

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

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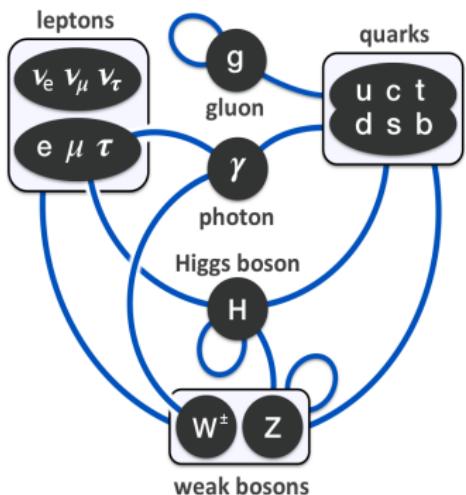
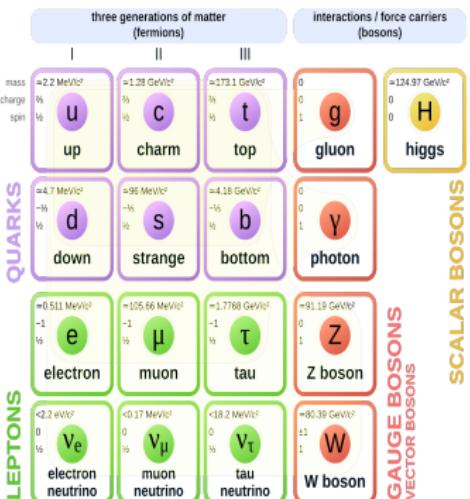
# Motivation for single top Higgs ( $tH$ )

- 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

## Standard Model of Elementary Particles



# 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	$\frac{2}{3}$	$\frac{1}{2}$	$1.1 \times 10^{-12}$	$5.21 \times 10^{-3}$
Top ( $t$ )	173100	$\frac{2}{3}$	$\frac{1}{2}$	$5 \times 10^{-25}$	$2.37 \times 10^{-15}$
Down ( $d$ )	4.6	$-\frac{1}{3}$	$\frac{1}{2}$	Stable	-
Strange ( $s$ )	96	$-\frac{1}{3}$	$\frac{1}{2}$	$1.24 \times 10^{-8}$	58.7
Bottom ( $b$ )	4180	$-\frac{1}{3}$	$\frac{1}{2}$	$1.3 \times 10^{-12}$	$6.16 \times 10^{-3}$
$W$	80379	$\pm 1$	1	$3 \times 10^{-25}$	$1.42 \times 10^{-15}$
$Z$	91187.6	0	1	$3 \times 10^{-25}$	$1.42 \times 10^{-15}$
Photon ( $\gamma$ )	0	0	1	Stable	-
Gluon ( $g$ )	0	0	1	Stable	-
Higgs ( $H$ )	125.18	0	0	$1.56 \times 10^{-22}$	$7.39 \times 10^{-13}$
Electron ( $e$ )	0.511	-1	$\frac{1}{2}$	Stable	-
Muon ( $\mu$ )	105.7	-1	$\frac{1}{2}$	$2.2 \times 10^{-6}$	10419.85
$\tau$	1776.86	-1	$\frac{1}{2}$	$2.9 \times 10^{-13}$	$1.37 \times 10^{-3}$
$\nu_e$ $\nu_\mu$ $\nu_\tau$	0	0	$\frac{1}{2}$	Stable	-

# Electroweak SM Lagrangian

## Higgs lagrangian

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

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.
- $\sigma^i$  are the Pauli matrices.
- $\Phi$  is higgs field which is a complex scalar field.  $\Phi$
- $\lambda$  and  $\mu^2$  are Higgs potential parameters



# SM Lagrangian

## Yukawa lagrangian

$$\mathcal{L}_{\text{yukawa}} = \sum_{m,n}^3 \Gamma_{mn}^u \bar{q}_{m,L} \tilde{\Phi} u_{n,R} \quad (2)$$

where h.c is hermitian conjugate. m and n are flavors of quarks and leptons.

The matrices  $\Gamma_{mn}$  describe the so called Yukawa couplings between higgs doublet  $\phi$  and the fermions.

Choosing

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

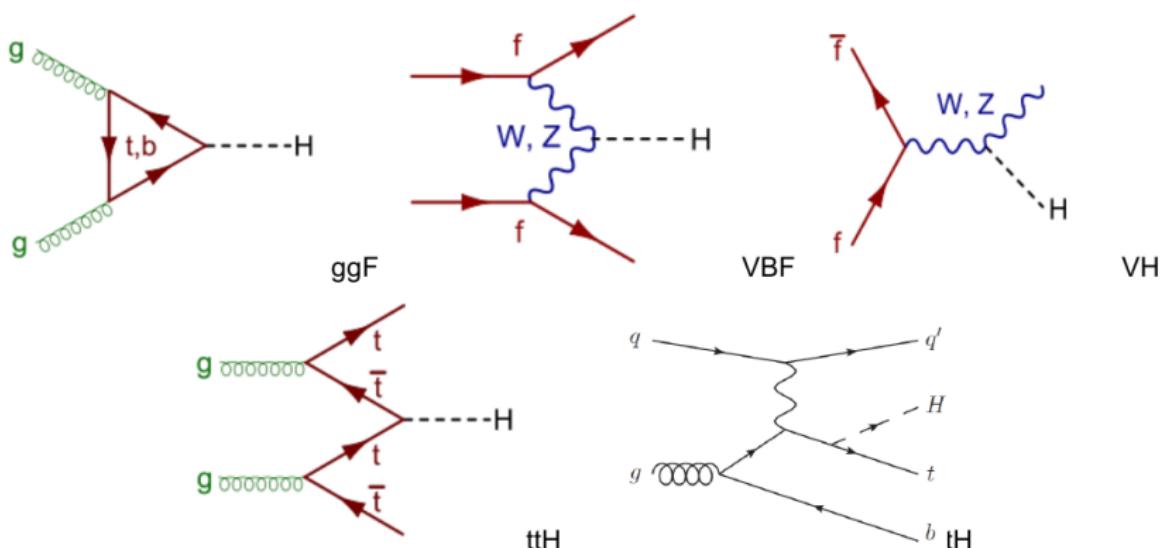
By using 3 it on  $\mathcal{L}_{\text{yukawa}}$ , it is obtained for u quark

