tt+X and t+X production in CMS: ttZ, ttW, ttγ, tZq, tγq

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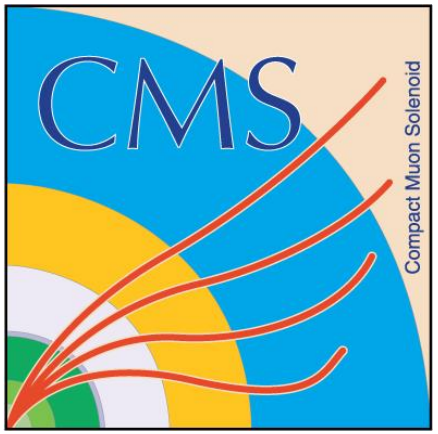

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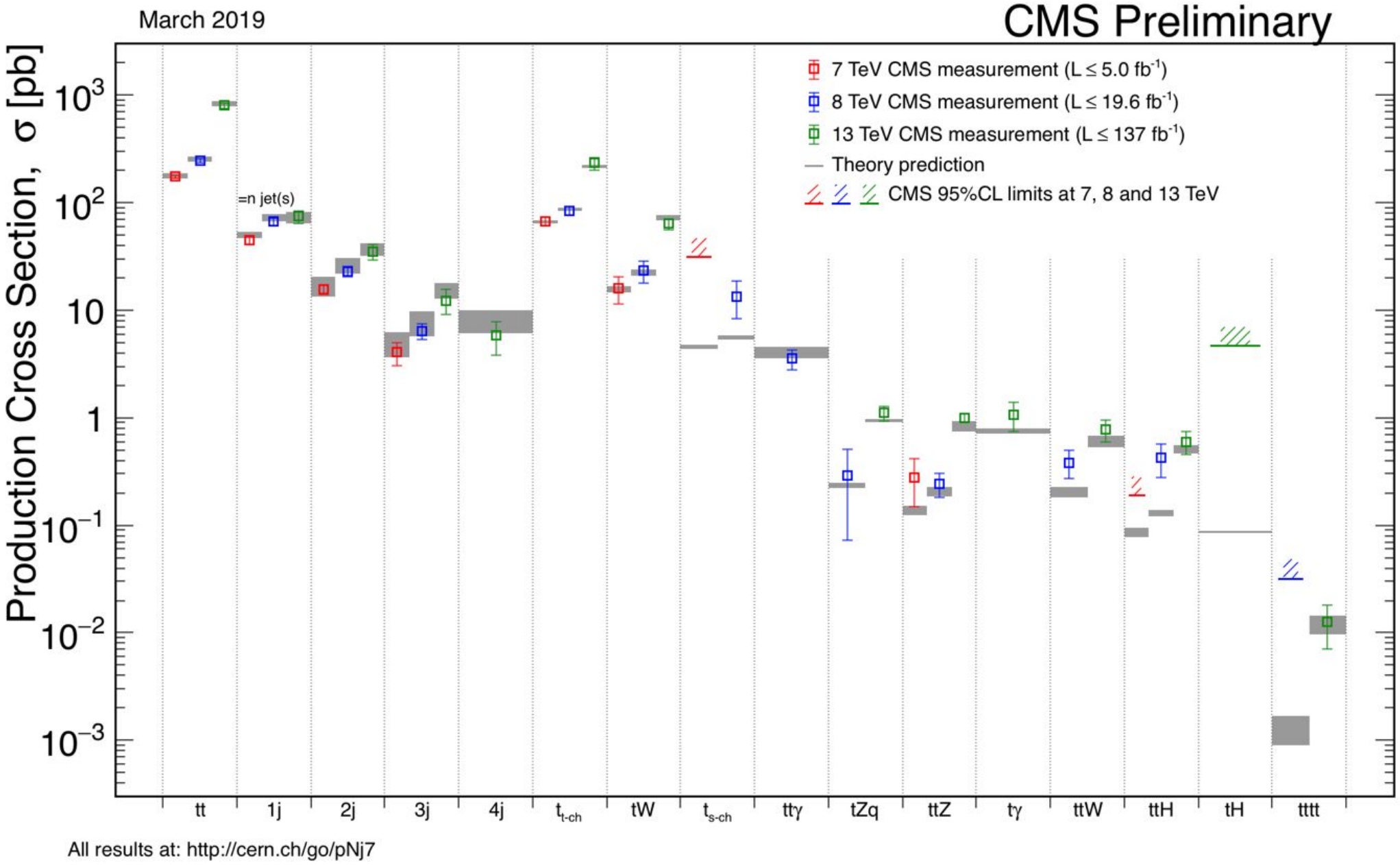
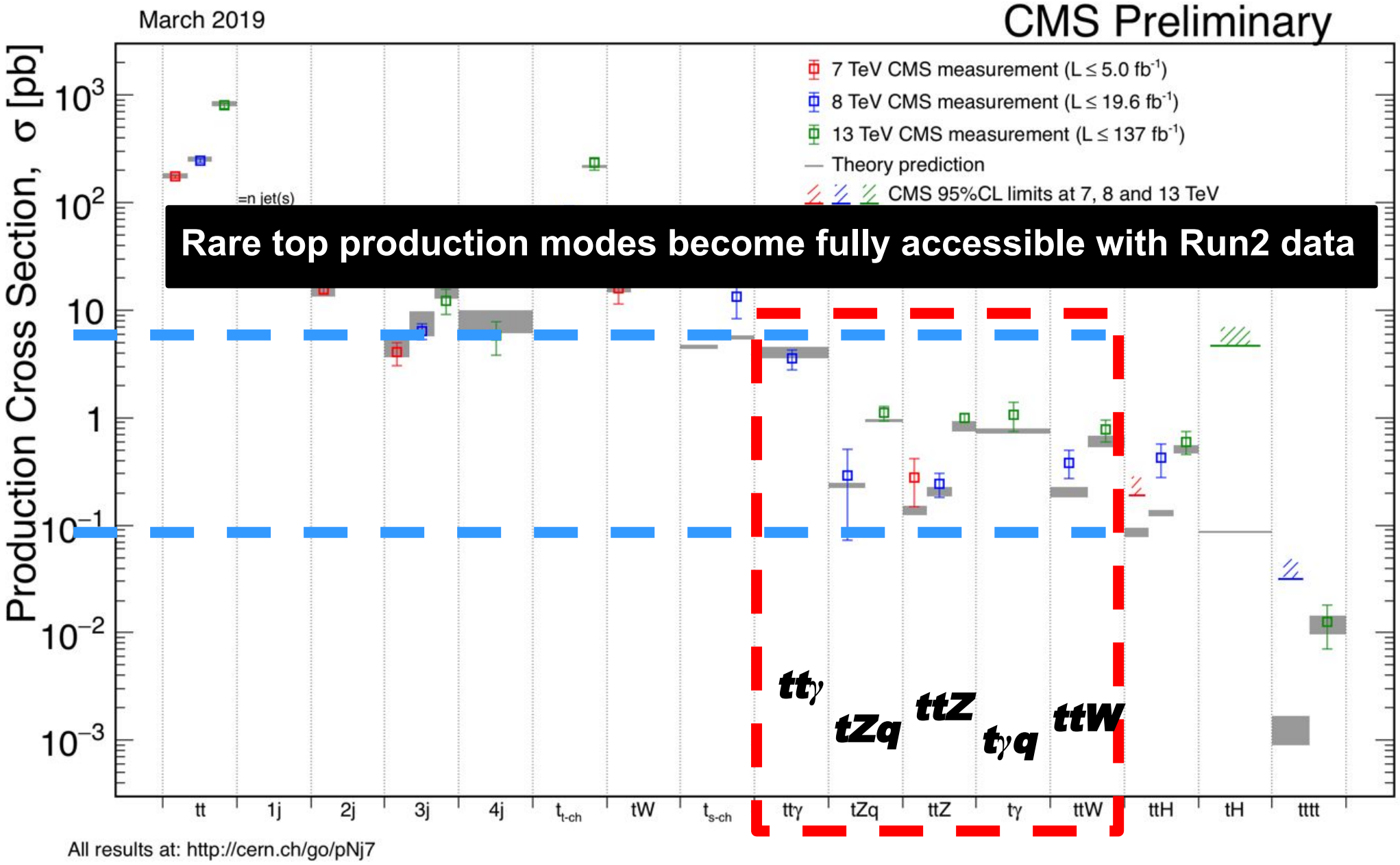
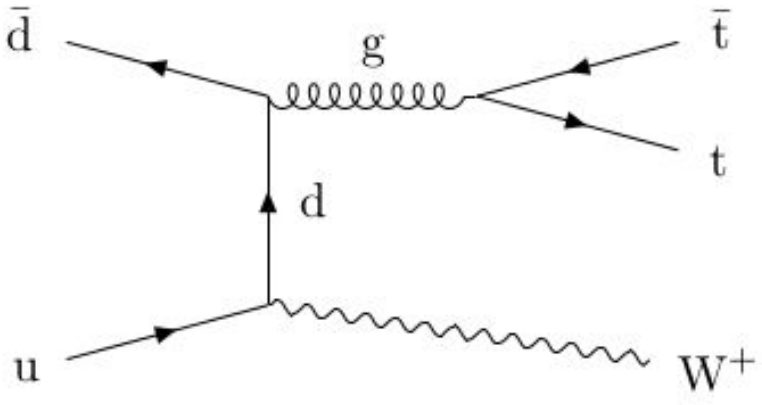
Top Quark Production

