Rare top quark production at the LHC

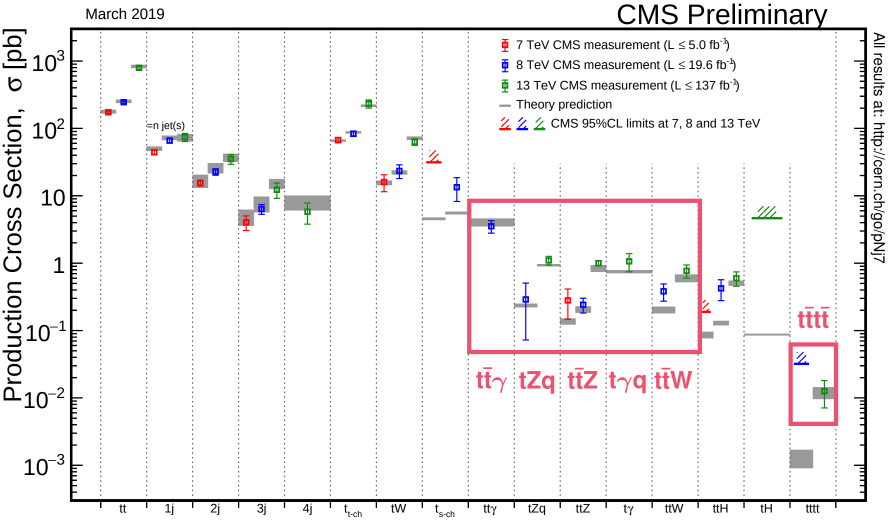
Results on $t\bar{t}Z$, $t\bar{t}W$, $t\bar{t}\gamma$, tZq, $t\gamma q$, and $t\bar{t}t\bar{t}$ with the ATLAS and CMS experiments

Joscha Knolle
on behalf of the ATLAS and CMS collaborations

WG5: Physics with Heavy Flavours
XVII International Workshop on Deep Inelastic Scattering
April 8th–12th, 2019, Torino

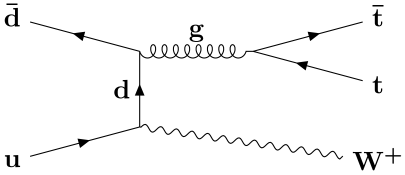
DIS 2019 TORINO 8-12 April

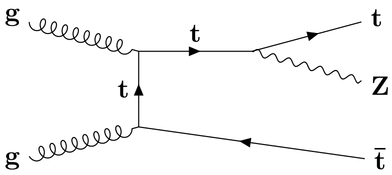
Top quark production at the LHC



- Top quark pairs and single tops produced plentiful.
- Rare top production modes become fully accessible with full run-2 data.

$t\bar{t}W$ and $t\bar{t}Z$ production





- $t\bar{t}Z$ cross section sensitive to tZ coupling, first direct test
- important backgrounds for measurements with leptons and b-quarks, e.g. $t\bar{t}H$

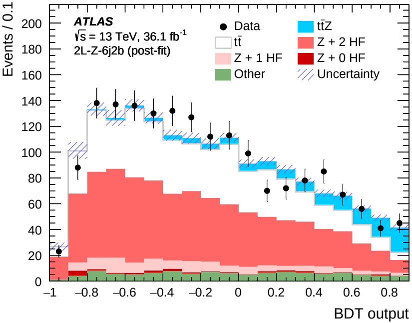
arXiv:1901.03584
(submitted to PRD)
$t\bar{t}W$ and $t\bar{t}Z$
with 2015 & 2016 data

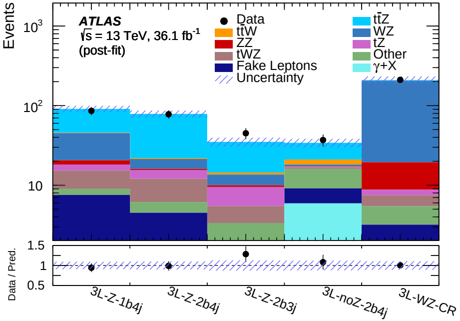
JHEP 1808 (2018) 011
$t\bar{t}W$ and $t\bar{t}Z$ with 2016 data

CMS-PAS-TOP-18-009
$t\bar{t}Z$ with 2016 & 2017 data

$t\bar{t}W$ & $t\bar{t}Z$ measurement

arXiv:1901.03584 (submitted to PRD)





