XXXIXth RENCONTRES DE MORIOND
ELECTROWEAK INTERACTIONS AND UNIFIED THEORIES
La Thuile, Aosta Valley, Italy
March 21 - 28, 2004

KTEV RESULTS ON CP VIOLATION IN $\mathbf{K_L \to \pi^+ \pi^- e^+ e^-}$

ALEXANDER LEDOVSKOY

University of Virginia
ledovskoy@virginia.edu
for KTEV Collaboration

outline

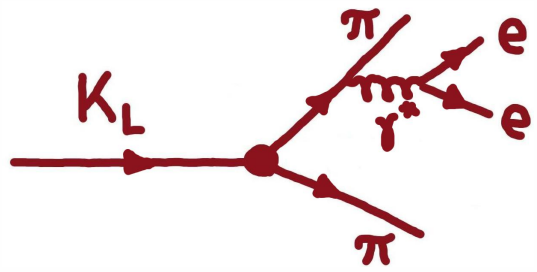
1. Introduction. Why $K_L \to \pi^+\pi^-e^+e^-$? CP-violation in this decay

2. KTeV detector. Data taking and event selection. KTeV sample of $K_L \to \pi^+\pi^-e^+e^-$ candidates. Observation of CP violation.

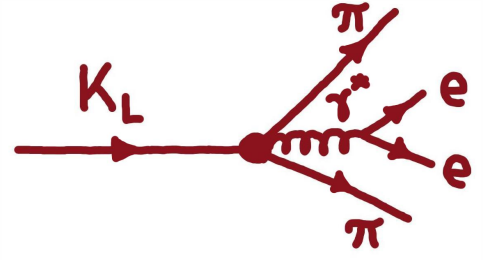
3. Theoretical model used in MC simulations. Measurement of several parameters for this model using maximum likelihood fit.

4. Measurement of CP-violation in $K_L \to \pi^+\pi^-e^+e^-$. Discussion of resutls.

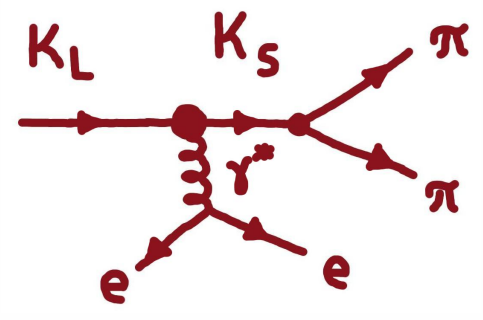
$K_L \to \pi^+\pi^-e^+e^-$ amplitude



inner bremsstrahlung
CP-violating



direct emission
M1: CP-conserving
E1: CP-violating



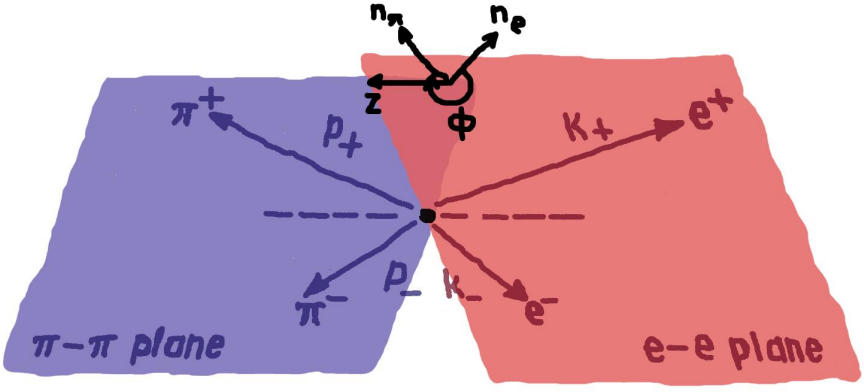
charge radius amplitude
CP-conserving
similar to kaon regeneration on free electons

cp violating asymmetry

Angle ϕ between normals to $\pi^+\pi^-$ and e^+e^- planes in kaon CM:

$$n_\pi = (p_+ \times p_-)/|p_+ \times p_-|$$
$$n_e = (k_+ \times k_-)/|k_+ \times k_-|$$
$$z = (p_+ + p_-)/|p_+ + p_-|$$

ϕ is CP-odd and T-odd



$$\sin\phi\cos\phi = (n_e \times n_\pi) \cdot z(n_e \cdot n_\pi)$$

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

$$\Gamma_3 \neq 0 \rightarrow \text{CP violation}$$

Asymmetry:

$$A = \frac{\int_0^{\pi/2}\frac{d\Gamma}{d\phi} + \int_\pi^{3\pi/2}\frac{d\Gamma}{d\phi} - \int_{\pi/2}^{\pi}\frac{d\Gamma}{d\phi} - \int_{3\pi/2}^{2\pi}\frac{d\Gamma}{d\phi}}{\int_0^{\pi/2}\frac{d\Gamma}{d\phi} + \int_\pi^{3\pi/2}\frac{d\Gamma}{d\phi} + \int_{\pi/2}^{\pi}\frac{d\Gamma}{d\phi} + \int_{3\pi/2}^{2\pi}\frac{d\Gamma}{d\phi}} = \frac{N_{\sin\phi\cos\phi>0} - N_{\sin\phi\cos\phi<0}}{N_{\sin\phi\cos\phi>0} + N_{\sin\phi\cos\phi<0}} \sim \Gamma_3$$

ktev collaboration

T. Alexopoulos[14], M. Arenton[13], S. Averitte[11], R.F. Barbosa[12], A.R. Barker[6], M. Barrio[5], L. Bellantoni[8], A. Bellavance[10], J. Belz[11], D.R. Bergman[11], E. Blucher[5], G.J. Bock[8], C. Bown[5], E. Cheu[1], S. Childress[8], R. Coleman[8], M.D. Corcoran[10], G. Corti[13], B. Cox[13], A.R. Erwin[14], R. Ford[8], A. Glazov[5], A. Golossanov[13], R.A. Gomes[4], J. Graham[5], J. Hamm[1], K. Hanagaki[9], Y.B. Hsiung[8], H. Huang[6], V. Jejer[13], D.A. Jensen[8], R. Kessler[5], H.G.E. Kobrak[3], K. Kotera[9], J. LaDue[6], A. Lath[11], A. Ledovskoy[13], P.L. McBride[8], E. Monnier[5], K.S. Nelson[13], H. Nguyen[8], V. Prasad[5], H. Ping[14], X.R. Qi[8], E.J. Ramberg[8], R.E. Ray[8], M. Ronquest[13], E. Santos[12], S. Schnetzer[11], P. Shanahan[8], J. Shields[13], W. Slater[2], D. Smith[13], N. Solomey[5], E.C. Swallow[5,7], R.J. Tesarek[8], G.B. Thomson[11], P.A. Toale[6], R. Tschirhart[8], C. Velissaris[14], Y.W. Wah[5], J. Wang[1], H.B. White[8], J. Whitmore[8], M. Wilking[6], B. Winstein[5], R. Winston[5], E.T. Worchester[5], T. Yamanaka[9]

