Measurement of $t\bar{t}W$ cross-section and charge asymmetry

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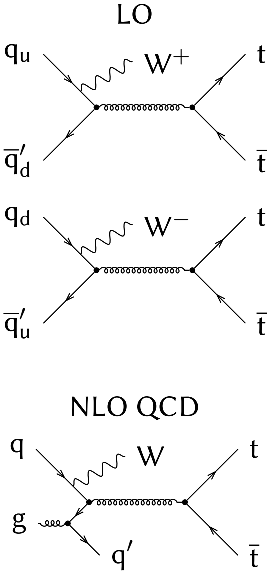
Outline

Why $pp \to t\bar{t}W$??

- Associated $W^{\pm}$ can only be radiated from an initial state quark
- Production at LHC: $q\bar{q}'$ (at LO) and qg (at NLO); QCD contribution from gg initial states only at NNLO
- Small cross-section (348 fb ($t\bar{t}W^{+}$) and 198 fb ($t\bar{t}W^{-}$) $\pm 12\%$ at 13 TeV (NLO QCD + EWK, NNLO)
- Large $t\bar{t}$ charge asymmetry observed in $t\bar{t}W^{\pm}$ than in $t\bar{t}$ production at the LHC
- At 13 GeV, top quark charge asymmetry A_C^t is $2.24^{+0.43}_{-0.32}$ in $t\bar{t}W$ production compared to $0.45^{+0.09}_{-0.06}$ in $t\bar{t}$
- $t\bar{t}$ pair is highly polarised due to the production of $W^{\pm}$, large spin correlations between the decay products



[arXiv:1904.05637] [PhysLett**B736**(2014)252]

- Asymmetry variable:

$$A_C^t = \frac{N(\Delta_\eta^t > 0) - N(\Delta_\eta^t < 0)}{N(\Delta_\eta^t > 0) + N(\Delta_\eta^t < 0)} \quad (1)$$

where $\Delta_\eta^t = |\eta_t - \eta_{\bar{t}}|$

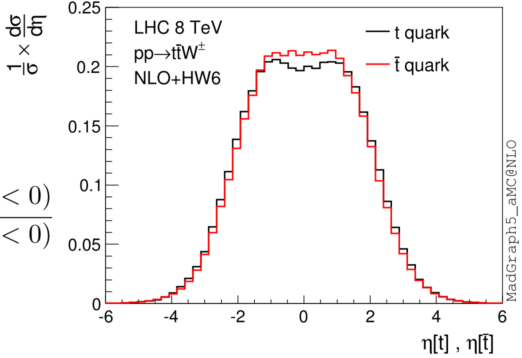
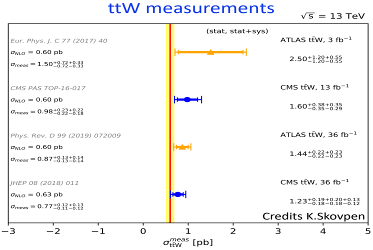
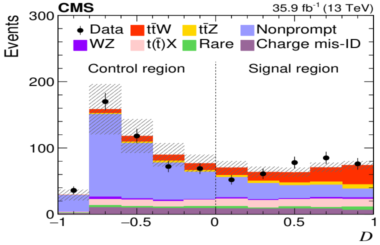


Figure 1: η distribution of t, $\bar{t}$ at NLO [PhysLett**B736**(2014)252]

Latest results



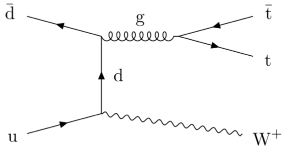
TOP-17-005



- Currently cross section is the only property of $t\bar{t}W$ that has been measured
- Both CMS and ATLAS observed slightly higher cross section than theory prediction.
- Observed [CMS TOP-17-005]: 0.77 pb (±15% stat, ±15% sys) at 5.3σ
- Predicted 0.628 ± 0.082 pb at NLO
- With full Run 2 data, reduce statistical uncertainties by half
- Aim to reduce systematic uncertainties by half (see slides from ttX roundtable)
- ttW asymmetry hasn't been measured at the LHC so this could be the first measurement of asymmetry variables