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

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

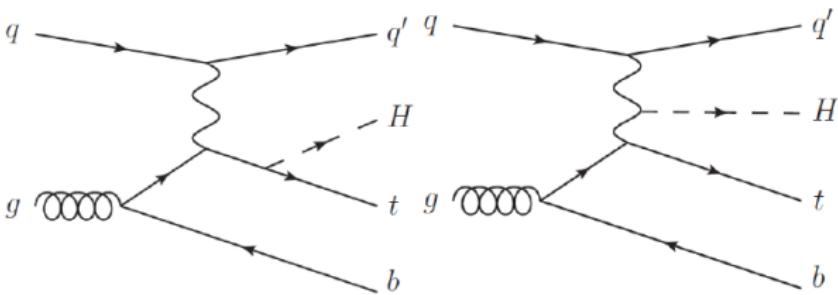
$$m_u = -\frac{\Gamma_{uu}^u v}{\sqrt{2}}$$

# 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, 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

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

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

$$N_R = \sigma L$$

(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  $35.9 \text{ fb}^{-1}$  for Run 2<sup>1</sup>

Production mechanism	$\sigma$ (picobarns pb)	Number of events
ggF	48.93	1756587
VBF	3.78	135702
WH	1.35	48465
ZH	0.88	31592
t <bar>t&gt;H</bar>	0.50	18255
tH (only)	0.015	560.39

<sup>1</sup>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.  
<sup>2</sup>.

$$\text{BR} = \frac{\Gamma_i}{\sum_i \Gamma_i} \quad (5)$$

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  $\Gamma$  is the inverse of time, in our system of natural units, it is measured in inverse seconds.<sup>0</sup>

<sup>0</sup> 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%
$H \rightarrow Z\gamma$	0.153%
$H \rightarrow \mu^+\mu^-$	0.0217%

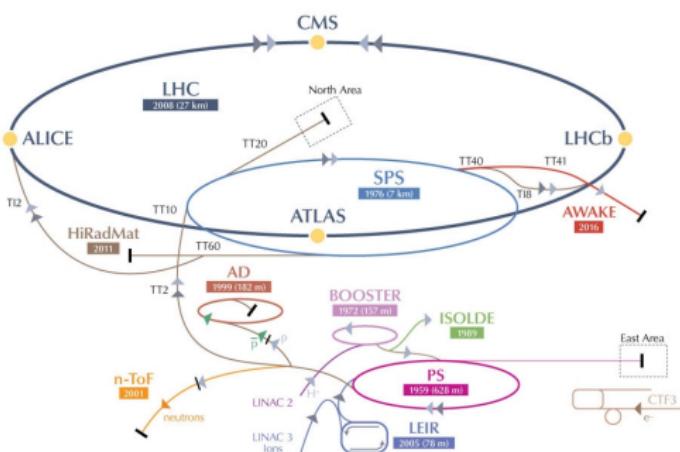
# $\mu\mu$ same sign decay rate

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
$tH \rightarrow W^+ b W^+ W^- \rightarrow \mu^+ \nu_\mu b \mu^+ \nu_\mu q \bar{q}'$	$2.096 \times 10^{-3}$	1.173
$tH \rightarrow W^+ b W^+ W^- \rightarrow \mu^+ \nu_\mu b \mu^+ \nu_\mu l^- \bar{\nu}_l$	$3.37 \times 10^{-4}$	0.899
$tH \rightarrow W^+ b \tau^+ \tau^- \rightarrow \mu^+ \nu_\mu b \mu^+ \nu_\mu \bar{\nu}_\tau l^- \bar{\nu}_l \nu_\tau$	$3.637 \times 10^{-4}$	0.203
$tH \rightarrow W^+ b W^+ W^- \rightarrow \tau^+ \bar{\nu}_\tau b \mu^+ \nu_\mu q \bar{q} \rightarrow \mu^+ \nu_\mu \bar{\nu}_\tau \bar{\nu}_\tau b \mu^+ \nu_\mu q \bar{q}$	$1.890 \times 10^{-4}$	0.105
$tH \rightarrow W^+ b \tau^+ \tau^- \rightarrow \mu^+ \nu_\mu b \nu_\tau \mu^+ \nu_\mu \bar{\nu}_\tau q \bar{q}$	$1.681 \times 10^{-4}$	0.094
$tH \rightarrow W^+ b W^+ W^- \rightarrow \tau^+ \bar{\nu}_\tau b \mu^+ \nu_\mu l^- \bar{\nu}_l \rightarrow \mu^+ \nu_\mu \bar{\nu}_\tau \bar{\nu}_\tau b \mu^+ \nu_\mu l^- \bar{\nu}_l$	$3.045 \times 10^{-5}$	0.017
$tH \rightarrow W^+ b ZZ \rightarrow q \bar{q} b ZZ \rightarrow q \bar{q} b \mu^+ \mu^- \mu^+ \mu^-$	$1.966 \times 10^{-5}$	0.011
$tH \rightarrow W^+ b \tau^+ \tau^- \rightarrow \tau^+ \bar{\nu}_\tau b \mu^+ \nu_\mu \bar{\nu}_\tau q \bar{q}' \nu_\tau \rightarrow \mu^+ \nu_\mu \bar{\nu}_\tau \bar{\nu}_\tau b \mu^+ \nu_\mu \bar{\nu}_\tau q \bar{q}' \nu_\tau$	$1.549 \times 10^{-5}$	0.008

