Universidad de Oviedo
Universidá d'Uviéu
University of Oviedo

ICTEA

TESIS DOCTORAL

Búsqueda de nueva física en eventos con leptones de alto momento transverso con el detector CMS del LHC

Search for new physics in events with high transverse momentum leptons with the CMS detector at the LHC

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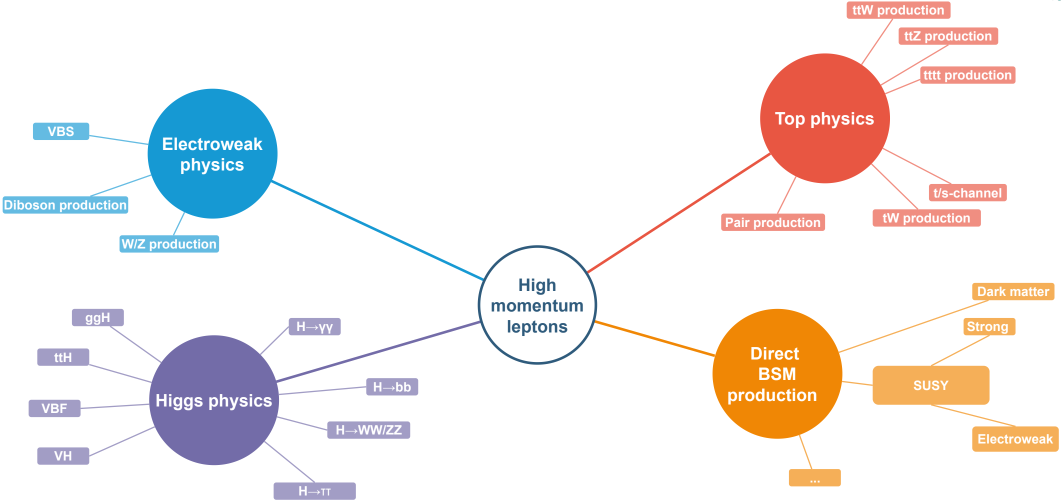
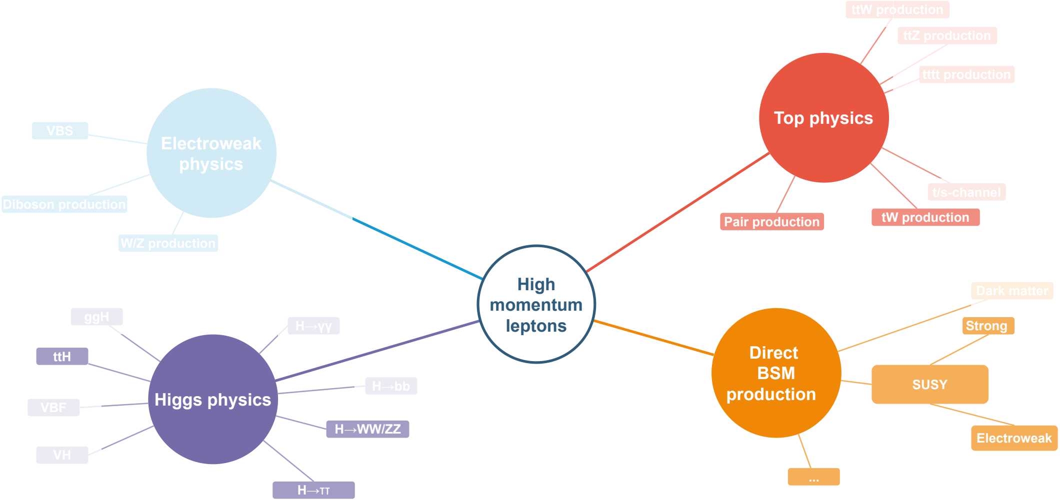
Oviedo, 11 de septiembre, 2020

- Exploring physics at the highest energy available in colliders



- Exploring physics at the highest energy available in colliders



Contribution to the CMS detector operation

- Developments in the trigger system
- Contribution to the muon object group

Top quark physics: $t\bar{t}$ and tW

- Benchmark for SM studies in hadron colliders
- Study of perturbative QCD
- Background for BSM searches

Searches for supersymmetric particles

- Exploring events with opposite-sign same-flavor lepton pair
- Particularly interesting for electroweak produced SUSY

Studies of the Higgs boson properties: $t\bar{t}H$ and tH production

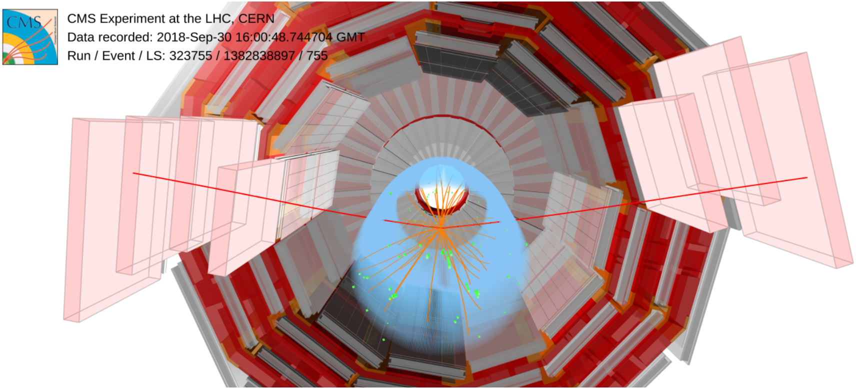
- Exploring the most sensitive channel in Run 2 $\Rightarrow$ multilepton final states
- Allow to explore the top Yukawa sector

OUTLINE

- Experimental set-up: LHC and the CMS detector
- Measurement of the inclusive and differential tW production cross sections
- Search for SUSY in events with opposite-charge same-flavor leptons
- Measurement of $\mathrm{t\bar{t}H}$ and tH production in the multilepton channel
- Conclusions

Section 1

Experimental set-up: LHC and the CMS detector

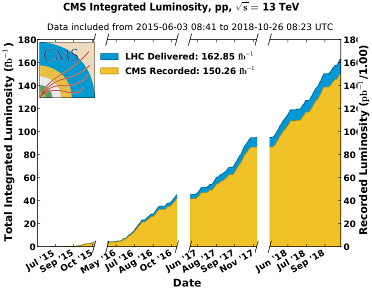


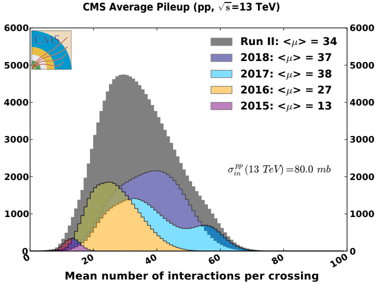
- CMS-DP-2019-026
- CMS-DP-2019-022
- CMS-DP-2918-042

Large Hadron Collider

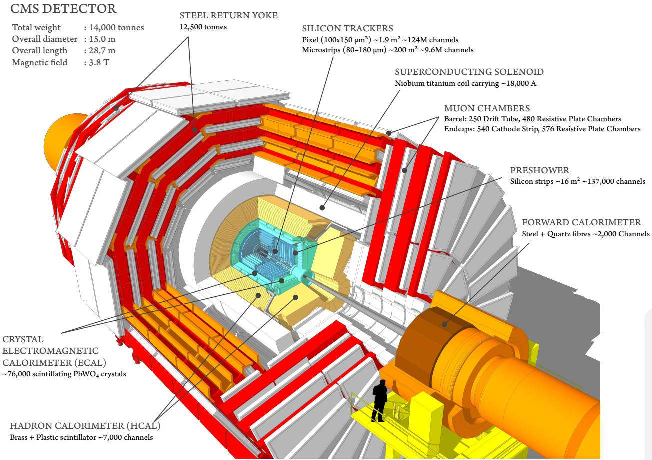
- Superb performance of the LHC during Run 2

- Delivering pp collisions at $\sqrt{s} = 13$ TeV during Run 2 (2015-2018)
- Peak luminosity of $2{\cdot}10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Average of 30-40 interactions per bunch crossing during Run 2
- Running conditions evolving in data taking periods





CMS DETECTOR



- High resolution tracker detector
  - Enhanced with a new layer
- Intense magnetic field
- Muon system with good coverage
- Hermetic calorimeters
- Efficient triggering system

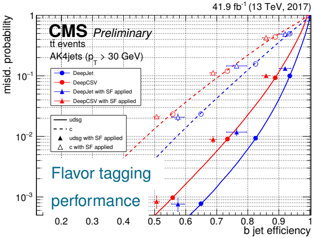
- Excellent performance of the detector
- Data taking efficiency of 93.4%
- More than 1000 articles released

CMS OBJECT PERFORMANCE

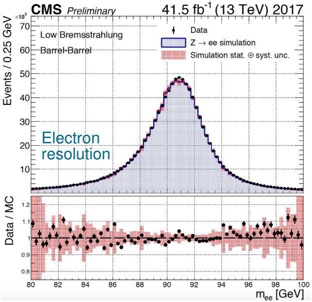
Object reconstruction

- Particle flow algorithm
- Dedicated algorithms
- Excellent object performance across the Run 2 data-taking

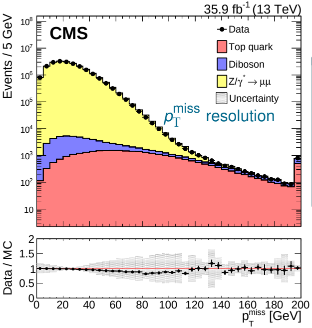
CMS-DP-2018-058



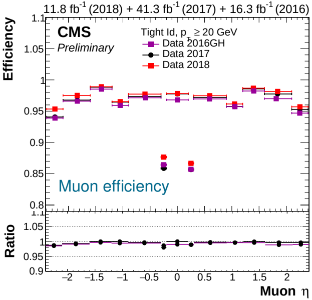
CMS-DP-2018-042



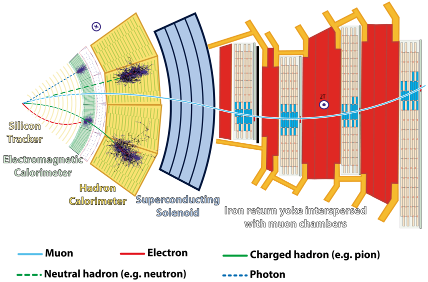
JINST 14.07 (2019), P07004



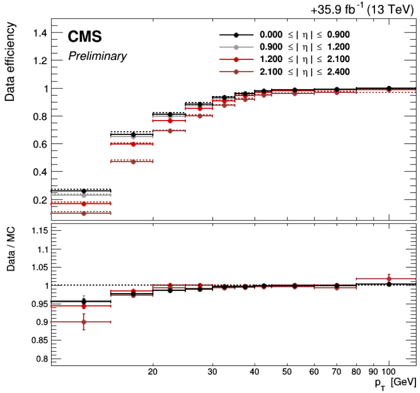
CMS-DP-2020-024



Muon reconstruction



- Muon reconstruction combines information from tracker and muon system
- Efficiency higher than 99%
- Quality criteria applied targeting different levels of purity and muon sources



- Coordinated the muon selection and calibration group (L3 responsibility)
- Developed the $t\bar{t}H$ lepton MVA for wider use in the collaboration
- Contributed to identification developments in Run 3

