KEK-E470

Branching Ratio Measurement of $K^+ \rightarrow \pi^+ \pi^0 \gamma$ Direct Emission

February 14, 2001

Kaon Decay Workshop

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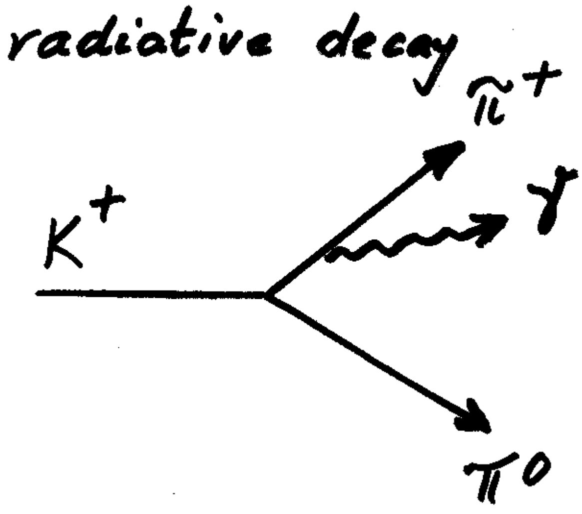
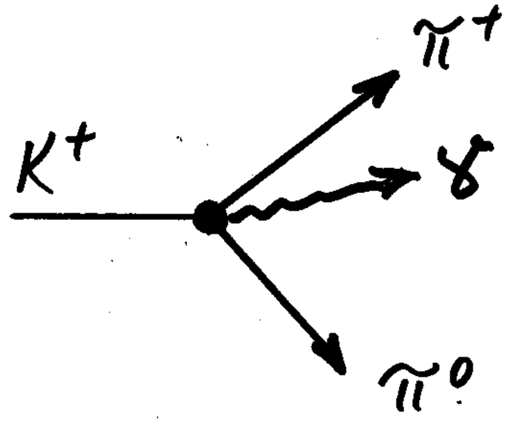
IPNS, KEK

1) Physics motivation
2) E246/470 setup
3) Monte Carlo simulation and event selection
4) Expected sensitibity

Physics Motivation



Internal Bremsstrahlung
(IB)
suppressed by ΔI=1/2 rule



Direct Emission
(DE)
leading term
||
magnetic transition of
Chiral Anomaly

Kaon decays are powerful to study

- low energy QCD
- Chiral Perturbation Theory

- non-leptonic decays
- radiative decays

$K^+ \to \pi^+ \pi^0 \gamma$ Decay

Decay amplitude

$$A = A_{IB} + A_{DE}$$
$$A_{IB} = E_{IB}$$
$$A_{DE} = E_{DE} + M_{DE}$$

E : electric amplitude

M: magnetic amplitude

Decay probability

$$d\Gamma = |A|^2$$
$$= |E_{IB} + E_{DE}|^2 + |M_{DE}|^2$$
$$= |E_{IB}|^2 + \underbrace{2\mathrm{Re}(E_{IB} E_{DE}^*)}_{\text{Interference term}} + \underbrace{|E_{DE}|^2 + |M_{DE}|^2}_{\text{DE term}}$$

c.f.

$$\not{CP} = (d\Gamma^+ - d\Gamma^-)/(d\Gamma^+ + d\Gamma^-) \sim E_{DE} \sin(\delta_1 - \delta_2)$$

Chiral Anomaly in CPT

(1) reducible term
Wess-Zumino-Witten functional

(2) direct anomaly term
uncertain about its existence

$K^+ \to \pi^+ \pi^0 \gamma$ in CPT

- $M_{DE} = M_4 = M_4^{anomaly} = M_4^{red} + M_4^{dir}$
  M_4 ∥ $O(p^4)$

$$M_4^{red} = -eG_8 M k^3/(2\pi F)$$
$$M_4^{dir} = eG_8 M k^3/(2\pi F)\ 16\pi^2\ [3N_{29}^{an} - N_{30}^{an}] \quad ①$$

- $E_{DE} = E_4 = 2ieG_8 M k^3/F)\ [N_{14} - N_{15} - N_{16} - N_{17}] + E_4^{loop}$ ②
  E_4 ∥ $O(p^4)$

<u>higher order</u>

- $M_6 = M_6^{VMD} + M_6^{FM}$ ③
  VMD : vector meson dominance
  FM : factorization model
  strong $E\pi^+$ dependence

Non-leptonic decay anomalous amplitudes of $O(p^4)$

G.Ecker et al. NP B413 (1994) 321

A complete list of local anomalous non-leptonic weak K decay amplitudes of $O(p^4)$ in the limit of CP conservation

Transition	$\mathcal{L}_{an}^{\Delta S=1}$	W_{28}	W_{29}	W_{30}	W_{31}	Expt.
$K^+ \to \pi^+\pi^0\gamma$	●		●	●		x
$K^+ \to \pi^+\pi^0\gamma\gamma$	●		●	●		
$K_L \to \pi^+\pi^-\gamma$			●		●	x
$K_L \to \pi^+\pi^-\gamma\gamma$	●		●		●	
$K^+ \to \pi^+\pi^0\pi^0\gamma$			●	●		x
$K^+ \to \pi^+\pi^0\pi^0\gamma\gamma$			●	●		
$K^+ \to \pi^+\pi^+\pi^-\gamma$			●		●	x
$K^+ \to \pi^+\pi^+\pi^-\gamma\gamma$			●		●	
$K_L \to \pi^+\pi^-\pi^0\gamma$		●	●	●		
$K_S \to \pi^+\pi^-\pi^0\gamma(\gamma)$			●	●	●	

↑ Reducible anomaly (under $\mathcal{L}_{an}^{\Delta S=1}$)

Direct anomaly (under W_{28}–W_{31})