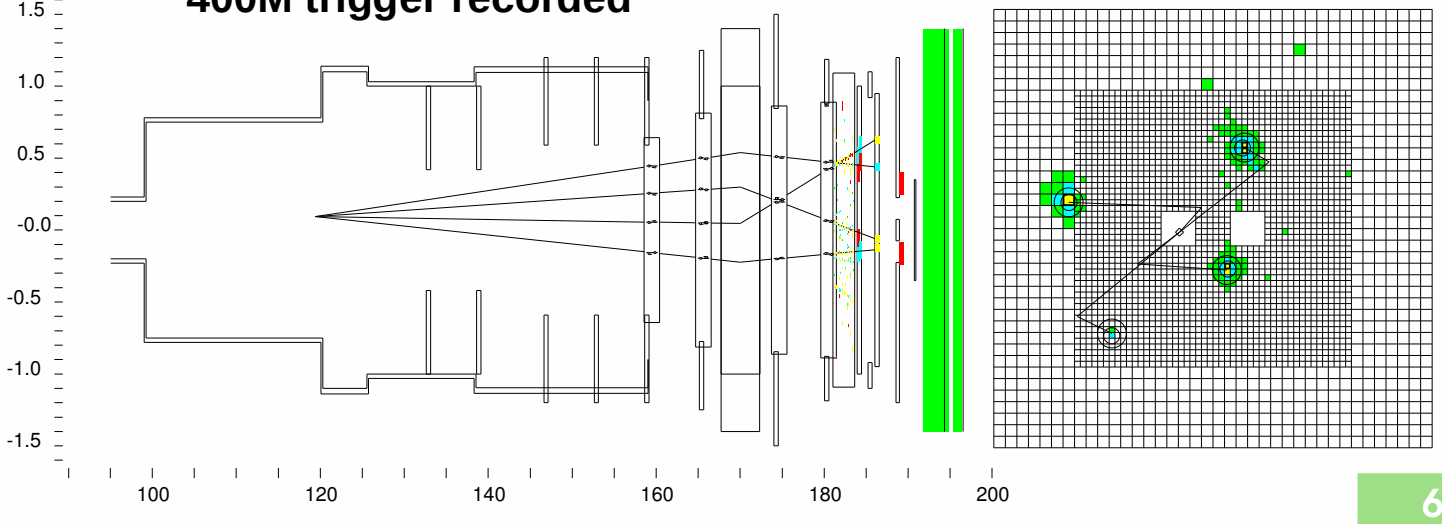
[1]**Arizona**
[2]**UCLA**
[3]**UC San Diego**
[4]**Campinas, Brazil**
[5]**Chicago**
[6]**Colorado**
[7]**Elmhurst College**
[8]**FNAL**
[9]**Osaka, Japan**
[10]**Rice**
[11]**Rutgers**
[12]**São Paulo, Brazil**
[13]**Virginia**
[14]**Wisconsin**

detector

Two K_L beams: 20-200 GeV, peaked at $\sim$50 GeV
Decay volume: Vacuum, 90-160 m from target
4 Drift Chambers: X,X',Y,Y' views, $\sim$100 μm pos.res.
Magnet kick: 200 MeV (1997), 150 MeV (1999)
EM Calorimeter: 3100 CsI cryst., $\sim$ 1 mm pos.res., $<$1% en.res.

4TRK Trigger: **L1)** $\geq$3 by trigger hodoscope, no escaping particles, no muons; **L2)** $\geq$3 by DC hits, $\geq$2 clusters above 1 GeV in EMCAL, $\geq$10 GeV in EMCAL; **L3)** $\geq$3 reconstructed tracks, good vertex

400M trigger recorded



off-line selection

Select $\mathbf{K_L \to \pi^+\pi^-e^+e^-}$ topology:

4 tracks with good vertex in decay region. Electrons identified as tracks with $0.95 < E/p < 1.05$. E is energy in EM Calorimeter, p is momentum in the spectrometer.

Reject signal candidates

that are misreconstructed events or events that are difficult to simulate with Monte Carlo.

