# Highlights on Rare Charged Kaon Decays

## ISTRA+ & KEK EXPERIMENTS

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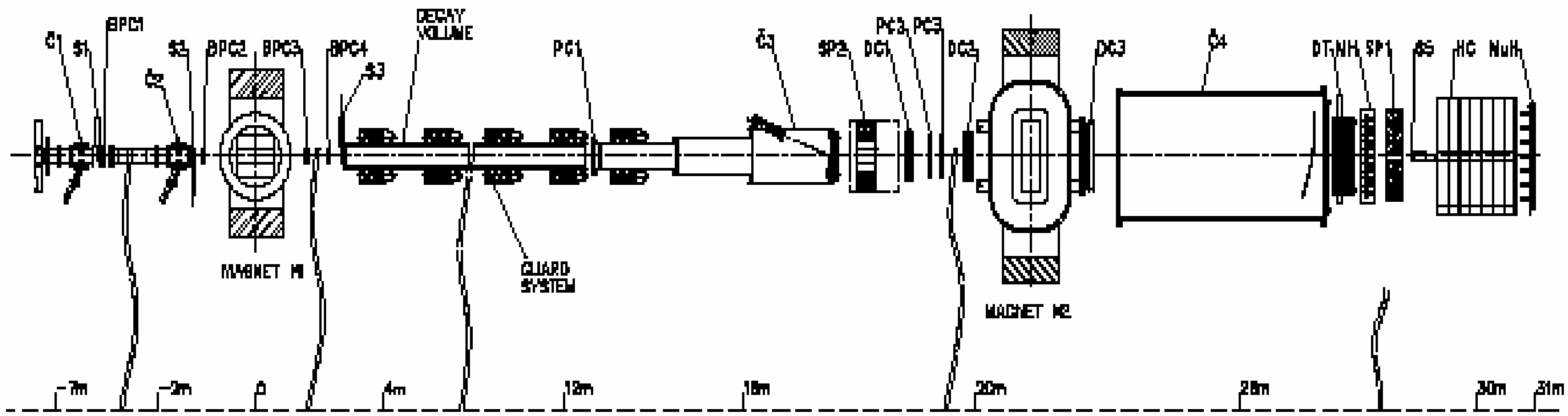
# Talk outline

- 1. Radiative weak decays at ISTRA+ experiment:
- 1.1 $K^- \rightarrow \mu^- \nu \gamma$
- 1.2 $K^- \rightarrow \mu^- \nu \pi^0 \gamma$
- 1.3 $K^- \rightarrow e^- \nu \pi^0 \gamma$
- 2. Recent result from KEK:
- 2.1 $K^+ \rightarrow \pi^+ \pi^0 \gamma$
- 3. Conclusions

# ISTRA+ experimental setup

## *for studying rare kaon decays*




$p \sim -25$ GeV ; $\Delta p/p \sim 1.5\%$; $K^{-} \sim 3\%$; $I \sim 3 \cdot 10^{6}/1.9$ sec

$T = S_1 \cdot S_2 \cdot S_3 \cdot \bar{S}_4 \cdot \check{C}_0 \cdot \bar{\check{C}}_1 \cdot \bar{\check{C}}_2 \cdot \bar{S}_5 \cdot (\Sigma_{SP1} > \text{mip})$

C1-C4 – thresh. cherenkov counters; S1-S5 – scintillation counters; PC1-PC3 – proportional chambers; SP2 – veto calorimeter; SP1 – lead-glass calorimeter; DC – drift chambers; DT-drift tubes; MH – matrix scintilation godoscope

# K→ μ ν γ : Theory

- Differential decay rate :

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

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

$$f_{SD+} = [x+y-1-r][(x+y-1)(1-x)-r],$$

$$f_{SD-} = [1-y+r][(1-x)(1-y)+r],$$

$$f_{INT+} = \left[\frac{1-y+r}{x(x+y-1-r)}\right][(1-x)(1-x-y)+r],$$

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

$$r = \left[\frac{M_\mu}{M_K}\right]^2,$$

$$A_{IB} = \Gamma_{K_{\mu 2}} \frac{\alpha}{2\pi} \frac{1}{(1-r)^2},$$

$$A_{SD} = \Gamma_{K_{\mu 2}} \frac{\alpha}{8\pi} \frac{1}{r(1-r)^2} \left[\frac{M_K}{F_K}\right]^2,$$

$$A_{INT} = \Gamma_{K_{\mu 2}} \frac{\alpha}{2\pi} \frac{1}{(1-r)^2} \frac{M_K}{F_K}.$$

- 3 main terms:

  IB – dominant

  SD±, INT± - most interesting (→ $F_V$, $F_A$)

- Kinematical variables:

  $x=2*E_\gamma(cm)/M_k$   $y=2*E_\mu(cm)/M_k$

# $K \rightarrow \mu \nu \gamma$ : event selection

- Decay signature:
- 1 charged track
- Muon flag in HCAL
- 1 shower in ECAL (not associated with charged track)

- Additional cuts:
- 300cm < $Z_{vertex}$ < 1650cm
- Missing energy > 1GeV
- No signal in veto system
- missing momentum points to ECAL aperture

# $K \to \mu\,\nu\,\gamma$ : background suppression

- Main background:
- $K \to \mu\,\nu\,\pi^0$ (Kμ3)

with 1 gamma lost (from $\pi^0 \to \gamma\gamma$)

- $K \to \pi\,\pi^0$ (Kπ2)

with 1 gamma lost (from $\pi^0 \to \gamma\gamma$) and π misidentification

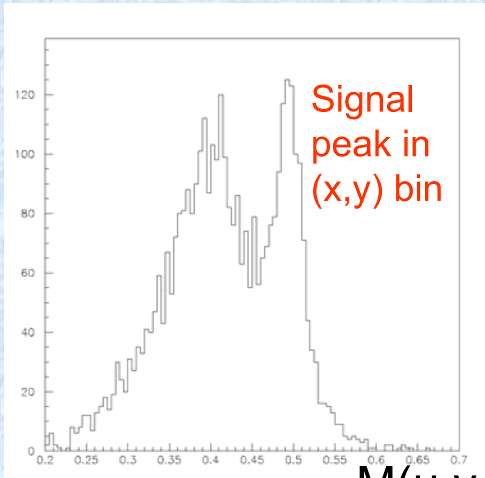
- Suitable variable:

$M(\mu\,\nu\,\gamma) = \sqrt{(P_\mu + P_\nu + P_\gamma)^2}$ where

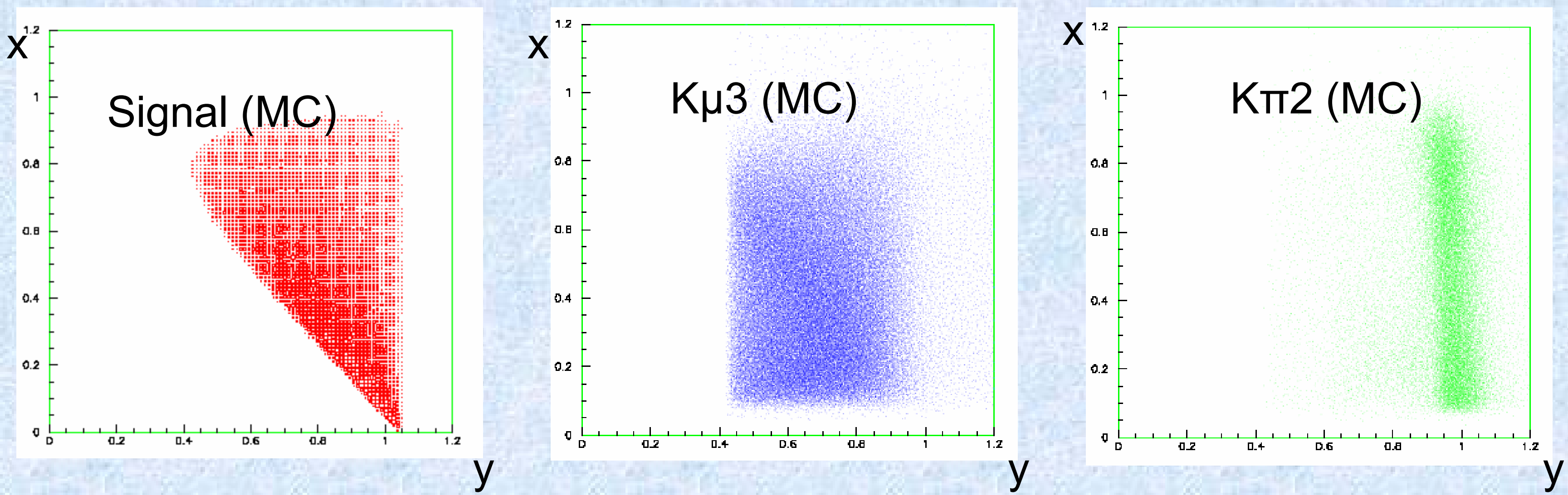
$\vec{p}_\nu = \vec{p}_k - \vec{p}_\mu - \vec{p}_\gamma$ ; $E_\nu = |\vec{p}_\nu|$

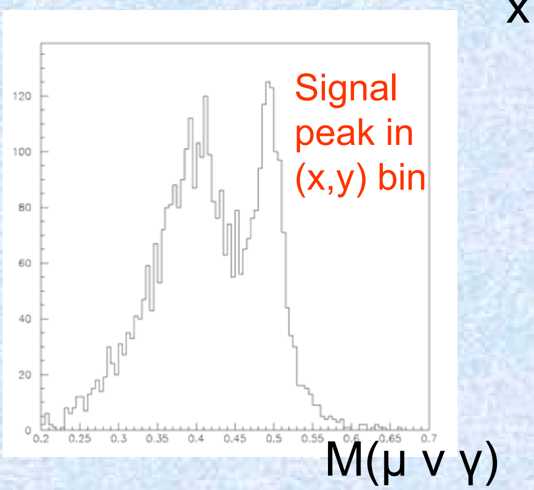
M(μ ν γ) peaks at 0.494 for signal

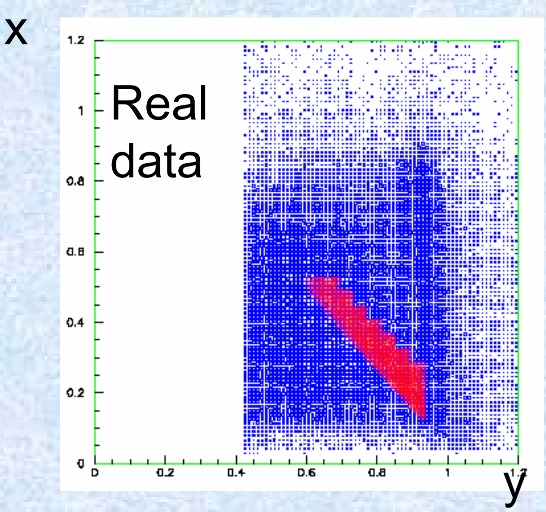
Background rejection procedure: scanning over Dalits-plot and fitting M(μνγ) in each bin



# K→ μ ν γ: Dalits-plot for signal, Kμ3 and Kπ2




**Experimental Dalits-plot after event selection and preliminary cuts**

**Selected bins (signal peak in $M_k$)**

# $K \to \mu \nu \gamma$: BR measured

- 22472±465 events of $K \to \mu \nu \gamma$ observed
- $BR(K \to \mu \nu \gamma)/BR(K\mu3)$ is measured
- Supposing $BR(K\mu3)=(3.27 \pm 0.06)\times10^{-2}$ (PDG)

