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Observability of Production of $t\bar{t}t\bar{t}$ quarks at pp-colliders in new physics models

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Abstract: The Standard Model production of four top quarks in the process $pp \to t\bar{t}t\bar{t}$ at a center-of-mass energy $\sqrt{s}$=13 Tev. The data collected by the ATLAS detector represents an impressive study potential, with an integrated luminosity of around 139 fb^{-1}. In this manuscript, we present the production process of four top quarks at the LHC as well as some new physics models associated with this process. These models are studied in analysis carried. Some preliminary results are presented, in particular those of a new method for estimating background noise due to false leptons developed.

Keywords: Standard Model; Top-quarks; *pp*-collider; New physics model

1. Introduction

The standard model (SM) of particle physics describes the elementary particles that make up matter and their interactions. Several limitations of this model, such as the absence of a coherent description of the gravitational interaction, lead to the development of new models or extensions of the standard model, qualified as "New Physics" beyond the standard model (BSM). At present, none of these new physics models has been sufficiently supported by experience, and physics beyond the standard model remains an open question.
The top quark is the most massive elementary particle known to date with $m_t = 173.0 \pm 0.4$ GeV [1]. Its coupling of Yukawa to the Higgs boson is neare to 1, which makes it a key element in many models of new physics. In particular, the cross section of the production process of four top $\sigma_{t\bar{t}t\bar{t}}$ quarks is increased in many BSM models. We are particularly interested in models showing new particles preferentially decay into top quarks: a model of additional dimensions and a model with two Higgs doublets (2HDM), but also a model developed within the framework of effective field theory. The measurement of $\sigma_{t\bar{t}t\bar{t}}$ is therefore a probe for these models, but also makes it possible to test the standard model in a complex and very energetic environment. The existence of the diagram on the left of figure 4 as well as other similar diagrams makes it possible in particular to constrain the Yukawa coupling of the top quark via the measurement of $\sigma_{t\bar{t}t\bar{t}}$, and thus to place constraints on the width of the boson of Higgs by combining this result with the measurement of the cross section of the process $pp \to t\bar{t}H$ [2]. This article describes the process of producing four top quarks and some new physics models that can lead to an increase in $\sigma_{t\bar{t}t\bar{t}}$. The best current results on $\sigma^{MS}_{t\bar{t}t\bar{t}}$ at the LHC at 13TeV are $12.6^{+5.8}_{-5.2}$ fb for the CMS experiment [3], and 28.5^{+12}_{-11} fb for the experiment ATLAS [4].

2. Production of 4-top quarks at the LHC

2.1. *Theoretical cross section*

At the LHC, the top quarks are most often produced in pairs with an effective cross section $pp \to t\bar{t}$ of around 800 bp at 13TeV [5], or even alone with an effective cross section of around 100 bp at 13TeV [6]. The production of four top $t\bar{t}t\bar{t}$ quarks is much rarer. At the LHC at 13TeV, four top quarks can be produced via an interaction between two gluons or between a quark and an anti-quark. The first case is most likely, accounting for approximately 90% of the total cross section [7].

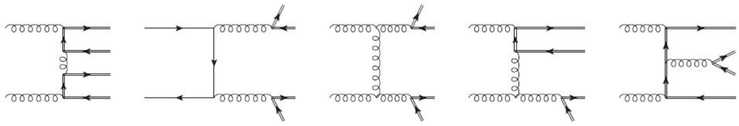

Figure 1. Feynman diagrams for the amplitude of Born $pp \to t\bar{t}t\bar{t}$. The diagrams are of order $\mathcal{O}\left(\alpha_s^2\right)$. The double lines represent the top quarks, the single lines correspond to the light quarks, and the loops are the gluons. [7]

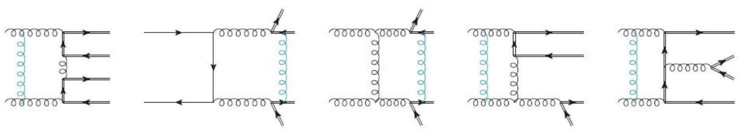

Figure 2. Feynman diagrams for the amplitude $pp \to t\bar{t}t\bar{t}$ at a loop. The diagrams are of order $\mathcal{O}\left(\alpha_s^3\right)$. The double lines represent the top quarks, the single lines correspond to the light quarks, and the loops are the gluons. [7]

