E246 :
Search for T violation in the $K^+ \rightarrow \pi^0 \mu^+ \nu$ Decay

E470 :
Branching ratio measurement of direct photon emission in $K^+ \rightarrow \pi^+ \pi^0 \gamma$

J. Imazato

IPNS, KEK

KEK-PS External Review 2004

June 7, 2004

E246 : main experiment

E470 : byproduct experiment

E246/E470 collaboration

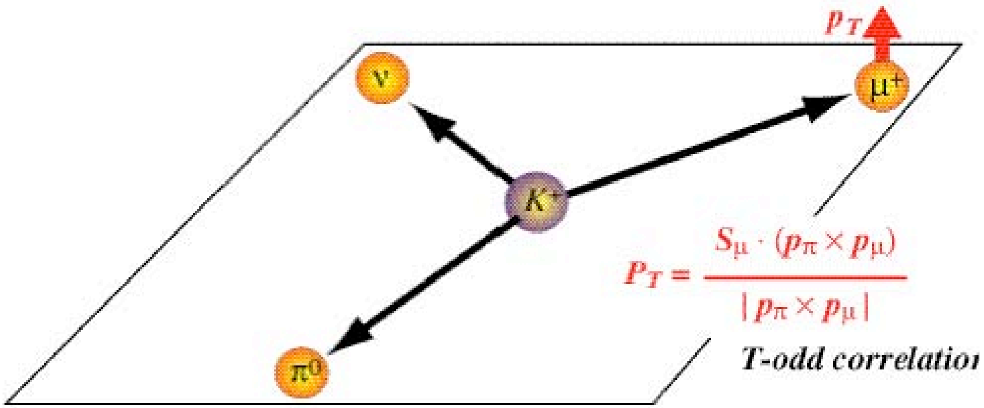
***E246* :**

Japan	(1) KEK (2) Univ. of Tsukuba,
	(3) Tokyo Institute of Technology
	(4) Univ. of Tokyo (5) Osaka Univ.
Russia	(6) Institute for Nuclear Research (RAS)
Canada	(7) TRIUMF (8) Univ. of British Columbia
	(9) Univ. of Saskatchewan (10) Univ. of Montreal
Korea	(11) Yonsei Univ. (12) Korea Univ.
U.S.A.	(13) Virginia Polytech Institute (14) Princeton Univ.
Taiwan	(15) National Taiwan Univ.

***E470* :** (1) (2) (5) (6) (7) (8) (9) (10)

(6) : CsI(Tl) calorimeter
(7) : fiber target, chamber gas recycler system
(14) : TD circuits

Transverse muon polarization in $K^+ \to \pi^0 \mu^+ \nu$



$P_T^{spurious}$ (Final State Interaction) = very small

$P_T \neq 0 \to$ T-violation

$K_{\mu 3}$ decay form factors and T violation

$$M \propto f_+(q^2)\,[2\,\tilde{p}_K^\lambda\, \bar{u}_\mu \gamma_\lambda (1-\gamma_5) u_\nu + (\xi(q^2) - 1)\, m_\mu \bar{u}_\mu (1-\gamma_5) u_\nu]$$

$$\xi(q^2) = f_-(q^2) / f_+(q^2)$$

$$P_T \sim \mathrm{Im}(\xi)\, \frac{m_\mu}{m_K}\, \frac{|p_\mu|}{E_\mu + |p_\mu|\, n_\mu \cdot n_\nu - m_\mu^2 / m_K}$$

$\mathrm{Im}(\xi) \neq 0 \longleftrightarrow$ T-violation

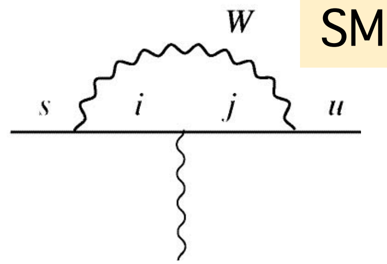
History of $K_{\mu 3}$ transverse polarization experiments

- $K_L \to \pi^- \mu^+ \nu$ Bevatron 1967 $\mathrm{Im}\xi = -0.02 \pm 0.08$
- $K_L \to \pi^- \mu^+ \nu$ Argonne 1973 $\mathrm{Im}\xi = -0.085 \pm 0.064$
- $K_L \to \pi^- \mu^+ \nu$ BNL-AGS 1980 $\mathrm{Im}\xi = 0.009 \pm 0.030$
- $K^+ \to \pi^0 \mu^+ \nu$ BNL-AGS 1983 $\mathrm{Im}\xi = -0.016 \pm 0.025$

Feature of $K^{+}_{\mu 3}$ P_T

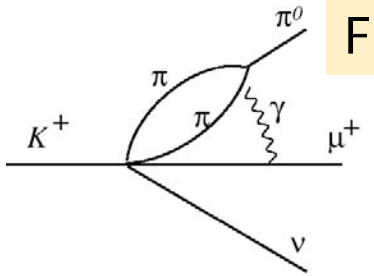
- Small standard model contribution
  - Bigi and Sanda “CP violation” (2000)
  - $P_T \sim 10^{-7}$

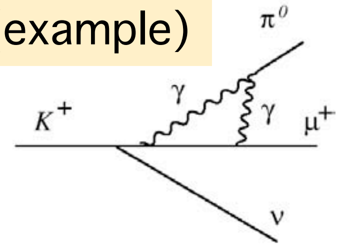
SM



- Small FSI spurious effects
  - Single photon contribution
    Zhitnitskii (1980)
    $P_T < \sim 10^{-6}$
  - Two photon contribution
    Efrosinin et al. PL B493 (2000) 293
    $P_T \sim 4 \times 10^{-6}$

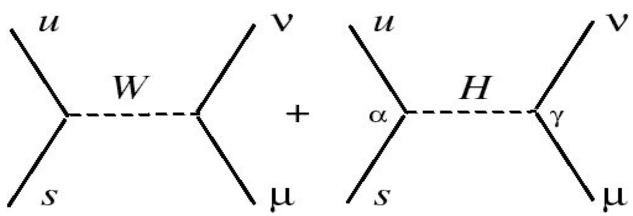
FSI (example)





- High sensitivity to CP violation beyond the SM
  - Mult- Higgs doublet model
  - Leptoquark model
  - Some Supersymmetric models
    $P_T \sim 10^{-4}$-10^{-3}

Three Higgs doublet model



KEK E246 experiment

Features

- Stopped K^+ experiment with a SC toroidal spectrometer
- Measurement of all decay kinematics directions
  - *Double ratio measurement with small systematic errors*
- An experiment which requested the highest-intensity beam

