# $t(\bar{t})H$ and $t\bar{t}t\bar{t}$ cross section measurements with ATLAS and CMS

## 14th International Workshop on Top Quark Physics

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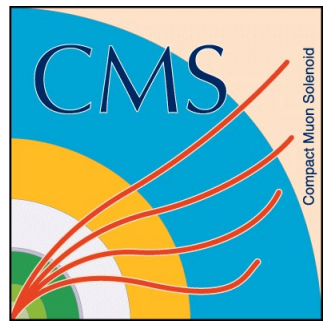
*on behalf of the ATLAS and CMS collaborations*

Humboldt-Universität zu Berlin

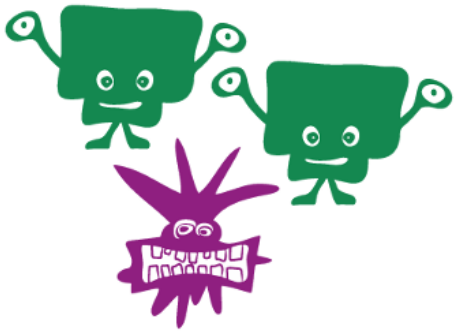
Tuesday, September 14$^{\text{th}}$ 2021





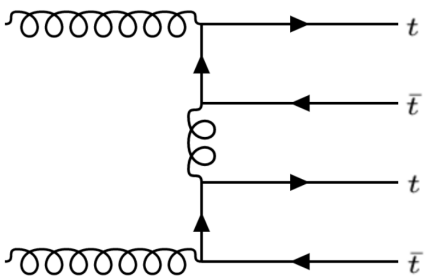
# Introduction

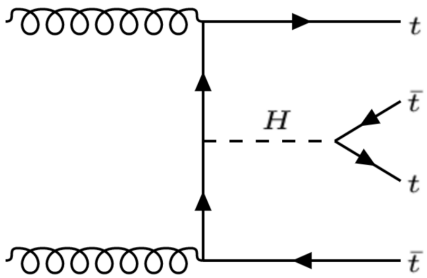
- $t\bar{t}t\bar{t}$ and $t\bar{t}H$ : two new processes at LHC run-2
- Direct probes of top Yukawa coupling, and specific sensitivity to BSM effects
  - → achieved precision on $t\bar{t}H$ now allows to probe top-Higgs coupling structure
  - → $t\bar{t}t\bar{t}$ moreover brings sensitivity to new mediators with strong couplings to the top quark
- Also, analyses targetting these two processes share similarities
  - → similar topologies, and hence similar backgrounds and challenges
- In this talk a brief summary will be made of the latest measurements at 13 TeV
  - → NB : several, very complex analyses - few details can be presented in such limited time !

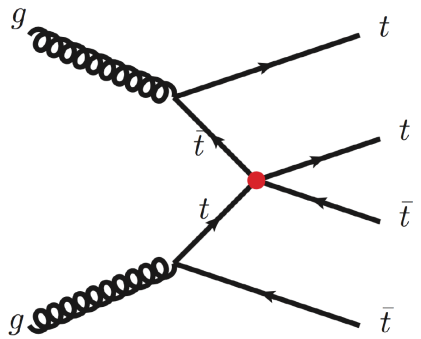


# $t\bar{t}t\bar{t}$ production and decay

- Production dominated by QCD - EW contribution, via e.g. off-shell Higgs
  - → sensitive to top Yukawa coupling, BSM effects
- Prediction : $\sigma_{t\bar{t}t\bar{t}} = 12.0\ \text{fb} \pm 20\%$ JHEP **02** (2018) 031
  - → NLO in QCD and w/ NLO EW corrections - uncert. dominated by $\mu_R/\mu_F$ scale variations




- Final state : 4 *b*-jets from top decays, other jets, leptons
- Topology defined by lepton ($\ell$=*e*, $\mu$, $\tau_{lep}$) multiplicity and charge

| Topology | Branching ratio |
|---|---|
| $0\ell$ | 31% |
| $1\ell$ | 42% |
| $2\ell$(OS) | 14% |
| $2\ell$(SS) | 7% |
| $\geq 3\ell$ | 5% |

# $t\bar{t}t\bar{t}$ cross-section measurements

- No analysis in all-hadronic topology, or using $\tau_{had}$
- ATLAS and CMS measurements divided in two main channels

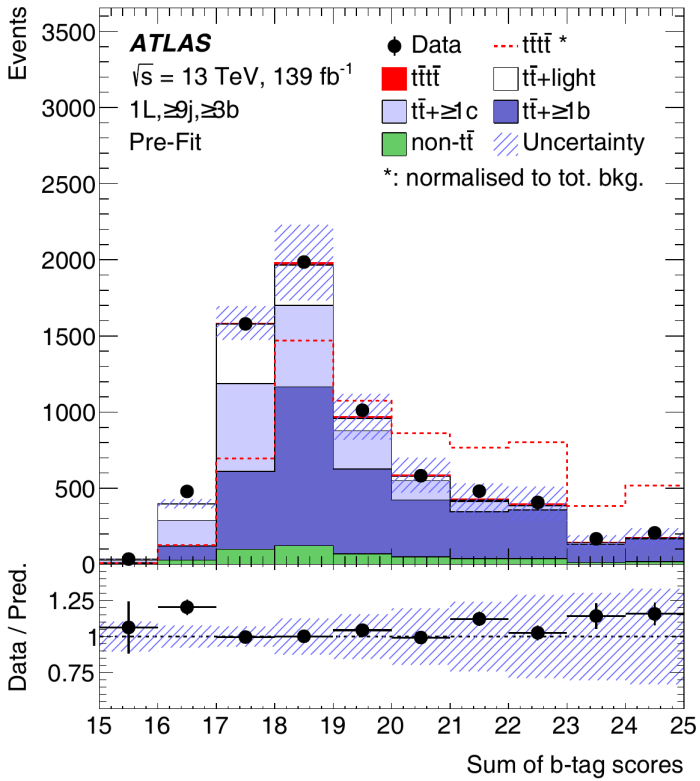
| | 1LOS : $1\ell$ or $2\ell$(OS) | SSML : $2\ell$(SS) or $\geq 3\ell$ |
|---|---|---|
| | $\rightarrow$ Combined BR : $\sim 57\%$ | $\rightarrow$ Combined BR : $\sim 13\%$ |
| | $\rightarrow$ Copious $t\bar{t}+(hf)$jets background | $\rightarrow$ Dominant $t\bar{t}V$ background |
| | $\rightarrow$ Fake & non-prompt $\ell$ negligible | $\rightarrow$ Fake & non-prompt $\ell$ significant |
| CMS | [36 $\text{fb}^{-1}$] JHEP **11** (2019) 082 | [137 $\text{fb}^{-1}$] Eur. Phys. J. C **80** (2020) 75 |
| ATLAS | [139 $\text{fb}^{-1}$] 2106.11683 | [139 $\text{fb}^{-1}$] Eur. Phys. J. C **80** (2020) 1085 |

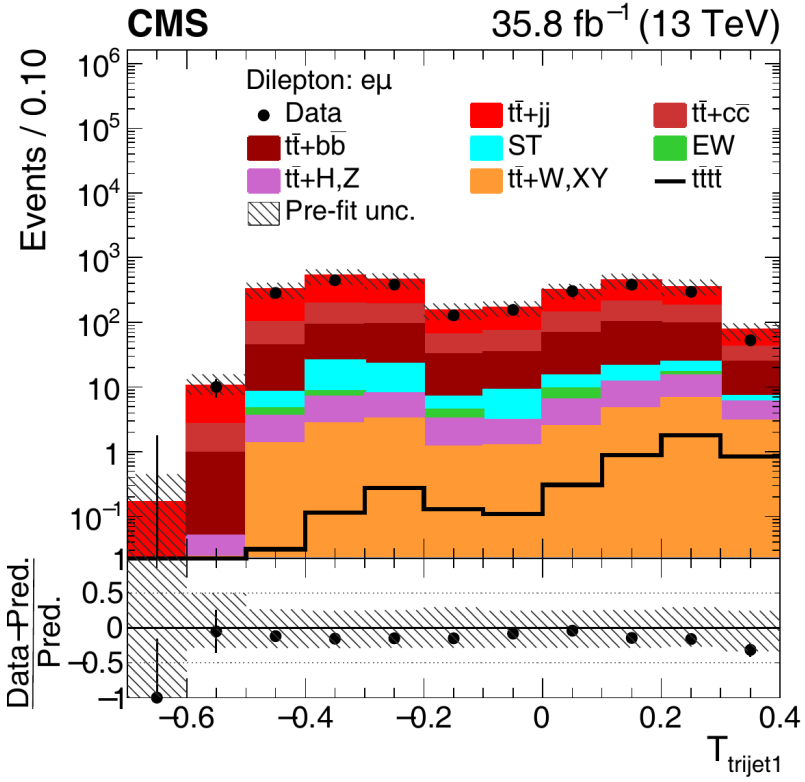
# $t\bar{t}t\bar{t}$ 1$\ell$OS : analysis strategies

- Events split in several categories for 1$\ell$ and 2$\ell$OS
  - $\rightarrow$ using ($b$-)jet multiplicity and different $b$-tagging working points
- BDT discriminants in signal regions to separate signal from backgrounds

ATLAS includes sum of pseudo-continuous $b$-tagging scores, $N_{jets}$, $\Delta R$ between $b$-tagged jets

CMS includes a BDT identifying 3-jets groups from hadronic top, $N_{jets}$, topology variables



# $t\bar{t}t\bar{t}$ 1$\ell$OS : background estimates

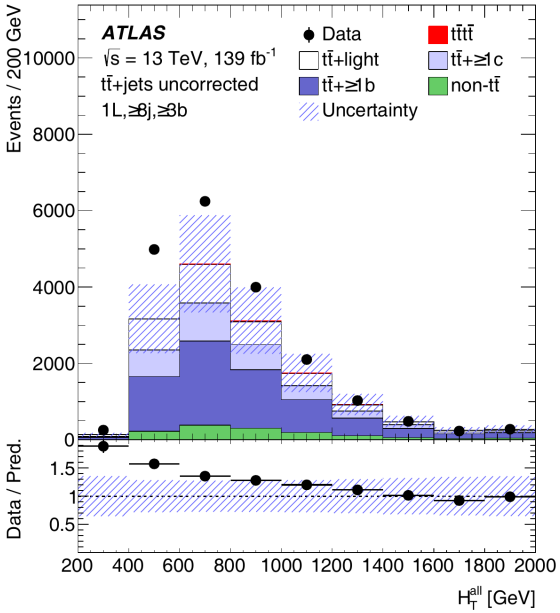
- Dominant background : $t\bar{t}+(hf)$jets production
- $t\bar{t}+\mathrm{HF}$ component fractions

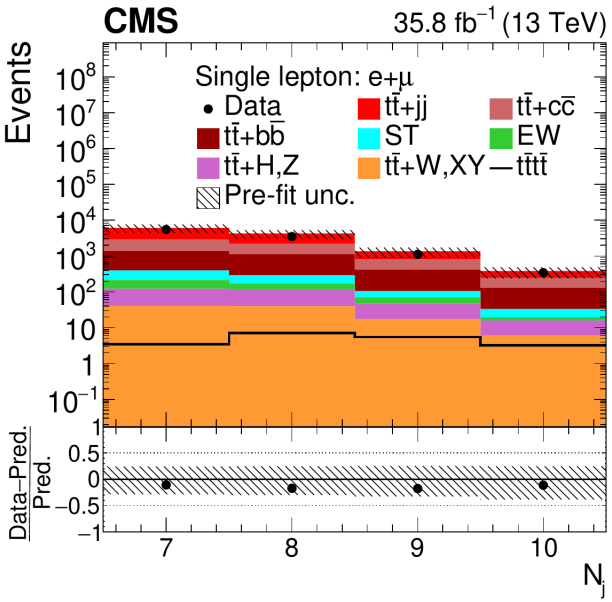
  CMS uncertainty from $t\bar{t}b\bar{b}$ cross-section measurement applied

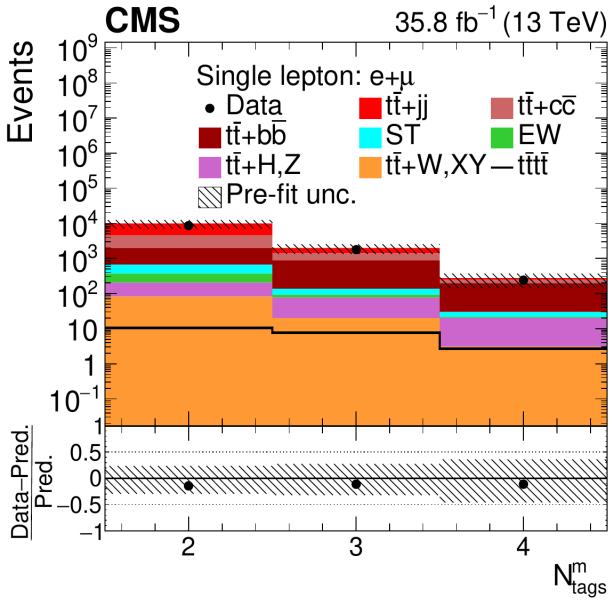
  ATLAS scale-factors derived in looser regions
- Jet multiplicity and event kinematics

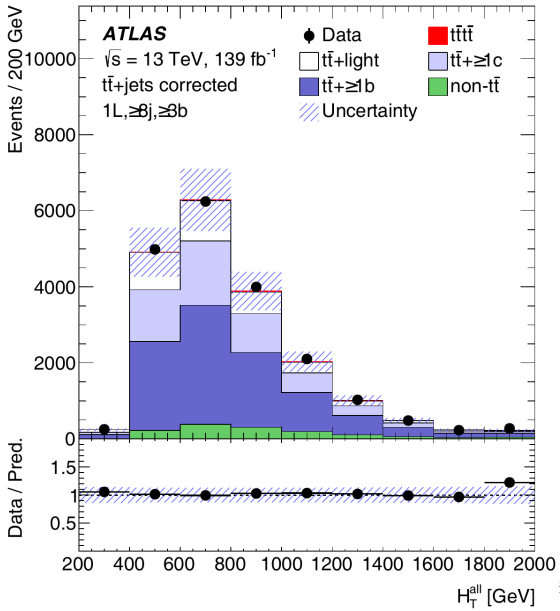
  CMS jet multiplicity and top $p_{\mathrm{T}}$ correction

  ATLAS sequential kinematic reweighting
- Other backgrounds estimated using simulation



