Search for production of a Higgs boson and a single top quark in $\mu\mu$ final states in proton collisions at $\sqrt{s} = 13$ TeV

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Contenido

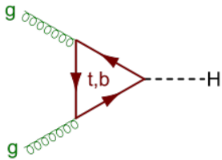
Overview

- Through this project we will investigate the production of Higgs boson in association with a single top quark (tH) in proton-proton collisions with the CMS experiment of the LHC. This mechanism of production of the Higgs boson has not been observed before by any experiment.
- Understanding the production of the Higgs boson, as well as its decays are an important part of the physical program of the CERN international laboratory experiments that try to complete the tests to verify the Standard Model, the theory of the fundamental particles

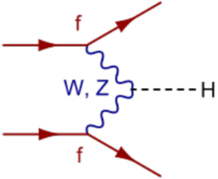
Motivation for single top Higgs (tH)

- 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.
- The tH study explores the relative sign of top-Higgs and W-Higgs.
  Small deviations from SM predictions could be associated with physics beyond the standard model (BSM)

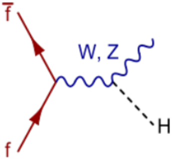
Higgs production mechanisms



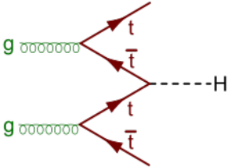
ggF



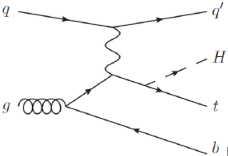
VBF



VH



ttH



tH

tH production mechanisms

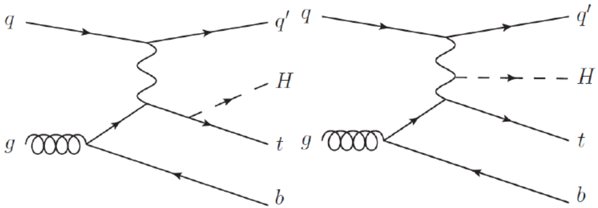


Figure: tH mechanism. Left. Higgs radiated from a top quark. Right.Higgs radiated from a W boson

Cross section

- Classical definition: When two particles interact, cross section is the area transverse to their relative motion within which they must meet in order to scatter from each other.
- Quantum definition: Cross section describes the likelihood of two particles interacting under certain conditions[1]
- Experimentally

$$d\sigma = \frac{\text{number of particles scattered into solid angle}\Delta\Omega/s}{(\text{number of particles incident/s})(\text{scattering centers/area})} \tag{1}$$

Cross section

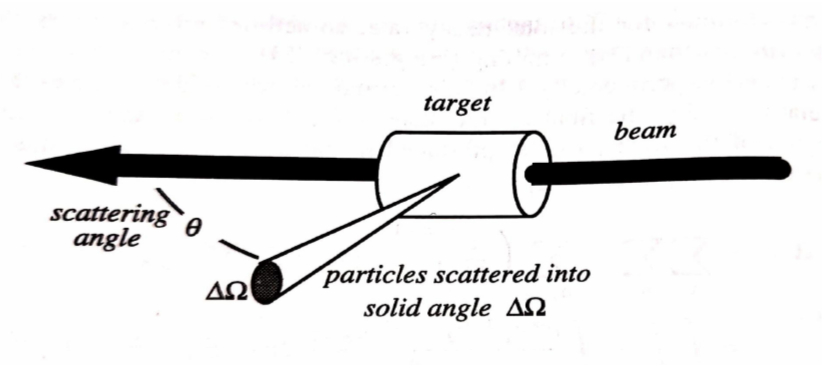


Figure: Drawing of an idealized scattering process showing the differential solid angle $\Delta\Omega$ and the scattering angle θ[1]

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
ttH	0.50	18255
tH (only)	0.015	560.39

