中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

# Single top production in association with a vector boson at CMS

Duncan Leggat
Institute of High Energy Physics, Beijing
on behalf of the CMS collaboration
25th October 2019

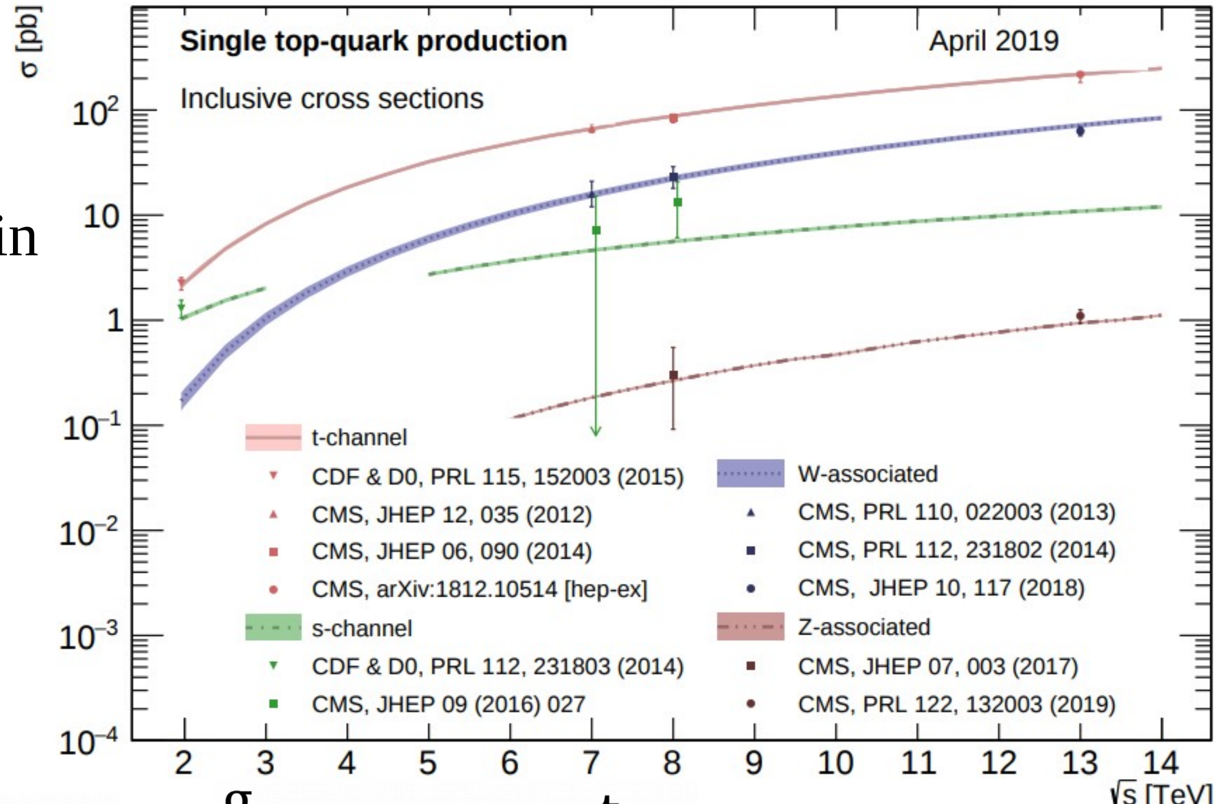
# Single top production at the LHC

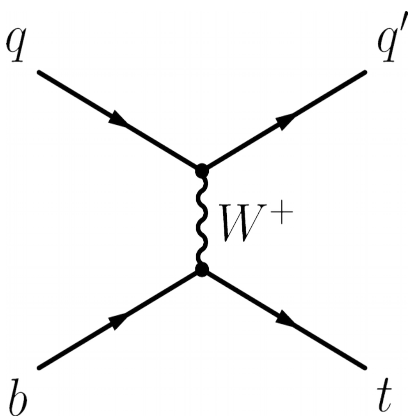
Most top quarks produced strongly in $t\bar{t}$ pairs,

- **Single top quarks** produced in electroweak interactions.

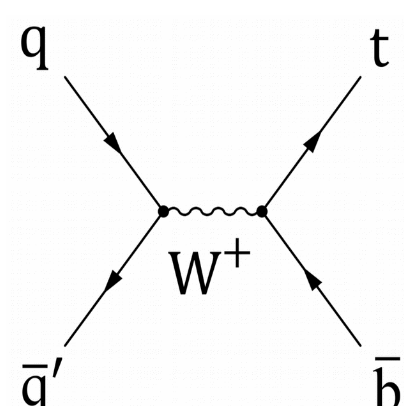
Measuring is important:

- Direct $|V_{tb}|$ access
- Higgs and BSM backgrounds
- Sensitivity to new physics