Progress

- 1992-1995 : detector construction
- 1996-2000 : data taking [450 + 180 (extension) shifts]
- 1999 : first result was published with 1/4 of data

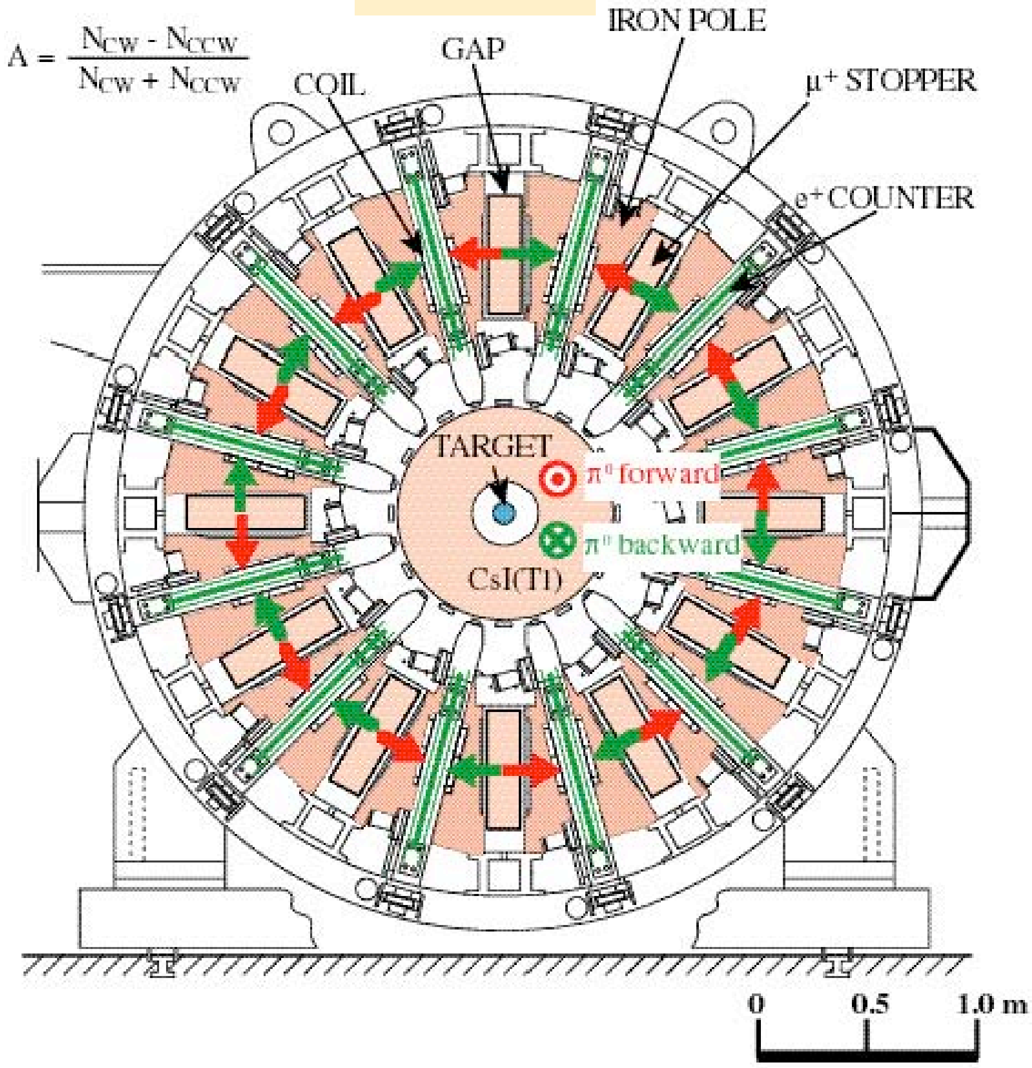
  $\mathrm{Im}\xi = -0.023 \pm 0.007(stat) \pm 0.003(syst)$

  [M.Abe *et al.*, Phys.Rev.Lett. 83(1999) 4253]
- 2001-2003 : analysis
- May 2004 : A paper submitted for publication with the final result

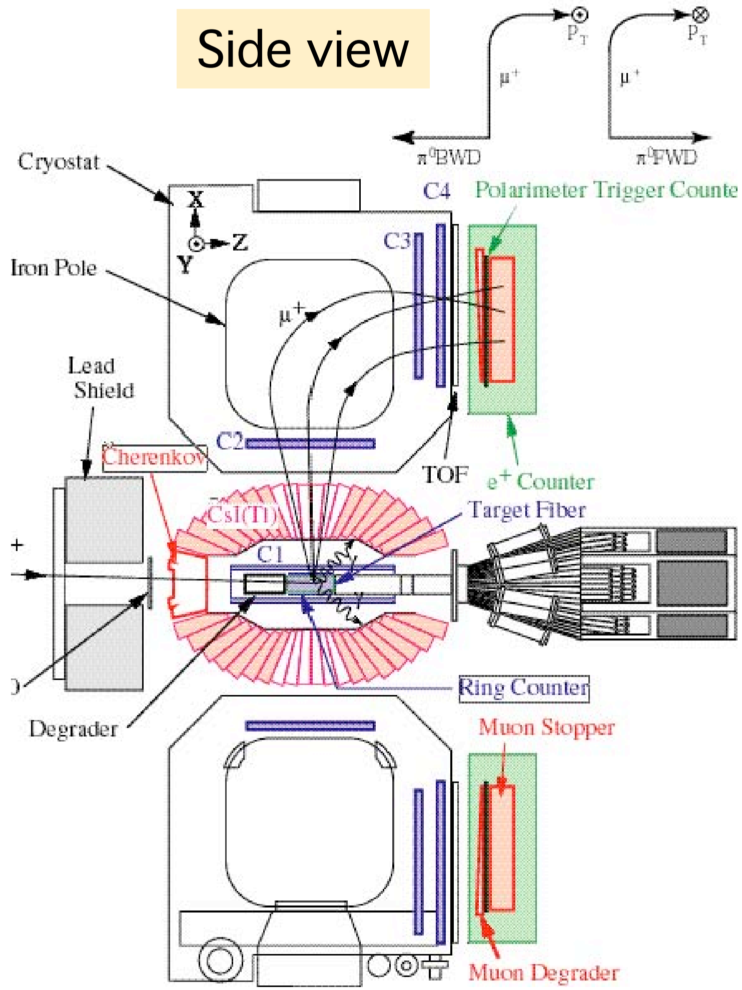
E246 experimental setup

[J.Macdonald *et al*.; NIM A506 (2003) 60]

