CP Violation Measurements using $K_L \to \pi^+\pi^-e^+e^-$ events

observed by the

KTeV(E799II) Experiment at Fermilab

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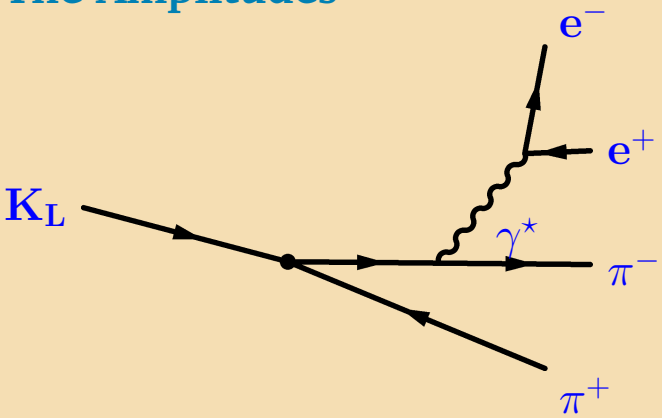
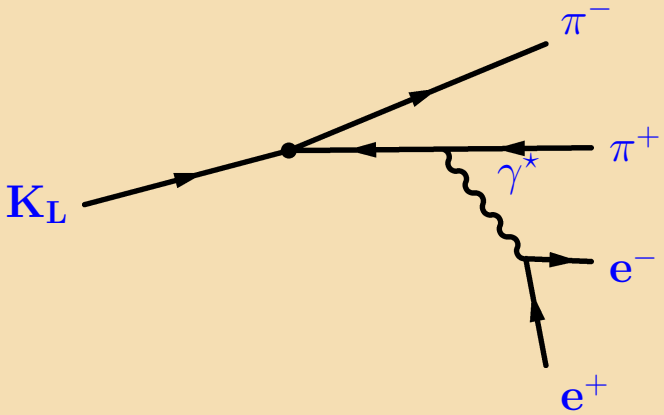
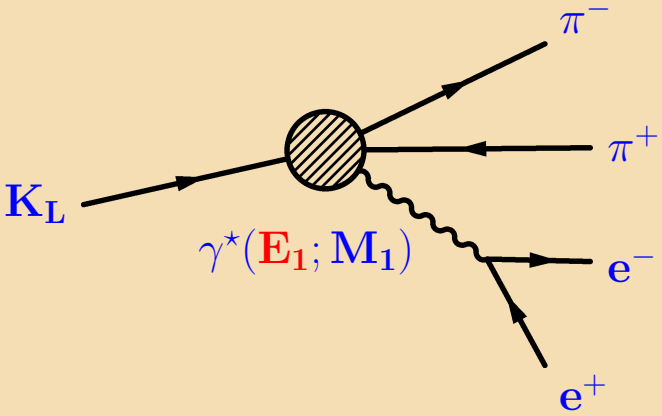
1. Introduction to the Decay $K_L \to \pi^+\pi^-e^+e^-$

1.1. The Amplitudes

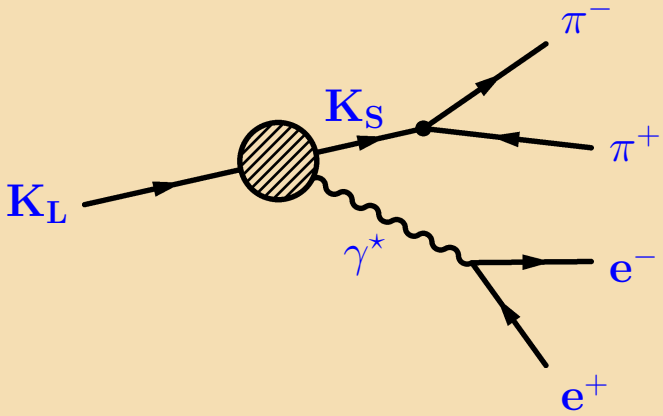




Inner Bremsstrahlung (IB) — Indirect $\not{C}\not{P}$



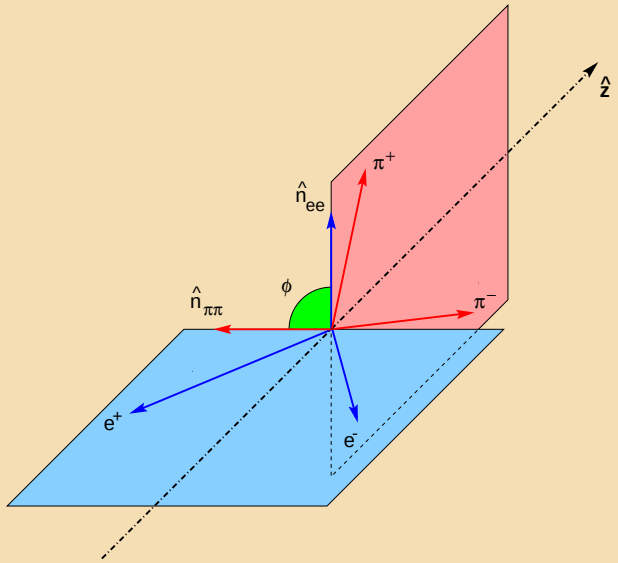
Direct Emission (DE)
E_1 — Indirect $\not{C}\not{P}$



K^0 Charge Radius (CR)