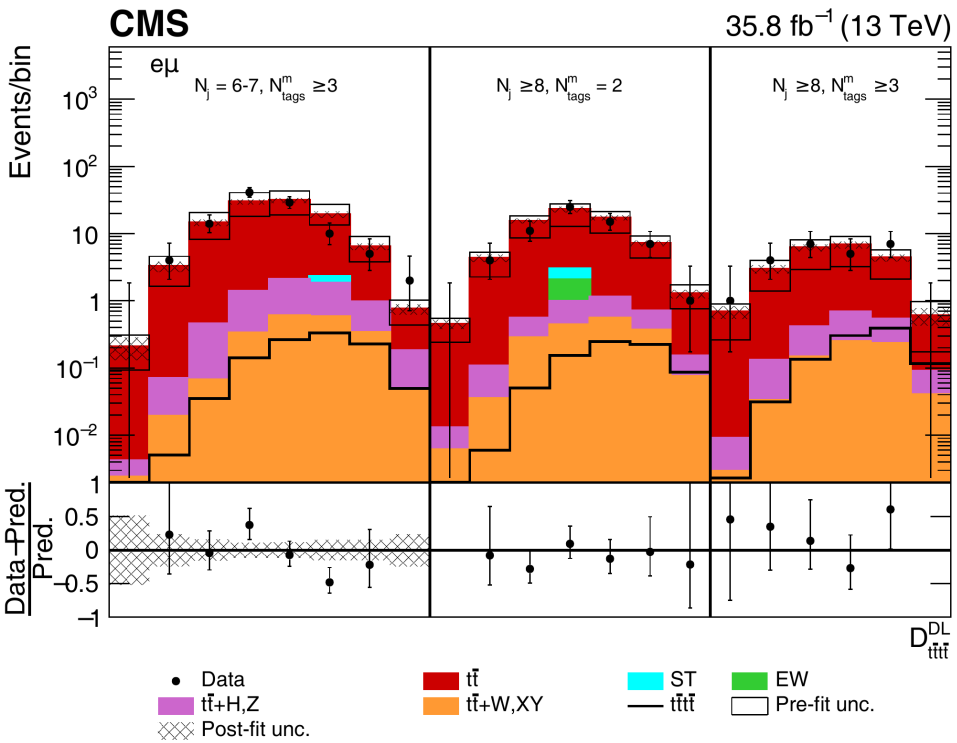



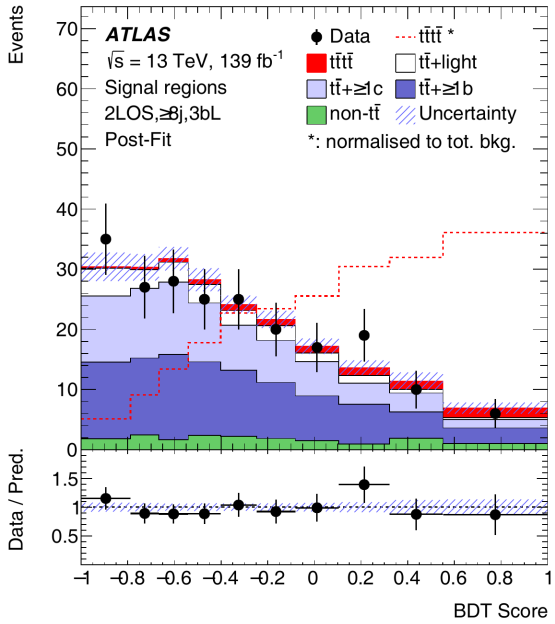



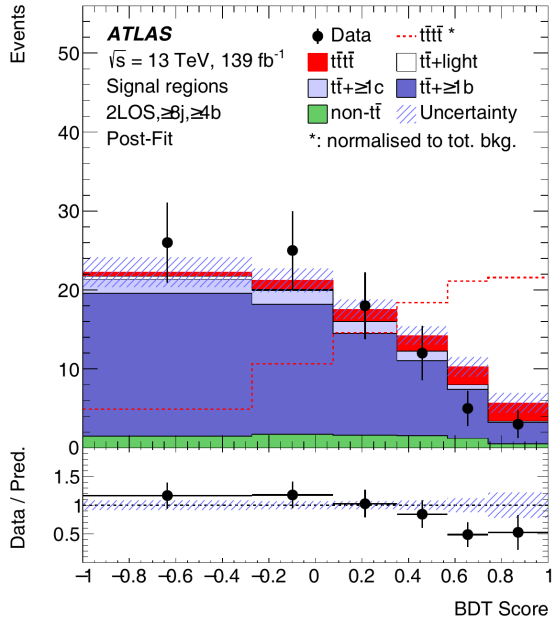



# $t\bar{t}t\bar{t}$ 1$\ell$OS : results

- Profile likelihood fit combining signal and control regions
  - → channel dominated by systematics
  - → $t\bar{t}+(hf)$jets & signal modelling (and : jets & b-tag)
- Measured cross-section : $26^{+17}_{-15}$fb [ATLAS], $0^{+20}$fb [CMS]
  - → obs. significance : 1.9 σ [ATLAS], 0.0 σ [CMS]
  - → exp. significance : 1.0 σ [ATLAS], 0.4 σ [CMS]
- Compatible with SM prediction $12.0 \pm 2.4$ fb
  - → channel not sensitive alone to observe signal



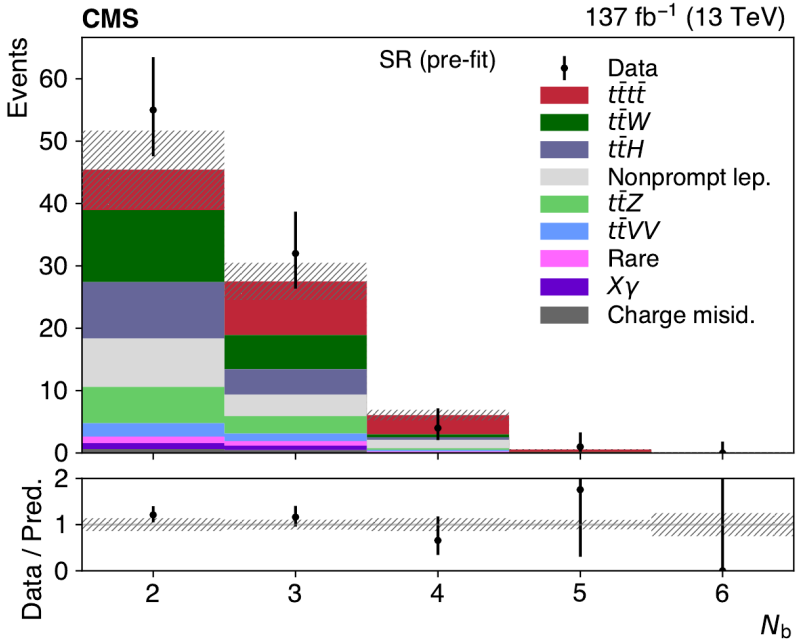



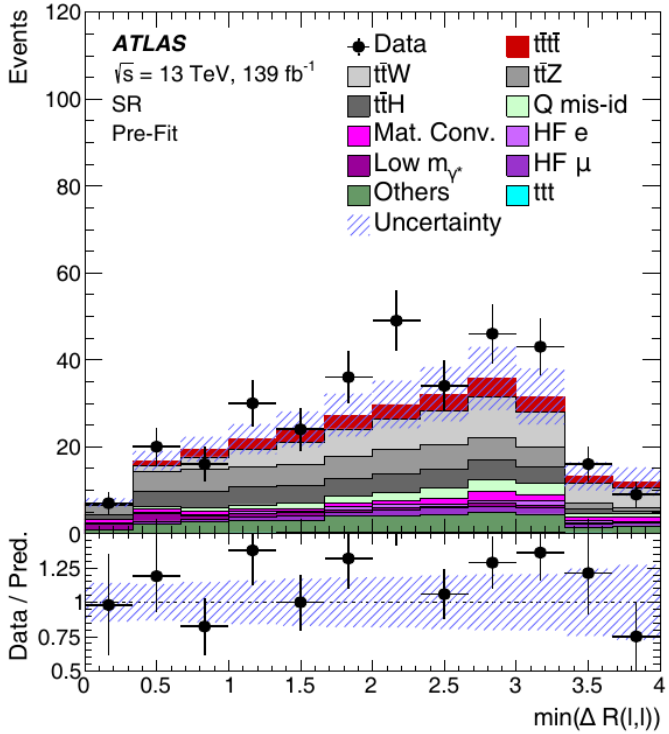
# $t\bar{t}t\bar{t}$ SSML : analysis strategies

- Signal region : $= 2\ell$ (SS) or $\geq 3\ \ell$, $\geq 5$ or 6 jets, $\geq 2$ b-tagged
- BDT to separate signal from the backgrounds

ATLAS 12 input variables, including sum of *b*-tagging scores, $\Delta$R between leptons

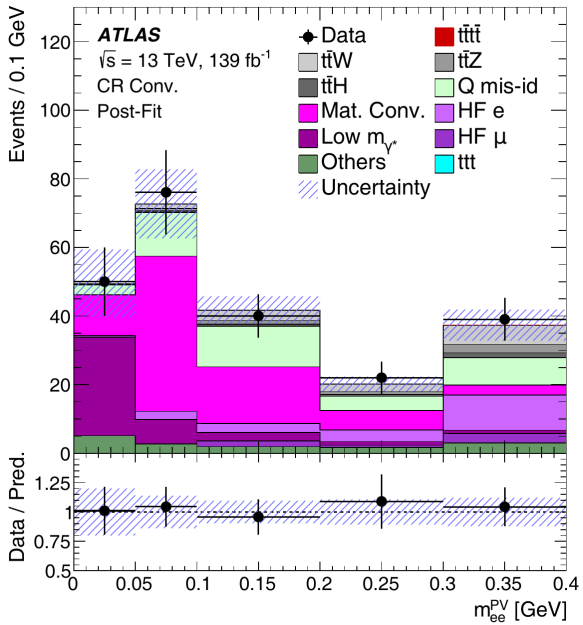
CMS 19 input variables, including (*b*-)jet multiplicity, number of leptons

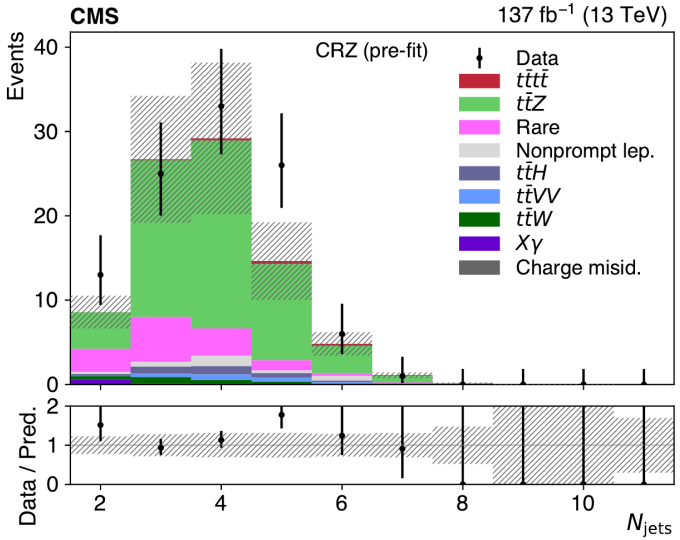


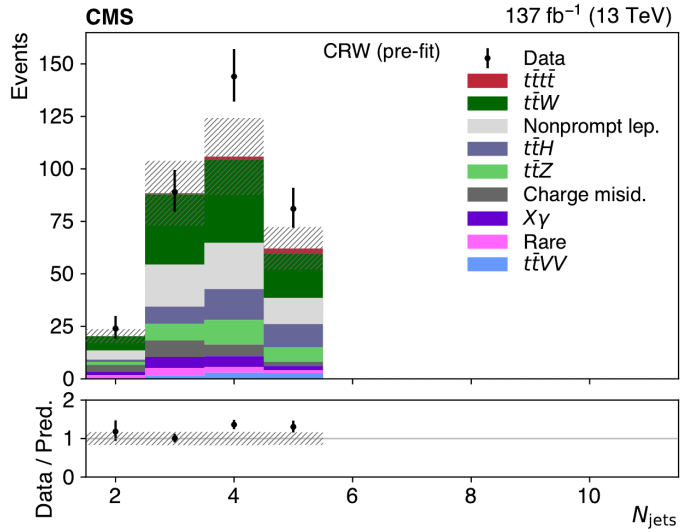



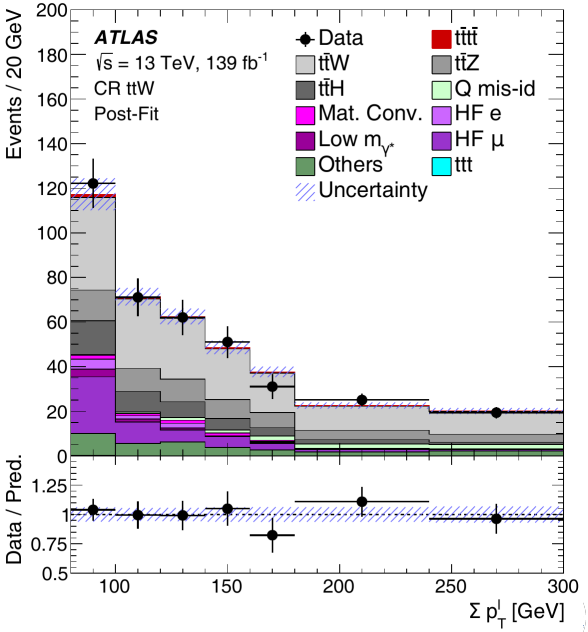
# $t\bar{t}t\bar{t}$ SSML : background estimates

- Dominant contribution of $t\bar{t}W/t\bar{t}Z/t\bar{t}H$
  - CMS ($b$-)jet multiplicity correction from $t\bar{t}$ and $t\bar{t}+\mathrm{HF}$ data
  - ATLAS $t\bar{t}W$ normalisation determined in dedicated control region
  - $\rightarrow$ $t\bar{t}W$ normalisation significantly scaled up in both analyses
- Contribution of non-prompt $b/c \rightarrow \ell$ and conversions
  - CMS 'tight-to-loose' ratio method for $b/c \rightarrow \ell$
  - ATLAS control regions for $b/c \rightarrow \ell$ and $\gamma \rightarrow e$
- Data-driven estimates for $e$ charge mis-ID



