Results on CP Violation from KTeV

- CP Violation in the decay $K_L \to \pi^+\pi^-e^+e^-$ A new observation in a dynamic, T odd variable.

- Status of Measurement of ϵ'/ϵ

KTeV Collaboration

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Direct CP-Violation: Measurement of ϵ'/ϵ in E832

$$\frac{\Gamma(K_L \to \pi^+\pi^-)/\Gamma(K_S \to \pi^+\pi^-)}{\Gamma(K_L \to \pi^0\pi^0)/\Gamma(K_S \to \pi^0\pi^0)} \approx 1 + 6\mathrm{Re}\,(\epsilon'/\epsilon)$$

Focus is on 20% of data:

- 7 weeks of 1996 $\pi^0\pi^0$ data (20% of total)
- 3 weeks of 1997 $\pi^+\pi^-$ data (17% of total)

The 1996 $\pi^+\pi^-$ data are *not* used for ϵ'/ϵ because a drift chamber pathology combined with the Level 3 software trigger rejected 20% of the events. Level 3 was modified in 1997 to recover this loss.

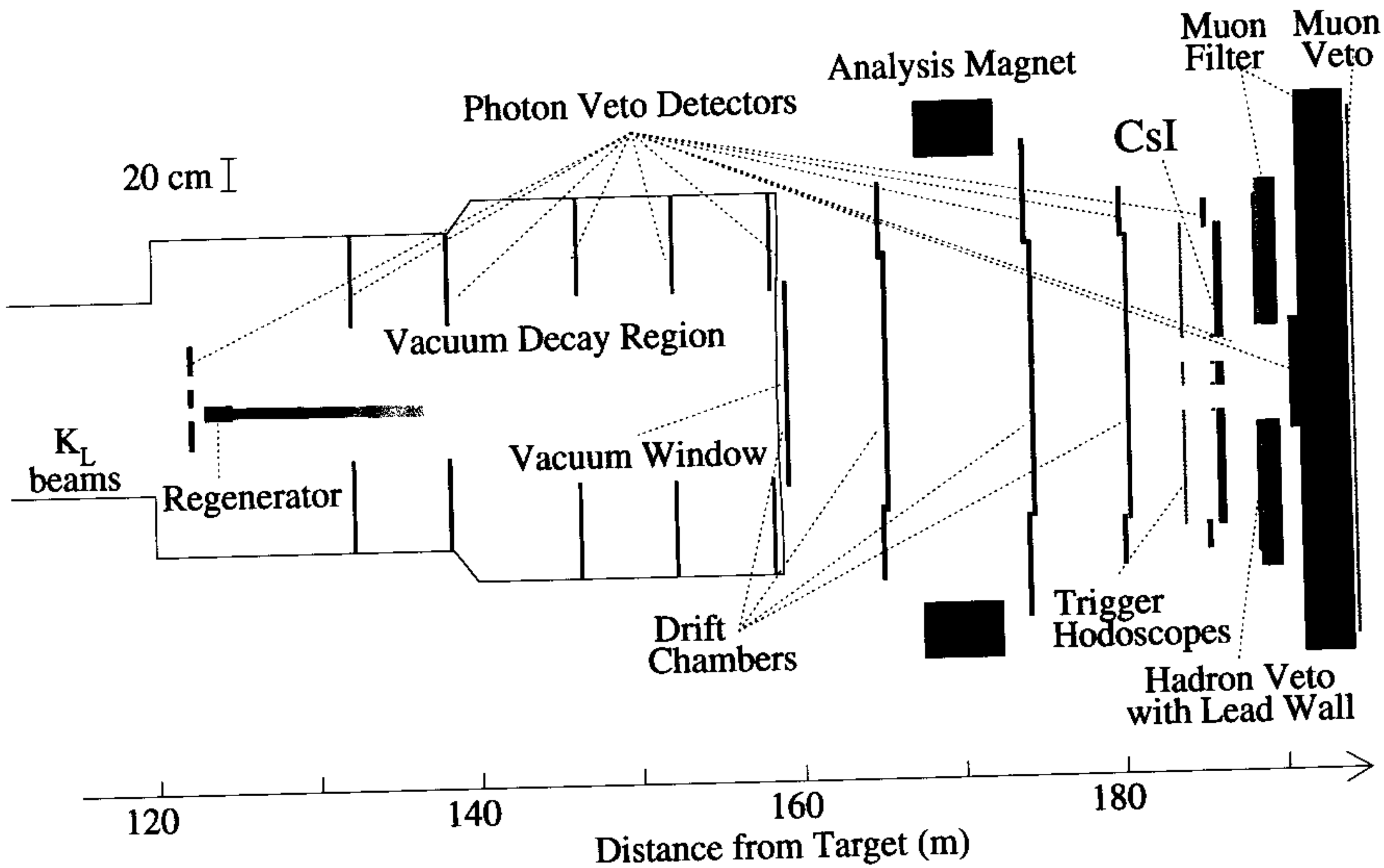
Statistics

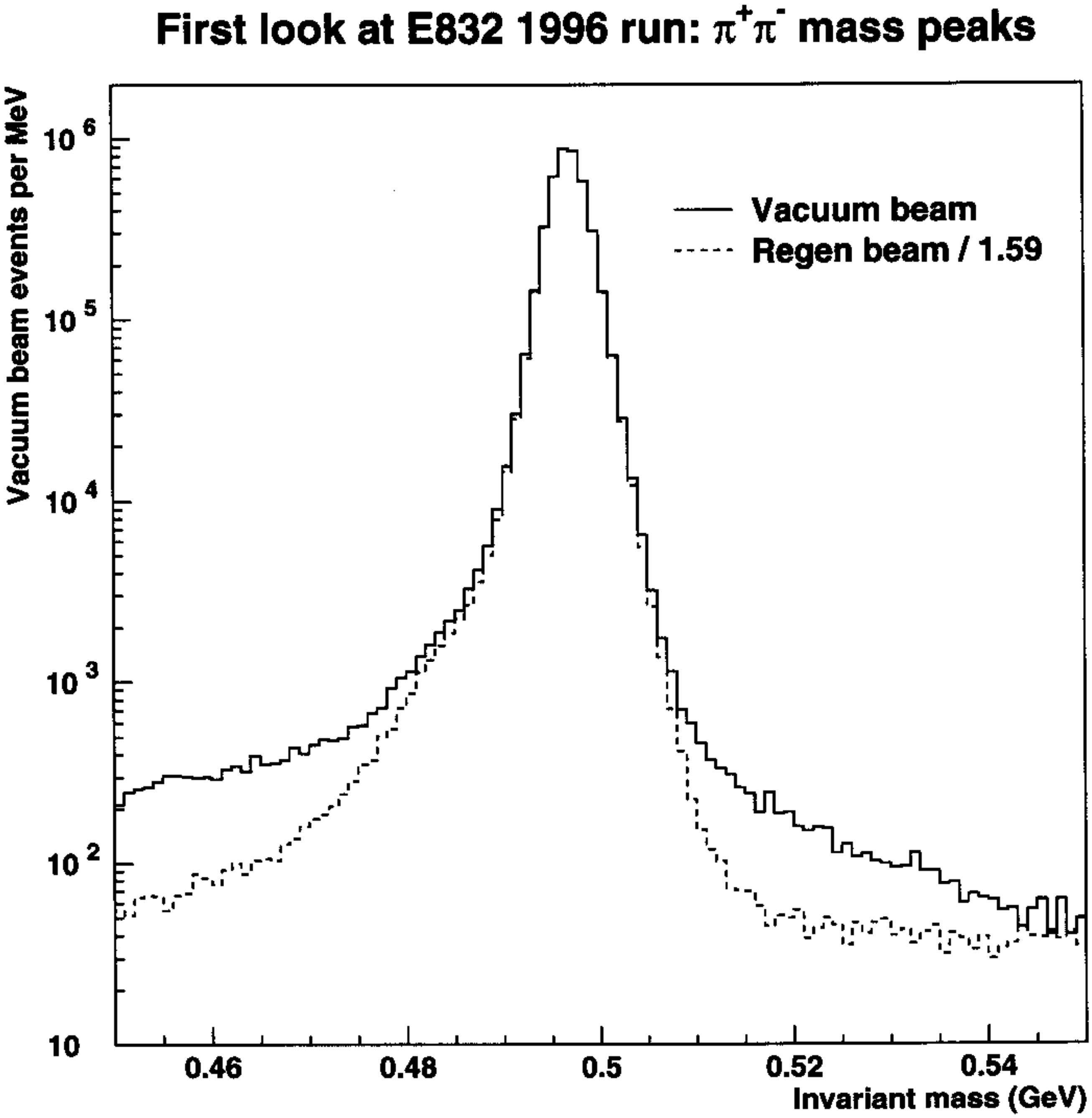
ϵ'/ϵ mode	events	bkg/signal
Vac ($K_L \to$) $\pi^0\pi^0$	1.0×10^6	0.8%
Reg ($K_S \to$) $\pi^0\pi^0$	1.6×10^6	1.5%
Vac ($K_L \to$) $\pi^+\pi^-$	1.9×10^6	0.1%
Reg ($K_S \to$) $\pi^+\pi^-$	3.9×10^6	0.1%

$\Longrightarrow \delta(\epsilon'/\epsilon)_{\mathrm{stat}} \sim 3 \times 10^{-4}$

Other modes with large statistics (1996 data):

- 200 million $K \to \pi e \nu$ events for CsI calibration.
- 20 million $K \to 3\pi^0$ for "neutral" systematic studies.


Muon Veto
Muon Filter
Analysis Magnet
Photon Veto Detectors
CsI
20 cm
Vacuum Decay Region
K_L beams
Regenerator
Vacuum Window
Trigger Hodoscopes
Drift Chambers
Hadron Veto with Lead Wall
120
140
160
180
Distance from Target (m)



$M_{\pi\pi}$, nominal cuts, before offline calibration

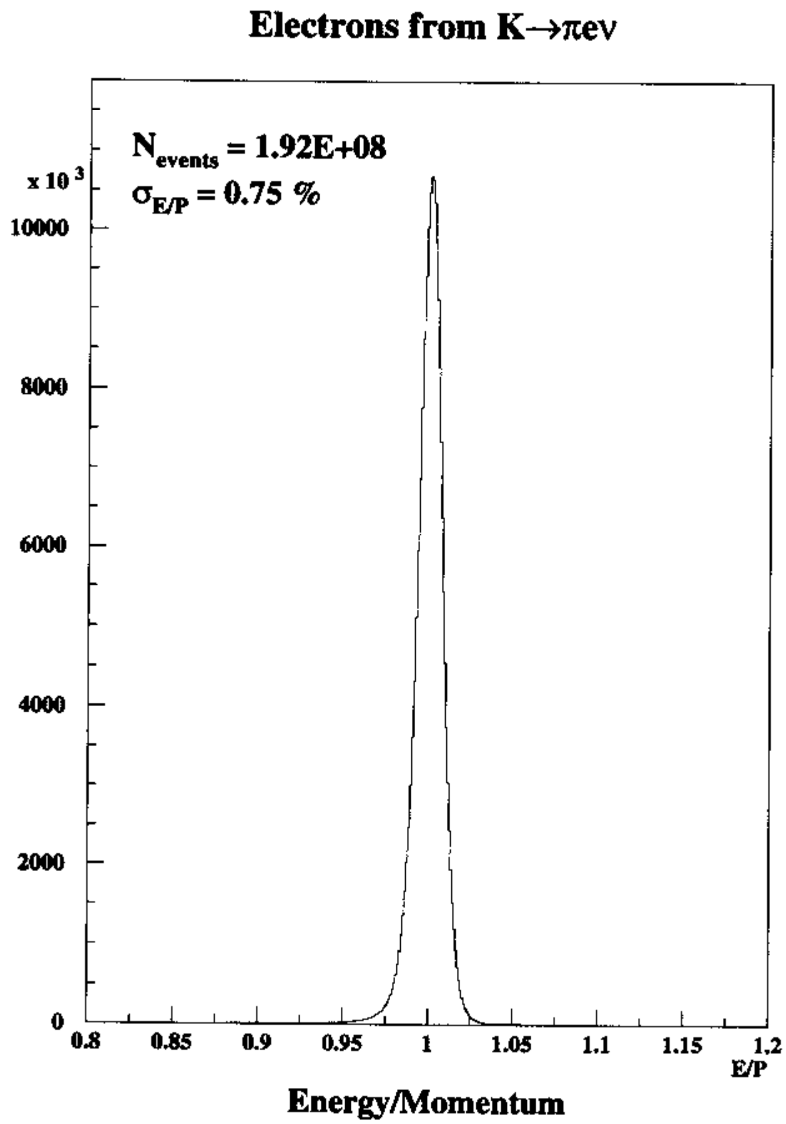


Figure 20: E/P for electrons from $K_L \to \pi^{\pm} e^{\mp} \nu$ decay

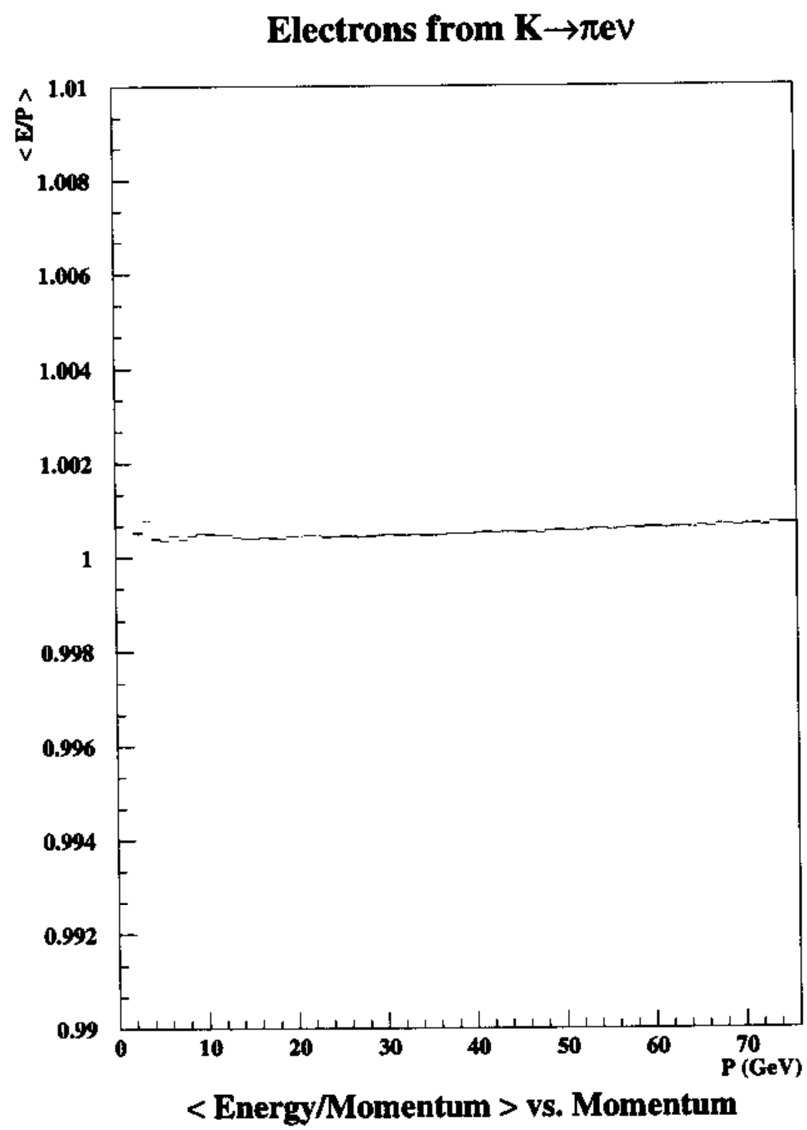


Figure 22: E/P vs. P for electrons from $K_L \to \pi^{\pm} e^{\mp} \nu$ decay

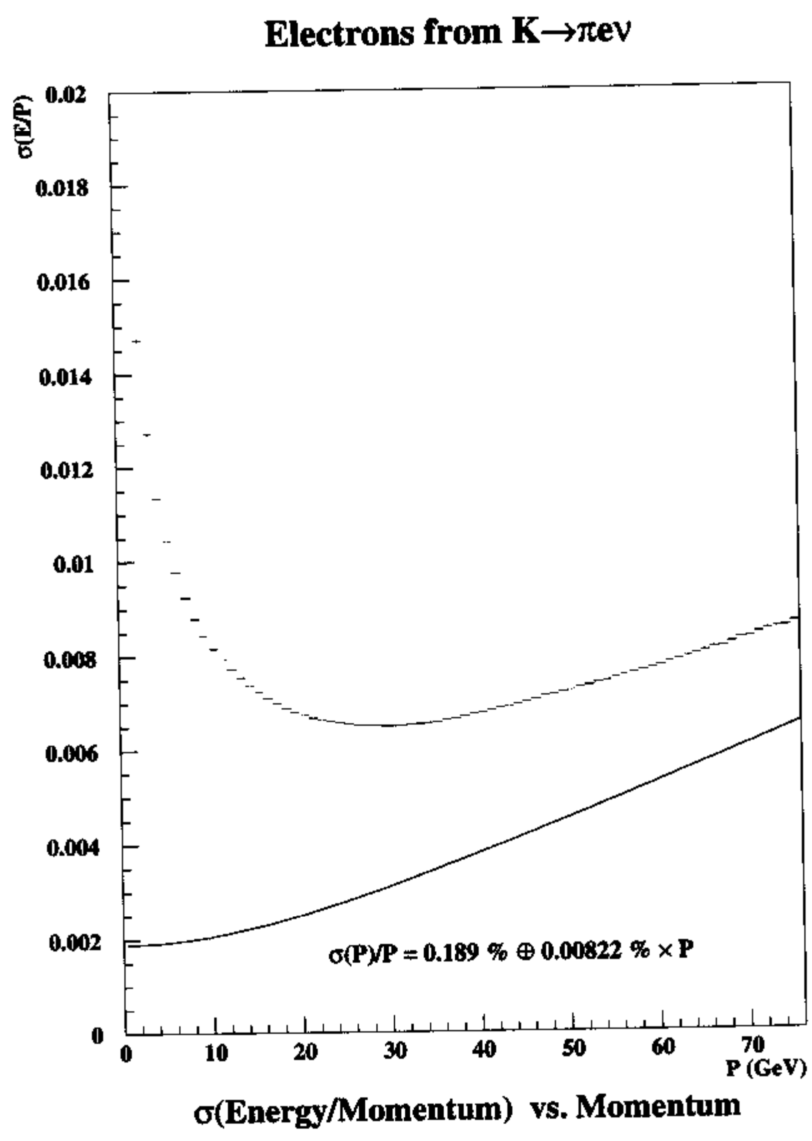


Figure 23: $\sigma(E/P)$ vs. P for electrons from $K_L \to \pi^{\pm} e^{\mp} \nu$ decay, also shown is