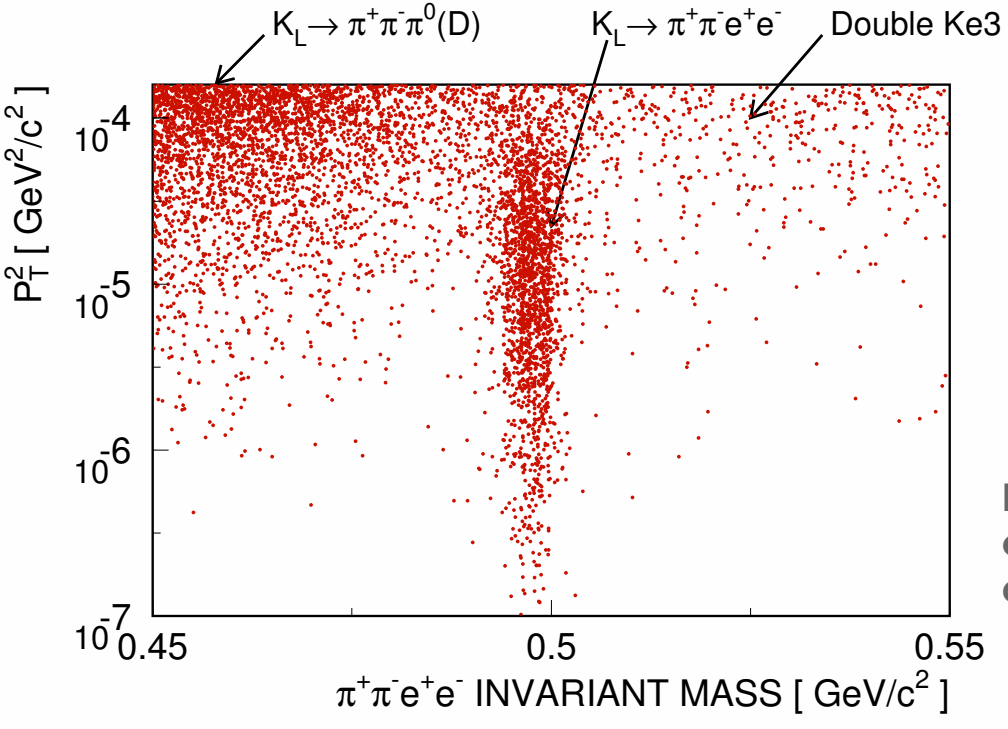
Reject background candidates

$K_L \to \pi^+\pi^-\pi^0$ with $\pi^0 \to e^+e^-\gamma$,
$K_L \to \pi^+\pi^-\gamma$ with external $\gamma \to e^+e^-$
Two $K_L \to \pi^\pm e^\mp \nu$ overlapped
$\Xi^0 \to \Lambda\pi^0$ with $\Lambda \to p\pi^-$ and $\pi^0 \to e^+e^-\gamma$
$K_S \to \pi^+\pi^-e^+e^-$

kaon P_T^2

Transverse momentum squared of 4 tracks w.r.t. kaon line of flight (from target center to vertex)

Signal is well separated in P_T^2 from backgrounds with missing partcles

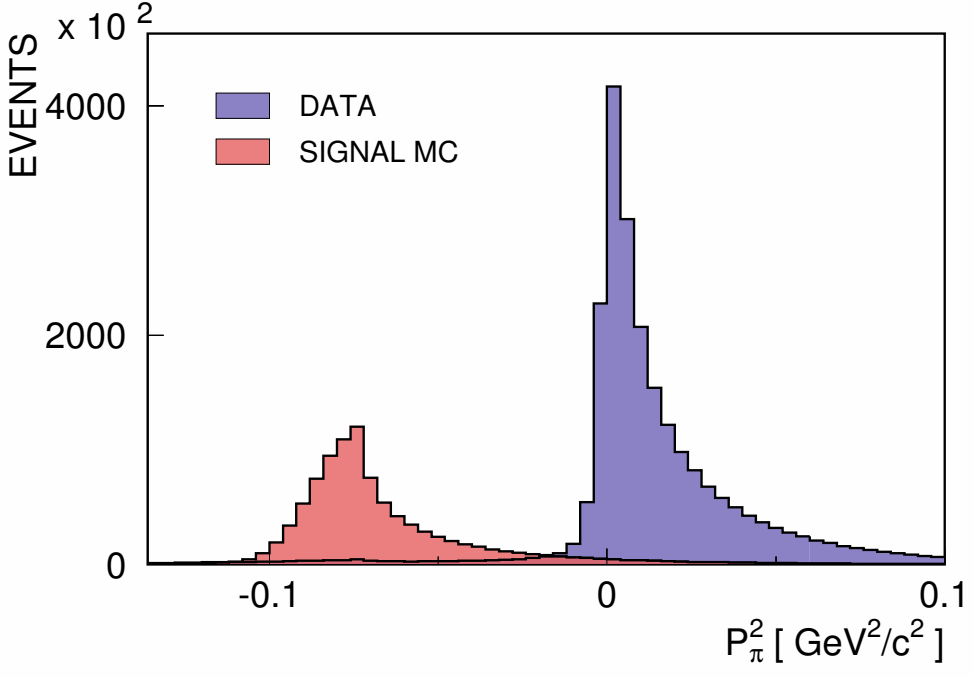


DATA events at earlier stage of analysis

$P^2_{\pi^0}$

Under $K_L \to \pi^+\pi^-\pi^0$ assumption, it is longitudinal momentum squared of kaon in reference frame where longitudinal momentum of $\pi^+\pi^-$ pair is zero

$$P^2_{\pi^0} = \frac{(M^2_K - M^2_{\pi^0} - M^2_{\pi\pi})^2 - 4M^2_{\pi^0}M^2_{\pi\pi} - 4(P^2_T)_{\pi\pi}M^2_K}{4(M^2_{\pi\pi} + (P^2_T)_{\pi\pi})}$$



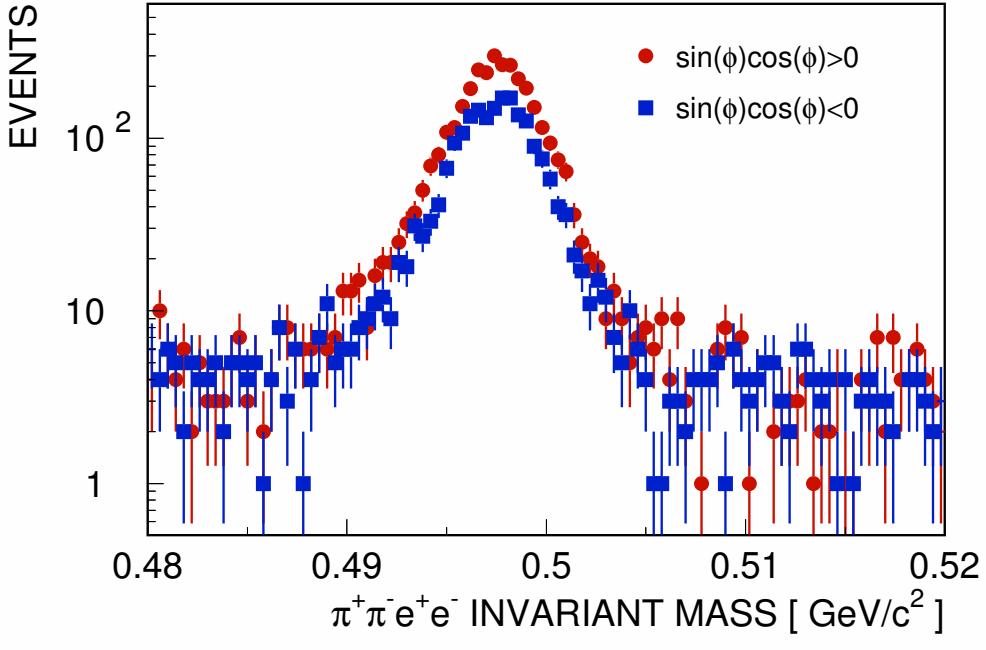
Very effective variable to suppress $K_L \to \pi^+\pi^-\pi^0_D$ background

DATA events are at earlier stage of analysis, it is mostly $K_L \to \pi^+\pi^-\pi^0_D$

final event sample

There are 5241 events within 0.492–0.504 GeV/c^2 mass range.
Estimated background is 185$\pm$14 events

To measure CP-violating asymmetry, acceptance calculations are required



Obvious asymmetry in signal region

Background has no asymmetry

KTeV sample of $K_L \to \pi^+\pi^-e^+e^-$ candidates. Events with positive and negative $\sin\phi\cos\phi$ are plotted separately.

