T-Violation in $K^+ \to \pi^0 \mu^+ \nu$ at KEK

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(E246 collaboration)

XXVI SLAC Summer Institute
Topical Conference

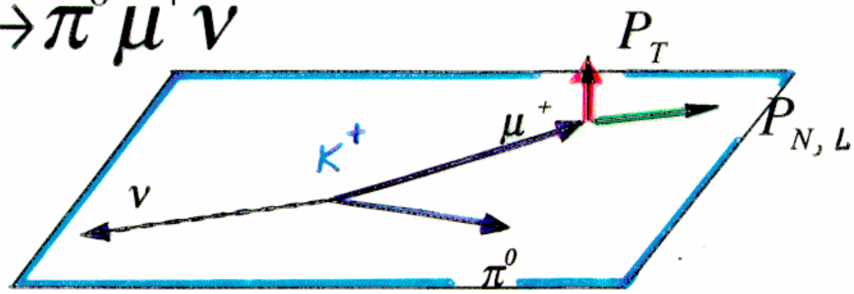
August 14, 1998

1. Transverse polarization in $K^+ \to \pi^0 \mu^+ \nu$ ($K_{\mu 3}$)
2. KEK-PS E246 experiment
3. Preliminary result from 1996-97 data

E246 Collaboration

Japan	KEK Univ. of Tsukuba Tokyo Institute of Technology Univ. of Tokyo Osaka Univ.
Russia	Institute for Nuclear Research
Canada	TRIUMF Univ. of British Columbia Univ. of Saskatchewan Univ. of Montreal
Korea	Yonsei Univ. Korea Univ.
U.S.A.	Virginia Polytech Institute Princeton Univ.
Taiwan	National Taiwan Univ.

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



$$P_T = \vec{\sigma}_\mu \cdot (\vec{p}_\mu \times \vec{p}_{\pi^0})$$

T-odd correlation

P_T^{spurious} (Final State Interaction) $\approx 10^{-6}$ (Zhitnitskii, 1980)

$P_T \neq 0$ ($> 10^{-6}$) ➡ T-violation

Decay amplitude of $K_{\mu 3}$ and P_T

$$M = \frac{G_F}{2} \sin\theta_C [\, f_+(q^2)\,(p_K^{\lambda} + p_\pi^{\lambda}) + f_-(q^2)\,(p_K^{\lambda} - p_\pi^{\lambda})\,] \cdot [u_\mu \gamma_\lambda (1-\gamma_5) u_\nu]$$

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

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

$\mathrm{Im}\xi \neq 0$ ⟷ T-violation

Search for P_T in $K_{\mu 3}$ decay

P_T (Standard Model) = 0 $\rightarrow$

$P_T \neq 0$ means *other sources of CP-violation*

- three Higgs doublet models [1,2]
- leptoquark models [1,2]
- some supersymmetric models [3,4]

may give a sizable contribution to P_T without conflicting with other experimental constraints.

$$P_T \approx 10^{-3}$$

<recent theories>

[1] R.Garisto and G.Kane; PR D44, 2038 (1991)

[2] G.Bélanger and C.Q.Geng; PR D44, 2789 (1991)

[3] M.Fabbrichesi and F.Vassani; PR D, 5334 (1997)

[4] G.H. Wu and J.N. Ng; PR D56, 93 (1997)

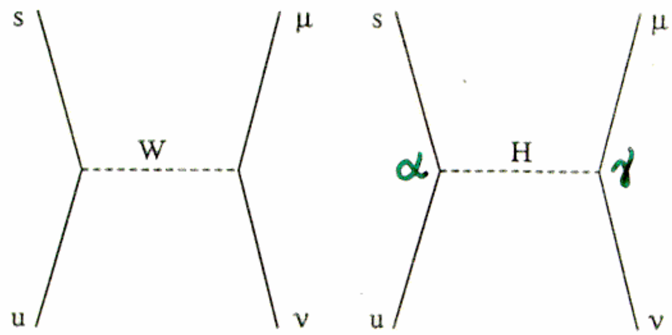
<Previous data>

	P_T	$\mathrm{Im}\xi$	
$K^+ \rightarrow \pi^0 \mu^+ \nu$	- 0.0031±0.0053	- 0.016±0.025	BNL-AGS
	(in-flight decay)		Blatt *et al.* 1983
$K_L^0 \rightarrow \pi \mu \nu$	0.0021±0.0048	0.009±0.030	BNL-AGS
	$(P_T^{spurious}(FSI) \approx 0.01)$		Morse *et al.* 1979

Theoretical Models for P_T

(1) Three Higgs doublet model

exchange of H^+

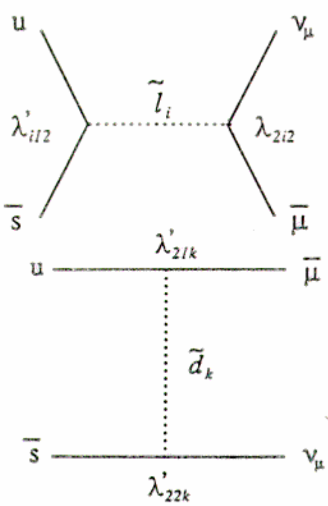


$$\mathrm{Im}\xi^K = -\mathrm{Im}(\gamma_1\alpha_1^*)\cdot\left(\frac{m_K}{m_{H_1^+}}\right)^2 = \mathrm{Im}(\alpha_1\beta_1^*)\cdot\left(\frac{v_2}{v_3}\right)^2\cdot\left(\frac{m_K}{m_{H_1^+}}\right)^2.$$

- *constraint on $Im(\alpha_1\beta_1{}^*)$ and (v_2/v_3)*

(2) R-parity violating SUSY

exchange of sleptons and down-type squarks



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

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

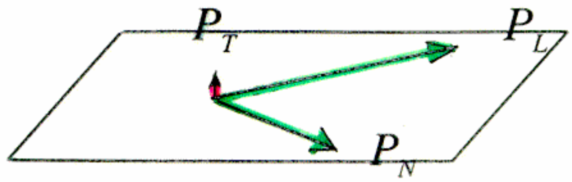
- *constraint on $Im[\lambda_{2i2}(\lambda_{i12}')^*]$ and $Im[\lambda_{21k}'(\lambda_{22k}')^*]$*

How to detect small P_T?

- *in the presence of large in-plane components P_L and P_N*
- *by suppressing systematic errors.*

$P_L \parallel \vec{p}_{\mu}$

$P_N \perp \vec{p}_{\pi 0}$ μ



KEK-PS E246 experiment

- stopped K^+ method
- Superconducting Toroidal Spectrometer
- ΔP_T (stat) $\approx 10^{-3}$, ΔP_T (sys) $< \Delta P_T$ (stat)

Advantage of stopped K^+ method

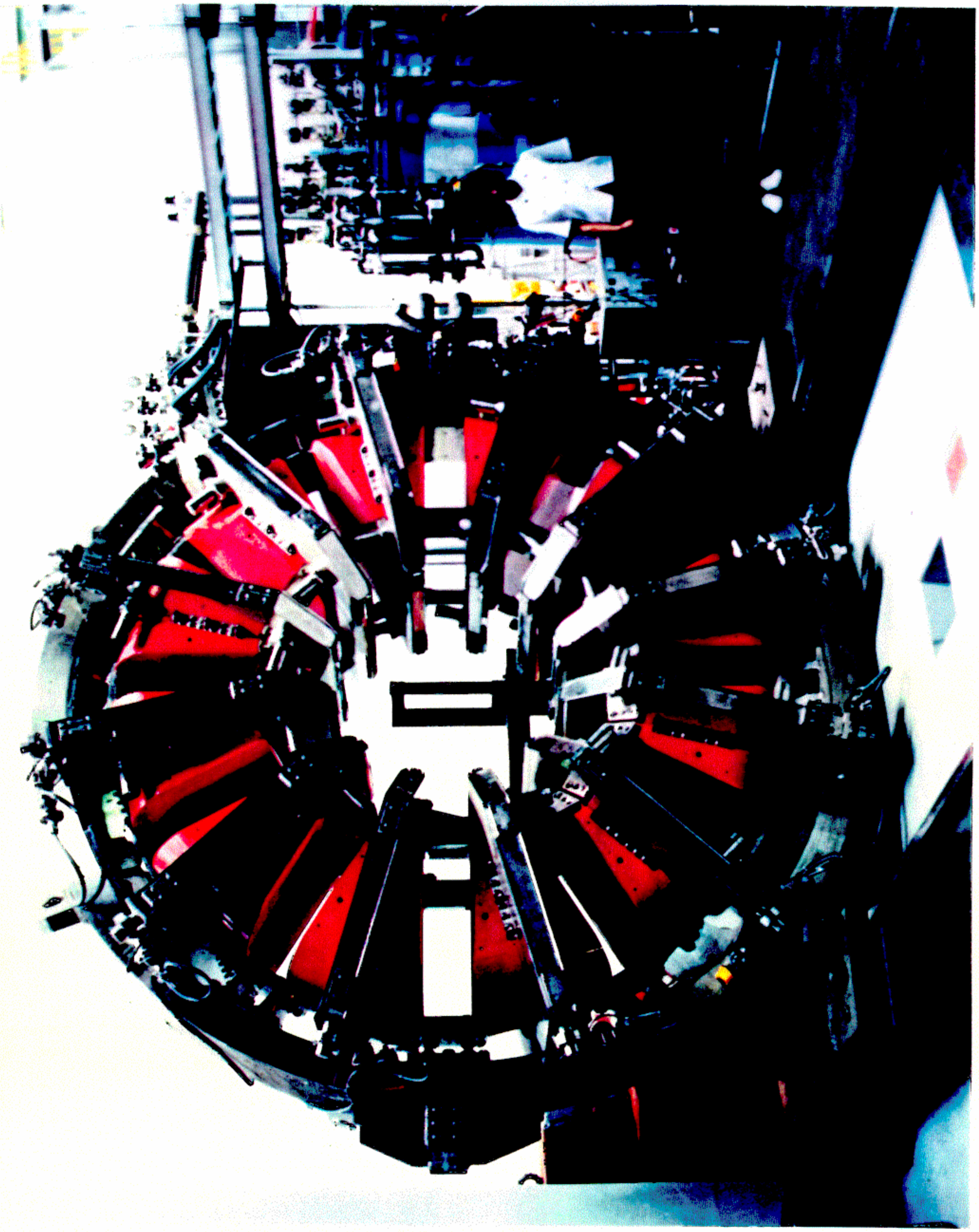
1) total coverage of decay kinematics
   - *double ratio measurement*