1.2. The CP Violating Asymmetry in the Angular Variable

It can be shown (*Sehgal and Wanninger, Phys. Rev. D.* ***46****, 1035 (1992)*) that the polarization of the photon will manifest itself as an asymmetry in the angular variable — angle ϕ.



$$\hat{n}_{\pi\pi} = \frac{\vec{p}_{\pi^+} \times \vec{p}_{\pi^-}}{|\vec{p}_{\pi^+} \times \vec{p}_{\pi^-}|} \quad \hat{n}_{ee} = \frac{\vec{p}_{e^+} \times \vec{p}_{e^-}}{|\vec{p}_{e^+} \times \vec{p}_{e^-}|}$$

$$\hat{z} = \frac{\vec{p}_{\pi^+} + \vec{p}_{\pi^-}}{|\vec{p}_{\pi^+} + \vec{p}_{\pi^-}|}$$

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

Both $\hat{n}_{ee}$ and $\hat{n}_{\pi\pi}$ are axial vectors while $\hat{z}$ is polar vector and therefore $\sin\phi\cos\phi$ is odd under CP and T transformations. The asymmetry is large and theory predicts the value of $\sim 14\%$. It can be defined as follows:

$$\mathbf{A}(\phi) \equiv \frac{\mathbf{N}_{\sin\phi\cos\phi>0} - \mathbf{N}_{\sin\phi\cos\phi<0}}{\mathbf{N}_{\sin\phi\cos\phi>0} + \mathbf{N}_{\sin\phi\cos\phi<0}}$$

1.3. The Form Factors

The Couplings for Each Contribution to the $K_L \to \pi^+\pi^-e^+e^-$ Decay:

- $g_{BR} = |\eta_{+-}|e^{i\delta_0(M_K) + \Phi_{+-}}$
- $g_{M_1} = ie^{i\delta_1(M_{\pi\pi}) + \Phi_{+-}} \times F\left(\frac{a_1}{a_2}; \tilde{g}_{M_1}\right)$
- $g_{E_1} = i|g_{E_1}|e^{i\delta_1(M_{\pi\pi}) + \Phi_{+-}} \times F\left(\frac{a_1}{a_2}; \tilde{g}_{M_1}\right)$
- $g_P = -\frac{1}{3} < R^2(K^0) > M_K^2 e^{i\delta_0(M_{\pi\pi})}$
- It was realized that the g_{M_1} coupling constant requires a non-trivial vector form factor $F\left(\frac{a_1}{a_2}; \tilde{g}_{M_1}\right)$ which can be parametrized (by analogy with $K_L \to \pi^+\pi^+\gamma$) in the following form:

Default Parametrization	
Parameter	**Value**
$\lvert\eta_{+-}\rvert$	$(2.285 \pm .019) \times 10^{-3}$
$\tilde{\mathbf{g}}_{\mathbf{M_1}}$	$\mathbf{1.35}^{+.20}_{-.17} \pm .04$
$\mathbf{a_1/a_2}$	$-\mathbf{.72} \pm .03 \pm .01$
$\mathbf{\Phi}_{+-}$	$43.7^\circ \pm .6^\circ$
$\lvert\mathbf{g_{E_1}}\rvert < .05 \cdot \tilde{g}_{M_1}$	$.038 \pm .038$
$\lvert g_P\rvert$	$.15 \pm .08$

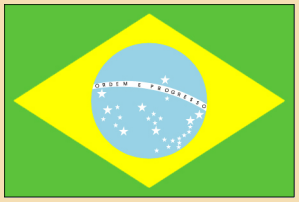
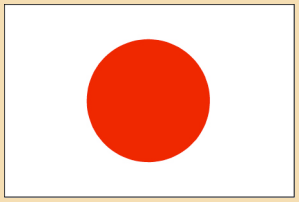
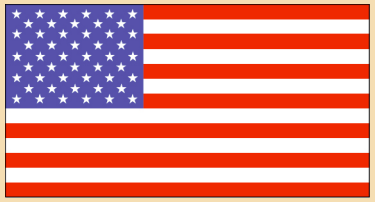
$$F = \tilde{\mathbf{g}}_{\mathbf{M_1}}\left[1 + \frac{\mathbf{a1/a2}}{(M_\rho^2 - M_K^2) + 2M_K E_{ee}}\right]$$

One can fit the data to the Monte Carlo simulation to extract the parameters.