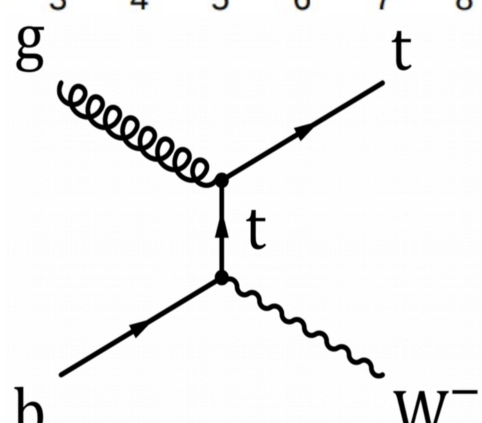



*t-channel*




*s-channel*



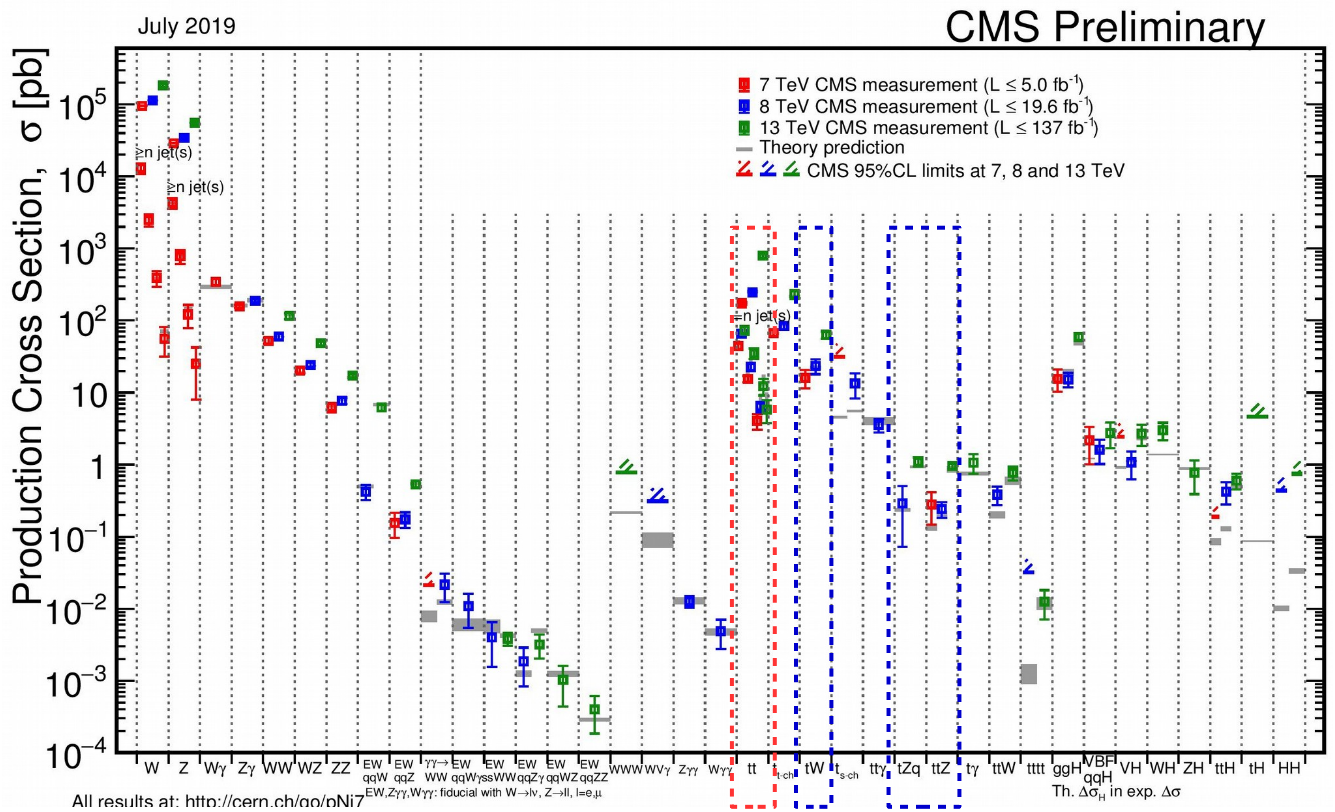

*W associated (tW)*

# Single tops produced with a vector boson

The top quark's high mass makes its interactions with electroweak bosons of particular interest;

- Triple gauge boson coupling,
- Direct top coupling to electroweak,
- Non-standard couplings (FCNC)

All these channels and beyond are becoming accessible as the LHC data accumulates




All inclusive cross sections measured at CMS

*tW, tZq & tγq*
Discussed in this talk

*$t\bar{t}$* – All processes' dominant background

# Why study tW?

**What is tW?**

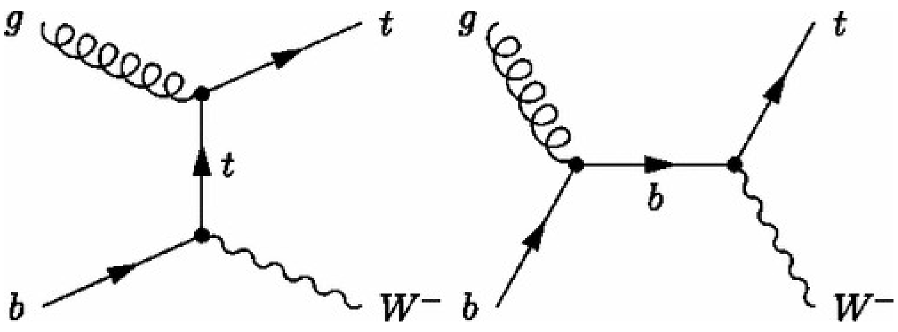
- The associated production of a single top quark with a W boson

**Why do we study it?**

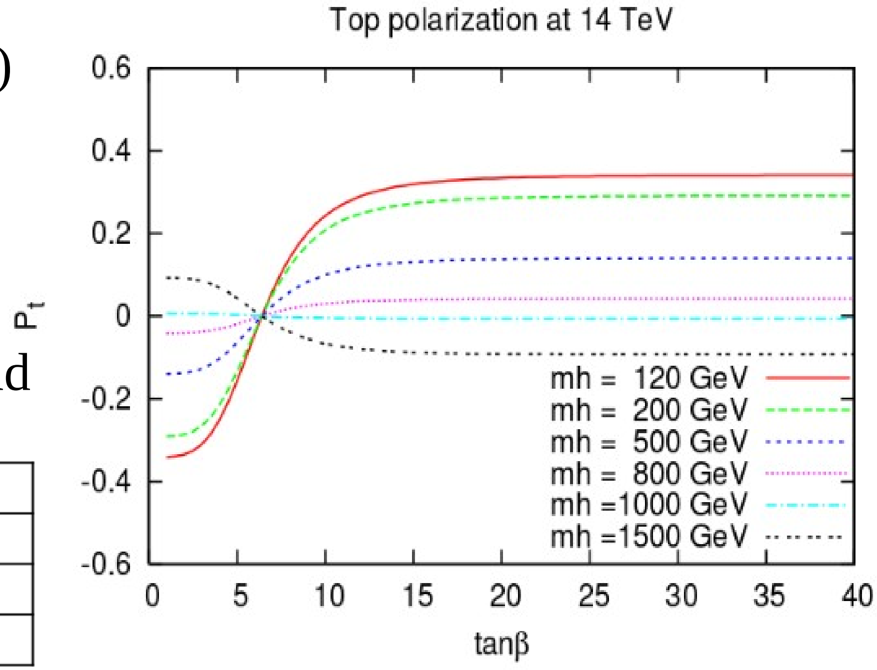
- Direct probe of $V_{tb}$
- Sensitive to new physics
- Background to dilepton searches (e.g. H->WW)
- Provides additional measurements of top properties

In comparison to the other single top channels, tW has scaled very favourably to the main $t\bar{t}$ background

| σ [pb] | ttbar | t-channel | tW | s-channel |
|---|---|---|---|---|
| LHC @ 8TeV | 252.89 | 84.69 | 22.2 | 5.24 |
| LHC @ 13TeV | 831.76 | 216.99 | 71.2 | 10.32 |
| From 8 to 13TeV | **3.3** | 2.6 | **3.2** | 1.9 |