$t\bar{t}W$: analysis regions for SS dilepton and trilepton channels

$t\bar{t}Z$: analysis regions for OS dilepton, trilepton and tetralepton channels

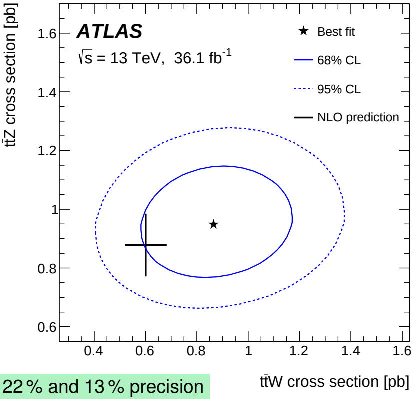
simultaneous **template fit** to signal and control regions

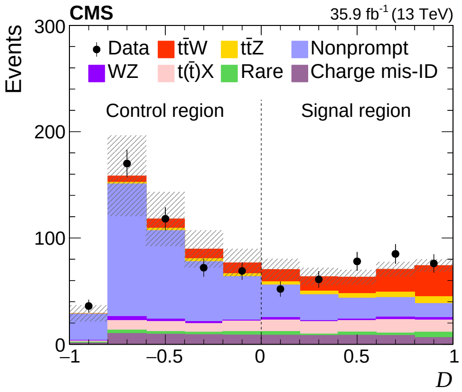
- BDT for OS dilepton channel
- (N_j, N_b) categories for other channels
- control regions for $t\bar{t}$, WZ+jets, ZZ
- nonprompt leptons & charge-flip from data

main systematics: signal modeling, backgrounds (modeling, normalization, statistics)

$t\bar{t}W$ & $t\bar{t}Z$ cross section results

arXiv:1901.03584 (submitted to PRD), JHEP 1808 (2018) 011





22 % and 13 % precision

$$\sigma(t\bar{t}W) = 0.87 \pm 0.13\,(\text{stat}) \pm 0.14\,(\text{syst})\,\text{pb}$$

$$\sigma(t\bar{t}Z) = 0.95 \pm 0.08\,(\text{stat}) \pm 0.10\,(\text{syst})\,\text{pb}$$

23 % precision

$$\sigma(t\bar{t}W) = 0.77\,^{+0.12}_{-0.11}\,(\text{stat})\,^{+0.13}_{-0.12}\,(\text{syst})\,\text{pb}$$

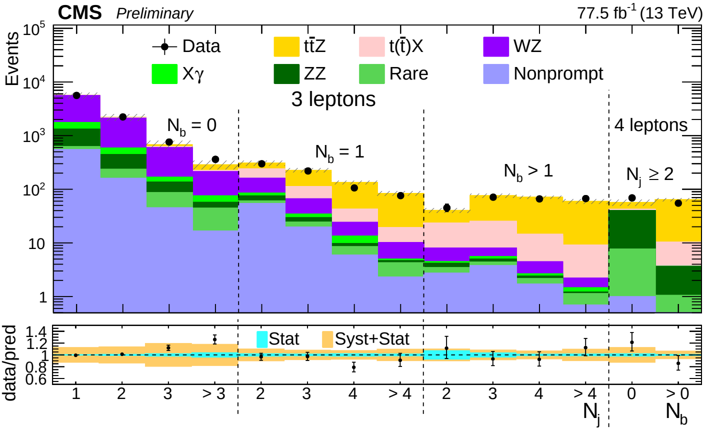
$\Rightarrow$ in good agreement with SM prediction:

$$\sigma(t\bar{t}W) = 0.628 \pm 0.082\,\text{pb}$$

$$\sigma(t\bar{t}Z) = 0.839 \pm 0.101\,\text{pb}$$

New inclusive $t\bar{t}Z$ result

CMS-PAS-TOP-18-009



nonprompt ℓ from data

WZ constraints from $N_b = 0$

WZ, $X\gamma$, ZZ validated in control regions

most important background: tZq

$t\bar{t}Z$ cross section from **template fit** to (N_j, N_b) categories of 3- and 4-lepton channels

$$\sigma(t\bar{t}Z) = 1.00\,^{+0.06}_{-0.05}\,(\text{stat})\,^{+0.07}_{-0.06}\,(\text{syst})\,\text{pb}$$

