# tH and $t\bar{t}$H measurements at the CMS experiment

Philip Keicher for the CMS Collaboration
Higgs Hunting 2023, September 12th, 2023

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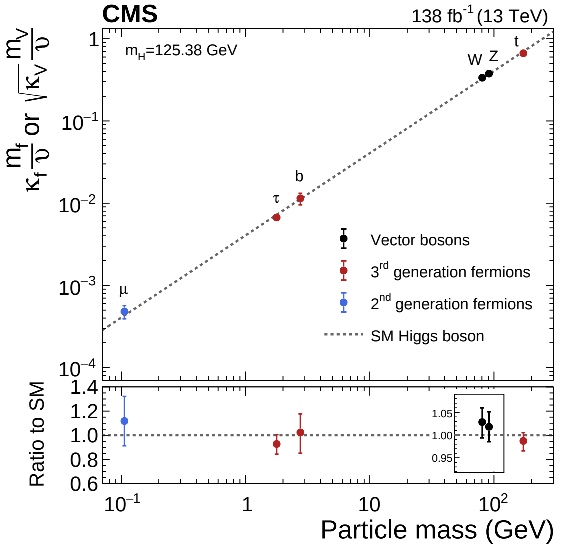
# Why tH and t$\bar{t}$H?

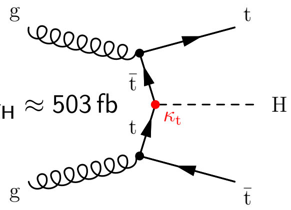
- **Higgs Physics** crucial for **checks of the Standard Modell** and **searches for physics beyond**
- This talk: precision measurements of coupling Higgs bosons to other particles



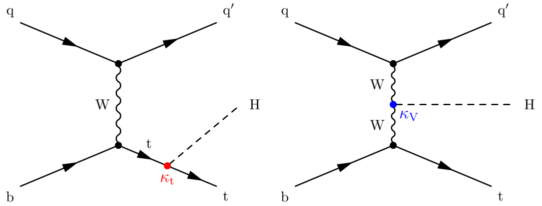

[Nature volume 607 (2022)]

# Why tH and $t\bar{t}H$?

- **Higgs Physics** crucial for **checks of the Standard Modell** and **searches for physics beyond**
- This talk: precision measurements of coupling Higgs bosons to other particles
- **Direct access** to $\kappa_t$ in $t\bar{t}H$ production
- **Additional sensitivity** to sign of $\kappa_t$ and $\kappa_V$ via tH production
- Also **sensitive to $\mathcal{CP}$-odd** contributions in Top-Higgs Yukawa coupling
- **Challenge**: small cross sections of the processes w.r.t. background

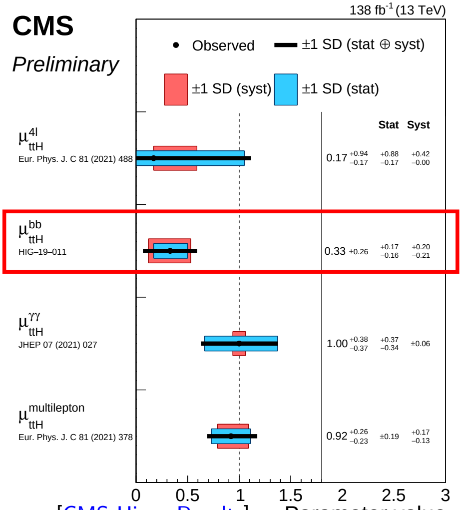



$\sigma_{t\bar{t}H} \approx 503$ fb




$\sigma_{tH} \approx 92$ fb

# Current status at CMS



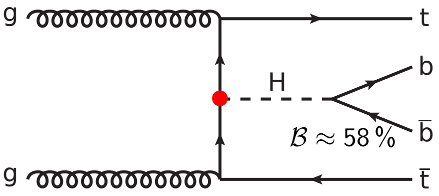

[CMS Higgs Results]

- Analyze tH and $t\bar{t}H$ production in **many final states** with full Run-II dataset
- Focus of this talk:
  New tH + $t\bar{t}H$, H $\rightarrow b\bar{b}$ measurement
  [CMS-PAS-HIG-19-011] [LHC Seminar, J. Steggemann]

# tH + t$\bar{t}$H, H $\rightarrow$ b$\bar{b}$ setup

[CMS-PAS-HIG-19-011]

- Profit from **large branching fraction**
- **Fully reconstructable Higgs** final state
- Analysis **divided according to t$\bar{t}$ final states**
  - fully hadronic (FH): 0 leptons
  - semi-leptonic (SL): 1 lepton
  - di-leptonic (DL): 2 leptons



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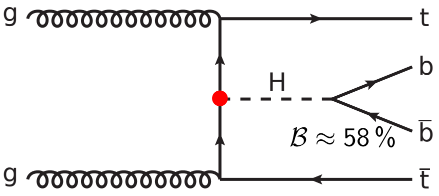
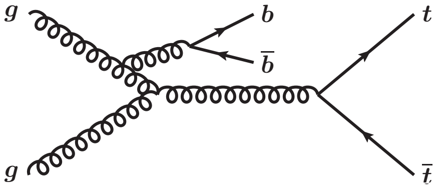
- **Main challenges**:
  - FH: **QCD multi-jet background**
    - $\rightarrow$ **data-driven estimation**
  - DL+SL: **$t\bar{t}$ + jets background** [Talk by A. Calandri]
    - $\rightarrow$ **dedicated MC** for irreducible background
    - $\rightarrow$ infer normalization **from data**

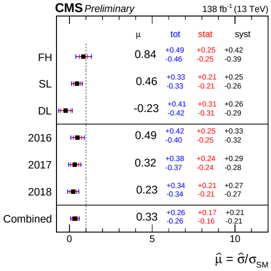


# tH + $t\bar{t}$H, H → $b\bar{b}$ statistical interpretations

[CMS-PAS-HIG-19-011]

- Perform **five interpretations**
  - inclusive $t\bar{t}H(b\bar{b})$ **signal strength** $\mu_{t\bar{t}H}$



# $\mathrm{tH} + \mathrm{t\bar{t}H}$, $\mathrm{H} \rightarrow \mathrm{b\bar{b}}$ statistical interpretations

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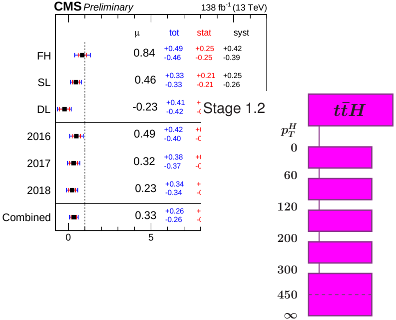
  - New: **Simplified Template Cross Section** (STXS)



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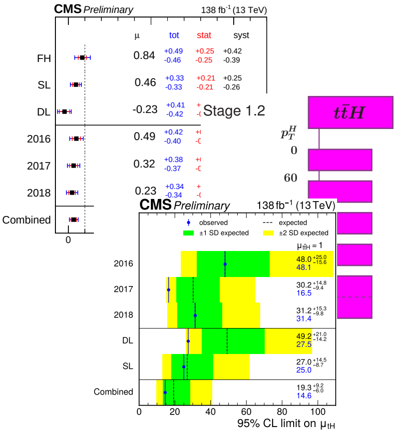

