Study of Higgs plus single top production using events with a same sign dimuon at the Large Hadron Collider

Departamento de Investigacion en Física
Maestría en Ciencias (Física)
Hiram Ernesto Damián

Universidad de Sonora

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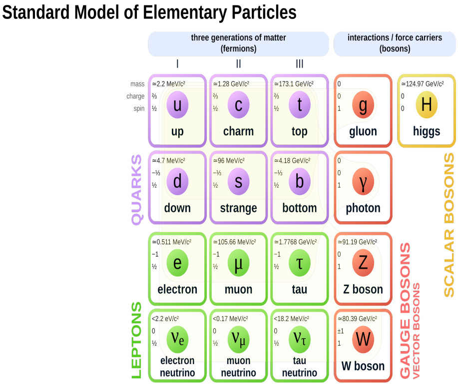
Overview

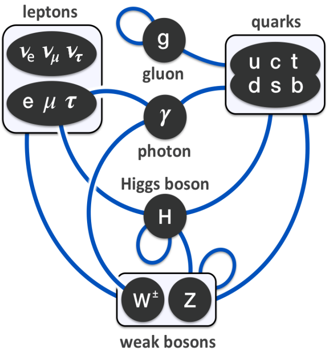
- Through this project it was studied the production of Higgs boson in association with a single top quark (tH) in proton-proton collisions. This mechanism of production of the Higgs boson has not been observed before by any experiment.
- Standard Model and the Higgs production mechanism
- A brief introduction to the LHC and CMS
- Event selection and reconstruction
- Creation and application of a statistical model for the analysis of events
- Making predictions for the future experiments.

Motivation for single top Higgs (tH)

- Coupling measurement is essential to establish the nature of the Higgs
- The exploration of Higgs production on the *tH* channel is subject relatively new. Measurements of CMS and ATLAS are compatible with SM predictions.
- The *tH* study explores the relative sign of top-Higgs and W-Higgs couplings.
  Small deviations from SM predictions could be associated with physics beyond the standard model (BSM) such as String Theory and Supersymmetry.

Standard Model





Particles Properties

Table of particles in SM

Particle	Mass (MeV/c^2)	Charge	spin	Lifetime (s)	Distance in lifetime (meters)
Up (u)	2.2	$\frac{2}{3}$	$\frac{1}{2}$	stable	-
Charm (c)	1280	$\frac{2}{3}$	$\frac{1}{2}$	1.1×10^{-12}	5.21×10^{-3}
Top (t)	173100	$\frac{2}{3}$	$\frac{1}{2}$	5×10^{-25}	2.37×10^{-15}
Down (d)	4.6	$-\frac{1}{3}$	$\frac{1}{2}$	Stable	-
Strange (s)	96	$-\frac{1}{3}$	$\frac{1}{2}$	1.24×10^{-8}	58.7
Bottom (b)	4180	$-\frac{1}{3}$	$\frac{1}{2}$	1.3×10^{-12}	6.16×10^{-3}
W	80379	± 1	1	3×10^{-25}	1.42×10^{-15}
Z	91187.6	0	1	3×10^{-25}	1.42×10^{-15}
Photon (γ)	0	0	1	Stable	-
Gluon (g)	0	0	1	Stable	-
Higgs (H)	125.18	0	0	1.56×10^{-22}	7.39×10^{-13}
Electron (e)	0.511	-1	$\frac{1}{2}$	Stable	-
Muon (μ)	105.7	-1	$\frac{1}{2}$	2.2×10^{-6}	10419.85
τ	1776.86	-1	$\frac{1}{2}$	2.9×10^{-13}	1.37×10^{-3}
ν_e ν_μ ν_τ	0	0	$\frac{1}{2}$	Stable	-

Stable means no decay, or lifetime almost infinite. Particles speeds at 0.998c

Electroweak SM Lagrangian

Higgs lagrangian

$$\mathcal{L}_{\text{Higgs}} = (D_\mu \Phi)^\dagger (D^\mu \Phi) - V(\Phi^\dagger \Phi) \tag{1}$$

with

- $D_\mu \Phi = \left(\partial_\mu + (ig/2)\sigma^i W_\mu^i - i\frac{1}{2} g' B_\mu \right) \Phi$
- $V(\Phi^\dagger \Phi) = -\mu^2 \Phi^\dagger \Phi + \frac{1}{2}\lambda(\Phi^\dagger \Phi)^2, \quad \mu^2 > 0$
- $\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$ is a SU(2) doublet.
- σ^i are the Pauli matrices.
- Φ is higgs field which is a complex scalar field. Φ
- λ and μ^2 are Higgs potential parameters