Main features of $\mathbf{K_L \to \pi^+\pi^-e^+e^-}$ Monte Carlo simulations

kaon simulation:

Generation at the BeO target.
Propagation along the beamline to the decay point.

kaon decay into appropriate final state:

Four amplitudes: Brem, DE(M1), DE(E1), Charge Radius.
Radiative corrections by PHOTOS package.

tracing through the detector:

GEANT-based parameterization of scattering, secondary particle generation, showering.
Detector responce simulation and digitization of the signals.
Accidental activity by real random snapshots of the detector.

The MC simulations of the detector responce were verified in DATA/MC comparisons for high statistics mode $\mathrm{K_L} \to \pi^+\pi^-\pi^0_\mathrm{D}$

matrix element

Inner Bremsstrahlung: $g_{BR} = |\eta_{+-}|e^{i(\delta_0(M_K)+\Phi_{+-})}$

M1 direct emission: $g_{M1} = i|g_{M1}|e^{i\delta_1(M_{\pi\pi})}$

E1 direct emission: $g_{E1} = -i\frac{|g_{E1}|}{|g_{M1}|}g_{M1}e^{i\Phi_{+-}}$

Charge radius amplitude: $g_{CR} = |g_{CR}|e^{i\delta_0(M_{\pi\pi})}$

δ_0 and δ_1 are phases of s- and p-wave $\pi\pi$ scattering. We used recent fits from G.Colangelo et al, Nucl. Phys. B603, 125 (2001)

$|g_{M1}|$ is energy dependent:

$$|g_{M1}| = \tilde{g}_{m1}\left[1 + \frac{a_1/a_2}{(M_\rho^2 + M_K^2) + 2M_K E_\gamma^*}\right]$$

Parameters $\tilde{g}_{m1}$, a_1/a_2, $\frac{|g_{E1}|}{|g_{M1}|}$, and $|g_{CR}|$ were measured using KTeV sample of $K_L \to \pi^+\pi^-e^+e^-$ decays

likelihood function

We used maximum likelihood method for measurement of parameters $\alpha = \{\tilde{g}_{m1}, a_1/a_2, \frac{|g_{E1}|}{|g_{M1}|}, |g_{CR}|\}$

Log-likelihood function, most general form,

$$\ln\mathscr{L}(\alpha) = \sum_{i=1}^{N_d} \ln\left[\frac{A(\beta_i)\frac{d\Gamma(\beta_i,\alpha)}{d\beta}}{\int_{PS} A(\beta)\frac{d\Gamma(\beta,\alpha)}{d\beta}d\beta}\right]$$

$\beta = \{M_{ee}, M_{\pi\pi}, \phi, \cos\theta_{\pi^+}, \cos\theta_{e+}\}$ are five independent kinematic variables for matrix element; $A(\beta)$ is the acceptance function; $\frac{d\Gamma(\beta,\alpha)}{d\beta}$ is the differential decay rate

We used MC sample of 1.4 million events generated at $\alpha_0 = \{\tilde{g}_{m1} = 1.2, a_1/a_2 = -1.73, \frac{|g_{E1}|}{|g_{M1}|} = 0.0, |g_{CR}| = 0.16\}$.
Log-likelihood function, more practical form,

$$\ln\mathscr{L}(\alpha) = \sum_{i=1}^{N_d} \ln\frac{d\Gamma(\beta_i,\alpha)}{d\beta} - N_d \ln\sum_{j=1}^{N_{mc}} \frac{d\Gamma(\beta_j,\alpha)/d\beta}{d\Gamma(\beta_j,\alpha_0)/d\beta}$$

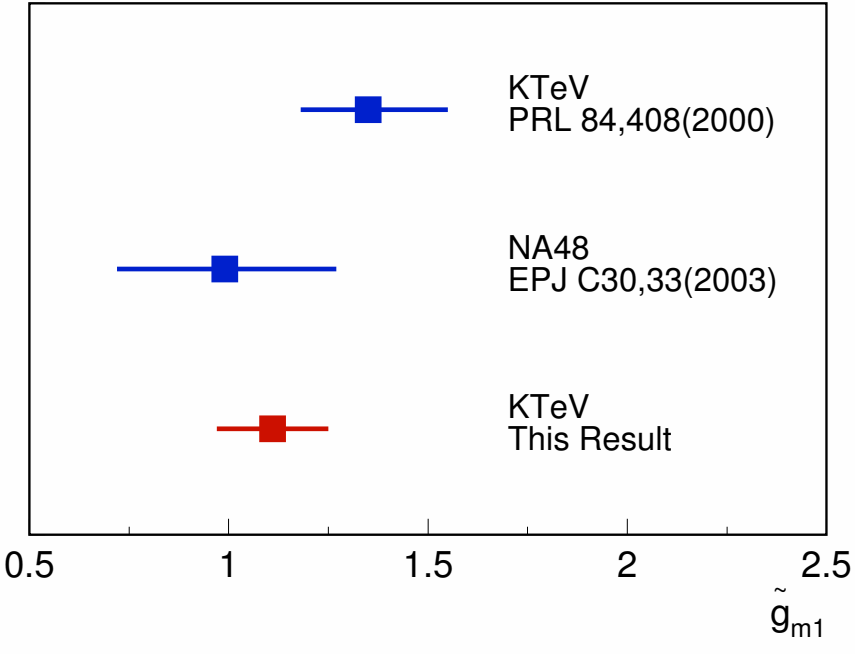
fit uncertainties

Source	$\|g_{CR}\|$	$\|g_{E1}\|/\|g_{M1}\|$	a_1/a_2	$\tilde{g}_{m1}$
MC statistics	0.001	0.001	0.002	0.001
Choice of α_0	0.001	0.001	0.005	0.02
DATA/MC disagr.	0.021	0.018	0.022	0.041
Background	0.01	0.008	0.022	0.05
Radiative Corr.	0.0	0.0	0.0	0.0
$\|\eta_{+-}\|$ uncertainty	0.002	0.0002	0.0001	0.01
Φ_{+-} uncertainty	0.0002	0.0005	0.0003	0.002
$\delta_{0,1}$ uncertainty	0.001	0.0003	0.001	0.004
Total Syst. Error	**0.023**	**0.020**	**0.032**	**0.07**
Total Stat. Error	**0.017**	**0.028**	**0.022**	**0.12**