# $tH + t\bar{t}H$, $H \to b\bar{b}$ statistical interpretations

[CMS-PAS-HIG-19-011]

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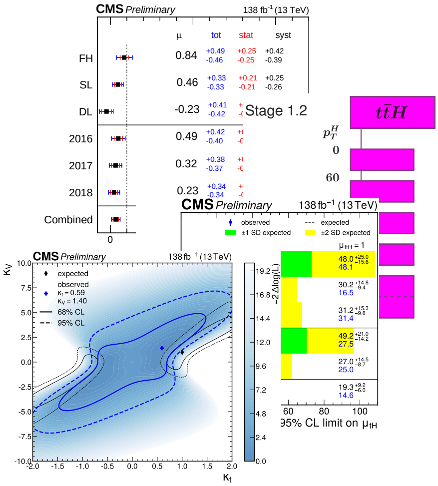

# $\mathrm{tH} + \mathrm{t\bar{t}H}$, $\mathrm{H} \rightarrow \mathrm{b\bar{b}}$ statistical interpretations

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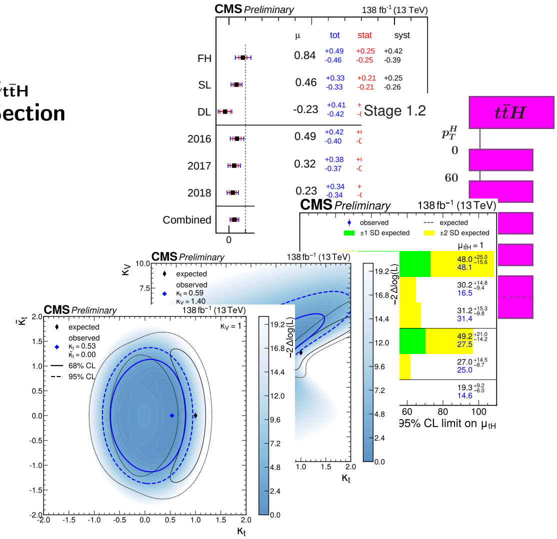
  - New: **Simplified Template Cross Section** (STXS)
  - Upper limit on $\mathrm{tH(b\bar{b})}$ production
  - Measurement of $\kappa_{\mathrm{t}}$ and $\kappa_{\mathrm{V}}$
  - $\mathcal{CP}$ measurement



# Inclusive $\mu_{t\bar{t}H}$ Strategy

[CMS-PAS-HIG-19-011]


Distribution in template fit, event yield (Y), ANN output (O), likelihood ratio of ANN outputs (R)

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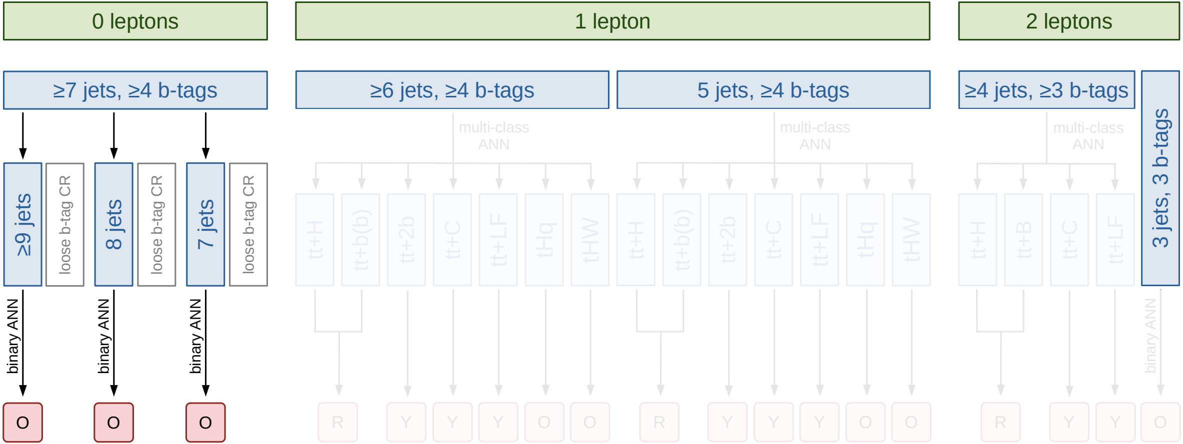


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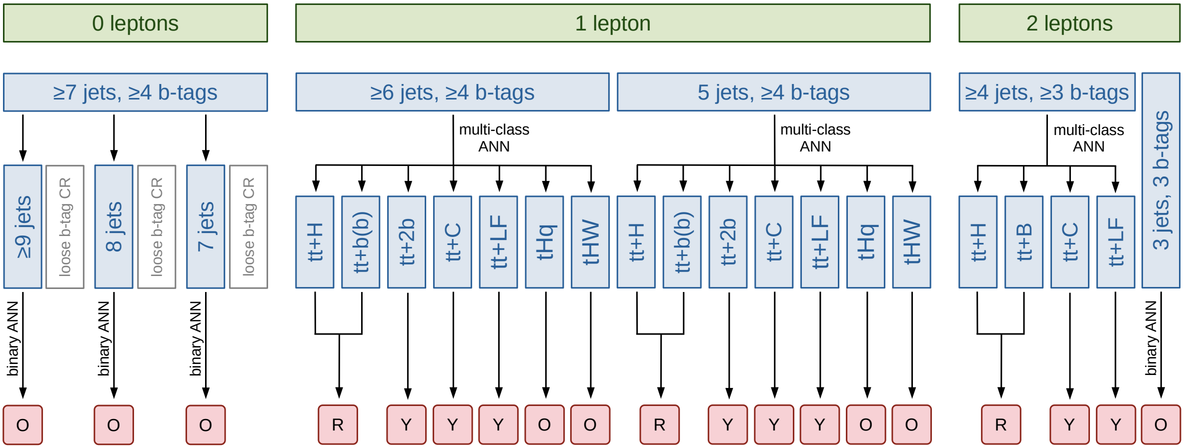


