FOUR TOP QUARKS PRODUCTION AT THE LHC (AND BEYOND)

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Four top quark production in LHC

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Summary and Outlook

MOTIVATION

Top quark is special

- Large mass – Higgs-top coupling ~ 1, vacuum meta-stability
- Large $|V_{tb}| \approx 1$
- Short lifetime

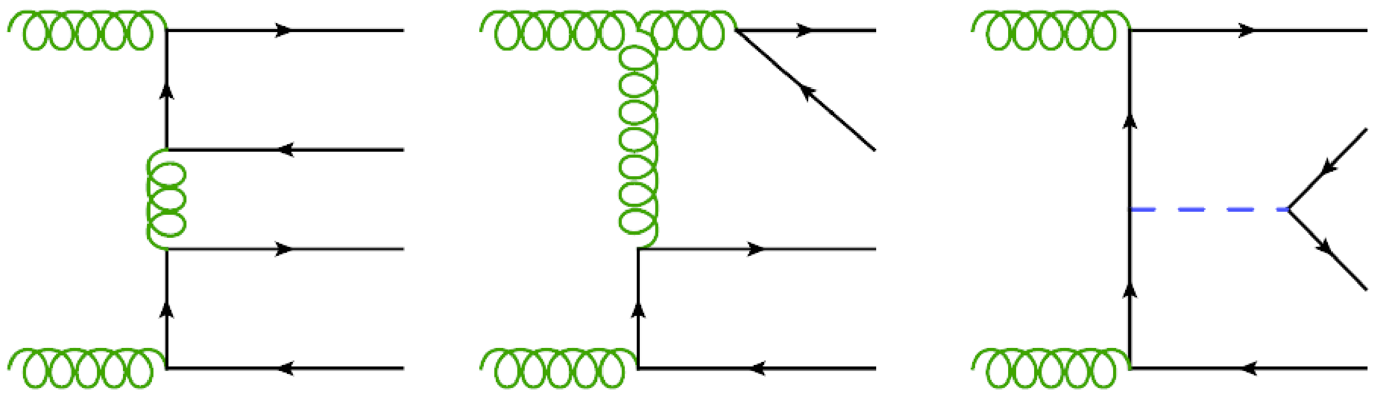
Avenues for beyond the SM with top quarks

- Search for deviation from SM : top couplings to SM particles, asymmetries, rare processes, FCNC, total top decay width
- Search for new particles stronger coupling to top quark

TOP QUARKS AT THE LHC

	13 TeV - 30 fb^{-1}	13/14 TeV - 3000 fb^{-1}
$t\bar{t}$	30 Mevts	3 Gevts
$t\bar{t}$ (fiducial)	1.55 Mevts	155 Mevts
$t\bar{t}$ with $M_{t\bar{t}}$ > 1 TeV (fiducial)	30 kevts	3 Mevts
$t\bar{t}$ with $M_{t\bar{t}}$ > 2 TeV (fiducial)	480 evts	48 kevts
t-channel	6 Mevts	600 Mevts
Wt-channel	2 Mevts	200 Mevts
s-channel	300 kevts	30 Mevts
ttV	30 kevts	3 Mevts
tZ	3 kevts	300 kevts
tH	300 evts	30 kevts

FOUR TOP QUARKS IN SM



Production

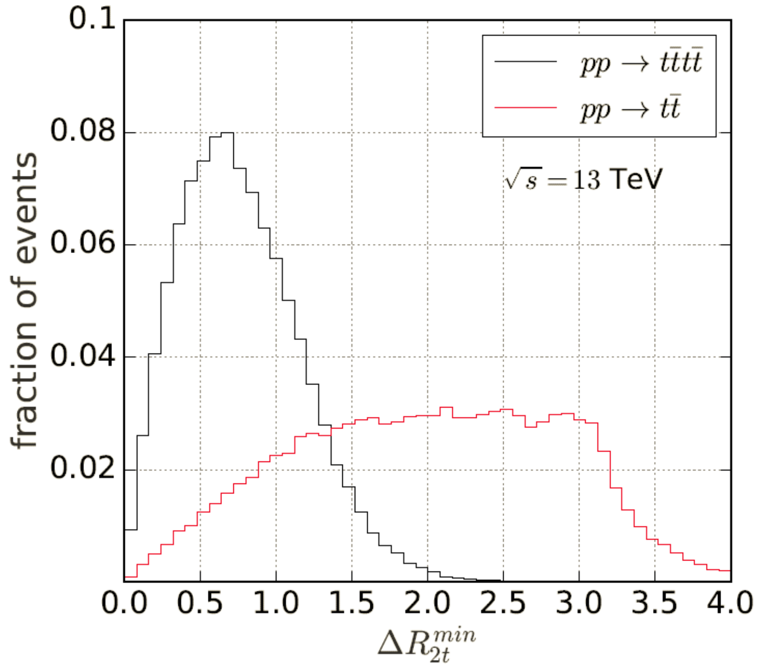
- Strong $O(\alpha_s^4)$
- Partially electroweak $O(\alpha_s^2 y_t^4)$, $O(\alpha_s^2 \alpha^2)$

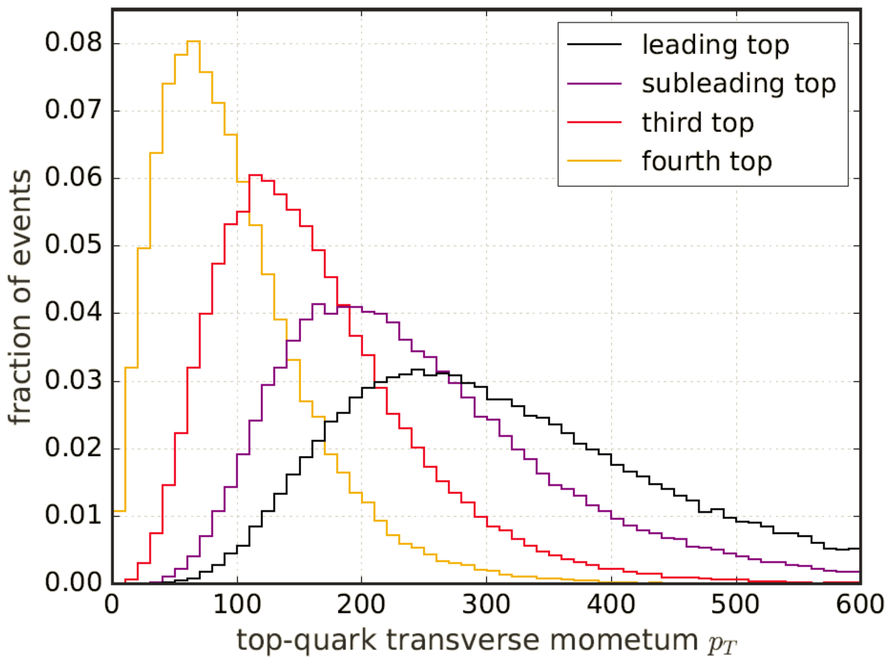
Production cross sections

- At $\sqrt{s} = 13$ TeV pp: 9.7 fb (LO) 12.2 (NLO)
- At $\sqrt{s} = 14$ TeV pp: 17 fb (NLO)
- $\sim 25\%$ uncertainties from scale

CHARACTERISTICS OF FOUR TOP EVENTS

Already at $\sqrt{s} = 13$ TeV, top quarks are produced close to each other





FINAL STATES OF THE FOUR TOP QUARKS

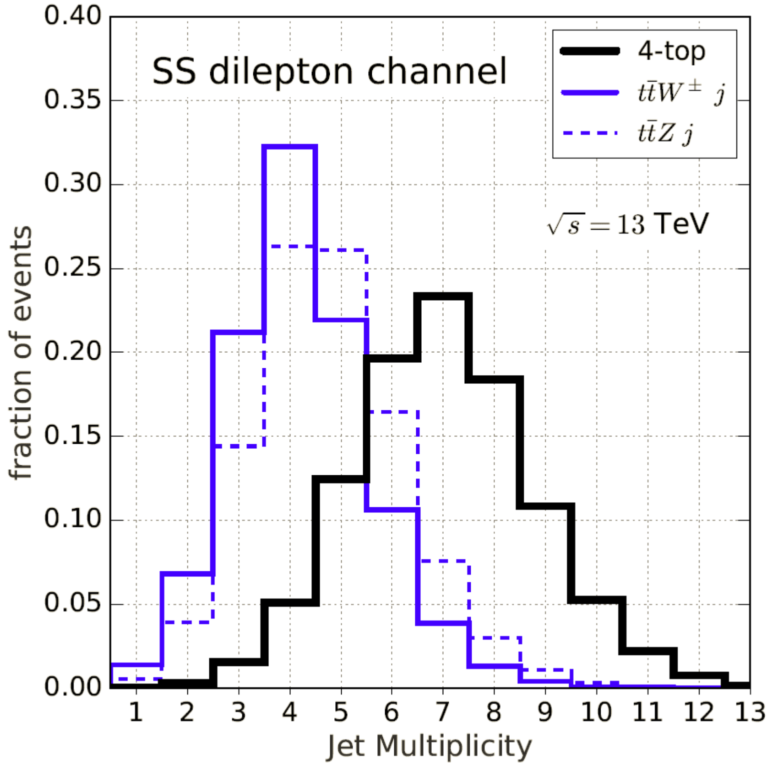
Single lepton: 40%

Dilepton: 29%

- Same sign dilepton : 9.7%

Trilepton: 9.8%

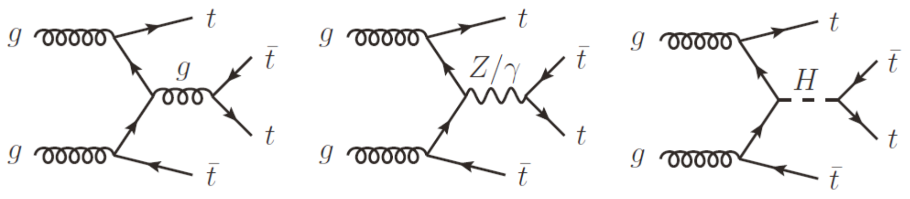
Full leptonic: 1.2%



FOUR TOP QUARKS CONNECTION WITH HIGGS

arXiv:1602.01934

Off-shell Higgs contribution to four top production

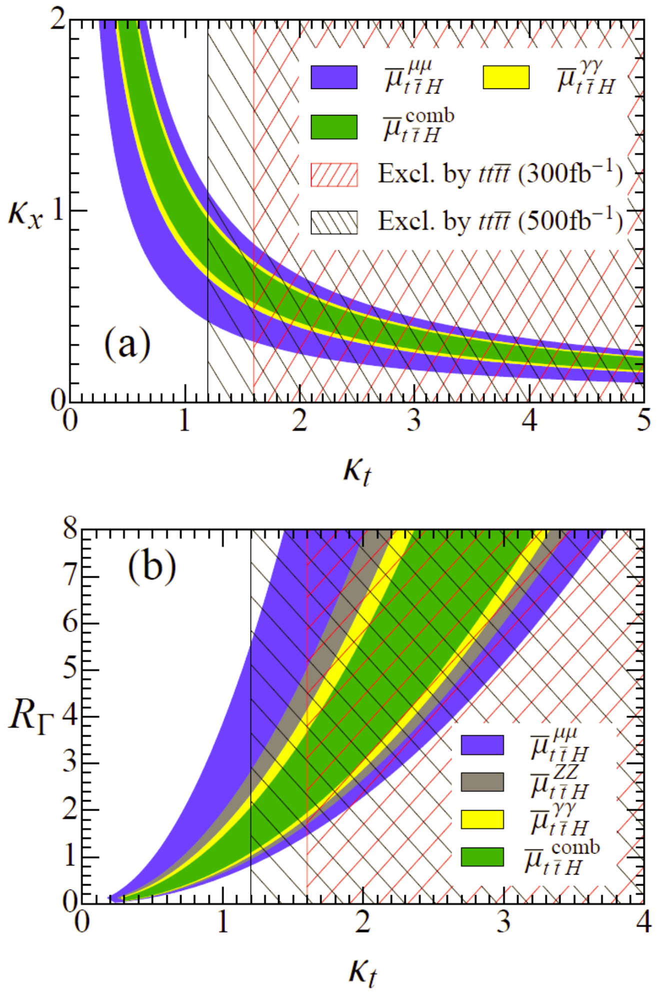


$\sim y_t^4$

	8 TeV	14 TeV
$\sigma^{\rm SM}(t\bar{t}t\bar{t})_{g+Z/\gamma}$:	1.193 fb,	12.390 fb,
$\sigma^{\rm SM}(t\bar{t}t\bar{t})_{H}$:	0.166 fb,	1.477 fb,
$\sigma^{\rm SM}(t\bar{t}t\bar{t})_{\rm int}$:	−0.229 fb,	−2.060 fb.

$$\sigma(pp \to t\bar{t}H \to t\bar{t}xx) = \sigma^{\rm SM}(pp \to t\bar{t}H \to t\bar{t}xx) \times \kappa_t^2 \kappa_x^2 \frac{\Gamma_H^{\rm SM}}{\Gamma_H}$$

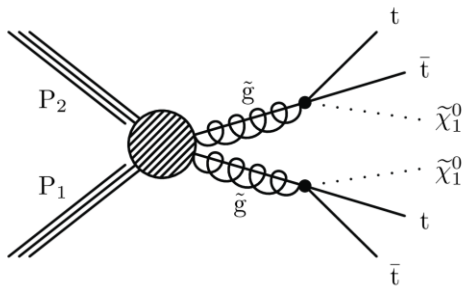
$$\sigma(t\bar{t}t\bar{t})_H \propto \kappa_t^4 \sigma^{\rm SM}(t\bar{t}t\bar{t})_H$$