# LHC

## CERN's Accelerator Complex



# 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

## CMS DETECTOR

Total weight : 14,000 tonnes  
Overall diameter : 15.0 m  
Overall length : 28.7 m  
Magnetic field : 3.8 T

STEEL RETURN YOKE  
12,500 tonnes

SILICON TRACKERS  
Pixel (100x150  $\mu\text{m}$ ) ~16 $m^2$  ~66M channels  
Microstrips (80x180  $\mu\text{m}$ ) ~200 $m^2$  ~9.6M channels

SUPERCONDUCTING SOLENOID  
Niobium titanium coil carrying ~18,000A

MUON CHAMBERS  
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers  
Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers

PRESHOWER  
Silicon strips ~16 $m^2$  ~137,000 channels

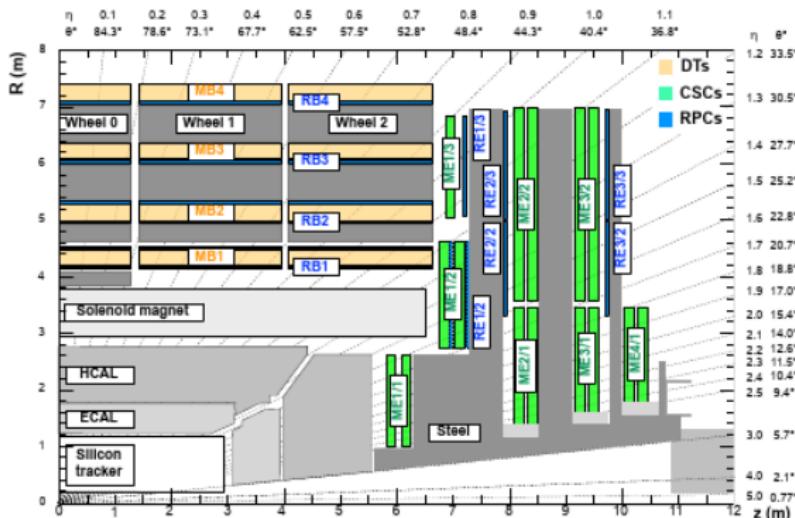
FORWARD CALORIMETER  
Steel + Quartz fibres ~2,000 Channels

CRYSTAL  
ELECTROMAGNETIC  
CALORIMETER (ECAL)  
~76,000 scintillating PbWO<sub>4</sub> crystals

HADRON CALORIMETER (HCAL)  
Brass + Plastic scintillators ~7,000 channels

Compact muon solenoid

LHC

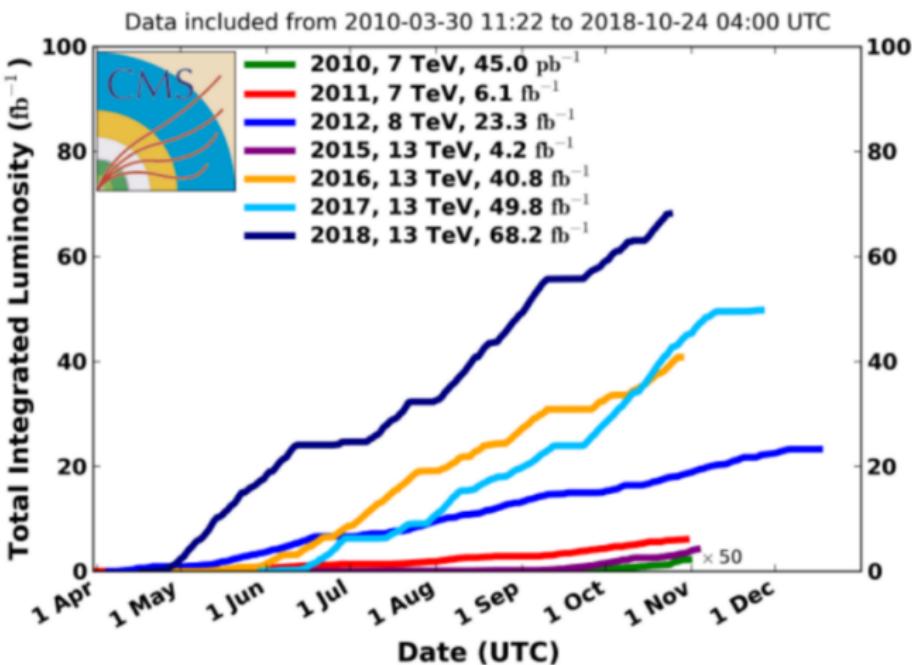


Slide view of the CMS in terms of pseudorapidity  $\eta = -\ln [\tan(\frac{\theta}{2})]$



# CMS integrated luminosity

CMS Integrated Luminosity, pp

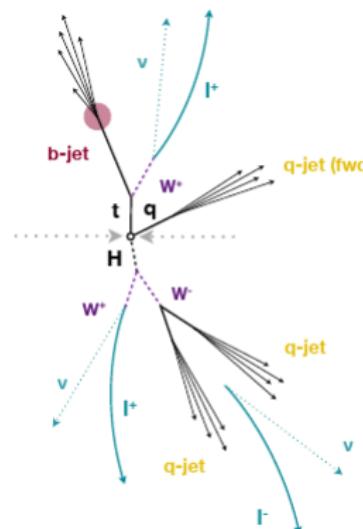


Integrated luminosity for CMS experiment

# Topology of events tH

The characteristics of the signal  $tH$ :