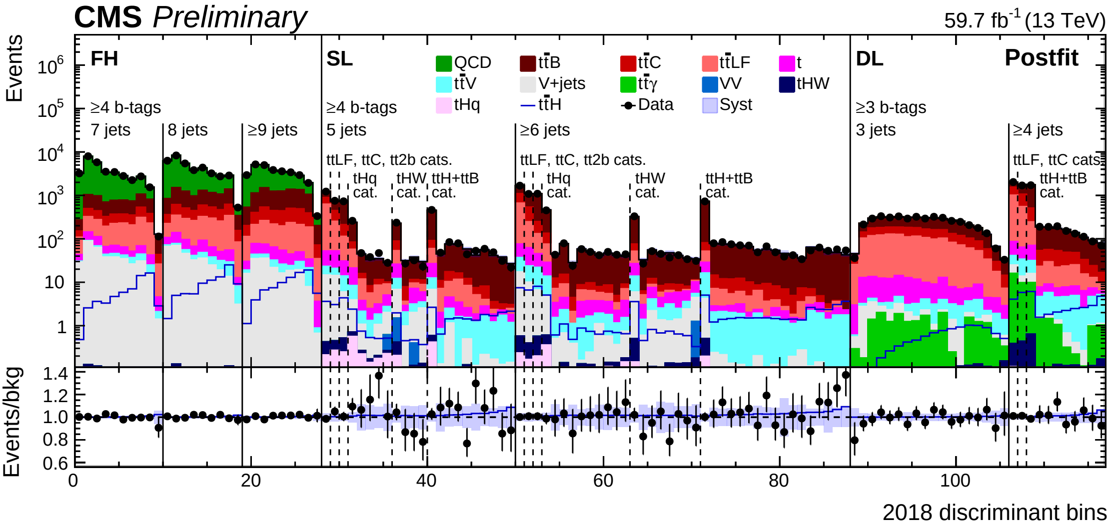

Distribution in template fit, event yield (Y), ANN output (O), likelihood ratio of ANN outputs (R)

$$R_{SL} = \frac{o(t\bar{t}H)}{o(t\bar{t}H)+o(t\bar{t}+b(b))+o(t\bar{t}+2b)}$$

$$R_{DL} = \frac{o(t\bar{t}H)}{o(t\bar{t}H)+o(t\bar{t}+B)}$$

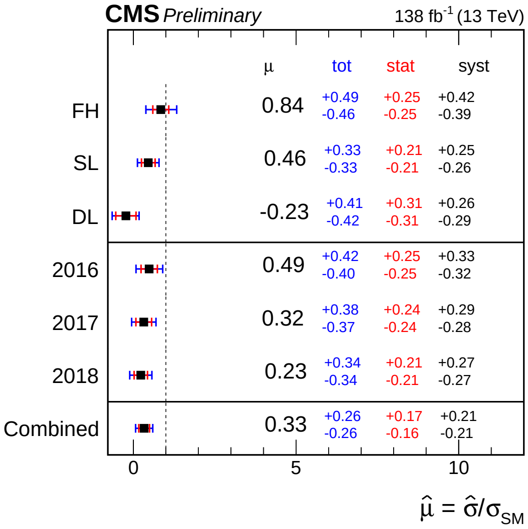
# Final discriminant distribution

[CMS-PAS-HIG-19-011]



# Inclusive $\mu_{t\bar{t}H}$ Results

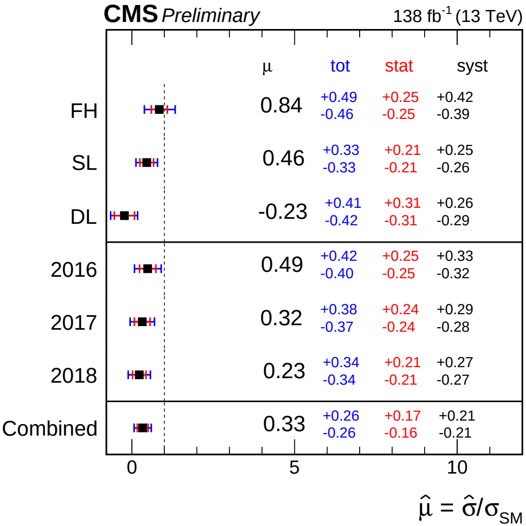
[CMS-PAS-HIG-19-011]




- Compatible with ATLAS result: $\mu_{t\bar{t}H} = 0.35^{+0.36}_{-0.34}$

# Inclusive $\mu_{t\bar{t}H}$ Results

[CMS-PAS-HIG-19-011]



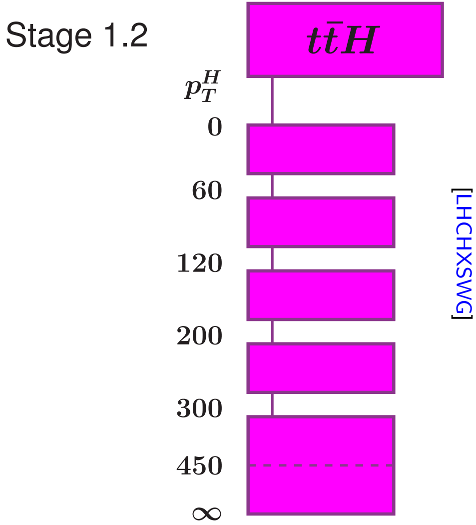

| Uncertainty source | $\Delta\mu_{t\bar{t}H}$ (observed) | $\Delta\mu_{t\bar{t}H}$ (expected) |
|---|---|---|
| Total experimental | $+0.10/-0.10$ | $+0.11/-0.10$ |
| jet energy scale and resolution | $+0.08/-0.07$ | $+0.09/-0.09$ |
| b tagging | $+0.07/-0.06$ | $+0.06/-0.02$ |
| luminosity | $+0.02/-0.02$ | $+0.01/-0.01$ |
| Total theory | $+0.16/-0.16$ | $+0.18/-0.14$ |
| $t\bar{t}$ + jets background | $+0.15/-0.16$ | $+0.12/-0.11$ |
| signal modelling | $+0.06/-0.01$ | $+0.13/-0.06$ |
| Size of the simulated event samples | $+0.13/-0.12$ | $+0.10/-0.10$ |
| Total systematic | $+0.20/-0.21$ | $+0.23/-0.19$ |
| Statistical | $+0.17/-0.16$ | $+0.17/-0.17$ |
| background normalisation | $+0.13/-0.13$ | $+0.13/-0.13$ |
| $t\bar{t}B$ and $t\bar{t}C$ normalisation | $+0.12/-0.12$ | $+0.12/-0.12$ |
| QCD normalisation | $+0.01/-0.01$ | $+0.01/-0.01$ |
| Total | $+0.26/-0.26$ | $+0.28/-0.25$ |

# STXS interpretation strategy

[CMS-PAS-HIG-19-011]

- Measure XS **in 5 $p_T^H$ bins**

→ Perform **reconstruction of bins with $\chi^2$ (FH)** or **neural networks (SL/DL)**



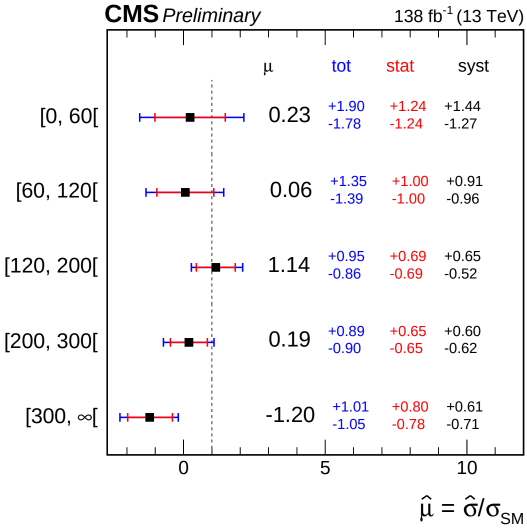
# STXS interpretation strategy

[CMS-PAS-HIG-19-011]

