TREK experiment to search for T violation in kaon decays at J-PARC

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KEK & J-PARC

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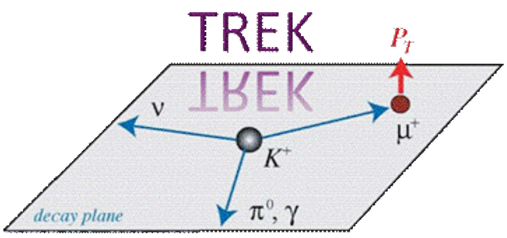
KAON 09 Conference

TREK/E06

Time Reversal Experiment with Kaons:

Search for New Physics beyond the Standard Model by Measurement of T-violating Transverse Muon Polarization (P_T) in $K^+ \rightarrow \mu^+\pi^0\nu$ Decays



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

New official website:
http://trek.kek.jp

Outline

- Transverse μ^+ polarization (P_T) in $K_{\mu 3}$
- Theoretical models
- Current experimental status
- J-PARC TREK experiment
- Detector upgrade
- Sensitivity
- Summary

TREK collaboration

CANADA

University of Saskatchewan
Department of Physics and Engineering
University of British Columbia
Department of Physics and Astronomy
TRIUMF
Universite de Montreal
Laboratoire de Physique Nucleaire

USA

Massachusetts Institute of Technology (MIT)
Laboratory for Nucl. Science & Bates Lin. Acc. Center
University of South Carolina
Department of Physics and Astronomy
Iowa State University
College of Liberal Arts & Sciences
Hampton University
Department of Physics
Jefferson Laboratory

RUSSIA

Russian Academy of Sciences (RAS)
Institute for Nuclear Research (INR)

JAPAN

Osaka University
Department of Physics
National Defense Academy
Department of Applied Physics
Tohoku University
Laboratory of Nuclear Science
High Energy Accel. Research Org. (KEK)
Institute of Particle and Nuclear Studies
Institute of Material Structure Science
Accelerator Laboratory
Kyoto University,
Department of Physics
Tokyo Institute of Technology (TiTech)
Department of Physics

VIETNAM

University of Natural Sciences

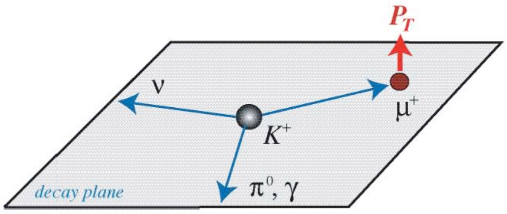
THAILAND

Kasetsart University

Transverse μ^+ polarization (P_T) in $K_{\mu3}$

$K^+ \rightarrow \pi^0 \mu^+ \nu$ decay

$$P_T = \frac{\sigma_\mu \cdot (p_{\pi^0,\gamma} \times p_{\mu^+})}{|(p_{\pi^0,\gamma} \times p_{\mu^+})|}$$



- P_T is T-odd, and spurious effects from final state interaction are small: $P_T(\mathrm{FSI}) < 10^{-5}$
  Non-zero P_T is a signature of T violation.
- Standard Model (SM) contribution to P_T : $P_T(\mathrm{SM}) < 10^{-7}$

> *P_T in the range $10^{-3} \sim 10^{-4}$ is a sensitive probe of CP violation beyond the SM.*

- There are theoretical models of new physics which allow a sizable P_T without conflicting with other experimental constraints.

Exotic scalar interactions

$$P_T = \mathrm{Im}\xi \cdot \frac{m_\mu}{m_K} \frac{|\vec{p}_\mu|}{[E_\mu + |\vec{p}_\mu|\vec{n}_\mu \cdot \vec{n}_\nu - m_\mu^2/m_K]}.$$

Kinematic factor

- Generic four fermion interaction Lagrangian analysis

$$\mathrm{Im}\xi = \frac{(m_K^2 - m_\pi^2)\mathrm{Im}G_S^*}{\sqrt{2}(m_s - m_u) m_\mu G_F \sin\theta_C}$$

- Effective field theory with Wilson coefficients

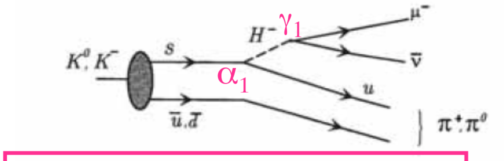
$$P_\perp \sim \left[0.38\,\mathfrak{Im}C_S^K - 0.27\frac{p_K \cdot (p_\nu - p_\mu) + m_\mu^2/2}{M_K^2 (f_+/f_T)}\mathfrak{Im}C_T^K\right]\left(\frac{\mathrm{TeV}}{\Lambda}\right)^2$$

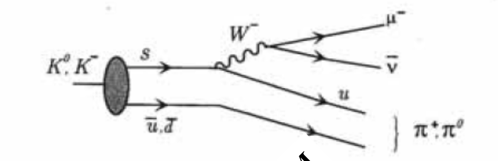
	E246	TREK
$\lvert \mathrm{ImG_S} \rvert / G_F$	$< 2.2 \times 10^{-4}$	$< 1 \times 10^{-5}$
$\lvert \mathrm{Im}\ C_S \rvert\ (\Lambda/\mathrm{TeV})^2$	$\leq 2 \times 10^{-3}$	$\leq 1 \times 10^{-4}$