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

Cross section

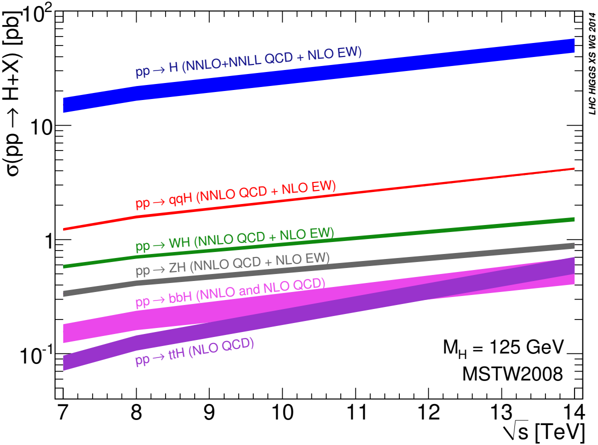


Figure: Higgs boson production cross sections as a function of the centre-of-mass-energies

Cross section

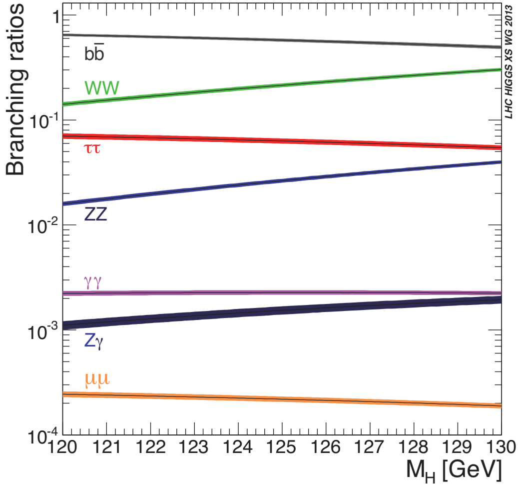


Figure: Standard Model Higgs boson decay branching ratios

Higgs Branching ratios and expected events per channel

SM Higgs boson branching ratios and number of events per decay for tH process M_H =125 GeV

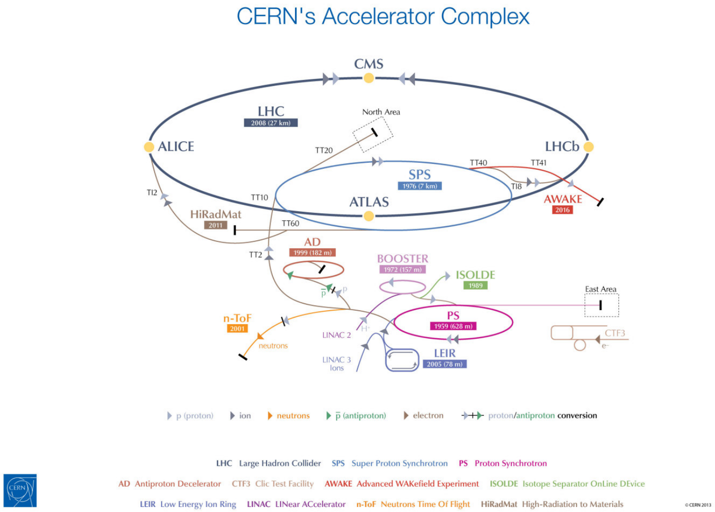
Higgs decay	Branching ratio (BR)
$\mathrm{H} \rightarrow \mathrm{b}\bar{b}$	5.82×10^{-1}
$\mathrm{H} \rightarrow W^+W^-$	2.15×10^{-1}
$\mathrm{H} \rightarrow \tau^+\tau^-$	6.27×10^{-2}
$\mathrm{H} \rightarrow \mathrm{ZZ}$	2.61×10^{-2}
$\mathrm{H} \rightarrow \gamma\gamma$	2.27×10^{-3}
$\mathrm{H} \rightarrow \mathrm{Z}\gamma$	1.53×10^{-3}
$\mathrm{H} \rightarrow \mu^+\mu^-$	2.17×10^{-4}

Decay chain

Table of decay chains for tH. Number of total events for tH=560.39.

