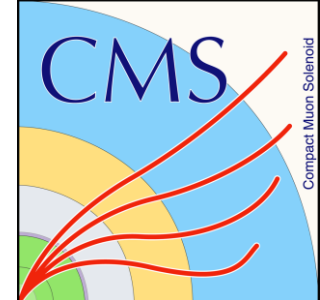




Universidad de Oviedo
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Top quark pair and single top cross sections in CMS

J. Cuevas

U. Oviedo (Spain)

on behalf of the **CMS** collaboration

Pheno2021: Phenomenology 2021 Symposium

24-26 May 2021

University of Pittsburgh

(Virtual)

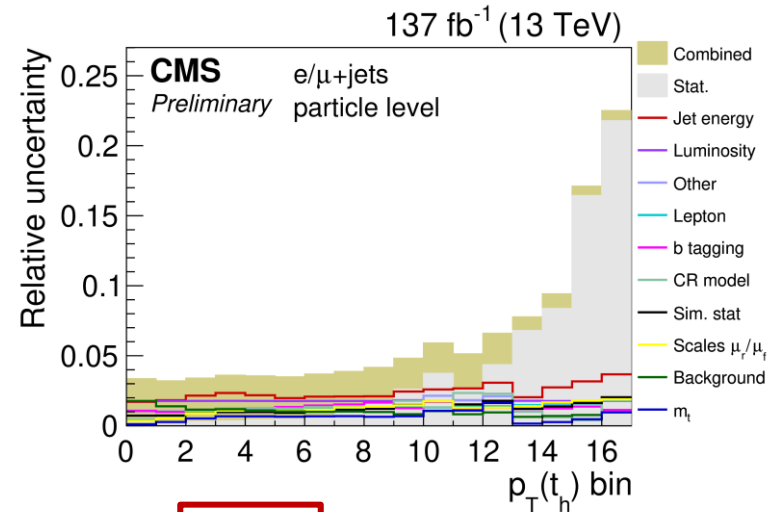
Outline

- **The CMS collaboration** covers a wide range of $t\bar{t}$ production and single-top related topics, **measuring inclusive and differential cross-sections** in different final states and kinematical regimes.
- **Results in agreement with SM predictions**
 - Differential $t\bar{t}$ cross-sections in the full kinematic range using lepton+jets final states [CMS-PAS-TOP-20-001](#)
 - $e/\mu, \tau_{\text{had}}$ inclusive cross section measurement by CMS: [JHEP 02 \(2020\) 191](#)
 - Differential $t\bar{t}$ cross-sections for high- p_T top quarks in l+jets and hadronic decay channels [Phys. Rev. D 103 \(2021\) 052008](#)
 - $t\bar{t}$ inclusive cross section at 5.02 TeV: [CMS-PAS-TOP-20-004](#)
 - tW production in the semileptonic channel: [CMS-PAS-TOP-20-002](#)
 - tW differential cross-section in the dilepton channel: [CMS-PAS-TOP-19-003](#)
 - t-channel inclusive and differential cross-sections: [Phys. Lett. B 800 \(2019\) 135042](#), [Eur. Phys. J. C 80 \(2020\) 370](#)

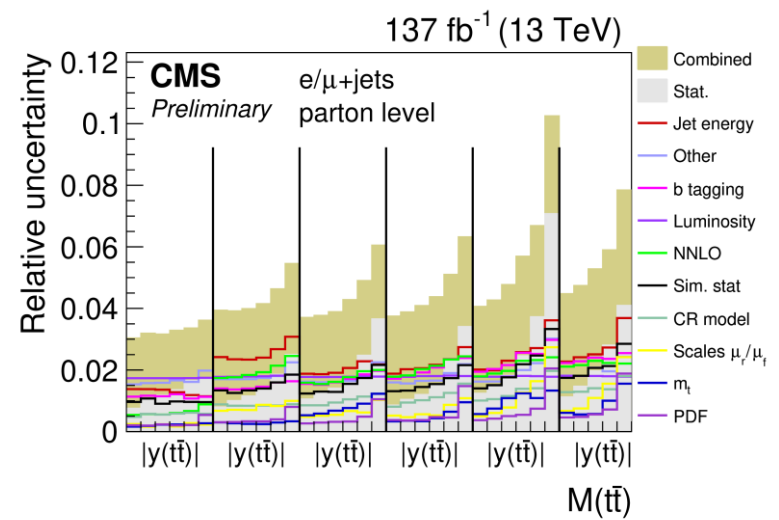
Single and double differential $\sigma_{t\bar{t}}$ at 13 TeV (ℓ +jets)

CMS-PAS-TOP-20-001

- Combined fit of resolved and boosted topology in ℓ +jets channel -> **first of this kind.**
- **Resolved selection:**
 - 1 lepton, ≥ 4 AK4 jets (Anti Kt with $R=0.4$), 2 of which are b-tagged. Events split according to quality of second b-tag.
- **Boosted top identified with NN approach**
 - Anti-kT 0.8 jets with a 21 variable NN used to identify boosted hadronic top decays (t_h^b).
 - Boosted leptonic top decays (t_l^b) are identified by using leptons (no isolation cuts) close to b-jets with a 5 variable NN.
 - Selections require a boosted hadronic top, leptonic side can be boosted or reconstructed with a standard lepton+b-jet requirement.
- **Use of multiple input channels allows to constrain syst. uncertainties**
 - Measurement has very good precision: $< 5\%$ in many bins
 - Largest systematics from jet energy scale and modelling of $t\bar{t}$ production.
 - Statistical uncertainty matters in the high p_T / mass tails.



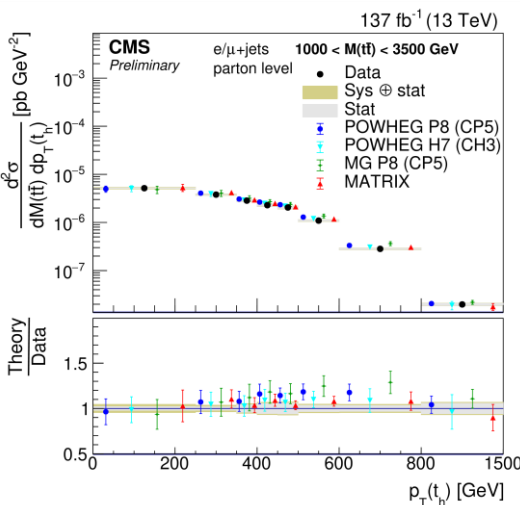
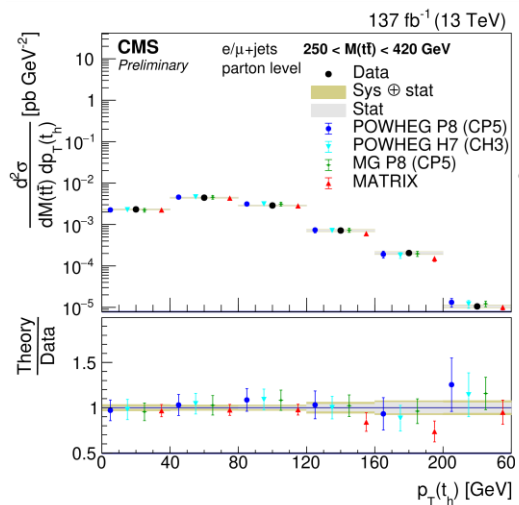
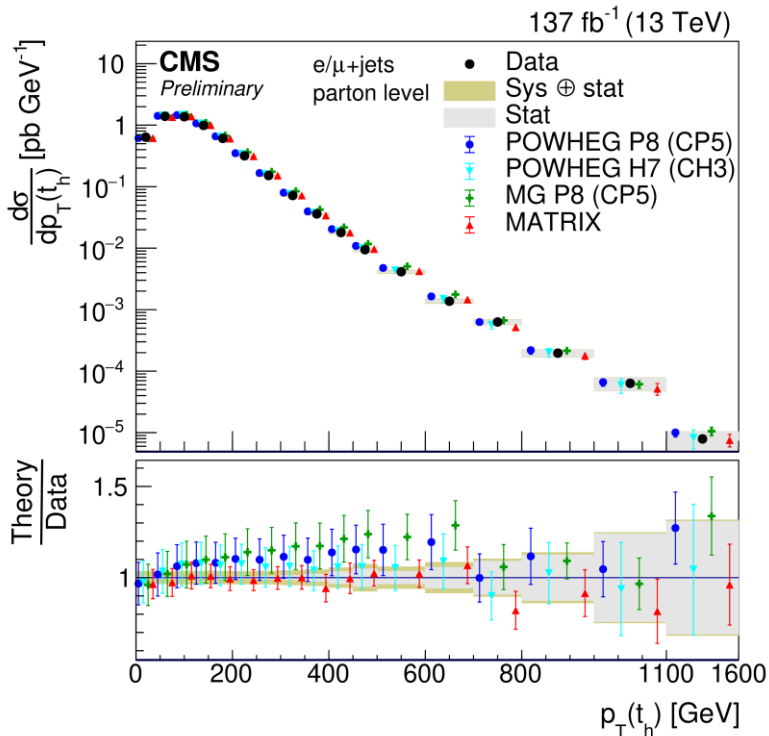
NEW