$\tilde{g}_{m1}$ results

$$\tilde{g}_{m1} = 1.11 \pm 0.12(\text{stat}) \pm 0.07(\text{syst})$$

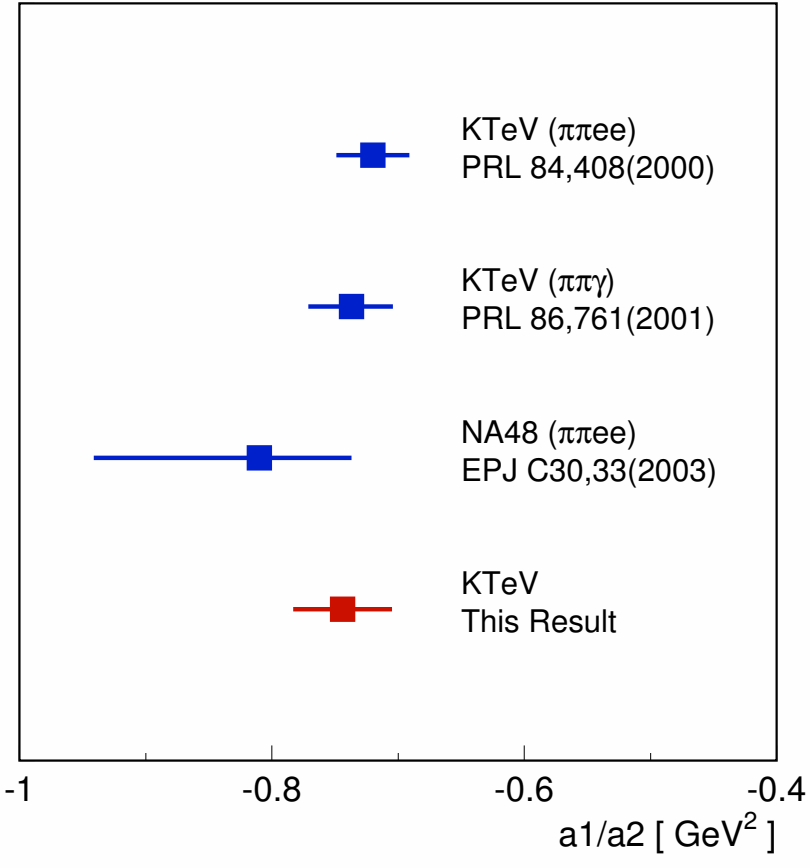
Good agreement with previous measurements
(all based on $K_L \to \pi^+\pi^-e^+e^-$)



Previous KTeV measurement is based on a subsample of this result but the method is different

a_1/a_2 results

$$a_1/a_2 = -0.744 \pm 0.022(\text{stat}) \pm 0.032(\text{syst})$$

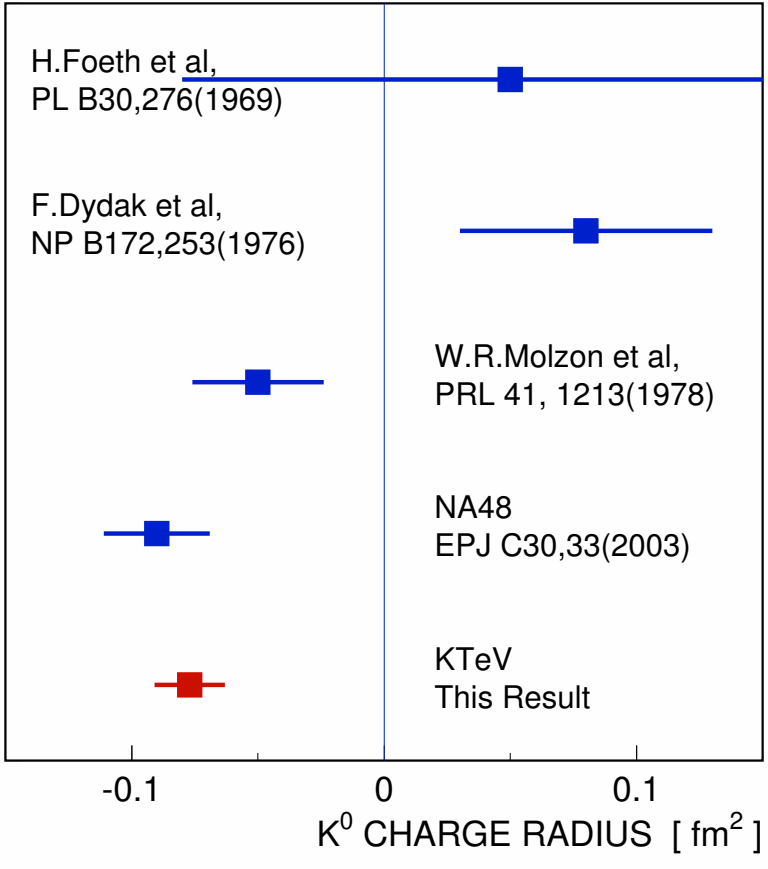


Good agreement with previous measurements

Previous KTeV ($\pi\pi$ee) measurement is based on a subsample of this result but the method is different

$|g_{CR}|$ results

$$|g_{CR}| = 0.163 \pm 0.017(\text{stat}) \pm 0.023(\text{syst})$$



$|g_{CR}| = -\frac{1}{3}\langle R_K^2 \rangle M_K^2$
$\langle R_K^2 \rangle$ is K^0 charge radius

Previous published measurements of $\langle R_K^2 \rangle$ are based on kaon regeneration on free electrons.

