

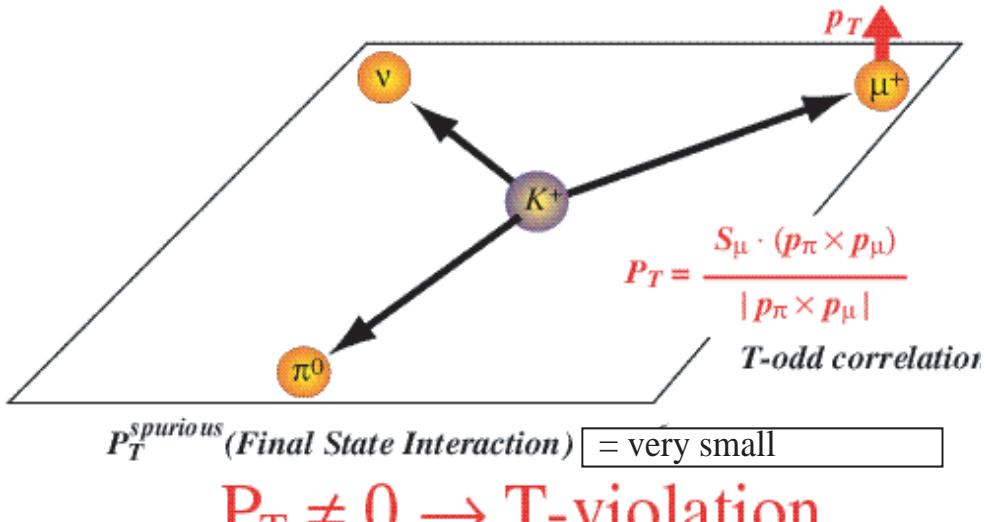
T violation in K decays using stopped K^+

J. Imazato
IPNS, KEK

*NP04 workshop
August 3, 2004 Tokai*

*Transverse muon polarization
KEK E246 experiment
J-PARC experiment
E246 upgrade?
LOI-19*

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



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

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

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

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

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

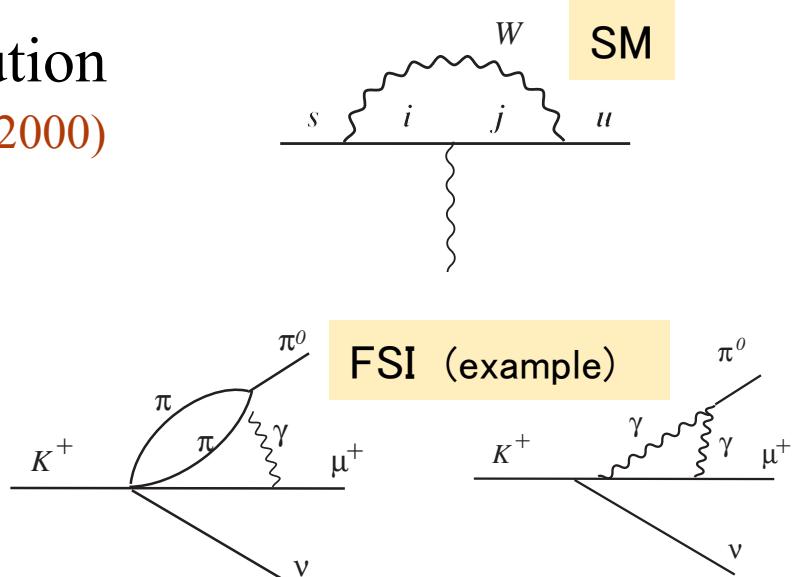
History of $K_{\mu 3}$ transverse polarization experiments

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

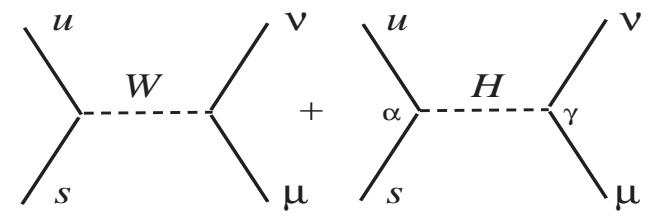
Feature of $K^+_{\mu 3} P_T$

- Small standard model contribution
 - Bigi and Sanda “CP violation” (2000)
 - $P_T \sim 10^{-7}$
- Small FSI spurious effects
 - Single photon contribution
Zhitnitskii (1980)
 $P_T < \sim 10^{-6}$
 - Two photon contribution
Efrosinin et al. PL B493 (2000) 293
 $P_T \sim 4 \times 10^{-6}$
- High sensitivity to CP violation beyond the SM
 - Mult- Higgs doublet model
 - Leptoquark model
 - Some Supersymmetric models

$P_T \sim 10^{-4}-10^{-3}$



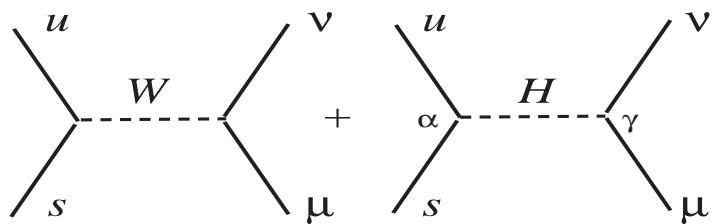
Three Higgs doublet model



Higgs doublet model

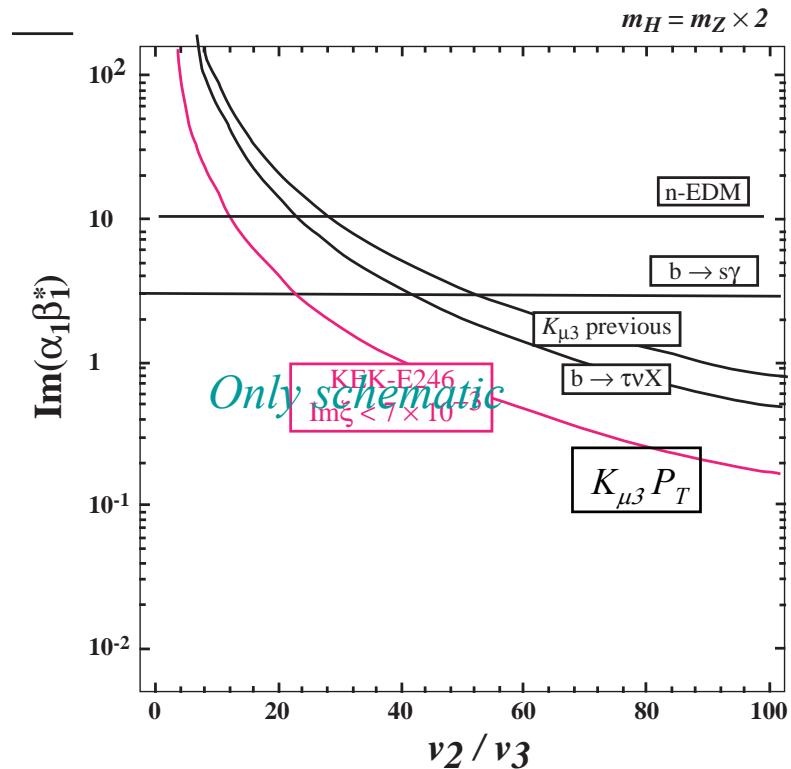
$$\mathcal{L} = (2\sqrt{2}G_F)^{1/2} \sum [\alpha_i U_L K M_D D_R + \beta_i U_R M_U K D_L + \gamma_i N_L M_E E_R] H_i^+ + h.c.$$

□ □ □ □ . □ □ □ □ □ flavor conservation



$$\begin{aligned} \text{Im}\xi &= \text{Im}(\alpha_I \gamma_I^*) \times (m_K / m_{H^+})^2 \\ &= \text{Im}(\alpha_I \beta_I^*) \times (\nu_2 / \nu_3)^2 \times (m_K / m_{H^+})^2 \end{aligned}$$

- ν_i : vacuum expectation values
- $\alpha_i, \beta_i, \gamma_i$: mixing matrix elements



