Result of T-violating Muon Polarization Measurement in the $K^+ \to \pi^0 \mu^+ \nu$ Decay

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for the KEK-E246 collaboration

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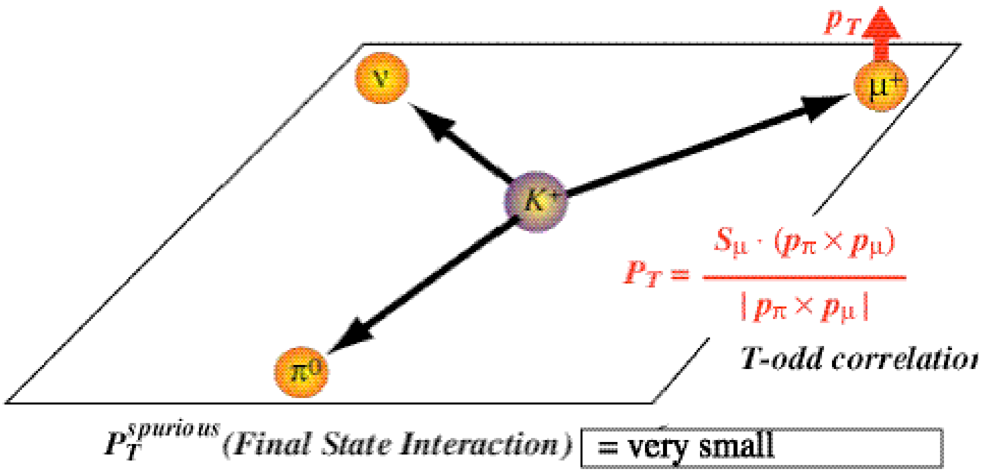
- Transverse muon polarization
- E246 experiment
- Analysis
- Result of the total data

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 Muon Polarization in $K^+ \rightarrow \pi^0 \mu^+ \nu$



$P_T \neq 0 \rightarrow$ T-violation

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

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

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

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

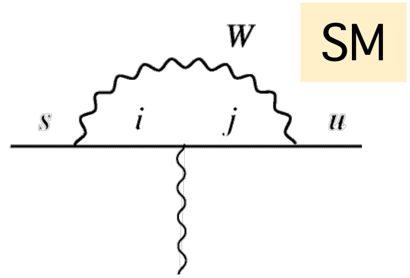
$\mathrm{Im}(\xi) \neq 0 \longleftrightarrow$ T-violation

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

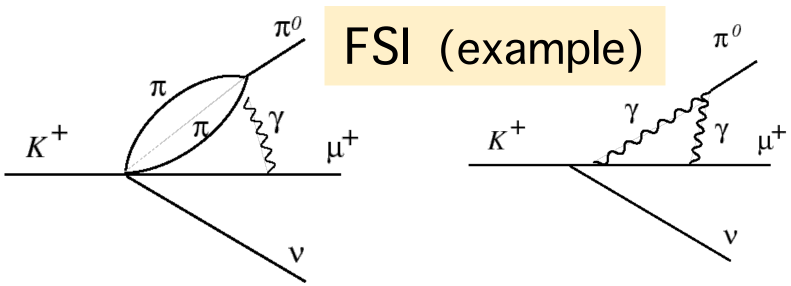
• $K_L \rightarrow \pi^- \mu^+ \nu$	Bevatron	1967	$\mathrm{Im}\,\xi$ = -0.02 ±0.08
• $K_L \rightarrow \pi^- \mu^+ \nu$	Argonne	1973	$\mathrm{Im}\,\xi$ = -0.085 ±0.064
• $K_L \rightarrow \pi^- \mu^+ \nu$	BNL-AGS	1980	$\mathrm{Im}\,\xi$ = 0.009 ±0.030
• $K^+ \rightarrow \pi^0 \mu^+ \nu$	BNL-AGS	1983	$\mathrm{Im}\,\xi$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

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

- Small standard model contribution
  - Bigi and Sanda "CP violation" (2000)
  - $P_T \sim 10^{-7}$

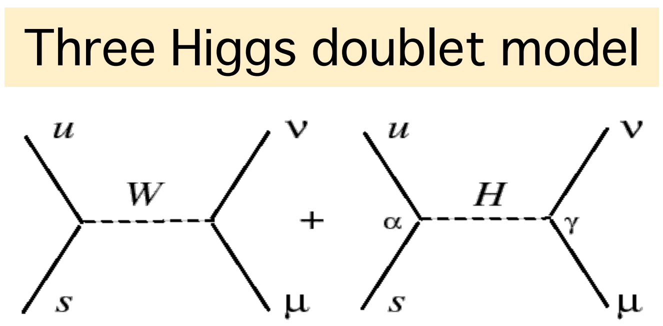


- Small FSI spurious effects
  - Single photon contribution
    Zhitnitskii (1980)
    $P_T <\sim 10^{-6}$
  - Two photon contribution
    Efrosinin et al. PL B493 (2000) 293
    $P_T \sim 4 \times 10^{-6}$



- High sensitivity to CP violation
- beyond the SM
  - Mult- Higgs doublet model
  - Leptoquark model
  - Some Supersymmetric models

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



KEK E246 experiment

Features

- <u>Stopped K^+</u> experiment with a SC <u>toroidal spectrometer</u>
- Measurement of <u>all decay kinematics directions</u>
  - Double ratio measurement with small systematic errors

History

- 1992-1995 : detector construction
- 1996-2000 : data taking
- 1999 : first result published with 1/4 of data

  $\mathrm{Im}\xi = -0.023 \pm 0.007(\mathrm{stat}) \pm 0.003(\mathrm{syst})$

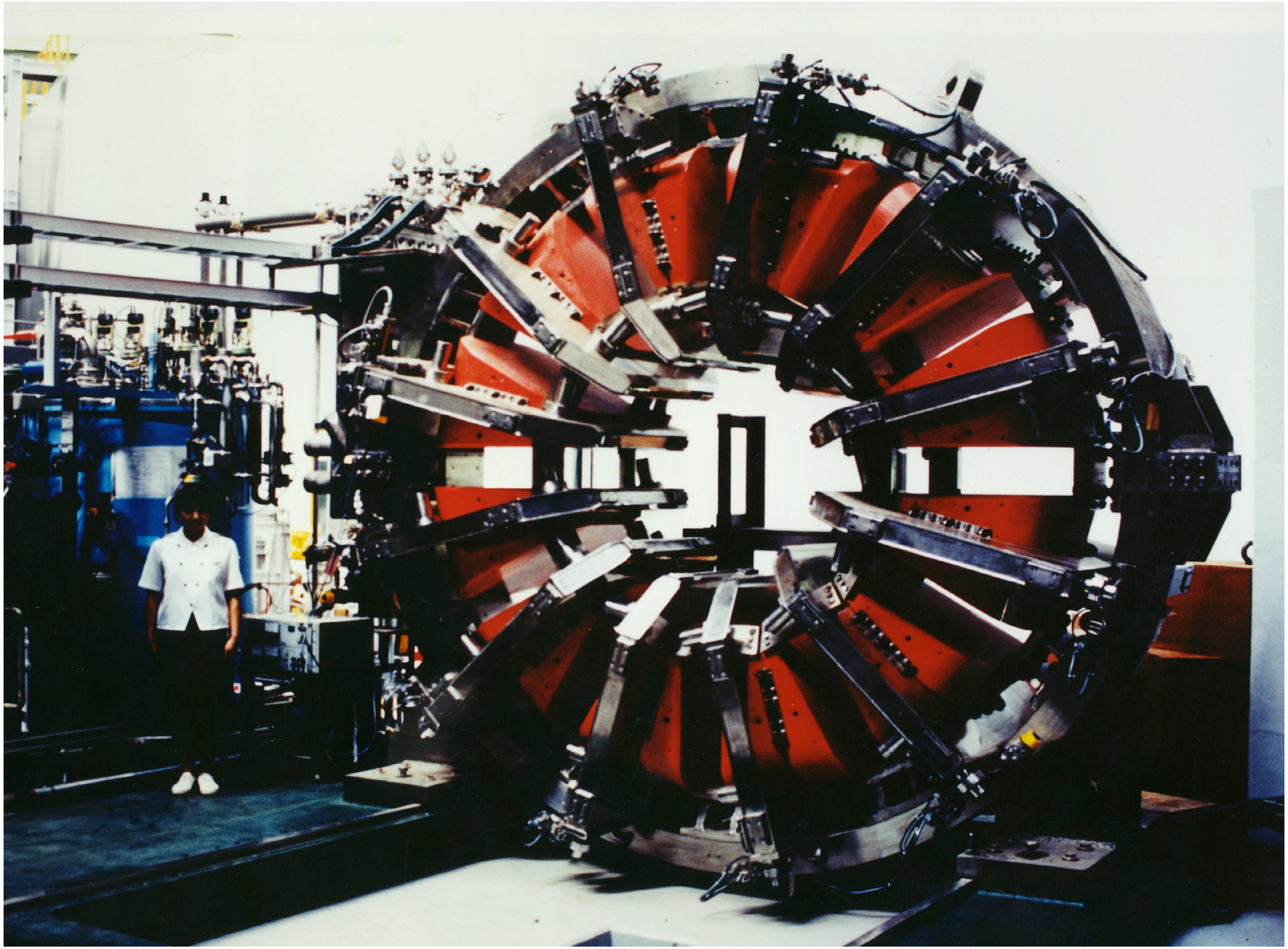
  [M.Abe *et al.*, Phys.Rev.Lett. 83(1999) 4253]
- 2001-2003 : analysis
- 2004 (this conference) : report of the final result