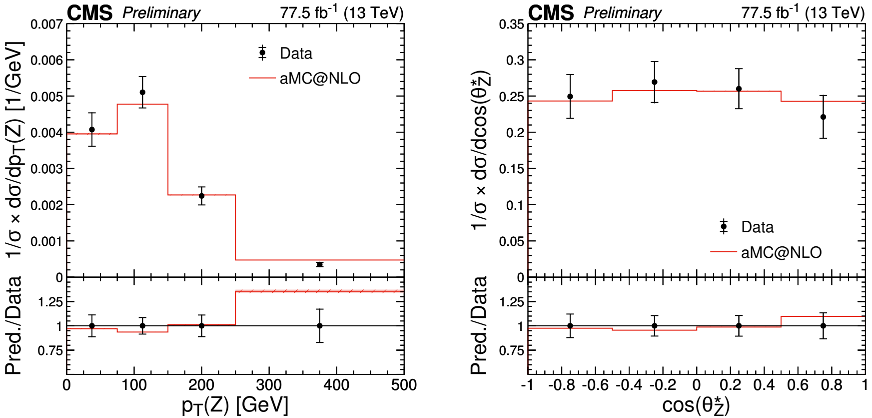
9 % precision

⇒ more precise than NLO prediction

⇒ main systematics: lepton ID, background normalization

First differential $t\bar{t}Z$ result

CMS-PAS-TOP-18-009



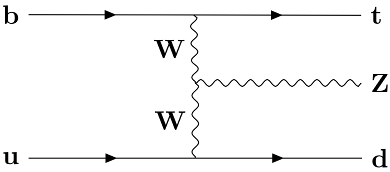
parton-level cross section, from cut-based measurement in 3-lepton channel

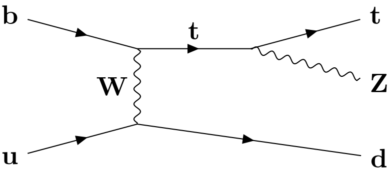
main systematics: lepton ID, jet energy, nonprompt background

$\Rightarrow$ good agreement with shape of SM prediction

EFT interpretation of $t\bar{t}Z$ measurement available, see talk by Brieuc François for details

tZq production





- t-channel production of single top quark in association with Z boson
- sensitive to tZ coupling, as well as to triboson WWZ coupling
- important feature: recoiling light jet (not present in FCNC scenario)

ATLAS EXPERIMENT

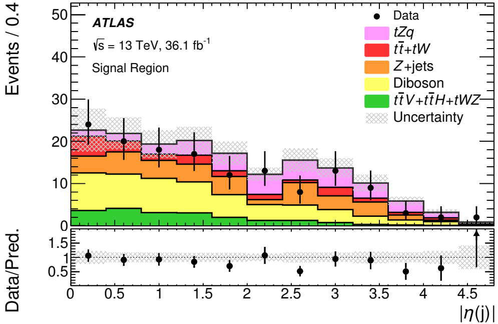
Phys. Lett. B780 (2018) 557
tZq with 2015 & 2016 data

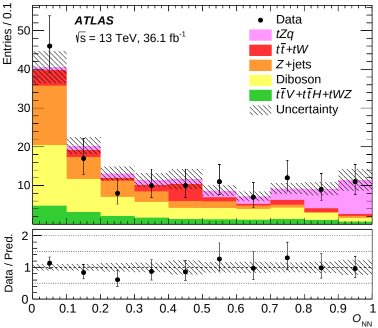
CMS

arXiv:1812.05900
(accepted by PRL)
tZq with 2016 & 2017 data

tZq measurement

Phys. Lett. B780 (2018) 557





train **neural network** to separate trileptonic **tZq** signal from backgrounds

template fit to NN output to extract cross section

- most discriminating input: $|\eta(\text{light jet})|$
- reconstructed Z boson and top quark
- WZ, ZZ, $t\bar{t}$+fake normalized in control regions
- Z+fake from data

$$\sigma(\text{tZq}) = 600 \pm 170\,(\text{stat}) \pm 140\,(\text{syst})\ \text{fb}$$

