Associated t/$t\bar{t}$ production at CMS

Nick Amin
for the CMS collaboration

TopAtLPC2019
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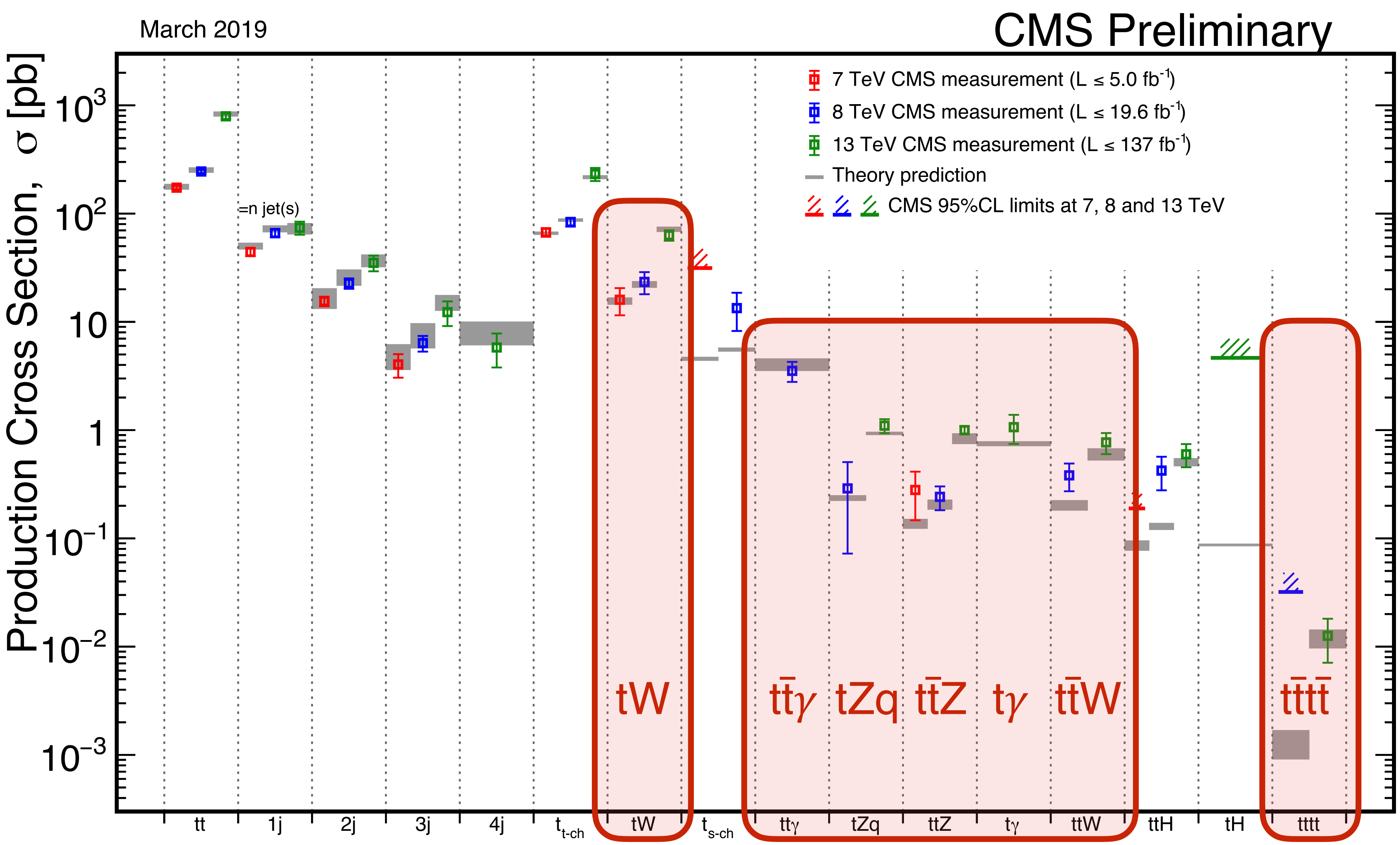
Overview

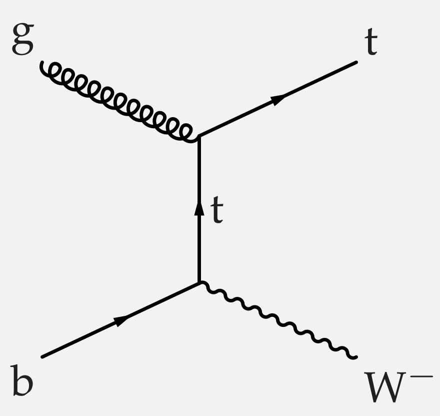
- Rare top-quark associated processes sensitive to **rich set of physics**
- Test SM theory and probe new physics from possible deviations
  - EFT, FCNC, 2HDM, SUSY, …
- While these are *signals* here, they are important *backgrounds* to **many** physics analyses
- Here, I will summarize the latest CMS results for the selected processes below



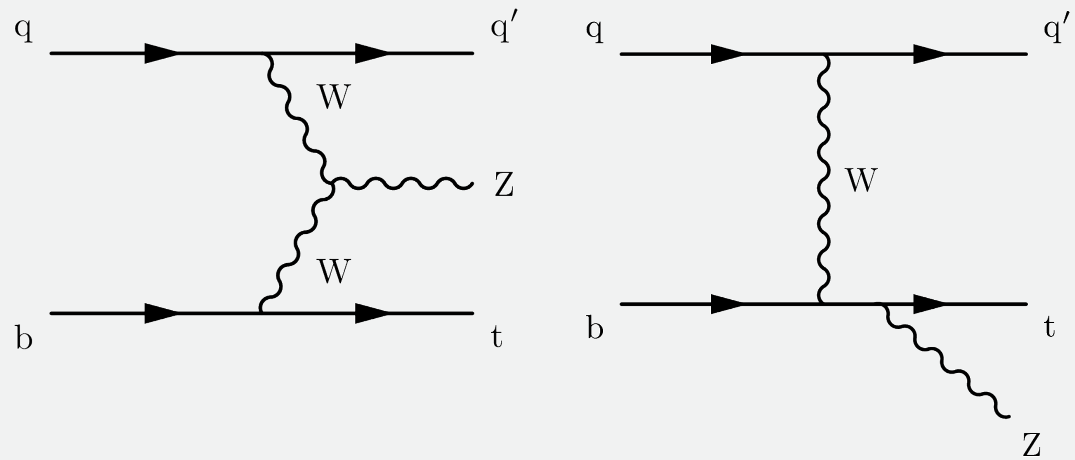
All results at: http://cern.ch/go/pNj7

Single top

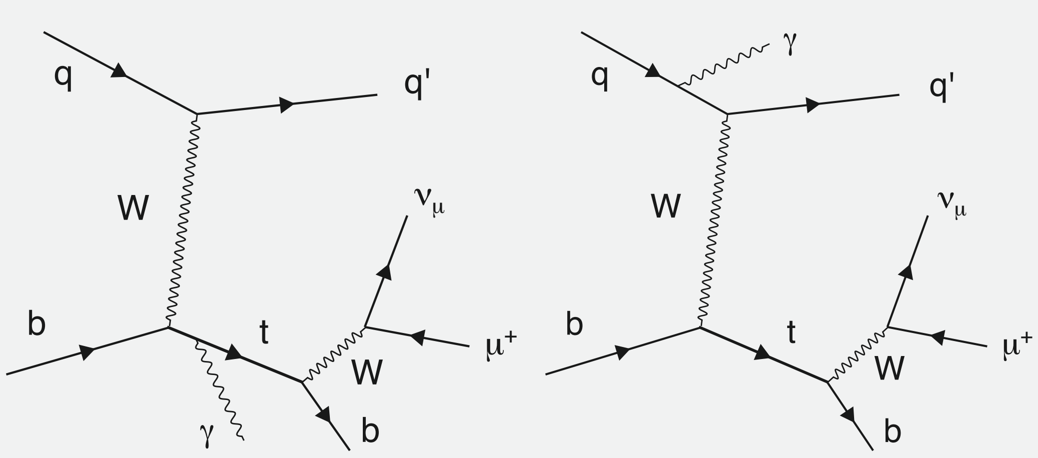
tW



tZq

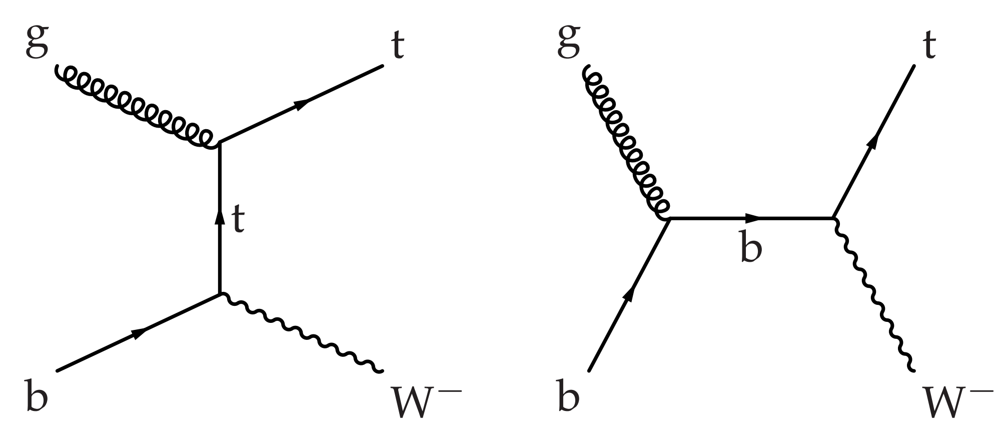


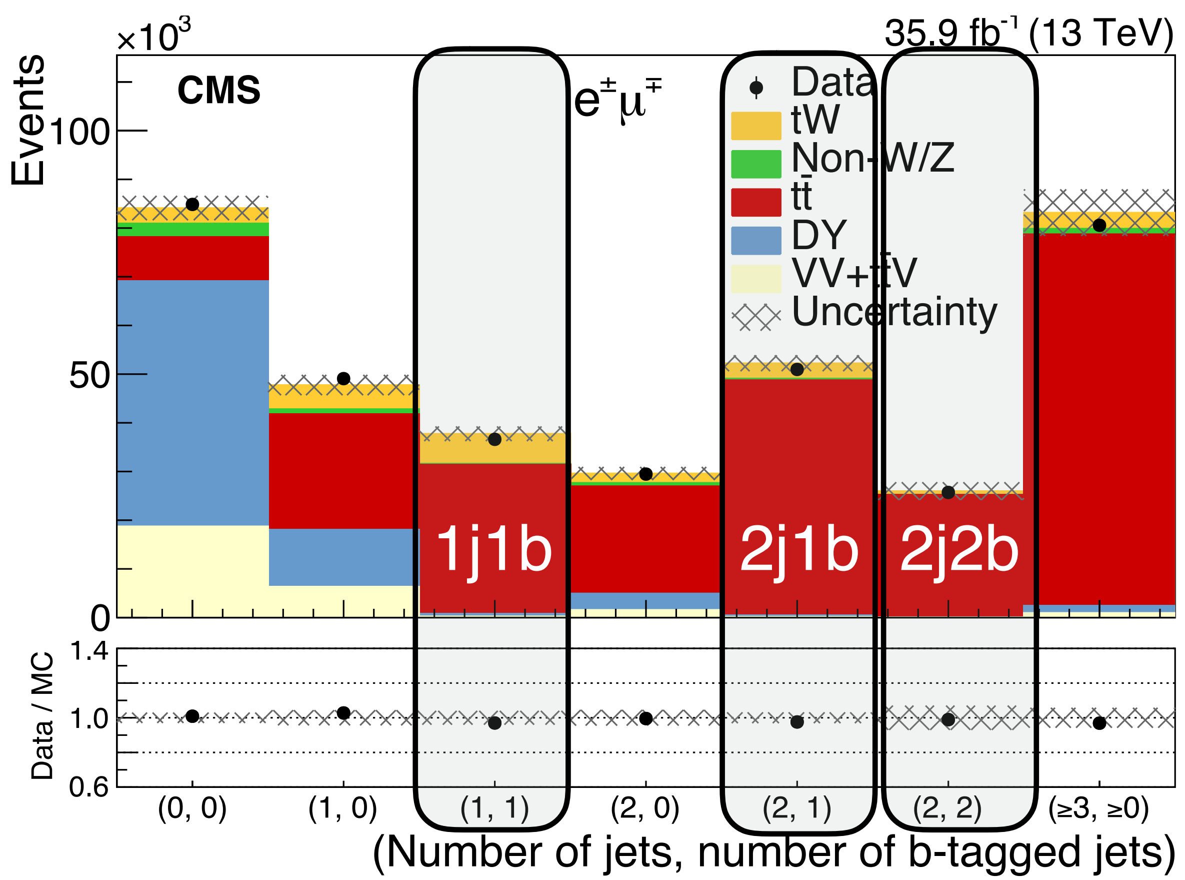
tγq



tW

- Measure tW cross-section in $e^{\pm}\mu^{\mp}$ + jets channel
  - Large background from $t\bar{t}$
- Three categories
  - 1 jet (1 b-tagged) ← **signal** enriched
  - 2 jets (1 b-tagged)
  - 2 jets (2 b-tagged) ← **bkg.** enriched
- Separate event-level BDTs trained to distinguish tW vs $t\bar{t}$ in **1j1b** and **2j1b**
  - jet p_Ts
  - $\Delta R(e/\mu,\text{jet})$
  - vec. sum of e/μ+jets+missing energy
  - …





tW

36fb^{-1}

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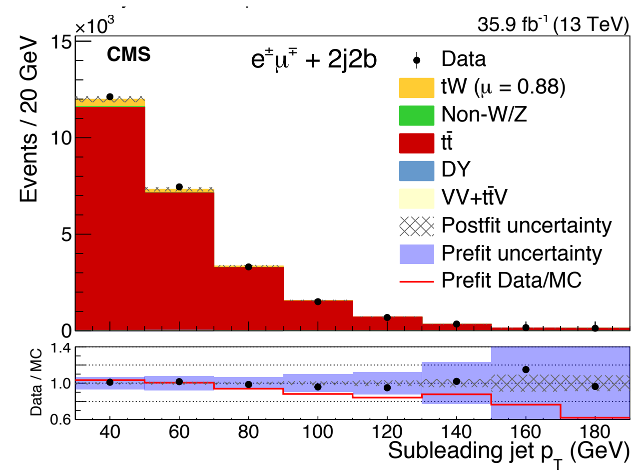
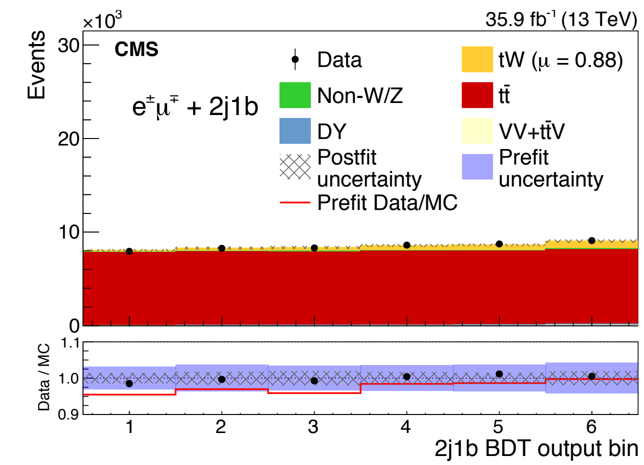
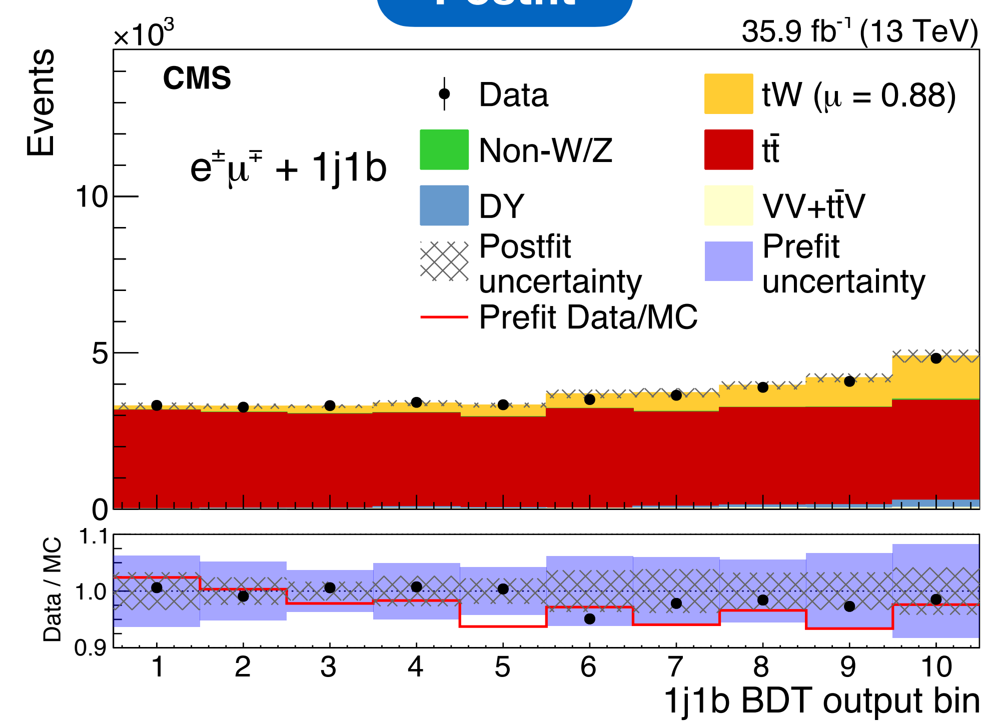
- Perform **max likelihood fit** to **BDT shapes** in first 2 categories and **subleading jet p$_T$** in 3rd category
- Leading experimental uncertainties in fit
  - Lepton ID, JES, pileup
- Measure σ(tW)=63.1±6.6pb, μ(tW)=0.88





Postfit



- tW process used by more recent analysis PAS TOP-17-020 (sub. to EPJC) to constrain 6 EFT parameters
  - 2016 dataset / 35.9fb^{-1}
  - Neural network signal discrimination

More in talks on Fri.

$$\mathscr{L}_{\text{eff}} = \mathscr{L}_{\text{SM}} + \frac{1}{\Lambda^2}\sum_i c_i \mathscr{O}_i + \ldots$$

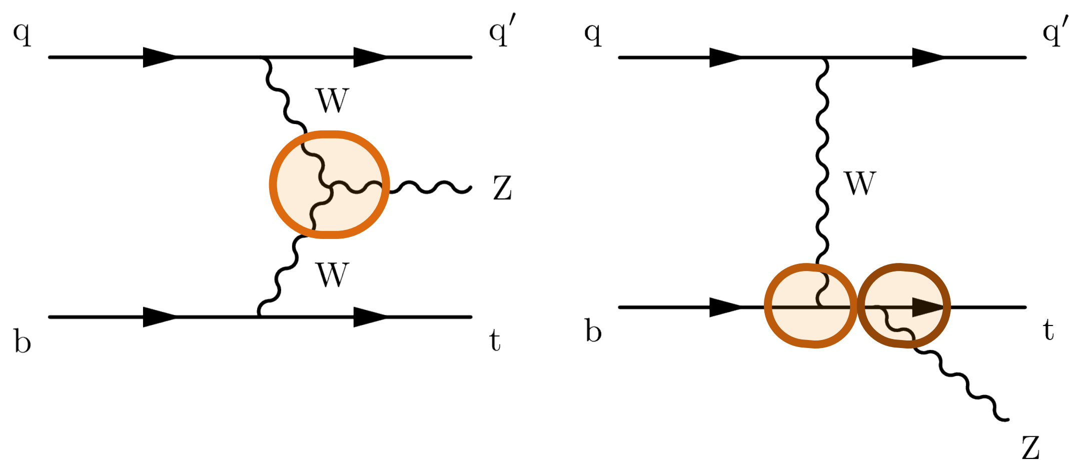
$$\sigma_{\text{exp}}(\text{tW}) = 63.1 \pm 1.8\ (\text{stat}) \pm 6.4\ (\text{syst}) \pm 2.1\ (\text{lumi})\ \text{pb}$$

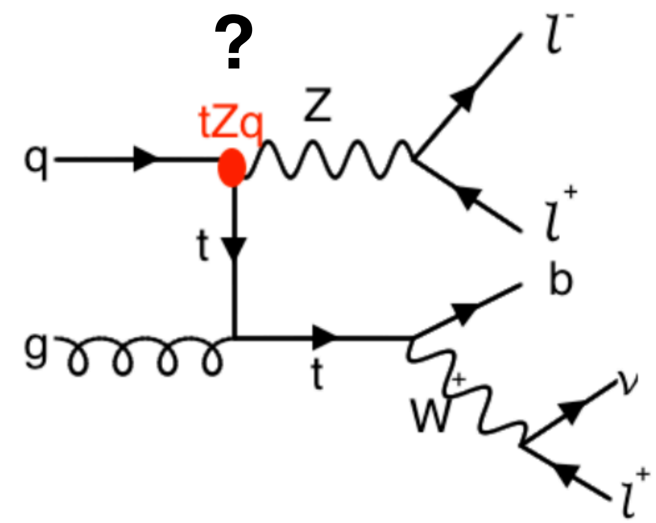
$$\sigma_{\text{theory}}(\text{tW}) = 71.7 \pm 1.8\ (\text{scale}) \pm 3.4\ (\text{PDF})\ \text{pb}$$