Byproducts

- $K^+ \to \mu^+ \nu \gamma$: $P_T = -0.0064 \pm 0.0185(\mathrm{stat}) \pm 0.0010(\mathrm{syst})$

  [V.Anisimovsky et al., Phys.Lett. B562 (2003) 166]
- K_{e3}, $K_{\pi 2\gamma}$, K_{e4}, …

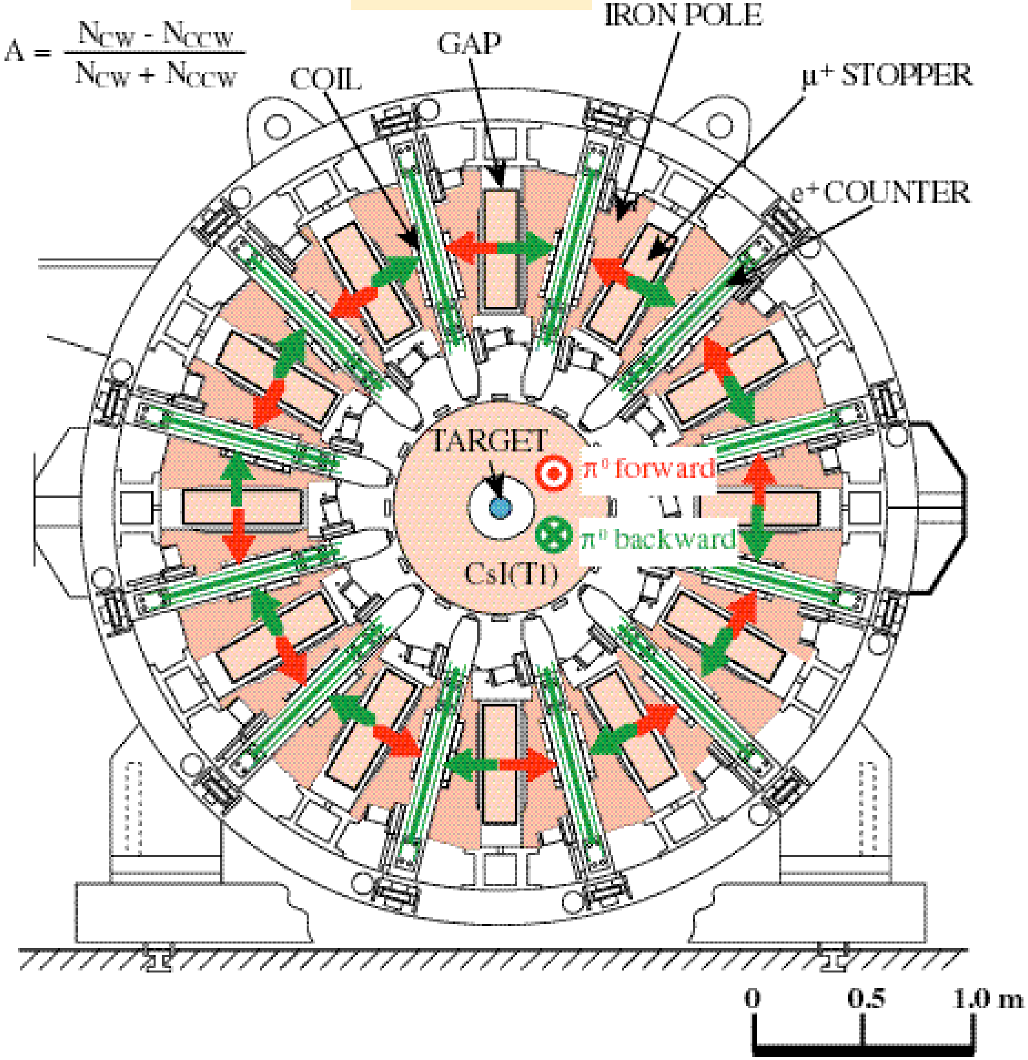
Superconducting toroidal magnet



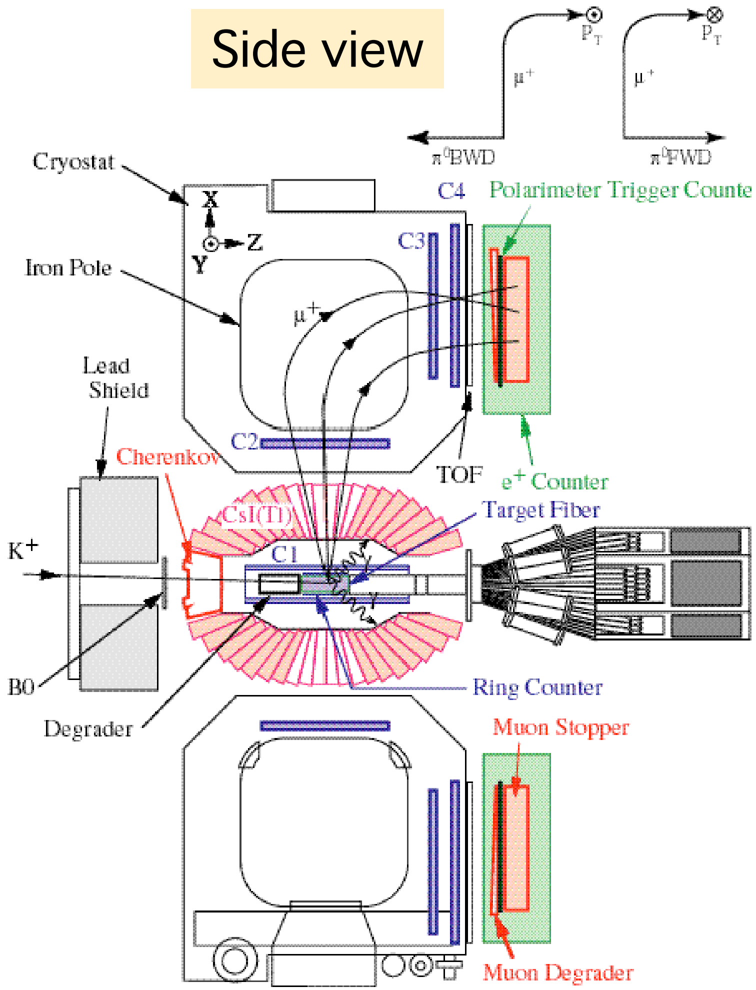
E246 experimental setup

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

End view

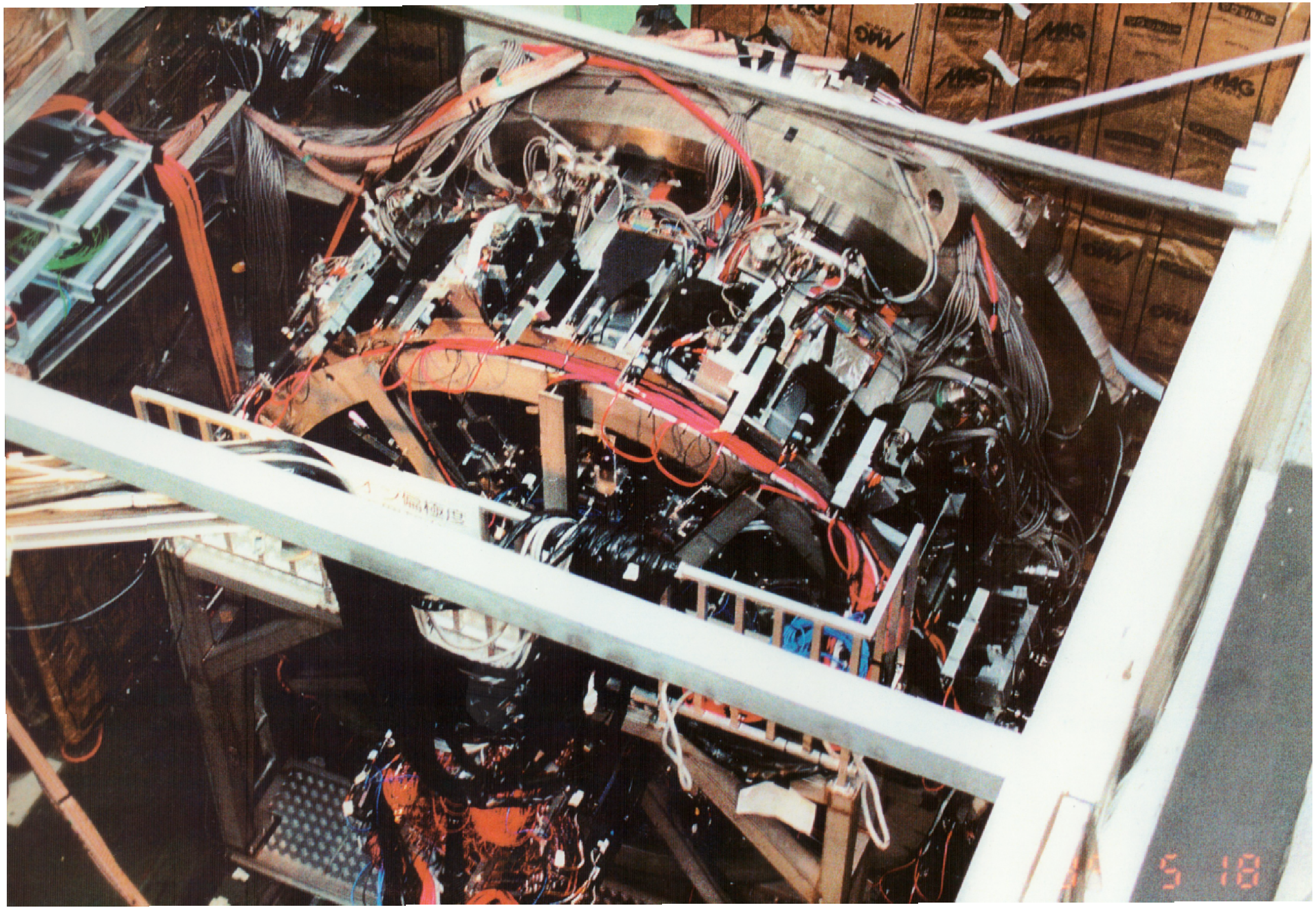


Side view



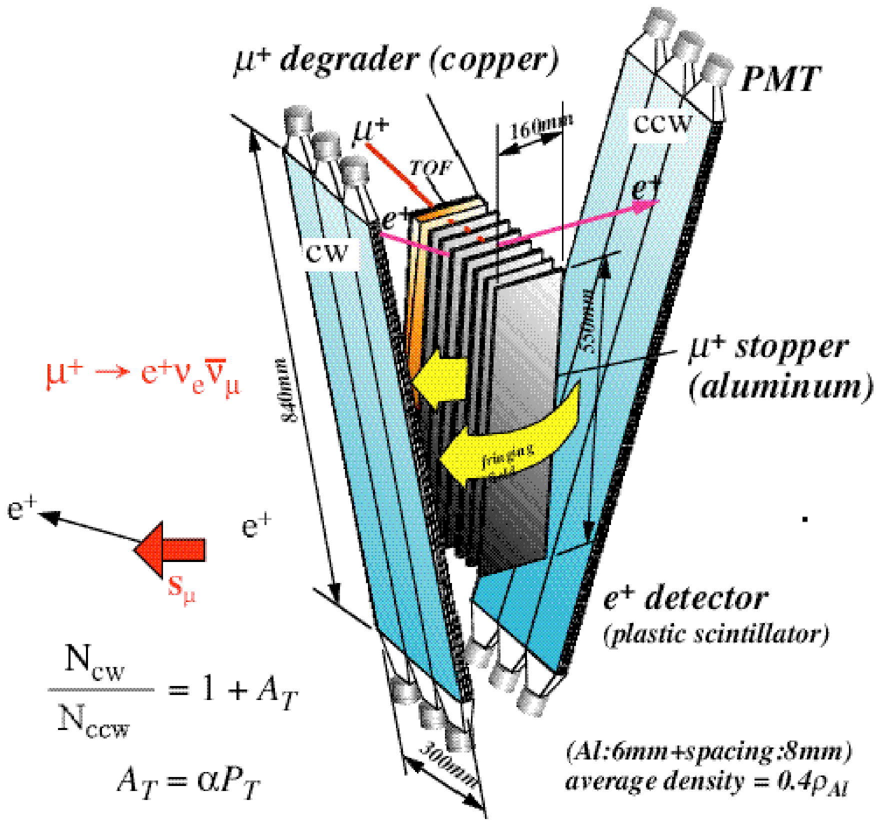
$$K^+ \rightarrow \pi^0 \mu^+ \nu$$

E246 detector



Muon polarimeter

