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CELLO Collaboration

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Coupling Strengths of Weak Neutral Currents from Leptonic Final States at 22 and 34 GeV

CELLO-Collaboration

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Abstract:
Differential cross sections for $e^+e^-\to e^+e^-$, $\mu^+\mu^-$, $\tau^+\tau^-$ measured with the CELLO detector at $<\sqrt{s}> = 34.2$ GeV have been analyzed for electroweak contributions. Vector and axial vector coupling constants were obtained in a simultaneous fit to the three differential cross sections assuming a universal weak interaction for the charged leptons. The results, $v^2 = -.12 \pm .33$ and $a^2 = 1.22 \pm .47$, are in good agreement with predictions from the standard SU(2) x U(1) model for $\sin^2\theta_W = .228$.

Combining this result with neutrino-electron scattering data gives a unique axial vector dominated solution for the leptonic weak couplings.

Assuming the validity of the standard model, a value of $\sin^2\theta_W = .21 {}^{+.14}_{-.09}$ is obtained for the electroweak mixing angle. Additional vector currents are not observed ($C < 0.031$ is obtained at the 95% C.L.).

At the highest PETRA energies, e^+e^- interactions start to be sensitive to weak neutral current effects, and the standard model of electromagnetic and weak interactions |1| can be tested. Studies of these effects have concentrated mainly on purely leptonic reactions because of clean experimental signatures and unambiguous theoretical predictions. Charge asymmetries in the angular distributions of $\mu^+\mu^-$ and $\tau^+\tau^-$ final states, generated via interference of the electromagnetic current with the weak neutral axial vector current, have been observed |2|. In $e^+e^- \to e^+e^-$, the differential cross section is quite sensitive to the weak vector current.

Furthermore, e^+e^- reactions are sensitive to additional weak neutral vector current contributions (not accounted for by the standard model) which are not observable in neutrino-electron scattering or electron-deuteron parity violation experiments |3|.

In this letter, we report on results on the weak vector and axial vector coupling constants, determination of $\sin^2\theta_W$ within the standard model and upper limits for a deviation from the standard model current structure at high energies, based on new data for $e^+e^- \to e^+e^-$ at $\langle\sqrt{s}\rangle = 34.2$ GeV and already published data for $e^+e^- \to \mu^+\mu^-$ and $e^+e^- \to \tau^+\tau^-$ from the CELLO detector |2|.

The detector is described in detail elsewhere |4|. The essential components for the analysis of leptonic final states are:

- a central detector consisting of cylindrical proportional and drift chambers in a magnetic field of 1.3 T covering 91% of the solid angle. The proportional chambers are equipped with cathode strip read-out for position measurements along the beam axis. The momentum resolution of the central detector is $\Delta p/p = 0.025\, p_\perp$ (GeV) allowing a sign determination for charged particles even at maximum p .

- a lead liquid argon calorimeter with high granularity (20 mrad) and fine longitudinal sampling consisting of 16 modules entirely surrounding the central detector and covering $|\cos\theta| < .86$ in polar angle, and 4 additional end cap modules covering $.92 < |\cos\theta| < .98$. The energy resolution is $\sigma_E/E = .13/\sqrt{E}$ (E in GeV). One of the 16 central modules was not operating.
- μ-chambers behind 80 cm of iron to separate hadrons from muons (.92 of 4π).
- a programmable charged particle trigger allowing us to trigger on only 2 tracks, independent calorimeter triggers and various combinations of track and calorimeter triggers resulting in an experimentally measurable trigger efficiency for all lepton channels.

Charged particle tracking, calorimetry, muon filters and triggers have uniform acceptance and cover $|\cos\theta| < .86$ in polar angle.

The data used in this analysis correspond to a total integrated luminosity of $\sim$11 pb^{-1} taken with the CELLO detector in the center of mass energy region between $\sqrt{s} = 33$ GeV and 36.7 GeV. The luminosity weighted average energy was $\langle\sqrt{s}\rangle = 34.2$ GeV.

