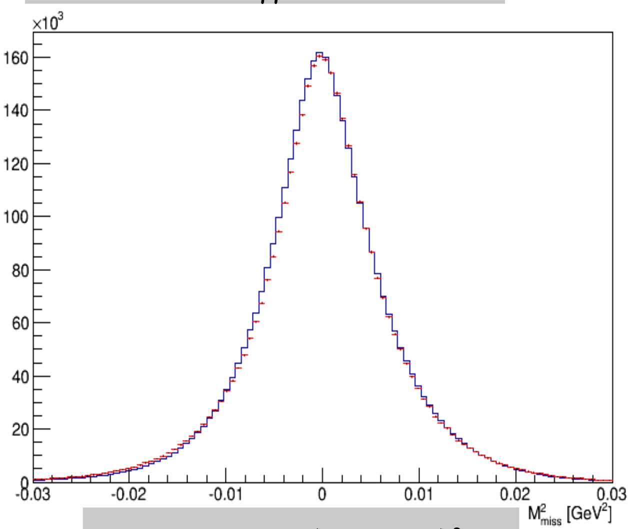


0.11 <Mγγ<0.16 GeV

- 1 ch. track θ>2mrad point to em-shower in ECAL: (r<3cm) .8 <E/P<1.2
- 2 extra showers (n_{cl}>3); 0.11 <Mγγ<0.16 GeV
- angle between $\vec{p}_K$ and $\vec{p}_e + \vec{p}_\pi$ α>2mrad
- 2C -constrained fit $\chi^2 < 20$



α - angle between $\vec{p}_K$ and $\vec{p}_e + \vec{p}_\pi$ α>2 mrad



$M^2_{mis} = (p_K - p_{e\pi})^2$

~3.15 M Ke3 events selected for the further analysis, background ~0.5%

Ke3 decay phenomenology

$$M = \frac{G_F V_{us}}{2} \bar{u}(p_\nu)(1+\gamma^5)[2m_K f_S + \frac{2if_T}{m_K}\sigma_{\alpha\beta}p_K^\alpha p_\pi^\beta - [f_+(p_K+p_\pi)_\alpha + f_-(p_K-p_\pi)_\alpha]\gamma^\alpha]v(p_l)$$

here $\frac{1}{\sqrt{2}}[f_+ \cdot (p_K + p_\pi)_\alpha + f_- \cdot (p_K - p_\pi)_\alpha] \equiv < \pi^0|\bar{s}\gamma_\alpha(1-\gamma_5)u|K^+ >$

Dalitz-plot density:

$$\rho(E_\pi, E_l) \sim A \cdot |V|^2 + B \cdot Re(V^* S) + C \cdot |S|^2$$

$$V = f_+ + (m_l/m_K)f_T \quad ; \quad S = f_S + (m_l/2m_K)f_- + \left(1 + \frac{m_l^2}{2m_K^2} - \frac{2E_l}{m_K} - \frac{E_\pi}{m_K}\right) f_T$$

$$A = m_K(2E_l E_\nu - m_K \Delta E_\pi) - m_l^2(E_\nu - \tfrac{1}{4}\Delta E_\pi) \; ; \; B = m_l m_K(2E_\nu - \Delta E_\pi) \; ; \; C = m_K^2 \Delta E_\pi$$

$$(\Delta E_\pi = E_\pi^{max} - E_\pi \; ; \; E_\pi^{max} = \frac{m_K^2 - m_l^2 + m_\pi^2}{2m_K})$$

Parametrization of t-dependence of the formfactors($f_0(t) = f_+(t) + \frac{t}{m_K^2 - m_\pi^2} f_-(t)$):

Taylor series:

$$f_+(t) = f_+(0)(1 + \lambda_+ t/m_\pi^2 + \tfrac{1}{2}\lambda'_+ t^2/m_\pi^4) \; ; \; f_0(t) = f_+(0)(1 + \lambda_0 t/m_\pi^2 + \tfrac{1}{2}\lambda'_0 t^2/m_\pi^4)$$

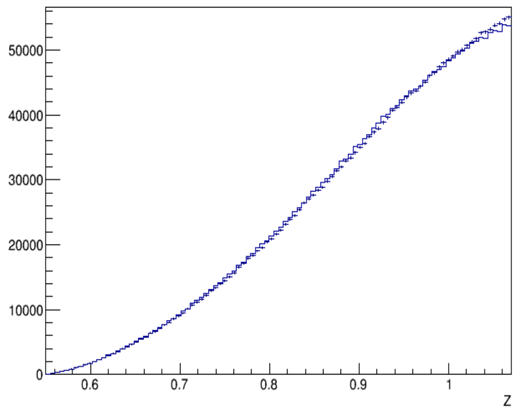
pole parametrization: $f_+(t) = \frac{m_V^2}{m_V^2 - t}$; $f_0(t) = \frac{m_S^2}{m_S^2 - t}$

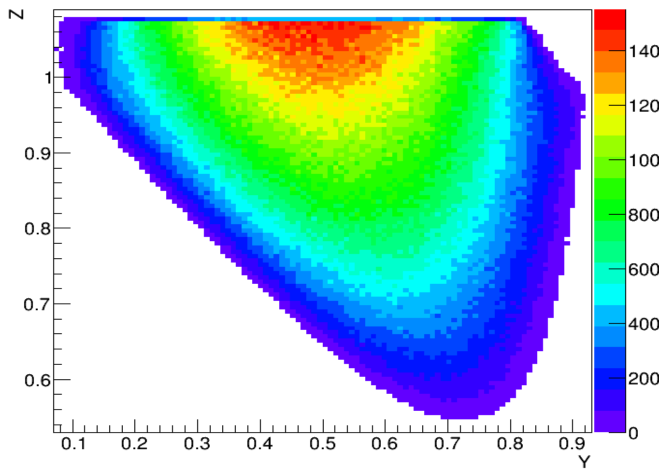
Dispersive parametrization (PLB638(2006) 480, PRD 80(2009)034034)