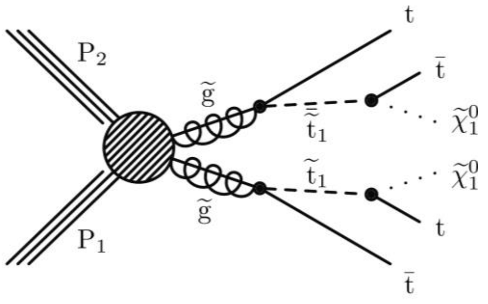
Projected uncertainties

FOUR TOP QUARKS BEYOND THE SM

Gluino pair production

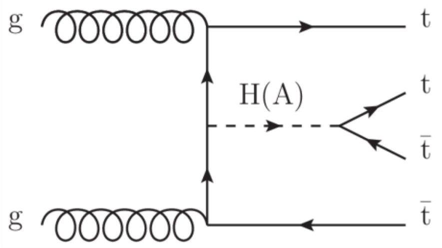


(a) T1tttt

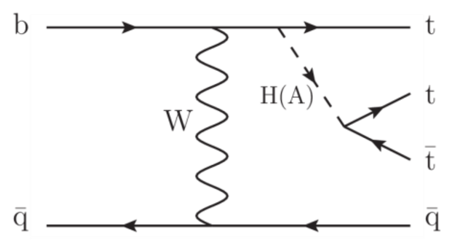


(c) T5tttt

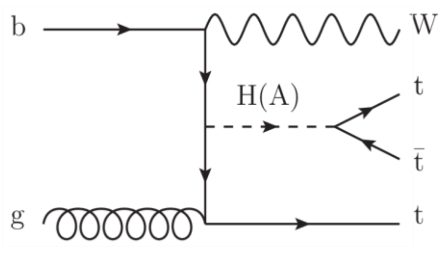
Pseudoscalar produced
in association with top pair



(a) $t\bar{t}H$



(b) tHq



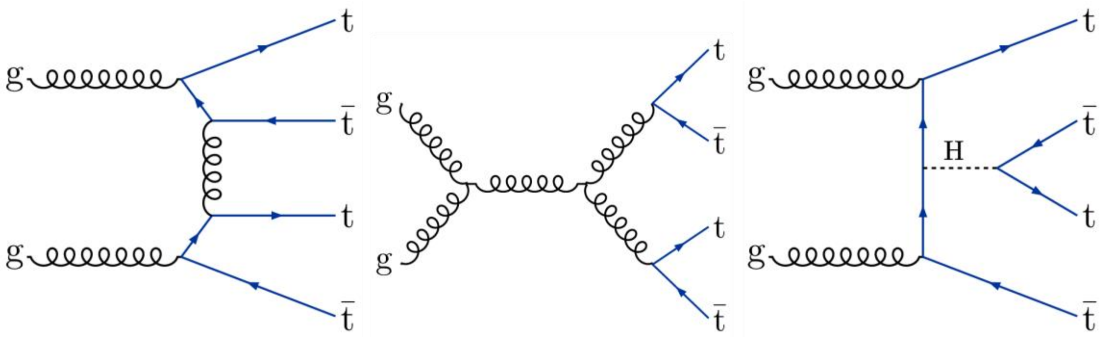
(c) tHW

Sgluon pair production

SEARCH FOR SM FOUR TOP QUARK PRODUCTION AT CMS

FOUR TOP QUARK PRODUCTION

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



Four top quark production

- $\sigma_{NLO}(pp \rightarrow t\bar{t}t\bar{t}) = 9.2^{+2.9}_{-2.4} fb$ 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}	$> 20\ GeV$

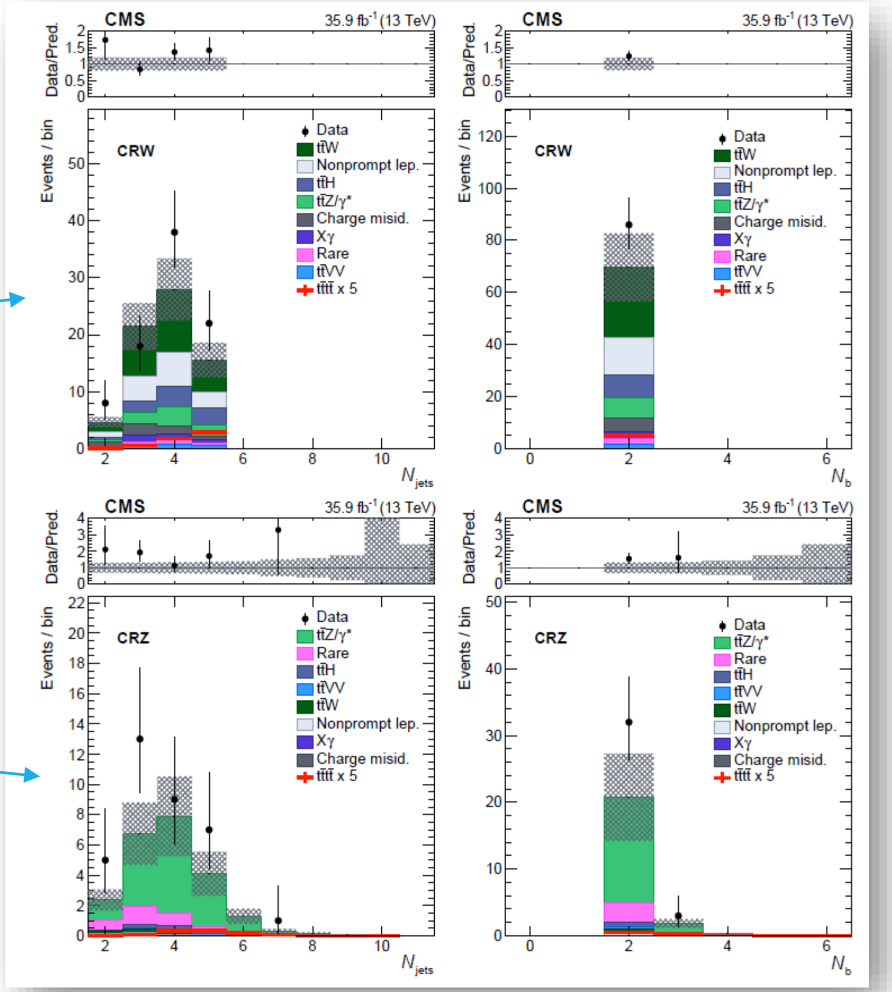
- Dilepton mass requirements to remove DY and onia

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



ANALYSIS

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

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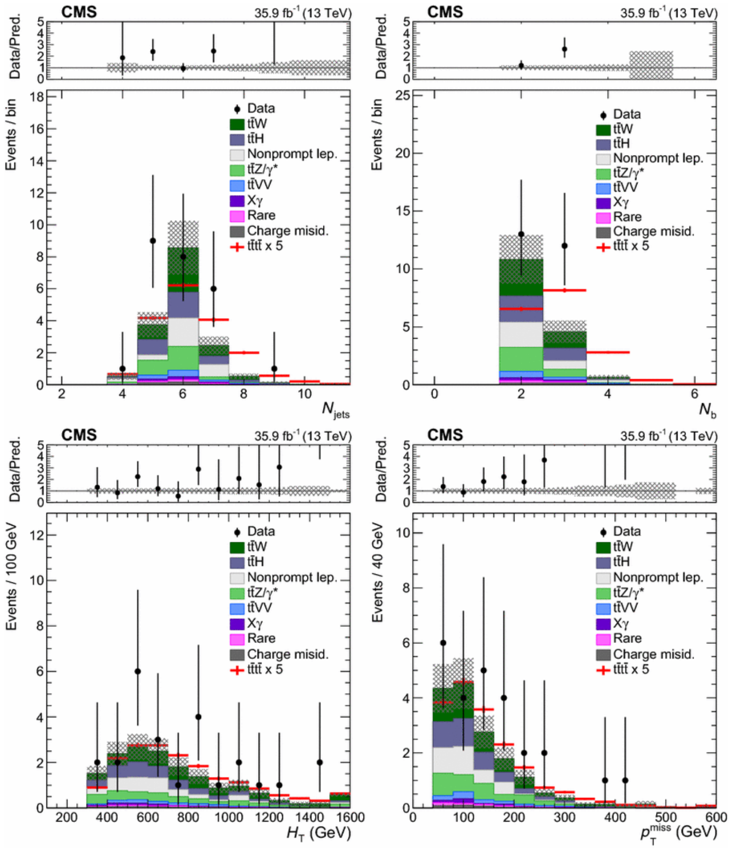
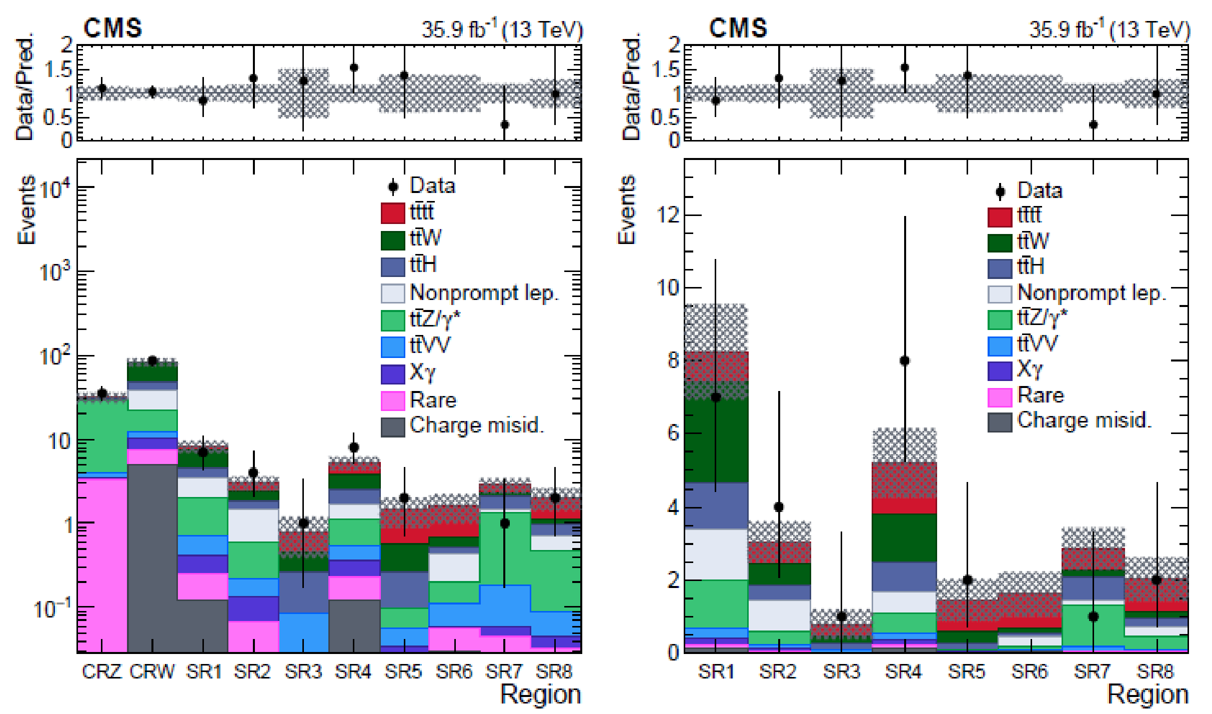


Signal region
Pre-fit

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 cross section upper limit

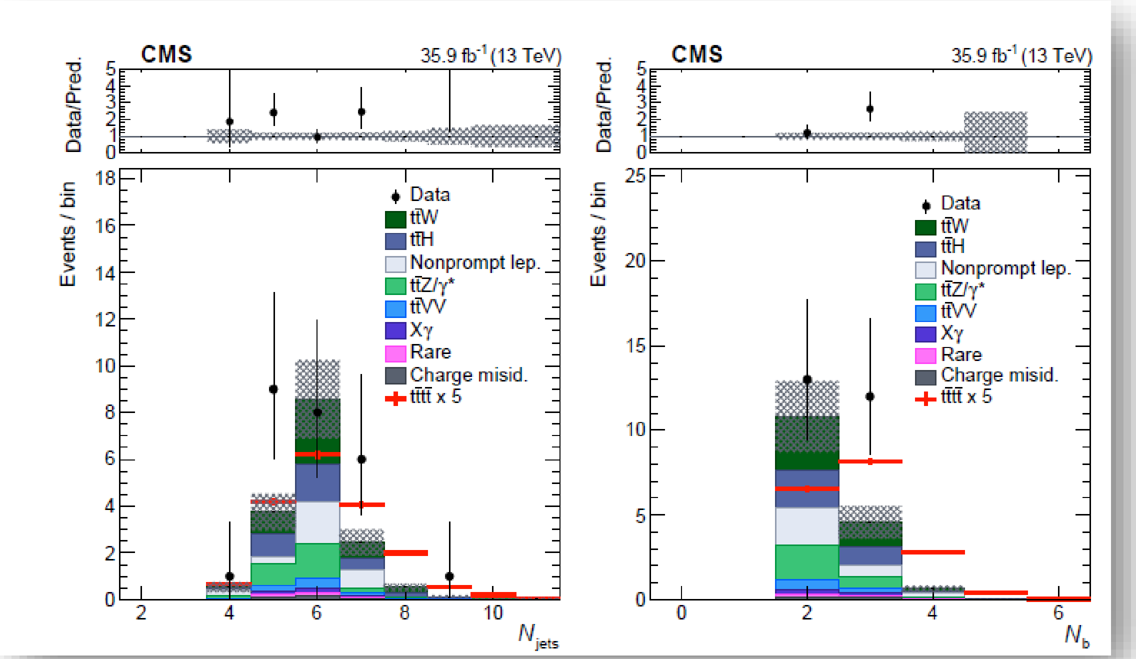
41.7

Cross section upper limit

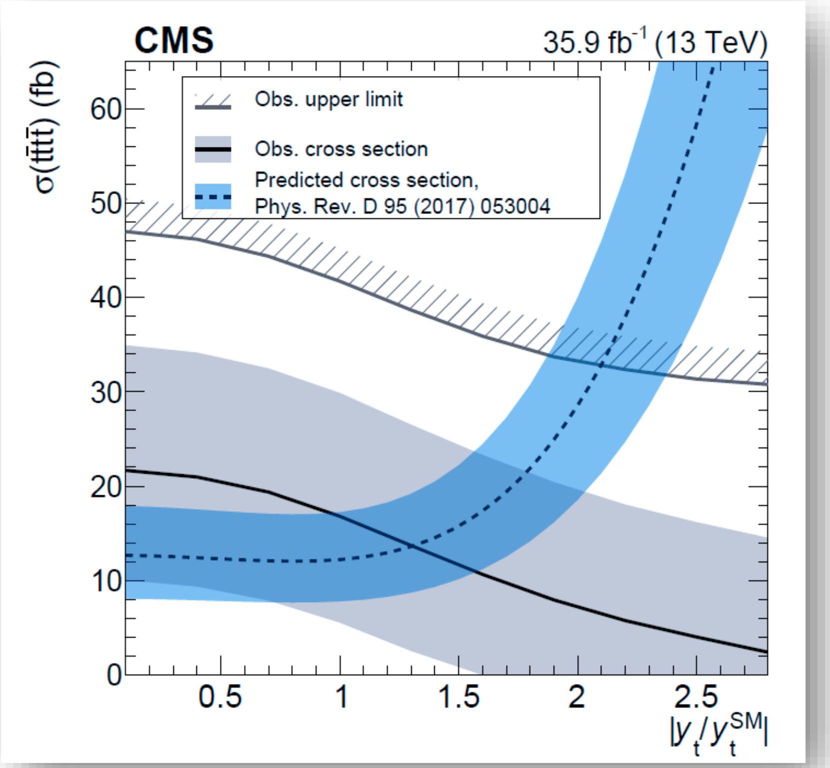
$20.8^{+11.2}_{-6.9}$fb

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



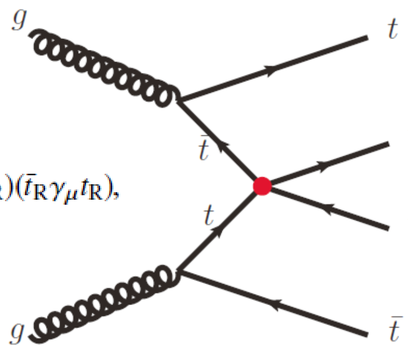
SEARCH FOR ANOMALOUS FOUR TOP PRODUCTION IN ATLAS

