Fourth Generation Pseudoscalar Quarkonium Production and Observability at Hadron Colliders

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Abstract

The pseudoscalar quarkonium state $\eta_4 (^1S_0)$, formed by the Standard Model (SM) fourth generation quarks, is the best candidate among the fourth generation quarkonia to be produced at the LHC and VLHC. The production of this $J^{PC} = 0^{+-}$ resonance is discussed and the background processes are studied to obtain the integrated luminosity limits for the discovery, depending on its mass.
The number of SM generations with light neutrinos are limited by the LEP data to \( N = 3.0 \pm 0.06 \) [1]. On the other hand, there are serious democracy arguments favoring the existence of a heavy fourth SM generation, with members having almost equal masses [2, 3, 4, 5]. Typical mass range considered is 300 GeV to 700 GeV. Within a democratic mass matrix approach, small masses for the first three neutrinos are compatible with large mixing angles, assuming that neutrinos are of the Dirac type [6]. Experimental lower bounds on the fourth SM generation fermions are as follows [1]: 92.4 GeV for charged lepton, 45(39.5) GeV for Dirac (Majorana) neutrino and 199(128) GeV for down quark decaying via neutral (charged) current.

Latest precision electroweak data allow the existence of a fourth SM generation with heavy Dirac neutrinos [7, 8]. Moreover, two or three extra generations with relatively light neutrinos (\( m_N \approx 50 \text{ GeV} \)) are also allowed [8]. The fourth generation quarks will be copiously produced at the LHC [3, 11, 12]. In addition, extra SM generations will yield an essential enhancement in Higgs production, via gluon-gluon fusion, at Tevatron and LHC [12, 13, 14, 15, 16]. Future lepton colliders will give an opportunity to investigate the fourth generation leptons [17, 18, 19].

Due to small inter-generation mixing, another expectation is the formation of the fourth generation quarkonia (\( Q_4 \bar{Q}_4 \)) , provided that the condition

\[
m_{Q_4} < (125 \text{ GeV})|V_{qQ_4}|^{-2/3}
\]  

is satisfied [20]. Here \( q \) denotes the known quarks and \( V_{qQ_4} \) is the extended Cabibbo-Kobayashi-Maskawa matrix element. The parametrization given in [2, 3], for the fourth SM generation, satisfies the above requirement. In hadron collisions, gluon-gluon fusion is the main process for the production of quarkonia [21]. The \( J^{PC} = 0^{-+} \) pseudoscalar quarkonium state \( \eta_4 \) (\( ^1S_0 \)) which is produced in the subprocess \( gg \rightarrow \eta_4 \), has a production cross section two orders of magnitude larger than the \( J^{PC} = 1^{--} \) vector state \( \Psi \), since \( gg \rightarrow g\Psi \) will be the mechanism for the vector quarkonium. For this reason, lepton colliders are more suitable for investigation of vector quarkonia [18, 19], whereas hadron machines are best for the investigation of pseudoscalar quarkonia.

In this work, we consider the process \( pp \rightarrow \eta_4 X \) for the production of \( (u_4 \bar{u}_4) \) pseudoscalar quarkonium at the LHC, including possible energy (\( \sqrt{s} = 28 \text{ TeV} \)) and luminosity (\( L = 10^{35} \))
FIG. 1: Branching ratios for $\eta_4$ as a function of its mass with $m_h = 150$ GeV

cm$^{-2}$s$^{-1}$ upgrades [22], and the VLHC Stage 1 (2) with $\sqrt{s} = 40$ (175) TeV and $L = 10^{34}$ $(2 \times 10^{34})$ cm$^{-2}$s$^{-1}$ [23]. For completeness we also consider the RLHC with $\sqrt{s} = 100$ TeV and $L = 10^{34}$ cm$^{-2}$s$^{-1}$ [24].

The decay modes of $\eta_4$ are $gg$, $f\bar{f}$, $\gamma\gamma$, $ZZ$, $Z\gamma$, $Zh$, $WW$; where the $\eta_4 \rightarrow Zh$ decay has the largest branching ratio (for $m_{\eta_4} \geq 600$ GeV). In Figure 1(2), we present the variation of the $\eta_4$ branching ratios as a function of the $m_{\eta_4}$ for the Higgs boson mass $m_h = 150$ (250) GeV. The total decay width is presented in Fig. 3 which is calculated using Coulomb potential for the $(u_4\bar{u}_4)$ bound state.