- *Typical models with scalar interactions allowing a sizable P_T:*
  - Multi-Higgs doublet model
  - SUSY with R-parity violation or large squark mixing

Three Higgs doublet model

$$L = (2\sqrt{2}G_F)^{\frac{1}{2}} \sum_{i=1}^{2} \{\alpha_i \bar{u}_L V M_D d_R H_i^+ + \beta_i \bar{u}_R M_U V d_L H_i^+ + \gamma_i \bar{\nu}_L M_E e_R H_i^+\} + \text{h.c.},$$



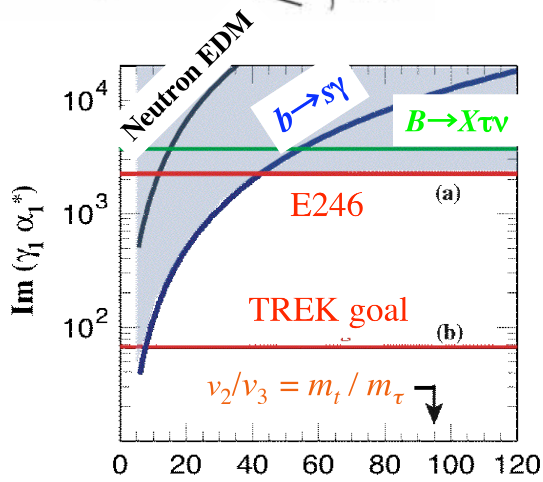


$$\mathrm{Im}\xi = \frac{m_K^2}{m_H^2} \mathrm{Im}(\gamma_1 \alpha_1^*)$$

- *c.f.* d_n, $b \to s\gamma$ $\propto \mathrm{Im}(\alpha_1\beta_1^*)$, $(\alpha_1\beta_1^*)$

  $\mathrm{Im}(\alpha_1\beta_1^*) = -v_2^2/v_3^2\, \mathrm{Im}(\gamma_1\alpha_1^*)$

  Higgs field *v. e. v.*



- $B \to X\tau\nu$ and $B \to \tau\nu$ at Super-Belle corresponds to $P_T < 3 \times 10^{-4}$

  c.f. TREK goal : $P_T \leq 1 \times 10^{-4}$

- *P_T is the most stringent constraint for* $\mathrm{Im}(\gamma_1\alpha_1^*)$ v_2/v_3

SUSY with R-parity violation

Super potential : $W = W_{SMMS} + W_{RPV}$

$$W_{RPV} = \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$$

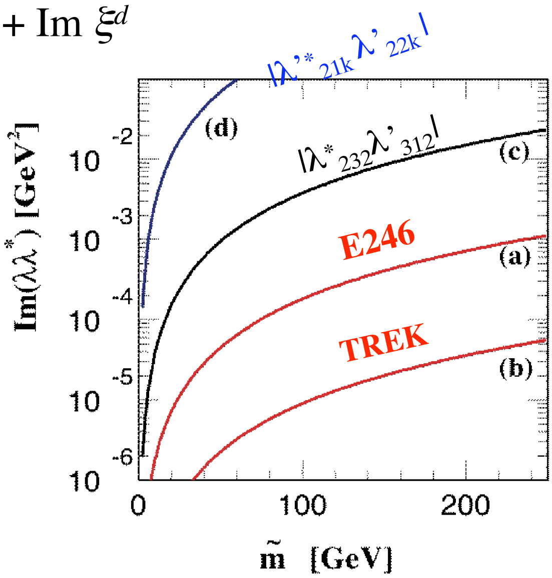
$$\mathrm{Im}\xi = \mathrm{Im}\ \xi^l + \mathrm{Im}\ \xi^d$$

$$\mathrm{Im}\xi^{\tilde{l}} = \sum_i \frac{\mathrm{Im}[\lambda_{2i2}(\lambda'_{i12})^*]}{4\sqrt{2}G_F \sin\theta_c (m_{\tilde{l}_i})^2} \cdot \frac{m_K^2}{m_\mu m_s}$$

$$\mathrm{Im}\xi^{\tilde{d}} = \sum_i \frac{\mathrm{Im}[\lambda'_{21k}(\lambda'_{22k})^*]}{4\sqrt{2}G_F \sin\theta_c (m_{\tilde{d}_k})^2} \cdot \frac{m_K^2}{m_\mu m_s}.$$