End view



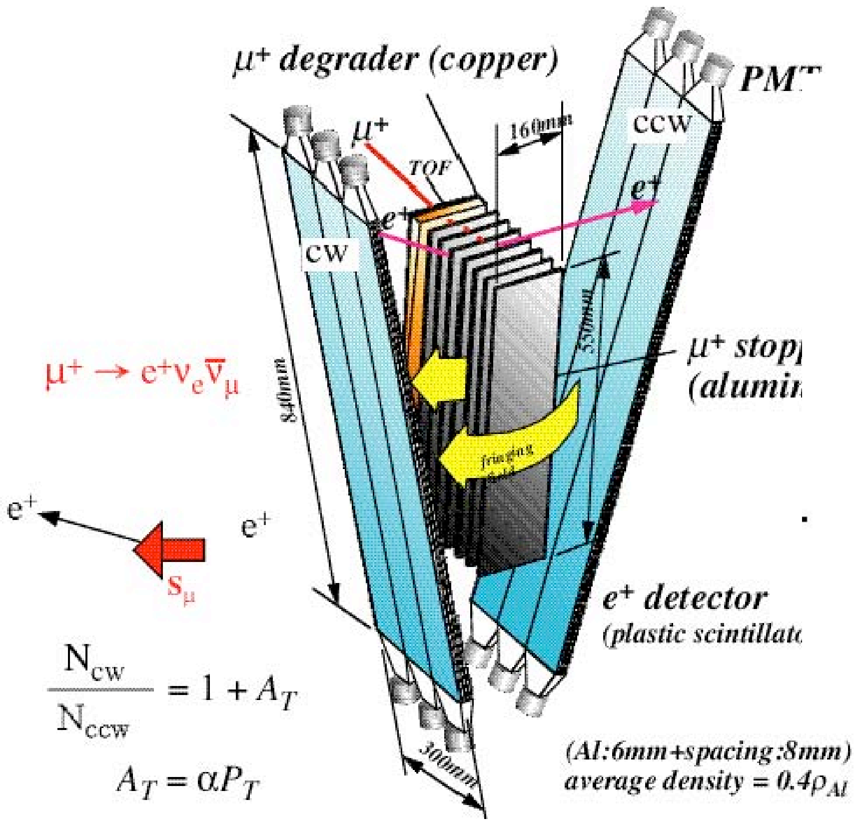
Side view



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

Muon polarimeter

One-sector view

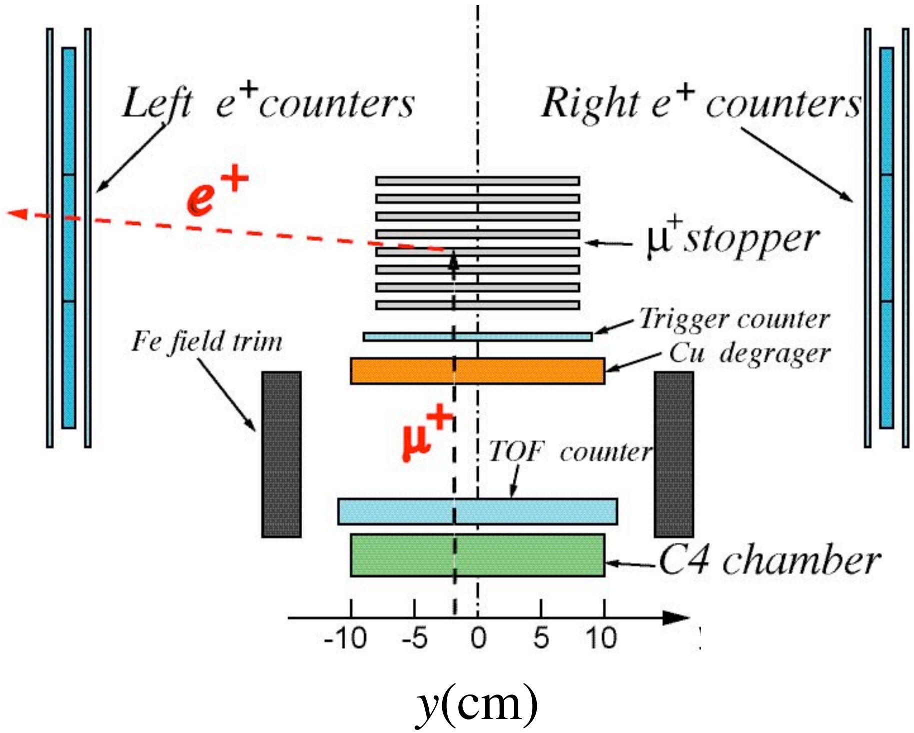


$\mu^+ \to e^+\nu_e\bar{\nu}_\mu$

$$\frac{N_{cw}}{N_{ccw}} = 1 + A_T$$

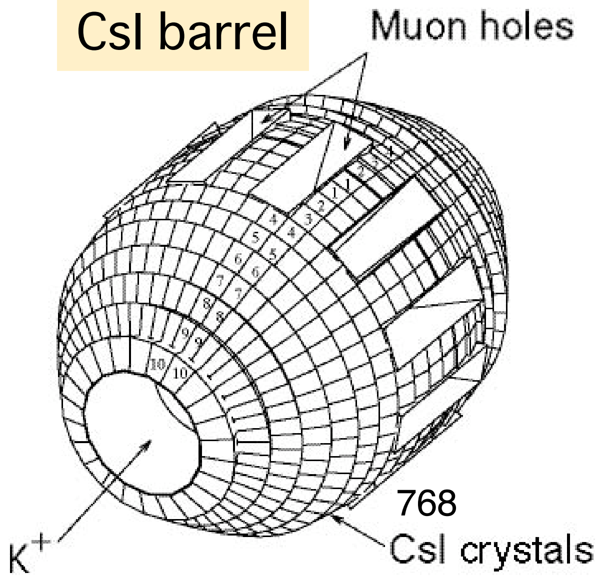
$$A_T = \alpha P_T$$

Cross section

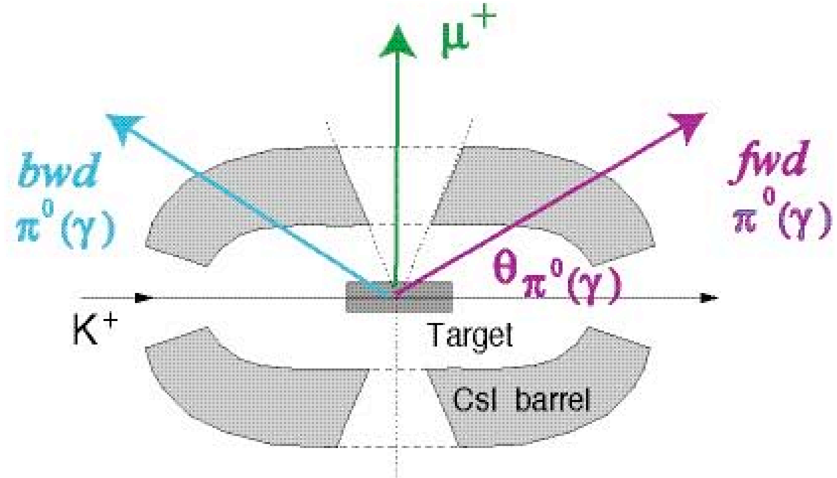


Double ratio measurement

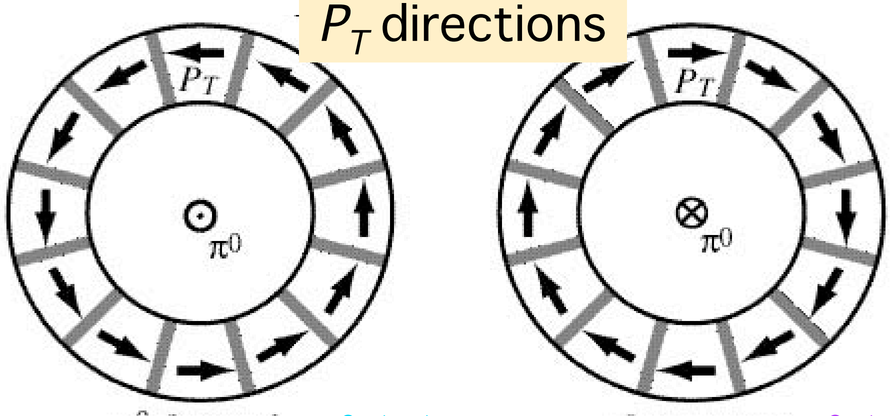
CsI barrel



fwd and *bwd* π^0 /γ



P_T directions



bwd **-π^0 (γ)** ***fwd*** **-π^0 (γ)**

Double ratio measurement

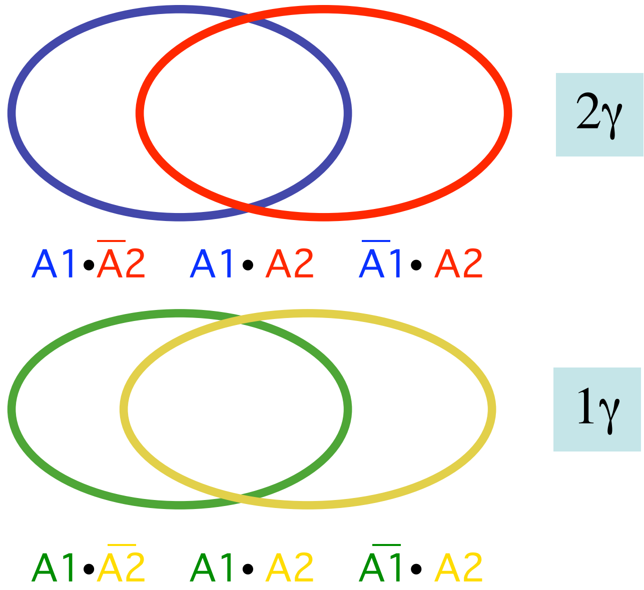
$$A_T = \frac{A_{fwd} - A_{bwd}}{2}$$

Two independent analyses

- Two analyses by two teams with
  - their own analysis policy and
  - event selection methods

Comparison of good $K\mu3$ event e.g. :1998

	2γ events	1γ events
A2	1221 k	1264 k
A1	918 k	909 k



