Search for standard model production of four top quarks in final states with same-sign and multiple leptons in proton-proton collisions at √s = 13 TeV

TOP-18-003 Approval

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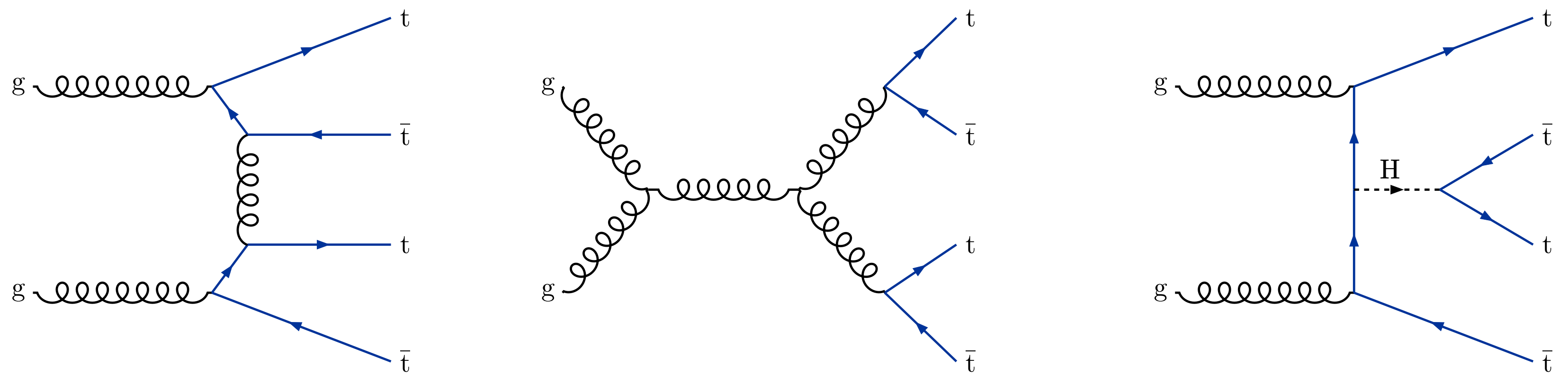
[UCSB, UCSD, FNAL, Nebraska, Boston U]

15 March 2019

Outline

Motivation
Documentation
Analysis changes since pre-approval
Objects/inputs
Strategy: cut-based and BDT
Backgrounds
Systematic uncertainties
Results
Conclusions

Motivation



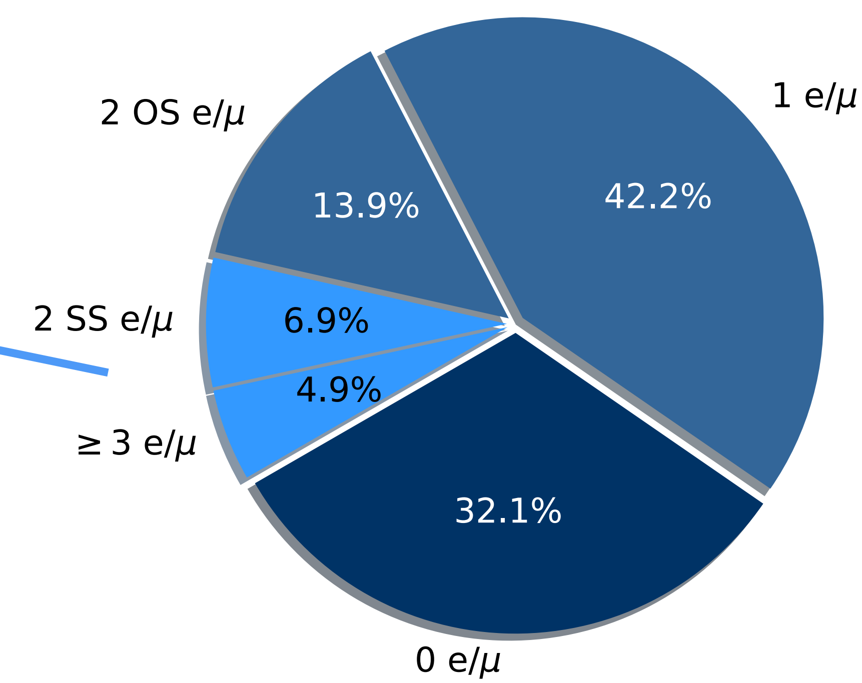
σ = 12fb @ NLO

- SM $t\bar{t}t\bar{t}$ production sensitive to a variety of new physics scenarios
  - EFTs
  - 2HDM/heavy mediators
  - top yukawa coupling
  - …

- **2L same-sign (SS) + multi-lepton (ML) represents nearly 12% of the BR**
  - Low background final state → statistically-dominated

- Latest measurements of 17^{+14}_{-11}fb (CMS) and 28^{+12}_{-11} (ATLAS) using 2016 datasets
  - ~1σ expected in both cases (using SM cross-section of 9.2fb)

- The analysis presented here improves upon the 2016 result and includes the full Run 2 dataset



* including τ→e/μ

Documentation

- CADI: TOP-18-003 (frozen V3)
- AN: AN-18-062 (frozen v12)
- Pre-approval
- 2016 reference: TOP-17-009

- **Many thanks to the ARC**
  - Francisco Yumiceva (FLORIDA-TECH)
  - Jacob Thomas Linacre (RAL)
  - Marc Fabio Dunser (CERN)
  - Jeremy Andrea (STRASBOURG)
  - CCLE: Claudio Campagnari (UCSB)

CMS PAPER TOP-18-003

CMS Paper

Search for standard model production of four top quarks in final states with same-sign and multiple leptons in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration

Abstract

The standard model (SM) production of four top quarks ($\mathrm{t\bar{t}t\bar{t}}$) is studied by the CMS Collaboration using proton-proton collision events collected in Run 2 of the LHC, with a center-of-mass energy of 13 TeV and corresponding to an integrated luminosity of 136.3 fb^{-1}. The events are required to contain a pair of same-sign leptons (e, μ) or at least three leptons, and several jets. Two approaches are used to enhance signal sensitivity: first a simple classification based on the number of jets and b-tagged jets, and second a boosted decision tree (BDT) taking advantage of kinematic variables related to leptons and jets. Control regions are used to constrain the dominant SM backgrounds. The two approaches find consistent results compatible with next-to-leading-order SM predictions. The observed (expected) significance of the BDT analysis is 2.6 (2.7) standard deviations, and the $\mathrm{t\bar{t}t\bar{t}}$ cross section is measured to be $12.8^{+5.9}_{-5.3}$ fb. These results are also used to constrain the Yukawa coupling of the top quark and to set limits on the production of a heavy scalar or pseudoscalar in a type II 2HDM scenario. These interpretations result in a 95% confidence level limit of $|y_t / y_t^{SM}| < 1.7$, where y_t^{SM} is the SM value of y_t, and in exclusions in the mass ranges of 350-430 GeV and 350-510 GeV for heavy scalar and pseudoscalar bosons, respectively, for the 2HDM scenarios considered.

Available on the CMS information server

CMS AN-18-062

CMS Draft Analysis Note

2019/03/09
Head Id: 491183
Archive Id: 491425M
Archive Date: 2019/03/07
Archive Tag: trunk

Search for SM tttt in the same-sign dilepton and multi-lepton final states at $\sqrt{s} = 13$ TeV with the full Run 2 dataset

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[3] University of California, Santa Barbara, CA, USA
[4] University of Nebraska, Lincoln, NE, USA

Abstract

This is the AN supporting the Run 2 tttt analysis. It is based on the 2016 tttt AN (AN-17-115) and the 2016 same-sign AN (AN-16-386).

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PDFAuthor:	N. Amin, C. Campagnari, C. Fangmeier, F. Golf, G. Zevi Della Porta
PDFTitle:	Search for SM tttt in the same-sign dilepton final state at 13 TeV with the full Run 2 dataset
PDFSubject:	CMS
PDFKeywords:	CMS, physics, software, computing

Please also verify that the abstract does not use any user defined symbols

ARC review and recent changes

During ARC review:

- Updated to latest recommendations (JECs, scale factors)
- Clarified documentation, both AN and Paper
- Increased uncertainty on the fraction of additional b jets in ttW/Z/H events (from 35% to 50%)
- Tested many variations of nuisances (increasing, decreasing, correlating, uncorrelating, ….), to check the sensitivity of our results to our choices
- Studied correlation between nuisances

After freezing:

- Applied final lepton SFs for 2018
- Recovered 50 pb in 2018 golden json
- Updated to latest luminosity (136.3 —> 137 fb)
- 2HDM interpretation includes 2018 samples instead of scaled-up 2017 samples

Data and Simulation

- Data - dilepton primary datasets
  - DoubleEG/EGamma, DoubleMuon, MuonEG
  - Corresponds to ~137fb^{-1}

Year	campaign	JSON file
2016	23Sep2016-v1	Cert_271036-284044_13TeV_23Sep2016ReReco_Collisions16
2017	31March2018-v1	Cert_294927-306462_13TeV_EOY2017ReReco_Collisions17
2018	17Sep2018-v1(2018A,B,C)-PromptReco(2018D)	Cert_314472-325175_13TeV_PromptReco_Collisions18_JSON.txt

- MC
  - Simulation available for all 3 years
  - Additionally, for fake rate estimation, single-lepton data PDs used, and lepton-enriched p_T-binned QCD samples used for MC closure studies

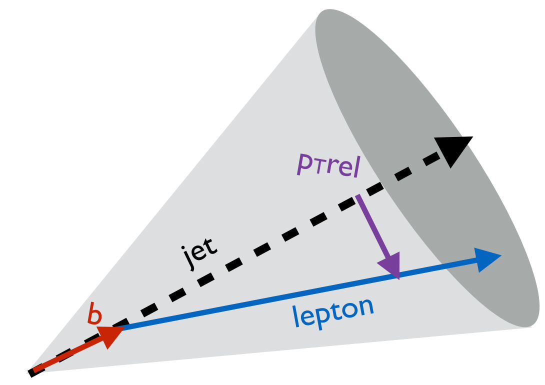
Year	MC campaign
2016	RunIISummer16MiniAODv2-PUMoriond17_80X
2017	RunIIFall17MiniAODv2-PU2017_12Apr2018_94X
2018	RunIIAutumn18MiniAOD-102X

sample name	σ (pb)	2016	2017	2018
/DYJetsToLL_M-50_TuneCUETP8M1_13TeV-madgraphMLM-pythia8	6020.85	X	X	X
/DYJetsToLL_M-10to50_TuneCUETP8M1_13TeV-madgraphMLM-pythia8	18610	X	X	X
/WJetsToLNu_TuneCUETP8M1_13TeV-madgraphMLM-pythia8	61334.9	X	X	X
/TT_TuneCUETP8M2T4_13TeV-powheg-pythia8	831.762	X	X	X
/TTJets_TuneCP5_13TeV-amcatnloFXFX-pythia8	831.762	X	X	X
/TTWJetsToLNu_TuneCUETP8M1_13TeV-amcatnloFXFX-madspin-pythia8	0.2043	X	X	X
/TTZToLLNuNu_M-10_TuneCUETP8M1_13TeV-amcatnlo-pythia8	0.2529	X	X	X
/TTZToLL_M-1to10_TuneCUETP8M1_13TeV-madgraphMLM-pythia8	0.0493	X	X	X
/ttHToNonbb_M125_TuneCUETP8M2_ttHtranche3_13TeV-powheg-pythia8	0.2710	X	X	X
/tZq_ll_4f_13TeV-amcatnlo-pythia8_TuneCUETP8M1 (ext1)	0.0758	X	X	X
/TTTT_TuneCP5_PSweights_13TeV-amcatnlo-pythia8	0.01197	-	X	X
/TTTT_TuneCUETP8M2T4_13TeV-amcatnlo-isrup-pythia8	0.01197	X	-	X
/TTTT_TuneCUETP8M2T4_13TeV-amcatnlo-fsrup-pythia8	0.01197	X	-	X
/TTTT_TuneCUETP8M2T4_13TeV-amcatnlo-isrdown-pythia8	0.01197	X	-	X
/TTTT_TuneCUETP8M2T4_13TeV-amcatnlo-fsrdown-pythia8	0.01197	X	-	X
/TGJets_TuneCUETP8M1_13TeV_amcatnlo_madspin_pythia8	2.967	X	X	X
/TTGamma_SingleLeptFromT_TuneCUETP8M2T4_13TeV-amcatnlo-pythia8	0.77	X	X	X
/TTGamma_SingleLeptFromTbar_TuneCUETP8M2T4_13TeV-amcatnlo-pythia8	0.769	X	X	X
/TTGamma_Dilept_TuneCUETP8M2T4_13TeV-amcatnlo-pythia8	0.632	X	X	X
/WGToLNuG_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8	405.271	X	-	X
/WGToLNuG_TuneCP5_13TeV-madgraphMLM-pythia8	405.271	-	X	-
/ZGTo2LG_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8	123.9	X	X	X
/WZTo3LNu_TuneCUETP8M1_13TeV-powheg-pythia8	4.4297	X	X	X
/ZZTo4L_13TeV_powheg_pythia8	1.256	X	X	X
/ZZZ_TuneCUETP8M1_13TeV-amcatnlo-pythia8	0.01398	X	X	X
/WZZ_TuneCUETP8M1_13TeV-amcatnlo-pythia8	0.05565	X	X	X
/WWZ_TuneCUETP8M1_13TeV-amcatnlo-pythia8	0.1651	X	X	X
/WZG_TuneCUETP8M1_13TeV-amcatnlo-pythia8	0.04123	X	X	X
/WWG_TuneCUETP8M1_13TeV-amcatnlo-pythia8	0.2147	X	X	X
/WWW_4F_TuneCUETP8M1_13TeV-amcatnlo-pythia8	0.2086	X	X	X
/WWTo2L2Nu_DoubleScattering_13TeV-pythia8	0.16975	X	X	X
/ST_tWll_5f_LO_13TeV-MadGraph-pythia8	0.01123	X	X	X
/WpWpJJ_EWK-QCD_TuneCUETP8M1_13TeV-madgraph-pythia8	0.03711	X	X	X
/GluGluHToZZTo4L_M125_13TeV_powheg2_JHUgenV6_pythia8	0.01181	X	X	X
/VHToNonbb_M125_13TeV_amcatnloFXFX_madspin_pythia8	0.9561	X	X	X
/TTHH_TuneCUETP8M2T4_13TeV-madgraph-pythia8	0.000757	X	X	X
/TTZH_TuneCUETP8M2T4_13TeV-madgraph-pythia8	0.001535	X	X	X
/TTZZ_TuneCUETP8M2T4_13TeV-madgraph-pythia8	0.001982	X	X	X
/TTWZ_TuneCUETP8M2T4_13TeV-madgraph-pythia8	0.003884	X	X	X
/TTTW_TuneCUETP8M2T4_13TeV-madgraph-pythia8	0.000788	X	X	X
/TTTJ_TuneCUETP8M2T4_13TeV-madgraph-pythia8	0.000474	X	X	X
/TTWH_TuneCUETP8M2T4_13TeV-madgraph-pythia8	0.001582	X	X	X
/TTWW_TuneCUETP8M2T4_13TeV-madgraph-pythia8	0.01150	X	X	X

Objects: leptons

- Electron ID
  - p_T>15 GeV, $|\eta|$<2.5
  - d_{xy}<0.5, d_0<0.1, IP3D/σ(IP3D)<4
  - Tight p_T,η-dependent MVA

- Muon ID
  - p_T>10 GeV, $|\eta|$<2.4
  - d_{xy}<0.5, d_0<0.1, IP3D/σ(IP3D)<4
  - dp_T/p_T<0.2
  - medium Muon POG ID



$$I_{\mathrm{mini}} < I_1 \wedge \left(\frac{p_{\mathrm{T}}(\ell)}{p_{\mathrm{T}}(\mathrm{jet})} > I_2 \vee \frac{|(\vec{p}(\mathrm{jet}) - \vec{p}(\ell)) \times \vec{p}(\ell)|}{|\vec{p}(\mathrm{jet}) - \vec{p}(\ell)|} > I_3 \right)$$

- Isolation for electrons, muons
  - Multi-isolation variable — result of [studies in fake lepton SUSY WG]
  - Requires
    - I_{mini}: relative isolation in p_T-dependent cone
    - $p_T$ratio: want lepton energy to dominate jet
    - $p_T$rel: protect against prompt-lepton overlap with random jets
  - Split JEC to avoid overcorrection due to constituent lepton
    - jet ← (jet*L1-lepton)*L2L3+lepton
  - Separate working points for 2016, 2017/2018

2016

isolation value	loose WP (e/μ)	μ (Medium) WP	e (Tight) WP
I_1	0.4	0.16	0.12
I_2	0	0.76	0.80
I_3	0	7.2	7.2

2017/2018

isolation value	loose WP (e/μ)	μ (Medium) WP	e (Tight) WP
I_1	0.4	0.11	0.07
I_2	0	0.74	0.78
I_3	0	6.8	8.0

Objects — jets/MET

- Jets
  - p_T>40 GeV, $|\eta|$<2.4
  - Recommended tight PF jet ID
  - Lepton-cleaned (ΔR>0.4)
  - H_T computed from scalar sum of p_Ts

- B-tagged jets
  - p_T>25 GeV, $|\eta|$<2.4 (note the lower threshold)
  - Medium DeepCSV WPs for each year
    - 70/12/1% b/c/udsg efficiencies

- MET
  - Type-I correction applied
  - For 2017, using the recommended "METv2" recipe, excluding some candidates from the MET calculation at high η
  - All recommended MET filters

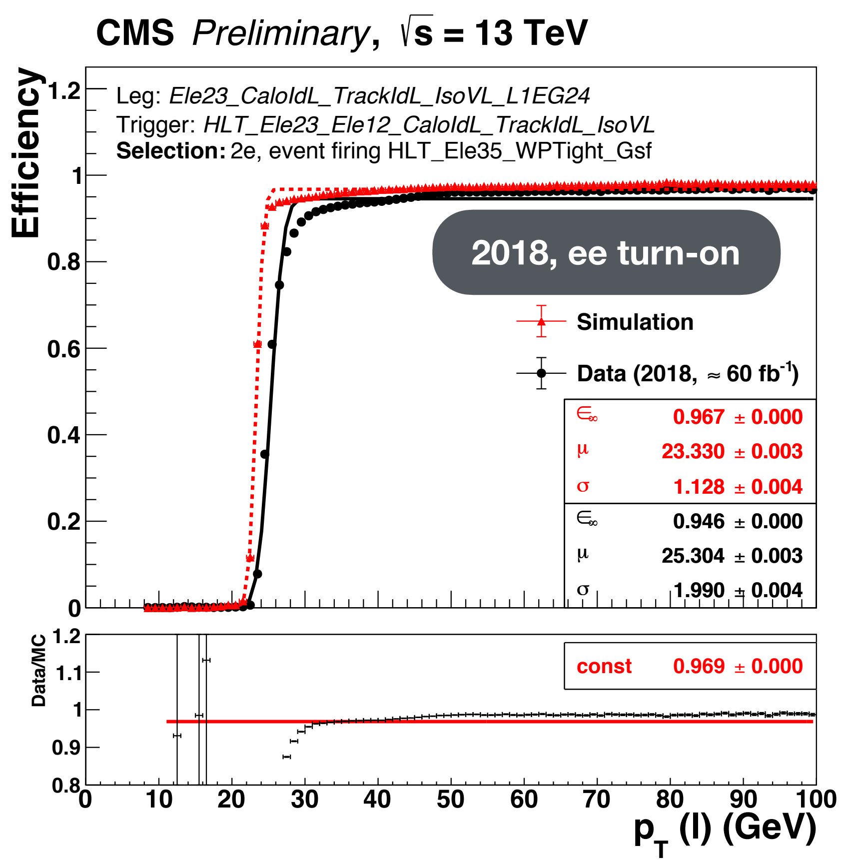
Triggers

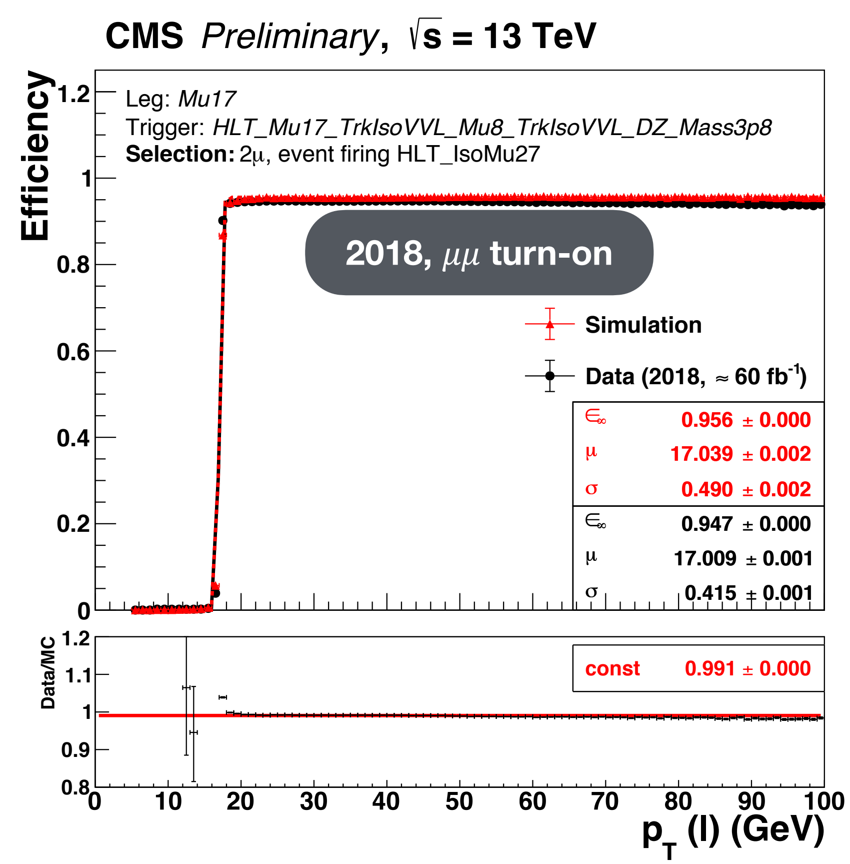
- Dilepton triggers for main analysis
  - non-isolated+HT in 2016
  - isolated for 2017, 2018
- Auxiliary single lepton triggers for fake rate computation
- Data/MC applied as corrections on top of simulated trigger decision
  - Trigger maps from Laurent Thomas and SUS-19-008 analysis

Analysis triggers

Table 3: Summary of the signal triggers

$H_{T,off}$	Channel	Trigger Name
2016		
> 300 GeV	$\mu\mu$	HLT_DoubleMu8_Mass8_PFHT300
	ee	HLT_DoubleEle8_CaloIdM_TrackIdM_Mass8_PFHT300
	$e\mu$	HLT_Mu8_Ele8_CaloIdM_TrackIdM_Mass8_PFHT300
2017		
$H_{T,off}$	Channel	Trigger Name
all	$\mu\mu$	HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL_DZ_Mass8
	ee	HLT_Ele23_Ele12_CaloIdL_TrackIdL_IsoVL_
	$e\mu$	HLT_Mu23_TrkIsoVVL_Ele12_CaloIdL_TrackIdL_IsoVL_DZ HLT_Mu8_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL_DZ
2018		
$H_{T,off}$	Channel	Trigger Name
all	$\mu\mu$	HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL_DZ_Mass3p8
	ee	HLT_Ele23_Ele12_CaloIdL_TrackIdL_IsoVL_
	$e\mu$	HLT_Mu23_TrkIsoVVL_Ele12_CaloIdL_TrackIdL_IsoVL_DZ HLT_Mu8_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL_DZ





Fake rate triggers

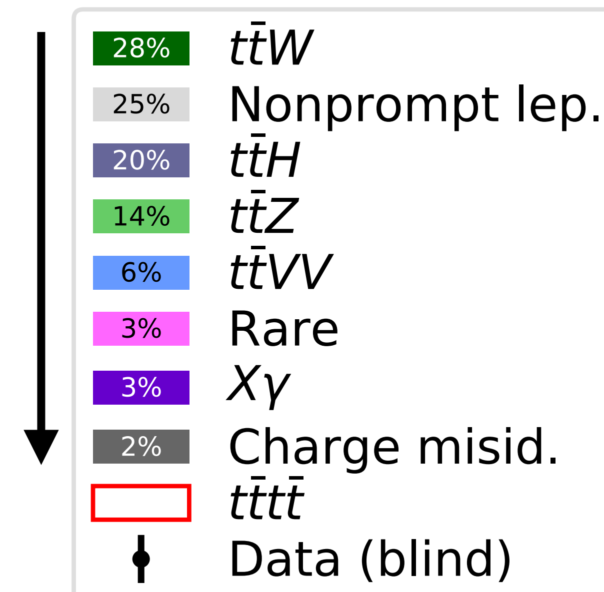
Table 4: Summary of the control triggers ordered by lepton flavor and p_T.