77fb^{-1}

[Phys. Rev. Lett. 122 (2019) 132003]

tZq





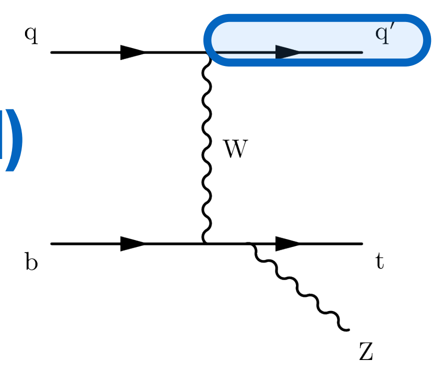
- σ(tZq) sensitive to
  - **SM couplings**: WWZ, tbW, ttZ
  - **BSM-enhanced** FCNC
- Measure cross-section in trilepton (eμ) + jets channel, requiring one SFOS pair consistent with m_Z
  - Main backgrounds from **fake leptons, WZ, $t\bar{t}Z$**
    - BDT-based lepton ID with data-driven fake lepton estimation from sideband
    - Rest from simulation
- Split events into three categories
  - 2/3 jets (1 b-tagged) / **SR23j1b** ← **signal** enriched
  - ≥4 jets (1 b-tagged) / **SR4j1b** ← **bkg.** enriched ($t\bar{t}Z$)
  - ≥2 b-tagged jets / **SR2b** ← **bkg.** enriched ($t\bar{t}Z$)

tZq

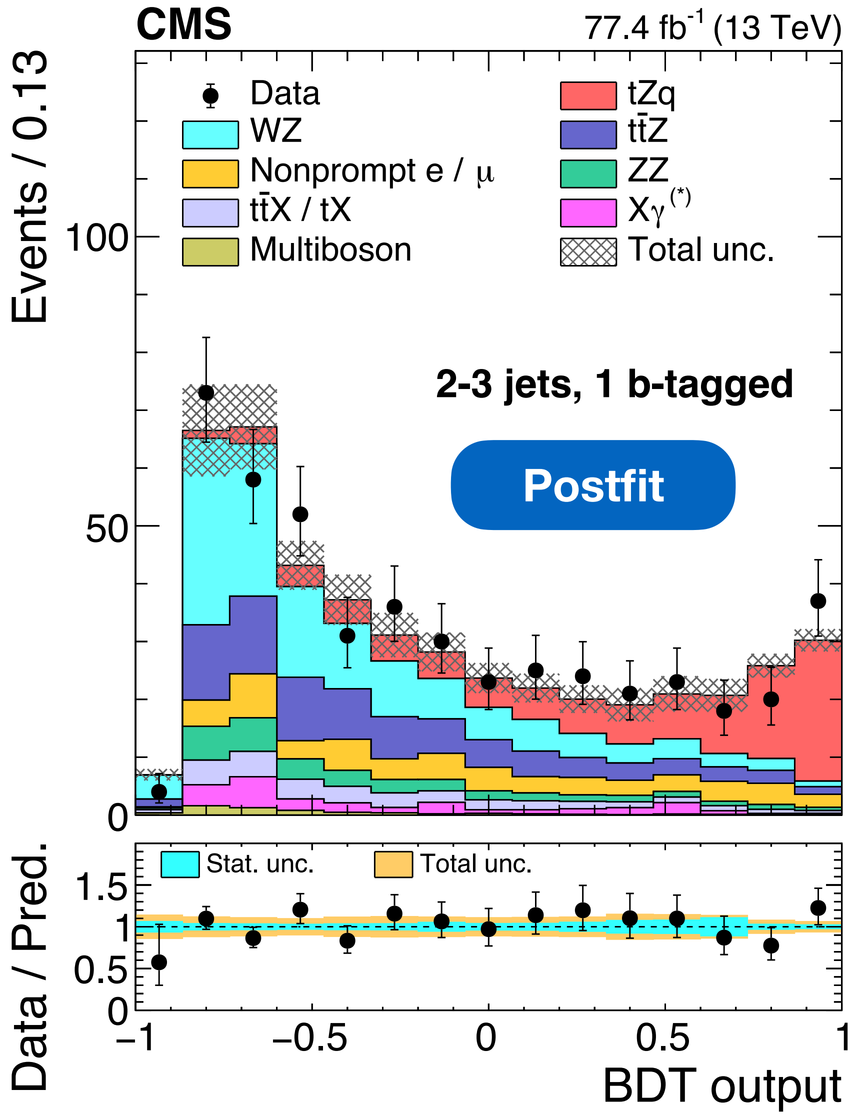
77fb^{-1}

Phys. Rev. Lett. 122 (2019) 132003

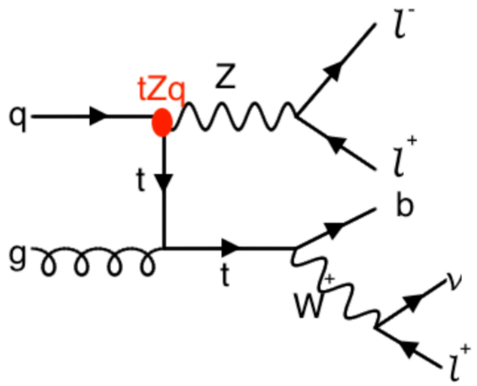
- In each category, event-level BDT trained to extract signal
  - $p_T(Z)$
  - Recoiling jet $|\eta|$ **(typically forward)**
  - …
- Perform **max likelihood fit** to **BDT shapes** over all 3 categories



→ **8.2σ obs. (7.7σ exp.)**



- This final state also used by PAS TOP-17-017 to constrain tZq FCNC couplings
  - 2016 dataset / 35.9fb^{-1}



$$\sigma_{\text{exp}}(\text{pp} \rightarrow \text{tZq} \rightarrow \text{tq}ll) = 111 \pm 13\ (\text{stat})\ ^{+11}_{-9}\ (\text{syst})\ \text{fb}$$

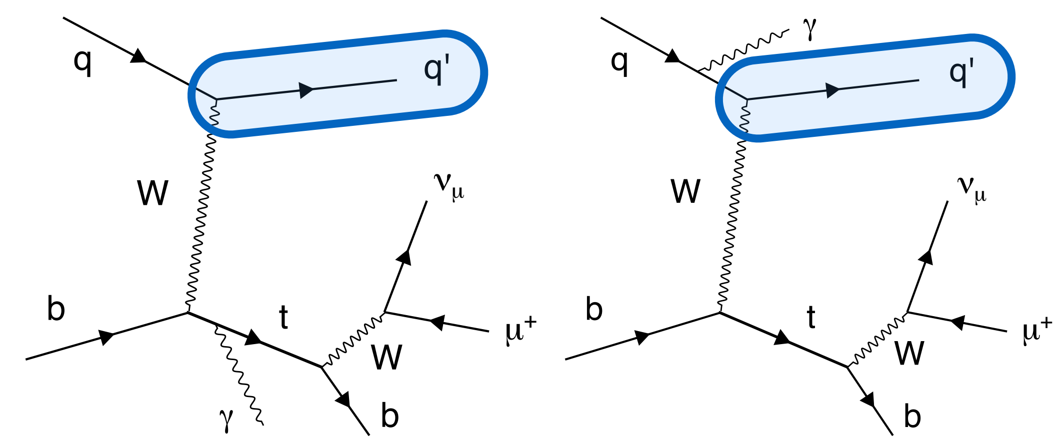
$$\sigma_{\text{theory}}(\text{pp} \rightarrow \text{tZq} \rightarrow \text{tq}ll) = 94.2 \pm 3.1\ \text{fb}$$

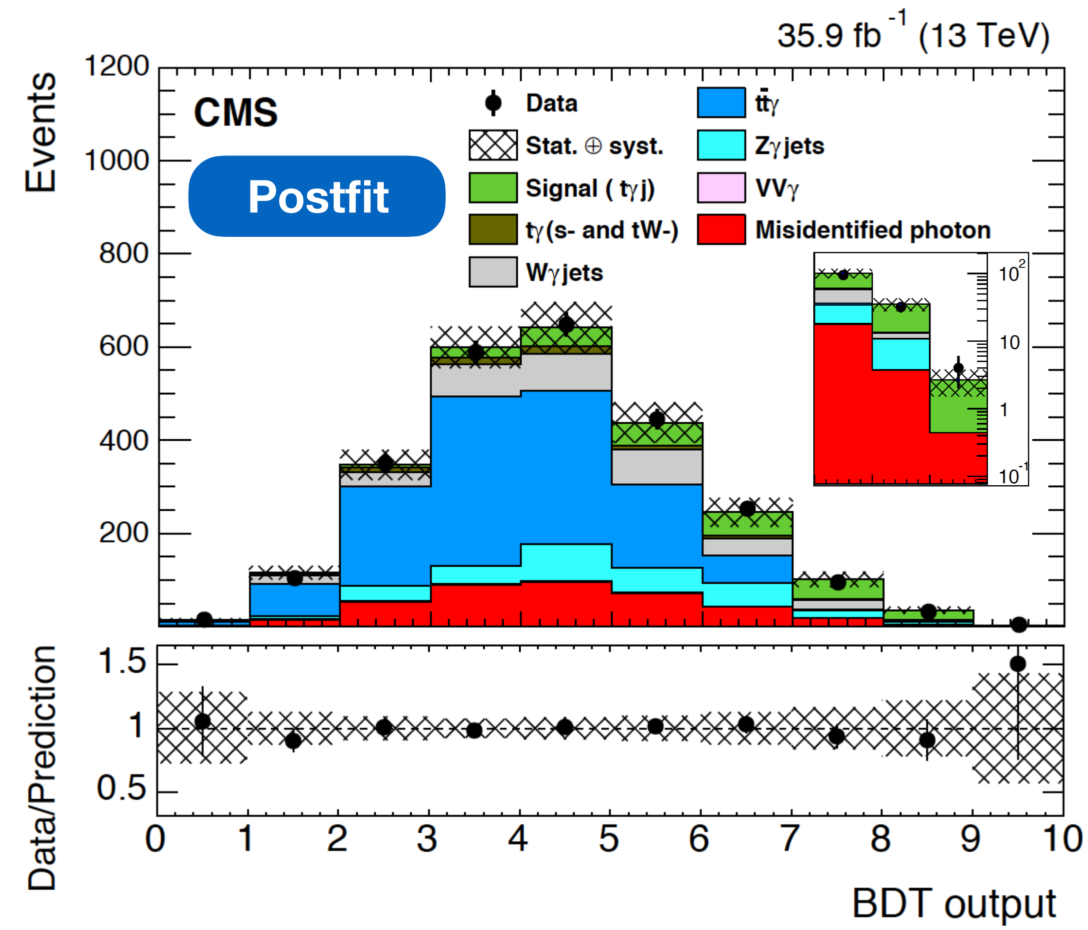
$$\left\{ m_{ll} > 30\ \text{GeV} \right.$$

tγq

- σ(tγq) sensitive to **anomalous magnetic, electric dipole moments**
- Select 1μ, 1γ, ≥2 jets (1 b tagged)
  - Isolated photon: $\Delta R(\mu/\text{jet},\gamma) > 0.5$
  - Over **half** of remaining background from **t$\bar{\text{t}}$+γ**
- True γ prediction from simulation
- Fake γ from data-driven sideband method
- **Fit event-level BDT** (η of forward jet, …) to data
  - includes t$\bar{\text{t}}\gamma$ control region with 2 b tag template
- Dominant syst. — JES (12%)

→ 4.4σ obs. (3.0σ exp.)





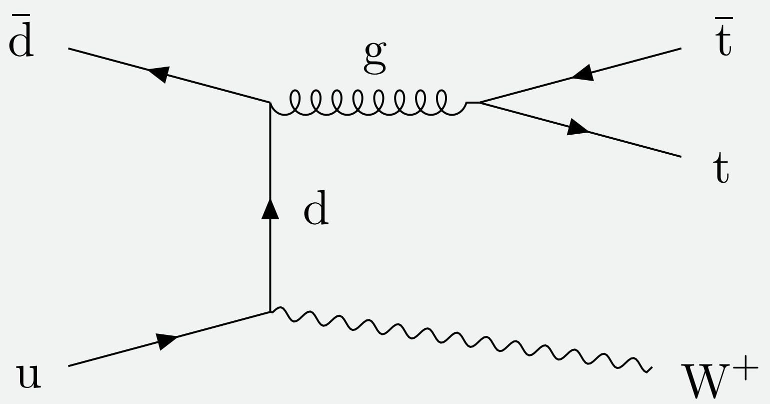
$$\sigma_{\text{exp}}(\text{pp} \rightarrow \text{t}\gamma\text{q}) \cdot B(\text{W} \rightarrow \mu\nu) = 115 \pm 17\ (\text{stat}) \pm 30\ (\text{syst})\ \text{fb}$$

$$\sigma_{\text{theory}}(\text{pp} \rightarrow \text{t}\gamma\text{q}) \cdot B(\text{W} \rightarrow \mu\nu) = 81 \pm 4\ \text{fb}$$

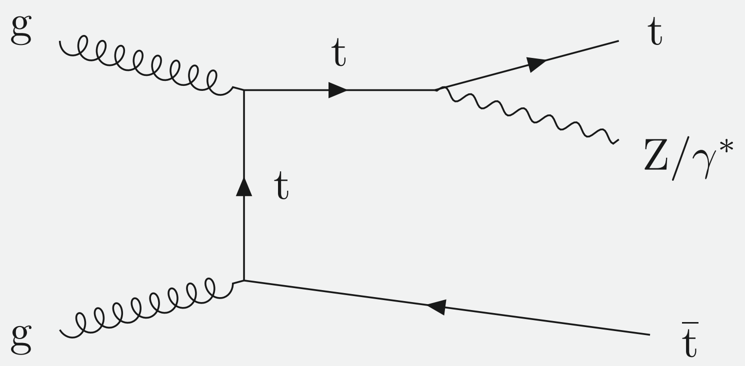
$$\begin{cases} p_{\text{T},\gamma} > 25\ \text{GeV} \\ |\eta_\gamma| < 1.44 \\ \Delta R(\mu/\text{jet},\gamma) > 0.5 \end{cases}$$

Top pairs

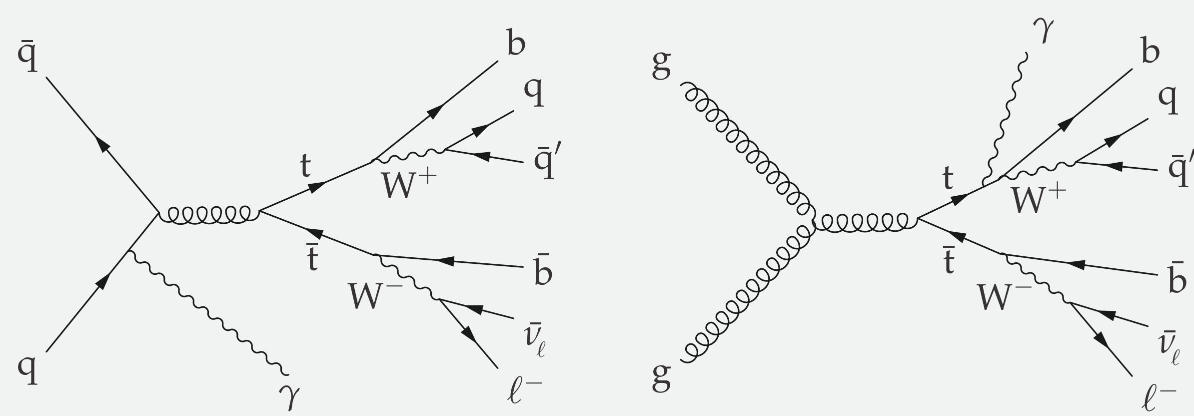
$t\bar{t}W$



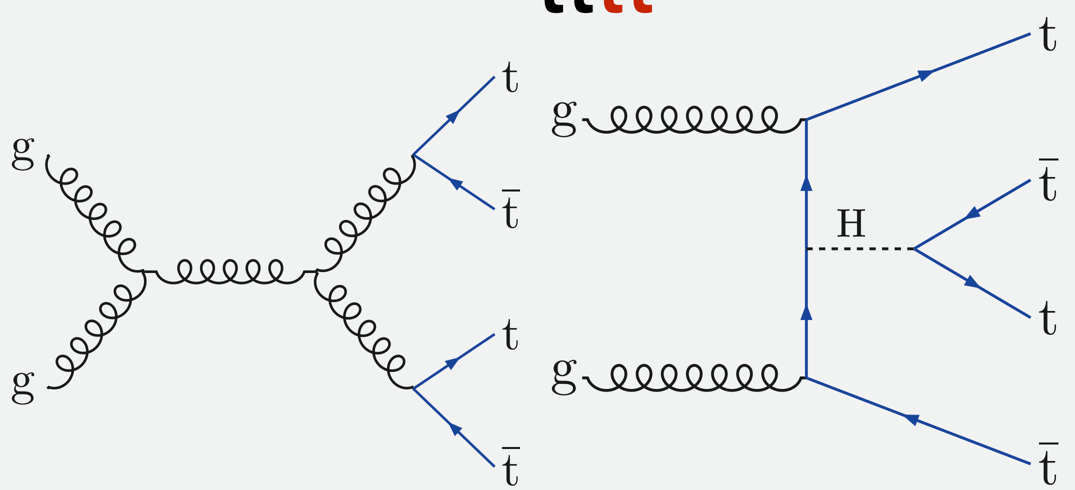
$t\bar{t}Z$



$t\bar{t}\gamma$

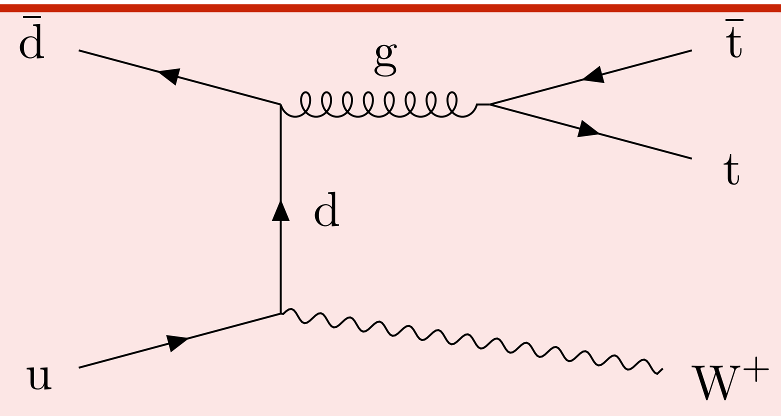


$t\bar{t}t\bar{t}$

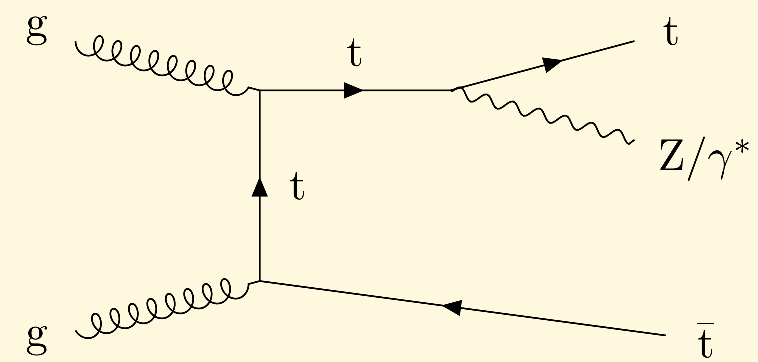


$t\bar{t}W$, $t\bar{t}Z$

Simultaneous measurement of $\sigma(t\bar{t}W)$ and $\sigma(t\bar{t}Z)$ with 2016 data



$\sigma(t\bar{t}W) = 0.61 \pm 0.08$ pb @ NLO



$\sigma(t\bar{t}Z) = 0.84 \pm 0.10$ pb @ NLO

- $t\bar{t}W$ → same-sign dilepton channel
- Multivariate discriminant in bins of jet multiplicity, lepton charge

