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# Recent COMPASS Results and Future Prospects for ALICE

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**Abstract**

The COMPASS Collaboration has accumulated the world's highest statistics on the reaction $\pi^- p \to \pi^+\pi^-\pi^- p$ at 190 GeV/$c$. The results, presented in Section 1, show that a new state $J^{PC} = 1^{++}$ state never reported before, the $a_1(1420)$, decaying to $f_0(980)\pi$ followed by $f_0(980) \to \pi\pi$. In addition, the Collaboration reports an exotic $J^{PC} = 1^{-+}$ state, the $\pi_1(1600)$, which cannot be a quarkonium. Both states are likely to be a tetra-quark, i.e. $q\bar{q} + q\bar{q}$ or a gluonic hybrid, a $q\bar{q}$ object with an excited gluon inside it.

Section 2 is devoted to a brief discussion of the central production of resonances, which is being investigated by both COMPASS and ALICE collaborations. However, the results are not yet released, so it is limited to a broad discussion of the central production, with emphasis on different analyses dictated by differences in the experimental setup.

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# 1 The COMPASS Experiment

The hadron physics component of the COMPASS Experiment is concerned with the diffractive and central production of mesons in the reactions

$$\pi^-(\text{beam}) + \text{p(target)} \to (\pi^+\pi^-\pi^-)(\text{forward}) + \text{p(recoil)} \tag{1a}$$

with an incoming $\pi^-$ beam at 190 GeV/$c$ on a liquid-hydrogen target. This report deals exclusively with the reaction (1$a$) taken in 2008 at the COMPASS detector facility[1] at CERN/Prévessin. The reader may wish to consult a number of notes and papers by the author and his collaborators[2][3][4][5][6], for a comprehensive account of the background material for the type of analysis employed in this report.

We show in Fig. 1 the mass spectrum of $\pi^+\pi^-\pi^-$ and the squared four-momentum transfer $t' = |t| - |t|_{\min}$ for the reaction (1$a$). From partial-wave analyses of previous experiments, as well as COMPASS, the mass spectrum exhibits a broad shoulder at the $a_1(1260)$ and a peak at the $a_2(1320)$, followed by a dip at 1.5 GeV, and finally an enhancement at 1.6 GeV corresponding to the $\pi_2(1670)$. Before we show the results of our partial-wave analysis, we