LO diagrams

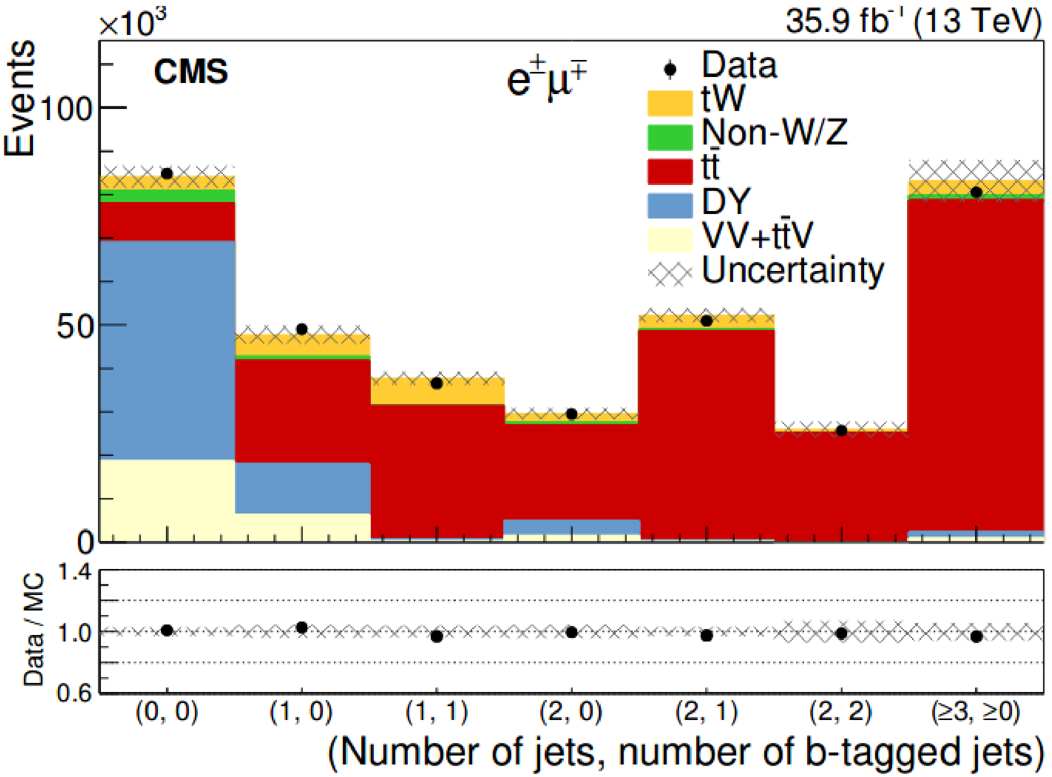


# tW dilepton cross section measurement

JHEP 10 (2018) 117

Dilepton measurement using 35.9 $fb^{-1}$ (2016) *pp* data @ 13 TeV

- *eμ* channel only, opposite sign isolated lepton pair,
  - events with loose leptons vetoed,
- 3 regions defined based on jet requirements;
  - 1j1t signal region
  - 2j1t/2t tt-enriched control regions
- Backgrounds
  - $t\bar{t}$ dominant
  - small contribution of DY
    - Small because *eμ* channel only
  - backgrounds estimates from MC
- $t\bar{t}/tW$ interference treatment
  - DR scheme implemented in MC
  - DS MC included as systematic



JHEP 10 (2018) 117

# tW signal extraction

## Distributions included in MLL fit:

### Signal region (1j1t) BDT

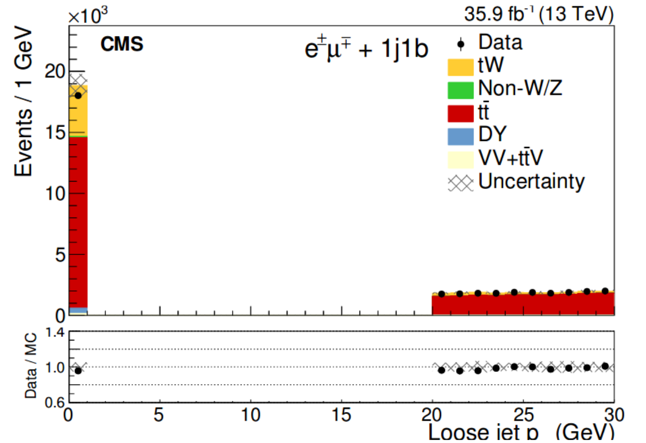
- 11 input variables
  - 3 most discriminating variable shown right
- Loose jet information is most powerful discriminating factor

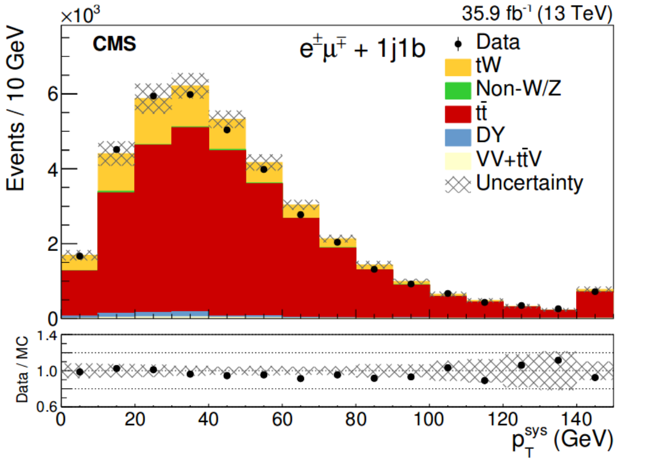
### 2j1t control region BDT

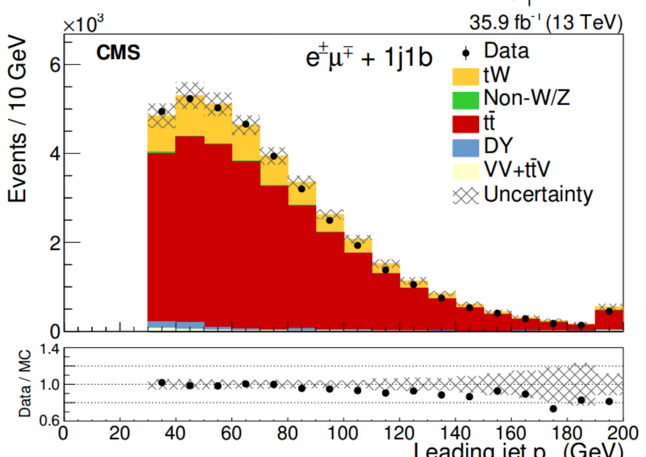
- 4 input variables
- Binning is sparser than signal region equivalent

### 2j2t control region

- Subleading jet $p_T$ included in fit
- Heavily influenced by JES, helps constrain this systematic