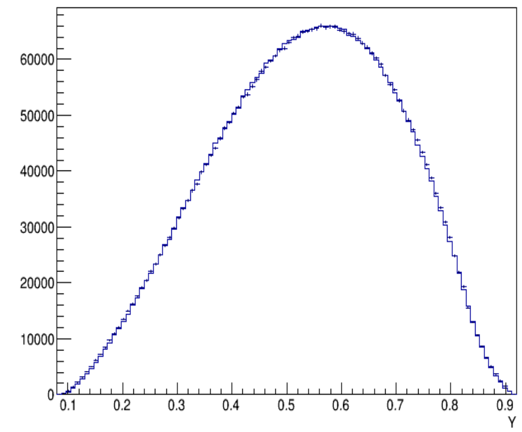
$$f_+(t) = exp(\frac{t}{m_\pi^2}(\Lambda_+ + H(t)); f_0(t) = exp(\frac{t}{\Delta_{K\pi}}(lnC + G(t))$$

Ke3 decay, analysis method

OKA experiment 3.15M Ke3 events







Dalitz-plot is subdivided into 100 $\times$100 bins ; $\rho(y,z)$ obeys a property of quasi-factorization, i.e

$$\rho(y,z) = \sum_{\alpha=1,18} F_\alpha(\lambda_+, \lambda_+^{'}, \lambda_0, \lambda_0^{'}, f_S, f_T) \cdot K_\alpha(y,z), \Rightarrow$$

$$r(i,j) = \sum_{\alpha=1,18} F_\alpha(\lambda_+, \lambda_+^{'}, \lambda_0, \lambda_0^{'}, f_S, f_T) \cdot W_\alpha(i,j) + Bkg(i,j)$$

The rad. cor. V.Cirigliano et al., Eur. Phys. J. C23(2002)121 are taken into account for Ke3

$$\chi^2 = 2\sum_j n_j \ln\left[\frac{n_j}{r_j}\left(1 - \frac{1}{m_j+1}\right)\right] + 2\sum_j (n_j + m_j + 1)\ln\left((1 + \frac{r_j}{m_j})/(1 + \frac{n_j}{m_j+1})\right),$$

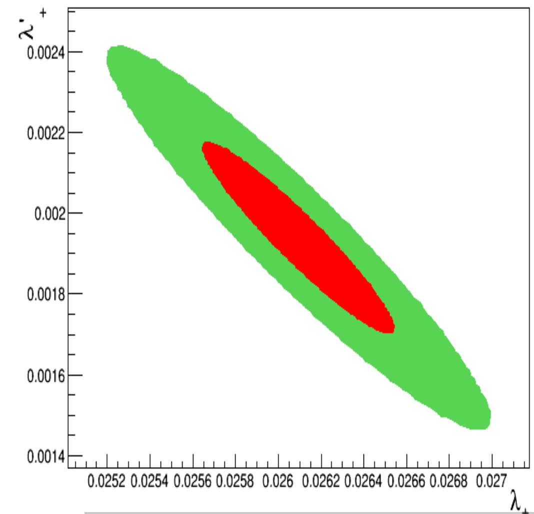
n_j, r_j and m_j are data , expected and MC events. For large m_j it reduces to

$$\chi^2 = \sum_j [2(r_j - n_j) + 2n_j \ln n_j/r_j]$$

MC statistics is at present 3 x data

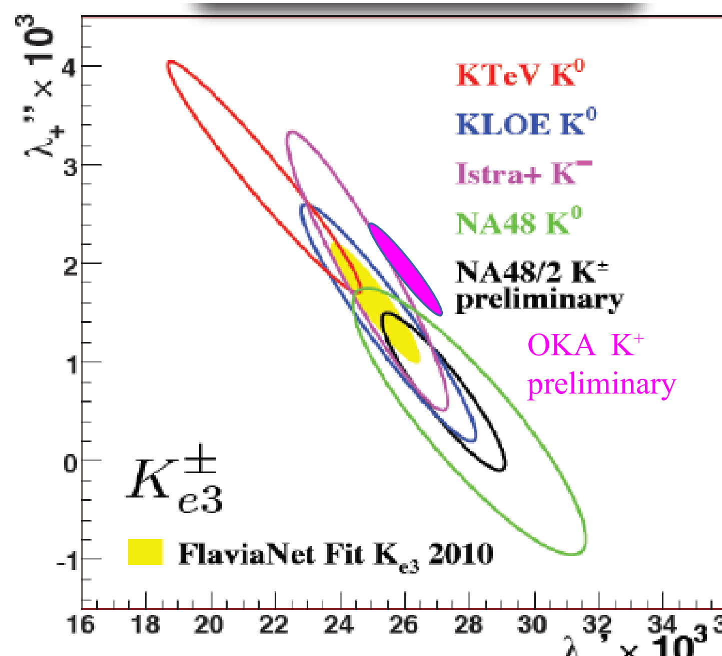
Ke3 decay, fits

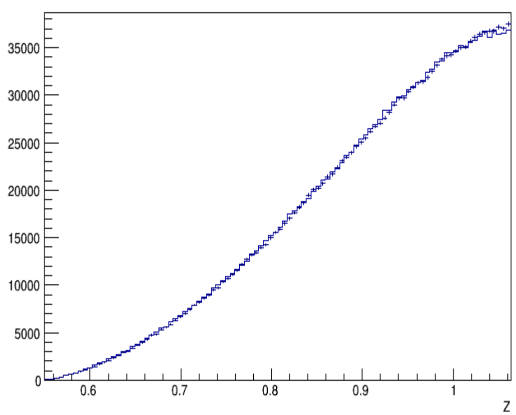
$\lambda'_+(\lambda_+)\times10^3$	$\lambda''_+\times10^3$	$F_s/f_+(0)\times10^2$	$F_T/f_+(0)\times10^2$
29.56±0.28			
26.1±0.45	1.94±0.24		
26.1±0.45	1.93±0.24	–0.44±0.7	0.16±2
26.1±0.45	1.93±0.24	–0.41±0.3	

