Karlsruhe Institute of Technology

Gefördert durch
Deutsche Forschungsgemeinschaft

Latest results from $t\bar{t}H$ and tH in $H \to b\bar{b}$ at CMS

12th Annual Meeting of the Helmholtz Alliance "Physics at the Terascale"

Michael Waßmer on behalf of the CMS collaboration | November 27, 2018

INSTITUTE OF EXPERIMENTAL PARTICLE PHYSICS (ETP)

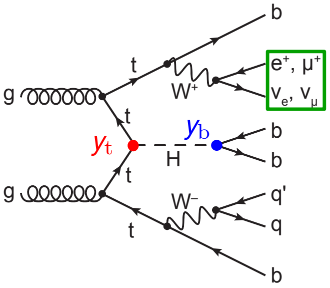
$t\bar{t}$H and tH

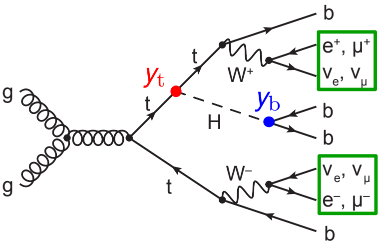
- SM: Yukawa-type coupling of Higgs boson to fermions ($y_f \propto m_f / v$)
  - $\rightarrow$ proportional to fermion mass
  - $\rightarrow$ expect largest coupling to top quark
- $t\bar{t}$H and tH: direct access to the coupling (no indirect loop contributions)
- $\sigma(t\bar{t}H) \approx 0.5\,\text{pb}$ and $\sigma(tH) \approx 90\,\text{fb}$ at $\sqrt{s} = 13\,\text{TeV}$
- $t\bar{t}$H: sensitive to magnitude of y_t
- tH: also sensitive to relative sign between top-Higgs coupling and coupling of Higgs to W boson
- This talk: H$\rightarrow b\bar{b}$ decay channel (coupling y_b) and total 2016 dataset collected by CMS corresponding to $35.9\,\text{fb}^{-1}$

	$t\bar{t}$H		tH
	leptonic	fully-hadronic	leptonic
H$\rightarrow b\bar{b}$	arXiv:1804.03682, submitted to JHEP	JHEP 06 (2018) 101	CMS-PAS-HIG-17-016

$t\bar{t}H$, $H \rightarrow b\bar{b}$ (leptonic)

arXiv:1804.03682, submitted to JHEP





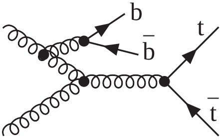
Signal and background modeling

Signal and background prediction from MC simulation

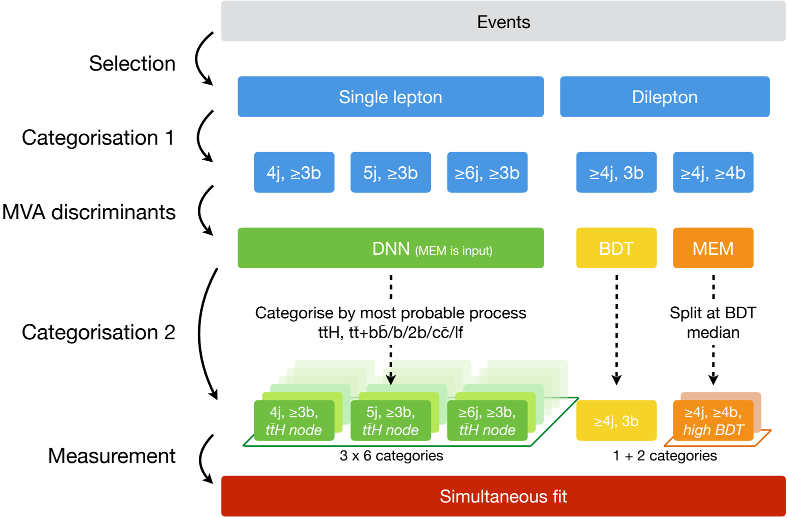
- Signal ($t\bar{t}H$): Powheg+Pythia8 @ NLO QCD (cross sections @ NLO QCD and EW)
- Backgrounds: $t\bar{t}$, single top, V+jets, $t\bar{t}$ +V, Diboson