3HDM : constraints from other experiments

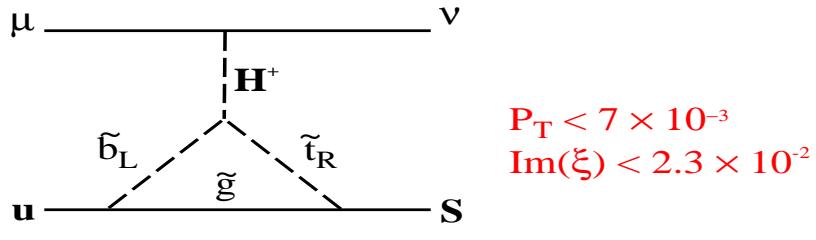
- Neutron EDM (*charged Higgs exchange*)
 - $d_n = C_n \text{Im}(\alpha_I \beta_I^*) < 0.63 \times 10^{-25} \text{ e cm}$
 $\Leftrightarrow \text{Im}(\alpha_I \beta_I^*) < \sim 10$
- $b \rightarrow s \gamma$
 - $A = A_{\text{SM}} + A_{\text{3HDM}}(\alpha_I \beta_I^*)$
 $\Leftrightarrow \text{Im}(\alpha_I \beta_I^*) \leq 3.2$ (for $m_H \sim 2m_Z$)
[Grossman and Nir (1993), Kiers et al.(2000)]
- $\varepsilon/\varepsilon = \square \square \square(\alpha_I \beta_I^*)$ but $\square \square$ stringent constraint
- $b \rightarrow X \tau \nu$
 - $A = A_{\text{SM}} + A_{\text{3HDM}}(\alpha_I \gamma_I^*)$
 $\text{Im}(\alpha_i \gamma_i^*) = \text{Im}(\alpha_I \beta_I^*) (v_2/v_3)^2 < 0.48$ (for $m_H \sim 2m_Z$)
[Grossman, Haber and Nir (1995)]
 - c.f. P_T : $\text{Im}(\alpha_I \beta_I^*) (v_2/v_3)^2 < \text{Im} \xi / 0.10$

For $v_2/v_3 > \sim 10$, P_T is the most stringent constraint on 3HDM
[Garisto and kane (1991)]

Other models

SUSY + squark mixing

Guo-Hon Wu and John N. Ng, Phys. Rev. D56 (1997) 93

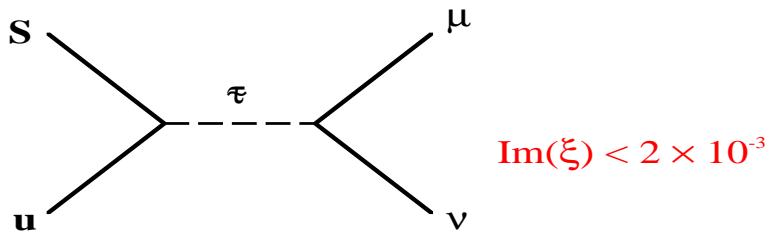


$$P_T < 7 \times 10^{-3}$$

$$\text{Im}(\xi) < 2.3 \times 10^{-2}$$

R-parity Breaking SUSY

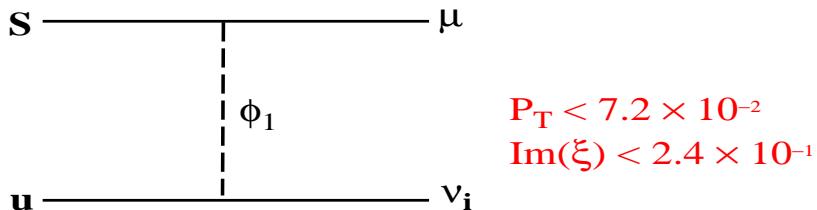
M. Fabbrichesi and F. Vissani, Phys. Rev. D55 (1997) 5334



$$\text{Im}(\xi) < 2 \times 10^{-3}$$

Leptoquark

G. Belanger and C. Q. Geng, Phys. Rev. D 44 (1991) 2789



$$P_T < 7.2 \times 10^{-2}$$

$$\text{Im}(\xi) < 2.4 \times 10^{-1}$$

Charged Higgs exchange Constraints on

$$M_{H^+}$$

$$\Lambda = \tan\beta (\mu + A_t \cot\beta)/m_{g^\sim}$$

$$\times \text{Im}[V_{33}^{H^+*} V_{32}^{D_L*} V_{31}^{U_R}]$$

slepton exchange + down-type squark exchange Constraints on

$$M_{H^+}$$

$$\text{Im}[\lambda'_{2i2}(\lambda'_{i12})^*] \text{ and } \text{Im}[\lambda'_{21k}(\lambda'_{22k})^*]$$

scalar leptoquark exchange Constraints on

$$\lambda_k^2/M\phi_k^2$$

$P_T(K^+ \rightarrow \mu^+ \nu \gamma)$

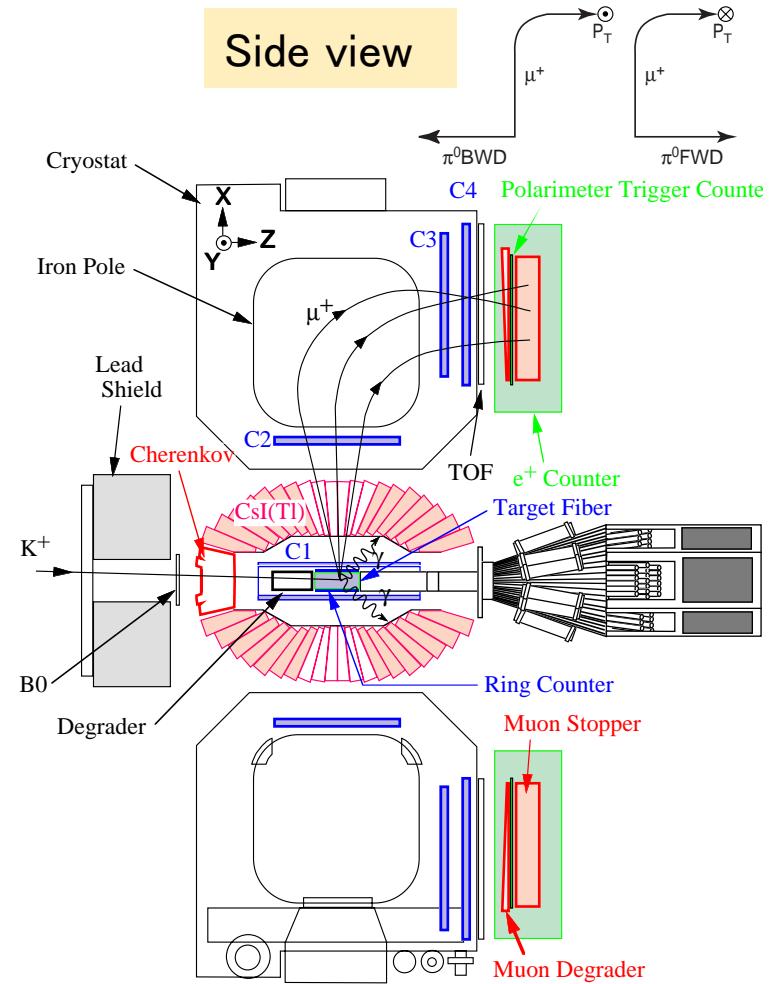
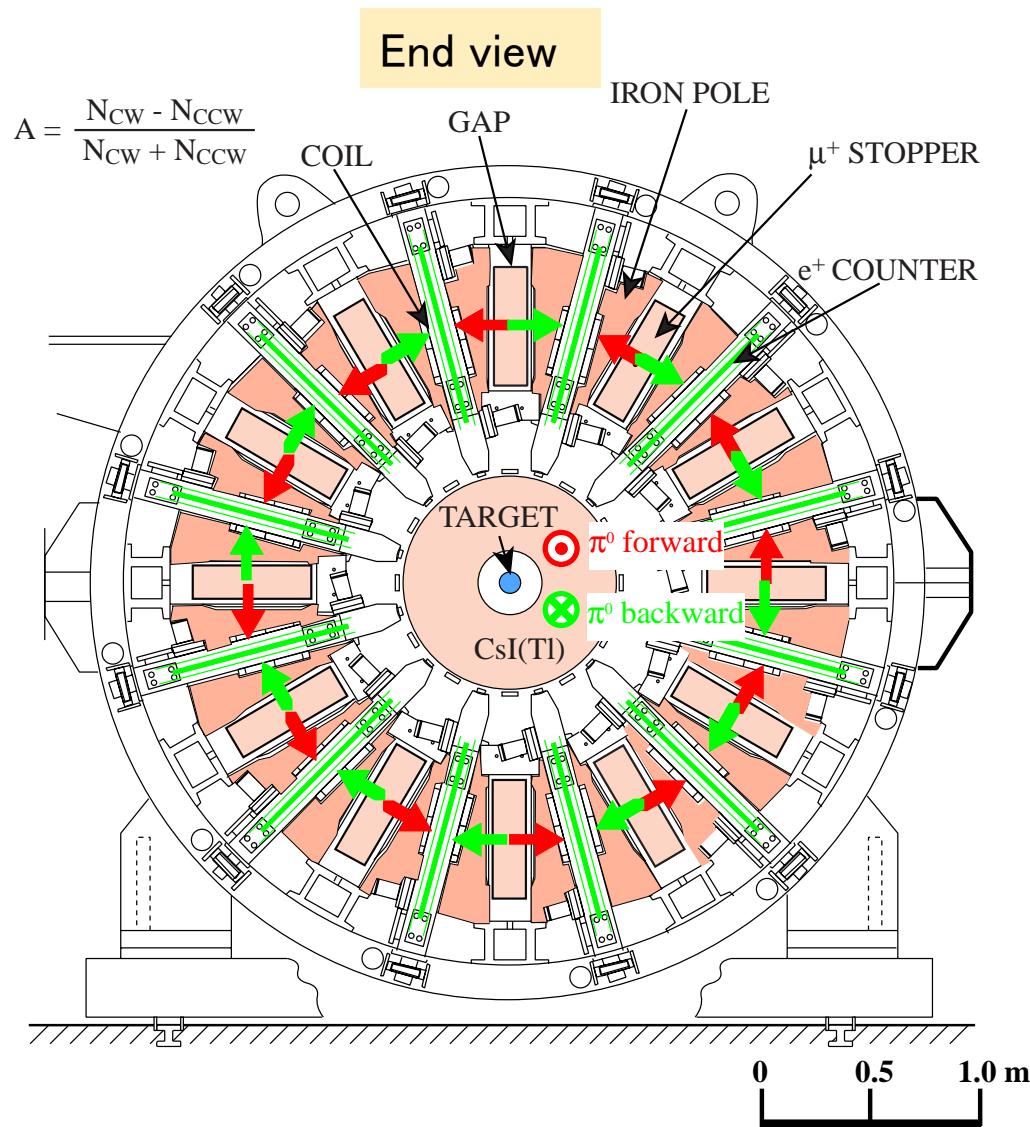
- no SM contribution, but induced by pseudoscalar
- complementary to $P_T(K \rightarrow \pi \mu \nu)$ [Kobayashi et al. (1996)]
- FSI is not large : $O(10^{-4})$ [Efrosinin and Kudenko (1999), Hiller and Isidori (1999)]