SM Lagrangian

Yukawa lagrangian

$$\mathcal{L}_{\text{yukawa}} = \sum_{m,n}^{3} \Gamma^{u}_{mn}\bar{q}_{m,L}\tilde{\Phi}u_{n,R} + \Gamma^{d}_{mn}\bar{q}_{m,L}\Phi d_{n,R} + \Gamma^{e}_{mn}\bar{l}_{m,L}\Phi e_{n,R} + h.c \tag{2}$$

where h.c is hermitian conjugate. m and n are flavors of quarks and leptons.
The matrices Γ_{mn} describe the so called Yukawa couplings between higgs doublet ϕ and the fermions.
Choosing

$$\Phi = -\frac{1}{2}\begin{pmatrix} 0 \\ v+h \end{pmatrix}$$

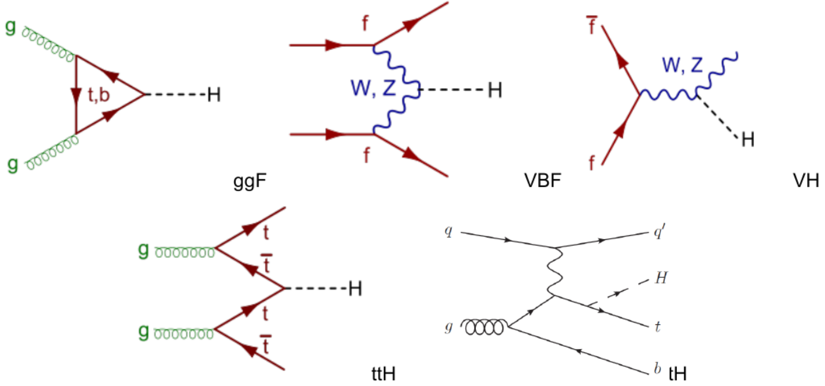
By using 3 it on $\mathcal{L}_{\text{yukawa}}$, it is obtained for u quark

$$\frac{\Gamma^{u}_{uu}v}{\sqrt{2}}(\bar{u}_L u_R + \bar{u}_R u_L)$$

from which the masses for the fermions shown to be proportional to the Yukawa couplings

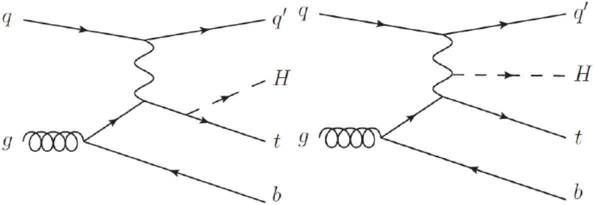
$$m_u = -\frac{\Gamma^{u}_{uu}v}{\sqrt{2}}$$

Higgs production mechanisms



Different Higgs production mechanism, from the most likely to least likely

tH production mechanisms



tH mechanism. Higgs radiated from a top quark (left). Higgs radiated from a W boson (right)

tH production mechanisms

- In a proton proton collision, the production cross section of the single top plus Higgs boson process is driven by a destructive interference of two main diagrams (see Fig. **??**.), where the Higgs couples to either the W boson or the top quark.
- A second process, where the Higgs and top quark are accompanied by a W boson (tHW) has similar behavior, albeit with a weaker interference pattern.
- However, in the presence of new physics, there may be relative opposite signs between the tH and WH couplings which lead to constructive interference and enhance the cross sections by an order of magnitude or more.

Cross section

- Cross section describes the likelihood of two particles interacting under certain conditions[1][8]
- Experimentally

$$d\sigma = \frac{\text{number of particles scattered into solid angle}\Delta\Omega}{(\text{number of particles incident})(\text{scattering centers/area})} \tag{3}$$

- Cross sections are expressed in barns , where 1 barn=10^{-34} cm^{-2}
- The reaction rate N_R is determined by the total cross section σ and the incident flux L.
  L is called luminosity and it is measured in $cm^{-1}s^{-1}$.[8]

$$N_R = \sigma L \tag{4}$$

Higgs production Cross section

Higgs boson production cross sections in pp collisions for $\sqrt{s} = 13\text{TeV}$ (in pico barn).Integrated luminosity of 35.9 fb^{-1} for Run 2[1]

Production mechanism	σ (picobarns pb)	Number of events
ggF	48.93	1756587
VBF	3.78	135702
WH	1.35	48465
ZH	0.88	31592
t$\bar{t}$H	0.50	18255
tH (only)	0.015	560.39

[1] Data taken from The cern collaborarion "Higgs Physics the HL-LHC and HE-LHC" 2019, CERN-LPCC-2018-04

Branching ratio

In particle physics, the branching ratio for a decay process is the ratio of the number of particles which decay via a specific decay mode with respect to the total number of particles which decay via all decay modes. [2].

$$\mathrm{BR} = \frac{\Gamma_i}{\sum_i \Gamma_i} \tag{5}$$

Where $\Gamma = \sum_i \Gamma_i$ is the total decay width (sum of all partial widths) of the particle and is related to lifetime of the particle: $\Gamma = 1/\tau$. Since the dimension of Γ is the inverse of time, in our system of natural units, it is measured in inverse seconds .[0]

[0] Cleaves H.J. (2011) Branching Ratio. In: Gargaud M. et al. (eds) Encyclopedia of Astrobiology. Springer, Berlin, Heidelberg