Dominant background: $t\bar{t}$

- $\sigma(t\bar{t}) \approx 832\,\text{pb}$ @ NNLO + NNLL @ 13 TeV
- Problematic: additional heavy flavor jets not from top
- Irreducible $t\bar{t} + b\bar{b}$ contribution with large uncertainties $\mathcal{O}(\sigma(t\bar{t} + b\bar{b})/\sigma(t\bar{t}H)) \approx 10$
- Inclusive $t\bar{t}$ simulation by Powheg @ NLO QCD
- Additional b-jets (not from top) modeled by parton shower
- Split according to flavor of additional jets and add 50% normalization uncertainties

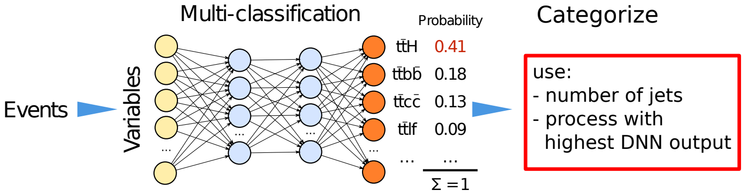


Analysis overview

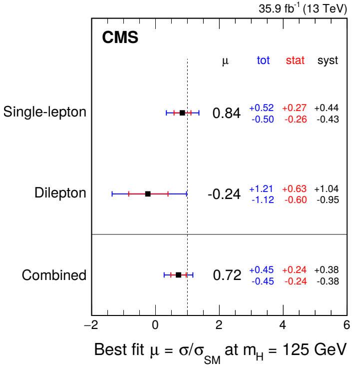


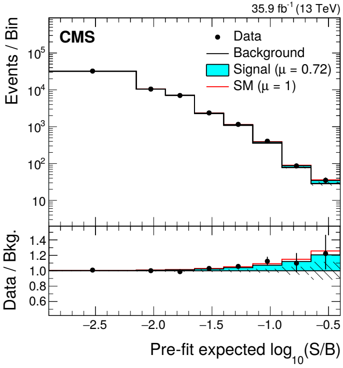
Classification semileptonic channel

- Split events according to number of jets (4, 5, $\geq$ 6)
- Multi-class DNN classifies events into classes corresponding to
  - Main $t\bar{t}$ +X backgrounds
  - $t\bar{t}H$ signal
- DNN uses kinematic, event-shape and b-tagging variables as well as matrix element method
- $t\bar{t}H$ node: signal enriched category
- Background nodes (control regions): constrain large systematic uncertainties on $t\bar{t}$ +hf processes



Results





Channel & Analysis	Significance
dilepton BDT+MEM	-
single lepton DNN	1.68σ
combination	1.59σ

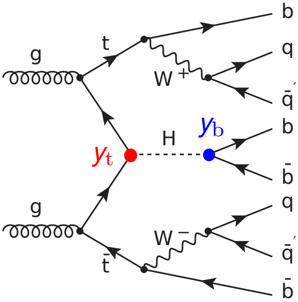
Systematic uncertainties

- Several experimental and theoretical uncertainties considered
- Considered as nuisance parameters in profile likelihood fit
- Most important uncertainties in table below

Uncertainty source	$\pm\Delta\mu$ (observed)	$\pm\Delta\mu$ (expected)
Total experimental	+0.15/-0.16	+0.19/-0.17
b tagging	+0.11/-0.14	+0.12/-0.11
jet energy scale and resolution	+0.06/-0.07	+0.13/-0.11
Total theory	+0.28/-0.29	+0.32/-0.29
$t\bar{t}$ +hf cross-section and parton shower	+0.24/-0.28	+0.28/-0.28
Size of MC samples	+0.14/-0.15	+0.16/-0.16
Total systematic	+0.38/-0.38	+0.45/-0.42
Statistical	+0.24/-0.24	+0.27/-0.27
Total	+0.45/-0.45	+0.53/-0.49