Trigger System

CMS-TRG-19-001

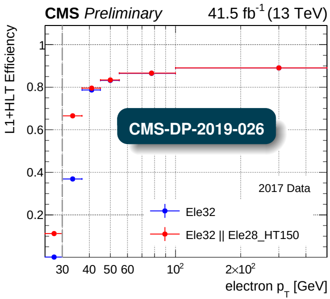
- Trigger system to keep acceptance rate under control
  - L1 $\Rightarrow$ built in hardware, coarse readout of calorimeters and muon system
  - HLT $\Rightarrow$ software-based, full detector readout

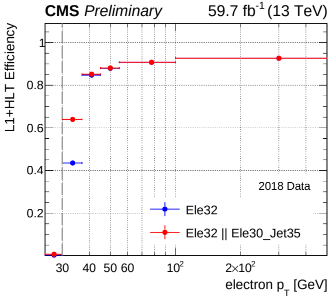
L1 trigger

- Contributed to the developments of the OMTF for the Phase-II upgrade

HLT

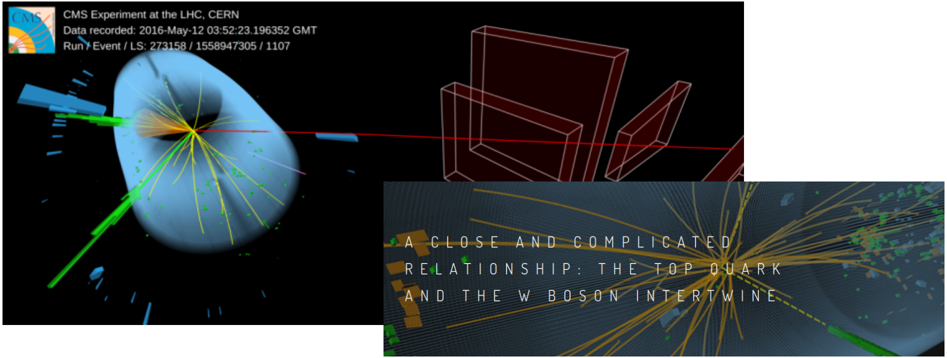
- Coordinated the trigger effort in the top physics group
- Participated in the development of trigger paths used in dilepton, single lepton and fully hadronic top and Higgs physics analyses





Section 2

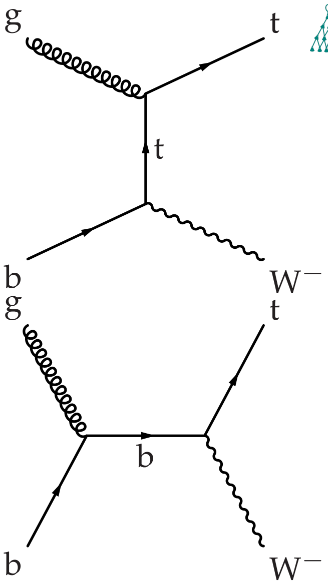
Measurement of the tW inclusive and differential production cross sections



- $t\bar{t}$ production [7, 8 TeV]. JHEP 08 (2016) 029
- $t\bar{t}$ production [13 TeV, 2016]. EPJC 79 (2019) 368
- tW production [13 TeV, 2016]. JHEP 10 (2018) 117
- tW differential [13 TeV, 2016]. CMS-PAS-TOP-19-003

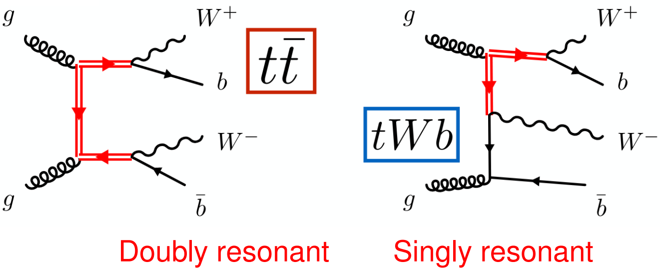
STUDY OF tW PRODUCTION

- Second-largest single top production mode at the LHC
- Observed at 8 TeV by CMS (PRL 112 (2014) 231802) and ATLAS (JHEP 01 (2016) 064)
- Entering the precision regime
- Provides sensitivity to the V_{tb} vertex
- Closely related to $t\bar{t}$ measurements
  - Interference between processes at NLO



tW-$t\bar{t}$ INTERFERENCE

- Overlapping diagrams between the two processes at NLO
- Different ad-hoc approaches to tackle interference
- Full NLO calculation exists in POWHEG (arXiv:1607.04538)

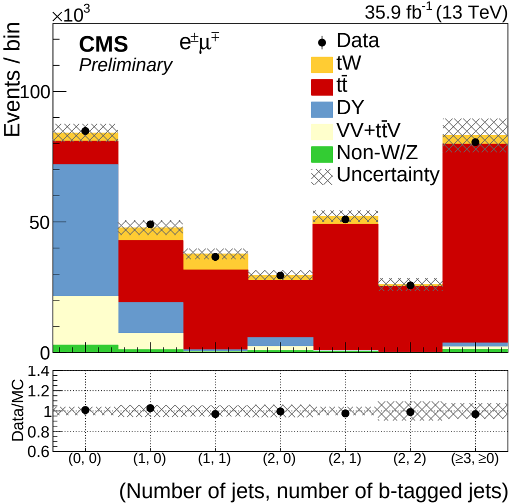


$$|\mathcal{A}_{WWbb}|^2 = |\mathcal{A}_{tt}|^2 + |\mathcal{A}_{tWb}|^2 + 2\mathrm{Re}\{\mathcal{A}_{tt}^{*}\mathcal{A}_{tWb}\}$$

- Interference not dominant in the bulk of $t\bar{t}$ and tW studies
- Significant source of uncertainty in BSM searches or boosted regimes

Event selection

- Selecting events with an $e^{\pm}\mu^{\mp}$ pair
- Jet and b-tagged jet multiplicity to discriminate signal and backgrounds
- Three regions of interest defined: 1j1b, 2j1b, 2j2b



Multivariate discriminators

- Make use of BDTs to discriminate signal from $t\bar{t}$ background
- Different features exploited in each ROI

1j1b region

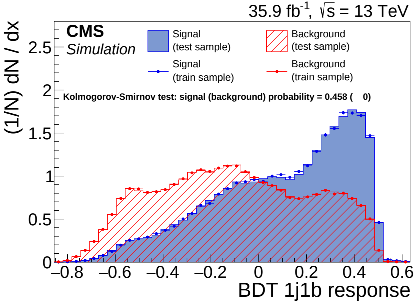
- Profit from one missing jet in $t\bar{t}$ events
- Number of low energy jets, total boost of the system, ...

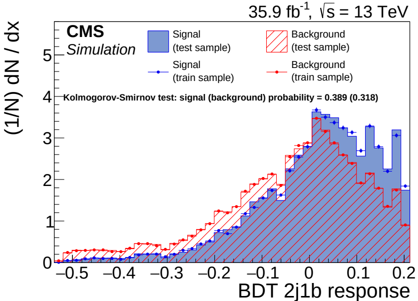
2j1b region

- Softer second jet in signal events
- Higher energy in the $t\bar{t}$ system

2j2b region

- Negligible contribution of signal, no BDT used
- Kinematic variable to constrain $t\bar{t}$





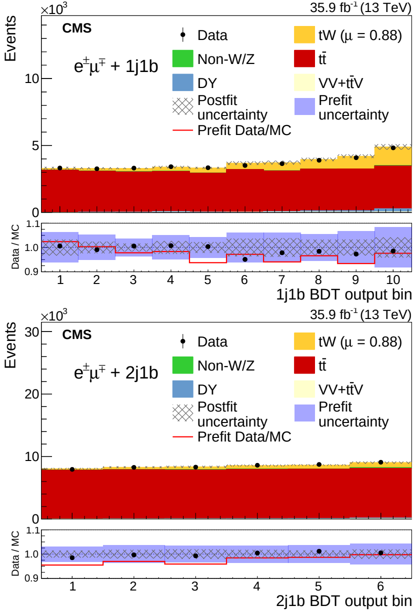
SIGNAL EXTRACTION

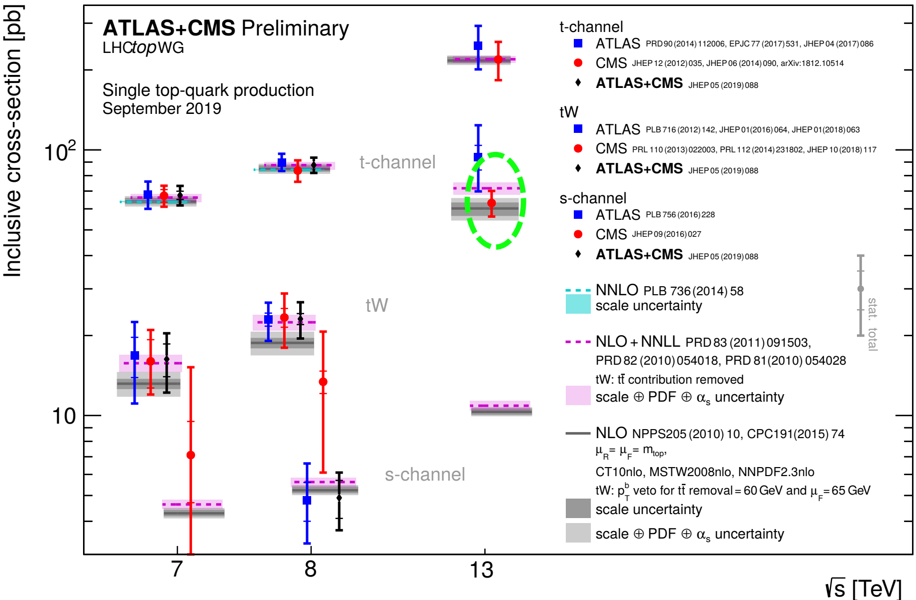
- Signal cross section determined by performing ML fit to distributions of BDT and sub-leading jet p_T
- Systematic uncertainties treated as nuisance parameters
- $\sigma_{tW} = 63.1 \pm 1.8\ (\mathrm{stat}) \pm 6.3\ (\mathrm{syst}) \pm 2.1\ (\mathrm{lumi})\ \mathrm{pb}$
- Consistent with aNNLO calculations:

  $\sigma_{tW}^{SM} = 71.7 \pm 1.8\ (\text{scale}) \pm 3.4\ (\text{PDF})\ \text{pb}$

  (arXiv:1506.04072)

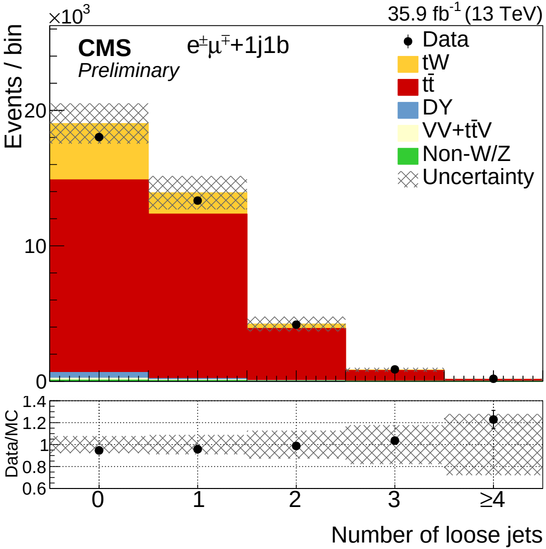
- Accuracy of 11%
  - Dominated by experimental uncertainties
  - Lumi (3.3%), pile-up (3.3%), ele. eff. (3.2%), ...
- Most precise measurement up to date




