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Original Article

Production of ZZ Boson Pairs from $\mu^+\mu^-$ Collisions when μ^+,μ^- Beams are Polarized in the Unparticle Physics Model

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Abstract: In this work, we study the production of ZZ *boson pairs* from $\mu^+\mu^-$ *collisions* in a muon collider within the framework of the Standart Model (SM) and the Unparticle Physics (UP) model, considering polarized muon and anti-muon beams. The results show that the total cross-section (TCS) increases as the center of mass energy ($\sqrt{s}$) increases, the TCS has the largest value when both the μ^+ *and* μ^- particle beams are left polarized. The contribution of scalar unparticles is substantial in the case of oppositely polarized μ^+,μ^- particle beams. For *scaling dimension* $d_U = 1.1; 1.3; 1.5; 1.7$ the differential cross-section (DCS) reaches a large value when $-1 \le \cos\theta \le 0.5$ and the kinetic energy of the resulting Z boson beam is greater than 4 TeV. For the case $d_U = 1.9$, the density of points representing DCS with large values is evenly distributed throughout the entire survey domain.

Keywords: $\mu^+\mu^-$ collisions, unparticle physics, *Z* boson, scalar unparticles, *cross-section*,...

1. Introduction

Muon colliders, with their high center of mass energy and ability to produce clean signals, are becoming a crucial tool for probing new physics [1]. Among the production of a pair of on-shell Z bosons is a vital process at the Large Hadron Collider (LHC). Due to its large production cross-section at the LHC, this process is highly valuable for precision studies within the Standard Model (SM), particularly in the electroweak symmetry breaking-sector, as well as for uncovering potential new

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physics phenomena [2]. The production of a pair of Z at the LHC is a significant process that has been extensively studied theoretically and experimentally. This process provides very clean signals, making it a valuable tool for precisely testing the predictions of the SM. For experiments, leading to measurements at both ATLAS and CMS for various center of mass energies, such as 5.02 TeV [3], 7 TeV [4-9], 8 TeV [7-12], 13 TeV [12-17], and 13.6 TeV [18]. Most recently, in the study of muon collisions, we have obtained research results on the production of scalar unparticle [19] and vector unparticle [20] in models beyond the SM. These measurements may help explore potential new physics. From a theoretical perspective, similar studies can be extended to the production of new massive gauge boson pairs.

In this work, we study the production of Z boson pairs from $\mu^+\mu^-$ collisions in a muon collider within the framework of the SM and the UP model, considering polarized muon and anti-muon beams. Unparticle physics has been first suggested by Georgi [21], the concept of unparticles gives rise to the possibility for physics beyond the SM. The speculative theory is a low-energy phenomenology associated with the scale invariant sector as the Banks-Zaks (BZ) sector [22]. The BZ field can interact with the SM fields through the exchange of a particle with a high mass scale M_U. We have the following from of operators

$$\frac{O_{SM}O_{BZ}}{M_U^k} \quad (k>0) \tag{1}$$

where O_{SM} and O_{BZ} are local operators for SM and BZ fields, respectively. The effects of renormalization in the BZ sector induce dimensional transmutation at an energy scale Λ_U. Below this energy scale, matching conditions must be imposed onto the operator to match an operator new set as follows

$$\left(\frac{C_{O_U}\Lambda^{d_{BZ}-d_U}}{M_U^k}\right)O_{SM}O_U \tag{2}$$

where d_{BZ} and d_U are the scaling dimension of O_{BZ} and the unparticle operator O_U respectively, C_{O_U} is a coefficient function fixed by the matching conditions.

Those unparticle operators are all Hermitian and the two operators O_U^μ and $O_U^{\mu\nu}$ are presumed to be transverse. As shown in [1], the common effective interactions satisfying the standard model gauge symmetry for the scalar, vector, tensor unparticle operators with SM fields are given,

$$\begin{gathered} i\frac{\lambda_0}{\Lambda_U^{d_U-1}},\ \frac{-\lambda_0}{\Lambda_U^{d_U-1}}\gamma^5,\ \frac{\lambda_0}{\Lambda_U^{d_U}}\not{p},\ 4i\frac{\lambda_0}{\Lambda_U^{d_U}}\left(-p_1.p_2g^{\mu\nu}+p_1^\nu p_2^\mu\right) \\ i\frac{\lambda_1}{\Lambda_U^{d_U-1}}\gamma^\mu,\ i\frac{\lambda_1}{\Lambda_U^{d_U-1}}\gamma^\mu\gamma^5 \end{gathered} \tag{3}$$

where λ_i are the effective couplings $(C_{O_U^i}\Lambda_U^{d_{BZ}})/M_U^{d_{SM}+d_{BZ}-4}$ and dimensionless from the form (2) with the index i = 0, 1, or 2 corresponding to the scalar, vector, and tensor unparticle operators, respectively. The scalar operator can couple to the SM fermions as well. Nevertheless, the effect is suppressed by the fermion mass. In this work, we only concentrate on the effective operators for scalar and vector unparticles.

2. The Production ZZ Boson Pair from Collision $\mu^+\mu^-$

The collision process $\mu^+\mu^-$ creates the ZZ boson pair described by the Feynman diagram in Fig.1:

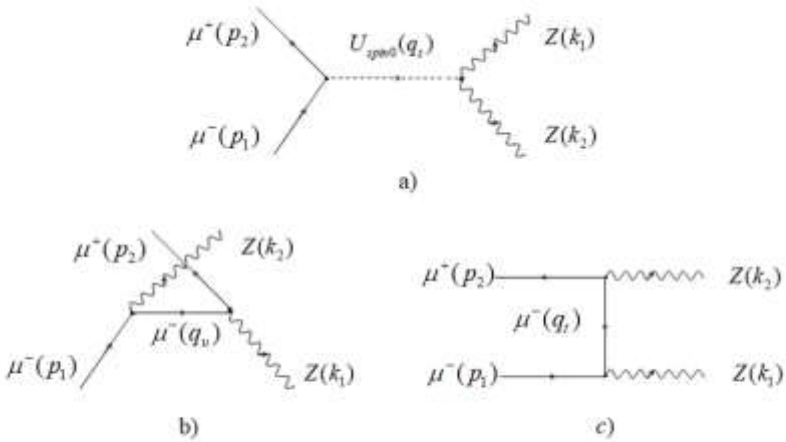


Figure 1. The Feynman diagrams of the process $\mu^+\mu^- \to ZZ$ in the Unparticle Physics model.

