Rare processes with top quark

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on behalf of the ATLAS and CMS collaborations

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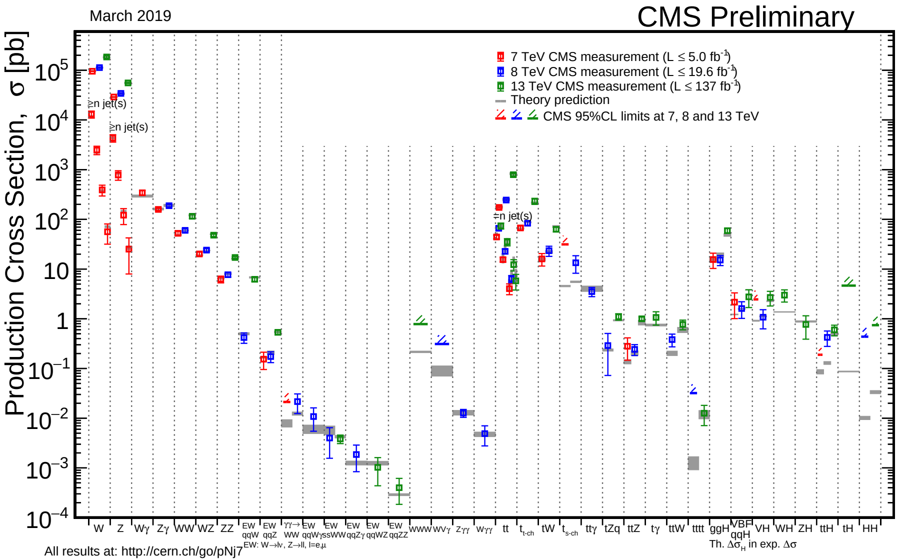
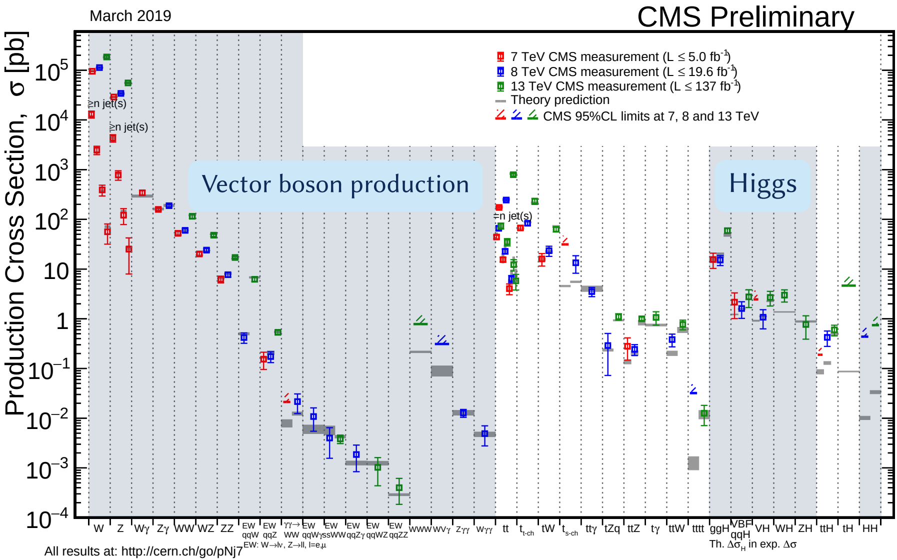
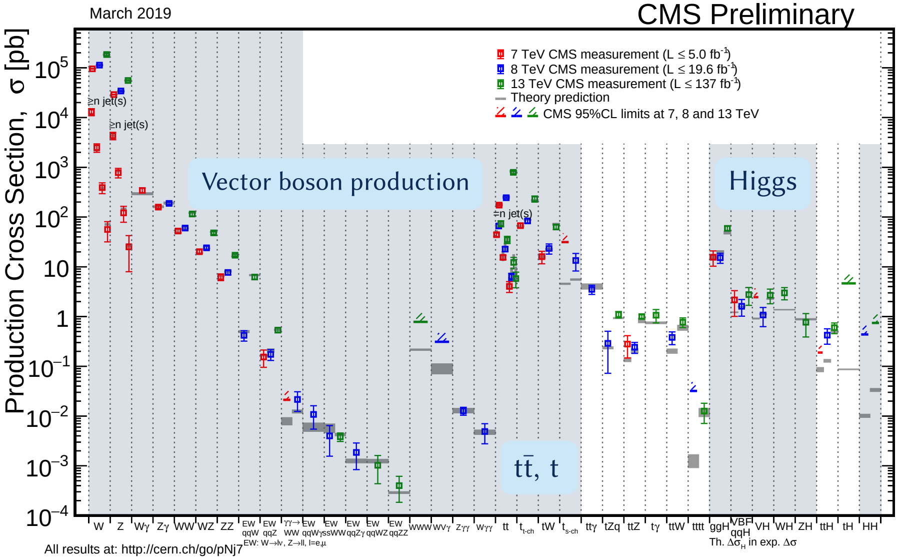
Rare processes with top quark