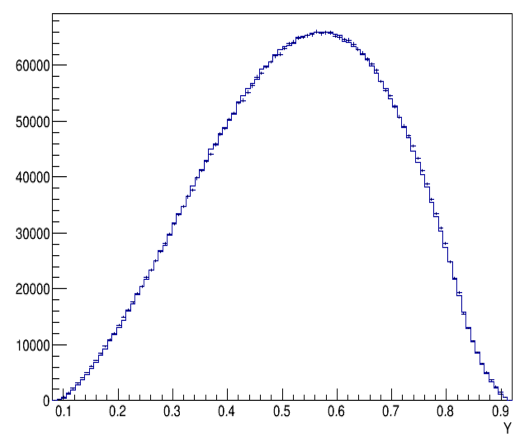


68% confidence level contours

Pole fit	Dispersive fit
M_V=890±3.7 MeV	Λ_+=(24.72±0.23)x10^{-3}

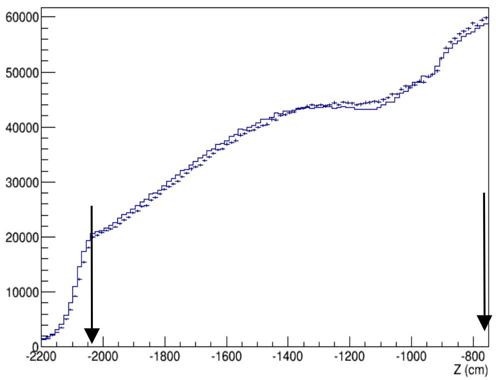


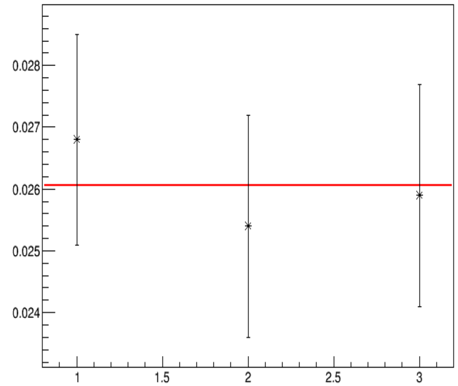


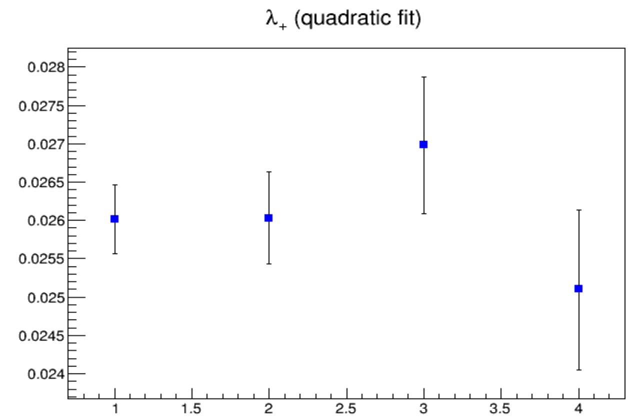


Ke3 decay, systematics, final results

The main contribution to systematics is coming from the variation of the cut on -z- coordinate of the vertex and The cut on the angle α between $\vec{p}_K$ and $\vec{p}_e + \vec{p}_\pi$. To study -z- systematics in details, the statistics was subdivided into three parts in -z- Another test was done using 3 parts of the statistics with different setup configuration.







Systematics in λ_+ :

- z-cut 0.3×10^{-3}
- α-cut 0.2×10^{-3}
- Other 0.12×10^{-3}
- Total 0.38×10^{-3}

$\lambda'_+(\lambda_+) \times 10^3$	$\lambda''_+ \times 10^3$	$F_S/f_+(0) \times 10^2$	$F_T/f_+(0) \times 10^2$
26.1±0.45±0.38	1.94±0.23±0.12		
26.1±0.45±0.38	1.93±0.24±0.12	−0.44±0.7±0.24	0.16±2±1.3

Comparison with theory

- The λ_+ - average slope parameter of the vector formfactor $f_+(t)$ is measured to be $(29.56\pm0.28)\times10^{-3}$

$\lambda^{th}_+(\chi PTO(p^4)) = (31.0\pm0.6)\times10^{-3}$

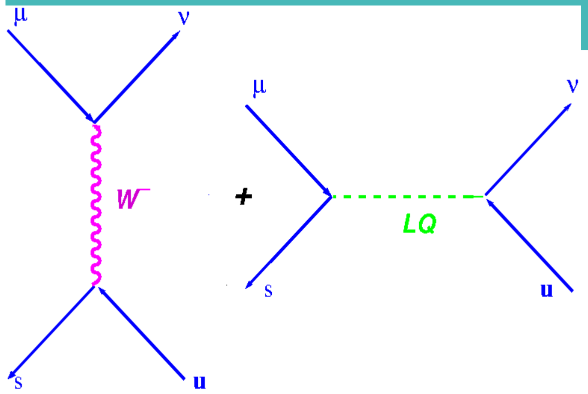
A significant nonlinearity in $f_+(t)$ is measured $\lambda''_+ = (1.94\pm0.23\pm0.12)\times10^{-3}$