The data sample on Bhabha scattering contains 3 times more statistics than were presented in a previous paper on QED reactions |5|. We briefly summarize the analysis procedure and discuss the errors and losses.

The data were preselected by requiring more than 2 x 1.2 GeV electromagnetic energy as measured by the hardware sums of the calorimeter trigger. Losses in the preselection are less than 0.5%. By a cross check of 3 independent triggers, the trigger efficiency was determined to be higher than 99.9% for each $\cos\theta$ bin.

Subsequently, all events were processed by a track and shower reconstruction programme. Total shower energy $\geqslant 1/3\sqrt{s}$ and between 2 and 6 charged particle tracks were requested. Clusters of charged particle tracks and calorimeter showers were formed, and 2 collinear clusters with charged tracks and an acollinearity of less than 250 mrad were required. By this method, even Bhabha events which radiate in the beam pipe or the inner detector (7.6%) were included in the analysis and polar angle dependent efficiency corrections were avoided.

Reconstruction inefficiencies were determined by relaxing the track and shower criteria and visually scanning events only found with the looser cuts. Bhabha events with a non-reconstructed track (0.7%) or a non-reconstructed shower (1.3%) were added to the final sample.

Contamination from tau pair production, relevant in the backward direction, was determined experimentally and was rejected on an event by event basis. A large fraction of events was scanned, in particular, all events in the backward direction and all those with more than 2 tracks.

In 0.9% of the Bhabha events, a unique charge determination was not possible. These events were subdivided into forward and backward scattering according to the measured distribution of events with good charge determination.

Finally, the differential cross section was corrected for radiative effects including hadronic vacuum polarisation |6|. The overall systematic uncertainty in the central region is estimated to be 2% (including uncertainty for radiative corrections). The systematic point to point uncertainty is 1%.

The normalisation was determined from the small angle region, $.75 < \cos\theta < .85$, of the central detector and was cross-checked for part of the statistics with data from the end cap calorimeter ($.96 < \cos\theta < .98$). Both measurements agreed within the errors; the relative normalisation uncertainty is estimated to be $\sim 3\%$.

The differential cross sections for $e^+e^- \rightarrow e^+e^-$ at $<\sqrt{s}> = 34.2$ GeV and, for comparison, at $\sqrt{s} = 22$ GeV, are shown in Fig. 1. The data sample contains $16.5 \cdot 10^3$ events for $<\sqrt{s}> = 34.2$ GeV and $11.5 \cdot 10^3$ events for $\sqrt{s} = 22$ GeV. In order to stress the features relevant to this analysis,

the data are presented normalized to the first order QED expectation.

At both energies, the data are consistent with QED.

For $\mu^+\mu^-$ and $\tau^+\tau^-$ final states at $<\sqrt{s}> = 34.2$ GeV, the measured forward-backward weighted asymmetries are shown in Fig. 2. For details of the data analysis see Ref. |2|.

The asymmetry is defined as

$$A\,(\cos\theta) = \frac{d\sigma(\cos\theta) - d\sigma(-\cos\theta)}{d\sigma(\cos\theta) + d\sigma(-\cos\theta)}$$

Since the data have been corrected for radiative effects, no asymmetry ($A(\cos\theta) = 0$) is expected for pure QED.

Assuming μ-τ universality, the asymmetries can be combined to yield $<A> = -8.7 \pm 4.0$ in good agreement with the expectation of -9.1% from the standard model. The total cross sections for both reactions agree well with the QED expectation, but are less sensitive to an electroweak contribution than the differential cross sections.