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

$\Rightarrow$ evidence for tZq production

$\Rightarrow$ in agreement with SM prediction: 800 fb $^{+6.1\%}_{-7.4\%}$

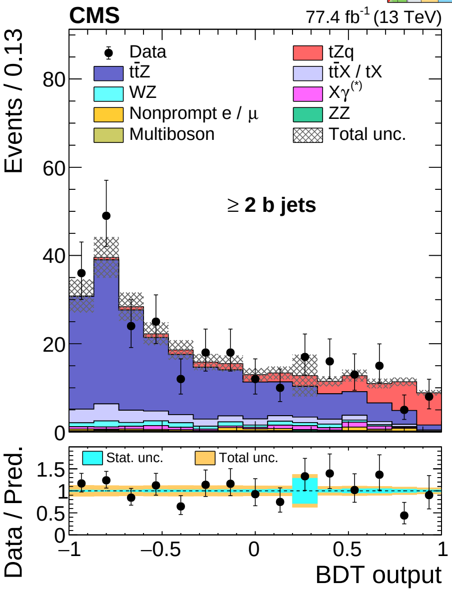
tZq measurement

arXiv:1812.05900 (accepted by PRL)

train **BDT** to separate trileptonic **tZq** signal from backgrounds

simultaneous **template fit** to BDT output and yields of control regions

- separate BDTs for (N_j, N_b) categories
- most discriminating input: $|\eta(\text{light jet})|$
- control regions for WZ, ZZ, Xγ
- nonprompt background from data
- $t\bar{t}Z$ constrained in low-BDT bins of high-multiplicity categories



First tZq observation

arXiv:1812.05900 (accepted by PRL)

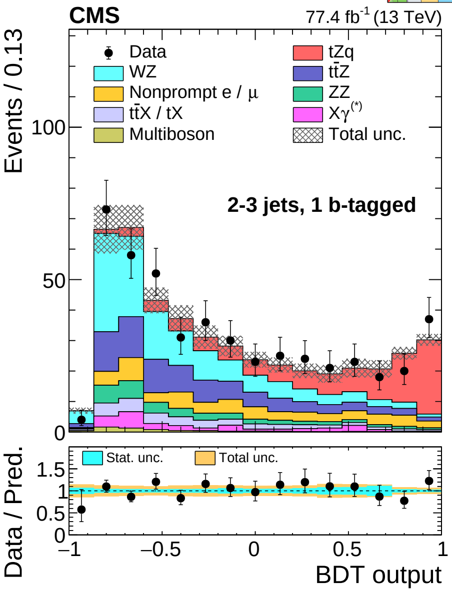
train **BDT** to separate trileptonic **tZq** signal from backgrounds

simultaneous **template fit** to BDT output and yields of control regions

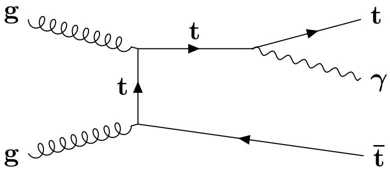
15 % precision

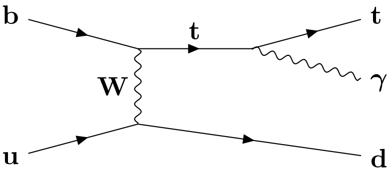
$\sigma(\text{tZq}, Z \to \ell\ell) = 111 \pm 13\,(\text{stat})\,^{+11}_{-9}\,(\text{syst})\text{ fb}$

- ⇒ first observation with observed significance $> 5\,\sigma$
- ⇒ in agreement with SM prediction: 94.2 ± 3.1 fb
- ⇒ main systematics:
  - nonprompt lepton background
  - lepton ID
  - FSR modeling
  - jet energy



Top quarks with a photon





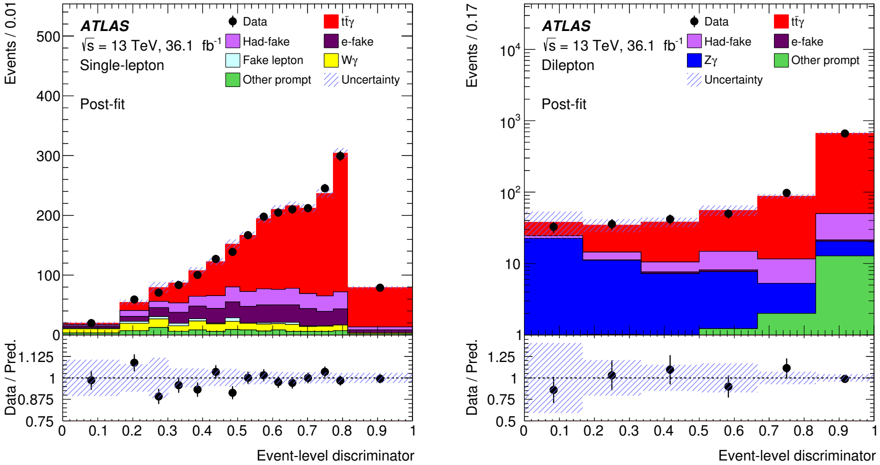
- photon radiation off top quarks sensitive to tγ coupling
- also contributions from initial and final state radiation
- fiducial phase space definition requires tightly isolated photon

arXiv:1812.01697
(submitted to EPJC)
$t\bar{t}\gamma$ with 2015 & 2016 data

Phys. Rev. Lett.
121 (2018) 221802
$t\gamma q$ with 2016 data

$t\bar{t}\gamma$ measurement

arXiv:1812.01697 (submitted to EPJC)