A series of Feynman diagrams representative of the $pp \to t\bar{t}t\bar{t}$ process are shown in Figures 1, 2, and 3. The diagrams in Figure 1 represent the Born amplitude of the process, that is, the diagrams representing the process with the minimum number of vertices, here four. The diagrams in Figure 2 represent the amplitude at a loop, and those in Figure 3 represent the amplitude with a real parton emission. These three figures present diagrams which exclusively contain strong interaction vertices since they are a priori dominant. However, the electroweak contributions to the process are not negligible, and Figure 4 shows Feynman diagrams including one or more electroweak vertexes. Other diagrams must be considered, for example those for which H is replaced by γ or Z.

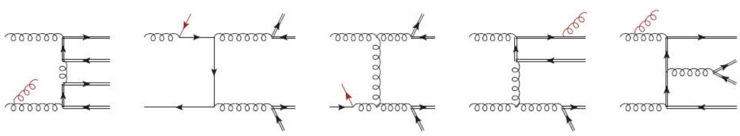

Figure 3. Representative Feynman diagrams for the amplitude $pp \to t\bar{t}t\bar{t}$ with a real parton emission (in red). The diagrams are of order $\mathcal{O}\left(\alpha_s^{5/2}\right)$. The double lines represent the top quarks, the single lines correspond to the light quarks, and the loops are the gluons. [7]

A cross section calculation involves the norm squared of a sum of amplitudes, each amplitude being able to be represented by a Feynman diagram. The order of a diagram is obtained by multiplying $\alpha_s^{1/2}$ by QCD vertex and $\alpha^{1/2}$ by electroweak vertex. The minimum number of vertexes in a Feynman diagram $pp \to t\bar{t}t\bar{t}$ being

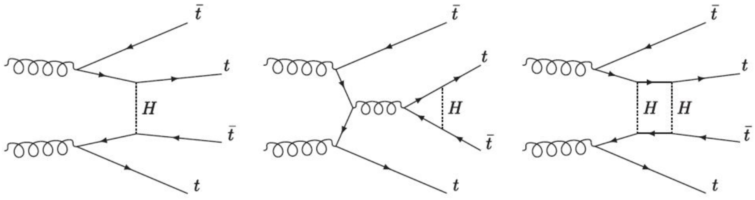

Figure 4. Feynman diagrams for the amplitude $pp \to t\bar{t}t\bar{t}$ with electroweak vertexes. The diagram on the left is representative of the amplitude of Born, while the other two are representative of the amplitude of a loop [8]. The diagram on the left is of order $\mathcal{O}\left(\alpha_s\alpha\right)$, the diagram in the middle is of order $\mathcal{O}\left(\alpha_s^2\alpha\right)$, and the diagram on the right is of order $\mathcal{O}\left(\alpha_s\alpha^2\right)$.

four, we deduce that the diagrams representing the amplitude of Born of the process are of order $\mathcal{O}\left(\alpha_s^i\alpha^j\right)$ with $i+j=2$. The cross section calculated at the dominant order (LO) is therefore of the order of the norm squared of a diagram, that is $\mathcal{O}\left(\alpha_s^i\alpha^j\right)$ with $i+j=4$. A complete calculation must take into account all the terms respecting $i+j=4$. Since $\alpha/\alpha_s \sim 0.1$ at the LHC energy, the diagrams with the most QCD vertex dominate the calculation a priori. This is why the LO_{QCD} terms, i.e. the terms for which i = 4 and j = 0 are often the only ones taken into account. These are the norms squared for the amplitudes represented by the diagrams similar to those in Figure 1 (order $(\alpha_s^2)^2 = \alpha_s^4$), as well as the terms corresponding to their interferences (order $\alpha_s^2 \times \alpha_s^2 = \alpha^4$).

