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

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

J. Imazato

IPNS, KEK

KEK-PS External Review 2008

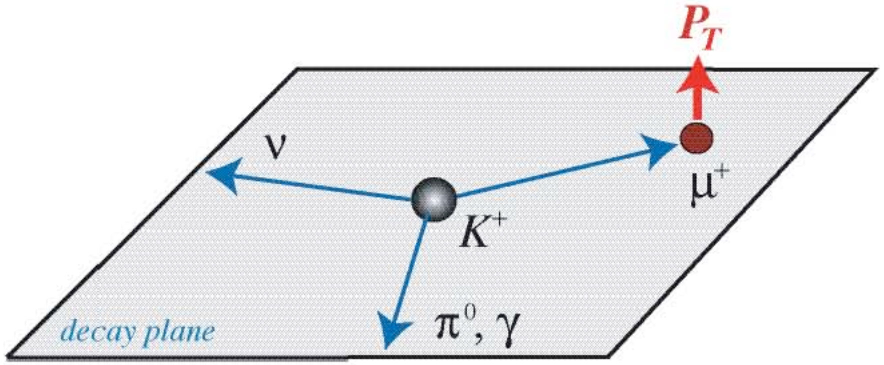
January 22, 2008

E246 : main experiment
E470 : byproduct experiment

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

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

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



- P_T is T-odd and spurious effects from final state interaction are small. Non-zero P_T is a signature of T violation.
- Standard Model contribution to P_T : $P_T(\mathrm{SM}) < 10^{-7}$
- Spurious effects from final state interactions : $P_T(\mathrm{FSI}) < 10^{-5}$
- **P_T of $\mathcal{O}(10^{-3} \sim 10^{-4})$ is a very sensitive probe of CP violation other than SM**
- There are theoretical models which allow sizeable P_T without conflicting with other experimental constraints.

Possible origins of P_T

Effective four-fermion interaction

$$L = -G_F/\sqrt{2}\sin\theta_C\,\bar{s}\gamma_\alpha(1-\gamma_5)u\,\bar{\nu}\gamma^\alpha(1-\gamma_5)\mu$$
$$+\,G_S\bar{s}u\,\bar{\nu}(1+\gamma_5)\mu + G_P\,\bar{s}\gamma_5 u\,\bar{\nu}(1+\gamma_5)\mu$$
$$+\,G_V\bar{s}\gamma_\alpha u\,\bar{\nu}\gamma^\alpha(1-\gamma_5)\mu + G_A\,\bar{s}\gamma_\alpha\gamma_5 u\,\bar{\nu}\gamma^\alpha(1-\gamma_5)\mu + h.c.$$

	$K_{\mu 3}$ ($K^+ \to \pi^0\mu^+\nu$)	$K_{\mu\nu\gamma}$ ($K^+ \to \mu^+\nu\gamma$)
P_T origin interfering with G_F	G_S (scalar)	G_P, $G_R = (G_V + G_A)/2$ (pseudoscalar & right-handed)
$< P_T > =$	$\sim 0.15\ \mathrm{Im}\ \Delta_S$ $\mathrm{Im}\ \Delta_S = \frac{\sqrt{2}(m_K^2 - m_\pi^2)\ \mathrm{Im}\ G_S^*}{(m_s - m_u)m_\mu G_F \sin\theta_C}$ $= 2\ \mathrm{Im}\xi$ $(\xi = f_- / f_+)$	$\sim 0.1\ \mathrm{Im}\ \Delta_P + 0.3\ \mathrm{Im}\ \Delta_R$ $\mathrm{Im}\ \Delta_P = \frac{\sqrt{2}\, m_K^2\ \mathrm{Im}\ G_P}{(m_s + m_u)m_\mu\, G_F \sin\theta_C}$ $\mathrm{Im}\ \Delta_R = \frac{\sqrt{2}\ \mathrm{Im}\ G_R}{G_F \sin\theta_C}$

Model descriptions of P_T

$$P_T = \mathrm{Im}\xi \cdot \frac{m_\mu}{m_K} \frac{|\vec{p}_\mu|}{[E_\mu + |\vec{p}_\mu|\vec{n}_\mu \cdot \vec{n}_\nu - m_\mu^2/m_K]} \qquad \mathrm{Im}\xi = \frac{(m_K^2 - m_\pi^2)\mathrm{Im}G_S^*}{\sqrt{2}(m_s - m_u)m_\mu G_F \sin\theta_C}$$

P_T is sensitive to scalar interactions

- Multi-Higgs doublet (3 Higgs doublet) model
  - $\mathrm{Im}\xi = (m_K^2/m_H^2)\ \mathrm{Im}(\gamma_1\alpha_1^*)$
  - $|\mathrm{Im}(\gamma_1\alpha_1^*)| < 544\ (m_H/\mathrm{GeV})^2$ from the E246 limit
  - $B \rightarrow \tau\nu X$ constraints also $\mathrm{Im}(\gamma_1\alpha_1^*)$ but weaker ($<1900\ (m_H/\mathrm{GeV})^2$)
  - n-EDM and $b \rightarrow s\gamma$ constraint differently $\mathrm{Im}(\alpha_1\beta_1^*)$
- SUSY with squark mixing
  - $\mathrm{Im}\xi \propto \mathrm{Im}[V_{33}^{H+} V_{32}^{DL*} V_{31}^{UR*}] / m_H^2$
  - $m_H \geq 140$ GeV from the E246 limit and no stringent limit from other modes
- SUSY with R-parity violation
  - $\mathrm{Im}\xi^l \sim \mathrm{Im}\ [\lambda_{2i2}(\lambda_{i12})^*]$, $\mathrm{Im}\xi^d \sim \mathrm{Im}\ [\lambda'_{21k}(\lambda'_{22k})^*]$
  - No stringent limits from other modes

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

KEK E246 experiment

Features

- One of the important particle physics experiments representing the KEK-PS
- Ultimate experiment which could run with the limited KEK-PS intensity
  - *the experiment which requested **the highest slow-extraction beam intensity***
- First large international collaboration at KEK-PS
- Successful high precision particle physics experiment

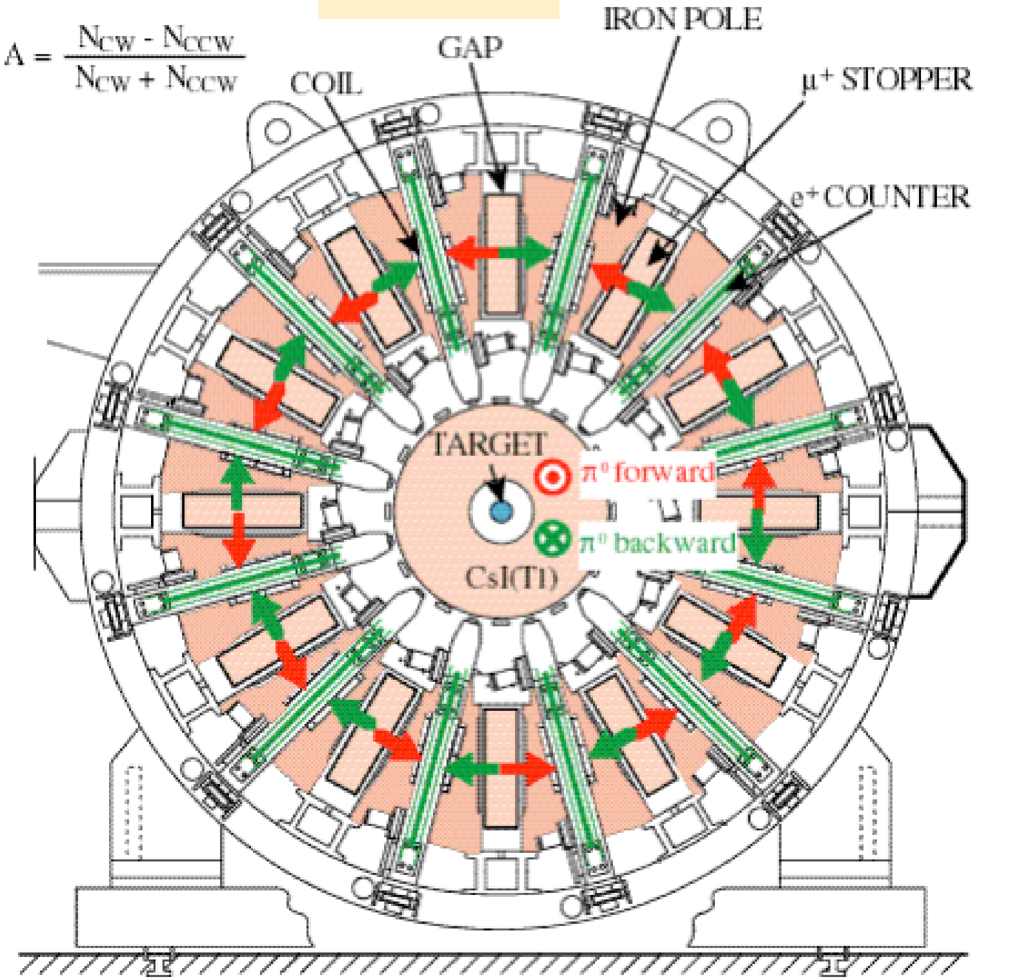
Progress

- 1991 : Experiment approved
- 1992-1995 : Detector construction
- 1995 : K5 beamline upgrade & tuning
- 1996-2000 : Data taking [450 + 180 (extension) shifts]
- 1999 : First result was published with 1/4 of data
- 2001 : E470 data taking
- 2001-2003 : Analysis
- 2004 : Letter paper publication of the final result
- 2006 : Final full paper publication

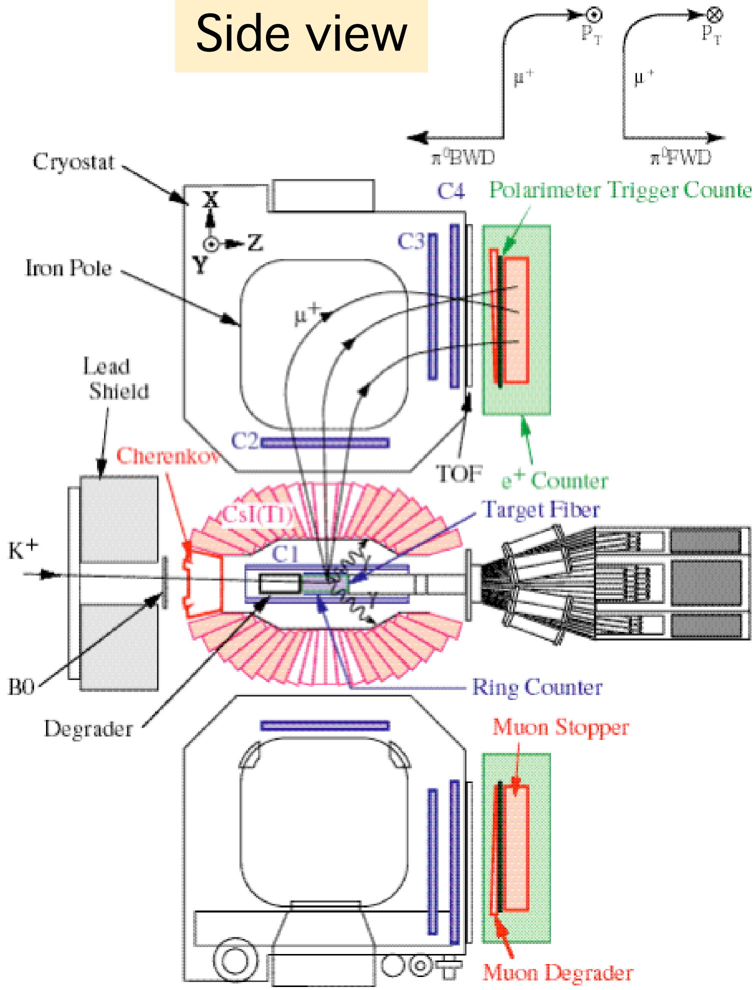
E246 experimental setup

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

End view



Side view



0 0.5 1.0 m

Decay e^+ asymmetry A_{e^+}

$K^+ \rightarrow \pi^0 \mu^+ \nu \ (K_{\mu 3})$

Experimental principle of E246

- Stopped beam method
  (at rest K^+ decay)
  - coverage of all π^0 directions
  - symmetric decay phase space

- Double ratio measurement

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

  - small systematic errors
  - null check with

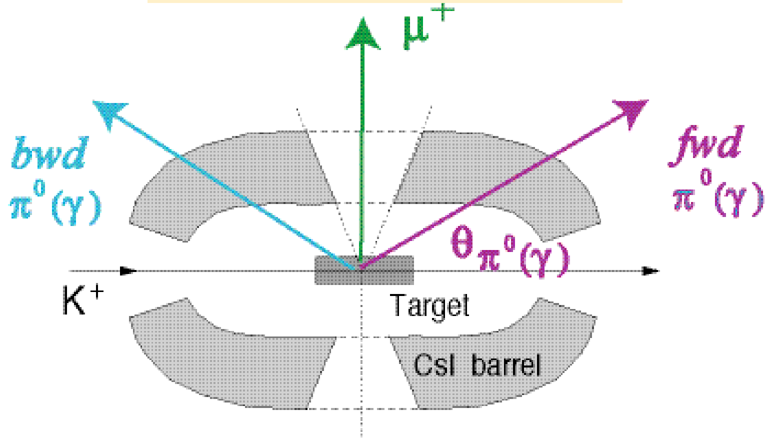
  $$A_0 = (A_{fwd} + A_{bwd}) / 2$$

- Longitudinal filed method

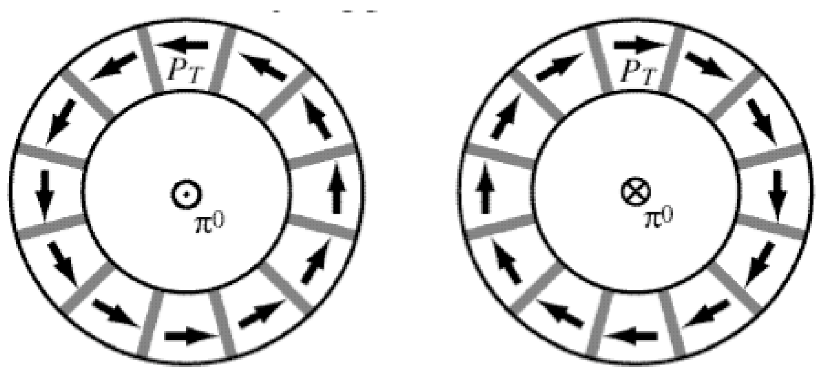
  $$\langle B \rangle // \langle P_T \rangle$$