- Combination of the two analyses
  by resorting of events to 6 data sets

Merits of two analysis method

- Cross check of data quality by A_0, decay plane rotation θ_r and θ_z and P_T
- Comparison of sensitivity by normal asymmetry A_N and $\langle\cos\theta_T\rangle$
- Check of data quality in e.g. A1 by comparing A1•A2 and A1• A2-bar
- Estimate of systematic error by comparing $\langle\cos\theta_T\rangle$ of A1• A 2 from A1 and A2

Analysis of asymmetry

$K_{\mu 3}$ event selection

fwd events : $\cos\theta_{\pi^0(\gamma)} > 0.341$

bwd events : $\cos\theta_{\pi^0(\gamma)} < -0.341$

e^+ time spectrum anlysis

$N_{cw(ccw)}$: integration from 20ns to 6 μs with constant BG subtracted

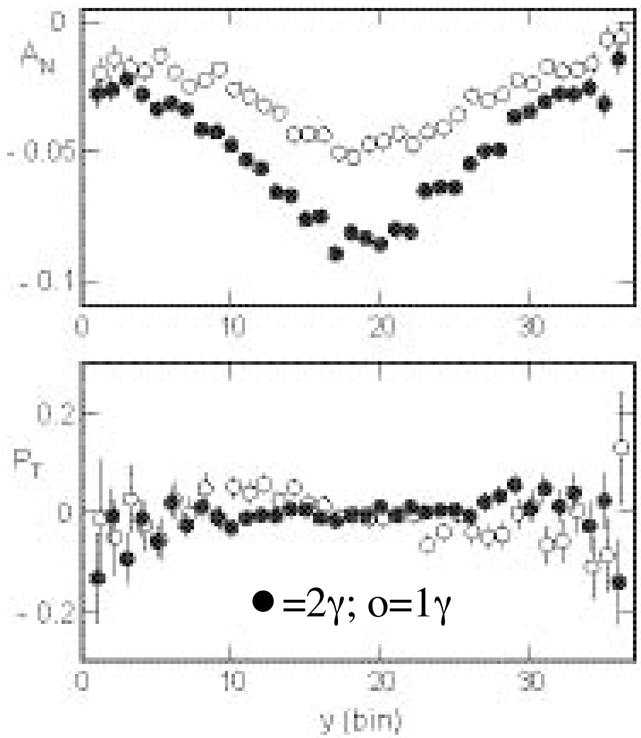
Asymmetry analysis

- $A_T(y)=[A(y)_{fwd} - A(y)_{bwd}]\ /2$

$$A(y)_{f(b)} = \frac{[N_{cw}(y)-N_{ccw}(y)]_{f(b)}}{[N_{cw}(y)+N_{ccw}(y)]_{f(b)}}$$