Decay chain	BR	Events
$th \rightarrow q\bar{q}(q=u,c)$ b+W^+W^- $\rightarrow$ q $\bar{q}$+b + $l\nu$ +$l\nu$	1.663×10^{-3}	0.9319
$th \rightarrow$Wb+W^+W^- $\rightarrow \mu^+\nu_\mu$+b + $l\nu$ +$l\nu$	3.37×10^{-4}	0.899
$tH \rightarrow$ Wb+ W^+W^- $\rightarrow \mu^+\nu_\mu$+b+$\mu^-\nu_\mu+\mu^+\nu_\mu$	3.235×10^{-4}	0.1888
$tH \rightarrow$ Wb+ $\tau^+\tau^-$ $\rightarrow \mu^+\nu_\mu$+b+$\mu^+\nu_\mu\nu_\tau+\mu^-\nu_\mu\nu_\tau$	2.540×10^{-4}	0.1423
$tH \rightarrow \tau\nu_\mu$b+ W^+W^- $\rightarrow \mu^+\nu_\mu\nu_\tau$+b+$\mu^+\mu^-+\mu^+\mu^-$	2.981×10^{-5}	0.016
$tH \rightarrow$ Wb+ $Z\gamma \rightarrow \mu^+\nu_\mu$+b+$\mu^-\nu_\mu+\mu^+\nu_\mu+\gamma$	6.902×10^{-6}	0.0038
$tH \rightarrow$ Wb+ZZ $\rightarrow \mu^+\nu_\mu+\mu^+\mu^-+\mu^+\mu^-$	3.962×10^{-6}	0.0022
$tH \rightarrow \tau\nu_\mu$b+ ZZ $\rightarrow \mu^+\nu_\mu$+b+$\mu^-\nu_\mu+\mu^+\nu_\mu$	3.650×10^{-7}	0.0002

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
n-ToF
2001
PS
1959 (628 m)
CTF3
LINAC 2
neutrons
LINAC 3
Ions
LEIR
2005 (78 m)
p (proton)
ion
neutrons
p̄ (antiproton)
electron
proton/antiproton conversion
LHC Large Hadron Collider
SPS Super Proton Synchrotron
PS Proton Synchrotron
AD Antiproton Decelerator
CTF3 Clic Test Facility
AWAKE Advanced WAKefield Experiment
ISOLDE Isotope Separator OnLine DEvice
LEIR Low Energy Ion Ring
LINAC LINear ACcelerator
n-ToF Neutrons Time Of Flight
HiRadMat High-Radiation to Materials
© CERN 2013

LHC

Quantity	Number
Circumference	26 659 m
Dipole operating temperature	1.9 K (-271.3°C)
Number of magnets	9593
Number of main dipoles	1232
Number of main quadrupoles	392
Number of RF cavities	8 per beam
Nominal energy, protons	6.5 TeV
Nominal energy, ions	2.56 TeV/u (energy per nucleon)
Nominal energy, protons collisions	13 TeV
No. of bunches per proton beam	2808
No. of protons per bunch (at start)	1.2×10^{11}
Number of turns per second	11245
Number of collisions per second	1 billion

Table. LHC characteristics for run 2.