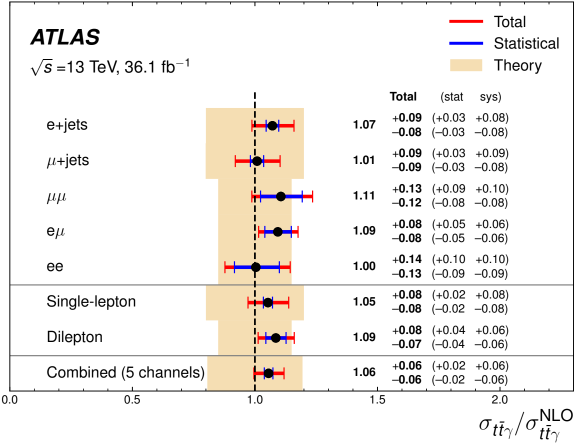
train **neural network** to separate $t\bar{t}\gamma$ signal from backgrounds

template fit to NN output

- single-lepton & dilepton channel
- fake photons & fake leptons estimated from data
- $W\gamma$, $Z\gamma$ validated in control regions

Inclusive $t\bar{t}\gamma$ cross section

arXiv:1812.01697 (submitted to EPJC)



fiducial cross sections

single-lepton channel:

$521 \pm 9\,(\text{stat}) \pm 41\,(\text{syst})$ fb

8 % precision

dilepton channel:

$69 \pm 3\,(\text{stat}) \pm 4\,(\text{syst})$ fb

7 % precision

SM prediction

$\sigma(t\bar{t}\gamma,\, 1\ell) = 495 \pm 99$ fb

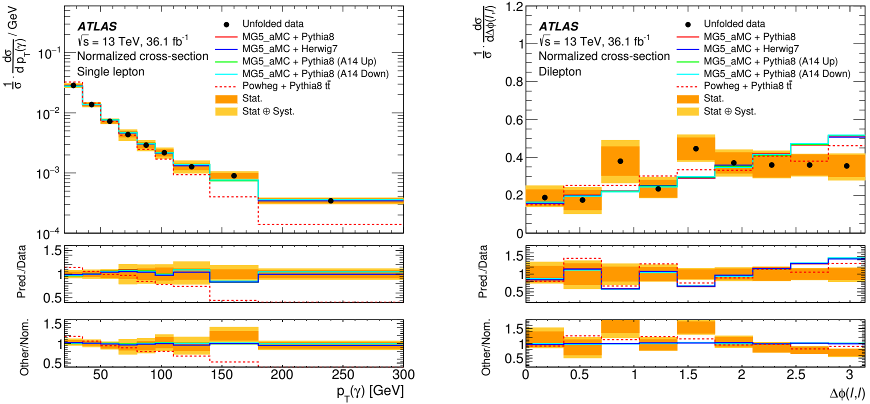
$\sigma(t\bar{t}\gamma,\, 2\ell) = 63 \pm 9$ fb

⇒ in agreement with and more precise than NLO prediction

⇒ main uncertainties:
- statistics (2ℓ only)
- background modeling
- jet systematics

Differential $t\bar{t}\gamma$ cross section

arXiv:1812.01697 (submitted to EPJC)



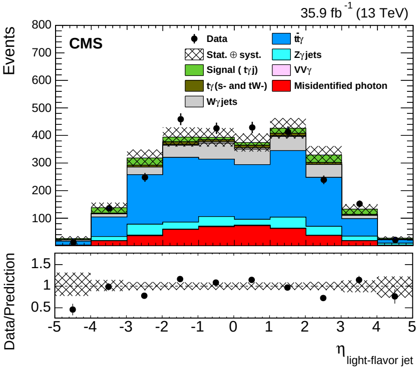
particle-level cross sections, from cut-based measurement in both channels