$H_{T,off}$	Channel	Trigger Name
2016		
> 300 GeV	μ	HLT_Mu8 HLT_Mu17
	e	HLT_Ele8_CaloIdM_TrackIdM_PFJet30 HLT_Ele17_CaloIdM_TrackIdM_PFJet30
2017		
$H_{T,off}$	Channel	Trigger Name
all	μ	HLT_Mu8_TrkIsoVVL HLT_Mu17_TrkIsoVVL
	e	HLT_Ele8_CaloIdL_TrackIdL_IsoVL_PFJet30 HLT_Ele23_CaloIdL_TrackIdL_IsoVL_PFJet30
2018		
$H_{T,off}$	Channel	Trigger Name
all	μ	HLT_Mu8_TrkIsoVVL HLT_Mu17_TrkIsoVVL
	e	HLT_Ele8_CaloIdL_TrackIdL_IsoVL_PFJet30 HLT_Ele23_CaloIdL_TrackIdL_IsoVL_PFJet30

Strategy: baseline selection

- Follow selections and strategy of published analysis with 2016 data (35.9fb^{-1}) selected events passing the baseline
  - same charge leptons or ≥3 leptons with p_T>25/20(/20)GeV
  - ≥2 jets, ≥2 b-tagged jets
  - H_T>300 GeV
  - $\not{E}_T$>50 GeV
  - Z-boson veto (loose OSSF in 15GeV Z-window; if tight, promote the event to a separate control region)

- After the baseline selections, backgrounds to deal with are
  - **$t\bar{t}W$**, **$t\bar{t}Z$** - constrain to data with dedicated control regions
  - **$t\bar{t}H$** - take from simulation with cross-section uncertainty
  - **fake leptons** - data-driven estimate of prompt-prompt from prompt-nonprompt × "fake-rate"
  - **ttVV**, **X+γ**, **Rares** - MC-based
  - **charge flips** - small background from $e^{\pm}e^{\mp} \to e^{\pm}e^{\pm}$ estimated in similar data-driven way to fake leptons



- Most discriminating variables are number of jets and number of b-tagged jets
  - For $t\bar{t}t\bar{t} \to$ 2L, expect **8** jets, **4** of which are from b-quarks

Strategy: cut-based

- Cut-based approach
  - Baseline events are separated into 14 bins depending on lepton and (b-tagged) jet multiplicities along with 2 high statistics regions enriched in $t\bar{t}W$ and $t\bar{t}Z$ (inverting the Z-veto) for normalization constraints

- Natural extension of 2016 analysis

N_{leps}	$N_{\text{b jets}}$	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

2016

Paper Table 1

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

Full Run 2

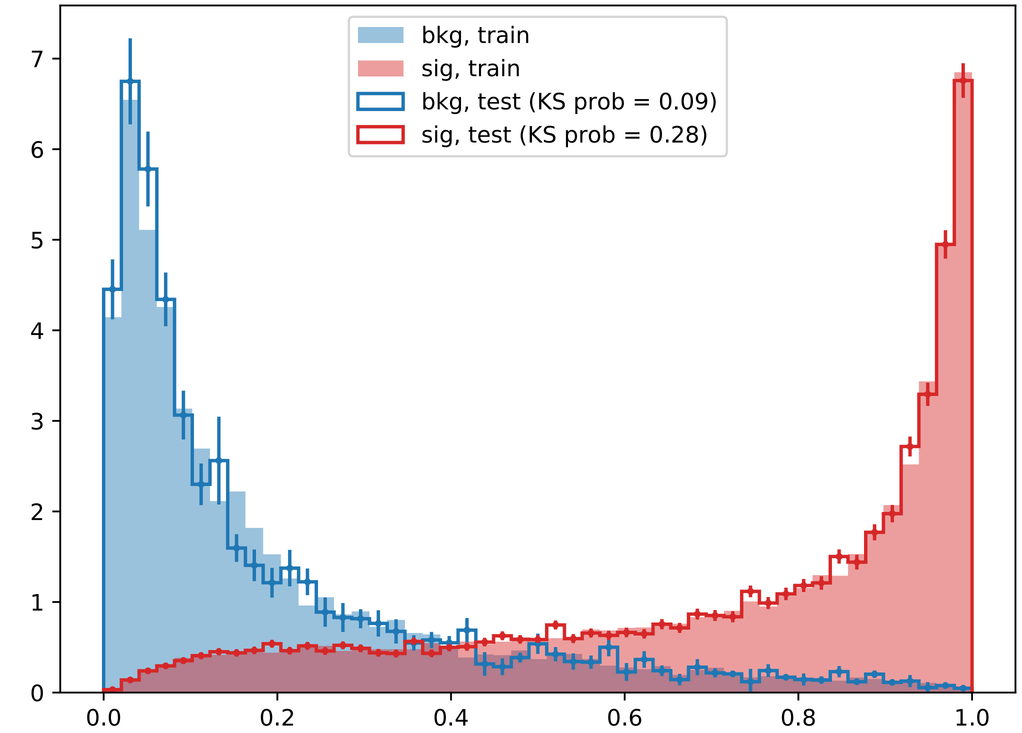
Strategy: BDT

- A multi-variate classifier is also trained to separate signal from background
  - Baseline events are passed through the classifier and the discriminator output is sliced into 17 bins
  - The $t\bar{t}Z$-enriched control region from the cut-based procedure is also included as another bin

- Both approaches are used with a **maximum-likelihood fit** to extract a **cross-section measurement and uncertainty**, and their results are quoted in the Results and Summary sections
  - Only BDT quoted in the abstract and used for interpretations

- The following details of the BDT are mentioned in the paper:
  - CRZ is the only control region [CRW events enter the BDT]
  - BDT is trained on simulation to separate tttt from Σ(SM backgrounds)
  - Gradient boosting, 500 trees, depth 4. Classifier binned in 17 bins.
  - List of all 19 variables used
  - A sentence about why we don't use top-tagging variables [ARC suggestion]

- (a) Nbtags
- (b) Njets
- (c) Nlooseb
- (d) MET
- (e) Ntightb
- (f) $p_T(\ell_2)$
- (g) $m(\ell_1, j_1)$
- (h) $p_T(j_1)$
- (i) $p_T(j_7)$
- (j) $\Delta\phi(\ell_1, \ell_2)$
- (k) $p_T(j_6)$
- (l) $\max(m(j)/p_T(j))$
- (m) Nleps
- (n) $p_T(\ell_1)$
- (o) $\Delta\eta(\ell_1, \ell_2)$
- (p) $p_T(j_8)$
- (q) H_T^b
- (r) $p_T(\ell_3)$
- (s) q_1



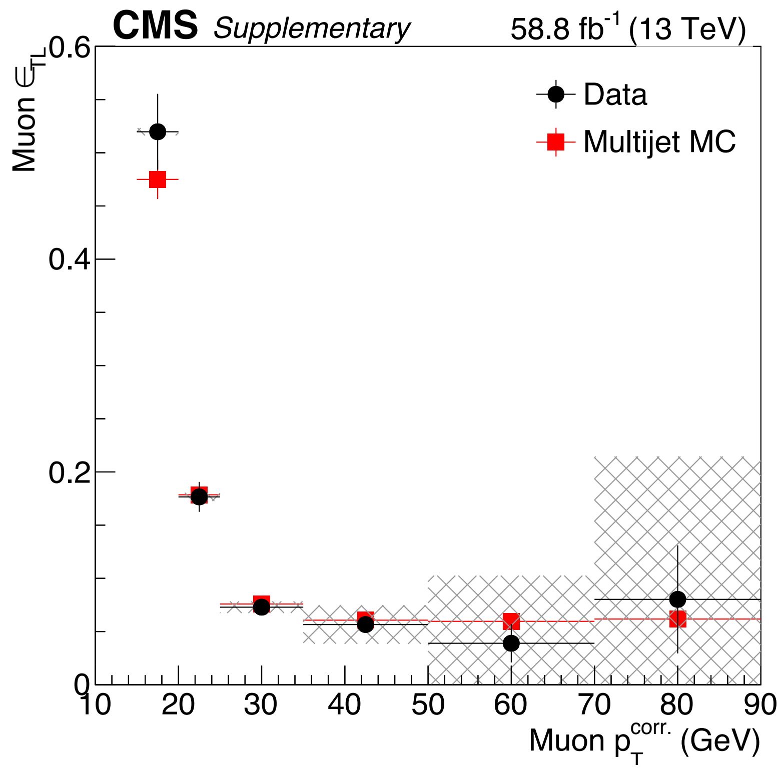
Nonprompt lepton background

25% Nonprompt lep.

Evaluate fake rate ($\varepsilon_{Tight/Loose}$) in a single-lepton control region dominated by QCD

- $\varepsilon_{T/L}$ binned in p_T, η, and lepton flavor
- Subtract EWK processes using MC
  - $\varepsilon_{T/L} = (Data_{Tight} - EWK_{Tight}) / (Data_{Loose} - EWK_{Loose})$
  - Up to 100% uncertainty from EWK subtraction at high p_T

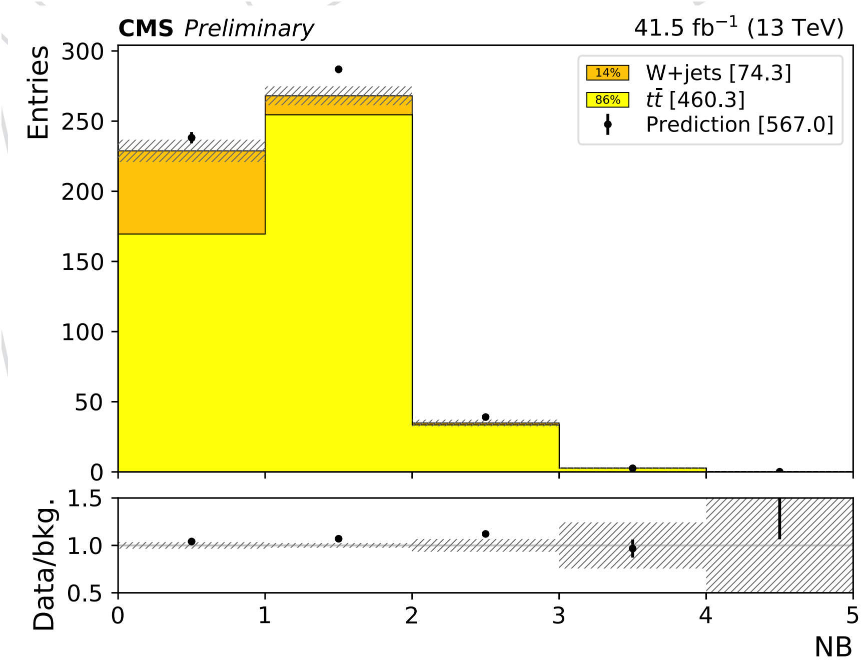
$\varepsilon_{T/L}$, 2018, μ



Apply $\varepsilon_{T/L}$ on SR-like events with at least one LooseNotTight lepton

- EWK contamination here is less than 1%, no additional uncertainty
- 30% uncertainty on yield based on MC closure tests

MC closure vs N(b-jets)



Charge misidentified lepton background

2% Charge misid.

Evaluate charge misidentification rate in MC

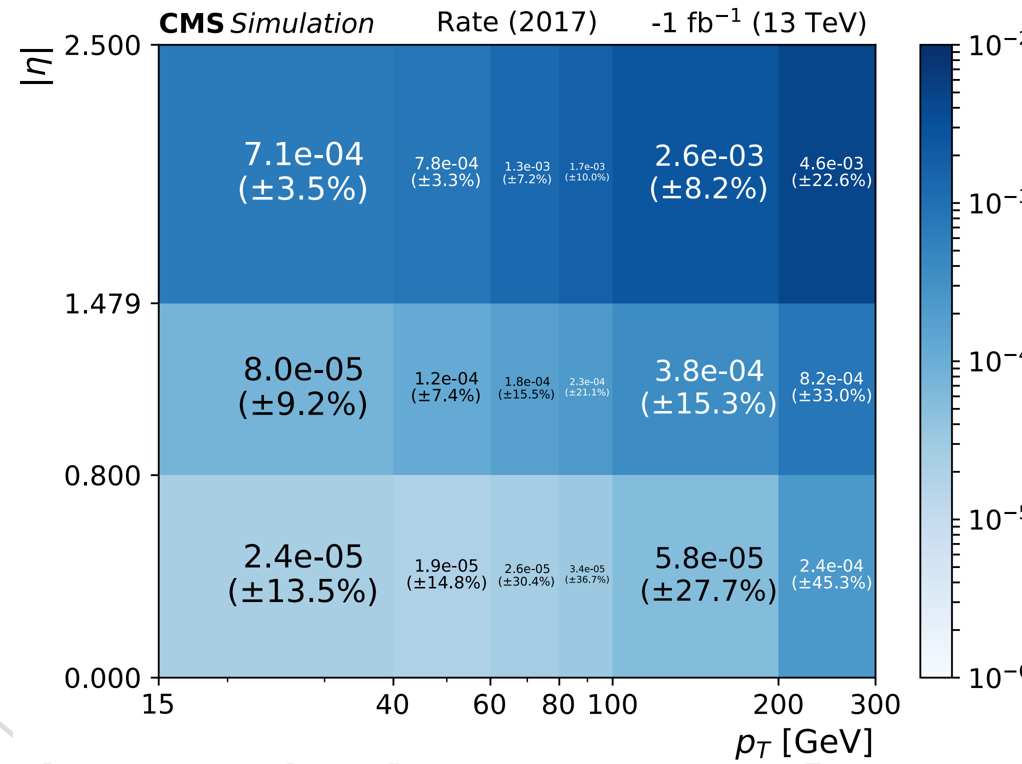
- Binned in p_T, η, and lepton flavor
- Between 10^{-3} and 10^{-5} for electrons
- An order of magnitude smaller for muons: ignored

Apply rate on SR-like events with opposite-sign leptons

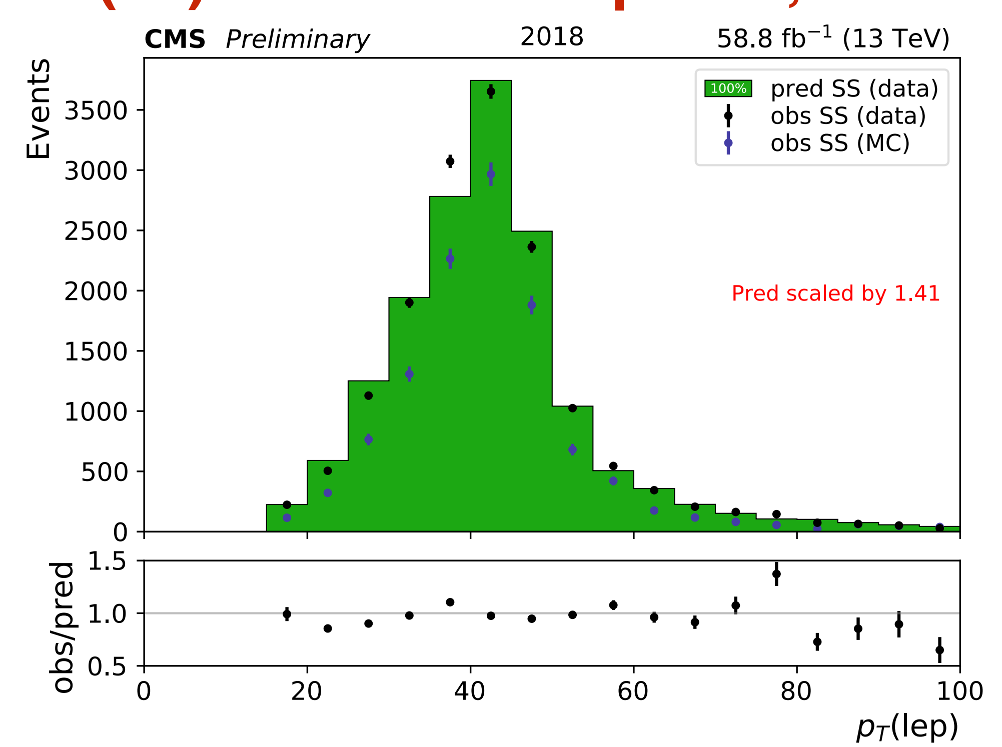
Test MC rate on same-sign Z(ee) events in data

- Good agreement in 2016
- 1.4 normalization correction needed in 2017 and 2018
- 20% uncertainty applied to account for possible kinematic dependence of the constant correction

Charge flip rate, 2017, e

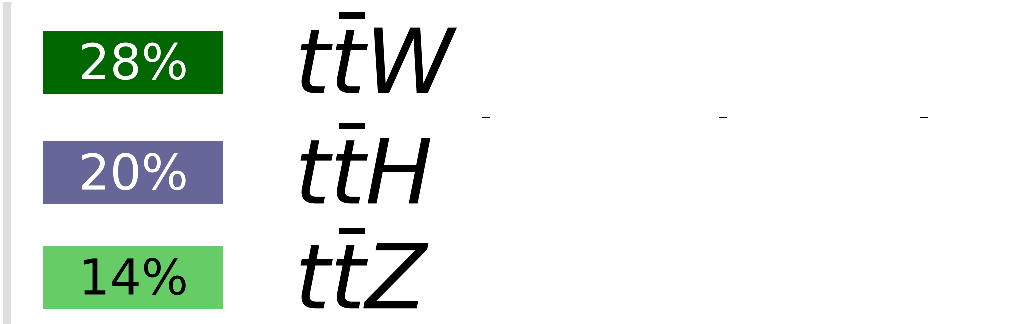


Z(ee) test of MC flip rate, 2018



Main prompt lepton backgrounds

ttW, ttH(WW), and ttZ are major backgrounds we take from MC



Normalization:

All recent measurements are high, so we allow significant uncertainty

In addition, ttW and ttZ need many extra jets to enter our SR

- 40% uncertainty for ttW and ttZ (same as 2016 paper)
- 25% for ttH, based on 1.25±0.25 signal strength measurement
  - was 50% in 2016 paper, due to 1.5±0.5 signal strength measurement

Shape and N(jets), N(b-jets) corrections:

Scale and PDF variations have small effects, around 15% and 1%

Since we have a large tt sample, we use tt measurements to correct ttW/ttZ/ttH

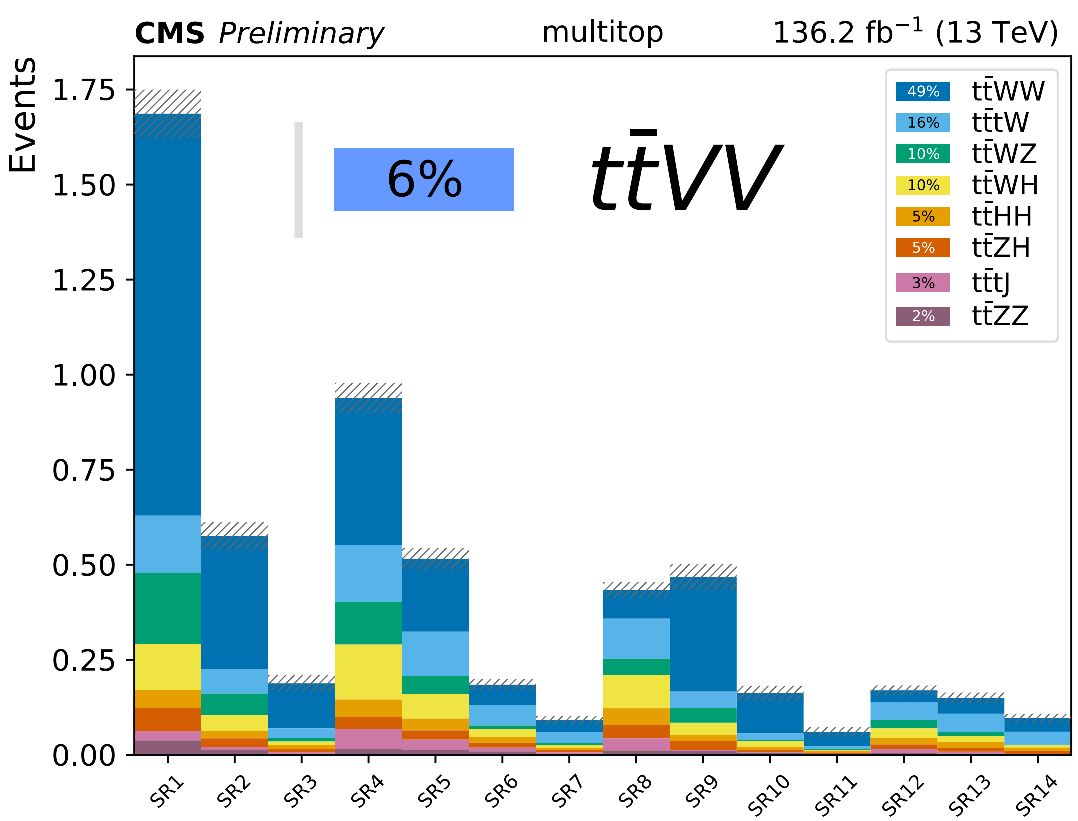
- **$N_{ISR/FSR}$ jets correction** (0.8 to 1.5): derived by ourselves per year (different tunes)
  - Uncertainty: half of the correction
- **Additional b jets correction** (1.7 ± 0.6): based on ttbb/ttjj measurement by CMS
  - Uncertainty: measurement uncertainty (0.6/1.7 = 35%)
  - Additional uncertainty: 30% from differences between tt and ttW [ARC suggestion, after freezing]
  - This is the dominant systematic uncertainty in the analysis (±12% impact on measurement)

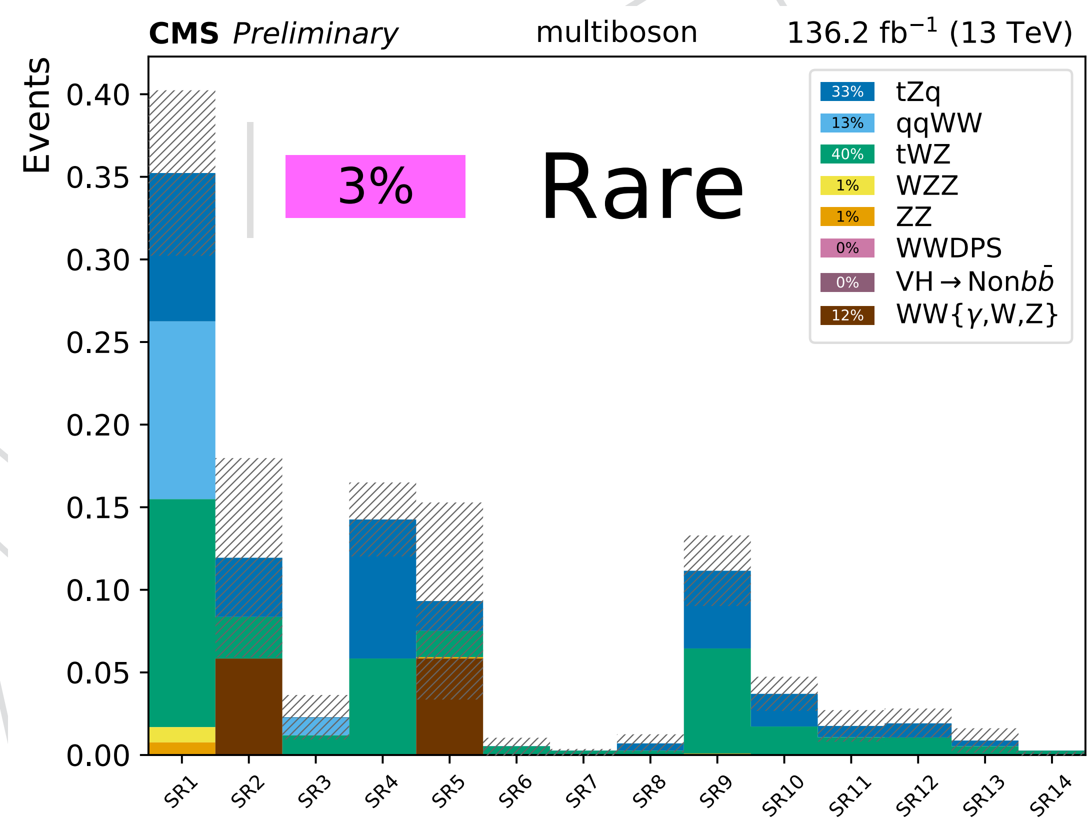
Other prompt lepton backgrounds

Other backgrounds grouped into three categories

6% $t\bar{t}VV$
3% Rare
3% $X\gamma$

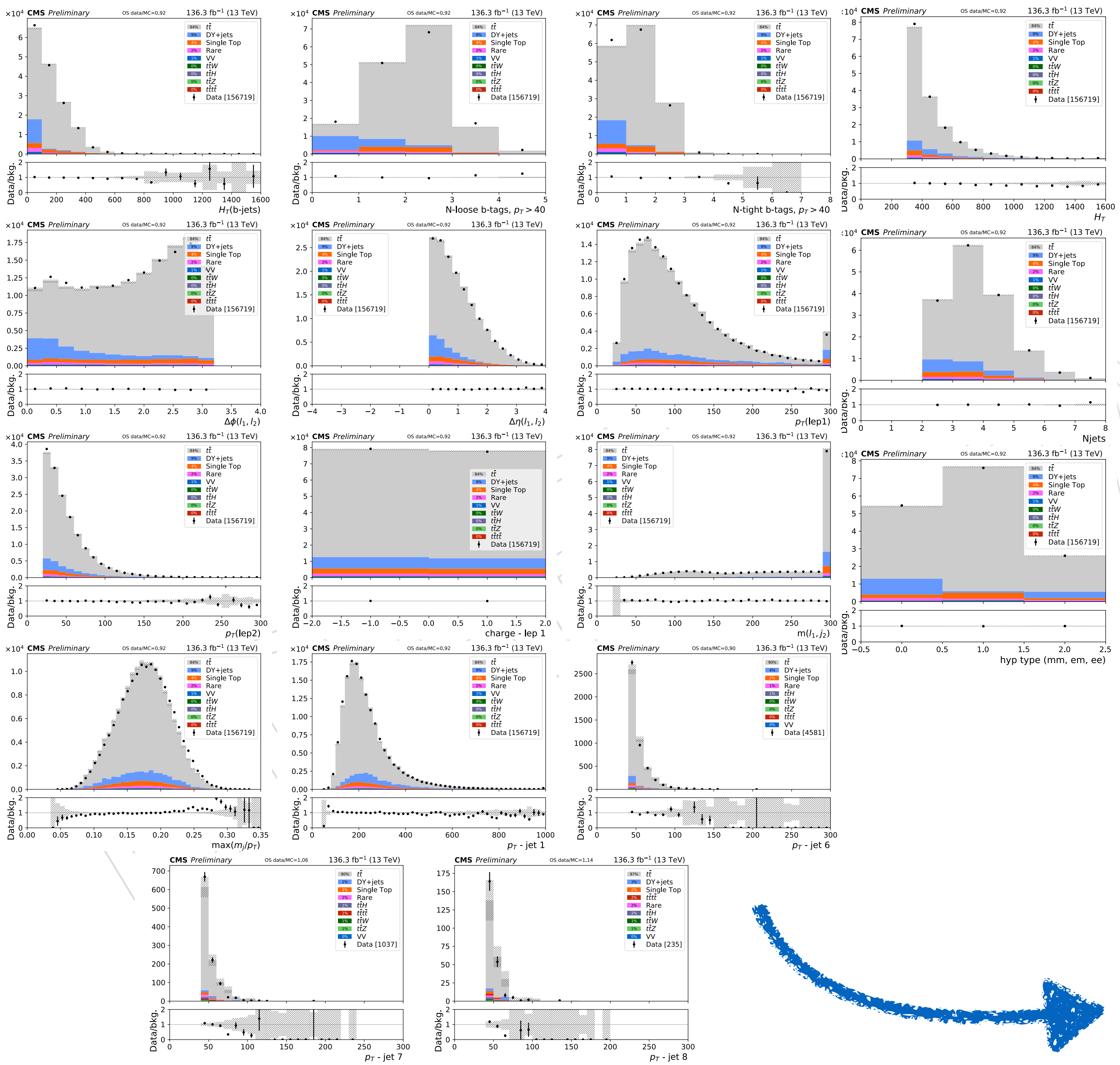
- Normalization uncertainty taken from the process with the largest uncertainty in each category: 11% for ttVV and Xγ, 20% for Rare
- Shape uncertainty taken from scales/PDF: 15% / 1%

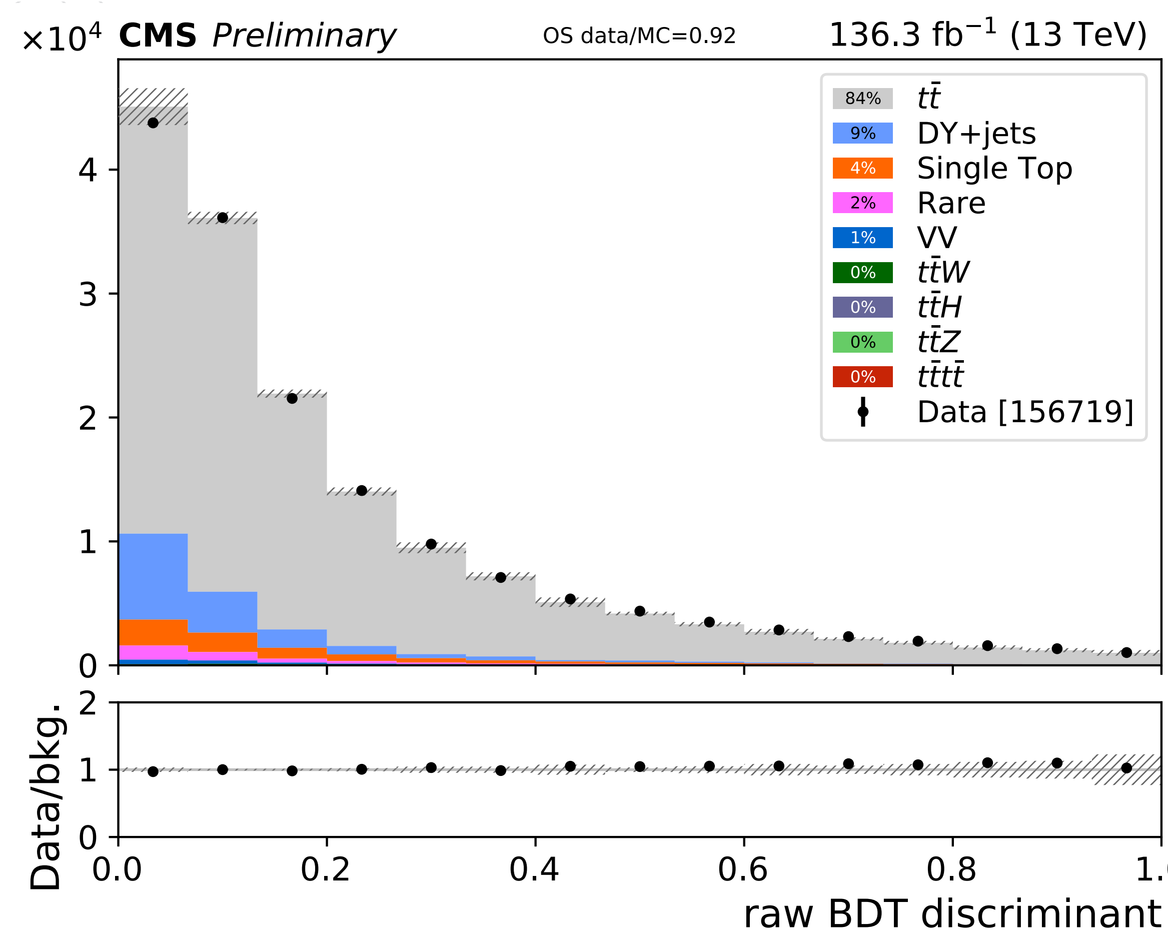




Control regions kinematics

Large use of tt-dominated CRs (opposite-sign and tight-loose) to validate kinematics entering the BDT