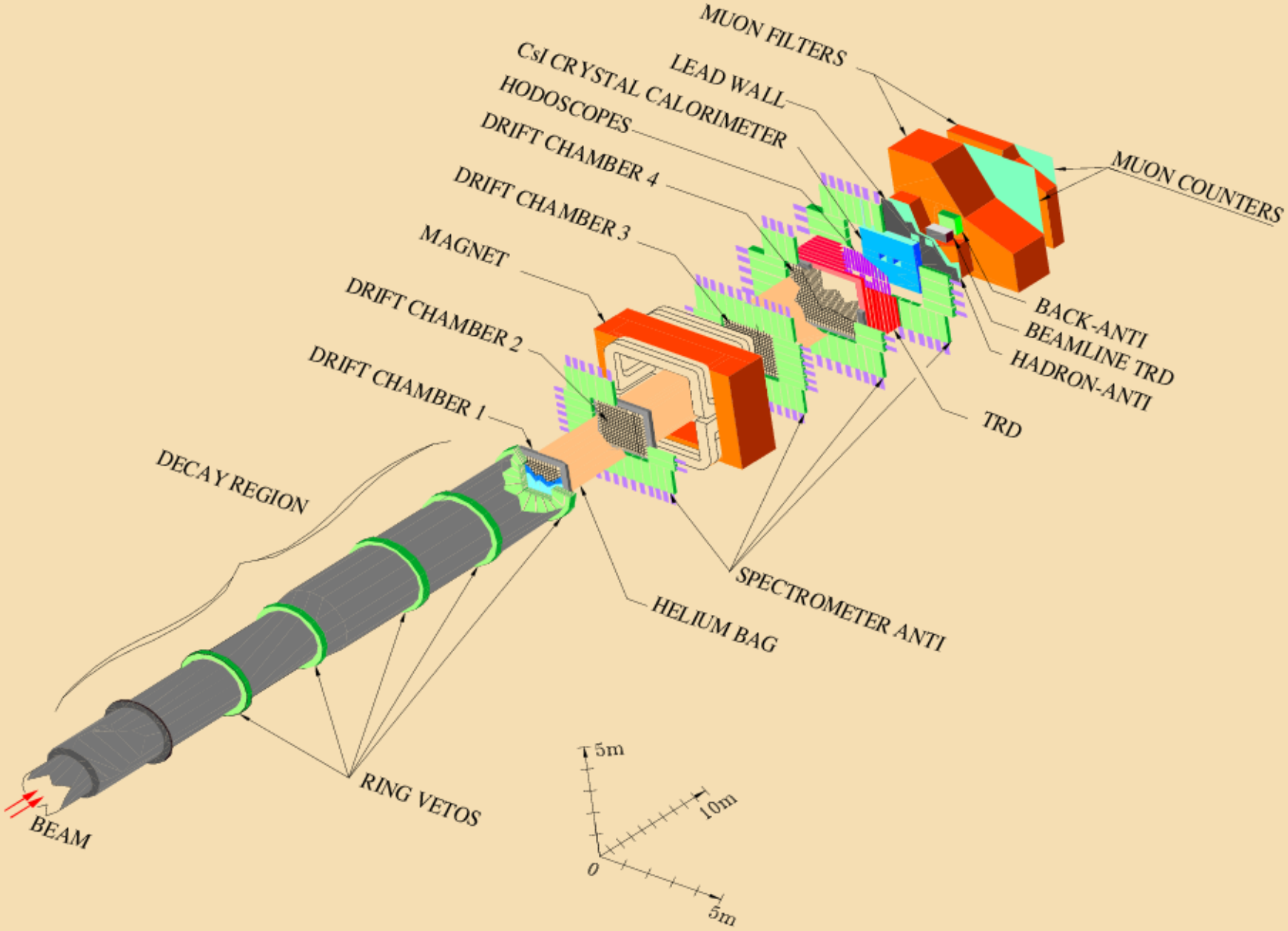
2. The KTeV Experiment

2.1. The International Collaboration

- University of Arizona
- UCLA
- University of California, San Diego
- Universidade Estadual de Campinas
- University of Chicago
- University of Colorado
- Elmhurst College
- Fermilab
- Osaka University
- Rice University
- Universidade de Sao Paulo
- University of Virginia
- University of Wisconsin

