Rare top quark production in CMS: $t\bar{t}Z$, $t\bar{t}W$, $t\bar{t}\gamma$, tZq, $t\gamma q$ and $t\bar{t}t\bar{t}$

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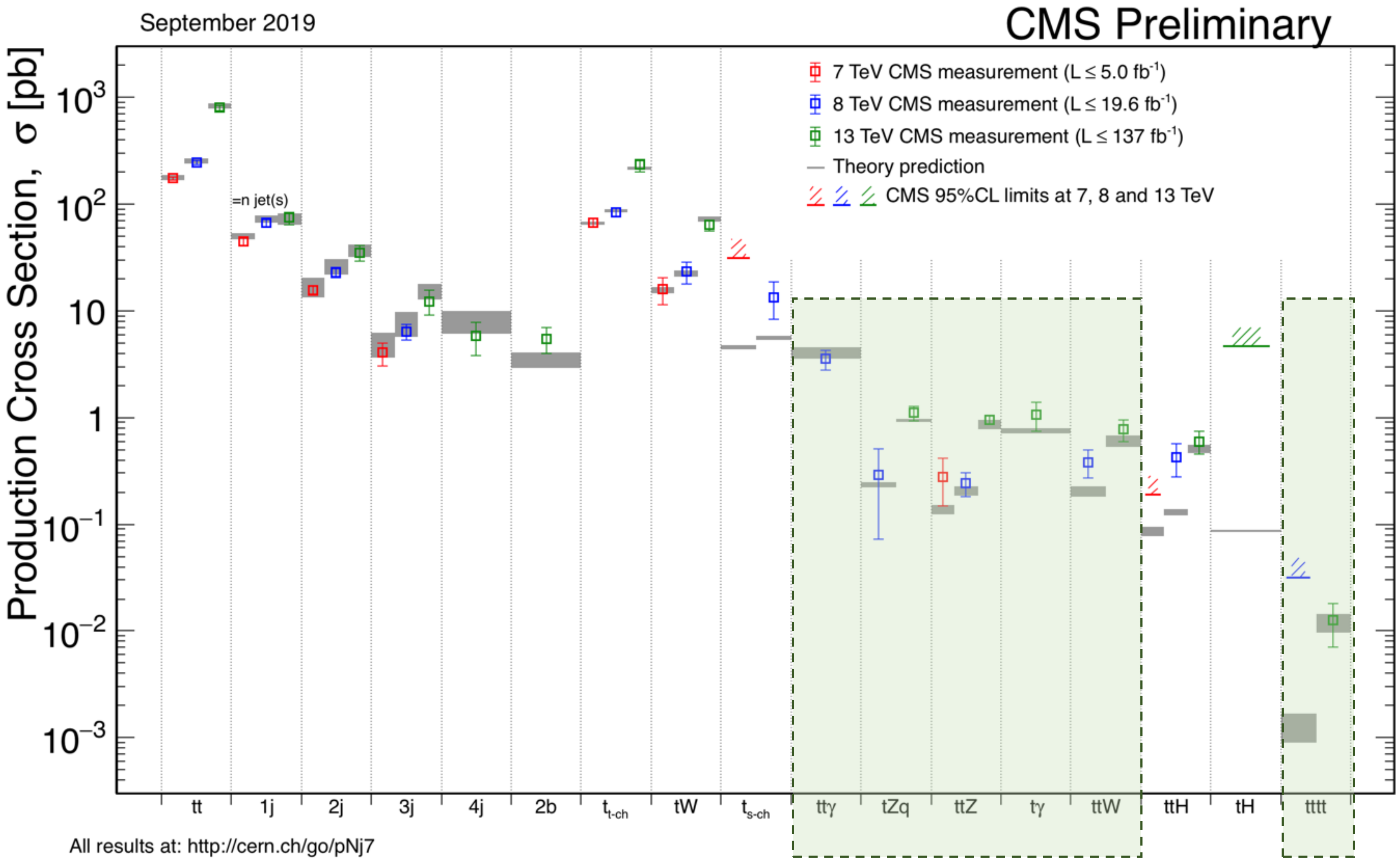
Introduction

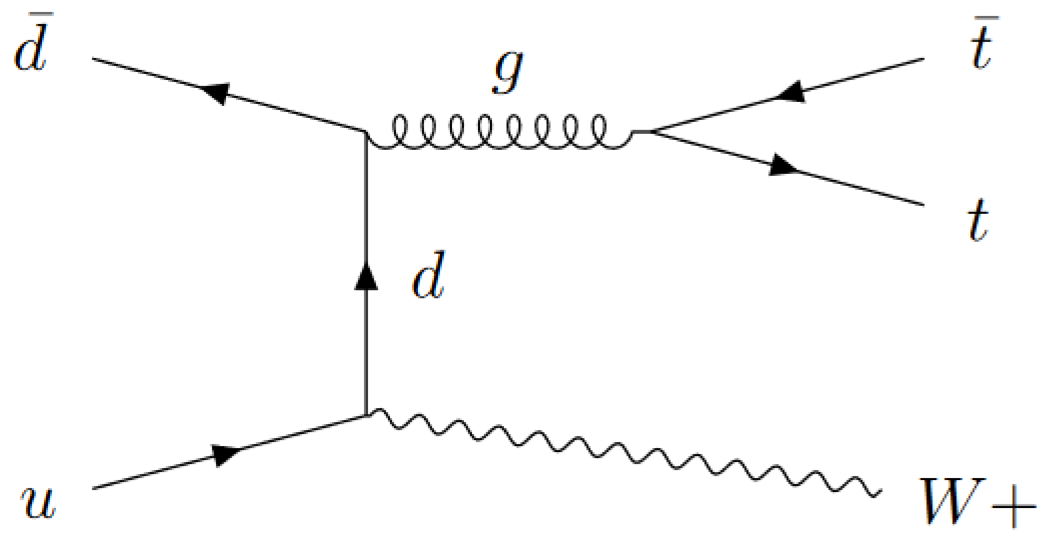
Rare top production is fully accessible with Run 2 data: $t\bar{t}W$, $t\bar{t}Z$, tZq, $t\bar{t}\gamma$, tγq, $t\bar{t}t\bar{t}$.

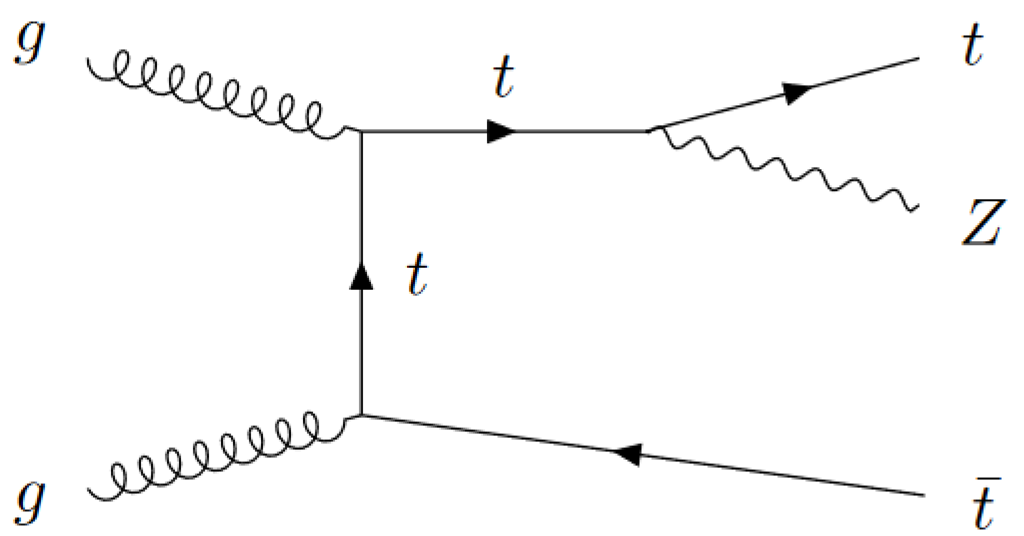


What we expect to learn:

- top coupling to Z and γ bosons.
- $t\bar{t}V$: one of the most massive signatures that can be studied with high precision.
- Searches for four top quark production starting to be sensitive at LHC.

