Search for T-violating Transverse Muon Polarization in $K^+ \to \pi^0 \mu^+ \nu_\mu$ Decay

28 July 2000
ICHEP2000, Osaka, Japan

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E246 Collaboration

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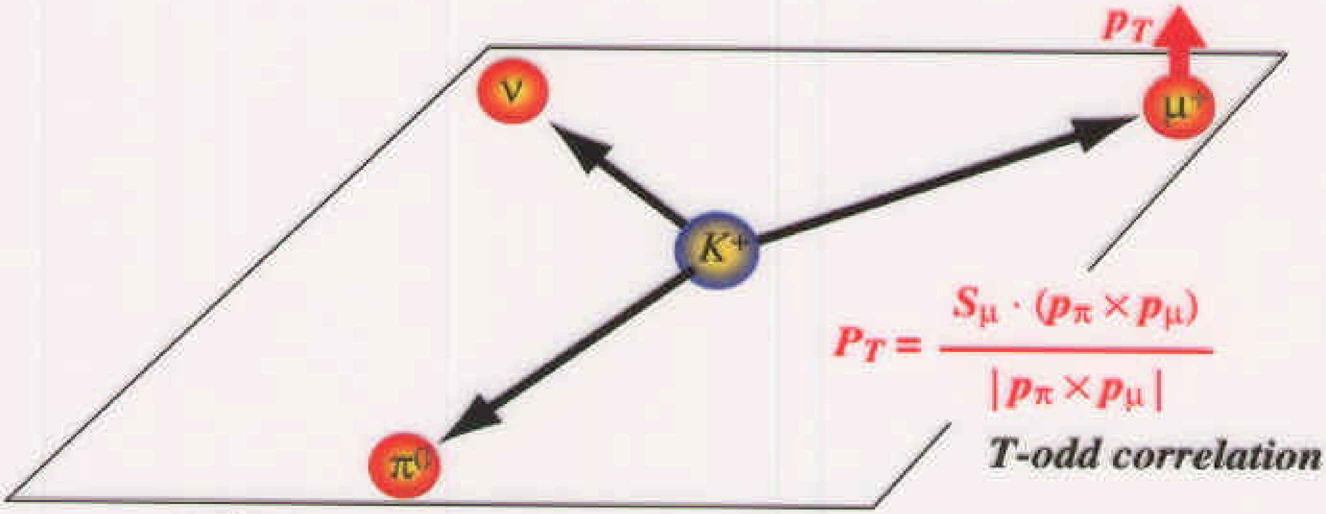
	Osaka Univ.
Russia	Institute for Nuclear Research
Canada	TRIUMF
	Univ. of British Columbia
	Univ. of Saskatchewan
	Univ. of Montreal
Korea	Yonsei Univ.
	Korea Univ.
U.S.A.	Virginia Polytech Institute
	Princeton Univ.
Taiwan	National Taiwan Univ.

Transverse μ^+ polarization in $K^+ \rightarrow \pi^0 \mu^+ \nu_\mu$



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

$P_T \neq 0 \rightarrow$ T-violation

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

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

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

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

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

P_T(Standard Model) = 0 →

$P_T \neq 0$ 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 theoretical works>