2.2. The KTeV Detector

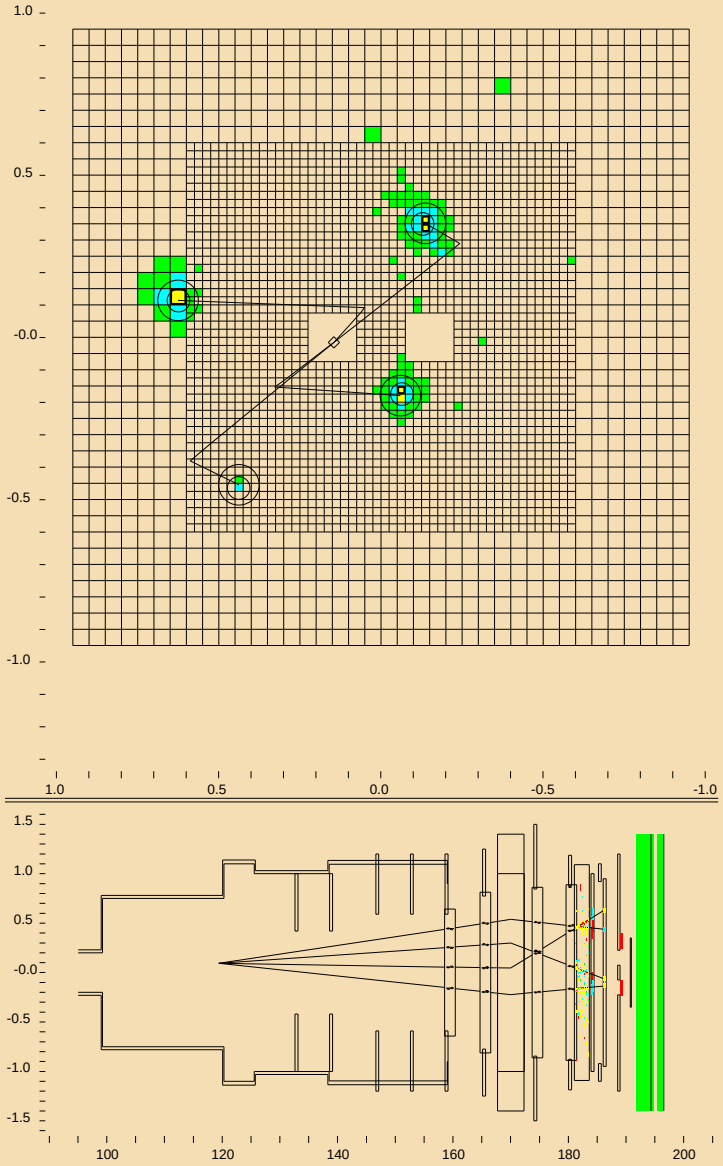


3. The Data

3.1. The Event Selection

The Trigger

- Veto events leaving fiducial volume.
- Veto muons which can reach through steel filter.
- Find a reasonable combination of tracks in the chambers.
- Make sure that events deposit enough energy in the calorimeter

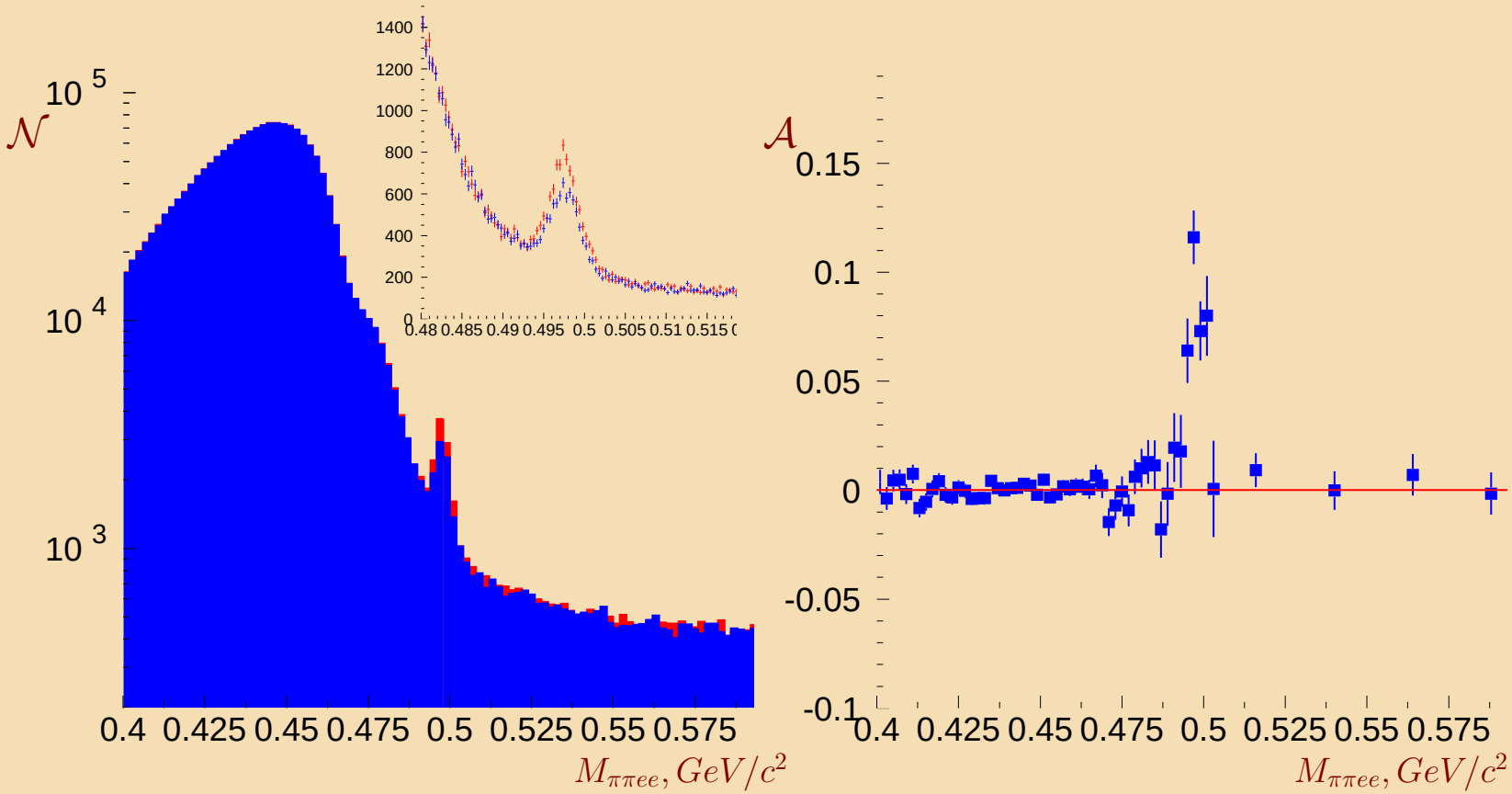


The Reconstruction

- Find 4 tracks with the same vertex.
- Isolate energy clusters in the calorimeter.
- Verify the event topology.
- Identify pions and electrons using the ratio of Energy over Momentum ($\frac{E}{P}$)

3.2. Observation of the Asymmetry

After this basic cuts one already can clearly see the $\mathbf{K_L \to \pi^+\pi^-e^+e^-}$ signal and observe the asymmetry!