Single and double differential $\sigma_{t\bar{t}}$ at 13 TeV (ℓ +jets)

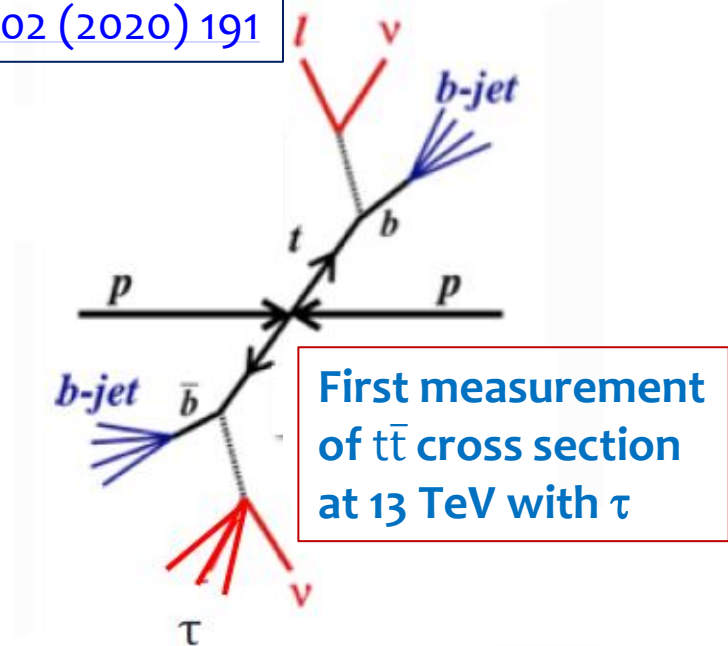
CMS-PAS-TOP-20-001

- The cross-section is extracted from a combined fit to the different channels, 3 selections x 2 lepton flavours x 3 years
- All calculations predict harder top p_T spectrum than observed in data
 - Improved description with NNLO
- Inclusive $\sigma_{t\bar{t}} \rightarrow 3.1\%$ uncertainty, most precise result in ℓ +jets channel
- Double differential, e.g. $p_T(t)$ vs $m(t\bar{t})$, and many variables well modelled, but $p_T(t)$ vs $m(t\bar{t})$ shows poor agreement (χ^2 calculation).



$t\bar{t}$ inclusive cross section: $e/\mu, \tau_{\text{had}}$ (35.9 fb^{-1} at 13 TeV)

JHEP 02 (2020) 191



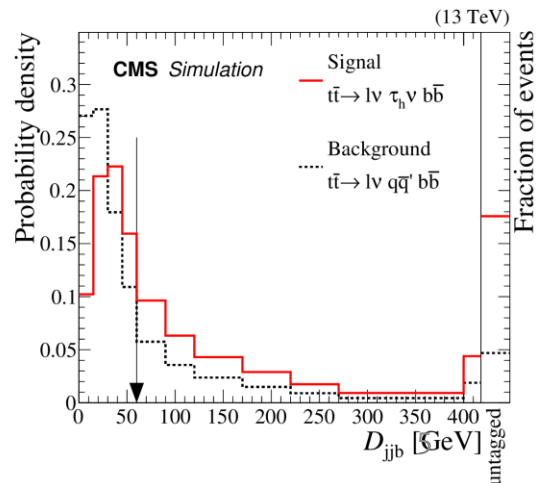
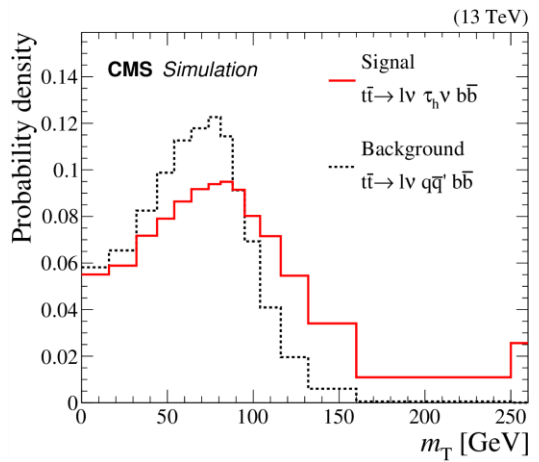
First measurement of $t\bar{t}$ cross section at 13 TeV with τ

$$m_T = \sqrt{2} |\vec{p}_T^\ell| |\vec{p}_T^{\text{miss}}| (1 - \cos \Delta\phi)$$

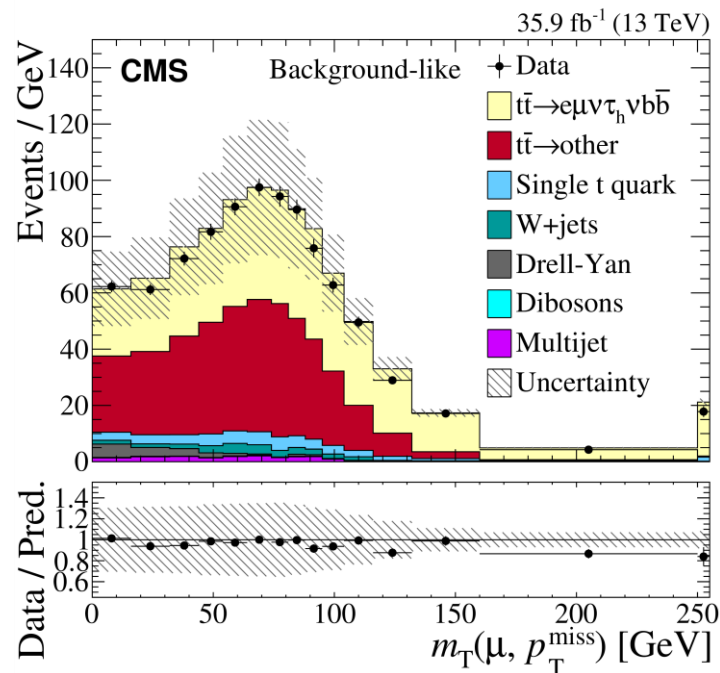
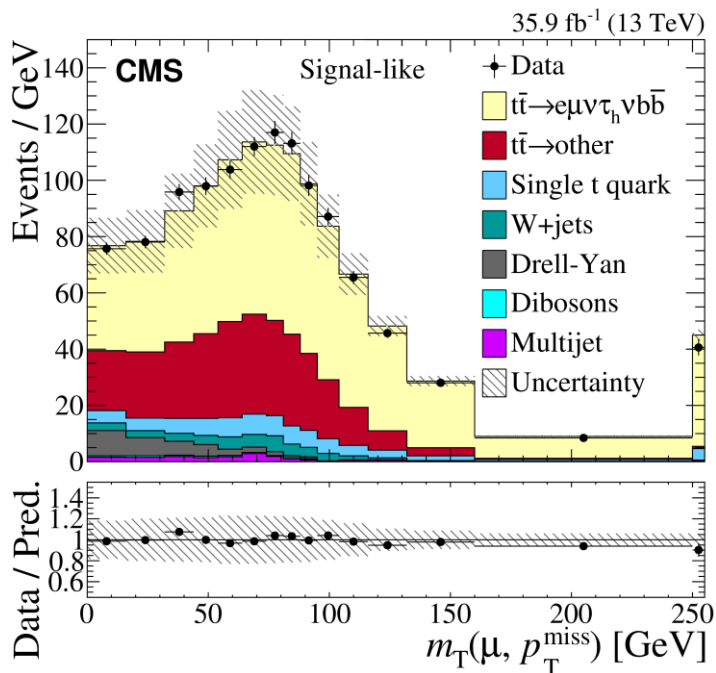
- One of the most recent inclusive cross section measurement by CMS: $e/\mu, \tau_{\text{had}}$
- Selection: 1 lepton (e or μ) and ≥ 3 jets (≥ 1 b-jet + one is identified as a τ_{had}).
- Main background coming from semileptonic $t\bar{t}$ decays (with a jet misidentified as a τ_{had}).
- m_T of the lepton and p_T^{miss} used in 2 categories, for each of the e, τ_{had} and μ, τ_{had} final states