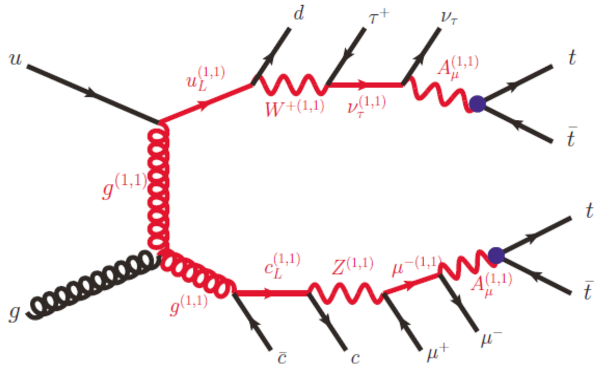
ANOMALOUS FOUR TOP SEARCH IN ATLAS

Four top search in ATLAS in BSM

- Composite Higgs
- Some UED models – 2UED/RPP

$$\mathcal{L}_{4t} = \frac{|C_{4t}|}{\Lambda^2}(\bar{t}_R\gamma^\mu t_R)(\bar{t}_R\gamma_\mu t_R),$$

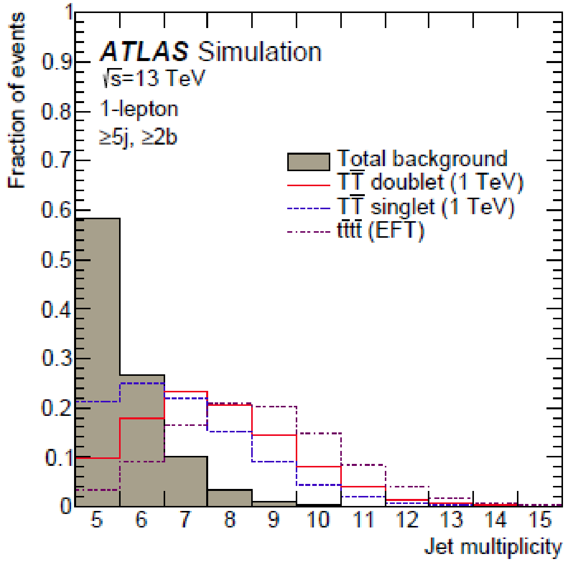




Based on 2015 – 2016 data (36.1 fb^{-1})

- Single lepton trigger used for four top search

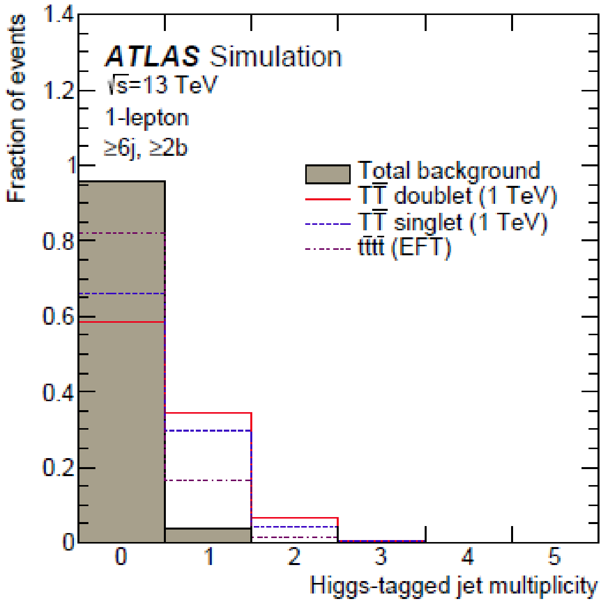
	Preselection requirements
Requirement	1-lepton channel
Trigger	Single-lepton trigger
Leptons	$=1$ isolated e or μ
Jets	≥ 5 jets
b-tagging	≥ 2 b-tagged jets
E_T^{miss}	$E_T^{miss} > 20$ GeV
Other E_T^{miss}-related	$E_T^{miss} + m_T^W > 60$ GeV

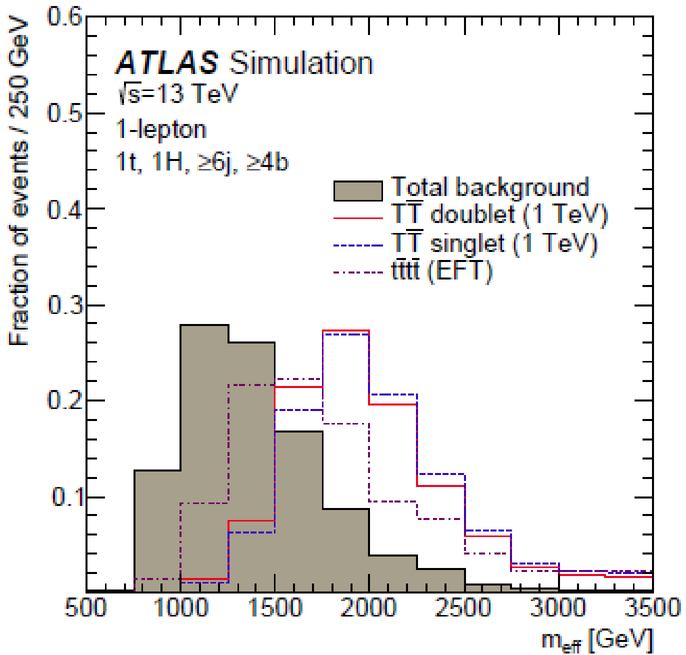


SEARCH STRATEGY

To be sensitive to boosted topology, $\Delta R = 0.4, 1.0$ jets used

- Reclustered large R jet using 0.4 jet candidates
- “Higgs-tagged” here means $p_T > 200\ GeV$ and $m_{jet}: 105 - 140\ GeV$
- “Top-tagged” - $p_T > 300\ GeV$ and $m_{jet} > 140\ GeV$

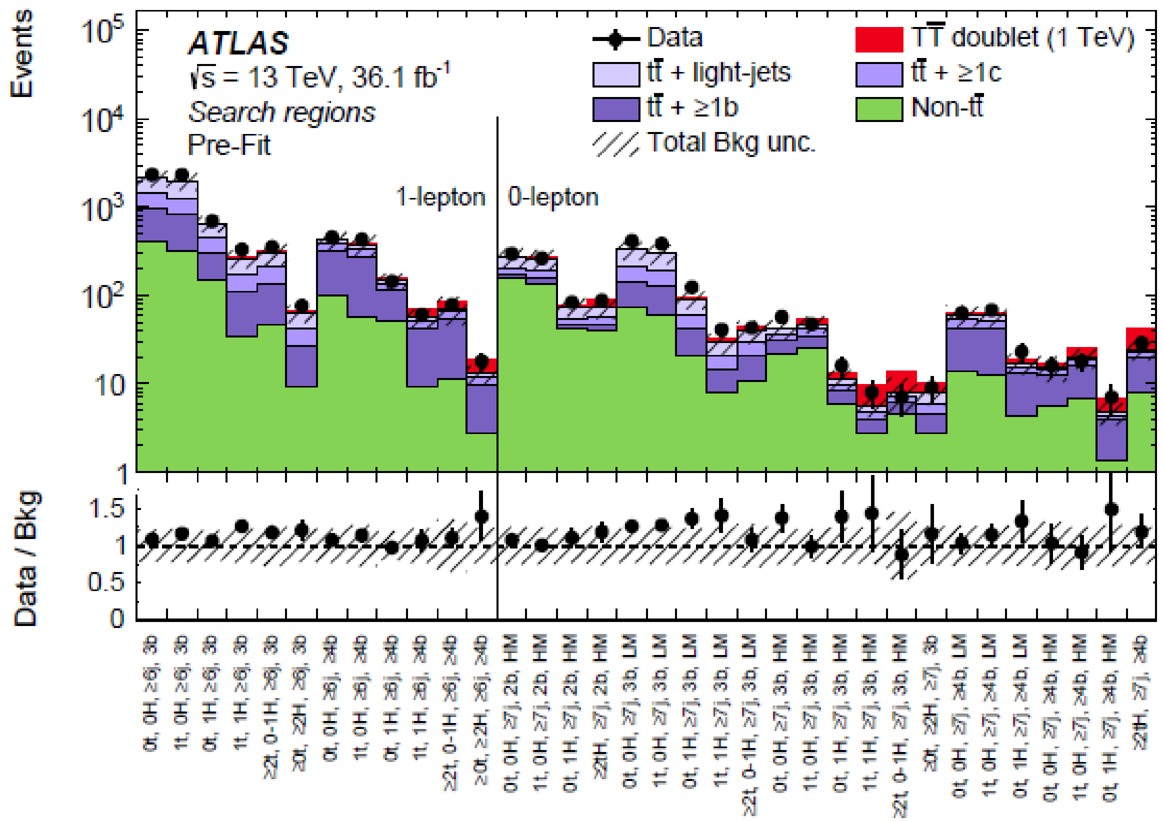




PRE-FIT

Divide sample into different
- # of b-tags
- # of top-tags
- # of Higgs-tags

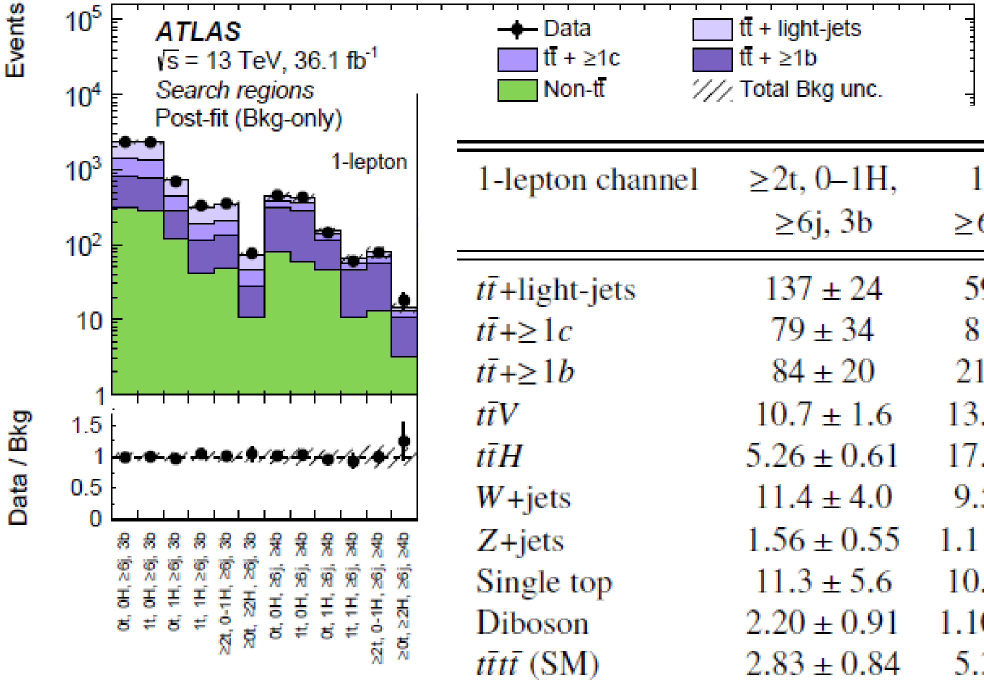
Likelihood fit performed simultaneously with all bins



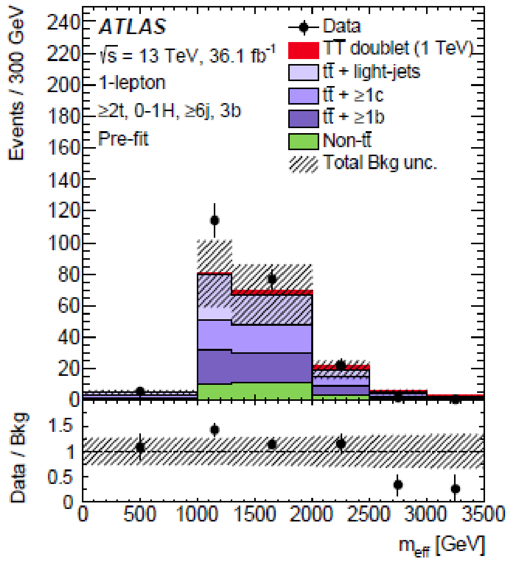
YIELDS PRE-FIT

1-lepton channel	$\geq$2t, 0–1H, $\geq$6j, 3b	1t, 0H, $\geq$6j, $\geq$4b	1t, 1H, $\geq$6j, $\geq$4b	$\geq$2t, 0–1H, $\geq$6j, $\geq$4b	$\geq$0t, $\geq$2H, $\geq$6j, $\geq$4b
$T\bar{T}$ (m_T = 1 TeV)					
$\mathcal{B}(T \rightarrow Ht) = 1$	19.6 ± 1.5	21.5 ± 2.6	24.3 ± 2.7	23.9 ± 2.8	14.6 ± 2.0
T doublet	14.2 ± 1.0	15.2 ± 1.6	12.5 ± 1.4	13.3 ± 1.5	5.96 ± 0.62
T singlet	7.88 ± 0.58	8.13 ± 0.94	5.47 ± 0.62	5.51 ± 0.69	2.18 ± 0.23
$t\bar{t}t\bar{t}$					
EFT ($\lvert C_{4t}\rvert/\Lambda^2 = 4\pi$ TeV^{-2})	535 ± 30	706 ± 80	171 ± 19	468 ± 55	34.3 ± 5.0
2UED/RPP (m_{KK} = 1.6 TeV)	9.77 ± 0.46	1.84 ± 0.35	1.00 ± 0.19	8.9 ± 1.4	0.39 ± 0.09
$t\bar{t}$+light-jets	91 ± 46	38 ± 17	4.8 ± 2.4	5.4 ± 3.3	0.99 ± 0.49
$t\bar{t}$+$\geq$1c	75 ± 45	64 ± 38	9.5 ± 5.6	11.8 ± 7.5	2.1 ± 1.3
$t\bar{t}$+$\geq$1b	86 ± 41	215 ± 83	32.4 ± 9.5	42 ± 22	7.1 ± 2.2
$t\bar{t}V$	9.7 ± 1.8	11.4 ± 2.4	1.73 ± 0.39	2.46 ± 0.53	0.41 ± 0.10
$t\bar{t}H$	4.90 ± 0.78	15.0 ± 2.8	3.79 ± 0.65	2.84 ± 0.62	1.19 ± 0.20
W+jets	9.4 ± 4.4	8.2 ± 4.2	0.69 ± 0.50	1.32 ± 0.71	0.54 ± 0.48
Z+jets	1.31 ± 0.64	0.95 ± 0.48	0.10 ± 0.07	0.13 ± 0.08	0.06 ± 0.05
Single top	13.1 ± 5.5	16.6 ± 7.0	1.69 ± 0.76	1.97 ± 0.95	0.26 ± 0.21
Diboson	1.8 ± 1.1	0.99 ± 0.55	0.11 ± 0.09	0.22 ± 0.14	0.01 ± 0.04
$t\bar{t}t\bar{t}$ (SM)	2.82 ± 0.86	4.9 ± 1.6	1.12 ± 0.36	2.55 ± 0.82	0.23 ± 0.07
Total background	299 ± 83	380 ± 110	56 ± 13	71 ± 25	12.9 ± 3.2
Data	353	428	60	78	18