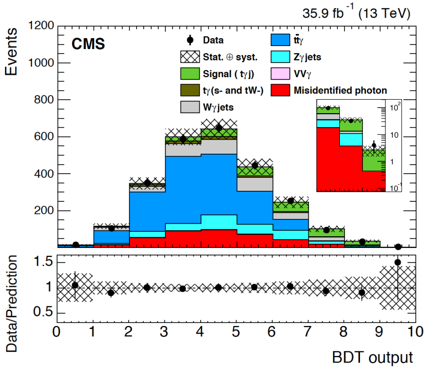
good agreement in all observables with SM prediction

- sensitive to $t\gamma$ coupling: $p_T(\gamma)$, $|\eta(\gamma)|$, $\Delta R(\gamma, \ell)$
- sensitive to $t\bar{t}$ spin correlations: $\Delta\phi(\ell\ell)$, $|\Delta\eta(\ell\ell)|$ (2ℓ only)
- main systematics: $t\bar{t}$ modeling (1ℓ), $Z\gamma$ modeling (2ℓ)

First evidence for tγq

Phys. Rev. Lett. 121 (2018) 221802





train **BDT** to separate **tγq** from backgrounds, **template fit** to BDT output

- only decay channel: $t \rightarrow \mu\nu b$
- main background: $t\bar{t}\gamma$

fiducial cross section:

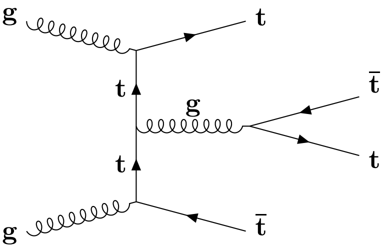
$$\sigma(t\gamma q) = 115 \pm 17\,(\text{stat}) \pm 30\,(\text{syst})\ \text{fb}$$

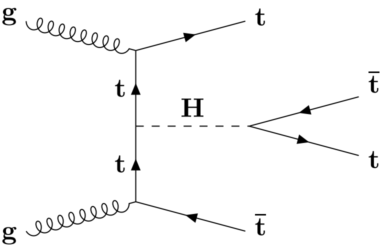
$4.4\,\sigma$ ($3.0\,\sigma$) obs. (exp.) significance

⇒ first evidence for tγq production

⇒ in agreement with SM prediction: 81 ± 4 fb

Search for $t\bar{t}t\bar{t}$ production





- sensitive to top quark Yukawa coupling
- many BSM models predict enhanced $t\bar{t}t\bar{t}$ cross section

JHEP 1812 (2018) 039
Phys. Rev. D99 (2019) 052009
$t\bar{t}t\bar{t}$ with 2015 & 2016 data

CMS-PAS-TOP-17-019
$t\bar{t}t\bar{t}$ with 2016 data

CMS-PAS-TOP-18-003
$t\bar{t}t\bar{t}$ with 2016–2018 data

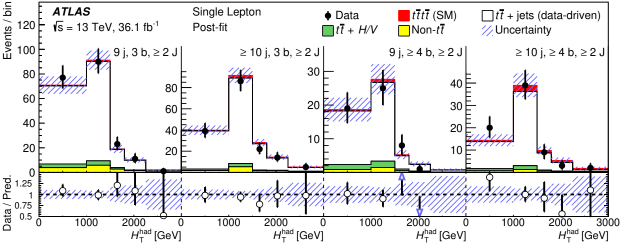
$t\bar{t}t\bar{t}$ search in 1ℓ, 2ℓ OS channels

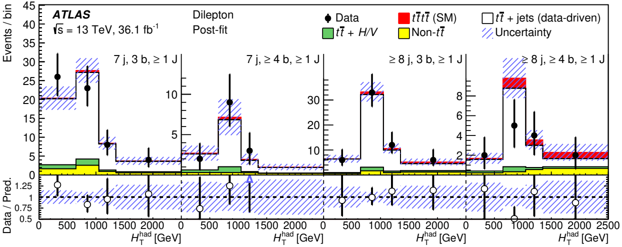
Phys. Rev. D99 (2019) 052009

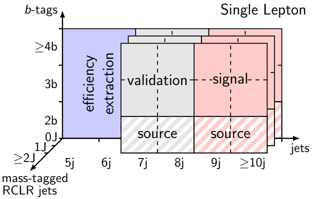
jets reclustered into mass-tagged large-R jets

template fit to hadronic activity distribution in signal regions

- (N_j, N_b, N_J) categories for both channels
- nonprompt lepton and $t\bar{t}$ background from data
- dominant systematic: $t\bar{t}$ modeling