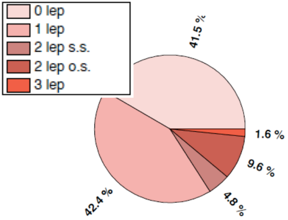
Analysis strategy

- First, measure $ttW^{\pm}$ cross section with full run 2 data
- Measure ttW^{+} and ttW^{-} separately
- Then measure asymmetric variables
- Signature: Same sign di-lepton, small yield but very clean



$$\sigma_{ttW} = 0.60\,\text{pb}$$

~100K ttW events @ 140 fb-1



Analysis strategy

- SS dilepton event selections:

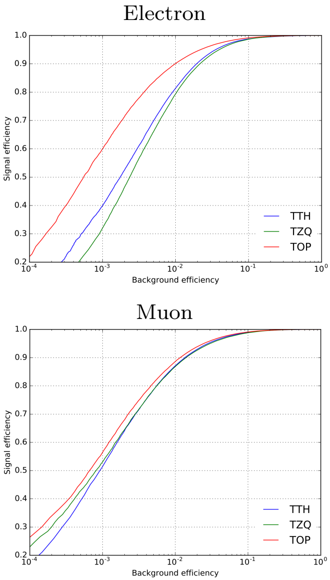
$m(ll) > 12$ GeV
$\|m(ee) - m(Z)\| > 15$ GeV
$E_T^{miss} > 30$ GeV
At least 2 jets and 1 b-jet
$P_T^{lead}(l) > 40/25$ GeV (e/μ)
$P_T^{trail} > 25$ GeV (e and μ)

- Main backgrounds: Non-prompt leptons, irreducible ttH, charge mis-identification electrons and di-boson
- Use BDT to optimise signal

Status

Tasks finished:

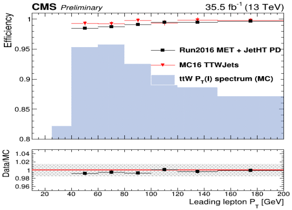
- Wrote my own analysis framework
- Measured trigger efficiencies and scale factor
- Estimated charge mis-identification background
- Studied non-prompt lepton background
- Developing multivariate discriminator



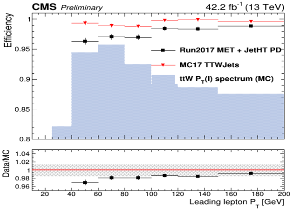
Trigger efficiency study

- Datasets: Full run-2 MET and JetHT datasets and TTWJetsToLNu MC
- Combine single lepton and di-lepton triggers [Slide 22] with logic "OR" in order to increase the efficiency
- Measured in di-leptons events that pass reference MET triggers [Slide. 23, 24]
- Measured in ee, $e\mu$ and $\mu\mu$ final states separately

