Search for the Standard Model Higgs boson in association with top quarks using the Matrix Element Method

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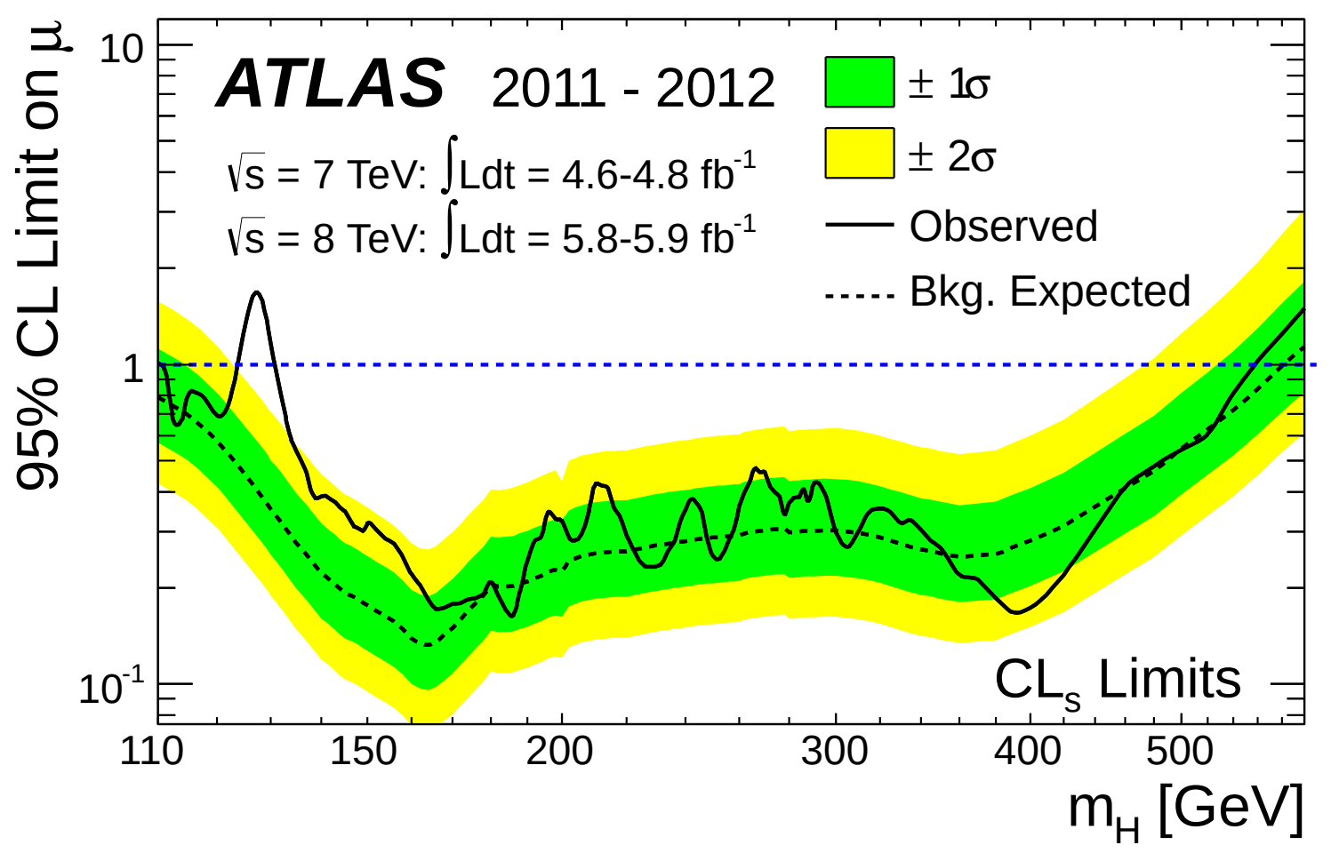
Abstract

Studies aiming for a search for a standard model Higgs boson using the Matrix Element Method (MEM) are presented. The Higgs boson is assumed to be produced in association with a pair of top quarks. This search focuses on the semileptonic decay mode for the $t\bar{t}$ system and the $b\bar{b}$ decay mode for the Higgs boson. The signal and background probabilities of a single event obtained with the MEM is a powerful discriminator which can be used together with other topological variables in a multivariate analysis.

