
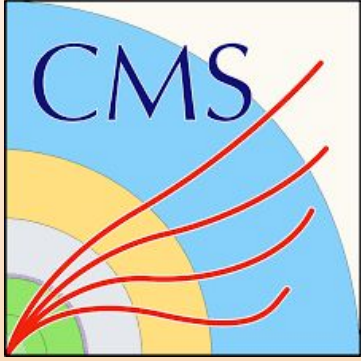


# Measurement of t(t)+X cross sections in CMS

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On behalf of the CMS Collaboration

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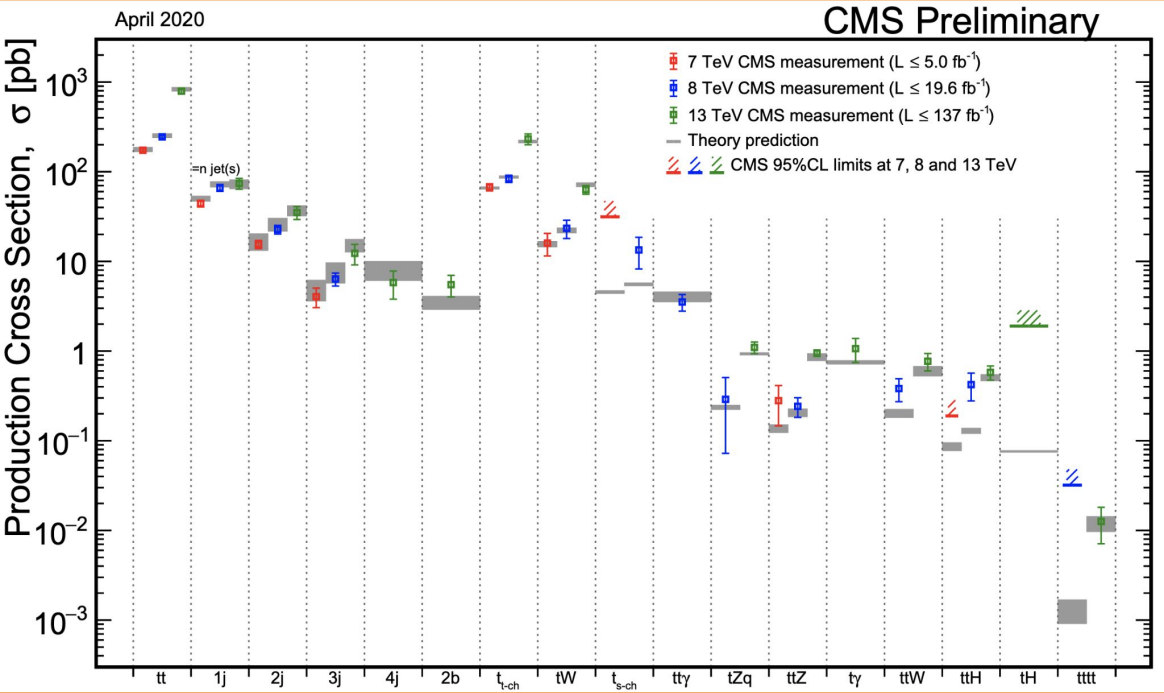
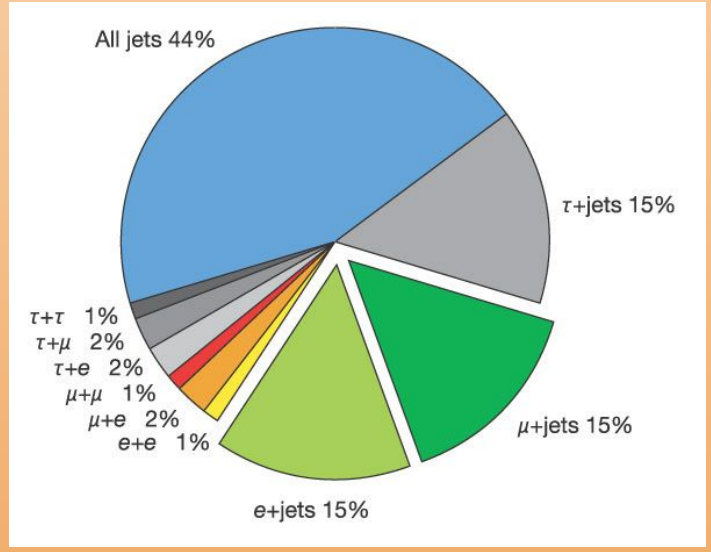
DIS2021: XXVIII International Workshop

# Physics motivation

- Precise measurement helps in the improvement of search sensitivity and test of perturbative QCD
- Differential cross section measurement is used to test fixed-order predictions and extract QCD parameters
- The tt production cross section is dominant at LHC
- Serve as backgrounds for many new physics searches

