Approval of HIG-18-019

Search for the associated production of a Higgs boson with a top quark pair in final states with electrons, muons and hadronically decaying τ leptons with data recorded at $\sqrt{s} = 13$ TeV in 2017

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On behalf of the ttH multilepton and tau-tau analysis group

Introduction

- Higgs boson production associated with a pair of top-anti top quarks
  - $t\bar{t}H$ provides the best sensitivity to probe Higgs-top Yukawa coupling y_t
- Focus on three Higgs decay modes
  - $H \rightarrow WW^*$
  - $H \rightarrow ZZ^*$ (except for $H \rightarrow ZZ^* \rightarrow 4\ell$)
  - $H \rightarrow \tau\tau$
- Data recorded in 2017 Runs B-F ($\mathcal{L} = 41.5\ \mathrm{fb}^{-1}$) + MC Fall17
- Overall strategy similar to 2016 analysis (HIG-17-018 paper)

Target: PAS for Higgs Coupling conference, on the way to legacy paper with full Run 2 dataset

PAS refers to tables and plots that we show in the PAS

NEW highlights the changes wrt 2016 analysis

Updates since pre-approval

- Updated lepton ID SFs
- Unblinded the results (summary)
- Combined the results with 2016 (HIG-17-018)
- Added unblinded post-fit plots, μ values, and limits to AN and PAS
- Added event yield tables for all categories

Documentation:

- Wiki for ARC review:
  https://twiki.cern.ch/twiki/bin/view/CMS/HIG18019Reviews
  ARC: Christopher Neu (chair), Michail Bachtis, Andrea Massironi, Mara Soares
- CADI line: HIG-18-019
- AN-2018/098 v18
- PAS HIG-18-019 v6

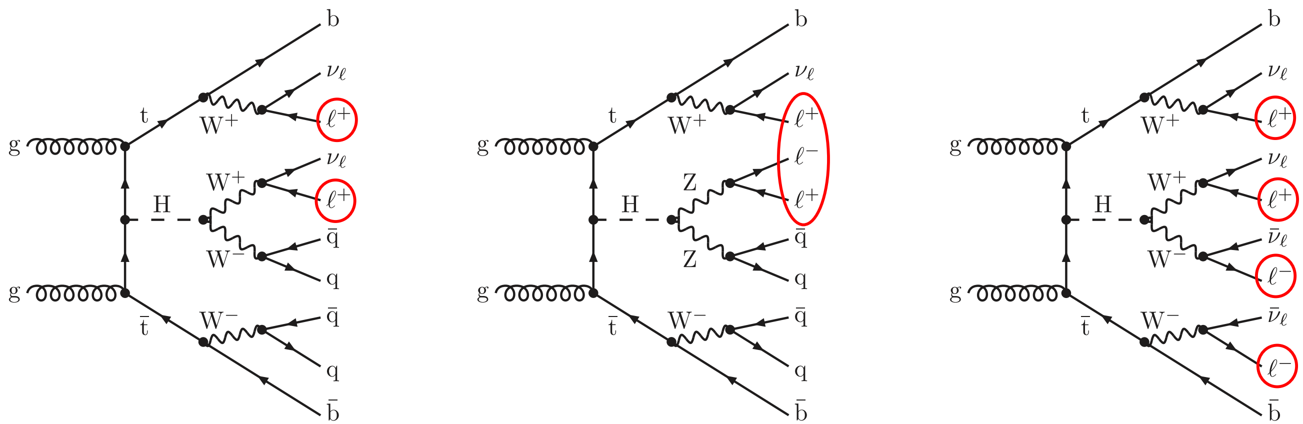
Datasets

- Fall17 ReReco data of 2017 Runs B-F (GT `94X_dataRun2_v6`)
  - SingleElectron, SingleMuon, DoubleEG, DoubleMuon, MuonEG
- Fall17 MC datasets (GT `94X_mc2017_realistic_v13`)
  - estimate the yields and shapes of signal and irreducible backgrounds
  - for data-driven methods & systematic uncertainties

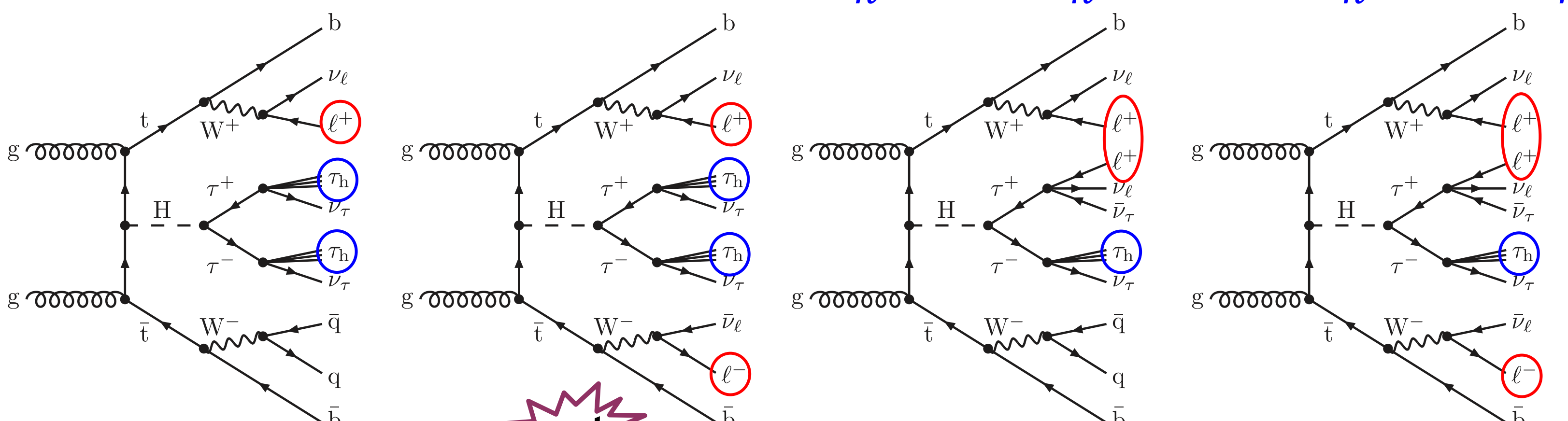
Process	Sample name	Cross section [pb]
$t\bar{t}H$	/ttHJetToNonbb_M125_TuneCP5_13TeV_amcatnloFXFX_madspin_pythia8/	2.12×10^{-1}
$t\bar{t}W$	/TTWJetsToLNu_TuneCP5_13TeV-amcatnloFXFX-madspin-pythia8/	2.04×10^{-1}
	/TTWJetsToLNu_TuneCP5_PSweights_13TeV-amcatnloFXFX-madspin-pythia8/	2.04×10^{-1}
$t\bar{t}WW$	/TTWW_TuneCP5_13TeV-madgraph-pythia8/	7.83×10^{-3}
$t\bar{t}Z$	/TTZToLL_M-1to10_TuneCP5_13TeV-amcatnlo-pythia8/	7.83×10^{-3}
	/TTZToLLNuNu_M-10_TuneCP5_13TeV-amcatnlo-pythia8/	2.53×10^{-1}
$t\bar{t} + \gamma +$ jets	/TTGJets_TuneCP5_13TeV-amcatnloFXFX-madspin-pythia8/	3.70
Single top quark $+\gamma+$ jets	/TGJets_TuneCUETP8M1_13TeV_amcatnlo_madspin_pythia8/	2.97
WW	/WWTo2L2Nu_NNPDF31_TuneCP5_13TeV-powheg-pythia8/	1.22×10^{1}
	/WWTo2L2Nu_DoubleScattering_13TeV-herwigpp/	1.74×10^{-1}
WZ	/WZTo3LNu_TuneCP5_13TeV-amcatnloFXFX-pythia8/	4.43
ZZ	/ZZTo4L_13TeV_powheg_pythia8/	1.26
WWW	/WWW_4F_TuneCP5_13TeV-amcatnlo-pythia8/	2.09×10^{-1}
WWZ	/WWZ_4F_TuneCP5_13TeV-amcatnlo-pythia8/	1.65×10^{-1}
WZZ	/WZZ_TuneCP5_13TeV-amcatnlo-pythia8/	5.57×10^{-2}
ZZZ	/ZZZ_TuneCUETP8M1_13TeV-amcatnlo-pythia8/	1.40×10^{-2}
Single top quark +Z	/tZq_ll_4f_ckm_NLO_TuneCP5_PSweights_13TeV-amcatnlo-pythia8/	7.58×10^{-2}
$t\bar{t}t\bar{t}$	/TTTT_TuneCP5_13TeV-amcatnlo-pythia8/	8.21×10^{-3}
$t\bar{t}$+jets	/TTTo2L2Nu_TuneCP5_13TeV-powheg-pythia8/	8.83×10^{1}
	/TTTo2L2Nu_TuneCP5_PSweights_13TeV-powheg-pythia8/	8.83×10^{1}
	/TTToSemiLeptonic_TuneCP5_13TeV-powheg-pythia8/	3.65×10^{2}
	/TTToSemiLeptonic_TuneCP5_PSweights_13TeV-powheg-pythia8/	3.65×10^{2}
	/TTToHadronic_TuneCP5_13TeV-powheg-pythia8/	3.78×10^{2}
	/TTToHadronic_TuneCP5_PSweights_13TeV-powheg-pythia8/	3.78×10^{2}
$Z/\gamma^* \to \ell\ell$	/DYJetsToLL_M-10to50_TuneCP5_13TeV-madgraphMLM-pythia8/	1.86×10^{4}
	/DYJetsToLL_M-50_TuneCP5_13TeV-amcatnloFXFX-pythia8/	5.77×10^{3}
W+jets	/WJetsToLNu_TuneCP5_13TeV-madgraphMLM-pythia8/	6.15×10^{4}
Single top quark	/ST_s-channel_4f_leptonDecays_TuneCP5_13TeV-amcatnlo-pythia8/	3.36
	/ST_t-channel_top_4f_inclusiveDecays_TuneCP5_13TeV-powhegV2-madspin-pythia8/	1.36×10^{2}
	/ST_t-channel_antitop_4f_inclusiveDecays_TuneCP5_13TeV-powhegV2-madspin-pythia8/	8.10×10^{1}
	/ST_tW_top_5f_inclusiveDecays_TuneCP5_13TeV-powheg-pythia8/	3.56×10^{1}
	/ST_tW_antitop_5f_inclusiveDecays_TuneCP5_13TeV-powheg-pythia8/	3.56×10^{1}

Analysis overview

- Mutually exclusive event categories based on the multiplicity of leptons ($\ell = e, \mu$) and hadronically decaying taus (τ_h)
  - pure multilepton final states: $2\ell SS$, 3ℓ, 4ℓ



  - final states with hadronic τ: $1\ell + 2\tau_h$, $2\ell + 2\tau_h$, $2\ell SS + 1\tau_h$, $3\ell + 1\tau_h$



Objects: lepton identification

- Final state ("prompt") leptons expected to come from W, Z and τ decays
- Dedicated lepton MVA to separate prompt lepton from non-prompt and fake leptons
- 12 input variables
  - kinematics (p_T, η)
  - isolation variables
  - impact parameters $(d_{xy}, d_z, \mathrm{SIP}_{3\mathrm{D}})$
  - nearest jet (# charged daughters, p_T^{rel}, p_T^{ratio}, b-tagging)
  - EGamma ID for e OR segment compatibility for μ
- Retrained for 2017 for e and μ separately

  - new EGamma ID
  - improved the definition of p_T^{ratio}
  - discriminative power improved compared to 2016

Objects: lepton selection

Three levels of selection

- Loose – basic selection
  - τ_h cleaning
  - applying mass vetos
- Fakeable – estimate non-prompt background with the fake rate method
  - jet cleaning
  - compute kinematic properties of the event
- Tight – event selection in the signal region (SR)
  - same as fakeable, but with prompt lepton MVA requirement

Objects: hadronic τ

- Reconstructed with HPS algorithm
- Hadronic 1-prong and 3-prong decay modes
- $p_T > 20$ GeV, $|\eta| < 2.3$
- No anti-e or anti-μ discriminants used as no improvement in sensitivity
- Tau POG retrained MVA (2017v2) with $R = 0.3$ cone size
  - separates hadronic τ decays from the quark-gluon jet background
  - updated WPs to recover old ID efficiencies NEW
- Fakeable and tight selection
  - VLoose WP – for fake τ_h background estimation
  - Loose ($2\ell SS + 1\tau_h, 3\ell + 1\tau_h$) or Medium WP ($1\ell + 2\tau_h, 2\ell + 2\tau_h$) – for selecting events in SR

Objects: jets + MET

- Standard AK4PFJetsCHS
  - $p_T > 25$ GeV, $|\eta| < 2.4$, tight PF Jet ID (as per POG recommendation)
  - b-tagging algorithms retrained by BTV POG
    - CSVv2 as an input to prompt lepton MVA
    - DeepCSV to define loose and medium b-jets 

  - `Fall17_17Nov2017_V6` JEC applied
- Standard Type-1 corrected PF MET
  - MHT = vectorial sum of selected jets, fakeable leptons and fakeable τ_h
    - less sensitive to pileup (PU) since the soft contribution excluded
  - $\mathrm{MET}_{\mathrm{LD}} = 0.6 \cdot |\mathrm{MET}| + 0.4 \cdot |\mathrm{MHT}|$
    - designed to reject background with fake MET (mainly Drell-Yan)

Event selection (I)

- Triggers: OR of
  - single lepton and lepton+tau cross-triggers in $1\ell + 2\tau_h$
  - single and double (and triple) lepton triggers in $2\ell + 2\tau_h$, $2\ell SS$ and $2\ell SS + 1\tau_h$ (3ℓ, $3\ell + 1\tau_h$ and 4ℓ)
- Minimum p_T cuts on leptons and τ_h motivated by trigger thresholds
  - * in $1\ell + 2\tau_h$: the electron or muon must be within $|\eta| < 2.1$
- Minimum number of jets
  - 2 in $2\ell + 2\tau_h$, 3ℓ, $3\ell + 1\tau_h$ and 4ℓ
  - 3 in $1\ell + 2\tau_h$ and $2\ell SS + 1\tau_h$
  - 4 in $2\ell SS$
- At least 1 medium b-jet or 2 loose b-jets

Event selection (II)

- Z-veto on a pair of SFOS loose leptons
- Low di-lepton mass cut: no pair of loose leptons with a mass $< 12\ \mathrm{GeV}$
- Charge sum of
  - all objects $= 0\ (\pm 1)$ in $2\ell + 2\tau_h, 3\ell + 1\tau_h, 4\ell\ (2\ell SS + 1\tau_h, 3\ell)$
  - leptons $= \pm 2$ plus additional charge quality requirements applied in $2\ell SS$ and $2\ell SS + 1\tau_h$
  - taus $= 0$ in $1\ell + 2\tau_h$
- Cuts on $\mathrm{MET_{LD}}$ applied in all channels but $1\ell + 2\tau_h$
- Veto events if $m_{4\ell} < 140\ \mathrm{GeV}$ to avoid overlap with $H \to ZZ^* \to 4\ell$ analysis

Data-to-MC corrections

- Trigger efficiency
  - in all categories but $1\ell + 2\tau_h$: measured using data and $t\bar{t}$ + jets events recorded by unbiased MET triggers
  - in $1\ell + 2\tau_h$: measured via Tag-and-Probe (TnP) technique in Drell-Yan (DY) events by the Tau POG
- e and μ identification efficiency
  - measured via TnP in DY events
- τ_h identification efficiency
  - using the SF measured in DY events by the Tau POG
- τ_h energy scale
- b-tagging efficiency and mis-tagging rate – derived by BTV POG
- MET resolution and response – recompute MET with rescaled and smeared jets

Background estimation

Irreducible backgrounds – modelled by MC: $t\bar{t}V$, diboson, rare SM, tH

NEW

- $t\bar{t}W(W)$, $t\bar{t}Z$ and WZ yields constrained by dedicated control regions in the final fit

Reducible

- “fake” background – estimated from data
  - typically due to $t\bar{t}$ where non-prompt leptons or jets pass tight lepton or τ_h criteria
  - dominant in $1\ell + 2\tau_h$ and $2\ell + 2\tau_h$
- charge “flip” background – estimated from data in $2\ell SS$ and $2\ell SS + 1\tau_h$
  - due to dileptonic $t\bar{t}$ + jets
- photon “conversion” background – estimated from MC
  - typically due to $\gamma \rightarrow e^+e^-$ conversions in $t\bar{t} + \gamma/\gamma^*$ events where either electron or positron fails to be reconstructed
  - relevant in $2\ell SS$ and $2\ell SS + 1\tau_h$

Background estimation: fake background

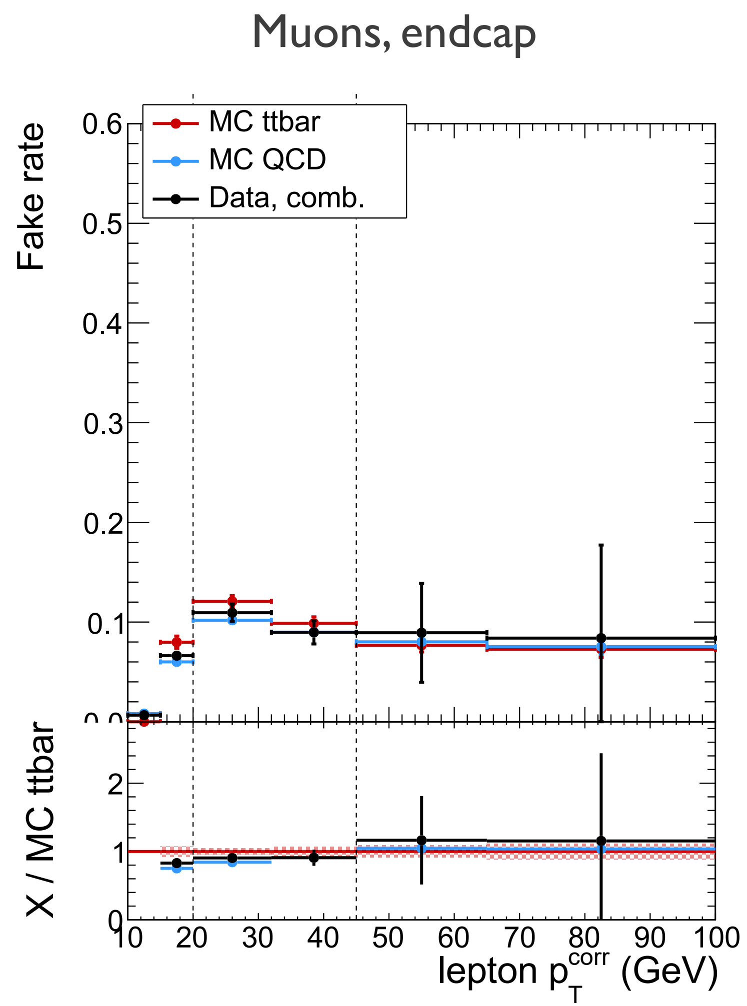
- Based on the fake factor (FF) method
- Fake application region (AR) – same as SR, but all e, μ, τ_h must pass fakeable selection while at least one must fail the tight selection
- Extrapolation from fake AR to the SR by reweighting events
- Weights depend on the # of objects passing (P) and failing (F) the tight selection criteria

$$(-1)^{F+1} \prod_{i=1}^{P+F} \begin{cases} 1 \text{ if } i\text{−th object passes tight selection} \\ \dfrac{f_i}{1-f_i} \text{ if } i\text{−th object fails tight selection} \end{cases}$$

where f_i represents the probability for i-th fakeable e, μ or τ_h to pass tight selection criteria

Lepton fake rate measurement

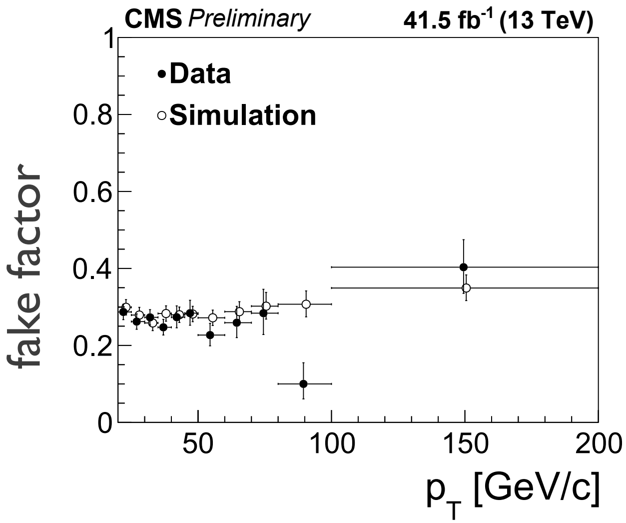
- Measurement region
  - QCD events
  - one fakeable e or μ
  - ≥ 1 jet ($\Delta R > 0.7$)
- FFs parametrized by p_T, η and flavor of the lepton
- Differences of FFs measured in QCD and $t\bar{t}$ samples taken as systematic uncertainties

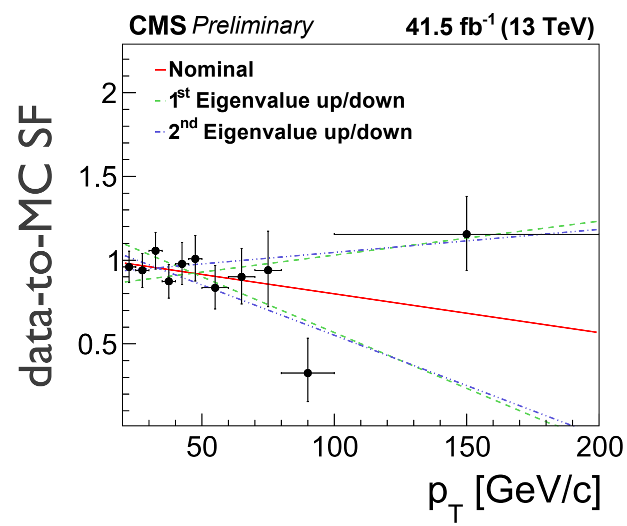


τ_h fake rate measurement

- FF for τ_h: probability of a jet passing fakeable τ_h selection to also pass the tight τ_h selection
- Measurement region:
  - $t\bar{t}$ dilepton ($e\mu$) + jets events
  - same as $2\ell SS$ SR except
    - oppositely signed e and μ
    - # jets ≥ 2
    - ≥ 1 fakeable τ_h
- Data-to-MC SFs for the FFs from linear fit
  - final event weight is FF measured in MC times data/MC ratio from fit to reduce statistical fluctuations
  - uncertainty on the fit parameters taken as systematic shape uncertainty

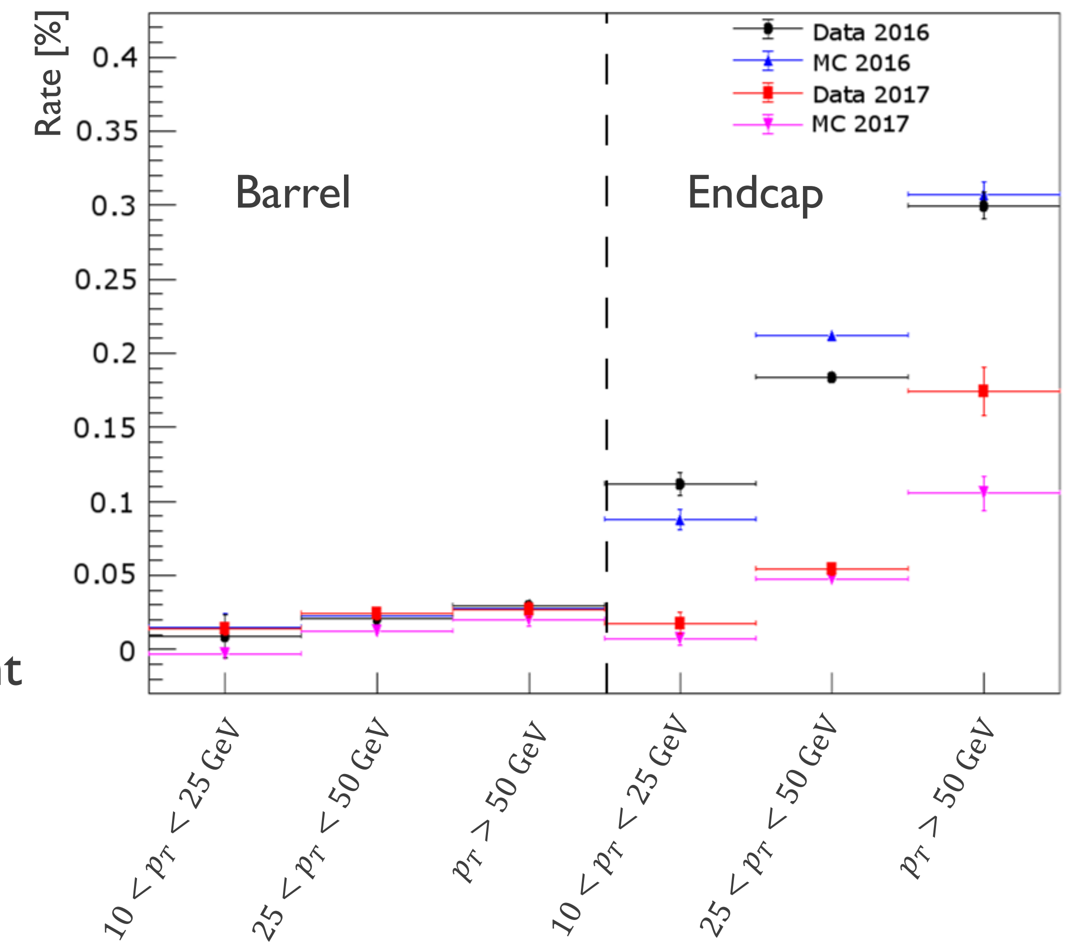
Medium WP, barrel





Charge flip background

- Electron charge mis-ID rate measured using $Z \to e^+e^-$ events
  - determined from the ratio of $Z \to e^+e^-$ events with SS to OS charge
  - charge mis-ID rate ~2x smaller compared to 2016 (new pixel detector)
  - negligible for μ



- Extrapolation from AR to SR:
  - select events with OS charge
  - assign charge mis-ID rates as the event weight

Systematic uncertainties

- Trigger efficiency: $1-5\%$
- Lepton ID efficiency: $2–5\%$
- τ_h ID efficiency: 5%
- jet & τ_h energy scale: shape
- b-tagging: shape
- MET: shape
- $t\bar{t}\gamma^*$, diboson and rare SM: 50%

Only relevant to $t\bar{t}H$, $t\bar{t}W$ and $t\bar{t}Z$:

- inclusive cross section: $7-13\%$ *
- PDF + α_S: $3-4\%$ *
- $\mathrm{Br}(H\to VV^*(\tau\tau))$: 1.5% (1.7%) *
- μ_R, μ_F: shape

- Fake background:
  - $\sim 30\%$ per lepton and τ_h
  - shape (uncertainty on p_T dependence)
- Charge flip background: 30%
- Luminosity: 2.3%
- Pileup: $<\ 1\%$

* following LHC Higgs XS WG recommendation

Systematic uncertainties

- Trigger efficiency: $1-5\%$
- Lepton ID efficiency: $2-5\%$
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- b-tagging: shape †
- MET: shape
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Only relevant to $t\bar{t}H$, $t\bar{t}W$ and $t\bar{t}Z$:

- inclusive cross section: $7-13\%$ *
- PDF + α_S: $3-4\%$ *
- $\mathrm{Br}(H \rightarrow VV^*(\tau\tau))$: 1.5% (1.7%) *
- μ_R, μ_F: shape

○ correlated in the combination with 2016 analysis

† only non-statistical sources correlated

* following LHC Higgs XS WG recommendation

Signal extraction

- Output of Boosted Decision Trees (BDT) as signal extraction observable in the final fit
- Event-level BDTs trained to separate $t\bar{t}H$ from $t\bar{t}V$ and $t\bar{t}$ + jets backgrounds
- Input variables kinematic
- Output of dedicated algorithms that exploit channel-specific features
  - Hadronic Top Tagger (HTT)
  - Higgs-jet (Hj) tagger
  - matrix element method (MEM)
- 4ℓ – cut & count due to low statistics

Signal extraction: $2\ell SS$ and 3ℓ categories

- 2 BDTs per category: $t\bar{t}H$ vs $t\bar{t}V$ and $t\bar{t}H$ vs $t\bar{t}$+jets
- Mapped into 1D distribution based on S/B likelihood ratio
- Input variables
  - $2\ell SS$ – HTT, Hj tagger
  - 3ℓ – HTT, MEM
- Training on inclusive $2\ell SS$ and 3ℓ categories
- Split into subcategories to take advantage of variations in the S/B ratio among the subcategories in the final fit

$2\ell SS$:

any 2 b	2 b loose		2 b tight	
e^-e^-	$e^-\mu^-$	$e^+\mu^+$	$e^-\mu^-$	$e^+\mu^+$
e^+e^+	$\mu^-\mu^-$	$\mu^+\mu^+$	$\mu^-\mu^-$	$\mu^+\mu^+$

3ℓ:

2 b loose & charge sum -1	2 b tight & charge sum -1
2 b loose & charge sum $+1$	2 b tight & charge sum $+1$

Signal extraction: categories with τ_h

- 1 BDT per category: $t\bar{t}H$ vs sum of $t\bar{t}V$ and $t\bar{t}$+jets
- Trained with `XGBoost` algorithm NEW
- Trained on privately produced `FastSim` samples with 2016 conditions
- Input variables updated
  - $1\ell + 2\tau_h$ and $2\ell SS + 1\tau_h$ – HTT NEW

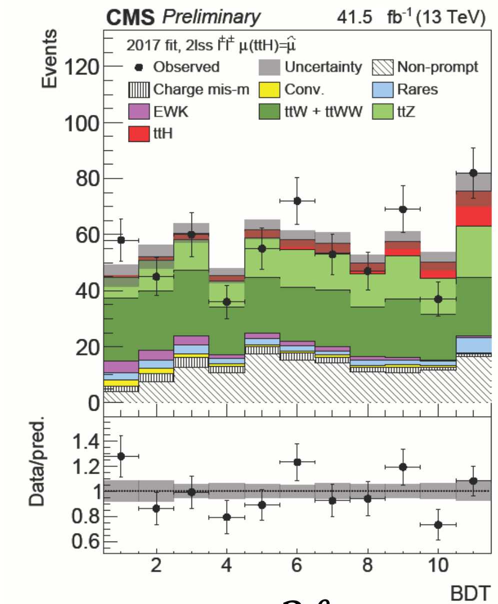
Results: post-fit event yields

Category	$2\ell SS$	3ℓ	4ℓ	$1\ell + 2\tau_h$	$2\ell + 2\tau_h$	$3\ell + 1\tau_h$	$2\ell SS + 1\tau_h$
$t\bar{t}H$	42.99 ± 7.05	18.79 ± 4.78	0.70 ± 0.30	6.57 ± 3.58	0.88 ± 0.47	0.99 ± 0.38	5.13 ± 2.11
$t\bar{t}W + t\bar{t}WW$	218.46 ± 13.71	51.03 ± 5.28	0.13 ± 0.03	1.13 ± 0.25	< 0.05	0.51 ± 0.12	13.11 ± 2.43
tH	2.38 ± 0.11	0.88 ± 0.10	< 0.05	0.25 ± 0.07	0.02 ± 0.09	< 0.05	0.45 ± 0.03
$WZ + ZZ$	< 0.05	12.04 ± 1.66	0.15 ± 0.10	1.50 ± 0.77	0.04 ± 0.03	0.13 ± 0.03	2.76 ± 1.95
ttZ/γ^*	138.23 ± 7.6	74.12 ± 6.32	3.91 ± 0.62	11.55 ± 2.64	1.55 ± 0.46	4.48 ± 0.68	15.35 ± 2.43
Fakes	132.14 ± 9.96	26.83 ± 4.03	< 0.05	299.60 ± 19.10	5.31 ± 2.19	0.25 ± 0.26	5.28 ± 2.18
Conversions	11.63 ± 3.01	6.62 ± 1.27	< 0.05	0.25 ± 0.11	< 0.05	< 0.05	< 0.05
Flips	22.79 ± 2.33	–	–	–	–	–	< 0.05
Other	26.66 ± 3.89	9.66 ± 2.16	0.09 ± 0.05	1.18 ± 0.46	0.06 ± 0.04	0.33 ± 0.15	3.23 ± 1.14
SM expectation	595.31 ± 20.60	199.96 ± 10.77	5.01 ± 0.70	322.02 ± 19.64	7.86 ± 2.29	6.7 ± 0.85	45.31 ± 5.11
Observed data	614	195	6	324	7	4	53

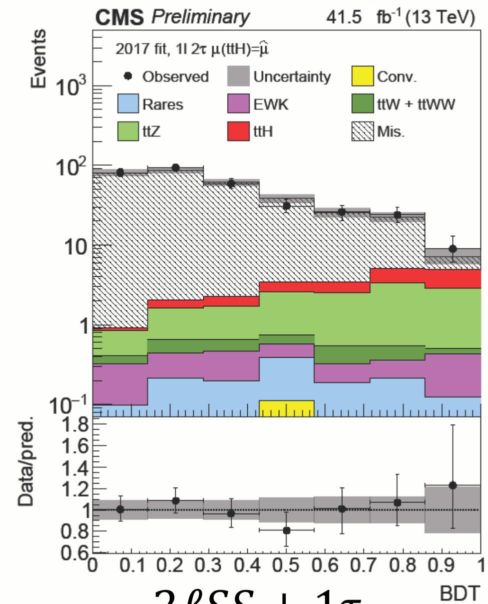
- SM expectation includes $t\bar{t}H$ signal contribution of SM strength
- Event yields of $2\ell SS$ and 3ℓ categories summed over subcategories
  - to see the event yields as shown in **PAS** see these backup slides for $2\ell SS$ and these for 3ℓ channel

Results: post-fit plots PAS

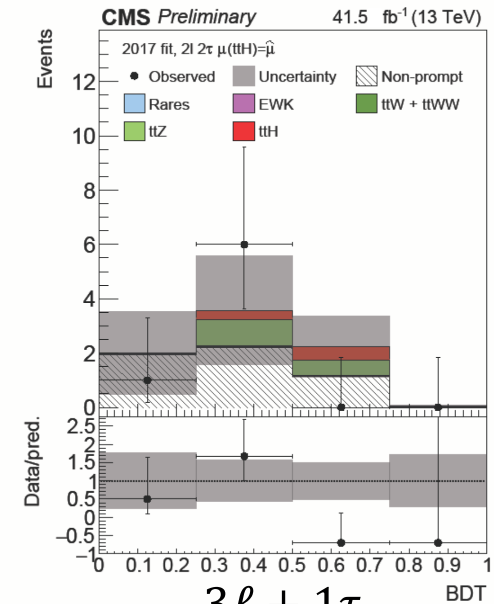
$2\ell SS$



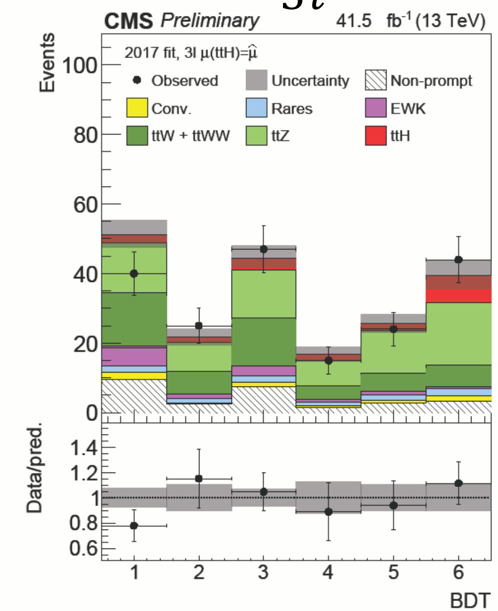
$1\ell + 2\tau_h$



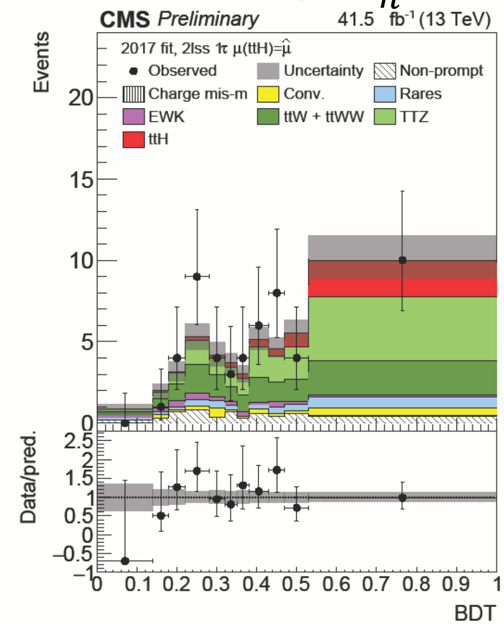
$2\ell + 2\tau_h$



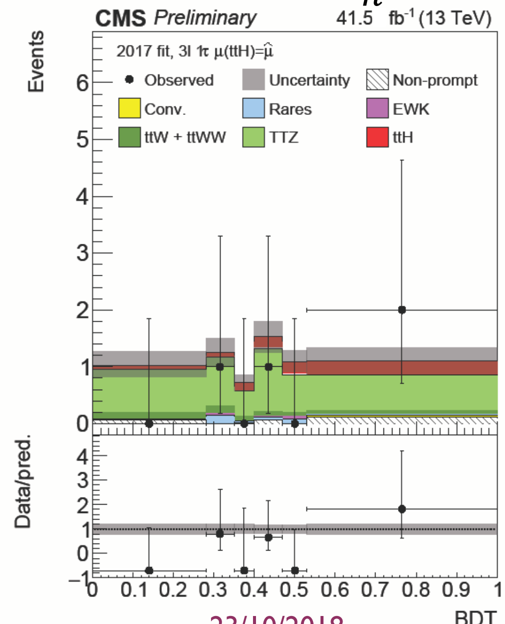
3ℓ



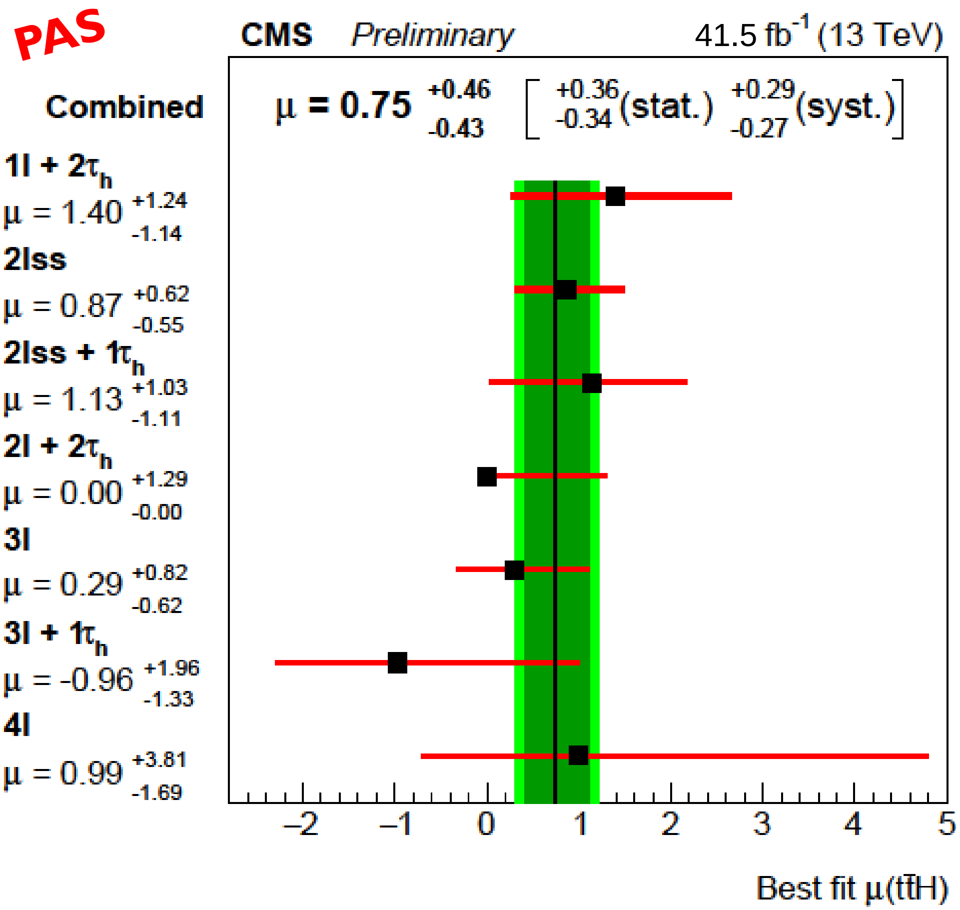
$2\ell SS + 1\tau_h$



$3\ell + 1\tau_h$



Results: signal rates μ



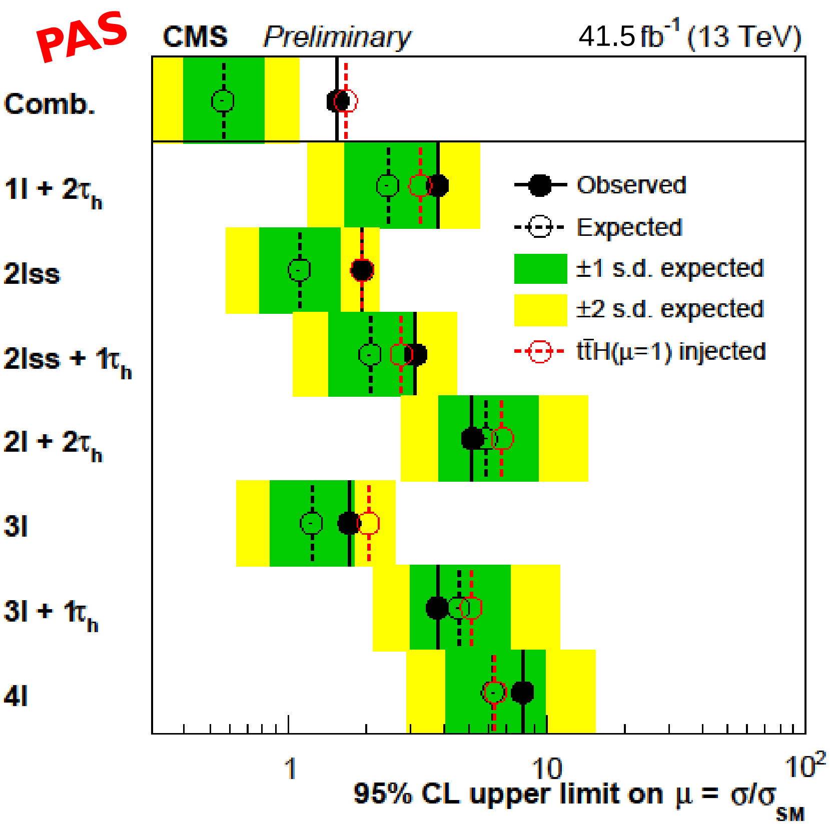
PAS

Category	Signal strength $\pm 1\sigma$ Measured	Signal strength $\pm 1\sigma$ Expected
$1\ell + 2\tau_h$	$1.40^{+1.24}_{-1.14}$	$1.00^{+1.14}_{-0.93}$
$2\ell SS$	$0.87^{+0.62}_{-0.55}$	$1.00^{+0.53}_{-0.49}$
$2\ell SS + 1\tau_h$	$1.13^{+1.03}_{-1.11}$	$1.00^{+0.93}_{-0.80}$
$2\ell + 2\tau_h$	$0.00^{+1.29}_{-0.00}$	$1.00^{+2.63}_{-1.56}$
3ℓ	$0.29^{+0.82}_{-0.62}$	$1.00^{+0.59}_{-0.52}$
$3\ell + 1\tau_h$	$-0.96^{+1.96}_{-1.33}$	$1.00^{+1.91}_{-1.37}$
4ℓ	$0.99^{+3.31}_{-1.69}$	$1.00^{+2.41}_{-1.72}$
Combined 2017	$0.75^{+0.46}_{-0.43}$	$1.00^{+0.39}_{-0.35}$
Combined 2016+2017	$\mathbf{0.96^{+0.34}_{-0.31}}$	$\mathbf{1.00^{+0.30}_{-0.27}}$

2017 combination: observed significance 1.7σ (expected 2.9σ)

2016+2017 combination: observed significance 3.2σ (expected 4.0σ)

Results: upper limits



PAS

Category	95% CL upper limits		
	Observed	Expected ($\mu = 0$)	Expected ($\mu = 1$)
$1\ell + 2\tau_h$	3.8	$2.4^{+1.3}_{-0.8}$	3.3
$2\ell SS$	2.0	$1.1^{+0.5}_{-0.3}$	1.9
$2\ell SS + 1\tau_h$	3.1	$2.1^{+1.0}_{-0.7}$	2.8
$2\ell + 2\tau_h$	5.2	$5.8^{+3.4}_{-2.0}$	6.8
3ℓ	1.7	$1.2^{+0.6}_{-0.4}$	2.1
$3\ell + 1\tau_h$	3.8	$4.6^{+2.7}_{-1.6}$	5.1
4ℓ	8.1	$6.2^{+3.6}_{-2.1}$	6.4
Combined 2017	1.6	$0.8^{+0.3}_{-0.2}$	1.7
Combined 2016+2017	**1.6**	$\mathbf{0.6^{+0.2}_{-0.2}}$	**1.5**

Summary

- A search for the associated $t\bar{t}H$ production in final states with electrons, muons and hadronically decaying τ leptons has been presented
  - performed with full 2017 dataset ($\mathcal{L} = 41.5\ \text{fb}^{-1}$)
  - analyzed 7 event categories: $2\ell SS,\ 3\ell,\ 4\ell,\ 1\ell + 2\tau_h,\ 2\ell + 2\tau_h,\ 2\ell SS + 1\tau_h,\ 3\ell + 1\tau_h$
  - sensitivity of the analysis enhanced by using MVA techniques, based on BDTs and MEM
  - combination with 2016 results of the same analysis

Combined 2016+2017 **results in agreement with SM expectation**:

- **measured signal rate of $\boldsymbol{\mu = 0.96^{+0.34}_{-0.31}}$** (expected $1.00^{+0.30}_{-0.27}$) corresponding to a significance of 3.2σ (expected 4.0σ)

Backup

Backup

Backup: prompt lepton MVA (I)

- p_T and η of the lepton
- relative "mini-isolation" of the lepton wrt charged & neutral particles:

$$I_\ell^{charged} = \sum_{charged} p_T,\ I_\ell^{neutrals} = \max\left(0, \sum_{neutrals} p_T - \rho A \left(\frac{R}{0.3}\right)^2\right)$$

- variables of the nearest jet j to the lepton ($p_T(j) > 15$ GeV, $\Delta R(\ell, j) < 0.4$) [or if no such jet]
  - number of charged particles in the jet [0]
  - CSVv2 b-tagging score [0]
  - $p_T^{rel}(\ell) = \left|\vec{p}(\ell) \times \|\vec{p}(j) - \vec{p}(\ell)\|\right|$ † [0]
  - $p_T^{ratio}(\ell) = p_T(\ell)/p_T(j)$ † [$p_T(\ell)/(p_T(\ell) + I_\ell)$ ‡ NEW]
- impact parameters ($|d_{xy}|$, $|d_z|$, $|\mathrm{SIP}_{3D}|$)
- EGamma ID that separates electrons from jets (e) OR segment compatibility (μ)

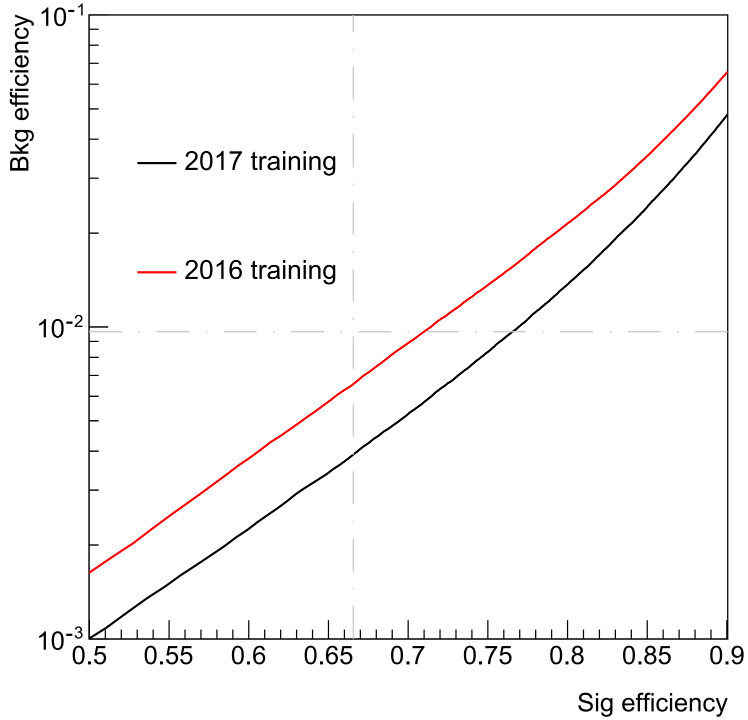
† $\vec{p}(j)$ computed with "lepton-aware" JEC approach (reference)

‡ $I_\ell = I_\ell^{charged} + I_\ell^{neutrals}$ – pileup-corrected PF isolation with cone size $R = 0.4$

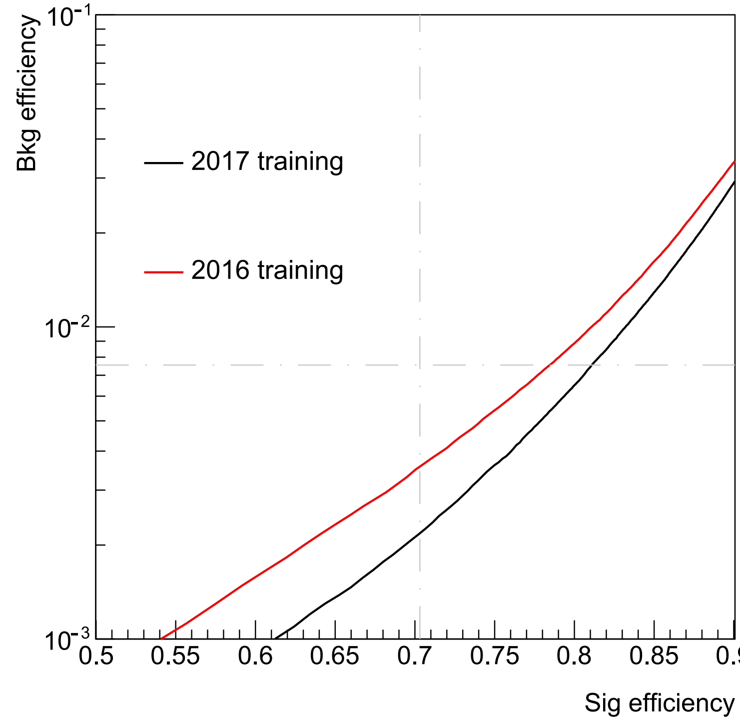
Backup: prompt lepton MVA (II)

- Improvements
  - previously used -1 as placeholder for p_T^{ratio} if there is no jet within $\Delta R = 0.4$
  - new EGamma ID
- Gain higher for electrons and at low p_T

Electrons



Muons



Backup: lepton selection (I)

Observable	Loose	Fakeable	Tight
p_{T}	> 7 GeV	> 10 GeV	> 10 GeV
$\|\eta\|$	< 2.5	< 2.5	< 2.5
$\|d_{xy}\|$	< 0.05 cm	< 0.05 cm	< 0.05 cm
$\|d_z\|$	< 0.1 cm	< 0.1 cm	< 0.1 cm
d/σ_d	< 8	< 8	< 8
I_{e}	$< 0.4 \times p_{\mathrm{T}}$	$< 0.4 \times p_{\mathrm{T}}$	$< 0.4 \times p_{\mathrm{T}}$
EGamma POG MVA	$> \{-0.86\ /\ -0.81\ /\ -0.72\}$[1]	$> \{-0.86\ /\ -0.81\ /\ -0.72\}$[2]	$> \{-0.86\ /\ -0.81\ /\ -0.72\}$[2]
$\sigma_{i\eta i\eta}$	–	$< \{0.011\ /\ 0.011\ /\ 0.030\}$	$< \{0.011\ /\ 0.011\ /\ 0.030\}$
H/E	–	< 0.10	< 0.10
1/E - 1/p	–	> -0.04	> -0.04
Conversion rejection	–	✓	✓
Missing hits	≤ 1	$= 0$	$= 0$
$p_{\mathrm{T}}^{\mathrm{e}}/p_{\mathrm{T}}^{\mathrm{j}}$	–	> 0.6 † (–)	–
CSVv2 of nearby jet	–	< 0.07 † (< 0.4941)	< 0.4941
Prompt-e MVA	–	–	> 0.90

[1] $> \{-0.13\ /\ -0.32\ /\ -0.08\}$ if $p_{\mathrm{T}} < 10$ GeV
[2] > 0.50 if prompt-e MVA < 0.90

Backup: lepton selection (II)

Observable	Loose	Fakeable	Tight
p_{T}	> 5 GeV	> 10 GeV	> 10 GeV
$\|\eta\|$	< 2.4	< 2.4	< 2.4
$\|d_{xy}\|$	< 0.05 cm	< 0.05 cm	< 0.05 cm
$\|d_z\|$	< 0.1 cm	< 0.1 cm	< 0.1 cm
d/σ_d	< 8	< 8	< 8
I_μ	$< 0.4 \times p_{\mathrm{T}}$	$< 0.4 \times p_{\mathrm{T}}$	$< 0.4 \times p_{\mathrm{T}}$
Loose PF muon	✓	✓	✓
Medium PF muon	–	–	✓
Segment compatibility	–	> 0.3 † (–)	–
$p_{\mathrm{T}}^{\mu} / p_{\mathrm{T}}^{\mathrm{j}}$	–	> 0.6 † (–)	–
CSVv2 of nearby jet	–	< 0.07 † (< 0.4941)	< 0.4941
Prompt-μ MVA	–	–	> 0.90