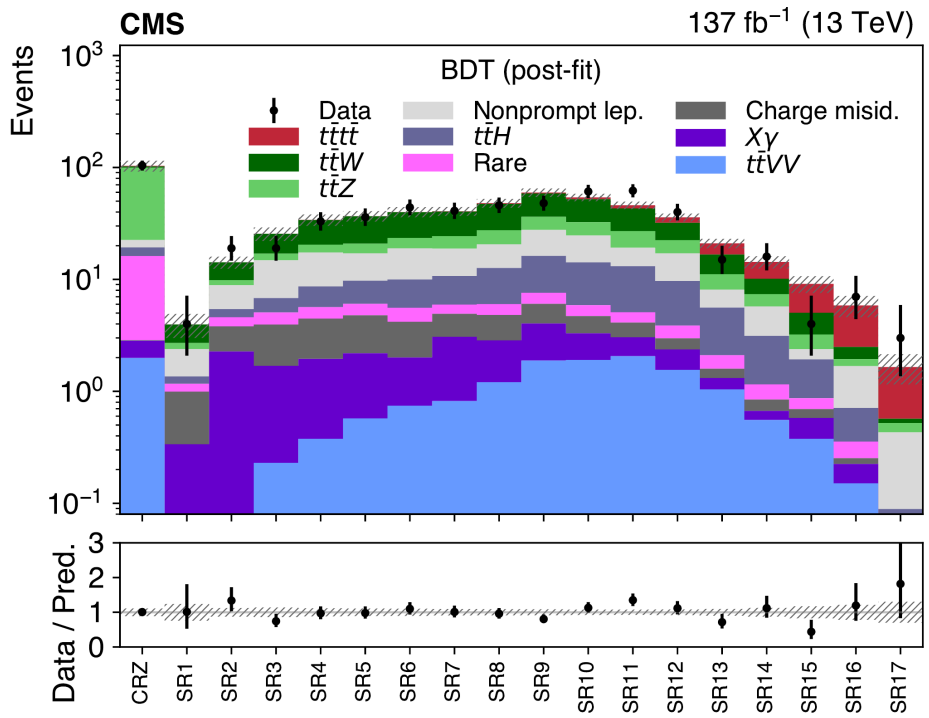



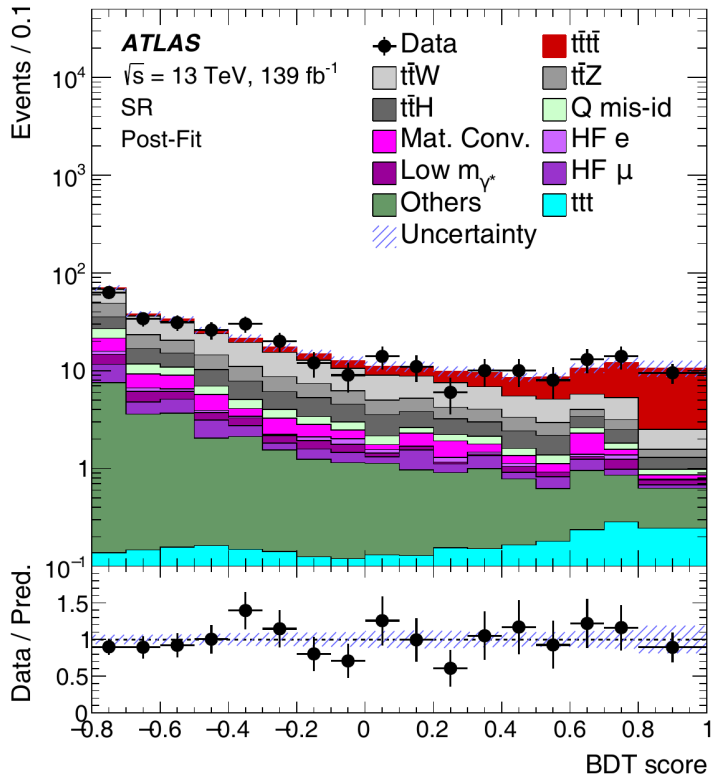



# $t\bar{t}t\bar{t}$ SSML : results

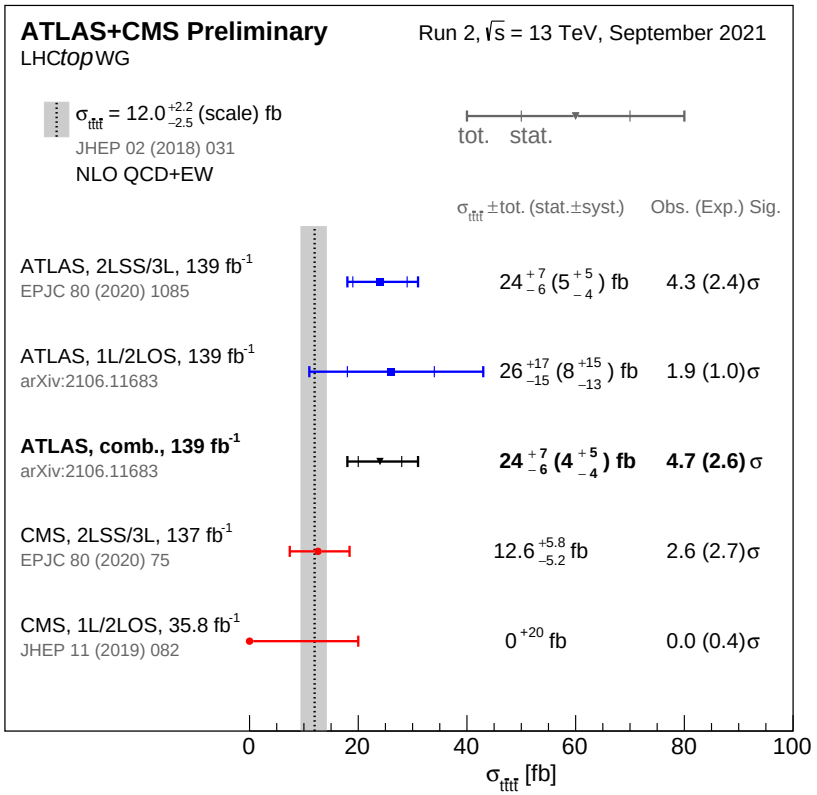
- Overal systematics have impact of similar magnitude as statistics
  - → systs. with largest impact : $t\bar{t}+X$ modelling (then jet, *b*-tagging, and signal modelling)
- Measured cross-section : $12.6^{+5.8}_{-5.2}$fb [CMS], $24^{+7}_{-6}$fb [ATLAS]
  - → obs. significance : 2.6 σ [CMS], 4.3 σ [ATLAS]
  - → exp. significance : 2.7 σ [CMS], 2.4 σ [ATLAS]
- Compatible with SM prediction $12.0 \pm 2.4$ fb
  - → ATLAS result shows largest deviation (1.7 σ)

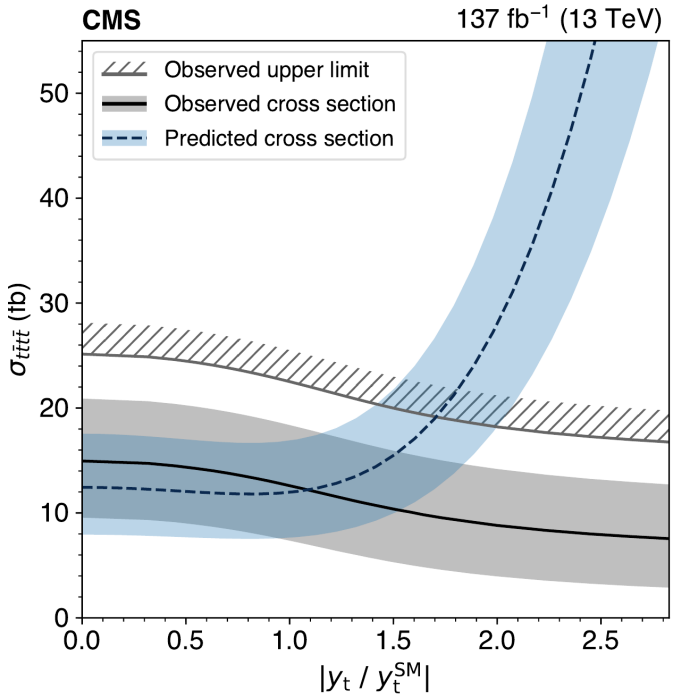


# $t\bar{t}t\bar{t}$ : summary

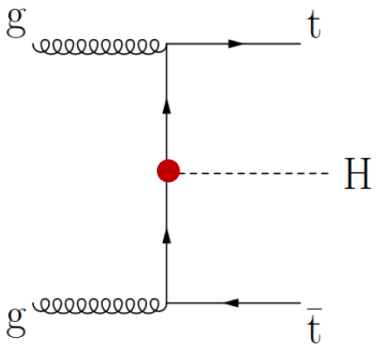
- ATLAS full run-2 combination : $\sigma_{t\bar{t}t\bar{t}} = 24^{+7}_{-6}\text{fb} = 24 \pm 4(\text{stat.})^{+7}_{-6}(\text{syst.})\text{fb}$
  - → observed (expected) significance : 4.7(2.6) σ
  - → result consistent with SM prediction within 2.0 σ
- No CMS full run-2 combination - 1$\ell$OS result yet only with partial dataset
  - → individual analyses well compatible with SM prediction
  - → 1$\ell$OS : EFT interpretation, limits on $O^1_{tt}$, $O^1_{QQ}$, $O^1_{Qt}$, $O^8_{Qt}$ Wilson coefficients
  - → SSML : limits on top-Yukawa coupling, $Z'/\phi$ $t\bar{t}$ resonance, 2HDM and DM models

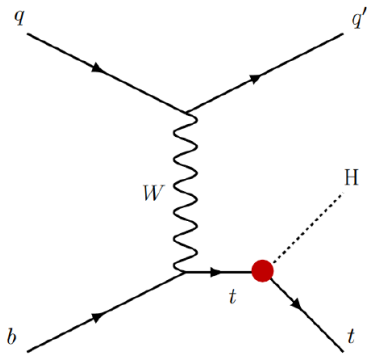


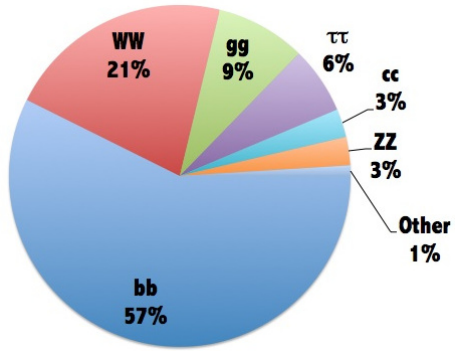



# $t(\bar{t})H$ production and decay

- $t\bar{t}H$ gives a direct access to the amplitude of the top Yukawa
  - → while loop-induced Higgs production or $H \to \gamma\gamma$ are indirect probes
  - → constrains from $t\bar{t}H$ and $t\bar{t}t\bar{t}$ would complement each other in BSM interpretations
  - → prediction (YR4) : $\sigma_{t\bar{t}H} = 507.1^{+6.8}_{-9.9}\text{fb}$ CERN-2017-002
- $tH$ gives access to the sign of the top Yukawa
  - → i.e. relative sign between top-Higgs and W-Higgs couplings
  - → prediction (YR4) : $\sigma_{tH} = 74.3^{+7.5}_{-15.4}\text{fb}$ for t-channel (main production mode)




- Similar final states as for $t\bar{t}t\bar{t}$ analyses, plus :
  - → 'golden' $H \to \gamma\gamma$ channel
  - → ML channel includes categories with $\tau_{had}$ in final state, targetting $H \to \tau\tau$

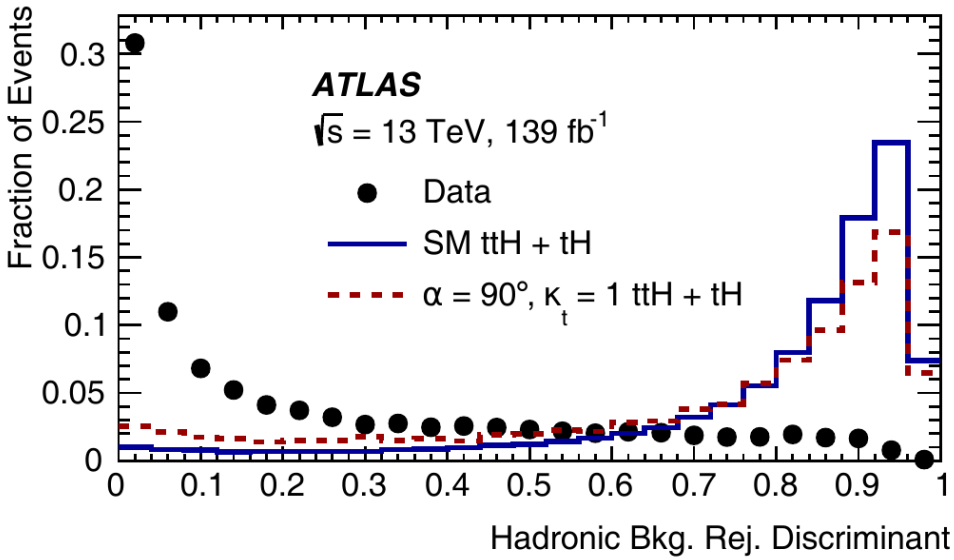
# $t\bar{t}H$ cross-section measurements

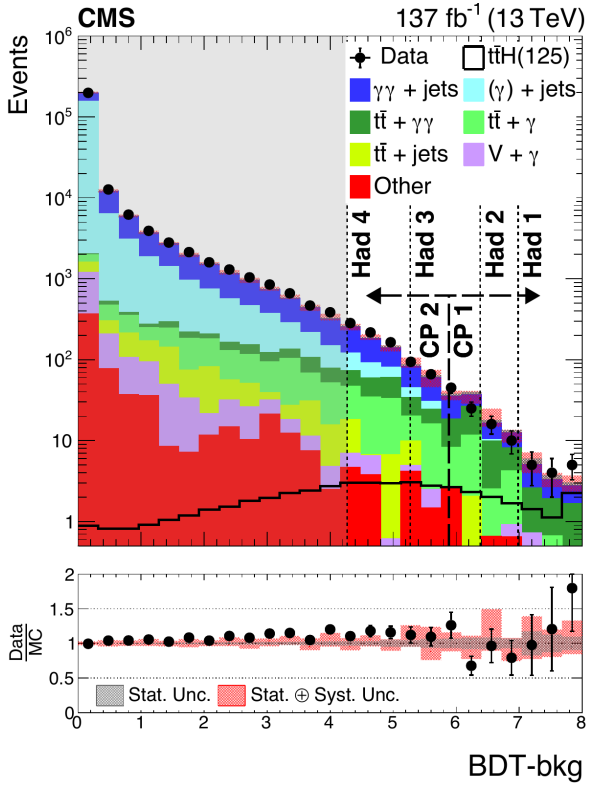
- $t\bar{t}H$ has been observed in 2018 by both collaborations, using partial run-2 datasets
- Now the time for full run-2 analyses has come - presenting here the latest ones
  - → some include differential measurement (STXS framework)
  - → and/or limits on $tH$ production
  - → and/or constrains on CP-odd top-Higgs coupling

| | ATLAS | CMS |
|---|---|---|
| $\gamma\gamma$ | [139 $\text{fb}^{-1}$] Phys. Rev. Lett. **125** (2020) 061802 | [137 $\text{fb}^{-1}$] Phys. Rev. Lett. **125** (2020) 061801 |
| | [139 $\text{fb}^{-1}$] ATLAS-CONF-2020-026 | [137 $\text{fb}^{-1}$] JHEP **07** (2021) 027 |
| $b\bar{b}$ | [139 $\text{fb}^{-1}$] ATLAS-CONF-2020-058 | [77.4 $\text{fb}^{-1}$] CMS-PAS-HIG-18-030 |
| ML | [79.9 $\text{fb}^{-1}$] ATLAS-CONF-2019-045 | [137 $\text{fb}^{-1}$] Eur. Phys. J. C **81** (2021) 378 |

# $t\bar{t}H(\gamma\gamma)$ inclusive measurements : stragegy

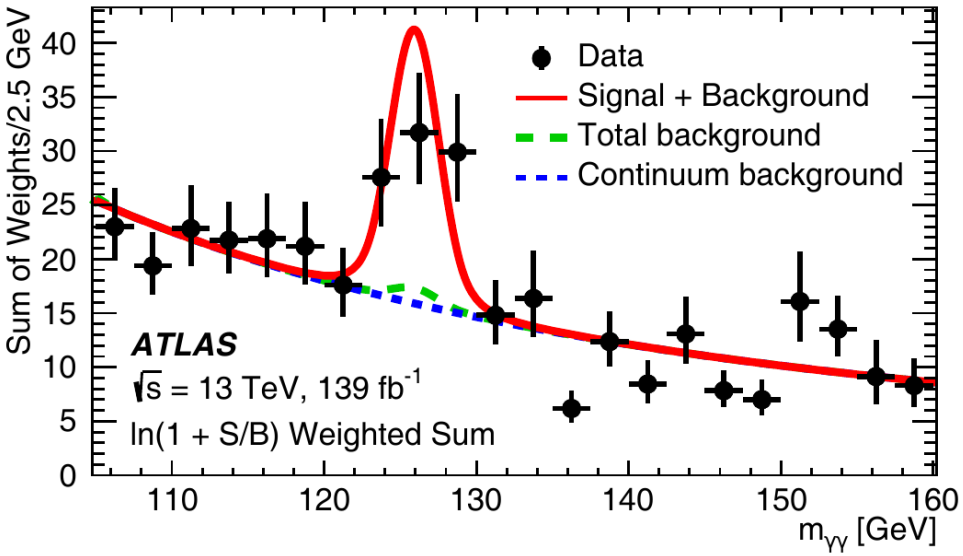
- Dedicated $t\bar{t}H(\gamma\gamma)$ analyses, measuring inclusive $t\bar{t}H$ cross-section
  - → $\gamma\gamma$ invariant mass fitted in several categories
  - → BDT to separate signal from backgrounds
- Also assessing CP-properties of top-Higgs coupling
  - → dedicated BDT to distinguish CP-even (SM-like) from CP-odd $t\bar{t}H$