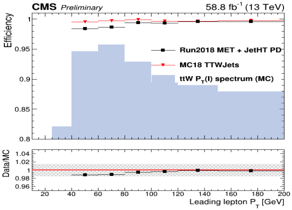
2016



2017



2018

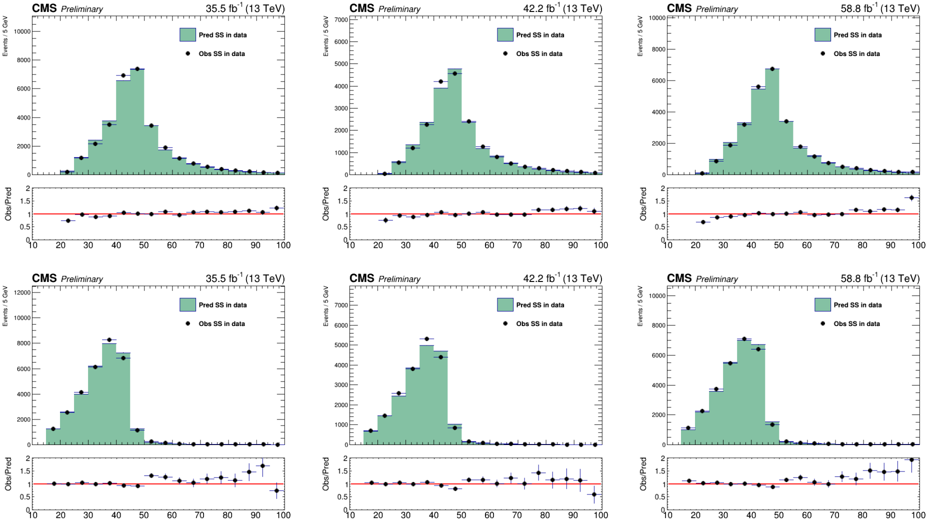


Data and MC agree within 1.5% in 2016 and 2018, while for 2017 the agreement is still within 2% A trigger systematic uncertainty of 1.5% is assigned to 2016 and 2018 and 2% to 2017

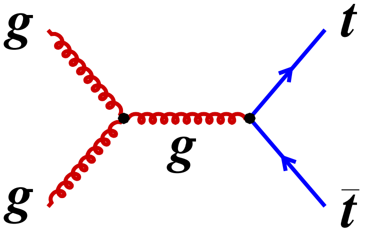
Charge mis-identification background

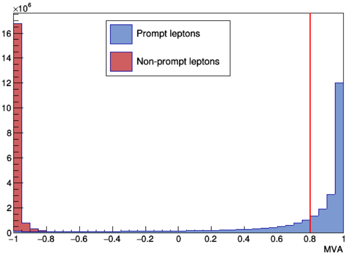
- Due to Bremsstrahlung effect as electrons traverse through the detector
- Dependent of lepton P_T and η
- Measure in DY and $t\bar{t}$ MC events by matching reconstructed charge and generated charge
- Muon charge flip rate is negligibly small
- Validated in $Z \rightarrow ee$ control region in data
- Apply charge flip rate to OS $Z \rightarrow ee$ events to get predicted SS events, then compare them with observed SS events

Charge mis-identification background - Closure test



Non-prompt lepton background

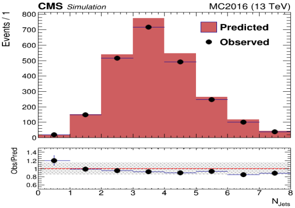


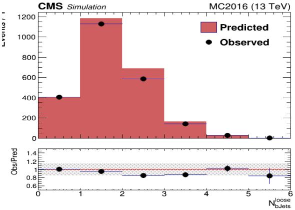


- Non-prompt leptons: non-isolated, coming from heavy flavour decays
- Main contribution: $t\bar{t}$
- Estimate non-prompt background contribution using fake-rate method
- Measured in QCD events with one lepton and at least 1 recoiling jet
- Fake rate: probability of a loose non-prompt lepton also pass tight selection
- Measured in lepton PT and eta bins
- Perform closure test on TTbar MC samples for validations

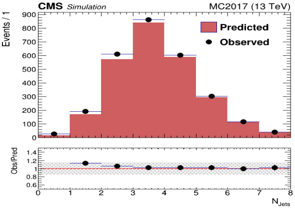
Non-prompt lepton background - Closure test in MC