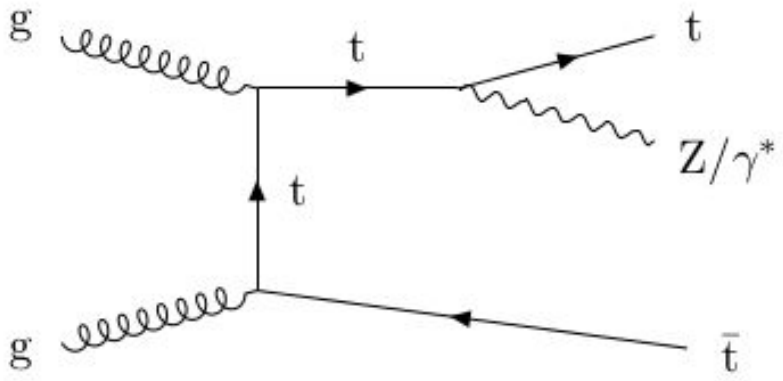


Top Quark Rare Production



ttW/ttZ Production

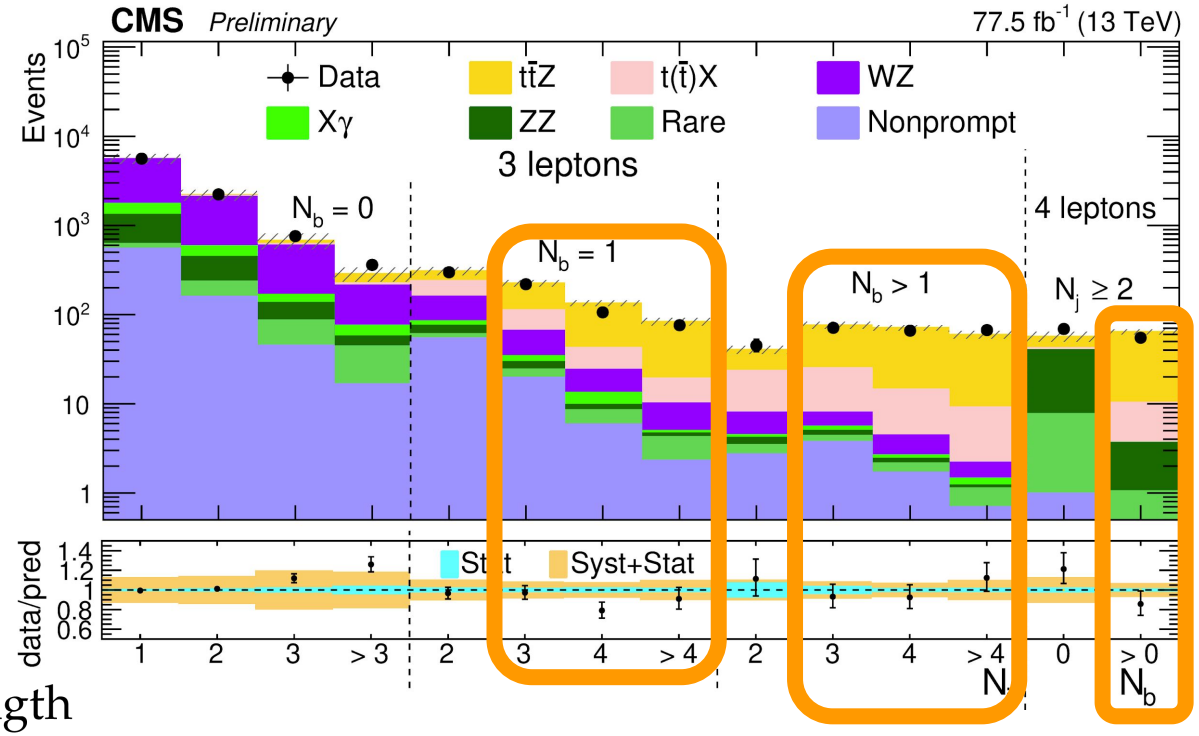




- Among the **most massive** signatures that can be studied at the LHC with **high precision**
- Important *backgrounds* for searches and measurements such as **ttH** in multilepton final states
- **ttZ** production is the **most sensitive** process for directly measuring the coupling of the top quark to the Z boson
- Receive significant enhancements in BSM models

ttZ Inclusive - 77.5 fb^{-1} @13 TeV - CMS-PAS-TOP-18-009

- Baseline selection: exactly 3 or 4 leptons and 0 jets
  - ➢ OS SF pair consistent with Z boson mass
- Events further classified according N_{jets} and $N_{b\text{-tags}}$
- Main backgrounds are from events with at least one top quark in association with a *W*, *Z* or *H*



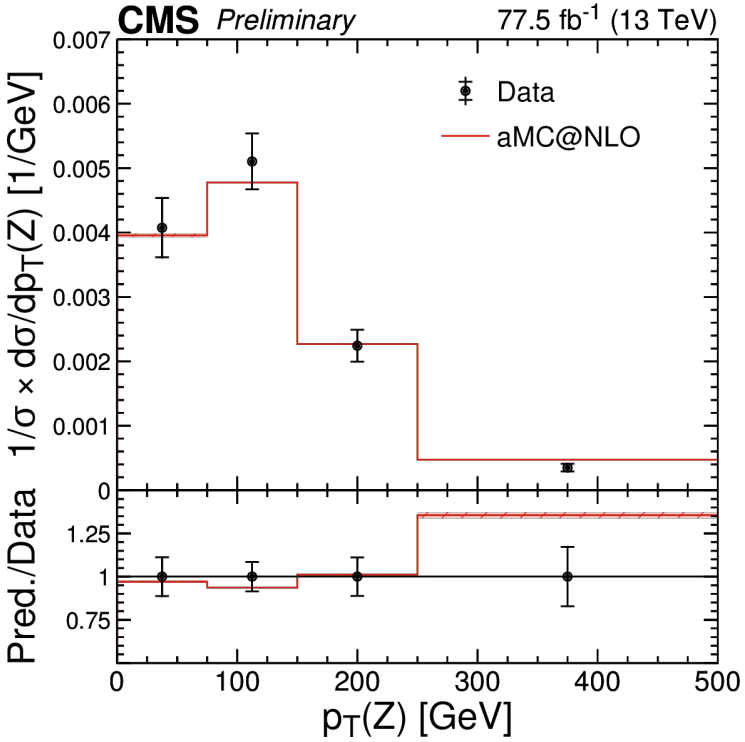
Fit configuration	Measured signal strength
3ℓ	$1.24\ ^{+0.07}_{-0.07}(\text{stat})\ ^{+0.08}_{-0.08}(\text{syst})$
4ℓ	$1.15\ ^{+0.18}_{-0.17}(\text{stat})\ ^{+0.10}_{-0.08}(\text{syst})$
Combined	$1.19\ ^{+0.07}_{-0.06}(\text{stat})\ ^{+0.08}_{-0.07}(\text{syst})$

