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R. Bertani and R. Del Fabbro: ON THE POSSIBLE EXPERIMENTAL SEARCH FOR THE PATI-SALAM NEUTRAL VECTOR GLUONS IN e^+e^- COLLISION.

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1. - PATI-SALAM QUARK-LEPTON THEORY.

New fondamental particles coupled to e^+e^- have been predicted in the unified gauge theory of quarks, leptons and gluons developed by J. C. Pati and A. Salam(1).

In this theory quarks have integer electrical charge, are not confined and can decay into leptons with a lifetime of the order of $10^{-13} \div 10^{-11}$ sec. This short lifetime could be the reason why they have escaped detection so far.

A coloured octet of gluons is also predicted in this theory, whose two neutral members (V_3 and V_8) can mix together into two orthogonal neutral gluons: $\tilde{U}$ and V^o. The former ($\tilde{U}$) can be coupled to e^+e^-, similarly to the photon, with coupling constant $-2/\sqrt{3}\, e^2/f$, where f is the strong gauge coupling parameter.

In the real world two neutral particles could exist coupled to e^+e^- with weights $\cos^2\xi$ and $\sin^2\xi$, according to the mixing scheme

$$\underset{\sim}{U} = \tilde{U} \cos\xi - V^o \sin\xi \;, \qquad \overline{V} = \tilde{U} \sin\xi + V^o \cos\xi \quad . \tag{1}$$

TABLE I

Decay modes	Width
$\tilde{U} \longrightarrow e^+e^-$ or $\mu^+\mu^-$	6 to 30 keV
$\longrightarrow \eta'\gamma$	40 to 1000 keV
$\longrightarrow 2\pi\gamma,\ 4\pi\gamma$	50 to 500 keV
$\longrightarrow 3\pi,\ 5\pi,\ \varrho\pi,\ K\overline{K}$	10 to 1000 keV
$\longrightarrow 2\pi,\ 4\pi,\ K\overline{K}$	10 to 1000 keV

The predicted particle widths as well as the branching ratios depend on the $\tilde{U}$ mass. Two possible ranges of values have been considered by the authors: the $1 \div 2$ GeV/c^2 region and the $8 \div 10$ GeV/c^2 region.

In the present note we report a study of a possible experimental search for the $\tilde{U}$ in the $1 \div 2$ GeV/c^2 mass-range. In Table I the partial $\tilde{U}$ widths are reported for the $\tilde{U}$ mass ranging from 1 to 2 GeV/c^2.

In particular we consider the decay

$$\tilde{U} \longrightarrow \eta'\gamma \tag{2}$$

which offers a clear experimental signature by means of a monochromatic photon. The present study was performed in the frame of the ALA-MDA project[2], with the aim of understanding the importance of measuring energies as well as angles of final state photons.

2. - EXPERIMENTAL METHOD.

Two possible decay channels :

$$e^+e^- \longrightarrow \tilde{U} \longrightarrow \eta'\gamma \quad \hookrightarrow \gamma\varrho \longrightarrow \pi^+\pi^- \qquad (3)$$

$$e^+e^- \longrightarrow \tilde{U} \longrightarrow \eta'\gamma \quad \hookrightarrow \pi^+\pi^-\eta^o \longrightarrow \gamma\gamma \qquad (4)$$

were considered corresponding to a probable occurrence of 30 % and 25 % respectively. A Montecarlo simulation of these decays and the successive detection of pions and photons in the final state by means the MDA apparatus was performed.

The detection efficiency was taken equal to zero below and equal to one above threshold (50 MeV/c for pions and 100 MeV/c for photons). The geometrical efficiency of the MDA detector was taken correctly into account.

We have also performed a Montecarlo simulation of the process :

$$e^+e^- \longrightarrow \text{hadrons} \qquad (5)$$

in those final state channels which are more likely to simulate the decay modes (3) and (4). Distributions of possible physical background for various reactions (5) are thus obtained. Successively cuts were applied to these distributions according to the signatures of reactions (3) and (4). The remaining events weighted with the corresponding cross sections in the regions where the "good events" are expected, represent an experimental sensitivity limit to the hunt for the $\tilde{U}$ particle.

In the next sections we discuss the results and the order of magnitude of the sensitivity that can be reached with this experimental set up.

3. - RESULTS ON DECAY MODE (3).

Two charged pions and two photons are present in the final state of decay mode (3). A suitable plot to represent the events is a scatter plot versus $E_{\gamma 1}$, $E_{\gamma 2}$.

