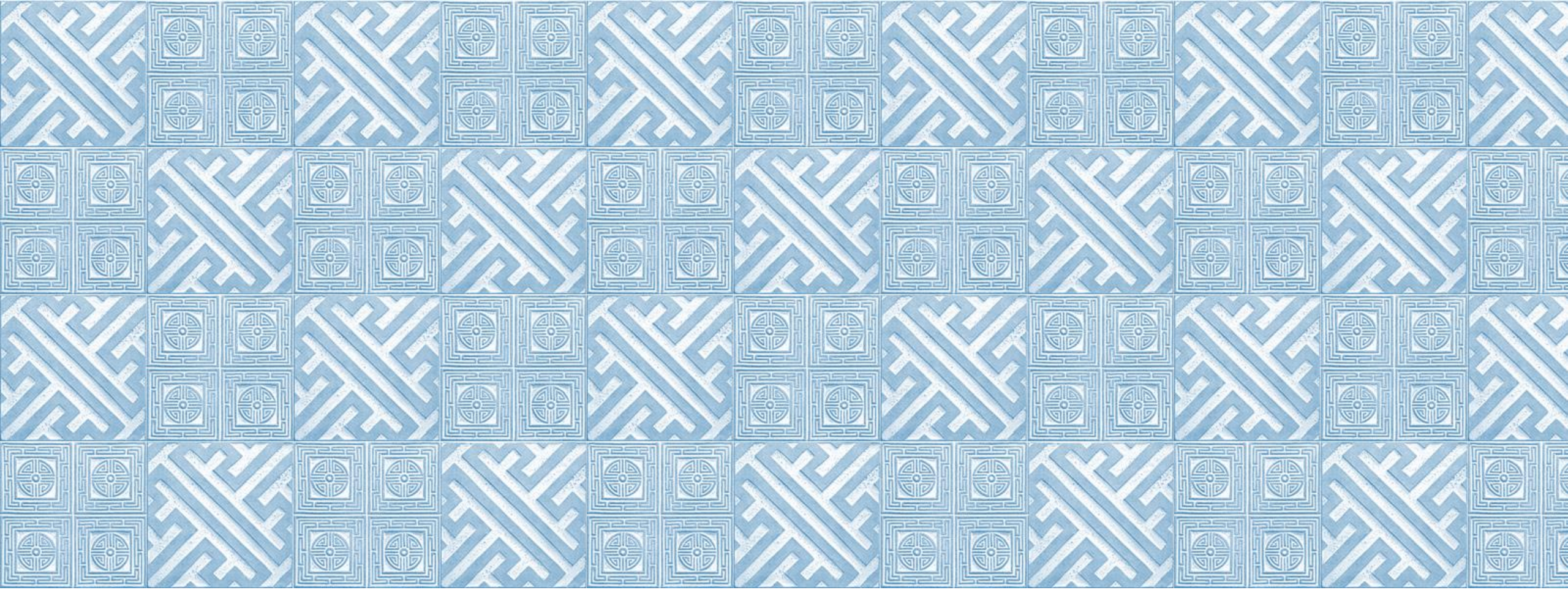


RARE TOP QUARK PROCESSES AT CMS: TOP QUARK PAIR OR SINGLE TOP QUARK WITH W/Z/γ FOUR TOP QUARK PRODUCTION

Suyong Choi
Korea University
for the CMS Collaboration

CONTENTS

INTRODUCTION

At the LHC, being a top quark factory, we can study the various production and decay processes involving top quarks

We will cover several measurements involving rare top quark processes at CMS

Top quark production in association with vector bosons ($t\bar{t} + W/Z/\gamma$ and tZq) allow us to probe the electroweak interactions of the top quark

Four top quark production has not been observed yet at the LHC. This channel is sensitive to some BSM that predict enhanced coupling to top quarks

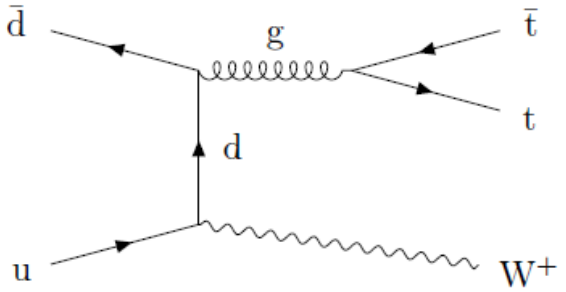
$t\bar{t}W$ AND $t\bar{t}Z$

INTRODUCTION

Probe of top quark and vector boson coupling

- Direct probe of top quark - Z coupling through $t\bar{t} + Z$

Backgrounds to many searches with leptons

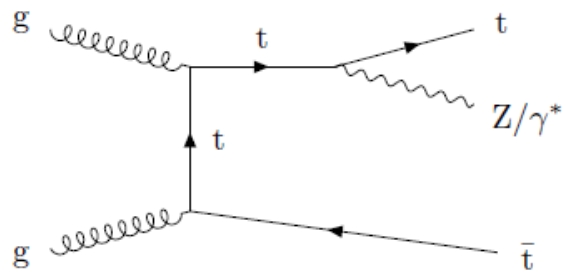


Data

- 35.9 fb^{-1} at $\sqrt{s} = 13\,TeV$
- Trigger: at least a single high p_T lepton (electron or muon)

Simulated samples

- Generators – Madgraph5, MG5_AMC@NLO, POWHEG v2
- Scaled to NLO or NNLO cross sections
- Fragmentation and hadronization – PYTHIA v8.2
- Detector simulation – GEANT4



EVENT SELECTION FOR $t\bar{t}W$

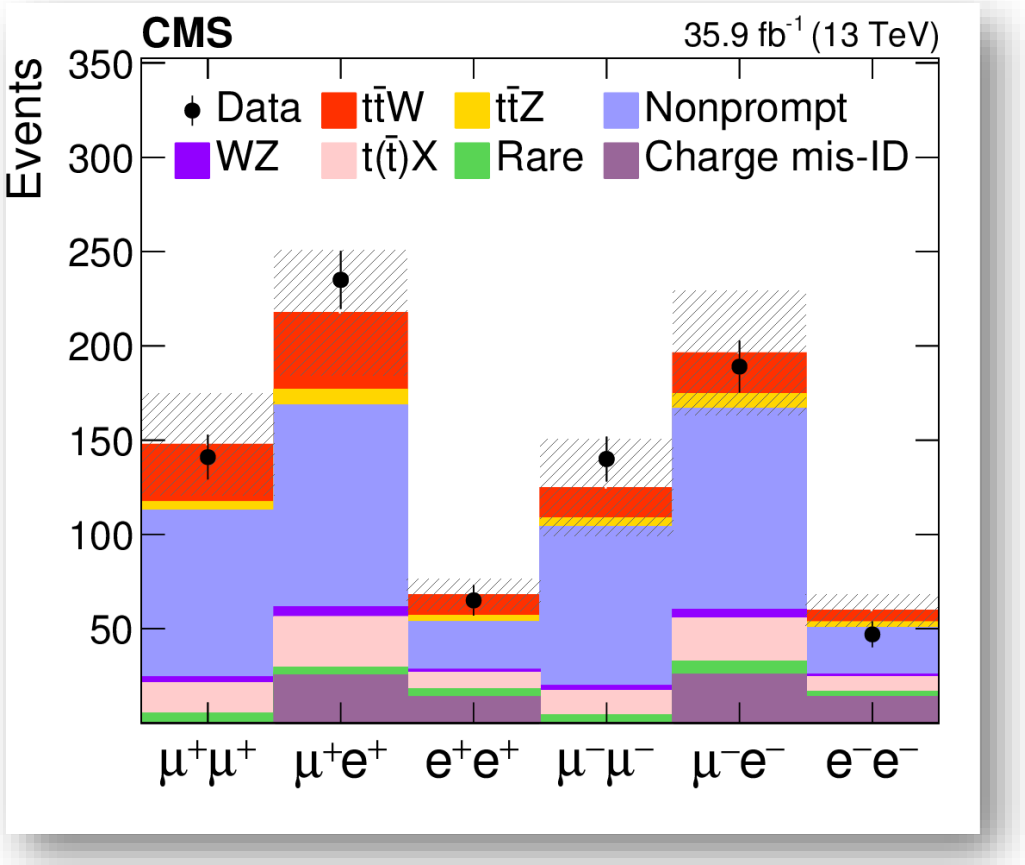
http://arxiv.org/abs/1711.02547

$t\bar{t}W$ in same-sign dileptons (SSDL)