$\lambda^{th}_+(\chi PTO(p^6)) = (1.12\pm0.1)\times10^{-3}$

- Results of the pole fit $f_+(t) = f_+(0)/(1-t/M^2_V)$ $M_V = (890\pm3.7)$ MeV

PDG $M_{K^*} = (890.4\pm0.26)$ MeV

Possible interpretation of limits on F_S, F_T: scalar LQ



Apply Fiertz transformation to LQ diagram →

$$(\bar{s}\mu)(\bar{\nu}u) = -\frac{1}{2}(\bar{s}u)(\bar{\nu}\mu) - \frac{1}{8}(\bar{s}\sigma_{\alpha\beta}u)(\bar{\nu}\sigma^{\alpha\beta}\mu)$$

First term is scalar, second- tensor. It can be shown (V.V. Kiselev et al., hep-ph/0204066)

$$\frac{f_S^{LQ}}{f_+(0)} = \frac{\sqrt{2}}{16G_F|V_{us}|}\frac{m_K^2-m_\pi^2}{(m_s-m_u)m_K}\frac{1}{\Lambda^2_{LQ}}; \quad \frac{f_T^{LQ}}{f_+(0)} = \frac{\sqrt{2}}{32G_F|V_{us}|}\frac{m_K}{m_{K^*}}\frac{1}{\Lambda^2_{LQ}}$$

Then from our estimates for F_S, F_T → $\Lambda_{LQ} > 3.5$ TeV

Study of the $K^+\to\pi^0\mu^+\nu\gamma$ ($K\mu3\gamma$) decay

$K^+\mu3\gamma$ 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 in χPT O(p4), in particular for the T-odd asymmetry. V. Braguta et al., PR D68(2003)

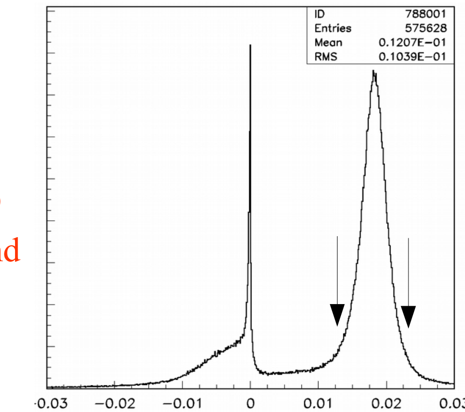
$$\xi = \vec{p}_\gamma \cdot (\vec{p}_l \times \vec{p}_\pi)/m_K^3 \qquad A_\xi = \frac{N(\xi>0)-N(\xi<0)}{N(\xi>0)+N(\xi<0)}$$

$A_\xi \sim 3\times10^{-4}$ for SM exentions

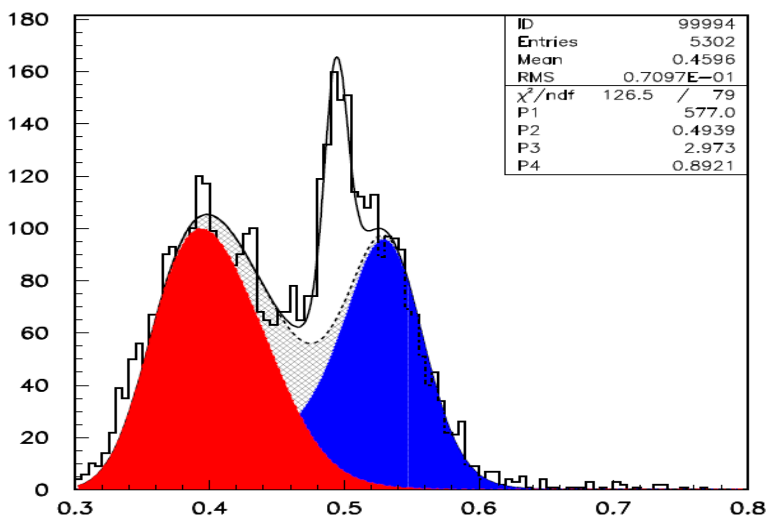
Signal selection   Statistics of Nov2012 and Apr2013 is used

- 1 ch. Track identified as muon in GAMS, HCAL and μ-counters
- 3 extra showers ($n_{cl}>3$); 0.11 < $M\gamma\gamma$ < 0.16 GeV
- Missing momentum points to active area of GAMS
- Total energy in E_{VETO} < 50 MeV in E_{BGD} < 100 MeV
- 30 < $E^*\gamma$ < 60 MeV ; M^2_{mis} < 0.013 or M^2_{mis} > 0.0225 GeV^2

$K\to\pi^+\pi^0\pi^0$ background



$M^2_{mis} = (p_K - p_{\pi+} - p_{\pi0})^2$



$K\to\pi^+\pi^0\pi^0$ $K\mu3$ $M\pi\mu\nu\gamma$ (GeV), $m_\nu=0$

~580 signal events observed (previous experiments ~150)
In the interval 30 < $E^*\gamma$ < 60 MeV
Normalisation is done on the events of the $K\mu3$ decay

R=Br($K\mu3\gamma$, 30 < $E\gamma$ < 60 MeV)/Br($K\mu3$) =
$(4.85\pm0.2(stat)\pm0.5(syst))\times10^{-4}$ $R(O(p^4)) = 4.7\times10^{-4}$
T-odd asymmetry $A_\xi = (-0.19\pm0.051\pm0.09)$ ~3×10^{-4}
Space asymm. $A(\cos\theta^*_{\mu\gamma}) = (0.61\pm0.05\pm0.1)$ ~0.05 ?