A dominant second order calculation (NLO) must take into account all the terms respecting $i+j=5$. Often, only the term NLO_{QCD} is considered since it is a priori dominant. It is about the term for which $i=5$ and $j=0$. It thus contains all the norms squared of the amplitudes of the diagrams with a real emission of parton of the type of those represented on figure 3 (order $(\alpha_s^{(5/2)})^2 = \alpha_s^5)$), as well as all the terms of interference between the diagrams representative of the amplitude of Born like those represented in figure 1 and the diagrams with a loop similar to those represented in figure 2 (order $\alpha_s^2 \times \alpha_s^2 = \alpha^5$).

A (NLO) calculation in QCD, that is to say $LO_{QCD} + NLO_{QCD}$, was carried out in reference [9]. The calculated cross section is $9.2^{+2.9}_{-2.4}$ fb at 13TeV. A more recent calculation provides a compatible but slightly higher value: $11.1^{+2.1}_{-2.6}$ fb [8]. The uncertainties on the cross sections include the uncertainties due to the dependence of the calculation on the scales (renormalization, factorization), as well as to the dependence on the functions of distribution of partons (FDP). Uncertainties due to scales dominate total uncertainty. The terms for which $j \neq 0$ are however not negligible and have been taken into account in the reference [8]. The cross section thus obtained is $12.0^{+2.2}_{-2.5}$ fb at 13TeV. This calculation takes into account additional terms (LO), ie all the terms for which $i+j=4$ and $j \neq 0$. For example the terms for which $i=2$ and $j=2$ are from the norm squared of the amplitude represented by the diagrams similar to the diagram on the left of figure 4 (order $(\alpha_s^2\alpha)^2 = \alpha_s^2\alpha^2$).

Another example, the terms for which $i=3$ and $j=1$ come from Interference between diagrams similar to the diagram on the left in Figure 4 and those in Figure 1 (order $\alpha_s\alpha \times \alpha_s^2 = \alpha_s^3\alpha$). The calculation also takes into account additional terms (NLO) for which $i+j=5$ and $j \neq 0$. For example, the interferences between the central diagram (respectively on the right) of figure 4 and the diagrams of figure 1 are terms of order $(\alpha_s^2\alpha)^2 = \alpha_s^4\alpha$ (respectively $(\alpha_s^2\alpha)^2 = \alpha_s^3\alpha^2$).
The complete (NLO) calculation uses a dynamic definition of the μ_f factorization and μ_r renormalization

scales having for common value

$$\mu_c = \frac{H_{\mathrm{T}}}{4} \tag{1}$$

where H_T is the sum of the transverse masses $m_{\mathrm{T}} = \sqrt{m^2 + p_{\mathrm{T}}^2}$ of all the particles in the event. The choice of scales greatly influences the calculation, in particular the relative importance of the electroweak terms in the total cross section. As evidenced by the uncertainties, the total cross section is increased (respectively decreased) by about 20% following a multiplication (respectively division) by 2 of μ_c [10].

2.2. *Experimental signatures*

A top quark decay almost exclusively into a bottom quark and a W boson: $t \to Wb$ [1]. Its life time is around 5×10^{-25} s, while the characteristic time of strong interaction is around 10^{-23} s. The top quark therefore decay too quickly to be hadronized, and moves for too short a time for its movement to be observable in a detector. Only its decay products can be observed. Events with four top quarks can therefore be considered as events with four b quarks and four W bosons. It is useful to note at this stage that the final state of the studied process is rich in b quarks, which justifies a criterion of selection of events based in part on the number of b quark throws in the event. Each W boson from a top quark also decays very quickly, with a lifetime of around 3×10^{-25} s. Thus only its decay products can be observed. Several decay channels exist, which can be summarized as follows:

$$W \to \begin{cases} \ell\nu_\ell (\sim 30\%) \\ qq' (\sim 70\%) \end{cases} \tag{2}$$

with ℓ denoting a charged lepton, ν_ℓ a neutrino (or anti-neutrino) with the same flavor as this lepton, and qq two light quarks for example $u\bar{d}$ or $c\bar{s}$. Leptons τ are not explicitly identified in this work presented, only their decay products are. A τ is therefore seen as an electron, a muon, or even quarks, according to its decay channel. Subsequently we call "leptonic" a decay of a W boson into an electron or muon, and "hadronic" a decay into quarks.