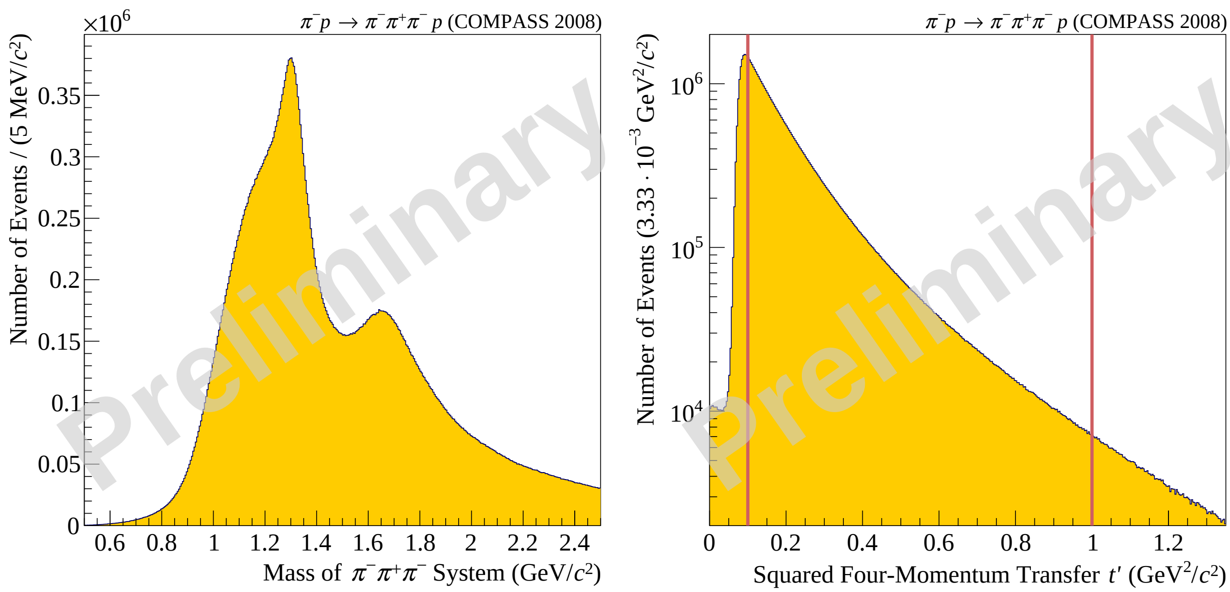


Figure 1: $(3\pi)^-$ mass spectrum and the squared four-momentum transfer $t' = |t| - |t|_{\min}$. The red vertical lines in the $t'$ spectrum indicate the limits used in the analysis i.e. $t'(0.100 \to 1.00)\,(\text{GeV}/c)^2$.

need to explain how we denote a partial wave in the $(3\pi)^-$ system

$$J^{PC}\, m^{\epsilon}\ (\text{isobar})\ \pi\, \text{L}, \quad 0 \le \text{J} \le 4, \quad 0 \le \text{L} \le 6, \quad 0 \le \text{m} \le 2, \quad \text{and} \quad \epsilon = \pm 1 \tag{2}$$

where $J$, $P$ and $C = +1$ are the spin, parity and the charge-conjugation quantum number $C$ (always +1 for a charged $3\pi$ system, since $G = -1$ and $I = 1$). We set up a plane in the momentum space, in which the reaction plane, i.e. $\pi^-$ (beam), $p$ (target) and $p$ (recoil) of reaction (1$a$) is embedded in the $x$-$z$ plane and the $y$ axis is aligned with the production normal. The quantum number $m$ is the $z$ component of the spin $J$, with the $z$-axis along the beam in the $(3\pi)$ rest frame, while the $\epsilon = \pm 1$ is the reflectivity[3], the quantum number for the reflection operator corresponding to the parity operator, followed or preceded, by a rotation by $\pi$ around the $y$ axis. For the reaction ($1a$), we choose the sign of the reflectivity to coincide with the 'naturality' i.e. the parity times $(-)^J$ of the exchanged Reggeon. The term 'isobar' in (2) refers to a neutral intermediate state $\pi^+\pi^-$, e.g. the $f_0(500)$, $\rho(770)$, $f_0(980)$, $f_2(1270)$, etc. The $L$ of (2) is the orbital angular momentum between the isobar and the bachelor pion.

Partial-wave fits are done by the extended maximum-likelihood method[4] for a suitably chosen set of waves in a given mass and $t'$ bins; 20-MeV mass bins from 0.5 to 2.5 GeV and 11 $t'$ bins from 0.100 to 1.00 $(\mathrm{GeV}/c)^2$, where the $t'$ bins have been chosen such that the number of events in each bin is approximately equal. Florian/TU-München[7] has used a total of 83 partial waves in the natural-parity sector ($\epsilon = +1$) and 7 partial waves in the unnatural-parity sector ($\epsilon = -1$). His study represents a definitive analysis, superseding all previous analyses of the $(3\pi)^-$ system, e.g. on VES[8], BNL E852(a)[9],[10] and the previous results from COMPASS[11]. We summarize here the essential features of F. Haas study, which include $\pi_1(1600)$, $J^{PC} = 1^{-+}\rho(770)\pi\ P$, one exotic resonance with all the characteristics of a genuine resonance with rising phase motions with respect to other waves. The original BNL-E852 analysis on the reaction ($2a$) at 18 GeV/$c$ was limited to 21 partial waves (insufficient number of waves, as it turned out). A later analysis[10], with 36 partial waves attempted to 'correct' the original analysis[9], but failed to take into account the presence of a resonance which can be inferred from the phase motion of a partial wave, the exotic $\pi_1(1600)$, $J^{PC} = 1^{-+}\rho(770)\pi\ P$, but not visible in the mass spectrum; the phase motion is proportional to $f$ whereas the partial-waves events are $f^2$ above background; if $f^2 = 0.01$, then $f = 0.10$[a] A more serious omission is that the later analysis[10] had failed to examine the exotic $J^{PC} = 1^{-+}$ wave above $t' > 0.50$ $(\mathrm{GeV}/c^2)$, where it becomes prominent with little background; the COMPASS data show that the exotic wave forms an unmistakable dominant peak in the mass spectrum in the vicinity of 1.6–1.7 GeV. This is demonstrated in Fig. 2, where the exotic wave $\pi_1(1600)$ appears as a shoulder for $0.100 < t' < 1.000$ (the left figure; the histogram shown is a sum of the partial-wave fits, performed separately over 11 individual $t'$ bins), but it becomes a prominent peak for $0.724 < t' < 1.000$ (the right figure).