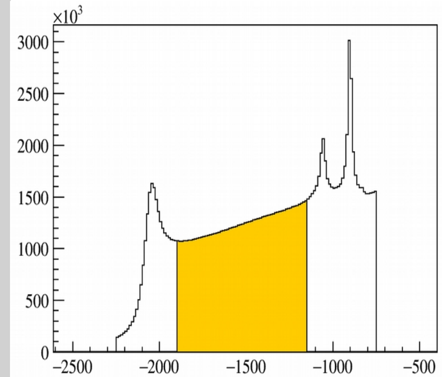
Search for heavy neutrino in $K \to \mu \nu_H$ decay

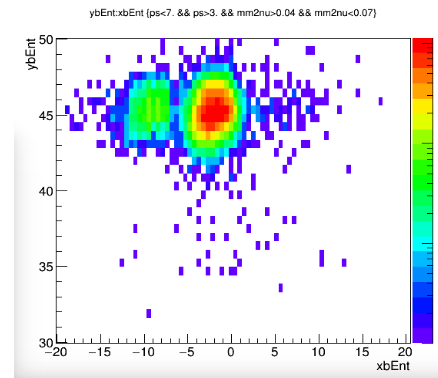
Signal selection(Statistics of Nov2012 is used)

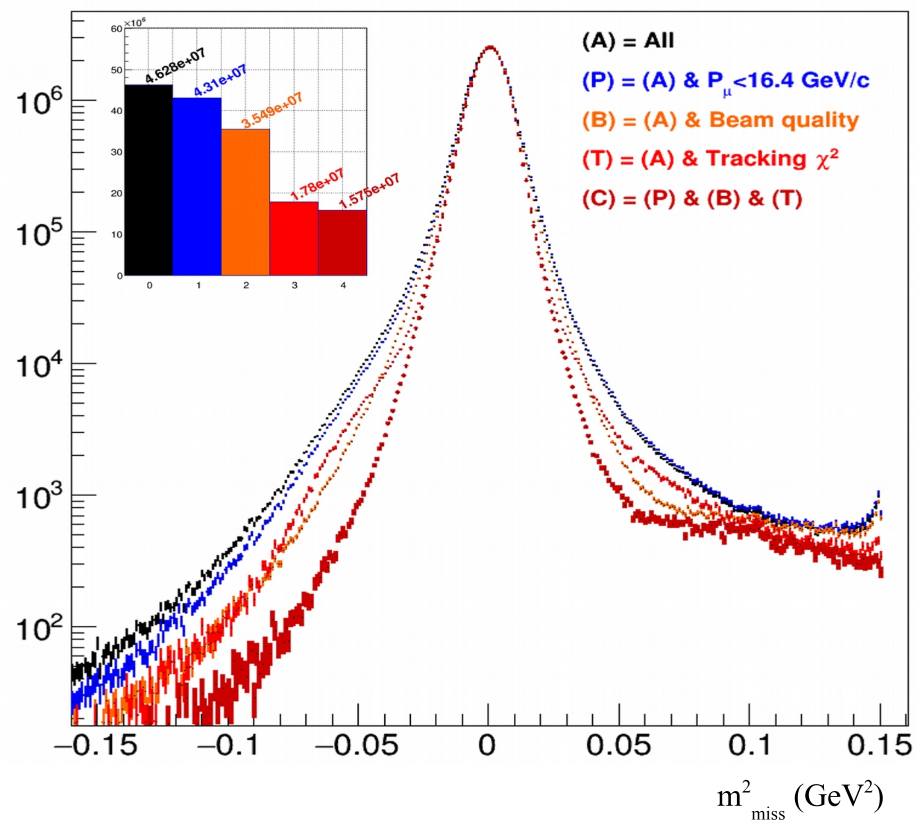
Triggers: $S_1 x S_2 x S_3 x C_1 x \bar{C}_2 x \bar{S}_{bk} x S_\mu$ /4; $S_1 x S_2 x S_3 x C_1 x \bar{C}_2 x \bar{S}_{bk}$ /10

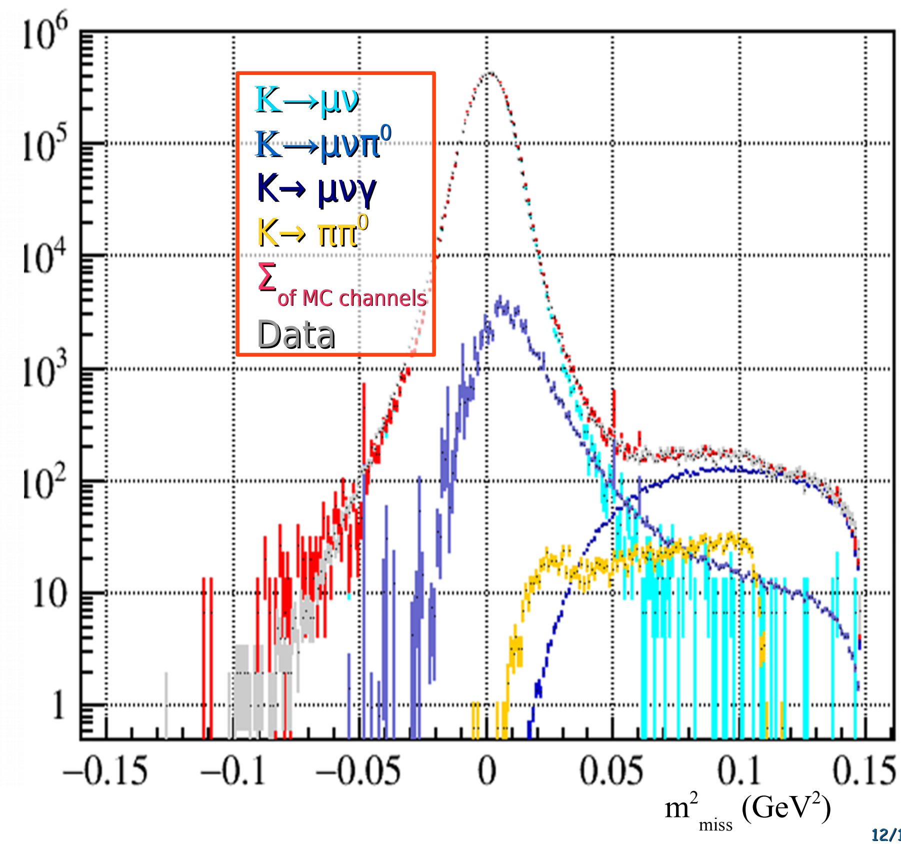
- 1 ch. Track identified as muon in GAMS, HCAL and μ-count.

