Search for T violation in $K^+ \rightarrow \pi^0 \mu^+ \nu$ Decays

J. Imazato
IPNS, KEK

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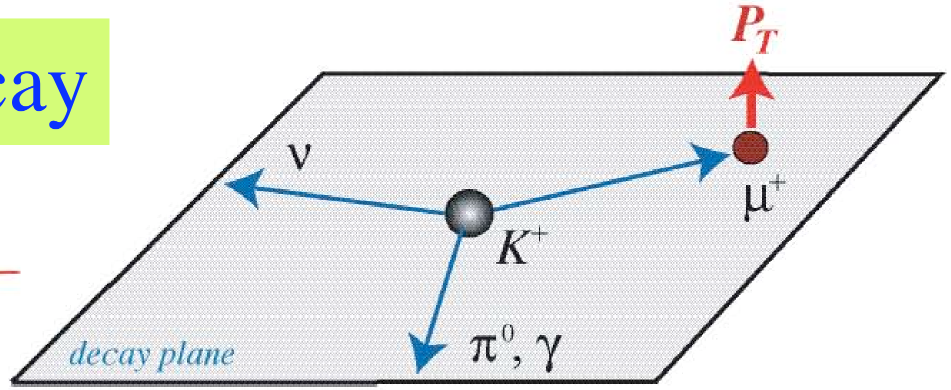
- Transverse muon polarization P_T
- KEK-PS E246 experiment
- J-PARC E06 experiment

Transverse muon polarization

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

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

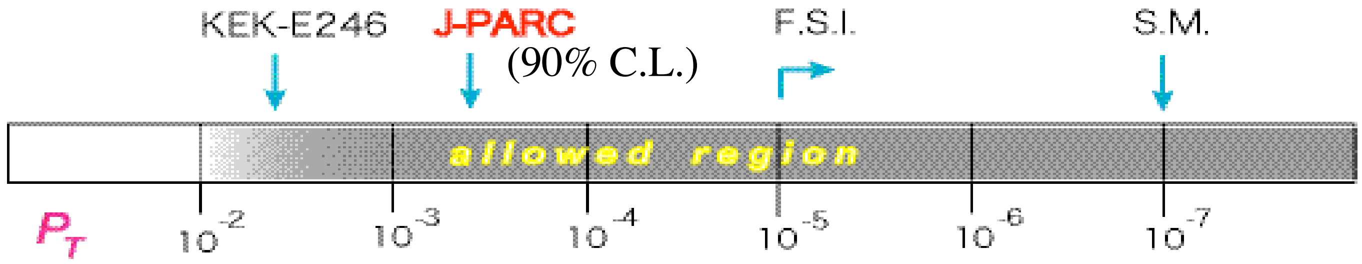


- P_T is T-odd and spurious effects from final state interaction are small. Non-zero P_T is a signature of T violation.
- Very clear channel to search for T violation. Long history of theoretical and experimental studies. (J.J. Sakurai, 1957)
- Powerful tool to study CP violation due to CTP theorem.
- One of the typical experiments of high-precision frontier.

  cf. neutron EDM, g_μ-2

Theoretical aspects

- Standard Model contribution to P_T :
  - Only from vertex radiative corrections and $P_T(SM) < 10^{-7}$
- Spurious effects from final state interactions (FSI)
  - Recent elaborate calculation : $P_T(FSI) < 10^{-5}$



- There is a large window for new physics in the region of

$$P_T = 10^{-3} \sim 10^{-5}$$

- There are theoretical models which allow sizeable P_T without conflicting with other experimental constraints.

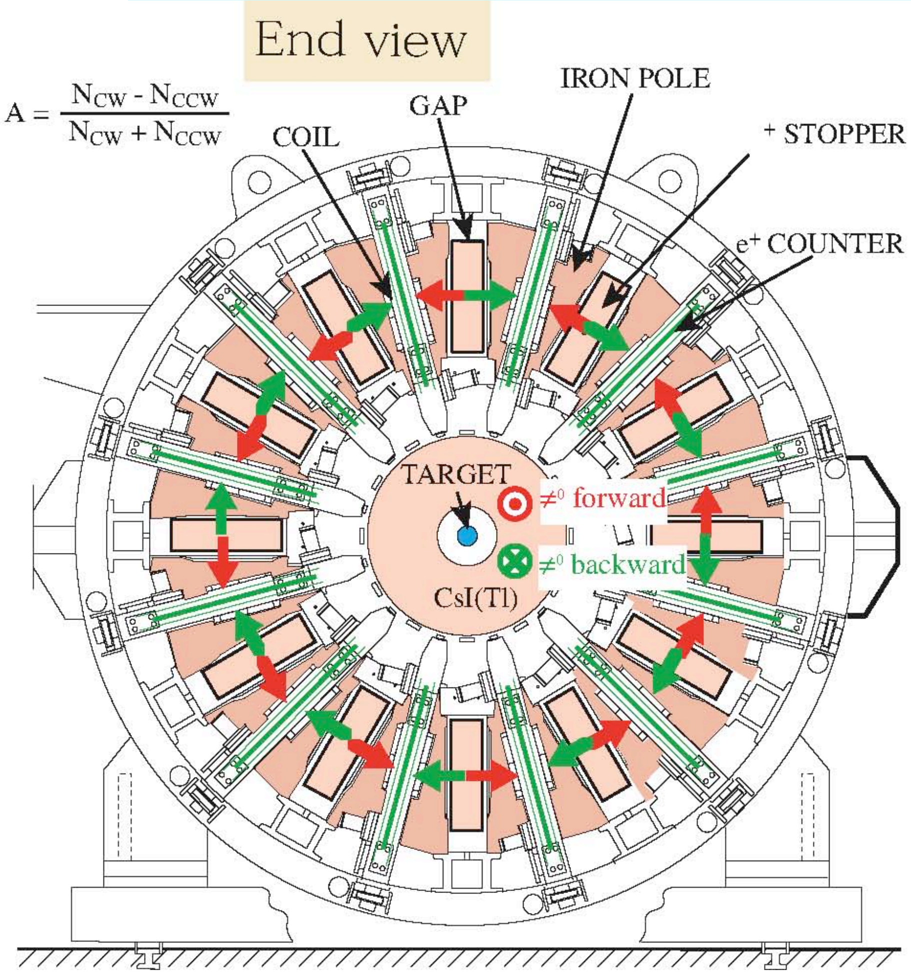
Model descriptions of P_T

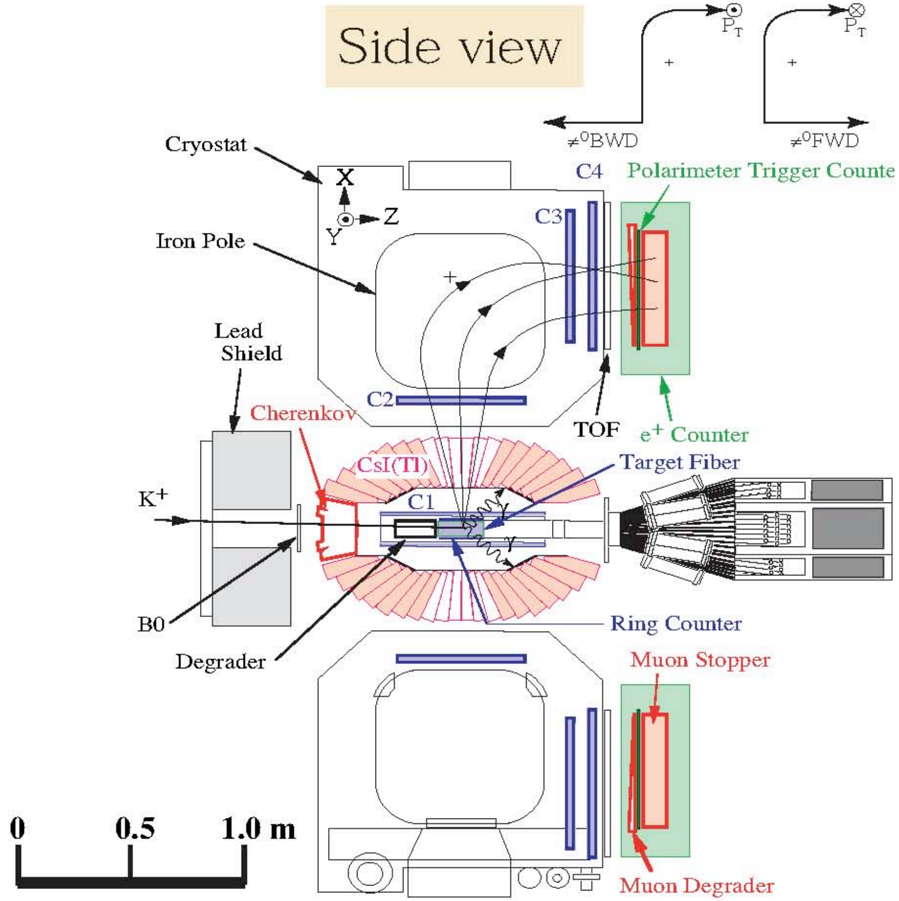
$$P_T = \mathrm{Im}\xi \cdot \frac{m_\mu}{m_K} \frac{|\vec{p}_\mu|}{[E_\mu + |\vec{p}_\mu| \vec{n}_\mu \cdot \vec{n}_\nu - m_\mu^2/m_K]} \qquad \mathrm{Im}\xi = \frac{(m_K^2 - m_\pi^2)\mathrm{Im}G_S^*}{\sqrt{2}(m_s - m_u)m_\mu G_F \sin\theta_C}$$

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
  - $B\to\tau\nu X$ constraints also $\mathrm{Im}(\gamma_1\alpha_1^*)$ but weaker ($<1900\,(m_H/\mathrm{GeV})^2$)
  - N-EDM and $b\to s\gamma$ 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
  - $\mathrm{Im}\xi^l \sim \mathrm{Im}\,[\lambda_{2i2}(\lambda_{i12})^*]$, $\qquad \mathrm{Im}\xi^d \sim \mathrm{Im}\,[\lambda'_{21k}(\lambda'_{22k})^*]$
  - No stringent limits from other modes