Applying Feynman's rule to the diagrams in Fig. 1, we obtain the scattering amplitude for the collision process $\mu^+\mu^-$ to create a pair of ZZ bosons according to the channels s, u, t, in the case where both beams μ^+,μ^- are left-polarized (M_{LL}); both are right-polarized (M_{RR}); beam μ^+ is right-polarized, beam μ^- is left-polarized (M_{RL}) and beam μ^+ is left-polarized, beam μ^- is right-polarized (M_{LR}) as follows:

$$M_{LL} = \frac{1}{2}\frac{\lambda_0}{\Lambda_U^{d_U}}\frac{A_{d_U}}{2\sin(d_U\pi)}(-q_s^2)^{d_U-2}\left(4i\frac{\lambda_0}{\Lambda_U^{d_U}}(-(k_1k_2)g^{\alpha\beta}+k_1^{\beta}k_2^{\alpha})\right)\varepsilon_\alpha^*(k_1)\varepsilon_\beta^*(k_2)$$
$$\times\bar{v}(p_2,s_2)\hat{q}_s(1-\gamma_5)u(p_1,s_1)$$
$$+\frac{i}{2}\left(\frac{g}{4c_{\rm W}}\right)^2\frac{1}{q_u^2-m_e^2}\varepsilon_\mu^*(k_1)\varepsilon_\nu^*(k_2)(v_e-a_e)^2\bar{v}(p_2,s_2)\gamma^\mu\hat{q}_u(1+\gamma_5)\gamma^\nu u(p_1,s_1)$$
$$+\frac{i}{2}\left(\frac{g}{4c_{\rm W}}\right)^2\frac{1}{q_t^2-m_e^2}(v_e-a_e)^2\varepsilon_\mu^*(k_2)\varepsilon_\nu^*(k_1)\bar{v}(p_2,s_2)\gamma^\mu\hat{q}_t(1+\gamma_5)\gamma^\nu u(p_1,s_1), \tag{4}$$

$$M_{\rm RR} = \frac{1}{2}\frac{\lambda_0}{\Lambda_U^{d_U}}\frac{A_{d_U}}{2\sin(d_U\pi)}(-q_s^2)^{d_U-2}\left(4i\frac{\lambda_0}{\Lambda_U^{d_U}}(-(k_1k_2)g^{\alpha\beta}+k_1^{\beta}k_2^{\alpha})\right)\varepsilon_\alpha^*(k_1)\varepsilon_\beta^*(k_2)$$
$$\times\bar{v}(p_2,s_2)\hat{q}_s(1+\gamma_5)u(p_1,s_1)$$
$$+\frac{i}{2}\left(\frac{g}{4c_{\rm W}}\right)^2\frac{1}{q_u^2-m_e^2}\varepsilon_\mu^*(k_1)\varepsilon_\nu^*(k_2)(v_e+a_e)^2\bar{v}(p_2,s_2)\gamma^\mu\hat{q}_u(1-\gamma_5)\gamma^\nu u(p_1,s_1)$$

$$+\frac{i}{2}\left(\frac{g}{4c_{\mathrm{W}}}\right)^{2}\frac{1}{q_t^2-m_e^2}\varepsilon_\mu^*(k_2)\varepsilon_\nu^*(k_1)(v_e+a_e)^2\bar{v}(p_2,s_2)\gamma^\mu\hat{q}_t(1-\gamma_5)\gamma^\nu u(p_1,s_1), \quad (5)$$

$$M_{RL(U-spin0)}=\frac{(i+1)}{2}\frac{\lambda_0}{\Lambda_U^{d_U-1}}\frac{A_{d_U}}{2\sin(d_U\pi)}(-q_s^2)^{d_U-2}\left(4i\frac{\lambda_0}{\Lambda_U^{d_U}}(-(k_1k_2)g^{\alpha\beta}+k_1^\beta k_2^\alpha)\right)\varepsilon_\alpha^*(k_1)\varepsilon_\beta^*(k_2)$$

$$\times\bar{v}(p_2,s_2)(1-\gamma_5)u(p_1,s_1)$$

$$+\frac{i}{2}\left(\frac{g}{4c_{\mathrm{W}}}\right)^{2}\frac{1}{q_u^2-m_e^2}\varepsilon_\mu^*(k_1)\varepsilon_\nu^*(k_2)(v_e^2-a_e^2)m_e\bar{v}(p_2,s_2)\gamma^\mu(1+\gamma_5)\gamma^\nu u(p_1,s_1)$$

$$+\frac{i}{2}\left(\frac{g}{4c_{\mathrm{W}}}\right)^{2}\frac{1}{q_t^2-m_e^2}m_e(v_e^2-a_e^2)\varepsilon_\mu^*(k_2)\varepsilon_\nu^*(k_1)\bar{v}(p_2,s_2)\gamma^\mu(1+\gamma_5))\gamma^\nu u(p_1,s_1), \quad (6)$$

$$M_{LR}=\frac{(i-1)}{2}\frac{\lambda_0}{\Lambda_U^{d_U-1}}\frac{A_{d_U}}{2\sin(d_U\pi)}(-q_s^2)^{d_U-2}\left(4i\frac{\lambda_0}{\Lambda_U^{d_U}}(-(k_1k_2)g^{\alpha\beta}+k_1^\beta k_2^\alpha)\right)\varepsilon_\alpha^*(k_1)\varepsilon_\beta^*(k_2)$$

$$\times\bar{v}(p_2,s_2)(1+\gamma_5)u(p_1,s_1)$$

$$+\frac{i}{2}\left(\frac{g}{4c_{\mathrm{W}}}\right)^{2}\frac{1}{q_u^2-m_e^2}\varepsilon_\mu^*(k_1)\varepsilon_\nu^*(k_2)(v_e^2-a_e^2)m_e\bar{v}(p_2,s_2)\gamma^\mu(1-\gamma_5)\gamma^\nu u(p_1,s_1)$$

$$+\frac{i}{2}\left(\frac{g}{4c_{\mathrm{W}}}\right)^{2}\frac{1}{q_t^2-m_e^2}m_e(v_e^2-a_e^2)\varepsilon_\mu^*(k_2)\varepsilon_\nu^*(k_1)\bar{v}(p_2,s_2)\gamma^\mu(1-\gamma_5)\gamma^\nu u(p_1,s_1) . \quad (7)$$

From equations (4) to (7), we calculate and obtain the square of the scattering amplitude of the $\mu^+\mu^-\to ZZ$ process when the μ^+,μ^- beams are polarized. In the center-of-mass reference frame with $p_1^\mu(E_1,\vec{p}),\ p_2^\mu(E_2,-\vec{p}),\ k_1^\mu(E_3,\vec{k}),\ k_2^\mu(E_4,-\vec{k}),\ E_1+E_2=E_3+E_4=\sqrt{s}$, we calculate the DCS and the TCS according to the formula:

$$\frac{d\sigma}{d\Omega}=\frac{1}{64\pi^2 s}\frac{|\vec{k}|}{|\vec{p}|}|M_{fi}|^2, \quad (8)$$

where $d\Omega = dcoc\theta d\varphi$.