2) detectors located off beam
   - *lower rate and lower background*

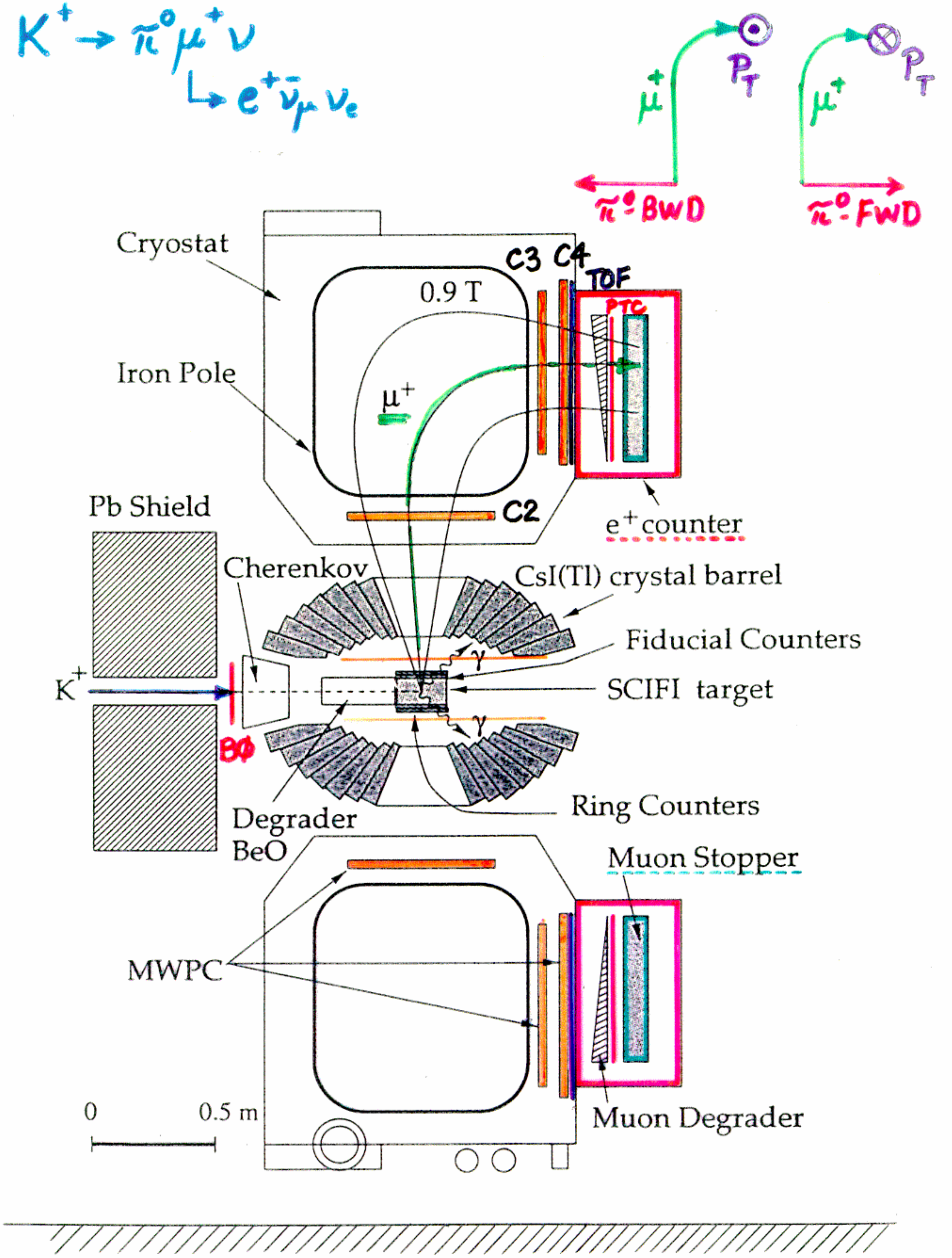
3) smaller size of setup
   - *controllable systematics*

Superconducting Totoidal Spectrometer

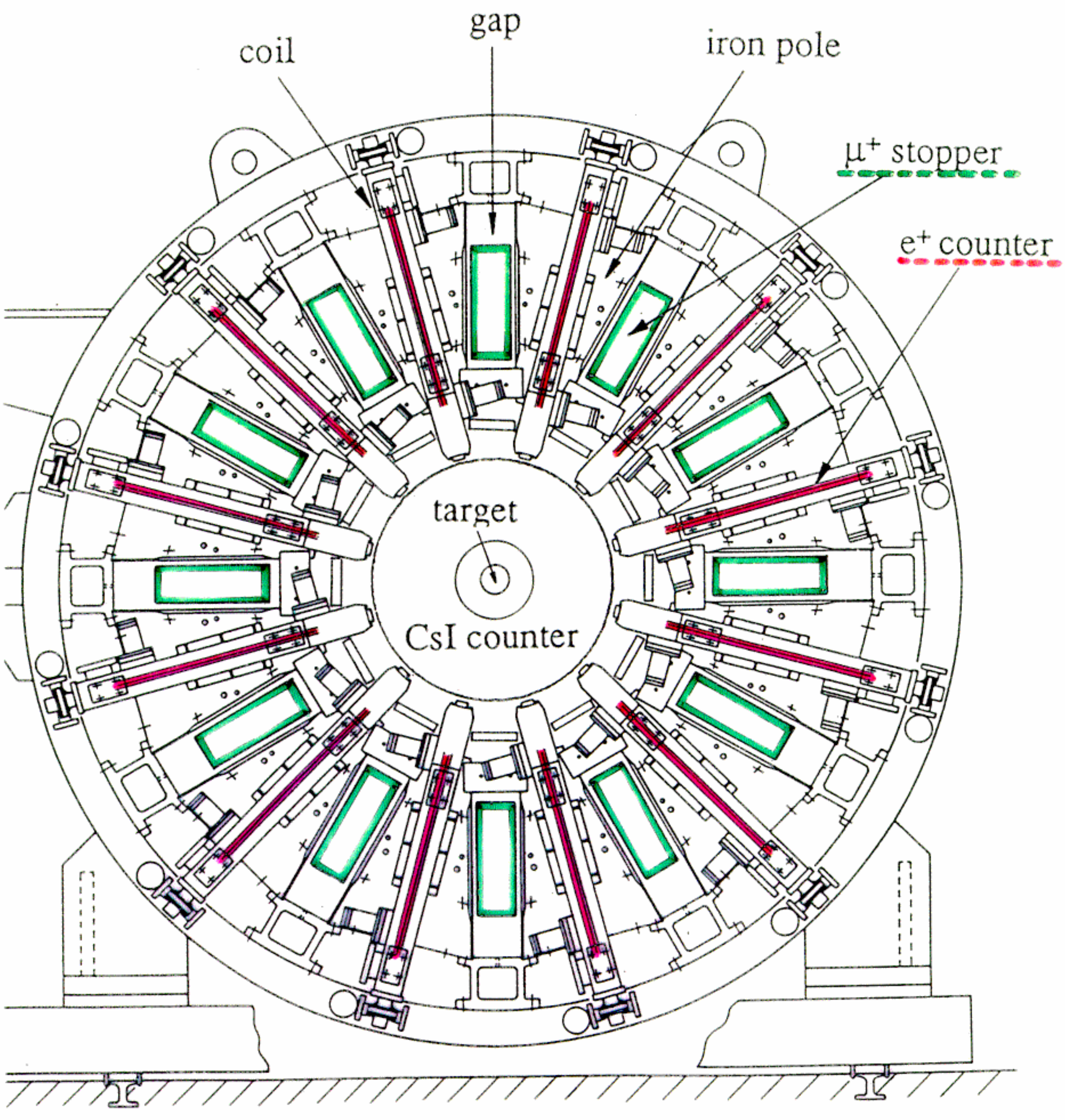
- *large acceptance for stopped decay*
- *high momentum resolution*
- *30° rotational symmetry*



J. Imazato, SSI 1998



Superconducting Toroidal Magnet

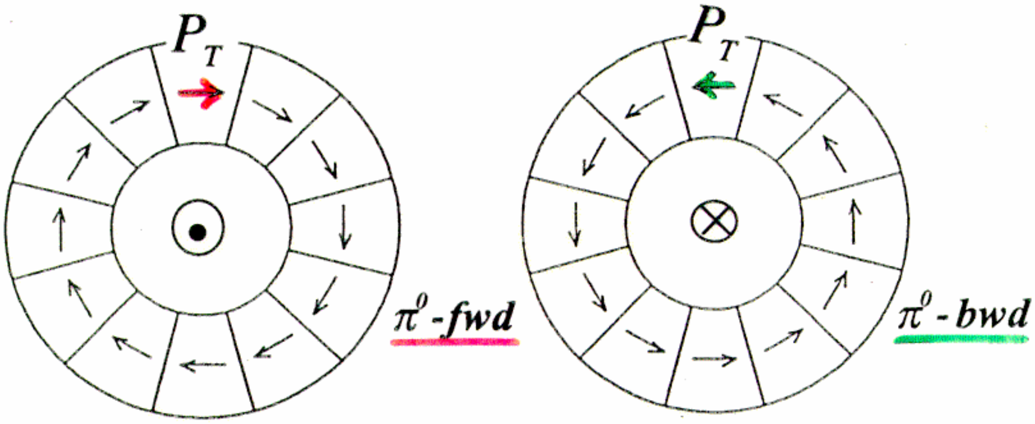


0 0.5 1M

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

$$W(\theta_{e^+}) \sim 1 + A P_\mu \cdot \cos\theta_{e^+}$$

Double ratio experiment E246



e^+ *cw/ccw* asymmetry

$$\frac{\Sigma_{i=1}^{12} N_i(cw)}{\Sigma_{i=1}^{12} N_i(ccw)} = 1 \pm 2\alpha <\cos\theta_T> P_T$$

α : analyzing power

$<\cos\theta_T>$: kinematical attenuation

- *most of systematics are cancelled by* $\Sigma_{i=1}^{12}$.

1) K^+ stopping distribution in target
2) e^+ counter efficiency
3) azimuthal distribution of π^0 detection efficiency

Ratio of asymmetry between *fwd* and *bwd*

$$\frac{[\Sigma_{i=1}^{12} N_i(cw) / \Sigma_{i=1}^{12} N_i(ccw)]_{fwd}}{[\Sigma_{i=1}^{12} N_i(cw) / \Sigma_{i=1}^{12} N_i(ccw)]_{bwd}} = 1+4\alpha <\cos\theta_T> P_T$$