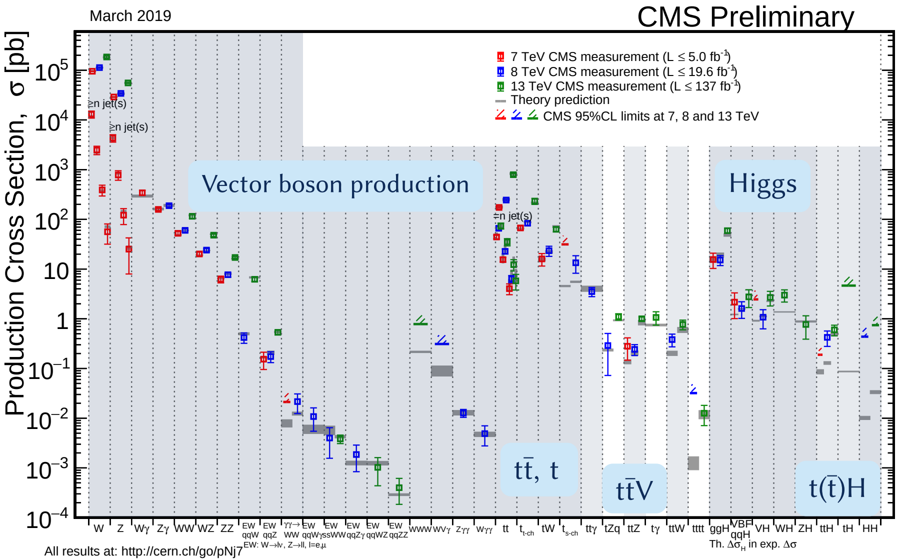
Rare processes with top quark



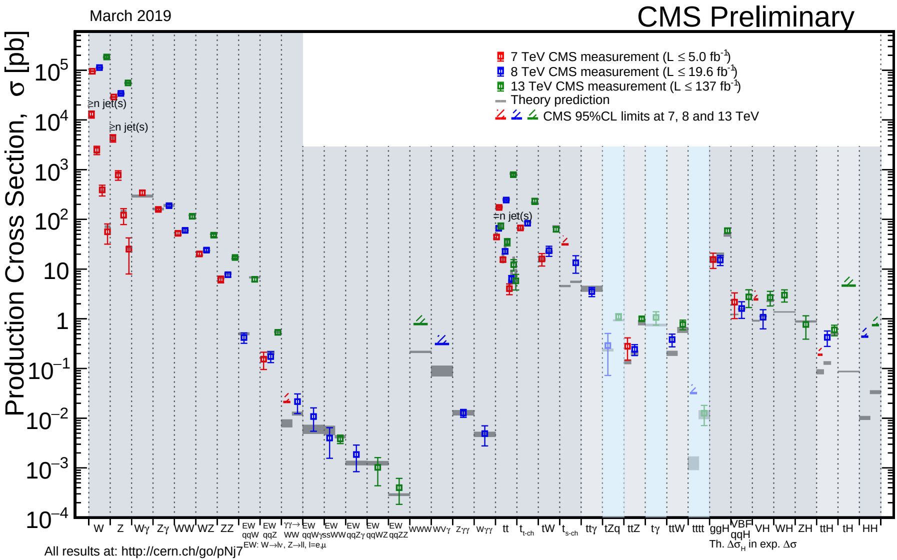
Rare processes with top quark



Rare processes with top quark



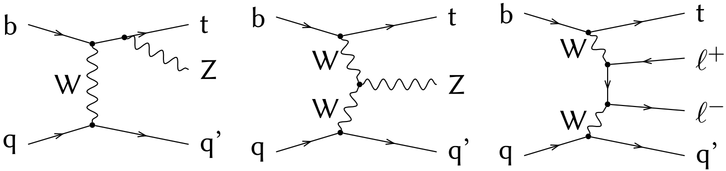
Rare processes with top quark



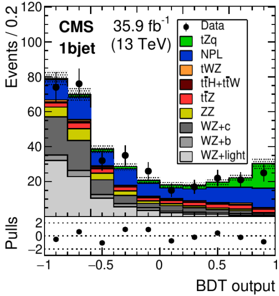
pp → tZq: previous results

$$\sigma_{SM}^{tZq,Z\to\ell^+\ell^-} = 94.2 \pm 3.1\text{ fb}$$

$m(\ell^+\ell^-) > 30$ GeV



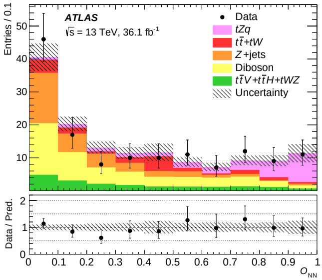
PhysLett**B779**(2018)358



$$\sigma/\sigma_{SM} = 1.31^{+0.35}_{-0.33}(\text{stat})^{+0.31}_{-0.25}(\text{syst})$$

$3.7(3.1)\sigma$ obs. (exp.)

PhysLett**B780**(2018)557



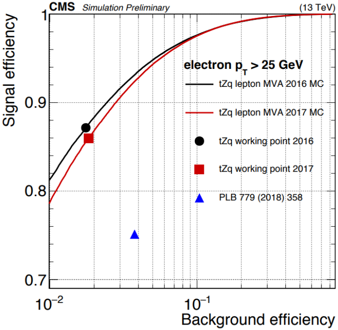
$$\sigma/\sigma_{SM} = 0.75 \pm 0.21(\text{stat}) \pm 0.17(\text{syst})$$

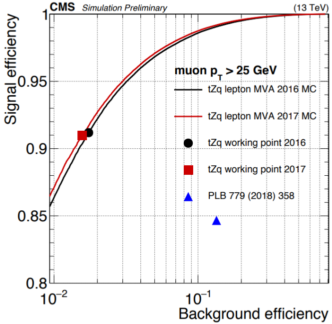
$4.2(5.4)\sigma$ obs. (exp.)

