

# The influence of unparticle and axion-like particle in Bhabha scattering

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**Abstract.** *The effect of the unparticle and axion-like particle (ALP) at Bhabha scattering is analyzed. We evaluate the total cross-section with the propagators of gauge boson  $\gamma, Z$ , unparticle (scalar and vector unparticle), and ALP which depends on the model parameters. Moreover, the comparison between scalar, vector unparticle contribution and ALP contribution is evaluated. The benchmark signal point of  $(d_U, \Lambda_U)$  in the Bhabha scattering is shown as  $(d_U, \Lambda_U) = (1.1, 1 \text{ TeV})$ .*

Keywords: axion like particles; cross-section; Bhabha scattering.

Classification numbers: 14.80.-j; 12.60.-i.

## 1. Introduction

Unparticle, proposed by Geogri in 2007 [1], can be a good dark matter candidate as viable mediators of long-range force [2]. As a result of non-canonical scaling dimensions, the long-range forces can be allowed. Suppose the existence of an infrared (IR) fixed point at the energy scale  $\Lambda_U$  in the ultraviolet (UV) theory causes the fields to become scale invariant. The effective coupling is expressed as  $\frac{1}{M_U^{d_U+d_{SM}-4}}$  where  $M_U$  is the heavy mass scale,  $d_U$  is the canonical dimension of the operator of the UV theory  $O_{UV}$ ,  $d_{SM}$  is the Standard model (SM) dimension of the SM operator  $O_{SM}$ . The fields of the UV theory become scale invariant below  $\Lambda_U \sim 1 \text{ TeV}$ . In the effective theory, the unparticle operator  $O_U$  coupled with the SM operator  $O_{SM}$  follows  $\left(\frac{\Lambda_U}{M_U}\right)^{d_U+d_{SM}-4} \frac{1}{\Lambda_U^{d_U+d_{SM}-4}} O_{SM} O_U$ . The dimension  $d_U$  in the range (1, 2) is the most natural and unparticle effects are the largest in this region [3, 4]. While the unparticle couplings with SM

particles, Higgs bosons are discussed in Refs. [5–13], the unparticle contribution on the colliders are studied in Refs. [14–18].

In recent years, the axion physics has been an increasing interest. Extending to a more general class of pseudo-scalar is known as axion-like particles (ALPs). ALPs stand out as promising candidates, capable of producing observable signatures across a broad range of experimental conditions [19]. ALPs, denoted by  $a$ , naturally arise in the theoretical scenarios beyond the Standard model (SM). Theoretical expectation for the ALP mass and the associated new physics scales span an extensive range from sub-eV to the TeV domain. The low-mass ALPs called light ALPs in the eV to MeV range are of particular cosmological and astrophysical relevance [20]. In the higher region, ALPs with masses from MeV to TeV have been as dark matter [21, 22]. The signal of the existence of light ALPs can be searched for astrophysical and cosmological phenomena. Light ALPs can influence stellar evolution, impact the dynamics of core-collapse supernova. The searches for light ALPs have been in the predictions of Big Bang Nucleosynthesis (BBN), in beam-dump experiments at CLEO and BaBar [23–25]. Meanwhile, heavier ALP signatures have been investigated in the accelerators, at the LEP and at the LHC in recent years [26–29] as well as in the flavor experimental programs [30–42]. The future electron-positron collider at the International Linear Collider (ILC), Future Circular Collider (FCC-ee), Circular Electron Positron Collider (CEPC) [43], the high energy muon collider and the electron hadron collider at the Large Hadron Electron Collider (LHeC) provide cleaner experiments and are well-suited for probing the properties of ALPs. At high energy colliders, ALPs can manifest their presence virtually, modifying standard QCD and electroweak processes [44–49].

Bhabha scattering is the electron-positron scattering process. Recently, Bhabha scattering in a massive Rarita-Schwinger model [50], the beam small angle radiative Bhabha scattering [51], unparticle in Bhabha scattering in the Randall-Sundrum model [52] have been considered.