- $t\bar{t}Z$ → 3 and 4 lepton categories
- Further bin in jet multiplicity

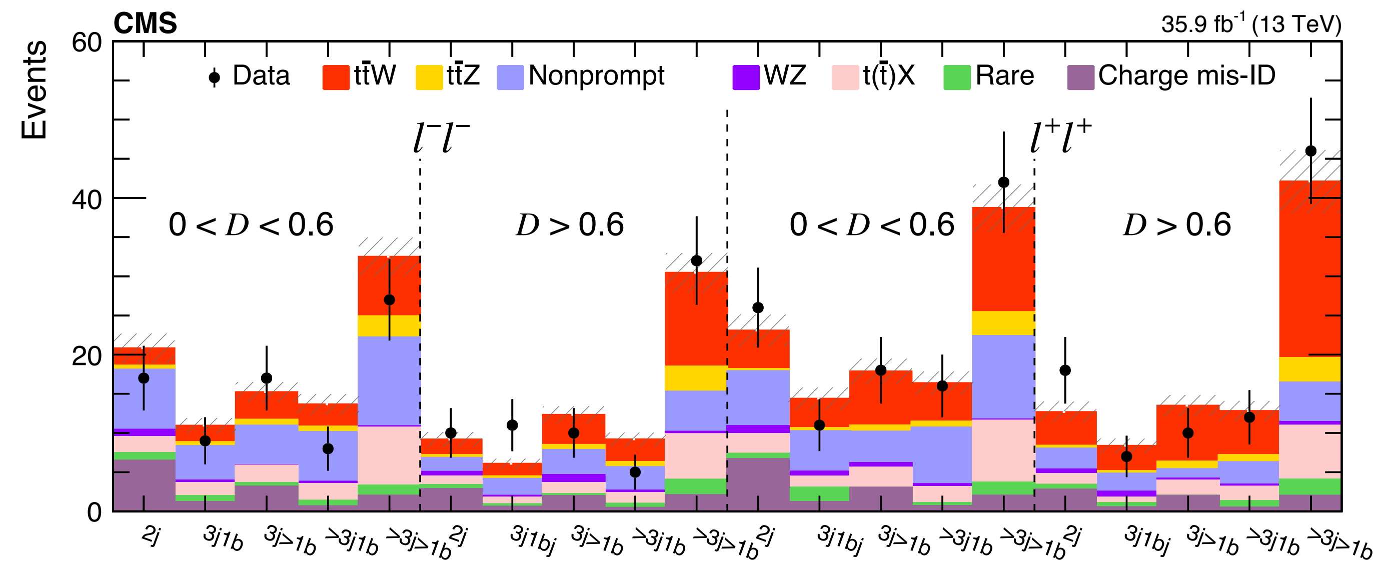
$t\bar{t}W$, $t\bar{t}Z$

36fb^{-1}

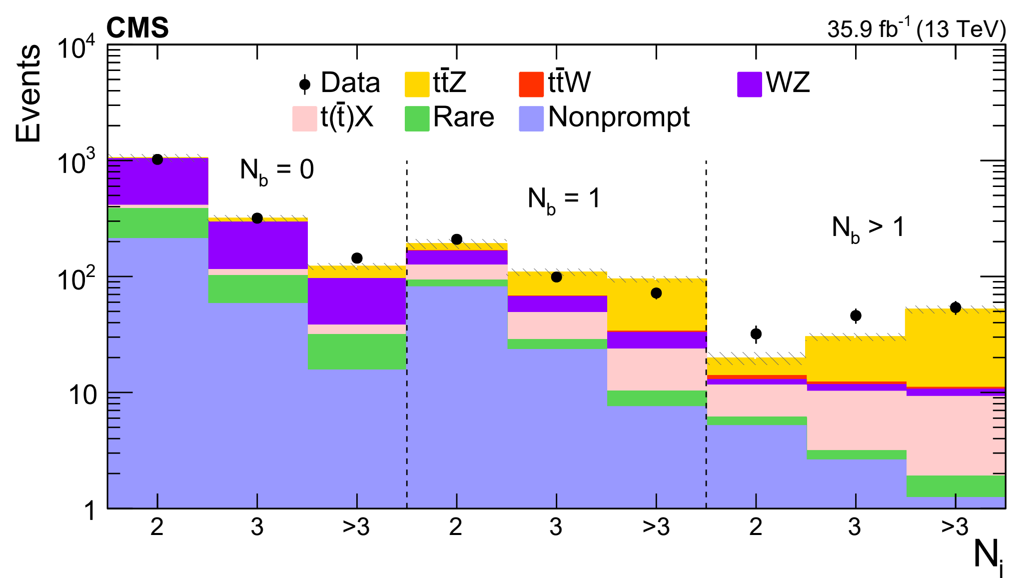
JHEP 08 (2018) 011

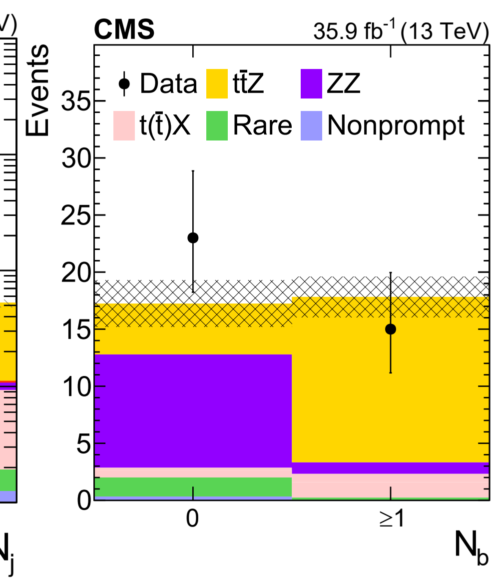
- Leading backgrounds
  - Nonprompt/charge misid. → data-driven estimate from sideband
  - WZ → normalization ~ 1 in dedicated CR
- $t\bar{t}W$ (2L SS)
  - BDT (*D*) trained on event kinematics
    - D < 0 used as nonprompt-enriched CR
    - Then split at D = 0.6 in SRs
  - 20 bins (*D* x charge x N_j x N_b)
- $t\bar{t}Z$
  - 3L: 9 bins (N_j x N_b)
  - 4L: 2 bins (N_j=2, N_b=0,≥1)
- Leading systematics
  - Lepton ID
  - Nonprompt estimation
  - B-tag, trigger

$t\bar{t}W$ Postfit



$t\bar{t}Z$ Postfit



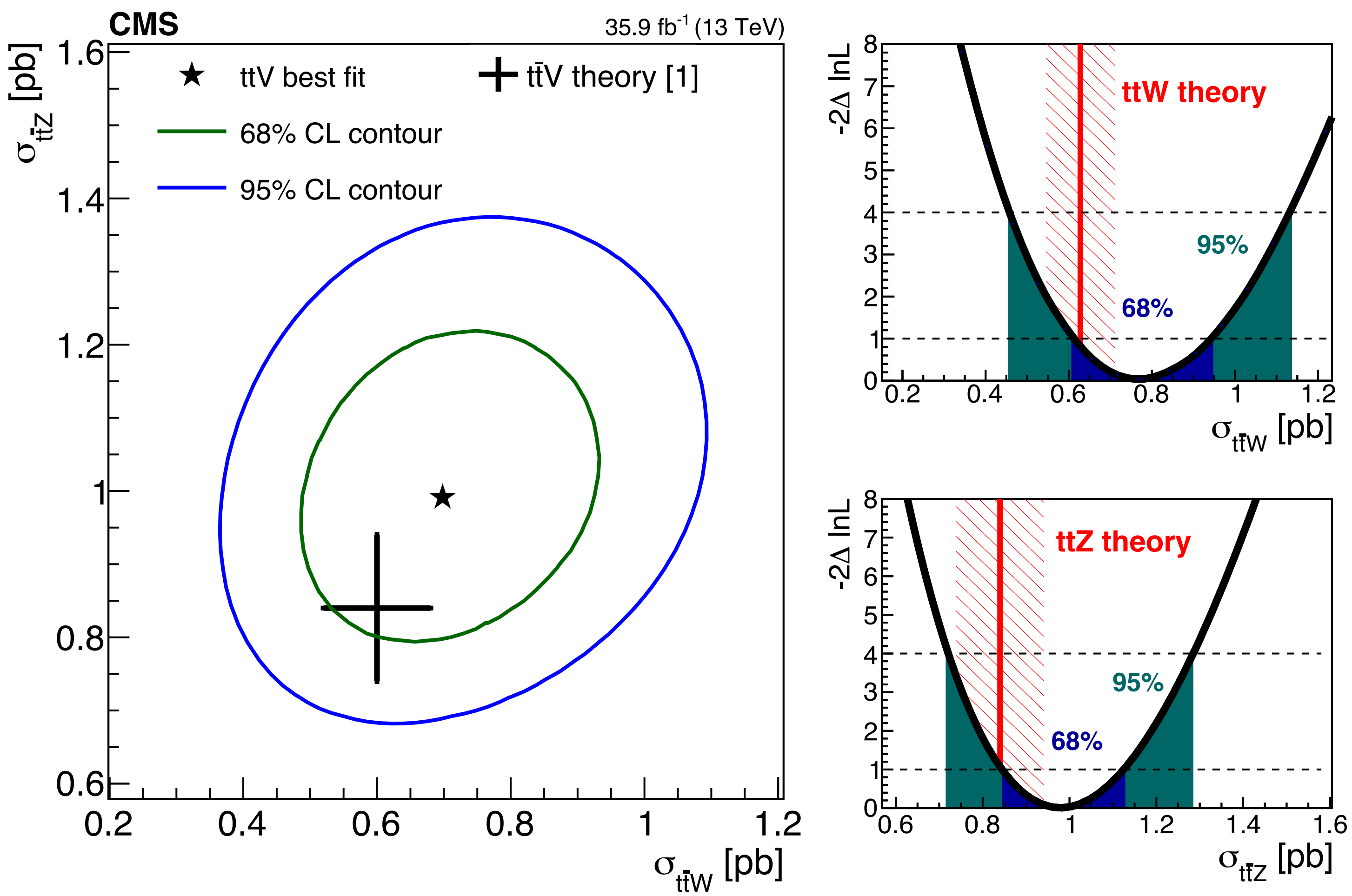


36fb-1
JHEP 08 (2018) 011

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

- Fit 31 bins to data to extract $t\bar{t}W$, $t\bar{t}Z$ cross-sections
- Results also used to constrain eight operators within **EFT**

More in talks on Fri.



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

5.3σ obs., 4.5σ exp.

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

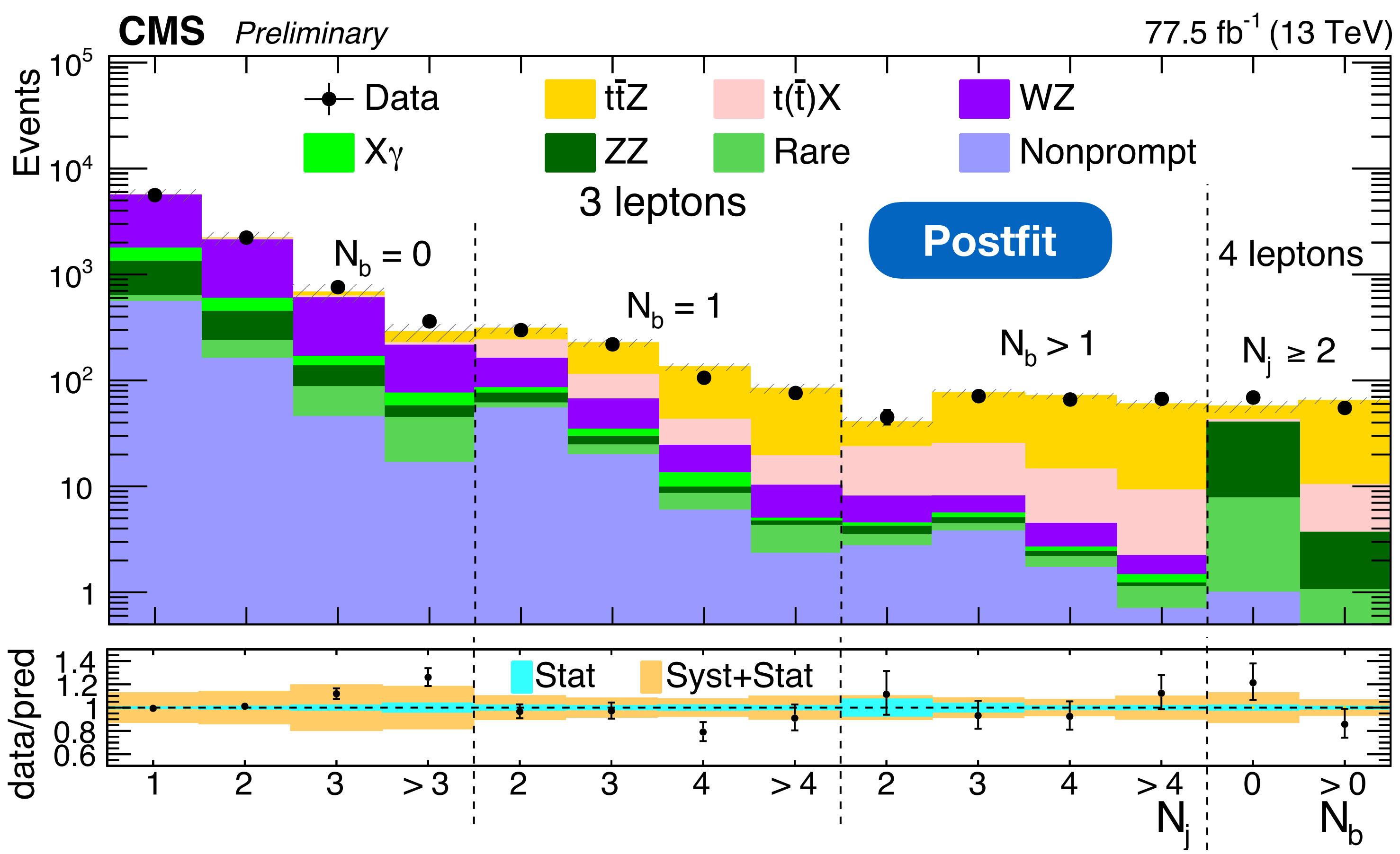
>5σ obs./exp.

Updated $t\bar{t}Z$

78fb^{-1}

PAS TOP-18-009

- Closely follows previous 2016 analysis (3 and 4 lepton categories, binned in N_j, N_b)
- Improvements
  - BDT-based lepton ID
    - up to 15% higher lepton efficiency
    - **Reduced** lepton ID systematic
  - Deep neural network b-tagging algorithm
  - More inclusive trigger selection
- Measured cross-section nearly identical to previous value (**14% precision → 8.5%**)



$$\sigma(t\bar{t}Z) = 1.00\ ^{+0.06}_{-0.05}\,(\text{stat})\ ^{+0.07}_{-0.06}\,(\text{syst})\,\text{pb}$$

Updated $t\bar{t}Z$

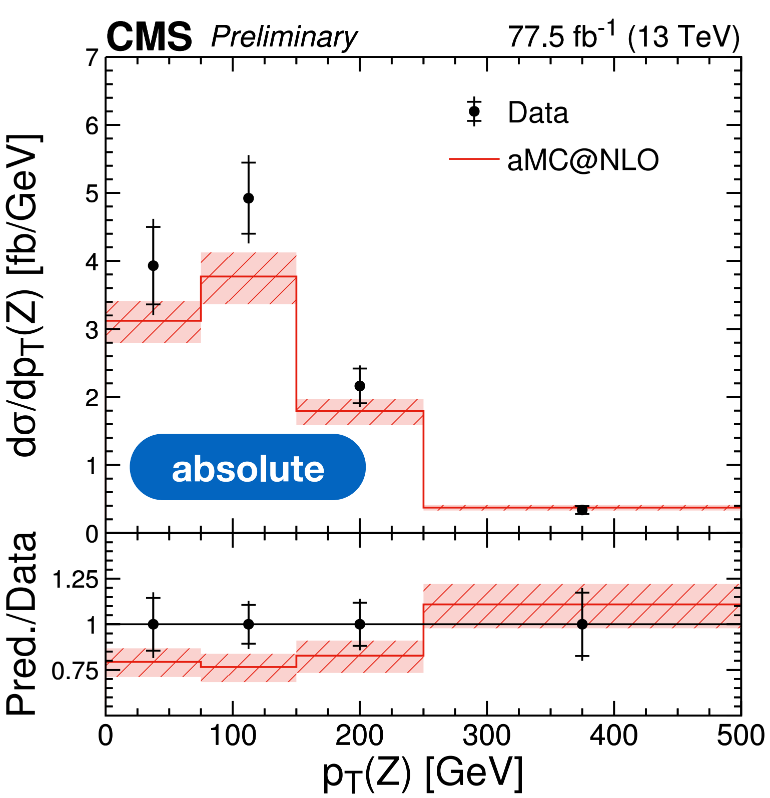
78fb-1

PAS TOP-18-009

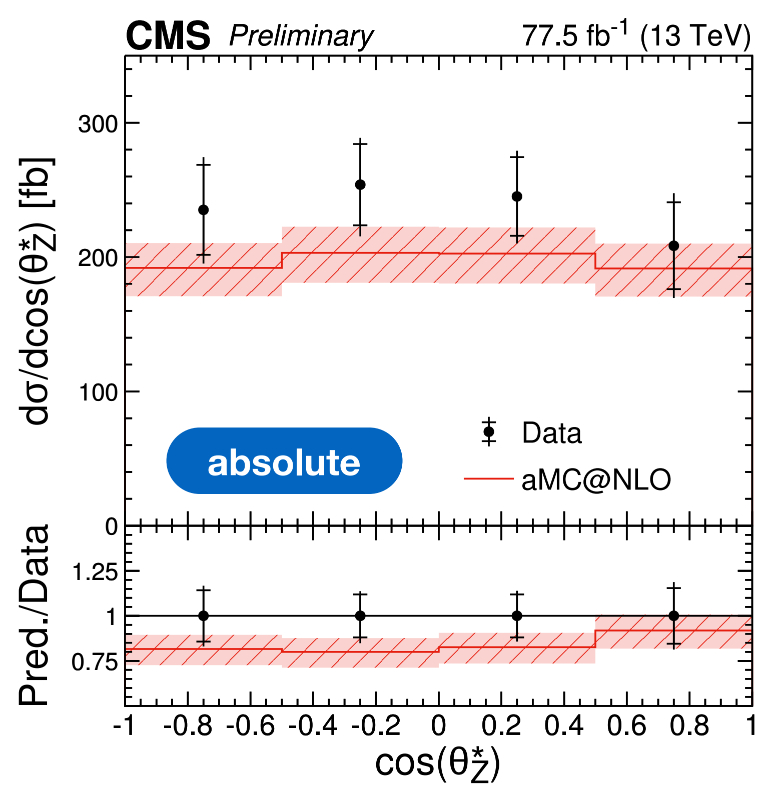
- Inclusive cross-section measurement **precision better than NLO predictions**
- With double the data, also perform a **differential** measurement in
  - $p_T(Z)$
  - $\cos(\theta^*_Z)$ — angle between Z and ℓ^- in Z rest frame (sensitive to polarization)
- Constrain anomalous t-Z couplings (2 vector/axial, 2 dipole parameters)
- Constrain 4 EFT operators associated with t-Z/γ deviations

More in talks on Fri.

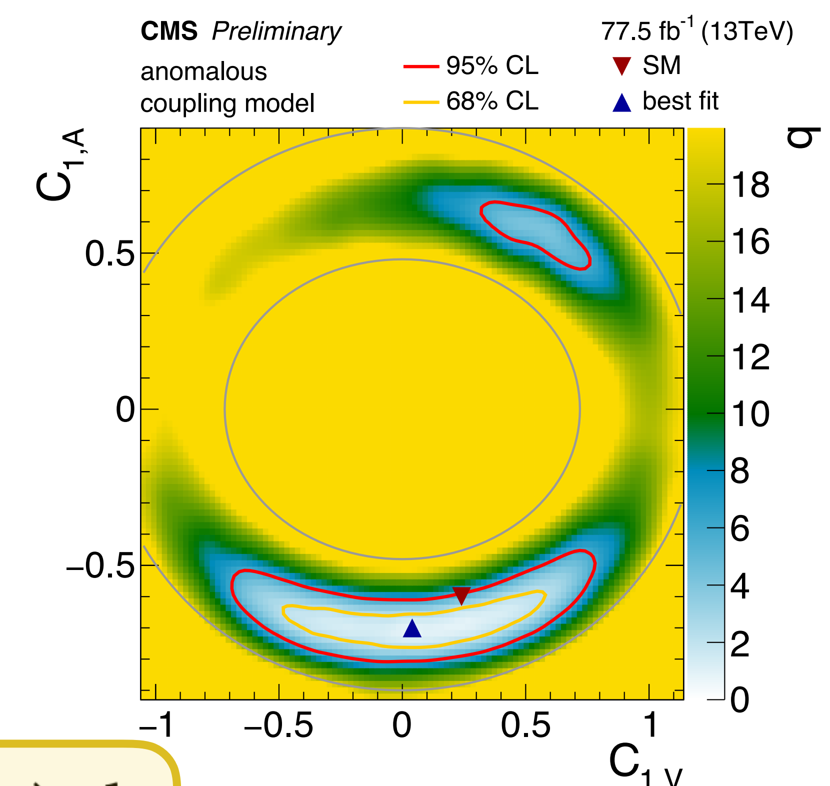
$p_T(Z)$



$\cos(\theta^*_Z)$



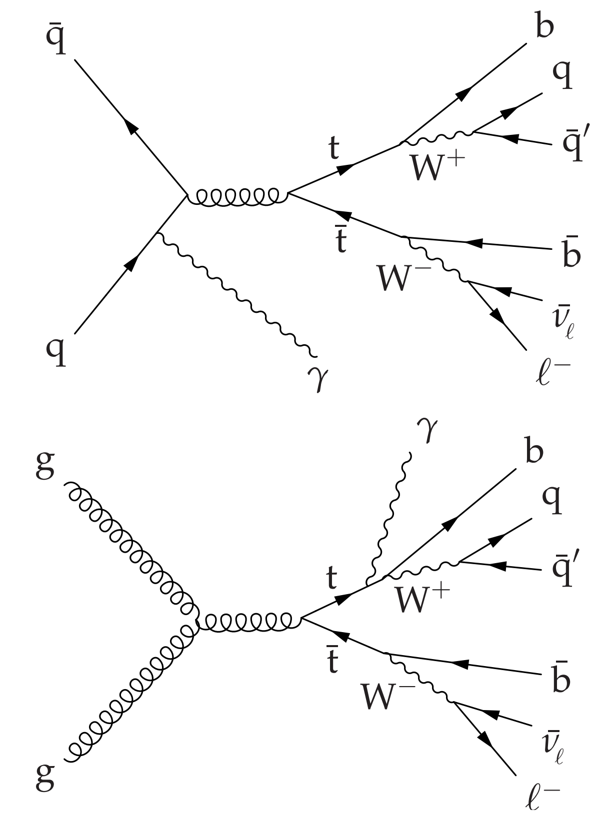
$$\mathcal{L} = e\bar{u}(p_t)\left[\gamma^\mu (C_{1,V} + \gamma_5 C_{1,A}) + \frac{i\sigma^{\mu\nu} q_\nu}{M_Z}(C_{2,V} + i\gamma_5 C_{2,A})\right] v(p_{\bar{t}}) Z_\mu,$$