CMS

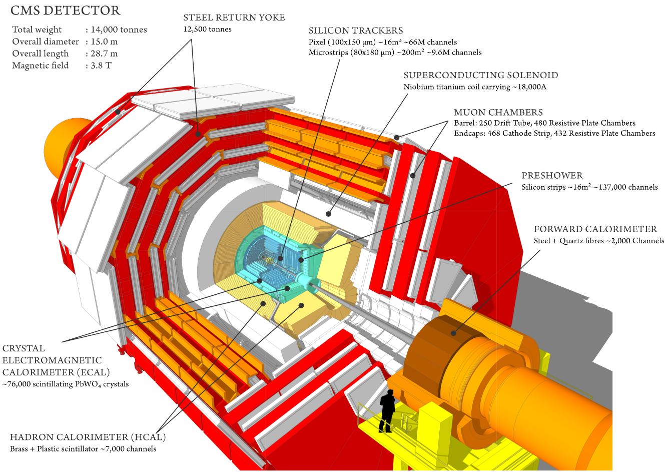


Figure: Compact muon solenoid

CMS

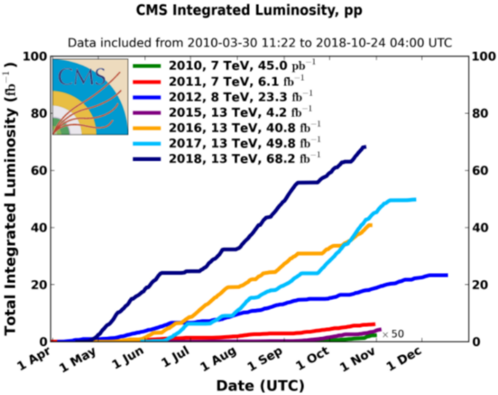
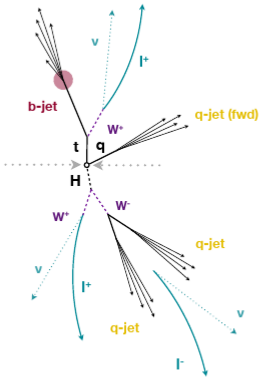


Figure: Luminosity scale for CMS experiment content...

Topology of events tH

The characteristics of the signal tHq:

- A Higgs Bosons decays two W boson H→ WW Same-sign dilepton (2lss): one W from Higgs decays hadronically, others decay Leptonically.
- W Boson decays to a lepton and a neutrino W→ $l\nu$
- W bosons decay leptonically with equal electrical charge, resulting in a signature of two same-sign leptons with two light-quark jets.[2]



Event selection

- The events are selected those that contain two leptons ($\mu\mu$) with the same sign.
- Using a boosted decision tree for discriminate the data.
- The main analysis strategy is to obtain a selection of events compatible with certain characteristics of the signal at pre-selection level
- Extract the signal contribution in a second analysis step, using multivariate discriminators against the main backgrounds of ttW$^{\pm}$ /ttZ and non prompt leptons from tt[2].

It is required:

- Transverse moment $p_t > 25$ and 15 GeV, for the muons.
- A front jet with $p_t > 40$ GeV, $\mid \eta \mid > 2.4$
- One or more b-jets with $(\mid \eta \mid < 2{,}4)(1)$

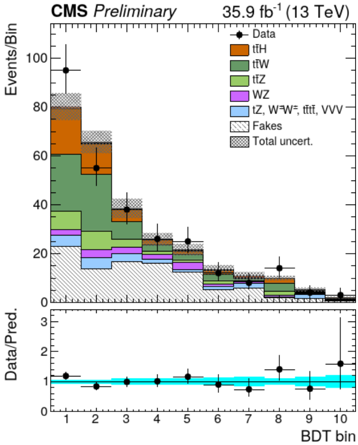
Previous results

- Direct searches for tHq production using all relevant Higgs decay modes have previously been carried out by CMS in the 8 TeV dataset and in the 2015 13 TeV dataset using the $H \rightarrow b\bar{b}$ channel .
- In the full 2016 13 TeV dataset, a search for ttH production in multilepton final states recently produced first evidence for associated production of top quarks and Higgs bosons[2]

[2] Taken from Search for production of a Higgs boson and a single top quark in multilepton final states in proton collisions at $\sqrt{s} = 13$ TeV CMS PAS HIG-17-005

Previous results

Process	$\mu\mu$
$t\bar{t}W^{\pm}$	68.03 ± 0.61
$t\bar{t}Z/t\bar{t}\gamma$	25.89 ± 1.12
WZ	15.07 ± 1.19
ZZ	1.16 ± 0.29
$W^{\pm}W^{\pm}qq$	3.96 ± 0.52
$W^{\pm}W^{\pm}$(DPS)	2.48 ± 0.42
VVV	2.99 ± 0.34
tttt	2.32 ± 0.45
tZq	5.77 ± 2.24
tZW	2.13 ± 0.13
γ conversions	–
Non-prompt	80.94 ± 2.02
Charge flips	–
Total Background	210.74 ± 3.61
$t\bar{t}H$	24.18 ± 0.48
tHq (SM)	1.43 ± 0.04
tHW (SM)	0.71 ± 0.03
Total SM	237.06 ± 3.64
tHq ($\kappa_V = 1 = -\kappa_t$)	18.48 ± 0.22
tHW ($\kappa_V = 1 = -\kappa_t$)	7.72 ± 0.17
Data	**280**



Post-fit categorized BDT classifier outputs as used in the maximum likelihood fit for the $\mu\mu$ channel for 35.9 fb^{-1}.In the box below each distribution, the ratio of the observed and predicted event yields is shown.