Systematics

Similar to 2016 analysis

Main changes in this table:

- smaller uncertainty on ttH (50% —> 25%)
- smaller uncertainties for Rare, Xγ, ttVV (50% —> 11-20%)

Year-to-year correlation model:

- Only systematics marked with † are correlated
- Since statistics dominates the measurement, extreme correlation models (all un/correlated) have at most a 2% effect on the signal strength
- Individually (un)correlating uncertainties has a less than 1% effect

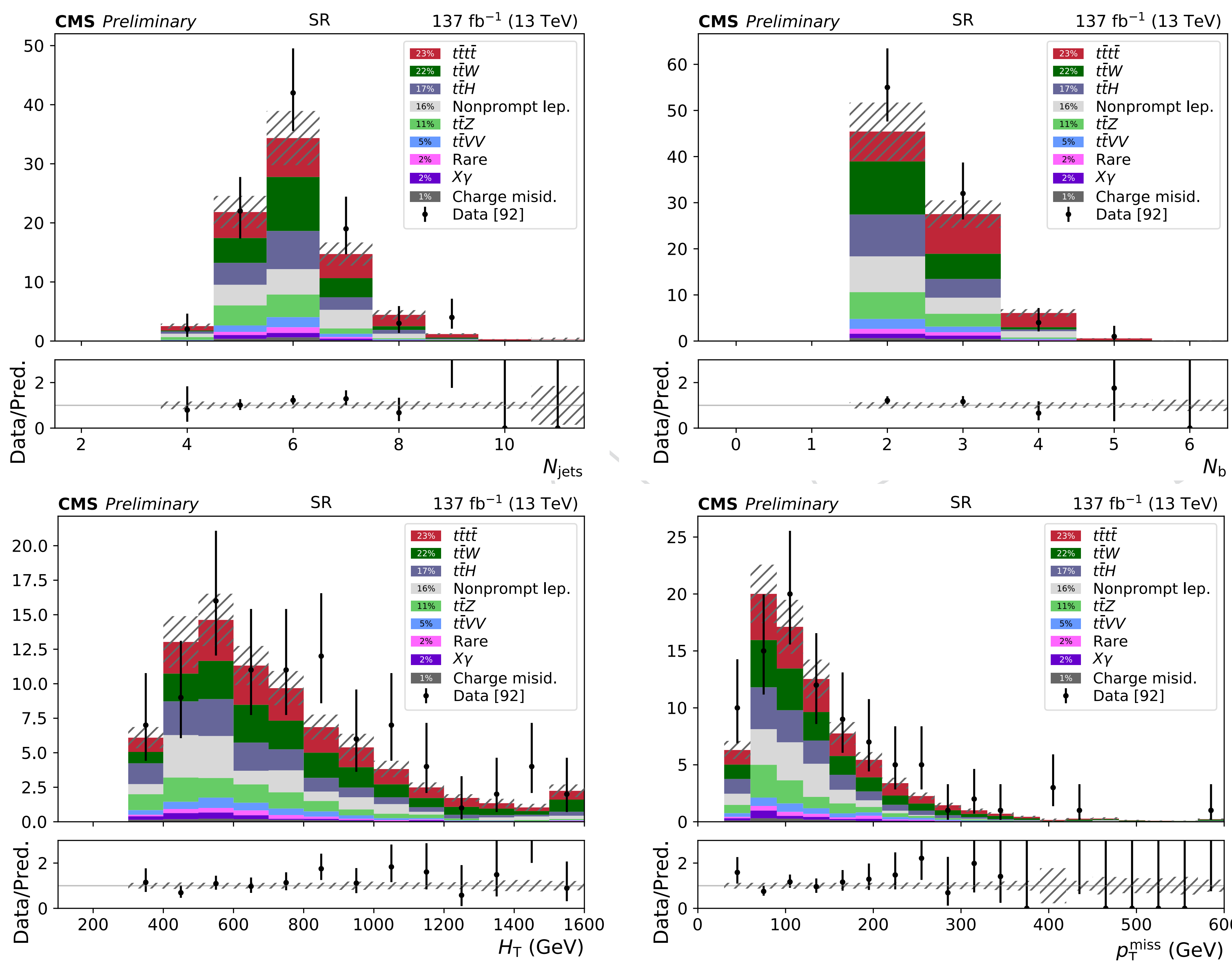
Paper Table 2

Source	Uncertainty (%)
Integrated luminosity	2.3–2.5
Pileup	0–5
Trigger efficiency	2–7
Lepton selection	2–10
Jet energy scale	1–15
Jet energy resolution	1–10
b tagging	1–15
Size of simulated sample	1–25
Scale and PDF variations †	10–15
ISR/FSR (signal) †	5–15
$\mathrm{t\bar{t}H}$ (normalization) †	25
Rare, Xγ, $\mathrm{t\bar{t}VV}$ (norm.) †	11-20
$\mathrm{t\bar{t}Z}$, $\mathrm{t\bar{t}W}$ (norm.) †	40
Charge misidentification †	20
Nonprompt leptons †	30–60

Results: sum of cut-based regions

Kinematic plots used to introduce cut-based results

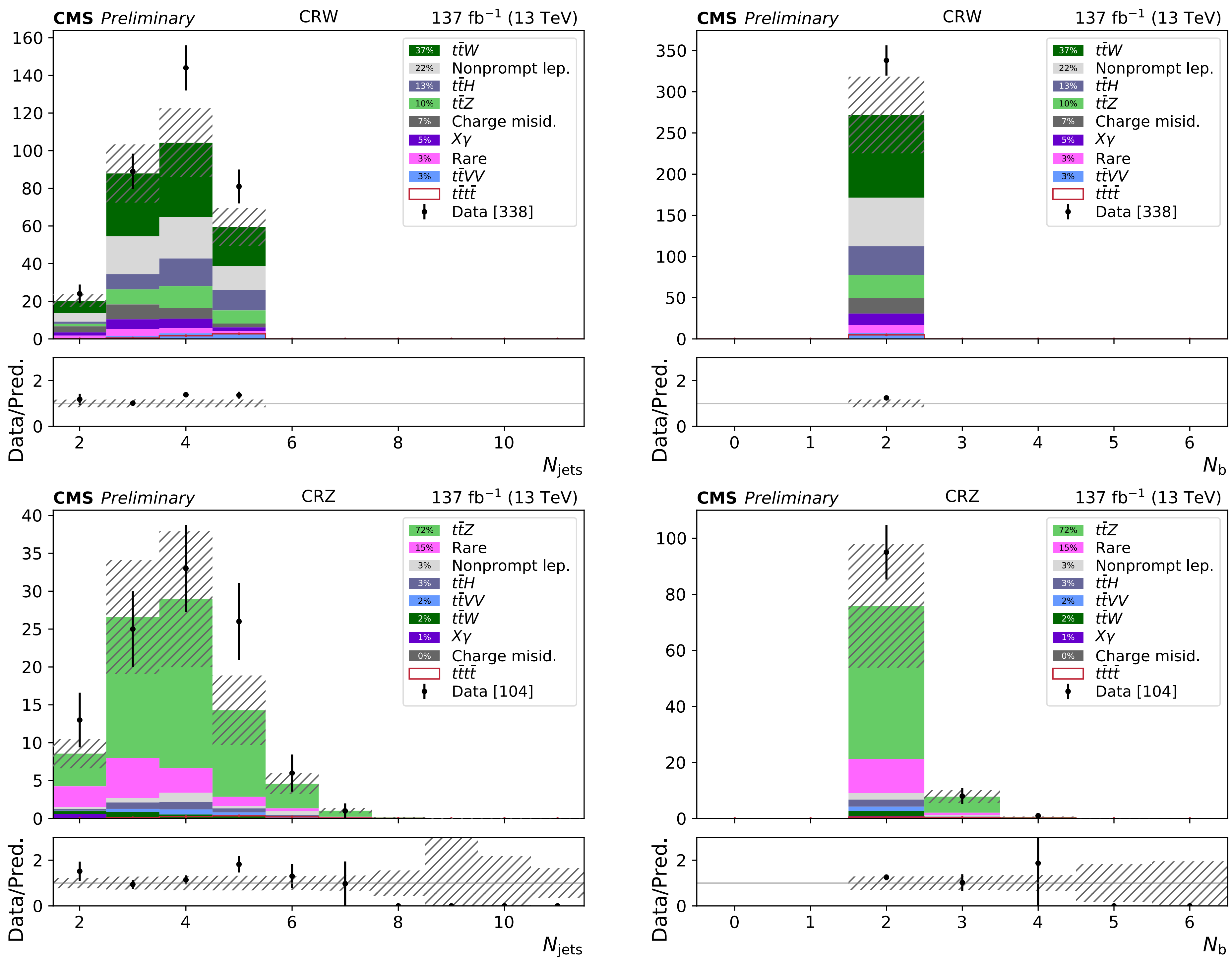
Pre-fit, stacked tttt with μ = 1 [was not stacked in frozen documentation]



Paper Figure 1

Results: ttW and ttZ control regions

- Control regions for **CRZ** and **CRW** show similar $t\bar{t}V$ scale factors to the 2016 analysis — roughly 1.3 for both ttZ and $t\bar{t}W$ (20% relative error from statistics), consistent with latest measurements



Paper Figure 2

Results: cut-based and BDT

Post-fit signal region yields

Post/pre-fit scale factors are consistent between years and BDT/cut-based →

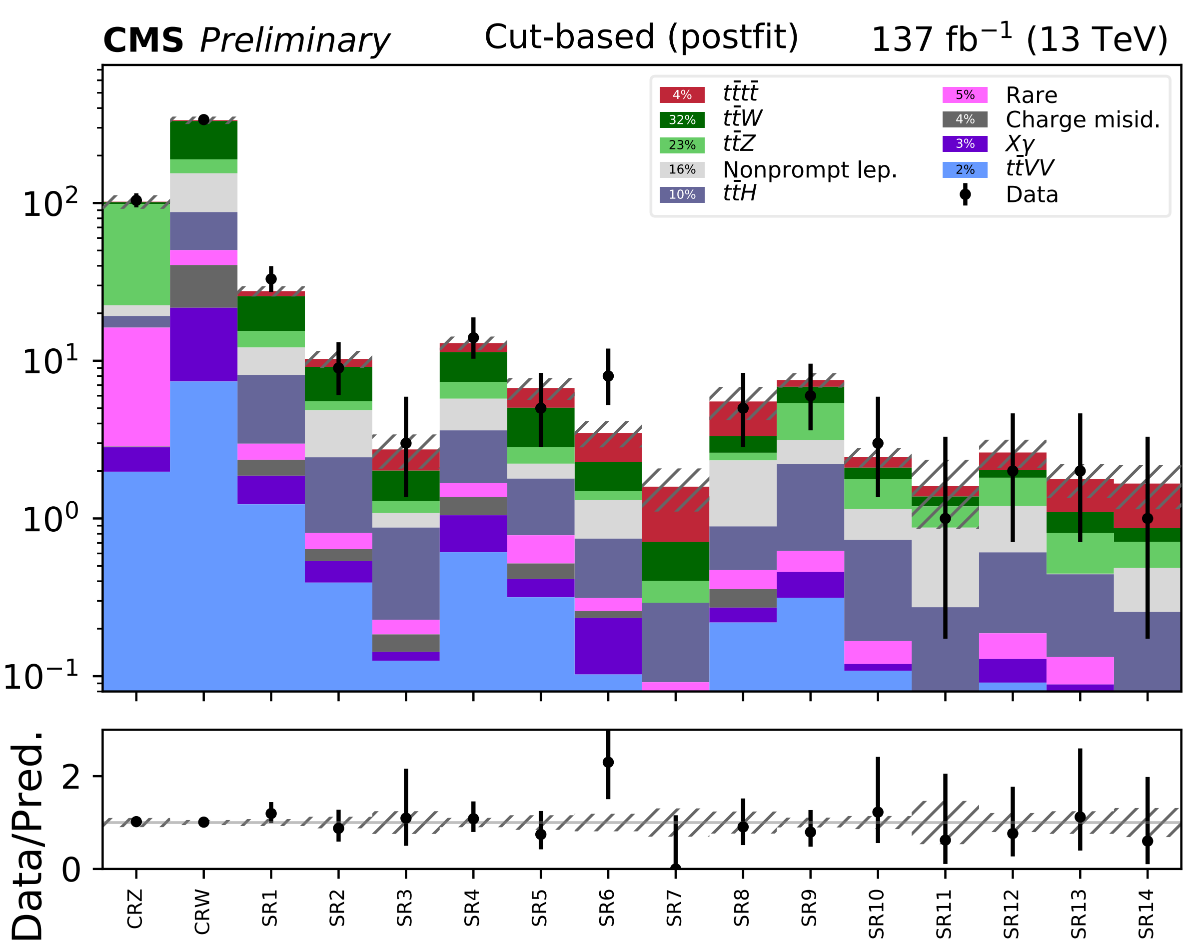
Fitted tttt signal strength close to 1

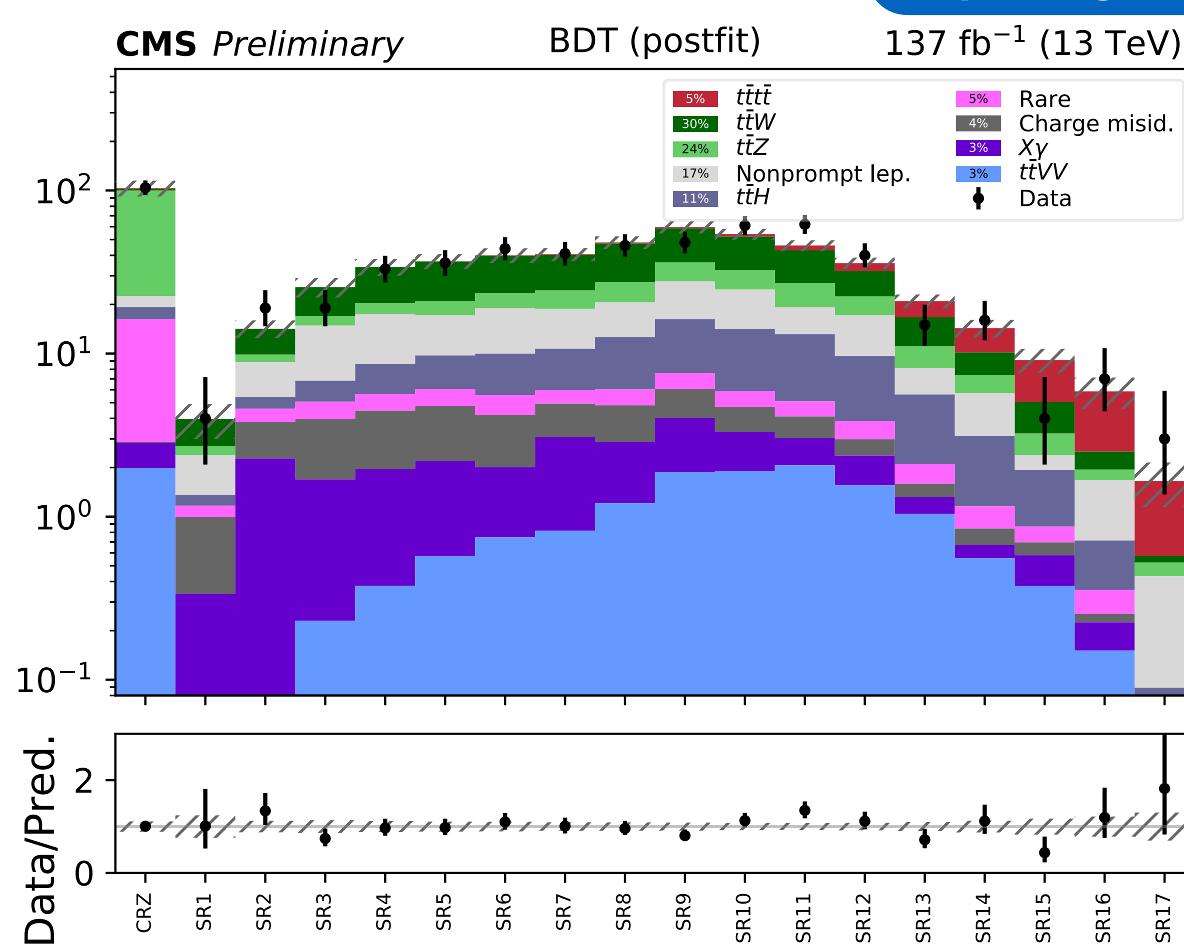
- cut-based: 0.781
- BDT: 1.048

Post-fit/pre-fit normalizations, BDT

process	SF (2016)	SF (2017)	SF (2018)	SF (Run2)
ttz	1.58	1.005	1.207	1.258
ttw	1.347	1.35	1.156	1.299
tth	1.087	1.089	1.045	1.088
tttt	1.175	0.845	1.451	1.053
fakes	1.064	1.163	1.081	1.125
xg	1.06	1.035	1.015	1.014
rares	1.055	1.017	1.023	1.017
ttvv	1.028	1.018	1.02	1.011
flips	1.016	1.007	0.999	1.001

Paper Figure 3





Results: cut-based and BDT

Post-fit signal region yields

Post/pre-fit scale factors are consistent between years and BDT/cut-based →

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ttvv	1.028	1.018	1.02	1.011
flips	1.016	1.007	0.999	1.001

Paper Table 3: cut-based yields

	SM background	$t\bar{t}t\bar{t}$	Observed
CRZ	101.17±10.12	0.83± 0.50	104
CRW	331.25±18.64	3.86± 2.30	338
SR1	25.65± 2.11	1.97± 1.19	33
SR2	9.15± 1.27	1.12± 0.65	9
SR3	2.01± 0.59	0.73± 0.42	3
SR4	11.36± 1.33	1.57± 0.91	14
SR5	5.04± 0.80	1.67± 0.96	5
SR6	2.29± 0.41	1.19± 0.68	8
SR7	0.71± 0.21	0.88± 0.48	0
SR8	3.32± 0.97	2.20± 1.28	5
SR9	6.84± 0.80	0.70± 0.39	6
SR10	2.10± 0.31	0.35± 0.22	3
SR11	1.38± 0.75	0.23± 0.14	1
SR12	2.04± 0.48	0.58± 0.34	2
SR13	1.10± 0.30	0.69± 0.40	2
SR14	0.87± 0.30	0.80± 0.45	1

Paper Table 4: BDT yields

	SM background	$t\bar{t}t\bar{t}$	Observed
CRZ	102.28±11.59	1.11± 0.43	104
SR1	3.95± 0.96	0.00± 0.00	4
SR2	14.19± 1.76	0.01± 0.01	19
SR3	25.53± 3.53	0.04± 0.03	19
SR4	33.96± 4.01	0.08± 0.05	33
SR5	36.67± 3.97	0.15± 0.07	36
SR6	39.81± 4.16	0.23± 0.12	44
SR7	40.32± 3.73	0.31± 0.16	41
SR8	47.29± 4.33	0.71± 0.28	46
SR9	58.51± 5.22	1.17± 0.47	48
SR10	52.16± 4.28	1.91± 0.74	61
SR11	43.02± 3.54	2.97± 1.19	62
SR12	32.12± 3.06	3.72± 1.41	40
SR13	16.73± 1.65	4.23± 1.64	15
SR14	10.16± 1.26	4.15± 1.60	16
SR15	5.05± 0.82	4.07± 1.56	4
SR16	2.50± 0.63	3.35± 1.26	7
SR17	0.57± 0.36	1.08± 0.42	3

Numerical results

Results are consistent between analyses and with the SM expectation, with the BDT observed results reaching 2.6 sigma significance

	Significance	95% U.L. [fb]	σ(tttt) [fb]
Run2 cut-based	1.7 (2.5)	20.1 ($9.4^{+4.4}_{-2.9}$)	$9.3^{+6.2}_{-5.7}$
Run2 BDT	2.5 (2.7)	22.6 ($8.6^{+3.9}_{-2.6}$)	$12.5^{+5.8}_{-5.3}$

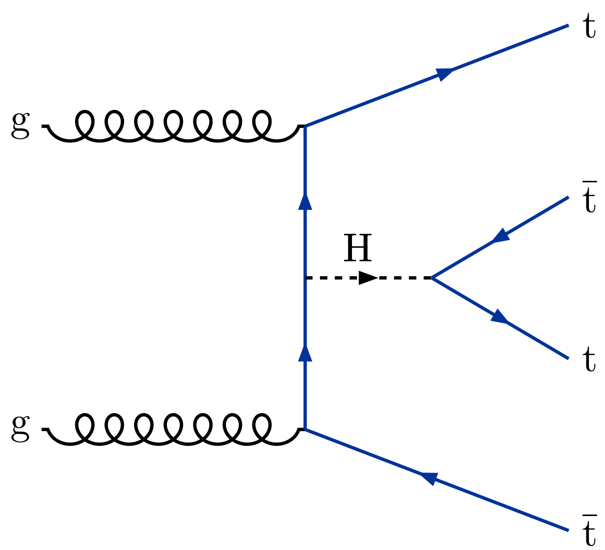
Note : expected U.L. assumes no SM tttt

Reminder: 2016 analysis measured σ(tttt) = 17^{+14}_{-11} fb

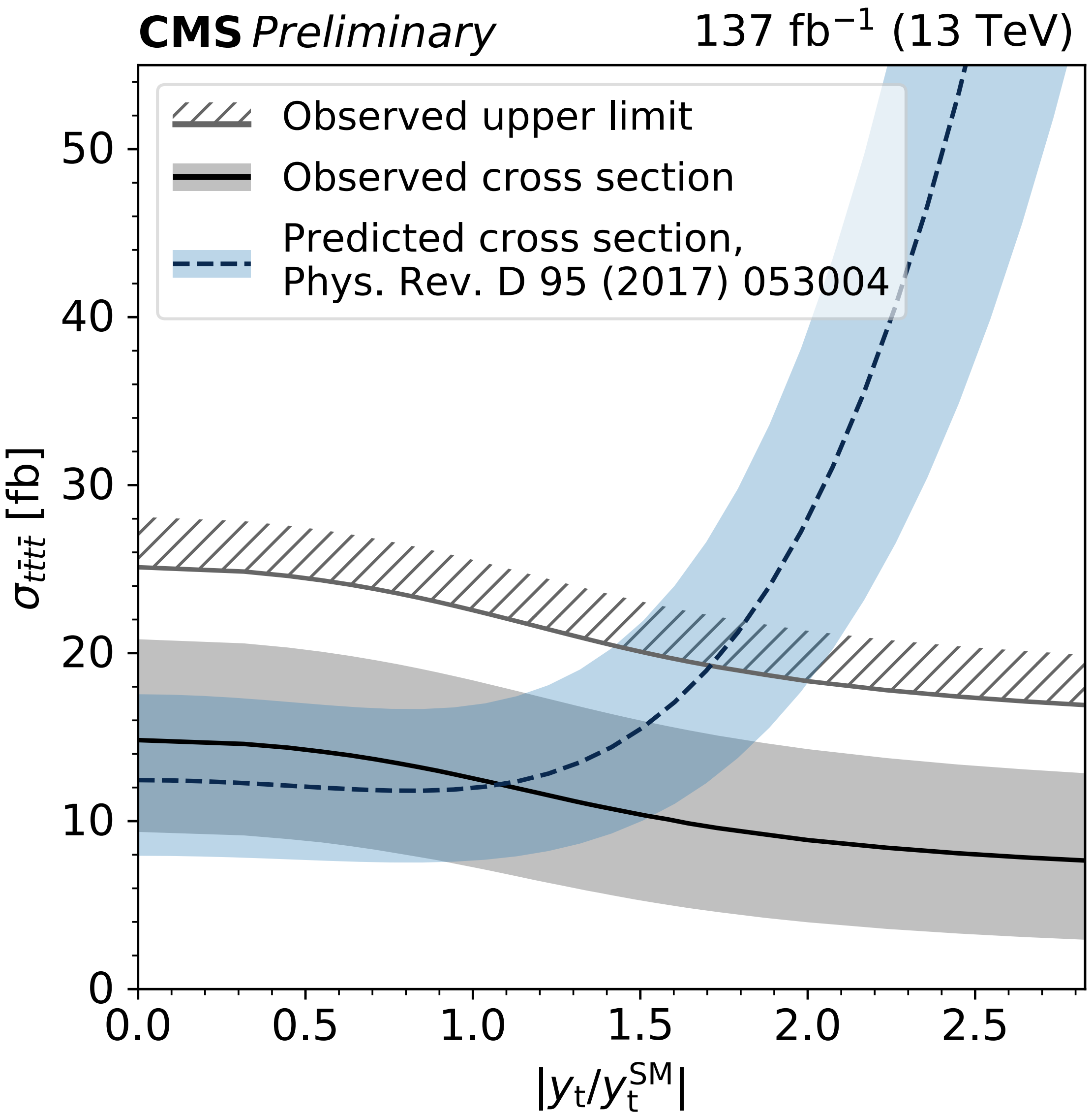
Reminder: SM tttt: $12^{+2.2}_{-2.5}$ fb

Top yukawa interpretation

- Diagrams with virtual Higgs bosons make $\sigma(pp \to t\bar{t}t\bar{t})$ a function of y_t
- We interpret the cross-section measurement and upper limits as constraints on the top yukawa coupling constant
- Results are not constant vs y_t because ttH background grows with y_t^2
- Result: $|y_t/y_t^{SM}| < 1.7$ @ 95%CL   [was 2.1 in 2016 analysis]