Red Histogram — events with $\sin\phi\cos\phi > \mathbf{0}$

Blue ” — ” $\sin\phi\cos\phi < \mathbf{0}$

3.3. The Possible Backgrounds

- $\mathbf{K_L} \rightarrow \pi^+\pi^-\pi^0_{\mathbf{D}}$ with the missing photon is the predominant background.
- $\mathbf{K_L} \rightarrow \pi^+\pi^+\gamma$ (where $\gamma \rightarrow \mathbf{e^+e^-}$ in the material) looks exactly like signal, except that the photon is softer and thus this background can be virtually eliminated by doing a cut on the $M_{e^+e^-}$.
- $\mathbf{K_L} \rightarrow \pi^\pm\mathbf{e}^\pm$ double decays can be eliminated by the 4 track vertex quality cut.
- $\mathbf{K_S} \rightarrow \pi^+\pi^-\mathbf{e^+e^-}$: only high energy K_S's will live long enough to reach the decay volume. Do cut on the energy of the kaon.
- Accidental activity in the detector.

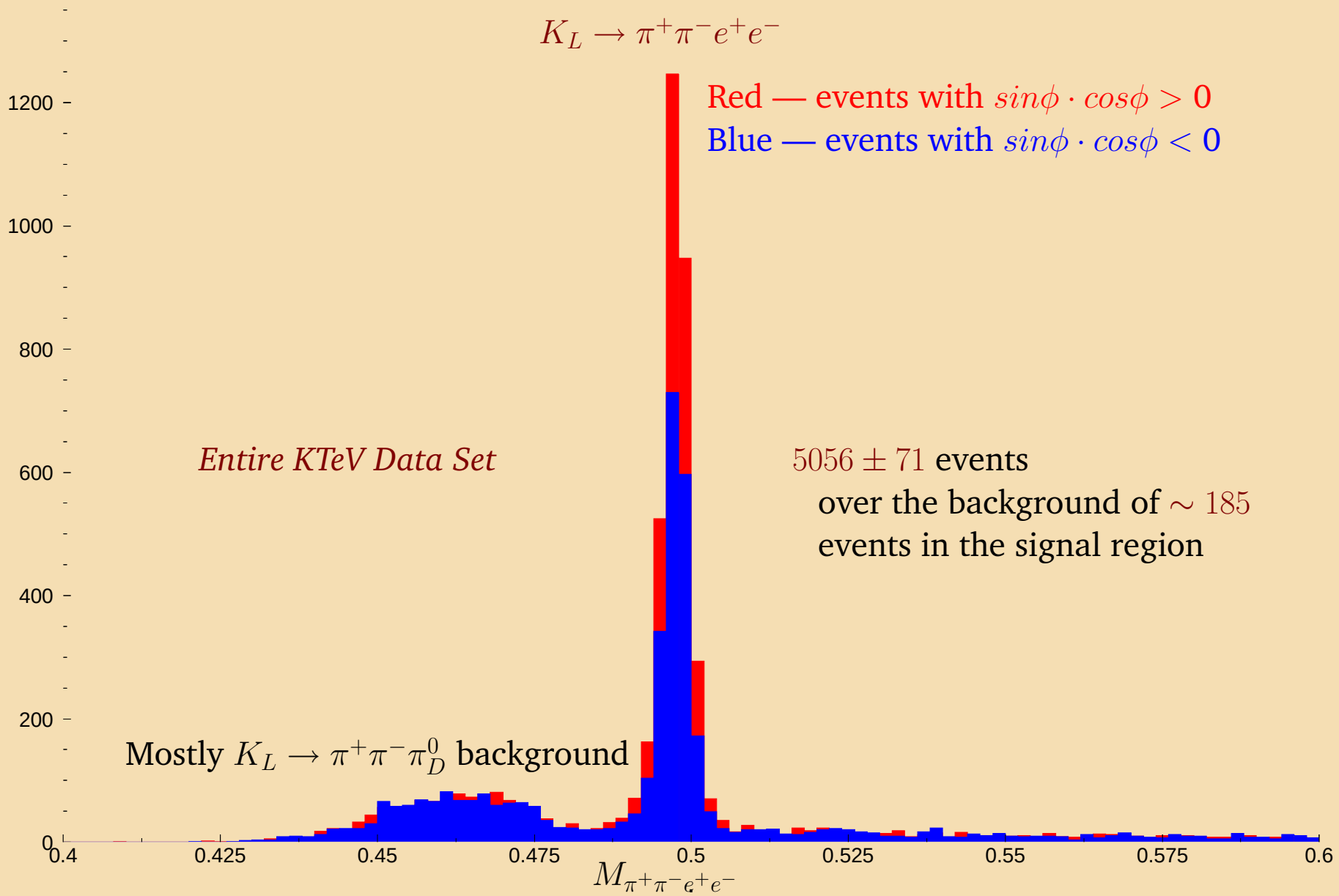
3.4. Background Suppression and Event Selection

- P_t^2 cut on the component of the total momentum (calculated for 4 tracks) transverse to the line connecting the target and decay vertex.
- $M_{e^+e^-}$ cut to remove $K_L \to \pi^+\pi^+\gamma$ background
- Verify trigger
- $pp0kine$: a special kinimatic cut against main background $K_L \to \pi^+\pi^-\pi_D^0$
- Do some other kimenatic cuts and finally
- Make the kaon mass cut