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

σ_{ttZ}(NLO) = 0.839 ± 0.101 pb

ttZ Differential - 77.5 fb^{-1} @13 TeV - CMS-PAS-TOP-18-009

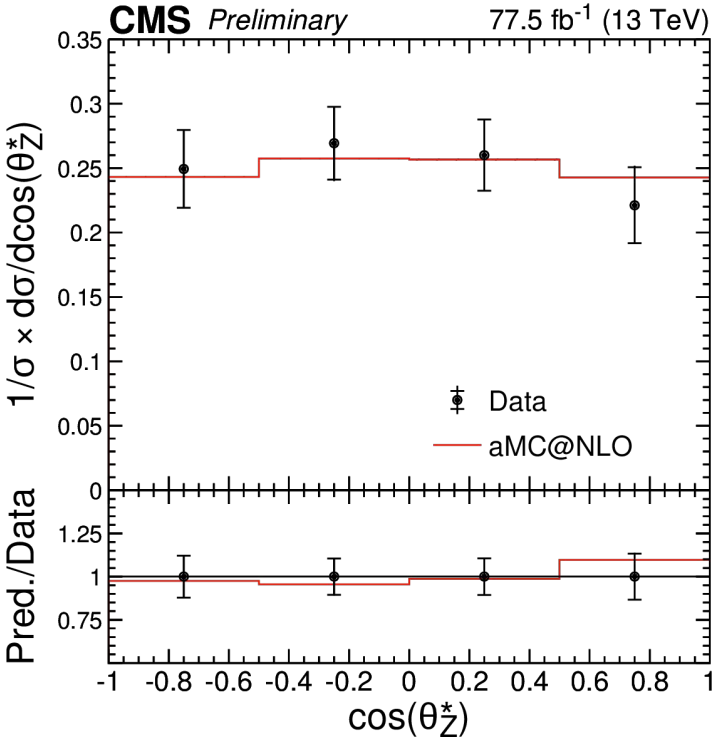
- Differential cross sections measured as a function of the ***transverse momentum of the Z boson*** and the ***angular distribution of the decay lepton***



Signal enriched region

- Exactly 3 leptons
- $N_{jets} \geq 3$
- $N_{b\text{-}tags} \geq 1$

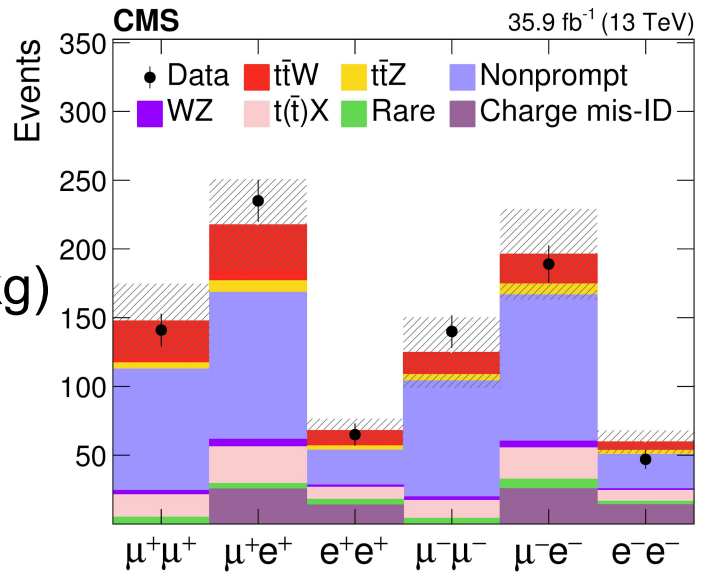
cos θ*$_Z$ (between the negative charged lepton and the Z candidates in the Z rest frame)

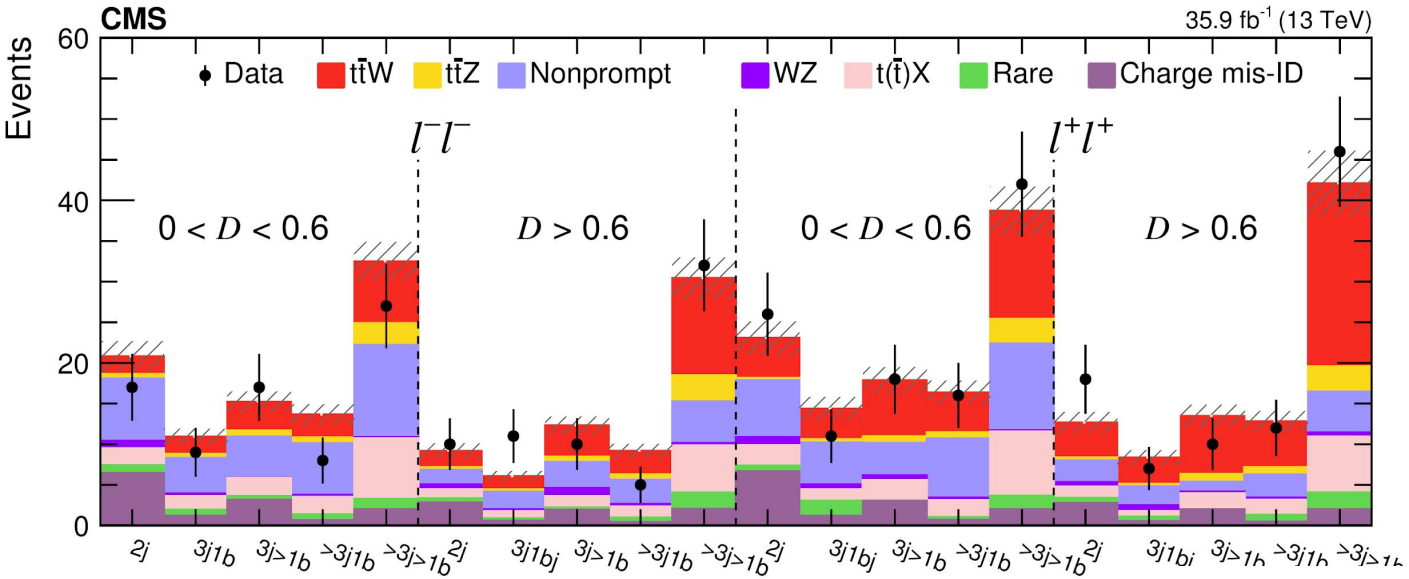


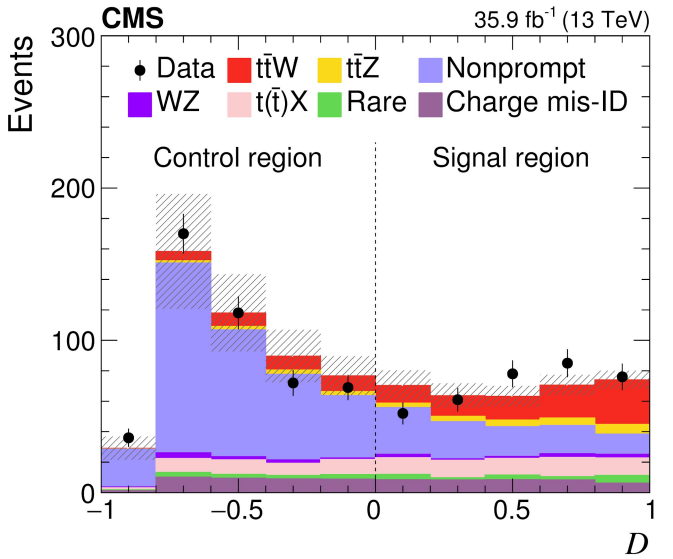
- **aMC@NLO** generator describes the shape well
- **Main systematics**: lepton ID, jet energy, non-prompt background
- For EFT interpretation, see K. Skovpen's talk

ttW - 35.9 fb^{-1} @13 TeV - JHEP 08 (2018) 011

- Baseline selection: 2 leptons with same charge
- BDT used: N_{jets}, $N_{b\text{-}tags}$, H_T, MET,...
- Select events with D > 0 (suppress nonprompt lepton bkg)
- Events further classified according to the value of BDT output, N_{jets} , $N_{b\text{-}tags}$ and lepton charge