How to observe INT and DE

Variable $w = (\boldsymbol{Pq})(\boldsymbol{pq})/(m_\pi^2 M_K^2)$

P = total momentum

q = photon momentum

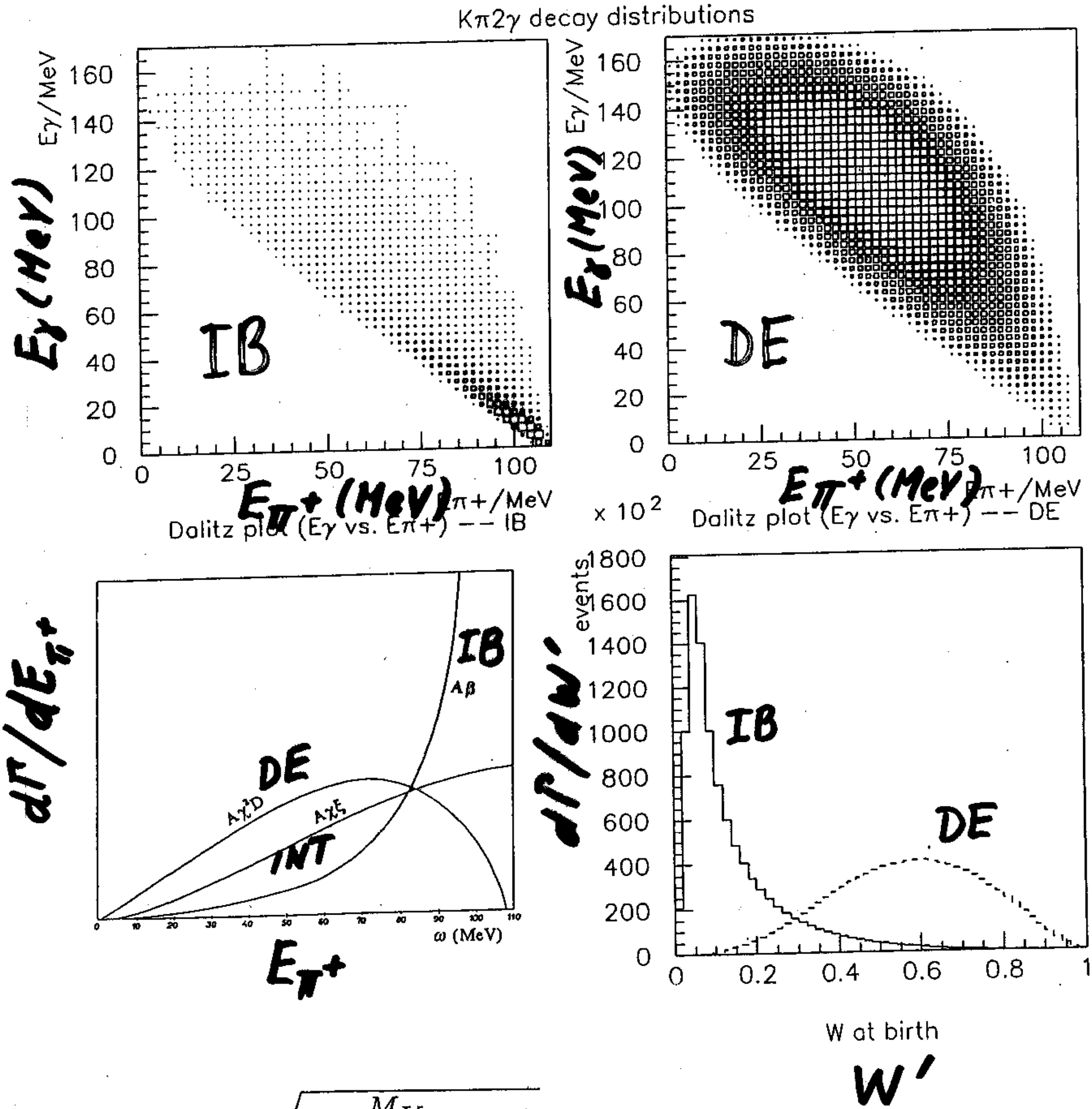
p = π^+ momentum

$$\frac{d^2\Gamma}{dE_\pi + dw} = \left(\frac{d^2\Gamma}{dE_\pi + dw}\right)_{IB} \left[\, 1 + 2a\, \mathrm{Re}E_{DE}\, w^2 + c\, (|E_{DE}|^2 + |M_{DE}|^2)\, w^4 \right]$$

w^2 dependence → Interference term

w^4 depemdence → Direct emission

$K_{\pi 2\gamma}$ spectra



$$W' = \frac{\sqrt{E_\gamma(\frac{M_K}{2} - E_{\pi 0})}}{m_\pi}$$

Previous Experiments

Group	Beam	Analysis	Events	BR(DE)/10^{-5}	DE/IB (%)
Abrams et. al.	$K^{\pm}$ (1.8 GeV/c)	$W',(E_\gamma)$	2100	$1.56 \pm 0.35 \pm 0.50$	6.1
Smith et. al.	$K^{\pm}$ (5 GeV/c)	p_{π^+}	2461	2.3 ± 3.2	8.0
Bolotov et. al.	K^- (24.5 GeV)	W',E_γ	140	$2.05 \pm 0.46^{+0.39}_{-0.23}$	8.2
BNL-E787	K^+ (stopped)	$W,(E_\gamma,\cos\theta_{\pi^+\gamma})$	20k	$0.47 \pm 0.08 \pm 0.03$	1.8 ± 0.3

These experiments have used $55 < T_c < 90$ MeV.

E470 K^+(stopped) $40 < T_c < 90$ MeV, DE/IB = 26%

KEK E470 Experiment

by E246 Collaboration

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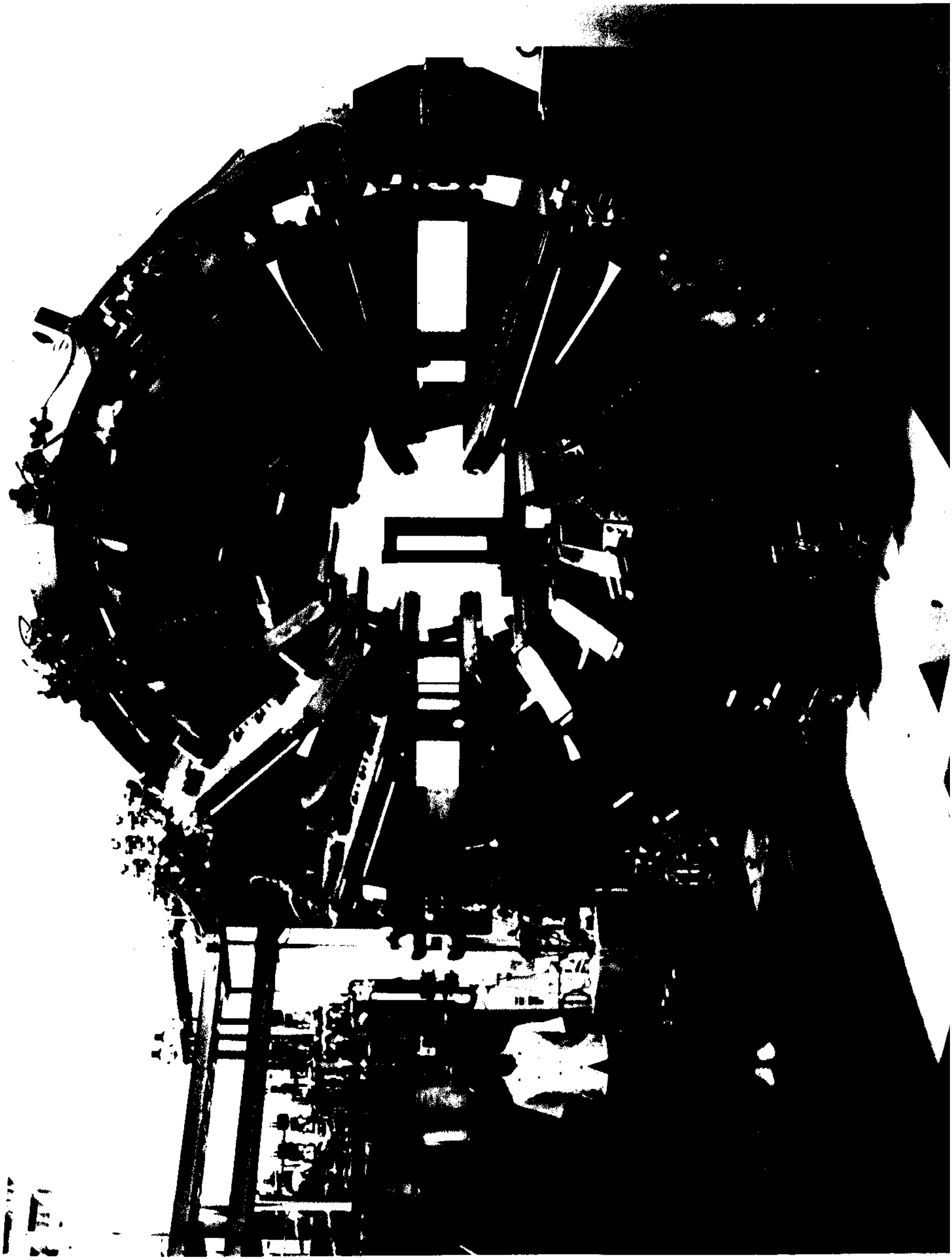
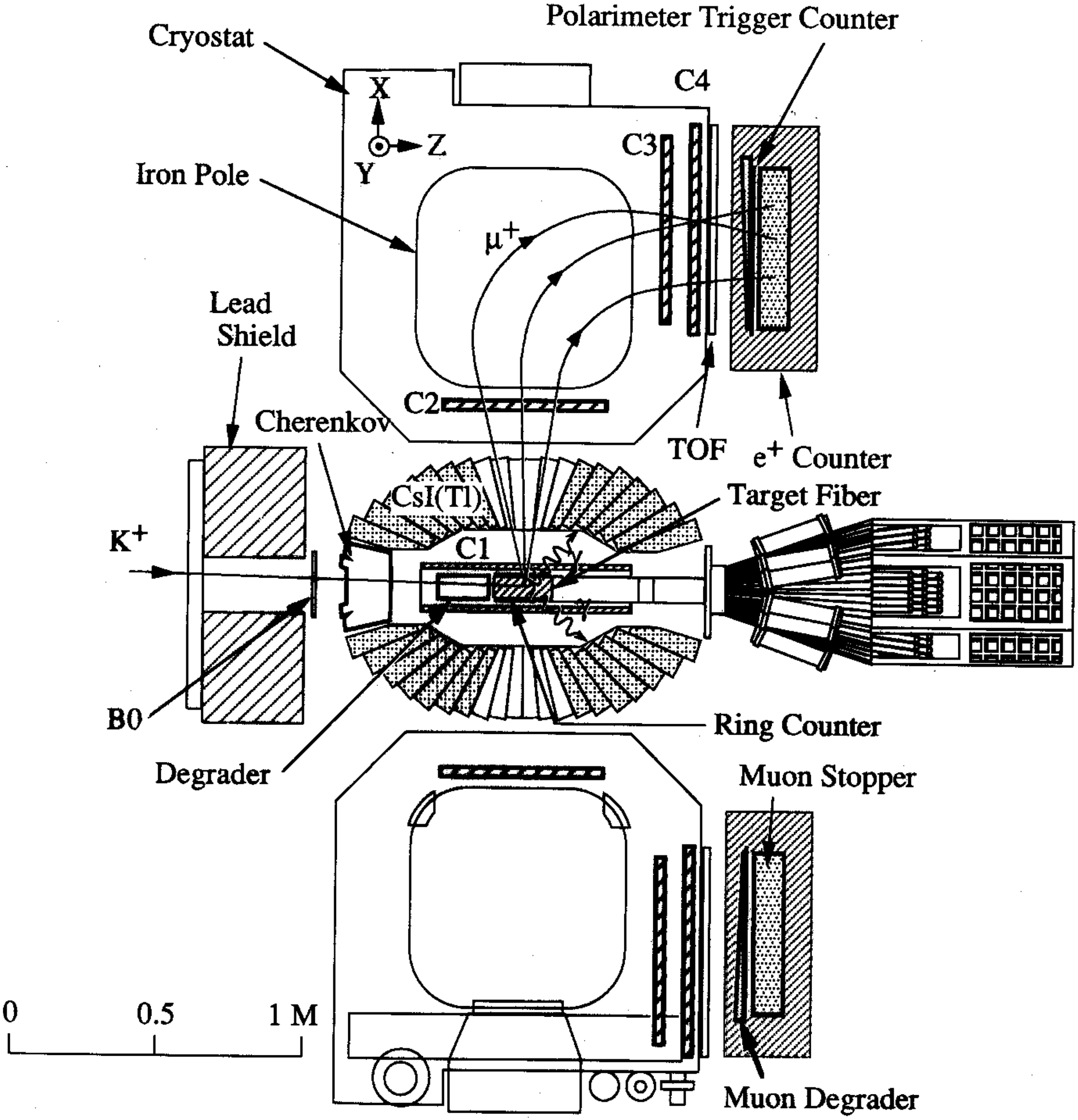