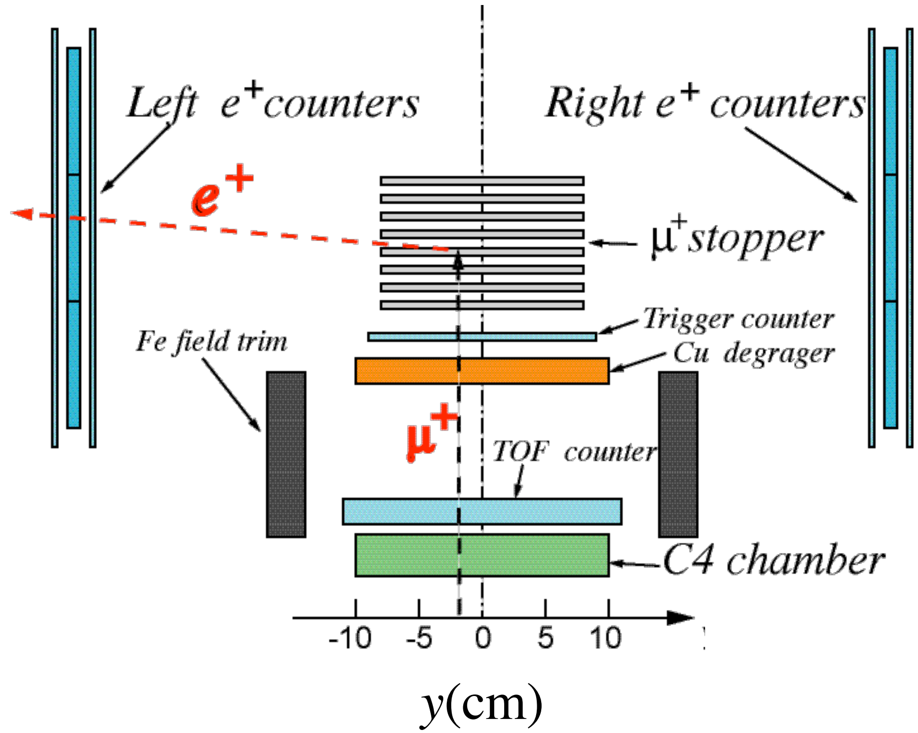
One-sector view



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

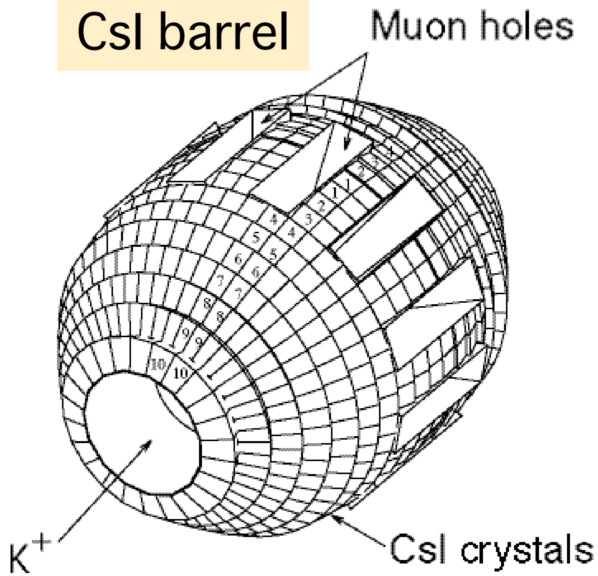
$$A_T = \alpha P_T$$

Cross section

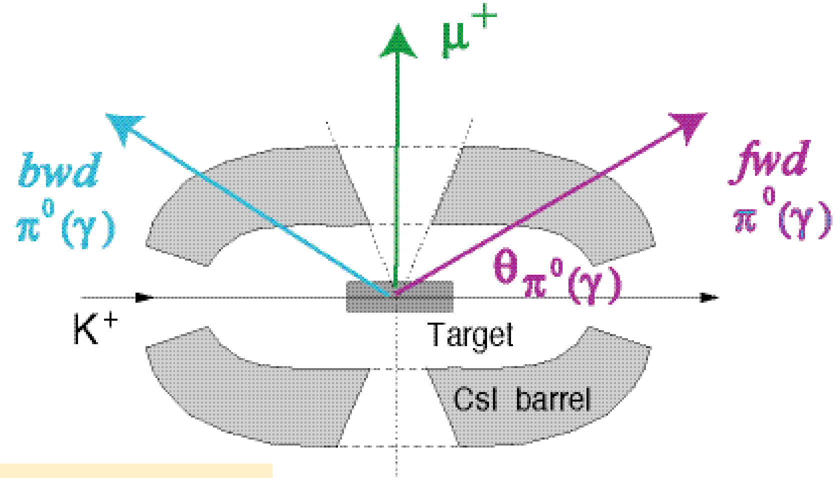


CsI(Tl) and kinematics

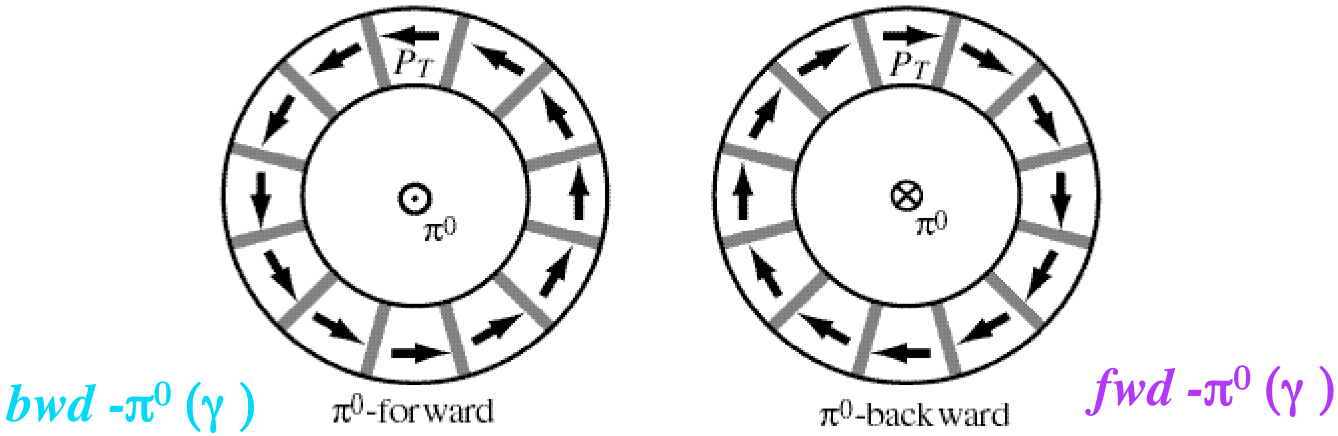
CsI barrel



fwd and *bwd* π^0 /γ



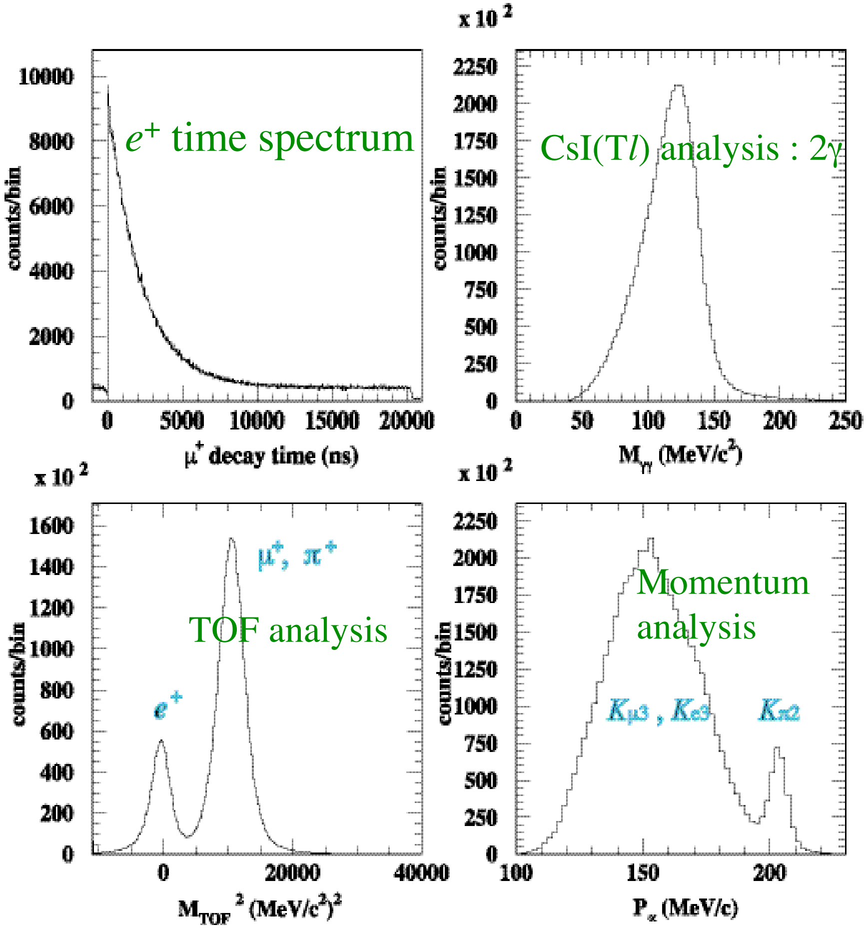
P_T directions



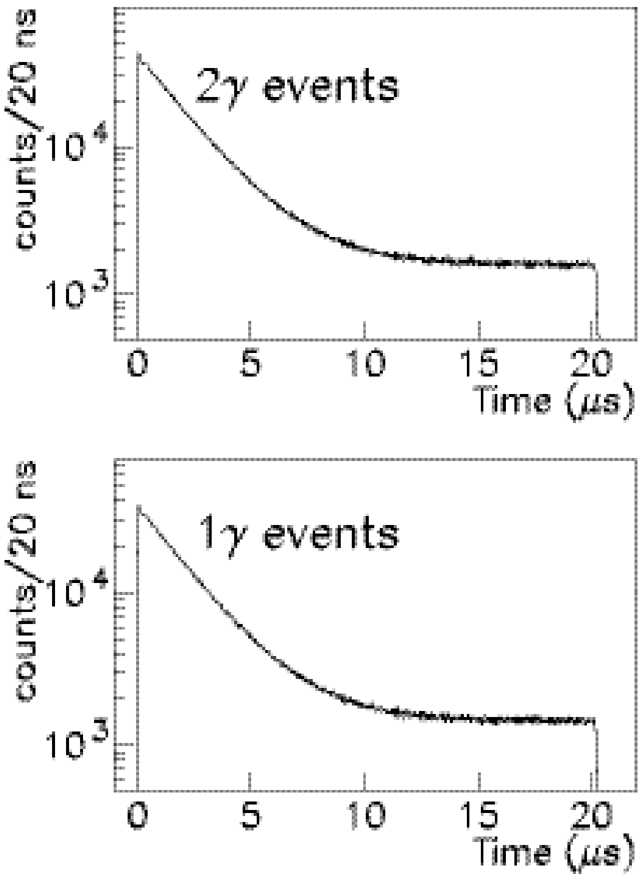
Double ratio measurement

Experimental data

$K^+_{\mu 3}$ event selection



e^+ time spectra



Analysis

$K_{\mu 3}$ event selection