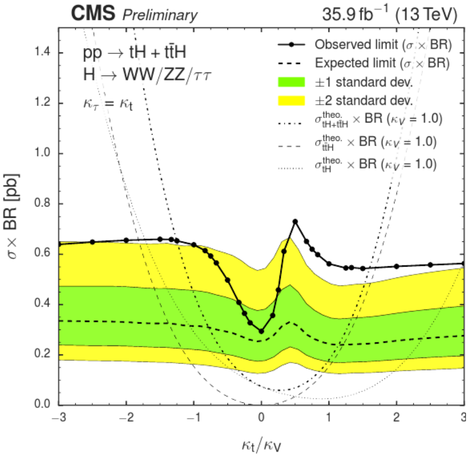


Figure: Observed and expected 95% C.L. upper limit on the tH + ttH cross section times H $\rightarrow$ WW + $\tau\tau$ + ZZ branching fraction for different 20 values of the coupling ratio κ_t/κ_v . The expected limit is derived from a background-only MC dataset.

Signal and background

Signal: Object of study tH as signal component Background components

- WZ
- ttZ
- ttH
- tV,VVV,WW,tttt
- Non prompt leptons are included

Include ttH to multilepton as signal component (σ SM 500 fb) (Previous result). Use lepton MVA developed for ttH analysis for optimal selection of prompt leptons and suppression of non-prompt leptons.

Boosted decision tree (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.

Pros:

- Fast
- Easy to tune
- Not sensitive to scale (The features can be a mix of categorical and continuous data)
- Good performance

Cons:

- Sensitive to overfitting and noise

Boosted decision tree (BDT)

Signal discrimination using BDT Two separate BDT trainings using MC samples for signal and backgrounds:

1. Signal is only tHq with κ_t = -1.0, κ_V = 1.0.
2. Against t$\bar{t}$: non-prompt lepton type background.
3. Against combined ttZ and ttW: prompt lepton type background.

BDT Variables

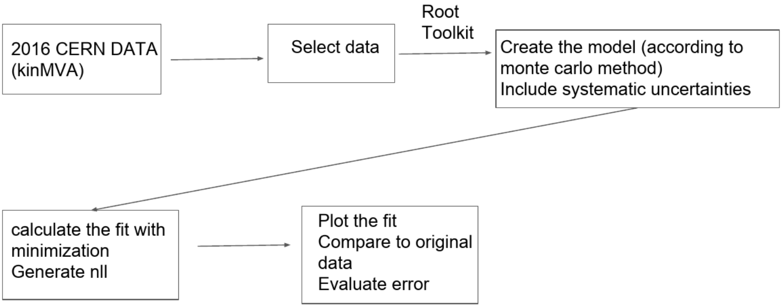
- Trailing lepton p_t
- Total charge of tight leptons
- min ΔR (lepton pairs)
- $\Delta\phi$ between highest p_t lepton pair
- Number of jets with $|\eta| < 2.4$
- Number of non b-tagged jets with $|\eta| > 1.0$
- Maximum $|\eta|$ for jets
- $\Delta\eta$ (most forward light jet, closest lepton)
- $\Delta\eta$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

Sources of systematic uncertainty

Luminosity measurement: 2.6Data/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, ttW, ttZ, ttH Systematic uncertainties (background normalization)

- tth 5%
- ttZ 10.7 %
- ttW 12.6 %
- tZ 50%
- WZ 50%
- Non prompt leptons /fakes 40%