We now move onto the observation of the $a_1(1420) \to f_0(980)\pi$. The partial wave $J^{PC} = 1^{++}\ f_0(980)\pi\ P$ shows a sharp peak at 1.42 GeV (Fig. 3, the left figure) for $m^\epsilon = 0^+$ but a broad shoulder at 1.42 GeV, followed by a destructive interference at $\simeq 1.65$ GeV, for $m^\epsilon = 1^+$ (Fig. 3, the right figure). If we surmise that the $a_1(1420)$ with $m^\epsilon = 0^+$ is produced by the Pomeron ($J^{PC} = 2^{++}$) exchange, then it consists mainly of the zero $z$-component. we recall that the Pomeron exchange for exclusive elastic $ab \to ab$ scattering proceeds via $m = 0$ component of the Pomeron. The resonance nature of the $a_1(1420)$ is clear by the relatively flat phase motion with respect to the $\pi_2(1670)$ (Fig. 4, the upper-left figure) and to the $\pi_1(1260)$ (Fig. 4, the bottom-right figure). Likewise, the falling phase with respect to the $a_4(2040)$ (Fig. 4, the upper-right figure) and to the $a_2(1320)$ (Fig. 4, the bottom-left figure) demonstrate the rising phase. These observations prove that the $a_1(1420)$ is a genuine resonance.

It appears likely that the $a_1(1420)$ and the $f_1(14320)$ form an isovector and an isoscalar partner of a $K\bar{K}\pi$ molecule[12]. The picture is as follows: let spin-zero $K\bar{K}$ form a nucleus

[a] For the purpose of illustration, assume that the background 1 and the signal is $f^2$ and fully coherent between the two. The amplitude squared is $(1+f)^2$, and so the signal is 1% above the background, practically impossible is observe, but the interference is 20%, which should be easy to detect.

of 'an atom' with the $\pi$ orbiting around the nucleus in a $P$ wave, so that the molecule forms $K^*\bar{K}$ and $\bar{K}^*K$ simultaneously. In the case of the $f_1(14320)$, the nucleus must be in a isovector state, so that the $K\bar{K}$ nucleus has a large $a_0(980)$ component, coupling to $\eta\pi$ and $K\bar{K}$, whereas the nucleus inside the $a_1(1420)$ constitutes largely of the $f_0(980)$, which should couple to $\pi\pi$ and $K\bar{K}$; this explains why the nucleus decays through $f_0(980) \to \pi\pi$ but NOT through $\rho(770)\pi$. This is, however, a personal observation by the author; a more detailed study must be carried out by performing a coupled-channel analysis of the final states $3\pi$, $\eta\pi\pi$ and $K\bar{K}\pi$.