Model	$K^+ \rightarrow \pi^0 \mu^+ \nu$	$K^+ \rightarrow \mu^+ \nu \gamma$
■ Standard Model	$< 10^{-7}$	$< 10^{-7}$
■ Final State Interactions	$< 10^{-5}$	$< 10^{-3}$
■ Multi-Higgs	$\leq 10^{-2}$	$\leq 10^{-2}$ $P_T(K^+ \rightarrow \pi^0 \mu^+ \nu) \approx 2 P_T(K^+ \rightarrow \pi^0 \mu^+ \gamma)$
■ SUSY with squarks mixing	$\leq 10^{-3}$	$\leq 3 \times 10^{-3}$
■ SUSY with R-parity breaking	$\leq 4 \times 10^{-4}$	$\leq 3 \times 10^{-4}$
■ Leptoquarks	$\leq 10^{-2}$	$\leq 5 \times 10^{-3}$

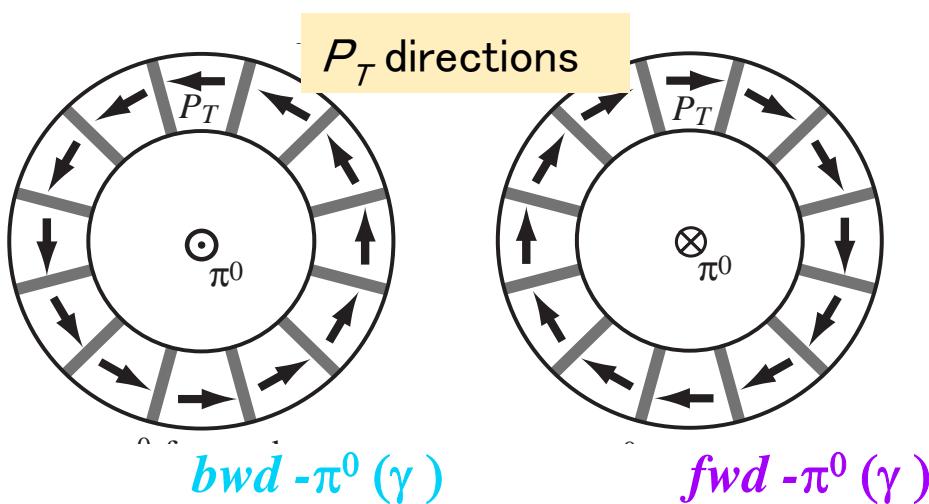
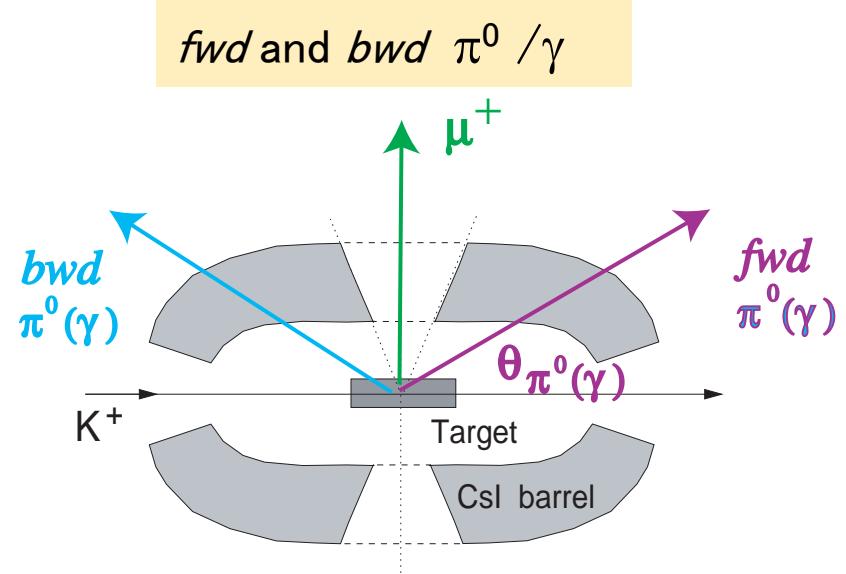
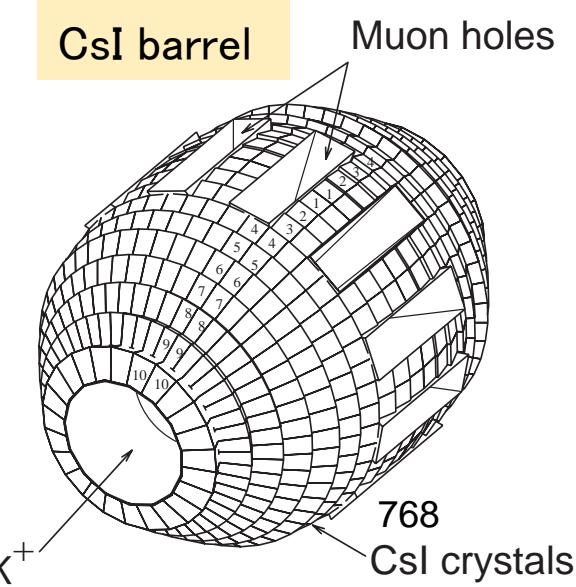
E246 : $P_T = -0.0064 \pm 0.0185 \text{ (stat)} \pm 0.0010 \text{ (syst)}$ Phys. Letters B561, 166 (2003)
 $P_T = -0.0067 \pm 0.0143 \text{ (stat)} \pm 0.0014 \text{ (syst)}$