Fitting

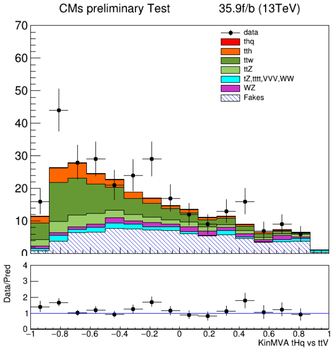

2016 CERN DATA (kinMVA)
Select data
Root Toolkit
Create the model (according to monte carlo method)
Include systematic uncertainties
calculate the fit with minimization
Generate nll
Plot the fit
Compare to original data
Evaluate error

Results

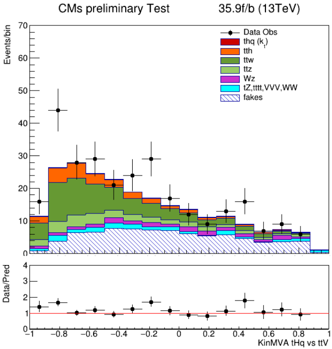
Table: Prefit and postfit table for each yield.

Process	Number of events prefit	Number of events Postfit
tH	2.13 ± 0.05	10.28 ± 26.17
ttH	24.18 ± 0.10	24.31 ± 0.13
ttW	68.03 ± 8.60	75.57 ± 7.85
ttZ	25.89 ± 2.78	26.43 ± 2.77
tZ	15.04 ± 7.52	16.25 ± 7.53
WZ	15.07 ± 7.53	15.95 ± 7.46
fakes	80.94 ± 32.37	96.80 ± 25.58

Results



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



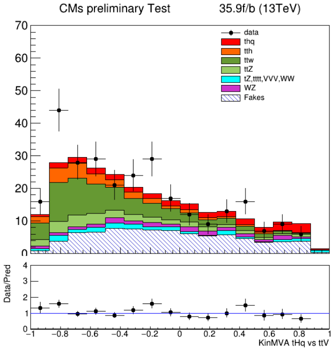
Post-fit signal and background yields for tH process. In the box below each distribution, the ratio of the observed and predicted event yields is shown

Results

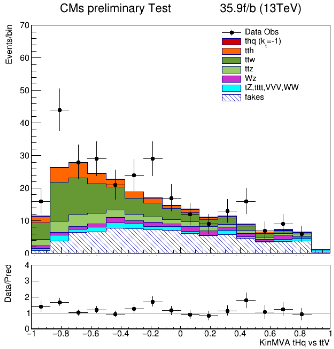
Table: Prefit and postfit table for each yield. k_t =-1

Process	Number of events prefit	Number of events Postfit
tH	26.2 $\pm$ 0.27	6.49 $\pm$ 25.38
ttH	24.18 $\pm$ 1.31	24.32 $\pm$ 0.14
ttW	68.03 $\pm$ 8.60	75.69 $\pm$ 8.178
ttZ	25.89 $\pm$ 2.78	26.44 $\pm$ 2.78
tZ	15.04 $\pm$ 7.52	16.40 $\pm$ 7.44
WZ	15.07 $\pm$ 7.53	16.10 $\pm$ 7.53
fakes	80.94 $\pm$ 32.37	99.45 $\pm$ 25.80

Results



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



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

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.

Results
Likelihood scan

The likelihood function is the product of Poisson probabilities for all bins

$$L(\mu,\theta) = \prod_{j=1}^{N} \frac{(\mu s_j + b_j)^{n_j}}{n_j!} e^{-(\mu s_j + b_j)} \qquad (2)$$

- N=number of bins
- μ=parameter of signal
- s=signal
- b=background
- n=number of events

Results

Likelihood scan

To test a hypothesized value of μ we consider the profile likelihood ratio

$$\lambda(\mu) = \frac{L(\mu, \hat{\hat{\theta}})}{L(\hat{\mu}, \hat{\theta})} \quad (3)$$

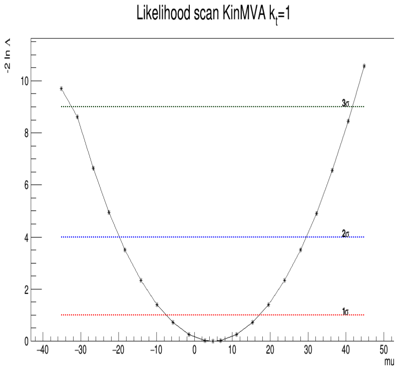
Here $\hat{\hat{\theta}}$in the numerator denotes the value of θ that maximizes L for the specified μ, it is the conditional maximum-likelihood (ML) estimator of $\hat{\theta}$ (and thus is a function of μ). The denominator is the maximized (unconditional) likelihood function, i.e., $\hat{\mu}$and $\hat{\theta}$are their ML estimators[3].