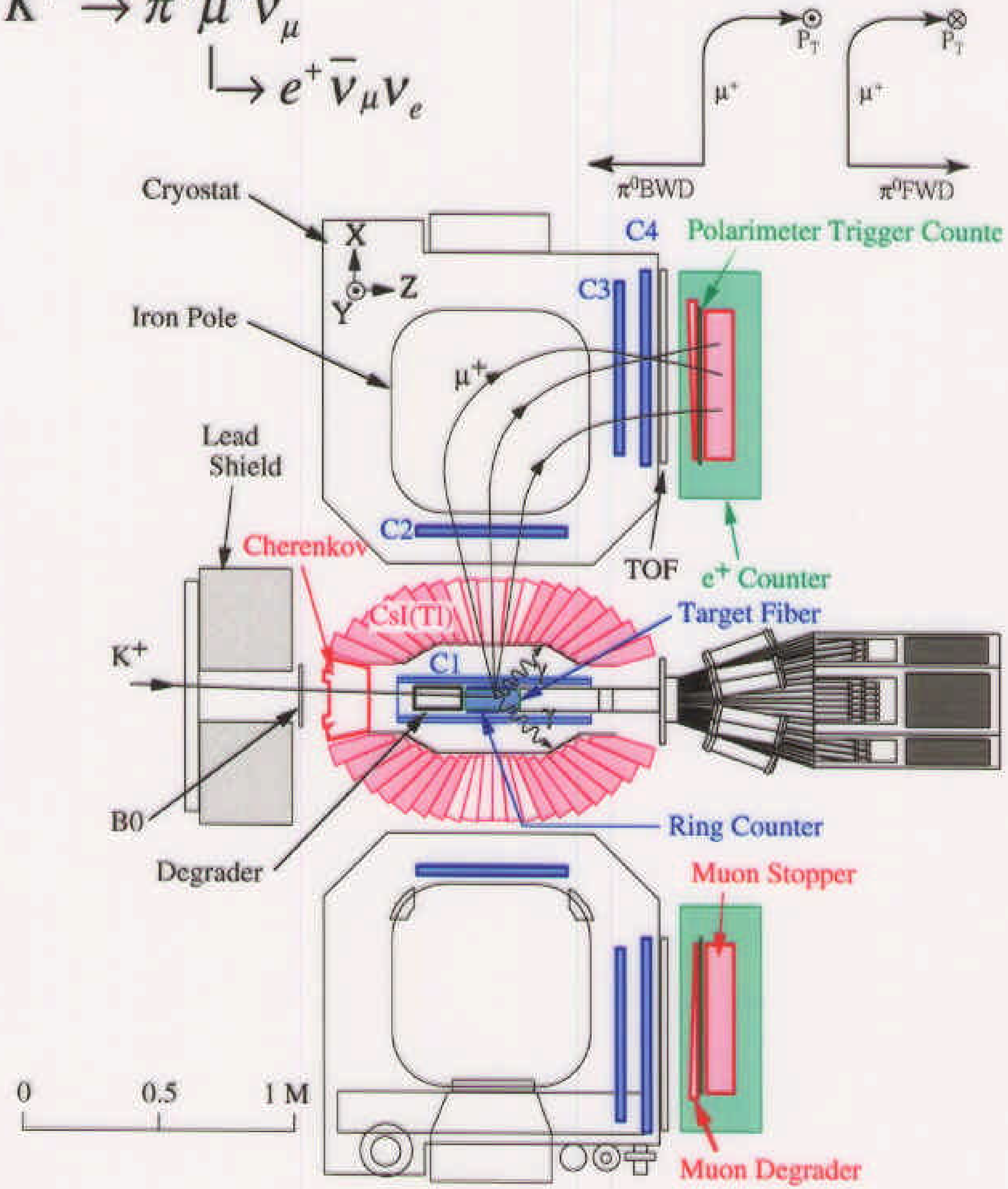
[1]R. Garisto and G. Kane; PR D44, 2038 (1991)
[2]G. Belanger and C. Q. Geng; PR D44, 2789 (1991)
[3]M. Fabbrichesi and F. Vassani; PR D55, 5334 (1997)
[4]G. H. Wu and J. N. Ng; PR D56, 93 (1997)