Introduction

One of the major goals of the physics program at the Large Hadron Collider (LHC) is the search for the Standard Model Higgs boson. Already wide mass ranges of a possible SM Higgs boson have been excluded by LEP, Tevatron and the two LHC experiments ATLAS and CMS [1, 2, 3], which gives the SM Higgs only an allowed mass window of $[116.6 - 119.4, 122.1 - 127]$ GeV. In addition, an excess of events have been observed which is consistent with a Higgs boson in the mass range of $125 - 127$ GeV with a local significance of $5.9\ \sigma$ and $5.0\ \sigma$ by ATLAS and CMS, respectively [4, 5].

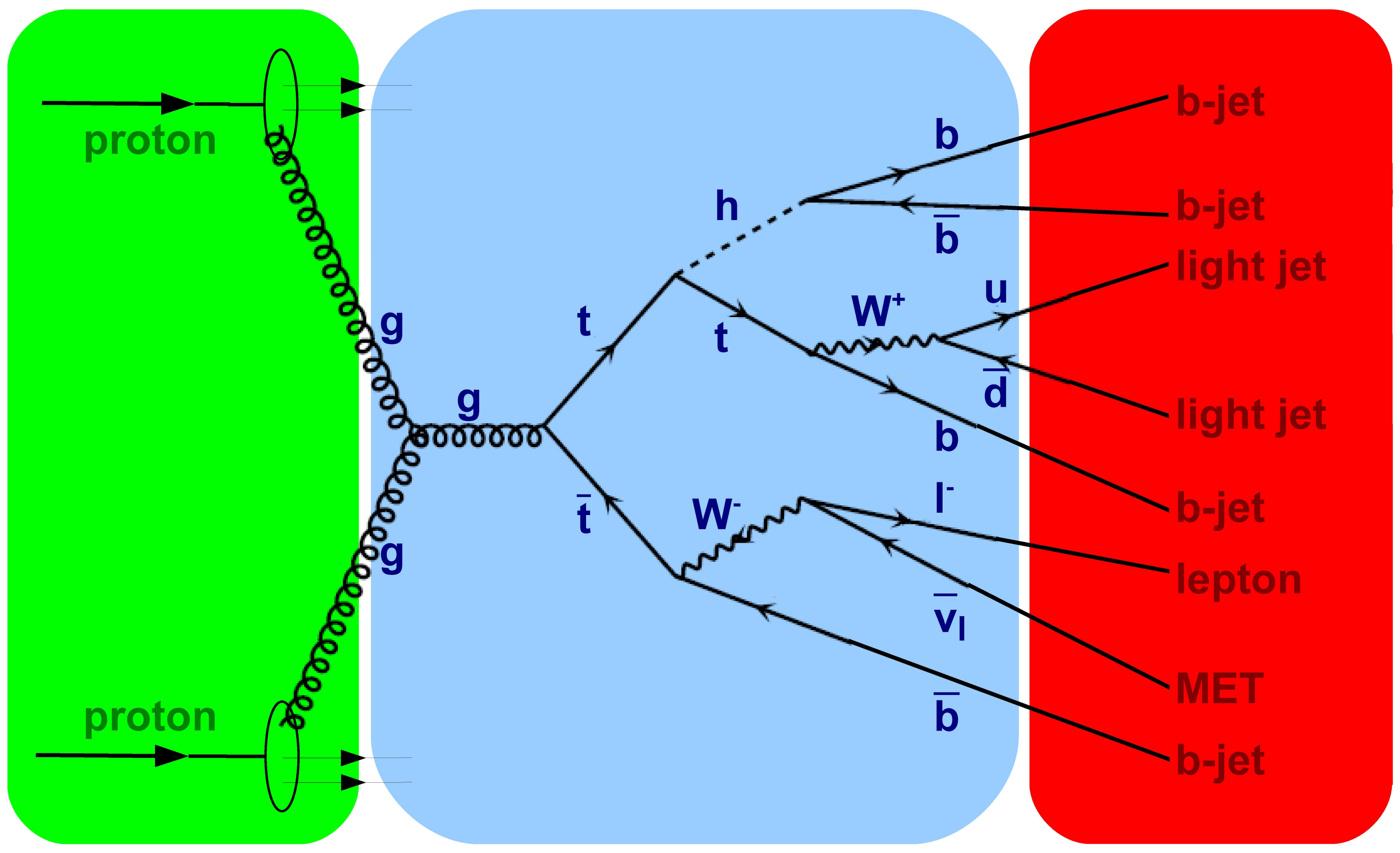


Higgs Boson Production in Association with a $t\bar{t}$ Decay

For the SM Higgs masses below 127 GeV, one of the dominant decay modes is $H \to b\bar{b}$. In order to be able to distinguish this decay from QCD background, in these studies the Higgs is required to be produced in association with a $t\bar{t}$ pair which decays semileptonically. This results typically in a final state with a high p_T isolated electron or muon, large transverse missing energy and at least six jets, of which four jets originate from b quarks. Requiring four b-tags reduces the number of possible jet-parton assignments in the event reconstruction from 180 to 12 permutations and leads to the largest relative signal contribution. This also leaves the $t\bar{t} + b\bar{b}$ decay as the main background source, which is irreducible. One powerful technique to discriminate the Higgs decay from this background is the Matrix Element Method.