ATLAS+CMS Preliminary
LHCtopWG
Single top-quark production
September 2019
t-channel
tW
s-channel
Inclusive cross-section [pb]
10^2
10
7
8
13
$\sqrt{s}$ [TeV]
t-channel
ATLAS PRD 90 (2014) 112006, EPJC 77 (2017) 531, JHEP 04 (2017) 086
CMS JHEP 12 (2012) 035, JHEP 06 (2014) 090, arXiv:1812.10514
ATLAS+CMS JHEP 05 (2019) 088
tW
ATLAS PLB 716 (2012) 142, JHEP 01(2016) 064, JHEP 01(2018) 063
CMS PRL 110 (2013) 022003, PRL 112 (2014) 231802, JHEP 10 (2018) 117
ATLAS+CMS JHEP 05 (2019) 088
s-channel
ATLAS PLB 756 (2016) 228
CMS JHEP 09 (2016) 027
ATLAS+CMS JHEP 05 (2019) 088
NNLO PLB 736 (2014) 58
scale uncertainty
NLO + NNLL PRD 83 (2011) 091503,
PRD 82 (2010) 054018, PRD 81 (2010) 054028
tW: $t\bar{t}$ contribution removed
scale ⊕ PDF ⊕ α_s uncertainty
NLO NPPS205 (2010) 10, CPC191(2015) 74
$\mu_R = \mu_F = m_{top}$,
CT10nlo, MSTW2008nlo, NNPDF2.3nlo
tW: p_T^b veto for $t\bar{t}$ removal = 60 GeV and μ_F = 65 GeV
scale uncertainty
scale ⊕ PDF ⊕ α_s uncertainty
stat. total

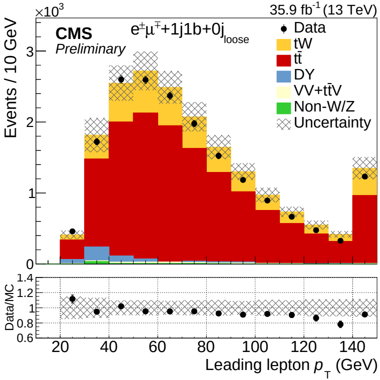
Differential measurement

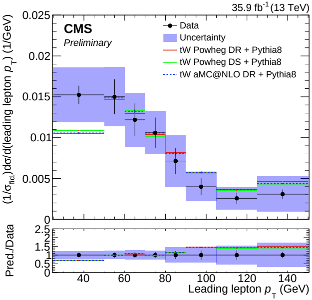
- Complementary strategy to the inclusive measurement approach
- Using events in the 1j1b region with no low energy jets
  - Defines the fiducial region
- Results extrapolated to particle level with matrix inversion

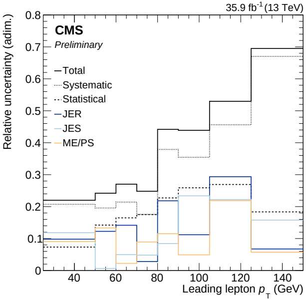


RESULTS OF DIFFERENTIAL MEASUREMENT

- 6 variables of interest studied
- Quantities measured at particle level
- 20-100% accuracy depending on the measured bin







- First CMS tW differential measurement
  - Using 2016 data
- Overall compatibility of data with the explored models

PROSPECTS FOR tW MEASUREMENTS

- Performed measurements set the first steps for precision studies of tW production

Almost four times luminosity collected at $\sqrt{s} = 13$ TeV

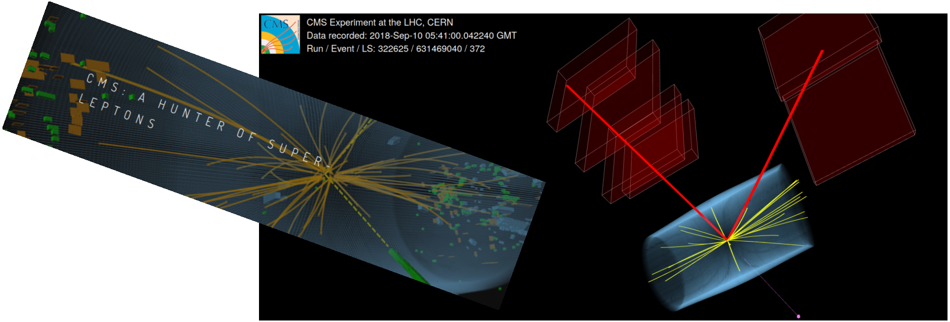
- Explore the possibility of increasing precision
- Measurement not statistics-limited, but
- Limited by experimental uncertainties: luminosity, leptons, ... $\Leftarrow$ can be improved

$t\bar{t}$-tW interference measurements

- Already explored by the ATLAS Collaboration (PRL 121, 152002 (2018))
- Perform differential measurements in phase spaces enriched in off-shell top quarks

Section 3

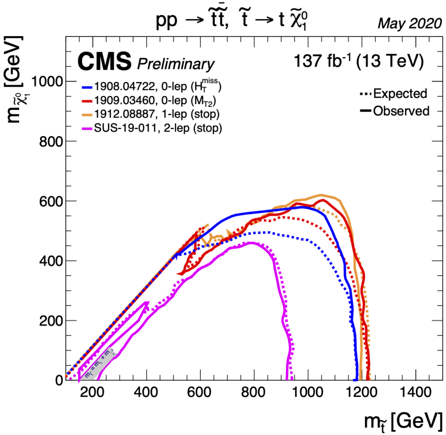
Search for SUSY in events with opposite-sign same-flavor leptons



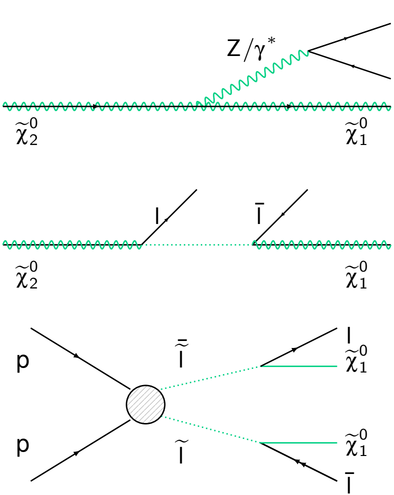
- OSSF lepton SUSY [2015]. JHEP 12 (2016) 013
- OSSF lepton SUSY [2016]. JHEP 03 (2018) 076
- EWK combination [2016]. JHEP 03 (2018) 160
- OSSF lepton SUSY [Run 2]. CMS-PAS-SUS-20-001

Introduction

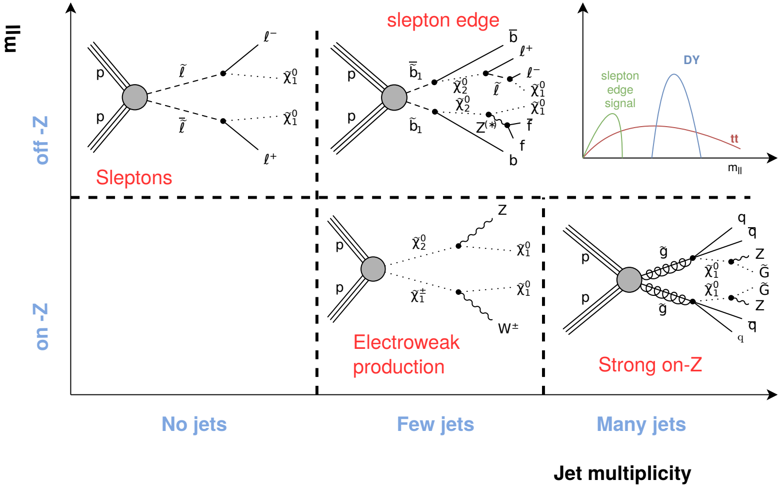
- Wide program of SUSY searches in the LHC experiments
- Motivated by natural SUSY
- Mainly driven by simplified scenarios that allow to
  - optimize searches in specific topologies
  - set upper limits on production and decay rate of SUSY particles
- Run 1 and early Run 2 searches do not show sign of new physics
- Full Run 2 analyses can set stringent limits on most SUSY models



Targeted topology



- Two opposite-charge same-flavor leptons
  - Z's in sparticles decay chains
  - Neutralino three-body-decay
  - Slepton pair production
- Significant $p_{\mathrm{T}}^{\mathrm{miss}}$
  - Predicted by R-parity conserving models



- Targeting different topologies, due to different initial states
- Dedicated signal regions developed for each one
- Common background estimation methods

BACKGROUND ESTIMATION

- Ad-hoc background estimation methods, developed during Run 1
  - Data-driven when possible

Flavor-symmetric backgrounds

- Dominated by $\mathrm{t\bar{t}}$, but contributions from WW
- Using different-flavor sideband to estimate contributions in the signal region
- Differences between electron and muon efficiencies are corrected

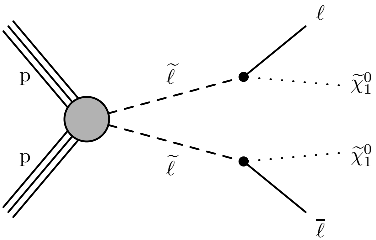
Instrumental $p_{\mathrm{T}}^{\mathrm{miss}}$

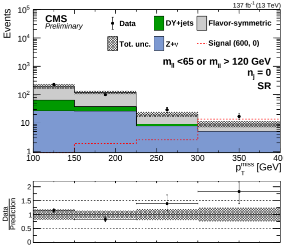
- Dominated by jet energy mismeasurements
- Distribution obtained in a γ+jets sample
- Slepton region $\Rightarrow$ DY+jets estimated from Z peak

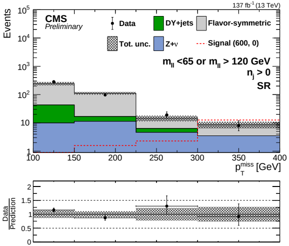
Z+ν processes

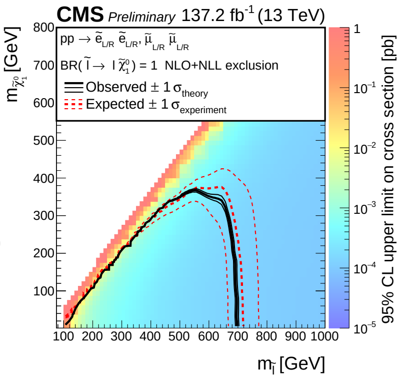
- Low cross-section but relevant in the tails
- Estimated with MC simulations, validated in control regions

Slepton search





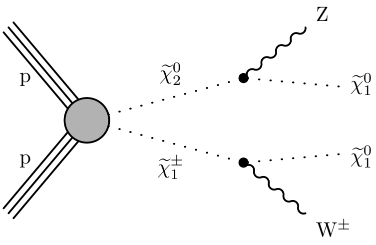


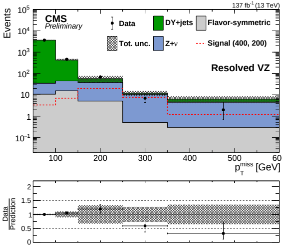


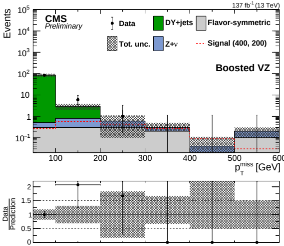
- Limited amount of hadronic activity
- Requirements on p_T^{miss} and $M_{T2}(ll)$
- Lepton pairs outside the Z peak
- Categories with:
  - No jets
  - With ISR jets