- "signal-like" category: one untagged jet or $D_{\text{jib}} > 60 \text{ GeV}$

$$D_{\text{jib}} = \sqrt{(m_W - m_{\text{jib}})^2 + (m_t - m_{\text{jib}})^2}$$



$t\bar{t}$ inclusive cross section: $e/\mu, \tau_{\text{had}}$

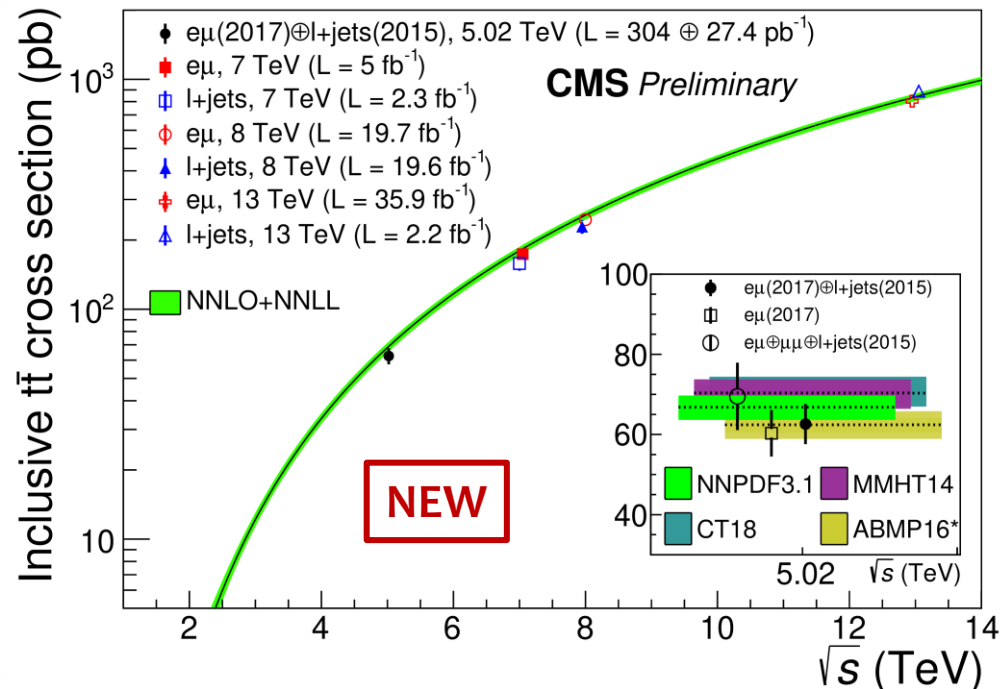
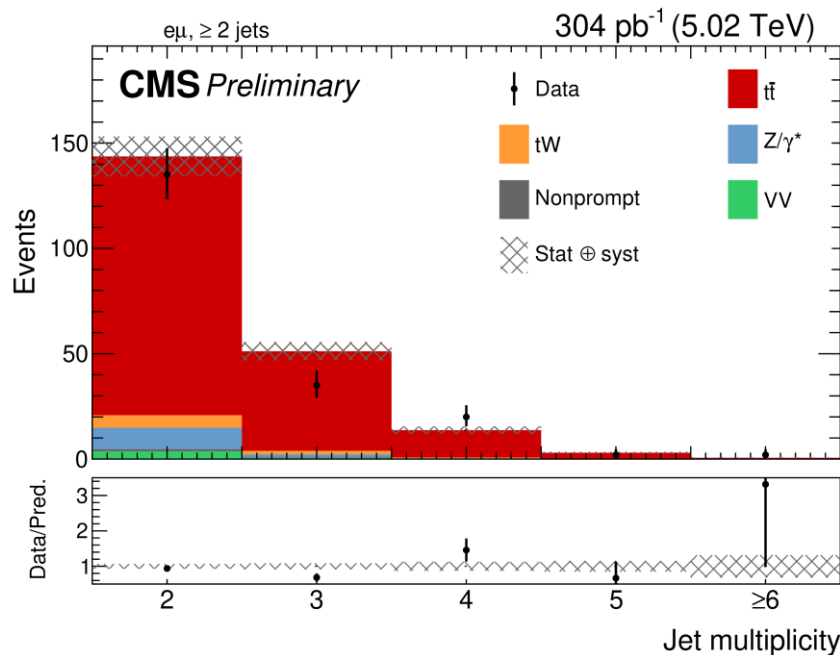


- Main syst. unc. τ_{had} id (4.5%), PLR fit of the binned distribution of m_T -> signal strength and main background obtained from the fit
- $\sigma_{t\bar{t}}(I_{\tau_{\text{had}}}) = 781 \pm 7$ (stat.) ± 62 (syst.) ± 20 (lumi.) pb. in agreement with NNLO+NNLL prediction (unc. 5.7%).
- $R_{I_{\tau_h/I}} = 0.973 \pm 0.009$ (stat.) ± 0.066 (syst.) (368) consistent with lepton flavour universality.
- $\Gamma(t \rightarrow \tau\nu_\tau b)/\Gamma_{\text{total}} = 0.1050 \pm 0.0009$ (stat.) ± 0.0071 (syst.) consistent with SM prediction (0.1083 \pm 0.0002)

