Rare Single Top-Quark production at CMS

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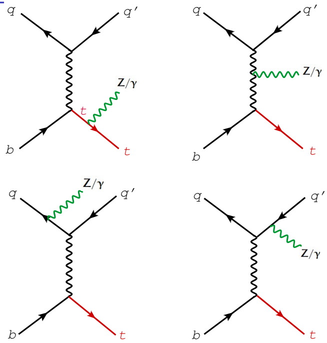
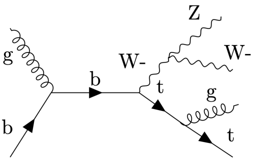
Rare single top production at LHC

- Single top quark production with $\gamma/Z/WZ$ are remarkably rare processes predicted by the SM.
- Measuring X-sections of these processes are crucial as:
  - Sesitive to top quark EW coupling
  - Sensitive to many BSM models and EFT operators.
- Production of $t\gamma/tZ$ at the LHC: t-channel, s-channel, and tW-channel (t-channel mode is the dominant one).





Results covered in this talk:

$t\gamma q$ first evidence: PRL 122(2019)132003

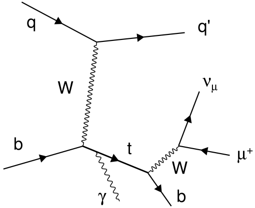
tZq Observation: JHEP 02 (2022)107

tWZ first evidence: CMS-PAS-TOP-22-008

CMS Result for tγq measurement

X-section measurement using 2016 Run II data

tqγ production at t-channel



- The X-section is sensitive to the top quark electric and magnetic dipole moments.
- μ channel, $35.9\,\mathrm{fb}^{-1}$

Object selections:

- Well isolated photon with $E_T > 25$ GeV in barrel region
- Single isolated muon with $p_T > 26$ GeV and $|\eta| < 2.4$ veto extra loose muon or electron.
- AK4PF Jet with $p_T > 40$GeV and $|\eta| < 4.7$
- One b-tagged jet with WP medium
- MET> 30GeV

Object reconstruction:

- W boson is reconstructed with μ+MET.
- Analytic neutrino solution(s).
- Top mass is reconstructed with W boson and a b-jet candidate.

Additional requirements:

- $\Delta R(\gamma, X) > 0.5$ with X=jets,b-jet,μ
- $\Delta R(\mu, X) > 0.5$ with X=jets,b-jet

Background estimation strategy

- Backgrounds with prompt photon:
  - Dominant BGs: $t\bar{t}\gamma$, Wγ+jets,Zγ+jets.
  - Estimated with both MC and data-driven method.
- Backgrounds with fake photon
  - Jets can be misreconstructed as photon.
  - $t\bar{t}$,W+jets, DY+jets.
  - Data driven method is applied to estimate fake photon.

Fake photon estimation

- Shape and normalization of events with fake photon is estimated by using data.
- $t\bar{t}$, W+jets,DY+jets, Single top, diboson have contribution.
- $j \rightarrow \gamma$**:**
  - **First**: fake photon fraction in the SR is estimated by using the ABCD method.
  - **Second**: A control region dominated by misidentified photon, known as Photon Like Jet (PLJ) is defined.
  - Correction factor depends on the p_T of photon.
  - Obtain normalization and shape of fake events in SR by weighting each event in PLJ sample with correction factor.

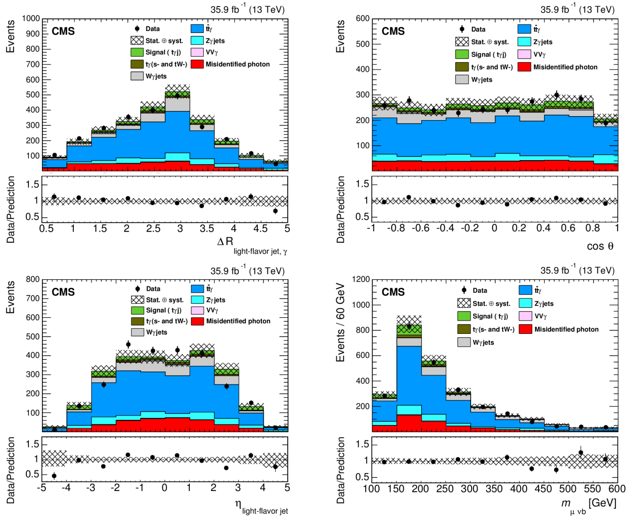
$t\bar{t}\gamma$ Control Region

- Main BG is $t\bar{t}\gamma$.
- Its shape is obtained from MC and normalization is estimated by using data with **relevant control region:**
  - Exactly 2 b-tagged jet is required.
  - Other selection criteria are the same as signal region.
- Normalization of $t\bar{t}\gamma$ is left floating in both SR & CR.
- Simultaneous fit into SR and CR is applied to extract the $t\bar{t}\gamma$ normalization in SR.

