

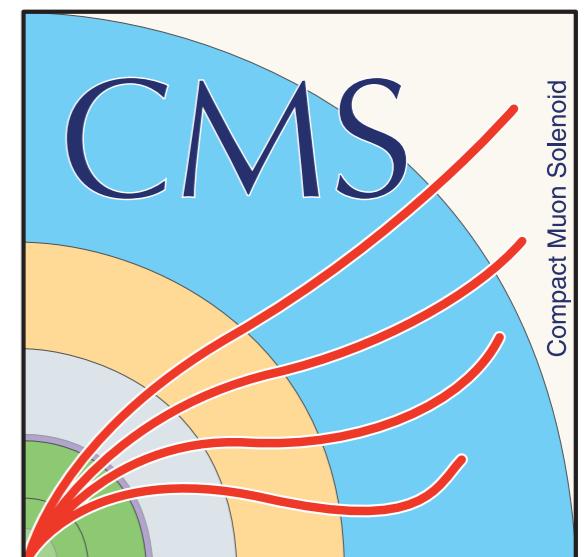
Top quark associated production at CMS

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Top Quark Physics at the Precision Frontier
January 17, 2018



*Florida Institute
of Technology*
High Tech with a Human Touch™



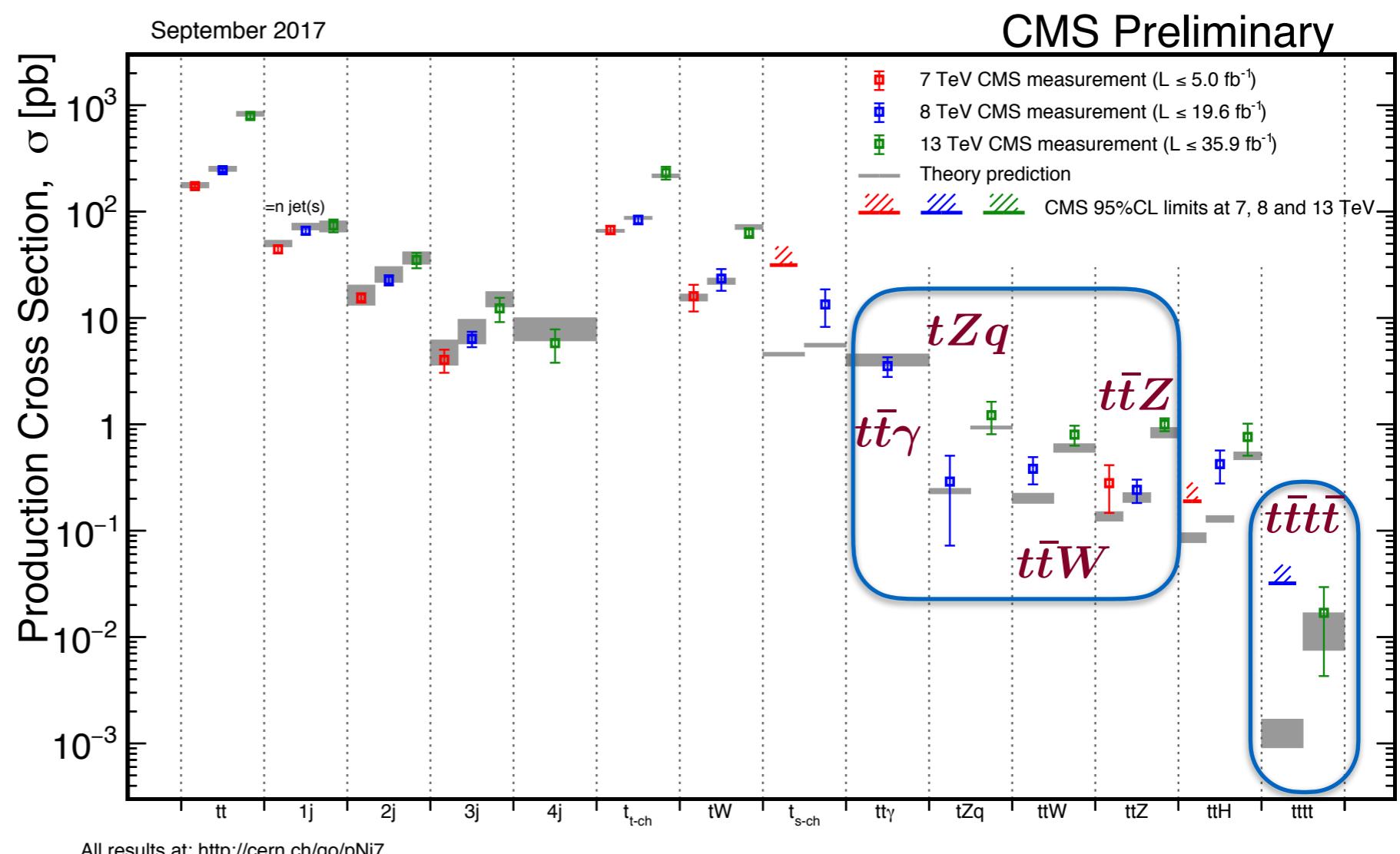
Associated Production



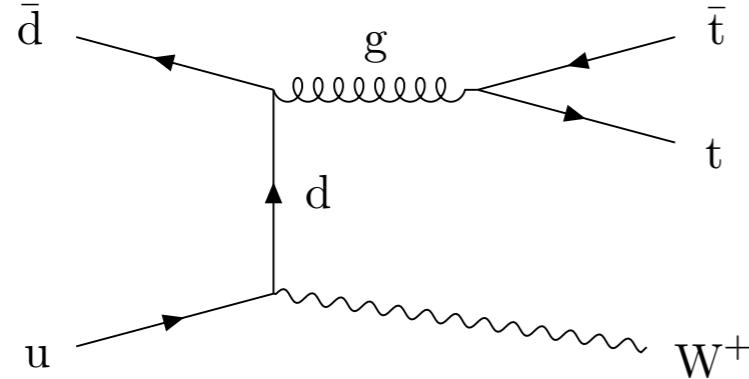
- Precision measurement of associated top quark production provides
 - Direct test of top couplings
 - Window to new physics
 - Important background for BSM or rare SM searches

$t\bar{t}+X$
 $(X = W, Z, \gamma, t\bar{t}, b\bar{b})$

tZq



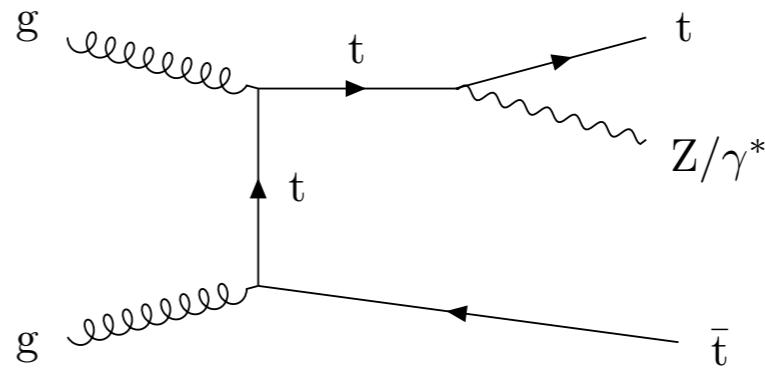
$t\bar{t}W$ & $t\bar{t}Z$



$t\bar{t}W$

$$\sigma_{\text{th.}}^{t\bar{t}W} = 0.61 \pm 0.08 \text{ pb}$$

- Measured in the same-sign (SS) dilepton final state
- Measured in 3 & 4 lepton final states, containing opposite sign same flavor (OSSF) pair
- Measured in 35.9 fb^{-1} of 13 TeV collisions collected during 2016