  $$A_{e^+} = \frac{N_{cw} - N_{ccw}}{N_{cw} + N_{ccw}}$$

fwd and *bwd* π^0 /γ



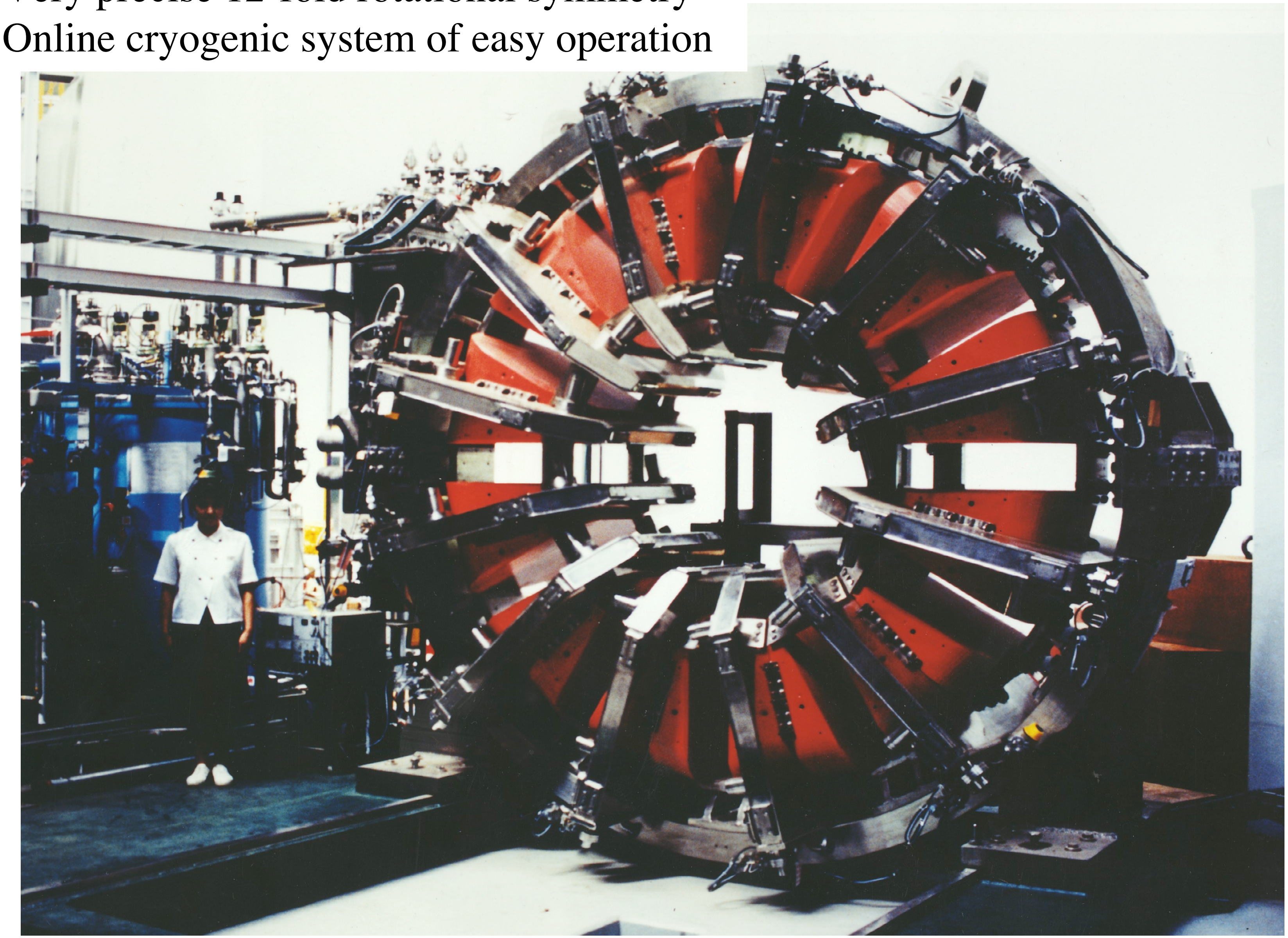
P_T directions



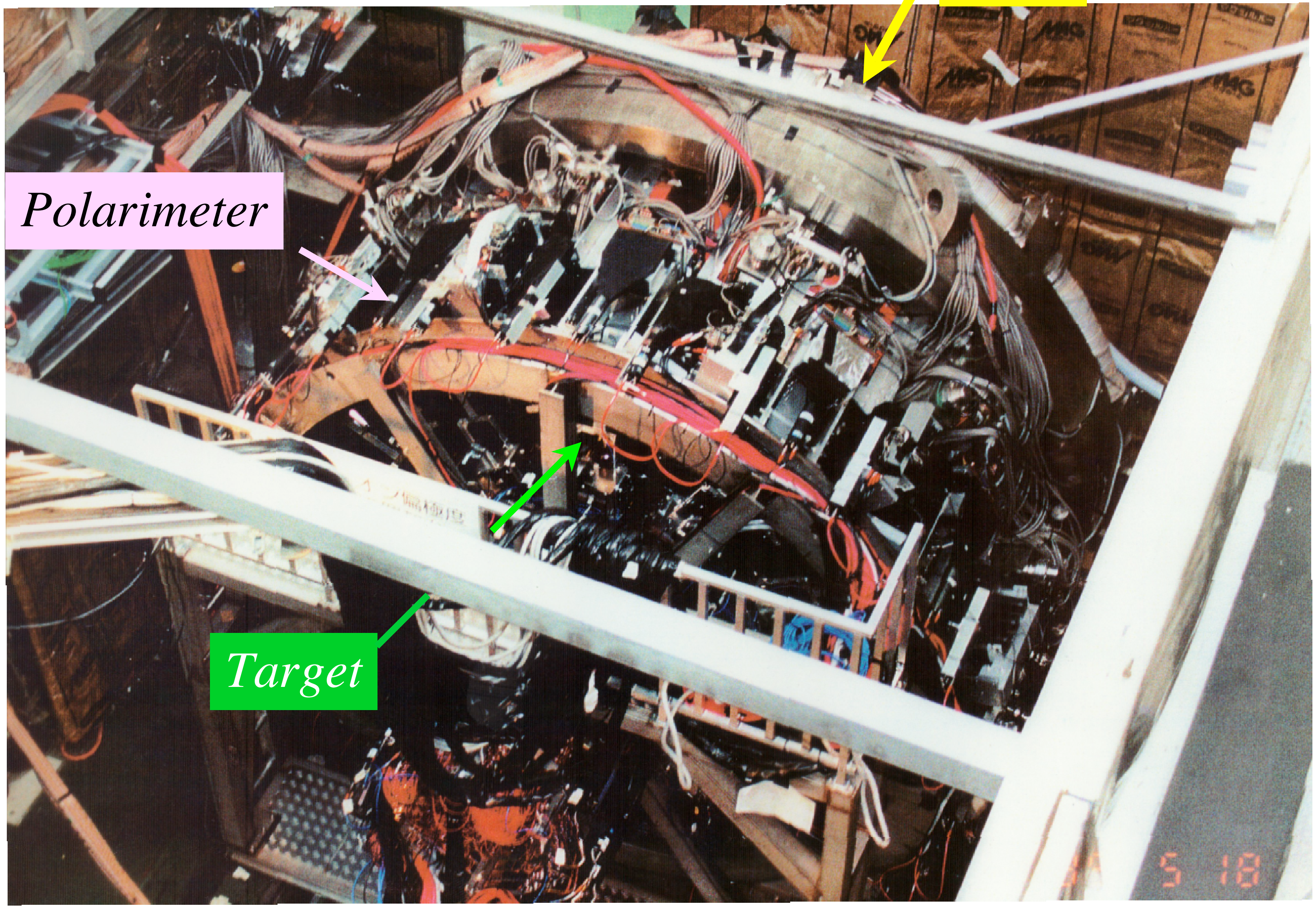
bwd -π^0 (γ)   *fwd* -π^0 (γ)

Superconducting toroidal magnet

- Very precise 12-fold rotational symmetry
- Online cryogenic system of easy operation

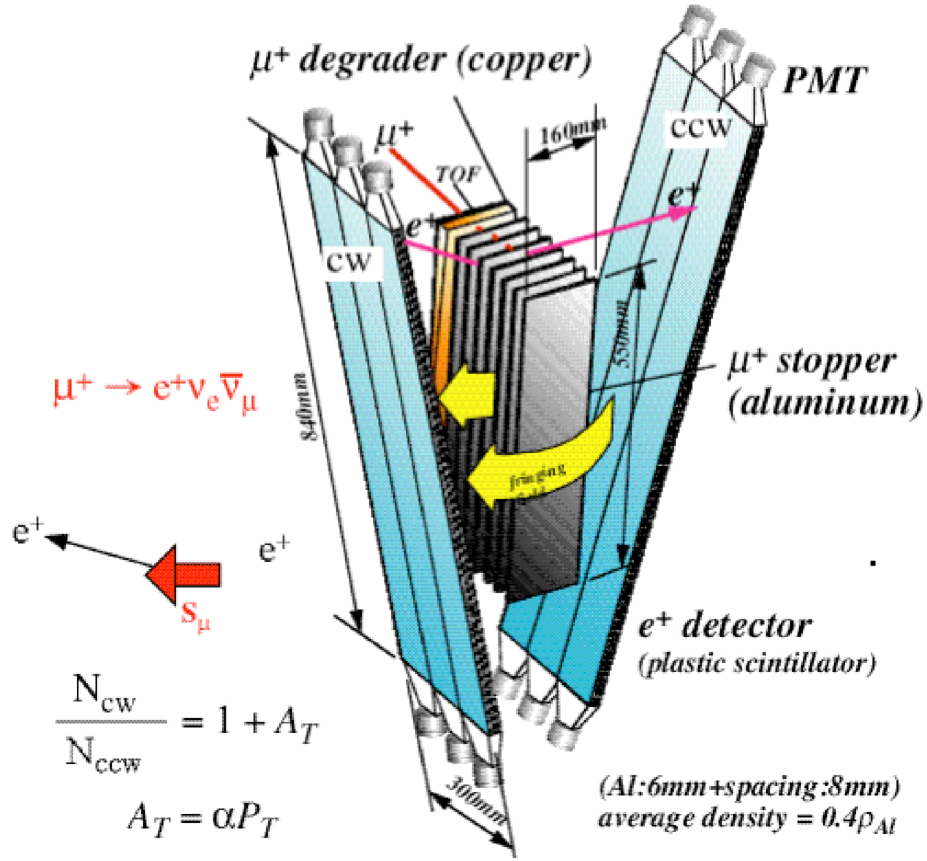


E246 detector at K5

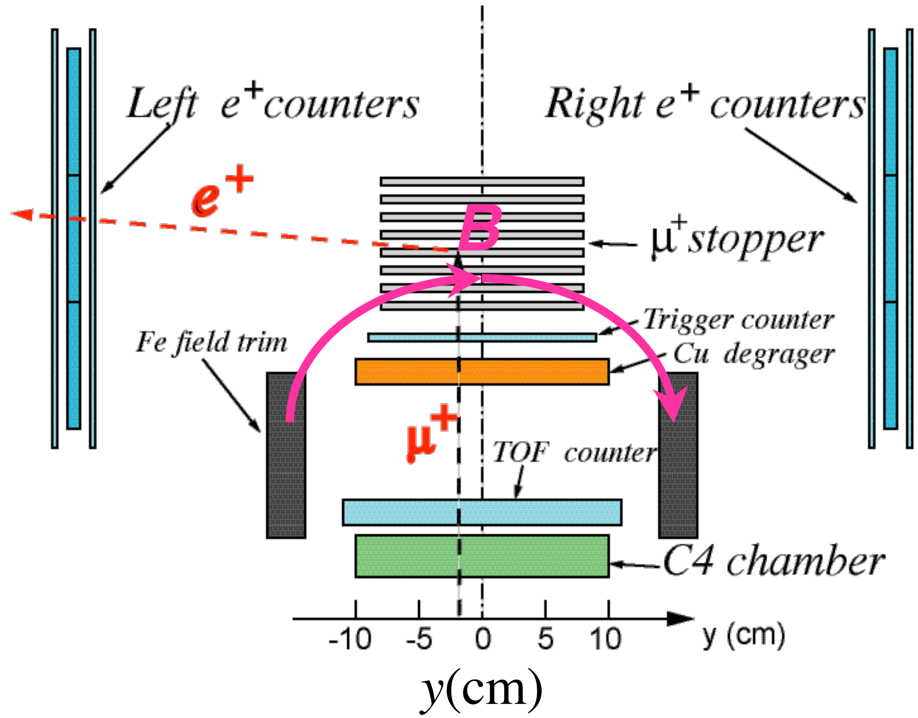


Muon polarimeter

One-sector view



Cross section



- Passive polarimeter with
  - *Al* muon stopper
  - *Left/Right* positron counters

Easy analysis and simple systematics

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

$$W(e^+) \propto 1 + A\cos\theta$$

Polarimeter analysis

Differential asymmetry analysis using C4 information

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

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

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

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

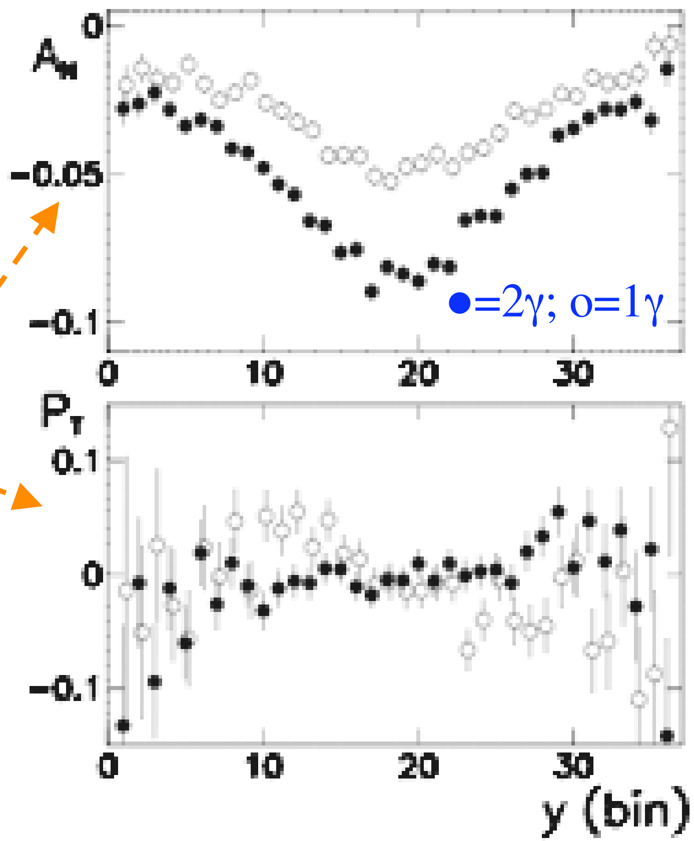
$\alpha(y) = A_N(y)\ /\ P_N$

$A_N(y) = [A(y)_{left} - A(y)_{right}]/\ 2$

P_N : MC calculation of in-plane P
$\langle\cos\theta_T\rangle$: kinematical attenuation of P_T