Higgs Branching ratios per channel

SM Higgs boson branching ratios for M_H =125 GeV

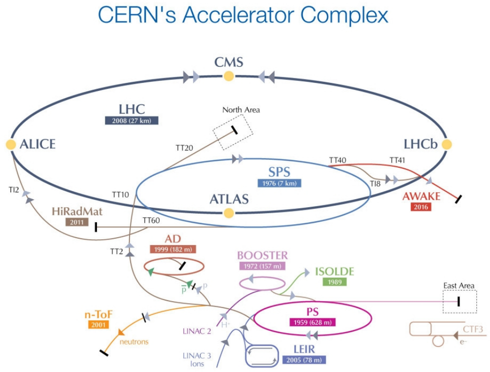
Higgs decay	Branching ratio (BR)
H $\rightarrow$ b$\bar{b}$	50.82%
H $\rightarrow$ W^+W^-	21.5%
H $\rightarrow$ $\tau^+\tau^-$	6.27%
H $\rightarrow$ ZZ	2.61%
H $\rightarrow$ $\gamma\gamma$	0.227%
H $\rightarrow$ Zγ	0.153%
H $\rightarrow$ $\mu^+\mu^-$	0.0217%

$\mu\mu$ same sign decay rate

Table of decay chains for tH. Expected number of final events assuming 560 produced tH events.l represents $\mu^{\pm}, e^{-}, \tau^{\pm}$.

Decay chain	BR	Events
$tH \rightarrow W^{+}bW^{+}W^{-} \rightarrow \mu^{+}\nu_{\mu}b\mu^{+}\nu_{\mu}\ q\bar{q}'$	2.096×10^{-3}	1.173
$tH \rightarrow W^{+}bW^{+}W^{-} \rightarrow \mu^{+}\nu_{\mu}b\mu^{+}\nu_{\mu}\ l^{-}\bar{\nu_l}$	3.37×10^{-4}	0.899
$tH \rightarrow W^{+}b\,\tau^{+}\tau^{-} \rightarrow \mu^{+}\nu_{\mu}\ b\ \mu^{+}\nu_{\mu}\bar{\nu_\tau}l^{-}\bar{\nu_l}\nu_{\tau}$	3.637×10^{-4}	0.203
$tH \rightarrow W^{+}bW^{+}W^{-} \rightarrow \tau^{+}\bar{\nu_\tau}b\ \mu^{+}\nu_{\mu}\ q\bar{q} \rightarrow \mu^{+}\nu_{\mu}\ \bar{\nu_\tau}\ \bar{\nu_\tau}\ b\mu^{+}\nu_{\mu}\ q\bar{q}$	1.890×10^{-4}	0.105
$tH \rightarrow W^{+}b\,\tau^{+}\tau^{-} \rightarrow \mu^{+}\nu_{\mu}b\ \nu_{\tau}\ \mu^{+}\nu_{\mu}\bar{\nu_\tau}\ q\bar{q}$	1.681×10^{-4}	0.094
$tH \rightarrow W^{+}b\,W^{+}W^{-} \rightarrow \tau^{+}\bar{\nu_\tau}b\mu^{+}\nu_{\mu}l^{-}\bar{\nu_l} \rightarrow \mu^{+}\nu_{\mu}\ \bar{\nu_\tau}\bar{\nu_\tau}\ b\mu^{+}\nu_{\mu}l^{-}\bar{\nu_l}$	3.045×10^{-5}	0.017
$tH \rightarrow W^{+}bZZ \rightarrow q\bar{q}bZZ \rightarrow q\bar{q}\ b\ \mu^{+}\mu^{-}\mu^{+}\mu^{-}$	1.966×10^{-5}	0.011
$tH \rightarrow W^{+}b\,\tau^{+}\tau^{-} \rightarrow \tau^{+}\bar{\nu_\tau}b\ \mu^{+}\nu_{\mu}\bar{\nu_\tau}\ q\bar{q}'\nu_{\tau} \rightarrow \mu^{+}\nu_{\mu}\bar{\nu_\tau}\bar{\nu_\tau}b\ \mu^{+}\nu_{\mu}\bar{\nu_\tau}\ q\bar{q}'\nu_{\tau}$	1.549×10^{-5}	0.008

LHC


CERN's Accelerator Complex
CMS
LHC
2008 (27 km)
North Area
ALICE
TT20
LHCb
TT40
TT41
SPS
1976 (7 km)
TI8
TI2
TT10
ATLAS
AWAKE
2016
HiRadMat
2011
TT60
AD
1999 (182 m)
TT2
BOOSTER
1972 (157 m)
ISOLDE
1989
East Area
PS
1959 (628 m)
n-ToF
2001
LINAC 2
CTF3
neutrons
LINAC 3
Ions
LEIR
2005 (78 m)

LHC parameters

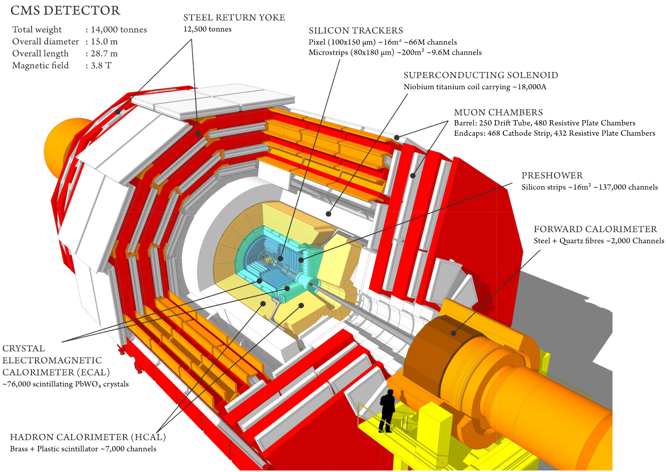
Characteristics of LHC

Quantity	Number
Circumference	26 659 m
Number of magnets	9593
Nominal energy, protons	6.5 TeV
Nominal energy, protons collisions	13 TeV
Number of collisions per second	1 billion
No. of bunches per proton beam	2808