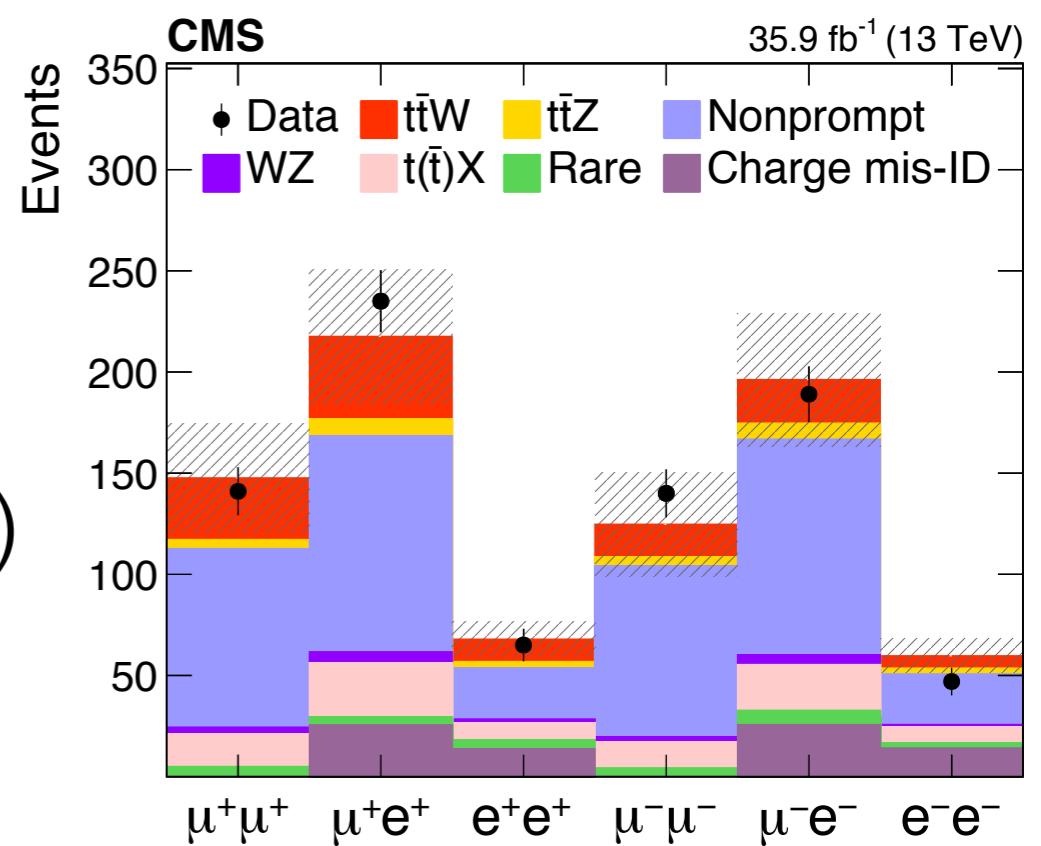
$t\bar{t}Z$

$$\sigma_{\text{th.}}^{t\bar{t}Z} = 0.84 \pm 0.10 \text{ pb}$$

$t\bar{t}W$ Analysis



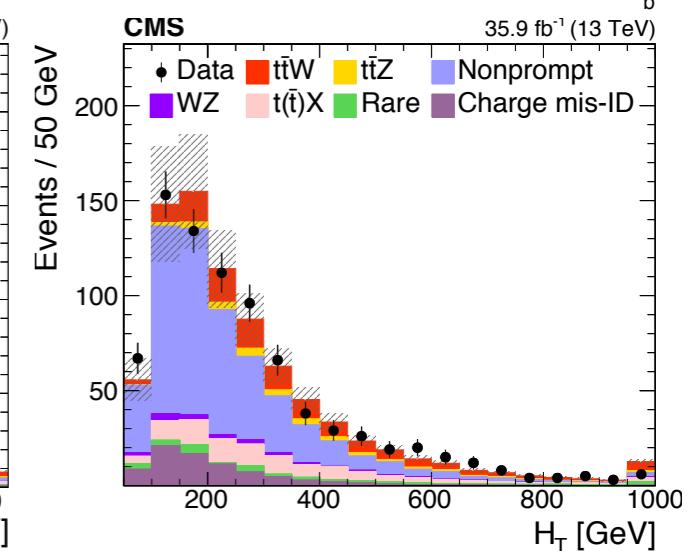
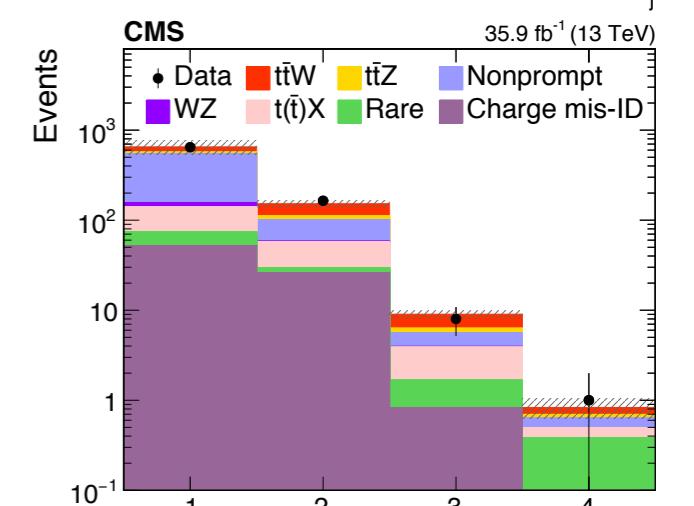
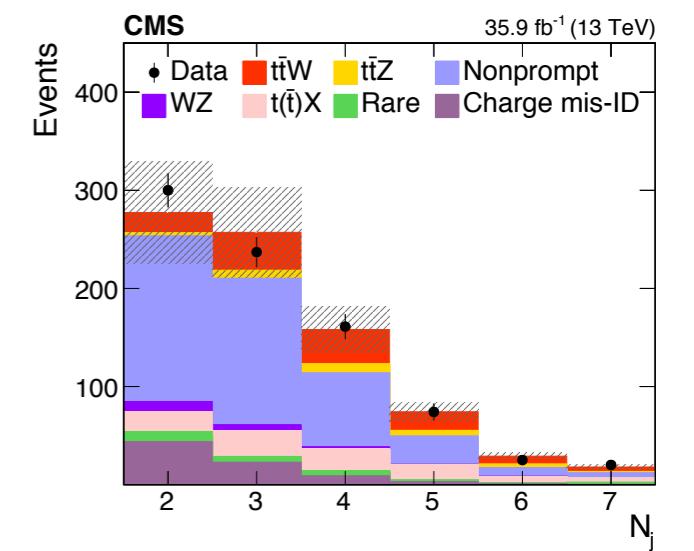
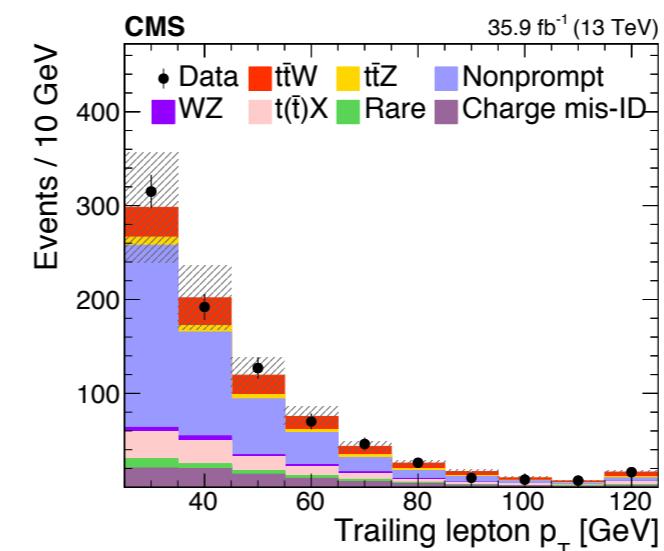
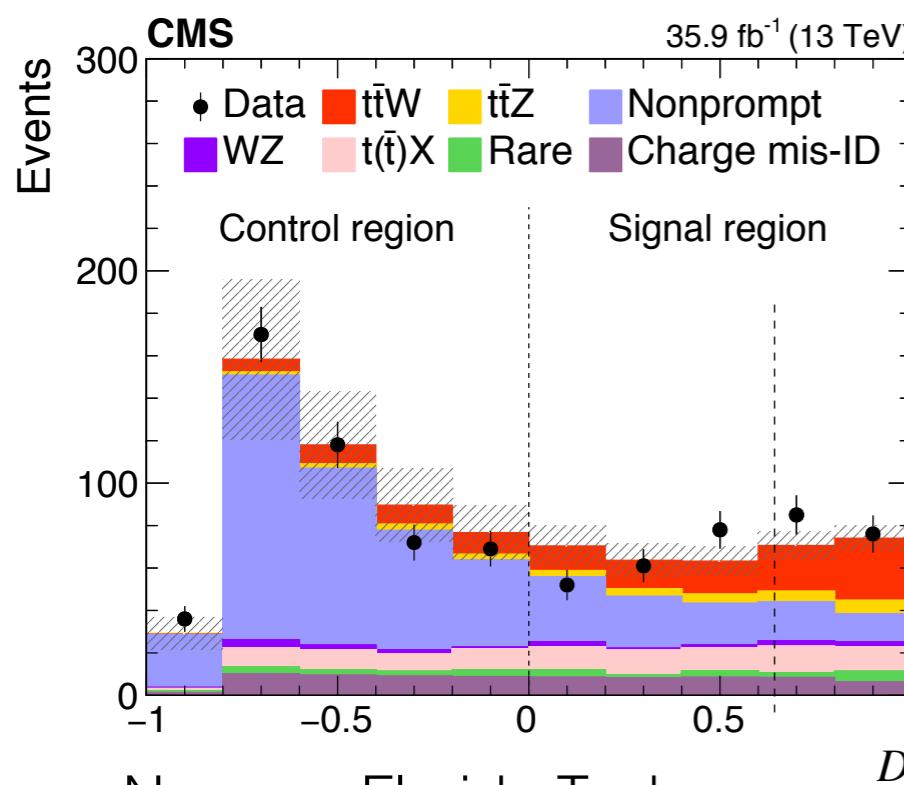
- Select SS dilepton events, with at least 2 jets and 1 b-tag
 - Veto events with $M(\ell\ell)$ within 15 GeV of $M(Z)$
- Backgrounds:
 - Nonprompt leptons
 - Misidentified Charge
 - $t(t)+X$ (ttH , tZq , tWZ , tWq , ...)
 - Rare (WW , ZZ , $W\gamma$, $Z\gamma$, triboson)



$t\bar{t}W$ Analysis



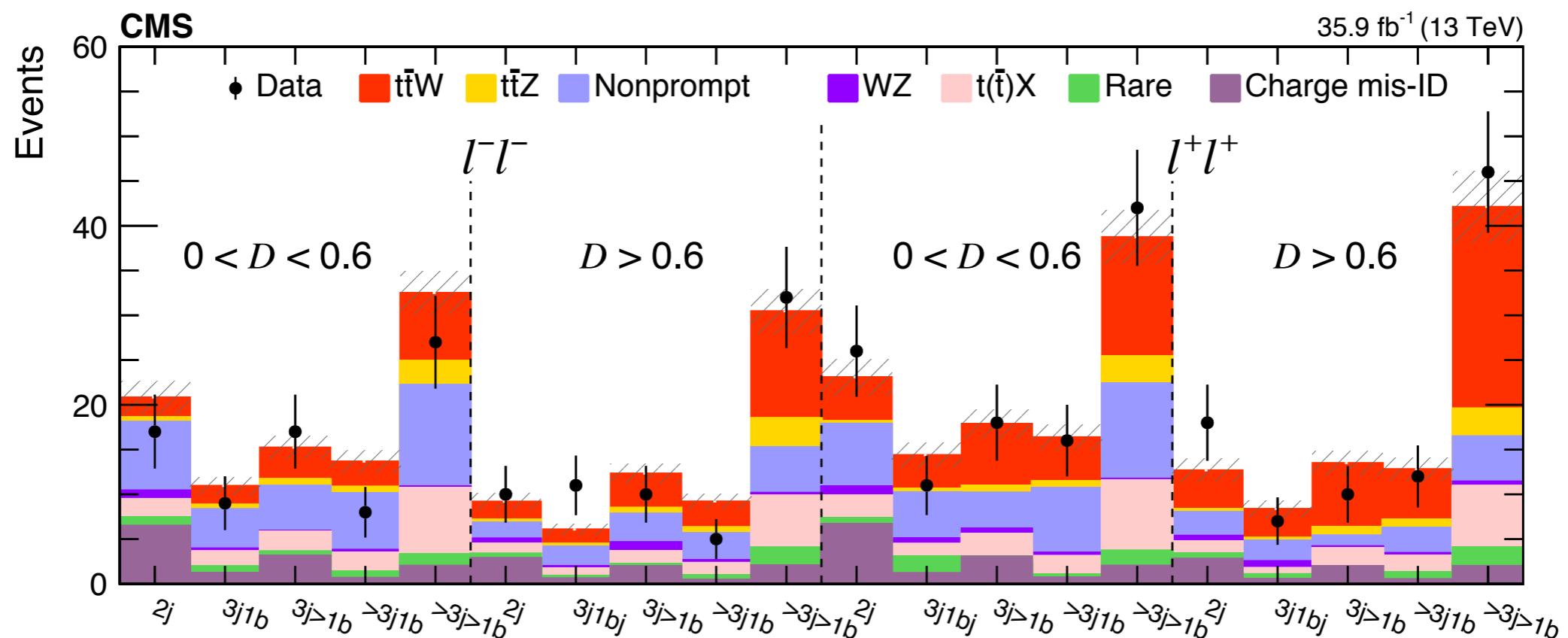
- Boosted Decision Tree classifier used to discriminate signal from background
 - Using jet/b-jet multiplicities, and lepton/jet kinematics
- BDT discriminant (D) used to separate signal region ($D>0$) and control region ($D<0$)



$t\bar{t}W$ Analysis



- Signal region split up to define 20 exclusive signal regions
 - Split in $0 < D < 0.6$ and $D > 0.6$
 - Split $\ell^+\ell^+$ from $\ell^-\ell^-$
 - Define exclusive jet/b-jet multiplicity bins ($=2j$, $=3j=1b$, $=3j>1b$, $>3j=1b$, $>3j>1b$)



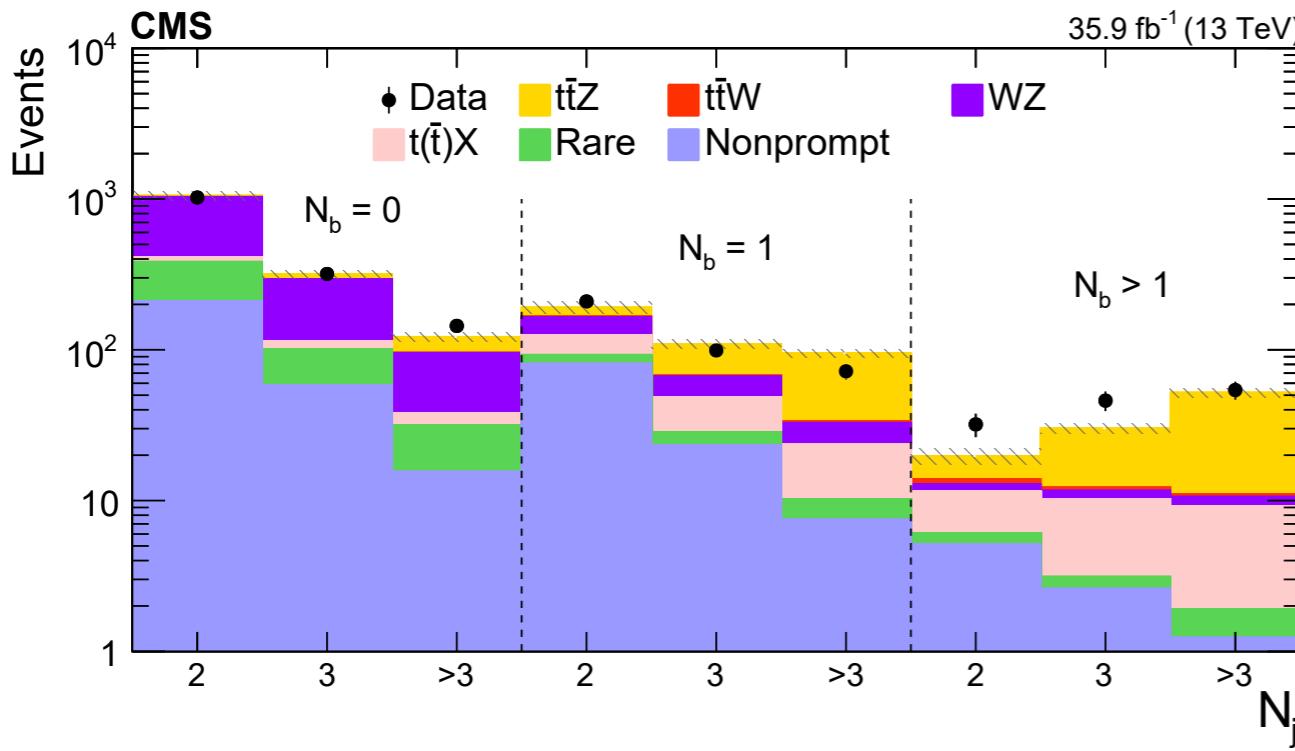
$t\bar{t}Z$ Analysis



- Event selection for both three-lepton and four-lepton final states

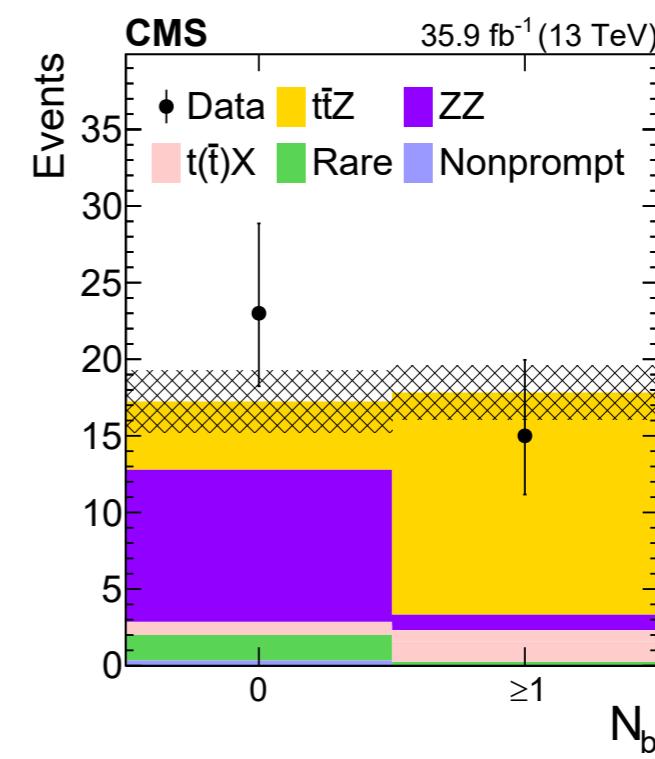
Three-leptons

- Exactly three leptons ($\mu\mu\mu, \mu\mu e, \mu e e, eee$)
- One OSSF pair with $|M(\ell\ell) - M(Z)| < 10$ GeV
- Form 9 exclusive bins
 - $N_j = 2, 3, >3$
 - $N_b = 0, 1, >1$



Four-leptons

- Exactly four leptons, 2 ℓ^+ , 2 ℓ^-
- One OSSF pair with $|M(\ell\ell) - M(Z)| < 20$ GeV
- Veto $\mu\mu\mu\mu, \mu\mu ee, ee ee$ events with second pair in mass peak
- Require ≥ 2 jets, split in 0b & ≥ 1 b