3. Results and Discussion

First, we investigate and evaluate the TCS of the $\mu^+\mu^-$ collision producing ZZ boson pairs according to the center-of-mass energy $(\sqrt{s})$ with $\sqrt{s}\le 14TeV$ in a muon collider in the SM and in the UP when the μ^+,μ^- beams are polarized. In the UP, Figure 2 shows the dependence of the TCS of the $\mu^+\mu^-\to ZZ$ process in the case where the μ^+,μ^- beams are unpolarized according to d_U, with the values of the scale dimension d_U chosen to be $1.1; 1.3; 1.5; 1.7; 1.9$ [23]. From Fig. 2, we see that the TCS decreases slowly when d_U increases from 1.1 to 1.7, and increases quickly when d_U increases from 1.7

to 1.9. From that, we choose $d_U = 1.1$, $d_U = 1.7$ and $d_U = 1.9$, with the energy scale $\Lambda_U = 1TeV$ to investigate the TCS according to the center-of-mass energy $\sqrt{s}$. This dependence is shown in Fig. 3, and Fig. 4.

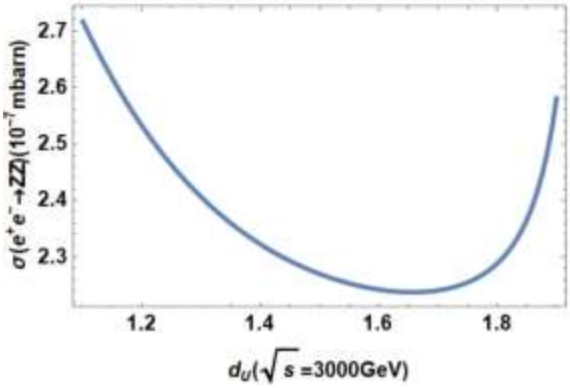


Figure 2. The dependence of the TCS on the d_U of the process $\mu^+\mu^- \to ZZ$ when the μ^+, μ^- beams unpolarized in the UP.

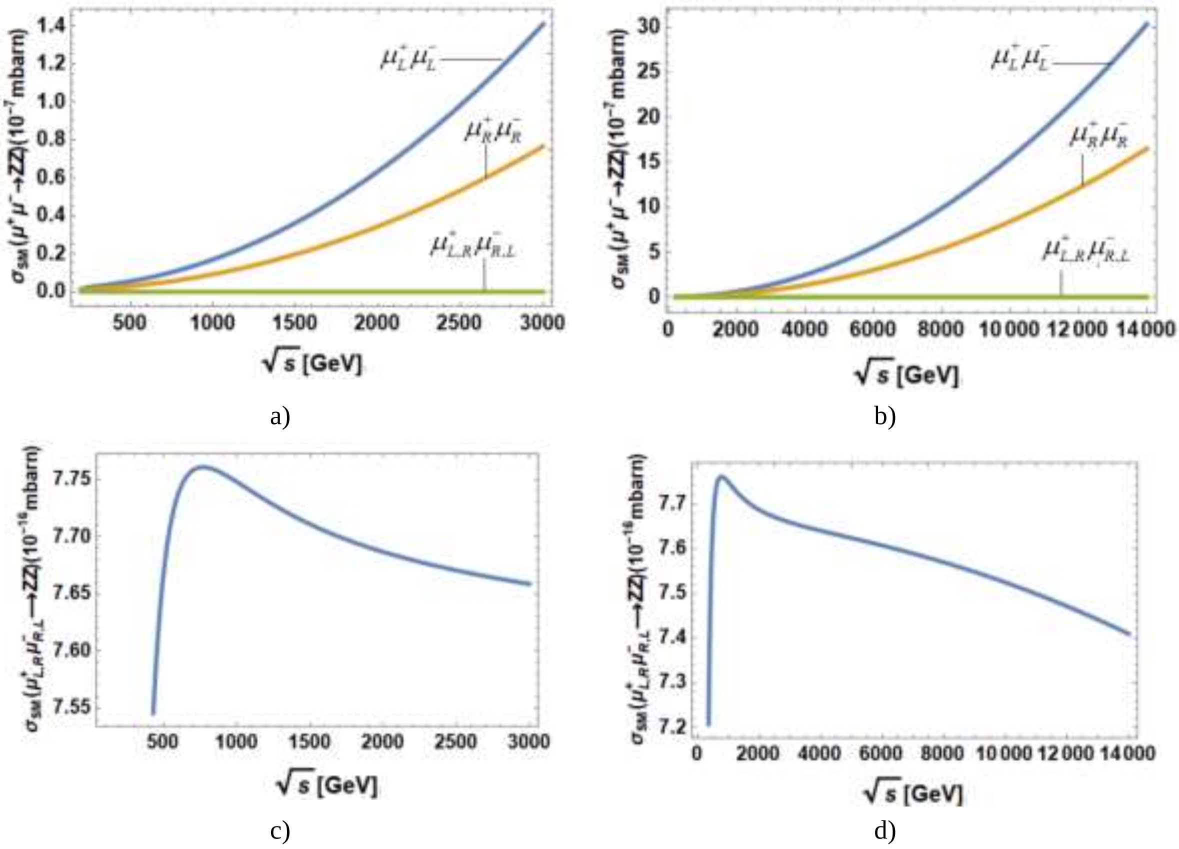


Figure 3. The dependence of the TCS on the center of mass energy $\sqrt{s}$ of the process $\mu^+\mu^- \to ZZ$ when the $\mu^+\mu^-$ beams polarized in the SM.

In the SM, from Fig. 3 we see that when the μ^+, μ^- beams are polarized the same, the TCS increases as $\sqrt{s}$ increases and is much larger than the case when the μ^+, μ^- beams are polarized in opposite. The TCS is largest in the case when the μ^+, μ^- beams are both left-polarized. For the case when the μ^+, μ^- beams are polarized in opposite, the TCS increases as $\sqrt{s}$ increases to a value of about $600 GeV$, but when $\sqrt{s}$ increases from $600 GeV$ to a value of about $14 TeV$, the TCS decreases.