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



# Main backgrounds

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

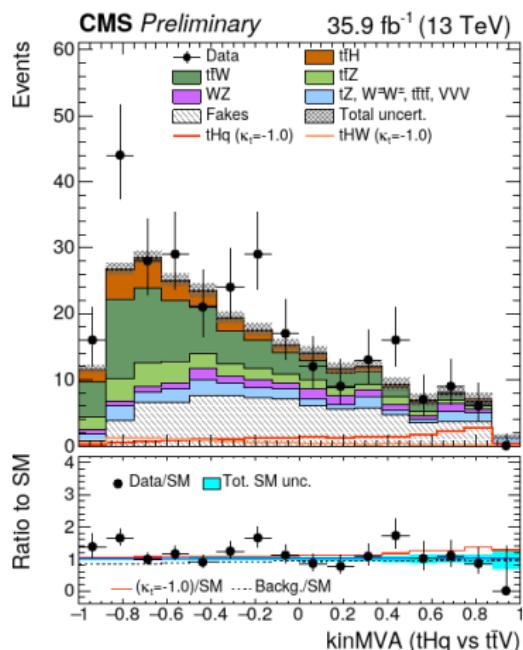
Background	Decay process
$t\bar{t}W$	$t\bar{t}W \rightarrow W^+ b W^- \bar{b} \mu^+ \nu_\mu \rightarrow \mu^+ \nu_\mu b \mu^- \bar{\nu}_\mu \bar{b} \mu^+ \nu_\mu$
$t\bar{t}Z$	$t\bar{t}Z \rightarrow W^+ b W^- \bar{b} \mu^+ \mu^- \rightarrow \mu^+ \nu_\mu b \mu^- \bar{\nu}_\mu \bar{b} \mu^+ \mu^-$
$W^+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

# 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  $|\eta| < 2.4$

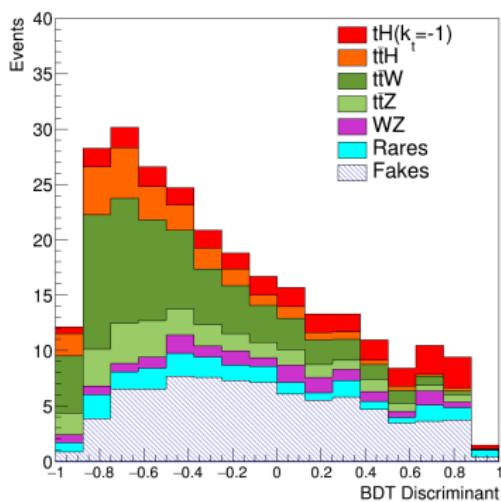
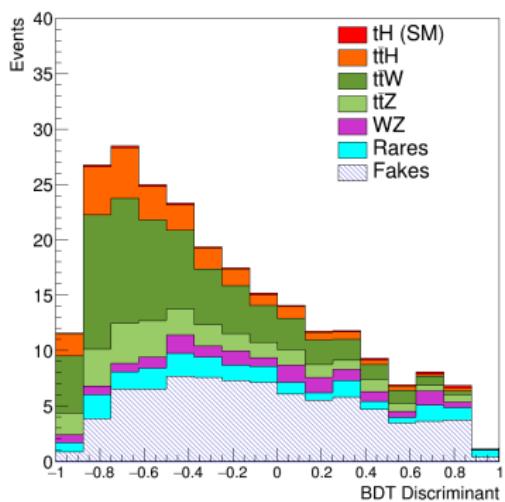
# Previous results for $t\bar{t}H+tH$ production



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

Event yields for signal and backgrounds after the event selection for a integrated luminosity of  $35.9 \text{ fb}^{-1}$ . 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)	$2.14 \pm 0.13$
$tH$ ( $k_t = -1$ )	$26.2 \pm 2.2$



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

# 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.



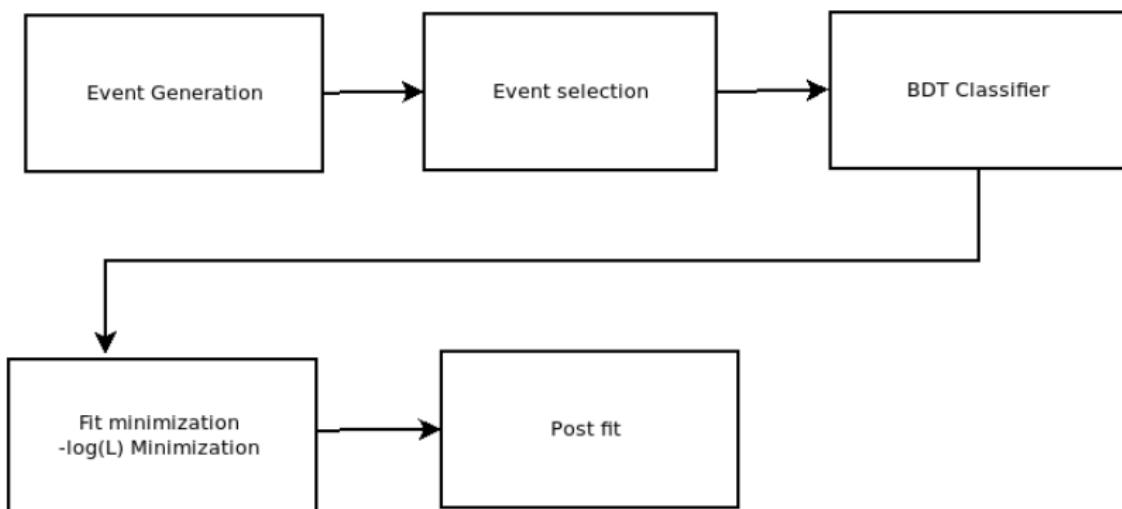
# BDT

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.

## BDT Variables

- Trailing lepton  $p_t$
- Total charge of tight leptons
- $\min \Delta R$  (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



# 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

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

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,  $\mu$  is a parameter that modifies the signal strength and  $b_j$  is the number of background events.



