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**MEASUREMENT OF THE $\phi\phi$ CROSS-SECTION
IN $p\bar{p}$ ANNIHILATIONS AT $E_{\text{cm}} \approx 3 \text{ GeV}$**

The R704 Collaboration

Annecy (LAPP)-CERN-Genoa-Lyon (IPN)-Oslo-Rome-Strasbourg-Turin

C. Baglin^{a)}, S. Baird^{b)}, G. Bassompierre^{a)}, C. Biino^{c)}, G. Borreani^{c,1)}, J.-C. Brient^{a)}, J.M. Brom^{d)},
L. Bugge^{e)}, T. Buran^{e)}, J.-P. Burq^{f)}, A. Bussire^{a)}, A. Buzzo^{g)}, A. Ceccucci^{c)}, R. Cester^{c)},
M. Chemarin^{f)}, M. Chevallier^{f)}, B. Escoubes^{d)}, J. Fay^{f)}, S. Ferroni^{g)}, V. Gracco^{g)}, J.-P. Guillaud^{a)},
B. Ille^{f)}, E. Khan-Aronsen^{b)}, K. Kirsebom^{e)}, M. Lambert^{f)}, L. Leistam^{b)}, A. Lundby^{b)}, M. Macri^{g)},
F. Marchetto^{c)}, E. Menichetti^{c,2)}, A. Migliori^{c)}, B. Mouellic^{b)}, R. Mussa^{c)}, S. Palestini^{c)},
N. Pastrone^{c)}, L. Pesando^{c)}, L. Petrillo^{h)}, M.G. Pia^{g)}, J. Poole^{b)}, M. Poulet^{a)}, G. Rinaudo^{c)},
A. Santroni^{g)}, M. Severi^{h)}, G. Skjevling^{e)}, S. Stapnes^{e)} and B. Stugu^{e)}

- a) LAPP, Annecy-le-Vieux, France.
- b) CERN, Geneva, Switzerland.
- c) University of Turin and INFN, Turin, Italy.
- d) CRN, Strasbourg, France.
- e) University of Oslo, Norway.
- f) IPN Lyon, Villeurbanne, France.
- g) University of Genoa and INFN, Genoa, Italy.
- h) University of Rome, Italy.

ABSTRACT

In an experiment performed at the CERN Intersecting Storage Rings as a part of an energy scan to detect the η_c formation in $p\bar{p}$ annihilation, we studied the reaction $p\bar{p} \rightarrow \phi\phi \rightarrow K^+K^-K^+K^-$. The total cross-section has been determined to be $25.0 \pm 7.4 \pm 3.8 \text{ nb}$.

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- 1) Present address: University of Ferrara and INFN, Ferrara, Italy.
 - 2) Present address: University of Udine, Italy.

1. INTRODUCTION

The OZI rule [1] postulates that disconnected quark diagrams are suppressed, whereas the connected ones are not. This rule has been introduced to explain the anomalously small decay amplitude of several particles in pre-charm and charm physics. A few cross-section measurements of exclusive channels also support its validity in interaction processes [2]. This paper describes a measurement of the total cross-section for the process $p\bar{p} \rightarrow \phi\phi$ by detecting the decay chain

$$\begin{array}{c}
 p\bar{p} \rightarrow \phi\phi \\
 \quad \swarrow \quad \searrow \\
 \quad K^+ K^- \quad K^+ K^-
 \end{array} \quad (1)$$

Since the p ($\bar{p}$) is a mixture of u and d ($\bar{u}$ and $\bar{d}$) quarks and the ϕ is composed of a strange quark and its antiquark, the reaction under study is expected to be greatly suppressed.

2. EXPERIMENTAL SET-UP

Experiment R704 was primarily designed to detect and measure the mass and the width of charmonium states, and it is described extensively elsewhere [3]. Here we summarize the most relevant features.

An unbunched coasting antiproton beam was circulated in Ring 2 of the CERN Intersecting Storage Rings (ISR) and interacted on a H_2 gas target crossing the beam vacuum pipe perpendicularly. The performance of the cooling system made it possible to obtain an E_{cm} r.m.s. spread of ≈ 660 keV at $E_{cm} = 3$ GeV. The interaction point was contained with a 90% probability in a $0.5 \times 0.8 \times 0.9$ cm³ region.