- Same-sign isolated high p_T leptons
- Veto events with 3rd loose lepton
- Dilepton mass selection to remove Z
- $p_T^{miss} > 30\ GeV$
- Require $N_{jet} \geq 2$ and $N_{bjet} \geq 1$

Backgrounds

- Non-prompt and fake leptons
- WZ – normalized to data in control-region
- Rare $t\bar{t}$ processes and other rare SM processes – est. from MC
- Charge mis-id for electrons

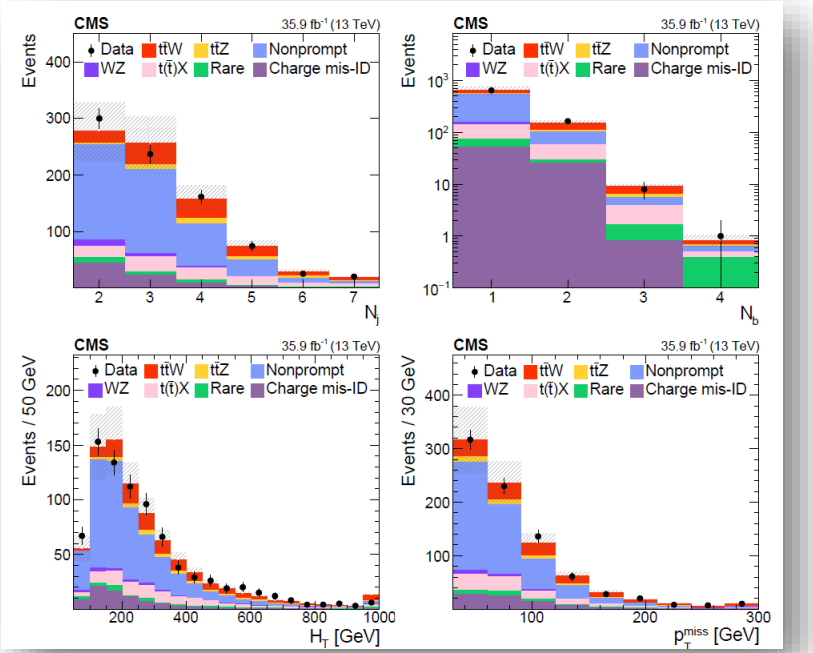


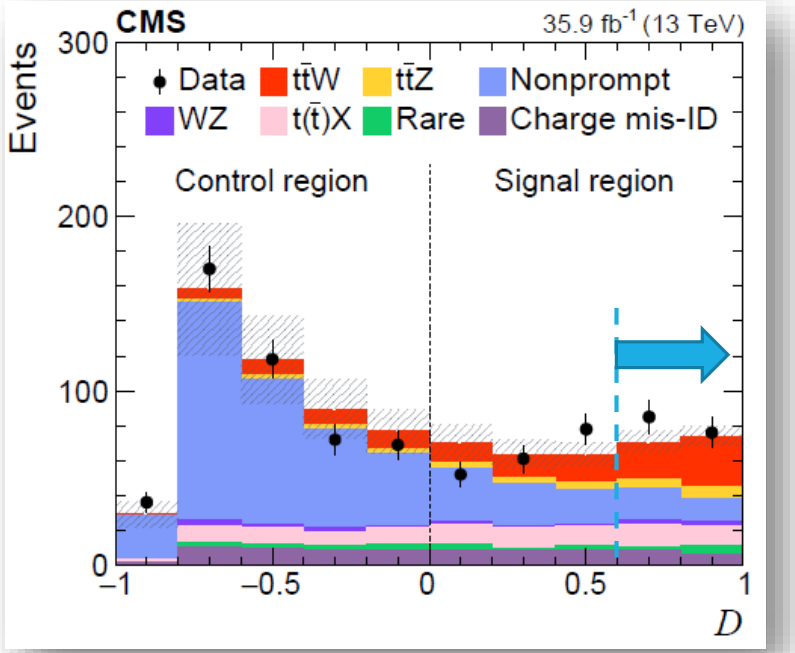
MULTI-VARIATE ANALYSIS FOR $t\bar{t}W$ SSDL

Multivariate analysis (MVA) using boosted-decision tree (BDT)

- Signal: $t\bar{t}W$, Background: events with ≥ 2 jets with ≥ 1 b-tagged jet
- Sample subdivided into different N_{jet} and N_{b-jet}, total lepton charge bins $(++, --)$

Some of the inputs to BDT





$D > 0.6$ for signal extraction

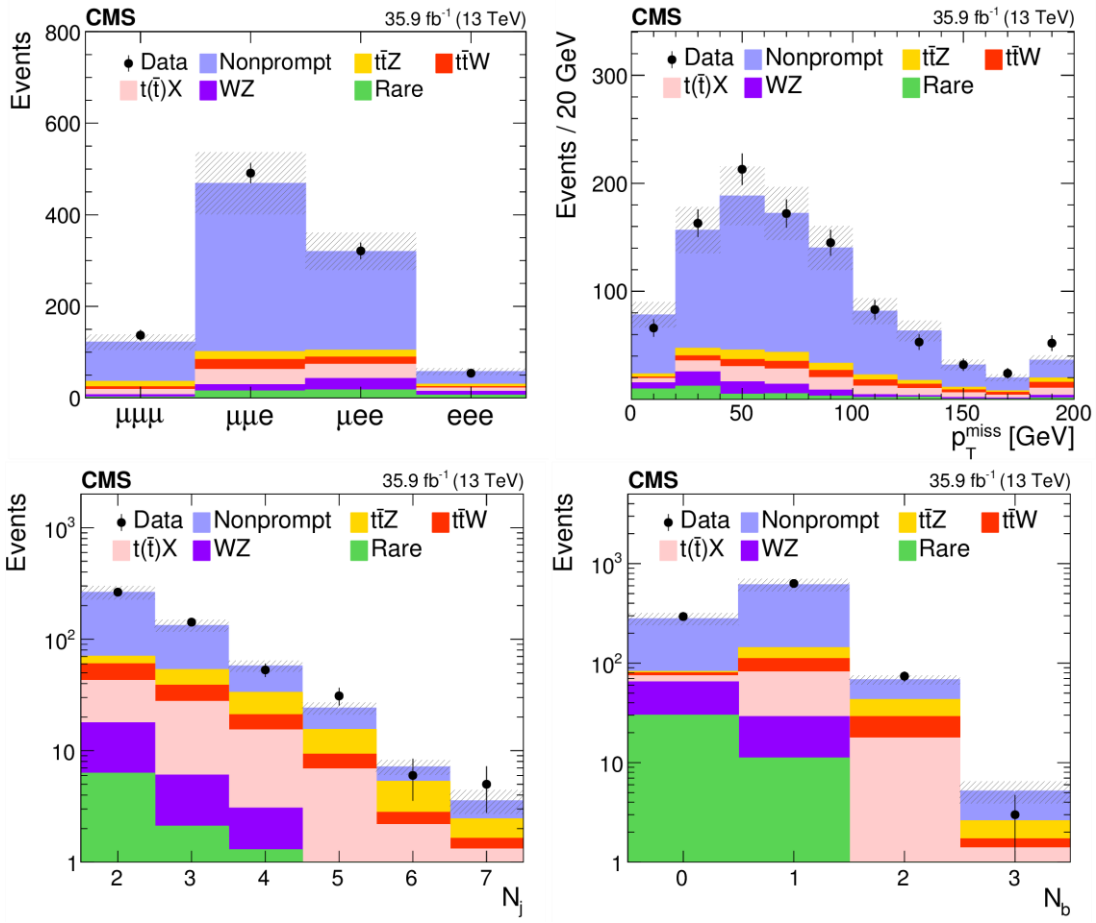
EVENT SELECTION FOR $t\bar{t}Z$

Trilepton channel

- Require exactly three isolated leptons
- $|m_{\ell\ell} - M_Z| < 10\ GeV$
- Require $N_{jet} \geq 2$ and $N_{bjet} \geq 0$