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

MC calculation



Gradients due to slightly different *x* and *z* distributions between *fwd* and *bwd*

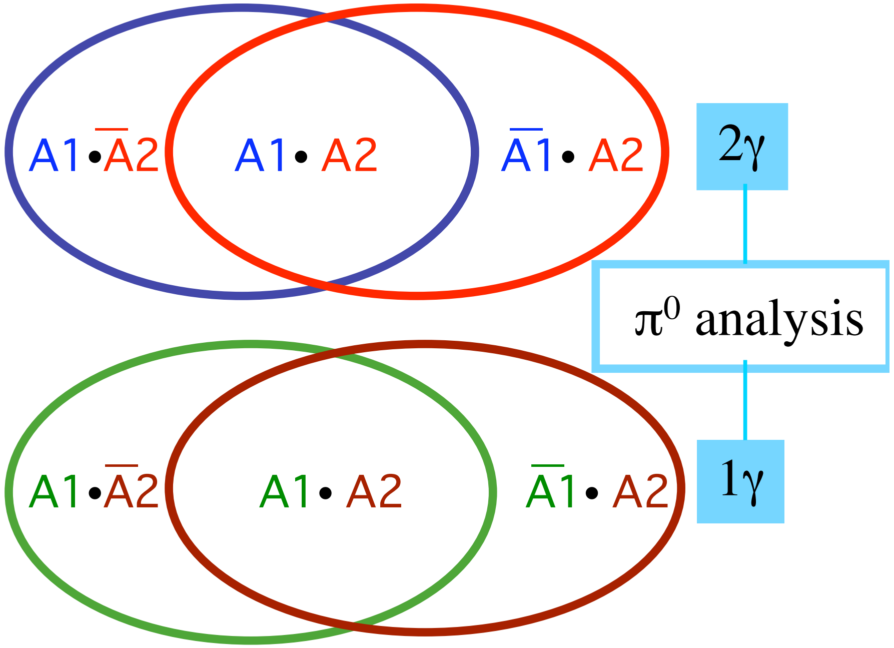
Two independent analyses

- Analyses A1 and A2 by two teams with
  - their own analysis policy and
  - event selection methods

Comparison of good $K_{\mu 3}$ events 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
  - averaging the 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

E246 systematic errors

Source of Error	$\Sigma 12$	*fwd/bwd*	$\delta P_T \times 10^4$
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
$\boldsymbol{B}$ offset (ε)	x	o	3.0
$\boldsymbol{B}$ rotation (δ_x)	x	o	0.4
$\boldsymbol{B}$ 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 Σ^{12} and/or ***fwd/bwd*** almost all systematics except for :

μ+ field alignment

μ+ multiple scattering

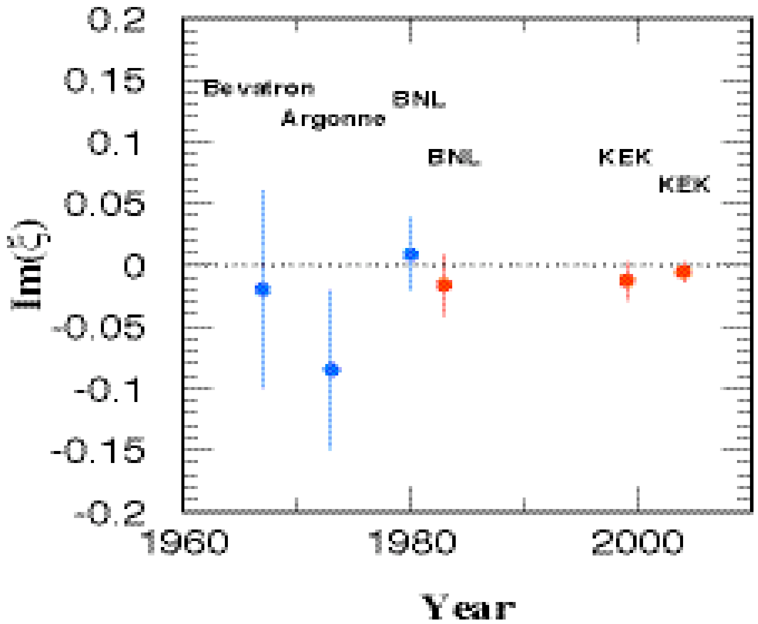
decay plane shifts
due to

- K^+ stopping distribution
- Detector inefficiency distribution *etc.*

Result

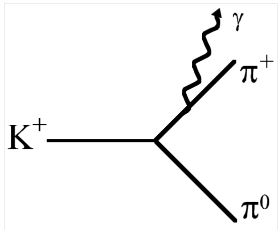
$$P_T = -\,0.0017 \pm 0.0023(stat) \pm 0.0011(syst)$$
$$(\ |P_T| < 0.0050 : 90\%\ C.L.\ )$$

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

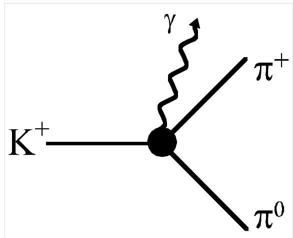


Phys. Rev. Letters 83, 4253 (1999) [first 1/4 data]
Phys. Rev. Letters 93, 131601 (2004) [full data]
Phys, Rev. D73, 072005 1~34 (2006) [same result as PRL 93]

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)

$BR^{ChPT}(DE) \sim 0.4 \times 10^{-5}$
($55 < T_p < 90$MeV)

- Total branching ratio:

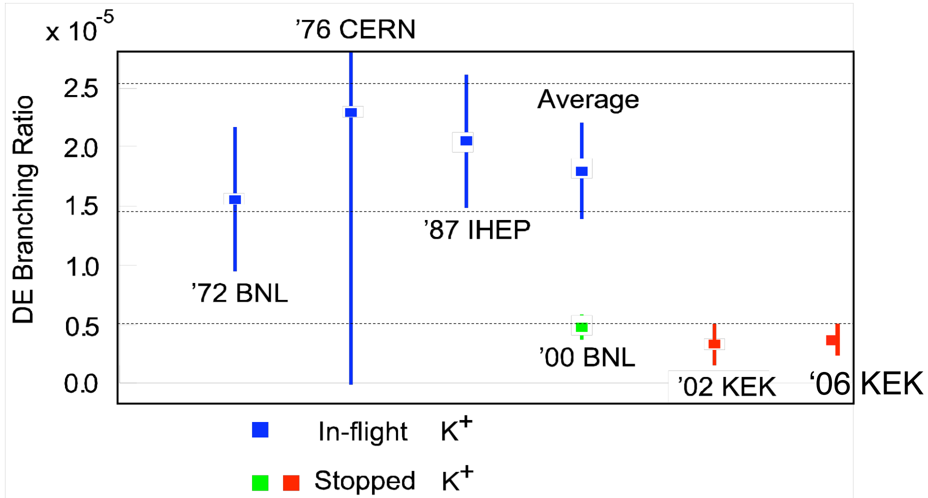
$BR(DE) = [\ 0.61 \pm 0.25(stat) \pm 0.19(syst)\ ] \times 10^{-5}$

- Partial branching ratio ($55 < T_\pi < 90$MeV):

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

No evnidece for E1 interference

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



- Improved statistics in analysis

$BR(DE) = [\ 0.38 \pm 0.08(stat) \pm 0.07(syst)\ ] \times 10^{-5}$

M.Aliev *et al.*, Euro. Phys. C46, 61 (2006)

Other byproduct physics

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

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

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

- $\Gamma(K_{\mu 3})/\Gamma(K_{e3})$ ratio : decay form factor f_0, q^2 dependence λ_0, ChPT

  λ_0 = 0.019 ± 0.005 (*stat*) ± 0.004 (*syst*) Phys. Letters B513, 311 (2001)

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

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

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

  P_T = -0.0064 ± 0.0185 (*stat*) ± 0.0010 (*syst*) Phys. Letters B562, 166 (2003)

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

  a_0^0 = 0.45 ± 0.43 Phys. Rev. D70 (2004) 037101

- $K^+ \to \pi^0 \mu^+ \nu \gamma$: branching ratio measurement

  Br = [2.4 ± 0.5 (stat) ± 0.6 (syst)]$\times 10^{-5}$ Phys. Letters B633, 190 (2006)

Toward much higher sensitivity to P_T

- *Recommendation of the 2004 review committee*

In most of its measurements, E246 was statistics limited. Additional kaon flux would have improved the results significantly. The experiment really requires a much more intense beam. However, in order to access $P_T \sim 10^{-4}$ which is the goal at J-PARC, obtaining a systematic uncertainty of $\delta P_T < 10^{-4}$ is essential. Having demonstrated their ability to reduce systematic backgrounds, this experiment is ideal for the high flux that will be provided at J-PARC. The possible order of magnitude sensitivity improvement in the muon transverse polarization attainable at that facility will explore interesting potential new sources of CP violation beyond the Standard Model.

- *Increasing physics motivation for P_T*

  e.g. Statement by I.I. Bigi (hep-ph/0707132)

  - P_T represents genuine T violation, and
  - Constitutes prima facie evidence for CP violation in *scalar* dynamics
  - While hoping for a 10^{-3} signal required considerable optimism, the prospect for an effect $\geqq 10^{-4}$ are more realistic.
  - We need a new round of experiments that can measure the rates for $K \to \pi\nu\nu$-*bar* accurately with sample sizes $\sim \mathcal{O}(10^3)$ and mount another serious effort to probe the muon transverse polarization in $K_{\mu 3}$ decays

Goal of J-PARC TREK experiment

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

$\delta P_T^{stat} \leq 0.05\ \delta P_T^{stat}$ (E246) $\sim 10^{-4}$ with

1) × 30 of beam intensity,
2) × 10 of detector acceptance, and
3) higher analyzing power

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

4) precise calibration of misalignments using data
5) correction of decay plane distribution offset

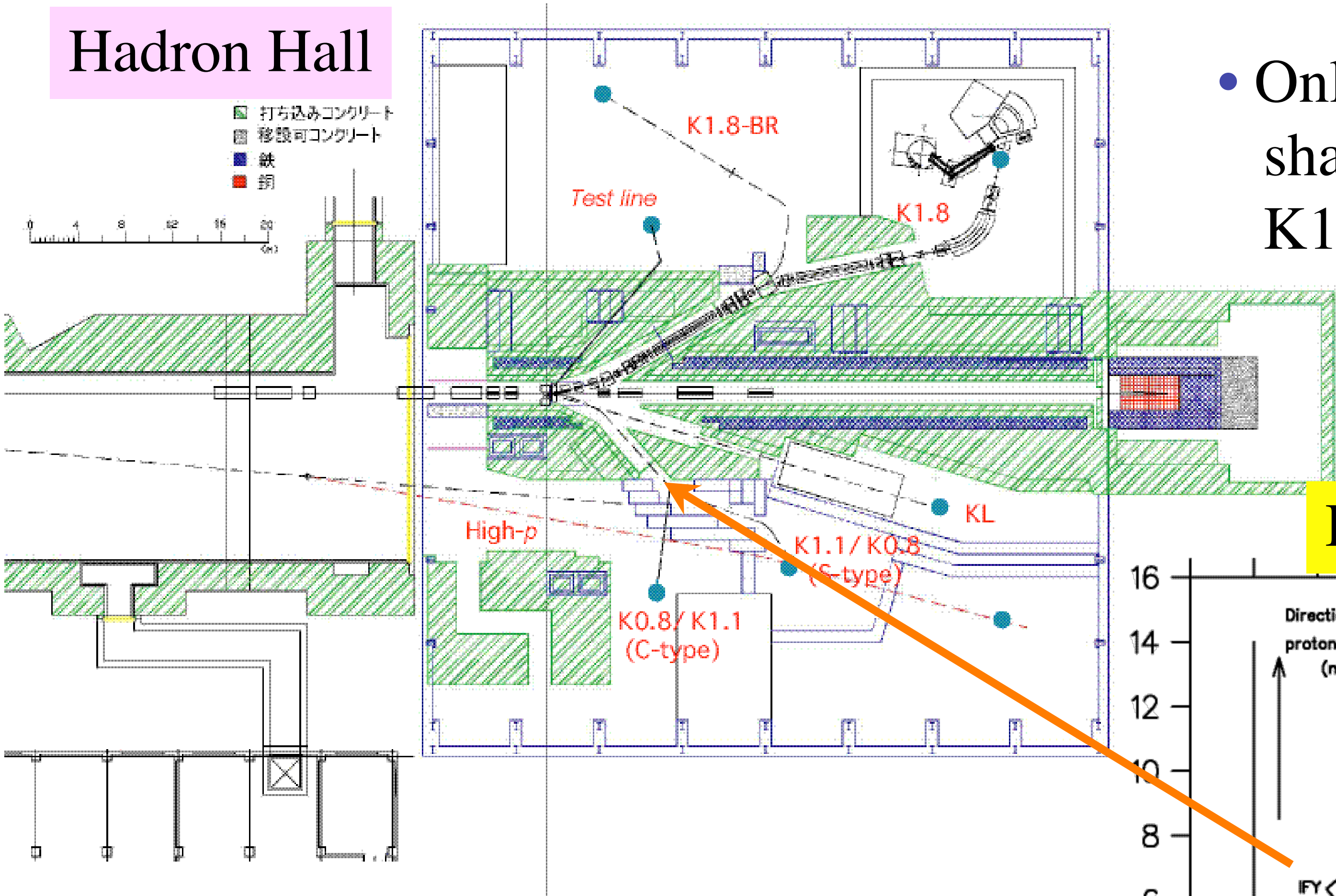
- Improvement of systematic errors

Source	δP_T in E246	J-PARC
μ^+ multiple scattering	7.1×10^{-4}	not existing
Decay plane angle (θ_r)	1.2×10^{-4}	corrected
Decay plane angle (θ_z)	0.7×10^{-4}	correcetd
B offset (ε)	3.0×10^{-4}	not existing
B field rotation (δ_r)	0.4×10^{-4}	measured by data and corrected
B field rotation (δ_z)	5.3×10^{-4}	measured by data and corrected
e^+ counter shits and rotations	2.9×10^{-4}	not existing
Shifts of other elements	3.2×10^{-4}	measured by data and corrected

- E06 (TREK) was approved for stage-1 in the first J-PARC PAC in 2006.