Experimental Setup
KEK-PS E246 (side view)

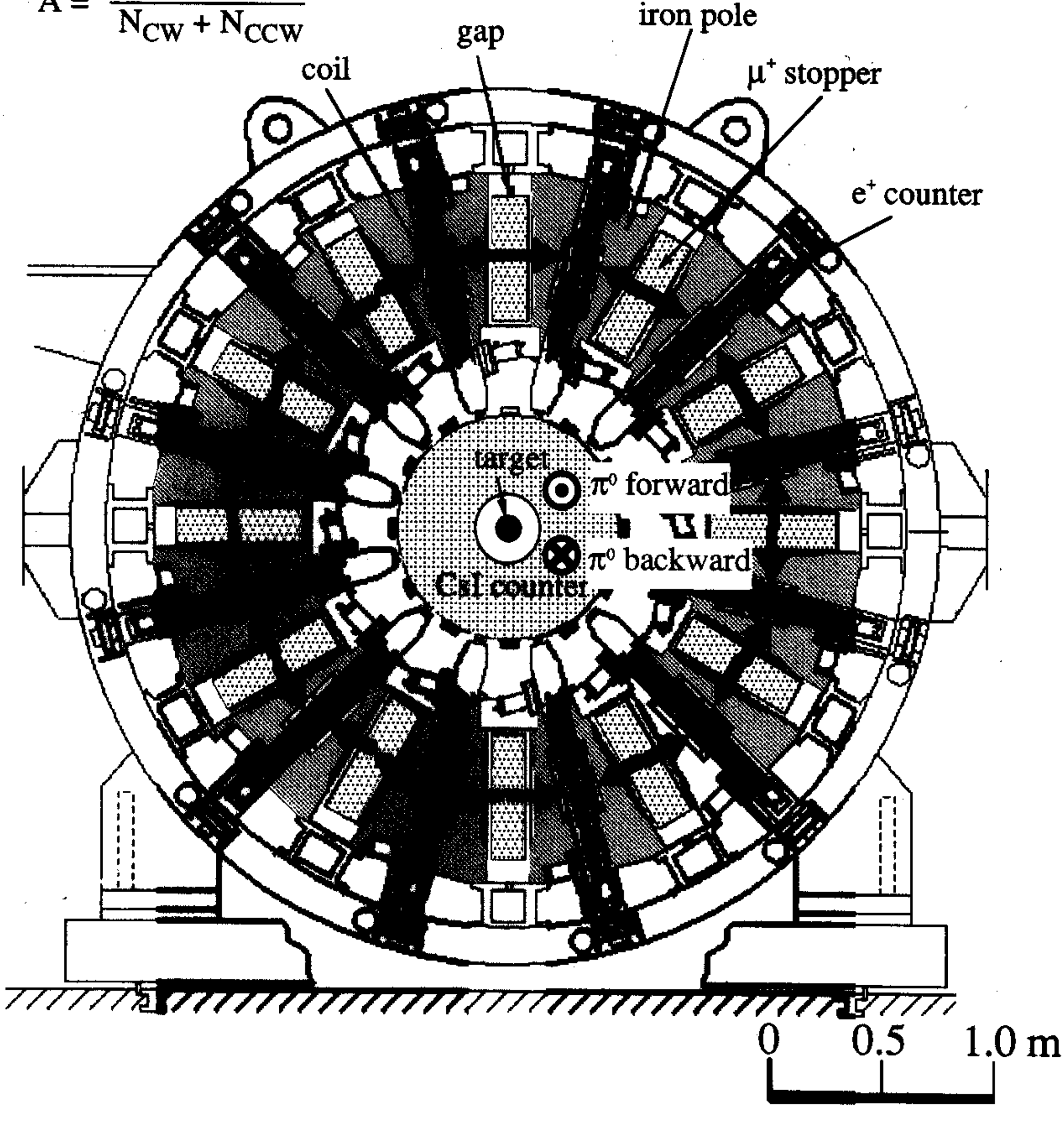
K decays at rest are used.



Experimental Setup KEK-PS E246 (End View)

12 rotational symmetry

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



Features of the Proposed Experiment

- Kinematically complete measurement: $\mathbf{p}_{K^0} = 0$, $\mathbf{p}_{\pi^0}$, $\mathbf{p}_{\pi^+}$, $\mathbf{p}_\gamma$

- High resolution for
  - $\mathbf{p}_{\pi^+}$ (Magnetic spectrometer)
  - $\mathbf{p}_{\pi^0}$ (Segmented CsI calorimeter)

- Good π^0 reconstruction (2γ pairing)

- Well known detector
  - small systematic error
  - reliable Monte Carlo code
  - reliable data acquistion system