Backup: data samples

Golden JSON: Cert_294927-306462_13TeV_EOY2017ReReco_Collisions17_JSON_v1.txt

Dataset name	Run-range	Luminosity (fb^{-1})
/SingleElectron/Run2017B-17Nov2017-v1/MINIAOD	297047–299329	4.79
/SingleElectron/Run2017C-17Nov2017-v1/MINIAOD	299368–302029	9.63
/SingleElectron/Run2017D-17Nov2017-v1/MINIAOD	302030–302663	4.25
/SingleElectron/Run2017E-17Nov2017-v1/MINIAOD	303818–304797	9.31
/SingleElectron/Run2017F-17Nov2017-v1/MINIAOD	305040–306460	13.54
/SingleMuon/Run2017B-17Nov2017-v1/MINIAOD	297047–299329	4.79
/SingleMuon/Run2017C-17Nov2017-v1/MINIAOD	299368–302029	9.63
/SingleMuon/Run2017D-17Nov2017-v1/MINIAOD	302031–302663	4.25
/SingleMuon/Run2017E-17Nov2017-v1/MINIAOD	303824–304797	9.31
/SingleMuon/Run2017F-17Nov2017-v1/MINIAOD	305040–306462	13.54
/DoubleEG/Run2017B-17Nov2017-v1/MINIAOD	297047–299329	4.79
/DoubleEG/Run2017C-17Nov2017-v1/MINIAOD	299368–302029	9.63
/DoubleEG/Run2017D-17Nov2017-v1/MINIAOD	302030–302663	4.25
/DoubleEG/Run2017E-17Nov2017-v1/MINIAOD	303818–304797	9.31
/DoubleEG/Run2017F-17Nov2017-v1/MINIAOD	305040–306460	13.54
/DoubleMuon/Run2017B-17Nov2017-v1/MINIAOD	297047–299329	4.79
/DoubleMuon/Run2017C-17Nov2017-v1/MINIAOD	299368–302029	9.63
/DoubleMuon/Run2017D-17Nov2017-v1/MINIAOD	302031–302663	4.25
/DoubleMuon/Run2017E-17Nov2017-v1/MINIAOD	303824–304797	9.31
/DoubleMuon/Run2017F-17Nov2017-v1/MINIAOD	305040–306462	13.54
/MuonEG/Run2017B-17Nov2017-v1/MINIAOD	297047–299329	4.79
/MuonEG/Run2017C-17Nov2017-v1/MINIAOD	299368–302029	9.63
/MuonEG/Run2017D-17Nov2017-v1/MINIAOD	302031–302663	4.25
/MuonEG/Run2017E-17Nov2017-v1/MINIAOD	303824–304797	9.31
/MuonEG/Run2017F-17Nov2017-v1/MINIAOD	305040–306460	13.54

Backup: event selection (I)

Selection	$2\ell ss$	$2\ell ss + 1\tau_h$
Targeted $t\bar{t}H$ decays	$t \to b\ell\nu$, $t \to bqq$, $H \to WW \to \ell\nu qq$	$t \to b\ell\nu$, $t \to bqq$, $H \to \tau\tau \to \ell\tau_h + \nu's$
Trigger	Single- and double-lepton triggers	
Lepton p_T	$p_T > 25$ / 15 GeV	$p_T > 25$ / 15 (e) or 10 GeV (μ)
Lepton η	$\lvert\eta\rvert < 2.5$ (e) or 2.4 (μ)	
τ_h p_T	—	$p_T > 20$ GeV
τ_h η	—	$\lvert\eta\rvert < 2.3$
Charge requirements	2 same-sign leptons and charge quality requirements	$\sum_{\ell,\tau_h} q = \pm 1$
Jet multiplicity	$\geq$4 jets	$\geq$3 jets
b tagging requirements	$\geq$1 tight b-tagged jet or $\geq$2 loose b-tagged jets	
Missing transverse momentum	$E_T^{miss} LD > 30$ GeV **	
Dilepton mass	$m_{\ell\ell} > 12$ GeV * and $\lvert m_{ee} - m_Z\rvert > 10$ GeV	

Selection	$1\ell + 2\tau_h$	$2\ell + 2\tau_h$
Targeted $t\bar{t}H$ decays	$t \to b\ell\nu$, $t \to bqq$, $H \to \tau\tau \to \tau_h\tau_h + \nu's$	$t \to b\ell\nu$, $t \to b\ell\nu$, $H \to \tau\tau \to \tau_h\tau_h + \nu's$
Trigger	Single-lepton and lepton+τ_h triggers	Single-, double-lepton triggers
Lepton p_T	$p_T > 25$ (e) or 20 GeV (μ)	$p_T > 25$ / 15 (e) or 10 GeV (μ)
Lepton η	$\lvert\eta\rvert < 2.1$	$\lvert\eta\rvert < 2.5$ (e) or 2.4 (μ)
τ_h p_T	$p_T > 30$ / 20 GeV	$p_T > 20$ GeV
τ_h η	$\lvert\eta\rvert < 2.3$	$\lvert\eta\rvert < 2.3$
Charge requirements	$\sum_{\tau_h} q = 0$	$\sum_{\ell,\tau_h} q = 0$
Jet multiplicity	$\geq$3 jets	$\geq$2 jets
b tagging requirements	$\geq$1 tight b-tagged jet or $\geq$2 loose b-tagged jets	
Missing transverse momentum	— — —	No requirement if $N_j \geq 4$ $E_T^{miss} LD > 45$ GeV † $E_T^{miss} LD > 30$ GeV otherwise
Dilepton mass	$m_{\ell\ell} > 12$ GeV *	

* Applied on all pairs of leptons that pass loose selection.

** If both leptons are electrons.

† If the event contains a SFOS lepton pair and $N_j \leq 3$.

Backup: event selection (II)

Selection	3ℓ	$3\ell + 1\tau_h$
Targeted $t\bar{t}H$ decays	$t \to b\ell\nu$, $t \to b\ell\nu$, $H \to WW \to \ell\nu qq$	$t \to b\ell\nu$, $t \to b\ell\nu$,
	$t \to b\ell\nu$, $t \to bqq$, $H \to WW \to \ell\nu\ell\nu$	$H \to \tau\tau \to \ell\tau_h + \nu$'s
Trigger	Single-, double- and triple-lepton triggers	
Lepton p_T	$p_T > 25$ / 15 / 10 GeV	$p_T > 20$ / 10 / 10 GeV
Lepton η	$\lvert\eta\rvert < 2.5$ (e) or 2.4 (μ)	
τ_h p_T	—	$p_T > 20$ GeV
τ_h η	—	$\lvert\eta\rvert < 2.3$
Charge requirements	$\sum_{\ell} q = \pm 1$	$\sum_{\ell,\tau_h} q = 0$
Jet multiplicity	$\geq$2 jets	
b tagging requirements	$\geq$1 tight b-tagged jet or $\geq$2 loose b-tagged jets	
Missing transverse momentum	No requirement if $N_j \geq 4$ $E_T^{miss} LD > 45$ GeV † $E_T^{miss} LD > 30$ GeV otherwise	
Dilepton mass	$m_{\ell\ell} > 12$ GeV * and $\lvert m_{\ell\ell} - m_Z\rvert > 10$ GeV ‡	
Four-lepton mass	$m_{4\ell} > 140$ GeV §	—

* Applied on all pairs of leptons that pass loose selection.

† If the event contains a SFOS lepton pair and $N_j \leq 3$.

‡ Applied to all SFOS lepton pairs.

§ Applied only if the event contains 2 SFOS lepton pairs.

Backup: event selection (III)

Selection	4ℓ
Targeted $t\bar{t}H$ decays	$t \to b\ell\nu$, $t \to b\ell\nu$, $H \to WW \to \ell\nu\ell\nu$ $t \to b\ell\nu$, $t \to b\ell\nu$, $H \to ZZ \to \ell\ell qq$ or $\ell\ell\nu\nu$
Trigger	Single-, double- and triple-lepton triggers
Lepton p_T	$p_T > 25$ / 15 / 15 / 10 GeV
Lepton η	$\lvert\eta\rvert < 2.5$ (e) or 2.4 (μ)
τ_h p_T	—
τ_h η	—
Charge requirements	$\sum_\ell q = 0$
Jet multiplicity	$\geq$2 jets
b tagging requirements	$\geq$1 tight b-tagged jet or $\geq$2 loose b-tagged jets
Missing transverse momentum	No requirement if $N_j \geq 4$ $E_T^{miss}LD > 45$ GeV † $E_T^{miss}LD > 30$ GeV otherwise
Dilepton mass	$m_{\ell\ell} > 12$ GeV * and $\lvert m_{\ell\ell} - m_Z\rvert > 10$ GeV ‡
Four-lepton mass	$m_{4\ell} > 140$ GeV §

* Applied on all pairs of leptons that pass loose selection.
† If the event contains a SFOS lepton pair and $N_j \leq 3$.
‡ Applied to all SFOS lepton pairs.
§ Applied only if the event contains 2 SFOS lepton pairs.

Backup: triggers

Single lepton triggers	HLT_Ele32_WPTight_Gsf HLT_Ele35_WPTight_Gsf HLT_IsoMu24 HLT_IsoMu27
Lepton+τ_h cross-triggers	HLT_Ele24_eta2p1_WPTight_Gsf_LooseChargedIsoPFTau30_eta2p1_CrossL1 HLT_IsoMu20_eta2p1_LooseChargedIsoPFTau27_eta2p1_CrossL1
Double lepton triggers	HLT_Ele23_Ele12_CaloIdL_TrackIdL_IsoVL HLT_Ele23_Ele12_CaloIdL_TrackIdL_IsoVL_DZ HLT_Mu23_TrkIsoVVL_Ele12_CaloIdL_TrackIdL_IsoVL HLT_Mu23_TrkIsoVVL_Ele12_CaloIdL_TrackIdL_IsoVL_DZ HLT_Mu12_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL_DZ HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL_DZ HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL_DZ_Mass3p8
Triple lepton triggers	HLT_Ele16_Ele12_Ele8_CaloIdL_TrackIdL HLT_Mu8_DiEle12_CaloIdL_TrackIdL HLT_DiMu9_Ele9_CaloIdL_TrackIdL_DZ HLT_TripleMu_12_10_5

Backup: MET filters

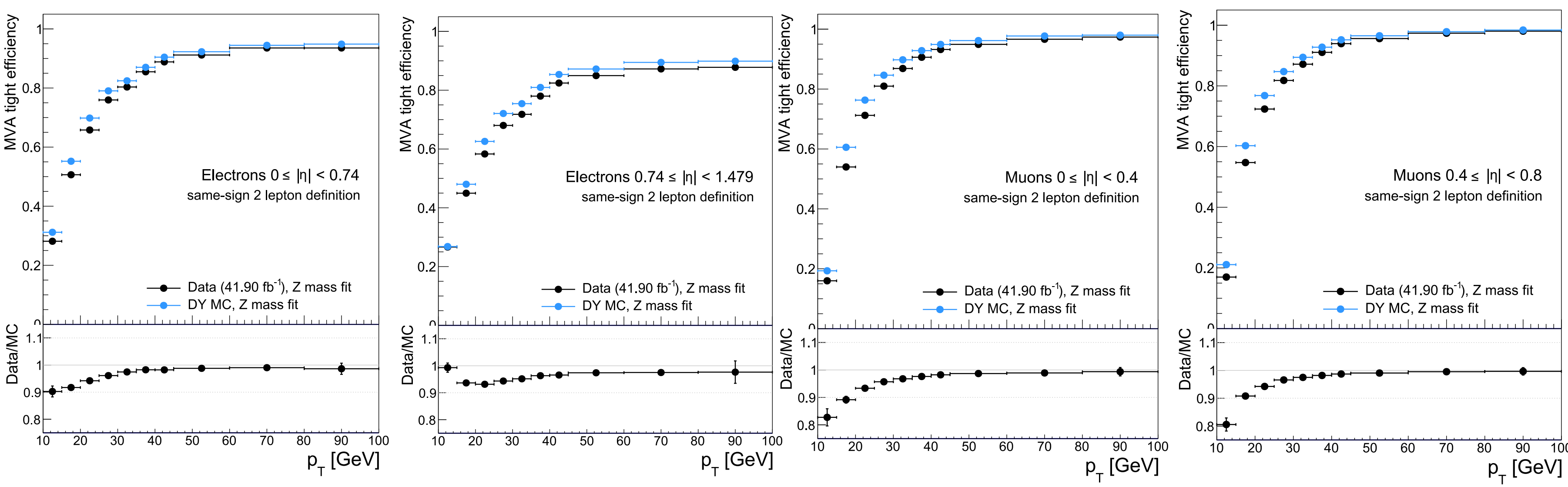
https://twiki.cern.ch/twiki/bin/viewauth/CMS/MissingETOptionalFiltersRun2?rev=115

Filter name	Applied to data	Applied to simulation
`Flag_goodVertices`	✓	✓
`Flag_globalTightHalo2016Filter`	✓	✓
`Flag_HBHENoiseFilter`	✓	✓
`Flag_HBHENoiseIsoFilter`	✓	✓
`Flag_EcalDeadCellTriggerPrimitiveFilter`	✓	✓
`Flag_BadPFMuonFilter`	✓	✓
`Flag_BadChargedCandidateFilter`	✓	✓
`Flag_eeBadScFilter`	✓	—
`Flag_ecalBadCalibFilter`	✓	✓

Backup: lepton ID SFs (I)

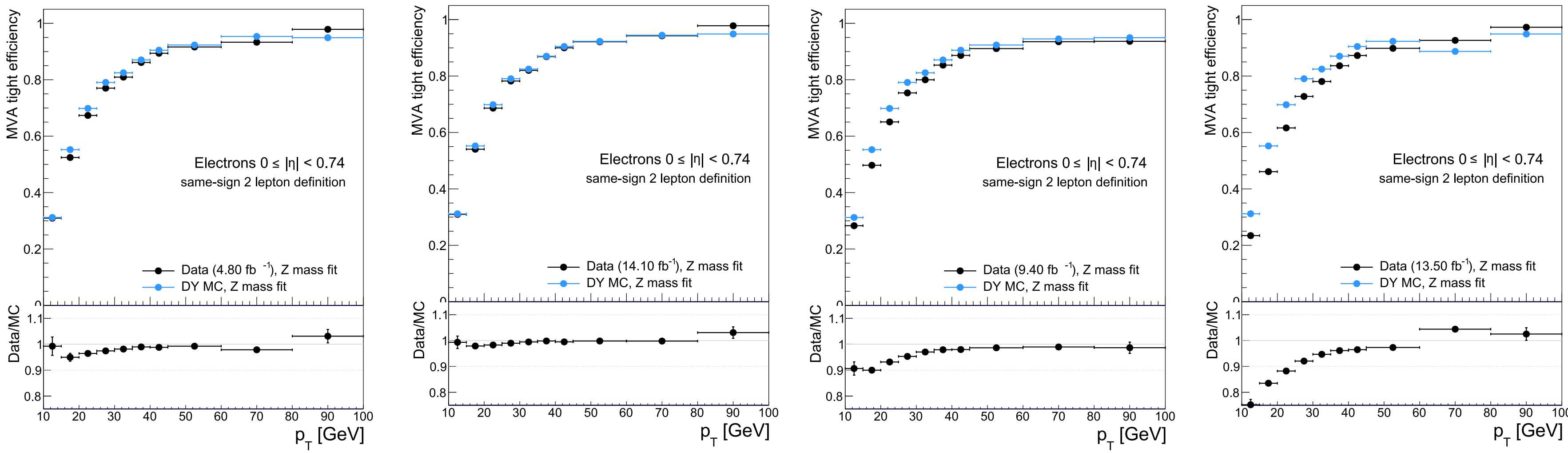
- Loose selection SFs taken from POG
- Tight-to-loose SF measured from DY samples using Tag-and-Probe technique
  - parametrized in bins of lepton p_T and η
  - separate measurements for e and μ
  - measurements for both with and without charge quality requirement
    - charge quality requirement applied only in $2\ell SS$ and $2\ell SS + 1\tau_h$ channels
    - determined separately for every run era (B, C+D, E, F)

Loose-to-tight efficiencies for e and μ in bins of p_T and various η ranges:

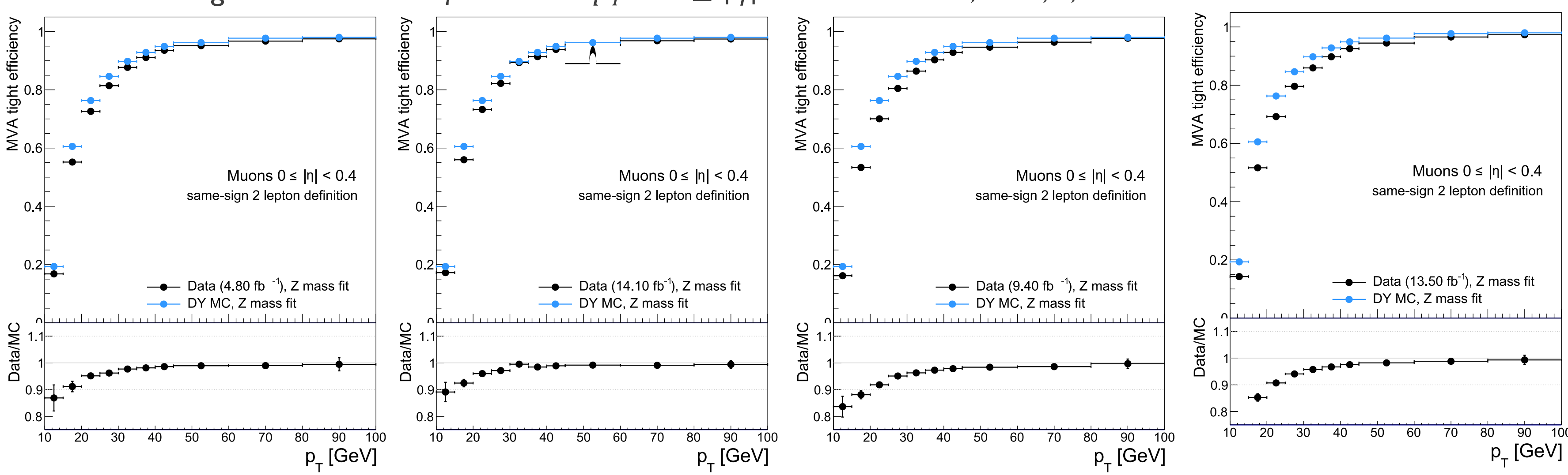


Backup: lepton ID SFs (II)

Loose-to-tight efficiencies for e in bins of p_T in $0 \leq |\eta| < 0.74$ for eras B, C+D, E, F



Loose-to-tight efficiencies for μ in bins of p_T in $0 \leq |\eta| < 0.4$ for eras B, C+D, E, F



Backup: lepton ID SFs (III)

- Event selection for the closure
  - OS different-flavor leptons
  - < 4 jets, ≥ 1 b-tagged
  - for e measurement e required to be tight (tag)
  - for μ measurement μ required to be tight (tag)
  - tag $p_T > 30$ GeV
- Efficiency defined as

$$\epsilon = \frac{N_{pass}^{prompt}}{N_{total}^{prompt}} = \frac{N_{pass}^{data} - N_{pass}^{fake}}{N_{total}^{data} - N_{total}^{fake}}$$

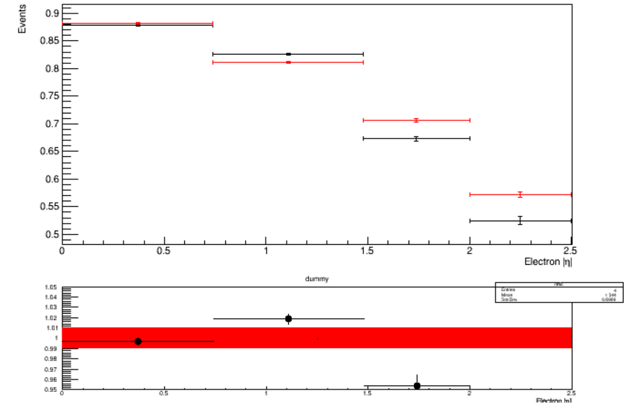
fakes estimated by

$$N^{fake} = R_{SS}^{OS}\left(N_{SS}^{data} - N_{SS}^{prompt}\right)$$

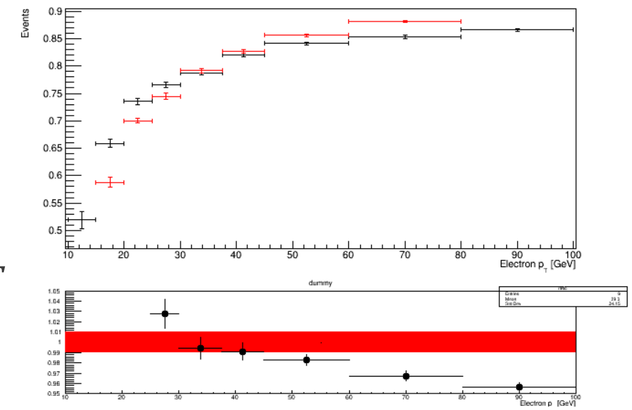
- Uncertainties on tight-to-loose SF
  - 2% for muons
  - 3% for electrons $p_T > 25$ GeV
  - 5% for electrons $p_T < 25$ GeV

Electrons:

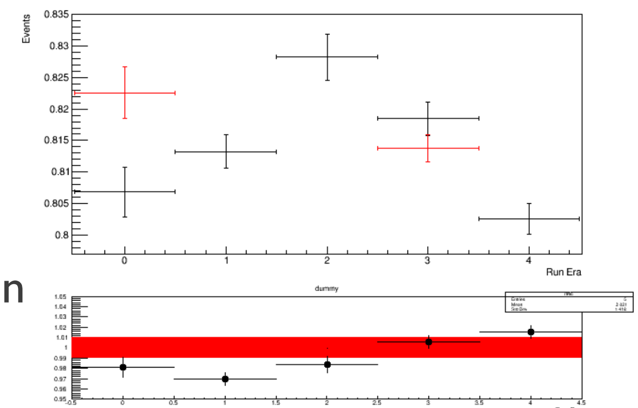
by $|\eta|$



by p_T



by run



Backup: lepton ID SFs (IV)

- Event selection for the closure
  - OS different-flavor leptons
  - < 4 jets, ≥ 1 b-tagged
  - for e measurement e required to be tight (tag)
  - for μ measurement μ required to be tight (tag)
  - tag $p_T > 30$ GeV
- Efficiency defined as

$$\epsilon = \frac{N_{pass}^{prompt}}{N_{total}^{prompt}} = \frac{N_{pass}^{data} - N_{pass}^{fake}}{N_{total}^{data} - N_{total}^{fake}}$$

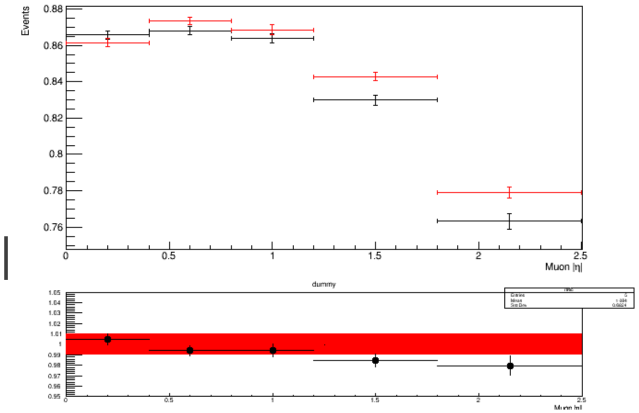
fakes estimated by

$$N^{fake} = R_{SS}^{OS}\left(N_{SS}^{data} - N_{SS}^{prompt}\right)$$

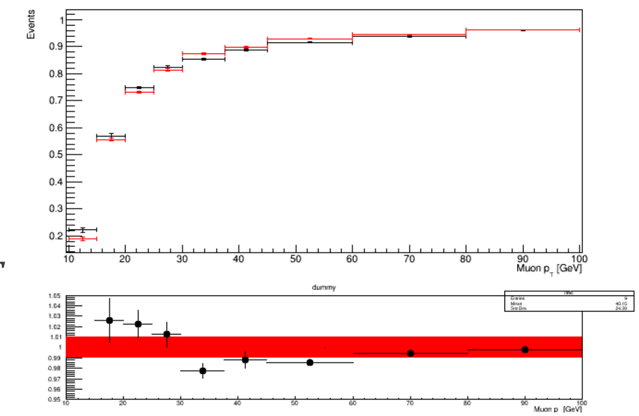
- Uncertainties on tight-to-loose SF
  - 2% for muons
  - 3% for electrons $p_T > 25$ GeV
  - 5% for electrons $p_T < 25$ GeV

Muons:

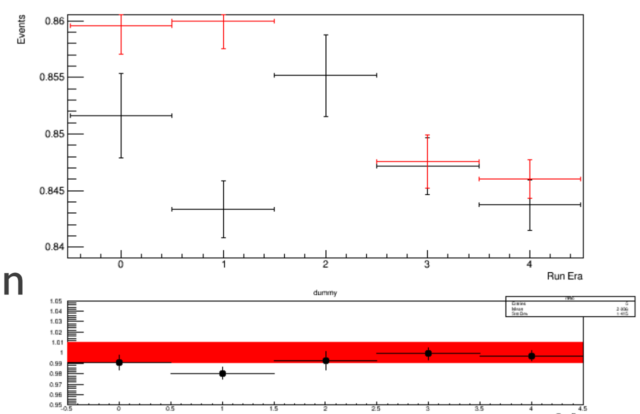
by $|\eta|$



by p_T



by run

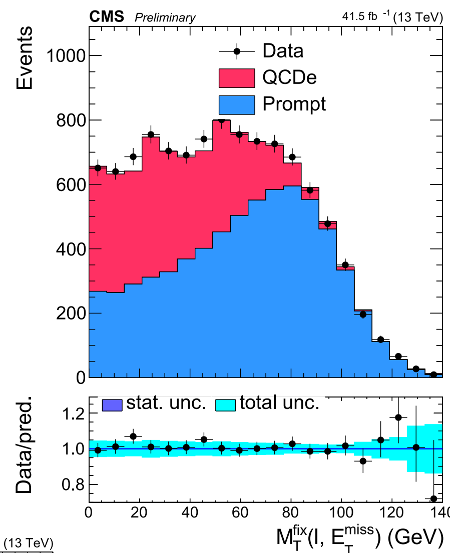


Backup: lepton fake rate (I)

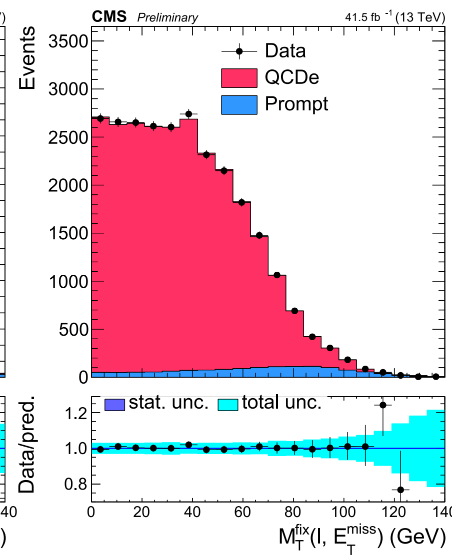
$$m_T^{fix} = \sqrt{2 p_T^{fix} E_T^{miss} (1 - \cos\Delta\phi)},$$
$$p_T^{fix} = 35\ \text{GeV}$$

Distribution of m_T^{fix} for e of
$25 < \text{cone}{-}p_T < 35\ \text{GeV}$
and $|\eta| < 1.479$