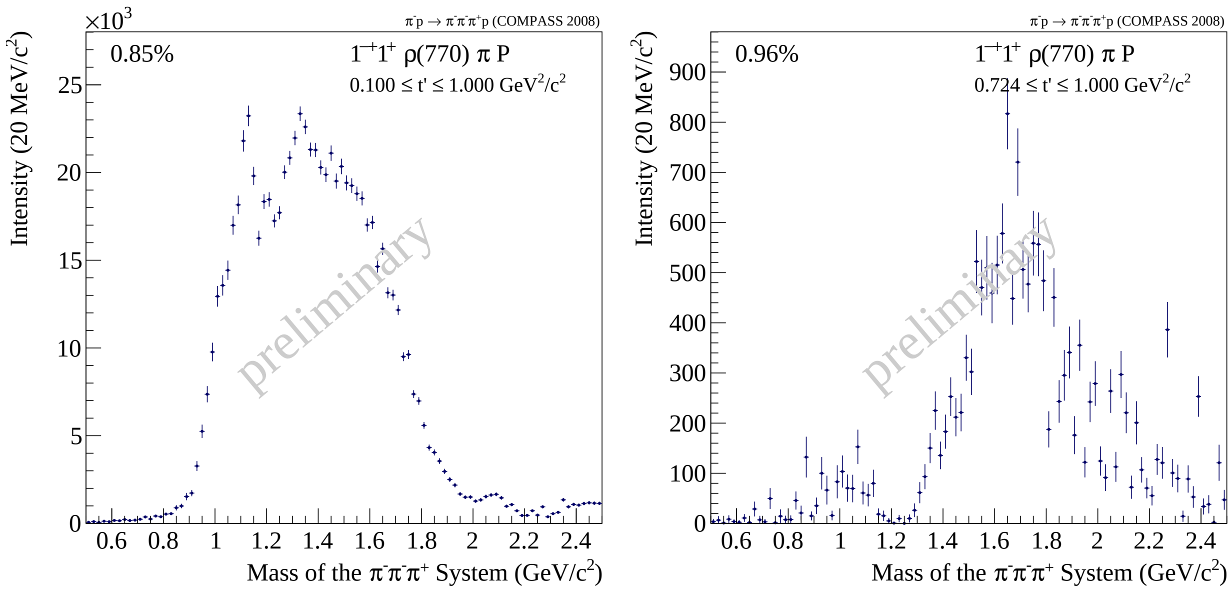


Figure 2: Partial-Wave $J^{PC}\, m^\epsilon = 1^{-+}1^+\rho\pi\mathrm{P}$
for $t'(0.100 \to 1.000)\,(\mathrm{GeV}/c)^2$ [the entire $t'$ interval (the left figure)]
and for $t'(0.724 \to 1.000)\,(\mathrm{GeV}/c)^2$ [the highest $t'$ bin (the right figure)].

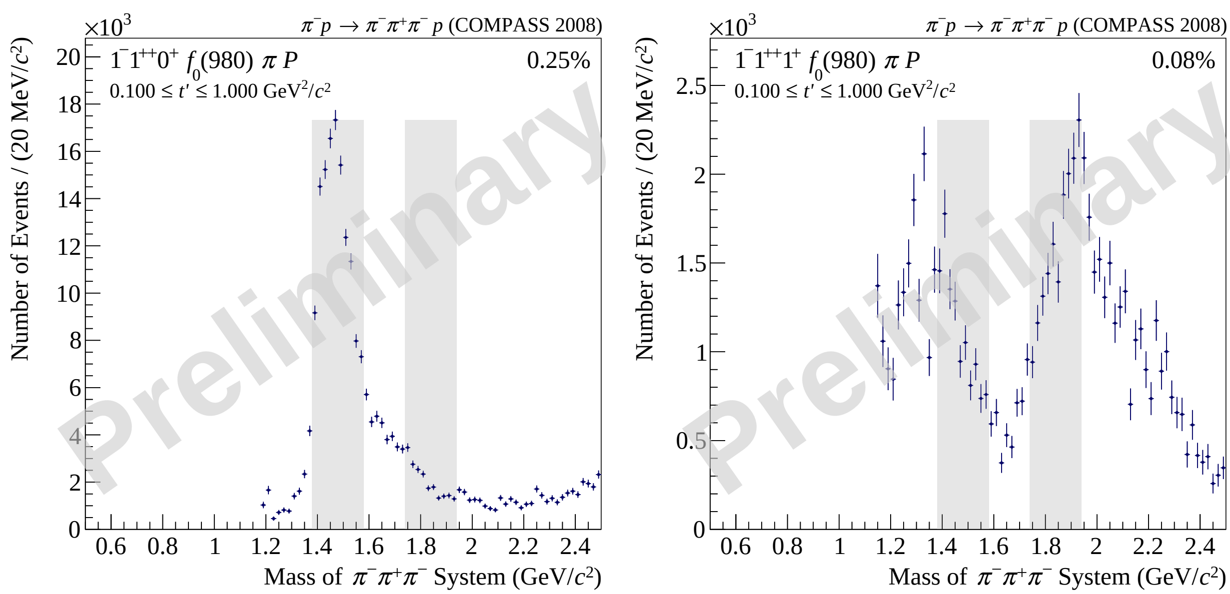


Figure 3: The partial wave $I^G(J^{PC}) = 1^-(1^{++})\ f_0(980)\pi\, P$;
$m^\epsilon = 0^+$ (the left figure) and $m^\epsilon = 1^+$ (the right figure).