There are three unparticle operators: scalar  $O_U$ , vector  $(O_U^\mu)$ , and tensor  $(O_U^{\mu\nu})$  unparticle operators, respectively. For our study, we consider the scalar and vector unparticle. We investigate the Bhabha cross-section through the SM, unparticle and ALP propagators at the ILC. This paper is arranged as follows. The Lagrangian and Feynman rules are introduced in Sec. 2. The results and discussions for the cross-section in Bhabha scattering are calculated in detail in Sec. 3. Finally, we give a summary and present conclusions.

## 2. Lagrangian and Feynman rules

ALPs are pseudo-scalars that feebly couple to SM particles [19]. The ALP effective Lagrangian can be expressed as follows [53]:

$$\begin{aligned}
L = & \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_a^2}{2}a^2 + C_{GG} \frac{\alpha_S}{4\pi f} a G_{\mu\nu}^A \bar{G}^{\mu\nu A} + C_{WW} \frac{\alpha_L}{4\pi f} a W_{\mu\nu}^I \bar{W}^{\mu\nu I} + C_{BB} \frac{\alpha_Y}{4\pi f} a B_{\mu\nu} \bar{B}^{\mu\nu} \\
& + \frac{\partial^\mu a}{f} \sum_F \bar{F} C_F \gamma_\mu F + \frac{C_H}{f} \partial^\mu a (H^+ i \overleftrightarrow{D}_\mu H) + \frac{C_{HH}}{f^2} (\partial^\mu a)(\partial_\mu a) H^+ H.
\end{aligned} \tag{1}$$

In this framework, the matrices  $C_F$  ( $F = q, u, d, l, e$ ) are  $3 \times 3$  Hermitian, while the coefficients  $C_{ii}$  ( $i = G, W, B, H$ ) are real couplings. Factors of  $\alpha_i/4\pi$  have pulled out from the interaction terms with the SM gauge fields.  $G_{\mu\nu}^A$ ,  $W_{\mu\nu}^I$ ,  $B_{\mu\nu}$  are the field-strength tensors of

$SU(3)_C, SU(2)_L, U(1)_Y$ .  $H$  is the Higgs doublet. The sum extends over the chiral fermion multiplets  $F$  of the SM. It is worth noting that the couplings of ALP to bosonic fields are loop suppressed, while the fermionic ALP couplings are present at tree level.

After electroweak symmetry breaking, the ALP couplings to SM mass eigenstates are

$$\begin{aligned}
L(\mu_{EW}) = & \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_a^2}{2}a^2 \\
& + \frac{a}{f} (g_{agg}G_{\mu\nu}^A\bar{G}^{\mu\nu A} + g_{a\gamma\gamma}F_{\mu\nu}\bar{F}^{\mu\nu} + g_{aZ\gamma}F_{\mu\nu}\bar{Z}^{\mu\nu} + g_{aZZ}Z_{\mu\nu}\bar{Z}^{\mu\nu} + g_{aWW}W_{\mu\nu}^+\bar{W}^{\mu\nu}) \\
& + \frac{2ea}{s_W f}g_{aWW} (W_\mu^+W_\nu^- (s_W\bar{F}^{\mu\nu} + c_W\bar{Z}^{\mu\nu}) + (s_W A_\mu + c_W Z_\mu) (W_\nu^+\bar{W}_-^{\mu\nu} - W_\nu^-\bar{W}_+^{\mu\nu})) \\
& + L_{ferm(\mu_{EW})} + \frac{C_{HH}}{2f^2}(\partial^\mu a)(\partial_\mu a)(h^2 + 2vh),
\end{aligned} \tag{2}$$

where the electromagnetic coupling constant  $e$ , the sine and cosine of the Weinberg angle  $s_W, c_W$ , respectively.  $L_{ferm(\mu_{EW})}$  is the ALP-fermion interaction. Due to the limit of infinite fermion masses, the couplings become constants as follows:

$$g_{agg} = \alpha_s(\chi_u + \chi_d), \tag{3}$$

$$g_{a\gamma\gamma} = \frac{2\alpha}{9}(4N_C\chi_u + N_C\chi_d + 9\chi_e), \tag{4}$$