$E_{\pi^+} \leq 40$ MeV

CsI(Tl) photon detector

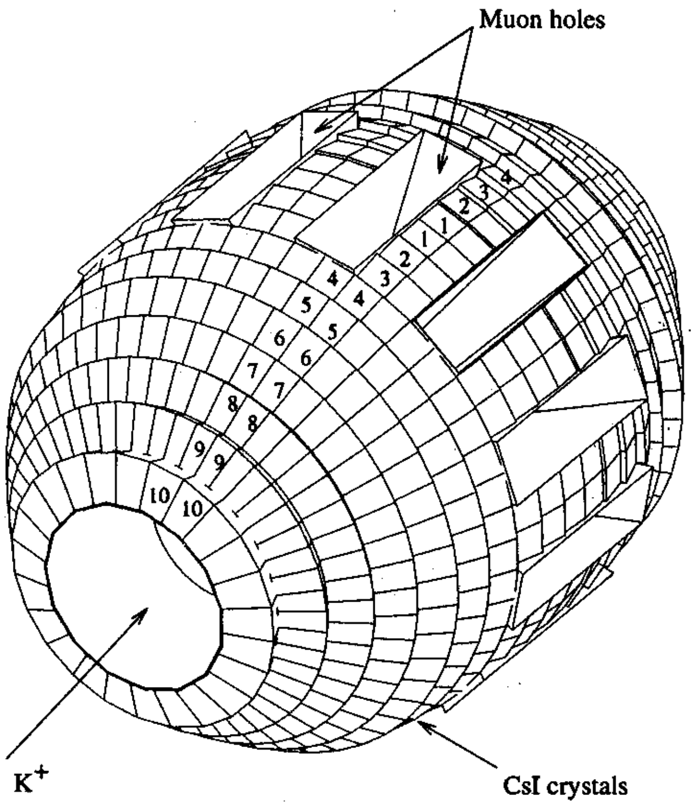
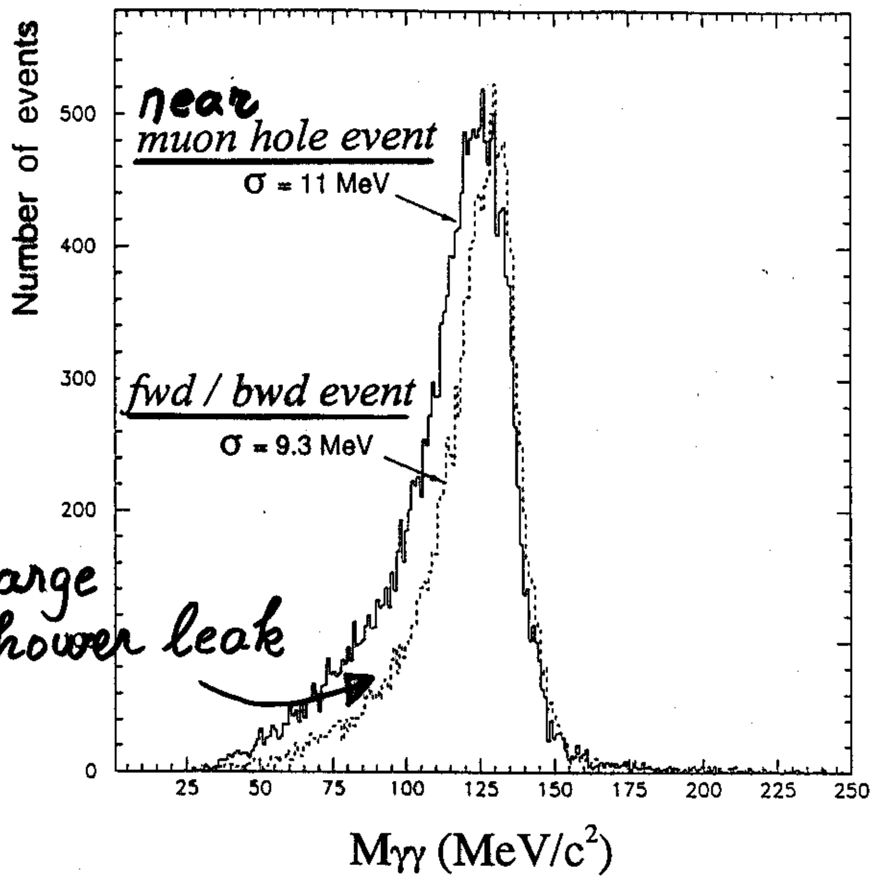
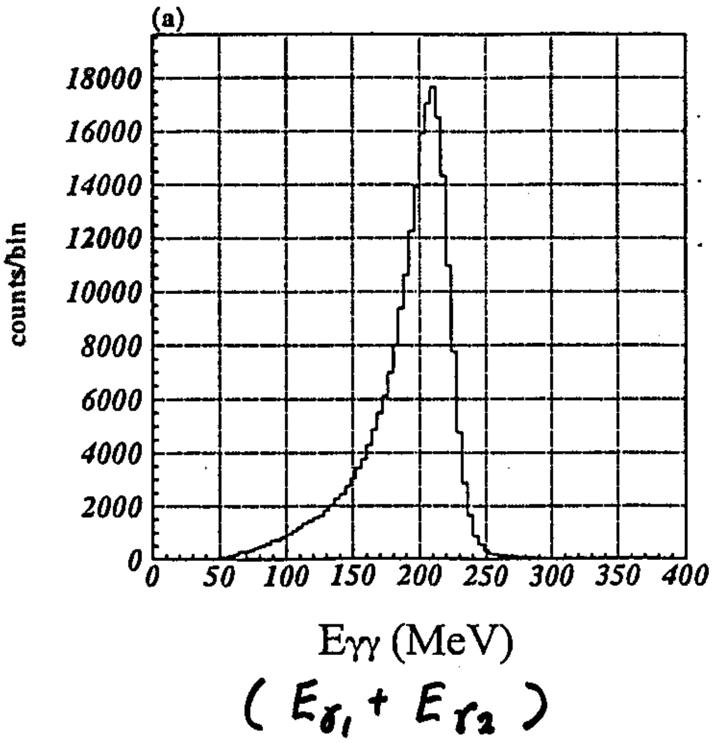


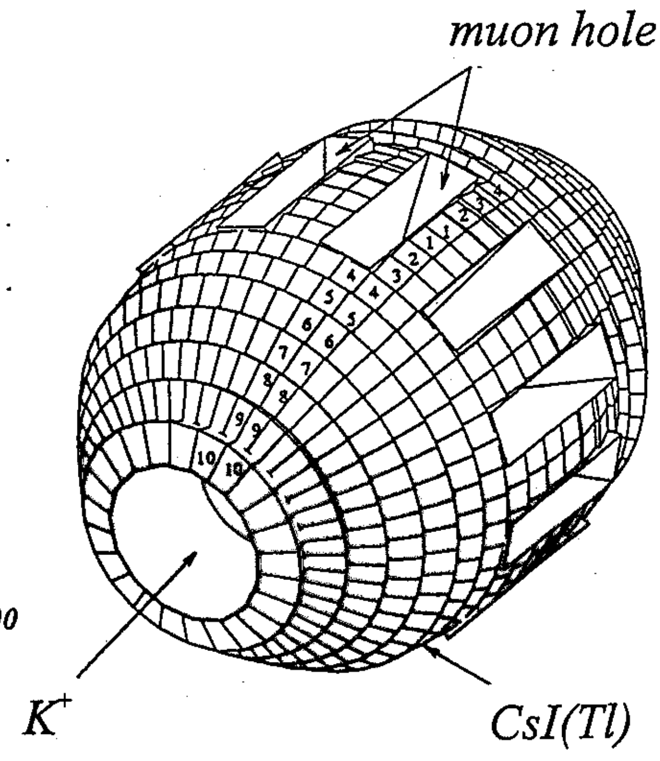
Table 3: Main parameters of the CsI(Tl) detector

number of crystals	768
segmentation	$\Delta\theta = \Delta\phi = 7.5$ degree
crystal length	25 cm (13.5 L_R)
solid angle coverage	3/4 of 4π
readout	PIN photodiode
light yield	11,000 pe /MeV
noise level (ENL)	65 keV
energy resolution	3.0%(σ) at 200 MeV
angular resolution	2.2°(σ) at 124 MeV
time resolution	3.5ns(σ) for $E_\gamma > 100$ MeV

π^0 from $K_{\mu 3}$ -2γ events -

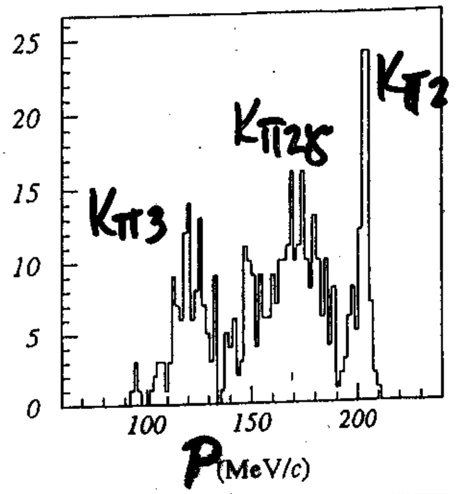


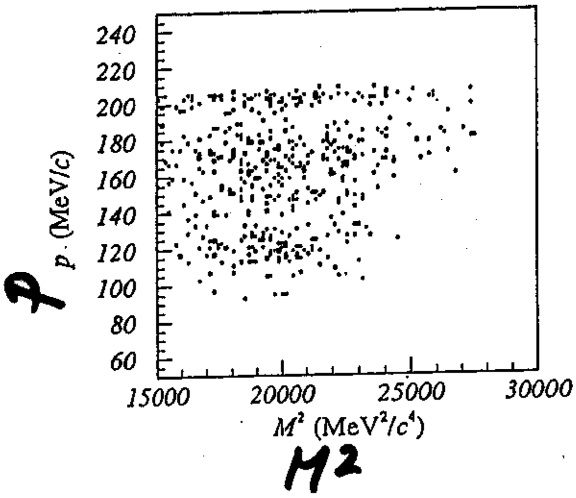




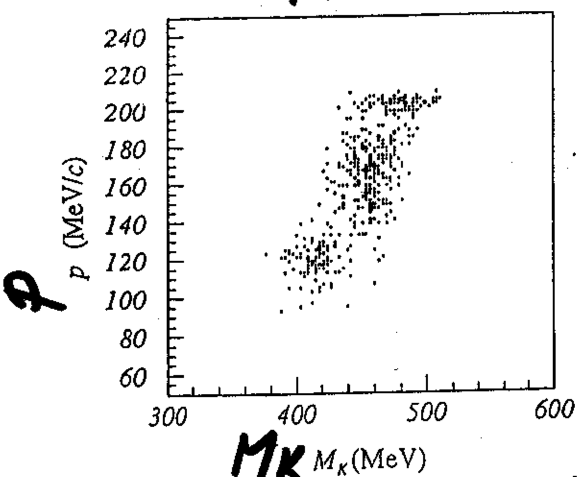
E246 Calibration run

Trigger=$C_K * Fid * TOF * \gamma$
B=0.90T, 0.65T
Check of $K_{\pi 2\gamma}$ event selection
Rough estimate of event rate
2γ pairing method