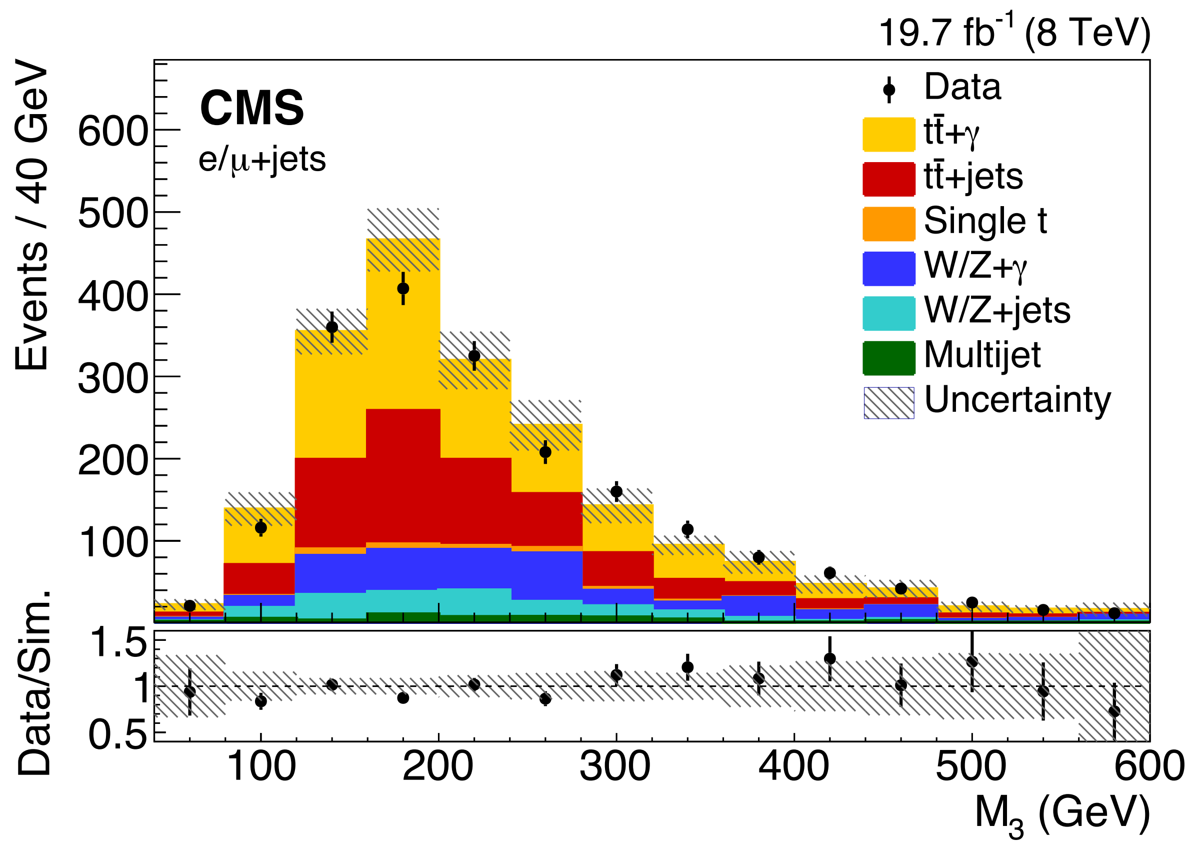


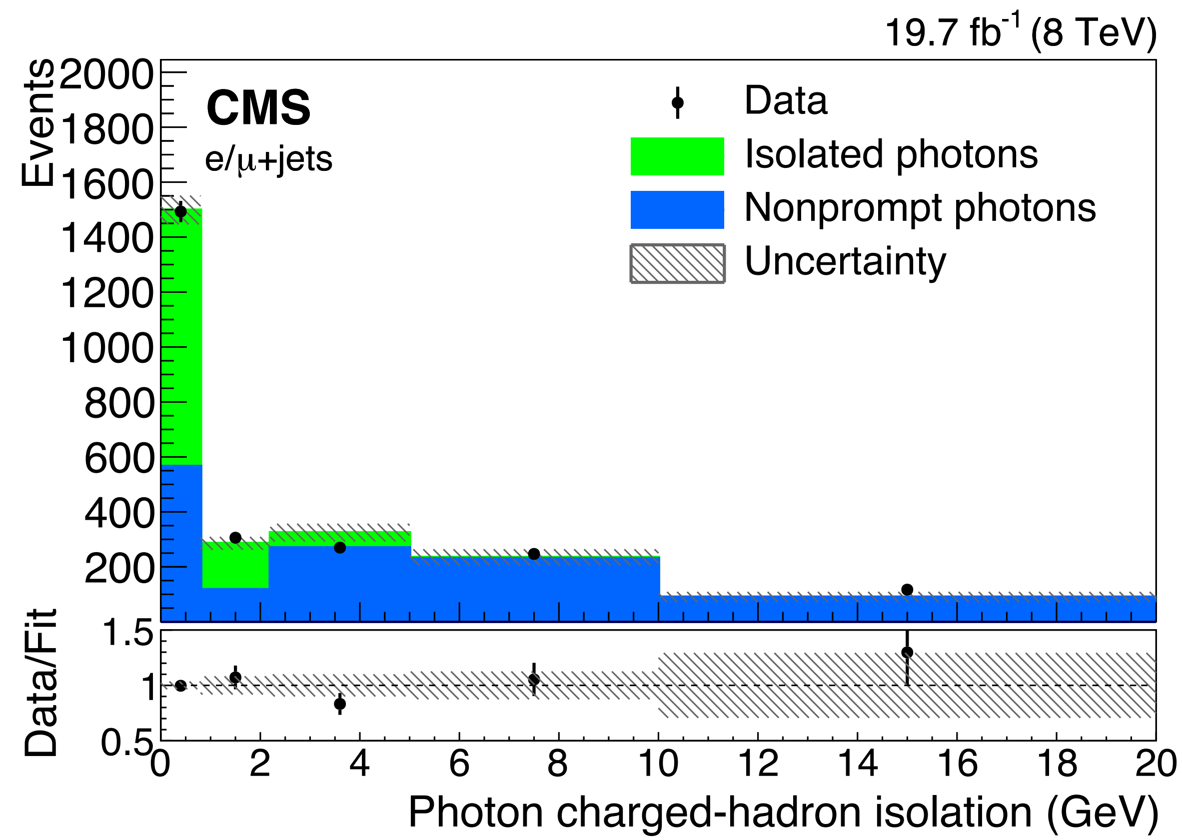
$$\sigma(t\bar{t}Z) = 1.00\ ^{+0.06}_{-0.05}\ (\text{stat})\ ^{+0.07}_{-0.06}\ (\text{syst})\ \text{pb}$$

$t\bar{t}\gamma$

- Measure with lepton+jets channel (≥3 jets, ≥1 b jet) + photon with **two leading backgrounds**
  - $t\bar{t}$+fake γ
  - W/Z+real γ
- $\sigma(t\bar{t}\gamma)$ extracted after performing two sequential fits
  - "top purity" from distribution M_3 = invariant mass of 3-jet system with maximum vector p_T sum
  - "photon purity" from photon isolation distribution







$t\bar{t}\gamma$

- Combined likelihood fit containing top and photon purities with expected and observed yields
- Electron and muon channels considered separately in the fit
- Cross-section reported with semileptonic branching ratio

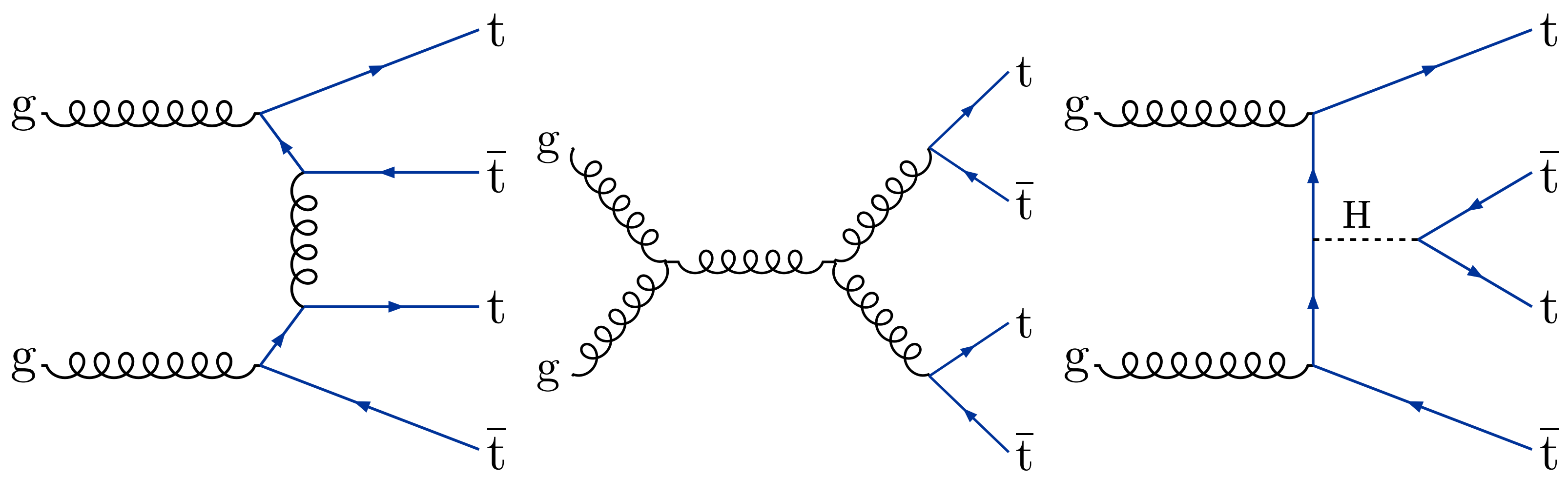
Category	R	$\sigma^{\text{fid}}_{t\bar{t}+\gamma}$ (fb)	$\sigma_{t\bar{t}+\gamma}\,\mathcal{B}$ (fb)
e+jets	$(5.7 \pm 1.8) \times 10^{-4}$	138 ± 45	582 ± 187
μ+jets	$(4.7 \pm 1.3) \times 10^{-4}$	115 ± 32	453 ± 124
Combination	$(5.2 \pm 1.1) \times 10^{-4}$	127 ± 27	515 ± 108
Theory	—	—	592 ± 71 (scales)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

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

$$\sigma_{\text{exp}}(\text{pp} \to t\bar{t}\gamma) \cdot B = 515 \pm 108 \text{ fb}$$

$$\sigma_{\text{theory}}(\text{pp} \to t\bar{t}\gamma) \cdot B = 592 \pm 77 \text{ fb}$$

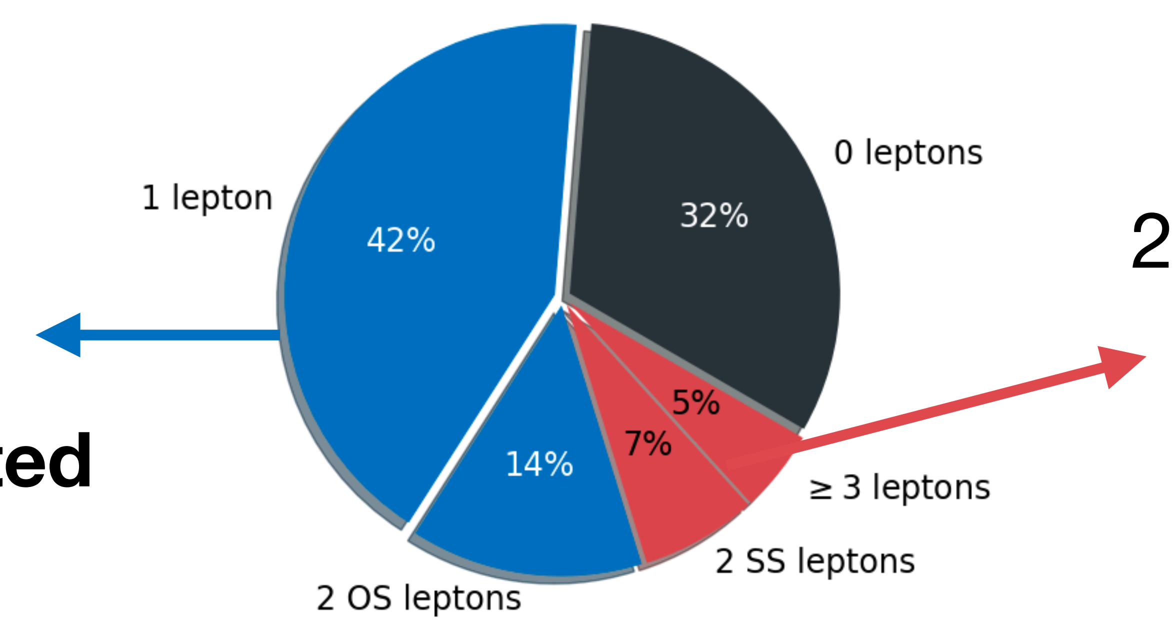
$t\bar{t}t\bar{t}$



- Four top quark final state sensitive to **higgs properties, 2HDM, EFT, strong SUSY**, …
- SM theory — $\sigma(pp \rightarrow t\bar{t}t\bar{t})$ = 12fb ± 20% @ NLO (1711.02116)
- **Two complementary search channels**

1, 2 OS leptons
- BR~56%
- **Syst. dominated**

PAS TOP-17-019



2 SS, ≥3 leptons
- BR~12%
- **Stat. dominated**

PAS TOP-18-003

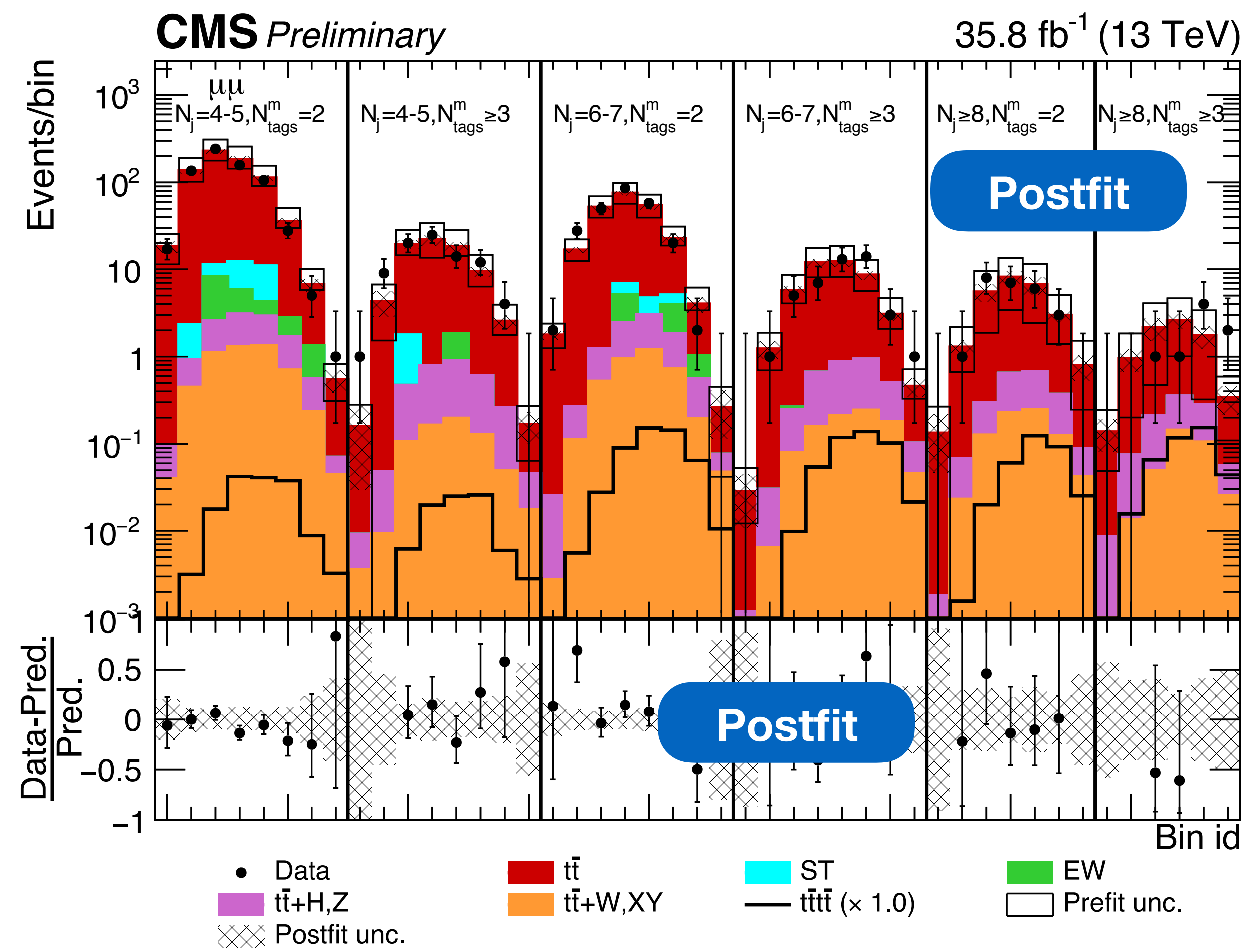
$t\bar{t}t\bar{t}$ — 1, 2 OS leptons

36fb^{-1}

PAS TOP-17-019

- **Main background is $t\bar{t}$** but $t\bar{t}$+X non-negligible
- **Strategy**
  - In bins of jet, b jet multiplicity and e/μ, use two BDTs and fit to data
    1. Identify triplets of jets from hadronic top decay via kinematic handles
    2. Event-level discriminator for $t\bar{t}t\bar{t}$ (includes output of 1.)
- **Results**
  - Also combined with 2016 multilepton channel
  - 1.4σ obs. (1.1σ exp) → $\sigma_{t\bar{t}t\bar{t}} = 13^{+11}_{-9}$fb
  - Constrained EFT operators

event discriminants in OS $\mu\mu$ channel



Channel	Best-fit μ	Best-fit $\sigma_{t\bar{t}t\bar{t}}$ (fb)	Exp. significance s.d.	Obs. significance s.d.
Single lepton	$1.6^{+4.6}_{-1.6}$	15^{+42}_{-15}	0.21	0.36
Dilepton	$0.0^{+2.7}$	0^{+25}	0.36	0.0
Combined (this analysis)	$0.0^{+2.2}$	0^{+20}	0.40	0.0
Multilepton	$1.8^{+1.5}_{-1.2}$	17^{+14}_{-11}	1.0	1.6
Combined (this analysis + multilepton)	$1.4^{+1.2}_{-1.0}$	13^{+11}_{-9}	1.1	1.4

* assuming SM $\sigma_{t\bar{t}t\bar{t}}$ = 9.2fb

$$\sigma_{t\bar{t}t\bar{t}} = \sigma^{SM}_{t\bar{t}t\bar{t}} + \frac{1}{\Lambda^2}\vec{C}^T \cdot \vec{\sigma}^{(1)} + \frac{1}{\Lambda^4}\vec{C}^T \sigma^{(2)} \vec{C},$$

$$\mathcal{O}^1_{tt} = (\bar{t}_R\gamma^\mu t_R)(\bar{t}_R\gamma_\mu t_R),$$
$$\mathcal{O}^1_{QQ} = (\bar{Q}_L\gamma^\mu Q_L)(\bar{Q}_L\gamma_\mu Q_L),$$
$$\mathcal{O}^1_{Qt} = (\bar{Q}_L\gamma^\mu Q_L)(\bar{t}_R\gamma_\mu t_R),$$
$$\mathcal{O}^8_{Qt} = \left(\bar{Q}_L\gamma^\mu T^A Q_L\right)\left(\bar{t}_R\gamma_\mu T^A t_R\right),$$

Operator	Expected C_k/Λ^2 (TeV^{-2})	Observed (TeV^{-2})
$\mathcal{O}^1_{tt}$	[−1.5, 1.3]	[−2.1, 2.0]
$\mathcal{O}^1_{QQ}$	[−1.5, 1.3]	[−2.2, 2.0]
$\mathcal{O}^1_{Qt}$	[−2.4, 2.4]	[−3.5, 3.5]
$\mathcal{O}^8_{Qt}$	[−5.6, 4.3]	[−7.9, 6.6]