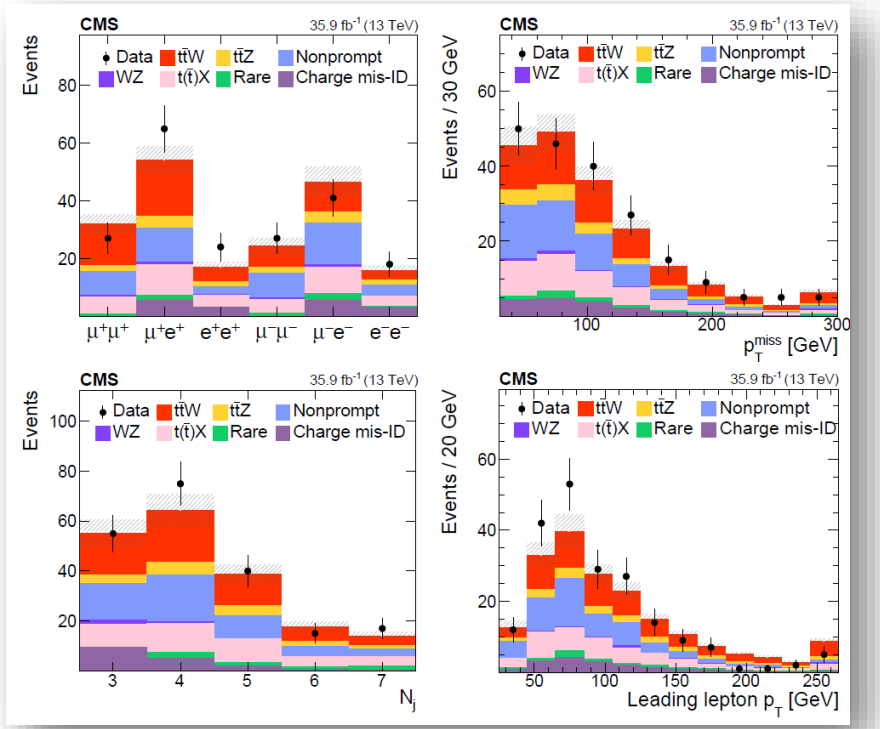
Four leptons channel

- Require four isolated leptons
- $|m_{\ell\ell} - M_Z| < 20\ GeV$
- For $(ee\mu\mu, eeee, \mu\mu\mu\mu)$ events, veto if the second OSSF pair satisfies $|m_{\ell\ell} - M_Z| < 20\ GeV$
- Require $N_{jet} = 2$, $N_{bjet} \geq 0$