$t\bar{t}H$, $H \rightarrow b\bar{b}$ (hadronic)

JHEP 06 (2018) 101

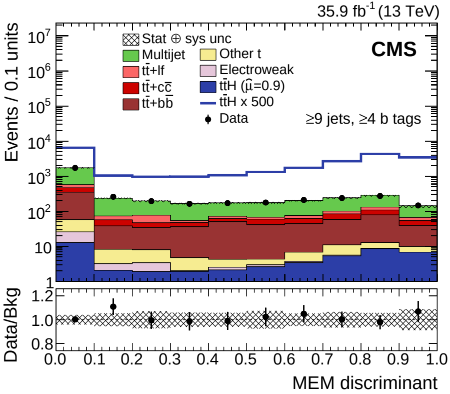


$t\bar{t}$H, H$\rightarrow$ $b\bar{b}$ hadronic

- Selection: $\geq$ 7 jets, $\geq$ 3 b-tagged jets, $H_T \geq$ 500 GeV, lepton veto
- Categorization: jet and b-tag multiplicity
- 2 main backgrounds: QCD multijet and $t\bar{t}$
- QCD multijet:
  - Discriminate against QCD multijet with Quark-Gluon-Likelihood-Ratio
  - Estimate shape from controlregion with low number of b-tags
  - Rate is obtained during final fit to data
- $t\bar{t}$:
  - Estimated from MC simulation (same as in leptonic analysis)
  - Difficult contribution: $t\bar{t}$ + $b\bar{b}$
- Final discrimination with matrix element method separating $t\bar{t}$H,H$\rightarrow$ $b\bar{b}$ with $t\bar{t}$ + $b\bar{b}$

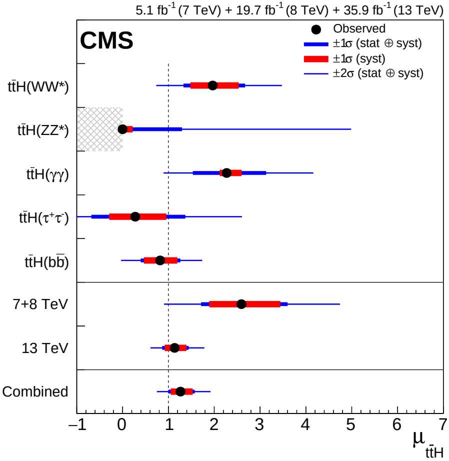
Results

- Best fit: $\mu = 0.9^{+1.5}_{-1.5}$
- Upper observed (expected) 95% C.L. limit: $\mu < 3.8(3.1)$
- Dominant uncertainties: QCD estimation, b-tagging, $t\bar{t}$ +hf contribution



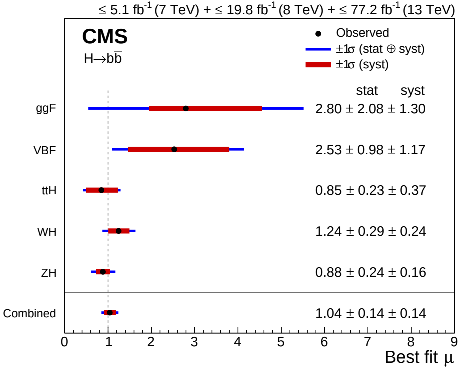
Input to $t\bar{t}$H observation, Phys. Rev. Lett. 120, 231801 (2018)

- Combination of several $t\bar{t}$H analyses in different decay channels
- Result: $\mu_{t\bar{t}H} = 1.26^{+0.31}_{-0.26}$ with 5.2σ significance above background-only hypothesis
- Higgs coupling to top quarks established
- $t\bar{t}$H (H$\rightarrow$ b$\bar{b}$) most sensitive input channel