<Previous data>

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

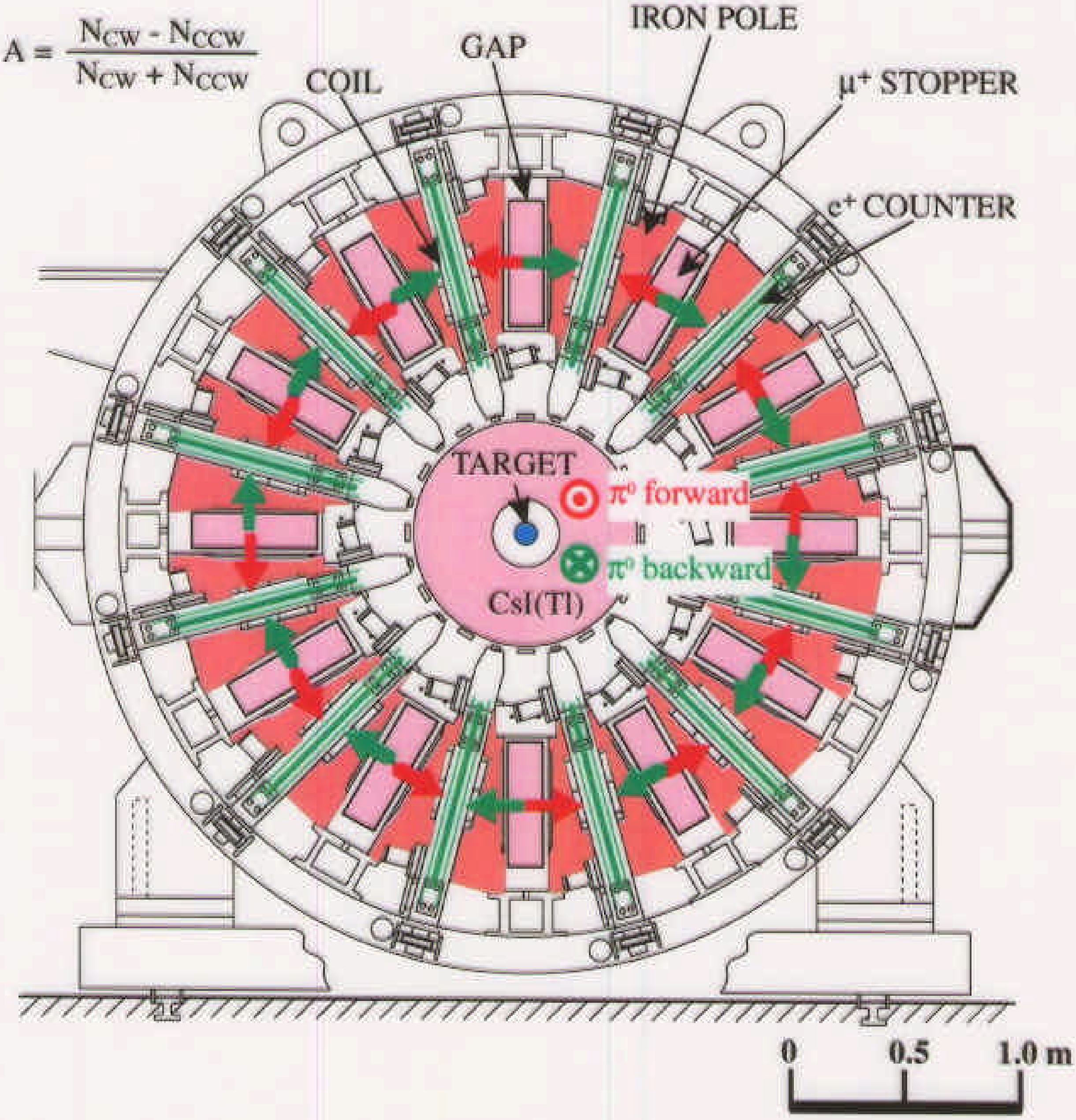
Experimental setup (side view)

$$K^+ \to \pi^0 \mu^+ \nu_\mu$$
$$\hookrightarrow e^+ \bar{\nu}_\mu \nu_e$$



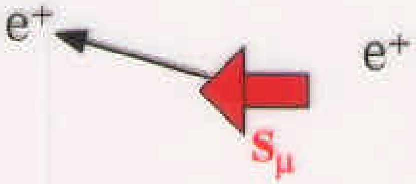
Experimental setup (end view)