For the model-independent determination of the vector and axial vector coupling constants, v^2 and a^2, weak-electromagnetic interference and purely weak terms are considered. The differential cross section for Bhabha scattering |7| reads

$$\begin{aligned}\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4s} \Bigg\{ & \left(\frac{3+x^2}{1-x}\right)^2 \\ & + 2\,\frac{3+x^2}{(1-x)^2}\left[(3+x)\,R_t - x(1-x)\,R_s\right] v^2 \\ & - \frac{2}{1-x}\left[(7+4x+x^2)\,R_t + (1+3x^2)\,R_s\right] a^2 \\ & + \left[\frac{8}{(1-x)^2}\,R_t^{\,2} + \frac{(1-x)^2}{2}\,R_s^{\,2}\right](v^2-a^2)^2 \\ & + \frac{(1+x)^2}{2}\left[\frac{2}{1-x}\,R_t - R_s\right]^2 (v^4+6v^2a^2+a^4) \Bigg\}\end{aligned}$$

The corresponding differential cross section for lepton pair production can be written as |8|

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4s}\left\{(1+x^2)\left[1+2v^2R_s+(v^2+a^2)^2 R_s^{\,2}\right] + 4x\left[a^2R_s + 2v^2a^2R_s^{\,2}\right]\right\}$$

$$x = \cos\ ; \quad t = -\frac{s}{2}(1-x)$$

$$R_s = \frac{G_F}{8\sqrt{2}\pi}\ \frac{M_{Z^0}^{\,2}\ s}{s-M_{Z^0}^{\,2}} \quad ; \quad R_t = \frac{G_F}{8\sqrt{2}\pi}\ \frac{M_{Z^0}^{\,2}}{t-M_{Z^0}^{\,2}}$$

Assuming lepton universality of the weak interaction, all the above described data were used in a simultaneous fit for v^2 and a^2. The mass of the vector boson, $M_Z^{\,o}$, was set to infinity, giving the weakest constraints. Including the normalisation uncertainty in the fit, the following results are obtained:

$$a^2 = 1.22 \pm .47$$
$$v^2 = -.12 \pm .33$$

The expectation from the standard model is

$$a^2 = 1$$
$$v^2 = (4\sin^2\theta_W-1)^2 = .008 \text{ for } \sin^2\theta_W = .228.$$

Our results are in agreement with this prediction obtained using the value measured for $\sin^2\theta_W$ at low q^2 |10|. We compare our results with determinations by other experiments in Table 1 |9|.

The 95% C.L. contours of the fit result in the $v^2 - a^2$ plane are shown in Fig. 3 together with the two allowed regions from neutrino-electron scattering |10|. The axial vector dominated solution from the neutrino data is favoured by our result over the vector dominated solution by more than 4 standard deviations.

For Bhabha scattering, v^2 and a^2 are correlated; the data prefer an a^2 contribution but mainly constrain v^2 to small values. The muon and tau pair asymmetry measurement gives the main constraint on a^2 and is responsible for the non-zero weak effect.

Within the framework of the standard model, the axial vector coupling is $a^2 = 1$. Only v^2 and the mass of the neutral intermediate vector boson, $M_Z^{\,o}$, are dependent on $\sin^2\theta_W$.

$$v^2 = (4\sin^2\theta_W-1)^2$$
$$M_Z^{\,o} = 37.2 \text{ GeV}/\sin\theta_W\ \cos\theta_W$$

Fitting all leptonic data with this single parameter, we obtain

$$\sin^2\theta_W = .21\ {}^{+\ .14}_{-\ .09}$$

This determination of the Weinberg angle is compared with results from other experiments in Table 1.

As mentioned above, the e^+e^- induced neutral current reactions are sensitive to contributions from vector currents not accounted for in the standard model and not observable in neutrino-electron scattering or e-D parity violation experiments |3|. This possible contribution may be characterized by the parameter, C, in the effective lagrangian of the neutral current

$$L_{eff}^{NC} = \frac{4G_F}{\sqrt{2}}\left[(j^{(3)} - \sin^2\theta_W j_{em})^2 + Cj_{em}^2\right]$$

and

$$a^2 = 1$$
$$v^2 = (4\sin^2\theta_W - 1)^2 + 16\ C$$

In the standard model, C is zero. Assuming $\sin^2\theta_W = .228$, our data are consistent with C = 0. Fitting for the parameter C with $\sin^2\theta_W = .228$, we obtain the 95% C.L. upper limit

$$C < .031.$$

Table 1 shows, for comparison, values of C obtained by other experiments.