- $BR(K \to \mu \nu \gamma)=[1.25 \pm 0.04(stat) \pm 0.02(norm)]\times10^{-3}$
- Region: $30 < E_{\gamma} < 130$ MeV $150 < E_{\mu} < 230$ MeV
- Theory: $BR(K \to \mu \nu \gamma) \sim 1.28\times10^{-3}$

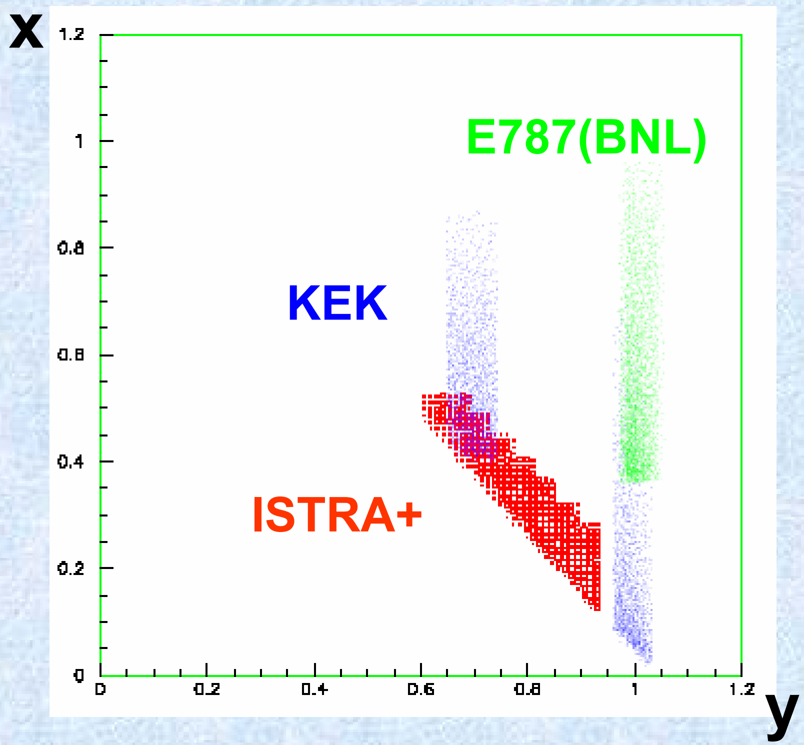
# $K \to \mu \nu \gamma$: comparison with other experiments

Main experiments:

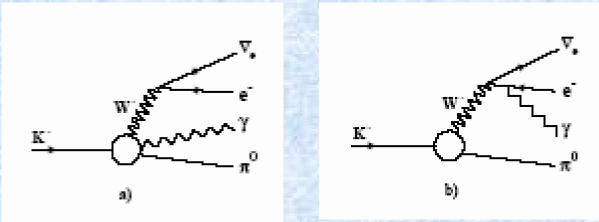
KEK: Akiba et al, 1985

BNL: E787, 2000

ISTRA+: 2006



# $K \rightarrow \mu\, \nu\, \pi^0\, \gamma$ : theory and experiment




**ChPT tests** → **Amplitudes and BR (known at $O(p^4)$ )**

**New Physics** →

$\xi = \vec{p}_\gamma (\vec{p}_\mu x \vec{p}_\pi) m_k^3$

$A_\xi = [N(\xi>0) - N(\xi<0)] / [N(\xi>0) + N(\xi<0)]$

SM: $A_\xi \sim 1.14x10^{-4}$

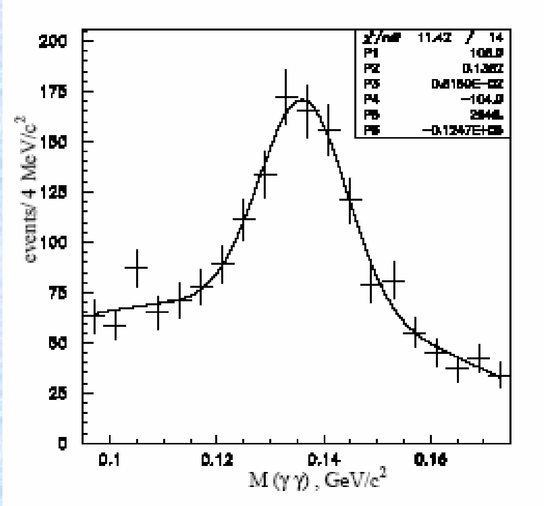
SM extensions: $A_\xi \leq 2.6x10^{-4}$

**Previous experiments** → **Not observed**

**BR < $6.1x10^{-5}$**

# $K \rightarrow \mu\, \nu\, \pi^0\, \gamma$ : event selection

- Decay signature:
- 1 charged track
- 3 showers in ECAL
- Effective mass $m(\gamma\gamma)$ within $\pm 20 MeV/c^2$ from $\pi^0$ mass




- Additional cuts:
- $400 cm < Z_{vertex} < 1600 cm$
- Missing energy > 1GeV
- No signal in veto system

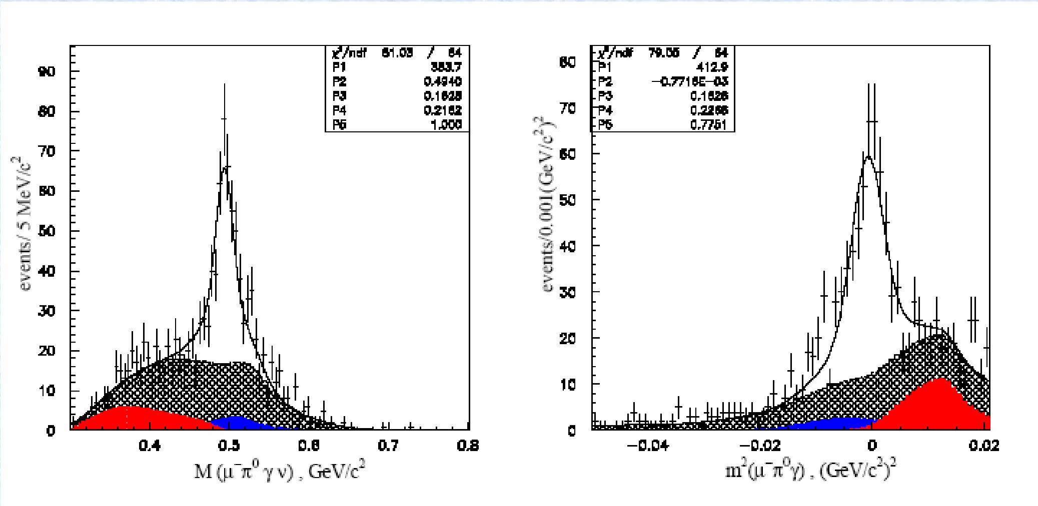
# $K \rightarrow \mu\,\nu\,\pi^0\,\gamma$ : background and kinematical regions