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

Analysis strategy

To enhance the signal and background separation, signal against the main background ($t\bar{t}\gamma$) is trained.

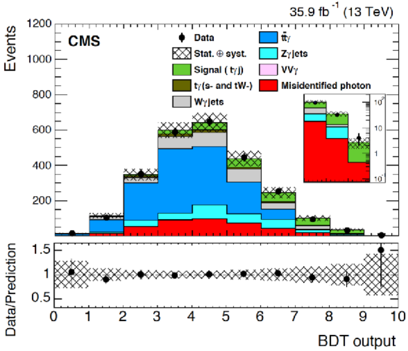


The most discriminant variables used as BDT input:

- η of the light-flavor jet
- Cosine of the angle between muon & light-flavor jet in top quark rest frame
- η of the muon
- ΔR(light-flavor jet, γ)
- Reconstructed top quark mass
- Jet multiplicity
- Transverse mass of the reconstructed W boson
- Muon charge

Signal extraction

- Binned likelihood fit on BDT output of 1-btagged and 2b-tagged regions.
- Normalization of $t\bar{t}\gamma$ determined from specific control region with 2 b-tagged jet.
- Main source of uncertainties:
  JEC (12%), signal modeling(9%) and b-tagging and mis-tagging rates (7%).



The fiducial X-section:

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

Observed (expected) significance: 4.4 (3.0) σ

Expected SM prediction: $\sigma^{\text{SM}}(t\gamma q)B(t \to \mu\nu b) = 81 \pm 4\text{fb}$

Recent CMS Result for tZq measurement

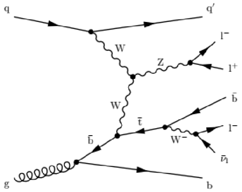
Inclusive and differential X-section measurements using full Run II data

tZq signal selection

- 3 leptons (e/μ) with $p_T > 25/15/10$ GeV.
  -Loose selection is used to estimate non-prompt background.
  -Tight selection (based on new lepton MVA) is used for prompt leptons.
- 2 leptons consistent with Z-boson mass within 15 GeV.
- at least 2 jets ($p_T > 25\text{GeV} \,\&|\eta| < 5$)
- at least one tagged as b-jet (differential measurement: 4 central jets)

Categorized based on number of jets and b-jets(inclusive):

- 2-3 jets with one b-tagged
- $\geq$ 4 jets with one b-tagged
- $\geq$ 2 b-tagged jets

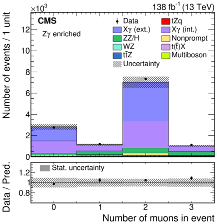


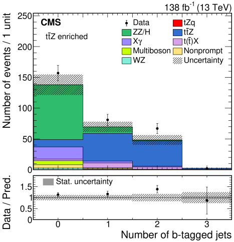
Inclusive vs. differential measurement:
Mostly similar strategy with some small differences:

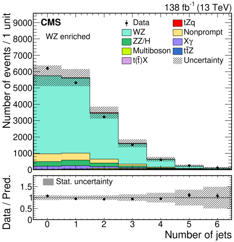
- Inclusive:
  - 3 signal categories based on number of jets and bjets.
  - Binary one vs. all classification with BDT.
- Differential:
  - Signal region inclusive in jets and b-jets.
  - Multiclass NN to regain discrimination between different BGs.

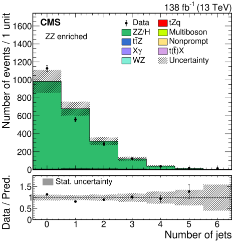
Prompt background estimation

- Most important BGs: WZ and $t\bar{t}Z$.
- Control region enriched with main backgrounds: WZ, ZZ, $t\bar{t}Z(4\ell)$, and $Z\gamma$.
- The agreement between the data and predictions is checked.
- The control regions are included in the final fit.