A mass of the intermediate vector boson considerably smaller than the standard model prediction should show up as a propagator effect which was neglected in the above fit for v^2 and a^2. Setting v^2 and a^2 to the values measured in neutrino-electron scattering [10], our data set a lower limit for the Z^0 mass:

$$M_Z^0 > 57 \text{ GeV} \quad 95\% \text{ C.L.}$$

In conclusion, we have analyzed the leptonic reactions $e^+e^-\to e^+e^-$, $\mu^+\mu^-$, $\tau^+\tau^-$ at energies between 22 and 36.7 GeV for contributions from weak effects. Our data can be described consistently with the standard model using the value of $\sin^2\theta_W$ measured at low q^2.

Limits on possible deviations from the standard model are given. Taking into account results from neutrino-electron scattering, a unique axial vector dominated solution for the leptonic coupling constants of the weak neutral current is determined.

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Experiment	a^2	v^2	$\sin^2\Theta_W$	C 95% C.L.	used reactions
CELLO	1.22±.47	-.12±.33	$.21^{+.14}_{-.09}$	<.031	ee, $\mu\mu$, $\tau\tau$
JADE	1.56±.44	.20±.32	.25±.15	<.039	ee, $\mu\mu$
MAC	0.16±.88	-	.25±.16	-	ee, $\mu\mu$
MARK II	0.96±.64	<.61	-	-	ee, $\mu\mu$
MARK J	1.12±.36	.04±.44	.24±.11	<.027	ee, $\mu\mu$, $\tau\tau$
PLUTO	-.76±.96	-.08±.66	.23±.17	<.06	ee, $\mu\mu$, $\tau\tau$
TASSO	1.40±.36	-.16±.24	$.27^{+.06}_{-.07}$	<.020	ee, $\mu\mu$

Electroweak Coupling Parameters from Leptonic Reactions in e^+e^- Annihilation [2], [9].

Table 1

Figure Captions

Fig. 1 The differential cross section $d\sigma/d\Omega$ for Bhabha scattering at $<\sqrt{s}>$ = 34.2 GeV and $\sqrt{s}$ = 22 GeV normalized to the QED cross section.
The full line is the QED prediction. The dotted line represents the best fit for a^2 and v^2.
The dotted-dashed line shows the prediction for the second solution for neutrino-electron scattering ($v^2 = 1.08$, $a^2 = 0.0$).

Fig. 2 The weighted asymmetry $(1+\cos^2\Theta)$ A $(\cos\Theta)$ for lepton pair production at $<\sqrt{s}>$ = 34.2 GeV.
The full line is the QED prediction.
The dotted line represents the best fit for a^2 and v^2.

Fig. 3 The 95% confidence level contours for the electroweak coupling constants a^2 and v^2.
The two shaded areas show the 95% confidence level contours obtained by neutrino-electron experiments.