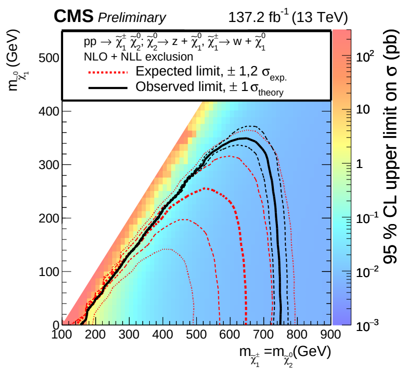
- Agreement with SM prediction
- Excluding slepton masses up to 700 GeV
- Exclusion reach extended by 200 GeV

Electroweak production





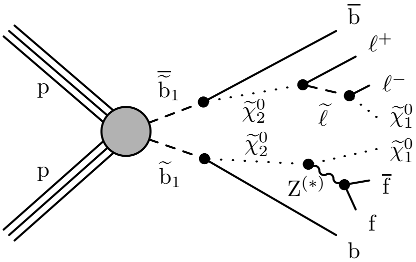




- Z boson in the final state
- Hadronic W decay
- Categories with:
  - Resolved W decay
  - Boosted W candidate

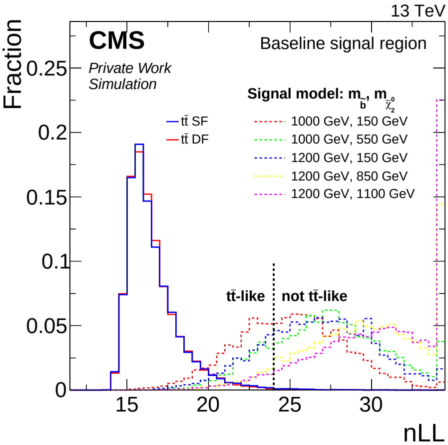
- Agreement with SM prediction
- Excluding chargino masses up to 750 GeV
- Exclusion reach extended by 100 GeV

Search for an edge



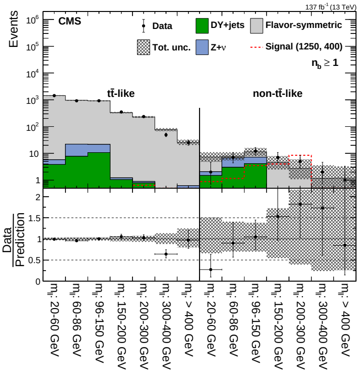
- Model motivated by edge-like "excess" observed in Run 1
- Features edge-like shape in the m_{ll} distribution

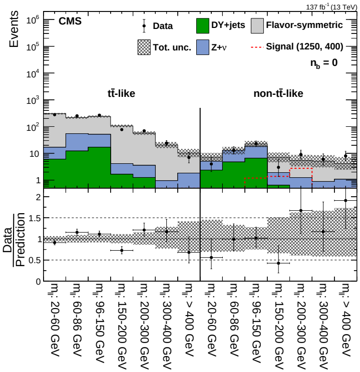
- Events with at least two jets and p_T^{miss} and $M_{T2}(ll)$
- Very significant contribution from $t\bar{t}$ events
- Naive Bayes classifier to select $t\bar{t}$-like and not $t\bar{t}$-like

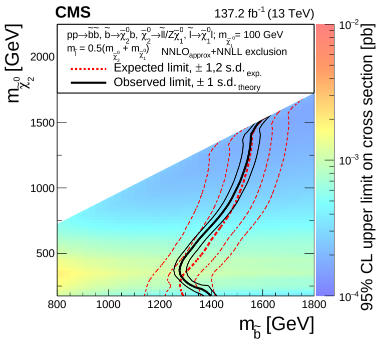


Search for an edge

- Regions with/without b-tagged jets and $t\bar{t}$/non-$t\bar{t}$ like
- Exploring the m_{ll} distribution for different edge positions



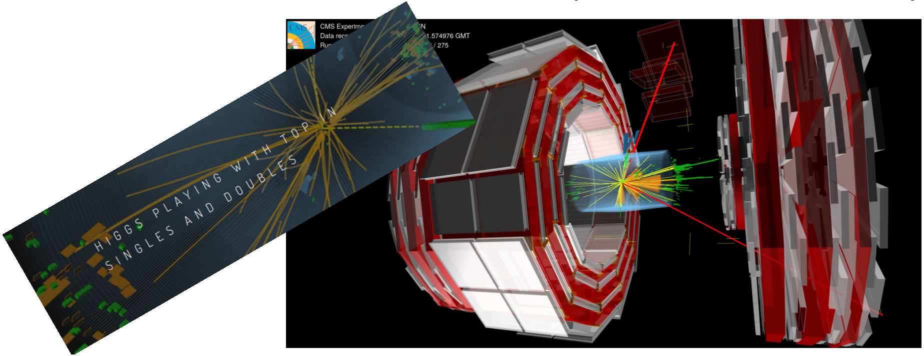




- Good agreement with SM processes
- Excluding sbottom masses up to 1.2-1.6 TeV
- Exclusion reach extended by 300 GeV

Section 4

Measurement of the $t\bar{t}H$ and tH production in the multilepton channel

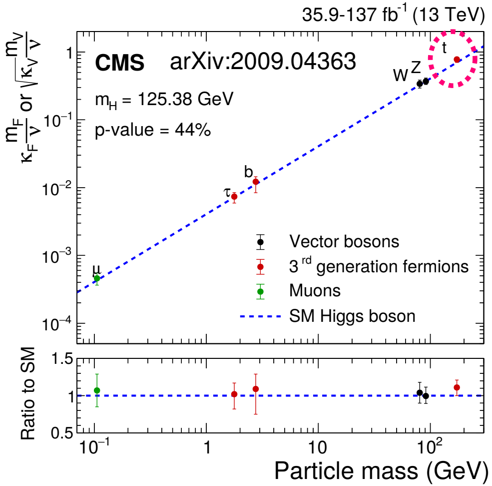


- $t\bar{t}H$ multilepton [2016]. JHEP 08 (2018) 066
- $t\bar{t}H$ combination [2016]. PRL 120, 231801 (2018) $\Leftarrow$ **Observation**
- $t\bar{t}H$ multilepton [2016+2017]. CMS-PAS-HIG-18-019
- $t\bar{t}H$ multilepton [Run 2]. CMS-PAS-HIG-19-008

Higgs physics

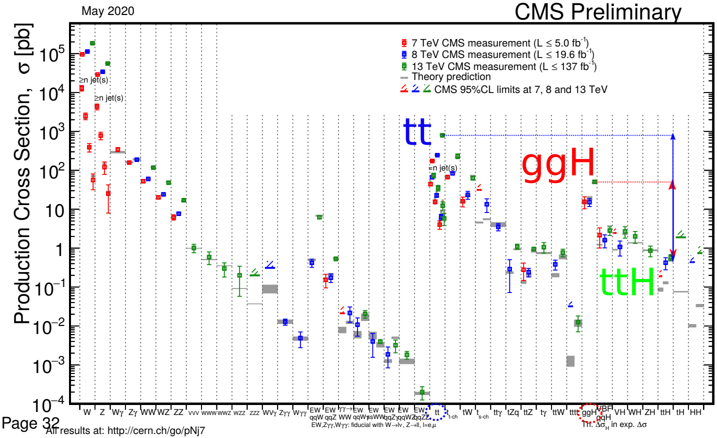
- Discovery of Higgs boson in 2012
- Study of its properties is ongoing
- Run 2 allowed to observe its interaction to all third generation particles

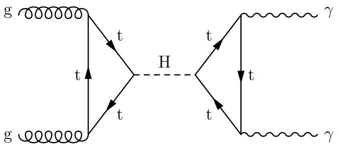
- Studying the Higgs Yukawa interaction with the top quark

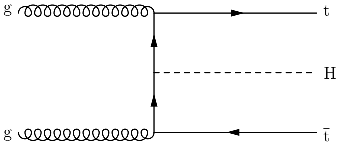


Top quark-Higgs boson interaction

- Gluon fusion Higgs production and $H \to \gamma\gamma$ decays sensitive to it - through loops
- $t\bar{t}H$ best process to study at tree level



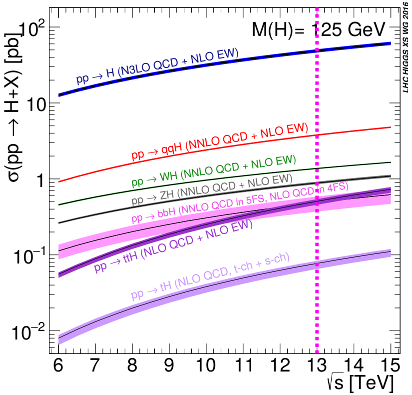


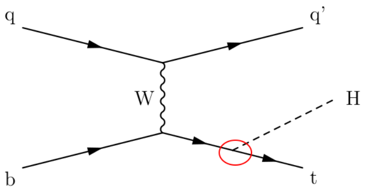


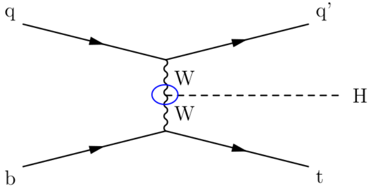
- Challenging process to study
- $\sigma_{t\bar{t}H} \simeq 0.5$ pb
- Sensitive to CP violation in the Yukawa sector
- Potentially sensitive to the trilinear Higgs coupling

tH PRODUCTION

- tH even more challenging
- $\sigma_{\mathrm{tH}} \simeq 70$ fb







- Three production modes: *t*-, *s*- and tW-channel
- y_{t} and g_{W}-proportional diagrams interfere destructively in the SM
- $\kappa_{\mathrm{t}}/\kappa_{\mathrm{W}} = -1$ enhances cross section by a factor of 10 (ITC)
- ITC does not affect the $\mathrm{t\bar{t}H}$ production rate

Decay modes

- Processes can be studied in different Higgs decays:

$H \to \gamma\gamma$

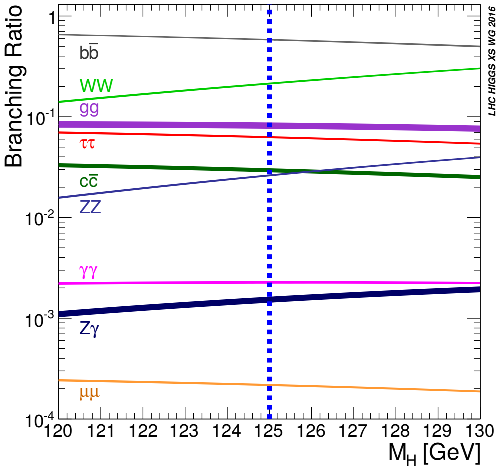
- Low branching ratio
- Clean final state
- Higgs system can be reconstructed

$H \to \bar{b}b$

- High branching ratio
- Large background contribution

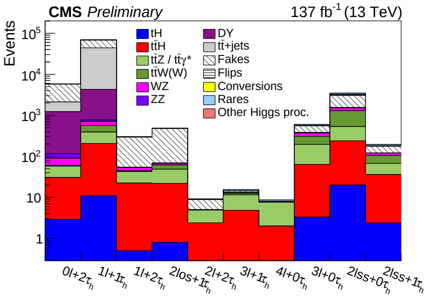
Multilepton: $H \to WW/ZZ/\tau\tau$

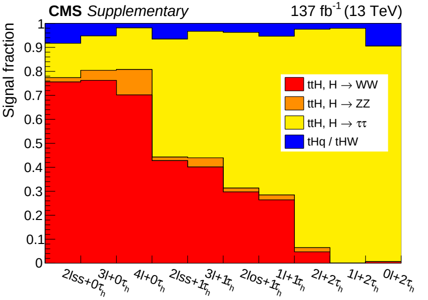
- Moderate branching ratio
- Moderate background contribution