Observation of $pp \rightarrow tZq$

PhysRevLett**122**(2019)132003

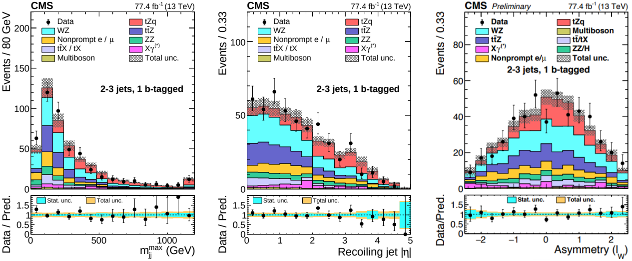
- 2016+2017 data: 77.4 fb^{-1} at 13 TeV
- $Z \rightarrow \ell^{+}\ell^{-}$ and $t \rightarrow bW(\rightarrow \ell'\nu)$: three-lepton final state, with a b-jet and a forward jet
- Non-prompt and fake lepton background: MVA classifier exploiting identification and isolation information (cone-based and nearest jet), significantly improved with respect to the previous analysis



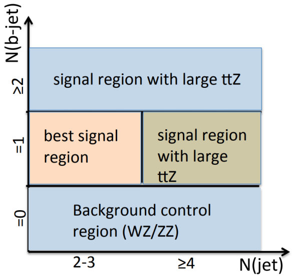


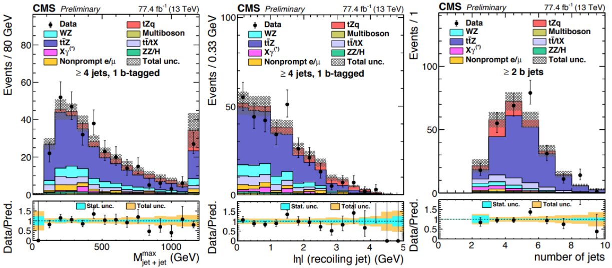
Observation of pp → tZq

PhysRevLett**122**(2019)132003



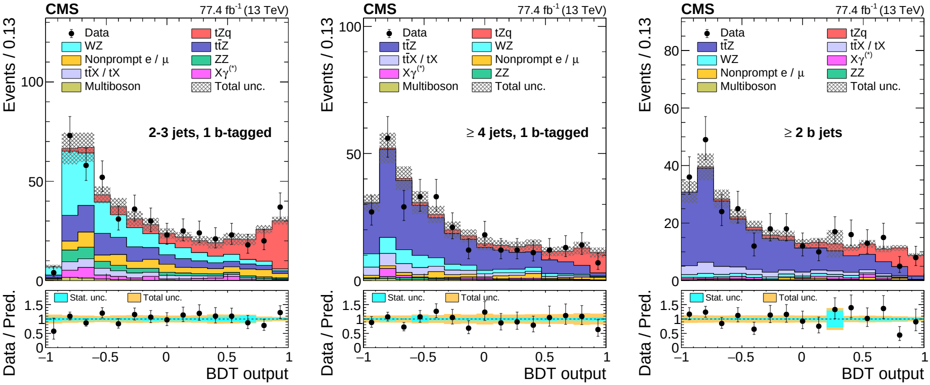
Several kinematic distributions with individually limited separating power, so a kinematic BDT discriminant is trained (in every signal region)





Observation of $pp \rightarrow tZq$

PhysRevLett**122**(2019)132003

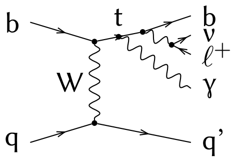


$$\sigma(pp \rightarrow tZ(\rightarrow \ell^+\ell^-)q) = 111 \pm 13(\text{stat})^{+11}_{-9}(\text{syst})\ \text{fb} \quad [m(\ell^+\ell^-) > 30\ \text{GeV}/c^2]$$

$$\sigma/\sigma_{SM} = 1.18^{+0.14}_{-0.13}(\text{stat})^{+0.11}_{-0.10}(\text{syst})^{+0.04}_{-0.04}(\text{theo})$$

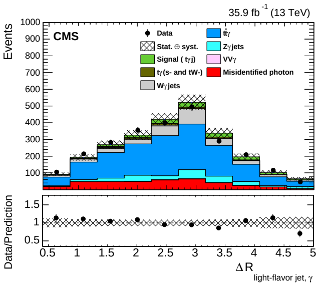
Evidence for pp → tγq

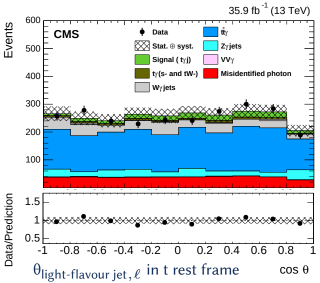
PhysRevLett**121**(2018)221802

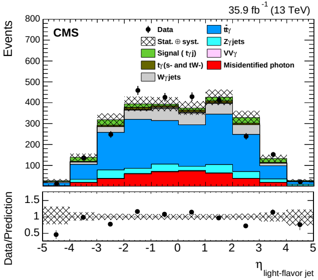


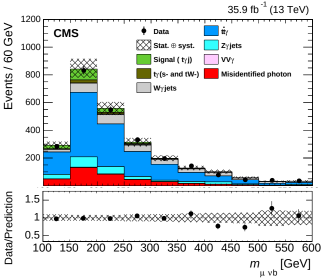
Fiducial region:
$p_{T,\gamma} > 25$ GeV,
$|\eta_\gamma| < 1.44$,
$\Delta R(\{\mu, b, j\}, \gamma) > 0.5$

Single-muon channel:
exactly one lepton,
photon, and b-jet,
$p_T^{miss} > 30$ GeV





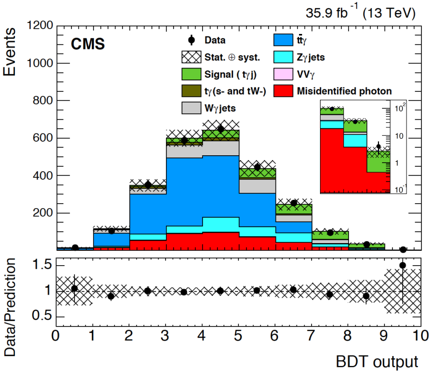




Evidence for pp → tγq

PhysRevLett **121** (2018) 221802

- Template fit to kinematic BDT classifier distribution
- Fake photon backgrounds: data-driven, exploiting independence of photon isolation and shower shape
- Genuine photon backgrounds: W/Zγ + jets from simulation, $t\bar{t}\gamma$ from 2b-tag control region



