CP Violation in the Decay $K_L \to p^+p^-e^+e^-$

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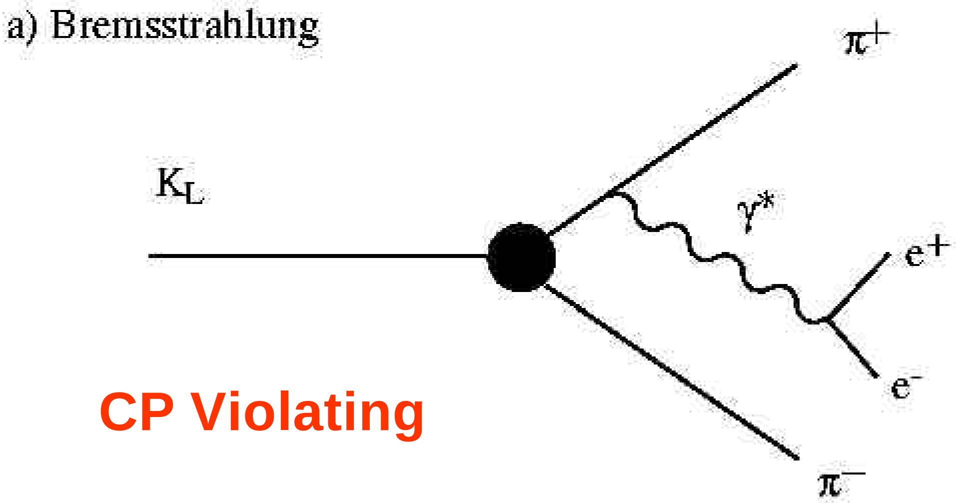
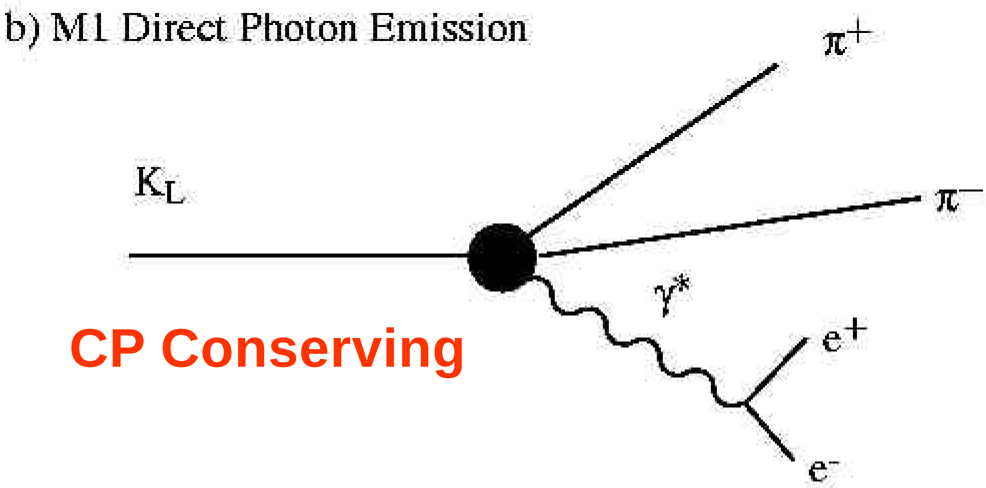
Contents

CP Violating Process in

$K_L \to p^+p^-e^+e^-$



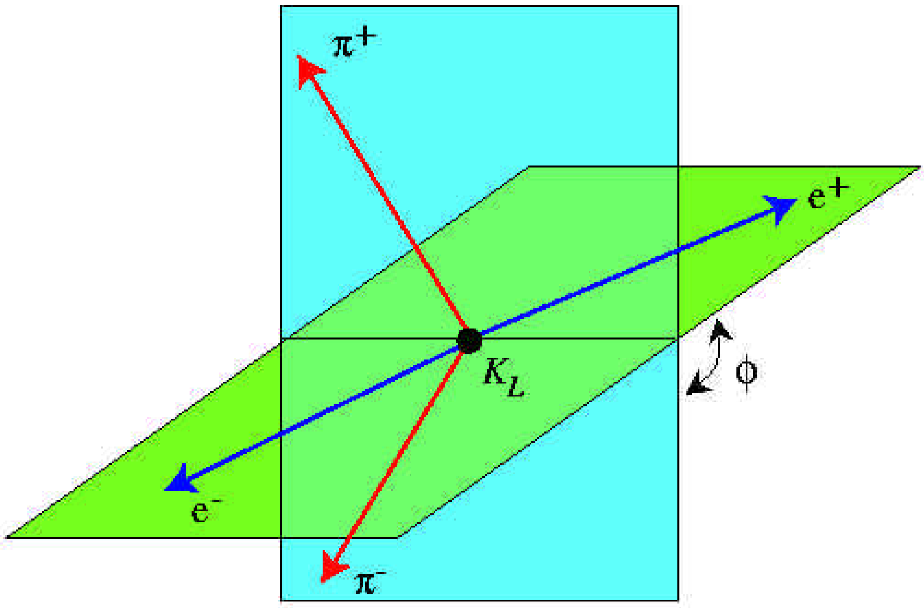
CP Violating



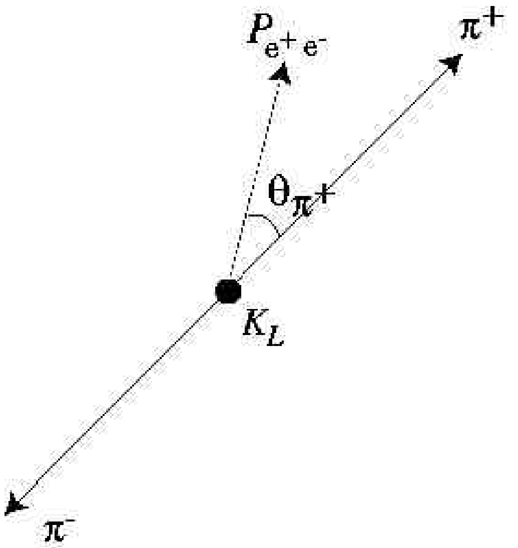
CP Conserving

CP violating effect comes from interference between IB and DE amplitudes.

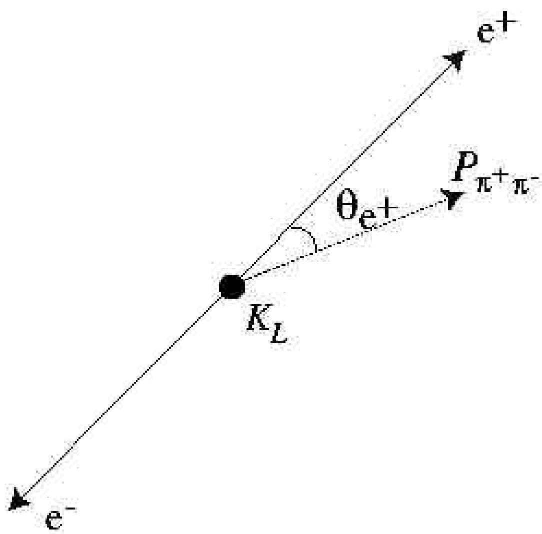
Critical Angles in $K_L \rightarrow p^+p^-e^+e^-$



φ is an angle between the normals to the ee and ππ planes in Kaon center of mass frame.



θπ+ is an angle between a center of mass of two electrons and π+ in pions' center of mass frame.



θe+ is an angle between a center of mass of two pions and e+ in electrons' center of mass frame.

Angular Asymmetry in Φ

$$\frac{d\Gamma}{d\phi} = \Gamma_1 \cos^2\phi + \Gamma_2 \sin^2\phi + \Gamma_3 \sin\phi\cos\phi$$

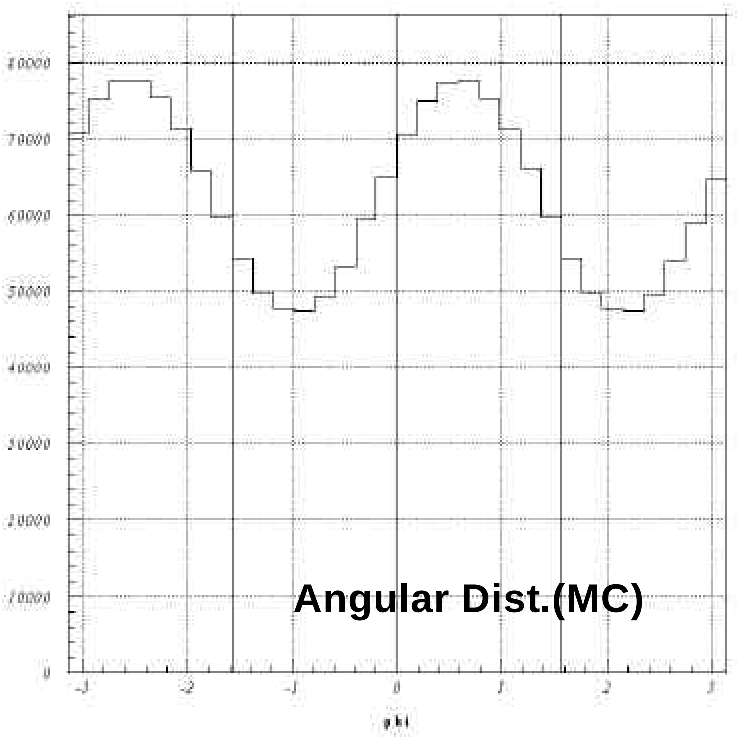
$$\sin\phi\,\cos\phi = n_{ee} \times n_{\pi\pi} \cdot \left(\frac{p_+ + p_-}{| p_+ + p_- |} \right) \cdot (n_{ee} \cdot n_{\pi\pi})$$

$n_{ee}(n_{\pi\pi})$: Normal to e^+e^- $(\pi^+\pi^-)$ plane

$p_+(p_-)$: Momentum of $\pi^+(\pi^-)$ in Kaon CM frame

$$A = \frac{\int_0^{\pi/2} \frac{d\Gamma}{d\phi} d\phi - \int_{\pi/2}^{\pi} \frac{d\Gamma}{d\phi} d\phi}{\int_0^{\pi/2} \frac{d\Gamma}{d\phi} d\phi + \int_{\pi/2}^{\pi} \frac{d\Gamma}{d\phi} d\phi} \approx 14\%$$

Sehgal and Wanninger
Phys. Rev. D46, 1035(1992);ibid D46,5209(E)(1992)



M1 Form factor

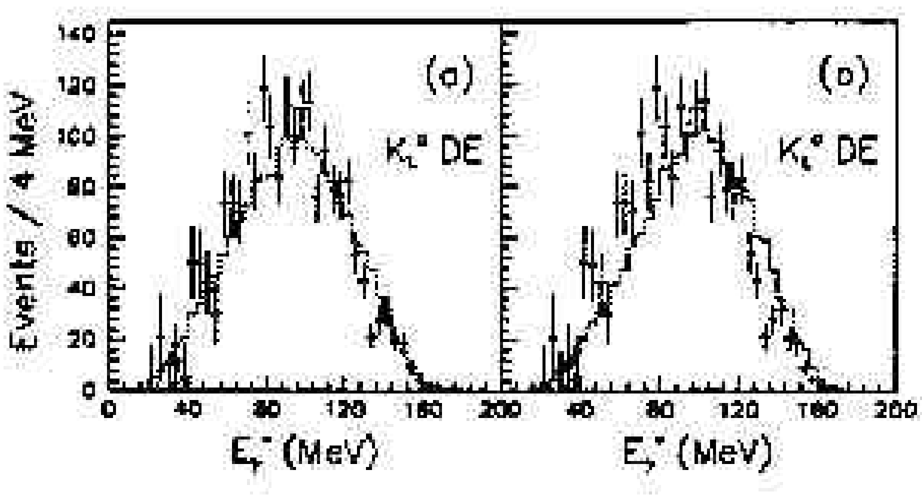
$$gM1 \rightarrow gM1 \cdot F$$

$$F = \frac{a_1}{(M_r^2 - M_K^2) + 2M_K E_g^*} + a_2$$

M_r : mass of r meson

M_K : mass of K meson

$E_g^* = E_{e^+} + E_{e^-}$: Virtual photon Energy in Kaon CM frame



a)With form factor **b)Without form factor**

E.J.Ramberg et al., Phys. Rev. Lett. 70, 2525(1993)

Recent Experimental Status

Recent Publication:

Branching Ratio

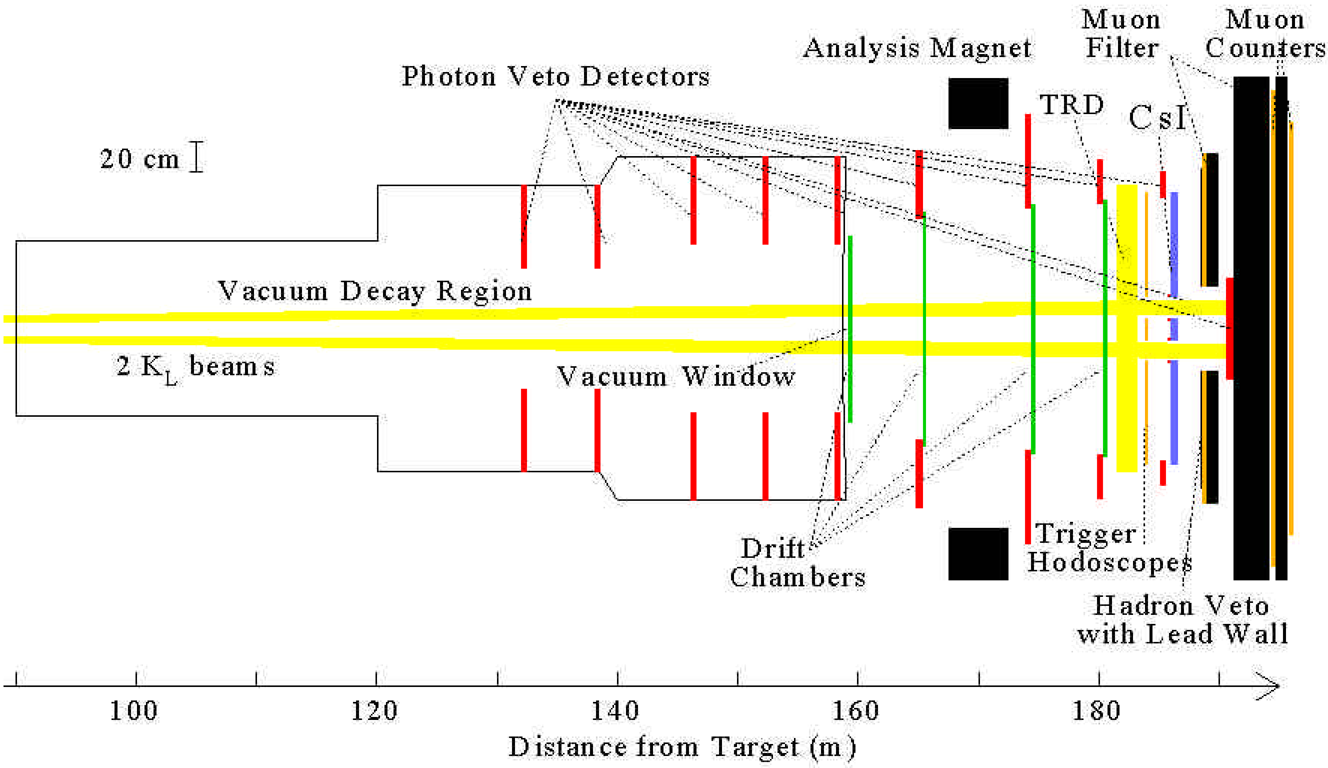
$$(3.2 \times 0.6(\text{stat.}) \times 0.4(\text{syst.})) \times 10^{-7}$$

Based on 46 events(one day of data) by KTeV

J.Adams et al., Phys. Rev. Lett. 80, 4123(1998)

Our analysis shown here based on whole(90 days) dataset.