- *most of the systematic errors are cancelled further*

Sensitivity (P_T/Imξ) distribution

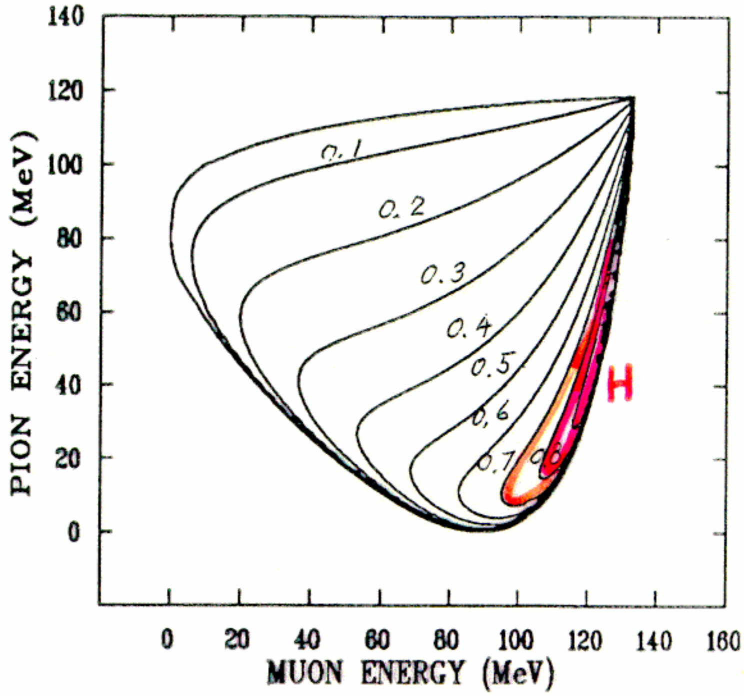
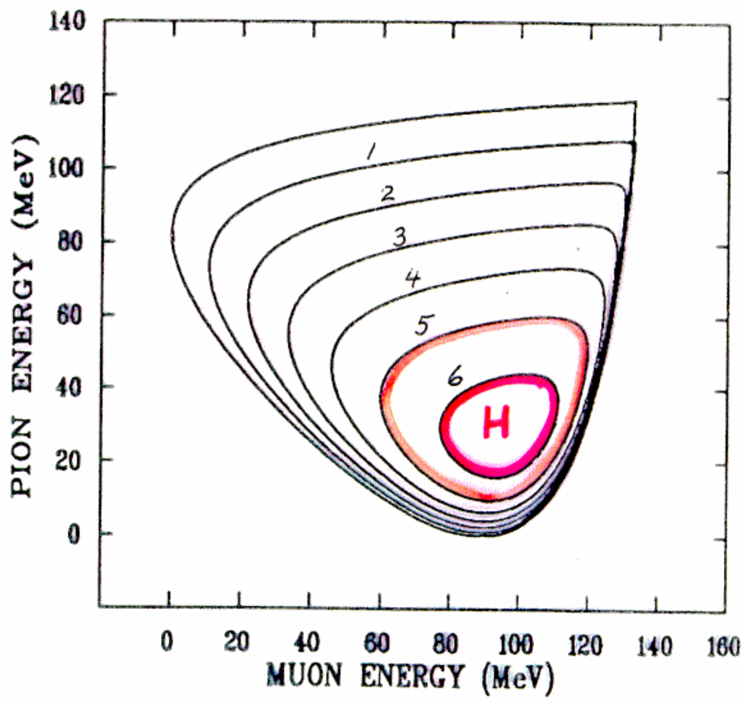
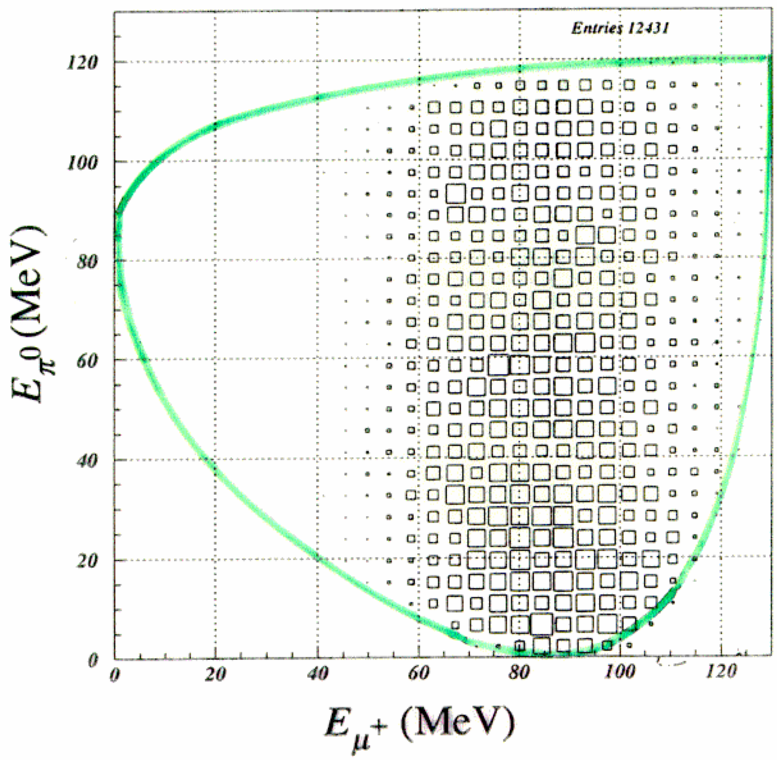


Figure of Merit (P_T/Imξ $\bullet\sqrt{N}$) distribution

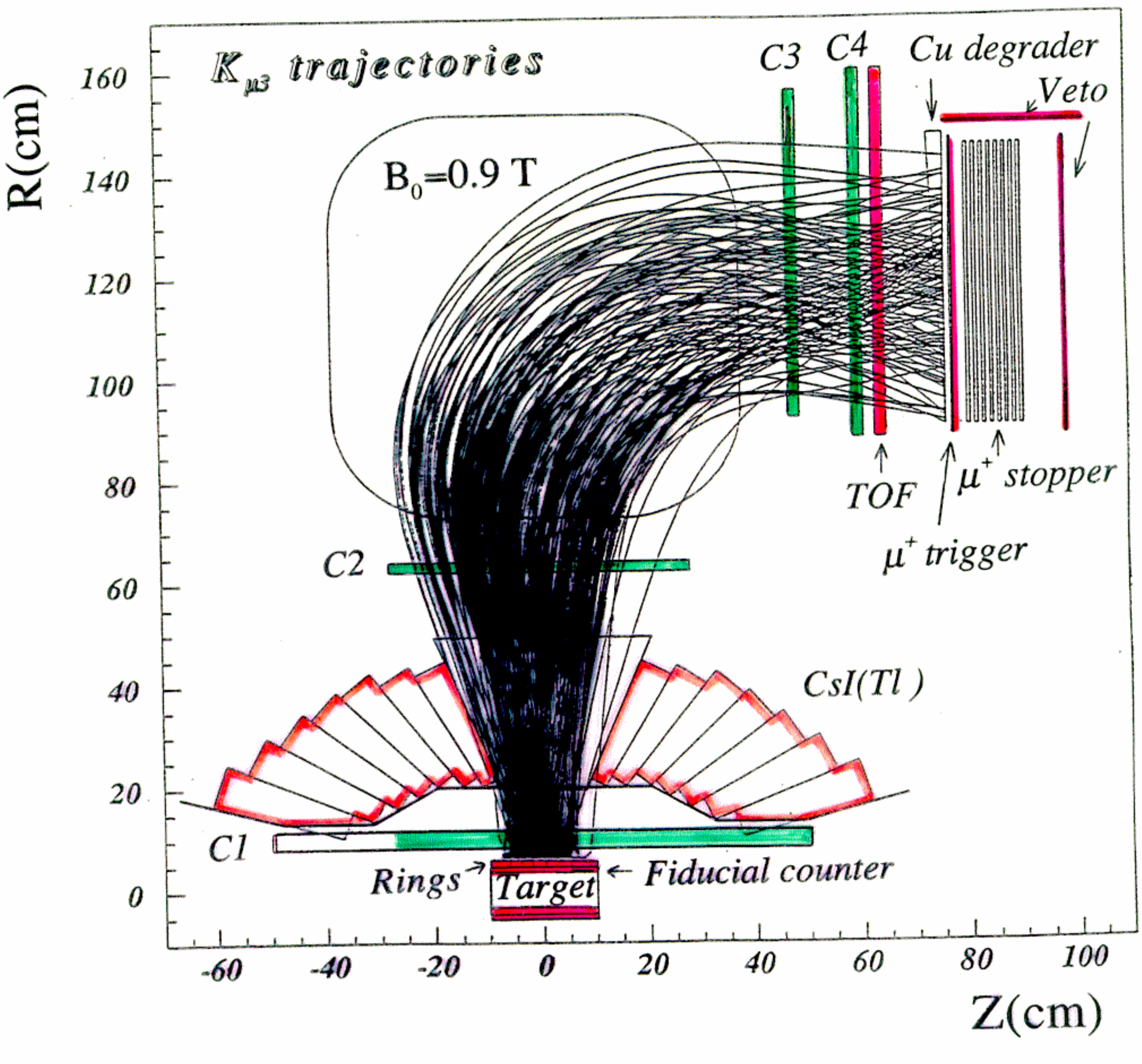


Detector Acceptance

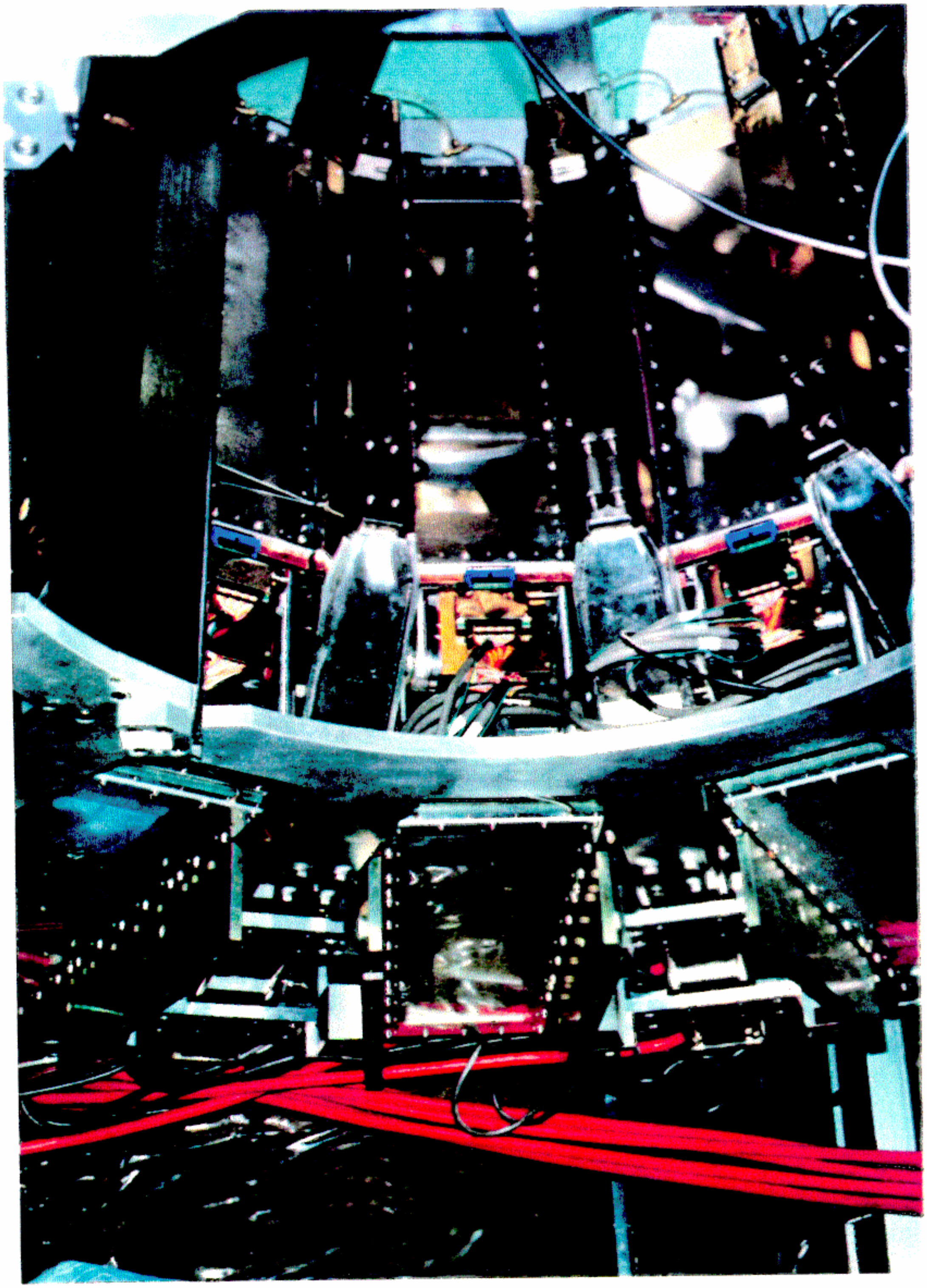


- K^+ beam intensity — 1.0×10^5 /sec
  @ KEK-PS K5 channel (660 MeV/c)
- K^+ stopping efficiency — 0.40
- $K_{\mu 3}$ branching ratio — 0.032
- Detector acceptance
  - spectrometer and
  - μ^+ stopping — 0.022
  - π^0 detection — 0.54
  - e^+ detection — 0.12
  - data taking — 0.8
  - analysis — 0.9
- Event rate — ≈ 1.0 /sec