Knowing the branching ratios of the decay of the boson W and the lepton τ [1], we can deduce the different final states generated by decaying of four bosons W. The latter are categorized according to the number of decay leptonic and hadronic, and are represented with their branching ratios in table **??**. We obtain a probability of about 25% (respectively 75%) for a leptonic (respectively hadronic) decay of a W boson, taking into account the decay of the leptons τ. Some analyzes focus on events containing a single lepton and jets, the category "ℓhhh" in the table. This channel is interesting because of its high branching ratio of around 40% of the total $pp \to t\bar{t}t\bar{t}$ events. In addition, these analyzes often include events of the "$\ell\ell hh$

OC" type, ie containing two leptons of opposite charge and jets, which can be analyzed with similar methods. By considering these two categories at the same time, we reach 56.5% of $pp \rightarrow t\bar{t}t\bar{t}$ events, more than half. However the two mentioned channels suffer from a very significant background noise, mainly coming from the $pp \rightarrow t\bar{t}$ process whose cross section is five orders of magnitude greater than $\sigma^{MS}_{t\bar{t}t\bar{t}}$. Consequently, the signal-to-noise ratio of the analysis is weak.

Table 1. Final states and their branching ratios for the decay of 4 W bosons. Symbols "ℓ" and "h" respectively denote a leptonic (e, μ, or $\tau \rightarrow e$, μ) and hadronic decay. The abbreviations "SC" and "OC" respectively designate events with two leptons of the same electrical charge, or of opposite charge.

type category	BR(in %)
ℓhhh	42.2%
hhhh	31.1%
$\ell\ell\ell\ell$	0.4%
$\ell\ell\ell h$	4.9%
$\ell\ell hh$ SC	7.2%
$\ell\ell hh$ OC	14.3%

Events comprising at least two leptons with the same electrical charge are also studied: "$\ell\ell h$ SC", "$\ell\ell\ell h$", and "$\ell\ell\ell\ell$". It is the final state chosen in this work and that studied by the analyzes presented. This final state represents only 12.5% of $pp \rightarrow t\bar{t}t\bar{t}$ events, but presents a noise very weak background. Indeed few standard model processes produce two leptons of the same charge, so we expect a good signal-to-noise ratio for this channel.

3. Production of 4-top quarks in the models of new physics

The cross section of the $pp \rightarrow t\bar{t}t\bar{t}$ process can be increased in several BSM models, via new particles or an effective interaction at four top quarks. These models introduce for example one or more new particles which can decaying into a pair of top quarks $X \rightarrow t\bar{t}$. Such a particle can be produced by pair $XX \rightarrow t\bar{t}t\bar{t}$ or associated with a pair of top quarks $t\bar{t}X \rightarrow t\bar{t}t\bar{t}$. If this particle can be produced at the energy of the LHC then it may be possible to observe a resonance. Otherwise the particle is too massive but its existence can generate lower energy effects, for example the energy of the LHC. It is therefore possible to probe several classes of resonant and non-resonant models by studying the production process of four top quarks. This section describes briefly the models influencing the cross section $\sigma_{t\bar{t}t\bar{t}}$ in proportions which could be observed at the LHC at 13TeV, and which have been studied experimentally, as will be discussed. This is a contact interaction model (CIM), a model of universal extra dimensions (2UED), and a model with two Higgs doublets

(2HDM), whose Feynman diagrams are represented in figures 5, 6, and 7. Other models have an impact on the production cross section of $\sigma_{t\bar{t}t\bar{t}}$ but are not presented here, such as, for example, supersymmetric models [11,12], topophile models [13], or models introducing for example sextet-uplets or octet-uplets having a color charge [14–18].