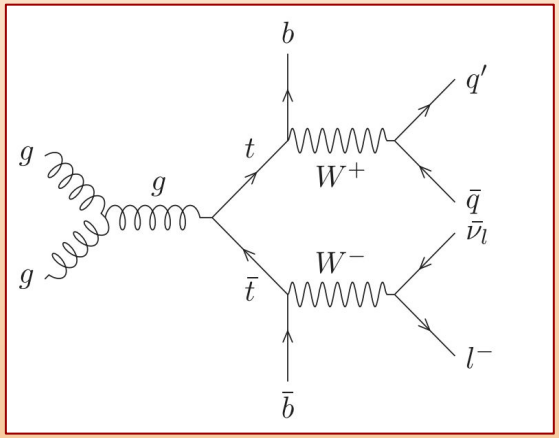



tt branching ratios

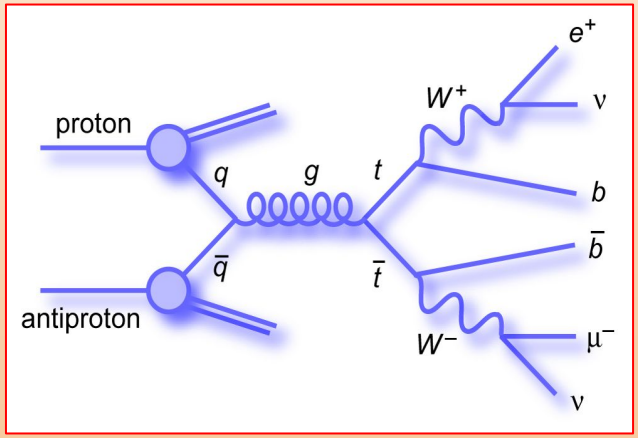


# Production processes

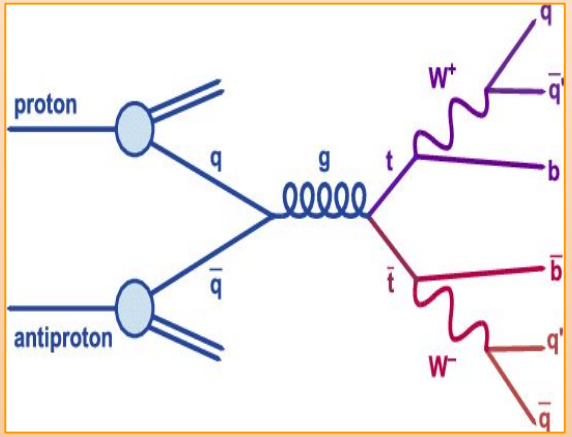
Recent measurements for the following production (final states) processes are covered in this talk



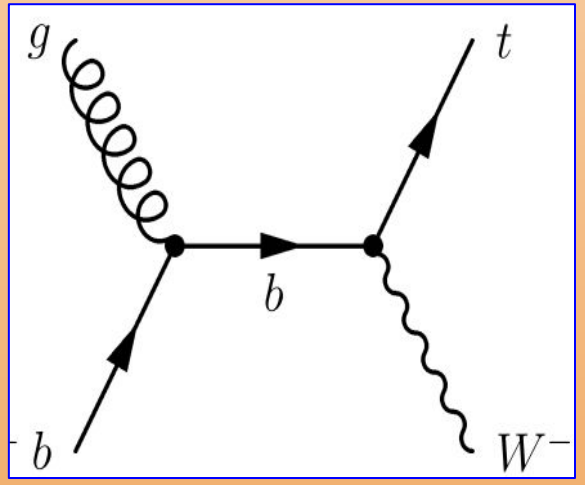

tt (ℓ + jets )



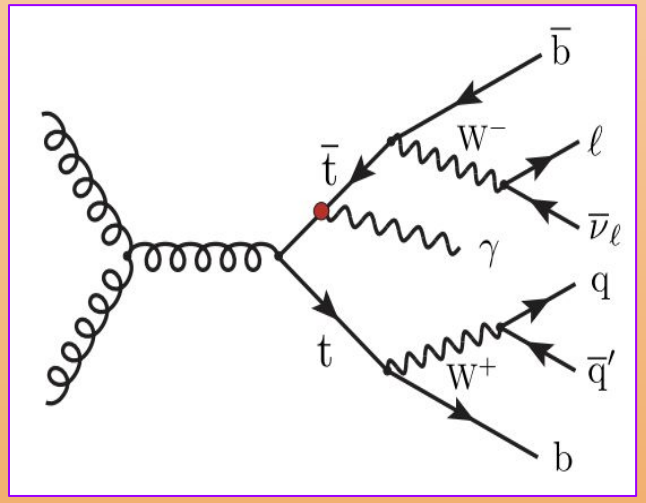

tt (2ℓ + jets)



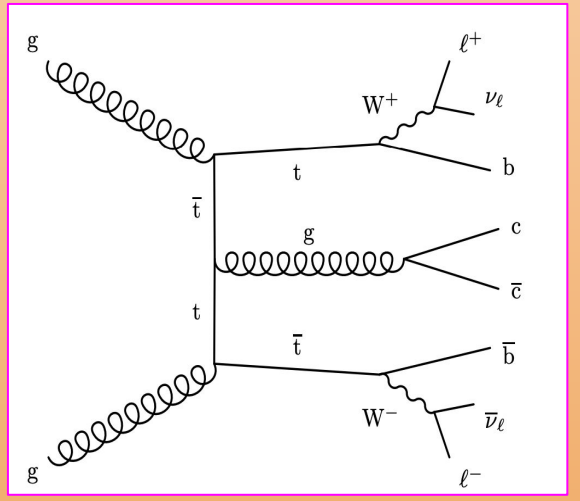

tt (all jets)




tW (ℓ + jets)
tW (2ℓ + jets)




ttγ (ℓ + jets)




ttcc (2ℓ + jets)
ttbb (2ℓ + jets)

# Inclusive and differential **tt** cross sections in ℓ + jets final states

CMS-PAS-TOP-20-001

- A **simultaneous** fit is performed for each distribution combining 24 categories
- Various distributions such as transverse moment of top quarks, invariant mass of tt is used to measure the cross-section
- **Differential** and **double** differential measurement is performed at **parton** and **particle** levels
- Neural network is exploited in the reconstruction of boosted tops
- A $\chi^2$ test is performed to compare the measurements with several predictions
- The dominant source of systematic uncertainty comes from the jet energy correction