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

e^+ time spectrum anlysis

$N_{cw(ccw)}$: integration from 20ns to 6 μs
with constant BG subtracted

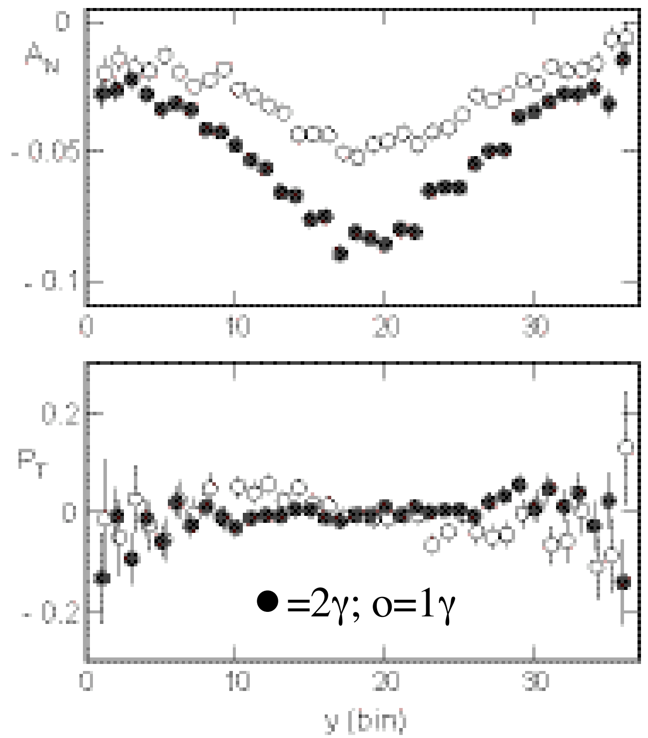
Asymmetry analysis

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

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

- $P_T(y) = A_T(y) / \alpha(y) <\cos\theta_T>$

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



$\Rightarrow$

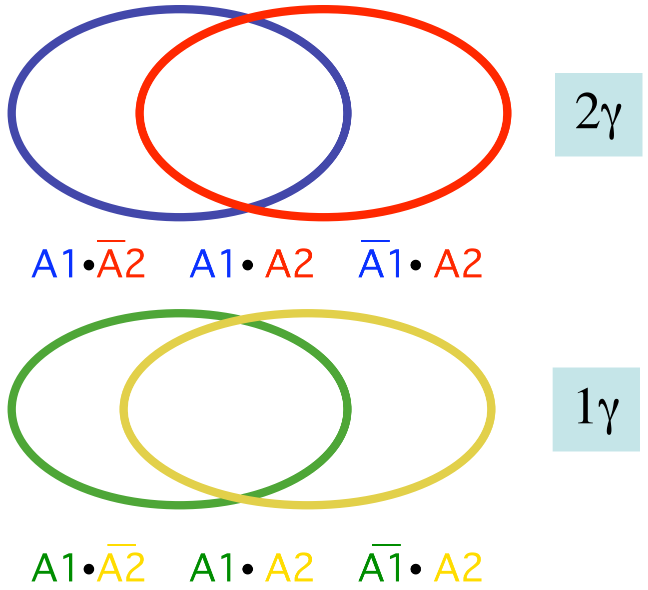
- $P_T = \int P_T(y)\, w(y) \mathrm{d}y$
- $\mathrm{Im}\xi = P_T / <P_T/\mathrm{Im}\xi>$

Two independent analyses