Accelerator operation energies

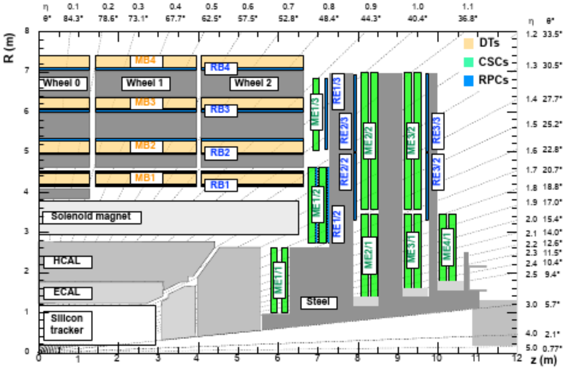
Accelerator	Energy
Linac 2	50 MeV
PS Booster	1.4 GeV
Proton Scyncroton (PS)	25 GeV
SPS	450 GeV
LHC	6.5 TeV

CMS detector



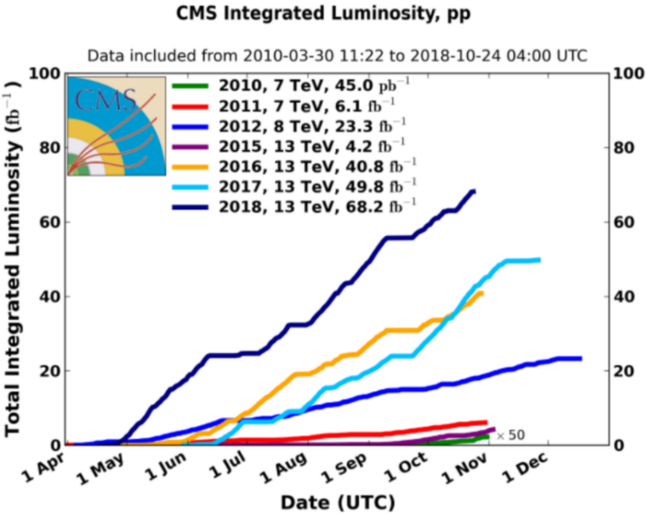
Compact muon solenoid

LHC



Slide view of the CMS in terms of pseudorapidity $\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$

CMS integrated luminosity

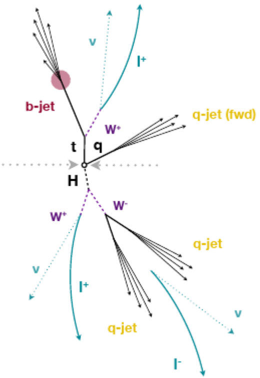


Integrated luminosity for CMS experiment

Topology of events tH

The characteristics of the signal tH:

- $t \rightarrow W^{+}\mathrm{b} \rightarrow l^{+}\nu_{\mu}b$
- $H \rightarrow W^{+}W^{-}$
  - $W \rightarrow l^{\pm}\nu$, where l can be $\mu^{\pm}$,e^{-} $\tau^{\pm}$
  - $W \rightarrow q\bar{q}$
  - W bosons decay leptonically resulting in a signature of two same-sign leptons
- a light-flavor quark
- A b-jet

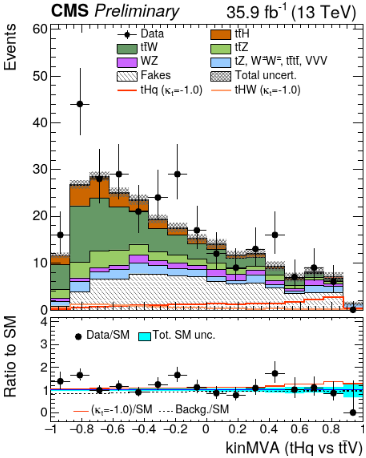


Event selection

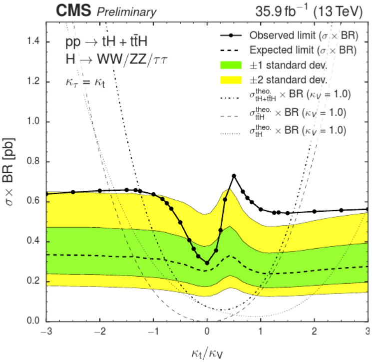
In order to detect signal events and reject background, the following selections are applied.