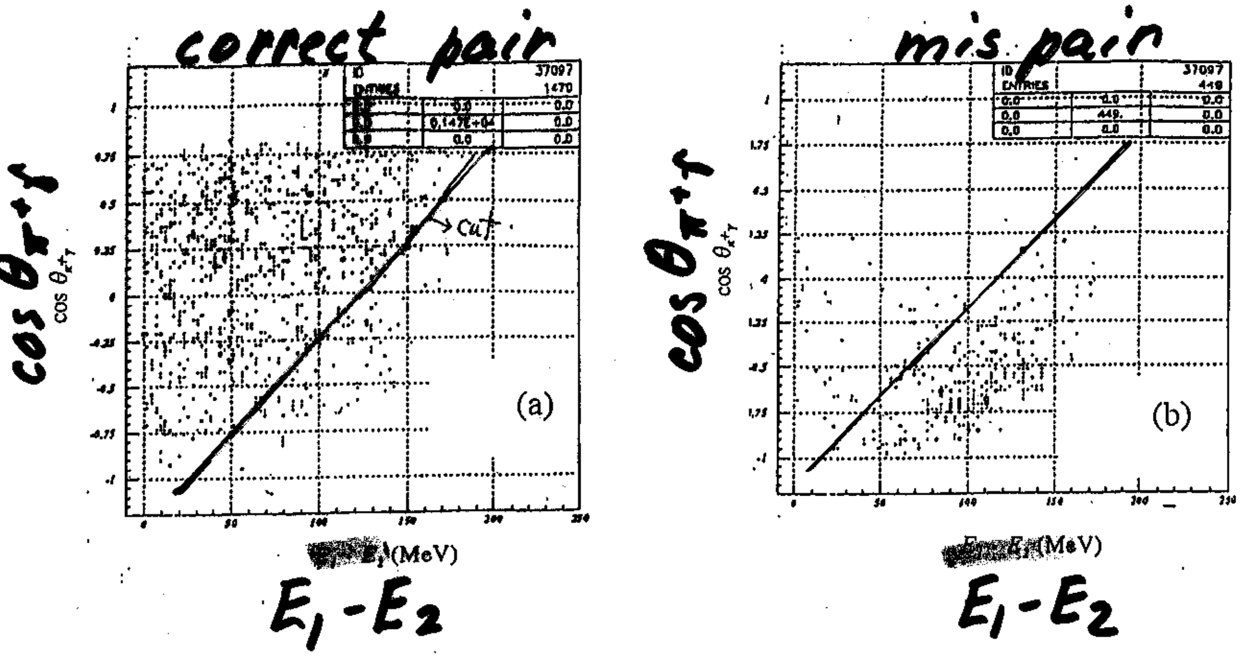
3γ-クラスター事象



Event Rate=$300/3.0\times10^9$ K^+ (in agreemen-
t with MC)

2γ pairing （MC 計算）

$$\chi^2 = [\cos\theta^{cal}_{\pi^+\gamma} - \cos\theta^{mea}_{\pi^+\gamma}]^2 + [\cos\theta^{cal}_{\pi^+\pi^0} - \cos\theta^{mea}_{\pi^+\pi^0}]^2$$



- efficieny=75%
- admixture of mispairing=4%

$K_{\pi 2\gamma}$ spectra

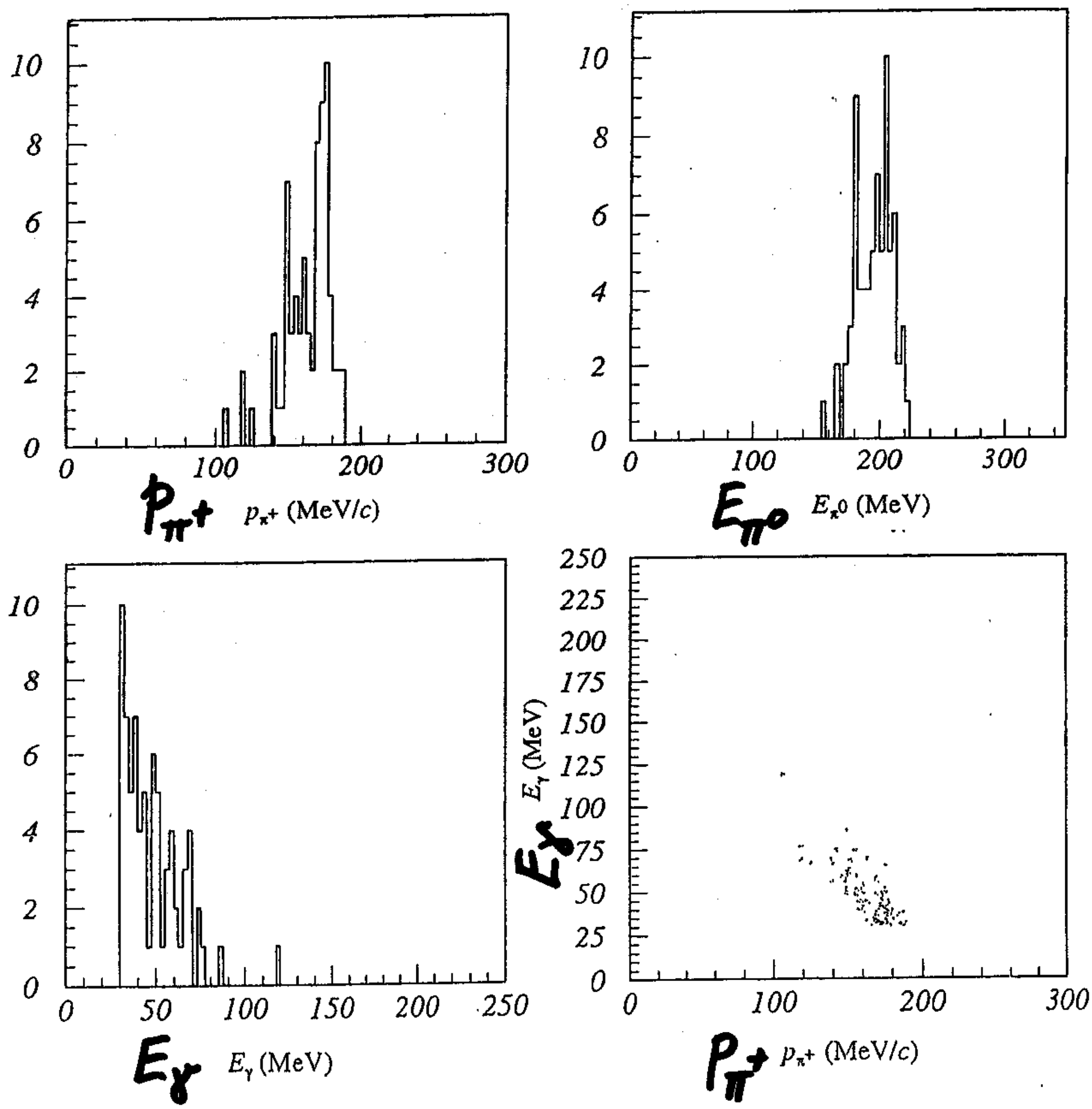
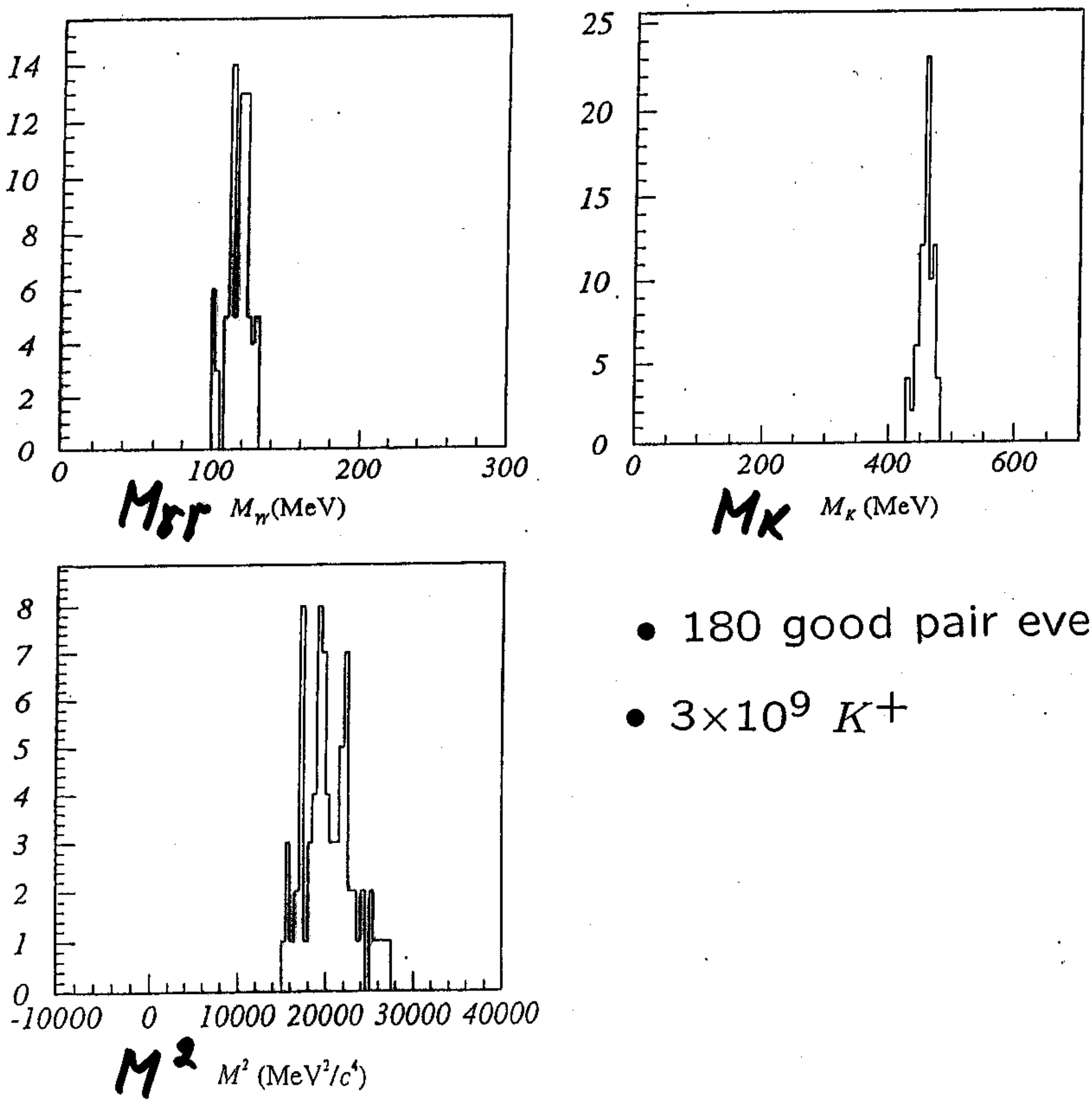