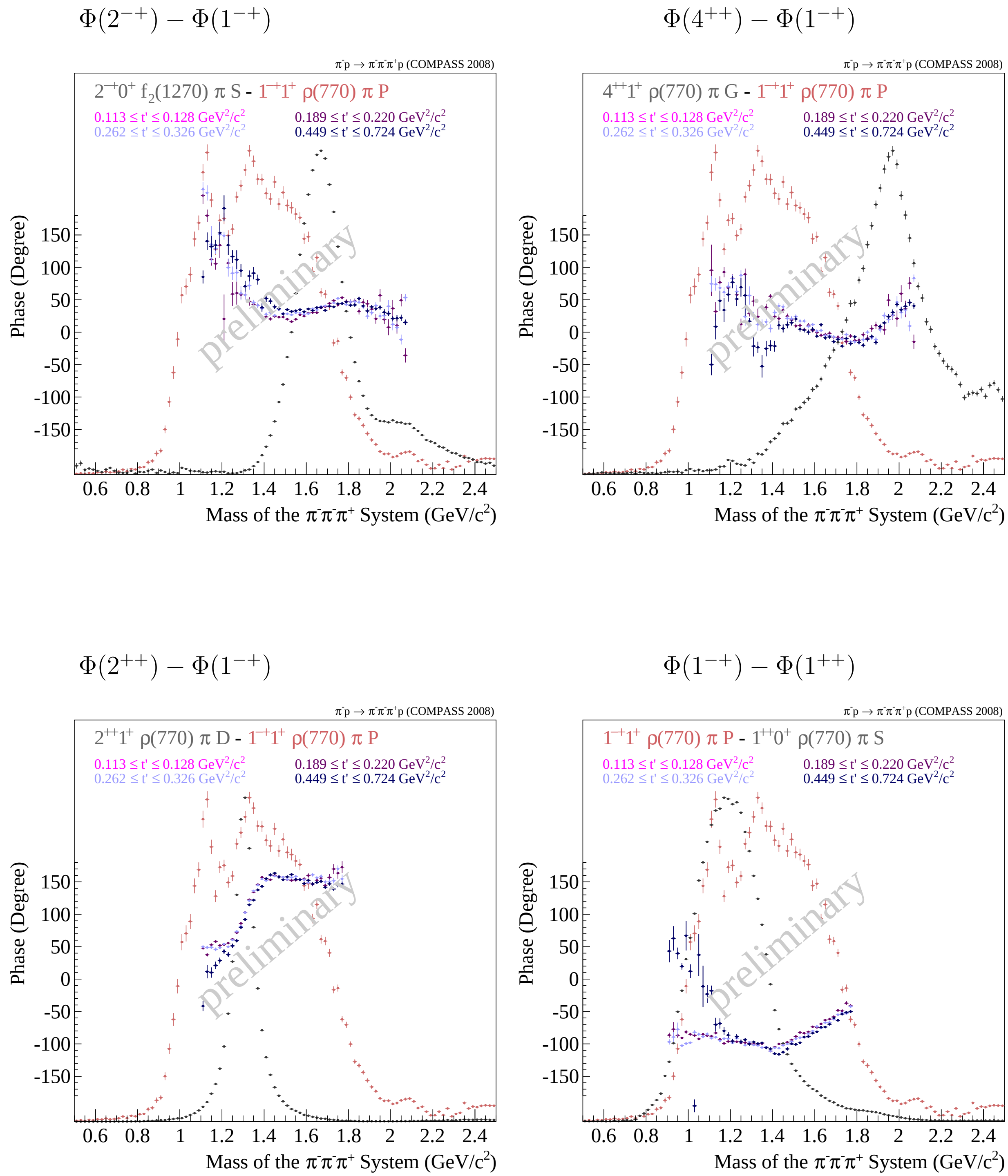


Figure 4: The phase differences ( $\Delta\Phi$) among different Partial-Waves $J^{PC}\, m^{\epsilon} \rho\pi\ L$ as a function of $(3\pi)^{-}$ mass (GeV).