μ^+ tracking

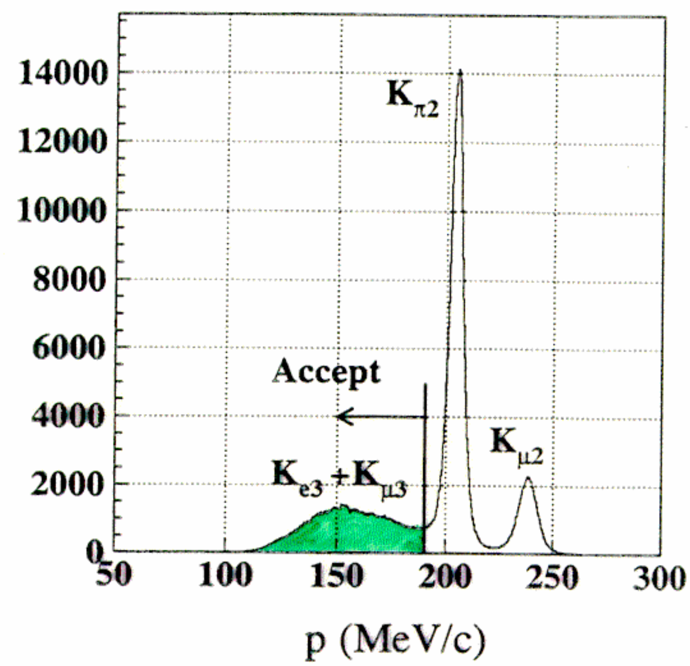


K_μ3 trajectories
B_0=0.9 T
R(cm)
Z(cm)
C1
C2
C3
C4
Cu degrader
Veto
TOF
μ+ stopper
μ+ trigger
CsI(Tl)
Rings
Target
Fiducial counter