- $P_T(y) = A_T(y) / \alpha(y) \langle\cos\theta_T\rangle$

$\alpha(y) = A_N(y) / P_N$

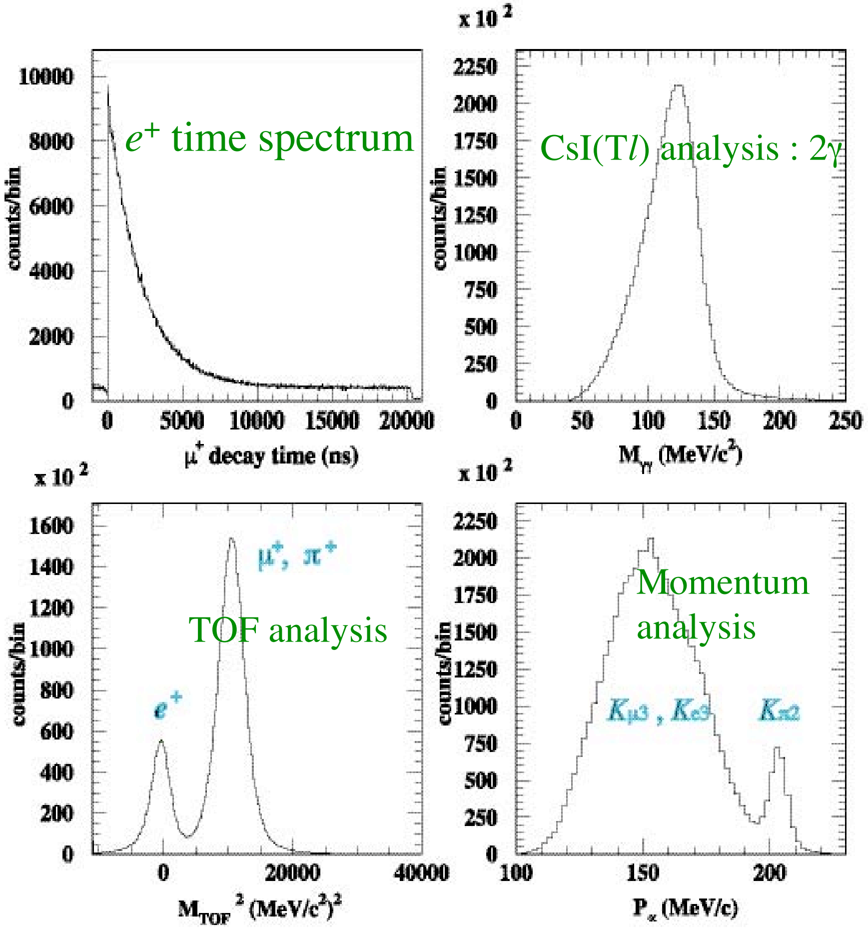


⇒

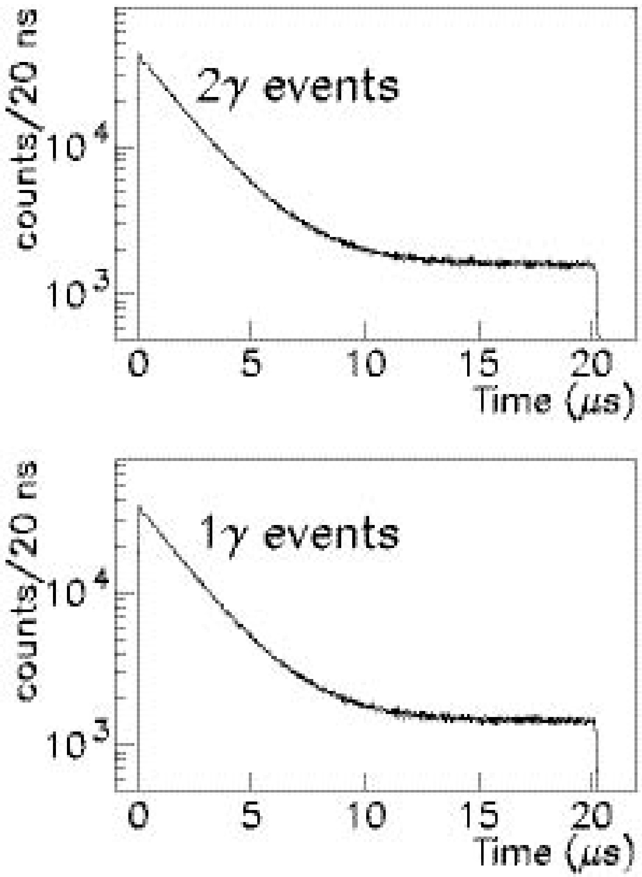
- $P_T = \int P_T(y)\, w(y) \mathrm{d}y$
- $\mathrm{Im}\xi = P_T / \langle P_T/\mathrm{Im}\xi\rangle$

Experimental data

$K^+_{\mu 3}$ event selection



e^+ time spectra

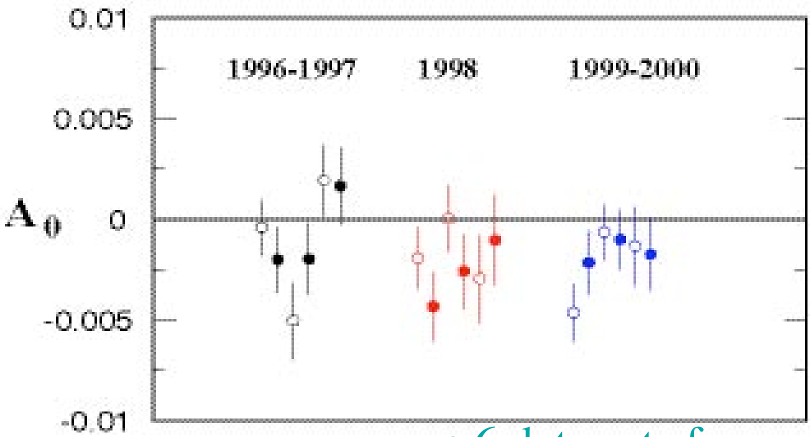


Quality check of data sets

Null asymmetry check

$A_0=[(N_{cw}/N_{ccw})_{total}-1]/2$

$total = fwd + bwd$

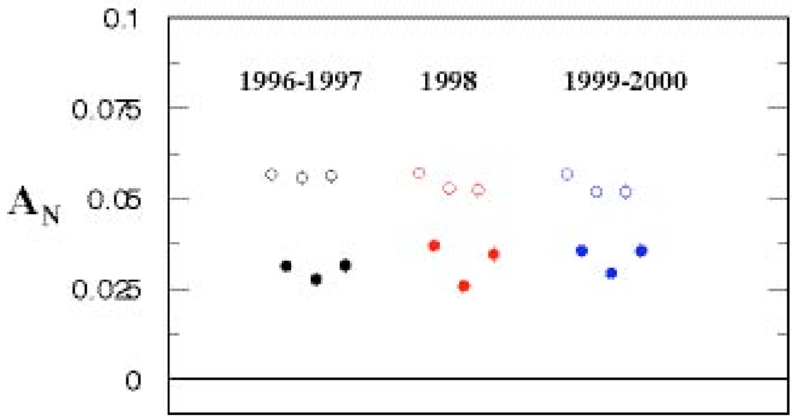


Sensitivity check

$A_N=(A_{left}-A_{right})/2$

$A_{left}=[(N_{cw}/N_{ccw})_{left}-1]/2$

$A_{right}=[(N_{cw}/N_{ccw})_{right}-1]/2$



- 6 data sets for each period
- Open circles are 2γ events and dots are 1γ events.