$t\bar{t}W$ & $t\bar{t}Z$ Results



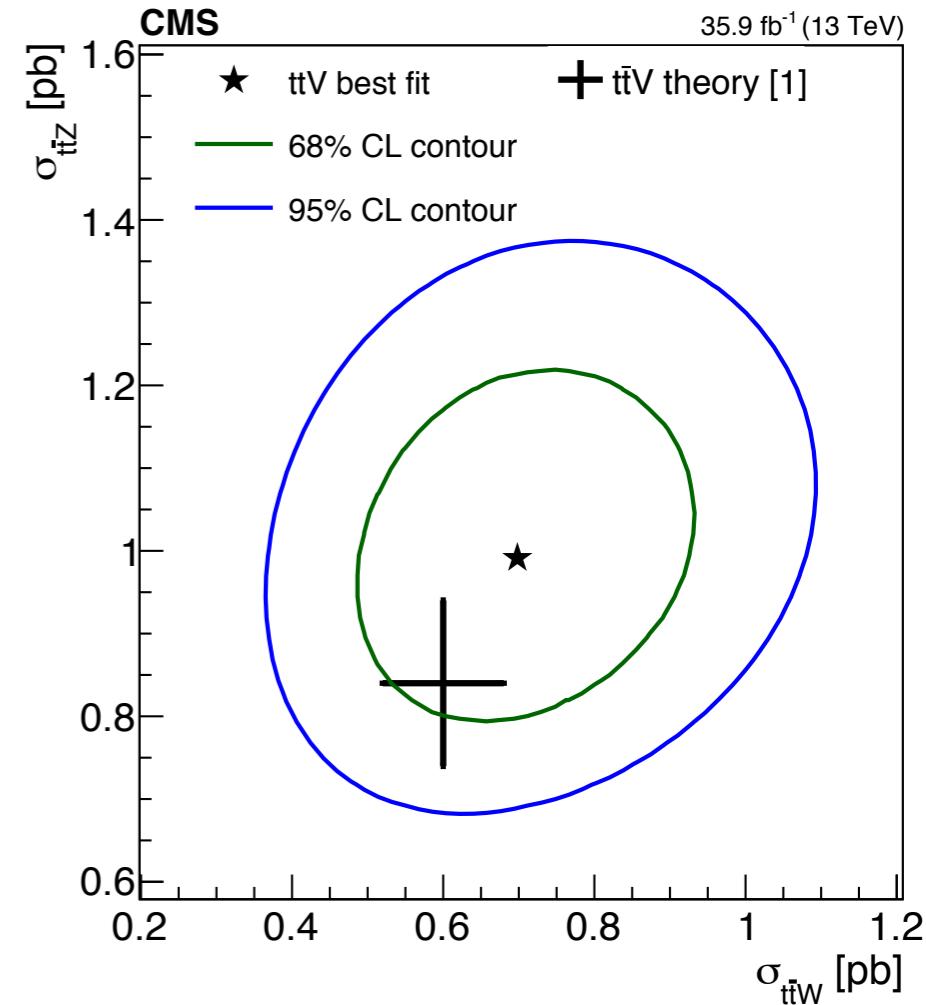
- Combine binned event yields in SS Dilepton, 3-lepton, and 4-lepton categories into likelihood function to extract $t\bar{t}W$ and $t\bar{t}Z$ cross sections

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

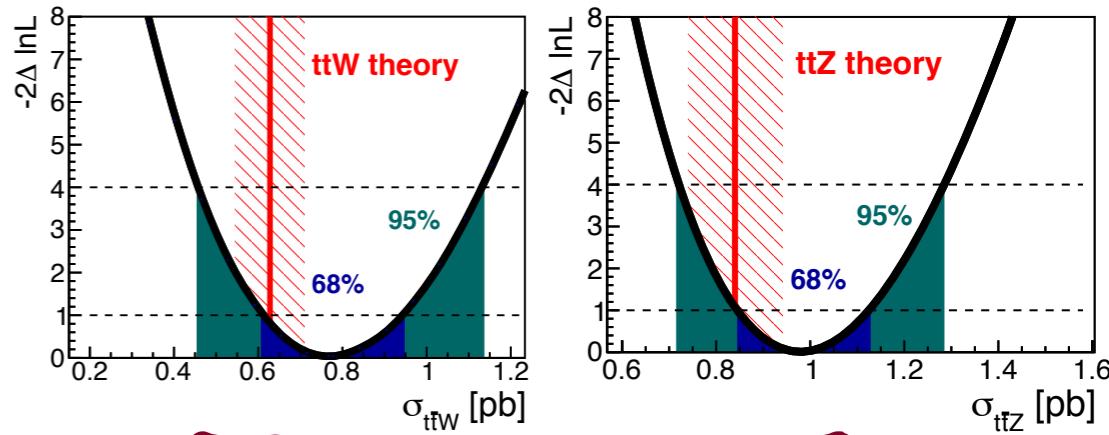
$$\sigma(pp \rightarrow t\bar{t}W^+) = 0.58 \pm 0.09(\text{stat})^{+0.09}_{-0.08}(\text{syst}) \text{ pb}$$

$$\sigma(pp \rightarrow t\bar{t}W^-) = 0.19 \pm 0.07(\text{stat}) \pm 0.06(\text{syst}) \text{ pb}$$

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



Channel	Expected significance	Observed significance
SS dilepton $\ell^-\ell^- (t\bar{t}W^-)$	2.4	2.3
SS dilepton $\ell^+\ell^+ (t\bar{t}W^+)$	4.2	5.5
SS dilepton $\ell^\pm\ell^\pm (t\bar{t}W^\pm)$	4.5	5.3
Three-lepton ($t\bar{t}Z$)	>5.0	>5.0
Four-lepton ($t\bar{t}Z$)	4.7	4.5
Three- and four-lepton combined ($t\bar{t}Z$)	>5.0	>5.0



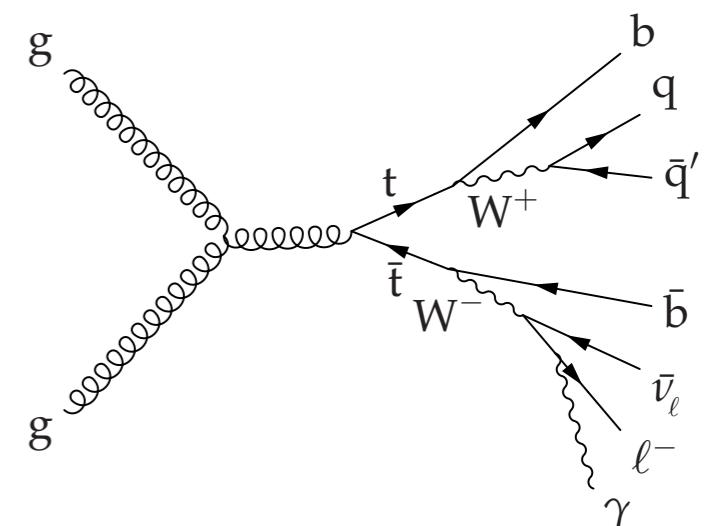
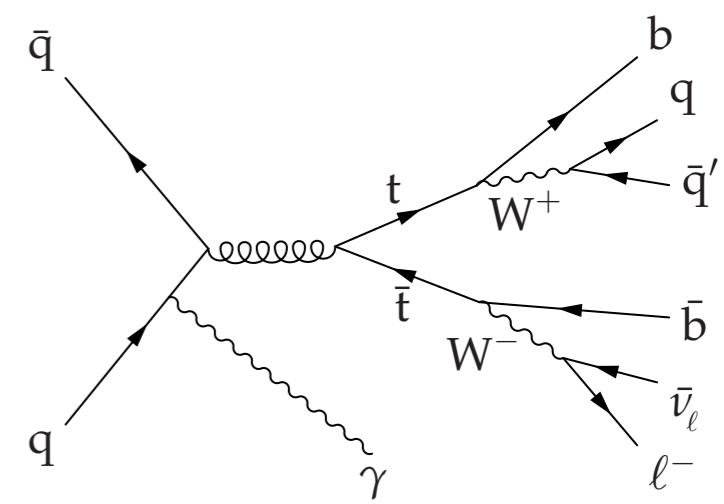
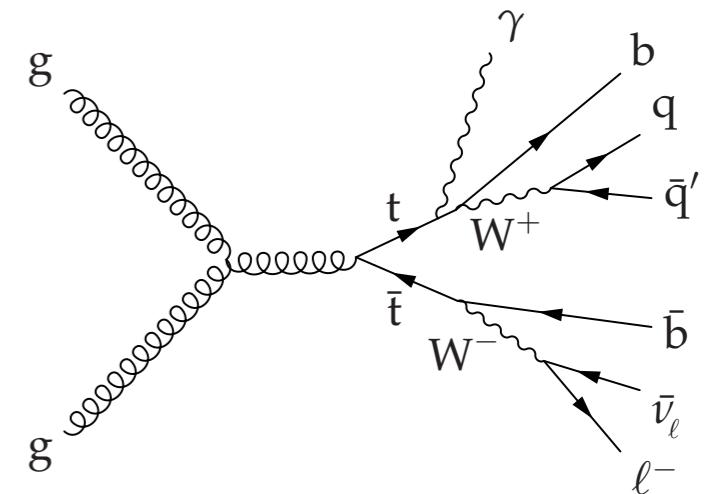
arXiv:1711.02547
Submitted to JHEP



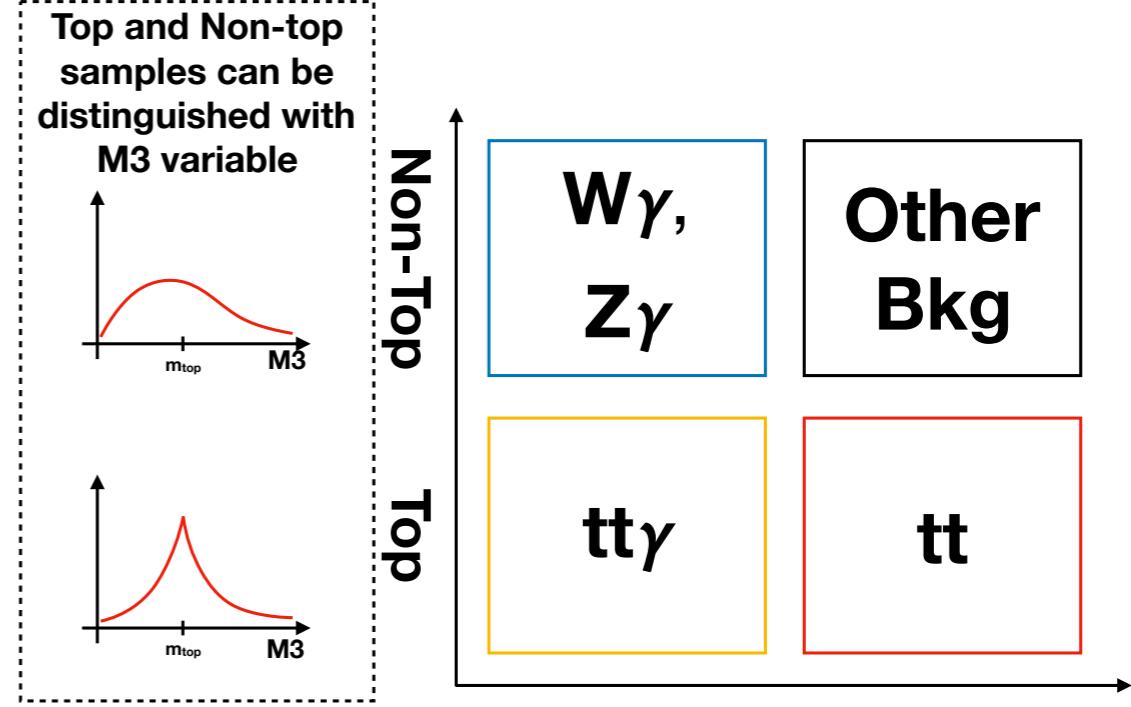
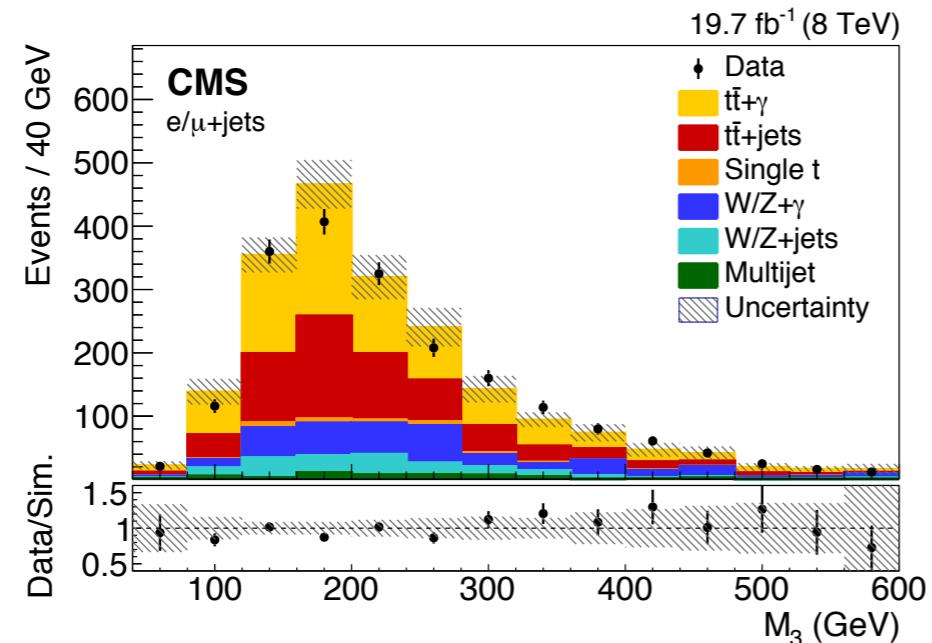
$t\bar{t}\gamma$ Analysis

- Analysis with 8 TeV data collected in 2012
- Measured in the lepton+jets final state
- Select events with leptons+jets signature with reconstructed photon
- Backgrounds come mainly from two categories:
 - Top pair events with a fake photon
 - Non-top events (V) with a real photon