- The events must contain two muons with the same sign.
- Transverse moment $p_t > 25$ GeV for the highest p_t muon and $p_t > 15$ GeV for the lowest p_t muon.
- A forward jet with $p_t > 40$ GeV and $|\eta| > 2.4$
- One or more b-tagged jets with $|\eta| < 2.4$

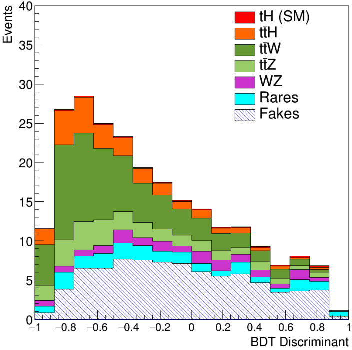
Previous results for $t\bar{t}H + tH$ production

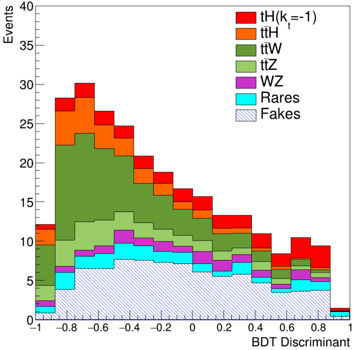


Pre-fit classifier outputs for same sign dimuon, for training against $t\bar{t}V$



Observed and expected 95% C.L. upper limit on the tH + $t\bar{t}$H cross section times H $\to$ WW + $\tau\tau$ + ZZ branching fraction for different 20 values of the coupling ratio κ_t/κ_V . The expected limit is derived from a background-only MC dataset.





SM signal and backgrounds (Left) and k_t=-1 model (Right).

Main backgrounds

Main backgrounds and their same sign $\mu\mu$ decay process

Background	Decay process
$t\bar{t}W$	$t\bar{t}W \to W^+bW^-\bar{b}\ \mu^+\nu_\mu \to \mu^+\nu_\mu b\ \mu^-\bar{\nu_\mu}\bar{b}\ \mu^+\nu_\mu$
$t\bar{t}Z$	$t\bar{t}Z \to W^+b\ W^-\bar{b}\mu^+\mu^- \to \mu^+\nu_\mu b\ \mu^-\bar{\nu_\mu}\bar{b}\mu^+\mu^-$
W^+Z	$W^+Z \to \mu^+\nu_\mu\mu^+\mu^-$
$W^\pm\ W^\pm$	$W^+W^+ \to \mu^+\nu_\mu\mu^+\nu_\mu$
tZq	$tZq \to W^+\ b\mu^+\mu^-q \to \mu^+\nu_\mu b\ \mu^+\mu^-q$
$t\bar{t}t\bar{t}$	$t\bar{t}t\bar{t} \to W^+b\ W^-\bar{b}\ W^+b\ W^-\bar{b} \to \mu^+\nu_\mu b\ \mu^-\bar{\nu_\mu}\bar{b}\ \mu^+\nu_\mu b\ \mu^-\bar{\nu_\mu}\bar{b}$
W^+W^-Z	$W^+W^-\ Z \to \mu^+\nu_\mu\ \mu^-\bar{\nu_\mu}\mu^+\mu^-$
ZZZ	$ZZZ \to \mu^+\mu^-\mu^+\mu^-l^+l^-$
W^+ZZ	$W^+ZZ \to \mu^+\nu_\mu\mu^+\mu^-l^+l^-$
tZW^+	$tZW^+ \to W^+b\mu^+\mu^-\mu^+\nu_\mu \to \mu^+\nu_\mu b\mu^+\mu^-\mu^+\nu_\mu$
ZZ	$ZZ \to \mu^+\mu^-\mu^+\mu^-$
$t\bar{t}H$	$t\bar{t}H \to W^+bW^-\bar{b}W^+W^- \to \mu^+\nu_\mu b\mu^-\bar{\nu_\mu}\bar{b}\ \mu^+\nu_\mu\ \mu^-\bar{\nu_\mu}$

Signal and Backgrounds

Event yields for signal and backgrounds after the event selection for a integrated luminosity of 35.9 fb^{-1}. The uncertainties of yields include statistical and systematic [2]

Process	Number of events
$t\bar{t}W$	68 $\pm$ 10
$t\bar{t}Z$	25.9 $\pm$ 3.9
WZ	15.1$\pm$7.7
Rares	20.9 $\pm$ 4.9
Fakes	80.9 $\pm$9.4
$t\bar{t}H$	24.2 $\pm$ 2.1
tH (SM)	2.14 $\pm$ 0.13
tH $(k_t = -1)$	26.2 $\pm$ 2.2

Systematic uncertainties

- The uncertainties on $t\bar{t}W$ and $t\bar{t}Z$ event yields are mainly due to the uncertainties of their production cross sections.
- The uncertainty on WZ background is estimated using real data events in a three lepton control region.
- In the Rare backgrounds, which are not measured, a 50% of uncertainty is assigned.
- The uncertainty on the Fakes background is estimated using real data in a control region, defined by the muon identification criteria.
- For the Higgs processes tH and ttH, the uncertainty are due to the theoretical parameters used in that simulation.

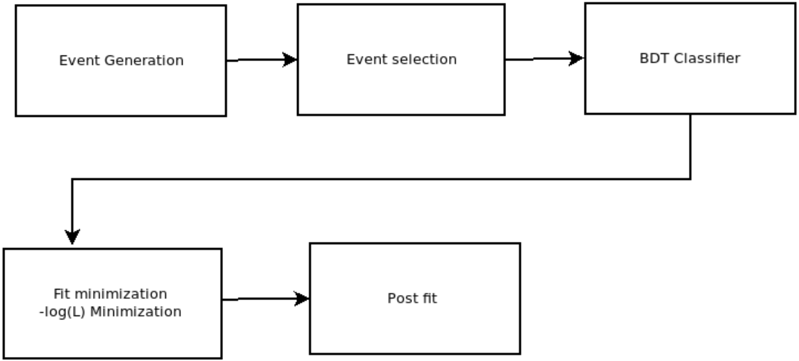
BDT

- A decision tree takes a set of input features and splits input data recursively based on those features. Boosting is a method of combining many weak learners (trees) into a strong classifier. The features can be a mix of categorical and continuous data.
- The BDT training is performed using several event variables for signal and background.