- Measure XS **in 5 $p_T^H$ bins**

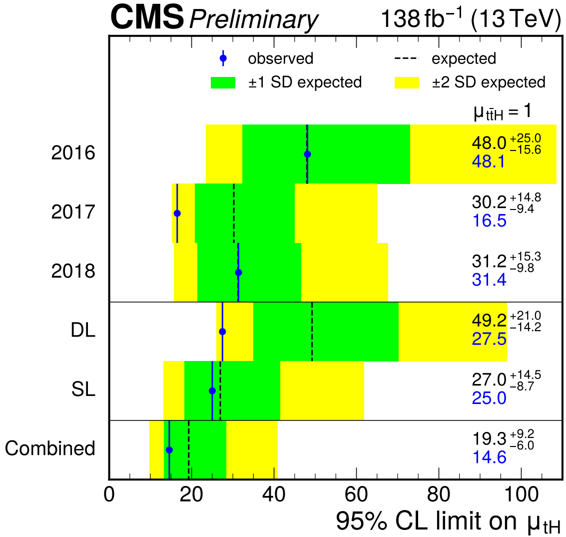
$\rightarrow$ Perform **reconstruction of bins with $\chi^2$ (FH)** or **neural networks (SL/DL)**

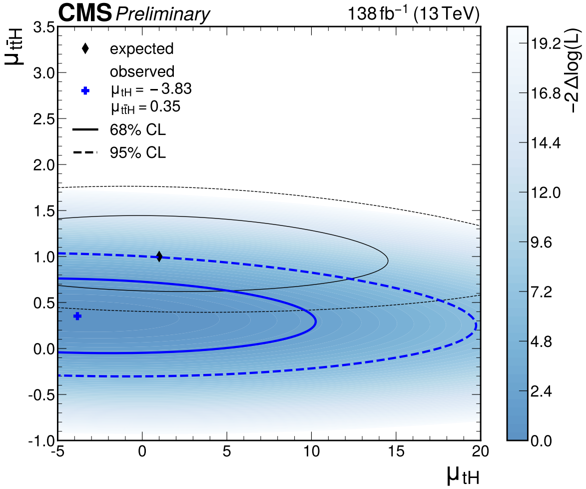
- Obtain varying degrees of sensitivity
- Result **completely compatible** with inclusive $\mu_{t\bar{t}H}$ measurement



# Upper limits for $tH(b\bar{b})$ production

[CMS-PAS-HIG-19-011]

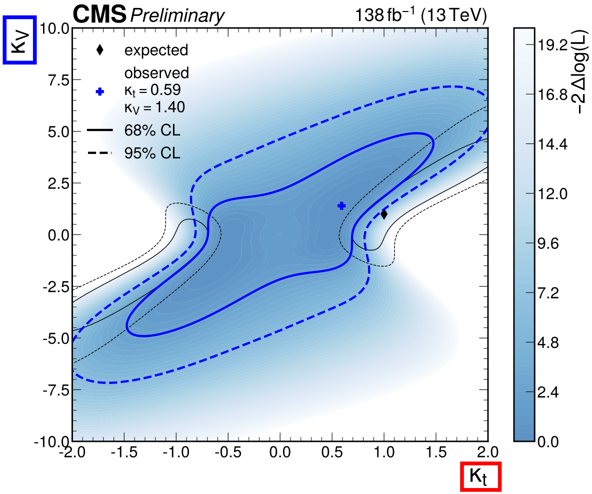


# Coupling interpretation

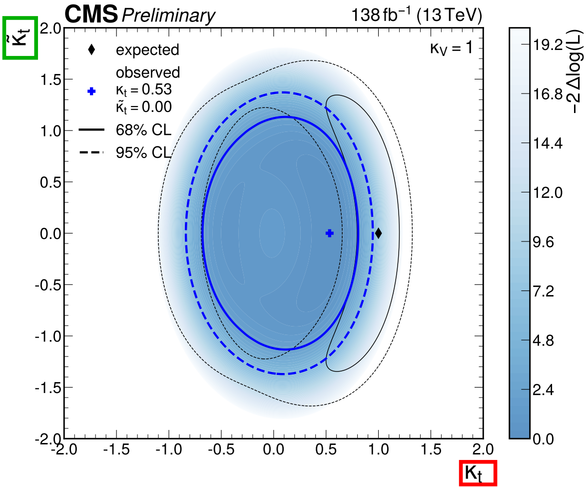
[CMS-PAS-HIG-19-011]

- **Re-parameterize analysis** in terms of $\kappa_t$ and $\kappa_V$
  - $t\bar{t}H \propto \kappa_t^2$
  - $tH \propto \kappa_t, \kappa_V$ via interference
- Fully compatible with other interpretations



# $\mathcal{CP}$ measurement

[CMS-PAS-HIG-19-011]



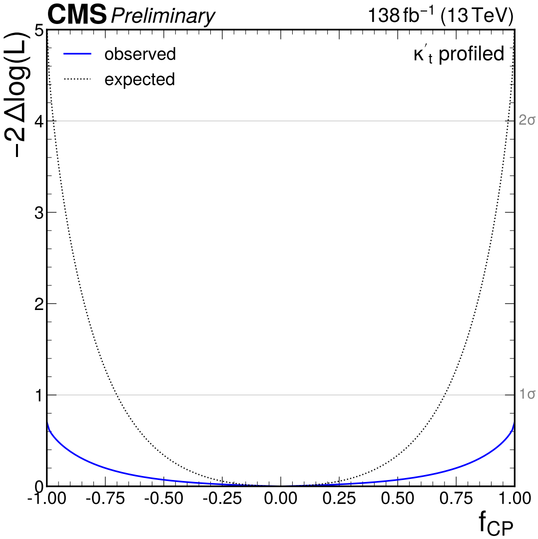

- Extend Top-Higgs Yukawa Lagrangian with $\mathcal{CP}$-odd component

$$\mathcal{L} \propto \bar{\psi}_t \left(\kappa_t + i\gamma_5 \tilde{\kappa}_t\right) \psi_t H$$

$\rightarrow$ both $t\bar{t}H$ and tH $\propto \tilde{\kappa}_t^{\,2}$

# $\mathcal{CP}$ measurement

[CMS-PAS-HIG-19-011]




- Extend Top-Higgs Yukawa Lagrangian with $\mathcal{CP}$-odd component

$$\mathcal{L} \propto \bar{\psi}_t \left( \kappa_t + i\gamma_5 \tilde{\kappa}_t \right) \psi_t H$$

→ both $t\bar{t}H$ and tH $\propto \tilde{\kappa}_t{}^2$

- Additional parameterization in $\kappa_t$-$\tilde{\kappa}_t$ plane

$$f_{\mathcal{CP}} = \frac{\tilde{\kappa}_t^2}{\kappa_t^2 + \tilde{\kappa}_t^2} \cdot \text{sign}\left(\frac{\tilde{\kappa}_t}{\kappa_t}\right)$$