$Z\gamma$ CR

- 3 leptons
- no lepton pair within the Z mass window
- 3 leptons invariant mass within the Z mass window

$t\bar{t}$Z CR

- 4 leptons
- $\geq$ 2 jet
- only one lepton pair within the Z mass window

WZ CR

- 3 leptons
- At least one bjet veto
- Z boson candidate

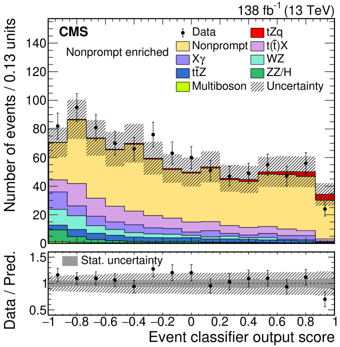
ZZ CR

- 4 leptons
- 2 lepton pairs within the Z mass window

Nonprompt background estimation

Jets can be misidentified as leptons.

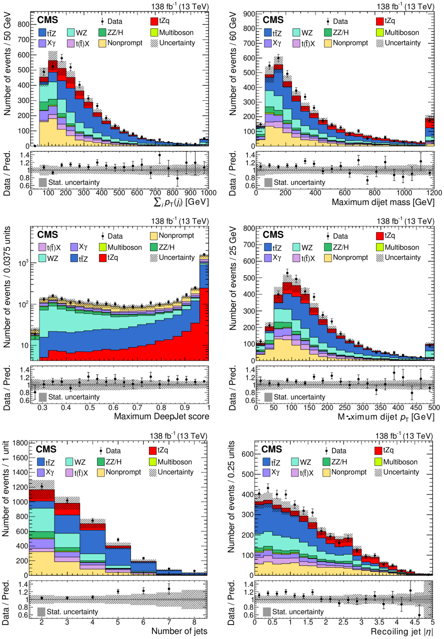
- Mainly DY+jet and $t\bar{t}$.
- BG with ≥ 1 nonprompt lepton(s).
- Strongly suppressed by lepton MVA, but still considerable.
- Estimated using data-driven technique naming fake rate method.



Fake rate:

- A CR in data enriched with multi-jet events is defined:
  - Only one loose lepton
  - At least one jet($p_T > 30$GeV and $|\eta| < 2.4$)
  - $\Delta R(\text{jet},\ell) > 0.7$
  - $p_T^{\text{miss}} < 20$ GeV
- Fake rate: probability that a nonprompt loose lepton also passes the tight identification in defined CR.
- The fake rate is measured as a function of the p_T and η of the nonprompt lepton.
- Apply in signal region side-bands:
  - with 3 looser leptons instead of 3 tight
  - 3 tight leptons are vetoed.

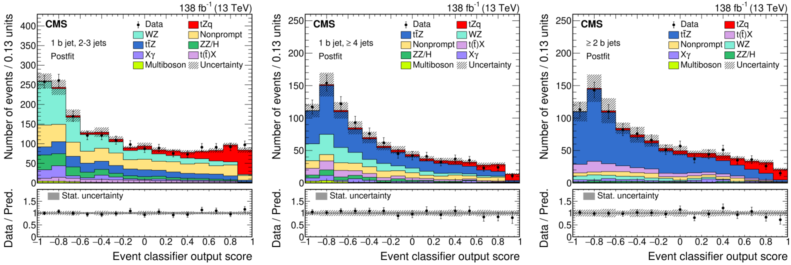
MVA input variables



BDT is trained to separate signal from background.
Some of the most discriminating features included in BDT training:

- $|\eta|$ of most forward jet
- Maximum deepFlavour b-tagging score
- Scalar sum of transverse momenta of all leptons + missing transverse momentum
- Maximum di-jet transverse momentum among all di-jet combinations
- Maximum deepFlavour b-tagging score among all jets
- Multiplicity of jets and bjets

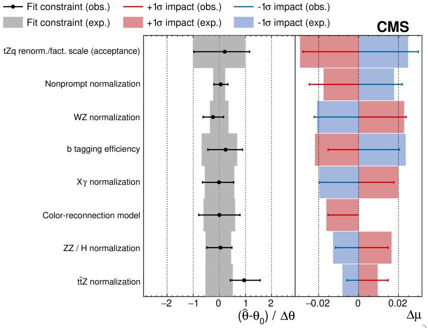
Results: inclusive measurement



Signal extraction:
Maximum-likelihood fit in the all SRs and CRs is performed on output distribution of BDT.

$$\sigma_{\text{tZq}}^{\text{Obs.}} = 87.9^{+7.5}_{-7.3}(\text{stat.})^{+7.3}_{-6.0}(\text{syst.})\text{fb}$$

for $m_{\ell\ell}$ >30 GeV.**Total uncertainty is** 11%. 3 – 4% lower uncertainty comparing to previous CMS and ATLAS results.