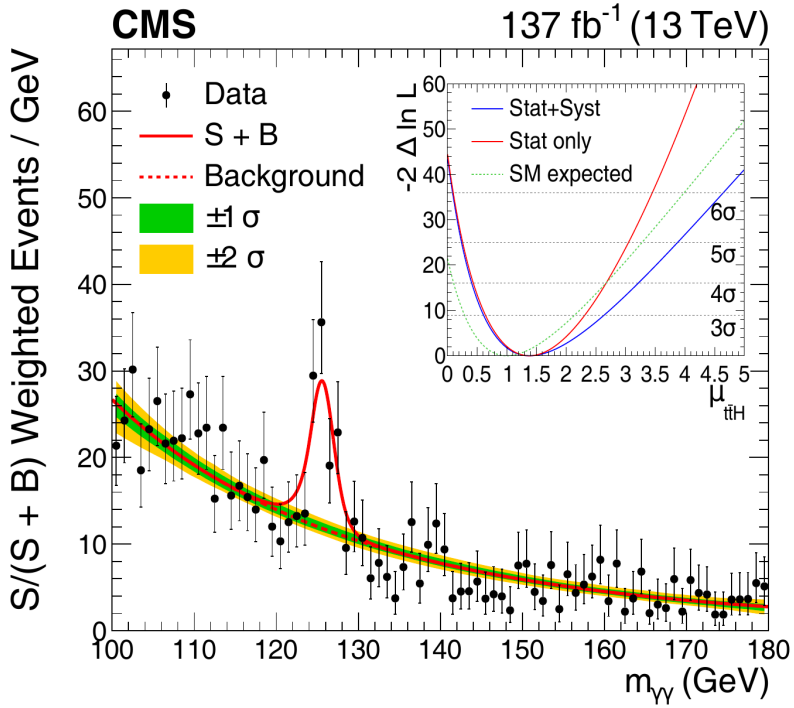


# $t\bar{t}H(\gamma\gamma)$ inclusive measurements : results

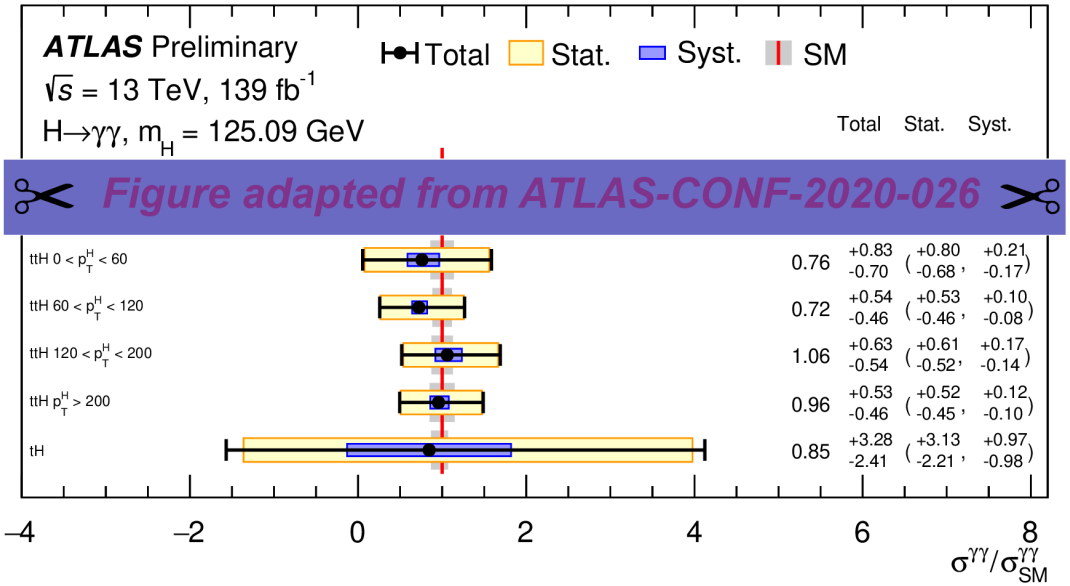
- Measurement limited by data statistics
- Signal strength : $1.43^{+0.33}_{-0.31}(stat)^{+0.17}_{-0.14}(syst)$ [ATLAS], $1.38^{+0.29}_{-0.27}(stat)^{+0.21}_{-0.11}(syst)$ [CMS]
  - → obs. significance : 5.2 σ [ATLAS], 6.6 σ [CMS]
  - → exp. significance : 4.4 σ [ATLAS], 4.7 σ [CMS]
- Pure pseudo-scalar model of CP structure excluded at 3.9 σ [ATLAS], 3.2 σ [CMS]

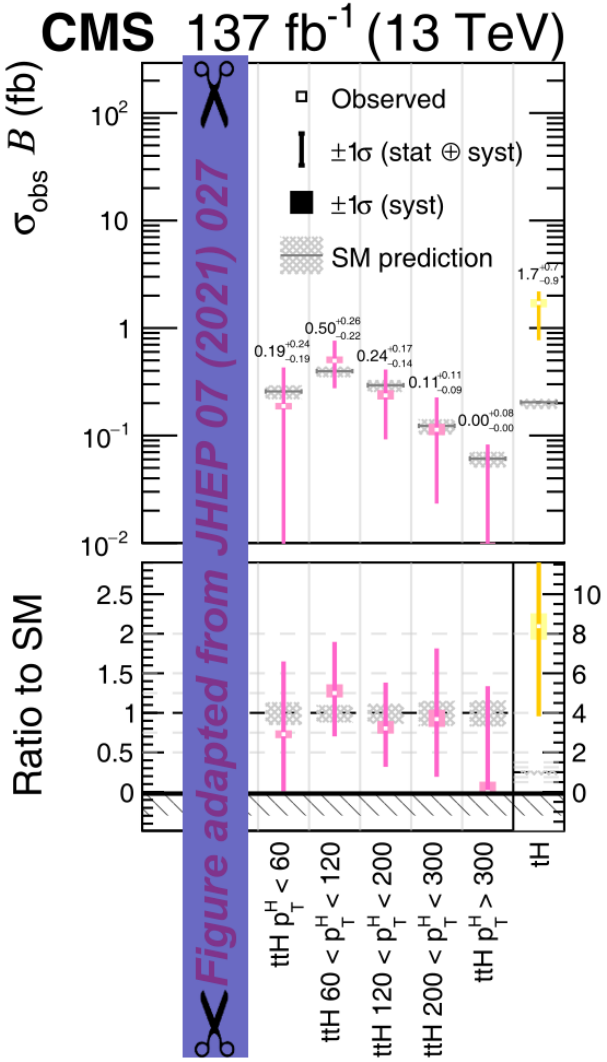


# $t\bar{t}H(\gamma\gamma)$ differential measurements ($H \to \gamma\gamma$ STXS)

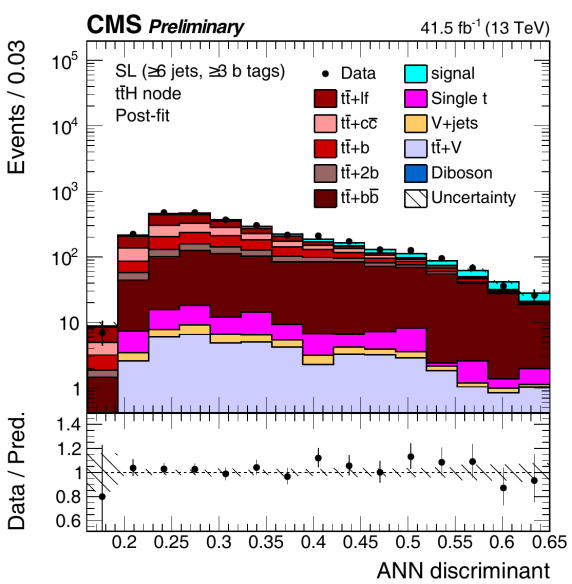
- $H \to \gamma$ analysis combining several production modes
- Simplified Template XSection framework
  - → signal events split in several categories at truth level
  - → categories vs. $p_{\mathrm{T}}(H)$, and one category for $tH$
- $p_{\mathrm{T}}(H)$ in $t\bar{t}H$ measured in 4(5) bins by ATLAS (CMS)
  - → last bin : 200 GeV $-\infty$ (300 GeV $-\infty$)
- $tH$ signal strengths also extracted
  - → $0.85^{+3.28}_{-2.41}$ [ATLAS], $8.38^{+3.48}_{-4.55}$ [CMS]

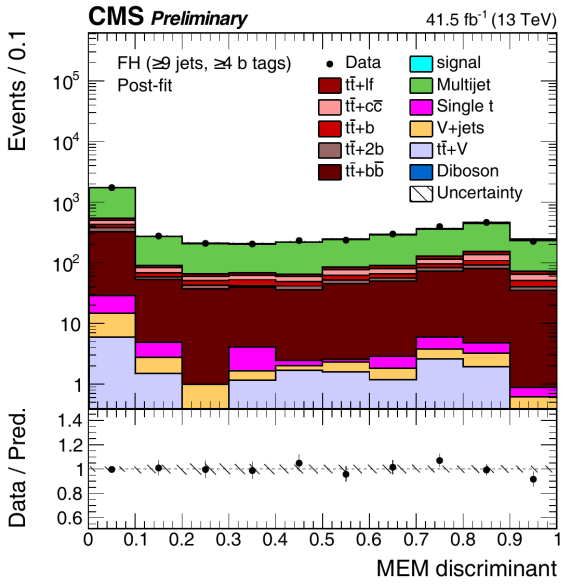


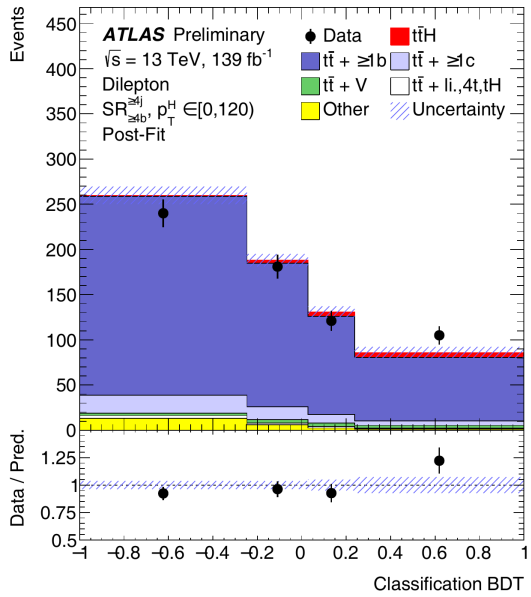



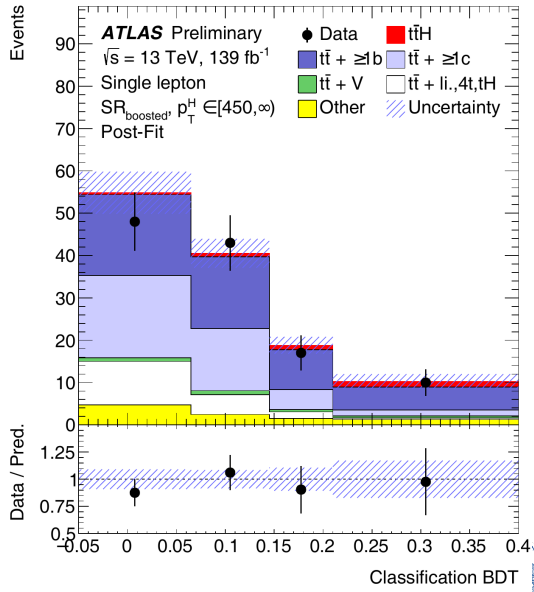
# $t\bar{t}H(b\bar{b})$ : analysis strategies

- Measurement of $t\bar{t}H$ cross-section in $H \to b\bar{b}$ channel
  - CMS dilepton, $\ell$+jets, and all-hadronic final states
  - ATLAS no all-hadronic, but dedicated $\ell$+jets boosted channel
- MVA strategy to separate signal from backgrounds
  - CMS multi-class NN (1 $\ell$), or MEM (2 $\ell$, 0 $\ell$)
  - ATLAS BDT, with additional MVAs to reconstruct Higgs kinematics
- Challenging $t\bar{t} \geq 1b$ background
  - CMS rate uncertainties added on each sub-components
  - ATLAS NLO $t\bar{t}b\bar{b}$(4fs) MC, free-floating normalisation



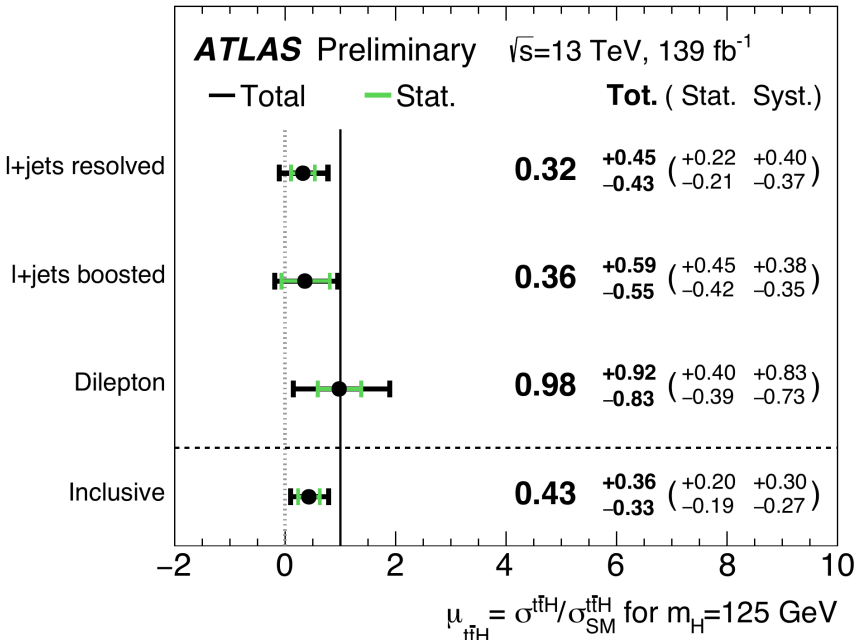



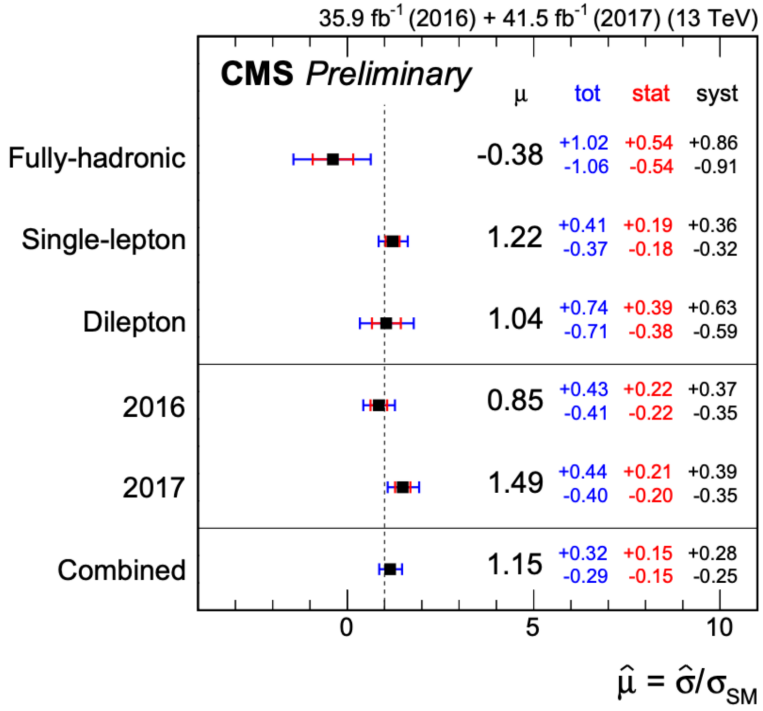



# $t\bar{t}H(b\bar{b})$ : results (inclusive)

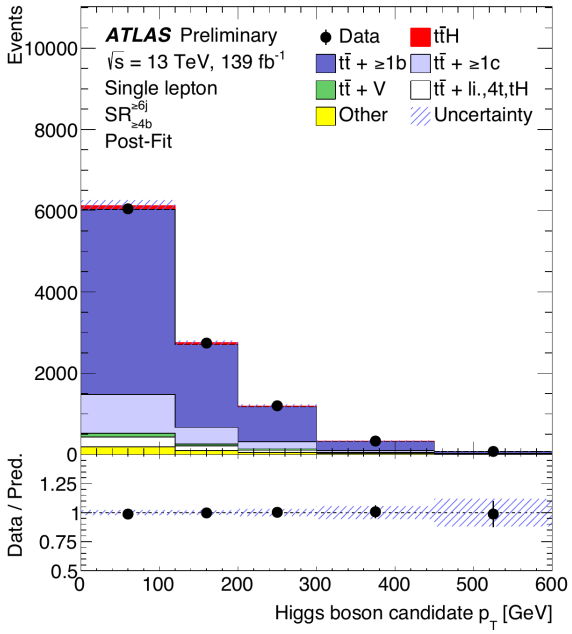
- Measurement dominated by systematic uncertainties
  - → especially uncertainties on $t\bar{t} \geq 1b$ modelling (before jets and b-tagging calibration)
  - → $t\bar{t} \geq 1b$ and $t\bar{t} \geq 1c$ normalisation higher than SM prediction
- Signal strength : $0.43^{+0.36}_{-0.33}$ [ATLAS], $1.15^{+0.32}_{-0.29}$ [CMS]
  - → obs. significance : 1.3 σ [ATLAS], 3.7 σ [CMS]
  - → exp. significance : 3.0 σ [ATLAS], 2.6 σ [CMS]
- Both all-hadronic and $\ell$+jets boosted channels have significant contribution