3.1. *Effective model of interaction of contact between 4-top quarks*

Numerous searches for heavy resonances decaying into top quarks $t\bar{t}$ have been carried out, but no significant deviation from the standard model has yet been observed [19–21]. The study of the $pp \rightarrow t\bar{t}t\bar{t}$ process can open a new window to phenomena that do not affect the production of top quark pairs. Many analyzes at the LHC notably interpret their results within the framework of the effective field theory (EFT). The idea of such a device is to assume that the new physics processes are at energies too high to be directly accessible to the LHC, but that they have detectable effects at low energy (that of the LHC). This is modeled by adding effective operators to the Lagrangian of the standard model. The operators of this Lagrangian are of order four in the standard model, and the EFT approach is interested in operators of higher orders. The advantage of the EFT approach and of not being based on any particular new physics model. It therefore makes it possible to study a class of models rather than a precise model. The measurement of the cross section $\sigma_{t\bar{t}t\bar{t}}$ can help to constrain certain operators of dimension 6. It is notably very competitive with regard to the contact operator with four fermions including two top quarks $qqtt$ [22]. The current limits on $\sigma_{t\bar{t}t\bar{t}}$ allow to constrain the operator $qqtt$ about as much as the measurements made on the $pp \rightarrow t\bar{t}$ process which have an accuracy of the order of a percent. Indeed if we write C/Λ^2 the coefficient of the operator $qqtt$, then the cross section of the production process of four top quarks depends on this coefficient to the power of four with a term of the form $(CE^2/\Lambda^2)^4$, E being the energy of the process $pp \rightarrow t\bar{t}t\bar{t}$. The large energy of the production process of four top quarks, as well as the presence of this term at the power of four greatly increases its sensitivity to the operator $qqtt$.

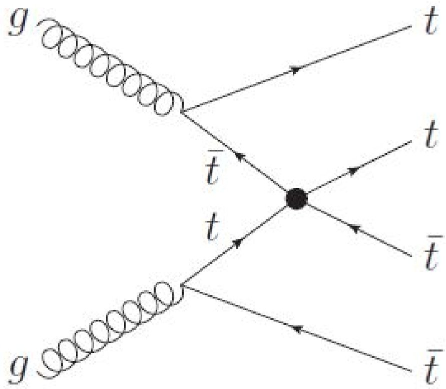

Figure 5. Feynman diagram of production of four top quarks via contact interaction (CIM).

An EFT model is studied in the analysis presented in [23]. This is an effective interaction model with four top quarks, called a contact interaction model (CIM). It follows the approach described in reference [24].

A Feynman diagram corresponding to this interaction is shown in Figure 5. The interference between the SM and CIM processes for producing four top quarks is negligible and therefore ignored. The Lagrangian associated with this interaction is:

$$\mathcal{L}_{4t} = \frac{C_{4t}}{\Lambda^2} \left(\bar{t}_R \gamma^\mu t_R\right) \left(\bar{t}_R \gamma_\mu t_R\right) \tag{3}$$

with t_R the right spin of the top quark, γ_μ the Dirac matrices, C_{4t} a dimensionless constant, and Λ the new physics energy scale.

The contact interaction term in equation 3 is an effective operator of dimension 6, which is not renormalizable. It can be seen as a low energy approximation of several theories introducing new heavy resonances and strongly coupled to the top quark, such as composite models [25–29], or even models of additional dimensions [30,31]. The new resonant particle exchanged between the four top quarks is too massive to be observed but has low energy effects, which is modeled by an effective interaction with four bodies. The establishment of limits on the cross section of such a process then indirectly makes it possible to constrain a class of models as explained above. This recalls the interaction of Fermi postulated in 1934 [32], namely an effective interaction with four bodies representing the exchange of a W boson, too massive to be observed at the time of the development of the model. The two parameters of the CIM model are the new physics scale which can be taken as the mass of the resonance, as well as its coupling with the right quark top. The analysis presented uses a simplified model by setting the scale of new at 100TeV in order to be in the contact interaction regime. There therefore remains only one free parameter, namely the C_{4t} coupling which directly controls the cross section value of the new physics process. Establishing a limit on the cross section of the CIM process therefore makes it possible to extract a limit on the parameter C_{4t}/Λ^2.