Total event categories = **3** x **2** x **4** = 24

- 3 years of data-taking
- 2 channels (μ/e + jets)
- 4 (2 resolved, 2 boosted) top decays

Inclusive cross section

Predicted (NNLO) = 832 ± 46 pb

Measured = 791 ± 25 pb

The measured cross section is more precise (3.16% uncertainty) as compared to the predicted value (5.5% uncertainty)

Differential cross sections are shown in the next slide

# Cross sections



Differential*

Double differential*

**Differential**

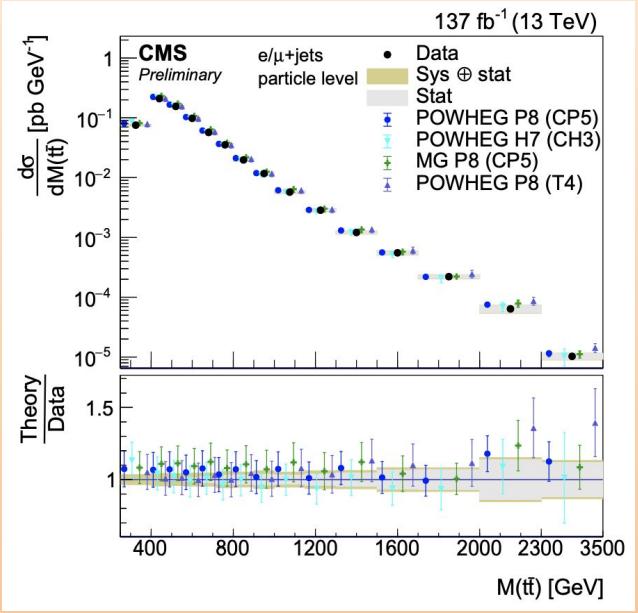
- Good agreement within the uncertainties

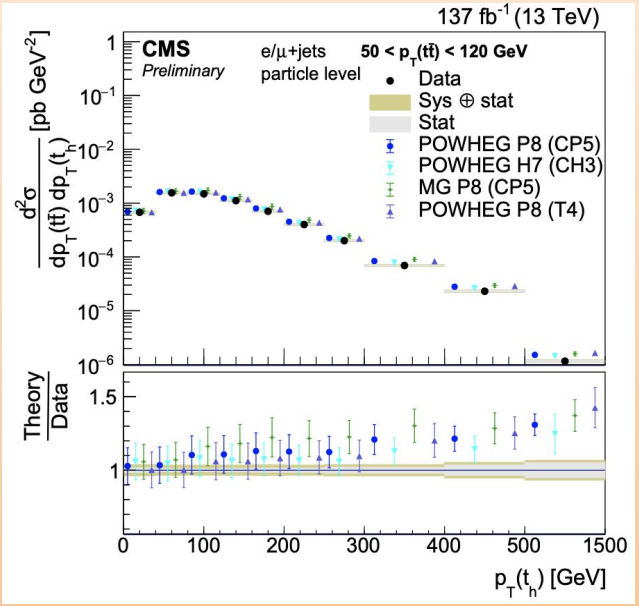
**Double differential**

- There is a slight discrepancy for higher $p_T$ ($t_h$) in the $0 < p_T$ (tt) <120 GeV
- Good agreement in higher ranges of $p_T$ (tt)

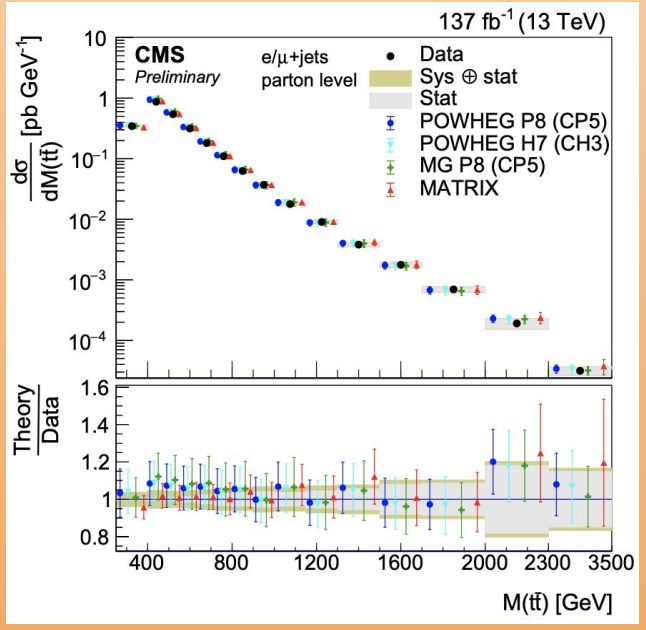
*For other variables and bins, refer to CMS-PAS-TOP-20-001