$t\bar{t}t\bar{t}$ — 2 SS, ≥3 leptons

137fb^{-1}

PAS TOP-18-003

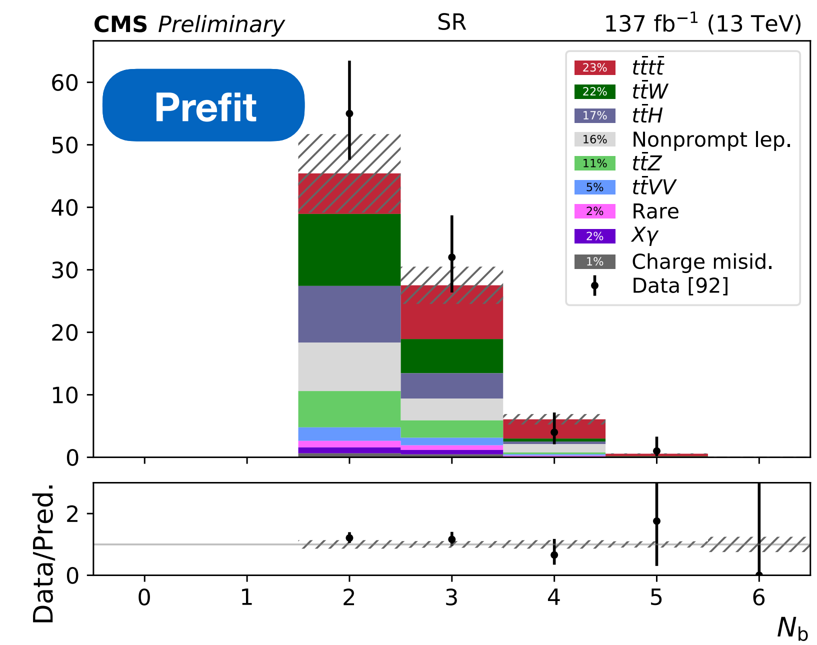
UCSB

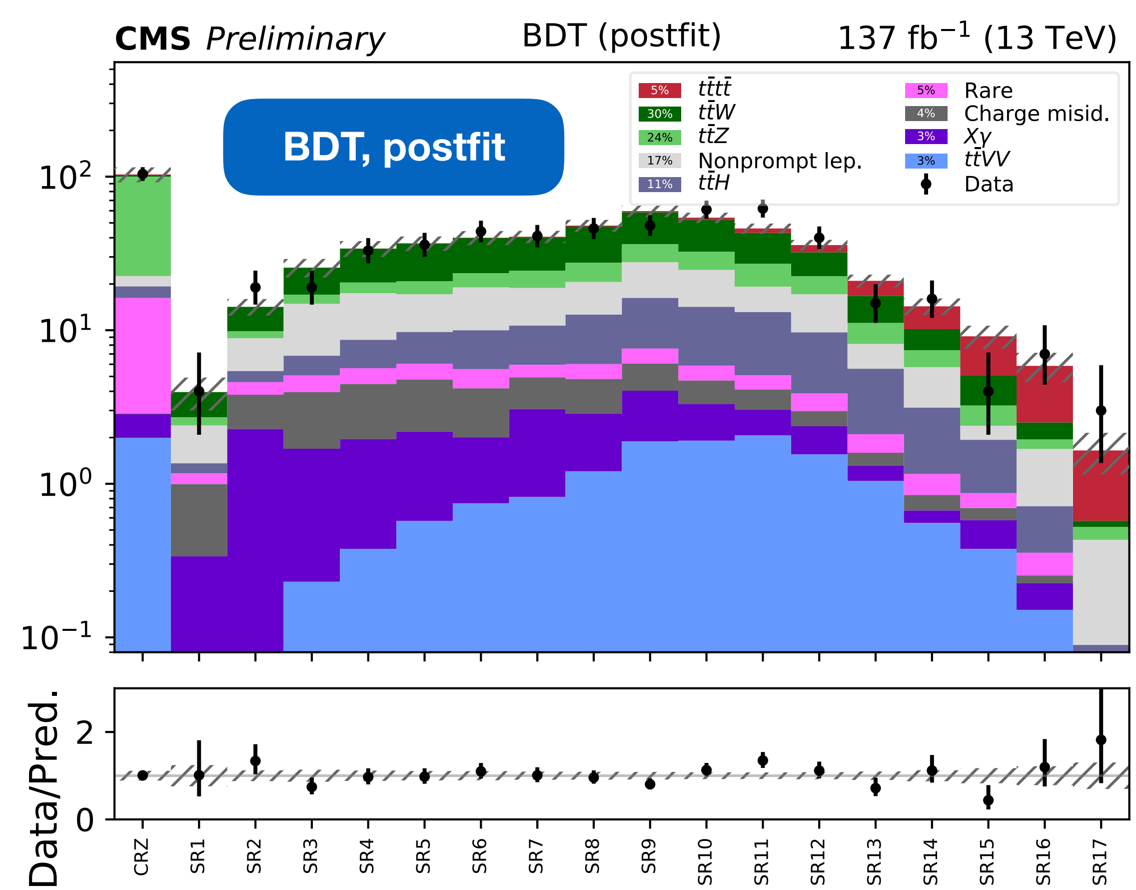
- Based on 35.9fb^{-1} result (Eur. Phys. J. C 78 (2018) 140)
  - 1.6σ obs. (1σ exp)
- **Main backgrounds** are **$t\bar{t}W$, $t\bar{t}Z$, $t\bar{t}H$, non-prompt leptons**
  - Data-driven/sideband estimation of non-prompt contribution
  - $t\bar{t}$+W/Z normalized to data in high stat. regions
- **Strategy — BDT analysis and cut-based cross-check**
  - Main handles are jet, b jet, lepton multiplicity
  - Baseline requirements of SS lepton pair, ≥2 jets, ≥2 b jets — retains ~20 $t\bar{t}t\bar{t}$ events
  - Train single event-level BDT for signal discrimination
  - Binned fit for cut-based and BDT analyses
- Leading syst. uncertainty from **$t\bar{t}X$+bb modeling**
- **Results**
  - With full Run 2 BDT analysis:
    2.6σ obs. (2.7σ exp) → $\sigma_{t\bar{t}t\bar{t}}$ =13$^{+6}_{-5}$fb
  - **Approaching 3σ evidence!**

	Significance	$\sigma(t\bar{t}t\bar{t})$ [fb]
BDT	2.6σ (2.7σ)	12.6$^{+5.8}_{-5.2}$
Cut-based	1.7σ (2.5σ)	9.4$^{+6.2}_{-5.6}$

* assuming SM $\sigma_{t\bar{t}t\bar{t}}$ = 9.2fb

b tagged jet multiplicity



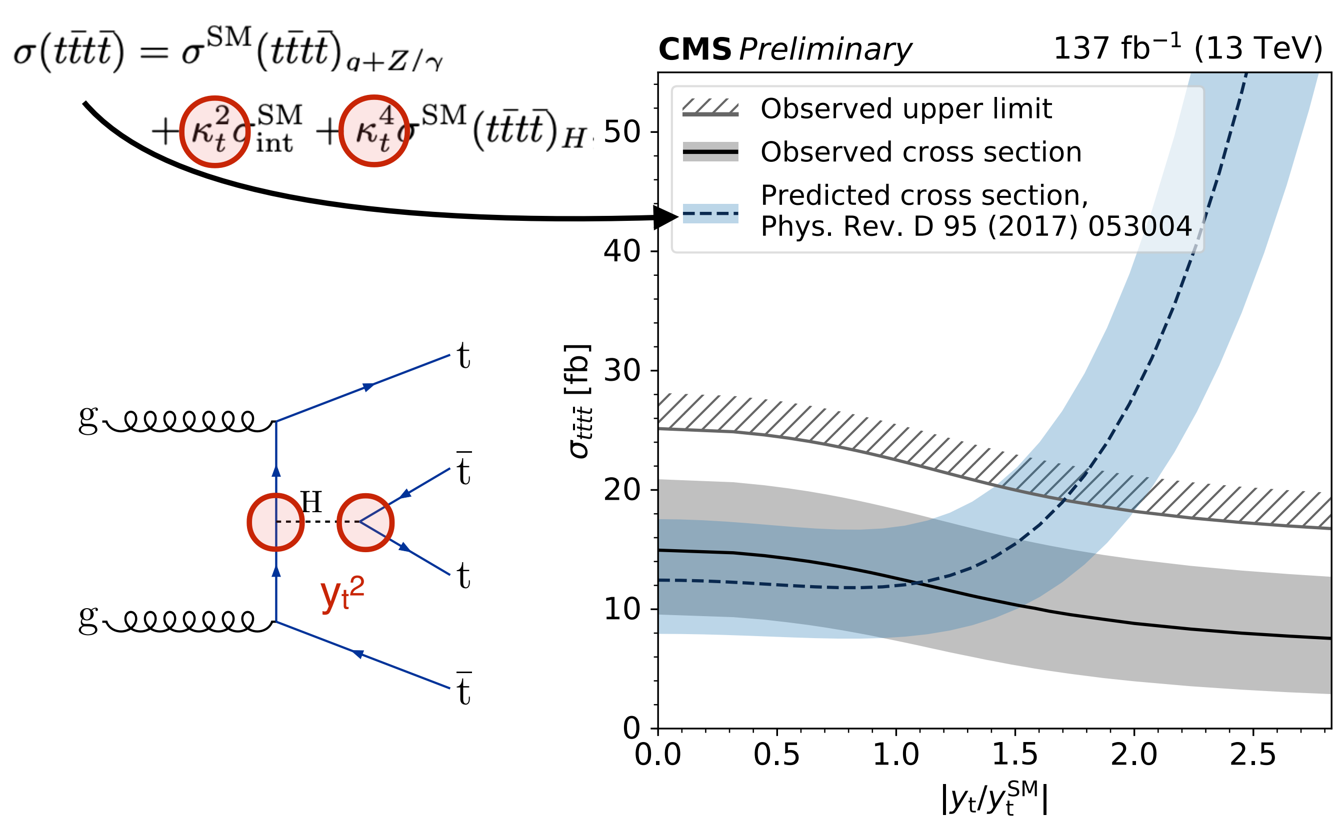


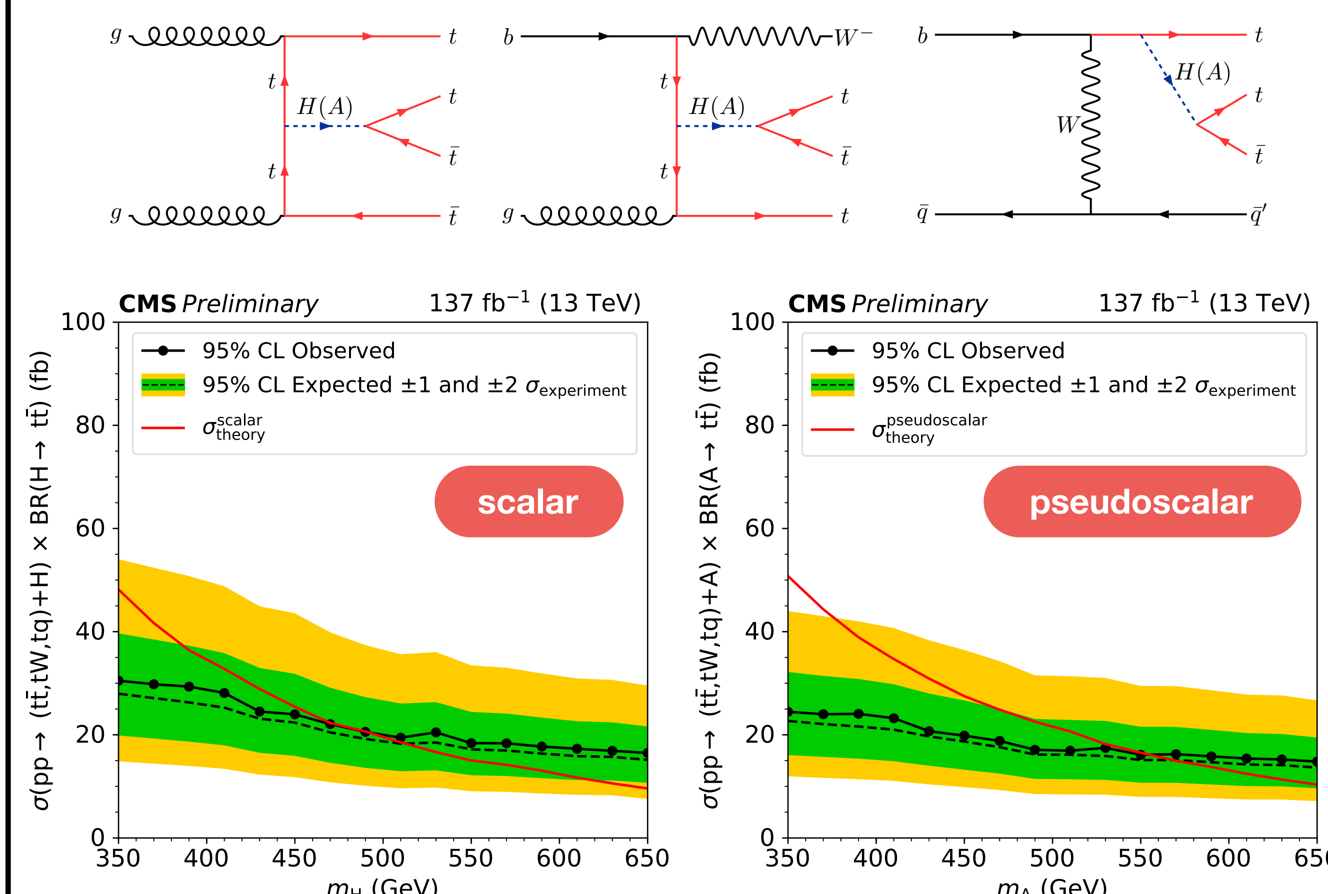
$t\bar{t}t\bar{t}$ — 2 SS, ≥3 leptons

137fb-1

PAS TOP-18-003

- **Interpretations**
  - Translate into constraint on top Yukawa coupling $|y_t/y_t^{SM}|<1.7$
    - Measurement of $\sigma(t\bar{t}t\bar{t})$ dependent on $t\bar{t}H$ background
      - $\sigma(t\bar{t}H) \sim |y_t/y_t^{SM}|^2$
  - Also exclude heavy ($m>2m_t$) scalar (pseudoscalar) bosons up to ~500 (550) GeV in type-II 2HDM (preferring $H\to t\bar{t}$ at low $\tan\beta$)





Summary

- Associated production processes sensitive to rich set of physics
- Analyses beginning to challenge and surpass NLO calculation precision
- And there is still much room to improve
  - 2016 → full Run2 dataset — almost **4x luminosity**

13 TeV summary table

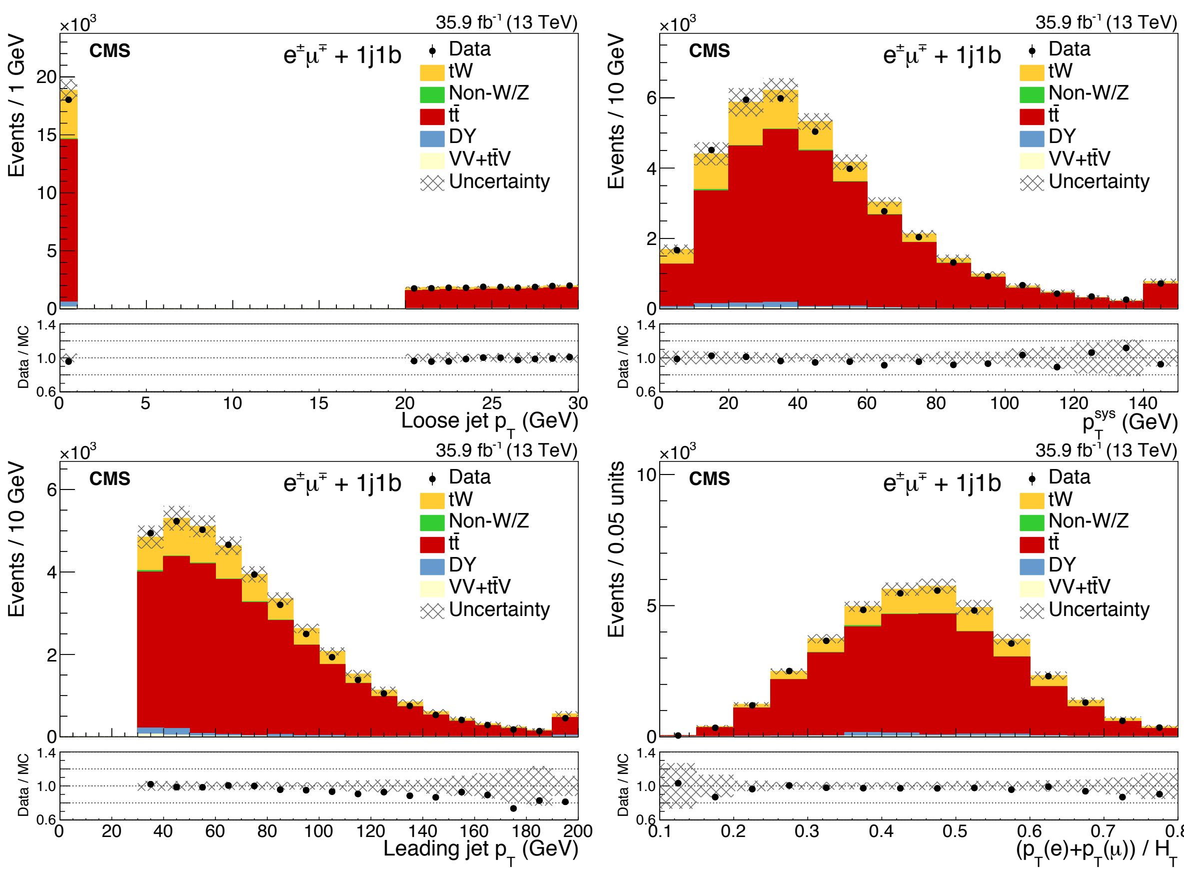
	int. lumi. (fb^{-1})	σ theory	σ experiment	
tW	36	71.7 ± 3.8 pb	63.1 ± 7.0 pb	
tγq	36	81 ± 4.0 fb	115 ± 34 fb	σ(pp→tγq)B(t→$\mu\upsilon$b)
t$\bar{t}$W	36	0.61 ± 0.08 pb	0.77 ± 0.17 pb	
tZq	78	94.2 ± 3.1 fb	111 ± 16 fb	σ(pp→tZq)B(Z→$\ell\ell$)
t$\bar{t}$Z	78	0.84 ± 0.10 pb	1.00 ± 0.09 pb	
t$\bar{t}$t$\bar{t}$	137	$12^{+2.2}_{-2.5}$ fb	$12.6^{+5.8}_{-5.2}$ fb	