KTeV Detector (plane view)



Spectrometer(Magnet + Drift Chambers)

Measure the momentum of a charged particle

Electromagnetic Calorimeter

Measure the energy of a photon
Particle identification

Spectrometer(Magnet + Drift Chamber)

Purpose: charged track trajectory reconstruction
vertex reconstruction
Measure the momentum of a charged particle

4 Drift Chambers(DC1 - DC4)

Spatial resolution : 100mm

Analysis Magnet (between DC3 and 4)

Transverse momentum kick: 205 MeV/c

Momentum Resolution:

$$\frac{s_p}{p} = 0.016\% \times p(\mathrm{GeV/c}) \oplus 0.38\%$$

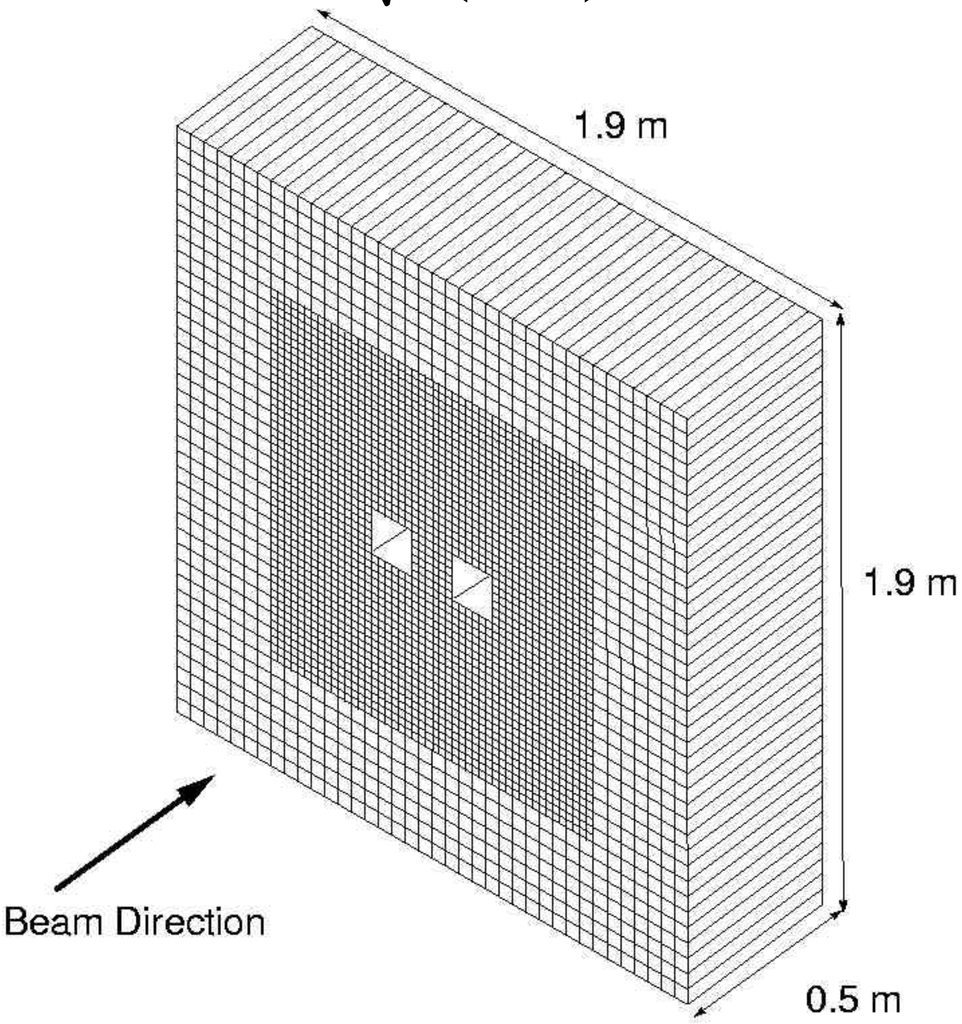
Electromagnetic Calorimeter

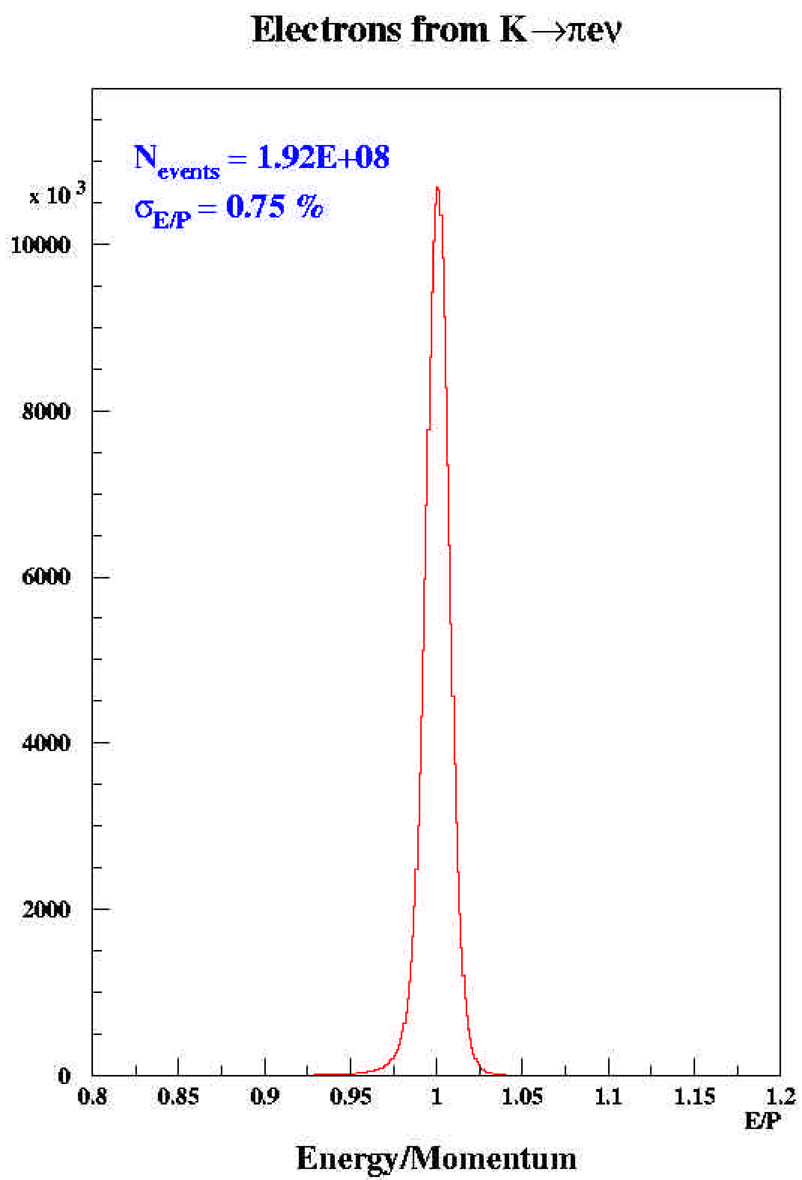
Measure the energy of a photon
Particle identification

3100 CsI crystals(27 rad. lengths)

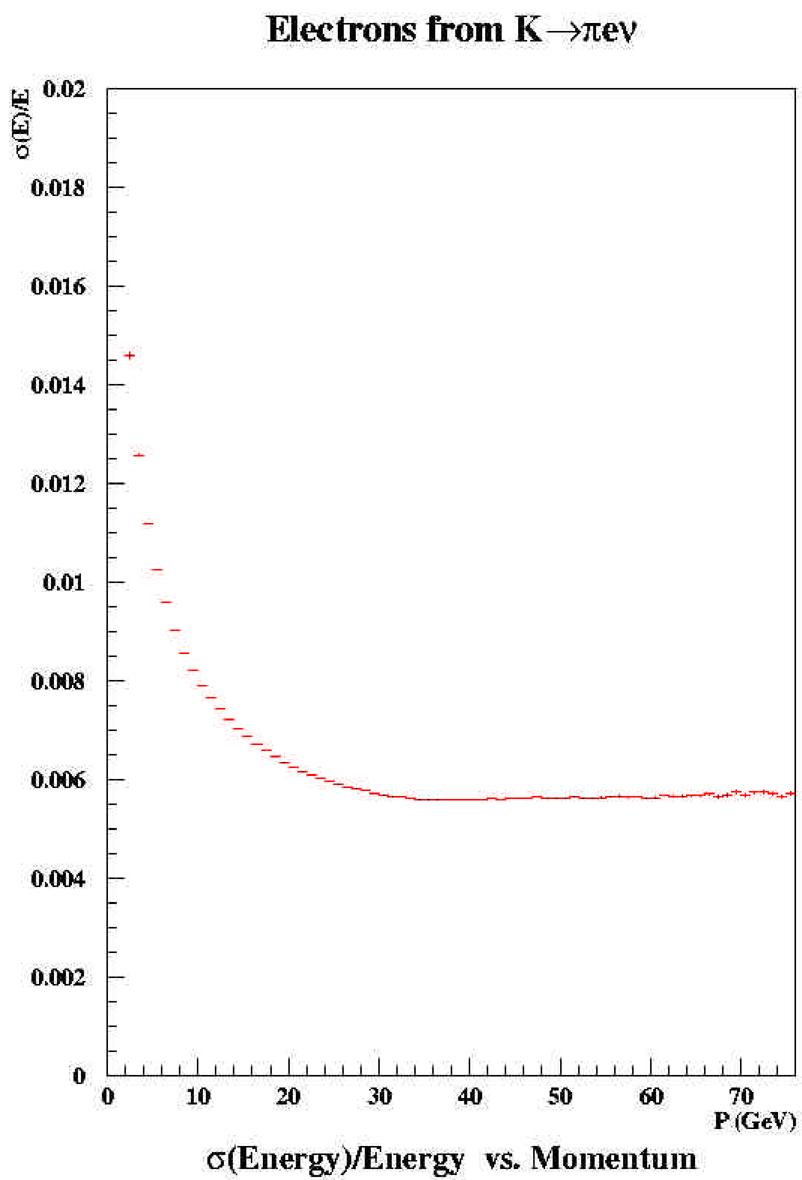
Energy Resolution:

$$\frac{s_E}{E} = \frac{0.6\%}{\sqrt{E(\mathrm{GeV})}} \times \oplus 0.6\%$$





Electrons from K→πeν
N_events = 1.92E+08
σ_E/P = 0.75 %
x 10^3
0
2000
4000
6000
8000
10000
0.8
0.85
0.9
0.95
1
1.05
1.1
1.15
1.2
E/P
Energy/Momentum

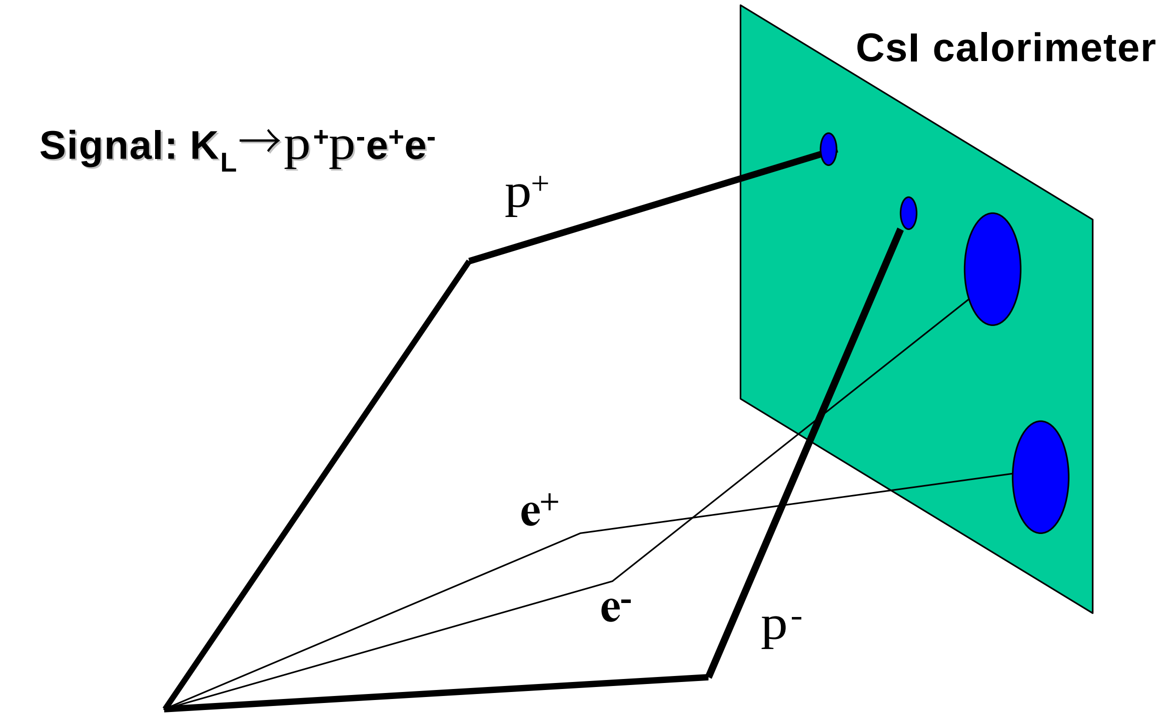


Electrons from K→πeν
σ(E)/E
0
0.002
0.004
0.006
0.008
0.01
0.012
0.014
0.016
0.018
0.02
0
10
20
30
40
50
60
70
P (GeV)
σ(Energy)/Energy vs. Momentum

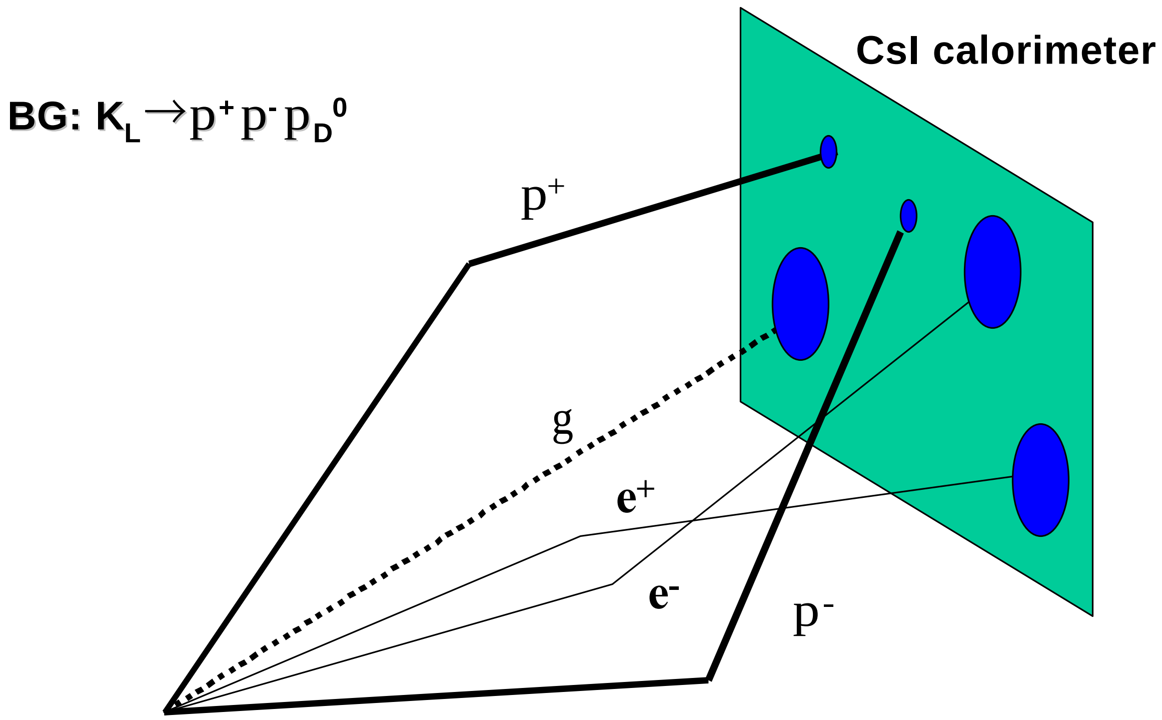
$K_L \to \pi^+\pi^- e^+e^-$ Signal Selection

Strategy

- **4 charged tracks sharing a common vertex.**
- **Identified 2 pions and 2 electrons including charge consistency**
- **Invariant mass forms K_L mass**
- **Total momentum consistent with KL flight direction**
- **Constraint from other kinematics relations**