- Total energy in E_{VETO} < 50 MeV in E_{BGD} < 100 MeV
- Decay vertex well inside decay volume ~46M events
- Beam quality cuts
- Track quality cuts: Np>6 for beam, Np>16 for the secondary, χ^2
  ~16M events



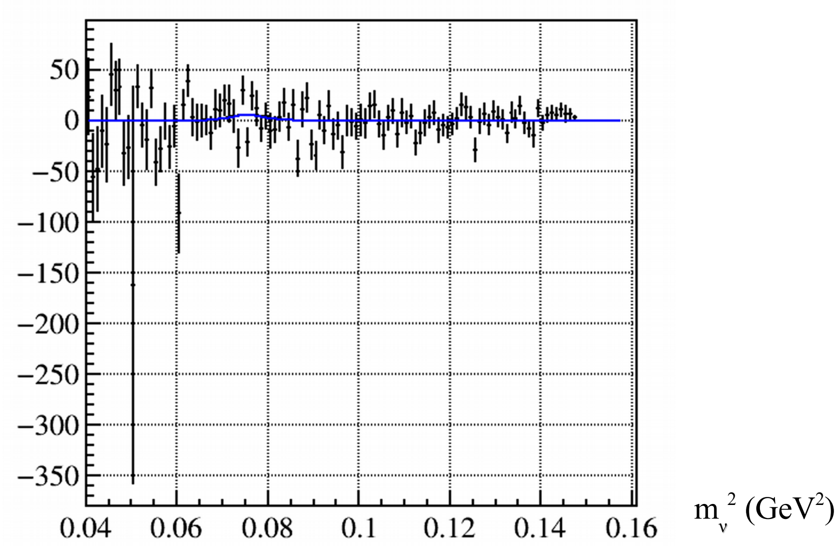




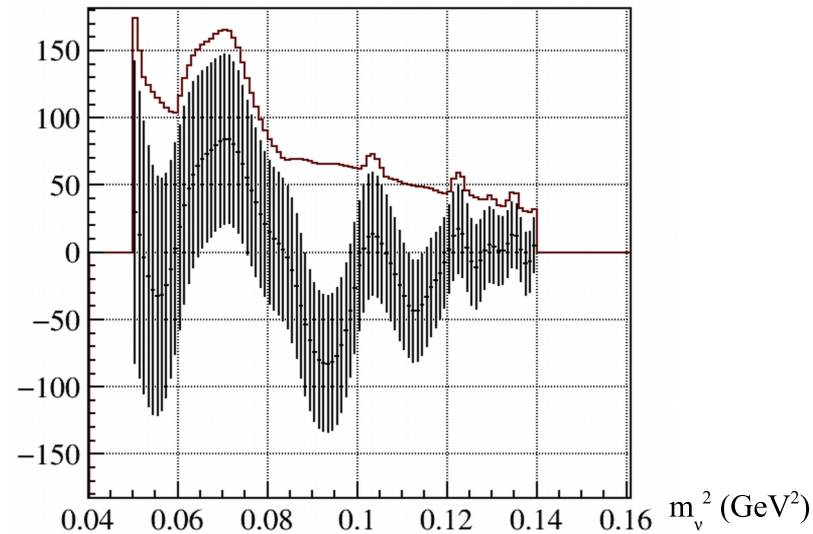


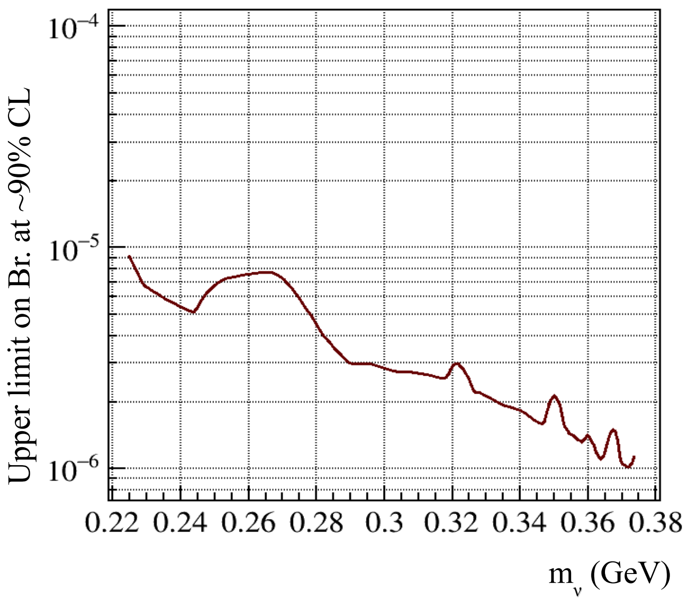
Search for heavy neutrino in $K \to \mu\, \nu_H$ decay