# Likelihood model

- $b_j$  is the sum of different background processes  $k$

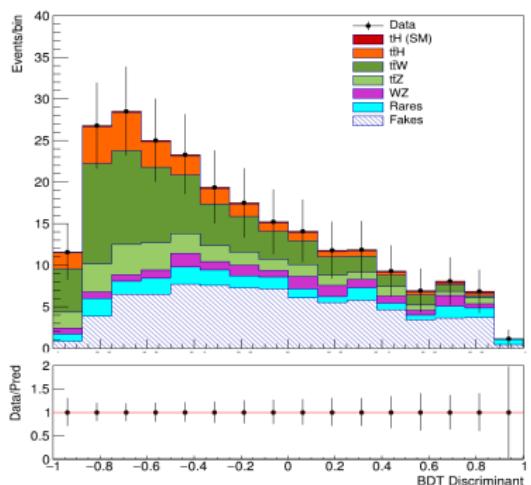
$$b_j = \sum_k^M b_j^k (1 + \alpha_k \sigma_k) \quad (7)$$

$\alpha_k$  is the parameter that modifies the expected background prediction and  $\sigma_k$  is the systematic uncertainty of the associated background.  $\sigma_k$  for the backgrounds are shown in the Table of yields.

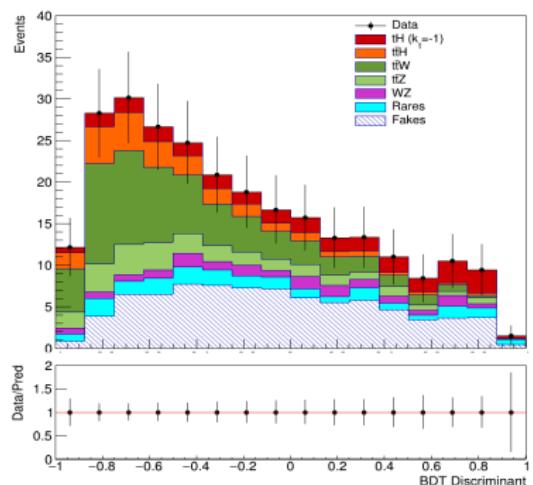
- The fit is applied by minimizing the  $-\log L$  (NLL) with respect to the parameter  $\mu$  and  $\alpha_k$ . The minimization is performed by using the package ROOFIT. In the next slides, it shows the results of the model fitting using the Asimov data for the SM and the  $k_t = -1$ .



# Results



Post-fit signal and background yields for  $t\bar{H}$  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  $t\bar{H}$  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  $35.9 \text{ fb}^{-1}$ .  
The uncertainty given is the combined statistical plus systematic.

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

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  $35.9 \text{ fb}^{-1}$  is consistent with zero. Therefore, we estimate an upper limit on the signal strength at 95% confidence level.
- We can define the likelihood ratio

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

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

- To determine an upper limit on the strength parameter  $\mu$ , we use the following statistical test

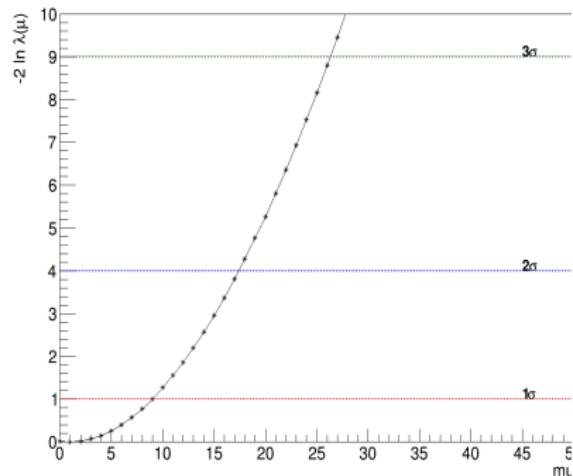
$$q(\mu, \alpha) = -2 \ln \lambda \quad (9)$$

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

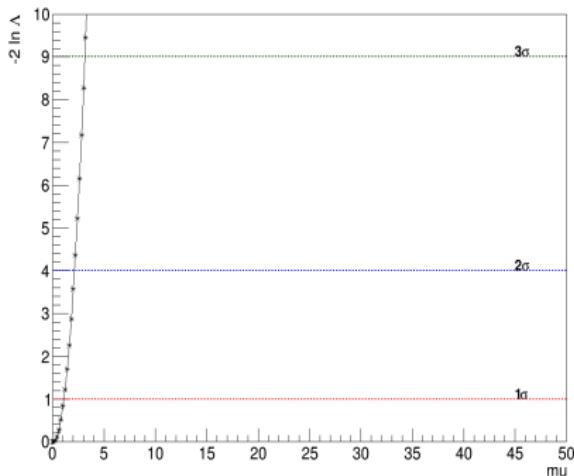


# Results

## Likelihood scan



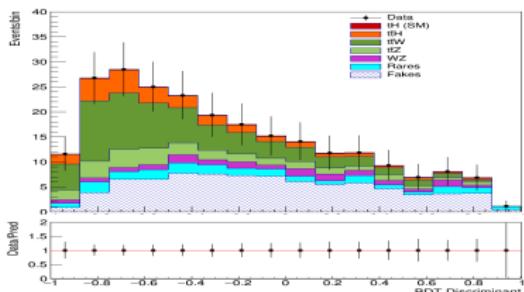
Likelihood scan for  $k_t=1$  (SM)