$t\bar{t}W/t\bar{t}Z$





- Cross sections that allow high precision measurements
- **Important background** process for **searches as $t\bar{t}$H** in multilepton final states
- **$t\bar{t}$Z** is sensitive to the direct **coupling of the top quark to the Z boson**
- Production would be enhanced in BSM models

tt̄W

2016 data

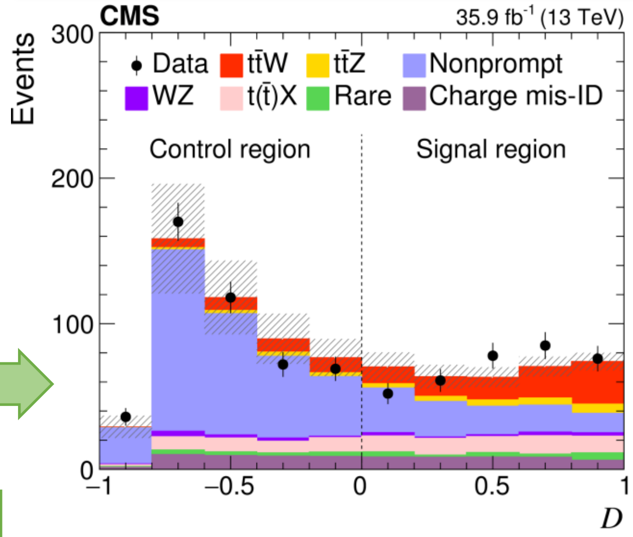
Baseline Selection:

- 2 leptons of same charge
- m_{ll} > 12 GeV (excluding Z mass window)
- $N_{Jet} \geq 2$
- $N_{B\text{-}tag} \geq 1$

Analysis strategy:

- **BDT** to discriminate signal vs. bkg. Most discriminant variables: N_{jet}, $N_{B\text{-}tag}$, H_T.
- Categories in BDT score, lepton charge, N_{jet} and $N_{B\text{-}tag}$

JHEP 08 (2018) 011



Main systematics:

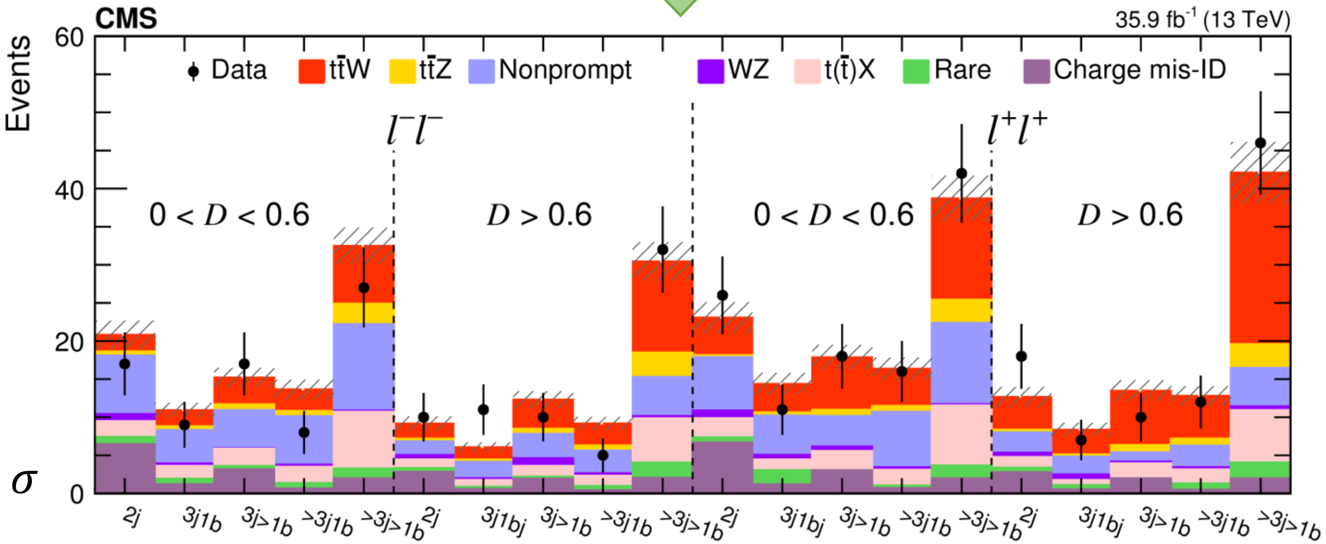
Luminosity, trigger, non-prompt bkg.

$$\mu = 1.23^{+0.19}_{-0.18}\,(\text{stat})^{+0.20}_{-0.18}\,(\text{syst})^{+0.13}_{-0.12}\,(\text{theo})$$

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

$$\sigma\,(\text{NLO}) = 0.628 \pm 0.082\ \text{pb}$$

Observed (expected) significance = 4.5(5.3) σ



$t\bar{t}Z$ Inclusive

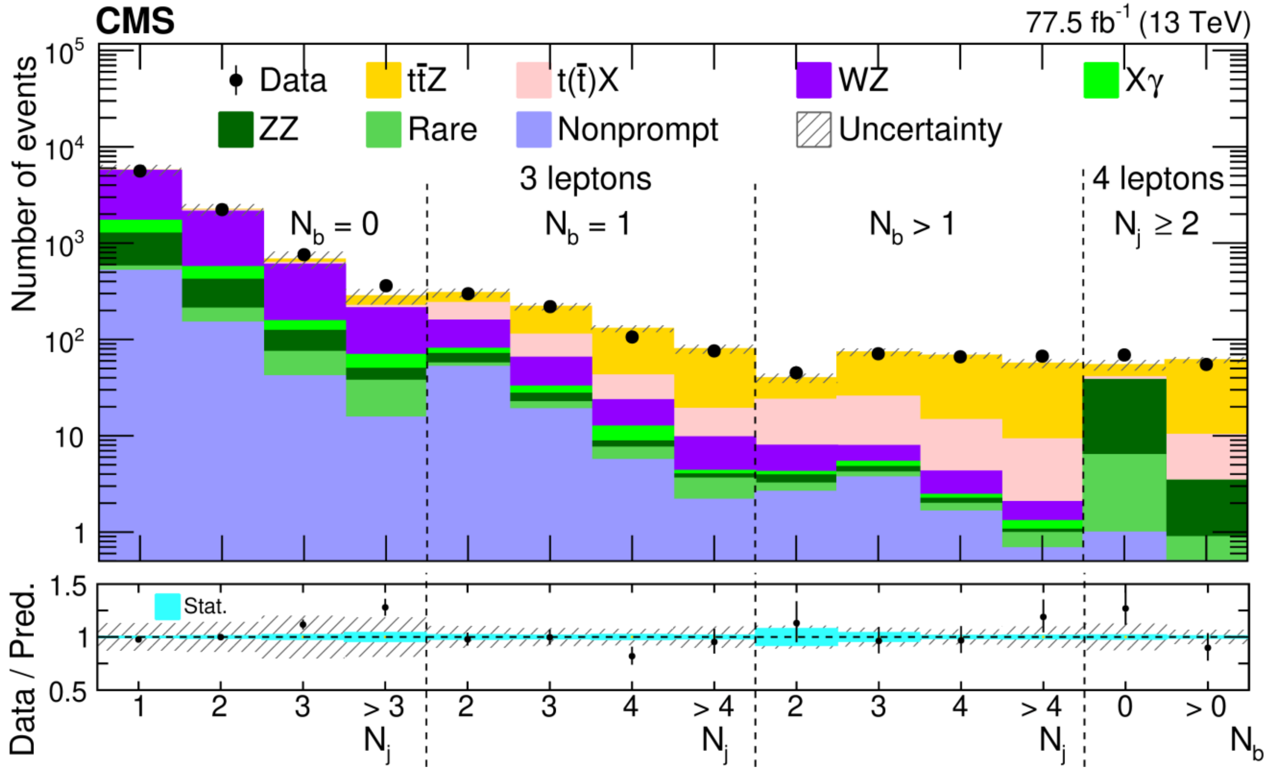
JHEP 03 (2020) 056

2016 and 2017 data

Baseline Selection:

- 3 or 4 leptons
- A pair of leptons is OSSF with m_{ll} in the Z mass window
- $N_{Jet} > 0$

N_{Jet} and N_B Classification



Improvements with respect to JHEP 08 (2018) 011 $t\bar{t}Z$ measurement:

- More inclusive trigger
- Lepton ID

Main Backgrounds:

at least one top quark in association with a W, Z or H

$$\sigma(pp \rightarrow t\bar{t}Z) = 0.95 \pm 0.05\,(\text{stat}) \pm 0.06\,(\text{syst})\,\text{pb}$$