JHEP 10 (2018) 117

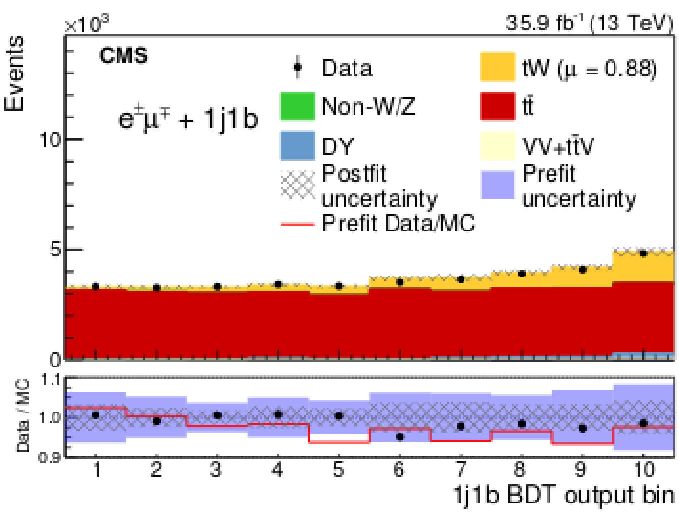
# tW measurement results

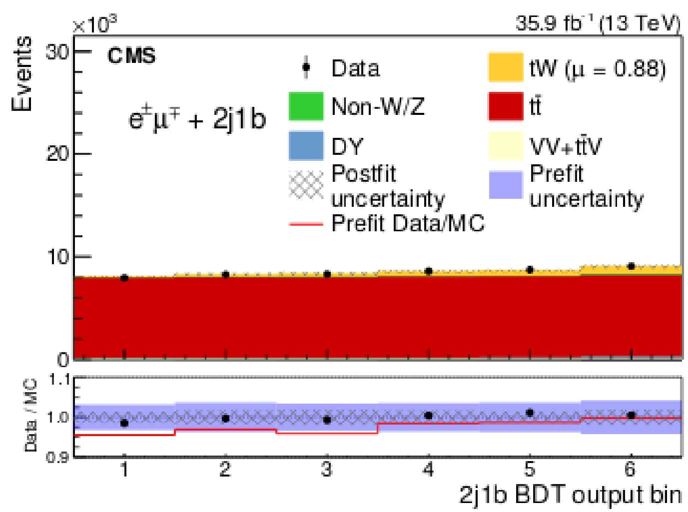
Result: **$\sigma_{tW}$ = 63.1 ± 1.8 (stat.) ± 6.4 (syst.) ± 2.1 (lumi) pb**

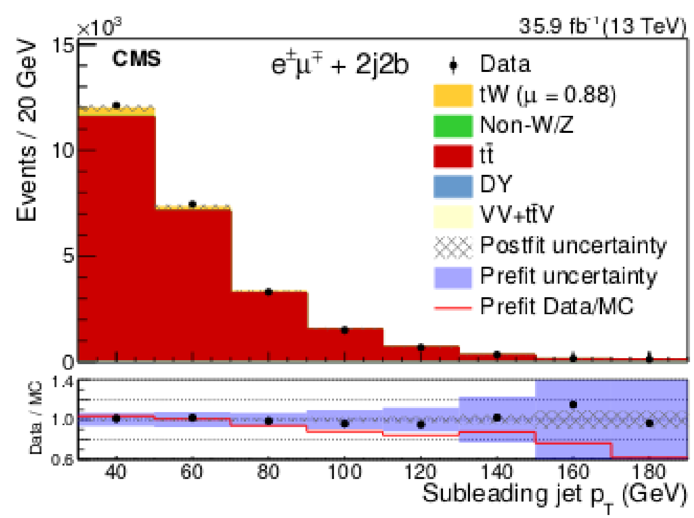
Error of 11%, agrees with NNLO SM agreement within 5.3%

**Dominant uncertainties:**

- Lepton efficiencies (3.3%)
- Pileup (3.3%)
- Data statistics (2.8%)
- tt background normalisation (2.8%)



# tZq production

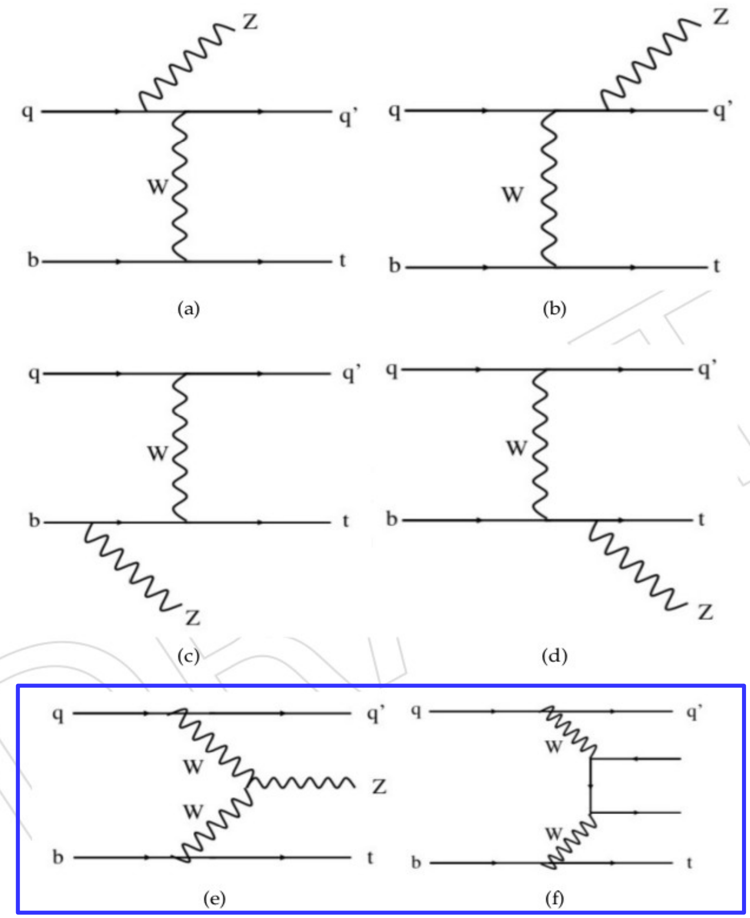
Search for associated production of a single top quark with a Z boson, with one recoiling quark

- Can produce single, double or triple lepton signatures

Predominantly occurs when t channel radiates a Z boson, but also includes 3 gauge coupling between W and Z

$\sigma(tZq) = 160^{+7}_{-2}(\text{scale})^{+11}_{-11}(\text{PDF})$ fb
$\sigma(\bar{t}Zq) = 76^{+4}_{-1}(\text{scale})^{+5}_{-5}(\text{PDF})$ fb
Phys.Rev.D: 87(2013)11406

$\sigma(tl^{+}l^{-}q) = 8.2^{+0.59}_{-0.03}(\text{scale})$ fb based on leptonic top decay, and $m_{ll} > 50$ GeV using MC@NLO