$Re(\epsilon'/\epsilon)$ at KTeV: Current Status

Analysis of 20% data subsample is at an advanced stage

- $K_{L,S} \to \pi^0\pi^0$ from 1996
- $K_{L,S} \to \pi^+\pi^-$ from 3 weeks of 1997 running
- Statistical error on $Re(\epsilon'/\epsilon)$ is $\sim 3 \times 10^{-4}$

Currently studying systematic effects, including:

- Early "accidental" activity in detector
- Drift chamber / tracking inefficiencies
- Simulation of the hardware triggers
- Biases in neutral reconstruction
- Backgrounds to $K_{L,S} \to \pi^0\pi^0$

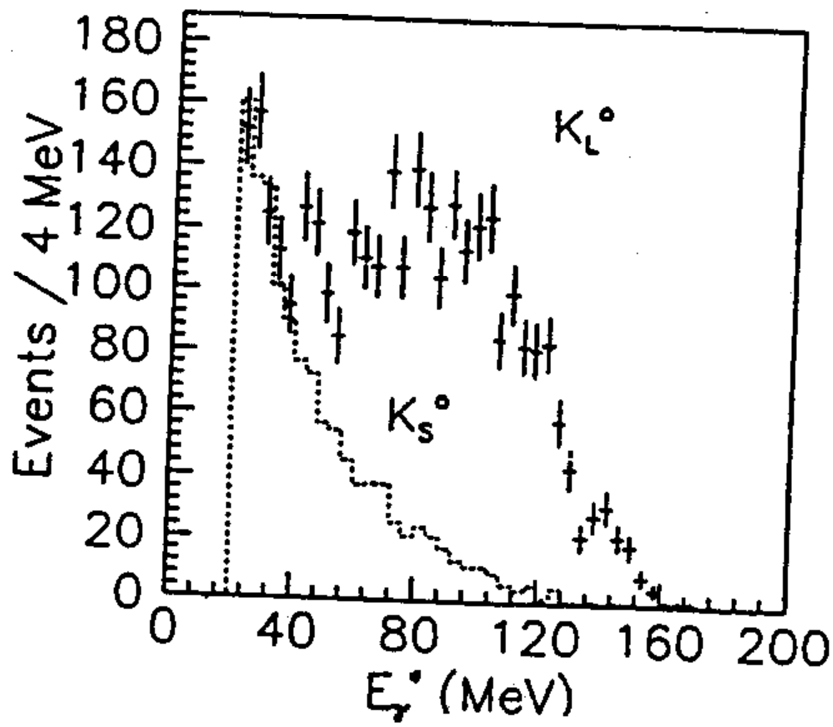
Fitting program hides value of $Re(\epsilon'/\epsilon)$ until we believe we have accounted for all possible biases

Expect to have a result from this data sample within a few months

CP Violation in $K_L \to \pi^+\pi^-e^+e^-$

Story starts with $K_L \to \pi^+\pi^-\gamma$ and $K_S \to \pi^+\pi^-\gamma$

K_S decays by CP conserving Inner Bremsstralung amplitude. K_L has both CP violating Inner Bremsstralung and CP conserving Direct Emission amplitudes, whose interference results in a polarization of the γ.



Events / 4 MeV
180
160
140
120
100
80
60
40
20
0
0
40
80
120
160
200
K_L°
K_S°
E_γ* (MeV)

It was soon recognized that in $K_L \to \pi^+\pi^-e^+e^-$ this interference shows up as an angular asymmetry.

References:

- L.M.Sehgal and M.Wanninger, Phys Rev **D46**,1035 (1992), **D46**,5209(E).
- P.Heiliger and L.M.Sehgal, Phys Rev **D48**, 4146 (1993)
- J.K.Elwood, M.B.Wise and M.J.Savage, Phys Rev **D52**, 5095 (1995), **D53**, 2855(E) (1996).
- J.K.Elwood, M.B.Wise, M.J.Savage and J.W.Walden, Phys Rev **D53** ,4078 (1996)

Define ϕ as the angle between the planes defined by the $\pi^+ \times \pi^-$ and $e^+ \times e^-$ momentum vectors in the K_L rest frame.

The Physics of K->ππee

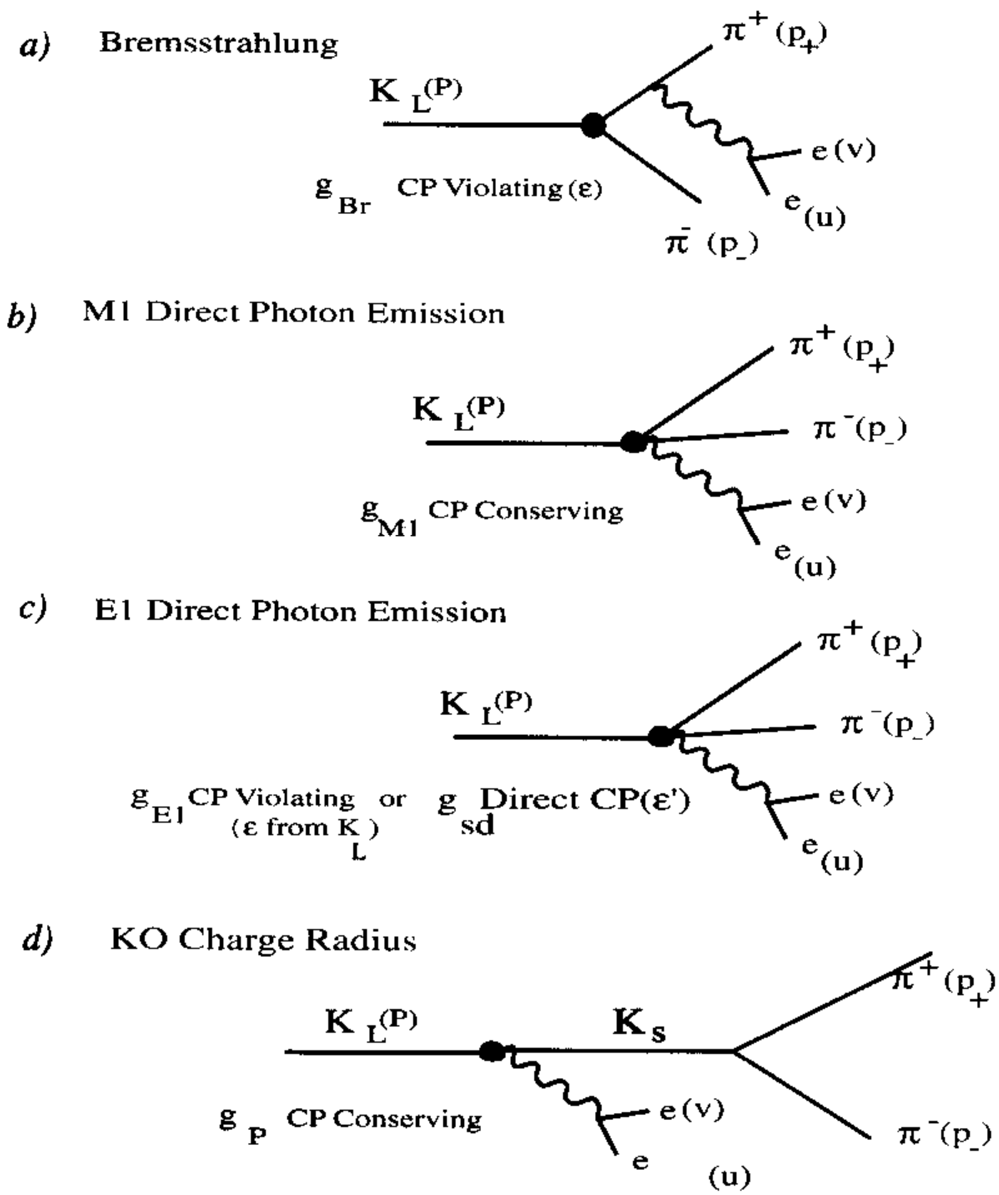


Figure 1: Amplitudes which contribute to the $K_L^0 \to \pi^+\pi^-e^+e^-$ decay

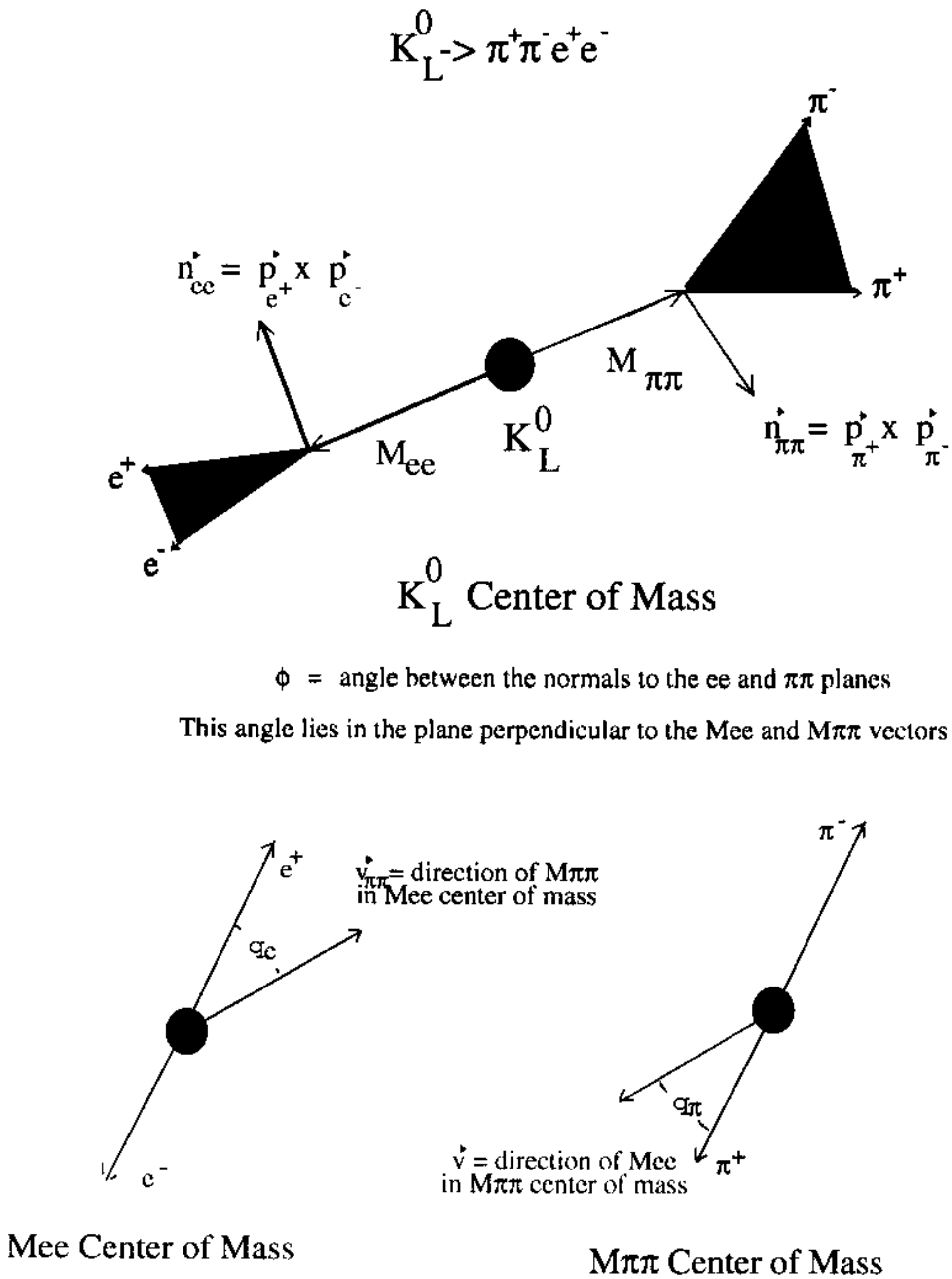


Figure 2: Critical Angles in the $K_L^0 \rightarrow \pi^+\pi^-e^+e^-$ Decay

In particular we can calculate:

$$\sin\phi\cos\phi = (\mathbf{n}_l \times \mathbf{n}_\pi)\cdot\hat{\mathbf{z}}(\mathbf{n}_l \cdot \mathbf{n}_\pi)$$

where

$$\mathbf{n}_l = (p_{e^+} \times p_{e^-})/|p_{e^+} \times p_{e^-}|$$

$$\mathbf{n}_\pi = (p_{\pi^+} \times p_{\pi^-})/|p_{\pi^+} \times p_{\pi^-}|$$

are the unit vectors normal to the planes of the e^+e^- and $\pi^+\pi^-$ pairs, respectively, and

$$\hat{\mathbf{z}} = (p_{\pi^+} + p_{\pi^-})/|p_{\pi^+} + p_{\pi^-}|.$$

Under T reversal, $\sin\phi\cos\phi$ changes sign.

The two main components of the decay amplitude are:

Bremsstrahlung Amplitude

$$M_{br} \propto g_{br}\frac{1}{k^2}[\frac{p_{+\mu}}{p_+ \cdot k} - \frac{p_{-\mu}}{p_- \cdot k}][\overline{u}(k_-)\gamma^\mu v(k_+)]$$

M1 Amplitude

$$M_{M1} \propto g_{mag}\frac{1}{k^2 M_K^4}[\epsilon_{\mu\nu\rho\sigma}k^\nu p_+^\rho p_-^\sigma][\overline{u}(k_-)\gamma^\mu v(k_+)]$$

Integrating the decay rate over all other variables the ϕ dependence is predicted to have the form:

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

The term in $sin\phi cos\phi$ is CP violating. Sehgal and Wanninger predict an asymmetry (ϕ quadrants $1 + 3 - 2 - 4$) of $\approx 14\%$. The branching fraction is predicted to be about 3×10^{-7}.

So to clearly see a $\approx 10\%$ asymmetry we need several 1000 events of a decay mode never previously observed!