$\sigma\,(\text{NLO}) = 0.839 \pm 0.101$ pb

Precision comparable to NLO th. prediction

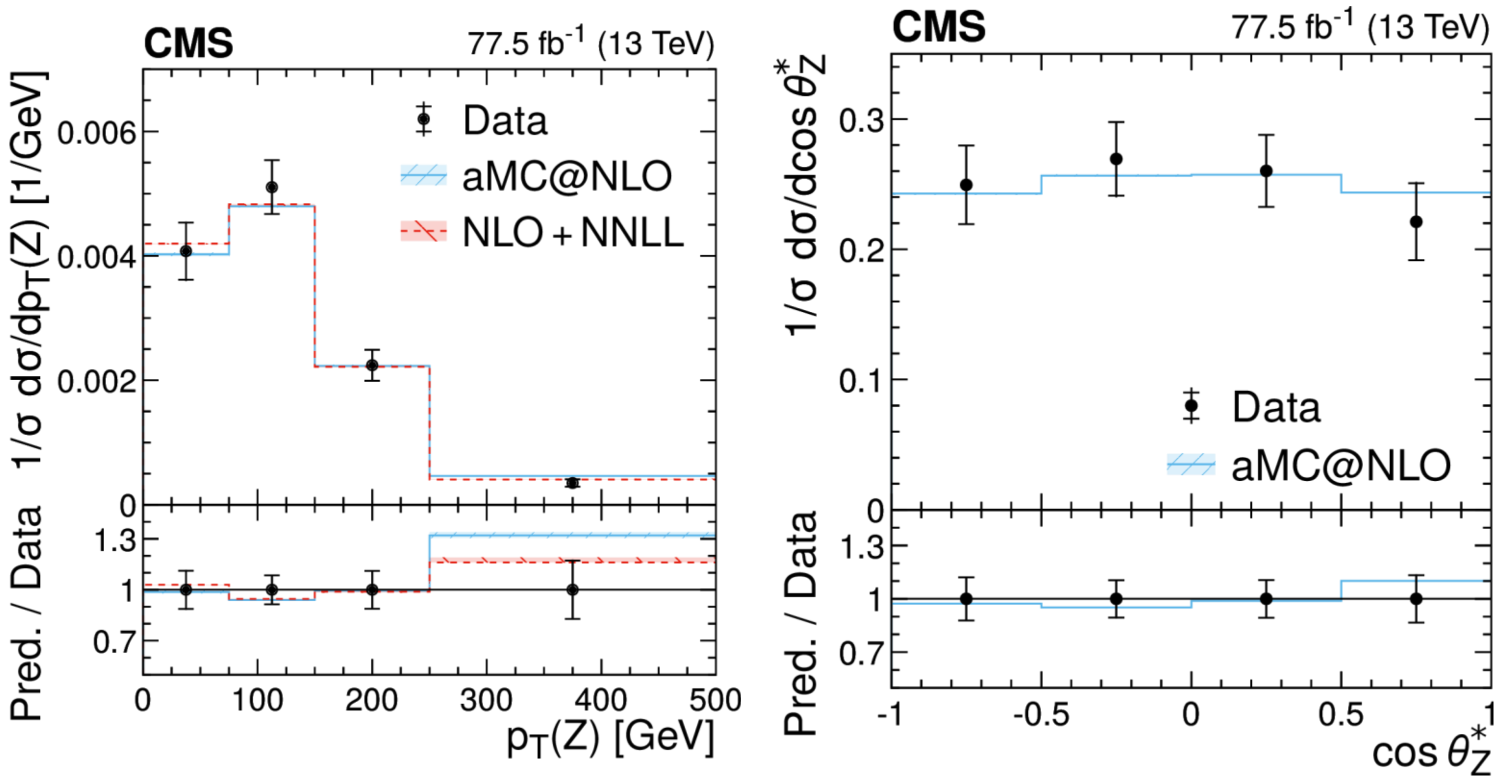
$t\bar{t}Z$ differential

JHEP 03 (2020) 056

Differential cross section is also measured as a **function of p_T of the Z boson** and of the **cosine of the angle between** the negative charged **lepton and the Z** candidate in the Z rest frame.

A signal enriched sample is used:

- 3 leptons
- $N_{B\text{-tags}} > 1$
- $N_{Jets} > 3$

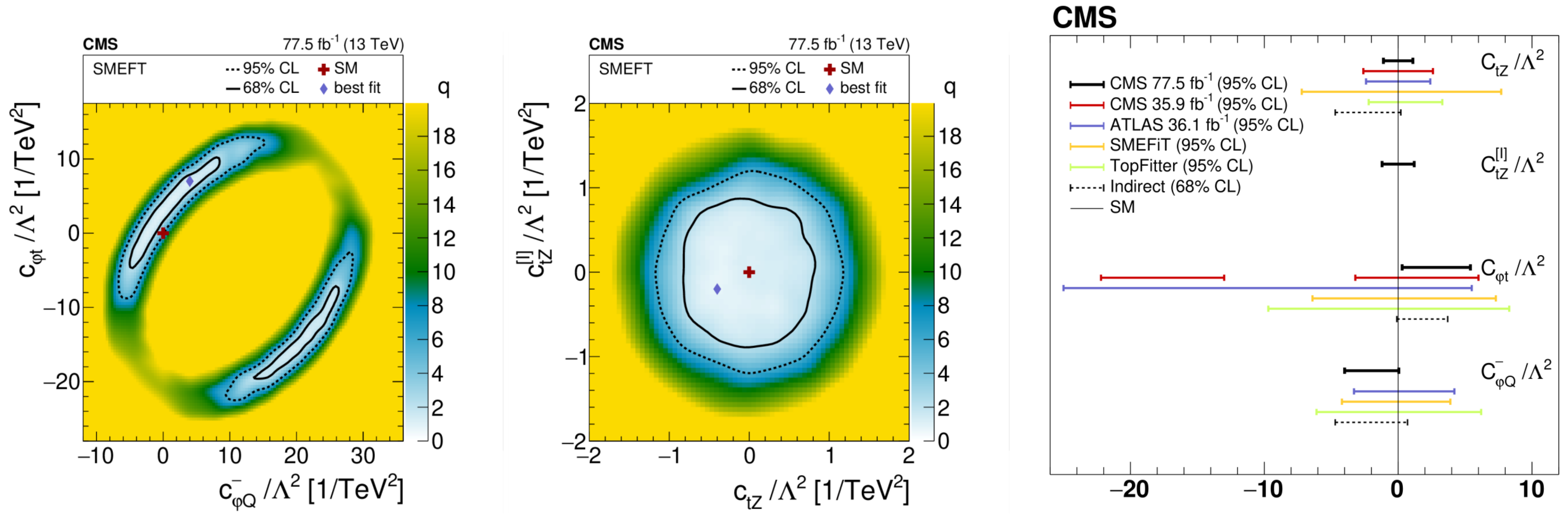


- ❑ Unfolding by χ^2 minimization without regularization
- ❑ aMC@NLO generator describes the shape well

$t\bar{t}Z$ - EFT Interpretation

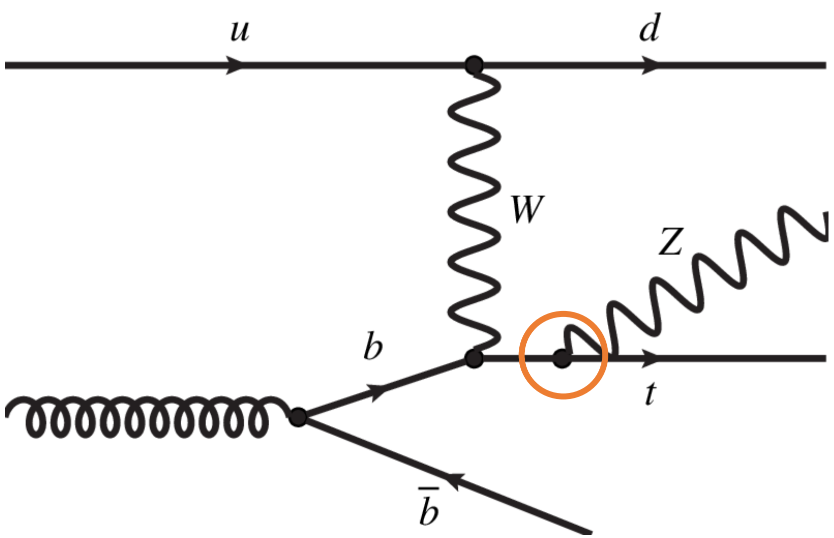
JHEP 03 (2020) 056

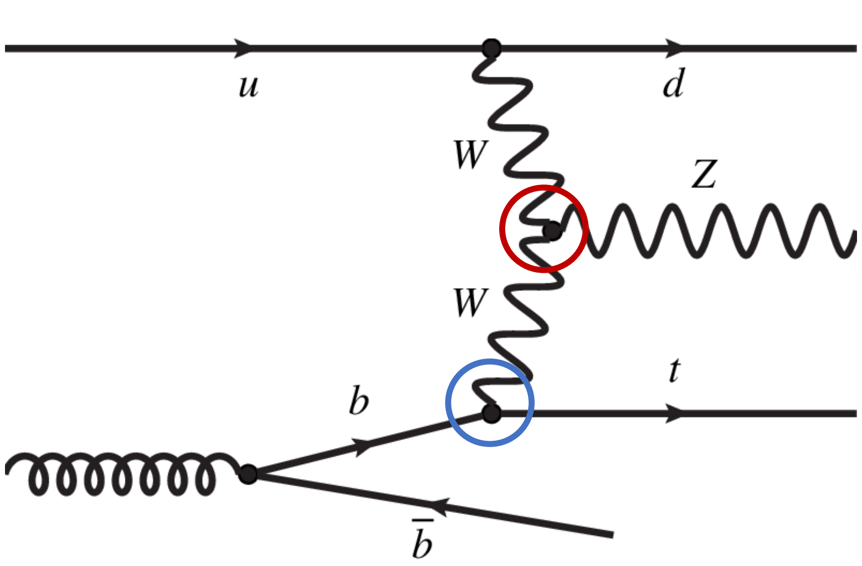
- Regions defined using $p_T(Z)$ and $cos(\theta_Z^*)$
- 59 Wilson coefficients of dimension 6 → 4 relevant, sensitive to t-Z coupling
- New stringent limits on the anomalous couplings of t-Z and estimates of the Wilson Coefficients of SM EFT are obtained