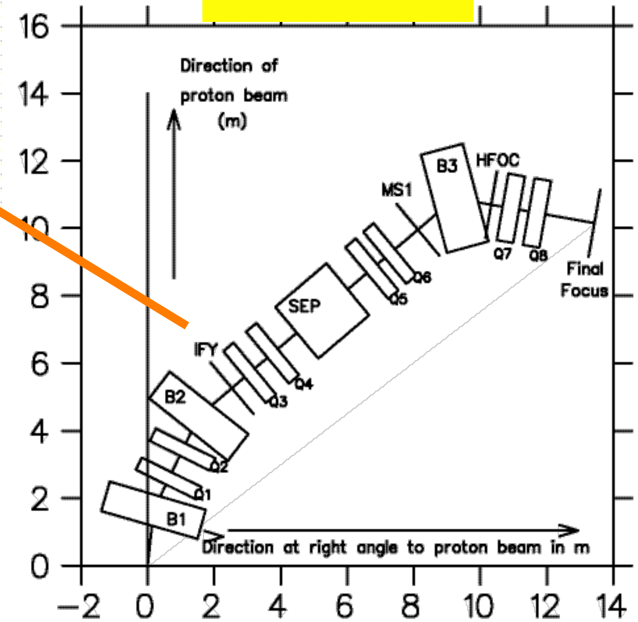
Possible secondary line in Phase 1

Hadron Hall



- Only T1 target sharing it with K1.8 and K_L

K1.1-BR



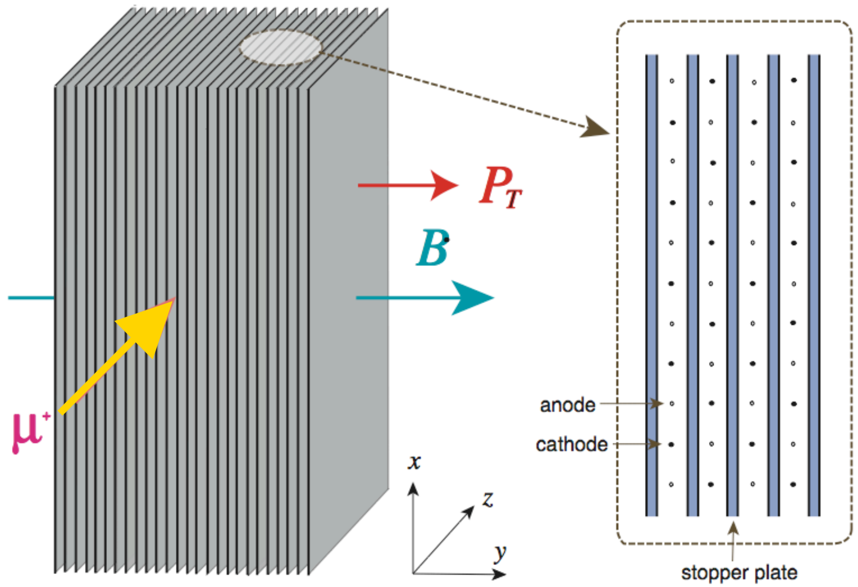
- A branch line of K1.1 for a 0.8 GeV/c beam
- $I_{K^+} \sim 2 \times 10^6$ /s ; $\pi^+/K^+ \sim 0.6$

Upgraded detector elements

Element	From E246 to E06 (TREK)	Reasons
Target	From 5 mm to 3.0 mm fiber Smaller and lighter	(1) rate performance (2) better background rejection (3) suppression of systematic errors
Tracking	Addition of C0 and C1)	(1) rate performance (2) better background rejection
Polarimeter	From passive to active	(1) acceptance improvement (2) analyzing power improvement (3) suppression of backgrounds (4) suppression of systematic errors
Muon field	From SCM to new magnets	(1) improvement of analyzing power (2) suppression of systematic errors
CsI(Tl) readout	From PIN diode to APD	(1) rate performance (2) better background rejection

Active muon stopper

- Identification of muon stopping point/ decay vertex
- Measurement of positron energy E_{e^+} and angle θ_{e^+}
- Large positron acceptance of nearly 4π
- Larger analyzing power
- Higher sensitivity
- Lower BG in positron spectra

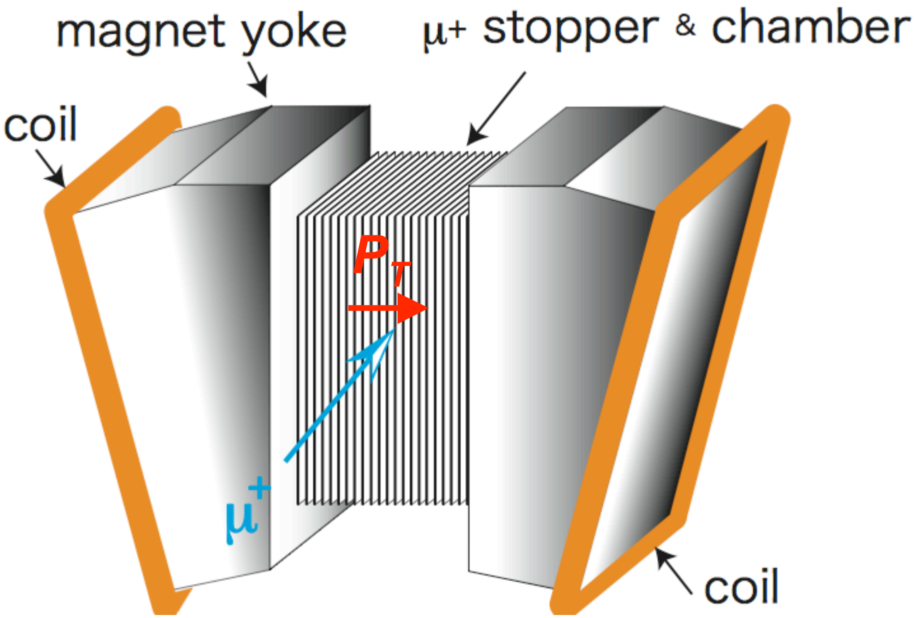


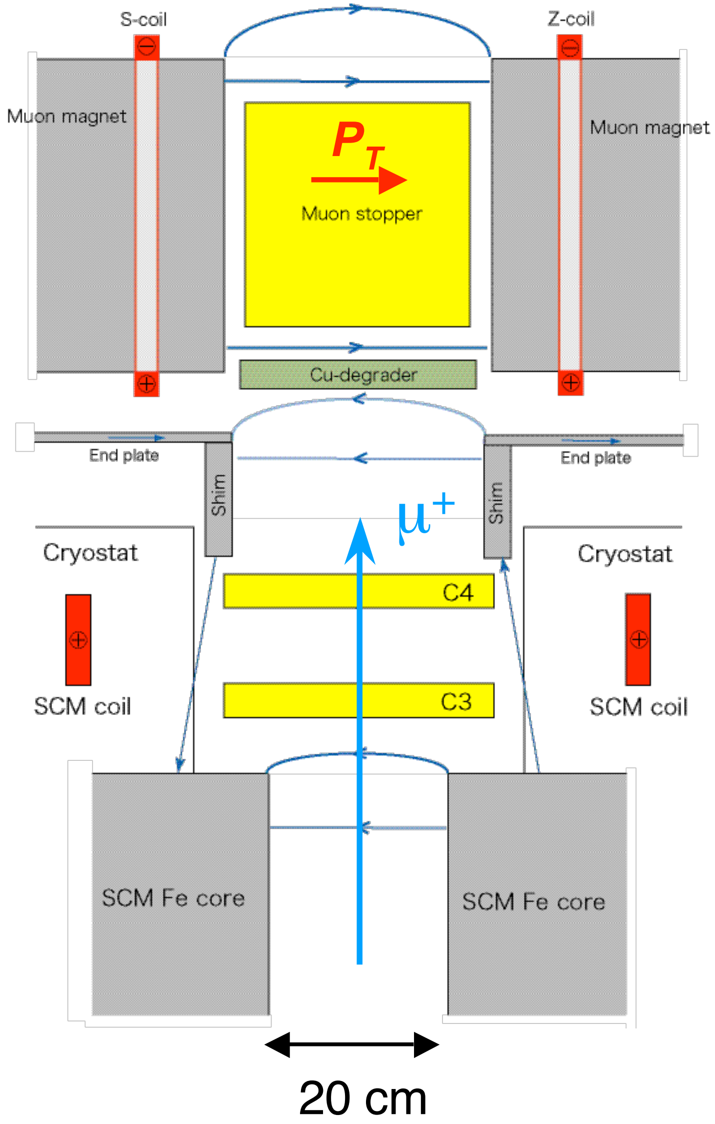
Parallel plate stopper with Gap wire chambers

Number of plates	31
Plate material	Al, Mg or alloy
Plate thickness	~ 2 mm
Plate gap	~ 8 mm
Ave. density	$0.24\ \rho_{Al}$
μ^+ stop efficiency	~ 85%

- Small systematics for *L/R* e^+ asymmetry measurement
- Fit for π^0 *fwd/bwd* measurement
- Simple structure

Muon field magnet



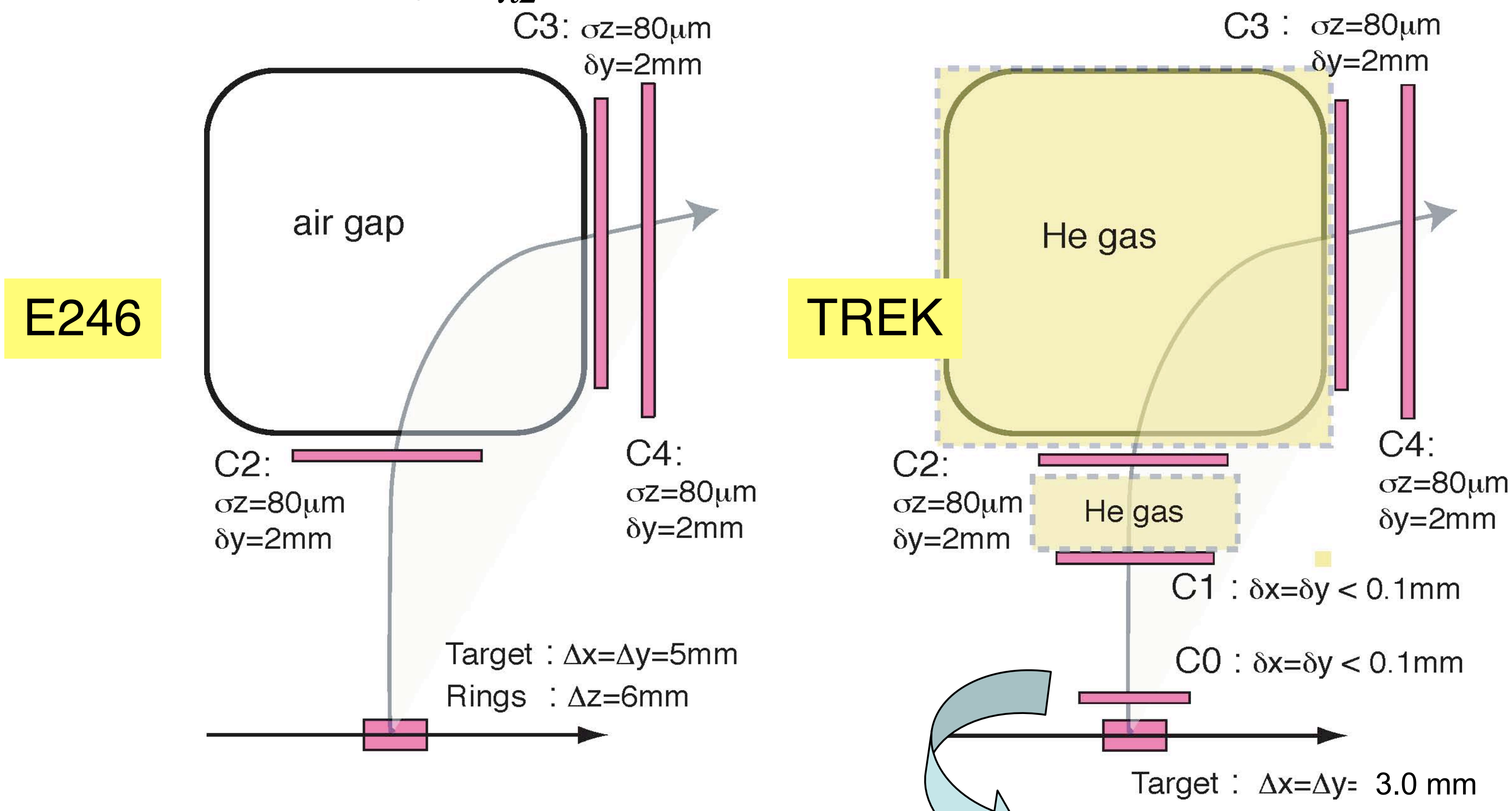


- Uniform field of 0.03 T
- Precise field alignment of 10^{-3}

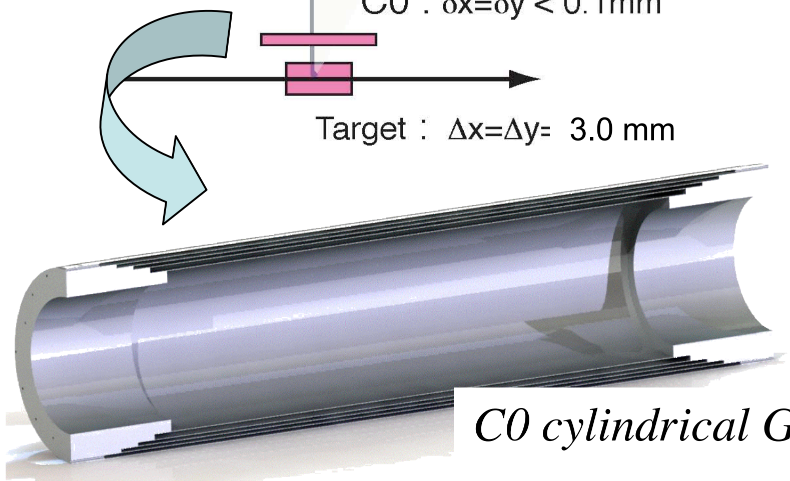
- Gap : 30 cm
- Pole face : 60 cm ×40 cm
- No. of coils : 24 or 12
- Mag. motive force : 3.6×10^3 A Turn/coil
- Total power : 6 kW
- Total weight : ~ 5 ton