- Main background:
- $K \rightarrow \mu\,\nu\,\pi^0$ (Kμ3)
- $K \rightarrow \pi\,\pi^0$ (Kπ2)
- $K \rightarrow \pi\,\pi^0\,\pi^0$ (Kπ3)

  with 1 gamma lost (from $\pi^0 \rightarrow \gamma\gamma$) or accidental gamma
- Suitable variable:
- $M(\mu\nu\pi^0\gamma)=\sqrt{(P_\mu+P_\nu+P_{\pi 0}+P_\gamma)^2}$ where
- $\vec{p}_\nu=\vec{p}_k-\vec{p}_\mu-\vec{p}_\gamma$ ; $E_\nu=|\vec{p}_\nu|$ ; $M(\mu\nu\pi^0\gamma)$ peaks at 0.494 for signal
- MMS $(M_\nu)^2=(P_k-P_\mu-P_{\pi 0}-P_\gamma)^2$ ; MMS peaks at 0 for signal
- 2 kinematical regions:
- I: $5 < E_\gamma < 30$ MeV small background
- II: $30 < E_\gamma < 60$ MeV large background

# $K \to \mu \nu \pi^0 \gamma$ : 1-st kinematical region
# $5 < E_\gamma < 30$ MeV

Signal observation for 2 kinematical variables: $M(\mu\nu\pi^0\gamma)$ and MMS




Non-$\pi^0$ background: normalized on side bands in $m(\gamma\gamma)$

$K \to \pi \pi^0 \pi^0$

$K \to \mu \nu \pi^0$

# $K \rightarrow \mu \nu \pi^0 \gamma$ : $5 < E_\gamma < 30$ MeV
# Results

- 384 ± 41 events in $M(\mu\nu\pi^0\gamma)$
- 413 ± 36 events in MMS
- $BR(K \rightarrow \mu \nu \pi^0 \gamma)/BR(K\mu3)$ is measured
- Using PDG value for $BR(K\mu3)$

  $BR=(8.82\pm0.94(stat)\pm0.86(syst))\times10^{-5}$

Theory: $6.86\times10^{-5}$

T-odd asymmetry: $A_\xi=-0.03\pm0.13$

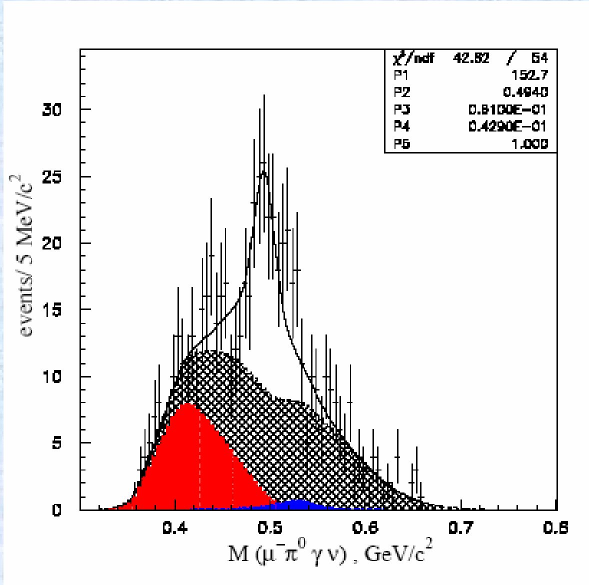
SM extensions: $A_\xi \sim 2\times10^{-4}$

# $K \to \mu \nu \pi^0 \gamma$ : 2-nd kinematical region $30 < E_\gamma < 60$ MeV

- Strong background from $K \to \pi \pi^0$, $K \to \pi \pi^0 \pi^0$

→ additional cut

$0.1 < p^*(\pi^-) < 0.185$ GeV/c



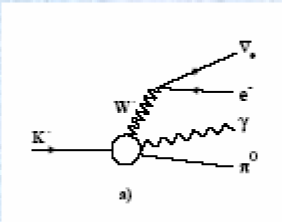

- 153±39 events observed
- BR=(1.46±0.22(stat)±0.32(syst))x$10^{-5}$
- Theory: 1.53x$10^{-5}$

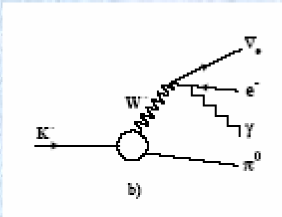
Non-$\pi^0$ background

$K \to \pi \pi^0 \pi^0$

$K \to \mu \nu \pi^0$

# $K \rightarrow e\,\nu\,\pi^0\,\gamma$ : theory and experiment




**ChPT tests** → **Amplitudes and BR (known at $O(p^4)$ )**

**New Physics** →

$\xi = \vec{p}_\gamma (\vec{p}_\mu \times \vec{p}_\pi) m_k^3$

$A_\xi = [N(\xi>0) - N(\xi<0)] / [N(\xi>0) + N(\xi<0)]$

SM: $A_\xi = -0.59 \times 10^{-4}$

SM extensions: $A_\xi \leq 0.8 \times 10^{-4}$

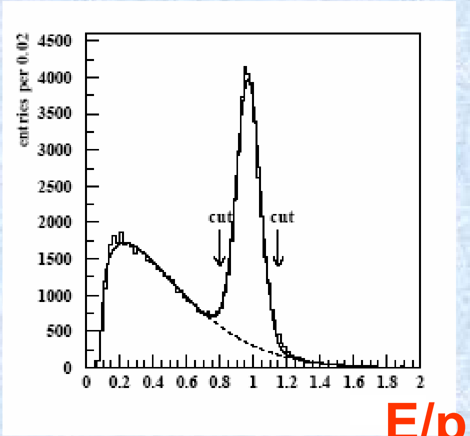
**Previous experiments** → **~200 events**