Good agreement with SM

tZq





- Sensitive to several SM interaction via triple gauge boson (WWZ), tbW and top-Z couplings. Also sensitive to tbW → tZ scattering amplitude.
  - Might be affected by **modified interaction** even if $t\bar{t}Z$ and single top production are not.
  - Could indicate the presence of **flavour-changing neutral currents**
- Presence of a forward jet is a significant difference with respect to background processes

tZq - Observation

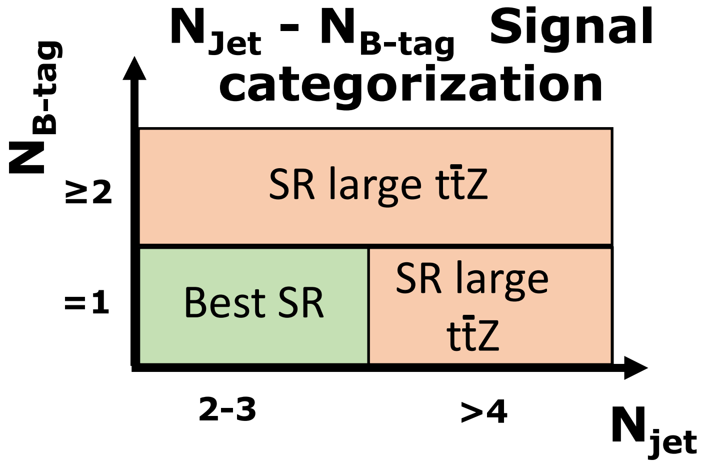
PRL 122 (2019) 132003

2016 and 2017 data

Baseline Selection:

- 3 isolated leptons
- A pair of leptons is OSSF with m_{ll} in the Z mass window

+



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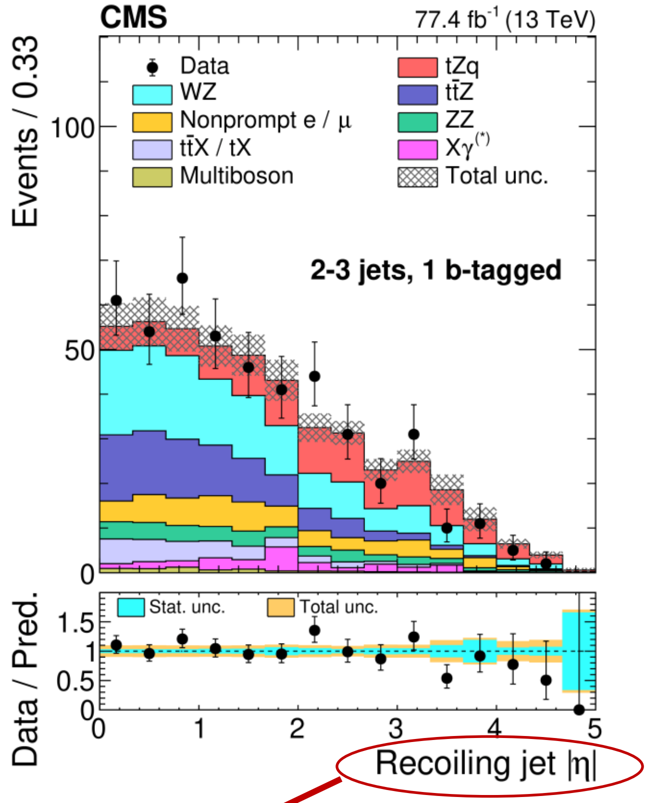
A BDT is trained for each SR



Most discriminant variable

Improvements with respect to PLB 779 (2018) 358**:**

- Luminosity increase
- Non-prompt lepton discrimination
- New analysis strategy: more inclusive categorization

Backgrounds:

- Diboson (WZ,ZZ) → CR for WZ and ZZ are implemented
- tt̄X and tX (mainly tt̄Z)
- Non-prompt lepton production (DY and tt̄)

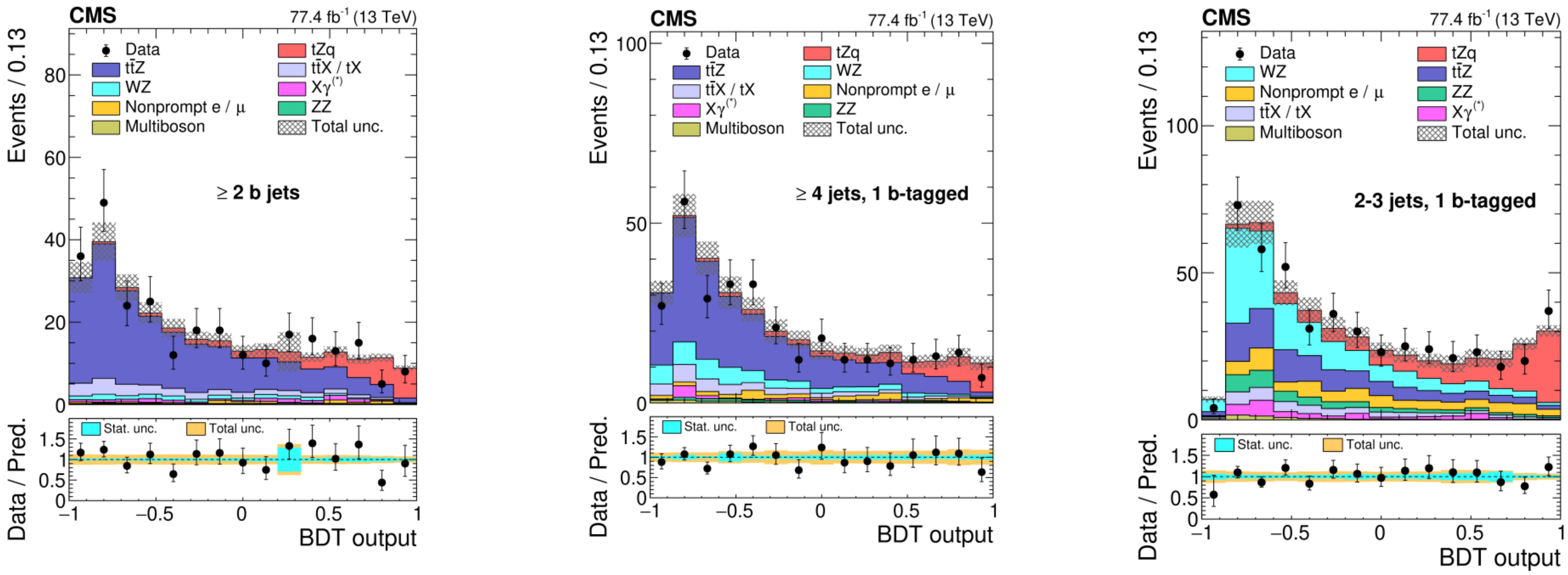
tZq - Observation

PRL 122 (2019) 132003

tZq is **observed** with a significance well **above 5 σ**, result in good agreement with SM prediction

$$\sigma(pp \to tZq \to t\ell^+\ell^-q) = 111\ ^{+13}_{-13}\ \text{(stat)}\ ^{+11}_{-9}\ \text{(syst) fb} \qquad m(\ell^+\ell^-) > 30\ \text{GeV}/c^2$$

$$\sigma(\text{NLO}) = 94.2 \pm 3.1\ \text{fb}$$



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

$t\bar{t}\gamma$

2012 data @ 8TeV

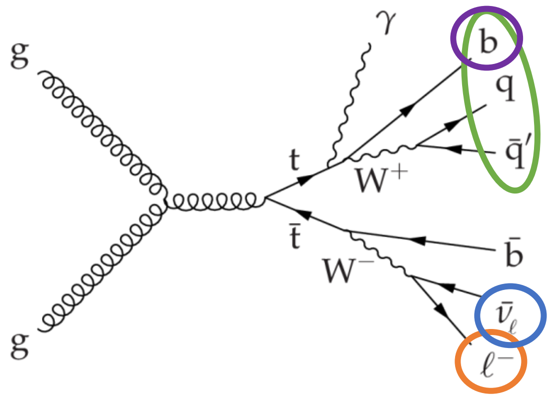
JHEP 10 (2017) 006

Top selection:

- 1 lepton ($e, \mu, \tau \rightarrow e, \mu$)
- $N_{Jet} \geq 3$
- $N_{B\text{-}tag} \geq 1$
- $p_T^{miss} > 20$ GeV

Photon selection:

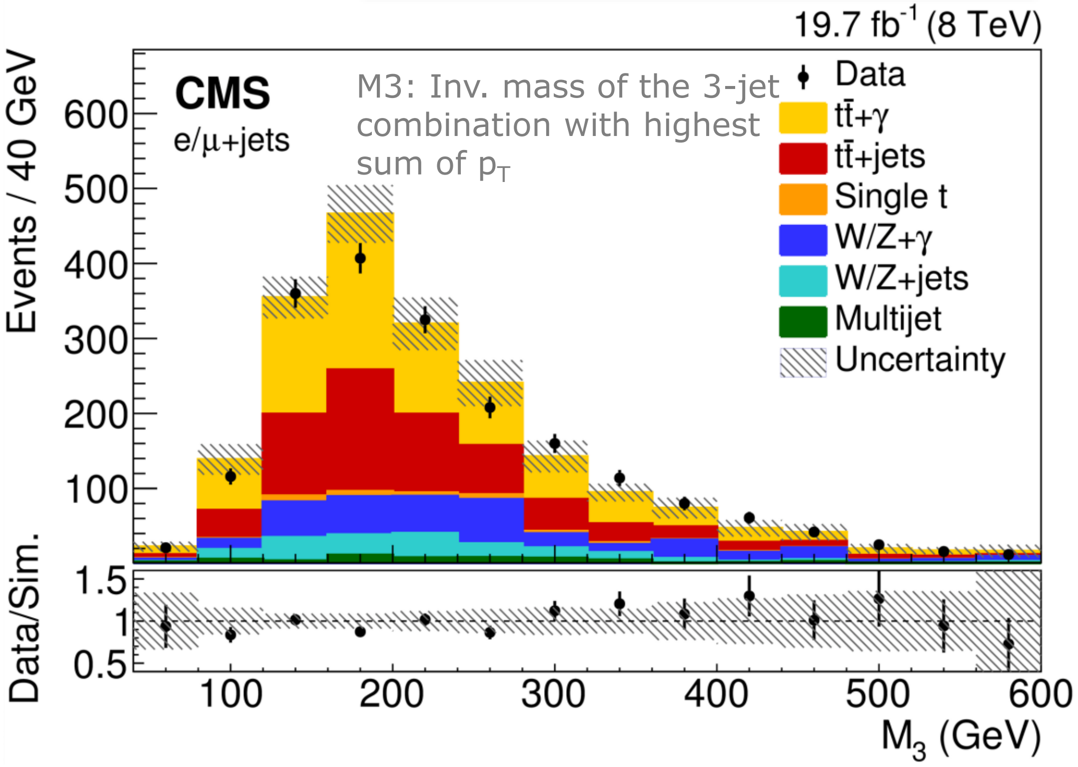
- ≥ 1 isolated prompt photon



Main backgrounds:

1) $t\bar{t}$ + fake γ → Evaluate photon purity using MC truth information

2) V+γ (V= Z/W) → Top reconstruction using M_3 →



Main Systematics:
fit stats., JES, modeling…

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

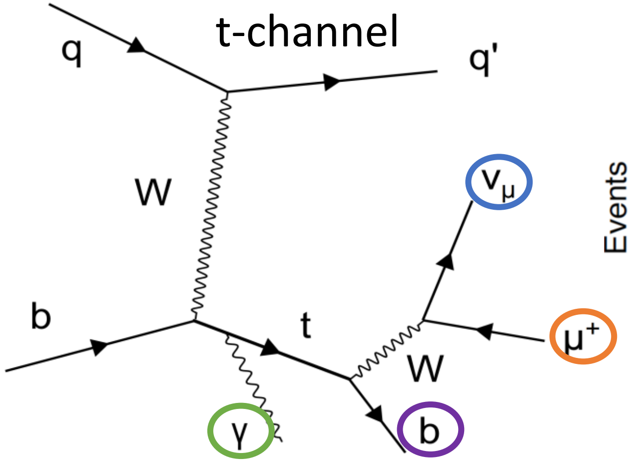
Category	R	$\sigma^{\text{fid}}_{t\bar{t}+\gamma}$ (fb)	$\sigma_{t\bar{t}+\gamma}\mathcal{B}$ (fb)
e+jets	$(5.7 \pm 1.8) \times 10^{-4}$	138 ± 45	582 ± 187
μ+jets	$(4.7 \pm 1.3) \times 10^{-4}$	115 ± 32	453 ± 124
Combination	$(5.2 \pm 1.1) \times 10^{-4}$	127 ± 27	515 ± 108
Theory	—	—	592 ± 71 (scales)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

tγq

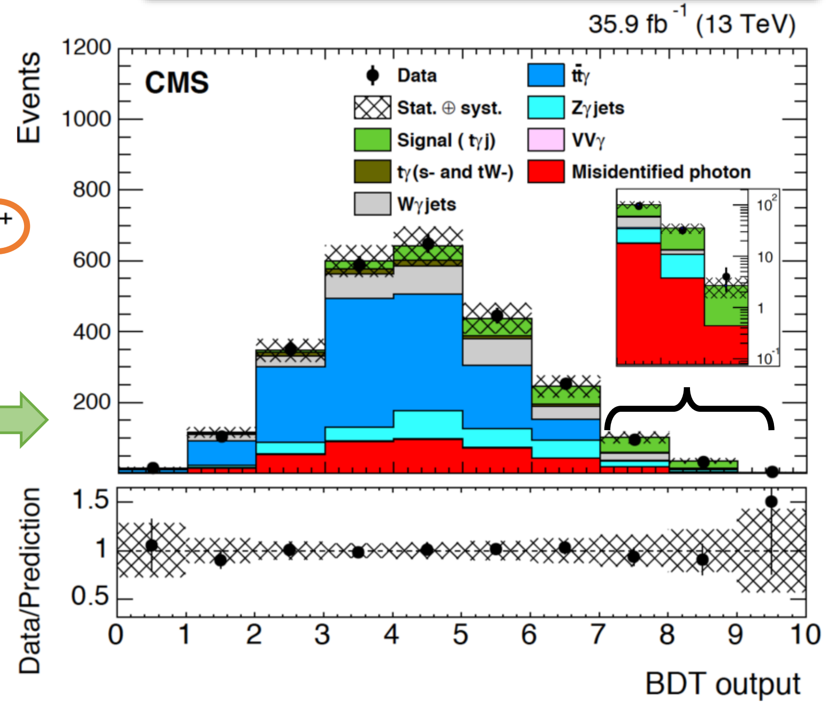
2016 data

Selection:

- 1 muon & 1 isolated photon
- $N_{Jet} \geq 2$
- 1 $N_{B\text{-tag}}$
- $p_T^{miss} > 30$ GeV



PRL 121 (2018) 221802



Strategy:

BDT constructed based on topological and kinematic properties

Main backgrounds:

1) fake γ background: data-driven estimation using photon isolation and shower shape
2) tt̄γ: CR defined with 2 b-tagged jets.

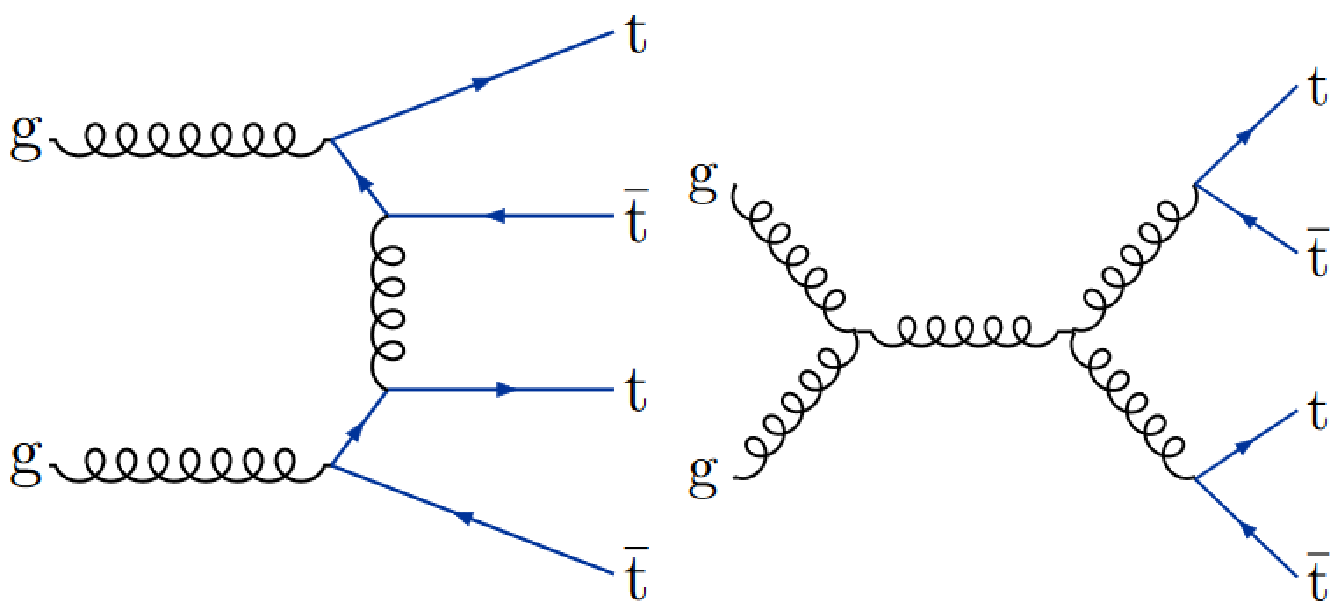
$$\sigma(pp \rightarrow t\gamma q)\, BR(t \rightarrow \mu\nu b) = 115 \pm 17\,(\text{stat.}) \pm 30\,(\text{syst.})\ \text{fb}$$