- Two analyses by two teams with
  - their own analysis policy and
  - event selection methods

Comparison of good $K\mu3$ event 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

Merits of two analysis method

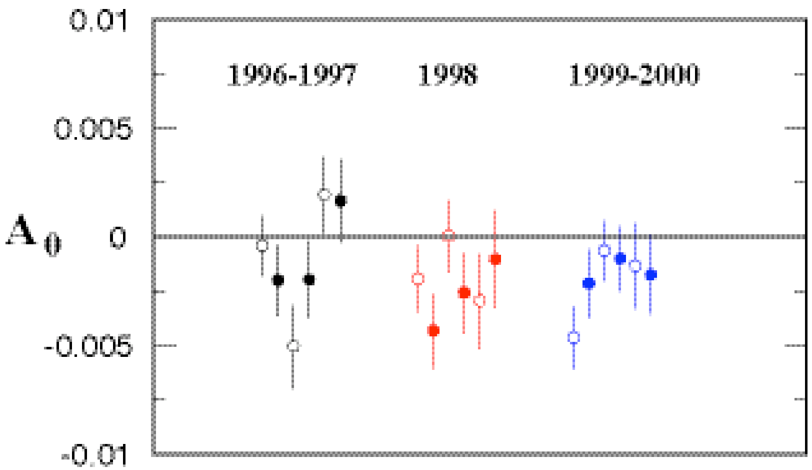
- Cross check of data quality by A_0, decay plane rotation θ_r and θ_z and P_T
- Comparison of sensitivity by normal asymmetry A_N and $<\cos\theta_T>$
- Check of data quality in e.g. A1 by comparing A1•A2 and A1• A2-bar
- Estimate of systematic error by comparing $<\cos\theta_T>$ of A1• A 2 from A1 and A2
- Improvement of statistical error