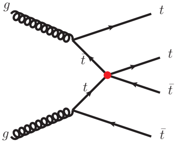
4.4σ (first evidence)

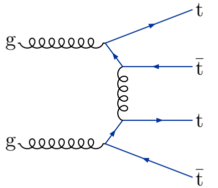
$$\sigma(pp \to t\gamma q) \times \mathcal{B}(t \to \mu\nu b) = 115 \pm 17(\text{stat}) \pm 30(\text{syst})\,\text{fb}$$

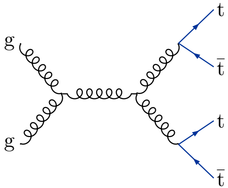
SM value: 81 ± 4 fb

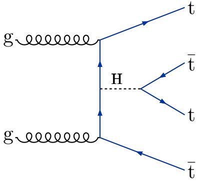
Four-top production in the SM and beyond

- SM NLO QCD: $9.2^{+2.9}_{-2.4}$ fb [JHEP**07**(2014)079],
  SM NLO QCD+EW: $12.0^{+2.0}_{-2.5}$ fb [JHEP**02**(2018)031]
- Enhanced in many BSM theories, also sensitive to the top quark Yukawa coupling $|y_t|$
- Large $t\bar{t}$ + jets background
- Multilepton ($\ell^{\pm}\ell'^{\pm}$, $\geq 3\ell$) final states: non-prompt lepton and $t\bar{t}V$ backgrounds, but much reduced $t\bar{t}$+jets
- Single lepton or opposite-sign dilepton final states: reconstruct almost complete final state (2–3 hadronic top decays)







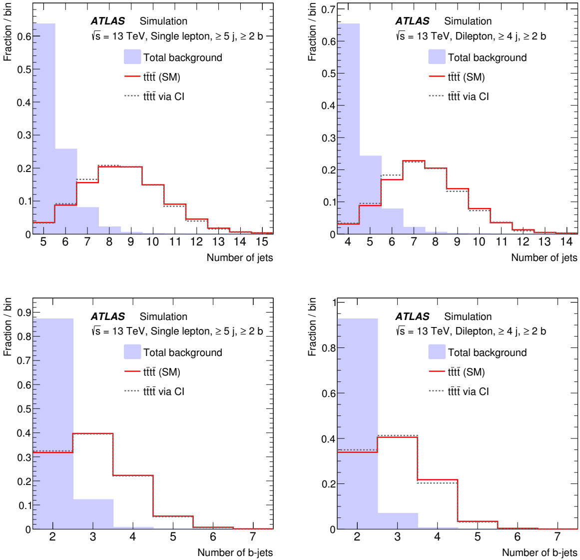


Four-top production in 1ℓ and $\ell^+\ell'^-$ final states

PhysRev**D99**(2019)052009

Preselection: 1 (2 opposite-sign) lepton(s) and least 5 (4) jets, with two b-tags; Z veto in same-flavour dilepton, and MET cuts in 1ℓ

Selected $R = 0.4$ jets reclustered in $R = 1.0$ jets to reconstruct hadronic top decays, "mass-tagged" if $p_T > 200$ GeV, $|\eta| < 2.0$, $m > 100$ GeV



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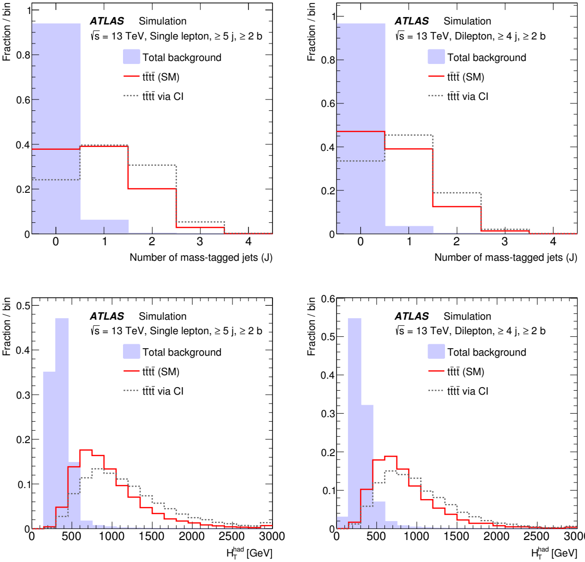
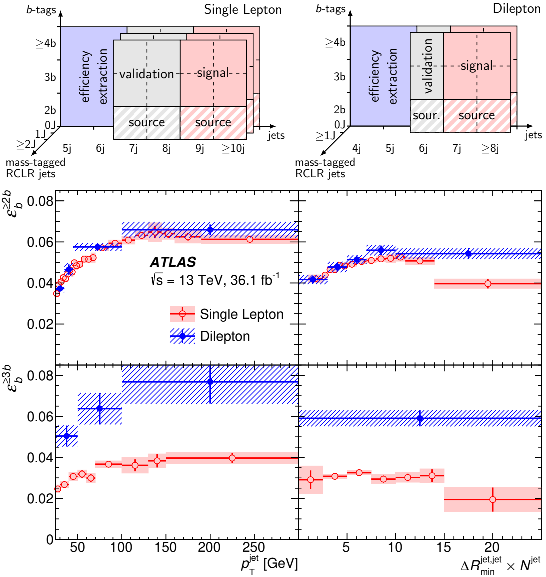