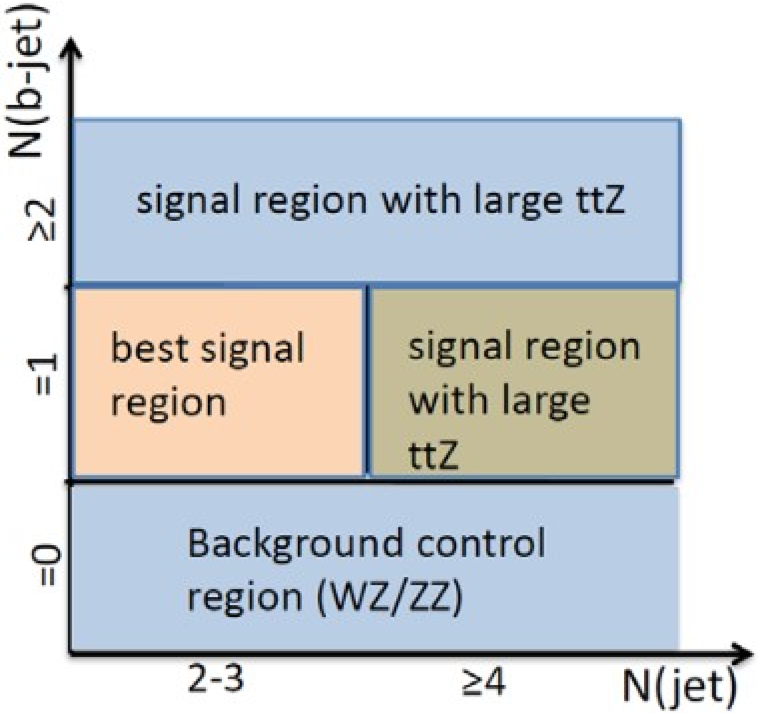

Includes coupling of W to a Z boson or ll pair

Phys. Rev. Lett. 122 (2019) 132003

# Measurement of tZq in trilepton channel at CMS

Trilepton measurement using 77 $fb^{-1}$ (2016-2017) *pp* data @ 13 TeV

- Single, double and trilepton triggers
- Exactly 3 isolated leptons
  - 2 must satisfy Z selections;
    - opposite sign same flavour
    - $|m_{ll} - m_Z| < 15$ GeV
  - BDT to discriminate prompt and non-prompt leptons
- Signal and control regions defined on jet/tag requirements
- Backgrounds
  - 2-3 jets, WZ is leading background
  - >4jets or >2 b-jets, ttZ is dominant



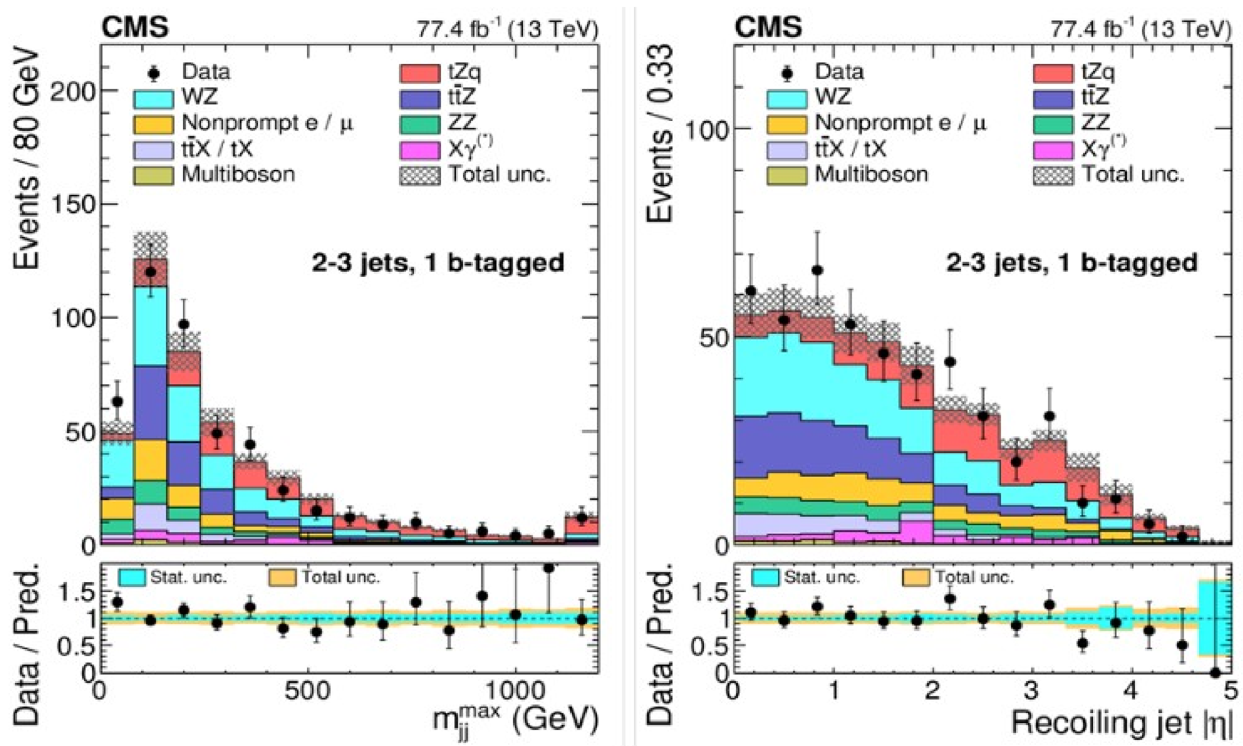
# Signal extraction for *tZq*

Various BDTs are defined in the different regions to optimise against different backgrounds

– Existence of a high $p_T$ forward jet is the main discriminator

**Additional CRs:**

- WZ control region
  - 0tag events
- ZZ control region
  - 4 lepton events
  - 2 pairs of leptons compatible with Z boson