$$g_{aZ\gamma} = \frac{\alpha}{6c_W s_W}(2N_C\chi_u + N_C\chi_d + 3\chi_e) - t_W g_{a\gamma\gamma}, \tag{5}$$

$$g_{aZZ} = \frac{\alpha}{6c_W^2 s_W^2}(N_C\chi_u + N_C\chi_d + \chi_e) - 2t_W g_{aZ\gamma} - t_W^2 g_{a\gamma\gamma}, \tag{6}$$

$$g_{aWW} = \frac{\alpha}{12s_W^2}(2N_C\chi_u + 2N_C\chi_d + 3\chi_e), \tag{7}$$

$$g_{aff} = \frac{m_f}{f}C_{af}. \tag{8}$$

Here  $\chi_{u,d,e}$  are the arbitrariness in the fermion couplings.  $\chi_u = \frac{\tan^2\beta}{1+\tan^2\beta}$ ,  $\chi_d = \chi_e = \frac{1}{1+\tan^2\beta}$ ,  $N_C = 1 + \frac{1}{\tan\beta}$  where  $\tan\beta$  is the ratio of the VEVs of the two Higgs doublets.

### 3. Results and discussion

We consider the Bhabha scattering in which the initial and final states contain electron and positron:

$$e^-(p_1) + e^+(p_2) \rightarrow e^-(k_1) + e^+(k_2). \tag{9}$$

Here  $p_i, k_i (i = 1, 2)$  stand for the momentums. There are Feynman diagrams contributing to reaction (9), depicted in Fig. 1. While the SM framework involves the  $\gamma, Z$  exchange in the  $s, t$ -channels, the new physics contributions encompass particles such as the vector ( $U^\mu$ ), scalar unparticle ( $U$ ) and ALP ( $a$ ) in the  $s, t$ -channels.

The transition amplitude representing the  $s$ -channel is given by:

$$M_s = M_{sZ} + M_{s\gamma} + M_{sU^\mu} + M_{sU} + M_{sa}, \tag{10}$$

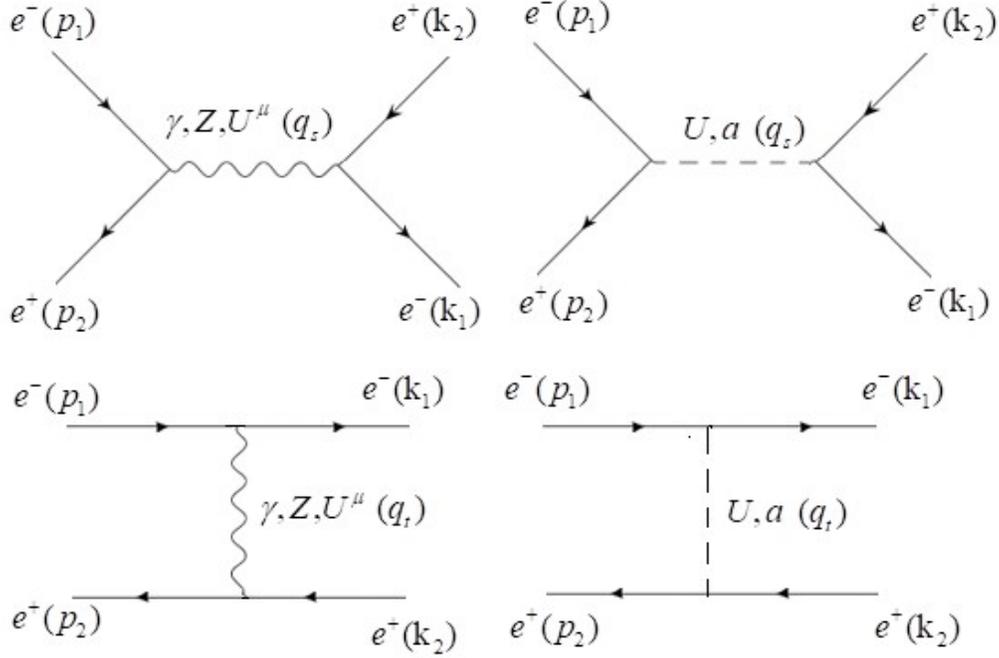


Fig. 1. Feynman diagrams for the process  $e^-e^+ \rightarrow e^-e^+$ .