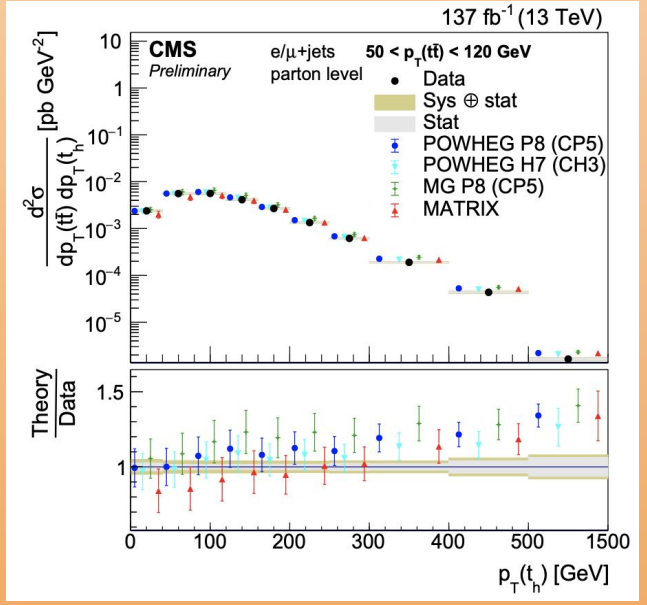
Particle level




Parton level



# Inclusive **tt** cross section in 2ℓ + jets final states at √s = 5.02 TeV

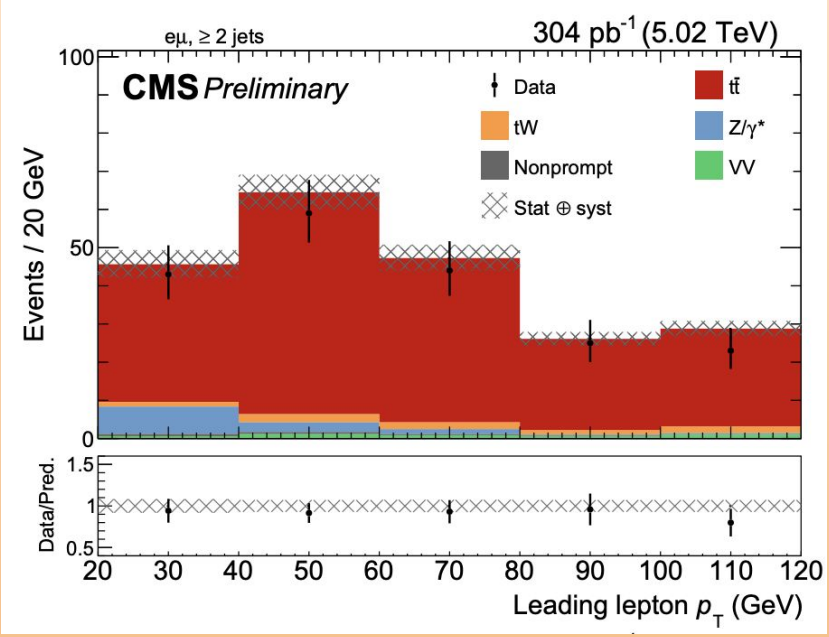
CMS-PAS-TOP-20-004

- First tt cross section measurement in the proton-proton collision at √s = 5.02 TeV
- Provides another check to the SM prediction at lower energy

- The $t\bar{t}$ production cross section is extracted by the counting experiment

$$\sigma_{t\bar{t}} = \frac{N - N_{bkg}}{\varepsilon \mathcal{A} \mathcal{B} \mathcal{R} \mathcal{L}}$$

- N is the number of observed events
- In the denominator, we have
  - Efficiency of event selection
  - Acceptance
  - Branching Ratio of W decaying to lepton and neutrino
  - Luminosity
- The dominant source of systematic uncertainty comes from the jet energy correction




Predicted $\sigma_{t\bar{t}}^{NNLO} = 66.8^{+1.9}_{-2.3}(\text{scale}) \pm 1.7(\text{PDF})^{+1.4}_{-1.3}(\alpha_S)$ pb

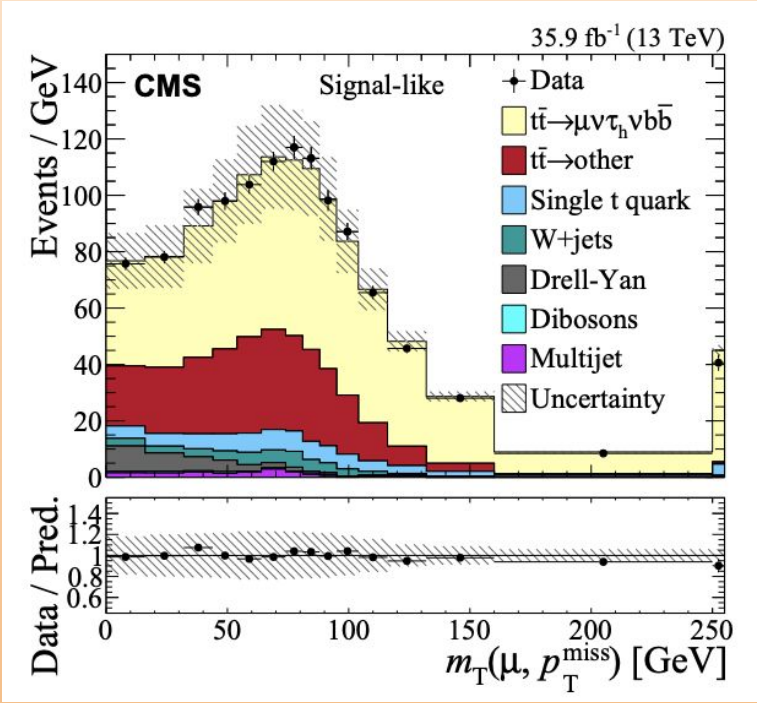
Measured $\sigma_{t\bar{t}} = 60.3 \pm 5.0\ (\text{stat}) \pm 2.8\ (\text{syst}) \pm 0.9\ (\text{lumi})$ pb

Predicted and measured cross sections are in agreement with in the uncertainties

# Inclusive **tt** cross sections in 2ℓ + jets final states including $\tau$

## CMS-TOP-18-005
## J. High Energ. Phys. 2020, 191 (2020)

- First measurement involving $\tau$ lepton
- Checks of lepton flavour universality violation
- With third generation of lepton and quarks, it is sensitive to beyond SM contributions such as production of charged Higgs boson