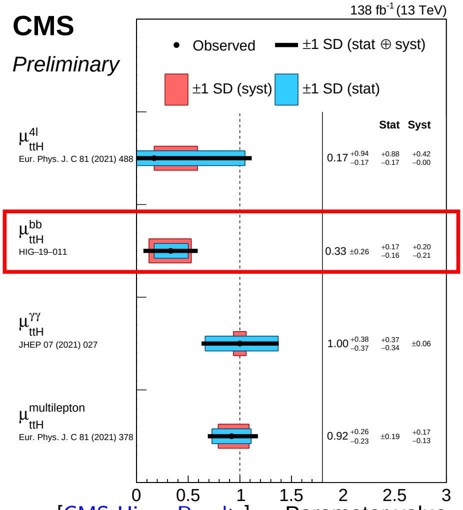
$$\kappa_t = \kappa'_t \sqrt{(1 - |f_{\mathcal{CP}}|)}$$

$$\tilde{\kappa}_t = \kappa'_t \sqrt{|f_{\mathcal{CP}}|}$$

→ Exclude $\mathcal{CP}$-odd component at almost $1\,\sigma$

# Conclusions

- tH + t$\bar{t}$H analyses especially interesting for **direct tests of Top-Higgs Yukawa coupling**
- Presented **new tH + t$\bar{t}$H, H $\rightarrow$ b$\bar{b}$ analysis** with full Run-II statistics [CMS-PAS-HIG-19-011]
  - Updated background modeling and analysis techniques
- tH + t$\bar{t}$H analyses **continue to be interesting in the future**




[CMS Higgs Results]

# Backup

# Kinematic selection criteria

[CMS-PAS-HIG-19-011]

| | FH channel | SL channel | DL channel |
|---|---|---|---|
| Number of leptons | 0 | 1 | 2 |
| Sign and flavour of leptons | — | $e^{\pm}$, $\mu^{\pm}$ | $e^{+}e^{-}$, $\mu^{\pm}e^{\mp}$, $\mu^{+}\mu^{-}$ |
| Min. $p_T$ of leading electron (GeV) | — | 29/30/30 | 25 |
| Min. $p_T$ of leading muon (GeV) | — | 26/29/26 | 25 |
| Min. $p_T$ of additional leptons (GeV) | — | — | 15 |
| Max. $p_T$ of additional leptons (GeV) | 15 | 15 | — |
| Max. $\lvert\eta\rvert$ of leptons | 2.4 | 2.4 | 2.4 |
| Min. $m_{\ell\ell}$ (GeV) | — | — | 20 |
| $m_{ee/\mu\mu}$ (GeV) | — | — | $< 76$ or $> 106$ |
| Min. number of jets | 7 | 5 | 3 |
| Min. $p_T$ of jets (GeV) | 30 | 30 | 30 |
| Min. $p_T$ of $6^{th}$ jet (GeV) | 40 | — | — |
| Max. $\lvert\eta\rvert$ of jets | 2.4 | 2.4 | 2.4 |
| Min. number of b-tagged jets | 2 | 4 | 3 |
| $m_{qq}$ (GeV) | $> 30$ and $< 250$ | — | — |
| Min. $H_T$ (GeV) | 500 | — | — |
| Min. $p_T^{miss}$ (GeV) | — | 20 | 40 |

# FH data-driven QCD estimation

[CMS-PAS-HIG-19-011]

| | $60(72)\,\text{GeV} < m_{qq} < 100(90)\,\text{GeV}$ | $30\,\text{GeV} < m_{qq} < 60(72)\,\text{GeV}$<br>or<br>$100(90)\,\text{GeV} < m_{qq} < 250\,\text{GeV}$ |
|---|---|---|
| 2 b tags<br>$\geq 4$ loose b tags | *training region (TR)*<br>QCD events for ANN training | *validation region (VR-TR)*<br>input variable validation |
| 3 b tags<br>$\geq 4$ loose b tags | *evaluation region (ER)*<br>discriminant shape for QCD | *validation region (VR-ER)*<br>discriminant shape for QCD |
| $\geq 4$ b tags | *signal region (SR)*<br>analysis region | *validation region (VR-SR)*<br>comparison of QCD shape with data |

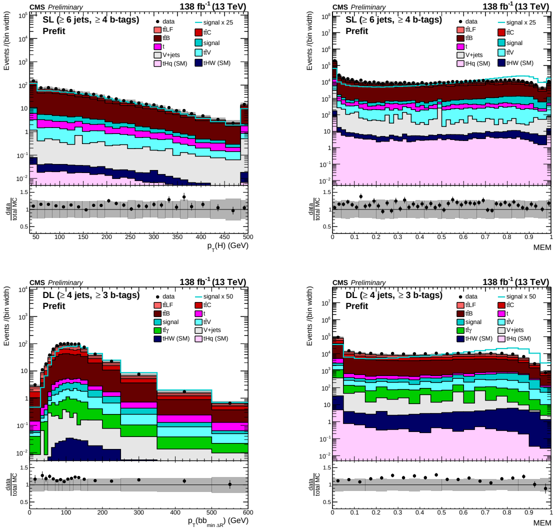
# ANN input features

[CMS-PAS-HIG-19-011]