The event distribution for $\tilde{U}$ particle decays is shown in Fig. 1 at $\sqrt{s} = m_{\tilde{U}} = 1600$ MeV. The width of the event distribution is determined by the mass resolution, which was assumed to be $\Delta E_\gamma/E_\gamma = 1.5/\sqrt{E_\gamma}$ (MeV). At this value of $\sqrt{s}$ the monochromatic photon has an energy of 513 MeV and the other photon ranges from 80 to 380 MeV. The events are thus distributed on a strip as shown in Fig. 1.

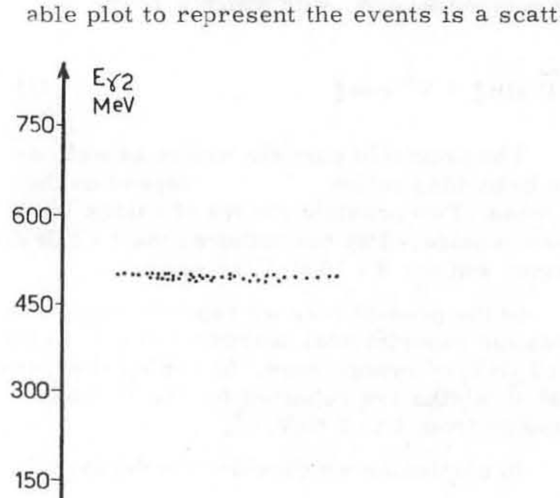


FIG. 1 - Event plot in the $E_{\gamma 1}/E_{\gamma 2}$ plane for the reaction $e^+e^- \longrightarrow \tilde{U} \longrightarrow \eta'\gamma \hookrightarrow \varrho\gamma \longrightarrow \pi^+\pi^-$.

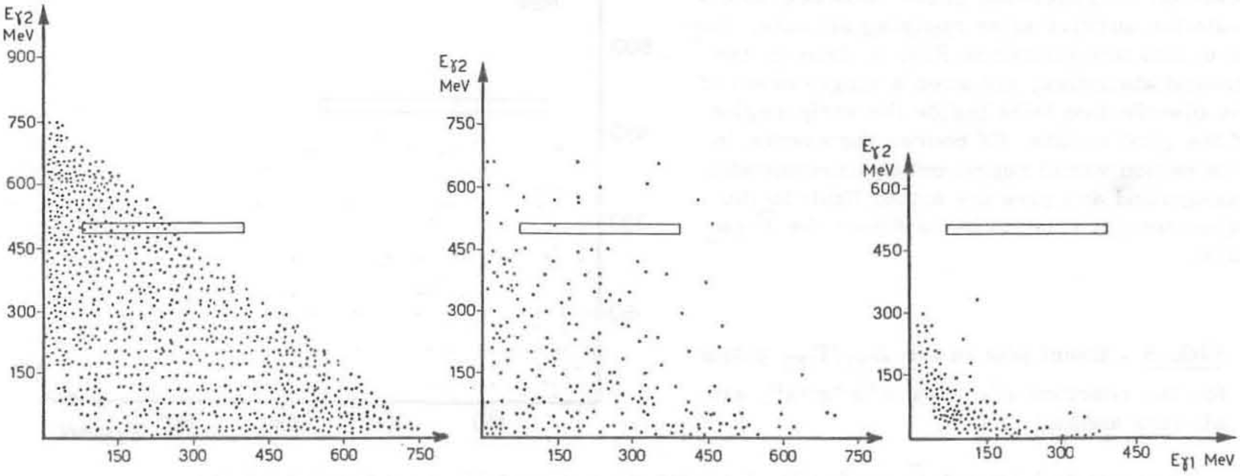
The following background reactions were considered:

$$e^+e^- \longrightarrow \pi^+\pi^-\pi^0 \qquad \text{with no particle lost}, \tag{6}$$

$$e^+e^- \longrightarrow \pi^+\pi^-\pi^0\pi^0 \qquad \text{with two photons lost}, \tag{7}$$

$$e^+e^- \longrightarrow \pi^+\pi^-\pi^+\pi^-\pi^0 \qquad \text{with two pions lost}. \tag{8}$$

The corresponding plots of these reactions are shown in Figs. 2, where the region where the good events are expected to be confined is also reported for comparison.



(a) (b) (c)

FIG. 2 - Event plot in the $E_{\gamma 1}/E_{\gamma 2}$ plane for the reactions: (a) $e^+e^- \longrightarrow \pi^+\pi^-\pi^0$; (b) $e^+e^- \longrightarrow \pi^+\pi^-\pi^0\pi^0$; (c) $e^+e^- \longrightarrow \pi^+\pi^-\pi^+\pi^-\pi^0$.