Four-top production in 1ℓ and $\ell^+\ell'^-$ final states

PhysRev**D99**(2019)052009

Data-driven technique to estimate $t\bar{t}$ + jets: probability to tag an additional b-jet derived from the low jet multiplicity region, as a function of p_T and $\Delta R^{jet,jet}_{min} \times N^{jet}$, and corrected bin-by-bin from MC

Uncertainty from the relative normalisation of different contributions is partially cancelled

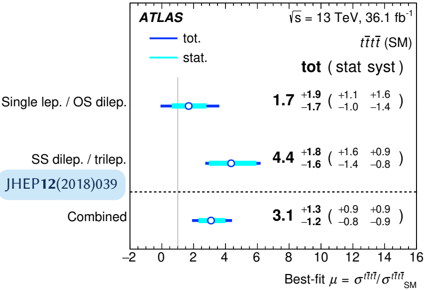


Four-top production in 1ℓ and $\ell^+\ell'^-$ final states

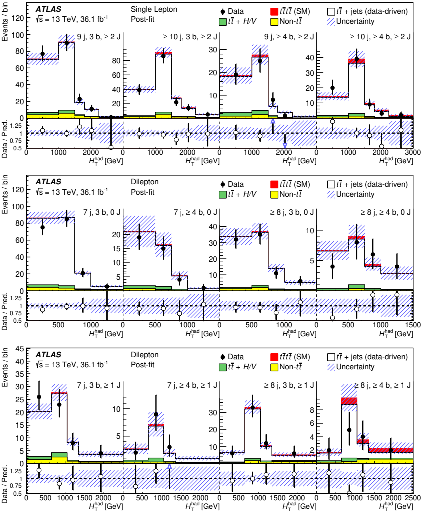
PhysRev**D99**(2019)052009

- Template fit to $H_T^{had} = \sum p_T^j$ in bins of (b-)jet multiplicity
- Remaining $t\bar{t} + b(c)$ modeling and background statistical uncertainty dominate systematic uncertainty

Observed (expected) upper limit:
47(33) fb, i.e. $5.1(3.6^{+2.9}_{-1.8}) \times$ SM



JHEP**12**(2018)039



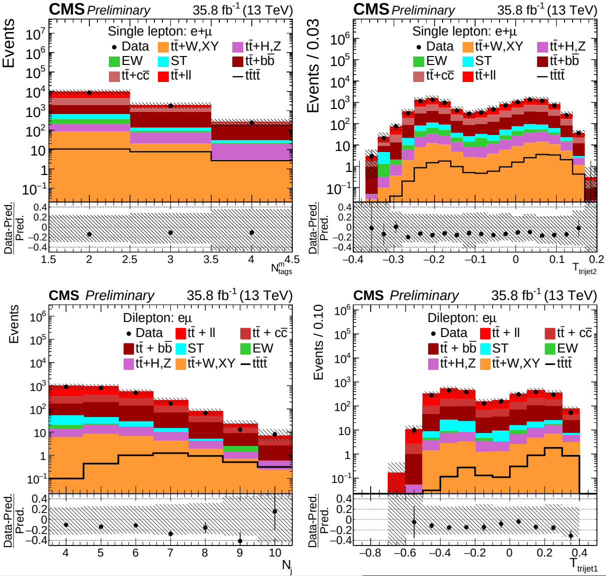
SM four-top production in 1ℓ and $\ell^+\ell'^-$ final states

CMS-PAS-TOP-17-019

$35.8\ \mathrm{fb}^{-1}$ (2016)

At least 7 ($\mu^\pm$), 8 ($e^\pm$) or 6 (dilepton) jets and at least two b-tags

A BDT (using dijet and trijet masses, angles, b-tags etc.) is used to identify hadronic top decays 3-jet combinations



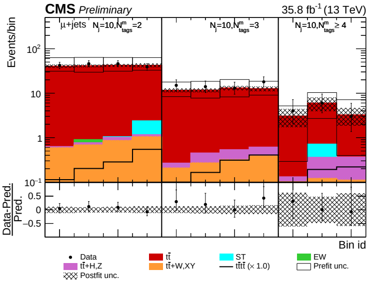
SM four-top production in 1ℓ and $\ell^+\ell'^-$ final states

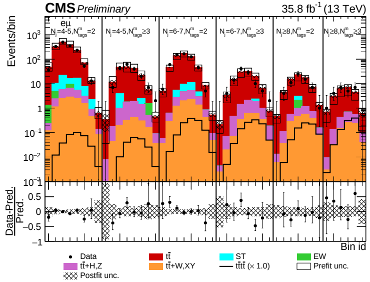
CMS-PAS-TOP-17-019

- A second BDT per jet multiplicity (final state) for single (di)lepton, using (b-)jet multiplicity, kinematic variables (H_T, “reduced” event variables for single lepton) and event topology information, combined fit to response in (b-)jet multiplicity bins

- $\sigma(t\bar{t}+b\bar{b})/\sigma(t\bar{t}+jj)$ constrained from the CMS measurement [PhysLett**B776**(2018)355]

Observed (expected) upper limit:
$48(52^{+26}_{-17})$ fb, i.e. $5.2(5.7^{+2.9}_{-1.8}) \times$ SM