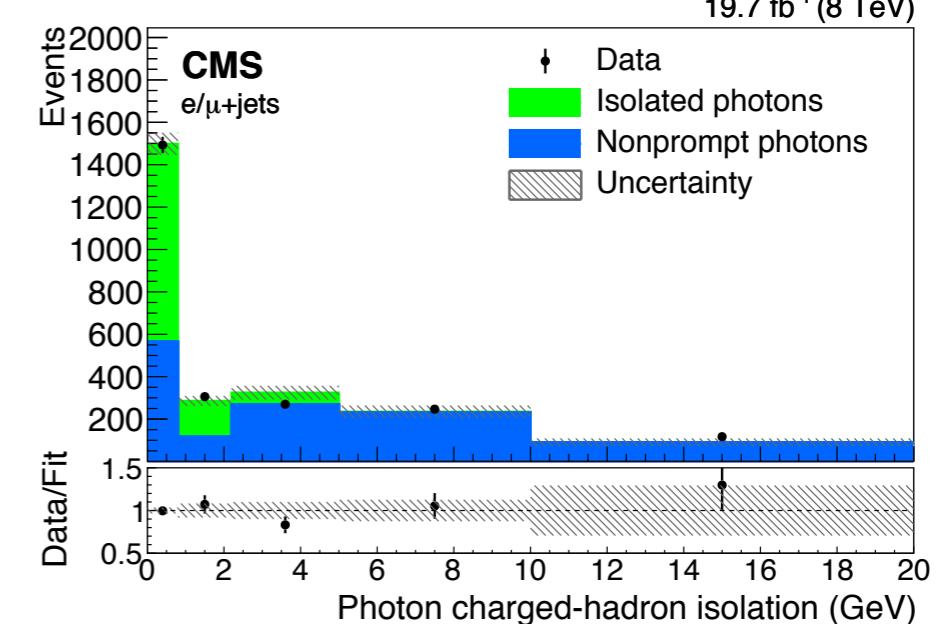
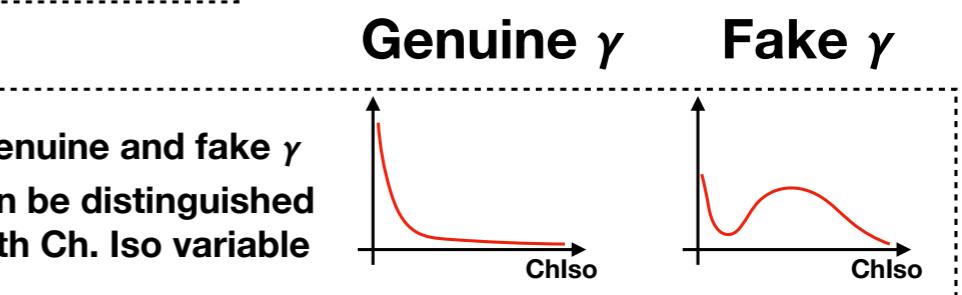
JHEP 10 (2017) 006
arXiv:1706.08128



$t\bar{t}\gamma$ Analysis



- Strategy used is to:
 - Fit M3 distribution to distinguish top from non-top events (measuring top purity)
 - Fit photon isolation to distinguish genuine and fake photons (measuring photon purity)





$t\bar{t}\gamma$ Results

- Combine measurements of photon purity and top quark purity in likelihood to extract number of $t\bar{t}\gamma$ events

$$\chi^2 = \frac{(\pi_{\gamma}^{\text{data}} - \pi_{\gamma}^{\text{MC}})^2}{\sigma_{\pi_{\gamma}}^2} + \frac{(\pi_{t\bar{t}}^{\text{data}} - \pi_{t\bar{t}}^{\text{MC}})^2}{\sigma_{\pi_{t\bar{t}}}^2} + \frac{(N^{\text{data}} - N^{\text{MC}})^2}{\sigma_N^2}$$

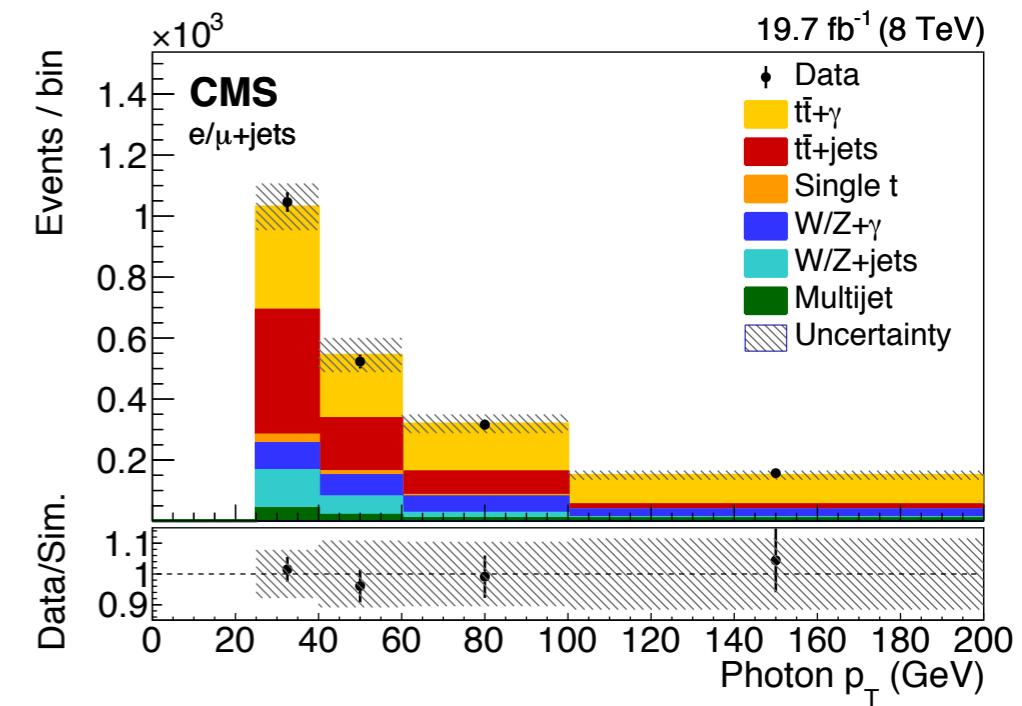
$N_{t\bar{t}\gamma} = 338 \pm 53$ (stat) in $e + \text{jets}$

$N_{t\bar{t}\gamma} = 442 \pm 69$ (stat) in $\mu + \text{jets}$

- Measure ratio to $t\bar{t}(R)$, extract cross section by multiplying ratio by measured top pair cross section

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

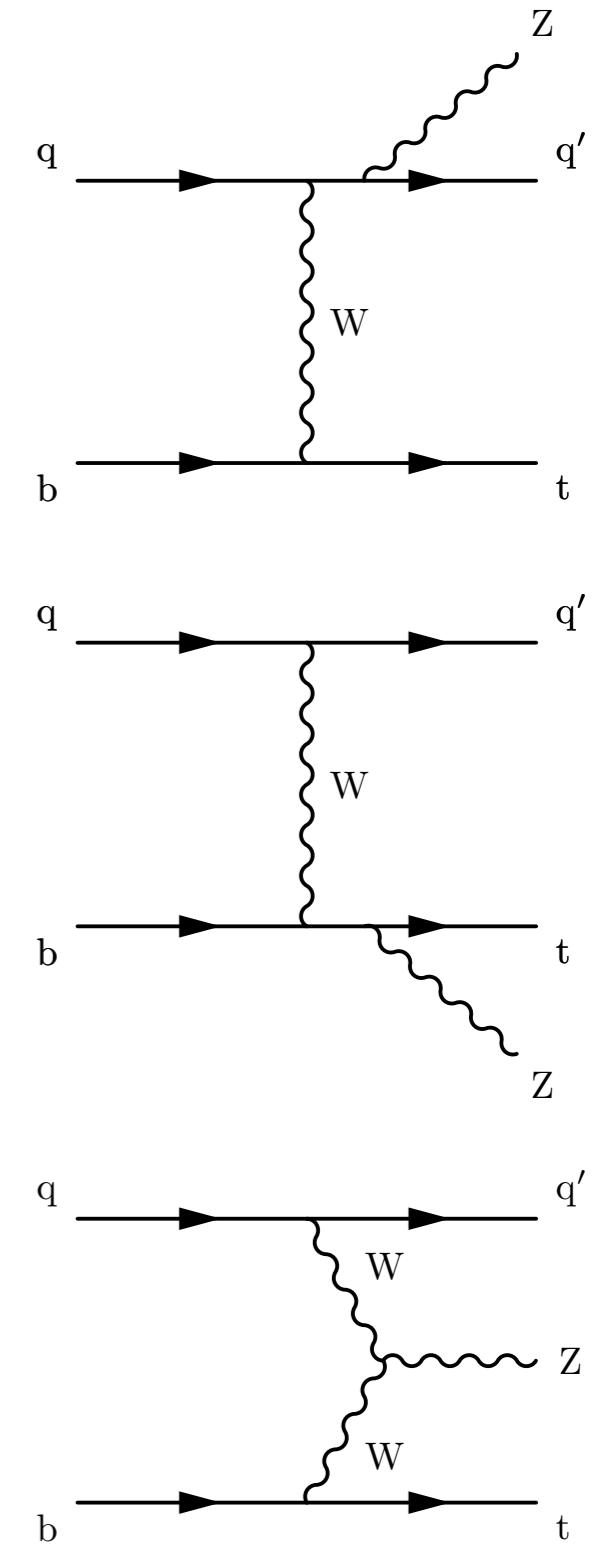
JHEP 10 (2017) 006
arXiv:1706.08128





tZq Analysis

- Associated top/Z production has sensitivity to new physics in tZ coupling, triple WWZ coupling, and FCNC
- Looking in the 3 lepton final state with at least 2 jets
 - eee, eee μ , e $\mu\mu$, $\mu\mu\mu$
 - Require an opposite sign same flavor lepton pair consistent with Z-boson mass
- Backgrounds come from ttZ , $WZ+jets$, and dilepton processes with non prompt leptons ($Z+jets$, tt)

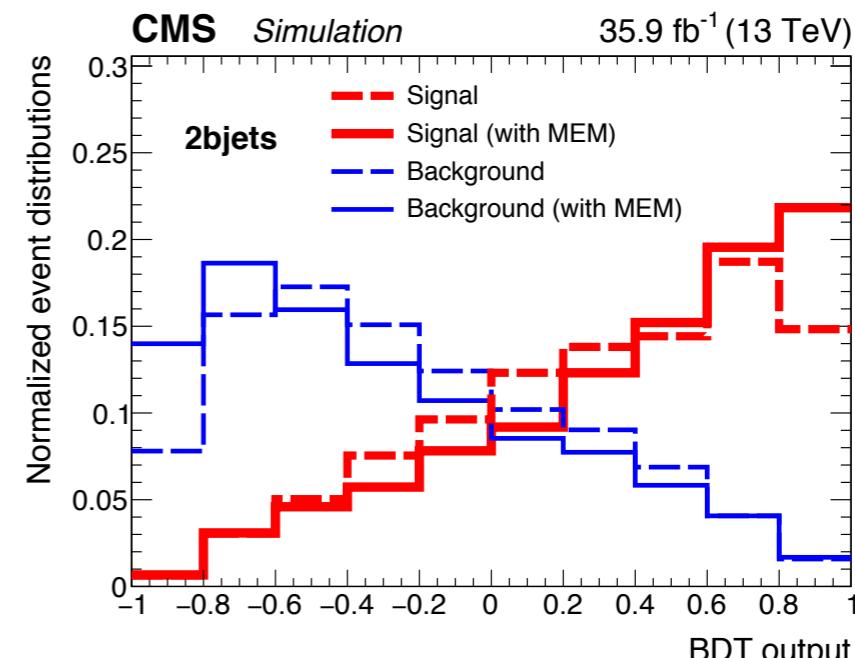
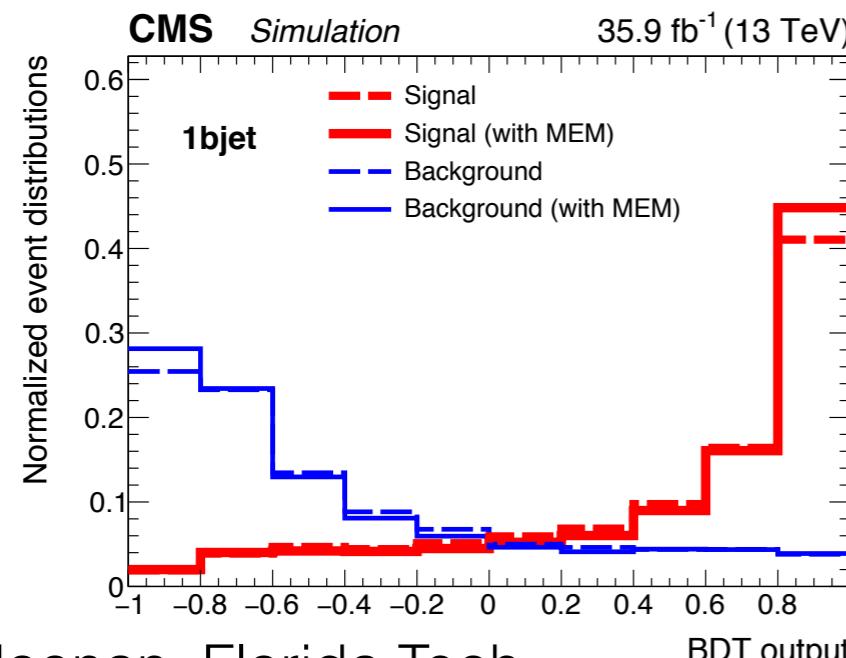