SIGNAL REGIONS

- Events selected and classified in 10 disjoint signal regions
  - According to lepton (e or μ) and τ_h multiplicity
  - Lepton charge consistent with final state
  - Jet multiplicity consistent with final state
- $2lss + 0\tau_h$, $2lss + 1\tau_h$, $3l + 0\tau_h$ enlarged to accept tH events
  - Events with one b-tagged jet and one (forward) light jet are accepted
- Different background and signal composition in each region
- Regions mostly dominated by background





Multivariate classifiers

Usage of MVA classifiers:

- Obtain regions pure in signal
- Regions pure in background $\Rightarrow$ constrain them
- Necessary to separate the different signals

Input variables:

- Careful study of the input variables
- Optimized separately for each region

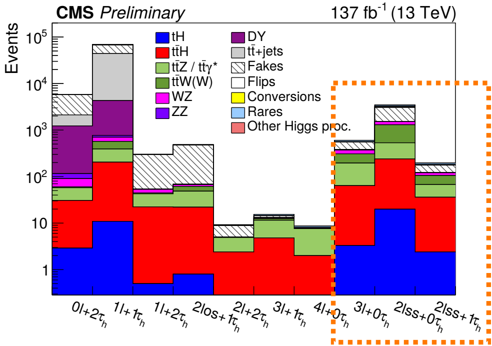
- 3-momenta of leptons, jets and τ_h's
- Invariant masses, angular distances, object multiplicities
- Taggers to identify top quark and Higgs decay products

MULTIVARIATE CLASSIFIERS

- Significant evolution during the different Run 2 analyses

$2lss + 0\tau_h$, $2lss + 1\tau_h$, $3l + 0\tau_h$ regions

- Multiclass DNNs to separate $t\bar{t}H$, tH and backgrounds
- Discriminate different backgrounds and different signals simultaneously
- Categories built on the DNN scores and event topology



Other regions

- No sensitivity expected for tH
- Not enough statistics for a multiclass approach
- Classifying according to a BDT score

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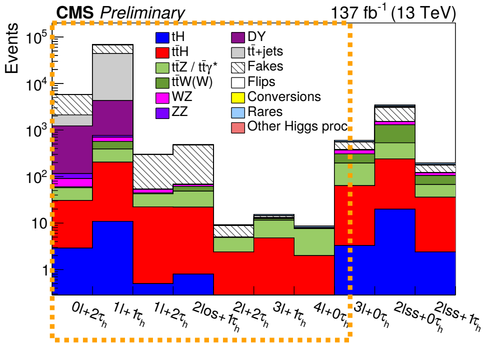

Other regions

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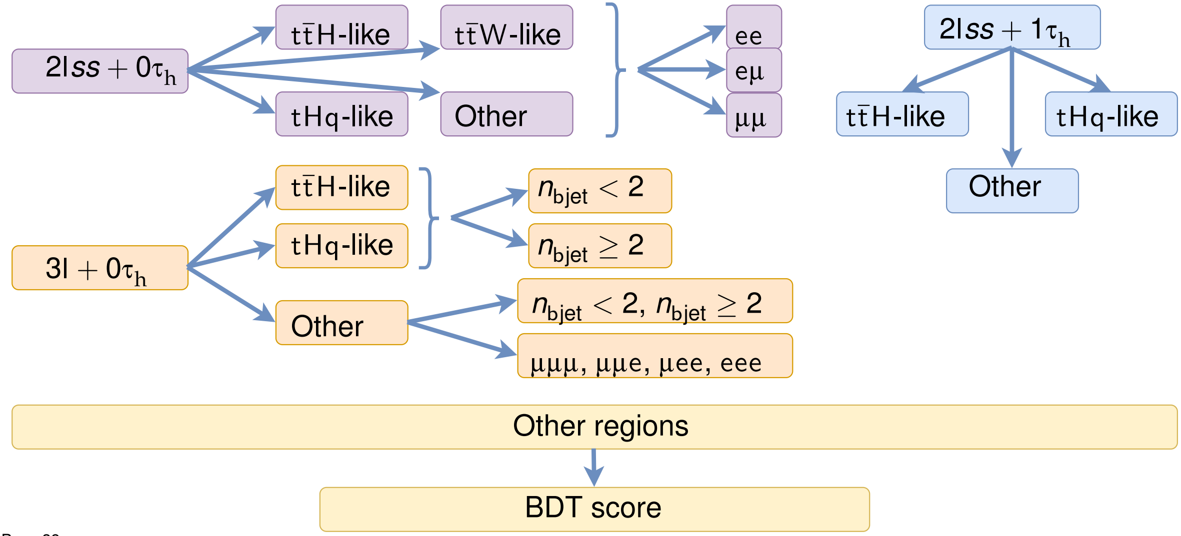
DNN SUBCLASSIFICATION



BACKGROUNDS

- Backgrounds dominate in all signal regions
- Their estimation is key

Reducible backgrounds due to

- Non-prompt leptons and misidentified τ_h
- Electron charge flips

} Estimated with data-driven methods

- Photon conversions

} Estimated with simulations

Irreducible backgrounds due to

- $t\bar{t}Z$, $t\bar{t}W$
- Less importantly, WZ, ZZ, rares (tZq, $t\bar{t}t\bar{t}$, ...)
- $t\bar{t}$ and DY events are also irreducible in the $1l + 1\tau_h$ and $0l + 2\tau_h$ categories
- Estimated using state-of-the-art MC simulations and normalized to the more precise theory calculations

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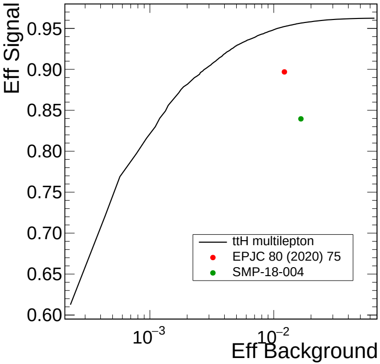
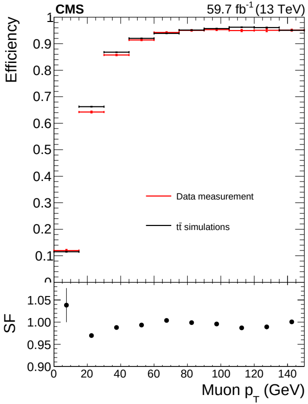
NON-PROMPT LEPTONS

- Largely suppressed with the usage of MVA techniques
- BDT trained to discriminate prompt and non-prompt leptons





Input variables

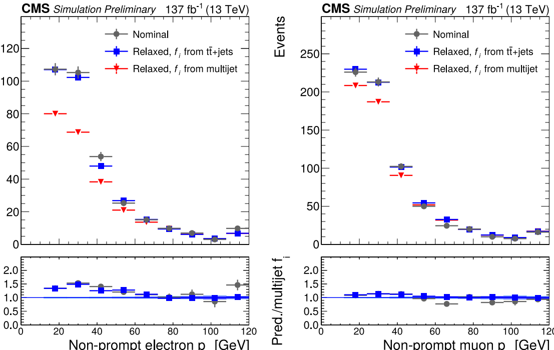
- Selection of low level input variables
- IP, deep jet, isolation variables

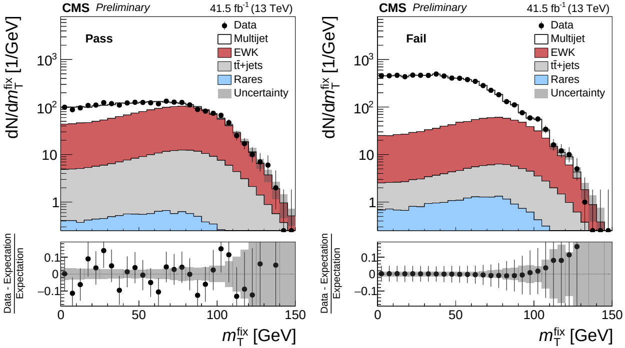
Lepton characterization

- Important to precisely calibrate selected leptons
- Efficiency measured in $Z \to l^{\pm}l^{\mp}$ events
- Extrapolation uncertainty evaluated in $\mathtt{t}\bar{\mathtt{t}}$ events

Fake rate-measurement

- Fake rate is measured in multijet events
- Fit is performed to m_T^{fix} variable to extract fake rate
- Parameterized as a function of cone-p_T



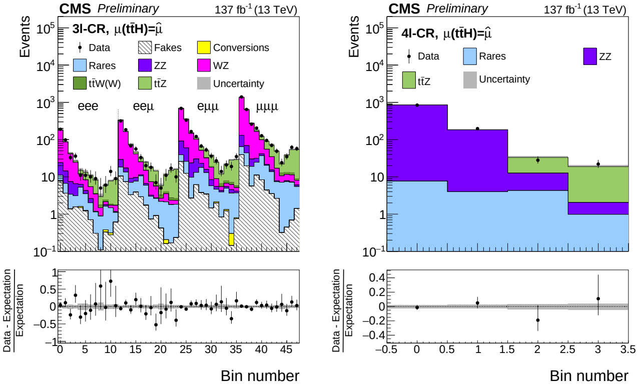


- FR may vary between multijet and $t\bar{t}$ events
- Difference checked on $t\bar{t}$ simulations
- Very good closure for muons, acceptable for electrons

IRREDUCIBLE BACKGROUNDS

Normalization

- $t\bar{t}Z$ and $t\bar{t}W$ normalization are determined in the signal extraction fit
  - No assumption made on the total cross section
- Dedicated control region for $t\bar{t}Z$
  - 3l with a Z boson candidate
  - 4l with a Z boson candidate
- Dedicated $t\bar{t}W$ category in the $2lss + 0\tau_h$, built with the DNN score



Acceptance and shapes

- $t\bar{t}Z$ and $t\bar{t}H$ simulated at NLO QCD accuracy
- tH simulated at LO

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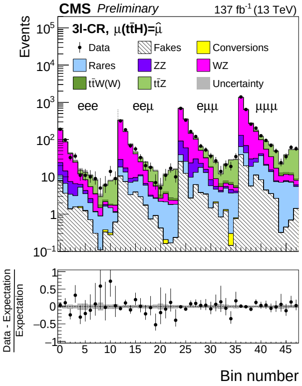

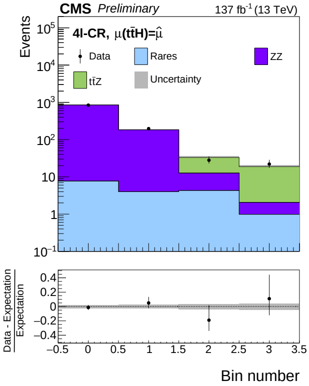

Acceptance and shapes

- $t\bar{t}Z$ and $t\bar{t}H$ simulated at NLO QCD accuracy
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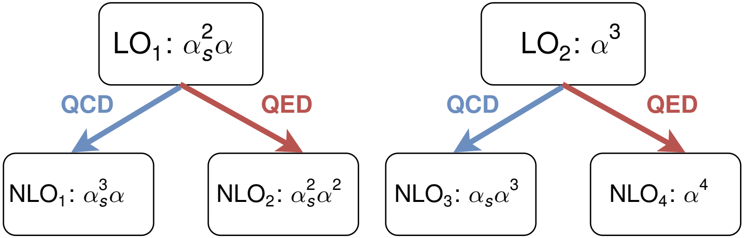
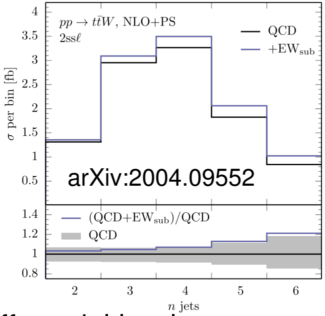
$t\bar{t}W$ MODELING