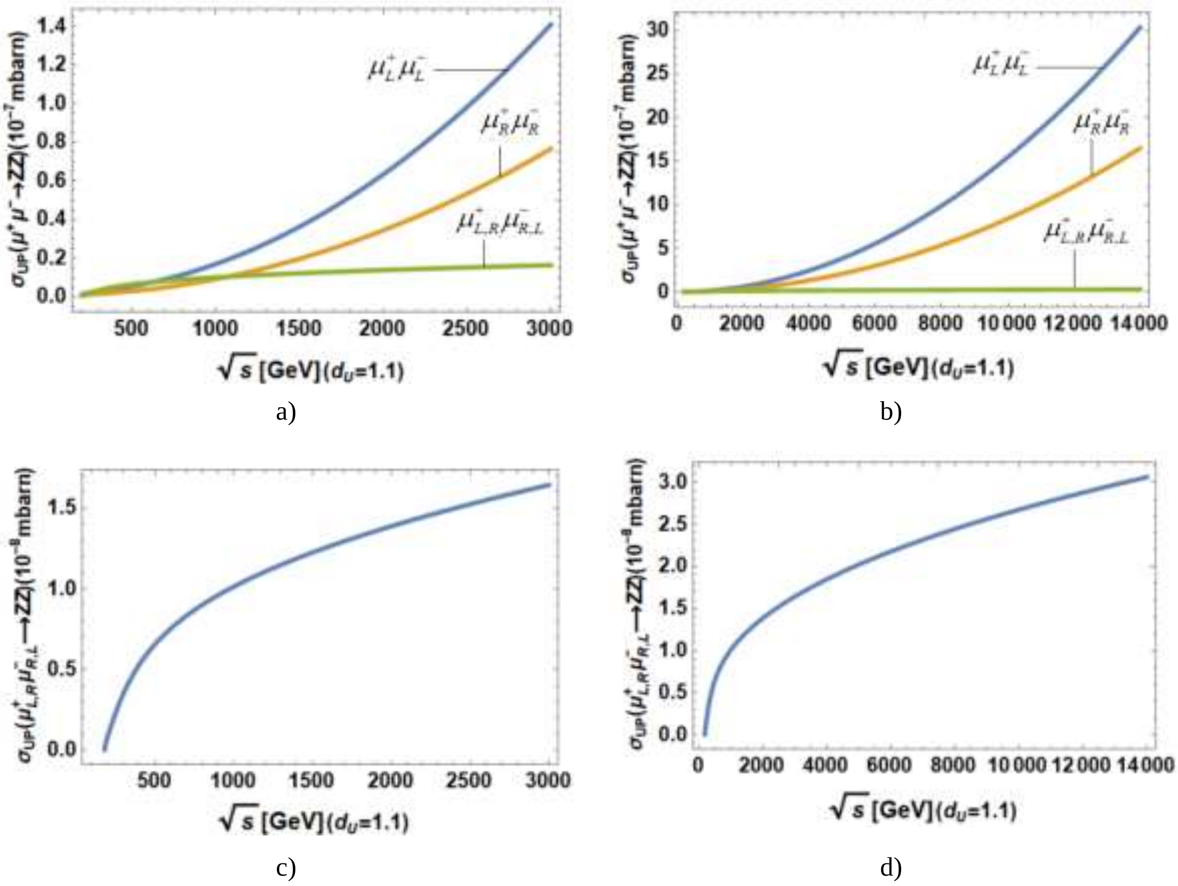


Figure 4. The dependence of the TCS on the center of mass energy $\sqrt{s}$ of the process $\mu^+\mu^- \to ZZ$ with $d_U = 1.1$ and when the $\mu^+\mu^-$ beams polarized in the UP.

In the UP, from Figs. 4 to 6, we see that in the polarization cases of the μ^+, μ^- beams, the TCS of the $\mu^+\mu^- \to ZZ$ process all have increasing values when $\sqrt{s}$ increases in the investigated domain. For the cases where the μ^+, μ^- beams are both left-polarized or right-polarized, the TCS in the SM and the UP does not change significantly. In the case where both the μ^+, μ^- beams are left polarized, the TCS has a larger value than in the case where both the μ^+, μ^- beams are right polarized. And in these two cases, the contribution of scalar unparticle can be considered negligible. However, in the case where the μ^+, μ^- beams are oppositely polarized, in the UP, the TCS has a much larger value than in the SM. And especially when $d_U = 1.9$ (Fig. 5), we see that the TCS in the case of oppositely polarized μ^+, μ^-

beams is larger than in the case of both μ^+, μ^- beams having the same polarization when $\sqrt{s}$ is larger than $13 TeV$. This shows that the scalar unparticles contribute greatly to the value of the TCS in the case of oppositely polarized μ^+, μ^- beams.