- ❑ The differential cross section is measured using the the transverse mass of the lepton and MET
- ❑ QCD multijet background is estimated from data
- ❑ The profile likelihood ratio method is used to extract the cross section for both channels
- ❑ The main sources of systematic uncertainty is from $\tau_h$ identification and misidentification

$$\sigma_{t\bar{t}}(e\tau_h) = 789 \pm 11\,(\text{stat}) \pm 71\,(\text{syst}) \pm 20\,(\text{lumi})\,\text{pb},$$
$$\sigma_{t\bar{t}}(\mu\tau_h) = 770 \pm 8\,(\text{stat}) \pm 63\,(\text{syst}) \pm 20\,(\text{lumi})\,\text{pb},$$
$$\sigma_{t\bar{t}}(\ell\tau_h) = 781 \pm 7\,(\text{stat}) \pm 62\,(\text{syst}) \pm 20\,(\text{lumi})\,\text{pb}.$$

$$R_{\ell\tau_h/\ell\ell} = 0.973 \pm 0.009\,(\text{stat}) \pm 0.066\,(\text{syst}),$$

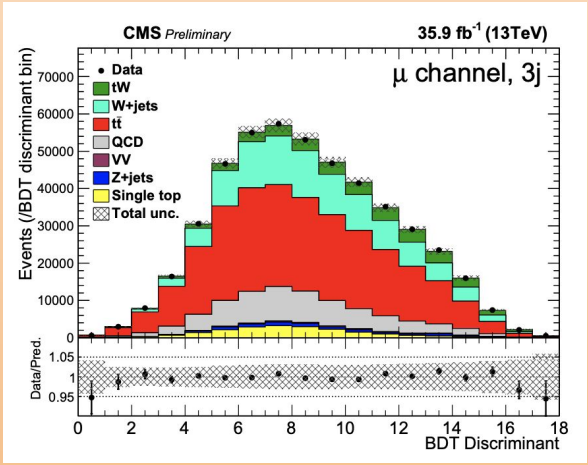
Lepton flavour universality is not observed

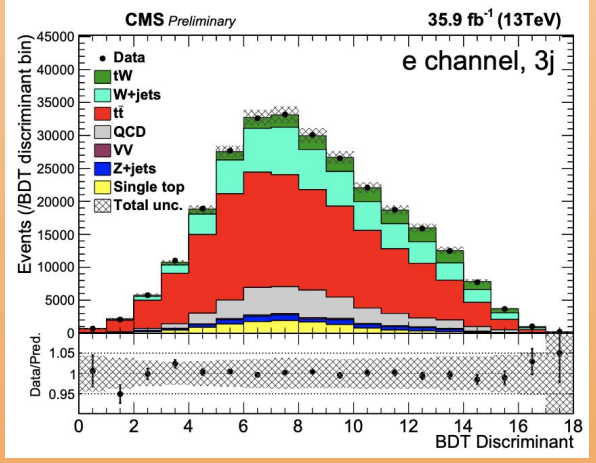
# Inclusive **tW** cross sections in the ℓ + jets final states

CMS-PAS-TOP-20-002

- Single top production is sensitive to the relevant CKM matrix element
- Any deviation from the predicted value may be indicative of physics beyond the SM

- ❑ An event-level discriminant based on BDT is used to measure the cross section
- ❑ The events are divided in three regions
  - ❑ 3 jets, 1 b-tagged (signal region)
  - ❑ 2 jets, 1 b-tagged (control region)
  - ❑ 4 jets, 1 b-tagged (control region)
- ❑ A **simultaneous** fit is performed for the distribution combining 3 categories and 2 channels
- ❑ The dominant source of systematic uncertainty comes from the jet energy correction




| | |
|---|---|
| Predicted: ([NNLO]) | $\sigma_{SM}$: 71.7 ± 1.8 (scale) ± 3.4 (PDF) pb |
| Measured: | σ = 89 ± 4 (stat.) ± 12 (syst.) pb |

Predicted and measured cross sections agree with in uncertainties

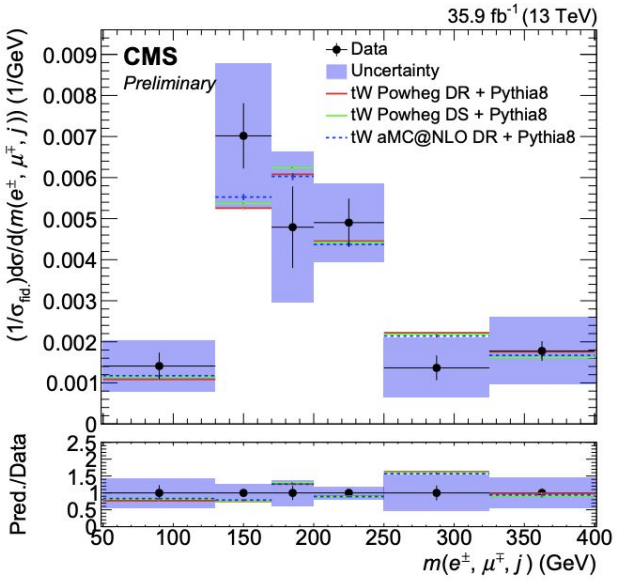
# Differential **tW** cross sections in 2ℓ + jets final states