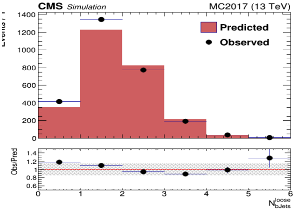
2016



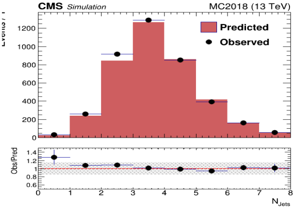


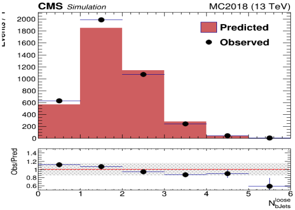
2017





2018



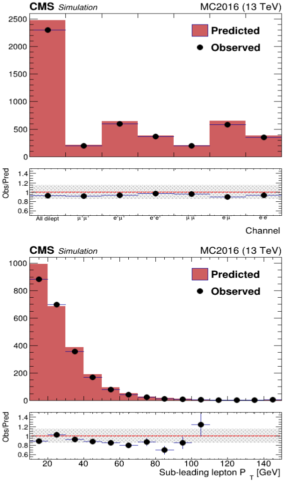


Jet and b-jet multiplicities are important observables that distinguish signal and background events

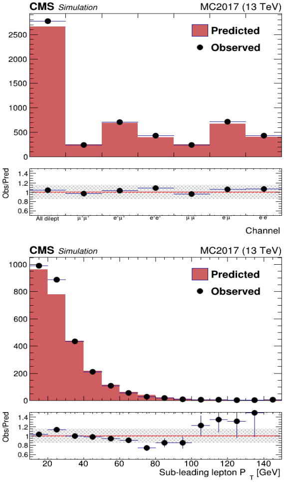
Number of predicted and observed non-prompt background events agree with in 30% shows that fake-rate method works well for non-prompt lepton background prediction

Non-prompt lepton background - Closure test in MC

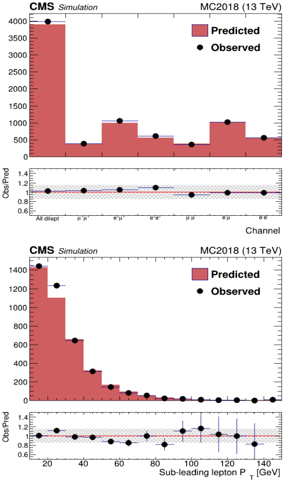
2016



2017



2018

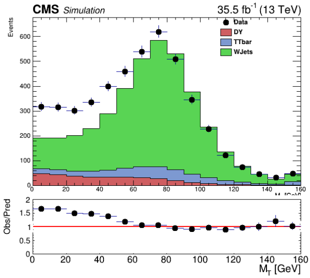


Good agreements in different lepton flavour compositions

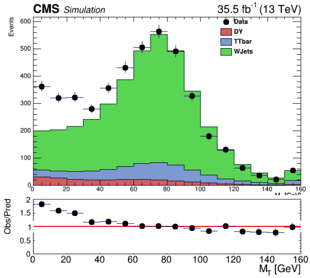
Non-prompt lepton background - Data driven

- Fake rate is measured in QCD enriched region in data
- Events with exactly 1 lepton and at least 1 recoiling jet
- Missing transverse energy and transverse mass < 20 GeV to remove EW contribution