The detector consisted of two non-magnetic arms surrounded by a veto counter system. Each arm (fig. 1) had 45° of azimuthal acceptance ϕ and covered from 17° to 66° in polar angle θ . A secondary particle, leaving the interaction region and going into an arm, crossed a scintillator S, two sets of multiwire proportional chambers (MWPCs), one before and one after the threshold Cherenkov counter C, a double-layer scintillator hodoscope with a θ , ϕ segmentation ($H\theta$ - $H\phi$), a lead-scintillator sandwich ($4.7X_0$), a single-plane scintillator hodoscope segmented in θ ($SH\theta$), a proportional analog readout chamber, and finally a lead-glass counter wall ($10X_0$). The veto system V, composed of lead-scintillator sandwiches ($\approx 4.7X_0$), surrounded the spectrometer arms with full azimuthal coverage and a polar acceptance ranging from 1.7° to 77°.

The trigger for reaction (1) required a coincidence in both arms of $S \times H\theta \times H\phi \times SH\theta$ vetoed by any signal from V. In the laboratory frame, at our energies and within the detector acceptance, the opening angle of the two kaons from the ϕ decay is such that the two daughter particles cannot go into different arms. This consideration led to the implementation of a second-level trigger, constraining the charged multiplicity in $H\theta$ and $H\phi$ in each arm to be less than 3.

A large fraction of data was taken with a third-level trigger to reduce the acquisition rate further. A MICE processor system [4] was set up to check the event topology (two charged tracks per arm) by scanning through the MWPC hit pattern, and to stop and reset the main acquisition system whenever the event was found to be inconsistent with the expected topology. The charged-particle tracking, which is relevant to the present analysis, was obtained by using the two MWPCs, located ~ 34 cm and ~ 87 cm from the interaction region. Each MWPC consisted of three wire planes (x , y , and v) with a 2 mm pitch.

The luminosity was monitored ($\pm 5\%$) by measuring the differential cross-section for large-angle $p\bar{p}$ elastic scattering with a silicon detector telescope.

3. DATA REDUCTION

During an energy scan made around the η_c mass to study the charmonium state through its decay into either $\gamma\gamma$ or $\phi\phi$, we accumulated $\sim 10^6$ triggers for charged final states. Results on the electromagnetic decay have already been published [5]. Here we report on an analysis done on the charged triggers. The relevant information about the scan is reported in table 1.

We applied an off-line filter to the above sample in order to select events that were topologically compatible with reaction (1) by requiring i) two tracks per arm reconstructed in the MWPC; ii) all the tracks to originate inside the small interaction volume; iii) no hits in the veto counters.

At this stage we were left with a sample of $\sim 5 \times 10^5$ four-charged-prong event candidates.

We tested the hypothesis that these events satisfy the kinematics of reaction (1) by imposing the constraints of energy momentum conservation for the process $p\bar{p} \rightarrow 4K$, and further requiring that the invariant mass of each of the two outgoing particle pairs in the same arm, interpreted as K , be equal to the ϕ mass (altogether six constraints). Since the four-momenta of p and $\bar{p}$ are precisely known and the final-state particle directions are measured, only the four outgoing particle energies must be determined, leading to a 2C fit. Explicitly, the six constraint equations are

$$\Sigma_i p_{xi} = 0 , \quad (2)$$

$$\Sigma_i p_{yi} = 0 , \quad (3)$$

$$\Sigma_i p_{zi} - p_{beam} = 0 , \quad (4)$$

$$\Sigma_i E_i - E_{lab} = 0 , \quad (5)$$

$$m_{KK} - m_\phi = 0 \quad \text{in arm 1} , \quad (6)$$

$$m_{KK} - m_\phi = 0 \quad \text{in arm 2} , \quad (7)$$

where p_{xi} , p_{yi} , p_{zi} , E_i ($i = 1, \dots, 4$) are the K momentum components and energies, p_{beam} and E_{lab} are the beam momentum and the total energy in the laboratory system, m_{KK} is the $K^+ K^-$ invariant mass, and $m_\phi (= 1019.5 \text{ MeV}/c^2)$ is the ϕ mass.

Before performing a kinematical fit, we applied preliminary cuts to reduce the sample size further. We calculated E_i by solving the system of eqs. (2) to (4) and (6) [or (7)]; then we required that eqs. (5) and (7) [or (6)] be verified within 200 MeV and 200 MeV/ c^2 , respectively. A total of 9913 events passed these kinematical cuts. A least-squares fit, based on the Lagrange multiplier method [6], was applied to these events. The fit method relies on an iterative procedure to minimize the Lagrange function, which, expressed in matrix notations, is

$$\chi^2 = (\alpha^m - \alpha^f)^T V_\alpha (\alpha^m - \alpha^f) + 2\lambda^T F(\alpha^f, p^f) .$$

In the first term, $\alpha^m - \alpha^f$ is an eight-component vector of the difference between the measured and the fitted final-state particle directions (four polar and four azimuthal angles) and V is the angle error matrix. In this matrix, error correlations in azimuthal and polar angle have been taken into account. The second term is the product of two six-component vectors: λ components are the usual Lagrange multipliers, whilst F consists of the constraint functions computed at the above-defined α^f values and at the fitted final-state particle momenta p^f . In this procedure the ϕ intrinsic width ($\Gamma = 4.22 \text{ MeV}$) was neglected.