Target and tracking

- *Improvement of $K_{\pi 2}$ BG rejection power*

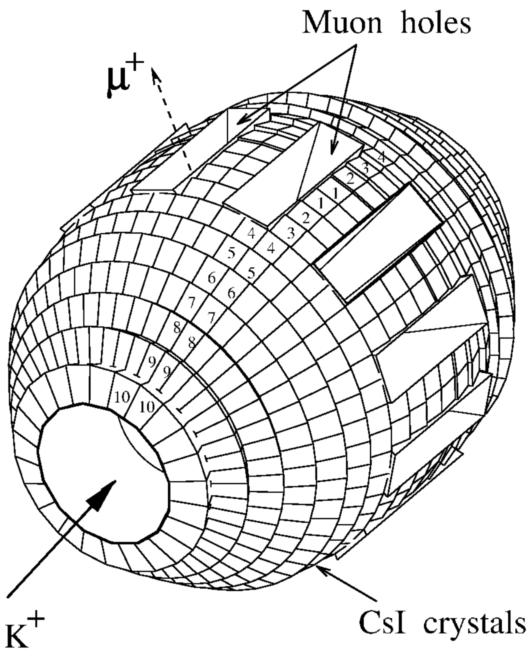


- Addition of C0 and C1 GEM chambers with
  - high position resolution
  - higher rate performance



C0 cylindrical GEM

APD readout of CsI(Tl)



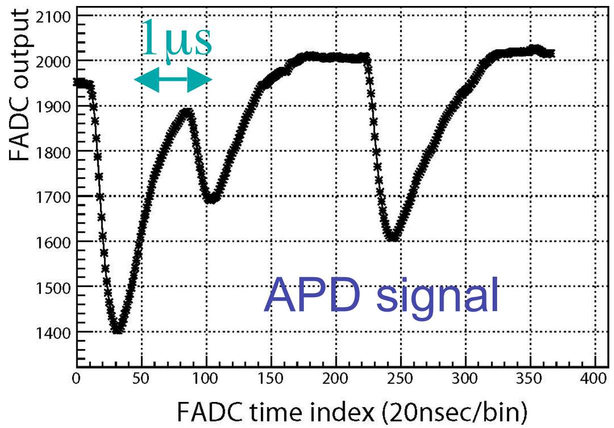
- We want to improve the timing characteristics of CsI(Tl) by replacing PIN diode with APD

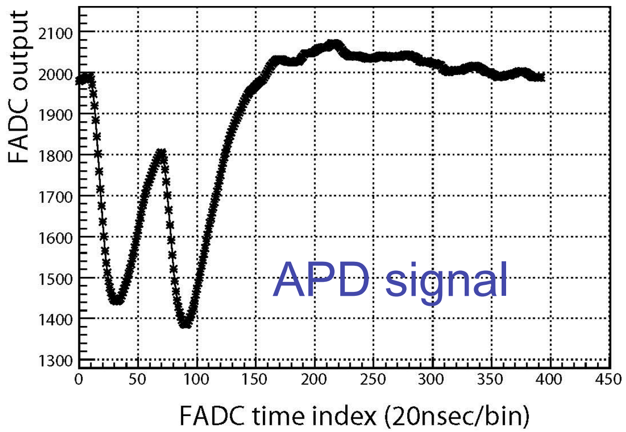
Parameter	E06 APD readout	E246 PIN readout
Electron yield	47,000/MeV	11,000/MeV
Noise level	not yet measured	70 keV
Energy resolution	~12% for C.R.	12% for C.R.
Time rsolution	3 ns for C.R.	12 ns for C.R. (9 ns for all)
Pulse width	$\sim 1.5\ \mu s$	$15\ \mu s$
Rate performance	~ 500 kHz	34 kHz

new requirement :
> 10 times for last two

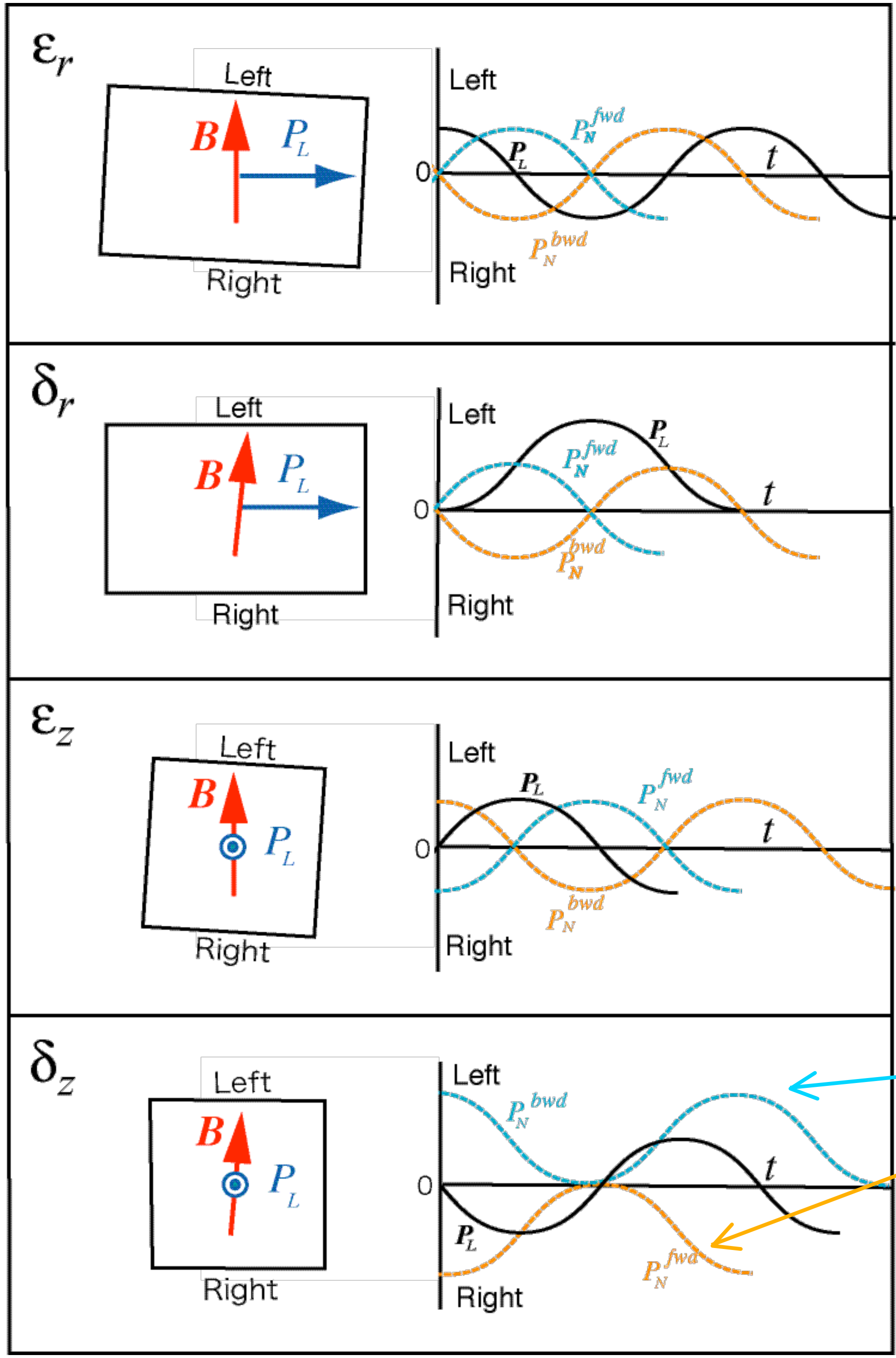
too slow

- One-module test was done to check higher-energy performance and high rate performance using e^+ beam at LNS of Tohoku U.





- Study of pileup characteristics with high-intensity beam
- Typical events



e^+ asymmetry due to polarimeter misalignment

	Rotation about	
Component	r-axis	z-axis
Polarimeter	ε_r	ε_z
Muon field	δ_r	δ_z

fwd - *bwd* : vanishes for ε_r , ε_z , δ_r when t-integrated

fwd - *bwd* : not vanishing for δ_z !

spurious A_T ?

Pol. misalignment analysis using $K_{\mu 3}$

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

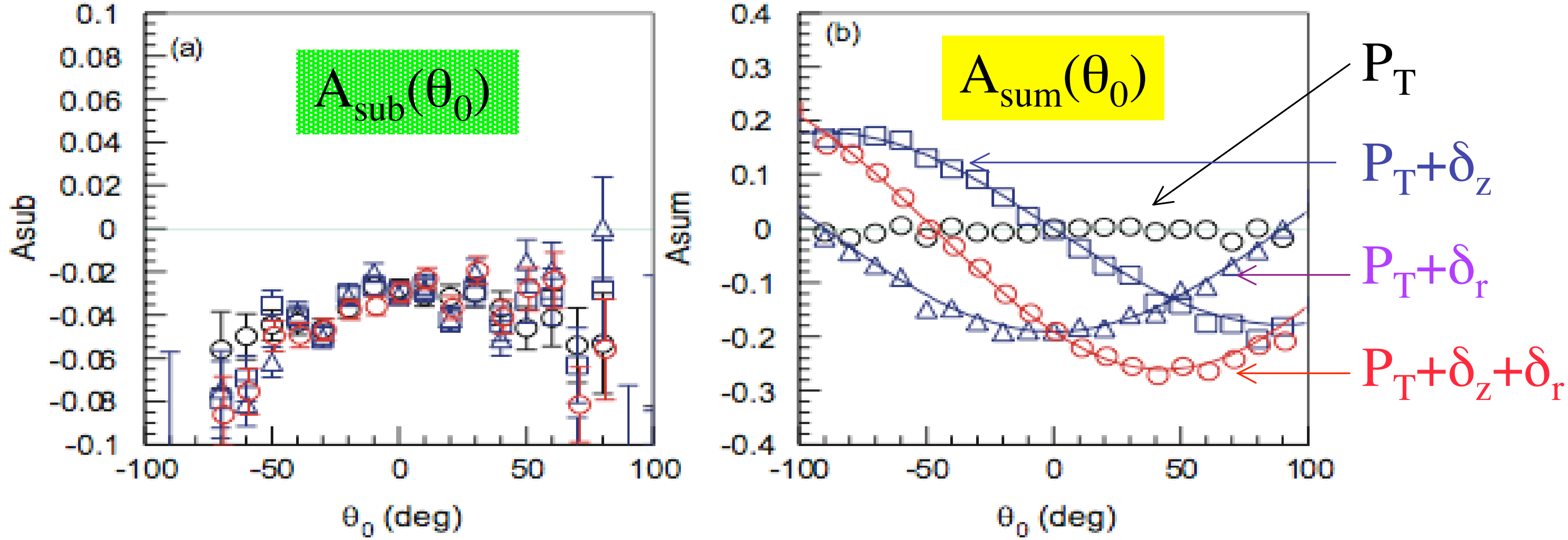
$$\bar{A}(\theta_0) = \int [\alpha_0\{(\epsilon_r - \delta_r)\cos(\omega t - \theta_0) + (\epsilon_z - \delta_z)\sin(\omega t - \theta_0)]dt + \delta_r\cos\theta_0 - \delta_z\sin\theta_0\}$$

Time-integrated asymmetry

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

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

small residual of oscillation



- $\delta P_T < 10^{-4}$ for P_T determination from A_{sub}

Suppression of systematic errors in E06

Old errors

- μ^+ field alignment : $\delta P_T < 10^{-4}$
  - P_T analysis free from misalignment
- μ^+ multiple scattering : $\delta P_T = 0$
  - no longer relevant with the active polarimeter
- decay plane shifts : $\delta P_T \ll 10^{-4}$
  - correction for P_T only with statistical uncertainty

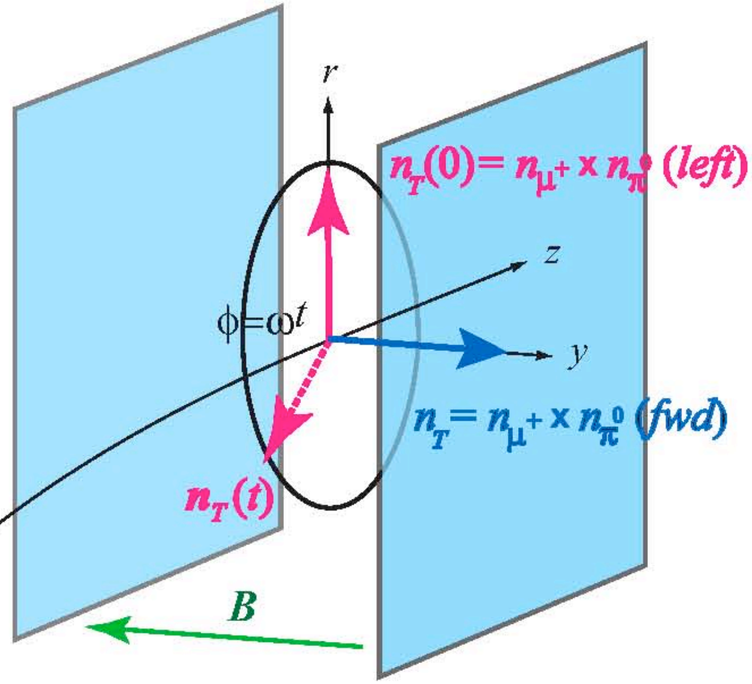
Newcomer

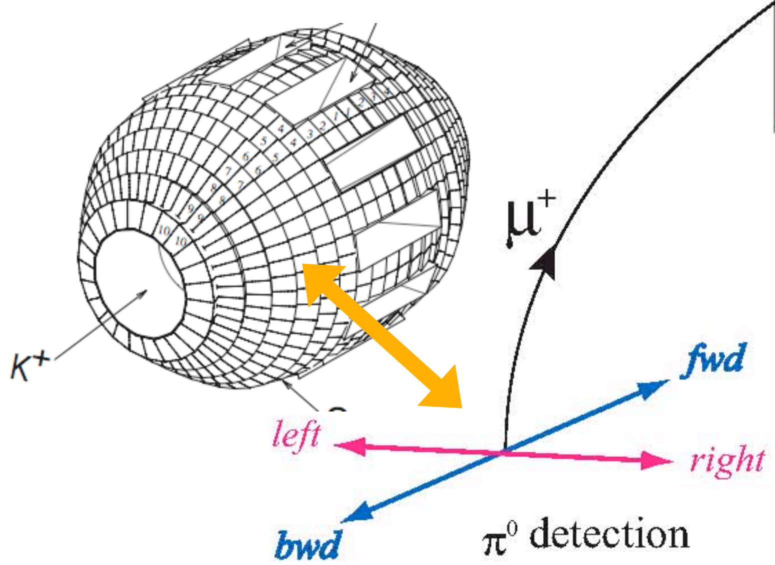
- active polarimeter e^+ analysis : $\delta P_T < 10^{-4}$
  - Perfect *fwd/bwd* cancellation mechanism