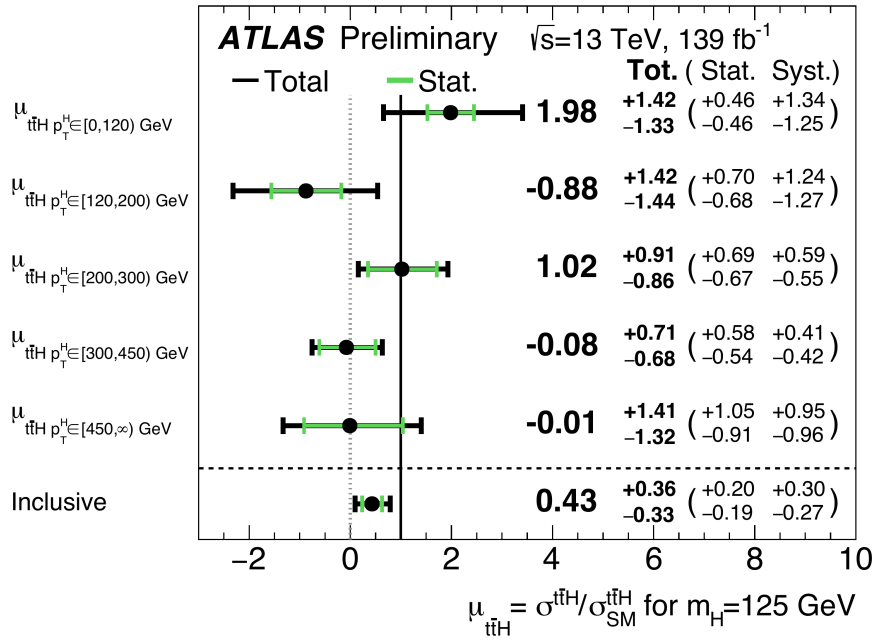


# $t\bar{t}H(b\bar{b})$ : results (differential)

- ATLAS uses Higgs kinematics reconstruction to perform a STXS measurement
  - → events categorised as function of Higgs $p_{\mathrm{T}}$
  - → requires additional care on $t\bar{t} \geq 1b$ background modelling
- Result : measurement of the cross-section in 5 $p_{\mathrm{T}}$ bins
  - → last bin : 450 GeV $-\infty$ (beyond the $\gamma\gamma$ range)
  - → contribution of $\ell$+jets boosted channel above 300GeV
  - → no significant deviation wrt. SM prediction



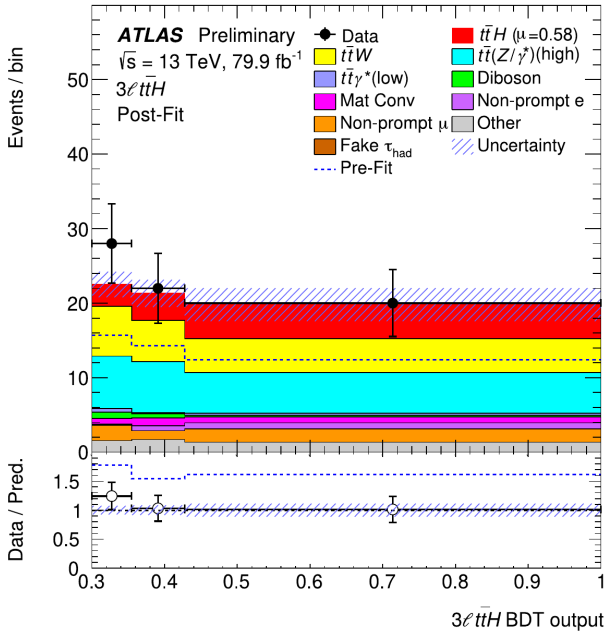



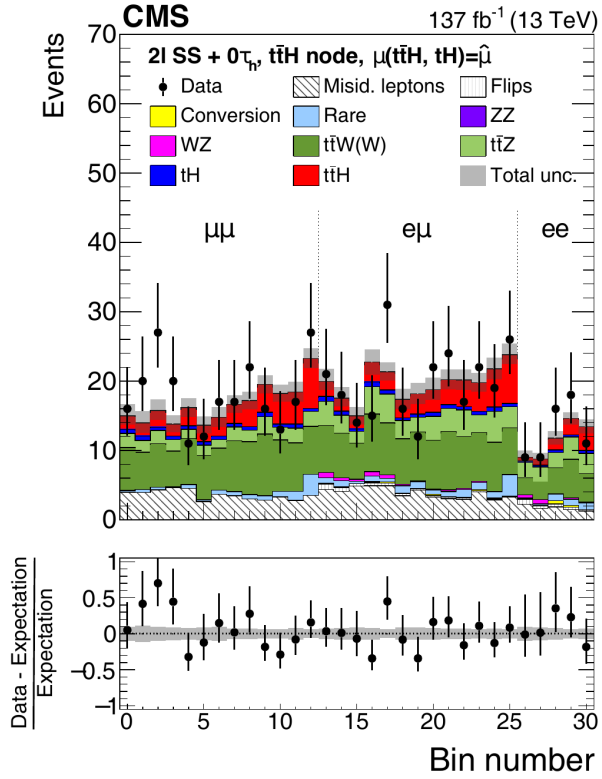
# $t\bar{t}H$(ML) : analysis strategies

- Events classified based on the number of $\ell$ and $\tau_{had}$, jets and *b*-jets
  - $\rightarrow$ 10(6) categories for CMS(ATLAS), targetting different $t\bar{t}H$ topologies
- MVA techniques used in the most sensitive categories

CMS multiclass NN in categories sensitive to $t\bar{t}H$ and $tH$, or BDT

ATLAS BDT, or multiclass BDT to distinguish the different backgrounds



# $t\bar{t}H$(ML) : background estimates

- Reducible : non-prompt $\ell$, $\tau_{had}$ fakes, conversions - data-driven techniques
- Dominant and challenging background : $t\bar{t}W$

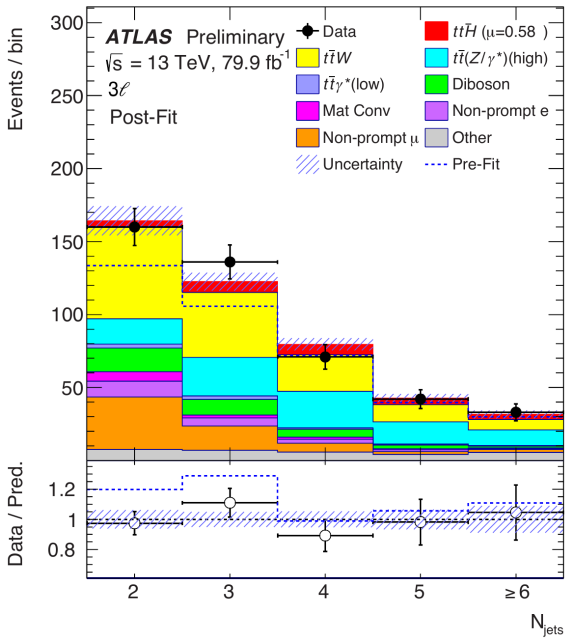
CMS normalisation floated in the fit, dedicated node in the NN

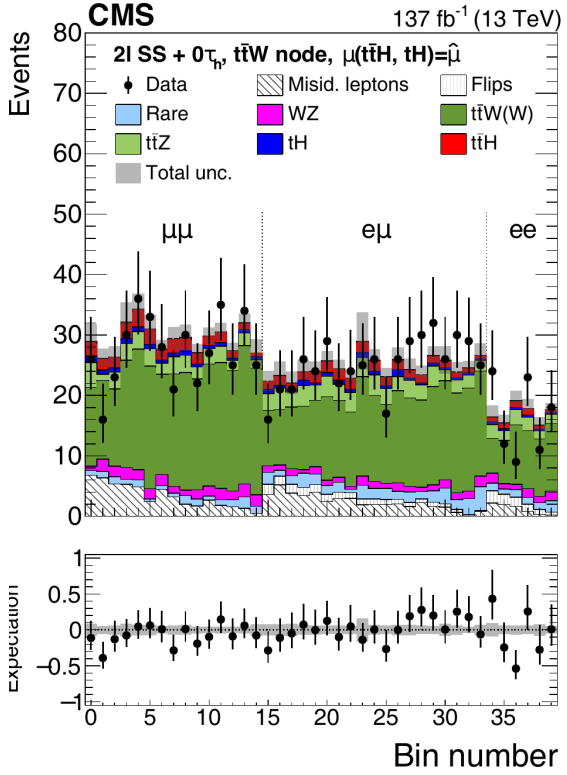
ATLAS 3 floated norm. factors ($2\ell$ at low/high Njets, and $3\ell$), uncertainties on QCD radiation

- Tension with $t\bar{t}W$ SM prediction - fitted norm factors :

CMS $1.43 \pm 0.21$ (and $1.03 \pm 0.14$ for $t\bar{t}Z$)

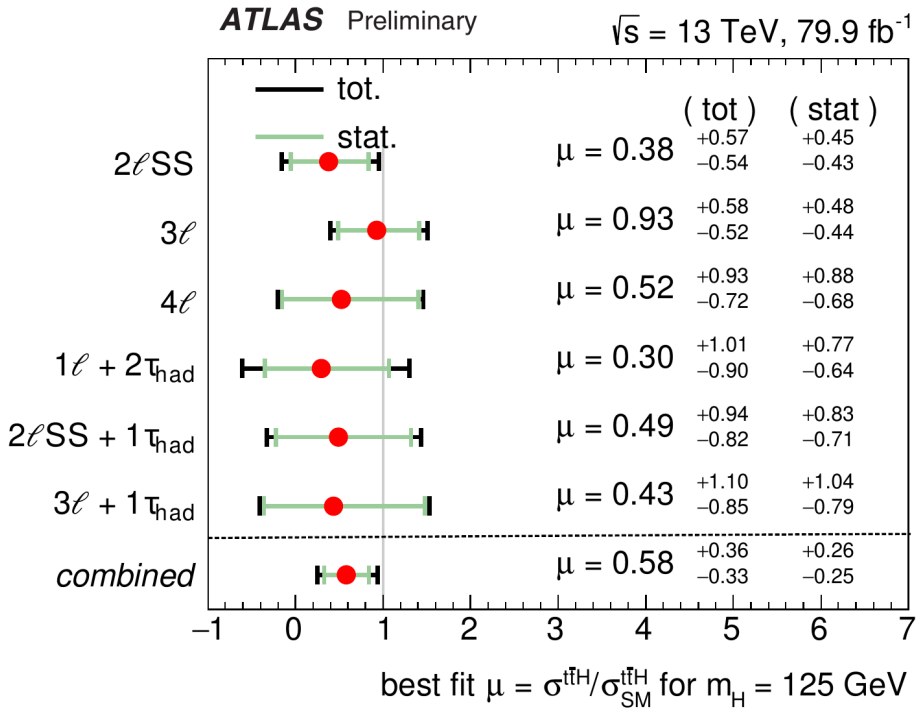
ATLAS $1.56^{+0.30}_{-0.33}$ ($2\ell$ low), $1.26^{+0.19}_{-0.18}$ ($2\ell$ high), and $1.68^{+0.30}_{-0.28}$ ($3\ell$)

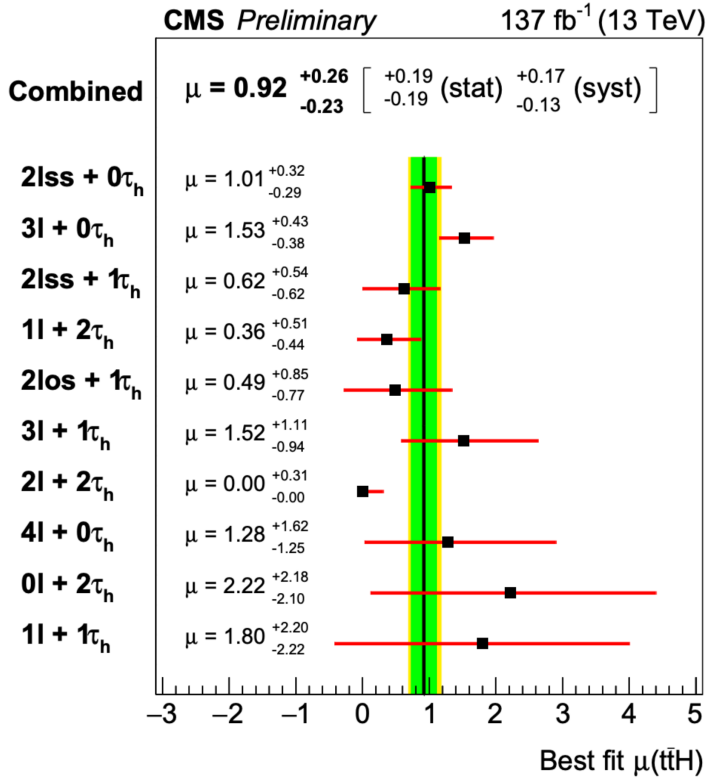


# $t\bar{t}H$(ML) : results

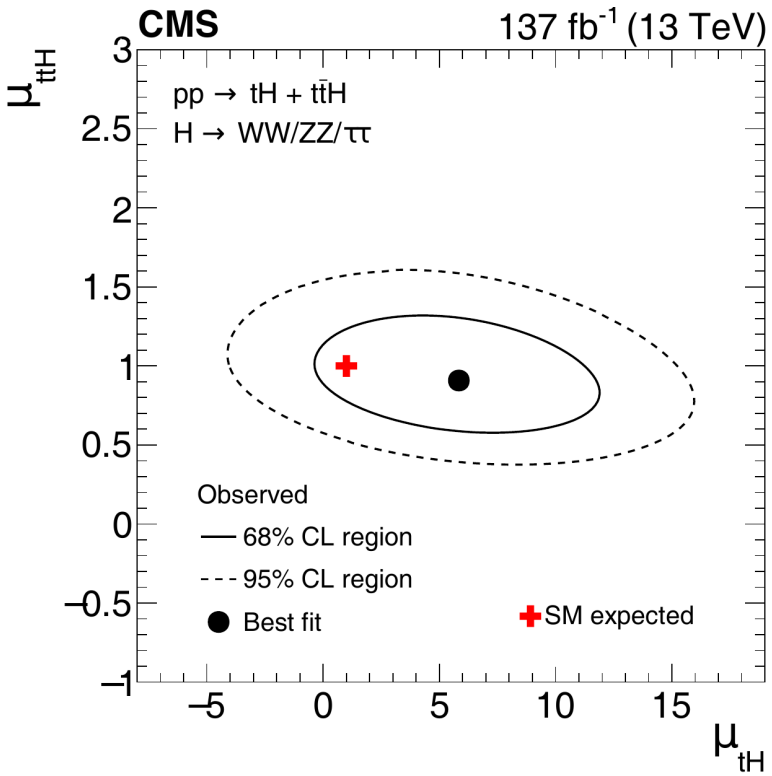
- Signal strength : $0.58^{+0.36}_{-0.33}$ [ATLAS], $0.92^{+0.26}_{-0.23}$ [CMS]
  - → obs. significance : 1.8 σ [ATLAS], 4.7 σ [CMS]
  - → exp. significance : 3.1 σ [ATLAS], 5.2 σ [CMS]
- Impact of syst. and stat. uncertainties at similar level
- No significant deviation wrt. SM prediction