In fig. 2 we show the distribution of the event probability (CL) resulting from the fit procedure. A large fraction of the sample does not fit the hypothesis: these events are characterized by a very low probability (CL < 0.01). We interpret the remaining events (CL > 0.01) as being due to two separate contributions: i) good $\phi\phi$ events (signal); ii) any four-charged-prong final-state event that — when all the outgoing particles are assumed to be K's — fakes a genuine $\phi\phi$ (background). Indeed, for CL < 0.3 the background contribution dominates, and only above CL = 0.3 does the probability distribution become almost flat, indicating that the signal-to-background ratio is more favourable. For the rest of this paper, only the events with CL > 0.3 will be considered as fitting the hypothesis.

4. RESULTS

As stated above, the K^+K^- invariant mass enters the fit as an input constraint. In order to estimate the background level, we applied a kinematical fit to the entire sample of 9913 events, imposing different values of the K^+K^- invariant mass. We expect that for values outside the ϕ mass region, $(1019.5 \pm 2.1) \text{ MeV}/c^2$, events that fit are predominantly background.

In fig. 3 we show the distribution of the number of events fitting reaction (1) as a function of the imposed K^+K^- invariant mass. The spacing between the five central data points is $2.1 \text{ MeV}/c^2$. Neighbouring samples have in common a fraction of events that is consistent with the expected overlap when the reconstructed mass spread (r.m.s. = $1.2 \text{ MeV}/c^2$) is taken into account. The first and the last two points are symmetrically spaced with respect to the central one placed at $m_{K^+K^-} = m_\phi$, separated from it by ~ 8.5 and $\sim 17 \text{ MeV}/c^2$, and are essentially independent.

To determine the background level, we fitted the two extreme pairs of points to a straight line, assuming that they are entirely due to background. The straight line represents the best fit, and by interpolation the expected number of background events at $m_{K^+K^-} = m_\phi$ is found to be 49.7 ± 3.5 . The resulting excess at the ϕ mass is of 33.3 ± 9.7 events, corresponding to a measured cross-section of $67.0 \pm 19.7 \text{ pb}^*$.

The extrapolation from the measured cross-section to the corrected cross-section relies on several correction factors:

$$\sigma_{\text{meas}} = \sigma_{\text{corr}} \cdot \text{BR}(\phi \rightarrow K^+K^-)^2 \cdot P_d \cdot \text{acc}_{\text{MC}} \cdot e_{\text{fit}} \cdot e_{\text{MICE}},$$

where

σ_{meas} and σ_{corr} are the measured and the corrected cross-section, respectively;

$\text{BR}(\phi \rightarrow K^+K^-) = 0.495$ is the $\phi \rightarrow K^+K^-$ branching ratio;

$P_d = 0.62$ is the average probability that all four K's reach the farther MWPC (at $\sim 87 \text{ cm}$) before decaying;

$\text{acc}_{\text{MC}} = 0.068$ is the geometrical detector acceptance evaluated by Monte Carlo assuming isotropic $\phi\phi$ production and decay;

$e_{\text{fit}} = 0.37 \pm 0.05$ represents the efficiency of the fit analysis. This was determined by processing, with the same program chain, a sample of $p\bar{p} \rightarrow \phi\phi$ Monte Carlo generated events. The fairly low efficiency is due to the combination of two contributions: i) the CL cut at 0.3, which in principle rejects only 30% of the signal; and ii) the ϕ natural width, which was not taken into account. The natural width is larger than the reconstructed mass resolution, and the tails of the Breit-Wigner (BW) distributions are partly rejected. This last contribution is affected by the uncertainty arising from the Monte Carlo reproducibility of the experimental errors, which gives a systematic error of ± 0.05 .

*) We checked that by varying the CL cut, the excess of events remains and the results are statistically compatible.

ϵ_{MICE} is the third-level trigger efficiency. A fraction of the luminosity (384.2 nb^{-1} out of 497 nb^{-1}) was accumulated with MICE in Master mode. Comparing data taken with MICE on and MICE off, we computed the trigger efficiency for tagging events with two tracks per arm. The overall efficiency of the third-level trigger was $\approx 0.70 \pm 0.05$.