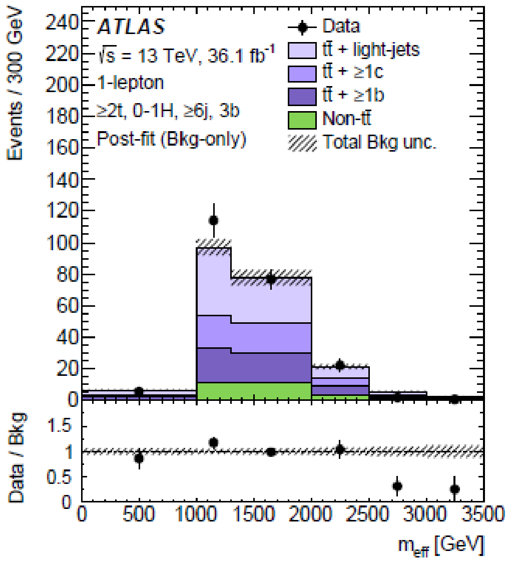
POST-FIT



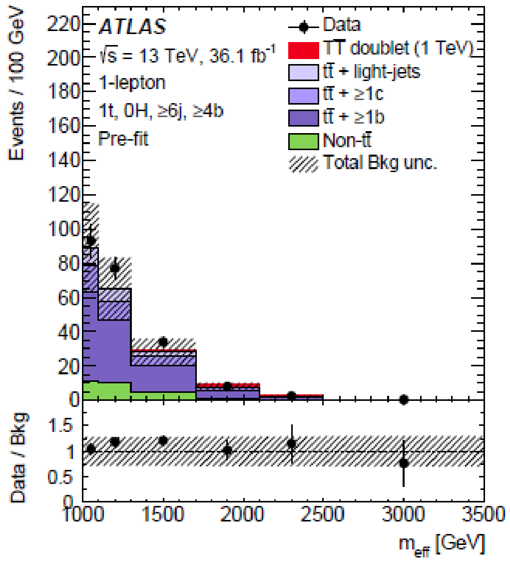
1-lepton channel	≥2t, 0–1H, ≥6j, 3b	1t, 0H, ≥6j, ≥4b	1t, 1H, ≥6j, ≥4b	≥2t, 0–1H, ≥6j, ≥4b	≥0t, ≥2H, ≥6j, ≥4b
$t\bar{t}$+light-jets	137 ± 24	59 ± 11	7.6 ± 1.6	9.0 ± 2.0	1.50 ± 0.34
$t\bar{t}+\geq 1c$	79 ± 34	81 ± 26	11.4 ± 3.8	12.4 ± 5.1	2.36 ± 0.84
$t\bar{t}+\geq 1b$	84 ± 20	217 ± 27	35.3 ± 5.6	44.1 ± 9.1	7.4 ± 1.2
$t\bar{t}V$	10.7 ± 1.6	13.2 ± 2.1	2.12 ± 0.34	2.82 ± 0.46	0.50 ± 0.08
$t\bar{t}H$	5.26 ± 0.61	17.4 ± 2.3	4.28 ± 0.56	3.25 ± 0.46	1.33 ± 0.17
W+jets	11.4 ± 4.0	9.5 ± 3.4	0.71 ± 0.36	1.68 ± 0.59	0.78 ± 0.31
Z+jets	1.56 ± 0.55	1.11 ± 0.41	0.08 ± 0.06	0.16 ± 0.06	0.07 ± 0.04
Single top	11.3 ± 5.6	10.8 ± 6.2	2.01 ± 0.62	1.85 ± 0.90	0.24 ± 0.15
Diboson	2.20 ± 0.91	1.10 ± 0.50	0.20 ± 0.08	0.30 ± 0.12	0.03 ± 0.07
$t\bar{t}t\bar{t}$ (SM)	2.83 ± 0.84	5.3 ± 1.5	1.20 ± 0.35	2.74 ± 0.79	0.24 ± 0.07
Total background	349 ± 20	416 ± 18	64.9 ± 4.7	78.2 ± 8.0	14.4 ± 1.2
Data	353	428	60	78	18


ATLAS
√s = 13 TeV, 36.1 fb-1
1-lepton
≥2t, 0-1H, ≥6j, 3b
Pre-fit
Data
TT doublet (1 TeV)
tt̄ + light-jets
tt̄ + ≥1c
tt̄ + ≥1b
Non-tt̄
Total Bkg unc.
Events / 300 GeV
Data / Bkg
m_eff [GeV]

(a)


ATLAS
√s = 13 TeV, 36.1 fb-1
1-lepton
≥2t, 0-1H, ≥6j, 3b
Post-fit (Bkg-only)
Data
tt̄ + light-jets
tt̄ + ≥1c
tt̄ + ≥1b
Non-tt̄
Total Bkg unc.
Events / 300 GeV
Data / Bkg
m_eff [GeV]

(b)


ATLAS
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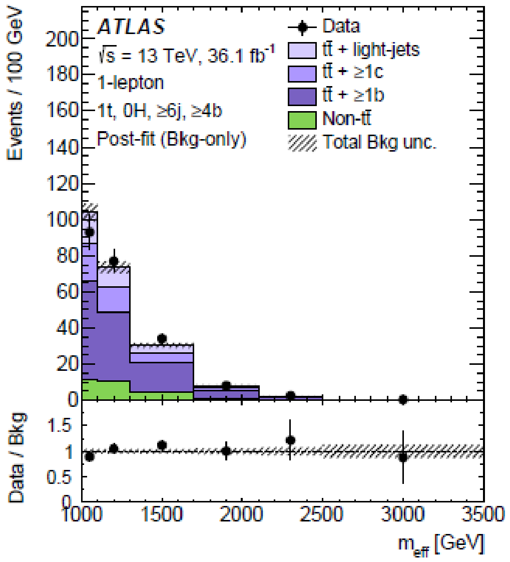
1-lepton
1t, 0H, ≥6j, ≥4b
Pre-fit
Data
TT doublet (1 TeV)
tt̄ + light-jets
tt̄ + ≥1c
tt̄ + ≥1b
Non-tt̄
Total Bkg unc.
Events / 100 GeV
Data / Bkg
m_eff [GeV]


ATLAS
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1-lepton
1t, 0H, ≥6j, ≥4b
Post-fit (Bkg-only)
Data
tt̄ + light-jets
tt̄ + ≥1c
tt̄ + ≥1b
Non-tt̄
Total Bkg unc.
Events / 100 GeV
Data / Bkg
m_eff [GeV]

RESULTS

Cross section upper limit : 16 fb

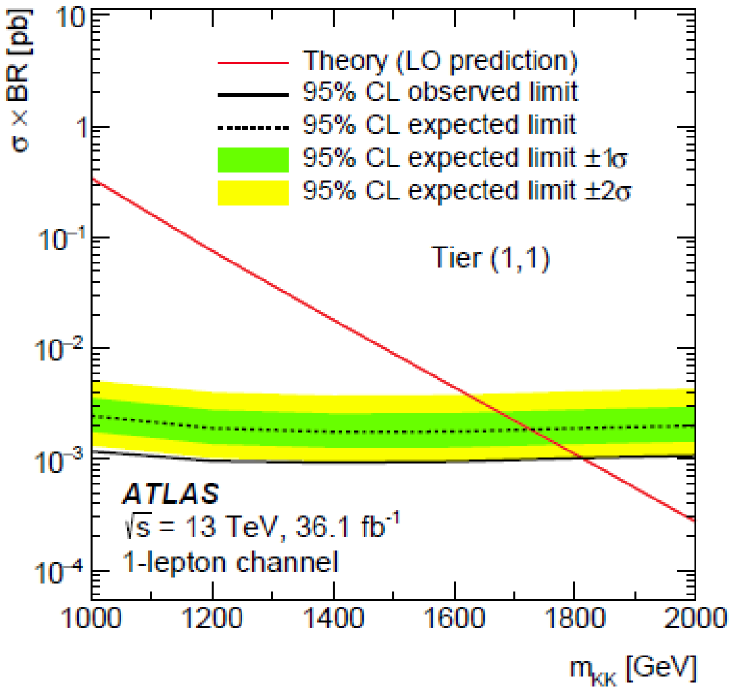
- Expected: 31^{+12}_{-9} fb

Contact type interaction upper limit:

$$\frac{|C_{4t}|}{\Lambda^2} < 1.6 \text{ TeV}^{-2}$$

- Expected: $2.3 \pm 0.4 \text{ TeV}^{-2}$

Limits on Kaluza-Klein



FOUR TOP QUARK PRODUCTION IN BSM

Due to small cross section, if the four top quarks is measured, it could be sensitive to new physics

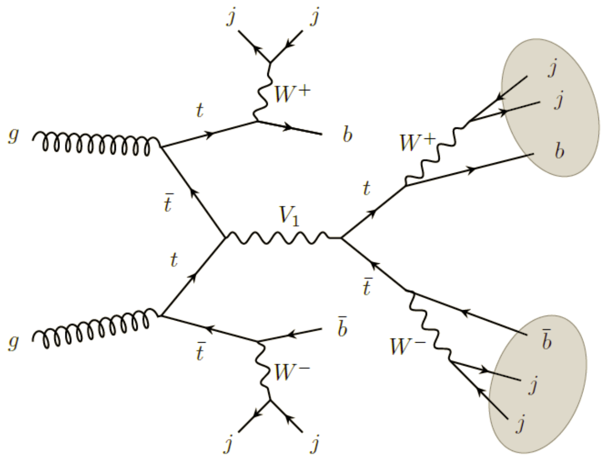
Direct production of a resonant state that decays into $t\bar{t}$

Higher-dimensional effective operators

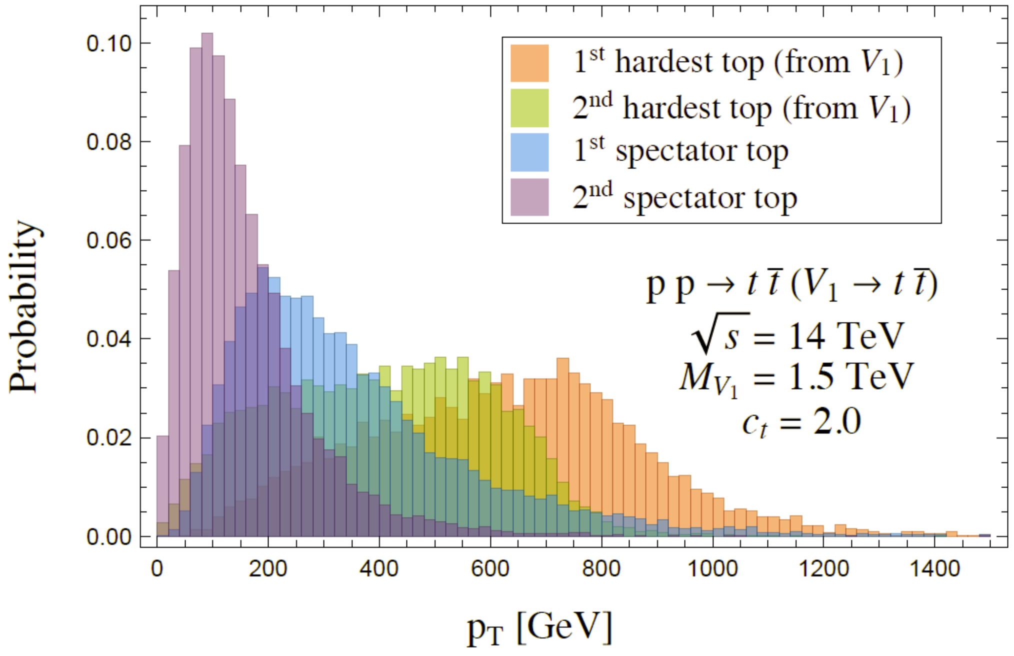
TOP-PHILIC BOSON

Top-philic boson production and decay leads to four top quarks

- Depending on the mass of the boson, it can be hard



$$\mathcal{L}_{int} = \bar{t}\,\gamma_\mu(c_L P_L + c_R P_R)\,t\,V_1^\mu$$
$$= c_t\,\bar{t}\,\gamma_\mu(\cos\theta P_L + \sin\theta P_R)\,t\,V_1^\mu$$