Electron

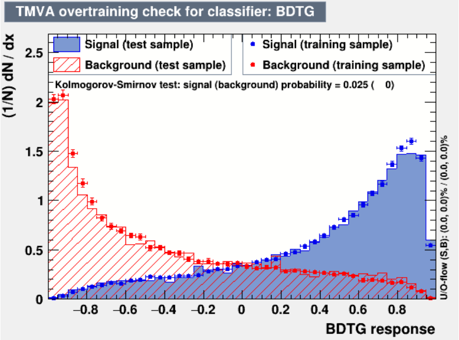


Muon



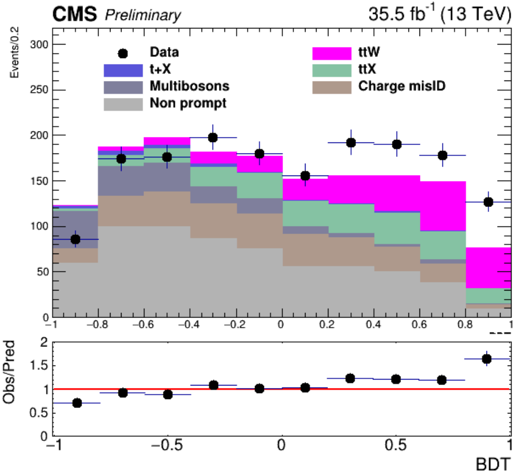
Multivariate background discrimination

- Discriminate between ttW signal and background events
- Backgrounds: Non-prompt lepton from TTbar and irreducible background from ttX, multiboson and charge misID
- Employed boosted decision tree algorithm
- With lepton and jet kinematic variables as input
- Response ranges from -1 to 1 with 1 being signal like



Multivariate background discrimination

- This the discriminator works quite well in discriminating ttW signal and the backgrounds
- However there are still some discrepancies between data and MC which can be improve by using the complete MC list



Steps forward

Immediate plans:

- Adding systematic uncertainties
- Measure inclusive cross section
- Finish AN and prepare for pre-approval

Medium-term plans (in the next 3 months):

- Write paper drafts
- Aim for Moriond 2021

Long-term plans:

- Then move on to asymmetry measurement

Backups

Lepton selection - Electron

Electrons			
Observable	Loose	Fakeable	Tight
Cone-p_T	> 7 GeV	> 10 GeV	> 10 GeV
$\lvert\eta\rvert$	< 2.5	< 2.5	< 2.5
$\lvert d_{xy}\rvert$	< 0.05 cm	< 0.05 cm	< 0.05 cm
$\lvert d_z\rvert$	< 0.1 cm	< 0.1 cm	< 0.1 cm
d/σ_d	< 8	< 8	< 8
I_e	$< 0.4 \times p_T$	$< 0.4 \times p_T$	$< 0.4 \times p_T$
$\sigma_{i\eta i\eta}$	–	$< \{ 0.011 / 0.030 \}^1$	$< \{ 0.011 / 0.030 \}^1$
H/E	–	< 0.10	< 0.10
1/E - 1/p	–	> -0.04	> -0.04
Conversion rejection	–	✓	✓
Missing hits	≤ 1	$= 0$	$= 0$
EGamma POG MVA	>WP-loose[2]	>WP-80 (>WP-loose)[2]†	>WP-loose[2]
Deep Jet of nearby jet	–	<WP-medium[3]	<WP-medium[3]
Jet relative isolation[4]	–	< 0.7 (–) †	–
Prompt-e MVA	–	< 0.80 (> 0.80)	> 0.80

[1] Barrel / endcaps.
[2] WPs as defined by EGamma POG (see Section 3.1.1).
[3] WPs as defined by JetMET POG (see Section 3.3).
[4] Defined as $1/p_T^{ratio}$-1 if the electron is matched to a jet within $\Delta R < 0.4$ or as the PF relative isolation with ΔR=0.4 otherwise.
† Fails (passes) the requirement prompt-e MVA > 0.80.

Lepton selection - Muon

Muons			
Observable	Loose	Fakeable	Tight
p_T	> 5 GeV	> 10 GeV	> 10 GeV
$\lvert\eta\rvert$	< 2.4	< 2.4	< 2.4
$\lvert d_{xy}\rvert$	< 0.05 cm	< 0.05 cm	< 0.05 cm
$\lvert d_z\rvert$	< 0.1 cm	< 0.1 cm	< 0.1 cm
d/σ_d	< 8	< 8	< 8
I_μ	$< 0.4 \times p_T$	$< 0.4 \times p_T$	$< 0.4 \times p_T$
PF muon	>WP-loose[1]	>WP-loose[1]	>WP-medium[1]
Deep Jet of nearby jet	–	<WP-interp. (<WP-medium)[2]	<WP-medium[2]
Jet relative isolation[3]	–	<0.5 (–) †	–
Prompt-μ MVA	–	< 0.85 (> 0.85)	> 0.85

[1] WPs as defined by Muon POG (see Section 3.1.2).
[2] Upper cut on the Deep Jet score defined with a linear interpolation from Deep Jet WP-medium at cone-p_T 20 GeV to Deep Jet WP-loose at cone-p_T 45 GeV, taking the Deep Jet WPs as defined by JetMET POG (see Section 3.3).
[3] Defined as 1/`jetPtRatio`-1 if the muon is matched to a jet within $\Delta R < 0.4$ or as the PF relative isolation with ΔR=0.4 otherwise.
† Fails (passes) the requirement prompt-μ MVA > 0.85.