CsI calorimeter
Signal: $K_L \rightarrow p^+p^-e^+e^-$
p^+
e^+
e^-
p^-



CsI calorimeter
BG: $K_L \rightarrow p^+ p^- p_D^0$
p^+
g
e^+
e^-
p^-

Background sources

$$K_L \to \pi^+\pi^-\pi^0_D(\pi^0 \to e^+e^-\gamma)$$

$$K_L \to \pi^+\pi^-\pi^0_{DD}(\pi^0 \to e^+e^-e^+e^-)$$

$$K_L \to \pi^+\pi^-\pi^0(\pi^0 \to \gamma\gamma)$$

γ **conversion at material($\gamma \to e^+e^-$)**

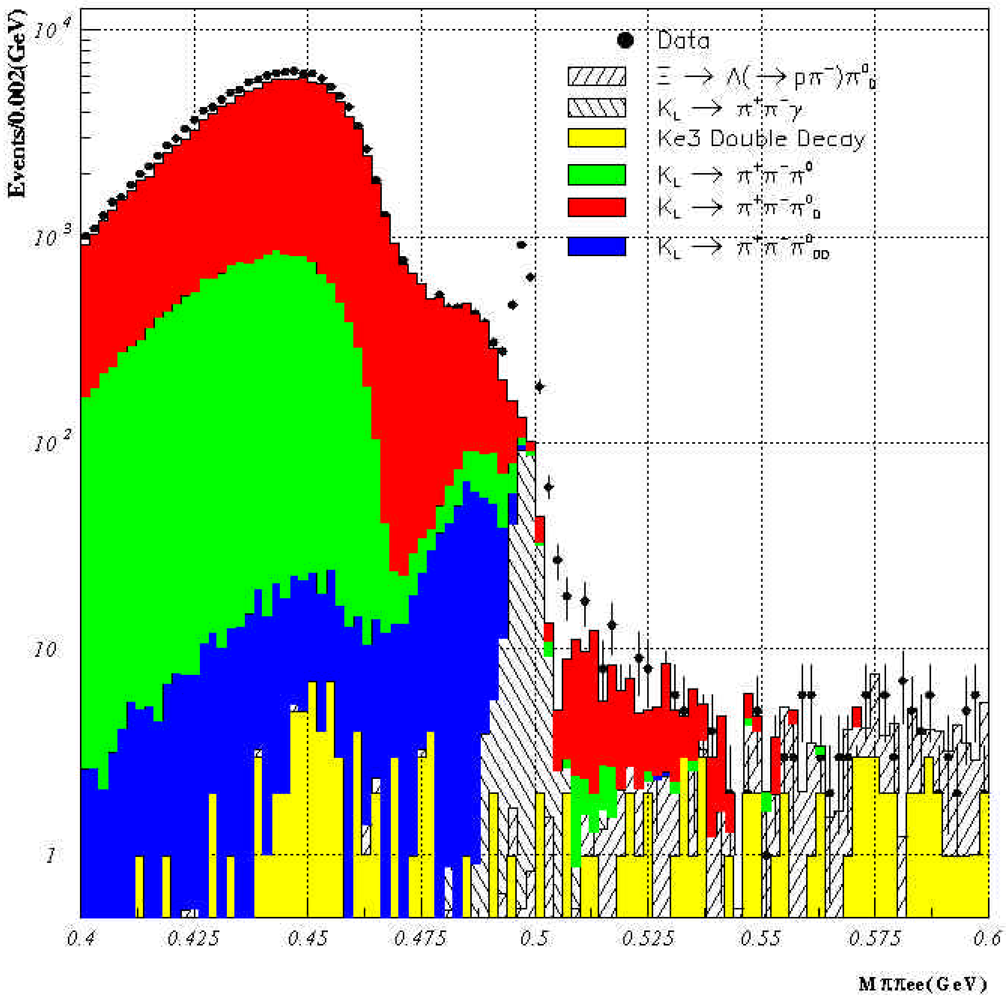
$$K_L \to \pi^+\pi^-\gamma$$

γ **conversion at material($\gamma \to e^+e^-$)**

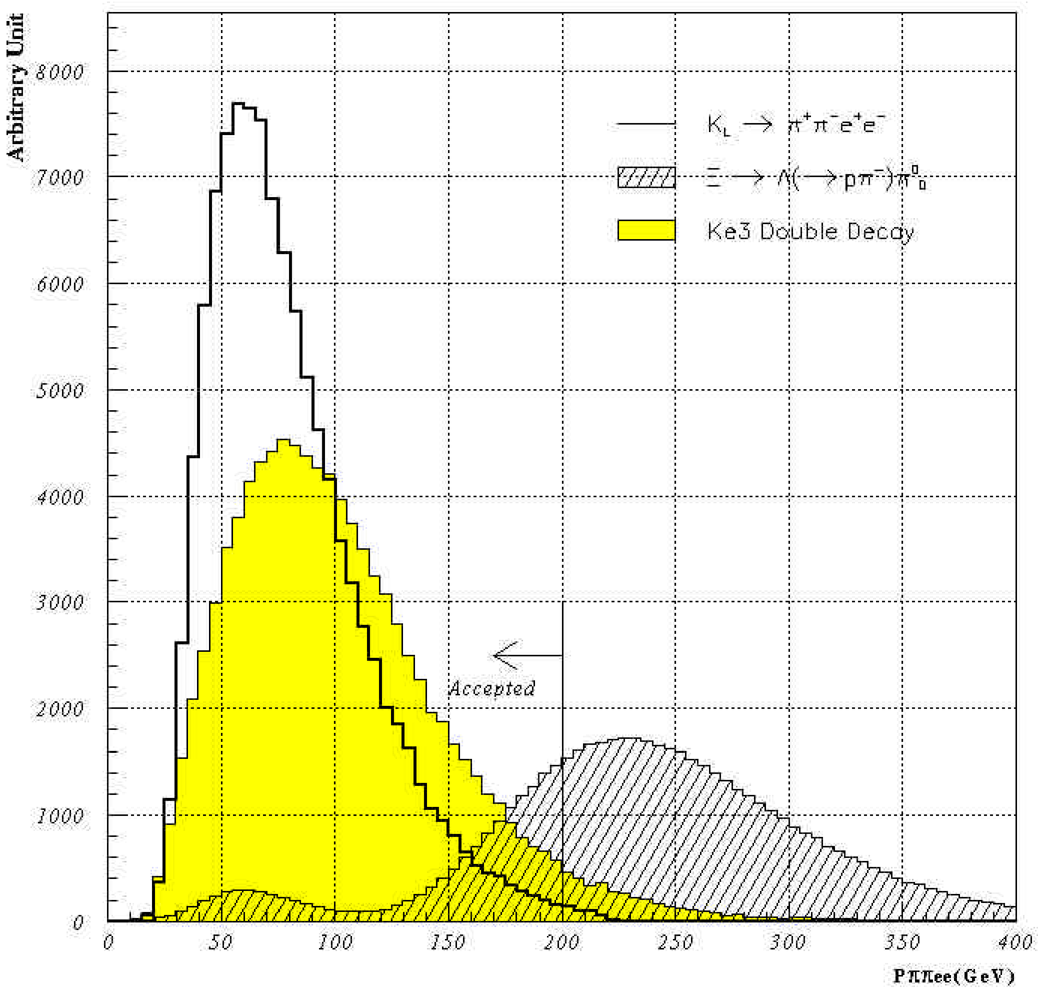
$$\Xi \to \Lambda(\to p\pi^-)\pi^0_D(\to e^+e^-\gamma)$$

$$(K_L \to \pi^+e^-\nu) + (K_L \to \pi^-e^+\nu)$$

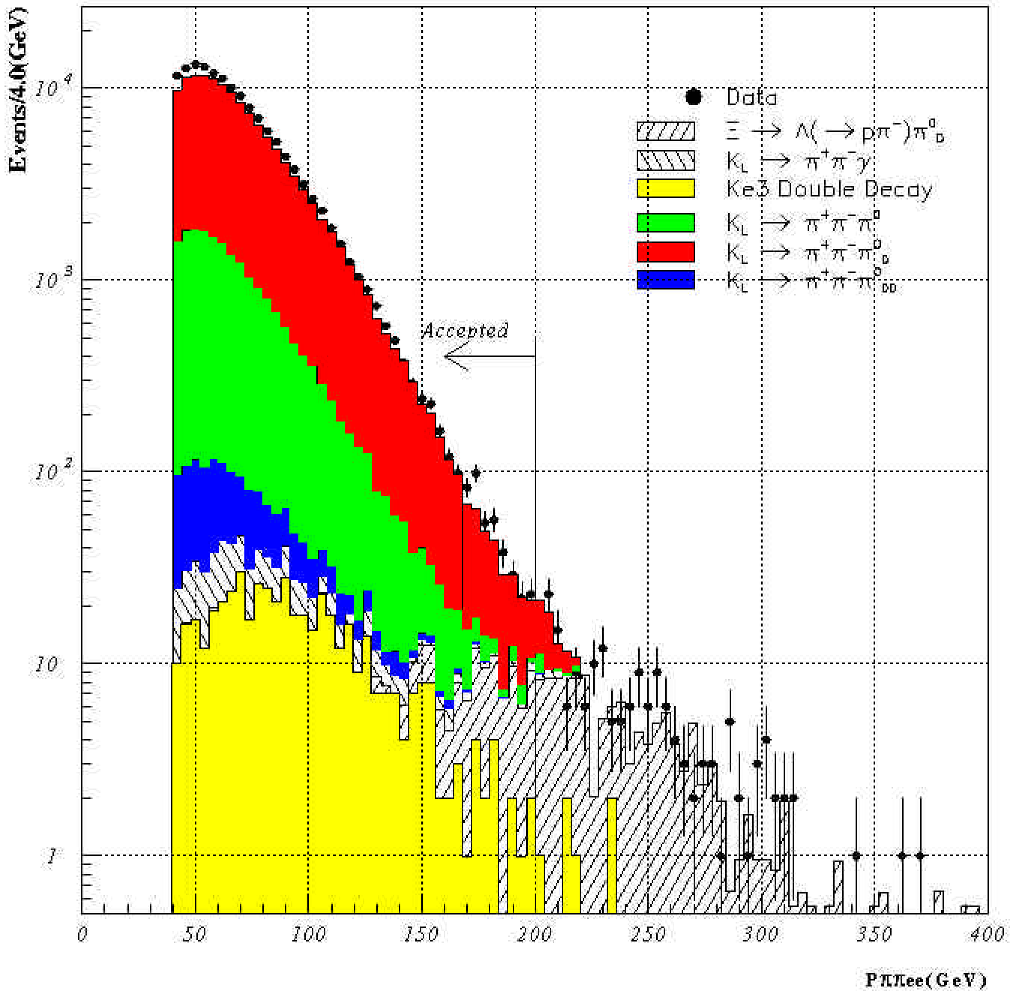
Background distribution



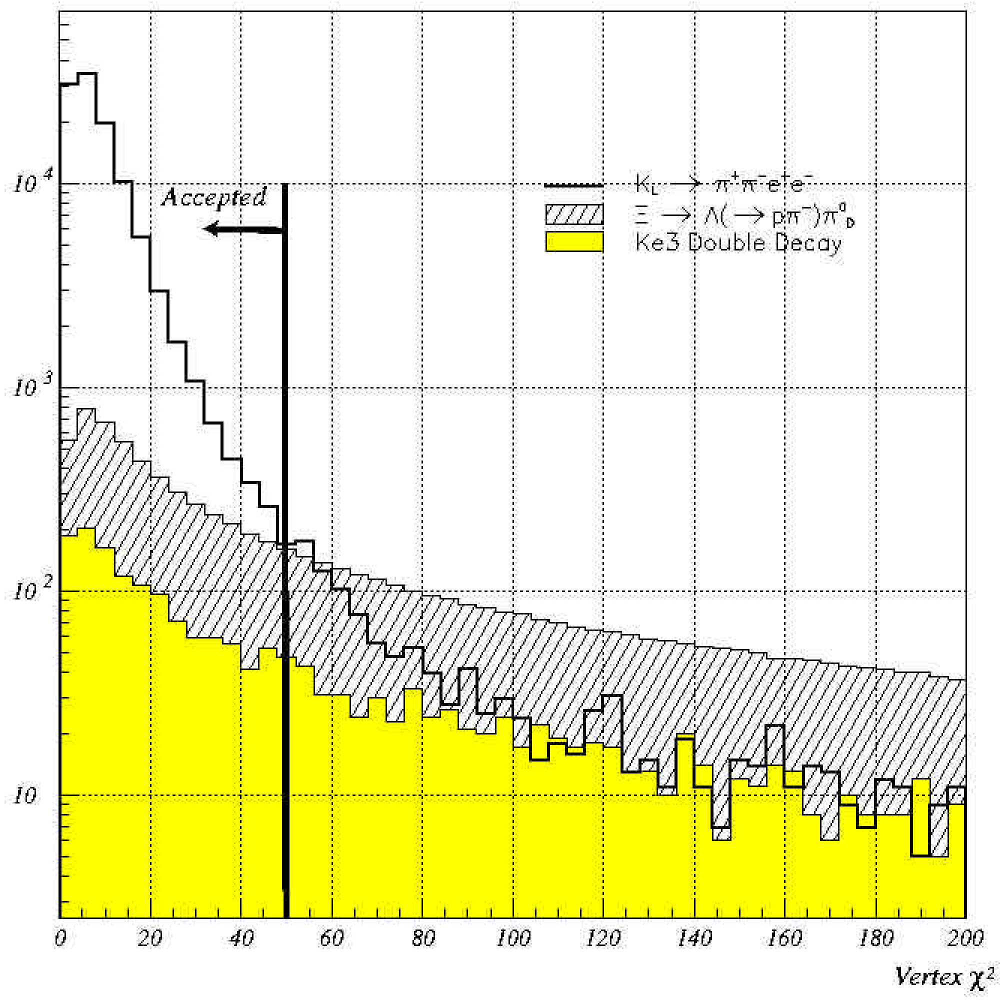
Total Momentum(ppee) Cut



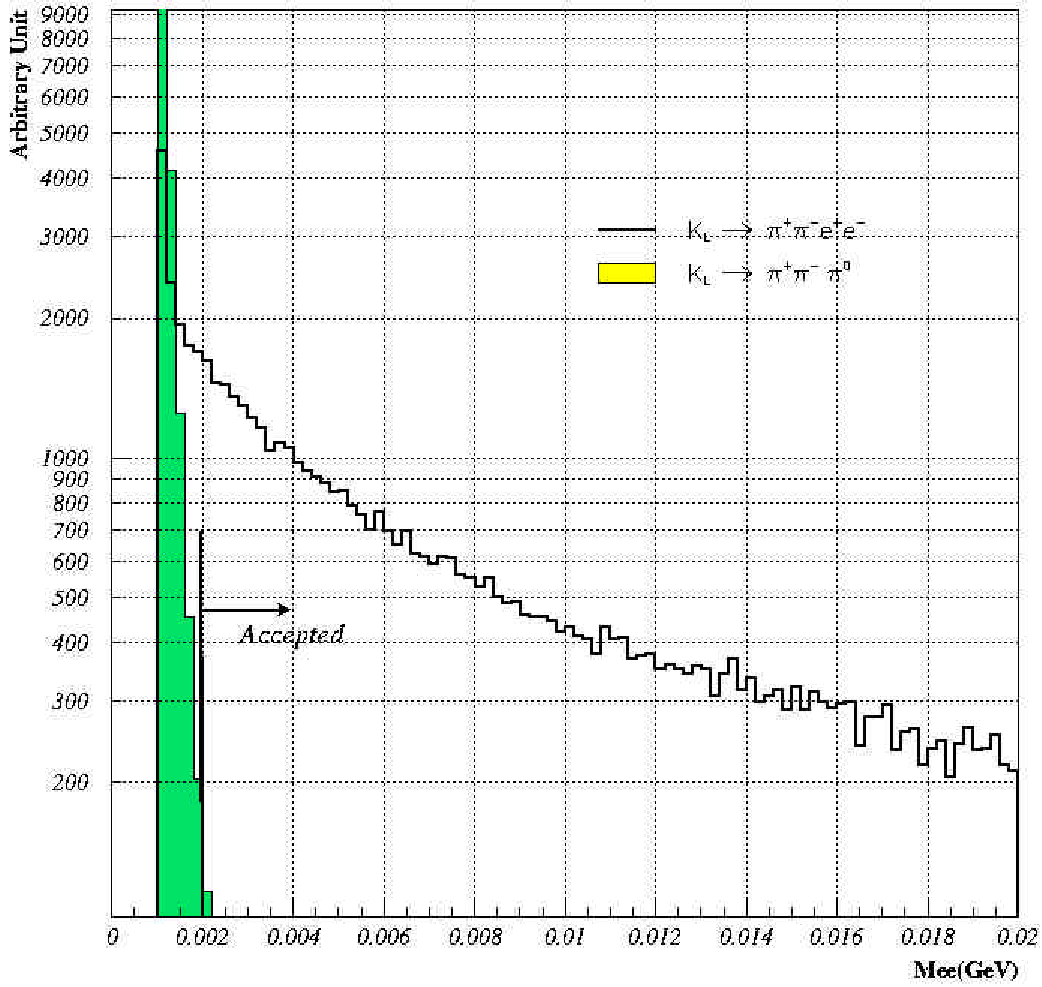
Total Momentum Cut:
Data and Background MC Overlay



Vertex c^2(quality) Cut:
Data and Background MC Overlay

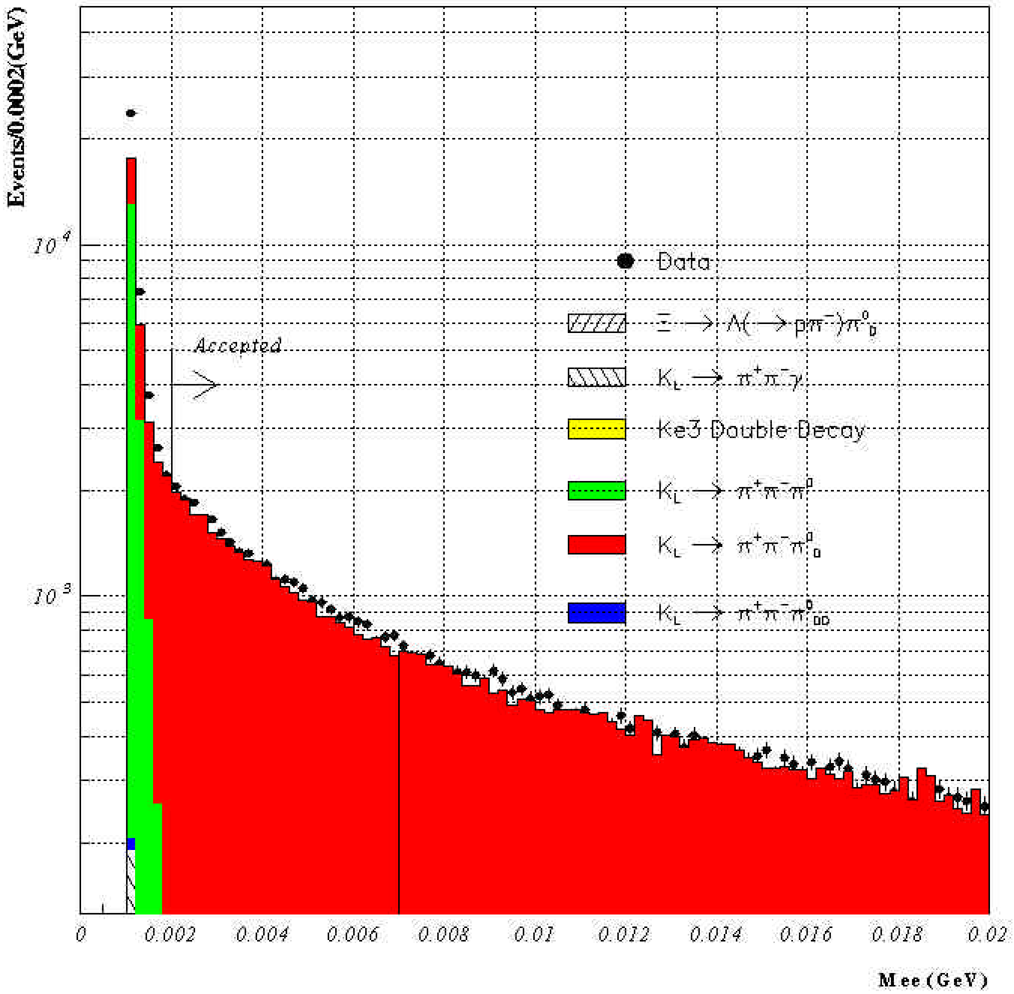


Mee Cut

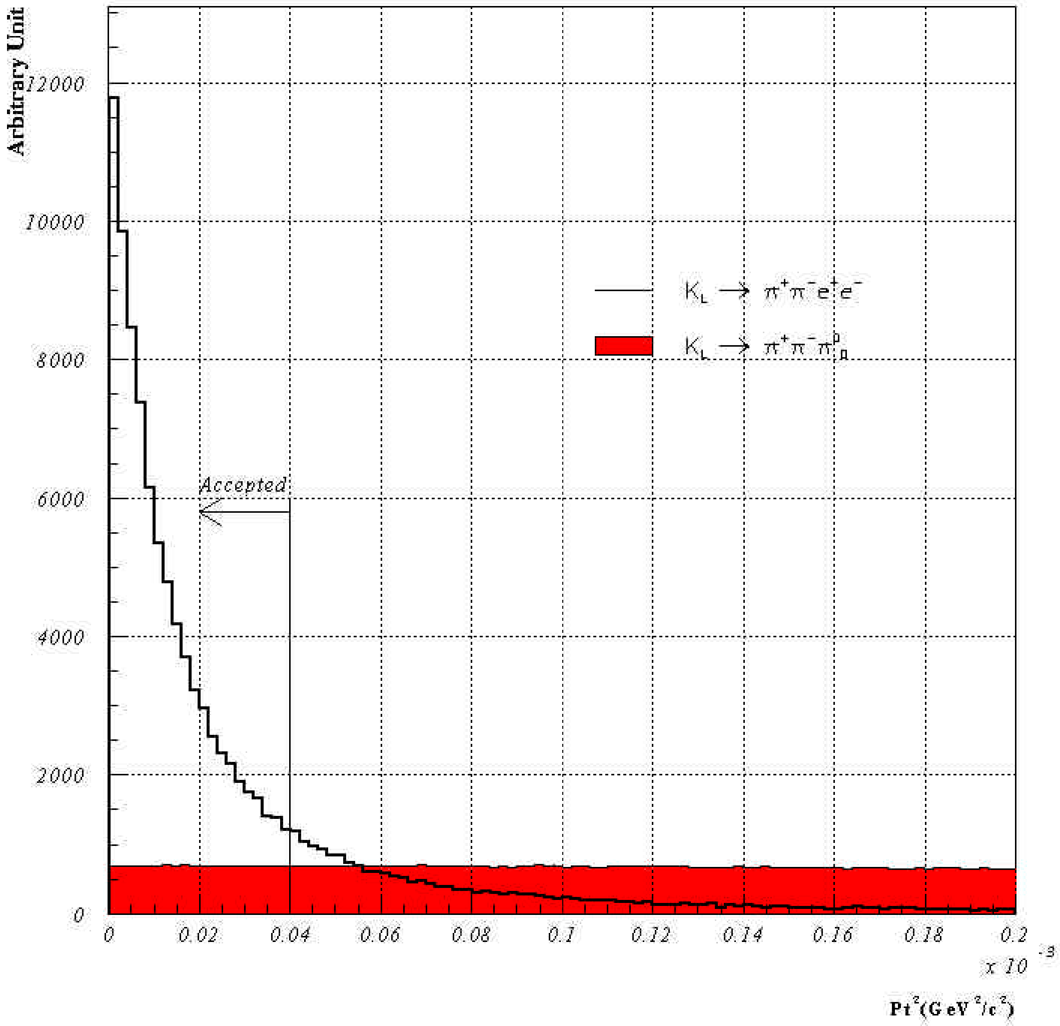


Arbitrary Unit
9000
8000
7000
6000
5000
4000
3000
2000
1000
900
800
700
600
500
400
300
200
$K_L \rightarrow \pi^+\pi^-e^+e^-$
$K_L \rightarrow \pi^+\pi^-\pi^0$
Accepted
0
0.002
0.004
0.006
0.008
0.01
0.012
0.014
0.016
0.018
0.02
Mee(GeV)