NA48 and KTeV measurements are based on
$K_L \to \pi^+\pi^- e^+ e^-$

KTeV result:
$\langle R_K^2 \rangle = -0.077 \pm 0.014\ \text{fm}^2$

$|g_{E1}|/|g_{M1}|$ results

CP-violating E1 direct emission amplitude is

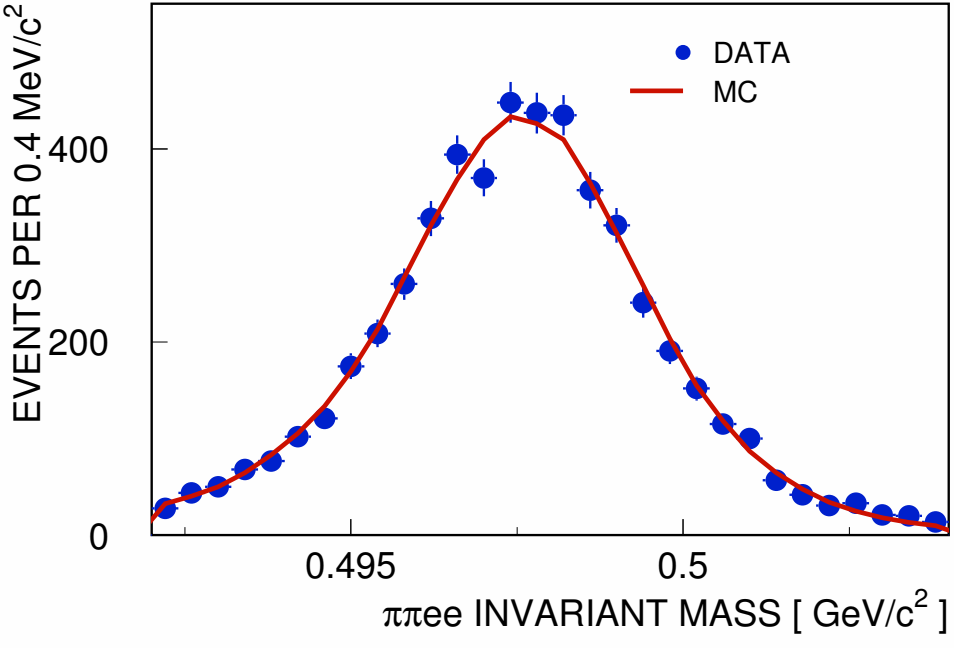
$$\frac{|g_{E1}|}{|g_{M1}|} \leq 0.04\ (90\%\mathrm{CL})$$

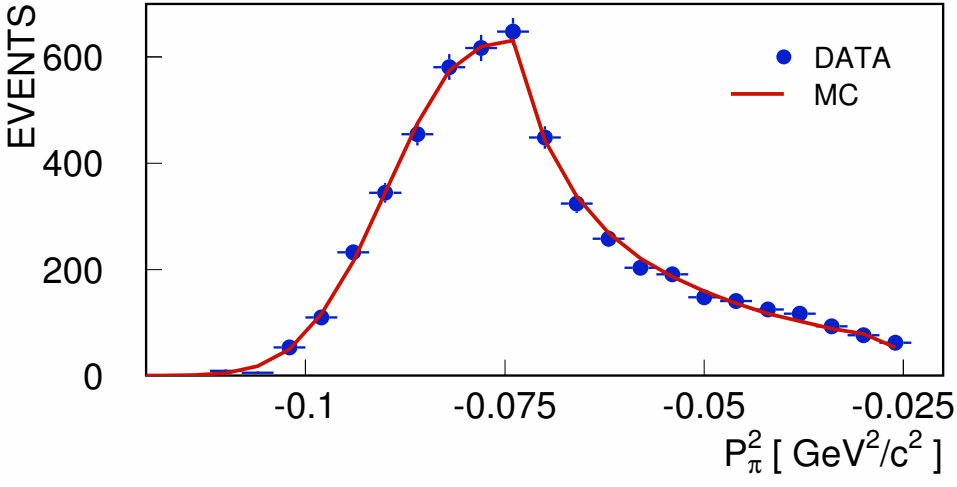
This is a first attempt for direct measurement of this amplitude in $K_L \to \pi^+\pi^- e^+ e^-$

data/mc comparison

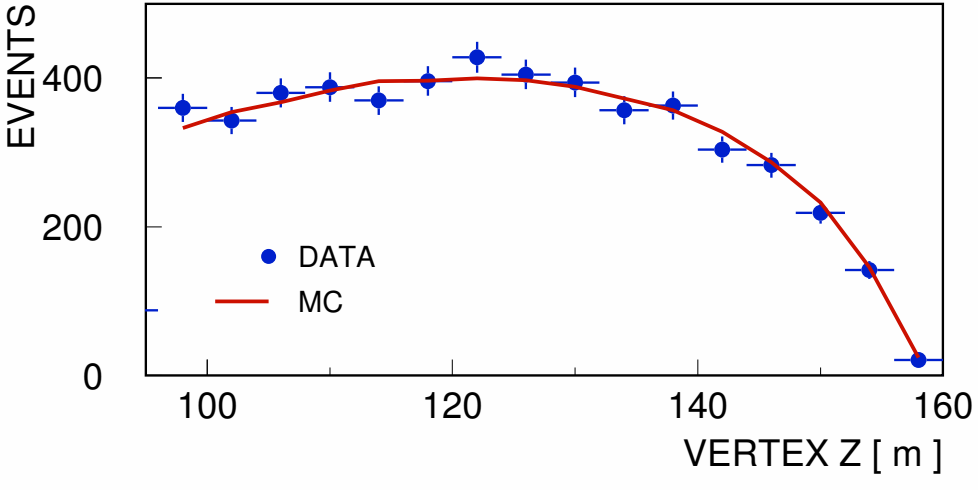
Monte Carlo simulation of $K_L \to \pi^+\pi^-e^+e^-$ events with newly determined parameters of the model

Invariant mass of $\pi^+\pi^-e^+e^-$ for sample of 5241 signal candidates (DATA) superimposed on MC simulations.