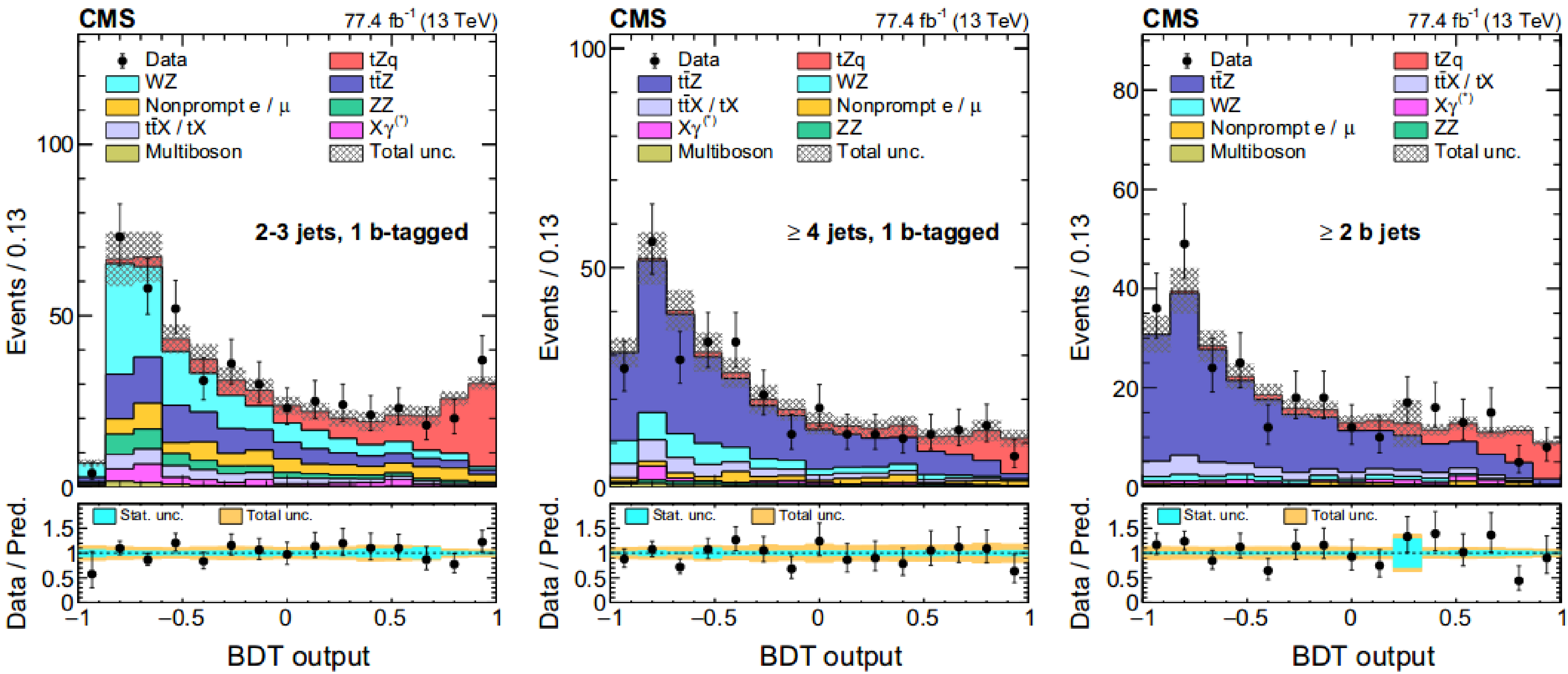



MLL fit applied simultaneously to all BDT output distributions and the yields of WZ and ZZ control regions

Phys. Rev. Lett. 122 (2019) 132003

# *tZq* measurement results

$$\sigma(pp \rightarrow tZq \rightarrow t\ell^+\ell^- q) = 111 \pm 13(\text{stat})^{+11}_{-9}(\text{syst})\ \text{fb} \rightarrow r = 1.18$$



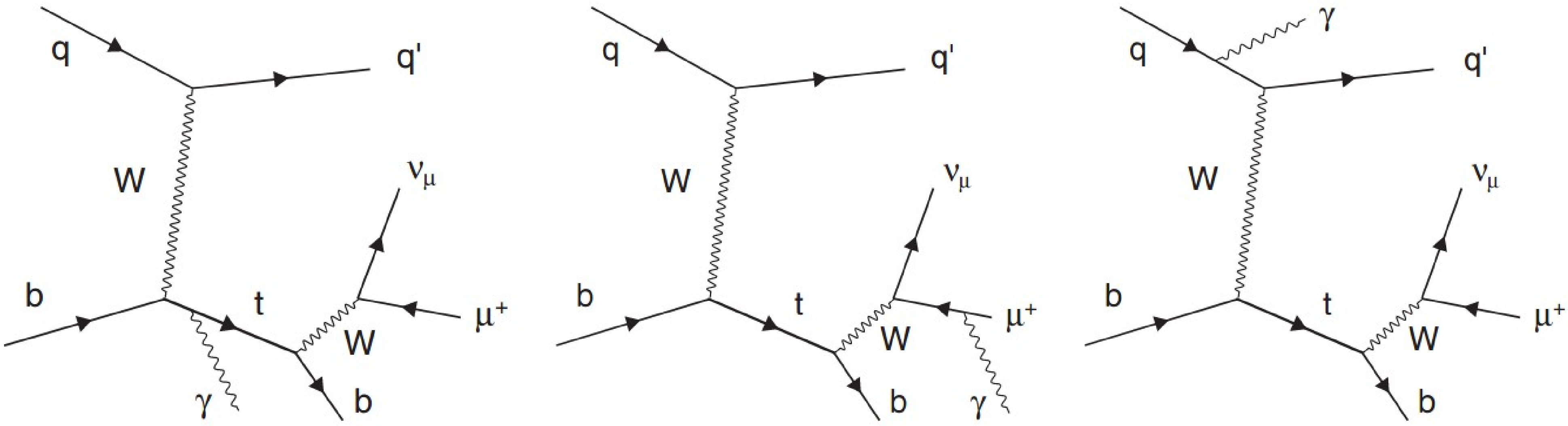

Observed significance > 8 s.d

First observation of tZq!

**Leading uncertainties:**

- non-prompt lepton background
- lepton selection efficiency
- modelling of final state radiation
- Jet energy scale

# Single top produced with a photon




**t-channel like process with a radiated photon**

Cross section sensitive to top quark charge, and electric and magnetic dipole moments.

Defining part of the signature is a forward light-flavoured 'recoil' jet,

- Identifying this jet is an important part of any SM *tγq* search

# $t\gamma q$ measurement at CMS

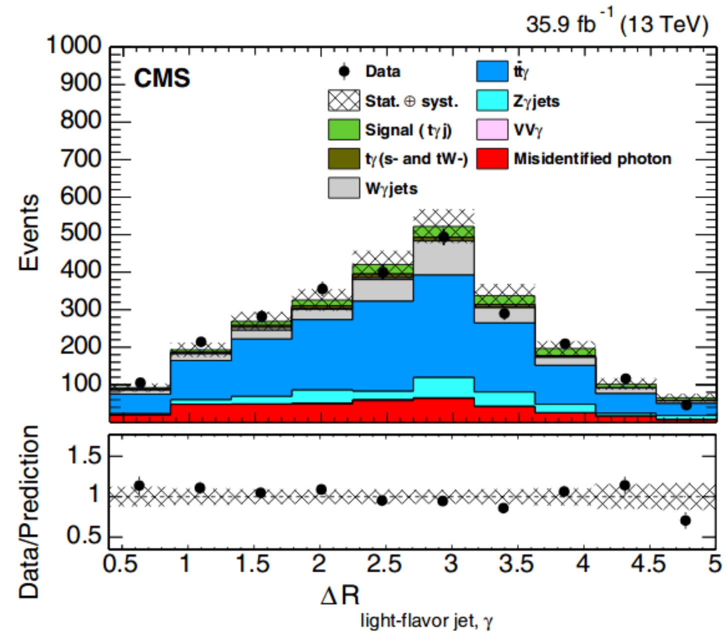
Single lepton measurement using 36 fb$^{-1}$ (2016) *pp* data @ 13 TeV