Fig. 8.5a Spectra of $K_{\pi 2\gamma}$ events selected in a calibration run of E246.

$K_{\pi 2\gamma}$ spectra



- 180 good pair events
- 3×10^9 K^+

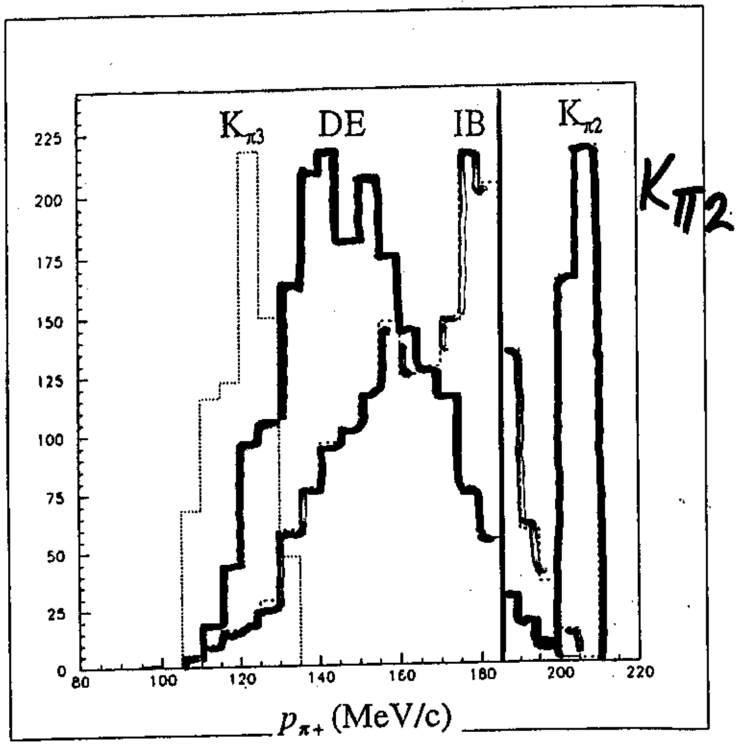


Fig. 7.1 Momentum spectrum of π^+ after the analysis of section 7.2 with arbitrary normalization. One sees that DE has lower energy while IB has a peak at 180 MeV/c. $K_{\pi2}$ events are rejected by taking the region of $p_{\pi+}$<182 MeV/c.

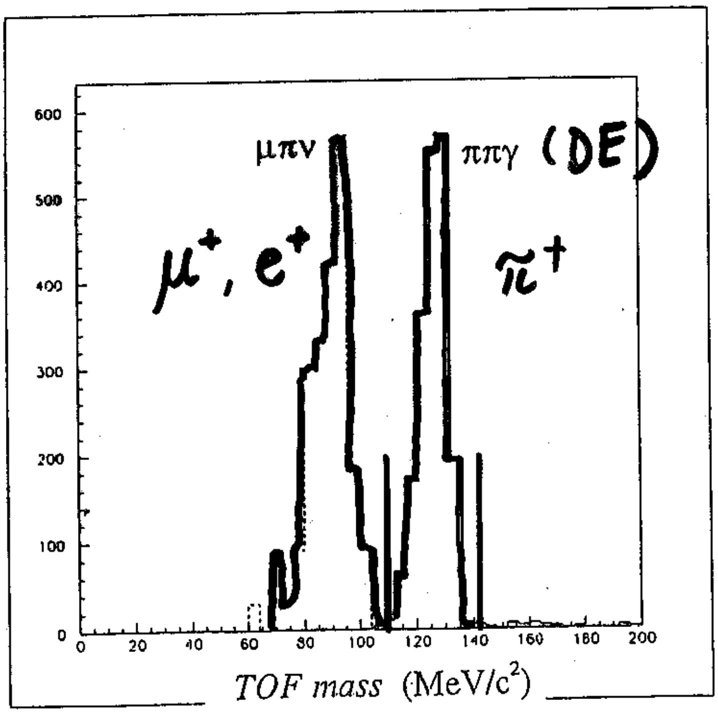


Fig. 7.2 TOF mass spectrum for $K_{\pi2\gamma}$ pions and $K_{\mu3}$ muons. Muons can be rejected completely with 110 <M <140 MeV/c^2.

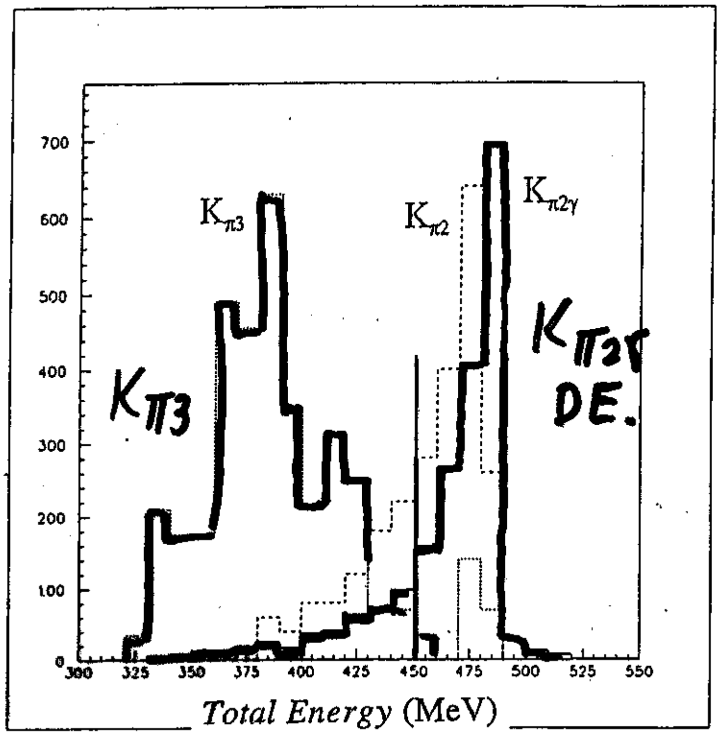
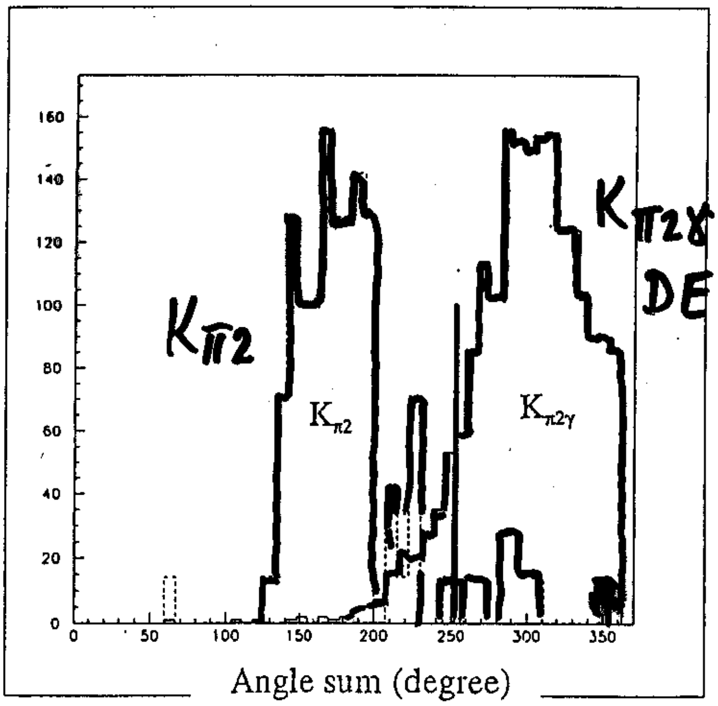


Fig. 7.3 Total energy spectrum calulated as $M_K = E_{\pi^+} + \Sigma E_{\gamma i}$. Most of $K_{\pi3}$ are rejected by setting a cut at *Total Energy* = 450 MeV.