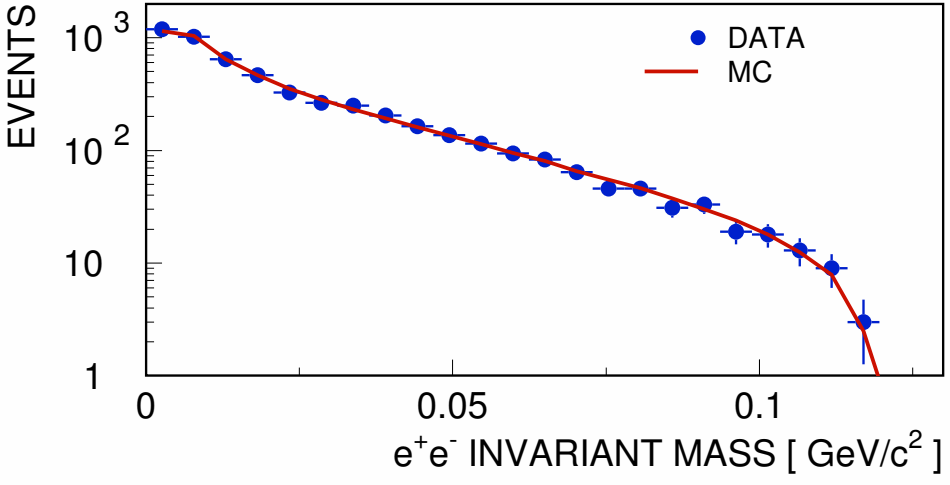




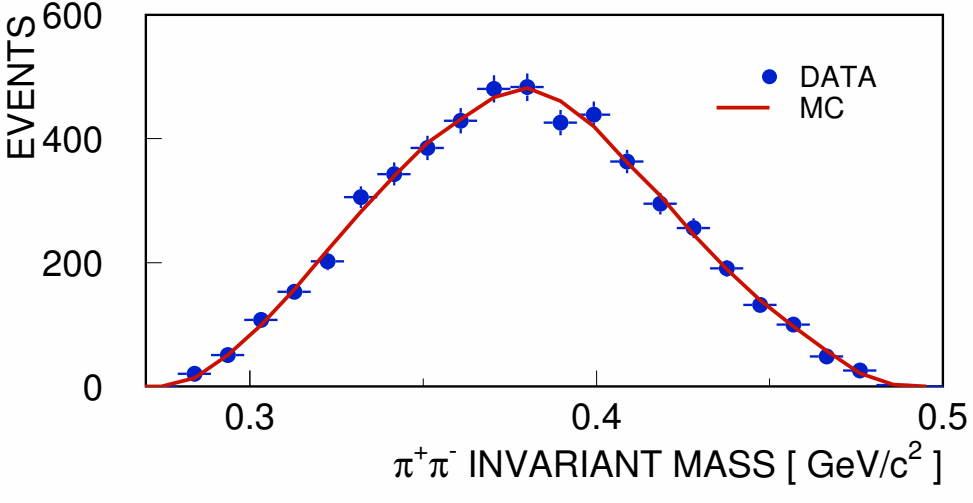
Kinematic parameter $P^2_{\pi^0}$ - longitudinal momentum squared of kaon in a rest frame where longitudinal momentum of $\pi^+\pi^-$ is zero under $K_L \to \pi^+\pi^-\pi^0$ hypothesis



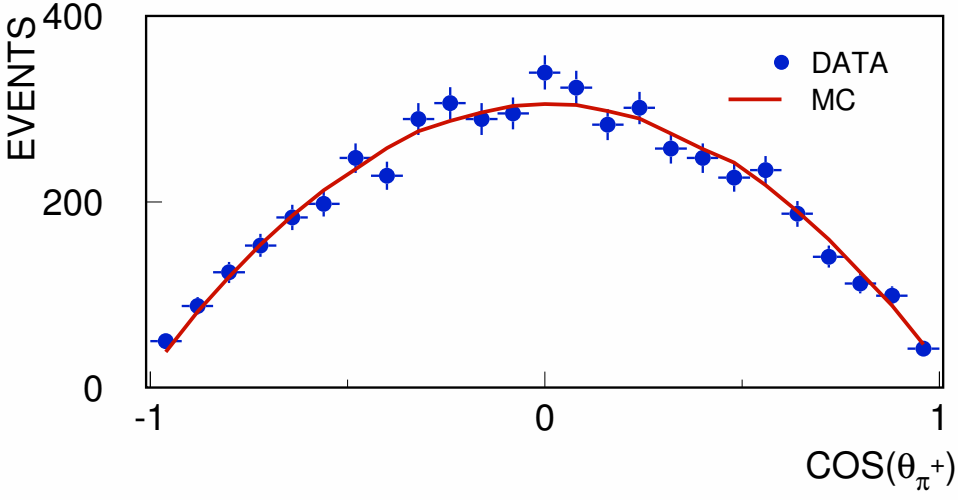
Z position of the decay vertex



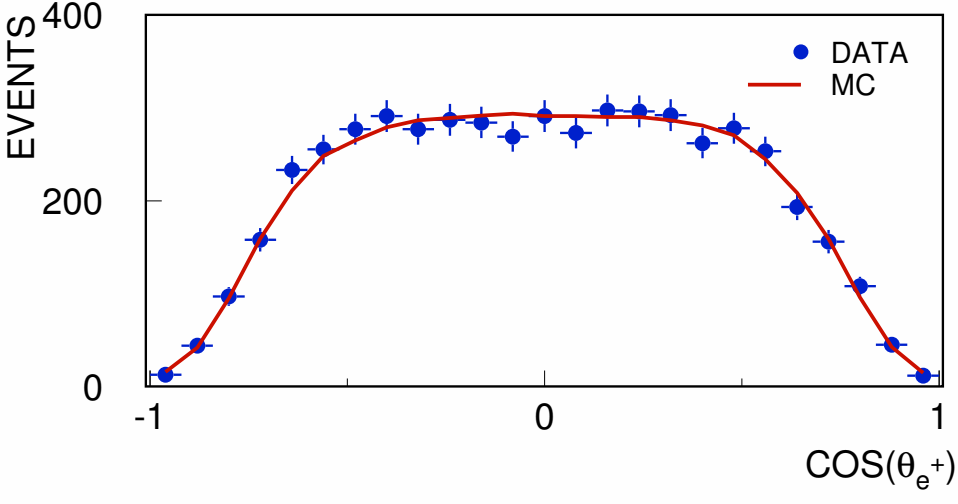
e^+e^- invariant mass for DATA and Monte Carlo events. The events are required to have $M_{ee} \geq 2\ MeV/c^2$ to suppress $K_L \to \pi^+\pi^-\gamma$ decays with external conversions