## 2 Central Production

This section is devoted to the central production[13][14] of $\pi\pi$ and $\pi\pi\pi\pi$ for $X^0$ in

$$a + b \to 1 + 3(X^0) + 2; \quad a \to 1 + c(\boldsymbol{P}); \quad b \to 2 + d(\boldsymbol{P}) \tag{3}$$

via double-Pomeron exchange at COMPASS and ALICE, see Fig. 5:

$$c(\boldsymbol{P}) + d(\boldsymbol{P}) \to 3(X^0) \to (\pi\pi)^0 \quad \text{or} \quad (\pi\pi\pi\pi)^0 \tag{4}$$

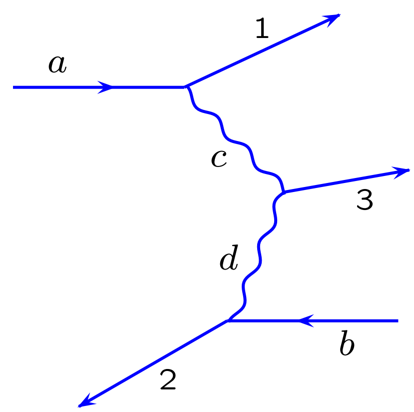


Figure 5: Production of a system 3 from the reaction $a + b \to 1 + 3 + 2$. Here $c$ and $d$ stand for the exchanged Reggeons (or Pomerons).

For COMPASS, we take the $x$-$z$ plane to be that formed by the vertex $c$-$d$-$3(X^0)$, so that the production normal (the $y$-axis) is along $\vec{c} \times \vec{d}$ in the $X^0$ rest frame. We choose the $z$-axis to be along the Reggeon (Pomeron) $c(\boldsymbol{P})$ such that $|t_c| \le |t_d|$. So Pomerons are distinguished by their $|t|$; so they are not identical particles. Since Pomerons are isoscalars with $J^{PC} = 2^{++}$ and for $\vec{J} = \vec{S} + \vec{\ell}$, the double-Pomeron initial systems satisfy

| $\ell$ | $S$ | $J^{PC}$ where $\lvert\ell - S\rvert \le J \le \ell + S$ |
|---|---|---|
| 0 | 0, 1, 2, 3, 4 | $0^{++}$, $1^{++}$, $2^{++}$, $3^{++}$, $4^{++}$ |
| 1 | 0, 1, 2, 3, 4 | $0^{-+}$, $1^{-+}$, $2^{-+}$, $3^{-+}$, $4^{-+}$, $5^{-+}$ |
| 2 | 0, 1, 2, 3, 4 | $0^{++}$, $1^{++}$, $2^{++}$, $3^{++}$, $4^{++}$, $5^{++}$, $6^{++}$ |
| 3 | 0, 1, 2, 3, 4 | $0^{-+}$, $1^{-+}$, $2^{-+}$, $3^{-+}$, $4^{-+}$, $5^{-+}$, $6^{-+}$, $7^{-+}$ |
| 4 | 0, 1, 2, 3, 4 | $0^{++}$, $1^{++}$, $2^{++}$, $3^{++}$, $4^{++}$, $5^{++}$, $6^{++}$, $7^{++}$, $8^{++}$ |
| 5 | 0, 1, 2, 3, 4 | $1^{-+}$, $2^{-+}$, $3^{-+}$, $4^{-+}$, $5^{-+}$, $6^{-+}$, $7^{-+}$, $8^{-+}$, $9^{-+}$ |

$$\begin{aligned} I^G(J^{PC}) &= 0^+(0^{++}),\ 0^+(2^{++}),\ 0^+(4^{++}),\ 0^+(6^{++}),\ 0^+(8^{++}), \cdots \text{ for } \quad (\pi\pi)^0 \\ &= 0^+(0^{\pm+}),\ 0^+(1^{\pm+}),\ 0^+(2^{\pm+}),\ 0^+(3^{\pm+}),\ 0^+(4^{\pm+}),\ 0^+(5^{\pm+}), \\ &\qquad 0^+(6^{\pm+}),\ 0^+(7^{\pm+}),\ 0^+(8^{\pm+}), \cdots \text{ for } \quad (4\pi)^0 \end{aligned} \tag{5}$$

For an even-pion system, the $G$-parity is always positive, and $I + \ell = \text{even}$[6] where $\ell$ is the spin of the $(\pi\pi)^0$ system. If the production proceeds via a double-Pomeron exchange, then an isovector cannot be produced. The isovector states are possible if one of the exchanged Reggeon is the $\rho(770)$. Note that the produced dipion system is always an isoscalar with even $G$-parity, i.e. $C$ is always positive. We note, in addition, that the exchanged Reggeon cannot be an $\omega(782)$, since we deal with a system with $G = +1$.