Leptonic triggers

Channel	Triggers
ee	HLT_Ele32_WPTight_Gsf
	HLT_Ele115_CaloIdVT_GsfTrkIdT
	HLT_Ele23_Ele12_CaloIdL_TrackIdL_IsoVL(_DZ)
$e\mu/\mu e$	HLT_IsoMu24
	HLT_Mu50
	HLT_Ele32_WPTight_Gsf
	HLT_Ele115_CaloIdVT_GsfTrkIdT
	HLT_Mu23(8)_TrkIsoVVL_Ele12(23)_CaloIdL_TrackIdL_IsoVL_DZ
$\mu\mu$	HLT_IsoMu24
	HLT_Mu50
	HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL_DZ_Mass8(3p8)

List of MET and HT triggers

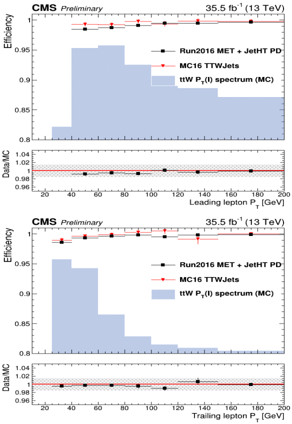
2016	HLT_MET200
	HLT_PFMET300
	HLT_PFMET170_HBHECleaned
	HLT_PFMET120_PFMHT120_IDTight
	HLT_PFHT300_PFMET110
	HLT_PFHT350_DiPFJetAve90_PFAlphaT0p53
	HLT_PFHT400_DiPFJetAve90_PFAlphaT0p52
	HLT_PFHT400_SixJet30_DoubleBTagCSV_p056
	HLT_PFHT900
	HLT_PFHT650_WideJetMJJ900DEtaJJ1p5
	HLT_CaloJet500_NoJetID
2017	HLT_PFJet500
	HLT_PFMET140_PFMHT140_IDTight
	HLT_PFHT500_PFMET100_PFMHT100_IDTight
	HLT_PFHT700_PFMET85_PFMHT85_IDTight
	HLT_PFHT800_PFMET75_PFMHT75_IDTight
	HLT_CaloJet500_NoJetID
	HLT_AK8PFJet500

List of MET and HT triggers

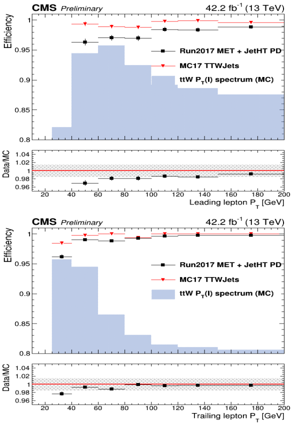
2018	HLT_CaloMET350_HBHECleaned
	HLT_CaloJet500_NoJetID
	HLT_AK8PFJet500
	HLT_AK8PFJet400_TrimMass30
	HLT_DiJet110_35_Mjj650_PFMET110
	HLT_PFHT800_PFMET75_PFMHT75_IDTight
	HLT_PFHT700_PFMET85_PFMHT85_IDTight
	HLT_PFHT500_PFMET100_PFMHT100_IDTight
	HLT_PFHT1050
	HLT_PFJet500
	HLT_PFMET120_PFMHT120_IDTight
	HLT_PFMET250_HBHECleaned
	HLT_PFMET200_HBHE_BeamHaloCleaned
	HLT_PFMETTypeOne140_PFMHT140_IDTight
	HLT_PFMETTypeOne200_HBHE_BeamHaloCleaned
	HLT_TripleJet110_35_35_Mjj650_PFMET110