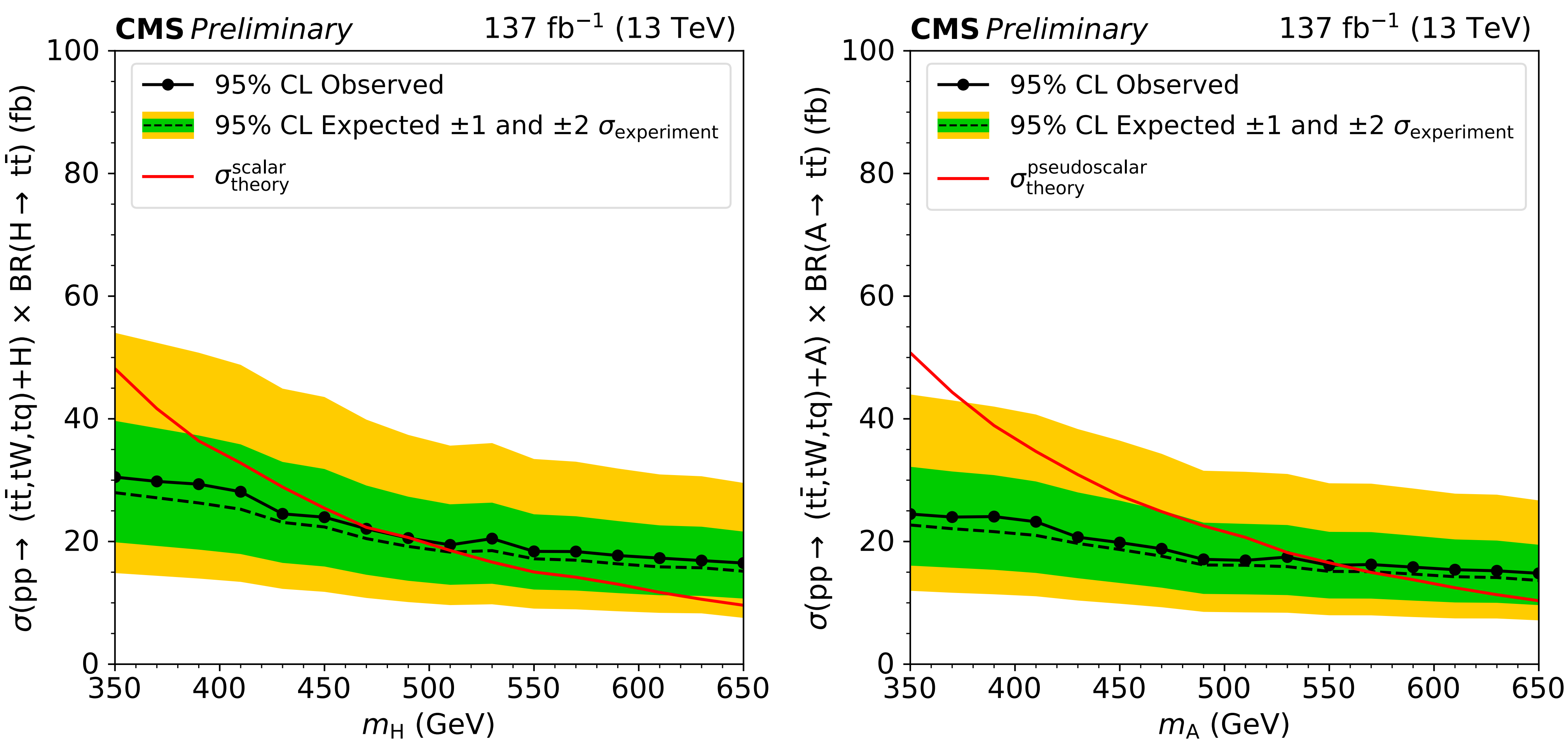
Paper Figure 4

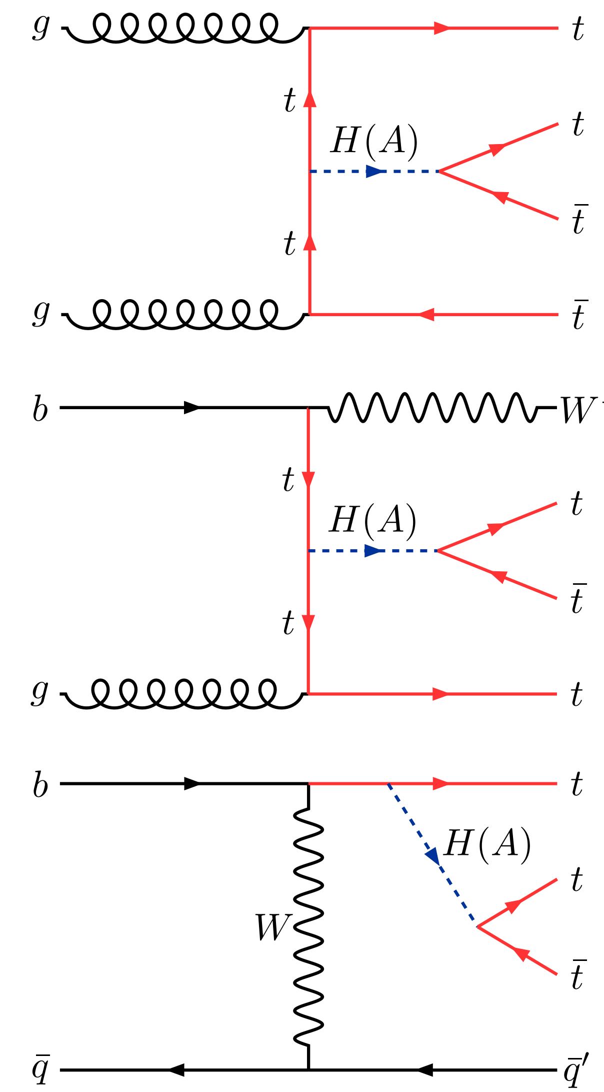


2HDM interpretation

- Originally part of the same-sign SUSY analysis, but now in tttt
- Type-II 2HDM with associated production of a heavy scalar H and pseudoscalar A decaying into $t\bar{t}$ ($\tan\beta\sim1$), giving rise to final states with 3 and 4 top quarks
- Excellent final state for the $t\bar{t}t\bar{t}$ analysis
  - Exclusion gain of 100-140 GeV w.r.t. 2016 SUSY analysis

Paper Figure 5





Summary and Next Steps

Summary:

Presented two analyses, cut-based and BDT, reaching ~2.5 sigma of expected significance for SM tttt production

- Significant improvement with respect to the 1.0 sigma of 2016 (ATLAS and CMS)

BDT result also used to constrain Top Yukawa and 2HDM

- Top Yukawa: 95% U.L. goes from 2.1 (2016) to 1.7 (full Run 2)
- 2HDM: 95% U.L. go from 360-410 GeV (2016) to 470-550 GeV (full Run 2)

Next steps:

CCLE is currently reviewing Paper for a quick conversion to PAS

Authors have no further analysis improvement planned for the Paper

- Possible exceptions would be updated ttH and tt+bb measurements, which could be easily integrated

Could consider adding additional interpretations, such as low-mass ($m<2m_t$) scalars or vectors with enhanced top couplings, if kinematics match SM tttt

Backup

Yearly lepton fake rate vs p_T

- Data fake rate as a function of p_T is similar across the years
- 2018 to be checked again with latest recipes/JECs
- In addition to statistics, a 30% normalization uncertainty is taken for fakes, as well as a shape uncertainty based on the electroweak subtraction method

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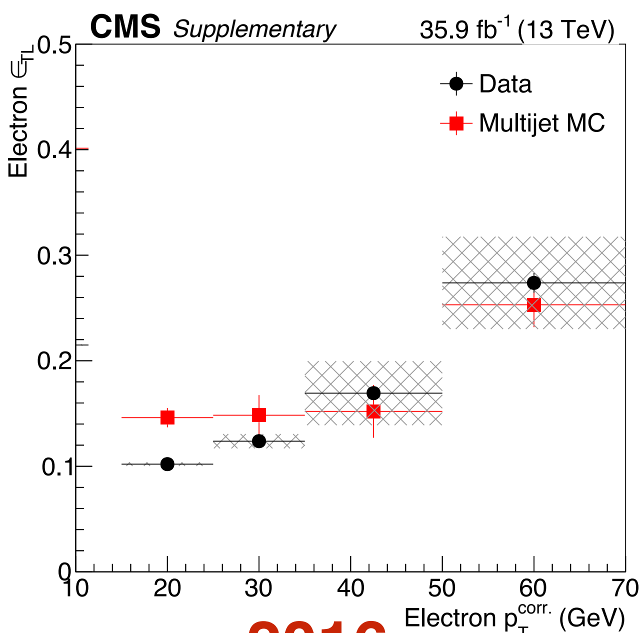
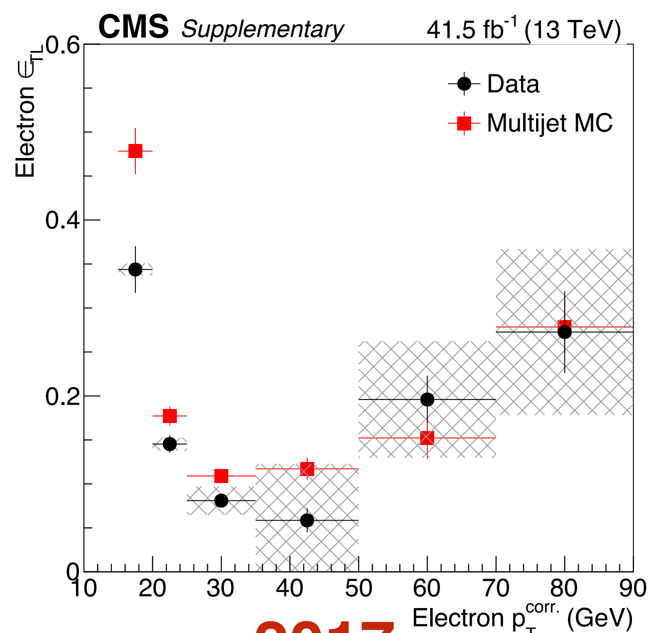
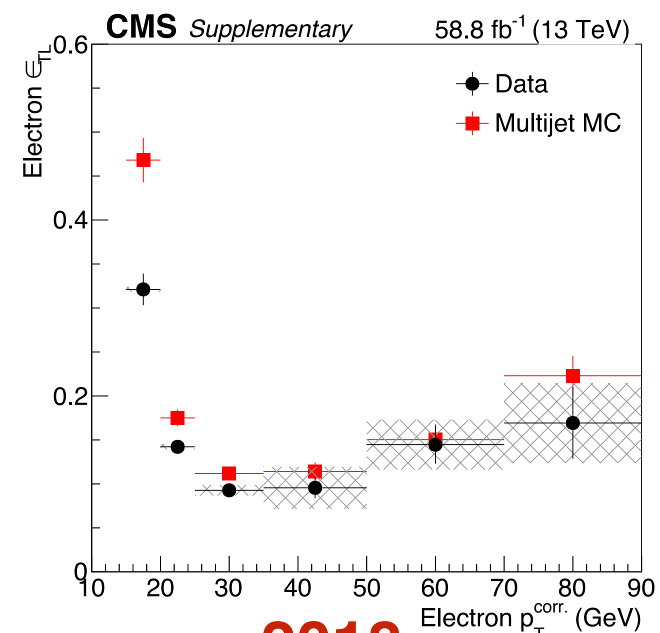


2016

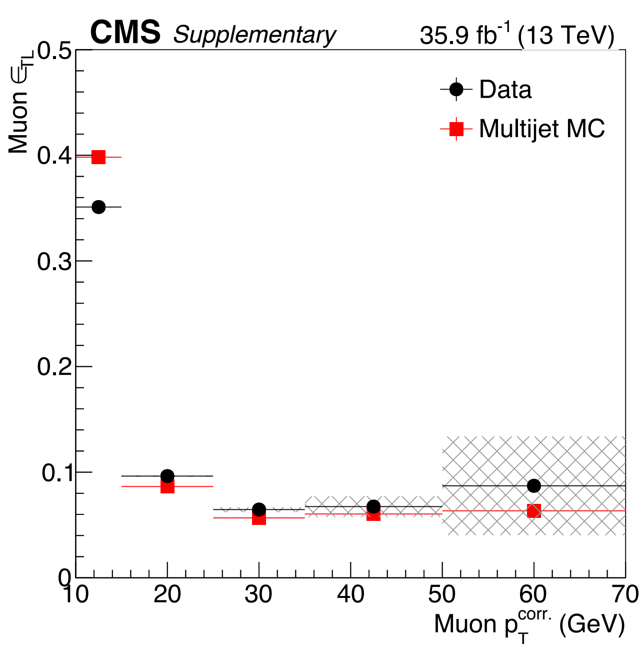


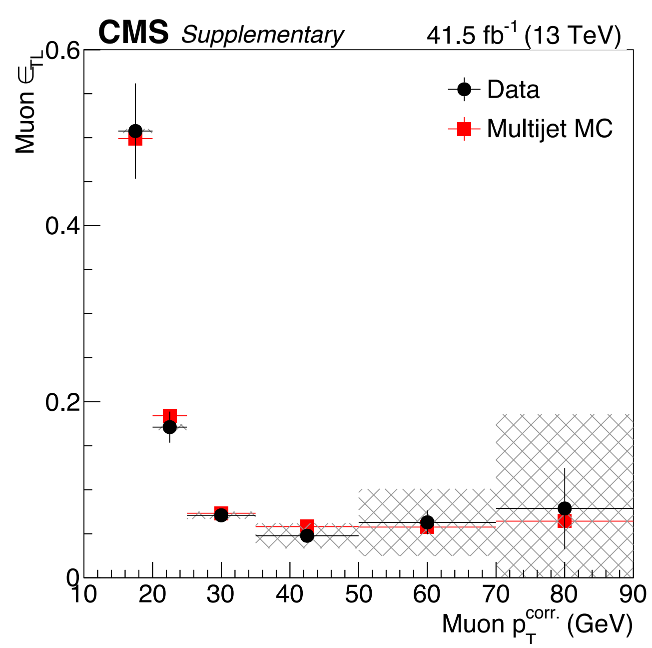
2017

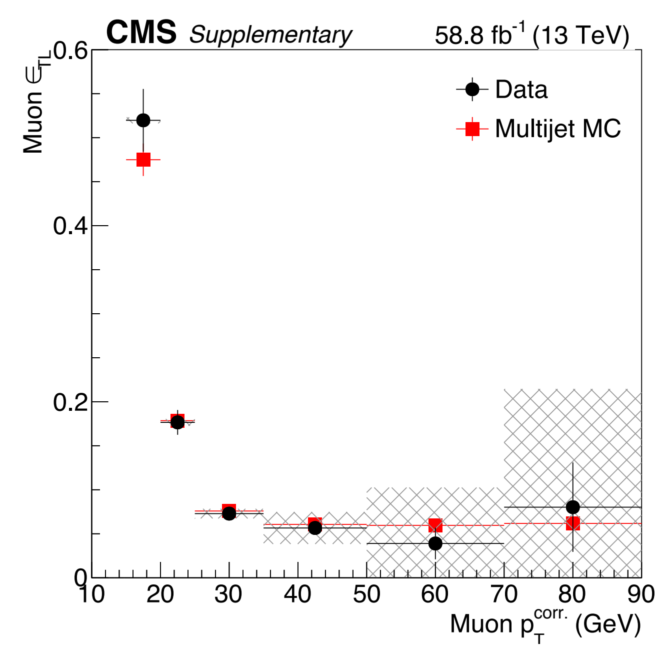


2018

μ

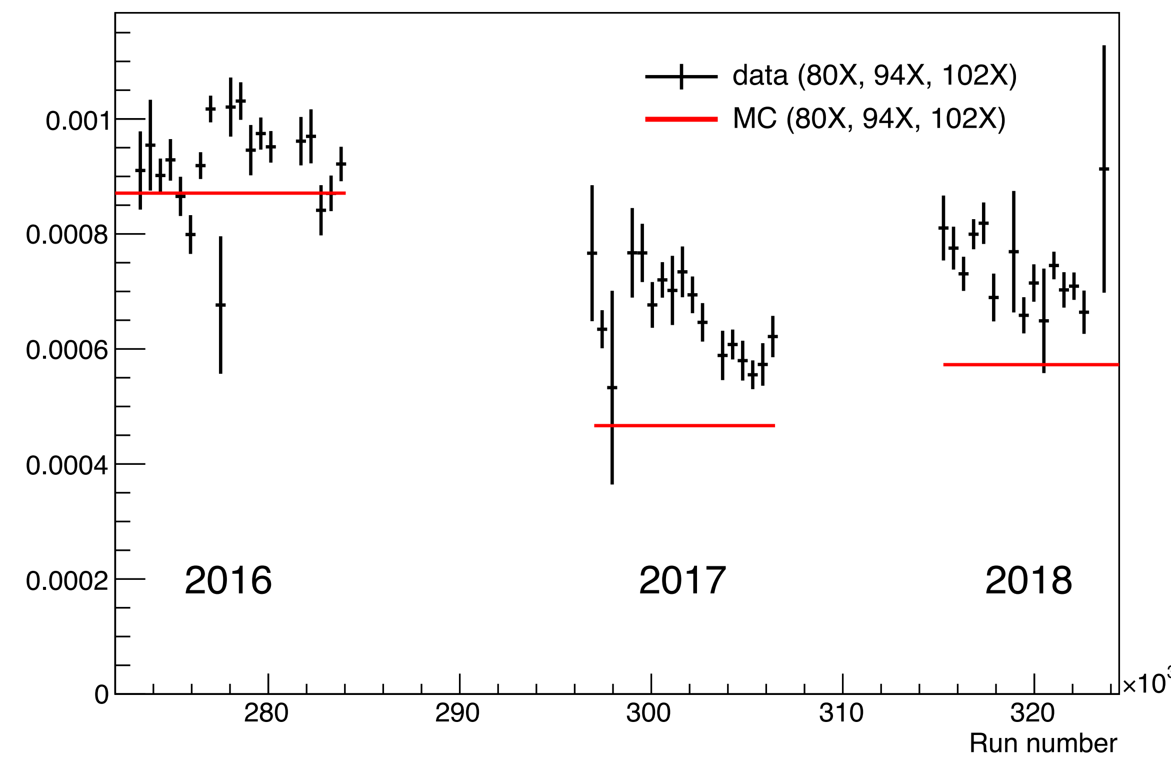


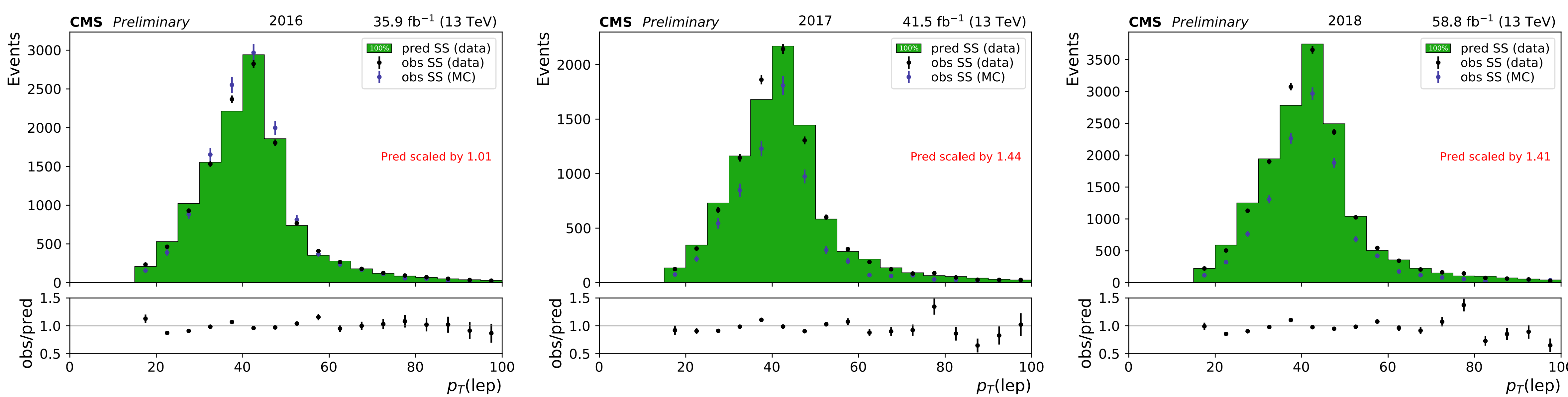




Electron charge flip rate

- Opposite-sign dilepton control region used to estimate (small) charge flip background in signal region with a *MC-based* flip rate transfer factor (SS prediction = OS * TF)
- Summary plot (*right*) shows **simulated flip rate** and **observed flip rate** (ratio of same-sign to opposite-sign in Z peak)
  - MC had good modeling of data flip rate in 2016, while it underpredicted starting in 2017 due to pixel issues
- A scaling factor to account for data/MC is applied per year for closure (*bottom*), and a 20% systematic is taken on the size of this background





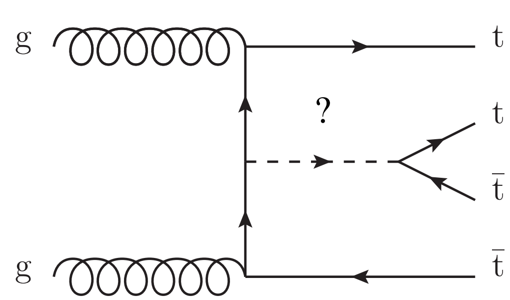
Data quality issues + corrections

- A few past updates on data comparisons with 2017 and 2018 datasets from SUS talk and TOP talk (e.g., pixel issues in 2017, HEM15/16 impact on fake background in 2018, impact of L1 prefiring in 2016 and 2017)

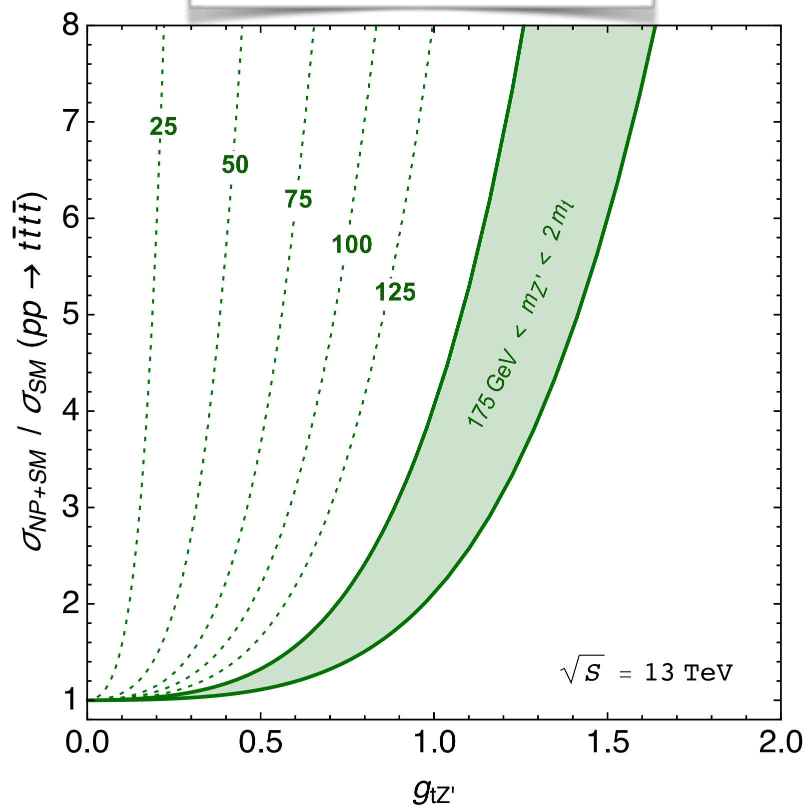
- Summary of main issues and actions
  - 2016/2017 (prefiring issue)
    - Apply event-level weights to simulation based on non-prefiring probability maps for 2016 and 2017
    - Results in a ~3% loss of $t\bar{t}t\bar{t}$ signal for those periods
  - 2017 (pixel issues)
    - No change made
    - Small loss of electron efficiency due to tight charge requirements for our electron ID, at the cost of keeping charge flip background small
  - 2018 (HEM)
    - No direct change made
    - Tight ID+Iso requirements for leptons largely protects us from fake leptons from HEM region — averaged over the Run2 dataset, the fake background increase is approximately 2%
    - Data-driven fake rate method, on average, accounts for fake rate differences

Z’, ϕ contributions to pp→$t\bar{t}t\bar{t}$

- In addition to 2HDM, there may be other contributors to $t\bar{t}t\bar{t}$ production
- In particular, [arxiv:1611.05032]() finds that a top-philic neutral Z’ boson, or a neutral scalar ϕ with yukawa couplings to top, can give significant off-shell contributions to pp→$t\bar{t}t\bar{t}$



$$\mathcal{L}_{Z'} = -g_{tZ'}\bar{t}_R \not{Z}' t_R$$



$$\mathcal{L}_{\phi} = -y_{t\phi}\bar{t}_L \phi t_R + \text{h.c.}\,.$$

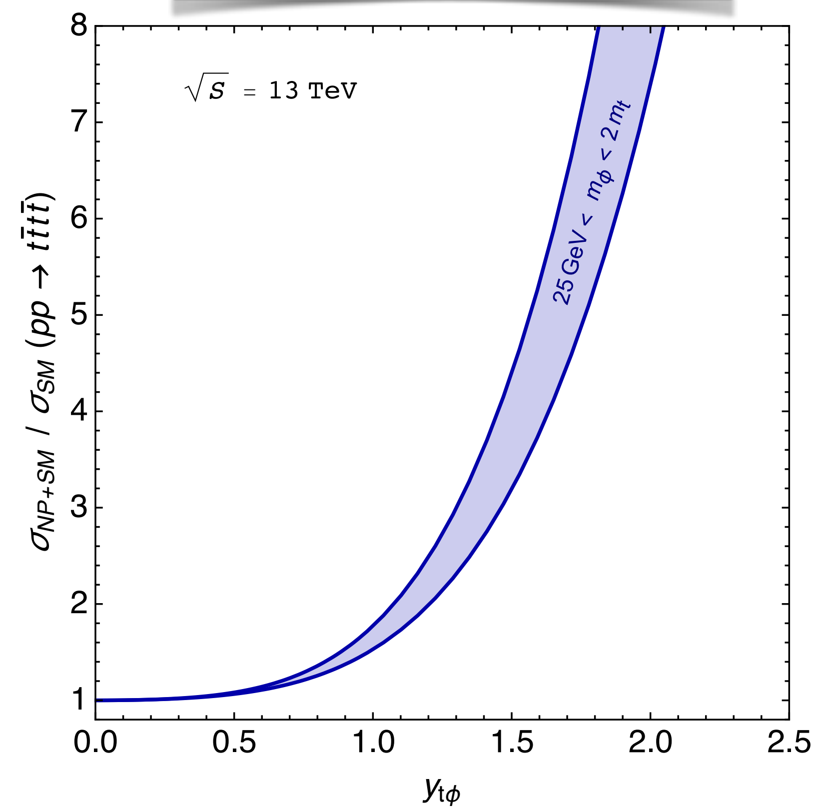


Figure 9: Predictions for the deviation $\sigma_{NP+SM}/\sigma_{SM}$ in the $pp \to t\bar{t}t\bar{t}$ cross-section at $\sqrt{s} = 13$ TeV within the simplified NP Z' (left-hand side) and ϕ (right-hand side) models as a function of the couplings $g_{tZ'}$ and $y_{t\phi}$, for different Z' and ϕ masses, respectively.