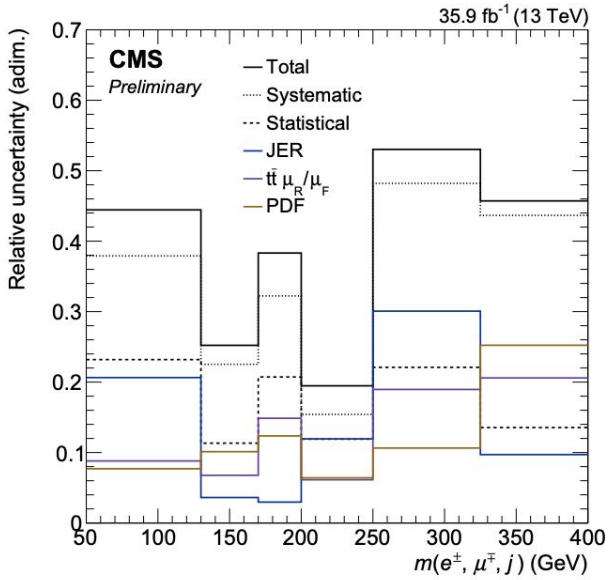
CMS-PAS-TOP-19-003

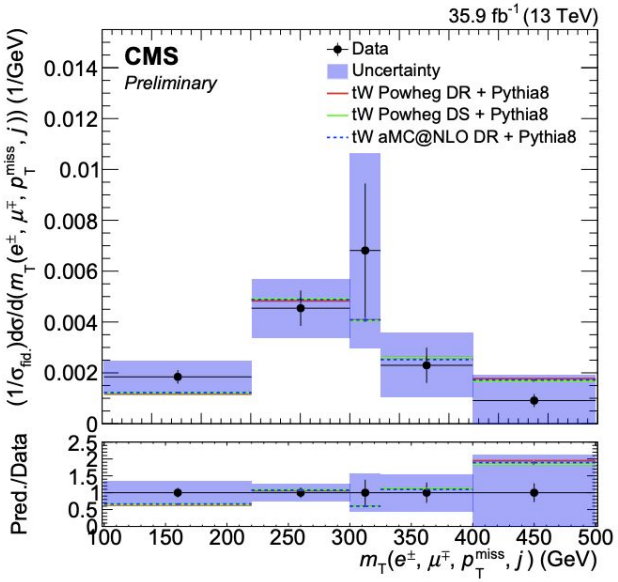
- Signal extraction is performed by subtracting background, estimated through simulations
- The jet energy correction uncertainties are the dominant ones
- The differential cross section is measured as a function of six variables

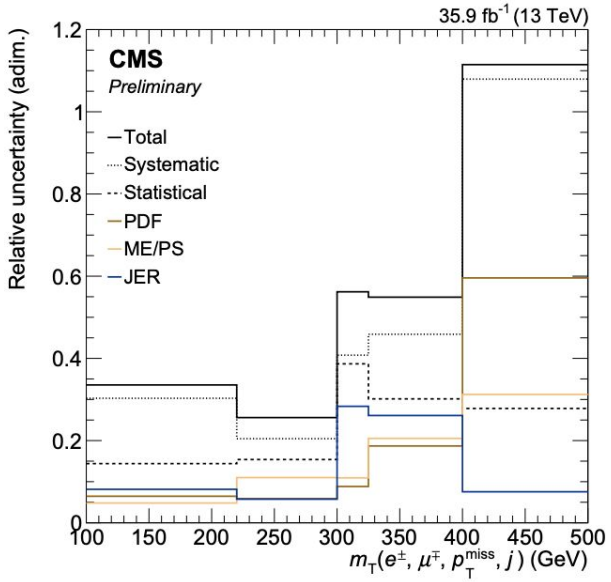
  (two are shown in this slide, for others refer to CMS-PAS-TOP-19-003)

Predicted and measured cross sections are in agreement within the uncertainties across all bins



# Inclusive and differential **tty** cross section in ℓ + jets final states

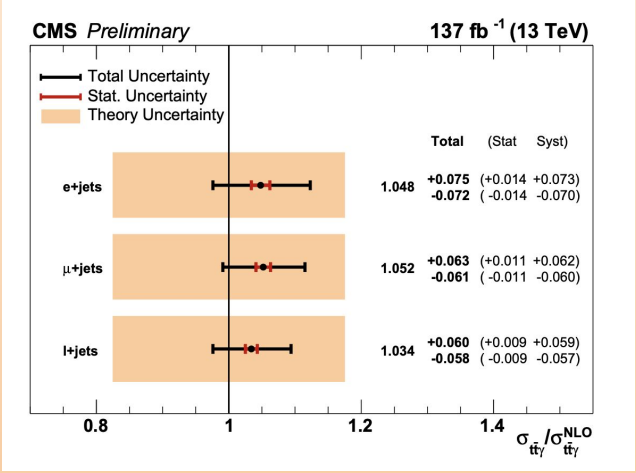
CMS-PAS-TOP-18-010

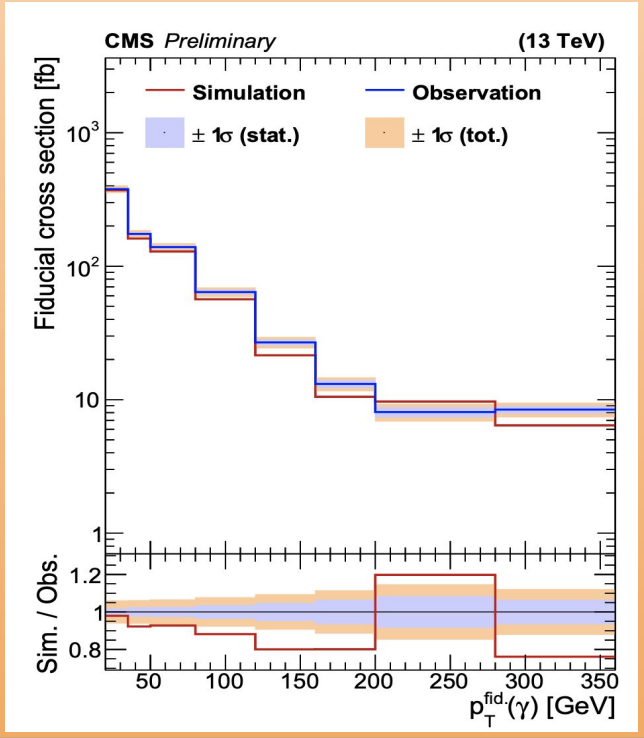
The tty measurement allows to constrain the ty electroweak coupling