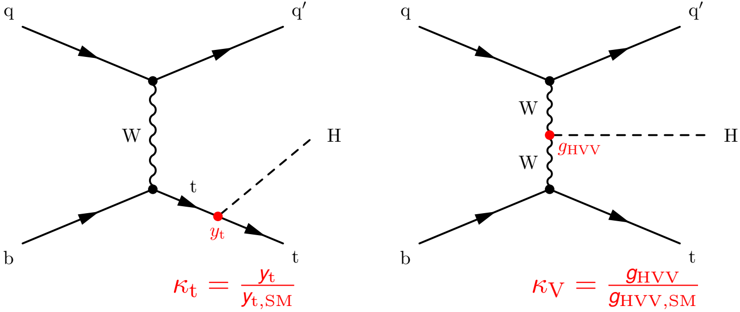
Input to H$\rightarrow$ b$\bar{b}$ observation, Phys. Rev. Lett. 121, 121801 (2018)

- Combination of several Higgs analyses in H$\rightarrow$ b$\bar{b}$ channel
- Result: $\mu = 1.04^{+0.20}_{-0.19}$ with 5.6σ signal significance
- Higgs coupling to bottom quarks established
- t$\bar{t}$H (H$\rightarrow$ b$\bar{b}$) significant contribution



tH, H→ b$\bar{b}$

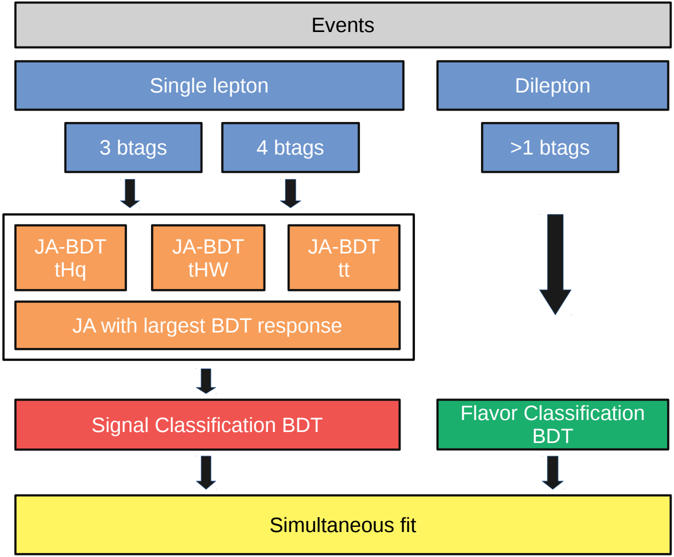
CMS-PAS-HIG-17-016



Signal and background modeling

- Signal and background from MC simulation
- Signal (tHq, tHW):
  - MadGraph @ LO (normalized to NLO cross section)
  - Generated for inverted top coupling (ITC) case: $\kappa_{\mathrm{t}} = -1$, $\kappa_{\mathrm{V}} = 1$
  - Reweighted to other $\kappa_{\mathrm{t}}/\kappa_{\mathrm{V}}$ scenarios $\rightarrow$ account not only for different cross sections and branching fractions but also kinematics
  - κ_{t} from -3 to 3, κ_{V} from 0.5 to 1.5
  - s-channel production neglected due to vanishingly small cross section
  - SM: σ(tHq)$\approx$ 71 fb, σ(tHW)$\approx$ 16 fb
  - ITC: σ(tHq)$\approx$ 739 fb, σ(tHW)$\approx$ 147 fb
- Main backgrounds: $\mathrm{t\bar{t}}$, single top, $\mathrm{t\bar{t}H}$, $\mathrm{t\bar{t}}$ +V
  - $\mathrm{t\bar{t}H}$, $\mathrm{t\bar{t}}$ and single top with Powheg @ NLO
  - $\mathrm{t\bar{t}}$ is also splitted into $\mathrm{t\bar{t}}$ +lf/$\mathrm{c\bar{c}}$/b/2b/$\mathrm{b\bar{b}}$