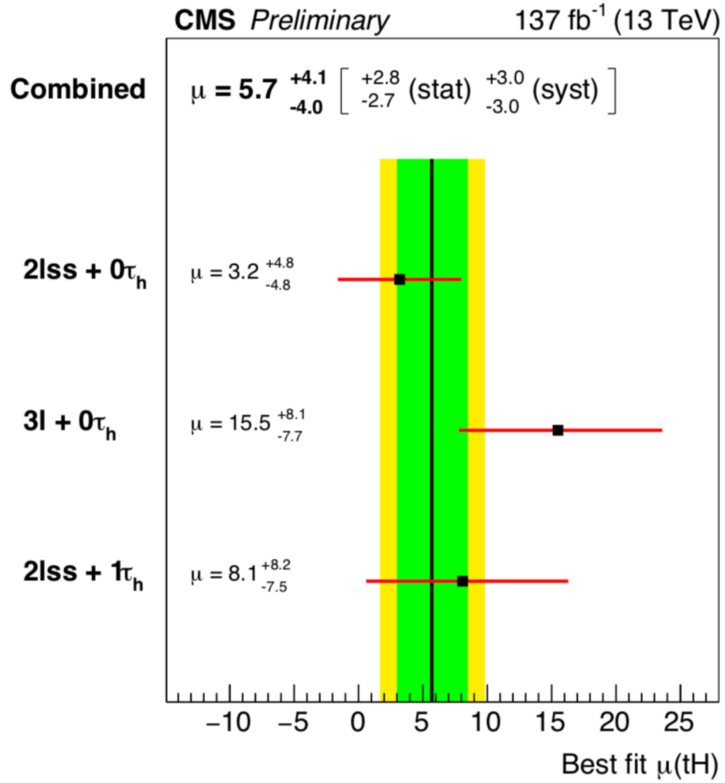


# $t\bar{t}H$(ML) : results ($tH$)

- CMS' analysis also provides a measurement of $tH$ cross-section
  - → 3 categories sensitive to $tH$
  - → simultaneous measurement of $t\bar{t}H$, $tH$, $t\bar{t}Z$, $t\bar{t}W$ - showing here $t\bar{t}H$ vs. $tH$
- Signal strength : $5.7^{+4.1}_{-4.0}$
  - → obs. (exp.) significance : 1.4(0.3) σ



# $t\bar{t}H$ : summary

- Inclusive signal strengths for the presented (preliminary) results :

| | | ATLAS | CMS |
|---|---|---|---|
| $\gamma\gamma$ | $t\bar{t}H$ | $[139\ \text{fb}^{-1}]\ 1.43^{+0.41}_{-0.36}$ | $[137\ \text{fb}^{-1}]\ 1.38^{+0.36}_{-0.29}$ |
| | $tH$ | $[139\ \text{fb}^{-1}]\ 0.85^{+3.28}_{-2.41}$ | $[137\ \text{fb}^{-1}]\ 1.7^{+0.7}_{-0.9}$ |
| $b\bar{b}$ | $t\bar{t}H$ | $[139\ \text{fb}^{-1}]\ 0.43^{+0.36}_{-0.33}$ | $[77.4\ \text{fb}^{-1}]\ 1.15^{+0.32}_{-0.29}$ |
| ML | $t\bar{t}H$ | $[79.9\ \text{fb}^{-1}]\ 0.58^{+0.36}_{-0.33}$ | $[137\ \text{fb}^{-1}]\ 0.92^{+0.26}_{-0.23}$ |
| | $tH$ | | $[137\ \text{fb}^{-1}]\ 5.7^{+4.1}_{-4.0}$ |

- Not presented in this talk : CMS earlier $tH$ result from Phys. Rev. D **99** (2019) 092005
  → using only 35.9 $\text{fb}^{-1}$ (2016), but all channels ($\gamma\gamma$/$b\bar{b}$/ML)

- STXS signal strengths for the presented (preliminary) results :

| $p_{\text{T}}(H)$ [GeV] | ATLAS ($b\bar{b}$) | ATLAS ($\gamma\gamma$) | CMS ($\gamma\gamma$) |
|---|---|---|---|
| 0-60 | $1.98^{+1.42}_{-1.33}$ | $0.76^{+0.83}_{-0.70}$ | $0.73^{+0.92}_{-0.73}$ |
| 60-120 | | $0.72^{+0.54}_{-0.46}$ | $1.25^{+0.65}_{-0.55}$ |
| 120-200 | $-0.88^{+1.42}_{-1.44}$ | $1.06^{+0.63}_{-0.54}$ | $0.80^{+0.58}_{-0.49}$ |
| 200-300 | $1.02^{+0.91}_{-0.86}$ | $0.96^{+0.53}_{-0.46}$ | $0.92^{+0.89}_{-0.73}$ |
| 300-450 | $-0.08^{+0.71}_{-0.68}$ | | $0.00^{+1.34}_{-0.00}$ |
| 450-$\infty$ | $-0.01^{+1.41}_{-1.32}$ | | |

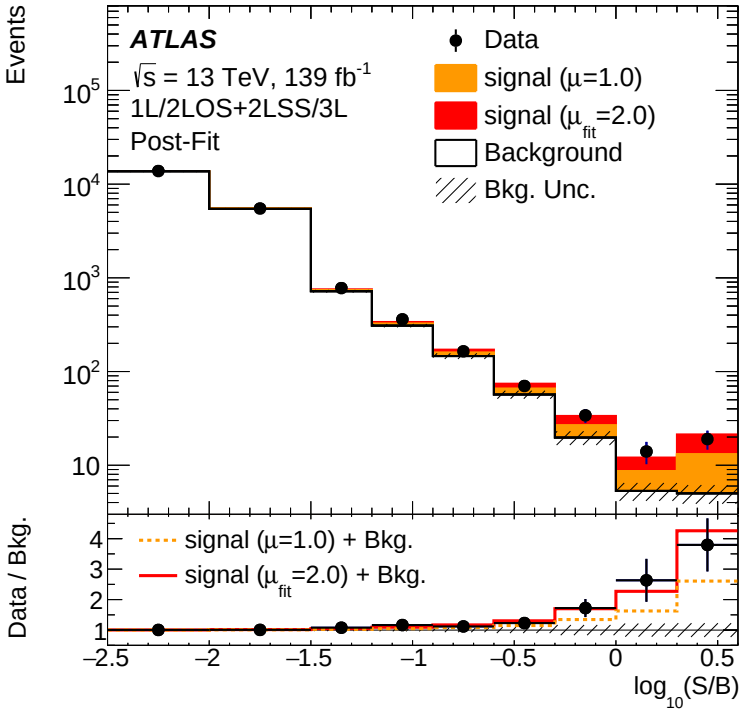
# Conclusion

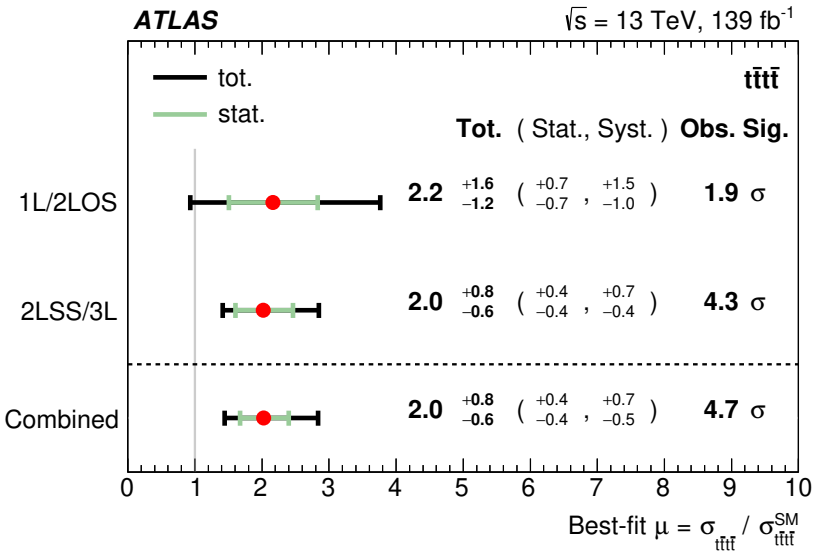
- $t\bar{t}H$ was been observed already with partial run-2 dataset
  - → more information can now be extracted from data : differential, CP-structure
  - → limits on more challenging $tH$ production are set
- $t\bar{t}t\bar{t}$ is not yet observed, but significance is getting close to 5 $\sigma$
- Analyses with similar headaches : modelling of $t\bar{t}W$ (multilepton), $t\bar{t}b\bar{b}$ (multi-$b$)
  - → improvements may come from better MC, and/or from ancillary measurements
- Measurements of great use in the context of EFT interpretation
  - → deviations wrt. SM predictions can be interpreted as limits on Wilson coefficients
  - → this is happening already, for individual channels or in global fits
- Some of the presented results are still preliminary, and/or use partial dataset
  - → the analysis of run-2 data is not over yet !

# Backup

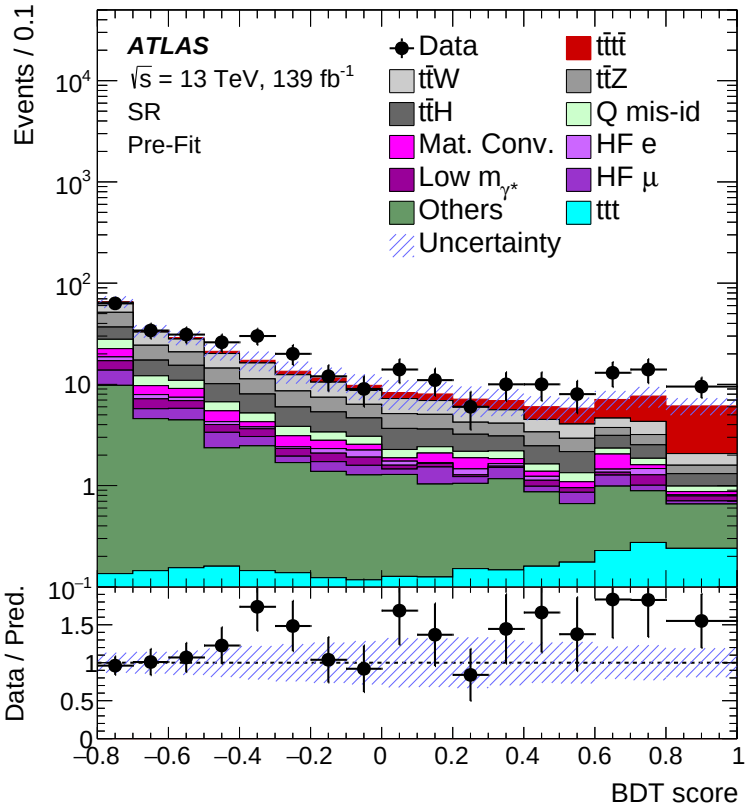
# Backup

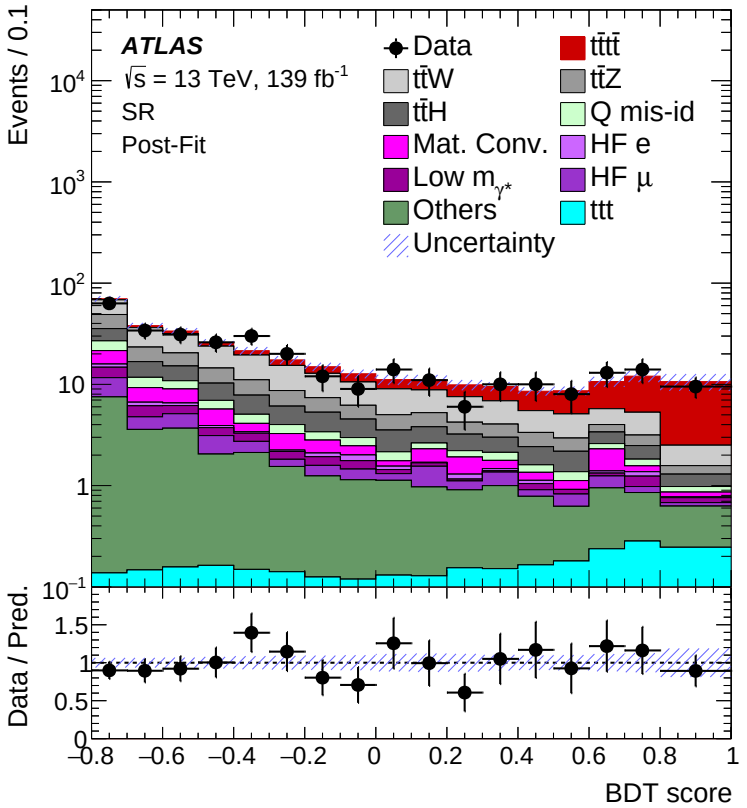
# ATLAS $t\bar{t}t\bar{t}$ combination - 2106.11683



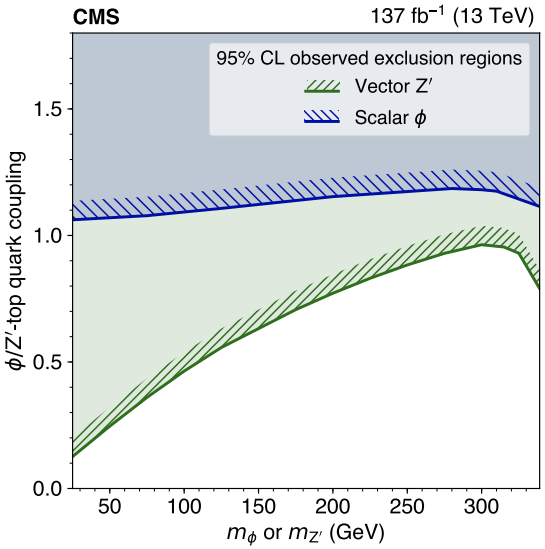



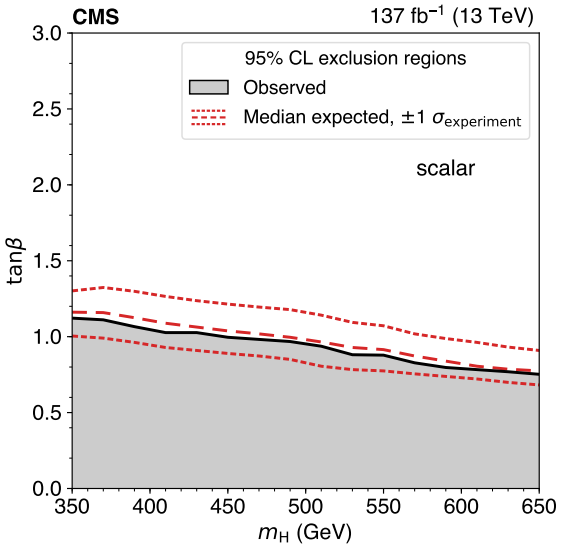
# ATLAS $t\bar{t}t\bar{t}$ SSML result - Eur. Phys. J. C **80** (2020) 1085