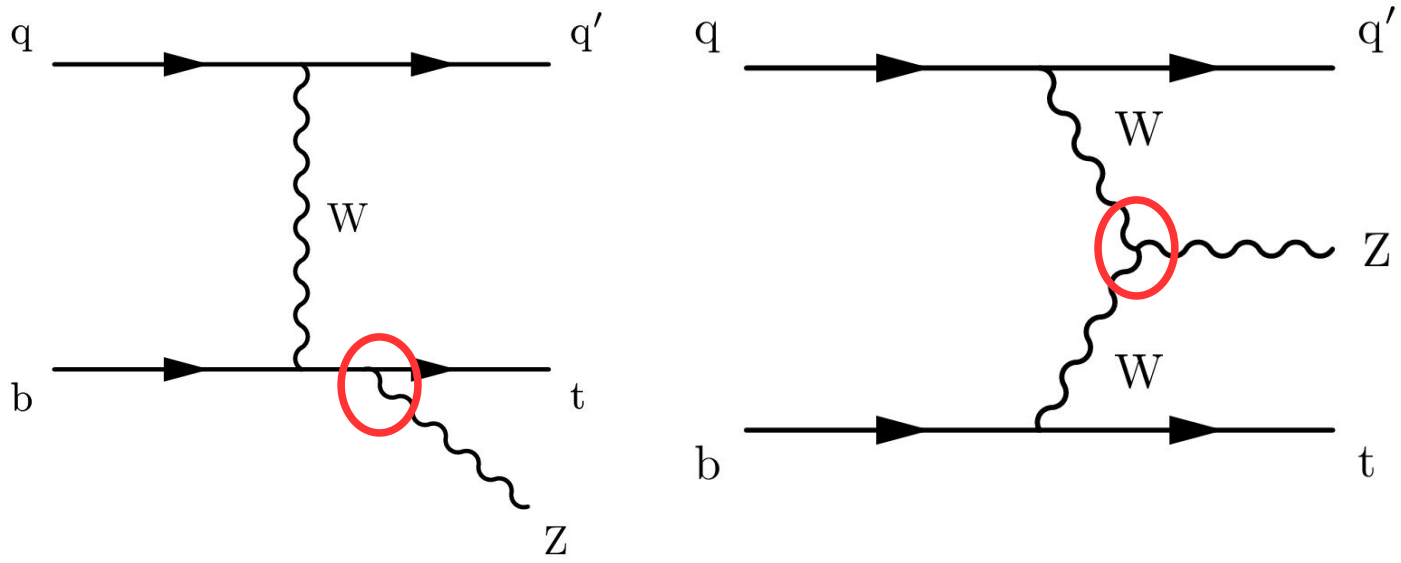
- Observed (expected) sign. of **5.3** **(4.5)** **σ**

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

σ_{ttW}(NLO) = 0.628 ± 0.082 pb

- **Main systematics**: luminosity, lepton ID, trigger, jet energy and non-prompt bkg

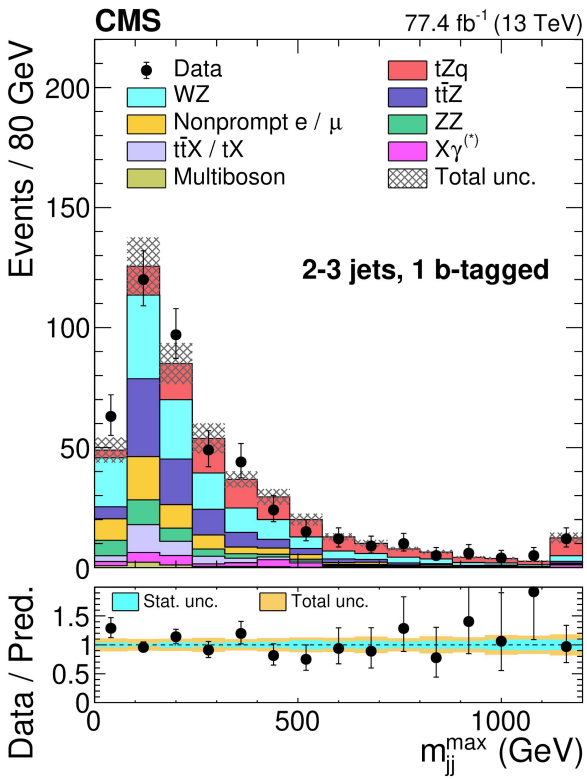
tZq Production

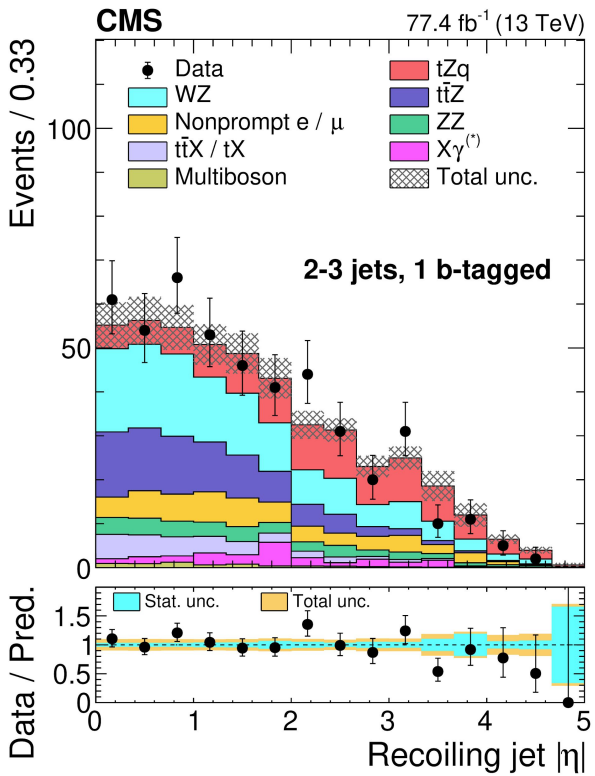


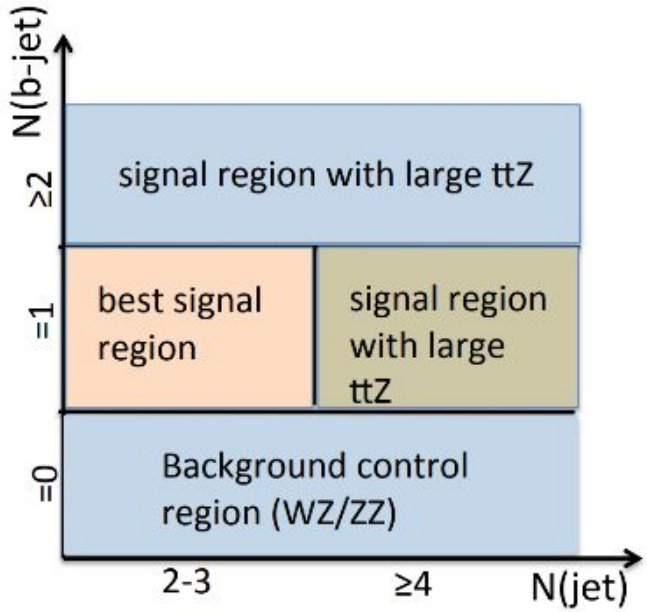
- Extremely rare process
- Sensitive to top-Z and triple gauge boson WWZ couplings
  - Possible deviations may indicate physics BSM (FCNC, anomalous couplings)
- Typically studied in the leptonic decay mode
  - Small BR but much cleaner than 1 and 2 leptons channels
- Main backgrounds from ttV, WZ and non-prompt lepton production

tZq Production - 77.4 fb^{-1} @13 TeV - PRL 122 (2019) 132003

- 3 isolated high-p_T leptons, with one OS SF pair consistent with Z boson mass
- Events are divided into 3 categories depending on N_{jets} and $N_{b\text{-}tags}$
  - Signal: at least 2 jets and exactly 1 b-tagged jet
- In each of these categories, a dedicated BDT is trained