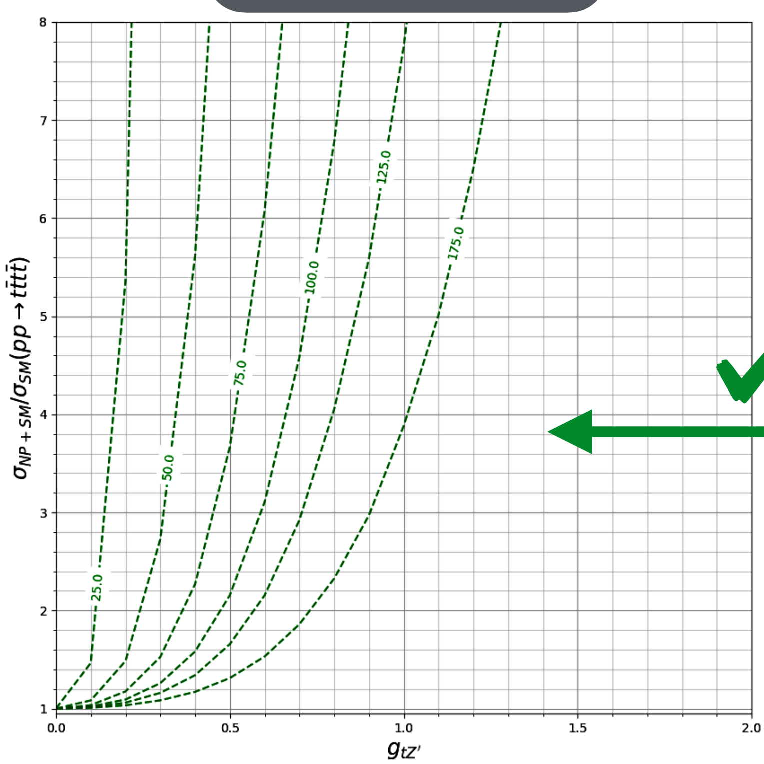
Z’, ϕ contributions to pp→$t\bar{t}t\bar{t}$

- In the range of $m_t < m_{Z'} < 2m_t$, or for full range of ϕ masses considered, kinematics do not play a role — $t\bar{t}t\bar{t}$ cross-section changes by a pure rescaling, as the authors verified
- While discussing with the authors, we have also simulated several mass points, reproducing the cross-section deviation curves (*left*) as well as showing the mass-independence of kinematics (*right*)

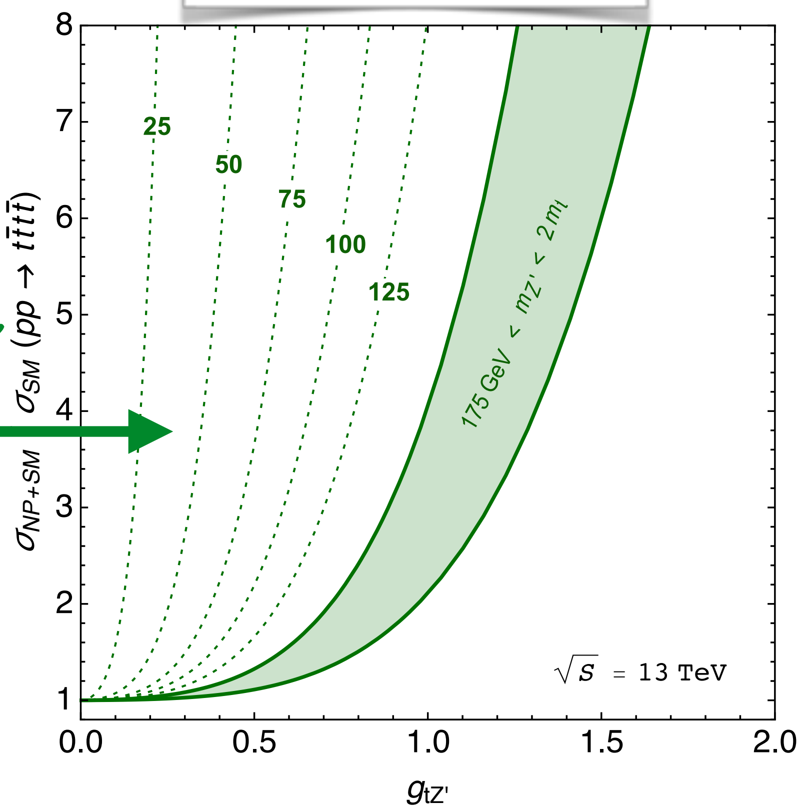
This interpretation is not yet in the analysis note, but…

→ SM $t\bar{t}t\bar{t}$ measurement results from this analysis can be directly converted into constraints on these mediators with no extra samples

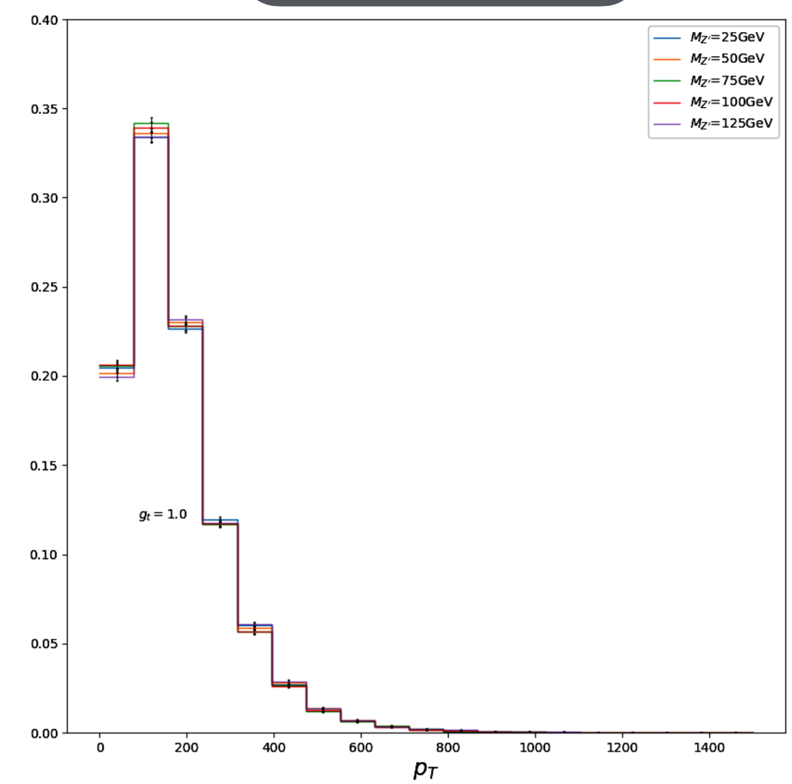
Private generation



$$\mathcal{L}_{Z'} = -g_{tZ'}\bar{t}_R \not{Z}' t_R$$



Private generation



top p_T

HEM: Before/after data comparisons

- ~14% higher **after** yield in $t\bar{t}\rightarrow 2l$ region (which has a H_T>300GeV requirement) attributed to trend in H_T (right)
- Variety of data-collection differences between the two periods

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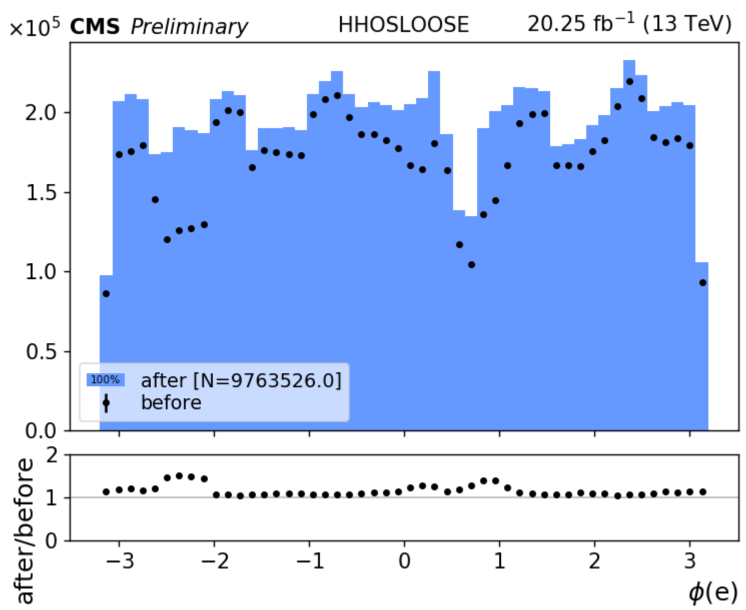

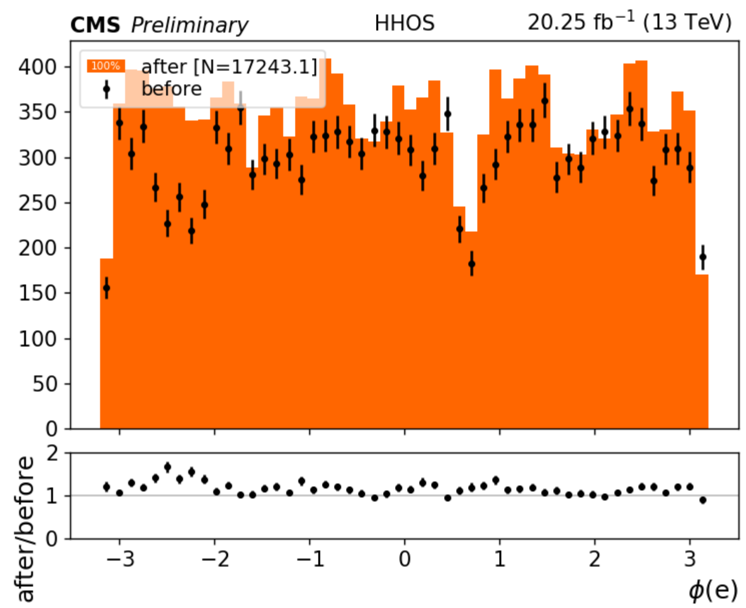

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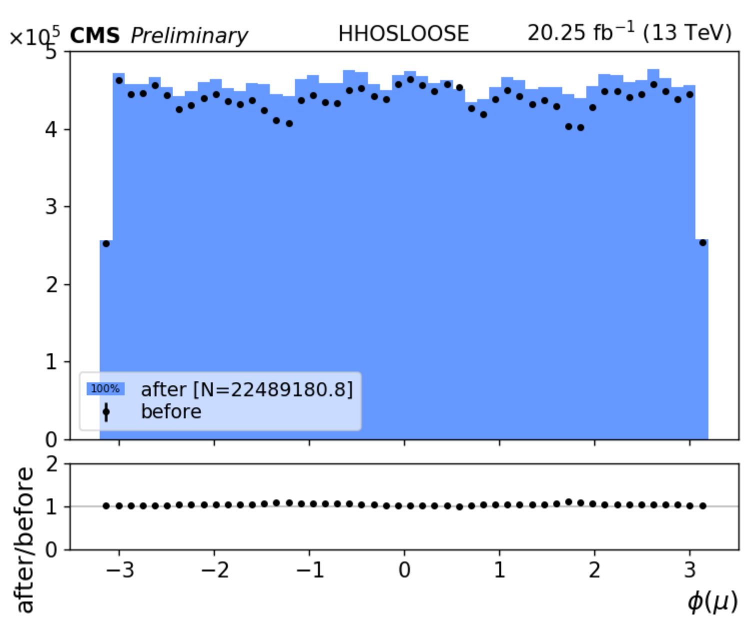
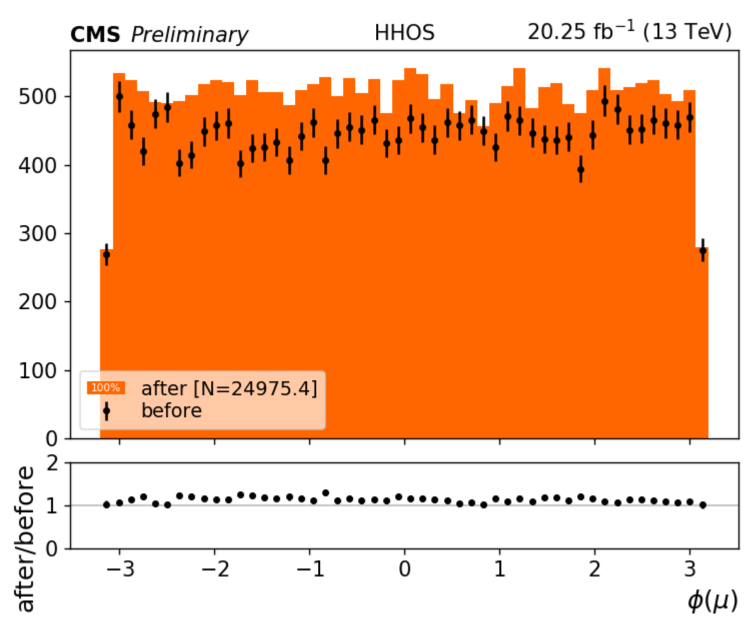
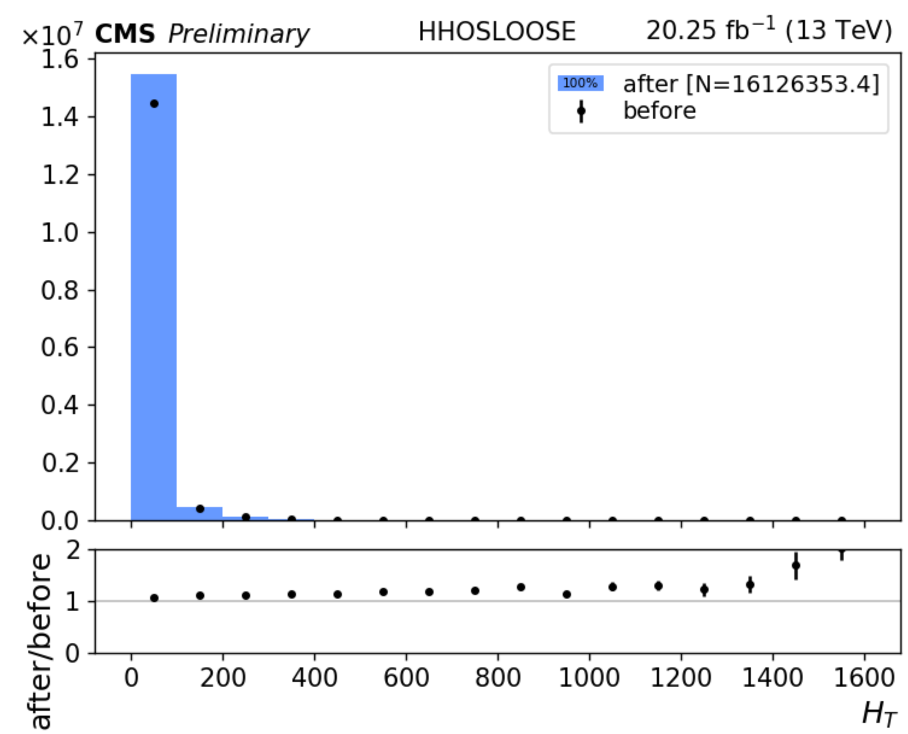






2016+2017 L1 prefiring

- Prefire issue in a nutshell (or more details) — we could be preferentially losing events with high energy, high η deposits (e.g., SUSY signal) due to bad timing + trigger rules

- Take inefficiency maps from
  - https://ncsmith.web.cern.ch/ncsmith/PrefireEfficiencyMaps/Preliminary/Jet_L1FinOReff_bxm1_looseJet_SingleMuon_Run2016B-H.pdf (Jet map 2016B-H)
  - https://lathomas.web.cern.ch/lathomas/TSGStuff/L1Prefiring/PrefiringMaps/ (Jet map 2017B-F)

- Consider **all** jets in the event and get a multiplicative scale factor < 1 to apply to MC → SF_{tot} = (1-SF($p_T(j_1)$,$\eta(j_1)$)) * (1-SF($p_T(j_2)$,$\eta(j_2)$)) * …

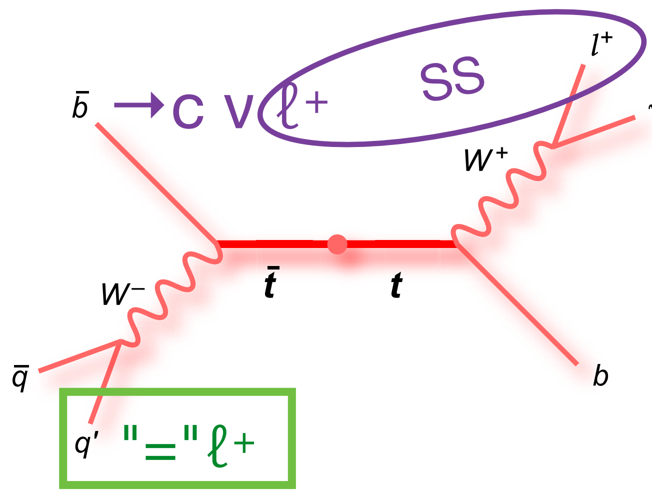
- Check scale factors for 2016 and 2017
  - Also have checked photon-based maps and found them to be sub 0.1%

- Links
  - Nick Smith's inefficiency maps (and prefire study github repo)
  - Laurent Thomas' inefficiency maps

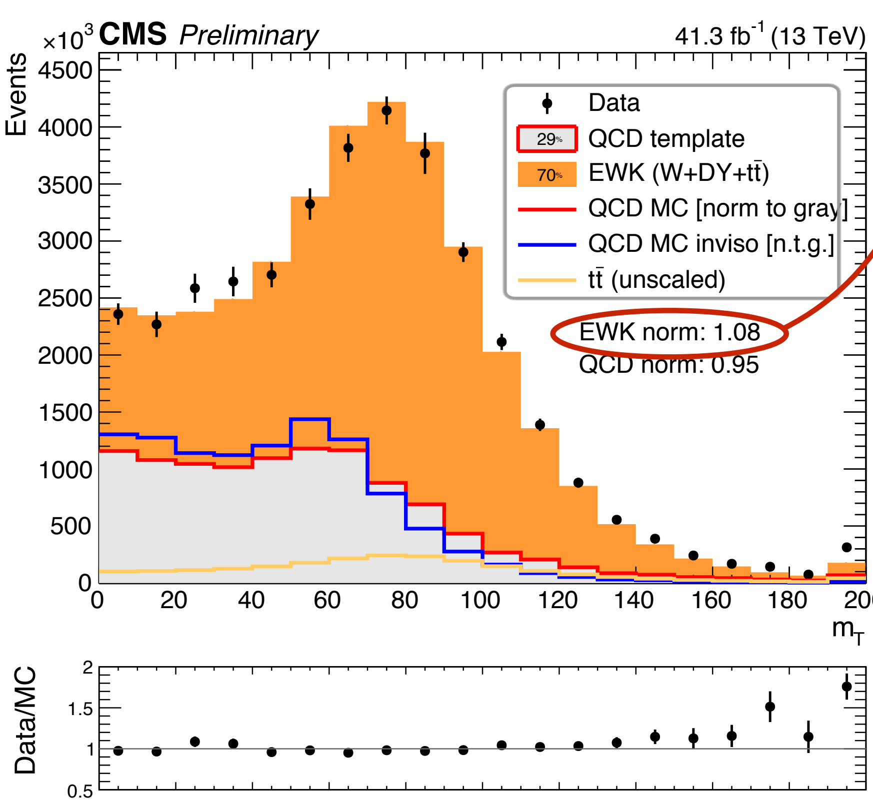
- $t\bar{t}t\bar{t}$ signal scaled down by 2.5% (4.7%) in 2016 (2017)
- For reference, the affected datasets (2016+2017) are 58% of the Run2 dataset by integrated luminosity

EWK normalization

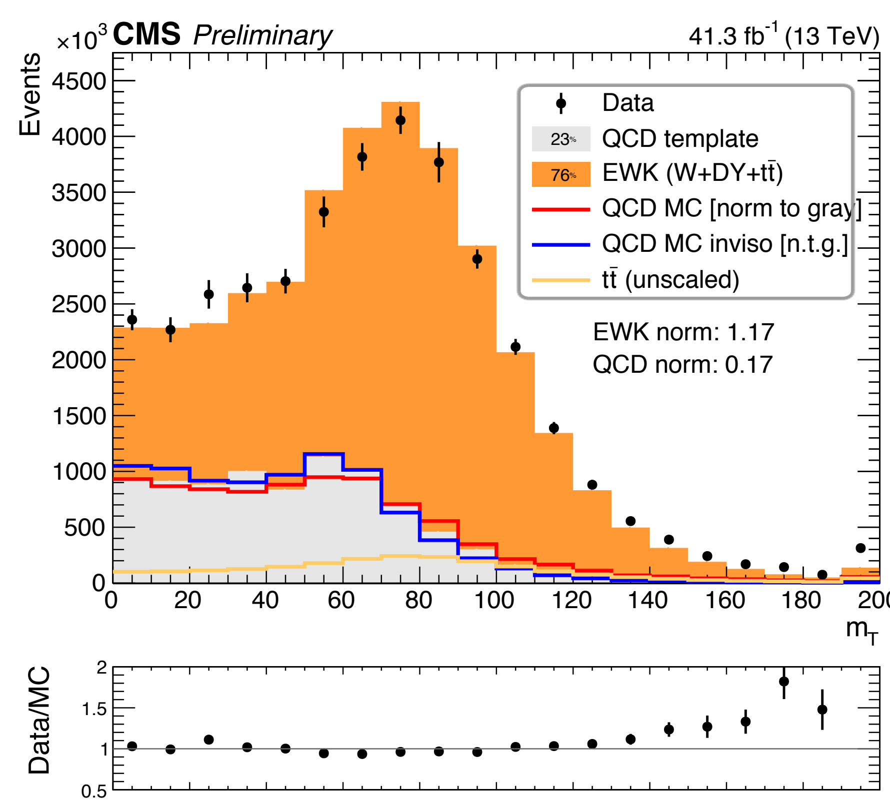
- Estimate fake or non-prompt leptons
- In QCD-enriched measurement region (E/T, mT<20 GeV), calculate fake rate (f) as probability for loose object to pass tight selection, as function of pT and η
- 2016 result normalizes EWK contribution (W+DY) in a MET>20, 70<MT<120 window
- To avoid QCD contamination, new method uses MET,MT>30 and a template fit of EWK contributions and QCD (from either data by inverting the isolation requirement, or directly from QCD MC)
- Fit variations can then be considered in the EWK systematic applied to the nonprompt background



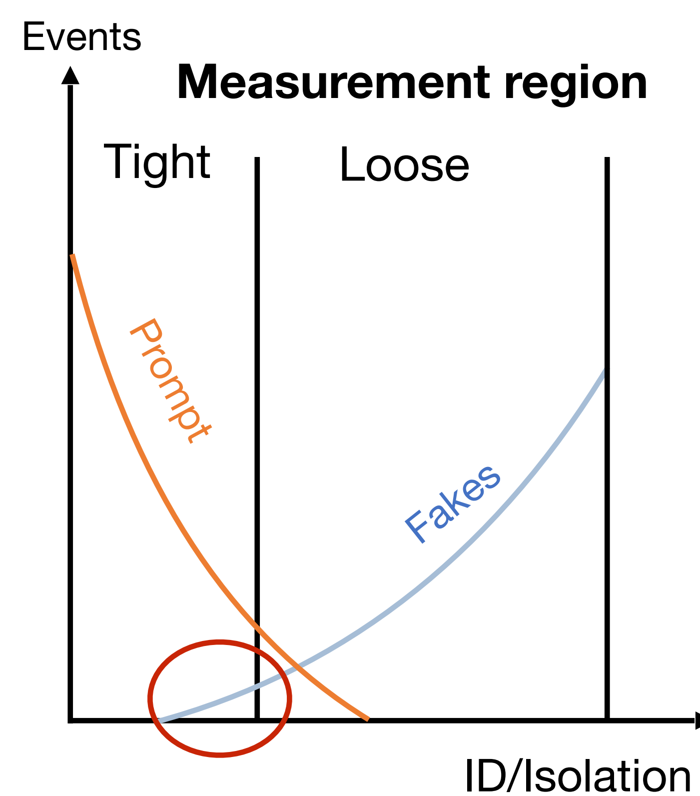
$$FR = \frac{N_{tight} - SF \times N_{tight}(EWK)}{N_{loose} - SF \times N_{loose}(EWK)}$$



MC template



Data template



Flip rate closure

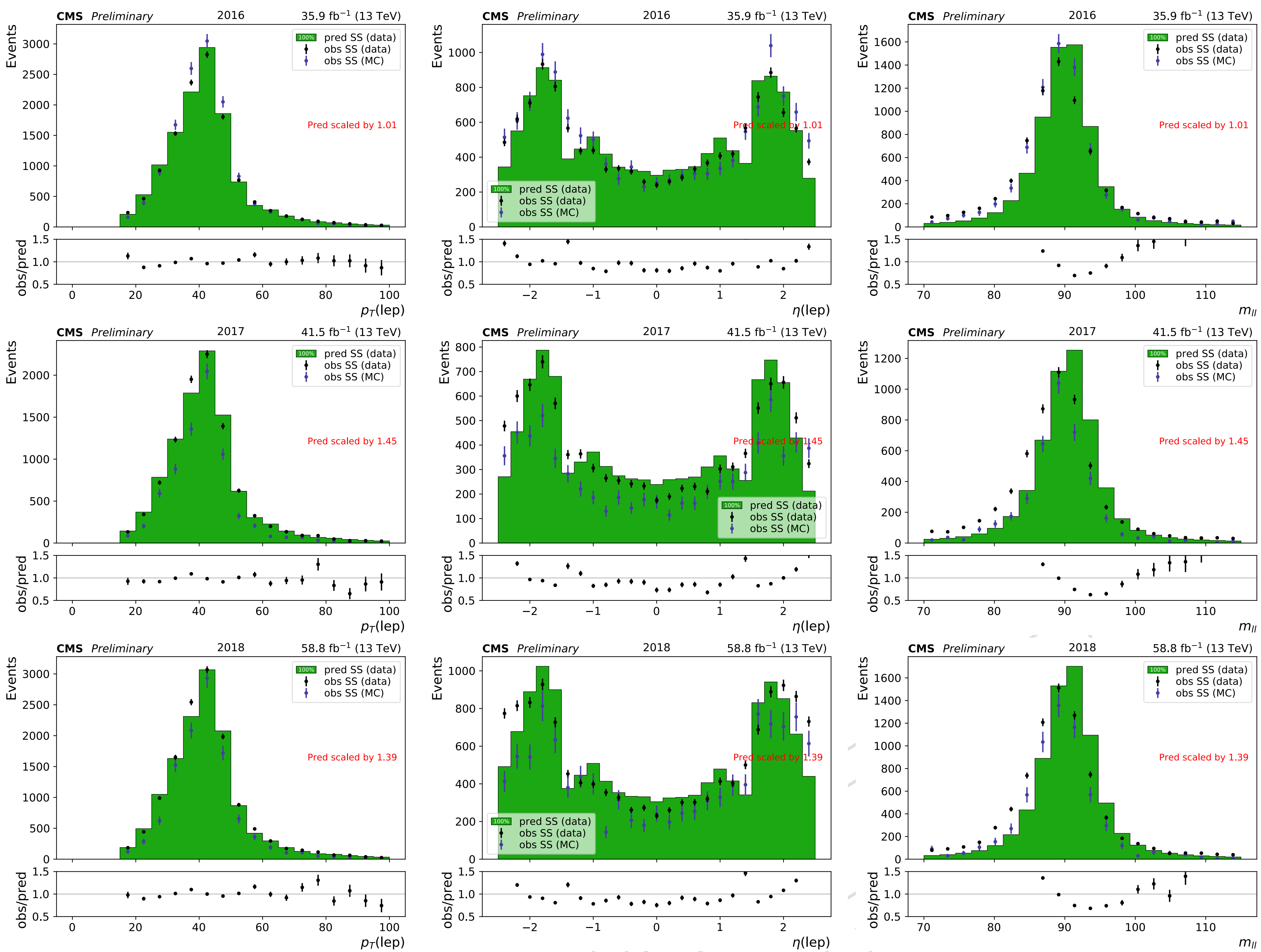
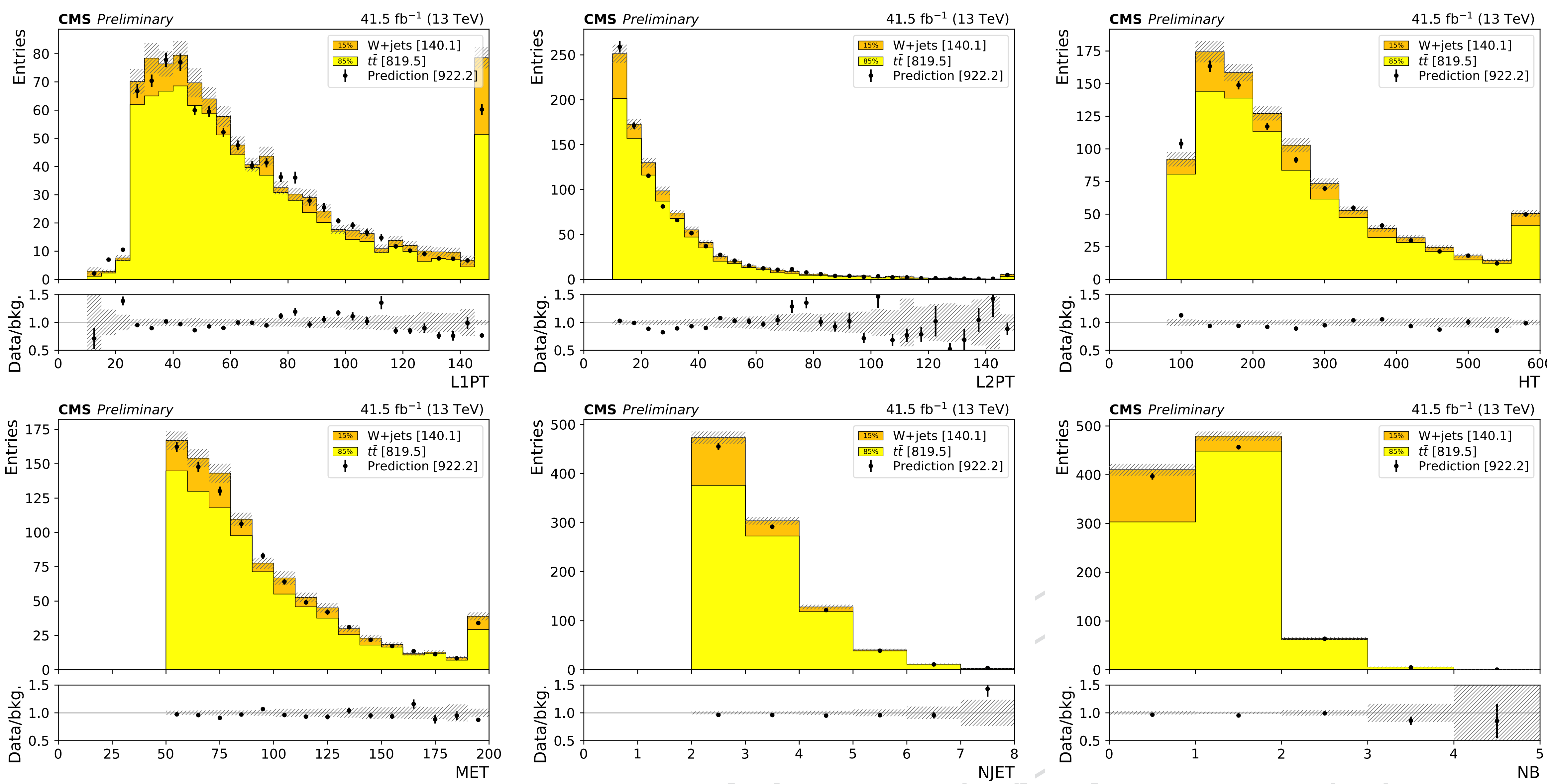


Figure 33: Predicted and observed lepton p_{T} (left) and η (middle) and $m_{\ell\ell}$ (right) in a same-sign Z→ee peak for years 2016, 2017, and 2018 from top to bottom. The prediction is normalized to the observed data.