here

$$M_{sZ} = i \frac{\bar{g}_{eeZ}^2}{q_s^2 - m_Z^2} u(p_1) \gamma^\sigma (-1 + 4s_W^2 + \gamma^5) \bar{v}(p_2) \left( \eta_{\sigma\beta} - \frac{q_{s\sigma} q_{s\beta}}{m_Z^2} \right) v(k_2) \gamma^\beta (-1 + 4s_W^2 + \gamma^5) \bar{u}(k_1), \quad (11)$$

$$M_{s\gamma} = i \frac{1}{q_s^2} u(p_1) \gamma^\sigma \bar{v}(p_2) \eta_{\sigma\beta} v(k_2) \gamma^\beta \bar{u}(k_1), \quad (12)$$

$$M_{sU^\mu} = -i \frac{\bar{g}_{eeU^\mu}^2 A_{dU}}{2 \sin(d_U \pi)} (-q_s^2)^{d_U - 2} u(p_1) \gamma^\sigma \bar{v}(p_2) \left( -\eta_{\sigma\beta} + \frac{q_{s\sigma} q_{s\beta}}{q_s^2} \right) v(k_2) \gamma^\beta \bar{u}(k_1), \quad (13)$$

$$M_{sU} = -i \frac{\bar{g}_{eeU}^2 A_{dU}}{2 \sin(d_U \pi)} (-q_s^2)^{d_U - 2} u(p_1) \bar{v}(p_2) v(k_2) \bar{u}(k_1), \quad (14)$$

$$M_{sa} = -i \frac{g_{aee}^2}{q_s^2 - m_a^2} u(p_1) \gamma^5 \bar{v}(p_2) v(k_2) \gamma^5 \bar{u}(k_1). \quad (15)$$

The transition amplitude representing the t-channel is given by:

$$M_t = M_{tZ} + M_{t\gamma} + M_{tU^\mu} + M_{tU} + M_{ta}, \quad (16)$$

here

$$M_{tZ} = i \frac{\bar{g}_{eeZ}^2}{q_t^2 - m_Z^2} \bar{u}(k_1) \gamma^\sigma (-1 + 4s_W^2 + \gamma^5) u(p_1) \left( \eta_{\sigma\beta} - \frac{q_t^\sigma q_{t\beta}}{m_Z^2} \right) v(k_2) \gamma^\beta (-1 + 4s_W^2 + \gamma^5) \bar{v}(p_2), \quad (17)$$

$$M_{t\gamma} = i \frac{1}{q_t^2} \bar{u}(k_1) \gamma^\sigma u(p_1) \eta_{\sigma\beta} v(k_2) \gamma^\beta \bar{v}(p_2), \quad (18)$$

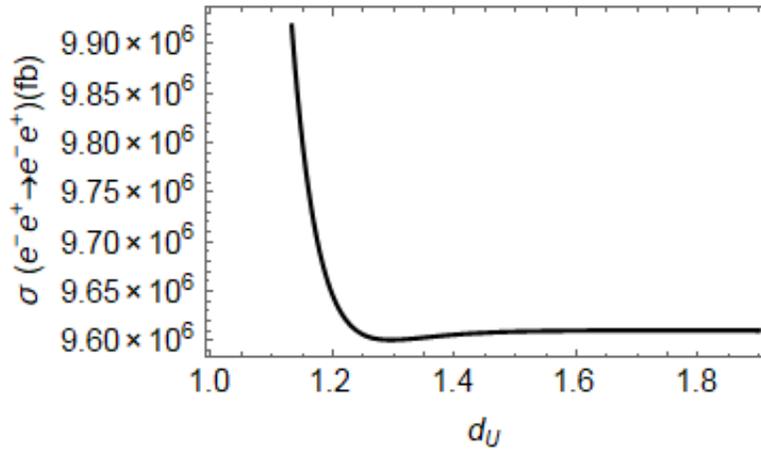
$$M_{tU^\mu} = -i \frac{\bar{g}_{eeU^\mu}^2 A_{d_U}}{2 \sin(d_U \pi)} (-q_t^2)^{d_U-2} \bar{u}(k_1) \gamma^\sigma u(p_1) \left( -\eta_{\sigma\beta} + \frac{q_{s\sigma} q_{s\beta}}{q_t^2} \right) v(k_2) \gamma^\beta \bar{v}(p_2), \quad (19)$$