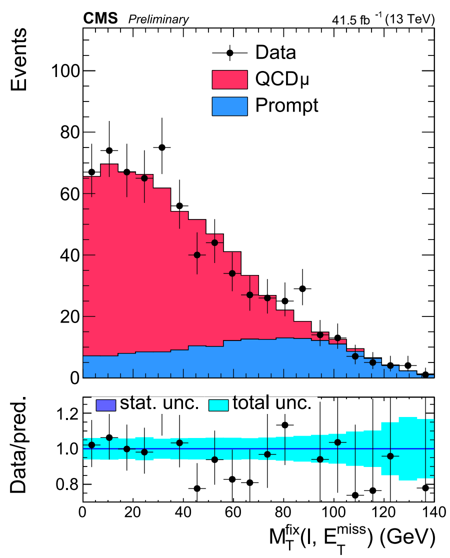
Pass



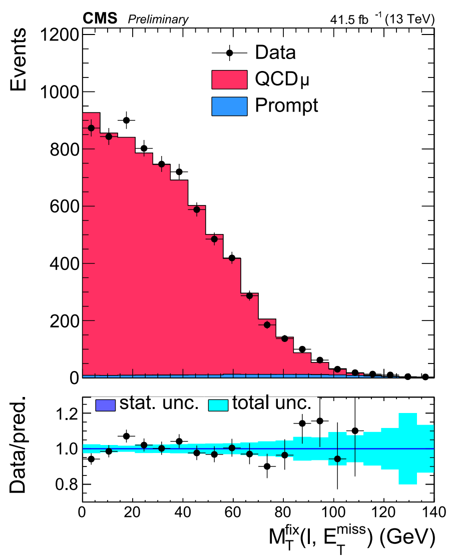
Fail



Pass



Fail



Distribution of m_T^{fix} for μ of
$25 < \text{cone}{-}p_T < 35\ \text{GeV}$
and $|\eta| > 1.2$

$$f_i = \frac{N_{pass}}{N_{pass} + N_{fail}}$$

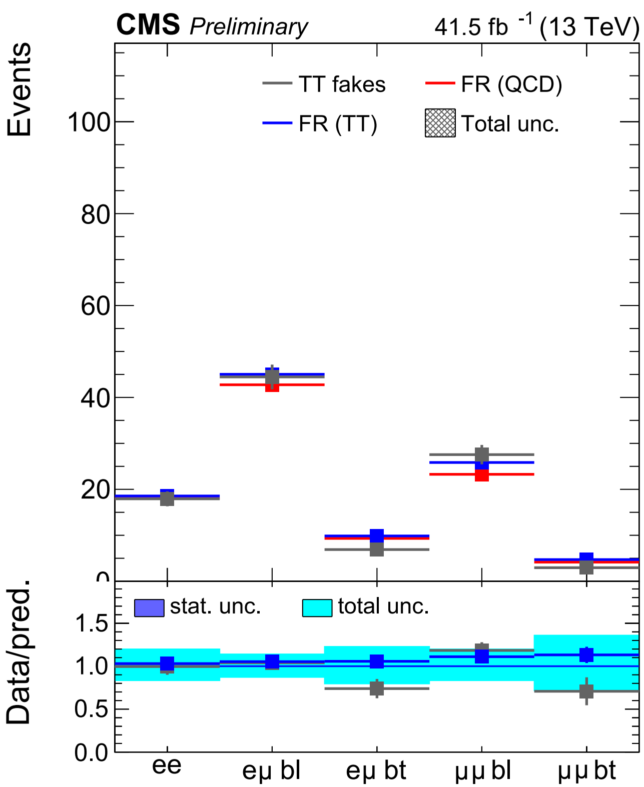
Backup: lepton fake rate (II)

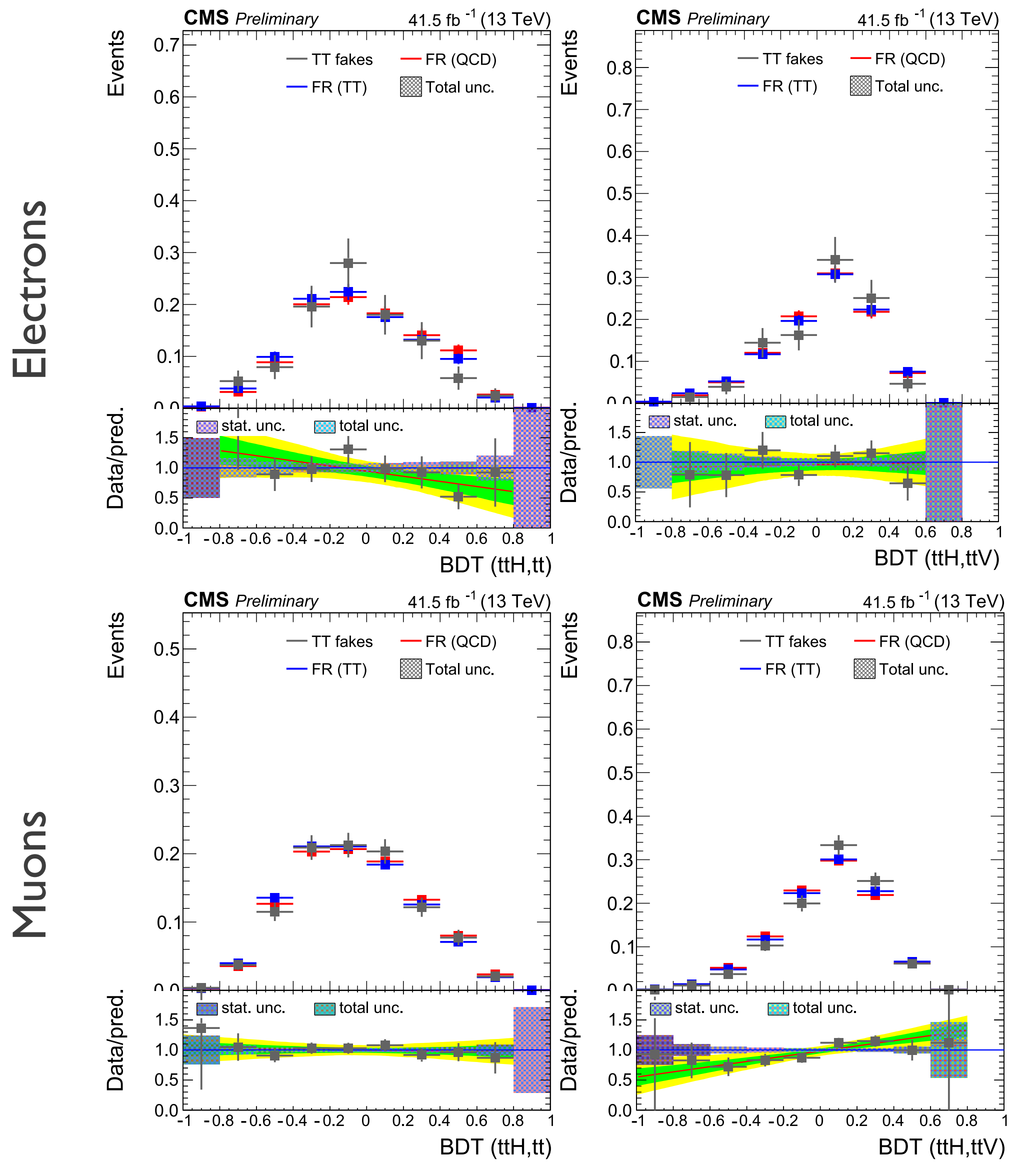
Sample name	Cross section [pb]
/QCD_Pt-20toInf_MuEnrichedPt15_TuneCP5_13TeV_pythia8/	2.38×10^5
/QCD_Pt-20to30_MuEnrichedPt5_TuneCP5_13TeV_pythia8/	2.49×10^6
/QCD_Pt-30to50_MuEnrichedPt5_TuneCP5_13TeV_pythia8/	1.36×10^6
/QCD_Pt-50to80_MuEnrichedPt5_TuneCP5_13TeV_pythia8/	3.78×10^5
/QCD_Pt-80to120_MuEnrichedPt5_TuneCP5_13TeV_pythia8/	8.84×10^4
/QCD_Pt-120to170_MuEnrichedPt5_TuneCP5_13TeV_pythia8/	2.13×10^4
/QCD_Pt-20to30_EMEnriched_TuneCP5_13TeV_pythia8/	4.93×10^6
/QCD_Pt-30to50_EMEnriched_TuneCP5_13TeV_pythia8/	6.41×10^6
/QCD_Pt-50to80_EMEnriched_TuneCP5_13TeV_pythia8/	1.99×10^6
/QCD_Pt-80to120_EMEnriched_TuneCP5_13TeV_pythia8/	3.71×10^5
/QCD_Pt-120to170_EMEnriched_TuneCP5_13TeV_pythia8/	6.68×10^4
/QCD_Pt_20to30_bcToE_TuneCP5_13TeV_pythia8/	3.14×10^5
/QCD_Pt_30to80_bcToE_TuneCP5_13TeV_pythia8/	3.62×10^5
/QCD_Pt_80to170_bcToE_TuneCP5_13TeV_pythia8/	3.38×10^4

HLT path	Prescale	Lepton cone-p_T	Lepton reco-p_T	Jet p_T
HLT_Ele8_CaloIdM_TrackIdM_PFJet30	1.14×10^4	15-45 GeV	> 27 GeV	> 30 GeV
HLT_Ele17_CaloIdM_TrackIdM_PFJet30	1.17×10^3	25-100 GeV	> 17 GeV	> 30 GeV
HLT_Ele23_CaloIdM_TrackIdM_PFJet30	1.07×10^3	32-100 GeV	> 23 GeV	> 30 GeV
HLT_Mu3_PFJet40	8.99×10^3	10-32 GeV	> 3 GeV	> 45 GeV
HLT_Mu8	1.59×10^4	15-45 GeV	> 8 GeV	> 30 GeV
HLT_Mu17	5.94×10^2	32-100 GeV	> 17 GeV	> 30 GeV
HLT_Mu20	2.25×10^2	32-100 GeV	> 20 GeV	> 30 GeV
HLT_Mu27	2.25×10^2	45-100 GeV	> 27 GeV	> 30 GeV

Backup: lepton fake rate (III)

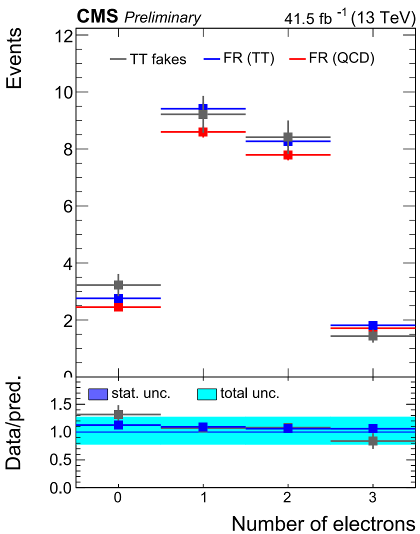
$2\ell SS$ closure plots



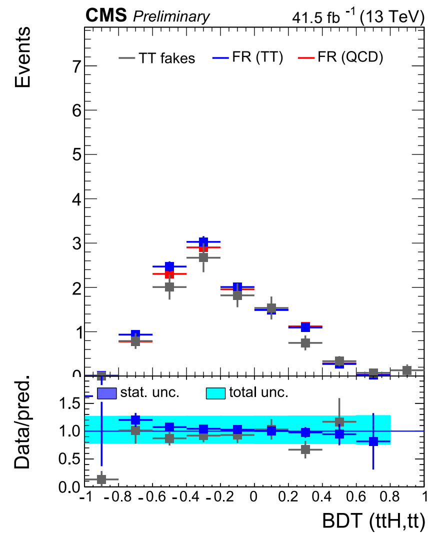


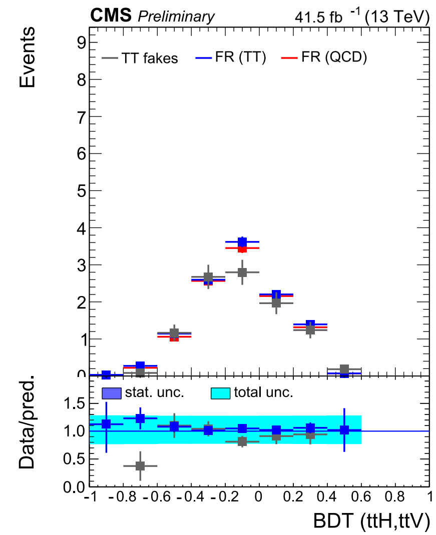
Backup: lepton fake rate (IV)

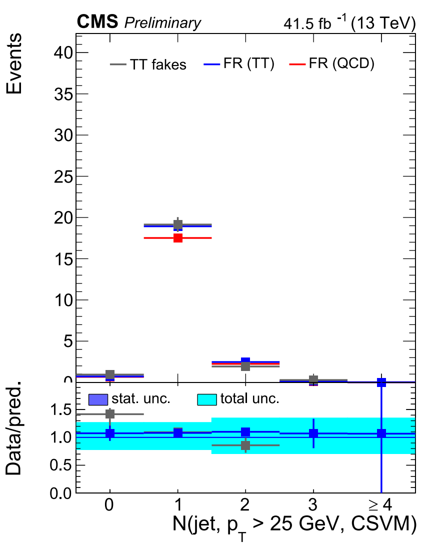
3ℓ closure plots



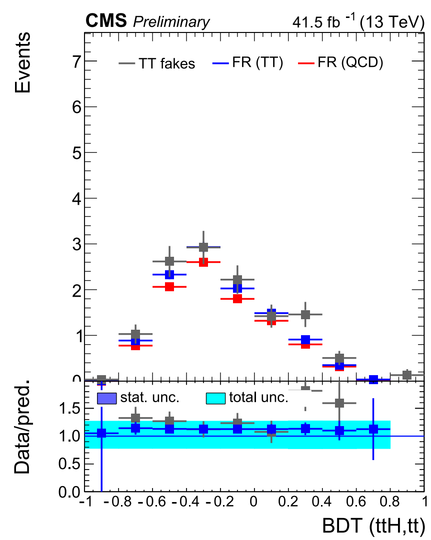
e fake

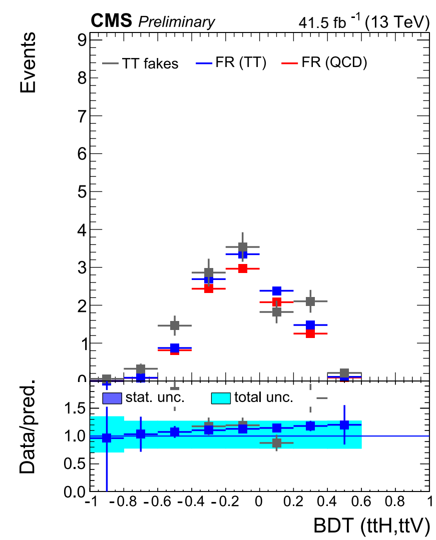




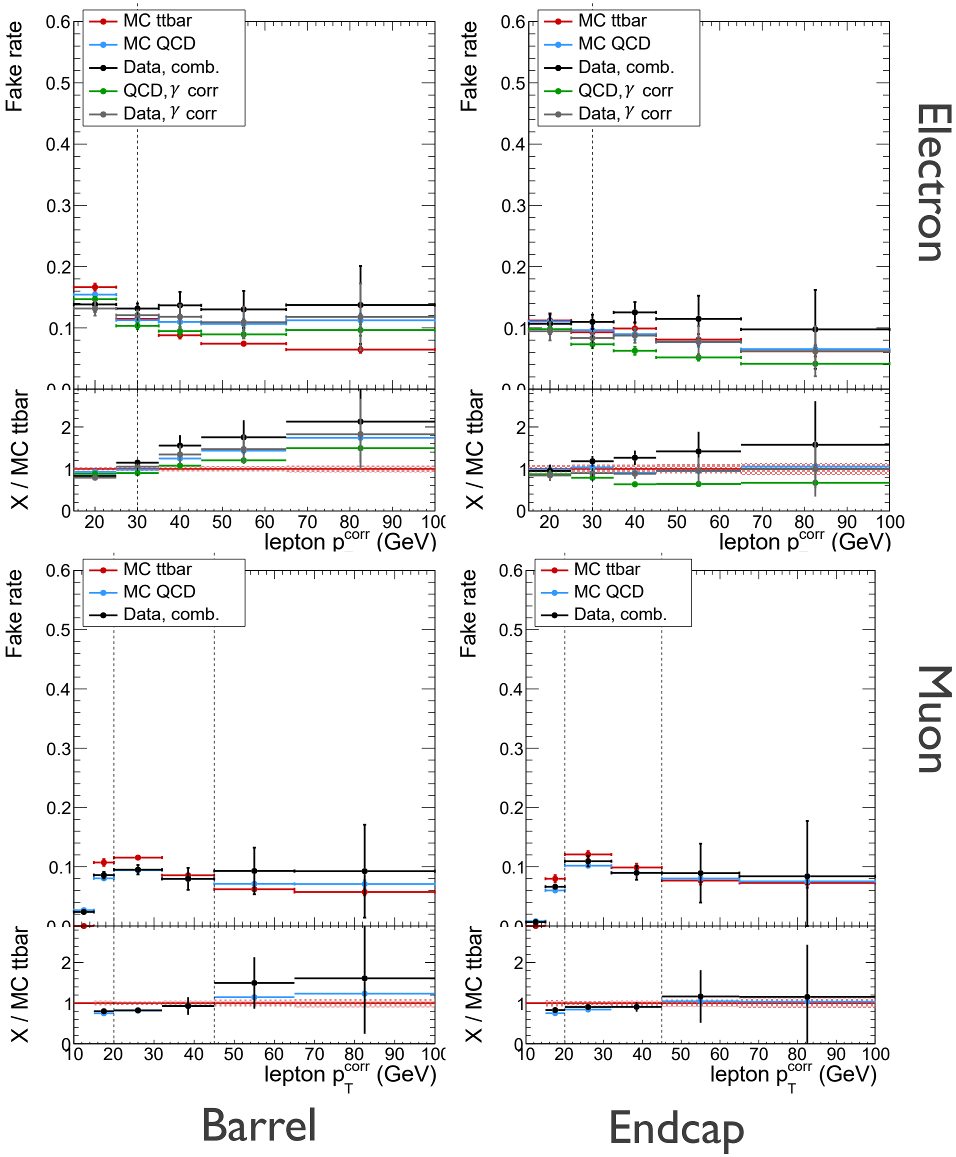


μ fake





Backup: lepton fake rate (V)



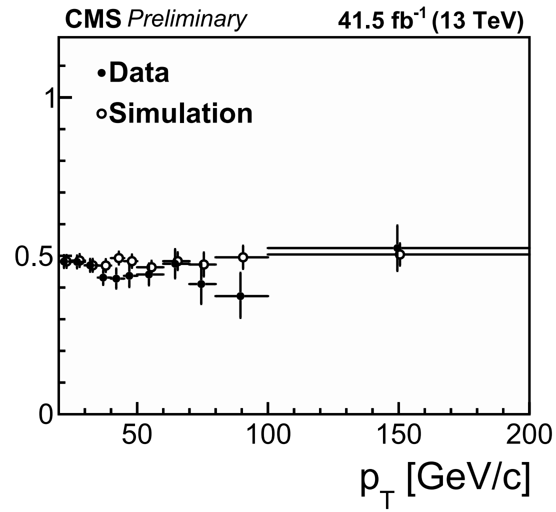
Backup: tau fake rate (I)

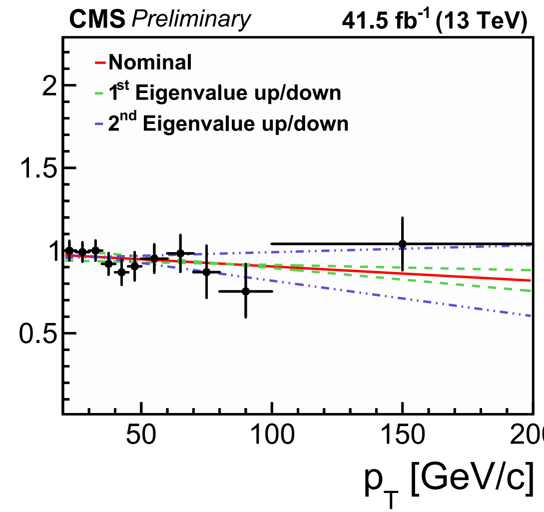
Loose WP

Fake rate

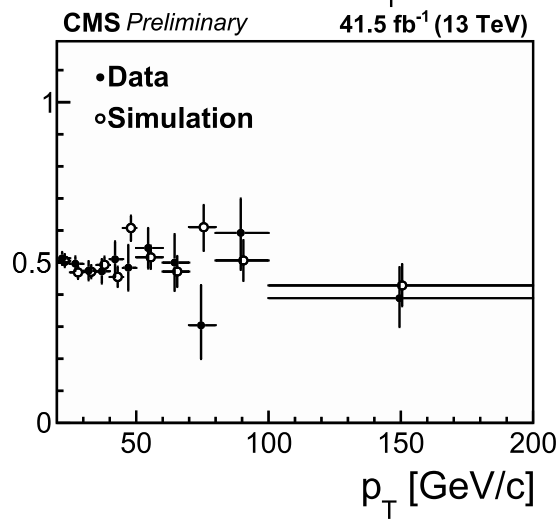
Data/MC SF

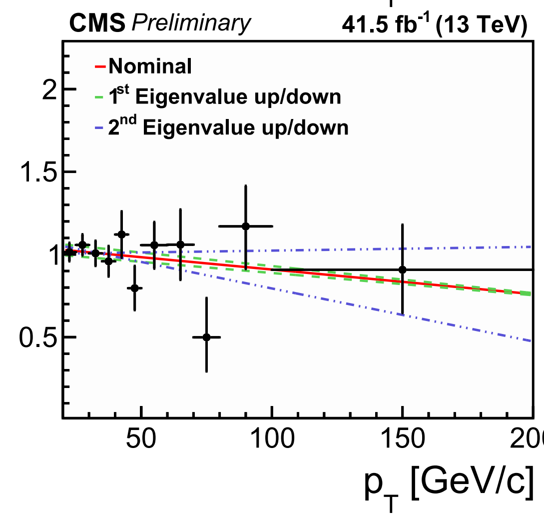
Barrel





Endcap



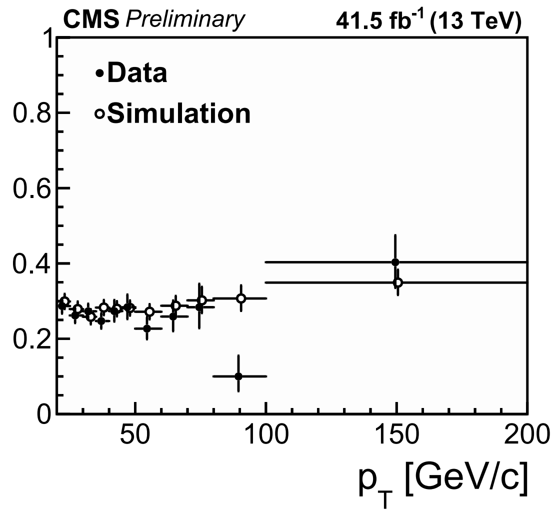


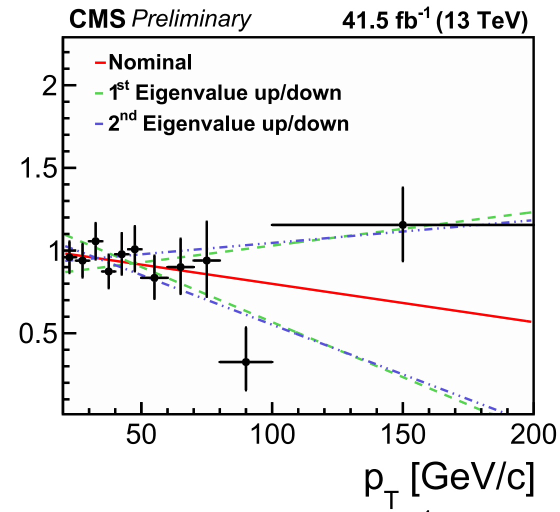
Backup: tau fake rate (II)

Medium WP

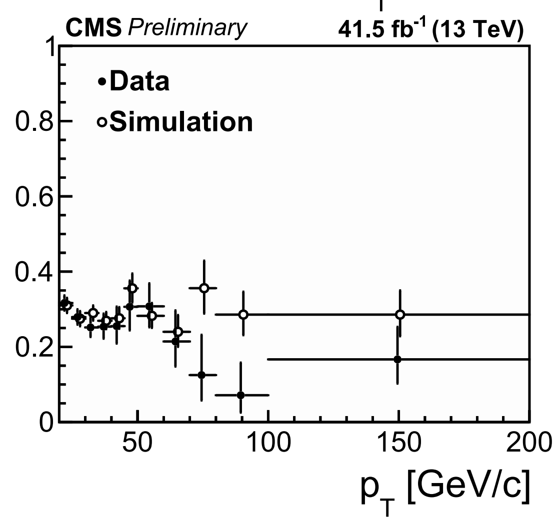
Fake rate | Data/MC SF

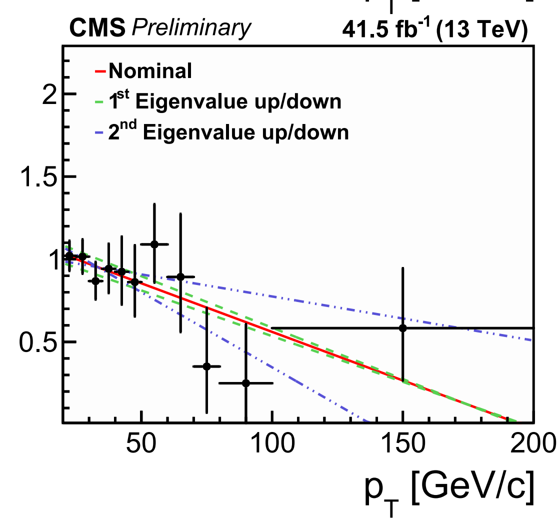
Barrel





Endcap





Backup: charge mis-ID rate

e_1 e_2	EH	BH	EM	BM	EL	BL
EH	**EH_EH**	**EH_BH**	**EH_EM**	**EH_BM**	**EH_EL**	**EH_BL**
BH	-	**BH_BH**	**BH_EM**	**BH_BM**	**BH_EL**	**BH_BL**
EM	-	-	**EM_EM**	**EM_BM**	**EM_EL**	**EM_BL**
BM	-	-	-	**BM_BM**	**BM_EL**	**BM_BL**
EL	-	-	-	-	**EL_EL**	**EL_BL**
BL	-	-	-	-	-	**BL_BL**