# $K \rightarrow e\, \nu\, \pi^0\, \gamma$ : event selection

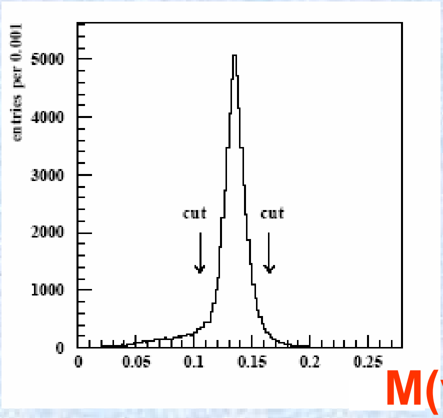
- Decay signature:
- 1 charged track
- 4 showers in ECAL
- E/p cut for electron identification

  (E - shower energy, p – track momentum)
- Effective mass m(γγ) within $\pm 30 MeV/c^2$ from $\pi^0$ mass

- Additional cuts:
- $400cm < Z_{vertex} < 1650cm$
- Missing energy > 1GeV
- No signal in veto system




E/p

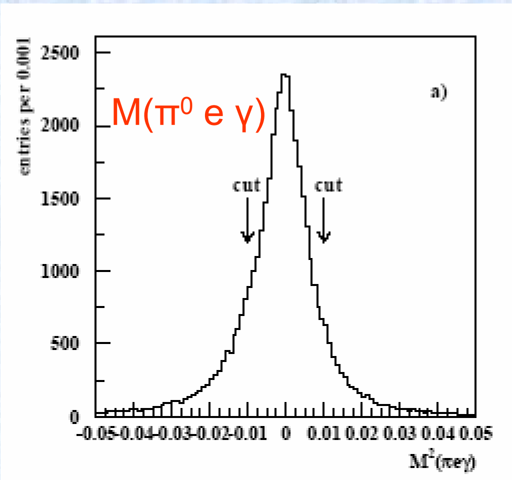


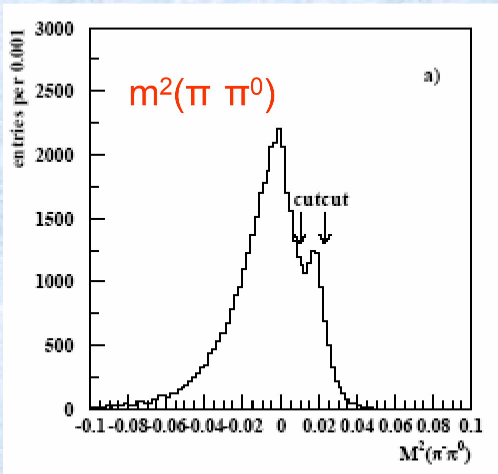

M(γγ)

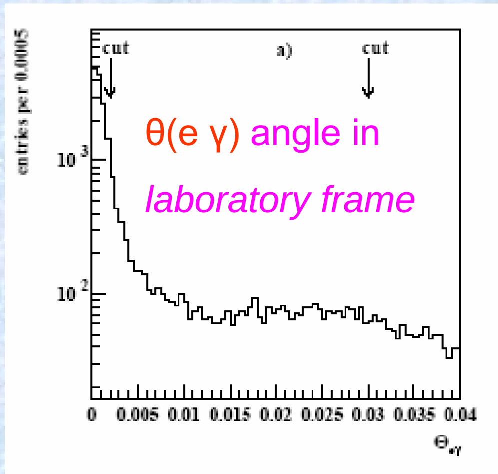
# $K \to e\, \nu\, \pi^0\, \gamma$ : background suppression

- Main background:

  $K \to \pi\, \pi^0\, \pi^0$, $K \to \pi\, \pi^0$, $K \to e\, \mathbf{(\gamma)}\, \nu\, \pi^0$, $K \to \pi\, \pi^0\, \gamma$ , $K \to e\, \nu\, \pi^0\, \pi^0$
- $M^2(\pi^0\, e\, \gamma)=(P_K-P_{\pi 0}-P_e-P_\gamma)^2$; $-0.01< M^2(\pi^0\, e\, \gamma)<0.01$
- $m^2(\pi\, \pi^0)=(P_K-P_\pi-P_{\pi 0})^2$; $0.009< m^2(\pi\, \pi^0)<0.024$ against $K \to \pi\, \pi^0$
- $0.002< \theta_{e\gamma}<0.030$ against $K \to e\, \mathbf{(\gamma)}\, \nu\, \pi^0$