The KTeV (E-799) Experiment

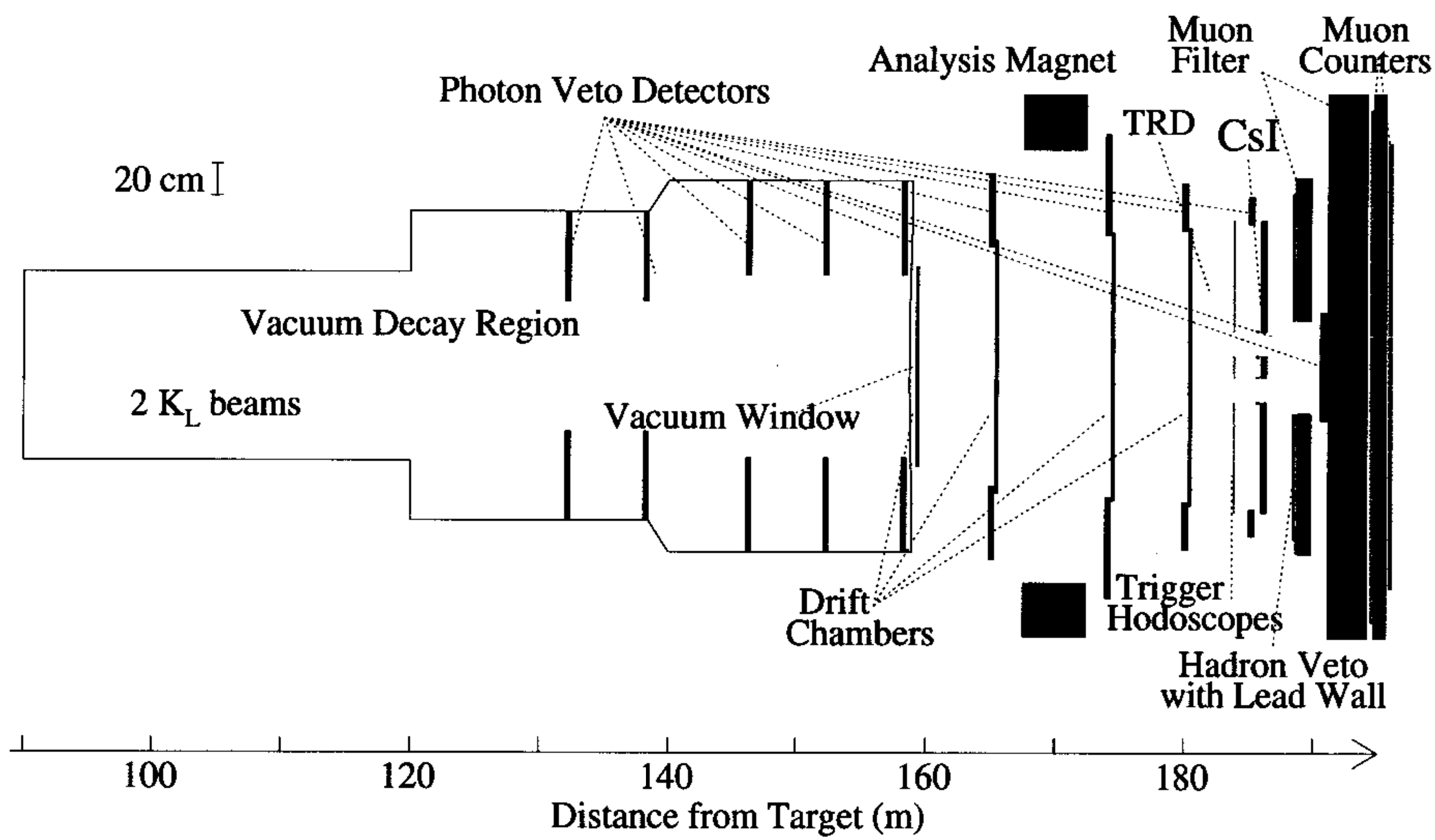
- New, High Intensity, Clean, Beams.
- High Acceptance, High Rate, Spectrometer.
- Trigger for 4 Track Events Required:
  - $\geq$3 hits is charged particle hodoscope.
  - $\geq$11 GeV total energy deposit in CsI calorimeter.
  - 2 or more clusters with energy $\geq$ 1 GeV in CsI.

  - 3 or 4 good hits in each drift chamber set in y view.
  - no hits in muon hodoscope.
  - no hits in outside veto counters.

- Resulting trigger rate was about 10% of total taken.

- Total 1997 run sensitive to $\approx 2.5 \times 10^{11} K_L$ decays

- 1.3×10^8 4 track triggers written to tape after Level 3 processing.



Muon Counters
Muon Filter
Analysis Magnet
Photon Veto Detectors
TRD
CsI
20 cm
Vacuum Decay Region
2 K_L beams
Vacuum Window
Drift Chambers
Trigger Hodoscopes
Hadron Veto with Lead Wall
100
120
140
160
180
Distance from Target (m)

KTEV Event Display

/duser7/userdata/arenton/select_summer_loose.dat

Run Number: 10477
Spill Number: 112
Event Number: 21767578
Trigger Mask: 8
All Slices

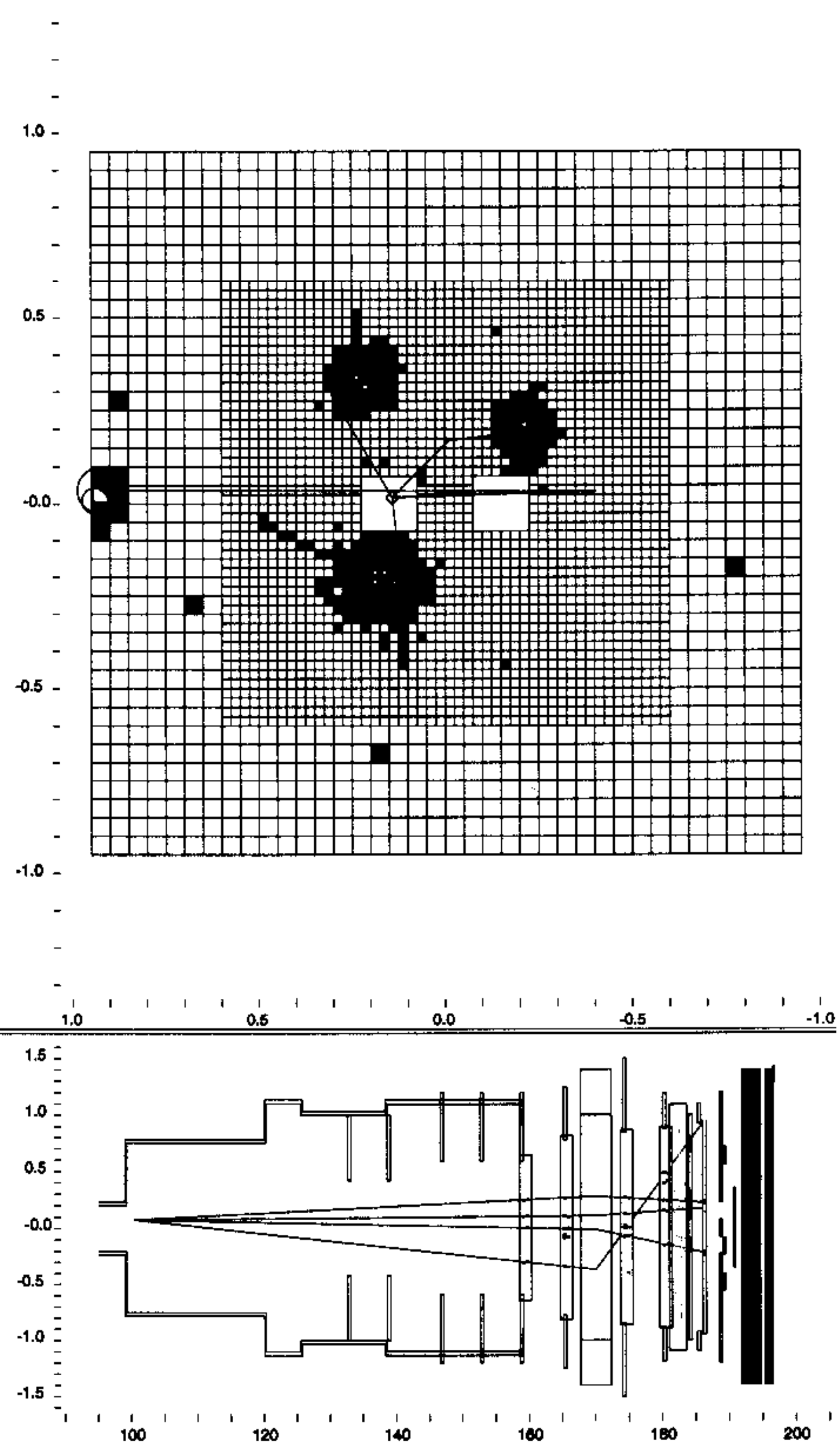
Track and Cluster Info
HCC cluster count: 5

ID	Xcsi	Ycsi	P or E
T 1:	-0.2131	0.1919	-18.08
C 5:	-0.2170	0.1926	17.84
T 2:	0.9246	0.0368	+2.37
C 1:	0.9402	0.0085	2.47
T 3:	0.1720	-0.2105	+60.48
C 3:	0.1730	-0.2068	36.62
T 4:	0.2245	0.3293	-32.50
C 2:	0.2213	0.3299	25.84
C 4:	0.1767	-0.2545	3.29

Vertex: 4 tracks

X	Y	Z
0.0762	0.0094	100.365

Chisq=5.60 Pt2v=0.000032



○ - Cluster

◯ - Track

■ - 10.00 GeV

- 1.00 GeV

■ - 0.10 GeV

■ - 0.01 GeV

Offline analysis requires 4 tracks forming a good vertex.

Electrons are identified by E/p in the CsI calorimeter. $(0.95 \geq E/p \leq 1.05)$

Pions are identified by low $E/p \leq 0.85$.

Even at this stage a signal appears in the plot of p_t^2 vs $\pi^+\pi^-e^+e^-$ mass.

Main background (and normalization) is $K_L \to \pi^+\pi^-\pi^0_D$ where π^0_D denotes the Dalitz decay $\pi^0 \to e^+e^-\gamma$.

This background may be suppressed by cutting on the variable:

$$P^2_{\pi^0} = \frac{[(M_K^2 - M_{\pi^0}^2 - M_c^2)^2 - 4M_{\pi^0}^2 M_c^2 - 4M_K^2(P_T^2)_c]}{4[(P_T^2)_c + M_c^2]}$$

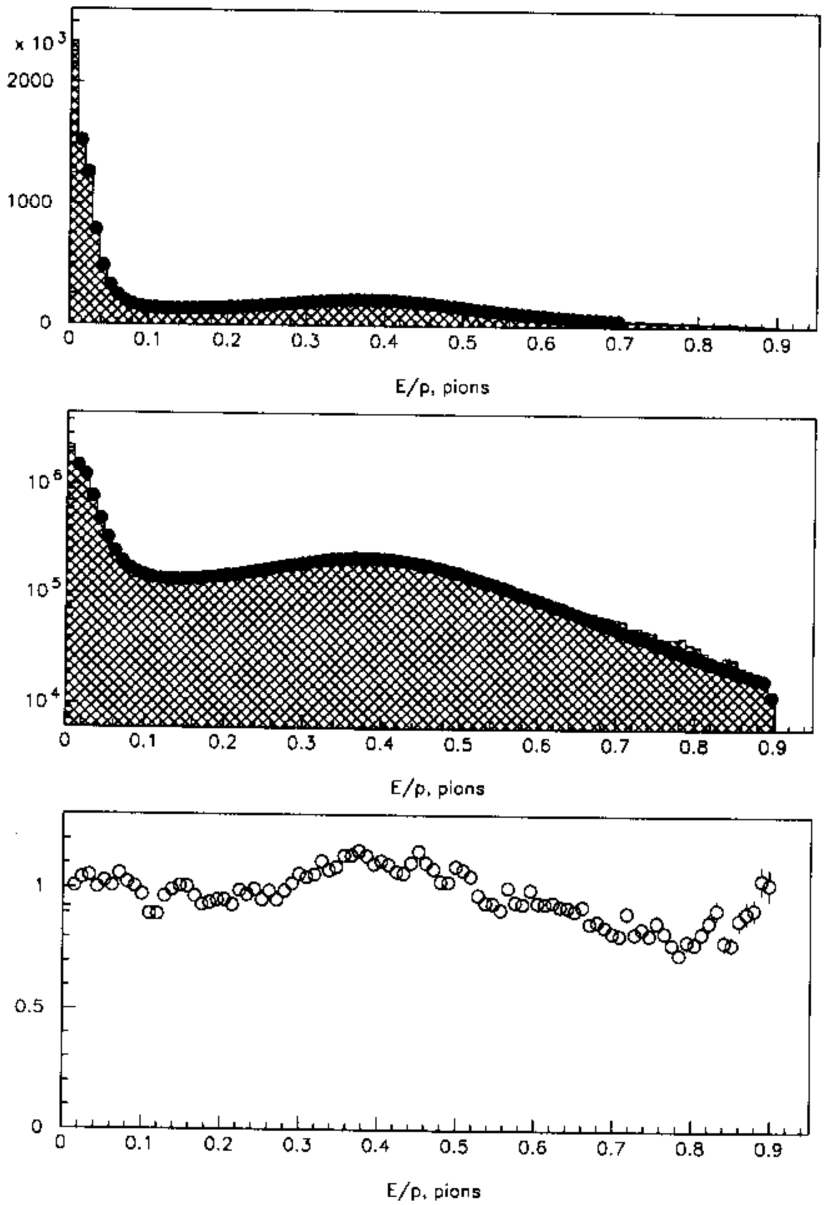


Figure 4: E/p for pions. Histogram is Monte Carlo events. Dots are DATA. Both distributions are normalized to the same number of entries in the histogram. Top plot is in linear scale, middle plot is in log scale and bottom plot is the ratio Data/MC