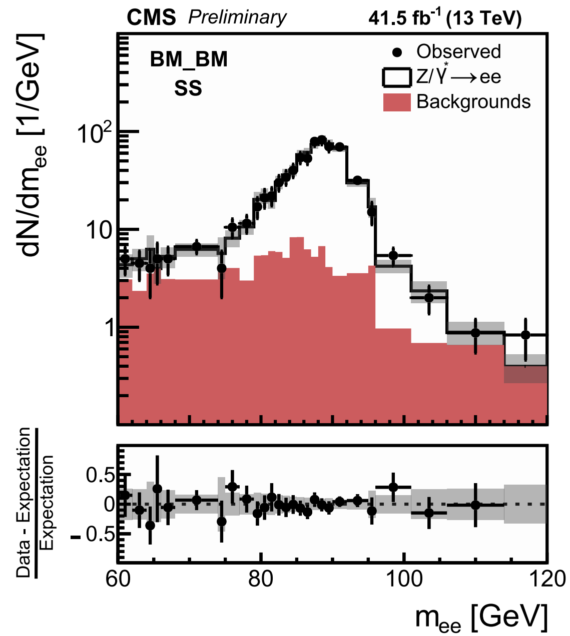
$r_{\mathrm{BL\_BL}} = 2\,p_{\mathrm{BL}}$
$r_{\mathrm{BM\_BL}} = p_{\mathrm{BM}} + p_{\mathrm{BL}}$
$r_{\mathrm{BM\_BM}} = 2\,p_{\mathrm{BM}}$
$r_{\mathrm{BH\_BL}} = p_{\mathrm{BH}} + p_{\mathrm{BL}}$
$r_{\mathrm{BH\_BM}} = p_{\mathrm{BH}} + p_{\mathrm{BM}}$
$r_{\mathrm{BH\_BH}} = 2\,p_{\mathrm{BH}}$
$r_{\mathrm{EL\_EL}} = 2\,p_{\mathrm{EL}}$
$r_{\mathrm{EM\_EL}} = p_{\mathrm{EM}} + p_{\mathrm{EL}}$
$r_{\mathrm{EM\_EM}} = 2\,p_{\mathrm{EM}}$
$r_{\mathrm{EH\_EL}} = p_{\mathrm{EH}} + p_{\mathrm{EL}}$
$r_{\mathrm{EH\_EM}} = p_{\mathrm{EH}} + p_{\mathrm{EM}}$

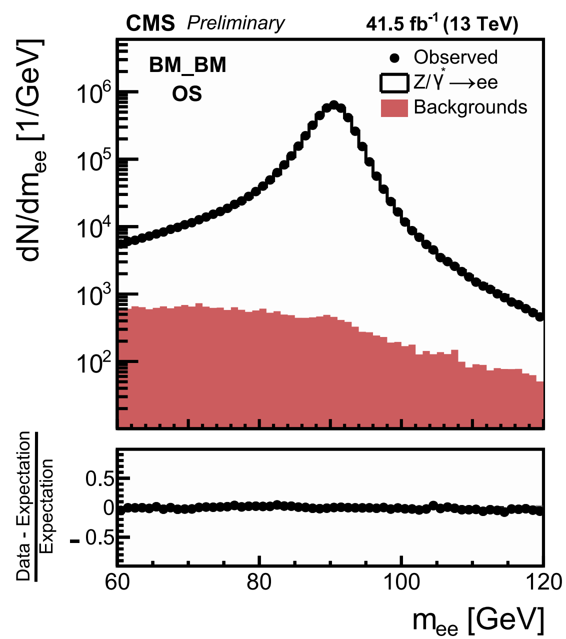
$r_{\mathrm{BH\_EH}} = p_{\mathrm{BH}} + p_{\mathrm{EH}}$
$r_{\mathrm{BL\_EL}} = p_{\mathrm{BL}} + p_{\mathrm{EL}}$
$r_{\mathrm{BM\_EL}} = p_{\mathrm{BM}} + p_{\mathrm{EL}}$
$r_{\mathrm{EM\_BL}} = p_{\mathrm{EM}} + p_{\mathrm{BL}}$
$r_{\mathrm{BM\_EM}} = p_{\mathrm{BM}} + p_{\mathrm{EM}}$
$r_{\mathrm{BH\_EL}} = p_{\mathrm{BH}} + p_{\mathrm{EL}}$
$r_{\mathrm{EH\_BL}} = p_{\mathrm{EH}} + p_{\mathrm{BL}}$
$r_{\mathrm{BH\_EM}} = p_{\mathrm{BH}} + p_{\mathrm{EM}}$
$r_{\mathrm{EH\_BM}} = p_{\mathrm{EH}} + p_{\mathrm{BM}}$
$r_{\mathrm{BH\_EH}} = p_{\mathrm{BH}} + p_{\mathrm{EH}}$

Category	r
BL_BL	0.047 ± 0.022
BM_BL	0.037 ± 0.004
BM_BM	0.016 ± 0.001
BH_BL	0.016 ± 0.009
BH_BM	0.020 ± 0.001
BH_BH	0.026 ± 0.014
EL_EL	0.000 ± 0.000
EM_EL	0.000 ± 0.000
EM_EM	0.181 ± 0.008
EH_EL	0.340 ± 0.070
EH_EM	0.191 ± 0.009

Category	r
EH_EH	0.337 ± 0.037
BL_EL	0.028 ± 0.017
BM_EL	0.042 ± 0.006
EM_BL	0.069 ± 0.007
BM_EM	0.078 ± 0.003
BH_EL	0.046 ± 0.012
EH_BL	0.198 ± 0.018
BH_EM	0.088 ± 0.007
EH_BM	0.119 ± 0.007
BH_EH	0.204 ± 0.022

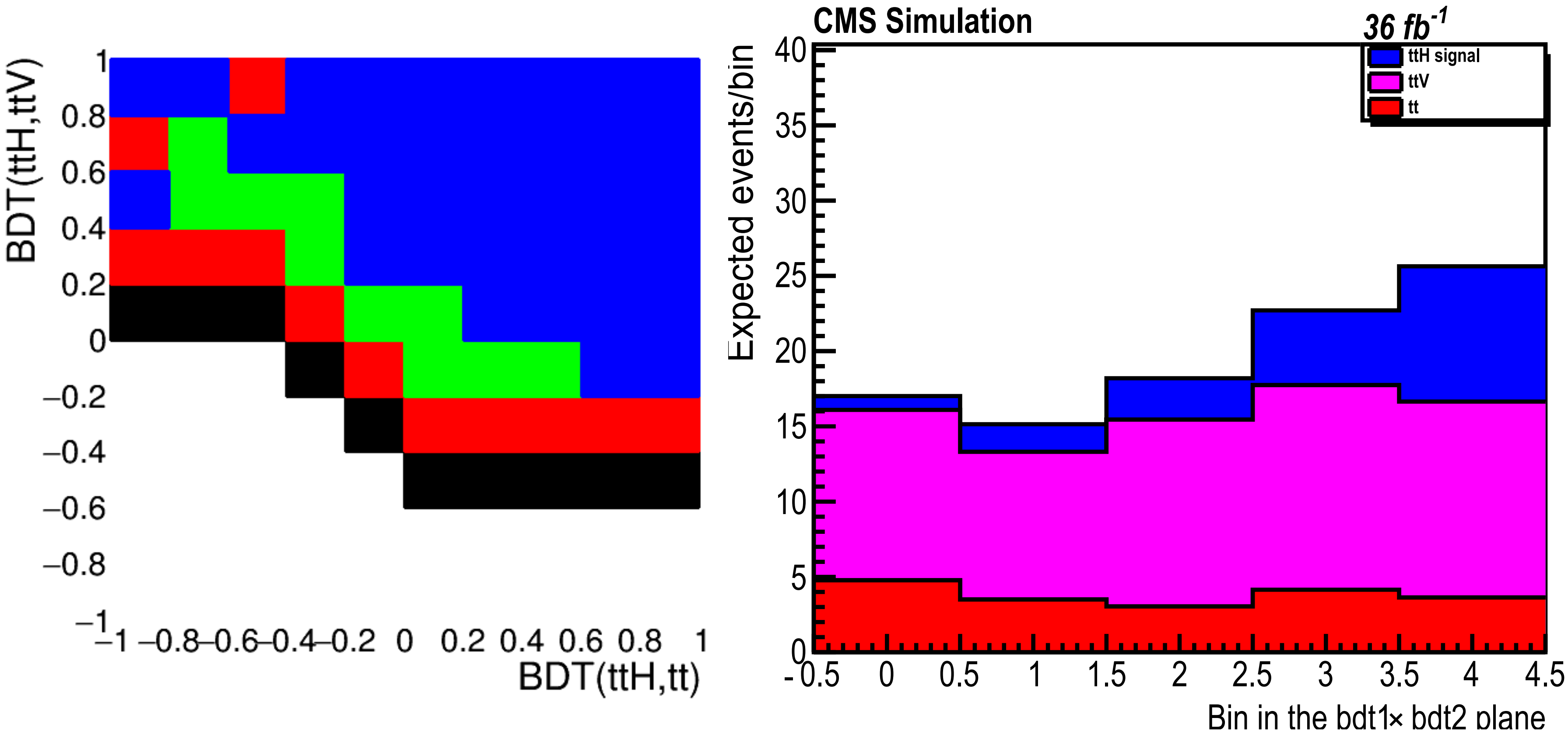
		$15 \leq p_T < 25$ GeV	$25 \leq p_T < 50$ GeV	$p_T \geq 50$ GeV
MC truth	$\lvert\eta\rvert < 1.479$	0.0081 ± 0.0015	0.0053 ± 0.0003	0.0071 ± 0.0009
	$1.479 \leq \lvert\eta\rvert < 2.5$	0.0579 ± 0.0068	0.0507 ± 0.0016	0.0915 ± 0.0061
Pseudodata	$\lvert\eta\rvert < 1.479$	0.0009 ± 0.0024	0.0096 ± 0.0027	0.0132 ± 0.0019
	$1.479 \leq \lvert\eta\rvert < 2.5$	0.0095 ± 0.0045	0.0507 ± 0.0028	0.0907 ± 0.0067
Data	$\lvert\eta\rvert < 1.479$	0.0134 ± 0.0041	0.0224 ± 0.0041	0.0228 ± 0.0053
	$1.479 \leq \lvert\eta\rvert < 2.5$	0.0199 ± 0.0070	0.0560 ± 0.0041	0.1387 ± 0.0087





Backup: 1D mapping of two BDTs

Fig 40 in AN 2017/029 v5

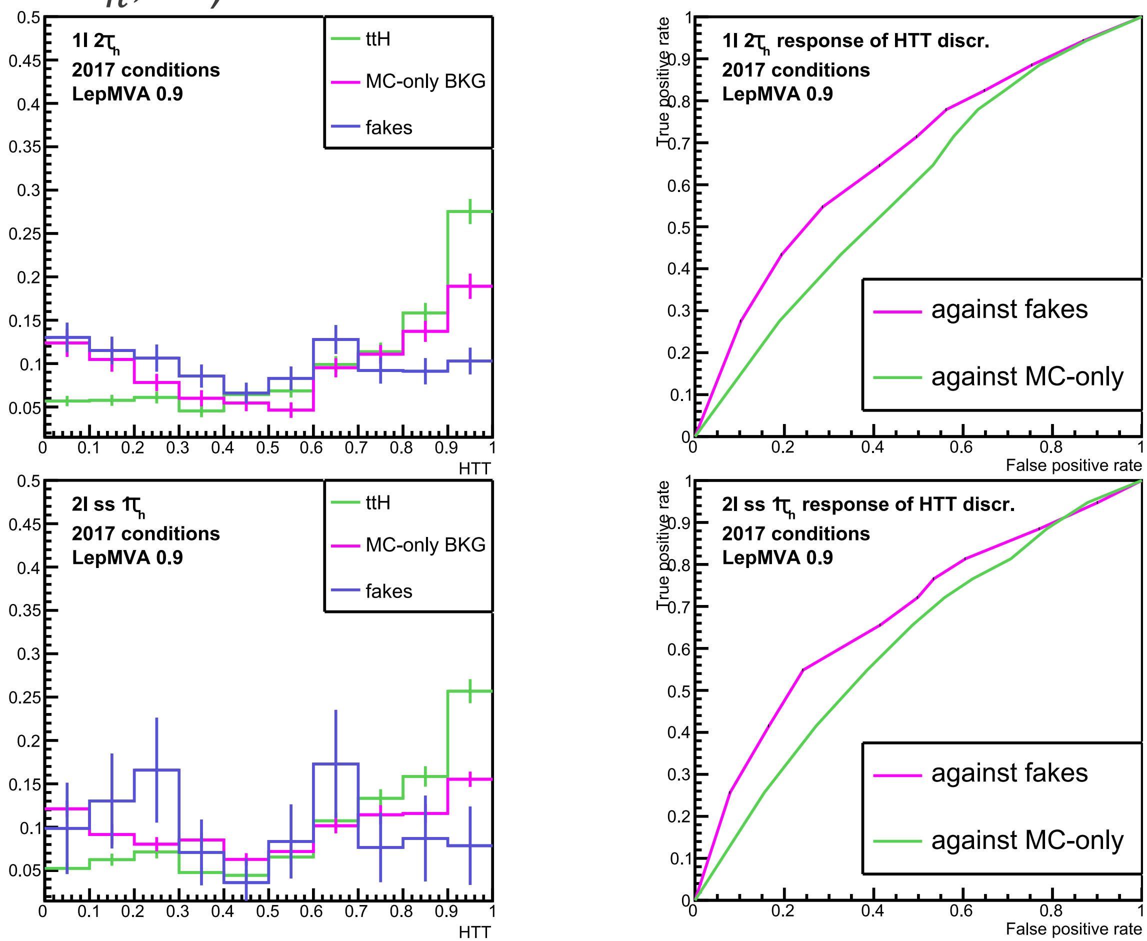


Backup: resolved Hadronic Top Tagger (I)

- BDT-based discriminator aiming to reconstruct hadronic top decay
- Computes the likelihood of a jet triplet to be compatible with hadronic top decay products
- Full combinatorics of jet triplets in an event are tried
  - jet triplet: 1 b-jet candidate + 2 W-jet candidates W_1 (higher in p_T) and W_2 (lower in p_T)
  - the one with the best score is used in the BDT for signal extraction
- 8 input variables
  - b-tagging score of the b-jet candidate
  - masses of $W_1 + W_2$ and $b + W_1 + W_2$ and p_T of $b + W_1 + W_2$
  - p_T and quark-gluon discriminator of W-jet candidate with lower p_T (ie W_2)
  - value of the likelihood function L used in kinematic fit subject to mass constraints $m_W = 80.4$ GeV and $m_t = 173.1$ GeV:
    $$L = W\left(p_T^b \middle| \hat{p}_T^b\right) W\left(p_T^{W1} \middle| \hat{p}_T^{W1}\right) W\left(p_T^{W2} \middle| \hat{p}_T^{W2}\right)$$
    where W refers to transfer function that relates true quantities (with hats) to reconstructed quantities (without hats)
  - ratio between the p_T of b-jet candidate before and after kinematic fit

Backup: resolved Hadronic Top Tagger (II)

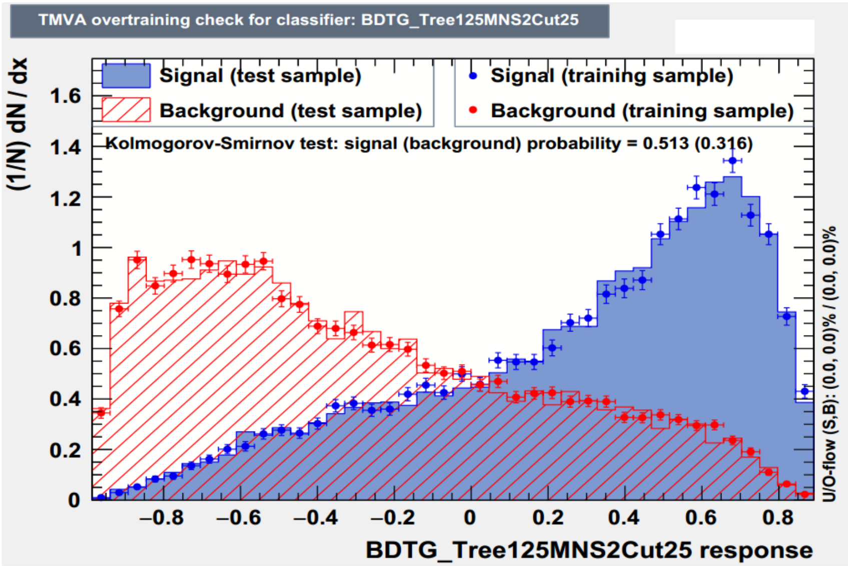
- Training performed on a mixture of $t\bar{t}H$, $t\bar{t}W$, $t\bar{t}Z$ and $t\bar{t}$+jets samples
- No special event selection so that the BDT is applicable in all channels where the top quarks are expected to decay hadronically ($1\ell + 2\tau_h$, $2\ell SS$, $2\ell SS + 1\tau_h$, 3ℓ)

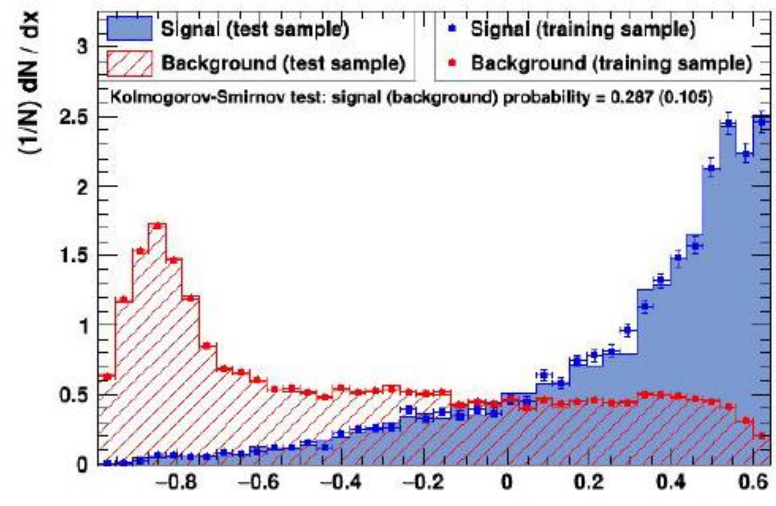


Backup: Hj tagger (I)

- BDT-based discriminator to assess likelihood of a jet originating from H decay
- Jets from $H \rightarrow WW^* \rightarrow \ell\nu qq'$ decay considered as signal, other jets treated as background
- Jets in the event selection allowed to fail jet object selection cuts $p_T > 25$ GeV and $|\eta| < 2.4$
- Trained on $t\bar{t}H$, $t\bar{t}W$ and $t\bar{t}Z$ events
- 5 input variables
  - minimum and maximum ΔR between the jet and any electron or muon that passes the fakeable lepton selection criteria
  - p_T, DeepCSV score and quark-gluon discriminator of the jet
- Retrained with 2017 detector conditions
- Performance similar to 2016 version

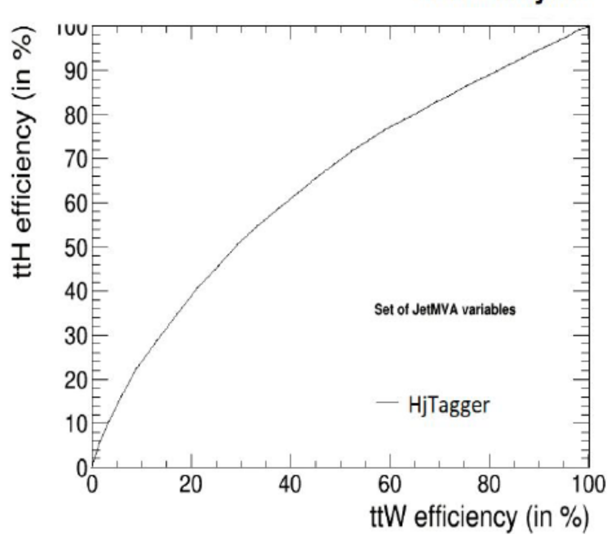
Backup: Hj tagger (II)

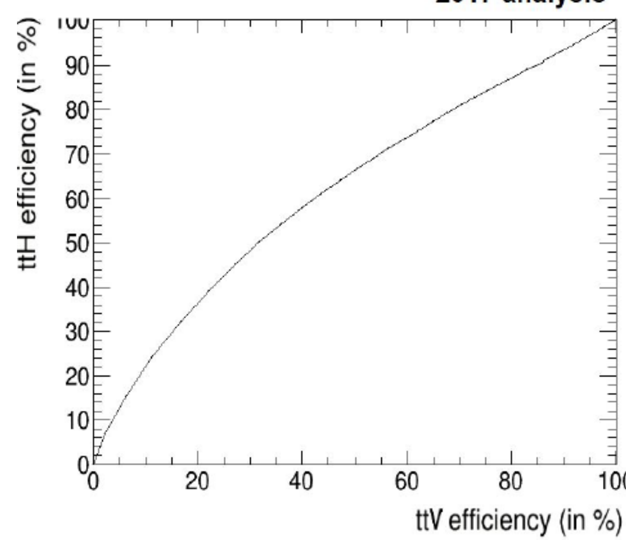




2016 analysis

2017 analysis





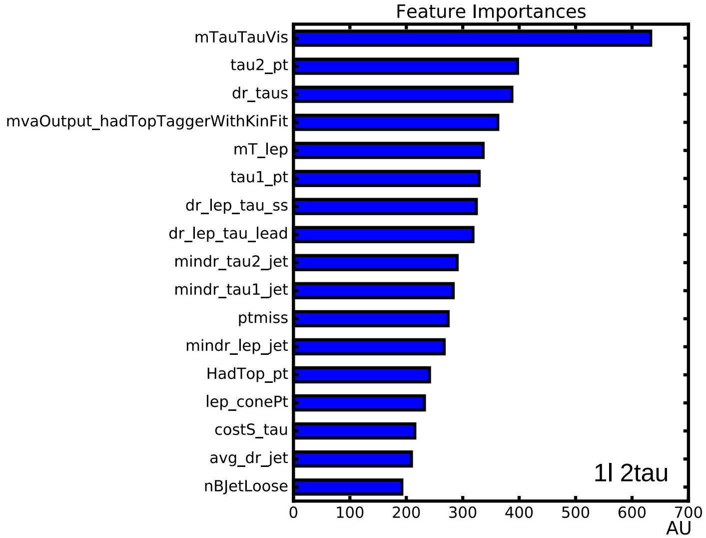
Backup: variables used in event-level BDT training (I)

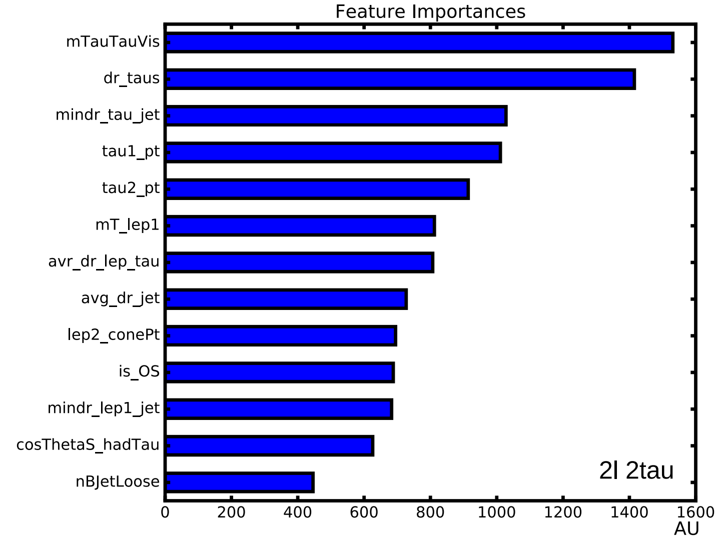
Category	$1\ell + 2\tau_h$	$2\ell ss + 1\tau_h$	$2\ell + 2\tau_h$	$3\ell + 1\tau_h$	$2\ell ss$		3ℓ	
Comment					$t\bar{t}$	$t\bar{t}V$	$t\bar{t}$	$t\bar{t}V$
Leading ℓ cone p_T	X		X	X		X		X
Trailing ℓ cone p_T		X		X		X		X
Minimum of ΔR(leading ℓ, j)	X	X	X	X	X	X	X	X
Minimum of ΔR(trailing ℓ, j)		X			X	X		
ΔR(leading ℓ, trailing ℓ		X		X				
Transverse Mass of leading ℓ	X	X			X	X	X	X
Transverse Mass of trailing ℓ		X					X	X
Maximum $\lvert\eta\rvert$ of ℓ collection		X		X	X	X	X	X
Signal leading $\ell \times$ signal trailing ℓ			X					
Average of ΔR(jj)	X	X	X					
Number of jets ($p_T > 25$ GeV)		X		X	X	X		
Number of loose b-jets	X		X					
Mass of leading medium b-jet pair		X						
Mass of leading loose b-jet pair				X				
E_T^{miss}	X	X		X				
res-hTT	X	X						
Hadronic t p_T	X	X						
$\mathcal{D}_{\rm thad}^{\rm max}$					X	X	X	X
$\mathcal{D}_{\rm Hj}^{\rm max}$					X	X	X	X

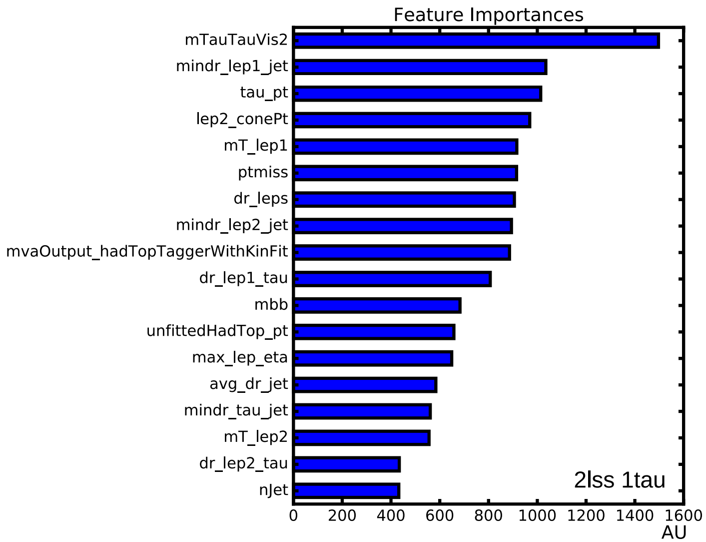
Backup: variables used in event-level BDT training (II)

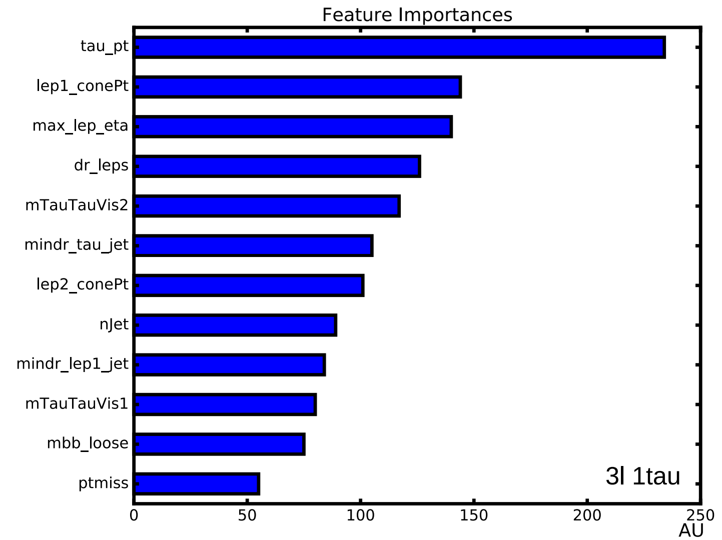
Category	$1\ell + 2\tau_h$	$2\ell ss + 1\tau_h$	$2\ell + 2\tau_h$	$3\ell + 1\tau_h$	$2\ell ss$		3ℓ	
Comment					$t\bar{t}$	$t\bar{t}V$	$t\bar{t}$	$t\bar{t}V$
Leading τ_h p_T	X	X	X	X				
Trailing τ_h p_T	X		X					
Mass of leading τ_h + trailing τ_h	X		X					
ΔR(leading τ_h, trailing τ_h)	X		X					
$cos(\theta)^*$(leading τ_h, trailing τ_h)	X		X					
Minimum of ΔR(leading τ_h, j)	X	X		X				
Minimum of ΔR(trailing τ_h, j)	X							
Minimum of $\Delta R(\tau_h, j)$			X					
Mass of leading ℓ+ leading τ_h				X				
Mass of trailing ℓ+ leading τ_h		X		X				
ΔR(leading ℓ, leading τ_h)	X	X						
ΔR(trailing ℓ, leading τ_h)		X						
$\Delta R(\ell, \tau_h)$ for same-sign pair of (ℓ, τ_h)	X							
Average of $\Delta R(\ell, \tau_h)$			X					
MEM								X
Number of variables	17	18	13	12	7	9	6	9