- Modeling of $t\bar{t}W$ is challenging
- Process usually observed consistently higher than SM expectation
  - ATLAS-CONF-2019-045, JHEP 08 (2018) 011

- Subleading electroweak corrections found to be significant
- $t\bar{t}W$ simulated at NLO QCD, including α^3 and $\alpha^3\alpha_s$ corrections

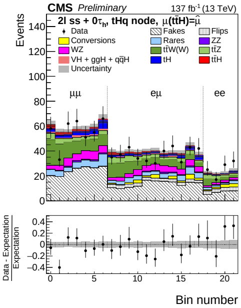


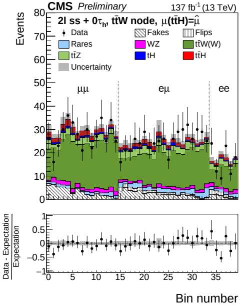


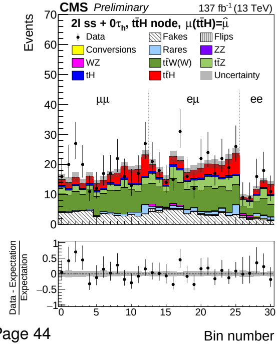
- First LHC analysis to implement these corrections at differential level

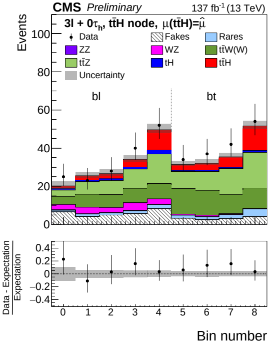
RESULTS

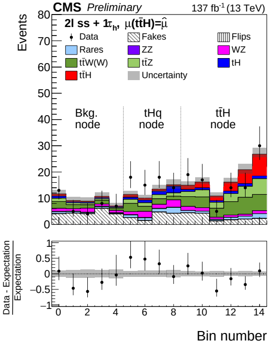
- Observed events in some signal categories
- Good agreement of data with the model
- Clear presence of $t\bar{t}H$ signal in the regions
- Very pure selection of $t\bar{t}W$ background











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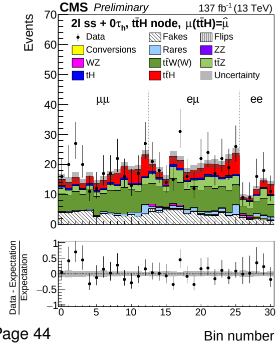

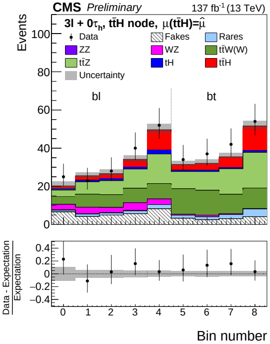

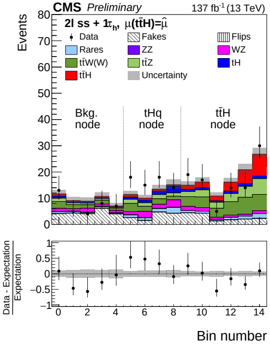

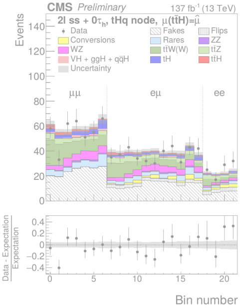

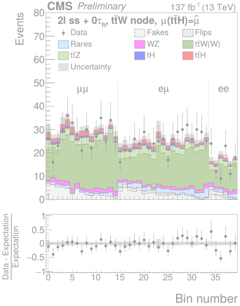

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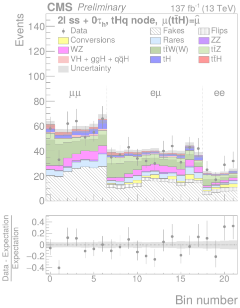
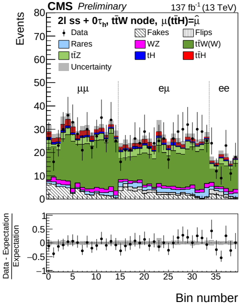
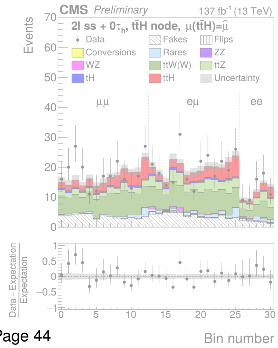
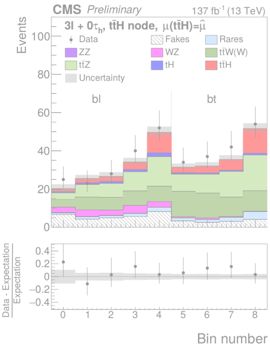
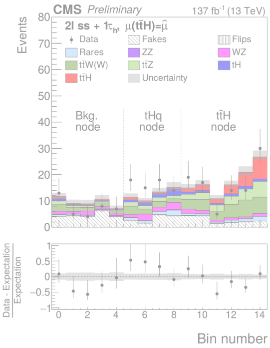


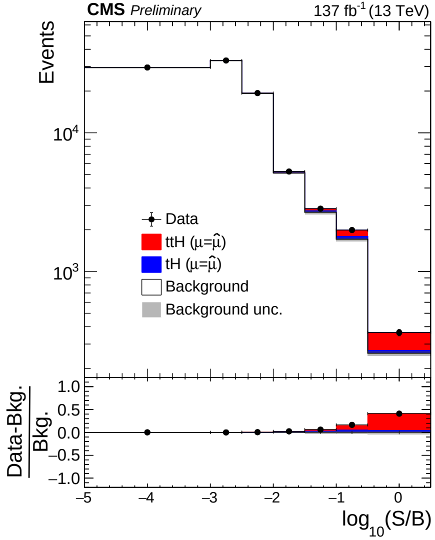






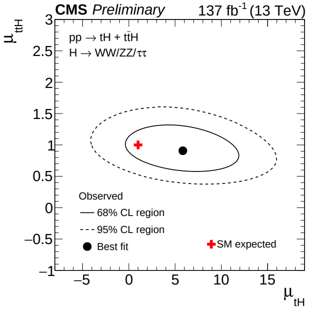


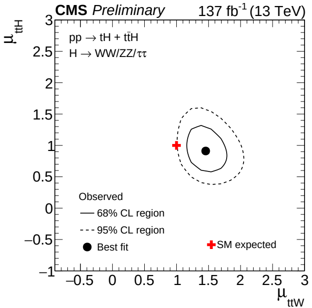
RESULTS



- ► Data is fitted in all categories

Process	Signal strength
$t\bar{t}H$	$0.92^{+0.26}_{-0.23}$
tH	$5.7^{+4.1}_{-4.0}$
$t\bar{t}Z$	1.03 ± 0.14
$t\bar{t}W$	1.43 ± 0.21





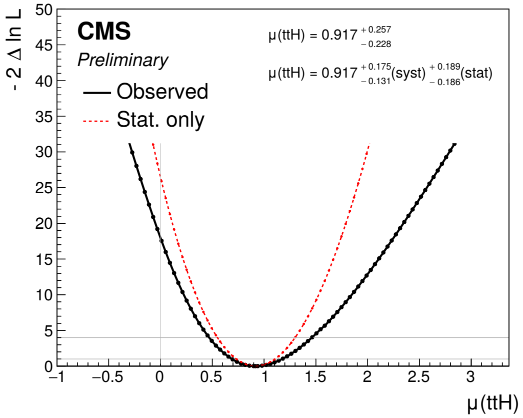
RESULTS

Expected significances

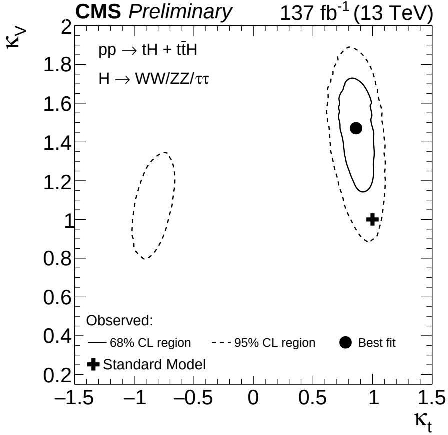
- Sensitivity to $t\bar{t}H$ production $\Rightarrow$ 5.2 σ
- Sensitivity to tH production $\Rightarrow$ 0.3 σ

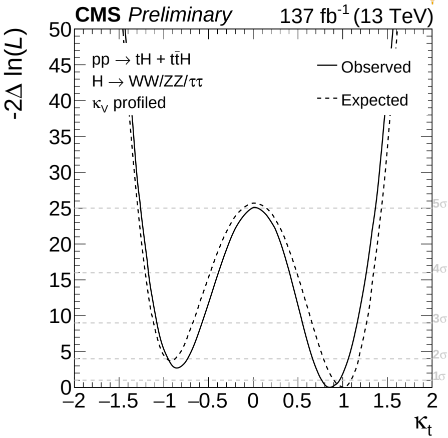
Observed significances

- Observed significance for $t\bar{t}H$ production: 4.7 σ
- Observed significance for tH production: 1.4 σ



INTERPRETATION





- Interpretation of yields in terms of κ_t and κ_V
- Best fit consistent with the SM expectation
- κ_t constrained to be within $-0.9 < \kappa_t < -0.7$ or $0.7 < \kappa_t < 1.1$ at 95% C.L.