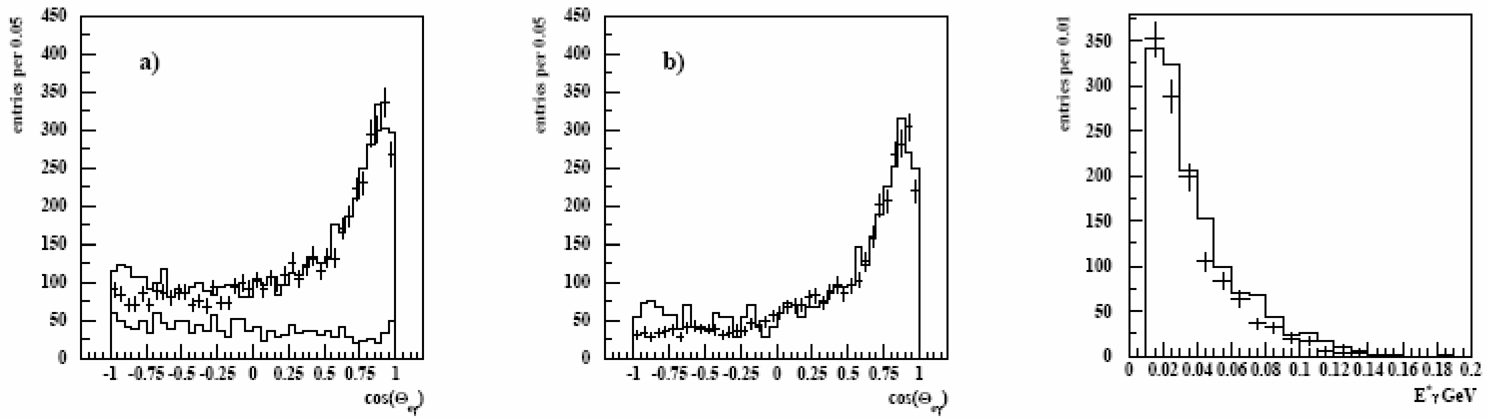


# $K \rightarrow e\ \nu\ \pi^0\ \gamma$ : resulting spectra

- 5378 events selected
  (3852 – signal, 1526 – background)




DATA, $cos(\theta_{e\gamma})$ DATA, $cos(\theta_{e\gamma})$ Bkg. subtracted DATA, $E_\gamma^*$

**Histogram – data** **Points with errors - MC**

# $K \to e \nu \pi^0 \gamma$ : results

- $R = BR(K \to e \nu \pi^0 \gamma, E^*_\gamma > 10 MeV)/BR(Ke3)$ is measured

***Comparison with previous experiments:***

➡ additional cut $0.6 < \cos\theta_{e\gamma} < 0.9$

**$R = (0.48 \pm 0.02(stat) \pm 0.03(syst)) x10^{-2}$**

better accuracy and larger statistics

| $R_{exp}$, $x10^{-2}$ | Events | experiment |
|---|---|---|
| *0.48±0.04* | *1382* | *ISTRA+* |
| 0.46±0.08 | 82 | XEBC |
| 0.56±0.04 | 192 | ISTRA |
| 0.76±0.28 | 13 | HLBC |

***Comparison with theory:***

➡ additional cuts $E^*_\gamma > 30 MeV$; $\theta^*_{e\gamma} > 20^o$

**$BR = (3.05 \pm 0.02) x10^{-4}$**

Theory: $2.8 x10^{-4}$ (tree level)

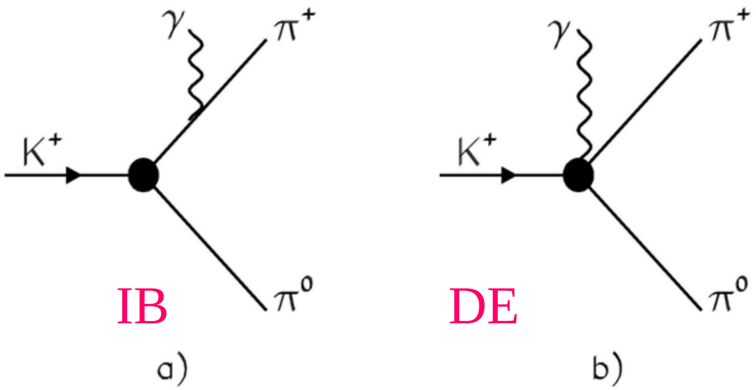
$3.0 x10^{-4}$ ($O(p^4)$ level)