Backup: ranking of BDT input variables in categories with τ_h

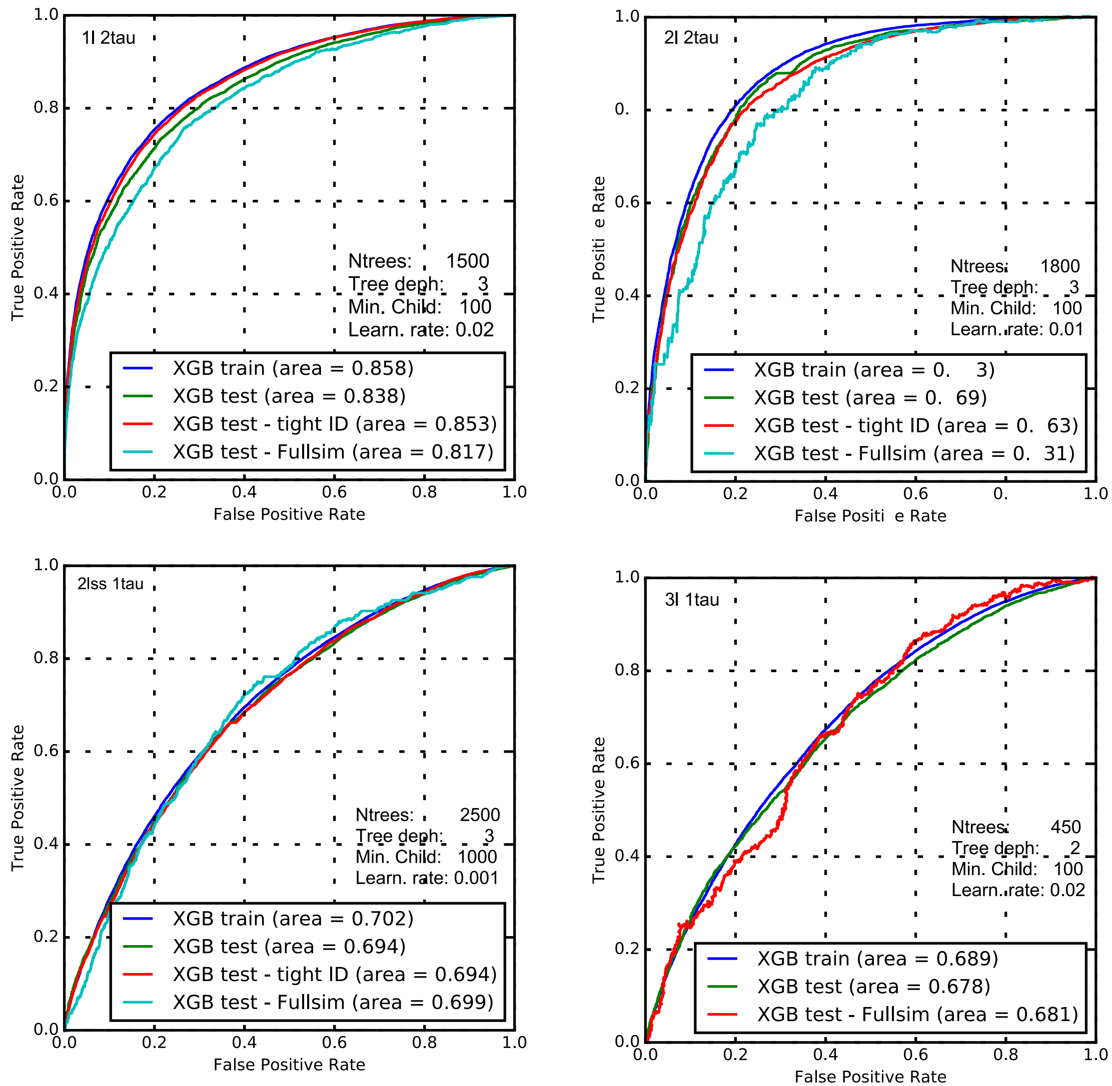






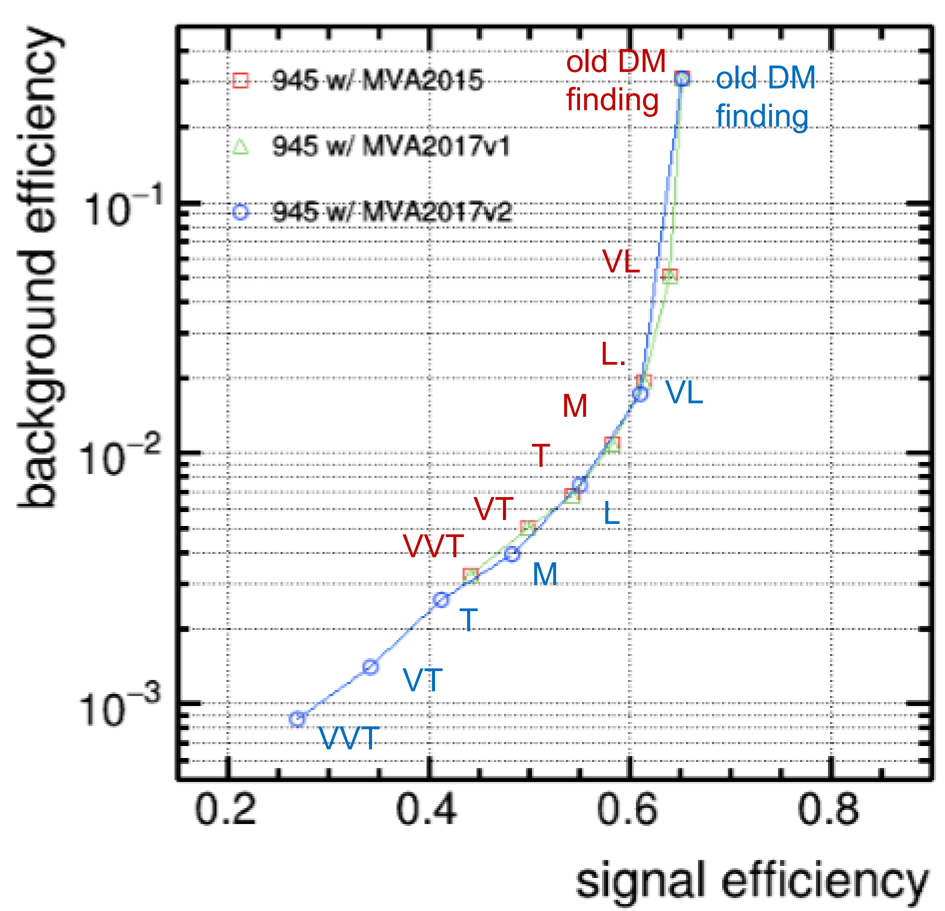


Backup: ROC curves of BDT in categories with τ_h

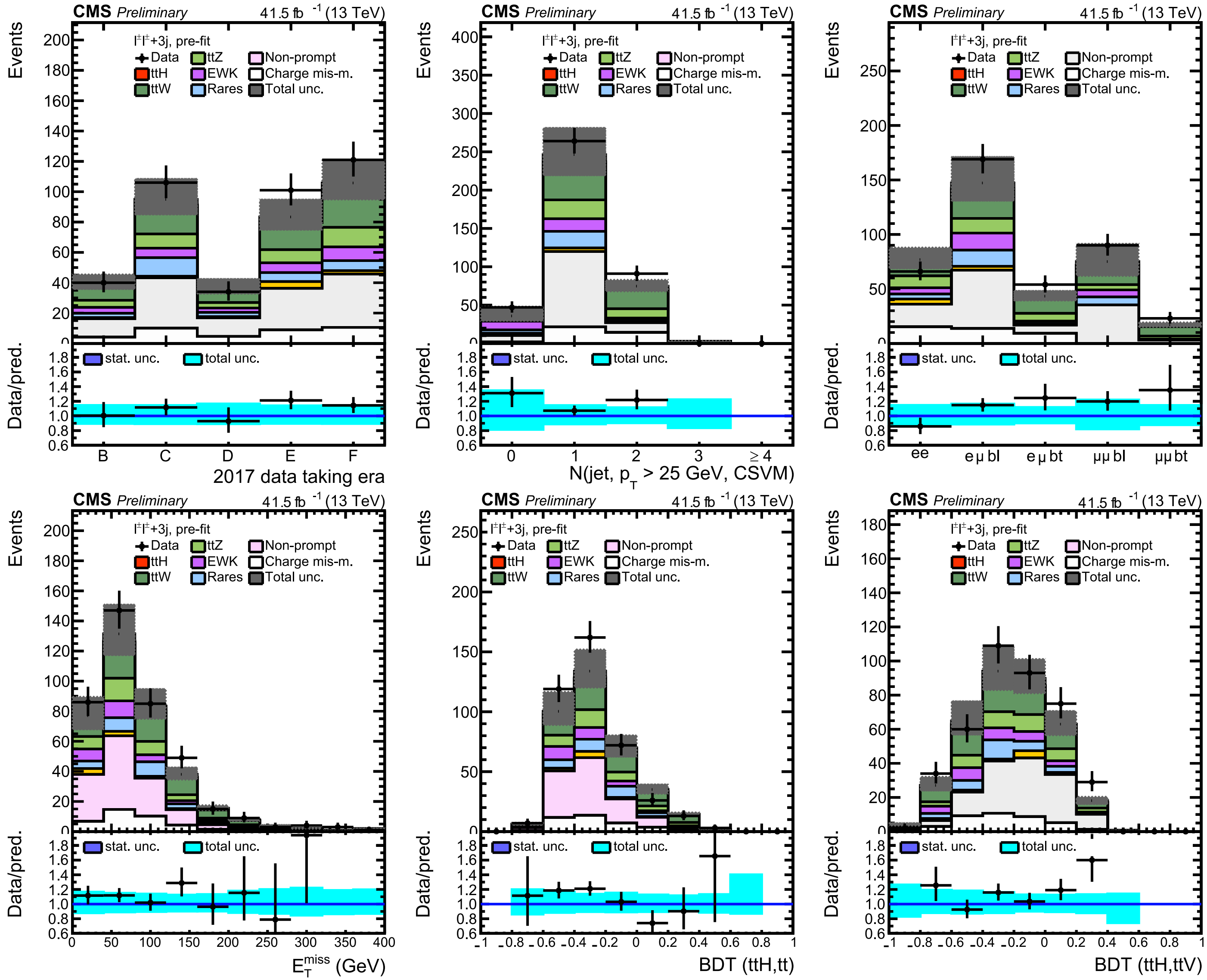


Backup: Tau POG MVA WPs

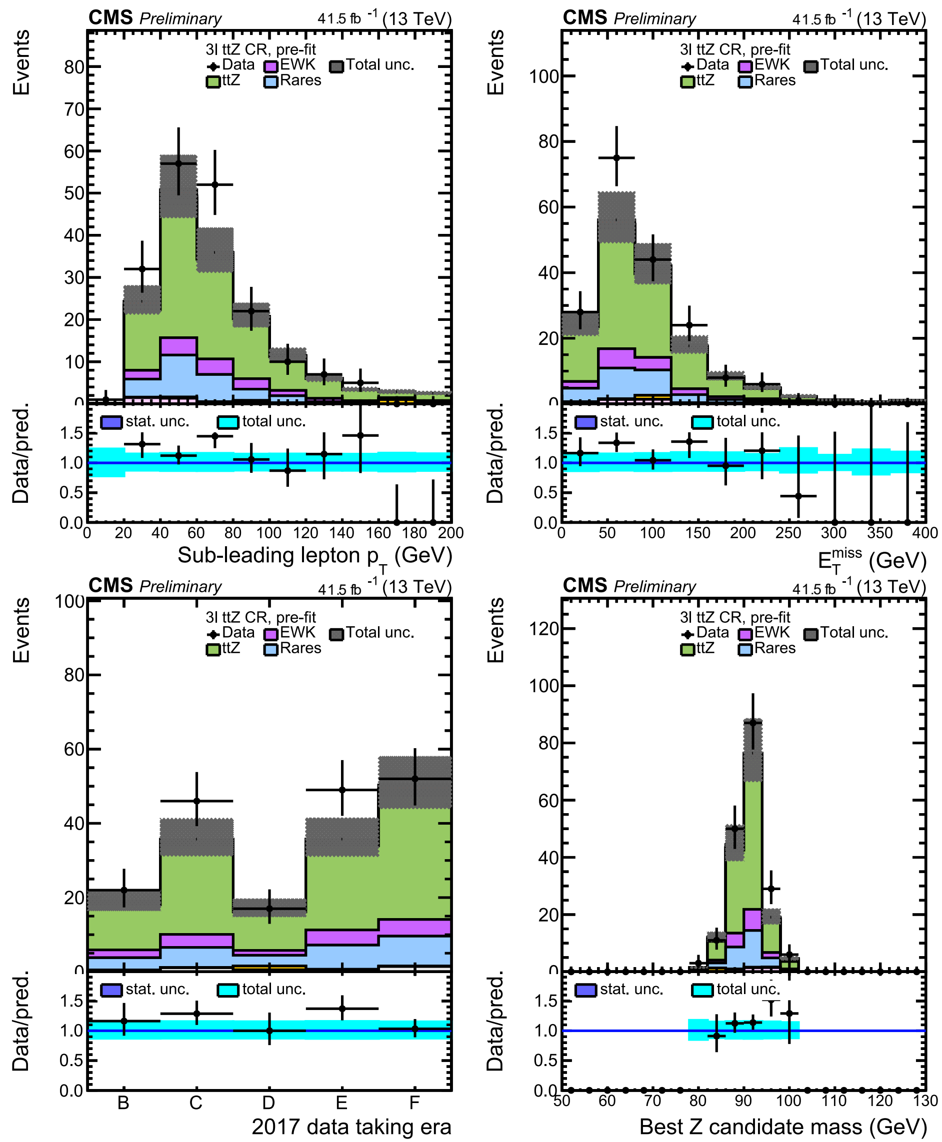
- WPs have shifted with `2017v2` wrt `2015` training (Loose → VLoose, Medium → Loose, Tight → Medium)
- See https://hypernews.cern.ch/HyperNews/CMS/get/tauid/822.html for more info



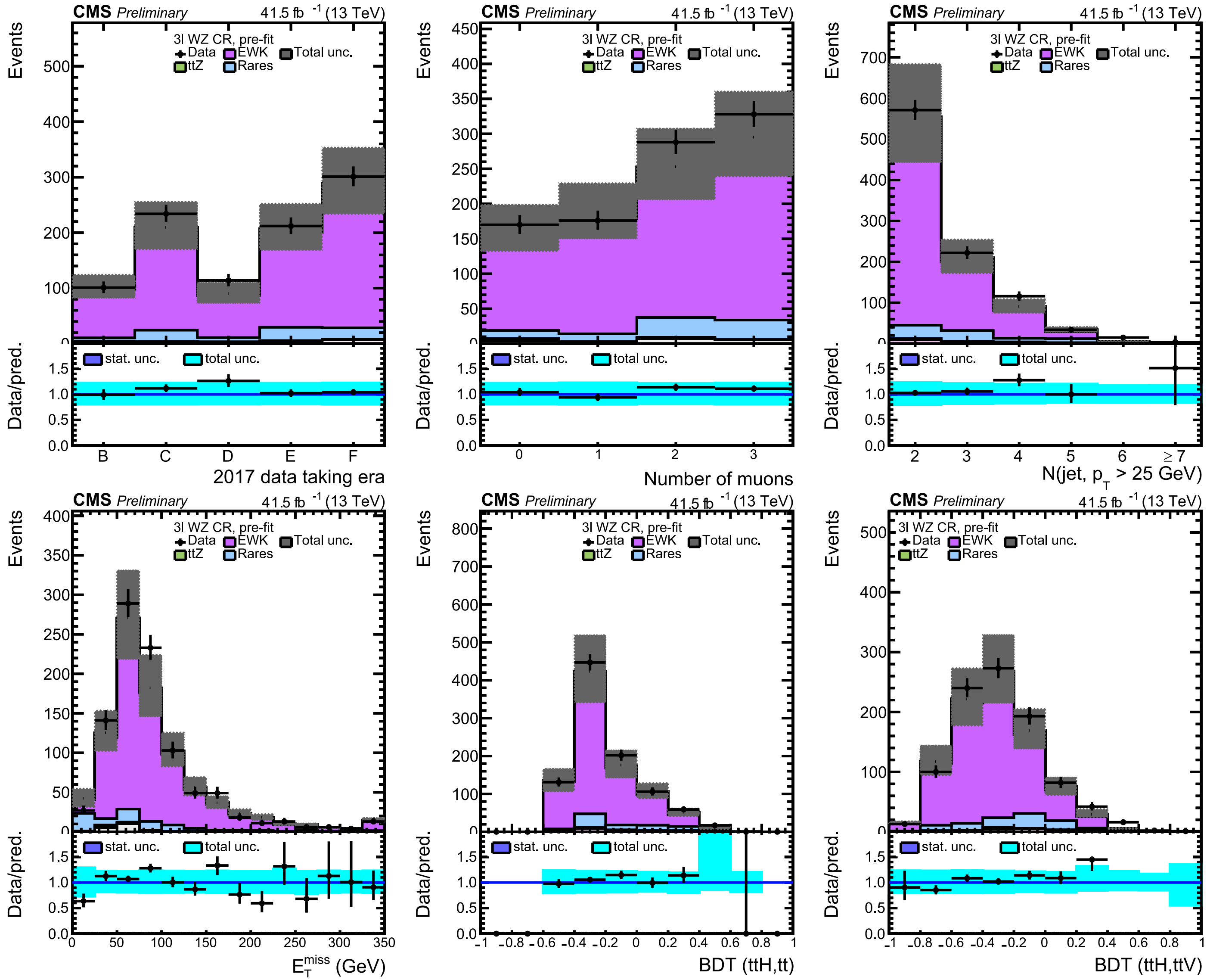
Backup: $t\bar{t}W$ control regions



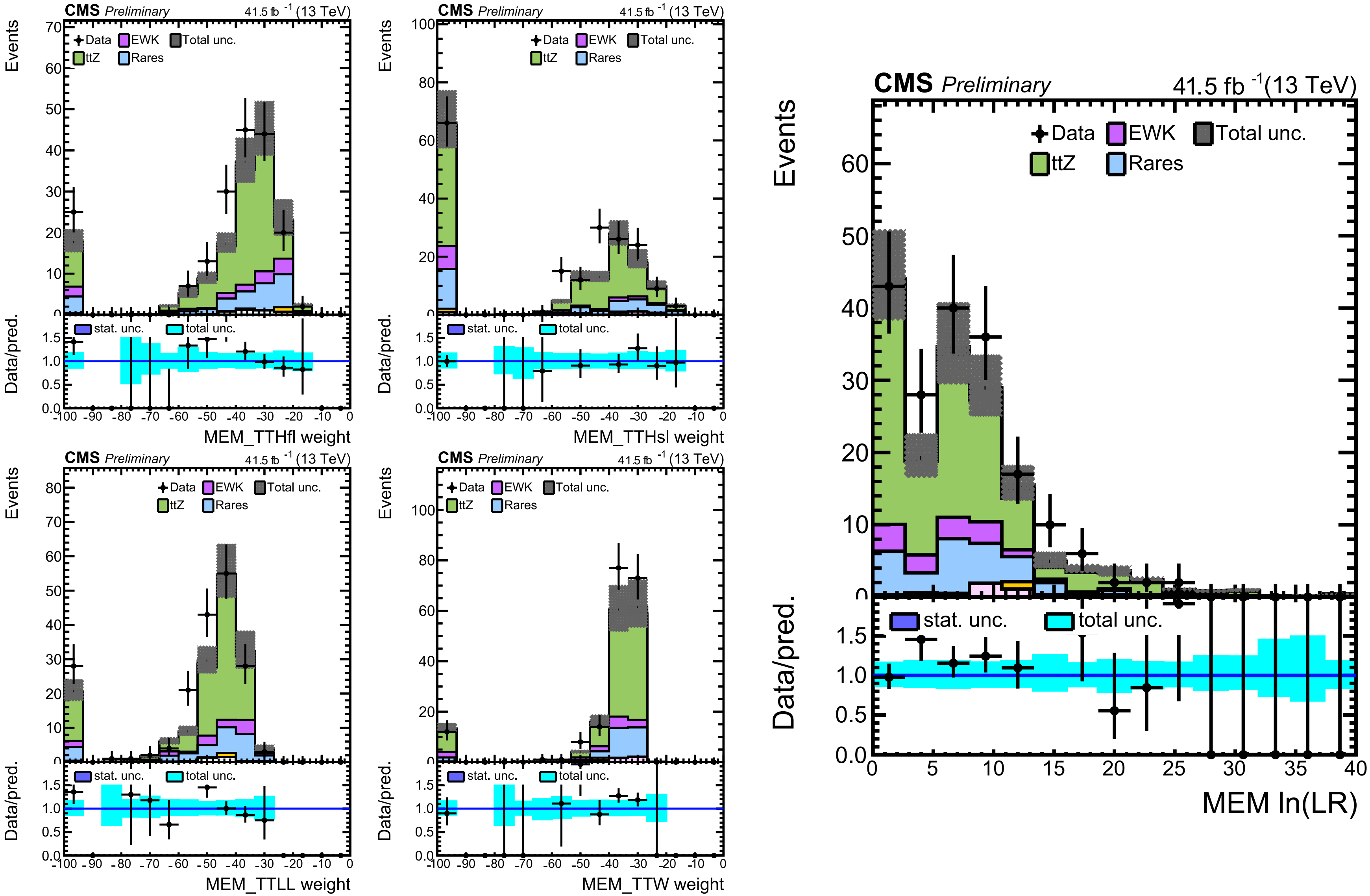
Backup: $t\bar{t}Z$ control regions



Backup: WZ control regions



Backup: MEM discriminant in $t\bar{t}Z$ control region



Backup: samples used in BDT training

Dataset name	Number of events
/TTTo2L2Nu_TuneCUETP8M2_ttHtranche3_13TeV-powheg-pythia8/matze-faster_v8_ttjets_dl_maod_p1_3a2fa29ab1d54ae0995b28f27b405be9-v1/USER	
/TTTo2L2Nu_TuneCUETP8M2_ttHtranche3_13TeV-powheg-pythia8/matze-faster_v8_ttjets_dl_maod_p2_3a2fa29ab1d54ae0995b28f27b405be9-v1/USER	
/TTTo2L2Nu_TuneCUETP8M2_ttHtranche3_13TeV-powheg-pythia8/matze-faster_v8_ttjets_dl_maod_p3_3a2fa29ab1d54ae0995b28f27b405be9-v1/USER	90528029
/TTToSemilepton_TuneCUETP8M2_ttHtranche3_13TeV-powheg-pythia8/matze-faster_v8_ttjets_sl_maod_p1_3a2fa29ab1d54ae0995b28f27b405be9-v1/USER	
/TTToSemilepton_TuneCUETP8M2_ttHtranche3_13TeV-powheg-pythia8/matze-faster_v8_ttjets_sl_maod_p2_3a2fa29ab1d54ae0995b28f27b405be9-v1/USER	
/TTToSemilepton_TuneCUETP8M2_ttHtranche3_13TeV-powheg-pythia8/matze-faster_v8_ttjets_sl_maod_p3_3a2fa29ab1d54ae0995b28f27b405be9-v1/USER	85311662
/ttHToNonbb_M125_TuneCUETP8M2_ttHtranche3_13TeV-powheg-pythia8/matze-faster_v8_ttH_maod_p1_3a2fa29ab1d54ae0995b28f27b405be9-v1/USER	
/ttHToNonbb_M125_TuneCUETP8M2_ttHtranche3_13TeV-powheg-pythia8/matze-faster_v8_ttH_maod_p2_3a2fa29ab1d54ae0995b28f27b405be9-v1/USER	
/ttHToNonbb_M125_TuneCUETP8M2_ttHtranche3_13TeV-powheg-pythia8/matze-faster_v8_ttH_maod_p3_3a2fa29ab1d54ae0995b28f27b405be9-v1/USER	16459381
/TTWJetsToLNu_TuneCUETP8M1_13TeV-amcatnloFXFX-madspin-pythia8/matze-faster_v9_ttW_maod_54aa74f75231422e9f4d3766cb92a64a-v1/USER	7158309
/TTZToLLNuNu_M-10_TuneCUETP8M1_13TeV-amcatnlo-pythia8/matze-faster_v9_ttZ_maod_54aa74f75231422e9f4d3766cb92a64a-v1/USER	8826709

Backup: signal rates of $t\bar{t}H$, $t\bar{t}Z$ and $t\bar{t}W + t\bar{t}WW$

Signal rates μ, in units of the SM $t\bar{t}H$ and $t\bar{t}Z$ and $t\bar{t}W + t\bar{t}WW$ production rates, measured including $t\bar{t}Z$ and $t\bar{t}W + t\bar{t}WW$ control regions on the fit:

	signal strength $\pm 1\sigma$	
	Measured	Expected
$\mu_{t\bar{t}H}$	$0.75^{+0.46}_{-0.43}$	$1.00^{+0.39}_{-0.35}$
$\mu_{t\bar{t}W}$	$1.42^{+0.34}_{-0.33}$	$1.00^{+0.27}_{-0.23}$
$\mu_{t\bar{t}Z}$	$1.69^{+0.39}_{-0.33}$	$1.00^{+0.23}_{-0.20}$

Backup: pre-fit yields (I)