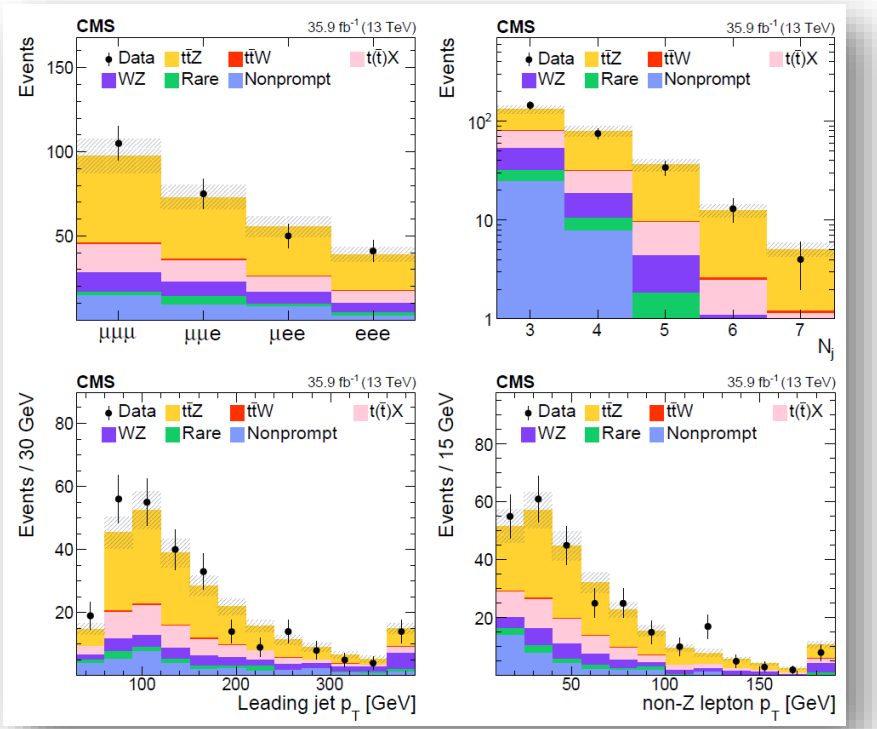
$t\bar{t} + W/Z$ IN HIGH S/B REGION

$t\bar{t}W$



SS dilepton in $N_{jet} \geq 3, N_{bjet} \geq 2$ category

$t\bar{t}Z$



Trilepton in $N_{jet} \geq 3, N_{bjet} \geq 1$ category

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

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

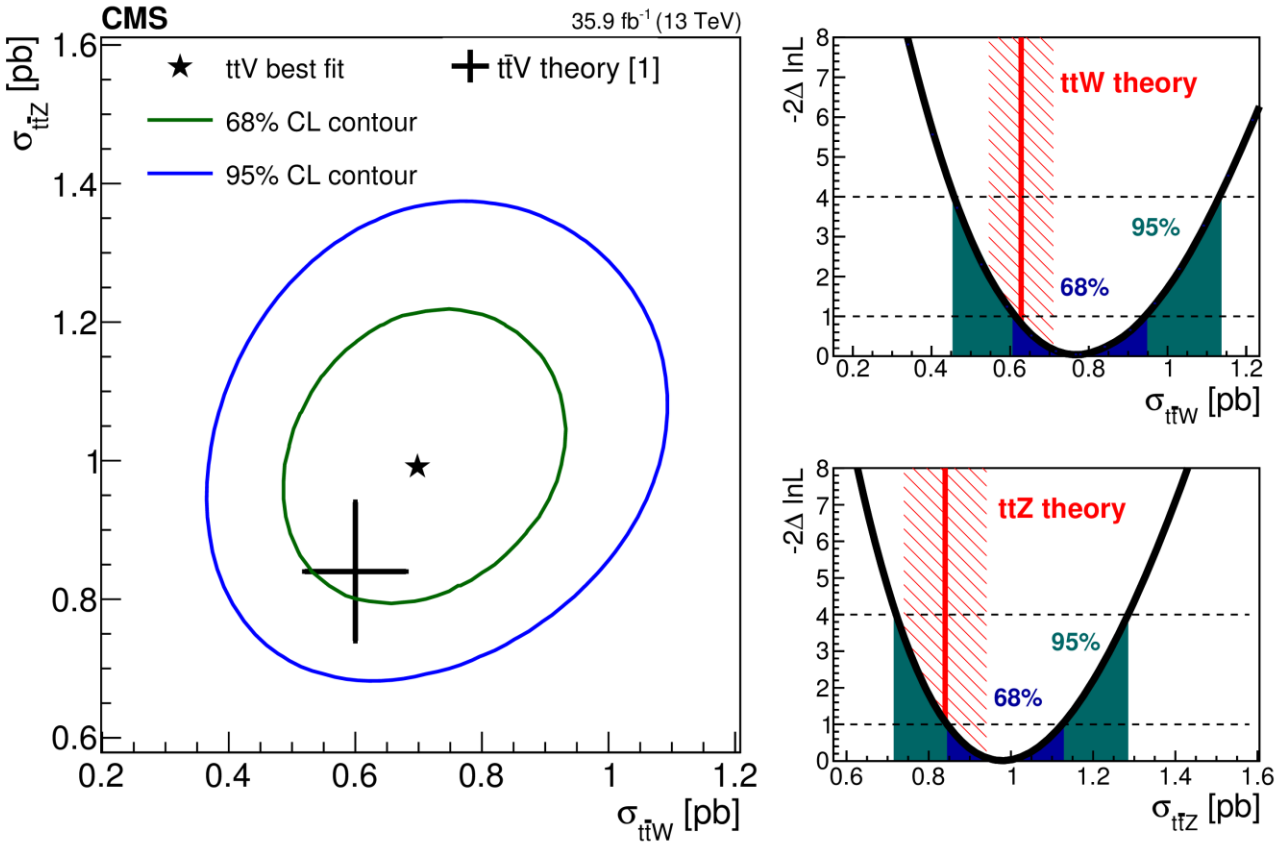
RESULTS

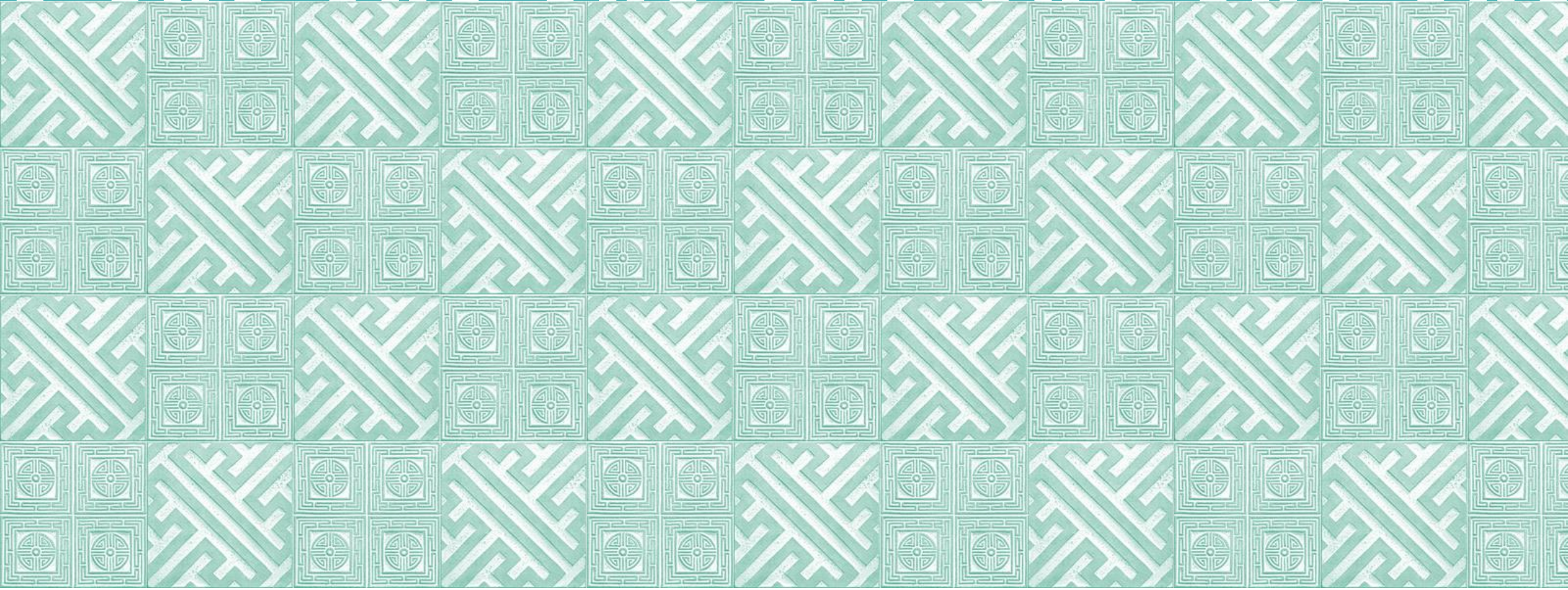
Significances >5 observed each for $t\bar{t} + W$ and $t\bar{t} + Z$

Measured Cross Sections through simultaneous fits

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

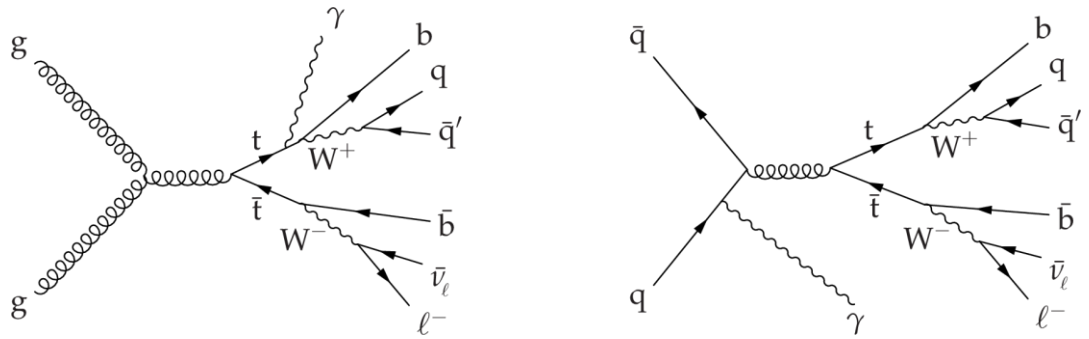
$$\sigma(\mathrm{pp} \to \mathrm{t\bar{t}Z}) = 0.99^{+0.09}_{-0.08}\,(\mathrm{stat})^{+0.12}_{-0.10}\,(\mathrm{syst})\,\mathrm{pb}.$$





$t\bar{t}\gamma$

INTRODUCTION



A probe of top-quark charge and could test some models of BSM

Data

- 19.7 fb^{-1} at $\sqrt{s} = 8\,TeV$
- Trigger: at least a single high p_T lepton (electron or muon)

EVENT SELECTION FOR $t\bar{t}\gamma$

J. High Energ. Phys. (2017) 2017: 6.

One high p_T isolated lepton (e or μ)