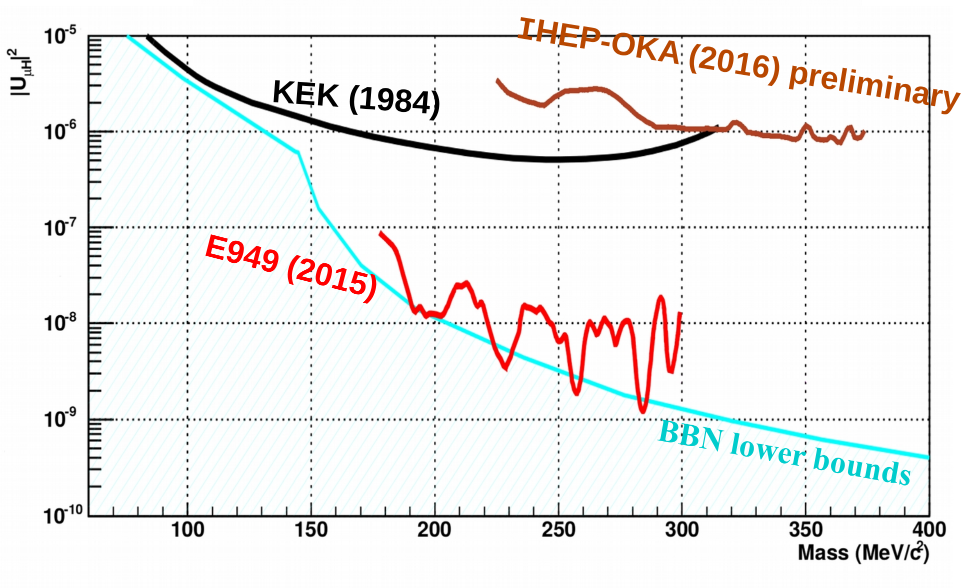
Residual of the fit by Kμ2+Kμ2g+Kμ3+Kπ2



Result of the fit by Gauss with MC width and 90% C.L.

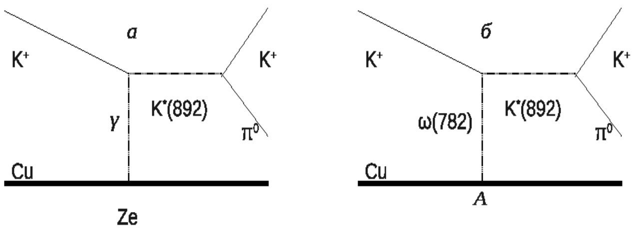






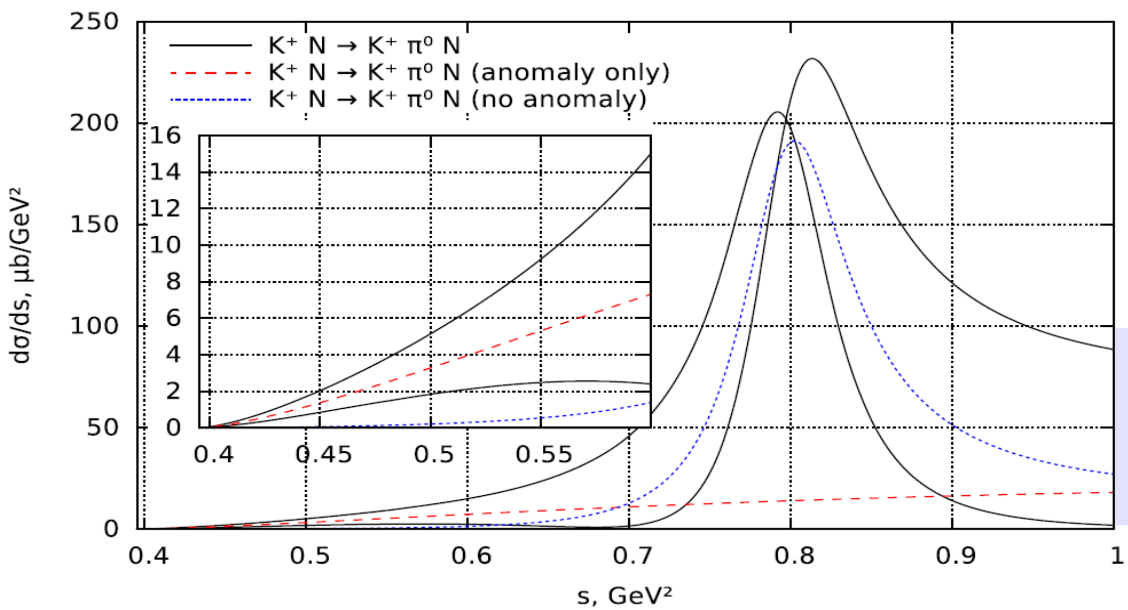
Study of the coherent production of $K^+ \pi^0$ $K^+ A \rightarrow K^+ \pi^0 A$ on Cu target @ p=17.7 GeV

Motivation: Measurement of the $\Gamma(K^* \rightarrow K\gamma)$, study of the EM-Strong Interaction interference; search for WZW-anomaly



$$\frac{d\sigma(K^+\gamma\to K^+\pi^0)}{dt} = \frac{1}{2^7\pi}\left(t+\frac{(st-m_{K^+}^2 m_{\pi^0}^2)(t-m_{\pi^0}^2)}{(s-m_{K^+}^2)^2}\right) \times \left|\frac{e}{4\pi^2F_\pi^3} \pm \frac{2f_{K^{*+}K^+\gamma}f_{K^{*+}K^+\pi^0}}{m_{K^{*+}}^2 - s - i\sqrt{s}\,\Gamma_{K^{*+}}(s)}\cdot\frac{s}{m_{K^{*+}}^2}\right|^2$$

WZW-anomaly, no anomaly in $K^0\pi^+$



Vysotsky, Zhemchugov PR D93, 2016
Burtovoy Phys.Atom.Nucl. V76 2013
Rogalyev Phys.Atom.Nucl. V64 2001