Category	$2\ell ss$									
b-tag	no req.		Loose				Tight			
Leptons	ee		eμ		$\mu\mu$		eμ		$\mu\mu$	
Charge	$-$	$+$	$-$	$+$	$-$	$+$	$-$	$+$	$-$	$+$
$t\bar{t}$H, H $\to$ ZZ	0.20 $\pm$ 0.03	0.17 $\pm$ 0.02	0.30 $\pm$ 0.04	0.21 $\pm$ 0.02	0.14 $\pm$ 0.02	0.18 $\pm$ 0.03	0.32 $\pm$ 0.04	0.21 $\pm$ 0.04	0.10 $\pm$ 0.02	0.10 $\pm$ 0.02
$t\bar{t}$H, H $\to$ WW	3.58 $\pm$ 0.50	3.79 $\pm$ 0.49	7.27 $\pm$ 0.80	6.84 $\pm$ 0.79	4.76 $\pm$ 0.53	4.90 $\pm$ 0.55	5.07 $\pm$ 0.75	5.60 $\pm$ 0.84	3.65 $\pm$ 0.52	3.22 $\pm$ 0.46
$t\bar{t}$H, H $\to$ $\tau\tau$	0.85 $\pm$ 0.12	0.82 $\pm$ 0.11	1.29 $\pm$ 0.14	1.38 $\pm$ 0.16	0.78 $\pm$ 0.08	0.88 $\pm$ 0.09	1.08 $\pm$ 0.15	0.91 $\pm$ 0.12	0.65 $\pm$ 0.09	0.56 $\pm$ 0.08
$t\bar{t}$H, H $\to$ $\mu\mu$	$<$ 0.05	$<$ 0.05	$<$ 0.05	$<$ 0.05	$<$ 0.05	$<$ 0.05	$<$ 0.05	$<$ 0.05	$<$ 0.05	$<$ 0.05
$t\bar{t}$H, H $\to$ Zγ	$<$ 0.05	$<$ 0.05	$<$ 0.05	$<$ 0.05	$<$ 0.05	$<$ 0.05	$<$ 0.05	$<$ 0.05	$<$ 0.05	$<$ 0.05
ttH (sum)	4.64 $\pm$ 0.52	4.81 $\pm$ 0.50	8.91 $\pm$ 0.81	8.47 $\pm$ 0.80	5.70 $\pm$ 0.54	5.98 $\pm$ 0.56	6.52 $\pm$ 0.77	6.75 $\pm$ 0.85	4.41 $\pm$ 0.53	3.89 $\pm$ 0.47
$t\bar{t}$W	9.32 $\pm$ 1.50	14.77 $\pm$ 2.39	16.00 $\pm$ 2.40	28.49 $\pm$ 4.27	10.00 $\pm$ 1.52	17.61 $\pm$ 2.64	11.13 $\pm$ 1.88	22.55 $\pm$ 3.86	7.98 $\pm$ 1.37	13.18 $\pm$ 2.21
$t\bar{t}$WW	0.68 $\pm$ 0.09	0.52 $\pm$ 0.07	1.36 $\pm$ 0.18	0.99 $\pm$ 0.13	0.67 $\pm$ 0.09	0.68 $\pm$ 0.10	1.03 $\pm$ 0.15	0.86 $\pm$ 0.13	0.51 $\pm$ 0.07	0.58 $\pm$ 0.10
ttW + ttWW	10.00 $\pm$ 1.50	15.29 $\pm$ 2.39	17.36 $\pm$ 2.41	29.48 $\pm$ 4.27	10.67 $\pm$ 1.53	18.29 $\pm$ 2.65	12.16 $\pm$ 1.89	23.41 $\pm$ 3.86	8.50 $\pm$ 1.38	13.75 $\pm$ 2.21
tHq H $\to$ $\tau\tau$	$<$ 0.05	0.09 $\pm$ 0.02	$<$ 0.05	$<$ 0.05	$<$ 0.05	$<$ 0.05	$<$ 0.05	$<$ 0.05	$<$ 0.05	$<$ 0.05
tHW H $\to$ $\tau\tau$	$<$ 0.05	$<$ 0.05	$<$ 0.05	0.12 $\pm$ 0.02	$<$ 0.05	0.13 $\pm$ 0.03	$<$ 0.05	$<$ 0.05	$<$ 0.05	$<$ 0.05
tHq H $\to$ WW	0.06 $\pm$ 0.01	$<$ 0.05	0.10 $\pm$ 0.02	0.15 $\pm$ 0.02	0.07 $\pm$ 0.01	0.14 $\pm$ 0.01	0.11 $\pm$ 0.02	$<$ 0.05	$<$ 0.05	$<$ 0.05
tHW H $\to$ WW	$<$ 0.05	$<$ 0.05	0.19 $\pm$ 0.04	0.12 $\pm$ 0.01	0.24 $\pm$ 0.07	0.14 $\pm$ 0.03	$<$ 0.05	0.23 $\pm$ 0.05	$<$ 0.05	0.13 $\pm$ 0.03
tHq H $\to$ ZZ	$<$ 0.05	$<$ 0.05	$<$ 0.05	$<$ 0.05	$<$ 0.05	$<$ 0.05	$<$ 0.05	$<$ 0.05	$<$ 0.05	$<$ 0.05
tHW H $\to$ ZZ	$<$ 0.05	0.10 $\pm$ 0.03	$<$ 0.05	$<$ 0.05	$<$ 0.05	$<$ 0.05	$<$ 0.05	$<$ 0.05	$<$ 0.05	$<$ 0.05
tH (sum)	0.12 $\pm$ 0.02	0.25 $\pm$ 0.03	0.31 $\pm$ 0.05	0.42 $\pm$ 0.03	0.32 $\pm$ 0.07	0.46 $\pm$ 0.05	0.17 $\pm$ 0.02	0.25 $\pm$ 0.05	0.05 $\pm$ 0.01	0.13 $\pm$ 0.03
ZZ	$<$ 0.05	$<$ 0.05	$<$ 0.05	$<$ 0.05	$<$ 0.05	$<$ 0.05	$<$ 0.05	$<$ 0.05	$<$ 0.05	$<$ 0.05
WZ	$<$ 0.05	$<$ 0.05	$<$ 0.05	$<$ 0.05	$<$ 0.05	$<$ 0.05	$<$ 0.05	$<$ 0.05	$<$ 0.05	$<$ 0.05
WZ + ZZ	$<$ 0.05	$<$ 0.05	$<$ 0.05	$<$ 0.05	$<$ 0.05	$<$ 0.05	$<$ 0.05	$<$ 0.05	$<$ 0.05	$<$ 0.05
$t\bar{t}$Z	11.33 $\pm$ 1.81	11.11 $\pm$ 1.73	12.75 $\pm$ 1.78	14.37 $\pm$ 1.91	4.61 $\pm$ 0.59	5.29 $\pm$ 0.73	9.32 $\pm$ 1.55	10.90 $\pm$ 1.76	3.71 $\pm$ 0.57	3.66 $\pm$ 0.55
Misidentified	9.82 $\pm$ 3.32	12.58 $\pm$ 3.81	29.71 $\pm$ 7.33	31.21 $\pm$ 7.85	20.20 $\pm$ 7.16	17.14 $\pm$ 6.43	6.08 $\pm$ 2.16	6.88 $\pm$ 2.23	2.91 $\pm$ 1.37	3.72 $\pm$ 1.64
Conversions	1.73 $\pm$ 0.53	4.27 $\pm$ 2.58	2.69 $\pm$ 0.80	6.34 $\pm$ 3.41	$<$ 0.05	$<$ 0.05	1.03 $\pm$ 0.35	1.19 $\pm$ 0.36	$<$ 0.05	$<$ 0.05
signal flip	4.82 $\pm$ 1.28	4.89 $\pm$ 1.30	3.95 $\pm$ 1.05	4.03 $\pm$ 1.07	$<$ 0.05	$<$ 0.05	3.30 $\pm$ 0.88	3.27 $\pm$ 0.87	$<$ 0.05	$<$ 0.05
Other	1.59 $\pm$ 0.69	2.77 $\pm$ 1.22	5.32 $\pm$ 2.42	6.52 $\pm$ 2.88	1.97 $\pm$ 0.89	3.69 $\pm$ 1.62	2.43 $\pm$ 1.06	2.64 $\pm$ 1.15	1.19 $\pm$ 0.54	1.94 $\pm$ 0.84
SM expectation	44.05 $\pm$ 4.38	55.97 $\pm$ 5.77	81.00 $\pm$ 8.42	100.84 $\pm$ 10.26	43.45 $\pm$ 7.42	50.86 $\pm$ 7.20	41.02 $\pm$ 3.64	55.29 $\pm$ 5.08	20.78 $\pm$ 2.16	27.09 $\pm$ 2.97
Observed data	54	67	86	108	41	79	50	70	32	27

Backup: pre-fit yields (II)

Category	3ℓ				4ℓ
b-tag	Loose		Tight		no req.
Total charge	$-$	$+$	$-$	$+$	no req.
$t\bar{t}H$, $H \to ZZ$	0.47 ± 0.12	0.17 ± 0.02	0.21 ± 0.03	0.19 ± 0.04	0.09 ± 0.01
$t\bar{t}H$, $H \to WW$	7.87 ± 1.02	7.03 ± 0.92	3.24 ± 0.50	2.84 ± 0.49	0.65 ± 0.09
$t\bar{t}H$, $H \to \tau\tau$	1.34 ± 0.22	0.54 ± 0.09	0.72 ± 0.11	1.00 ± 0.13	0.19 ± 0.03
$t\bar{t}H$, $H \to \mu\mu$	0.09 ± 0.02	0.24 ± 0.03	0.07 ± 0.02	0.17 ± 0.03	0.07 ± 0.01
$t\bar{t}H$, $H \to Z\gamma$	< 0.05	< 0.05	< 0.05	0.04 ± 0.01	< 0.05
ttH (sum)	9.78 ± 1.05	7.98 ± 0.93	4.24 ± 0.51	4.24 ± 0.51	0.99 ± 0.10
$t\bar{t}W$	9.04 ± 1.56	14.42 ± 2.36	4.31 ± 0.89	6.50 ± 1.44	< 0.05
$t\bar{t}WW$	0.88 ± 0.11	0.97 ± 0.13	0.57 ± 0.09	0.52 ± 0.08	0.09 ± 0.01
ttW + ttWW	9.91 ± 1.57	15.39 ± 2.36	4.89 ± 0.89	7.01 ± 1.44	0.09 ± 0.01
tHq $H \to \tau\tau$	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
tHW $H \to \tau\tau$	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
tHq $H \to WW$	0.08 ± 0.01	0.28 ± 0.04	0.34 ± 0.13	< 0.05	< 0.05
tHW $H \to WW$	0.06 ± 0.01	0.04 ± 0.01	< 0.05	< 0.05	< 0.05
tHq $H \to ZZ$	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
tHW $H \to ZZ$	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
tH (sum)	0.16 ± 0.02	0.36 ± 0.04	0.36 ± 0.13	0.09 ± 0.01	< 0.05
ZZ	0.21 ± 0.03	0.18 ± 0.04	< 0.05	< 0.05	0.09 ± 0.05
WZ	3.96 ± 0.71	7.41 ± 1.30	0.24 ± 0.06	0.45 ± 0.06	< 0.05
WZ + ZZ	4.17 ± 0.71	7.59 ± 1.30	0.24 ± 0.06	0.45 ± 0.06	0.09 ± 0.05
$t\bar{t}Z$	16.37 ± 2.59	13.65 ± 2.32	9.25 ± 1.79	8.28 ± 1.55	2.46 ± 0.37
Misidentified	13.24 ± 4.11	11.39 ± 4.07	1.79 ± 0.73	2.37 ± 0.96	< 0.05
Conversions	1.84 ± 0.79	2.21 ± 0.80	2.69 ± 1.11	0.96 ± 0.36	< 0.05
signal flip	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
Other	2.70 ± 1.16	4.33 ± 1.89	1.77 ± 0.77	2.05 ± 0.89	0.10 ± 0.07
SM expectation	58.17 ± 5.44	62.90 ± 5.86	25.23 ± 2.58	25.45 ± 2.57	3.78 ± 0.39
Observed data	55	84	23	33	6

Backup: pre-fit yields (III)

Category	$1\ell + 2\tau_h$	$2\ell + 2\tau_h$	$3\ell + 1\tau_h$	$2\ell ss + 1\tau_h$
$t\bar{t}H$, $H \to ZZ$	0.10 ± 0.02	< 0.05	0.05 ± 0.01	0.09 ± 0.01
$t\bar{t}H$, $H \to WW$	0.46 ± 0.07	0.09 ± 0.03	0.54 ± 0.08	2.34 ± 0.30
$t\bar{t}H$, $H \to \tau\tau$	8.27 ± 1.24	1.08 ± 0.20	0.74 ± 0.11	4.52 ± 0.58
$t\bar{t}H$, $H \to \mu\mu$	< 0.05	< 0.05	< 0.05	< 0.05
$t\bar{t}H$, $H \to Z\gamma$	< 0.05	< 0.05	< 0.05	< 0.05
ttH (sum)	8.83 ± 1.24	1.18 ± 0.20	1.36 ± 0.14	6.96 ± 0.65
$t\bar{t}W$	0.73 ± 0.14	< 0.05	0.25 ± 0.07	8.49 ± 1.49
$t\bar{t}WW$	0.07 ± 0.01	< 0.05	0.10 ± 0.01	0.49 ± 0.07
ttW + ttWW	0.80 ± 0.14	< 0.05	0.35 ± 0.08	8.98 ± 1.49
tHq	< 0.05	< 0.05	< 0.05	0.32 ± 0.03
tHW	0.23 ± 0.06	< 0.05	< 0.05	0.13 ± 0.01
tH (sum)	0.26 ± 0.06	< 0.05	< 0.05	0.45 ± 0.03
WZ + ZZ	1.58 ± 0.73	0.05 ± 0.02	0.13 ± 0.03	2.17 ± 1.46
$t\bar{t}Z$	7.07 ± 1.24	0.94 ± 0.19	2.69 ± 0.33	9.21 ± 0.95
Misidentified	287.30 ± 120.82	5.27 ± 2.56	0.22 ± 0.17	5.56 ± 2.38
Conversions	0.27 ± 0.13	< 0.05	< 0.05	< 0.05
signal flip	< 0.05	< 0.05	< 0.05	< 0.05
Other	1.24 ± 0.54	0.06 ± 0.03	0.34 ± 0.16	3.33 ± 1.12
SM expectation	307.35 ± 120.83	7.52 ± 2.58	5.11 ± 0.43	36.66 ± 3.55
Observed data	324	7	4	53

Backup: post-fit yields (I) PAS

Category	2ℓss									
b-tag	no req.		Loose				Tight			
Leptons	ee		eμ		$\mu\mu$		eμ		$\mu\mu$	
Charge	−	+	−	+	−	+	−	+	−	+
$t\bar{t}$H, H $\rightarrow$ ZZ	0.15 ± 0.09	0.12 ± 0.07	0.22 ± 0.13	0.16 ± 0.09	0.11 ± 0.06	0.13 ± 0.08	0.22 ± 0.13	0.14 ± 0.09	0.07 ± 0.04	0.07 ± 0.04
$t\bar{t}$H, H $\rightarrow$ WW	2.52 ± 1.45	2.68 ± 1.75	5.27 ± 3.11	4.90 ± 2.95	3.48 ± 2.15	3.62 ± 2.12	3.54 ± 2.17	3.89 ± 2.50	2.59 ± 1.62	2.29 ± 1.33
$t\bar{t}$H, H $\rightarrow \tau\tau$	0.60 ± 0.35	0.58 ± 0.34	0.93 ± 0.54	1.01 ± 0.59	0.57 ± 0.33	0.65 ± 0.39	0.76 ± 0.43	0.65 ± 0.40	0.46 ± 0.29	0.39 ± 0.24
$t\bar{t}$H, H $\rightarrow \mu\mu$	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
$t\bar{t}$H, H $\rightarrow Z\gamma$	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
ttH (sum)	3.27 ± 1.49	3.41 ± 1.79	6.46 ± 3.16	6.09 ± 3.01	4.17 ± 2.18	4.43 ± 2.15	4.56 ± 2.22	4.70 ± 2.54	3.14 ± 1.65	2.76 ± 1.35
$t\bar{t}$W	12.64 ± 2.36	20.06 ± 3.86	22.19 ± 4.49	39.43 ± 7.92	14.00 ± 2.61	24.95 ± 5.04	15.07 ± 2.76	30.39 ± 5.31	11.00 ± 1.99	17.97 ± 3.41
$t\bar{t}$WW	0.93 ± 0.23	0.70 ± 0.17	1.86 ± 0.45	1.36 ± 0.33	0.92 ± 0.23	0.95 ± 0.25	1.40 ± 0.35	1.14 ± 0.27	0.71 ± 0.17	0.77 ± 0.19
ttW + ttWW	13.58 ± 2.37	20.75 ± 3.87	24.06 ± 4.52	40.80 ± 7.93	14.92 ± 2.62	25.90 ± 5.04	16.47 ± 2.78	31.53 ± 5.32	11.71 ± 2.00	18.74 ± 3.42
tHq H $\rightarrow \tau\tau$	< 0.05	0.08 ± 0.02	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
tHW H $\rightarrow \tau\tau$	< 0.05	< 0.05	< 0.05	0.12 ± 0.02	< 0.05	0.14 ± 0.03	< 0.05	< 0.05	< 0.05	< 0.05
tHq H $\rightarrow$ WW	0.06 ± 0.01	< 0.05	0.10 ± 0.02	0.14 ± 0.01	0.07 ± 0.01	0.14 ± 0.01	0.10 ± 0.01	< 0.05	< 0.05	< 0.05
tHW H $\rightarrow$ WW	< 0.05	< 0.05	0.19 ± 0.04	0.12 ± 0.01	0.24 ± 0.07	0.14 ± 0.02	< 0.05	0.22 ± 0.04	< 0.05	0.11 ± 0.02
tHq H $\rightarrow$ ZZ	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
tHW H $\rightarrow$ ZZ	< 0.05	0.10 ± 0.02	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
tH (sum)	0.11 ± 0.02	0.24 ± 0.02	0.30 ± 0.04	0.41 ± 0.03	0.31 ± 0.07	0.46 ± 0.04	0.16 ± 0.01	0.23 ± 0.04	0.05 ± 0.00	0.11 ± 0.02
ZZ	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
WZ	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
WZ + ZZ	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
$t\bar{t}$Z	17.86 ± 2.86	17.62 ± 2.71	20.03 ± 3.10	23.08 ± 3.77	7.55 ± 1.22	8.68 ± 1.42	14.79 ± 2.43	16.97 ± 2.67	5.91 ± 0.99	5.74 ± 0.93
Misidentified	7.89 ± 2.05	10.44 ± 2.49	26.61 ± 4.30	28.27 ± 4.80	20.60 ± 4.40	18.23 ± 3.92	5.64 ± 1.87	6.60 ± 1.87	3.67 ± 1.59	4.19 ± 1.75
Conversions	1.52 ± 0.46	2.18 ± 1.83	2.52 ± 0.87	3.48 ± 2.13	< 0.05	< 0.05	0.88 ± 0.29	1.05 ± 0.32	< 0.05	< 0.05
signal flip	4.53 ± 1.10	4.59 ± 1.14	3.71 ± 0.90	3.79 ± 0.99	< 0.05	< 0.05	3.10 ± 0.75	3.07 ± 0.76	< 0.05	< 0.05
Other	1.44 ± 0.61	2.45 ± 1.06	4.62 ± 1.99	5.69 ± 2.22	1.65 ± 0.64	3.33 ± 1.29	2.18 ± 0.91	2.39 ± 1.01	1.11 ± 0.45	1.80 ± 0.81
SM expectation	50.20 ± 4.69	61.68 ± 6.12	88.32 ± 8.00	111.60 ± 10.94	49.21 ± 5.73	61.03 ± 7.01	47.78 ± 4.85	66.54 ± 6.86	25.60 ± 3.22	33.35 ± 4.26
Observed data	54	67	86	108	41	79	50	70	32	27

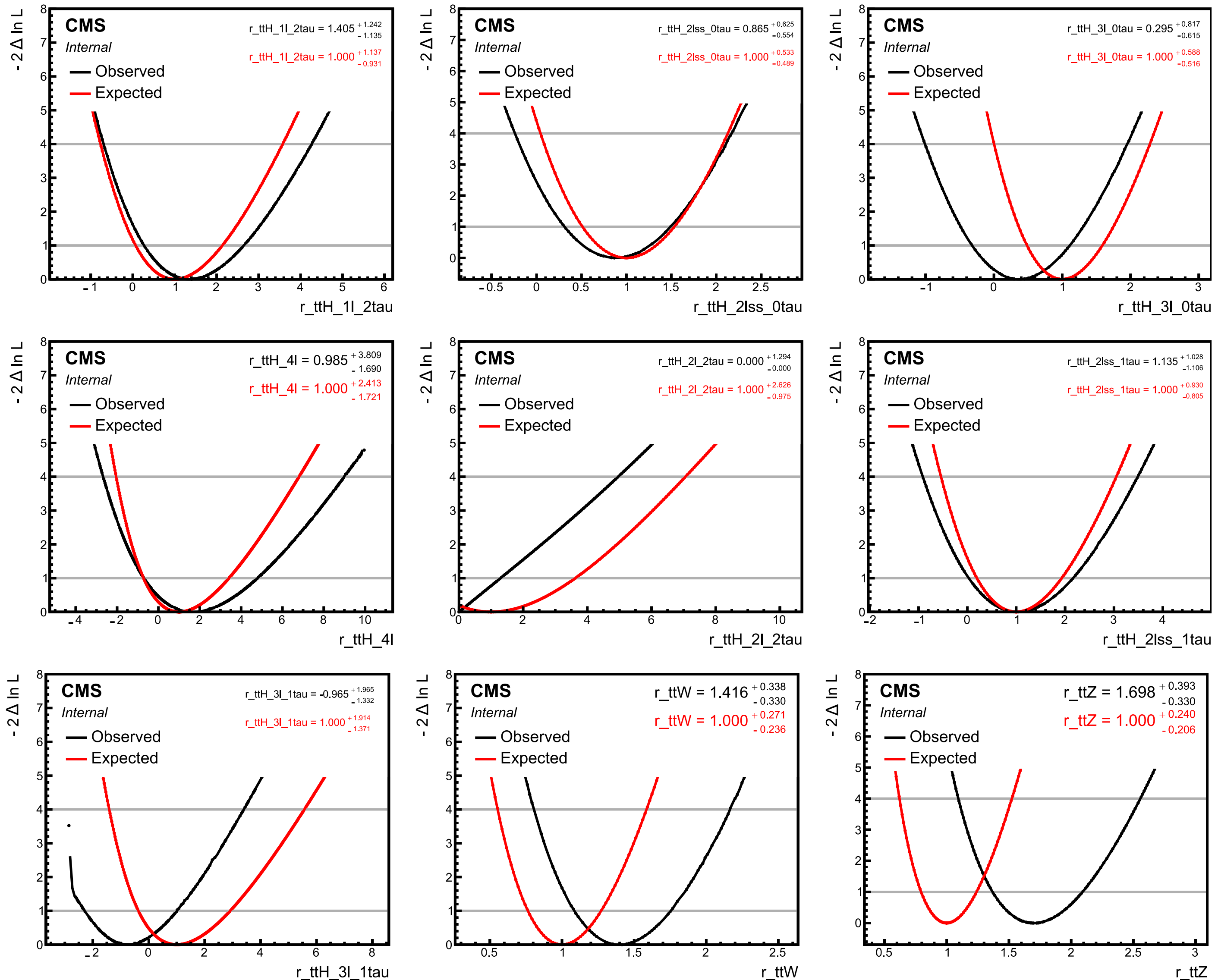
Backup: post-fit yields (II) PAS

Category	3ℓ				4ℓ
b-tag	Loose		Tight		no req.
Total charge	$-$	$+$	$-$	$+$	no req.
$t\bar{t}H$, $H \to ZZ$	0.34 ± 0.21	0.12 ± 0.07	0.14 ± 0.09	0.13 ± 0.08	0.06 ± 0.04
$t\bar{t}H$, $H \to WW$	5.60 ± 3.22	5.14 ± 2.94	2.28 ± 1.35	2.04 ± 1.15	0.46 ± 0.29
$t\bar{t}H$, $H \to \tau\tau$	0.93 ± 0.55	0.40 ± 0.24	0.50 ± 0.30	0.71 ± 0.43	0.13 ± 0.08
$t\bar{t}H$, $H \to \mu\mu$	0.07 ± 0.04	0.18 ± 0.11	0.05 ± 0.03	0.12 ± 0.07	0.05 ± 0.03
$t\bar{t}H$, $H \to Z\gamma$	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
ttH (sum)	6.94 ± 3.27	5.84 ± 2.95	2.98 ± 1.39	3.03 ± 1.23	0.70 ± 0.30
$t\bar{t}W$	12.12 ± 2.52	20.72 ± 4.15	5.64 ± 1.16	8.55 ± 1.64	< 0.05
$t\bar{t}WW$	1.22 ± 0.30	1.34 ± 0.33	0.76 ± 0.18	0.69 ± 0.16	0.13 ± 0.03
ttW + ttWW	13.34 ± 2.54	22.05 ± 4.17	6.40 ± 1.17	9.24 ± 1.64	0.13 ± 0.03
tHq $H \to \tau\tau$	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
tHW $H \to \tau\tau$	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
tHq $H \to WW$	0.08 ± 0.01	0.28 ± 0.03	0.27 ± 0.09	< 0.05	< 0.05
tHW $H \to WW$	0.05 ± 0.01	< 0.05	< 0.05	< 0.05	< 0.05
tHq $H \to ZZ$	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
tHW $H \to ZZ$	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
tH (sum)	0.15 ± 0.01	0.36 ± 0.03	0.29 ± 0.09	0.08 ± 0.01	< 0.05
ZZ	0.37 ± 0.07	0.29 ± 0.08	< 0.05	< 0.05	0.15 ± 0.10
WZ	3.67 ± 0.76	7.05 ± 1.46	0.22 ± 0.05	0.44 ± 0.09	< 0.05
WZ + ZZ	4.04 ± 0.76	7.34 ± 1.47	0.22 ± 0.05	0.44 ± 0.09	0.15 ± 0.10
$t\bar{t}Z$	24.86 ± 3.98	23.18 ± 3.82	13.15 ± 2.23	12.93 ± 2.13	3.91 ± 0.62
Misidentified	12.30 ± 2.96	10.27 ± 2.44	1.67 ± 0.59	2.59 ± 1.10	< 0.05
Conversions	1.48 ± 0.52	1.97 ± 0.63	2.35 ± 0.93	0.82 ± 0.29	< 0.05
signal flip	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
Other	2.40 ± 1.09	3.86 ± 1.62	1.57 ± 0.63	1.83 ± 0.69	0.09 ± 0.05
SM expectation	65.52 ± 6.62	74.87 ± 7.19	28.61 ± 3.15	30.96 ± 3.24	5.01 ± 0.70
Observed data	55	84	23	33	6

Backup: post-fit yields (III) PAS

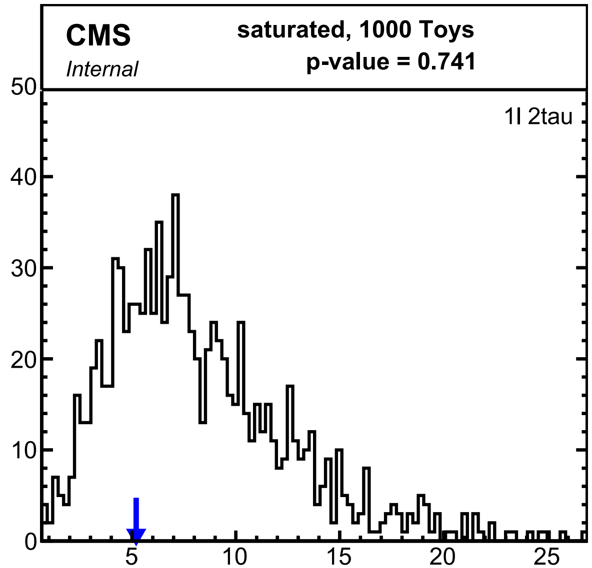
Category	$1\ell + 2\tau_h$	$2\ell + 2\tau_h$	$3\ell + 1\tau_h$	$2\ell ss + 1\tau_h$
$t\bar{t}H$	6.57 ± 3.58	0.88 ± 0.47	0.99 ± 0.38	5.13 ± 2.11
$t\bar{t}W + t\bar{t}WW$	1.13 ± 0.25	< 0.05	0.51 ± 0.12	13.11 ± 2.43
tH	0.25 ± 0.07	0.02 ± 0.09	< 0.05	0.45 ± 0.03
WZ + ZZ	1.50 ± 0.77	0.04 ± 0.03	0.13 ± 0.03	2.76 ± 1.95
$t\bar{t}Z/\gamma^*$	11.55 ± 2.64	1.55 ± 0.46	4.48 ± 0.68	15.35 ± 2.43
Misidentified	299.60 ± 19.10	5.31 ± 2.19	0.25 ± 0.26	5.28 ± 2.18
Conversions	0.25 ± 0.11	< 0.05	< 0.05	< 0.05
signal flip	< 0.05	< 0.05	< 0.05	< 0.05
Other	1.18 ± 0.46	0.06 ± 0.04	0.33 ± 0.15	3.23 ± 1.14
SM expectation	322.02 ± 19.64	7.86 ± 2.29	6.70 ± 0.85	45.31 ± 5.11
Observed data	324	7	4	53