3.5. Summary of Main Cuts

- Event has 4 tracks
- Particle ID, i.e. electrons have $.95 < \frac{E}{P} < 1.05$
- pp0kine $< -.025$
- $M_{e^+e^-} > .002\ GeV/c^2$
- $\chi^2_{vtx} < 30.$
- $95m < Z_{vtx} < 158m$
- $P_t^2 < 6.E-5\ GeV^2/c^2$
- $E_{\pi\pi ee} < 200\ GeV$
- $.492\ Gev/c^2 < M_{\pi\pi ee} < .504\ GeV/c^2$

3.6. The Final Event Sample



4. The Measurements

4.1. Maximum Likelihood Fit for the Vector Form Factor

The likelihood function can be defined as follows:

$$\mathcal{L}\left(\vec{\alpha}\right) = \frac{\prod_{k=1}^{N} P_M^k\left(\vec{x};\vec{\alpha}\right) P_{acc}^k\left(\vec{x}\right)}{\left(\int_V P_M P_{acc} d\vec{x}\right)^N}$$

where $\vec{x}$ is the vector of measured variables and $\vec{\alpha}$ is the vector of parameters to be estimated. In our particular case

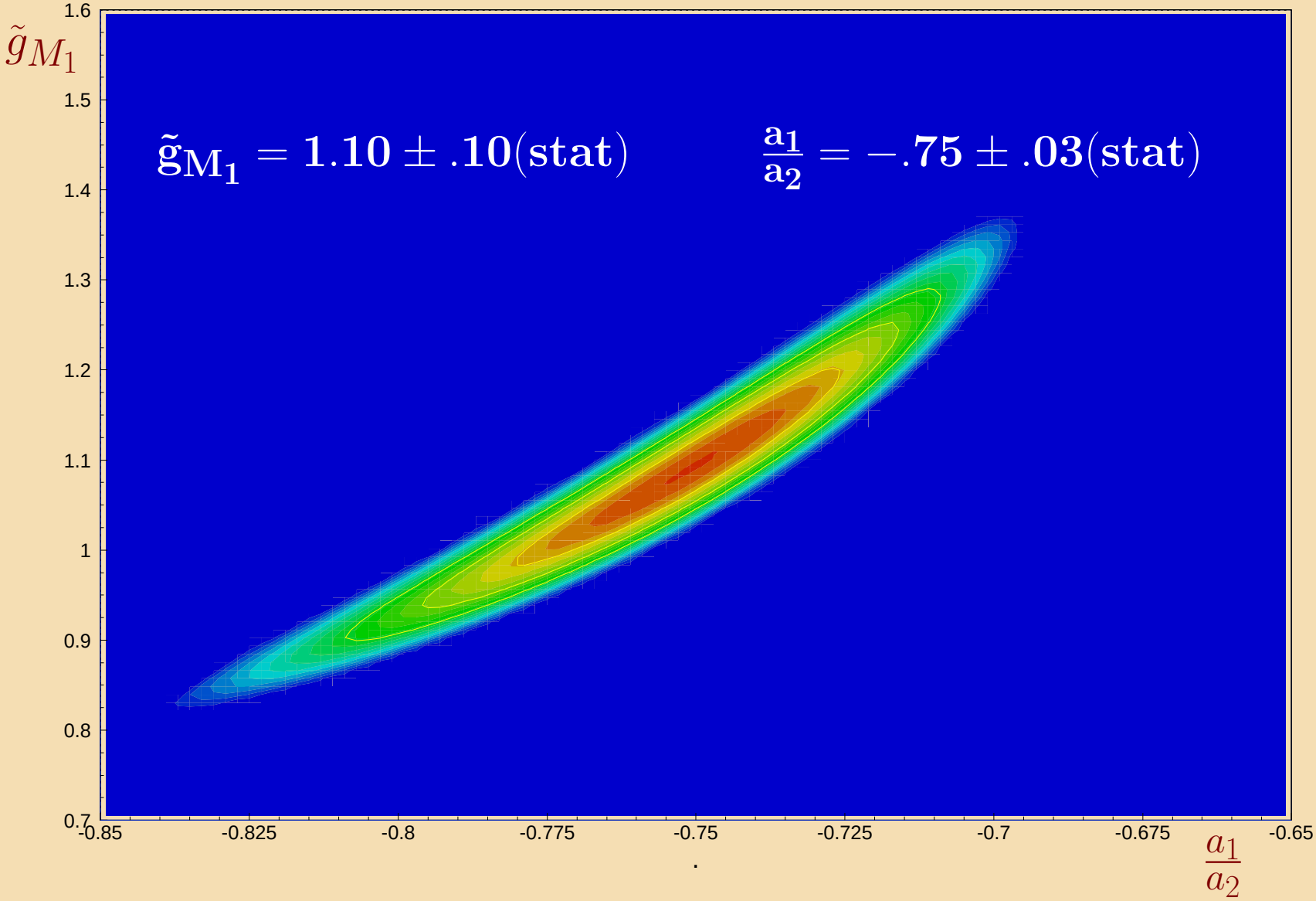
$$\vec{\alpha} = \left(\frac{\mathbf{a_1}}{\mathbf{a_2}}; \mathbf{g_{M_1}}\right) \qquad \vec{\mathbf{x}} = \left(\phi, \theta_{\mathbf{e}^+}, \theta_{\pi^-}, \mathbf{M}_{\pi\pi}, \mathbf{M}_{\mathbf{ee}}\right)$$

and the logarithm of the likelihood function can be written in terms of the relative weights of the event (data and Monte Carlo)

$$log\mathcal{L}\left(\vec{\alpha}\right) = \left[\sum_{i=1}^{N_d} logw_i\left(\vec{\alpha}\right)\right] - N_d log \sum_{j=1}^{N_{mc}} \frac{w_i(\vec{\alpha})}{w_i(\vec{\alpha_0})}$$

A large sample of Monte Carlo events was generated with nominal values of the parameters $\vec{\alpha_0}$ and then each event was re-weighted for any other set of parameters.