Backup

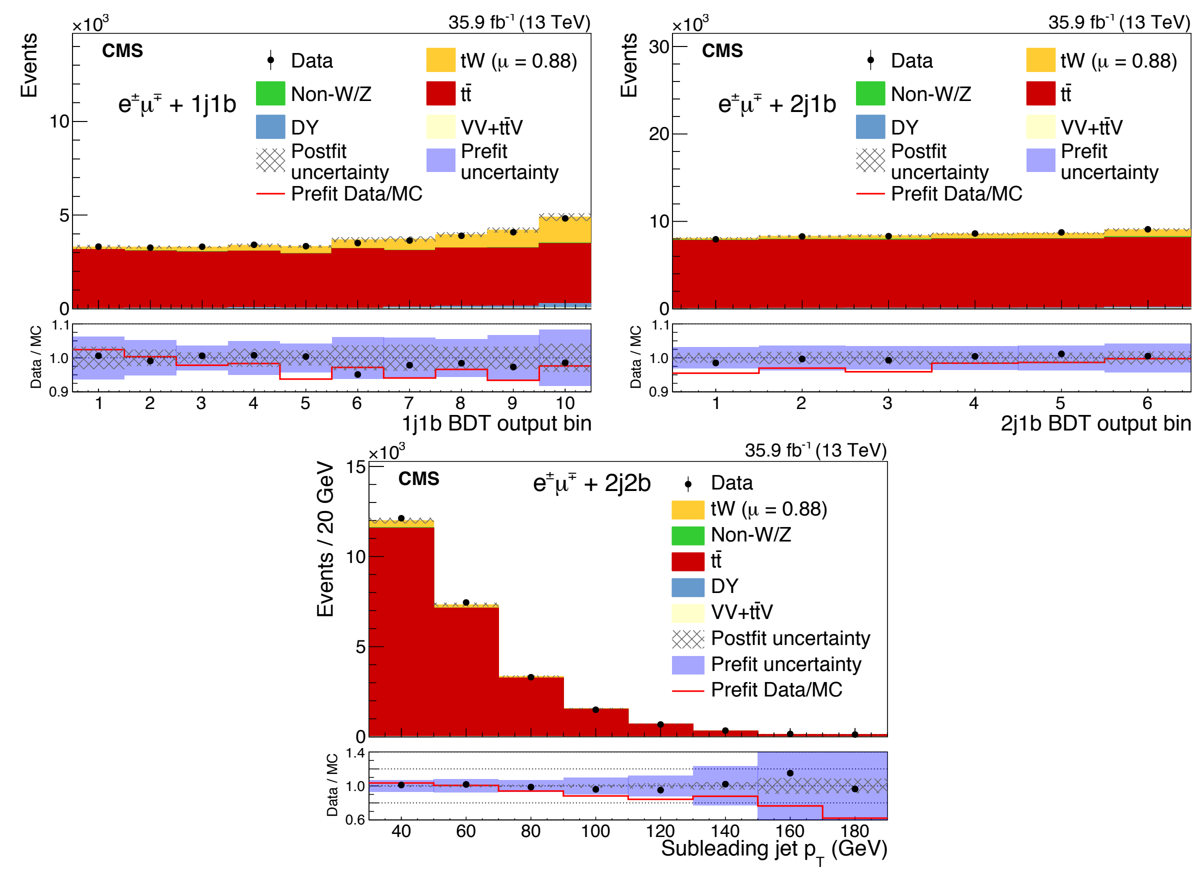
tW

tW

most discriminating BDT variables



inputs to fit

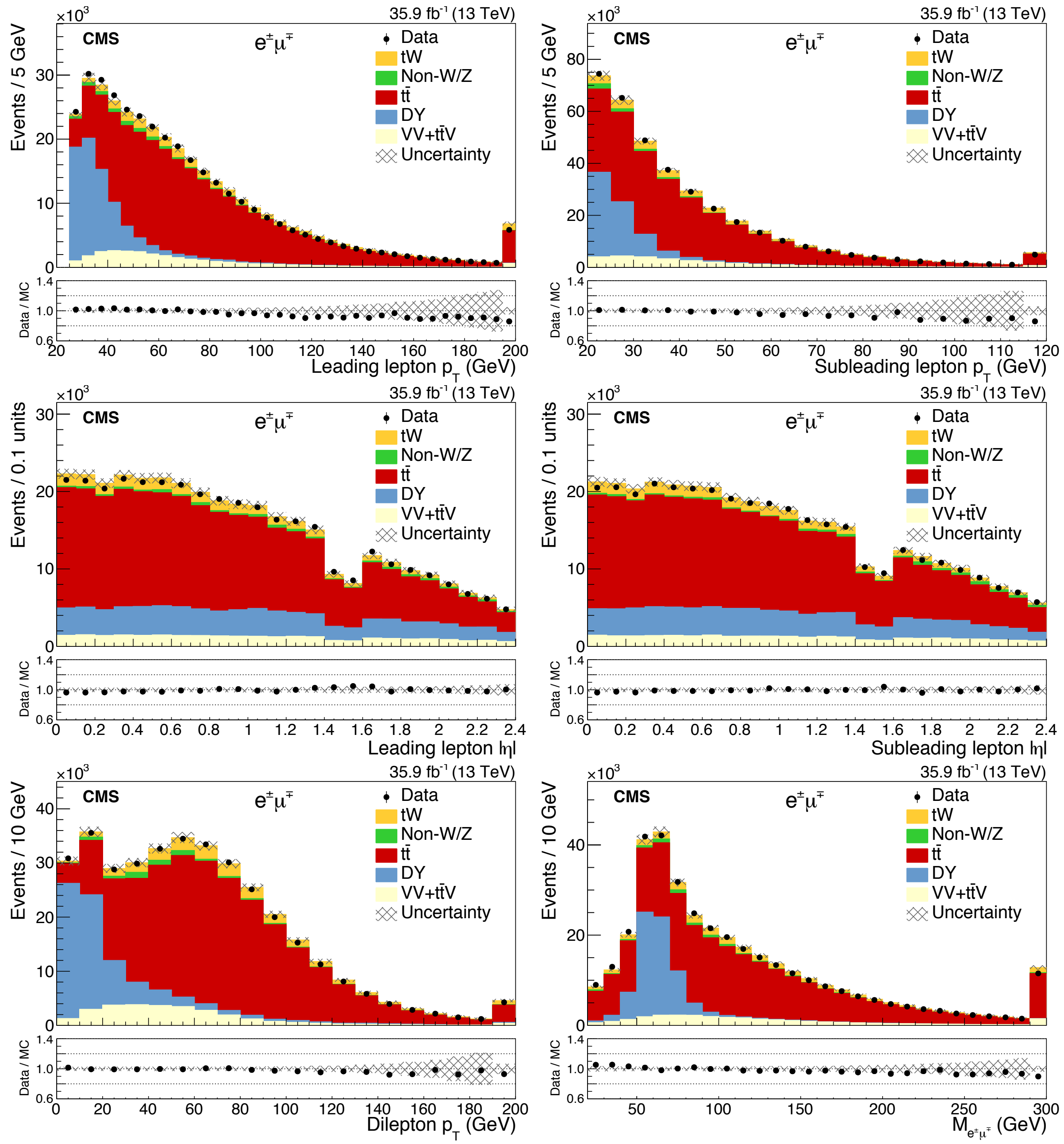


36fb^{-1}

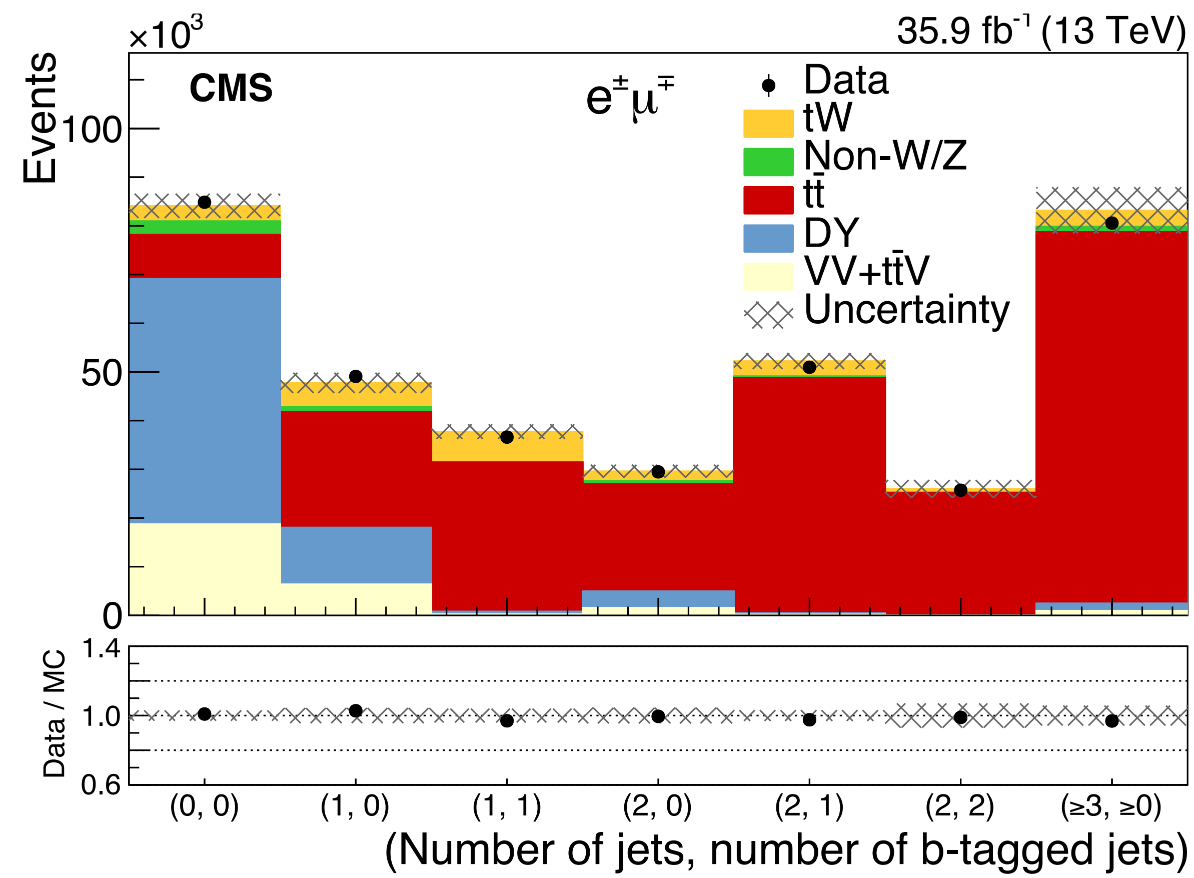
[JHEP 10 (2018) 117]

tW

kinematics (baseline dilep.)



N_j x N_b (baseline dilep.)



tW

Source	Uncertainty (%)
Experimental	
Trigger efficiencies	2.7
Electron efficiencies	3.2
Muon efficiencies	3.1
JES	3.2
Jet energy resolution	1.8
b tagging efficiency	1.4
Mistag rate	0.2
Pileup	3.3
Modeling	
$t\bar{t}$ μ_R and μ_F scales	2.5
tW μ_R and μ_F scales	0.9
Underlying event	0.4
Matrix element/PS matching	1.8
Initial-state radiation	0.8
Final-state radiation	0.8
Color reconnection	2.0
B fragmentation	1.9
Semileptonic B decay	1.5
PDFs	1.5
DR-DS	1.3

Source	Uncertainty (%)
Background normalization	
$t\bar{t}$	2.8
VV	0.4
Drell–Yan	1.1
Non-W/Z leptons	1.6
$t\bar{t}$V	0.1
MC finite sample size	1.6
Full phase space extrapolation	2.9
Total systematic (excluding integrated luminosity)	10.1
Integrated luminosity	3.3
Statistical	2.8
Total	11.1

	Prefit		Postfit	
Region	tW	$t\bar{t}$	tW	$t\bar{t}$
1j1b	6147 ± 442	30622 ± 1862	5440 ± 604	30592 ± 582
2j1b	3125 ± 294	48484 ± 1984	2888 ± 321	47436 ± 612
2j2b	725 ± 85	25052 ± 2411	719 ± 88	25114 ± 281

tZq

77fb-1

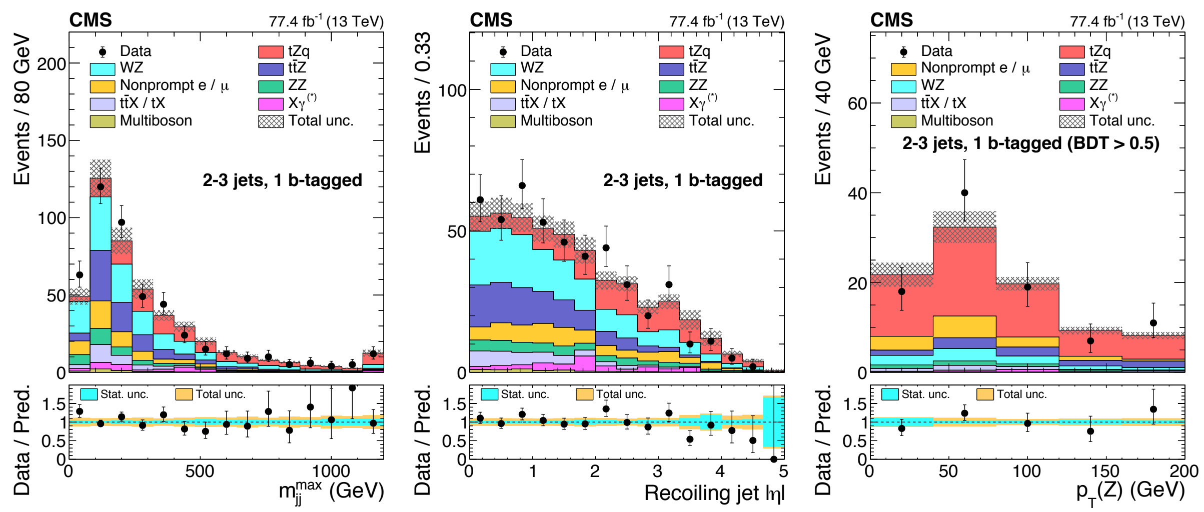
Phys. Rev. Lett. 122 (2019) 132003

tZq

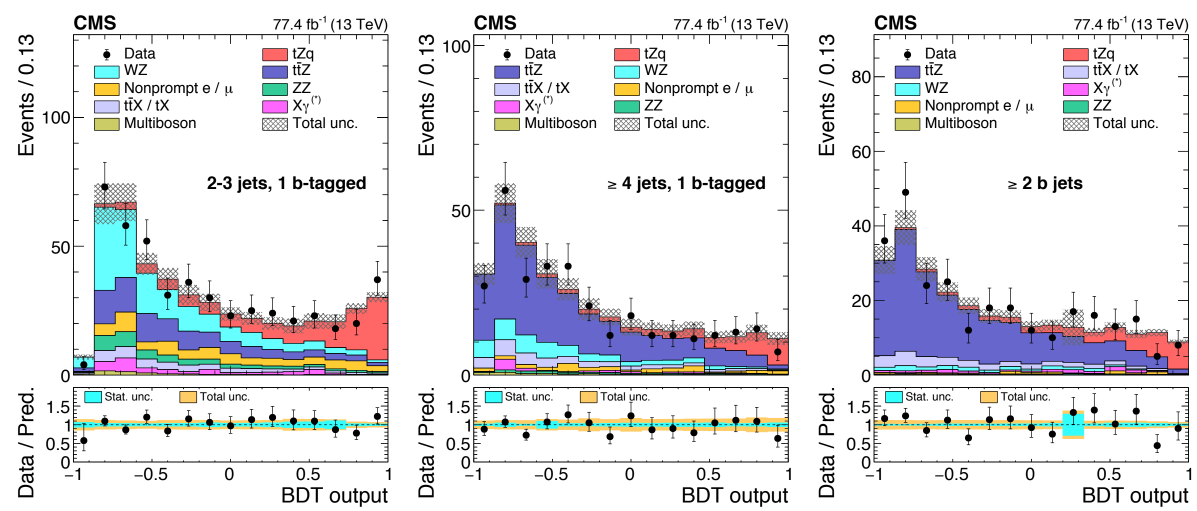
Uncertainty	Impact (%)
Experimental	
lepton selection	3.2
trigger efficiency	1.4
jet energy scale	3.3
b-tagging efficiency	1.7
nonprompt normalization	4.1
$t\bar{t}Z$ normalization	1.0
luminosity	1.7
pileup	1.9
other	1.3
Theoretical	
final-state radiation	2.0
tZq QCD scale	2.0
$t\bar{t}Z$ QCD scale	1.4

Source	2–3 jets, 1 b-tagged SR-2/3j-1b	$\geq$ 4 jets, 1 b-tagged SR-4j-1b	$\geq$ 2 b jets SR-2b
Exp. background	357 ± 34	278 ± 32	228 ± 25
Exp. tZq	103 ± 5.1	38 ± 5.3	37 ± 1.8
Total exp.	460 ± 37	316 ± 35	265 ± 25
Observed	475	310	278

leading BDT inputs



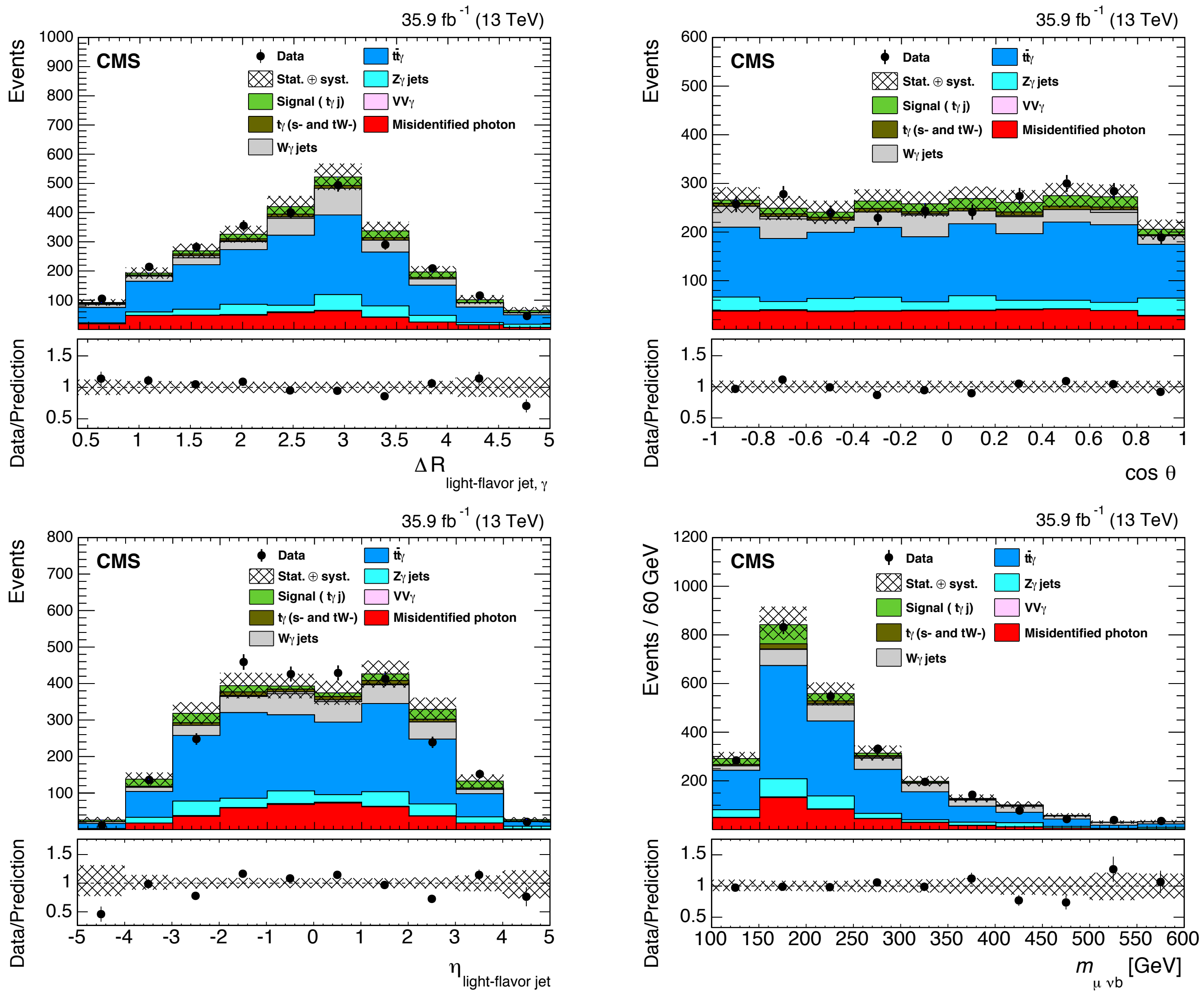
inputs to fit



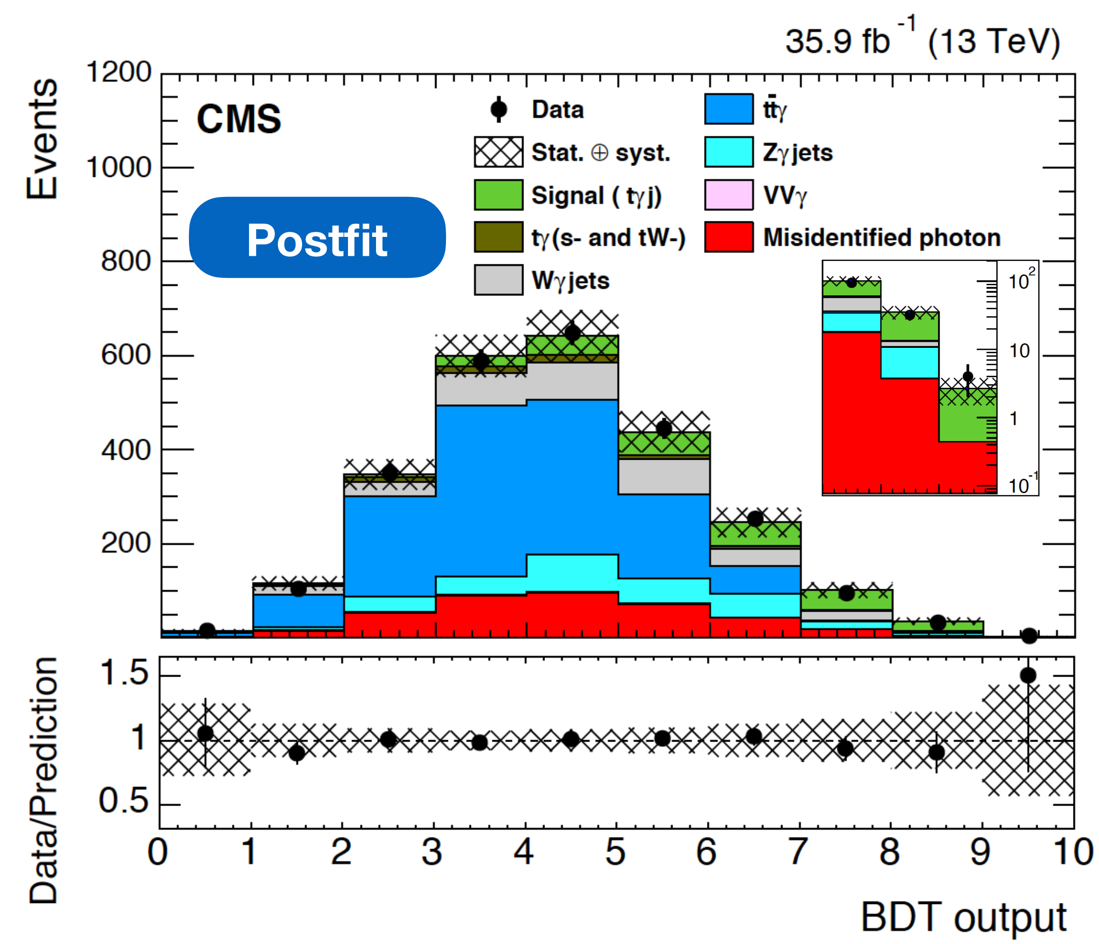
$t\gamma q$

tγq

most discriminating BDT variables



Process	Event yield
$t\bar{t}+\gamma$	1401 ± 131
Wγ+jets	329 ± 78
Zγ+jets	232 ± 55
Misidentified photon	374 ± 74
tγ (s- and tW-channel)	57 ± 8
VVγ	8 ± 3
Total background	2401 ± 178
Expected signal	154 ± 24
Total SM prediction	2555 ± 180
Data	2535



have Gaussian constraints, while rate uncertainties have log-normal forms. The main systematic uncertainties in the signal cross section arise from the JES, signal modeling, normalization of Zγ+jets, and b tagging and mistagging rates, and amount to 12, 9, 8, and 7%, respectively.

tγq

$$\mathcal{L}_{\rm eff} = -\frac{1}{2}\left[c\,\bar{t}_L\sigma_{\mu\nu}t_R + c^*\,\bar{t}_R\sigma_{\mu\nu}t_L\right]F^{\mu\nu},$$

$$|c| = \sqrt{\left(a_t\frac{Q_t e}{2m_t}\right)^2 + d_t^2},$$

a_t → anomalous magnetic moment

d_t → anomalous electric dipole moment

SM predicts
$$\begin{cases} d_t < 10^{-30} e\ \mathrm{cm} \\ Q_t \cdot a_t \approx 0.02 \end{cases}$$

https://arxiv.org/pdf/1307.1349.pdf

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

36fb^{-1}

JHEP 08 (2018) 011

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

UCSB

$t\bar{t}W$ (SSDL)

		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
			>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
			>1	22.2 ± 2.0	7.6 ± 1.2	2.7 ± 0.4	32.5 ± 2.4	27
	$D > 0.6$	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
			>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
			>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
			>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
			>1	22.4 ± 2.0	13.3 ± 2.2	3.0 ± 0.5	38.7 ± 3.0	42
	$D > 0.6$	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
			>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
			>1	16.5 ± 1.5	22.5 ± 3.7	3.1 ± 0.5	42.1 ± 4.0	46

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

$t\bar{t}Z$ (3 leptons)

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

$t\bar{t}Z$ (4 leptons)