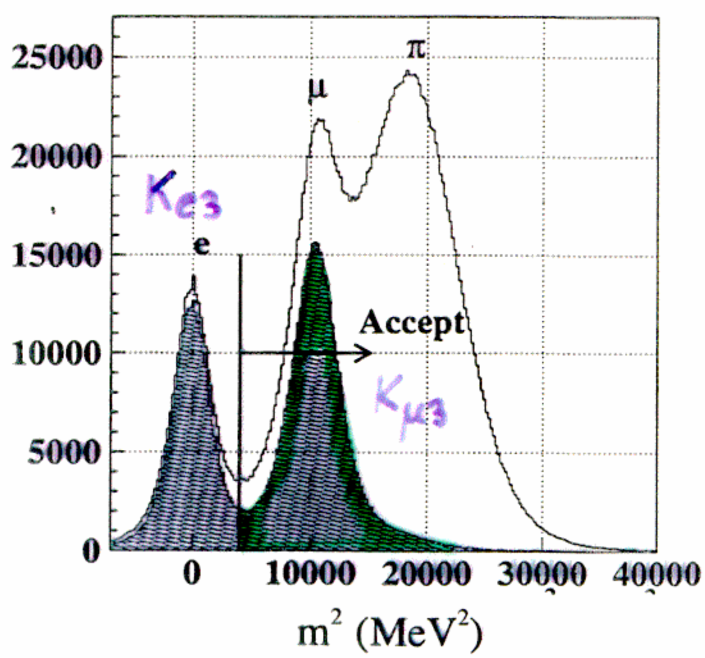


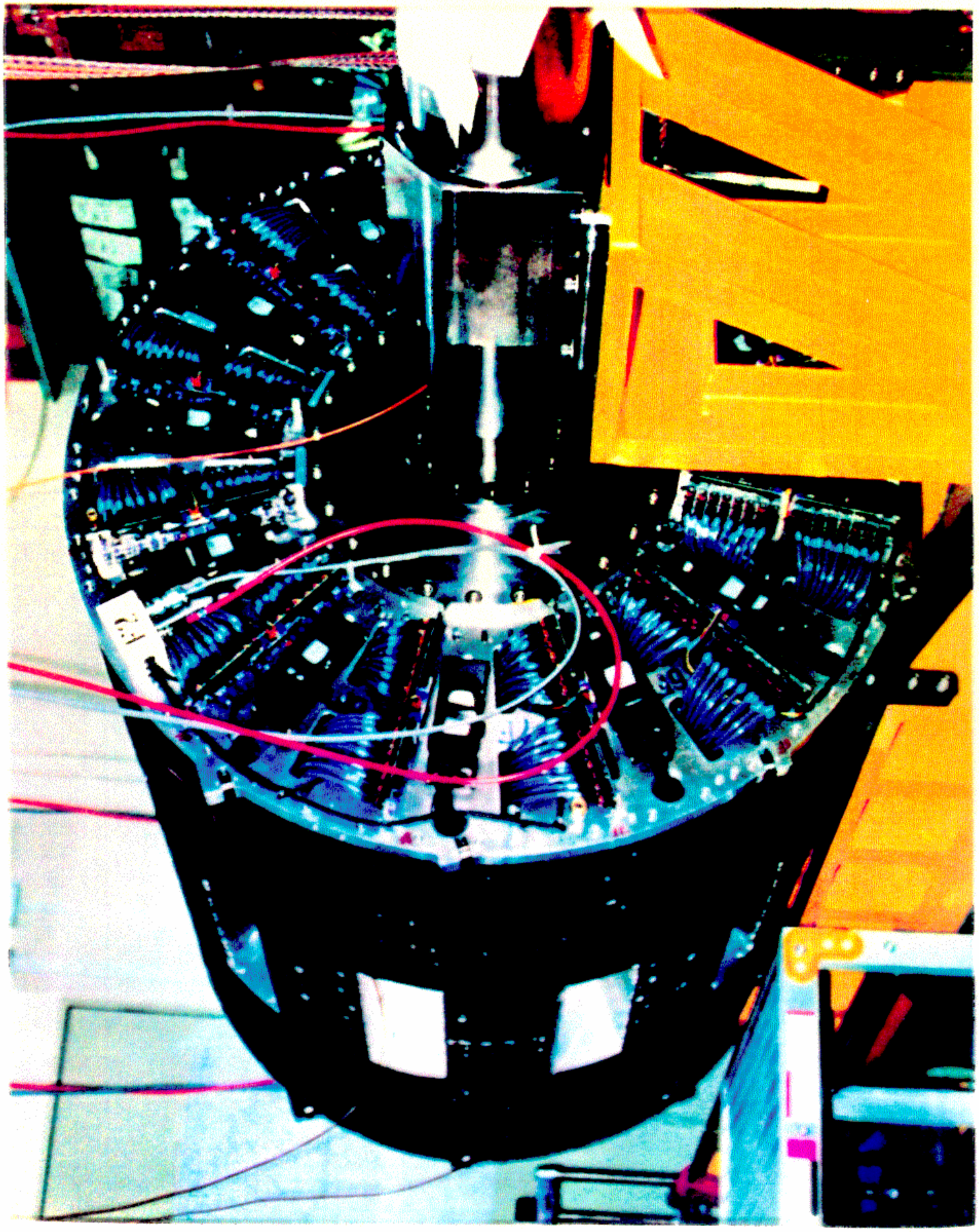
μ^+ from $K_{\mu 3}$

Momentum spectrum



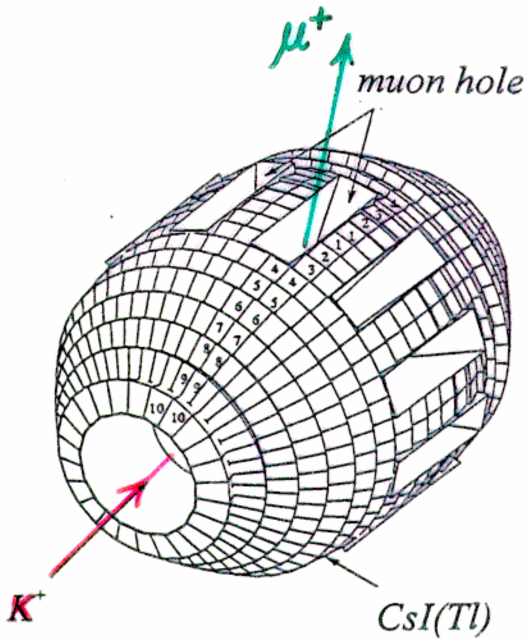
TOF mass spectrum

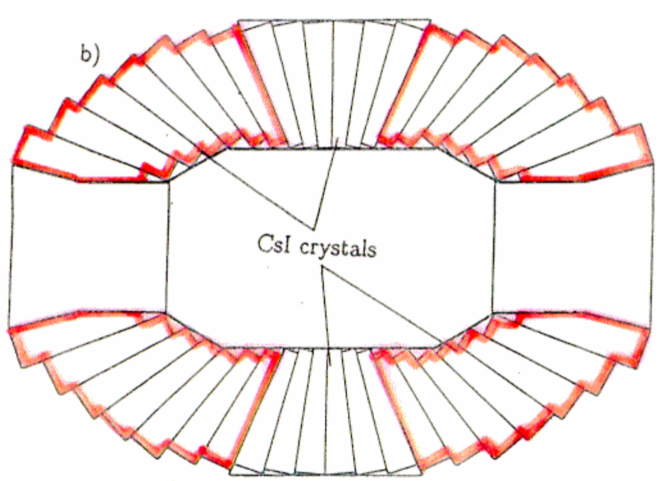




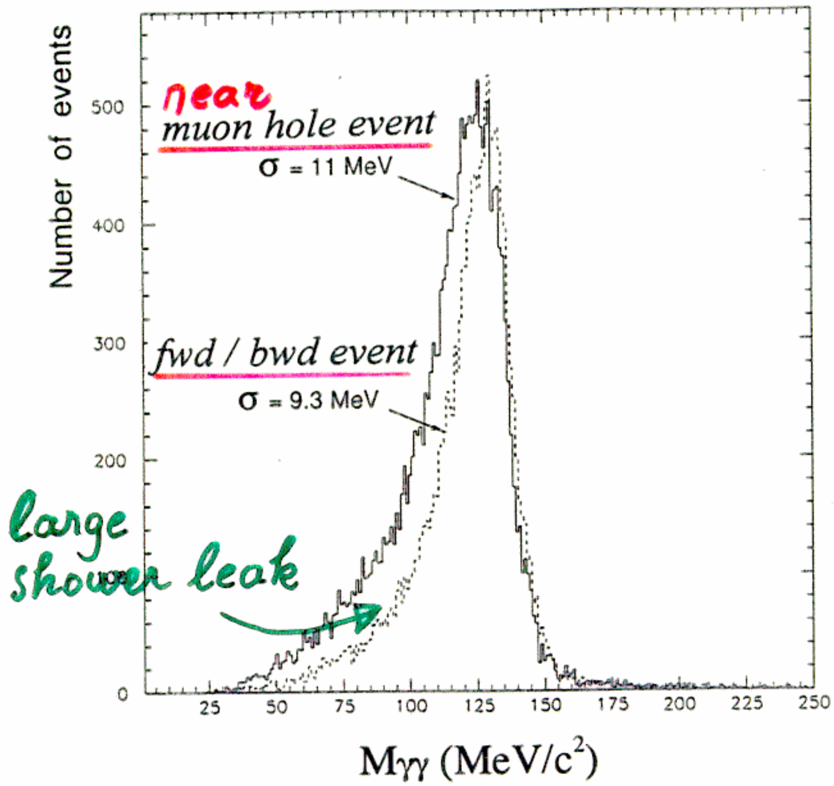
Main Parameters of CsI(Tl) π^0 Detector

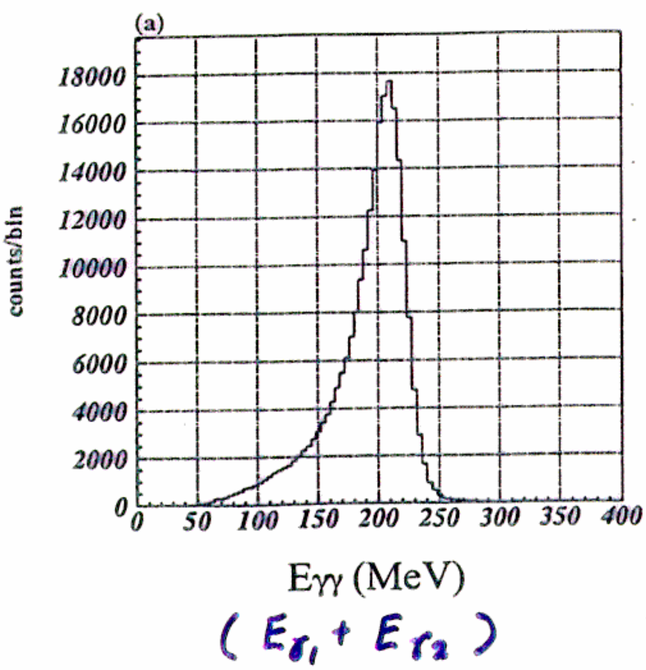
Segmentation	$\Delta\theta = \Delta\phi = 7.5°$
Number of crystals	768
Length of crystals	25 cm (13.5 X_0)
Inner radius	20 cm
Outer radius	50 cm
Solid angle	75 % of 4π $\pi^0 \to 2\gamma, 1\gamma$
Readout	PIN diode (18x18, 28x28 mm)
Light yield	11000 pe / MeV
Equiv. noise level	65 keV (one module)
Energy resolution	σ_E/E = 3.0 % @ 200 MeV
Position resolution	σ_p = 1.0 cm
Time resolution	σ_T = 6.5 ns for 10-220 MeV
π^0-mass resolution	$\sigma_{\pi 0\text{-mass}}$ = 14 MeV/c^2

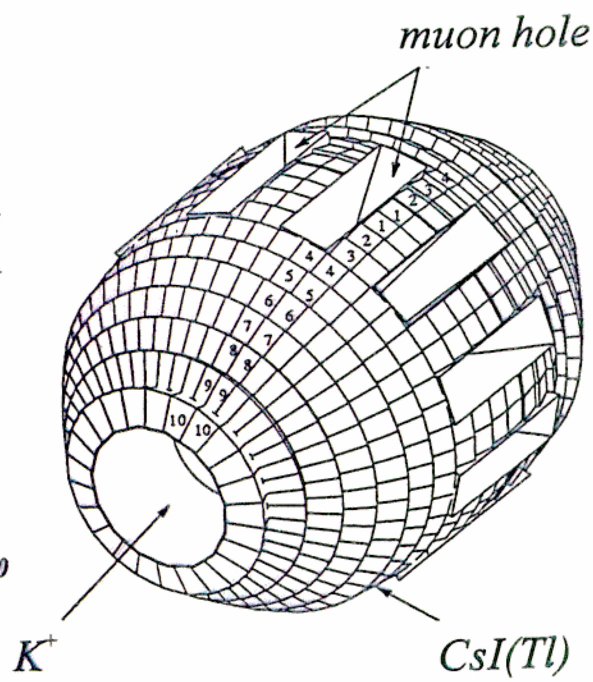




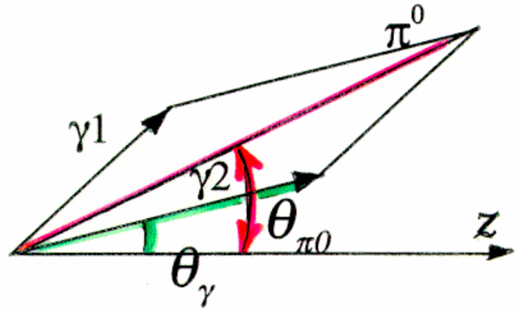
π^0 from $K_{\mu3}$ -2γ events -



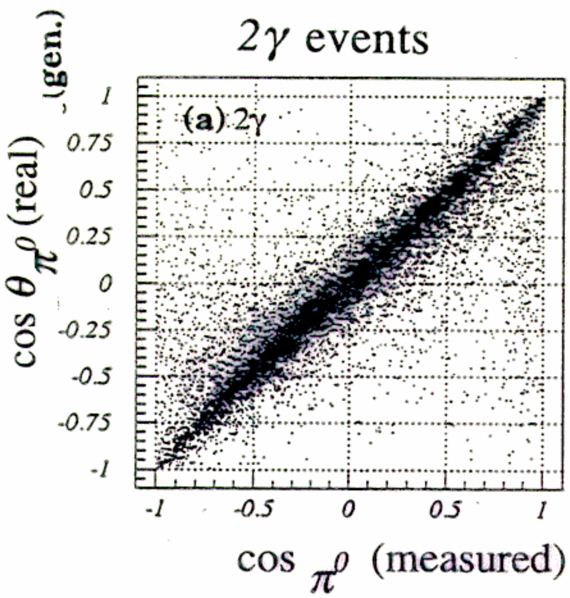


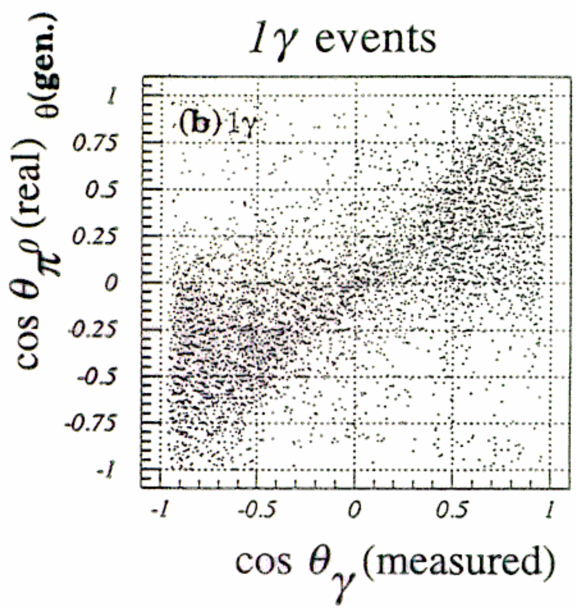


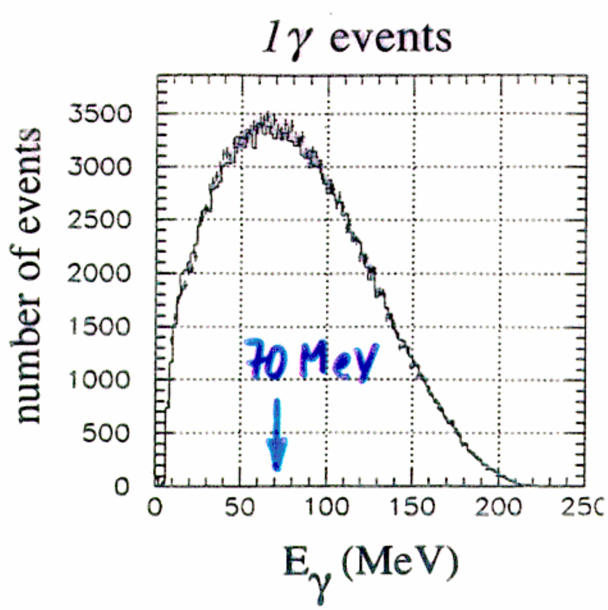
π^0 from $K_{\mu 3}$ -1γ events -

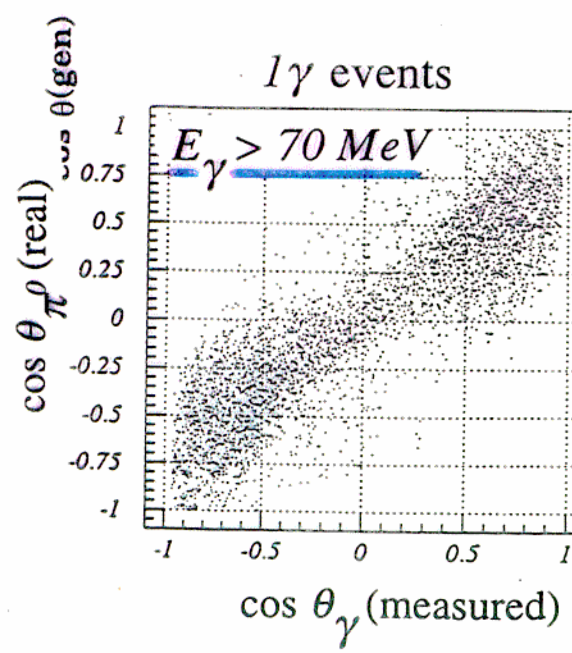


- strong correlation between θ_{π^0} and θ_γ
- high sensitivity also in 1γ events