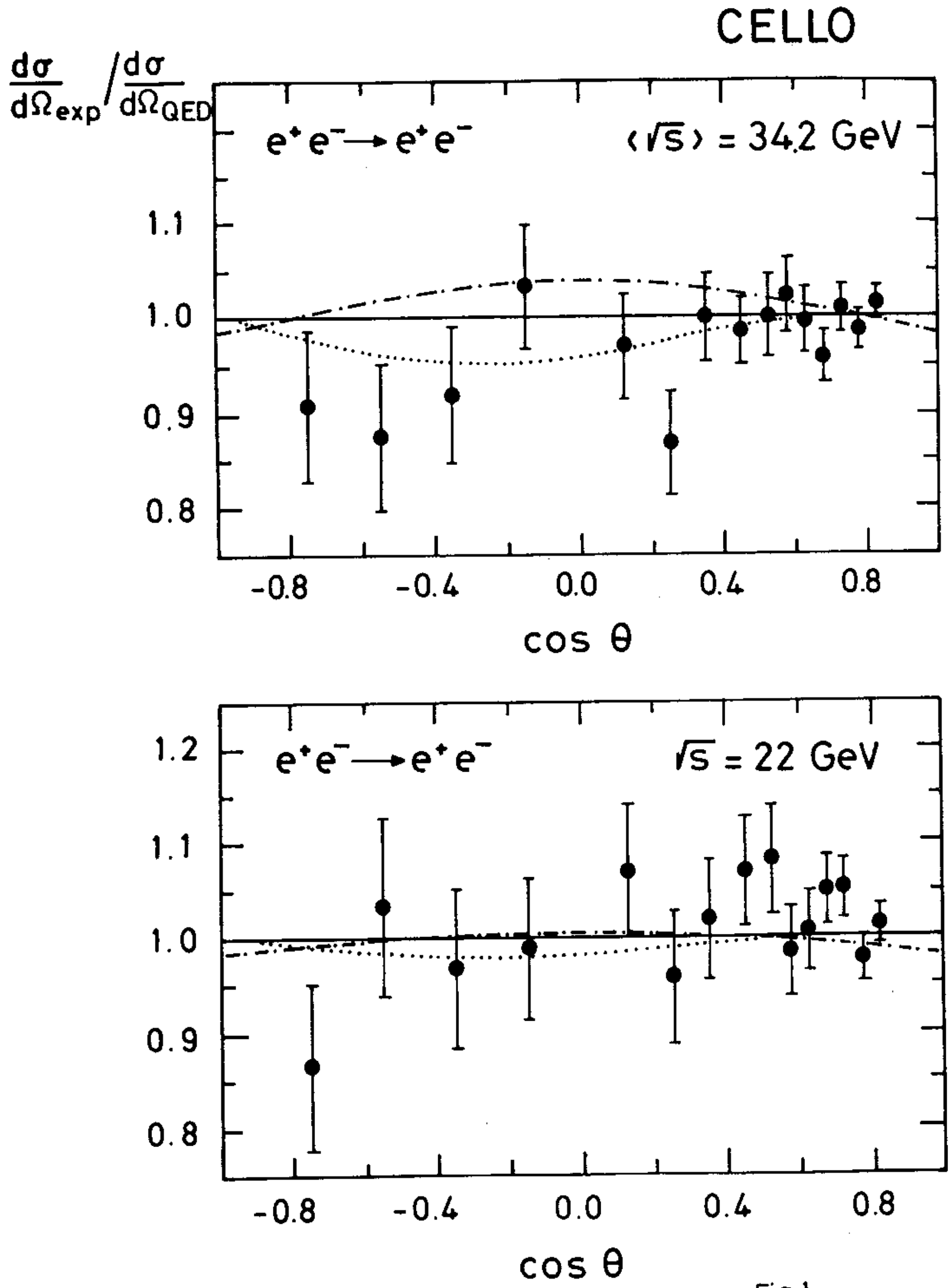
CELLO
$\frac{d\sigma}{d\Omega_{exp}} / \frac{d\sigma}{d\Omega_{QED}}$
$e^+e^- \to e^+e^-$
$\langle\sqrt{s}\rangle = 34.2$ GeV
1.1
1.0
0.9
0.8
-0.8
-0.4
0.0
0.4
0.8
$\cos\theta$
1.2
1.1
1.0
0.9
0.8
$e^+e^- \to e^+e^-$
$\sqrt{s} = 22$ GeV
-0.8
-0.4
0.0
0.4
0.8
$\cos\theta$