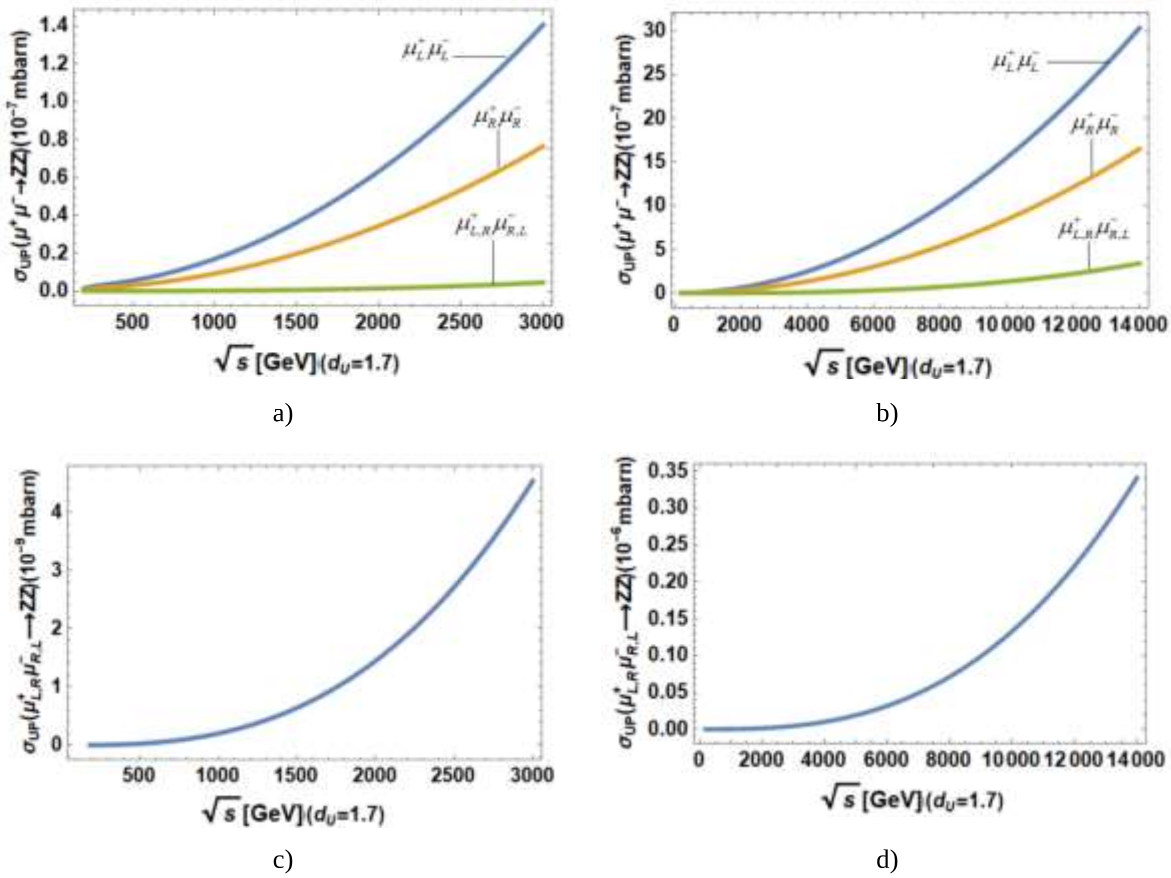
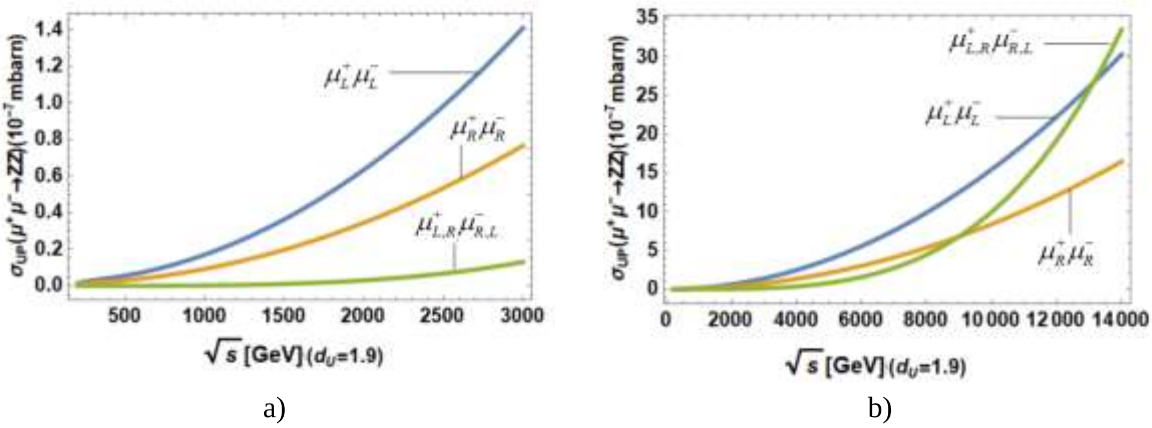
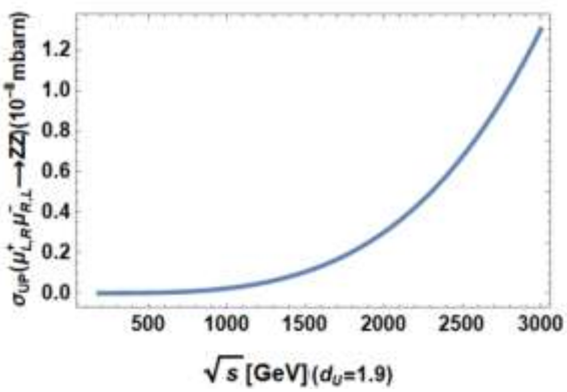
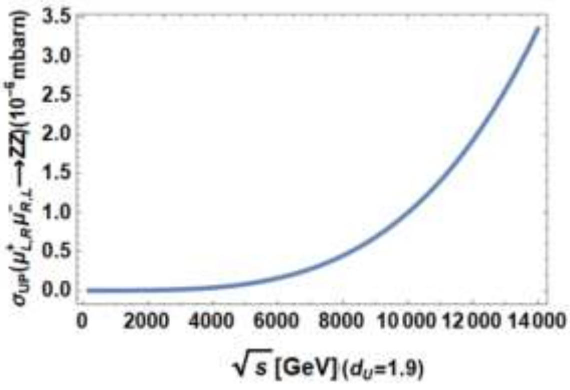


Figure 5. The dependence of the TCS on the center of mass energy $\sqrt{s}$ of the process $\mu^+\mu^- \to ZZ$ with $d_U = 1.7$ and when the $\mu^+\mu^-$ beams polarized in the UP.





c)



d)

Figure 6. The dependence of TCS on the center of mass energy $\sqrt{s}$ of the process $\mu^+\mu^- \to ZZ$ with.

Next, we evaluate the DCS of the $\mu^+\mu^- \to ZZ$ process depending on the kinetic energy W_Z of the Z boson beams with $W_Z \le 7000 GeV$ [24-26], the cosine of the scattering angle $\cos\theta$ in the SM. In the UP, we evaluate the TCS depending on the the kinetic energy W_Z , the cosine of the scattering angle $\cos\theta$, and the energy scale Λ_U $(\Lambda_U \le 10 TeV)$, with d_U chosen to be $1.1; 1.3; 1.5; 1.7; 1.9$. Figs. 7 and 8 show the distribution of the TCS depending on the above parameters in the SM and the UP.