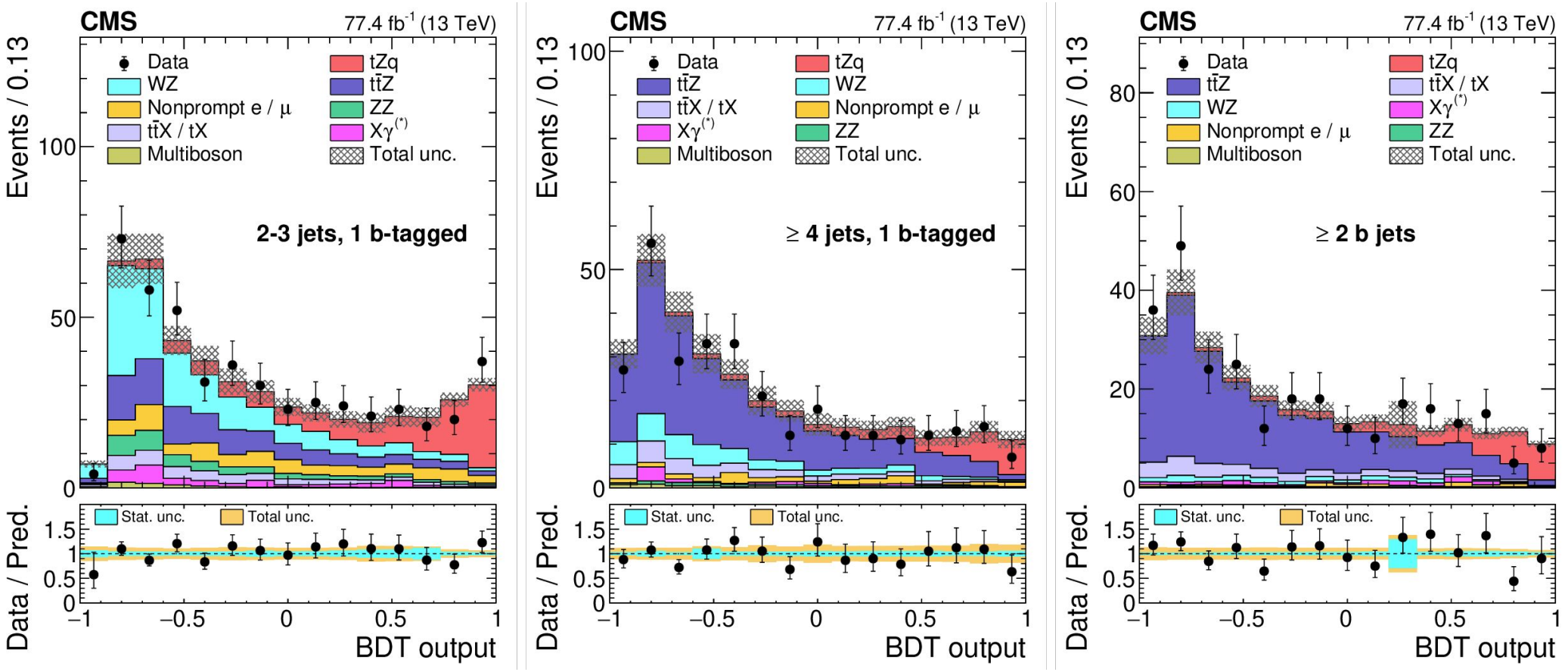






- Non-prompt and fake lepton bkg: MVA classifier exploiting ID and isolation information

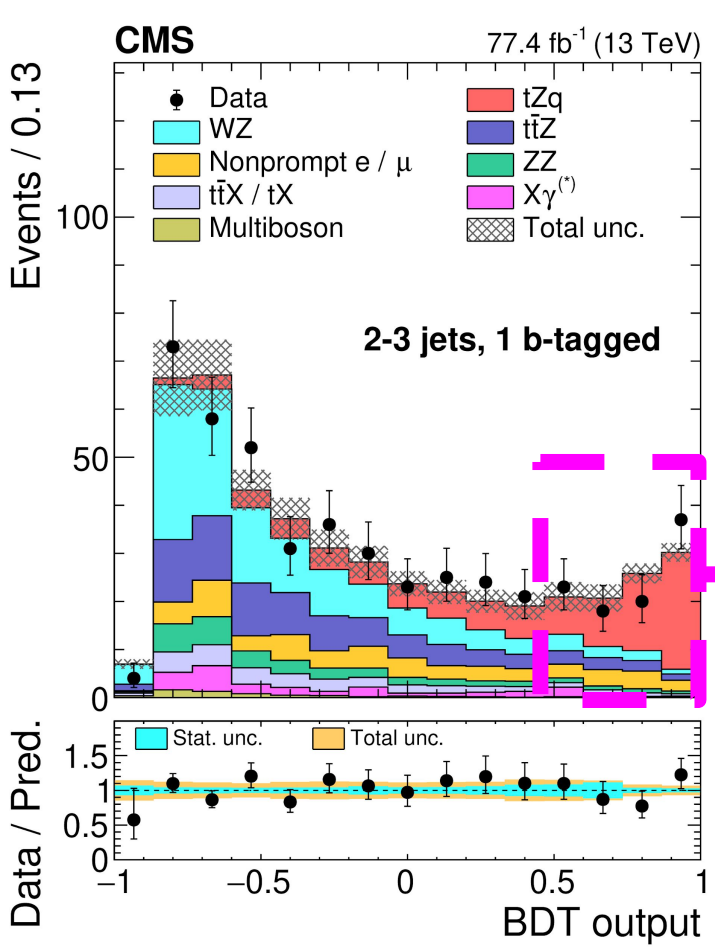
tZq Production - 77.4 fb^{-1} @13 TeV - PRL 122 (2019) 132003

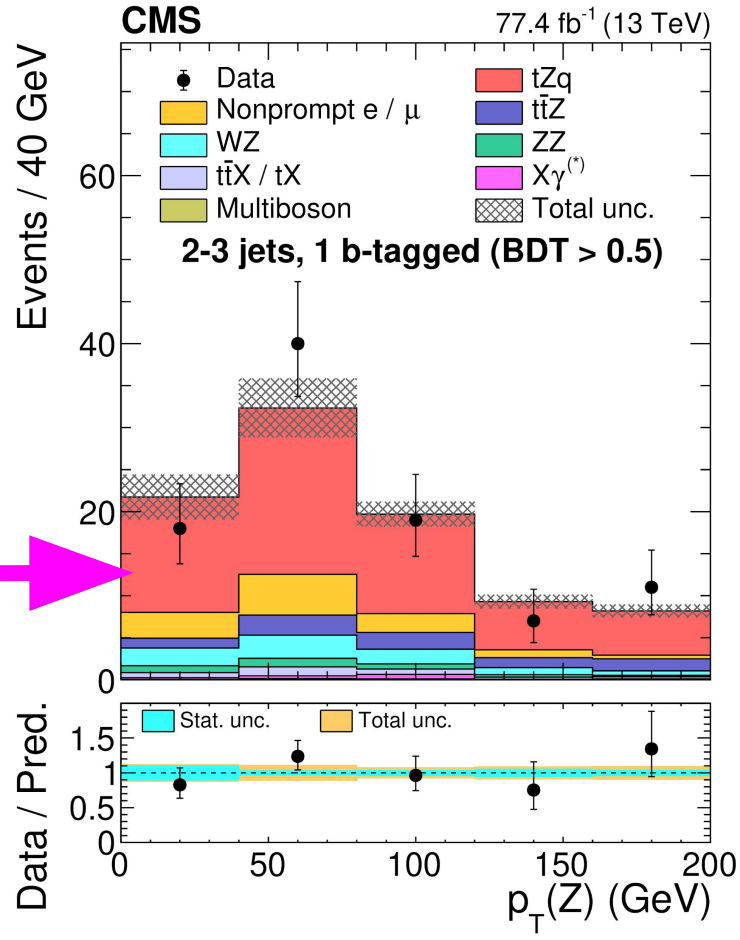


❖ Simultaneous template fit to BDT outputs and yields of control regions is performed

tZq Observation - 77.4 fb^{-1} @13 TeV - PRL 122 (2019) 132003

- The tZq signal is **observed** with a **significance well above 5σ**
  - $\sigma(pp \to tZ(\to \ell^+\ell^-)q) = 111 \pm 13(stat)^{+11}_{-9}(syst)\,fb$ $[m(\ell^+\ell^-) > 30\,GeV/c^2]$
  - In agreement with the NLO SM expectation: **94.2 ± 3.1 fb**