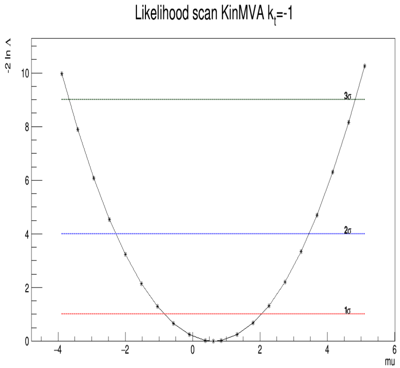
Results
Likelihood scan

The presence of the nuisance parameters broadens the profile likelihood as a function of μ relative to what one would have if their values were fixed. This reflects the loss of information about μ due to the systematic uncertainties[3][4].

Results

Likelihood scan





Likelihood scan for k_t=1 (SM)

Likelihood scan for k_t=-1

References

Gross F. *Relativistic quantum mechanics and field theory* 1994 Wiley

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-PAS-HIG-17- 005

Verkerke W *Dealing with systematic uncertainties* 2014. From `https://indico.cern.ch/event/287744/contributions/1641261/attachments/535763/738679/Verkerke_Statistics_3.pdf`

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

Back up

BDT parameters

- Gradient boosted (BDTG)
- No. of trees = 800
- No. of cuts = 50
- Maximum depth = 3
- Found to be most discriminating, minimal overtraining.

List of histograms used in the analysis

Data taken from the file `plots-thq-2lss-kinMVA.root` 2016 CERN

```
thqMVA_ttv_2lss_40_tZq
thqMVA_ttv_2lss_40_ttZ
thqMVA_ttv_2lss_40_VVV
thqMVA_ttv_2lss_40_ttW
thqMVA_ttv_2lss_40_data_fakes
thqMVA_ttv_2lss_40_ttH
thqMVA_ttv_2lss_40_tHW_hww
thqMVA_ttv_2lss_40_WWss
thqMVA_ttv_2lss_40_tttt
thqMVA_ttv_2lss_40_WZ
thqMVA_ttv_2lss_40_tHq_hww
```

Backgrounds and signal histograms

tHq: Signal (tH)

- thqMVA_ttv_2lss_40_tHq_hww
- thqMVA_ttv_2lss_40_tHW_hww

Backgrounds

ttW

- thqMVA_ttv_2lss_40_ttW

ttZ

- thqMVA_ttv_2lss_40_ttZ

WZ

- thqMVA_ttv_2lss_40_WZ

Backgrounds and signal histograms

Backgrounds

tZ, VVV,tttt,WW:

- thqMVA_ttv_2lss_40_tZq
- thqMVA_ttv_2lss_40_WWss
- thqMVA_ttv_2lss_40_VVV
- thqMVA_ttv_2lss_40_tttt

ttH

- thqMVA_ttv_2lss_40_ttH

Non prompt leptons (fakes)

- thqMVA_ttv_2lss_40_data_fakes

Sources of systematic uncertainty in HEP (high energy physics)

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]

α values for post fit

```
Floating Parameter      FinalValue +/- Error
--------------------------------------------
--------------------------------------------
Lumi                    1.0000e+00 +/- 1.00e-04
alpha_sample_B_sys      2.0316e-01 +/- 9.90e-01
alpha_sample_F_sys      5.2474e-01 +/- 8.11e-01
alpha_sample_H_sys      1.1984e-01 +/- 9.92e-01
alpha_sample_T_sys      9.1741e-01 +/- 9.44e-01
alpha_sample_W_sys      1.2297e-01 +/- 9.89e-01
alpha_sample_Z_sys      7.3604e-02 +/- 9.76e-01
mu                      5.2836e+00 +/- 1.17e+01
```