$t\bar{t}$ inclusive cross section at 5.02 TeV

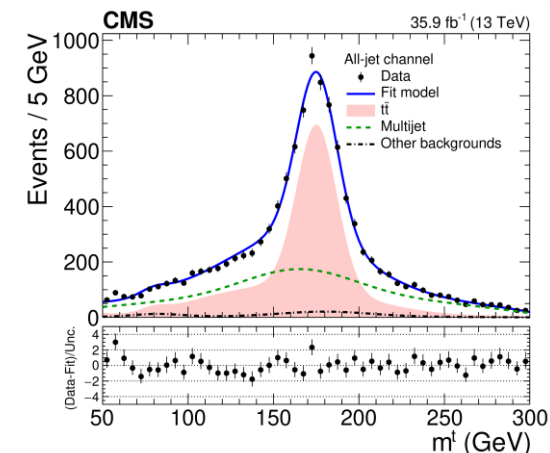
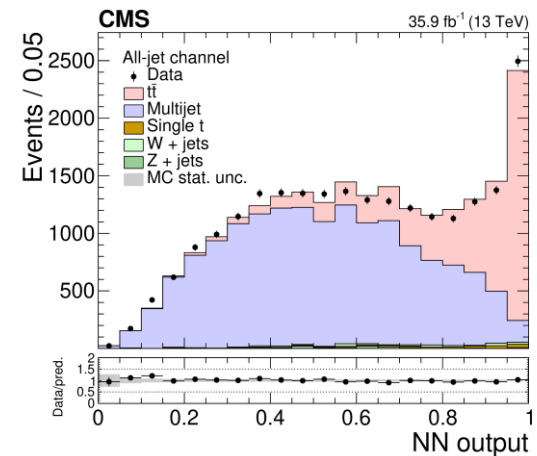
CMS-PAS-TOP-20-004

- The identification criteria are specifically designed to separate the leptons from W decays from the leptons that arise from fakes.
- Event count in $e\mu$ channel (304 pb⁻¹ 2017 data) combined with measurement in $l+jets$ final state (27.4 pb⁻¹ 2015). No b-tagging is used. Dominant syst. unc., JES. (2.2%)
- $\sigma_{t\bar{t}} = 62.6 \pm 4.1$ (stat.) ± 3.0 (syst.+lumi.) pb \rightarrow **7.9% precision, in good agreement with NNLO+NNLL** using the NNPDF3.1 PDF set calculated with TOP++, $\sigma_{t\bar{t}} = 66.8^{+1.9}_{-2.3}$ (scale) ± 1.7 (PDF) $^{+1.4}_{-1.3}$ ($\alpha_s(m_Z)$) pb, about **4.8% total uncertainty.**



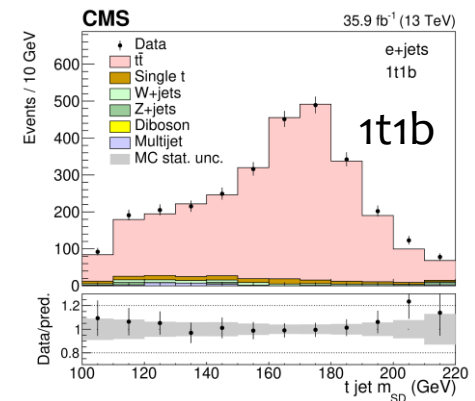
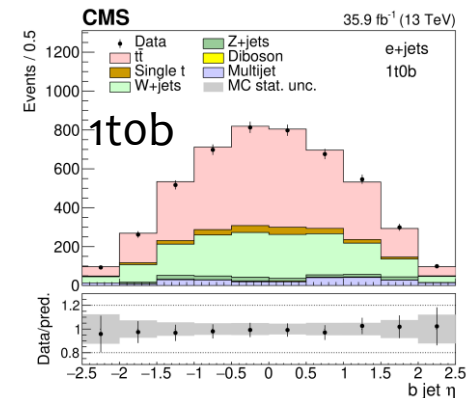
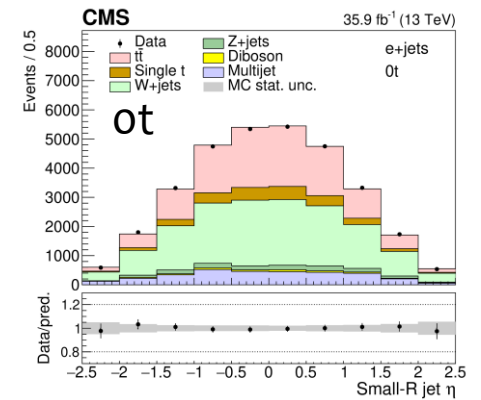
Differential $t\bar{t}$ cross-sections for high- p_T top quarks in l+jets and hadronic decay channels

- Start to access the high p_T with precision, beyond the reach of the resolved analyses, $p_T \sim 2M_t/R \sim 400$ GeV
- Sensitive to new physics, and very important test for perturbative QCD
- **Absolute and normalized differential $t\bar{t}$ cross-sections**, unfold to parton and particle levels. Unfolding with **TUnfold** matrix inversion **without regularisation**
- **Hadronic:** Two AK8 jets with $p_T > 400$ GeV.
 - “ $t\bar{t}$ event tagging” NN using jet substructure variables
 - **Categories** based on subjet b tagging: 0-btag control, 2-btag: signal
 - **Backgrounds:** QCD dominant: taken from data, Others (ST, W/Z+jets): negligible
 - **ML fit** to the mass of the leading jet
 - **Diff. cross-sections:** leading and subleading top p_T and $|y|$, $t\bar{t}$ system, mass, p_T & rapidity



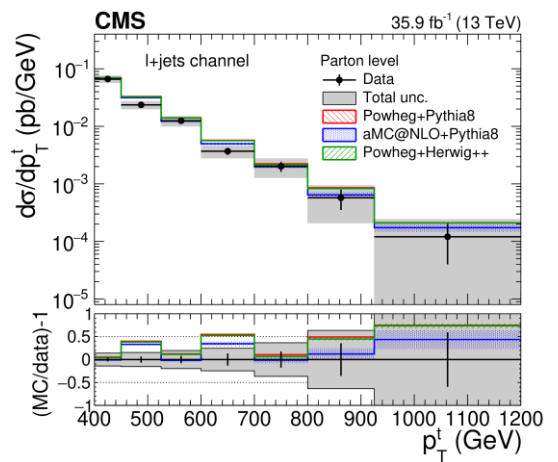
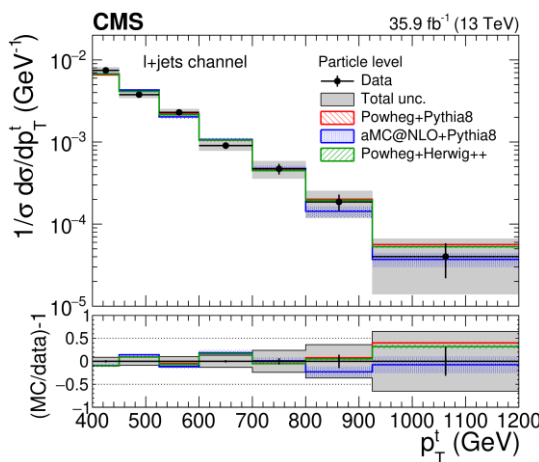
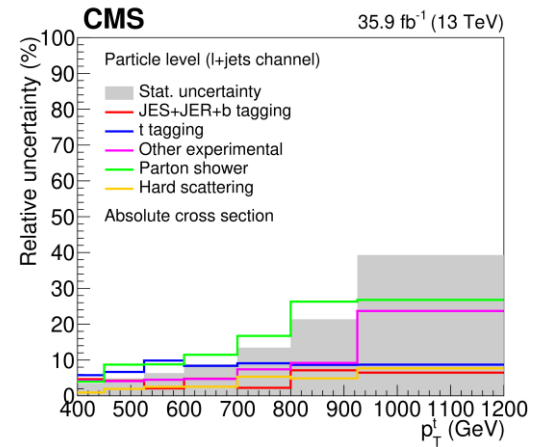
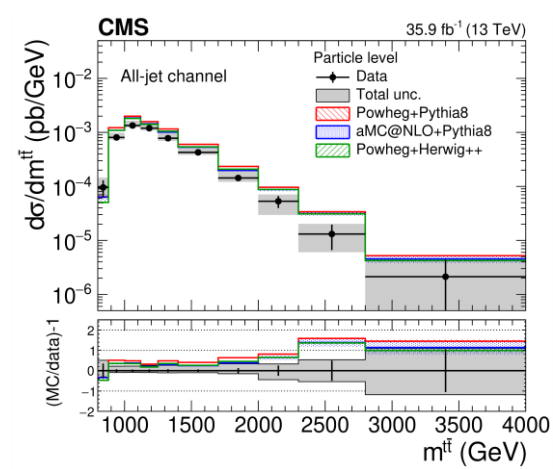
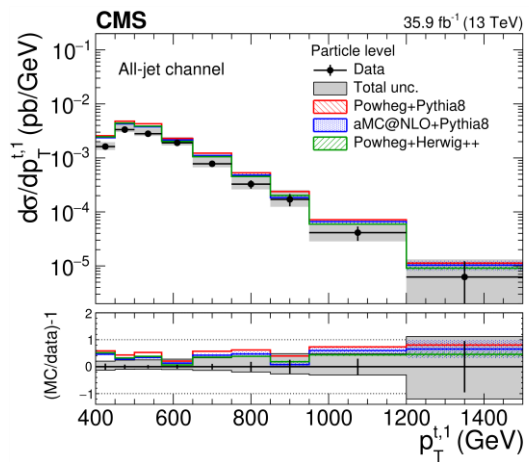
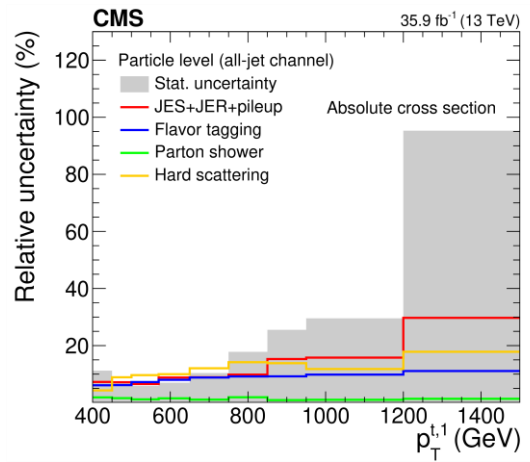
Differential $t\bar{t}$ cross-sections for high- p_T top quarks in 1+jets and hadronic decay channels