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

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

36fb^{-1}

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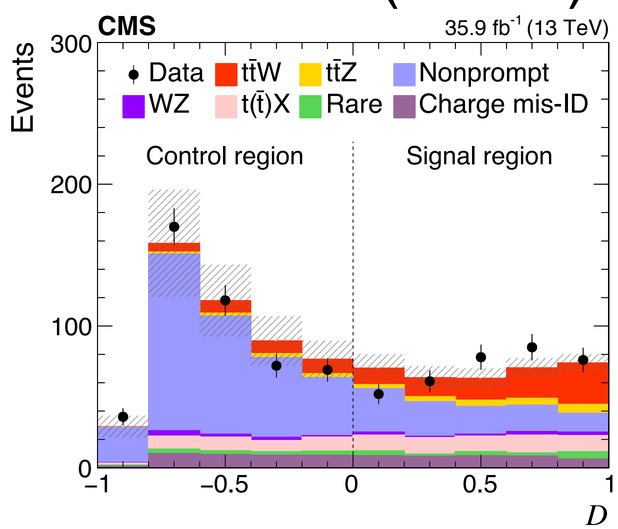
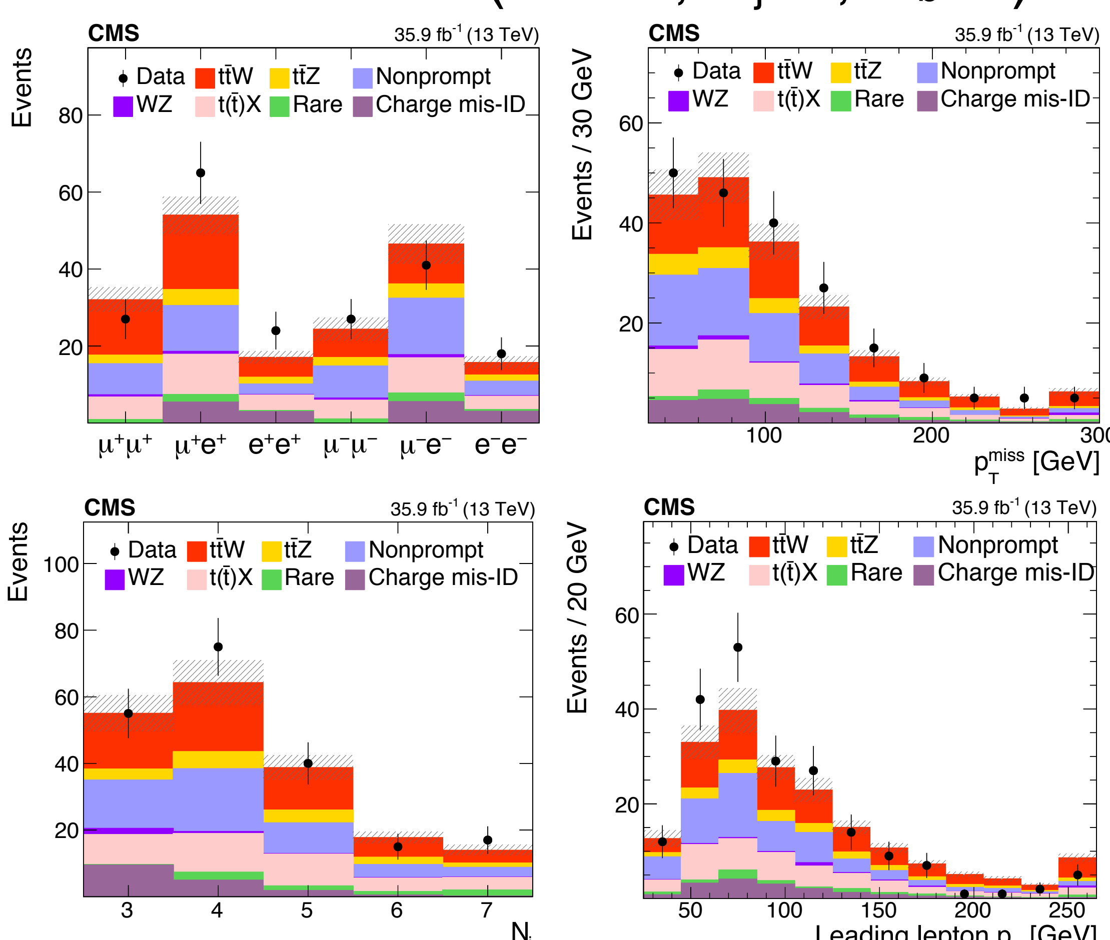
$t\bar{t}W$, $t\bar{t}Z$

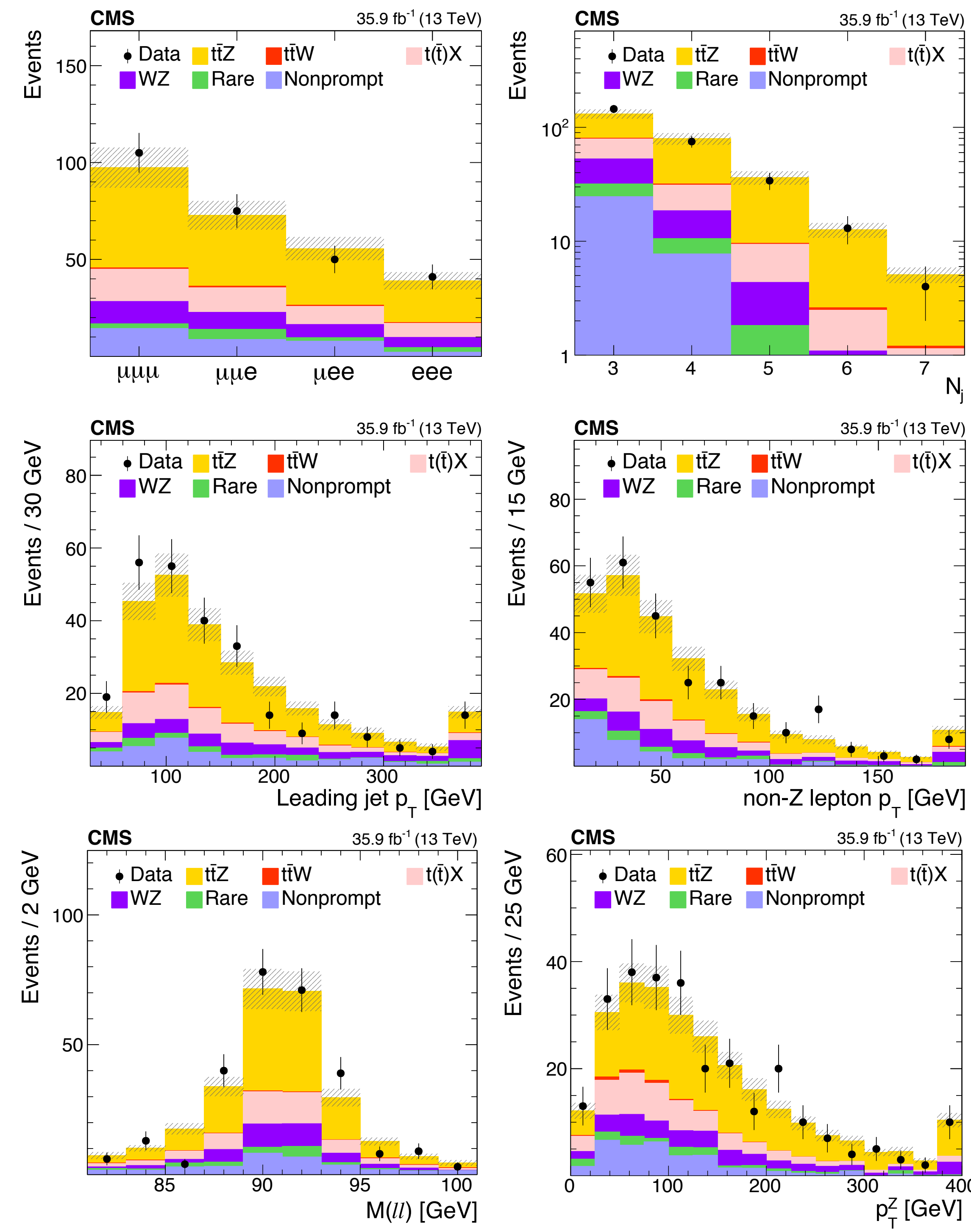
$t\bar{t}W$ BDT (SSDL)



$t\bar{t}W$ kinem. (SSDL, $N_j \geq 3$, $N_b \geq 2$)



$t\bar{t}Z$ kinem. (3 lep., $N_j \geq 3$, $N_b \geq 1$)



78fb-1

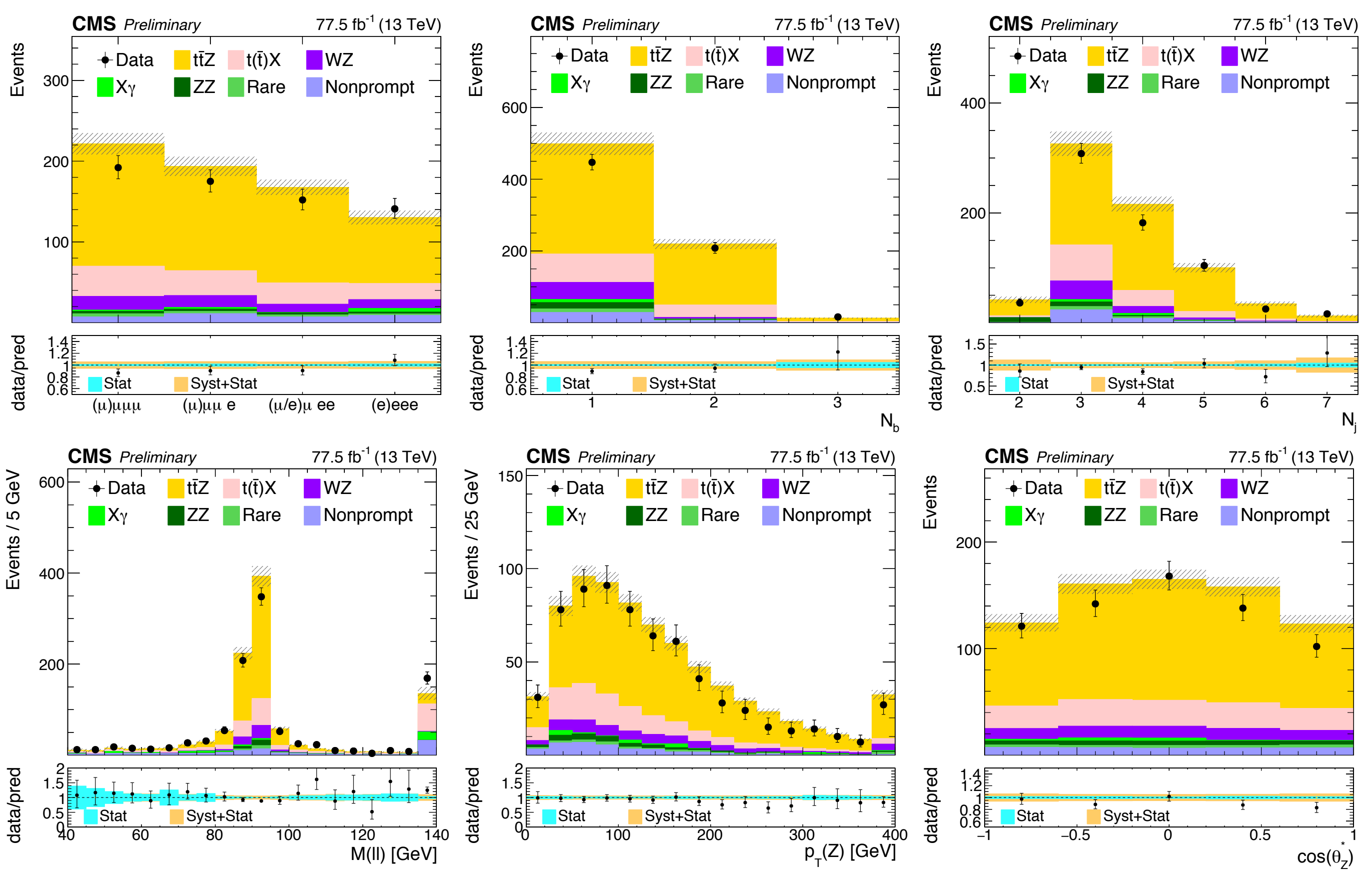
PAS TOP-18-009

$t\bar{t}Z$

Systematics

Source	Uncertainty range (%)	Correlated in 2016 and 2017	Impact on the $t\bar{t}Z$ cross section (%)
Integrated luminosity	2.5	×	2
PU modeling	1–2	✓	1
Trigger	2	×	2
Lepton ID efficiency	4.5–6	✓	4
Jet energy scale	1–9	✓	2
Jet energy resolution	0–1	✓	1
B tagging light flavor	0–4	×	1
B tagging heavy flavor	1–4	×	2
Choice in μ_R and μ_F	1–4	✓	1
PDF choice	1–2	✓	1
Color reconnection	1.5	✓	< 1
Parton shower	1–8	✓	1
WZ cross section	10–20	✓	3
WZ + heavy flavor	8	✓	1
ZZ cross section	10	✓	1
$t(\bar{t})X$ bg.	10–15	✓	3
$X\gamma$ background	20	✓	1
Nonprompt background	30	✓	< 1
Rare SM background	50	✓	2
Stat. unc. in nonprompt bg.	5–50	×	< 1
Stat. unc. in rare SM bg.	5–100	×	< 1
Total uncertainty			7

$t\bar{t}Z$ kinematics

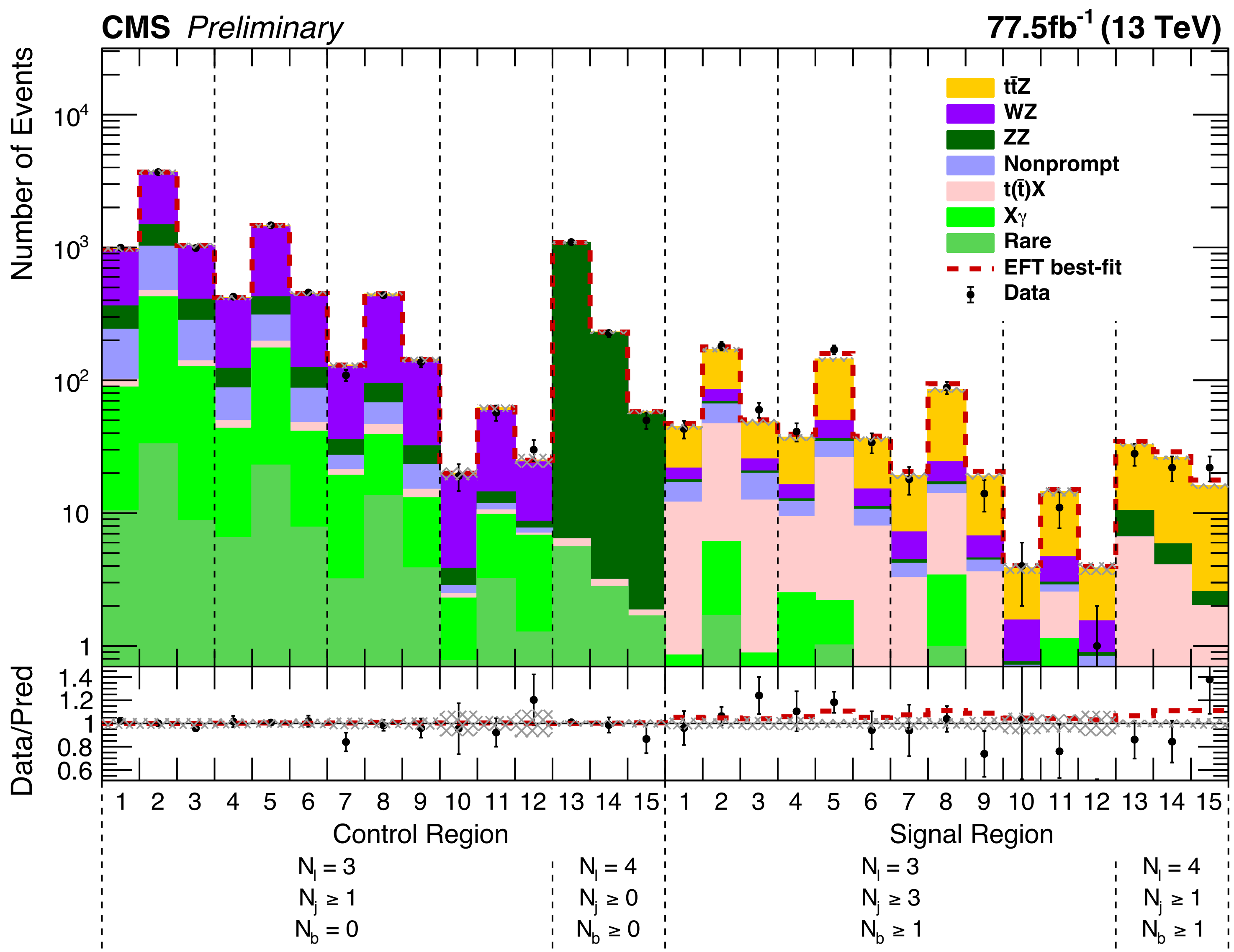


Process	$(\mu)\mu\mu\mu$	$(\mu)\mu\mu$ e	$(\mu/e)\mu$ ee	(e)eee	Total
$t\bar{t}Z$	152 ± 8	129 ± 7	118 ± 6	82 ± 4	481 ± 24
$t\bar{t}H$	4.0 ± 0.5	3.5 ± 0.4	3.2 ± 0.4	2.1 ± 0.3	12.7 ± 1.5
$t(\bar{t})X$	33.3 ± 4.1	27.4 ± 3.4	$23. \pm 2.9$	17.9 ± 2.2	102 ± 12
WZ	17.1 ± 4.6	14.7 ± 4.1	10.0 ± 2.8	10.9 ± 3.0	52.8 ± 14.2
$X\gamma$	1.6 ± 1.6	2.1 ± 2.5	0.6 ± 0.6	4.5 ± 1.6	8.8 ± 3.7
ZZ	2.8 ± 0.4	2.7 ± 0.4	2.6 ± 0.3	2.2 ± 0.3	10.3 ± 1.3
Rare	3.9 ± 2.0	2.9 ± 1.5	2.6 ± 1.3	2.0 ± 1.0	11.3 ± 5.7
Nonprompt	7.3 ± 3.0	11.2 ± 4.2	7.2 ± 3.0	8.9 ± 3.6	34.5 ± 13.1
Total	222 ± 13	194 ± 12	168 ± 9	130 ± 8	713 ± 41
Observed	192	175	152	141	660

$78 fb^{-1}$

PAS TOP-18-009

$t\bar{t}Z$



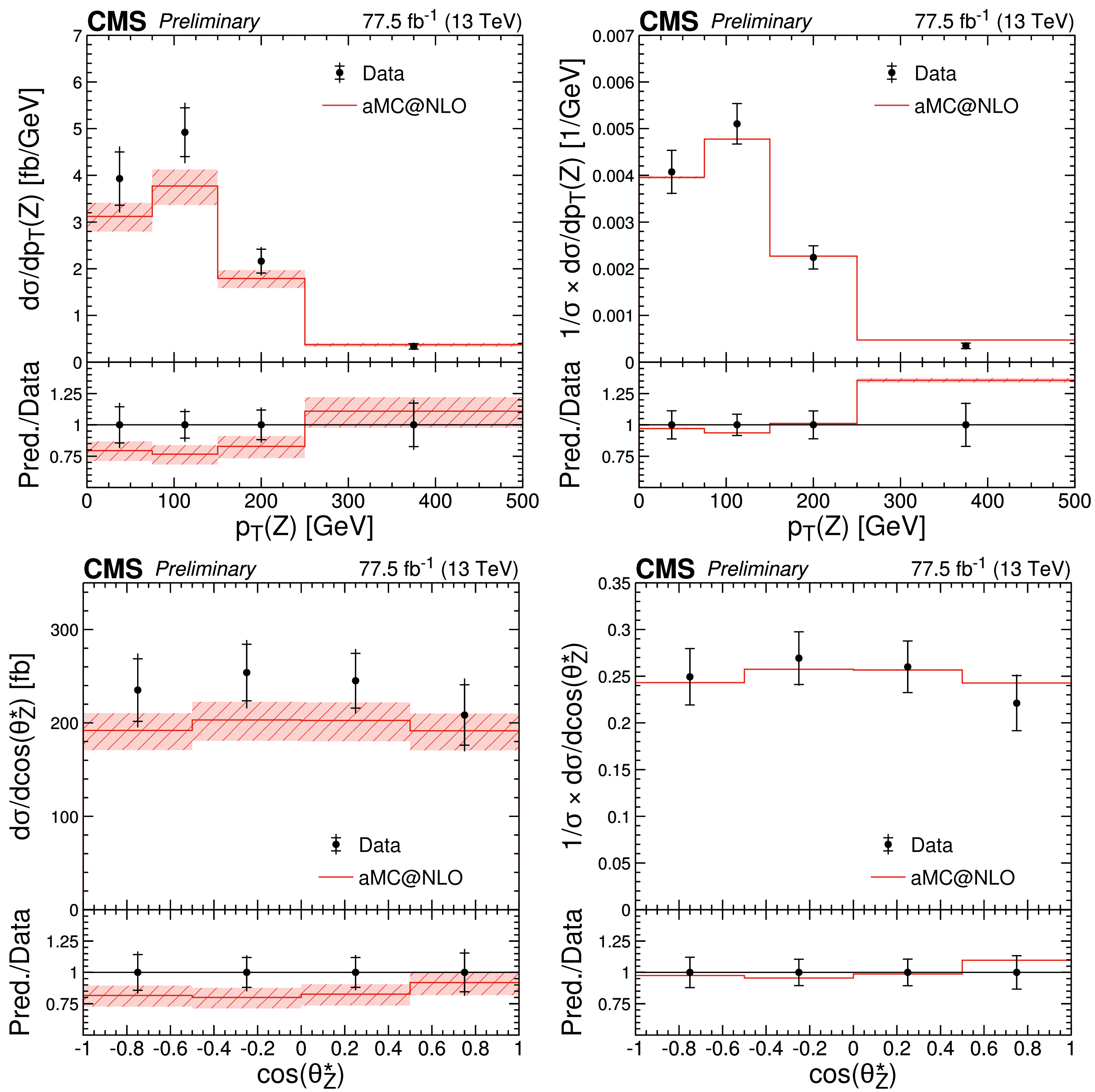
N_ℓ	N_j	N_b	N_Z	$p_T(Z)$ (GeV)	$-1 \leq \cos(\theta^*) < -0.6$	$-0.6 \leq \cos(\theta^*) < 0.6$	$0.6 \leq \cos(\theta^*)$
3	≥ 3	≥ 1	1	0–100	SR1	SR2	SR3
				100–200	SR4	SR5	SR6
				200–400	SR7	SR8	SR9
				≥ 400	SR10	SR11	SR12
4	≥ 1	≥ 1	1	0–100		SR13	
				100–200		SR14	
				≥ 200		SR15	
3	≥ 1	0	1	0–100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