E246 experimental setup

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



Double ratio measurement



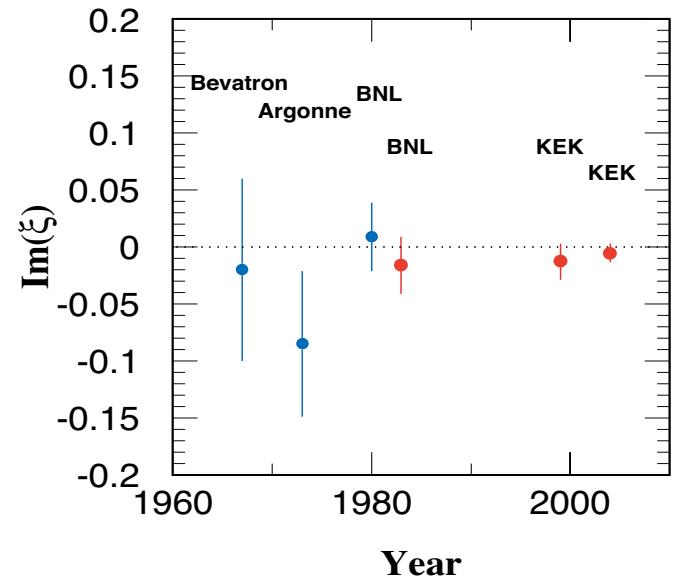
Double ratio measurement

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

E246 result and model implication

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

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



Three Higgs doublet model

- $|\text{Im}\xi| < 0.016 \text{ (90\% C.L.)} \Rightarrow \text{Im}(\alpha_1 \gamma_1^*) < 544 \text{ (at } m_H = m_Z\text{)}$
 cf. $\text{BR}(B \rightarrow X \tau \nu_\tau) \Rightarrow \text{Im}(\alpha_1 \gamma_1^*) < 1900 \text{ (at } m_H = m_Z\text{)}$
- [R.Garisto and G.Kane, Phys. Rev. D44 (1991)2789]

$$\begin{aligned} V_2/V_3 &= m_t/m_\tau \\ d_n &\approx 4/3 d_d \propto \text{Im}(\alpha_1 \beta_1^*) \times m_d / m_H^2 \\ |\text{Im}\xi| < 0.016 \text{ (90\% C.L.)} &\Rightarrow d_n < 5 \times 10^{-27} e \text{ cm} \\ \text{cf. } d_n^{\text{exp}} &< 6.3 \times 10^{-26} e \text{ cm} \end{aligned}$$

Systematic errors

- Σ_{12} : 12-fold rotational cancellation
- fwd/bwd : π^0 forward/backward cancellation

Source of Error	Σ_{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 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_r)	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

E246 upgrade at J-PARC?

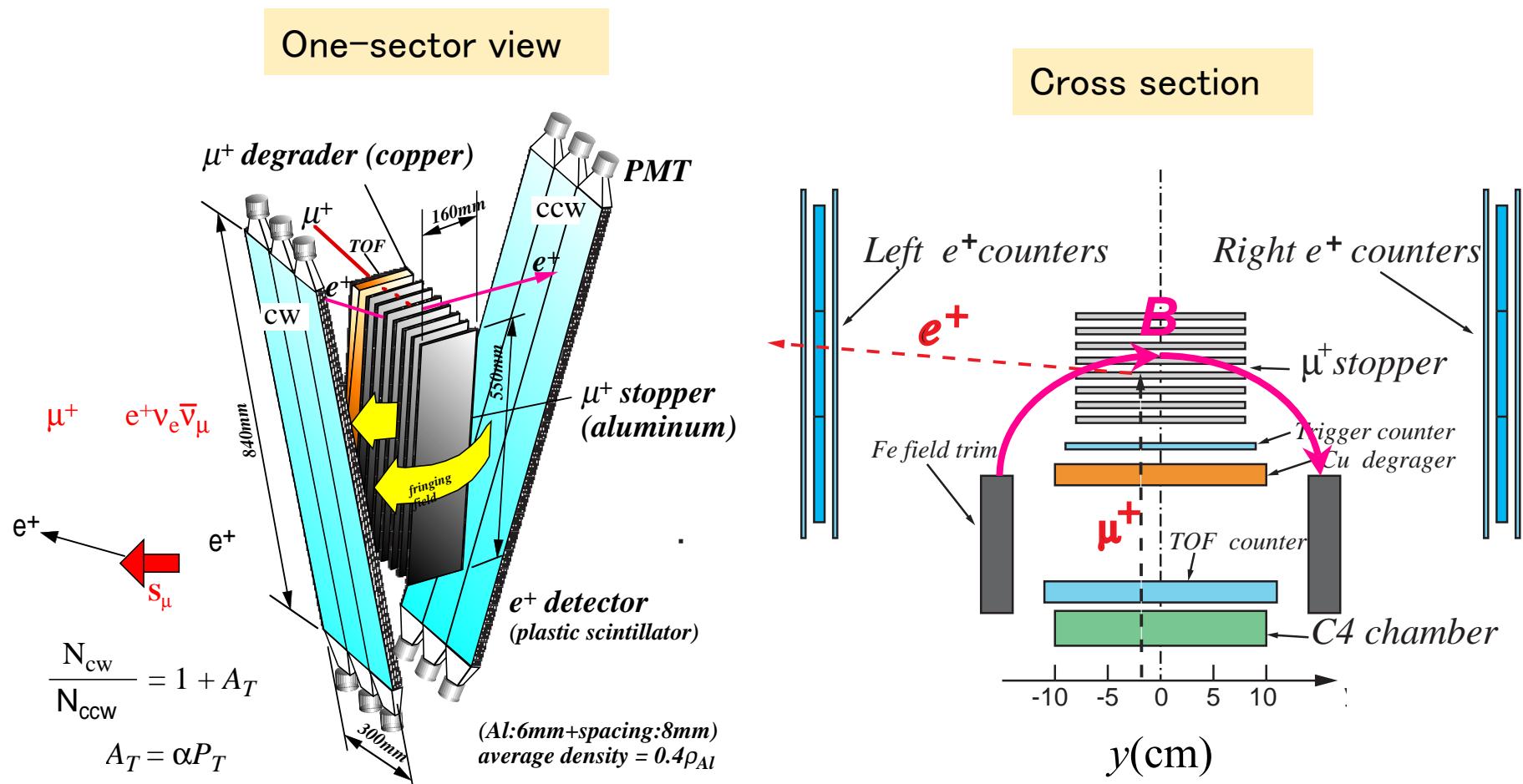
E246 was statistically limited.

- Polarimeter field by a new magnet
 - Parallel holding field of P_T
 - Precise field distribution alignment
 - reduction of the most serious systematic error*
- Active polarimeter
 - 4π solid angle for decay positron
 - Energy and angle of positrons
 - $FoM = \alpha\sqrt{\Omega} = 3.8 \times E246$
- Time digitizer readout of CsI(T)
 - Rate performance = $10 \times E246$*
 - under the condition of $K/\pi \gg 1$*

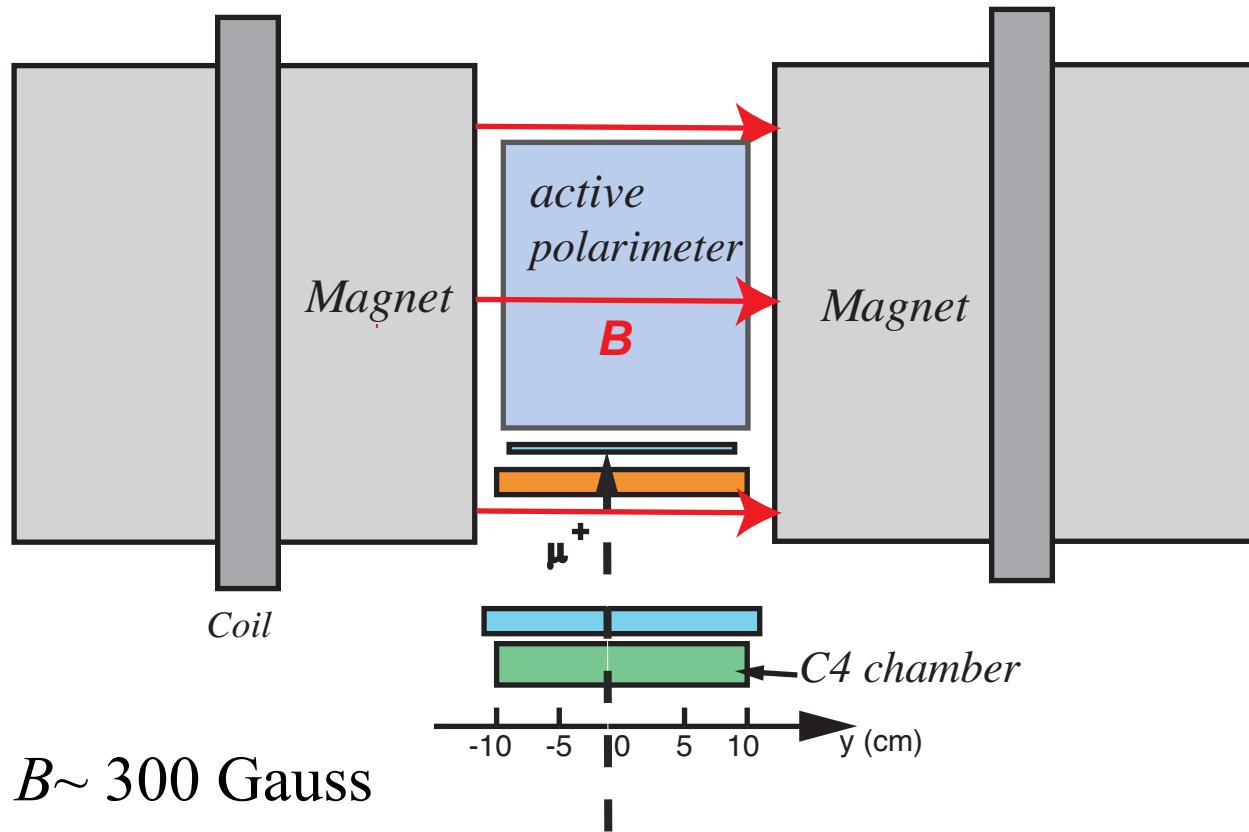
Merit

- Lower cost than a completely new setup
- Well known detector performance and systematics
- Many possibilities for kaon decay spectroscopy