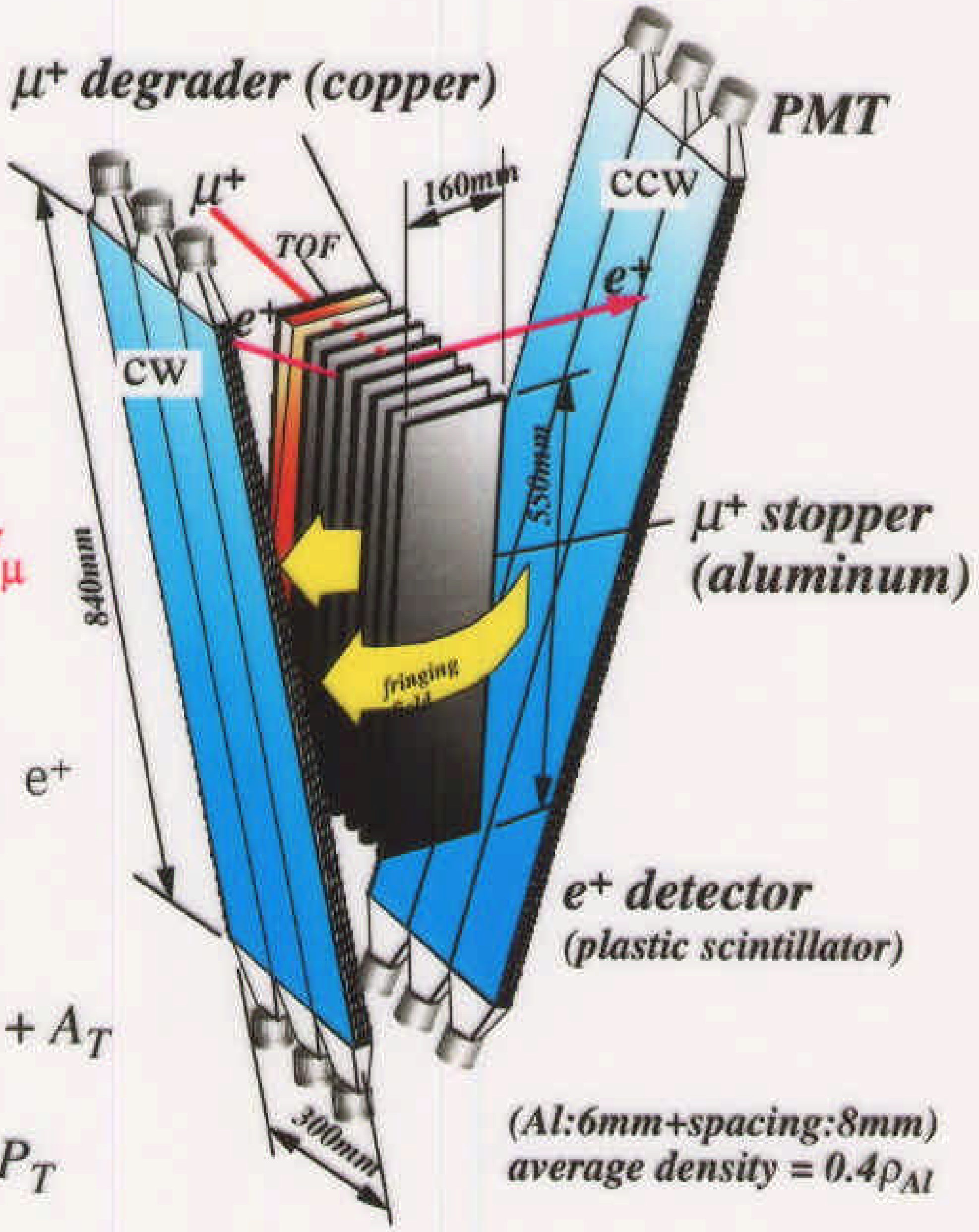
$$A = \frac{N_{CW} - N_{CCW}}{N_{CW} + N_{CCW}}$$



Experimental setup (polarimeter)

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





$$\frac{N_{cw}}{N_{ccw}} = 1 + A_T$$

$$A_T = \alpha P_T$$

(Al:6mm+spacing:8mm)
average density = $0.4\rho_{Al}$

Double Ratio Measurement

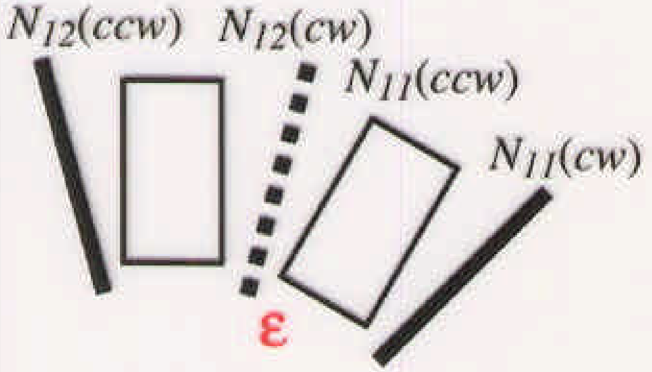
12-fold rotational symmetry

$$\frac{\sum_{i=1}^{12} N_i(cw)}{\sum_{i=1}^{12} N_i(ccw)} = 1 + 2\alpha \langle \cos\theta_{P_T} \rangle P_T$$

i : sequential number of magnet gaps(1..12)

α : analyzing power

- Inefficiencies of the positron counters
- Differences of the geometrical size of the positron counters
- Offset of the kaon stopping distribution