The cross section for $\eta_4$ production at hadron colliders, can be expressed as

$$\sigma(pp \rightarrow \eta_4 X) = K \frac{\pi^2}{8 \, m_{\eta_4}^3} \Gamma(\eta_4 \rightarrow gg) \tau \int_\tau^1 \frac{dx}{x} \, g(x, Q^2) \, g(\frac{\tau}{x}, Q^2)$$  \hspace{1cm} (2)

where

$$\Gamma(\eta_4 \rightarrow gg) = 8 \, \alpha_s^2(Q^2) \, |R_S(0)|^2 / (3 \, m_{\eta_4}^2),$$  \hspace{1cm} (3)
FIG. 2: Branching ratios for $\eta_4$ as a function of its mass with $m_h = 250$ GeV

FIG. 3: Total decay width of $\eta_4$ as a function of its mass for $m_h = 150$ and 250 GeV
\( \alpha_s(Q^2) \) is the strong coupling constant and \( \tau = m_{\eta_4}^2/s \) with \( \sqrt{s} \) being the center of mass energy of the collider. \( R_S(0) \) is the radial wave function of the S-state evaluated at the origin \([21]\). \( K \approx 2 \) is the enhancement factor for next-to-leading order QCD effects. For the gluon distribution function \( g(x, Q^2) \) we have used CTEQ5L \([26]\) with \( Q^2 = m_{u_4}^2 \).

In Figure 4, \( \eta_4 \) production cross section is plotted for the LHC, upgraded LHC, RLHC and VLHC. In Tables I and II the production cross sections and branching ratios for all the decay modes are given for different values of \( m_{\eta_4} \). The most promising channels are \( \eta_4 \rightarrow \gamma\gamma \) and \( \eta_4 \rightarrow Zh \). For the background calculations we use PYTHIA 6.2 \([25]\).

\( \gamma\gamma \) Channel. The dominant backgrounds to this channel are \( f\bar{f} \rightarrow \gamma\gamma \) and \( gg \rightarrow \gamma\gamma \) with cross sections \( 2 \times 10^4 \) pb and \( 3 \times 10^5 \) pb, respectively. In order to suppress the backgrounds we apply a cut \( p_T > 0.4m_{\eta_4} \) on transverse momentum of both photons. This requirement reduces the signal by \( \sim 40\% \), whereas the background drops drastically. Furthermore, we use \( |\eta| < 2.5 \) for pseudorapidity coverage, and also consider 60% efficiency for two photon identification. Finally, we use a mass window \( m_{\gamma\gamma} \pm 2\sigma_m \) for two photons invariant mass.
using:

\[ \sigma_m = m_{\gamma\gamma} \left( \frac{0.07}{\sqrt{E_{\gamma}}} + 0.005 \right) \]  \hspace{1cm} (4)

The number of signal and background events and the corresponding statistical significances satisfying the conditions above are given in Table III for \( L_{\text{int}} = 100 \text{fb}^{-1} \). In the last two columns of the Table, the integrated luminosities needed to achieve 3\( \sigma \) and 5\( \sigma \) discovery criteria are presented. One can see that LHC with \( \sqrt{s} = 14 \text{ TeV} \) and \( L_{\text{int}} = 100 \text{fb}^{-1} \) is able to explore the quarkonia with mass around 400 GeV. The luminosity upgrade will allow the observation up to \( m_{\eta_4} = 500 \text{ GeV} \). The same mass region could be covered by the energy upgraded LHC with \( L_{\text{int}} = 100 \text{fb}^{-1} \). With both the energy and luminosity upgrades LHC can reach \( m_{\eta_4} = 600 \text{ GeV} \). The achievable upper mass limits at VLHC are 600 GeV and 800 GeV for stage 1 and stage 2, respectively.