[arXiv:1712.02825](https://arxiv.org/abs/1712.02825)
Submitted to
Phys. Lett. B

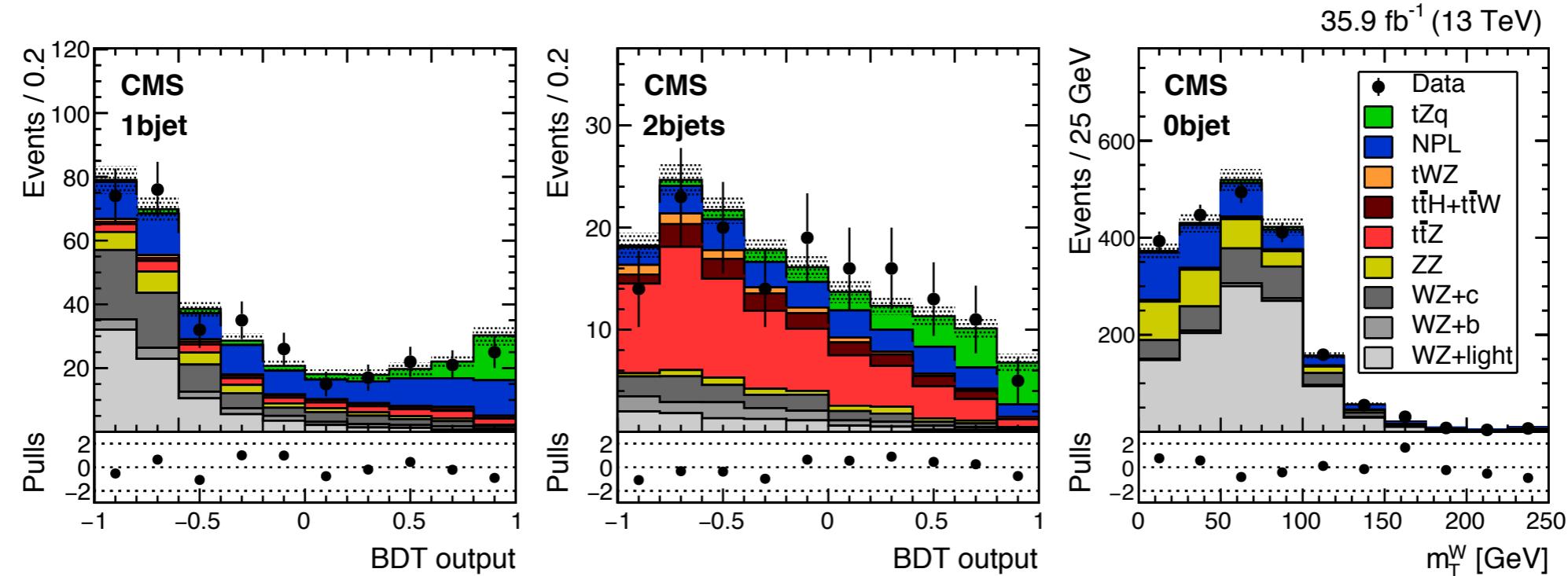


tZq Analysis

- Events are split into three exclusive b-jet multiplicity regions
 - 1 b-jet**, 2 or 3 jets(signal region)
 - ≥2 b-jet**, ≥ 2 jets($t\bar{t}Z$ enriched)
 - 0 b-jet**, ≥ 1 jets($WZ+jets$ enriched)
- BDT's are used to discriminate signal and background in 1 & 2 b-jet regions, using kinematics of the reconstructed top quark, Z boson, and recoiling jet as well as matrix element likelihood ratios for signal and background hypotheses



tZq Result



- Signal extracted in fit to BDT outputs in 1 and 2 bjet regions, and m_T^W in the 0 bjet region
- $$\sigma(t\ell^+\ell^-q) = 123^{+33}_{-31}(\text{stat})^{+29}_{-23}(\text{syst}) \text{ fb}$$
- Evidence for tZq production seen with observed significance of 3.7σ (3.1σ expected)

arXiv:1712.02825
 Submitted to
 Phys. Lett. B



$t\bar{t}b\bar{b}$ Analysis

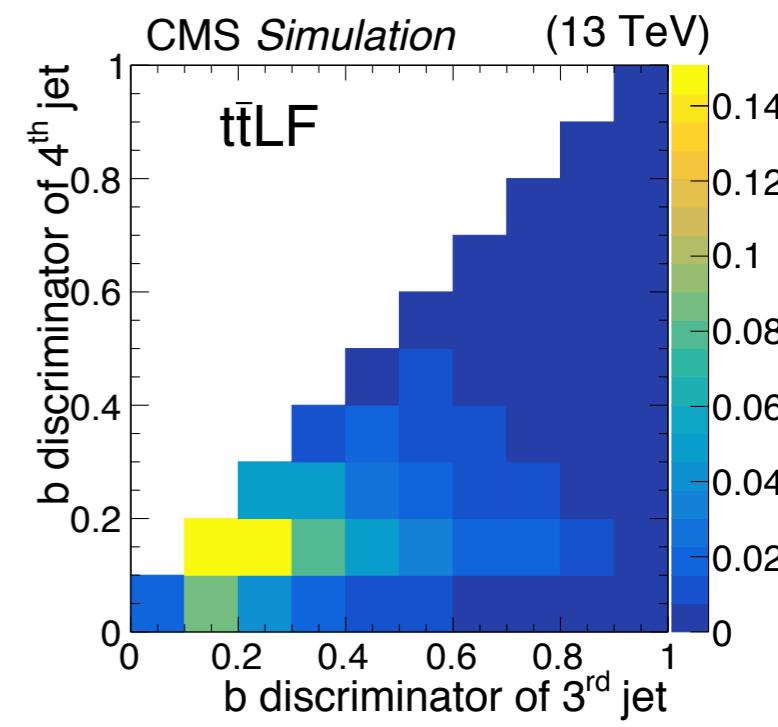
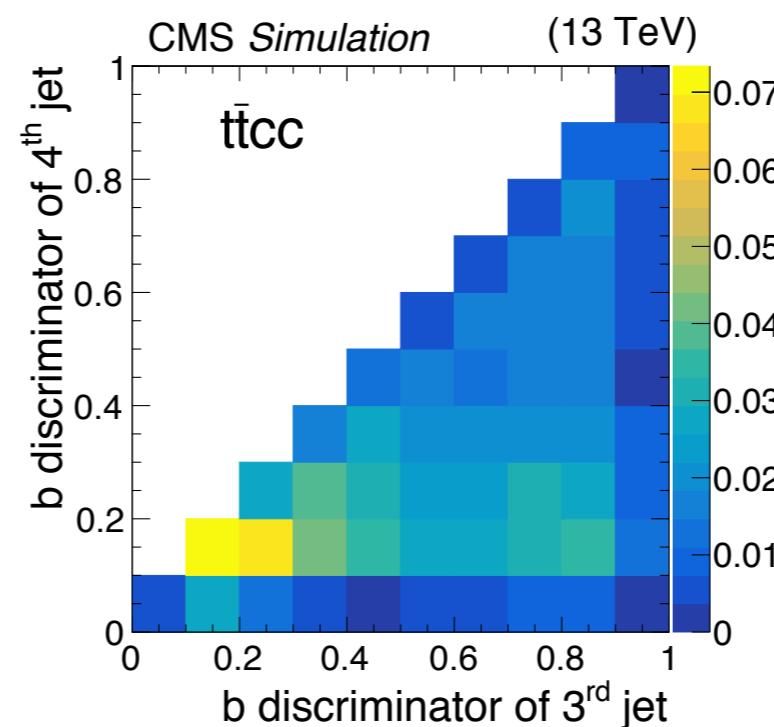
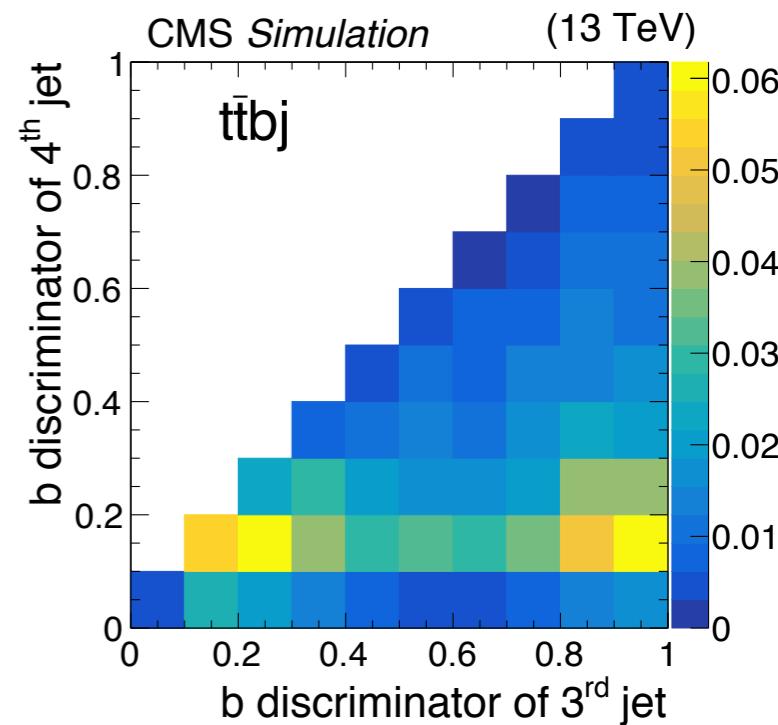
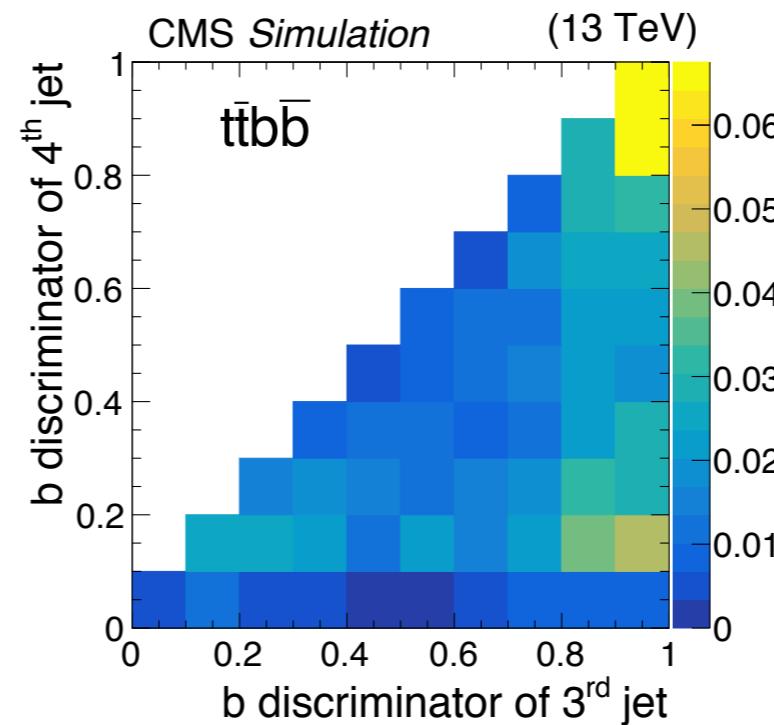
- Measurement of $\sigma_{t\bar{t}b\bar{b}}/\sigma_{t\bar{t}jj}$ and cross sections
 - Cross sections are important check of NLO QCD calculations, as well as backgrounds to other rare processes (ttH)
- Performed in dilepton final state with 2.3 fb^{-1} of 13 TeV data
 - Selecting events with at least 4 jets, and at least 2 bags

Phys. Lett. B 776
(2018) 355
arXiv:1705.10141

$t\bar{t}b\bar{b}$ Analysis



- In decreasing order of b-tagging discriminant value, the first two jets are usually originating from the top quark pairs
- B-tagging discriminant of 3rd and 4th jets provide discriminating power between $ttbb$ and $ttjj$

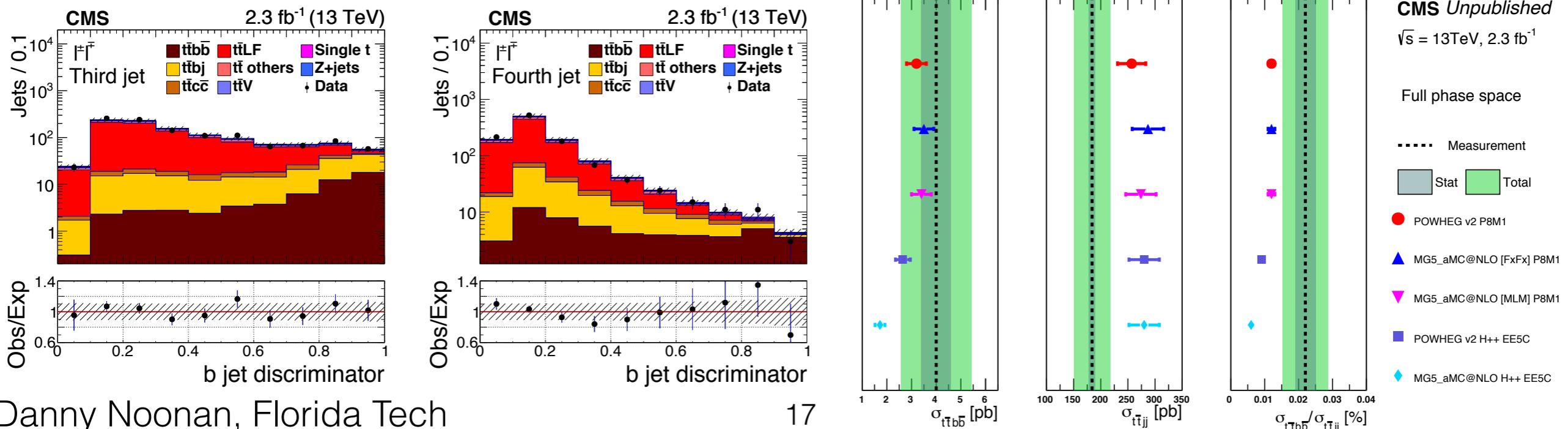


$t\bar{t}b\bar{b}$ Results



- Fit to 2-D spectrum of 3rd and 4th leading CSV discriminants, fitting to number of ttjj events, and the $N_{t\bar{t}b\bar{b}}/N_{t\bar{t}jj}$ ratio
- Measured in visible and full phase spaces

Phase space		$\sigma_{t\bar{t}b\bar{b}}$ [pb]	$\sigma_{t\bar{t}jj}$ [pb]	$\sigma_{t\bar{t}b\bar{b}}/\sigma_{t\bar{t}jj}$
Visible	Measurement	$0.088 \pm 0.012 \pm 0.029$	$3.7 \pm 0.1 \pm 0.7$	$0.024 \pm 0.003 \pm 0.007$
	SM (POWHEG)	0.070 ± 0.009	5.1 ± 0.5	0.014 ± 0.001
Full	Measurement	$4.0 \pm 0.6 \pm 1.3$	$184 \pm 6 \pm 33$	$0.022 \pm 0.003 \pm 0.006$
	SM (POWHEG)	3.2 ± 0.4	257 ± 26	0.012 ± 0.001