- No "loose" second lepton

$N_{jet} \geq 3$ and $N_{bjet} \geq 1$

$p_T^{miss} > 20\ GeV$

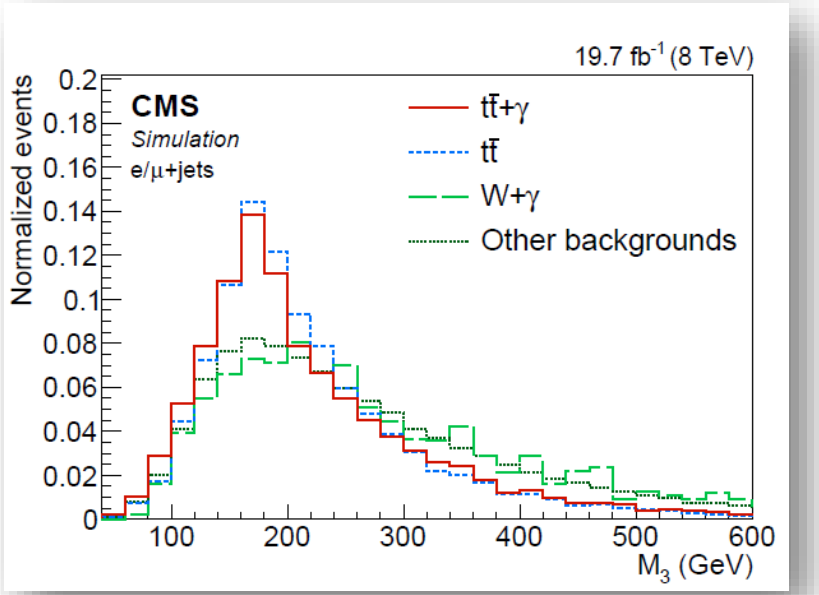
One photon $p_T > 25\ GeV$ in barrel

- Charged hadron isolation within $\Delta R < 0.3$
- Shower shape requirement

Backgrounds after selection

- $t\bar{t}$ + photon from jets
- $V + \gamma$
- $Z + jets$ and QCD

3-jet invariant mass (M_3) distribution



- Good discriminator against backgrounds

$t\bar{t}\gamma$ SIGNAL EXTRACTION

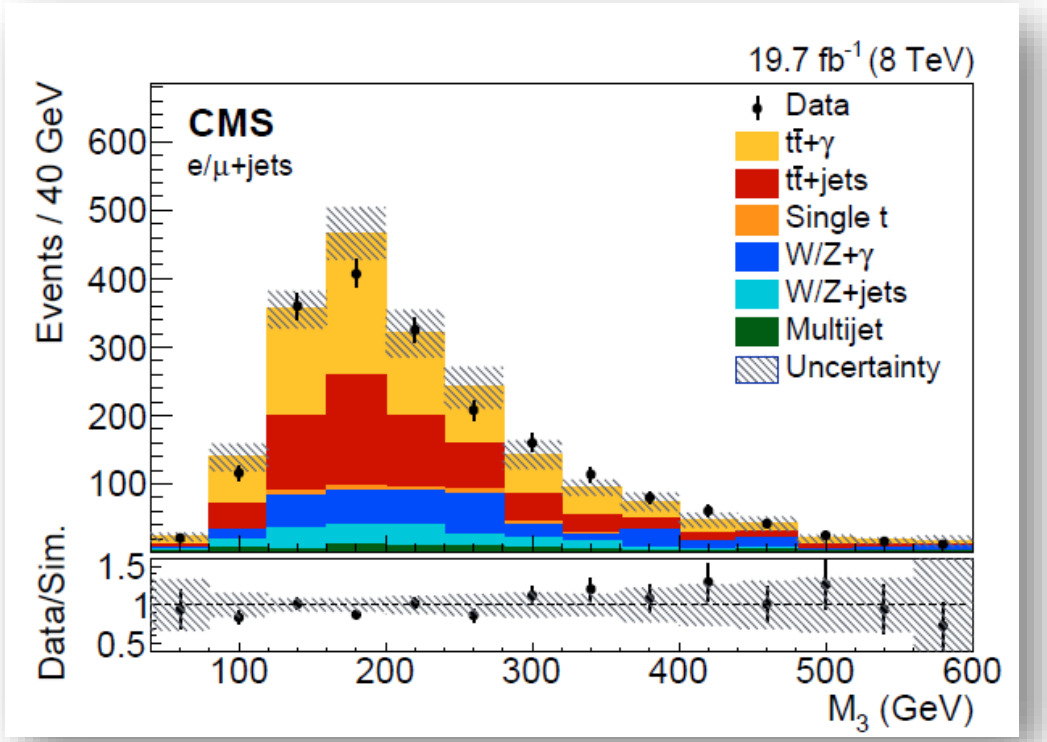
Binned maximum likelihood fits to M_3 distribution to estimate $t\bar{t}$ contribution after selection

Photon purity need to be estimated

- Prompt photons
- Photons from jets
- Electron with no matching track

Simultaneous fit of $t\bar{t} + \gamma, V + jets,$ $jet \rightarrow \gamma$ performed using the purity measurements

Post-fit M_3 distribution



$t\bar{t}\gamma$ RESULTS

Systematic uncertainties

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

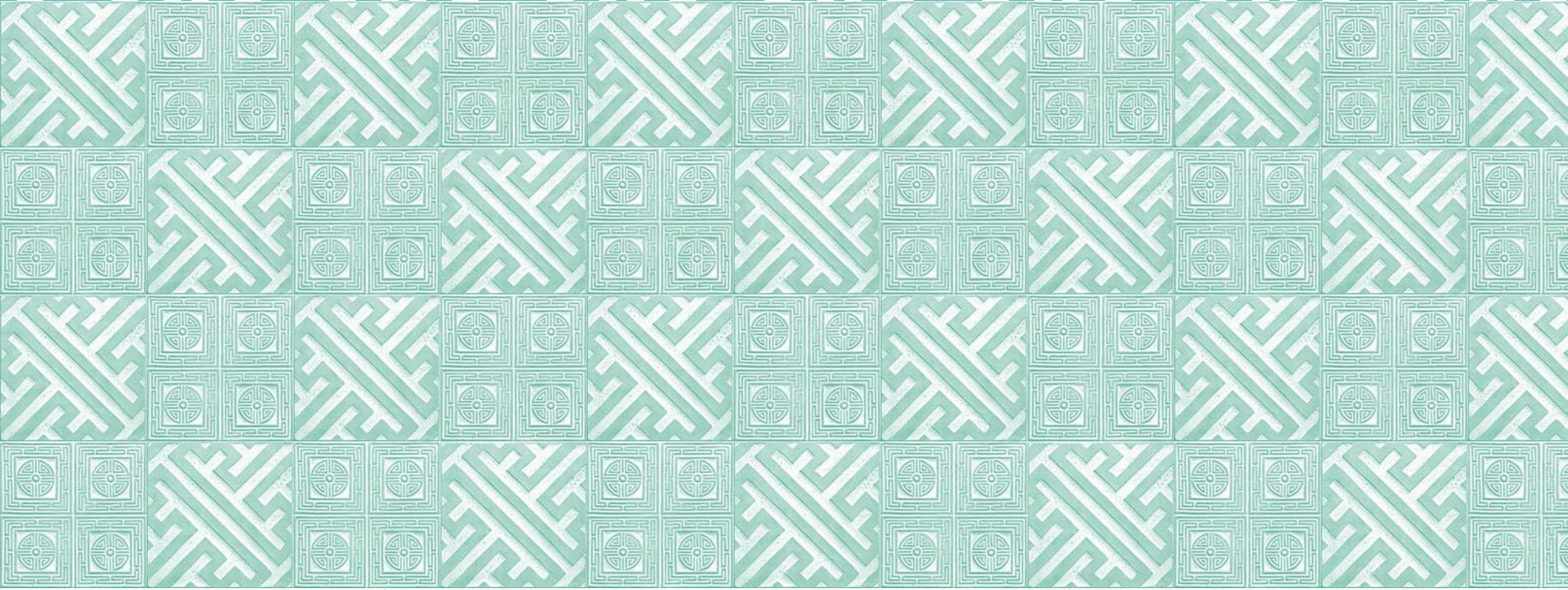
Primarily due to Purity Meas.

Cross section results

- Kinematic fiducial region: $p_T^\gamma > 13\ GeV$, $|\eta^\gamma| < 3.0$, separated from other objects by $\Delta R > 0.3$

Category	R	$\sigma^{\text{fid}}_{\text{t}\bar{\text{t}}+\gamma}$ (fb)	$\sigma_{\text{t}\bar{\text{t}}+\gamma}\,\mathcal{B}$ (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)

- In agreement with theory



SINGLE TOP +Z

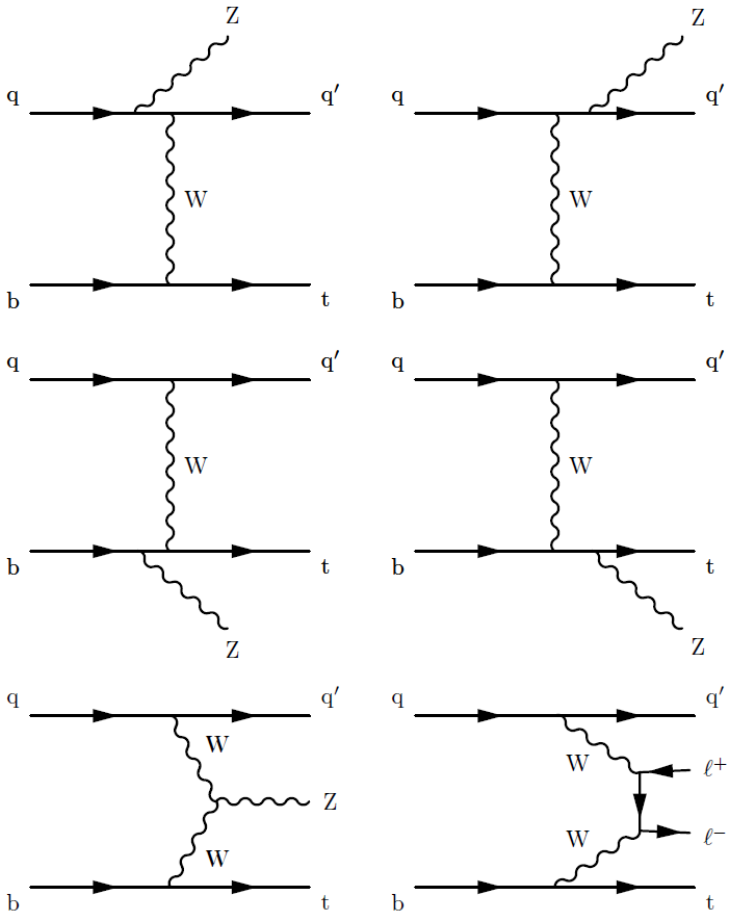
INTRODUCTION

Single top + Z as a probe of

- Top quark and Z coupling
- WWZ triboson coupling
- VBF contribution
- FCNC

Data

- 35.9 fb^{-1} at $\sqrt{s} = 13\,TeV$
- Trigger: 1 or 2 or 3 high p_T leptons (electron or muon)