Combining all the above factors, we quote $\sigma_{\text{corr}} = 25.0 \pm 7.4 \pm 3.8 \text{ nb}$, where the first error is statistical and the second one is systematic.

Besides the direct coupling of the $p\bar{p}$ annihilation process to $\phi\phi$, a contribution to the total cross-section might come through the η_c formation and subsequent decay to $\phi\phi$. This latter contribution should appear as a cross-section increase at the η_c mass.

The measured cross-section distribution, corrected to count for energy-dependent effects in the third-level trigger efficiency, is shown in fig. 4 as a function of the centre-of-mass energy. The significance of the data is limited by the small number of events in our sample.

However, to check the consistency of our data with previously published measurements, we performed a fit analysis using the maximum-likelihood method as described in ref. [7], by parametrizing the cross-section distribution as

$$\sigma(E_{\text{cm}}) = a + bE_{\text{cm}} + \text{BW}(E_{\text{cm}}, m_{\eta}, \Gamma_{\eta}) \text{BR}(\eta_c \rightarrow p\bar{p}) \text{BR}(\eta_c \rightarrow \phi\phi),$$

where $a + bE_{\text{cm}}$ describes the non-resonant behaviour of the cross-section, assumed to be energy-dependent, and the last term is the resonant η_c contribution consisting of the product of the Breit-Wigner cross-section BW times the $\eta_c \rightarrow p\bar{p}$ and $\eta_c \rightarrow \phi\phi$ branching ratios; a , b , and $\text{BR}(\eta_c \rightarrow \phi\phi)$ were considered to be free parameters, whilst m_{η} and Γ_{η} were fixed at $2976.9 \text{ MeV}/c^2$ and 10.3 MeV , respectively [8]. For the product of the branching ratios we found: $\text{BR}(\eta_c \rightarrow p\bar{p}) \cdot \text{BR}(\eta_c \rightarrow \phi\phi) = (4.0 \pm 3.5 \pm 3.2) \times 10^{-6}$.

Combining published results, namely $\text{BR}(\eta_c \rightarrow p\bar{p}) = (1.1 \pm 0.6) \times 10^{-3}$ [9] and $\text{BR}(\eta_c \rightarrow \phi\phi) = (8.2 \pm 2.0 \pm 2.5) \times 10^{-3}$ as measured by the MARK III Collaboration [10], or $\text{BR}(\eta_c \rightarrow \phi\phi) = (3.1 \pm 0.7 \pm 0.4) \times 10^{-3}$ as measured by the DCI Collaboration [11], we find that our data are consistent with the previous measurements.

5. CONCLUSIONS

In Experiment R704 at the CERN ISR, which was mainly devoted to a charmonium state study, we measured the $p\bar{p} \rightarrow \phi\phi$ total cross-section in the centre-of-mass energy region of η_c formation.

The limited integrated luminosity accumulated during the η_c scan did not allow us to make a complete study of the $\phi\phi$ production through η_c resonance formation, as much larger statistics would have been necessary in order to observe a clear signal. With our data sample, we are only able to quote $\text{BR}(\eta_c \rightarrow p\bar{p}) \cdot \text{BR}(\eta_c \rightarrow \phi\phi) = (4.0 \pm 3.5 \pm 3.2) \times 10^{-5}$, which is consistent with the previously published data.

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Table 1

Summary of the energy scan conditions and fit results.

The quoted centre-of-mass energies represent the peak value of the beam energy distribution.

The number of events refers to those fitting the reaction (1) hypothesis with $CL > 0.3$ (see text).

E_{cm} (MeV)	Integrated luminosity (nb ⁻¹)	MICE	No. of events
2967	40.4	Off	4
2967	45.7	On	4
2974	28.6	Off	5
2978	84.0	On	14
2984	18.9	Off	10
2984	71.3	On	9
2984	52.1	On	8
2987	61.3	On	12
3024	24.9	Off	8
3024	69.8	On	9

Figure captions

Fig. 1 Longitudinal layout of an arm of the detector.

Fig. 2 Fit confidence level distribution. The upper limit of the first bin edge is equal to 0.01.

Fig. 3 Number of fitting ($CL > 0.3$) events as a function of the $K^+ K^-$ invariant mass. The line is the result of a straight-line fit to the first and last two points.

Fig. 4 Measured $\phi\phi$ cross-section as a function of the centre-of-mass energy.

Fig. 2

Fig. 1

Fig. 3

Fig. 4