Relevant parameters and constraints

	Paraneter	Upper bound	Experiment
$\mathrm{Im}\xi^{\tilde{l}}$	$\lvert\lambda^*_{232}\lambda'_{312}\rvert$	$3.8 \times 10^{-6} m^2$	$K_L \to \mu^+\mu^-$[19]
	$\lvert\lambda^*_{212}\lambda'_{112}\rvert$	no constraint	
	$\lvert\lambda^*_{222}\lambda'_{212}\rvert$	no constraint	
$\mathrm{Im}\xi^{\tilde{d}}$	$\lvert\lambda'^*_{211}\lambda'_{221}\rvert$	$2.8 \times 10^{-5} m^2$	$K^+ \to \pi^+\nu\bar{\nu}$[20]
	$\lvert\lambda'^*_{212}\lambda'_{222}\rvert$	$2.8 \times 10^{-5} m^2$	$K^+ \to \pi^+\nu\bar{\nu}$[20]
	$\lvert\lambda'^*_{213}\lambda'_{223}\rvert$	$2.8 \times 10^{-5} m^2$	$K^+ \to \pi^+\nu\bar{\nu}$[20]

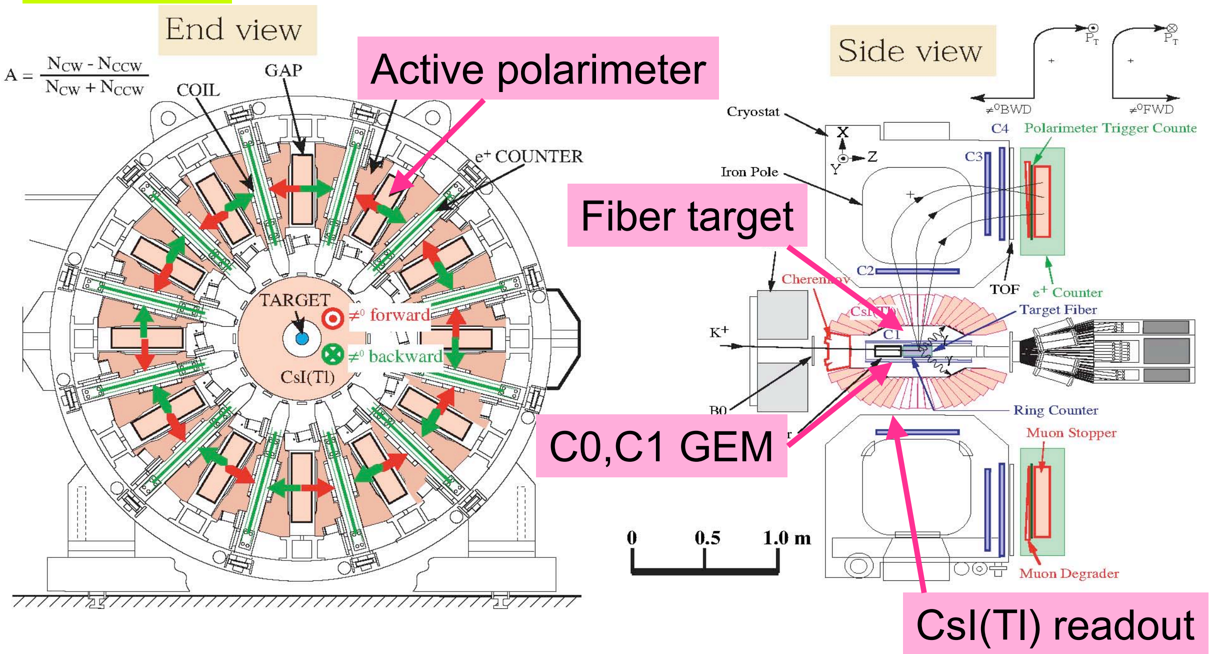


- *P_T is a very stringent constraint for these parameters !*

P_T measurement

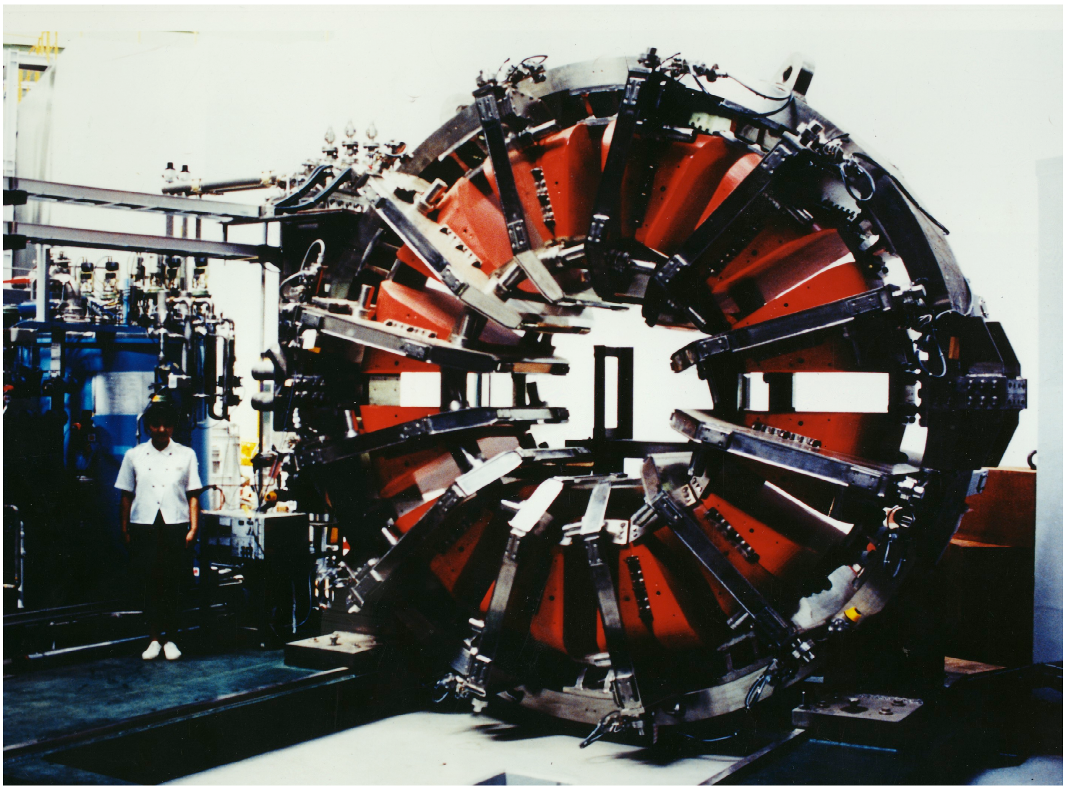
Use of upgraded E246 detector

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