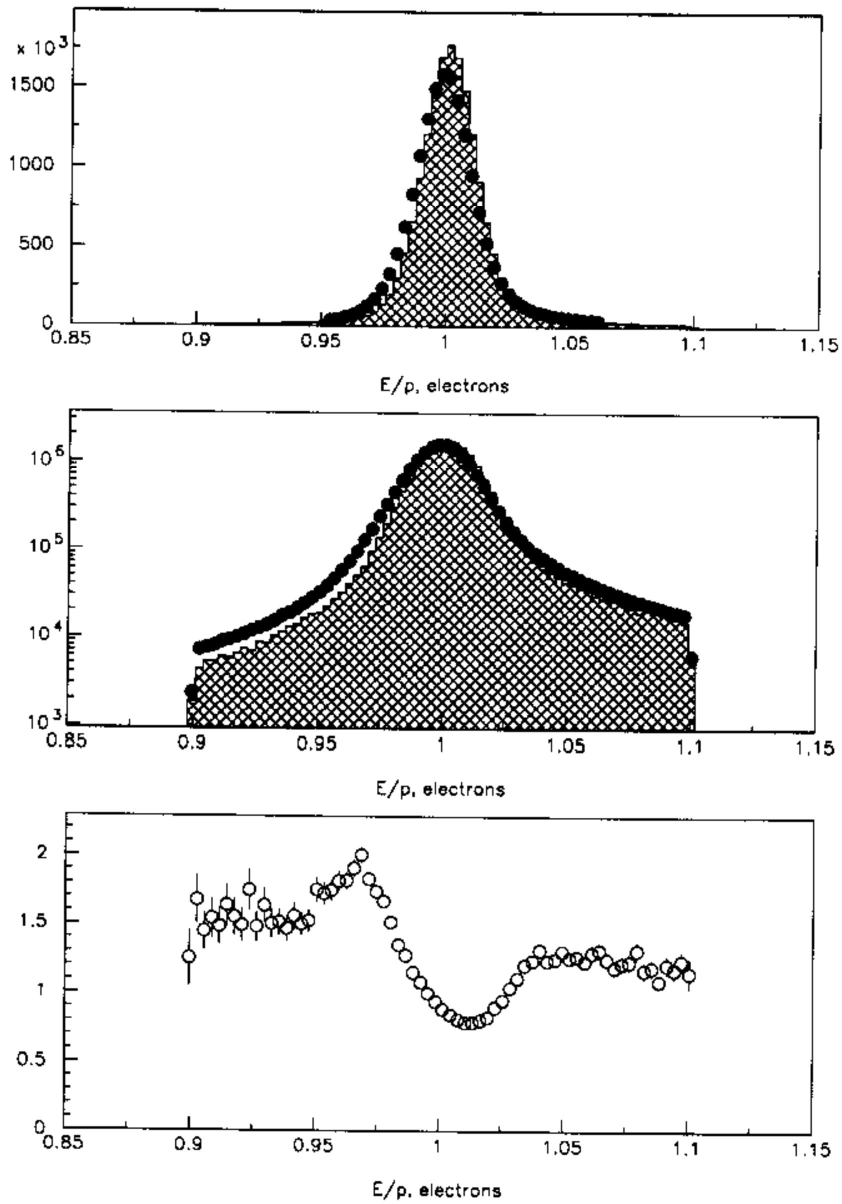
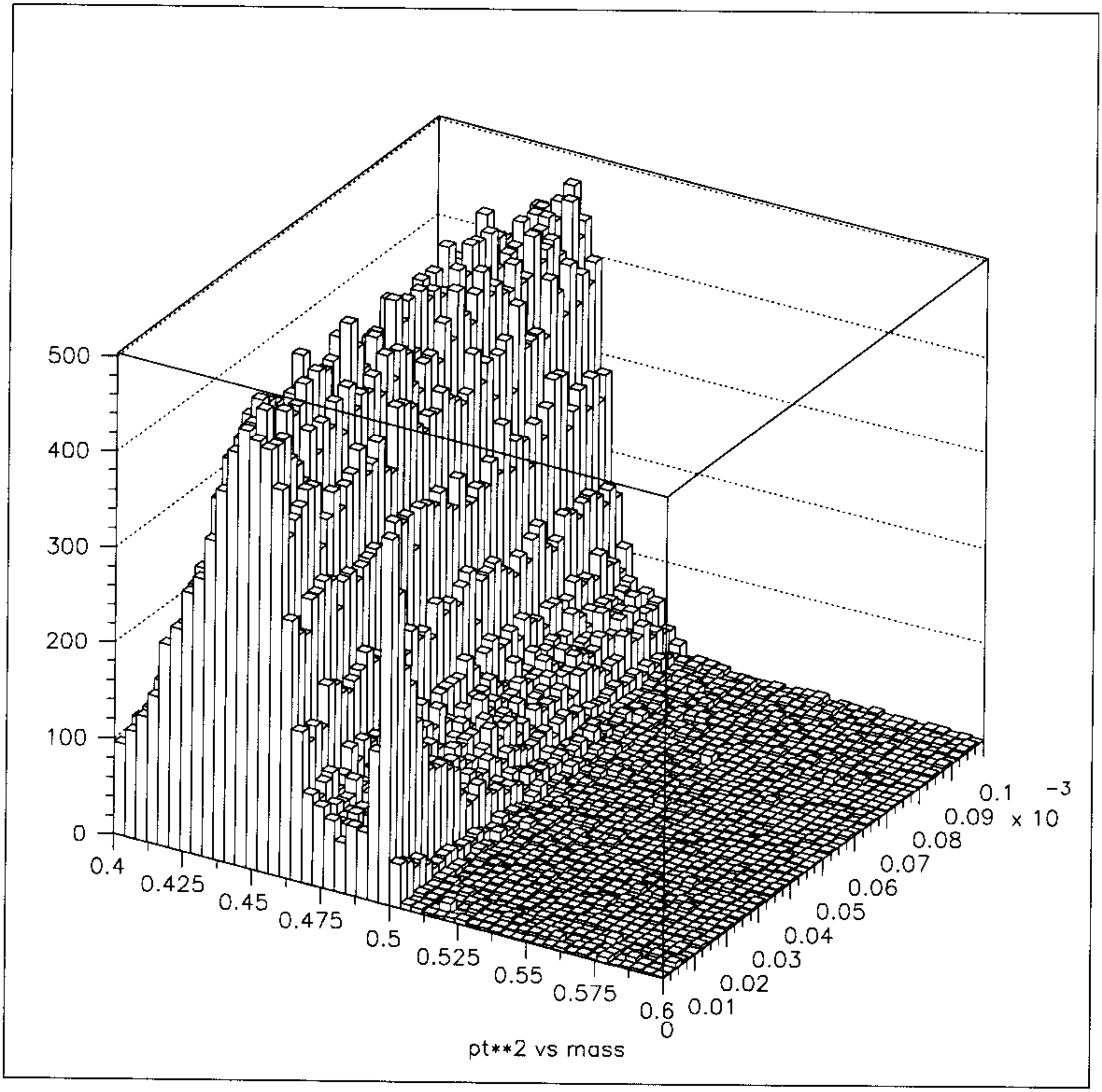
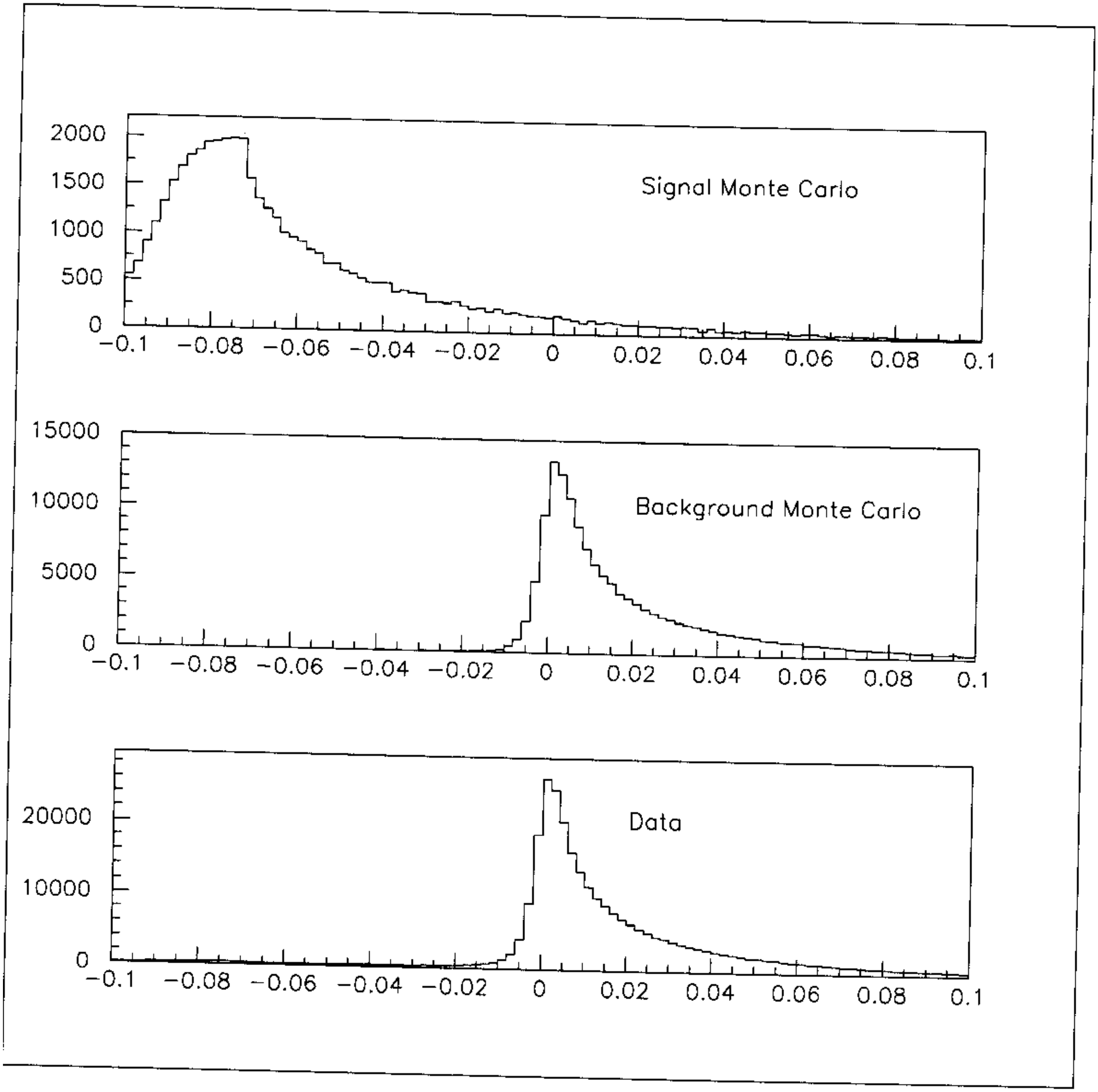


Figure 3: E/p for electrons. Histogram is Monte Carlo events. Dots are DATA. Both distributions are normalized to the same number of entries in the histogram. Top plot is in linear scale, middle plot is in log scale and bottom plot is the ratio Data/MC



500
400
300
200
100
0
0.4
0.425
0.45
0.475
0.5
0.525
0.55
0.575
0.6
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1
x 10^-3
pt**2 vs mass



Signal Monte Carlo
Background Monte Carlo
Data
2000
1500
1000
500
0
15000
10000
5000
20000
−0.1
−0.08
−0.06
−0.04
−0.02
0
0.02
0.04
0.06
0.08
0.1

Other backgrounds include two overlapping $K_L \to \pi^{\pm}e^{\mp}\nu$ (Ke3) decays and hyperon decays. These backgrounds are suppressed by data quality cuts.

A background that is indistinguishable from the signal is $K_L \to \pi^+\pi^-\gamma$ where the γ converts to an e^+e^- pair in the apparatus, mostly in the window of the vacuum decay region. These events have, however, very low e^+e^- mass and are removed with a mass cut of 0.002 GeV. Signal events are lost by this cut as well.

A possible additional problem at low e^+e^- mass is that with small e^+e^- opening angle, the measured ϕ may have poor resolution, which would lower the measured asymmetry. Monte Carlo studies show only small effects above 0.002 GeV, should unfold this eventually, not done yet.

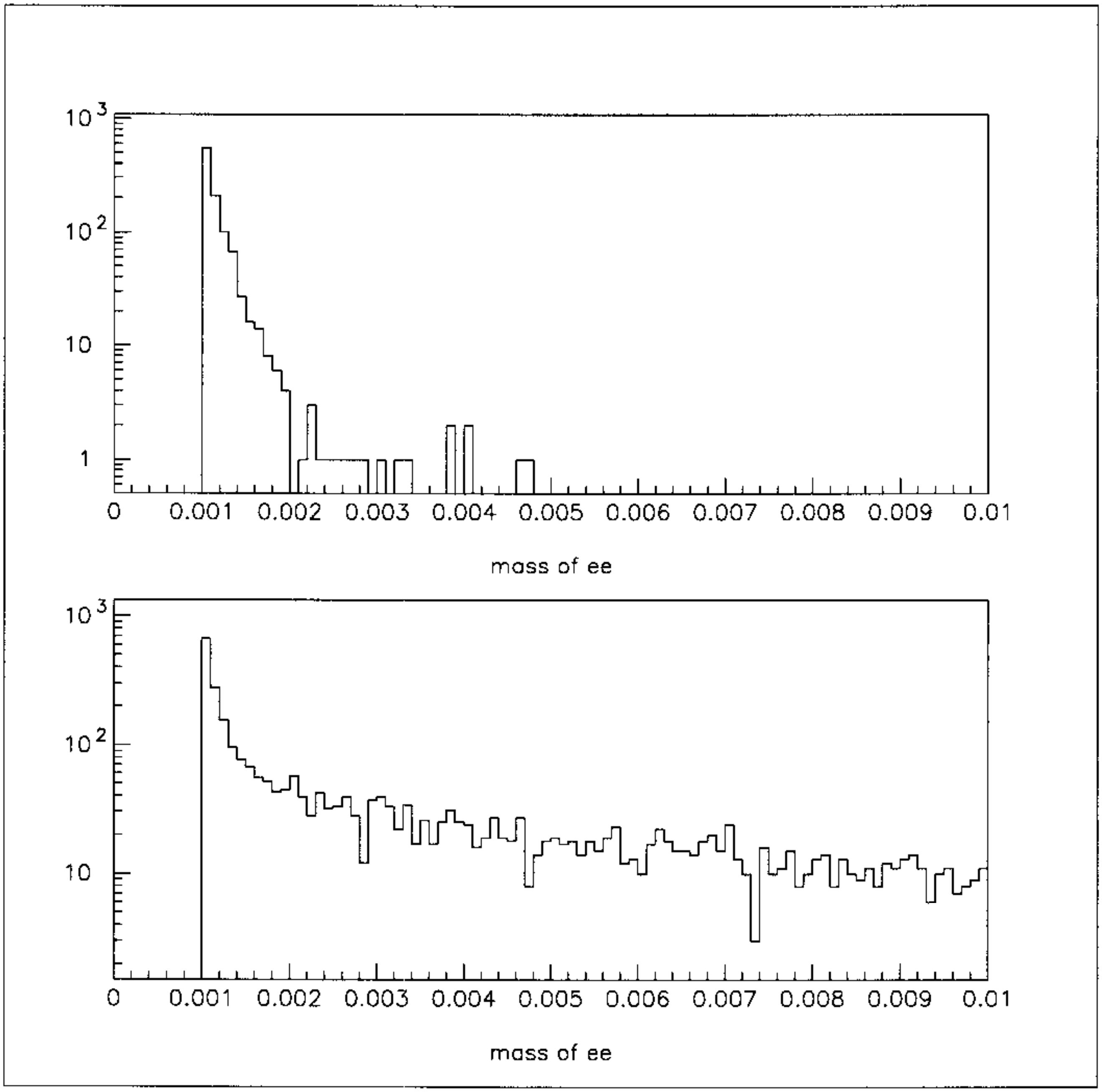


Figure 5: The low mass region of the e^+e^- mass distribution. The upper plot is from a Monte Carlo of the process $K_L^0 \to \pi^+\pi^-\gamma$ where the γ converts to an e^+e^- pair in the apparatus. The lower plot is for the $K_L \to \pi^+\pi^-e^+e^-$ data events.

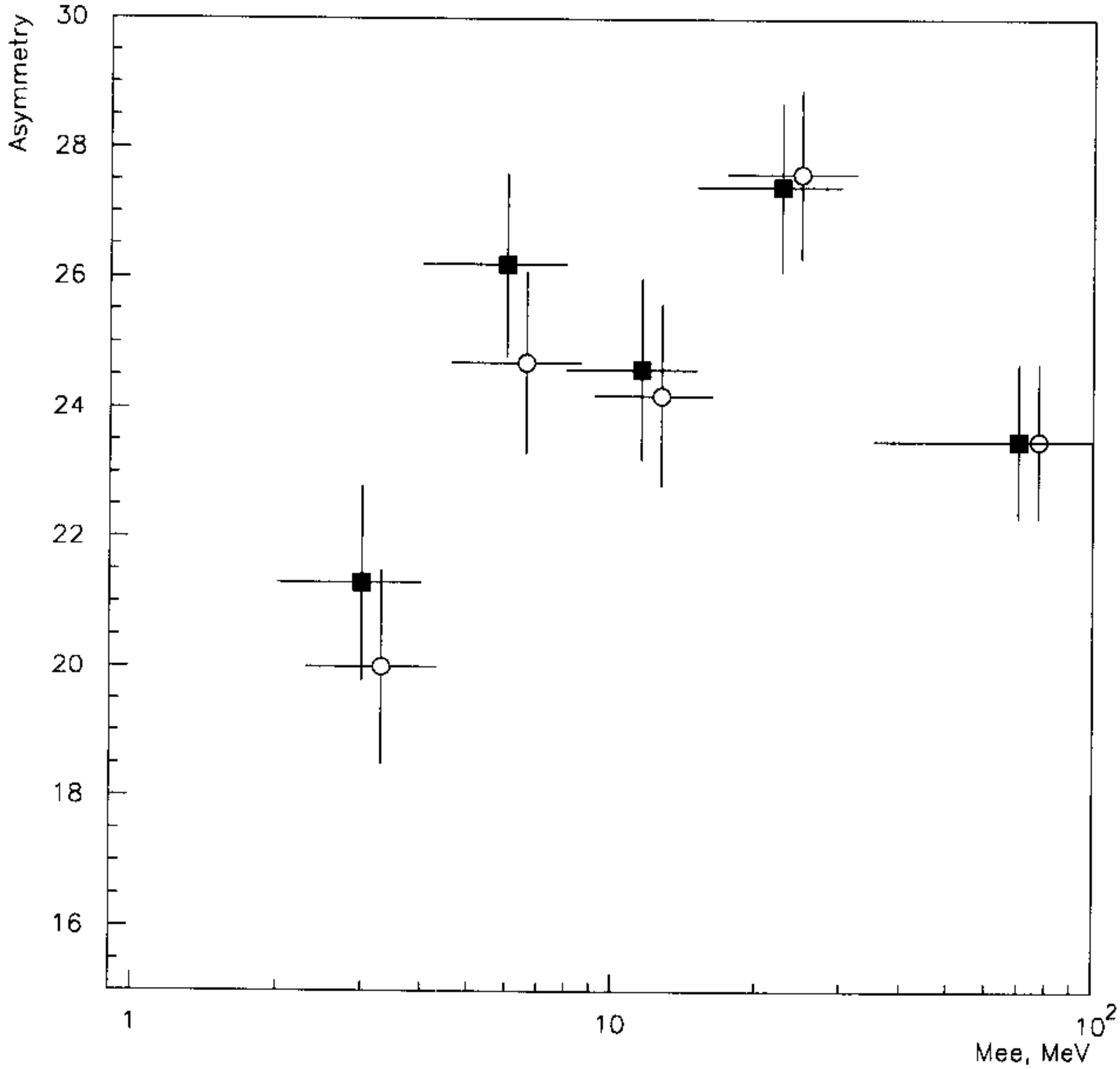


Figure 6: *True* (filled) and *reconstructed* (opened) "raw" asymmetry as a function of M_{ee} *True* value is calculated with generated Monte Carlo 4-vectors. *Reconstructed* value is calculated with track parametes as found by KTEVANA.