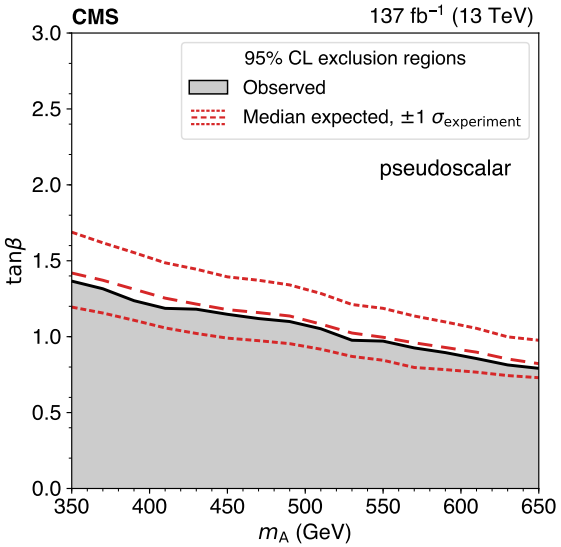


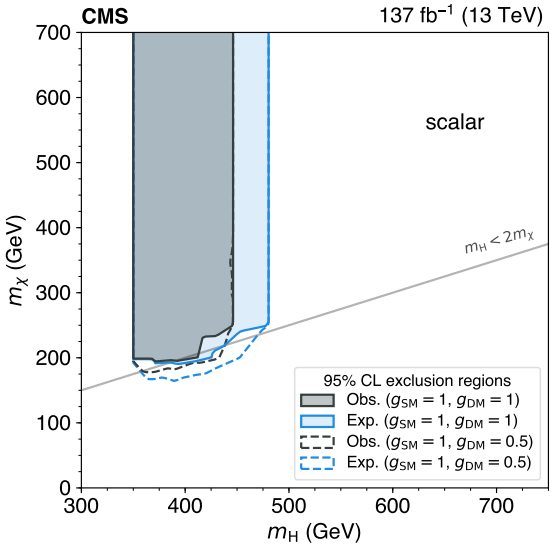



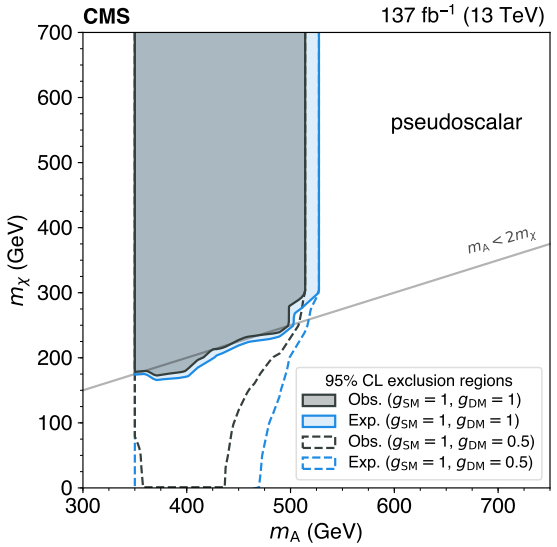
# CMS $t\bar{t}t\bar{t}$ SSML re-interpretations - Eur. Phys. J. C **80** (2020) 75



# CMS $t\bar{t}t\bar{t}$ 1$\ell$OS EFT interpretations - JHEP **11** (2019) 082

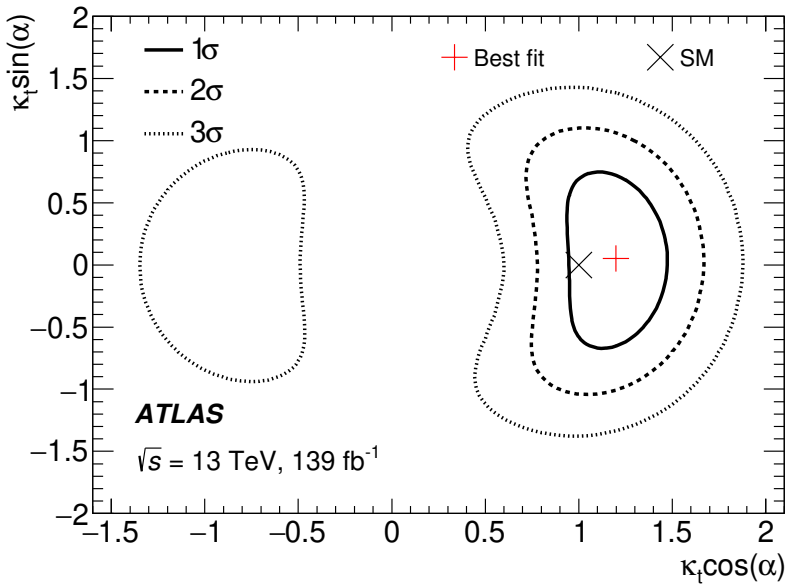
| Operator | Expected $C_k/\Lambda^2$ (TeV$^{-2}$) | Observed (TeV$^{-2}$) |
|---|---|---|
| $\mathcal{O}^1_{tt}$ | $[-2.0, 1.8]$ | $[-2.1, 2.0]$ |
| $\mathcal{O}^1_{QQ}$ | $[-2.0, 1.8]$ | $[-2.2, 2.0]$ |
| $\mathcal{O}^1_{Qt}$ | $[-3.3, 3.2]$ | $[-3.5, 3.5]$ |
| $\mathcal{O}^8_{Qt}$ | $[-7.3, 6.1]$ | $[-7.9, 6.6]$ |

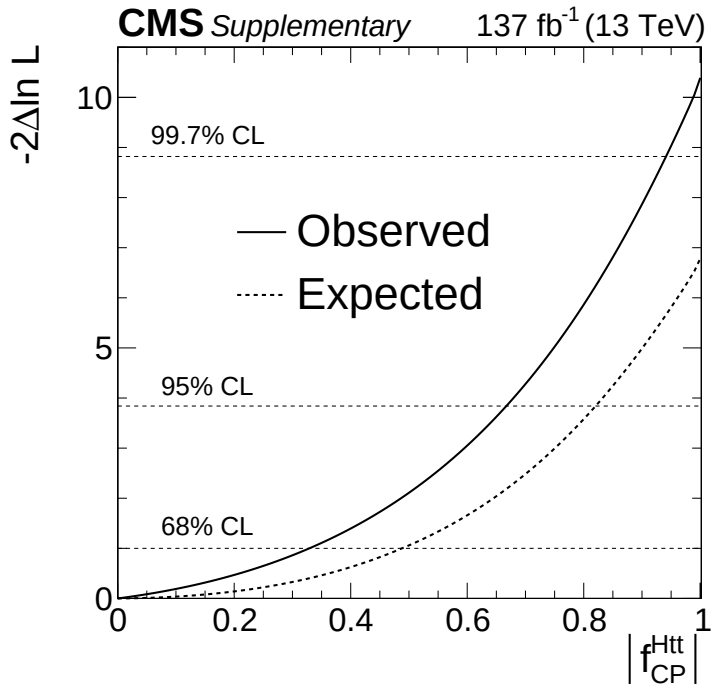
vanishing contribution of other operators

| Operator | Expected $C_k/\Lambda^2$ (TeV$^{-2}$) | Observed (TeV$^{-2}$) |
|---|---|---|
| $\mathcal{O}^1_{tt}$ | $[-2.0, 1.9]$ | $[-2.2, 2.1]$ |
| $\mathcal{O}^1_{QQ}$ | $[-2.0, 1.9]$ | $[-2.2, 2.0]$ |
| $\mathcal{O}^1_{Qt}$ | $[-3.4, 3.3]$ | $[-3.7, 3.5]$ |
| $\mathcal{O}^8_{Qt}$ | $[-7.4, 6.3]$ | $[-8.0, 6.8]$ |

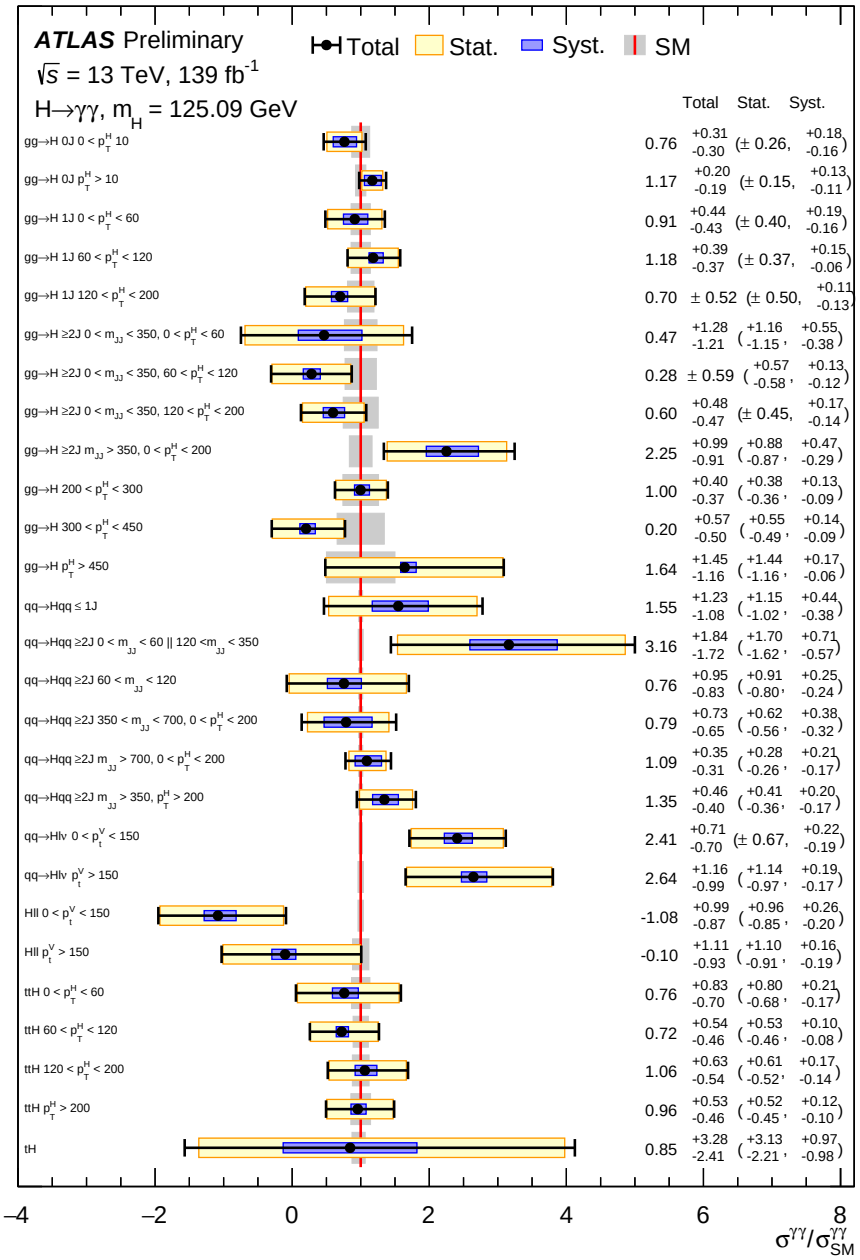
contribution of other operators marginalised

# $t\bar{t}H(\gamma\gamma)$ - Phys. Rev. Lett. **125** (2020) 061802, Phys. Rev. Lett. **125** (2020) 061801

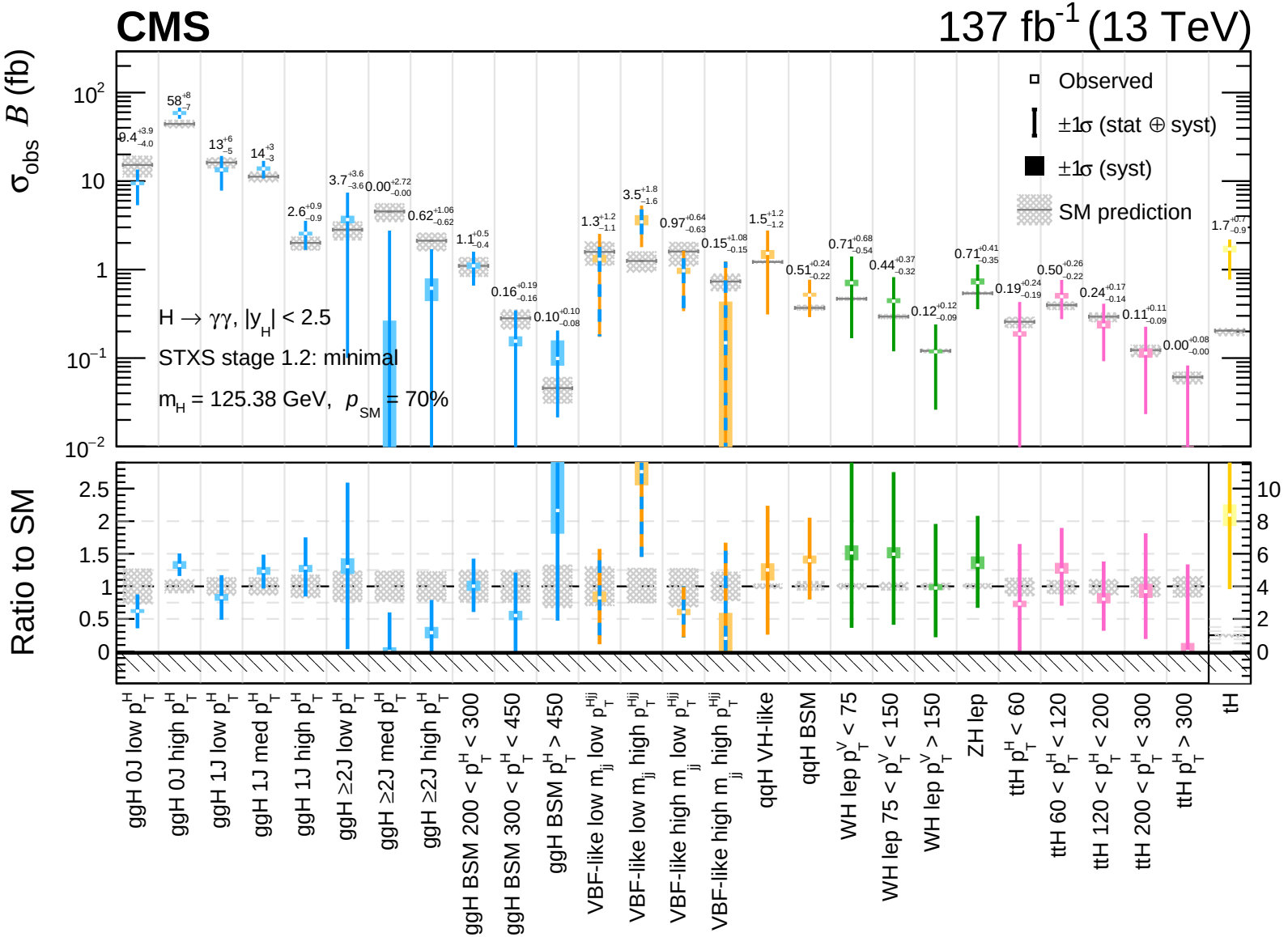


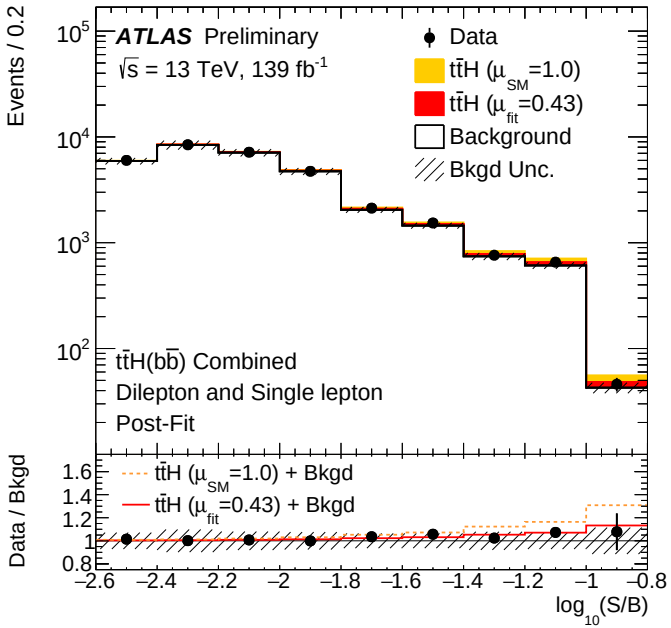
# ATLAS $H \to \gamma\gamma$, STXS - ATLAS-CONF-2020-026