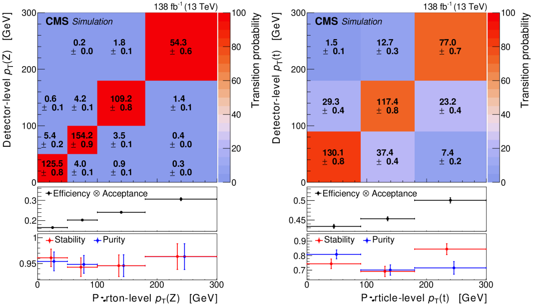
The SM predictions for $m_{\ell\ell}$ >30 GeV at NLO:

$$\sigma_{\text{tZq}}^{\text{SM}} = 94.2^{+1.9}_{-1.8}(\text{scale.}) \pm 2.5(\text{PDF})\text{fb}$$

Differential measurement

- Differential tZq cross section measurements as functions of several observables at the parton and particle levels are performed.
- A likelihood-based **unfolding procedure** is performed to measure the X-section in each kinematic region defined by each generator-level (parton or particle) bin.

- **Parton level**
  - Generator level objects after ISR/FSR, before hadronization.
  - Whole phase space
  - Strong dependency to used generator.
- **Particle level**
  - Stable particles after parton showering.
  - Collected into jets, MET and leptons.
  - Less dependency on used generator.
  - Object cannot be directly mapped to matrix element objects.
  - Unfolding in fiducial phase space.



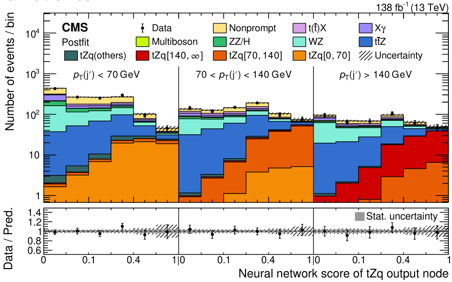
Results: differential measurement

Multi-class NN with several input variables and five separate class (tZq,ttZ, WZ,$t(\bar{t})X$ and other BGs) is performed to classify the signal events.

Signal extraction:

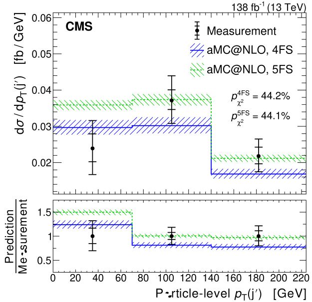
- σ^k_{tqz}: X-section at generator level with generator level bin k as a function of physical quantities(x):

$$\sigma^k_{tqz} = \int_{x_k^{low}}^{x_k^{high}} \frac{d\sigma_{tqz}}{dx} dx$$

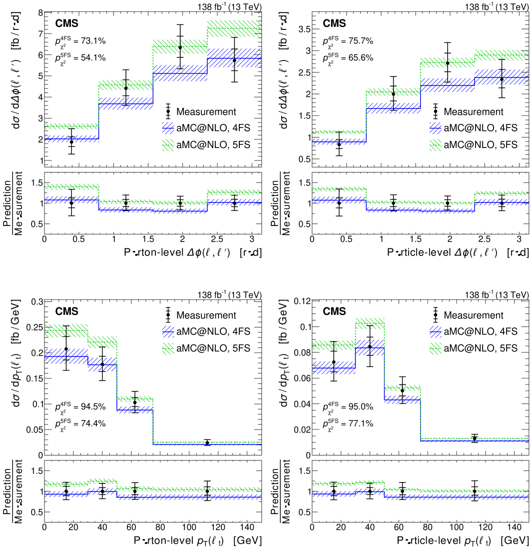


Signal region: $N_{\text{jets}} < 4 \rightarrow$ to get rid of the contribution of $t\bar{t}Z$ backgrounds.

- Maximum likelihood based unfolding:
  - SR is break into subregions based on the observable at detector level.
  - each subregion dominated by signals from its generator bin.
  - each subregion fit to classifier output to separate signal from BGs.
  - all CRs are into the fit.
  - all systematic are considered as nuisance parameter.