Fig.1

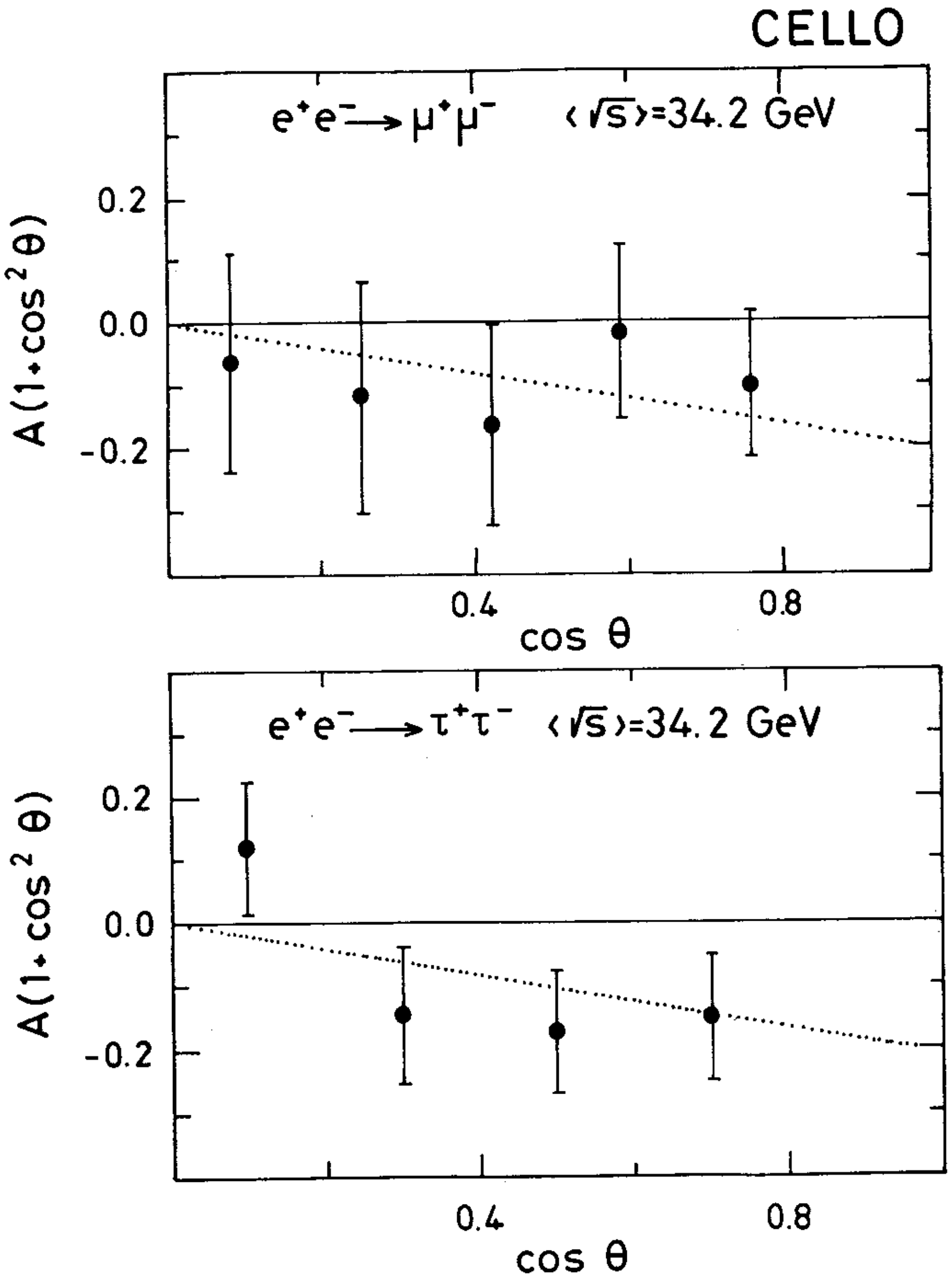
CELLO
$e^+e^- \to \mu^+\mu^-$
$\langle\sqrt{s}\rangle = 34.2$ GeV
$A(1+\cos^2\theta)$
0.2
0.0
-0.2
0.4
0.8
$\cos\theta$
$e^+e^- \to \tau^+\tau^-$
$\langle\sqrt{s}\rangle = 34.2$ GeV
$A(1+\cos^2\theta)$
0.2
0.0
-0.2
0.4
0.8
$\cos\theta$