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

Positron asymmetry measurement

E246:
- π^0- forward *(fwd)* and backward *(bwd)*
- integral analysis



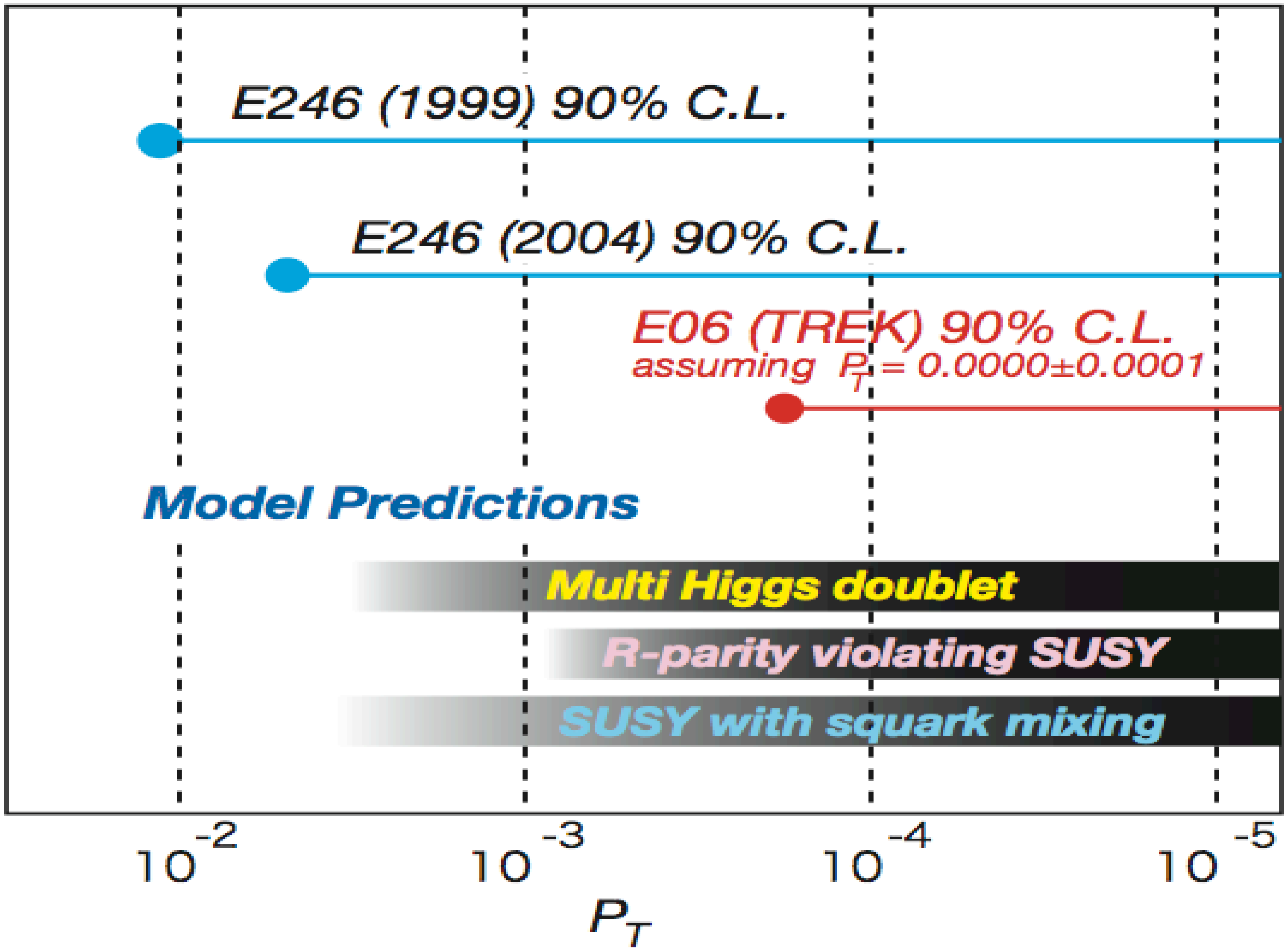


E06:
- conservative estimate now by *fwd/bwd*
- ambitious analysis including *left/right*
- event-by-event analysis: future option

Expected limit of E06 (TREK)

After 1.4 × 10^7 s of running

$\sigma(P_T^{stat}) = 1.0 \times 10^{-4}, \quad \sigma(P_T^{syst}) < 10^{-4}$



Summary

- P_T is a very sensitive probe of CP violation from new physics and an important quantity to study scalar interactions.
- The E246 experiment was performed successfully as a first big international collaboration at KEK-PS.
- Limits were given constraining several model parameters as;

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

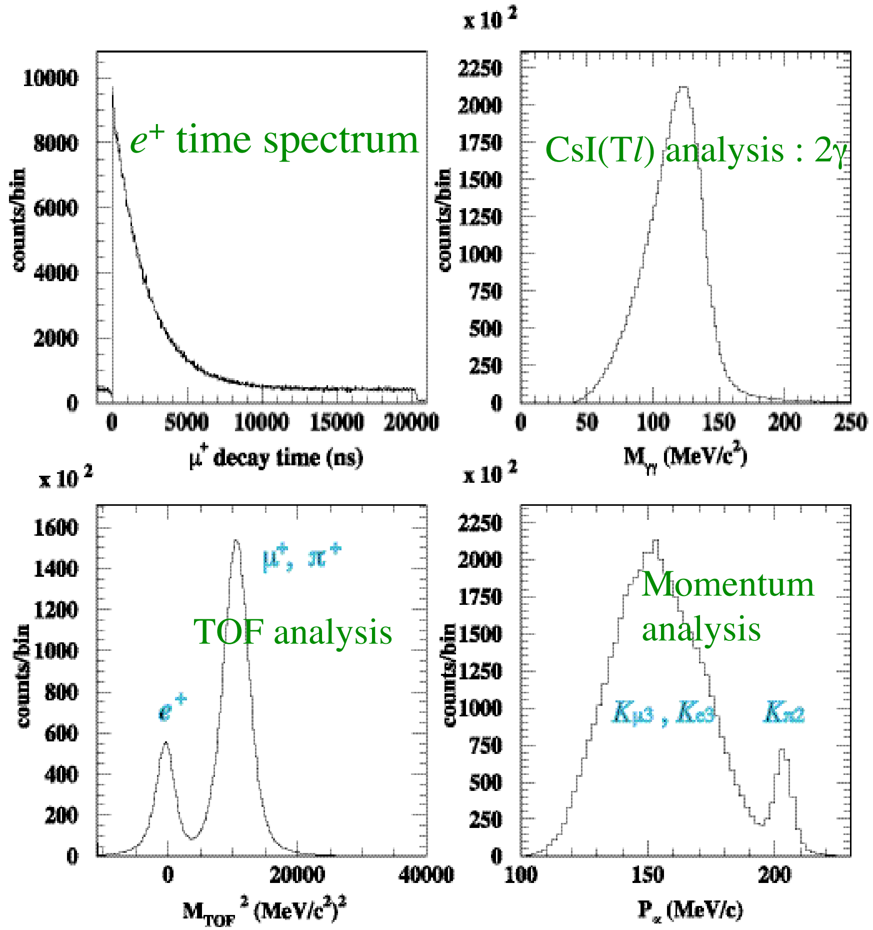
$$\mathrm{Im}\xi = -0.0053 \pm 0.0071 (stat) \pm 0.0036\ (syst)$$
$$(\ |\mathrm{Im}\xi| < 0.016 : 90\%\ C.L.\ )$$

- The J-PARC TREK experiment will further pursue P_T with the sensitivity of 10^{-4}.

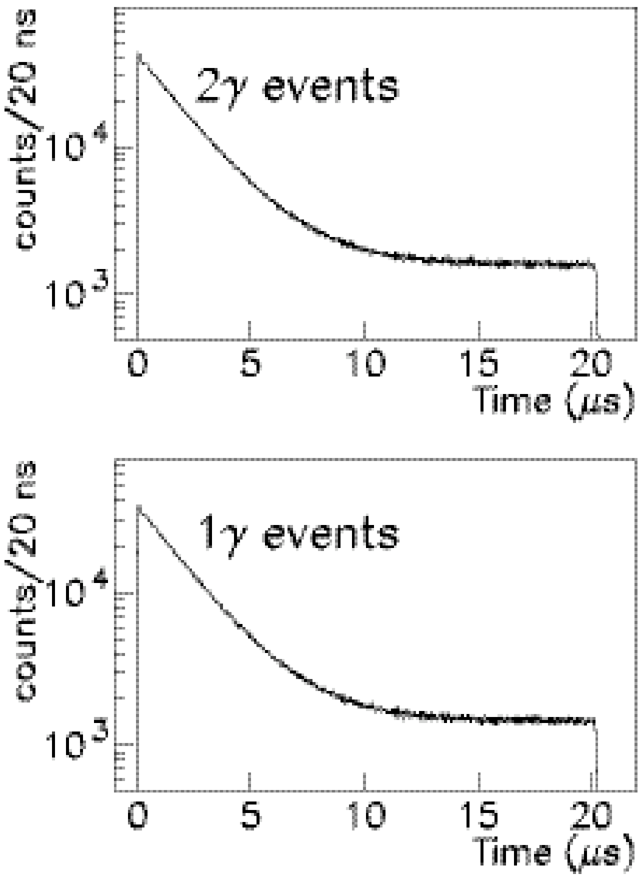
END of SLIDES

Experimental data

$K^+_{\mu3}$ event selection



e^+ time spectra

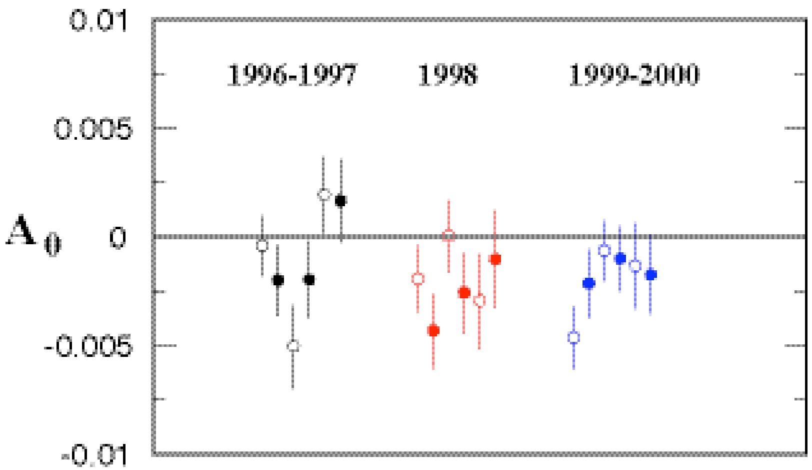


Data quality check

Null asymmetry check

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

total = fwd + bwd

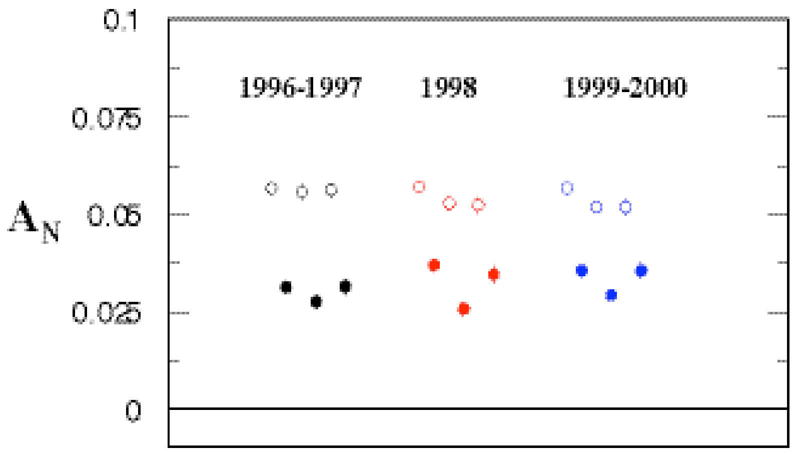


Sensitivity check

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

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

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

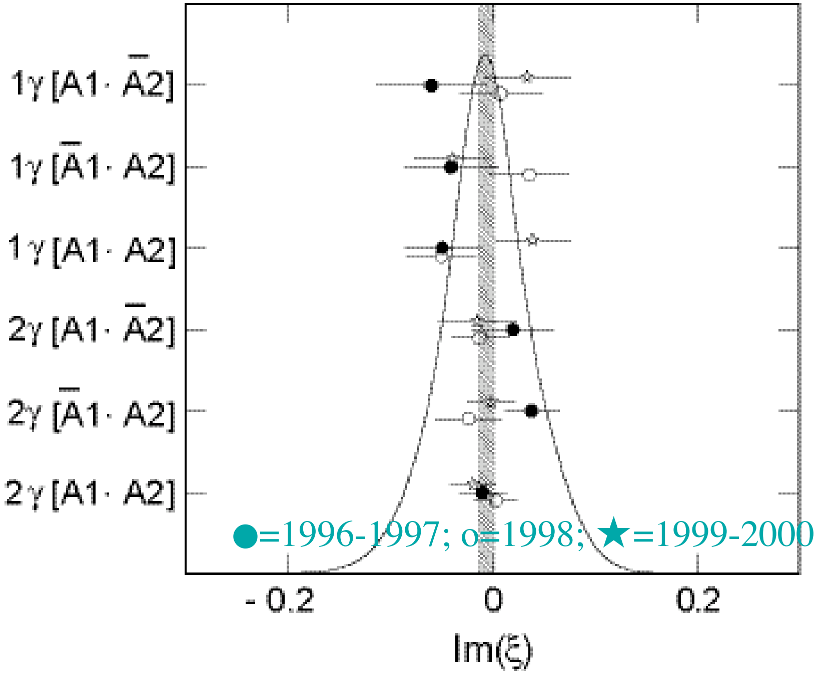


- 6 data sets for each period
- Open circles are 2γ events and dots are 1γ events.