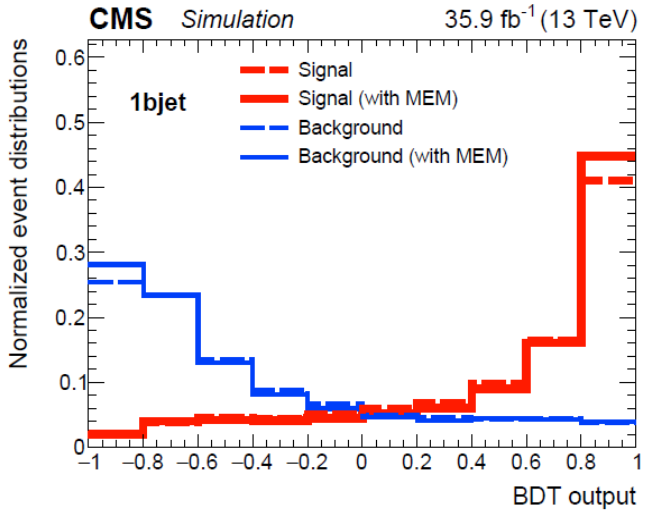


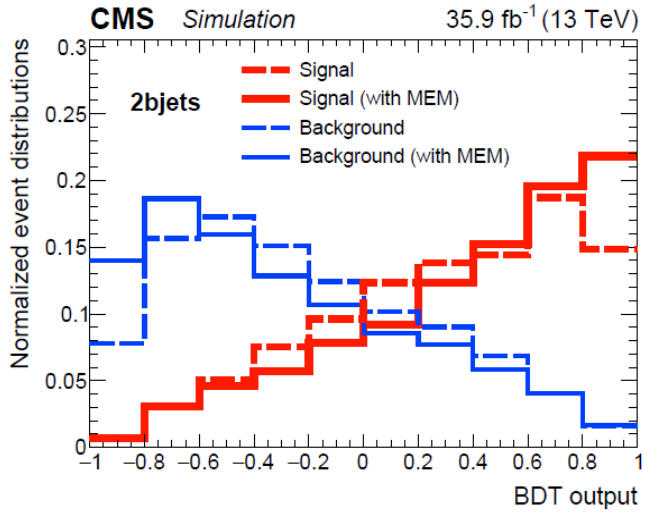
SINGLE TOP + Z EVENT SELECTION

Phys. Lett. B 779 (2018) 358

$tZq \rightarrow W(\rightarrow \ell'\nu)b\ell^+\ell^-q$

- Isolated trileptons
  - Events with loose 4th lepton vetoed
- Dilepton mass selection
- Hadronic jets $p_T > 30\ GeV$, $|\eta| < 4.5$





Backgrounds

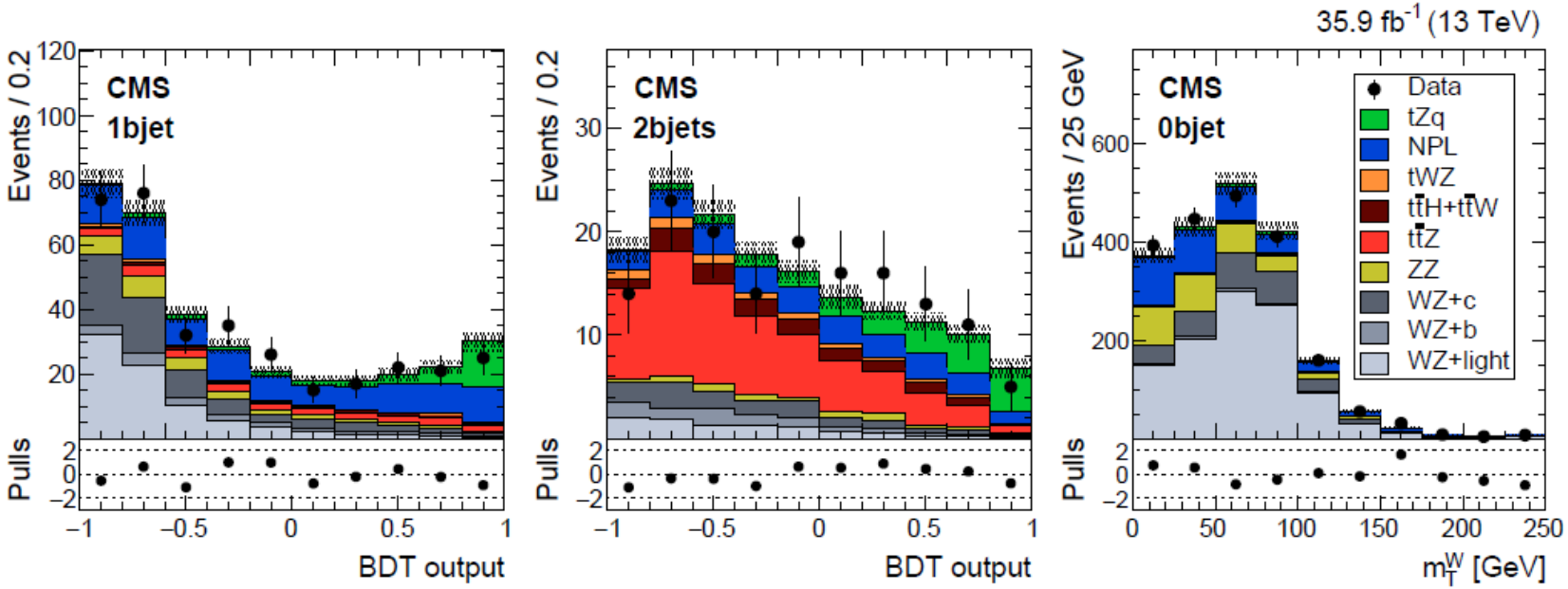
- $t\bar{t}Z$
- $WZ + jets$
- Non-prompt leptons (NPL)
- Bin samples : 0 bjet – WZ+jets, NPL enriched, 1 b-jet – signal, 2 b-jet - $t\bar{t} + Z$ enriched

Multivariate BDT analysis provides effective separation

- Kinematics of reconstructed Top, Z and decay products + Matrix-element method weights

SINGLE TOP + Z RESULT

Simultaneous fit to the data in 0,1,2 b-jet bins to BDT templates



SINGLE TOP + Z RESULTS

Signal strength: $\mu = 1.31^{+0.35}_{-0.33}\,(\text{stat})^{+0.31}_{-0.25}\,(\text{syst})$