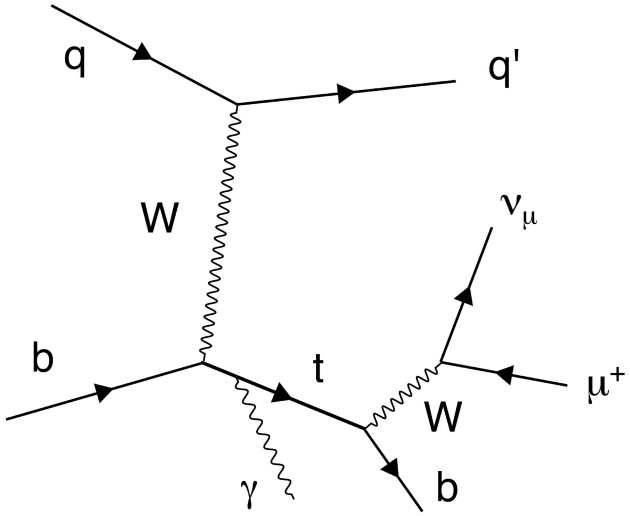


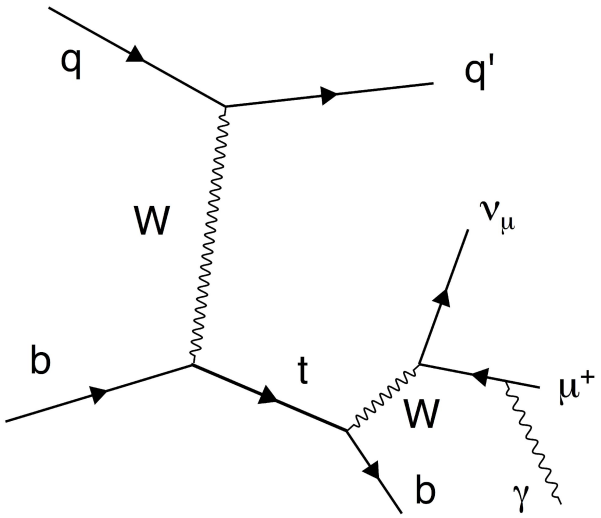


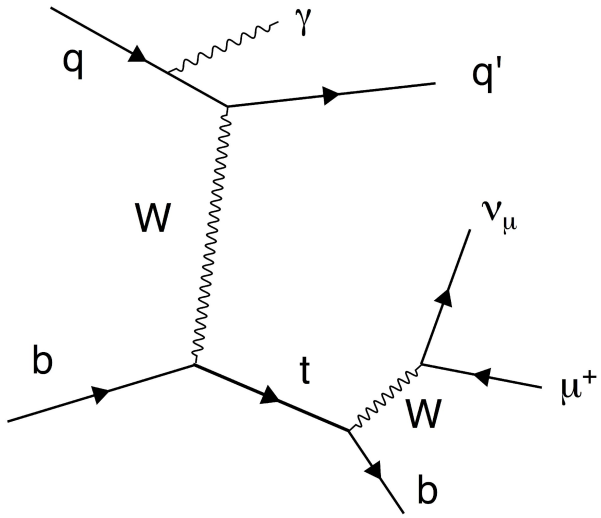
For more details, see W. Verbeke's poster

- **Main systematics**: non-prompt bkg, lepton ID, FSR modeling, jet energy

tγq Production





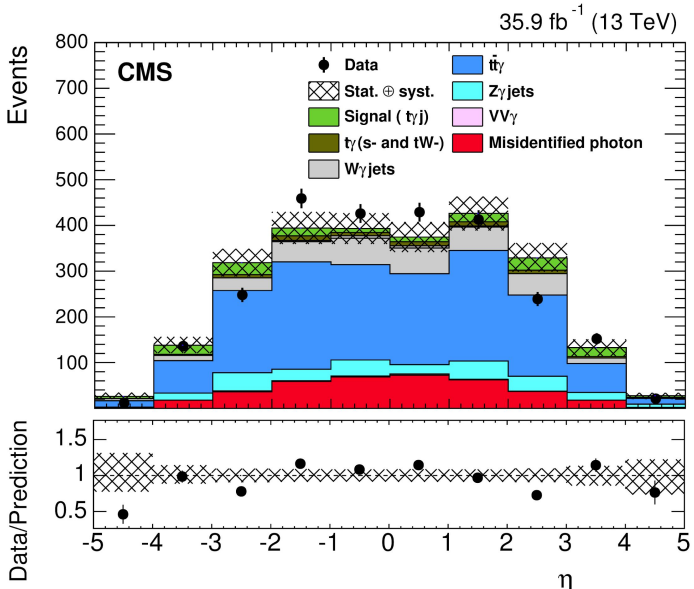


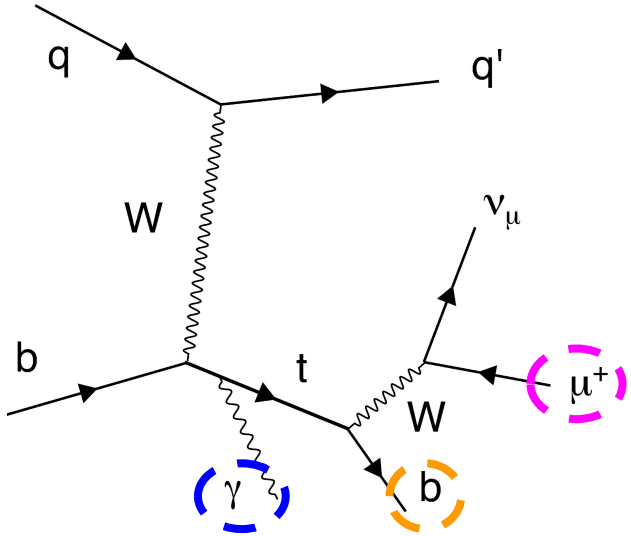
- Extremely rare process
- Sensitive to the top quark charge and the top quark electric and magnetic dipole moments

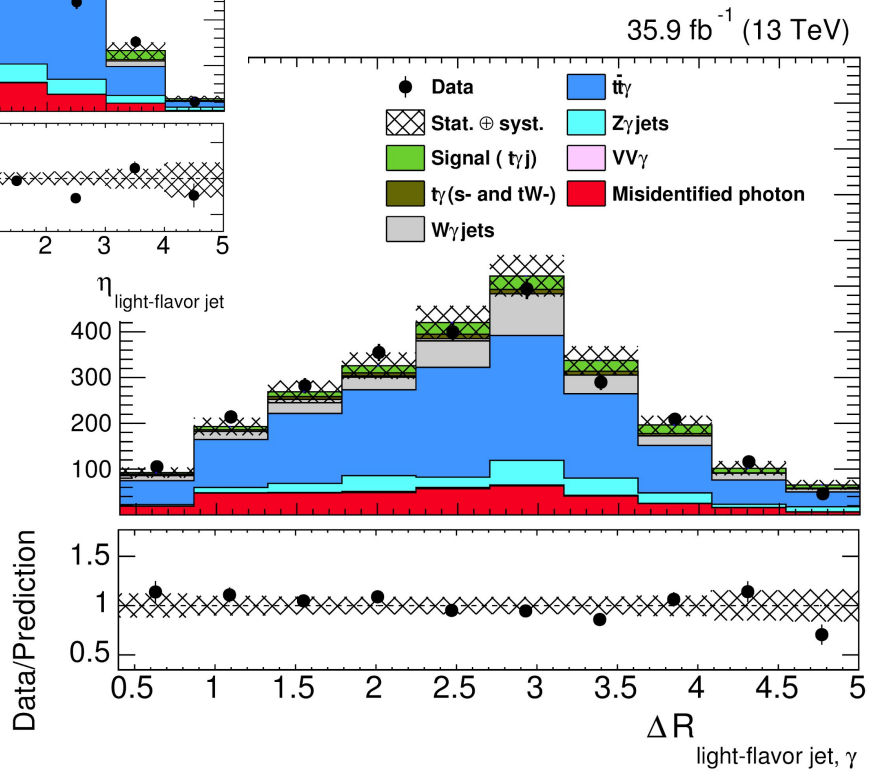
tγq Production - 35.9 fb^{-1} @13 TeV - PRL 121 (2018) 221802