- Null asymmetry is canceled by double ratio (*fwd-bwd*).

Systematics check

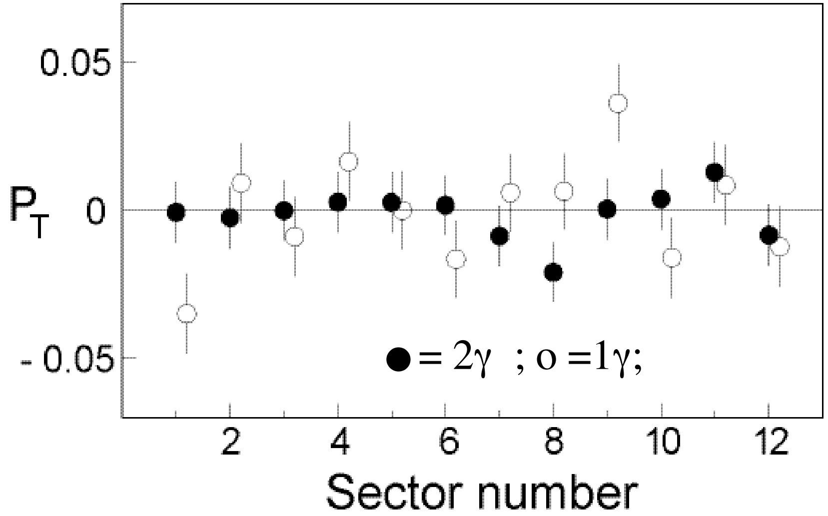
Consistency among data



$\mathrm{Im}\xi = -0.0055 \pm 0.0073$

$(\chi^2/d.o.f. = 0.78)$

Sector dependence



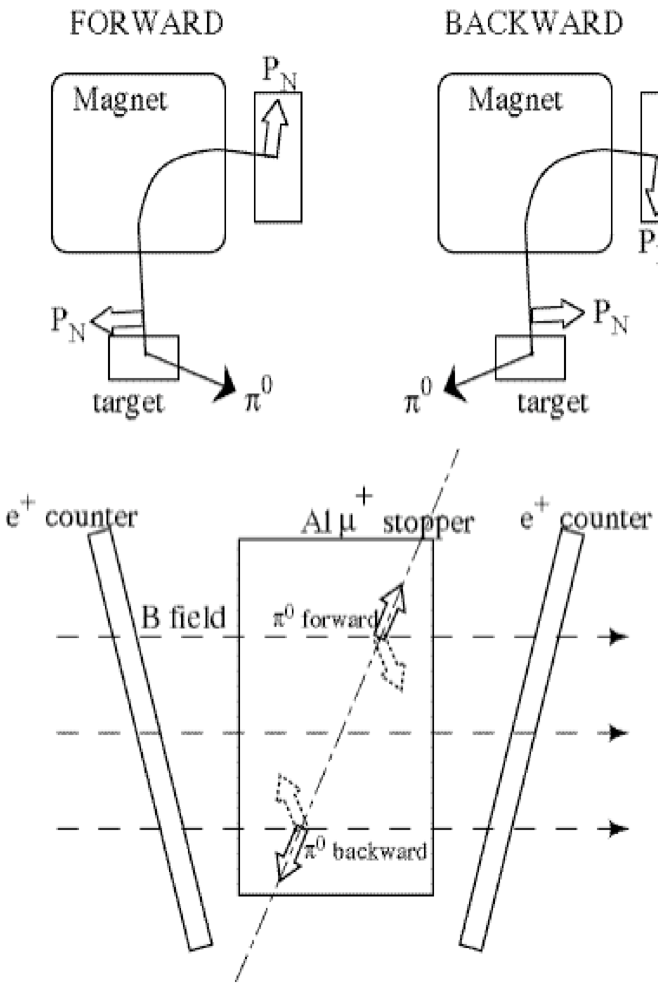
Decay plane rotation

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

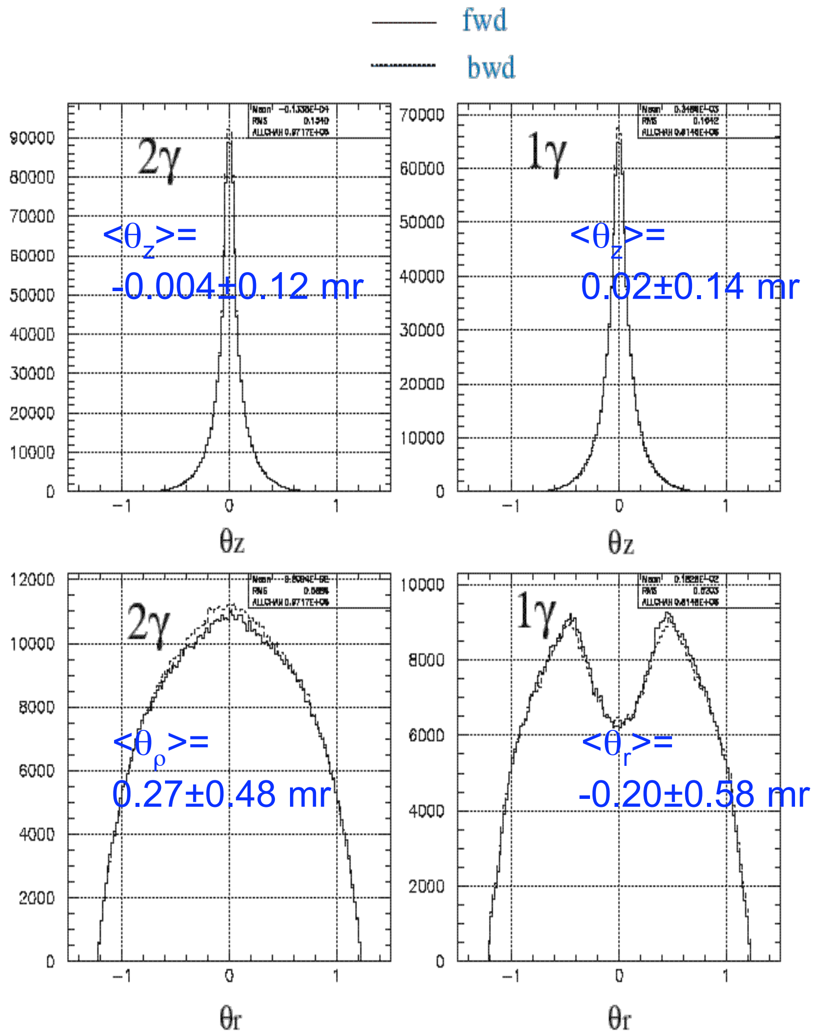
$$|\theta_z(fwd) + \theta_z(bwd)| \leq 2.6 \times 10^{-4} \text{ rad}$$

$$\delta P_T \sim 0.5\, \Delta\theta$$

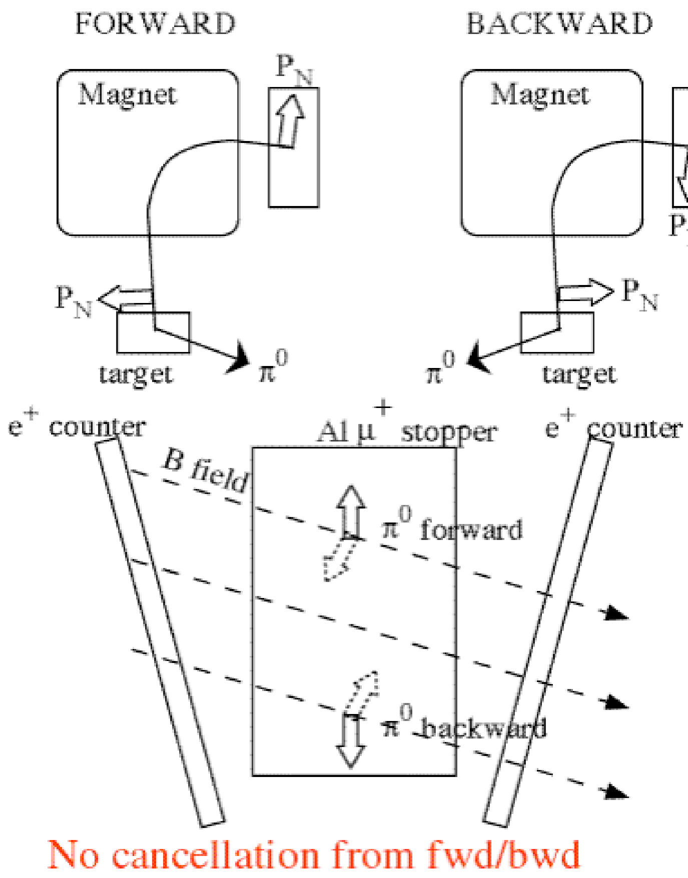
Decay plane rotation

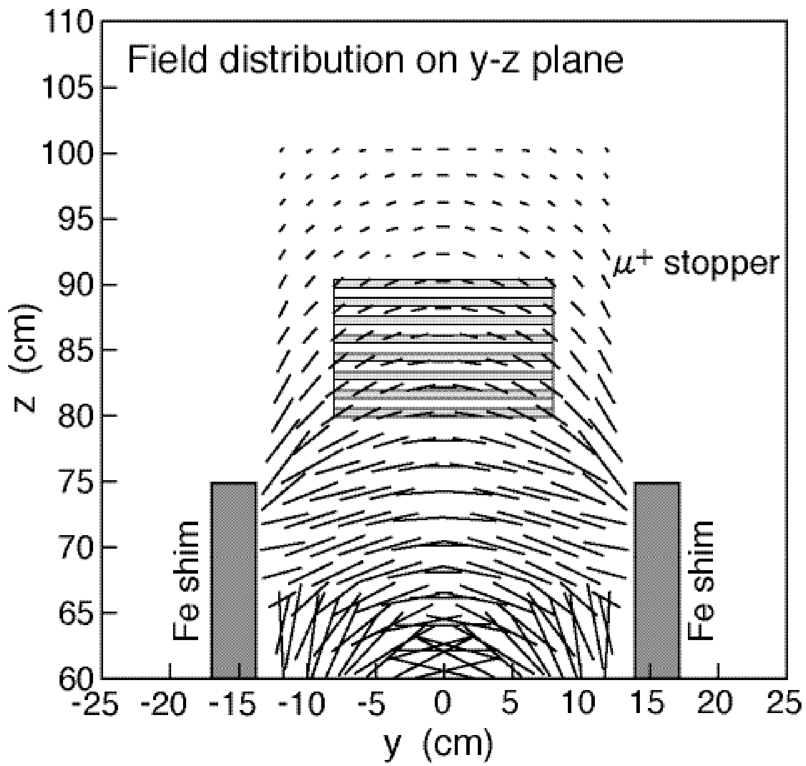


No cancellation from fwd/bwd



B field rotation



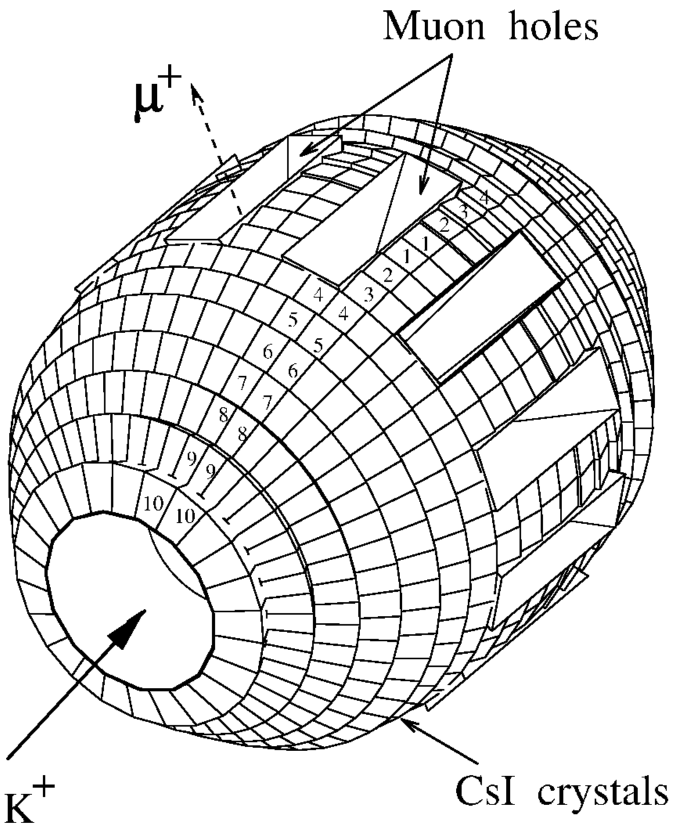


- Field Measurement
  T. Ikeda, *et al.*, Nucl. Instr. and Meth. in Phys. Res. A 401 (1997) 243-262

- δ_z = 1.3 mrad $\rightarrow \delta P_T(\delta_z) = 5 \times 10^{-4}$

$$\delta P_T \sim 0.4\ \delta_z$$

CsI(Tl) photon detector



Segmentation	$\Delta\theta = \Delta\phi = 7.5^{o}$
Number of crystals	768
Length of crystals	25 cm (13.5 X_0)
Inner radius	20 cm
Outer radius	50 cm
Solid angle	~75%of 4π
Readout	PIN diode
Light yield	11000 p.e./MeV
Equiv. noise level	65 keV

D.V.Dementyev et al. Nucl. Instr. Method A440 (2000) 51

$K_{\mu 3}$ event rate and sensitivity

- Standard event selection conditions as in E246 :

1. $65 < M_{\gamma\gamma} < 185$ MeV/c^2
2. $3500 < M^2_{TOF} < 18{,}000$ (MeV/c^2)^2
3. $p_{\mu^+} < 185$ MeV/c
4. μ^+ incident into the polarimeter
5. $\theta_{\mu^+\pi^0} < 160^{\circ}$
6. $M^2_{missing} > -15{,}000$ (MeV/c^2)^2

⇒ Detector acceptance $\Omega(K_{\mu 3}) = 1.14 \times 10^{-2}$

$$N(K_{\mu 3}) = N(K^+) \cdot \varepsilon_{stop} \cdot Br(K_{\mu 3}) \cdot \Omega(K_{\mu 3})$$
$$= 3.3 \times 10^9 \text{ (total E06 good events)}$$

- MC calculation for 10^8 events and using $P_T = A_T / 0.258$:

Standard *fwd* / *bwd* analysis

$$\delta P_T = 6.9 / \sqrt{N(K_{\mu 3})}$$
$$= 1.2 \times 10^{-4}$$

Systematic error (1) associated with misalignment analysis

- P_T can be deduced regardless of the existence of the polarimeter misalignments, ε_r, ε_z, δ_r and δ_z.
- But, how much is the systematic error induced in this misalignment analysis?