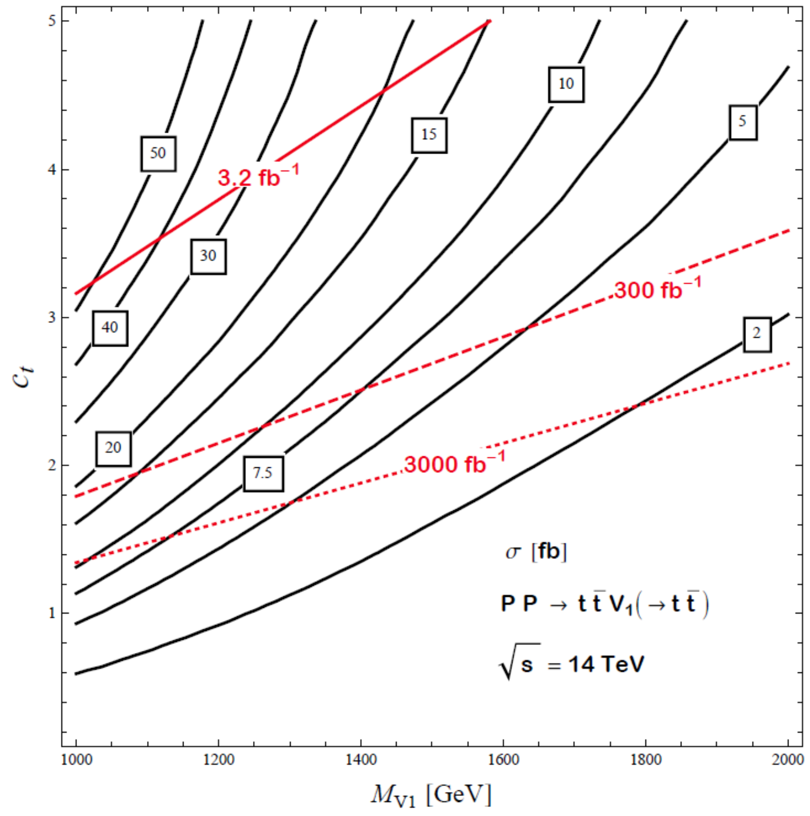
LIMITS ON TOP-PHILIC BOSON

Based on contact-type interaction

$$\frac{1}{2}\frac{c_t^2}{M_{V_1}^2}\left(\bar{t}_R\,\gamma_\mu\,t_R\right)\left(\bar{t}_R\,\gamma^\mu\,t_R\right)$$

From ATLAS result based on 3.2 fb-1 search for contact interactions

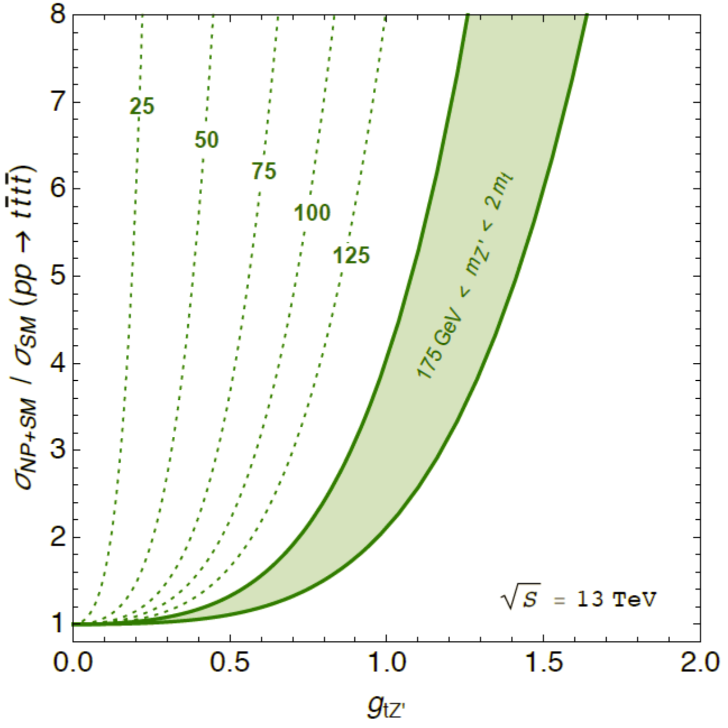
arXiv:1604.07421

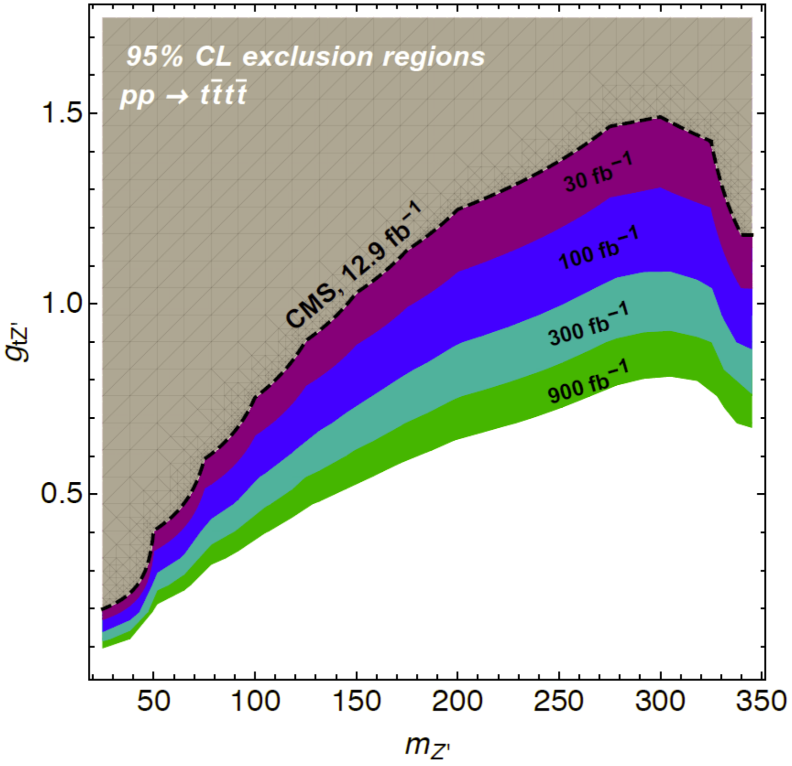


LIMITS ON TOP-PHILIC BOSON

For masses below $2m_t$

arXiv:1611.05032





SCALAR COLOR OCTET

arXiv:1805.1083

Simple model with scalar color octet model

$$\mathcal{L} = \frac{1}{2} D_\mu O^a D^\mu O^a - \frac{1}{2} m_O^2 O^a O^a + g_8 d_{abc} O^a G^b_{\mu\nu} G^{\mu\nu c} + \tilde{g}_8 d_{abc} O^a G^b_{\mu\nu} \tilde{G}^{\mu\nu c} + \left\{ \bar{q} \left[\mathbf{y}_8^{\mathbf{L}} P_L + \mathbf{y}_8^{\mathbf{R}} P_R \right] O^a T^a q + \text{h.c.} \right\} ,$$

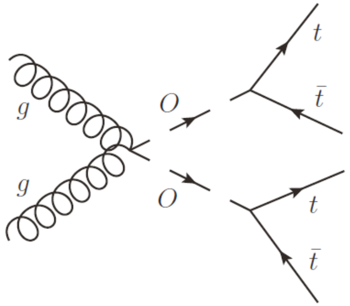
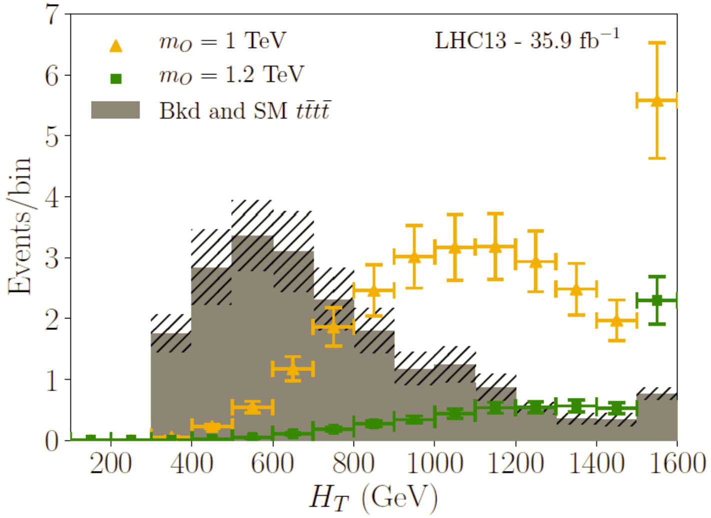
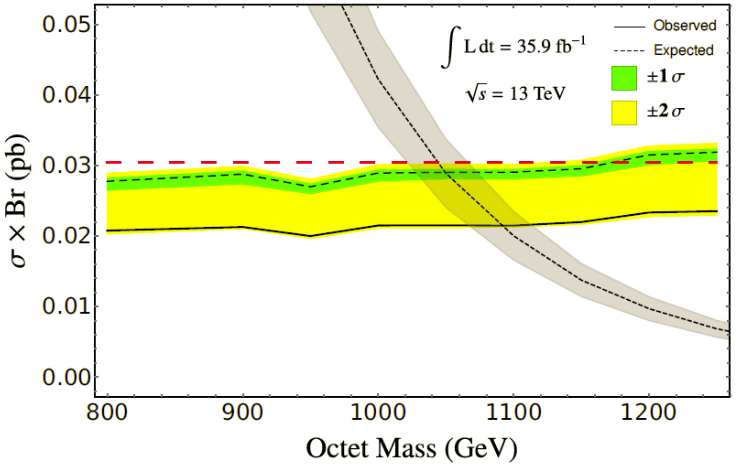


FIG. 1. Representative Feynman diagram illustrating sgluon pair production and decay into a four-top system.





Using Event Counting only

CONSTRAINING QQTT

From arXiv:1711.09592

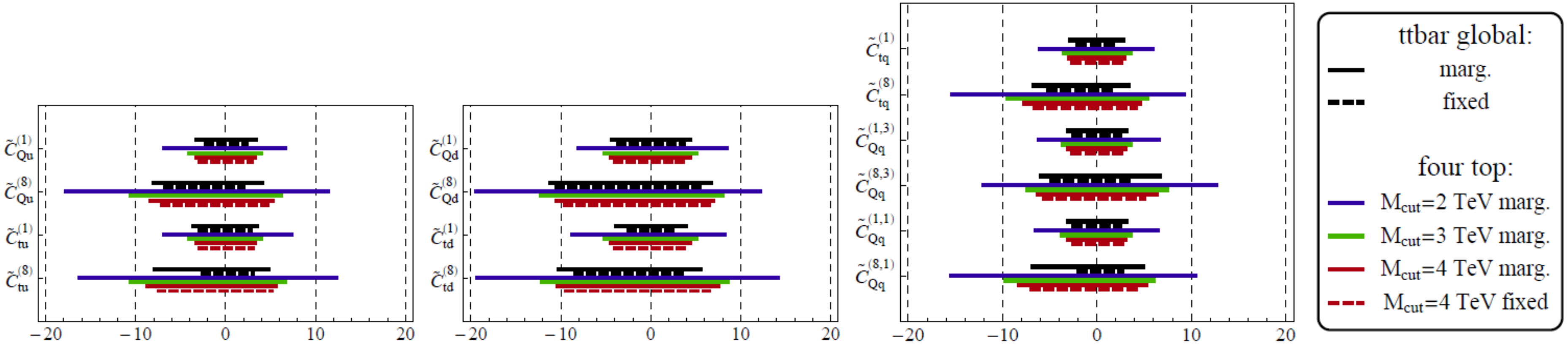


Figure 1: Fixed (i.e. one operator at a time) and fully marginalized (i.e. all other operators floated) constraints for all *qqtt* operators, from four-top and from $t\bar{t}$ measurements, at 95% CL. The $t\bar{t}$ constraints are from our global fit, while the four-top constraints are from the 300 fb^{-1} projection.

GOING FORWARD

SM search limit at x2~3 that of SM with 36 fb-1

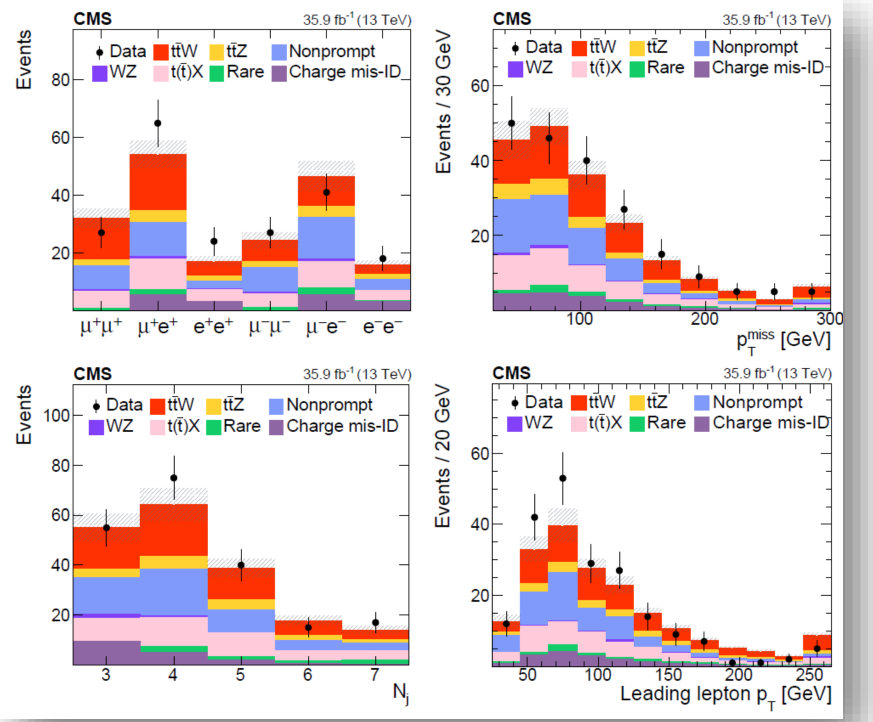
- With full Run II, we could be close to an evidence

Items to tackle

- $t\bar{t}+V$ is the largest background – need to understand $t\bar{t}+V$ differentially esp. at large H_T and n_{jet}
- Multijet background will still remain important – data-driven background in complex topologies
- Trilepton should be more sensitive with more integrated luminosities
- Can we show there are really four tops – top reconstruction for four tops

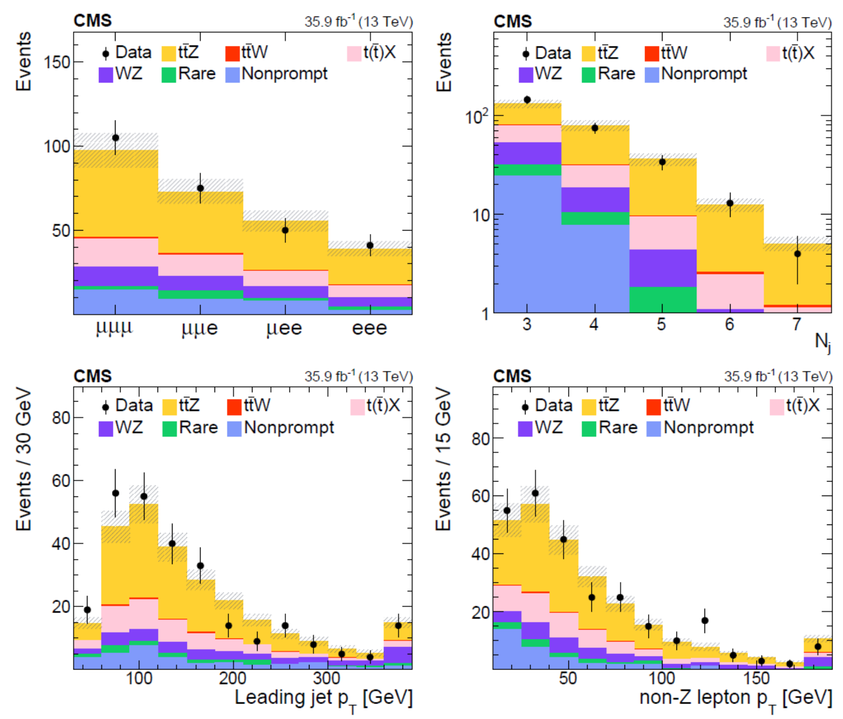
$t\bar{t} + W/Z$ IN HIGH S/B REGION

$t\bar{t}W$



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

MULTIJET BACKGROUND

Multijet backgrounds are difficult to simulate

- Almost always leading order with no NLO. Large uncertainty in normalization and shape.
- Time consuming to generate
- Usual “tight-loose” method may have problems with correlations.