Analysis overview



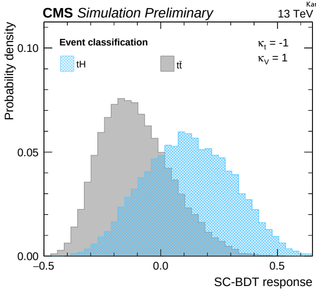
Event classification

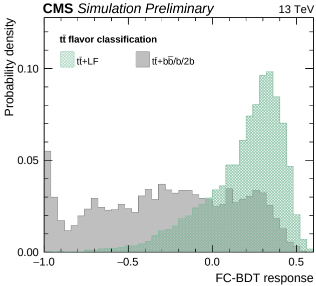
Signal classification:

- BDT used in signal regions
- Discriminate tHq, tHW (signal) from $t\bar{t}$ (background)
- Uses jet assignment, kinematic, and event-shape variables

Flavor classification:

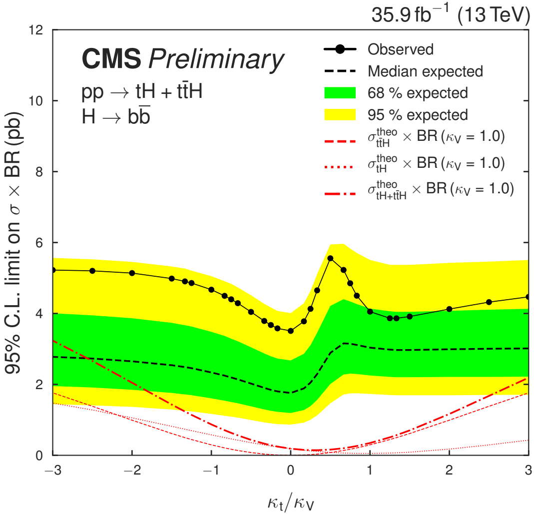
- BDT used in dilepton control region
- Discriminate $t\bar{t}$ +lf events from $t\bar{t}$ +b/2b/$b\bar{b}$ events
- Constrain normalization uncertainties regarding $t\bar{t}$ processes (main background)





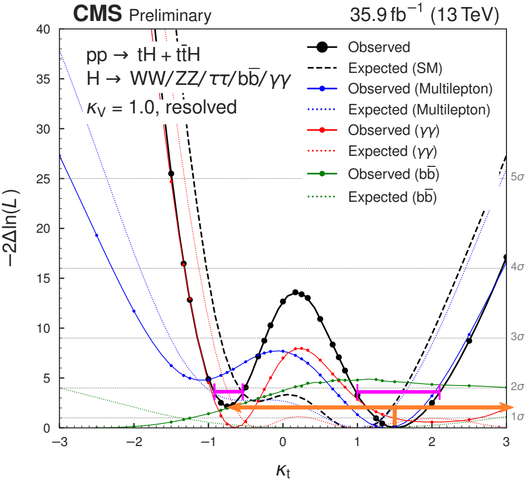
Results

- Observed (expected) upper limits on cross section times branching fraction
- dominant uncertainties are: $t\bar{t}$ + hf normalizations, b-tagging, JES
- H→ $b\bar{b}$ channel starting to get sensitive



tH combination, CMS-HIG-18-009, submitted to Phys. Rev. D

- Profile likelihood scan as function of κ_t
- κ_t affects cross section, branching fractions, and kinematics
- $-2\Delta\ln(\mathcal{L}) = -2\ln(\mathcal{L}(\kappa_t)/\mathcal{L}(\hat{\kappa_t}))$
- Data favors positive κ_t value over negative with around 1.5σ
- κ_t outside of $[-0.9, -0.5]$ and $[1.0, 2.1]$ excluded @ 95% C.L. for $\kappa_V = 1$