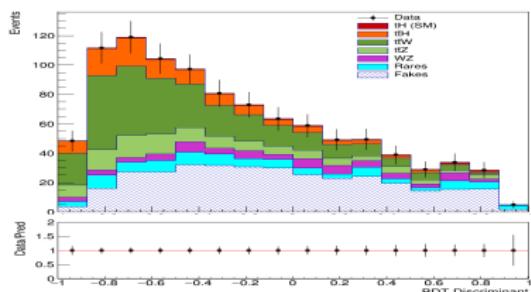
Likelihood scan for  $k_t=-1$



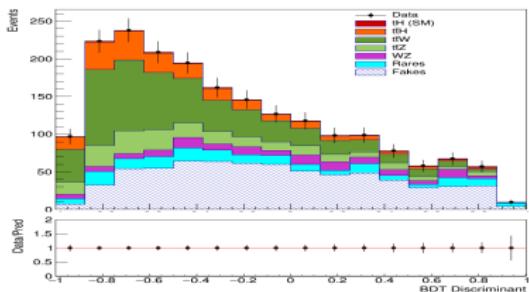
# Extrapolation of luminosity for SM



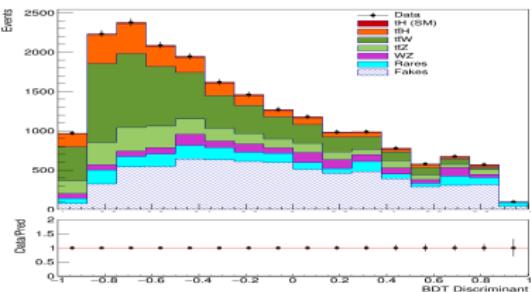
$35.9 \text{ fb}^{-1}$



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

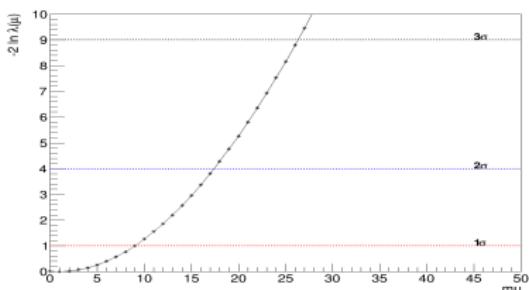


$300 \text{ fb}^{-1}$

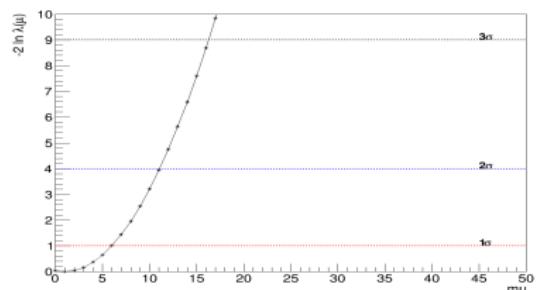


$3000 \text{ fb}^{-1}$

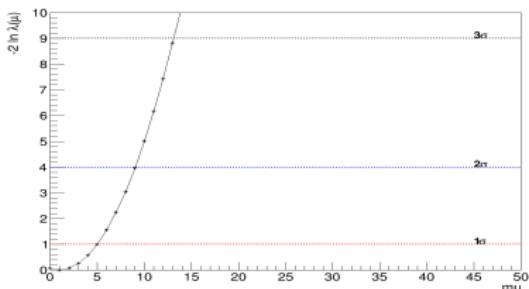
# Likelihood scan for SM



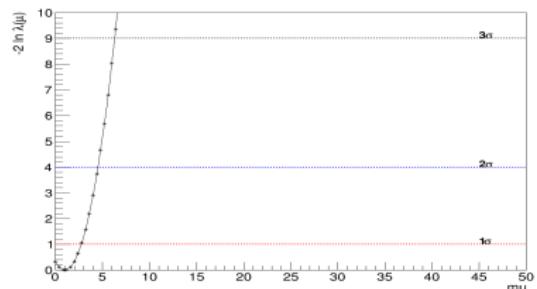
$35.9 \text{ fb}^{-1}$



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

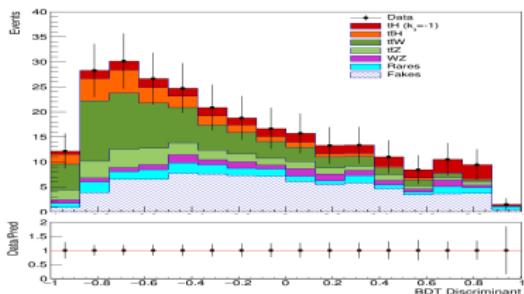


$300 \text{ fb}^{-1}$

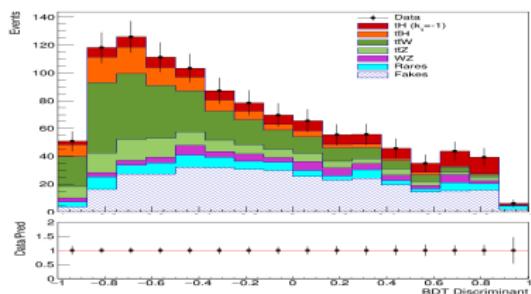


$3000 \text{ fb}^{-1}$

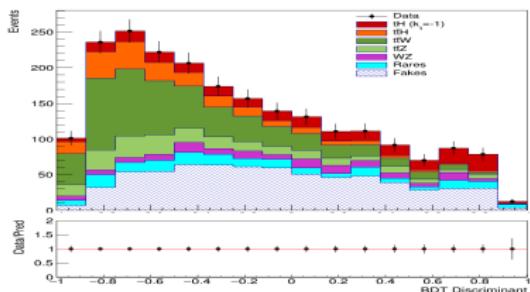
# Extrapolation of luminosity for $k_t = -1$