One idea could be to use the data and use a generative GAN method

- way of generating backgrounds with correct correlations among final state objects

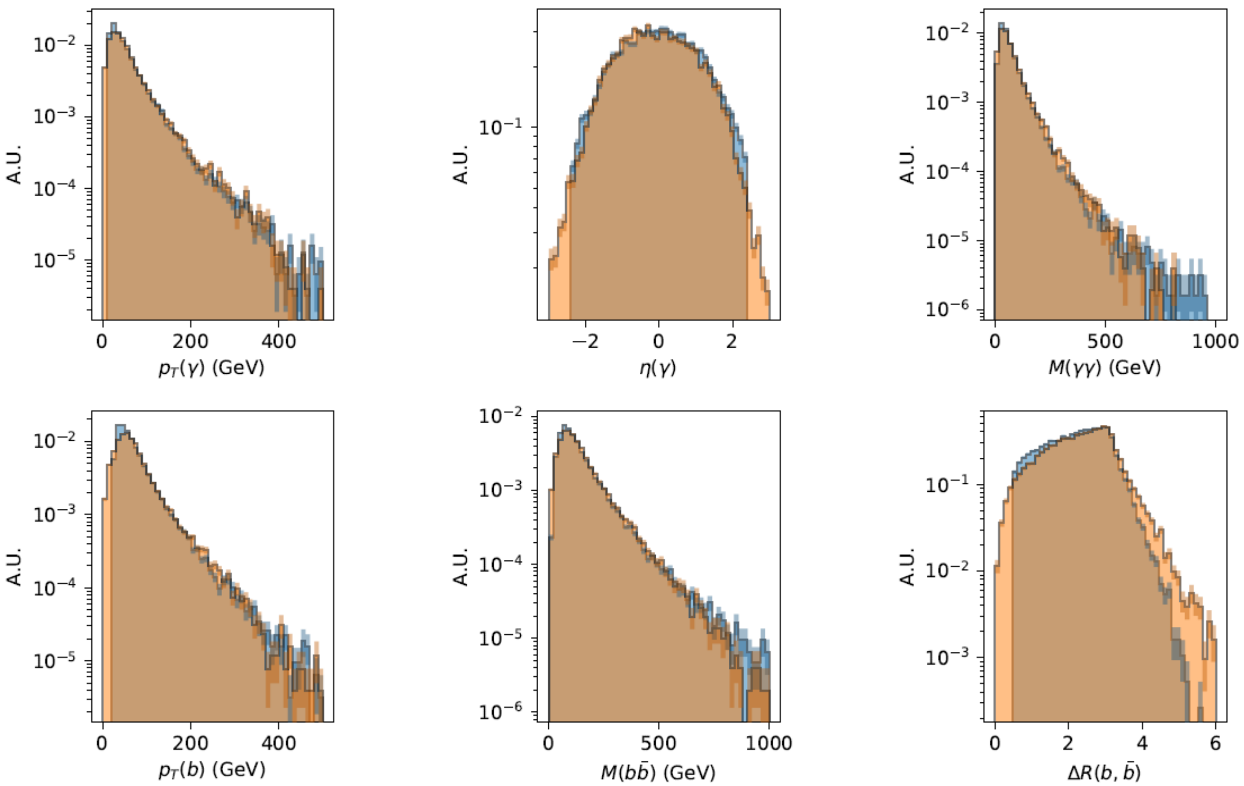
USING GENERATIVE METHOD TO GENERATE FAKE EVENTS

Non-resonant production of $b\bar{b}\gamma\gamma$ is a background to $HH \to b\bar{b}\gamma\gamma$

- $pp \to b\bar{b} + \gamma\gamma$ at $\sqrt{s} = 14$ TeV
- Generated with Madgraph 5 + PYTHIA 8 + Delphes
- Although this example is not for four top, just to illustrate an idea

Generative method for learning from data

- Use as feature inputs px, py, pz of γ's and b-jets – 12 inputs
- Wasserstein GAN – outputs px, py, pz of the γ's and b-jets
- We can use these vectors to calculate various quantities



REWEIGHTING

"Sharp" features can be obtained through event selection, but won't be able to fill the missing parts

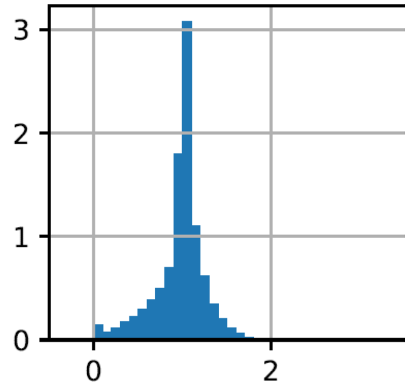
If certain distribution is deemed to be important to get right it is possible to reweight without spoiling other distributions

Reweighting using DNN

- Augment data to include the additional feature input (ΔR_{bb} etc)
- Fit a weighting function w: $\mathbb{R}^n \to \mathbb{R}$ such that the loss function

$$\frac{1}{m}\sum_{i=1}^{m} L_i \to \frac{\sum_{i=1}^{m} w_i L_i}{\sum_{i=1}^{m} w_i}$$

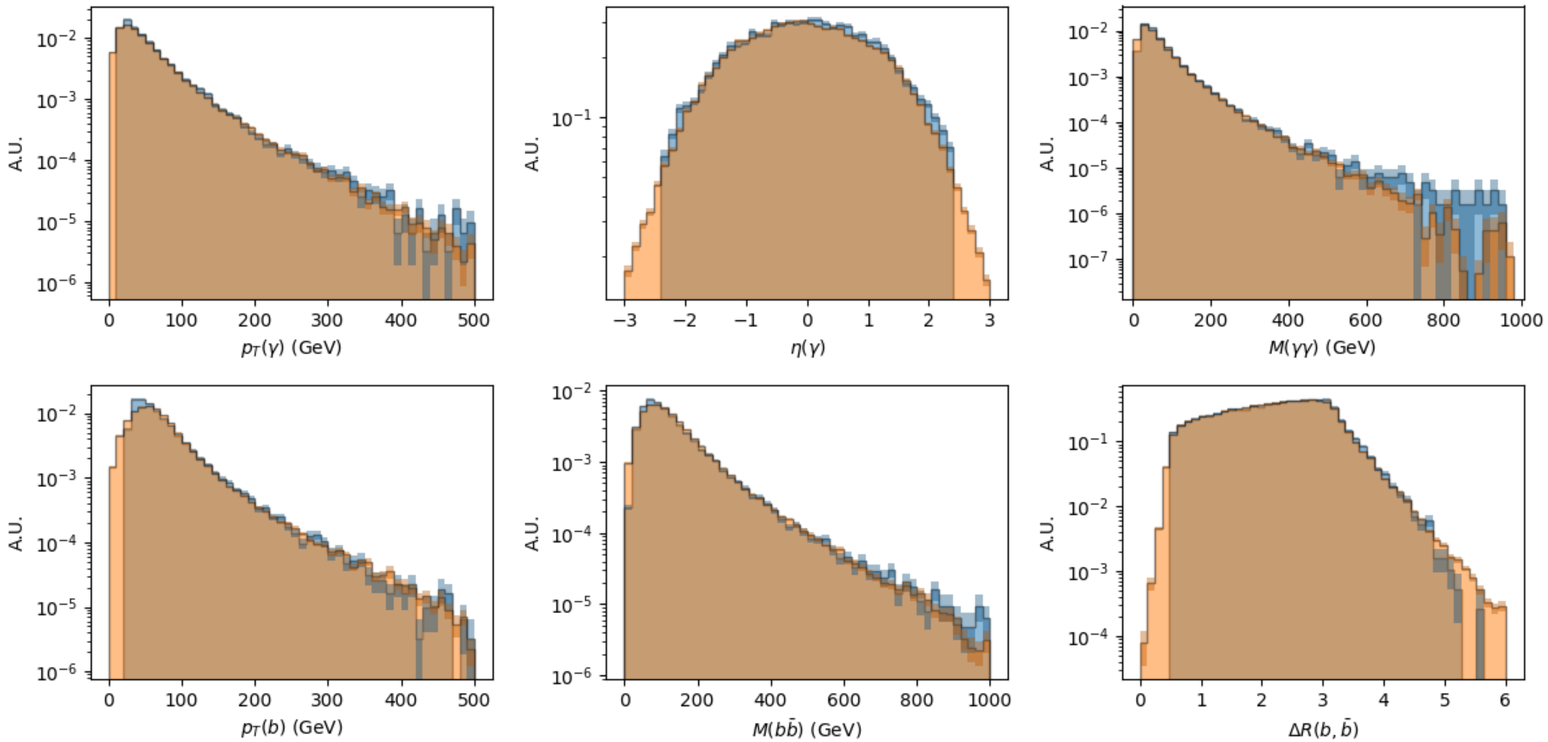
- It will learn the new feature without spoiling too much other distributions



Event weight distribution

REWEIGHTED

Added $\Delta R_{b\bar{b}}$ as additional variable



RECONSTRUCTION OF TOP IN FOUR TOPS

To show that we really have top quarks, we should be able to show mass peak

Boosted top quarks

- Three jets fall within a single large cone jet. We can use jet-mass variable.
- Important for heavy resonance decaying into $t\bar{t}$
- For SM production, ~10% of hadronic four top events have one or more boosted top quarks. In SM four top search we do not make use of this

For the resolved cases, reconstructing top using kinematic fitting fails for fully hadronic, single lepton and dilepton channels

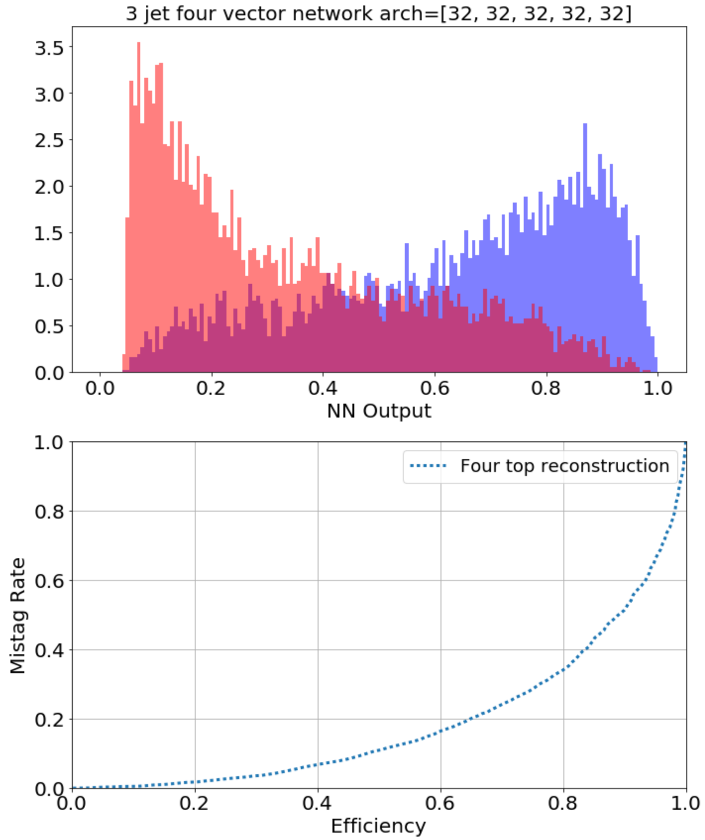
- Almost always bad combination gives sharper top mass and W mass peaks

DEEP LEARNING FOR $t \rightarrow bjj$

Deep learning to identify good pairings

- 5 layers deep 32 hidden nodes each
- Inputs are four vectors of three jets
  - First jet is b-tagged jet
  - Signal: 3 jets matched to Monte Carlo truth
  - Background: 3 jets failing to fully match Monte Carlo truth

- Signal to Background is about 1/10 before training



SUMMARY AND OUTLOOK

Four top quark

- Small cross section in SM – We might see evidence soon.
- Sensitive to Higgs-top coupling
- Way to probe bosons that primarily couple to top quarks
- Constrain some operators in the EFT

BACKUP

DO WE KNOW ENOUGH ABOUT TOP?

Null results of searches for new physics from direct searches involving top quark

Higgs-top coupling consistent with SM prediction

Coefficients of higher-dimensional operator consistent with 0 from data

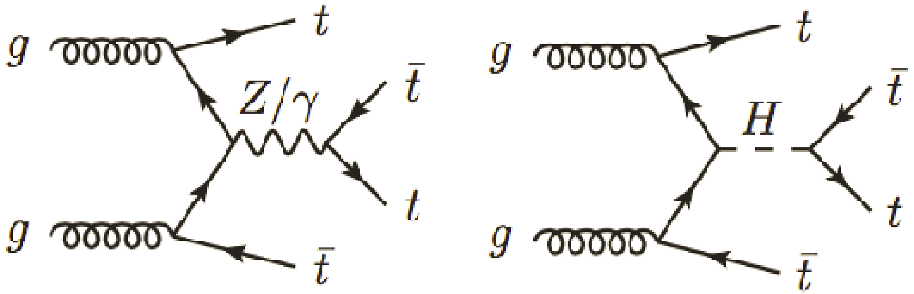
However, the $\Delta\phi_{\ell\ell}$ distribution in the lab-frame deviates from SM prediction

- What are we missing?