Fig. 2

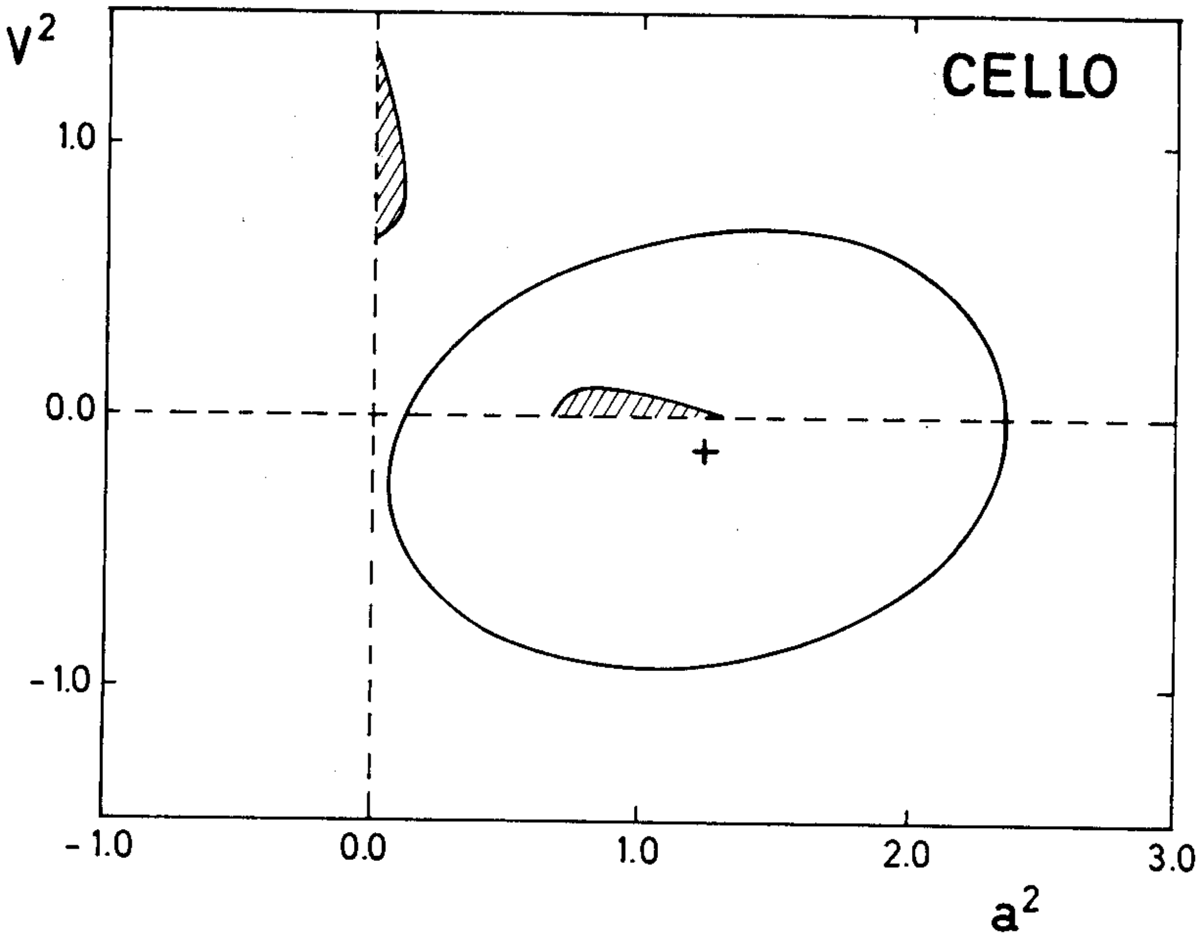

Fig. 3