4.1.1. The Contour Plot for the $log\mathcal{L}$



4.1.2. The New Values for the Vector Form Factor

We performed a maximum likelihood fit of our Monte Carlo Simulation to the Data and found the following new values for the two parameters in the Vector Form Factor.

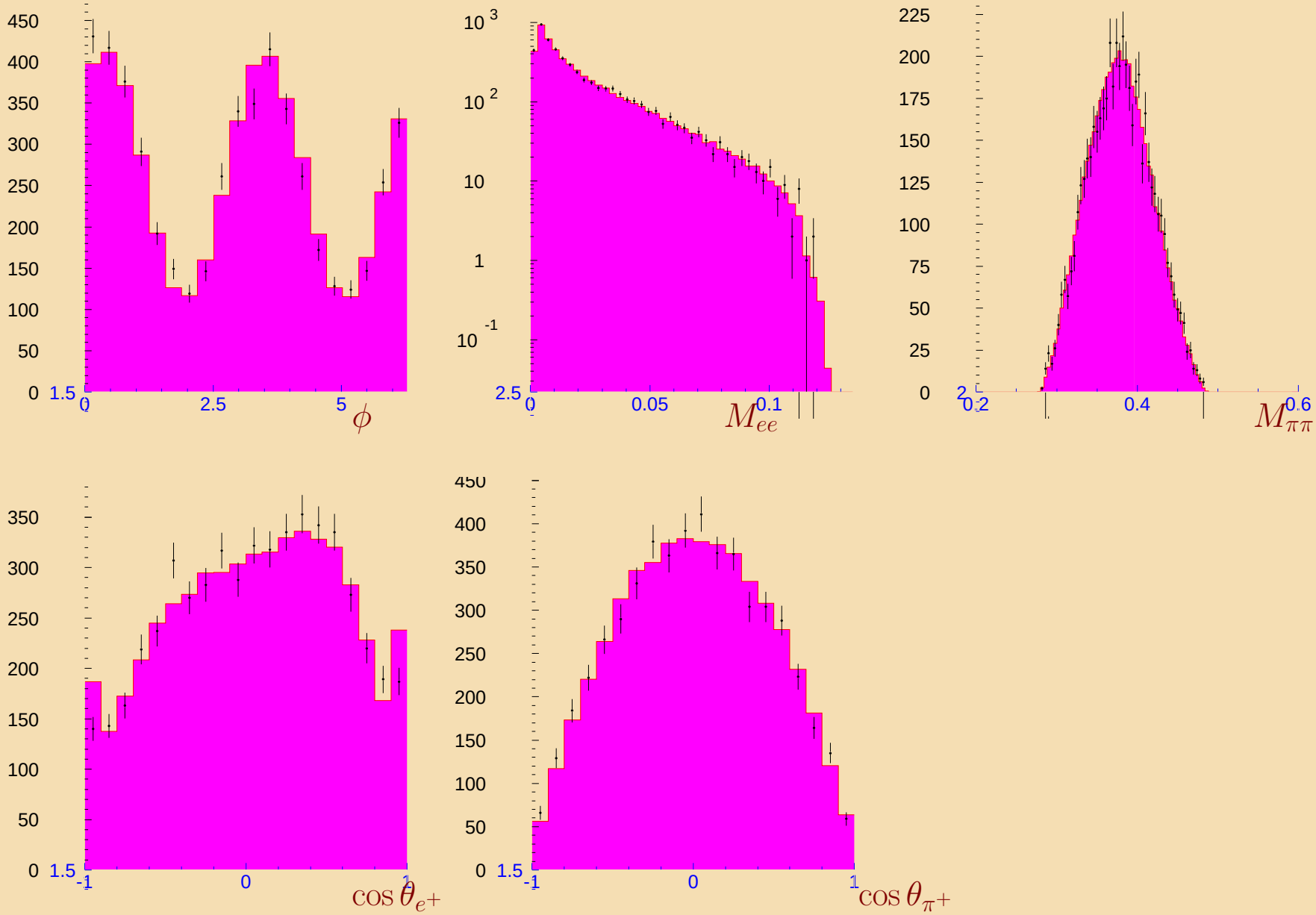
$$\tilde{g}_{M_1} = 1.10 \pm .10(stat) \qquad \frac{a_1}{a_2} = -.75 \pm .03(stat)$$

These numbers are in agreement with the earlier published KTeV results:

- $\frac{a_1}{a_2}$ = -0.72 $\pm$ 0.03(stat)$\pm$ .009(syst) GeV^2/c^2
  $\tilde{g}_{M_1}$ = $1.35^{+0.20}_{-0.17}$(stat)$\pm$ 0.04(syst)
  (*Published in Phys. Rev. Lett.* ***84****, 408 (2000)*)

- $\frac{a_1}{a_2}$ = -0.737$\pm$ 0.026(stat)$\pm$ .022(syst) GeV^2/c^2
  (*Published in Phys. Rev. Lett.* ***86****, 761 (2001)*)

4.1.3. Data / Monte Carlo Comparison Plots



4.2. The New Preliminary Measurement of the Asymmetry

Now we can use the new values of the Form Factors in our matrix element to measure the Asymmetry.