Backup: likelihood scans

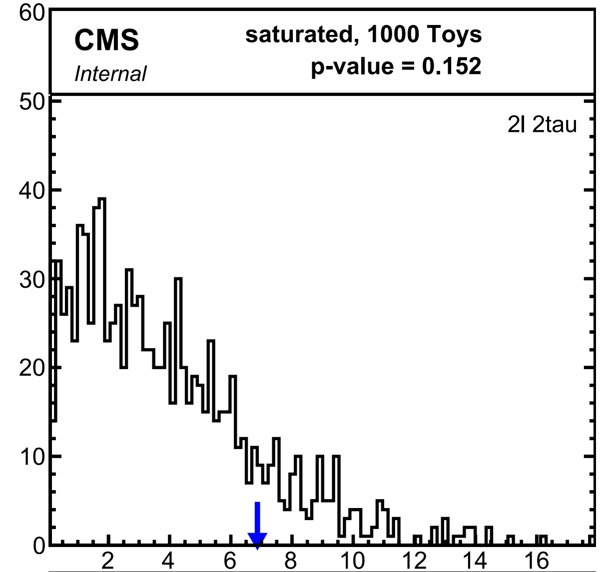


Backup: goodness of fit (I)

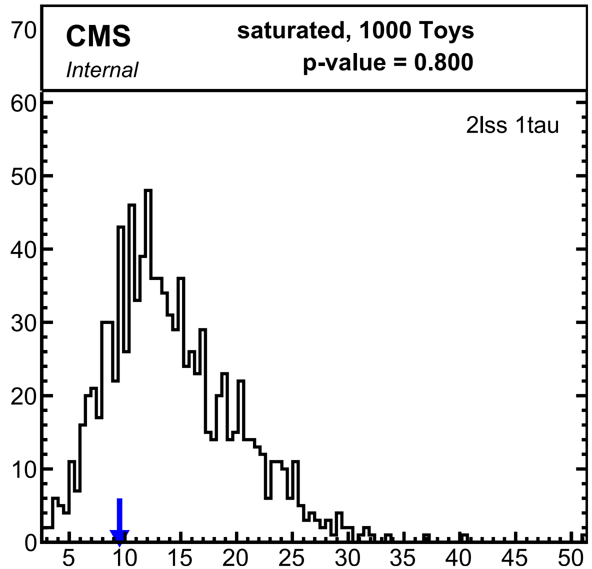
$1\ell + 2\tau_h$



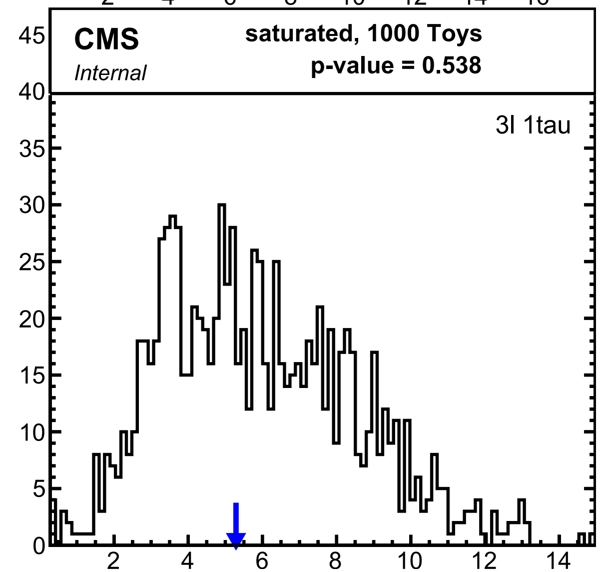
$2\ell SS + 1\tau_h$



$2\ell + 2\tau_h$

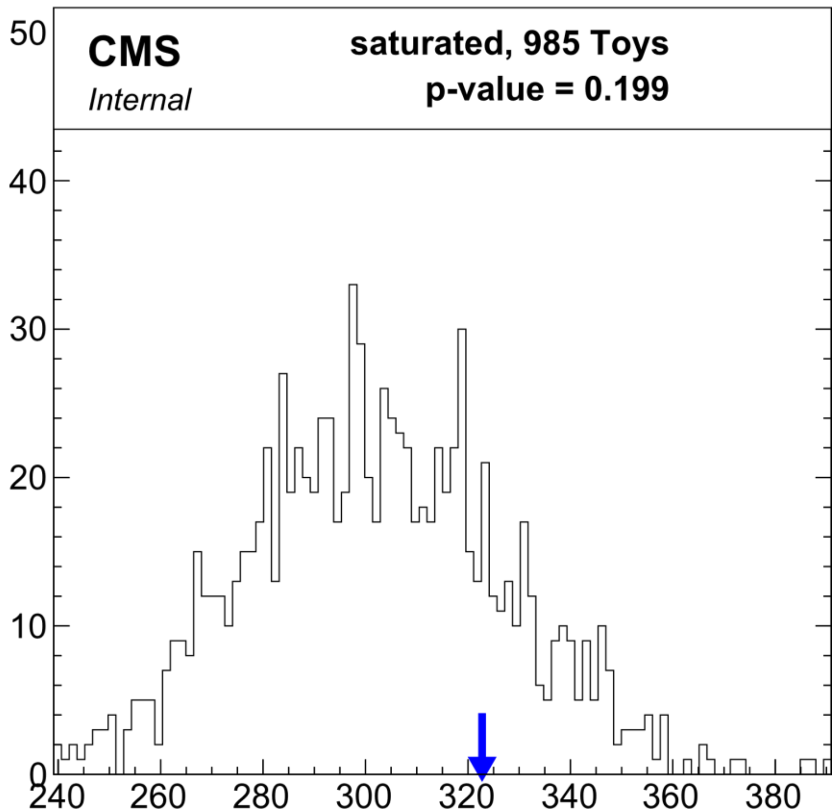


$3\ell + 1\tau_h$

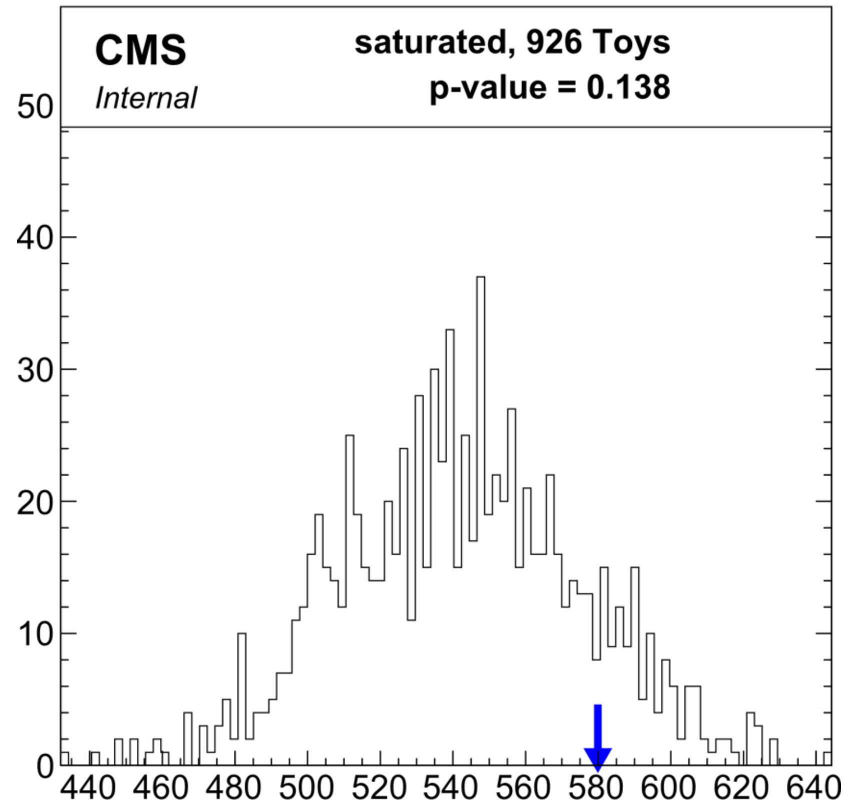


Backup: goodness of fit (II)

2017

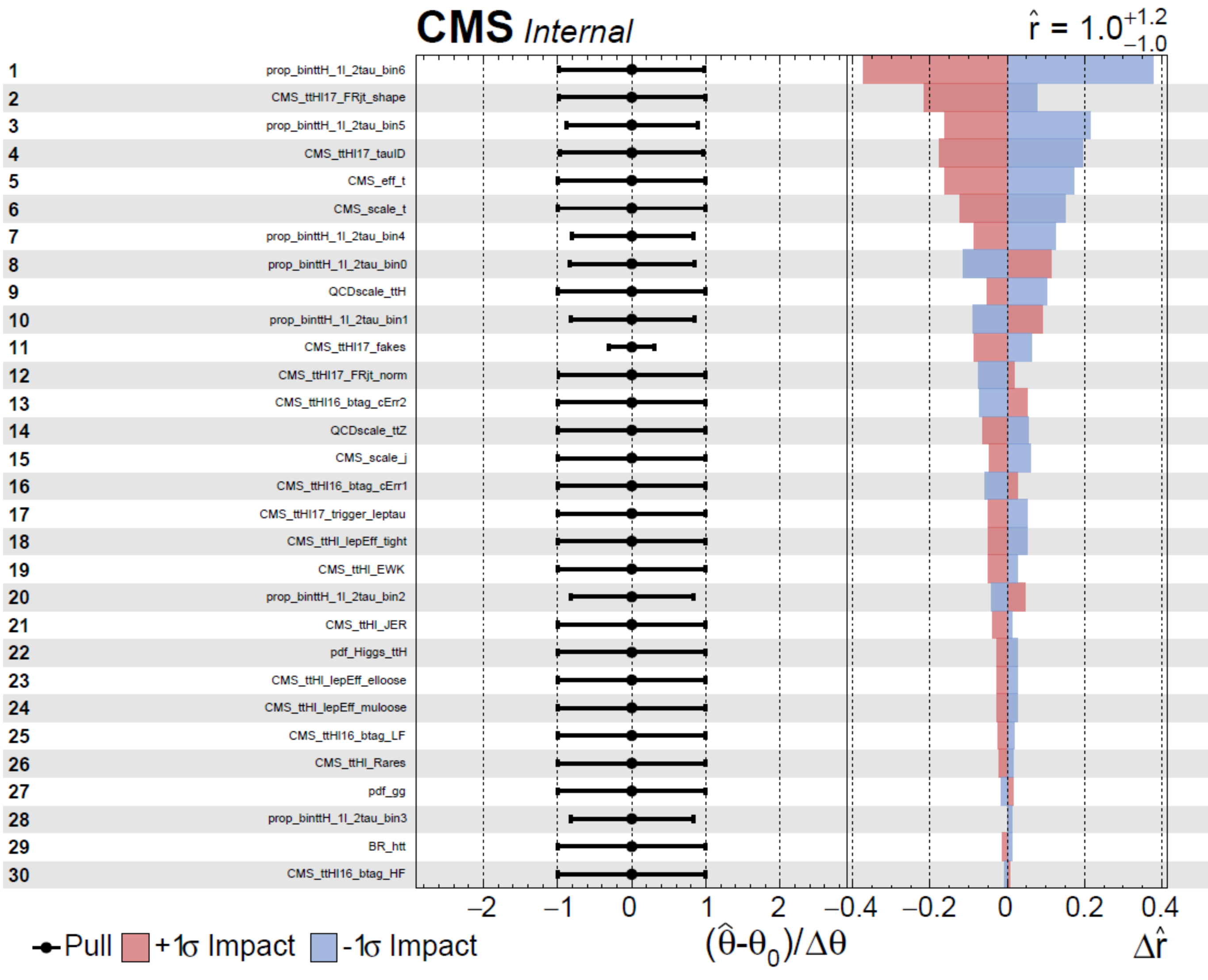


2016 & 2017



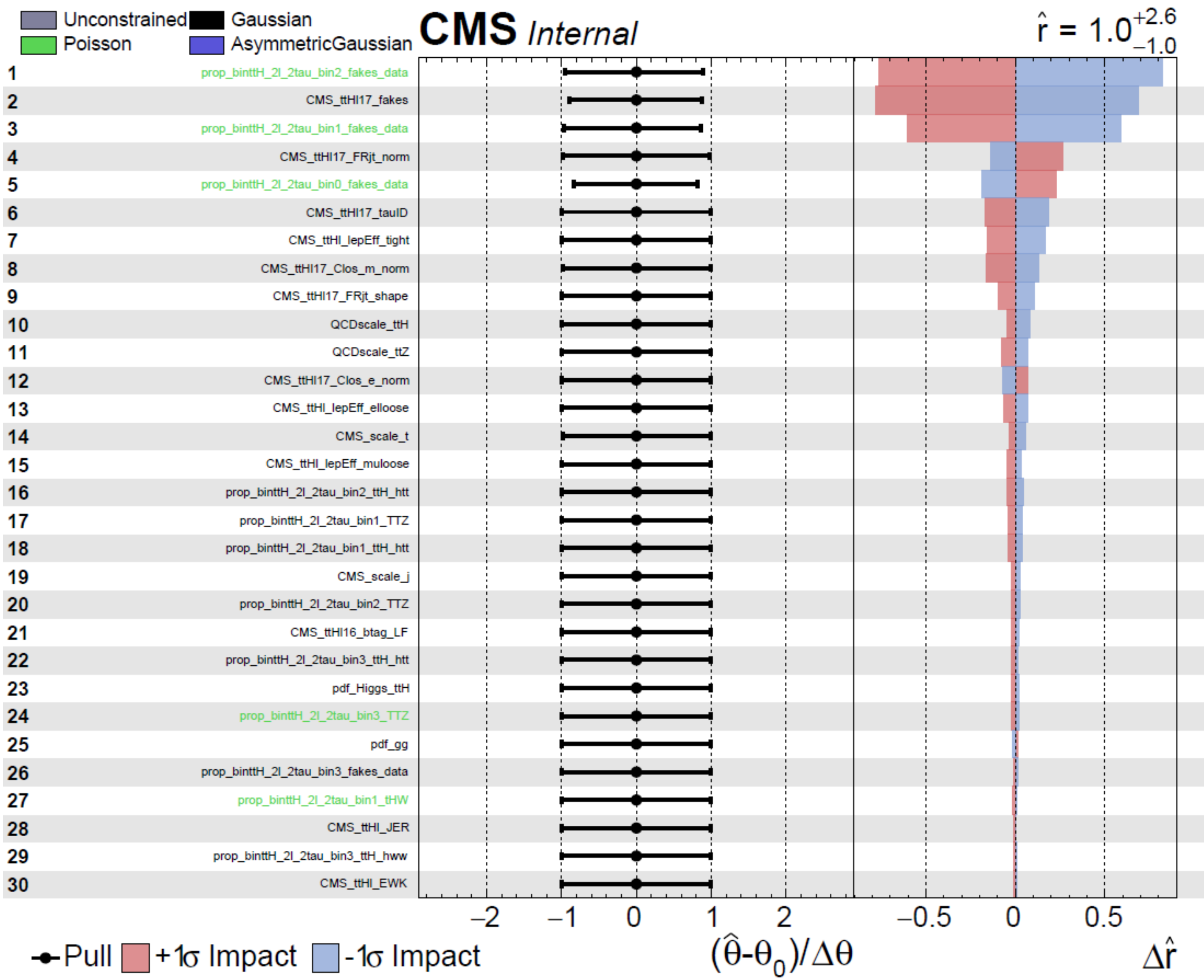
Backup: impact plots (I)

$1\ell + 2\tau_h$



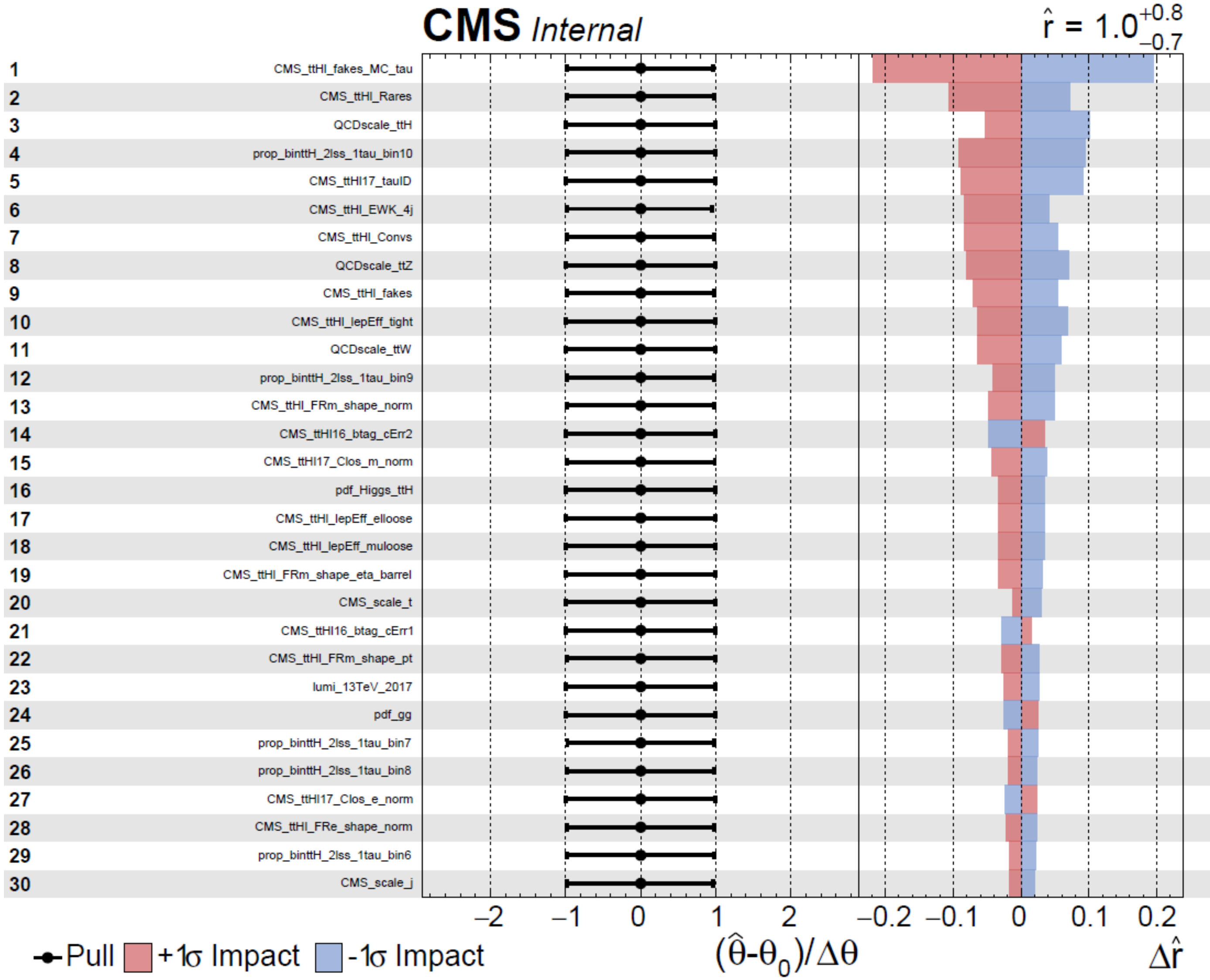
Backup: impact plots (II)

$2\ell + 2\tau_h$



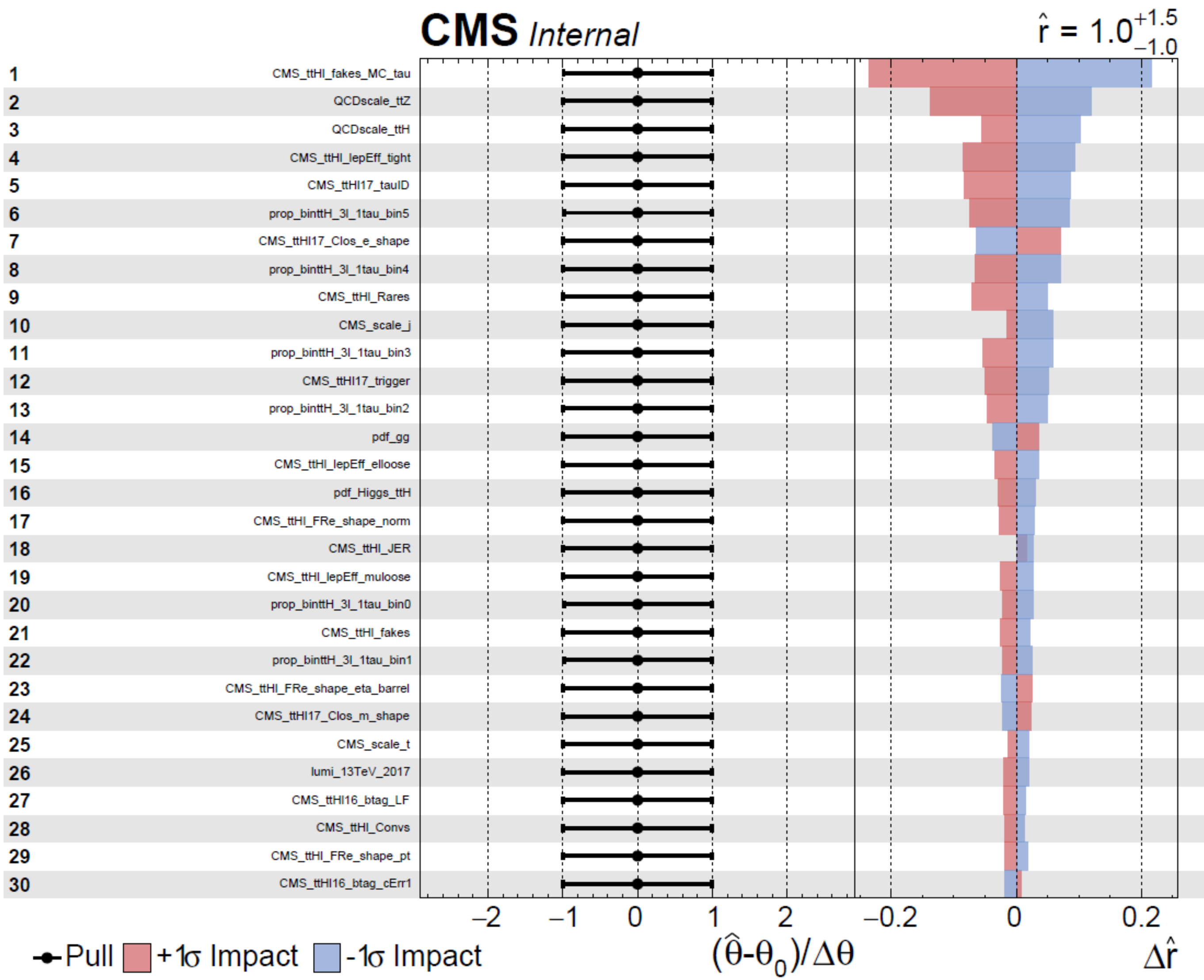
Backup: impact plots (III)

$2\ell SS + 1\tau_h$



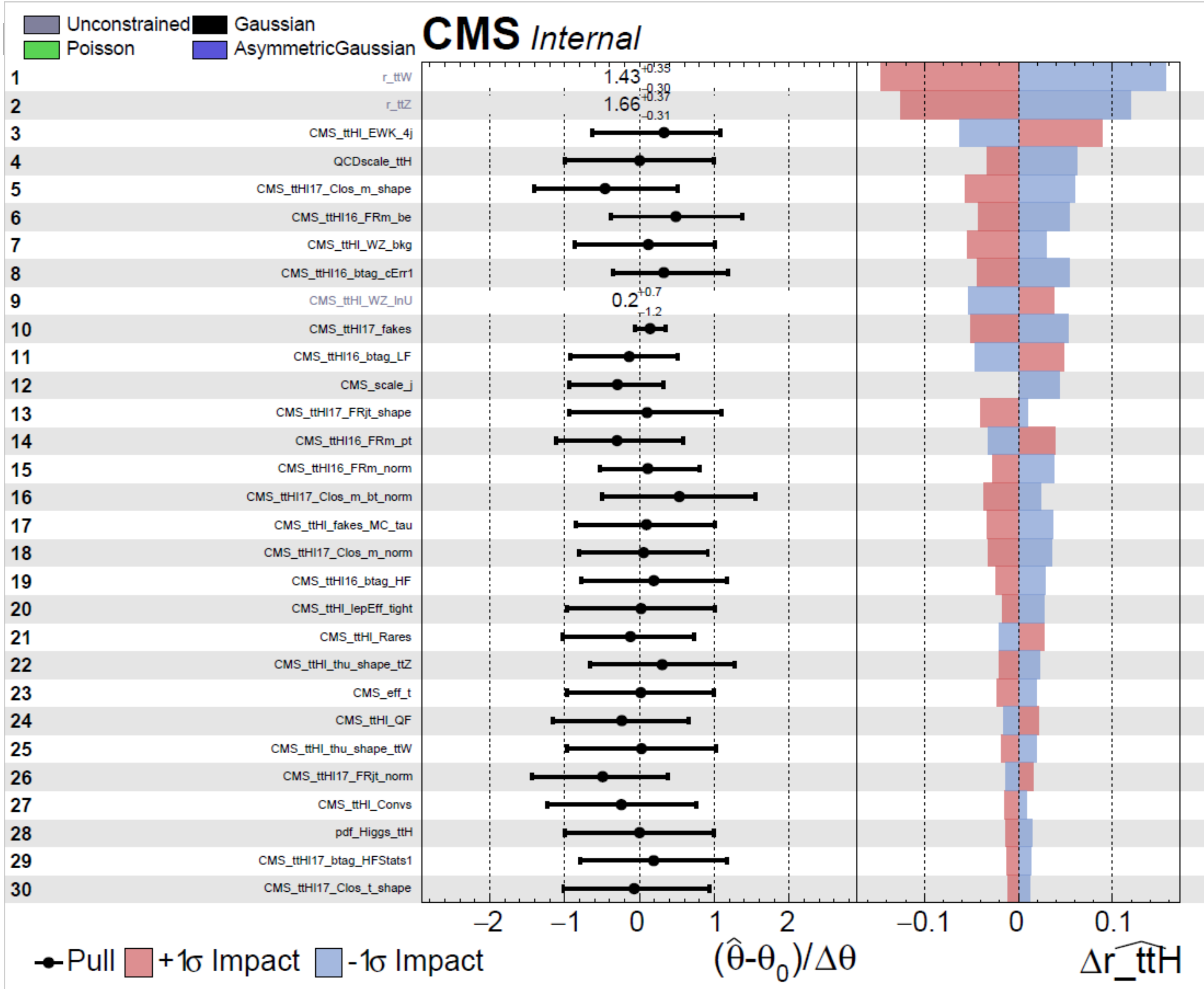
Backup: impact plots (IV)

$3\ell + 1\tau_h$



Backup: impact plots (V)

2017 ful



Backup: impact plots (VI)

2016+
2017 full