- *P_T is measured as the azimuthal asymmetry A_{e^+} of the μ^+ decay positrons*

Superconducting toroidal magnet



Stopped beam method

Double ratio experiment

$A_T = (A^{fwd} - A^{bwd}) / 2$

$$A^{fwd(bwd)} = \frac{N_{cw} - N_{ccw}}{N_{cw} + N_{ccw}}$$

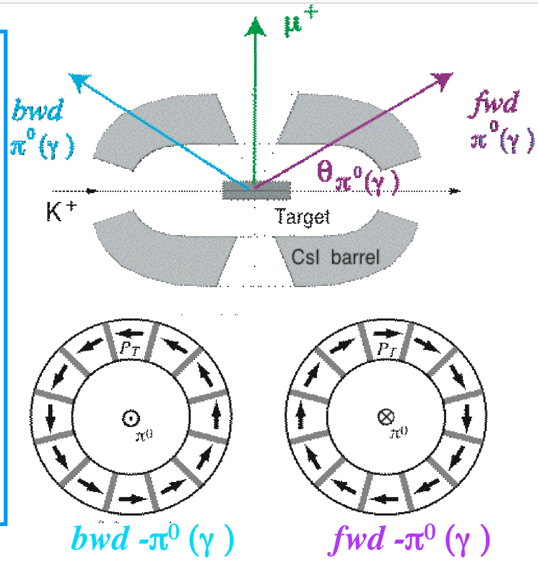
$P_T = A_T / \{\alpha <\cos\theta_T>\}$

α : analyzing power

$<\cos\theta_T>$: attenuation factor

$\mathrm{Im}\xi = P_T / KF$: physics parameter

KF : kinematic factor



Current limit from E246

$P_T = -0.0017 \pm 0.0023(stat) \pm 0.0011(syst)$

($|P_T| < 0.0050$: 90% C.L.)

$\mathrm{Im}\xi = -0.0053 \pm 0.0071(stat) \pm 0.0036(syst)$

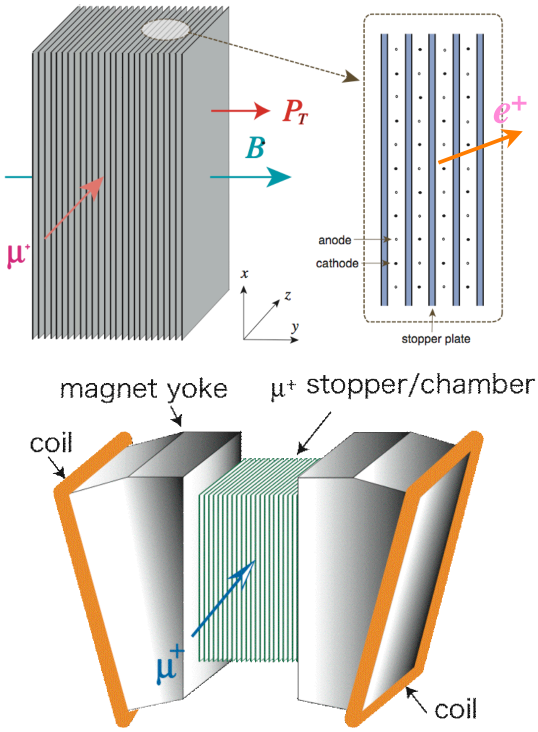
($|\mathrm{Im}\xi| < 0.016$: 90% C.L.) **PRD 73, 072005 (2006)**

- *E246 was Statistical error dominant*

J-PARC TREK Experiment

- Stopped K^+ method with SC Toroidal Magnet
- Upgraded E246 detector
- Sensitivity goal : $\delta P_T \sim 10^{-4}$