- **1 + jets:** One boosted hadronically decaying top quark and resolved leptonically decaying top quark.
- Categories: b and t jet candidate pass tagging requirements
 - **b tagging:** AK4 jet Medium b-tag WP
 - **t tagging:** AK8 jet, $105 < m_{\text{top}} < 220$ GeV N-subjetiness ratio $\tau_{32} < 0.81$ (Loose WP)
- Background: Non-signal $t\bar{t}$, single top quark, W+jets, Z+jets, diboson, (All modelled using MC) QCD: data driven technique
- Simultaneous binned ML fit ($t\bar{t}$ signal strength, t tagging efficiency SF and bkg normalisations) to 3 categories: 1t1b AK8 jet mass, 1tob AK4 jet η , ot AK4 jet η .
 - **$t\bar{t}$ signal strength = 0.81 ± 0.05**
- Diff. cross-sections for hadronically decaying top p_T & $|y|$



Differential $t\bar{t}$ cross-sections for high- p_T top quarks in $l+jets$ and hadronic decay channels: Results

Phys. Rev. D 103 (2021) 052008



- Comparison with MC models: Powheg+Pythia8, Powheg+Herwig++, aMC@NLO+Pythia8
 - **Hadronic:** Shapes overall compatible with theory: **no top p_T slope**
 - **l + jets:** Differential distributions generally well described

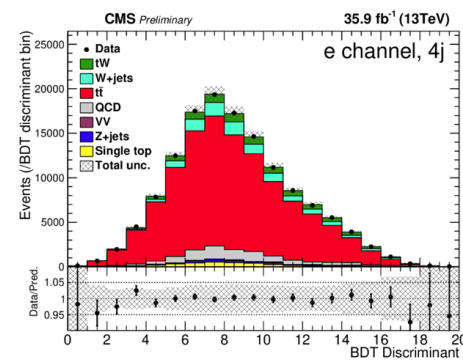
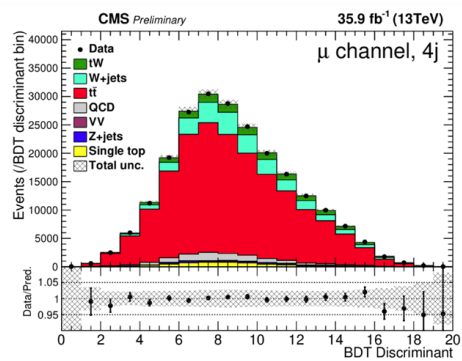
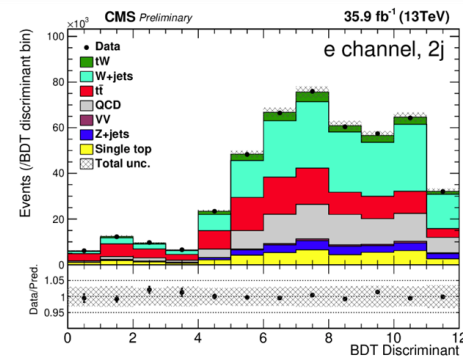
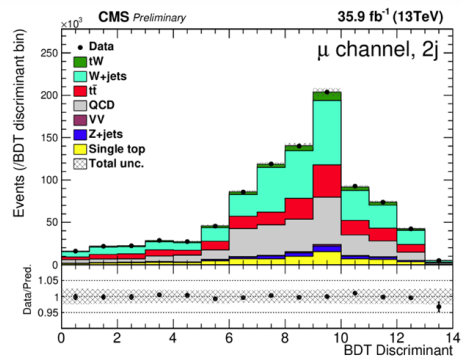
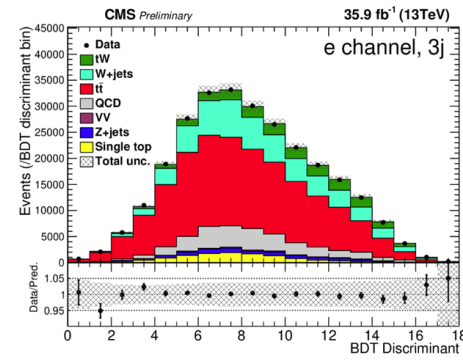
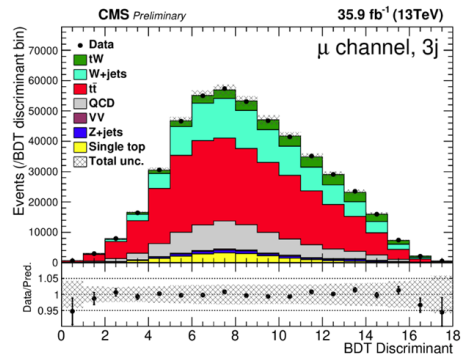
tW production in the semileptonic channel (35.9 fb⁻¹)

NEW

CMS-PAS-TOP-20-002

- Events are selected with 1 lepton and ≥ 2 jets
 - Signal region: 3 jets, 1 b-jet.
 - $t\bar{t}$ control region: 4 jets, 1 b-jet.
 - W+jets CR: 2 jets, 1 b-jet.
- BDT is used to separate signal from background, and a binned likelihood fit is performed on the BDT discriminants (SR+ 2 CR) to extract the tW signal strength:
 - $\mu = 1.24 \pm 0.18$, consistent with unity
 - **First observation** in this final state, with an observed significance clearly exceeding 5σ