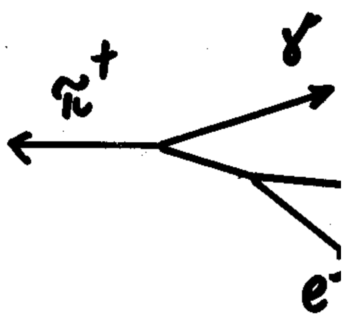
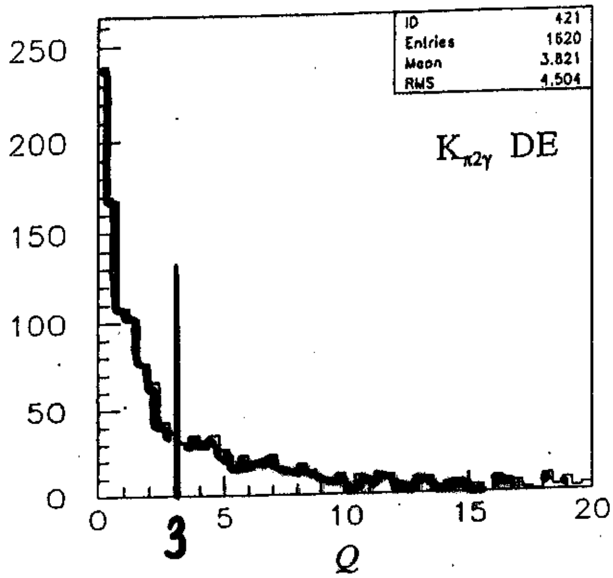
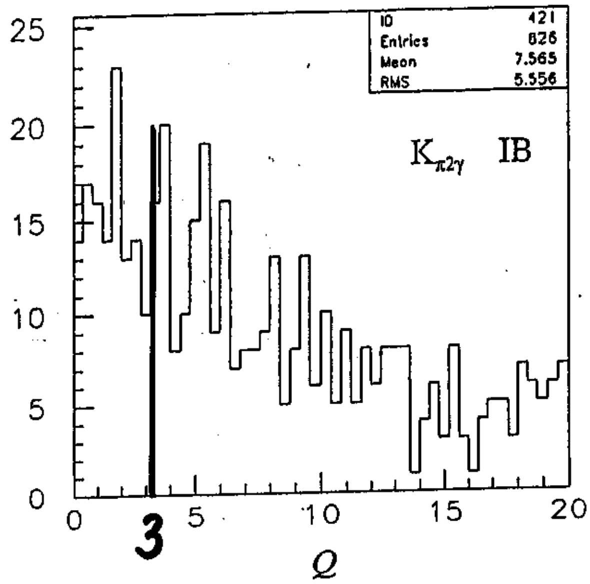
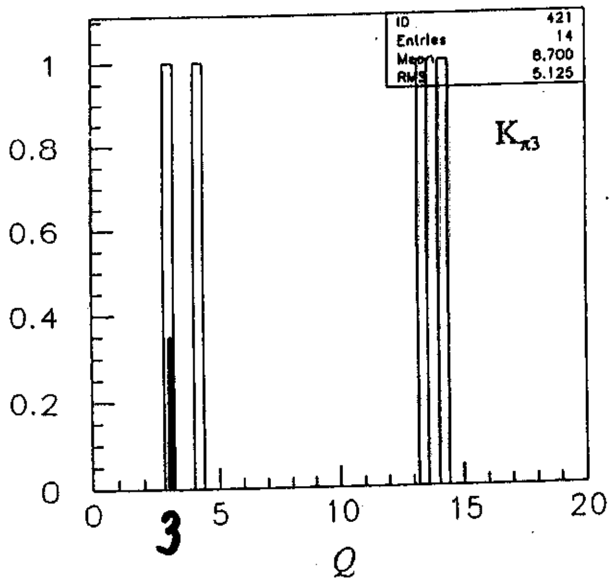


Fig. 7.4 Angle sum spectrum for $K_{\pi2\gamma}$ (solid line) and $K_{\pi2}$ (dotted line). The angle sum is defined as the sum of the three angles between three photons. It is shown that two of three photons are only slightly open for $K_{\pi2}$.

2γ pairing







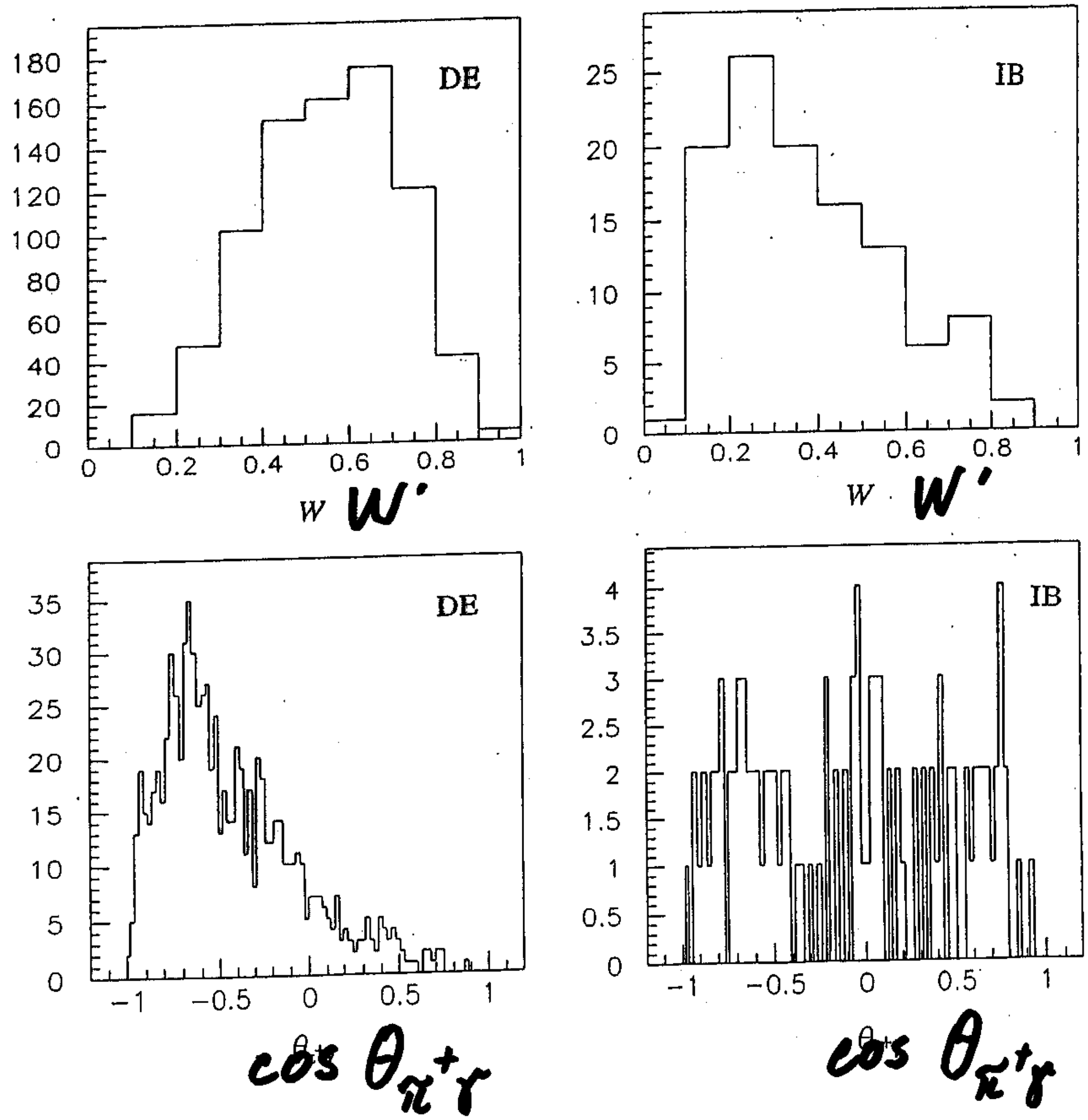
- $$Q = \frac{(m_{\gamma\gamma} - m_{\pi^0})^2}{\sigma_m^2} + \frac{(\cos\theta^{CALC}_{\pi^+\gamma} - \cos\theta^{MEAS}_{\pi^+\gamma})^2}{\sigma^2_{\pi^+\gamma}} + \frac{(\cos\theta^{CALC}_{\pi^+\pi^0} - \cos\theta^{MEAS}_{\pi^+\pi^0})^2}{\sigma^2_{\pi^+\pi^0}}$$

Q min の対を選ぶ.