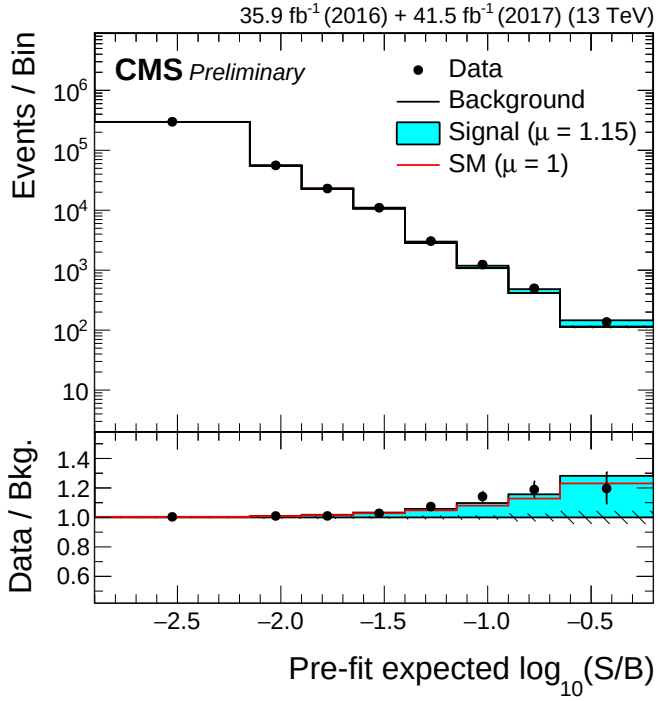


# CMS $H \to \gamma\gamma$, STXS - JHEP **07** (2021) 027

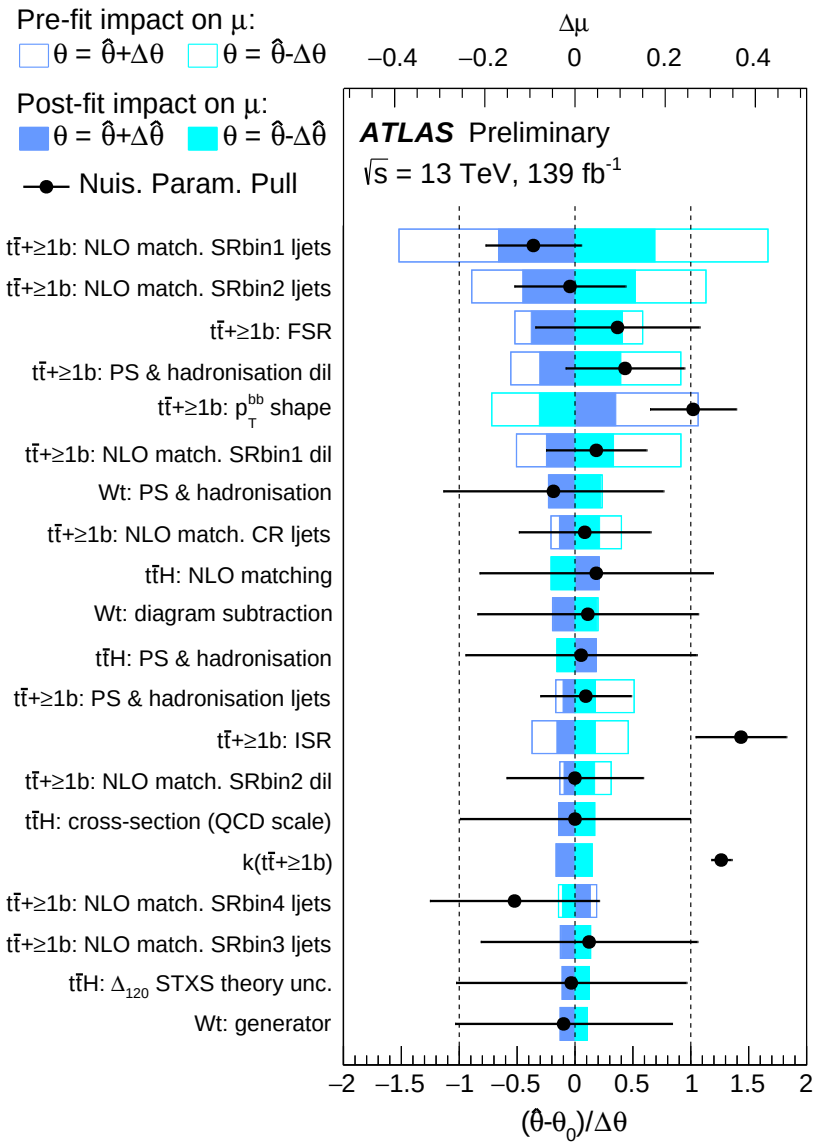


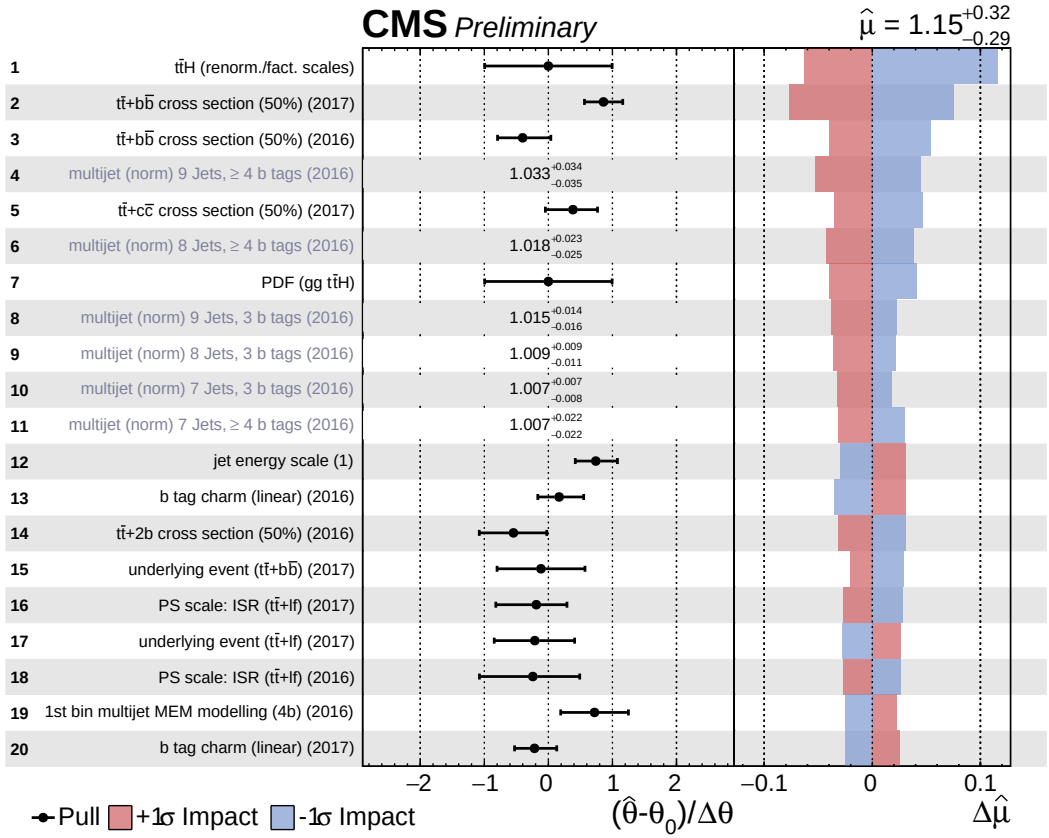
# $t\bar{t}H(b\bar{b})$ - ATLAS-CONF-2020-058, CMS-PAS-HIG-18-030



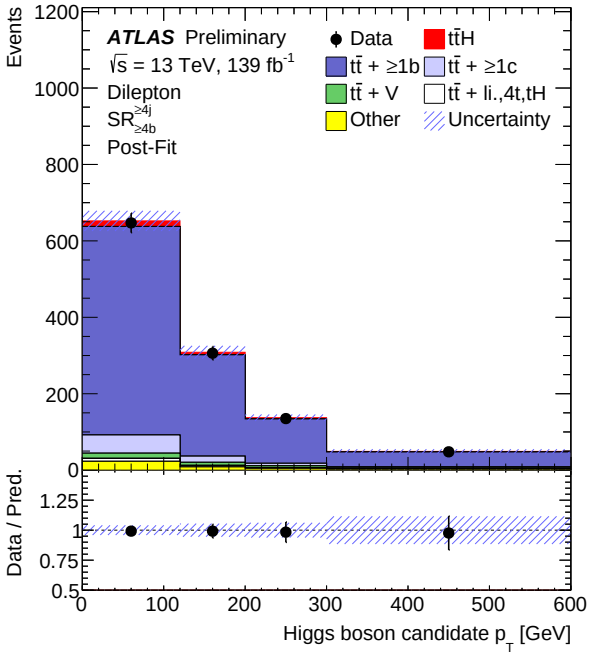



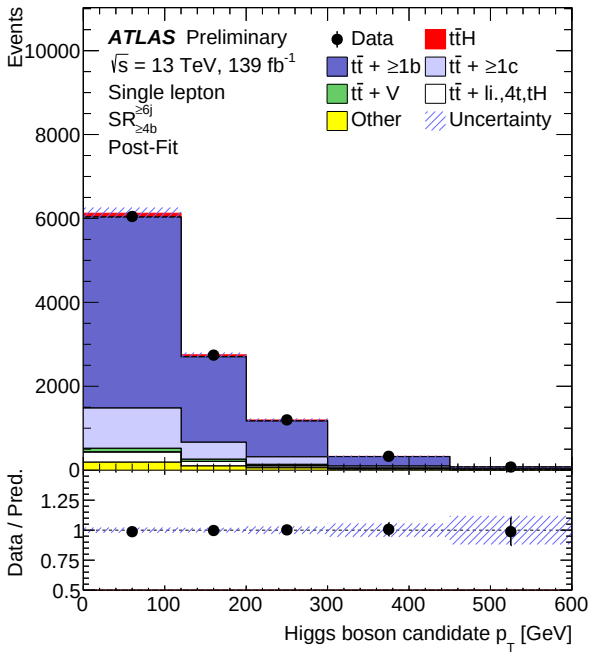
# $t\bar{t}H(b\bar{b})$ - ATLAS-CONF-2020-058, CMS-PAS-HIG-18-030

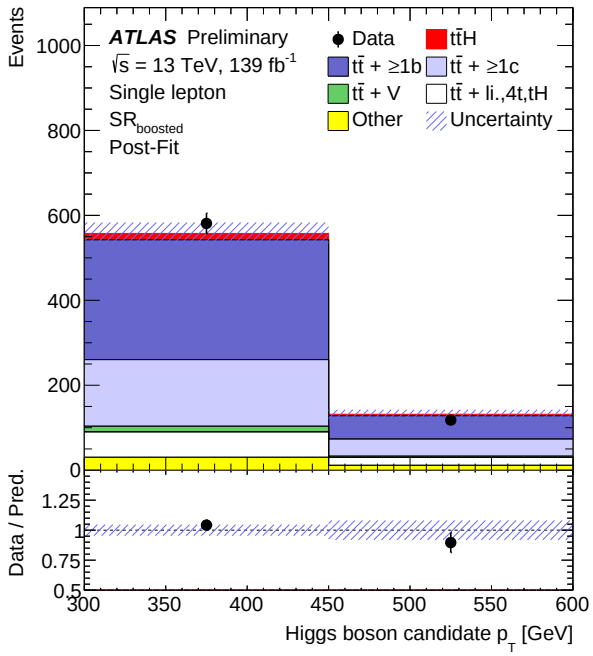


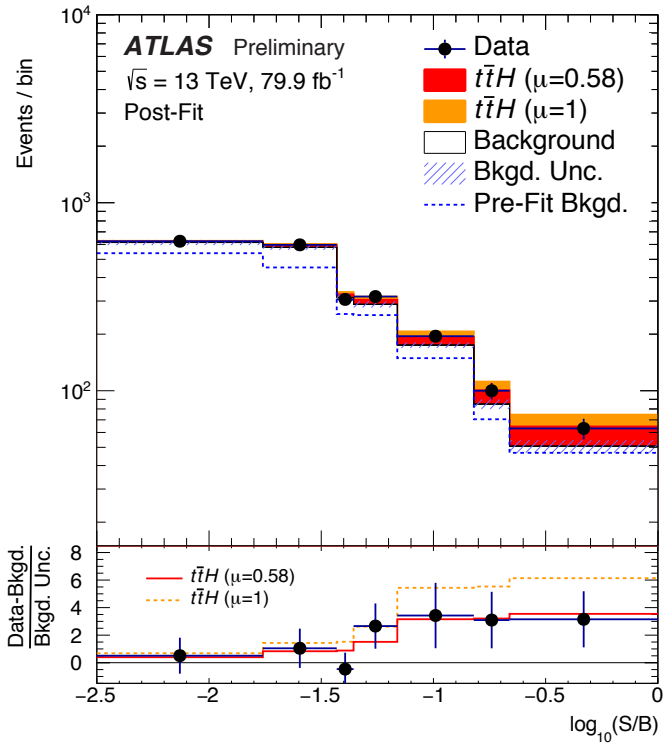
# ATLAS $t\bar{t}H(b\bar{b})$ - ATLAS-CONF-2020-058

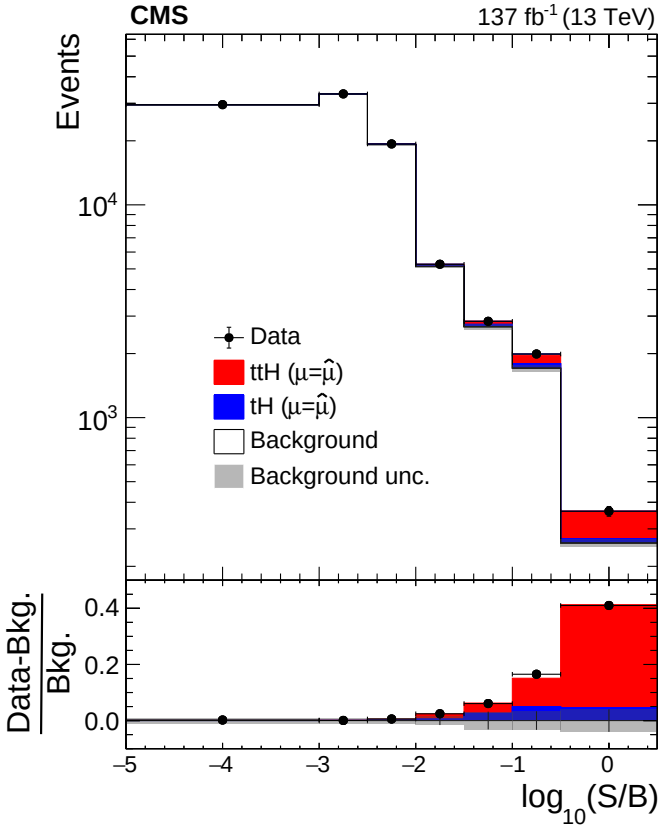


# $t\bar{t}H$ ML - ATLAS-CONF-2019-045, Eur. Phys. J. C **81** (2021) 378



# CMS $t\bar{t}H$ ML - Eur. Phys. J. C **81** (2021) 378