Mee Cut:
Data and Background MC Overlay

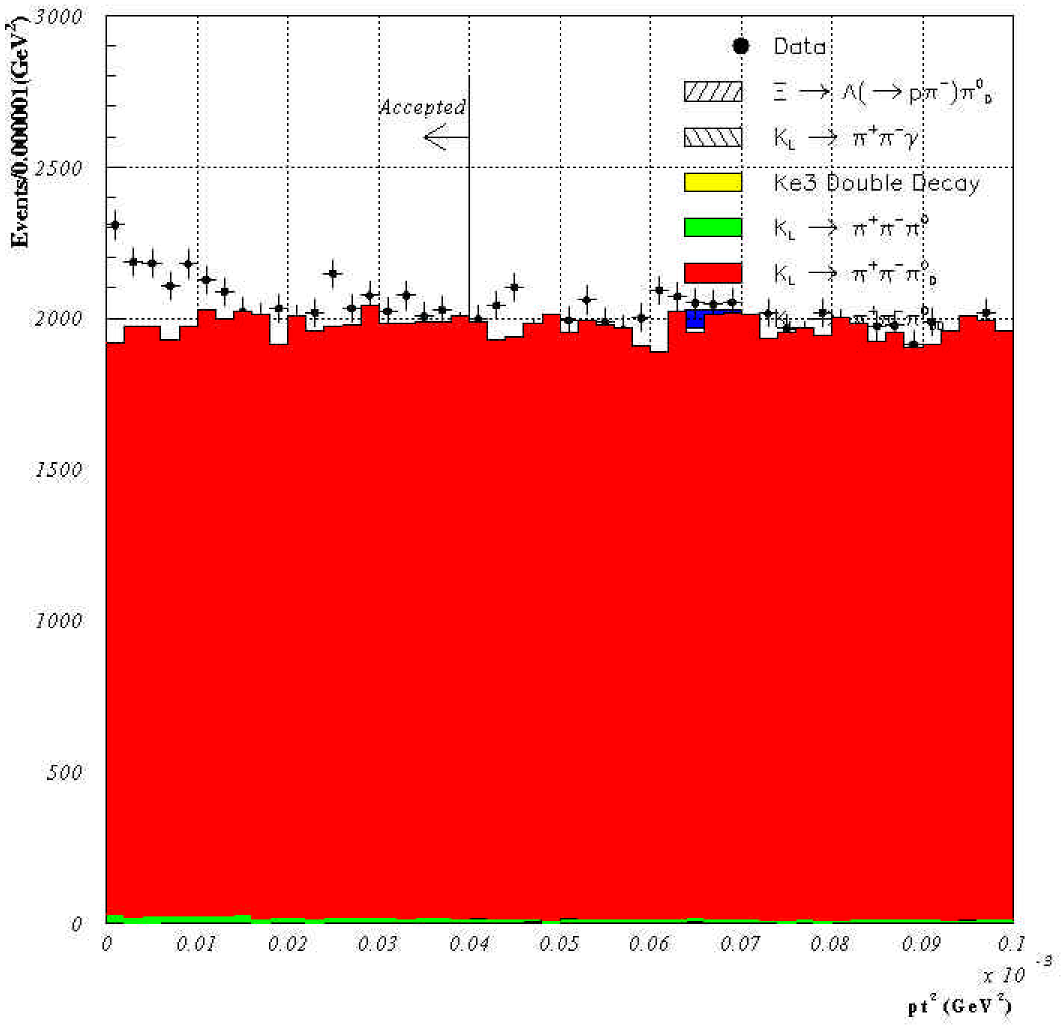


p_t^2 Cut

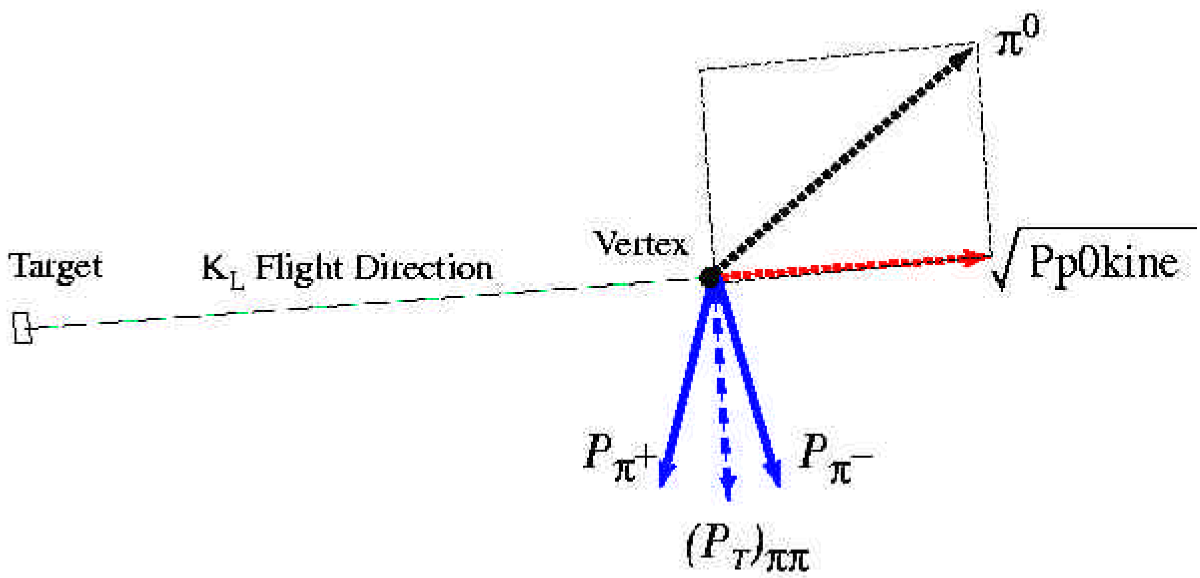


Arbitrary Unit
12000
10000
8000
6000
4000
2000
0
$K_L \rightarrow \pi^+\pi^-e^+e^-$
$K_L \rightarrow \pi^+\pi^-\pi^0_D$
Accepted
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
x 10 -3
Pt²(GeV²/c²)

p_t^2 Cut:
Data and Background MC Overlay



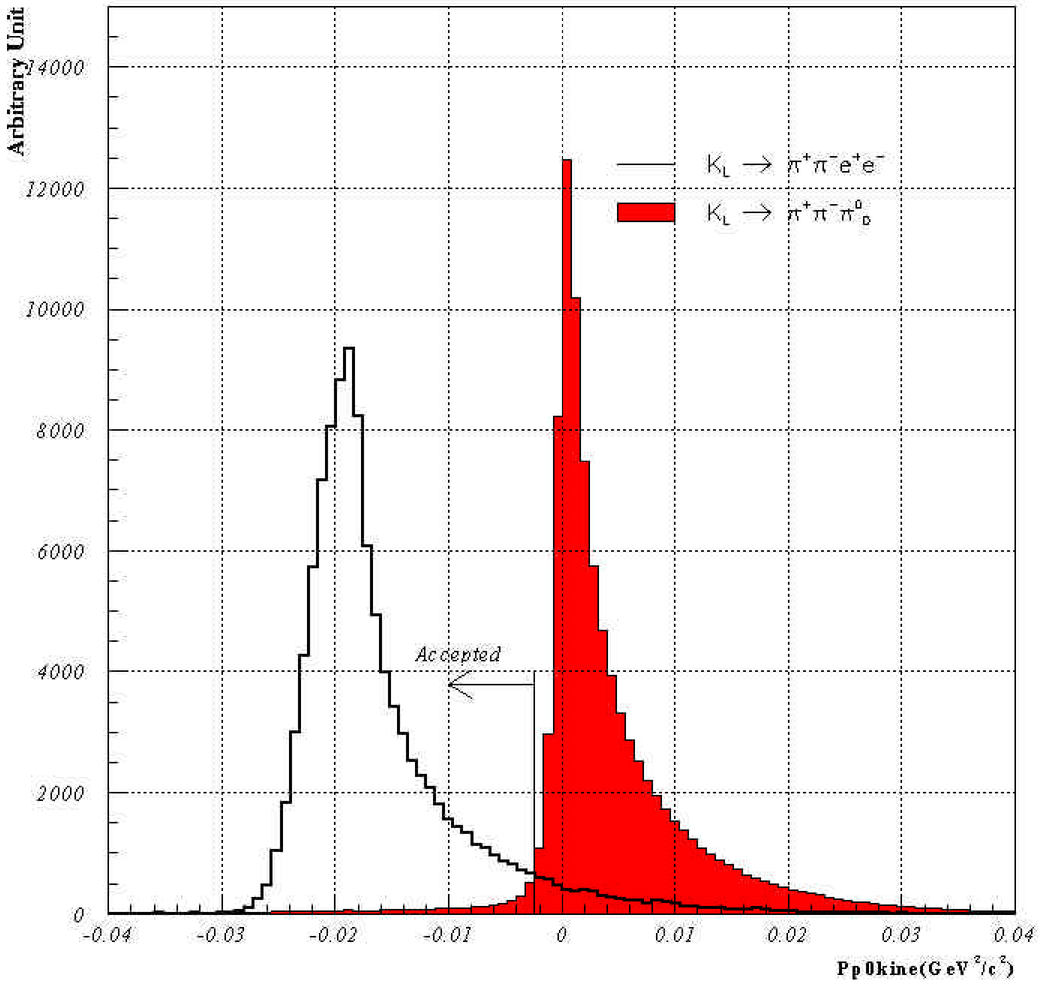
Pp0kine Cut



- **Assuming $K_L \to p^+p^-p^0$ kinematics**

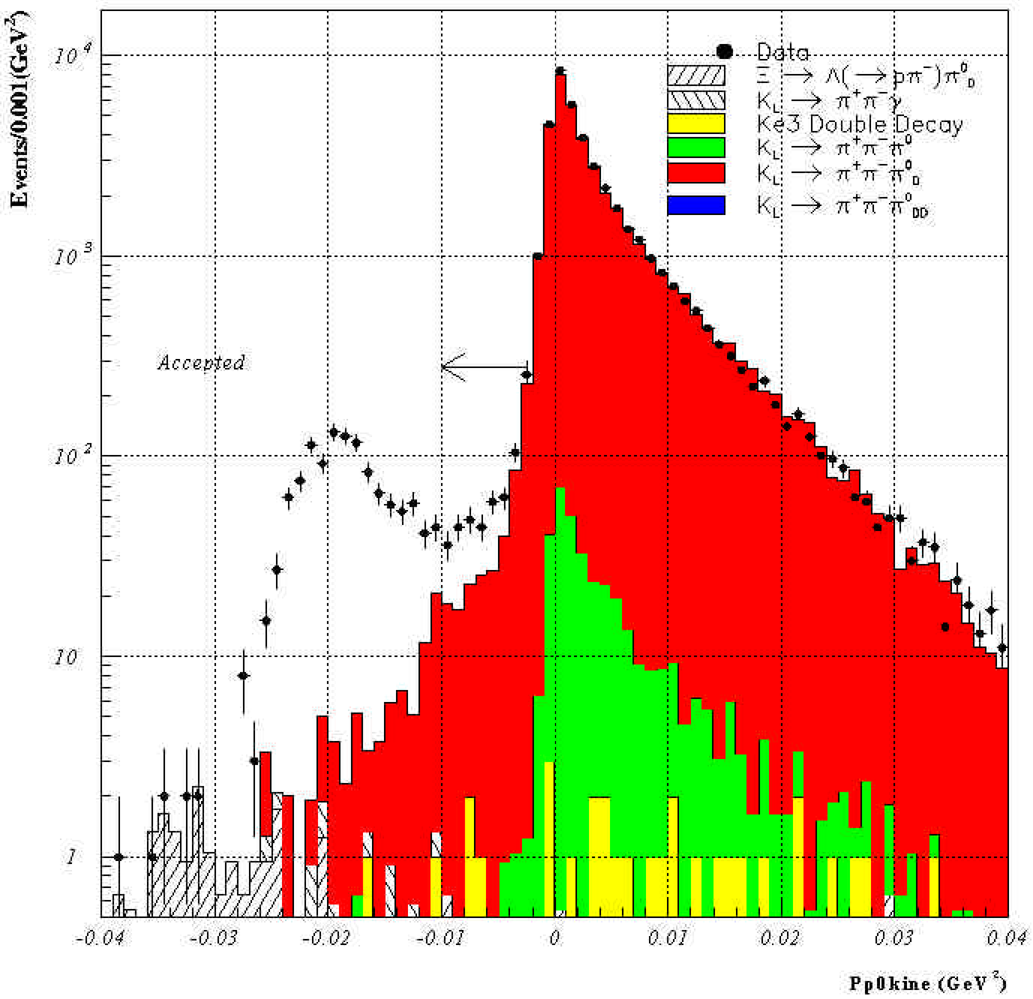
- **Reject physically allowed region of $K_L \to p^+p^-p^0$**

Pp0kine Cut

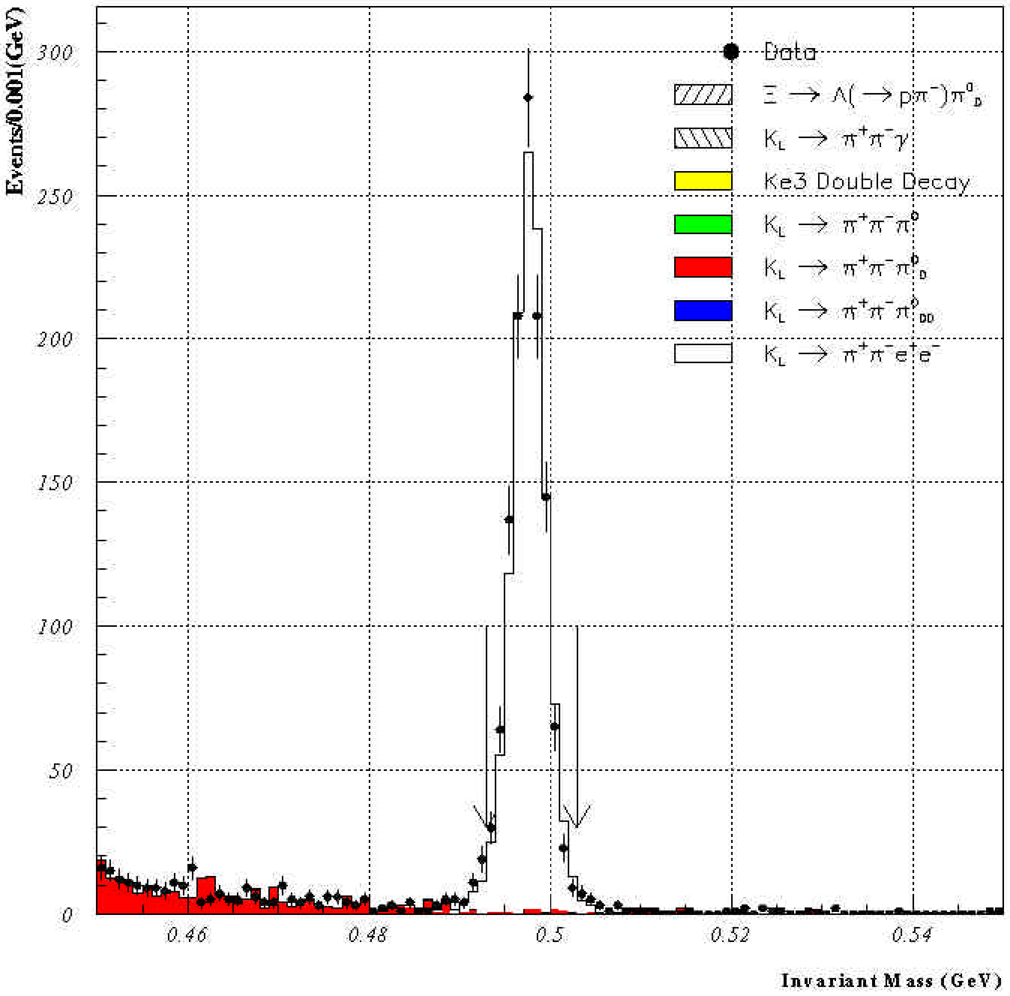


Arbitrary Unit
14000
12000
10000
8000
6000
4000
2000
0
-0.04
-0.03
-0.02
-0.01
0
0.01
0.02
0.03
0.04
Pp0kine(GeV^2/c^2)
$K_L \rightarrow \pi^+\pi^-e^+e^-$
$K_L \rightarrow \pi^+\pi^-\pi^0_D$
Accepted