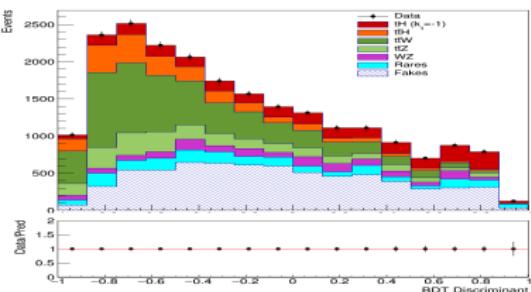
$35.9 \text{ fb}^{-1}$



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

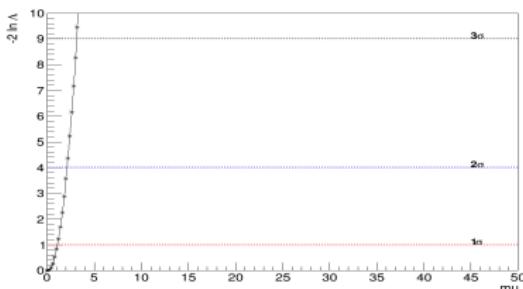


$300 \text{ fb}^{-1}$

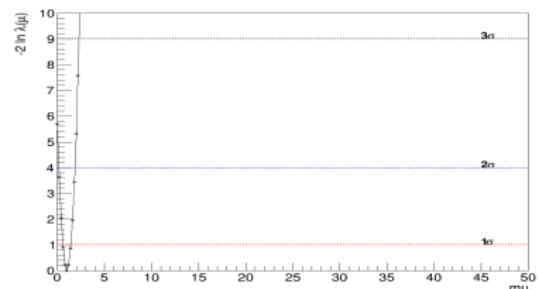


$3000 \text{ fb}^{-1}$

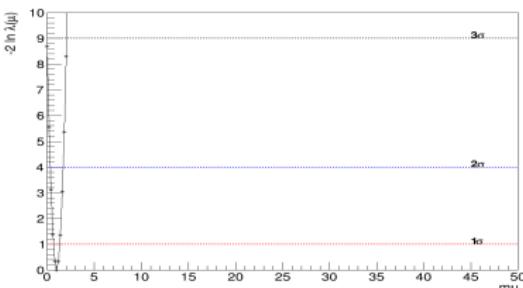
# Likelihood scan for $k_t = -1$



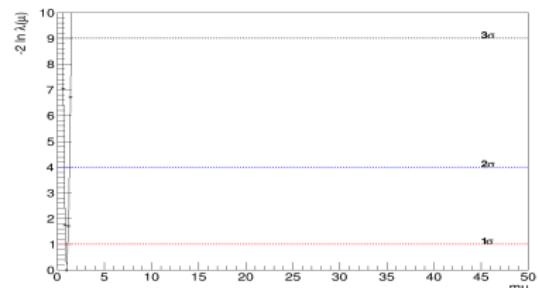
$35.9 \text{ fb}^{-1}$



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



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



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

# Results

## Upper limit

Results of  $\mu$  and upper limits for Asimov extrapolations for SM and  $k_t=-1$  models.

Luminosity ( $\text{fb}^{-1}$ )	$\mu$ (SM)	$\mu$ (SM) upper limit	$\mu$ ( $k_t=-1$ )	$\mu$ ( $k_t=-1$ ) upper limit
35.9	$1.0 \pm 7.7$	17	$1.0 \pm 0.5$	2.3
150	$1.0 \pm 6.7$	11	$1.0 \pm 0.4$	1.8
300	$1.0 \pm 4.3$	8.7	$1.0 \pm 0.3$	1.5
3000	$1.0 \pm 1.7$	4.3	$1.0 \pm 0.1$	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.

# References

-  Gross F. *Relativistic quantum mechanics and field theory*, 1994 ,WILEY-VCH Verlag GmbH & Co. KGaA
-  Griffiths, D. *Introduction to Elementary Particles*, 2<sup>o</sup> edition, 2008,WILEY-VCH Verlag GmbH & Co. KGaA
-  The CMS collaboration, *Search for production of a Higgs boson and a single top quark in multilepton final states in proton collisions at 13 TeV*, CMS-HIG-18-009, Phys. Rev. D 99, 092005
-  Verkerke W *Dealing with systematic uncertainties* 2014. From [https://indico.cern.ch/event/287744/contributions/1641261/attachments/535763/738679/Verkerke\\_Statistics\\_3.pdf](https://indico.cern.ch/event/287744/contributions/1641261/attachments/535763/738679/Verkerke_Statistics_3.pdf)



-  ATLAS and CMS Collaborations, *Combined measurement of the Higgs boson mass in pp collisions at  $\sqrt{s} = 7$  and 8 TeV with the ATLAS and CMS experiments*, Phys. Rev. Lett. 114 (2015)  
doi:10.1103/PhysRevLett.114.191803, arXiv:1503.07589
-  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
-  CMS collaboration *High-Luminosity Large Hadron Collider (HL-LHC)*, 2017,CERN-2017-007-M



# 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

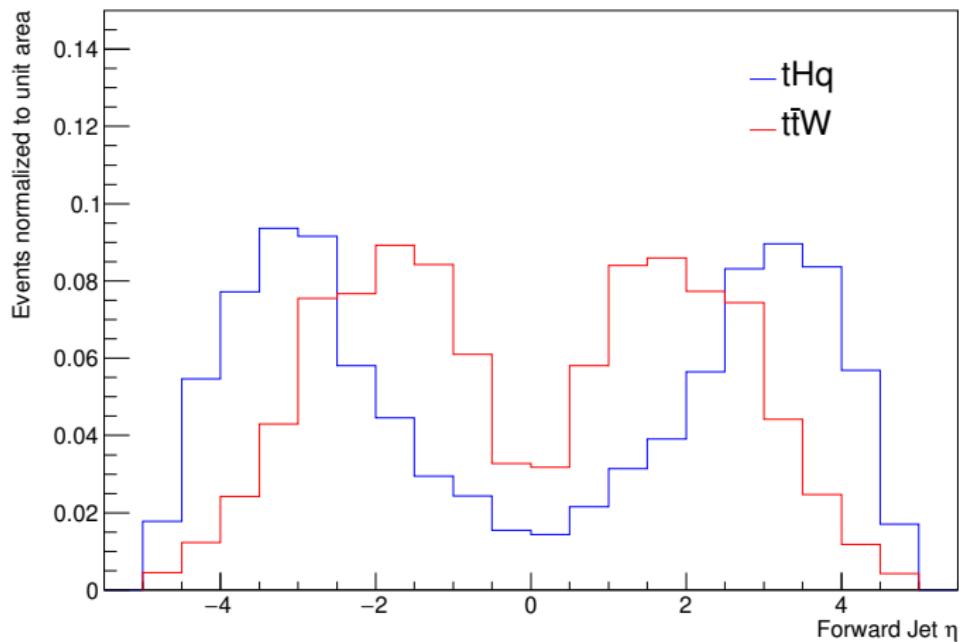
- Calibrations (electron, jet energy scale)
- Efficiencies (particle ID, reconstruction)
- Resolutions (jet energy, muon momentum)