- Photon is classified based on matched generator particle
  - Genuine photon
  - Hadronic photon
  - Misidentified photon
- Different phase space based on object selections and kinematic cuts is exploited to improve the precision
- QCD multijet and electroweak backgrounds are measured from data
- A simultaneous fit over all event categories is performed to extract the cross section
- The dominant uncertainties in the cross section come from Wy normalization and misidentified y estimation

Agreement between the cross sections

- Inclusive -> good
- Differential -> slight mismatch in high pT bins



# Inclusive **ttcc** cross section in 2ℓ + jets final states

CMS-PAS-TOP-20-003

- First measurement of ttcc cross section
- Provide a useful test of NLO QCD calculations

- Event level neural network predicts output probabilities for five output classes

$P(\mathrm{t\bar{t}c\bar{c}})$, $P(\mathrm{t\bar{t}cL})$, $P(\mathrm{t\bar{t}b\bar{b}})$, $P(\mathrm{t\bar{t}bL})$, and $P(\mathrm{t\bar{t}LL})$

- Two variables are derived based on these:

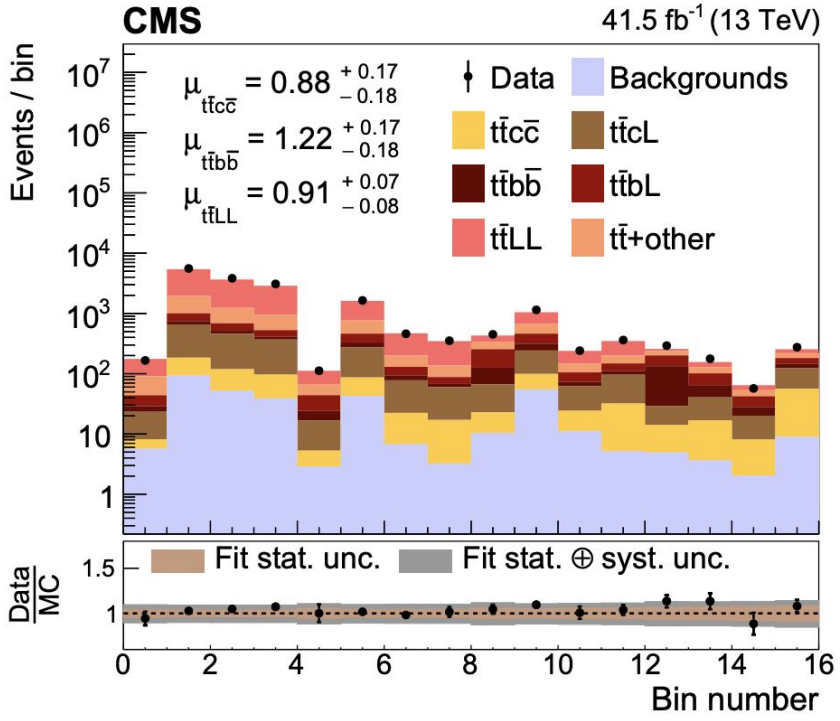
$$\Delta_{\mathrm{b}}^{\mathrm{c}} = \frac{P(\mathrm{t\bar{t}c\bar{c}})}{P(\mathrm{t\bar{t}c\bar{c}}) + P(\mathrm{t\bar{t}b\bar{b}})},$$

$$\Delta_{\mathrm{L}}^{\mathrm{c}} = \frac{P(\mathrm{t\bar{t}c\bar{c}})}{P(\mathrm{t\bar{t}c\bar{c}}) + P(\mathrm{t\bar{t}LL})}.$$

- A 1-d histogram is constructed from the 16 bins of the 2-d plane of these two variables

$$\Delta_{\mathrm{L}}^{\mathrm{c}} \otimes \Delta_{\mathrm{b}}^{\mathrm{c}} : [0, 0.45, 0.6, 0.9, 1.0] \otimes [0, 0.3, 0.45, 0.5, 1.0].$$

- The dominant source of systematic uncertainty comes from the jet energy correction and c-tagging calibration




| | Result | POWHEG | MadGraph5_aMC@NLO |
|---|---|---|---|
| $\sigma_{\mathrm{t\bar{t}c\bar{c}}}$ [pb] | $8.0 \pm 1.1 \pm 1.3$ | $9.1 \pm 1.8$ | $8.9 \pm 1.5$ |
| $\sigma_{\mathrm{t\bar{t}b\bar{b}}}$ [pb] | $4.09 \pm 0.34 \pm 0.55$ | $3.34 \pm 0.72$ | $3.39 \pm 0.66$ |
| $\sigma_{\mathrm{t\bar{t}LL}}$ [pb] | $231 \pm 5 \pm 21$ | $255 \pm 43$ | $261 \pm 37$ |