E246 muon polarimeter



New polarimeter system



Expectation for E246-upgrade

- Gain from E246

Polarimeter : 3.8

Beam intensity : $\sqrt{10}$

Run time : $\sqrt{0.66}$

Total = 9.8

- Statistical error : $\delta P_T = 3.0 \times 10^{-4}$

- Systematic errors

Table 5: Prospect for systematic error improvements

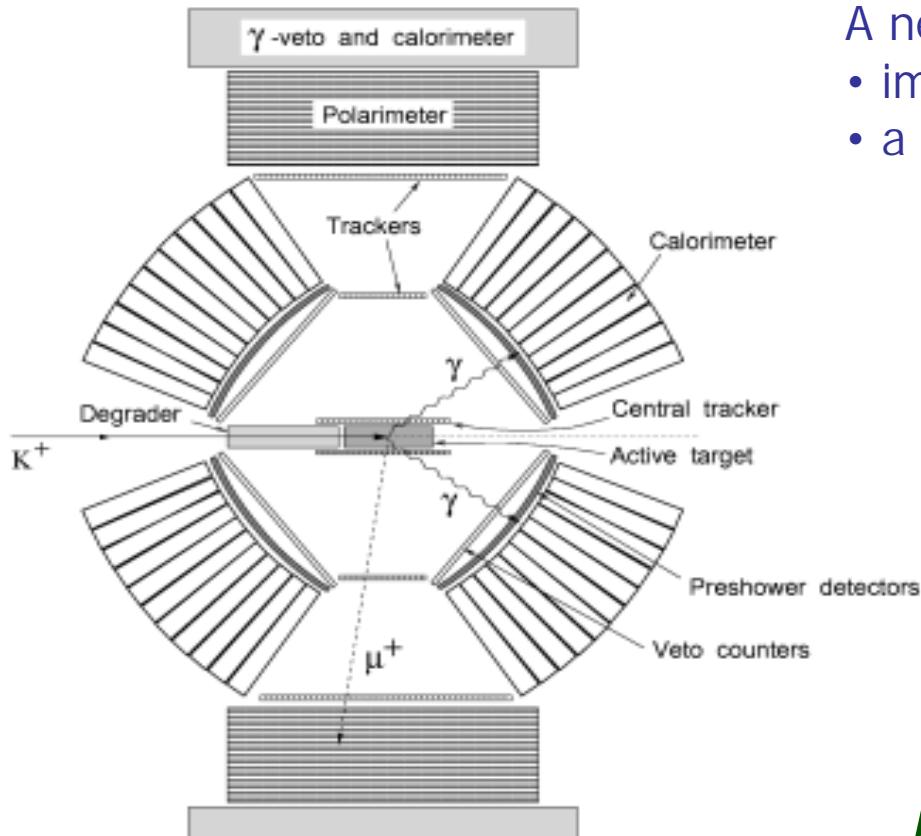
Source	$\delta P_T \times 10^4$ (E246)	$\delta P_T \times 10^4$ (E246-mod)
e^+ counter misalignment	2.9	none
Misalignments of other counters	2.6	2.6
Misalignment of \vec{B} field	6.1	negligible
Misalignment of the active polarimeter	-	not known
K^+ stopping distribution	< 3.0	< 3.0
Decay plane rotation	1.4	none
μ^+ multiple scattering	7.1	none
Backgrounds	< 2.0	not known
Analysis	4.0	not known

Total error : $\delta P_T^{syst} \sim 10^{-4}$

J-PARC proposal Lol-19

- *Experiment principle*
 - stopped kaons
 - double ratio
 - detector azimuthal symmetry
 - complete reconstruction of kinematics
- *Detector concept*
 - larger μ^+ acceptance
 - high resolution π^0 measurement
 - active polarimeter
 - photon veto
- *Most important requirement*
 - suppression of systematic errors to the 10^{-4} level

Original design



A new detector with

- improved charged particle acceptance
- a high resolution photon detection

$$E_{\pi^0}^2 = \frac{2m_{\pi^0}^2}{(1-\cos\eta)(1-X^2)}$$

$$X = \frac{E_1 - E_2}{E_1 + E_2}$$

$$\Delta E_{\pi^0}(\text{rms}) = \sqrt{(\Delta E_{\pi^0}^\gamma)^2 + (\Delta E_{\pi^0}^\eta)^2}$$

$$\Delta E_\pi^\eta = 0.5 m_\pi \gamma^2 \beta \sigma_\eta$$

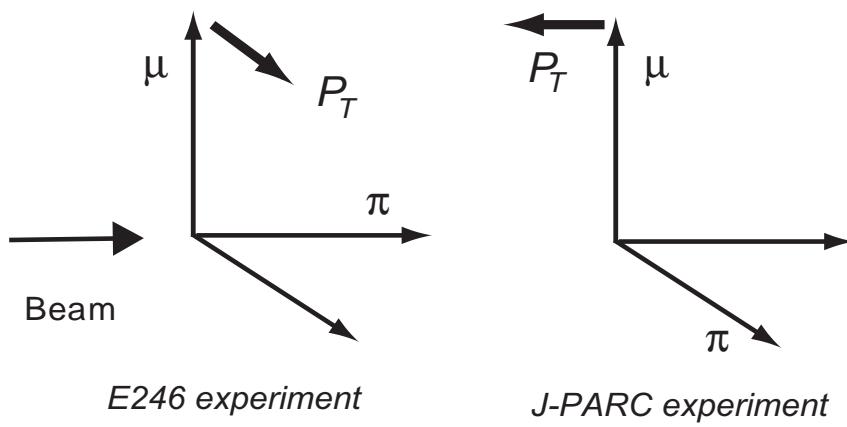
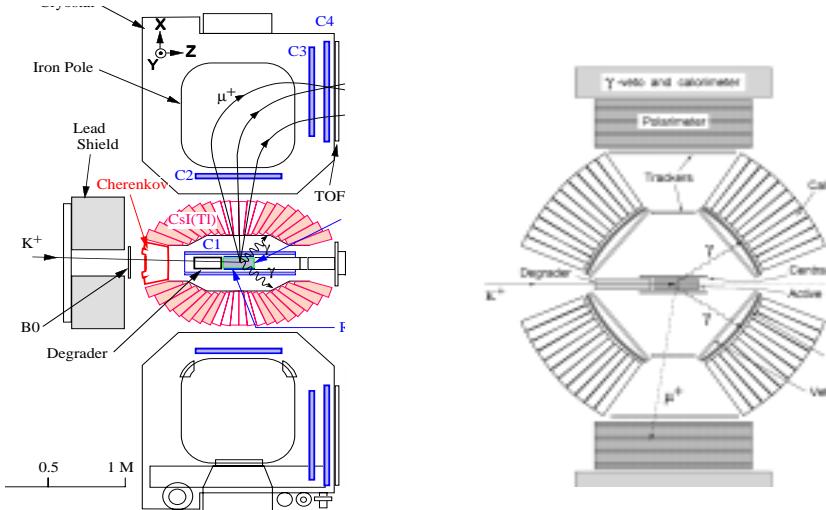
angular contribution = small for $X \rightarrow 0$

Further optimization are necessary taking into account ;

- Detector acceptance
- Systematic errors
- Event selection performance

“ P_T in $K^+ \rightarrow \pi^0 \mu^+ \nu$ and $K^+ \rightarrow \mu^+ \nu \gamma$
with $\delta P_T < 10^{-4}$ and $\delta P_T \sim 10^{-4}$ ”