- Simulation calculation with:

$P_T = 0$ and $\delta_z = \delta_r = 5^{\circ} = 87$ mr
==> $\delta P_T = (2\pm7)\times10^{-4}$ for 10^8 events

- Essentially statistical error of P_T
- No significant effect beyond the statistical error
- In reality, $\delta_z \sim \delta_r \sim 1$ mr :

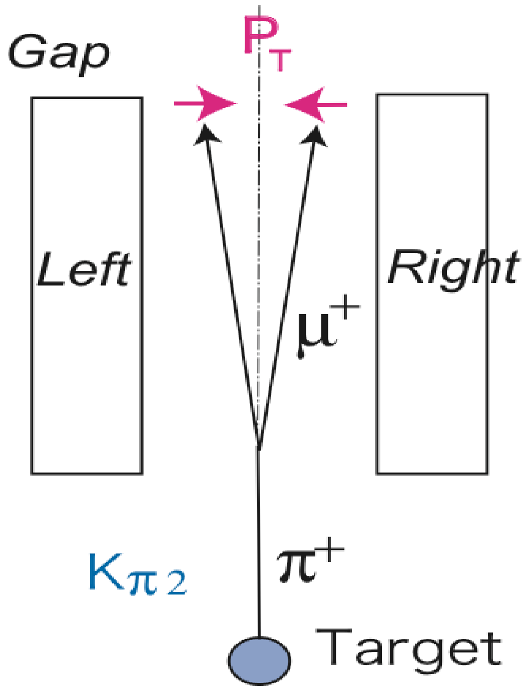
δP_T^{syst} should be $< 10^{-4}$

Systematic error (2) due to $K_{\pi 2}$ BG

- Dangerous $\pi^+ \to \mu^+\nu$ background with a P_T component
- Substantial reduction due to the addition of the C0 chamber

	Momentum resolutions			Consistency		
	ΔP_{gap}	ΔP_{loss}	ΔP_{cor}	ΔK_{diff}	A_{diff}	$K_{\pi 2}$-dif BG
E246	1.0 MeV/c	2.5 MeV/c	2.5 MeV/c	20 mm	~2.0°	2.4%
E06 (TREK)	0.5 MeV/c	0.85 MeV/c	1.0 MeV/c	0.6 mm	0.3°	0.2%

MC simulation



- Cancellation in gap integration
  ==> averaging to < 1/10 (<0.02%)
- π^0 - *fwd/bwd* cancellation
  ==> suppression to < 1/10 (<0.002%)

$$\delta P_T < 10^{-4}$$

Systematic error (3) associated with decay plane rotation correction

- Two rotation angles of θ_z and θ_r
- Relation: $\delta P_T \sim 0.5 <\theta>$ due to P_N and P_L admixture

  $<\theta_r>$ is *fwd/bwd* cancelling, but

  $<\theta_z>$ is not *fwd/bwd* cancelling.

- P_T will be corrected for $<\theta_z>$ and $<\theta_r>$
- Statistical error of the correction

$$\delta <\theta_z> = \sigma(\theta_z) / \sqrt{N_{total}}$$

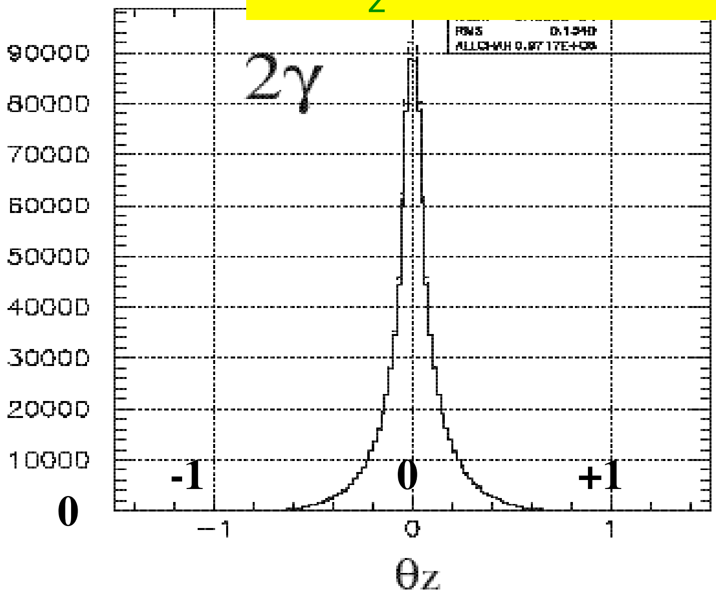
$$\delta P_T(<\theta_z>) \ll \delta P_T^{stat} \sim 10^{-4}$$

$$\delta P_T(<\theta_z>) \ll 10^{-4}$$

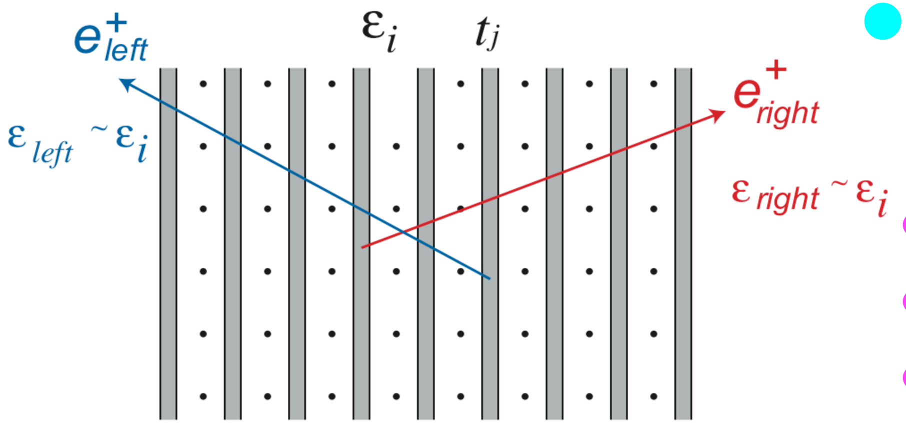
$$\delta P_T(<\theta_r>) \sim \delta P_T^{stat} \,\&\, fwd/bwd \ll 10^{-4}$$

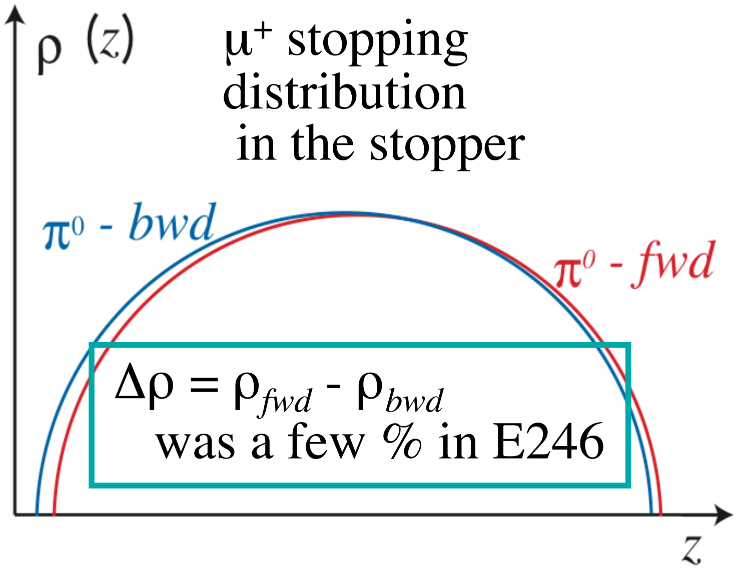
θ_z distribution in E246

$<\theta_z>= -0.004 \pm 0.12$ mr



Systematic errors (4) associated with positron analysis





- Systematics in the chamber measurement is *left-right* cancelling :
  - cell inefficiency
  - plate non-uniform thickness
  - *etc.*
- further cancellation by *fwd-bwd* up to small $\Delta\rho = \rho_{fwd} - \rho_{bwd}$
- symmetrization of ρ with bias

  $\rho^{fwd}(r,y,z) = \rho^{bwd}(r,y,z)$

  $P_T^{fwd} = P_T + \delta P_T'$

  $P_T^{bwd} = -P_T + \delta P_T''$ *No problem*

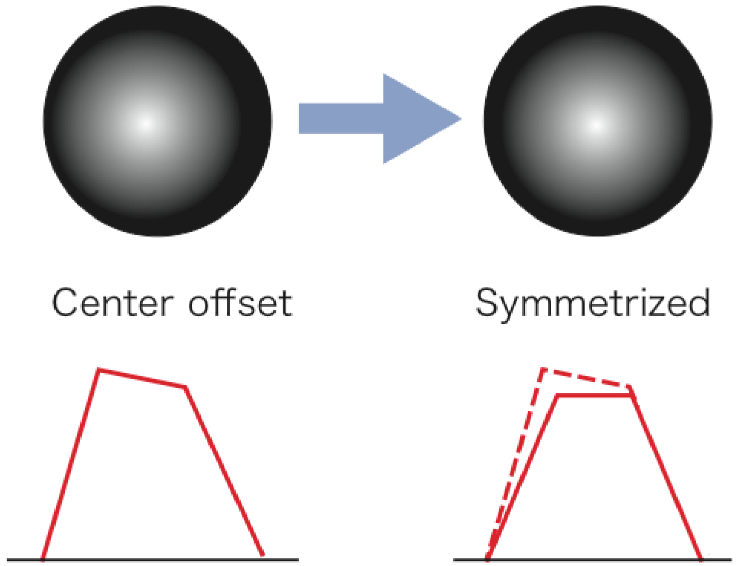
- *Cancellation power will be calculated using data.*

δP_T should be $< 10^{-4}$

Data symmetrization

- Suppression of systematic errors -

- K^+ stopping distribution
  - non-bias cut
  - small loss of events



- μ^+ stopping distributions

$$\rho^{fwd}(r,y,z) \neq \rho^{bwd}(r,y,z)$$
$$\Downarrow$$
$$\rho^{fwd}(r,y,z) = \rho^{bwd}(r,y,z)$$

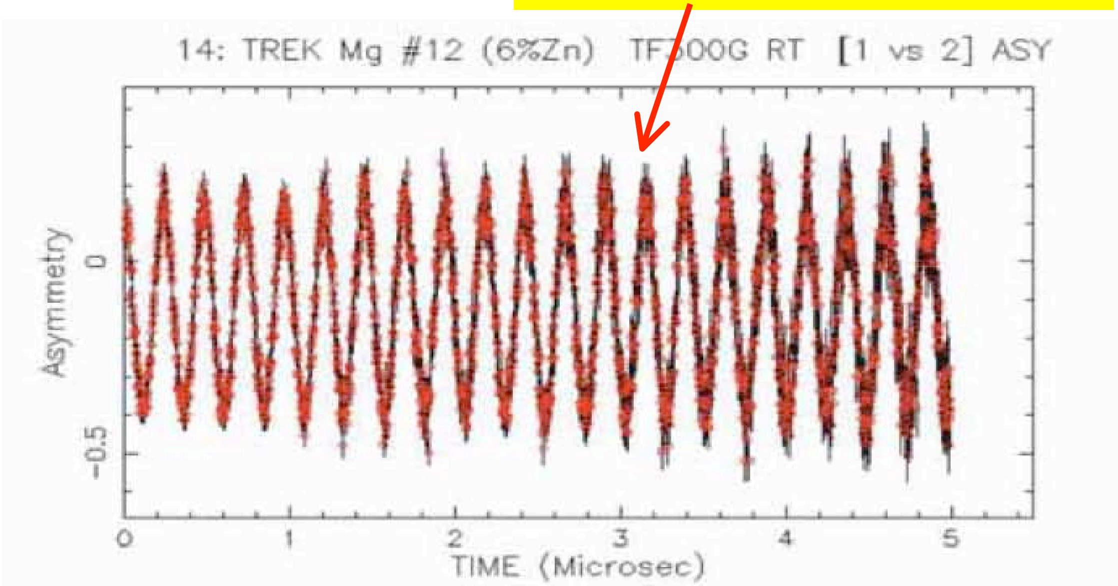
$$P_T^{fwd} = P_T + \delta P_T'$$
$$P_T^{bwd} = -P_T + \delta P_T''$$

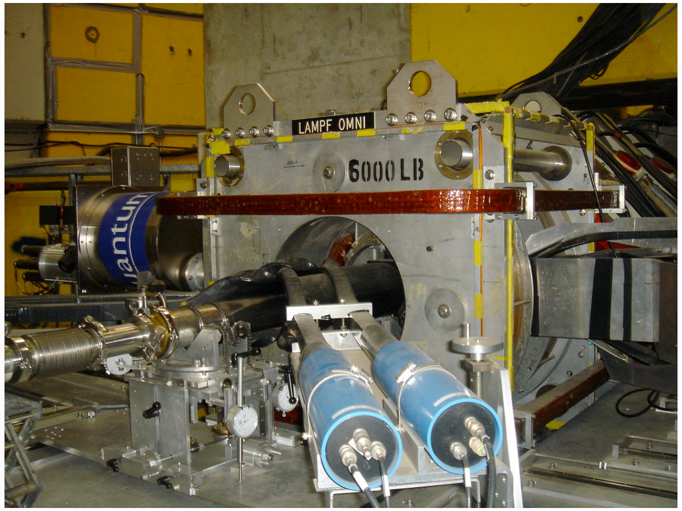
eliminates systematics in the polarimeter

Stopper μSR study (Canada, Japan)

- Muon spin behavior was studied for candidate stopper materials

Typical TF precession pattern





- TRIUMF surface muon beam with full polarization
- E1120 experiment to study μSR in Al and Mg alloys
- Transverse field (*TF*) and longitudinal field (*LF*) relaxation rates were measured with a 0.03 T field.
- Several candidate stopper materials were confirmed.

Al alloys: A5052, A6063, Mg alloys: AZ31, ZK60, Z6, AM60, AZ91