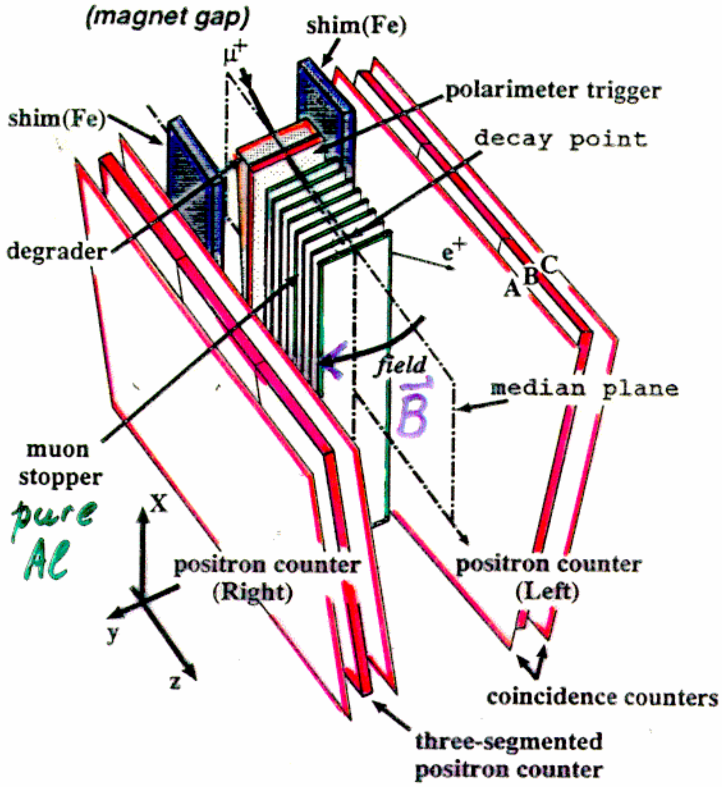








μ^+ Polarimeter



$$\mu^+ \rightarrow e^+ \overline{\nu_\mu} \nu_e$$

$$\frac{N(cw)-N(ccw)}{N(cw)+N(ccw)} = A_T$$

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

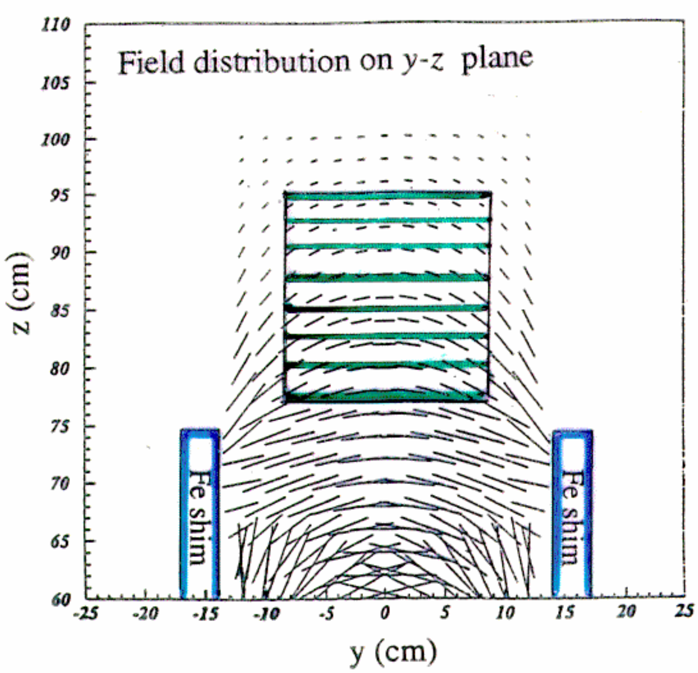
α : *analyzing power*

$\langle\cos\theta_T\rangle$: *kinematic attenuation*

$\langle P_T \rangle$ // B ≈ 150 Gauss

$\langle P_T \rangle$: *preserved*

P_L, P_N : *precess*

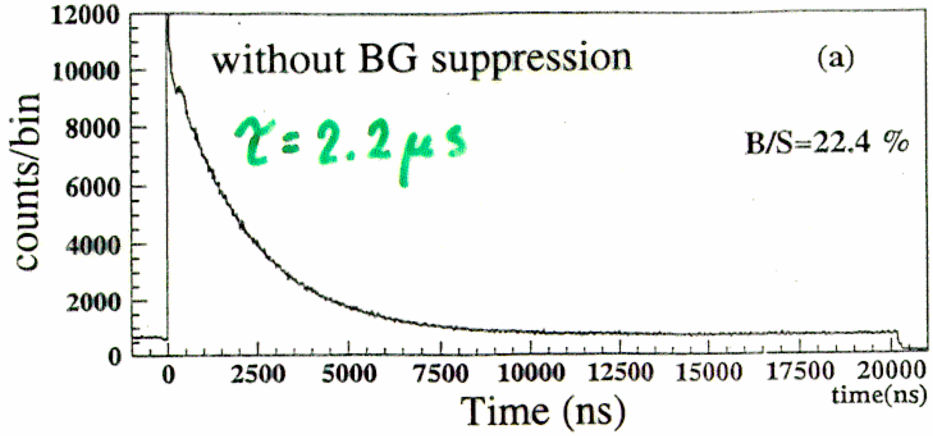


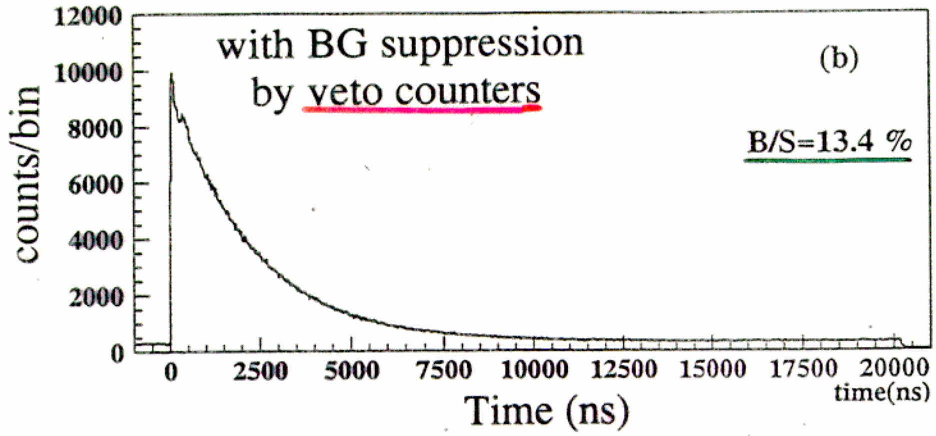
Symmmeric field distribution required

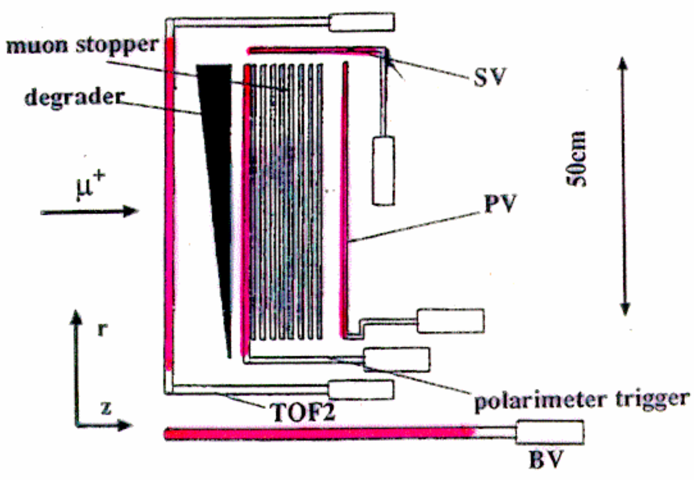
- *precise field trimming with iron shim plates*
- *accurate field mapping*

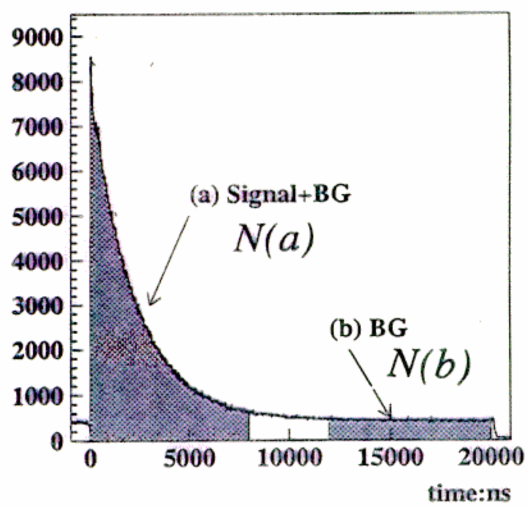
Precise alignment of counters and stopper

e^+ time spectrum







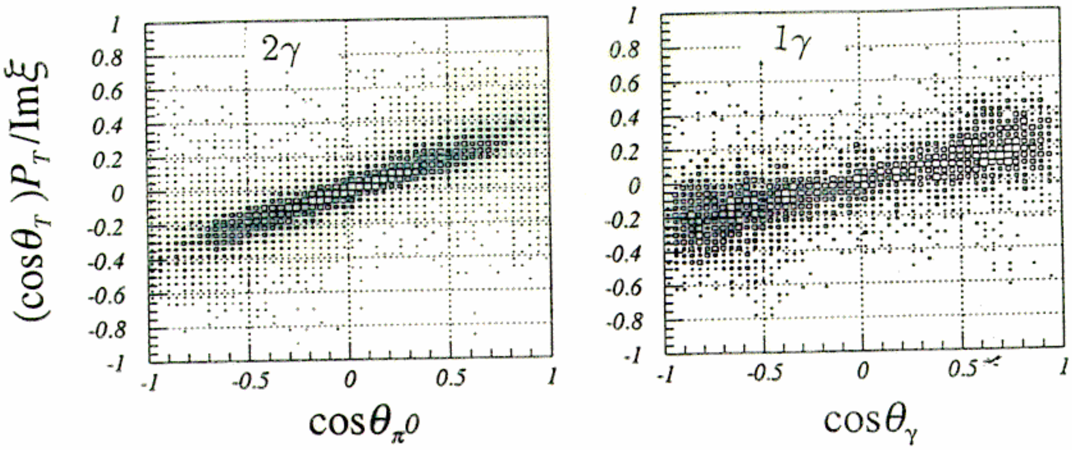


$$N(S) = N(a) - N(b)$$

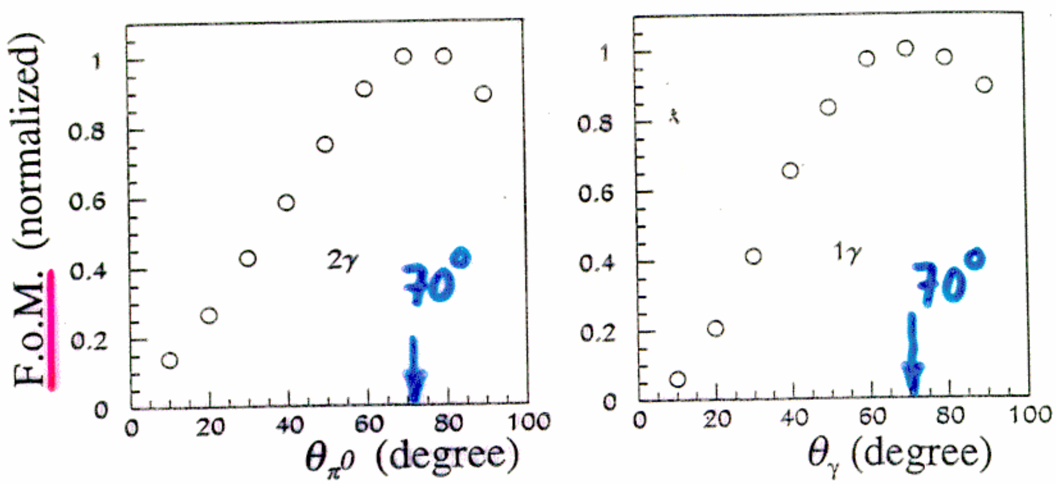
$$\Delta N(S) = \sqrt{N(S)\,\{1 + 2N(b)/N(S)\}}$$

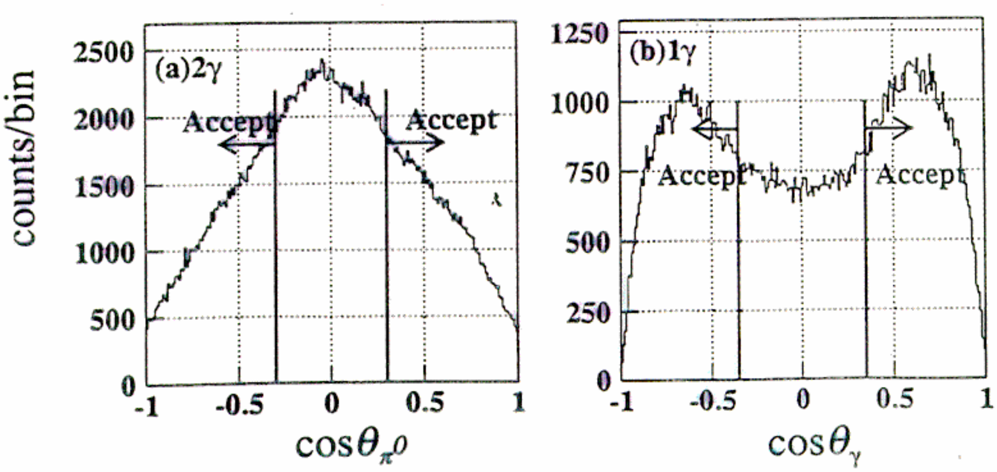
Optimum *fwd/bwd* region

Sensitivity distribution



$$F.o.M. = <\cos(\theta_T) \times \frac{P_T}{\mathrm{Im}\xi}> \times \sqrt{N}$$





A_T, P_T and Imξ

$$A_T = \frac{1}{4}\left\{\frac{[\Sigma_{i=1}^{12} N_i(cw) / \Sigma_{i=1}^{12} N_i(ccw)]_{fwd}}{[\Sigma_{i=1}^{12} N_i(cw) / \Sigma_{i=1}^{12} N_i(ccw)]_{bwd}} - 1\right\}$$