Fake rate closure

- 2017 MC



Leptons (ID)

- *Electrons* [$|\eta| < 2.5$]
  - Tight p_T, η-dependent MVA
  - dz, dxy, sip3D(=IP3D/σ_{IP3D}) cuts
- *Muons* [$|\eta| < 2.4$]
  - Muon POG: medium muon ID
  - dz, dxy, sip3D cuts
  - $dp_T/p_T<0.2$

Table 9: Summary of the lepton selection. (all years)

variable	muons loose	muons fakable	muons tight	electrons loose	electrons fakable	electrons tight
identification	loose ID	medium ID	medium ID	loose WP	loose WP	tight WP
isolation	loose WP	loose WP	μ WP	loose WP	loose WP	e WP
HLT emulation	–	–	–	–	×	×
$\|d_0\|$ (cm)	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
$\|d_z$ (cm)	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
SIP_{3D}	–	< 4	< 4	–	< 4	< 4
missing inner hits	–	–	–	≤ 1	$= 0$	$= 0$
conversion veto	–	–	–	×	×	×
tight charge	-	×	×	-	×	×

Table 5: Lower cut on the electron MVA discriminant for the various electron ID used in this analysis.

2016

pseudorapidity region	momentum [GeV]	loose WP (non iso trigger)	loose WP (iso trigger)	tight WP
$0 < \|\eta\| < 0.8$	$5 < p_T < 10$	-0.30	-0.46	N/A
$0 < \|\eta\| < 0.8$	$10 < p_T < 15$	-0.86	-0.48	0.77
$0 < \|\eta\| < 0.8$	$p_T > 25$	-0.96	-0.85	0.52
$0.8 < \|\eta\| < 1.479$	$5 < p_T < 10$	-0.36	-0.03	N/A
$0.8 < \|\eta\| < 1.479$	$10 < p_T < 15$	-0.85	-0.67	0.56
$0.8 < \|\eta\| < 1.479$	$p_T > 25$	-0.96	-0.91	0.11
$1.479 < \|\eta\| < 2.5$	$5 < p_T < 10$	-0.63	0.06	N/A
$1.479 < \|\eta\| < 2.5$	$10 < p_T < 15$	-0.81	-0.49	0.48
$1.479 < \|\eta\| < 2.5$	$p_T > 25$	-0.95	-0.83	-0.01

2017

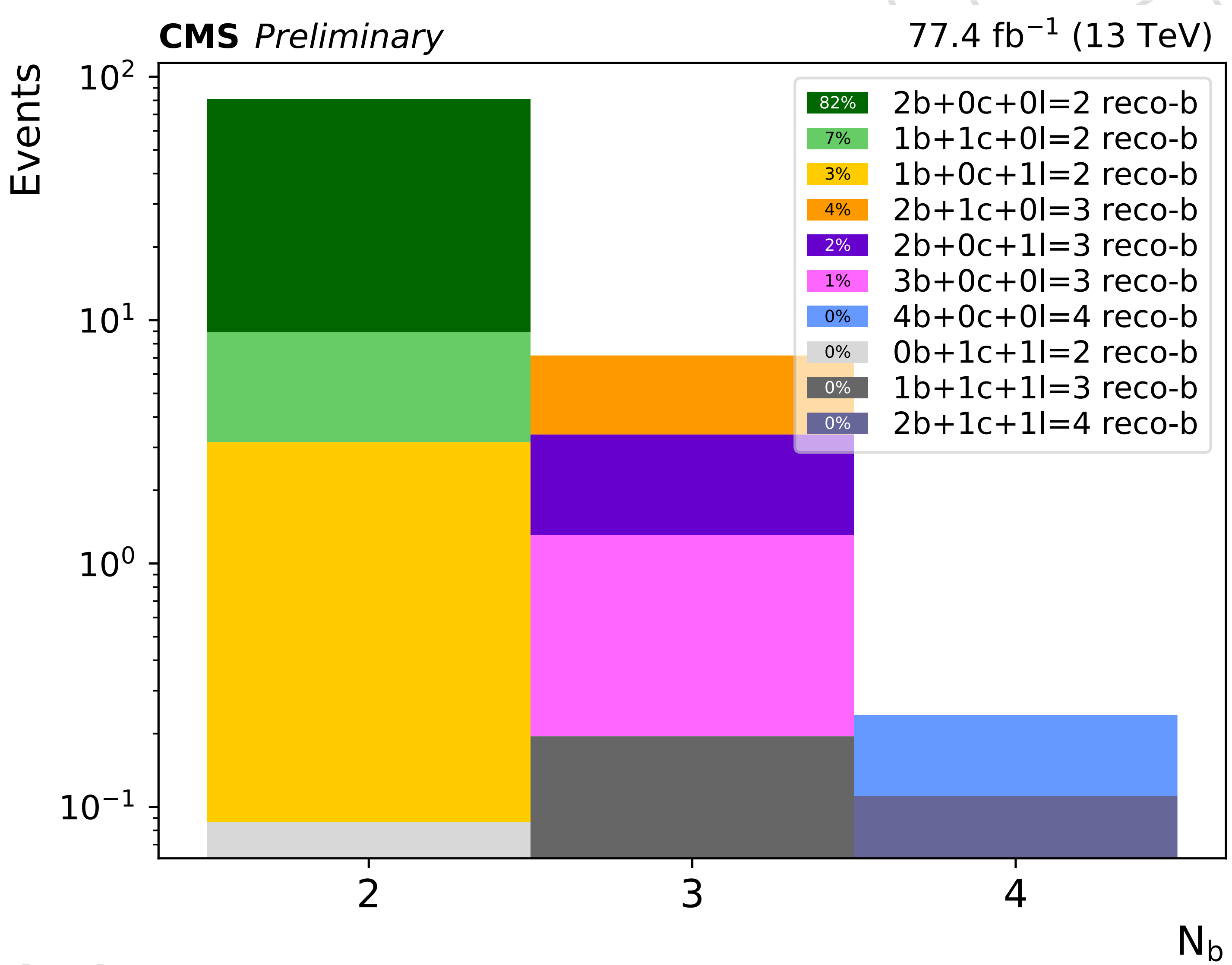
pseudorapidity region	momentum [GeV]	loose WP (non iso trigger)	loose WP (iso trigger)	tight WP
$0 < \|\eta\| < 0.8$	$5 < p_T < 10$	-0.135	0.488	N/A
$0 < \|\eta\| < 0.8$	$10 < p_T < 25$	$-0.930 + \frac{0.043}{15}\times(p_T\text{-}10)$	$-0.788 + \frac{0.148}{15}\times(p_T\text{-}10)$	$0.2 + 0.032\times(p_T\text{-}10)$
$0 < \|\eta\| < 0.8$	$p_T > 25$	-0.887	-0.64	0.68
$0.8 < \|\eta\| < 1.479$	$5 < p_T < 10$	-0.417	-0.045	N/A
$0.8 < \|\eta\| < 1.479$	$10 < p_T < 25$	$-0.930 + \frac{0.04}{15}\times(p_T\text{-}10)$	$-0.850 + \frac{0.075}{15}\times(p_T\text{-}10)$	$0.1 + 0.025\times(p_T\text{-}10)$
$0.8 < \|\eta\| < 1.479$	$p_T > 25$	-0.890	-0.775	0.475
$1.479 < \|\eta\| < 2.5$	$5 < p_T < 10$	-0.470	0.176	N/A
$1.479 < \|\eta\| < 2.5$	$10 < p_T < 25$	$-0.942 + \frac{0.032}{15}\times(p_T\text{-}10)$	$-0.810 + \frac{0.077}{15}\times(p_T\text{-}10)$	$-0.1 + 0.028\times(p_T\text{-}10)$
$1.479 < \|\eta\| < 2.5$	$p_T > 25$	-0.910	-0.733	0.320

2018

pseudorapidity region	momentum [GeV]	loose WP (non iso trigger)	loose WP (iso trigger)	tight WP
$0 < \|\eta\| < 0.8$	$5 < p_T < 10$	0.053	1.320	N/A
$0 < \|\eta\| < 0.8$	$10 < p_T < 25$	$-0.106 + 0.062\times(p_T\text{-}25)$	$1.204 + 0.066\times(p_T\text{-}25)$	$4.277 + 0.112\times(p_T\text{-}25)$
$0 < \|\eta\| < 0.8$	$p_T > 25$	-0.106	1.204	4.277
$0.8 < \|\eta\| < 1.479$	$5 < p_T < 10$	-0.434	0.192	N/A
$0.8 < \|\eta\| < 1.479$	$10 < p_T < 25$	$-0.769 + 0.038\times(p_T\text{-}25)$	$0.084 + 0.033\times(p_T\text{-}25)$	$3.152 + 0.060\times(p_T\text{-}25)$
$0.8 < \|\eta\| < 1.479$	$p_T > 25$	-0.769	0.084	3.152
$1.479 < \|\eta\| < 2.5$	$5 < p_T < 10$	-0.956	0.362	N/A
$1.479 < \|\eta\| < 2.5$	$10 < p_T < 25$	$-1.461 + 0.042\times(p_T\text{-}25)$	$-0.123 + 0.053\times(p_T\text{-}25)$	$2.359 + 0.087\times(p_T\text{-}25)$
$1.479 < \|\eta\| < 2.5$	$p_T > 25$	-1.461	-0.123	2.359

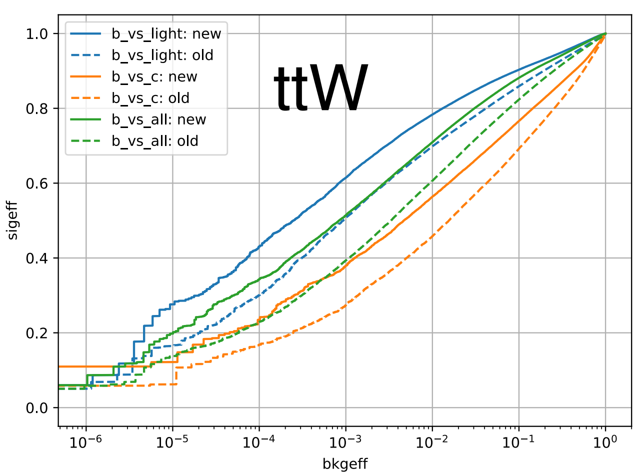
B-tag composition of $t\bar{t}W$

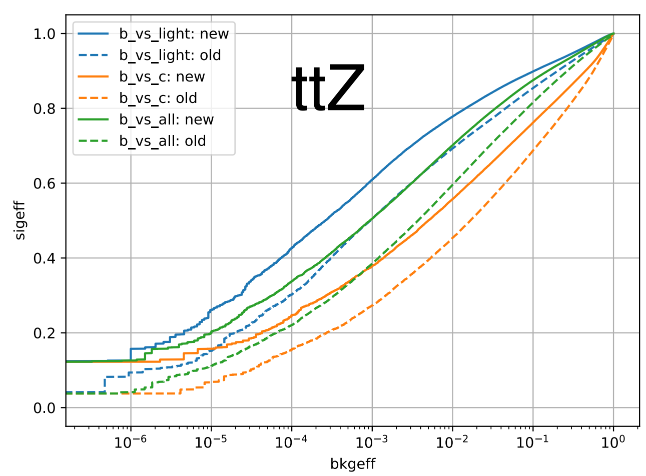
- Truth-level b-tag composition of $t\bar{t}W$ events passing the baseline selection for 2016+2017 MC (unweighted events) shows that the
  - 3 reco-btag bin is dominated by charm mistags
  - 4 reco-btag bin is dominated by 4 true b-jets ($t\bar{t}$+(gluon→$b\bar{b}$))

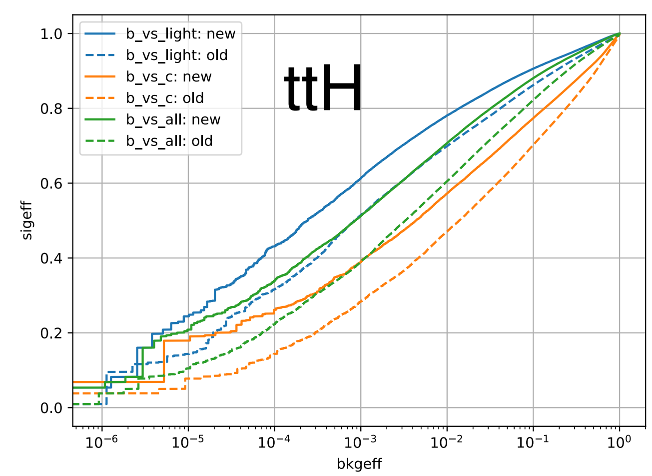


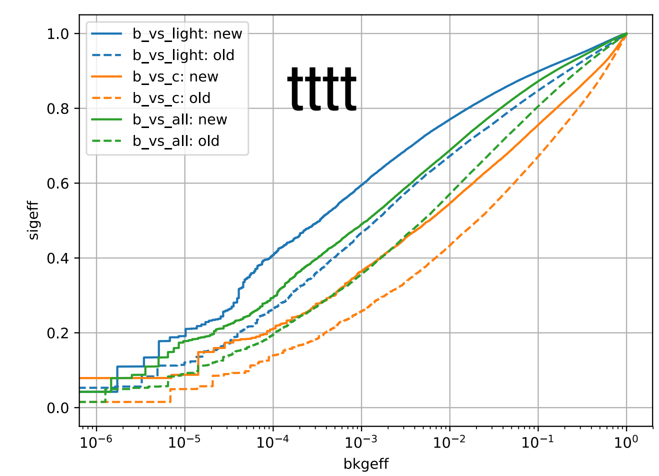
DeepCSV vs DeepFlavour

- DeepFlavour exists in 102X MC and can be re-run by the user on 94X MC (WPs,SFs exist for 2017 MC)
- ROC curves below for signal and main bgs
- Charm mistag eff. relatively increases by ~20% from DeepCSV to DeepFlavour
- Explore using tighter WP on next slide
    - But bottom line is that medium WP increases backgrounds too much (charm mistags), but tight WP loses too much signal efficiency to warrant usage









which	WP	old sig	new sig	old bkg	new bkg
b_vs_light	L	86.67	91.12	**11.28**	12.03
b_vs_light	M	71.16	80.54	1.20	1.45
b_vs_light	T	53.75	64.03	**0.14**	0.13
b_vs_c	L	86.67	91.12	43.74	49.03
b_vs_c	M	71.16	80.54	11.93	15.39
b_vs_c	T	53.75	64.03	2.23	2.46
b_vs_all	L	86.67	91.12	16.61	16.93
b_vs_all	M	71.16	80.54	2.96	3.30
b_vs_all	T	53.75	64.03	0.48	0.44

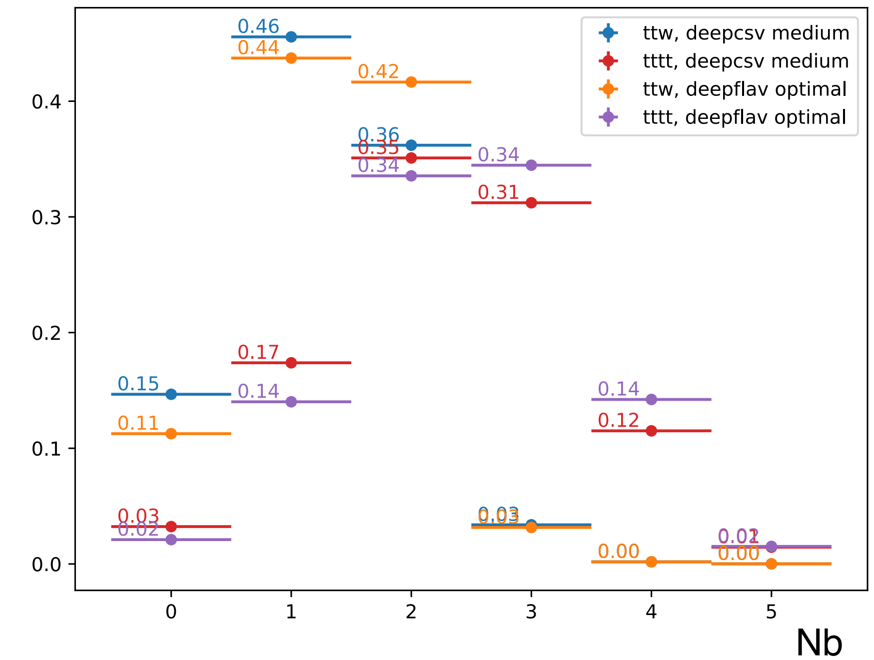
which	WP	old sig	new sig	old bkg	new bkg
b_vs_light	L	86.56	91.02	**11.87**	12.99
b_vs_light	M	71.03	80.28	1.27	1.52
b_vs_light	T	53.52	63.63	**0.14**	0.14
b_vs_c	L	86.56	91.02	44.47	49.64
b_vs_c	M	71.03	80.28	12.26	15.70
b_vs_c	T	53.52	63.63	2.39	2.47
b_vs_all	L	86.56	91.02	17.62	18.20
b_vs_all	M	71.03	80.28	3.20	3.54
b_vs_all	T	53.52	63.63	0.54	0.47

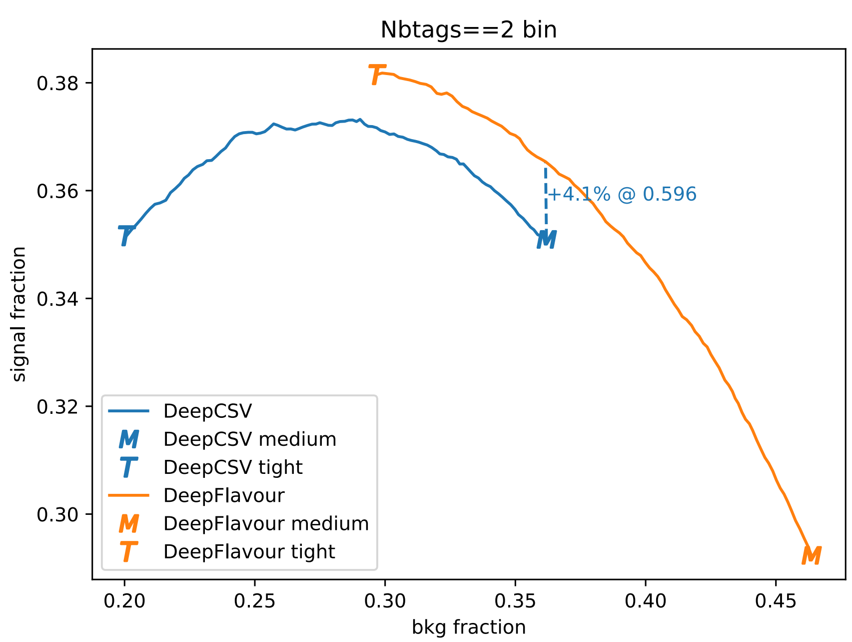
which	WP	old sig	new sig	old bkg	new bkg
b_vs_light	L	87.58	91.91	**12.28**	13.44
b_vs_light	M	72.49	81.53	1.43	1.80
b_vs_light	T	55.07	65.03	**0.15**	0.15
b_vs_c	L	87.58	91.91	44.64	49.92
b_vs_c	M	72.49	81.53	12.28	16.06
b_vs_c	T	55.07	65.03	2.34	2.49
b_vs_all	L	87.58	91.91	18.34	18.96
b_vs_all	M	72.49	81.53	3.46	3.96
b_vs_all	T	55.07	65.03	0.56	0.51

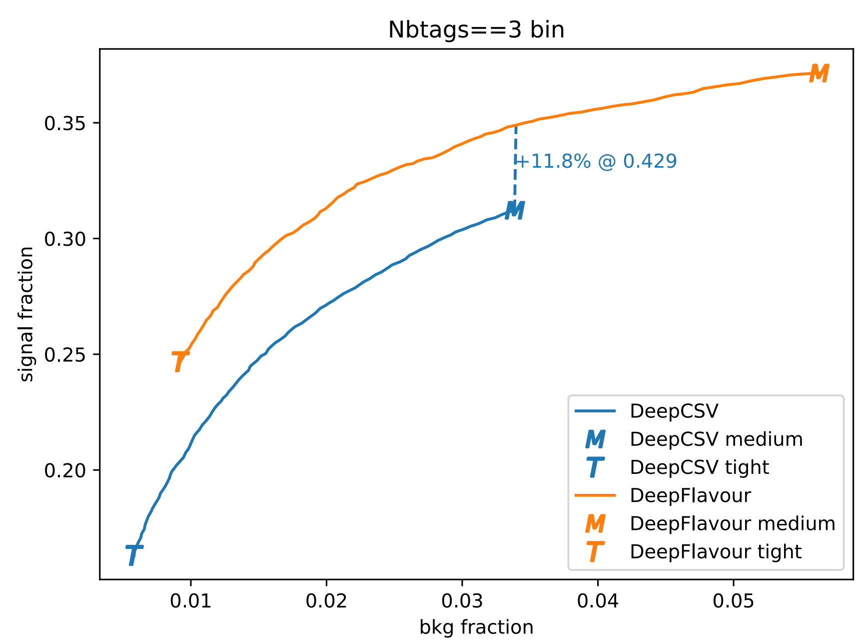
which	WP	old sig	new sig	old bkg	new bkg
b_vs_light	L	86.04	91.03	**12.02**	12.96
b_vs_light	M	69.58	80.01	1.33	1.60
b_vs_light	T	51.19	62.98	**0.16**	0.15
b_vs_c	L	86.04	91.03	44.30	50.21
b_vs_c	M	69.58	80.01	12.31	16.03
b_vs_c	T	51.19	62.98	2.32	2.54
b_vs_all	L	86.04	91.03	17.95	18.51
b_vs_all	M	69.58	80.01	3.35	3.75
b_vs_all	T	51.19	62.98	0.56	0.51

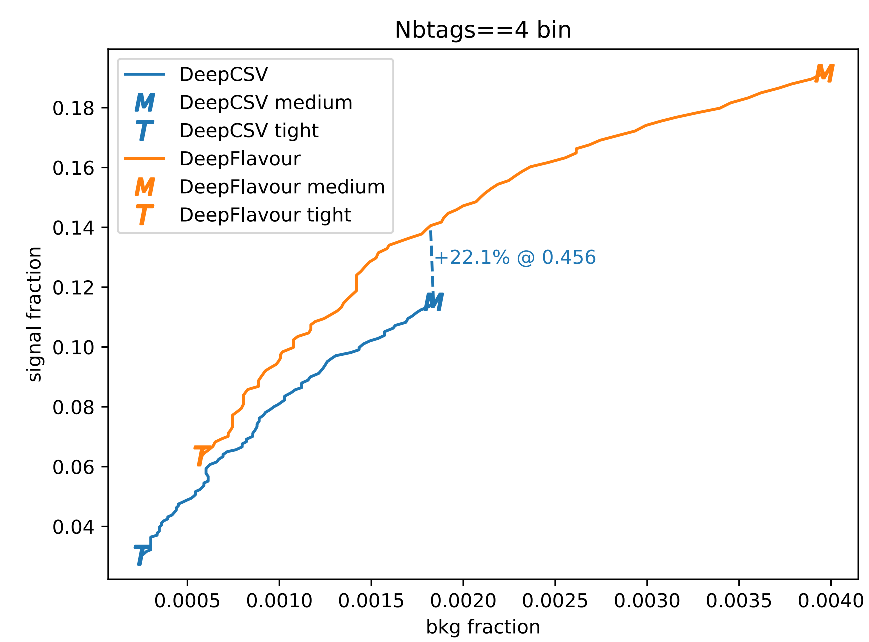
DeepFlavour M→T WP

- Below are plots of signal/background fraction (wrt baseline selection with relaxed Nb≥0) moving along discriminator cut values from medium to tight, separately for Nb==2,3,4 bins
  - **Note, background is just ttW**
- **Moving from medium DeepCSV WP to medium DeepFlavour increases signal efficiency at the cost of big background increases (compare orange M with blue M)**
- The tight WP for DeepFlavour loses quite a bit of signal efficiency to warrant going from DeepCSV M→DeepFlavour T
- Try to find DeepFlavour cut value that maintains DeepCSV background efficiency and write the relative signal efficiency gain. For Nb==3/4, cut values around 0.43/0.46 give 12/22% relative signal efficiency gain for the same bkg eff.
- Now using 0.45 as the cut value for DeepFlavour and make ttW/ttttt Nb distributions on the right — orange and blue match in Nb==3/4 bins by construction