## 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

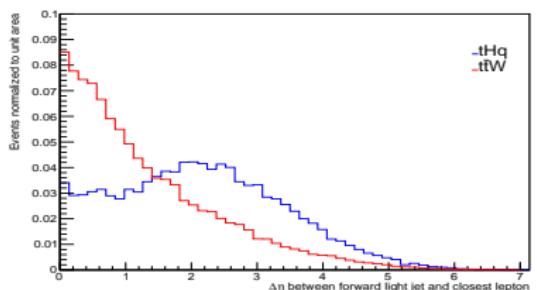
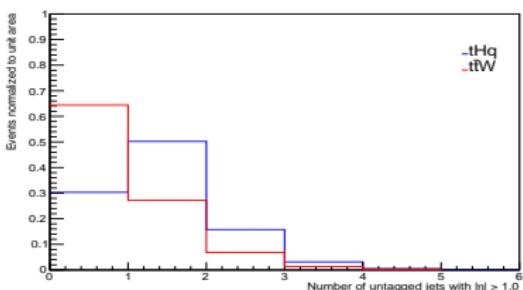
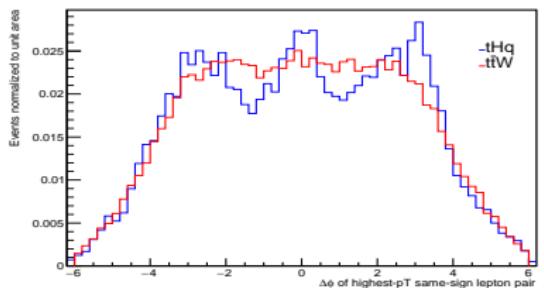
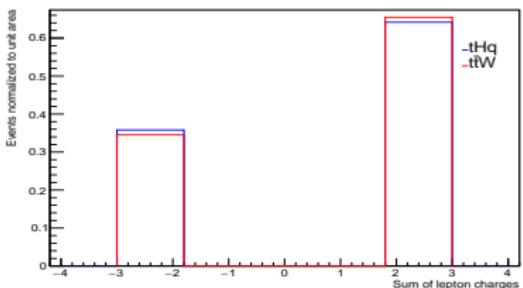


# Results

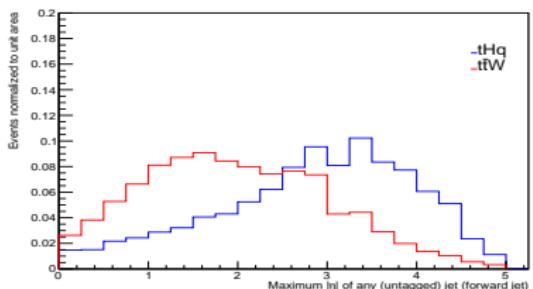
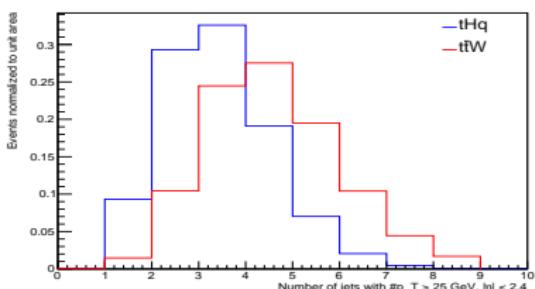
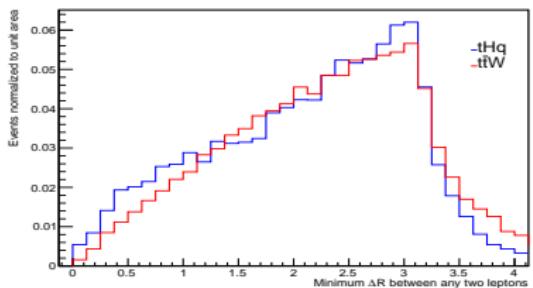
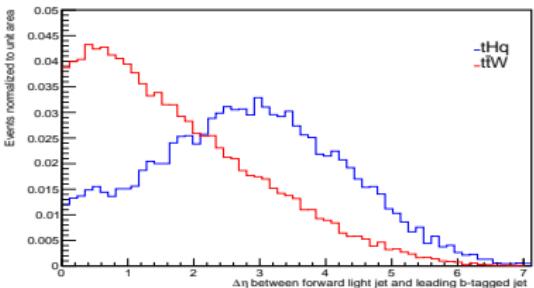
## Likelihood scan

- 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.



Distribution of events of  $|\Delta\eta|$  between a forward jet and the closest leptonDistribution of jet events for  $|\eta| > 1$ Distribution of events of  $|\Delta\phi|$  between the higher pt pair of leptons

Distribution of events of the sum of same sign leptons charge.

Distribution of selected events as a function of  $|\eta|$  of the jet with largest value of  $|\eta|$ Distribution of selected events with higher  $p_T$  with a  $|\eta| < 2.4$ Distribution of events with a  $\Delta R$  between the lepton pairs (highest and lowest  $p_T$ )Distribution of events as function of  $|\eta|$  between a forward jet and a b-tagged jet