Pp0kine Cut:
Data and Background MC Overlay



Data after all the cuts

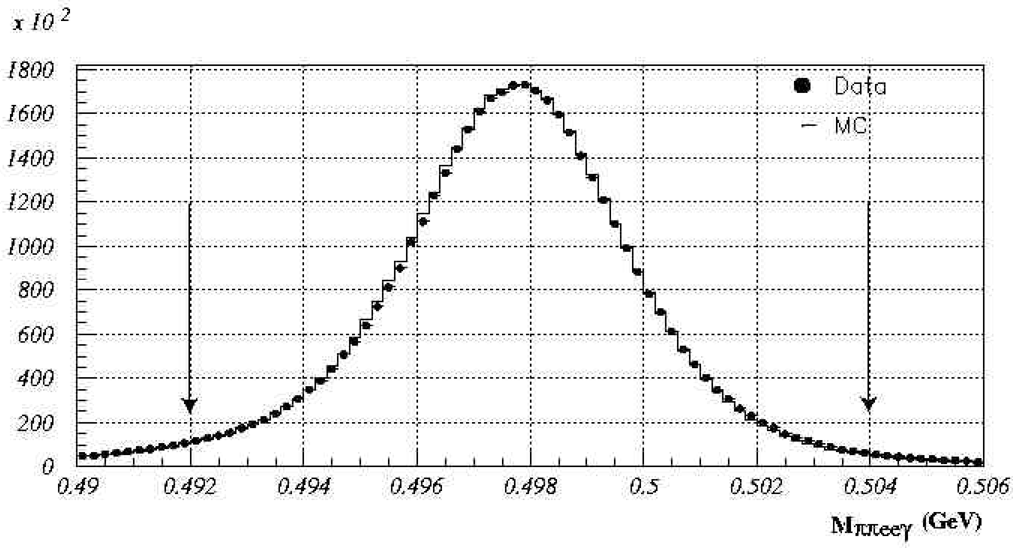


1173 ± 34.2 events in the signal region

Background Estimation

Background	Efficiency	#Background
$K_L \rightarrow p^+ p^- p_D^0 (p^0 \rightarrow e^+ e^- g)$	2.4 x 10^{-8}	9.0 ± 3.0
$K_L \rightarrow p^+ p^- p_{DD}^0 (p^0 \rightarrow e^+ e^- e^+ e^-)$	2.7 x 10^{-7}	0.3 ± 0.2
$K_L \rightarrow p^+ p^- p^0 (p^0 \rightarrow gg)$	< 1.2 x 10^{-11}	<0.8(90%CL)
$K_L \rightarrow p^+ p^- g$	< 3.0 x 10^{-8}	<0.7(90%CL)
$\Xi \rightarrow \Lambda(\rightarrow pp^-) p_D^0 (\rightarrow e^+ e^- g)$		<0.7(90%CL)
$(K_L \rightarrow p^+ e^- n) + (K_L \rightarrow p^- e^+ n)$		2.0 ± 1.4
		11.3 ± 3.5

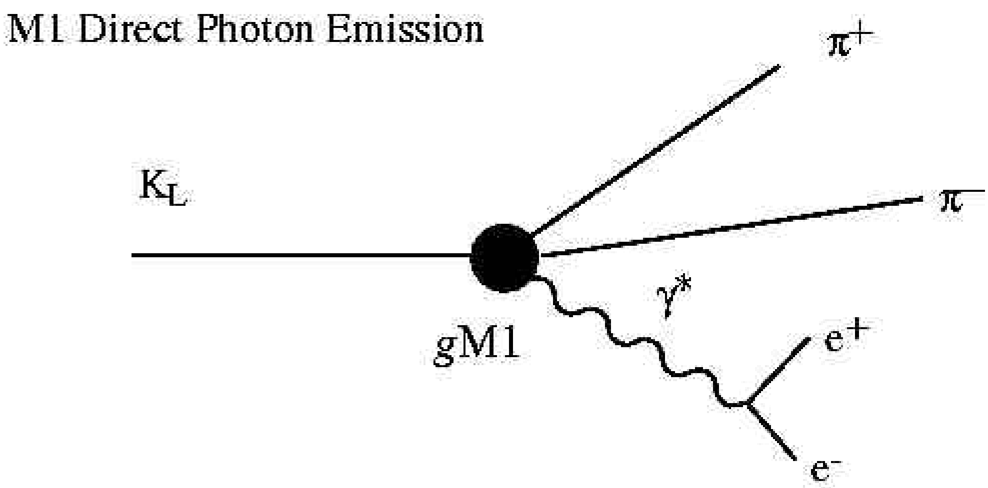
Normalization with $K_L \to p^+ p^- p^0_D$



Dataset	#events	K_L flux
Winter	1301650	1.421×10^{11}
Summer	814227	0.922×10^{11}
Total	2115877	

$(2.343 \pm 0.002(\text{stat.}) \pm 0.085(\text{syst.})) \times 10^{11}$

Form Factor Measurement



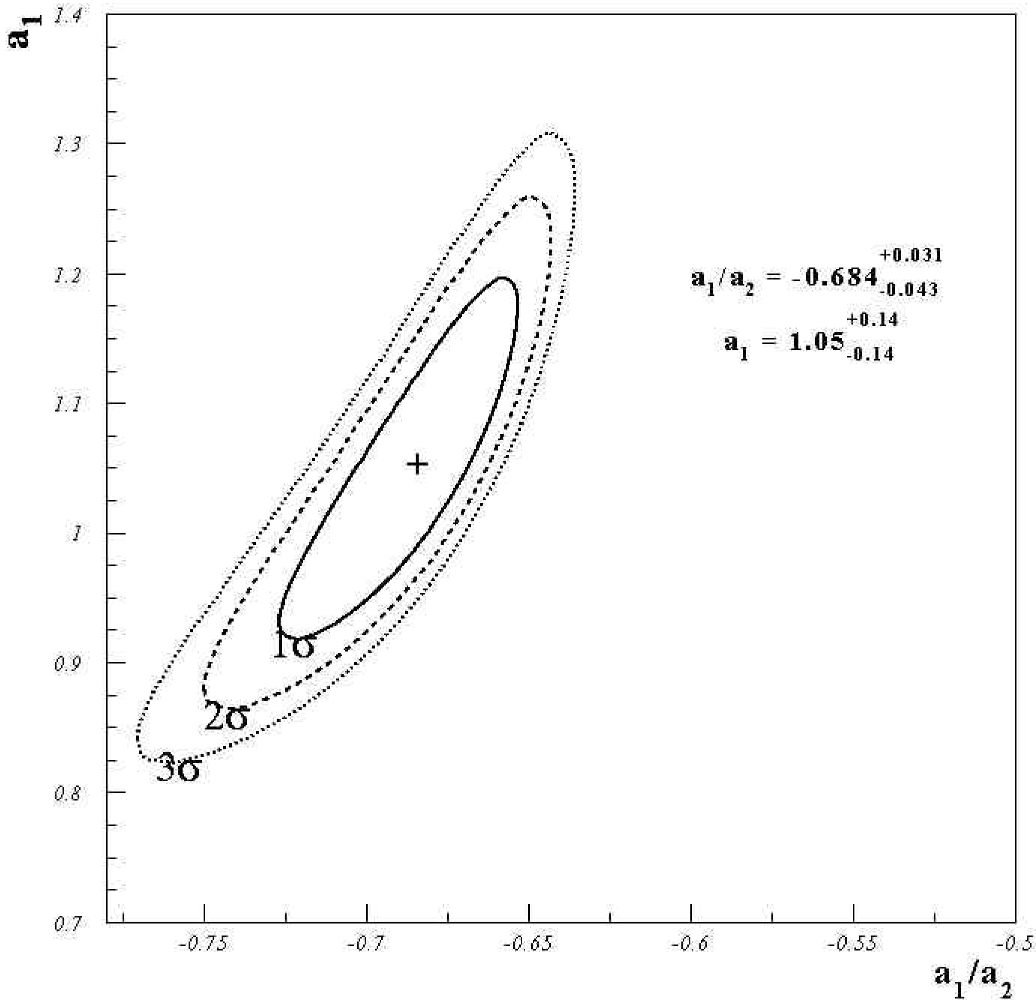
$$gM1 \rightarrow gM1 \cdot F$$

$$F = \frac{a_1}{(M_r^2 - M_K^2) + 2M_K E_g^*} + a_2$$

$a_1 / a_2, a_1$ **Extracted from 5 parameter Maximum likelihood method.**

$\mathrm{M}_{pp}, \mathrm{M}_{\mathrm{ee}}, f, \cos q_{p^+}, \cos q_{e^+}$ **In Kaon CM frame**

Form Factor Fit Result

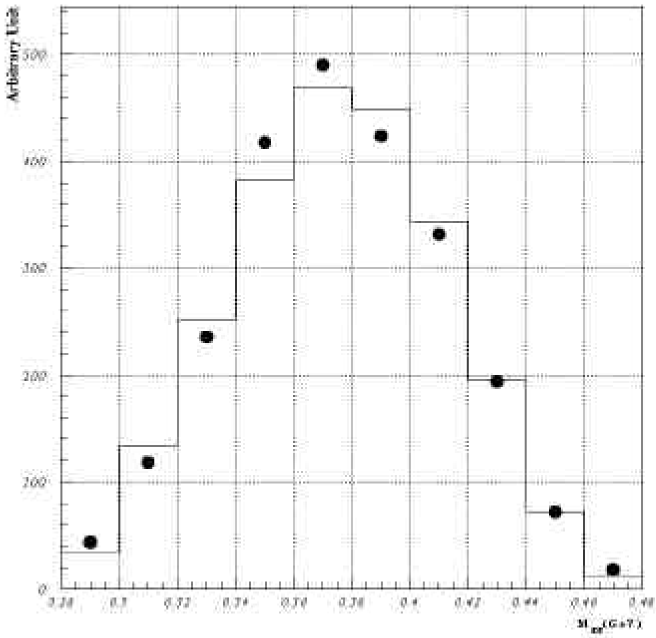


$$a_1 / a_2 = -0.684^{+0.031}_{-0.043}$$

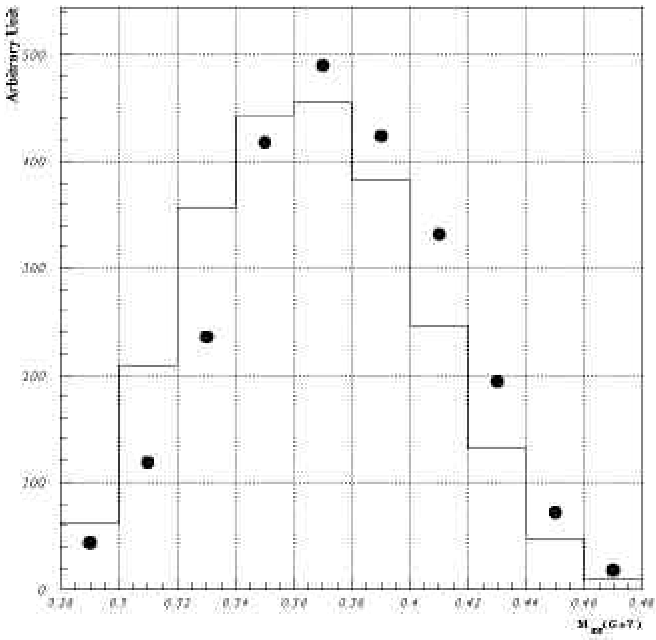
$$a_1 = 1.05 \pm 0.14$$

Mpp Comparison

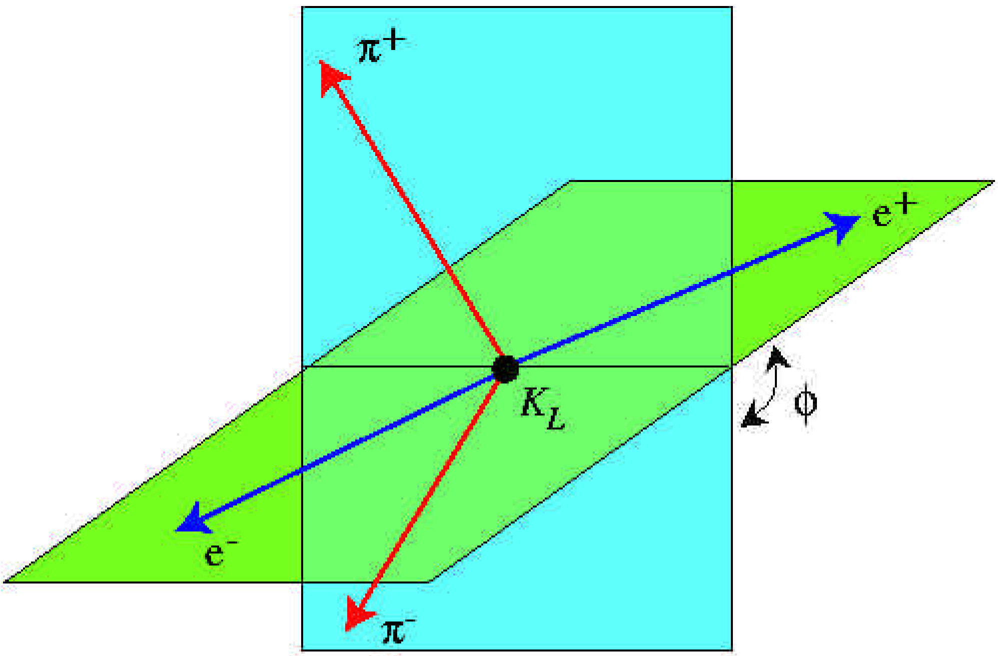
Form Factor



Constant gM1



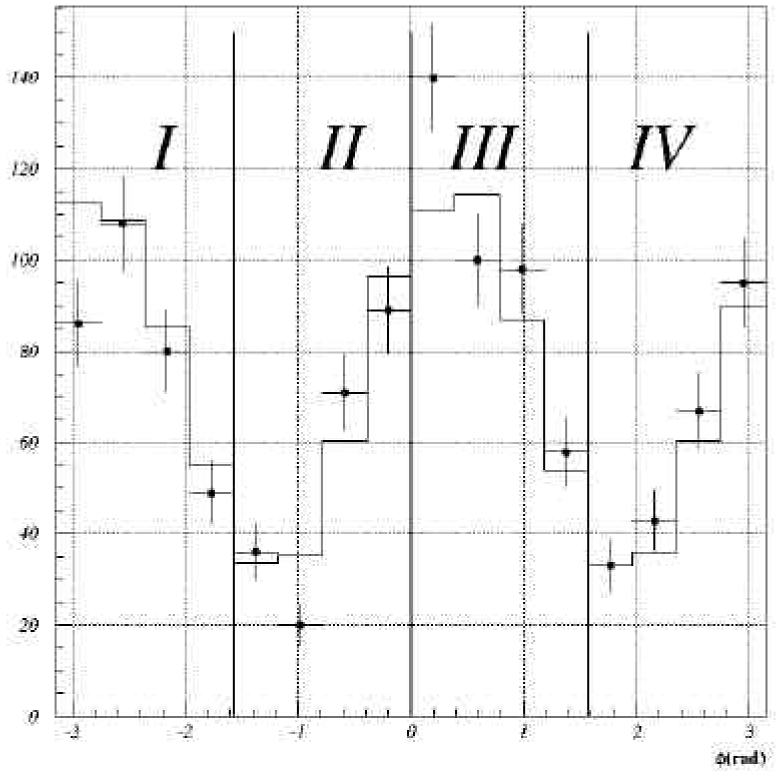
CP violating Angular Asymmetry

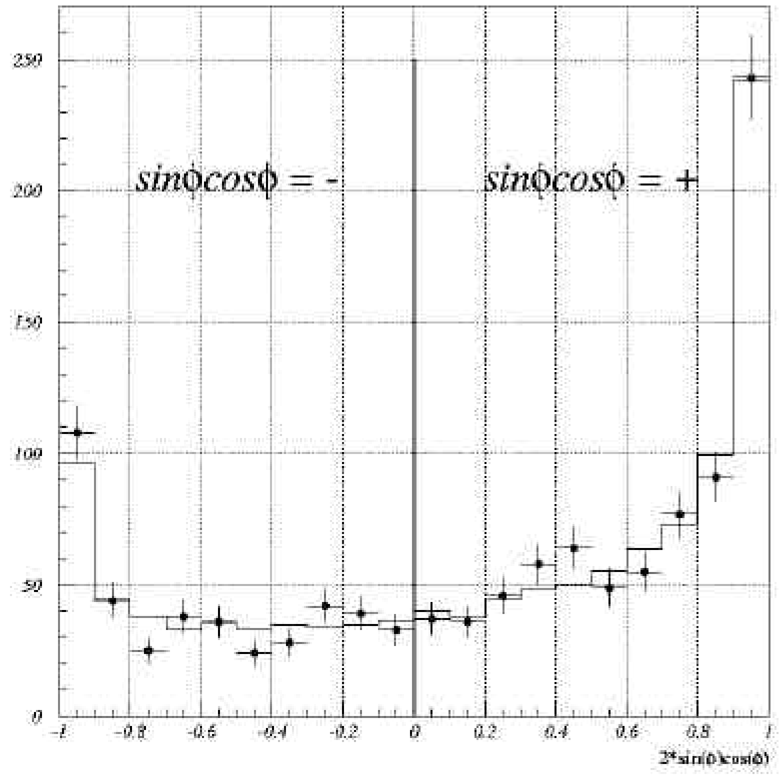


$$A = \frac{\int_0^{p/2} \frac{d\Gamma}{df} df - \int_{p/2}^{p} \frac{d\Gamma}{df} df}{\int_0^{p/2} \frac{d\Gamma}{df} df + \int_{p/2}^{p} \frac{d\Gamma}{df} df} \approx 14\%$$