PROSPECTS FOR $t\bar{t}H$ MEASUREMENTS

Precision measurements of the top Yukawa interaction

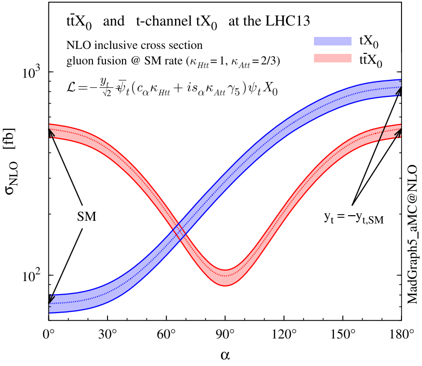
- Combination with other decay modes
- Dedicated $t\bar{t}W$ studies and measurements
- Increased precision with higher luminosity

CP violation in top Yukawa sector

- Still allowed by experimental data (EPJ C 75 (2015) 6, 267)

$$\mathcal{L} = \bar{\psi}_t \left(\cos(\alpha)\kappa_{Htt} + i\sin(\alpha)\kappa_{Att}\gamma^5 \right) \frac{y_t}{\sqrt{2}} \psi_t \phi$$

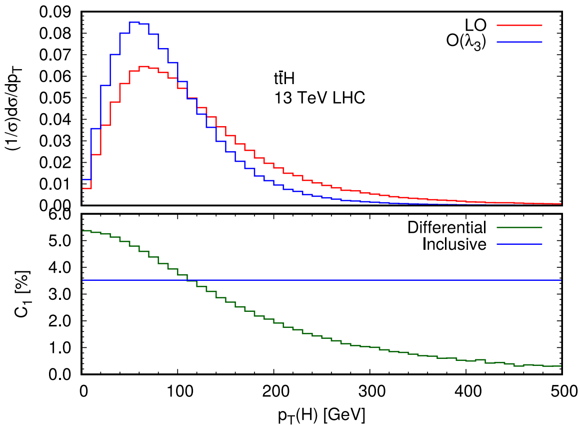
- Highly disfavored by $t\bar{t}H(\to \gamma\gamma)$, sensitivity can be gained with multilepton channel



PROSPECTS FOR $t\bar{t}H$ MEASUREMENTS

Differential measurements, EFT interpretations

- Differential $t\bar{t}H$ measurements could bring sensitivity to λ_3 (EPJ C 77 (2017) 12, 887)‘
- Measurements in tails of distributions can be interpreted in terms of constrains on EFTs (JHEP 10 (2016) 123)



Section 5

Conclusions

Conclusions

- Study of pp collisions at $\sqrt{s} = 13$ TeV during the Run 2 of the LHC collected with CMS
- Focusing in processes with high p_{T} leptons in the final state
  - Allows to explore a wide range of physics observables
  - Characteristic experimental signature
- Strong contributions to the trigger and lepton reconstruction
- Developments made increase the precision of the physics analyses performed in this thesis

Conclusions

- Precision measurements of tW production are crucial for $\mathrm{t\bar{t}}$ production measurements
  - Together with $\mathrm{t\bar{t}}$ production, relevant for BSM searches
- Inclusive cross section measured to be compatible with state-of-the-art calculations

$$\sigma_{\mathrm{tW}} = 63.1 \pm 1.8\,(\mathrm{stat}) \pm 6.3\,(\mathrm{syst}) \pm 2.1\,(\mathrm{lumi})\ \mathrm{pb}$$

- Differential cross section measured as a function of variables of interest
  - Consistent with the reference generators used in CMS

CONCLUSIONS

- Searched for SUSY in events with an opposite-sign same-flavor lepton pair
  - Using the complete Run 2 dataset
- Signal regions built targeting different production modes
- Developed data-driven background estimation methods suitable for the search
- Results observed are consistent with the SM expectations
- Upper limits on sparticle production cross section are set

- Exclusion limits are extended by hundreds of GeV with respect to previous searches
- Results of the search will be combined with other electroweak SUSY searches

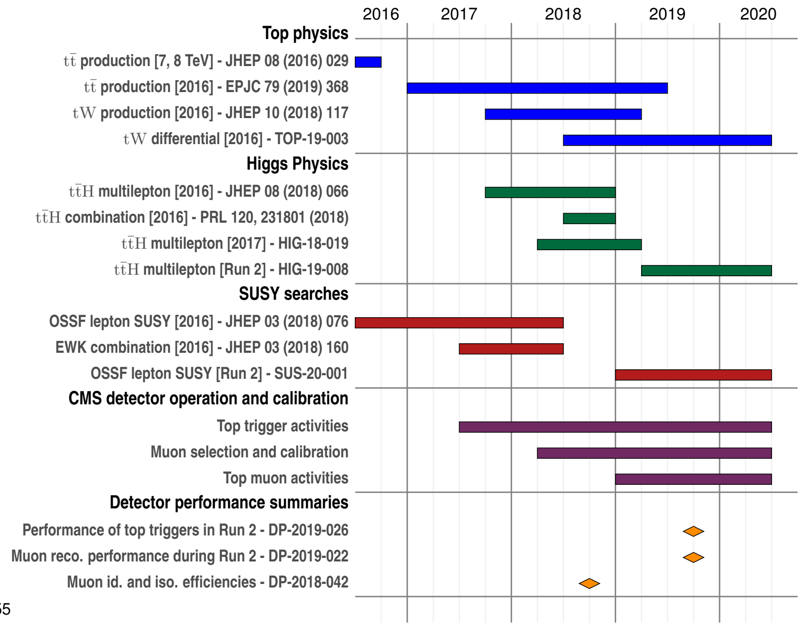
Conclusions

- $\mathrm{t\bar{t}H}$ and tH production rates have been measured in the multilepton channel
  - Using the complete Run 2 dataset
- Signal strengths are compatible with the SM expectation

$$\mu_{\mathrm{t\bar{t}H}} = 0.92 \pm 0.19\ \text{(stat.)}^{+0.17}_{-0.13}\ \text{(syst.+lumi.)}$$

$$\mu_{\mathrm{tH}} = 5.7 \pm 2.7\ \text{(stat.)} \pm 3.0\ \text{(syst.+lumi.)}$$

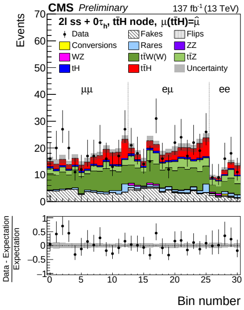
- Observed (expected) significance of 4.7 (5.2) σ for $\mathrm{t\bar{t}H}$ production
- Results constrain the top-Higgs coupling modifier to be within $-0.9 < \kappa_{\mathrm{t}} < -0.7$ or $0.7 < \kappa_{\mathrm{t}} < 1.1$

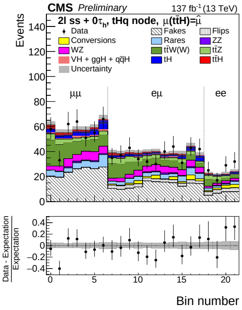

2016
2017
2018
2019
2020
Top physics
$t\bar{t}$ production [7, 8 TeV] - JHEP 08 (2016) 029
$t\bar{t}$ production [2016] - EPJC 79 (2019) 368
tW production [2016] - JHEP 10 (2018) 117
tW differential [2016] - TOP-19-003
Higgs Physics
$t\bar{t}H$ multilepton [2016] - JHEP 08 (2018) 066
$t\bar{t}H$ combination [2016] - PRL 120, 231801 (2018)
$t\bar{t}H$ multilepton [2017] - HIG-18-019
$t\bar{t}H$ multilepton [Run 2] - HIG-19-008
SUSY searches
OSSF lepton SUSY [2016] - JHEP 03 (2018) 076
EWK combination [2016] - JHEP 03 (2018) 160
OSSF lepton SUSY [Run 2] - SUS-20-001
CMS detector operation and calibration
Top trigger activities
Muon selection and calibration
Top muon activities
Detector performance summaries
Performance of top triggers in Run 2 - DP-2019-026
Muon reco. performance during Run 2 - DP-2019-022
Muon id. and iso. efficiencies - DP-2018-042

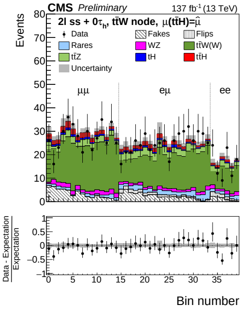
Back-up

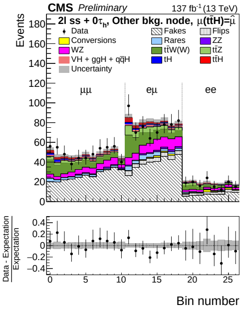
Results

$2lss + 0\tau_h$



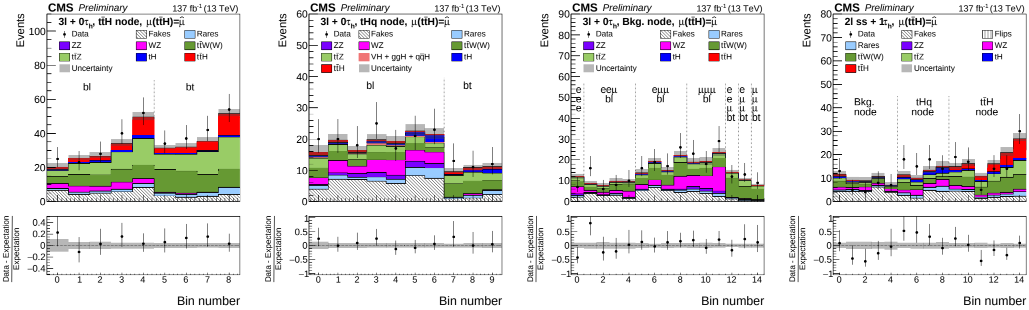




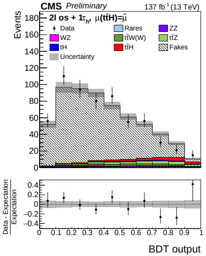


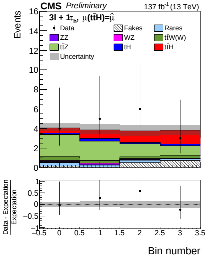
Results

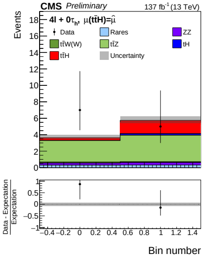
$3l + 0\tau_h$ and $2lss + 1\tau_h$

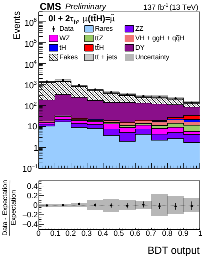


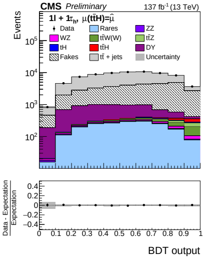
RESULTS

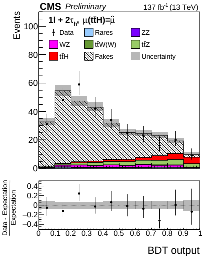

CMS Preliminary
137 fb-1 (13 TeV)
2l os + 1τh, μ(tt̄H)=μ̂
Data
Rares
ZZ
WZ
tt̄W(W)
tt̄Z
tH
tt̄H
Fakes
Uncertainty
Events
Data - Expectation / Expectation
BDT output

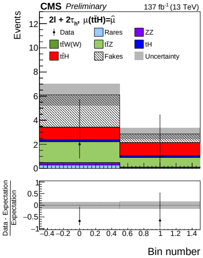

CMS Preliminary
137 fb-1 (13 TeV)
3l + 1τh, μ(tt̄H)=μ̂
Data
Fakes
Rares
ZZ
WZ
tt̄W(W)
tt̄Z
tH
tt̄H
Uncertainty
Events
Data - Expectation / Expectation
Bin number


CMS Preliminary
137 fb-1 (13 TeV)
4l + 0τh, μ(tt̄H)=μ̂
Data
Rares
ZZ
tt̄W(W)
tt̄Z
tH
tt̄H
Uncertainty
Events
Data - Expectation / Expectation
Bin number


CMS Preliminary
137 fb-1 (13 TeV)
0l + 2τh, μ(tt̄H)=μ̂
Data
Rares
ZZ
WZ
tt̄Z
VH + ggH + qq̄H
tH
tt̄H
DY
Fakes
tt̄ + jets
Uncertainty
Events
Data - Expectation / Expectation
BDT output


CMS Preliminary
137 fb-1 (13 TeV)
1l + 1τh, μ(tt̄H)=μ̂
Data
Rares
ZZ
WZ
tt̄W(W)
tt̄Z
tH
tt̄H
DY
Fakes
tt̄ + jets
Uncertainty
Events
Data - Expectation / Expectation
BDT output