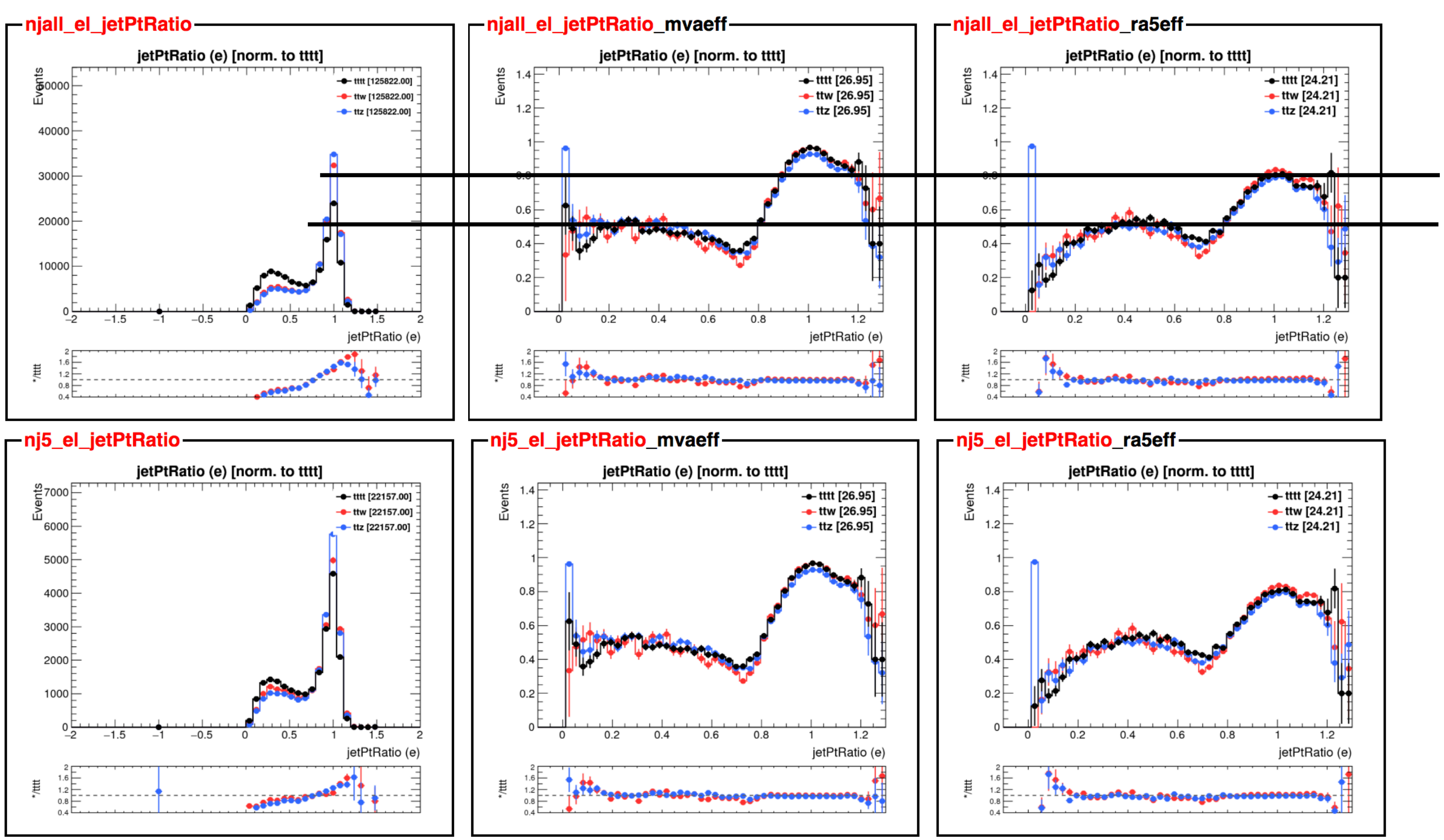






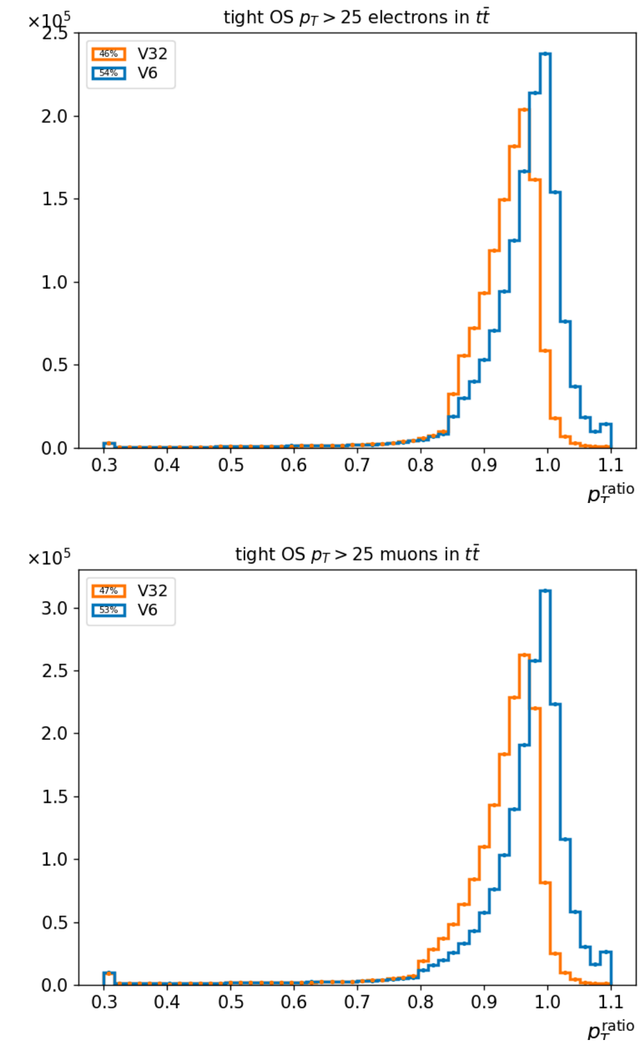
LeptonMVA

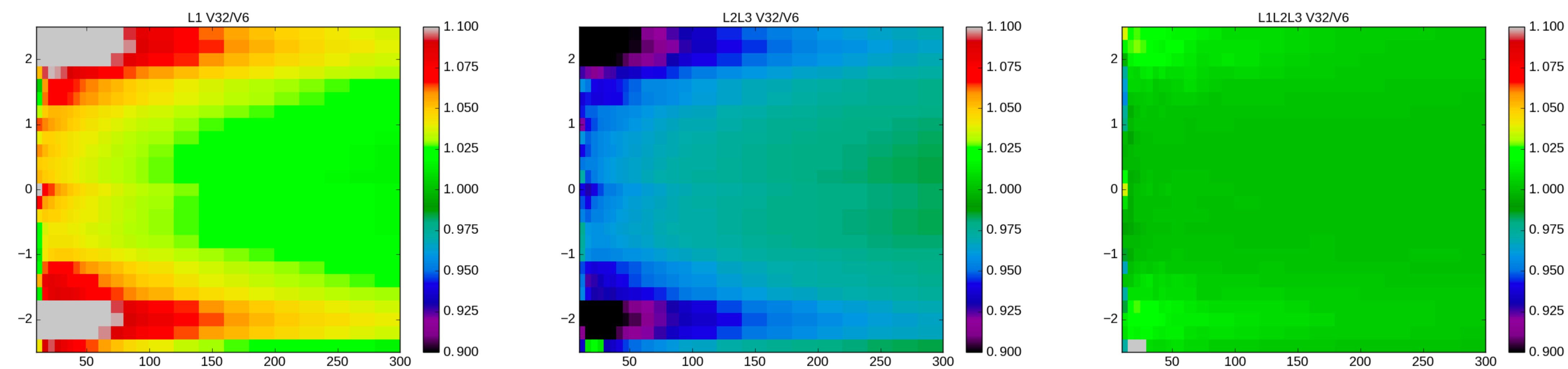
- Why does the $t\bar{t}V$ analysis see more gain than $t\bar{t}t\bar{t}$ when going from nominal→leptonMVA
- Plot efficiency of LeptonMVA and nominal selection vs jet pTratio
- LeptonMVA has higher efficiency overall coming from the good leptons in the peak at jet pt ratio ~ 1, whereas it still only matches the efficiency of RA5 in the secondary peak since RA5 uses an OR of high pTratio, high pTrel
    - This would cause tttt to suffer more/gain less than less busy events like ttV



New JEC for 2017

- Going from old to new recommendation in 2017 JECs (V6→V10), $t\bar{t}t\bar{t}$ signal efficiency suffers by nearly 10% (HyperNews)
  - Due to large shifts in pTratio, pTrel variables (**right**), which are constituents of the multi-isolation selection
  - Shifts induced by L1 and L2L3 increase and decrease in V32 with respect to V6 — ratios for L1, L2L3, L1L2L3 (**below**)
  - L1L2L3 is nearly identical between the two versions
- Current practical solution is to re-derive multi-iso WPs → in progress





Analysis changes for Run2

- More data — $35.9 fb^{-1} \rightarrow 136.3 fb^{-1}$ (35.9+41.5+58.3)
  - Finer binning of signal regions
- Latest NLO cross-section of 11.97fb (compared to 9.2fb before)
- Explored event-level BDT in addition to cut-based
- Fake background
  - Lepton isolation WP re-tuning starting in 2017 to deal with increased fakes
  - Template fit for better normalization in electroweak subtraction

Analysis changes for Run2

- Investigated, but did not pursue, a few other possible changes
  - Top-tagging (resolved/merged)
  - LeptonMVA (performance degradation compared to multi-iso approach)
  - Hadronically-decaying tau leptons (fake background significantly larger)
  - Jet, b-tagged jet, lepton p_T thresholds (negligible impact)
  - DeepFlavour (larger background from increased charm mistag efficiency)

ttbb/ttjj

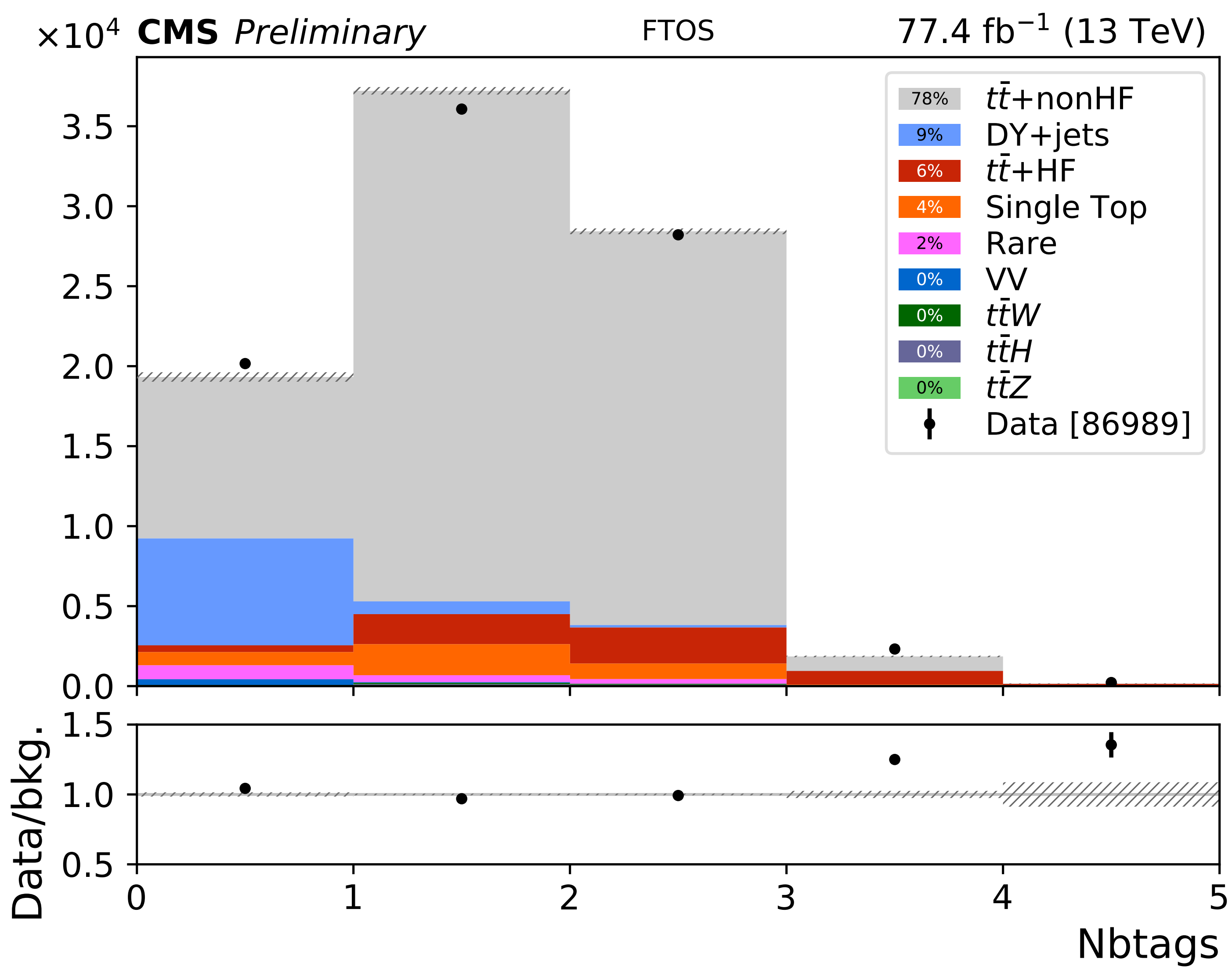
After accounting for all corrections and systematic effects, the cross section ratio $\sigma_{t\bar{t}b\bar{b}}/\sigma_{t\bar{t}jj}$ is measured in the visible phase space from a fit to the measured CSV b tagging discriminator distributions. The measured cross section ratio in the visible phase space for events with particle-level jets is

$$(\sigma_{t\bar{t}b\bar{b}}/\sigma_{t\bar{t}jj})^{\text{vis}} = 0.024 \pm 0.003\,(\text{stat}) \pm 0.007\,(\text{syst}). \quad (3)$$

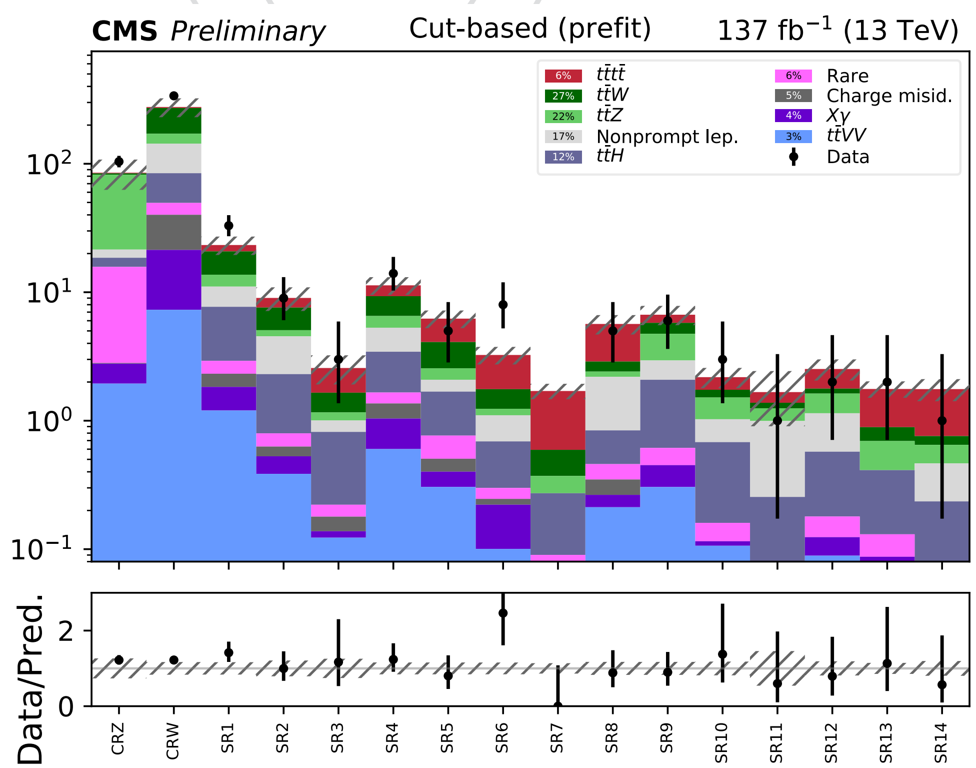
The predicted values from POWHEG are 0.014 ± 0.001 and 0.012 ± 0.001 for the visible and full phase space, respectively, where the uncertainty in the simulation is the sum in quadrature of the statistical, and the μ_F/μ_R scale systematic uncertainties. The prediction obtained from POWHEG simulation (interfaced with PYTHIA) underpredicts the measured cross section ratio by a factor of 1.8, but it is compatible with the observation within two standard deviations. The measured cross sections in the visible and the full phase space are presented in Table 3.

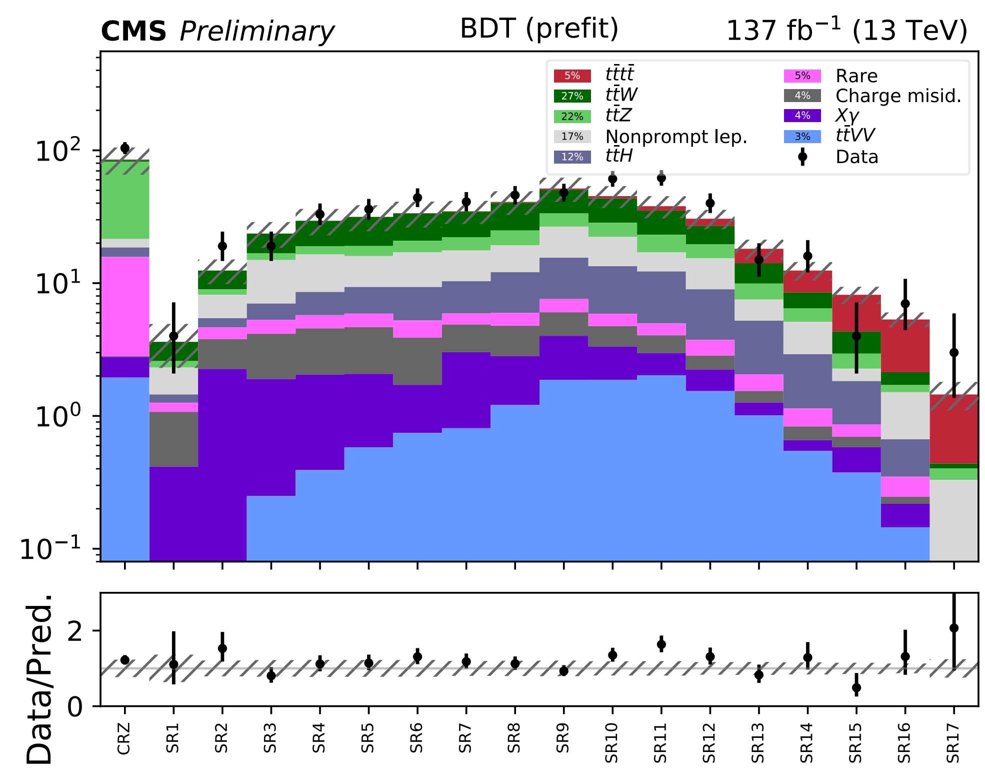
$t\bar{t}$+HF correction

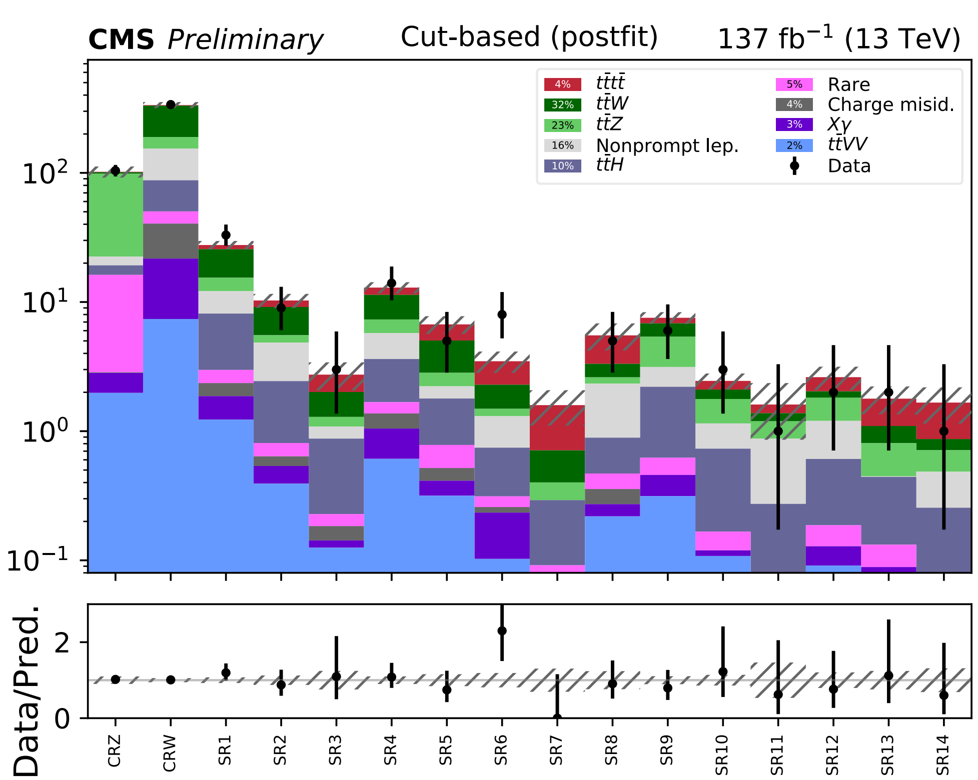
- Separate $t\bar{t}$+HF if there is a b not from a top
- Would need to scale this contribution by ~50% to account for the ratio in N_b=3 bin
- No $t\bar{t}b\bar{b}/t\bar{t}jj$ correction of 1.7 here

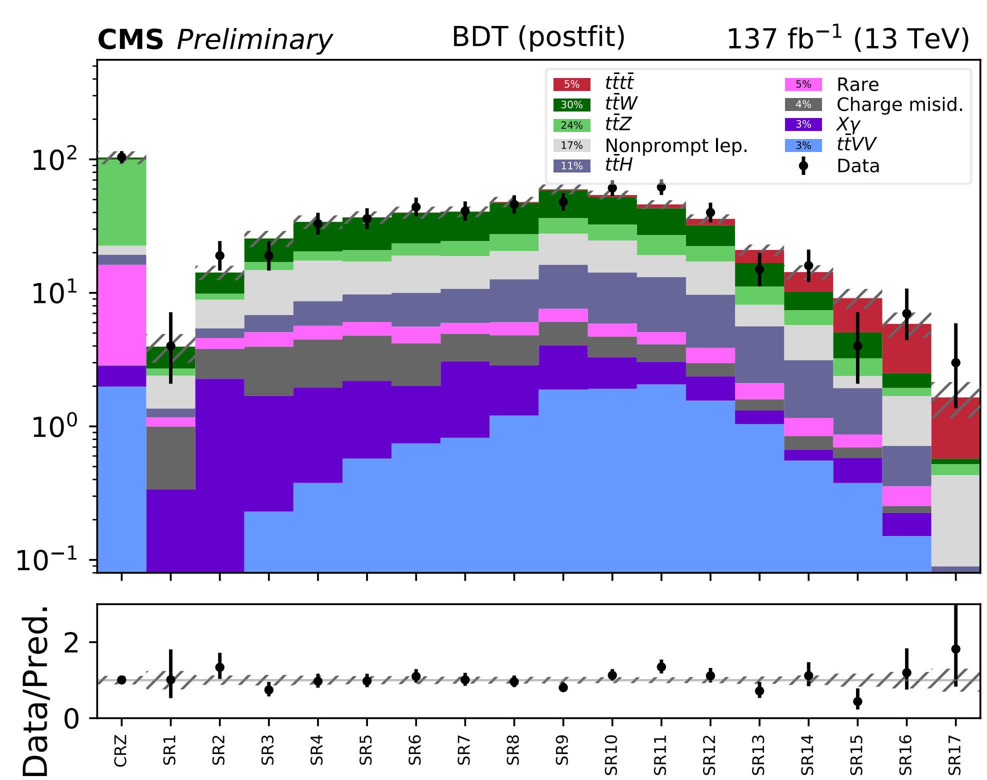


Prefit (top) and postfit (bottom)









Postfit tables

Table 26: Postfit event yields in SR+CR regions for 2016+2017+2018.

	$t\bar{t}W$	$t\bar{t}Z$	$t\bar{t}H$	$t\bar{t}VV$	X+γ	Rares	Charge misid.	Nonprompt lep.	SM expected	Data	$t\bar{t}t\bar{t}$
CRZ	2.72± 0.56	75.98±10.55	3.00± 0.67	1.98± 0.24	0.85± 0.37	13.37± 2.24	0.03± 0.00	3.24± 1.03	101.17±10.12	104	0.83± 0.50
CRW	142.09±27.80	34.87± 4.83	37.34± 8.06	7.39± 0.83	14.30± 1.78	9.82± 1.74	18.78± 2.53	66.65±19.91	331.25±18.64	338	3.86± 2.30
SR1	10.23± 2.19	3.29± 0.47	5.16± 1.17	1.23± 0.15	0.64± 0.13	0.62± 0.12	0.49± 0.07	3.99± 1.61	25.65± 2.11	33	1.97± 1.19
SR2	3.62± 0.88	0.69± 0.23	1.63± 0.41	0.39± 0.06	0.15± 0.05	0.17± 0.04	0.10± 0.01	2.40± 1.04	9.15± 1.27	9	1.12± 0.65
SR3	0.72± 0.34	0.20± 0.10	0.65± 0.20	0.13± 0.02	0.02± 0.02	0.04± 0.01	0.04± 0.01	0.21± 0.17	2.01± 0.59	3	0.73± 0.42
SR4	4.03± 0.99	1.58± 0.34	1.94± 0.46	0.61± 0.07	0.44± 0.13	0.31± 0.06	0.32± 0.04	2.13± 0.84	11.36± 1.33	14	1.57± 0.91
SR5	2.21± 0.60	0.61± 0.13	1.01± 0.27	0.32± 0.04	0.10± 0.04	0.26± 0.05	0.10± 0.02	0.44± 0.27	5.04± 0.80	5	1.67± 0.96
SR6	0.80± 0.22	0.18± 0.09	0.43± 0.13	0.10± 0.02	0.13± 0.04	0.05± 0.01	0.02± 0.00	0.56± 0.29	2.29± 0.41	8	1.19± 0.68
SR7	0.31± 0.12	0.12± 0.04	0.20± 0.06	0.04± 0.01	0.01± 0.01	0.03± 0.01	0.01± 0.00	0.00± 0.08	0.71± 0.21	0	0.88± 0.48
SR8	0.71± 0.34	0.28± 0.11	0.42± 0.15	0.22± 0.03	0.05± 0.02	0.11± 0.02	0.08± 0.01	1.44± 0.81	3.32± 0.97	5	2.20± 1.28
SR9	1.46± 0.42	2.24± 0.34	1.58± 0.35	0.31± 0.05	0.14± 0.02	0.16± 0.09	0.00± 0.00	0.94± 0.46	6.84± 0.80	6	0.70± 0.39
SR10	0.33± 0.11	0.63± 0.14	0.57± 0.14	0.11± 0.02	0.01± 0.01	0.05± 0.01	0.00± 0.00	0.42± 0.26	2.10± 0.31	3	0.35± 0.22
SR11	0.19± 0.07	0.32± 0.07	0.20± 0.05	0.04± 0.01	0.01± 0.01	0.02± 0.01	0.00± 0.00	0.60± 0.72	1.38± 0.75	1	0.23± 0.14
SR12	0.22± 0.10	0.61± 0.12	0.42± 0.10	0.09± 0.01	0.04± 0.01	0.06± 0.01	0.00± 0.00	0.59± 0.39	2.04± 0.48	2	0.58± 0.34
SR13	0.29± 0.12	0.36± 0.12	0.31± 0.09	0.07± 0.01	0.02± 0.01	0.04± 0.01	0.00± 0.00	0.00± 0.11	1.10± 0.30	2	0.69± 0.40
SR14	0.16± 0.05	0.23± 0.07	0.18± 0.06	0.04± 0.01	0.00± 0.00	0.03± 0.01	0.00± 0.00	0.23± 0.27	0.87± 0.30	1	0.80± 0.45

Table 27: Postfit event yields in BDT regions for 2016+2017+2018.