As far as the rejection of these reactions is concerned, we note that in reactions (6) and (8) the invariant mass of the two photons is the π^0 mass. The expected mass resolution is shown in Fig. 3 versus the π^0 momentum. These events can be rejected by requiring that the $\gamma\gamma$ mass be different from the π^0 mass by more than 50 MeV, corresponding to two standard deviations of the measurement error. By considering the two photon invariant mass distribution for $\tilde{U}$ decays shown in Fig. 4 we observe that only about 5 % of good events are lost in this way, while back-

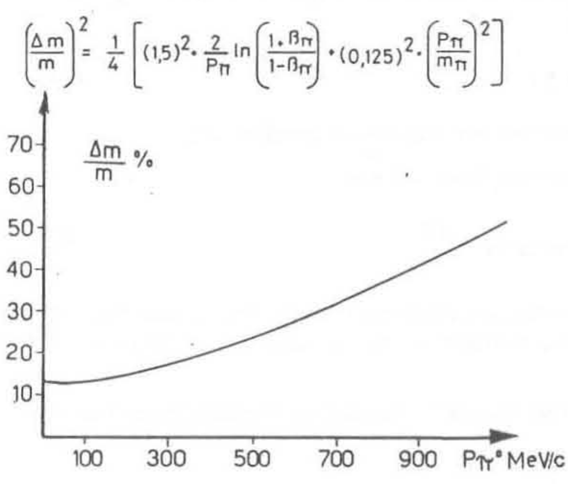


FIG. 3 - π^0-mass resolution as a function of the π^0 momentum.

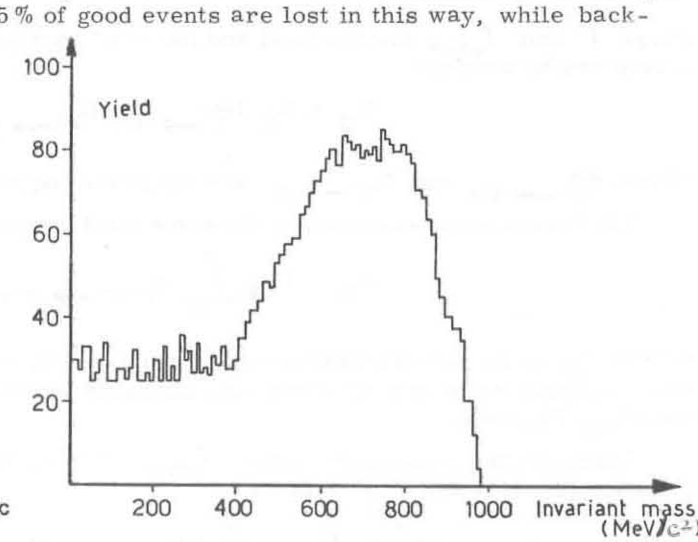


FIG. 4 - Invariant mass distribution of the two final state photons of the reaction

$$e^+e^- \longrightarrow \tilde{U} \longrightarrow \eta'\gamma$$
$$\hookrightarrow \rho\gamma \longrightarrow \pi^+\pi^-.$$

grounds (6) and (8) are totally and background (7) is partially rejected. As a matter of fact, reaction (7) is rejected when the two detected photons come from a π^o decay, while some background is left when the two photons come from different π^o decays.

Further cuts can be applied to further reduce this background. One can request that the two pion invariant mass equals the ϱ mass within $\pm$ 80 MeV, and that the invariant mass of the two pions and of the lowest energy photon equals the η' mass within the $\pm$ 50 MeV (corresponding to two standard deviations of the η' mass resolution).

Only a few events out of 10000 events of reaction (7) generated in our Montecarlo simulation survive after applying all cuts. These events are plotted in Fig. 5. Due to the limited statistics, not even a single event of the distribution falls inside the strip region of the good events. Of course the events in this region would represent an unremovable background and give the actual limit to the experimental sensitivity to detect the $\tilde{U}$ particle.