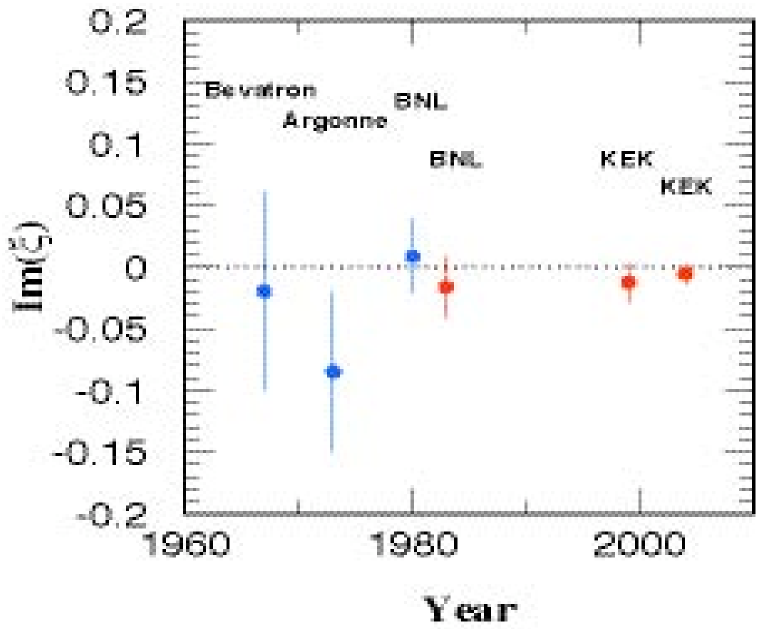
- Decay plane rotation
- P_T cut point dependence with unknown bias
- *Blind analysis*

Result

$$P_T = -\,0.0017 \pm 0.0023(stat) \pm 0.0011(syst)$$
$$(\ |P_T| < 0.0050 : 90\%\ C.L.\ )$$

$$\mathrm{Im}\xi = -\,0.0053 \pm 0.0071(stat) \pm 0.0036(syst)$$
$$(\ |\mathrm{Im}\xi| < 0.016 : 90\%\ C.L.\ )$$

[submitted to a journal]



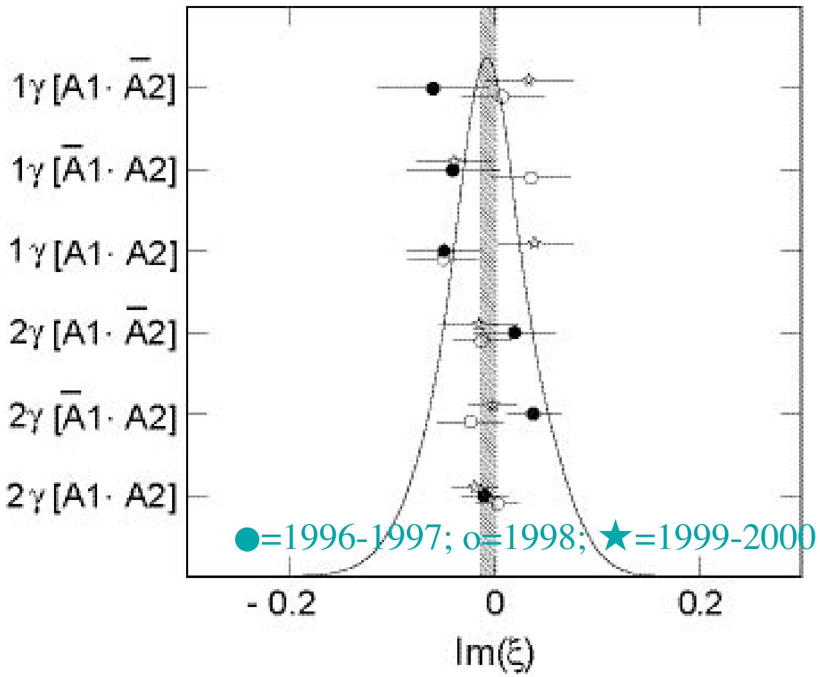
Systematic errors

- Σ12 : 12-fold rotational cancellation
- *fwd/bwd* : π^0 forward/backward cancellation

Source of Error	Σ12	*fwd/bwd*	δP_T x 10^4
e^+ counter r-rotation	x	o	0.5
e^+ counter z-rotation	x	o	0.2
e^+ counter f-offset	x	o	2.8
e^+ counter r-offset	o	o	<0.1
e^+ counter z-offset	o	o	<0.1
μ^+ counter f-offset	x	o	<0.1
MWPC ϕ-offset (C4)	x	o	2.0
CsI misalignment	o	o	1.6
B offset (ε)	x	o	3.0
B rotation (δ_x)	x	o	0.4
B rotation (δ_z)	x	x	5.3
K^+ stopping distribution	o	o	<3.0
μ^+ multiple scattering	x	x	7.1
Decay plane rotation (θ_r)	x	o	1.2
Decay plane rotation (θ_z)	x	x	0.7
$K_{\pi 2}$ DIF background	x	o	0.6
K^+ DIF background	o	x	< 1.9
Analysis	-	-	3.8
Total			11.4