Application of the MEM to the $t\bar{t}H$ Process

Obtain event probability to be a $t\bar{t}H$ Decay:



$$\underbrace{P_{t\bar{t}H}\left(\vec{x}_{\text{Detector}}, m_H\right)}_{\text{probability}} = \underbrace{\frac{1}{\sigma_{t\bar{t}H}\left(m_H\right)}}_{\text{normalization}} \int \boxed{\underbrace{\mathrm{dp_{g1}dp_{g2}f\left(p_{g1}\right)f\left(p_{g2}\right)}}_{\text{parton density function}}} \boxed{\underbrace{\mathrm{d}\sigma_{\mathrm{t\bar{t}H}}\left(\tilde{\mathrm{x}}_{\text{Parton}}, \mathrm{m_H}\right)}_{\text{differential cross section}}} \boxed{\underbrace{W\left(\vec{x}_{\text{Parton}}, \vec{x}_{\text{Detector}}\right)}_{\text{transfer functions}}}$$

- Normalized by total cross section (considering efficiency & acceptance)
- PDFs account for production mechanism
- Differential cross section proportional to $|\mathrm{M}|^2$
- Transfer functions map detector response to parton level

References

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[2] CMS Collaboration, Phys. Lett. B 710 (2012) 26
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[4] ATLAS Collaboration, arXiv:1207.7214v1 [hep-ex] (2012)
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[6] J. Alwall, M. Herquet, F. Maltoni, O. Mattelaer, T. Stelzer, "MadGraph 5: Going Beyond.", JHEP 1106 (2011)
[7] Jerzy Neyman, Egon Pearson, Phil. Trans. R. Soc. Lond. A 1 vol. 231 no. 694-706 289-337 (1933)

The Matrix Element Method (MEM)

The MEM is universal and can be applied to any theoretically described process. Amongst all data analysis techniques in particle physics this method is unique due to its direct link between theoretical calculation and reconstructed event and it makes most efficient use of theoretical assumptions and kinematic information. The method requires a calculation of the probability of observing an event in the detector consistent with the model under study:

$$P^{\text{evt}}\left(\vec{x}|\vec{a}\right) = \sum_i f_i P_i\left(\vec{x}|\vec{a}\right) \tag{1}$$

where $\vec{x}$ are the observed quantities and $\vec{a}$ are the model parameters which might be of theoretical or instrumental nature. The f_i are the single fractions of all possible and non interfering processes in the event. Calculating the probabilities P_i of the these processes is challenging due to the complexity and high dimensionality of the integration, thus simplifications and approximations are needed in order to reduce the CPU time. Once one has obtained them, one can combine all n event probabilities into one likelihood