Vector correlation



At J-PARC

- Higher beam rate
- Different conditions for up- and down-stream side

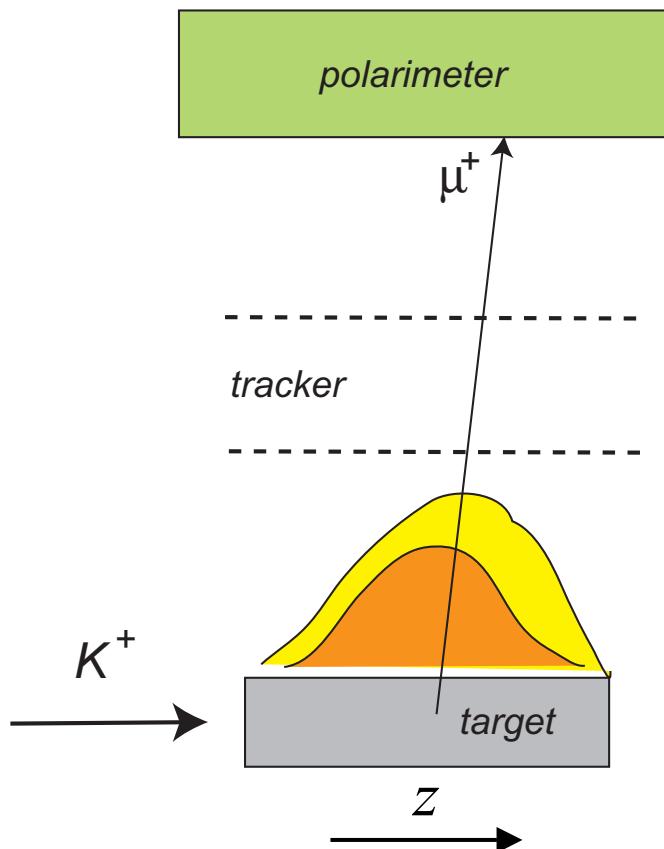
Double ratio between
left-going π^0 and
right-going π^0

$$A_T = \frac{A_{left} - A_{right}}{2}$$

$$A_{left} = \alpha \vec{\sigma}_\mu \cdot (\vec{p}_\mu \times \vec{p}_\pi^{left})$$

$$A_{right} = \alpha \vec{\sigma}_\mu \cdot (\vec{p}_\mu \times \vec{p}_\pi^{right})$$

Symmetrization of K^+ stopping distribution



Adjustment of null asymmetry

$$A_0 = (A_{left} + A_{right})/2$$

- $N(z_K)$ =symmetric $\Rightarrow A_0 = 0$
- $N(z_K)$ =asymmetric $\Rightarrow A_0 \neq 0$

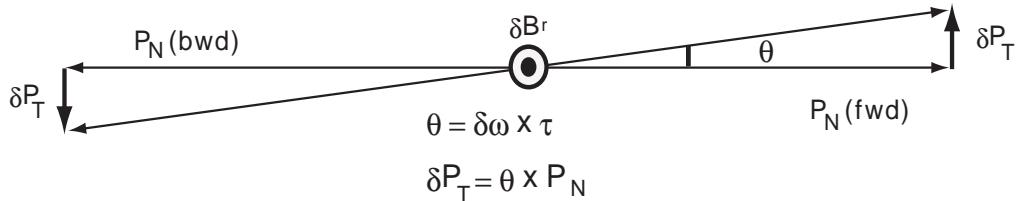
$$A_T = (A_{left} - A_{right})/2$$

No effect in A_T from asymmetric z-distribution due to left-right cancellation
but
unknown higher order systematics

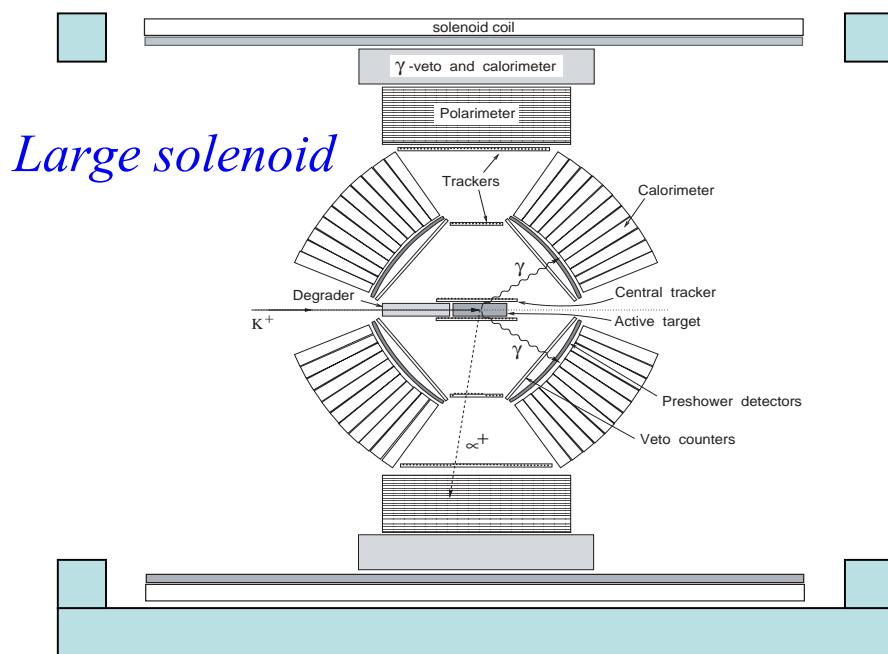
Artificial z- symmetrization by using tracker

$$\implies A_0 = 0$$

Necessity of magnetic field



Zero field experiment
necessary condition=
 $\delta Br < 1 \text{ m Gauss}$
very difficult to make



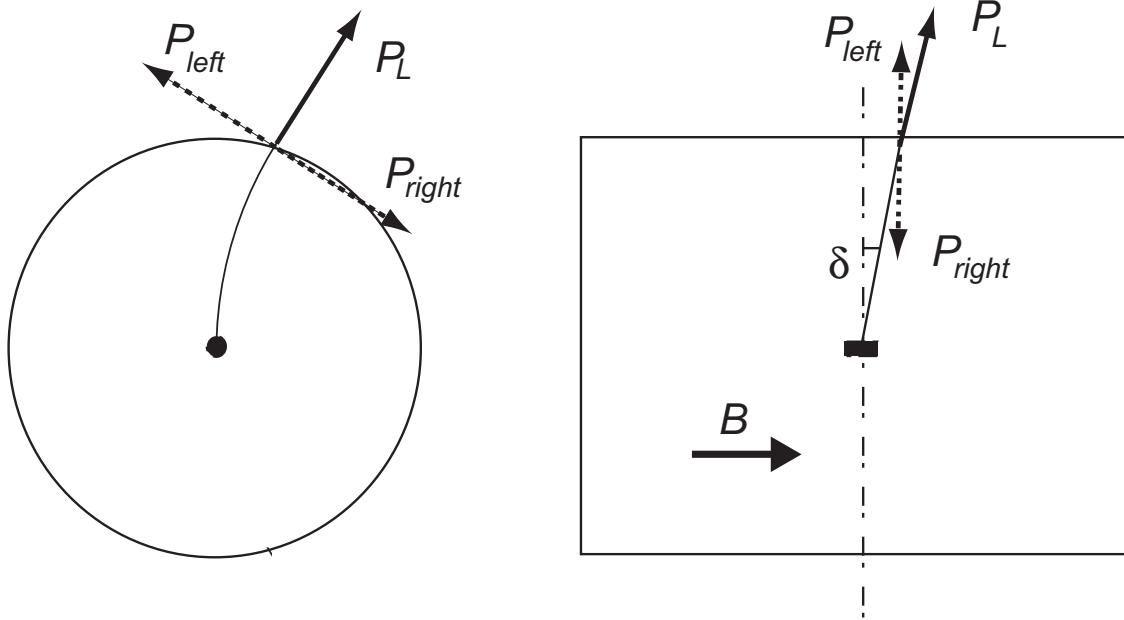
Large solenoid

Field parameters

- Strength : 1-3 kG
- Alignment+symmetry : 10^{-4}
• 100μ over 1m
- Field measurement with a rotating coils
- Allowed stray field : 100 mG