Data quality check

Null asymmetry check

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

$total = fwd + bwd$

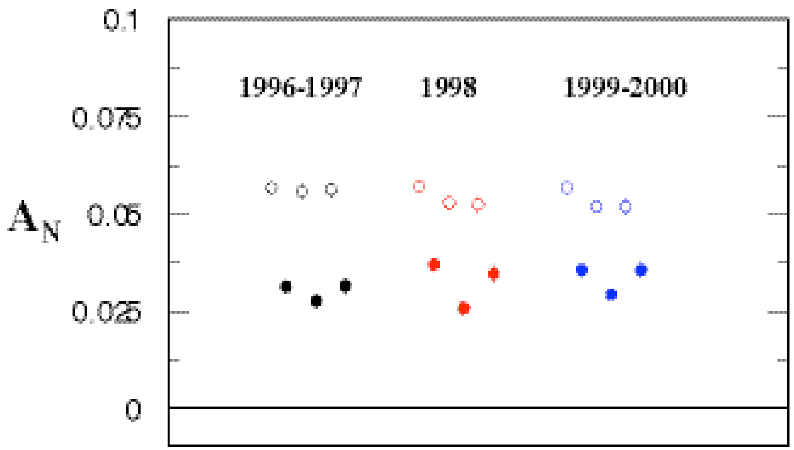


Sensitivity check

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

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

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



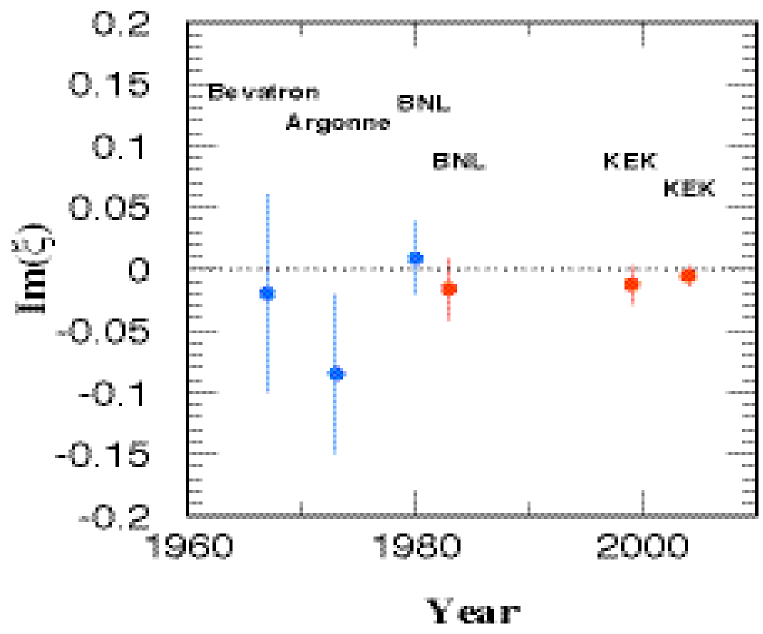
- 6 data sets for each period
- Open circles are 2γ events and dots are 1γ events.

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

Result

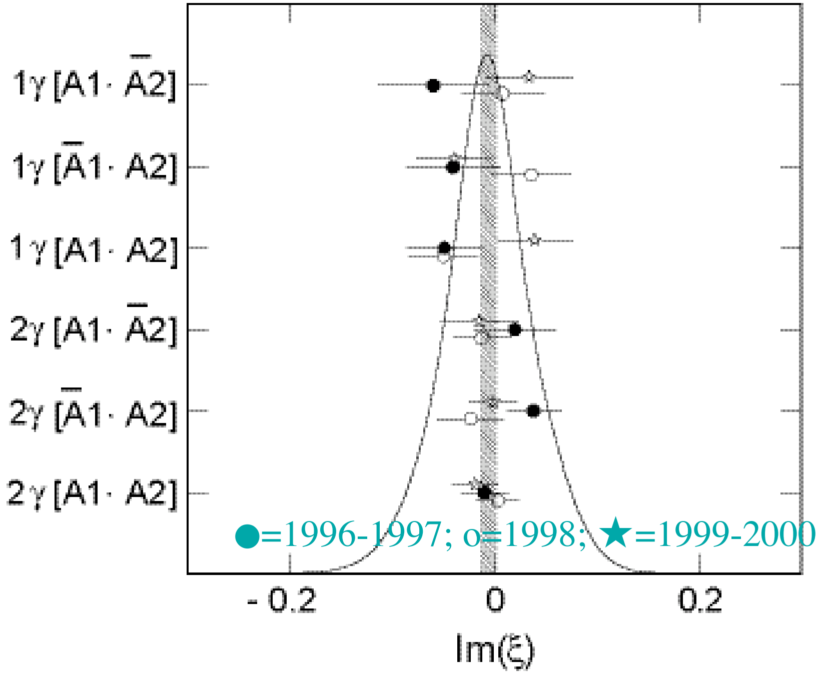
P_T = - 0.0018 ± 0.0023(stat) ± 0.0011(syst)
($|P_T|$ < 0.0051 : 90% C.L.)

Imξ = - 0.0055 ± 0.0073(stat) ± 0.0036(syst)
($|\mathrm{Im}\xi|$ <0.016 : 90% C.L.)



Systematics check

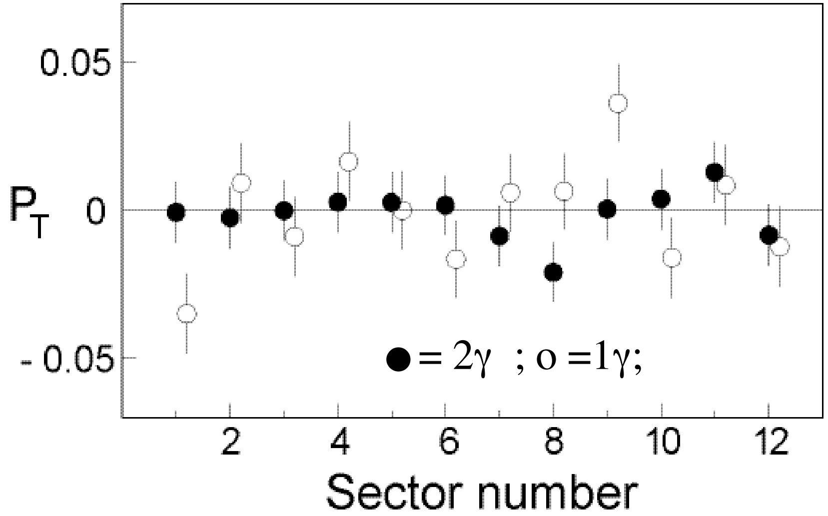
Consistency among data



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

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

Sector dependence



Decay plane rotation

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

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

Systematic errors

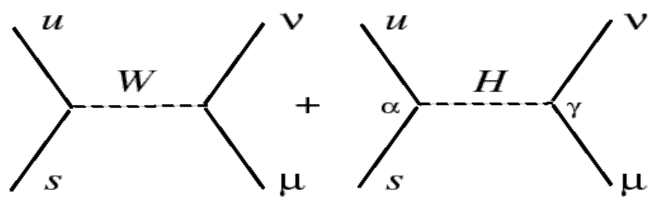
- $\Sigma 12$: 12-fold rotational cancellation
- *fwd/bwd* : π^0 forward/backward cancellation

