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# Determination of differential cross sections from $t\bar{t}$ fully leptonic, using the matrix element method

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**Summary.** — The purpose of this work is the development of a new analysis technique that allows the determination of differential cross sections with respect to arbitrary kinematic variables. This is illustrated for top quark pairs production where two leptons are present in the final state together with two neutrinos that cannot be detected. By estimating the $t\bar{t}$ invariant mass and the angle between the top quarks in the $t\bar{t}$ rest frame, the sensitivity to the presence of new physics is demonstrated. This technique, based on the matrix element method, makes the optimal use of the experimental information given a set of theoretical hypotheses.

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## 1. – Introduction

Evidences for new physics in top quark pair production are predicted in many theories and can be observed by estimating differential cross section with respect to arbitrary quantities. However, in high energy collider physics, some observables cannot be fully reconstructed using the detector information only. Techniques like kinematical fitting (KF) or matrix weighted template (MWT) have been developed to handle this difficulty — see for example [1]. This is for instance the case for top quark pair production, where two leptons are present in the final state together with two neutrinos that cannot be detected.

In this proceeding, we present a technique named Differential Matrix Element Method (DMEM) [2] which estimates differential cross section using for each event a density of probability. This method will be developed in sect. **2**. Section **3** presents first results in the case of standard model hypothesis and afterwards in presence of an additional vector boson decaying in a top-quark pair (*e.g.*, $Z' \to t\bar{t}$). Finally the efficiency of this method is quantified.

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## 2. – Differential matrix element method (DMEM)

The matrix element method [3] is a model-dependent technique providing a probability that an observed event is compatible with a partonic configuration. The whole theoretical information is used to constrain the unobserved kinematic variables. A weight is allocated to each event considering a specific theoretical frame, parametrized by $\vec{\alpha}$. It can be computed as the integral over all the possible partonic state of these probabilities as described by

$$\mathcal{P}(p^{vis}|\vec{\alpha}) = \frac{1}{\sigma_{\vec{\alpha}}} \int \mathrm{d}x_1 \mathrm{d}x_2 f(x_1) f(x_2) d\Phi |M_{\vec{\alpha}}(p)|^2 W(p, p^{vis}), \tag{1}$$

where $|M_{\vec{\alpha}}(p)|^2$ is the square of the matrix element at leading order for $t\bar{t}$ production and decay, $f(\cdot)$ is the parton density function, $W(p, p^{vis})$ is the transfer functions and $d\Phi$ is the measure of phase space. The technique has been adapted to be able to estimate differential cross sections by estimating the probability density functions (pdf) of arbitrary variables as

$$\frac{\partial \mathcal{P}}{\partial m}(p^{vis})|m_0 = \frac{1}{\sigma} \int \mathrm{d}x_1 \mathrm{d}x_2 f(x_1) f(x_2) d\Phi |M_(p)|^2 W(p, p^{vis}) \times \delta(m_{(p^{vis})} - m_0). \tag{2}$$

Differential cross section estimator are built by combining all the normalized event pdf's, $\frac{1}{\mathcal{P}} \frac{\mathrm{d}\mathcal{P}}{\mathrm{d}m}$. We dubbed this technique, Differential Matrix Element Method (DMEM) and implemented it in a private version of MadWeight [4]. An analysis based on a similar method was performed at CDF II to search resonant productions of $t\bar{t}$ pairs decaying semileptonically with an integrated luminosity of $4.8\,\mathrm{fb}^{-1}$ [5].

## 3. – Prospect at LHC

In order to observe the feasibility of the techniques MadGraph [6] samples of $t\bar{t}$ events decaying in the di-muons channel have been generated ($\sqrt{s} = 14\,\mathrm{TeV}$) and passed through PYTHIA [7] with ISR activated. A fast detector response simulation is performed using Delphes [8]. Some selection criteria are applied, events are required to have exactly two jets with transverse momentum larger than 30 GeV, and of two opposite-sign leptons with $pT > 20\,\mathrm{GeV}$. Additionally, a transverse missing energy larger than 30 GeV is required.

Looking at the transfer function on jets energies, a double Gaussian shape allows to reproduce the resolution as simulated by Delphes (see fig. 1). Lepton energy as observed particles directions are well reconstructed and parametrized by $\delta$ functions. We observed that the differential curve, obtained with the DMEM, reproduces the theoretical curves without any significant bias as represented by fig. 1.

A theoretical frame [9] with a spin-1 resonance decaying in $t\bar{t}$ ($Z' \to t\bar{t} \to lb\nu lb\nu$) has been chosen to illustrate the efficiency of the method by the reconstruction of two differential cross section. The first one is the $t\bar{t}$ invariant mass spectrum and the second one the angle in the centre of mass frame $\cos(\theta^*_{t\bar{t}})$. The considered model includes a $Z'$ with a mass of 1 TeV. Several configurations have been tested according to different contaminations $\frac{N_{Z'}}{N_{tot}} = (2, 3, 5, 8, 10)\%$. It is important to stress that the square matrix element used in eq. (2) is the standard model one. Samples of 5000 events have been analyzed, corresponding to an integrated luminosity of $5\,\mathrm{fb}^{-1}$.