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

- α : analyzing power

  Estimate using P_N and A_N

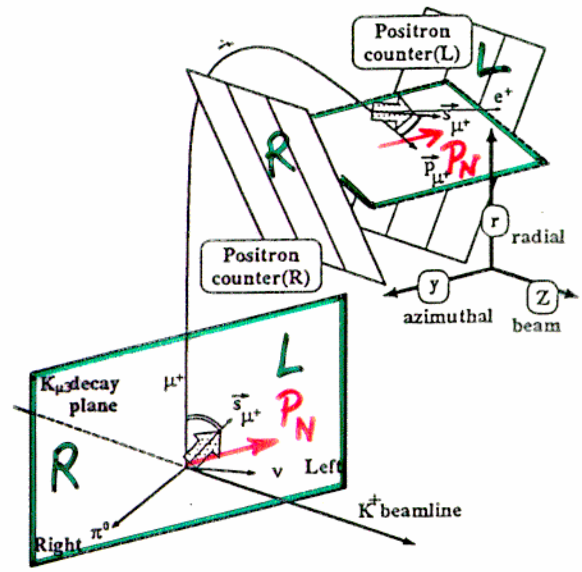
- $\langle\cos\theta_T\rangle$: kinematical attenuation

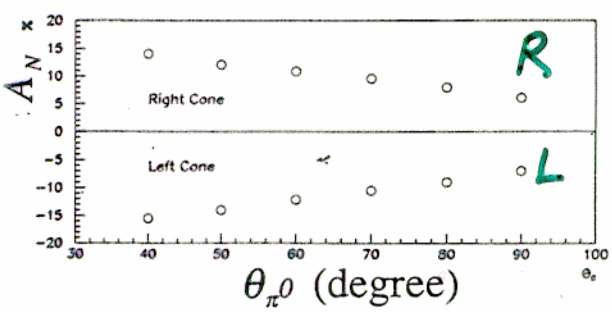
  Estimate by MC calculation aking into account acc. BG

$$\mathrm{Im}\xi = \frac{P_T}{\langle P_T / \mathrm{Im}\xi\rangle}$$

- $\langle P_T / \mathrm{Im}\xi\rangle$: aver. sensitivity

  Estimate by MC calculation taking into account acc. BG

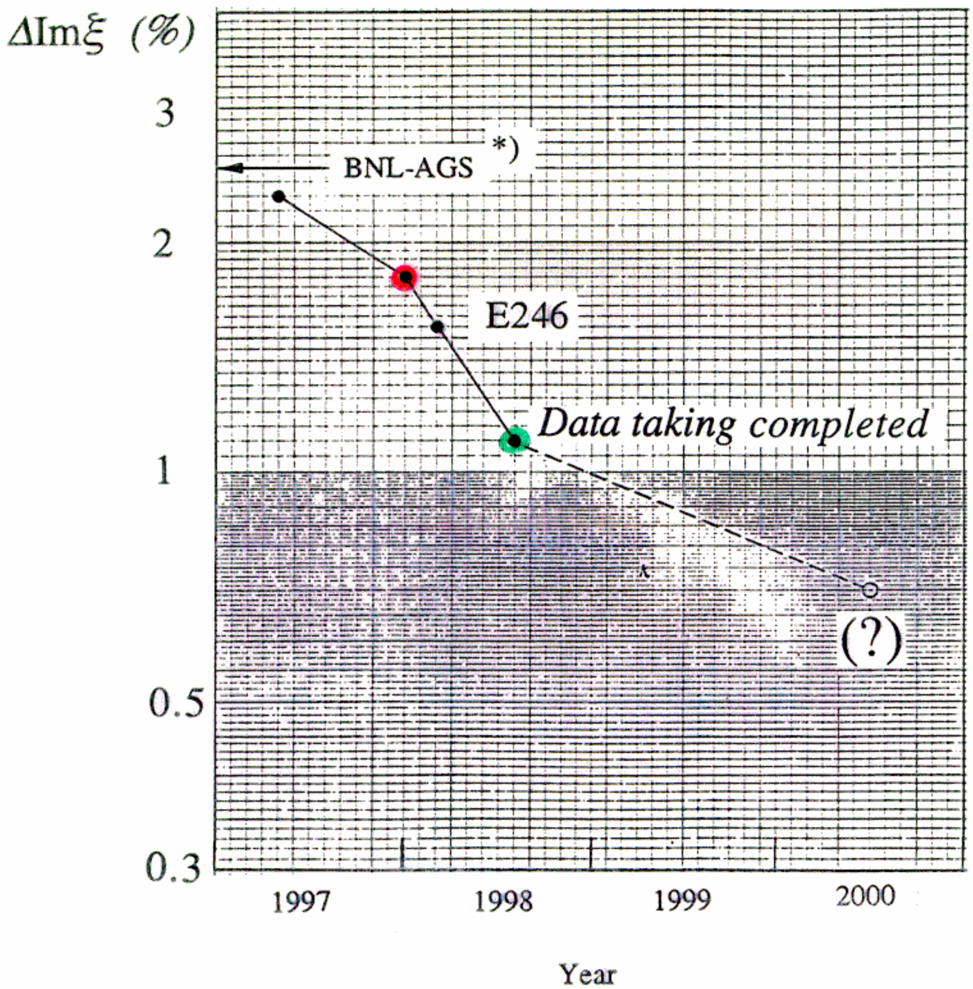




	Analysis-1	Analysis-2
α	0.198	0.194
$\langle\cos\theta_T\rangle$	0.733 (2γ) / 0.637 (1γ)	0.770 (2γ) / 0.649 (1γ)
$\langle P_T/\mathrm{Im}\xi\rangle$	0.314 (2γ) / 0.284 (1γ)	0.337 (2γ) / 0.288 (1γ)

Current status of E246

- The 1998 run was completed in June. One σ sensitivity of $\Delta \mathrm{Im}\xi = 1.1 \times 10^{-2}$ is expected.
- 70 days of further running is planned in next years. The final sensitivity will be $\Delta \mathrm{Im}\xi = 7 \times 10^{-3}$.



*) S.R. Blatt et al.; Phys. Rev. D27 (1983) 1056
(in-flight decay experiment)

Physics Background

(1) $K^+ \to \pi^0 \pi^+$

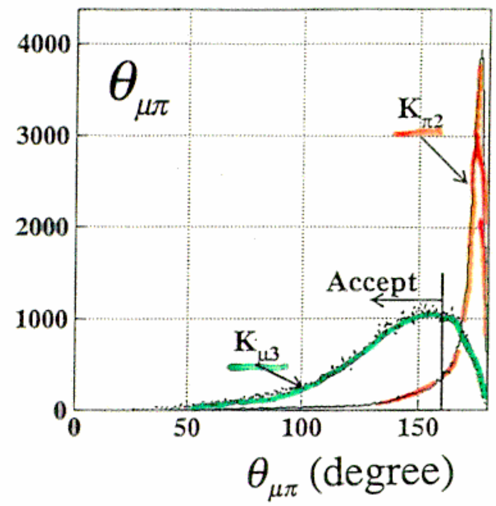
$\quad \hookrightarrow \mu^+ \nu$

$(p_\mu < 190\ MeV/c)$

[Rejection by angle $\theta_{\mu\pi}$]

Analysis-1 : 3.0 %
Analysis-2 : <1.0 %

- There is P_T but $<P_T>=0$
- *fwd/bwd cancellation*



(2) $K^+ \to \pi^0 \pi^0 \pi^+$ <0.5 %

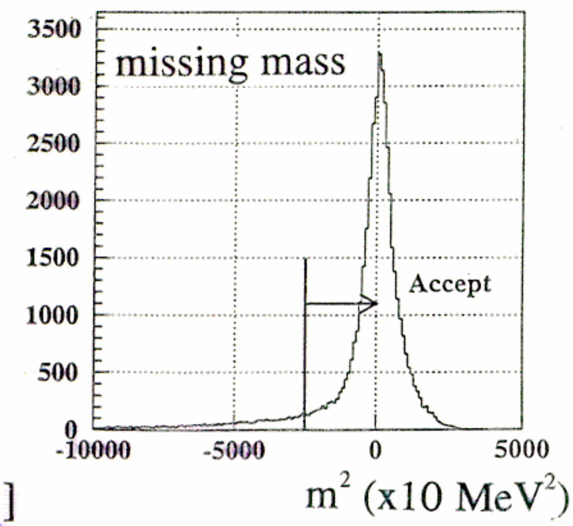
- *no* P_T
- *fwd/bwd cancellation*

(3) K^+ decay in flight

[Rejection by missing mass]

Analysis-1 : <1.0 % (2γ), ≃2.5 % (1γ)
Analysis-2 : ≃1.2 % (2γ), ≃ 4.5 % (1γ)

- *no spurious* P_T *was observed in data*



(4) μ^+ scattering from magnet pole face

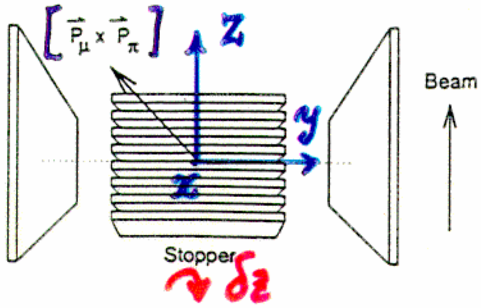
[Tracking]

<1.0 %

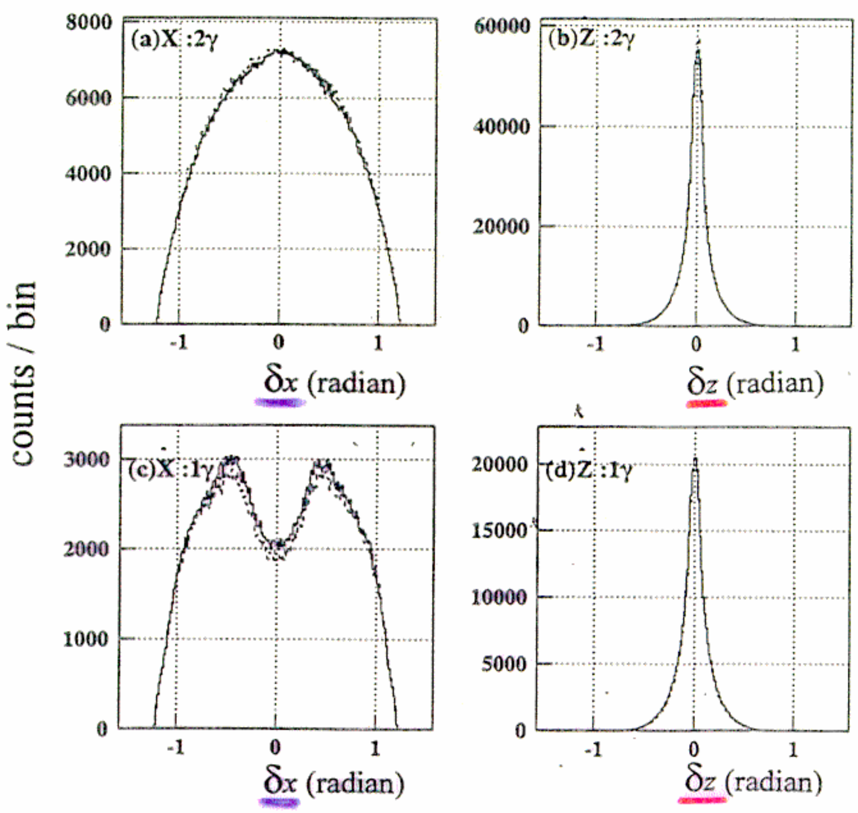
- $\delta P_T < 10^{-5}$ *(calculation)*

Systematics *-Decay plane rotation -*

reflecting CsI and chamber alignment



- Rotation around x-axis δx induces P_L mixing
  fwd/bwd cancellation
- Rotation around z-axis δz induces P_N mixing
  No fwd/bwd cancellation !