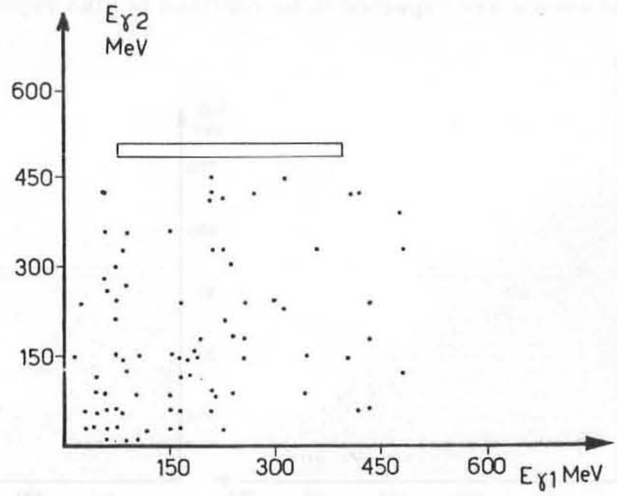


FIG. 5 - Event plot in the $E_{\gamma 1}/E_{\gamma 2}$ plane for the reaction $e^+e^- \to \pi^+\pi^-\pi^o\pi^o$, with all cuts applied.

The expected rate of $\tilde{U}$ production integrated on the machine energy spread is:

$$N_{\tilde U} = L\,\varepsilon_{\tilde U}\int_{\Delta E}\sigma\, dE = 6\pi^2 L\,\varepsilon_{\tilde U}\,\Gamma_{e^+e^-}\frac{1}{m^2_{\tilde U}} \tag{9}$$

where L is the machine integrated luminosity, $\varepsilon_{\tilde U}$ is the detection efficiency and σ is the $\tilde U$ production cross section:

$$\sigma = 12\pi\,\frac{m_{\tilde U}\Gamma_{e^+e^-}}{s}\,\frac{m_{\tilde U}\Gamma}{(s-m^2_{\tilde U})^2+(m_{\tilde U}\,\Gamma)^2} \tag{10}$$

where Γ and $\Gamma_{e^+e^-}$ are the total and the e^+e^- partial widths respectively. The rate of good events can be written:

$$N_G = N_{\tilde U}\,B_{\tilde U \to \eta'\gamma}\,B_{\eta' \to \varrho\gamma} \tag{11}$$

where $B_{\tilde U \to \eta'\gamma}$ and $B_{\eta' \to \varrho\gamma}$ are the branching ratios for the decay modes (3).

The backgrounds events over the same machine energy interval are:

$$N_B = L\,\varepsilon_B\int_{\Delta E}\sigma_{e^+e^- \to \pi^+\pi^-\pi^o\pi^o}\, dE \tag{12}$$

where ε_B is the detection efficiency of reaction (7), with two photons coming from different π^o's, after applying the ϱ and η' mass cuts discussed above, and for events inside the strip region of the $(E_{\gamma 1}, E_{\gamma 2})$ plot.

Assuming the pessimistic value $\Gamma_{e^+e^-}$ = 1 keV, the signal to background ratio from the expression (9), (11) and (12) becomes:

$$\frac{N_G}{N_B} = \frac{6\pi^2\varepsilon_{\tilde U}\;\Gamma_{e^+e^-}/m^2_{\tilde U}\;B_{\tilde U \to \eta'\gamma}\;B_{\eta' \to \varrho\gamma}}{\varepsilon_B\int_{\Delta E}\sigma_{e^+e^- \to \pi^+\pi^-\pi^o\pi^o}\,dE} \simeq 1.9\times 10^8\,\frac{\varepsilon_{\tilde U}}{\varepsilon_B\, m^2_{\tilde U}\,(\mathrm{MeV}/c^2)^2} \tag{13}$$

where we have used rough values for the following quantities :

$$B_{\tilde{U} \to \eta'\gamma} = 0.4 ; \quad B_{\eta' \to \varrho\gamma} = 0.3 ; \quad \int_{\Delta E} \sigma_{e^+e^- \to \pi^+\pi^-\pi^o\pi^o} \, dE = 15 \text{ nb MeV}$$

(the cross section was taken to be $\sim$ 15 nb(3), and the machine energy spread to be $\approx$ 1 MeV).

In Table II we show the values of expression (13) as well as the corresponding coefficients $\varepsilon_{\tilde{U}}$ and ε_B for three different total energies.

Our results for the decay mode (3) of a possible $\tilde{U}$ particle suggest a very low level of background from reactions (6), (7), (8). Moreover, we estimate that other reactions with more than 5 pions in the final state should provide an even lower background contamination.