| | | FH | | | SL | | DL | |
|---|---|---|---|---|---|---|---|---|
| Observable | | (≥ 9 jets, ≥ 4 b tags) | (8 jets, ≥ 4 b tags) | (7 jets, ≥ 4 b tags) | (≥ 6 jets, ≥ 4 b tags) | (5 jets, ≥ 4 b tags) | (≥ 4 jets, ≥ 3 b tags) | (3 jets, 3 b tags) |
| MEM | matrix element method discriminant | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | |
| BLR | b tagging likelihood ratio discriminant | | | | | | ✓ | |
| $\ln\left(\frac{\mathrm{BLR}}{1-\mathrm{BLR}}\right)$ | transformed b tagging likelihood ratio discriminant | | | | ✓ | ✓ | | |
| $p_T(j^2)$ | $p_T$ of second leading jet, ranked in $p_T$ | | | | | | ✓ | |
| $p_T(j^3)$ | $p_T$ of third leading jet, ranked in $p_T$ | | | | | | | ✓ |
| $p_T(j^7)$ | $p_T$ of seventh leading jet, ranked in $p_T$ | ✓ | | | | | | |
| $p_T(b^i)$ | $p_T$ of $i^{th}$, $i$ =1–4, leading b-tagged jet, ranked in $p_T$ | | | | | | ✓ | |
| $\eta(j^i)$ | $\eta$ of $i^{th}$, $i$ =1–2, leading jet, ranked in b tagging discriminant value | ✓ | ✓ | ✓ | | | | |
| $\langle d_b(j)\rangle$ | average b tagging discriminant value of all jets | | | | ✓ | ✓ | | |
| $\langle d_b(b)\rangle$ | average b tagging discriminant value of all b-tagged jets | | | | ✓ | ✓ | | |
| $d_b^3(j)$ | third highest b tagging discriminant value of all jets | | | | ✓ | ✓ | | |
| $\mathrm{Var}(d_b(j))$ | variance of b tagging discriminant values of all jets | | | | ✓ | ✓ | | |
| $\langle \Delta R(bb)\rangle$ | average of $\Delta R$ between two b-tagged jets | | | | | | ✓ | |
| $\langle \Delta R(jj)\rangle$ | average of $\Delta R$ between two jets | ✓ | ✓ | | | | | |
| $\min \Delta R(jj)$ | minimum of $\Delta R$ between two jets | | ✓ | ✓ | | | | ✓ |
| $\max \Delta R(jj)$ | maximum of $\Delta R$ between two jets | ✓ | ✓ | ✓ | | | | |
| $\langle \Delta\eta(bb)\rangle$ | average of $\Delta\eta$ between two b-tagged jets | | | | ✓ | ✓ | | |
| $\langle \Delta\eta(jj)\rangle$ | average of $\Delta\eta$ between two jets | ✓ | ✓ | ✓ | ✓ | ✓ | | |
| $\langle m(b)\rangle$ | average invariant mass of all b-tagged jets | | | | ✓ | ✓ | | |
| $\langle m(j)\rangle$ | average invariant mass of all jets | | | | ✓ | ✓ | | |
| $m(bb_{\min \Delta R})$ | invariant mass of pair of b-tagged jets closest in $\Delta R$ | | | | ✓ | ✓ | ✓ | |
| $m(jb_{\min \Delta R})$ | invariant mass of pair of jet and b-tagged jet closest in $\Delta R$ | | | | | | ✓ | |
| $m(jj_{125\,GeV})$ | invariant mass of pair of jets with mass closest to 125 GeV | ✓ | | | | | | |
| $m(bb_{\max m})$ | maximum invariant mass of pairs of b-tagged jets | ✓ | ✓ | | | | ✓ | ✓ |
| $m(jbb_{\max p_T})$ | invariant mass of jet and pair of b-tagged jets with highest $p_T$ | | | | | | ✓ | |
| $\langle p_T(j)\rangle$ | average $p_T$ of all jets | | | | ✓ | ✓ | | |
| $\langle p_T(b)\rangle$ | average $p_T$ of all b-tagged jets | | | | ✓ | ✓ | | |
| $p_T(bb_{\min \Delta R})$ | $p_T$ of pair of b-tagged jets closest in $\Delta R$ | | | | ✓ | ✓ | ✓ | ✓ |
| $p_T(jj_{\min \Delta R})$ | $p_T$ of pair of jets closest in $\Delta R$ | | | | | | | ✓ |
| $p_T(jb_{\min \Delta R})$ | $p_T$ of pair of jet and b-tagged jet closest in $\Delta R$ | | | | | | | ✓ |
| $H_T(j)$ | scalar sum of $p_T$ of all jets | | | | ✓ | ✓ | ✓ | |
| $H_T(b)$ | scalar sum of $p_T$ of all b-tagged jets | | | | ✓ | ✓ | ✓ | |
| $N(j)$ | number of jets | | | | ✓ | | | |
| $N(b^{loose})$ | number of jets with loose b tag | | | | | | ✓ | |
| $d_b(b_{top}^{tHW})^{\dagger}$ | b tagging discriminant value of b jet from t quark decay from tHW reconstruction | | | | ✓ | ✓ | | |
| $\lvert\eta(q^{tHq})\rvert^{\dagger}$ | $\lvert\eta\rvert$ of light-quark jet from tHq reconstruction | | | | ✓ | ✓ | | |
| $m(t_{lep}^{t\bar{t}H})^{\dagger}$ | inv. mass of leptonically decaying t quark from $t\bar{t}H$ reconstruction | | | | ✓ | ✓ | | |
| $\mathrm{BDT}^{i\dagger}$ | reconstruction BDT output for tHq, $t\bar{t}H$, $t\bar{t}$ hypotheses | | | | ✓ | ✓ | | |
| $A, S$ | event aplanarity and sphericity [76] | ✓ | ✓ | ✓ | | | | |
| $H_i^{FW}$ | $i^{th}$, $i$ =0–5, Fox–Wolfram moment [77] | ✓ | ✓ | ✓ | | | | |
| $H_i^{FW} / H_0^{FW}$ | ratio of Fox–Wolfram moments, $i$ =1–4 | ✓ | ✓ | ✓ | | | | |

# Observable construction

[CMS-PAS-HIG-19-011]

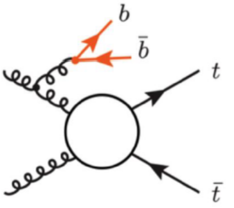



- Generally observe **good data/MC agreement**
- But: **no strong separation power**

⇒ **Utilize Artifical Neural Networks**

# $t\bar{t}$ + jets modeling

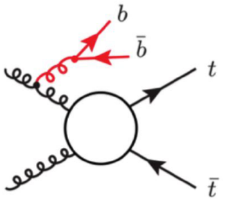
Largest background in the leptonic channels. Divided into three sources depending on flavour of additional particle-level jets with $p_T$>20 GeV and $|\eta|$<2.4




- ttB : >= 1 additional b jet ⇒ largest contribution
- ttC : >= 1 additional c jet but no b jet
- ttLF : all other events

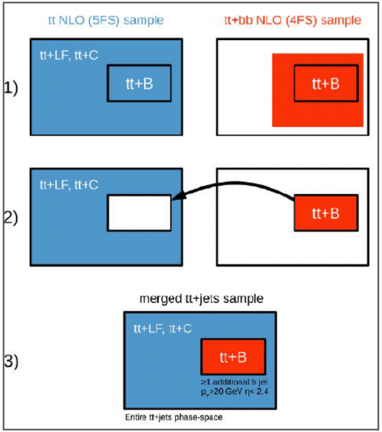
ttB is difficult to model and to measure, XS underpredicted by 20-30%

- New in this analysis: state-of-art MC simulation for ttB at NLO (4FS)
  - additional b jets from matrix element instead of parton shower
  - acceptance better described
  - better coverage by scale uncertainties



# $t\bar{t}$ + jets merging

- ttB prediction from ttbb NLO simulation (4FS)
- ttC and ttLF taken from the POWHEG tt NLO sample (5FS)
  - ttB normalised to the expected yield from 5FS sample
  - ttB and ttC normalisation freely floating in the fit
  - measured in control regions built with ANN multiclassifiers in leptonic channels



# Uncertainty model

## Theory

- QCDscale
- pdfscale
- ME+PS matching
- Underlying event
- ISR/FSR
- $\mu_R/\mu_F$
- PDF
- 100 % additional gluon splitting uncertainty