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

$$\sigma^{SM}_{\text{fiducial}}(\text{scale} + \text{pdf}) = 81 \pm 4\ \text{fb}$$

Observed (expected) significance of **4.4** (3.0) **σ** ⇒ **First evidence of the process**

$t\bar{t}t\bar{t}$



- Very low cross section process $\sigma(\text{NLO}) = 12.0\ ^{+2.0}_{-2,5}\ \text{fb}$
- The cross section can be used to constrain the magnitude and CP properties of the **Yukawa coupling** of the **top to the Higgs**.
- Can be enhanced due to **BSM particles** such as a heavy pseudoscalar or scalar boson produced in association with $t\bar{t}$ pair in 2HDM

$t\bar{t}t\bar{t}$

2016+2017+2018 data

Baseline Selection:

2ℓSS and 3ℓ final states

Selection: H_T >300 GeV, $p_T^{miss} > 50$ GeV, $N_{Jet} \geq 2$, $N_{B\text{-}tag} \geq 2$

Two approaches: cut-based and BDT

variables: N_{jet}, $N_{B\text{-}tag}$, N_{lep}, H_T, p_T^{jet}...

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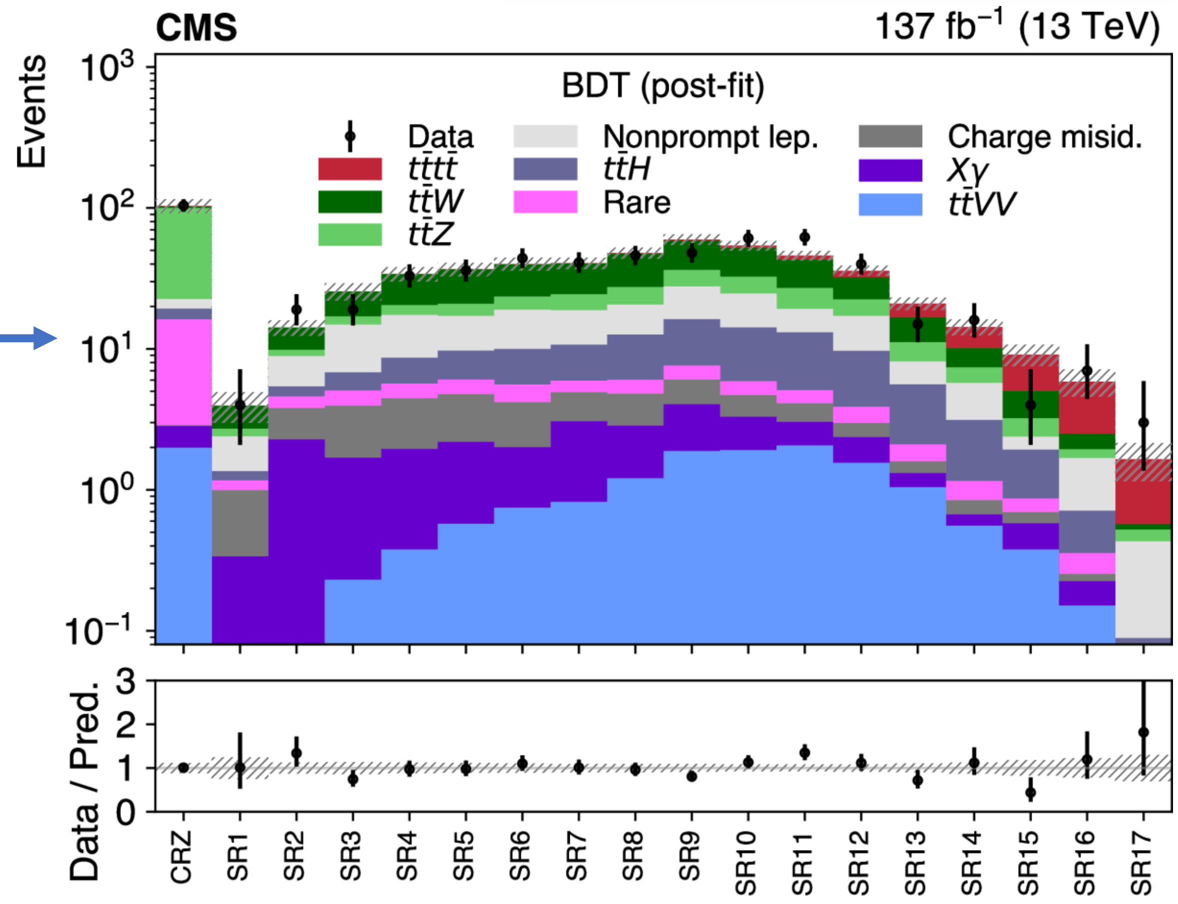

Main Backgrounds:

$t\bar{t}W$, $t\bar{t}Z$, $t\bar{t}H$, $t\bar{t}$ (with a misidentified charge of one of the leptons)

Main syst:

jet energy, b-tagging, $t\bar{t}H$ normalization

$$\sigma = 12.6^{+5.8}_{-5.2}\ \text{fb}$$

Observed (expected) significance = 2.6 (2.7) σ

$t\bar{t}t\bar{t}$ - interpretation

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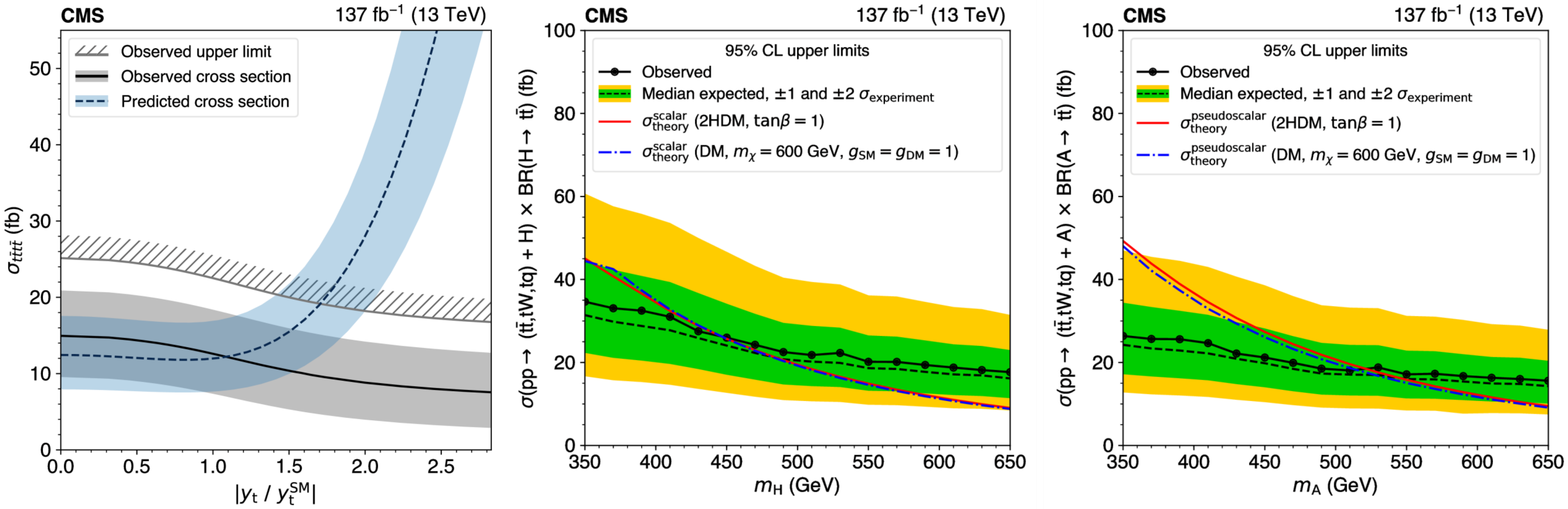


A constrain on the Yukawa coupling is imposed: $|y_t \,/ y_t^{SM}| < 1.7$ with a 95% confidence level

Limits also set on the production of heavy scalar and pseudoscalar boson in a type II 2HDM scenario.