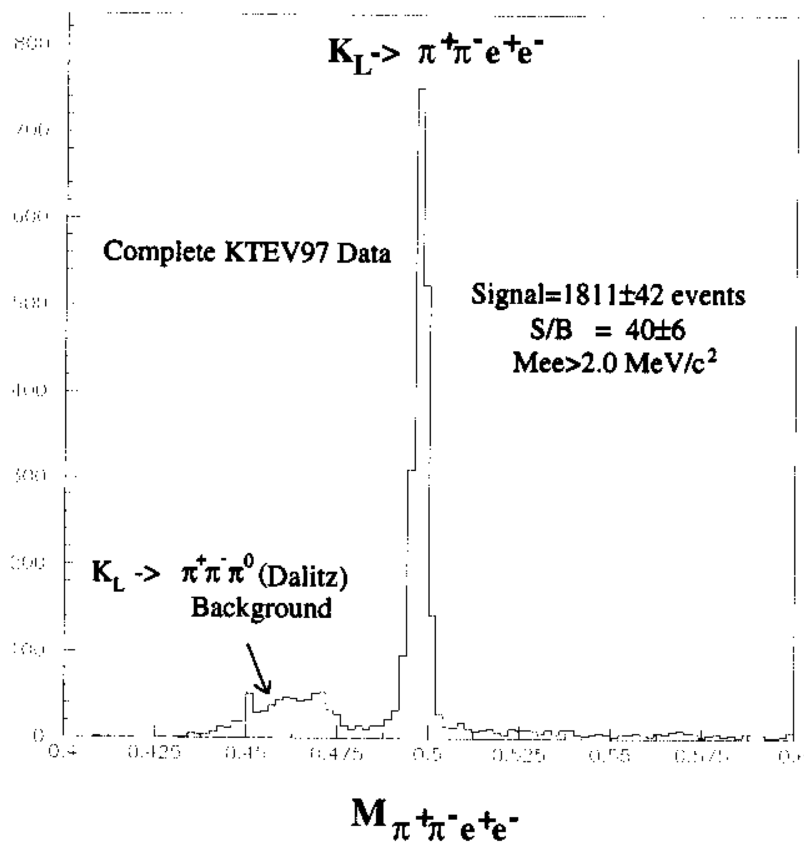


Figure 7: Mass spectrum of four track events with an identified $\pi^+\pi^-e^+e^-$ topology

$K_L \to \pi^+\pi^-e^+e^-$ Branching Fraction:

We have published (Phys Rev Lett **80**,4123 (1998)) based on 2% of the total data sample a branching fraction of:

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

Based on 60% of the data we quoted at the Vancouver conference:

$$(3.32 \pm 0.14(stat) \pm 0.28(syst)) \times 10^{-7}$$

$K_L \to \pi^+\pi^-e^+e^-$ Monte Carlo

Based on matrix element from Sehgal and Wanninger.

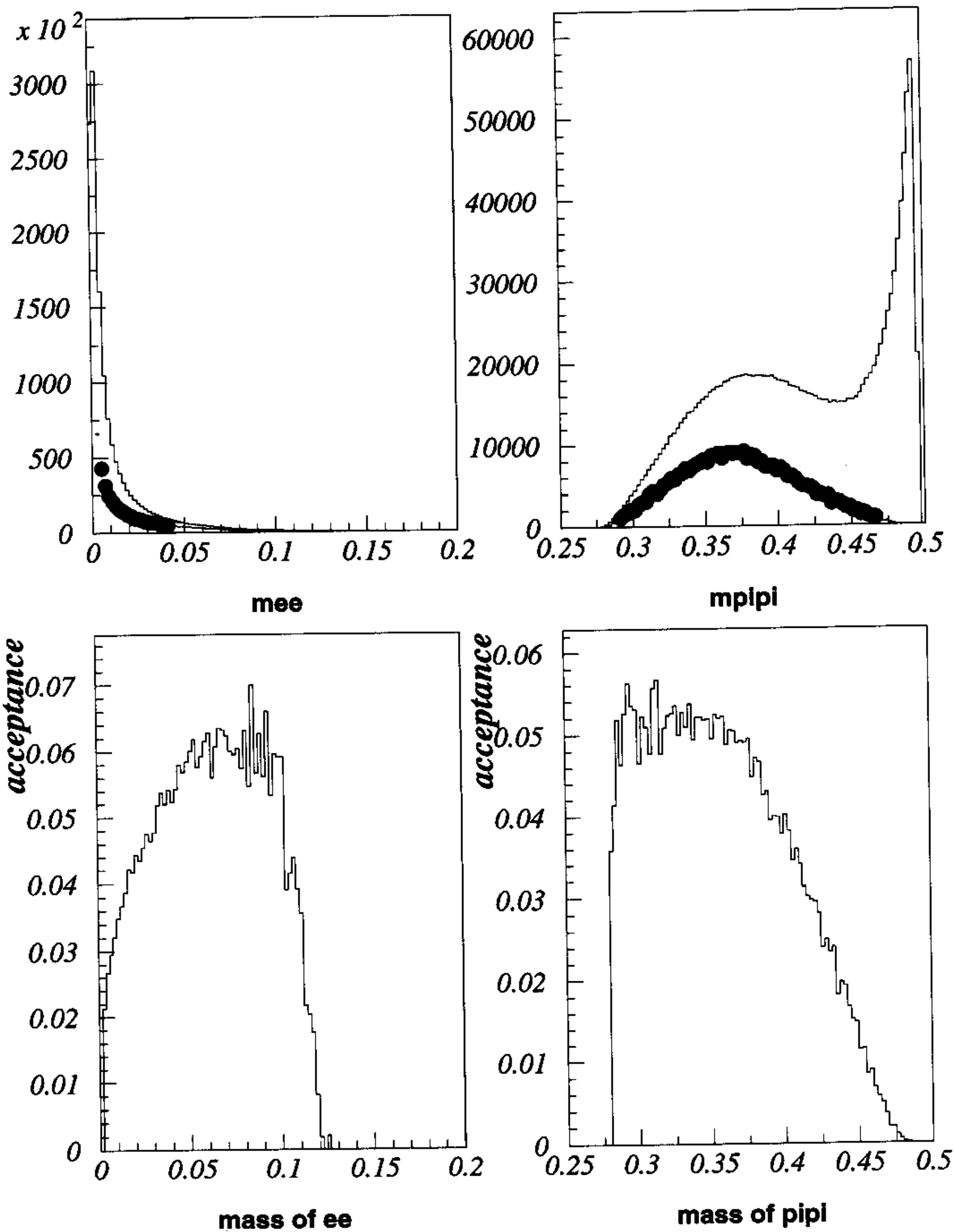
A function of 5 kinematic variables, m_{ee}, $m_{\pi\pi}$, $cos\theta_e$, $cos\theta_\pi$ and ϕ.

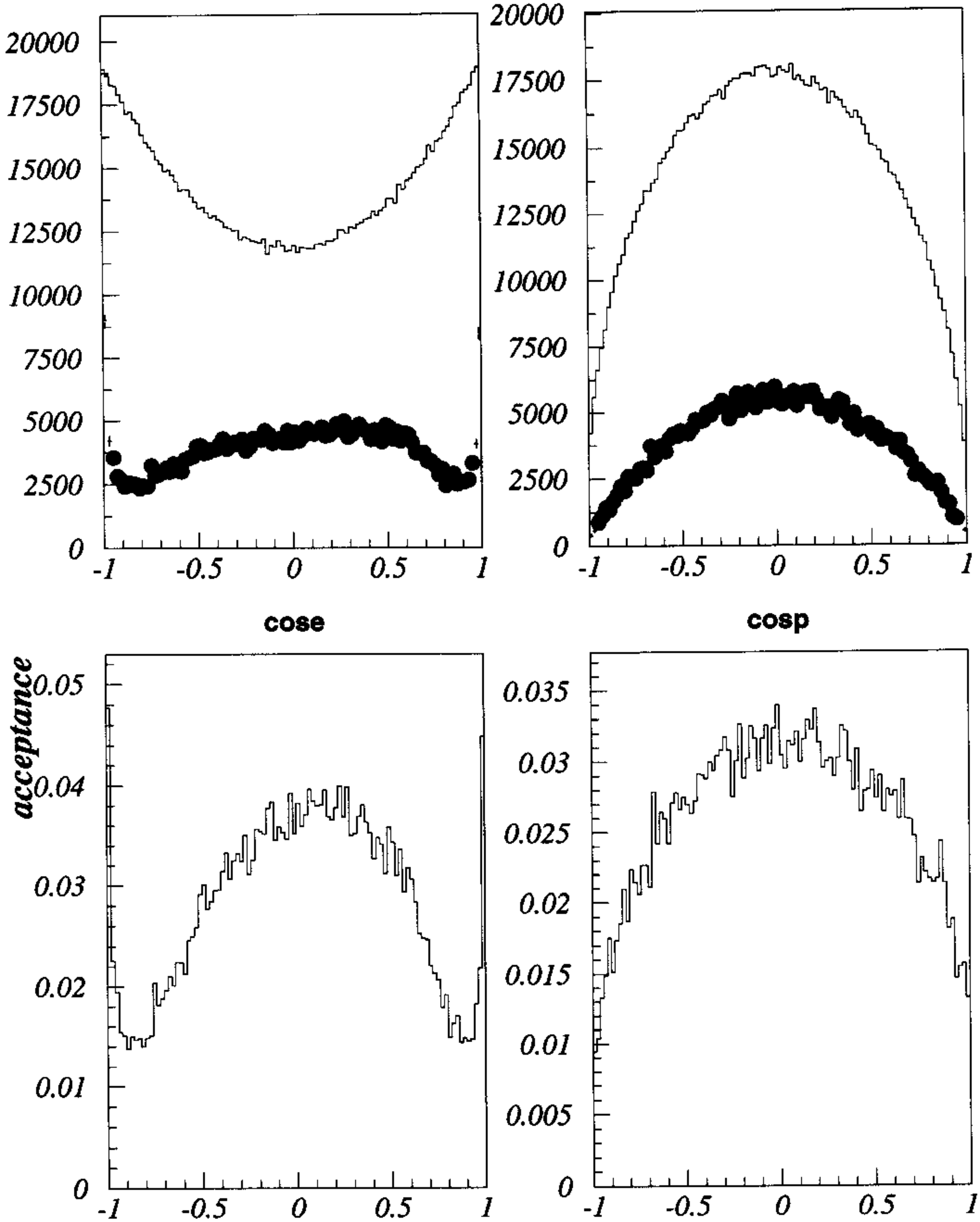
There is a major drop in acceptance at high $m_{\pi\pi}$

Good agreement between data and Monte Carlo in most variables, but $m_{\pi\pi}$ data is shifted to higher masses. To account for this we modify matrix element with a form factor taken from earlier result on $K_L \to \pi^+\pi^-\gamma$:

$$F = a_1[(M_\rho^2 - M_K^2) + 2M_K(E_{e^+} + E_{e^-})]^{-1} + a_2$$

We take $a_1/a_2 = -1.8 \pm 0.2$ from the E731 result, but will eventually fit this from the data.


x 10 2
3000
2500
2000
1500
1000
500
0
0
0.05
0.1
0.15
0.2
mee
60000
50000
40000
30000
20000
10000
0
0.25
0.3
0.35
0.4
0.45
0.5
mpipi
acceptance
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
0.05
0.1
0.15
0.2
mass of ee
acceptance
0.06
0.05
0.04
0.03
0.02
0.01
0
0.25
0.3
0.35
0.4
0.45
0.5
mass of pipi


20000
17500
15000
12500
10000
7500
5000
2500
0
-1
-0.5
0
0.5
1
cose
cosp
acceptance
0.05
0.04
0.03
0.02
0.01
0.035
0.025
0.015
0.005

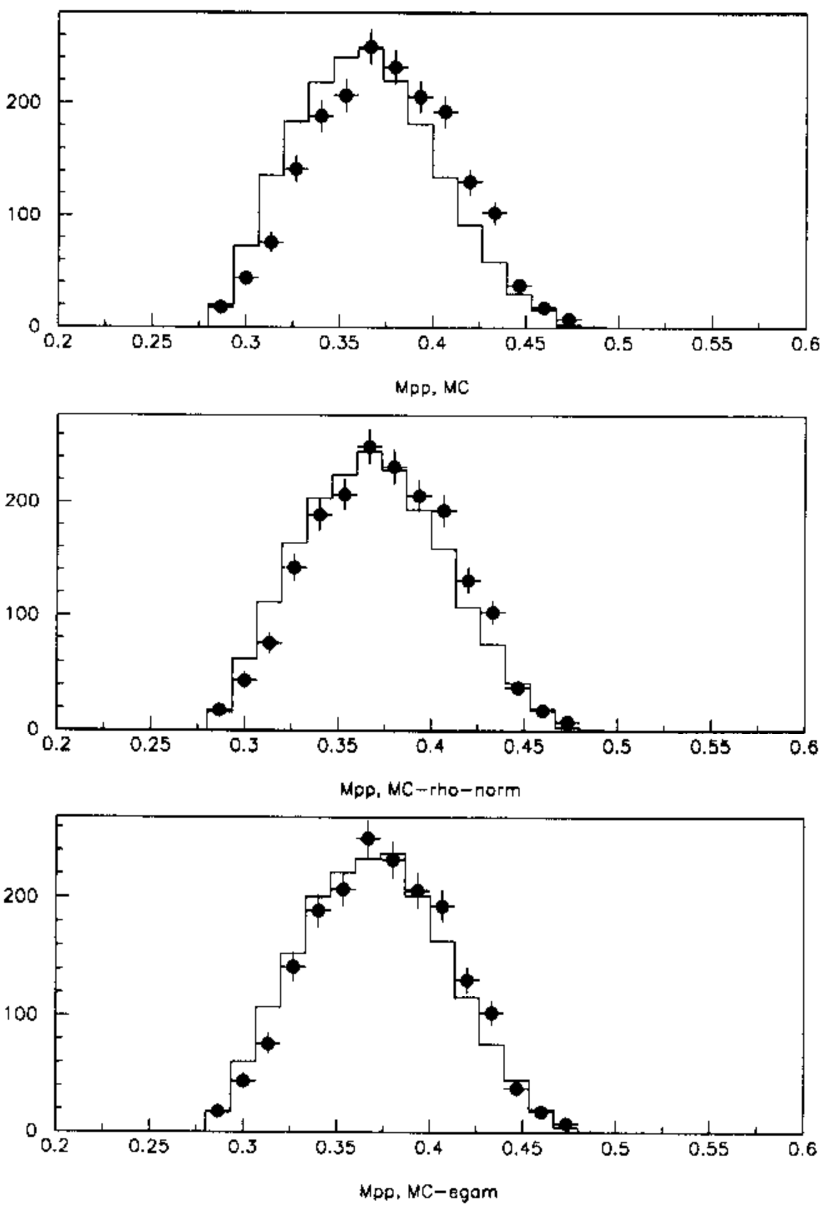


Figure 8: Comparison of data and Monte Carlo $M_{\pi\pi}$ mass spectrum with no g_{M1} form factor, with a form factor suggested by Seghal and Wanninger and with a form factor derived from Ramberg *et al.*

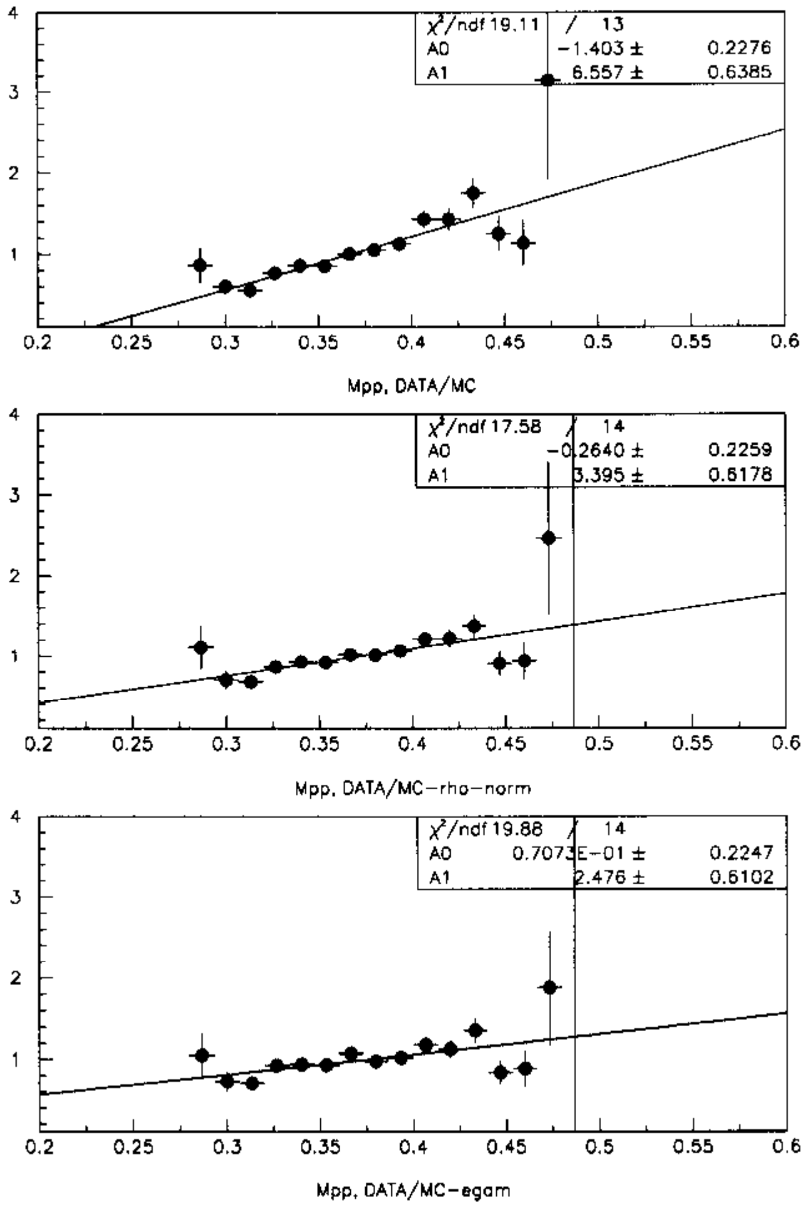


Figure 10: Ratio of data to Monte Carlo for $M_{\pi\pi}$ for the three cases described in Fig. 8

Acceptance effects on ϕ and asymmetry.