T-odd asymmetry: **$A_\xi = -0.015 \pm 0.021$**

SM: $A_\xi = -0.59 x10^{-4}$ SM extensions: $A_\xi \sim 0.8 x10^{-4}$

# Measurement of the direct photon emission in the $K^+ \to \pi^+\pi^0\gamma$ decay (E470 experiment at KEK)

$$A(K^+ \to \pi^+\pi^0\gamma) = A_{IB}^{(2)} + A_{DE}^{(4)}$$




$$A_{DE}^{(4)} = A_{DE,M}^{(4)} = A_{DE,ra}^{(4)} + A_{DE,dwa}^{(4)}$$

*Br(DE,dwa)=?*

*Br(DE,ra)*$=3.5\times10^{-6}$ ← ChPT prediction

*Br*(*DE*,$1/N_c$)$=19.4\times10^{-6}$ ← $1/N_c$ prediction

IB – inner bremsstrahlung

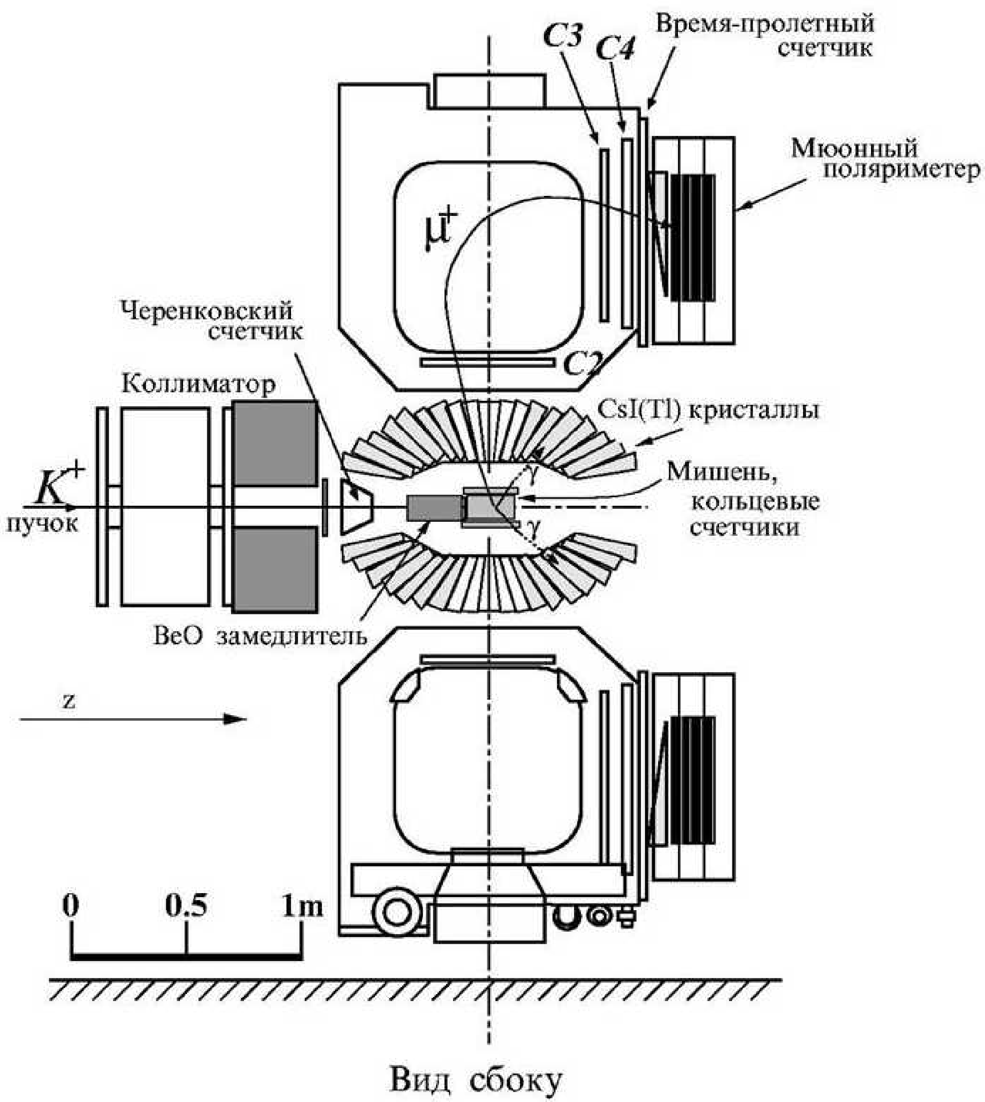
DE – direct emission

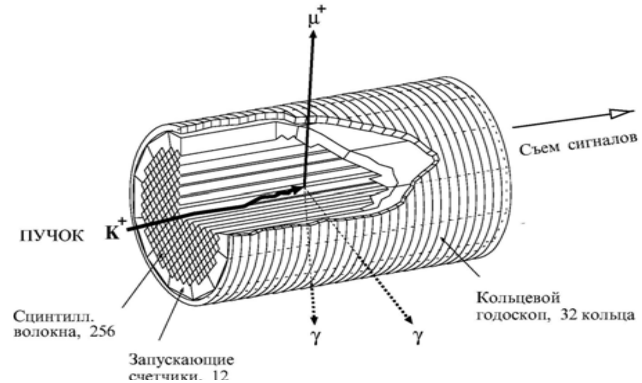
# Experimental situation in the measurement of the direct photon emission in the $K^+ \to \pi^+\pi^0\gamma$ decay

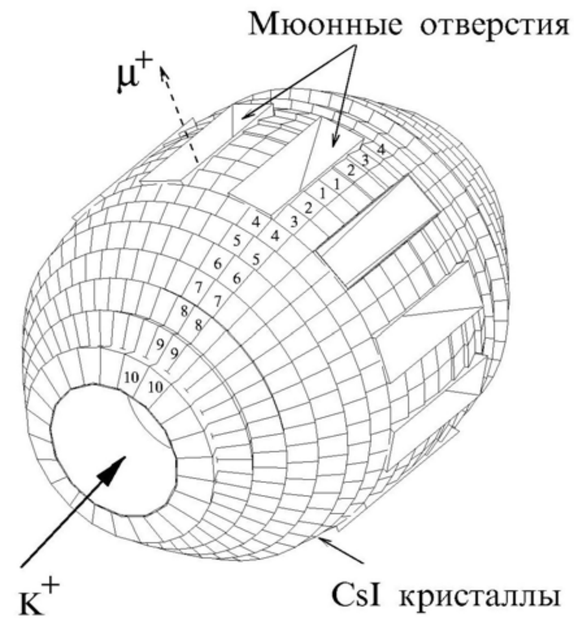
| Experiment | | Experiment | Kaon | Number of events | $Br(DE)\times 10^5$ |
|---|---|---|---|---|---|
| **1. BNL** | **1972** | in-flight | $K^\pm$ | 2100 | $1.56 \pm 0.35 \pm 0.5$ |
| **2. CERN** | **1976** | in-flight | $K^\pm$ | 2461 | $2.3 \pm 3.2$ |
| **3. ISTRA** | **1986** | in-flight | $K^-$ | 140 | $2.05 \pm 0.46^{+0.39}_{-0.23}$ |
| **4. BNL E787** | **2000** | stopped | $K^+$ | $2\times 10^4$ | $0.47 \pm 0.08 \pm 0.03$ |
| **5. KEK E470** | **2003** | stopped | $K^+$ | 4434 | $0.32 \pm 0.13 \pm 0.10$ |
| **6. ISTRA+** | **2004** | in-flight | $K^-$ | 930 | $0.37 \pm 0.39 \pm 0.10$ |

$$Br(\mathrm{av}_{1\text{-}3}) = (1.8 \pm 0.4)\times 10^{-5} \qquad Br(\mathrm{av}_{4-6}) = (0.44 \pm 0.07)\times 10^{-5}$$

# Experimental setup E470



## Analysis of 3 photon cluster events and extraction of $K^+ \to \pi^+\pi^0\gamma$ decay

1. Kaon identification
2. Momentum analysis
3. Charged particle separation by TOF method
4. Analysis of events in the CsI(Tl) calorimeter
5. Neutral pion reconstruction from 3 photon events
6. $K^+ \to \pi^+\pi^0\pi^0$ background suppression