Use of the field for tracking

Effects of magnetic field on polarization

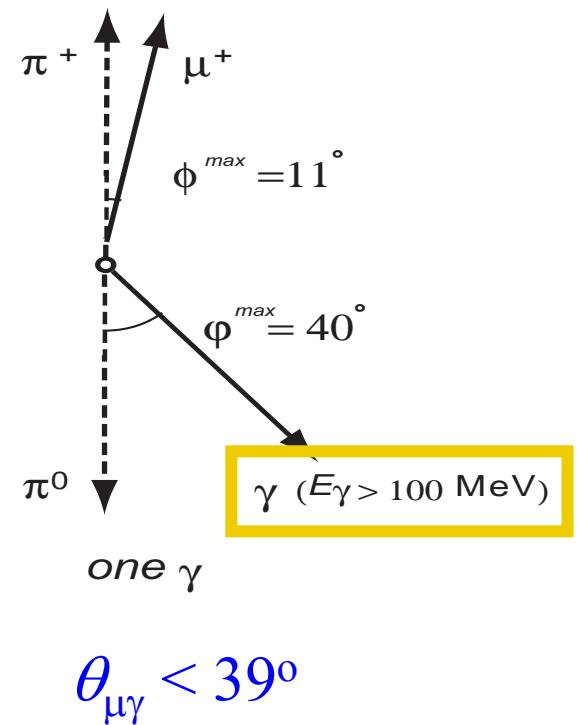
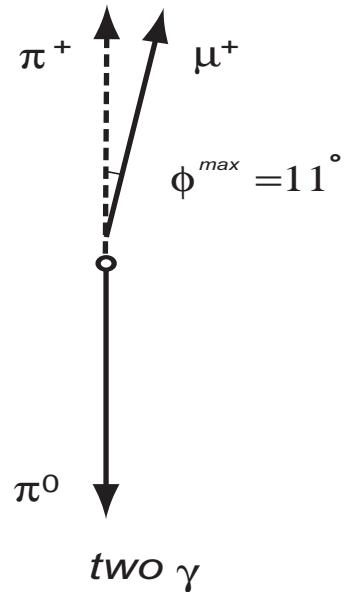
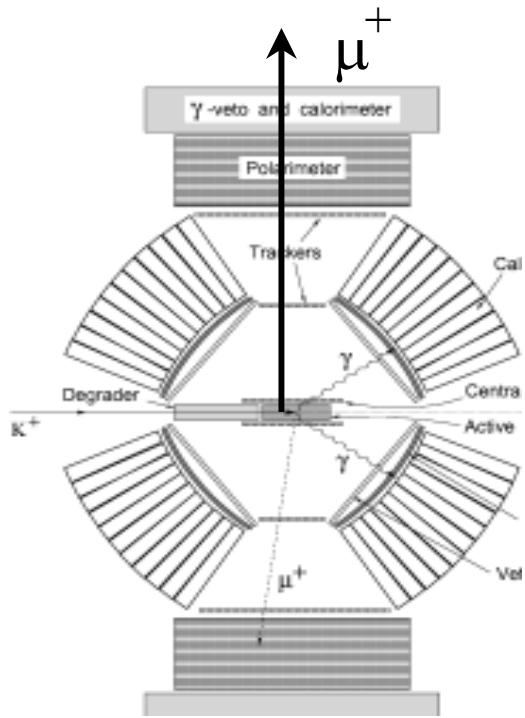


$$\delta P_T = P_L \times \sin \delta$$

- Cancellation between $+\delta$ and $-\delta$
- Null asymmetry check
- Cancellation between *left* and *right*

Same situation as in the zero field case

Rejection of $K_{\pi 2}$ background



Optimization of $K_{\pi 2}$ background rejection by

- Opening angle cuts, and
- X-parameter cut

Active polarimeter

Analysis

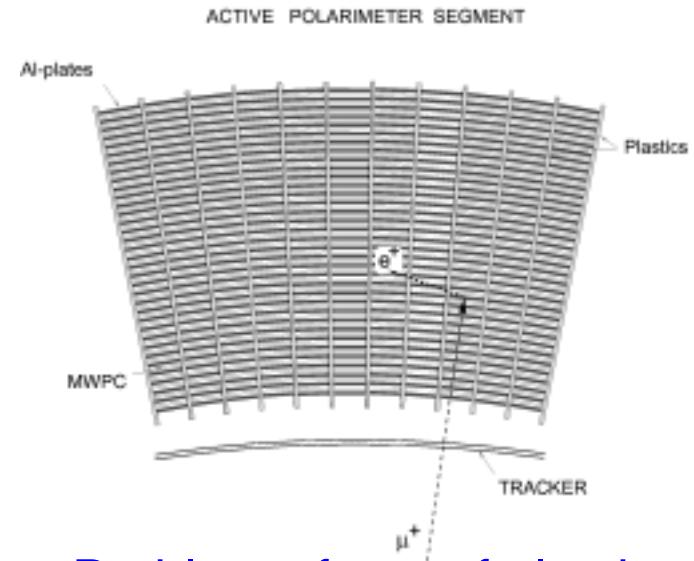
Michel spectrum

$$W(E_e, \theta) = 1 + P^k \alpha(E_e) \cos \theta_e^k.$$

$$P^k = \int_0^{E_e^{\max}} \frac{<\cos \theta_e^k>_E}{\alpha(E_e)} w(E_e) dE_e$$

Measurement of

- Muon stopping position
- Positron emission direction
- Positron energy
- Electromagnetic shower
 - location
 - energy deposit



Problem of use of plastics

- formation of muonium
- muon spin depolarization

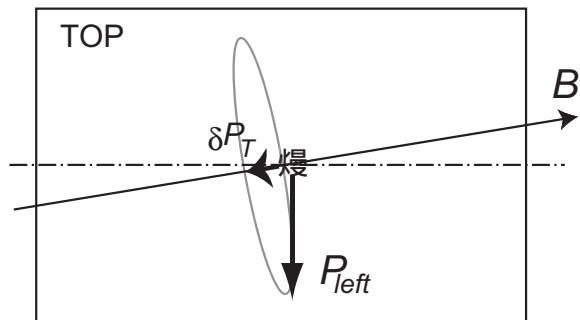
B=3kG enough for decoupling?