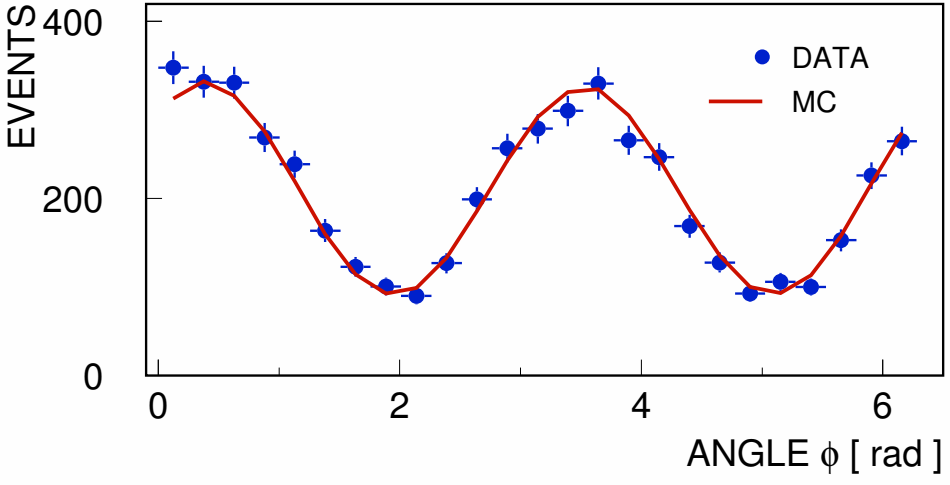
$\pi^+\pi^-$ invariant mass for DATA and Monte Carlo events.



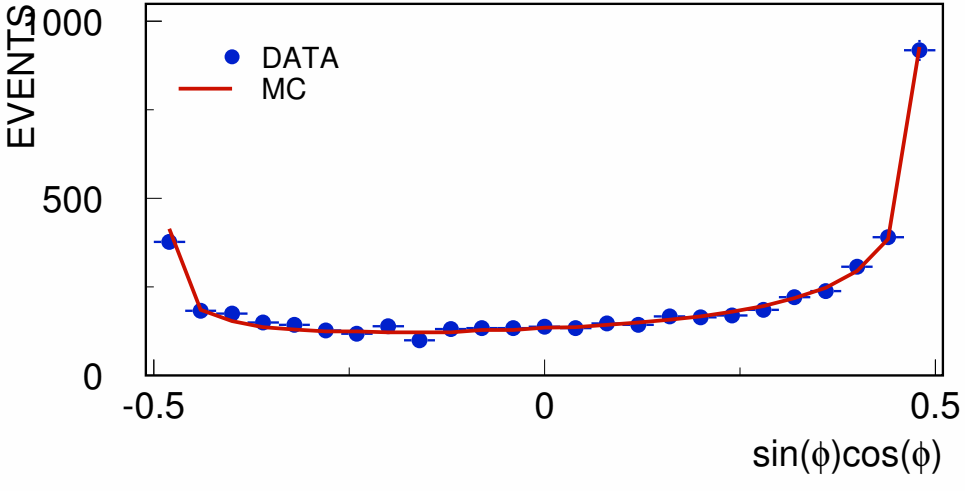
Angle between π^+ and e^+e^- system in $\pi^+\pi^-$ rest frame for DATA and Monte Carlo events



Angle between e^+ and $\pi^+\pi^-$ system in e^+e^- rest frame for DATA and Monte Carlo events



Angle ϕ between $\pi^+\pi^-$ and e^+e^- planes for DATA and Monte Carlo events



Parameter $\sin\phi\cos\phi$ for an angle between $\pi^+\pi^-$ and e^+e^- planes for DATA and Monte Carlo events

cp-violation results

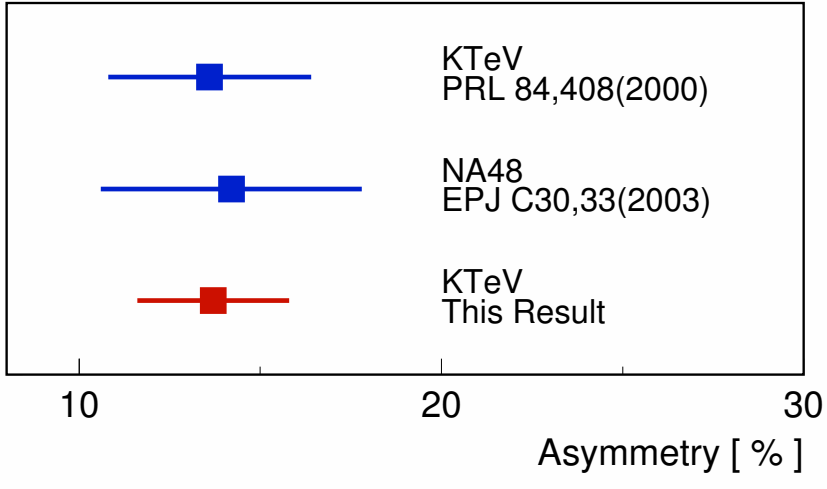
Asymmetry after acceptance corrections:

$$A = 13.7 \pm 1.4(\text{stat}) \pm 1.5(\text{syst})[\%]$$

Systematics:

Source	[%]
DATA/MC disagr.	0.71
Background	0.3
$\lvert\eta_{+-}\rvert$ uncertainty	0.16
Φ_{+-} uncertainty	0.11
$\delta_{0,1}$ uncertainty	0.33
$\lvert g_{E1}\rvert$ uncertainty	0.33
$\lvert g_{CR}\rvert$ uncertainty	0.34
$\tilde{g}_{m1}$, a_1/a_2 errors	0.34
Total Syst. Error	1.46

The result is in very good agreement with previously published measurements



conclusions

Entire KTeV data set is analyzed. We selected 5241 $K_L \to \pi^+\pi^- e^+ e^-$ candidates with estimated background of 185±14 events

We obtained several parameters for various decay amplitudes from this data sample:

$$\tilde{g}_{M1} = 1.11 \pm 0.12(\text{stat}) \pm 0.07(\text{syst})$$

$$a_1/a_2 = -0.744 \pm 0.022(\text{stat}) \pm 0.032(\text{syst})$$

$$|g_{E1}|/|g_{M1}| \leq 0.04 \ (90\%\text{CL})$$

$$|g_{CR}| = 0.163 \pm 0.017(\text{stat}) \pm 0.023(\text{syst})$$

K^0 charge radius is -0.077 ± 0.014 fm^2

Using these parameters, we measured CP-violating asymmetry integrated over phase space:

$$A = 13.7 \pm 1.4(\text{stat}) \pm 1.5(\text{syst})[\%]$$