- ϵ_{good} =61% (IB), 89% (DE)
- δ_{miss} =39% (IB), 11% (DE)

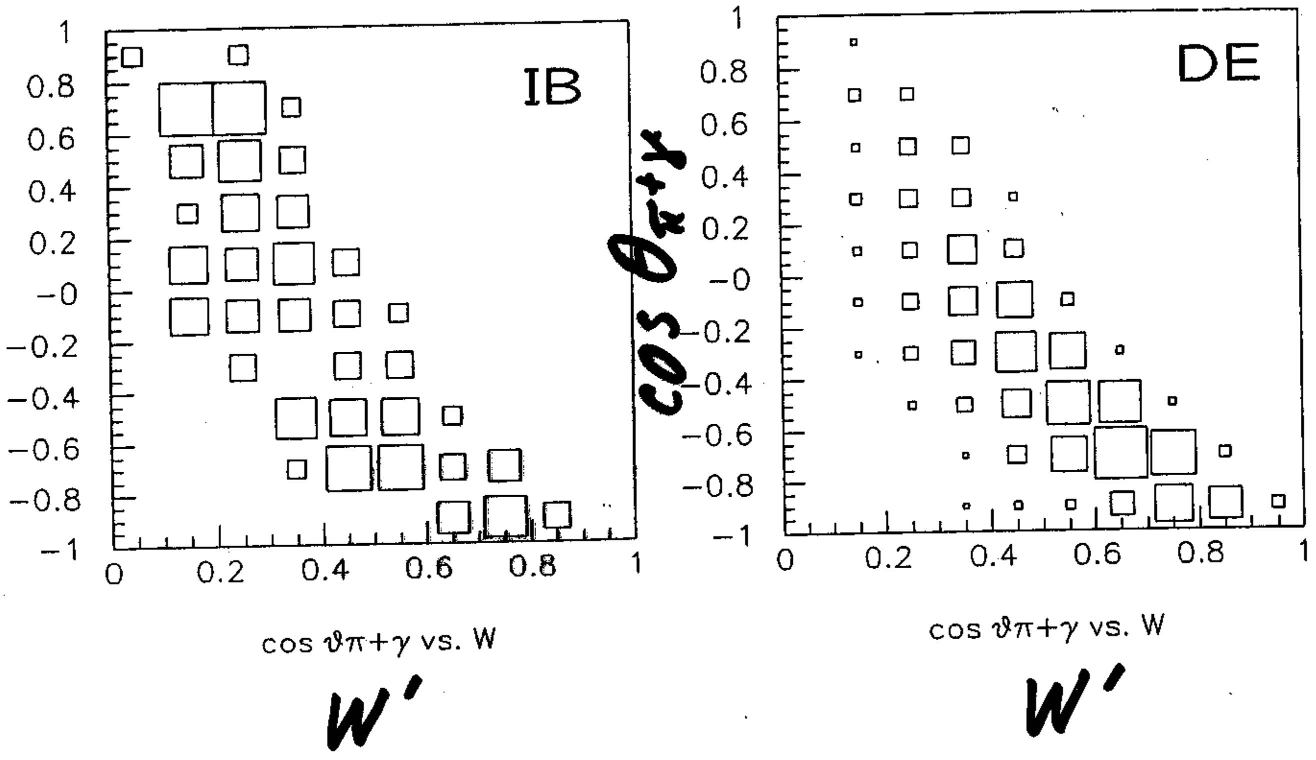
$K_{\pi 2\gamma}$ spectra

conditions: $110 < M_{TOF} < 140$ MeV, $T_{\pi^+} < 90$ MeV, $\theta_{sum} > 250°$, $M_K > 450$ MeV, $Q < 3$

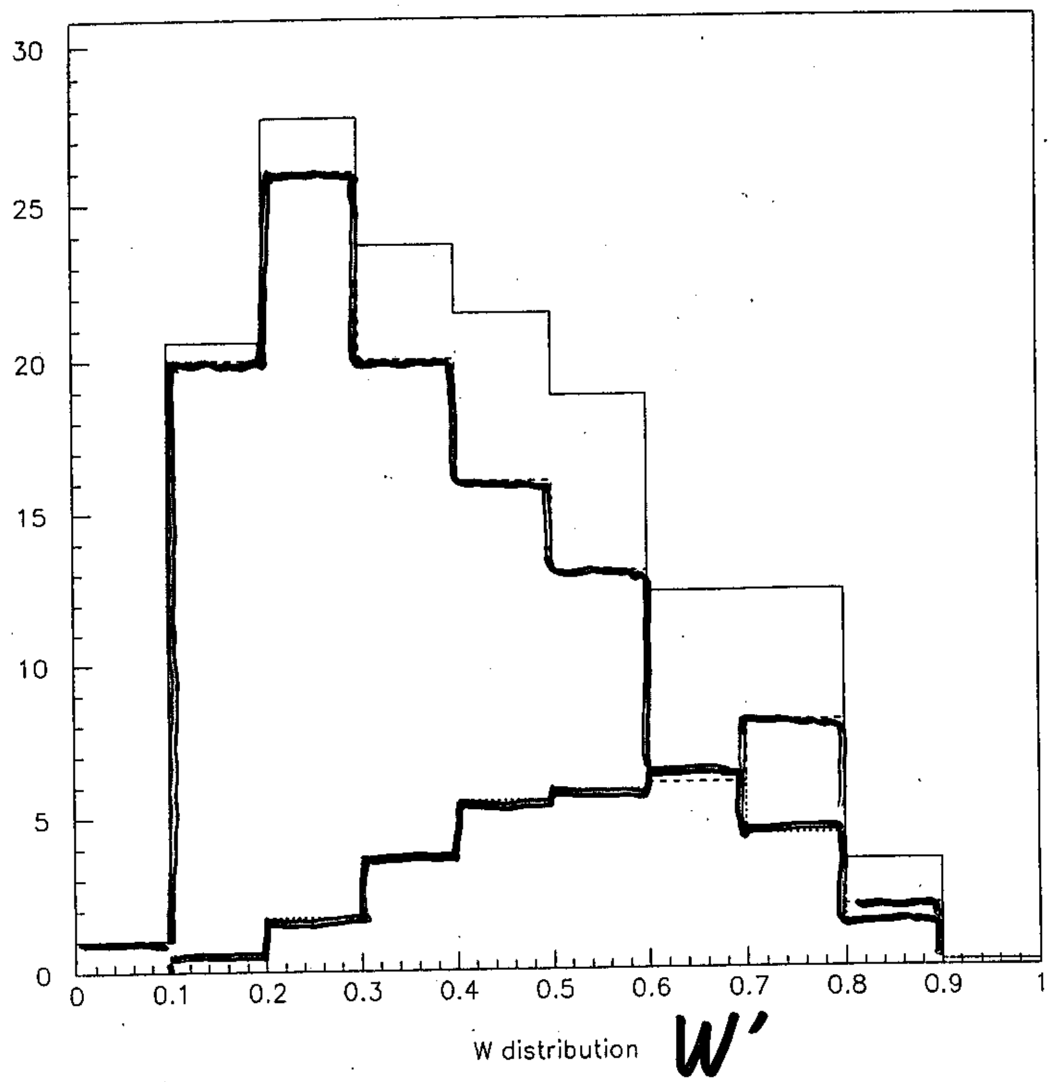


- $\frac{DE}{IB} \approx 0.3$

2D Distributions



Fit sensitivity



Test fit – $\delta BR/BR = 30\%$ for 140 events

Extrapolates to <u>$\delta BR/BR = 5\%$ for 5000 events</u>

Summary

Beam Condition

1) Beam	K^+ @ K5
2) I_p	3.0×10^{12} ppp
3) structure	0.7s spill/3.0s cycle
4) I_{K^+}	2.0×10^5

Run time

80 shifts after E246 finished

Event rates

1) Trigger rate	120/p
2) $K_{\pi2\gamma}$	7.3×10^{-3} /p
3) Total $K_{\pi2\gamma}$	5000, DE=1500
4) Expected Accuracy	δBR(DE)/BR(DE)<10%
	@ BR(DE)$\approx 10^{-5}$