KEK-PS E246 experiment



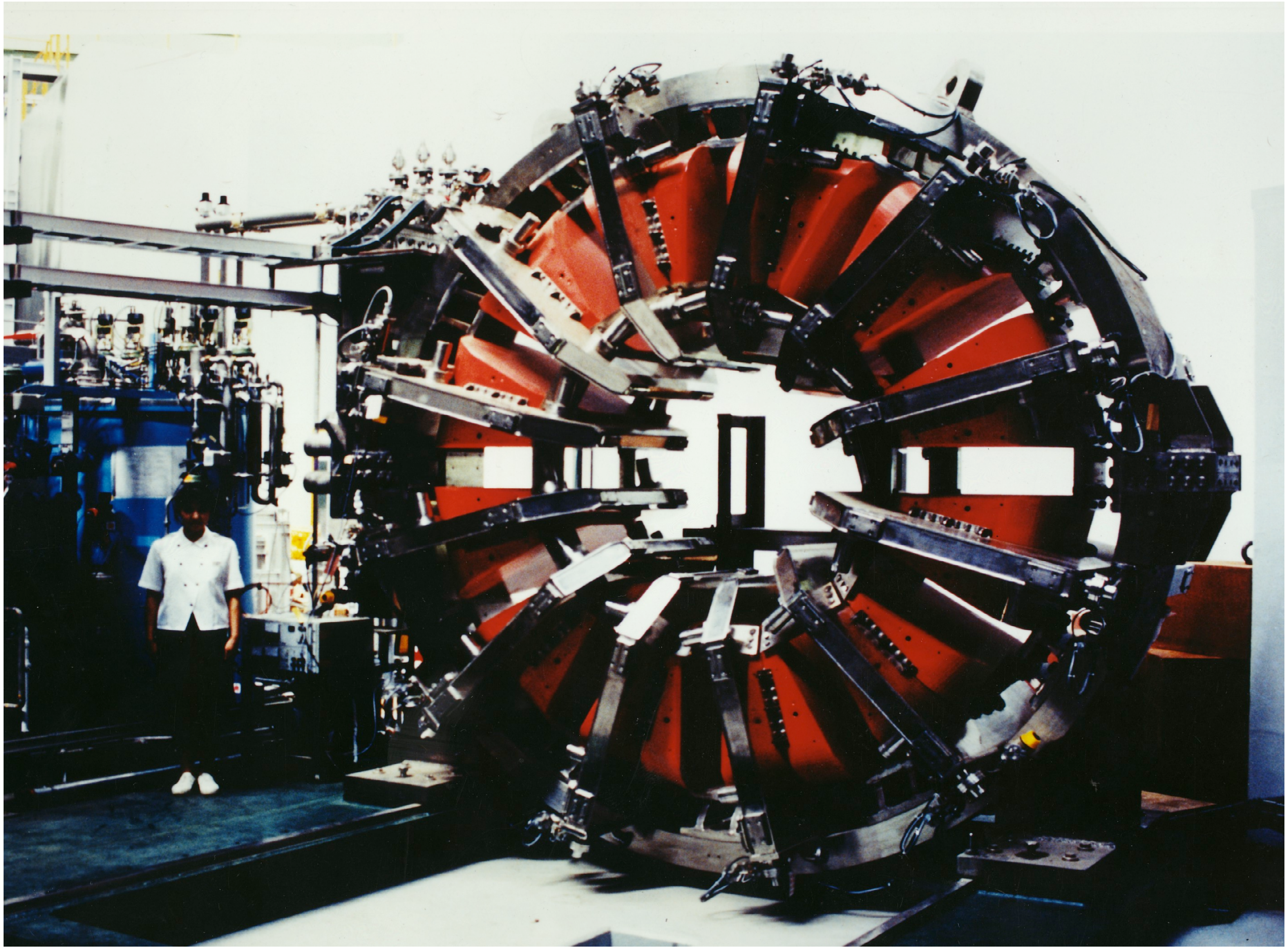


- Stopped K^+ decay at K5
- SC Toroidal spectrometer

- Measurement of e^+ emission *cw/ccw* asymmetry when π^0 in *fwd/bwd* directions

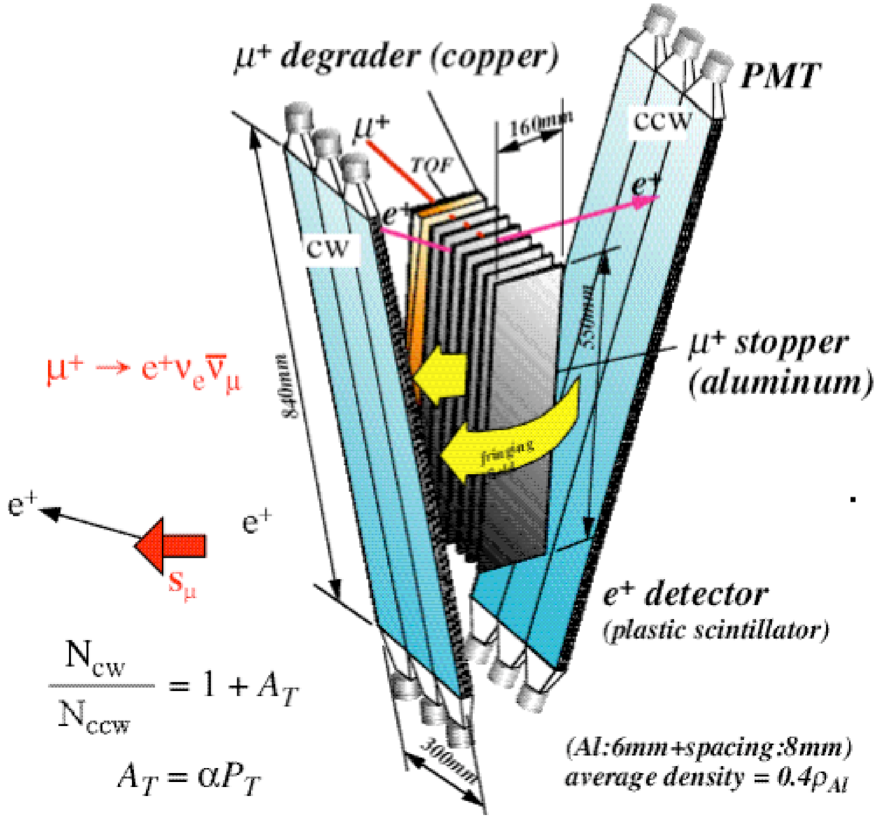
Data taking 1996-2000 ; Final result **Phys. Rev. D73, 072005 (2006)**

Superconducting toroidal magnet

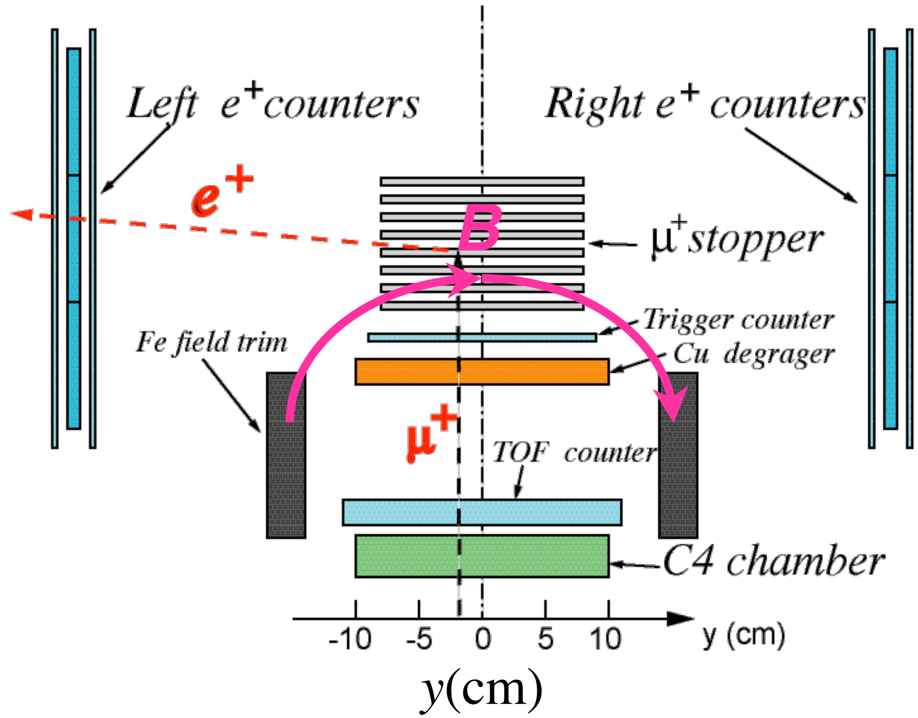


E246 muon polarimeter

One-sector view



Cross section



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

simple analysis and systematics

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

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

E246 result (2004)

Double ratio experiment

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

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

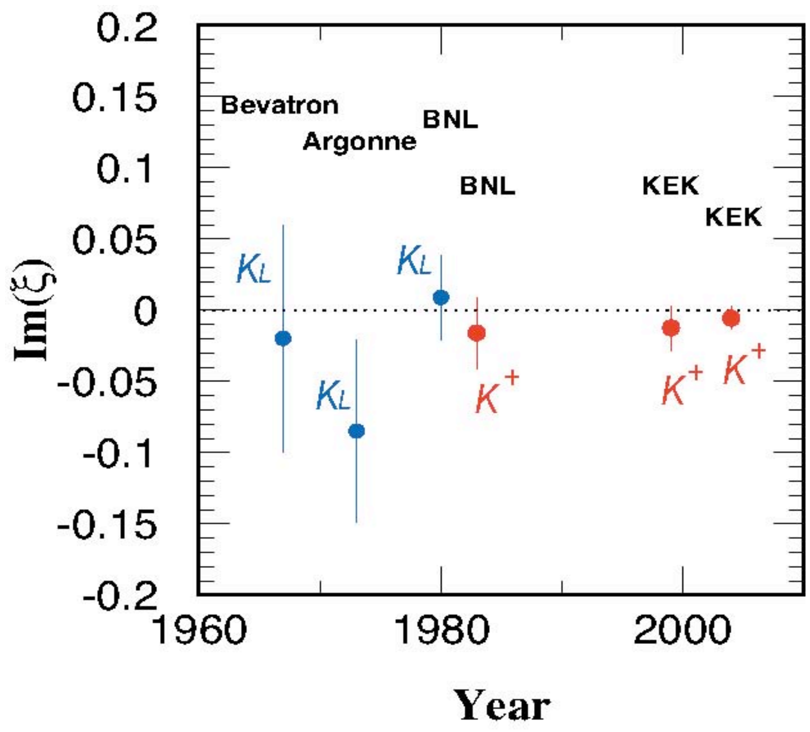
$$P_T = A_T / \{\alpha \langle\cos\theta_T\rangle\}$$

α : analyzing power

$\langle\cos\theta_T\rangle$: attenuation factor

$$\mathrm{Im}\xi = P_T / KF$$

KF : kinematic factor



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

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

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

($|\mathrm{Im}\xi| < 0.016$: 90% C.L.)