SM four-top production in $\ell^{\pm}\ell'^{\pm}$ and $\geq 3\ell$ final states

CMS-PAS-TOP-18-003

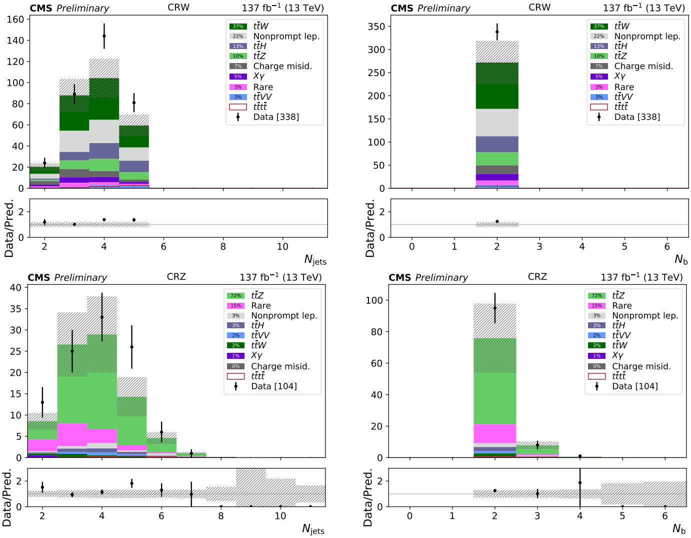
- 137 fb^{-1} (2016+2017+2018)
- $t\bar{t}W$, $t\bar{t}Z$ and $t\bar{t}H$ background: NLO QCD with $N_{\mathrm{jets}}^{\mathrm{ISR/FSR}}$ reweighting (from dileptonic $t\bar{t}$), and heavy flavour fraction corrected using the measured $t\bar{t}b\bar{b}/t\bar{t}jj$ ratio from [PhysLett**B776**(2018)355] ($\times 1.7 \pm 0.6$)
- Baseline selection: $H_T > 300$ GeV, $p_T^{\mathrm{miss}} > 50$ GeV, ≥ 2 jets, b-tagged jets and leptons, $Z \to \ell^+\ell^-$ control region for $t\bar{t}Z$
- Cut-based: $t\bar{t}W$ control region $N_j \leq 5$
- BDT: trained on lepton, jet, and b-tag mulitplicities and kinematic variables

Cut-based signal regions

N_ℓ	N_b	N_{jets}	Region
2	2	≤ 5	CRW
		6	SR1
		7	SR2
		≥ 8	SR3
	3	5	SR4
		6	SR5
		7	SR6
		≥ 8	SR7
	≥ 4	≥ 5	SR8
≥ 3	2	5	SR9
		6	SR10
		≥ 7	SR11
	≥ 3	4	SR12
		5	SR13
		≥ 6	SR14
inverted Z-veto			CRZ

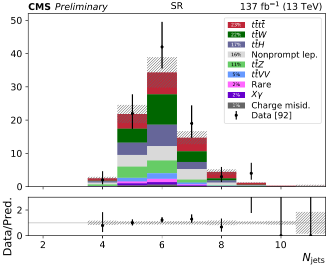
SM four-top production in $\ell^{\pm}\ell'^{\pm}$ and $\geq 3\ell$ final states

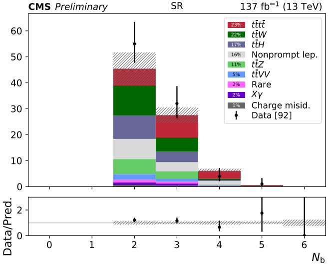
CMS-PAS-TOP-18-003

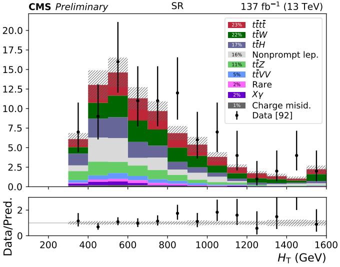


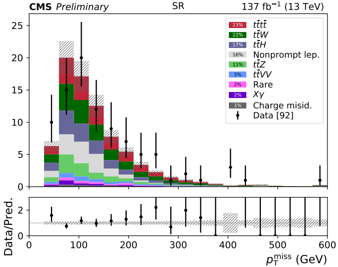
SM four-top production in $\ell^{\pm}\ell'^{\pm}$ and $\geq 3\ell$ final states

CMS-PAS-TOP-18-003









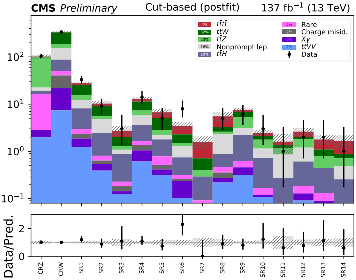
SM four-top production in $\ell^{\pm}\ell'^{\pm}$ and $\geq 3\ell$ final states

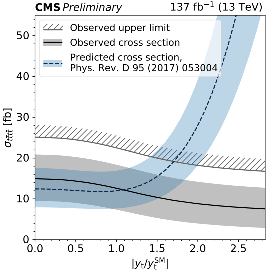
CMS-PAS-TOP-18-003

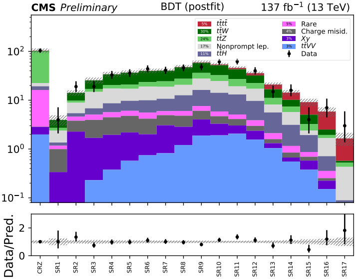
Observed (expected) upper limit:
22.5 fb ($8.4^{+3.9}_{-2.6}$) (BDT)

Best-fit: $12.6^{+5.8}_{-5.2}$ fb, 2.6(2.7)σ from zero

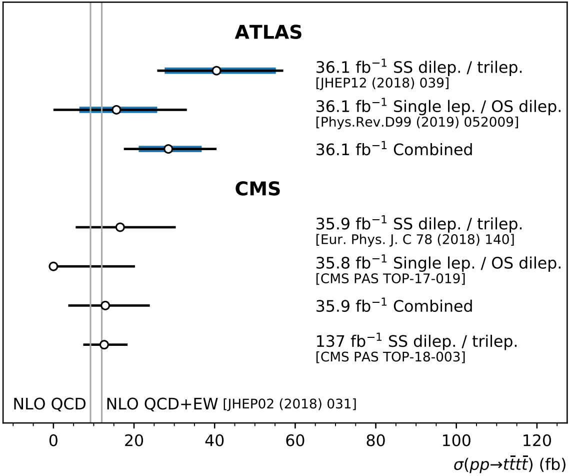
Systematic on $t\bar{t}X$+(b-)jets (from measured $t\bar{t}b\bar{b}/t\bar{t}jj$ ratio): 11% impact on $\sigma(t\bar{t}t\bar{t})$, most important, together with experimental jet-related uncertainties