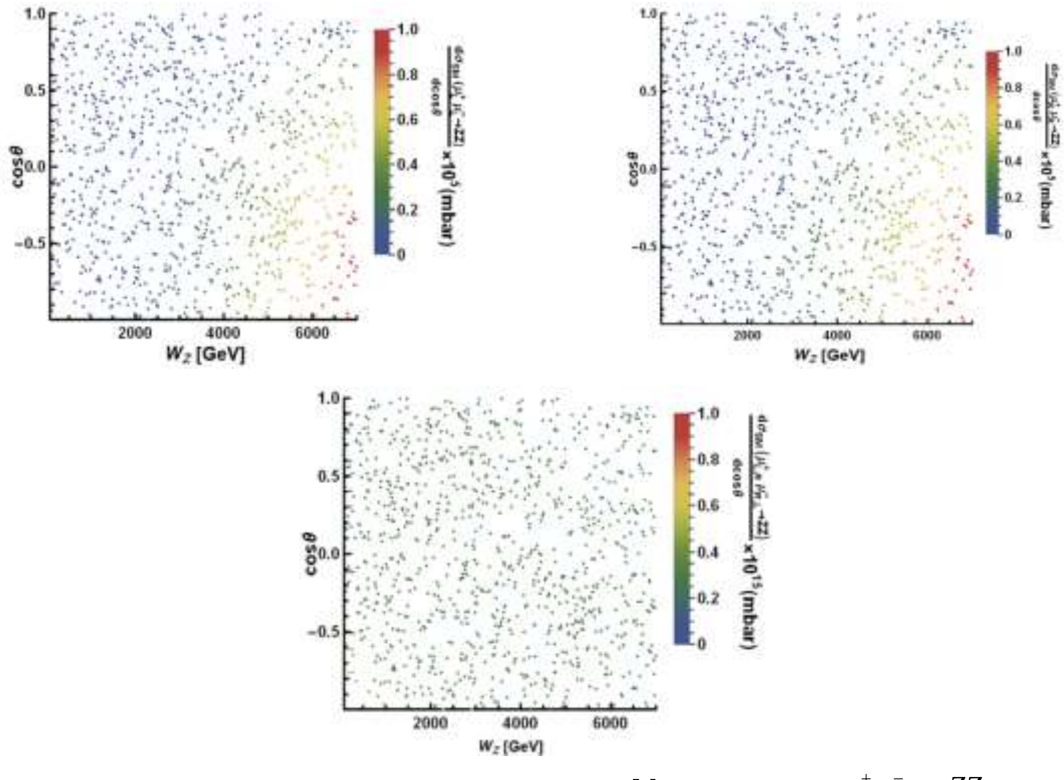
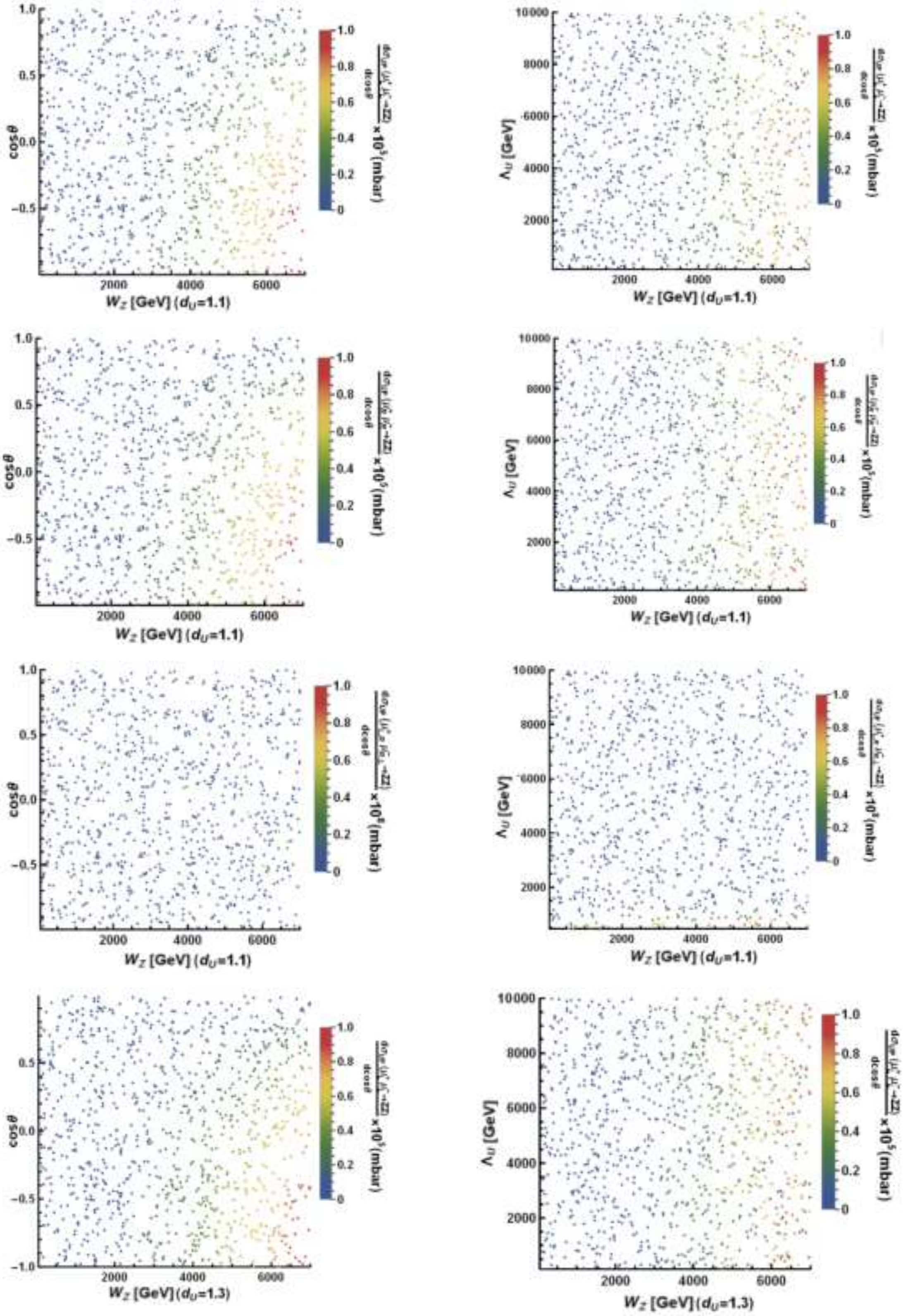
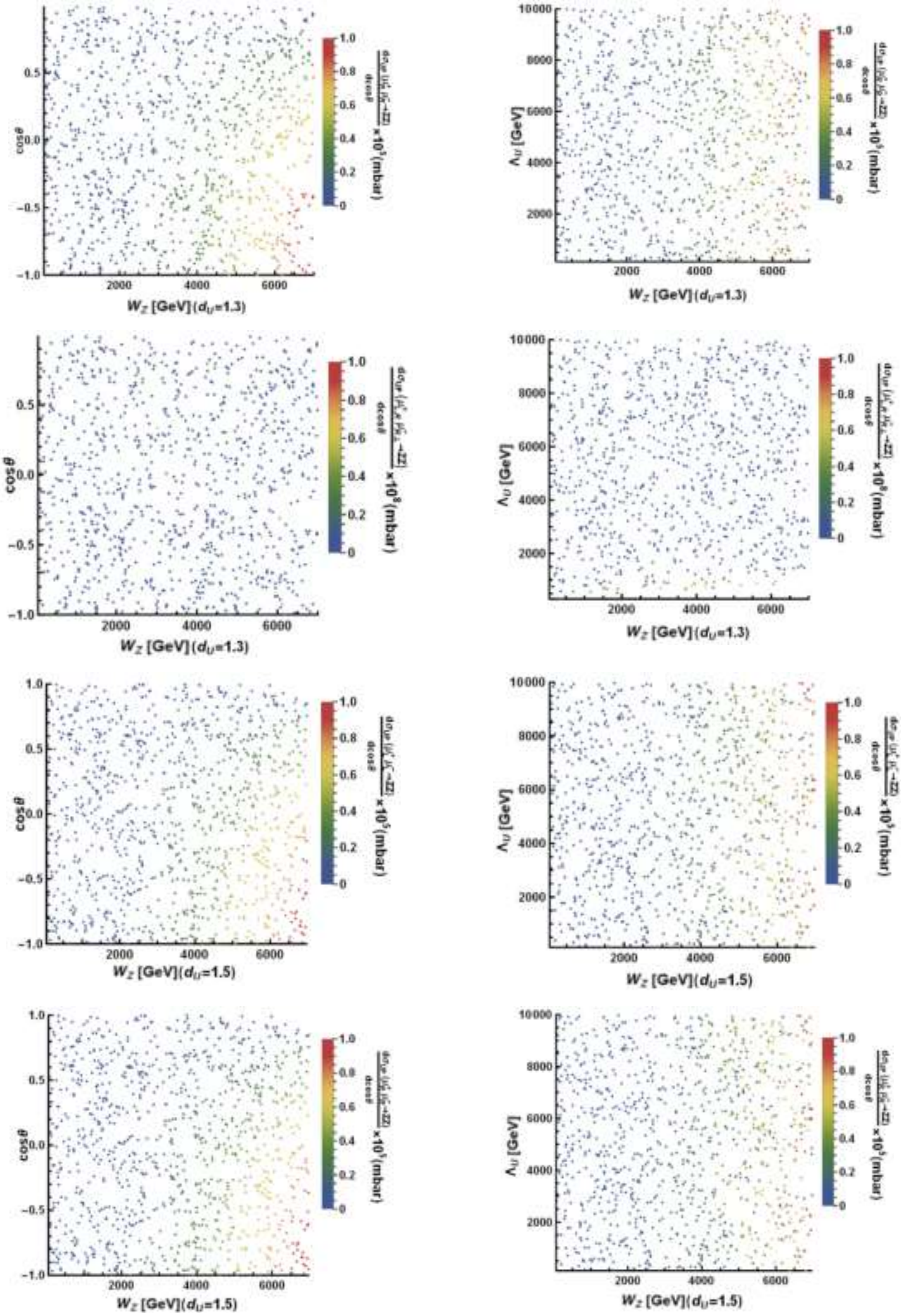