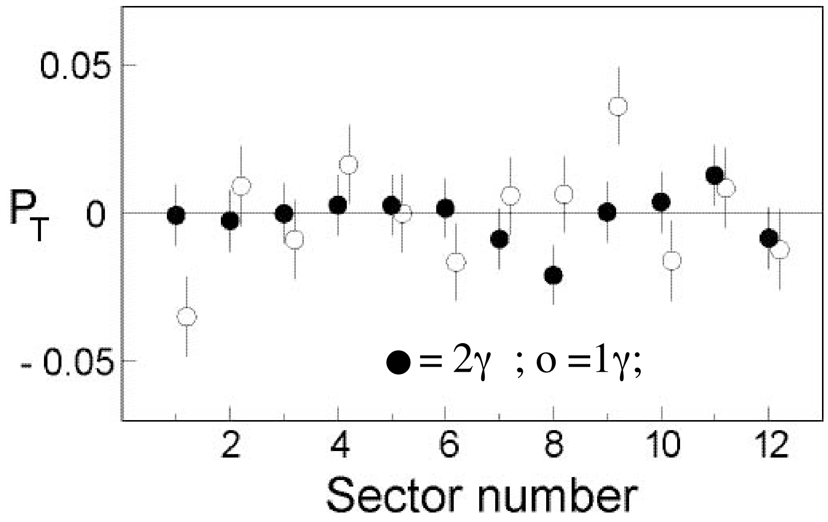
Systematics check

Consistency among data



$\mathrm{Im}\xi = -0.0055 \pm 0.0073$
$(\chi^2/d.o.f = 0.78)$

Sector dependence



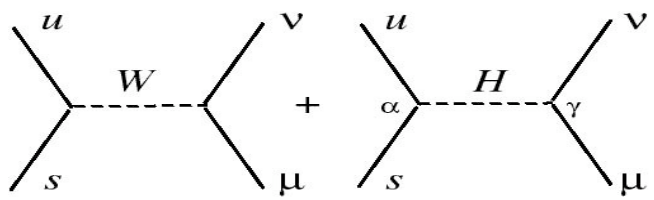
Decay plane rotation

$$|\theta_r(fwd) - \theta_r(bwd)| \leq 4.6 \times 10^{-4}\ \mathrm{rad}$$
$$|\theta_z(fwd) - \theta_z(bwd)| \leq 2.6 \times 10^{-4}\ \mathrm{rad}$$

Model implications

Three Higgs doublet model

$$\boldsymbol{L} = (2\sqrt{(2)}G_F)^{1/2}\,\Sigma[\alpha_i U_L K M_D D_R + \beta_i U_R M_U K D_L + \gamma_i N_L M_E E_R]\, H_i^+ + h.c.$$



$$\mathrm{Im}\xi = \mathrm{Im}(\alpha_1\gamma_1^*) \times (m_K / m_{H^+})^2$$
$$= \mathrm{Im}(\alpha_1\beta_1^*) \times (v_2/v_3)^2 \times (m_K / m_{H^+})^2$$

v_i : vacuum expectation values
α_i, β_i, γ_i : mixing matrix elements

- $|\mathrm{Im}\xi| < 0.016$ (90% C.L.) $\Rightarrow \mathrm{Im}(\alpha_1\gamma_1^*) < 544$ (at $m_H = m_Z$)
  cf. BR $(B \to X\tau\bar{\nu}_\tau)$ $\Rightarrow \mathrm{Im}(\alpha_1\gamma_1^*) < 1900$ (at $m_H = m_Z$)

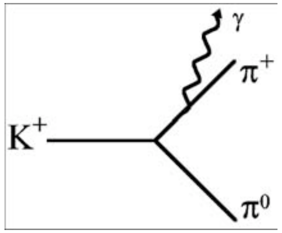
Neutron EDM in 3HD model

$$d_n \approx 4/3\, d_d \propto \mathrm{Im}(\alpha_1\beta_1^*) \times m_d / m_H^2$$

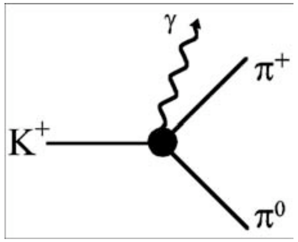
$v_2/v_3 = m_t/m_\tau$ [R.Garisto and G.Kane, Phys. Rev. D44 (1991)2789]

- $|\mathrm{Im}\xi| < 0.016$ (90% C.L.) $\Rightarrow d_n < 9 \times 10^{-27}\, e$ cm
  cf. $d_n^{\mathrm{exp}} < 6.3 \times 10^{-26}\, e$ cm

E470 : Direct emission in $K^+ \to \pi^+ \pi^0 \gamma$



Internal Brems.(IB)



Direct (DE)

IB : Strong suppression due to $\Delta I=1/2$ rule for $K^+ \to \pi^+ \pi^0$

DE:

- Magnetic (M1) *chiral anomalous term*
- Electric (E1) ? ⇒ Interference with IB

BR(DE) :
Important input for Chiral Perturbation Theory (ChPT) (determination of $O(p^4)$ terms)

$BR^{ChPT}(DE) \sim 0.4 \times 10^{-5}$

- Total branching ratio:

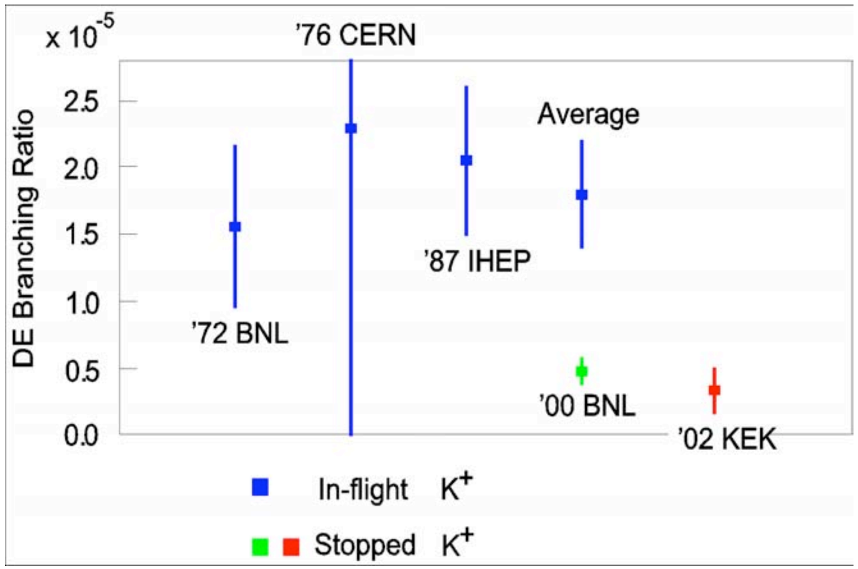
$BR(DE) = [\ 0.61 \pm 0.25(stat) \pm 0.19(syst)\ ] \times 10^{-5}$

- Partial branching ratio In the region of $55 < T_\pi < 90$MeV:

$BR(DE) = [\ 0.32 \pm 0.13(stat) \pm 0.10(syst)\ ] \times 10^{-5}$

No evidence for E1 interference

M.Aliev *et al.* , Phys. Lett. B554,7 (2003)