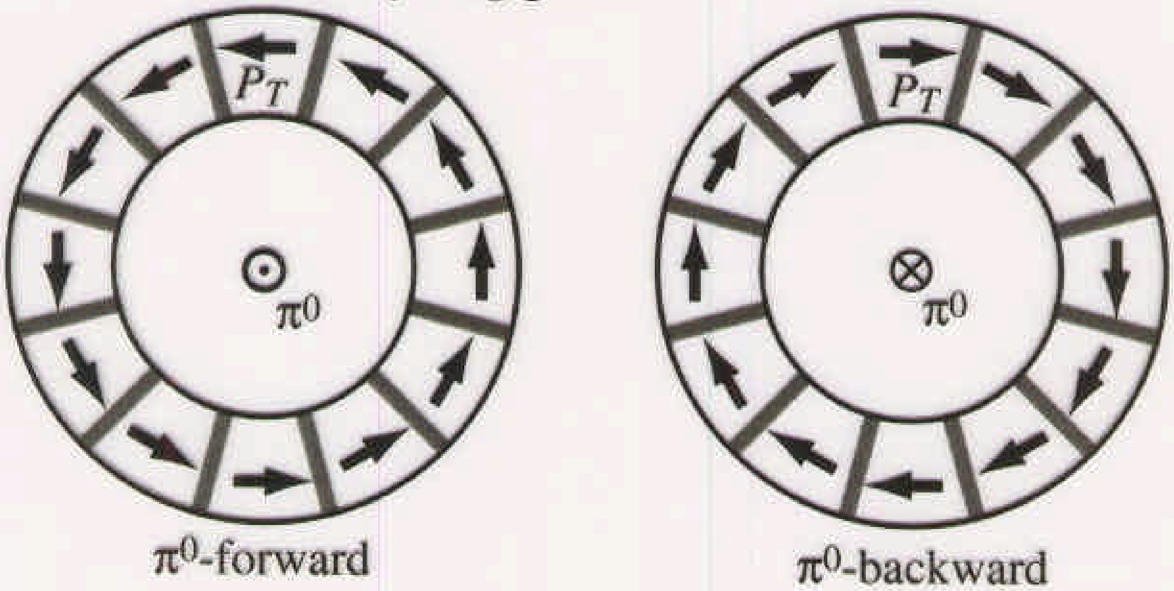
$$\frac{\sum_{i=1}^{12} N_i(cw) - \varepsilon N_{12}(cw)}{\sum_{i=1}^{12} N_i(ccw) - \varepsilon N_{11}(ccw)} \sim \frac{\sum_{i=1}^{12} N_i(cw)}{\sum_{i=1}^{12} N_i(ccw)} (1 + \varepsilon/100)$$

Double Ratio Measurement

$$\frac{\left[\sum_{i=1}^{12} N_i(cw) \,/\, \sum_{i=1}^{12} N_i(ccw)\right]_{fwd\text{-}\pi^0}}{\left[\sum_{i=1}^{12} N_i(cw) \,/\, \sum_{i=1}^{12} N_i(ccw)\right]_{bwd\text{-}\pi^0}} = 1 + 4\alpha \langle\cos\theta_{P_T}\rangle P_T$$

i : sequential number of magnet gaps(1..12)

α : analyzing power



- Offset of the positron counter position
- Offset of the magnetic field
- Inefficiencies of MWPC, etc.