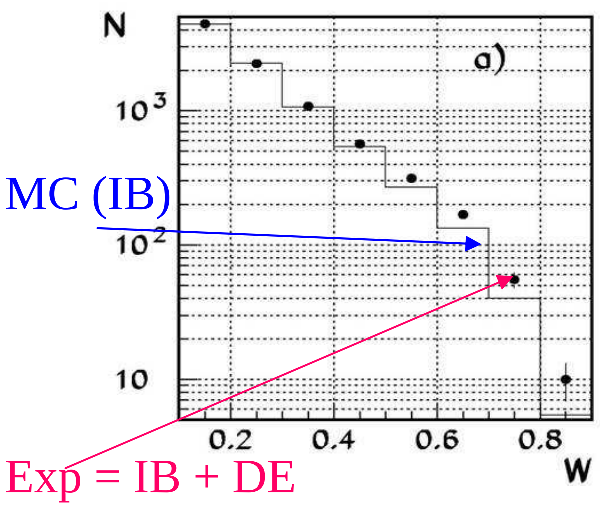
Total number of $K^+ \to \pi^+\pi^0\gamma$ events extracted in the analysis in the $\pi^+$ momentum region of 115 to 180 MeV/c in the $K^+$ rest frame is 10154.

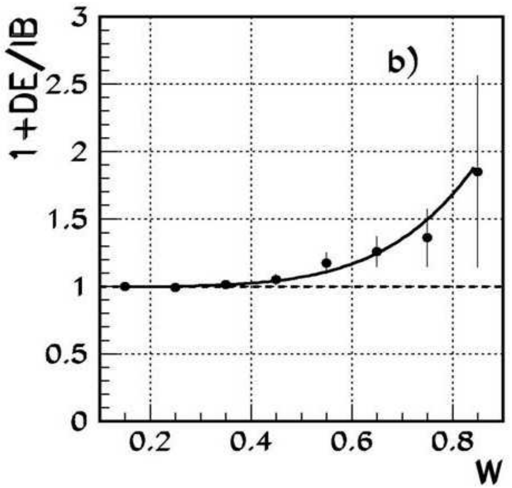
# Fitting of the experimental spectrum

The fitting was done using next sensitive to DE component parameters:

$\theta(\pi^+\pi^0)$ – opening angle between $\pi^+$ и $\pi^0$
$E(\gamma 3)$ – energy of the free photon
$W$ – parameter defined as $W=(P_{K+}\cdot q_\gamma)(p_{\pi+}\cdot q_\gamma)/(m^2(\pi^+)\cdot M^2(K^+))$

The fraction of the DE component in the experimental spectrum obtained from the fitting is $(2.6 \pm 0.6)\cdot 10^{-2}$, to which corresponds ~ 260 events of DE component




Experimental spectrum of *W* normalized to IB one from the MC simulation.

# Results

The experimentally measured branching ratio of the direct photon emission in the $K^+ \to \pi^+\pi^0\gamma$ decay in the $\pi^+$ kinetic energy region of 55 to 90 MeV in the $K^+$ rest frame is

$$Br(DE)=[3.8\pm0.8(stat)\pm0.7(syst)]\times10^{-6}.$$

The measurement of the branching was carried out in the assumption that the there is no component due to interference with the inner bremsstrahlung. The good agreement of the result with the theoretical prediction for the branching ratio of the DE component of $3.5\times10^{-6}$ in the framework of ChPT supports the hypothesis that the dominant contribution to the DE component is entirely due to pure magnetic transition given by the reducible anomalous amplitude.

| Experiment | Experiment | Kaon | Number of events | $Br(DE)\times10^5$ |
|---|---|---|---|---|
| **1. BNL 1972** | in-flight | $K^{\pm}$ | 2100 | $1.56 \pm 0.35 \pm 0.5$ |
| **2. CERN 1976** | in-flight | $K^{\pm}$ | 2461 | $2.3 \pm 3.2$ |
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| **6. ISTRA+ 2004** | in-flight | $K^{-}$ | 930 | $0.37 \pm 0.39 \pm 0.10$ |
| **5. KEK E470 2006** | stopped | $K^{+}$ | 10154 | $0.38 \pm 0.08 \pm 0.07$ |

# Recent *ISTRA+/KEK* Results

**$K^- \to \mu^- \nu \gamma$ :**

- $BR=(1.25\pm0.05)\times10^{-3}$ (Theory: $BR=1.28\times10^{-3}$)
- Region: $30 < E_\gamma < 130$ MeV, $150 < E_\mu < 230$ MeV (~22500 events)

**$K^- \to \mu^- \nu \pi^0 \gamma$ :**

- First observation (~800 events)
- $BR=(8.82\pm1.27)\times10^{-5}$ (Theory: $BR=6.86\times10^{-5}$)

  Region 1: $5 < E_\gamma < 30$ MeV

  $BR=(1.46\pm0.39)\times10^{-5}$ (Theory: $BR=1.53\times10^{-5}$)

  Region 2: $30 < E_\gamma < 60$ MeV
- T-odd asymmetry $A_\xi=-0.03\pm0.013$

**$K^- \to e^- \nu \pi^0 \gamma$ :**

- $BR=(3.05\pm0.02)\times10^{-4}$ (Theory: $BR=3\times10^{-4}$)
- Region: $E_\gamma > 30$ MeV, $\theta_{e\gamma} > 20^o$ ( ~3850 events)
- T-odd asymmetry $A_\xi=-0.015\pm0.021$

**$K^+ \to \pi^+ \pi^0 \gamma$ :**

- $Br(DE)=[3.8\pm0.8(stat)\pm0.7(syst)]\times10^{-6}$

  (Theory: $BR=3.5\times10^{-6}$)
- Region: $55 < E_\gamma < 90$ MeV (~260 events)

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