Figure 7. The dependence of TCS on $\cos\theta$, the kinetic energy W_Z of the process $\mu^+\mu^- \to ZZ$ when the $\mu^+\mu^-$ beams polarized in the SM.


cosθ
W_Z [GeV] (d_U=1.1)
Λ_U [GeV]
W_Z [GeV] (d_U=1.3)
×10^5 (mbar)
0
0.2
0.4
0.6
0.8
1.0


cosθ
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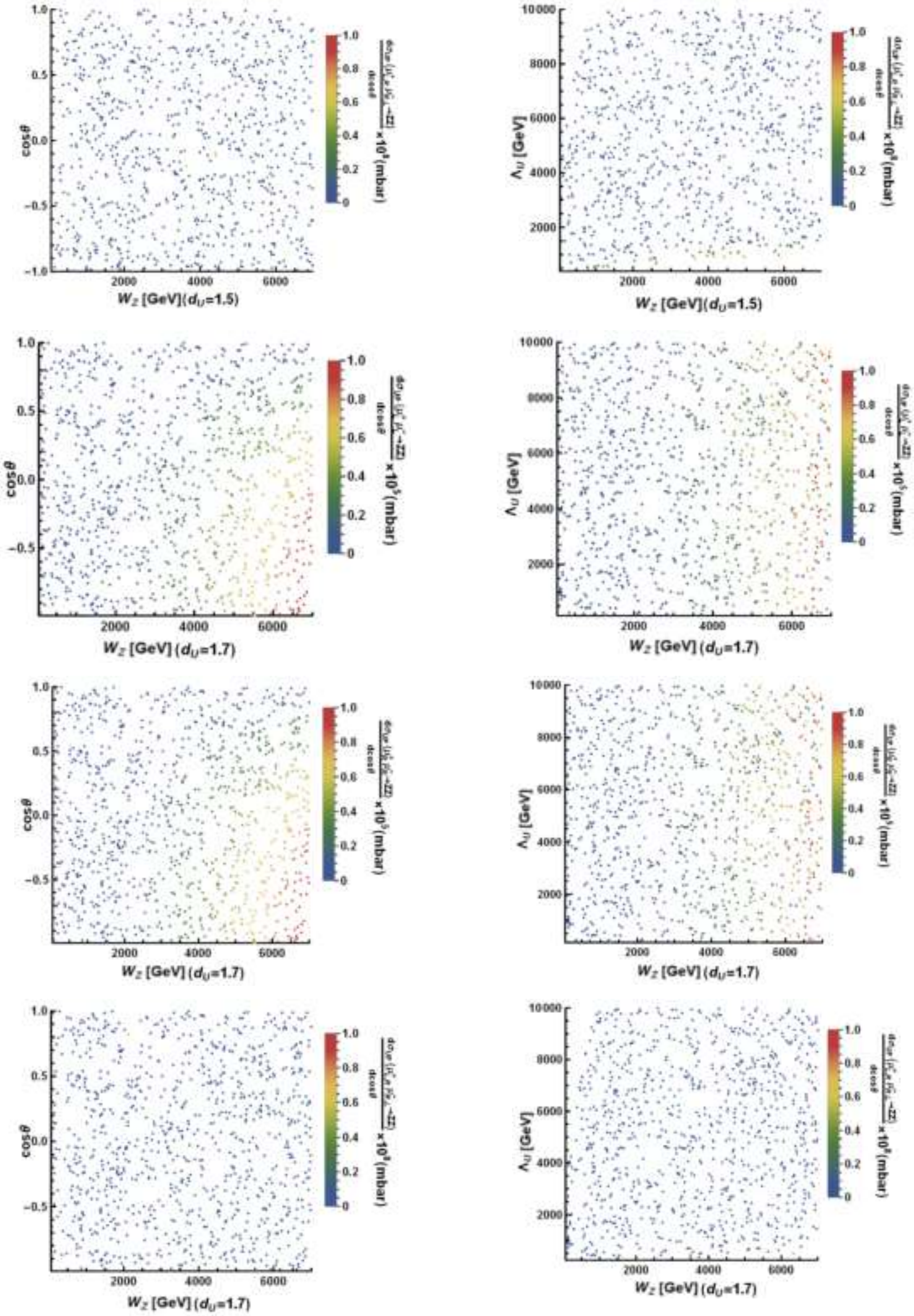
cosθ
W_Z [GeV](d_U=1.5)
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W_Z [GeV] (d_U=1.7)