Source of Error	$\Sigma 12$	*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	-	-	38
Total			11.4

Model implications

Three Higgs doublet model

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



$$\begin{aligned}\mathrm{Im}\xi &= \mathrm{Im}(\alpha_1\beta_1^*) \times (v_2/v_3)^2 \times (m_K/m_{H^+})^2 \\ &= \mathrm{Im}(\alpha_1\gamma_1^*) \times (m_K/m_{H^+})^2\end{aligned}$$

v_i : vacuum expectation values
α_i, β_i, γ_i : mixing matrix elements

- $|\mathrm{Im}\xi| < 0.016$ (90% C.L.) $\Rightarrow \mathrm{Im}(\alpha_1\gamma_1^*) < 544$ (at $m_H = m_Z$)
  cf. BR $(B \to X\tau\bar{\nu}_\tau)$ $\Rightarrow \mathrm{Im}(\alpha_1\gamma_1^*) < 1900$ (at $m_H = m_Z$)

Neutron EDM in 3HD model

$$d_n \approx 4/3\, d_d \propto \mathrm{Im}(\alpha_1\beta_1^*) \times m_d / m_H^2$$

$v_2/v_3 = m_t/m_\tau$ [R.Garisto and G.Kane, Phys. Rev. D44 (1991)2789]

- $|\mathrm{Im}\xi| < 0.016$ (90% C.L.) $\Rightarrow d_n < 9 \times 10^{-27}\, e$ cm
  cf. $d_n^{\exp} < 6.3 \times 10^{-26}\, e$ cm

Summary

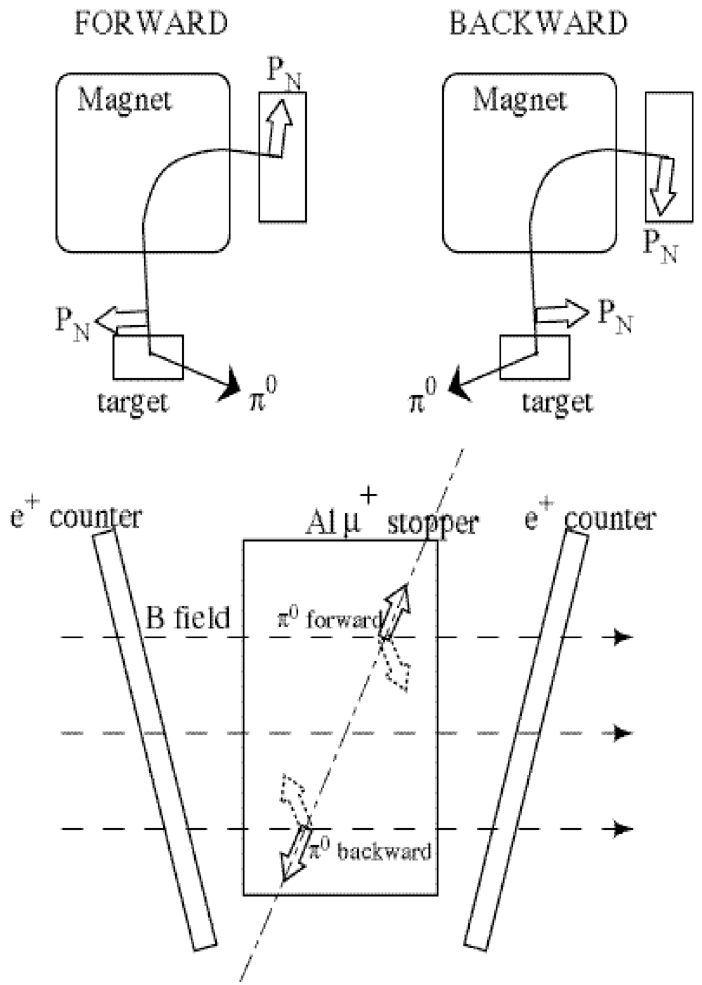
- Transverse muon polarization in $K^+ \rightarrow \pi^0 \mu^+ \nu$ decay is a good probe of CP violation beyond the standard model.

- The final result of the KEK-E246 experiment showed no evidence for T violation with $\mathrm{Im}\xi = -0.0055 \pm 0.0073(\mathrm{stat}) \pm 0.0036(\mathrm{syst})$, or $|\mathrm{Im}\xi| < 0.016$ (90% C.L.).

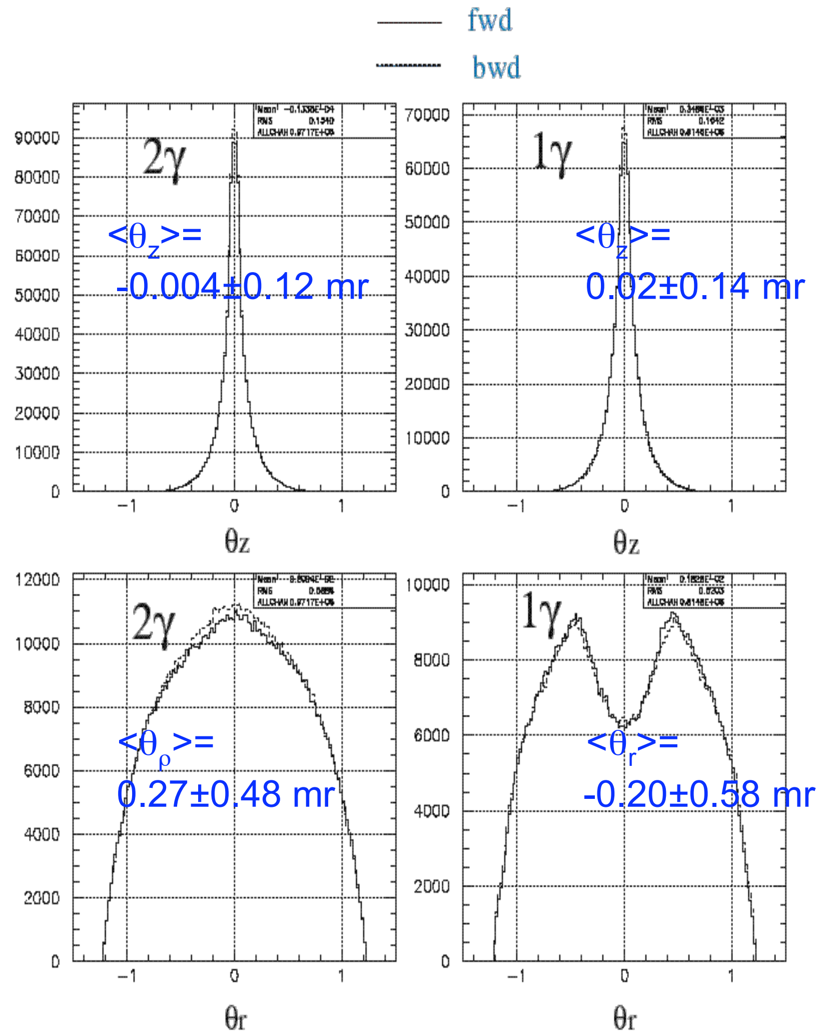
- This limit constrains the parameters of some non-standard CP violation models with high sensitivity.