78fb^{-1}

PAS TOP-18-009

$t\bar{t}Z$

absolute | normalized



$t\bar{t}\gamma$

$t\bar{t}\gamma$

electron+jets

Sample	Genuine photon	Misid. electron	Nonprompt photon	Total
$t\bar{t}+\gamma$	312 ± 17	0.2 ± 0.1	8.5 ± 0.9	321 ± 17
$t\bar{t}$+jets	—	22 ± 3	215 ± 13	237 ± 14
$W+\gamma$	75 ± 25	—	—	75 ± 25
W+jets	—	—	60 ± 15	60 ± 15
$Z+\gamma$	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

muon+jets

Sample	Genuine photon	Misid. electron	Nonprompt photon	Total
$t\bar{t}+\gamma$	407 ± 23	0.4 ± 0.3	11 ± 1	418 ± 24
$t\bar{t}$+jets	—	31 ± 5	291 ± 16	322 ± 17
$W+\gamma$	140 ± 41	—	9.0 ± 6.7	149 ± 45
W+jets	—	—	57 ± 14	57 ± 14
$Z+\gamma$	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

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

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

$t\bar{t}t\bar{t}$ — 1, 2 OS leptons

measurements

Channel	Best-fit μ	Best-fit $\sigma_{t\bar{t}t\bar{t}}$ (fb)	Exp. significance s.d.	Obs. significance s.d.
Single lepton	$1.6^{+4.6}_{-1.6}$	15^{+42}_{-15}	0.21	0.36
Dilepton	$0.0^{+2.7}$	0^{+25}	0.36	0.0
Combined (this analysis)	$0.0^{+2.2}$	0^{+20}	0.40	0.0
Multilepton [?]	$1.8^{+1.5}_{-1.2}$	17^{+14}_{-11}	1.0	1.6
Combined (this analysis + multilepton)	$1.4^{+1.2}_{-1.0}$	13^{+11}_{-9}	1.1	1.4

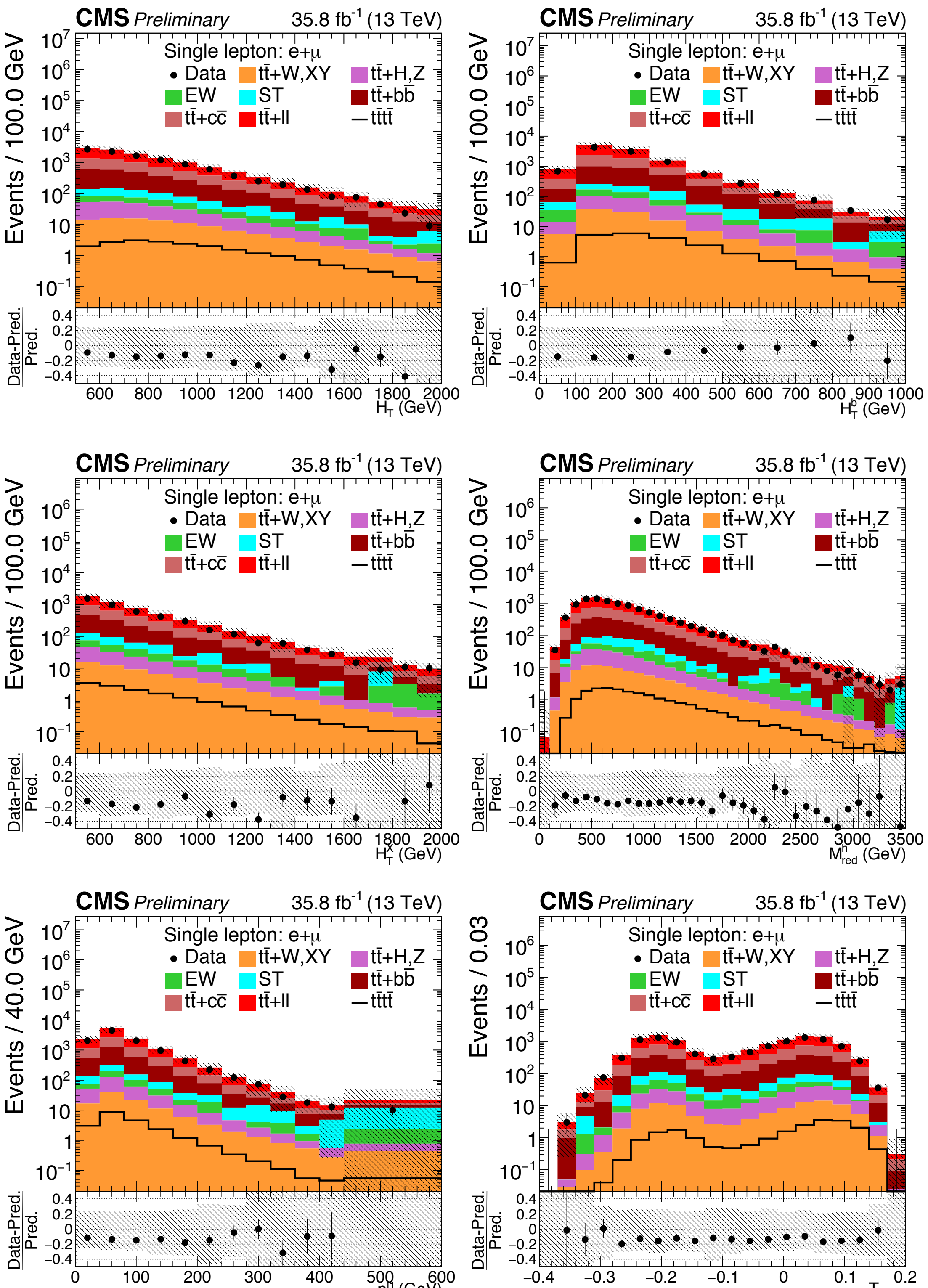
upper limits

Channel	Expected limit ($\times\sigma^{SM}_{t\bar{t}t\bar{t}}$)	Observed limit ($\times\sigma^{SM}_{t\bar{t}t\bar{t}}$)	Expected limit (fb)	Observed limit (fb)
Single lepton	$9.4^{+4.4}_{-2.9}$	10.6	86^{+40}_{-26}	97
Dilepton	$7.3^{+4.5}_{-2.5}$	6.9	67^{+41}_{-23}	64
Combined (this analysis)	$5.7^{+2.9}_{-1.8}$	5.2	52^{+26}_{-17}	48
Multilepton [?]	$2.5^{+1.4}_{-0.8}$	4.6	23^{+12}_{-8}	42
Combined (this analysis + multilepton)	$2.2^{+1.1}_{-0.7}$	3.6	20^{+10}_{-6}	33

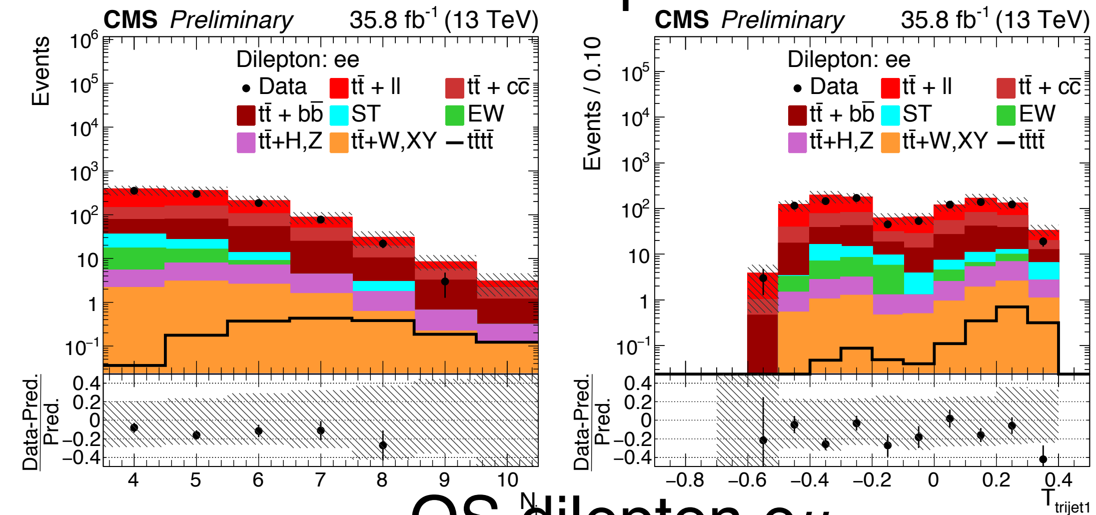
Systematic uncertainty	Normalization	Shape
Luminosity	X	
Pileup re-weighting	X	X
Lepton scale factors	X	
Jet energy corrections	X	X
b-tagging CSVv2	X	X
Ren. and fact. scales	X	X
PDF	X	X
ME-PS matching	X	
ISR and FSR scales	X	
Top quark p_T re-weighting	X	X
Heavy flavor re-weighting	X	X

$t\bar{t}t\bar{t}$ — 1, 2 OS leptons

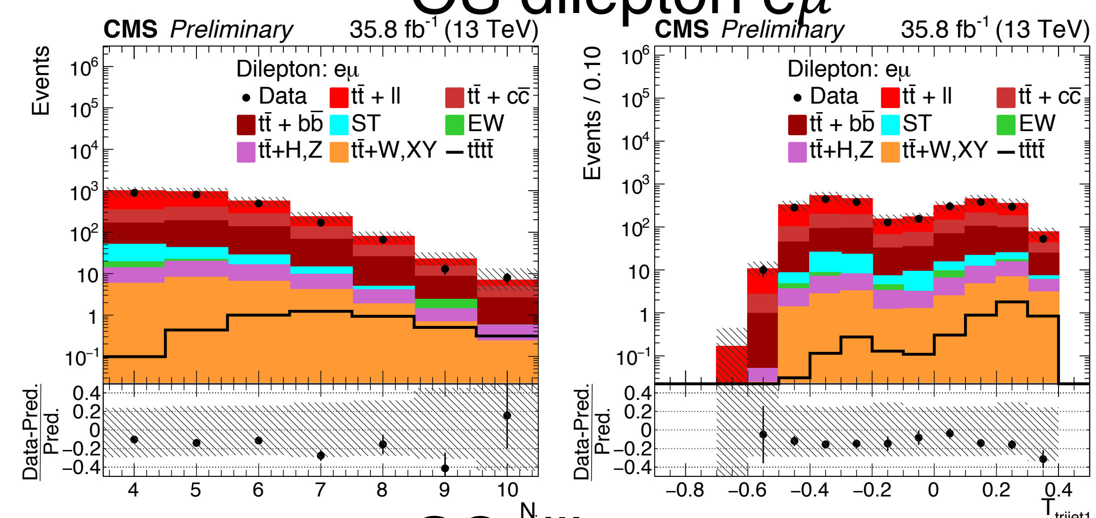
single lepton kinematics



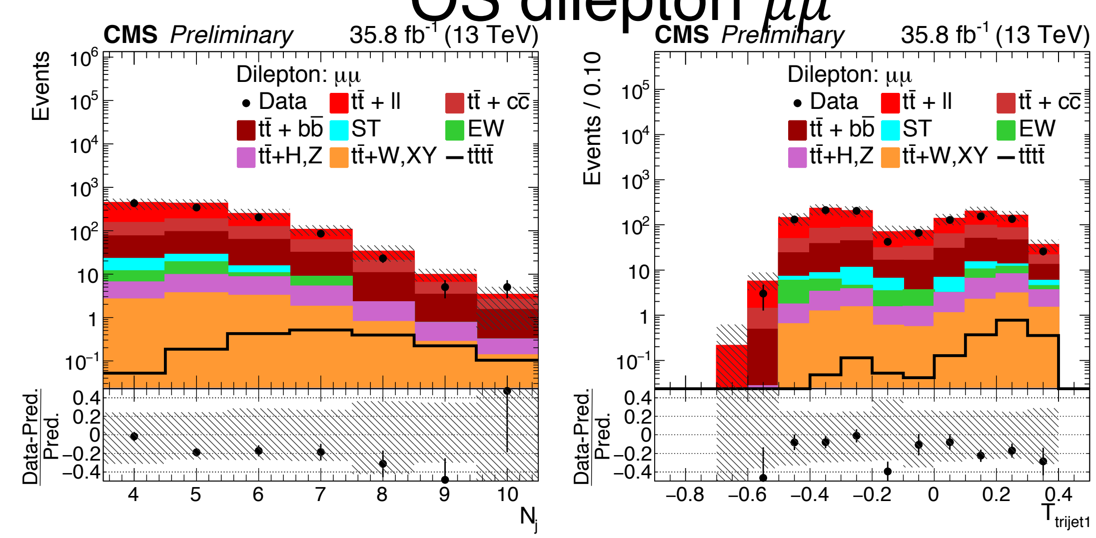
OS dilepton ee



OS dilepton eμ



OS dilepton μμ

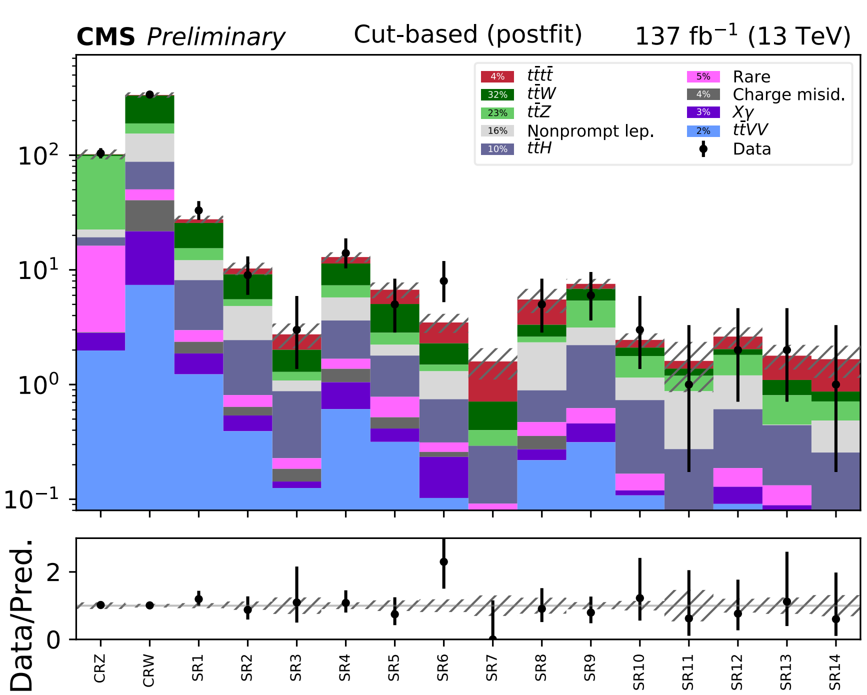


$t\bar{t}t\bar{t}$ — 2 SS, ≥3 leptons

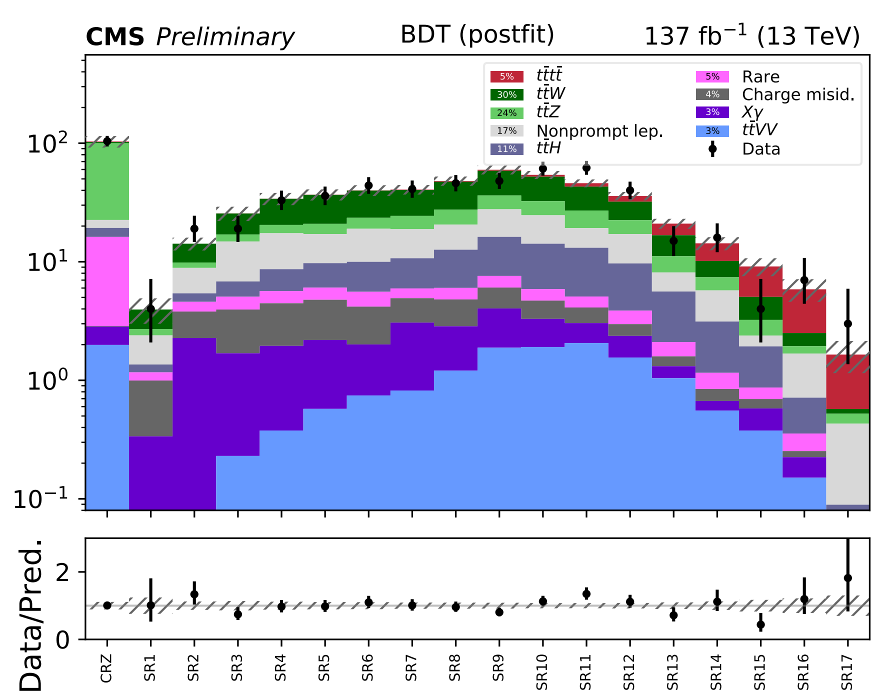
	Significance	$\sigma(t\bar{t}t\bar{t})$ [fb]
BDT	2.6σ (2.7σ)	$12.6^{+5.8}_{-5.2}$
Cut-based	1.7σ (2.5σ)	$9.4^{+6.2}_{-5.6}$

N_ℓ	N_b	N_{jets}	Region
2	2	≤ 5	CRW
		6	SR1
		7	SR2
		≥ 8	SR3
	3	5	SR4
		6	SR5
		7	SR6
		≥ 8	SR7
	≥ 4	≥ 5	SR8
≥ 3	2	5	SR9
		6	SR10
		≥ 7	SR11
	≥ 3	4	SR12
		5	SR13
		≥ 6	SR14
inverted Z-veto			CRZ

	SM background	$t\bar{t}t\bar{t}$	Observed
CRZ	101±10	0.8±0.5	104
CRW	331±19	3.9±2.3	338
SR1	25.6±2.1	2.0±1.2	33
SR2	9.1±1.3	1.1±0.6	9
SR3	2.0±0.6	0.7±0.4	3
SR4	11.3±1.3	1.6±0.9	14
SR5	5.0±0.8	1.7±0.9	5
SR6	2.3±0.4	1.2±0.7	8
SR7	0.71±0.20	0.9±0.5	0
SR8	3.3±0.9	2.2±1.3	5
SR9	6.8±0.8	0.7±0.4	6
SR10	2.10±0.31	0.35±0.22	3
SR11	1.4±0.7	0.23±0.14	1
SR12	2.0±0.5	0.59±0.34	2
SR13	1.09±0.28	0.7±0.4	2
SR14	0.87±0.30	0.8±0.4	1



	SM background	$t\bar{t}t\bar{t}$	Observed
CRZ	102±12	1.1±0.4	104
SR1	4.0±1.0	0.0±0.0	4
SR2	14.2±1.8	0.0±0.0	19
SR3	25.5±3.5	0.05±0.03	19
SR4	34±4	0.08±0.05	33
SR5	37±4	0.15±0.07	36
SR6	40±4	0.23±0.12	44
SR7	40±4	0.31±0.16	41
SR8	47±4	0.72±0.28	46
SR9	59±5	1.2±0.5	48
SR10	52±4	1.9±0.7	61
SR11	43.0±3.5	3.0±1.2	62
SR12	32.1±3.0	3.7±1.4	40
SR13	16.7±1.6	4.3±1.6	15
SR14	10.1±1.2	4.2±1.6	16
SR15	5.0±0.8	4.1±1.5	4
SR16	2.5±0.6	3.4±1.3	7
SR17	0.6±0.4	1.1±0.4	3



Source	Uncertainty (%)	Impact on the $t\bar{t}t\bar{t}$ cross section (%)
Integrated luminosity	2.3–2.5	3
Pileup	0–5	1
Trigger efficiency	2–7	2
Lepton selection	2–10	2
Jet energy scale	1–15	9
Jet energy resolution	1–10	6
b tagging	1–15	6
Size of simulated sample	1–25	<1
Scale and PDF variations †	10–15	2
ISR/FSR (signal) †	5–15	2
$t\bar{t}H$ (normalization) †	25	5
Rare, $X\gamma$, $t\bar{t}VV$ (norm.) †	11-20	<1
$t\bar{t}Z$, $t\bar{t}W$ (norm.) †	40	3-4
Charge misidentification †	20	<1
Nonprompt leptons †	30–60	3
$N_{jets}^{ISR/FSR}$ †	1-30	2
$\sigma(t\bar{t}b\bar{b})/\sigma(t\bar{t}jj)$ †	35	11

$t\bar{t}t\bar{t}$ — 2 SS, ≥3 leptons

Signal regions, prefit