Acceptance is not flat in ϕ.

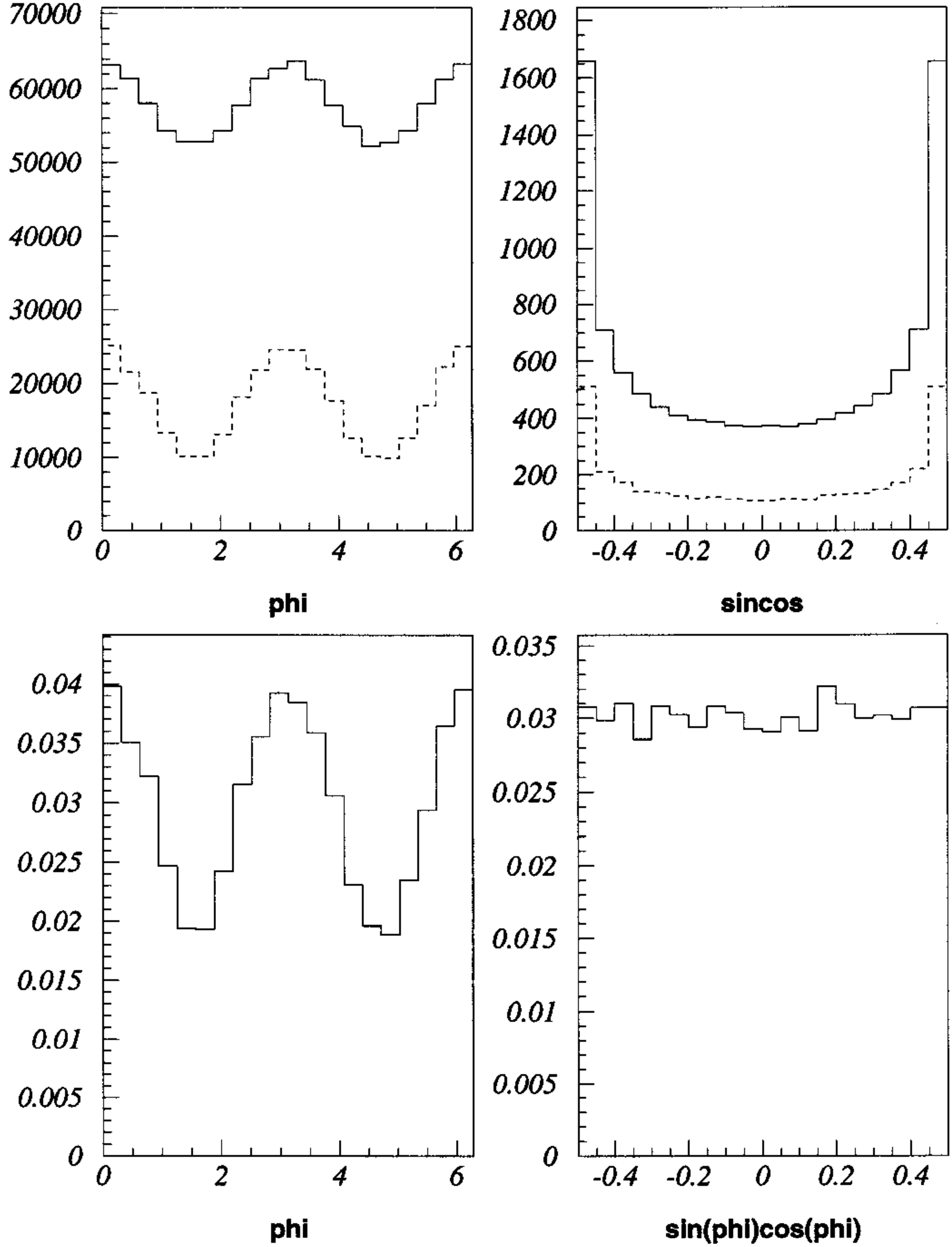
If initial asymmetry is zero, accepted asymmetry is also zero.

If initial asymmetry is non-zero, accepted asymmetry is different (and larger) than initial asymmetry. Due to correlations with other kinematic variables.

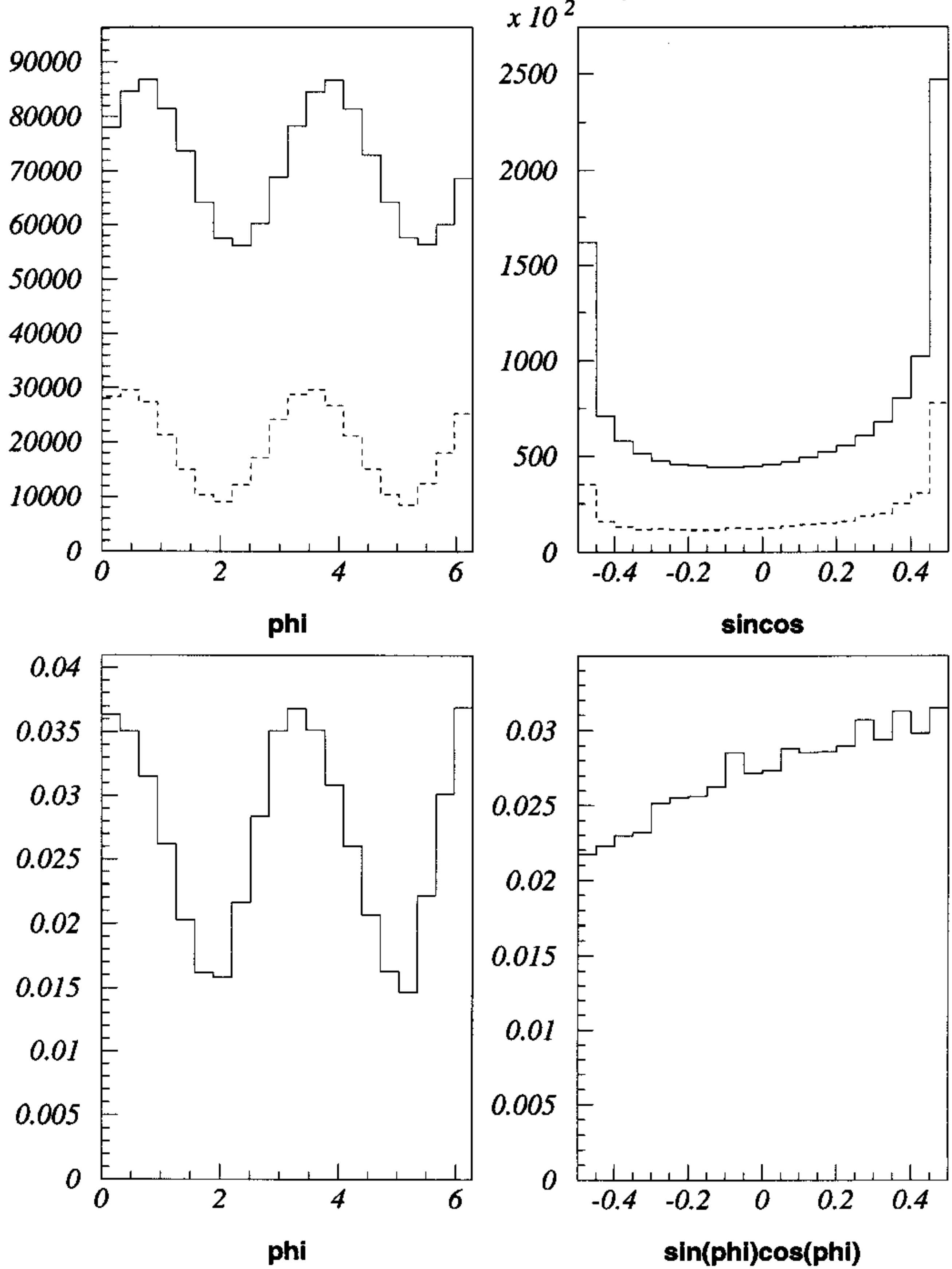
Must use a Monte Carlo whose accepted distributions agree with data to correct the asymmetry.

Further check is $K_L \to \pi^+\pi^-\pi^0_D$ data, when analysed like $\pi^+\pi^-e^+e^-$ should have zero asymmetry.

Monte Carlo with zero asymmetry



Monte Carlo with asymmetry



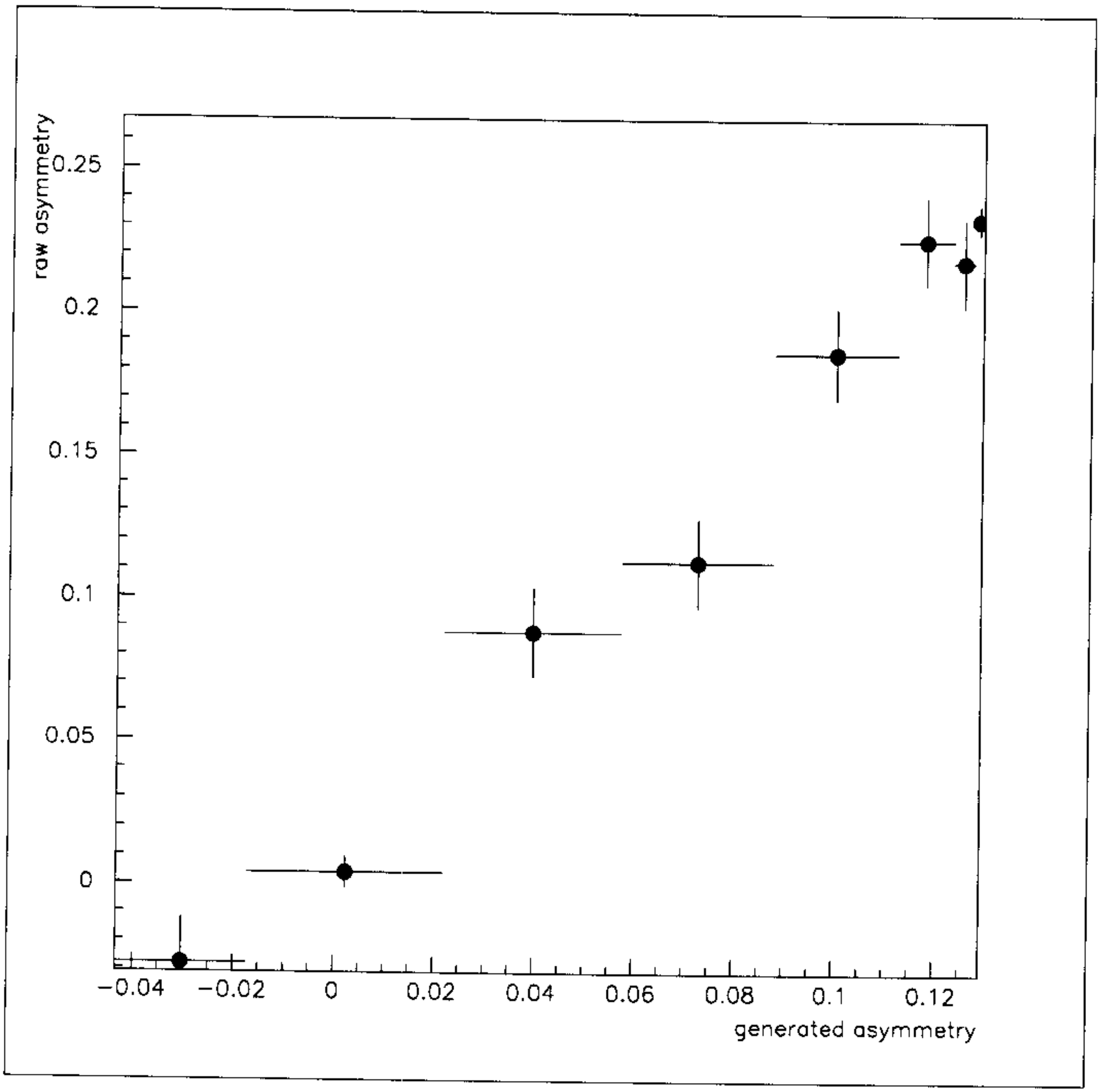
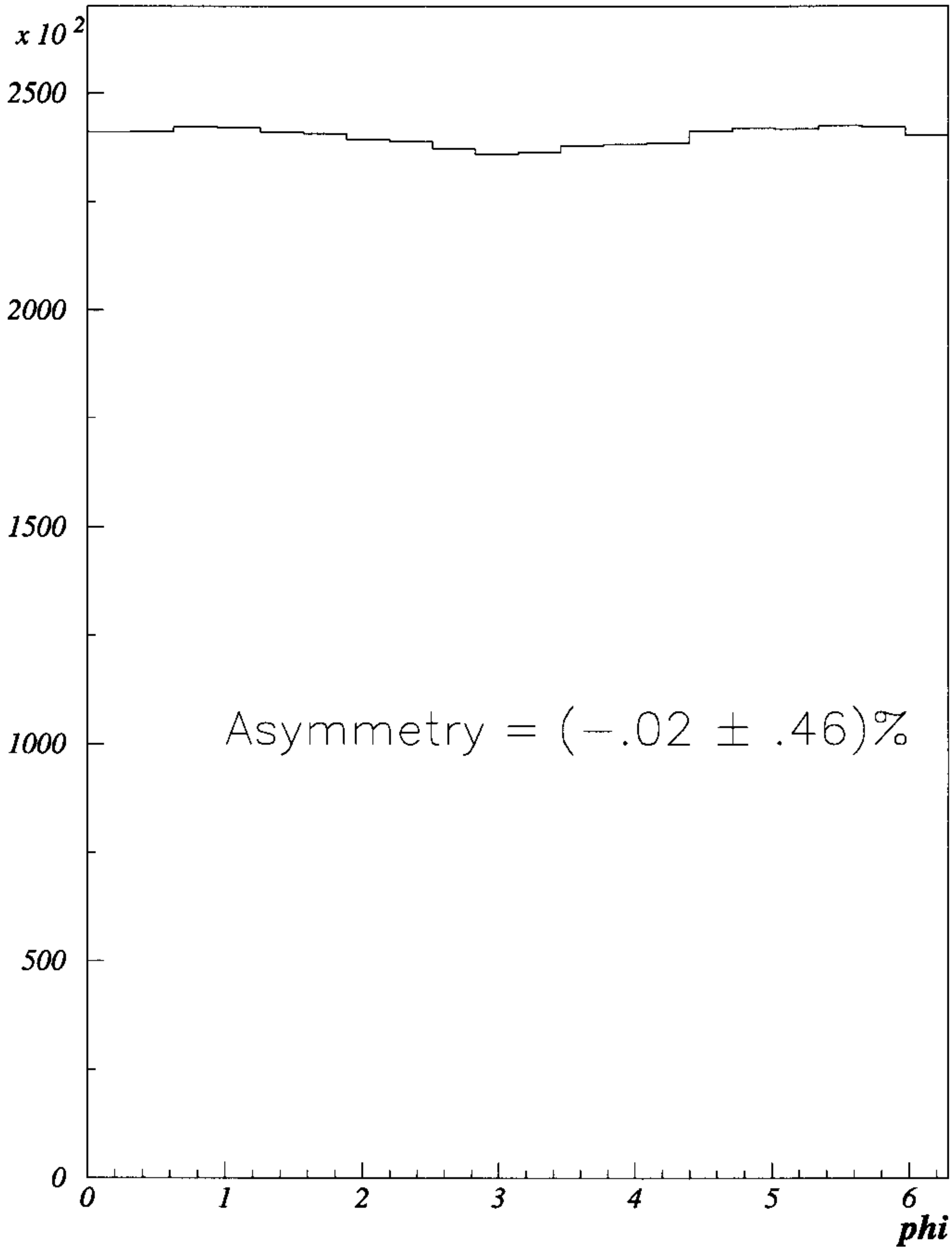


Figure 9: Reconstructed asymmetry versus generated asymmetry for Monte Carlo data samples. Note that the horizontal error bars are incorrect, the actual errors on the generated asymmetry are 0.002 or less.

Dalitz data



From either the ϕ or $sin\phi cos\phi$ distributions, after background subtraction we get asymmetry before acceptance correction of $(23.3 \pm 2.3(stat))\%$. This is from a signal of 1811 ± 42 events over a background of 45 ± 7 events.

Altough we subtract background, it is interesting to look at asymmetry versus $\pi^+\pi^-e^+e^-$ mass.