SM four-top production: LHC run 2 results so far



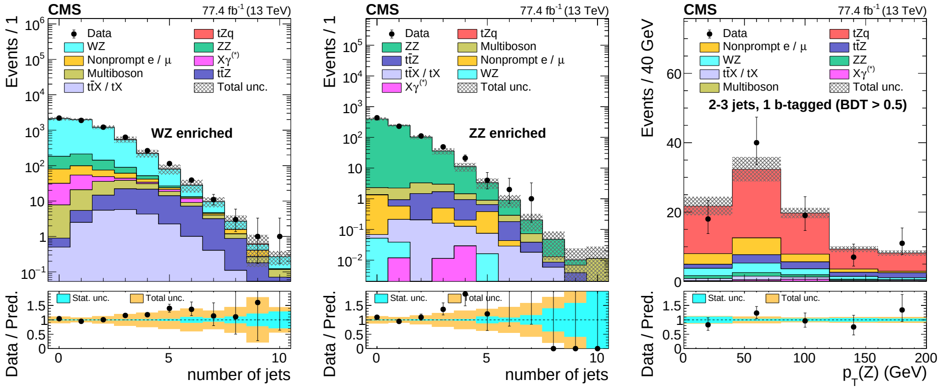
Conclusions

- Rare processes with top quarks are sensitive to beyond the SM interactions
- Many processes are explored for the first time at the LHC — and most presented analyses do not use the full $\sqrt{s} = 13\,\text{TeV}$ data sample yet
- Experimental challenge: large backgrounds ($t\bar{t}$+(b/c-)jets, $t\bar{t}Z$...)
- With increasing statistical sensitivity, precise theory predictions — also (and sometimes especially) for backgrounds — become more and more important to make the most out of the data

Additional material

Evidence for pp → tZq

PhysRevLett **122**(2019)132003



SM four-top production in $\ell^{\pm}\ell'^{\pm}$ and $\geq 3\ell$ final states

CMS-PAS-TOP-18-003

Source	Uncertainty (%)	Impact on the $t\bar{t}t\bar{t}$ cross section (%)
Integrated luminosity	2.3–2.5	3
Pileup	0–5	1
Trigger efficiency	2–7	2
Lepton selection	2–10	2
Jet energy scale	1–15	9
Jet energy resolution	1–10	6
b tagging	1–15	6
Size of simulated sample	1–25	<1
Scale and PDF variations †	10–15	2
ISR/FSR (signal) †	5–15	2
$t\bar{t}H$ (normalization) †	25	5
Rare, Xγ, $t\bar{t}VV$ (norm.) †	11-20	<1
$t\bar{t}Z$, $t\bar{t}W$ (norm.) †	40	3-4
Charge misidentification †	20	<1
Nonprompt leptons †	30–60	3
$N_{\text{jets}}^{\text{ISR/FSR}}$ †	1-30	2
$\sigma(t\bar{t}b\bar{b})/\sigma(t\bar{t}jj)$ †	35	11

$t\bar{t}(X)$+(b/c) in SM four-top 1ℓ and $\ell^+\ell'^-$ searches

PhysRev**D99**(2019)052009

- $t\bar{t}+\geq 1b$ fraction: 50% (NLO Powheg + Pythia versus Sherpa + OpenLoops)
- $t\bar{t}+\geq 1c$ fraction: 50% (same as above, no theory prediction)
- PS: Herwig++ instead of Pythia,
- ME: MG5_aMC@NLO instead of Powheg
- ISR/FSR and scale variations: by changing μ_R, μ_F, and h_{damp} ($\times 2$)
- NNLO top p_T reweighting
- Additional $t\bar{t}+\geq 1b$ uncertainty from comparing 4-flavour SherpaOL with nominal 5-flavour Powheg+Pythia

Uncertainty source	$\pm\Delta\mu$	
$t\bar{t}$+jets modeling	1.2	−0.96
Background-model statistical uncertainty	0.91	−0.85
Jet energy scale and resolution, jet mass	0.38	−0.16
Other background modeling	0.26	−0.20
b-tagging efficiency and mis-tag rates	0.33	−0.10
JVT, pileup modeling	0.18	−0.073
$t\bar{t}+H/V$ modeling	0.053	−0.055
Luminosity	0.050	−0.026
Total systematic uncertainty	1.6	−1.4
Total statistical uncertainty	1.1	−1.0
Total uncertainty	1.9	−1.7

Data-driven method removes “normalization“ uncertainties, only changes in kinematic distributions and “bin migrations” remain

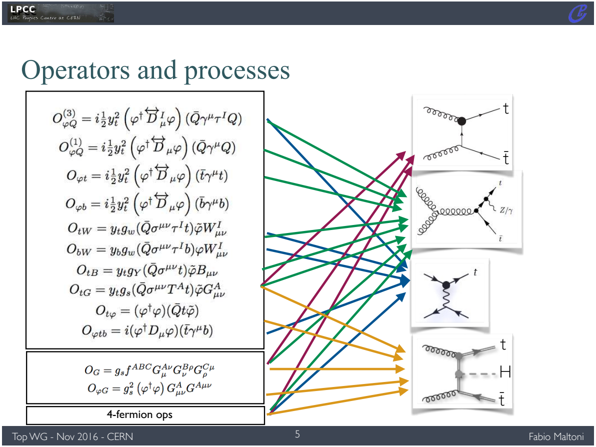
tt(X)+(b/c) in SM four-top 1ℓ and $\ell^+\ell'^-$ searches