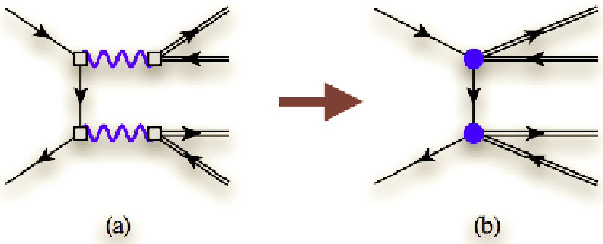
Direct top quark decay width measurement not accurate enough

FOUR TOPS BEYOND QCD

Resonances



EFT



Two dim-6

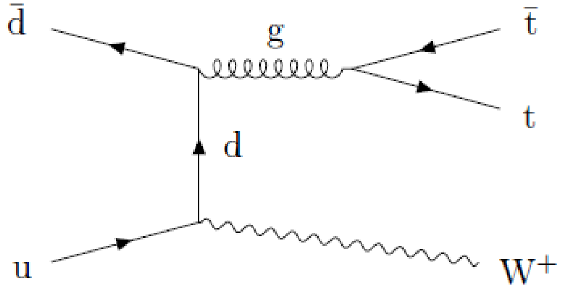
$t\bar{t}W$ AND $t\bar{t}Z$

INTRODUCTION

Probe of top quark and vector boson coupling

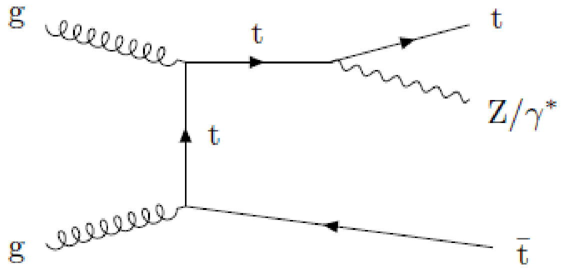
- Direct probe of top quark - Z coupling through $t\bar{t} + Z$

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 $t\bar{t}W$

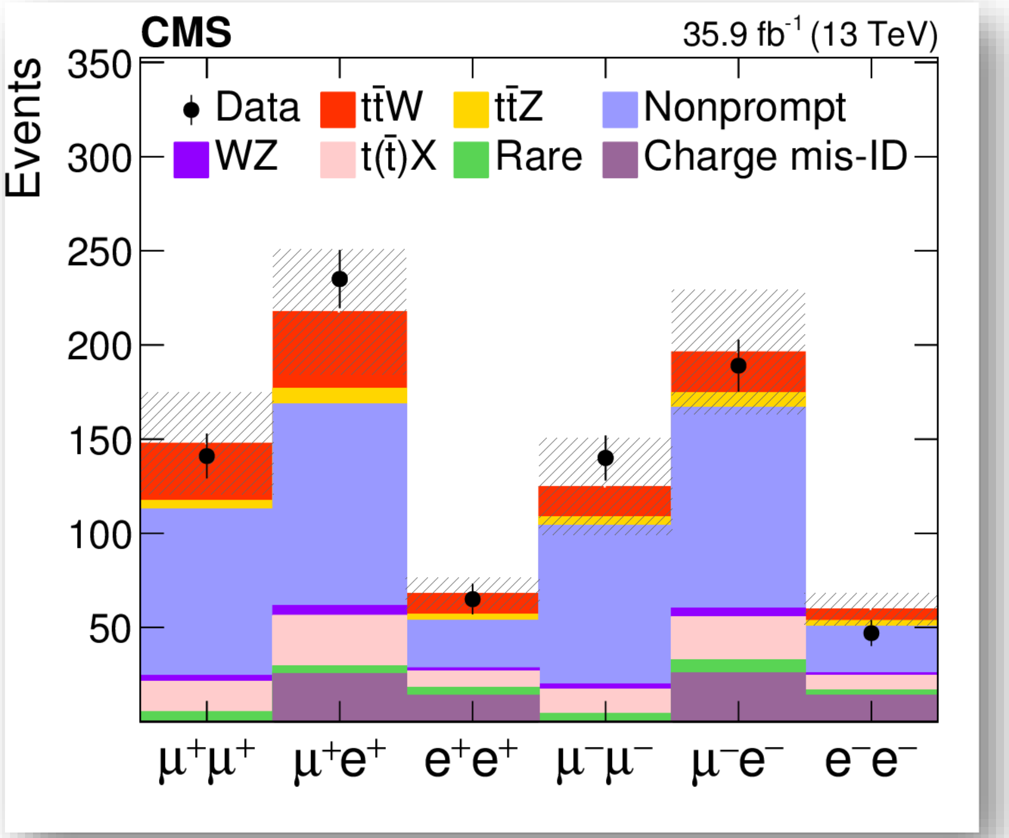
http://arxiv.org/abs/1711.02547

$t\bar{t}W$ 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

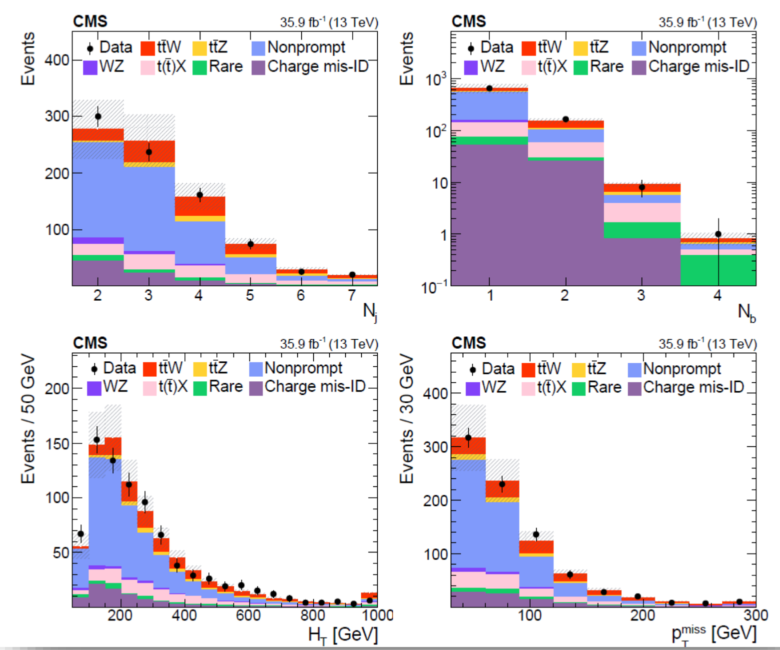


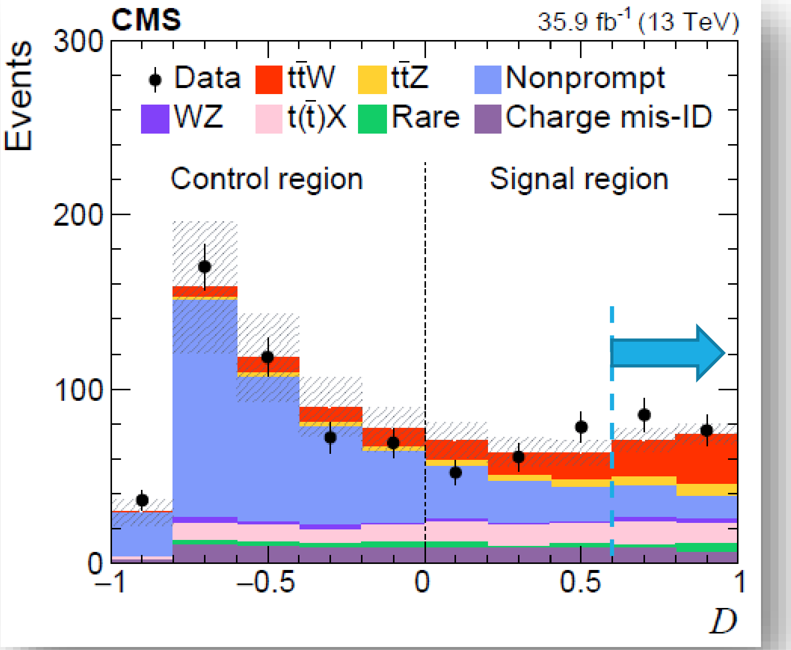
MULTI-VARIATE ANALYSIS FOR $t\bar{t}W$ SSDL

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

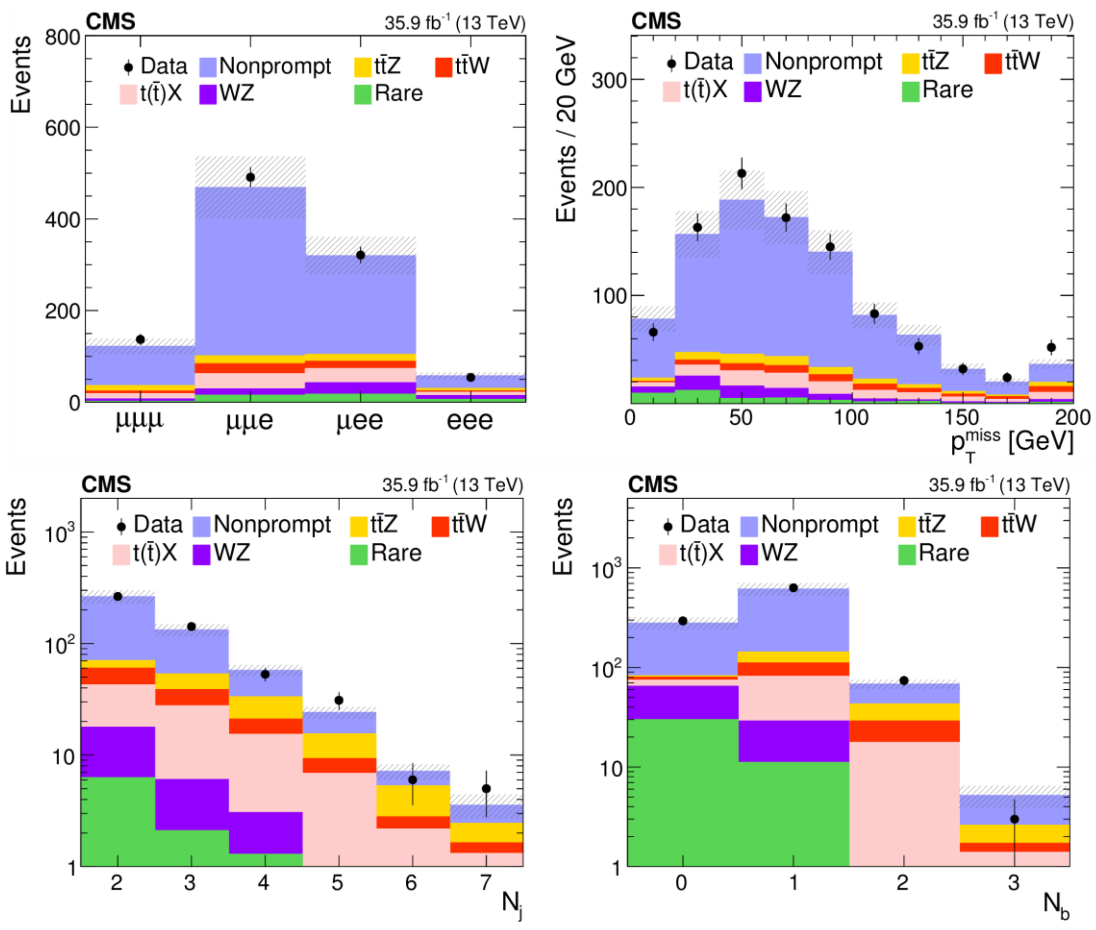
EVENT SELECTION FOR $t\bar{t}Z$

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 $N_{jet} = 2$, $N_{bjet} \geq 0$



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

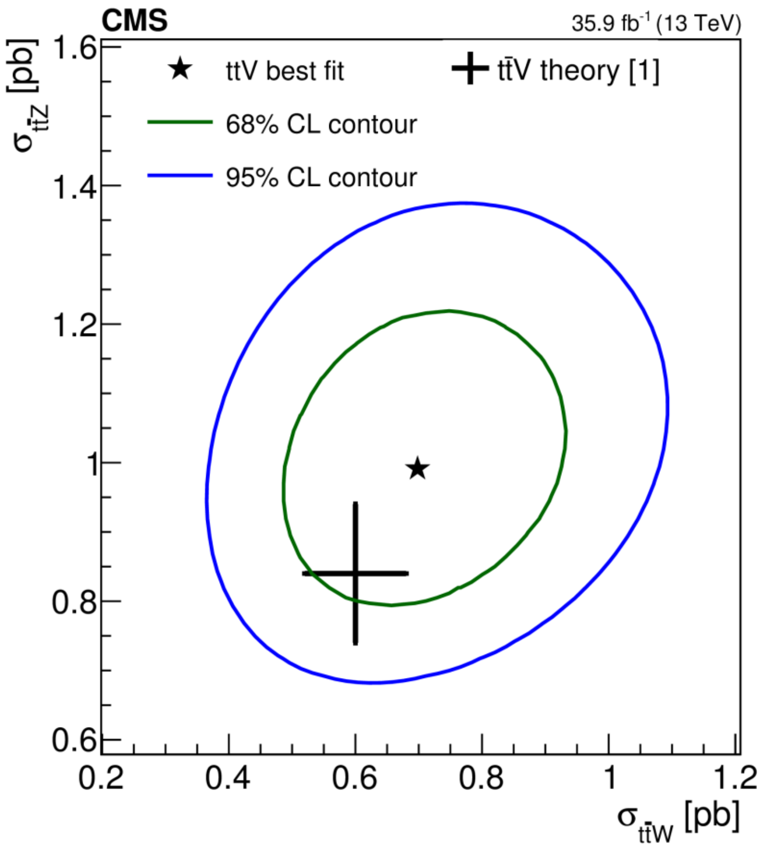
$t\bar{t} + W/Z$ RESULTS

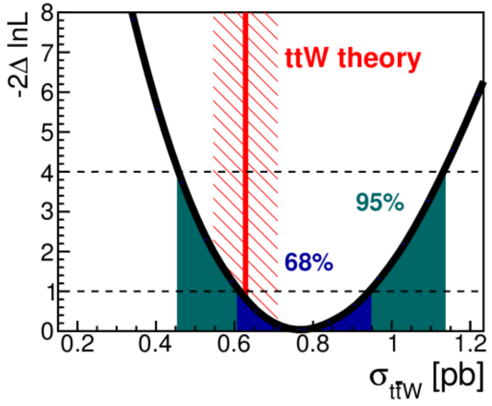
Significances >5 observed each for $t\bar{t} + W$ and $t\bar{t} + Z$