The $t\bar{t}$ invariant mass spectrum shows the presence of new resonances as illustrated by fig. 2. Selecting the events contributing above 700 GeV in this spectrum, the angular

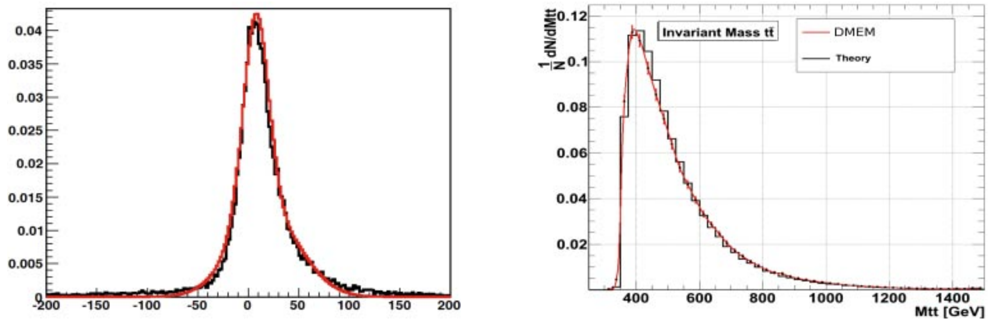


Fig. 1. – Left: Probabilty of $(E_{parton} - E_{jet})$ obtained by the jet energy transfer function, $W(Ep, E_{jet})$, estimated with 100000 jet-parton pairs. Right: $M_{t\bar{t}}$ normalised differential cross section of 5000 top-quark pair events decaying in fully leptonic channel. The theoretical curve is the expected one at tree-level when neither ISR and UE are taken into account.

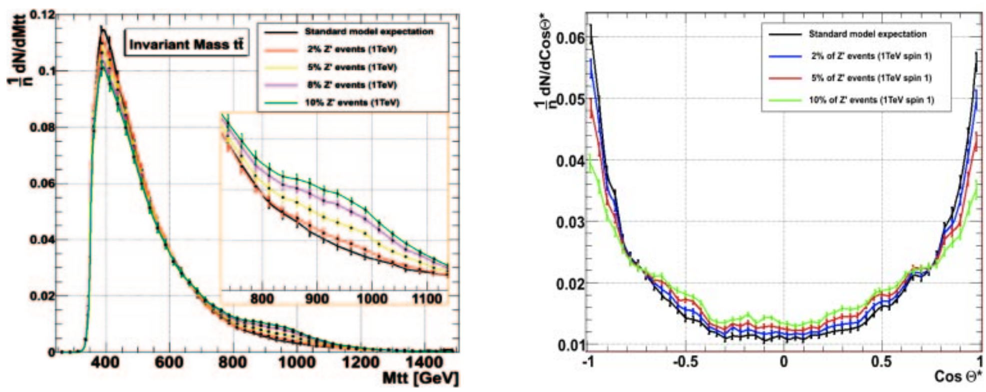


Fig. 2. – Normalized differential cross section for $M_{t\bar{t}}$ and $\cos(\theta^*_{t\bar{t}})$ for several samples of 5000 events ($5\,\mathrm{fb}^{-1}$) containing different ratios of $Z'$ events. Standard Model expected curves have been estimated on a sample of 100000 events.

distribution $\cos(\theta^*_{t\bar{t}})$ was built. This variable is sensitive to the spin of the new physics decaying in top-quark pairs [9]. Deviations from the standard model are clearly visible, on both distributions, when the ratio of new physics increases. The shape of the $\cos(\theta^*_{t\bar{t}})$ distribution is in agreement with what is expected for a spin-1 hypothesis.

To be able to quantify these tendencies, a $\chi^2$ estimator has been defined. Since each event provides a binned pdf, all bins are correlated to each other. Using 100000 $t\bar{t}$ fully

TABLE I. – *Confidence level for standard model exclusion computed on several samples for different contamination of $Z'$ events.*

| $\frac{N_{Z'}}{N_{tot}}$ | 2% | 3% | 5% | 8% | 10% |
|---|---|---|---|---|---|
| C.L. for S.M. exclusion | 72% | 95.6% | $> 99.998\%$ | | |

leptonic events theses correlations have been computed. The $\chi^2$ is constructed as

$$\sum_{ij} C_{ij}^{-1} \frac{(x_i - x_i^{th})}{\sigma_i} \frac{(x_j - x_j^{th})}{\sigma_j},$$

where $i$ and $j$ are the bins, $\sigma_i$ the variance of bin $i$ and $C_{ij}$ the covariance matrix element.

This estimator is converted to a confidence level value of standard model exclusion, as shown in table I. With an integrated luminosity of $5\,\text{fb}^{-1}$ looking at selected event samples, containing 2% of $Z'$, the standard model is excluded at 72%. Increasing the new physics proportions in the samples, the standard model can be excluded at 99.998% above 5% of $Z'$ events.

## 4. – Conclusions

For top physics at LHC, MadWeight in combination with the Differential Matrix Element Method provides variables sensitive to new resonances decaying in top quarks pairs. The deviations observed in the $t\bar{t}$ invariant mass spectrum have been quantified to estimate the power to discriminate between the standard model and beyond. Moreover, the angular variable $\cos(\theta^*_{t\bar{t}})$ provides information about the spin of the resonance. The current integrated luminosity recorded by CMS/ATLAS is sufficient to perform a first analysis with this method.

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