Systematic Errors

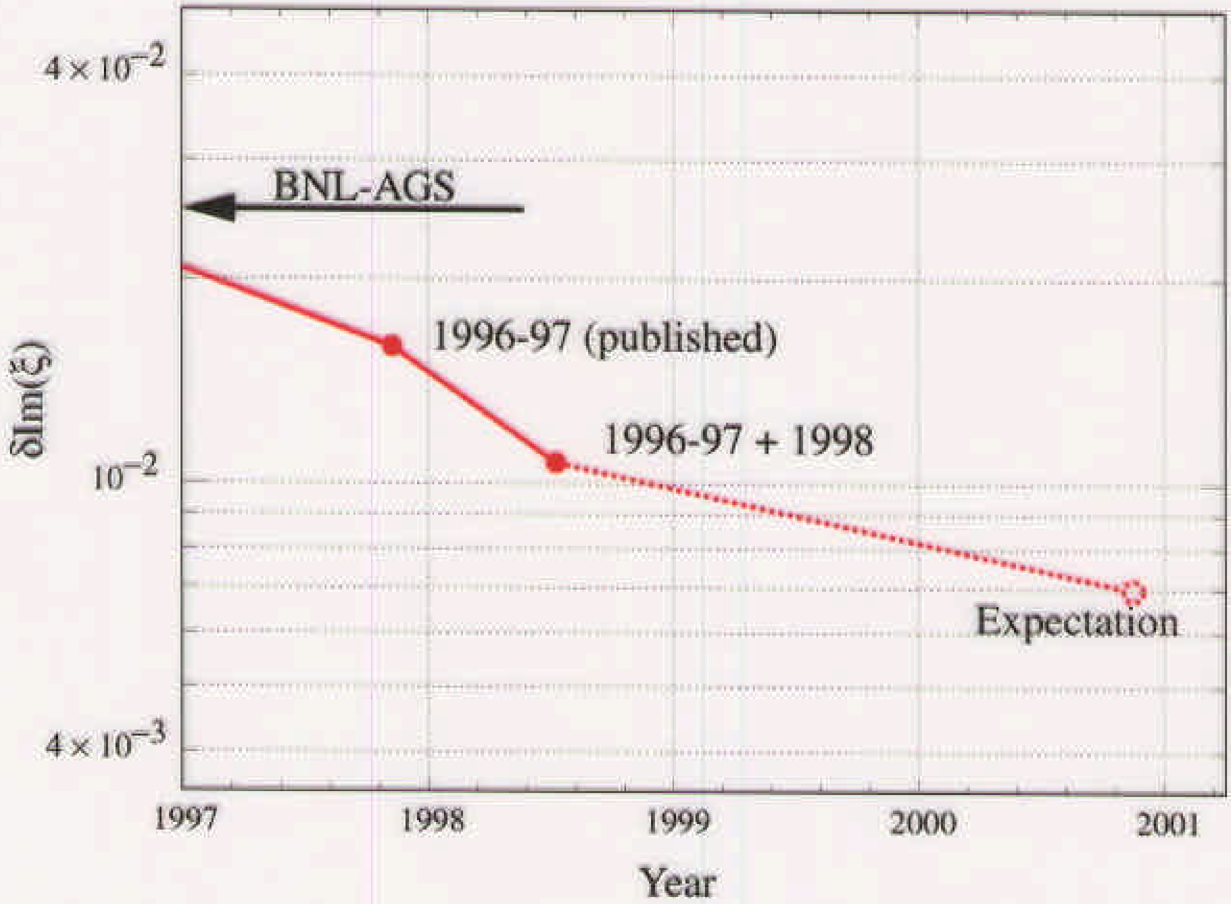
$\Sigma 12$	12-fold rotational cancellation
fwd/bwd	π^0forward/backward cancellation

Source of Error	$\Sigma 12$	fwd/bwd	$\delta P_T \times 10^5$
e^+ counter r-rotation	×	○	5
e^+ counter z-rotation	×	○	2
e^+ counter ϕ-offset	×	○	22
e^+ counter r-offset	○	○	< 1
e^+ counter z-offset	○	○	< 1
μ^+ counter ϕ-offset	×	○	< 1
MWPC ϕ-offset (C4)	×	○	25
CsI(Tl) misalignment	○	○	16
B offset (ε)	×	○	30
B rotation (δ_x)	×	○	4
B rotation (δ_z)	×	×	53
K^+ stopping distribution	○	○	< 30
Decay plane angle (θ_r)	×	○	20
Decay plane angle (θ_z)	×	×	9
$K_{\pi 2}$ DIF background	×	○	6
K^+ DIF background	○	×	< 19
e^+ spectrum background	○	○	8
Analysis	-	-	38
TOTAL			92

Result from 1996-97 data

M. Abe, *et al*. Phys. Rev. Lett. **83**, 4253 (1999)

$$P_T = (-4.2 \pm 4.9(\text{stat.}) \pm 0.9(\text{sys.})) \times 10^{-3}$$
$$\text{Im}(\xi) = (-1.3 \pm 1.6(\text{stat.}) \pm 0.3(\text{sys.})) \times 10^{-2}$$