## Experiment

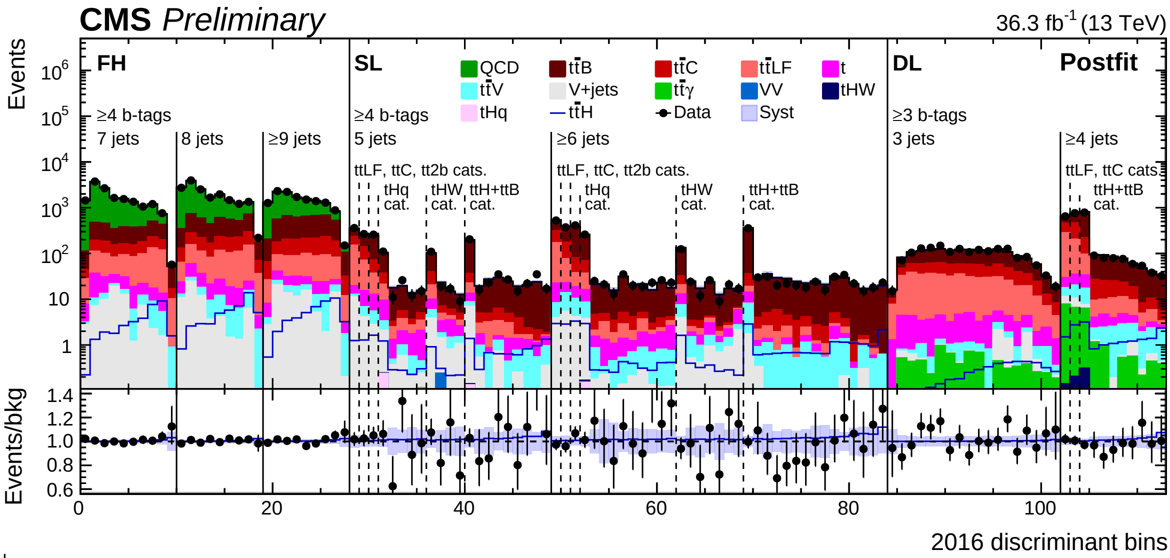
- btag (lf, hf, cf)
- lepton trigger eff.
- lepton ID eff.
- Jet energy scale + resolution
- TF Loose
- L1 Prefire
- Luminosity

## Misc

- Size of MC samples
- freely-floating norms for $t\bar{t} + b\bar{b}$, $t\bar{t} + c\bar{c}$ and data-driven QCD estimation

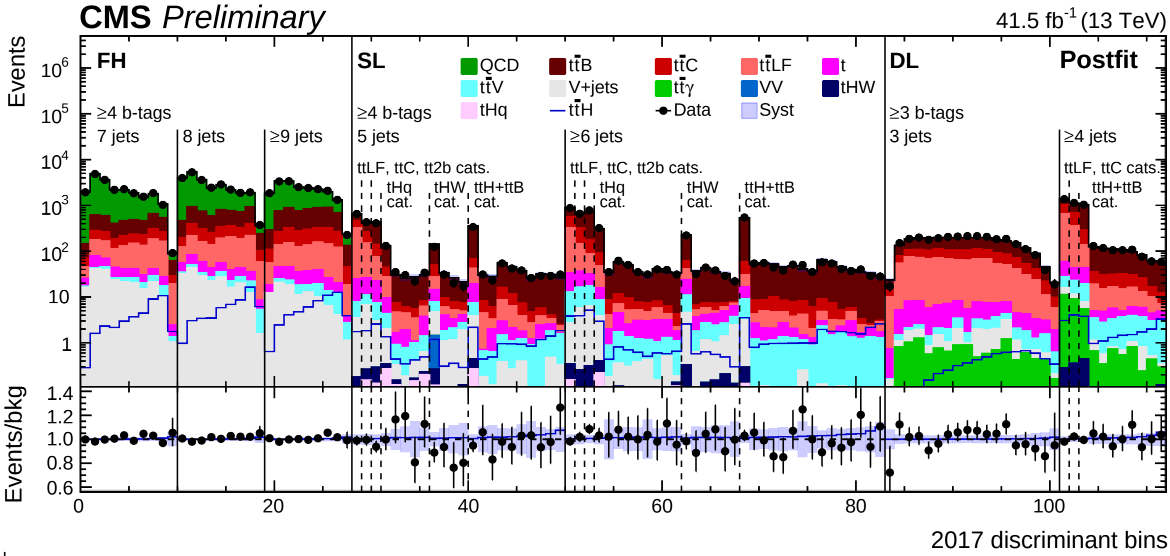
# Final discriminant distribution - 2016

[CMS-PAS-HIG-19-011]



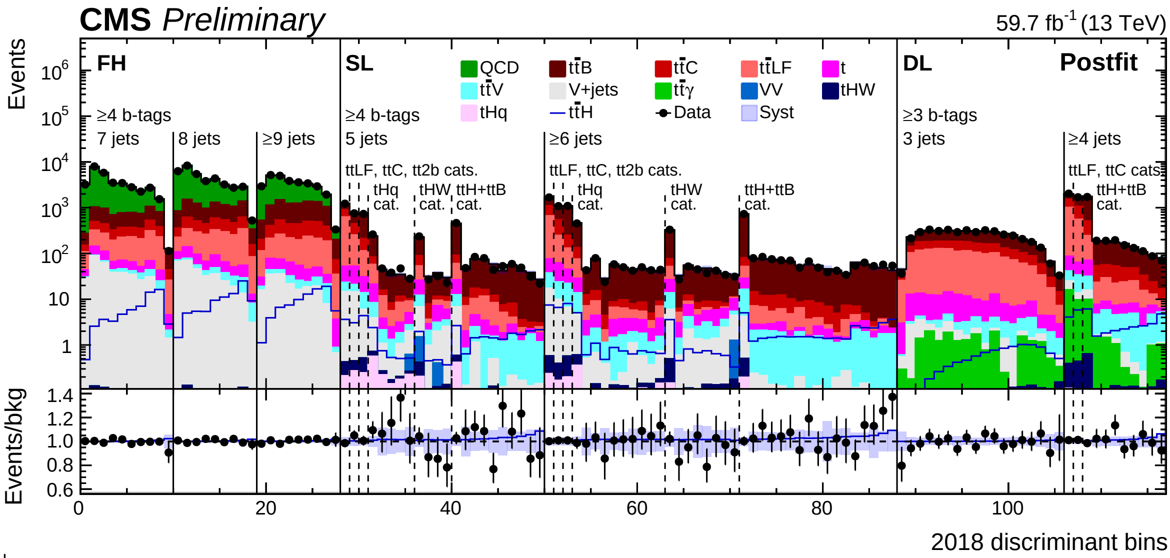
# Final discriminant distribution - 2017

[CMS-PAS-HIG-19-011]



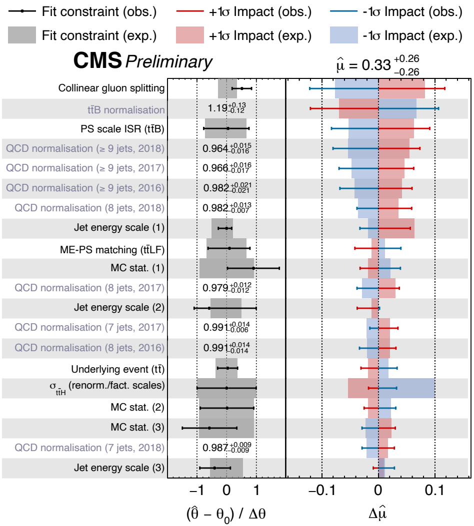
# Final discriminant distribution - 2018