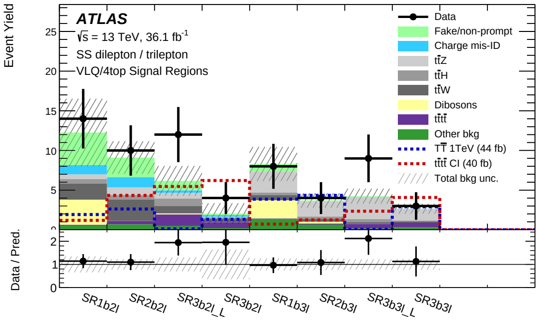






$t\bar{t}t\bar{t}$ search in 2ℓ SS, 3ℓ channels

JHEP 1812 (2018) 039, Phys. Rev. D99 (2019) 052009



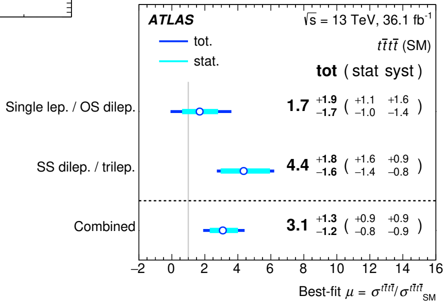
cut-based search for new phenomena in events with leptons and b-jets

interpreted as **$t\bar{t}t\bar{t}$** search

- N_b categories for different signals
- high MET & hadronic activity
- nonprompt lepton & charge-flip backgrounds from data

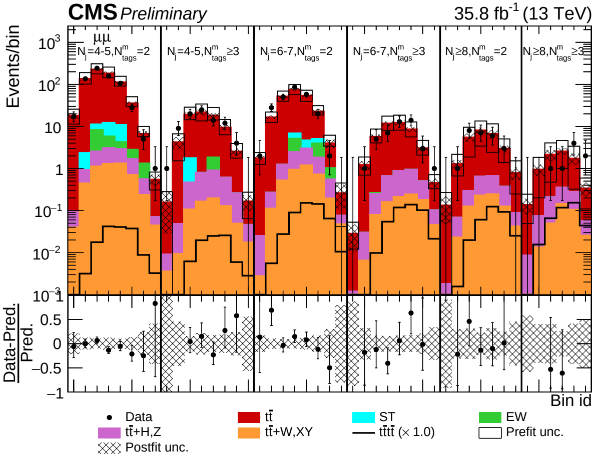
combination of both searches

obs. (exp.) significance: 2.8 σ (1.0 σ)



$t\bar{t}t\bar{t}$ search in 1ℓ, 2ℓ OS channels

CMS-PAS-TOP-17-019, Eur. Phys. J C78 (2018) 140



train **BDT** to separate $t\bar{t}t\bar{t}$ signal from background

template fit to BDT output in signal regions

- BDT-based top tagging
- (N_j, N_b) categories
- main background: $t\bar{t}$+jets

EFT interpretation of $t\bar{t}t\bar{t}$ search available, see

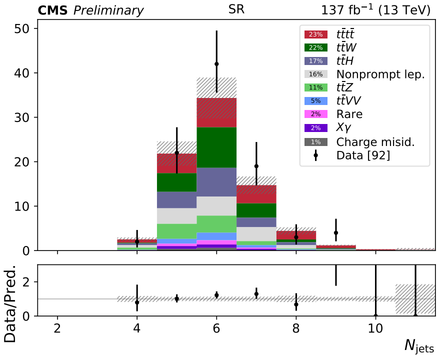
talk by Brieuc François

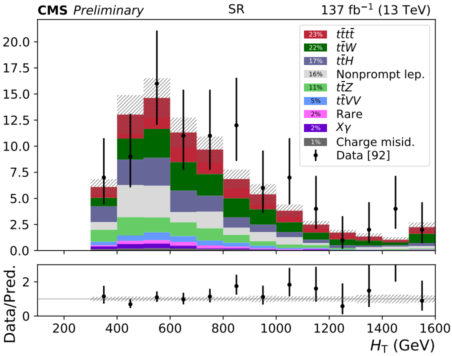
combination with previous 2ℓ SS & 3ℓ search (also 2016 data)

obs. (exp.) significance: 1.1 σ (1.4 σ)