Trigger efficiency in ee events

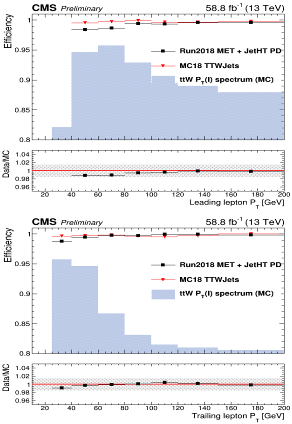
2016



2017



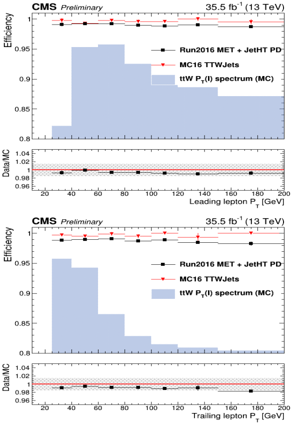
2018



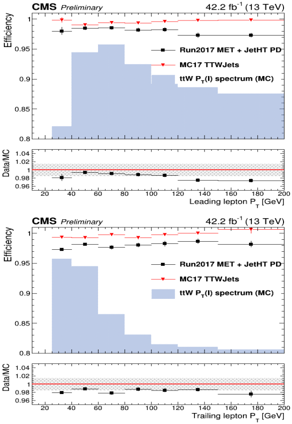
Data and MC agree within 1.5% in 2016 and 2018, while for 2017 the agreement is still within 2% A trigger systematic uncertainty of 1.5% is assigned to 2016 and 2018 and 2% to 2017