[CMS-PAS-HIG-19-011]



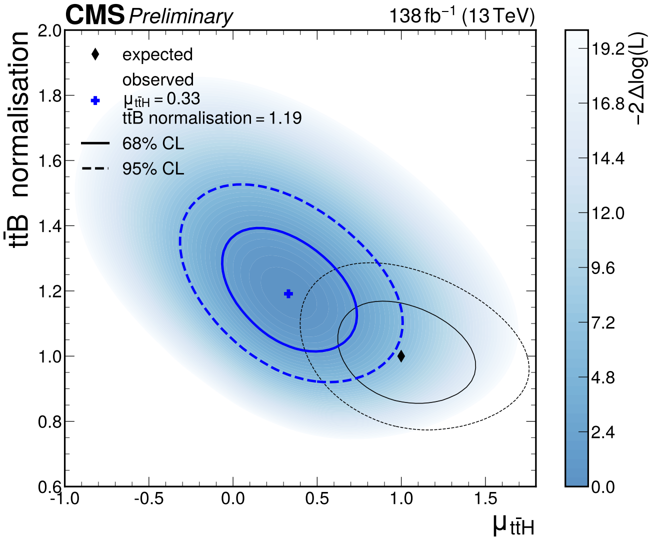
# $t\bar{t}H(b\bar{b})$ measurement: Impacts

[CMS-PAS-HIG-19-011]



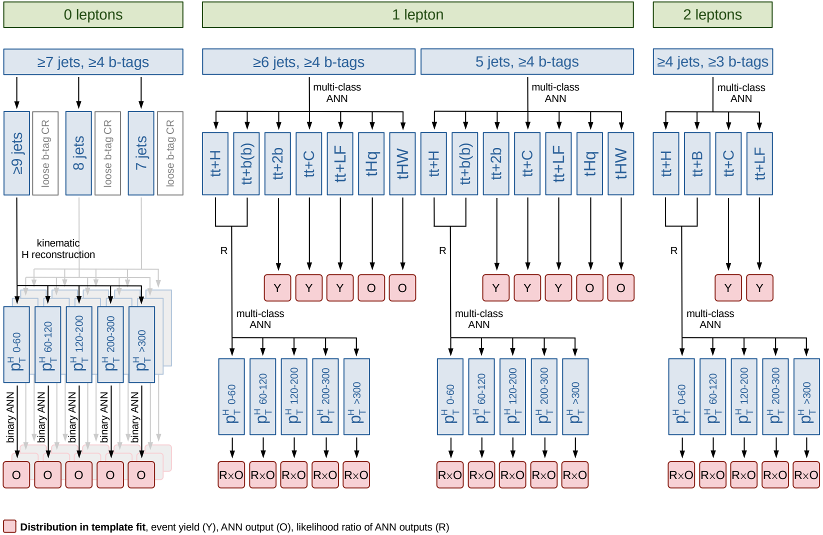
# $t\bar{t}H(b\bar{b})$ measurement: Comparison to $t\bar{t} + B$ norm

[CMS-PAS-HIG-19-011]



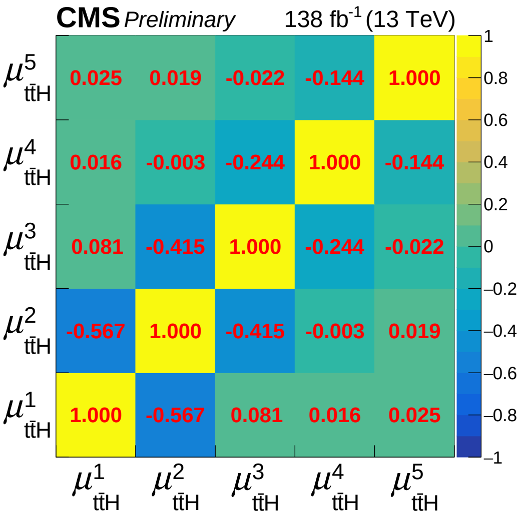
# STXS strategy

[CMS-PAS-HIG-19-011]



# STXS POI correlations

[CMS-PAS-HIG-19-011]



# Statistical model for coupling interpretation

- Introduce additional signal templates for tH and $t\bar{t}H$ for inter-/extrapolation
- $t\bar{t}H$ template calculated with:

$$c_{t\bar{t}H}(\kappa_t, \kappa_V, \tilde{\kappa}_t) = A \cdot \kappa_t{}^2 + B \cdot \tilde{\kappa}_t{}^2$$

  with pure $\mathcal{CP}$-even template $A$ (SM) and pure $\mathcal{CP}$-odd template $B$
- tH template calculated with:

$$c_{tH}(\kappa_t, \kappa_V, \tilde{\kappa}_t) = A \cdot \kappa_t(\kappa_t - \kappa_V) + B \cdot \tilde{\kappa}_t{}^2 + C \cdot \kappa_V(\kappa_V - \kappa_t) + (D + A + C) \cdot \kappa_t \kappa_V$$

  with templates $A$ ($\kappa_t =1$, $\tilde{\kappa}_t =0$, $\kappa_V =0$), $B$ ($\kappa_t =0$, $\tilde{\kappa}_t =1$, $\kappa_V =0$), $C$ ($\kappa_t =0$, $\tilde{\kappa}_t =0$, $\kappa_V =1$) and term $D + A + C$ (SM, $\kappa_t =1$, $\tilde{\kappa}_t =0$, $\kappa_V =1$)
- Everything else same as in tH and $t\bar{t}H$ interpretations

# Compatibility to previous results

The p-values are calculated by evaluating the postfit likelihood of HIG-19-011 at the nominal signal strength measured in the previous analysis. **Caveat: these are approx. numbers (!)**, assuming uncorrelated datasets among analyses and neglecting the uncertainty on the signal strength of the analysis we compare to. The compatibility to the SM (last row) is not subject to such approximations.

| **Reference:** | | **Tested against:** | | **Compatibility** | |
|---|---|---|---|---|---|
| **Analysis** | **Combination** | **Analysis** | **Combination** | **p-value** | **in S.D.** |
| HIG-19-011 | SL+DL<br>2016 | HIG-17-026 | SL+DL<br>2016 | 0.41 | 0.8 $\sigma$ |
| HIG-19-011 | FH+SL+DL<br>2016+2017 | PAS-HIG-18-030 | FH+SL+DL<br>2016+2017 | 0.06 | 1.9 $\sigma$ |
| HIG-19-011 | FH+SL+DL<br>2017 | PAS-HIG-18-030 | FH+SL+DL<br>2017 | 0.02 | 2.4 $\sigma$ |
| HIG-19-011 | FH+SL+DL<br>2016 | PAS-HIG-18-030 | FH+SL+DL<br>2016 | 0.53 | 0.6 $\sigma$ |
| HIG-19-011 | FH+SL+DL<br>2016+2017+2018 | Standard Model hypothesis | | 0.02 | 2.4 $\sigma$ |