**Zh Channel.** The decay \( \eta_4 \to Zh \) where both \( Z \) and \( h \) decaying into charged leptons has a negligible branching ratio. The final states with \( Z \to ll \) where \( l = e, \mu \) and \( h \to b\bar{b} \) have an overall branching ratio of about 0.5\%. If \( m_h < 160 \text{ GeV} \), this mode will be the best one, otherwise, \( h \to WW^{(*)}, ZZ^{(*)} \) final states may be preferable at LHC (for branching

| \( m_\eta (\text{GeV}) \) | 400 | 500 | 600 | 700 | 800 | 900 |
|------------------|-----|-----|-----|-----|-----|-----|
| \( \sigma (\text{pb}) \) | LHC (14 TeV) | 1.43 \times 10^6 | 4.61 \times 10^{-1} | 1.77 \times 10^{-1} | 7.68 \times 10^{-2} | 3.66 \times 10^{-2} | 1.87 \times 10^{-2} |
| | LHC (28 TeV) | 6.35 \times 10^6 | 2.19 \times 10^6 | 9.11 \times 10^{-1} | 4.29 \times 10^{-1} | 2.21 \times 10^{-1} | 1.22 \times 10^{-1} |
| | VLHC (40 TeV) | 1.28 \times 10^3 | 4.61 \times 10^6 | 1.96 \times 10^6 | 9.39 \times 10^{-1} | 4.95 \times 10^{-1} | 2.79 \times 10^{-1} |
| | VLHC (100 TeV) | 5.82 \times 10^3 | 2.35 \times 10^4 | 1.09 \times 10^4 | 5.69 \times 10^4 | 3.17 \times 10^4 | 1.89 \times 10^4 |
| | VLHC (175 TeV) | 5.28 \times 10^2 | 2.58 \times 10^2 | 1.39 \times 10^2 | 8.13 \times 10^2 | 4.99 \times 10^2 | 2.95 \times 10^2 |
ratios of the Higgs boson decays see [13]). The main background comes from the pair production of $t$ quarks, associated $Zh$ production and $Zb\bar{b}$ with the cross sections 23 pb, $4 \times 10^{-3}$ pb and 21 pb, respectively. We use the cuts on the invariant mass of two leptons and two $b$–jets by requiring $|m_{ll} - m_Z| < 5$ GeV and $|m_{bb} - m_h| < 10$ GeV. These cuts reduce the $t\bar{t}$ and $Zb\bar{b}$ backgrounds by two orders, whereas the signal and $Zh$ background drop to $\approx 85\%$. Furthermore, we assume two $b$–tagging efficiency as 25% and two lepton identification efficiency 80%. For this channel, we define a variable mass window $m_{llbb} \pm 2\sigma_m$ where

$$\sigma_m = \sqrt{\left(\frac{\Gamma_{\eta_4}}{2.36}\right)^2 + (0.05 m_{\eta_4})^2}.$$  \hspace{1cm} (5)

Since the resolution for $b$–jets is worse than that for leptons, we use an overall mass resolution of 5% in Eq. (5) which is an average value for $b$–jets.

The number of signal and background events and the corresponding statistical significances satisfying the conditions above are given in Table IV and for $L_{int} = 100 fb^{-1}$. In the last two columns of the Table, the integrated luminosities needed to achieve $3\sigma$ and $5\sigma$ are presented. One can see that upgraded LHC with $\sqrt{s} = 14$ TeV and $L_{int} = 1000 fb^{-1}$ cover the quarkonia mass up to 800 GeV. The same mass region could be covered by the energy upgraded LHC with $L_{int} = 100 fb^{-1}$. With both the energy and luminosity upgrades LHC can reach $m_{\eta_4} = 1200$ GeV. The same region will be covered by the VLHC stage 1. The whole predicted mass region for $\eta_4$ quarkonia will be covered by VLHC stage 2 and RLHC.

In conclusion, the fourth family pseudoscalar quarkonium $\eta_4$ will be copiously produced at future hadron colliders. However, attainable mass ranges are restricted by the large backgrounds. The vector partner of $\eta_4$ quarkonium, namely $\psi_4$ will clearly manifest itself as resonance in lepton collisions. In Table V, we give the correspondence between the hadron \cite{22, 23, 24} and lepton \cite{27, 28, 29} colliders in view of their potentials to observe the fourth family quarkonia.