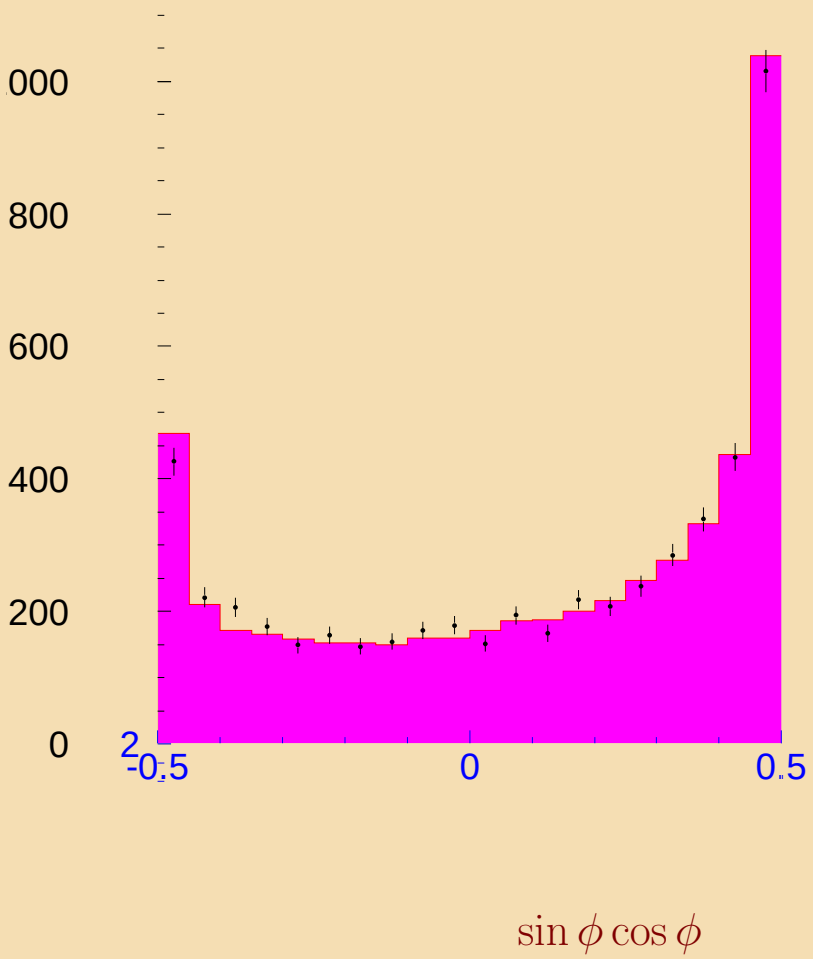
$$\mathbf{A} = (\mathbf{13.3} \pm \mathbf{1.4}(\mathbf{stat}))\,\%$$

Extracted from the 5241 $K_L \to \pi^+\pi^-e^+e^-$ events (including $\sim$ 185 background events).

Agrees with the earlier published KTeV result:

$\mathbf{A} = (\mathbf{13.6} \pm \mathbf{2.5}(\mathbf{stat}) \pm \mathbf{1.2}(\mathbf{syst}))\,\%$

(*Published in Phys. Rev. Lett.* ***84****, 408 (2000)*)



The Study of Systematic Uncertainty			
Source	**Uncertainty on the Parameter**		
	$\Delta a_1/a_2$	Δg_{M_1}	ΔA
Background	.012	.04	.004
Variation of Cuts	.012	.024	.0028
Resolution	.003	.008	.005
Limited MC	.01	.03	.002
Δg_{E_1}	.005	.001	.004
Δg_P	**.04**	**.10**	.002
$\Delta \eta_{+-}$	.002	.0003	.003
$\Delta \Phi_{+-}$	.0002	.00015	.0015
Combined	**.045**	**.11**	**.009**

4.4. Plans — What Else Can Be Done?

- Update BR measurement.
- Measure K^0 Charge Radius.
- Ettempt to estimate the existance of the E_1 Form Factor, i.e. search for CP violating E_1 emission.

5. The Summary

All Results are Preliminary !

- Identified **5241** $\mathbf{K_L \to \pi^+\pi^-e^+e^-}$ Events with ~ 185 background
- Reported New Preliminary Measurements
  - CP Violating Asymmetry in the ϕ angular variable.
    - ⋆ $\mathbf{A = (13.3 \pm 1.4(stat) \pm .9(syst))\,\%}$
  - Vector Form Factor Parameters
    - ⋆ $\mathbf{\tilde{g}_{M_1} = 1.10 \pm .10(stat) \pm .11(syst)}$
    - ⋆ $\mathbf{\frac{a_1}{a_2} = -.75 \pm .03(stat) \pm .045(syst)}$
- These results are in agreement with the previously published measurements and theoretical predictions.
- Plans and Future Prospectives:
  - Measure new value for the Branching Ratio
  - Fit for the parameter $\mathbf{g_P}$ related to the K^0 Charge Radius
  - Attempt to fit for the parameter $\mathbf{g_{E_1}}$ to search for CP Violating E_1 direct emission.