*Better choice will be
muon tubes made of Al*

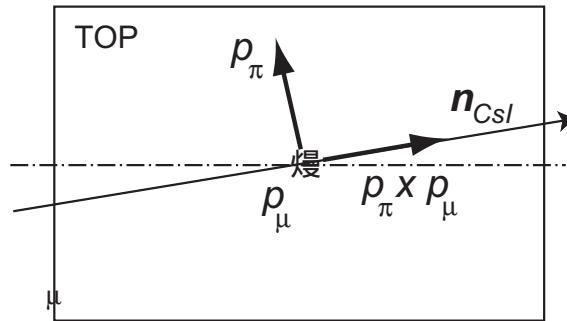
Instrumental systematics

Misalignments

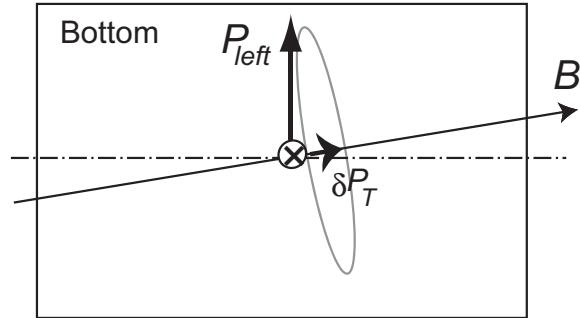
Magnet



π^0 calorimeter

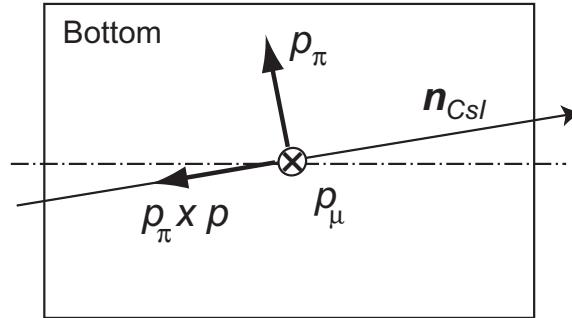


Bottom



spurious δP_T

Bottom

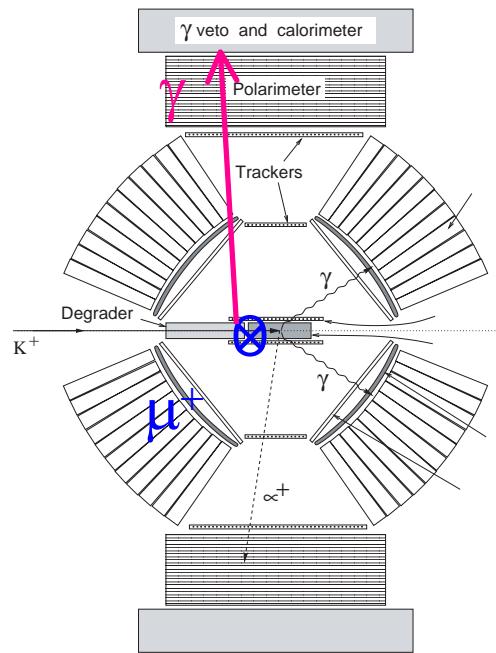


decay plane rotation

Cancellation by azimuthal integration

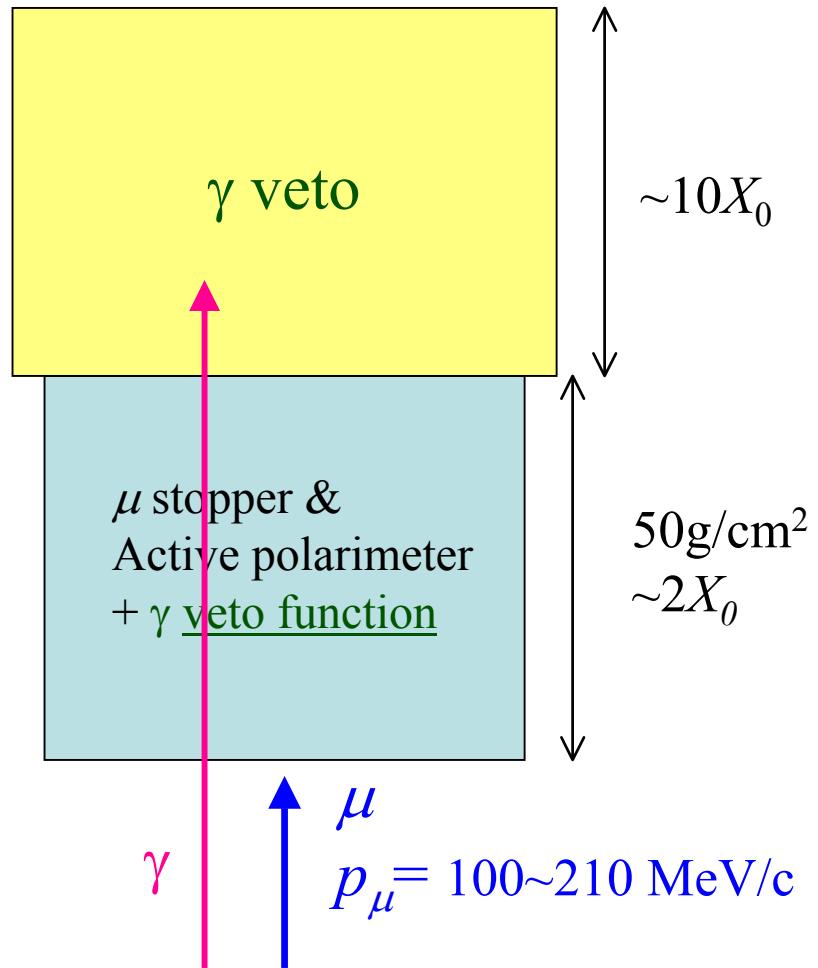
Photon veto and $K_{\mu\nu\gamma}$

- Identification of one γ events
- Rejection of $\pi^0 \rightarrow 2\gamma$ events



$$P_T = \sigma_\mu \cdot (p_\mu \times p_\gamma)$$

Both μ and γ in the polarimeter



Sensitivity for $K_{\mu 3} P_T$

Table 2: Comparison of statistical sensitivity

	E246	E246-mod.	Loi-19
Analyzing power	0.270	0.44	0.44
Polarimeter FoM (rel.)	0.101	0.38	0.38
Detector acceptance	1.1×10^{-4}	1.1×10^{-4}	2×10^{-4}
Kaon intensity (/sec)	$10^5/\text{s}$	$10^6/\text{s}$	$10^7/\text{s}$
Run time (relative)	1.5	0.66	1
Number of $K_{\mu 3}$	1.1×10^7	4.4×10^7	1.3×10^{10}
Statistical error δP_T	2.3×10^{-3}	3.0×10^{-4}	4×10^{-5}

- $FoM = \alpha \sqrt{\Omega}$

- Run time 1 = 10^7 s

- Loi-19 estimate based on fwd/bwd scheme

Rough estimate of $K_{\mu\nu\gamma} P_T$

- | | |
|-------------------------|------------------|
| 1. Photon energy | 20 – 200 MeV |
| 2. Muon energy | ≥ 200 MeV |
| 3. $\theta_{\gamma\mu}$ | $\leq 120^\circ$ |

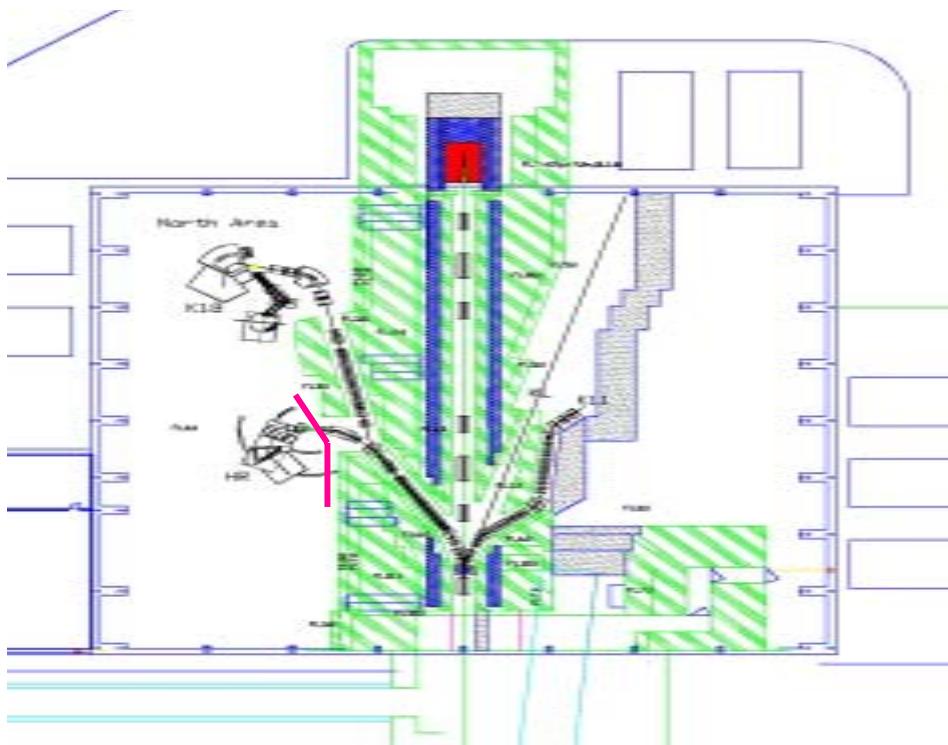
Acceptance per K^+	$\sim 0.7 \times 10^{-4}$
$N(K^+ \rightarrow \mu^+\nu\gamma)$	$\sim 0.7 \times 10^{10}$

Statistical sensitivity $\Delta P_T(1\sigma) \sim 0.7 \times 10^{-4}$
(estimate based on fwd/bwd scheme)

High rate performance

- Detector elements are designed from now on.
- R&D of pre-shower counter started at INR.
- Each element will be highly segmented.
 - Target : fiber target
 - Tracker: high rate chamber + Scifi
 - γ -detector: pre-shower counter + fast crystal or
fiber sampling shower counter
 - γ -veto : highly segmented
 - Polarimeter: highly segmented.

Kaon beam



K0.8 at T1 target

In Phase 1 for stopped $K^{+/-}$ beam

- $p = 650 \sim 800 \text{ MeV}/c$
- $K/\pi > 1$ with two DCSs
- $\Delta p/p < 3\%$
- K^+ intensity = $10^6 \sim 10^7 /s$

T2 target in Phase2

- Is it possible to use the K1.1 line?
- C-type branch of K1.1
 - how to optimize beam optics?
 - how to put two DCS?
 - how to coexist with the future High- p line?

Summary

- Search for T-violation in K decays at J-PARC is very promising:

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

$$\delta P_T(\text{stat}) \leq 10^{-4}$$

$$K^+ \rightarrow \mu^+ \nu \gamma$$

$$\delta P_T(\text{syst}) \sim 10^{-4}$$

- We seek for the possibility to run in Phase 1.
- A stopped K^+ beam in the K hall is very important.
- Detector design will be done toward a full proposal.