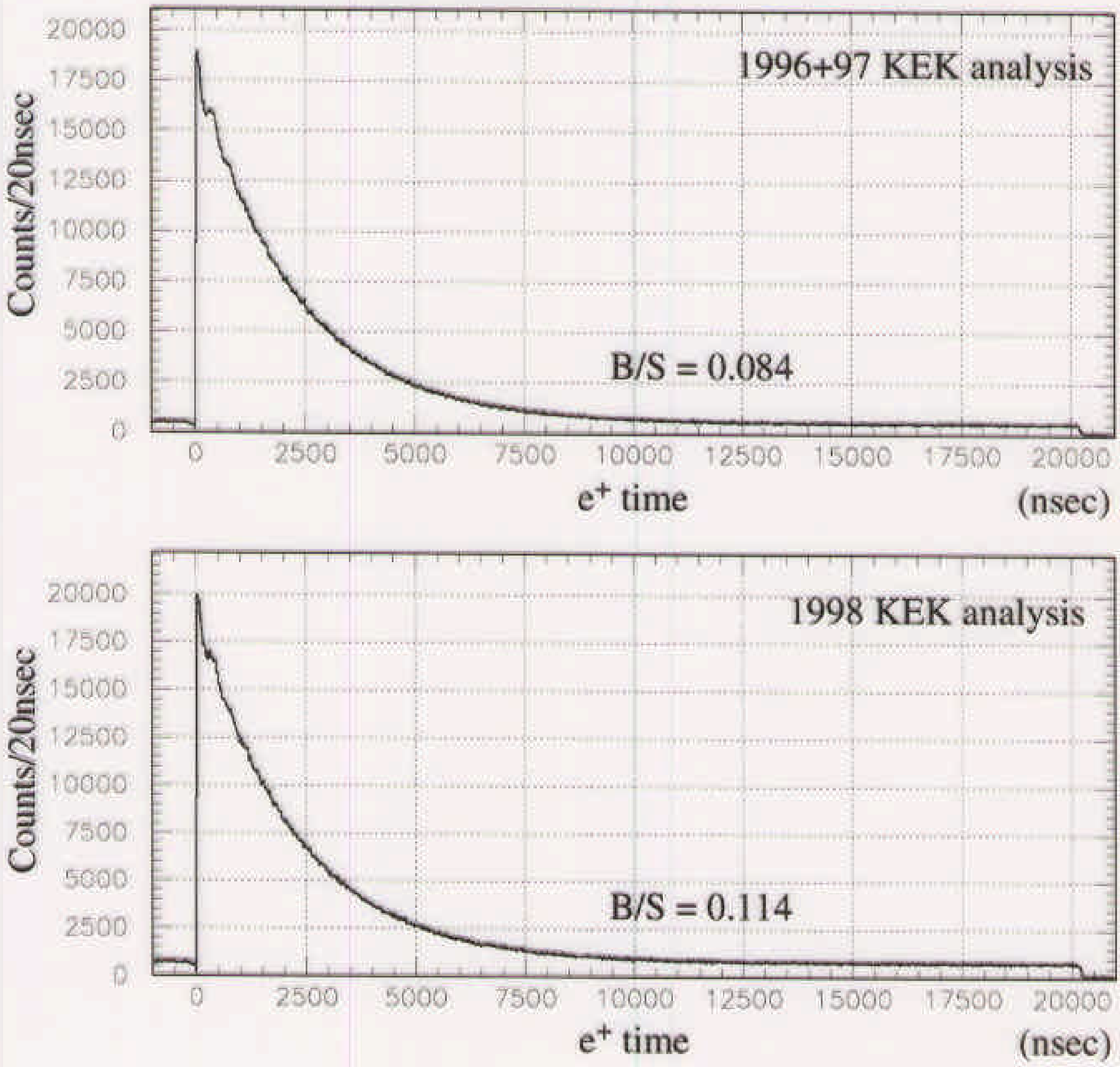
Analysis Methodology

- Two independent analyses in two different institutions
  - easy to find any trivial mistakes in the analysis codes
  - rapid improvements of the analysis codes in competition with each others
  - minimizing possible analysis biases
- Blind Analysis
  - Never look at A_T during the cut optimization
- Combination of two analysis results
  - Analyzing common events and uncommon events to understand the quality of event selection
  - Estimation of analysis-driven systematic errors
  - Improvement in the statistical error