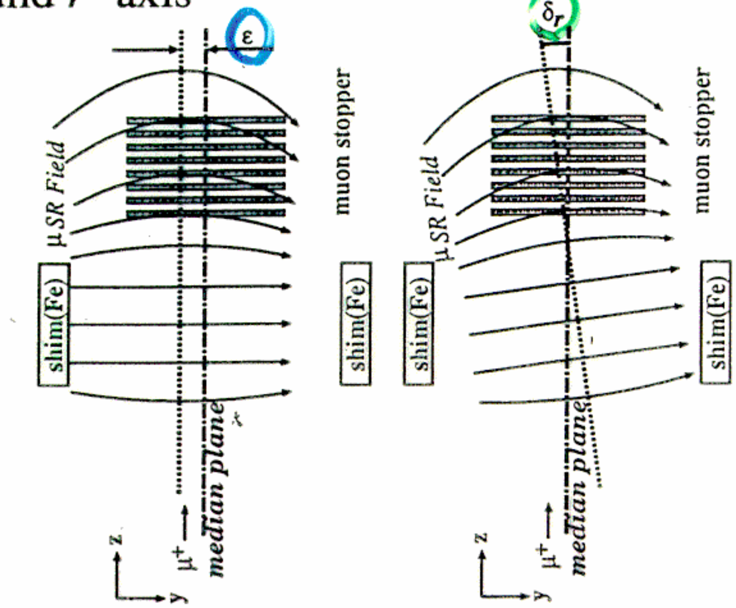
solid line: fwd π^0 dashed line : bwd π^0

	1γ	2γ	δP_T
$(\delta x^{fwd} - \delta x^{bwd})/2$	1.01 ± 0.55 mr	0.06 ± 0.35 mr	4×10^{-4}
$(\delta z^{fwd} + \delta z^{bwd})/2$	0.45 ± 0.15 mr	0.58 ± 0.10 mr	3×10^{-4}

Systematics

- Asymmetry of magnetic field -

(1) Field distribution offset (ε) and rotation (δ_r) around r- axis



- They introduce P_L admixture, but
- *fwd / bwd* cancellation works.

$\delta P_T \approx 3.5 \times 10^{-4}$

(2) Field rotation around z- axis (δ_z)

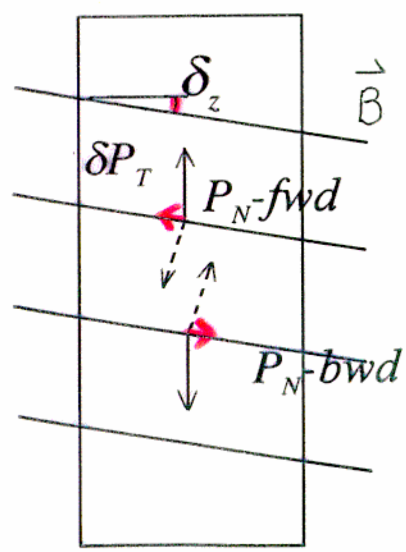
- introduces P_N admixture.
- There is no *fwd/bwd* cancellation

$<\sigma\delta_z> = 1.0$ mr

$<\sigma\delta_z>_{\text{meas.}} \leq 1.0$ mr

$<\sigma\delta_z>^{\text{total}} \leq 1.4$ mr

$\delta P_T \approx 0.8\, P_N\, \delta_z$
$\leq 6 \times 10^{-4}$



Summary of systematic errors

Source of error		δA_T after Σ12		δA_T after F/B
Target shift	o	2×10^{-4}	o	$< 10^{-5}$
e^+ counter r-rotation	o	1.6×10^{-4}	o	5×10^{-6}
e^+ counter z-rotation	o	5.2×10^{-5}	o	2×10^{-6}
e^+ counter ϕ-offset	x	5.7×10^{-3}	o	1.9×10^{-5}
e^+ counter r-offset	o	$< 1.5 \times 10^{-6}$	o	$< 10^{-6}$
e^+ counter z-offset	o	$< 1.0 \times 10^{-3}$	o	$< 10^{-6}$
B y-offset (ε)	x	5.2×10^{-4}	o	5×10^{-5}
B r-rotation (δ_r)	x	1.0×10^{-4}	o	$< 10^{-5}$
B z-rotation (δ_z)	x	8×10^{-5}	x	8×10^{-5}
CsI(Tl) efficiency	o	$< 8 \times 10^{-4}$	o	$< 5 \times 10^{-5}$
μ^+ counter y-offset	x	$< 10^{-4}$	o	$< 10^{-5}$
MWPC y-offset	x	-	ox	3.5×10^{-5}
$[\bar{n}_{\pi^0} \times \bar{n}_{\mu^+}]$ rotation (δ_r)	ox	-	o	6×10^{-5}
$[\bar{n}_{\pi^0} \times \bar{n}_{\mu^+}]$ rotation (δ_z)	x	-	x	4×10^{-5}
beam background	x	$< 2 \times 10^{-3}$	o	$< 5 \times 10^{-5}$
TOTAL				1.4×10^{-4}

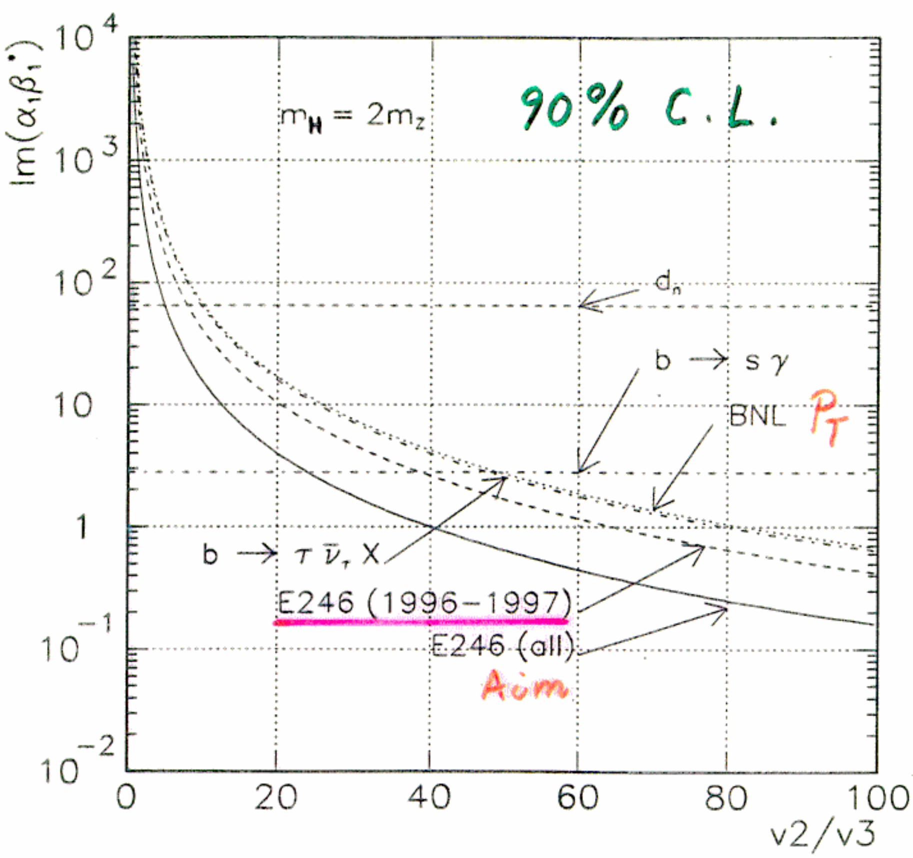
x : no cancellation
o : cancellation

$$\delta P_T \approx 1 \times 10^{-3}$$

Constraint on Models

(1) Three Higgs doublet model

$$\mathrm{Im}\xi^K = \mathrm{Im}(\alpha_1\beta_1^*)\cdot\left(\frac{v_2}{v_3}\right)^2\cdot\left(\frac{m_K}{m_{H_1^+}}\right)^2$$

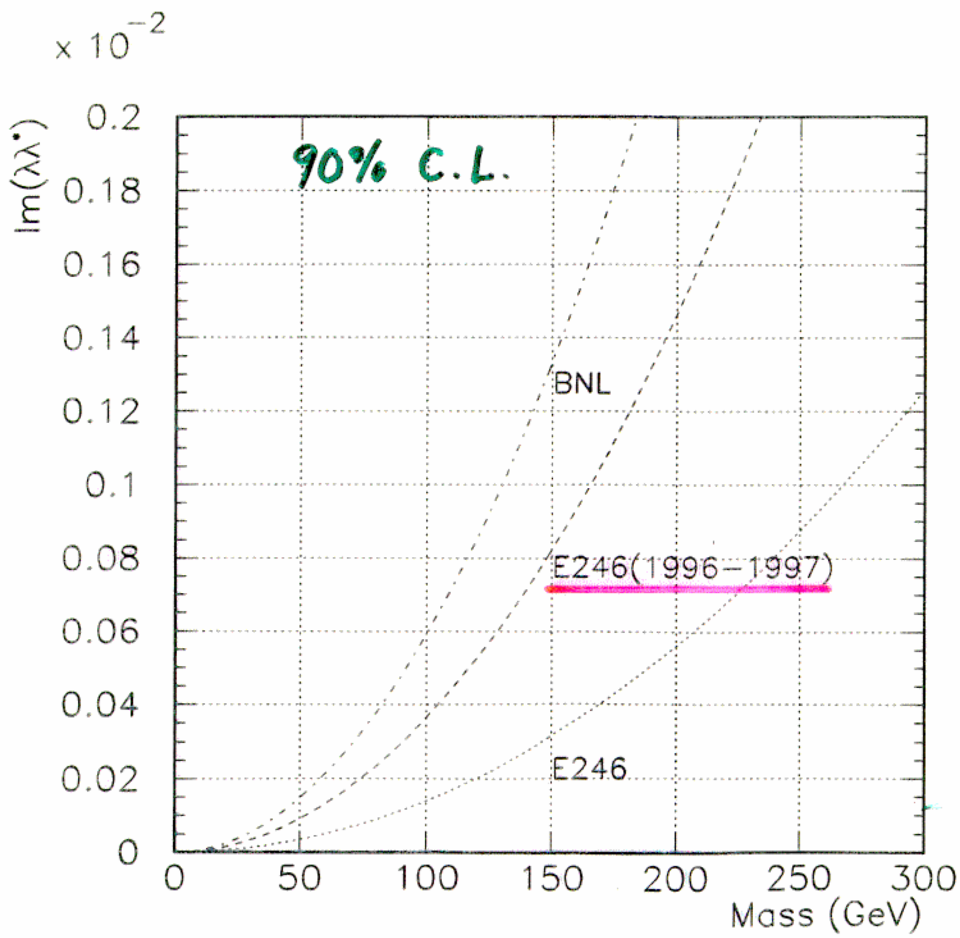


Constraint on Models

(2) *R*-pariry violating SUSY

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

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



CONCLUSIONS

- Transverse μ^+ polarization (P_T) probes new physics such as 1) multi-Higgs doublet models and 2) a class of SUSY.
- E246 experiment is searching for P_T with a potential sensitivity of $\Delta P_T \approx 10^{-3}$. (Systematic error is of this magnitude.)
- No evidence for P_T has been found from the 96 and 97 data. Analysis of 98 data is now in progress.
- After 70 days of data taking in the future, we will achieve the sensitivity of $\Delta \mathrm{Im}\xi = 0.007$.