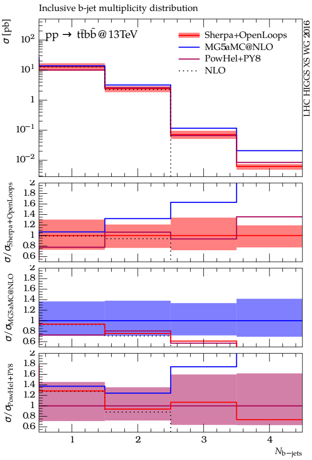


Summary

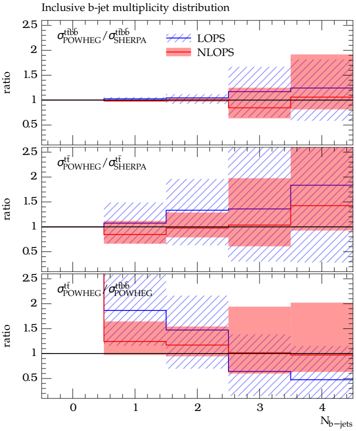
- Overview about latest tH and $t\bar{t}$H results with H$\rightarrow$ $b\bar{b}$ and 35.9 fb^{-1} of 2016 data collected by CMS
- All analyses rely heavily on b-tagging and description of $t\bar{t}$ + hf processes (dominant uncertainties)
- $t\bar{t}$H, H$\rightarrow$ $b\bar{b}$: most sensitive input to $t\bar{t}$H observation
- tH, H$\rightarrow$ $b\bar{b}$: starting to get sensitive, more data will help

Backup

$t\bar{t}$ + additional b-jets



[2]



[1]

Conclusion: account for uncertainties of around 30% (left plot) and consider differences between inclusive $t\bar{t}$ and $t\bar{t}$ +$b\bar{b}$ simulation (right plot) ⇒ 50% uncertainties on $t\bar{t}$ +hf processes

References

[1] D. de Florian et al. *Handbook of LHC Higgs Cross Sections: 4. Deciphering the Nature of the Higgs Sector*. Tech. rep. FERMILAB-FN-1025-T. 869 pages, 295 figures, 248 tables and 1645 citations. Working Group web page: https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWG. Oct. 2016. URL: `https://cds.cern.ch/record/2227475`.

[2] Tomáš Ježo et al. "New NLOPS predictions for $t\bar{t} + b$ -jet production at the LHC". In: *Eur. Phys. J.* C78.6 (2018), p. 502. DOI: `10.1140/epjc/s10052-018-5956-0`. arXiv: `1802.00426 [hep-ph]`.

$t\bar{t}$ + heavy flavor splitting

$t\bar{t}$ sample split further according to gen-jets containing additional b/c hadrons with CMSSW GenHFHadronMatcher tool

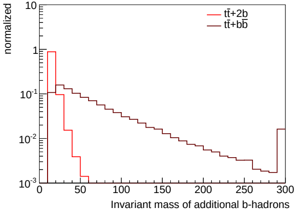
- gen-jets: clustered from final state generator particles, $p_T > 20$, $|\eta| < 2.4$
- containing hadrons: jets into which b/c hadrons (before decay) that are injected as “ghosts” (energy scaled $\rightarrow 0$) are clustered
- additional hadrons: cannot be traced back to top-decay products

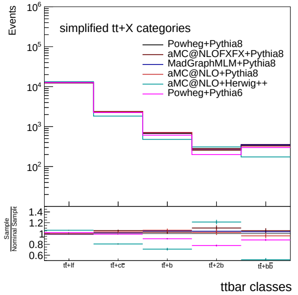
$t\bar{t}$ +HF classes:

$t\bar{t} + b\bar{b}$: at least two add. b-jets
$t\bar{t} + b$: one add. b-jet from a single b hadron
$t\bar{t} + 2b$: one add. b-jet from two or more overlapping b hadrons
$t\bar{t} + c\bar{c}$: at least one add. c-jet, no add. b-jets
$t\bar{t} + lf$: does not belong to any of the above