Sehgal and Wanninger
Phys. Rev. D46, 1035(1992);ibid D46,5209(E)(1992)

Angular Distributions





The Raw Asymmetry

$$N_{\sin f \cos f > 0} = 719$$

$$N_{\sin f \cos f > 0} = 454$$

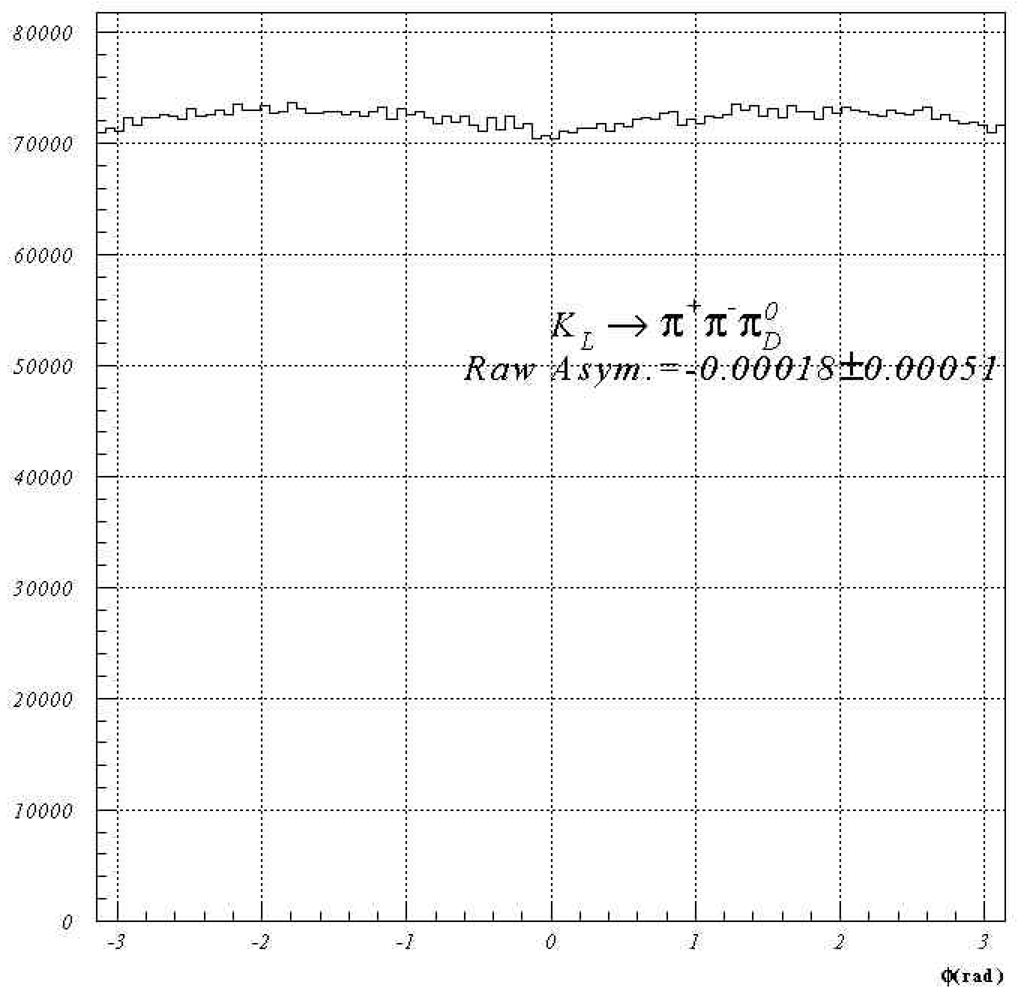
$$Asym = \frac{N_{\sin f \cos f > 0} - N_{\sin f \cos f < 0}}{N_{\sin f \cos f > 0} + N_{\sin f \cos f < 0}}$$
$$= 0.237 \pm 0.029(stat.)$$

MC study

MC with input asymmetry of 0.147 gave the raw asymmetry of 0.258.

Acceptance correction should be applied to the *raw asymmetry*.

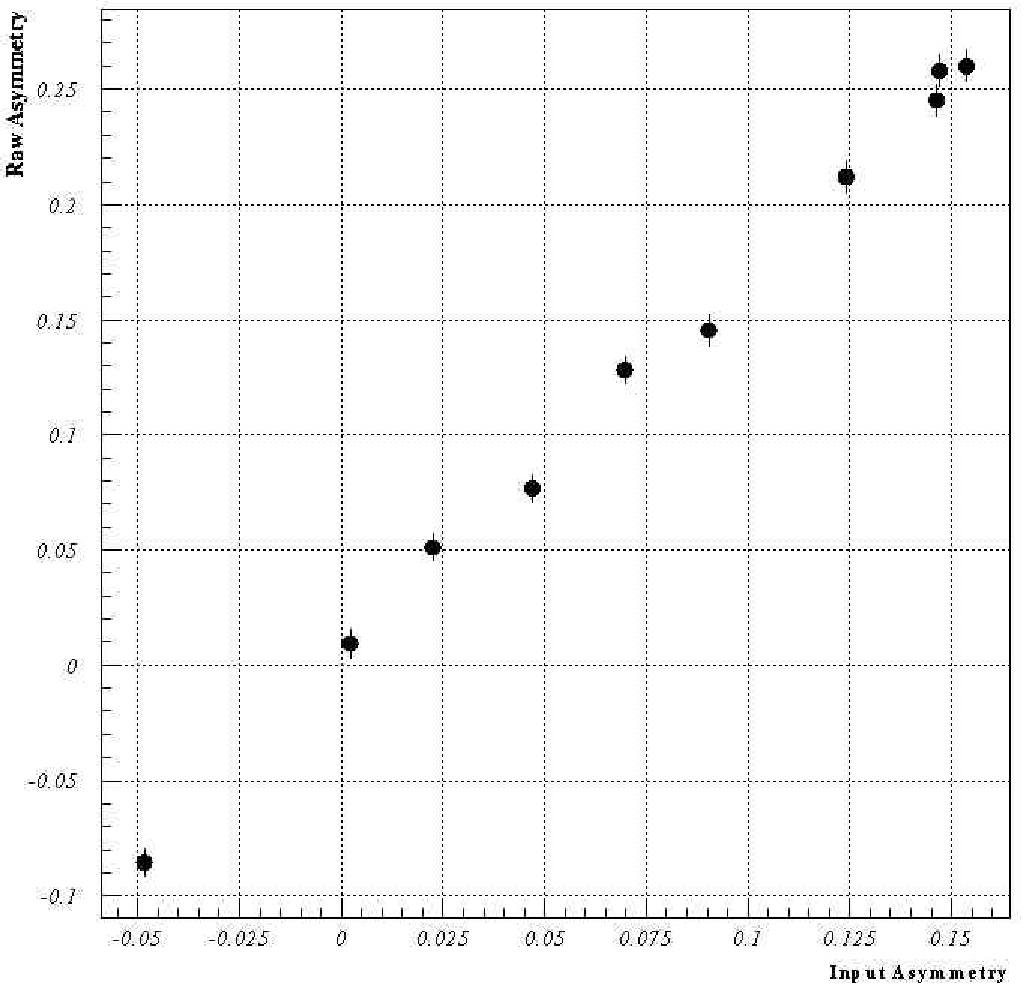
Before proceeding to
the acceptance correction...



Raw Asymmetry = -0.00015 ± 0.00051

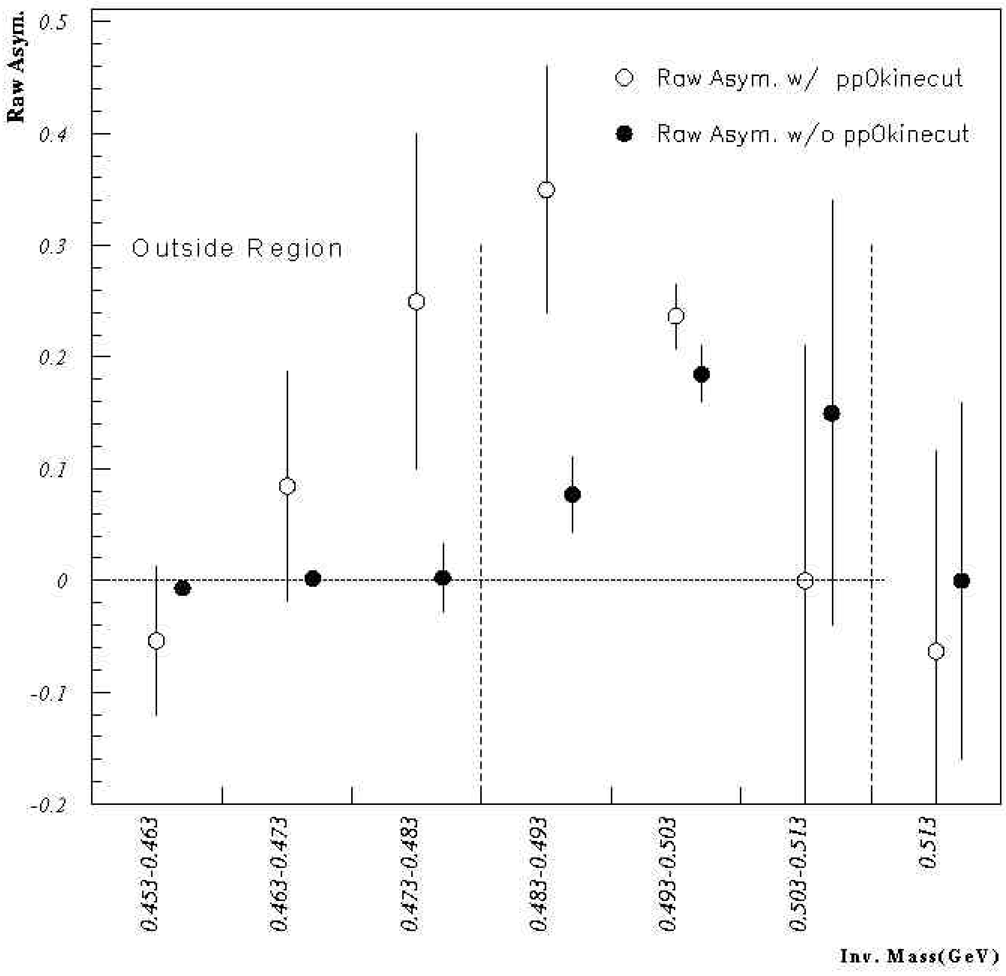
Consistent with zero asymmetry

Input-Raw asymmetry relation with Monte Carlo Simulation



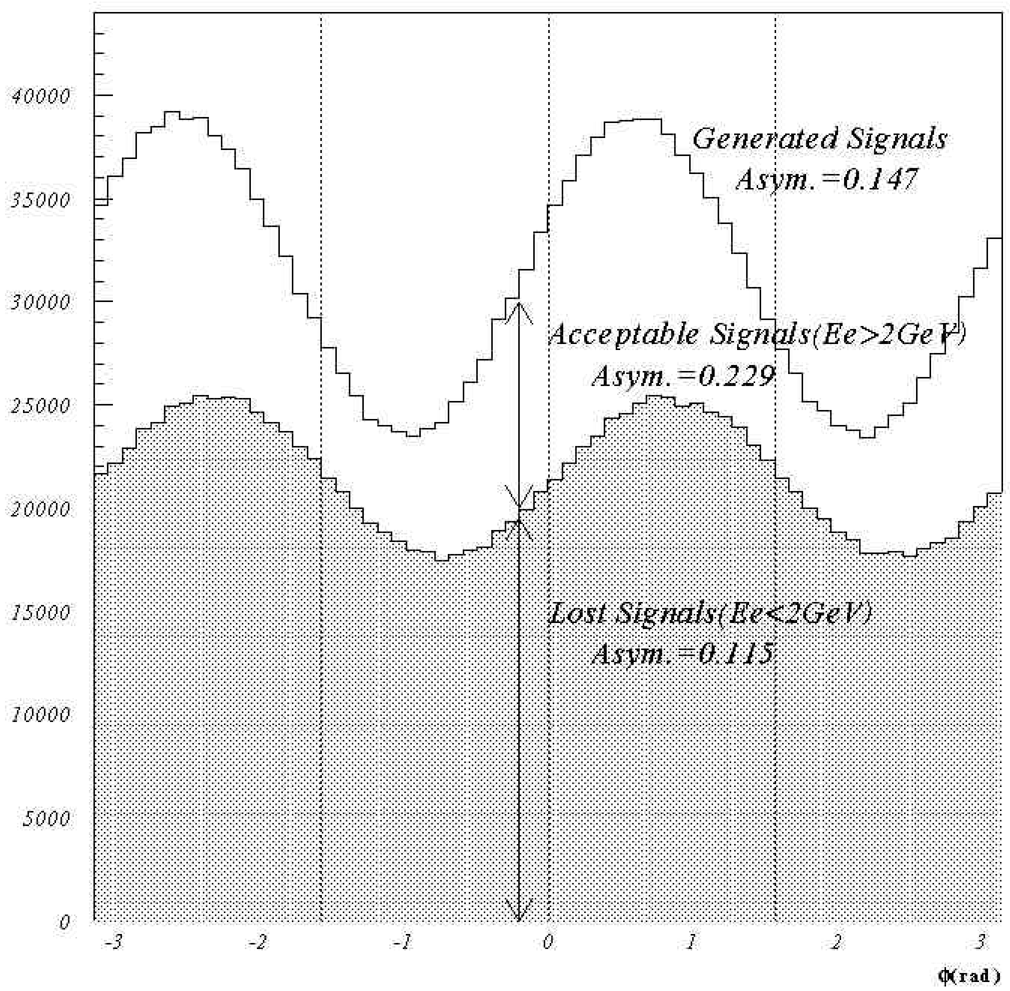
Raw Asym. = 1.75 × Input Asym.

Raw asymmetry in different Mass region



No obvious asymmetry found in outside region.

MC study on the relation between input and raw asymmetries



Distribution in acceptable region has larger asymmetry.

Raw Asymmetry...

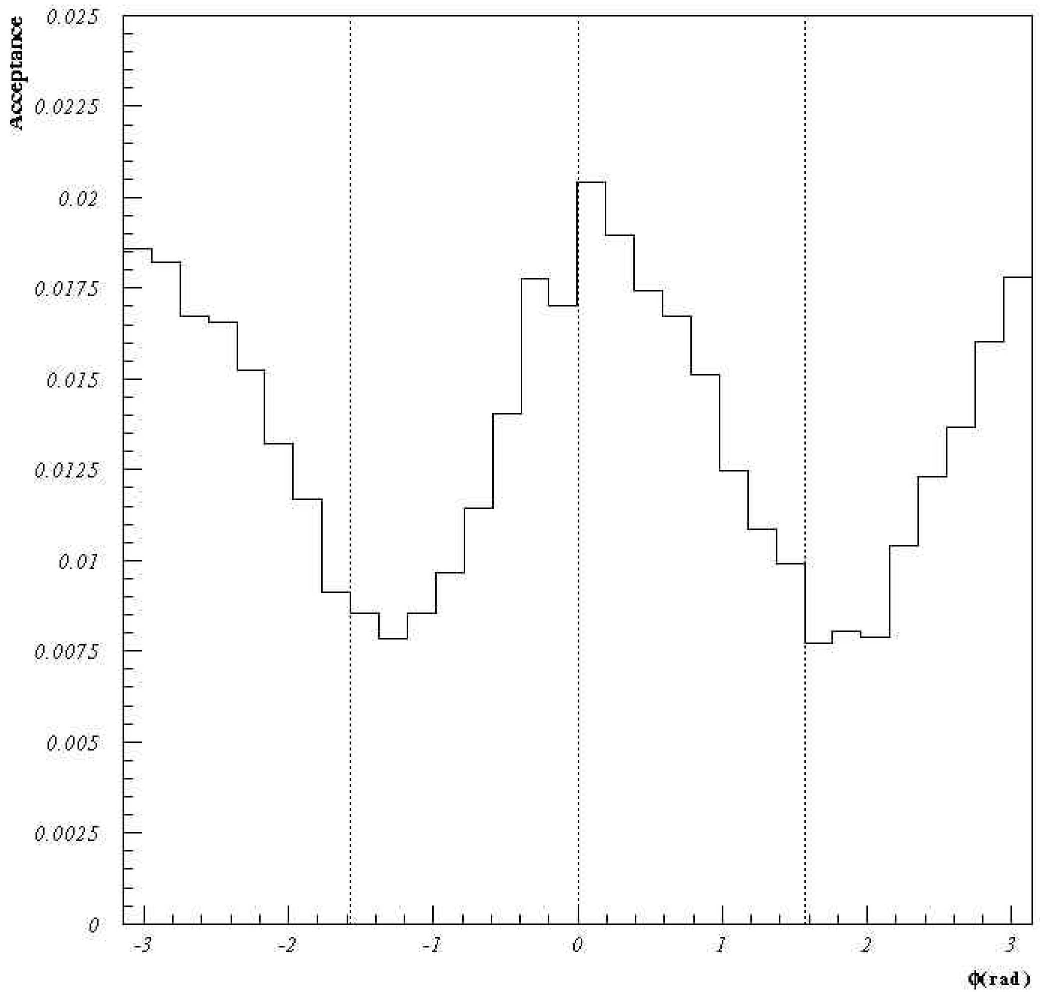
Measured raw asymmetry of data is 0.237$\pm$0.029(stat.) while the MC with input parameter of 0.147 gave the raw asymmetry of 0.258.