3.2. *Extra dimensions model*

Models introducing two dimensions in addition to the usual four dimensions, called Two Universal Extra Dimensions (2UED), can also increase the production cross-section by four top quarks. These dimensions are compacted in the geometry of the real projective plane, as described in [33], which introduces two rays R_5 and R_6. The actual projective plane can be constructed from a rectangle, similar to the torus which can be obtained by identifying the opposite sides of the rectangle. In the case of the real projective plane, it is also a question of identifying the opposite sides of a rectangle but by applying a half-turn to them in the manner of a Möbius strip. This construction is not concretely achievable in our space with three spatial dimensions. The compactification leads to the discretization of the impulses along these new dimensions, and each impulse state can be interpreted as a new particle, called Kaluza-Klein (KK) excitation. The states are indexed by two integers l and k representing the level of excitement in each of the new dimensions. A couple of indices (l, k) are called "level". The excitations $KK(0, 0)$ correspond to the particles of the standard model, one can thus see the new particles introduced as excitations of the particles of the standard model in the two new dimensions. The specificity of this model is that all the fields of the standard model can propagate in the new dimensions, hence the name Universal. The mass of a KK excitation is

$$m^2 = m_0^2 + \frac{l^2}{R_5^2} + \frac{k^2}{R_6^2} \tag{4}$$

with m_0 the mass of the corresponding particle in the standard model. There are next-to-leading order (NLO) corrections differentiating particles at the same level (l, k), but they are small compared to the masses of the particles [31]. By introducing the notations $m_{KK} = \frac{1}{R_5}$ and $\xi = \frac{R_5}{R_6}$, the previous equation is written:

$$m^2 = m_0^2 + m_{\mathrm{KK}}^2 \left(l^2 + k^2\xi^2\right) \tag{5}$$

According to this model, it is possible to produce at the LHC pairs of particles in level (1,1), which disintegrate into a cascade of other particles of level (1,1) given the small difference between the masses of particles of the same level. The particle at the end of the cascade is the lightest particle of the level (1,1), namely a heavy photon $A_\mu^(1,1)$.

It is assumed that the latter decays exclusively into a pair of top $t\bar{t}$ quarks, because the top quark is the most massive particle in the standard model and could therefore couple most strongly with the KK excitations. It is therefore possible to obtain four top quarks as well as other low energy quarks and leptons in the final state, as illustrated with the Feynman diagram shown in Figure 6.

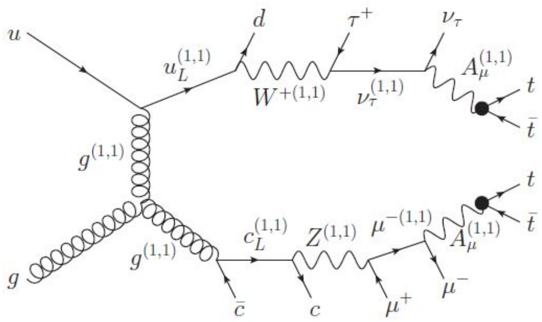

Figure 6. Feynman's diagram of the production of four top quarks in the compacted two-dimensional model (2UED).

Certain cosmological observations constrain the value of the parameter m_{KK}, which must be at most of the order of 1TeV [31,34]. The analysis presented probes the 2UED model for different values of the m_{KK} parameter with $\xi = 1$. These values range from $m_{KK} = 600$ GeV to $m_{KK} = 2$TeV, for a cross section varying between around 300 fb and around 1 fb.