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| \( m_\eta \) (GeV) | 1000 | 1200 | 1400 | 1600 | 1800 | 2000 |
|----------------|------|------|------|------|------|------|
| \( \sigma (pb) \) | \(| LHC \ (14 \ T e V) \) | \(| LHC \ (28 \ T e V) \) | \(| VLHC \ (40 \ T e V) \) | \(| VLHC \ (100 \ T e V) \) | \(| VLHC \ (175 \ T e V) \) |
| 1.01 \times 10^{-2} | 7.11 \times 10^{-2} | 1.67 \times 10^{-1} | 1.17 \times 10^{0} | 3.22 \times 10^{3} |
| 3.37 \times 10^{-3} | 2.72 \times 10^{-3} | 6.71 \times 10^{-2} | 5.09 \times 10^{-1} | 1.48 \times 10^{0} |
| 1.28 \times 10^{-3} | 1.18 \times 10^{-2} | 3.06 \times 10^{-2} | 2.48 \times 10^{-1} | 7.57 \times 10^{-1} |
| 5.31 \times 10^{-4} | 5.62 \times 10^{-3} | 1.52 \times 10^{-2} | 1.32 \times 10^{-1} | 4.19 \times 10^{-1} |
| 2.38 \times 10^{-4} | 2.88 \times 10^{-3} | 8.12 \times 10^{-2} | 7.49 \times 10^{-2} | 2.46 \times 10^{-1} |
| 1.33 \times 10^{-4} | 1.55 \times 10^{-3} | 4.58 \times 10^{-3} | 4.51 \times 10^{-2} | 1.52 \times 10^{-1} |

| \( BR(\eta \to ZZ) \) \( m_\eta = 150 \ GeV \) | \( m_\eta = 250 \ GeV \) | \( m_\eta = 150 \ GeV \) | \( m_\eta = 250 \ GeV \) | \( m_\eta = 150 \ GeV \) | \( m_\eta = 250 \ GeV \) |
| 8.17 \times 10^{-5} | 4.08 \times 10^{-5} | 4.72 \times 10^{-5} | 2.59 \times 10^{-5} | 1.54 \times 10^{-5} | 9.70 \times 10^{-6} |
| 2.25 \times 10^{-5} | 1.34 \times 10^{-4} | 2.75 \times 10^{-5} | 1.61 \times 10^{-5} | 1.00 \times 10^{-5} | 6.60 \times 10^{-6} |
| 8.40 \times 10^{-6} | 5.60 \times 10^{-6} | 6.40 \times 10^{-6} | 6.00 \times 10^{-6} | 2.04 \times 10^{-5} | 2.10 \times 10^{-5} |

| \( BR(\eta \to WW) \) \( m_\eta = 150 \ GeV \) | \( m_\eta = 250 \ GeV \) | \( m_\eta = 150 \ GeV \) | \( m_\eta = 250 \ GeV \) | \( m_\eta = 150 \ GeV \) | \( m_\eta = 250 \ GeV \) |
| 2.99 \times 10^{-4} | 1.49 \times 10^{-4} | 1.61 \times 10^{-4} | 1.13 \times 10^{-4} | 1.20 \times 10^{-4} | 1.50 \times 10^{-4} |
| 4.90 \times 10^{-5} | 3.08 \times 10^{-5} | 8.73 \times 10^{-5} | 6.20 \times 10^{-6} | 3.80 \times 10^{-6} | 2.40 \times 10^{-6} |
| 9.00 \times 10^{-5} | 2.04 \times 10^{-5} | 3.20 \times 10^{-5} | 2.30 \times 10^{-5} | 1.60 \times 10^{-5} | 1.60 \times 10^{-5} |

| \( BR(\eta \to f \bar{f}) \) \( m_\eta = 150 \ GeV \) | \( m_\eta = 250 \ GeV \) | \( m_\eta = 150 \ GeV \) | \( m_\eta = 250 \ GeV \) | \( m_\eta = 150 \ GeV \) | \( m_\eta = 250 \ GeV \) |
| 1.56 \times 10^{-1} | 1.14 \times 10^{-1} | 1.23 \times 10^{-1} | 9.17 \times 10^{-2} | 9.13 \times 10^{-2} | 6.67 \times 10^{-2} |
| 8.66 \times 10^{-2} | 6.76 \times 10^{-2} | 7.07 \times 10^{-2} | 7.06 \times 10^{-2} | 4.42 \times 10^{-2} | 4.42 \times 10^{-2} |
| 5.41 \times 10^{-2} | 5.11 \times 10^{-2} | 5.11 \times 10^{-2} | 5.11 \times 10^{-2} | 4.42 \times 10^{-2} | 4.42 \times 10^{-2} |