$$M_{tU} = -i \frac{\bar{g}_{eeU}^2 A_{d_U}}{2 \sin(d_U \pi)} (-q_t^2)^{d_U-2} \bar{u}(k_1) u(p_1) v(k_2) \bar{v}(p_2), \quad (20)$$

$$M_{ta} = -i \frac{g_{aee}^2}{q_t^2 - m_a^2} \bar{u}(k_1) \gamma^5 u(p_1) v(k_2) \gamma^5 \bar{v}(p_2). \quad (21)$$

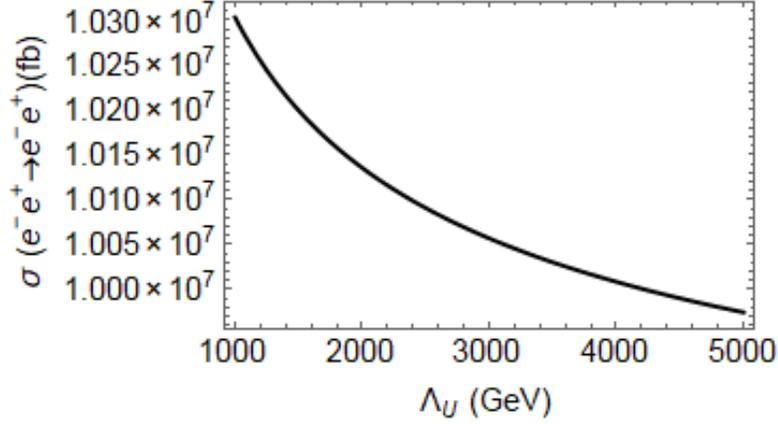
For ALP models with dominant ALP-electron coupling, the ALP masses are probed in the range  $[5, 20] \times 10^5$  eV and ALP-electron coupling is shown as  $g_{aee} \sim 10^{-8}$  [19]. Therefore, in this work, we choose the range of parameters as follows: the ALP masses  $m_a = [5, 20] \times 10^5$  eV,  $\Lambda_U = [1, 5]$  TeV, the collision energy  $\sqrt{s} = [500, 1000]$  GeV (ILC).

In Fig. 2, we evaluate the dependence of total cross-section on the scaling dimension of the unparticle operator  $d_U$ . The parameters are chosen as  $d_U = [1.1, 1.9]$  [3], the collision energy  $\sqrt{s} = 500$  GeV (ILC), the effective couplings  $\lambda_0 = \lambda_1 = 1$ , the energy  $\Lambda_U = 1$  TeV [14, 15], the ALP mass  $m_a = 5 \times 10^5$  eV [19]. The total cross-section decreases fast in the region  $d_U \approx [1.1, 1.3]$  and gradually in the region  $d_U \approx [1.3, 1.9]$ . The cross-section reaches the maximum value  $\sigma = 1.0303 \times 10^7$  fb when  $d_U = 1.1$ .



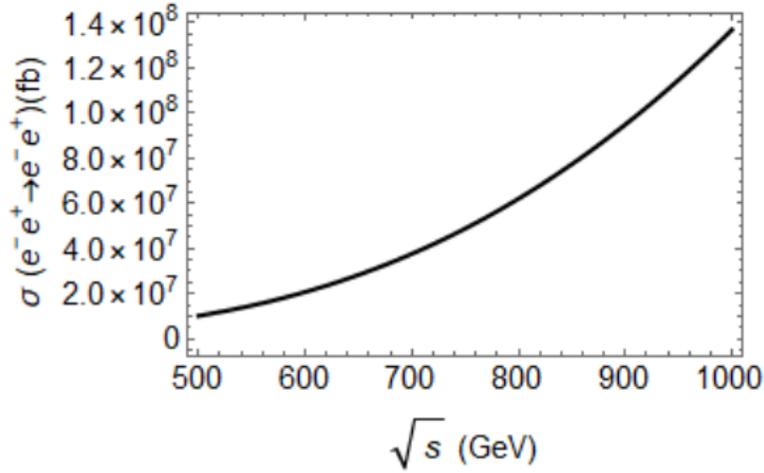
**Fig. 2.** The total cross-section as a function of the scaling dimension  $d_U$ .