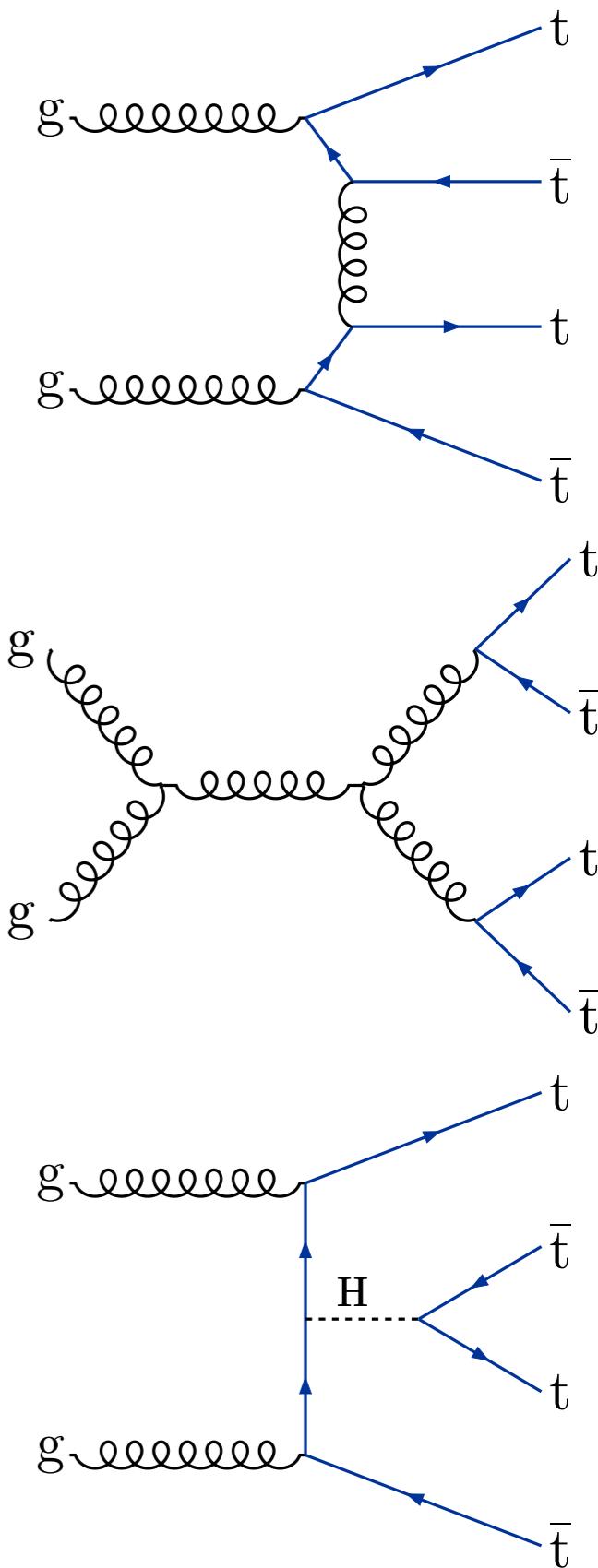


$t\bar{t}t\bar{t}$ Analysis

- Search for SM 4-top production
 $\sigma(pp \rightarrow t\bar{t}t\bar{t}) = 9.2^{+2.9}_{-2.4} \text{ fb}$
 - Small in SM, but enhanced in many BSM theories
- Measured in same-sign dilepton and 3+ lepton final states
- Selection requires ≥ 2 jets, ≥ 2 b-jets, $H_T > 300 \text{ GeV}$, and MET $> 50 \text{ GeV}$
- Define signal regions based on lepton, jet, and b-jet multiplicities

arXiv:1710.10614
Submitted to
Eur. Phys. J. C

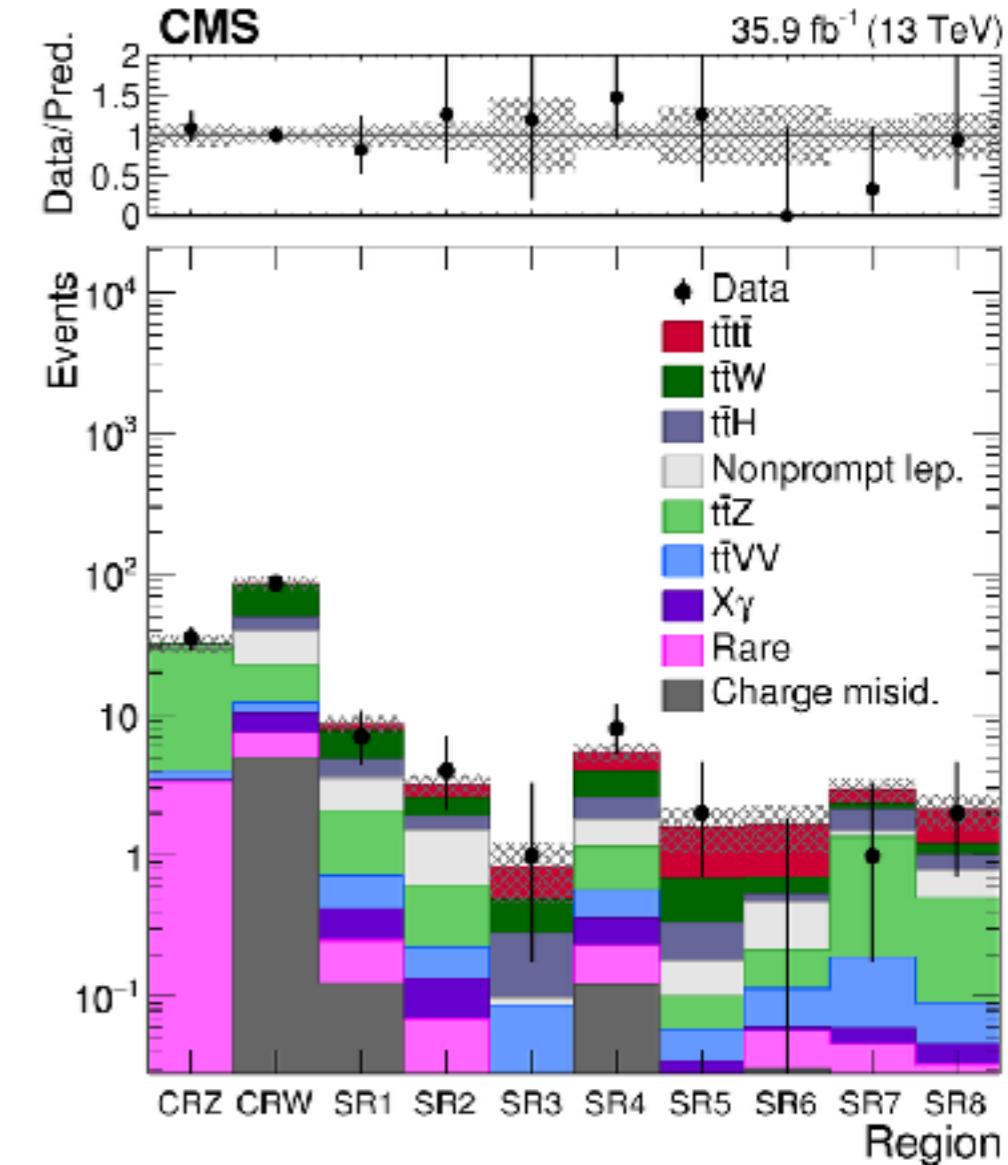
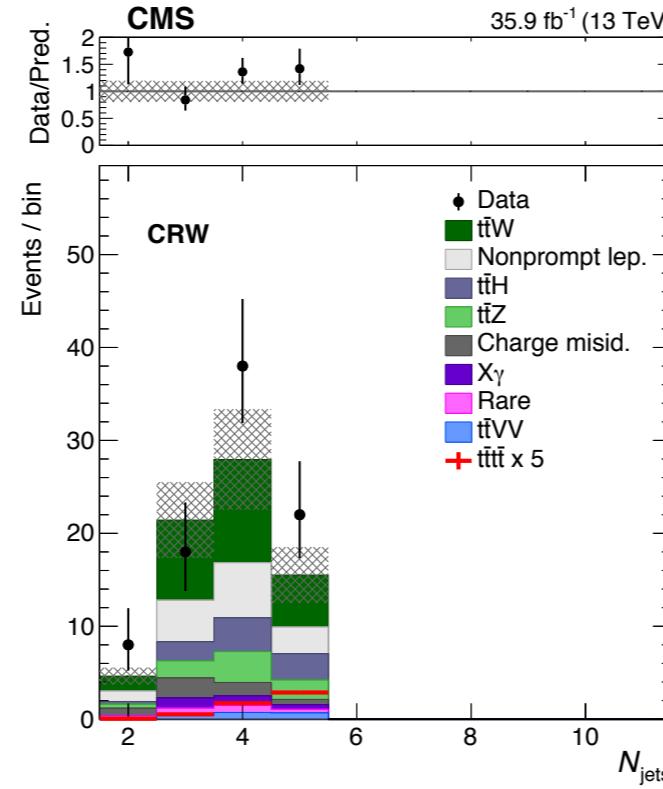
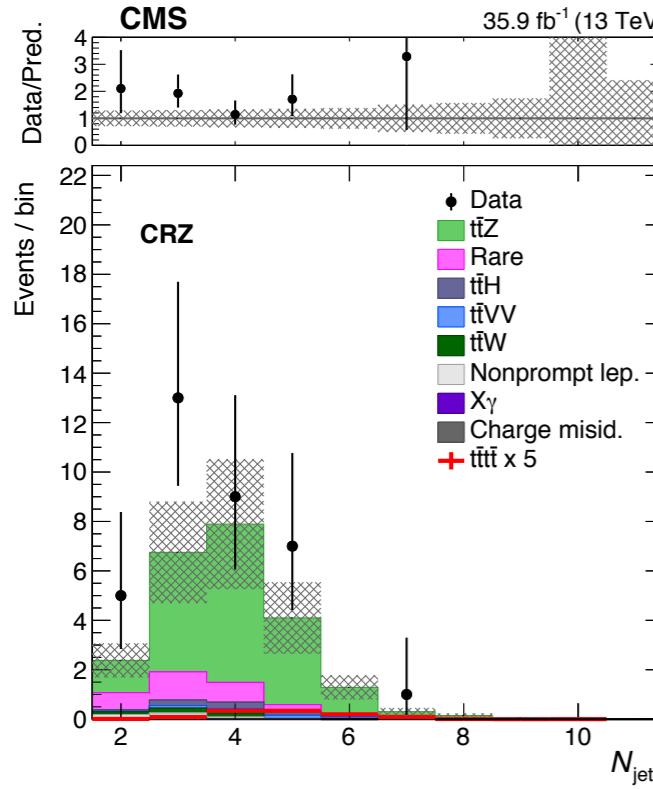
N_ℓ	N_b	N_{jets}	Region
2	2	≤ 5	CRW
		6	SR1
		7	SR2
		≥ 8	SR3
	3	5, 6	SR4
		≥ 7	SR5
		≥ 4	SR6
	≥ 3	2	SR7
		≥ 3	SR8
Inverted Z veto			CRZ





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

- Backgrounds come from two main categories
- Rare top multilepton processes ($t\bar{t}W$, $t\bar{t}Z$, $t\bar{t}H$, ...):
 - Estimated with simulation, and verified in control regions (CRW, CRZ)
- Non prompt leptons events:
 - Estimated in each region with “tight-to-loose” method
- Maximum-likelihood fit in 2 CR’s and 8 SR’s to extract $t\bar{t}t\bar{t}$ signal



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



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

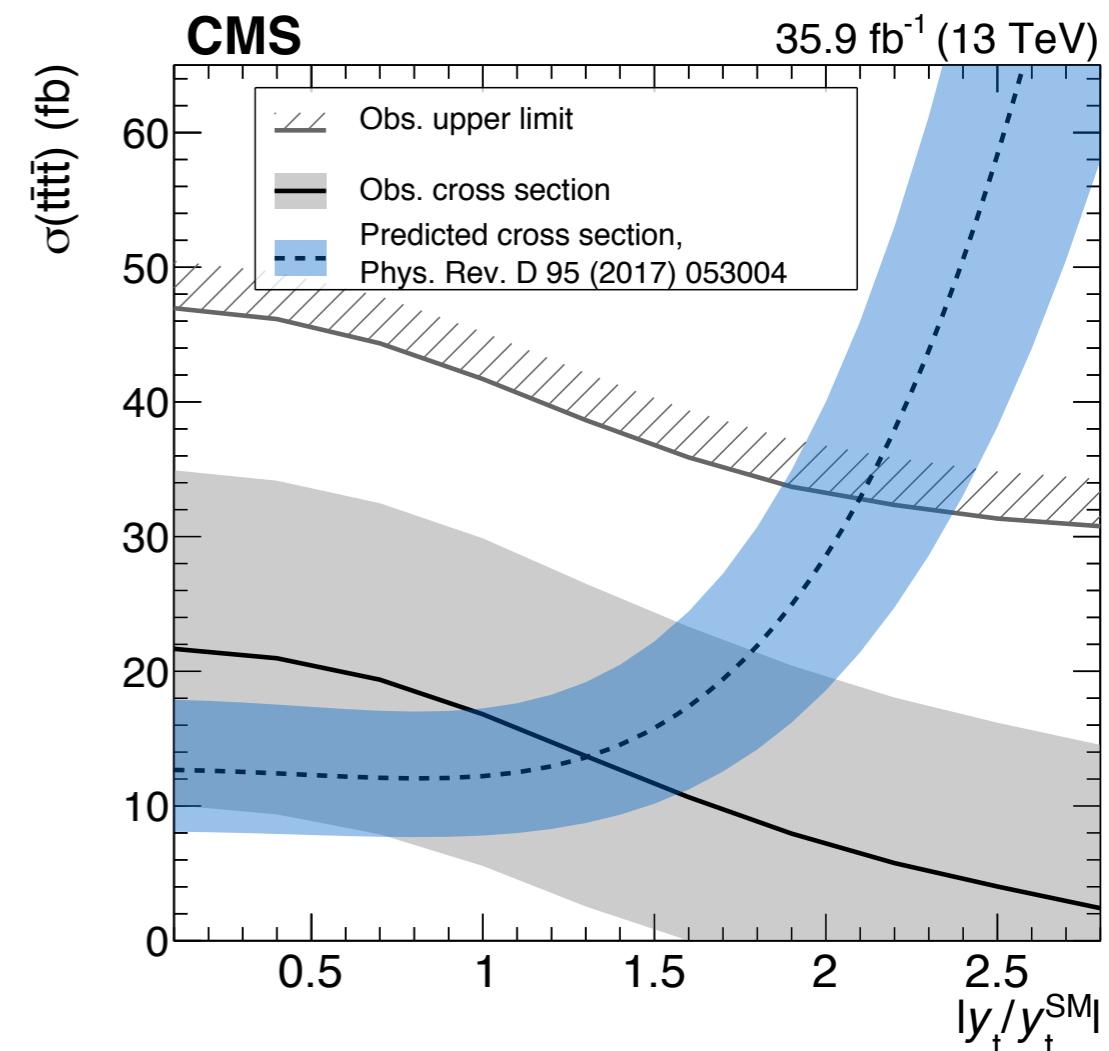
$$\sigma^{\text{meas.}}(\text{pp} \rightarrow t\bar{t}t\bar{t}) = 16.9^{+13.8}_{-11.4} \text{ fb}$$
$$\sigma^{\text{th.}}(\text{pp} \rightarrow t\bar{t}t\bar{t}) = 9.2^{+2.9}_{-2.4} \text{ fb}$$