Byproduct physics

- $K^+ \rightarrow \pi^0 e^+ \nu$ (K_{e3}) : denial of scalar and tensor couplings,

  $f_S/f_+(0) = -0.002 \pm 0.026$ (*stat*) ± 0.014 (*syst*);

  $f_T/f_+(0) = -0.01 \pm 0.14$ (*stat*) ± 0.09 (*syst*) Phys.Letters B495, 33 (2000)

- $\Gamma(K_{\mu3})/\Gamma(K_{e3})$ ratio : decay form factor f_0, q^2 dependence λ_0, ChPT

  $\lambda_0 = 0.019 \pm 0.005$ (*stat*) ± 0.004 (*syst*) Phys. Letters B513, 311 (2001)

- $K^+ \rightarrow \mu^+ \nu \gamma$: T violation by transverse polarizarion P_T

  $P_T = -0.0064 \pm 0.0185$ (*stat*) ± 0.0010 (*syst*) Phys. Letters B561, 166 (2003)

  $P_T = -0.0067 \pm 0.0143$ (*stat*) ± 0.0014 (*syst*)

- $K^+ \rightarrow \pi^+ \pi^0 \pi^0$: form factors ; g and k parameters

  $g = 0.518 \pm 0.039$, $k = 0.043 \pm 0.020$ Eur.Phys.J. C12,627 (2000)

- $K^+ \rightarrow \pi^0 \pi^0 e^+ \nu$: form factors, $\pi\pi$ scattering length (methodology)

  $a_0^0 = 0.45 \pm 0.43$ submitted to Phys.Rev. D

Doctor theses

1) S. Shimizu; Precise Measurement of $K^+ \to \pi^0 e^+ \nu$ Form Factors using Stopped K^+; Tokyo Institute of Technology, 1997.
2) Y. Igarashi; Measurement of the form factors in $K^+ \to \pi^0 \mu^+ \nu$ decay; University of Tsukuba, 1997.
3) T. Ikeda; Measurement of Muon In-Plane Polarization in the Decay of $K^+ \to \pi^0 \mu^+ \nu$; University of Tsukuba, 1998.
4) T. Yokoi; Search for T-violating Muon Polarization in $K^+ \to \pi^0 \mu^+ \nu$ decay; University of Tokyo, 1998.
5) C. Mindas; Search for T Violation in the $K^+ \to \pi^0 \mu^+ \nu$ decay; Princeton University, 1998.
6) H.C. Huang; Search for T-violating Muon Polarization in $K^+ \to \gamma \mu^+ \nu$ Decay; National Taiwan University, 1998.
7) Y.H. Shin; Kinematically Complete Measurement of $K^+ \to \pi^+ \pi^0 \pi^0$ Decays; Yonsei University, 1998.
8) A.P. Ivashkin; Search for T violation in the $K^+ \to \pi^0 \mu^+ \nu$ decay using a CsI(Tl) calorimeter as a neutral pion detector (in Russian); INR, Russian Academy of Sciences, 1998.
9) T. Baker; Measurement of scattering length using $K_{\pi 3}$ decay; University of Saskatchewan, 1999.
10) O. Mineev; Development and design of analogue electronics and trigger system in the experiment to measure T-violating muon polarization in positive kaon decays (in Russian); INR, Russian Academy of Sciences, 2000.
11) K. Horie; Measurement of $\Gamma(K_{\mu 3})/\Gamma(K_{e3})$ ratio using stopped positive kaons; Osaka University, 2002.
12) M. Khabibullin; Measurement of T-violating muon polarization in the decay of positive kaons and limits on the parameters of non-standard models of CP violation (in Russian); INR, Russian Academy of Sciences, 2003.

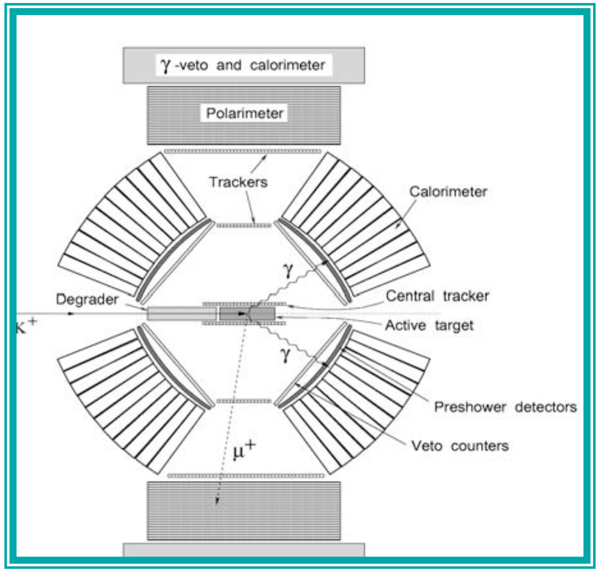
Future plan

- T-violation experiment of new generation at J-PARC
  LoI-19 :
  "P_T measurements in $K^+ \to \pi^0\mu^+\nu$ and $K^+ \to \mu^+\nu\gamma$
  with the accuracy of $\delta P_T < 10^{-4}$ and $\delta P_T \sim 10^{-4}$"
  Theoretical importance: [M.Kobayashi, T.-T.Lin and Y.Okada;
  Prog.Theor.Phys. 95, 361 (1995)]

- Development of a stopped K^+ beam of high quality
  at J-PARC in Phase 1: K0.8 channel with 2 DCS's

- Detailed design of experiment : ⇒ Full Proposal
  (this year) (next year)

- Possibility of detector development at IHEP(Protvino)
  now under consideration
  1) Prototype detector
  2) Development of a stopped K^+ beam at the 70-GeV PS



A new detector with a high-resolution photon detection

Summary

- The final result of the KEK-E246 experiment showed no evidence for T violation with $\mathrm{Im}\xi = -0.0055 \pm 0.0073(\mathrm{stat}) \pm 0.0036(\mathrm{syst})$, or $|\mathrm{Im}\xi| < 0.016$ (90% C.L.).
- This limit constrains the parameters of some non-standard CP violation models with high sensitivity.
- We are going to propose a next generation P_T experiment at the high intensity accelerator J-PARC.
- A few comments on the PS performance from our experiment:
  - E246 was an extraction-efficiency-limited experiment.
    (The maximum extraction beam intensity of 2.7~2.8 $\times 10^{12}$ /spill was determined by the extraction loss of more than 10^{12} /spill.)
  - The E246 data would have been more valuable statistically as well as qualitatively, if we were always provided with a flat-spill beam.