	$t\bar{t}W$	$t\bar{t}Z$	$t\bar{t}H$	$t\bar{t}VV$	X+γ	Rares	Charge misid.	Nonprompt lep.	SM expected	Data	$t\bar{t}t\bar{t}$
CRZ	2.51± 0.54	77.26±11.72	3.09± 0.64	1.99± 0.21	0.85± 0.35	13.33± 2.56	0.03± 0.00	3.23± 1.19	102.28±11.59	104	1.11± 0.43
SR1	1.25± 0.49	0.31± 0.10	0.19± 0.10	0.02± 0.01	0.32± 0.25	0.17± 0.19	0.66± 0.07	1.04± 0.64	3.95± 0.96	4	0.00± 0.00
SR2	4.35± 1.28	0.97± 0.32	0.83± 0.29	0.08± 0.02	2.20± 0.54	0.79± 0.23	1.53± 0.17	3.46± 1.45	14.19± 1.76	19	0.01± 0.01
SR3	8.53± 2.40	2.17± 0.50	1.75± 0.53	0.23± 0.05	1.46± 0.47	1.12± 0.38	2.26± 0.26	8.01± 2.77	25.53± 3.53	19	0.04± 0.03
SR4	13.52± 3.37	3.04± 0.68	3.00± 0.76	0.38± 0.08	1.57± 0.51	1.19± 0.40	2.52± 0.29	8.74± 3.08	33.96± 4.01	33	0.08± 0.05
SR5	15.80± 3.68	3.73± 0.93	3.68± 0.92	0.57± 0.08	1.61± 0.49	1.27± 0.46	2.59± 0.29	7.41± 2.62	36.67± 3.97	36	0.15± 0.07
SR6	16.33± 3.87	4.50± 0.99	4.41± 1.03	0.75± 0.08	1.26± 0.69	1.40± 0.33	2.18± 0.25	8.99± 3.45	39.81± 4.16	44	0.23± 0.12
SR7	15.96± 3.61	5.53± 1.27	4.75± 1.10	0.82± 0.12	2.25± 0.31	1.03± 0.26	1.86± 0.21	8.12± 3.06	40.32± 3.73	41	0.31± 0.16
SR8	19.81± 4.39	6.88± 1.74	6.61± 1.47	1.21± 0.14	1.65± 0.32	1.21± 0.34	1.95± 0.22	7.96± 2.81	47.29± 4.33	46	0.71± 0.28
SR9	22.23± 4.95	8.56± 2.22	8.63± 1.89	1.88± 0.21	2.15± 0.30	1.53± 0.42	2.02± 0.24	11.50± 3.92	58.51± 5.22	48	1.17± 0.47
SR10	19.70± 4.29	7.79± 1.84	8.31± 1.78	1.91± 0.21	1.39± 0.37	1.18± 0.29	1.40± 0.16	10.48± 3.94	52.16± 4.28	61	1.91± 0.74
SR11	15.98± 3.69	7.82± 1.52	8.03± 1.73	2.06± 0.23	0.98± 0.17	0.97± 0.22	1.07± 0.12	6.10± 2.63	43.02± 3.54	62	2.97± 1.19
SR12	9.68± 2.25	5.30± 1.00	5.81± 1.25	1.56± 0.18	0.81± 0.21	0.89± 0.24	0.61± 0.07	7.46± 3.03	32.12± 3.06	40	3.72± 1.41
SR13	5.59± 1.37	3.02± 0.66	3.51± 0.77	1.04± 0.12	0.27± 0.05	0.51± 0.12	0.28± 0.03	2.52± 0.93	16.73± 1.65	15	4.23± 1.64
SR14	2.75± 0.78	1.67± 0.28	1.97± 0.47	0.56± 0.07	0.11± 0.07	0.31± 0.06	0.18± 0.02	2.60± 1.23	10.16± 1.26	16	4.15± 1.60
SR15	1.82± 0.58	0.85± 0.23	1.06± 0.26	0.38± 0.04	0.20± 0.10	0.17± 0.03	0.12± 0.01	0.45± 0.22	5.05± 0.82	4	4.07± 1.56
SR16	0.56± 0.25	0.26± 0.10	0.36± 0.12	0.15± 0.02	0.07± 0.04	0.10± 0.02	0.03± 0.00	0.97± 0.54	2.50± 0.63	7	3.35± 1.26
SR17	0.05± 0.04	0.09± 0.05	0.04± 0.02	0.02± 0.00	0.00± 0.00	0.02± 0.00	0.00± 0.00	0.34± 0.35	0.57± 0.36	3	1.08± 0.42

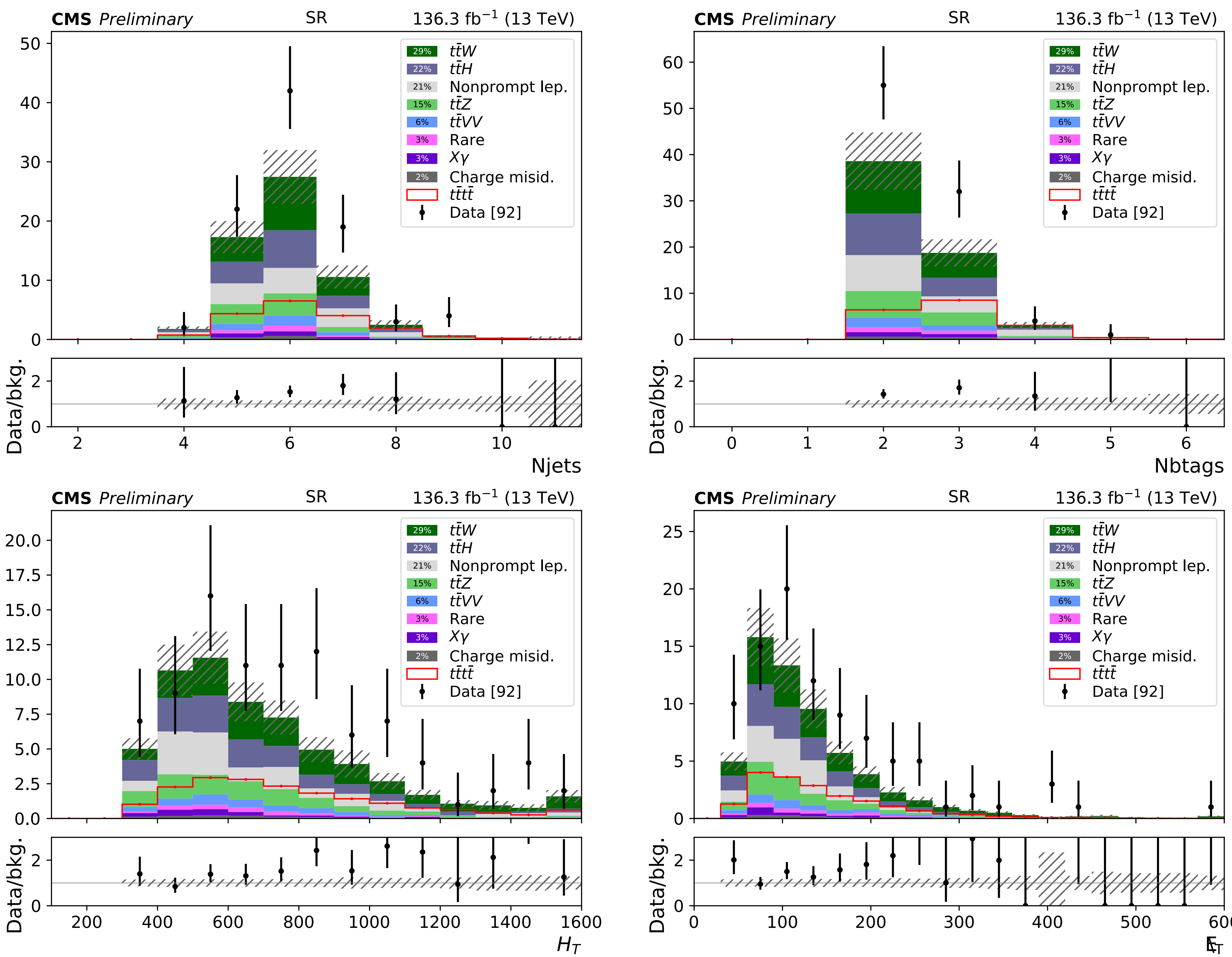
Frozen plots

Results: sum of cut-based regions

Kinematic plots used to introduce cut-based results

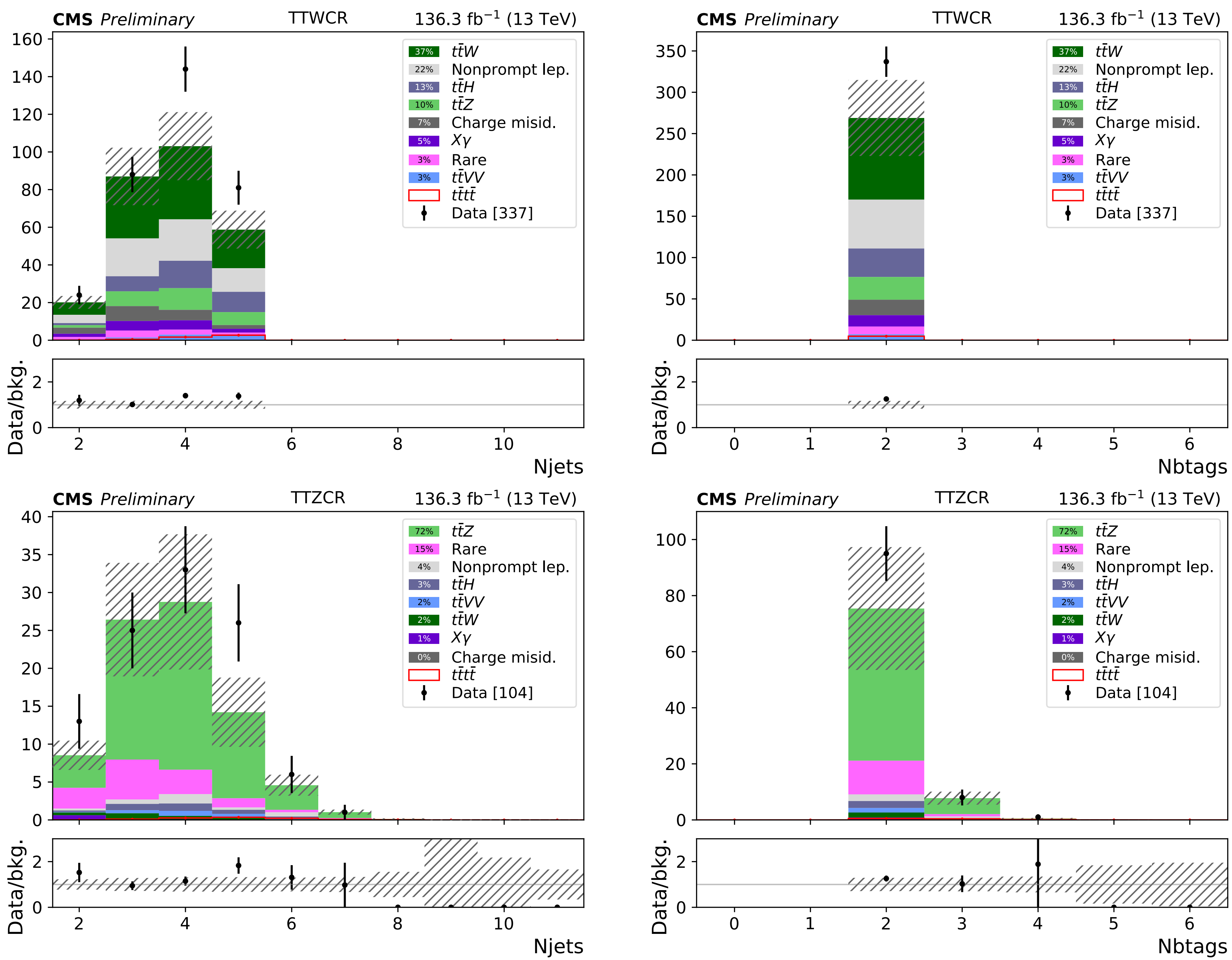
Pre-fit, stacked tttt with μ = 1 [was not stacked in frozen documentation]

Paper Figure 1



Results: ttW and ttZ control regions

- Control regions for **CRZ** and **CRW** below for full Run 2 luminosity show similar $t\bar{t}V$ scale factors to the 2016 analysis — roughly 1.3 for both ttZ and $t\bar{t}W$ (20% relative error from statistics), consistent with latest measurements



Paper Figure 2

Results: cut-based and BDT

Show post-fit signal region yields

Post/pre-fit scale factors are consistent between years and BDT/cut-based

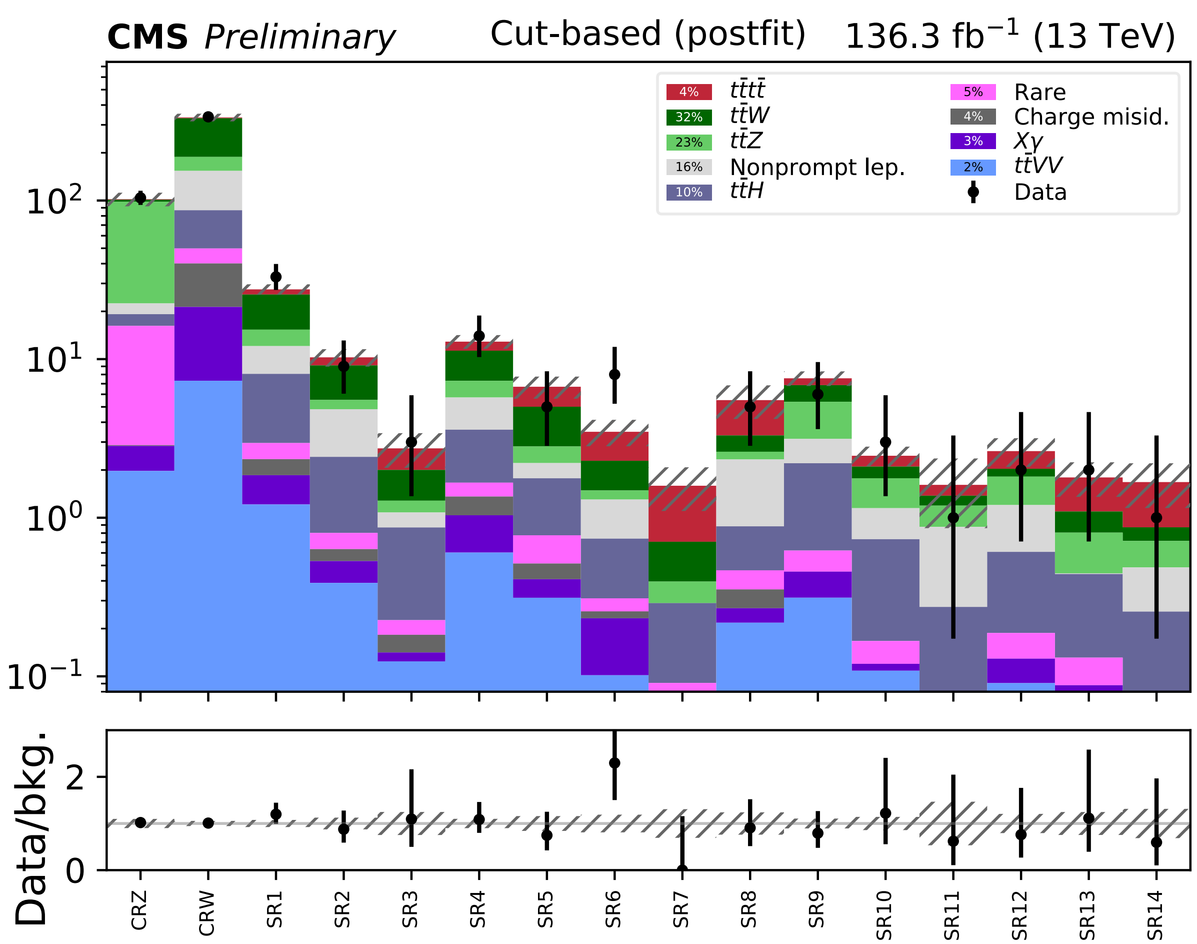
Fitted tttt signal strength close to 1

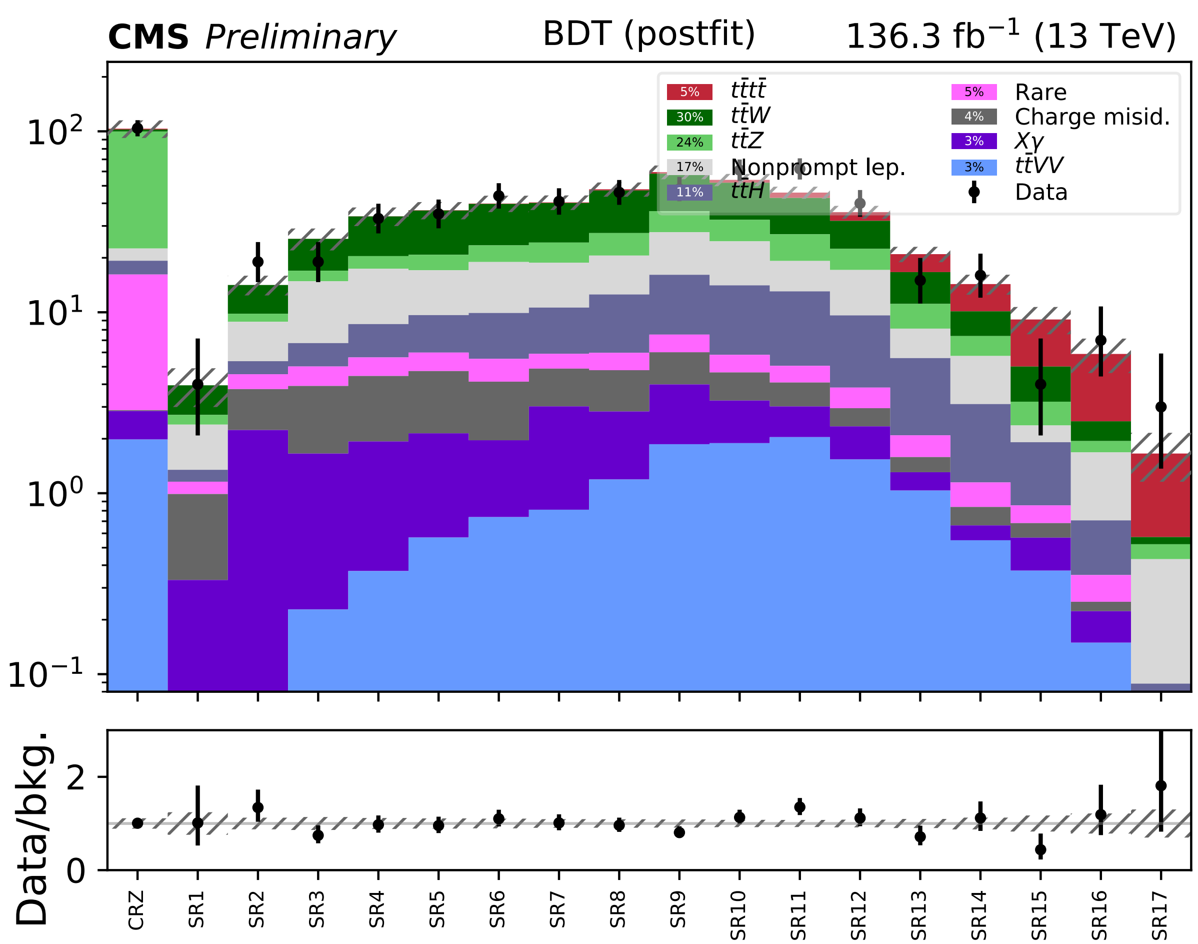
- cut-based: 0.781
- BDT: 1.069

Post-fit/pre-fit normalizations, BDT

process	SF (2016)	SF (2017)	SF (2018)	SF (Run2)
ttz	1.58	1.005	1.207	1.266
ttw	1.347	1.35	1.156	1.31
tth	1.087	1.089	1.045	1.094
tttt	1.175	0.845	1.451	1.076
fakes	1.064	1.163	1.081	1.133
xg	1.06	1.035	1.015	1.017
rares	1.055	1.017	1.023	1.02
ttvv	1.028	1.018	1.02	1.014
flips	1.016	1.007	0.999	1.001

Paper Figure 3





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fakes	1.064	1.163	1.081	1.133
xg	1.06	1.035	1.015	1.017
rares	1.055	1.017	1.023	1.02
ttvv	1.028	1.018	1.02	1.014
flips	1.016	1.007	0.999	1.001

Paper Table 3: cut-based yields

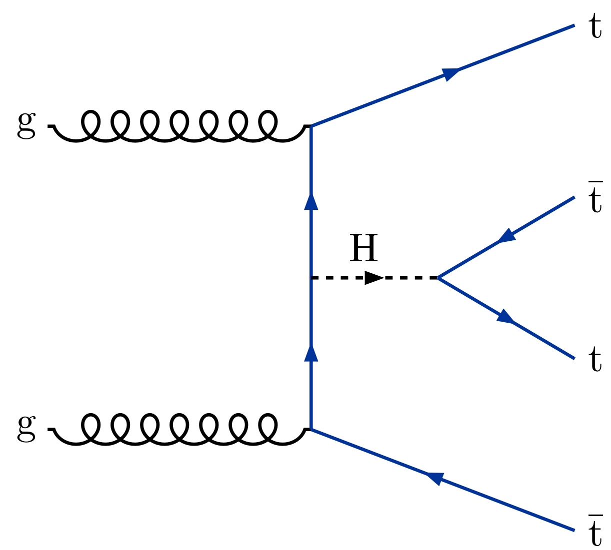
	SM background	Observed	$t\bar{t}t\bar{t}$
CRZ	102.30±11.59	104	1.12± 0.43
SR1	3.95± 0.95	4	0.00± 0.00
SR2	14.15± 1.77	19	0.01± 0.01
SR3	25.45± 3.53	19	0.04± 0.03
SR4	33.86± 4.00	33	0.08± 0.05
SR5	36.48± 4.00	35	0.15± 0.07
SR6	39.68± 4.14	44	0.23± 0.12
SR7	40.17± 3.72	41	0.32± 0.16
SR8	47.11± 4.34	46	0.72± 0.28
SR9	58.35± 5.27	48	1.18± 0.46
SR10	52.01± 4.30	61	1.92± 0.74
SR11	42.86± 3.51	62	3.00± 1.19
SR12	32.03± 3.07	40	3.76± 1.41
SR13	16.67± 1.62	15	4.28± 1.63
SR14	10.12± 1.25	16	4.19± 1.59
SR15	5.01± 0.77	4	4.11± 1.55
SR16	2.50± 0.61	7	3.39± 1.26
SR17	0.57± 0.36	3	1.08± 0.42

Paper Table 4: BDT yields

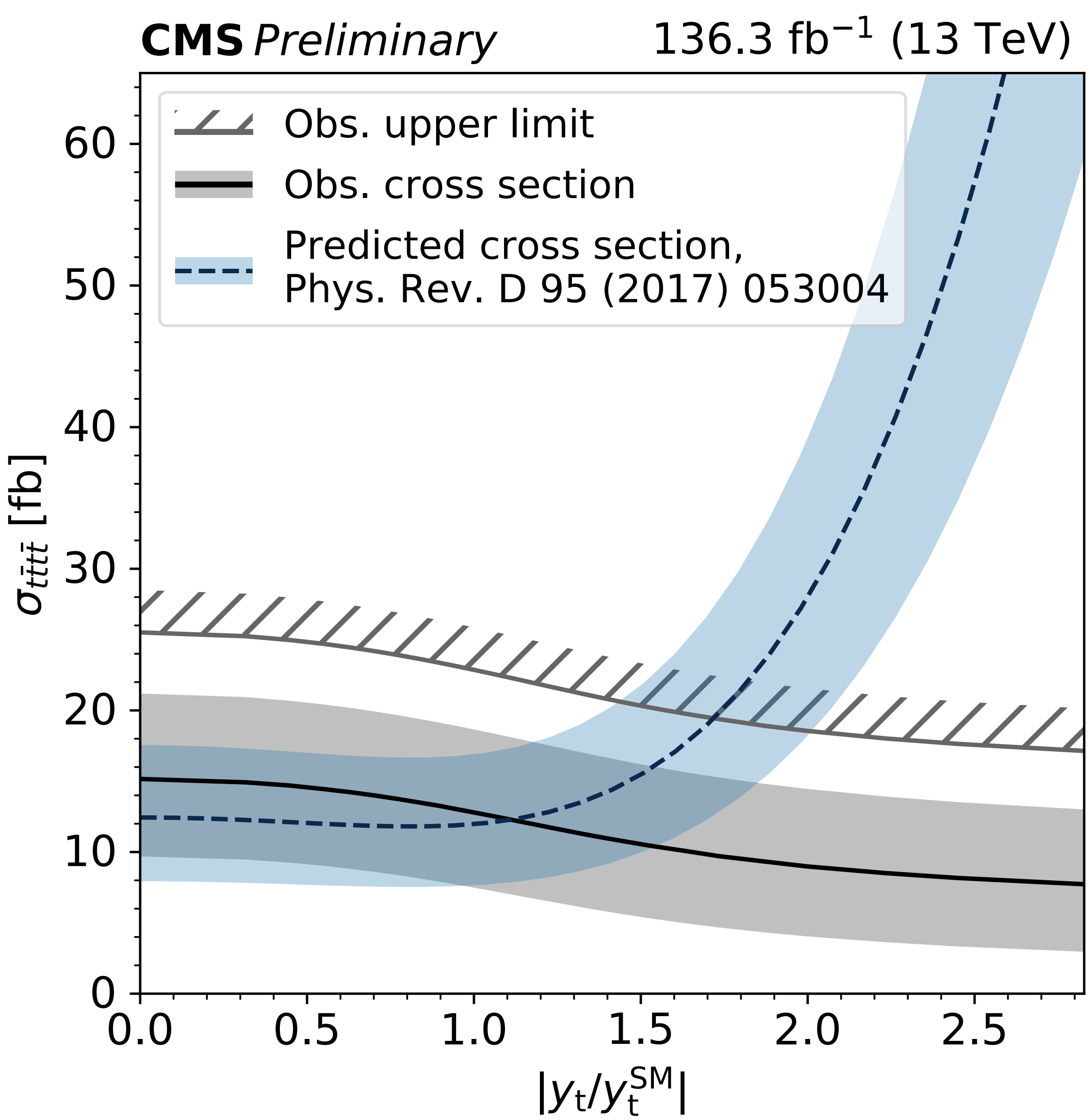
	SM background	Observed	$t\bar{t}t\bar{t}$
CRZ	101.14±10.08	104	0.84± 0.50
CRW	330.16±18.88	337	3.88± 2.28
SR1	25.55± 2.11	33	1.98± 1.18
SR2	9.13± 1.27	9	1.13± 0.65
SR3	2.00± 0.59	3	0.73± 0.42
SR4	11.30± 1.26	14	1.58± 0.90
SR5	5.01± 0.77	5	1.69± 0.95
SR6	2.29± 0.40	8	1.20± 0.67
SR7	0.71± 0.20	0	0.89± 0.48
SR8	3.30± 0.95	5	2.21± 1.27
SR9	6.85± 0.80	6	0.72± 0.39
SR10	2.10± 0.31	3	0.36± 0.22
SR11	1.38± 0.75	1	0.23± 0.14
SR12	2.04± 0.48	2	0.59± 0.34
SR13	1.10± 0.28	2	0.70± 0.40
SR14	0.87± 0.30	1	0.81± 0.45

Top yukawa interpretation

- Diagrams with virtual Higgs bosons make $\sigma(pp \rightarrow t\bar{t}t\bar{t})$ a function of y_t
- We interpret the cross-section measurement and upper limits as constraints on the top yukawa coupling constant
- Result: $|y_t/y_t^{SM}| < 1.7$ @ 95%CL [was 2.1 in 2016 analysis]

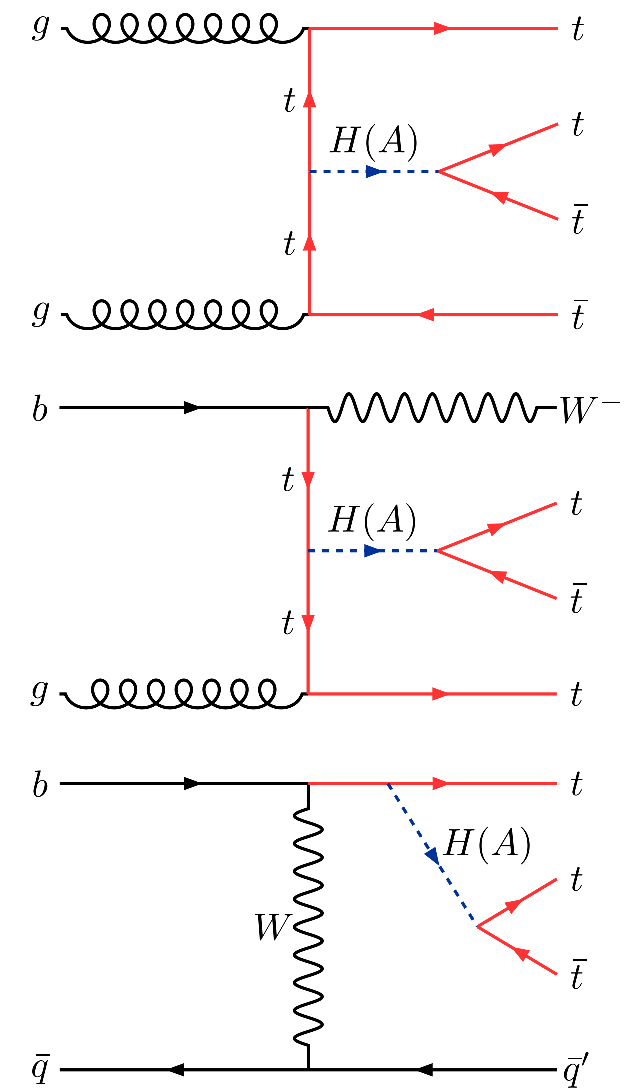


Paper Figure 4



2HDM interpretation

- Originally part of the same-sign SUSY analysis, but now in tttt
- Type-II 2HDM with associated production of a heavy scalar H and pseudoscalar A decaying into $t\bar{t}$ ($\tan\beta$~1), giving rise to final states with 3 and 4 top quarks
- Excellent final state for the $t\bar{t}t\bar{t}$ analysis
  - Exclusion gain of 70-100 GeV w.r.t. 2016 SUSY analysis



Paper Figure 5