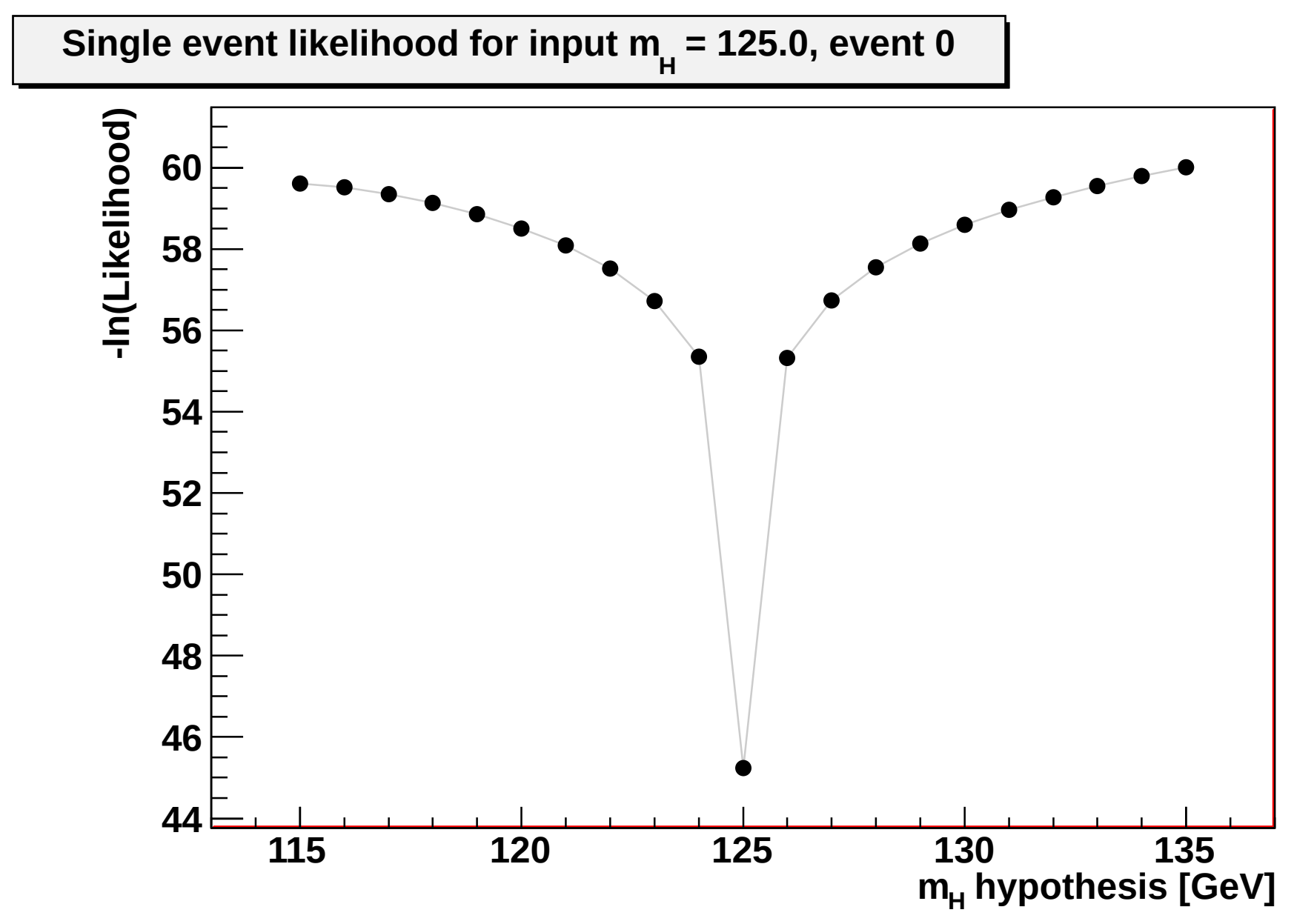
$$L\left(\vec{a}\right) = \prod_{j=1}^{n} P_j^{\text{evt}}\left(\vec{x}|\vec{a}\right) \tag{2}$$

Maximizing the likelihood function will return the best estimators for the model parameters $\vec{a}$. Another option is to calculate for every single event a parameter dependent likelihood ratio of the signal and background processes:

$$r_{\text{sig}}\left(\vec{x}|\vec{a}\right) = \frac{P_{\text{sig}}\left(\vec{x}|\vec{a}\right)}{\sum_{\text{bkg}} f_{\text{bkg}} P_{\text{bkg}}\left(\vec{x}|\vec{a}\right)} \tag{3}$$

which is according to Neyman-Pearson [7] the most powerful discriminant between background and signal. This discriminator can be used in a multivariate analysis along with other topological variables.

First Method Test



In order to test the method in the $t\bar{t}H$ production a simple test on parton level MadEvents has been performed. Leading order (LO) matrix elements generated by MadGraph have been used in event probability calculation [6]. For simplicity only transition matrices of the process $\mathrm{gg \to t\bar{t}H \to b\bar{b}b\bar{b}u\bar{d}e\bar{\nu}_e}$ are considered. As PDFs the LO CTEQ6L1 distributions are chosen. Due to the absence of a detector resolution delta functions have been used as transfer functions for the energies of the quarks and lepton and the p_T components of the neutrino. This leaves the neutrino p_z component as the only integration variable. The summed likelihood of the 12 jet permutations of a single event has been calculated for Higgs masses in the range of $115 - 135$ GeV. The negative Loglikelihood distribution shows a very narrow minimum which peaks exactly at the expected value of 125 GeV, which was the chosen generated Higgs mass.

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