Systematic errors (Work still in progress)

- Resolution effects: $\pm 0.5\%$.
- Backgrounds and cut variations: $\pm 2.0\%$
- Variations in Monte Carlo parameters: $\pm 1.3\%$

Total systematics: $\pm 3\%$

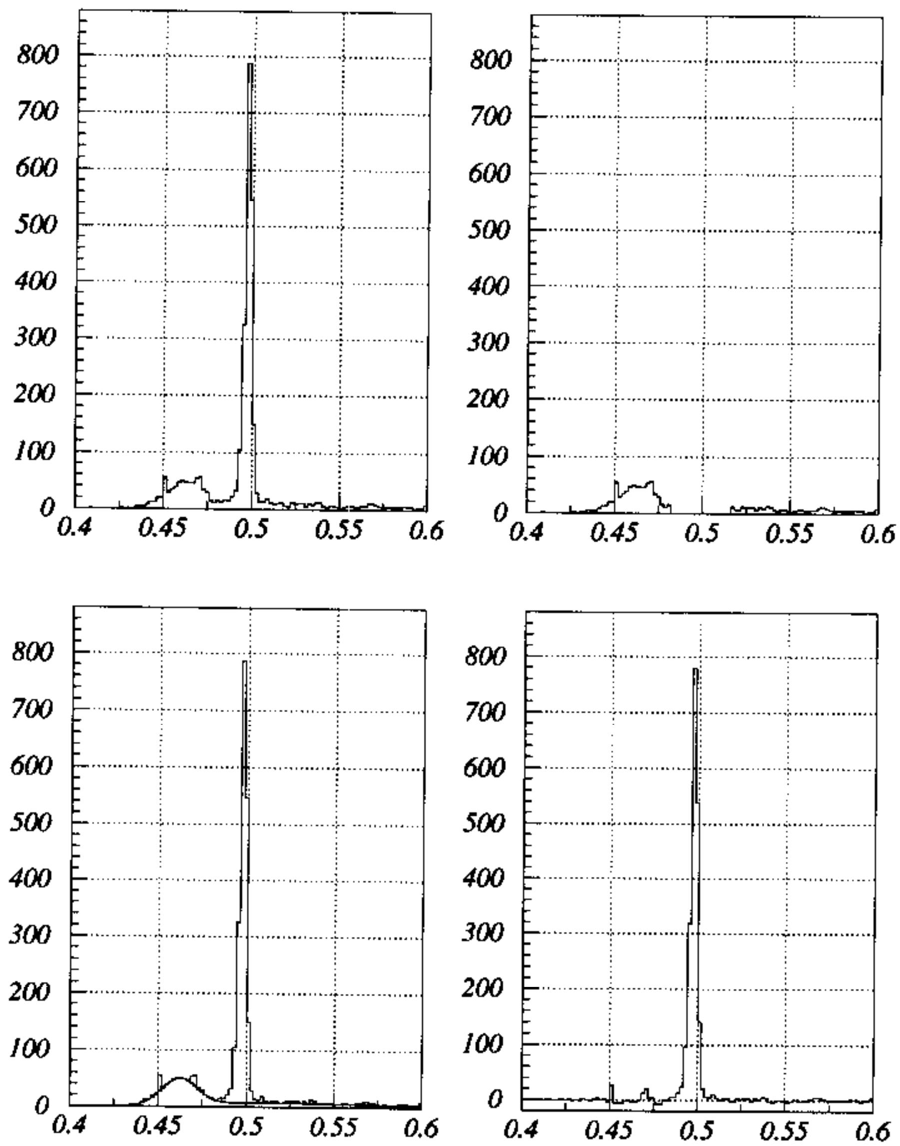
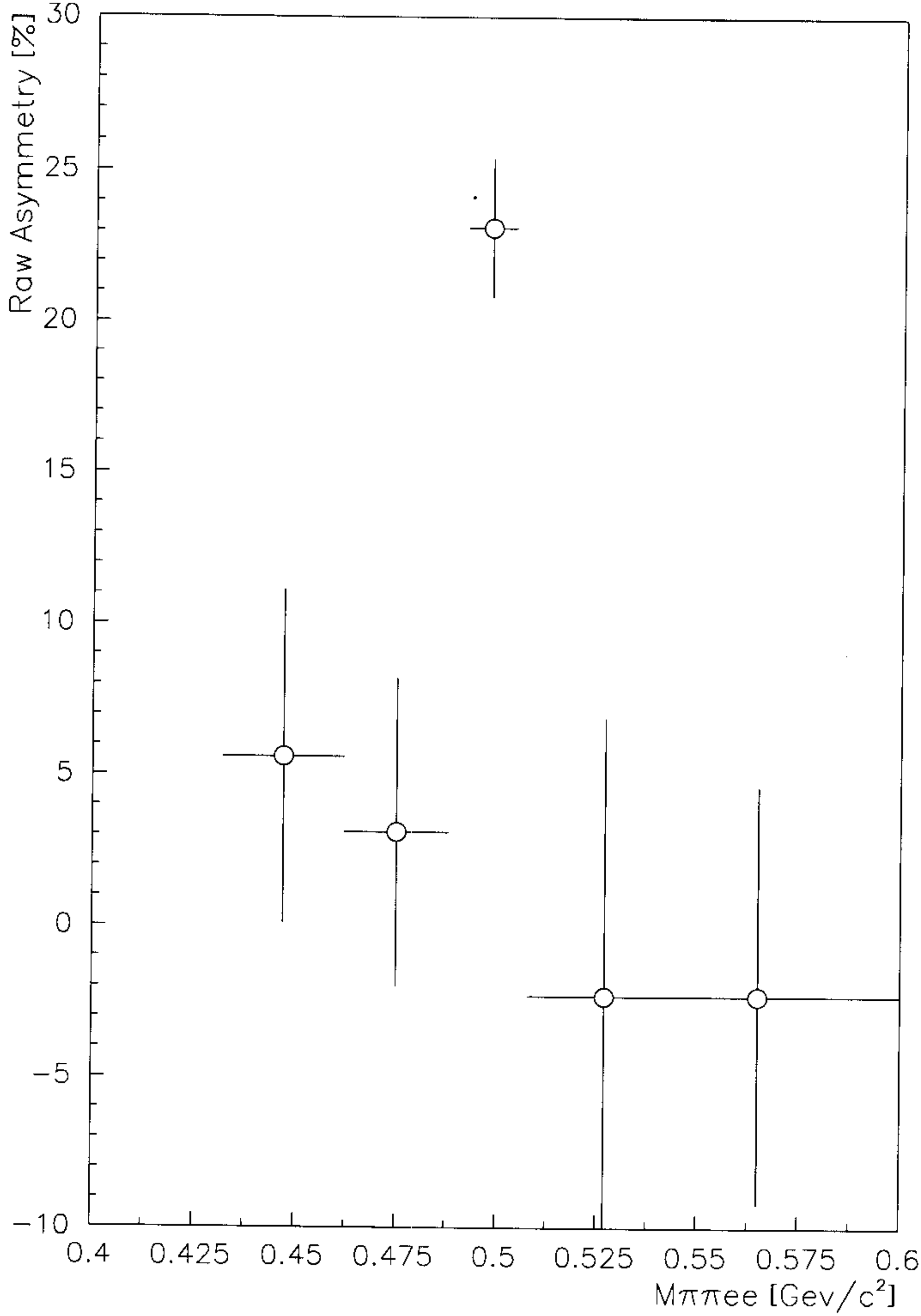


Figure 12: (a) Original $M_{\pi\pi ee}$, (b) $M_{\pi\pi ee}$ to use in the fit, (c) Original $M_{\pi\pi ee}$ (empty) with fit result superimposed (gray) (d) "Signal" $M_{\pi\pi ee}$ obtain from subtracting the fit result from the original histogram



Raw Asymmetry [%]
30
25
20
15
10
5
0
−5
−10
0.4
0.425
0.45
0.475
0.5
0.525
0.55
0.575
0.6
Mππee [Gev/c²]

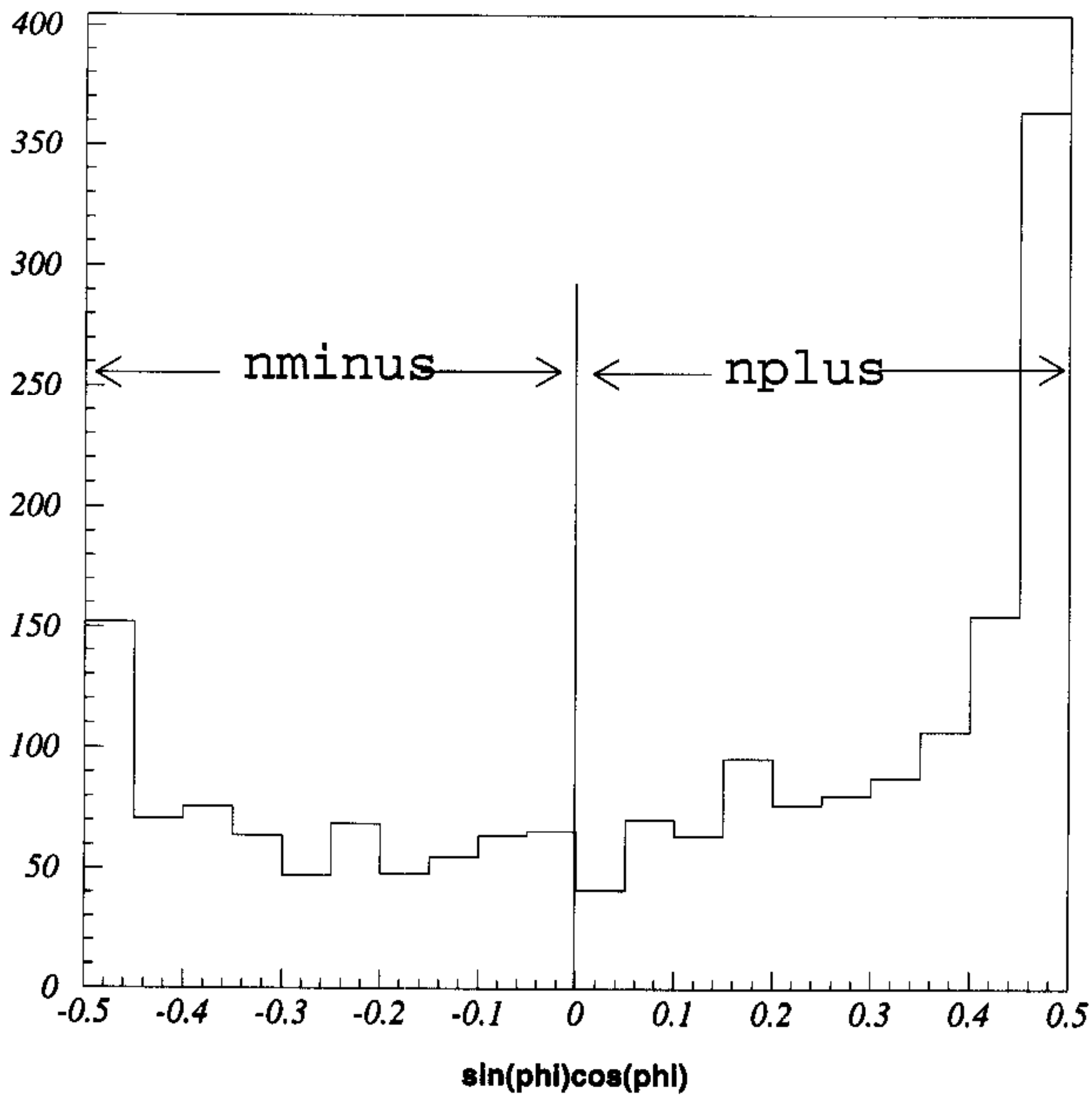


Figure 14: $sin\phi cos\phi$ distribution for the total data sample, where nplus and nminus are also shown

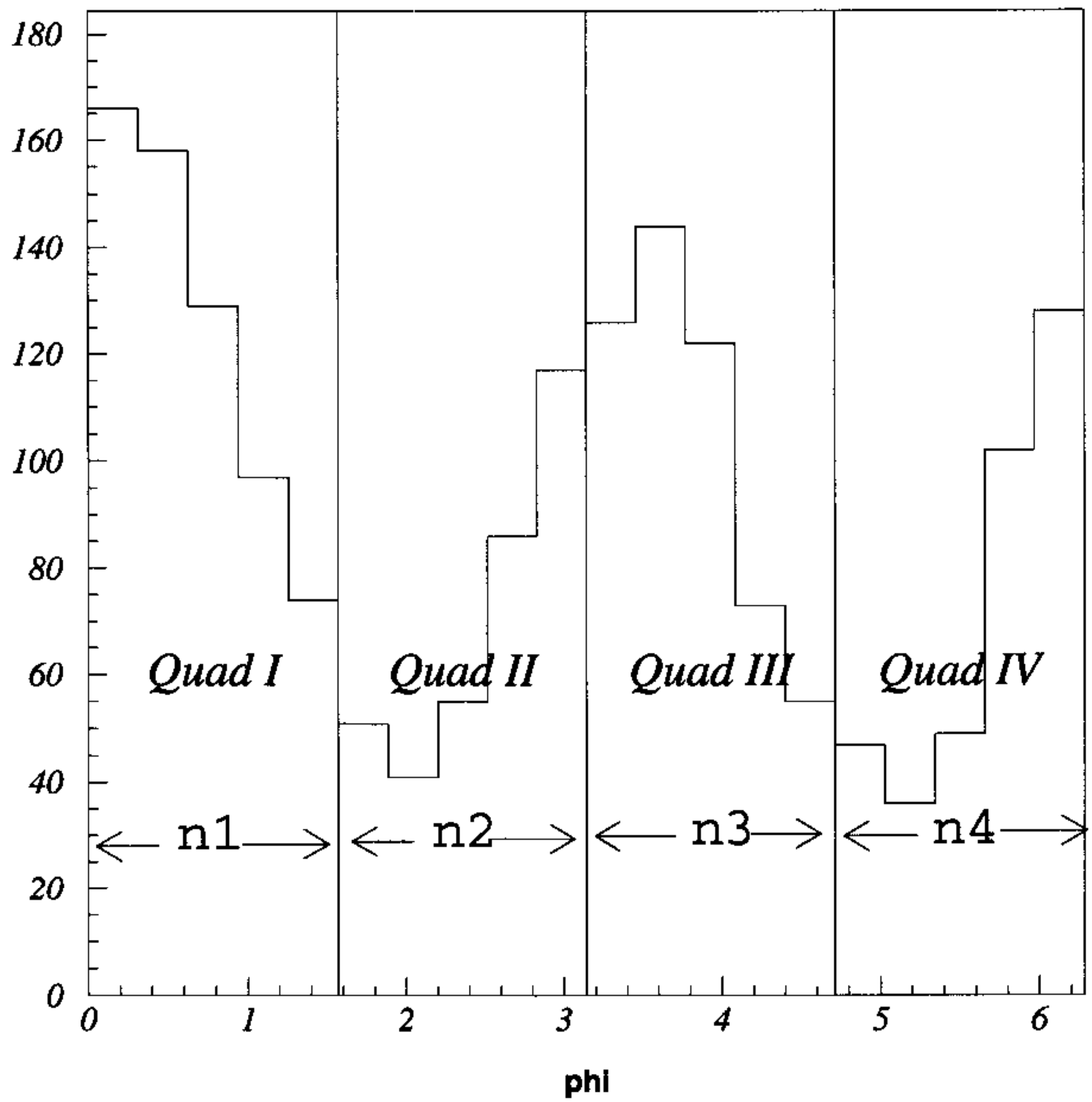


Figure 15: *sinφcosφ* distribution for the total data sample, where the Quadrants, n1, n2, n3 and n4 are also shown