$t\bar{t}$ + heavy flavor splitting

- Physics motivation
  - $t\bar{t} + b\bar{b}$ and $t\bar{t} + b$ in principle same process, well separated jets ⇒ can be treated perturbatively
    $t\bar{t} + b\bar{b}$ signal-like in terms of jets and tags
  - $t\bar{t} + 2b$ different: collinear gluon splitting within one jet ⇒ depends on parton shower tuning
  - $t\bar{t} + c\bar{c}$ Similar issues, but less signal-like
- Scheme developed in coordination with ATLAS
- Assigning 50% rate uncertainty for $t\bar{t}$ subprocesses





Systematic uncertainties

CMS-PAS-HIG-17-026

Source	Type	Notes
Luminosity	lnN	Signal and all backgrounds
Lepton ID/Iso	shape	Signal and all backgrounds
Trigger efficiency	shape	Signal and all backgrounds
Pileup	shape	Signal and all backgrounds
JES and JER	shape	Signal and all backgrounds
b-Tag HF fraction	shape	Signal and all backgrounds
b-Tag HF stats (linear)	shape	Signal and all backgrounds
b-Tag HF stats (quadratic)	shape	Signal and all backgrounds
b-Tag LF fraction	shape	Signal and all backgrounds
b-Tag LF stats (linear)	shape	Signal and all backgrounds
b-Tag LF stats (quadratic)	shape	Signal and all backgrounds
b-Tag Charm (linear)	shape	Signal and all backgrounds
b-Tag Charm (quadratic)	shape	Signal and all backgrounds
QCD Scale ($t\bar{t}H$)	lnN	Scale uncertainty for NLO $t\bar{t}H$ prediction
QCD Scale ($t\bar{t}$)	lnN	Scale uncertainty for NLO $t\bar{t}$ prediction
QCD Scale ($t\bar{t}$+HF)	lnN	Additional scale uncertainty for NLO $t\bar{t}$+HF predictions
QCD Scale (t)	lnN	Scale uncertainty for NLO single top prediction
QCD Scale (V)	lnN	Scale uncertainty for NNLO W and Z prediction
QCD Scale (VV)	lnN	Scale uncertainty for NLO diboson prediction

Systematic uncertainties

CMS-PAS-HIG-17-026

Source	Type	Notes
pdf (*gg*)	lnN	Pdf uncertainty for *gg* initiated processes except $t\bar{t}H$ ($t\bar{t}$, $t\bar{t}Z$)
pdf ($ggt\bar{t}H$)	lnN	Pdf uncertainty for $t\bar{t}H$
pdf ($q\bar{q}$)	lnN	Pdf uncertainty for $q\bar{q}$ initiated processes ($t\bar{t}W$, W, Z).
pdf (*qg*)	lnN	Pdf uncertainty for *qg* initiated processes (single top)
Q2 Scale ($t\bar{t}$)	shape	Renormalization and factorization scale uncertainties of the $t\bar{t}$ ME generator, independent for additional jet flavors
PS Scale: ISR ($t\bar{t}$)	lnN	Parton-shower scale uncertainties (for $t\bar{t}$ events), independent for additional jet flavors
PS Scale: FSR ($t\bar{t}$)	lnN	Parton-shower scale uncertainties (for $t\bar{t}$ events), independent for additional jet flavors
ME-PS matching ($t\bar{t}$)	lnN	NLO parton-shower matching, hdamp (for $t\bar{t}$ events), independent for additional jet flavors
Underlying Event ($t\bar{t}$)	lnN	Underlying event (for $t\bar{t}$ events)
NNPDF3.0 ($t\bar{t}$)	shape	Pdf uncertainty for $t\bar{t}$
Bin-by-bin statistics	shape	statistical uncertainty of the signal and background prediction due o the limited sample size

Matrix Element for ttH(bb) vs ttbb

Karlsruhe Institute of Technology

- Signal extraction via Matrix Element Methods (MEM):
  - Event-by-event discriminator build upon matrix elements, combined with reconstruction-level information.