Summary

- LHC is now capable of measuring **rare SM** processes **with top quarks.**
- These processes are **sensitive to beyond the SM** interactions.
- Most of the analyses are not using the full Run 2 data sample yet.
- Some of the processes are studied for the first time are the LHC.
- All presented results show good agreement with the SM.
- **Highlights:**
  - ➢ Differential $t\bar{t}Z$
  - ➢ First observation of tZq
  - ➢ First evidence of tγ
  - ➢ 4-top search increase in sensitivity
- **Stay tuned!**

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

Back up

-

$t\bar{t}W$

JHEP 08 (2018) 011

Summary of sources of systematic uncertainties

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

$t\bar{t}Z$ Inclusive

Summary of sources of systematic uncertainties

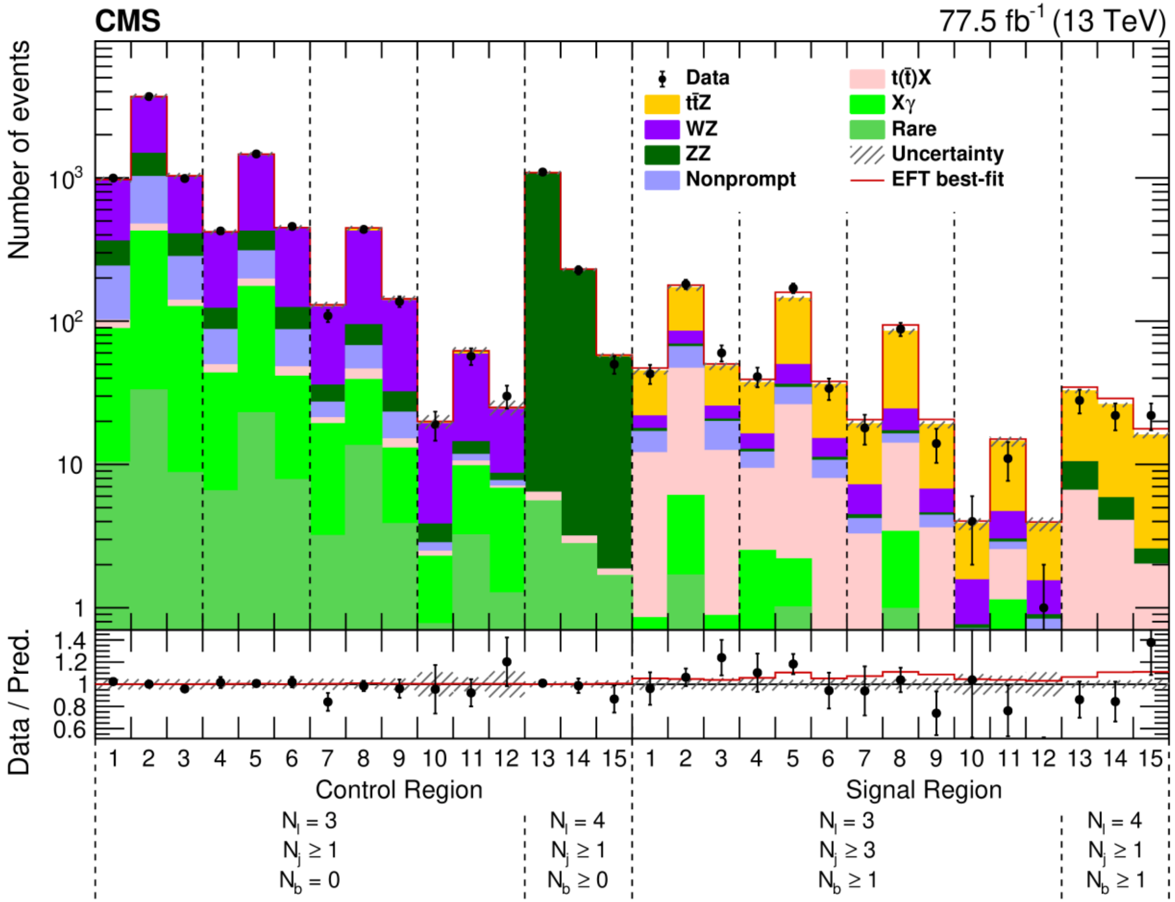
JHEP 03 (2020) 056

Source	Uncertainty range (%)	Correlated between 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	✓	3
WZ high jet multiplicity	20	✓	1
WZ + heavy flavor	8	✓	1
ZZ cross section	10	✓	1
$t(\bar{t})X$ background	10–15	✓	2
$X\gamma$ background	20	✓	1
Nonprompt background	30	✓	1
Rare SM background	50	✓	1
Stat. unc. in nonprompt bkg.	5–50	×	<1
Stat. unc. in rare SM bkg.	5–100	×	<1
Total systematic uncertainty			6
Statistical uncertainty			5
Total			8

$t\bar{t}Z$ - EFT Interpretation

JHEP 03 (2020) 056

- Regions defined using $p_T(Z)$ and $cos(\theta_Z^*)$

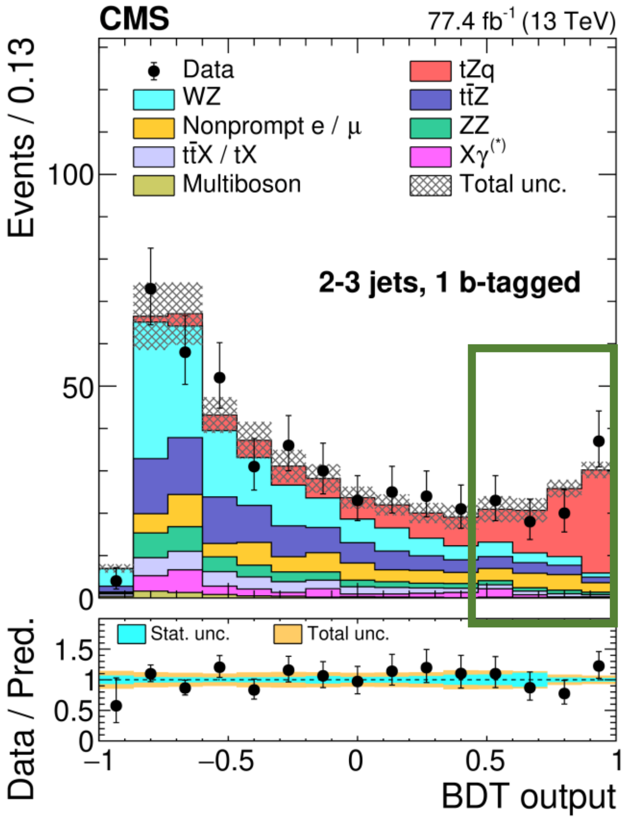


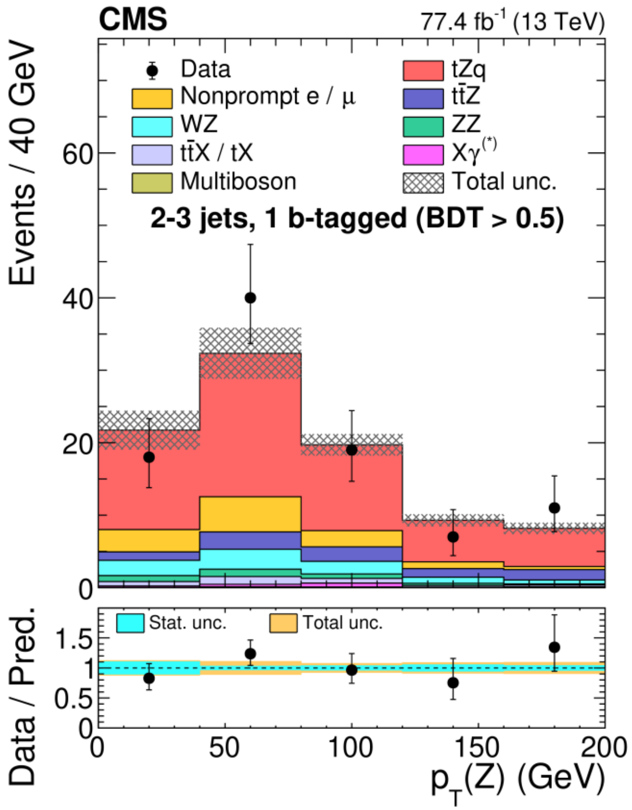
N_ℓ	N_b	N_j	N_Z	$p_T(Z)$ (GeV)	$-1 \leq \cos\theta_Z^* < -0.6$	$-0.6 \leq \cos\theta_Z^* < 0.6$	$0.6 \leq \cos\theta_Z^*$
3	≥1	≥3	1	0–100	SR1	SR2	SR3
				100–200	SR4	SR5	SR6
				200–400	SR7	SR8	SR9
				≥400	SR10	SR11	SR12
4	≥1	≥1	1	0–100		SR13	
				100–200		SR14	
				≥200		SR15	
3	0	≥1	1	0–100	CR1	CR2	CR3
				100–200	CR4	CR5	CR6
				200–400	CR7	CR8	CR9
				≥400	CR10	CR11	CR12
4	≥0	≥1	2	0–100		CR13	
				100–200		CR14	
				≥200		CR15	

tZq - Observation

Signal enriched region and
summary of most important sources of systematic uncertainties

PRL 122 (2019) 132003





Uncertainty	Impact (%)
Experimental	
lepton selection	3.2
trigger efficiency	1.4
jet energy scale	3.3
b-tagging efficiency	1.7
nonprompt normalization	4.1
tt̄Z normalization	1.0
luminosity	1.7
pileup	1.9
other	1.3
Theoretical	
final-state radiation	2.0
tZq QCD scale	2.0
tt̄Z QCD scale	1.4

$t\bar{t}\gamma$

JHEP 10 (2017) 006

Table 4: Uncertainties in the cross section ratio R for the combination of the e+jets and μ+jets final states.