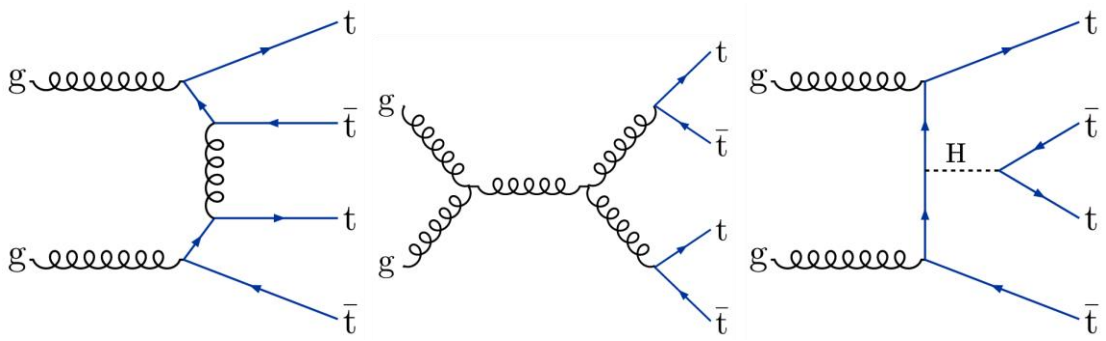
Cross section: $\sigma(\text{t}\ell^+\ell^-\text{q}) = 123^{+33}_{-31}\,(\text{stat})^{+29}_{-23}\,(\text{syst})\,\text{fb}$

- Agrees with theory calculation $94.2\ fb$ for $m_{\ell\ell} > 30\ GeV$ calculated at NLO using 5 FS

SEARCH FOR FOUR TOP QUARK PRODUCTION

FOUR TOP QUARK PRODUCTION

Eur. Phys. J. C (2018) 78: 140



Four top quark production

- $\sigma_{NLO}(pp \to t\bar{t}t\bar{t}) = 9.2^{+2.9}_{-2.4} fb$ at $\sqrt{s} = 13\ TeV$
- Direct top-Higgs coupling
- Many BSM predict enhancement

Data

- pp collision at $\sqrt{s} = 13\ TeV$ with $\int \mathcal{L}dt = 35.9\ fb^{-1}$
- Trigger: Require dilepton and $H_T > 300\ GeV$

Event selection

Variable	Requirement
H_T	$> 300\ GeV$
p_T^{miss}	$> 50\ GeV$
N_{jet}	≥ 2
N_{bjet}	≥ 2
Leading p_T^{ℓ}	$> 25\ GeV$
Same charge 2nd leading p_T^{ℓ}	$> 20\ GeV$

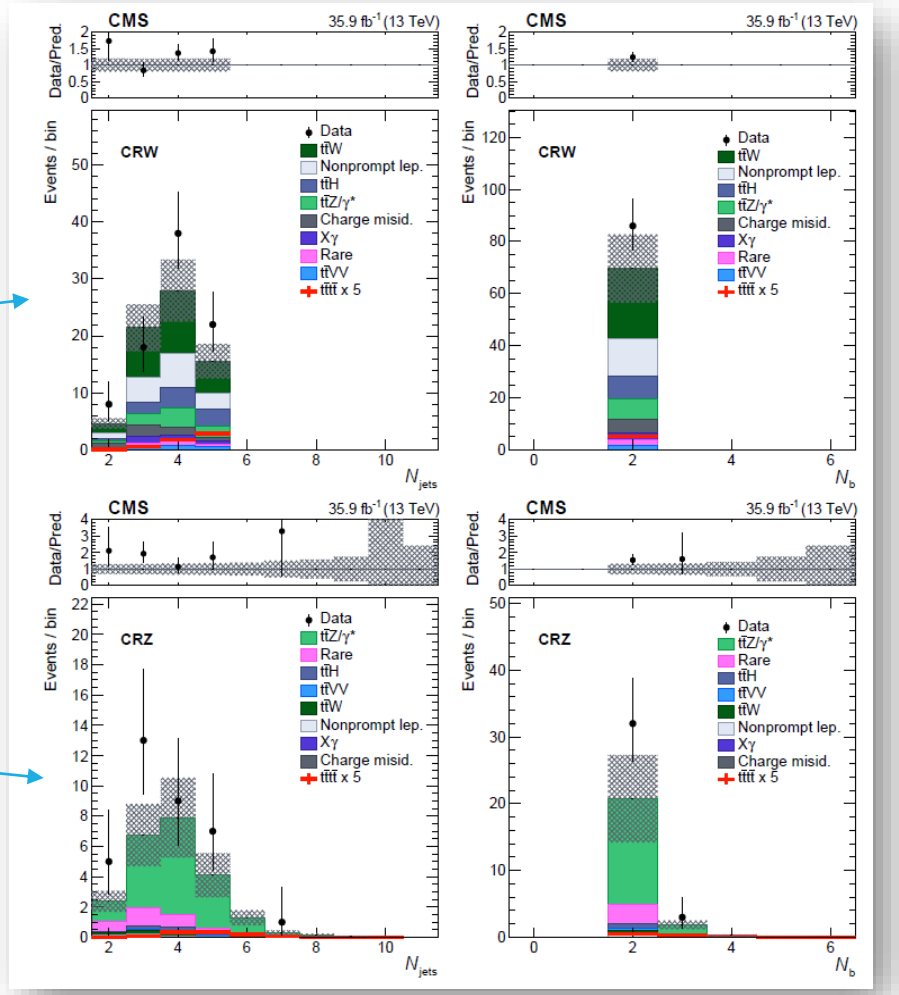
- Dilepton mass requirements to remove DY and onia

ANALYSIS

Several control and signal regions defined

N_ℓ	N_b	N_{jets}	Region
2	2	≤ 5	CRW
		6	SR1
		7	SR2
		≥ 8	SR3
	3	5, 6	SR4
		≥ 7	SR5
	≥ 4	≥ 5	SR6
≥ 3	2	≥ 5	SR7
	≥ 3	≥ 4	SR8
Inverted Z veto			CRZ

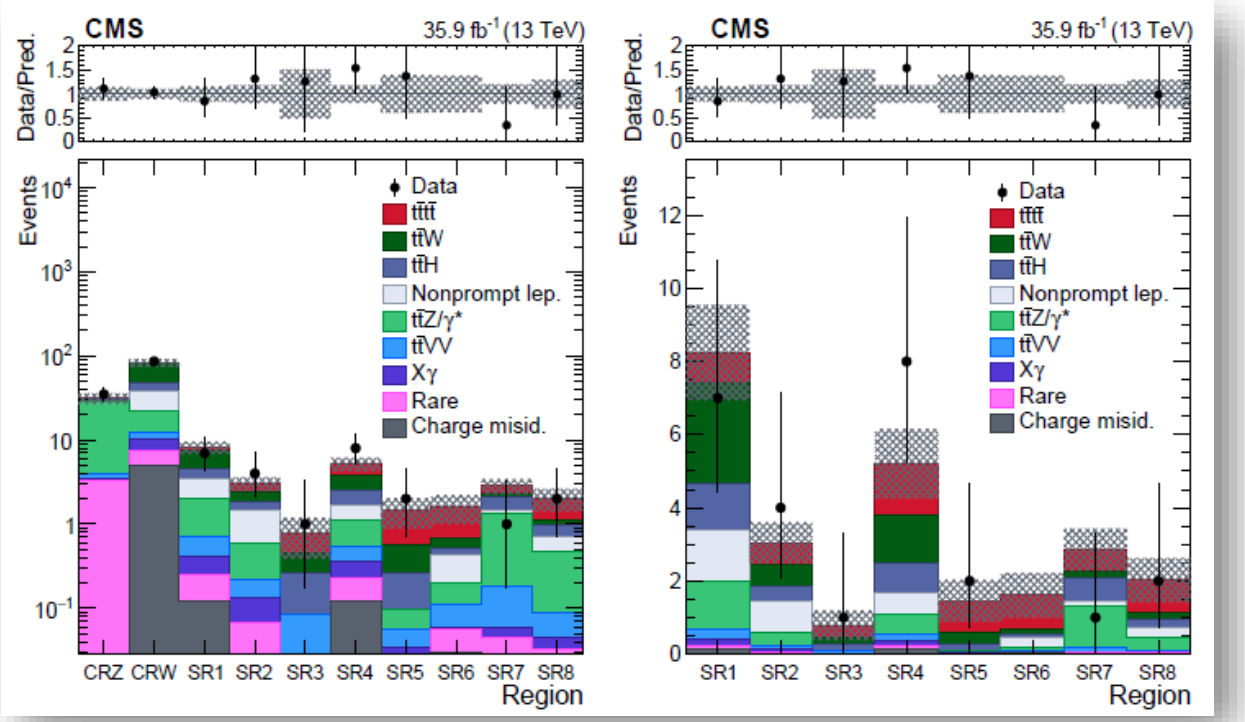
- A third lepton $p_T > 20\ GeV$ and within the Z mass when paired with OS same flavor lepton, it is kept in control region