Results: absolute differential X-sections



- Good agreement between prediction and measurement.
- 4FS and 5FS predictions compared.
- Down to 25% uncertainties in including jets observables.
- Down to 15% uncertainties in purely leptonic observables.
- **Dominant uncertainties:** Statistical, b-tag identification, BG modeling.

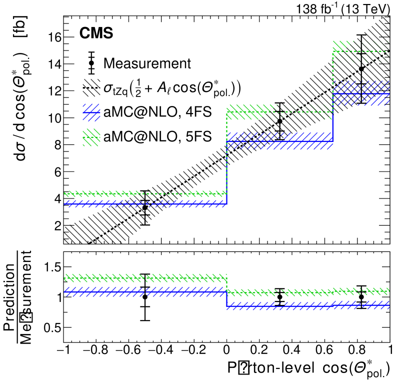
Results: spin asymmetry

- In tZq production, due to **V-A electroweak coupling**, generated top quark is polarized.
- Deviations could potentially indicate **anomalous coupling** structure.
- At the parton level, spin asymmetry is connected to the differential cross-section as a function of the polarization angle:

$$\frac{d\sigma}{dcos(\theta^{\star}_{\text{pol}})} = \sigma_{tZq}.(\frac{1}{2} + A_{\ell}cos(\theta^{\star}_{\text{pol}}))$$

$$cos(\theta^{\star}_{\text{pol}}) = \frac{\overrightarrow{p}(q'^{\star}).\overrightarrow{p}(\ell^{\star}_{t})}{|\overrightarrow{p}(q'^{\star})||\overrightarrow{p}(\ell^{\star}_{t})|}$$

A_{ℓ} is directly extracted from a re-parameterized fit using the full likelihood and uncertainties. Dominant uncertainty is statistical Uncert.



Measurement result:

$$A_{\ell} = 0.54 \pm 0.16(\text{stat}) \pm 0.06(\text{syst})$$

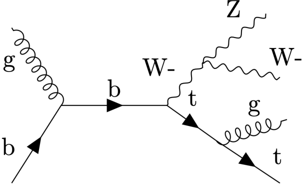
The SM prediction:

$$A_{\ell}^{4FS} = 0.44, A_{\ell}^{5FS} = 0.45$$

CMS Result for tWZ measurement

X-section measurement using full Run II data

tWZ production



Low energy region:

Search Semi-leptonic final states

- One OSSF lepton pair compatible with Z mass.
- **One of the W** decay **leptonically**.
- jets multiplicity ($p_T > 25$GeV,$|\eta| < 2.5$):
  - **SR1:** at least 3j & at least 1b-jet.
  - **SR2:** exactly 2j & at least one b-jets.

Search in fully leptonic final states

SR3:

- One OSSF lepton pair compatible with Z mass.
- **Both W bosons** decay **leptonically**.
- at least one jet & at least one b-jet.

Boosted (high energy) region:

Hadronic top (two jets from W decay are reconstructed as a fat jet)

- Hadronic top
  - SR1 selection
  - at least one fat jet ($p_T > 300$GeV & 105 GeV$< m_{SD} <$210 GeV)
  - ΔR(fat jet , b-jet)<0.8
- Leptonic top
  - SR1 selection
  - veto hadronic selection
  - $p_T^{\ell_3} > 30$GeV
  - at least one b-jet ($p_T > 200$GeV)
  - Δ R(b-jet , ℓ_3)<2

Background estimation

Main BG: ttZ

- Very similar kinematically to signal.
- ttZ differ via one b-jet in the final state with signal.
- ttZ BG is estimated from MC then constrained from DNN output score.

Multi-lepton Control Regions:

Are estimated from MC and normalizations are constrained in dedicated control regions.

ZZ CR

- 4 leptons
- 2 pairs OSSF compatible with Z mass
- no jet is required

WZ+jet CR

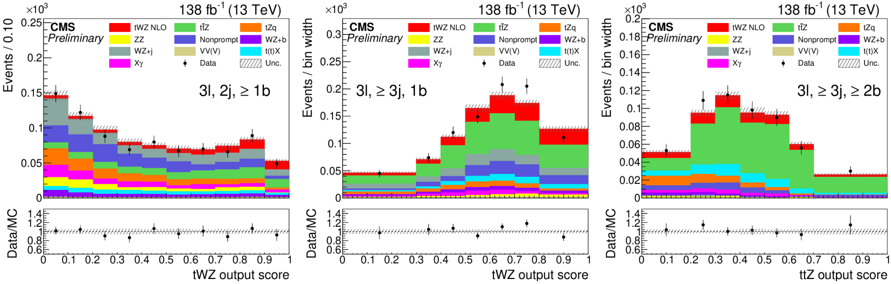
- Exactly 3 leptons
- one OSSF lepton pair from Z mass
- any b-jet veto
- MET >50 GeV

Non-prompt backgrounds: Fake rate method is used to estimate this BG.