| \( BR(\eta \to gg) \) \( m_\eta = 150 \ GeV \) | \( m_\eta = 250 \ GeV \) | \( m_\eta = 150 \ GeV \) | \( m_\eta = 250 \ GeV \) | \( m_\eta = 150 \ GeV \) | \( m_\eta = 250 \ GeV \) |
| 1.77 \times 10^{-2} | 9.46 \times 10^{-3} | 4.49 \times 10^{-2} | 4.76 \times 10^{-3} | 9.13 \times 10^{-2} | 1.82 \times 10^{-2} |
| 8.46 \times 10^{-2} | 2.58 \times 10^{-3} | 1.58 \times 10^{-2} | 1.64 \times 10^{-2} | 1.58 \times 10^{-2} | 1.58 \times 10^{-2} |
| 4.94 \times 10^{-2} | 4.94 \times 10^{-2} | 3.12 \times 10^{-2} | 3.12 \times 10^{-2} | 3.12 \times 10^{-2} | 3.12 \times 10^{-2} |

| \( BR(\eta \to Zh) \) \( m_\eta = 150 \ GeV \) | \( m_\eta = 250 \ GeV \) | \( m_\eta = 150 \ GeV \) | \( m_\eta = 250 \ GeV \) | \( m_\eta = 150 \ GeV \) | \( m_\eta = 250 \ GeV \) |
| 8.25 \times 10^{-1} | 8.77 \times 10^{-1} | 9.08 \times 10^{-1} | 9.26 \times 10^{-1} | 9.42 \times 10^{-1} | 9.53 \times 10^{-1} |
TABLE III: $\eta_4 \rightarrow \gamma \gamma$ channel: Number of signal, background events and corresponding statistical significances for $L_{int} = 100fb^{-1}$. Integrated luminosities needed to achieve 3$\sigma$ and 5$\sigma$ levels are also given. $m_h = 150$ GeV is assumed.

| $\sqrt{s}$ (TeV) | $m_{\eta}$ (GeV) | Signal | Background | $S/\sqrt{B}$ | $L_{int}$ (fb$^{-1}$) for 3$\sigma$ | $L_{int}$ (fb$^{-1}$) for 5$\sigma$ |
|------------------|------------------|--------|------------|-------------|-------------------------------|-------------------------------|
| LHC              | 14               |        |            |             |                               |                               |
|                  | 400              | 87     | 534        | 3.8         | 64                            | 178                           |
|                  | 500              | 15     | 261        | 0.9         | 1073                          | 2980                          |
|                  | 28               |        |            |             |                               |                               |
|                  | 400              | 385    | 1184       | 11.2        | 7                             | 20                            |
|                  | 500              | 70     | 599        | 2.9         | 109                           | 303                           |
|                  | 600              | 16     | 312        | 0.9         | 1048                          | 2910                          |
| VLHC Stage 1     | 40               |        |            |             |                               |                               |
|                  | 400              | 776    | 1800       | 18.3        | 3                             | 7                             |
|                  | 500              | 148    | 909        | 4.9         | 37                            | 104                           |
|                  | 600              | 35     | 456        | 1.6         | 331                           | 920                           |
|                  | 700              | 10     | 282        | 0.6         | 2570                          | 7130                          |
| RLHC Stage 1     | 100              |        |            |             |                               |                               |
|                  | 400              | 3527   | 5284       | 48.5        | 0.4                           | 1                             |
|                  | 500              | 754    | 2616       | 14.7        | 4                             | 11                            |
|                  | 600              | 196    | 1338       | 5.3         | 31                            | 87                            |
|                  | 700              | 60     | 787        | 2.1         | 195                           | 542                           |
|                  | 800              | 20     | 527        | 0.9         | 1104                          | 3068                          |
| VLHC Stage 2     | 175              |        |            |             |                               |                               |
|                  | 400              | 7575   | 9780       | 76.6        | 0.2                           | 0.4                           |
|                  | 500              | 1695   | 5022       | 23.9        | 2                             | 4                             |
|                  | 600              | 464    | 2574       | 9.1         | 11                            | 30                            |
|                  | 700              | 147    | 1488       | 3.8         | 62                            | 172                           |
|                  | 800              | 53     | 990        | 1.7         | 315                           | 875                           |
|                  | 900              | 21     | 684        | 0.8         | 1382                          | 3840                          |
TABLE IV: $\eta_4 \rightarrow Zh$ channel: Number of signal, background events and corresponding statistical significances for $L_{int} = 100 fb^{-1}$. Integrated luminosities needed to achieve 3$\sigma$ and 5$\sigma$ levels are also given. $m_h = 150$ GeV is assumed.