- 95% CL upper limit of 41.7 fb
- Observed significance of 1.6σ (expected 1.0σ)
- Yukawa coupling limit at 95% of

$$|y_t/y_t^{\text{SM}}| < 2.1$$

[arXiv:1710.10614](https://arxiv.org/abs/1710.10614)
Submitted to
Eur. Phys. J. C

	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





Summary

- Results of many CMS measurements of top quark associated production presented $t\bar{t}W$, $t\bar{t}Z$, tZq , $t\bar{t}\gamma$, $t\bar{t}b\bar{b}$, $t\bar{t}t\bar{t}$
 - Great start to the precision top frontier, but still a lot more can be done to improve the reach of these channels
- ttW: 13 TeV using SS dilepton
$$\sigma(pp \rightarrow t\bar{t}W) = 0.77^{+0.12}_{-0.11}(\text{stat})^{+0.13}_{-0.12}(\text{syst}) \text{ pb}$$
- ttZ: 13 TeV using 3 & 4 leptons
$$\sigma(pp \rightarrow t\bar{t}Z) = 0.99^{+0.09}_{-0.08}(\text{stat})^{+0.12}_{-0.10}(\text{syst}) \text{ pb}$$
- tt γ : 8 TeV l+jets
$$\sigma(t\bar{t}\gamma) \times B = 515 \pm 118 \text{ fb}$$
- tZq: 13 TeV 3-lepton
$$\sigma(t\ell^+\ell^-q) = 123^{+33}_{-31}(\text{stat})^{+29}_{-23}(\text{syst}) \text{ fb}$$
- ttbb: 13 TeV (2.3 fb^{-1}) dilepton
$$\sigma(pp \rightarrow t\bar{t}b\bar{b}) = 4.0 \pm 0.6(\text{stat}) \pm 1.3(\text{syst}) \text{ fb}$$
- tt $t\bar{t}$: 13 TeV SS dilepton and ≥ 3 leptons
$$\sigma(pp \rightarrow t\bar{t}t\bar{t}) = 16.9^{+13.8}_{-11.4} \text{ fb}$$



Backup Slides



ttW/ttZ Supporting Material

$t\bar{t}W$ Selection



- ## BDT Variables
- SS dilepton, $p_T > 25 \text{ GeV}$
 - ≥ 2 jets, ≥ 1 b-tag
 - $p_T > 30 \text{ GeV}$
 - N_j
 - N_b
 - H_T : scalar sum of p_T of jets
 - p_T^{miss}
 - p_T leading lepton
 - p_T trailing lepton
 - M_T leading lepton
 - p_T leading and second leading jets
 - ΔR between trailing lepton and nearest jet



$t\bar{t}W$ Event Yields

SS Dilepton
 $D > 0$

		N_j	N_b	Background	$t\bar{t}W$	$t\bar{t}Z$	Total	Observed
$\ell^-\ell^-$	$0 < D < 0.6$	2	>0	18.1 ± 1.8	2.2 ± 0.4	0.5 ± 0.1	20.8 ± 1.9	17
		3	1	8.3 ± 0.9	2.1 ± 0.4	0.5 ± 0.1	10.9 ± 0.9	9
		>3	>1	10.9 ± 1.1	3.5 ± 0.6	0.8 ± 0.1	15.2 ± 1.3	17
		>3	1	10.1 ± 1.1	2.8 ± 0.5	0.7 ± 0.2	13.7 ± 1.3	8
	$D > 0.6$	2	>0	6.8 ± 0.9	2.0 ± 0.3	0.4 ± 0.1	9.2 ± 0.9	10
		3	1	4.1 ± 0.6	1.6 ± 0.3	0.3 ± 0.1	6.1 ± 0.6	11
		>3	>1	7.8 ± 0.9	3.8 ± 0.6	0.7 ± 0.1	12.3 ± 1.1	10
		>3	1	5.6 ± 0.7	2.9 ± 0.5	0.7 ± 0.2	9.2 ± 0.9	5
		>3	>1	15.3 ± 1.5	12.0 ± 1.9	3.2 ± 0.5	30.5 ± 2.5	32
$\ell^+\ell^+$	$0 < D < 0.6$	2	>0	17.9 ± 1.8	4.9 ± 0.8	0.3 ± 0.1	23.1 ± 2.0	26
		3	1	10.2 ± 1.3	3.7 ± 0.6	0.4 ± 0.1	14.4 ± 1.4	11
		>3	>1	10.2 ± 1.2	6.9 ± 1.1	0.8 ± 0.2	17.9 ± 1.6	18
		>3	1	10.7 ± 1.2	4.9 ± 0.8	0.8 ± 0.2	16.4 ± 1.4	16
	$D > 0.6$	>3	>1	22.4 ± 2.0	13.3 ± 2.2	3.0 ± 0.5	38.7 ± 3.0	42
		2	>0	8.0 ± 1.1	4.3 ± 0.7	0.4 ± 0.1	12.7 ± 1.3	18
		3	1	4.8 ± 0.7	3.2 ± 0.5	0.3 ± 0.1	8.4 ± 0.9	7
		>3	>1	5.4 ± 0.7	7.1 ± 1.2	1.0 ± 0.2	13.5 ± 1.4	10
		>3	1	6.3 ± 0.8	5.6 ± 0.9	0.9 ± 0.2	12.8 ± 1.2	12
		>3	>1	16.5 ± 1.5	22.5 ± 3.7	3.1 ± 0.5	42.1 ± 4.0	46

SS Dilepton
 $D < 0$

Process	$N_j = 2$	$N_j = 3$	$N_j > 3$
Nonprompt	136.5 ± 13.9	110.3 ± 11.3	57.3 ± 6.1
Total background	192.1 ± 15.6	137.7 ± 11.7	74.0 ± 6.4
$t\bar{t}W$	13.1 ± 0.3	17.6 ± 0.3	13.8 ± 0.3
$t\bar{t}Z$	1.6 ± 0.4	3.1 ± 0.7	4.4 ± 1.0
Total	206.8 ± 15.7	158.4 ± 11.8	92.3 ± 6.5
Observed	229	144	92

$t\bar{t}Z$ Event Yields



Three-lepton

N_b	N_j	Background	$t\bar{t}W$	$t\bar{t}Z$	Total	Observed
0	2	1032.8 ± 77.1	0.9 ± 0.1	18.2 ± 3.2	1051.9 ± 77.2	1022
	3	293.5 ± 21.4	0.4 ± 0.1	22.3 ± 3.9	316.3 ± 21.8	318
	>3	95.4 ± 7.4	0.3 ± 0.1	26.1 ± 4.6	121.8 ± 8.7	144
1	2	164.6 ± 17.8	1.9 ± 0.3	24.3 ± 4.3	190.7 ± 18.3	209
	3	66.6 ± 6.7	0.9 ± 0.2	41.2 ± 7.2	108.7 ± 9.8	99
	>3	32.8 ± 3.3	0.8 ± 0.1	61.3 ± 10.8	94.9 ± 11.3	72
>1	2	12.9 ± 2.4	1.0 ± 0.2	5.9 ± 1.0	19.8 ± 2.6	32
	3	11.6 ± 1.7	0.6 ± 0.1	17.9 ± 3.2	30.1 ± 3.6	46
	>3	10.6 ± 1.6	0.4 ± 0.1	41.0 ± 7.2	52.0 ± 7.4	54

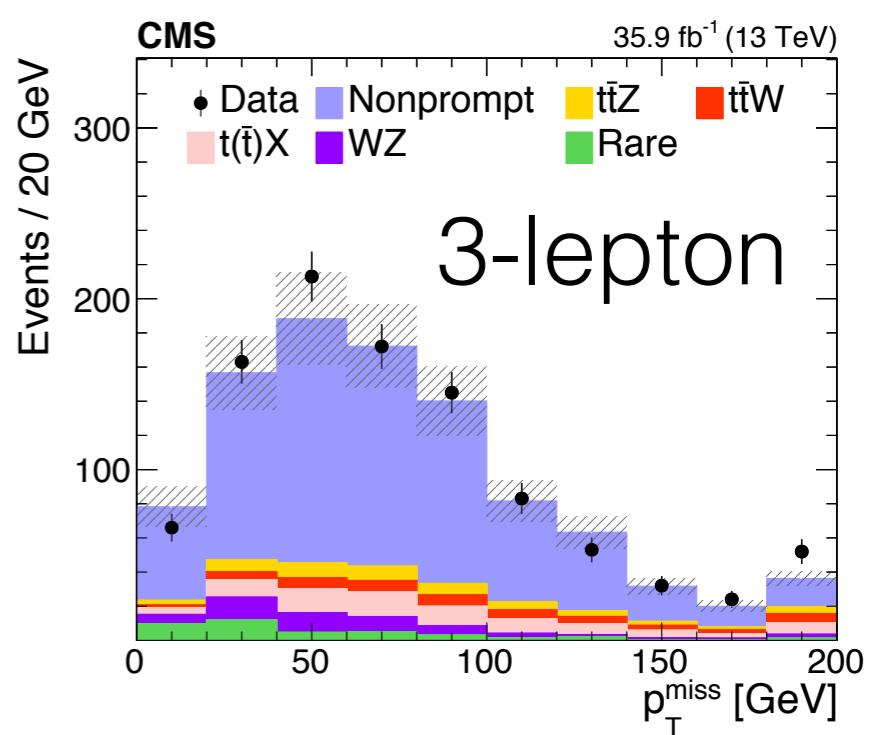
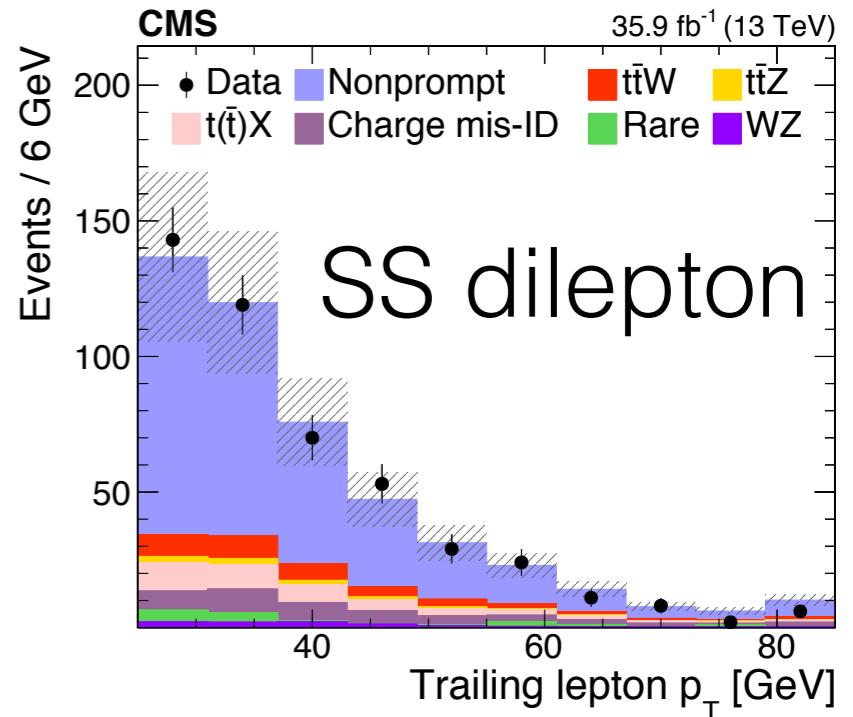
Four-lepton

Process	$N_b = 0$	$N_b > 0$
Total background	12.8 ± 2.0	3.3 ± 0.3
$t\bar{t}Z$	4.5 ± 0.6	14.5 ± 1.8
Total	17.2 ± 2.0	17.8 ± 1.8
Observed	23	15

Nonprompt Lepton Background



- Measure tight-to-loose lepton ratio (probability lepton passing loose selection passes tight selection)
 - Measured in non prompt lepton enriched control region
 - Parameterized as a function of lepton p_T and η
- Define sideband regions, same as signal regions, but where one lepton passes only loose criteria
 - Tight-to-loose ratio used to extrapolate from application region to signal regions
- Verified in MC, and non prompt enriched control regions:
 - BDT < 0 in SS dilepton
 - In 3 lepton, look for OSSF pair outside Z-window





ttGamma Supporting Material

tt+gamma Event Yields



Sample	Genuine photon	Misid. electron	Nonprompt photon	Total
t̄t+γ	312 ± 17	0.2 ± 0.1	8.5 ± 0.9	321 ± 17
t̄t+jets	—	22 ± 3	215 ± 13	237 ± 14
W+γ	75 ± 25	—	—	75 ± 25
W+jets	—	—	60 ± 15	60 ± 15
Z+γ	14 ± 5	1.3 ± 1.1	0.5 ^{+0.7} _{-0.5}	16 ± 5
Z+jets	—	43 ± 28	11 ± 6	54 ± 30
Single t	11 ± 3	2.0 ± 1.3	16 ± 4	29 ± 7
QCD multijet	—	—	31 ± 18	31 ± 18
Total	412 ± 31	69 ± 29	342 ± 28	823 ± 52
Data	—	—	—	935

Sample	Genuine photon	Misid. electron	Nonprompt photon	Total
t̄t+γ	407 ± 23	0.4 ± 0.3	11 ± 1	418 ± 24
t̄t+jets	—	31 ± 5	291 ± 16	322 ± 17
W+γ	140 ± 41	—	9.0 ± 6.7	149 ± 45
W+jets	—	—	57 ± 14	57 ± 14
Z+γ	21 ± 7	—	1.4 ± 0.9	23 ± 7
Z+jets	—	—	9.6 ± 5.8	10 ± 6
Single t	12 ± 3	1.5 ± 1.3	25 ± 13	38 ± 14
QCD multijet	—	—	36 ± 20	36 ± 20
Total	580 ± 48	33 ± 5	440 ± 33	1053 ± 61
Data	—	—	—	1136