Trigger efficiency in $\mu\mu$ events

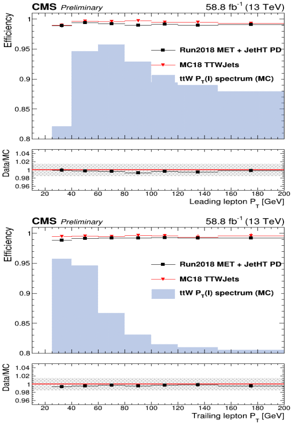
2016



2017



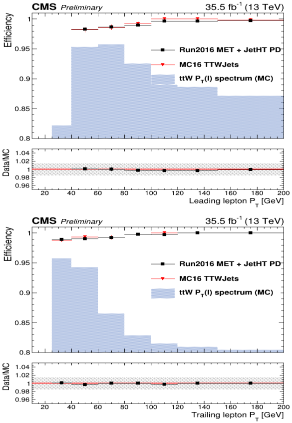
2018



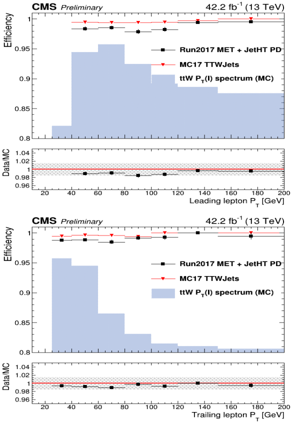
Trigger efficiency in $e\mu$ events

Leading electron and trailing muon

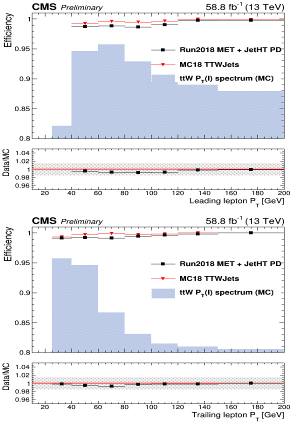
2016



2017



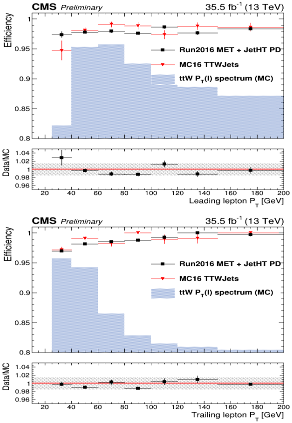
2018



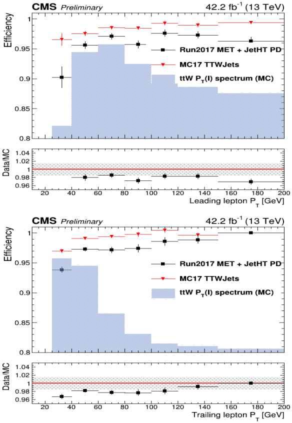
Trigger efficiency in μe events

Leading muon and trailing electron

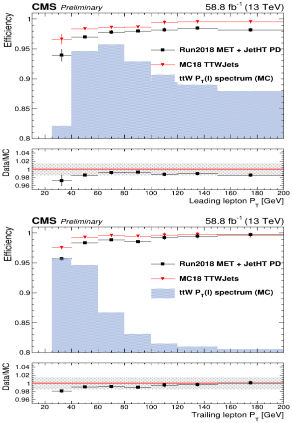
2016



2017



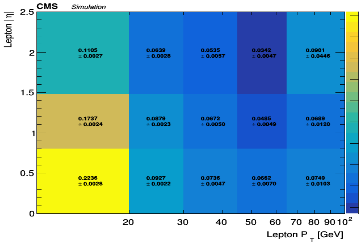
2018

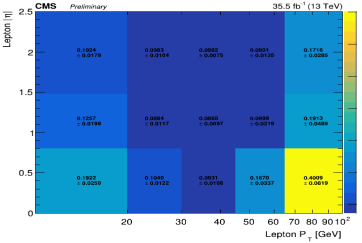


Fake rate - 2016

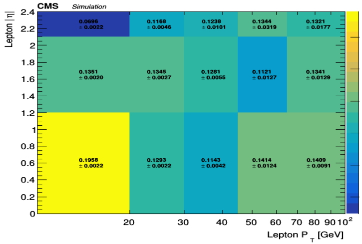
Top: from QCD MC, bottom: data driven

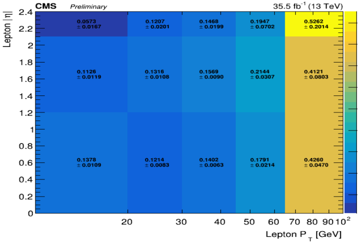
Electron





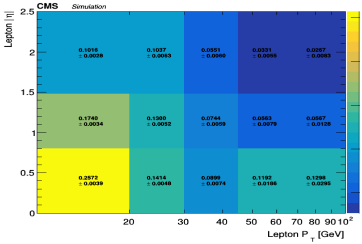
Muon



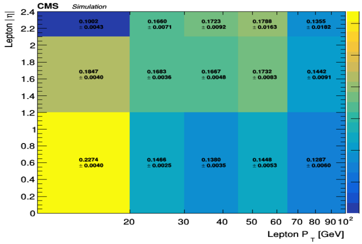


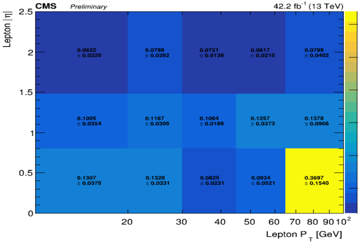
Top: from QCD MC, bottom: data driven

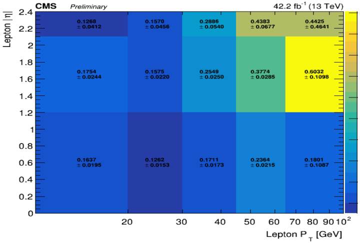
Electron



Muon







Fake rate - 2018

Top: from QCD MC, bottom: data driven

Electron

Muon