Statistical error dominant

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 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**	

$\delta P_T^{\,syst} \sim 10^{-3}$

- Systematic error suppression is essential for a high-precision experiment
- Cancellation by Σ^{12} and/or *fwd/bwd* scheme
  - Muon field alignment
  - Detector misalignment
  - Decay plane asymmetry
- Suppressed to < 10^{-3} by actual position/field measurements,

J-PARC experiment E06

- J-PARC : Proton Accelerator Research Complex in Japan *now under construction for completion in 2008*

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

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

  1) precise calibration of misalignments using data
  2) correction of systematic effects

- "Stage-1 Approval" was given in the 1st PAC meeting

Upgrade of the detector

E246 detector is upgraded for E06

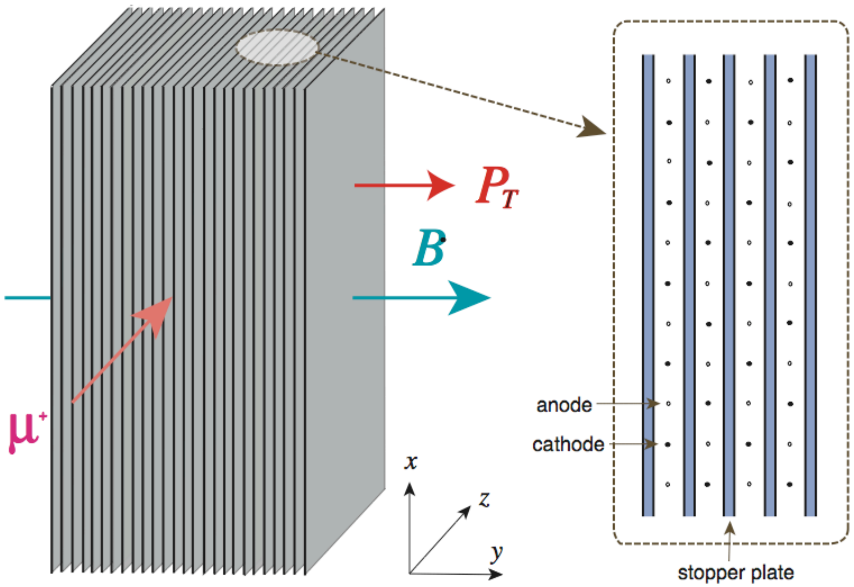
- *possible to achieve the level of* $P_T \sim 10^{-4}$
- *well known systematics*

- Muon polarimeter : passive → active
- Muon magnetic field : toroid → muon field magnet
- Target : smaller and finer segmentation
- Charged particle tracking : addition of two chambers
- CsI(Tl) readout : PIN diode → APD
- Electronics and data taking : TKO → KEK-VME & COPPER

- New analysis scheme

Active muon polarimeter

- 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

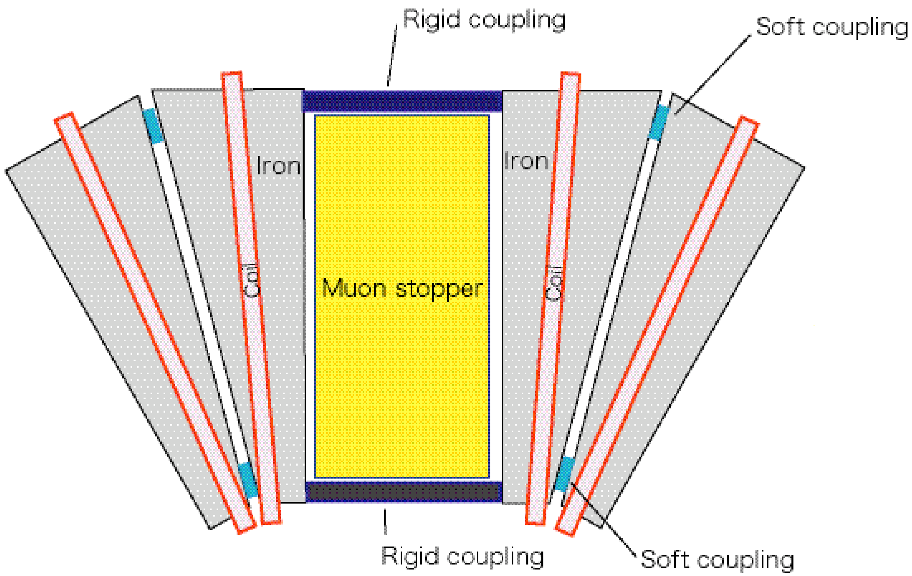


Parallel plate stopper with Gap drift chambers

Number of plates	33
Plate material	Al, Mg or alloy
Plate thickness	~ 2 mm
Plate gap	~ 8 mm
Ave. density	$0.24\ \rho_{Al}$
μ^+ stop efficiency	~ 85%

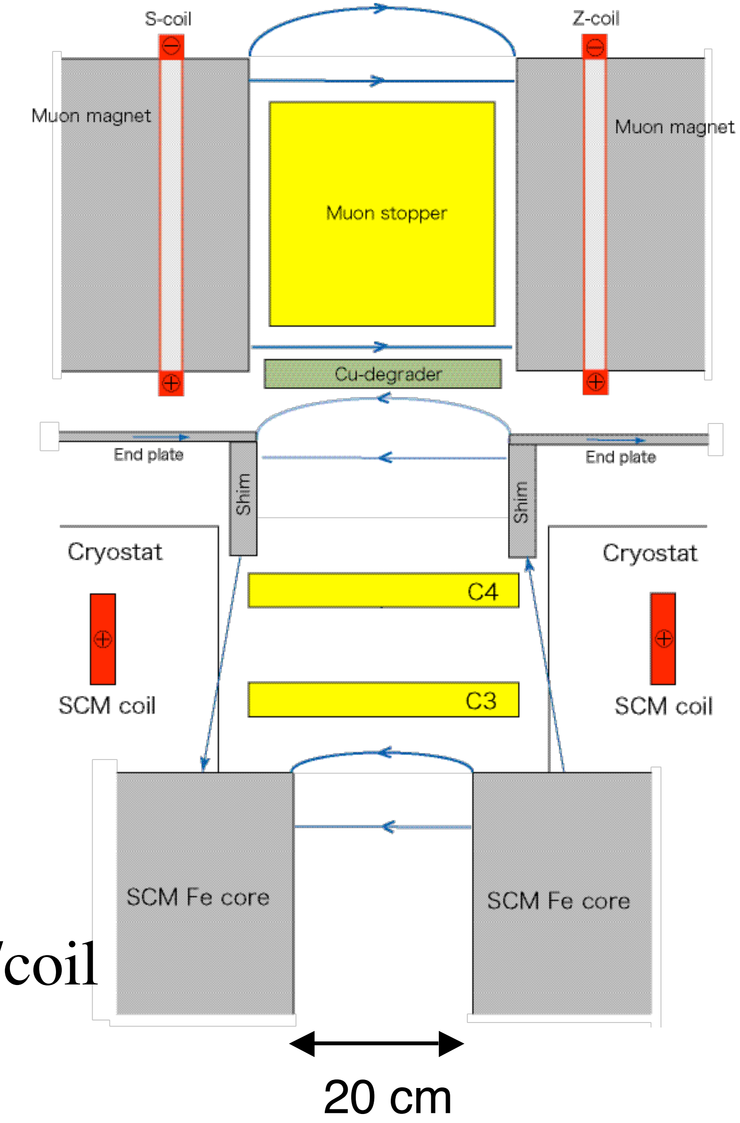
- Small systematics for *L/R* e^+ asymmetry measurement
- Fit for π^0 *fwd/bwd* measurement
- Simple structure