Numerical integration — Momentum conservation — Resolution function (allow ISR)

$$w(\vec{y}|\mathcal{H}) = \sum_{i=1}^{\mathrm{N_C}} \int \frac{dx_a dx_b}{2x_a x_b s} \int \prod_{k=1}^{8} \left(\frac{d^3\vec{p}_k}{(2\pi)^3 2E_k} \right) (2\pi)^4 \delta^{(E,z)} \left(p_a + p_b - \sum_{k=1}^{8} p_k \right) \mathcal{R}^{(x,y)} \left(\vec{\rho}_T, \sum_{k=1}^{8} p_k \right)$$
$$\times g(x_a, \mu_F) g(x_b, \mu_F) |\mathcal{M}(p_a, p_b, p_1, \ldots, p_8)|^2 W(\vec{y}, \vec{p})$$

Parton density functions — LO scattering amplitude (Open Loops) — Detector transfer function

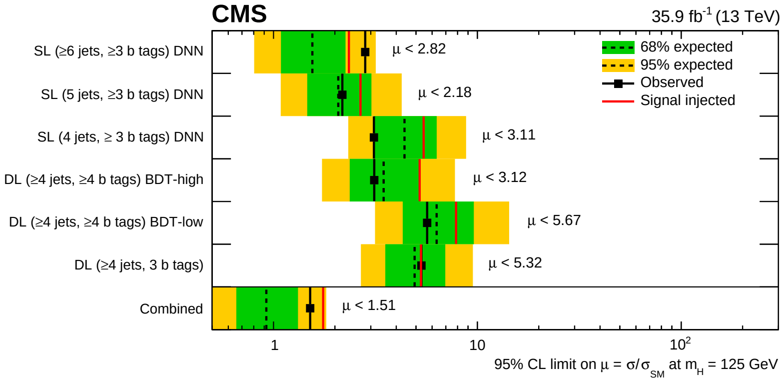
- Construct per-event signal/background probability using full kinematic information in an analytic approach

$$P_{s/b} = \frac{w(\vec{y}|t\bar{t}H)}{w(\vec{y}|t\bar{t}H) + k_{s/b} w(\vec{y}|t\bar{t}+b\bar{b})}$$

- $t\bar{t}$ +$b\bar{b}$ taken as background hypothesis, permuting over all jet assignments

Upper limits, $t\bar{t}H$, $H \to b\bar{b}$ leptonic

arXiv:1804.03682, submitted to JHEP



Jet assignment

Karlsruhe Institute of Technology

- 3 final state hypotheses used: tHq, tHW, $t\bar{t}$
- Search for best possible assignment between reconstructed jets and final-state quark
- BDTs used to discriminate between correct and incorrect assignments
- "Correct" assignment for one jet: $\Delta R \leq 0.3$
- Overall assignment with lowest sum of all ΔR considered to be "correct"
- Jet assignment with highest BDT response (3 hypotheses) chosen
- JA-BDTs use kinematics, b-tagging information and angular variables

tHq and tHW cross sections

$$\sigma_{\mathrm{tHq}} = (2.633\kappa_{\mathrm{t}}^2 + 3.578\kappa_{\mathrm{V}}^2 - 5.211\kappa_{\mathrm{t}}\kappa_{\mathrm{V}}) \times \sigma_{\mathrm{tHq}}^{\mathrm{SM}} \quad (1)$$

$$\sigma_{\mathrm{tHW}} = (2.909\kappa_{\mathrm{t}}^2 + 2.310\kappa_{\mathrm{V}}^2 - 4.220\kappa_{\mathrm{t}}\kappa_{\mathrm{V}}) \times \sigma_{\mathrm{tHW}}^{\mathrm{SM}} \quad (2)$$

tH only limits