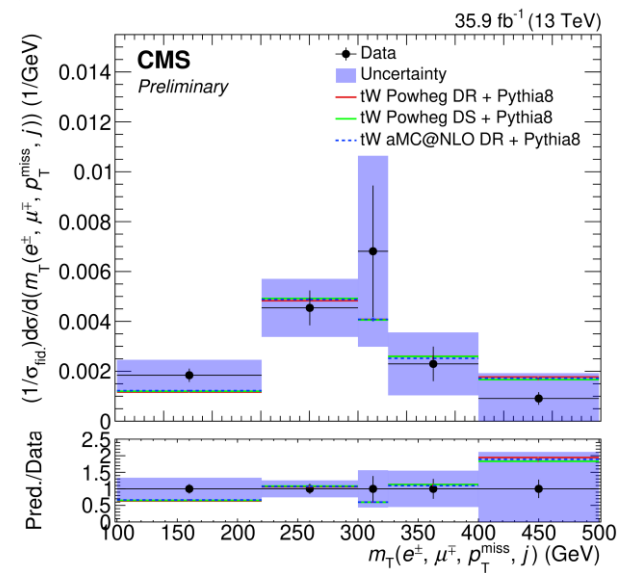
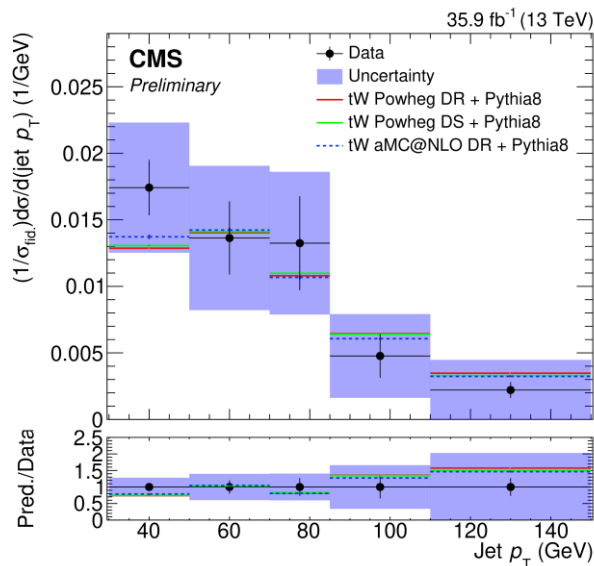
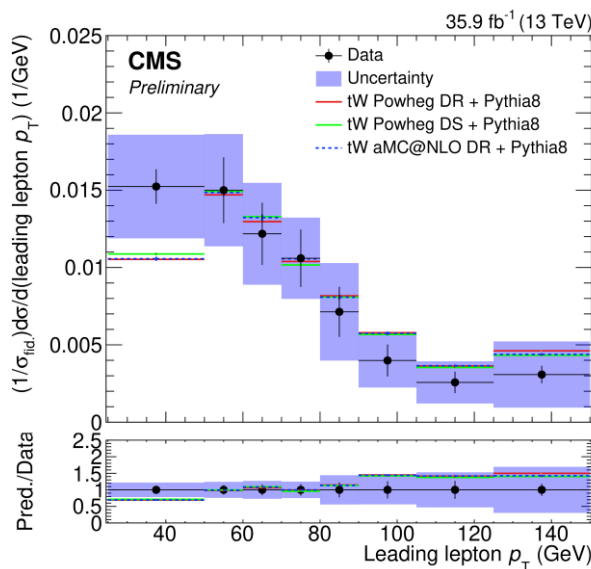
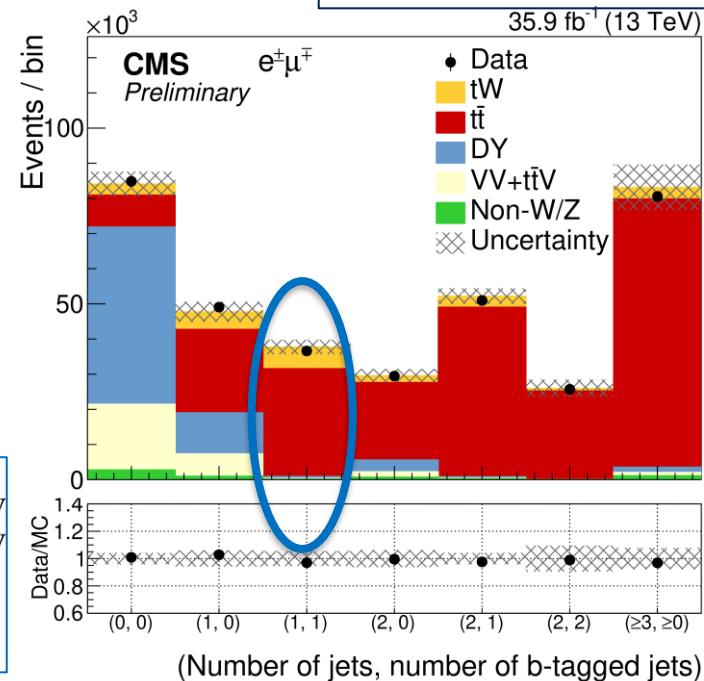
$\sigma_{tW} = 89 \pm 4 \text{ (stat)} \pm 12 \text{ (syst)} \text{ pb}$
 Rel. unc. = 14%
 $\sigma_{tW} \text{ (NLO+NNLL)} = 71.7 \pm 1.8 \pm 3.4 \text{ pb}$



tW diff. cross-section in the dilepton channel

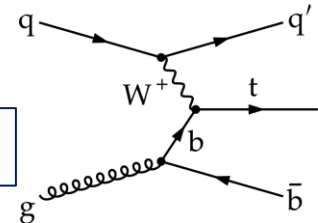
- Events are selected with 1 e and 1 μ , and 1 b-tagged jet
- Uncertainties dominated by JES/JER ($t\bar{t}$ bkg.)
- Unfolding using TUnfold
- Tested models agree with data
 - Powheg+Pythia8 DR & DS
 - MG5_aMC@NLO DR
- Fiducial selection:

Number of leptons	≥ 2
$p_T(\ell_1)$	> 25 GeV
$m_{e\mu}$	> 20 GeV
Number of jets	1
Number of loose jets	0
Number of b jets	1