Muon field magnet



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

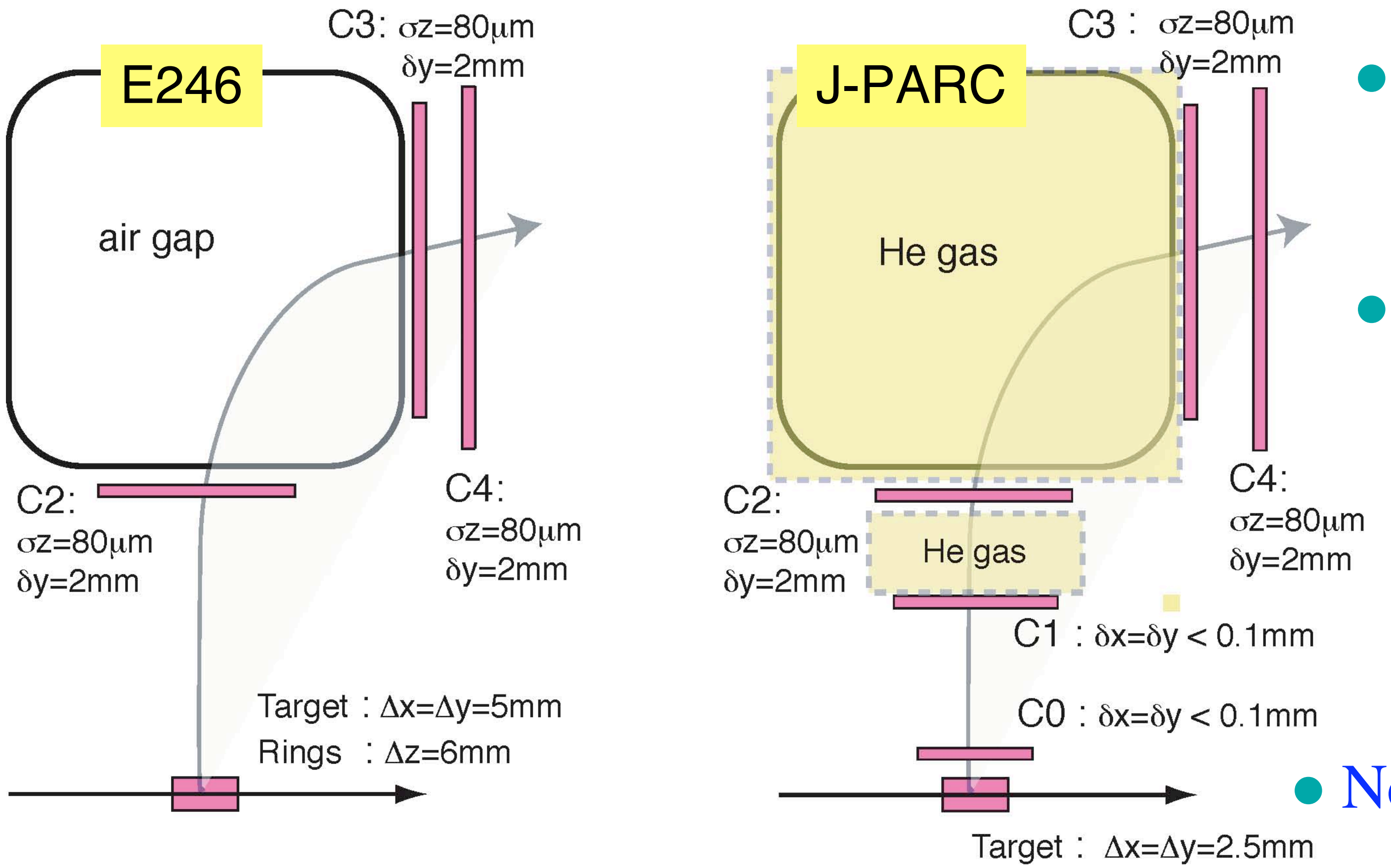
- Gap   : 30 cm
- Pole face : 60 cm ×40 cm
- No. of coils : 24
- Mag. motive force : 3.6×10^3 A Turn/coil
- Total power : 6 kW
- Total weigt : ~ 5 t



Target and tracking

- Better kinematical resolution
- Stronger $K_{\pi 2}$ *dif* μ^+ BG suppression

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

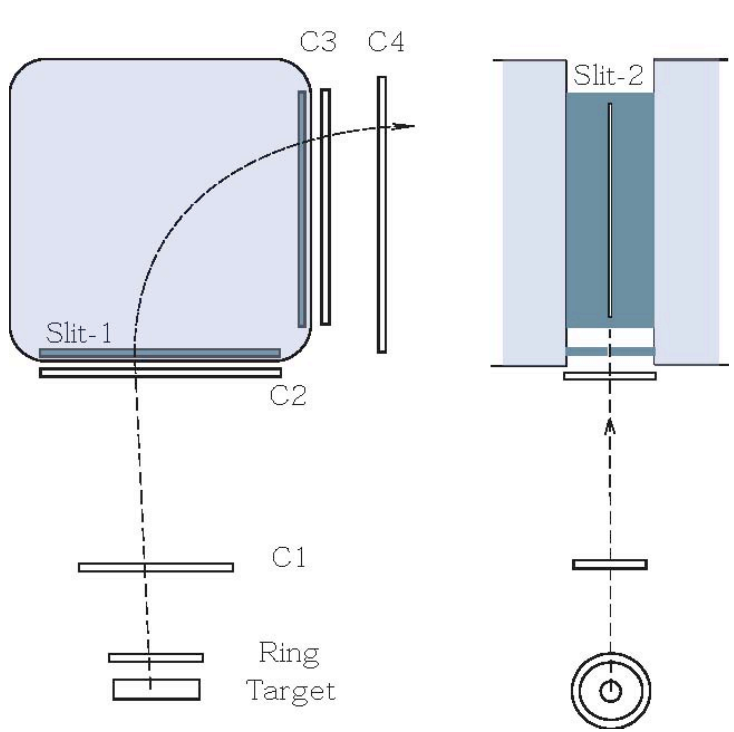


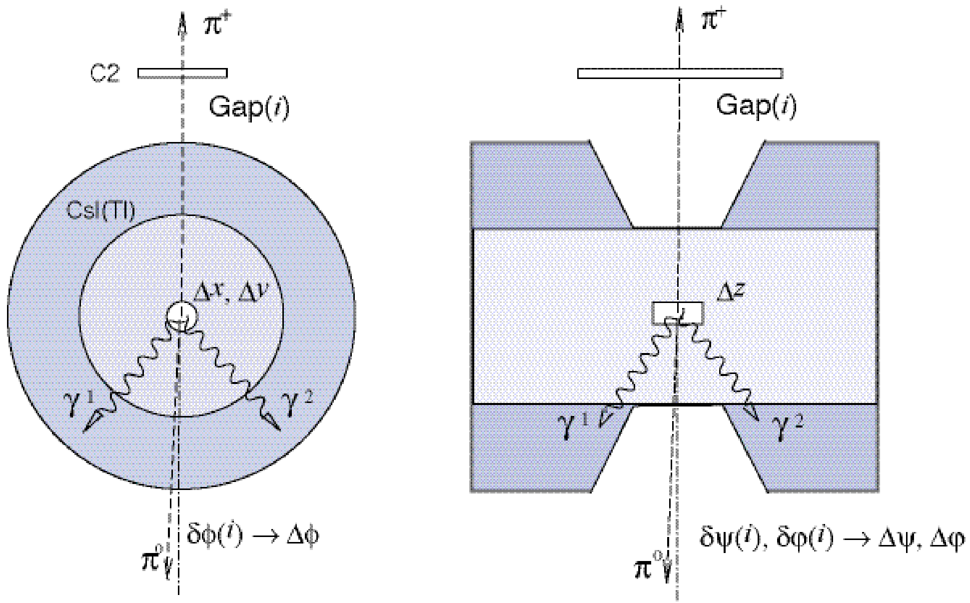
- Larger C3-C4 distance
- Use of He bags
- New target

Alignment calibration

E246 : real measurement with precision of 10^{-3}

J-PARC E06 : alignment using data for precision of 10^{-4}





(1) Reference frame = magnet gap

(2) Tracking system (using slits)

(3) CsI(Tl) π^0 detector (using $K_{\pi 2}$)

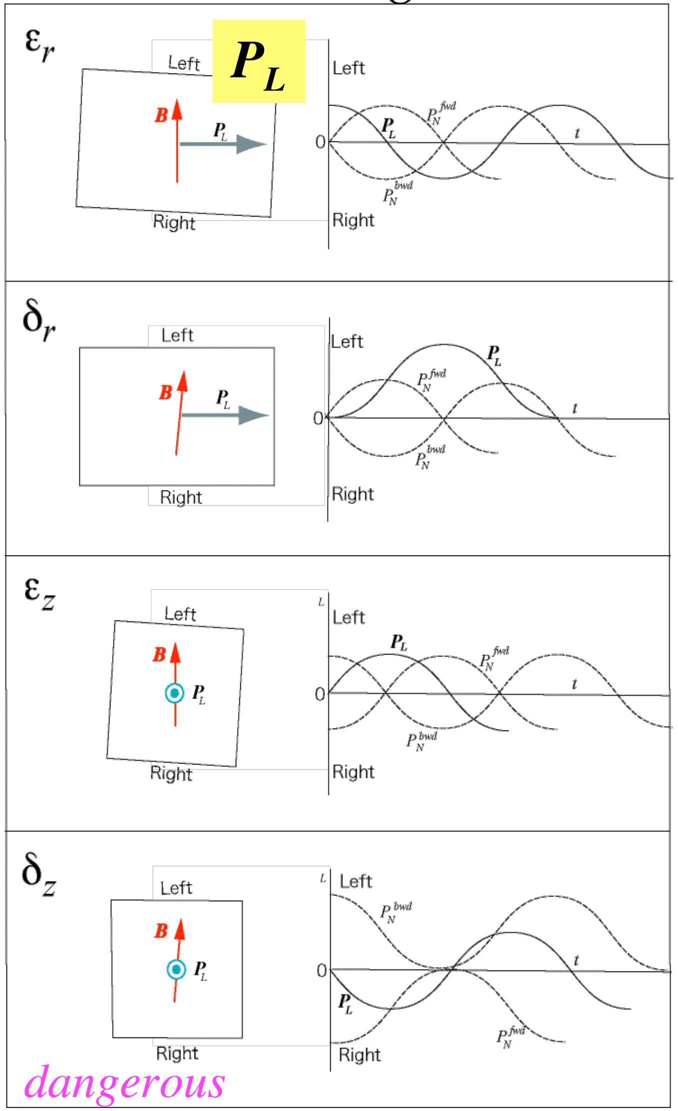
$\Delta\phi$, $\Delta\psi$, $\Delta\varphi$