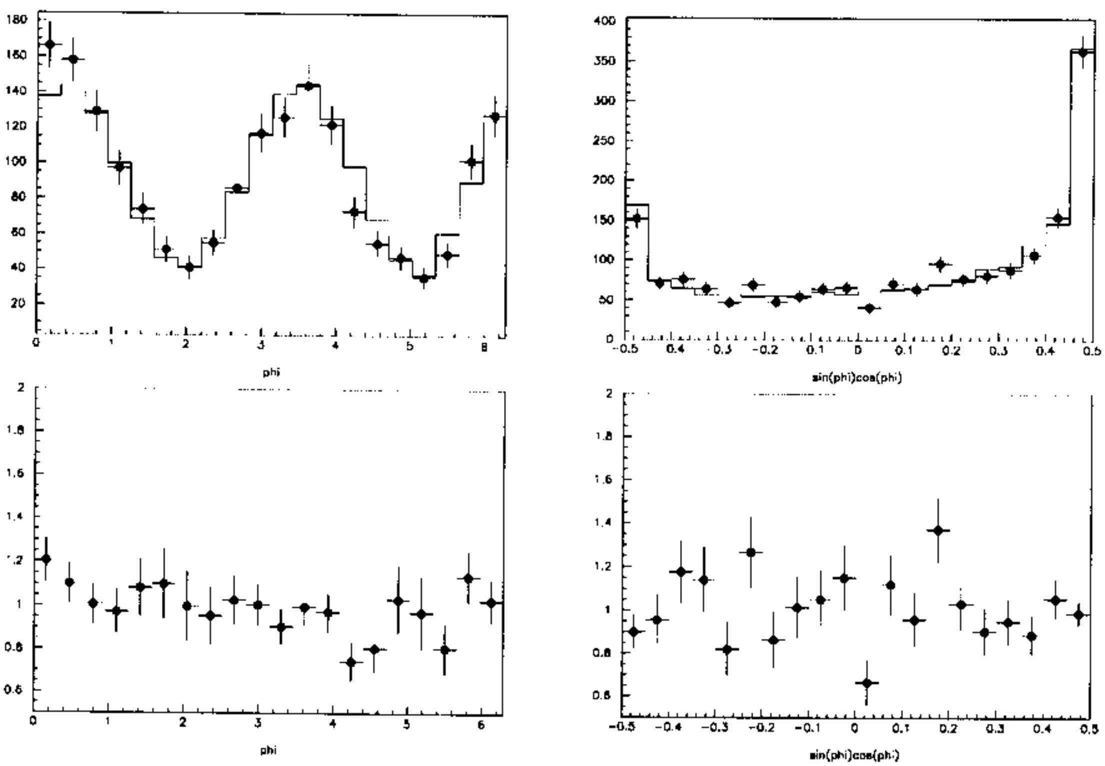
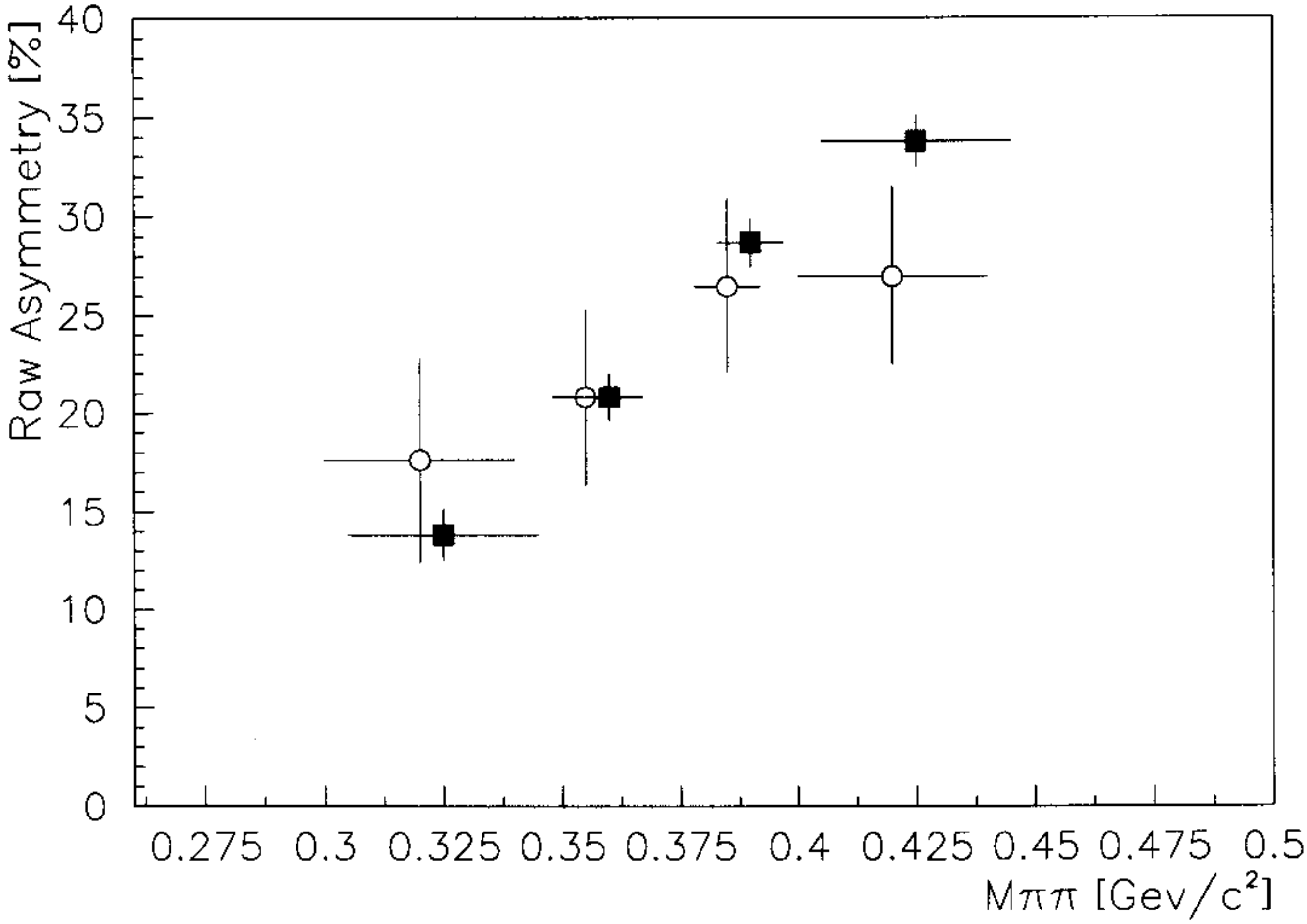
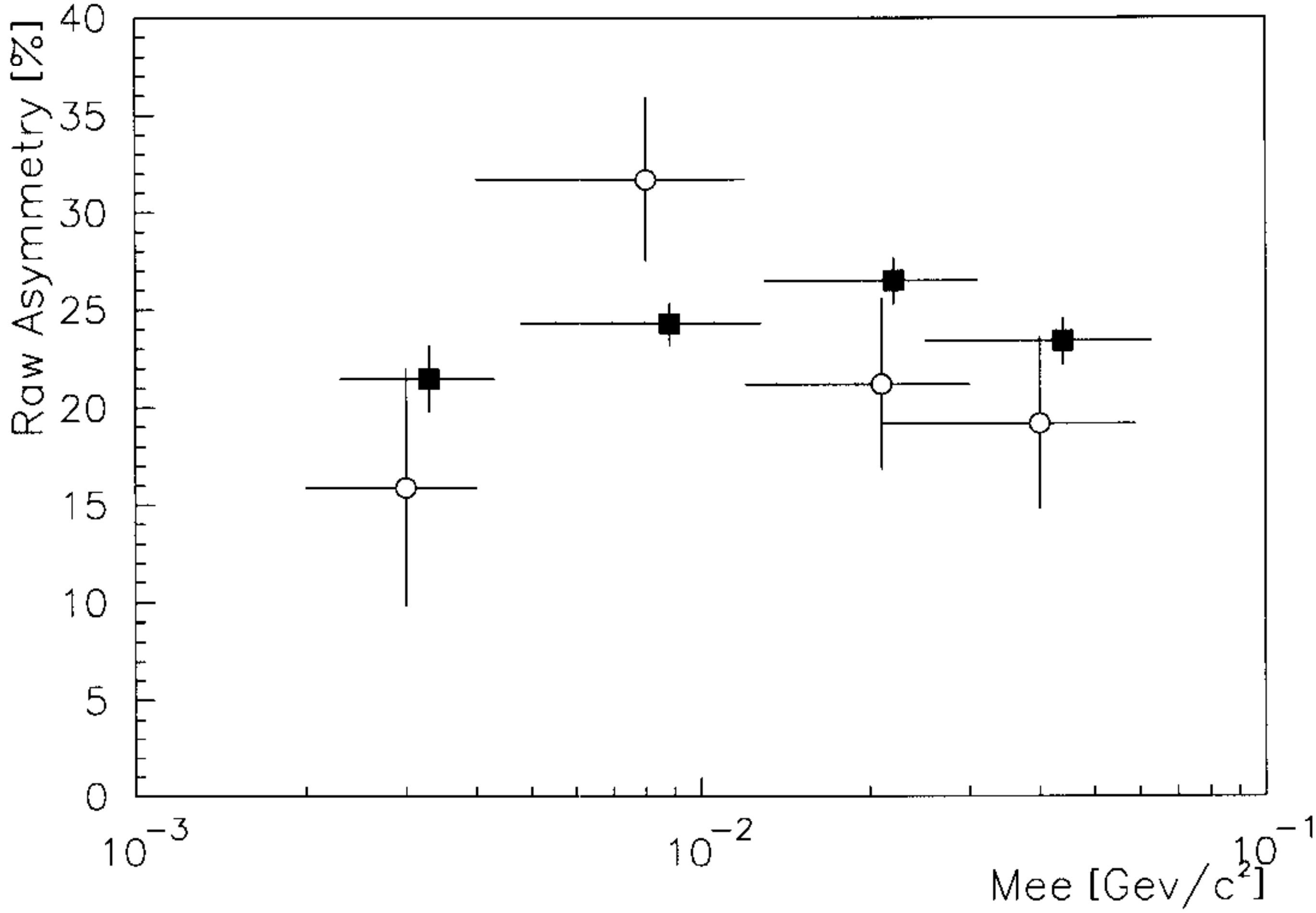
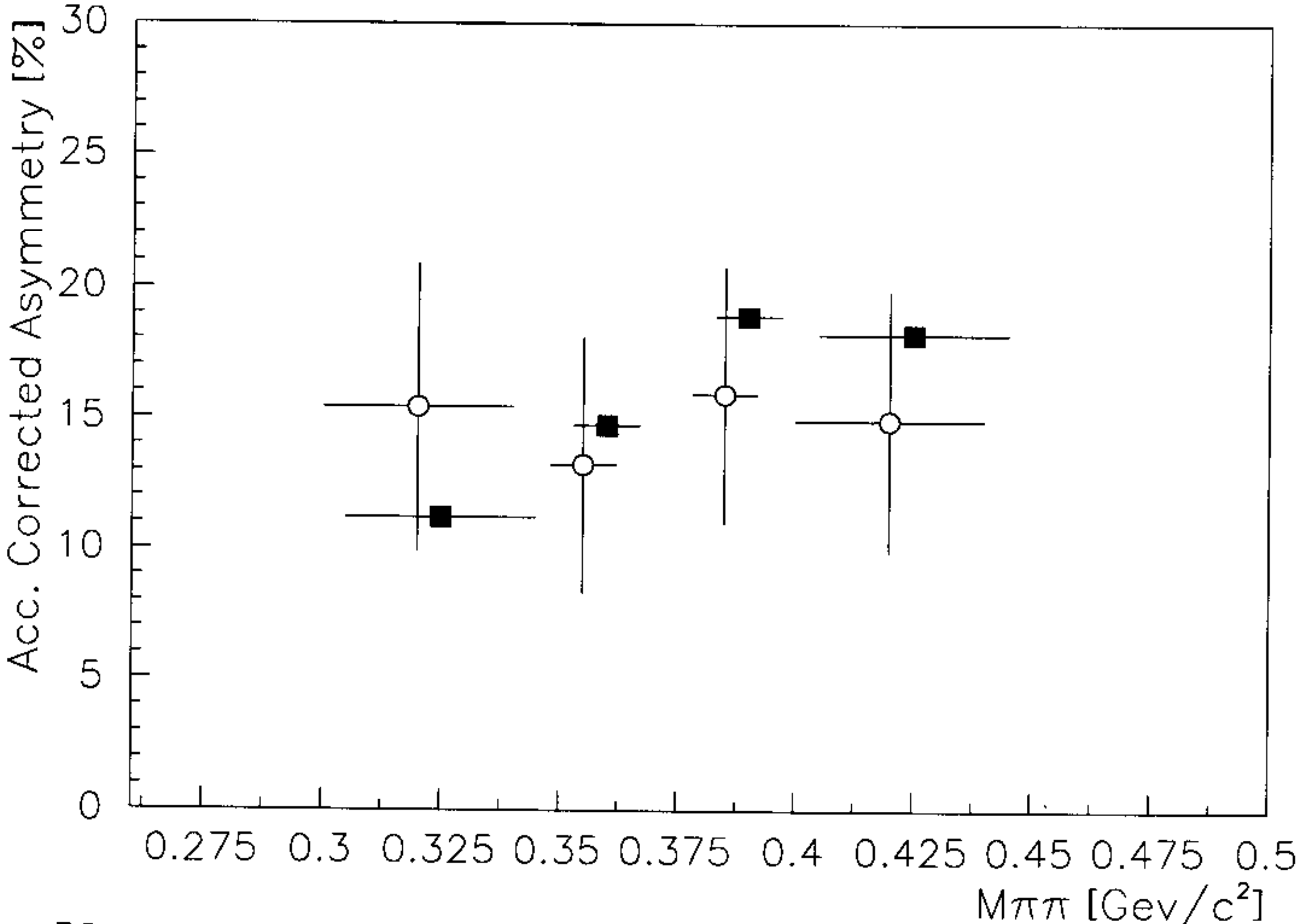


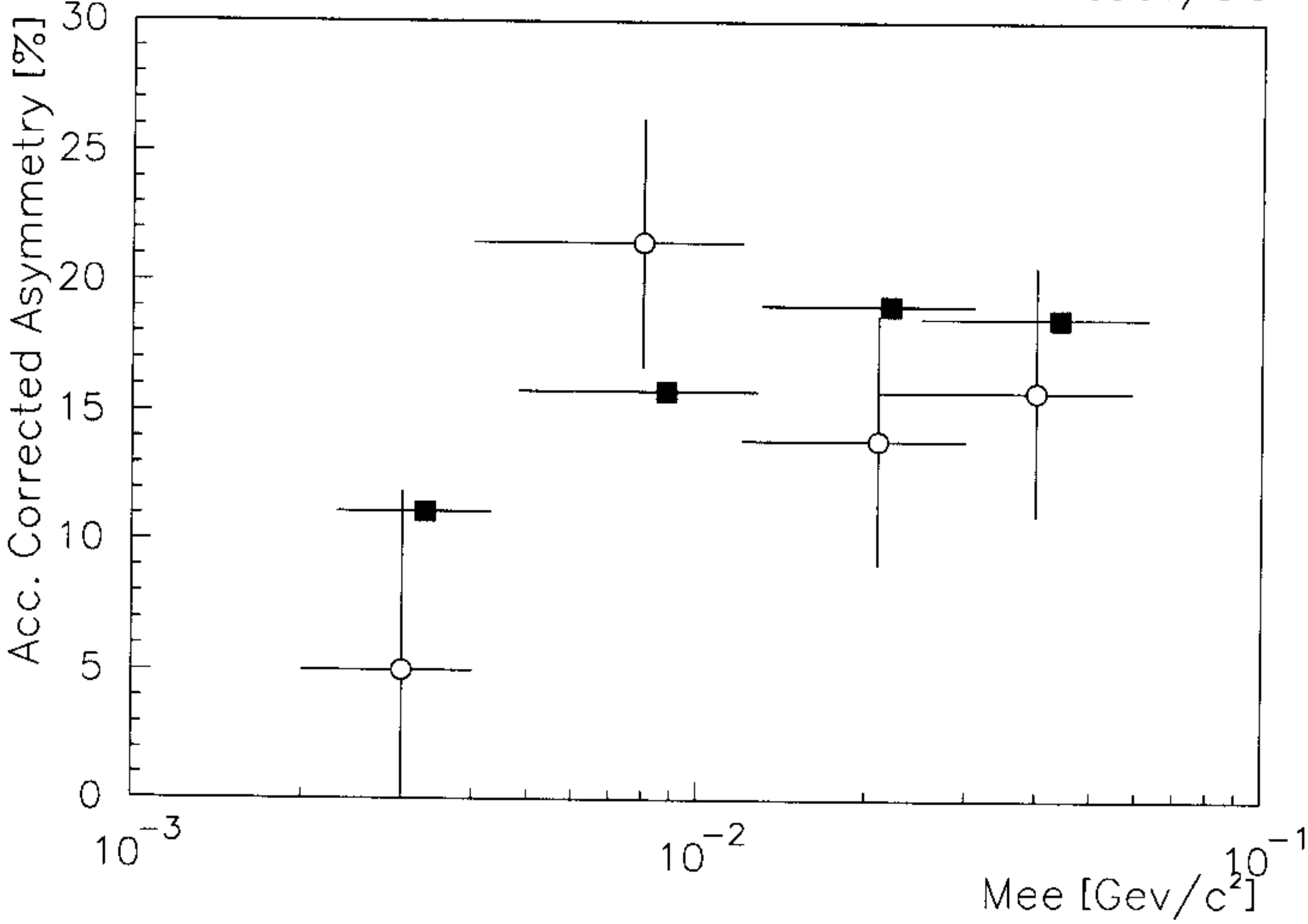
Figure 16: "Raw" ϕ and $sin\phi cos\phi$ data distributions (dots) compared to the Monte Carlo (histogram); the ratio of data/MC


Raw Asymmetry [%]
0
5
10
15
20
25
30
35
40
0.275
0.3
0.325
0.35
0.375
0.4
0.425
0.45
0.475
0.5
Mππ [Gev/c²]


Raw Asymmetry [%]
0
5
10
15
20
25
30
35
40
10⁻³
10⁻²
10⁻¹
Mee [Gev/c²]



Acc. Corrected Asymmetry [%]
0
5
10
15
20
25
30
0.275
0.3
0.325
0.35
0.375
0.4
0.425
0.45
0.475
0.5
Mππ [Gev/c²]



Acc. Corrected Asymmetry [%]
0
5
10
15
20
25
30
10⁻³
10⁻²
10⁻¹
Mee [Gev/c²]

Conclusions:

We have observed a T violating asymmetry in the decay $K_L \to \pi^+\pi^-e^+e^-$. Our preliminary value is:

$$(13.5 \pm 2.5(stat) \pm 3.0(syst))\%$$

Agreement with theoretical expectations is good.

Future: Further analysis should reduce systematics. A new run is scheduled for spring 1999 that should triple the data sample.

Finally what about Direct CP violation? Direct CP violating effects are predicted as asymmetries in $cos\theta_e$ and $cos\theta_\pi$. Standard expectations are only for very small effects.