Next, to clarify the influence of unparticle, we consider the total cross-section as the function of the energy scale  $\Lambda_U$  with the fixed  $d_U = 1.1$  in Fig. 3. The parameters are chosen as in Fig. 2. The total cross-section decreases as the energy scale increases.



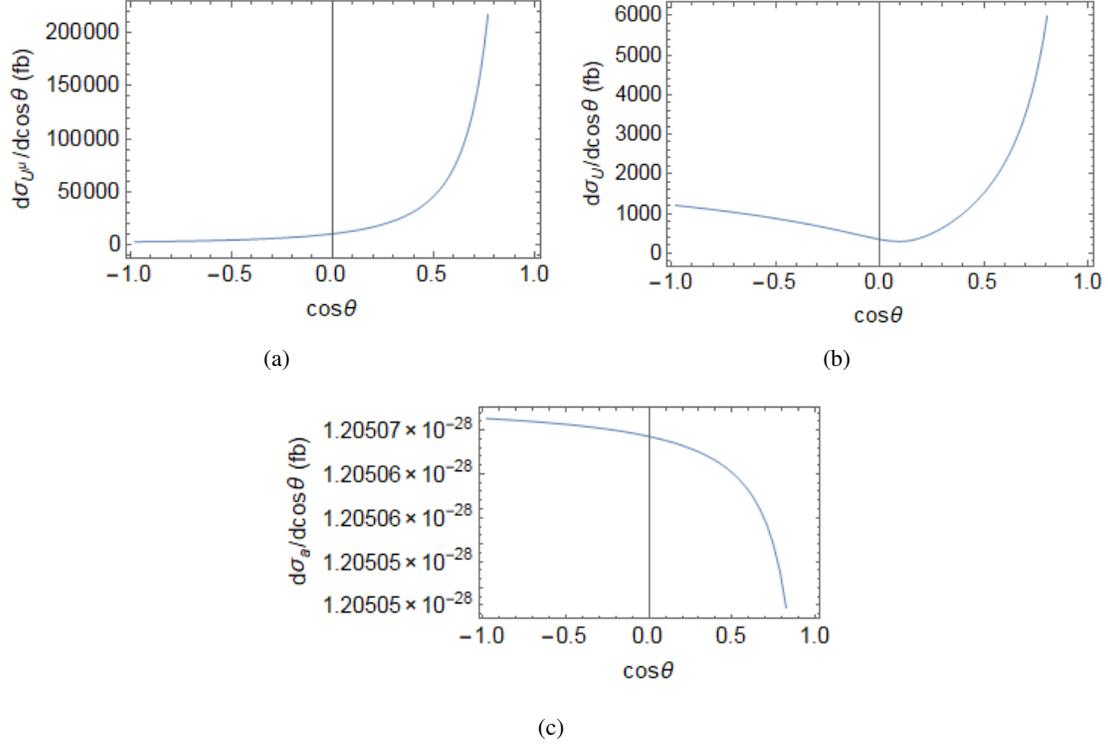
**Fig. 3.** The total cross-section as a function of the energy scale  $\Lambda_U$ .

With the fixed parameters  $(d_U, \Lambda_U) = (1.1, 1 \text{ TeV})$ , the total cross-section which depends on the collision energy  $\sqrt{s}$  is plotted in Fig. 4. The parameters are chosen as in Fig. 2. The total cross-section increases as the collision energy  $\sqrt{s}$  increases in the range  $[500, 1000]$  GeV.