Active muon polarimeter



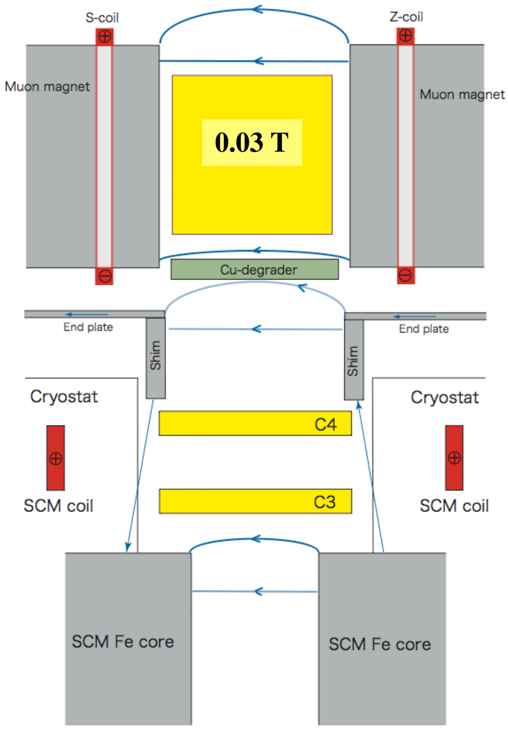
- Full angular acceptance for positrons
  - higher statistics
- Determination of decay vertex
  - lower background
- Measurement of e^+ angle and approx. energy
  - higher analyzing power
- Improved field alignment
  - suppressed systematic error

Gap wire chambers

Number of plates	24
Plate material	Al, Mg or alloy
Plate thickness	~ 2.5 mm
Plate gap	~ 8 mm
Ave. density	0.24 ρ_{Al}
μ^+ stop efficiency	~ 85%

- *Prototype chambers are currently made and tested*

Muon field magnet for TREK



- Control of muon spin motion
- Decoupling of stray field
  - ~0.3 G / 300 G ~ 10^{-3}
- Mechanical alignment of the 300 G field
  - $\delta P \sim \delta\theta \approx 10^{-3}$
- Further alignment using $K_{\mu 3}$ data
  - $\delta P \sim \delta\theta \approx 10^{-4}$

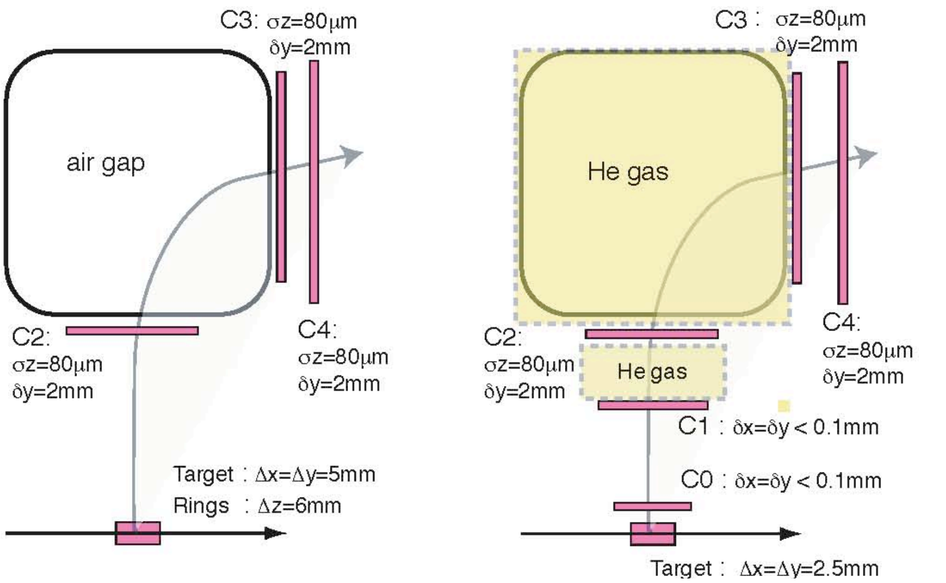
Muon Field Magnet

Field srength	0.03 T
Gap	31 cm
Pole face	68 × 44 cm
Number of coils	24
Total power	20 kW
Cooling	indirect water

- *High-precision magnets with good symmetry are being made*

Tracking system

- Higher kinematic resolution
- Better $K\pi 2$ background suppression



E246 J-PARC E06

- *New C0 (cylindrical) and C1(planer) are GEM chambers*

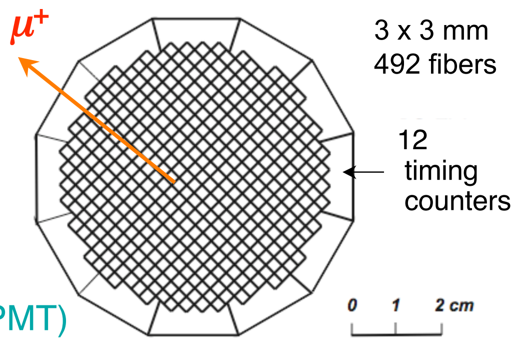
Active fiber target

1. Finer segmentation for
   - Higher μ^+ tracking resolution
   - Higher K^+ stop point resolution
   - $K\pi 2$ background suppression