- t-channel: 1 μ, 1 γ, MET, ≥ 2 jets, 1 b-tagged jet
- Fake photon bkg: data-driven, using photon isolation and shower shape

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



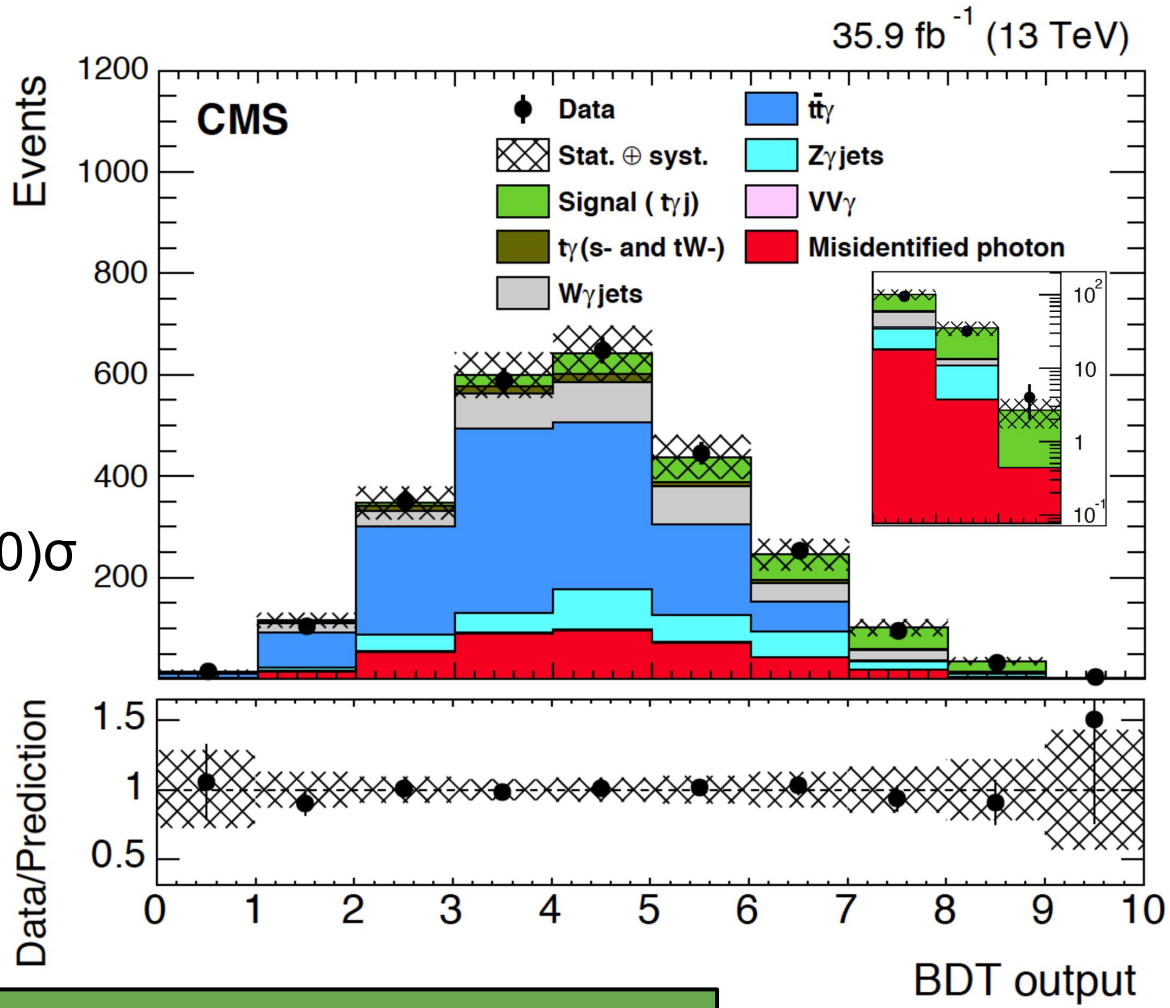




- BDT based on topological and kinematic properties

tγq Evidence - 35.9 fb^{-1} @13 TeV - PRL 121 (2018) 221802

- Binned likelihood fit is performed to the BDT in the SR and the tt+γ CR (2 b-tagged jets)
- Observed (expected) sign. of **4.4** (3.0)σ
  - First evidence of this process!
- **Main systematics**
  - JES and signal modeling



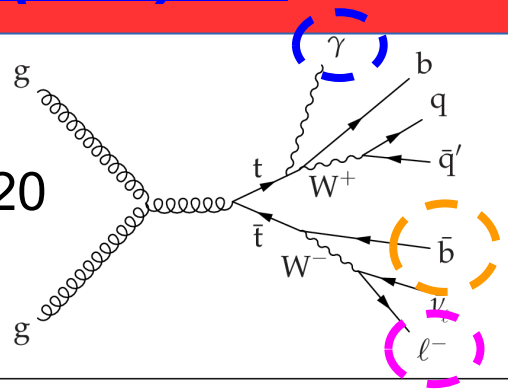
Fiducial xs: σ(pp → tγq) × BR(t → μνb) = 115 ± 17 (stat) ± 30 (syst) fb

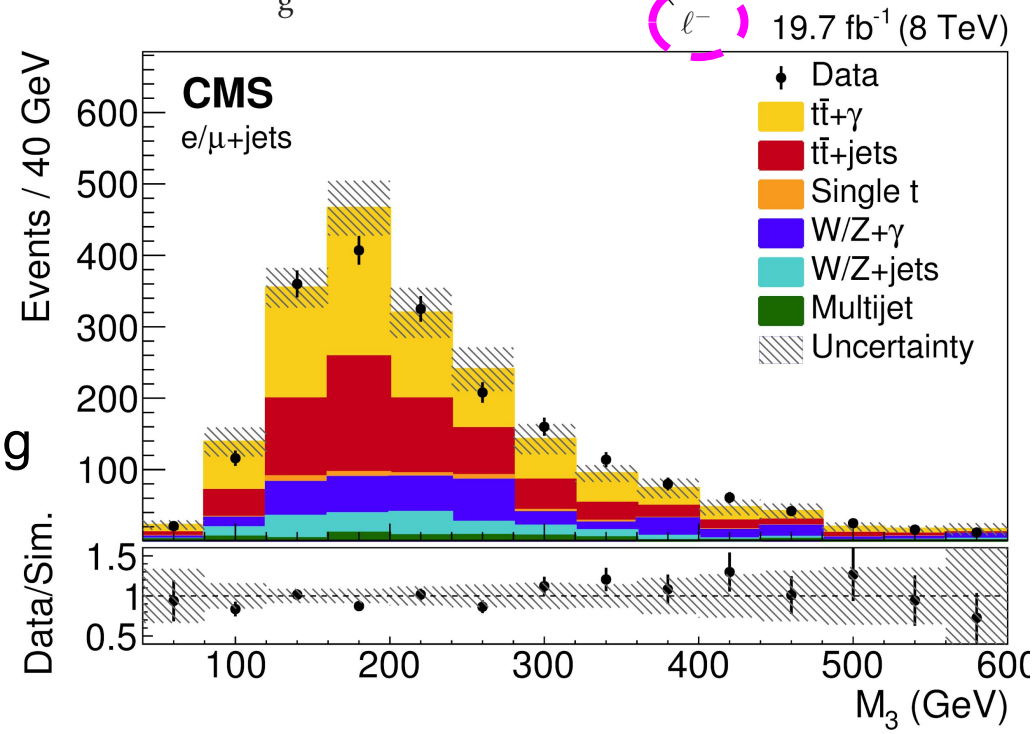
$\sigma_{t\gamma}$(NLO) = 81 ± 4(scale+PDF) fb