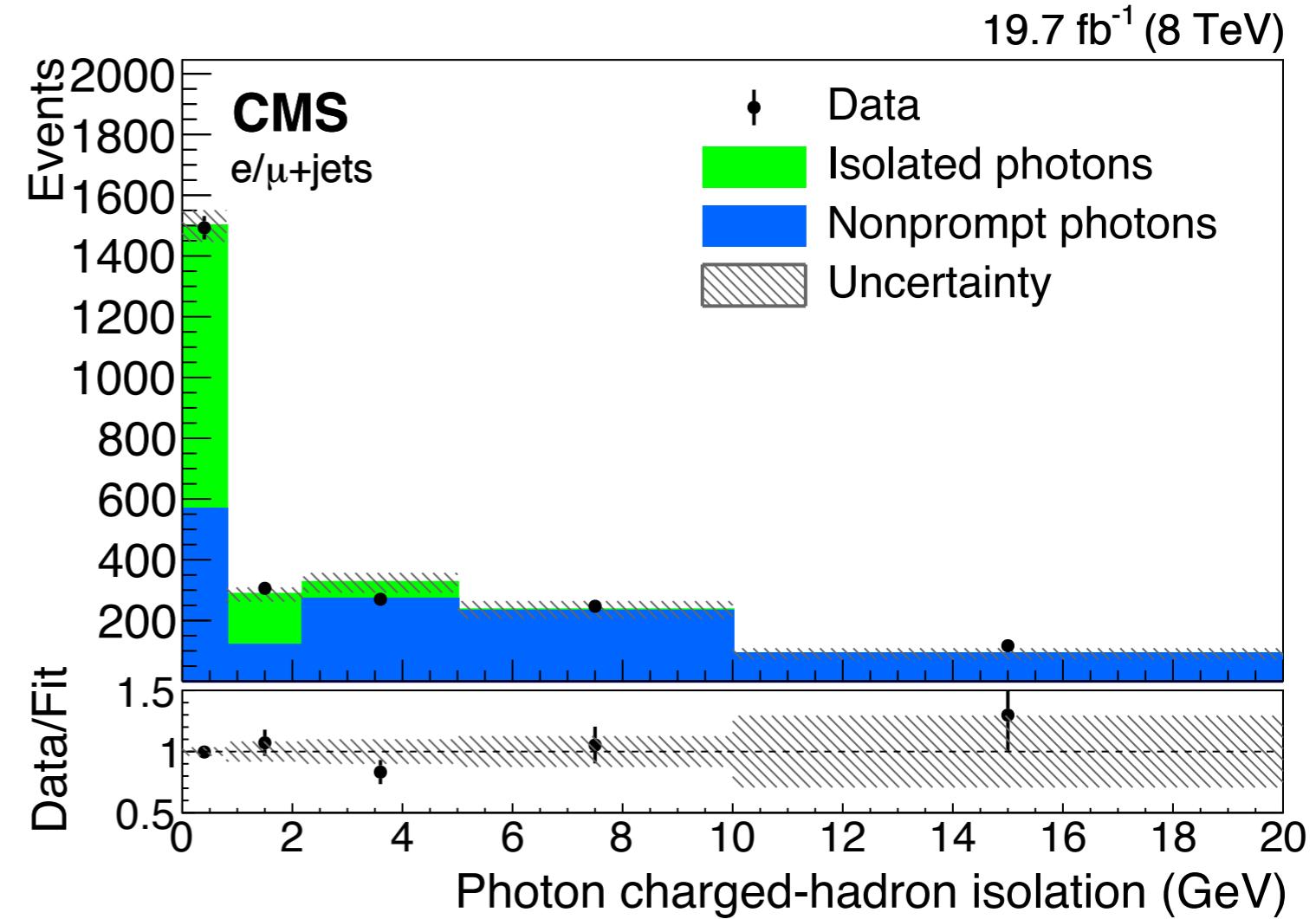
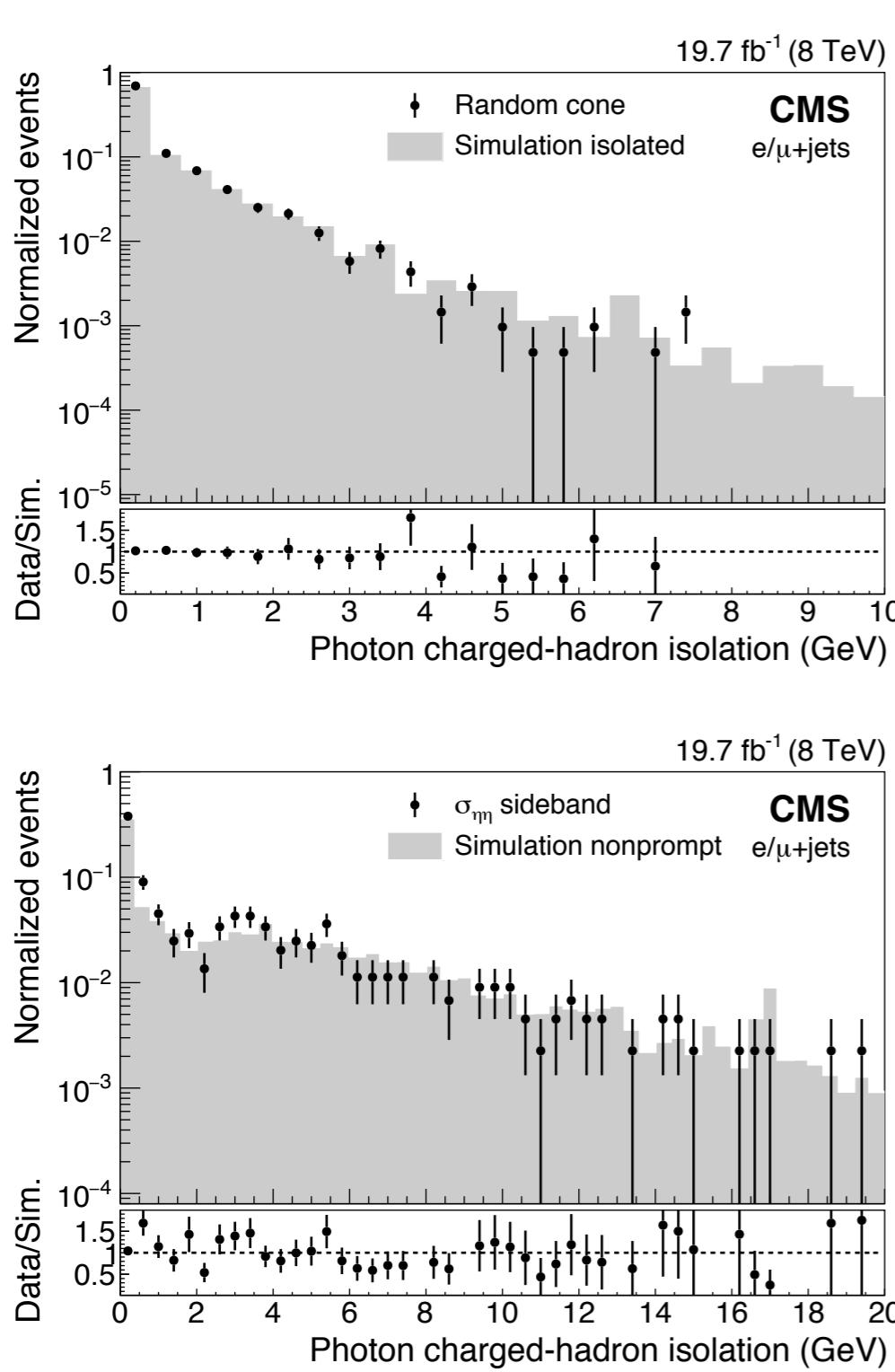
tt+gamma Uncertainties



- Largest contribution is statistical (likelihood fit uncertainty)
- Followed by modeling uncertainties:
 - Top mass
 - Q2 scale

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

tt+gamma



- Fit to photon charged-hadron isolation to extract photon purity (percent of photons coming from genuine sources)
- Data driven templates of isolated (genuine) photons and non-prompt (fake)



tZq Supporting Material



BDT Variables

Variable	Ranking BDT (3l,2-3j,1bj region)	Ranking BDT (3l,>1j,>1bj region)
$p_T(j)$	1	11
MEM Kin. Fit w_{tZq}	2	3
l^W asymmetry	3	6
dR_{jj}	4	10
CSV btag discriminant	5	2
$\Delta R(l^W - j_{closest})$	6	14
$\Delta\phi(Z - l^W)$	7	12
$\Delta\phi(l^W - b)$	8	21
MEM Kin. Fit $w_{t\bar{t}Z}$	9	23
MEM Likelihood Ratio tZq-t \bar{t} Z-WZ	10	-
$ \eta(j') $	11	4
MEM Likelihood Ratio tZq-t \bar{t} Z	12	5
top quark mass m_t	13	7
$ \eta(j^{lead}) $	14	-
$\eta(Z)$	15	9
$\eta(l^W)$	16	18
jet multiplicity	17	1
$\Delta R(l^W - j')$	18	15
$\Delta R(Z - l^W)$	19	19
$p_T(Z)$	20	8
$p_T(tZq)$	21	17
$\Delta R(Z - top)$	-	13
TopPT	-	16
b-jet multiplicity	-	20
Trilepton mass	-	22



Event Yields

Table 1: Observed and post-fit expected yields for each production process in the 1bjet region. The yields of columns 2–5 correspond to each channel, and column 6 displays the total for all channels. The last column displays the ratio between post-fit and pre-fit yields.

Process	eee	ee μ	e $\mu\mu$	$\mu\mu\mu$	All channels	N ^{post-fit} / N ^{pre-fit}
tZq	5.0 ± 1.5	6.6 ± 1.9	8.5 ± 2.5	12.3 ± 3.6	32.3 ± 5.0	—
t \bar{t} Z	3.7 ± 0.7	4.7 ± 0.9	6.1 ± 1.2	8.0 ± 1.5	22.4 ± 2.2	0.9 ± 0.2
t \bar{t} W	0.3 ± 0.1	0.3 ± 0.1	0.7 ± 0.2	0.6 ± 0.2	1.9 ± 0.3	1.0 ± 0.2
ZZ	4.8 ± 1.3	3.2 ± 0.9	9.0 ± 2.5	7.8 ± 2.2	24.7 ± 3.6	1.3 ± 0.3
WZ+b	3.0 ± 0.9	3.4 ± 1.1	4.6 ± 1.4	5.5 ± 1.7	16.6 ± 2.6	1.0 ± 0.2
WZ+c	9.0 ± 2.4	13.7 ± 3.7	18.0 ± 4.9	24.2 ± 6.5	64.8 ± 9.3	1.0 ± 0.2
WZ+light	12.2 ± 1.6	16.6 ± 2.0	22.4 ± 2.8	29.1 ± 3.4	80.3 ± 5.1	0.7 ± 0.1
t \bar{t} H	0.6 ± 0.2	0.9 ± 0.3	1.0 ± 0.3	1.5 ± 0.4	4.0 ± 0.6	1.0 ± 0.2
tWZ	1.0 ± 0.3	1.3 ± 0.4	1.7 ± 0.5	2.4 ± 0.7	6.5 ± 1.0	1.0 ± 0.2
NPL: electrons	19.2 ± 3.1	0.6 ± 0.1	17.9 ± 2.8	—	37.7 ± 4.2	—
NPL: muons	—	7.2 ± 2.3	31.1 ± 9.9	15.3 ± 4.9	53.6 ± 11.3	—
Total	58.8 ± 4.8	58.4 ± 5.5	121 ± 12	107 ± 10	345 ± 18	
Data	56	58	104	125	343	



ttbb Supporting Material

Event Yields & Systematics



Process	e^+e^-	$\mu^+\mu^-$	$e^\pm\mu^\mp$	All
$t\bar{t}bb$	6.3 ± 0.4	8.6 ± 0.4	24 ± 1	39 ± 1
$t\bar{t}bj$	16 ± 1	21 ± 1	57 ± 2	95 ± 2
$t\bar{t}cc\bar{c}$	7.7 ± 0.4	11 ± 1	27 ± 1	46 ± 1
$t\bar{t}LF$	157 ± 2	220 ± 2	596 ± 3	972 ± 4
$t\bar{t}$ others	18 ± 1	19 ± 1	61 ± 1	99 ± 1
$t\bar{t} V$	2.5 ± 0.1	3.2 ± 0.2	7.3 ± 0.2	14 ± 1
Single t	6.6 ± 0.8	8.4 ± 0.8	23 ± 2	39 ± 2
Z+jets	$0.8^{+1.0}_{-0.8}$	5.4 ± 1.5	0.6 ± 0.5	6.8 ± 1.9
Total	215 ± 2	297 ± 3	796 ± 4	1311 ± 6
Data	186	288	682	1156

Source	$\sigma_{t\bar{t}bb\bar{b}}$	$\sigma_{t\bar{t}jj}$	$\sigma_{t\bar{t}bb\bar{b}}/\sigma_{t\bar{t}jj}$
Pileup	0.4	<0.1	0.4
JES & JER	7.8	7.4	2.6
b tag (b quark flavour)	19	4.7	19
b tag (c quark flavour)	14	1.3	14
b tag (light flavour)	14	9.8	9.7
Ratio of $t\bar{t}bb\bar{b}$ and $t\bar{t}bj$	2.6	0.5	2.6
Background modelling	3.8	3.5	1.6
$t\bar{t}cc\bar{c}$ fraction in the fit	5.2	1.9	4.8
Lepton trigger/identification	3.0	3.0	0
MC generator	9.4	6.2	3.0
μ_F and μ_R scale	2.0	2.0	1.0
scale in PS	13	9.9	10
PDFs	0.5	0.5	<0.1
Efficiency ($t\bar{t}cc\bar{c}$ fraction)	0	1.3	1.3
Jet multiplicity modelling	5.0	5.0	5.0
Top quark p_T modelling	0.8	0.3	0.5
Simulation (statistical)	1.5	1.5	1.5
Integrated Luminosity	2.3	2.3	0
Total uncertainty	34	19	28



Four top Supporting Material

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
t̄H (normalization)	50
Rare, Xγ, t̄tVV (norm.)	50
t̄Z, t̄W (normalization)	40
Charge misidentification	20
Nonprompt leptons	30–60