CMS Preliminary
137 fb-1 (13 TeV)
1l + 2τh, μ(tt̄H)=μ̂
Data
Rares
ZZ
WZ
tt̄W(W)
tt̄Z
tt̄H
Fakes
Uncertainty
Events
Data - Expectation / Expectation
BDT output


CMS Preliminary
137 fb-1 (13 TeV)
2l + 2τh, μ(tt̄H)=μ̂
Data
Rares
ZZ
tt̄W(W)
tt̄Z
tH
tt̄H
Fakes
Uncertainty
Events
Data - Expectation / Expectation
Bin number

Irreducible backgrounds

- Signals, $t\bar{t}Z$ and $t\bar{t}W$ normalization are freely floating
  - No assumption on total cross section
- Modeling of irreducible processes follows the most accurate calculations available

$t\bar{t}H$ and $t\bar{t}Z$ production

- Generated at NLO QCD with MadGraph5_aMC@NLO
- Normalized NLO QCD+EWK (**arXiv:1610.07922**)

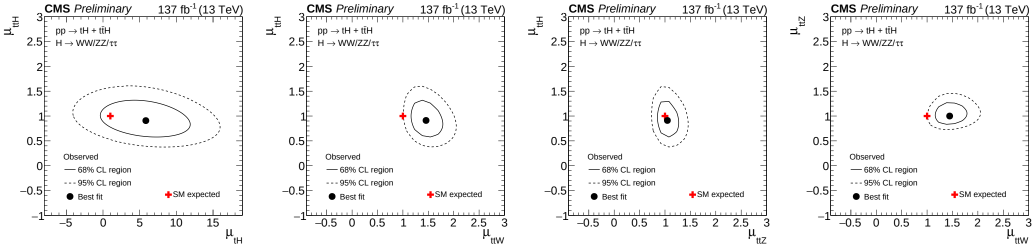
tHq and tHW

- Generated at LO with MadGraph5_aMC@NLO
- Normalized at NLO QCD (**arXiv:1610.07922**)

$t\bar{t}W$ production

- Generated at NLO QCD with MadGraph5_aMC@NLO
  - Normalized to NLO QCD + EWK (**arXiv:1610.07922**)
- α^3 and $\alpha_s\alpha^3$ corrections are added on top (**arXiv:2004.09552**)

2D LIKELIHOOD SCANS



Systematic uncertainties

Source	$\Delta\mu_{ttH}/\mu_{ttH}$ [%]	$\Delta\mu_{tH}/\mu_{tH}$ [%]	$\Delta\mu_{ttW}/\mu_{ttW}$ [%]	$\Delta\mu_{ttZ}/\mu_{ttZ}$ [%]
Trigger efficiency	2.3	8.1	1.2	1.9
e, μ reconstruction and identification efficiency	2.9	7.1	1.7	3.2
τ_h identification efficiency	4.6	9.1	1.7	1.3
b tagging efficiency and mistag rate	3.6	13.6	1.3	2.9
Misidentified leptons and flips	6.0	36.8	2.6	1.4
Jet energy scale and resolution	3.4	8.3	1.1	1.2
MC and sideband statistical uncertainty	7.1	27.2	2.4	2.3
Theory-related sources	4.6	18.2	2.0	4.2
Normalization of MC-estimation processes	13.3	12.3	13.9	11.3
Luminosity	2.2	4.6	1.8	3.1
Statistical uncertainty	20.9	48.0	5.9	5.8

Selection step	$2\ell ss + 0\tau_h$	$2\ell ss + 1\tau_h$
Targeted $t\bar{t}H$ decay	$t \to b\ell\nu$, $t \to bqq'$ with $H \to WW \to \ell\nu qq'$	$t \to b\ell\nu$, $t \to bqq'$ with $H \to \tau\tau \to \ell\nu\nu\tau_h\nu$
Targeted tH decays	$t \to b\ell\nu$, $H \to WW \to \ell\nu qq$	$t \to b\ell\nu$, $H \to \tau\tau \to \ell\tau_h + \nu$'s
Trigger	Single- and double-lepton triggers	
Lepton p_T	$p_T > 25$ / 15 GeV	$p_T > 25$ / 15 GeV (e) or 10 GeV (μ)
Lepton η	$\lvert\eta\rvert < 2.5$ (e) or 2.4 (μ)	
τ_h p_T	—	$p_T > 20$ GeV
τ_h η	—	$\lvert\eta\rvert < 2.3$
τ_h identification	—	very-loose
Charge requirements	2 same-sign leptons and charge quality requirements	2 same-sign leptons and charge quality requirements $\sum_{\ell,\tau_h} q = \pm 1$
Multiplicity of central jets	$\geq$3 jets	$\geq$3 jets
b tagging requirements	$\geq$1 tight b-tagged jet or $\geq$2 loose b-tagged jets	
Missing transverse momentum	$L_D > 30$ GeV†	
Dilepton invariant mass	$\lvert m_{\ell\ell} - m_Z\rvert > 10$ GeV‡ and $m_{\ell\ell} > 12$ GeV	

Selection step	$3\ell + 0\tau_h$	$3\ell + 1\tau_h$
Targeted $t\bar{t}H$ decays	$t \to b\ell\nu, t \to b\ell\nu$ with $H \to WW \to \ell\nu qq'$ $t \to b\ell\nu, t \to bqq'$ with $H \to WW \to \ell\nu\ell\nu$ $t \to b\ell\nu, t \to bqq'$ with $H \to ZZ \to \ell\ell qq'$ or $\ell\ell\nu\nu$	$t \to b\ell\nu, t \to b\ell\nu$ with $H \to \tau\tau \to \ell\nu\nu\tau_h\nu$
Targeted tH decays	$t \to b\ell\nu, H \to WW \to \ell\nu\ell\nu$	—
Trigger	Single-, double- and triple-lepton triggers	
Lepton p_T	$p_T > 25$ / 15 / 10 GeV	
Lepton η	$\|\eta\| < 2.5$ (e) or 2.4 (μ)	
τ_h p_T	—	$p_T > 20$ GeV
τ_h η	—	$\|\eta\| < 2.3$
τ_h identification	—	very-loose
Charge requirements	$\sum_\ell q = \pm 1$	$\sum_{\ell,\tau_h} q = 0$
Multiplicity of central jets	$\geq$2 jets	
b tagging requirements	$\geq$1 tight b-tagged jet or $\geq$2 loose b-tagged jets	
Missing transverse momentum	$L_D > 0$ / 30 / 45 GeV‡	
Dilepton invariant mass	$m_{\ell\ell} > 12$ GeV and $\|m_{\ell\ell} - m_Z\| > 10$ GeV§	
Four-lepton invariant mass	$m_{4\ell} > 140$ GeV¶	—

Selection step	$0\ell + 2\tau_\mathrm{h}$	$1\ell + 1\tau_\mathrm{h}$
Targeted $\mathrm{t\bar{t}H}$ decays	$\mathrm{t} \to \mathrm{bqq'}$, $\mathrm{t} \to \mathrm{bqq'}$ with $\mathrm{H} \to \tau\tau \to \tau_\mathrm{h}\nu\tau_\mathrm{h}\nu$	$\mathrm{t} \to \mathrm{bqq'}$, $\mathrm{t} \to \mathrm{bqq'}$ with $\mathrm{H} \to \tau\tau \to \ell\nu\nu\tau_\mathrm{h}\nu$
Trigger	Double-τ_h trigger	Single-lepton and lepton+τ_h triggers
Lepton p_T	—	$p_\mathrm{T} > 30$ (e) or 25 GeV (μ)
Lepton η	—	$\|\eta\| < 2.1$
τ_h p_T	$p_\mathrm{T} > 40$ GeV	$p_\mathrm{T} > 30$ GeV
τ_h η	$\|\eta\| < 2.1$	
τ_h identification	loose	medium
Charge requirements	$\sum_{\tau_\mathrm{h}} q = 0$	$\sum_{\ell,\tau_\mathrm{h}} q = 0$
Multiplicity of central jets	$\geq$4 jets	
b tagging requirements	$\geq$1 tight b-tagged jet or $\geq$2 loose b-tagged jets	
Dilepton invariant mass	$m_{\ell\ell} > 12$ GeV	

Selection step	$1\ell + 2\tau_h$	$2\ell + 2\tau_h$
Targeted $t\bar{t}H$ decays	$t \to b\ell\nu$, $t \to bqq'$ with $H \to \tau^+\tau^- \to \tau_h\nu\tau_h\nu$	$t \to b\ell\nu$, $t \to b\ell\nu$ with $H \to \tau^+\tau^- \to \tau_h\nu\tau_h\nu$
Trigger	Single-lepton and lepton+τ_h triggers	Single- and double-lepton triggers
Lepton p_T	$p_T > 30$ (e) or $25\,GeV$ (μ)	$p_T > 25$ / 10 (15) GeV (e)
Lepton η	$\|\eta\| < 2.1$	$\|\eta\| < 2.5$ (e) or 2.4 (μ)
τ_h p_T	$p_T > 30$ / $20\,GeV$	$p_T > 20\,GeV$
τ_h η	$\|\eta\| < 2.1$	$\|\eta\| < 2.3$
τ_h identification	medium	medium
Charge requirements	$\sum_{\ell,\tau_h} q = \pm 1$	$\sum_{\ell,\tau_h} q = 0$
Multiplicity of central jets	$\geq$3 jets	$\geq$2 jets
b tagging requirements	$\geq$1 tight b-tagged jet or $\geq$2 loose b-tagged jets	
Missing transverse momentum	—	$L_D > 0$ / 30 / $45\,GeV^{\dagger}$
Dilepton invariant mass	$m_{\ell\ell} > 12\,GeV$	

Selection step	$2\ell\text{os} + 1\tau_h$	$4\ell + 0\tau_h$
Targeted $t\bar{t}H$ decays	$t \to b\ell\nu$, $t \to bqq'$ with $H \to \tau^+\tau^- \to \ell\nu\nu\tau_h\nu$	$t \to b\ell\nu$, $t \to b\ell\nu$ with $H \to WW \to \ell\nu\ell\nu$ $t \to b\ell\nu$, $t \to b\ell\nu$ with $H \to ZZ \to \ell\ell qq'$ or $\ell\ell\nu\nu$
Trigger	Single- and double-lepton triggers	Single-, double- and triple-lepton triggers
Lepton p_T	$p_T > 25 / 15$ GeV (e) or 10 GeV (μ)	$p_T > 25 / 15 / 15 / 10$ GeV
Lepton η	$\lvert\eta\rvert < 2.5$ (e) or 2.4 (μ)	
τ_h p_T	$p_T > 20$ GeV	—
τ_h η	$\lvert\eta\rvert < 2.3$	—
τ_h identification	tight	—
Charge requirements	$\sum_\ell q = 0$ and $\sum_{\ell,\tau_h} q = \pm 1$	$\sum_\ell q = 0$
Multiplicity of central jets	$\geq$3 jets	$\geq$2 jets
b tagging requirements	$\geq$1 tight b-tagged jet or $\geq$2 loose b-tagged jets	
Missing transverse momentum	$L_D > 30$ GeV†	$L_D > 0 / 30 / 45$ GeV‡
Dilepton invariant mass	$m_{\ell\ell} > 12$ GeV	$\lvert m_{\ell\ell} - m_Z\rvert > 10$ GeV§ and $m_{\ell\ell} > 12$ GeV
Four-lepton invariant mass	—	$m_{4\ell} > 140$ GeV¶