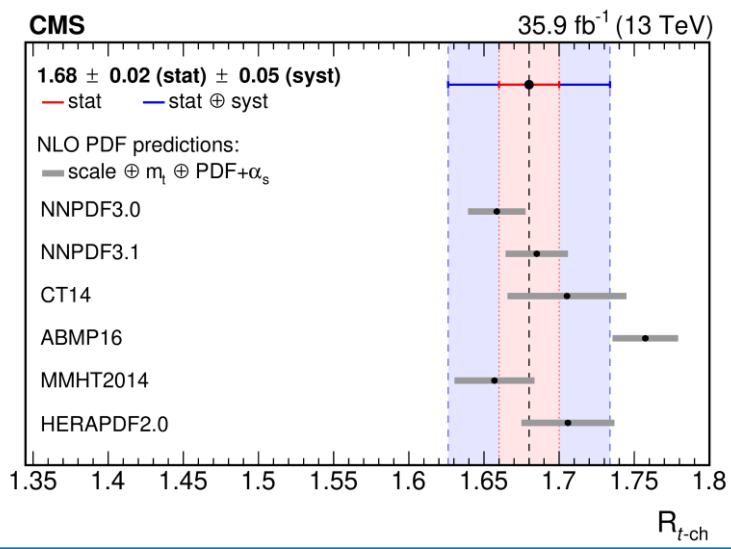
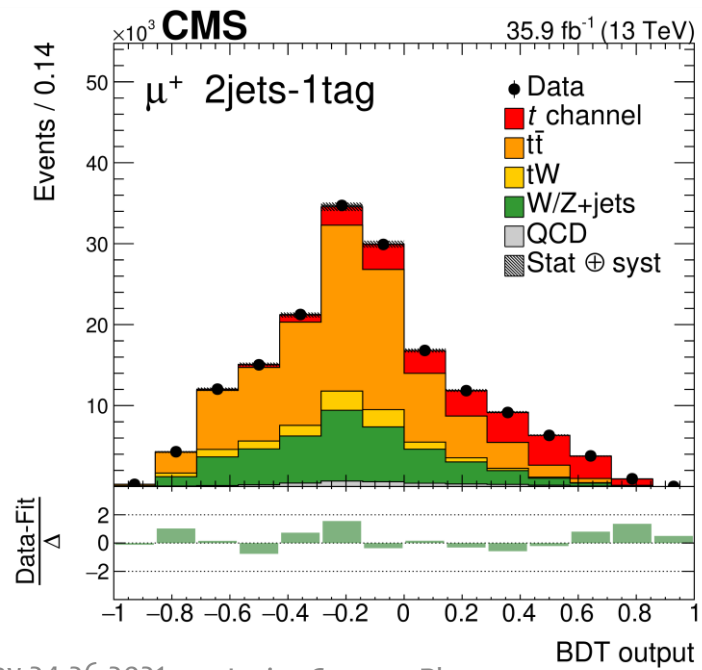
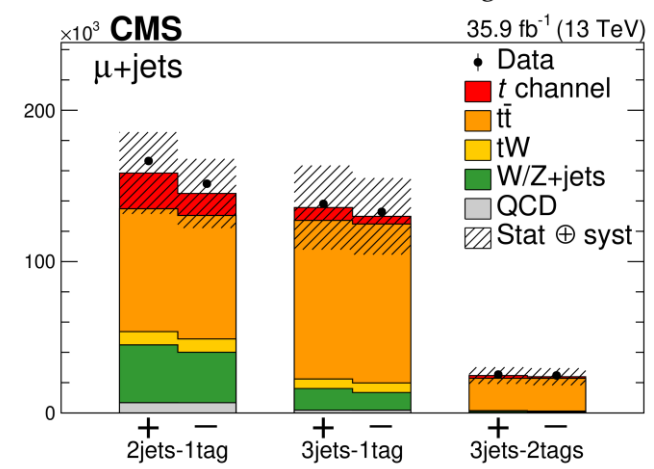


t-channel single top-quark production

Phys. Lett. B 800 (2019) 135042



- Events selected with 1 electron or muon and 2 or 3 jets with 1 or 2 btags
 - Cuts to suppress QCD multijet background
- Signal and backgrounds are separated using BDTs and signal fraction is estimated using a profile-likelihood fit.
- Main syst. unc.: JES, μ_R/μ_S , ME-PS, and signal PDFs.

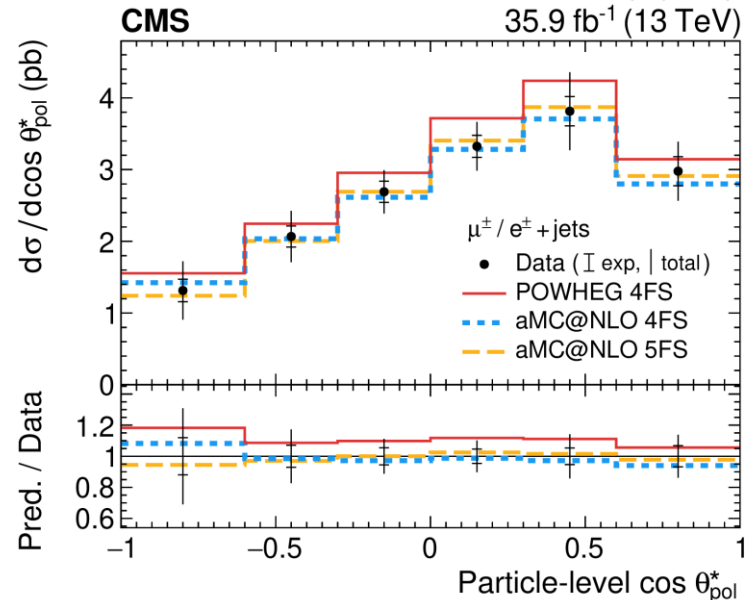
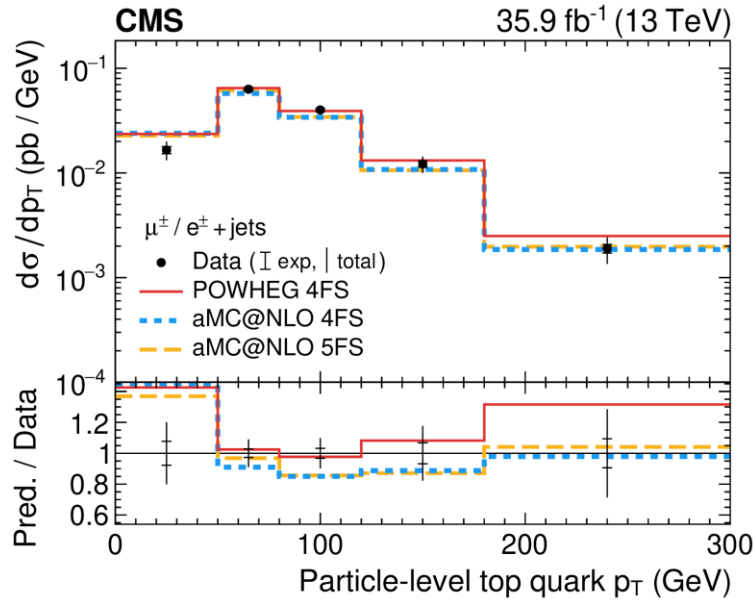
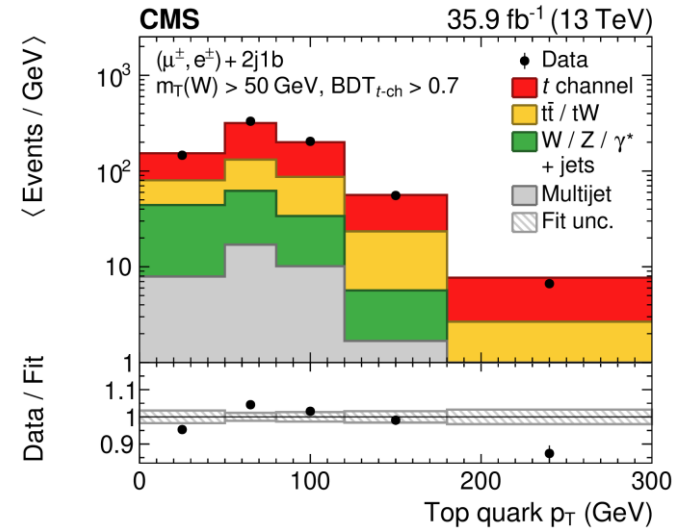
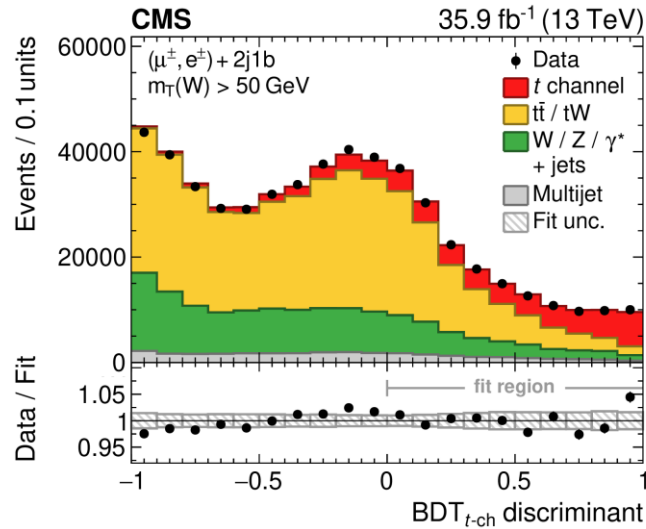