   (E246 : 256 fibers with 5 x5 mm^2)
2. Compact and light system
   - using SiPMT (MPPC)

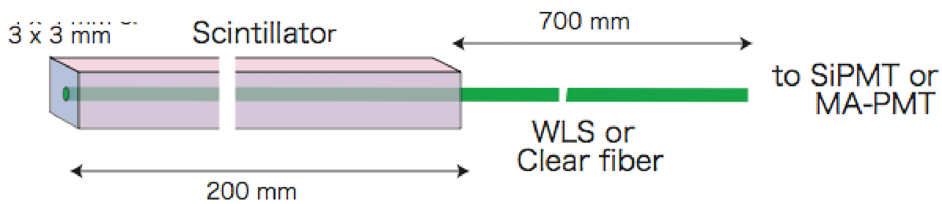
   (E246 : each fiber was read by a1/2" PMT)

Cross section



One element

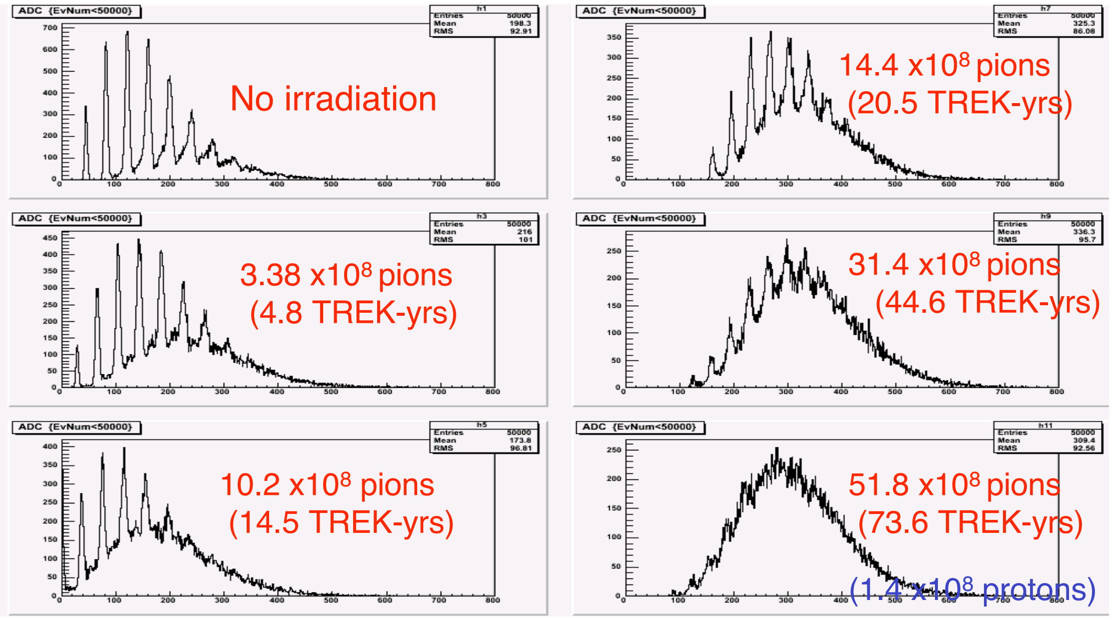
Current baseline design



- *Beam test of MPPC damage was performed using pions*

MPPC deterioration by irradiation

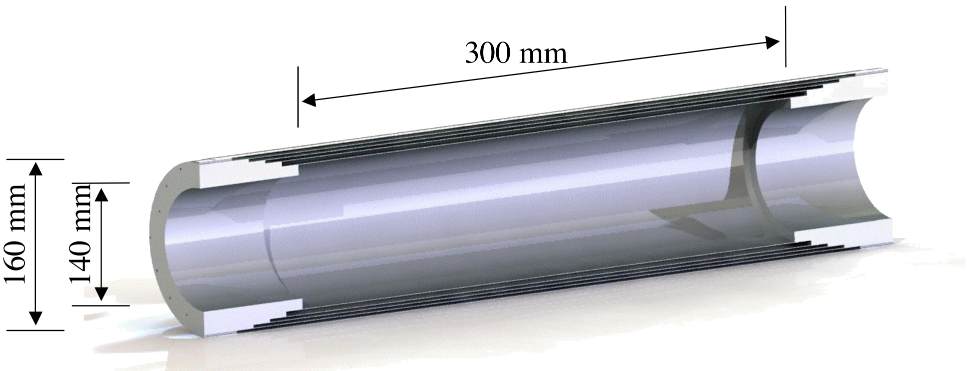
- Irradiation test under the realistic beam halo condition
- 100 MeV/c π^+ beam at TRIUMF



- *It was shown that MPPC has long enough lifetime*

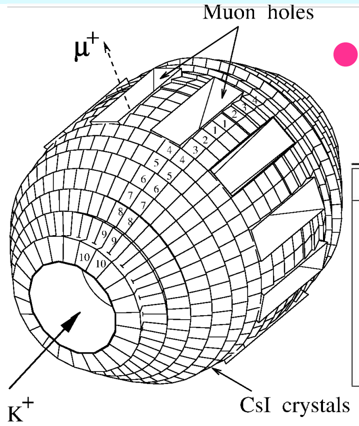
C0 Cylindrical GEM for TREK

- Suppression of Kπ2 BG: as close to the target as possible
- Complete rotational symmetry : seamless structure