CMS-PAS-TOP-17-019

- Powheg + Pythia, with NNLO top p_T reweighting (varied within $\pm 1\sigma$)
- Scale variations: μ_R, μ_F $\times 2$, $h_{damp} = 1.581 m_t \times_{0.6}^{1.4}$ (1σ)
- ISR and FSR parton shower scales varied by a factor two up and down
- UE CUETP8M2T4 tune variations
- PDF uncertainty: NNPDF, MMHT14 and CT10
- $t\bar{t}$+$b\bar{b}$: varied within $\pm 1\sigma$ from the measured [PhysLett**B776**(2018)355]
  $\sigma(t\bar{t}b\bar{b})/\sigma(t\bar{t}jj) = 0.022 \pm 0.003(\text{stat}) \pm 0.006(\text{syst})$

Top quark associated production

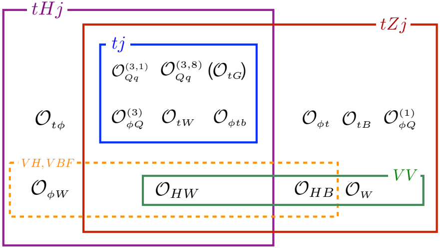
- Top quark decay: dominated by $t \rightarrow Wb$ (V_{tb} coupling)
- Associated production gives access to top-boson and to BSM couplings



EFT sensitivity of pp → tVj(tHj)

JHEP**10**(2018)005

- tγj and tZj probe the same dim-6 operators as $t\bar{t}\gamma$ and $t\bar{t}Z$, but without (at LO) the QCD and 4-fermion operators that also enter inclusive $t\bar{t}$ production
- No QCD interactions at LO, so QCD corrections are small and well-predicted
- High-energy tail sensitive to $\mathcal{O}_{\varphi Q}^{(3)}$
- Complementary constraints to those from other processes



$\mathcal{O}_W$	$\varepsilon_{IJK}\, W^I_{\mu\nu}\, W^{J,\nu\rho}\, W^{K,\mu}_{\rho}$	$\mathcal{O}^{(3)}_{\varphi Q}$	$i\big(\varphi^\dagger \overleftrightarrow{D}_\mu\, \tau_I \varphi\big)\big(\bar{Q}\,\gamma^\mu\,\tau^I Q\big) + \text{h.c.}$
$\mathcal{O}_{\varphi W}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) W_I^{\mu\nu}\, W^I_{\mu\nu}$	$\mathcal{O}^{(1)}_{\varphi Q}$	$i\big(\varphi^\dagger \overleftrightarrow{D}_\mu\, \varphi\big)\big(\bar{Q}\,\gamma^\mu\, Q\big) + \text{h.c.}$
$\mathcal{O}_{\varphi WB}$	$(\varphi^\dagger \tau_I \varphi)\, B^{\mu\nu} W^I_{\mu\nu}$	$\mathcal{O}_{\varphi t}$	$i\big(\varphi^\dagger \overleftrightarrow{D}_\mu\, \varphi\big)\big(\bar{t}\,\gamma^\mu\, t\big) + \text{h.c.}$
$\mathcal{O}_{\varphi D}$	$(\varphi^\dagger D^\mu \varphi)^\dagger (\varphi^\dagger D_\mu \varphi)$	$\mathcal{O}_{\varphi tb}$	$i\big(\tilde{\varphi}\, D_\mu\, \varphi\big)\big(\bar{t}\,\gamma^\mu\, b\big) + \text{h.c.}$
$\mathcal{O}_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$\mathcal{O}^{(1)}_{\varphi q}$	$i\big(\varphi^\dagger \overleftrightarrow{D}_\mu\, \varphi\big)\big(\bar{q}_i\,\gamma^\mu\, q_i\big) + \text{h.c.}$
$\mathcal{O}_{t\varphi}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) \bar{Q}\, t\, \tilde{\varphi} + \text{h.c.}$	$\mathcal{O}^{(3)}_{\varphi q}$	$i\big(\varphi^\dagger \overleftrightarrow{D}_\mu\, \tau_I \varphi\big)\big(\bar{q}_i\,\gamma^\mu\,\tau^I q_i\big) + \text{h.c.}$
$\mathcal{O}_{tW}$	$i\big(\bar{Q}\sigma^{\mu\nu}\, \tau_I\, t\big)\, \tilde{\varphi}\, W^I_{\mu\nu} + \text{h.c.}$	$\mathcal{O}_{\varphi u}$	$i\big(\varphi^\dagger \overleftrightarrow{D}_\mu\, \varphi\big)\big(\bar{u}_i\,\gamma^\mu\, u_i\big) + \text{h.c.}$
$\mathcal{O}_{tB}$	$i\big(\bar{Q}\sigma^{\mu\nu}\, t\big)\, \tilde{\varphi}\, B_{\mu\nu} + \text{h.c.}$	$\mathcal{O}^{(3,1)}_{Qq}$	$\big(\bar{q}_i\,\gamma_\mu\,\tau_I q_i\big)\big(\bar{Q}\,\gamma^\mu\,\tau^I Q\big)$
$\mathcal{O}_{tG}$	$i\big(\bar{Q}\sigma^{\mu\nu}\, T_A\, t\big)\, \tilde{\varphi}\, G^A_{\mu\nu} + \text{h.c.}$	$\mathcal{O}^{(3,8)}_{Qq}$	$\big(\bar{q}_i\,\gamma_\mu\,\tau_I T_A q_i\big)\big(\bar{Q}\,\gamma^\mu\,\tau^I T^A Q\big)$

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