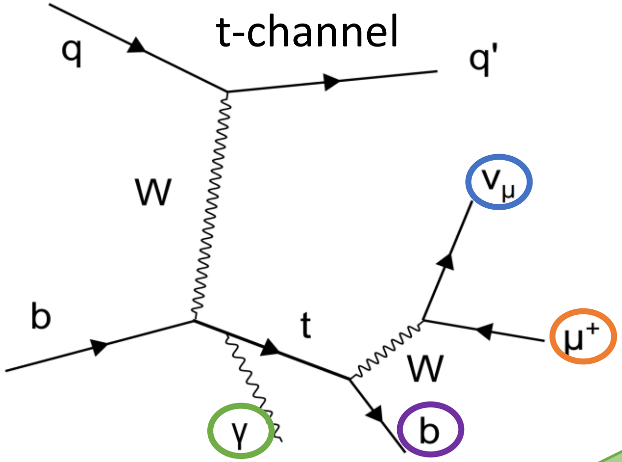
Source	Uncertainty (%)
Statistical likelihood fit	15.5
Top quark mass	7.9
JES	6.9
Fact. and renorm. scale	6.7
ME/PS matching threshold	3.9
Photon energy scale	2.4
JER	2.3
Multijet estimate	2.0
Electron misid. rate	1.3
Z+jets scale factor	0.8
Pileup	0.6
Background normalization	0.6
Top quark p_T reweighting	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

tγq

2016 data

Selection:

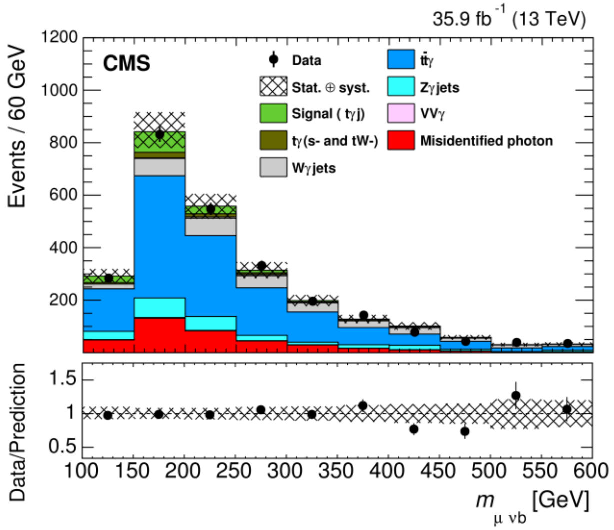
- 1 muon & 1 isolated photon
- $N_{Jet} \geq 2$
- 1 $N_{B\text{-tag}}$
- $p_T^{miss} > 30$ GeV

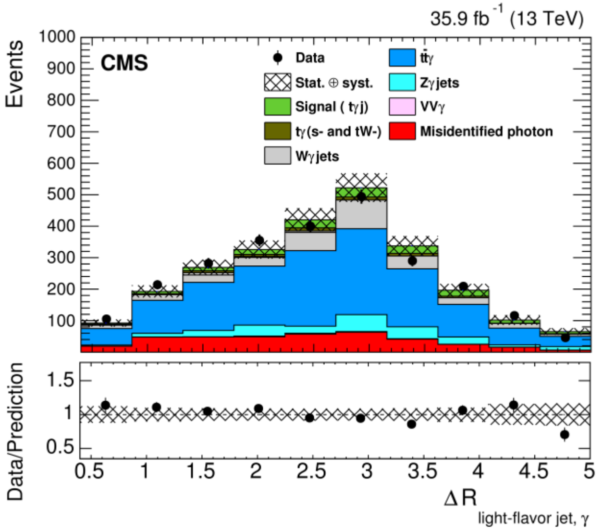


[PRL 121 (2018) 221802]

Strategy:
BDT constructed based on topological and kinematic properties

Two of the most discriminant input variables





Main backgrounds:

1) fake γ background: data-driven estimation using photon isolation and shower shape
2) tt̄γ: CR defined with 2 b-tagged jets.

Main Systematics:
JES (12%), signal modeling (9%), Z γ + jets normalization (8%) and b-tagging and mistagging rates (7%)

Summary of sources of systematic uncertainties

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Table 2: Summary of the sources of uncertainty, their values, and their impact, defined as the relative change of the measurement of $\sigma(t\bar{t}t\bar{t})$ induced by one-standard-deviation variations corresponding to each uncertainty source considered separately. The first group lists experimental and theoretical uncertainties in simulated signal and background processes. The second group lists normalization uncertainties in the estimated backgrounds. Uncertainties marked (not marked) with a † in the first column are treated as fully correlated (fully uncorrelated) across the three years of data taking.

Source	Uncertainty (%)	Impact on $\sigma(t\bar{t}t\bar{t})$ (%)
Integrated luminosity	2.3–2.5	2
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, $X\gamma$, $t\bar{t}VV$ (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
$N_{jets}^{ISR/FSR}$	1–30	2
$\sigma(t\bar{t}b\bar{b})/\sigma(t\bar{t}jj)$ †	35	11

$t\bar{t}t\bar{t}$

2016 data

Baseline Selection:

2ℓOS and single lepton final states

	ee	$\mu\mu$	$e\mu$	e	μ
$m_{\ell\ell}$	>20 GeV + Z veto		> 20 GeV	-	
N_{jet}	≥4			≥8	≥7
$N_{B\text{-}tag}$	≥2			≥ 2	

Strategy:

BDT used to identify hadronic top decays. A second **BDT** is used to discriminate $t\bar{t}t\bar{t}$ from $t\bar{t}$. This takes as input the first BDT, event topology, event activity, $N_{B\text{-}tag}$

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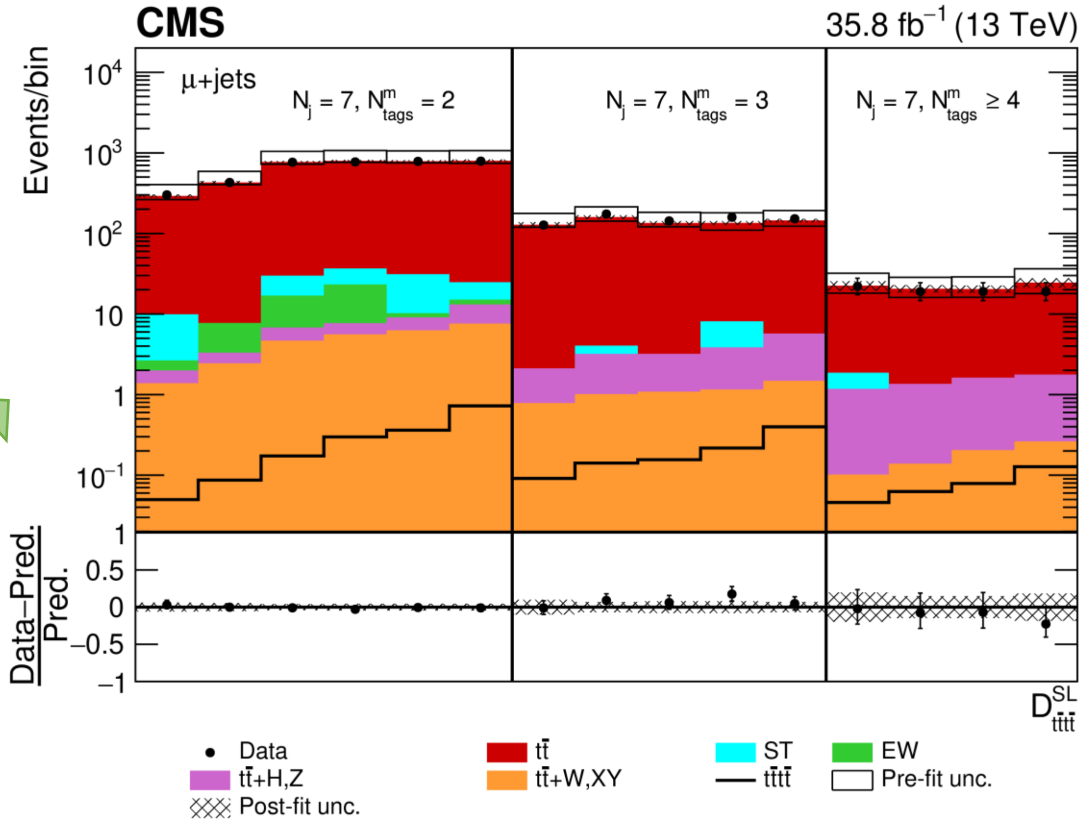

Combination with EPJC 78 (2018) 140 (2016 multilepton):

$$\sigma = 13^{+11}_{-9}\ \text{fb}$$

Observed (expected) significance = 1.4 (1.1)