(4) Polarimeter & Muon field

ε_r, ε_z, δ_r, δ_z

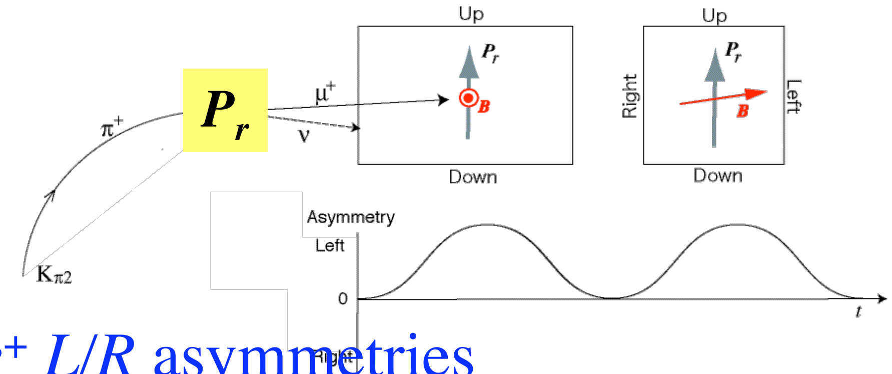
Polarimeter alignment

Four misalignments



■ Use of :

- longitudinal pol. P_L from $K_{\mu 3}$ or $K_{\mu 2}$
- radial polarization P_r from $K_{\pi 2}$ -π^+ decay in flight or r component of P_L



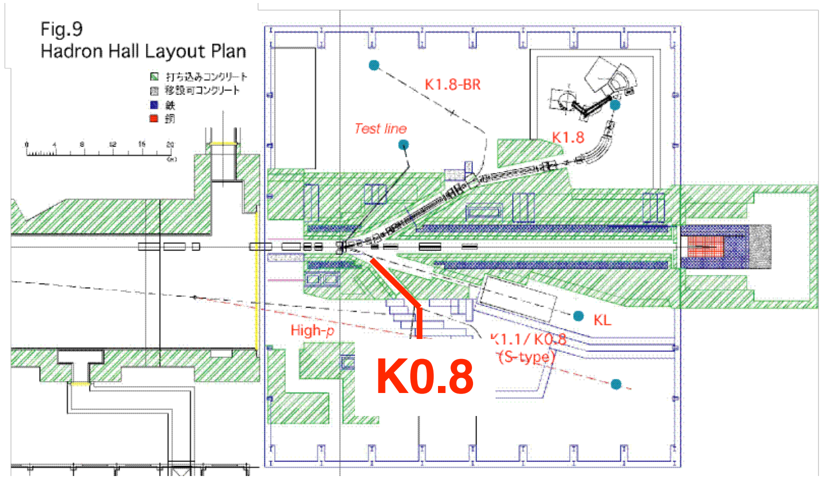
■ e^+ *L/R* asymmetries

$$A(P_L) = \varepsilon_r \cos\omega t + \delta_r (1-\cos\omega t) + (\varepsilon_z - \delta_z) \sin\omega t$$
$$A(Pr) = (\varepsilon_r - \delta_r) \sin\omega t + \delta_z - (\varepsilon_z - \delta_z) \cos\omega t$$

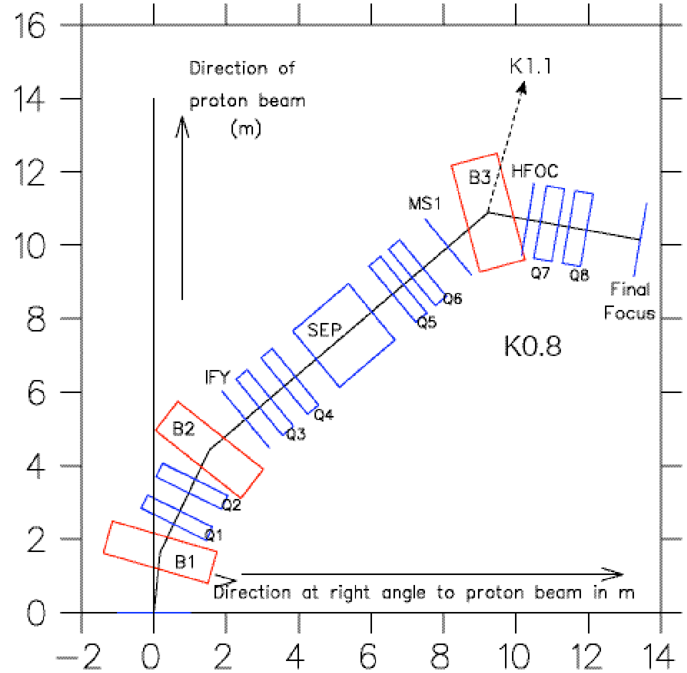
■ Unique determination of
ε_r ε_z δ_r δ_z
verified with a MC study

Beamline at J-PARC

K0.8 (K1.1-BR)



Momentum	800 MeV/c
Momentum bite	±2.5%
Acceptance	6.5 msr % $\Delta p/p$
K^+ intensity	3×10^6 /s
K/π ratio	> 2
Beam spot	1.04 ×0.78 cm (FWQM)
Final focus	achromatic



- Good K/π ratio due to two vertical focuses, FY and MS1, and a horizontal focus HFOC
- Better performance than K5
- Alternate use with K1.1 by replacing B3

Sensitivity estimate

Statistical sensitivity

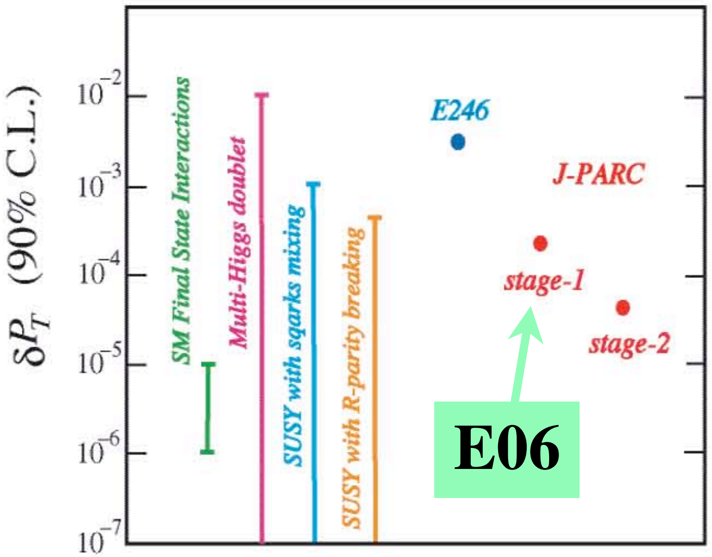
Standard analysis

• Net run time	1.0×10^{7} s
• Proton beam intensity	9μA on T1
• K^{+} beam intensity	3×10^{6} /s
• Total number of good $K_{\mu 3}$	2.4×10^{9}
• Total number of *fwd/bwd* (N)	7.2×10^{8}
• Sensitivity coefficient	$3.73\sqrt{N}$
• δP_T	1.35×10^{-4}

including left/right regions

• δP_T	0.8×10^{-4}

(A careful systematic error study is necessary)



Systematic errors

Source	δP_T
δ_z	$< 10^{-4}$
θ_z	$< 10^{-4}$
θ_{e^+}, E_{e^+}	$< 10^{-4}$
Total	$\sim 10^{-4}$

Time schedule & collaboration

Proposed time schedule

Year	Construction	Run
2006	Stage-1 Approval in July 1) Detector MC studies 2) Start of budget application 3) Formation of collaboration	
2007	1) Detector element R&D 2) Muon field magnet 3) C0 chamber prototype 4) Modification of CsI(Tl) readout	
2008	1) Transfer of SCM and He-Refrogerator 2) Installation of K1.1-BR (K0.8) beamline 3) Production of GEM chambers 4) Production of target and polarimeters	
2009	1) Spectrometer setup 2) Magnet field mapping 3) Detector setup	Beam tuning
2010		Engineering run
2011		Data taking
2012		Analysis

Collaboration

- **Canada**: U.Saskatchewan, TRIUMF, UBC, U. Montreal
- **USA**: MIT, U. South Carolina, Iowa State U.
- **J apan**: KEK, Tohoku U., Osaka U., NDA

We are looking for more collaborators

Summary

- P_T in $K_{\mu 3}$ is a very sensitive probe of new physics
- KEK-PS E246 obtained:

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

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

- J-PARC E6 experiment in the early stage of Phase 1 to pursue a limit of

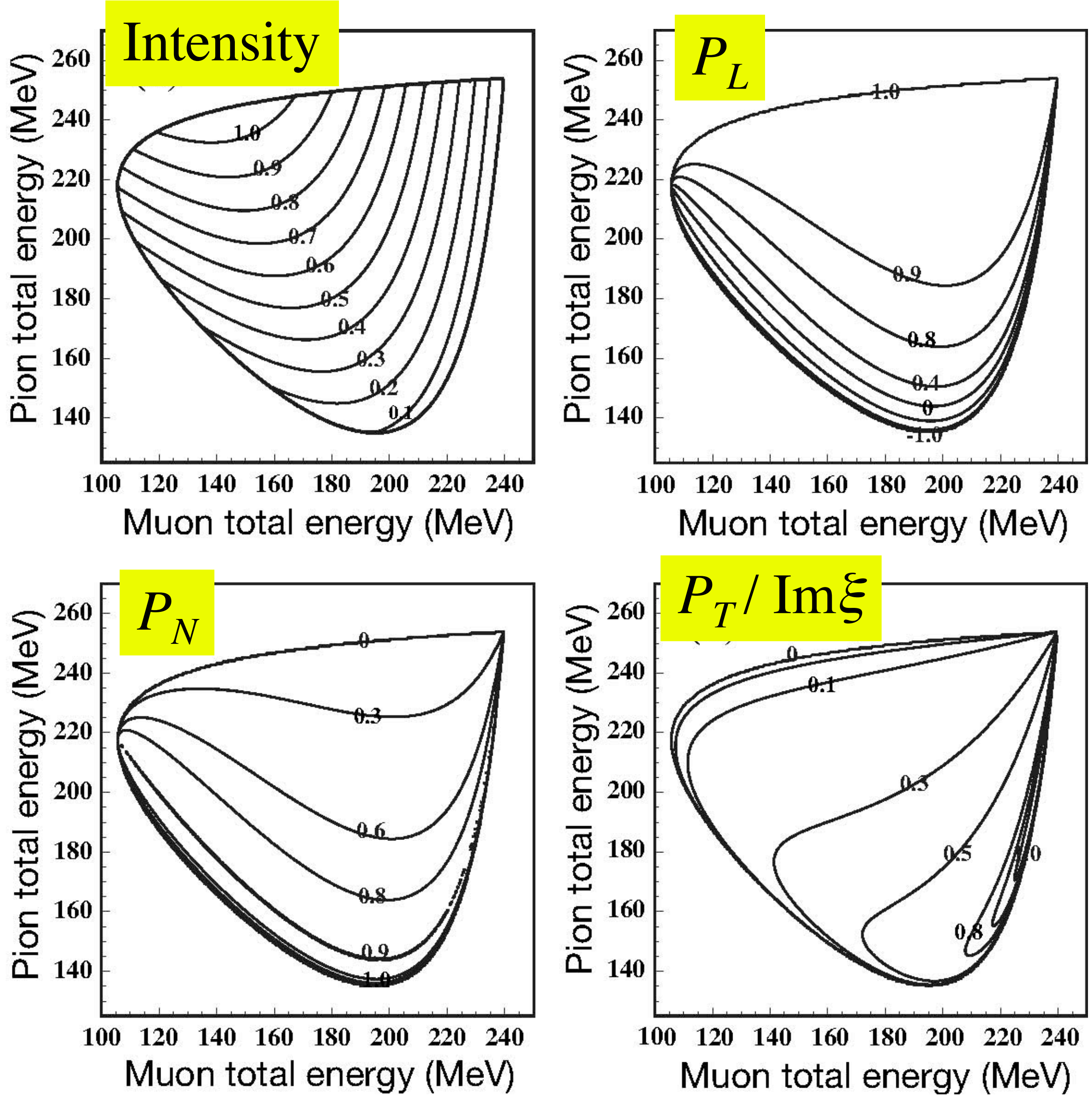
$$\delta P_T \sim 10^{-4}.$$

- E246 detector will be upgraded for this sensitivity.
- We start now the first step toward:

Collaboration forming / Fund application / Detector R&D

End of Slides

Dalitz plot

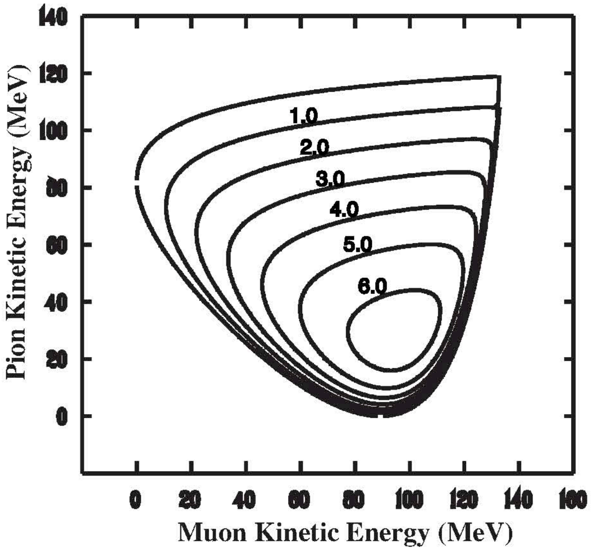

Intensity
P_L
P_N
P_T / Imξ
Pion total energy (MeV)
Muon total energy (MeV)
140
160
180
200
220
240
260
100
120
140
160
180
200
220
240
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
1.0
0.9
0.8
0.4
0
-1.0
0
0.3
0.6
0.8
0.9
1.0
0
0.1
0.3
0.5
0.8
1.0

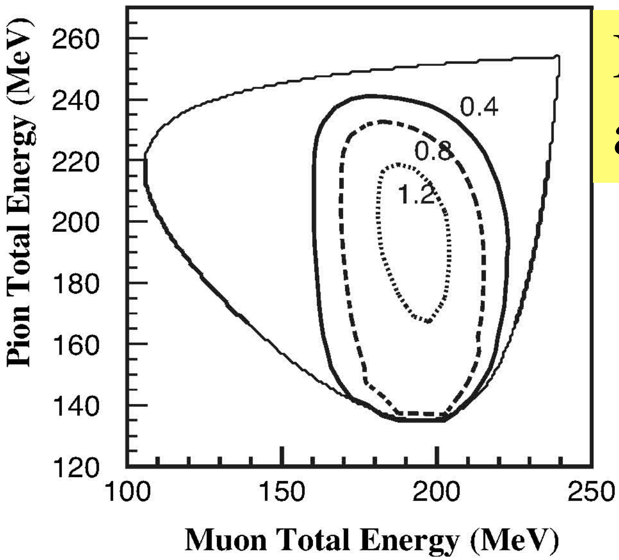
Method of experiment

- Stopped K^+ decay
  - Superior to in-flight decay
- Toroidal spectrometer

- E246 detector upgrade
  - –Well known performance
  - –Well studied systematics
  - –Good alignment in magnet and CsI(Tl)
  - –Lower cost

FoM ($A\sqrt{N}$) distribution





Detector acceptance

Features of E246

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

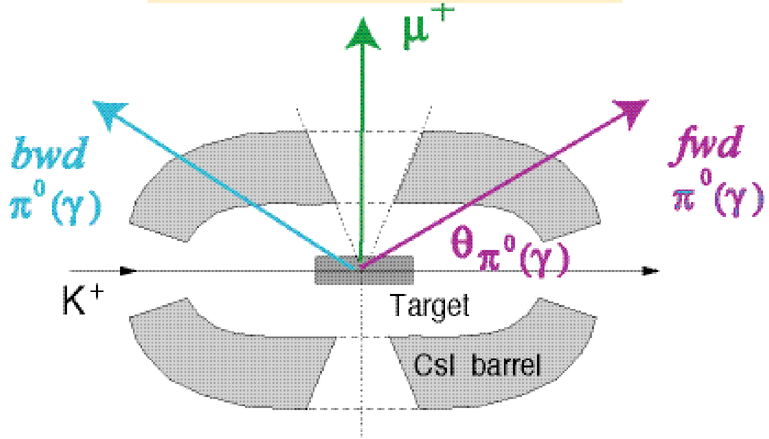
  $$A_T = (A_{fwd} - A_{bwd}) / 2$$

  - small systematic errors
- **Longitudinal filed method**

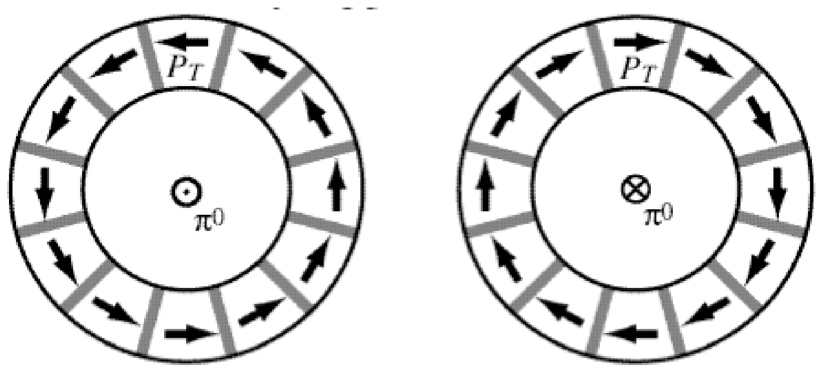
  $$\boldsymbol{B \,//\, P_T}$$

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

fwd and *bwd* π^0 / γ



P_T directions



bwd -π^0 (γ)   *fwd* -π^0 (γ)

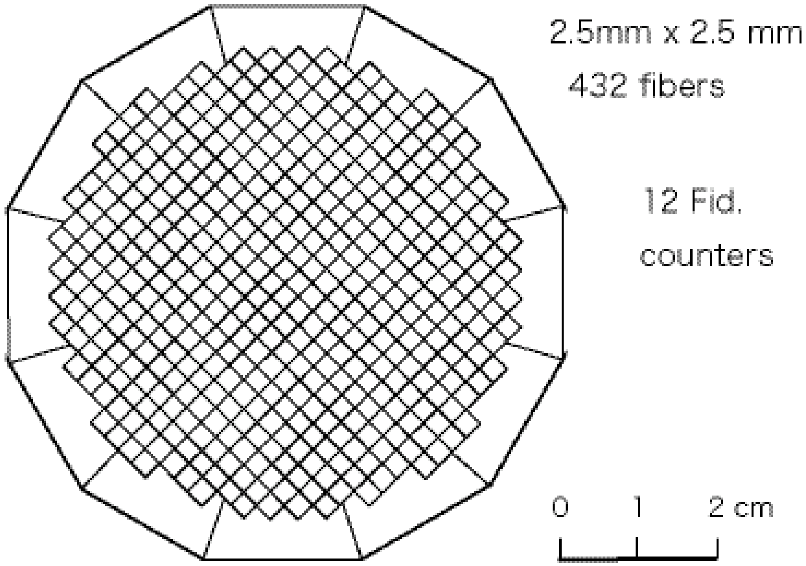
Possible origins of P_T

Effective four-fermion interaction

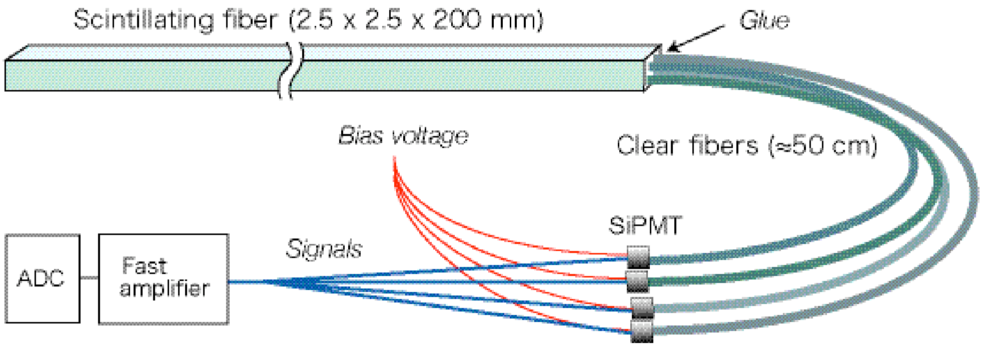
$$L = -\, G_F/\sqrt{2}\, \sin\theta_C\, \bar{s}\gamma_\alpha(1-\gamma_5)u\; \bar{\nu}\gamma^\alpha(1-\gamma_5)\mu$$
$$+\, G_S\, \bar{s}u\; \bar{\nu}(1+\gamma_5)\mu + G_P\, \bar{s}\gamma_5 u\; \bar{\nu}(1+\gamma_5)\mu$$
$$+\, G_V\, \bar{s}\gamma_\alpha u\; \bar{\nu}\gamma^\alpha(1-\gamma_5)\mu + G_A\,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