- High position resolution; $\delta < 0.1$ mm
- Very high rate capability; 25 kHz/mm^2
- Radiation-hardness ; 4 x10^{10} MIPs/mm^2
- TREK: Rates <250 Hz/mm^2 (halo < 5 Hz/mm^2), Total dose: 7 x10^7 particles

APD readout of CsI(Tl)



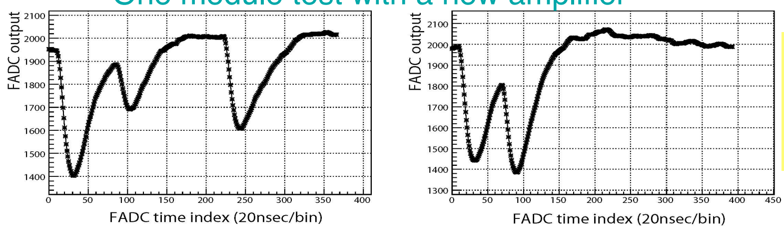
- Improvement of timing and rate performance by using APD diodes and FADC

Parameter	E06 APD readout	E246 PIN readout
Electron yield	47,000/MeV	11,000/MeV
Noise level	not yet measured	70 keV
Energy resolution	~12% for C.R.	12% for C.R.
Time rsolution	3 ns for C.R.	12 ns for C.R. (9 ns for all)
Pulse width	~ 1.5 μs	15 μs
Rate performance	~ 500 kHz	34 kHz

too slow

new requirement : > 10 times faster

One module test with a new amplifier



Typical pileup signals (FADC spectra) in one modue test with e+beam:

- *Pileup signal could be analyzed resulting in good high rate performance*

E246 systematic errors

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 ϕ-offset	x	o	2.8
e^+ counter r-offset	o	o	<0.1
e^+ counter z-offset	o	o	<0.1
μ^+ counter ϕ-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**

- Cancellation by $\Sigma 12$ and/or *fwd/bwd* almost all systematics except for :

← μ^+ field alignment

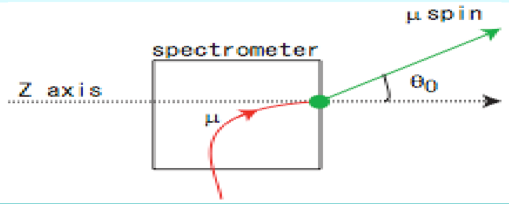
← μ^+ multiple scattering

← decay plane shifts due to
- K^+ stopping distribution
- Detector inefficiency distribution *etc.*

- *Systematic error will be suppressed to 1/10 in TREK*

Misalignment analysis using $K_{\mu3}$

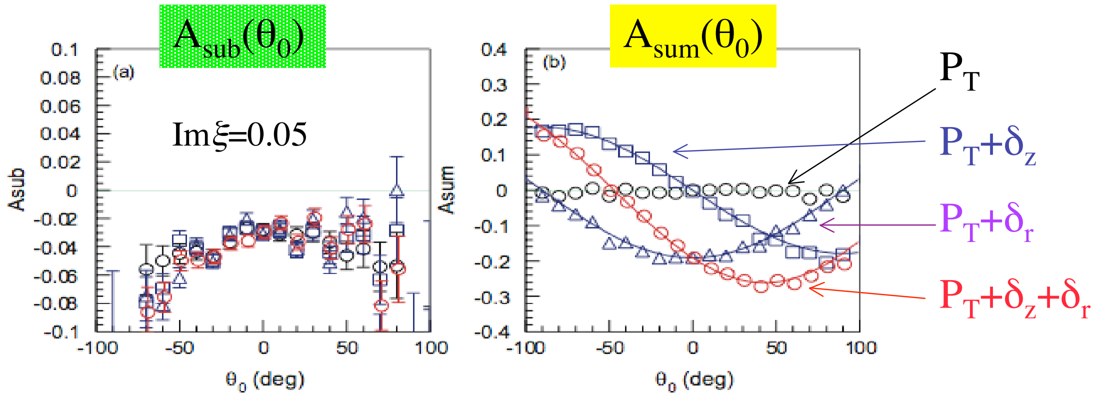
- *Asymmetry analysis in terms of θ_0 : in-plane spin angle from z-axis*



$$A_{sum}(\theta_0) = (\bar{A}_{fwd}(\theta_0) + \bar{A}_{bwd}(\theta_0)/2 = \alpha_0\{\delta_r\cos\theta_0 - \delta_z\sin\theta_0 + \eta(\theta_0)\} + \gamma$$

$$A_{sub}(\theta_0) = (\bar{A}_{fwd}(\theta_0) - \bar{A}_{bwd}(\theta_0))/2 = F(P_T, \theta_0).$$