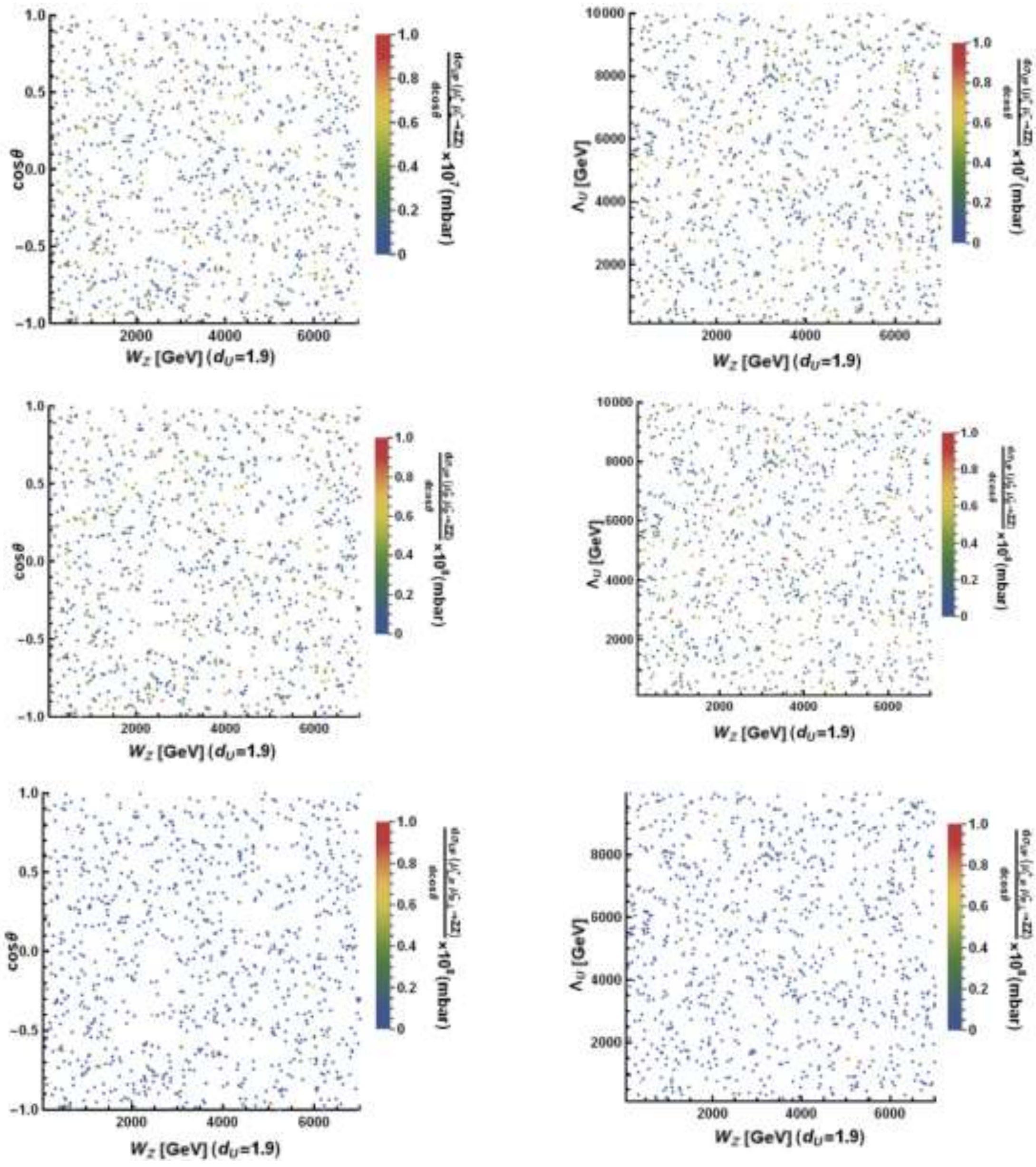

Figure 8. The dependence of DCS on the $\cos\theta$, the kinetic energy W_Z, the energy scale Λ_U, of the process $\mu^+\mu^- \to ZZ$ when the $\mu^+\mu^-$ beams polarized in the UP.

From Figs. 7 and 8 one can see:

The dependence of DCS on $\cos\theta$ and kinetic energy W_Z in the cases where the μ^+ and μ^- beams are both left-polarized or right-polarized in SM and UP with the values $d_U = 1.1; 1.3; 1.5; 1.7$, the density of points representing DCS has a large value in the domain $-1 \le \cos\theta \le 0.5$ and kinetic energy $W_Z \ge 4TeV$. Particularly for the case $d_U = 1.9$, we see that the density of points representing DCS has a large value is densely and evenly distributed throughout the entire survey domain. For the case where the μ^+ and μ^- beams are oppositely polarized, we see that the density of points representing DCS has the same color and is evenly distributed throughout the survey domain. This proves that DCS changes very little when the survey parameters change. When the μ^+ and μ^- beams are oppositely polarized, the DCS obtained in UP is much larger than in SM.

The dependence of DCS on kinetic energy W_Z and parameter Λ_U, we see that with $d_U = 1.1; 1.3; 1.5; 1.7$, when the μ^+, μ^- beams are polarized the same, the density of points representing DCS with large values is distributed evenly in the kinetic energy domain $W_Z \geq 4TeV$. When the μ^+, μ^- beams are oppositely polarized, the density of points representing DCS with large values appears in the domain $\Lambda_U \leq 1TeV$. For the case of $d_U = 1.9$, when the μ^+, μ^- beams are polarized the same, the density of points representing TCS with large values is evenly and densely distributed throughout the entire survey domain, when the μ^+, μ^- beams are polarized in opposite directions, the density of points representing DCS with large values is evenly and sparsely distributed in the domain of interest.

5. Conclusion

In this work, we have calculated and evaluated the scattering cross-section of the ZZ boson pair production process from μ^+, μ^- collisions in SM and UP when the μ^+, μ^- particle beams are polarized. The obtained results show that TCS gradually increases when d_U takes on increasing values from 1.1 to 1.7, and increases rapidly when d_U has increasing values from 1.7 to 1.9. TCS increases when $\sqrt{s}$ rises. TCS has the largest value when the μ^+, μ^- beams are both left polarized. The contribution of scalar unparticles is very large in the case of μ^+, μ^- particle beams with opposite polarization. With $d_U = 1.1; 1.3; 1.5; 1.7$, DCS reaches a large value when $-1 \leq \cos\theta \leq 0.5$ and the kinetic energy of the resulting Z boson beam is greater than $4TeV$. For $d_U = 1.9$, the density of points representing large DCS values is evenly distributed throughout the entire survey domain.

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