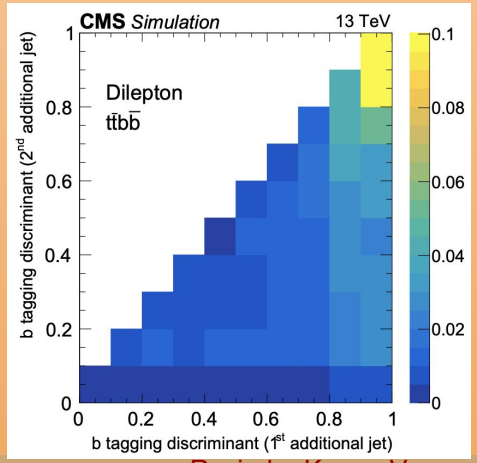
Predicted and measured cross sections are in agreement with in the uncertainties

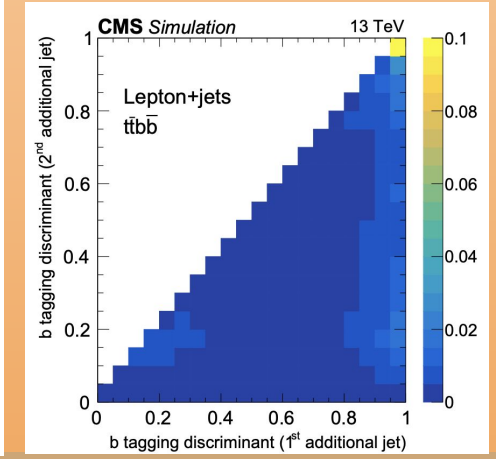
# Inclusive **ttbb** cross sections in ℓ + jets and 2ℓ + jets final states

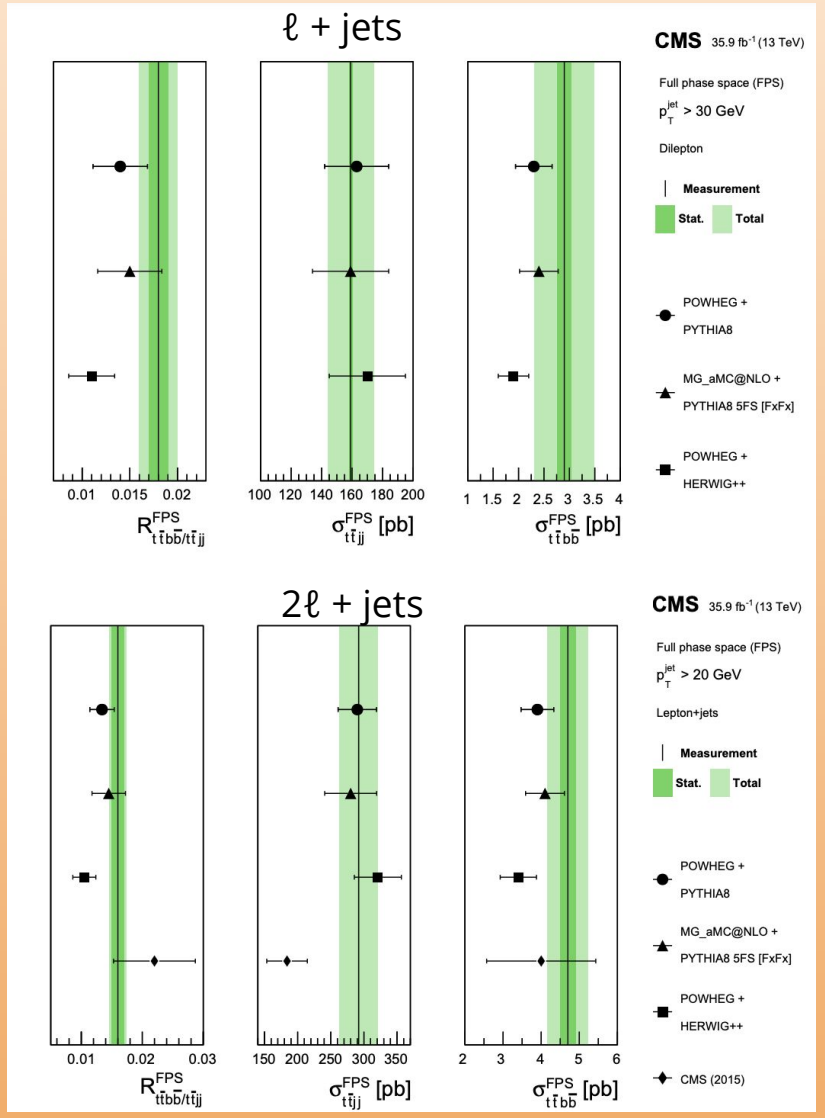
CMS-TOP-18-002

J. High Energ. Phys. 2020, 125 (2020)

- The measurement from single and di-lepton channels have been performed separately
- The cross section for ttbarbar, ttjj final states and the their ratio is obtained in the visible and full phase space (FPS)
- The fit is performed on the b-tagger discriminant value of the two jets
- A 1-d histogram is constructed from the 10×10 (20×20) bins of the 2-d plane of these two variables for semilepton (dilepton) channel
- Theoretical uncertainties from the FSR and ME-PS matching are the dominant




Good agreement with most of the generators

# Summary

- Precise measurement of top quark production cross sections help in testing the SM, searching for new physics beyond it, etc
- Latest cross section measurements from CMS is presented from tt, tW, tt**γ**, ttcc, and ttbb production process
- Inclusive and differential measurements are performed
- The measured cross sections are in agreement with the prediction within the systematic and statistical uncertainties
- The outcome of new measurements are made public
- The ATLAS collaboration has also performed similar measurements