BDT Variables

- Trailing lepton p_t
- Total charge of tight leptons
- min ΔR (lepton pairs)
- $\Delta\phi$ between highest p_t lepton pair
- Number of jets with $|\eta| < 2.4$
- Number of non b-tagged jets with $|\eta| > 1.0$
- Maximum $|\eta|$ for jets
- $\Delta\eta$ (most forward light jet, closest lepton)
- $\Delta\eta$ (most forward light jet, hardest loosely b-tagged jet)
- $\Delta\eta$ (most forward light jet, 2nd hardest loosely b-tagged jet)

Fitting


Event Generation
Event selection
BDT Classifier
Fit minimization
-log(L) Minimization
Post fit

Likelihood model

To estimate the sensibility of the tH signal, we define an Asimov dataset, made by replacing the ensemble of simulated backgrounds and signal by a single one. The statistical uncertainty of the Asimov data is calculated as $\sqrt{n}$, with n the number of events.
The likelihood function is the product of Poisson probabilities for all bins

$$L(\mu,\alpha) = \prod_{j=1}^{N} \frac{(\mu s_j + b_j)^{n_j}}{n_j!} e^{-(\mu s_j + b_j)} \prod_{k=1}^{M} e^{\frac{-\alpha_k^2}{2}} \tag{6}$$

where N is the total number of bins, n_j is the number of events in a bin j, s_j is the number of signal events, μ is a parameter that modifies the signal strength and b_j is the number of background events. b_j is the sum of different background processes k

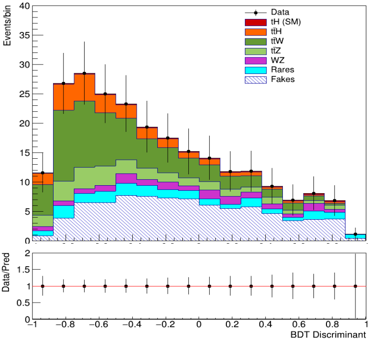
$$b_j = \sum_{k}^{M} b_j^k (1 + \alpha_k \sigma_k) \tag{7}$$

α_k is the parameter that modifies the expected background prediction and σ_k is the systematic uncertainty of the associated background. σ_k for the backgrounds are shown in the Table of yields.

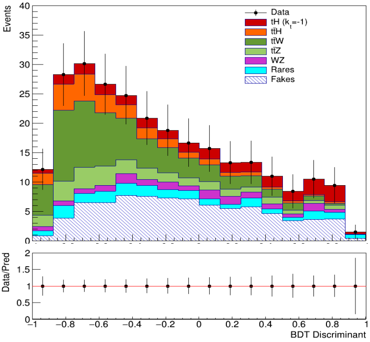
Results

The fit is applied by minimizing the $-\log L$ (NLL) with respect to the parameter μ and α_k. The minimization is performed by using the package ROOFIT. In the next slides, it shows the results of the model fitting using the Asimov data for the SM and the $k_t = -1$.

Results



Post-fit signal and background yields for tH process in the SM. In the box below each distribution, the ratio of the observed and event yields is shown



Post-fit signal and background yields for tH process in the k_t=-1. In the box below each distribution, the ratio of the observed and event yields is shown

Results

Postfit yields for the fit to the Asimov data corresponding to 35.9 fb^{-1}. The uncertainty given is the combined statistical plus systematic.

Process	SM	k_t=-1
$t\bar{t}W$	68±8.9	68 ±8.9
$t\bar{t}Z$	25.9±3.8	25.9±3.8
WZ	15.1±7.4	15.1±7.4
Rares	20.8±4.8	20.8±4.8
Fakes	80.9±9.0	80.9±8.9
$t\bar{t}H$	24.2±2.0	24.2±2.0
tH	2.1±16.5	26.2±13.1

Prefit uncertainty is statistical only. Postfit uncertainty is statistical + systematic.

Results

Likelihood scan

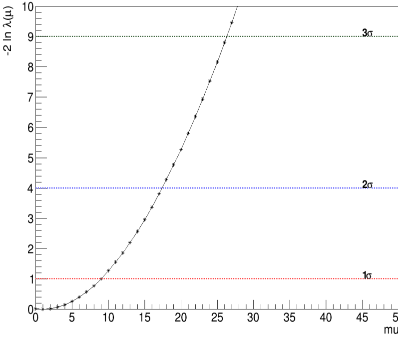
Due to the large background, the signal strength for the Asimov data with 35.9 fb^{-1} is consistent with zero. Therefore, we estimate an upper limit on the signal strength at 95% confidence level.
We can define the likelihood ratio

$$\lambda(\mu, \alpha) = \frac{L(\mu, \alpha)}{L(\hat{\mu}, \hat{\alpha})} \tag{8}$$

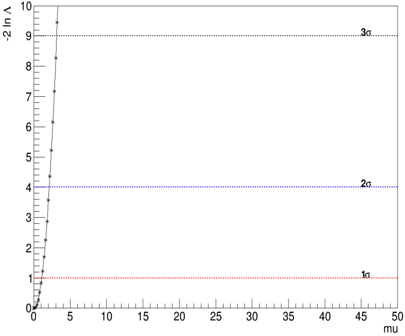
Where $\hat{\alpha}$ and $\hat{\mu}$ are the parameters obtained in the previous section which correspond to the minimal of the NLL.