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

Target for E06

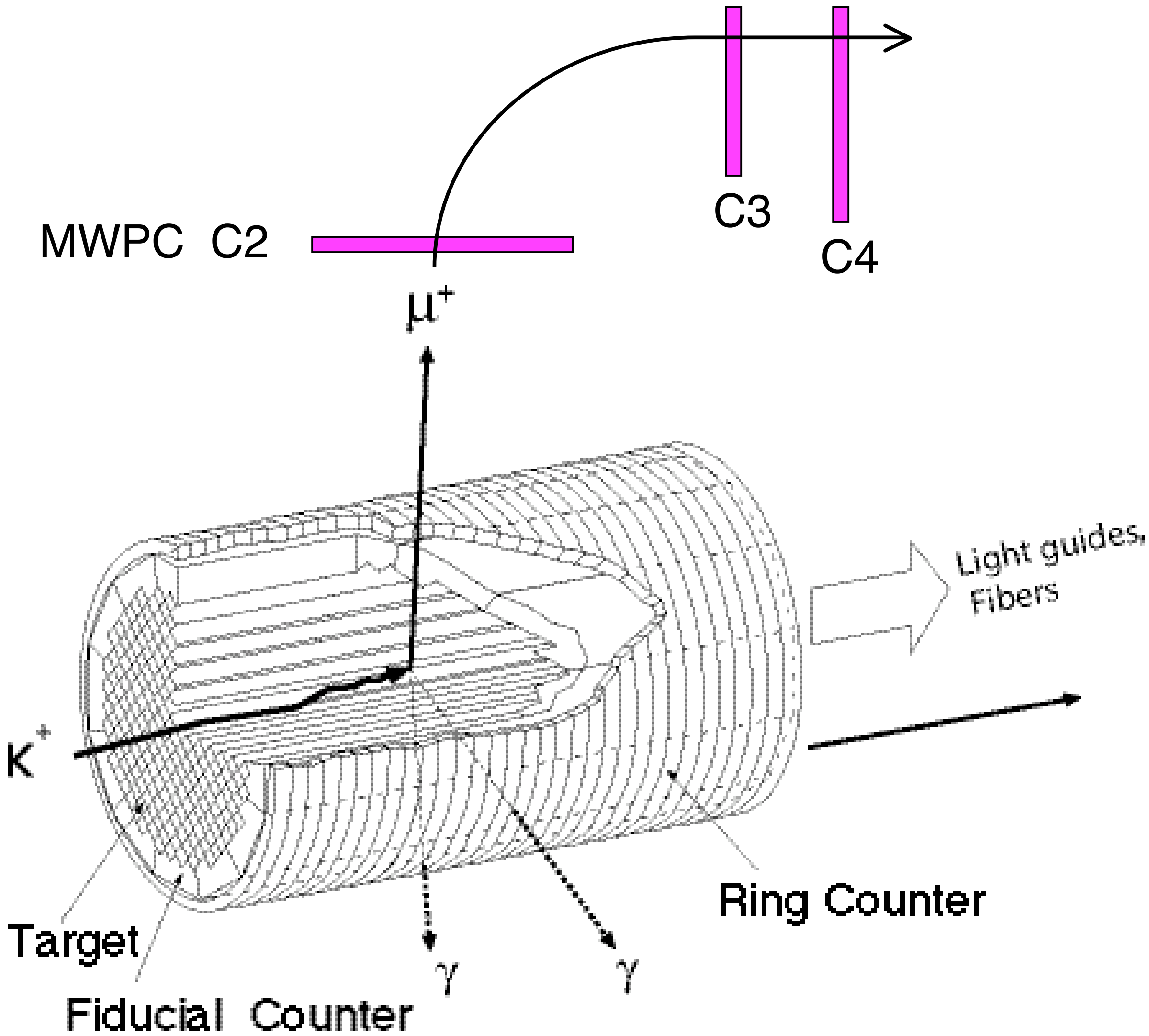


- Smaller size (smaller beam spot)
- Finer segmentation
- Sci. fiber of 20 cm length
- Clear optical fiber
- Light readout by SiPMTs

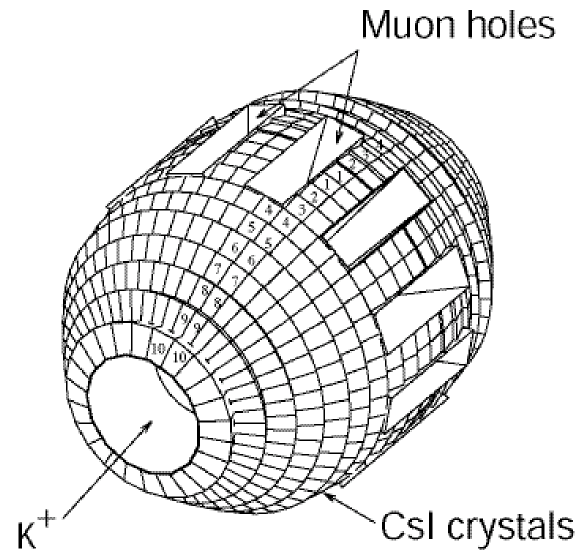


Diameter	6 cm
Active length	20 cm
Fiber size	2.5×2.5 mm
No. of fibers	432
Light readout	4 clear fibers
Light yield	~ 10/SiPMT

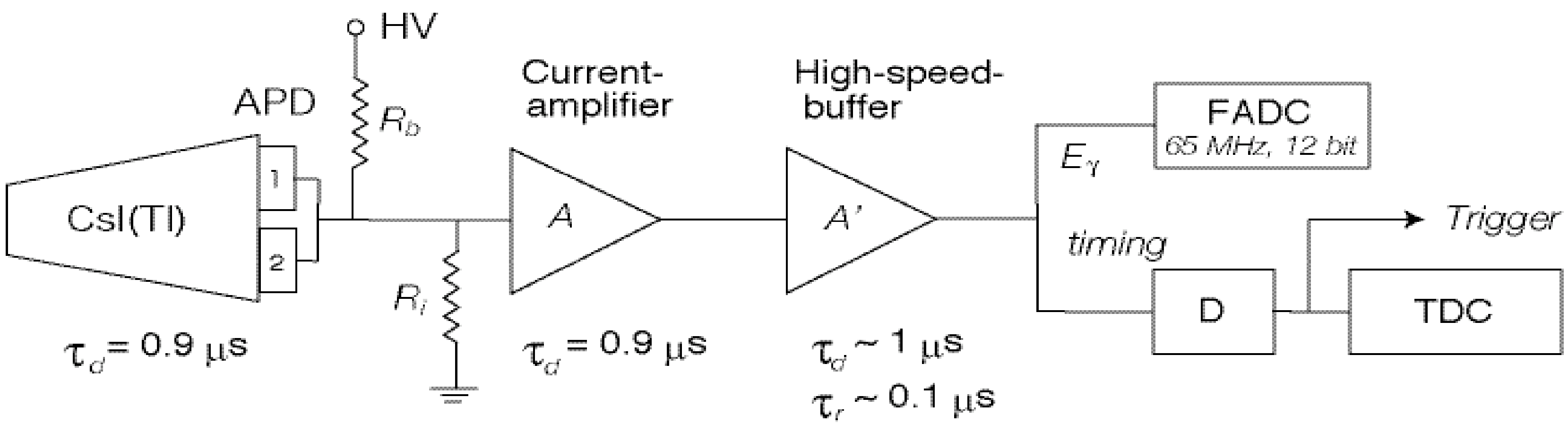
Tracking system



CsI(Tl) readout

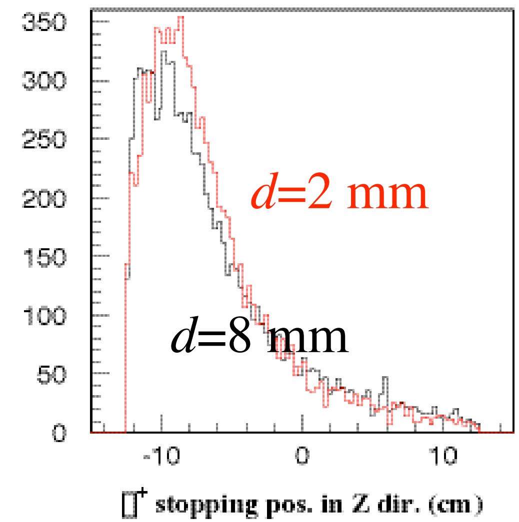


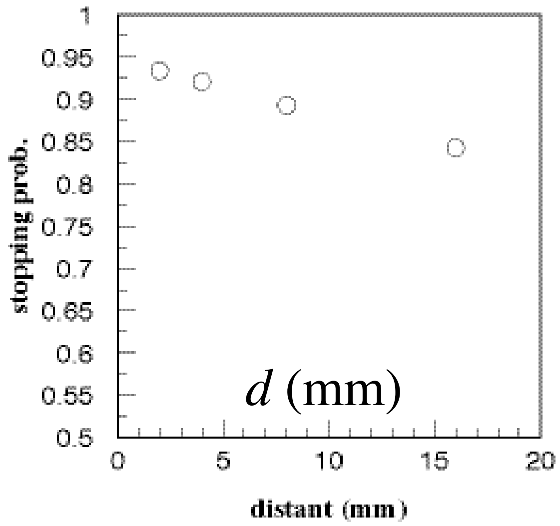
- CsI(Tl) + APD + Amplifier + FADC
- Electrons after APD : ~ 2 $\times 10^7$ @ 100 MeV
- Max count rate / module : ~ 100 kHz
- Max K^+ decay rate : ~ 20 MHz
  - enough for the beam intensity in Phase 1
- Noise level : to be tested
- Module energy resolution : to be tested
  -Energy resolution is determined by lateral shower leakage