TABLE II

$\sqrt{s} = m_{\tilde{U}}$ (MeV)	$\varepsilon_{\tilde{U}}$	ε_B	N_G/N_B
1200	0.53	5×10^{-4}	10^5
1600	0.57	$< 10^{-4}$	$> 4 \times 10^5$
2000	0.59	3×10^{-5}	9×10^5

4. - RESULTS ON THE DECAY MODE (4).

The results quoted in the previous section show that the decay mode (3) is very good tool for detecting the $\tilde{U}$ particle. In addition, we estimated that decay mode (4) offers a comparably good experimental possibility.

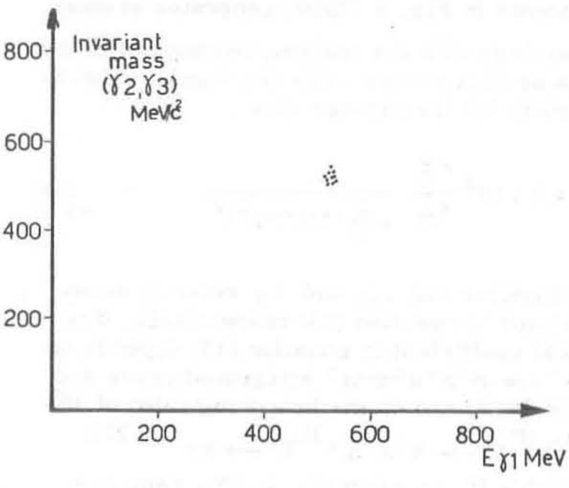


FIG. 6 - Event plot versus the invariant mass of ($\gamma 2$, $\gamma 3$) and the energy of $\gamma 1$ (the most energetic photon) for the reaction $e^+e^- \to \tilde{U} \to \eta'\gamma$, $\eta' \to \pi^+\pi^-\eta^o \to \gamma\gamma$.

In decay mode (4) there are two charged pions and three photons in the final state. We can represent the events of this channel in a scatter plot versus the energy of the hardest photon (the monochromatic photon) and the invariant mass of the other two photons (the η^o mass). Such a distribution is shown in Fig. 6 for $\sqrt{s} = m_{\tilde{U}} = 1600$ MeV, and is essentially a small spot region, whose size depends both on the photon energy resolution ($\approx$ 30 MeV, FWHM) and on the two photon invariant mass resolution ($\approx$ 50 MeV/c^2, FWHM).

We have considered the following background reactions

$$e^+e^- \to \pi^+\pi^-\pi^o\pi^o\pi^o \quad \text{with three photon lost} \qquad (14)$$

$$e^+e^- \to \pi^+\pi^-\pi^o\pi^o \quad \text{with one photon lost} \qquad (15)$$

From our Montecarlo simulation we give in Figs. 7 the distributions of reactions (14) and (15) respectively, in the same plot of Fig. 6. The region where the good events are expected is also shown.

In the case of reaction (15) the event distribution is so well separated from the region of good events that the background coming from this reaction can be completely neglected. The background shown in Fig. 7a can be further rejected by requesting that no one of the three $\gamma\gamma$ combinations be in the π^o mass range (within $\pm$ 50 MeV/c^2), in such a way that the only events with each photon coming from a different π^o are accepted. Further cuts are applied to this background : the lowest $\gamma\gamma$ invariant mass must be around the η^o mass (within two standard deviations) and the η^o + two charged pion invariant mass must be around the η' mass (within two standard deviations.