$\sigma_{t\text{-ch},t} = 130 \pm 1 \text{ (stat)} \pm 4 \text{ (prof)} \pm 18 \text{ (sig-mod)} \pm 3 \text{ (lumi)} \text{ pb}$

$\sigma_{t\text{-ch},\bar{t}} = 77 \pm 1 \text{ (stat)} \pm 2 \text{ (prof)} \pm 11 \text{ (sig-mod)} \pm 2 \text{ (lumi)} \text{ pb}$

t-channel differential cross sections

- Events selected with 1 electron or muon and 2 or 3 jets with 1 btag
- Cut on a BDT to enrich S/B



Results in agreement with SM predictions using various next-to-leading-order event generators and sets of parton distribution functions

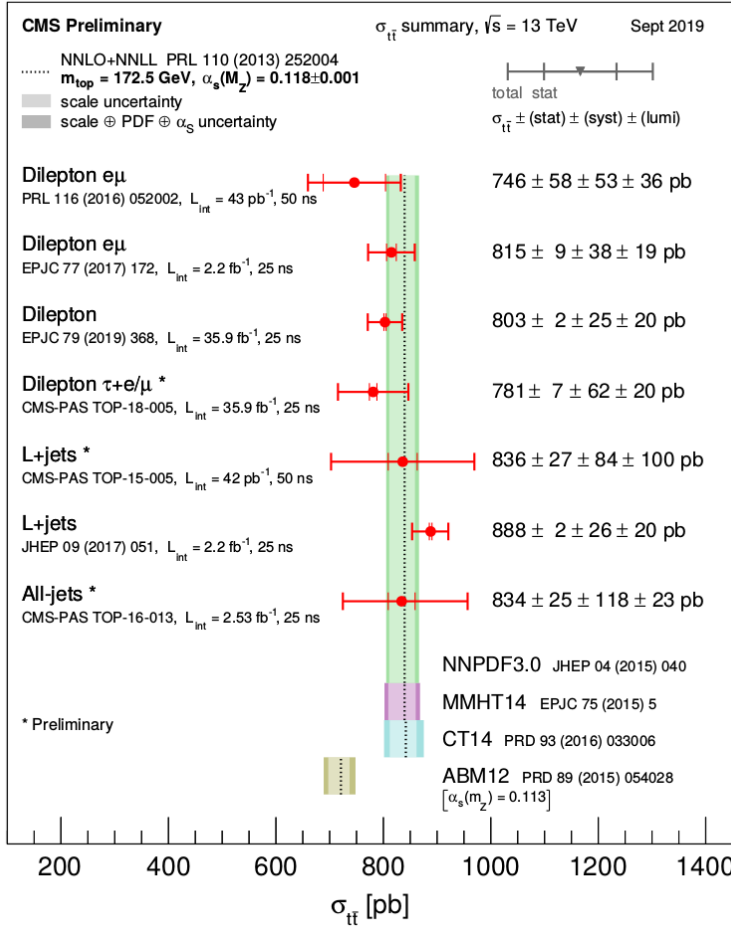
Summary

- Differential $t\bar{t}$ cross-sections in the full kinematic range using lepton+jets final states:
 - **Double differential**, e.g. $p_T(t)$ vs $m(t\bar{t})$, and **many variables well modelled**, but $p_T(t)$ vs $m(t\bar{t})$. Inclusive $\sigma_{t\bar{t}} \rightarrow$ **3.1%** uncertainty, most precise result in ℓ +jets channel
- First measurement of $t\bar{t}$ cross section at 13 TeV with τ_{had}
 - $\sigma_{t\bar{t}}(I\tau_{\text{had}}) = 781 \pm 7$ (stat.) ± 62 (syst.) ± 20 (lumi.) pb. in agreement with NNLO+NNLL (unc. 5.7%).
 - $R_{I\text{th/ll}} = 0.973 \pm 0.009$ (stat.) ± 0.066 (syst.) consistent with lepton flavour universality.
- $t\bar{t}$ inclusive cross section at 5.02 TeV: $\sigma_{t\bar{t}} = 62.6 \pm 4.1$ (stat.) ± 3.0 (syst.+lumi.) pb
- Differential $t\bar{t}$ cross sections with boosted top quarks in hadronic and l + jets channels using 36fb^{-1} of 13 TeV data.
 - Prediction overestimates the integrated cross section by about 35 (25)% in the hadronic (l +jets) channel, in agreement with previous results
 - normalized differential cross section distributions, good agreement between the data and theory predictions
- tW production in the semileptonic channel, **first observation** in this final state.
- t -channel single top-quark production inclusive and differential, results in agreement with NLO predictions.

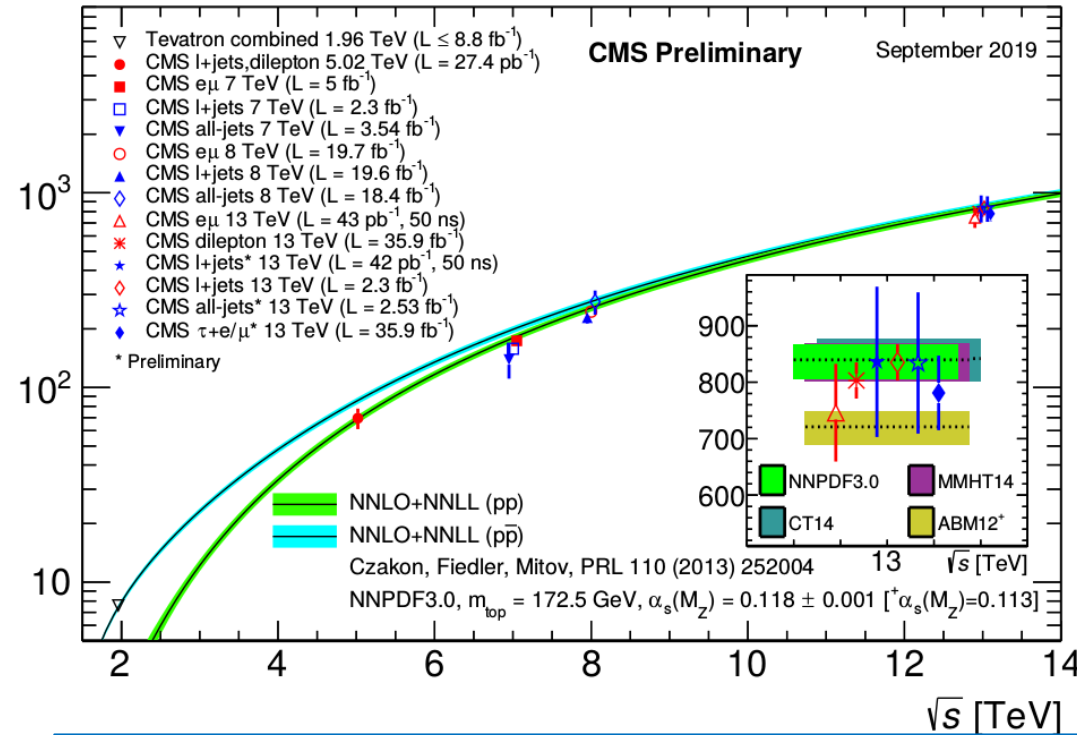
Backup

$t\bar{t}$ inclusive cross section

$e\mu$ channels provide the best sensitivity. Main systematic uncertainties: modelling, lepton/trig. eff., luminosity, not so easy to improve.



Inclusive $t\bar{t}$ cross section [pb]



All channels already considered at 13 TeV. Not all luminosity collected at this energy used. Systematics limited

Rapid rise: reflecting the gluon density
 Measurements at different centre of mass energies and in many channels, provide consistent results, and good agreement with full NNLO+NNLL calculations.
Experimental sensitivity at the level of 3.5%