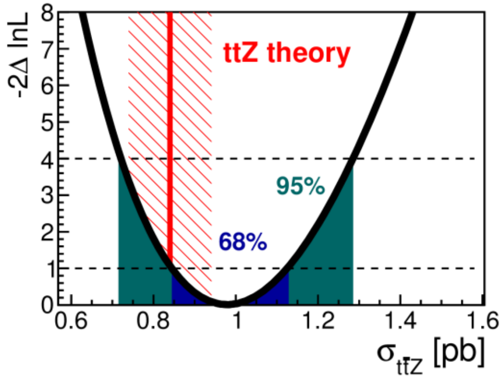
Measured Cross Sections through simultaneous fits

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

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

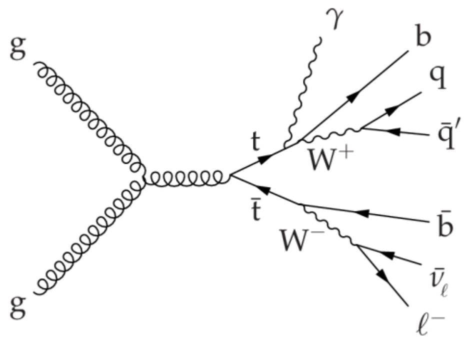


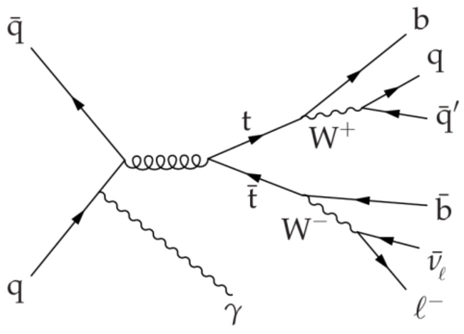




$t\bar{t}\gamma$

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 $N_{bjet} \geq 1$

$p_T^{miss} > 20\ GeV$

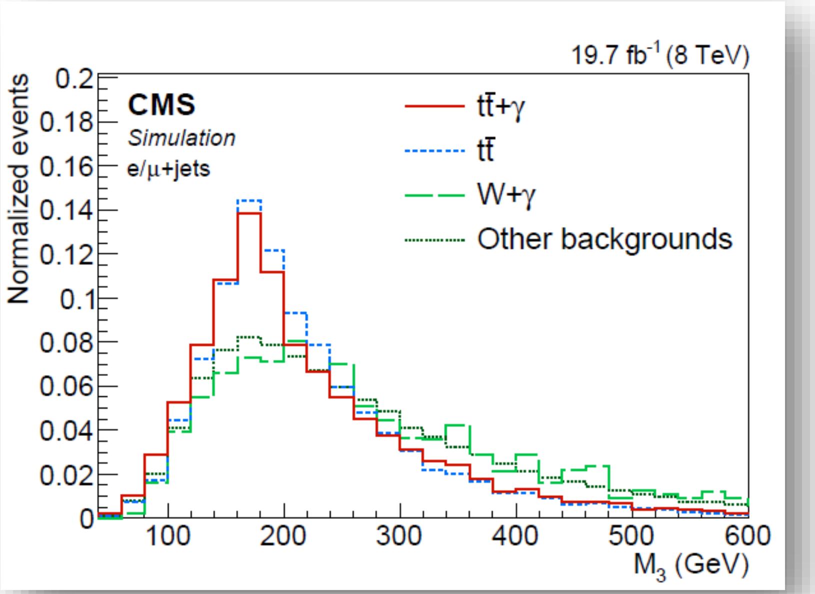
One photon $p_T > 25\ GeV$ in barrel

- 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

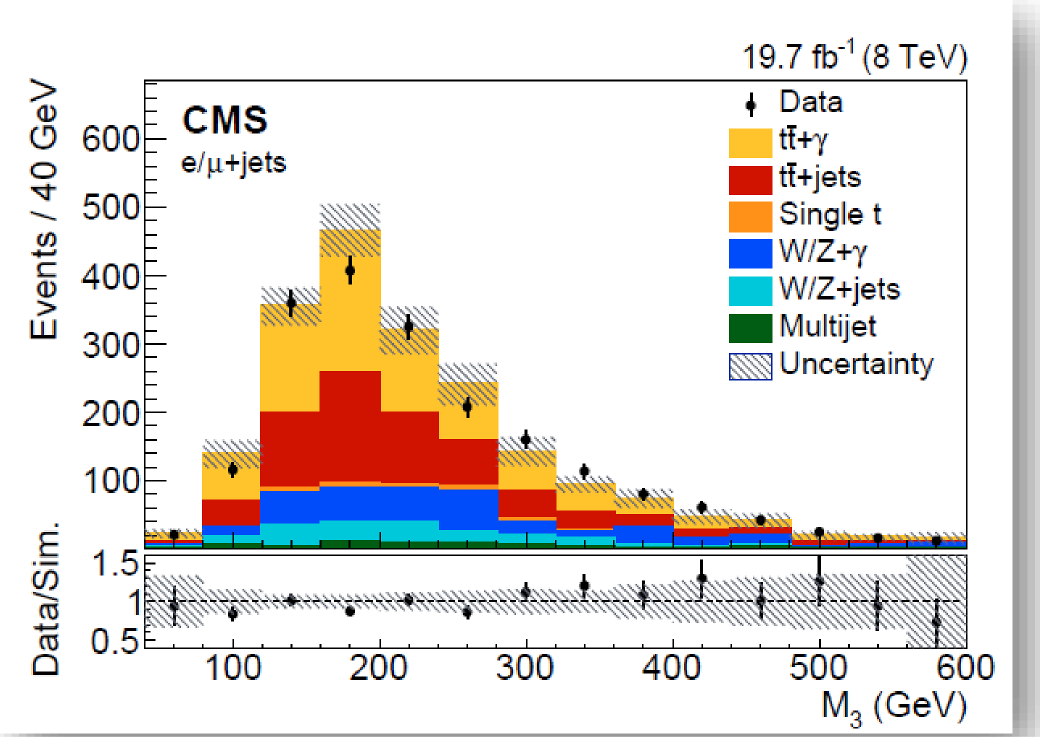
Binned maximum likelihood fits to M_3 distribution to estimate $t\bar{t}$ contribution after selection

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	$\sigma^{\text{fid}}_{t\bar{t}+\gamma}$ (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)

- In agreement with theory

SINGLE TOP +Z

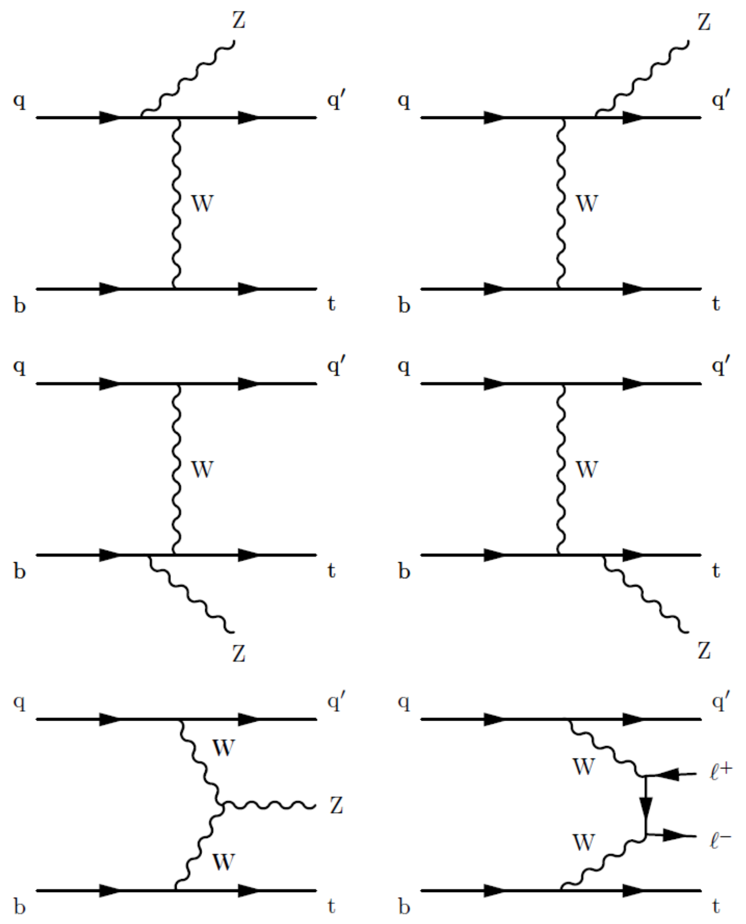
INTRODUCTION

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)

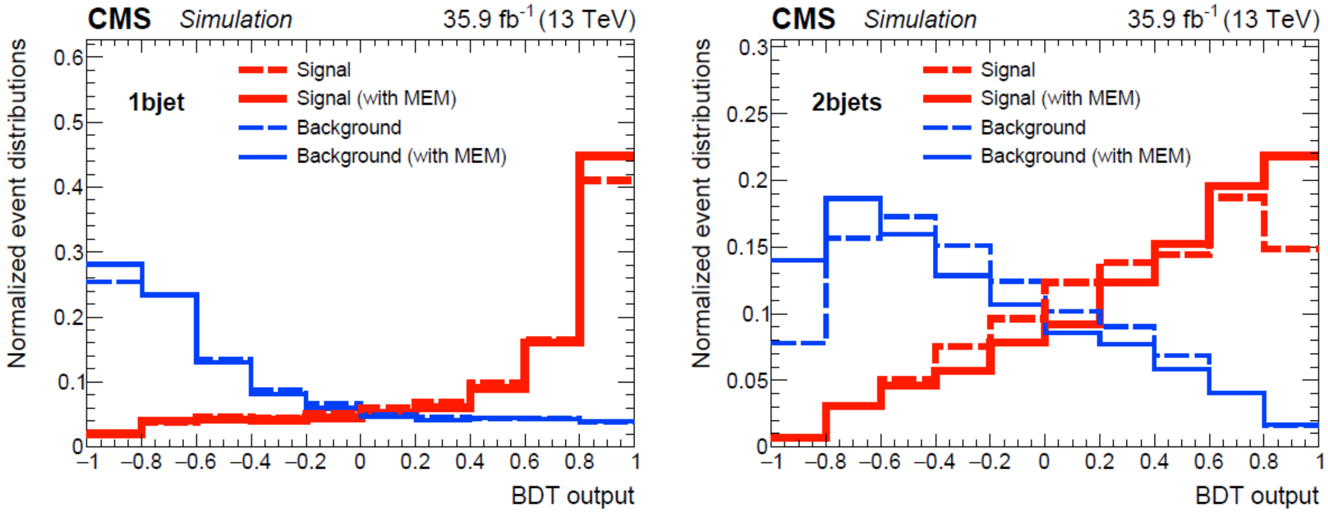


SINGLE TOP + Z EVENT SELECTION

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

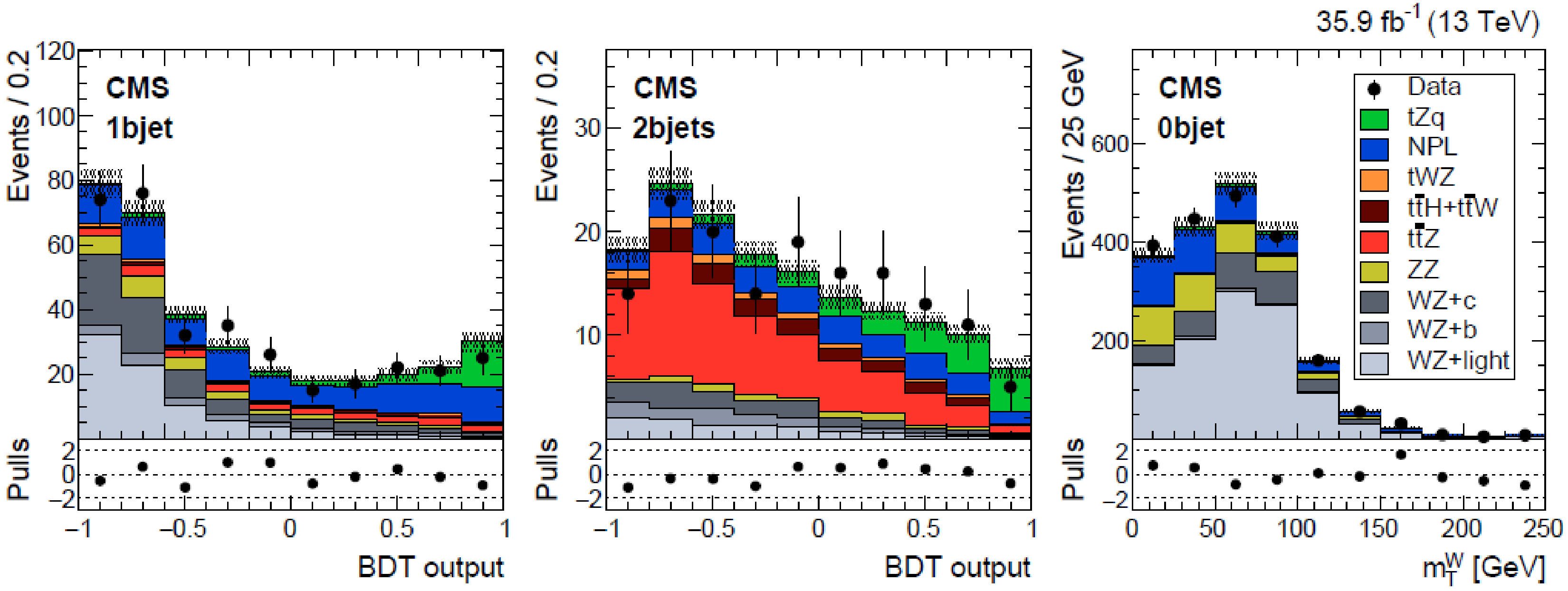
- $t\bar{t}Z$
- $WZ + jets$
- Non-prompt leptons (NPL)
- Bin samples : 0 bjet – WZ+jets, NPL enriched, 1 b-jet – signal, 2 b-jet - $t\bar{t} + Z$ enriched

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

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  - 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 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