3.3. *Model with two Higgs doublets*

Another model of new physics studied proposes an extension of the Higgs boson sector. The massive scalar boson discovered around 125 GeV is described by a Higgs doublet, but does not exclude the existence of other doublets. We consider here a model with two Higgs doublets Φ_1 and Φ_2 which spontaneously break the electroweak symmetry $SU(2)_L \times U(1)_Y$ [35]. We call this Two-Higgs Doublet Model (2HDM). Besides its interest in the framework of the study presented here, this model is motivated by supersymmetric models, models of axions, or again by the fact that it introduces new sources of CP-violation and that it could thus generate a matter/antimatter asymmetry of sufficient magnitude to comply with the observations. The Lagrangian of the 2HDM model is similar to that of the Higgs sector of the standard model:

$$\mathcal{L}_{2HDM} = y_1^{ij}\bar{\psi}_i\Phi_1\psi_j + y_2^{ij}\bar{\psi}_i\Phi_2\psi_j \tag{6}$$

where i and j are the indices of the generations of fermions. Among the different 2HDM models, the Type-II model is considered. It is the most studied 2HDM model because it is used in supersymmetric models. It introduces a difference between quarks of charge $+2/3$ on one side and quarks of charge $-1/3$ and charge leptons on the other. Indeed the field Φ_1 interacts with the quarks d, s, b, as well as the charged leptons, while Φ_2 interacts with the quarks u, c, t. Two mean values in the vacuum v_1 and v_2 are present, and we have $v = \sqrt{v_1^2 + v_2^2} = 246$ GeV, which is the mean value in the vacuum of the standard model. This model reveals several Higgs bosons: the usual scalar boson h, conforming to that discovered at the LHC, a heavy neutral scalar boson H^0, a pseudo-scalar boson A^0, as well as two charged bosons $H^\pm$. The six free parameters of the model are the four masses of the Higgs bosons, as well as $\tan\beta = v_2/v_1$ and the mixing angle α between the two scalar particles of the model at the origin of the bosons h and H^0.

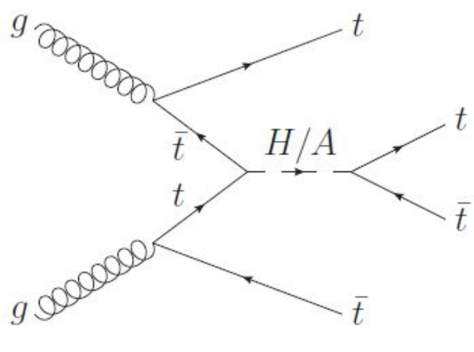

Figure 7. Feynman's diagram of the production of four top quarks in the model with two Higgs doublets (2HDM).

We are interested in the production of H^0 or A^0 bosons associated with a pair of top quarks, which can lead to the final state $t\bar{t}t\bar{t}$ if these bosons preferentially decay into $t\bar{t}$ pairs. This hypothesis is verified as soon as the mass of the bosons is sufficient, and that the value of $\tan\beta$ is low: $1 \tan\beta \lesssim 5$. For higher values of $\tan\beta$, the decay in pair $b\bar{b}$ becomes dominant. The study therefore relates to the following reaction, illustrated in Figure 7:

$$gg \rightarrow t\bar{t}H/A \rightarrow t\bar{t}t\bar{t} \quad (7)$$

Measuring the properties of the Higgs boson discovered at the LHC constrains the 2HDM models, which must be within the alignment limit [?], namely $\alpha = \beta$. Thus, the boson h is very similar to the Higgs boson of the standard model, and the other bosons are significantly heavier. The H^0 and A^0 bosons also have the same mass $m_{H/A}$ within the alignment limit. The cross section predicted by this model for the production process of four top quarks therefore depends only on $m_{H/A}$ as well as on the parameter $\tan\beta$. For $\tan\beta$ values between 1 and 5 and $m_{H/A}$ values between $2m_t$ and around 1000 GeV, the production cross section of the predicted top four quarks varies between around 10 fb and around 0.1 fb.

Conclusion

the production process of four top quarks has been studied. It is a rare process that is sensitive to many models of new physics. The measurement of its cross section could also make it possible to constrain the Yukawa coupling of the top quark. The search for this process was carried out in the channel with two leptons of the same electrical charge, which allows the best sensitivity. This work mainly focused on the analysis of the four-point process. This work turned to a new method for estimating background noise due to false leptons. Finally, the analysis will acquire a multivariate discriminant in order to improve its sensitivity. Preliminary results as well as recent results from the CMS collaboration suggest that this analysis will meet its objectives.

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