small residual of oscillation

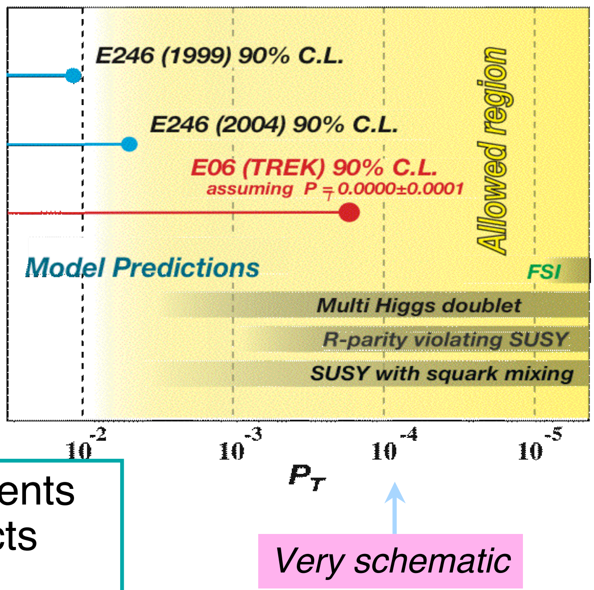


- $A_{sub}(\theta_0)$ *is independent of polarimeter misalignments*

Expected sensitivity in TREK

- $\delta P_T^{stat} \leq 0.05\ \delta P_T^{stat}$ (E246) $\leq 10^{-4}$: 1.4 x 10^7 sec of run

1) × 30 beam intensity 2) × 10 detector acceptance 3) Higher analyzing power



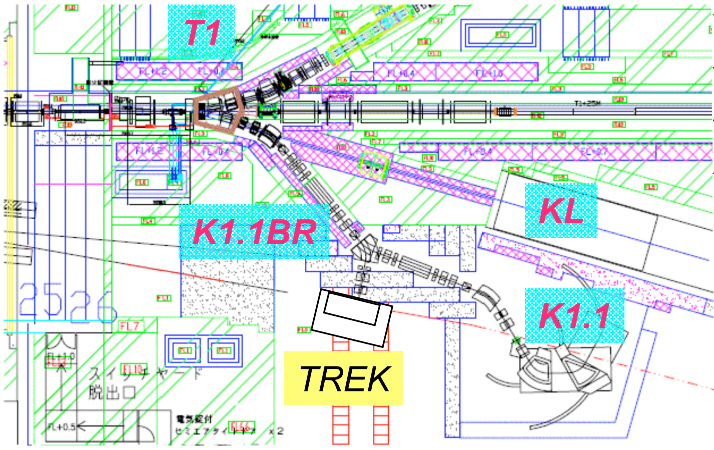
- $\delta P_T^{syst} \leq 0.1\ \delta P_T^{syst}$ (E246) $\leq 10^{-4}$

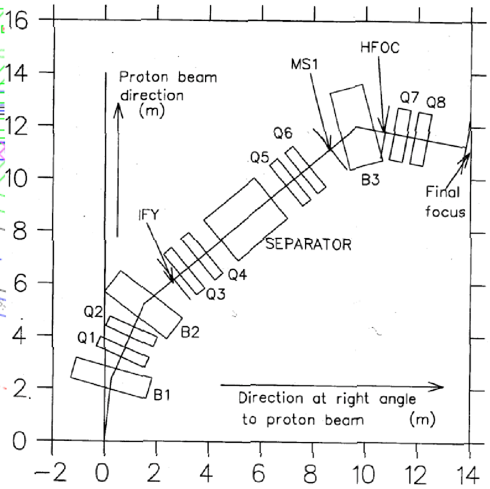
1) Precise calibration misalignments 2) Correction of systematic effects 3) Precise *fwd-bwd* cancellation

- *We aim at a sensitivity of $\delta P_T \sim 10^{-4}$*

K0.8 (K1.1-BR) for stopped K^+

- Low momentum (p=0.8 GeV/c) separated beam
- Macroscopic time sharing with K1.1 once it is installed





- $I_{K^+} = 2.1 \times 10^6$ /s @ 9 μA- 30 GeV protons on T1
- K/π ratio > 1.0
- *The beamline will be completed in 2010*

TREK time schedule

- 2006 : Proposal and Stage-1 approval
- 2007-2010 : Detector R&D,
  Construction of Active polarimeter
- 2009 : Budget request for detector
- 2009-2010 : Construction of the K0.8 beamline
- 2010-2012 : Detector construction
- 2012-2013 (?) : Run

More than 100 kW of beam power is necessary

Summary

- Transverse μ^+ polarization in $K^+ \rightarrow \pi^0\mu^+\nu$ decay is a sensitive probe of new physics through CP violation beyond the SM.
- J-PARC TREK experiment aims at a sensitivity of 10^{-4} improving the current limit from KEK E246 by a factor more than 20.
- An upgraded E246 detector and a stopped K^+ beam method are employed to realize the smallest possible systematic error.
- Currently the active polarimeter is under construction.
- We aim to run the experiment in the early stage of J-PARC operation in the near future.