The detector or analysis did not induce the raw asymmetry. This is also supported by the signal MC with zero input asymmetry.

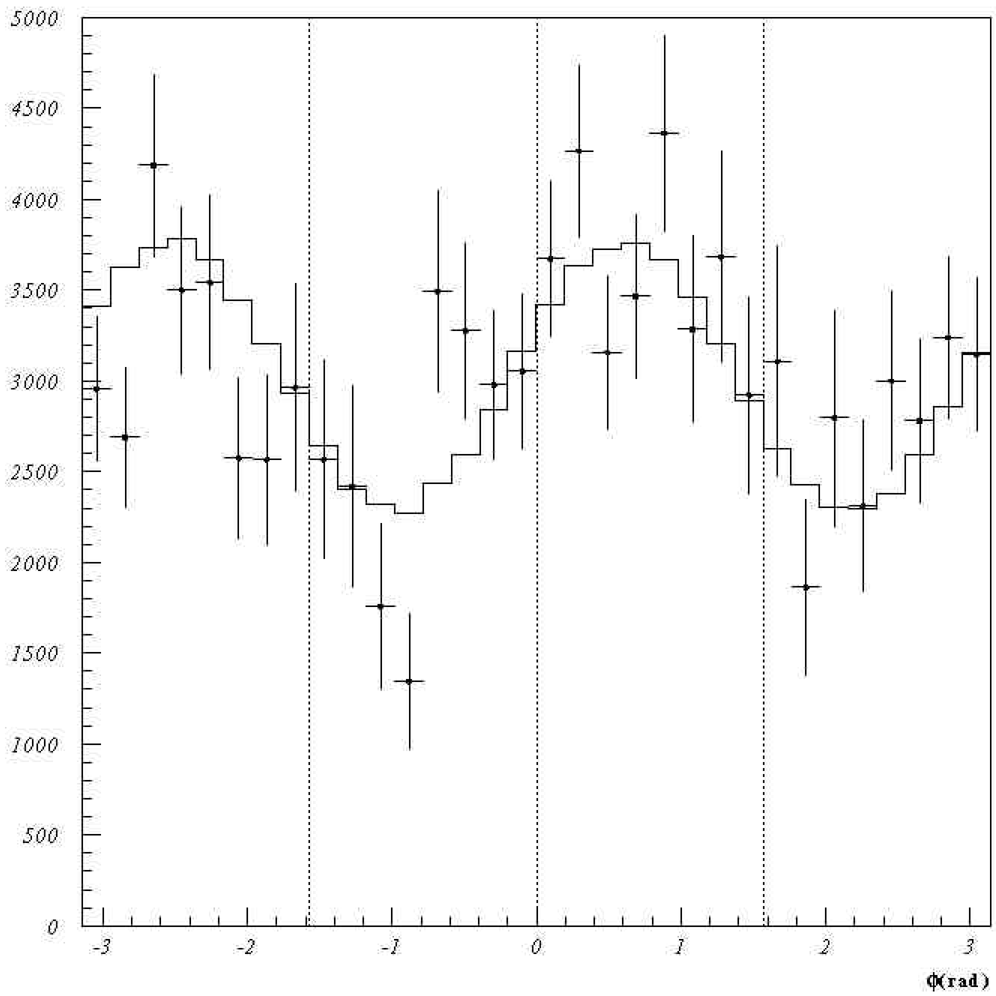
The input and raw asymmetry have the simple linear relation which suggests the asymmetry enhancement.

The KTeV detector only accepted events with high momentum electrons. Those events showed the large asymmetry.

Singal Acceptance in *f*



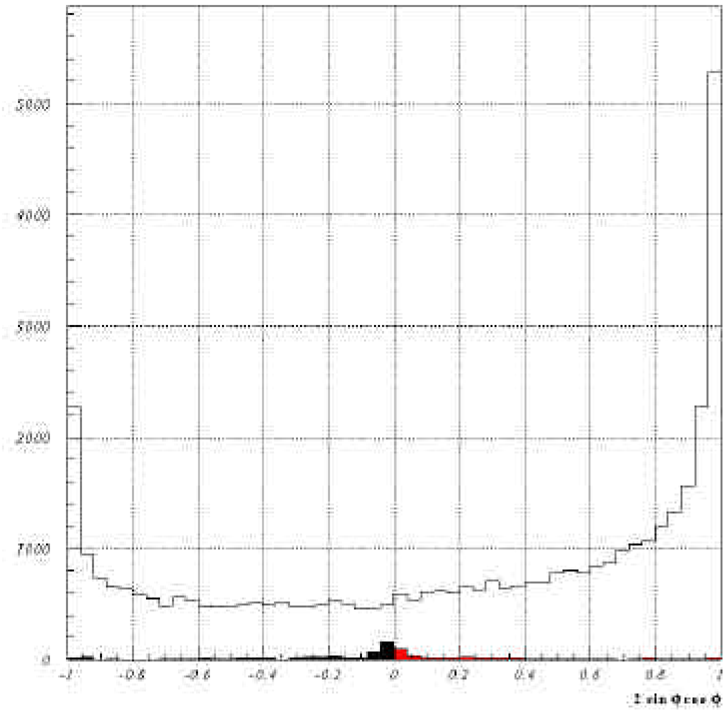
Acceptance Corrected Data and MC

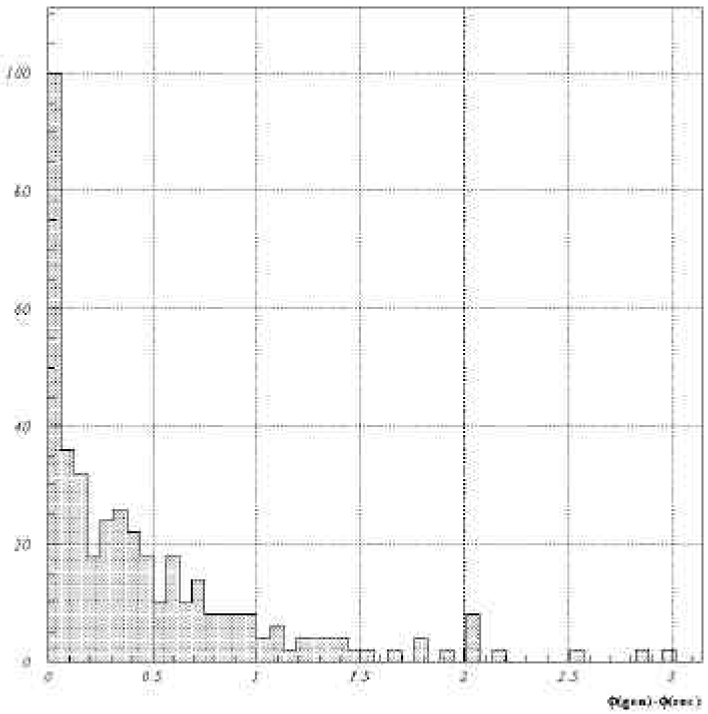


Acceptance Corrected Asymmetry

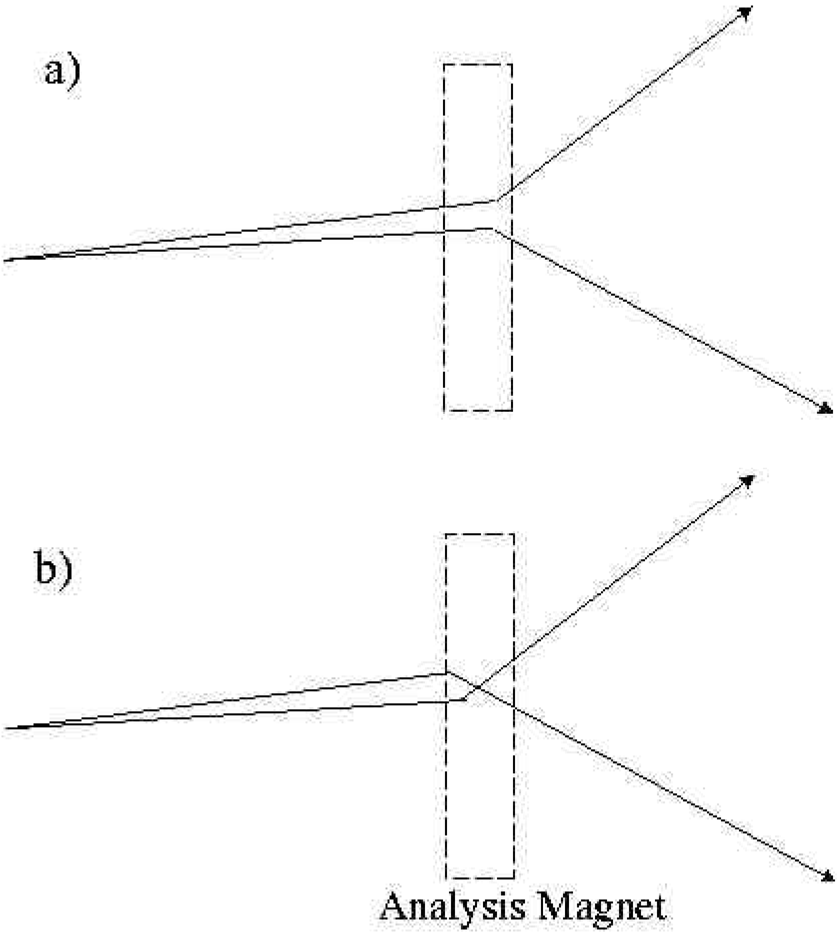
0.127±0.029

Detector Smearing





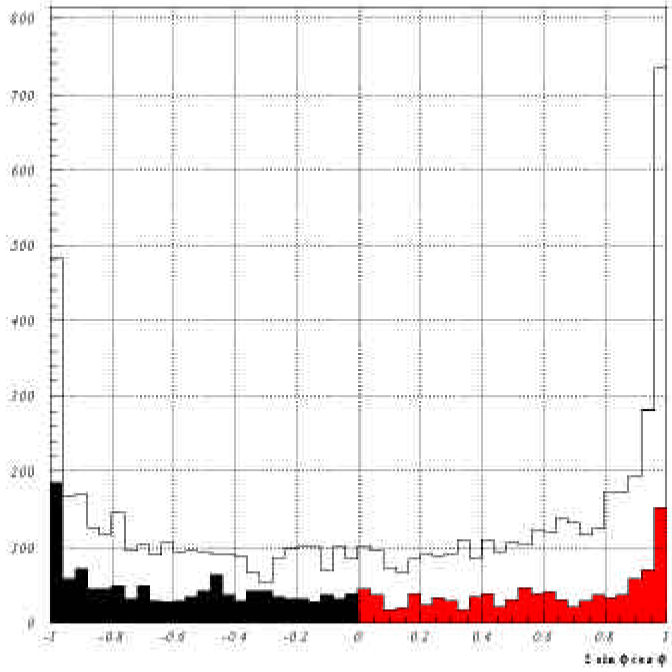
Detector Smearing; continue

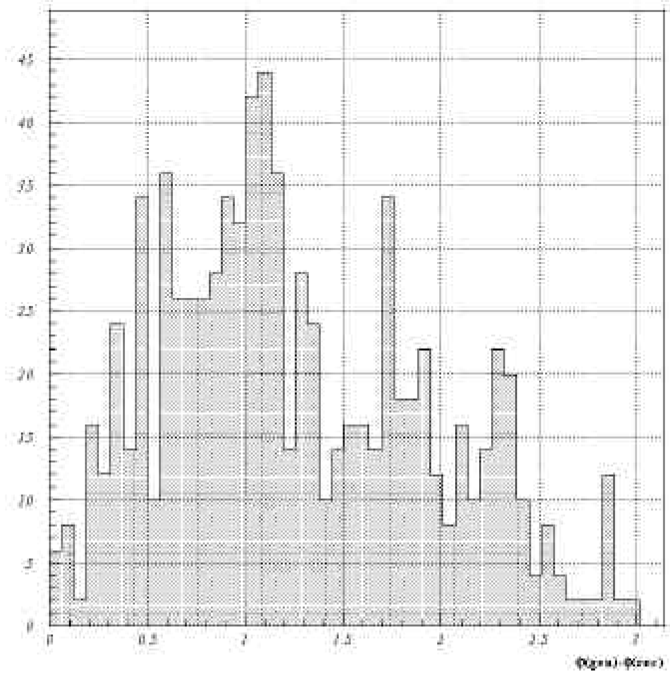


X track swapping causes the dilution.

$$\text{Track in } \sin f \cos f \text{ region} \rightarrow -\sin f \cos f \text{ region}$$

Detector Smearing; continue





Systematic Uncertainty

Detector resolution	8.7%(0.011)
M1 form factor	2.4%(0.003)
Physics Input parameter	6.9%(0.007)
Vertex quality	0.8%(0.001)
DC ineff.	<0.1%(0.000)
Background subtraction	0.9%(0.001)
Analysis dependency	4.7%(0.005)
Total	12.4%(0.016)

Asymmetry: Result

Asym. = 0.127 ± 0.029(stat.) ± 0.016(syst.)

Theoretical Prediction

Asym. ~ 14%

Sehgal and Wanninger
Phys. Rev. D46, 1035(1992);ibid D46,5209(E)(1992)

Branching Ratio Measurement

Recent Publication:

$$(3.2 \times 0.6(\text{stat.}) \times 0.4(\text{syst.})) \times 10^{-7}$$

Based on 46 events(one day of data) by KTeV

J.Adams et al., Phys. Rev. Lett. 80, 4123(1998)

Data Selection

Relax pt2 cut and Pp0kine cut to increase acceptance.

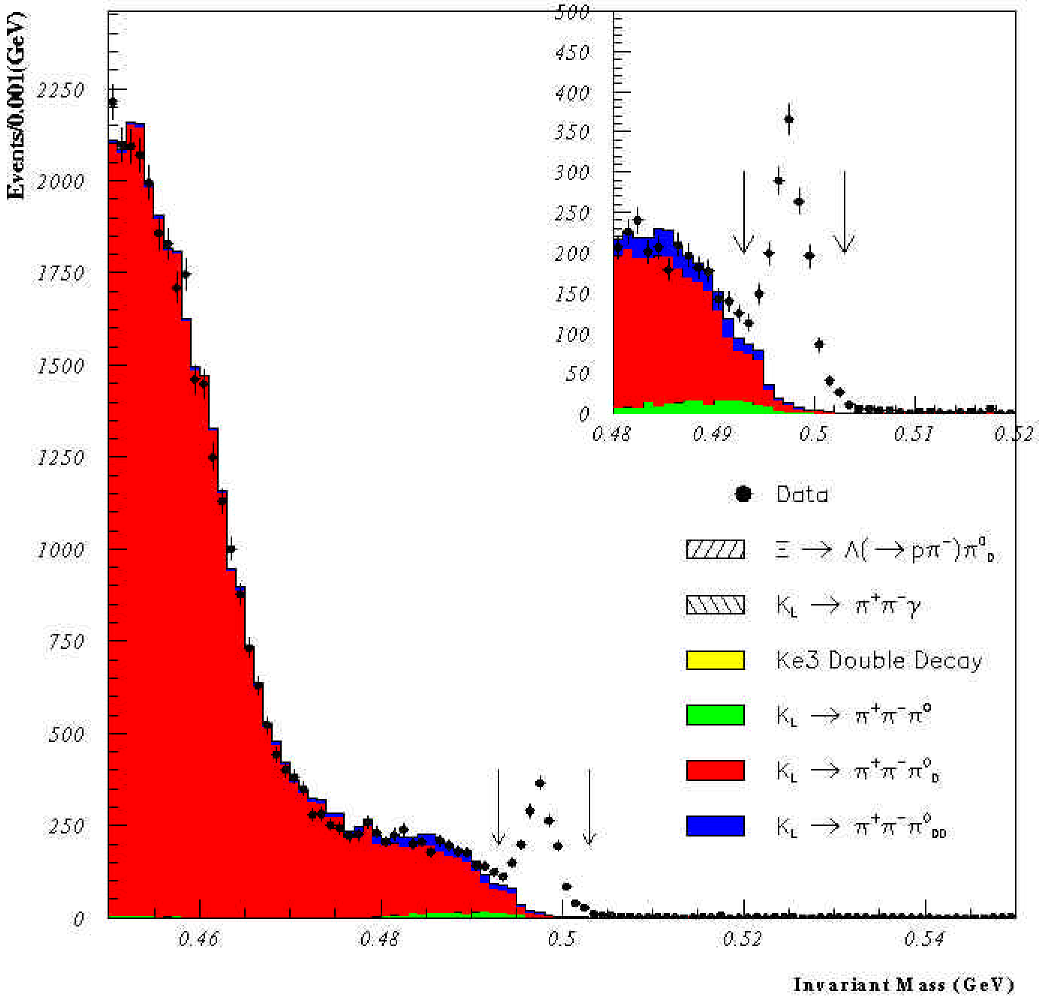
Pt2 cut : $<0.00006\ GeV^2/c^2 \rightarrow <0.00010\ GeV^2/c^2$