Results

Likelihood scan

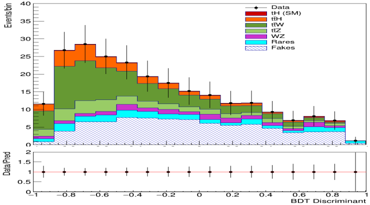


Likelihood scan for k_t=1 (SM)

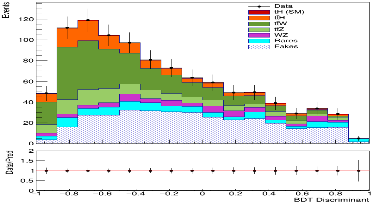


Likelihood scan for k_t=-1

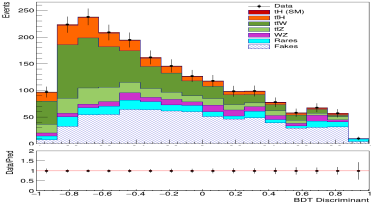
Extrapolation of luminosity for SM



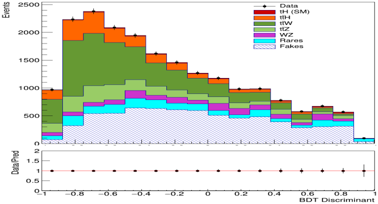
$35.9\ \mathrm{fb}^{-1}$



$150\ \mathrm{fb}^{-1}$

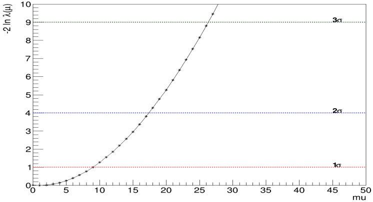


$300\ \mathrm{fb}^{-1}$

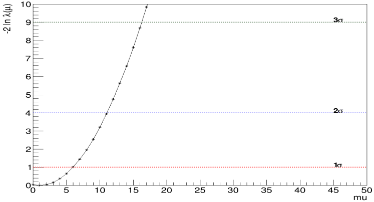


$3000\ \mathrm{fb}^{-1}$

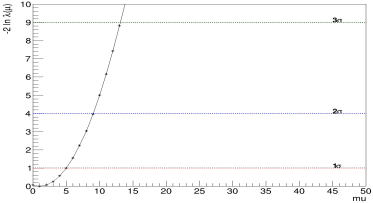
Likelihood scan for SM



35.9 fb^{-1}



150 fb^{-1}



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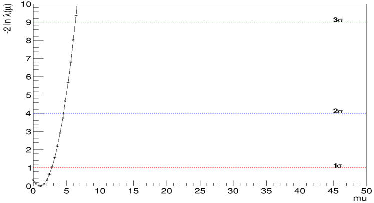
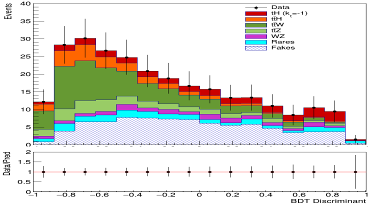


3000 fb^{-1}

Extrapolation of luminosity for $k_t = -1$



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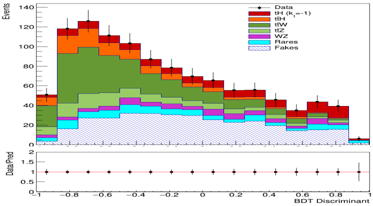
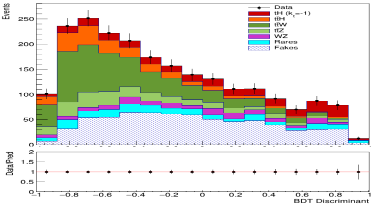
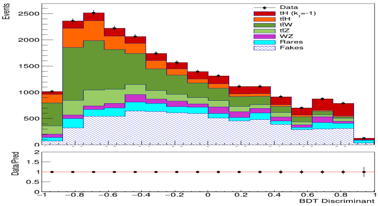


150 fb^{-1}

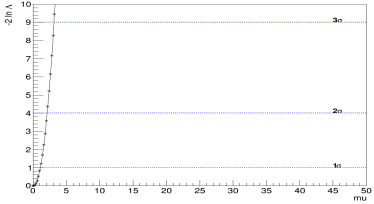


300 fb^{-1}

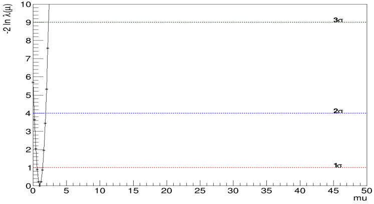


3000 fb^{-1}

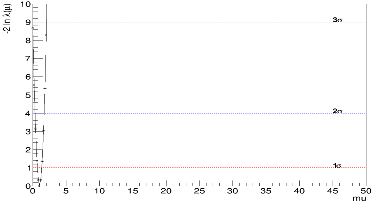
Likelihood scan for $k_t = -1$



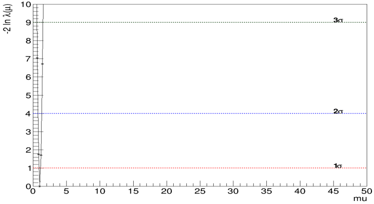
35.9 fb^{-1}



150 fb^{-1}



300 fb^{-1}



3000 fb^{-1}

Results

Upper limit

To determine an upper limit on the strength parameter μ, we use the following statistical test

$$q(\mu, \alpha) = -2 \ln \lambda \tag{9}$$

High values of q represent greater incompatibility between the data and the fit model. q is a random variable with a χ^2 distribution.