1998 data

Comparison between 1996-97 and 1998

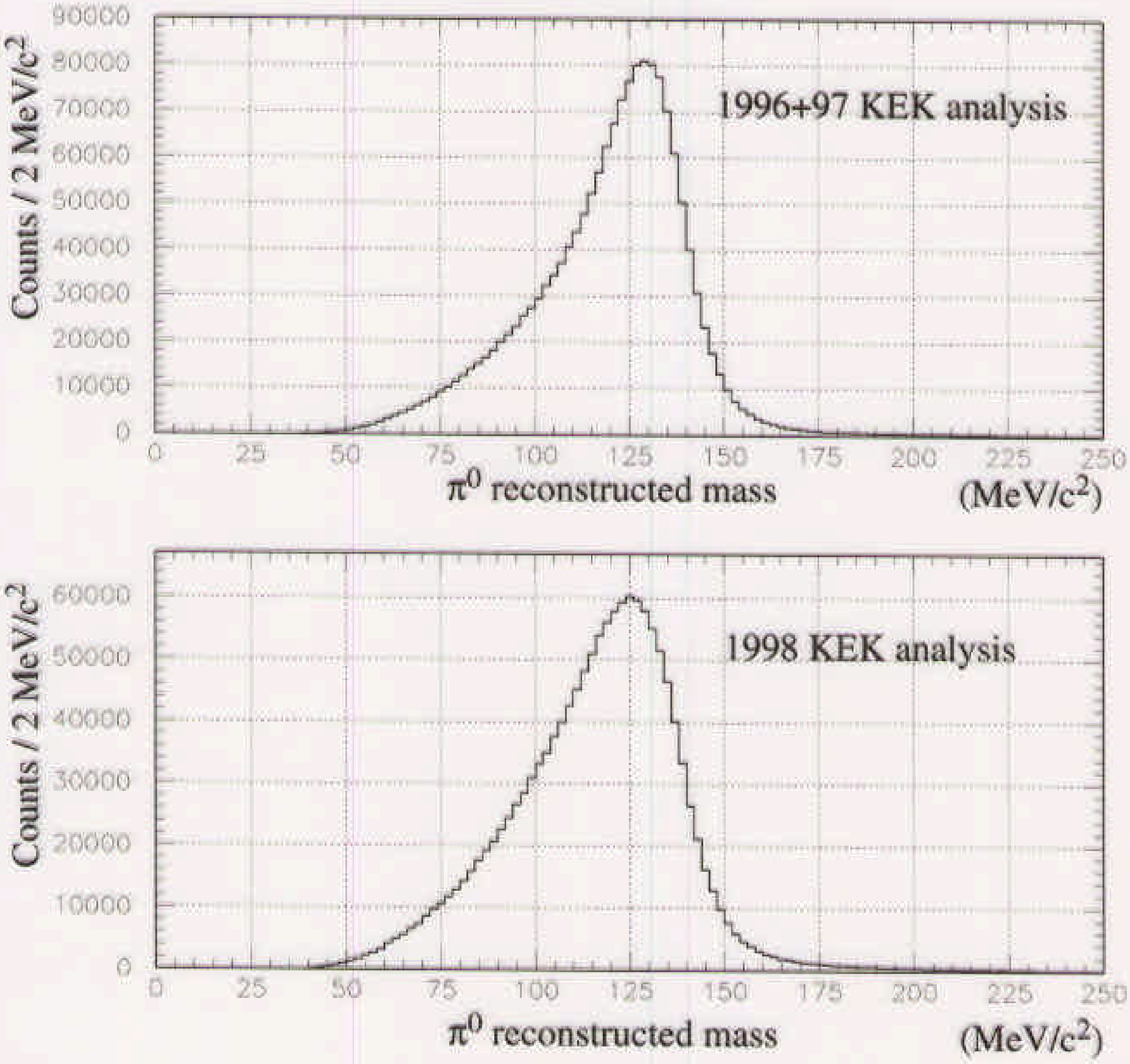
Muon decay time spectra



1998 data

Comparison between 1996-97 and 1998

Reconstructed π^0 mass



1998 results

⇒ 1998 data quality

- KEK analysis

		1996-97	1998	
$\langle\cos\theta_\gamma\rangle$	2γ	0.770 →	0.733	-5%
	1γ	0.633 →	0.628	<-1%

- INR analysis

		1996-97	1998	
$\langle\cos\theta_\gamma\rangle$	2γ	0.770 →	0.763	<-1%
	1γ	0.649 →	0.590	-9%

⇒ Results from 1998 data

- KEK result

  $P_T^{1\gamma/2\gamma} = \quad -0.0010 \pm 0.0059$

- INR result

  $P_T^{1\gamma/2\gamma} = \quad 0.0002 \pm 0.0056$

⇒ Combination of KEK/INR results should be done

Conclusion

- 1998 data quality is as good as 1996-97 data
- 1998 results from 2 independent analyses were obtained
  - both consistent with $P_T = 0$
- combination of those two results should be done

$$\Delta \mathrm{Im}\,\xi = 0.011$$