- We are going to propose a next generation P_T experiment at the high intensity accelerator J-PARC.

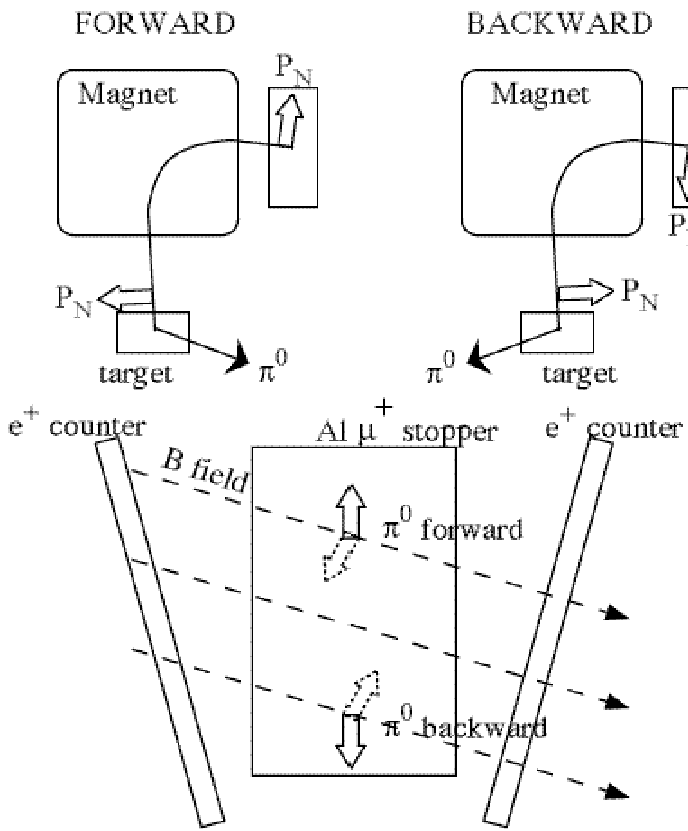
Decay plane rotation

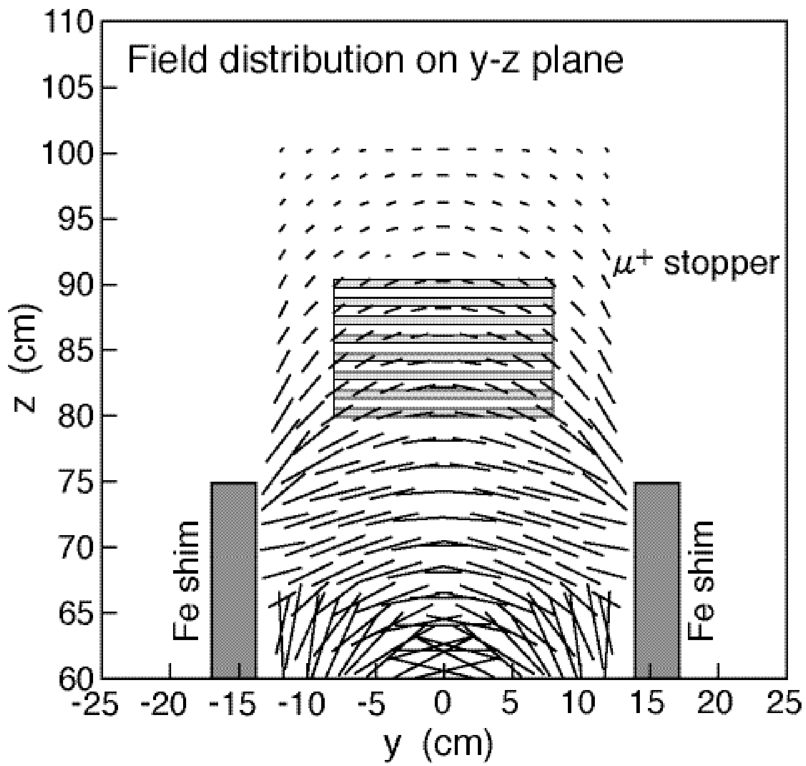


No cancellation from fwd/bwd



B field rotation

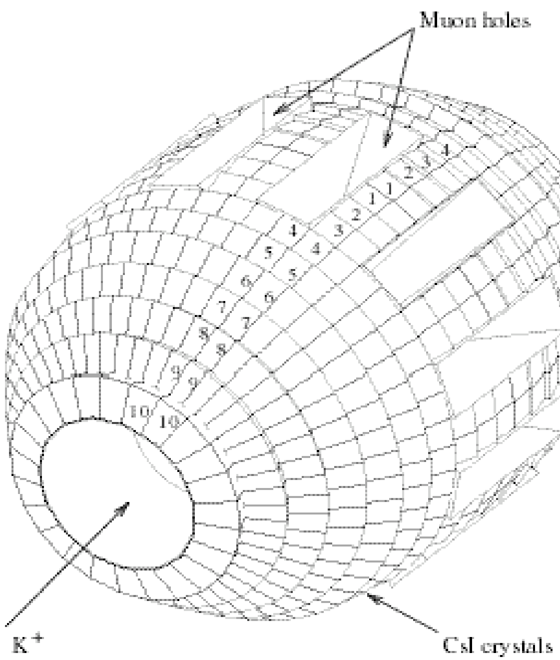




No cancellation from fwd/bwd

- Field Measurement
  T. Ikeda, *et al.*, Nucl. Instr. and Meth. in Phys. Res. A 401 (1997) 243-262
- δ_z = 1.3 mrad $\rightarrow \delta P_T(\delta_z) = 5 \times 10^{-4}$

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

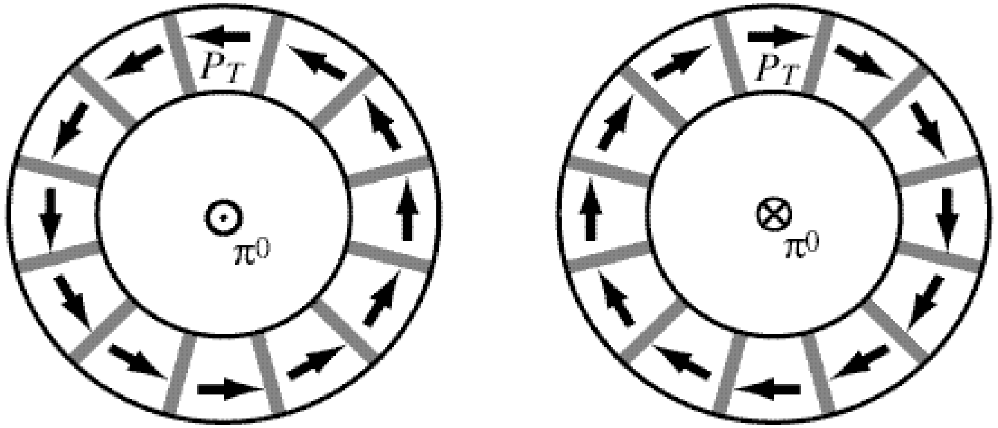
[D.V.Dementyev et al. Nucl. Instr. Method A440 (2000) 151]

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



π^0-forward π^0-backward

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

Analysis: methodology

- Blind analysis
  - Event selection optimization before looking at A_T
- Two independent analyses
  - Easy to find any trivial mistakes in data reduction and analysis codes
  - Competition with each other for better analysis codes
  - Minimize potential human bias in the analysis
- Combination of two results
  - Analysis of “common” and “uncommon” events to check the event quality
  - Makes it possible to estimate systematic error associated with analysis
  - Improves the statistical accuracy

1998 data: π^0 mass spectrum

comparison with 1996-97