$\sigma(0.4<s<0.6)=0.64$ μb (with anomaly)
$\sigma(0.7<s<0.9)=19.5$ μb
A=(L-R)/(L+R) ~ 12% or -60% with anomaly
~ -20% without

Study of the coherent reaction $K^+ A \rightarrow K^+ \pi^0 A$

Selection procedure (main background is $K^+ \rightarrow \pi^+ \pi^0$)

$\overline{C}_3$, $P_{K+} > 7$ GeV

$P_{cm} < 160$ or $P_{cm} > 240$ (MeV/c); $P_{cm}(K^+ \Rightarrow \pi^+ \pi^o) = 205$ MeV/c

$\cos\theta_{GJ} > -0.7$

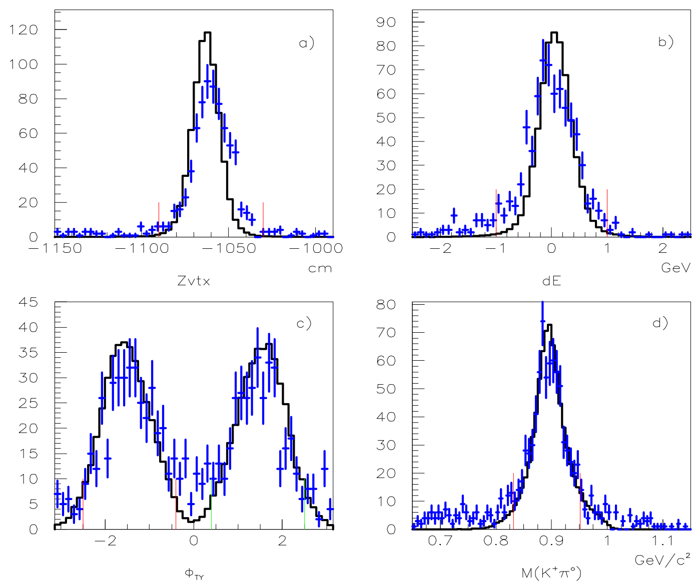
$|dE| < 1$GeV; $dE = E_{K^+} + E_{\pi^o} - E_b$

$E_{GS} < 40$ MeV

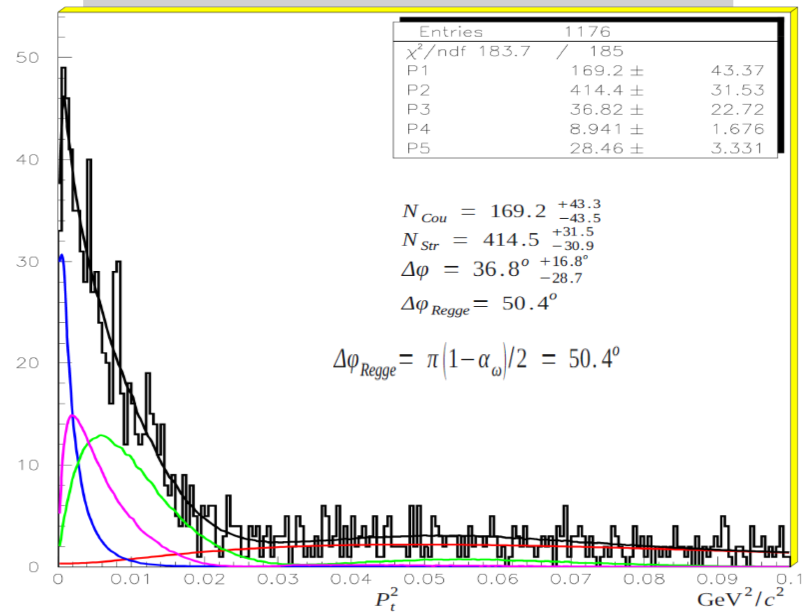
$E_{BGD} < 100$ MeV

$-1030 < Zvtx < -1090$ (cm)

$0.4 < |\Phi_{TY}| < 2.5$



Fit of P^2_T by Coulomb+Strong+Interference



Using number of events from the fit : Nc=169.2 ±43 ; Ns=414.5± 31 and K^+ flux $=4.88\times10^9$ from number of $K^+ \rightarrow \pi^+\pi^0$

$\sigma_c = 34.9 \pm 9$ μb ; $\sigma_S = 84.9 \pm 6.5$ μb ; $\Delta\varphi = (36.8^{+17}_{-29})°$. From σ_c value → $\Gamma_{K\gamma} = 126 \pm 32$ KeV (PDG 50± 5 KeV)

Asymmetry A= 1 ± 10 %

Summary

"OKA" collaboration, operating at IHEP Protvino U-70 PS in RF-separated beam has accumulated large statistics of K^+ decays.

- First results on Ke3 decay on statistics of 3.15M events are presented: $f_+(t)$ Taylor series coefficients λ_+, λ'_+, λ''_+ are measured, as well as parameters of the Pole and Dispersive fit.

- Limits on NP are presented: Ke3 F_S and F_T formfactors are constrained, from that a limit on Λ_{LQ} - leptoquark mass scale is derived.

- The decay $K^+\mu3\gamma$ is studied on statistics of 580 ev. For the 30 MeV <E<60 MeV region. Br is measured As well as space and T-odd asymmetry .

- Search for heavy neutrino in the decay $K\rightarrow\mu\, \nu_H$ is performed, new limits on $|U_{\mu H}|^2$ are provided.

- Coherent process $K^+ Cu \rightarrow K^+ \pi^0 Cu$ is studied at P_b=17.7 GeV, xsections for the Coulomb, Strong and their Interference are determined, $\Gamma_{K+\gamma}$ is measured, some constraints on WZW anomaly are obtained