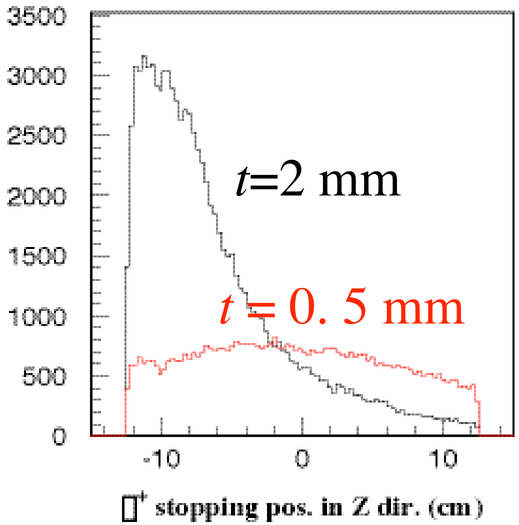
Muon stopping distribution
in the stopper

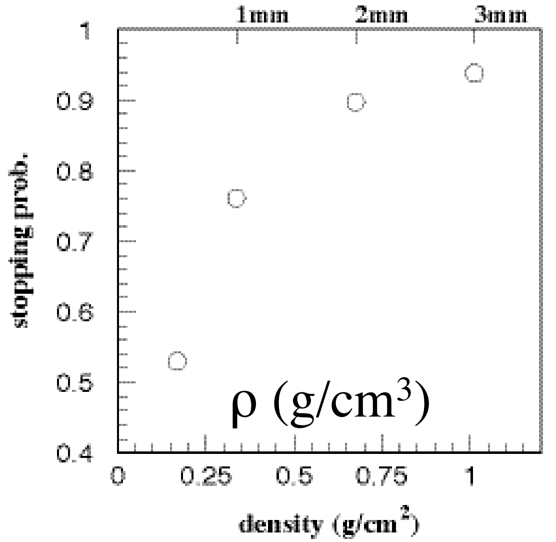
t = 2 mm





d = 8 mm





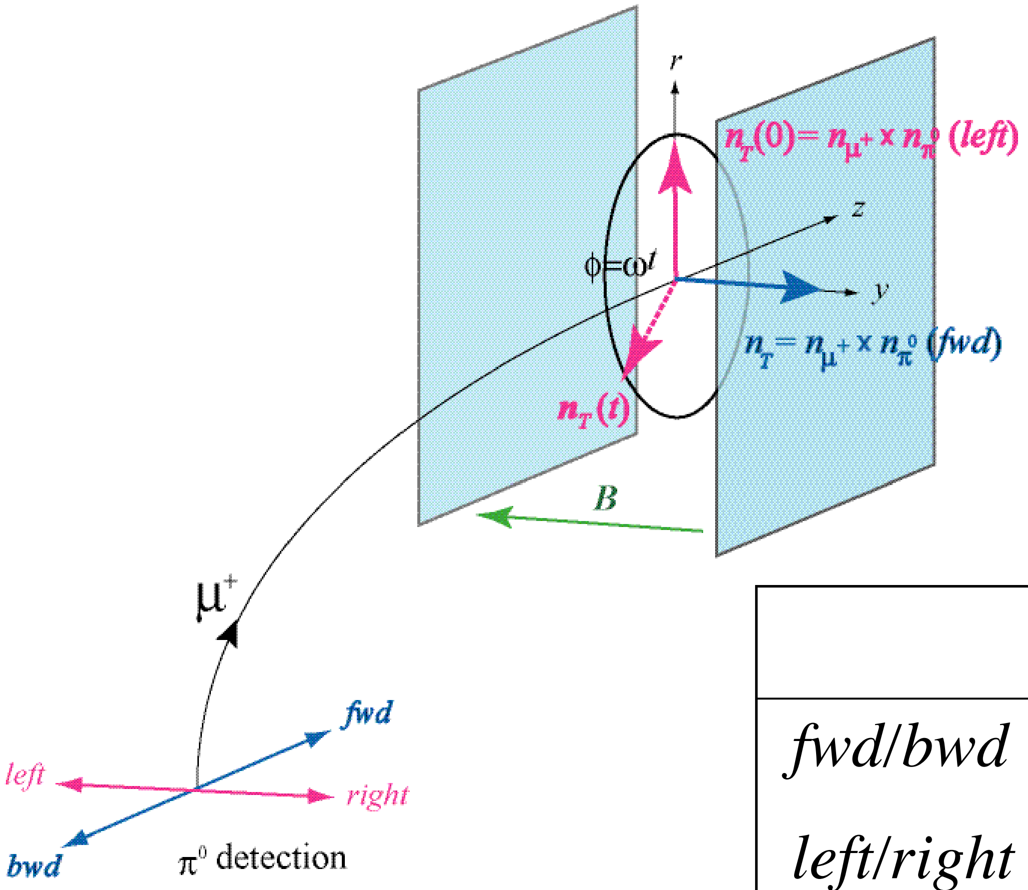
$\rho = 0.2\rho_{Al}$
$= 0.54$ g/cm^3

$\varepsilon_{stop} > 85\%$

for
t = 2 mm
d = 8 mm

Analysis method

Not only *fwd/bwd* but also *left/right*



$$P_T = \frac{3}{N} \sum_{i=1}^{N} \frac{\cos\theta^i_{e^+}}{\alpha(E_i)}$$

$$\cos\theta_{e^+} = \boldsymbol{n}(t) \cdot \boldsymbol{n}_{e^+}$$

$$\boldsymbol{n}(t) = \boldsymbol{n}_{\mu^+} \times \boldsymbol{n}_{\pi^0}$$

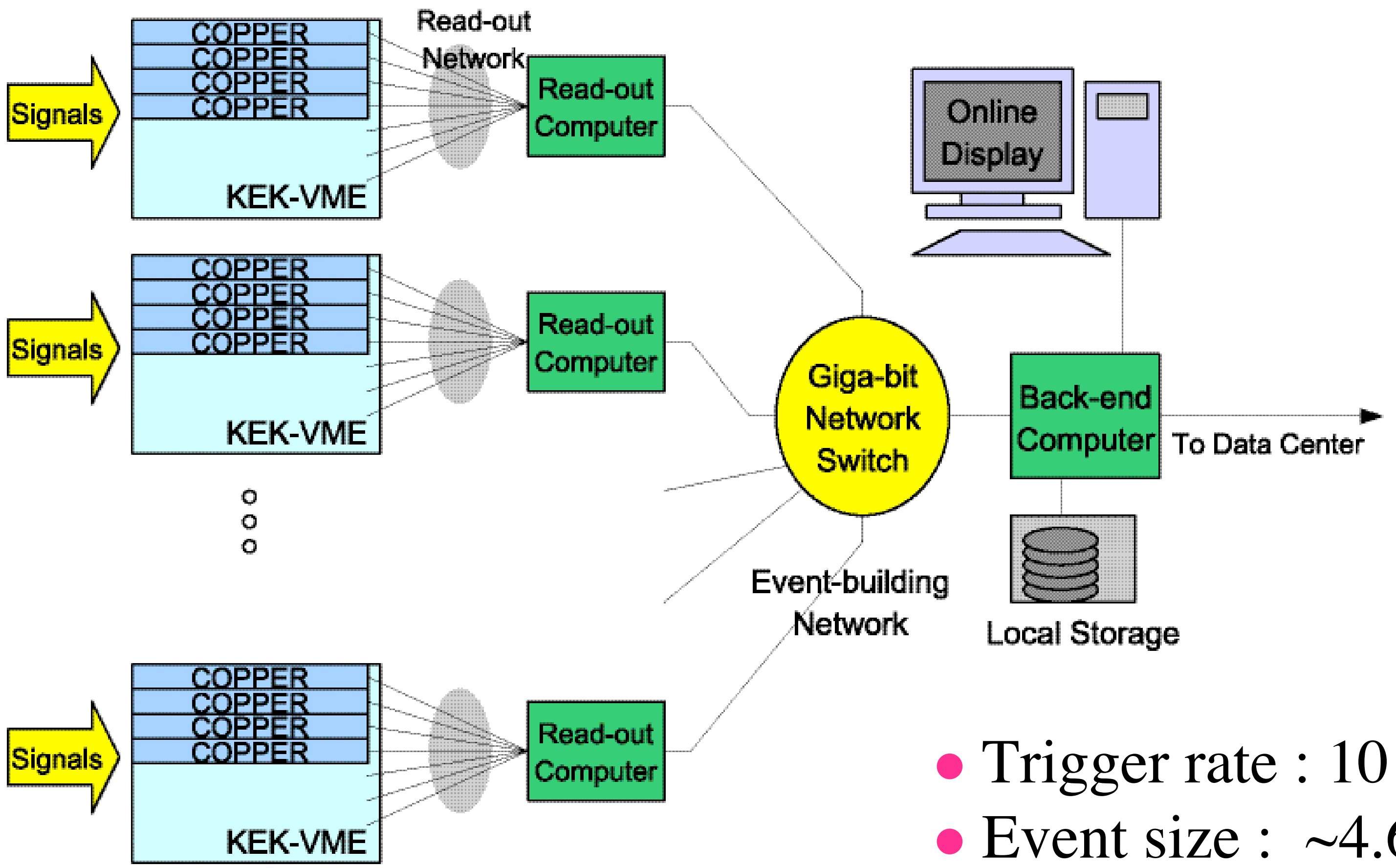
$\alpha(E)$: asymmetry coefficient

	integral	event-by-event
fwd/bwd	○ ◎	◎ ○
left/right	△ ○	○ △

■ sensitivity ■ systematics

Electronics and data taking

- KEK-VME system with COPPER and FINESSE
- Full use of FADC-FINESSE, QTC+TDC FINESSE



DAQ configuration

- Trigger rate : 10 kHz
- Event size : ~4.6 kbyte
- Data flow rate : 46 Mbyte/s
- Dead time : < 5%