- Estimated from data

Other BGs are estimated from MC

Signal extraction



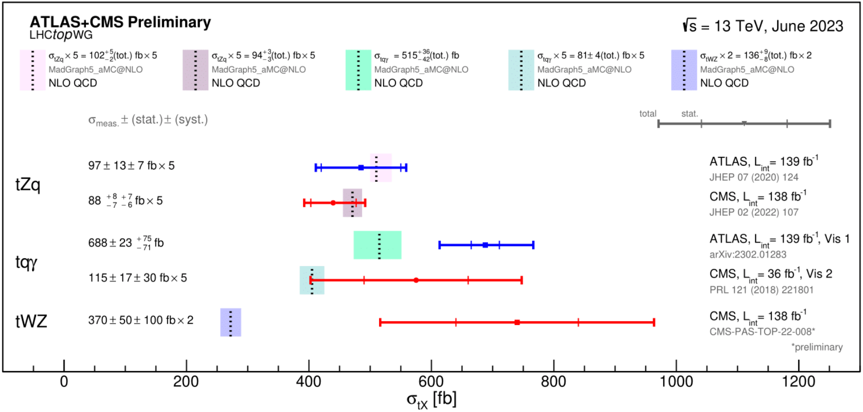
- MVA techniques employed to separate signal from ttZ and other backgrounds.
- Binned maximum likelihood fit is used to extract the tWZ signal significance and cross section.
- Evidence of tWZ with an **observed(expected) significance of 3.5 (1.4) standard deviations**.
- Cross section (2.1 standard deviations away from the SM prediction):

$$\sigma_{\mathrm{tWZ}} = 0.37 \pm 0.05(\mathrm{stat}) \pm 0.10(\mathrm{sys})\ \mathrm{pb}$$

  Expected SM prediction: $\sigma^{\mathrm{SM}} = 136$ fb
- **Most impactful source of uncertainties:** ttZ normalization, b-tagging efficiency corrections and estimation of nonprompt leptons.

Summary of tX measurements

- $t\gamma q$ analysis
  - First evidence by CMS (2016 data).
  - Observation by ATLAS(full Run II).
  - Upcoming: full Run II results for CMS.
- tZq analysis
  - Observed by CMS and ATLAS.
  - Good agreement with the SM.
- tWZ analysis
  - First evidence by CMS.
  - 2.1 standard deviation from the SM.



Summary

- First evidence of tWZ production with 3.5 standard deviation, performed in multilepton final states using the full Run II data at CMS experiment.

- Inclusive and differential measurements of tZq production have been done with full Run II data at CMS experiment.
- CMS collaborations has observed tZq production with significance greater than 5σ.
- The measured inclusive X-section is in agreement with the SM prediction.
- Compared to the SM differential cross section, all observables are in good agreement within the uncertainties with one exception.

- CMS has reported first evidence of $t\gamma$q process using $35.9\,\text{fb}^{-1}$ of data at 13 TeV with 4.4 observed significance.
- Measurement of $t\gamma$q X-section via full Run II data is in progress.

Backup

Previous tZq search by CMS

First evidence (2016 data):

$$\sigma(PP \to tZq \to t\ell^+\ell^- q) = 123^{+33}_{-31}(\text{stat.})^{+29}_{-23}(\text{syst.})\text{fb}$$

Significance =3.7(obs.)/3.1(exp.)

Phys.Lett. B 779 (2018)358

Observation at CMS (2016&2017) data

$$\sigma(PP \to tZq \to t\ell^+\ell^- q) = 111^{+13}_{-13}(\text{stat.})^{+11}_{-9}(\text{syst.})\text{fb}$$

Significance = 8.2(obs.)/7.7(exp.)

Phys. Rev. Lett. 122, 132003

Observation at ATLAS (full Run II):

$$\sigma(PP \to tZq \to t\ell^+\ell^- q) = 97 \pm 13(\text{stat.})7(\text{syst.})\text{fb}$$

Significance $\gg 5\sigma$ JHEP 07 (2020) 124