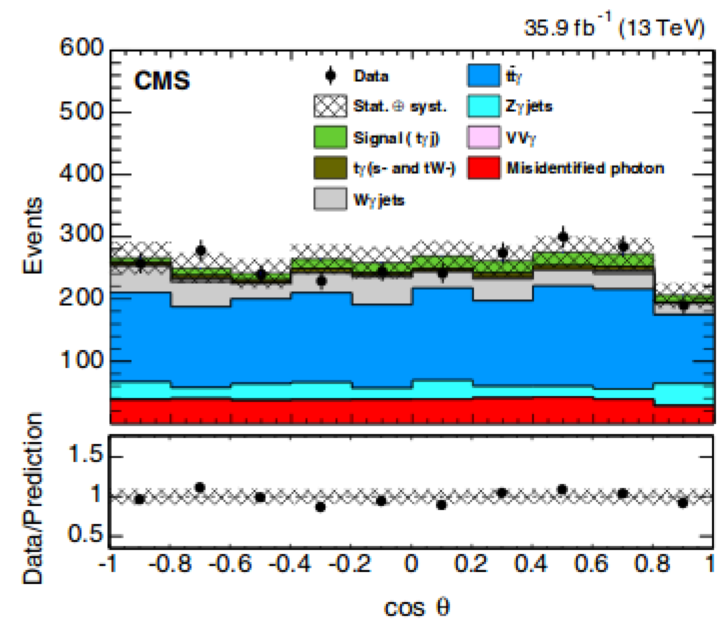
## Event selections

- Single muon channel only,
- Single photon required ($|\eta| < 1.44$),
  - electron conversion veto required,
  - $\Delta R(\gamma,X) > 0.5$, where X is other objects in the event,
- $p_T^{miss} > 30$ GeV,
- Signal region defined with ≥ 2 jets, 1 of which is b-tagged,
- $t\bar{t}\gamma$ CR with exactly 2 b-jets.

## Backgrounds

- $V\gamma$ + jets, $WW\gamma$ +jets, single top + $\gamma$ estimated from simulation,
- Misidentified photon background estimated from $p_T$ dependent probability of a jet being identified as a photon.

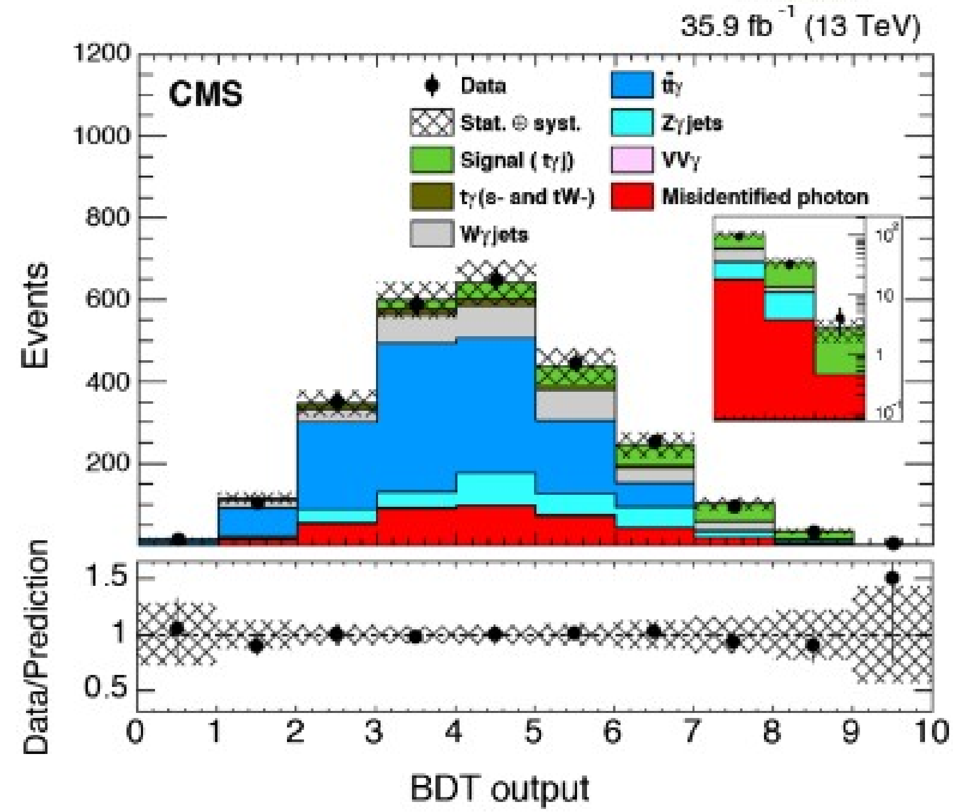


Phys. Rev. Lett. 121 (2018) 221802

# $t\gamma q$ results

- MLL fit on BDT response for signal and $t\bar{t}\gamma$ control regions
  - Most important variables;
    - $\eta$ of different objects
    - $\cos\theta$ between the muon and the light jet




- Fiducial cross section measurement:

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

Agrees with SM prediction: 81± 4 fb

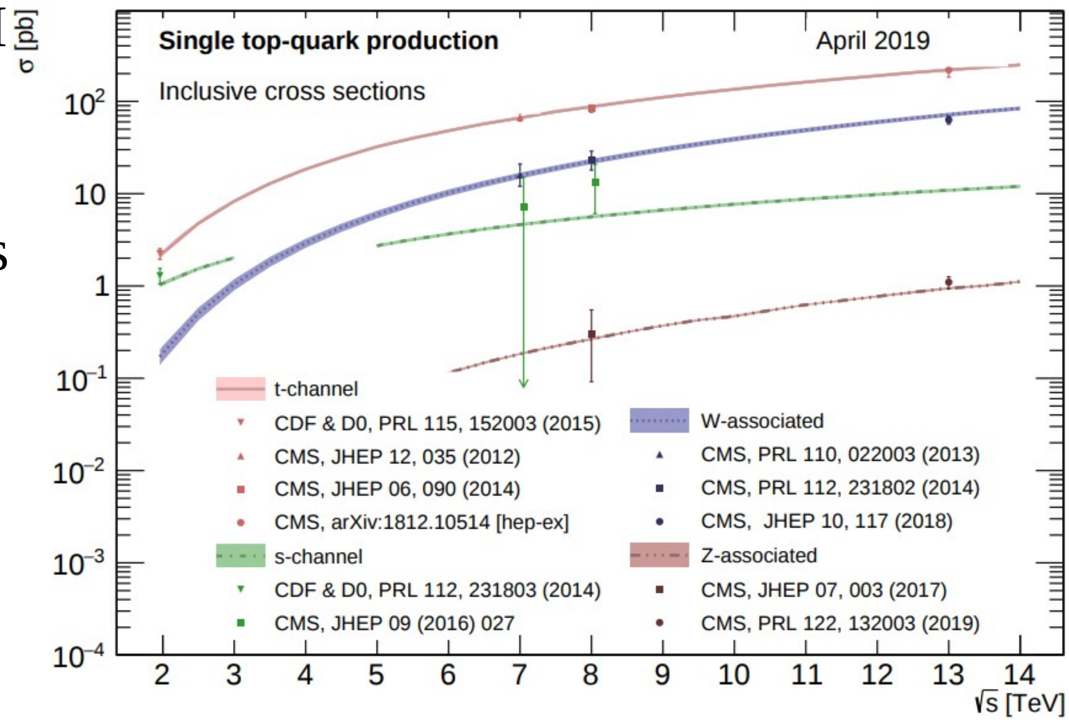
4.4 (3.0) s.d. observed (expected)
First evidence of $t\gamma q$ production

**Leading systematics:**
- Jet energy Scale (12%)
- Signal modelling (9%)
- $Z\gamma$ + jets normalisation (8%)
- b-tag/mistag rates (7%)

# Conclusions

Top physics offers a unique test of the SM thanks to the unique properties of the quark

- Single top physics allows direct probes of EW couplings and BSM models




CMS has been making cutting edge measurements in single top physics for years, and now we are able to push the boundaries on rarer processes

- First observations of tW and tZq carried out by CMS
- First evidence for tγq reported by CMS


We look forward to many new results to come!

BACKUP

# tW signal BDT input variables

- $p_{\mathrm{T}}$ of leading loose jet, set to 0 for events with no loose jets present;
- magnitude of the vector sum of the $p_{\mathrm{T}}$'s of leptons, jet, and $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$ ($p_{\mathrm{T}}^{\mathrm{sys}}$);
- $p_{\mathrm{T}}$ of the jet;
- ratio of the scalar sum of the $p_{\mathrm{T}}$ of the leptons to the scalar sum ($H_{\mathrm{T}}$) of the $p_{\mathrm{T}}$'s of leptons, jet, and $p_{\mathrm{T}}^{\mathrm{miss}}$;
- number of loose jets;
- centrality (ratio between the scalar sums of the $p_{\mathrm{T}}$ and of the total momentum) of the jet and the two leptons;
- magnitude of the vector sum of the $p_{\mathrm{T}}$ of the jet and leptons;
- $H_{\mathrm{T}}$;
- ratio of $p_{\mathrm{T}}^{\mathrm{sys}}$ to $H_{\mathrm{T}}$ for the event;
- invariant mass of the combination of the leptons, jet, and $p_{\mathrm{T}}^{\mathrm{miss}}$;
- number of b-tagged loose jets.

# tW 2j1t BDT input variables

- separation in the $\phi-\eta$ space between the dilepton and dijet systems, $\Delta R\,(e^{\pm}\mu^{\mp}, j_1j_2)$;
- separation in the $\phi - \eta$ space between the dilepton system and the dijet and $p_T^{miss}$ system, $\Delta R$ $(e^{\pm}\mu^{\mp}, j_1j_2p_T^{miss})$;
- $p_T$ of the subleading jet;
- separation in the $\phi - \eta$ space between the leading lepton and the leading jet, $\Delta R$ $(\ell_1, j_1)$.

Event yields:

| | Prefit | | Postfit | |
|---|---|---|---|---|
| Region | tW | $t\bar{t}$ | tW | $t\bar{t}$ |
| 1j1b | 6147 ± 442 | 30622 ± 1862 | 5440 ± 604 | 30592 ± 582 |
| 2j1b | 3125 ± 294 | 48484 ± 1984 | 2888 ± 321 | 47436 ± 612 |
| 2j2b | 725 ± 85 | 25052 ± 2411 | 719 ± 88 | 25114 ± 281 |

**Table 1**. Number of expected prefit and postfit signal and $t\bar{t}$ background events.

# tW systematics

| Source | Uncertainty (%) |
|---|---|
| Experimental | |
| Trigger efficiencies | 2.7 |
| Electron efficiencies | 3.2 |
| Muon efficiencies | 3.1 |
| JES | 3.2 |
| Jet energy resolution | 1.8 |
| b tagging efficiency | 1.4 |
| Mistag rate | 0.2 |
| Pileup | 3.3 |
| Modeling | |
| $t\bar{t}$ $\mu_R$ and $\mu_F$ scales | 2.5 |
| tW $\mu_R$ and $\mu_F$ scales | 0.9 |
| Underlying event | 0.4 |
| Matrix element/PS matching | 1.8 |
| Initial-state radiation | 0.8 |
| Final-state radiation | 0.8 |
| Color reconnection | 2.0 |
| B fragmentation | 1.9 |
| Semileptonic B decay | 1.5 |
| PDFs | 1.5 |
| DR-DS | 1.3 |
| Background normalization | |
| $t\bar{t}$ | 2.8 |
| VV | 0.4 |
| Drell-Yan | 1.1 |
| Non-W/Z leptons | 1.6 |
| $t\bar{t}V$ | 0.1 |
| MC finite sample size | 1.6 |
| Full phase space extrapolation | 2.9 |
| Total systematic (excluding integrated luminosity) | 10.1 |
| Integrated luminosity | 3.3 |
| Statistical | 2.8 |
| Total | 11.1 |

# tgammq

- phase space: $p_{T,\gamma} > 25\ GeV$, $|\eta_\gamma| < 1.44$, $\Delta R(X,\gamma) > 0.5$

fiducial phase space

| Process | Event yield |
|---|---|
| $t\bar{t} + \gamma$ | $1401 \pm 131$ |
| $W\gamma$ + jets | $329 \pm 78$ |
| $Z\gamma$ + jets | $232 \pm 55$ |
| Misidentified photon | $374 \pm 74$ |
| $t\gamma$ ($s$ and $tW$ channel) | $57 \pm 8$ |
| VV$\gamma$ | $8 \pm 3$ |
| Total background | $2401 \pm 178$ |
| Expected signal | $154 \pm 24$ |
| Total SM prediction | $2555 \pm 180$ |
| Data | 2535 |