| $\sqrt{s}$ (TeV) | $m_\eta$ (GeV) | Signal | Background | $S/\sqrt{B}$ | $L_{int} (fb^{-1})$ for 3$\sigma$ | $L_{int} (fb^{-1})$ for 5$\sigma$ |
|------------------|----------------|--------|------------|-------------|--------------------------------|--------------------------------|
| LHC 14           | 400            | 56     | 1035       | 1.8         | 295                          | 820                          |
|                  | 500            | 31     | 315        | 1.8         | 290                          | 800                          |
|                  | 600            | 16     | 124        | 1.5         | 430                          | 1190                         |
|                  | 700            | 8      | 46         | 1.2         | 605                          | 1680                         |
|                  | 800            | 4      | 19         | 1.0         | 890                          | 2470                         |
|                  | 900            | 2      | 12         | 0.7         | 1940                         | 5380                         |
| VLHC Stage 1 40  | 400            | 503    | 8868       | 5.4         | 31                           | 87                           |
|                  | 600            | 178    | 817        | 6.2         | 23                           | 64                           |
|                  | 800            | 59     | 202        | 4.2         | 52                           | 145                          |
|                  | 1000           | 22     | 53         | 3.1         | 96                           | 267                          |
|                  | 1200           | 10     | 11         | 2.8         | 111                          | 310                          |
|                  | 1400           | 5      | 5          | 2.1         | 201                          | 559                          |
| RLHC 100         | 400            | 2289   | 39268      | 11.6        | 7                            | 19                           |
|                  | 600            | 991    | 4834       | 14.3        | 4                            | 12                           |
|                  | 800            | 377    | 1118       | 11.3        | 7                            | 20                           |
|                  | 1000           | 156    | 426        | 7.6         | 16                           | 44                           |
|                  | 1200           | 72     | 171        | 5.5         | 30                           | 82                           |
|                  | 1400           | 36     | 128        | 3.2         | 87                           | 240                          |
| VLHC Stage 2 175 | 400            | 4916   | 89213      | 16.5        | 3                            | 9                            |
|                  | 600            | 2347   | 11928      | 21.5        | 2                            | 5                            |
|                  | 800            | 967    | 2290       | 20.2        | 2                            | 6                            |
|                  | 1000           | 429    | 663        | 16.7        | 3                            | 9                            |
|                  | 1200           | 211    | 379        | 10.8        | 8                            | 21                           |
|                  | 1400           | 111    | 283        | 6.6         | 21                           | 57                           |

12
TABLE V: The comparison of hadron and lepton colliders potentials in view of the fourth family quarkonia searches.

| pp Colliders     | $e^+e^-$ Colliders               |
|------------------|----------------------------------|
| LHC 14, 100 fb$^{-1}$ | JLC/NLC, TESLA, CLIC - stage 1  |
| LHC 14, 1000 fb$^{-1}$    | JLC/NLC, TESLA, CLIC - stage 2 |
| LHC 28, 100 fb$^{-1}$     | JLC/NLC, TESLA, CLIC - stage 2 |
| LHC 28, 1000 fb$^{-1}$    | CLIC - stage 3                   |
| VLHC 40, 100 fb$^{-1}$    | JLC/NLC, CLIC - stage 2         |
| RLHC 100, 100 fb$^{-1}$   | CLIC - stage 3                   |
| VLHC 175, 200 fb$^{-1}$   | CLIC - stage 3                   |