Pp0kine cut : $<-0.0025\ GeV^2/c^2 \rightarrow$ N/A

#events in the signal region

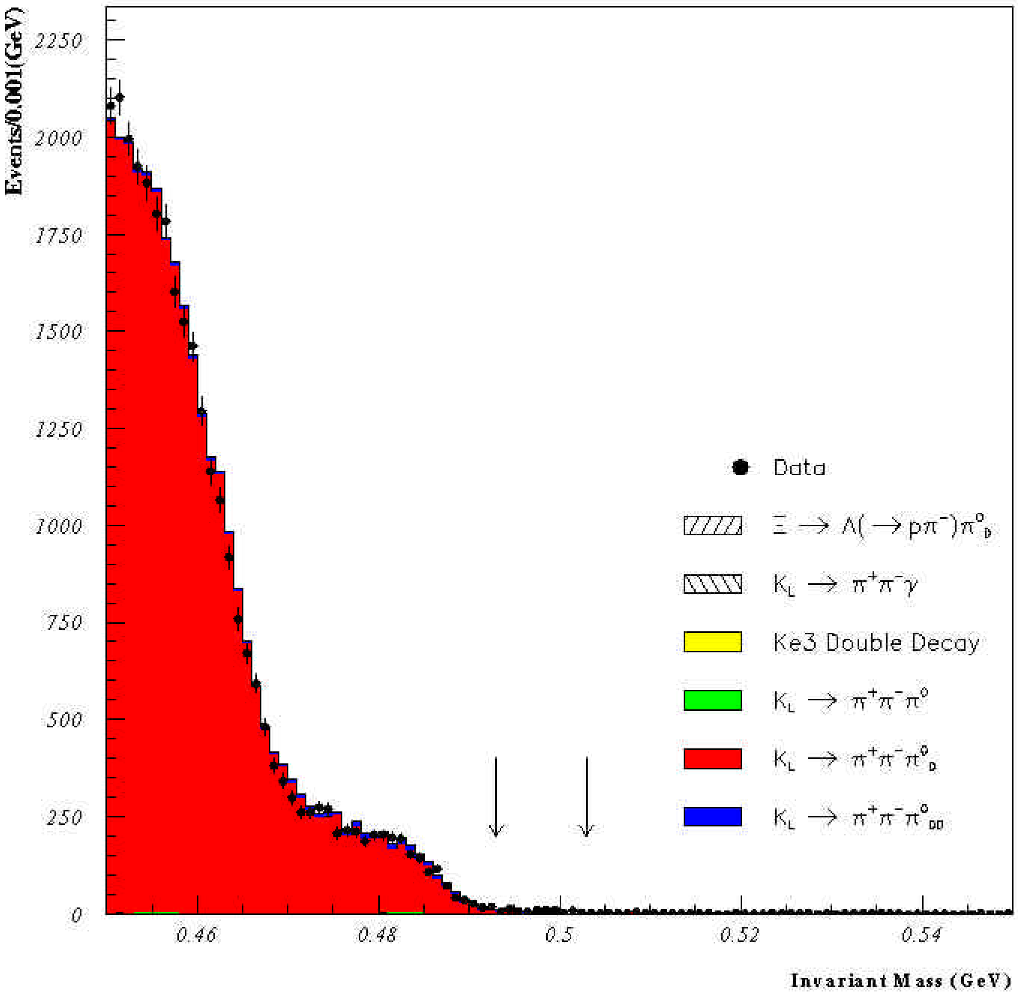
1173 events $\rightarrow$ 1731 events

Mass distribution after final cuts



Pt2 Sideband

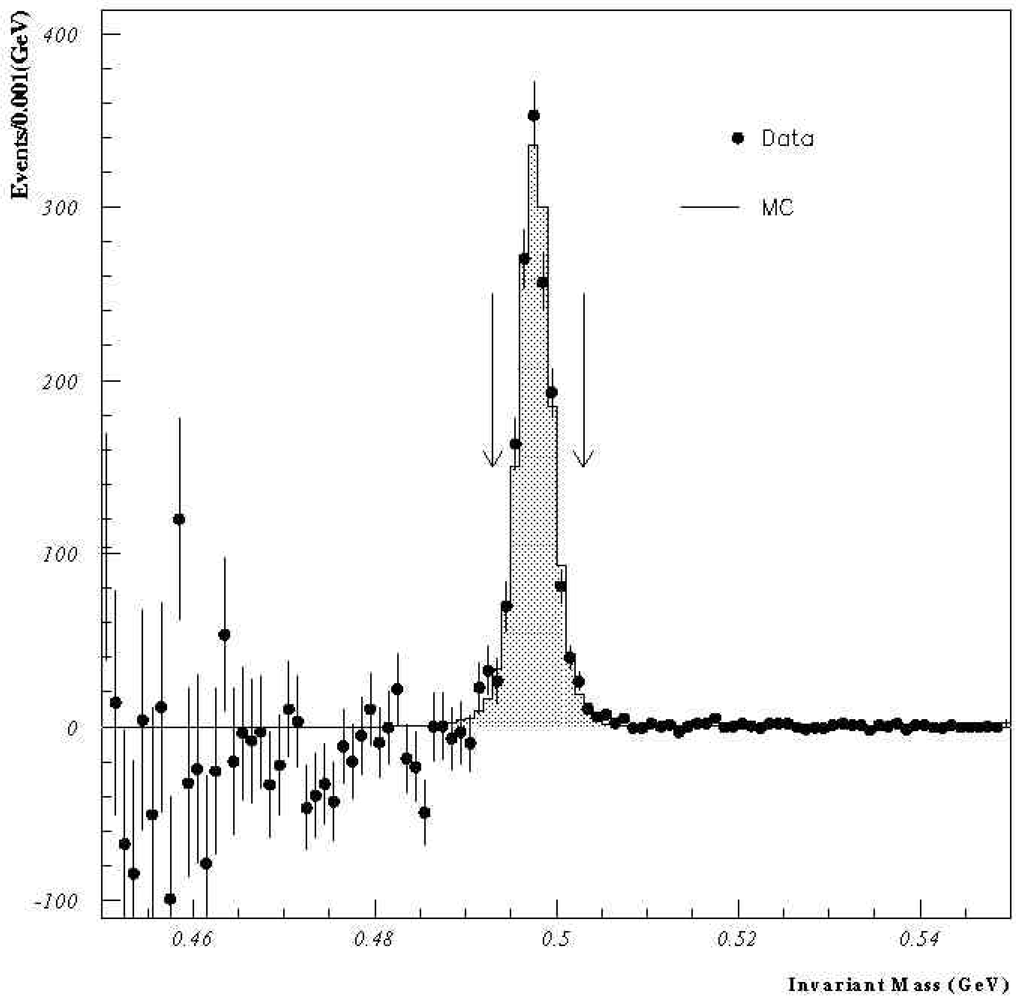
$0.00010\ GeV^2/c^2 < pt^2 < 0.00020\ GeV^2/c^2$



Background Estimation

Background	#Background
$K_L \to p^+ p^- p^0_D (p^0 \to e^+ e^- g)$	169.2 ± 13.0
$K_L \to p^+ p^- p^0_{DD} (p^0 \to e^+ e^- e^+ e^-)$	32.2 ± 3.2
$K_L \to p^+ p^- p^0 (p^0 \to gg)$	46.7 ± 2.0
$K_L \to p^+ p^- g$	3.3 ± 0.6
$\Xi \to \Lambda(\to pp^-) p^0_D (\to e^+ e^- g)$	0.99 ± 0.14
$(K_L \to p^+ e^- n) + (K_L \to p^- e^+ n)$	3.0 ± 1.7
	255.4 ± 13.7

Signal peak after background subtraction



#signal after background subtraction:

1475.6 events

Statistical/Systematic Uncertainty(BR)

Statistical Error	**3.13%**
$BR(K_L \rightarrow p^+ p^- p^0_D)$	**3.14%**
Physics Input parameter	**2.60%**
Normalization	**0.33%**
Chamber inefficiency	**0.17%**
Vertex quality	**0.87%**
MC statistics	**0.25%**
Background subtraction	**1.6%**
Analysis dependency	**0.7%**

Total $(3.13(stat.) \oplus 2.00(syst._{internal}) \oplus 4.08(syst._{external}))\%$

Branching Ratio: Result

$$(3.55 \pm 0.11(\text{stat.}) \pm 0.07(\text{syst.}_{\text{internal}}) \pm 0.14\ (\text{syst.}_{\text{external}})) \times 10^{-7}$$

Based on 1475.6 events

Good agreement with recent experimental result;

$$(3.2 \times 0.6(\text{stat.}) \times 0.4(\text{syst.})) \times 10^{-7}$$

J.Adams et al., Phys. Rev. Lett. 80, 4123(1998)

And theoretical prediction;

$$\sim 3 \times 10^{-7}$$

Sehgal and Wanninger
Phys. Rev. D46, 1035(1992);ibid D46,5209(E)(1992)

Discussion: Asymmetry Measurement

Origin of the asymmetry

Final State Interaction: **negligible.**

(M.J.Savage,1999)

T Violation: **(strictly speaking,)rejected.**

CPT Violation: **unnatural, but not yet rejected.**

(J. Ellis and N.E. Mavromatos, 1999)

(I.I.Bigi and A.I.Sanda, 1999)

CP Violation/CPT Conservation:

Most probable interpretation.

(L.M.Sehgal and M.Wanninger, 1992)

Conclusion

CP Violating Angular Asymmetry

Asym. = 0.127 $\pm$ 0.029(stat.) $\pm$ 0.016(syst.)

Form Factor Measurement:

$$a_1 / a_2 = -0.684^{+0.031}_{-0.043}$$

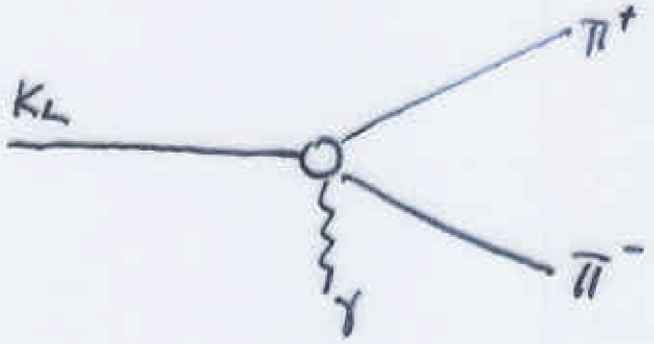
$$a_1 = 1.05 \pm 0.14$$

Branching Ratio

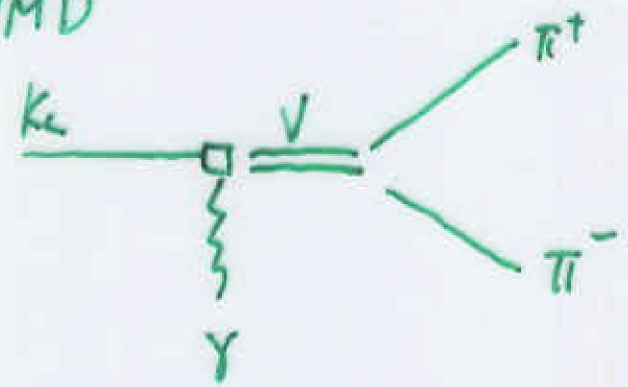
(3.55 $\pm$ 0.11(stat.) $\pm$ 0.07(syst.$_{\text{internal}}$) $\pm$ 0.14 (syst.$_{\text{external}}$)) $\times$ 10^{-7}

Based on 1475.6 events

Vector Meson Dominance in M1 direct emission



☆ VMD



- Lin and Valencia PRD37-143 (1988)

Table 6.7: Systematic uncertainties.

Sources	a_1/a_2	a_1
Fit procedure	0.35%	1.0 %
Detector smearing	0.1%	0.2 %
Vertex quality	0.3%	1.0 %
DC ineff.	0.3%	0.6 %
Input Param.	6.4%	12.4 %
BG subtraction	1.5%	4.8 %
Analysis dep.	4.2%	11.7 %
Total	7.8%	17.8 %

$a_1/a_2 = -0.684^{+0.031}_{-0.043}$ (stat.) $\pm$ 0.053 (sys)

$a_1 = 1.05 \pm 0.14$ (stat.) $\pm$ 0.18 (syst.)

Form Factor Measurement (discussion)

☆ experimental facts

- Direct Emission BR of $K_L \to \pi^+\pi^-\gamma$

  $BR_{DE} = 3.0 \times 10^{-5}$

- a_1/a_2 Direct measurement ($K_L \to \pi^+\pi^-\gamma$, $\pi^+\pi^-e^+e^-$)

  $a_1/a_2 = -0.70$

☆ Lin-Valencia model (Phys. Rev. D37, 143 (1988)) ChPT

$BR_{DE} = 3.0 \times 10^{-5} \implies a_1/a_2 = -1.8 \pm 0.2$

or

$a_1/a_2 = -0.70 \implies BR_{DE} < 1.0 \times 10^{-5}$

- Experimental Facts do not support Lin-Valencia Model.

$K_L \to \pi^+\pi^-\gamma$ results

$$\frac{DE}{DE+IB}\,(E_\gamma^* > 20\,\text{MeV}) = 0.685 \pm 0.009 \pm 0.017 \,(\text{syst.})$$

$$DE\ BR\,(E_\gamma^* > 20\,\text{MeV}) = (3.19 \pm 0.09) \times 10^{-5}$$

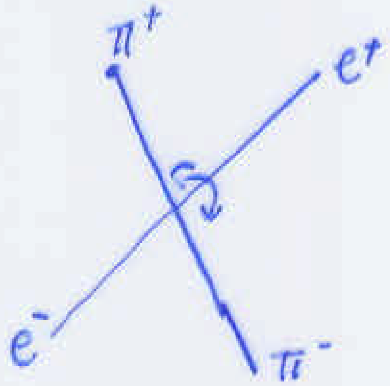
$$a_1/a_2 = -0.729 \pm 0.026 \pm 0.015\,(\text{syst.})$$

Lin and Valencia (1988) predicted

$$a_1/a_2 = -1.8 \quad \text{when } DE\ BR = 3.0 \times 10^{-5}$$

FINAL STATE INTERACTION

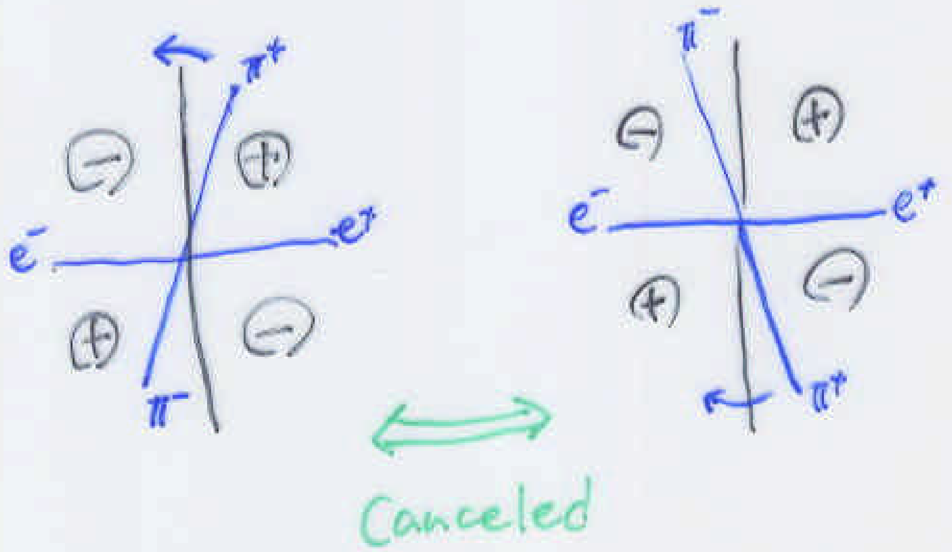
a) $\pi^+ - \pi^-$



$\pi^+ - \pi^-$ 平面上での作用

→ No effect

b) $\pi^+ - e^+$



Numerically, FSI is negligible.

(Savage, Kaon 99)

• CP violation, CPT holds (Sehgal - Wanninger)

$$\text{Asym} = \underbrace{A_1 \cos\theta_1}_{\text{DE - IB}} + \underbrace{A_2 \cos\theta_2 \left|\frac{g_{E1}}{g_{M1}}\right|}_{\text{E1 - DE}}$$

$$\theta_1 = \Phi_{+-} + \delta_0 - \delta_1 - \frac{\pi}{2} - \delta\varphi$$

$$\theta_2 = \Phi_{+-} - \frac{\pi}{2} \qquad - \delta\varphi$$

$\delta\varphi$: CPT violating Phase ~ 0.

$A_1 = 0.15$, $A_2 = 0.38$

$$\text{Asym} = 0.14$$

• CP holds, CPT violation (Ellis - Mavromatos)

Assuming $A_1 \cos\theta_1^{(0)} + A_2 \cos\theta_2^{(0)} \left|\frac{g_{E1}}{g_{M1}}\right| = 0$

$$\text{Asym} \simeq A_1 \sin\delta\varphi \left(\sin\theta_1^{(0)} - \cos\theta_1^{(0)} \tan\theta_2^{(0)}\right)$$

$$0.13 \lesssim A_1 \sin\delta\varphi \lesssim 0.22 \quad (1\sigma)$$

If $A_1 = 0.15$, $\delta\varphi \gtrsim 58^\circ$.

CPLEAR

$p\bar{p} \to K^- \pi^+ K^0$ and $K^+ \pi^- \bar{K}^0$

$$A_{CP} = \frac{\Gamma(\bar{K} \to e^+ \nu \pi^-) - \Gamma(K \to e^- \nu \pi^+)}{\Gamma(\bar{K} \to e^+ \nu \pi^-) + \Gamma(K \to e^- \nu \pi^+)} = (6.6 \pm 1.3 \pm 1.0) \times 10^{-3}$$

$A_{CP} \sim A_T$

↓

(assuming $\Delta S = \Delta Q$

CPT Invariance $(-0.4 \pm 0.6) \times 10^{-3}$ from $K_{\ell 3}$

If CPT does not hold,

$$A_{CP} = A_1 \cos\Theta_1 + A_2 \cos\Theta_2 \left|\frac{g_{E1}}{g_{M1}}\right|$$

$$\Theta_1 \equiv \phi_{+-} + \delta_0 - \bar{\delta}_1 - \frac{\pi}{2} - \overline{\delta\varphi} \mod \pi$$

$$\Theta_2 \equiv \phi_{+-} - \frac{\pi}{2} - \overline{\delta\varphi} \mod \pi$$

CPT violating phase shift

$A_1 \sim 0.15$ (related to Bremshtrahlung)
$A_2 \sim 0.38$ (〃 M1)

$$\Rightarrow A \simeq A_1 \sin\overline{\delta\varphi}\,[\sin\Theta_1^{(0)} - \cos\Theta_1^{(0)} \tan\Theta_2^{(0)}]$$

If T holds, KTeV result can be reproducted as:

$$0.13 \leq A_1 \sin\overline{\delta\varphi} \leq 0.22$$

$$\Rightarrow \quad \overline{\delta\varphi} \gtrsim 58^\circ \text{ when } A_1 \sim 0.15.$$

(A₁ has still large umbiguity.)