If $t'_c \simeq t'_c \sim 0$, then the two Pomerons must be treated as identical particles, i.e. $S + \ell = \text{even}$. The double-Pomeron initial systems satisfy

| $\ell$ | $S$ | $J^{PC}$ where $\lvert\ell - S\rvert \leq J \leq \ell + S$ |
|---|---|---|
| 0 | 0, 2, 4 | $0^{++}$, $2^{++}$, $4^{++}$ |
| 1 | 1, 3 | $0^{-+}$, $1^{-+}$, $2^{-+}$, $3^{-+}$, $4^{-+}$ |
| 2 | 0, 2, 4 | $0^{++}$, $1^{++}$, $2^{++}$, $3^{++}$, $4^{++}$, $5^{++}$, $6^{++}$ |
| 3 | 1, 3 | $0^{-+}$, $1^{-+}$, $2^{-+}$, $3^{-+}$, $4^{-+}$, $5^{-+}$, $6^{-+}$ |
| 4 | 0, 2, 4 | $0^{++}$, $1^{++}$, $2^{++}$, $3^{++}$, $4^{++}$, $5^{++}$, $6^{++}$, $7^{++}$, $8^{++}$ |
| 5 | 1, 3 | $2^{-+}$, $3^{-+}$, $4^{-+}$, $5^{-+}$, $6^{-+}$, $7^{-+}$, $8^{-+}$ |

Or, we can summize this result as follows

$$I^G = 0^+ \quad \text{and} \quad J^{PC} = 0^{\pm+}, 1^{\pm+}, 2^{\pm+}, 3^{\pm+}, 4^{\pm+}, 5^{\pm+}, 6^{\pm+}, 7^{\pm+}, 8^{\pm+}, \cdots \tag{6}$$

So we see that this result is consistent with the double-Pomerons coupling to $\pi\pi$ and $\pi\pi\pi\pi$, as shown in (5). The relationships (6) are a general result, regardless of the relative magnitudes of $t'_c$ and $t'_d$ and/or whether the two Pomerons should be considered 'identical.' *The allowed $J^{PC}$'s as shown in (6) apply equally well for all $t'_c$ and $t'_d$, i.e. whether the two Pomerons should be considered identical or not, i.e. the Bose symmetry for the two Pomerons is immaterial—a remarkable result.*

For ALICE, we take the $x$-$z$ plane to be that formed by $\vec{a}$ and $\vec{b}$. Then the $y$-axis is proportional to $\vec{a} \times \vec{b}$, again in the $X^0$RF (rest frame). A system consisting of two $J^{PC} = 2^{++}$ Pomerons forms $I^G = 0^+$ and $\vec{J} = \vec{S} + \vec{L}$ and $L$ is the orbital angular momentum between the two Pomerons. So $P(\text{parity}) = (-)^{\text{L}}$, where $S$ is the total intrinsic spin $S = 0, 1, 2, 3, 4$. The Bose symmetry of the two Pomerons requires that $S + L = \text{even}$[6]. So for $L = 0$ we obtain $J = S = 0, 2, 4$ and $P = +$; if $L = 1$, then $S = 1$ or $3$ and $J = 0, 1, 2, 3, 4$ and $P = -$; if $L = 2$, then we must have $S = 0, 2, 4$ so that $J = 0, 1, 2, 3, 4, 5, 6$ and $P = +$; and, finally, if $L = 3$, we find $S = 1$ or $3$ so that $J = 0, 1, 2, 3, 4, 5, 6$ and $P = -$. We see that the list of $I^G(J^{PC})$ is exactly the same as shown in (5). *It is remarkable, indeed, to note that the allowed $I^G(J^{PC})$ are the same, even with the Bose symmetry imposed on the two Pomerons.*

For the foreseeable future, the Roman pots are not planned for ALICE detector. We need to work out, therefore, the case in which the recoil particles 1 and 2 are *not* measured, and so we will need to integrate over their degrees of freedom, to arrive at the formulas appropriate for ALICE. Mr. Taesoo Kim, a PhD student at CERN from Yonsei University, Republic of Korea, is working the partial-wave decomposition of the $\pi^+\pi^-$ and $\pi^+\pi^-\pi^+\pi^-$ systems, centrally produced at ALICE. The results of his analysis are not yet publicly available; the parties involved are hopeful that the results could be released in the near future.

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