**Fig. 4.** The total cross-section  $\sigma$  as a function of the collision energy  $\sqrt{s}$ .

To investigate the influence of vector, scalar unparticle and ALP on the Bhabha scattering, we plot the differential cross-sections in Fig. 5:  $d\sigma_{U^\mu}/d\cos\theta$  (the differential cross-section with the vector unparticle propagator  $U^\mu$ ),  $d\sigma_U/d\cos\theta$  (the differential cross-section with the scalar unparticle propagator  $U$ ),  $d\sigma_a/d\cos\theta$  (the cross-section with the ALP propagator). With the fixed parameters  $(d_U, \Lambda_U) = (1.1, 1 \text{ TeV})$ , the parameters are chosen as Fig. 2. The differential cross-sections with the vector and scalar unparticle propagators increase, while that with the ALP propagator when  $\cos\theta$  increases.

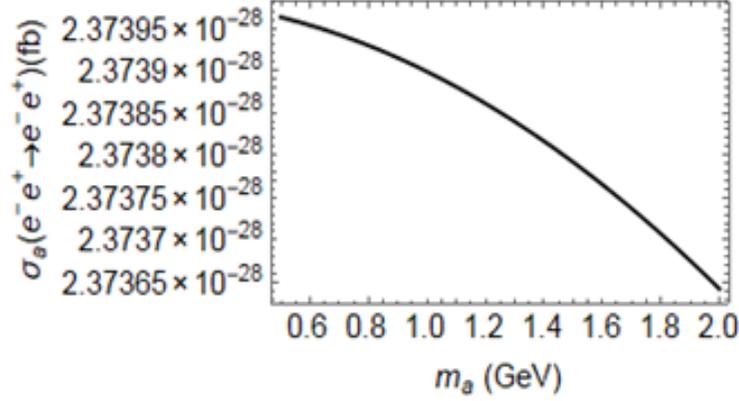


**Fig. 5.** The differential cross-section in cases of (a) vector unparticle propagator, (b) scalar unparticle propagator, and (c) ALP propagator as the function of the  $\cos \theta$ .

**Table 1.** The cross-section values at the fixed collision energy.

$\sqrt{s}$ (GeV)	500	600	700	800	900	1000
$\sigma_{\text{total}} (10^6 \text{ fb})$	10.303	20.883	37.806	62.234	95.128	137.172
$\sigma_{\text{SM}} (10^6 \text{ fb})$	9.576	20.318	37.336	61.828	94.750	136.811
$\sigma_{U^\mu} (10^5 \text{ fb})$	7.003	5.232	4.088	3.302	2.735	2.310
$\sigma_U (10^3 \text{ fb})$	4.005	2.992	2.338	1.888	1.564	1.321
$\sigma_a (10^{-28} \text{ fb})$	2.374	1.649	1.211	0.927	0.733	0.593

Finally, to compare the cross-sections in case of SM, vector, scalar unparticle and ALP propagators, we calculate the cross-section values at the fixed collision energy in Table 1. While the SM cross-section  $\sigma_{\text{SM}}$  increases, the cross-sections with the vector, scalar unparticle, ALP propagators denoted by  $\sigma_{U^\mu}$ ,  $\sigma_U$ ,  $\sigma_a$  decrease as the collision energy increases. The results show that the SM propagators are principal in the Bhabha scattering. However, the contribution of scalar and vector unparticle propagators is considerable. Besides, we also evaluate the dependence of the



**Fig. 6.** The cross-section in case of ALP propagator as the function of ALP mass.

ALP cross-section on the ALP mass in Fig. 6. The ALP cross-section changes insignificantly. In general, the  $\sigma_a$  is quite small, so the influence of ALP is negligible.

#### 4. Conclusion

In this study, we evaluate the contribution of the unparticle and ALP propagators on the Bhabha scattering. The results show that the cross-section  $\sigma_U$  is larger than the cross-section  $\sigma_a$ . With the unparticle and ALP contributions, the total cross-section is larger than the cross-section in SM. With the fixed parameters  $(d_U, \Lambda_U) = (1.1, 1 \text{ TeV})$ , the total cross-section reaches the maximum value. While the cross-section with ALP propagator is quite small, the contribution of scalar and vector unparticle propagators is considerable. The influence of vector unparticle is larger than that of scalar unparticle.

#### Conflict of interest

The authors have no conflict of interests to declare.

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