α values for post fit thq k_t=-1

Floating Parameter	FinalValue +/- Error
Lumi	1.0000e+00 +/- 1.00e-04
alpha_sample_B_sys	2.0279e-01 +/- 9.87e-01
alpha_sample_F_sys	5.2541e-01 +/- 8.02e-01
alpha_sample_H_sys	1.1946e-01 +/- 9.90e-01
alpha_sample_T_sys	9.1778e-01 +/- 9.36e-01
alpha_sample_W_sys	1.2155e-01 +/- 9.73e-01
alpha_sample_Z_sys	7.2960e-02 +/- 9.67e-01
mu	6.1286e-01 +/- 1.39e+00

Statistical test

It is convenient to use the statistic

$$t_\mu = -2 \ln \lambda(\mu) \tag{4}$$

as the basis of a statistical test. Higher values of t_μ thus correspond to increasing incompatbility between the data and μ. We may define a test of a hypothesized value of μ by using the statistic t_μ directly as measure of discrepancy between the data and the hypothesis, with higher values of t_μ correspond to increasing disagreement[4]

Statistical test

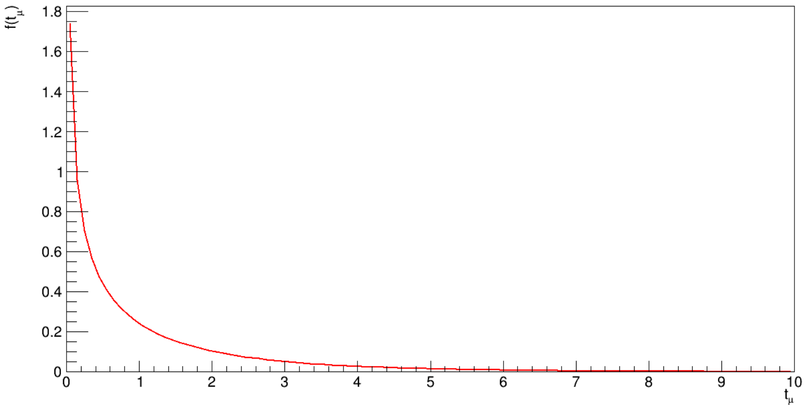


Figure: Statistic test plot $f(t_\mu)$ vs t_μ with $t_\mu = -2\ln\lambda(\mu)$

P value

To quantify the level of disagreement we compute the P-value

$$P_\mu = \int_{t_\mu}^{\infty} f(t\mu|\mu)dt_\mu \tag{5}$$

where t μ is the value of the statistic tμ observed from the data and $f(t\mu|\mu)$ denotes the PDF (Probability density function) of tμ under the assumption of the signal strength μ[4]

P value

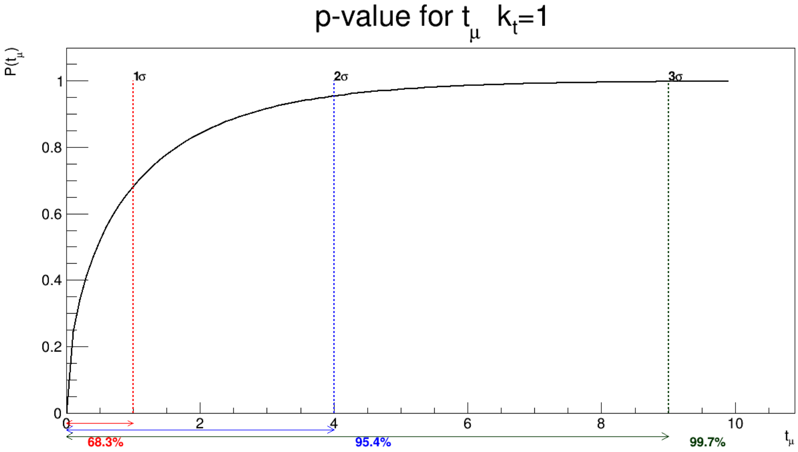


Figure: P_μ vs f$(t_\mu|\mu)$