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

$t\bar{t}\gamma$ - 19.7 fb^{-1} @8 TeV - JHEP 10 (2017) 006

- Semileptonic decays
  - 1 lepton, 1 γ, ≥ 3 jets, ≥ 1 b-tagged jet, MET>20
- Main bkgs:
  - tt + fake γ: M_3
  - V+γ: γ charged hadron isolation
- l+jets fiducial region of top and γ
- **Main systematics**: fit stats., JES, modeling





$$\sigma^{\text{fid.}}_{t\bar{t}+\gamma} = \frac{N_{t\bar{t}+\gamma}}{\epsilon^{t\bar{t}+\gamma} L}$$

$$R = \frac{\sigma^{\text{fid}}_{t\bar{t}+\gamma}}{\sigma_{t\bar{t}}} = \frac{N_{t\bar{t}+\gamma}}{\epsilon^{t\bar{t}+\gamma}} \frac{\epsilon^{t\bar{t}}_{\text{top}} A^{t\bar{t}}_{\text{top}}}{N_{t\bar{t}}}$$

Category	R	$\sigma^{\text{fid}}_{t\bar{t}+\gamma}$ (fb)	$\sigma_{t\bar{t}+\gamma}\,\mathcal{B}$ (fb)
e+jets	$(5.7 \pm 1.8) \times 10^{-4}$	138 ± 45	582 ± 187
μ+jets	$(4.7 \pm 1.3) \times 10^{-4}$	115 ± 32	453 ± 124
Combination	$(5.2 \pm 1.1) \times 10^{-4}$	127 ± 27	515 ± 108
Theory	—	—	592 ± 71 (scales) ± 30 (PDFs)

Summary

- The large amount of LHC data recorded up to date allows probing very rare SM processes, very small production cross sections
- 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 13 TeV data sample yet
- All results are in good agreement with **SM** prediction
- **Highlights:**
  - First ttZ differential cross section measurement
  - First observation of tZq
  - First evidence for tγq
- **Stay tuned:** New results with more data are on their way…

http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/TOP/index.html

Back-up Slides

ttZ Inclusive - CMS-PAS-TOP-18-009

Source	Uncertainty range (%)	Correlated in 2016 and 2017	Impact on the $t\bar{t}Z$ cross section (%)
Integrated luminosity	2.5	×	2
PU modeling	1–2	✓	1
Trigger	2	×	2
Lepton ID efficiency	4.5–6	✓	4
Jet energy scale	1–9	✓	2
Jet energy resolution	0–1	✓	1
B tagging light flavor	0–4	×	1
B tagging heavy flavor	1–4	×	2
Choice in μ_R and μ_F	1–4	✓	1
PDF choice	1–2	✓	1
Color reconnection	1.5	✓	< 1
Parton shower	1–8	✓	1
WZ cross section	10–20	✓	3
WZ + heavy flavor	8	✓	1
ZZ cross section	10	✓	1
$t(\bar{t})X$ bg.	10–15	✓	3
$X\gamma$ background	20	✓	1
Nonprompt background	30	✓	< 1
Rare SM background	50	✓	2
Stat. unc. in nonprompt bg.	5–50	×	< 1
Stat. unc. in rare SM bg.	5–100	×	< 1
Total uncertainty			7

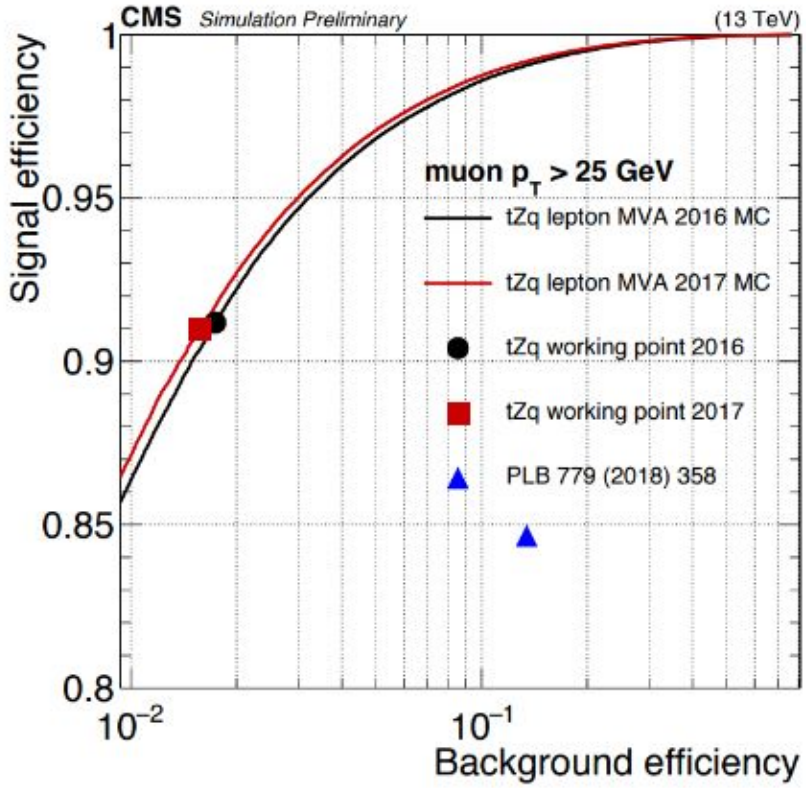
ttZ Inclusive - 77.5 fb^{-1} @13 TeV - CMS-PAS-TOP-18-009

- Compared to previous 2016 search, several factors improve significantly the sensitivity
- More inclusive trigger
- Multivariate lepton identification
- Better lepton and b-tagging efficiency measurements

Source	Uncertainty from each source (%)	Impact on the measured $t\bar{t}W$ cross section (%)	Impact on the measured $t\bar{t}Z$ cross section (%)
Integrated luminosity	2.5	4	3
Jet energy scale and resolution	2–5	3	3
Trigger	2–4	4–5	5
B tagging	1–5	2–5	4–5
PU modeling	1	1	1
Lepton ID efficiency	2–7	3	6–7
Choice in μ_R and μ_F	1	<1	1
PDF	1	<1	1
Nonprompt background	30	4	<2
WZ cross section	10–20	<1	2
ZZ cross section	20	—	1
Charge misidentification	20	3	—
Rare SM background	50	2	2
$t(\bar{t})X$ background	10–15	4	3
Stat. unc. in nonprompt background	5–50	4	2
Stat. unc. in rare SM backgrounds	20–100	1	<1
Total systematic uncertainty	—	14	12

tZq Production - PRL 122 (2019) 132003

- Compared to previous searches, several factors improve significantly the sensitivity
- The increased **integrated luminosity**
  - Added 2017 data: 35.9 to 77.4 fb^{-1}
- **Multivariate lepton identification**
- **Redesigned analysis strategy**



Source	Uncertainty (%)
Statistical likelihood fit	15.5
Top quark mass	7.9
JES	6.9
Fact. and renorm. scale	6.7
ME/PS matching threshold	3.9
Photon energy scale	2.4
JER	2.3
Multijet estimate	2.0
Electron misid. rate	1.3
Z+jets scale factor	0.8
Pileup	0.6
Background normalization	0.6
Top quark p_{T} reweighting	0.4
b tagging scale factor	0.3
Muon efficiency	0.3
Electron efficiency	0.1
PDFs	0.1
Muon energy scale	0.1
Electron energy scale	0.1
Total	20.7