RESULTS

Likelihood fit done using shapes in various regions

Post-fit result



EVENT YIELDS AND SYSTEMATICS

Event Yields

	SM background	$t\bar{t}t\bar{t}$	Total	Observed
CRZ	31.7 ± 4.6	0.4 ± 0.3	32.1 ± 4.6	35
CRW	83.7 ± 8.8	1.9 ± 1.2	85.6 ± 8.6	86
SR1	7.7 ± 1.2	0.9 ± 0.6	8.6 ± 1.2	7
SR2	2.6 ± 0.5	0.6 ± 0.4	3.2 ± 0.6	4
SR3	0.5 ± 0.3	0.4 ± 0.2	0.8 ± 0.4	1
SR4	4.0 ± 0.7	1.4 ± 0.9	5.4 ± 0.9	8
SR5	0.7 ± 0.2	0.9 ± 0.6	1.6 ± 0.6	2
SR6	0.7 ± 0.2	1.0 ± 0.6	1.7 ± 0.6	0
SR7	2.3 ± 0.5	0.6 ± 0.4	2.9 ± 0.6	1
SR8	1.2 ± 0.3	0.9 ± 0.6	2.1 ± 0.6	2

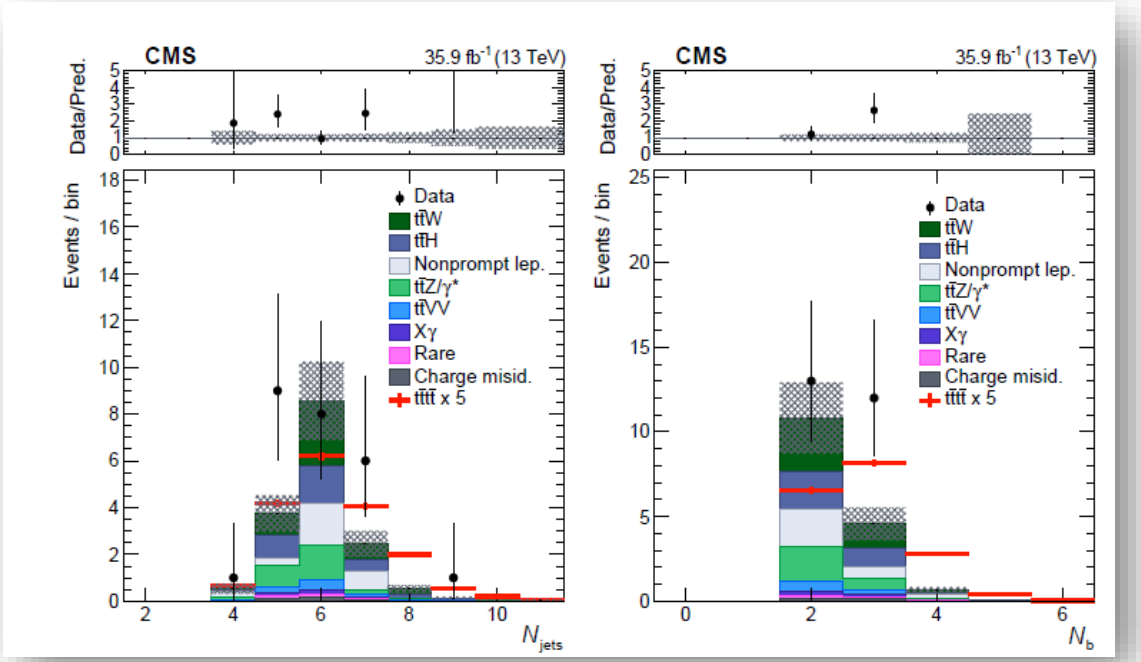
Systematics

Source	Uncertainty (%)
Integrated luminosity	2.5
Pileup	0–6
Trigger efficiency	2
Lepton selection	4–10
Jet energy scale	1–15
Jet energy resolution	1–5
b tagging	1–15
Size of simulated sample	1–10
Scale and PDF variations	10–15
ISR/FSR (signal)	5–15
$t\bar{t}H$ (normalization)	50
Rare, $X\gamma$, $t\bar{t}VV$ (norm.)	50
$t\bar{t}Z/\gamma^*$, $t\bar{t}W$ (normalization)	40
Charge misidentification	20
Nonprompt leptons	30–60

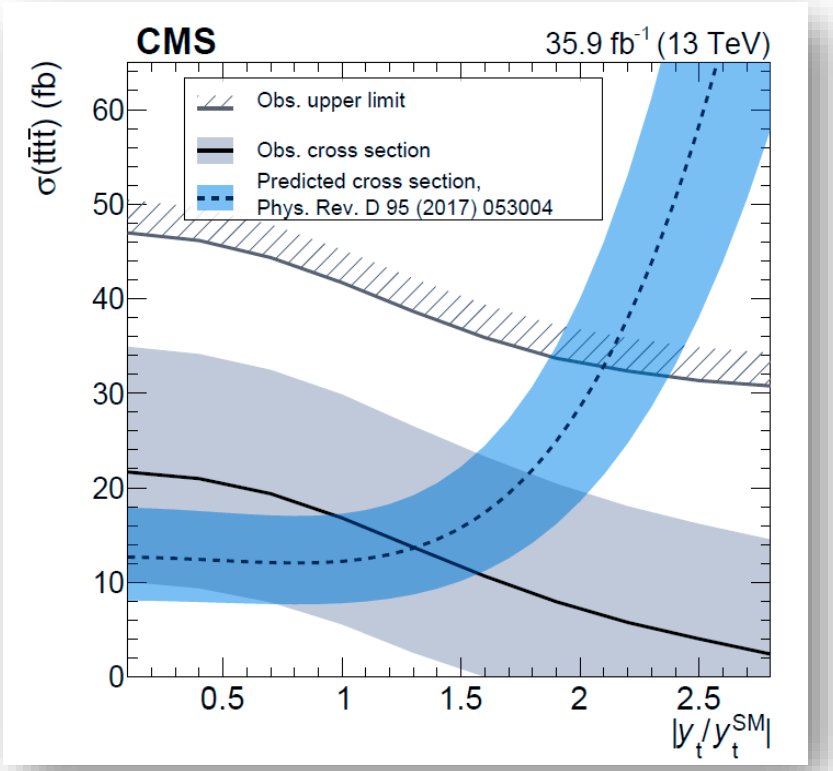
RESULTS

Observed significance: 1.6σ

- Expected significance 1.0σ
- Best fit cross section: $\sigma(t\bar{t}t\bar{t}) = 16.9^{+13.8}_{-11.4}\ fb$



Interpretations on top-Higgs coupling



SUMMARY AND OUTLOOK

Top quark rare processes, sensitive to the electroweak couplings, have been probed using the CMS data.

The results are in agreement with the Standard Model predictions.

The statistical errors are comparable to systematic errors in many of these results. We can expect reduced uncertainties with the full Run 2 data.

REFERENCES

- Measurement of the cross section for top quark pair production in association with a W or Z boson in proton-proton collisions at $\sqrt{s} = 13$ TeV
  - Submitted to JHEP
  - http://arxiv.org/abs/1711.02547
- Measurement of the semileptonic $t\bar{t} + \gamma$ production cross section in pp collisions at $\sqrt{s} = 8$ TeV
  - J. High Energ. Phys. (2017) 2017: 6
  - https://doi.org/10.1007/JHEP10(2017)006
- Measurement of the associated production of a single top quark and a Z boson in pp collisions at $\sqrt{s} = 13$ TeV
  - Phys. Lett. B 779 (2018) 358
  - https://doi.org/10.1016/j.physletb.2018.02.025
- Search for standard model production of four top quarks with same-sign and multilepton final states in proton–proton collisions at $\sqrt{s} = 13$ TeV
  - Eur. Phys. J. C (2018) 78: 140
  - https://doi.org/10.1140/epjc/s10052-018-5607-5