Results

Upper limit

Results of μ and upper limits for Asimov extrapolations for SM and k_t=-1 models.

Luminosity (fb^{-1})	μ (SM)	μ (SM) upper limit	μ (k_t=-1)	μ (k_t=-1) upper limit
35.9	1.0 ± 7.7	17	1.0 ± 0.5	2.3
150	1.0 ± 6.7	11	1.0 ± 0.4	1.8
300	1.0 ± 4.3	8.7	1.0 ± 0.3	1.5
3000	1.0 ± 1.7	4.3	1.0 ± 0.1	1.1

Conclusions

- We analyzed the tH process produced from PP collisions for the production of $\mu\mu$ final states
- We discussed about events selections for the 2016 Run 2 from CMS.
- The creation of an Asimov model with systematic uncertainties to make a minimization (fit) and obtain a fit which is compatible with Standard Model.
- Generation of likelihood scan for the exclusion of data and obtain the probability of detection of a Higgs boson.
- Generating simulations for predict results with higher luminosities, according to the future experiments.

Conclusions

- The results of the analysis for the SM case indicates that it is impossible to detect a Higgs boson using same sign dimuon channel in the tH process due to the low number of events and a huge uncertainty.
- For the SM scenario the expected uncertainty even at the largest luminosities is not enough to observe the signal and only an upper limit can be placed.
- For the k_t=-1, the uncertainty is low due to higher number of events for tH process and it is possible to detect a Higgs boson, but this model is purely theoretical and not related with the SM.
- It requires a new analysis that includes more channels such as three leptons in the final state for improve the sensibility of the signal.

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Cowan G. , Cranmer K., Gross E. , Vitells O. *Asymptotic formulae for likelihood-based tests of new physics* 2013 , arXiv:1007.1727

CMS collaboration *Search for tHq production in multilepton final states at 13 TeV* ,2017,CMS AN-16-378

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Back up

Sources of uncertainty on event yields

- Luminosity measurement: 2.6%.
- Data/MC scale factors for lepton selection (ID, iso) and trigger efficiencies 5% per lepton.
- Choice of PDF set:
  - 3.7% for tHq
  - 4% for tHW $t\bar{t}$W, $t\bar{t}$Z, $t\bar{t}$H
  - Scale uncertainties: 12%, 4 for $t\bar{t}$W, 10% for $t\bar{t}$Z, +5.8/-9.2% for $t\bar{t}$H.
- Background: WZ, ZZ sample modelling and statistics: 50%.
- Rare SM (tZ,tri-bosons, WWqq, tttt) : 50%
- Fake rate estimation: The predicted event yield has a normalization uncertainty of 30-50% [7]

Sources of systematic uncertainty

Detector-simulation related uncertainty

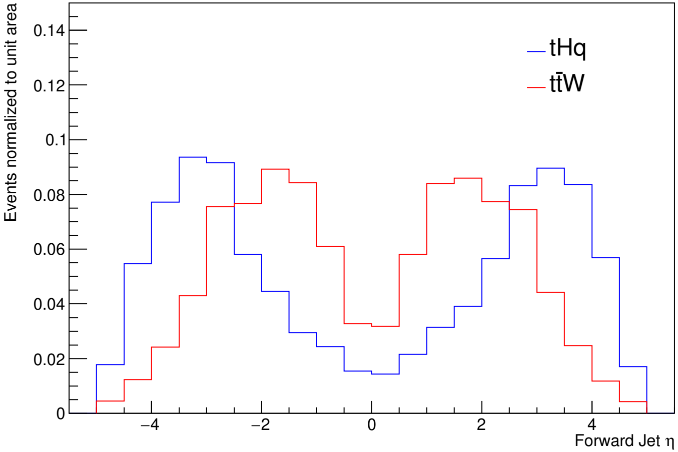
- Calibrations (electron, jet energy scale)
- Efficiencies (particle ID, reconstruction)
- Resolutions (jet energy, muon momentum)

Theoretical uncertainties

- Factorization/Normalization scale of MC generators
- Choice of MC generator (ME and/or PS, e.g. Herwig vs Pythia)

Monte Carlo Statistical uncertainties

- Statistical uncertainty of simulated samples[2]



Signal and background kinematic distributions

Results

Likelihood scan

- Likelihood function (often simply the likelihood) is a function of the parameters of a statistical model, given specific observed data.
- Likelihood functions play a key role in frequentist inference, especially methods of estimating a parameter from a set of statistics.
- In informal contexts, "likelihood" is often used as a synonym for probability.