$t\bar{t}t\bar{t}$ search with full run-2 data

2ℓ SS, 3ℓ channels, CMS-PAS-TOP-18-003





both **cut-based** and **BDT**-based analysis performed, with compatible results

simultaneous **template fit** to signal and control regions

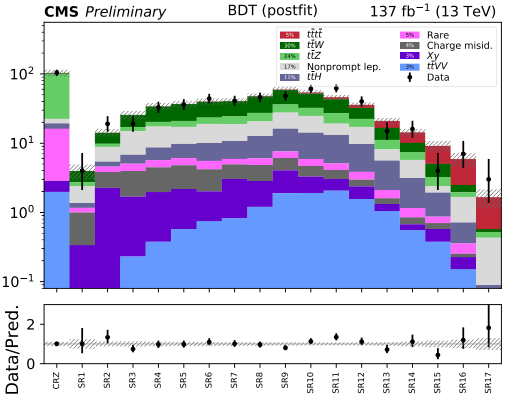
- cut-based categories in (N_ℓ, N_j, N_b)
- control regions for $t\bar{t}Z$, $t\bar{t}W$ normalization
- nonprompt lepton and charge-flip backgrounds from data

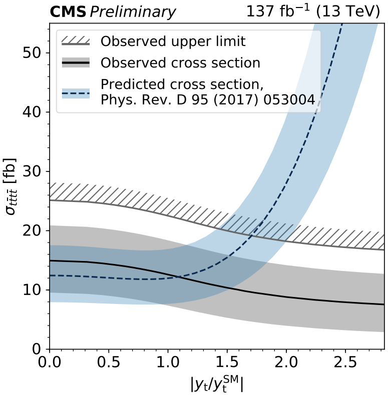
main systematics: $t\bar{t}+b\bar{b}$ normalization, jet energy, b-tagging

$t\bar{t}t\bar{t}$ search with full run-2 data

2ℓ SS, 3ℓ channels, CMS-PAS-TOP-18-003

NEW!





result with BDT-based analysis

constraint on Yukawa coupling

obs. (exp.) significance: 2.6 σ (2.7 σ)

95 % CL limit: $|y_t/y_t^{SM}| < 1.7$

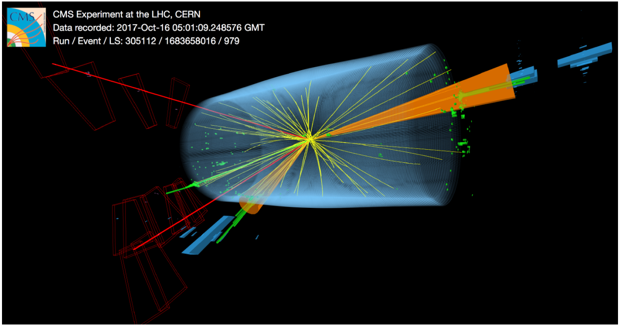
Summary

- Large amount of run-2 data and refined analysis techniques allowed for measurements of several rare top quark production processes.
- All results are in good agreement with standard model predictions.
- Stay tuned: New results with more data are on their way!

some highlights:

- differential $t\bar{t}Z$ and $t\bar{t}\gamma$ cross section measurements
- first observation of tZq
- first evidence for $t\gamma q$
- first $t\bar{t}t\bar{t}$ search results with full run-2 dataset

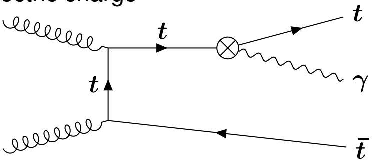
tZq candidate event:



Backup: Why study rare tops?

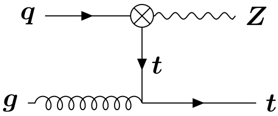
Test of SM Couplings

e.g. $t\bar{t}\gamma$: direct probe of top quark's electric charge



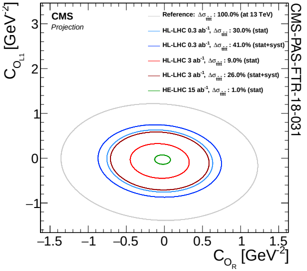
Flavor-Changing Neutral Currents

e.g. tZ: presence of FCNC vertex changes experimental signature



EFT Constraints

e.g. $t\bar{t}t\bar{t}$: constrains 4-fermion operators



Important Backgrounds

e.g. $t\bar{t}W$, $t\bar{t}Z$: relevant backgrounds to $t\bar{t}H$ in multilepton final states

Phys. Rev. D97 (2018) 072003