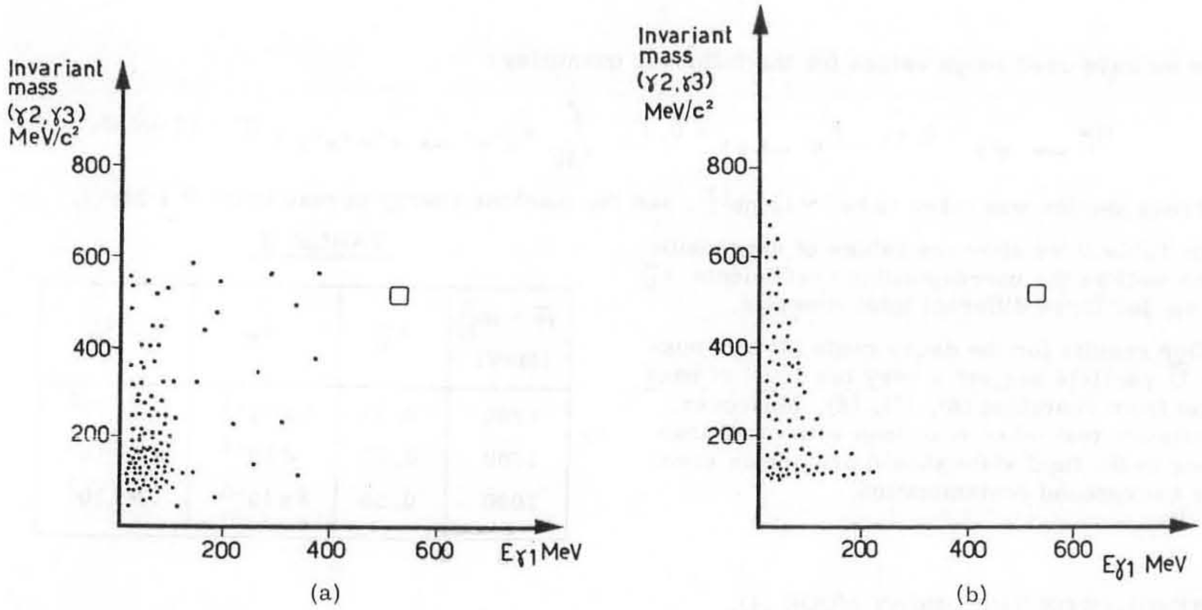


FIG. 7 - Event plot versus the invariant mass of ($\gamma 2$, $\gamma 3$) and $E_{\gamma 1}$ for the reactions : (a) $e^+e^- \rightarrow \pi^+\pi^-\pi^o\pi^o\pi^o$; (b) $e^+e^- \rightarrow \pi^+\pi^-\pi^o\pi^o$.

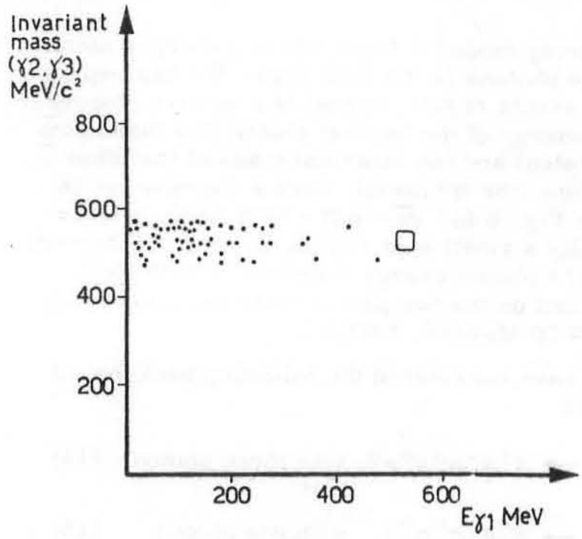


FIG. 8 - Event plot versus the invariant mass of ($\gamma 2$, $\gamma 3$) and $E_{\gamma 1}$) for the reaction $e^+e^- \rightarrow \pi^+\pi^-\pi^o\pi^o\pi^o$ with all cuts applied.

The distribution of events passing all these cuts is shown in Fig. 8 (30000 generated events).

In analogy with the analysis performed in the previous section we can write the signal to background ratio for the present case :

$$\frac{N_G}{N_B} = 4.7 \times 10^8 \frac{\varepsilon_{\tilde{U}}}{\varepsilon_B} \frac{1}{m^2_{\tilde{U}} \, (\mathrm{MeV}/c^2)^2} \tag{16}$$

where of course the $\varepsilon_{\tilde{U}}$ and ε_B refer to decay mode (4) and to reaction (14) respectively. The numerical coefficient in equation (16) depends on the $e^+e^- \rightarrow \pi^+\pi^-\pi^o\pi^o\pi^o$ integrated cross section (5 nb MeV) and on the branching ratio of the η' decay ($B_{\eta' \rightarrow \eta^o\pi^+\pi^-} \cdot B_{\eta^o \rightarrow \gamma\gamma} = 0.25$).

In Table III we quote the N_G/N_B ratio (16) together with $\varepsilon_{\tilde{U}}$ and ε_B at the same three energies.

TABLE III

$\sqrt{s} = m_{\tilde{U}}$ (MeV)	$\varepsilon_{\tilde{U}}$	ε_B	N_G/N_B
1200	0.34	3×10^{-5}	4×10^6
1600	0.34	$< 3 \times 10^{-5}$	$> 2 \times 10^6$
2000	0.36	$< 3 \times 10^{-5}$	$> 10^6$

Table III shows that also decay mode (4) offers an experimentally suitable way to search for the possible Pati-Salam vector gluon.

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